

# SM Precision Physics

Jonas M. Lindert

US

University of Sussex

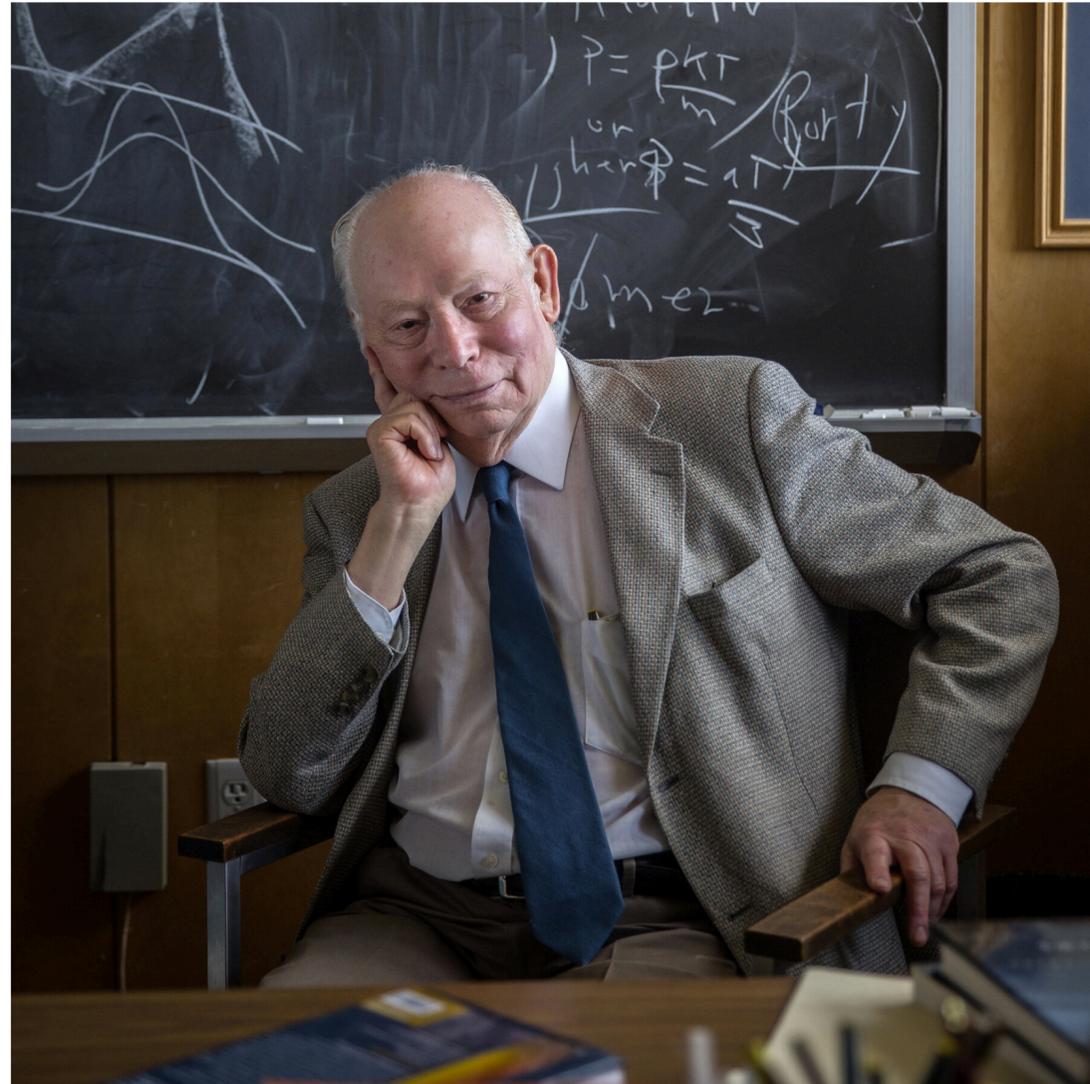


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# In memory of Steven Weinberg



<sup>11</sup> In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

<sup>12</sup>M. Ademollo and R. Gatto, *Nuovo Cimento* 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, *Phys. Rev. Letters* 17, 888 (1966).

<sup>13</sup>The predicted ratio [eq. (12)] from the current algebra

is slightly larger than that (0.23%) obtained from the  $\rho$ -dominance model of Ref. 2. This seems to be true also in the other case of the ratio  $\Gamma(\eta \rightarrow \pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$  calculated in Refs. 12 and 14.

<sup>14</sup>L. M. Brown and P. Singer, *Phys. Rev. Letters* 8, 460 (1962).

## A MODEL OF LEPTONS\*

Steven Weinberg†

Laboratory for Nuclear Science and Physics Department,  
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite<sup>1</sup> these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We

and on a right-handed singlet

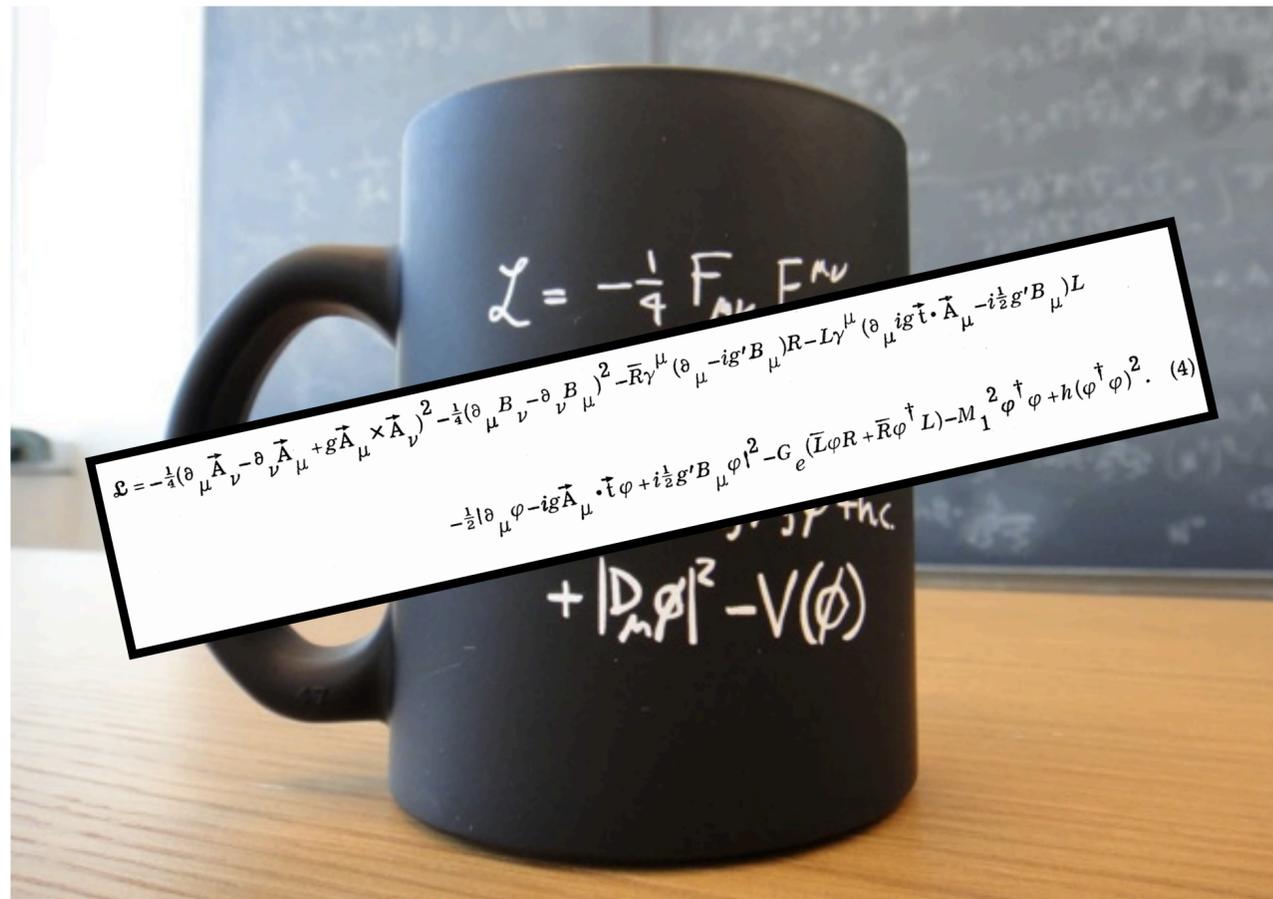
$$R \equiv [\frac{1}{2}(1-\gamma_5)]e. \quad (2)$$

The largest group that leaves invariant the kinematic terms  $-\bar{L}\gamma^\mu\partial_\mu L - \bar{R}\gamma^\mu\partial_\mu R$  of the Lagrangian consists of the electronic isospin  $\vec{T}$  acting on  $L$ , plus the numbers  $N_L, N_R$  of left- and

$$\mathcal{L} = -\frac{1}{4}(\partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g\vec{A}_\mu \times \vec{A}_\nu)^2 - \frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R}\gamma^\mu(\partial_\mu - ig'B_\mu)R - L\gamma^\mu(\partial_\mu + ig\vec{t} \cdot \vec{A}_\mu - i\frac{1}{2}g'B_\mu)L$$

$$- \frac{1}{2}|\partial_\mu \varphi - ig\vec{A}_\mu \cdot \vec{t}\varphi + i\frac{1}{2}g'B_\mu\varphi|^2 - G_e(\bar{L}\varphi R + \bar{R}\varphi^\dagger L) - M_1^2\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2. \quad (4)$$

# Theoretical Predictions for the LHC



$$\hookrightarrow |\mathcal{M}|^2 \curvearrowright \sigma$$

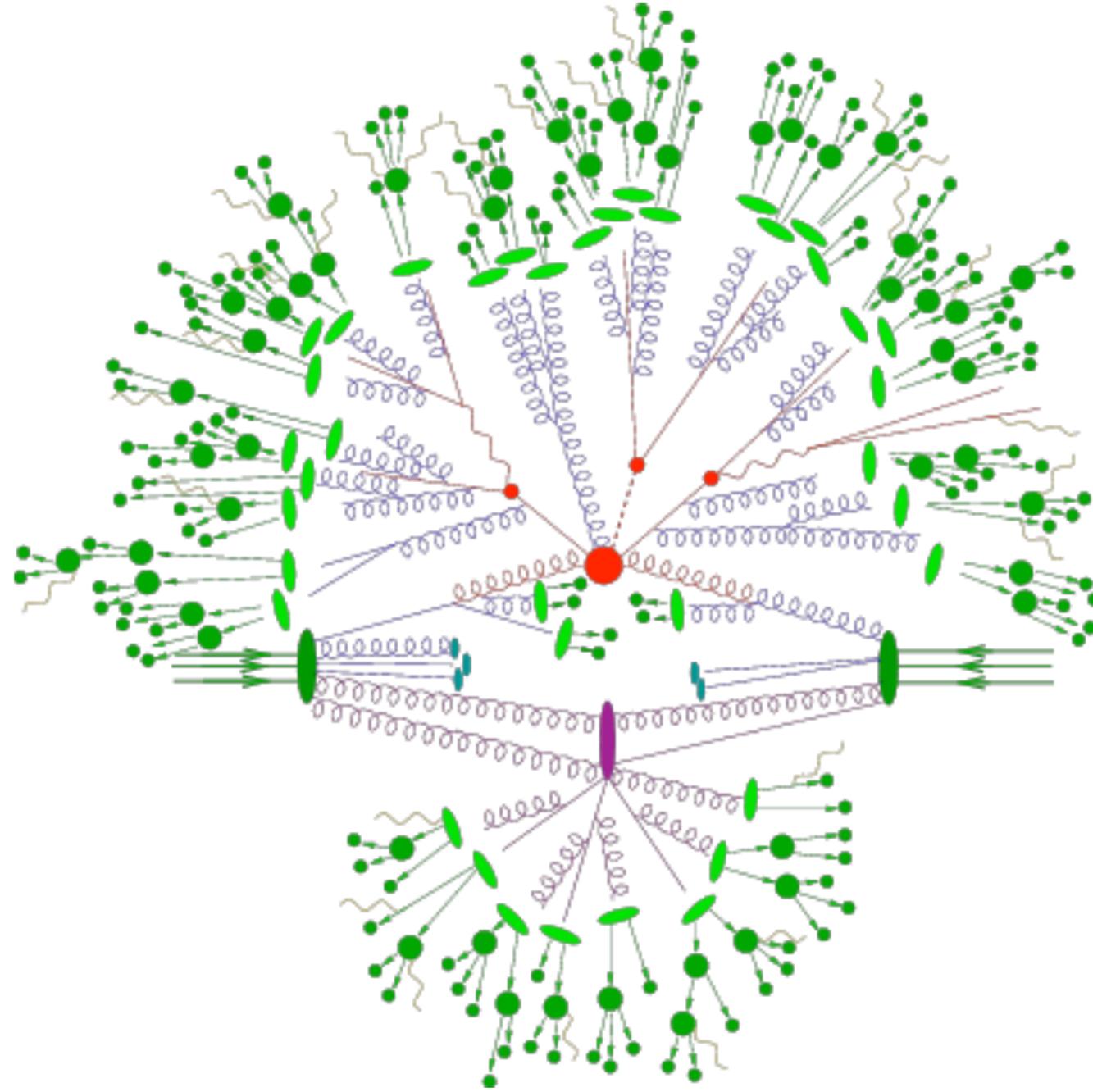
# Theoretical Predictions for the LHC

$$\begin{aligned}
\mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^b g_\mu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
& M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w (\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\nu^+)) - \\
& ig s_w (\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\mu W_\nu^- - \\
& W_\nu^- \partial_\mu W_\nu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\
& Z_\nu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
& \beta_h \left( \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^4} \alpha_h - \\
& g\alpha_h M (H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\
& \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
& gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \\
& \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
& \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
& M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - \\
& W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
& \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\
& \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
& g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_{ij}^a (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda (\gamma \partial + m_\nu^\lambda) \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + \\
& m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig s_w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + \\
& \frac{ig}{4c_w} Z_\mu^0 \{ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\
& (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 + \gamma^5) u_j^\lambda) \} + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)) + \\
& \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\kappa U^{lep}{}_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\
& \frac{ig}{2M\sqrt{2}} \phi^+ (-m_e^\kappa (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m_\nu^\lambda (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 + \gamma^5) e^\kappa) + \\
& \frac{ig}{2M\sqrt{2}} \phi^- (m_e^\lambda (\bar{e}^\lambda U^{lep}{}_{\lambda\kappa}^\dagger (1 + \gamma^5) \nu^\kappa) - m_\nu^\kappa (\bar{e}^\lambda U^{lep}{}_{\lambda\kappa}^\dagger (1 - \gamma^5) \nu^\kappa) - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
& \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa - \\
& \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \\
& \frac{ig}{2M\sqrt{2}} \phi^- (m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
& \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c + \\
& \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
& \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
& \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \\
& \partial_\mu \bar{X}^- X^+) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^- - \\
& \partial_\mu \bar{X}^- X^+) - \frac{1}{2}gM (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
& \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
& \frac{1}{2}igM (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) .
\end{aligned}$$

A diagram illustrating the relationship between the squared magnitude of the amplitude,  $|\mathcal{M}|^2$ , and the cross-section,  $\sigma$ . A large curved arrow points from the expression  $|\mathcal{M}|^2$  to the symbol  $\sigma$ .

# Theoretical Predictions for the LHC

$$\begin{aligned}
 \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- \\
 & - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w (\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)) - \\
 & ig s_w (\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\
 & Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
 & \beta_h \left( \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^4} \alpha_h - \\
 & g\alpha_h M (H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\
 & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
 & gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \\
 & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
 & \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
 & M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+)) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\
 & \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_{ij}^a (\bar{q}_i^\alpha \gamma^\mu q_j^\alpha) g_\mu^a - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda (\gamma \partial + m_\nu^\lambda) \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + \\
 & m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig s_w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + \\
 & \frac{ig}{4c_w} Z_\mu^0 \{ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 + \gamma^5) u_j^\lambda) \} + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)) + \\
 & \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\kappa U^{lep}{}_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_e^\kappa (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m_\nu^\kappa (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 + \gamma^5) e^\kappa) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_e^\lambda (\bar{e}^\lambda U^{lep}{}_{\lambda\kappa}^\dagger (1 + \gamma^5) \nu^\kappa) - m_\nu^\kappa (\bar{e}^\lambda U^{lep}{}_{\lambda\kappa}^\dagger (1 - \gamma^5) \nu^\kappa) - \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa - \\
 & \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c + \\
 & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
 & \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
 & \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \\
 & \partial_\mu \bar{X}^- X^+) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^- - \\
 & \partial_\mu \bar{X}^- X^+) - \frac{1}{2}gM (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
 & \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
 & \frac{1}{2}igM (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) .
 \end{aligned}$$



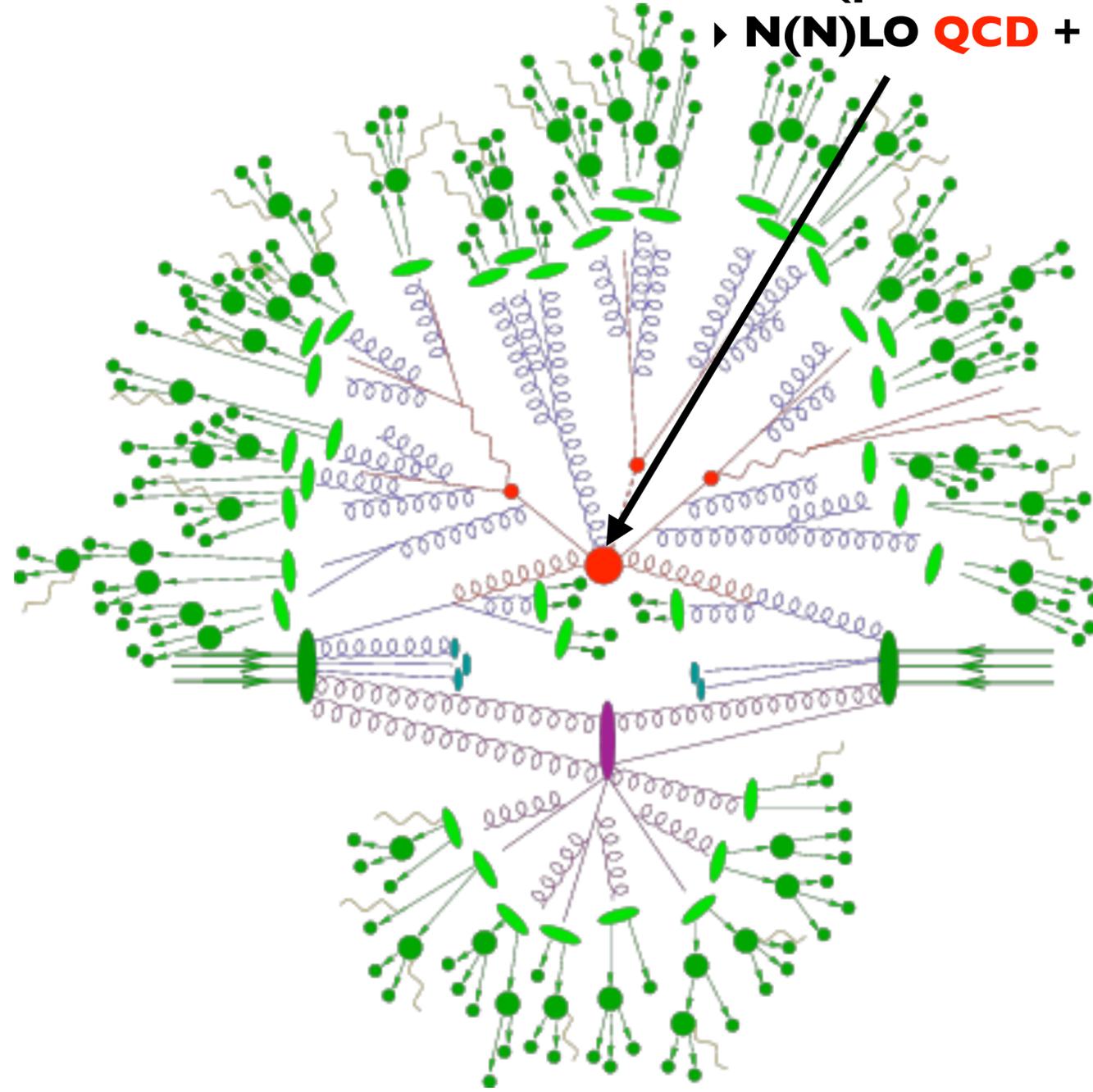
$$\curvearrowright |\mathcal{M}|^2 \curvearrowleft \sigma$$

# Theoretical Predictions for the LHC

Hard (perturbative) scattering process

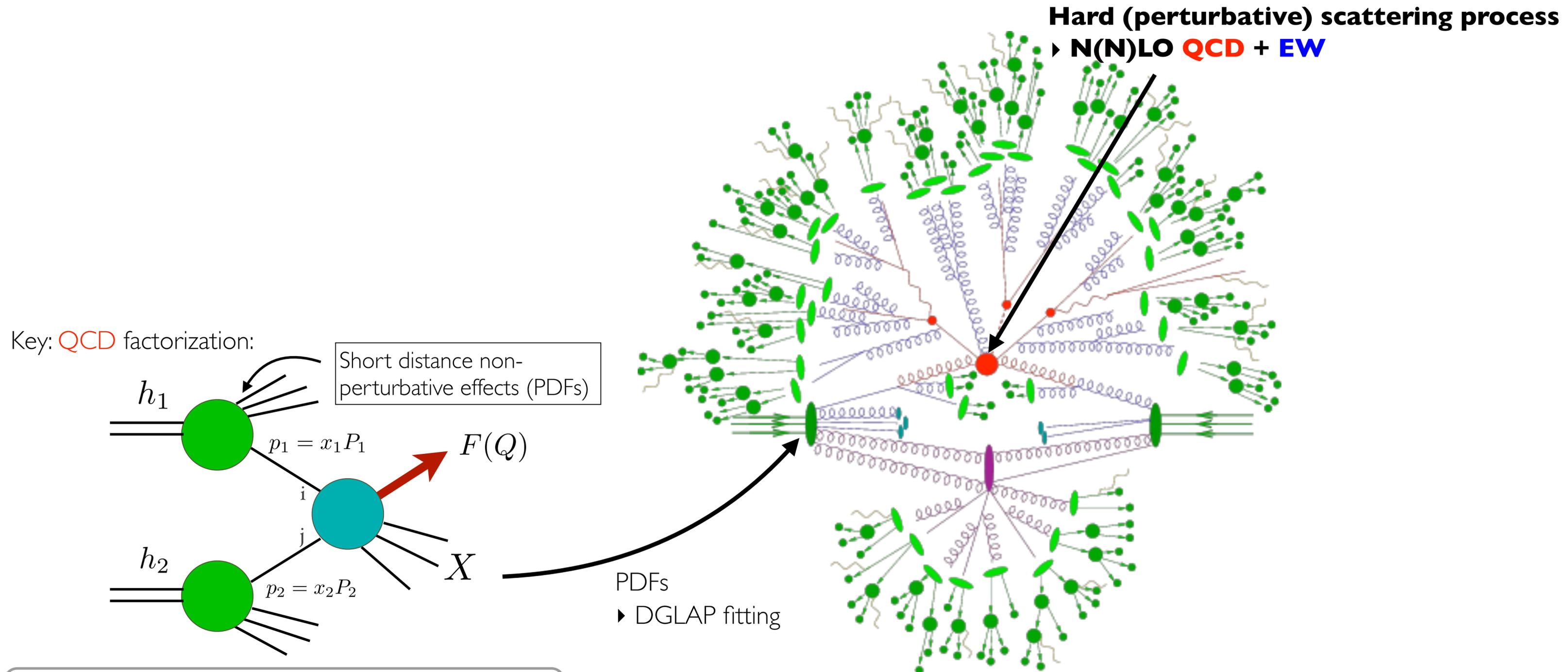
► **N(N)LO QCD + EW**

$$\begin{aligned}
 \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- \\
 & - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w (\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\nu^0 (W_\nu^+ \partial_\mu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+)) - \\
 & ig s_w (\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\
 & Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
 & \beta_h \left( \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^4} \alpha_h - \\
 & g \alpha_h M (H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-) - \\
 & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \\
 & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
 & \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
 & M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+)) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\
 & \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_{ij}^a (\bar{q}_i^c \gamma^\mu q_j^c) g_\mu^a - \bar{e}^\lambda (\gamma \partial + m_e) e^\lambda - \bar{\nu}^\lambda (\gamma \partial + m_\nu) \nu^\lambda - \bar{u}_j^c (\gamma \partial + \\
 & m_u) u_j^c - \bar{d}_j^c (\gamma \partial + m_d) d_j^c + ig s_w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^c \gamma^\mu u_j^c) - \frac{1}{3}(\bar{d}_j^c \gamma^\mu d_j^c) + \\
 & \frac{ig}{4c_w} Z_\mu^0 \{ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^c \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) d_j^c) + \\
 & (\bar{u}_j^c \gamma^\mu (1 - \frac{8}{3}s_w^2 + \gamma^5) u_j^c) \} + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}_j^c \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^c)) + \\
 & \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\kappa U^{lep}{}_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^c C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^c)) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_e^\kappa (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m_\nu^\kappa (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 + \gamma^5) e^\kappa) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_e^\lambda (\bar{e}^\lambda U^{lep}{}_{\lambda\kappa}^\dagger (1 + \gamma^5) \nu^\kappa) - m_\nu^\kappa (\bar{e}^\lambda U^{lep}{}_{\lambda\kappa}^\dagger (1 - \gamma^5) \nu^\kappa) - \frac{g}{2} \frac{m_\lambda}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\lambda}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\lambda}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa - \\
 & \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_d^\kappa (\bar{u}_j^c C_{\lambda\kappa} (1 - \gamma^5) d_j^c) + m_u^\kappa (\bar{u}_j^c C_{\lambda\kappa} (1 + \gamma^5) d_j^c)) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_d^\lambda (\bar{d}_j^c C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^c) - m_u^\kappa (\bar{d}_j^c C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^c)) - \frac{g}{2} \frac{m_\lambda}{M} H (\bar{u}_j^c u_j^c) - \\
 & \frac{g}{2} \frac{m_\lambda}{M} H (\bar{d}_j^c d_j^c) + \frac{ig}{2} \frac{m_\lambda}{M} \phi^0 (\bar{u}_j^c \gamma^5 u_j^c) - \frac{ig}{2} \frac{m_\lambda}{M} \phi^0 (\bar{d}_j^c \gamma^5 d_j^c) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c + \\
 & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
 & \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
 & \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \\
 & \partial_\mu \bar{X}^- X^+) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^- - \\
 & \partial_\mu \bar{X}^- X^+) - \frac{1}{2}gM (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
 & \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
 & \frac{1}{2}igM (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) .
 \end{aligned}$$



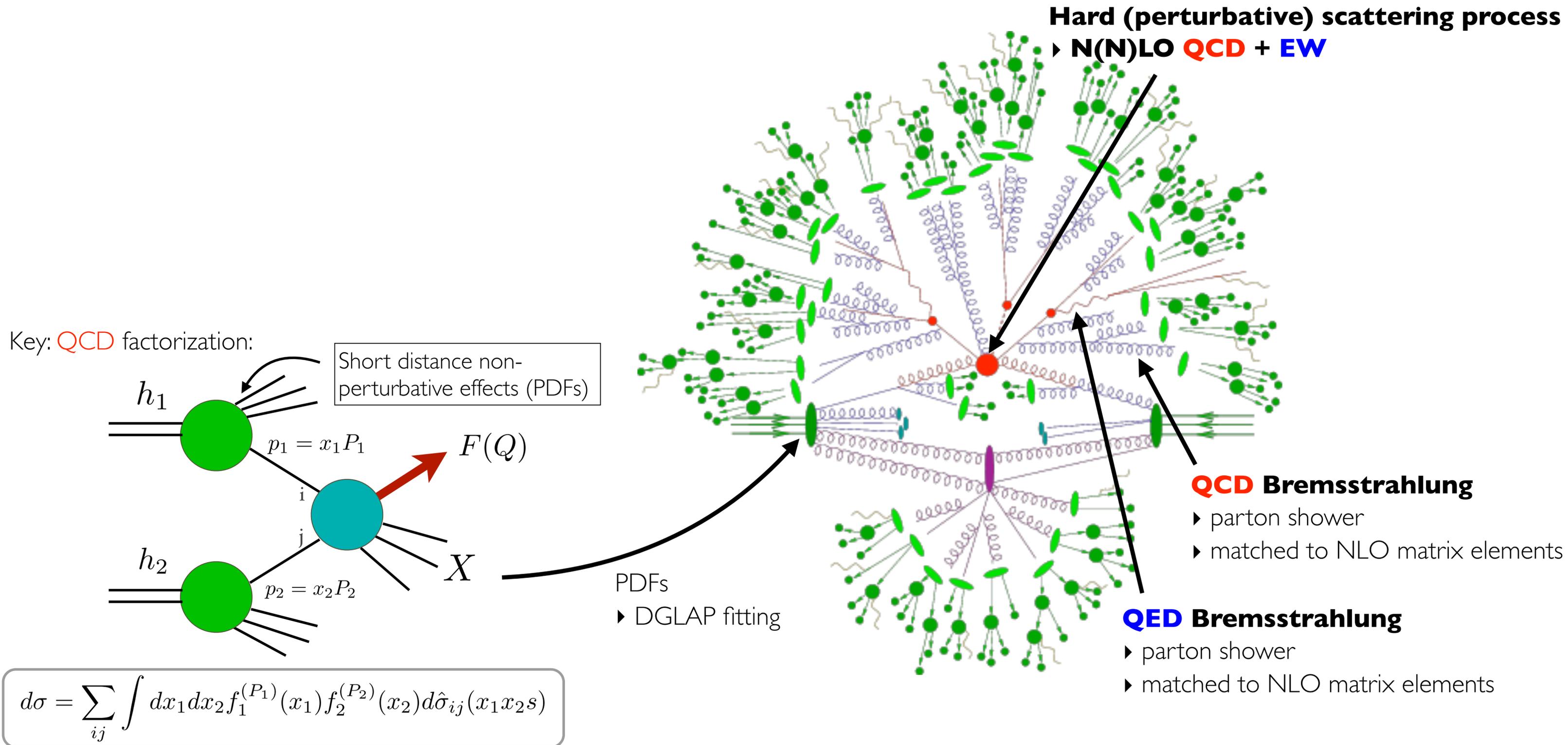
$$\curvearrowright |\mathcal{M}|^2 \curvearrowleft \sigma$$

# Theoretical Predictions for the LHC

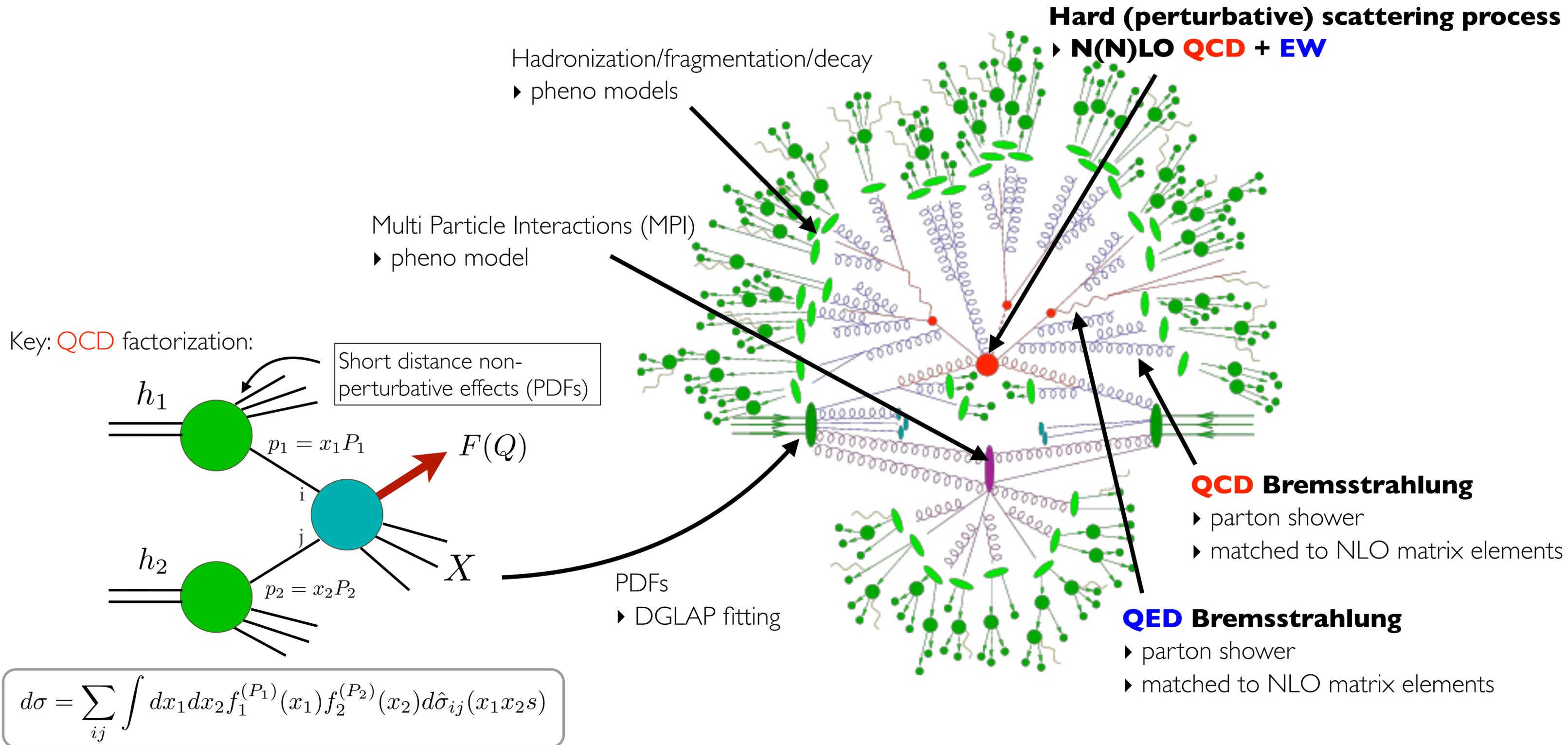


$$d\sigma = \sum_{ij} \int dx_1 dx_2 f_1^{(P_1)}(x_1) f_2^{(P_2)}(x_2) d\hat{\sigma}_{ij}(x_1 x_2 s)$$

# Theoretical Predictions for the LHC



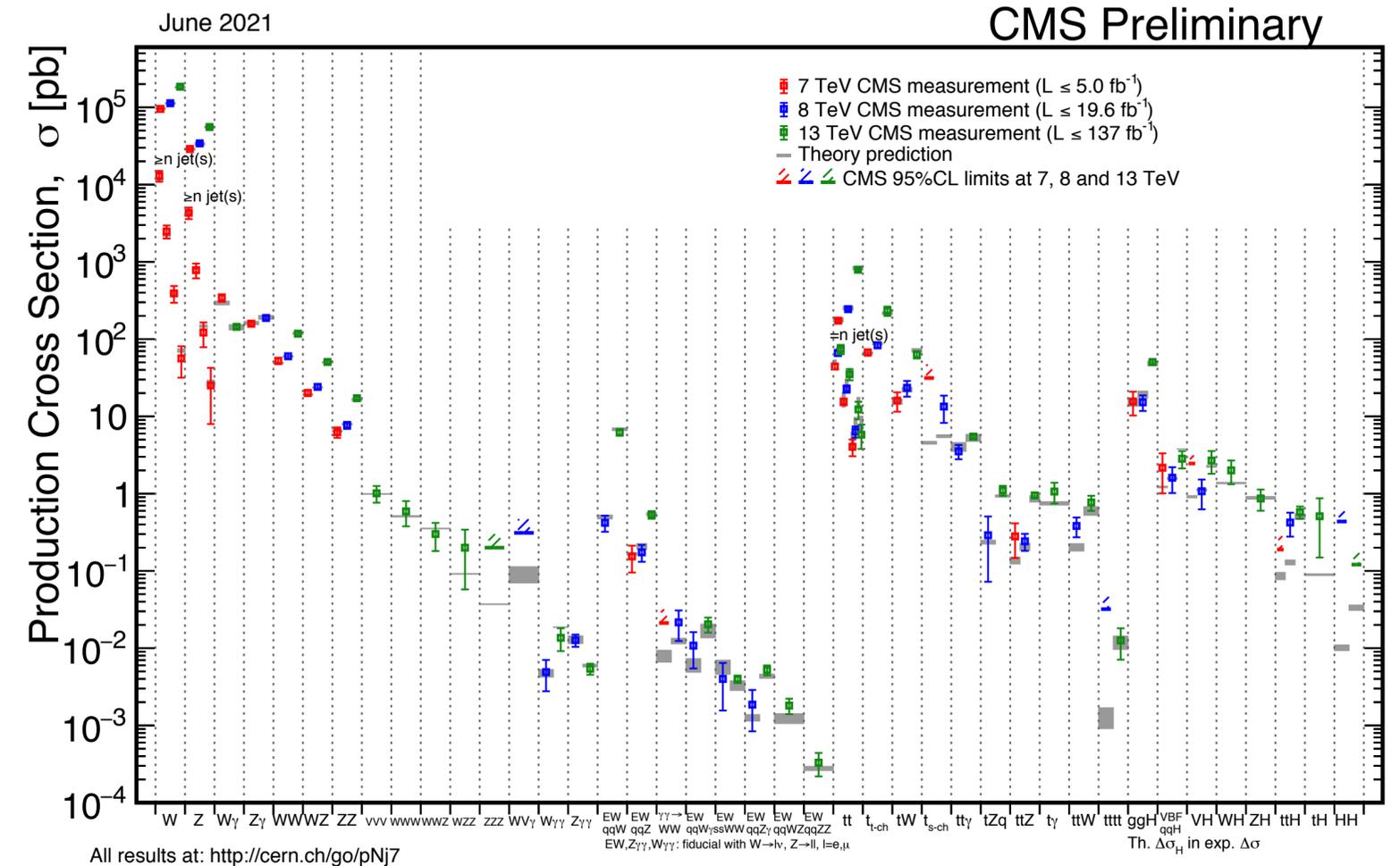
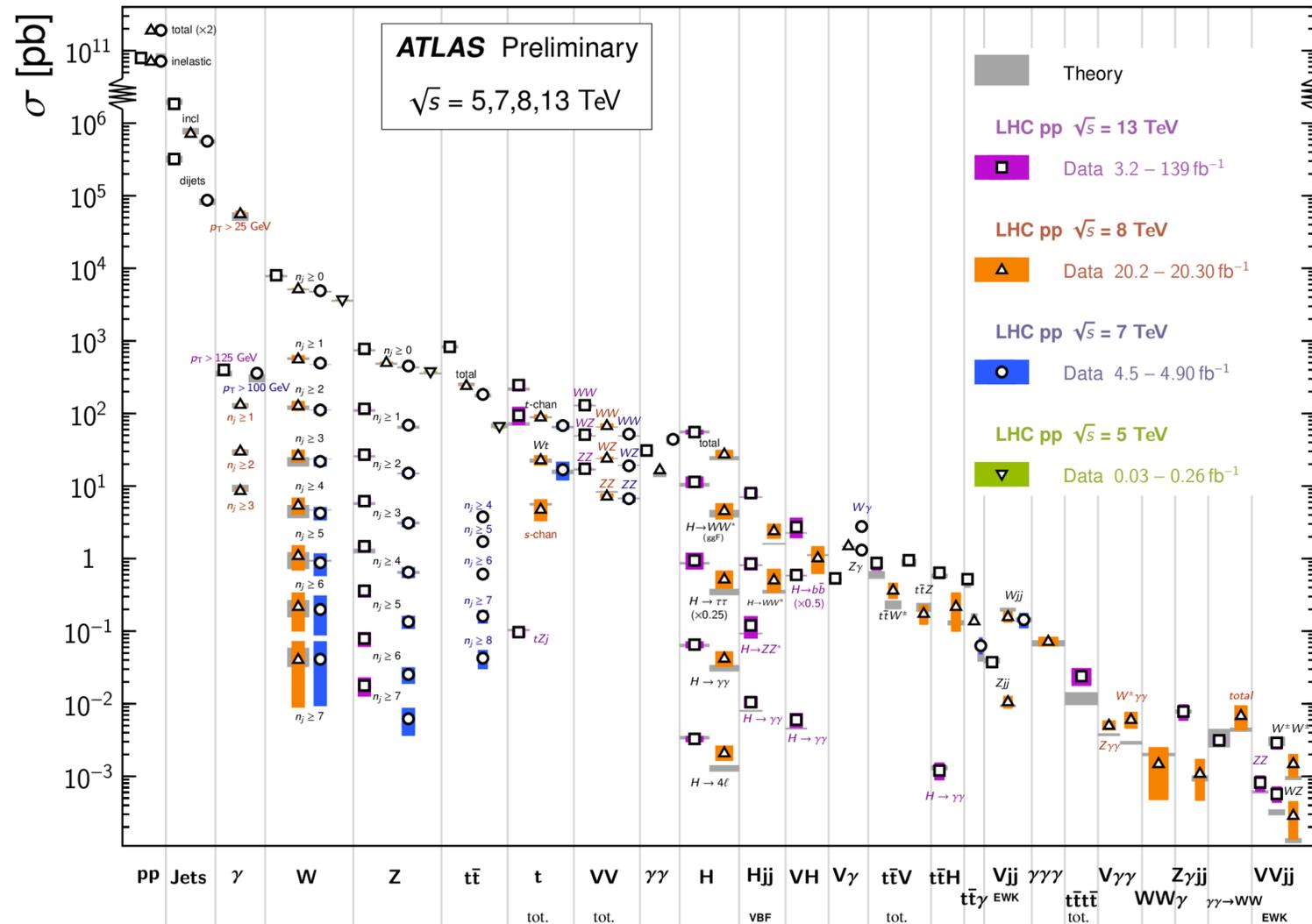
# Theoretical Predictions for the LHC



# Success of Run-I & Run-II of the LHC

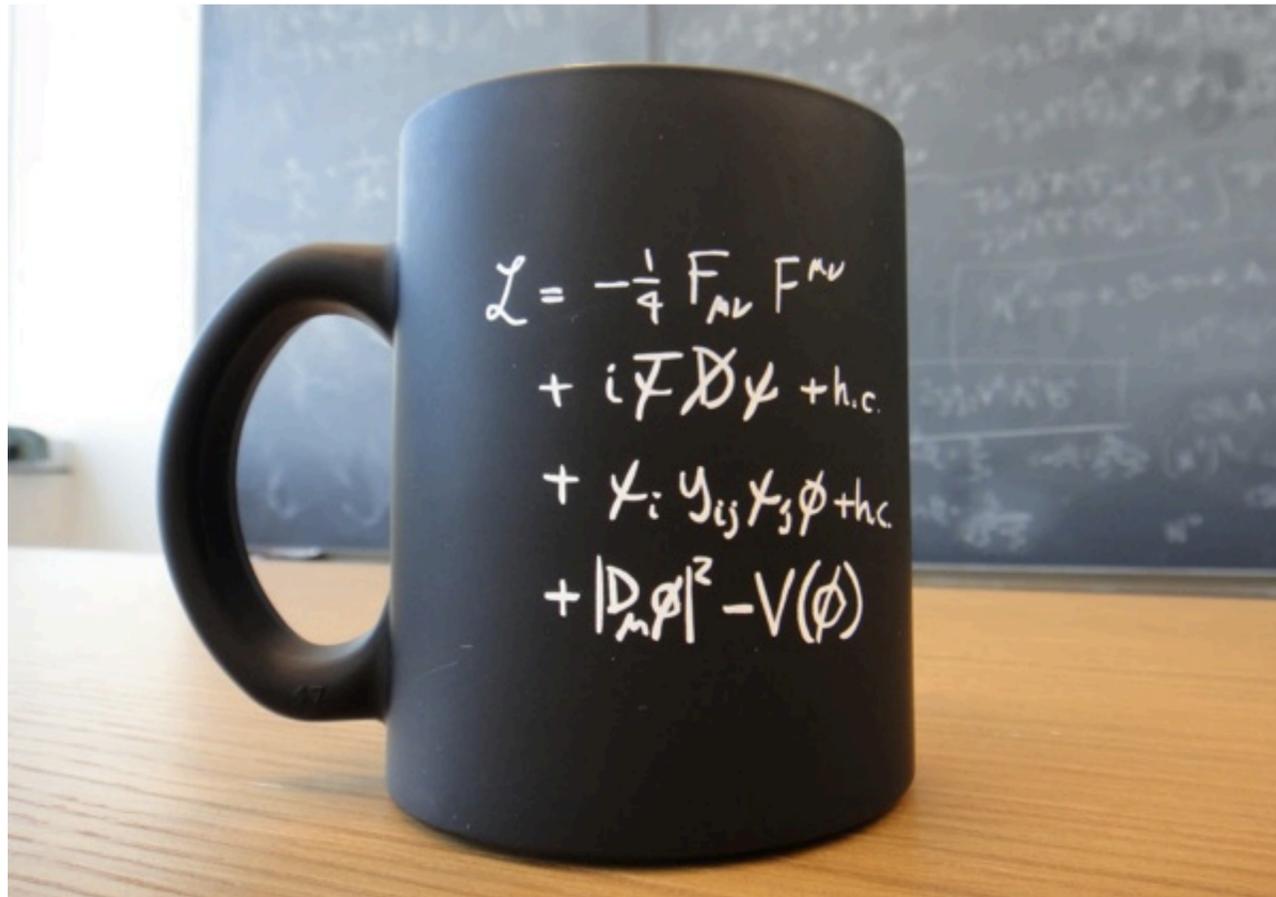
Standard Model Production Cross Section Measurements

Status: March 2021



Overall remarkable data vs. theory agreement  
 ➔ Precision tests of the SM at the quantum level in a multitude of processes

# With the discovery of the Higgs the SM is 'complete'



## Standard Model of Elementary Particles

		three generations of matter (fermions)				
		I	II	III		
mass		$\approx 2.4 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 172.44 \text{ GeV}/c^2$	0	$\approx 125.09 \text{ GeV}/c^2$
charge		$2/3$	$2/3$	$2/3$	0	0
spin		$1/2$	$1/2$	$1/2$	1	0
		<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> Higgs
	<b>QUARKS</b>	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
		$-1/3$	$-1/3$	$-1/3$	0	
		$1/2$	$1/2$	$1/2$	1	
		<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>\gamma</b> photon	
		$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.67 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
		-1	-1	-1	0	
		$1/2$	$1/2$	$1/2$	1	
		<b>e</b> electron	<b>\mu</b> muon	<b>\tau</b> tau	<b>Z</b> Z boson	
	<b>LEPTONS</b>	$< 2.2 \text{ eV}/c^2$	$< 1.7 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
		0	0	0	$\pm 1$	
		$1/2$	$1/2$	$1/2$	1	
		<b>\nu_e</b> electron neutrino	<b>\nu_\mu</b> muon neutrino	<b>\nu_\tau</b> tau neutrino	<b>W</b> W boson	
						<b>SCALAR BOSONS</b>
						<b>GAUGE BOSONS</b>

With the discovery of the Higgs the SM is 'complete'

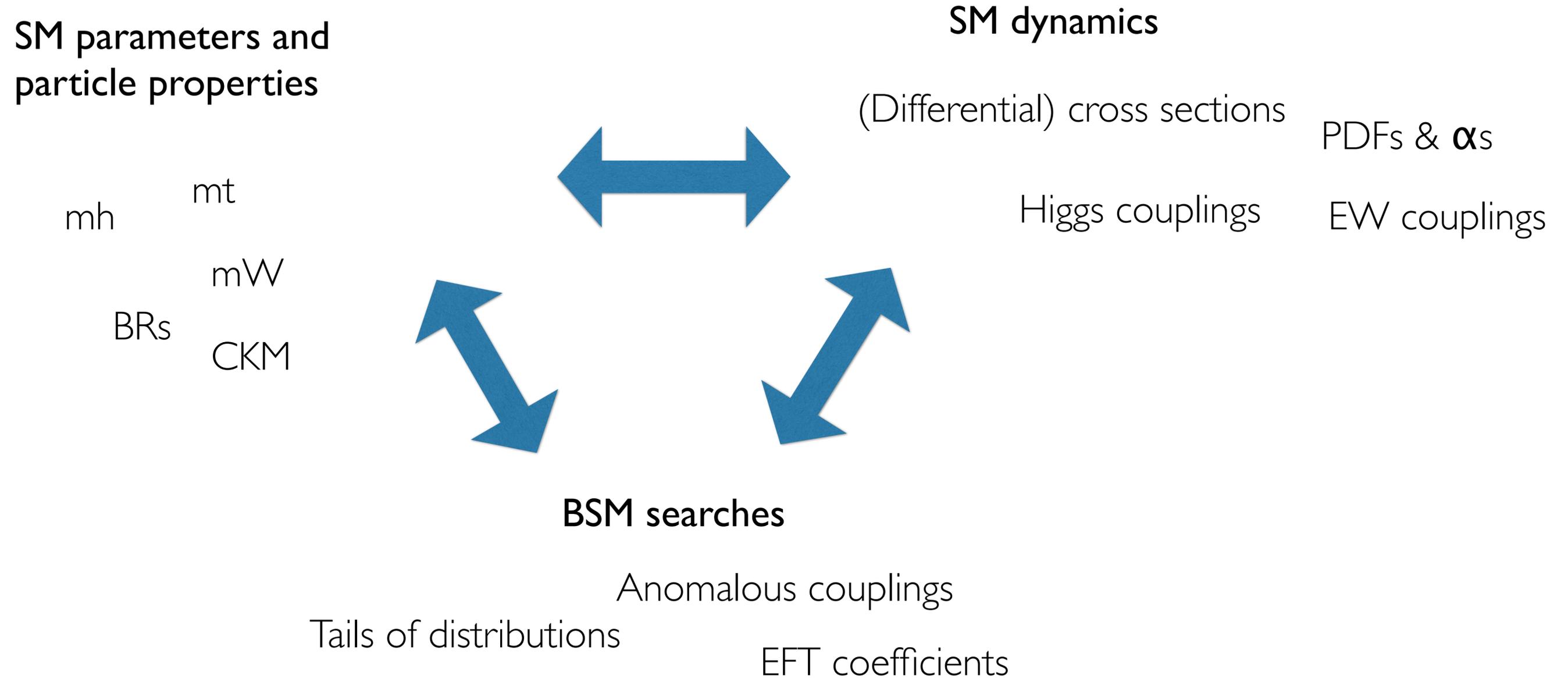
### Standard Model of Elementary Particles

		three generations of matter (fermions)				
		I	II	III		
mass		≈2.4 MeV/c <sup>2</sup>	≈1.275 GeV/c <sup>2</sup>	≈172.44 GeV/c <sup>2</sup>	0	≈125.09 GeV/c <sup>2</sup>
charge		2/3	2/3	2/3	0	0
spin		1/2	1/2	1/2	1	0
	<b>QUARKS</b>	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> Higgs
		≈4.8 MeV/c <sup>2</sup>	≈95 MeV/c <sup>2</sup>	≈4.18 GeV/c <sup>2</sup>	0	
		-1/3	-1/3	-1/3	0	
		1/2	1/2	1/2	1	
		<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>γ</b> photon	
		≈0.511 MeV/c <sup>2</sup>	≈105.67 MeV/c <sup>2</sup>	≈1.7768 GeV/c <sup>2</sup>	≈91.19 GeV/c <sup>2</sup>	
		-1	-1	-1	0	
		1/2	1/2	1/2	1	
	<b>LEPTONS</b>	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>Z</b> Z boson	
		<2.2 eV/c <sup>2</sup>	<1.7 MeV/c <sup>2</sup>	<15.5 MeV/c <sup>2</sup>	≈80.39 GeV/c <sup>2</sup>	
		0	0	0	±1	
		1/2	1/2	1/2	1	
		<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>W</b> W boson	
						<b>SCALAR BOSONS</b>
						<b>GAUGE BOSONS</b>

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \sum_i \bar{\psi}_i \gamma_3 \psi_i \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Is the 'nightmare scenario' becoming reality?

