SM Precision Physics

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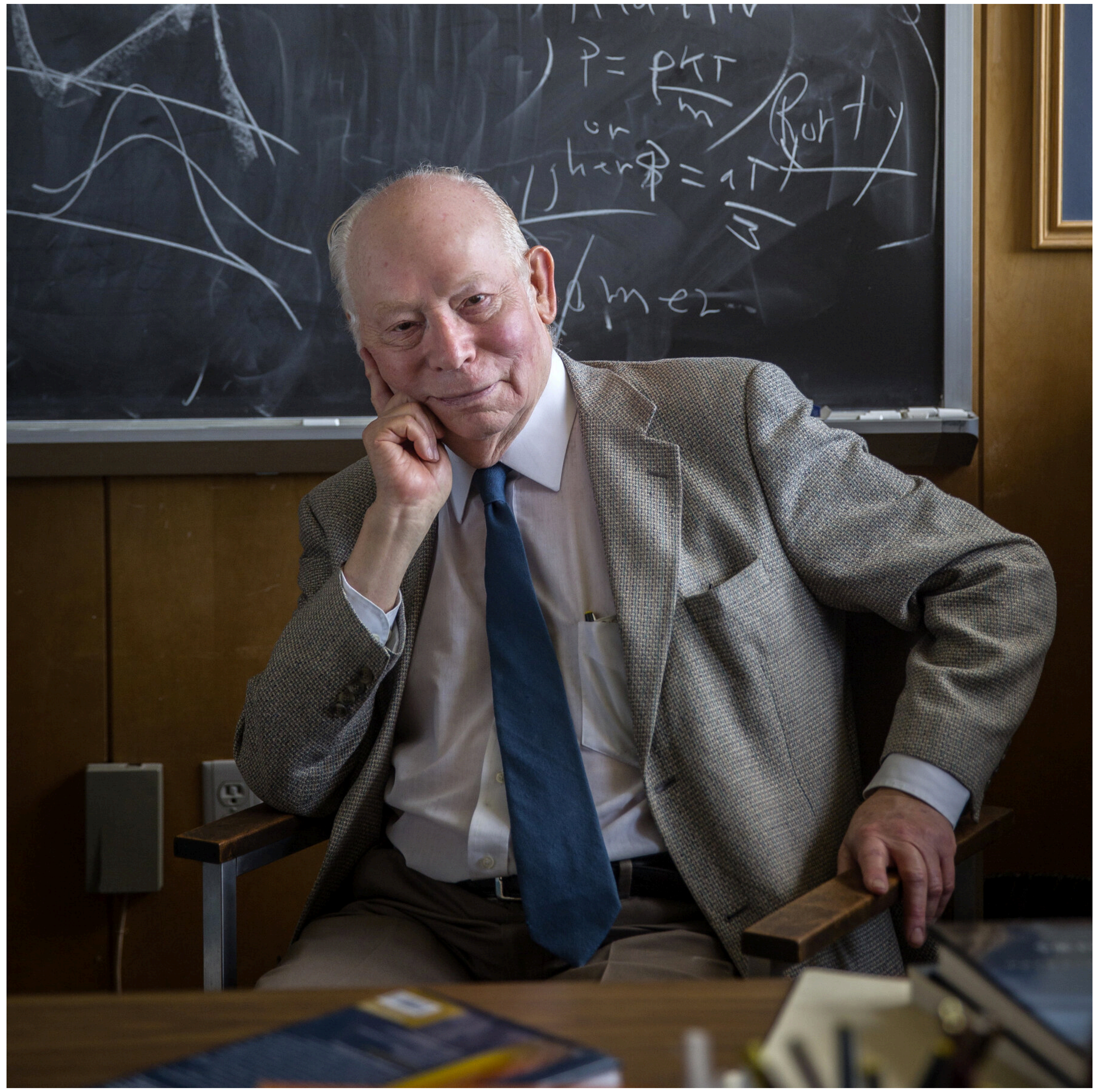
In memory of Steven Weinberg



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[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

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

[13] The predicted ratio [eq. (12)] from the current algebra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta\to\pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$ calculated in Refs. 12 and 14.

[14] L. M. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962).

A MODEL OF LEPTONS*

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(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[1] 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

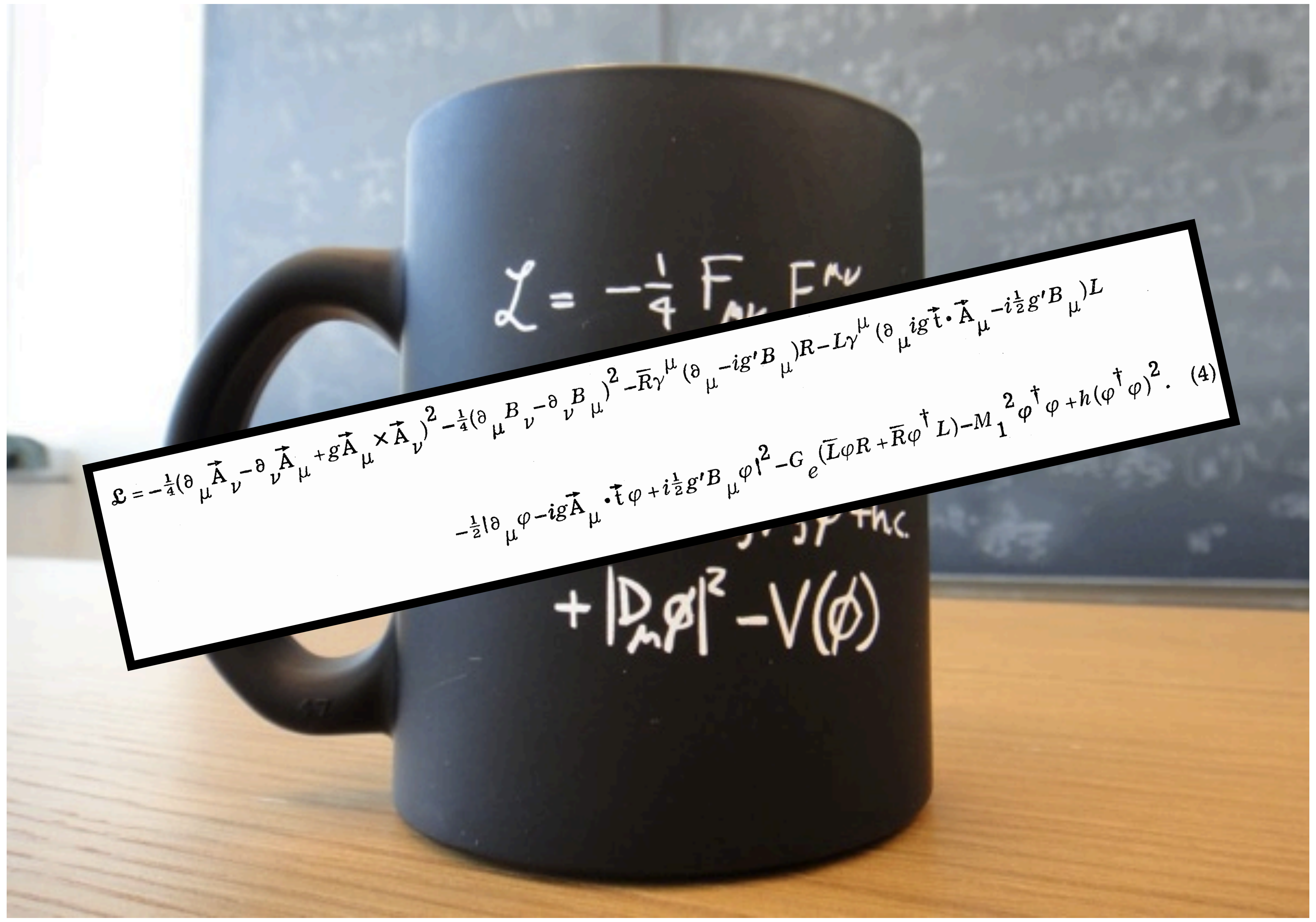
$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e. \quad (2)$$

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

$$\mathcal{L} = -\tfrac14(\partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g\vec{A}_\mu\times\vec{A}_\nu)^2 - \tfrac14(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R}\gamma^\mu(\partial_\mu - ig'B_\mu)R - L\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu - i\tfrac12 g'B_\mu)L$$

$$-\tfrac12|\partial_\mu\varphi - ig\vec{A}_\mu\cdot\vec{t}\varphi + i\tfrac12 g'B_\mu\varphi|^2 - G_e(\bar{L}\varphi R + \bar{R}\varphi^\dagger L) - M_1^{\,2}\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2. \quad (4)$$

Theoretical Predictions for the LHC



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

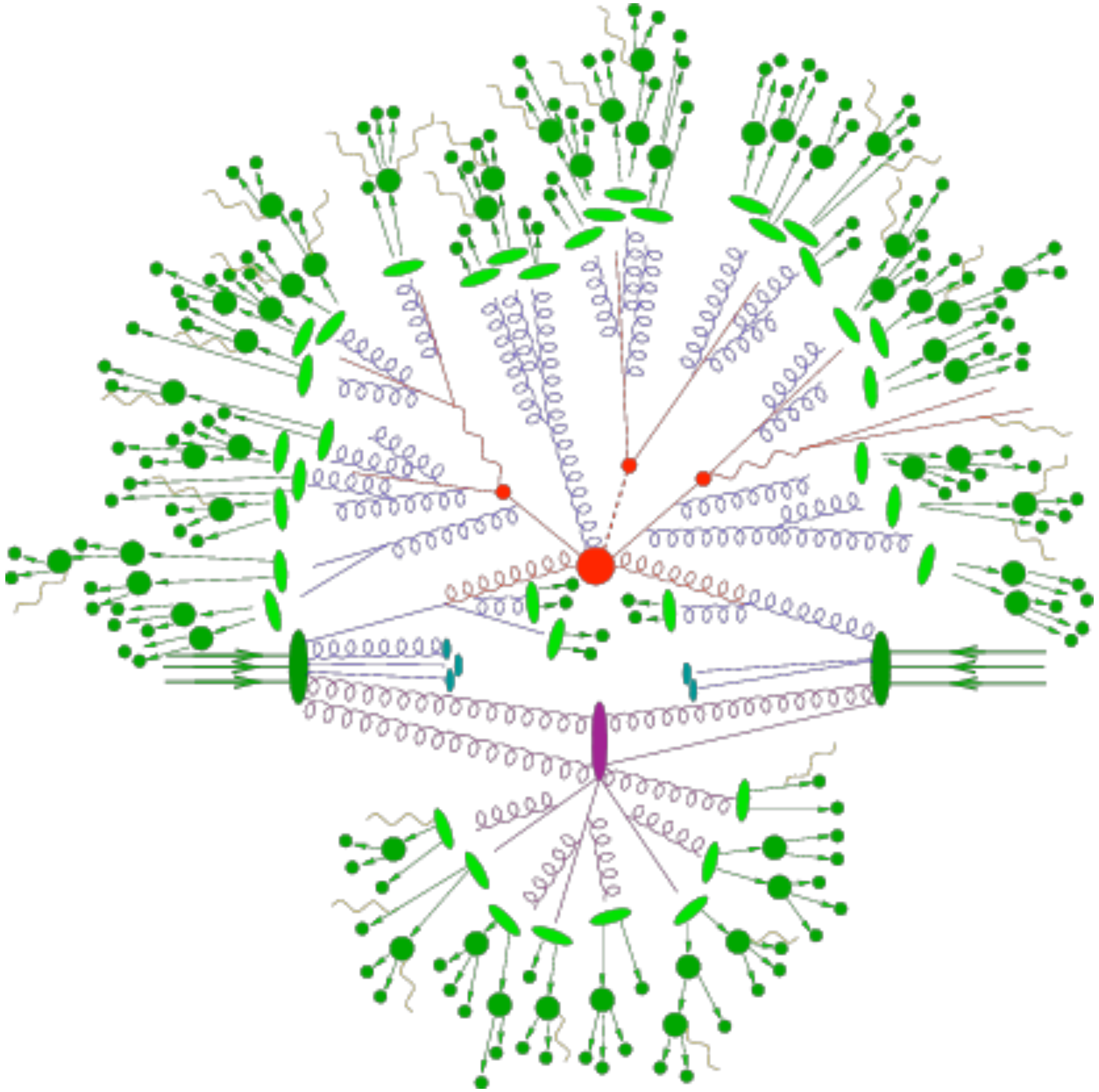
Theoretical Predictions for the LHC

$$\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_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)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu 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^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\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}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{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) + igs_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^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).
\end{gathered}$$

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

Theoretical Predictions for the LHC

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_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)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu 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^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\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}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{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) + igs_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^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).
\end{gathered}
$$



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

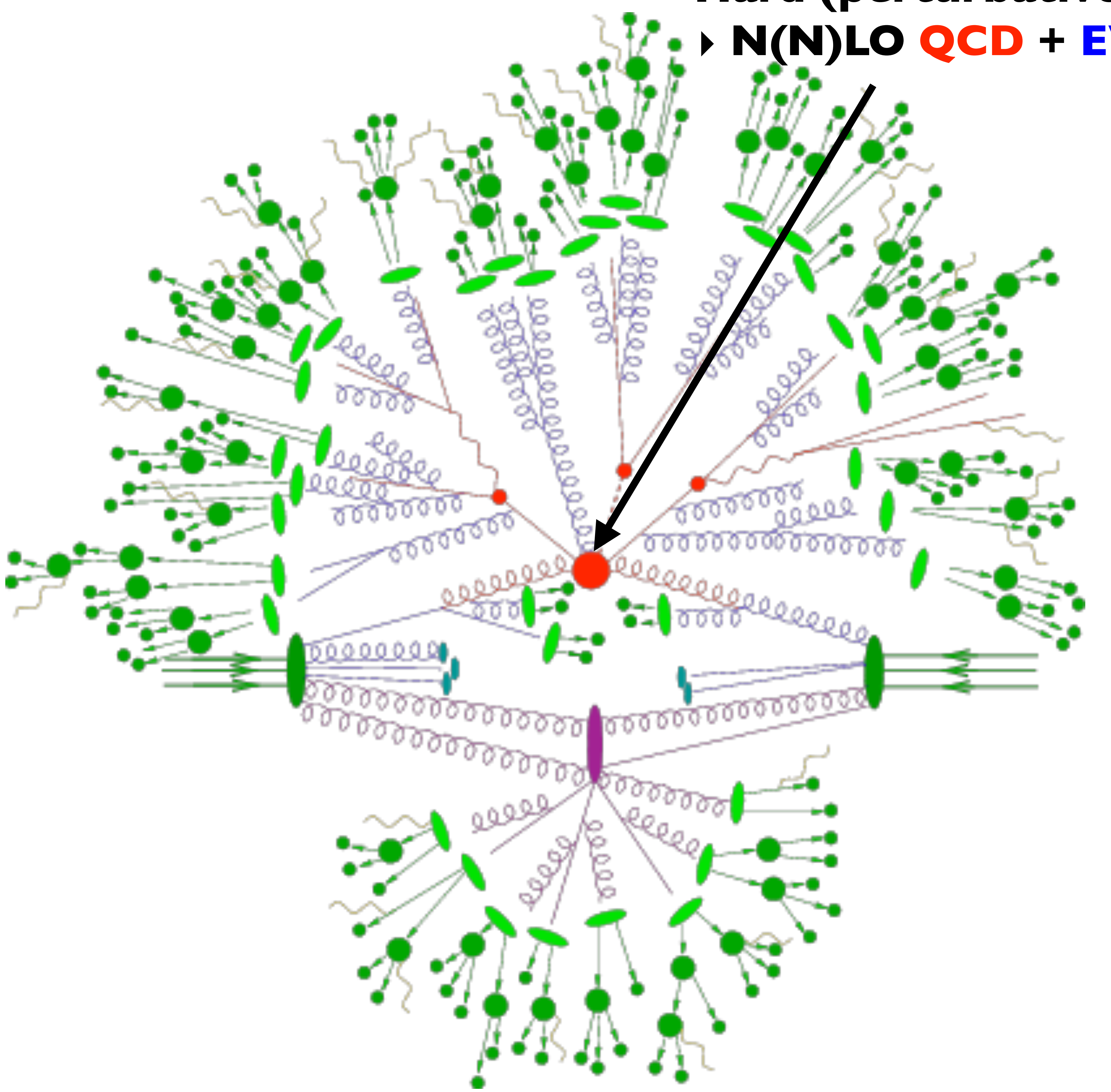
Theoretical Predictions for the LHC

$$\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_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)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu 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^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\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}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{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) + igs_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^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).
\end{gathered}$$

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

Hard (perturbative) scattering process

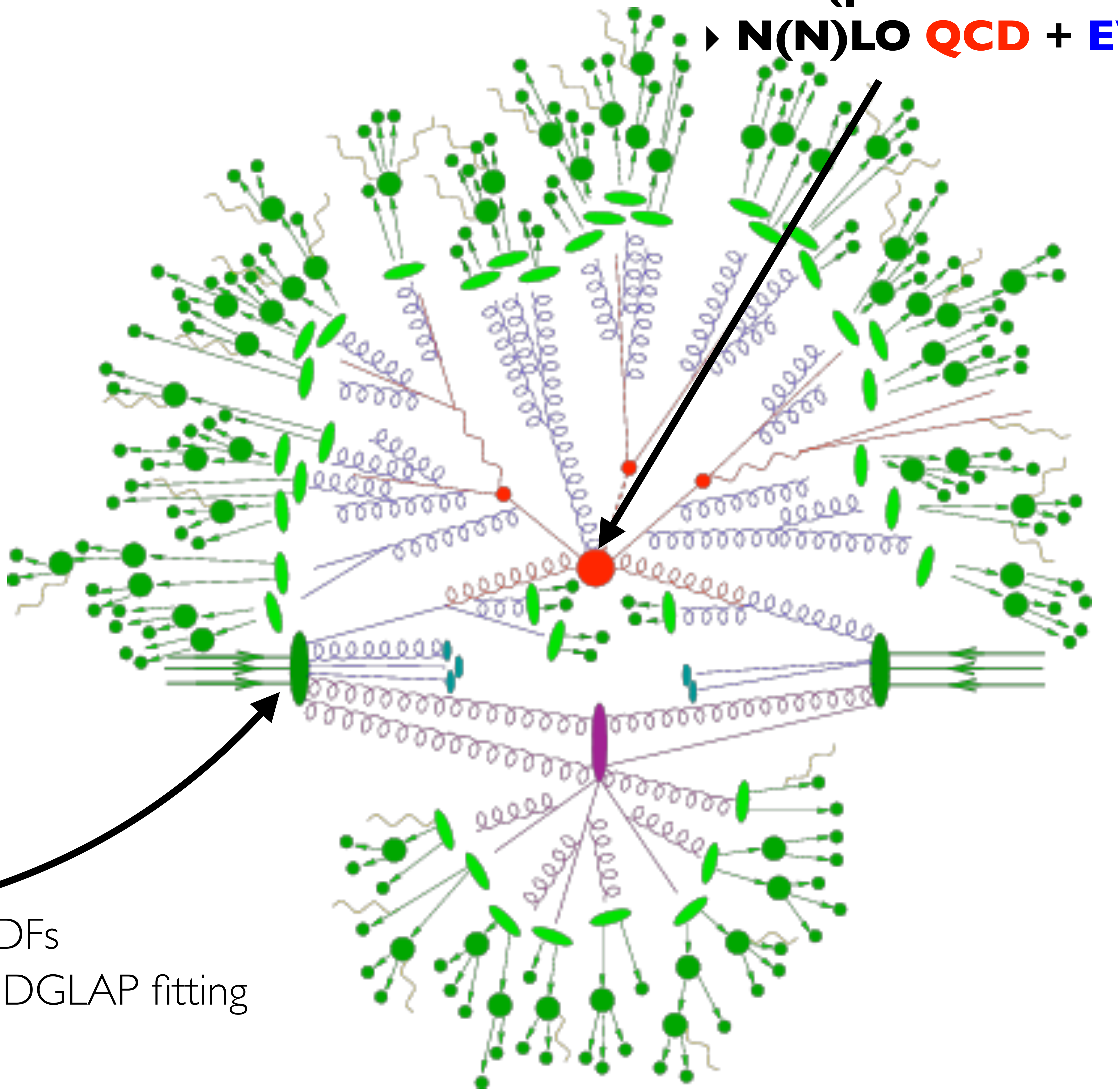
- **N(N)LO QCD + EW**



Theoretical Predictions for the LHC

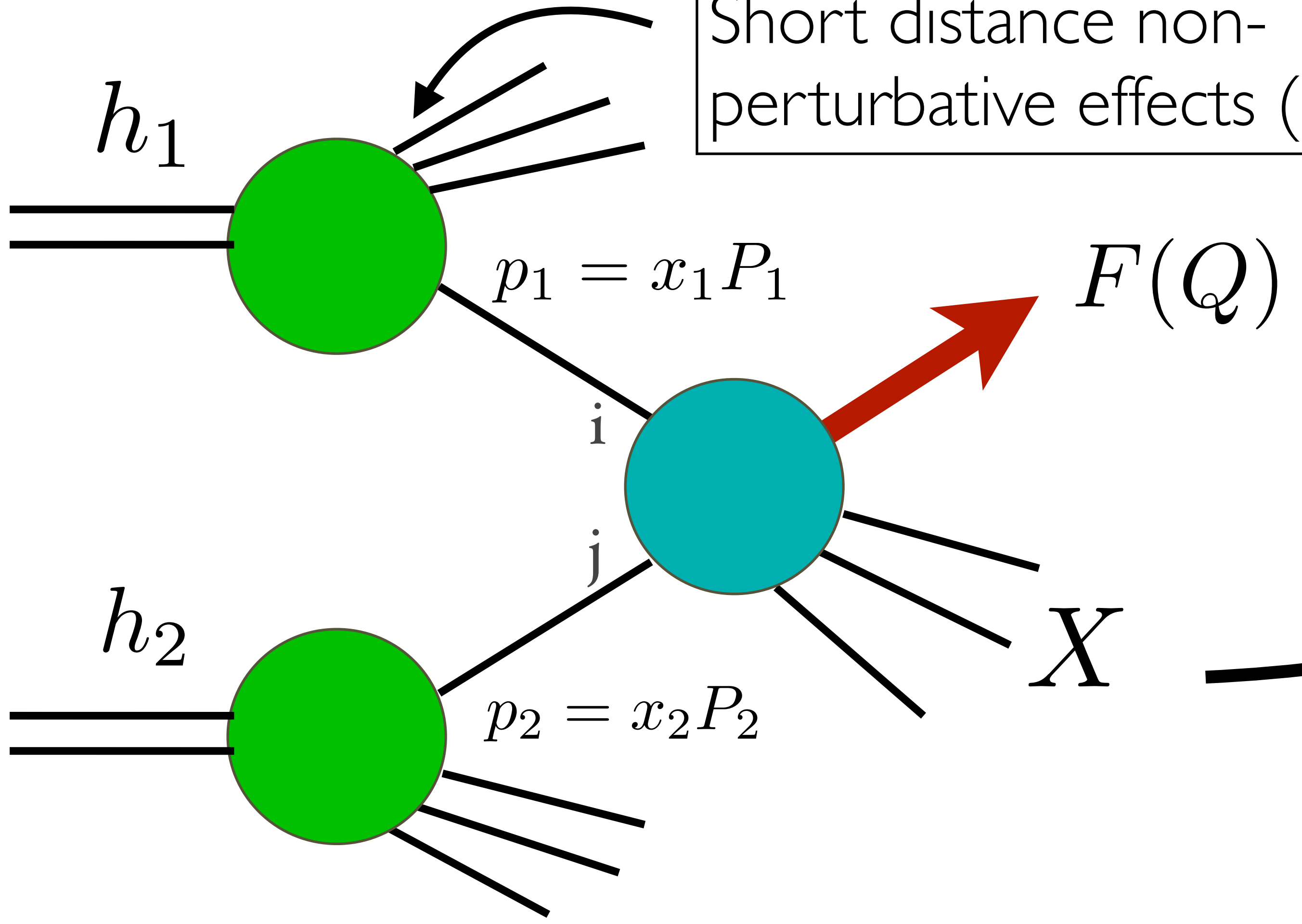
Hard (perturbative) scattering process

- **N(N)LO QCD + EW**



Key: QCD factorization:

Short distance non-perturbative effects (PDFs)



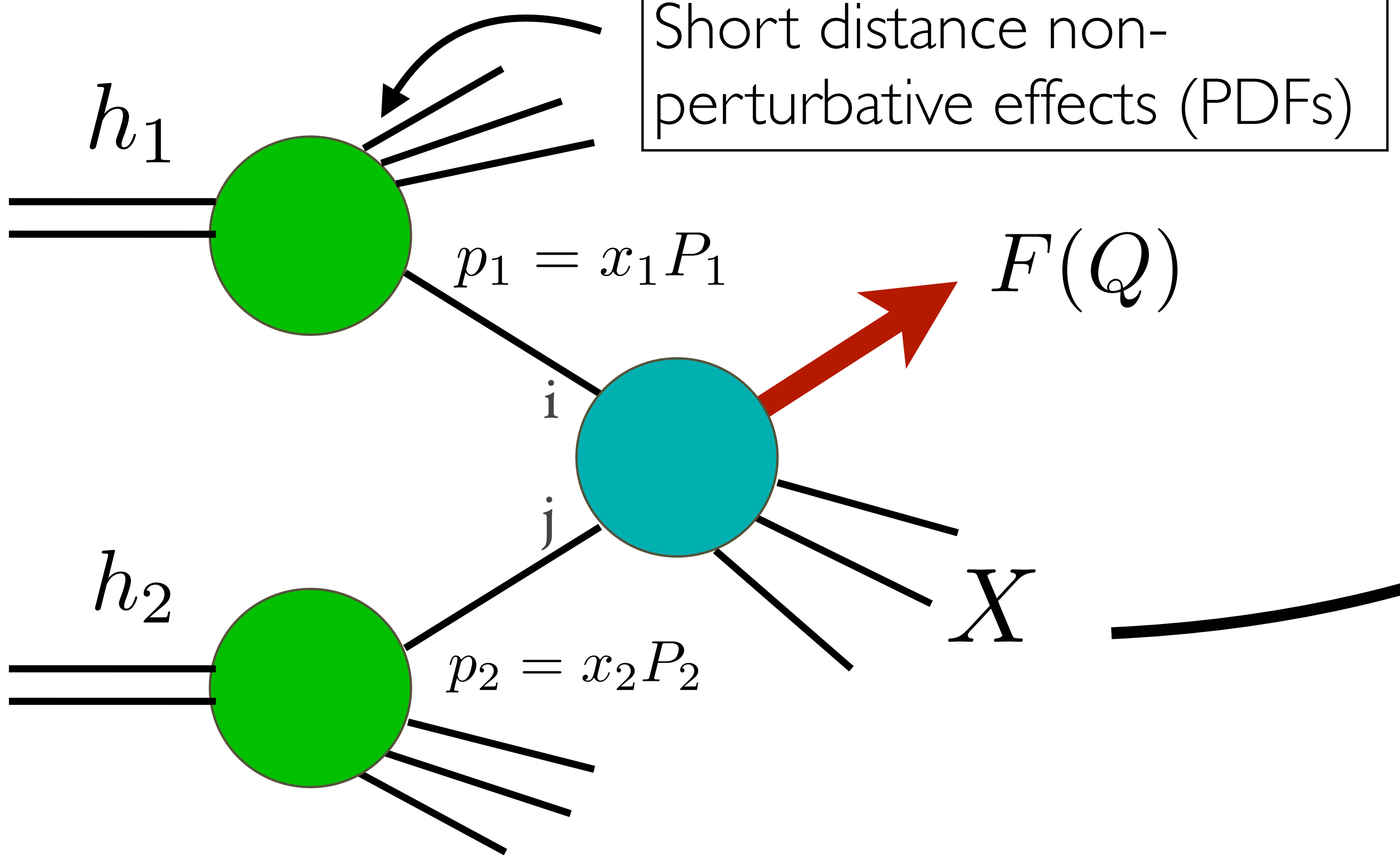
$$d\sigma = \sum_{ij} \int dx_1 dx_2 f_1^{(P_1)}(x_1) f_2^{(P_2)}(x_2) d\hat{\sigma}_{ij}(x_1 x_2 s)$$