# Why do we need SM theory?

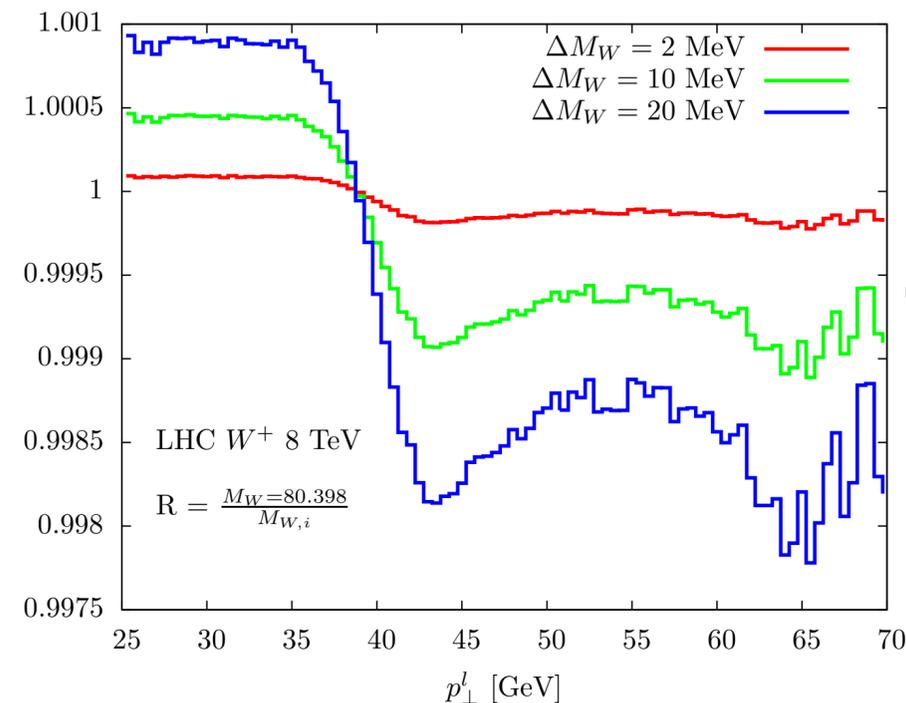
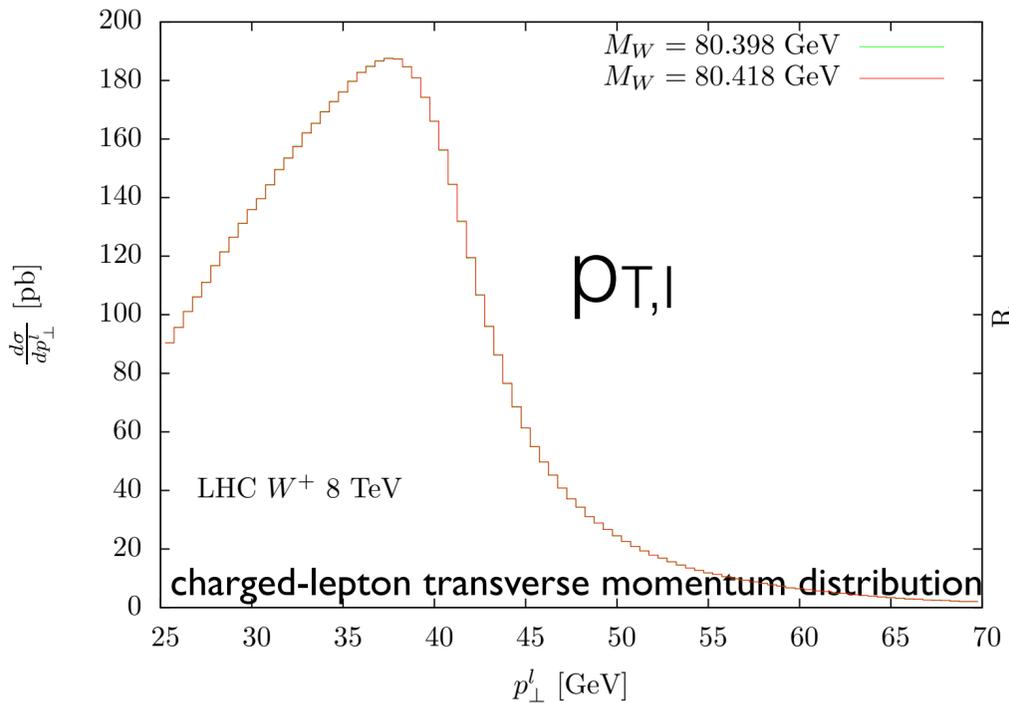


**This is not the 'nightmare scenario'.  
However, precision key!**

# Drell-Yan: $M_W$ measurements

- Motivation:  $M_W$  is a derived quantity  $\rightarrow$  precise measurement is a stringent test of SM!
- Method: **template fits** of sensitive CC DY distributions ( $p_{T,l}$ ,  $M_T$ ,  $E_{\text{miss}}$ )

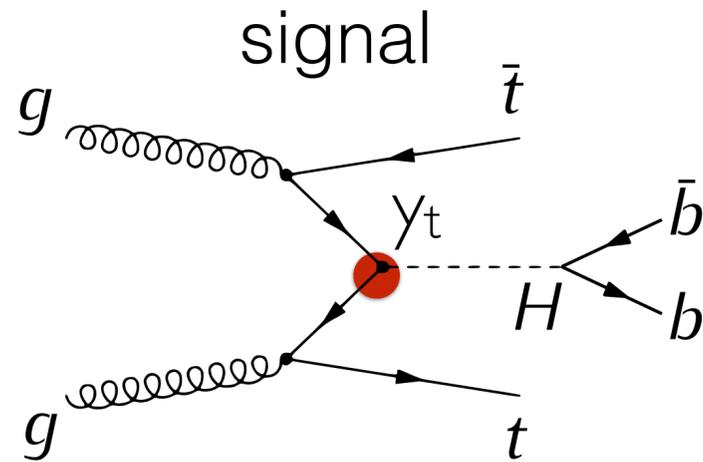
$$M_W = 80.385 \pm 0.015 \text{ GeV}$$



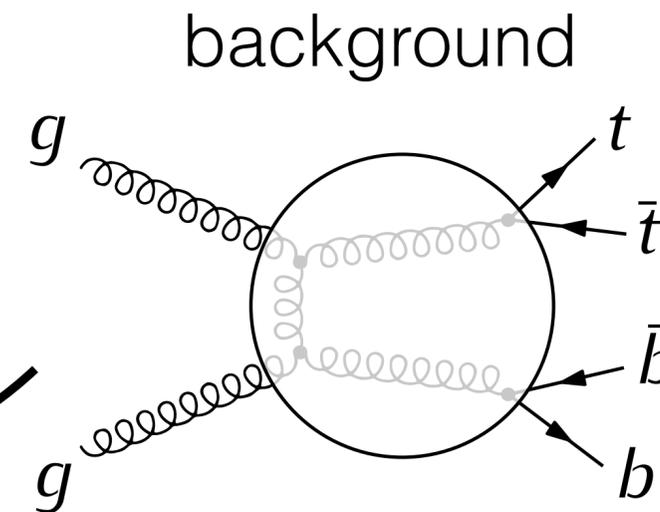
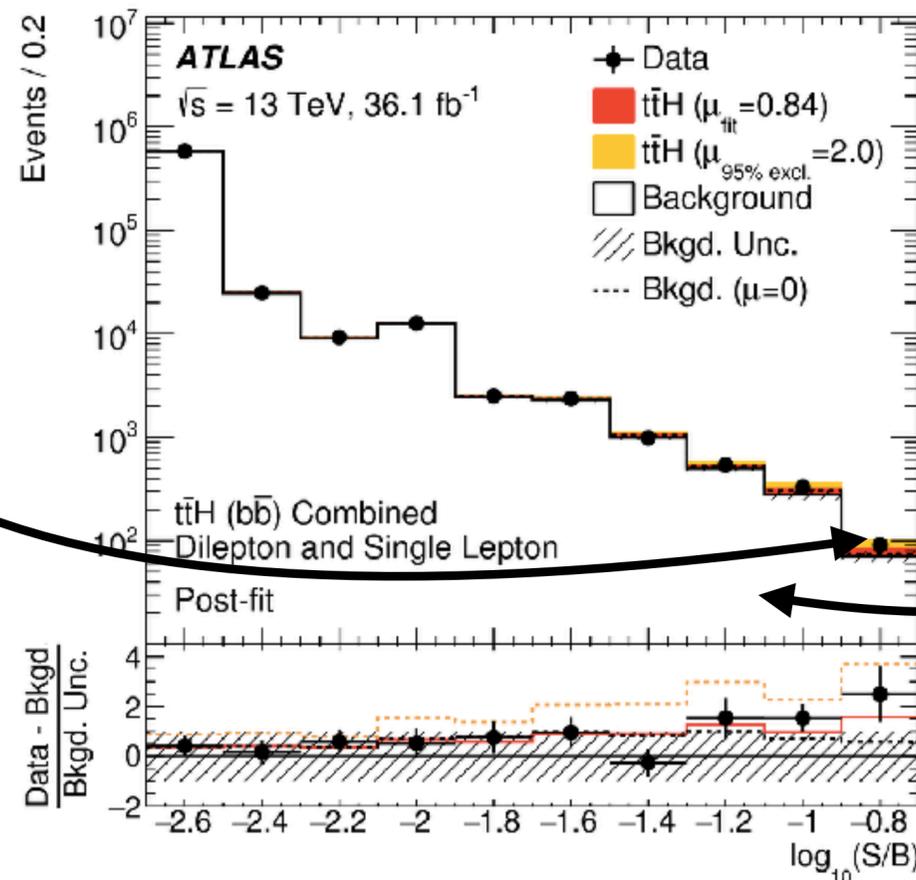
- Need to control shape effects at the sub-1% level!
- Dominant effects: **QCD** ISR and **QED** FSR

$\rightarrow$  Theory precision essential for improvements in  $m_W$  determination!

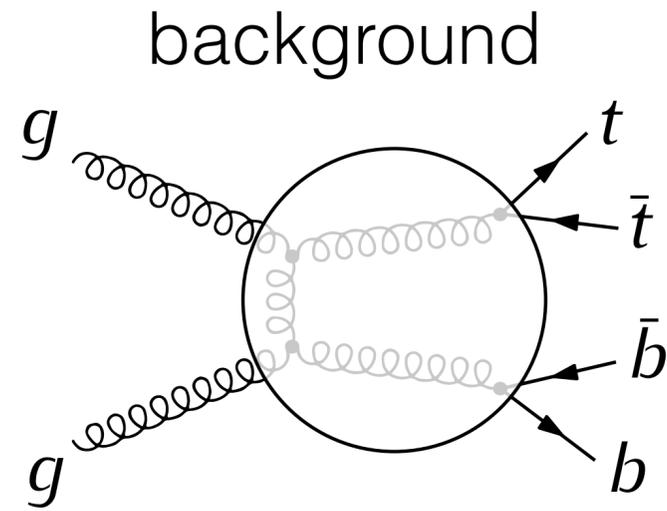
# Higgs couplings: $t\bar{t}b\bar{b}$ backgrounds to $t\bar{t}H(b\bar{b})$



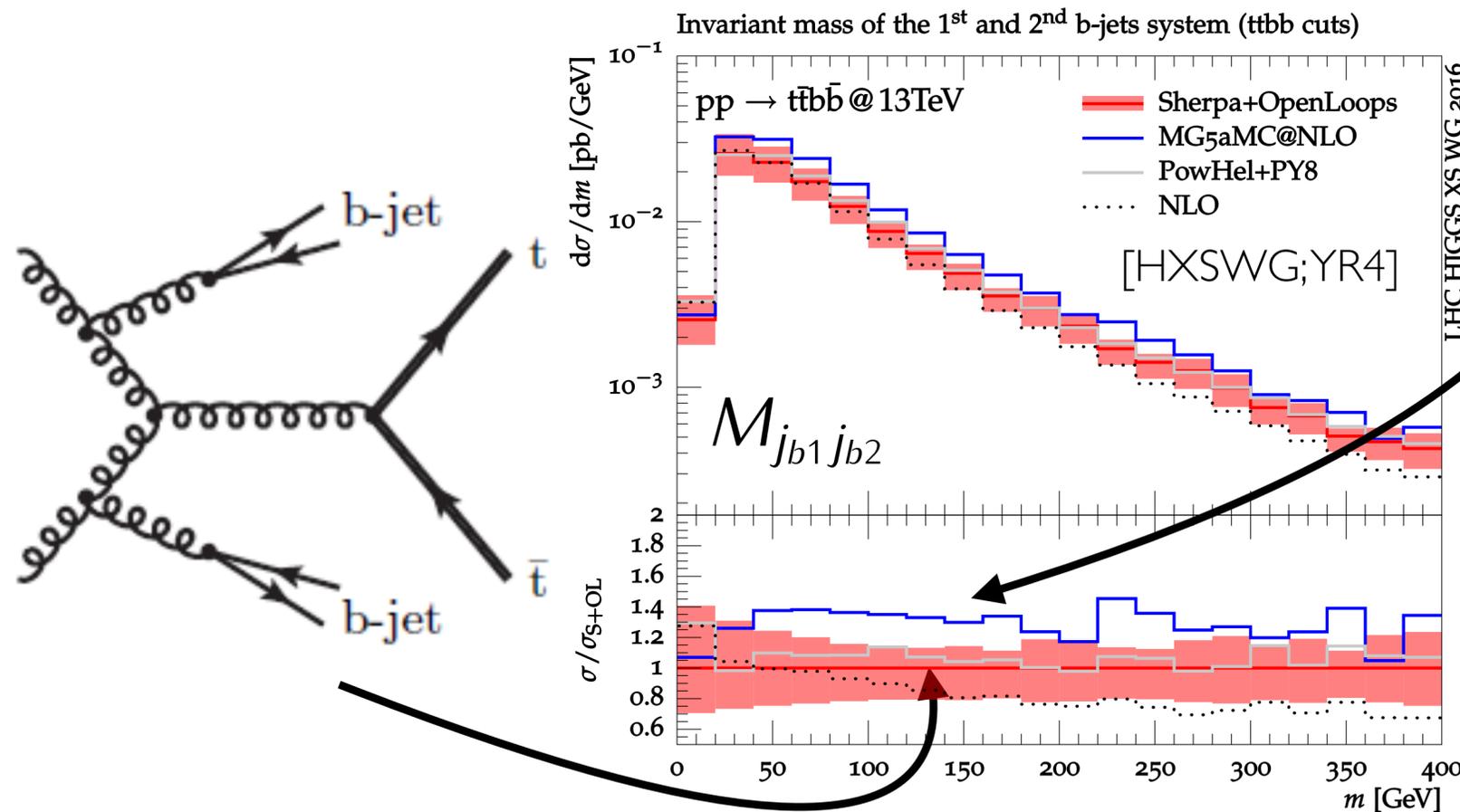
- ➔ direct probe of the top Yukawa coupling
- ➔ unfortunately very small cross section
- ➔ have to consider  $H \rightarrow b\bar{b}$  decay with large BR
- ➔ large QCD background:  $t\bar{t}+b$ -jets with sizeable uncertainties



# Higgs couplings: $t\bar{t}b\bar{b}$ backgrounds to $t\bar{t}H(b\bar{b})$



- ➔ in principle this process can be calculated out of the box at NLO+PS: NLO reduces scale uncertainties from 80% to 20-30%
- ➔ However: notoriously difficult multi-scale problem:  $ET_t, ET_{\bar{t}}, ET_b, ET_{\bar{b}}$
- ➔ Large shower effects, in particular from double  $g \rightarrow b\bar{b}$  splittings
- ➔ Large systematic uncertainties from parton shower matching



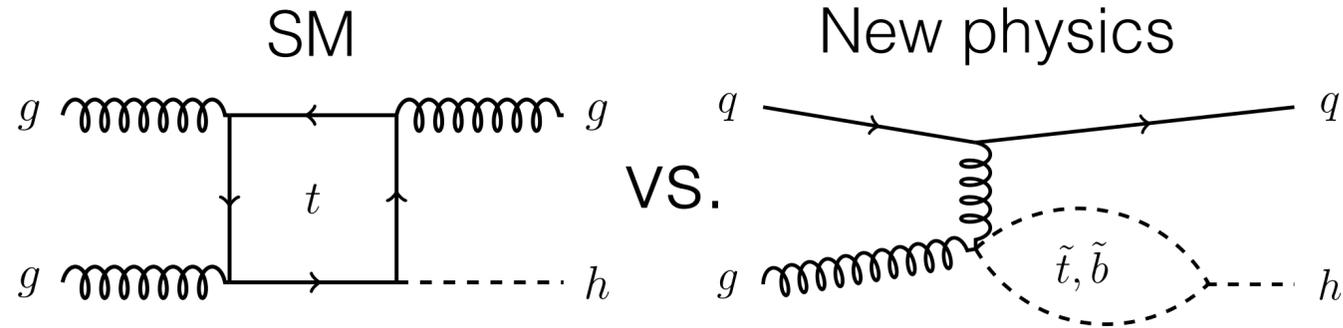
~20% in the signal region

→ Need to open NLO+PS black boxes

→ Need for revised theory systematics

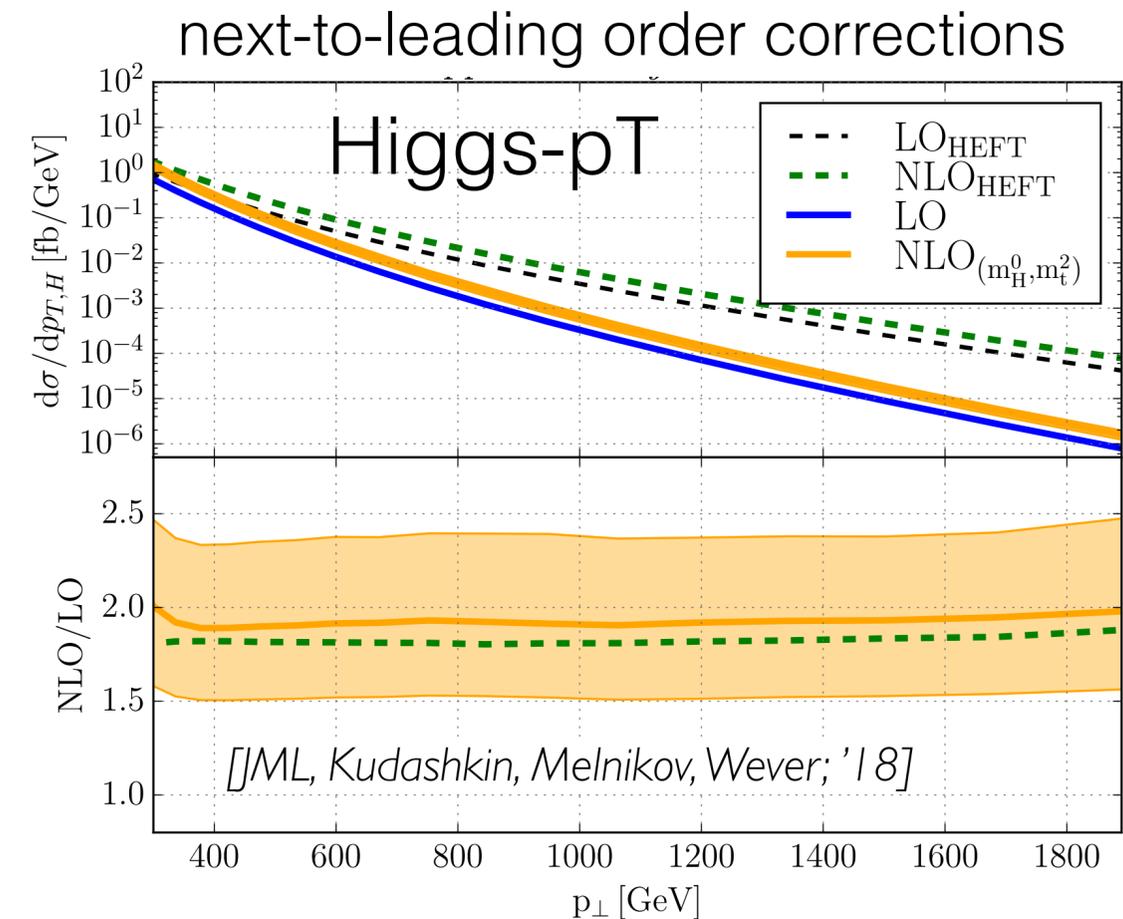
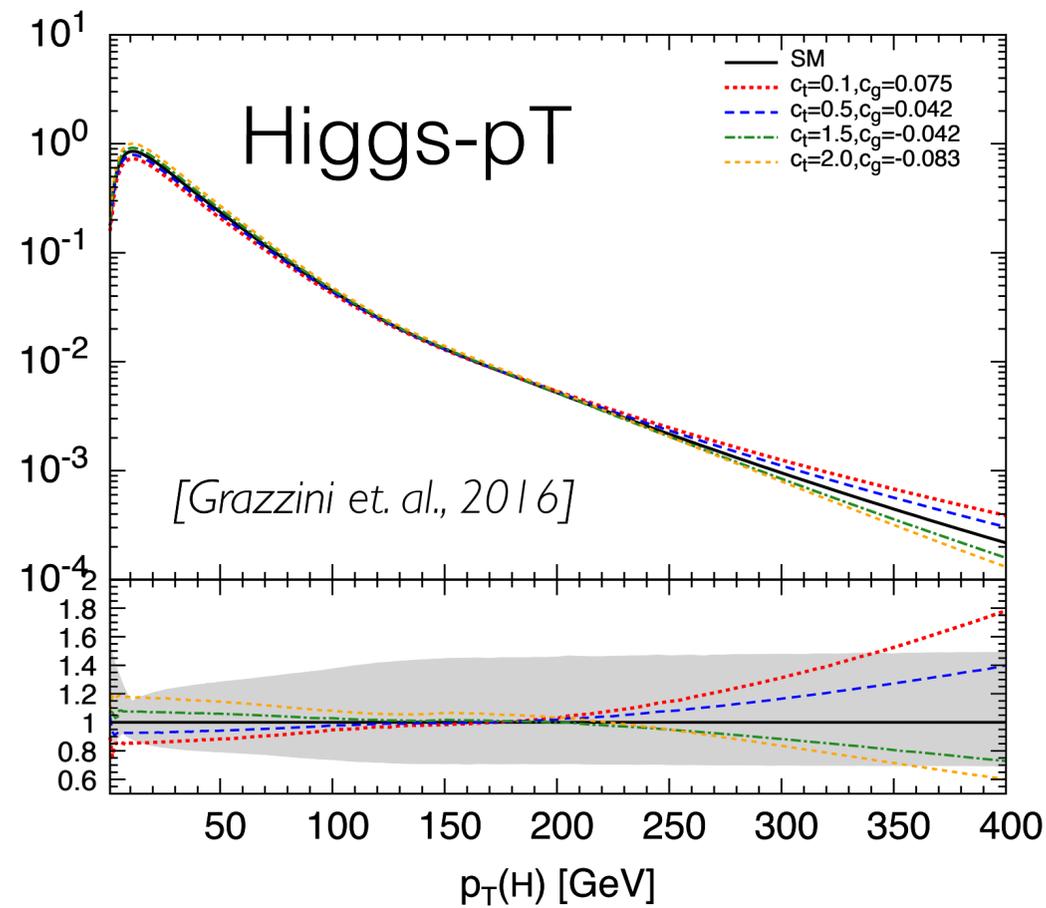
# Indirect searches: disentangling very small effects

e.g.



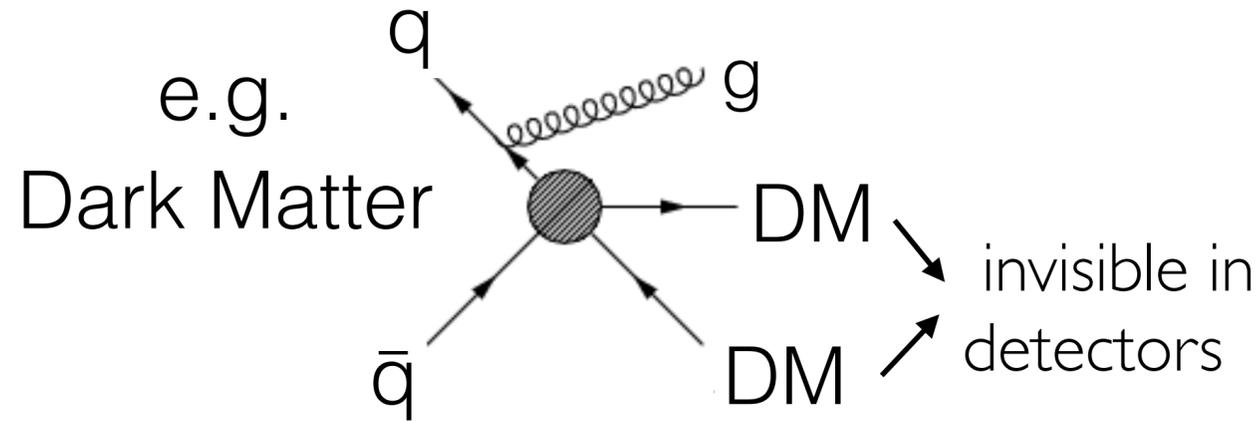
Look for BSM effects in small deviations from SM predictions:

- Higgs processes natural place to look at
- **very good control on theory necessary!**

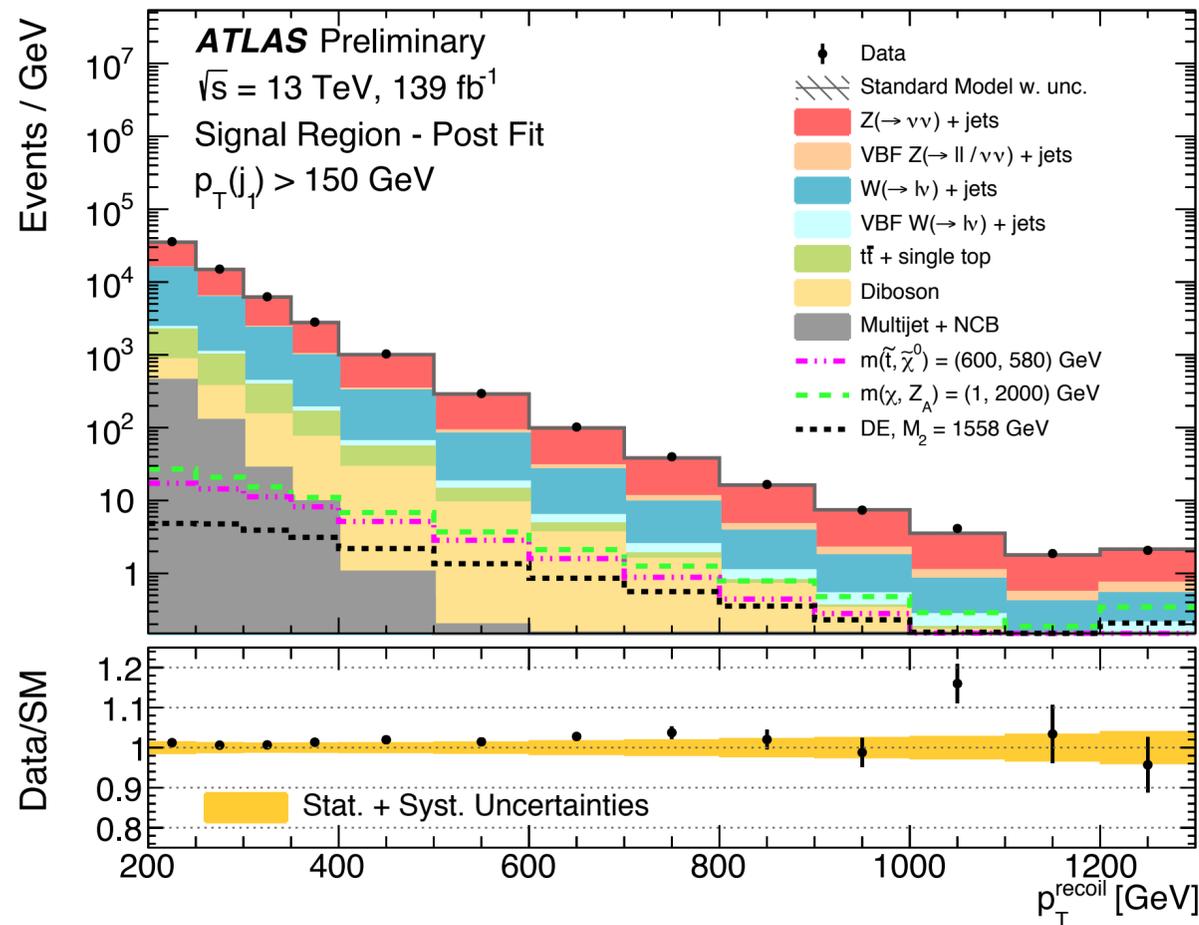
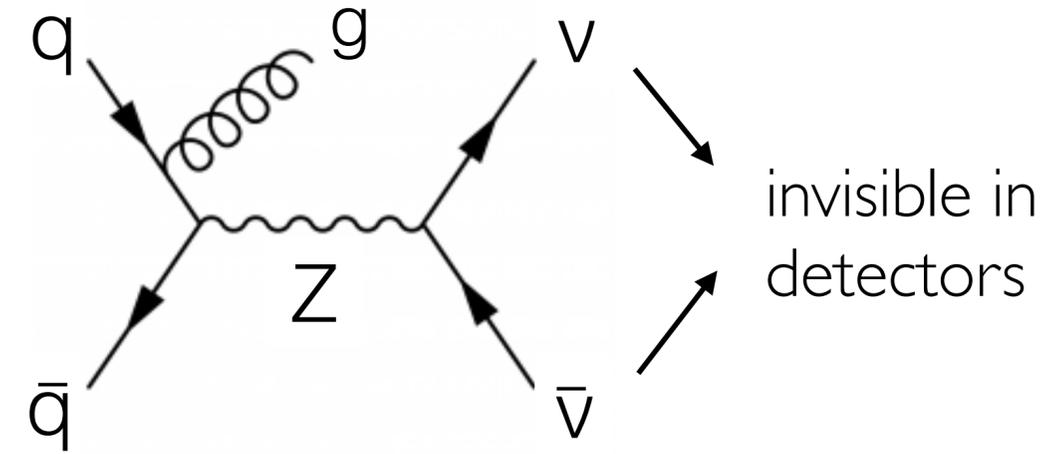


→ Theory precision opens the door to new analysis strategies!

# Direct searches for new physics: overwhelming SM backgrounds

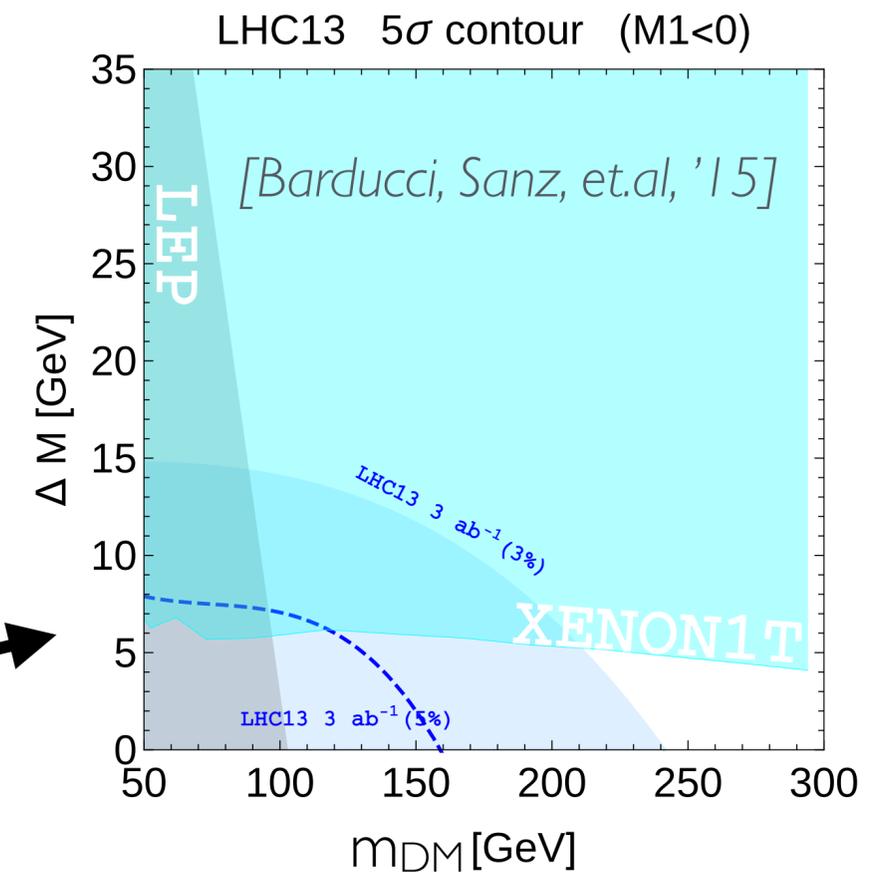


vs.



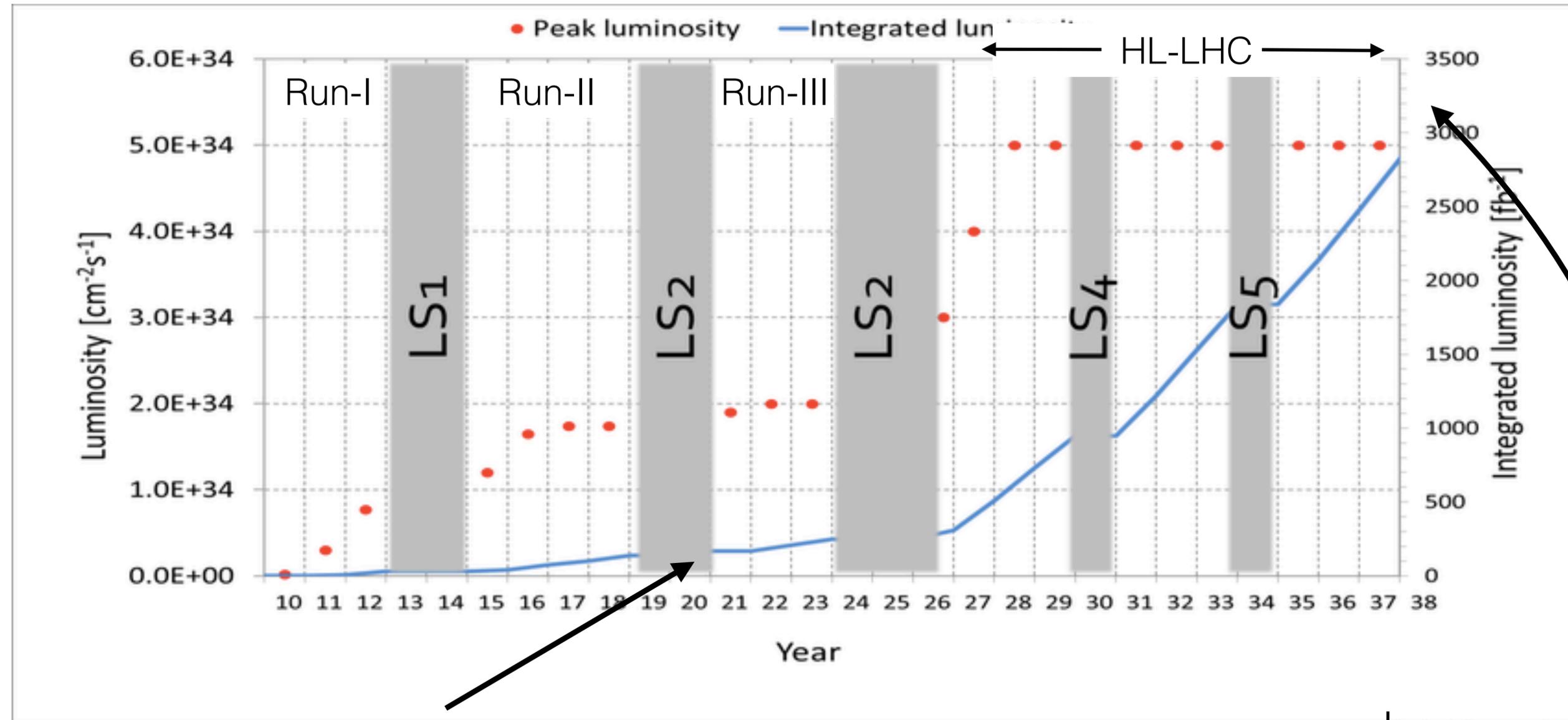
Thanks to state-of-the-art theory predictions+uncertainties for SM backgrounds [JML, et.al., '17]

few percent!



→ Theory precision is key to harness full potential of LHC data!

# Timescale of the LHC



we are here:  
 $L=150 \text{ fb}^{-1}$

where we are going:  
 $L=3000 \text{ fb}^{-1}$

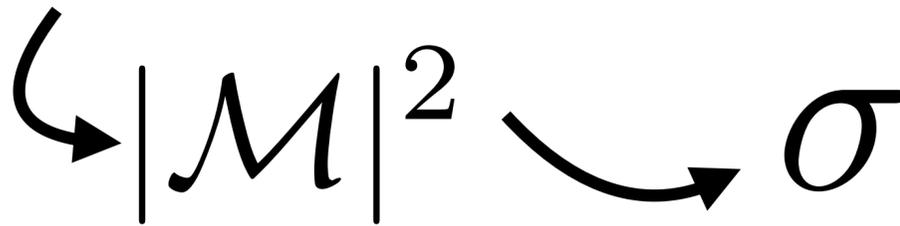
Experimental uncertainties will dramatically decrease in the future. Often reaching  $O(1\%)$ .