PDFs

- DGLAP fitting

Theoretical Predictions for the LHC

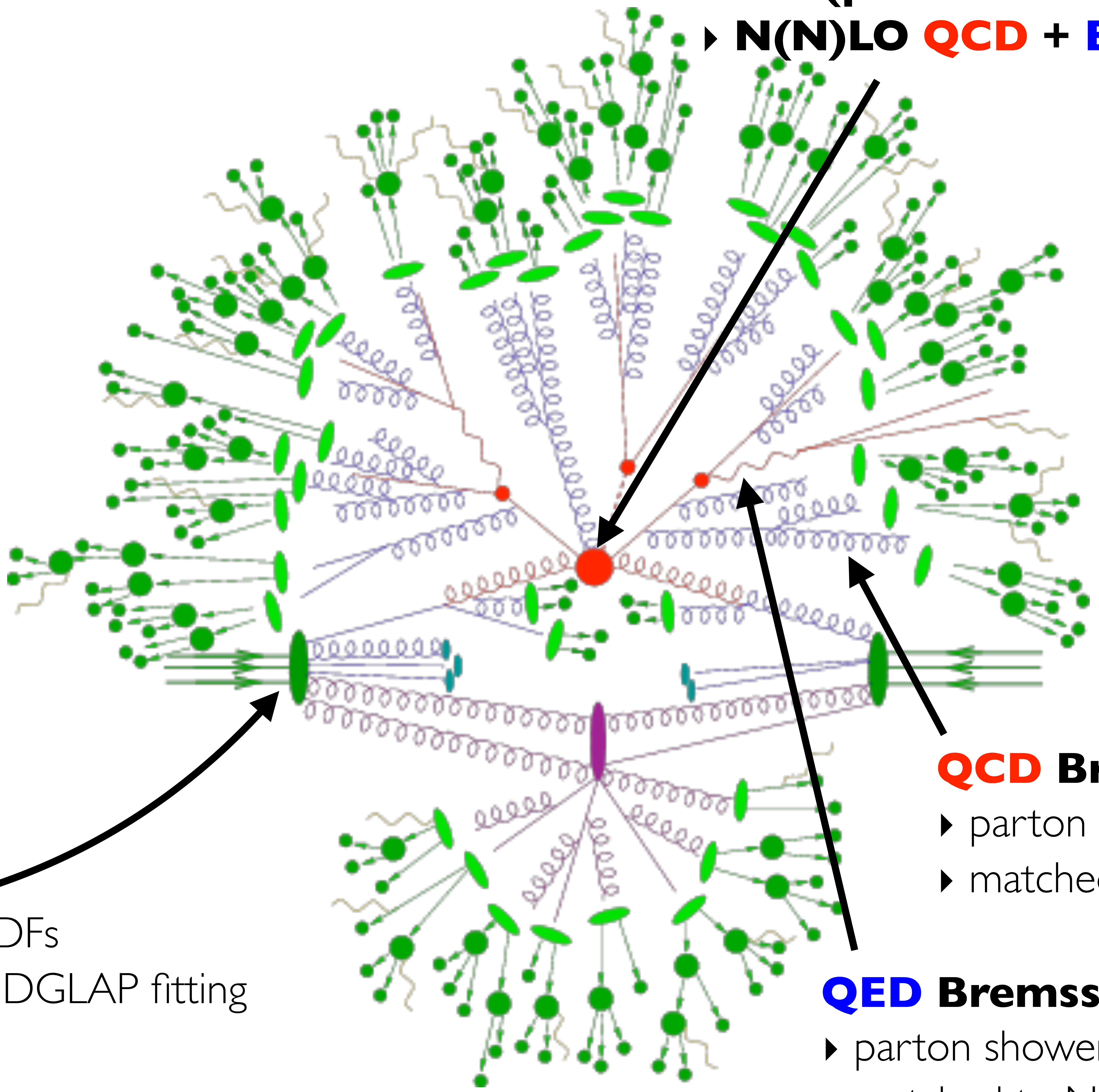
Key: QCD factorization:



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

PDFs
- DGLAP fitting

Hard (perturbative) scattering process
- **N(N)LO QCD + EW**

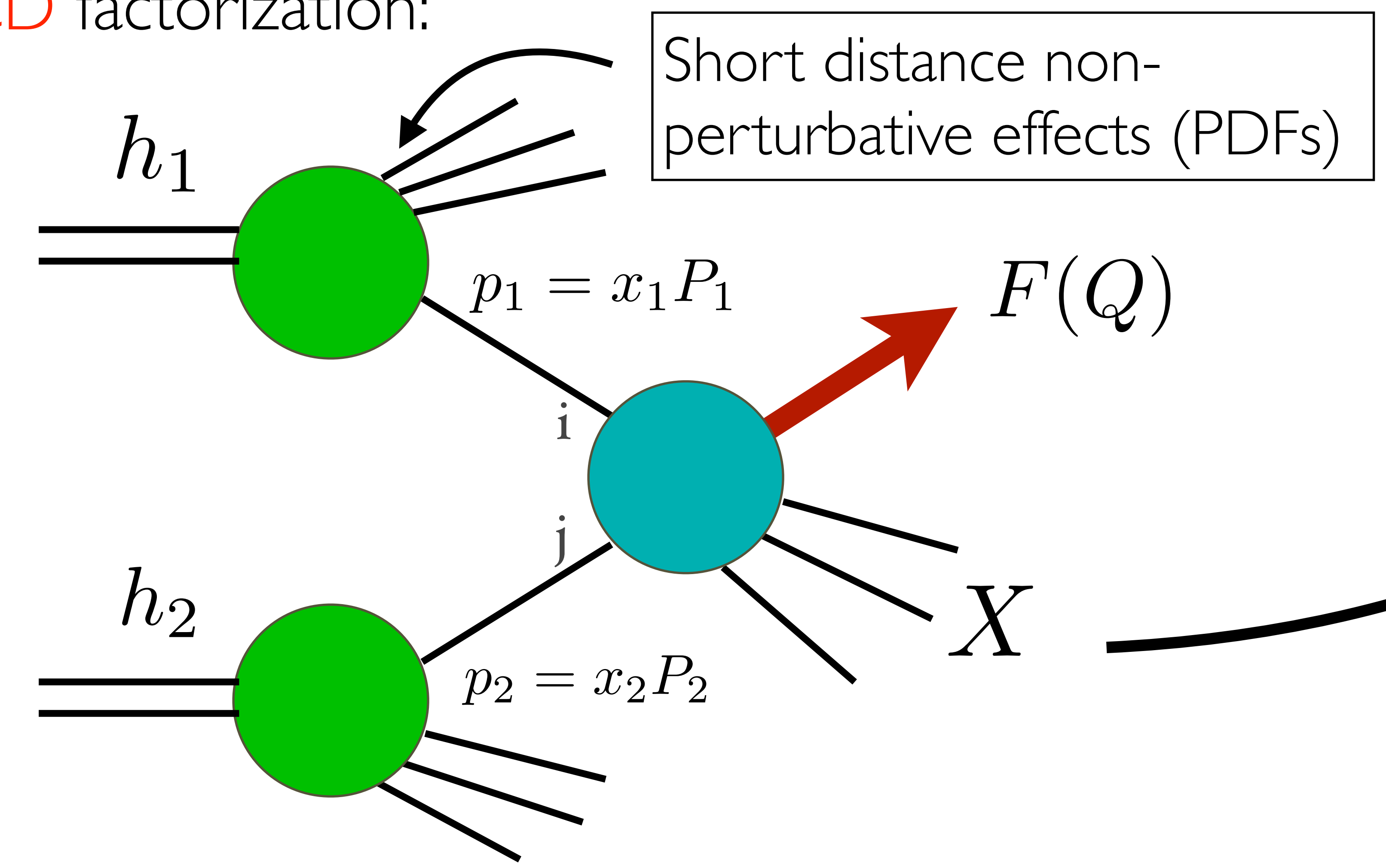


QCD Bremsstrahlung
- parton shower
- matched to NLO matrix elements

QED Bremsstrahlung
- parton shower
- matched to NLO matrix elements

Theoretical Predictions for the LHC

Key: QCD factorization:



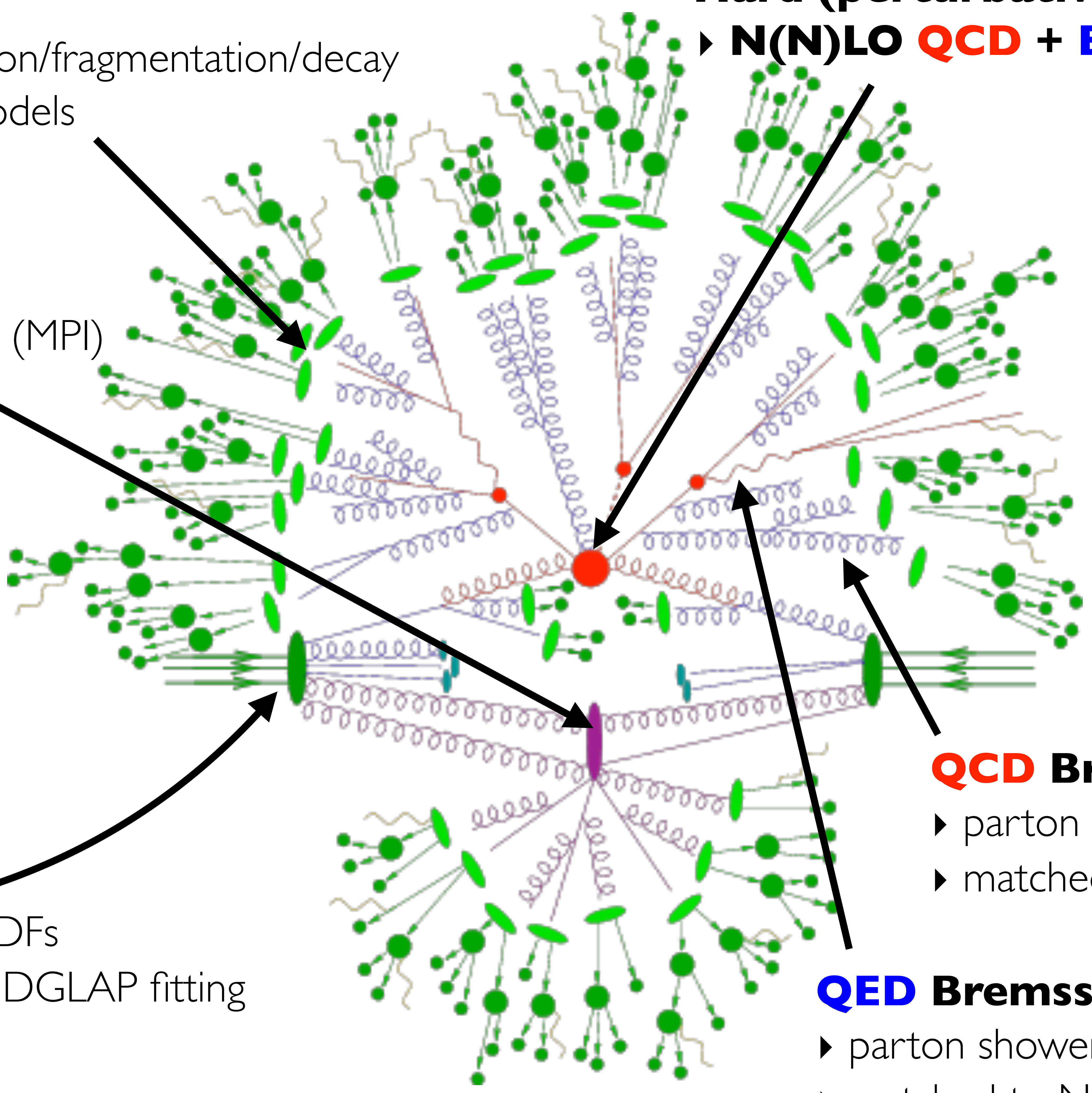
$$d\sigma = \sum_{ij} \int dx_1 dx_2 f_1^{(P_1)}(x_1) f_2^{(P_2)}(x_2) d\hat{\sigma}_{ij}(x_1 x_2 s)$$

Hadronization/fragmentation/decay
- pheno models

Multi Particle Interactions (MPI)
- pheno model

PDFs
- DGLAP fitting

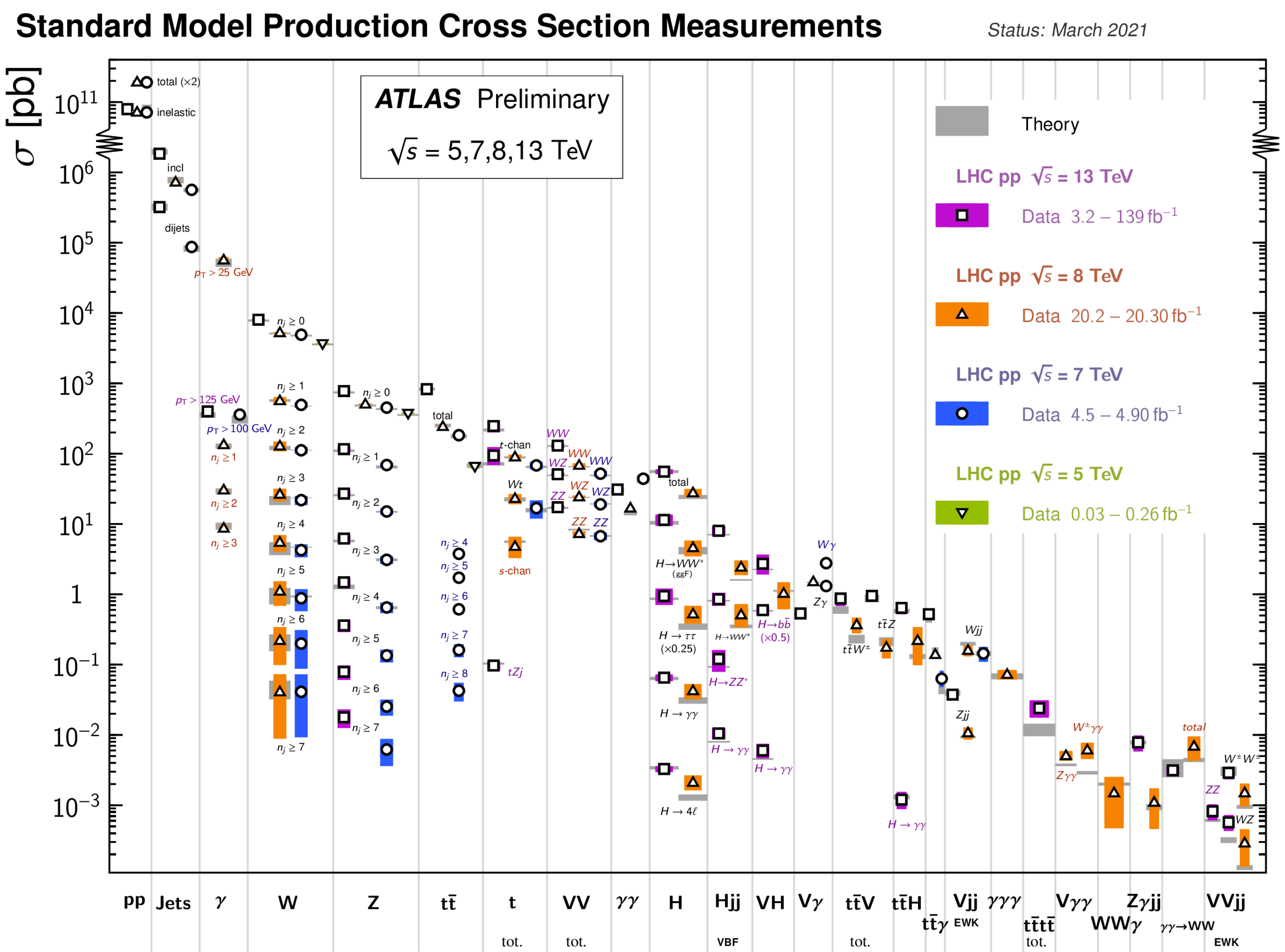
Hard (perturbative) scattering process
- **N(N)LO QCD + EW**

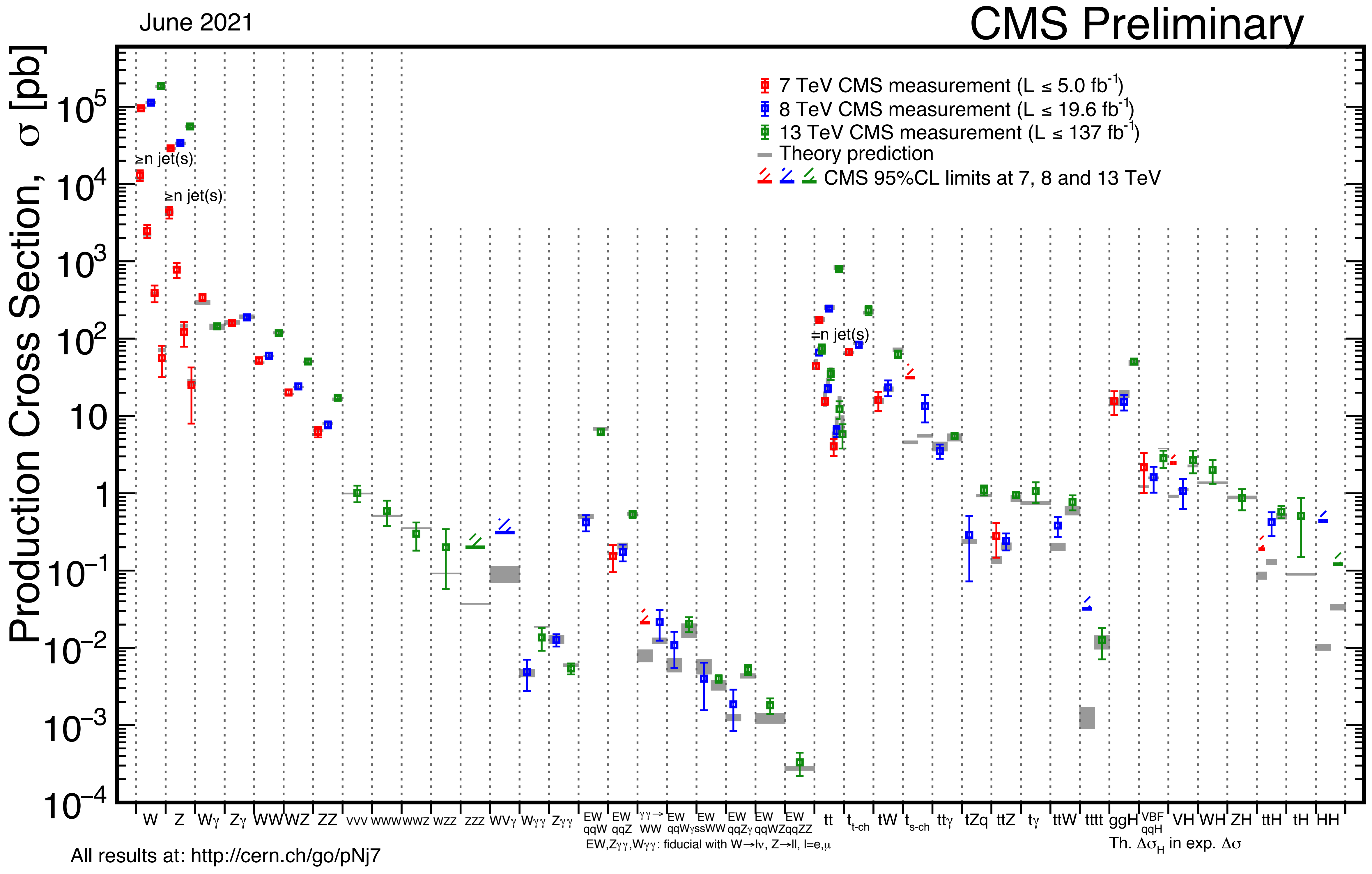


QCD Bremsstrahlung
- parton shower
- matched to NLO matrix elements

QED Bremsstrahlung
- parton shower
- matched to NLO matrix elements

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

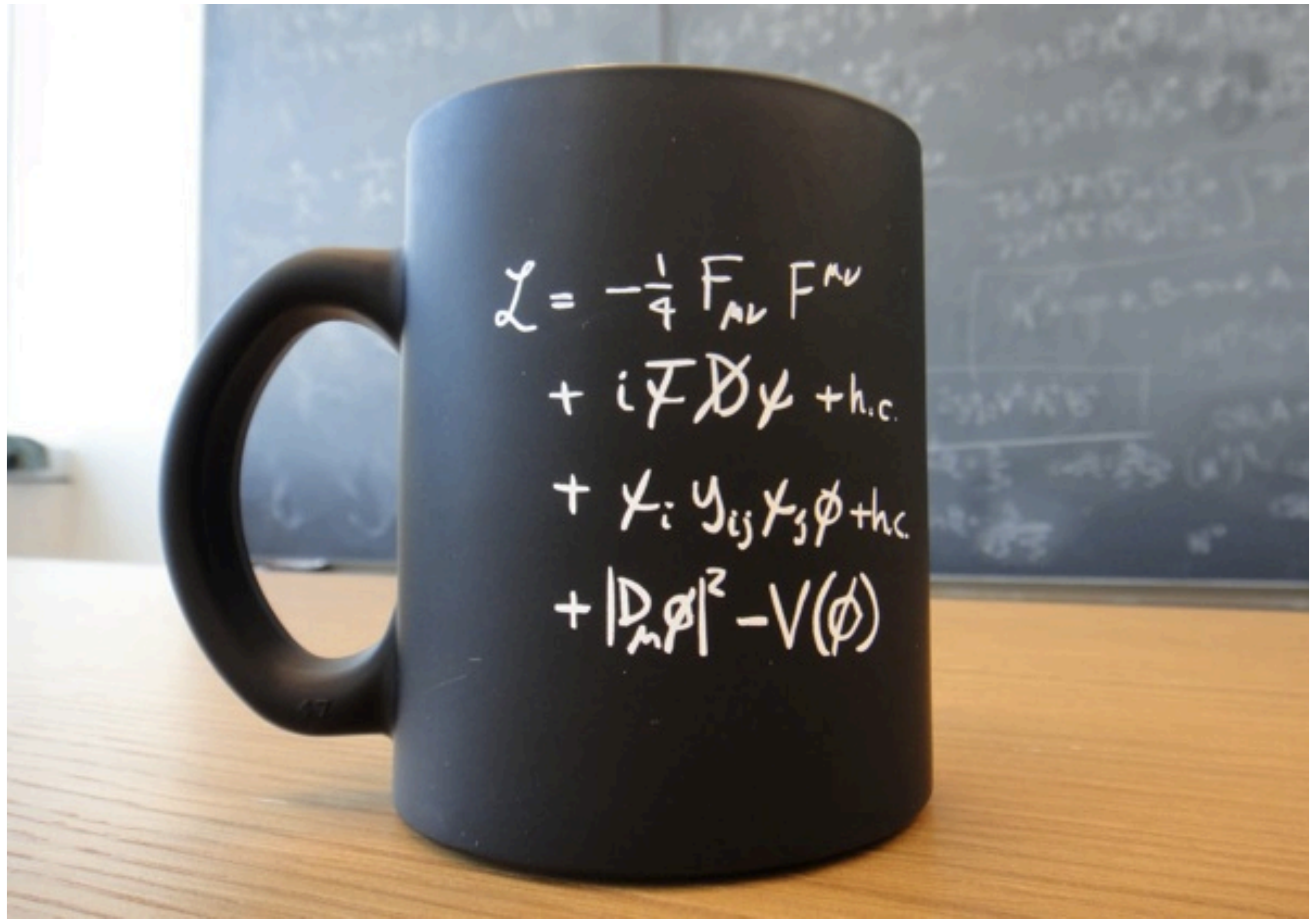


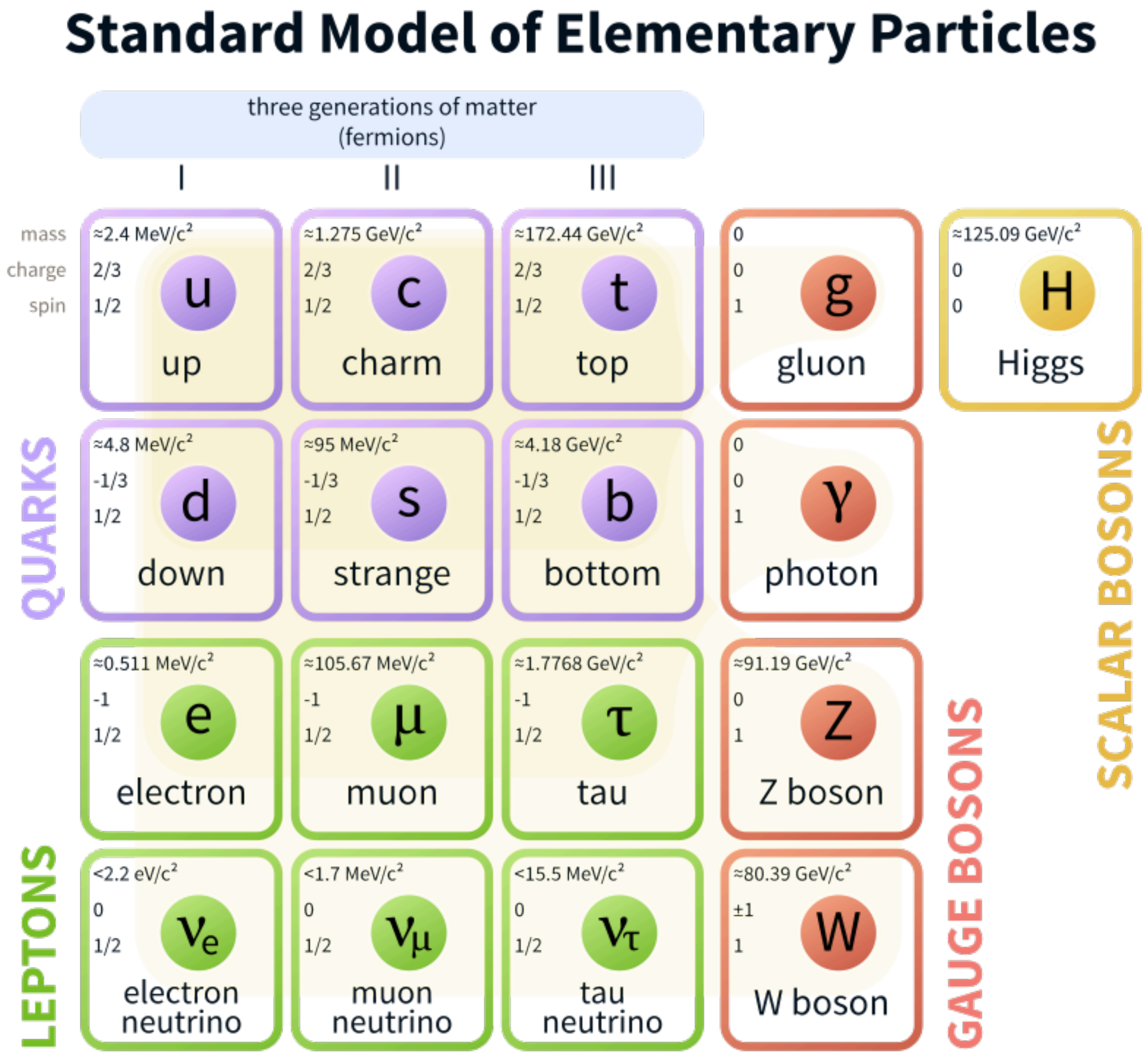


Overall remarkable data vs. theory agreement

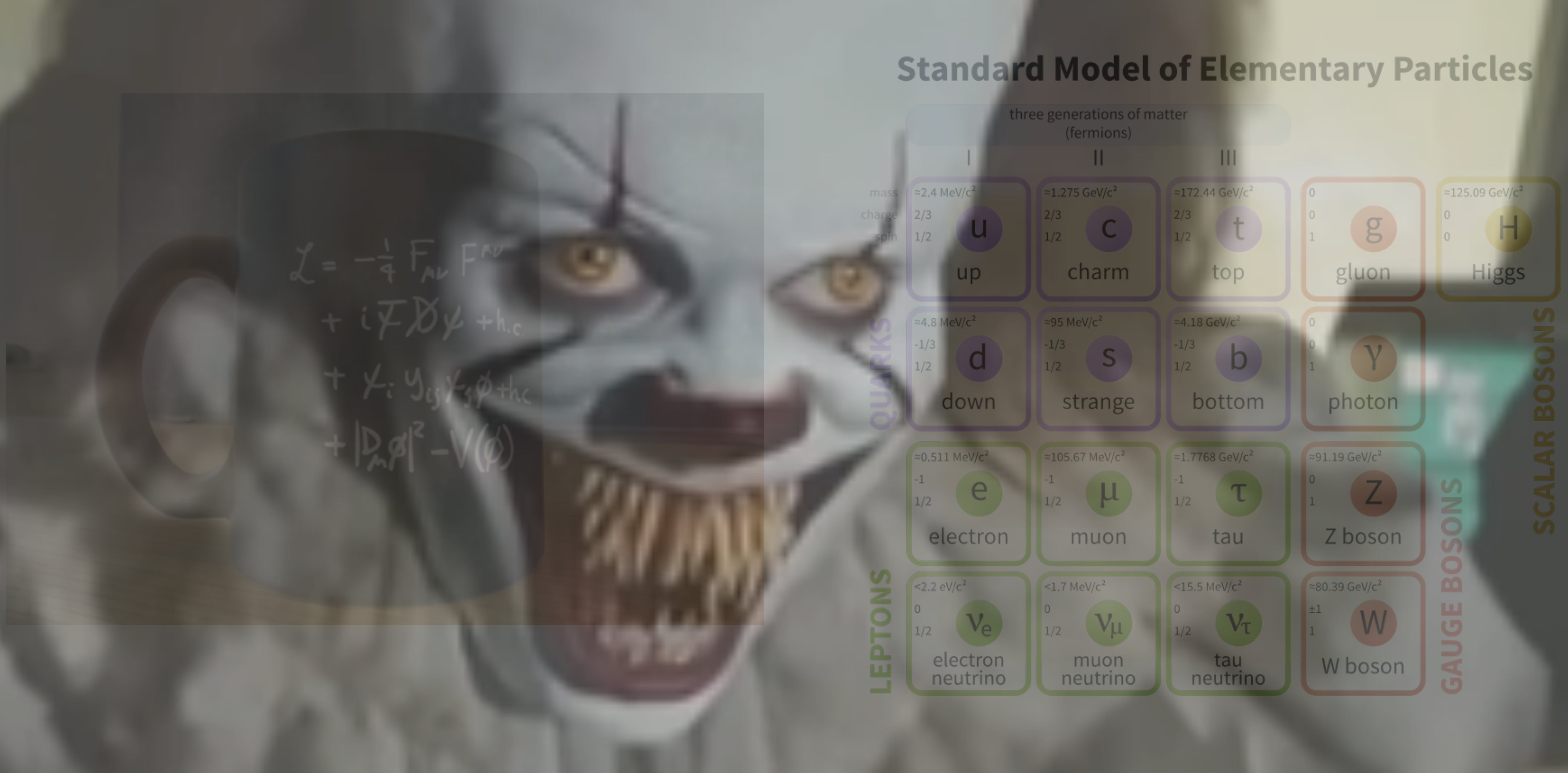
➡Precision tests of the SM at the quantum level in a multitude of processes

With the discovery of the Higgs the SM is ‘complete’





With the discovery of the Higgs the SM is ‘complete’



Is the ‘nightmare scenario’ becoming reality?