# Theoretical Predictions for the LHC

Hard (perturbative) scattering process:

$$d\sigma = d\sigma_{\text{LO}} + \alpha_S d\sigma_{\text{NLO}} + \alpha_S^2 d\sigma_{\text{NNLO}} + \alpha_S^3 d\sigma_{\text{N3LO}} + \dots$$

$$\begin{aligned} \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- \\ & - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2\alpha_h} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - ig_{c_w} (\partial_\nu W_\mu^+ W_\nu^- - \\ & W_\mu^+ \partial_\nu W_\nu^-) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+) + Z_\mu^0 (W_\mu^+ \partial_\nu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+) - \\ & ig_{s_w} (\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+) + A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\ & W_\nu^- \partial_\mu W_\mu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\ & Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\mu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\ & \beta_h \left( \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\ & \frac{g\alpha_h M}{2} (H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\ & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\ & g M W_\mu^+ W_\nu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\nu^0 H - \\ & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\nu^- (\phi^0 \partial_\nu \phi^+ - \phi^+ \partial_\nu \phi^0)) + \\ & \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\nu^- (H \partial_\nu \phi^+ - \phi^+ \partial_\nu H)) + \frac{1}{2}g \frac{M}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\ & M (\frac{1}{c_w} Z_\mu^0 \partial_\nu \phi^0 + W_\mu^+ \partial_\nu \phi^- + W_\nu^- \partial_\nu \phi^+) - ig \frac{M}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\nu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - \\ & W_\nu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\ & \frac{1}{4}g^2 W_\mu^+ W_\nu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\nu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\ & \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\nu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\nu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\ & W_\nu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\nu^- \phi^+) - g^2 \frac{2s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\nu \phi^+ \phi^- - \\ & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_{ij}^a (\bar{q}^i \gamma^\mu q^j) g_\mu^a - e^2 (\gamma^\partial + m_\nu^2) e^\lambda - \bar{\nu}^\lambda (\gamma^\partial + m_\nu^2) \nu^\lambda - \bar{u}_j^\lambda (\gamma^\partial + \\ & m_u^2) u_j^\lambda - \bar{d}_j^\lambda (\gamma^\partial + m_d^2) d_j^\lambda + ig s_w A_\mu (-e^2 \gamma^\mu e^\lambda + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)) + \\ & \frac{ig}{4c_w} Z_\mu^0 (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^2 \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{2}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\ & (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{2}{3}s_w^2 + \gamma^5) u_j^\lambda)) + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}{}_{\lambda e} e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda e} d_j^\lambda)) + \\ & \frac{ig}{2\sqrt{2}} W_\mu^- ((e^2 U^{lep}{}_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\ & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\nu^2 (\bar{\nu}^\lambda U^{lep}{}_{\lambda e} (1 - \gamma^5) e^\lambda) + m_\nu^2 (\bar{\nu}^\lambda U^{lep}{}_{\lambda e} (1 + \gamma^5) e^\lambda) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_\nu^2 (e^\lambda U^{lep}{}_{\lambda e} (1 + \gamma^5) \nu^\lambda) - m_\nu^2 (e^\lambda U^{lep}{}_{\lambda e} (1 - \gamma^5) \nu^\lambda) - \frac{g}{M} M_{\lambda e}^R H (\bar{\nu}^\lambda \nu^\lambda) - \\ & \frac{g}{M} M_{\lambda e}^L H (e^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (e^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda e}^R (1 - \gamma_5) \nu_\lambda - \\ & \frac{1}{4} \bar{\nu}_\lambda M_{\lambda e}^L (1 - \gamma_5) \nu_\lambda + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\nu^2 (\bar{u}_j^\lambda C_{\lambda e} (1 - \gamma^5) d_j^\lambda) + m_\nu^2 (\bar{u}_j^\lambda C_{\lambda e} (1 + \gamma^5) d_j^\lambda) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_\nu^2 (\bar{d}_j^\lambda C_{\lambda e}^\dagger (1 + \gamma^5) u_j^\lambda) - m_\nu^2 (\bar{d}_j^\lambda C_{\lambda e}^\dagger (1 - \gamma^5) u_j^\lambda) - \frac{g}{M} M_{\lambda e}^L H (\bar{u}_j^\lambda u_j^\lambda) - \\ & \frac{g}{M} M_{\lambda e}^R H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{C}^a \partial^2 C^a + g_s f^{abc} \partial_\mu \bar{C}^a G^b g_\mu^c + \\ & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig_{c_w} W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\ & \partial_\mu \bar{X}^+ X^0) + ig_{s_w} W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + ig_{c_w} W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\ & \partial_\mu \bar{X}^0 X^+) + ig_{s_w} W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig_{c_w} Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \\ & \partial_\mu \bar{X}^- X^+) + ig_{s_w} A_\mu (\partial_\mu \bar{X}^+ X^- - \\ & \partial_\mu \bar{X}^- X^+) - \frac{1}{2}igM (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\ & \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\ & \frac{1}{2}igM (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) . \end{aligned}$$



# Theoretical Predictions for the LHC

Hard (perturbative) scattering process:

$$d\sigma = d\sigma_{\text{LO}} + \alpha_S d\sigma_{\text{NLO}} + \alpha_S^2 d\sigma_{\text{NNLO}} + \alpha_S^3 d\sigma_{\text{N3LO}} + \dots$$

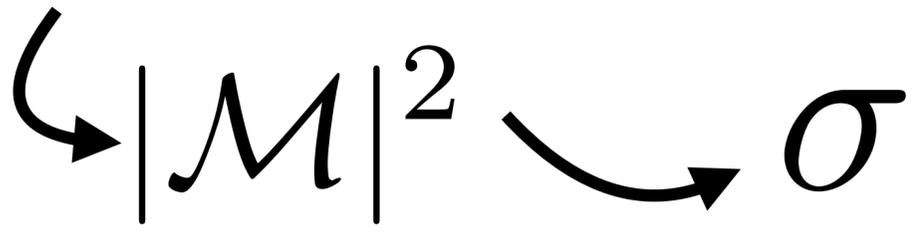
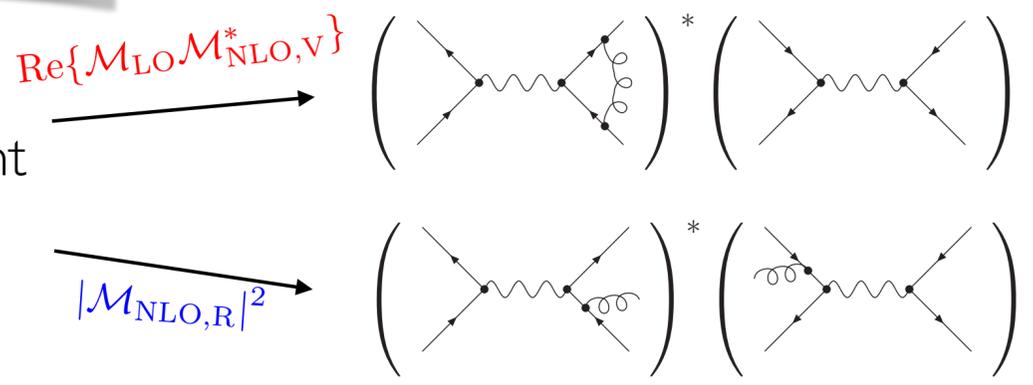
$$\begin{aligned} \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\mu g_\nu^a \partial_\mu g_\nu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\mu W_\nu^+ \partial_\mu W_\nu^- \\ & - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\mu Z_\nu^0 \partial_\mu Z_\nu^0 - \frac{1}{2}M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - ig_{cw}(\partial_\mu Z_\nu^0(W_\mu^+ W_\nu^- \\ & - W_\mu^- W_\nu^+) - Z_\nu^0(W_\mu^+ \partial_\mu W_\nu^- - W_\mu^- \partial_\mu W_\nu^+) + Z_\nu^0(W_\mu^+ \partial_\mu W_\nu^- - W_\mu^- \partial_\mu W_\nu^+)) \\ & - ig_{sw}(\partial_\mu A_\nu(W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+) - A_\nu(W_\mu^+ \partial_\mu W_\nu^- - W_\mu^- \partial_\mu W_\nu^+) + A_\nu(W_\mu^+ \partial_\mu W_\nu^- \\ & - W_\mu^- \partial_\mu W_\nu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\nu^+ W_\mu^- W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\nu^+ Z_\mu^0 W_\nu^- \\ & - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\nu^+ A_\nu W_\mu^- - A_\mu A_\nu W_\nu^+ W_\mu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- \\ & - W_\mu^- W_\nu^+) - 2A_\mu Z_\nu^0 W_\mu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 \\ & \beta_h \left( \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\ & \frac{g\alpha_h M}{2} (H^2 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\ & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\ & g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \\ & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\ & \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{M}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\ & M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+) - ig \frac{M}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- \\ & - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\ & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\ & \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 s_w (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\ & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_{ij}^3 (\bar{q}_i^c \gamma^\mu q_j^c) g_\mu^a - e^2 (\gamma^\mu + m_\nu^2) e^\lambda - \bar{\nu}^\lambda (\gamma^\mu + m_\nu^2) \nu^\lambda - \bar{u}_j^\lambda (\gamma^\mu + \\ & m_u^2) u_j^\lambda - \bar{d}_j^\lambda (\gamma^\mu + m_d^2) d_j^\lambda + ig_s A_\mu (-e^2 \gamma^\mu e^\lambda + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)) + \\ & \frac{ig}{4c_w} Z_\mu^0 (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^2 \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{2}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\ & (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{2}{3}s_w^2 + \gamma^5) u_j^\lambda)) + \frac{ig}{2\sqrt{2}} W_\mu^+ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep} \nu_e) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda e} d_j^\lambda) + \\ & \frac{ig}{2\sqrt{2}} W_\mu^- ((e^c U^{lep} \nu_e (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda C_{\lambda e} \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\ & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\nu^2 (\bar{\nu}^\lambda U^{lep} \nu_e (1 - \gamma^5) e^\lambda) + m_\nu^2 (\bar{\nu}^\lambda U^{lep} \nu_e (1 + \gamma^5) e^\lambda) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_\nu^2 (\bar{e}^\lambda U^{lep} \nu_e (1 + \gamma^5) \nu^\lambda) - m_\nu^2 (\bar{e}^\lambda U^{lep} \nu_e (1 - \gamma^5) \nu^\lambda) - \frac{g}{M} M_\nu^R H (\bar{\nu}^\lambda \nu^\lambda) - \\ & \frac{g}{2M} H (e^2 e^\lambda) + \frac{ig}{2M} m_\nu^2 \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2M} m_\nu^2 \phi^0 (e^2 \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_\nu^R (1 - \gamma_5) \nu_\lambda - \\ & \frac{1}{4} \bar{\nu}_\lambda M_\nu^R (1 - \gamma_5) \nu_\lambda + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\nu^2 (\bar{u}_j^\lambda C_{\lambda e} (1 - \gamma^5) d_j^\lambda) + m_\nu^2 (\bar{u}_j^\lambda C_{\lambda e} (1 + \gamma^5) d_j^\lambda) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_\nu^2 (\bar{d}_j^\lambda C_{\lambda e} (1 + \gamma^5) u_j^\lambda) - m_\nu^2 (\bar{d}_j^\lambda C_{\lambda e} (1 - \gamma^5) u_j^\lambda) - \frac{g}{2M} H (\bar{u}_j^\lambda u_j^\lambda) - \\ & \frac{g}{2M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2M} m_\nu^2 \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2M} m_\nu^2 \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{C}^a \partial^2 C^a + g_s f^{abc} \partial_\mu \bar{C}^a G^b G^c + \\ & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{2}) X^0 + \bar{Y} \partial^2 Y + ig_{cw} W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\ & \partial_\mu \bar{X}^+ X^+) + ig_{sw} W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + ig_{cw} W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\ & \partial_\mu \bar{X}^0 X^+) + ig_{sw} W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig_{cw} Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \\ & \partial_\mu \bar{X}^- X^0) + ig_{sw} A_\mu (\partial_\mu \bar{X}^+ X^- + \\ & \partial_\mu \bar{X}^- X^0) - \frac{1}{2}ig M (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{2} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} ig M (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\ & \frac{1}{2c_w} ig M (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + ig M s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\ & \frac{1}{2}ig M (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) . \end{aligned}$$

$$d\sigma_{\text{NLO}} = \frac{1}{2s} \int d\Phi_n [ |\mathcal{M}_{\text{LO}}|^2 + 2\text{Re}\{\mathcal{M}_{\text{LO}} \mathcal{M}_{\text{NLO,V}}^*\} ] + \frac{1}{2s} \int d\Phi_{n+1} |\mathcal{M}_{\text{NLO,R}}|^2$$

$$\text{NLO} = \text{B} + \text{V} + \text{R}$$

$\mathcal{M}_{\text{NLO,V}}$  virtual one-loop matrix element

$\mathcal{M}_{\text{NLO,R}}$  real tree-level matrix element



- UV renormalisation  $\Rightarrow$  reduction of  $\mu_R$  dependence
- soft/collinear cancellations+PDF renormalisation  $\Rightarrow$  reduction of  $\mu_F$  dependence

# Theoretical Predictions for the LHC

Hard (perturbative) scattering process:

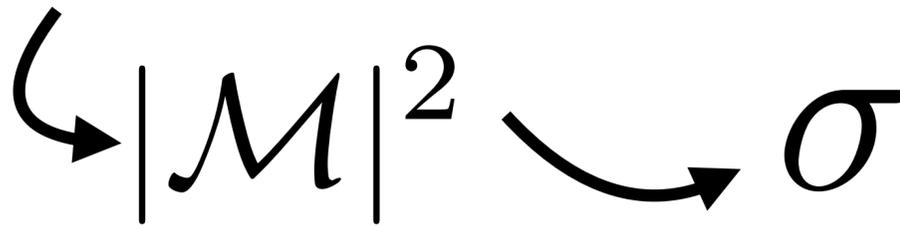
$$d\sigma = d\sigma_{\text{LO}} + \alpha_S d\sigma_{\text{NLO}} + \alpha_S^2 d\sigma_{\text{NNLO}} + \alpha_S^3 d\sigma_{\text{N3LO}} + \dots$$

$$\begin{aligned} \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\mu g_\nu^\rho \partial_\nu g_\mu^\rho - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\mu W_\nu^+ \partial_\nu W_\mu^- \\ & - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\mu Z_\nu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\nu A_\mu - ig_{cw}(\partial_\nu W_\mu^+ W_\nu^- - W_\nu^+ \partial_\mu W_\mu^-) \\ & - W_\nu^+ W_\nu^- - Z_\nu^0(W_\mu^+ \partial_\nu W_\mu^- - W_\nu^+ \partial_\mu W_\mu^-) + Z_\nu^0(W_\mu^+ \partial_\nu W_\mu^- - W_\nu^+ \partial_\mu W_\mu^-) \\ & - ig_{sw}(\partial_\nu A_\mu(W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu(W_\mu^+ \partial_\nu W_\mu^- - W_\nu^+ \partial_\mu W_\mu^-) + A_\nu(W_\mu^+ \partial_\nu W_\mu^- - W_\nu^+ \partial_\mu W_\mu^-) \\ & - W_\nu^+ \partial_\mu W_\mu^-) - \frac{1}{2}g^2 W_\mu^+ W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\nu^+ Z_\nu^0 W_\mu^- - Z_\nu^0 Z_\mu^0 W_\nu^+ W_\mu^-) \\ & + g^2 s_w^2 (A_\mu W_\nu^+ A_\nu W_\mu^- - A_\mu A_\nu W_\nu^+ W_\mu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - 2A_\mu Z_\nu^0 W_\mu^+ W_\nu^-) \\ & - \frac{1}{2}\partial_\mu H \partial_\nu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\nu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\nu \phi^0 - \beta_h \left( \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\ & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\ & g M W_\mu^+ W_\nu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\nu^0 H - \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\nu \phi^- - \phi^- \partial_\nu \phi^0) - W_\nu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\ & \frac{1}{2}g (W_\mu^+ (H \partial_\nu \phi^- - \phi^- \partial_\nu H) + W_\nu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{M}{c_w} (Z_\mu^0 (H \partial_\nu \phi^0 - \phi^0 \partial_\nu H) + \\ & M (\frac{1}{c_w} Z_\mu^0 \partial_\nu \phi^0 + W_\mu^+ \partial_\nu \phi^- + W_\nu^- \partial_\nu \phi^+) - ig \frac{M}{c_w} Z_\mu^0 (W_\mu^+ \phi^- - W_\nu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - \\ & W_\nu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\nu \phi^- - \phi^- \partial_\nu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\nu \phi^- - \phi^- \partial_\nu \phi^+) - \\ & \frac{1}{4}g^2 W_\mu^+ W_\nu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\nu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\ & \frac{1}{2}g^2 \frac{M}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\nu^- \phi^+) - \frac{1}{2}ig^2 \frac{M}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\nu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu (W_\mu^+ \phi^- + \\ & W_\nu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\nu^- \phi^+) - g^2 \frac{2s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\nu \phi^+ \phi^- - \\ & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_{ij}^a (\bar{q}_i^c \gamma^\mu q_j^c) g_\mu^a - e^2 (\gamma^\theta + m_\nu^2) e^\lambda - \bar{\nu}^\lambda (\gamma^\theta + m_\nu^2) \nu^\lambda - \bar{u}_j^2 (\gamma^\theta + \\ & m_u^2) u_j^2 - \bar{d}_j^2 (\gamma^\theta + m_d^2) d_j^2 + ig_s A_\mu (-e^2 \gamma^\mu e^\lambda + \frac{2}{3}(\bar{u}_j^2 \gamma^\mu u_j^2) - \frac{1}{3}(\bar{d}_j^2 \gamma^\mu d_j^2)) + \\ & \frac{ig}{4c_w} Z_\mu^0 (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^2 \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^2 \gamma^\mu (\frac{2}{3}s_w^2 - 1 - \gamma^5) d_j^2) + \\ & (\bar{u}_j^2 \gamma^\mu (1 - \frac{2}{3}s_w^2 + \gamma^5) u_j^2)) + \frac{ig}{2\sqrt{2}} W_\mu^+ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep} \nu_\lambda e^\mu) + (\bar{u}_j^2 \gamma^\mu (1 + \gamma^5) C_{\lambda c} d_j^2) + \\ & \frac{ig}{2\sqrt{2}} W_\mu^- ((e^c U^{lep} \nu_\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^2 \gamma^\mu C_{\lambda c} (1 + \gamma^5) u_j^2)) + \\ & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\nu^2 (\bar{\nu}^\lambda U^{lep} \nu_\lambda (1 - \gamma^5) e^\mu) + m_\nu^2 (\bar{\nu}^\lambda U^{lep} \nu_\lambda (1 + \gamma^5) e^\mu) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_\nu^2 (\bar{e}^\lambda U^{lep} \nu_\lambda (1 + \gamma^5) \nu^\mu) - m_\nu^2 (\bar{e}^\lambda U^{lep} \nu_\lambda (1 - \gamma^5) \nu^\mu) - \frac{g}{M} \frac{m_\nu}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\ & \frac{g}{M} \frac{m_\nu}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2M} \frac{m_\nu^2}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2M} \frac{m_\nu^2}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda c}^R (1 - \gamma_5) \nu_\lambda - \\ & \frac{1}{4} \bar{\nu}_\lambda M_{\lambda c}^L (1 - \gamma_5) \nu_\lambda + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\nu^2 (\bar{u}_j^2 C_{\lambda c} (1 - \gamma^5) d_j^2) + m_\nu^2 (\bar{u}_j^2 C_{\lambda c} (1 + \gamma^5) d_j^2) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_\nu^2 (\bar{d}_j^2 C_{\lambda c} (1 + \gamma^5) u_j^2) - m_\nu^2 (\bar{d}_j^2 C_{\lambda c} (1 - \gamma^5) u_j^2) - \frac{g}{M} \frac{m_\nu}{M} H (\bar{u}_j^2 u_j^2) - \\ & \frac{g}{M} \frac{m_\nu}{M} H (\bar{d}_j^2 d_j^2) + \frac{ig}{2M} \frac{m_\nu^2}{M} \phi^0 (\bar{u}_j^2 \gamma^5 u_j^2) - \frac{ig}{2M} \frac{m_\nu^2}{M} \phi^0 (\bar{d}_j^2 \gamma^5 d_j^2) + \bar{C}^a \partial^2 C^a + g_s f^{abc} \partial_\mu \bar{C}^a C^b g_\mu^c + \\ & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig_{cw} W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\ & \partial_\mu \bar{X}^+ X^0) + ig_{sw} W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + ig_{cw} W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\ & \partial_\mu \bar{X}^0 X^+) + ig_{sw} W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig_{cw} Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \\ & \partial_\mu \bar{X}^- X^0) + ig_{sw} A_\mu (\partial_\mu \bar{X}^+ X^- + \\ & \partial_\mu \bar{X}^- X^0) - \frac{1}{2}ig M (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} ig M (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\ & \frac{1}{2c_w} ig M (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + ig M s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\ & \frac{1}{2}ig M (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) . \end{aligned}$$

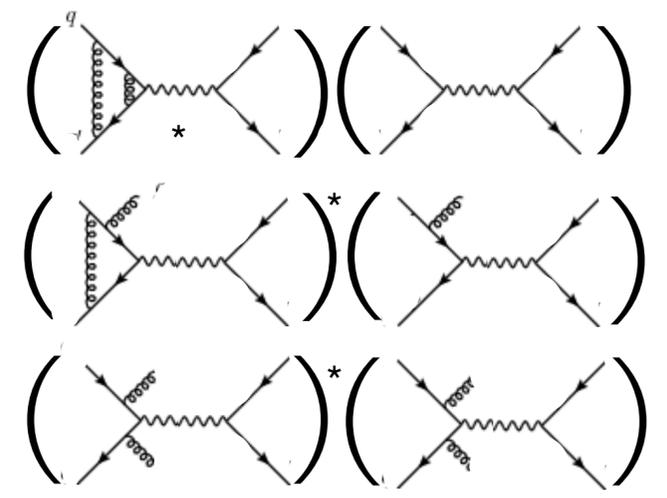
$$d\hat{\sigma}_{\text{NNLO}} = \frac{1}{2s} \int d\Phi_n [ |\mathcal{M}_{\text{LO}}|^2 + 2\text{Re}\{\mathcal{M}_{\text{LO}} \mathcal{M}_{\text{NLO},V}^*\} + 2\text{Re}\{\mathcal{M}_{\text{LO}} \mathcal{M}_{\text{NNLO},V}^*\} ]$$

$$+ \frac{1}{2s} \int d\Phi_{n+1} [ |\mathcal{M}_{\text{NLO},R}|^2 + 2\text{Re}\{\mathcal{M}_{\text{NLO},R} \mathcal{M}_{\text{NNLO},RV}^*\} ] + \frac{1}{2s} \int d\Phi_{n+2} |\mathcal{M}_{\text{NNLO},RR}|^2$$

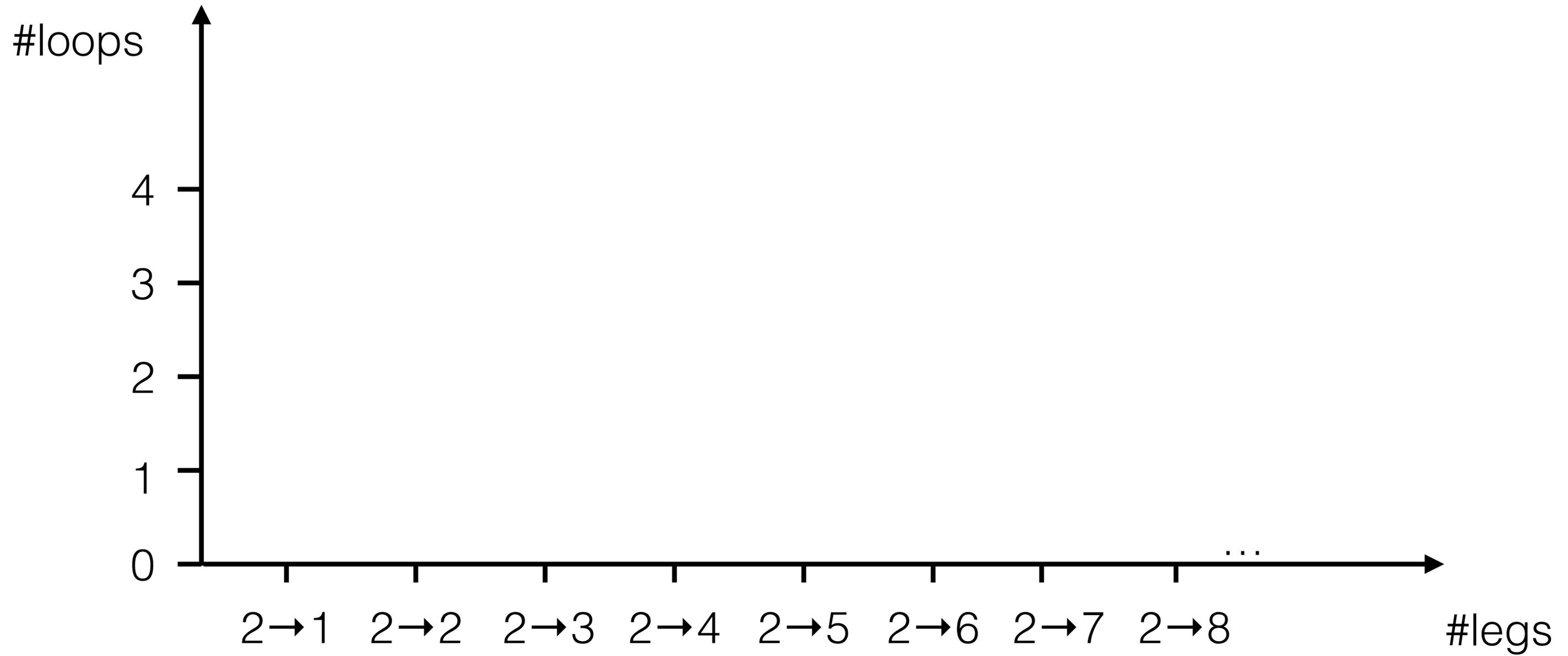
$\text{NNLO} = \text{B} + \text{V} + \text{V2} + \dots$   
 $+ \text{R} + \text{RV} + \text{RR}$



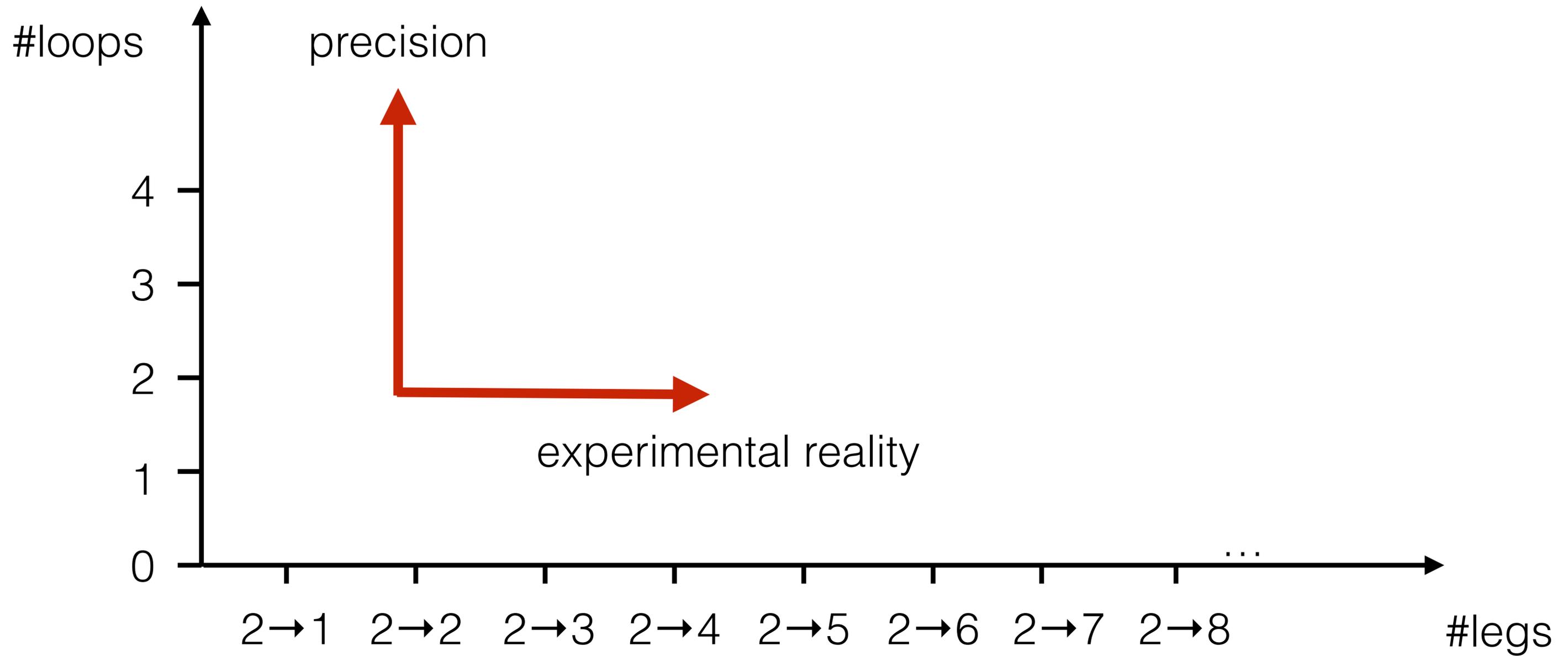
- $\Delta_{\text{NNLO}} \propto \alpha^2$
- $M_{\text{NNLO},V}$  double-virtual two-loop matrix element
  - $M_{\text{NNLO},RV}$  real-virtual one-loop matrix element
  - $M_{\text{NNLO},RR}$  double-real tree-level matrix element



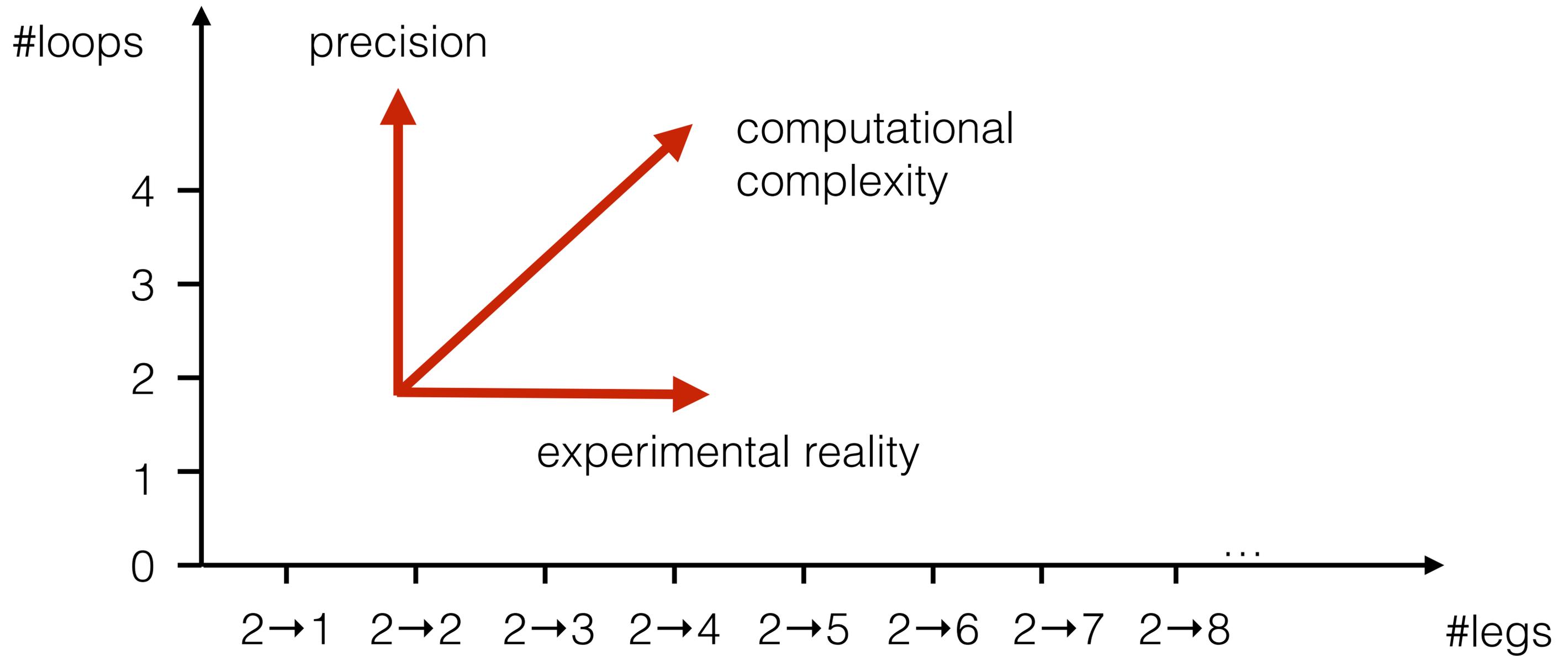
# Theory frontier



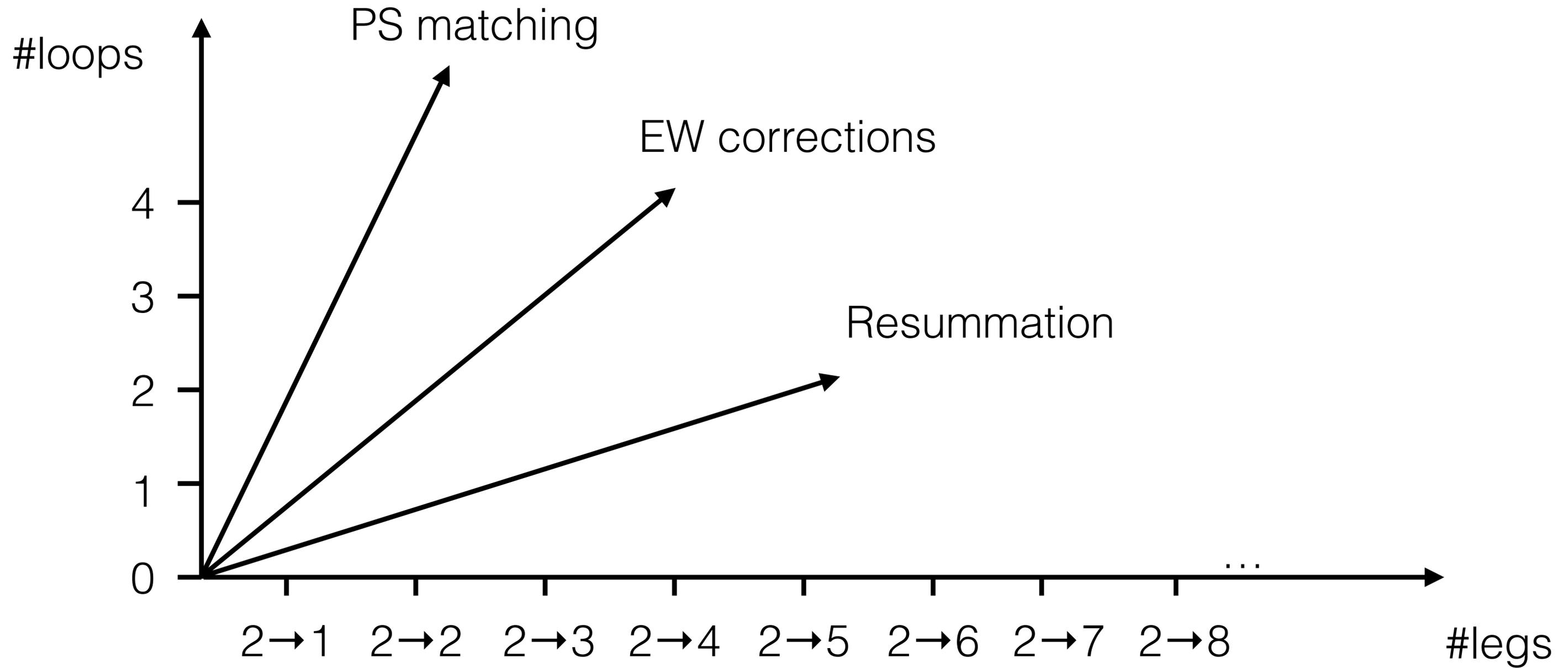
# Theory frontier



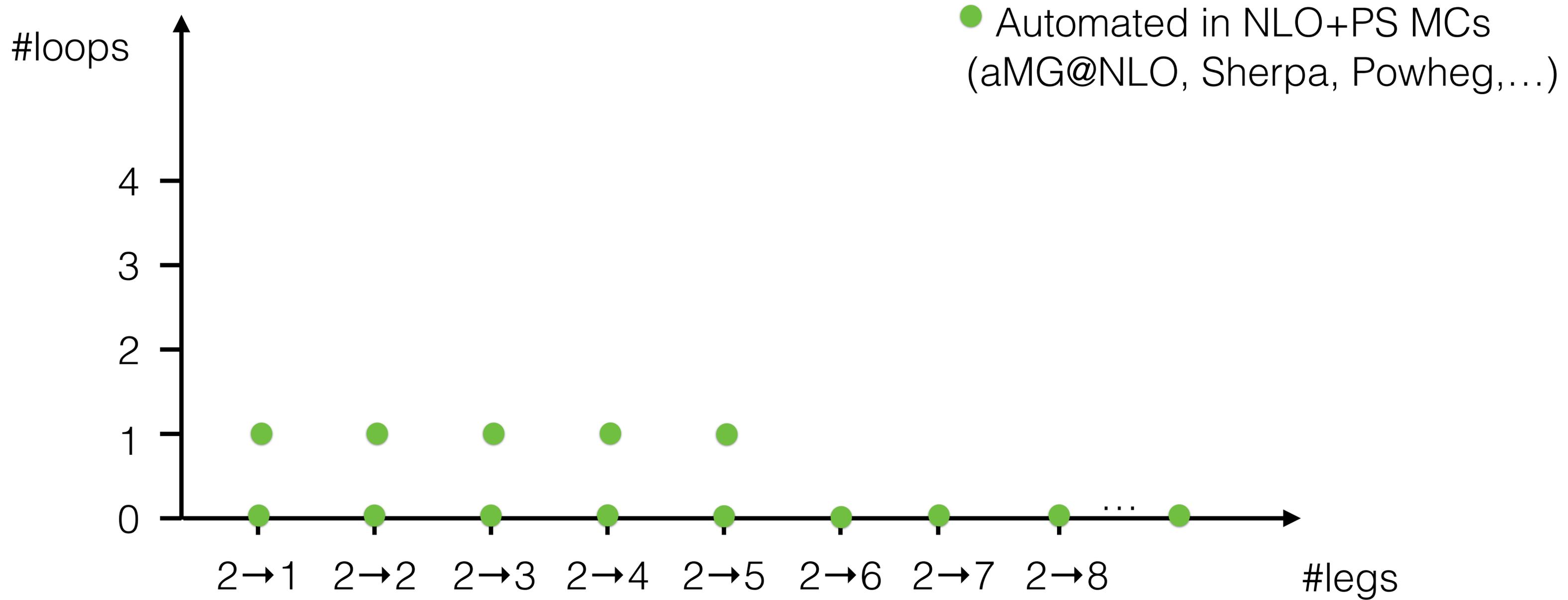
# Theory frontier



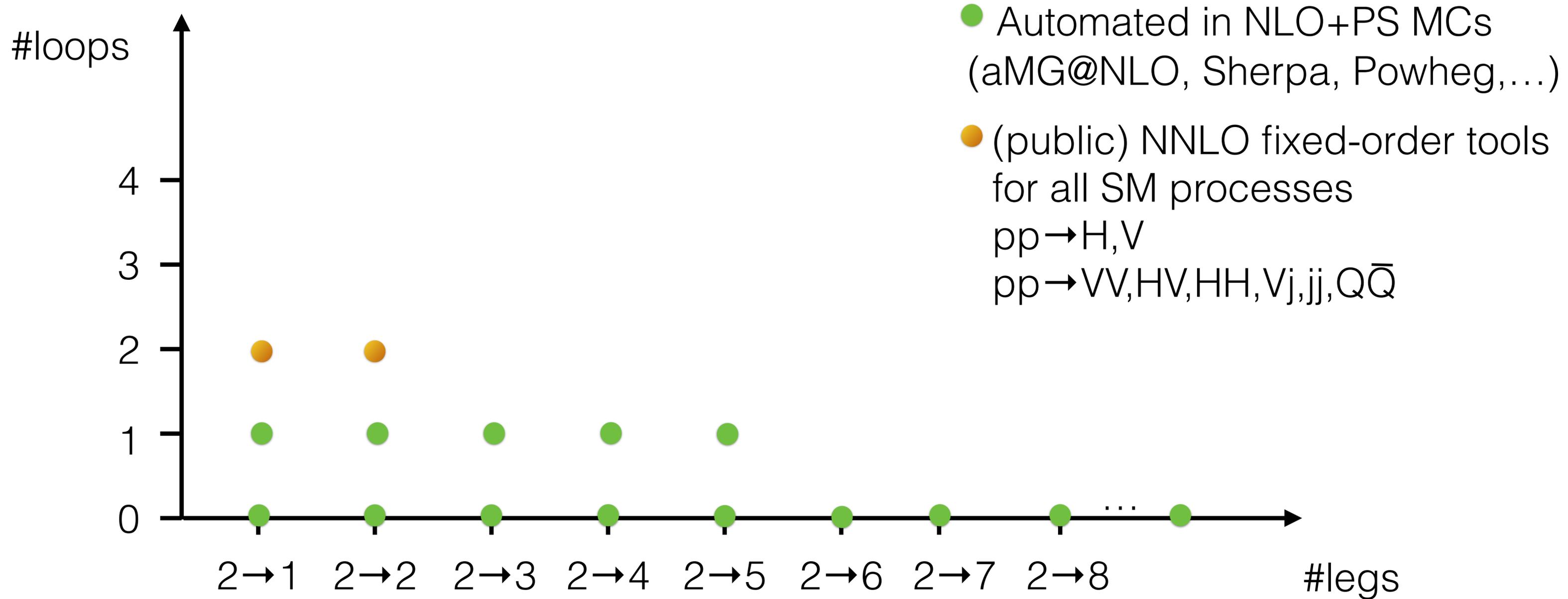
# Theory frontier



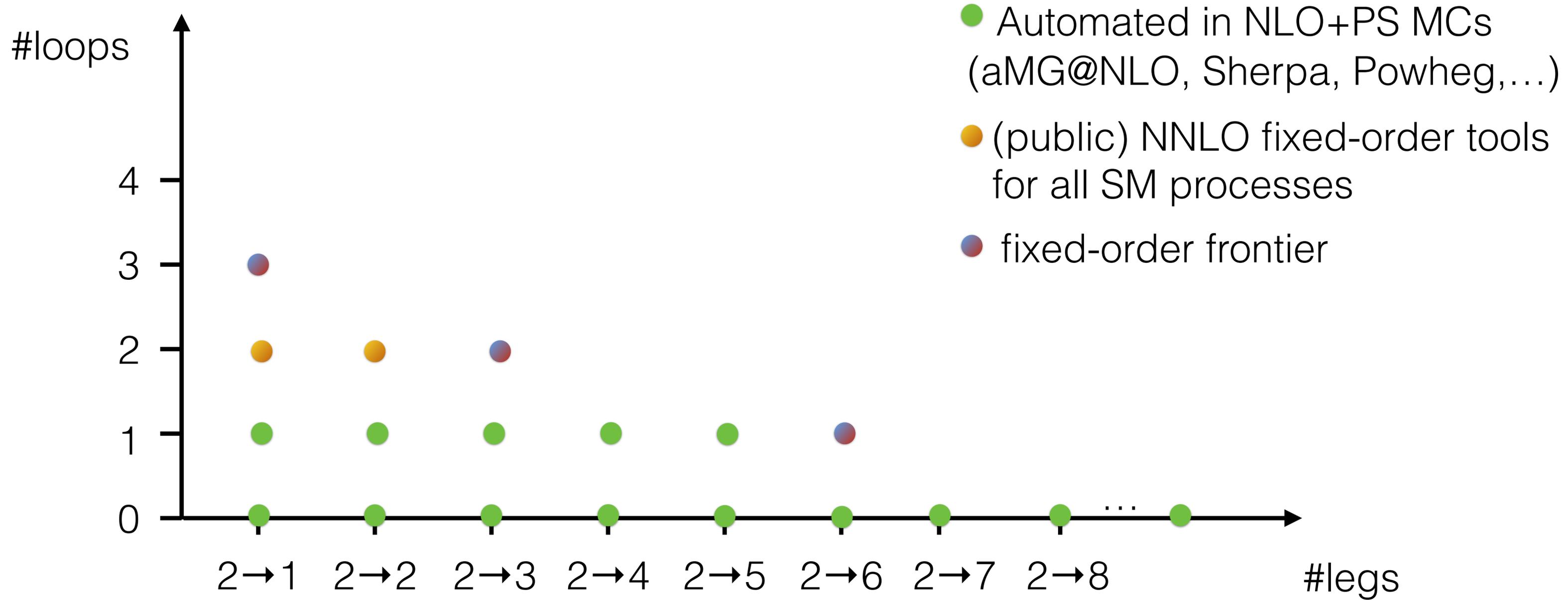
# Theory frontier



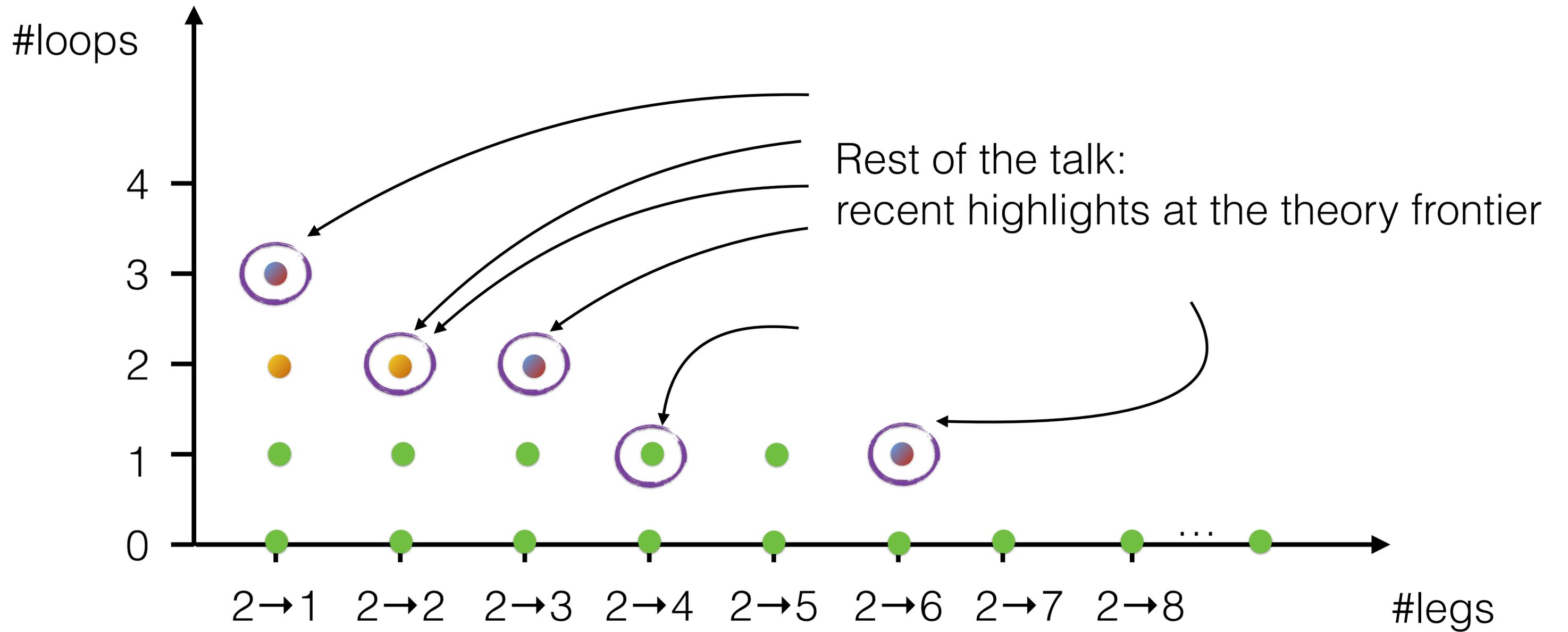
# Theory frontier



# Theory frontier



# Theory frontier



# 2→3 at NNLO QCD

- over the last 1.5y the 2→3 NNLO barrier has been broken.
- pioneering new results:

$$pp \rightarrow \gamma\gamma\gamma$$

[Chawdhry, Czakon, Mitov, Poncelet '19]

[Kallweit, Sotnikov, Wiesemann '20]

$$pp \rightarrow \gamma\gamma j$$

[Chawdhry, Czakon, Mitov, Poncelet '21]

$$pp \rightarrow jjj$$

[Czakon, Mitov, Poncelet '21]

- thanks to recent progress on 5-point two-loop integrals and amplitudes in massless QCD



[Papadopoulos, Tommasini, Wever '15]

[Gehrmann, Henn, Lo Presti '18]

[Gehrmann, Henn, Wasser, Zhang, Zoia '18]

[Abreu, Ita, Moriello, Page, Tschernow '20]



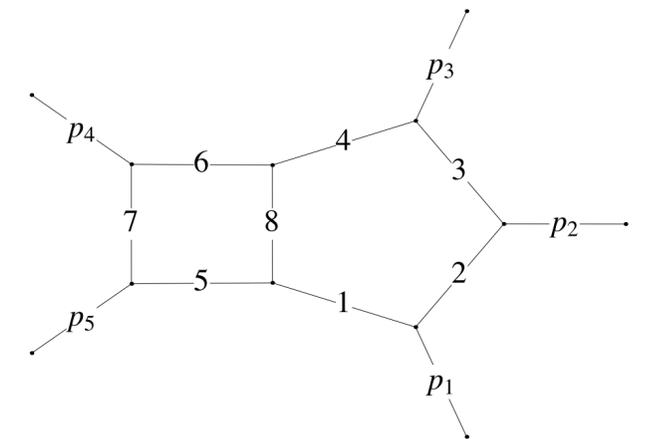
[Badger, Chicherin, Gehrmann, et. al. '19]

[Abreu, Dormans, Febres Cordero, Ita, Page, Sotnikov '19]

[Abreu, Page, Pascual, Sotnikov '20]

[Abreu, Febres Cordero, Ita, Page, Sotnikov '21]

[Agarwal, Buccioni, v. Manteuffel, Tancredi '21]

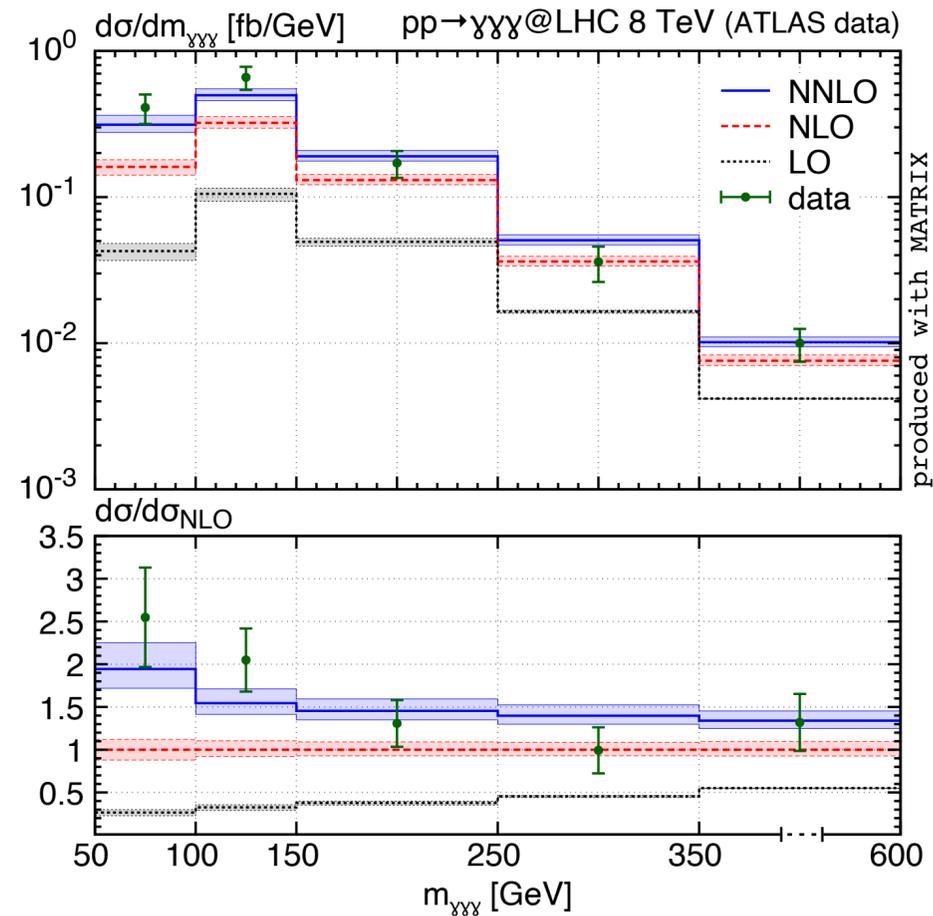


# 2 → 3 at NNLO

$$pp \rightarrow \gamma\gamma\gamma$$

[Chawdhry, Czakon, Mitov, Poncelet '19]