Why do we need SM theory?

SM parameters and particle properties

mh

mt

mW

BRs

CKM

SM dynamics

(Differential) cross sections

PDFs & α_s

Higgs couplings

EW couplings

BSM searches

Anomalous couplings

Tails of distributions

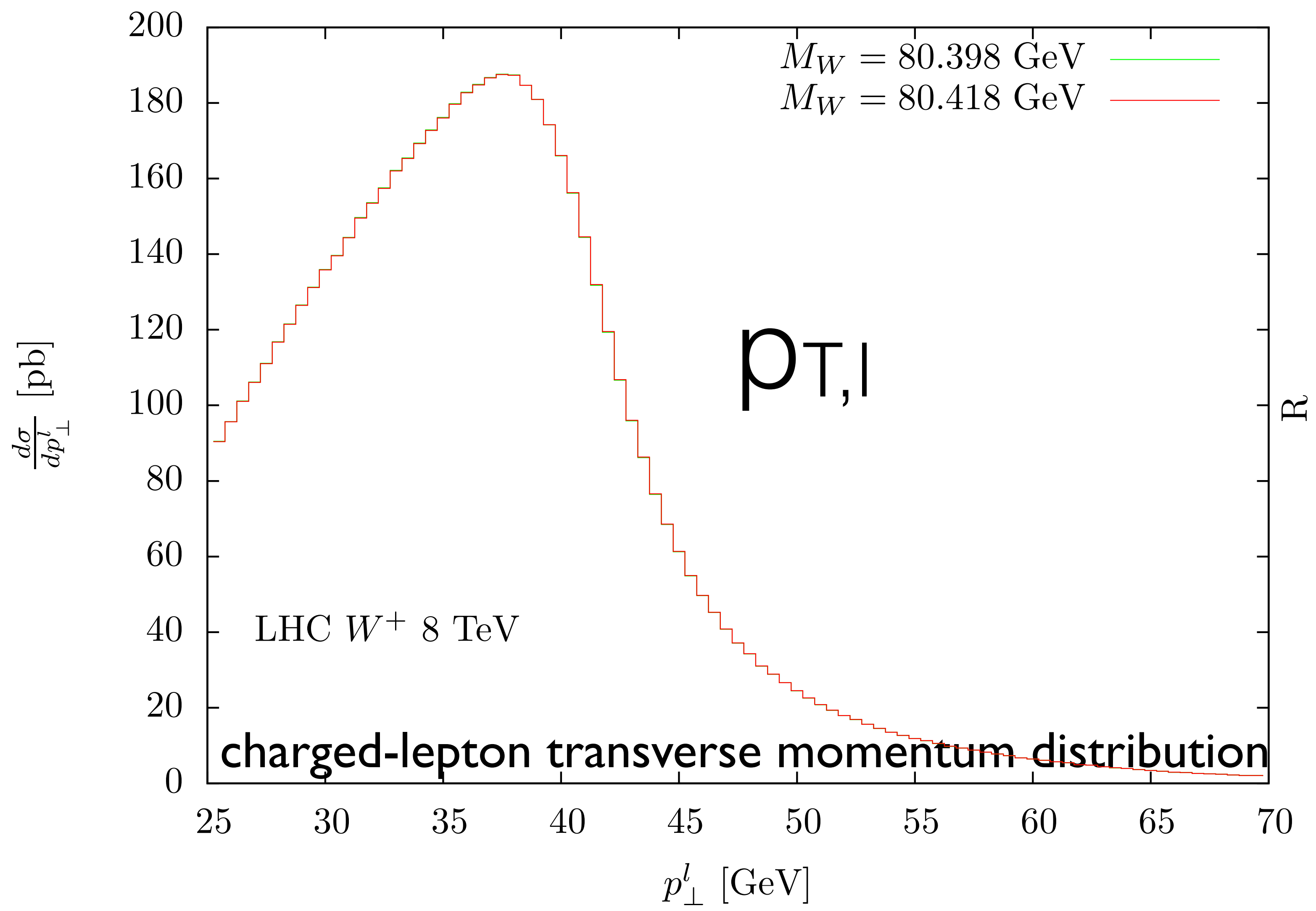
EFT coefficients

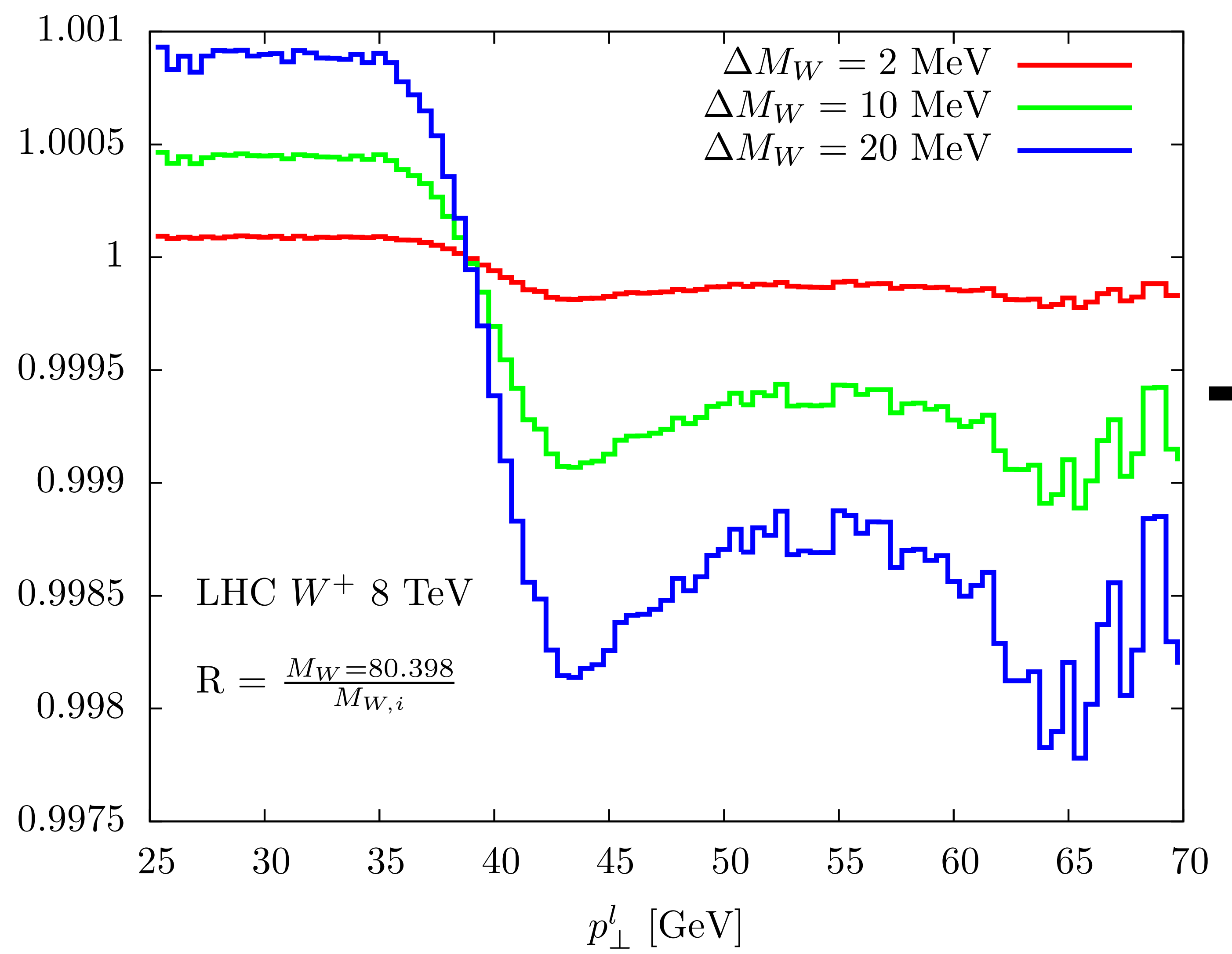
This is not the 'nightmare scenario'. However, precision key!

Drell-Yan: M_W measurements

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

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





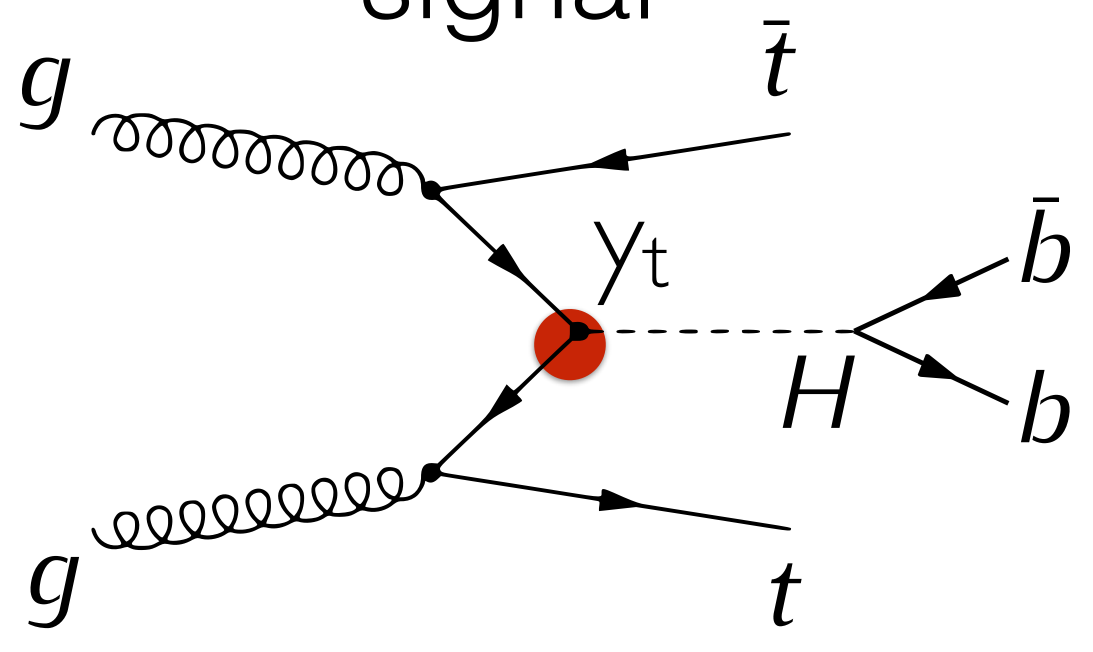
[Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, Vicini;'16]

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

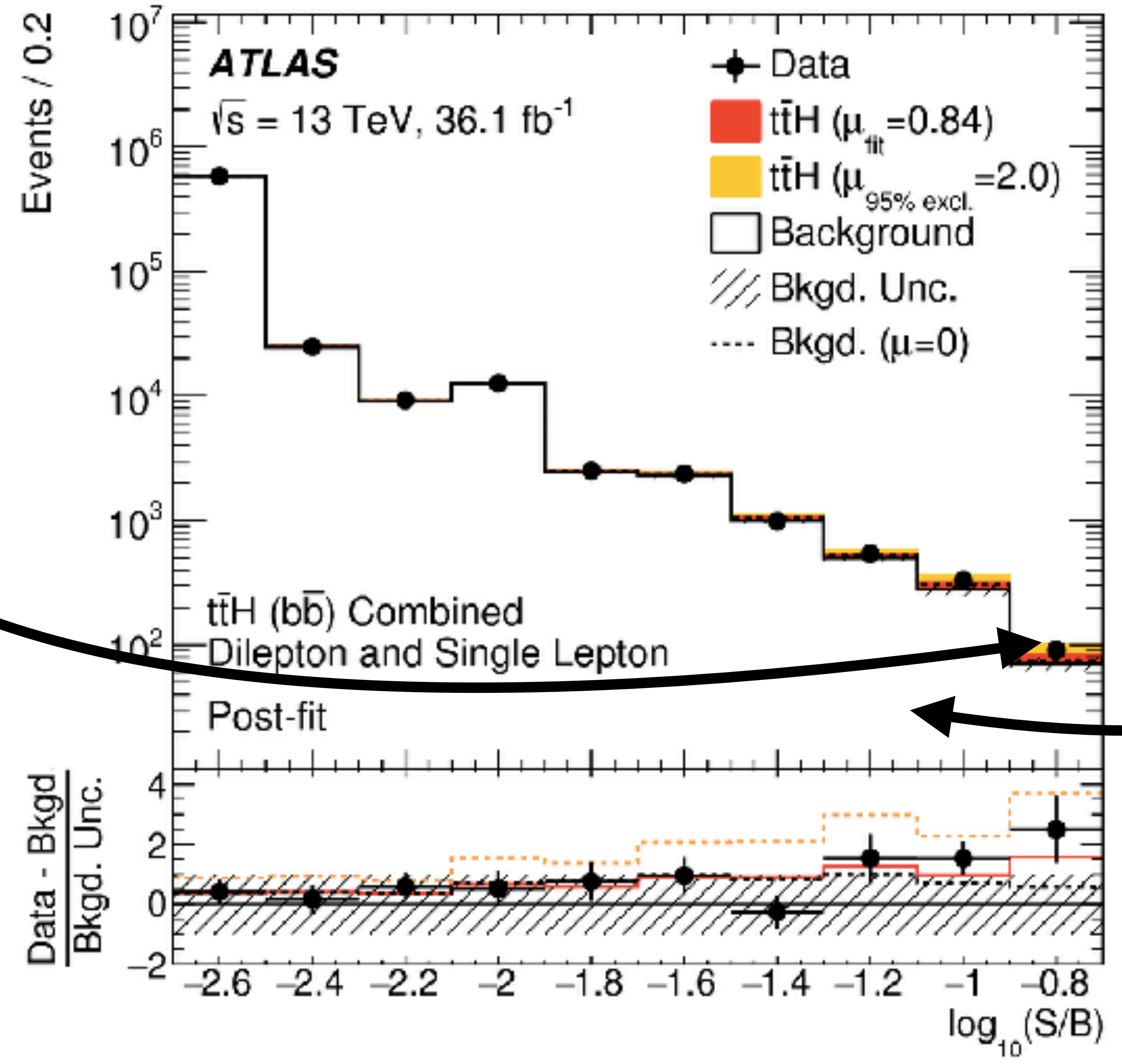
→Theory precision essential for improvements in mW determination!