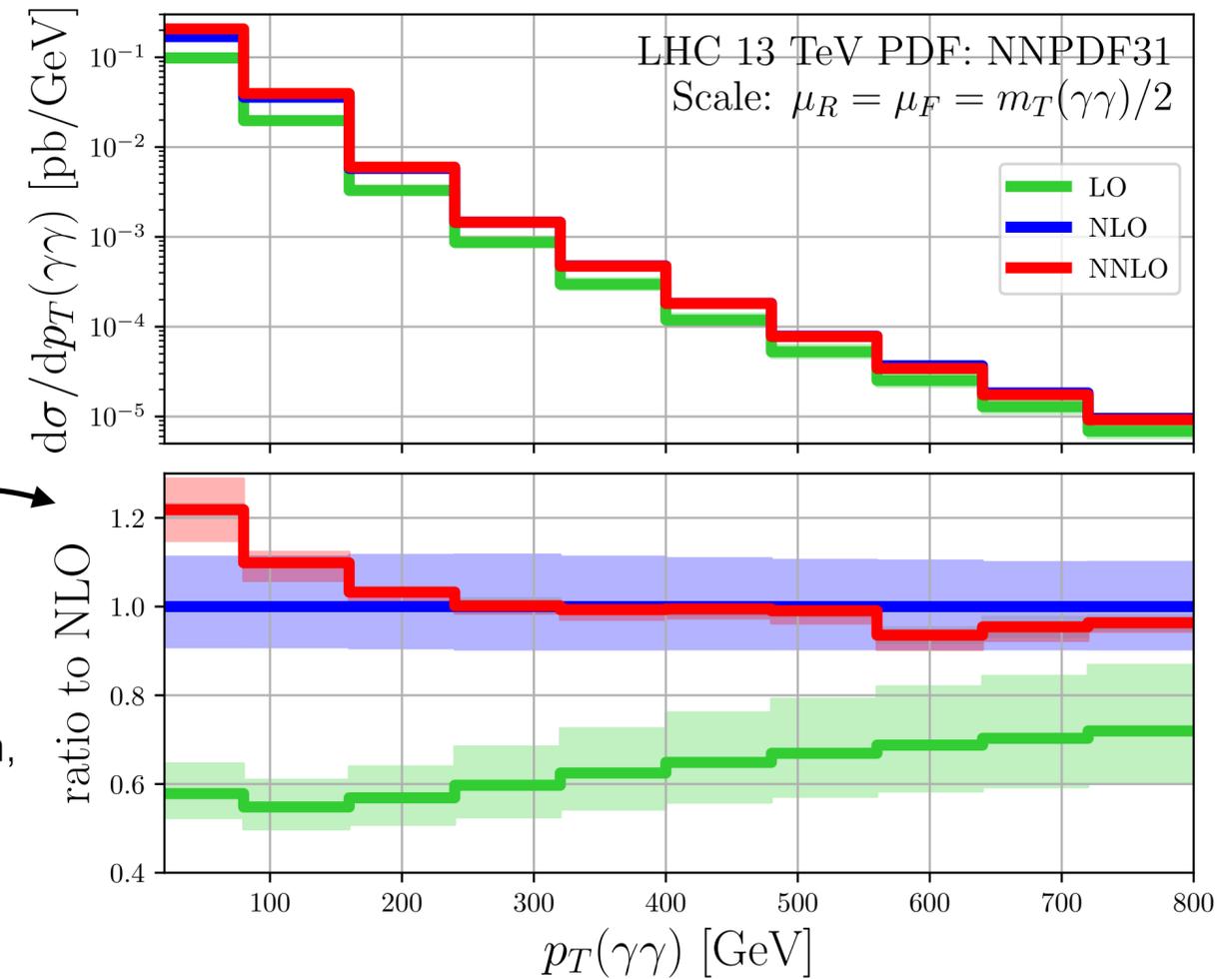
[Kallweit, Sotnikov, Wiesemann '20]



- significant NNLO/NLO corrections
- improved data/theory agreement at NNLO

$$pp \rightarrow \gamma\gamma j$$

[Chawdhry, Czakon, Mitov, Poncelet '21]



- NNLO mandatory due to large NLO/LO corrections

$$gg \rightarrow \gamma\gamma g$$

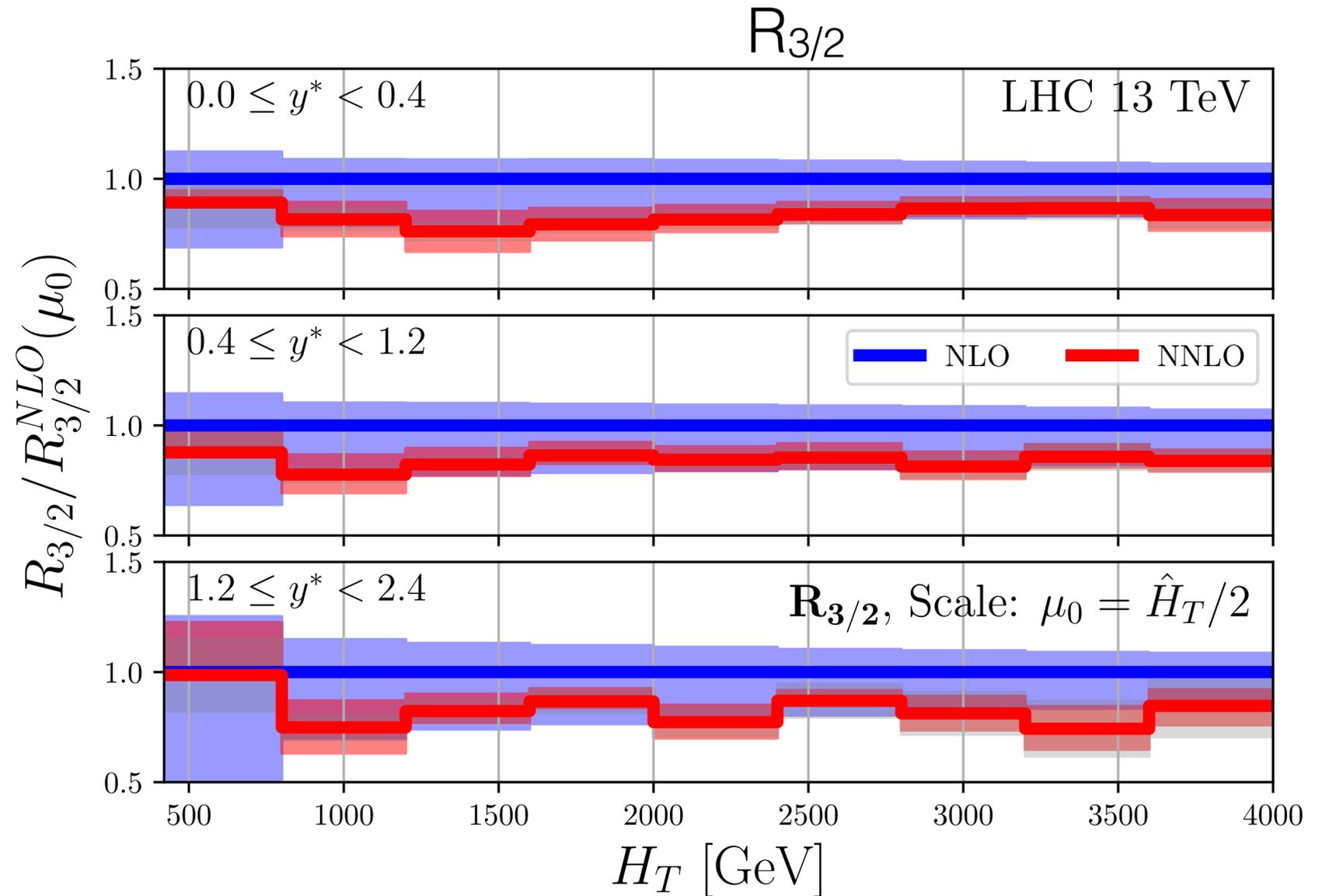
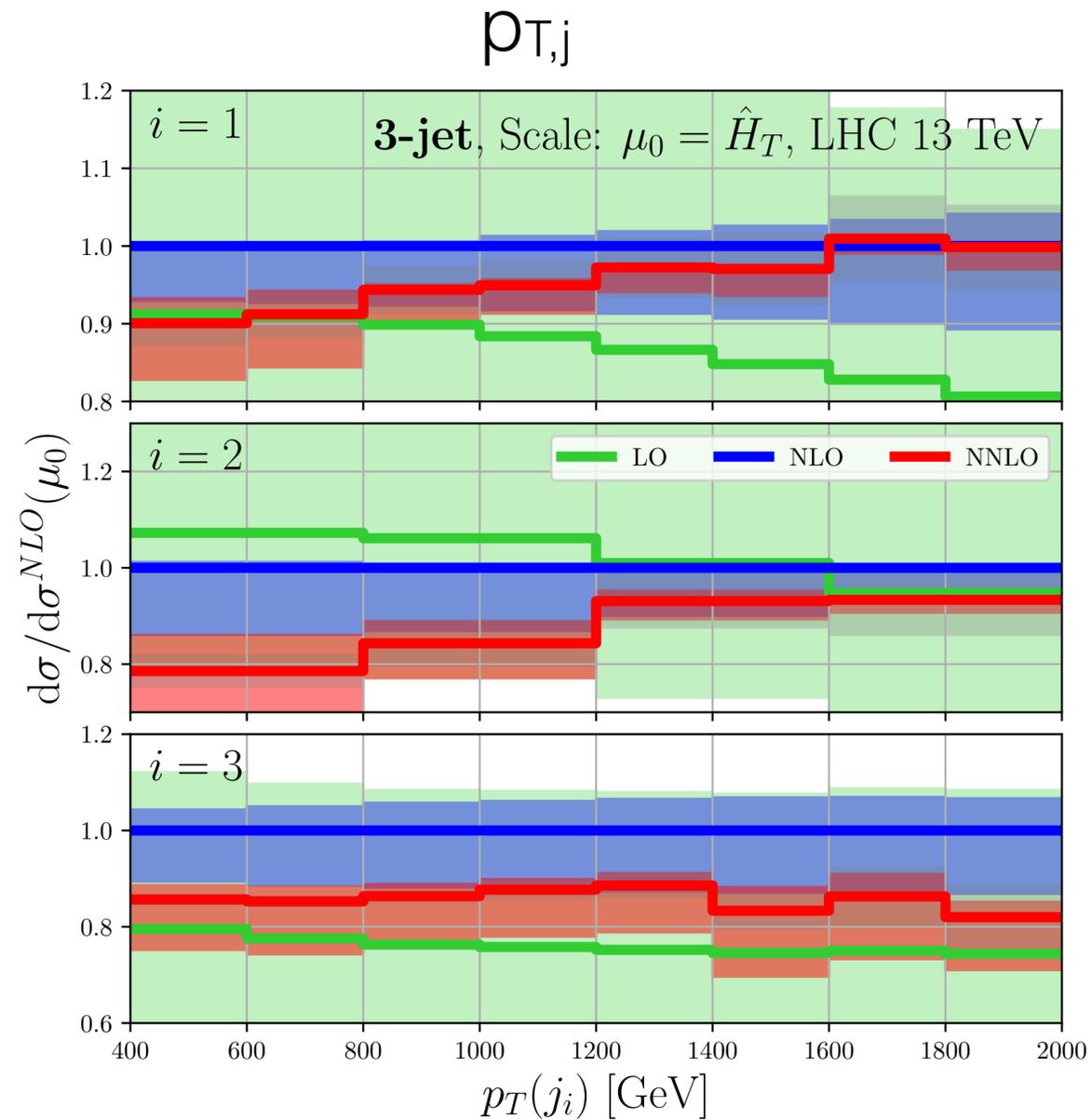
► [Badger, Brønnum-Hansen, Chicherin et. al. '21]

➡ precision probes of QCD dynamics

# pp → jjj at NNLO

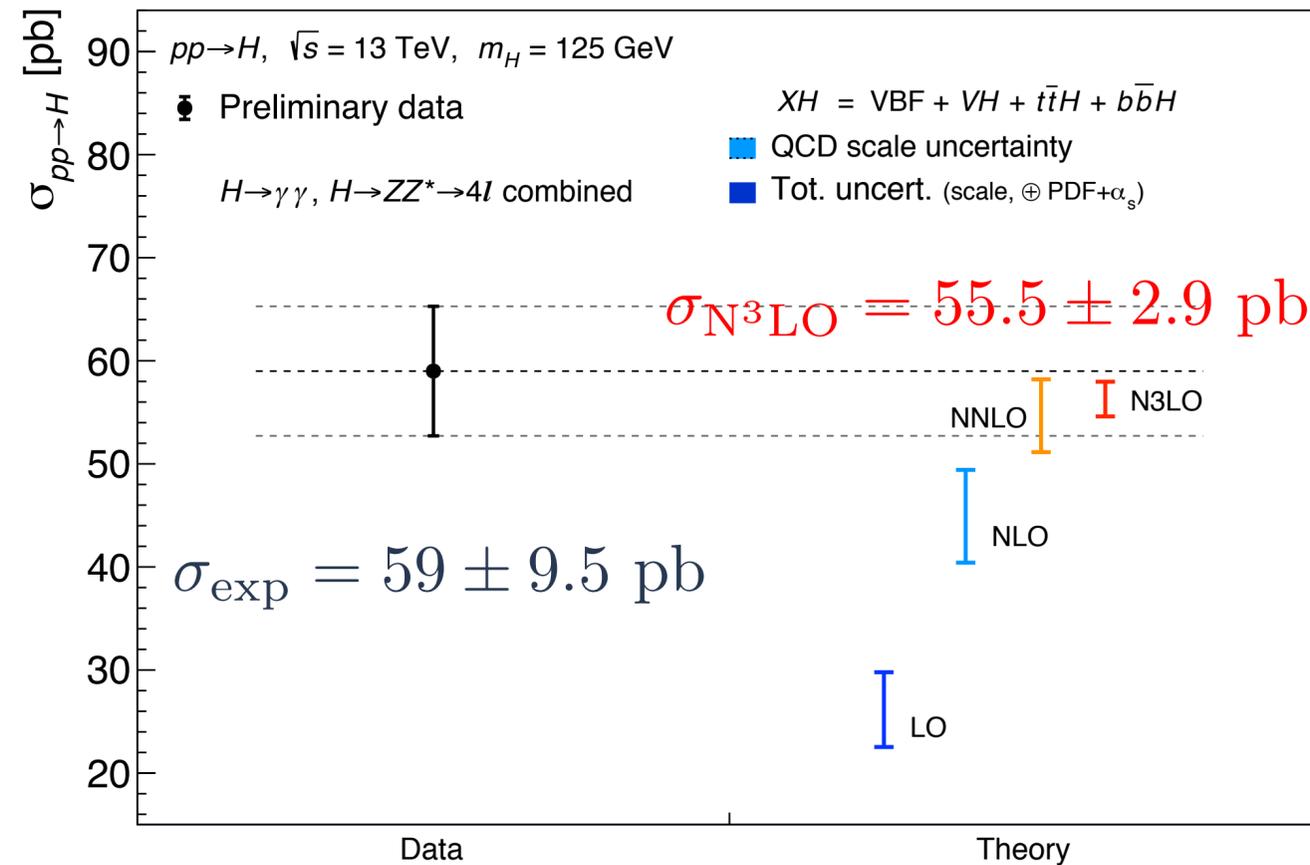
"Tour de force in Quantum Chromodynamics"

[Czakon, Mitov, Poncelet '21]

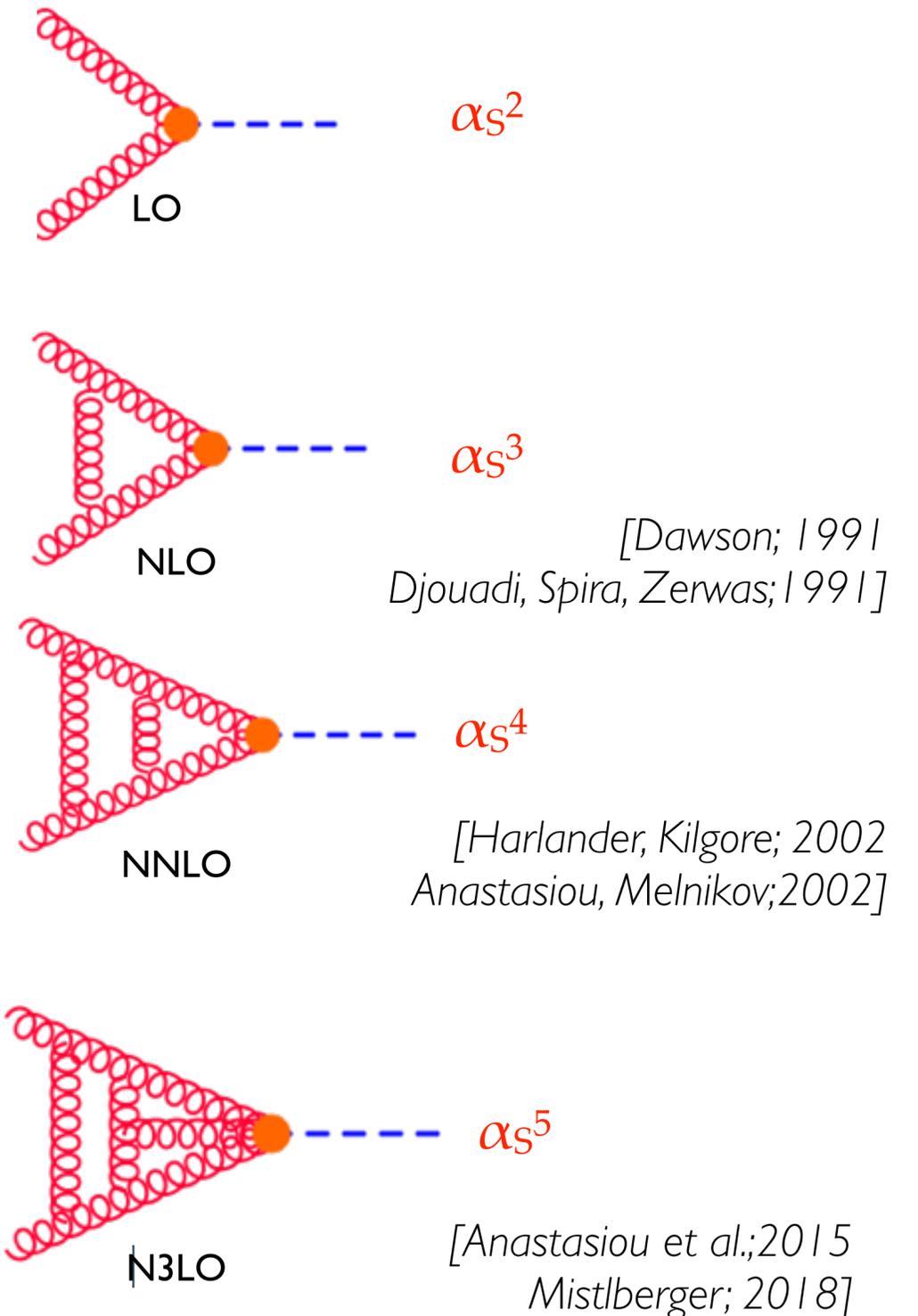


- ➡ clear stabilisation of perturbative expansion at NNLO
- ➡ opens the door to  $a_s(\mu)$  determination up to TeV scale

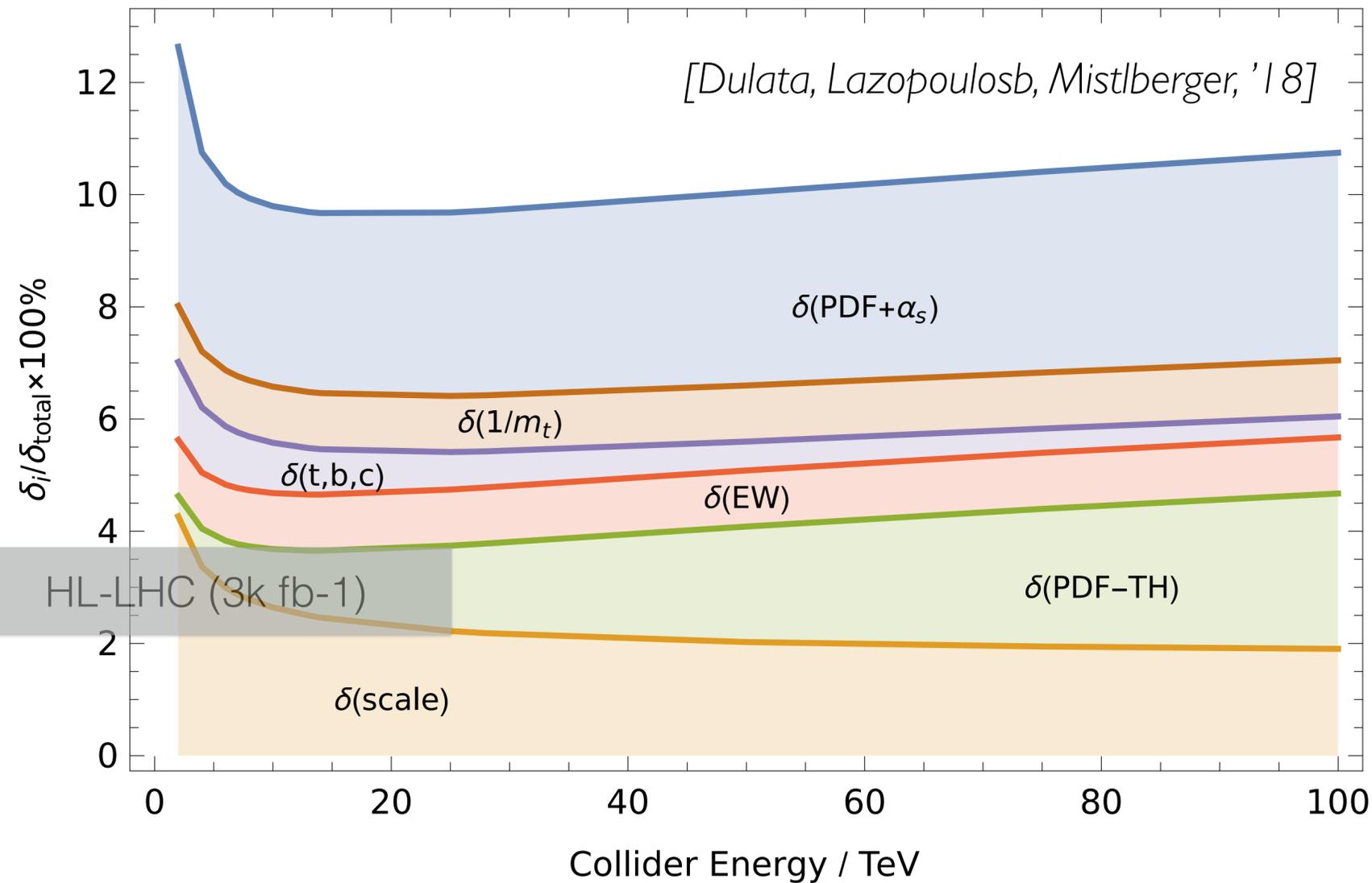
# Convergence of the perturbative expansion: inclusive Higgs



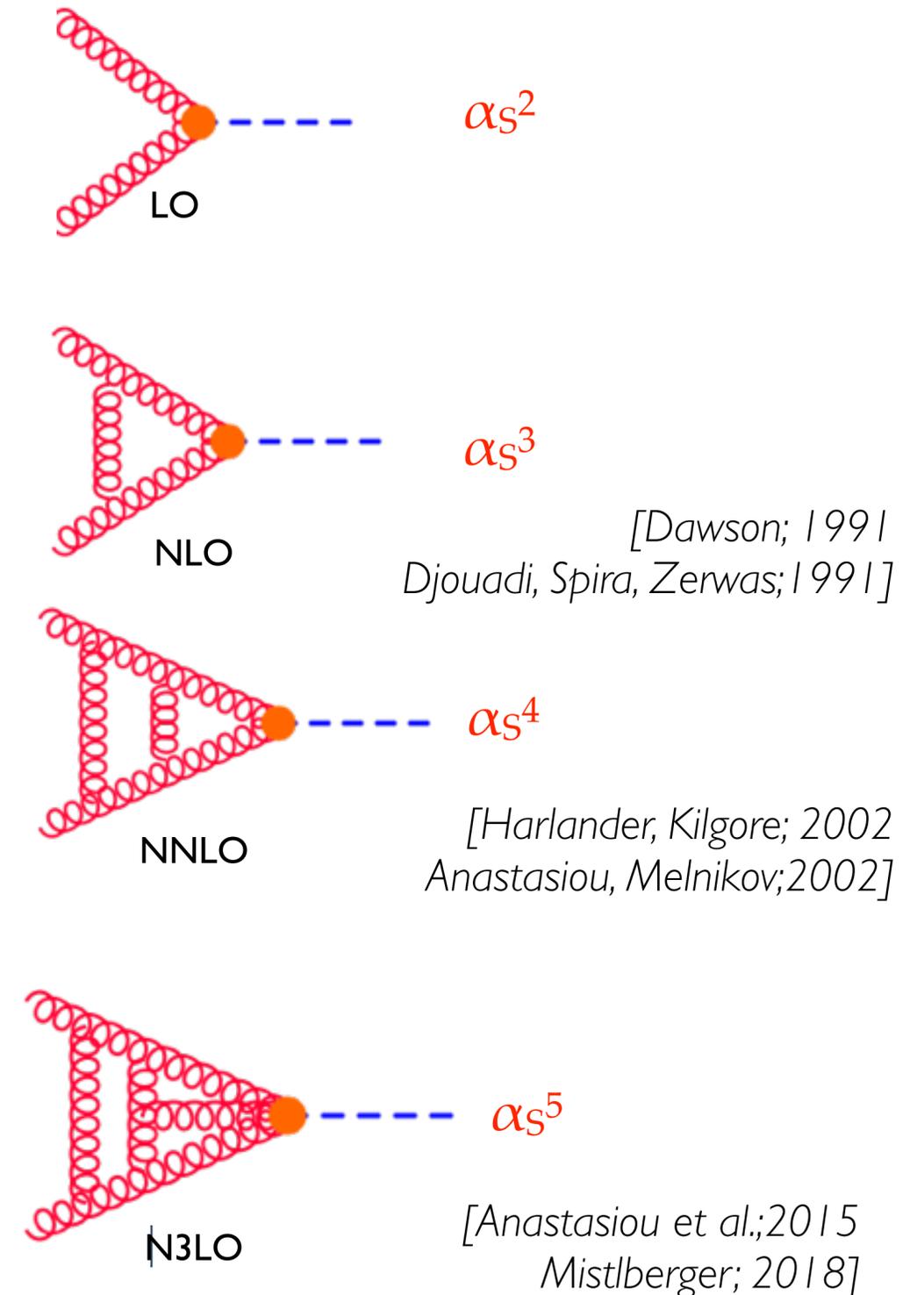
- ➔ Error estimate at LO largely underestimated!
- ➔ N3LO  $\sim 2$  LO
- ➔ Higher-orders are crucial for reliable predictions and precision tests of Higgs properties



# Convergence of the perturbative expansion: inclusive Higgs up to N3LO

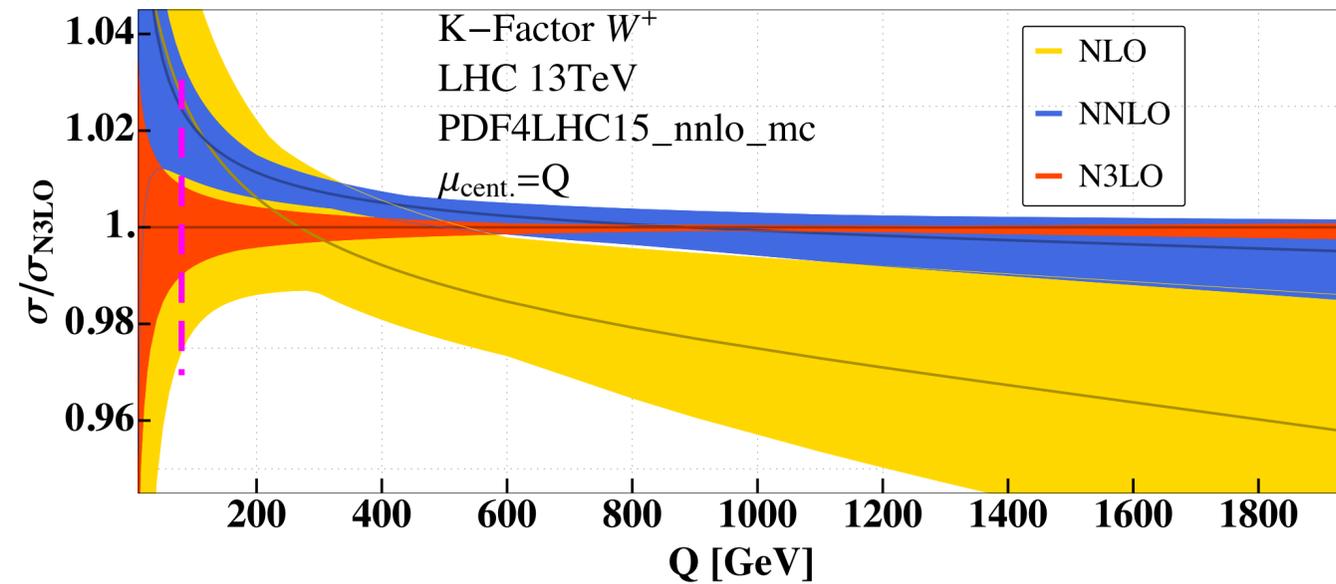


➔ At this level: crucial to investigate any possible uncertainty beyond naive scale variations



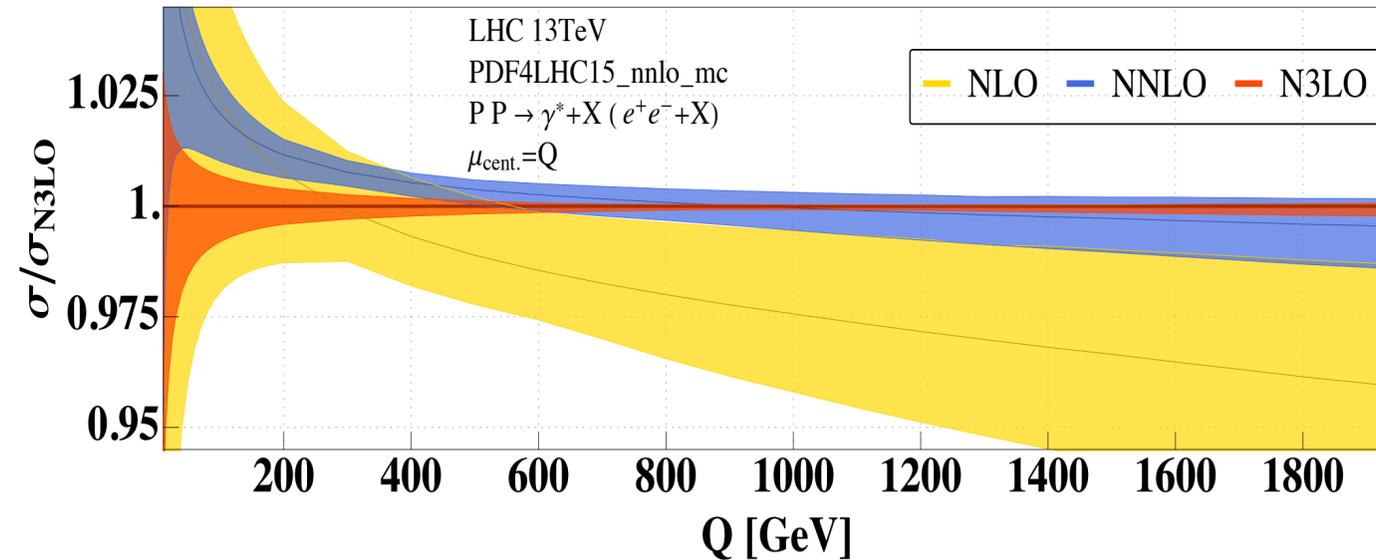
# DY @ N3LO: inclusive

[Duhr, Dulat, Mistlberger, '20-1, '20-2]



$W^+$

- ➔ Very similar behaviour in CC and NC DY
- ➔ At large Q scale variations bands are nicely overlapping, i.e. convincing convergence of perturbative series.
- ➔ However, for  $Q < 400$  GeV NNLO and N3LO do not overlap! (Here:  $\delta N3LO \sim 1-2\%$ )
- ➔ Origin: quite large cancellation of quark and gluon initial state.
- ➔ Might be compensated by currently missing N3LO PDFs

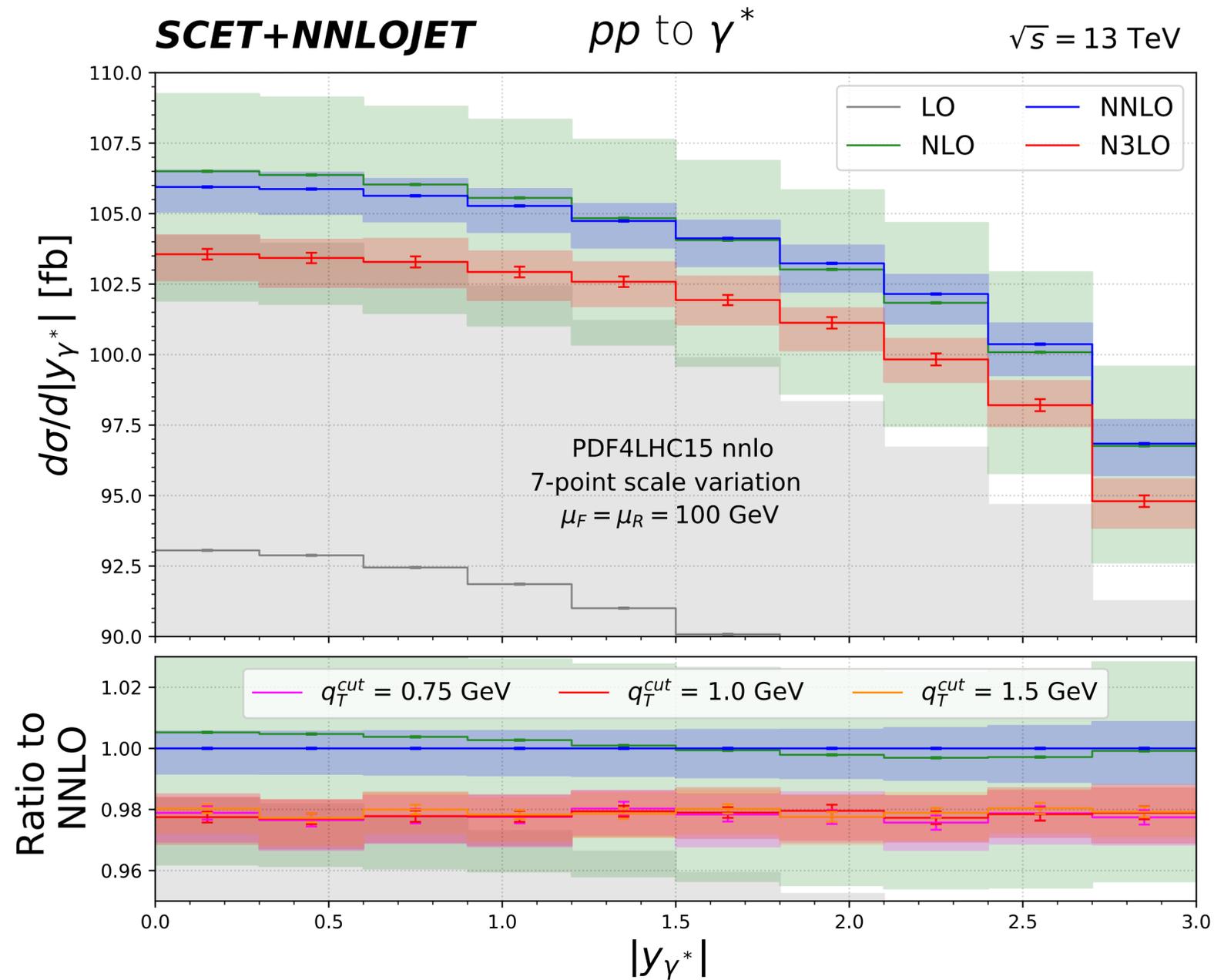


$\gamma^*$

Note: very precise measurements of high-mass DY can be used to constrain BSM, see Farina et. al. '16 (1609.08157)

# DY @ N3LO: differential

[Chen, Gehrmann, Glover, et. al., '21]



- ▶ method:  $q_T$  subtraction at N3LO:  
requires  $V$ +jet at NNLO
- ▶ N3LO/NNLO: -2% (validation of inclusive computation)
- ▶ N3LO not covered by NNLO band
- ▶ 7-pt scale variation might not be good enough to estimate perturbative uncertainties at the percent level.

# Theoretical Predictions for the LHC

Hard (perturbative) scattering process:

aMC@NLO, POWHEG,  
Sherpa, MATRIX, ...

$$d\sigma = d\sigma_{\text{LO}} + \alpha_S d\sigma_{\text{NLO}} + \alpha_{\text{EW}} d\sigma_{\text{NLO EW}}$$

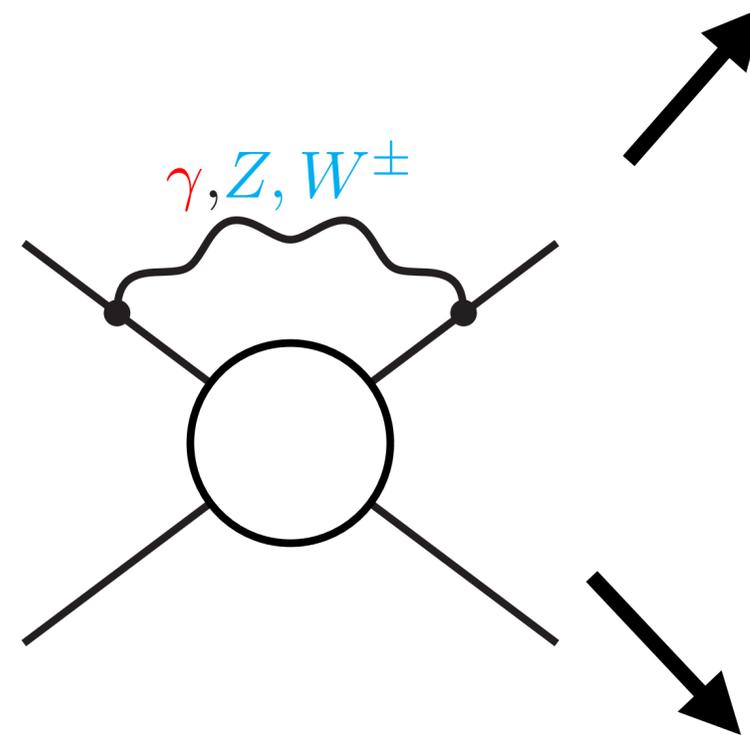
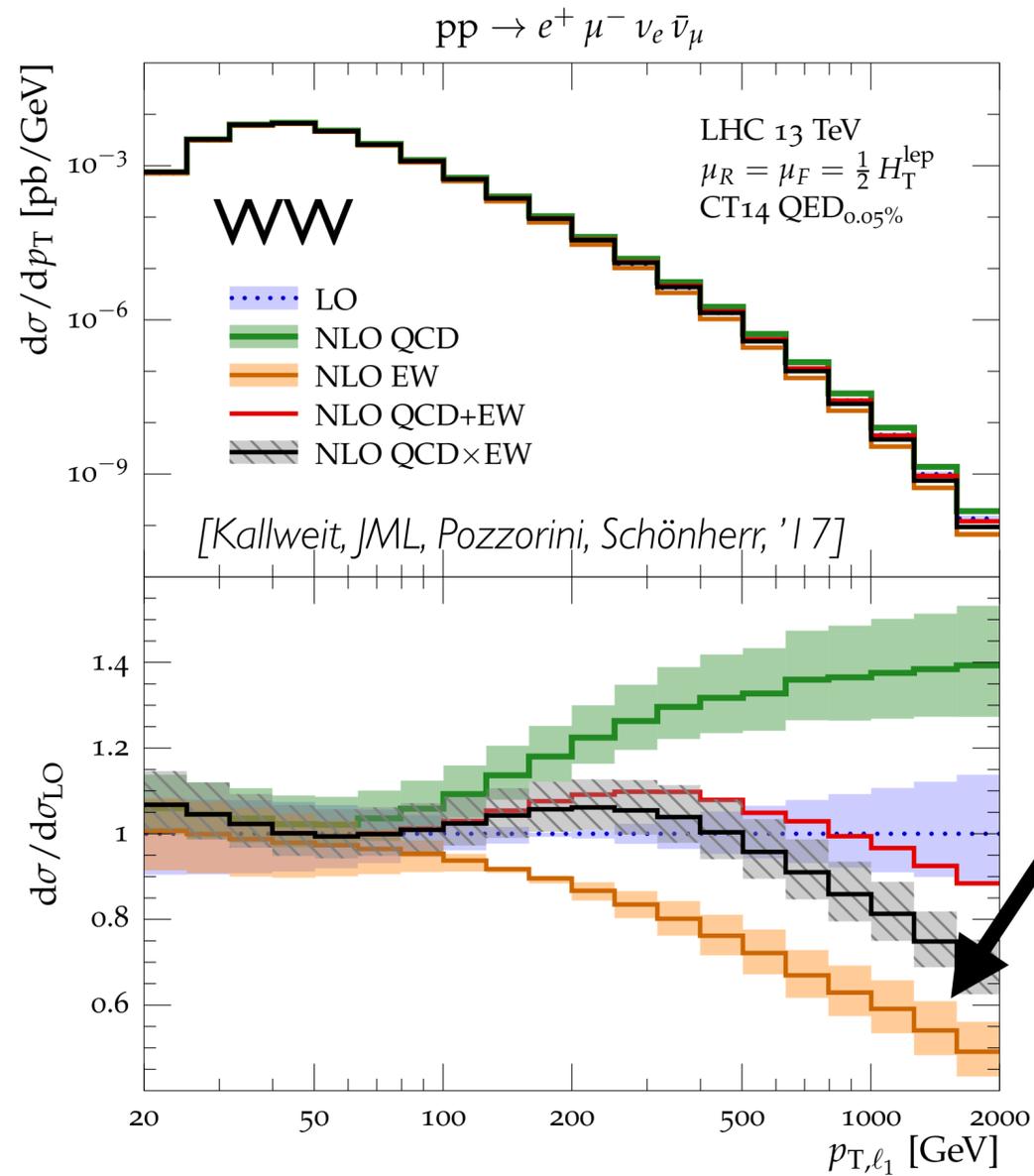
$$+ \alpha_S^2 d\sigma_{\text{NNLO}} + \alpha_{\text{EW}}^2 d\sigma_{\text{NNLO EW}} + \alpha_S \alpha_{\text{EW}} d\sigma_{\text{NNLO QCD} \times \text{EW}}$$

$$\begin{aligned} \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\mu g_\nu^\rho \partial_\nu g_\mu^\rho - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\mu W_\nu^+ \partial_\nu W_\mu^- \\ & - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}M_Z^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\nu A_\mu - ig_{cw}(\partial_\nu W_\mu^+ W_\nu^- - W_\nu^+ \partial_\mu W_\mu^-) \\ & - Z_\mu^0(W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+) + Z_\mu^0(W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+) - \\ & ig_{sw}(\partial_\nu A_\mu(W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu(W_\mu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+) + A_\nu(W_\nu^+ \partial_\nu W_\mu^- \\ & - W_\nu^- \partial_\mu W_\mu^+) - \frac{1}{2}g^2 W_\mu^+ W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\nu^+ Z_\nu^0 W_\mu^- \\ & - Z_\nu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\nu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\nu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\nu^+ W_\nu^- \\ & - W_\nu^+ W_\nu^-) - 2A_\mu Z_\nu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\nu \phi^0 \partial_\nu \phi^0 \\ & - \beta_h \left( \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\ & \frac{g\alpha_h M}{2} (H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\ & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\ & gMW_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \\ & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\ & \frac{1}{2}g (W_\mu^+ (H\partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H\partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{M}{c_w} (Z_\mu^0 (H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\ & M (\frac{1}{c_w} Z_\mu^0 \partial_\nu \phi^0 + W_\mu^+ \partial_\nu \phi^- + W_\mu^- \partial_\nu \phi^+) - ig \frac{M}{c_w} Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig_{sw} M A_\mu (W_\mu^+ \phi^- \\ & - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig_{sw} A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\ & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\nu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\ & \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{2s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\nu \phi^+ \phi^- - \\ & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_{ij}^a (\bar{q}_i^c \gamma^\mu q_j^c) g_\mu^a - e^2 (\gamma^\mu + m_\nu^2) e^\nu - \bar{\nu}^\lambda (\gamma^\mu + m_\nu^2) \nu^\lambda - \bar{u}_j^3 (\gamma^\mu + \\ & m_u^2) u_j^3 - \bar{d}_j^3 (\gamma^\mu + m_d^2) d_j^3 + ig_{sw} A_\mu (-e^2 \gamma^\mu e^\lambda + \frac{2}{3}(\bar{u}_j^3 \gamma^\mu u_j^3) - \frac{1}{3}(\bar{d}_j^3 \gamma^\mu d_j^3)) + \\ & \frac{ig}{4c_w} Z_\mu^0 (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^2 \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^3 \gamma^\mu (\frac{2}{3}s_w^2 - 1 - \gamma^5) d_j^3) + \\ & (\bar{u}_j^3 \gamma^\mu (1 - \frac{2}{3}s_w^2 + \gamma^5) u_j^3)) + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep} e^\nu) + (\bar{u}_j^3 \gamma^\mu (1 + \gamma^5) C_{\lambda c} d_j^3)) + \\ & \frac{ig}{2\sqrt{2}} W_\mu^- ((e^2 U^{lep} \kappa_\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^3 C_{\lambda c}^\dagger \gamma^\mu (1 + \gamma^5) u_j^3)) + \\ & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\nu^2 (\bar{\nu}^\lambda U^{lep} \lambda_\nu (1 - \gamma^5) e^\nu) + m_\nu^2 (\bar{\nu}^\lambda U^{lep} \lambda_\nu (1 + \gamma^5) e^\nu) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_\nu^2 (e^\lambda U^{lep} \lambda_\nu (1 + \gamma^5) \nu^\lambda) - m_\nu^2 (e^\lambda U^{lep} \lambda_\nu (1 - \gamma^5) \nu^\lambda) - \frac{g}{M} M_{\lambda c}^R H (\bar{\nu}^\lambda \nu^\lambda) - \\ & \frac{g}{M} M_{\lambda c}^L H (e^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (e^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda c}^R (1 - \gamma_5) \nu_\lambda - \\ & \frac{1}{4} \bar{\nu}_\lambda M_{\lambda c}^L (1 - \gamma_5) \nu_\lambda + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\nu^2 (\bar{u}_j^3 C_{\lambda c} (1 - \gamma^5) d_j^3) + m_\nu^2 (\bar{u}_j^3 C_{\lambda c} (1 + \gamma^5) d_j^3) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_\nu^2 (\bar{d}_j^3 C_{\lambda c}^\dagger (1 + \gamma^5) u_j^3) - m_\nu^2 (\bar{d}_j^3 C_{\lambda c}^\dagger (1 - \gamma^5) u_j^3) - \frac{g}{M} M_{\lambda c}^L H (\bar{u}_j^3 u_j^3) - \\ & \frac{g}{M} M_{\lambda c}^R H (\bar{d}_j^3 d_j^3) + \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{u}_j^3 \gamma^5 u_j^3) - \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{d}_j^3 \gamma^5 d_j^3) + \bar{C}^a \partial^2 C^a + g_s f^{abc} \partial_\mu \bar{C}^a G_\mu^b g_\mu^c + \\ & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig_{cw} W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\ & \partial_\mu \bar{X}^+ X^0) + ig_{sw} W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + ig_{cw} W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\ & \partial_\mu \bar{X}^0 X^+) + ig_{sw} W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig_{cw} Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \\ & \partial_\mu \bar{X}^- X^+) + ig_{sw} A_\mu (\partial_\mu \bar{X}^+ X^- - \\ & \partial_\mu \bar{X}^- X^+) - \frac{1}{2}gM (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\ & \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\ & \frac{1}{2}igM (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) . \end{aligned}$$

$$\hookrightarrow |\mathcal{M}|^2 \hookrightarrow \sigma$$

# Relevance of EW higher-order corrections: Sudakov logs in the tails

I. Possible large (negative) enhancement due to soft/collinear **logs** from virtual EW gauge bosons:



[Ciafaloni, Comelli, '98;  
 Lipatov, Fadin, Martin, Melles, '99;  
 Kuehen, Penin, Smirnov, '99;  
 Denner, Pozzorini, '00]

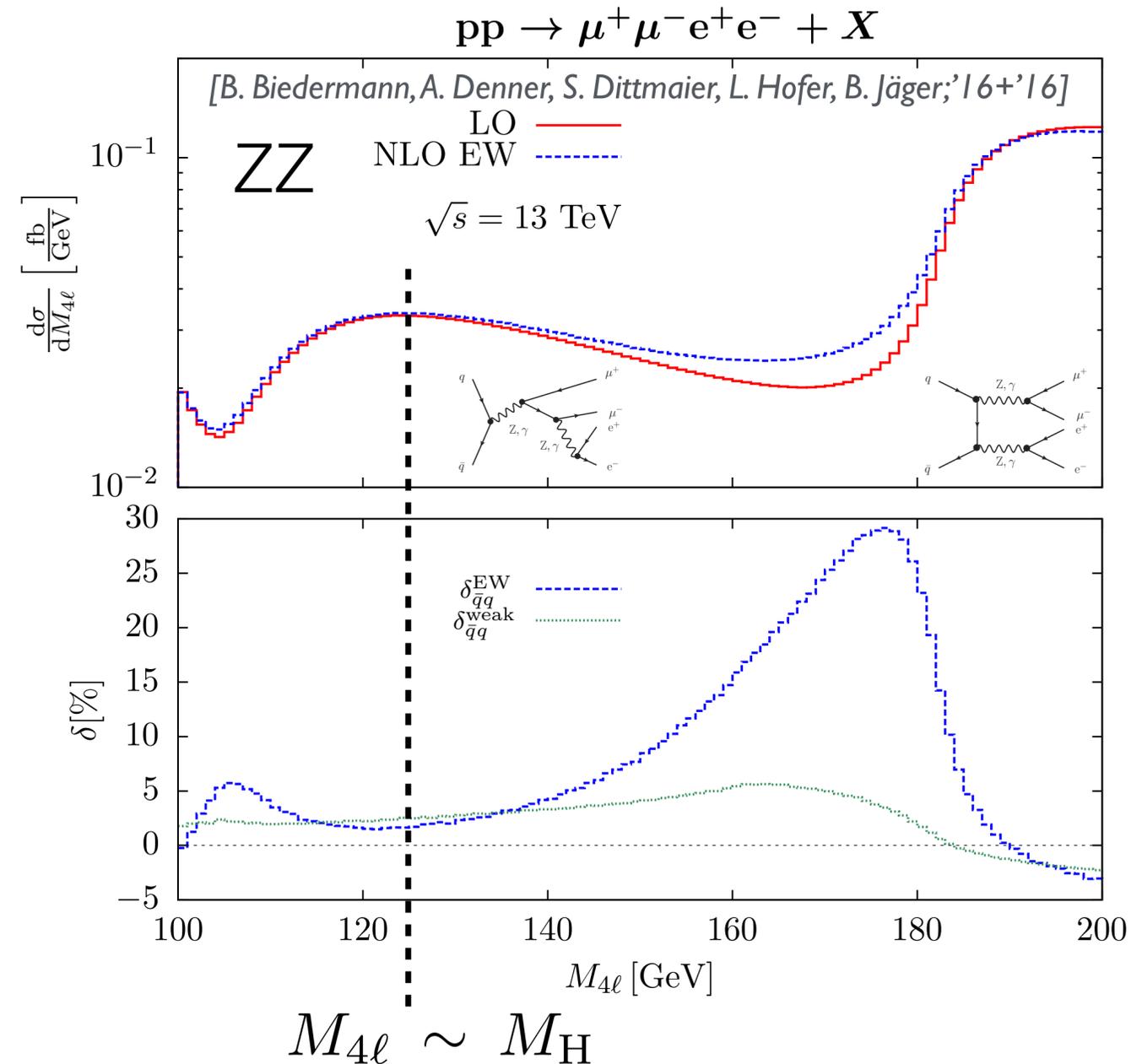
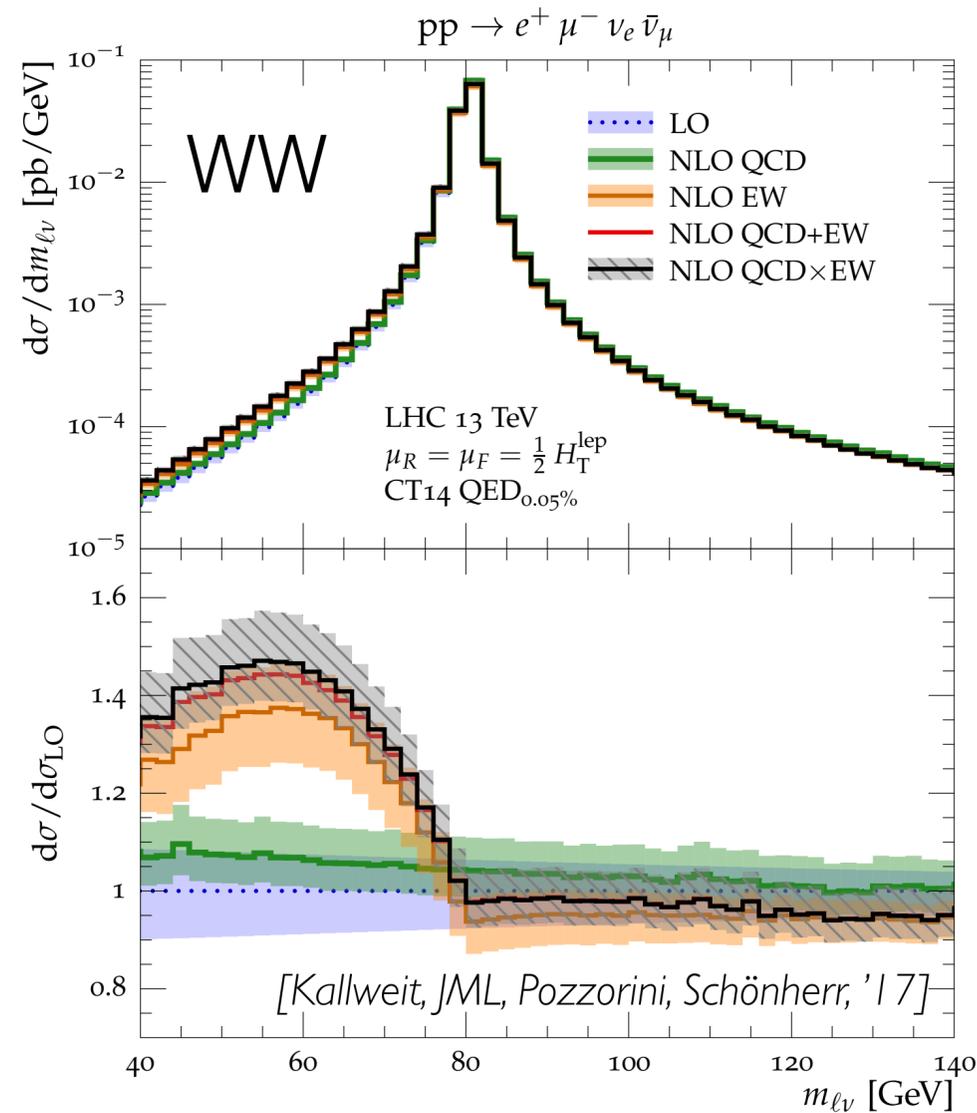
Universality and factorisation: [Denner, Pozzorini, '01]

$$\delta \mathcal{M}_{\text{LL+NLL}}^{1\text{-loop}} = \frac{\alpha}{4\pi} \sum_{k=1}^n \left\{ \frac{1}{2} \sum_{l \neq k} \sum_{a=\gamma, Z, W^\pm} I^a(k) I^{\bar{a}}(l) \ln^2 \frac{\hat{s}_{kl}}{M^2} + \gamma^{\text{ew}}(k) \ln \frac{\hat{s}}{M^2} \right\} \mathcal{M}_0$$

→ overall large (negative) effect in the tails of distributions:  
 $p_T, m_{\text{inv}}, H_T, \dots$  (relevant for BSM searches!)

# Relevance of EW higher-order corrections: collinear QED radiation

- II. Possible large enhancement due to soft/collinear **logs** from photon radiation  $\sim \alpha \log\left(\frac{m_f^2}{Q^2}\right)$  in sufficiently exclusive observables.



→ important for radiative tails, Higgs backgrounds etc.

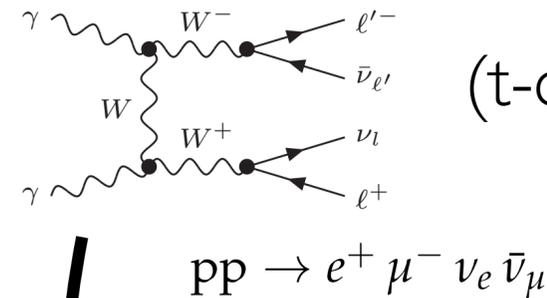
→ typically considered via QED PS (PHOTOS / YFS)

# Relevance of EW higher-order corrections: photon-induced channels

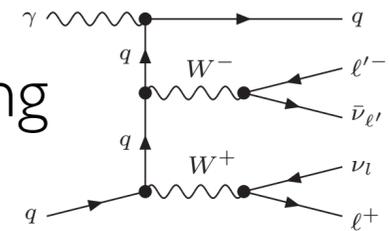
III. QED factorisation and thus photon luminosities needed to absorb IS photon singularities.

→ Possible large enhancement due to photon-induced channels in the tails of kinematic distributions,

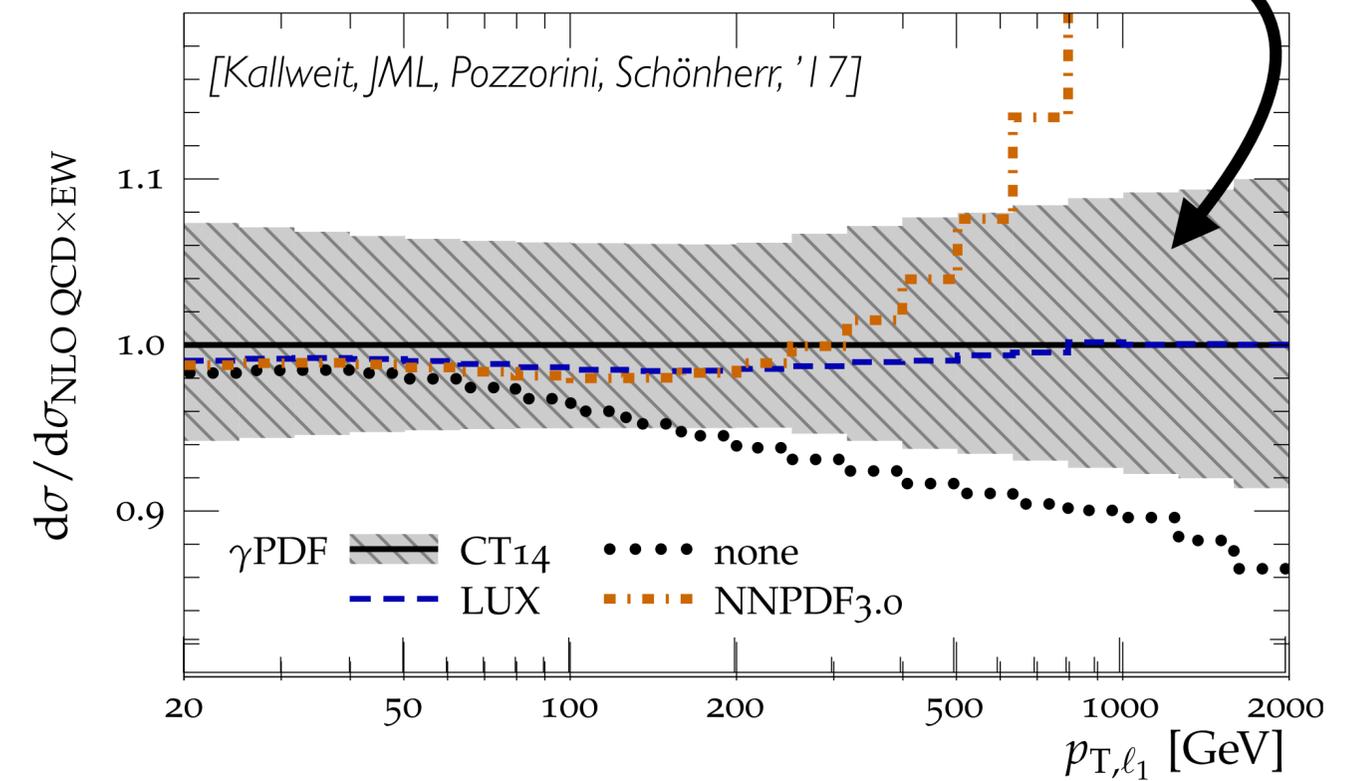
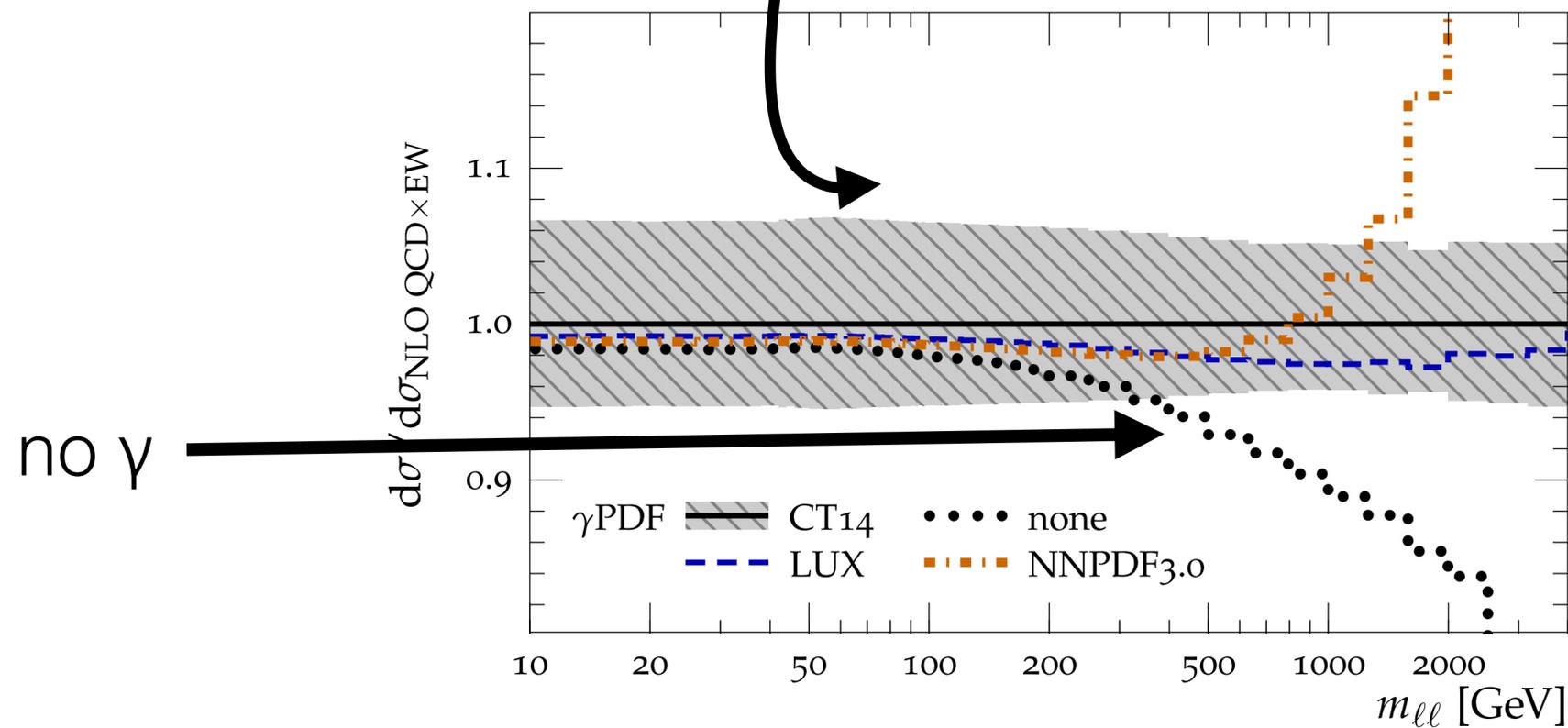
in particular in WW:



(t-channel enhancement), but also in Bremsstrahlung



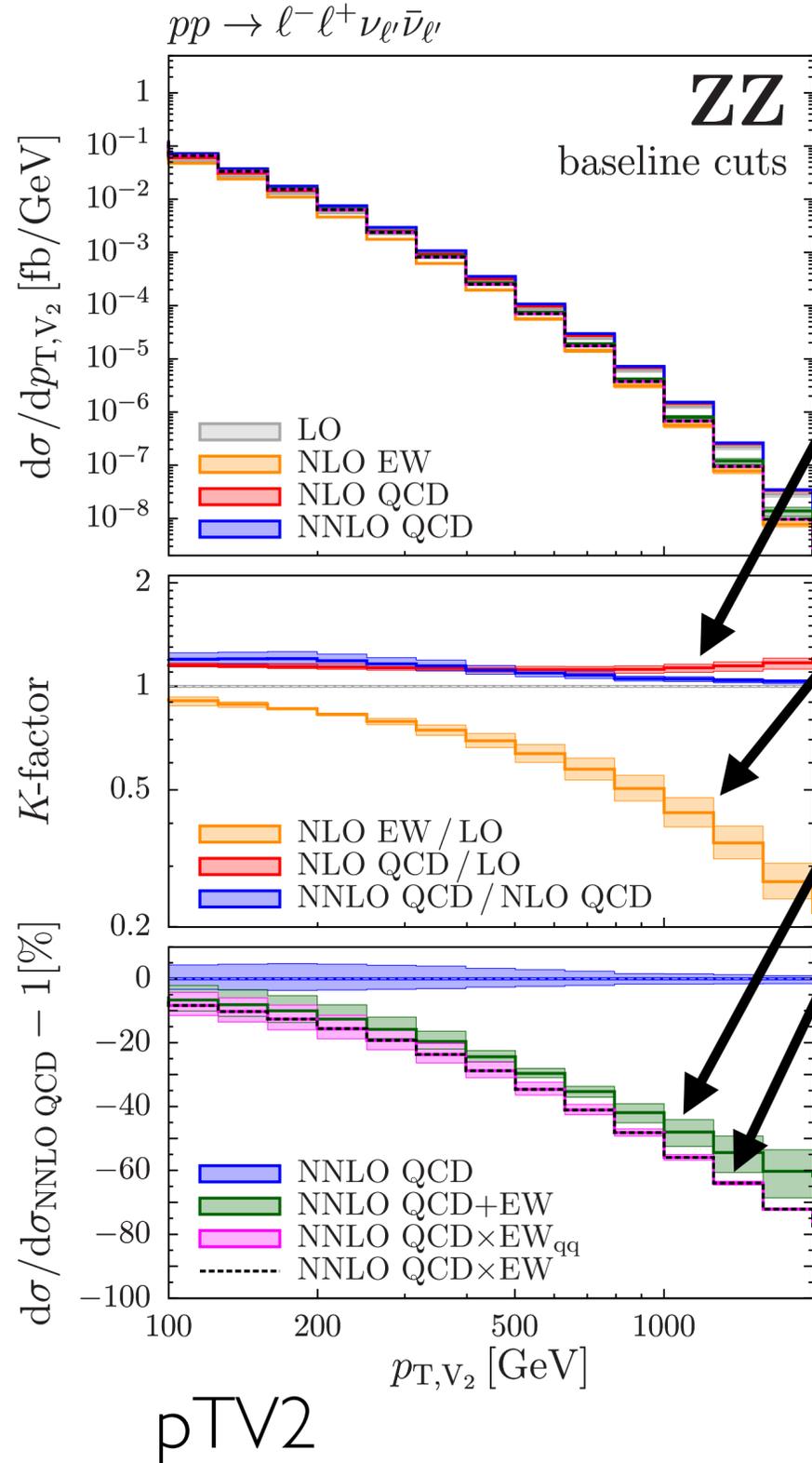
$$d\sigma_{\text{LO}} = d\sigma_{\text{LO}}^{q\bar{q}} + d\sigma_{\text{LO}}^{\gamma\gamma}$$



→ O(10%) contributions from photon-induced channels

# NNLO QCD + NLO EW for dibosons: pTV2

[M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; 1912.00068]



- moderate QCD corrections
  - ▶ NNLO/NLO QCD very small at large pTV2
  - ▶ NNLO QCD uncertainty: few percent
- NLO EW/LO = -(50-60)% @ 1 TeV

NNLO QCD + NLO EW in Matrix+OpenLoops		
4l-SF-ZZ	$pp \rightarrow l^+ l^- l^+ l^-$	ZZ
4l-DF-ZZ	$pp \rightarrow l^+ l^- l'^+ l'^-$	ZZ
3l-SF-WZ	$pp \rightarrow l^+ l^- l \nu_e$	WZ
3l-DF-WZ	$pp \rightarrow l^+ l^- l' \nu_e$	WZ
2l-SF-ZZ	$pp \rightarrow l^+ l^- \nu_e \bar{\nu}_e$	ZZ
2l-SF-ZZWW	$pp \rightarrow l^+ l^- \nu_e \bar{\nu}_e$	ZZ, WW
2l-DF-WW	$pp \rightarrow l^+ l^- \nu_e \bar{\nu}_e$	WW

$$d\sigma_{\text{NNLO QCD+EW}} = d\sigma_{\text{LO}} (1 + \delta_{\text{QCD}} + \delta_{\text{EW}}) + d\sigma_{\text{LO}}^{gg}$$

$$d\sigma_{\text{NNLO QCD} \times \text{EW}} = d\sigma_{\text{LO}} (1 + \delta_{\text{QCD}}) (1 + \delta_{\text{EW}}) + d\sigma_{\text{LO}}^{gg}$$

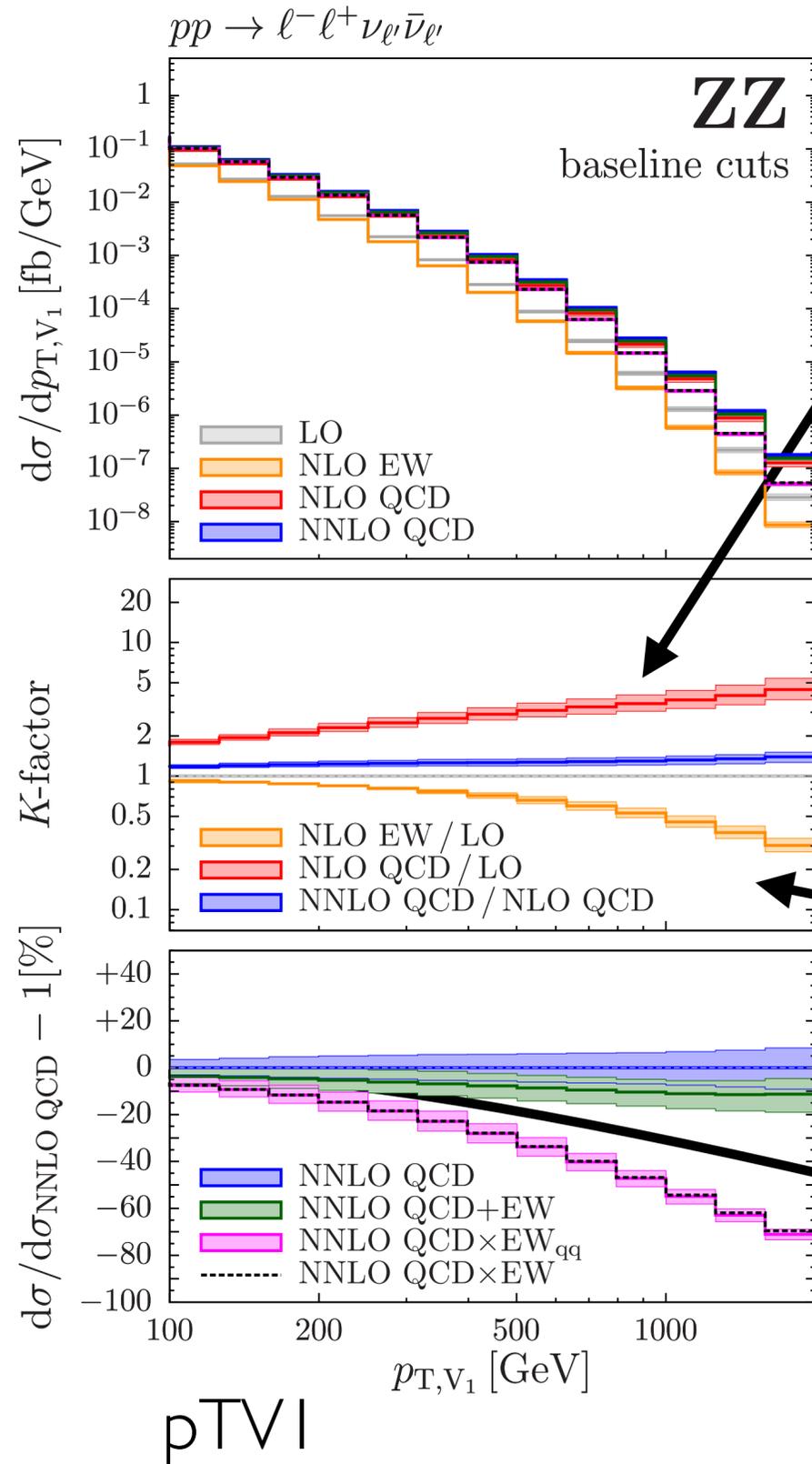
$$= d\sigma_{\text{NNLO QCD+EW}} + d\sigma_{\text{LO}} \delta_{\text{QCD}} \delta_{\text{EW}}$$

- difference very conservative upper bound on  $\mathcal{O}(\alpha_s \alpha)$
- multiplicative/factorised combination clearly superior (EW Sudakov logs x soft QCD)
- dominant uncertainty at large pTV2:  $\mathcal{O}(\alpha^2) \sim \alpha_w^2 \log^4(Q^2/M_W^2)$

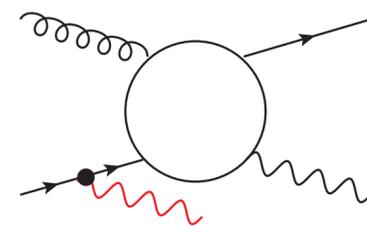
Estimate:  $\frac{1}{2} \delta_{\text{EW}}^2$

# Giant QCD K-factors and EW corrections: pTVI

[M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; 1912.00068]



- NLO QCD/LO=2-5! (“giant K-factor”)
- at large pTVI: VV phase-space is dominated by V+jet (w/ soft V radiation)



$$\frac{d\sigma^{V(V)j}}{d\sigma_{VV}^{\text{LO}}} \propto \alpha_S \log^2 \left( \frac{Q^2}{M_W^2} \right) \simeq 3 \quad \text{at } Q = 1 \text{ TeV}$$

- NNLO / NLO QCD moderate and NNLO uncert. 5-10%
- NLO EW/LO=-(40-50)%

• Very large difference  $d\sigma_{\text{NNLO QCD+EW}}$  vs.  $d\sigma_{\text{NNLO QCD} \times \text{EW}}$

• Problems:

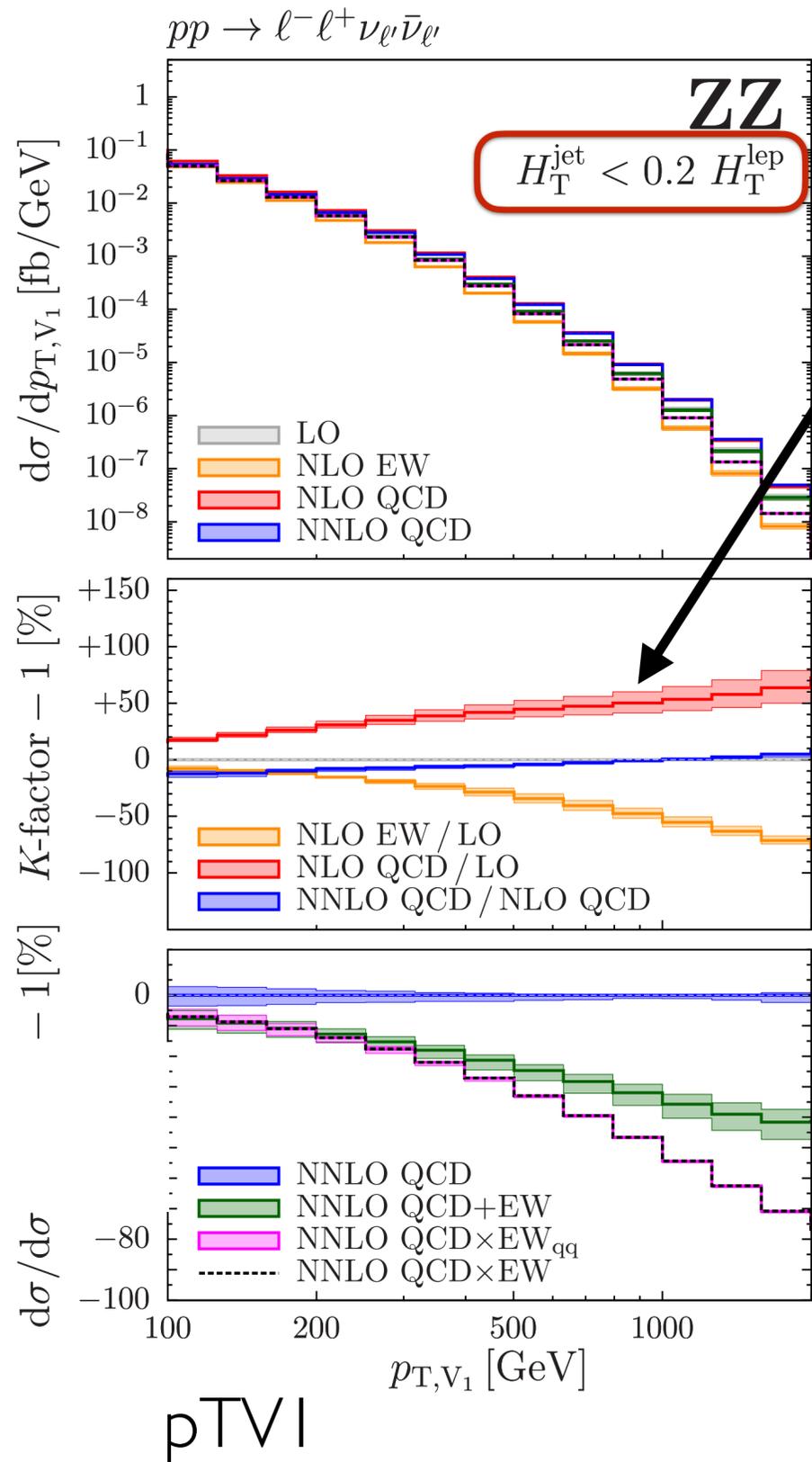
1. In additive combination dominant Vj topology does not receive any EW corrections
2. In multiplicative combination EW correction for VV is applied to Vj hard process

- **Pragmatic solution I: take average as nominal and spread as uncertainty**
- **Pragmatic solution II: apply jet veto to constrain Vj topologies**

• **Rigorous solution: merge VVj incl. EW corrections with VV retaining NNLO QCD + EW**

# Giant QCD K-factors and EW corrections: pTVI

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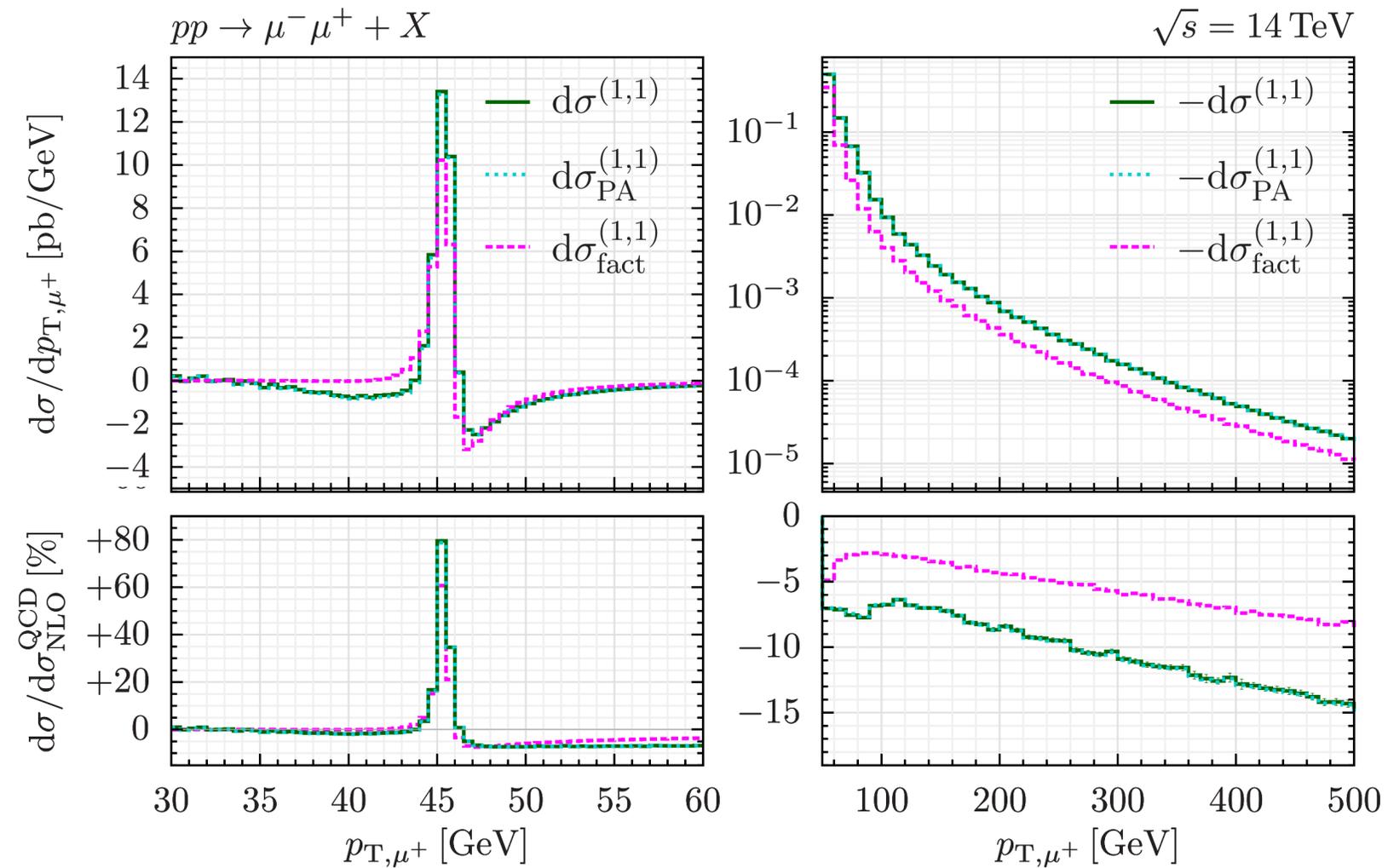
- NLO QCD/LO =  $\sim < 1.5$  ("normal K-factor")
- very small NNLO / NLO QCD corrections and  $\sim 5\%$  NNLO uncert

- Problems:
  1. In additive combination dominant Vj topology does not receive any EW corrections
  2. In multiplicative combination EW correction for VV is applied to Vj hard process
- Pragmatic solution I: **take average as nominal and spread as uncertainty**
- Pragmatic solution II: **apply jet veto to constrain Vj topologies**
- Rigorous solution: **merge VVj incl. EW corrections with VV retaining NNLO QCD + EW**

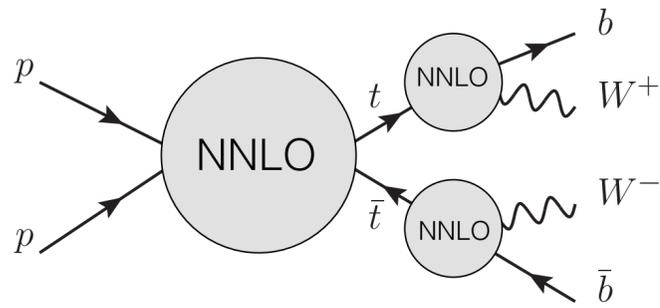


# Mixed QCD-EW corrections to NC-DY production: beyond the pole approximation

[Bonciani, Buonocore, Grazzini, Kallweit et. al. '21]



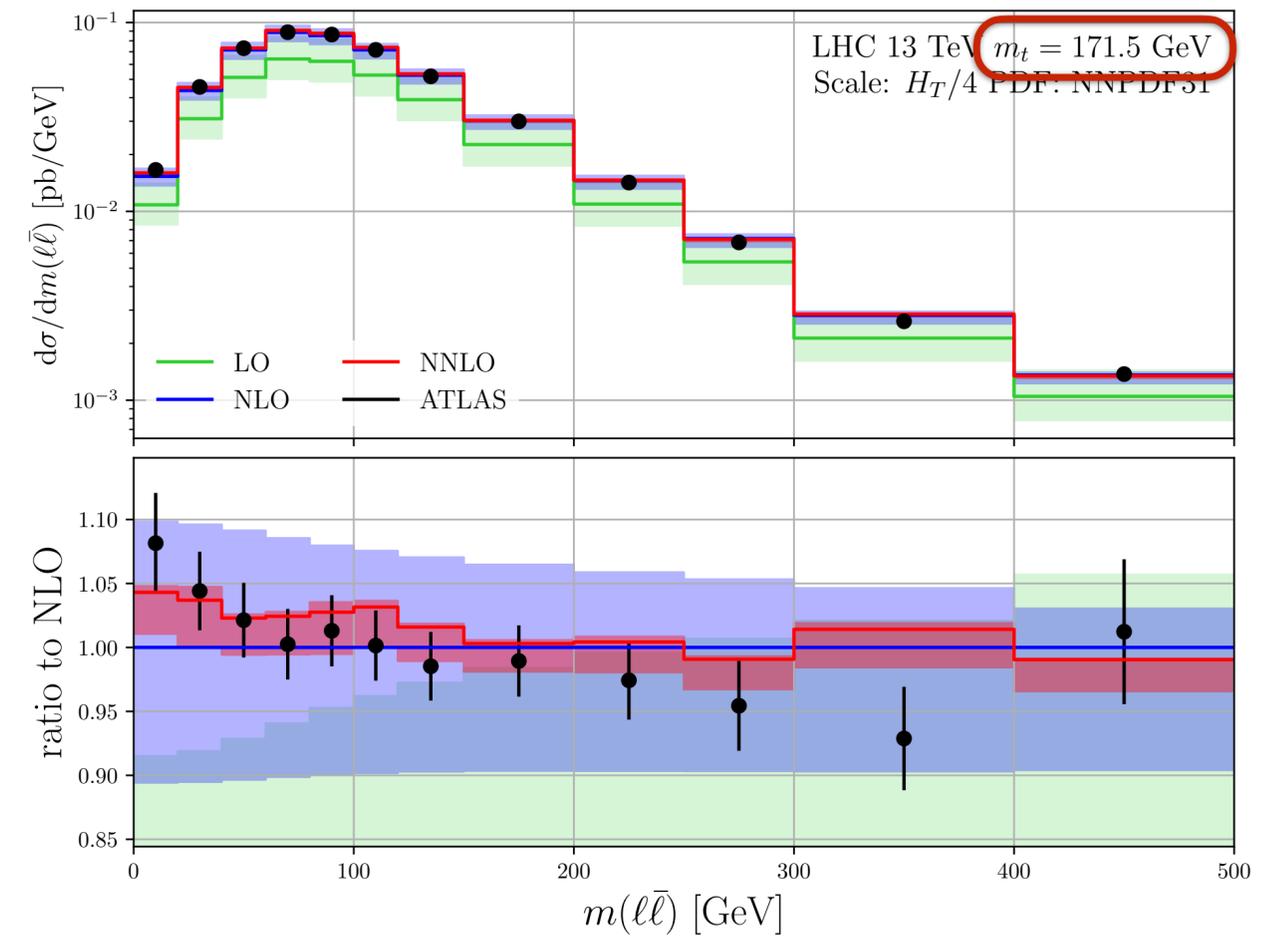
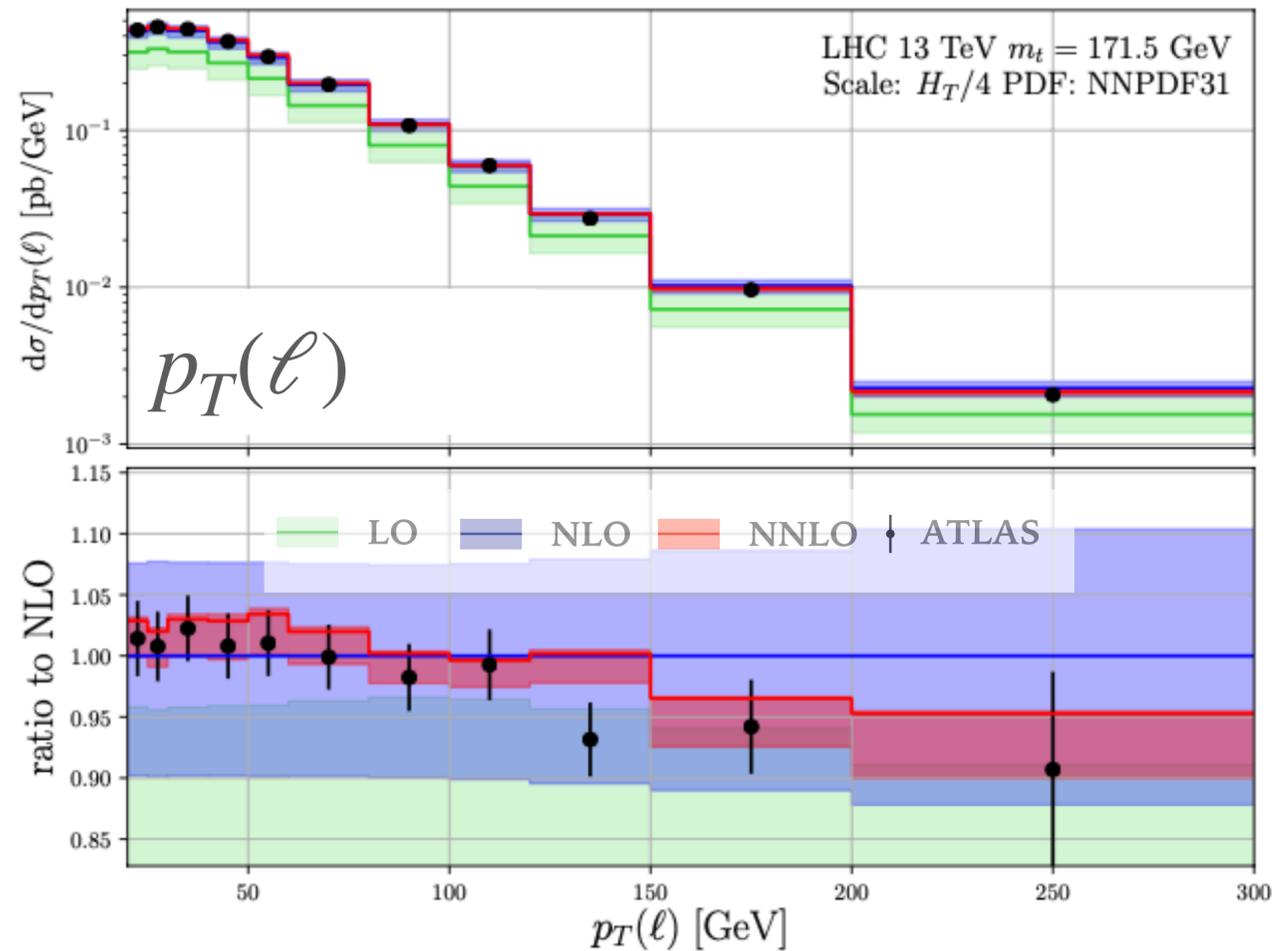
- ▶ Comparison against naive factorised NLO QCD  $\times$  NLO EW ansatz: fail at the 5-10% level
- ▶ pole approximation vs. full computation: agree below the percent level



# Top-quark spin correlations at NNLO

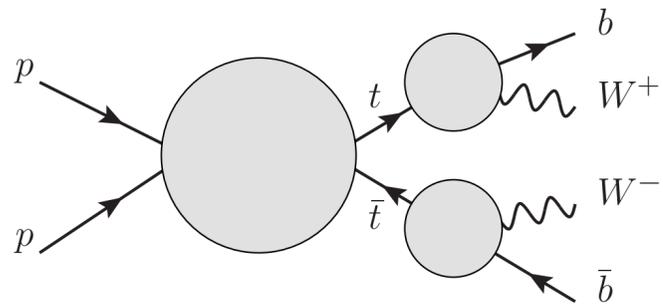
[Czakon, Mitov, Poncelet `20]

$$pp \rightarrow t\bar{t} \rightarrow 2\ell 2\nu b\bar{b}$$



- Small corrections and uncertainties in leptonic observables
- Excellent data-theory agreement

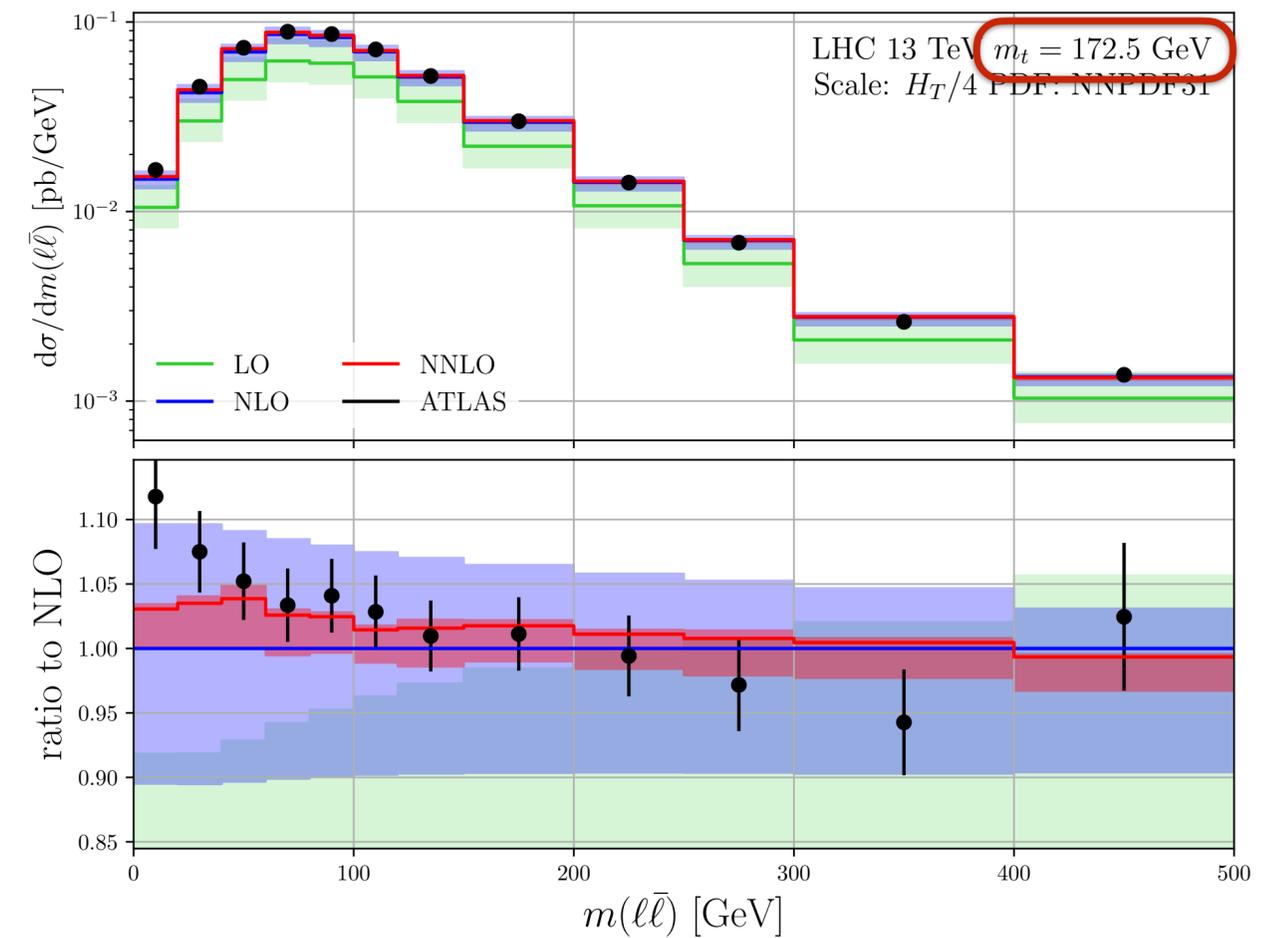
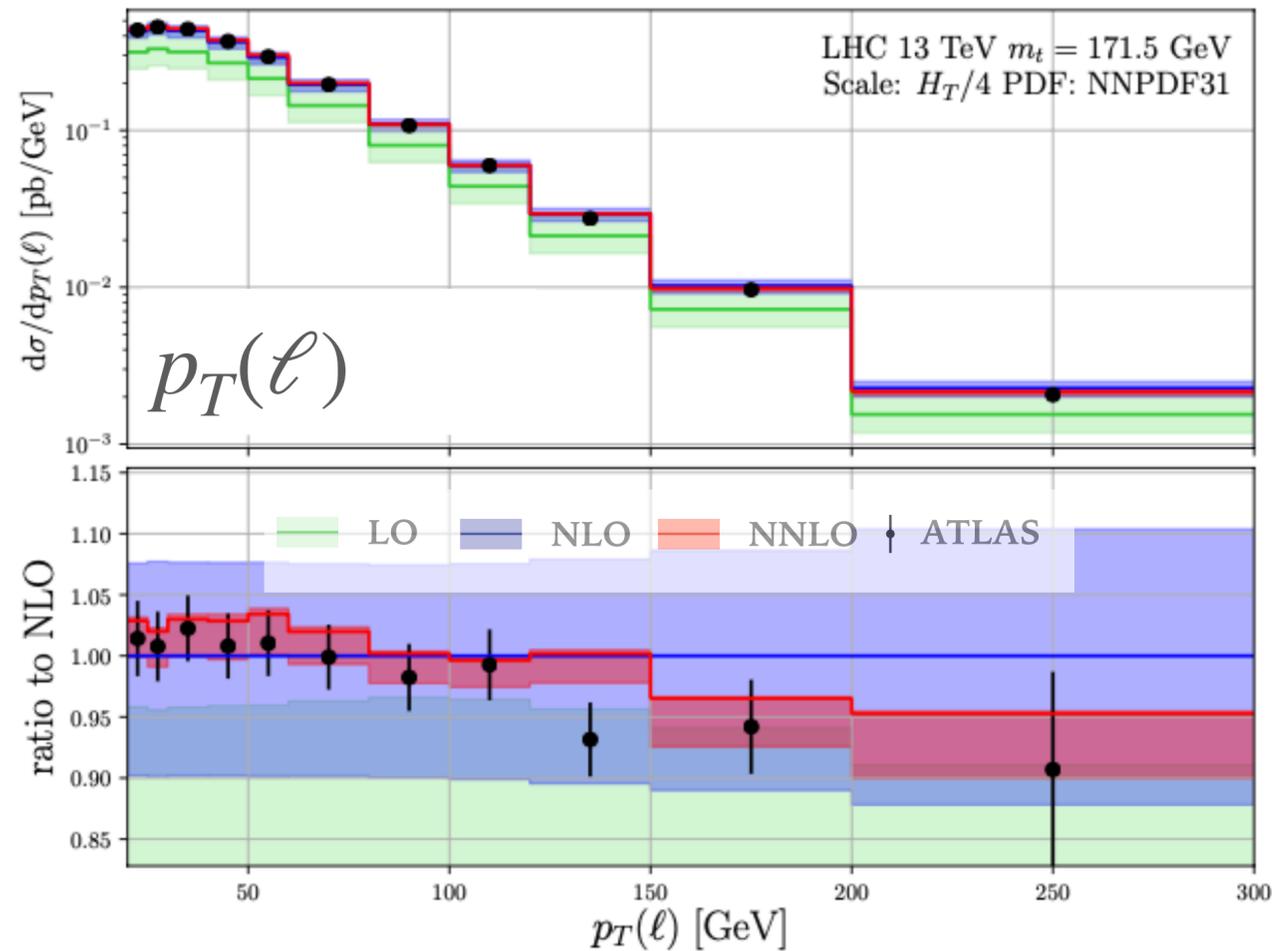
- Might allow for an additional handle on  $M_{\text{top}}$
- Need to understand systematics at small  $m_{\ell\bar{\ell}}$  (EW corrections, finite width effects, ...)