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

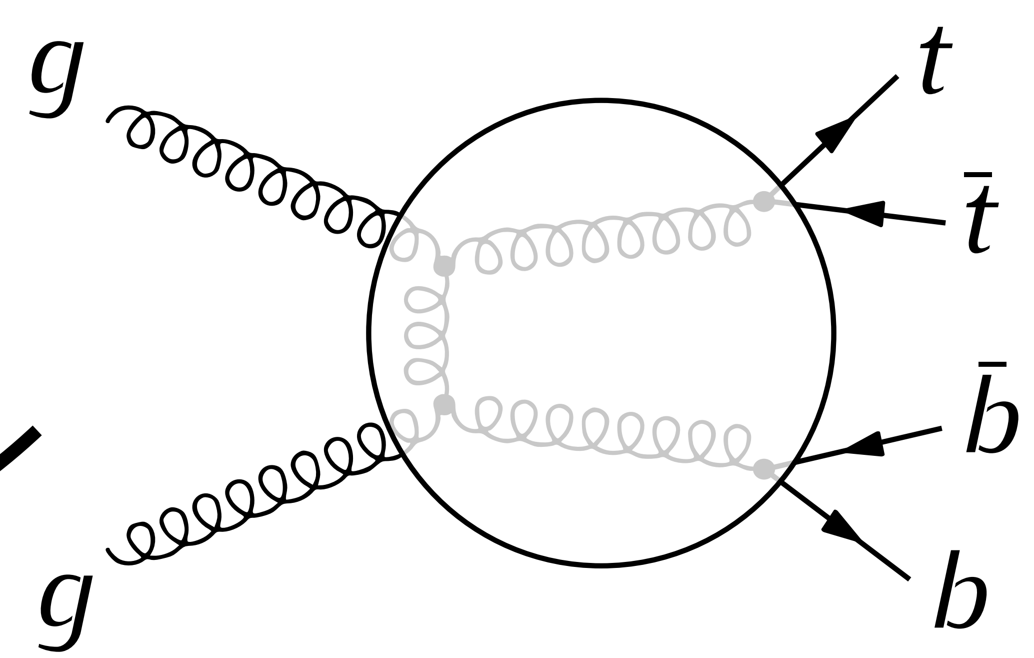
signal



- ➡ 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

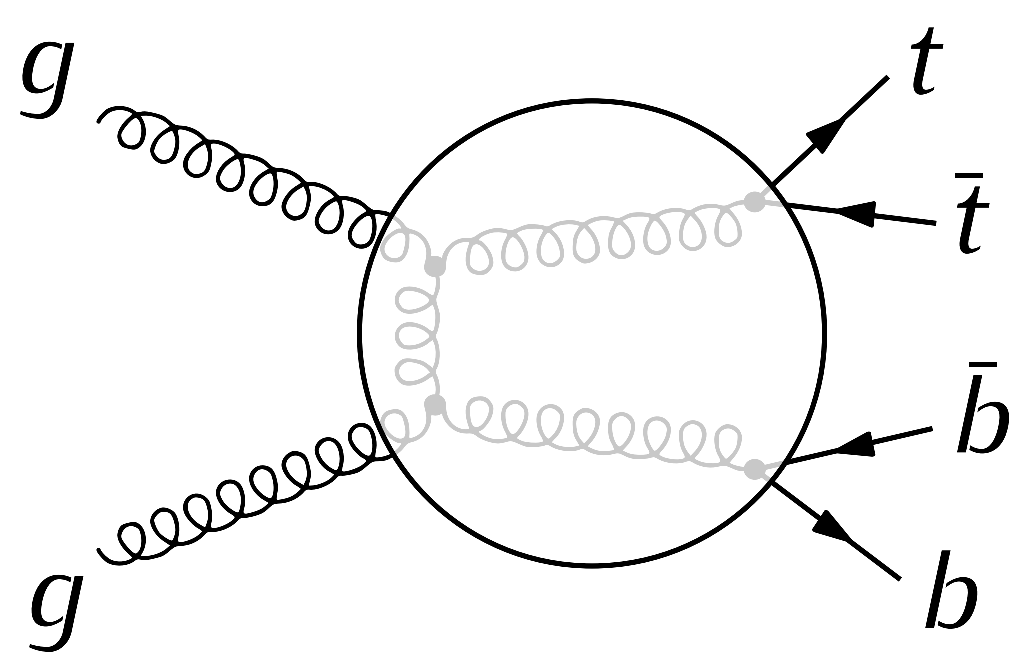


background

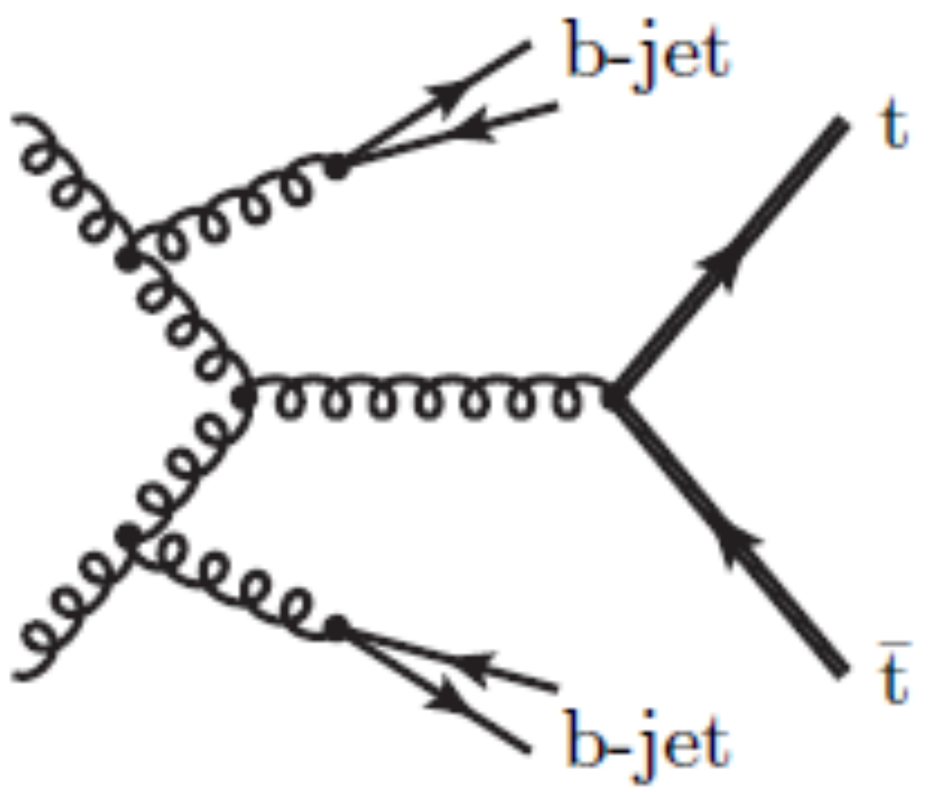


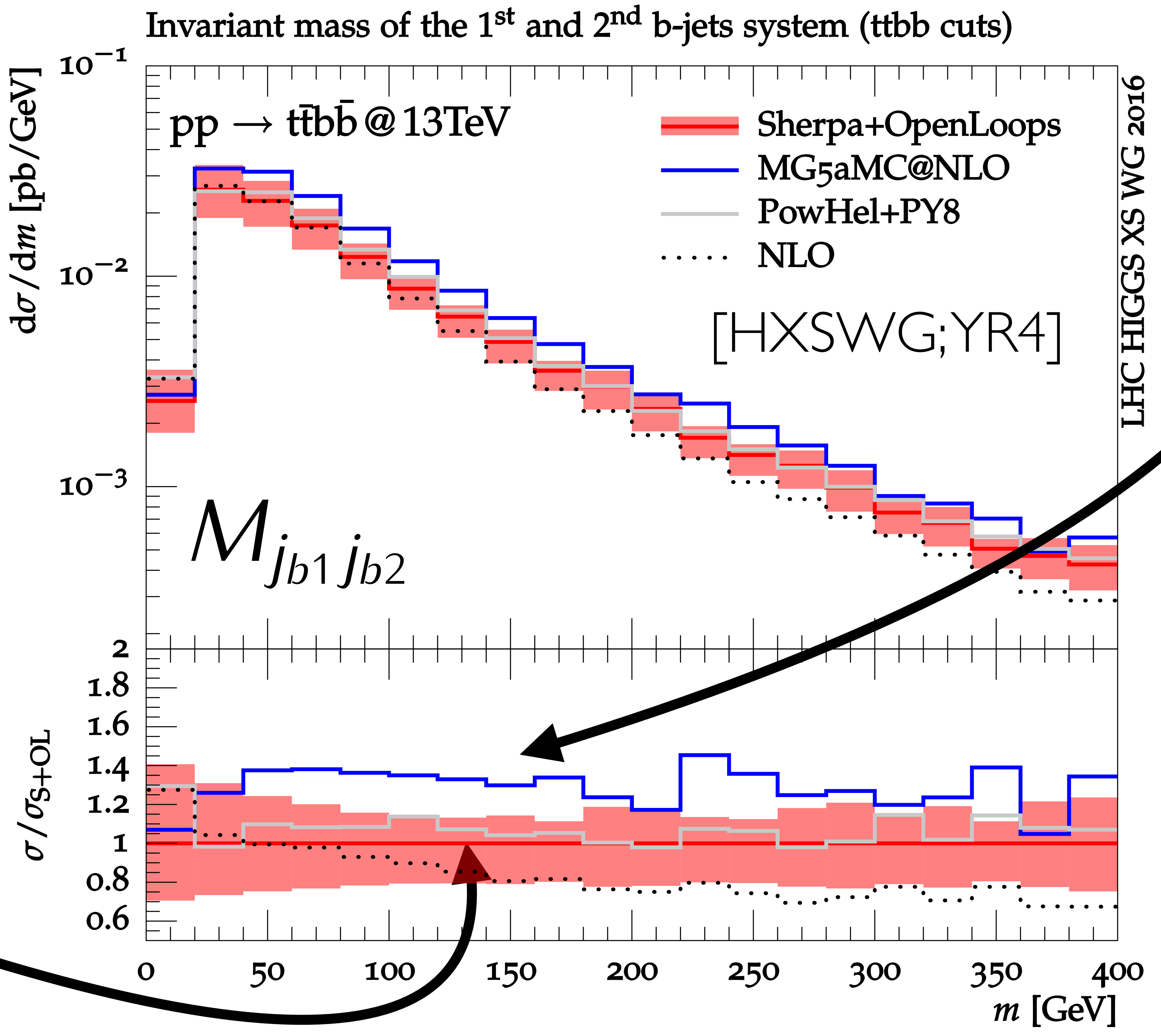
Higgs couplings: $t\bar{t}b\bar{b}$ backgrounds to $t\bar{t}H(b\bar{b})$

background



- ➡ 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 $g \to b\bar{b}$ splittings
- ➡ Large systematic uncertainties from parton shower matching





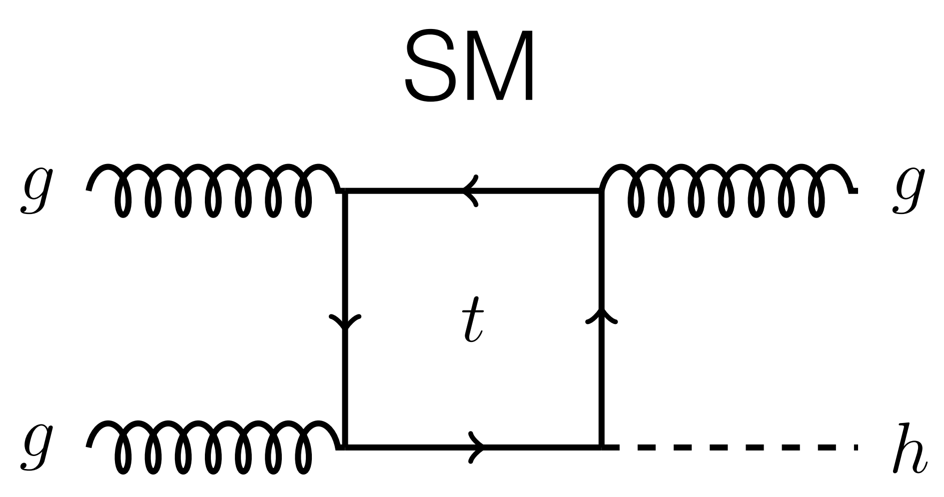
~20% in the signal region

→Need to open NLO+PS black boxes

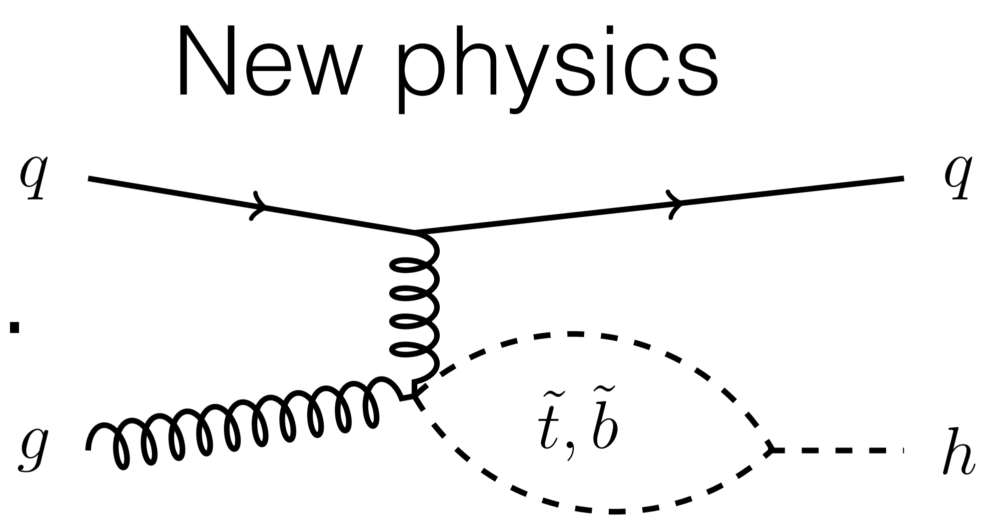
→Need for revised theory systematics

Indirect searches: disentangling very small effects

e.g.