# Top-quark spin correlations at NNLO

[Czakon, Mitov, Poncelet `20]

$$pp \rightarrow t\bar{t} \rightarrow 2\ell 2\nu b\bar{b}$$

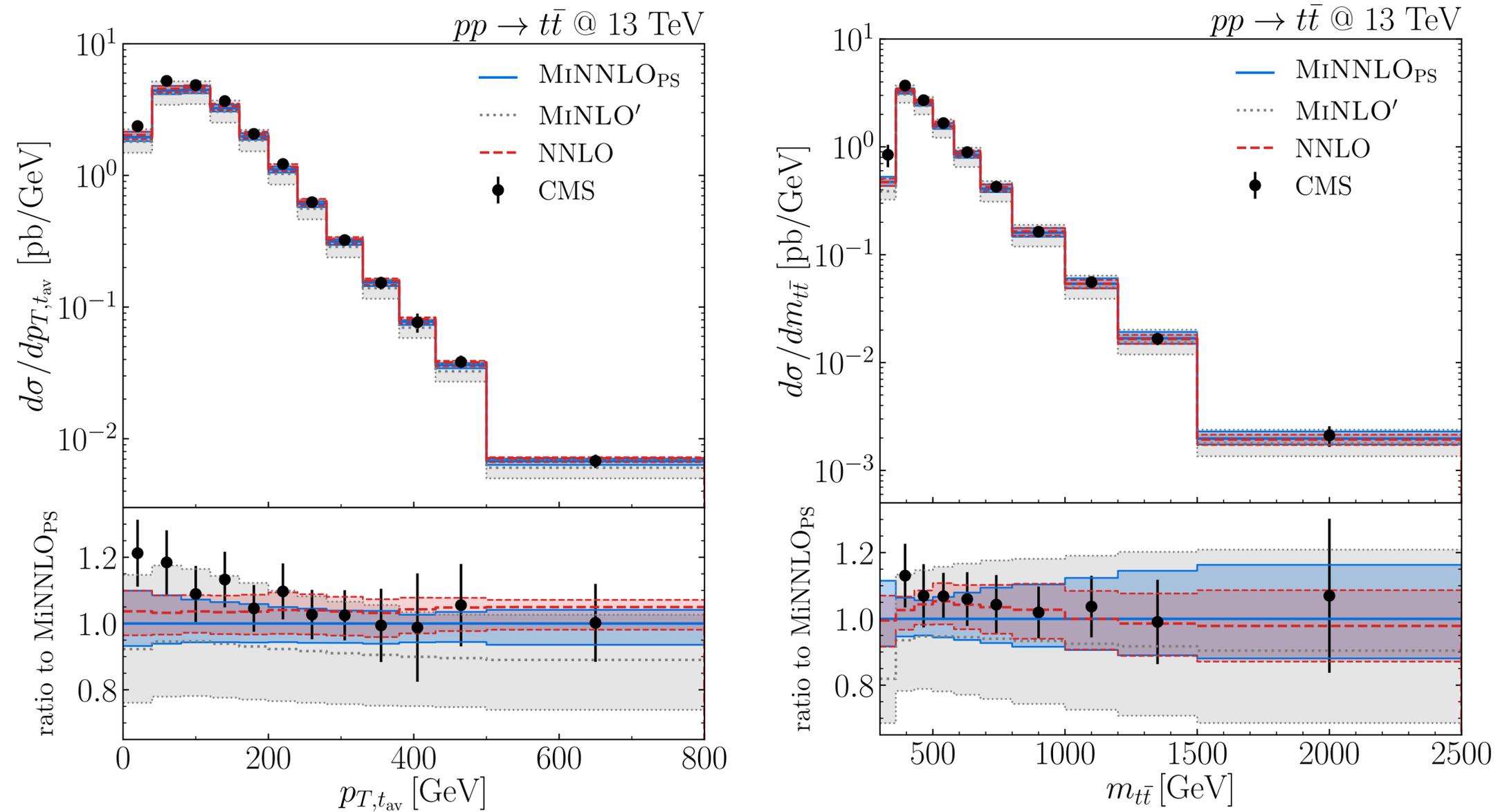


- Small corrections and uncertainties in leptonic observables
- Excellent data-theory agreement

- Might allow for an additional handle on  $M_{\text{top}}$
- Need to understand systematics at small  $m_{ll}$  (EW corrections, finite width effects, ...)

# Top-quark pair production at NNLO+PS

[Mazzitelli, Monni, Nason, Re. Wiesemann, Zanderighi '20]

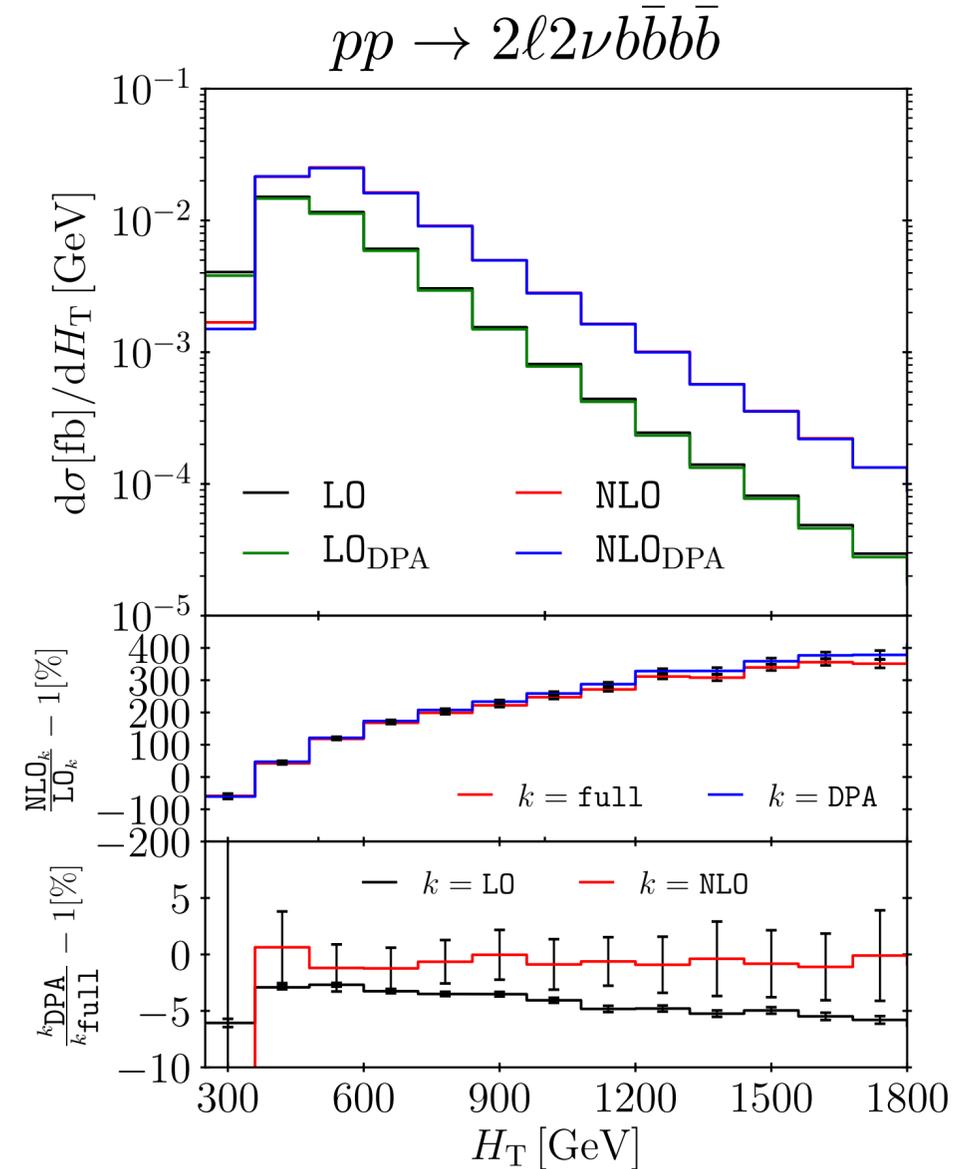
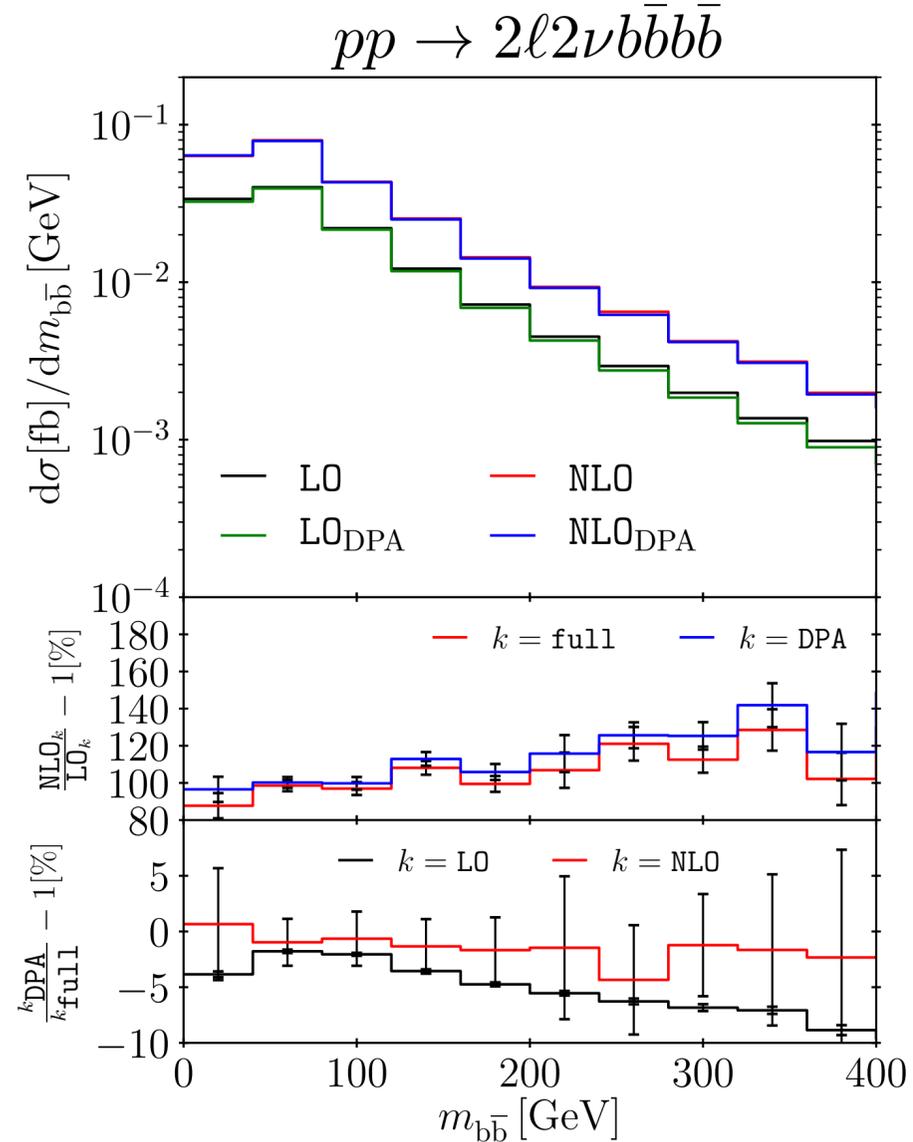
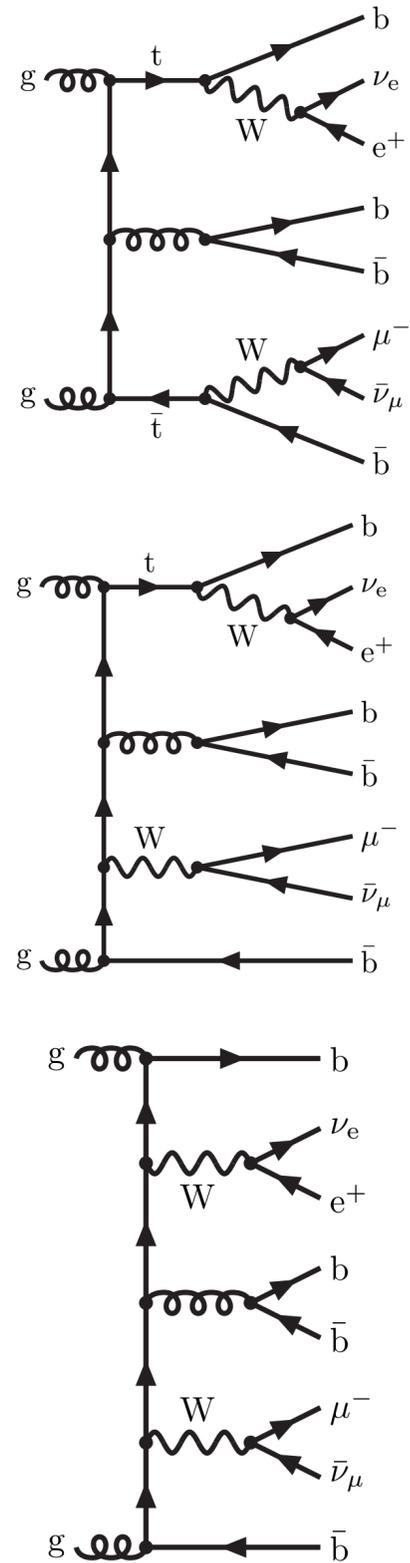


- Requires highly non-trivial extension of MiNNLO<sub>PS</sub> method to final state radiation
- NNLO accuracy mandatory given data accuracy
- Allows for NNLO top-pair production at detector level

# $t\bar{t}b\bar{b}$ x decays @ NLO: precision for the highest multiplicities

[Denner, Lang, Pellen '20]

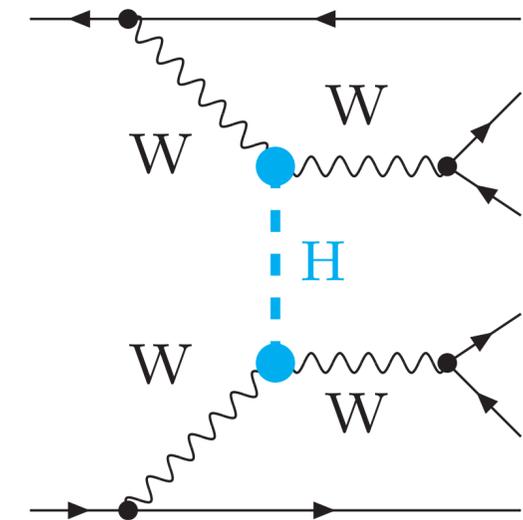
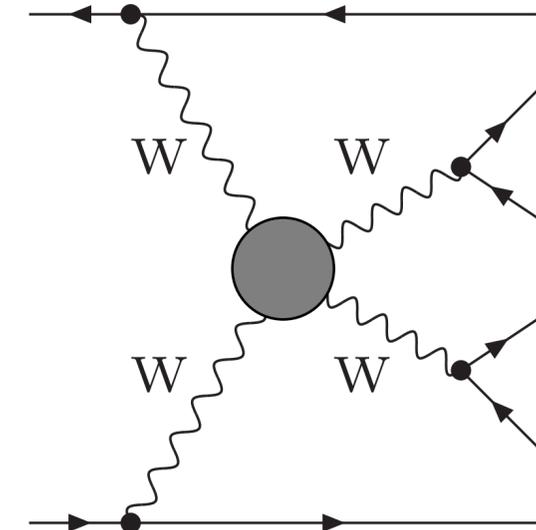
[Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, '21]



- Thorough understanding of theory systematics in this channel crucial for  $t\bar{t}H$  measurements where  $H \rightarrow b\bar{b}$
- $t\bar{t}b\bar{b}$  receives sizeable QCD corrections
- Very important confirmation of  $(t\bar{t}b\bar{b})$  double pole approximation

# Vector-boson scattering

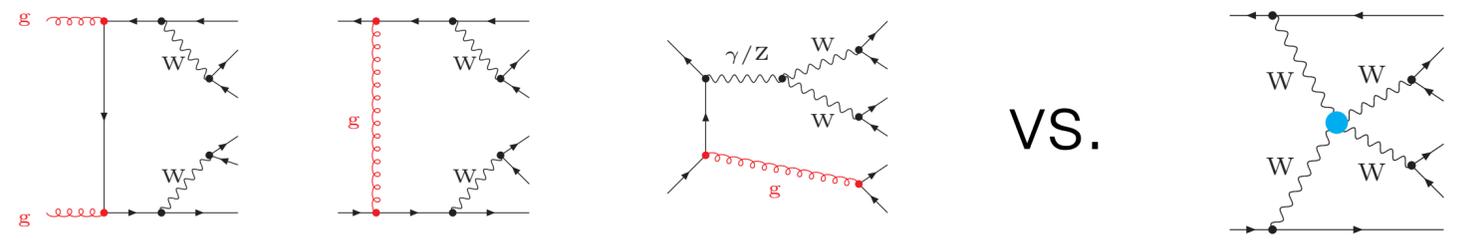
- direct access to quartic EW gauge couplings
- VBS: longitudinal gauge bosons at high energies
- window to electroweak symmetry breaking via off-shell Higgs exchange



# Perturbative expansion revised: VBF-V, VBS-W

$$\begin{aligned}
 \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- \\
 & - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - ig_{cw}(\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\nu^- - W_\mu^- \partial_\nu W_\nu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\nu^+)) \\
 & - ig_{sw}(\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\nu (W_\nu^+ \partial_\mu W_\nu^- - \\
 & W_\nu^- \partial_\mu W_\nu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^+ W_\mu^- + \frac{1}{2}g^2 W_\mu^- W_\nu^+ W_\nu^- W_\mu^+ + g^2 s_w^2 (Z_\mu^0 W_\nu^+ Z_\nu^0 W_\mu^- - \\
 & Z_\mu^0 W_\nu^- Z_\nu^0 W_\mu^+) + g^2 s_w^2 (A_\mu W_\nu^+ A_\nu W_\mu^- - A_\mu A_\nu W_\nu^+ W_\mu^-) + g^2 s_w c_w (A_\mu Z_\mu^0 (W_\nu^+ W_\nu^- - \\
 & W_\nu^+ W_\nu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
 & \beta_h \left( \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^4} \alpha_h - \\
 & \frac{g\alpha_h M}{3} (H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\
 & \frac{1}{3}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
 & g M W_\mu^+ W_\nu^- H - \frac{1}{2}g \frac{M}{g_w} Z_\mu^0 Z_\nu^0 H - \\
 & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
 & \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
 & M (\frac{1}{c_w} Z_\mu^0 \partial_\nu \phi^0 + W_\mu^+ \partial_\nu \phi^- + W_\mu^- \partial_\nu \phi^+) - ig_{cw} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig_{sw} M A_\mu (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) - ig \frac{1-2s_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig_{sw} A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{2}g^2 W_\mu^+ W_\nu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\nu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\
 & \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\nu \phi^+ \phi^- - \\
 & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_\nu^a (\bar{q}^i \gamma^\mu q_j^i) g_\nu^a - e^2 (\gamma^\mu + m_\nu^2) e^\lambda - \bar{\nu}^\lambda (\gamma^\mu + m_\nu^2) \nu^\lambda - \bar{u}_j^\lambda (\gamma^\mu + \\
 & m_\nu^2) u_j^\lambda - \bar{d}_j^\lambda (\gamma^\mu + m_\nu^2) d_j^\lambda + ig_{sw} A_\mu (-e^\lambda \gamma^\mu e^\lambda + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)) + \\
 & \frac{ig}{c_w} Z_\mu^0 \{ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{2}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{2}{3}s_w^2 + \gamma^5) u_j^\lambda) \} + \frac{ig}{2s_w} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep} \lambda_\nu e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\nu} d_j^\lambda)) + \\
 & \frac{ig}{2\sqrt{2}} W_\mu^- ((e^\lambda U^{lep} \lambda_\nu \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda C_{\lambda\nu} \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\nu^2 (\bar{\nu}^\lambda U^{lep} \lambda_\nu (1 + \gamma^5) \nu^\lambda) + m_\nu^2 (\bar{\nu}^\lambda U^{lep} \lambda_\nu (1 + \gamma^5) e^\lambda) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_\nu^2 (\bar{e}^\lambda U^{lep} \lambda_\nu (1 + \gamma^5) \nu^\lambda) - m_\nu^2 (\bar{e}^\lambda U^{lep} \lambda_\nu (1 - \gamma^5) \nu^\lambda) - \frac{g}{2} \frac{m_\nu^2}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
 & \frac{g}{2} \frac{m_\nu^2}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{2} \bar{\nu}_\lambda M_{\lambda\nu}^R (1 - \gamma_5) \nu_\lambda - \\
 & \frac{1}{2} \bar{\nu}_\lambda M_{\lambda\nu}^L (1 - \gamma_5) \nu_\lambda + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\nu^2 (\bar{u}_j^\lambda C_{\lambda\nu} (1 - \gamma^5) d_j^\lambda) + m_\nu^2 (\bar{u}_j^\lambda C_{\lambda\nu} (1 + \gamma^5) d_j^\lambda) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_\nu^2 (\bar{d}_j^\lambda C_{\lambda\nu} (1 + \gamma^5) u_j^\lambda) - m_\nu^2 (\bar{d}_j^\lambda C_{\lambda\nu} (1 - \gamma^5) u_j^\lambda) - \frac{g}{2} \frac{m_\nu^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
 & \frac{g}{2} \frac{m_\nu^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + G^a \partial^2 G^a + g_s f^{abc} \partial_\mu G^a G^b G_\mu^c + \\
 & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig_{cw} W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
 & \partial_\mu \bar{X}^+ X^0) + ig_{sw} W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + ig_{cw} W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
 & \partial_\mu \bar{X}^0 X^+) + ig_{sw} W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig_{cw} Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \\
 & \partial_\mu \bar{X}^- X^+) + ig_{sw} A_\mu (\partial_\mu \bar{X}^+ X^- + \\
 & \partial_\mu \bar{X}^- X^+) - \frac{1}{2}gM (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H) + \frac{1-2s_w^2}{2c_w} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
 & \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
 & \frac{1}{2}igM (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) .
 \end{aligned}$$

Example: WW+2jets

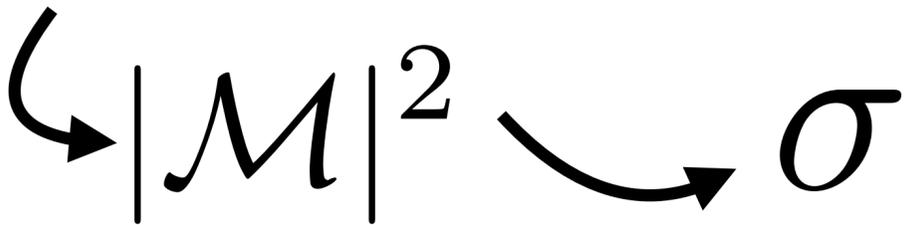


$$d\sigma = d\sigma(\alpha_S^2 \alpha^4) + d\sigma(\alpha_S \alpha^5) + d\sigma(\alpha^6) + \dots$$

QCD-background

interference

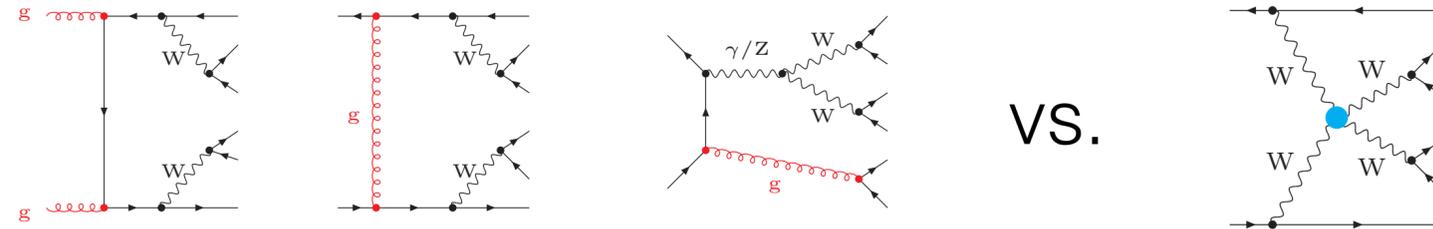
VBS-signal



# Perturbative expansion revised: VBF-V, VBS-W

$$\begin{aligned} \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^\nu \partial_\nu g_\mu^\nu - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- \\ & - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - ig_{cw}(\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\ & W_\mu^- W_\nu^+) - Z_\mu^0 (W_\nu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\nu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\nu^+)) \\ & - ig_{sw}(\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^- W_\mu^+) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+) + A_\nu (W_\nu^+ \partial_\mu W_\mu^- - \\ & W_\nu^- \partial_\mu W_\mu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^- W_\mu^+ + \frac{1}{2}g^2 W_\mu^- W_\nu^+ W_\nu^+ W_\mu^- + g^2 s_w c_w (Z_\mu^0 W_\nu^+ Z_\nu^0 W_\mu^- - \\ & Z_\mu^0 W_\nu^- Z_\nu^0 W_\mu^+) + g^2 s_w^2 (A_\mu W_\nu^+ A_\nu W_\mu^- - A_\mu A_\nu W_\nu^+ W_\mu^-) + g^2 s_w c_w (A_\nu Z_\mu^0 (W_\nu^+ W_\mu^- - \\ & W_\nu^- W_\mu^+) - 2A_\nu Z_\mu^0 W_\nu^+ W_\mu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\ & \beta_h \left( \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^4} \alpha_h - \\ & \frac{g \alpha_h M}{g^2} (H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-) - \\ & \frac{1}{8} g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\ & \frac{g M W_\mu^+ W_\nu^- H - \frac{1}{2} g \frac{M}{g^2} Z_\mu^0 Z_\nu^0 H - \\ & \frac{1}{2} ig (W_\mu^+ (\phi^0 \partial_\nu \phi^- - \phi^- \partial_\nu \phi^0) - W_\mu^- (\phi^0 \partial_\nu \phi^+ - \phi^+ \partial_\nu \phi^0)) + \\ & \frac{1}{2} g (W_\mu^+ (H \partial_\nu \phi^- - \phi^- \partial_\nu H) + W_\mu^- (H \partial_\nu \phi^+ - \phi^+ \partial_\nu H)) + \frac{1}{2} g \frac{1}{c_w} (Z_\mu^0 (H \partial_\nu \phi^0 - \phi^0 \partial_\nu H) + \\ & M (\frac{1}{c_w} Z_\mu^0 \partial_\nu \phi^0 + W_\mu^+ \partial_\nu \phi^- + W_\mu^- \partial_\nu \phi^+) - ig_{cw} M Z_\mu^0 (W_\nu^+ \phi^- - W_\nu^- \phi^+) + ig_{sw} M A_\mu (W_\nu^+ \phi^- - \\ & W_\nu^- \phi^+) - ig \frac{1-2s_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\nu \phi^- - \phi^- \partial_\nu \phi^+) + ig_{sw} A_\mu (\phi^+ \partial_\nu \phi^- - \phi^- \partial_\nu \phi^+) - \\ & \frac{1}{2} g^2 W_\mu^+ W_\nu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{2} g^2 \frac{1}{c_w} Z_\mu^0 Z_\nu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\ & \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\nu^+ \phi^- + W_\nu^- \phi^+) - \frac{1}{2} ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\nu^+ \phi^- - W_\nu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\nu^+ \phi^- + \\ & W_\nu^- \phi^+) + \frac{1}{2} ig^2 s_w A_\mu H (W_\nu^+ \phi^- - W_\nu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\nu \phi^+ \phi^- - \\ & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2} ig_s \lambda_\nu^2 (\bar{q}^i \gamma^\mu q_j^i) g_\nu^\mu - e^3 (\gamma \partial + m_e^2) e^\lambda - \bar{\nu}^\lambda (\gamma \partial + m_\nu^2) \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + \\ & m_u^2) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^2) d_j^\lambda + ig_{sw} A_\mu (-e^\lambda \gamma^\mu e^\lambda + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)) + \\ & \frac{ig}{4c_w} Z_\mu^0 \{ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{2}{3} s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\ & (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{2}{3} s_w^2 + \gamma^5) u_j^\lambda) \} + \frac{ig}{2s_w} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep} \nu_\lambda e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\mu} d_j^\lambda)) + \\ & \frac{ig}{2s_w} W_\mu^- ((e^\lambda U^{lep} \nu_\lambda (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda C_{\lambda\mu} \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\ & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\nu^2 (\bar{\nu}^\lambda U^{lep} \nu_\lambda (1 + \gamma^5) \nu^\lambda) + m_\nu^2 (\bar{\nu}^\lambda U^{lep} \nu_\lambda (1 + \gamma^5) e^\lambda) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_\nu^2 (\bar{e}^\lambda U^{lep} \nu_\lambda (1 + \gamma^5) \nu^\lambda) - m_\nu^2 (\bar{e}^\lambda U^{lep} \nu_\lambda (1 - \gamma^5) \nu^\lambda) - \frac{g}{2} \frac{m_\nu^2}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\ & \frac{g}{2} \frac{m_\nu^2}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{2} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa - \\ & \frac{1}{2} \bar{\nu}_\lambda M_{\lambda\kappa}^L (1 - \gamma_5) \bar{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\nu^2 (\bar{u}_j^\lambda C_{\lambda\mu} (1 - \gamma^5) d_j^\lambda) + m_\nu^2 (\bar{u}_j^\lambda C_{\lambda\mu} (1 + \gamma^5) d_j^\lambda) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_\nu^2 (\bar{d}_j^\lambda C_{\lambda\mu} (1 + \gamma^5) u_j^\lambda) - m_\nu^2 (\bar{d}_j^\lambda C_{\lambda\mu} (1 - \gamma^5) u_j^\lambda) - \frac{g}{2} \frac{m_\nu^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\ & \frac{g}{2} \frac{m_\nu^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + G^a \partial^2 G^a + g_s f^{abc} \partial_\mu G^a G^b G_\mu^c + \\ & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig_{cw} W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\ & \partial_\mu \bar{X}^+ X^0) + ig_{sw} W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + ig_{cw} W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\ & \partial_\mu \bar{X}^0 X^+) + ig_{sw} W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig_{cw} Z_\mu^0 (\partial_\mu \bar{X}^- X^+ - \\ & \partial_\mu \bar{X}^+ X^-) + ig_{sw} A_\mu (\partial_\mu \bar{X}^+ X^- + \\ & \partial_\mu \bar{X}^- X^+) - \frac{1}{2} g M (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H) + \frac{1-2s_w^2}{2c_w} ig M (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\ & \frac{1}{2c_w} ig M (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + ig M s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\ & \frac{1}{2} ig M (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) . \end{aligned}$$

Example: WW+2jets



$$d\sigma = d\sigma(\alpha_S^2 \alpha^4) + d\sigma(\alpha_S \alpha^5) + d\sigma(\alpha^6) + \dots$$

LO

QCD-background

(interference

VBS-signal

$O(\alpha_s)$

$O(\alpha)$

$$\dots + d\sigma(\alpha_S^3 \alpha^4) + d\sigma(\alpha_S^2 \alpha^5) + d\sigma(\alpha_S \alpha^6) + \sigma(\alpha^7)$$

NLO

“NLO QCD”

“NLO EW”

“NLO QCD”

“NLO EW”

$$\mathcal{M} \rightarrow |\mathcal{M}|^2 \rightarrow \sigma$$

➔ separation formally meaningless at NLO

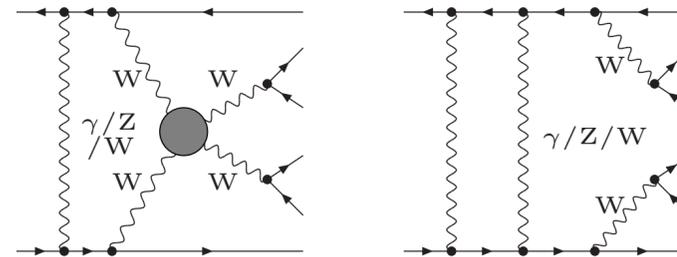
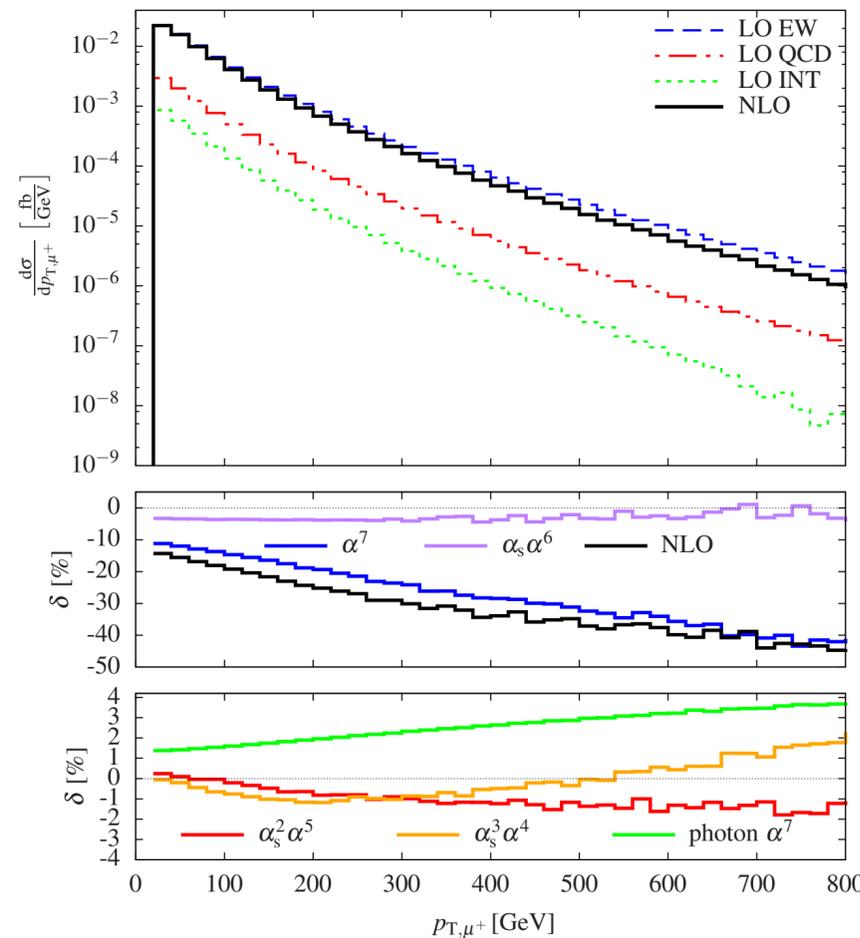
➔ strictly well defined measurements: fiducial cross sections

# VBS-@ full NLO

WW full NLO: [Biedermann, Denner, Pellen '16+'17]

WZ-EW NLO QCD+EW: [Denner, Dittmaier, Maierhöfer, Pellen, Schwan, 19]

ZZ-EW NLO QCD+EW: [Denner, Franken, Pellen, Schmidt, '20]



- 2 → 6 particles at NLO EW !
- highly challenging computation!

- NLO corrections dominated by  $\alpha^7$  :

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s \alpha^6)$	$\mathcal{O}(\alpha_s^2 \alpha^5)$	$\mathcal{O}(\alpha_s^3 \alpha^4)$	Sum
$\delta\sigma_{\text{NLO}}$ [fb]	-0.2169(3)	-0.0568(5)	-0.00032(13)	-0.0063(4)	-0.2804(7)
$\delta\sigma_{\text{NLO}}/\sigma_{\text{LO}}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

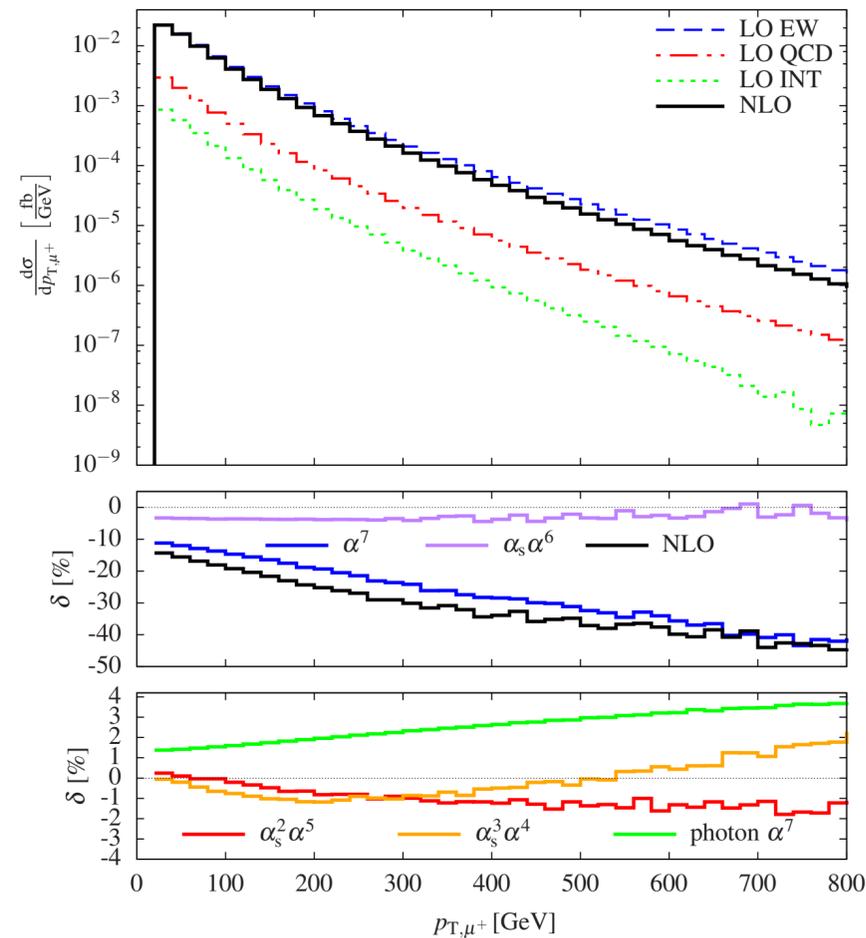
with  $M_{jj} > 500 \text{ GeV}$ ,  $p_{T,j} > 30 \text{ GeV}$ ,  $p_{T,\ell} > 20 \text{ GeV}$ ,

LO: $\mathcal{O}(\alpha^6)$	$\sigma^{\text{LO}}$ [fb]	$\sigma_{\text{EW}}^{\text{NLO}}$ [fb]	$\delta_{\text{EW}}$ [%]
NLO: $\mathcal{O}(\alpha^7)$	1.5348(2)	1.2895(6)	-16.0

- VERY large inclusive EW corrections (dominated by Sudakov logs)

# VBS- $W^+W^+$ @ full NLO

[Biedermann, Denner, Pellen '16+'17]



- VERY large EW corrections (dominated by Sudakov logs)

LO: $\mathcal{O}(\alpha^6)$	$\sigma^{\text{LO}}$ [fb]	$\sigma_{\text{EW}}^{\text{NLO}}$ [fb]	$\delta_{\text{EW}}$ [%]
NLO: $\mathcal{O}(\alpha^7)$	1.5348(2)	1.2895(6)	-16.0

Leading logarithm approximation [Denner, Pozzorini; hep-ph/0010201]

$$\sigma_{\text{LL}} = \sigma_{\text{LO}} \left[ 1 - \frac{\alpha}{4\pi} 4C_W^{\text{ew}} \log^2 \left( \frac{Q^2}{M_W^2} \right) + \frac{\alpha}{4\pi} 2b_W^{\text{ew}} \log \left( \frac{Q^2}{M_W^2} \right) \right]$$

$$= -16\% (!)$$

$$\text{For } Q = \langle m_{4\ell} \rangle \sim 390 \text{ GeV}$$

$\langle m_{4\ell} \rangle$  larger for VBS

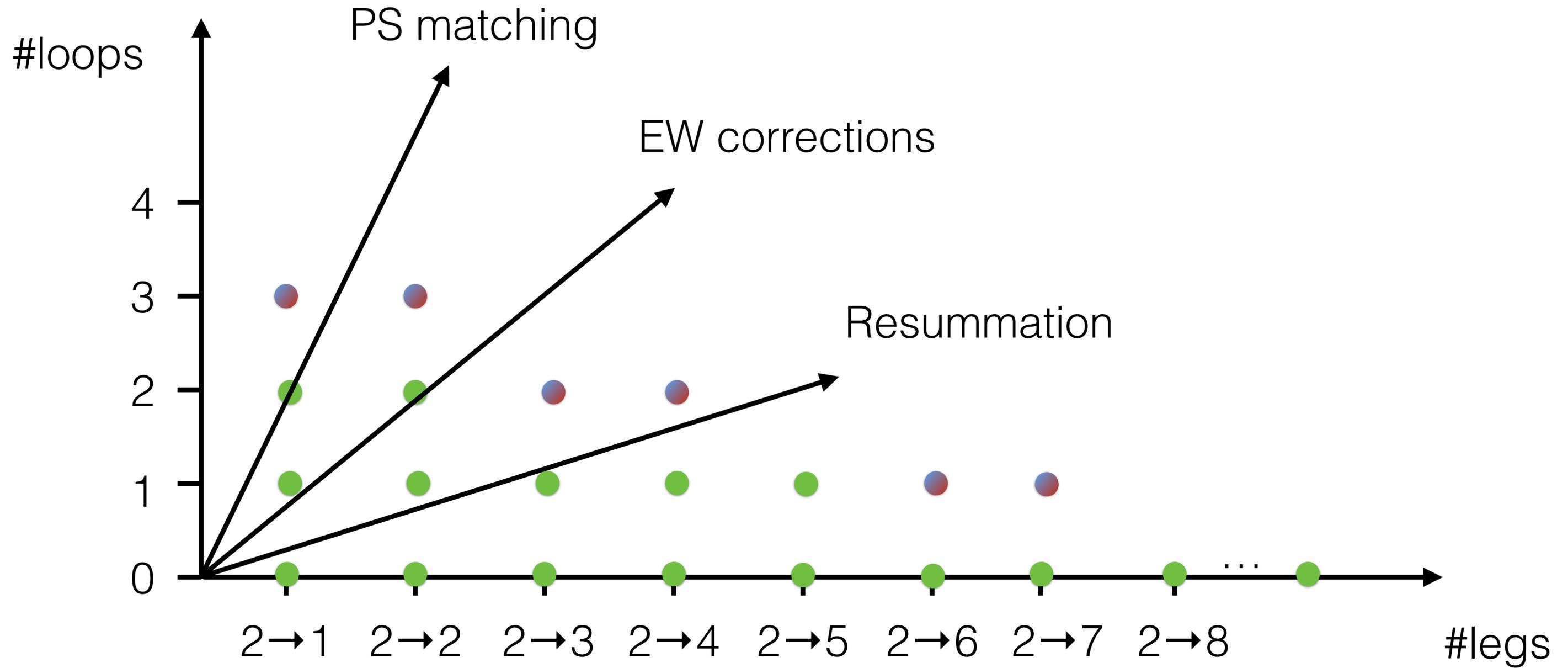
- ➔ Large NLO EW corrections: intrinsic feature of VBS at the LHC

# Conclusions

- ▶ There is no clear scale/signature for new physics effects:  
Let's explore the unknown leaving no stone unturned!
- ▶ Precision is key for SM (QCD/EW/Higgs) measurements,  
SM parameter determination, as well as for BSM searches.
- ▶ First  $2 \rightarrow 3$  NNLO results are becoming available.
- ▶ N3LO for some  $2 \rightarrow 2$  processes within reach
- ▶ At the 1% level a multitude of relevant effects might play  
an important role:  
PDFs, EW, QCD-EW, resummation/PS, off-shell/finite width...
- ▶ EW corrections become large at the TeV scale
- ▶ Let's push the SM precision frontier!



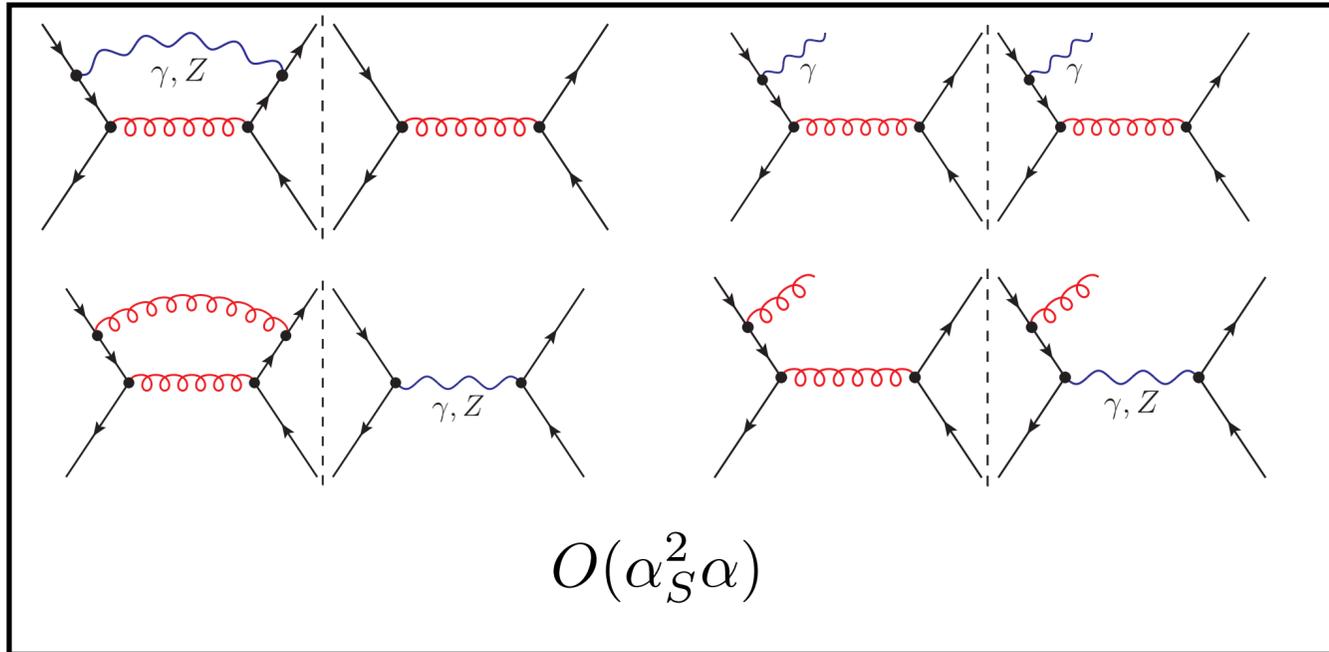
# Theory frontier



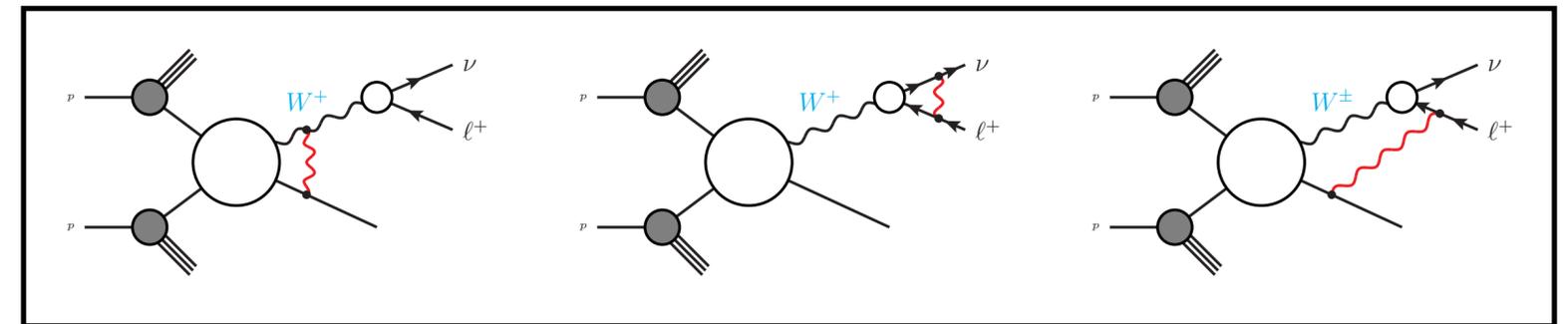
BACKUP

# Nontrivial features in NLO QCD → NLO EW

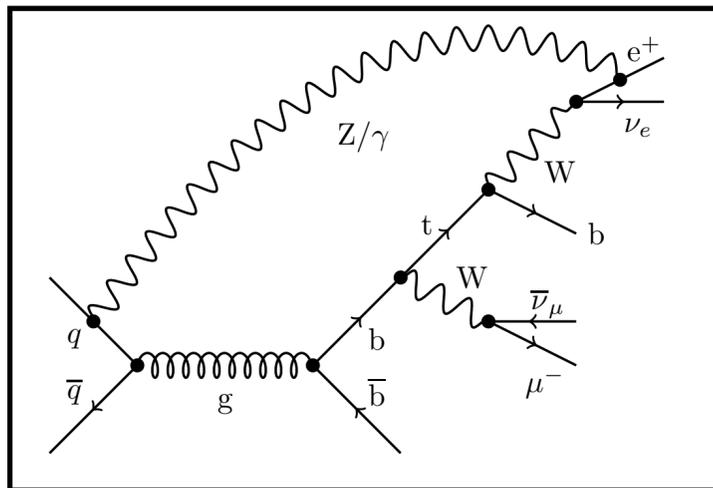
## 1. QCD-EW interplay



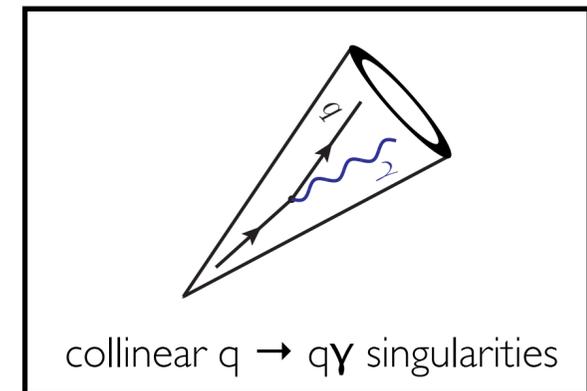
2. At NLO EW corrections in production, decay and non-factorizable contributions for V decays  
→ **complex-mass-scheme**



3. **virtual EW corrections** more involved than QCD (many internal masses)



4. photon contributions in jets and proton  
→ **photon-jet separation, γPDF**



# The motivation for BSM searches are as compelling as ever

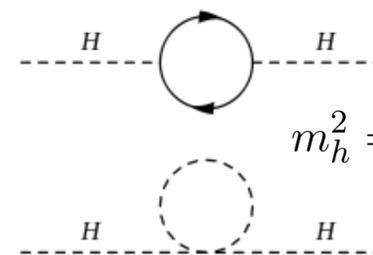
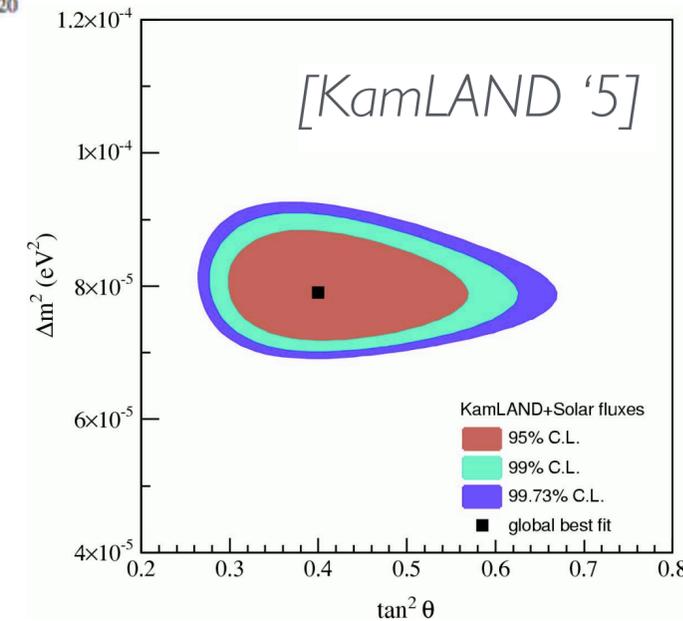
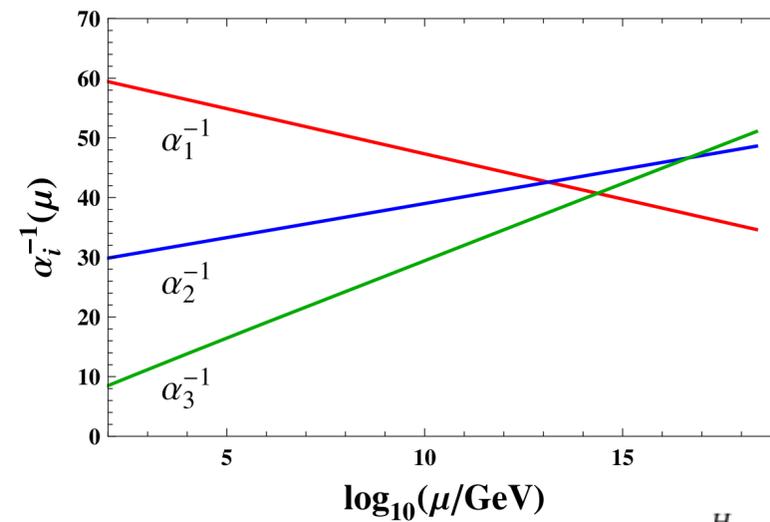
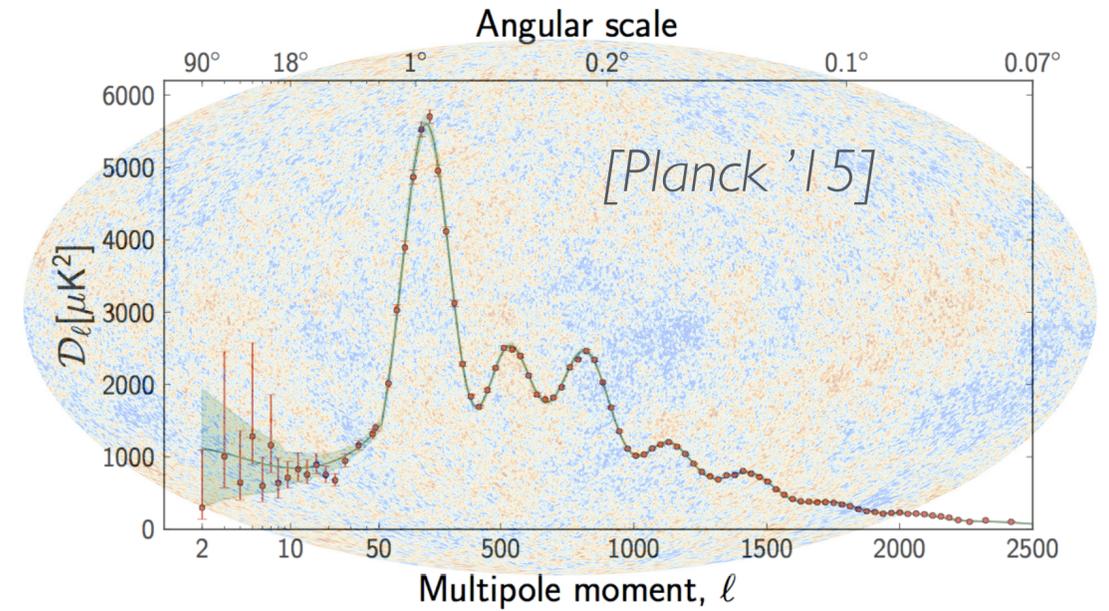
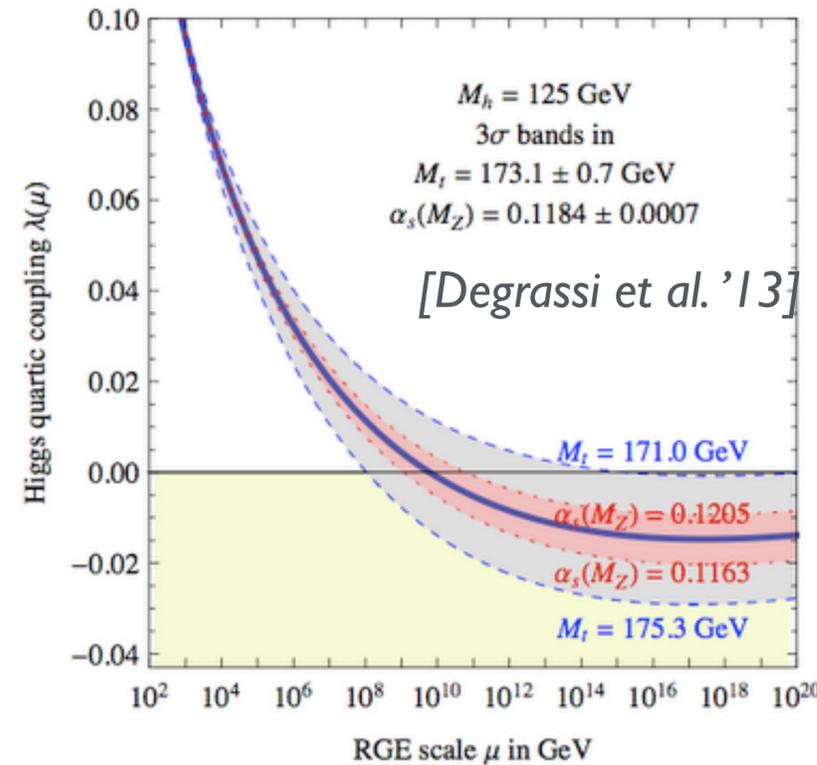
EW vacuum stability

Dark Matter

GUT unification

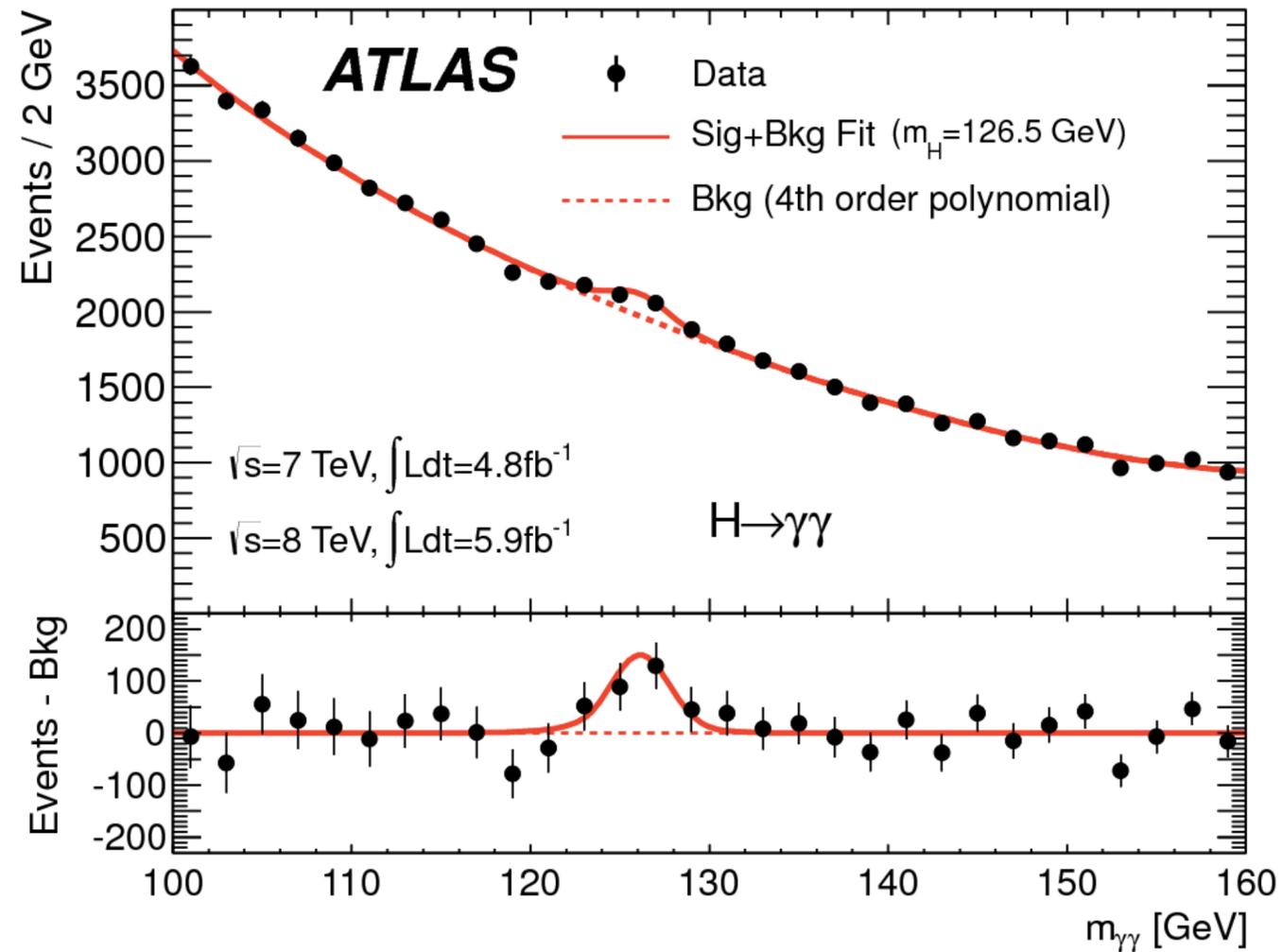
Neutrino masses

Hierarchy problem

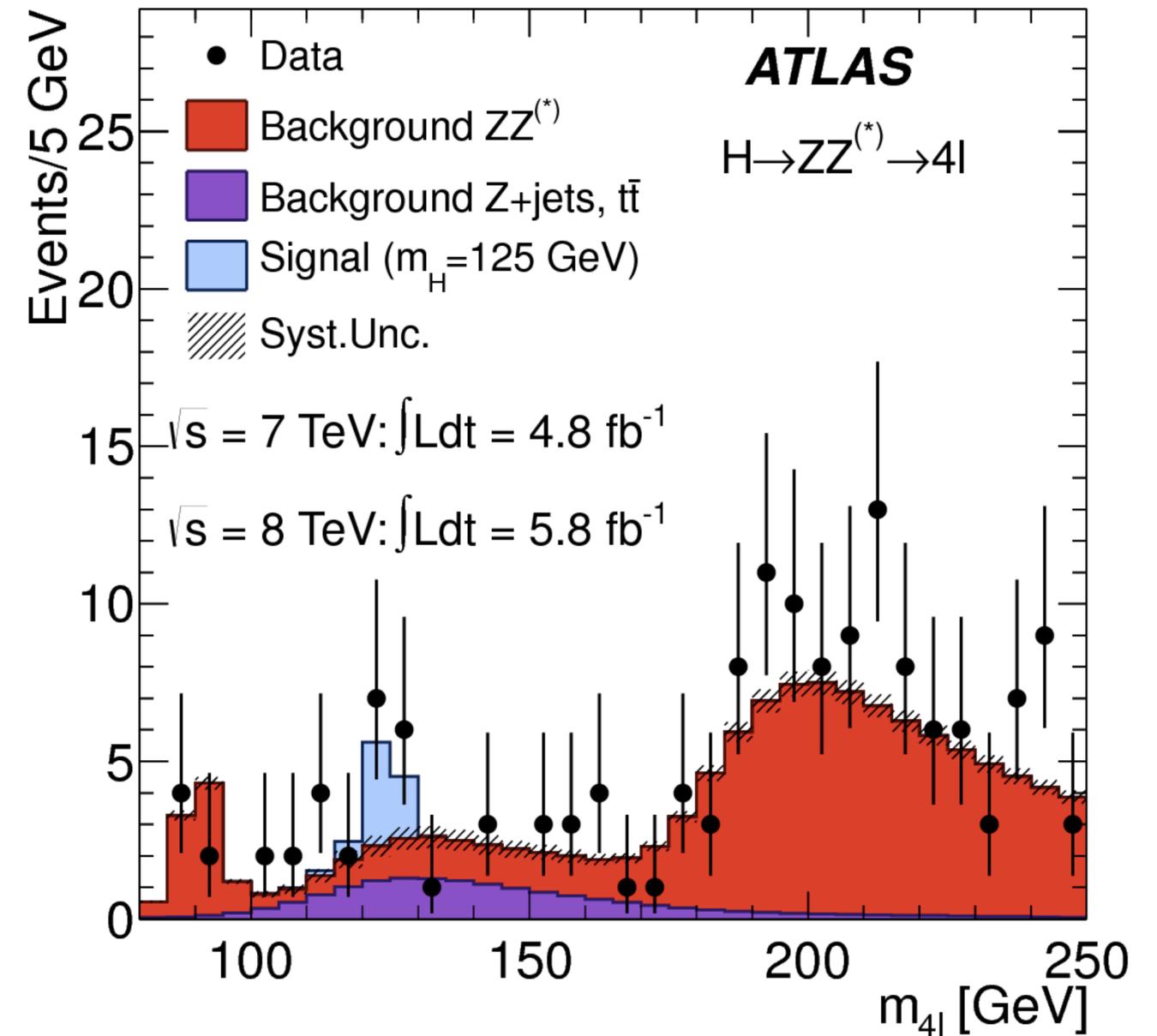


$$m_h^2 = (m_h^0)^2 + \frac{3\Lambda_{UV}^2}{8\pi v^2} (m_h^2 + 2m_W^2 + m_Z^2 - 4m_t^2)$$

From a pheno perspective finding the Higgs was “easy” ...



- Higgs at 125 GeV allowed for very clean discovery in  $\gamma\gamma$  &  $4l$  channels



- Bump hunting: little to no theoretical input needed.

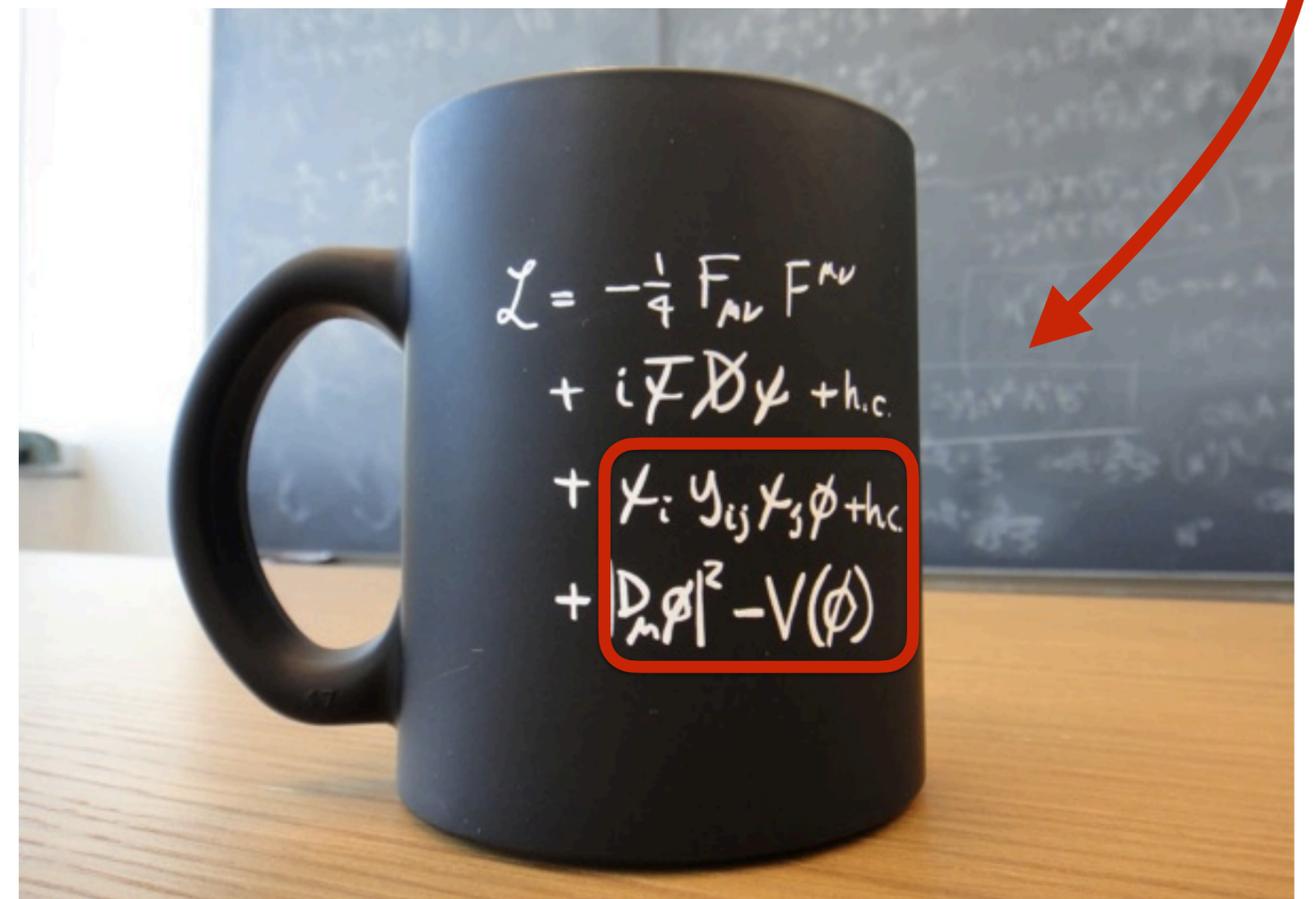
...understanding the Higgs and its properties is tough!

Is the S(125 GeV) really the SM Higgs?

- CP properties? Is there a small CP-odd admixture?
- Precise couplings with vector-bosons/fermions as in SM?
- what is the Higgs width? Is there a significant invisible decay?
- only one Higgs doublet?
- what is the Higgs potential? self-coupling?

➔ the hunt to pin down the SM has just started.

➔ precision is key!



# Theoretical Predictions for the LHC

$$d\sigma_{\text{NLO}} = \frac{1}{2s} \int d\Phi_n [|\mathcal{M}_{\text{LO}}|^2 + 2\text{Re}\{\mathcal{M}_{\text{LO}}\mathcal{M}_{\text{NLO},\text{V}}^*\} + I] + \frac{1}{2s} \int d\Phi_{n+1} |\mathcal{M}_{\text{NLO},\text{R}}|^2 - S$$

General solution to “NLO problem” exist since long time:

- tensor reduction (since 1970s)
- IR subtraction methods (since 1990s)

However: for a long time one-loop amplitudes bottleneck due to exploding algebraic expressions for multi-particle processes ( $2 \rightarrow 4,5,6$ )

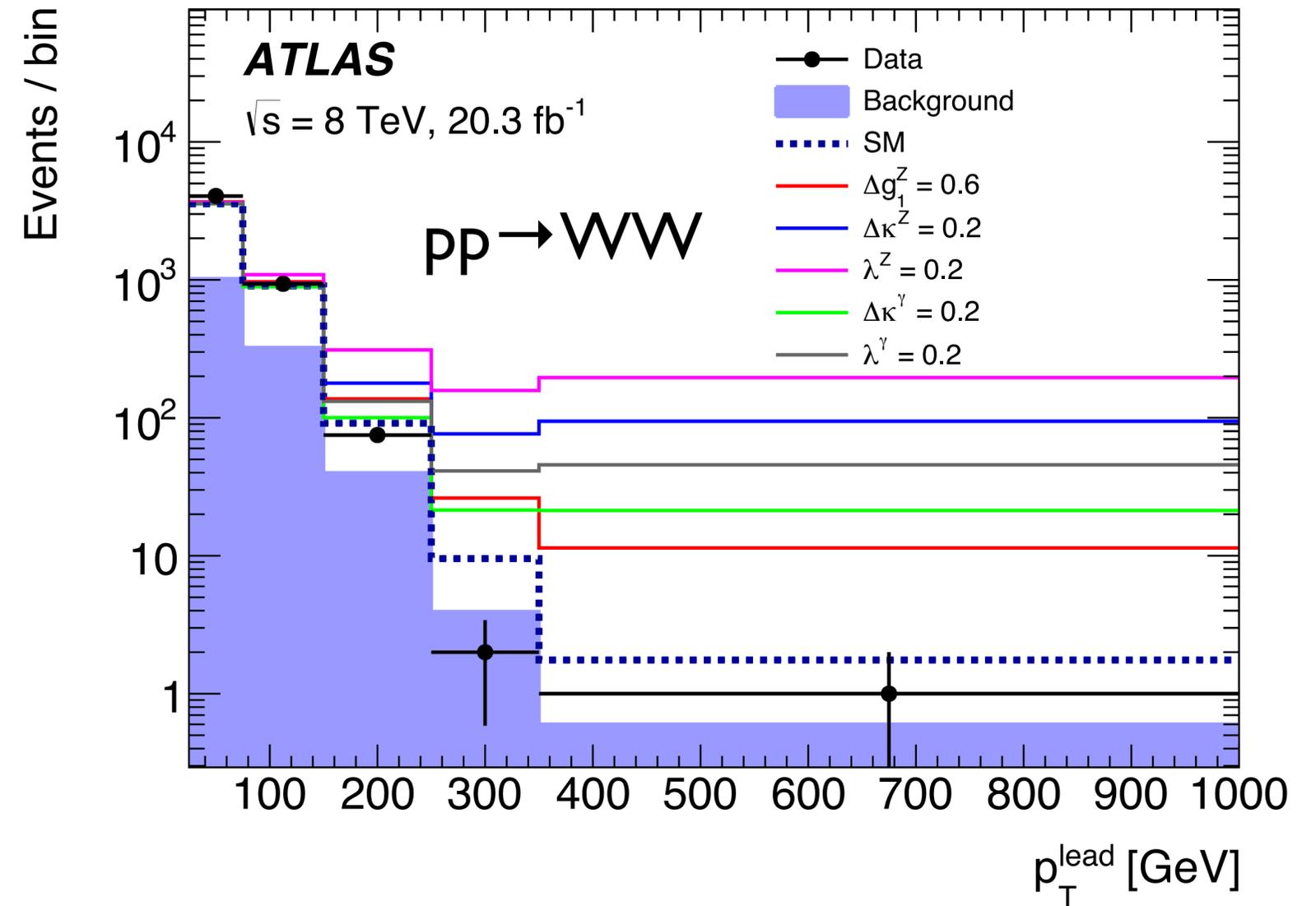
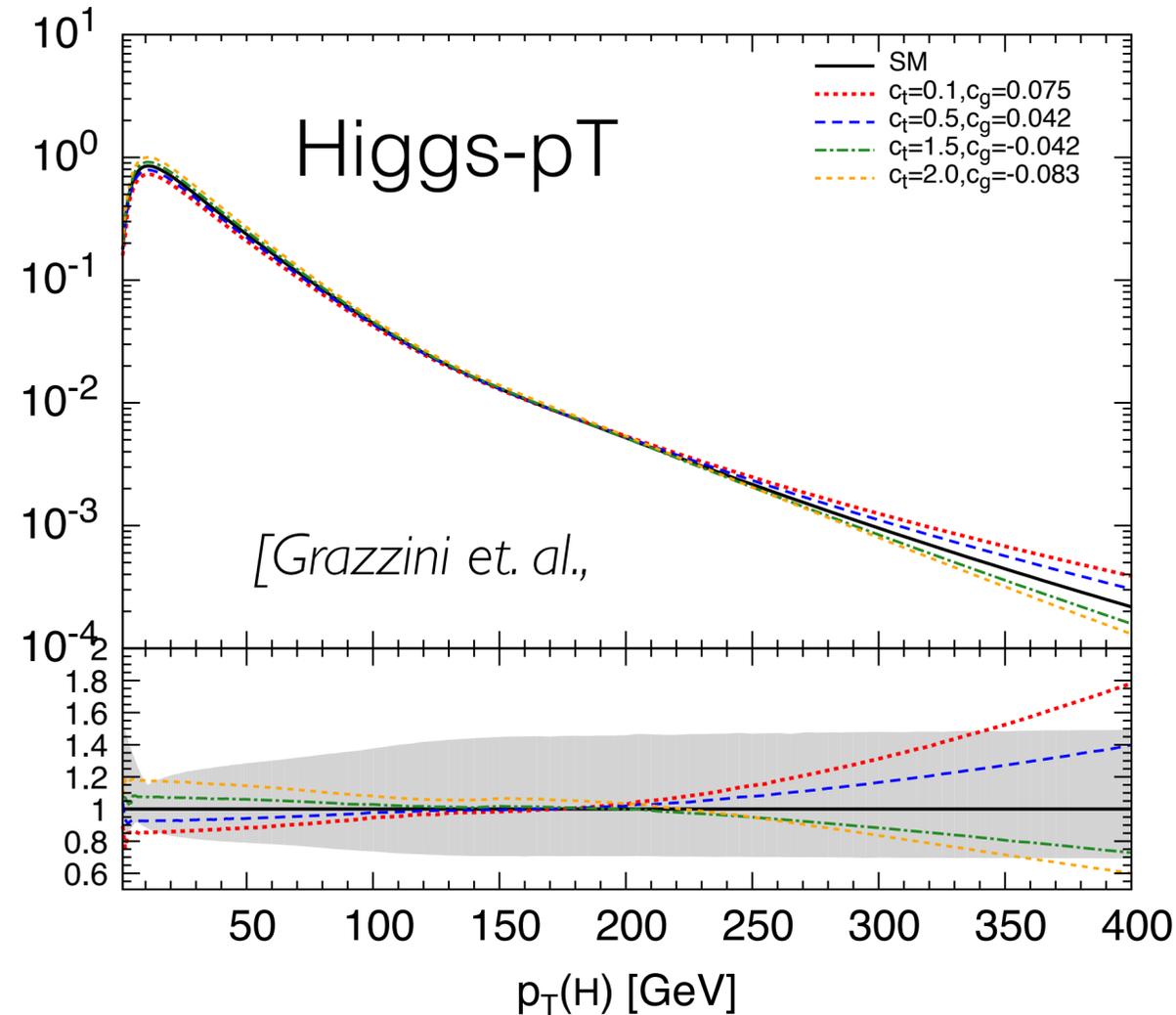
NLO Revolution (last ~20years):

- radically new approaches: on-shell methods, OPP reduction, recursion-relations at NLO...
- automation of one-loop algorithms (BlackHat, CutTools, Collier, GoSam, HELAC 1-loop, MadLoop, NGluon, **OpenLoops**, Recola, Samurai, Ninja,...) and NLO MCs (MadGraph\_aMC@NLO, Sherpa, POWHEG,...)
- vast range of multi-particle NLO predictions at LHC  
( $pp \rightarrow 5j, W + 5j, H + 3j, WWjj, WZjj, \Upsilon\Upsilon + 3j, W\Upsilon\Upsilon j, WWbb(+jet), bbbb, ttbb, ttjj, tttt, \dots$ )
- Recent important achievement: extension to NLO EW (Sherpa+OpenLoops/Recola and MadGraph\_aMC@NLO)

→ Opened the door for very detailed pheno analyses.

→ Still room for important improvements: speed, stability, flexibility.

# The need for precision in tails



- many effective BSM operators yield growth with energy
- expect small deviations in high energy shapes of distributions
- **very good control on SM predictions necessary!**

# Search limits

## ATLAS SUSY Searches\* - 95% CL Lower Limits

December 2017

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	Reference	
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	1.57 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q}) = m(2^{\text{nd}} \text{ gen. } \tilde{q})$	1712.02332
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$	710 GeV	$m(\tilde{q}) = m(\tilde{\chi}_1^0) < 5 \text{ GeV}$	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow g\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.02 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow g\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.01 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(\tilde{\chi}^{\pm}) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{g}))$	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow g\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	Yes	14.7	$\tilde{g}$	1.7 TeV	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}$	1611.05791
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow g\tilde{\chi}_1^0$	$3e, \mu$	4 jets	-	36.1	$\tilde{g}$	1.87 TeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow g\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$	1.8 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	1708.02794
	GMSB ( $\tilde{\ell}$ NLSP)	1-2 $\tau$ + 0-1 $\ell$	0-2 jets	Yes	3.2	$\tilde{g}$	2.0 TeV	-	1607.05979
	GGM (bino NLSP)	$2\gamma$	-	Yes	36.1	$\tilde{g}$	2.15 TeV	$\tau(\text{NLSP}) < 0.1 \text{ mm}$	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	$\gamma$	2 jets	Yes	36.1	$\tilde{g}$	2.05 TeV	$m(\tilde{\chi}_1^0) = 1700 \text{ GeV}, \tau(\text{NLSP}) < 0.1 \text{ mm}, \mu > 0$	ATLAS-CONF-2017-080
Gravitino LSP	0	mono-jet	Yes	20.3	$\tilde{g}$	$R^{1/2}$ scale	865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g}) = m(\tilde{q}) = 1.5 \text{ TeV}$	1502.01518
3 <sup>rd</sup> gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$	1.92 TeV	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	1711.01901
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}_1^0$	0-1 $e, \mu$	3 b	Yes	36.1	$\tilde{g}$	1.97 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	1711.01901
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	$\tilde{b}_1$	950 GeV	$m(\tilde{\chi}_1^0) < 420 \text{ GeV}$	1708.09266
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	$2e, \mu$ (SS)	1 b	Yes	36.1	$\tilde{b}_1$	275-700 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(\tilde{\chi}^{\pm}) = m(\tilde{\chi}_1^0) + 100 \text{ GeV}$	1706.03731
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	0-2 $e, \mu$	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$	117-170 GeV	$m(\tilde{\chi}_1^0) = 2m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0) = 55 \text{ GeV}$	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	0-2 $e, \mu$	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$	90-198 GeV	$m(\tilde{\chi}_1^0) = 1 \text{ GeV}$	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1	$\tilde{t}_1$	90-430 GeV	$m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	-
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	$2e, \mu$ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-600 GeV	$m(\tilde{\chi}_1^0) > 150 \text{ GeV}$	1403.5222
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Z$	$3e, \mu$ (Z)	1 b	Yes	36.1	$\tilde{t}_1$	290-790 GeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 $e, \mu$	4 b	Yes	36.1	$\tilde{t}_2$	320-880 GeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 $e, \mu$	4 b	Yes	36.1	$\tilde{t}_2$	320-880 GeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	1706.03986
	EW direct	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$	$2e, \mu$	0	Yes	36.1	$\tilde{\chi}_1^0$	90-500 GeV	$m(\tilde{\chi}_1^0) = 0$
$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$		$2e, \mu$	0	Yes	36.1	$\tilde{\chi}_1^0$	750 GeV	$m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}_1^0) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-039
$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$		$2\tau$	0	Yes	36.1	$\tilde{\chi}_1^0$	760 GeV	$m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}_1^0) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_1^0))$	1708.07875
$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$		$3e, \mu$	0	Yes	36.1	$\tilde{\chi}_1^0, \tilde{\chi}_2^0$	580 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}_1^0) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0))$	ATLAS-CONF-2017-039
$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$		$2-3 e, \mu$	0-2 jets	Yes	36.1	$\tilde{\chi}_1^0, \tilde{\chi}_2^0$	580 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$		$e, \mu, \gamma$	0-2 b	Yes	20.3	$\tilde{\chi}_1^0, \tilde{\chi}_2^0$	270 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \tilde{\ell}$ decoupled	1501.07110
$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$		$4e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^0, \tilde{\chi}_2^0$	635 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}_1^0) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0))$	1405.5086
GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$		$1e, \mu + \gamma$	-	Yes	20.3	$\tilde{W}$	115-370 GeV	$cr < 1 \text{ mm}$	1507.05493
GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$		$2\gamma$	-	Yes	36.1	$\tilde{W}$	1.06 TeV	$cr < 1 \text{ mm}$	ATLAS-CONF-2017-080
Long-lived particles		Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^0$	460 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_1^0) \sim 160 \text{ MeV}, \tau(\tilde{\chi}_1^0) = 0.2 \text{ ns}$
	Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^0$	495 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_1^0) \sim 160 \text{ MeV}, \tau(\tilde{\chi}_1^0) < 15 \text{ ns}$	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	850 GeV	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$	1.58 TeV	-	1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$	1.57 TeV	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}, \tau > 10 \text{ ns}$	1604.04520
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow g\tilde{\chi}_1^0$	displ. vtx	-	Yes	32.8	$\tilde{g}$	2.37 TeV	$\tau(\tilde{g}) = 0.17 \text{ ns}, m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	1710.04901
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{\chi}_1^0) + \tau(e, \mu)$	$1-2 \mu$	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	$10 < \tan\beta < 50$	1411.6795
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ , long-lived $\tilde{\chi}_1^0$	$2\gamma$	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	$1 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns}, \text{SPS8 model}$	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow e\tilde{\nu}/e\tilde{\nu}/\mu\tilde{\nu}$	displ. $ee/\mu\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$7 < cr(\tilde{\chi}_1^0) < 740 \text{ mm}, m(\tilde{g}) = 1.3 \text{ TeV}$	1504.05162
	RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	$e\mu, \tau\mu$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	$\lambda_{111} = 0.11, \lambda_{132}/\lambda_{233} = 0.07$
Bilinear RPV CMSSM		$2e, \mu$ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.45 TeV	$m(\tilde{q}) = m(\tilde{g}), cr_{\tilde{L}, \tilde{R}} < 1 \text{ mm}$	1404.2500
$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow e\tilde{\nu}, \mu\tilde{\nu}, \mu\tilde{\nu}$		$4e, \mu$	-	Yes	13.3	$\tilde{\chi}_1^0$	1.14 TeV	$m(\tilde{\chi}_1^0) > 400 \text{ GeV}, \lambda_{12k} \neq 0 (k = 1, 2)$	ATLAS-CONF-2016-075
$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\nu_e, \tau\nu_\tau$		$3e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^0$	450 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^0), \lambda_{133} \neq 0$	1405.5086
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}, \tilde{\chi}_1^0 \rightarrow q\tilde{q}$		0	4-5 large-R jets	-	36.1	$\tilde{g}$	1.875 TeV	$m(\tilde{\chi}_1^0) = 1075 \text{ GeV}$	SUSY-2016-22
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}, \tilde{\chi}_1^0 \rightarrow q\tilde{q}$		$1e, \mu$	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	2.1 TeV	$m(\tilde{\chi}_1^0) = 1 \text{ TeV}, \lambda_{123} \neq 0$	1704.08493
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}, \tilde{\chi}_1^0 \rightarrow q\tilde{q}$		$1e, \mu$	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	1.65 TeV	$m(\tilde{\chi}_1^0) = 1 \text{ TeV}, \lambda_{123} \neq 0$	1704.08493
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$		0	2 jets + 2 b	-	36.7	$\tilde{t}_1$	100-470 GeV	1710.07171	1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\ell}$		$2e, \mu$	2 b	-	36.1	$\tilde{t}_1$	480-610 GeV	$BR(\tilde{t}_1 \rightarrow b\ell/\mu) > 20\%$	1710.05544
Other		Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	510 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