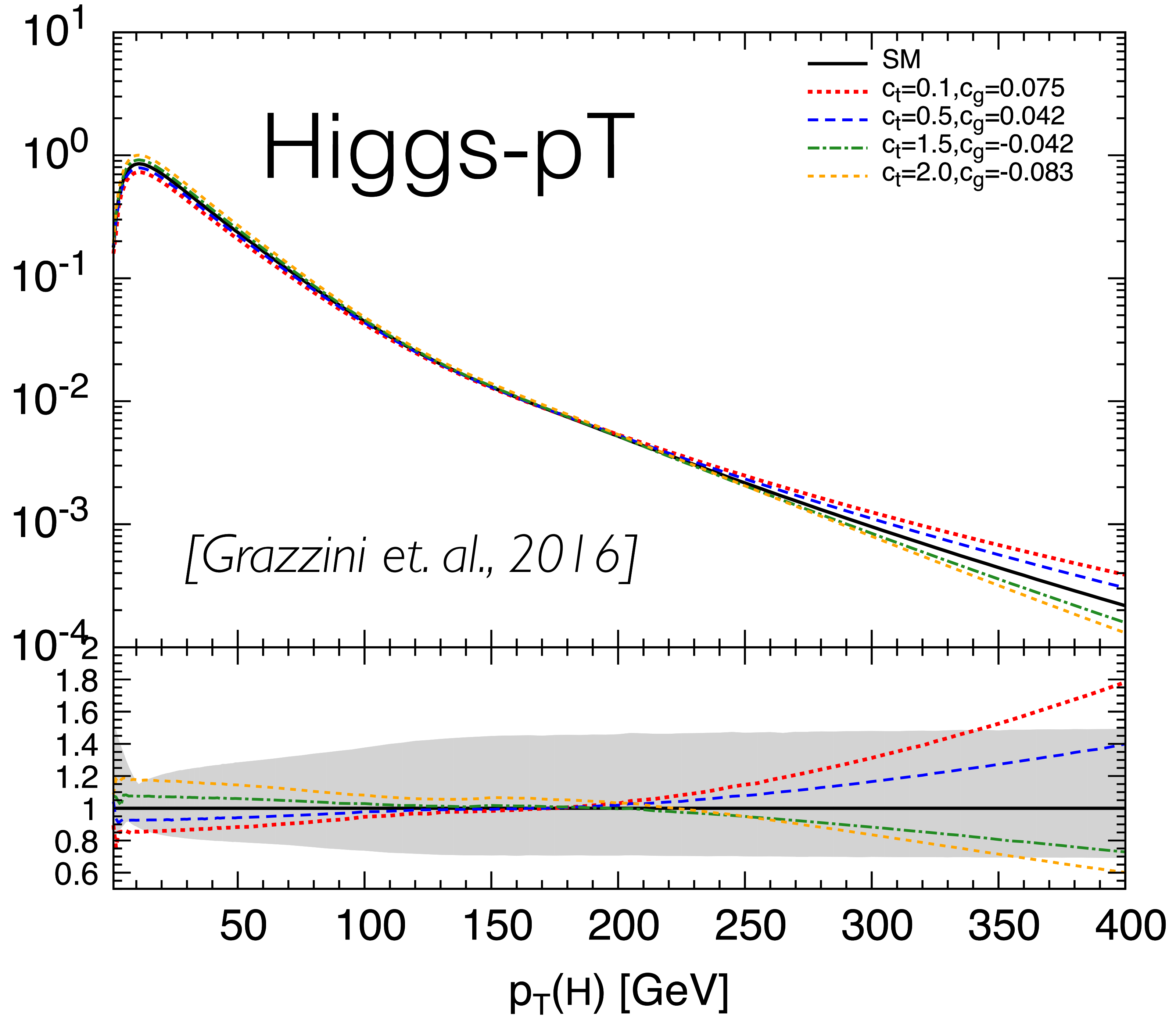
vs.

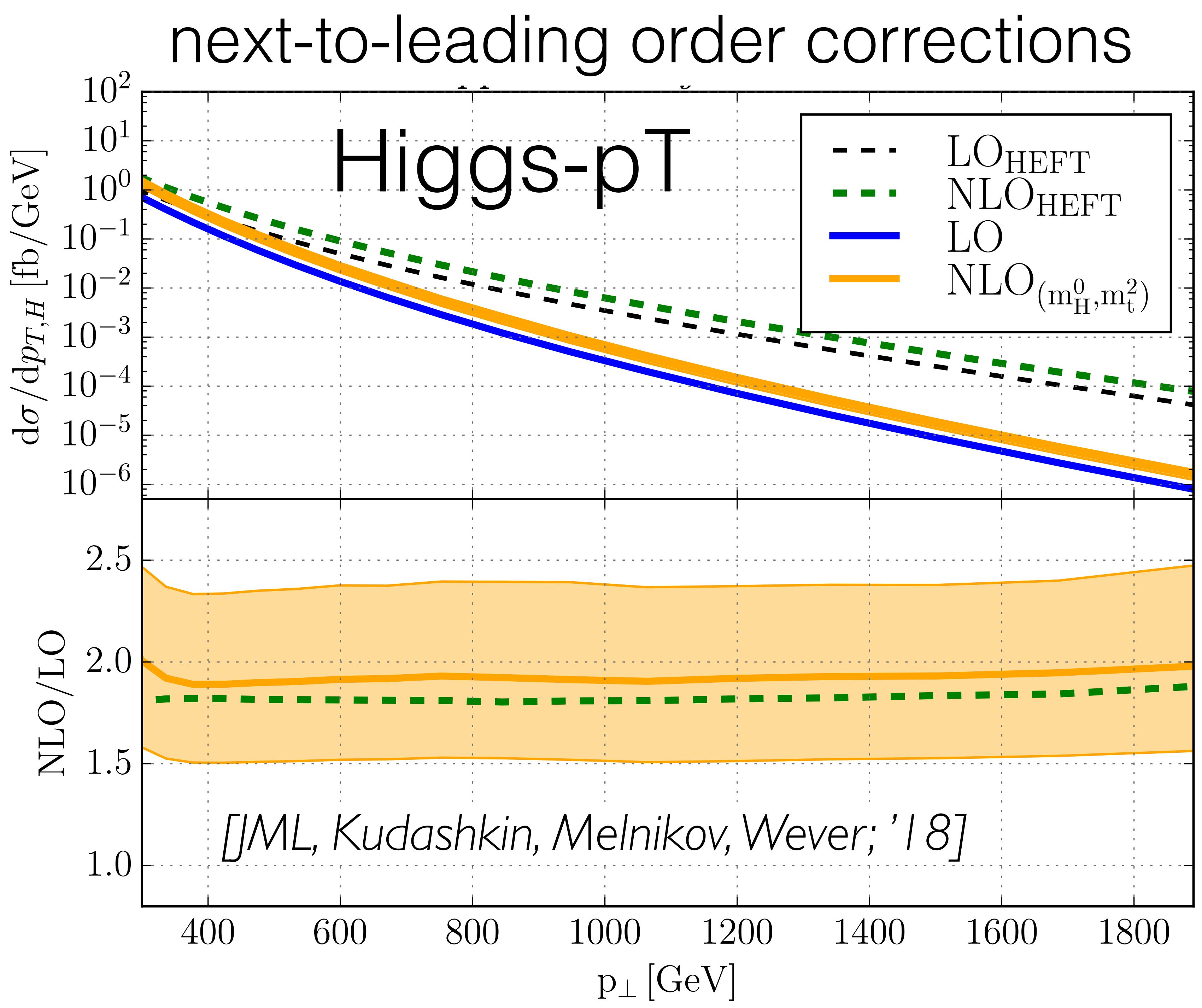


Look for BSM effects in small deviations from SM predictions:

→ Higgs processes natural place to look at

→ **very good control on theory necessary!**

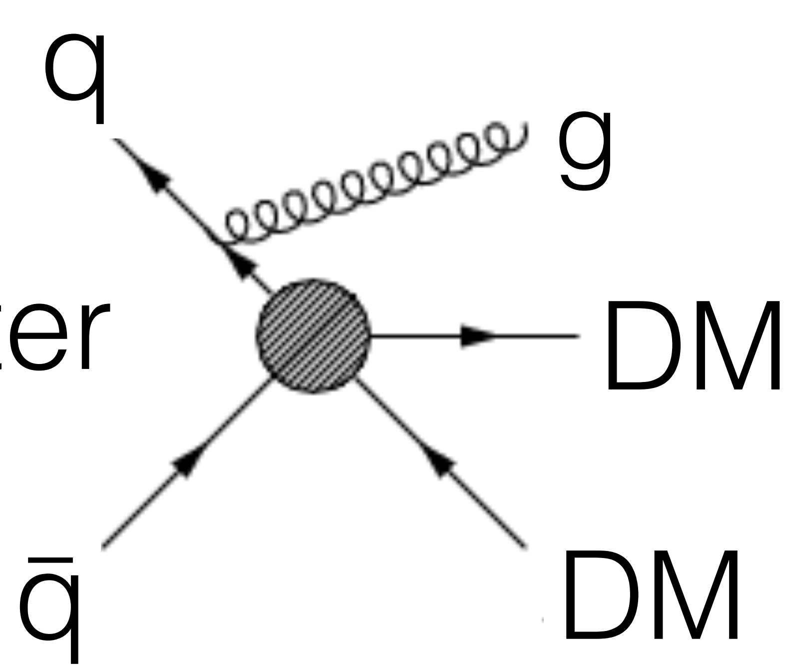




→Theory precision opens the door to new analysis strategies!

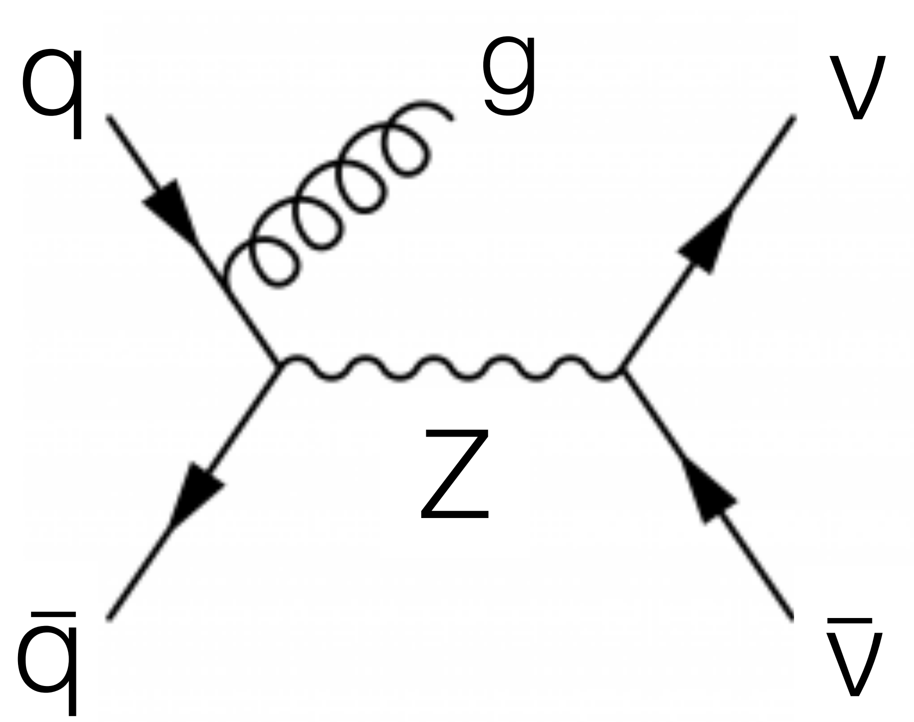
Direct searches for new physics: overwhelming SM backgrounds

e.g.
Dark Matter

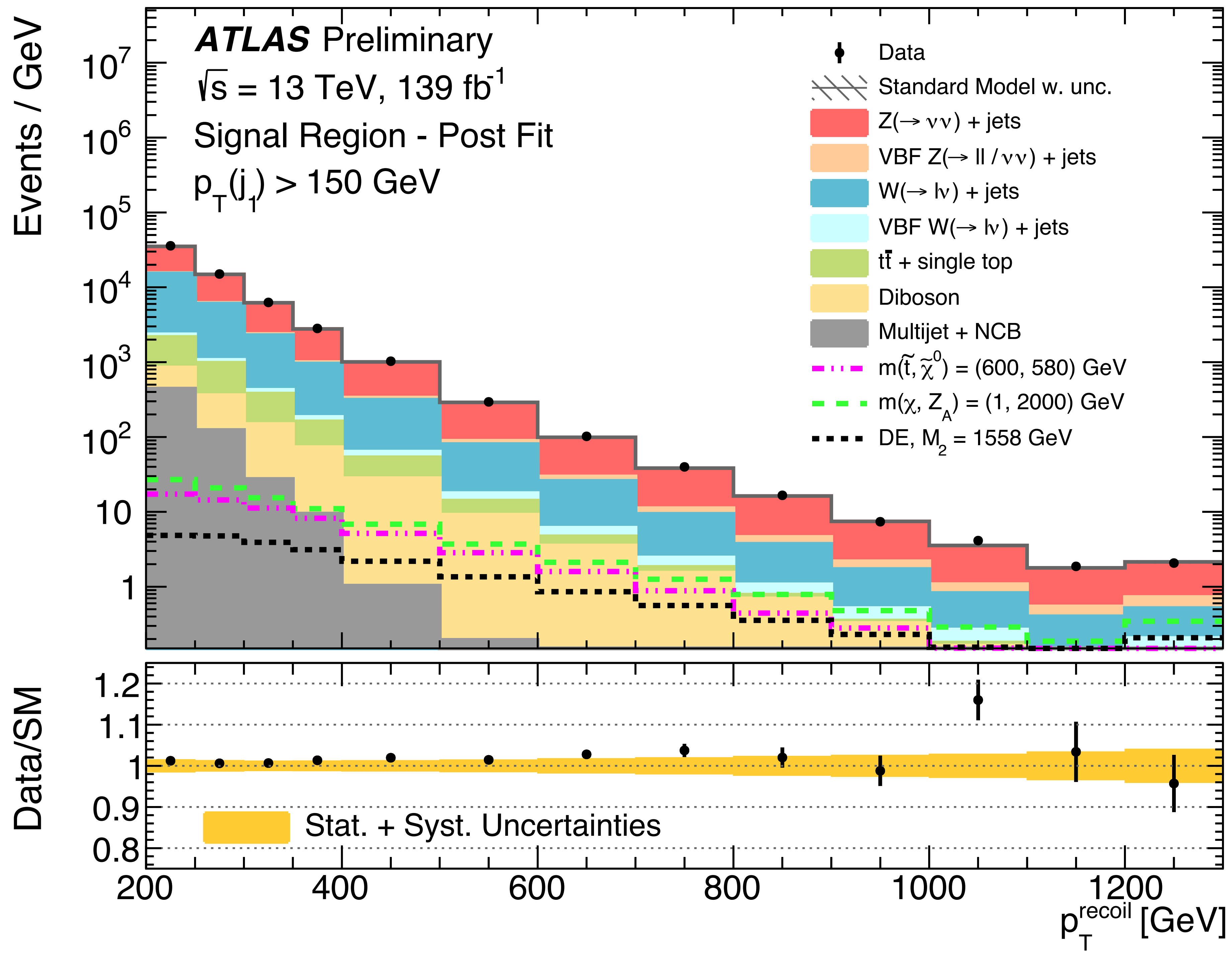


invisible in detectors

vs.