## ATLAS Preliminary

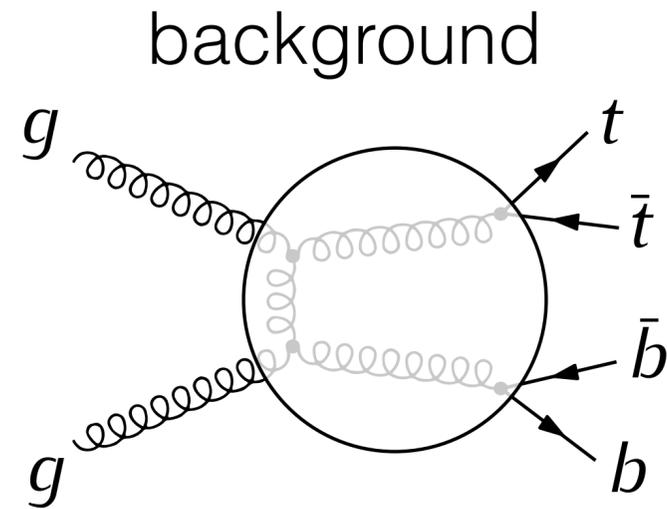
$\sqrt{s} = 7, 8, 13 \text{ TeV}$

## ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

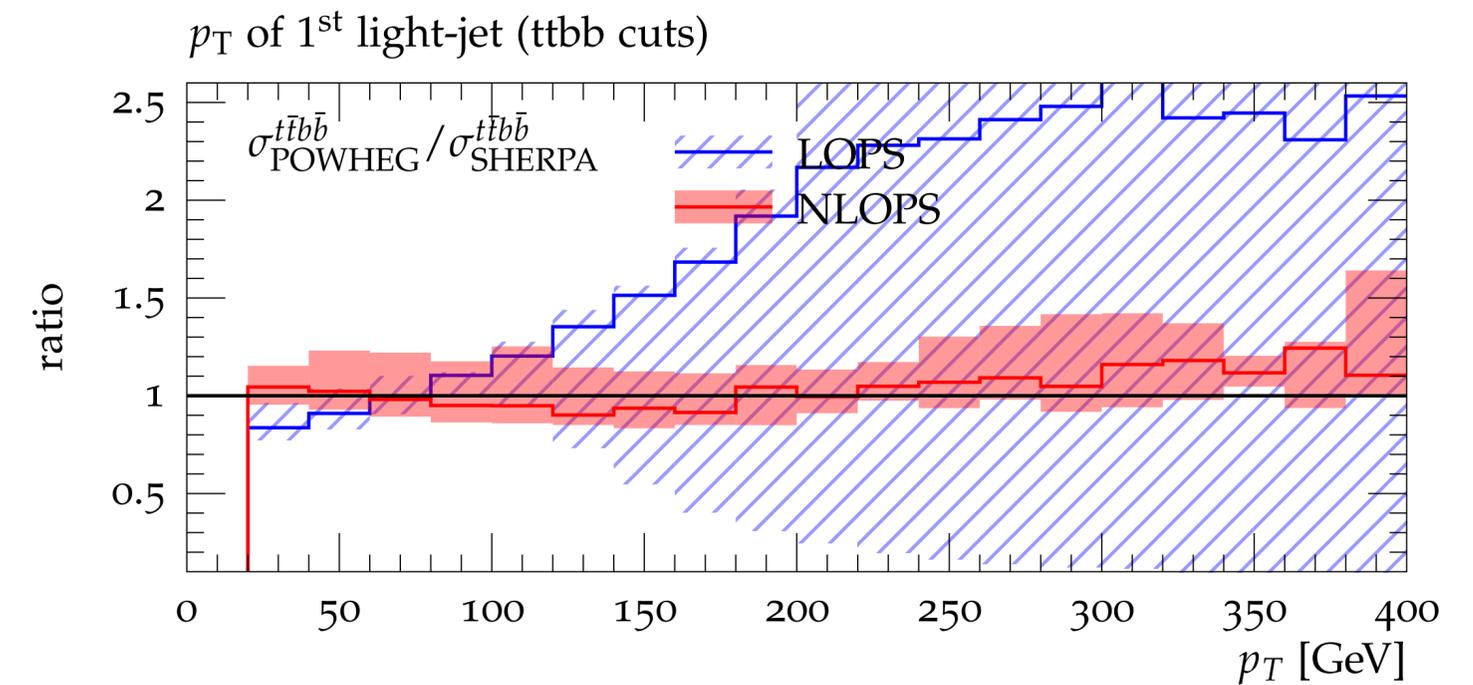
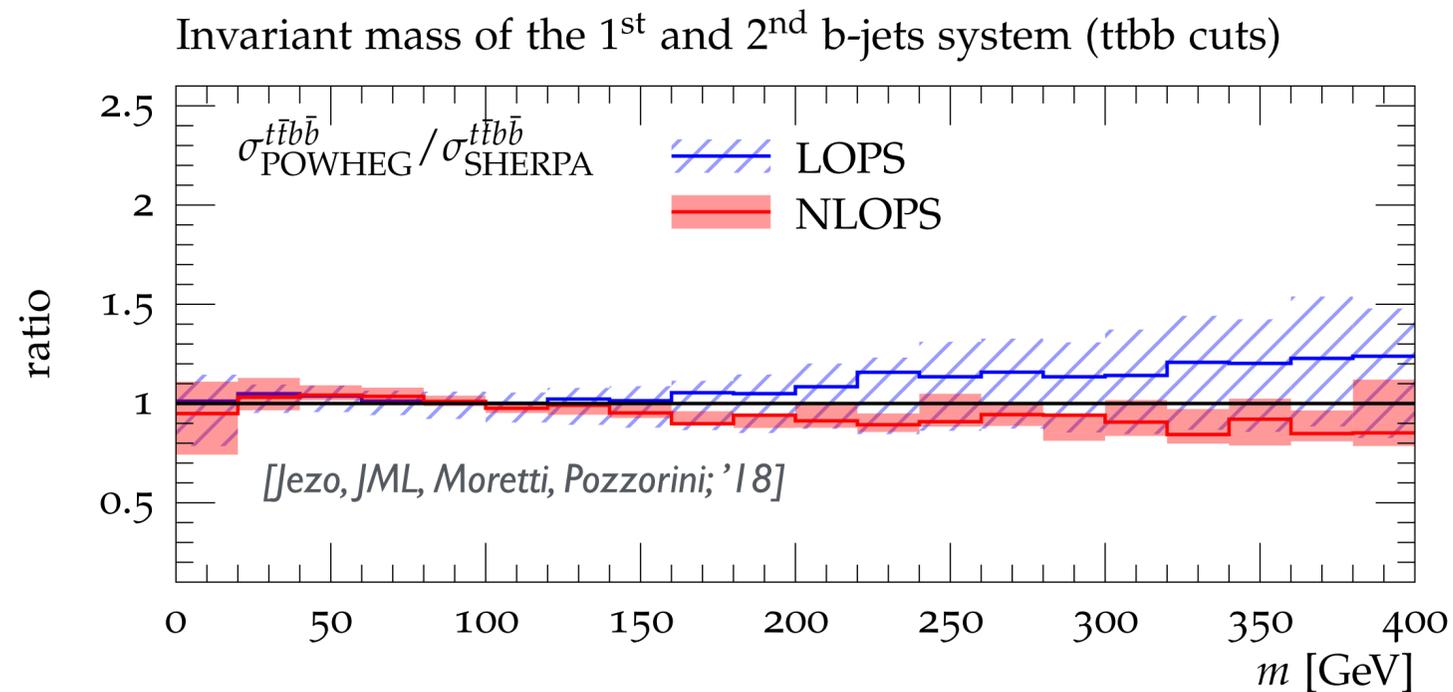
Status: July 2017

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference				
Extra dimensions	ADD $G_{KK} + g/q$	0 $e, \mu$	1-4 j	Yes	36.1	$M_0$	7.75 TeV	$n = 2$	ATLAS-CONF-2017-060	
	ADD non-resonant $\gamma\gamma$	$2\gamma$	-	-	36.7	$M_5$	8.6 TeV	$n = 3 \text{ HLZ NLO}$	CERN-EP-2017-132	
	ADD QBH	-	2 j	-	37.0	$M_{bh}$	8.9 TeV	$n = 6$	1703.09217	
	ADD BH high $\Sigma p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	$M_{bh}$	8.2 TeV	$n = 6, M_D = 3 \text{ TeV}, \text{rot BH}$	1606.02265	
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{bh}$	9.55 TeV	$n = 6, M_D = 3 \text{ TeV}, \text{rot BH}$	1512.02586	
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2\gamma$	-	-	36.7	$G_{KK}$ mass	4.1 TeV	$k/\tilde{M}_{Pl} = 0.1$	CERN-EP-2017-132	
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1e, \mu$	1 J	Yes	36.1	$G_{KK}$ mass	1.75 TeV	$k/\tilde{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051	
	2UED / RPP	$1e, \mu$	$\geq 2 b, \geq 3 j$	Yes	13.2	KK mass	1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow t\bar{t}) = 1$	ATLAS-CONF-2016-104	
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2e, \mu$	-	-	36.1	$Z'$ mass	4.5 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2017-027
		SSM $Z' \rightarrow \tau\tau$	$2\tau$	-	-	36.1	$Z'$ mass	2.4 TeV	-	ATLAS-CONF-2017-050
Leptophobic $Z' \rightarrow bb$		-	2 b	-	3.2	$Z'$ mass	1.5 TeV	-	1603.08791	
Leptophobic $Z' \rightarrow tt$		$1e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	3.2	$Z'$ mass	2.0 TeV	-	ATLAS-CONF-2016-014	
SSM $W' \rightarrow \ell\nu$		$1e, \mu$	-	Yes	36.1	$W'$ mass	5.1 TeV	-	1706.04786	
HVT $V' \rightarrow WW \rightarrow qq\ell\nu$ model B		$0e, \mu$	2 J	-	36.7	$V'$ mass	3.5 TeV	$g_V = 3$	CERN-EP-2017-147	
HVT $V' \rightarrow WH/ZH$ model B		multi-channel	-	-	36.1	$V'$ mass	2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055	
LRSM $W'_R \rightarrow tb$		$1e, \mu$	2 b, 0-1 j	Yes	20.3	$W'$ mass	1.92 TeV	-	1410.4103	
LRSM $W'_R \rightarrow tb$		$0e, \mu$	$\geq 1 b, 1 J$	-	20.3	$W'$ mass	1.76 TeV	-	1408.0886	
CI		CI $qqqq$	-	2 j	-	37.0	A	21.8 TeV	$\eta_{LL}$	1703.09217
	CI $\ell\ell qq$	$2e, \mu$	-	-	36.1	A	40.1 TeV	$\eta_{LL}$	ATLAS-CONF-2017-027	
	CI $uutt$	$2(SS) \geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	20.3	A	4.9 TeV	$ C_{RR}  = 1$	1504.04605		
DM	Axial-vector mediator (Dirac DM)	$0e, \mu$	1-4 j	Yes	36.1	$m_{\text{med}}$	1.5 TeV	$g_q = 0.25, g_\ell = 1.0, m(\chi) < 400 \text{ GeV}$	ATLAS-CONF-2017-060	
	Vector mediator (Dirac DM)	$0e, \mu, 1\gamma$	$\leq 1 j$	Yes	36.1	$m_{\text{med}}$	1.2 TeV	$g_q = 0.25, g_\ell = 1.0, m(\chi$		

# Taming $t\bar{t}H$ backgrounds



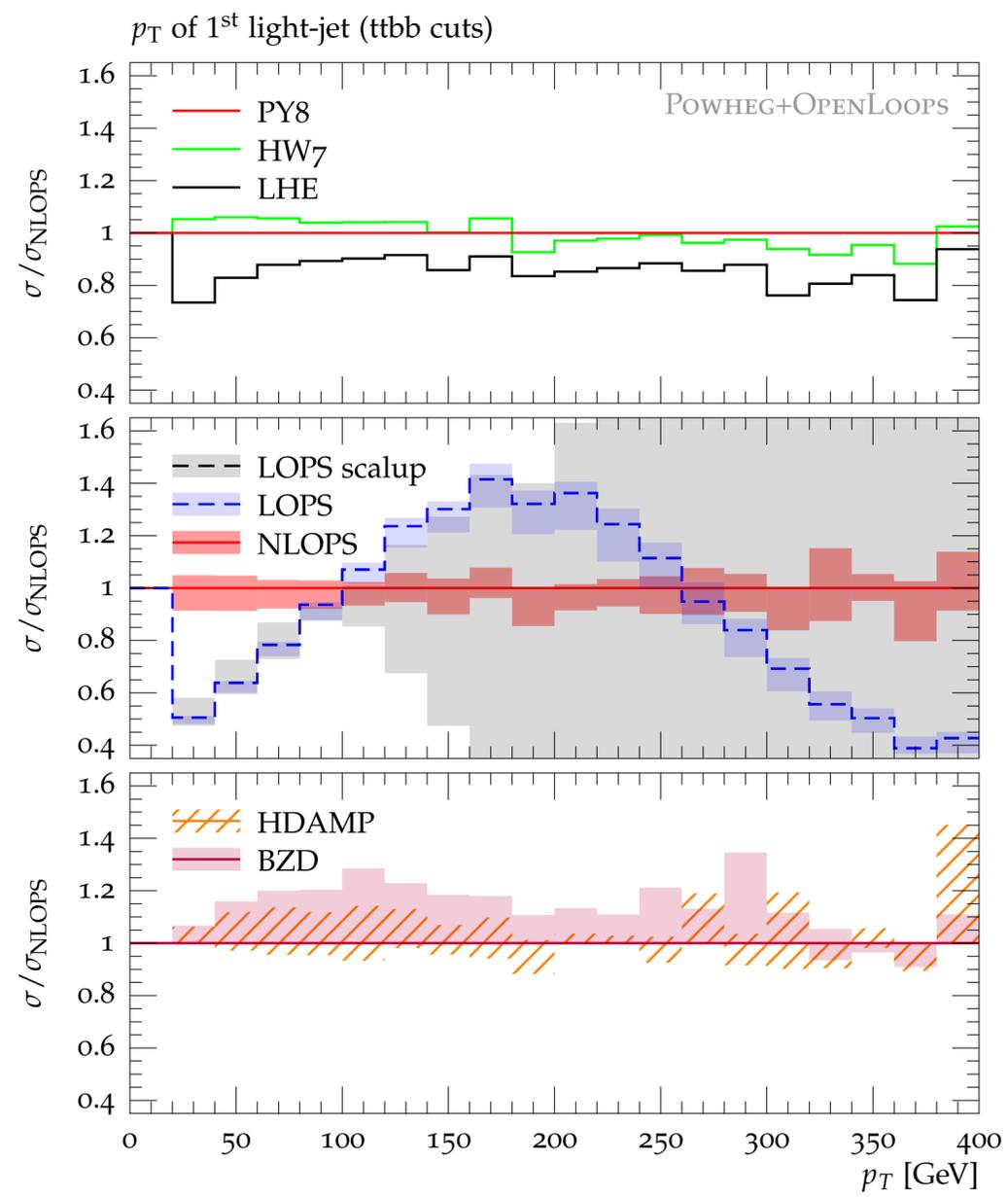
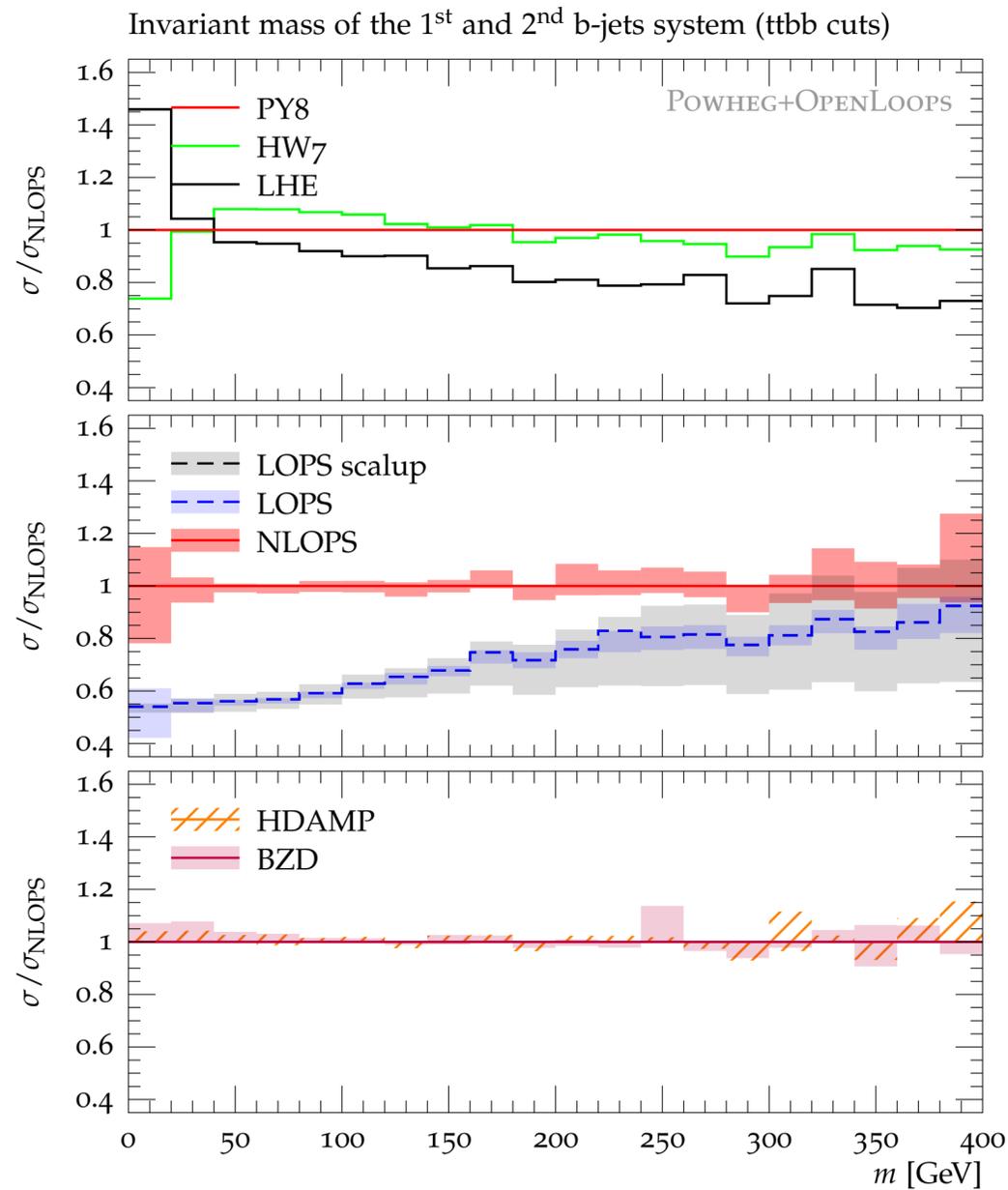
- ➔ in principle this process can be calculated out of the box at NLO+PS: NLO reduces scale uncertainties from 80% to 20-30%
- ➔ However: notoriously difficult multi-scale problem:  $ET_t, ET_{\bar{t}}, ET_b, ET_{\bar{b}}$
- ➔ Large shower effects, in particular from double  $g \rightarrow b\bar{b}$  splittings
- ➔ Large systematic uncertainties from parton shower matching
- ➔ Careful study required to understand these systematics



➔ Sherpa vs. POWHEG+PY8 (both in 4-FS) in very good agreement

# Taming $t\bar{t}H$ backgrounds

[Jezo, JML, Moretti, Pozzorini; '18]



► Shower variations

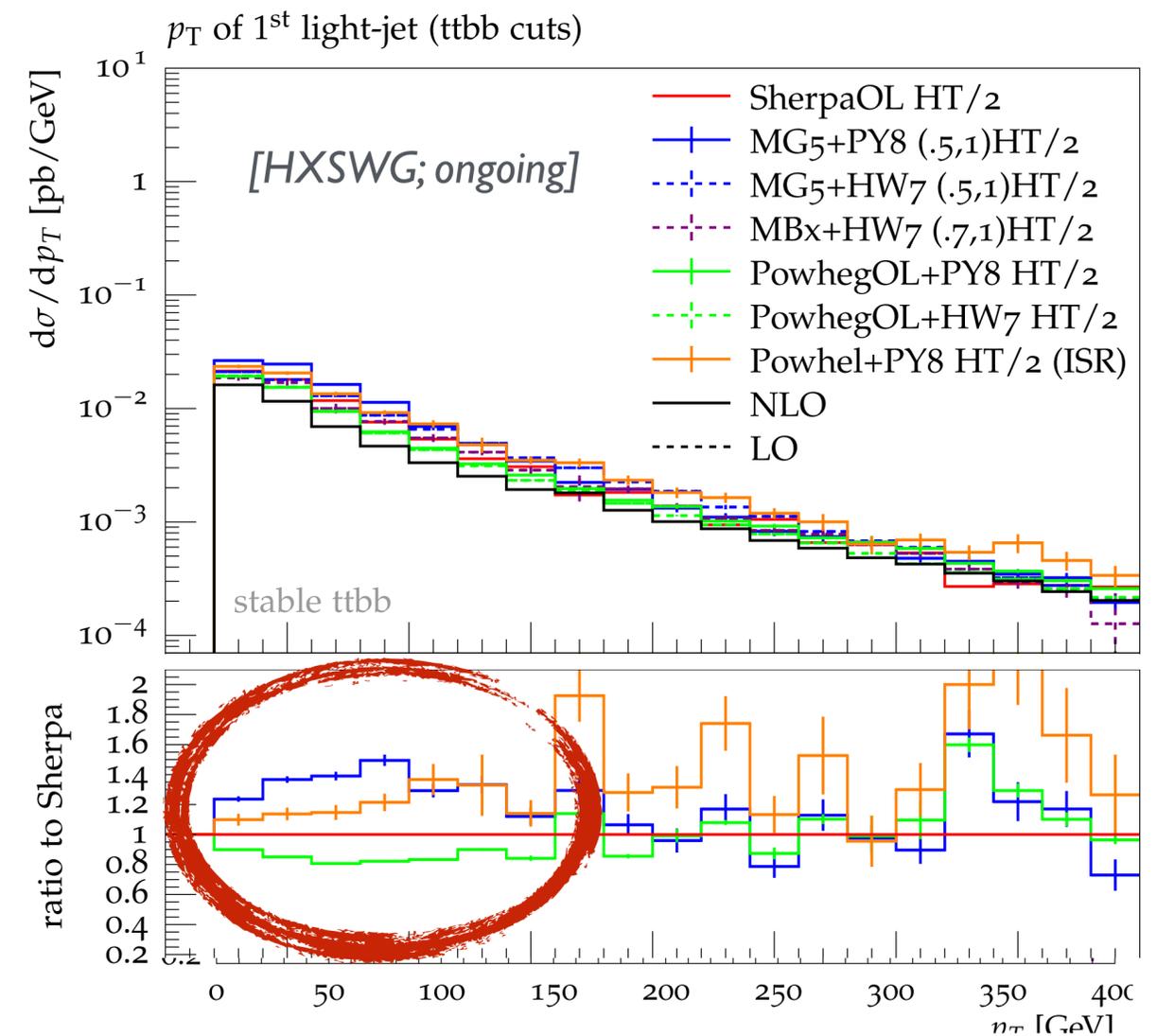
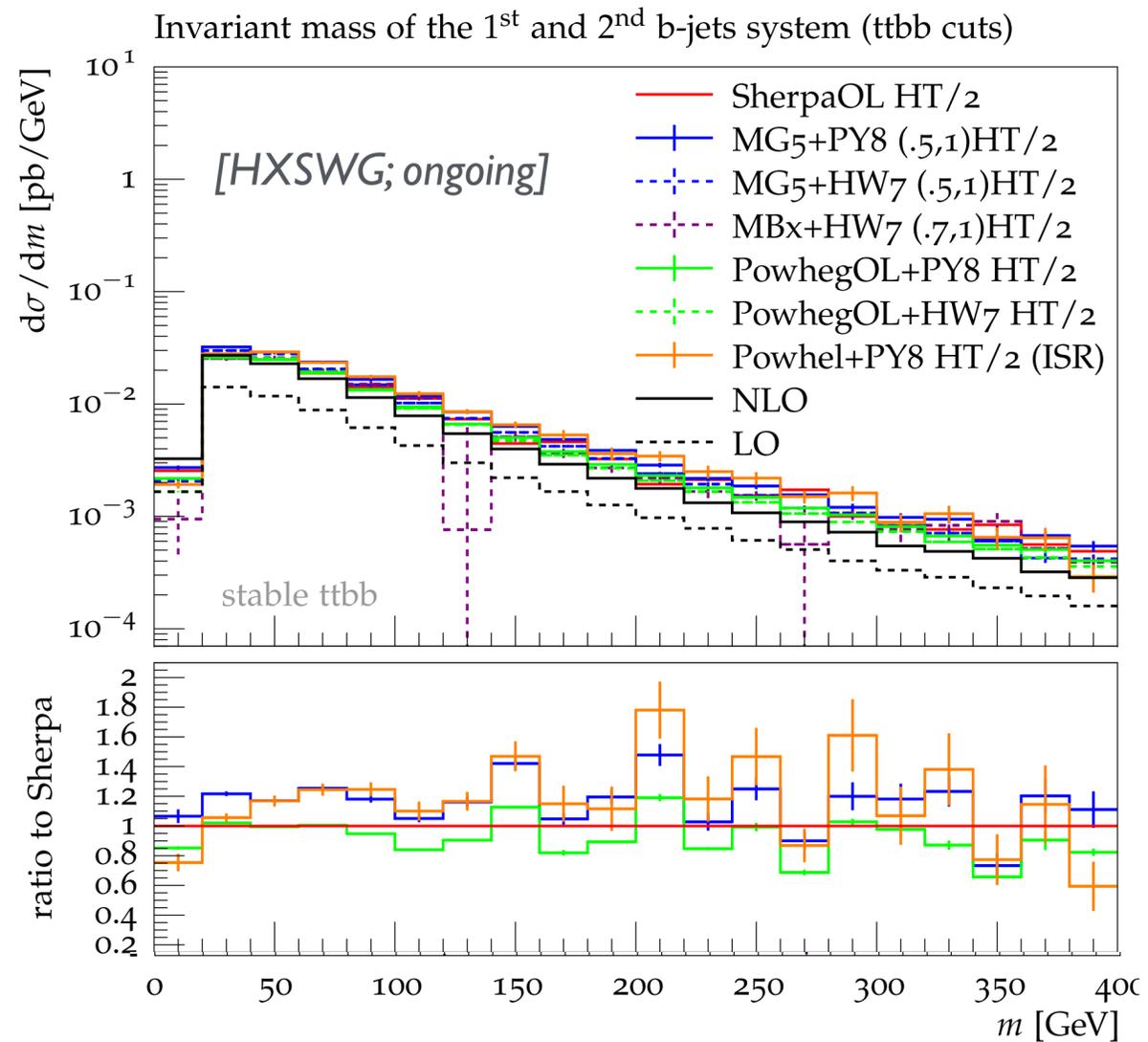
►  $\alpha_s$  &  $g \rightarrow b\bar{b}$  variations

► hdamp & bzd variations

$$g_{\text{soft}}(\Phi_{\text{rad}}, h_{\text{damp}}, h_{\text{bzd}}) = \frac{h_{\text{damp}}^2}{h_{\text{damp}}^2 + k_T^2} \theta\left(h_{\text{bzd}} B(\Phi_B) \otimes K_{\text{soft/coll}}(\Phi_{\text{rad}}) - R(\Phi_R)\right)$$

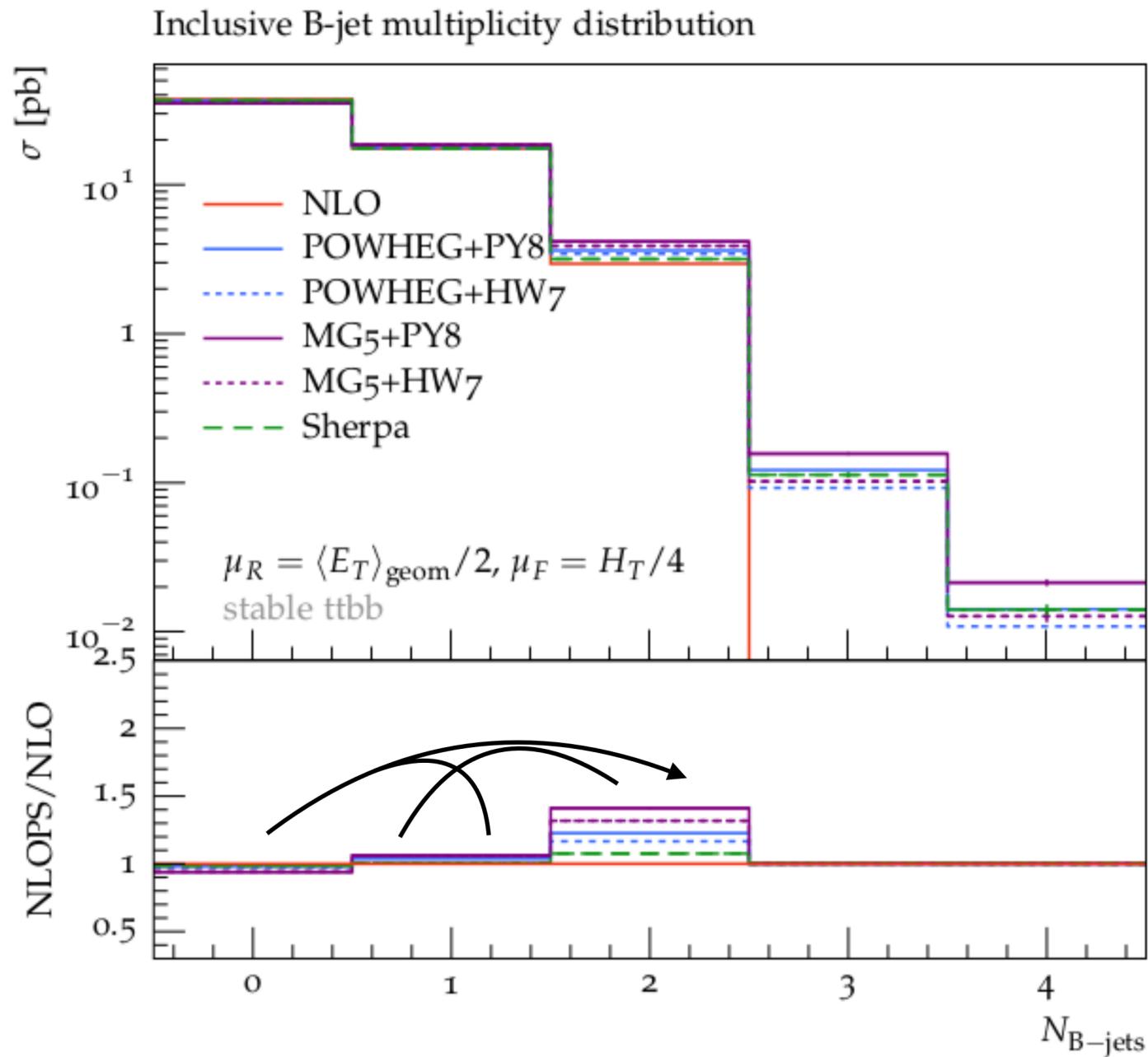
► Intrinsic shower systematics in POWHEG+PY8/HW7 under very good control

# Taming $t\bar{t}H$ backgrounds



- ➔ Sizable differences between different generators: in particular in radiation/recoil spectrum
- ➔ Without understanding their origin (physical or not?) we should not use MC differences as theory uncertainty!
- ➔ **Careful look inside the NLO+PS black-boxes necessary:** ongoing within HXSWG!

# Origin of these differences



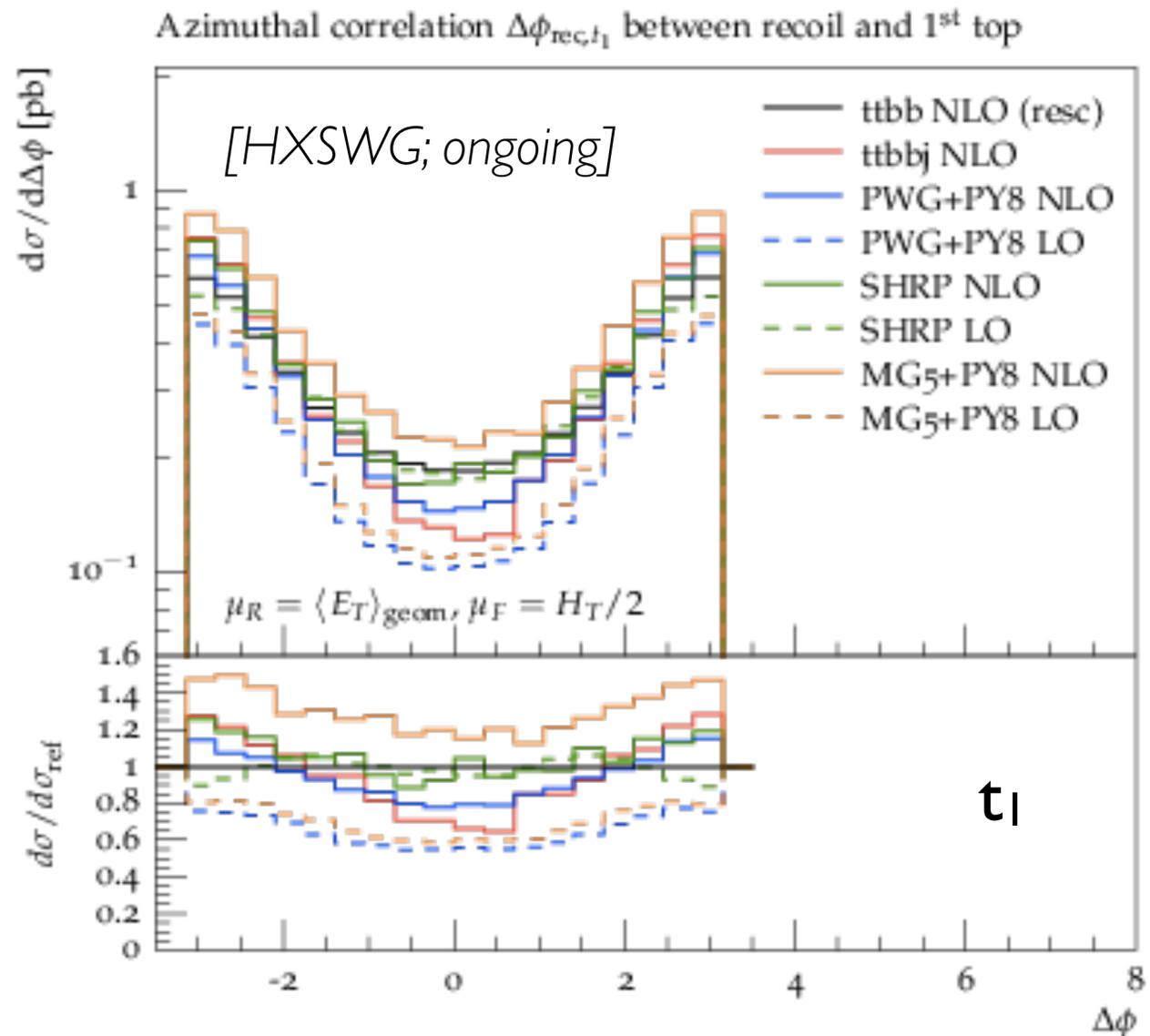
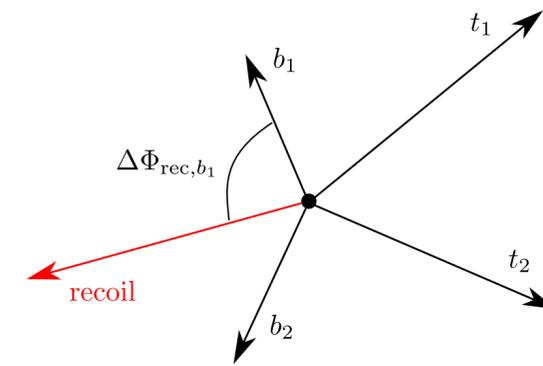
- origin: different shower-induced bins migrations across b-jets cuts

anti- $k_t$ ,  $R = 0.4$

cuts:  $p_T > 25$  GeV,  $\eta < 2.5$

# The smoking gun

Study recoil observables:  $\Delta\phi_{\text{rec},X} = \Delta\phi(\vec{p}_{\text{rec}}, \vec{p}_X)$ ,  $\vec{p}_{\text{rec}} = -\sum_{t,\bar{t},b_1,b_2} \vec{p}_i$

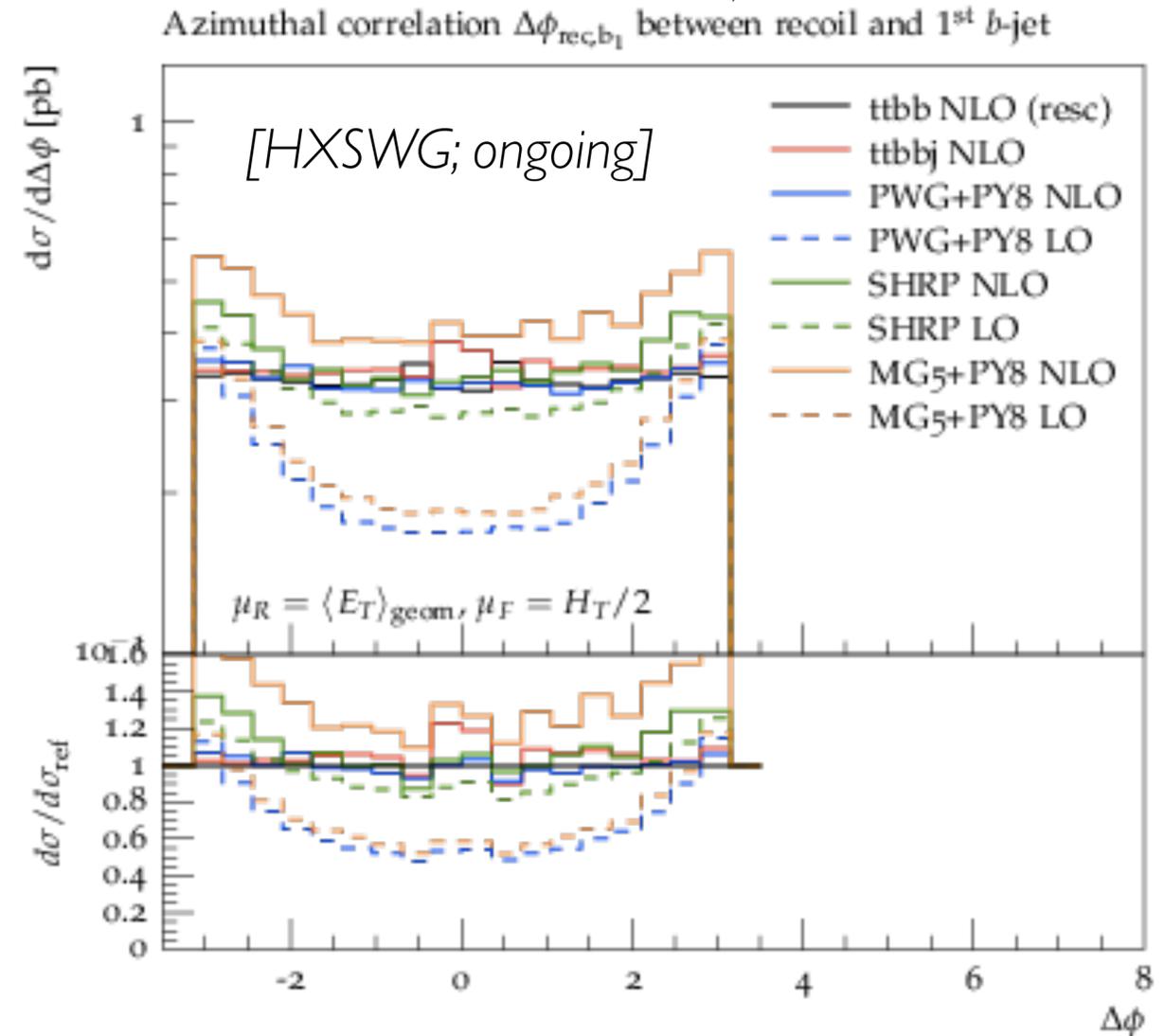
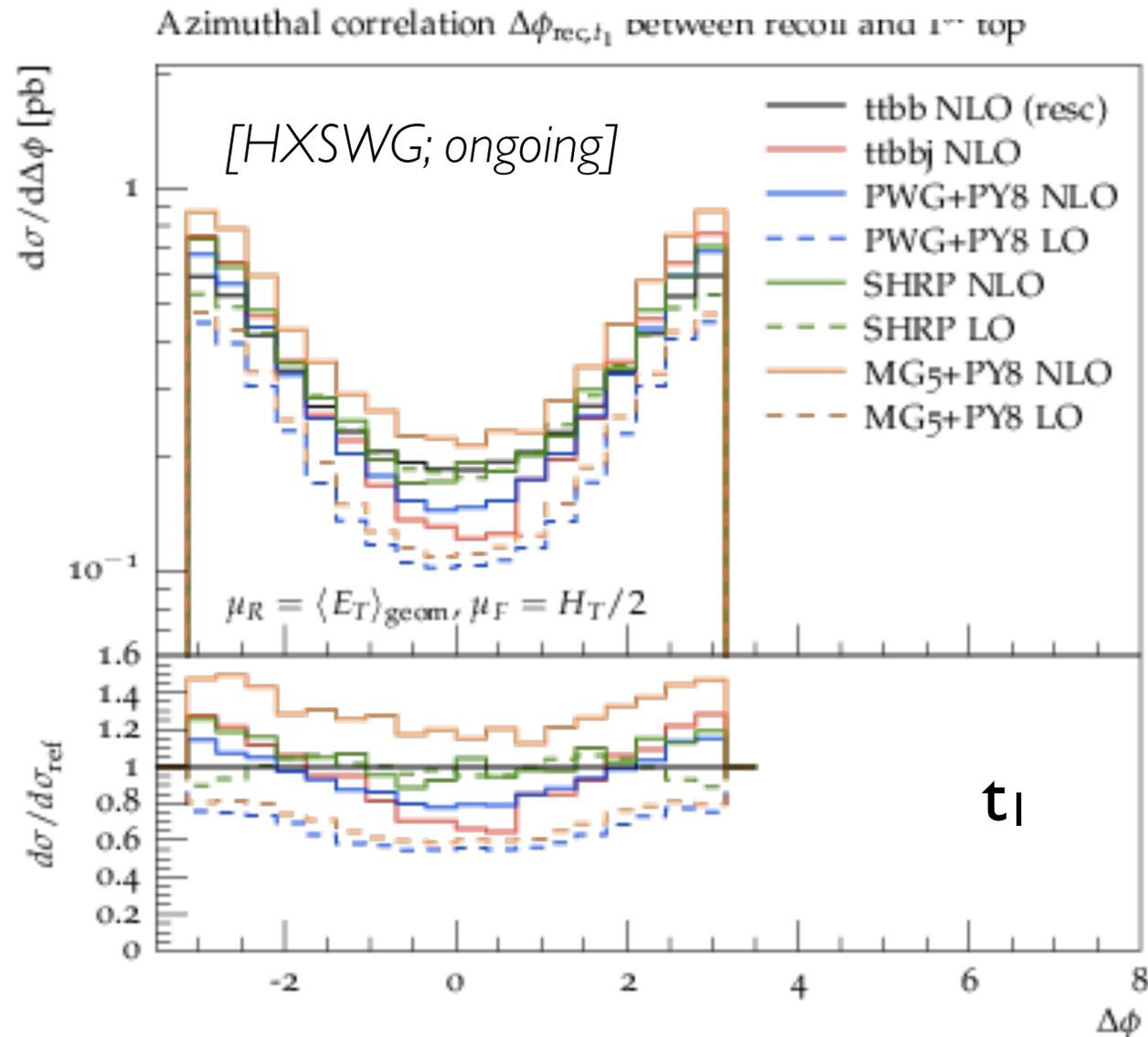
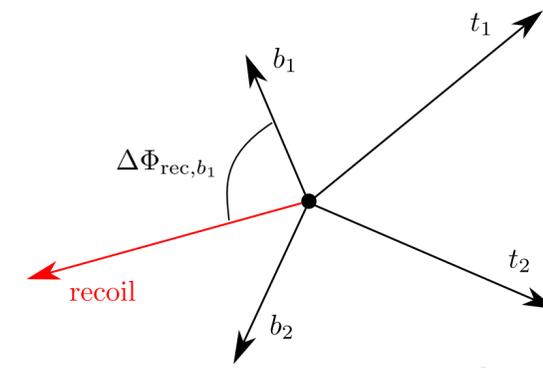


- leading top absorbs **strong recoil** from QCD radiation
- NLOPS enhancement of recoil well consistent with ttbbj at NLO (nontrivial!)

[Buccioni, Pozzorini, Zoller, 1907.13624]

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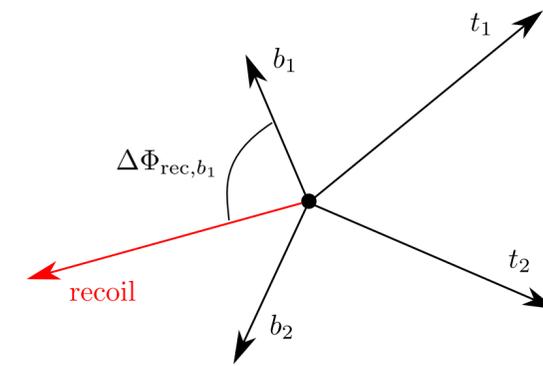
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*[Buccioni, Pozzorini, Zoller, 1907.13624]*

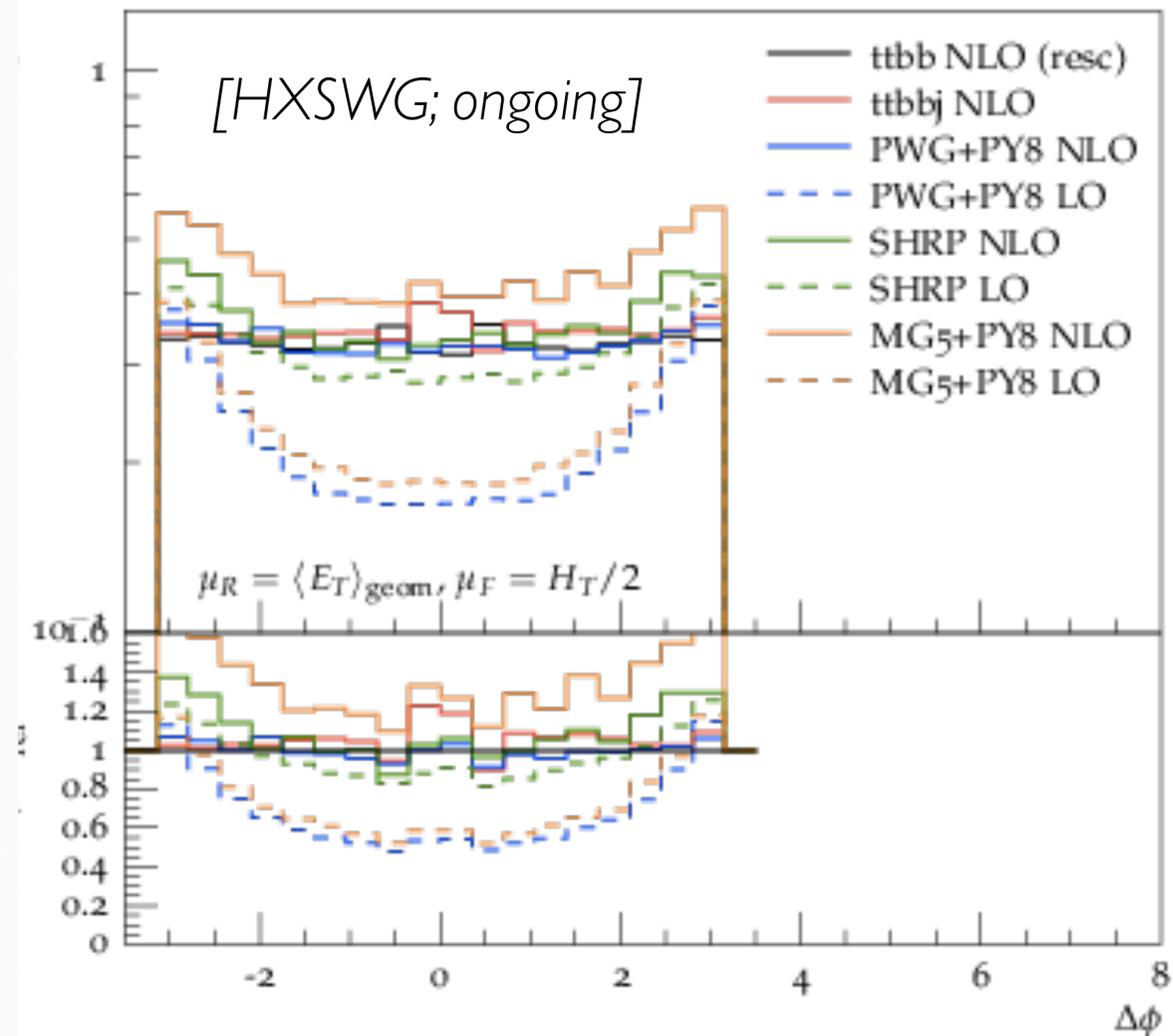
- leading bottom gets strong **UNPHYSICAL** recoil in LO+PY8
- unphysical since no evidence of recoil in ttbb, ttbbj, or PWG+PY8 at NLO
- unphysical recoil strongly suppressed only by Powheg / attenuated by MC@NLO matching (MG and Sherpa)

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Azimuthal correlation  $\Delta\phi_{\text{rec},b_1}$  between recoil and 1<sup>st</sup>  $b$ -jet



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