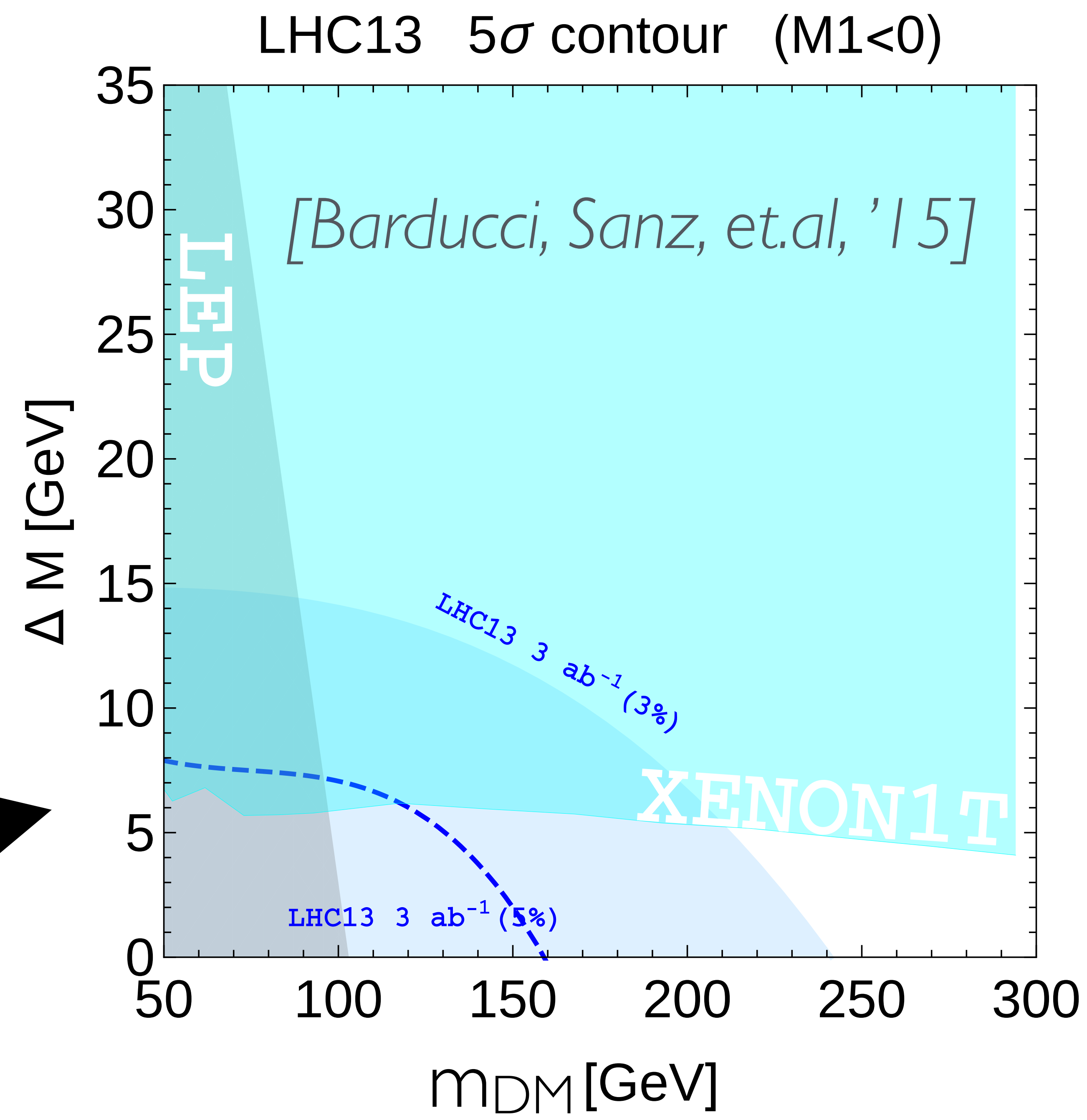


invisible in detectors



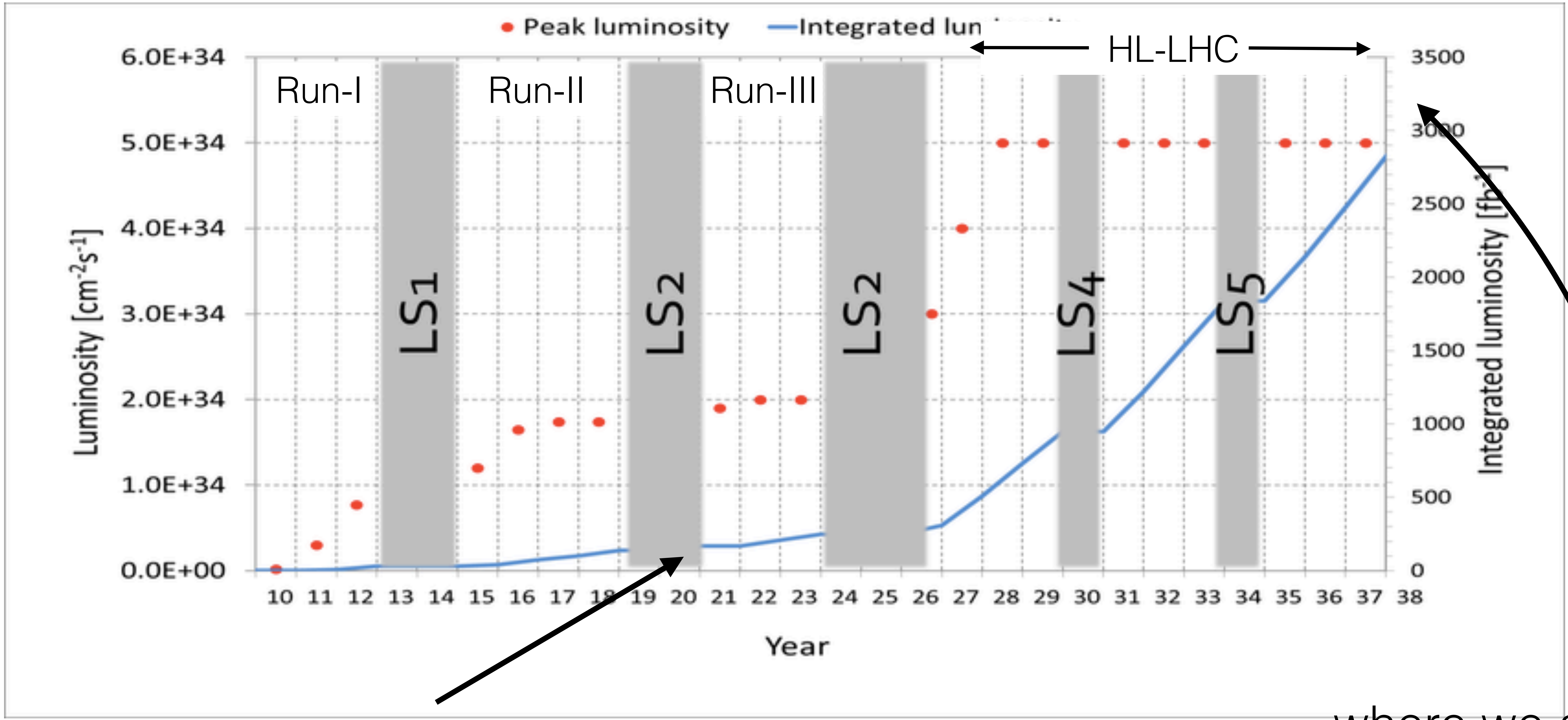
Thanks to state-of-the-art theory predictions+uncertainties for SM backgrounds
[JML, et.al., '17]

few percent!



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

Timescale of the LHC

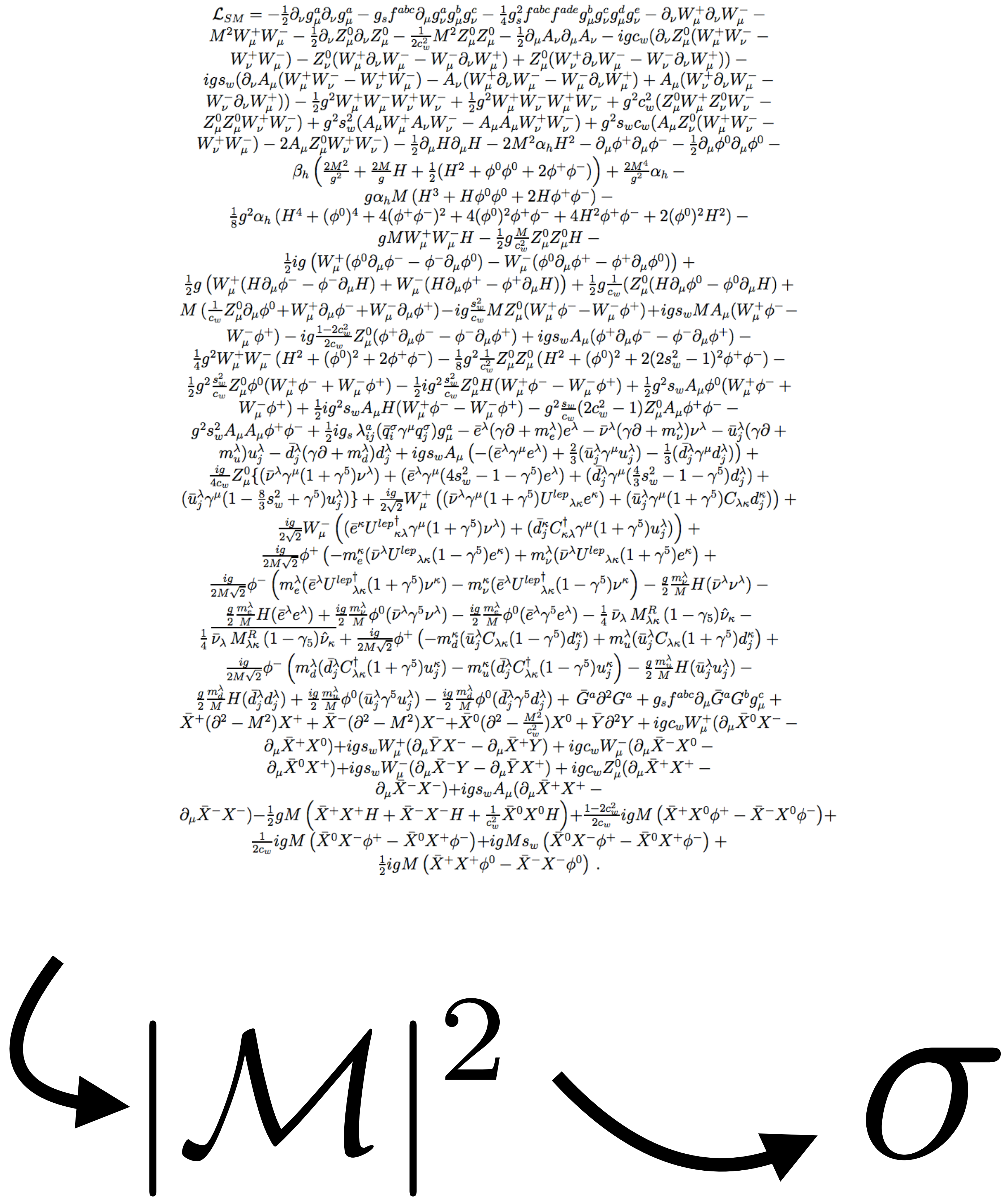


we are here:
$L=150\ fb^{-1}$

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

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

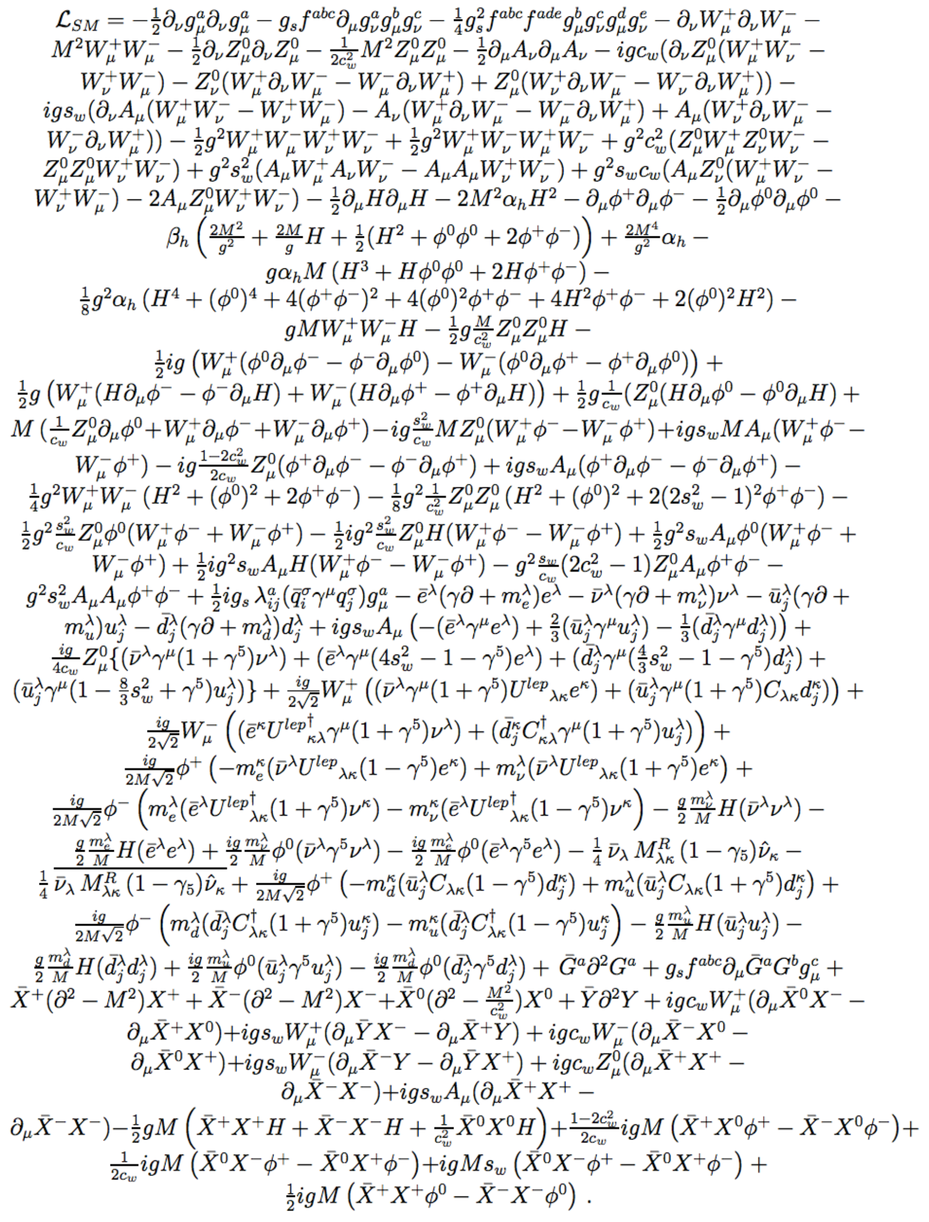
Theoretical Predictions for the LHC



Hard (perturbative) scattering process:

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{LO}} + \alpha_S\, \mathrm{d}\sigma_{\mathrm{NLO}} + \alpha_S^2\, \mathrm{d}\sigma_{\mathrm{NNLO}} + \alpha_S^3 \mathrm{d}\sigma_{\mathrm{N3LO}} + \ldots$$

Theoretical Predictions for the LHC



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

Hard (perturbative) scattering process:

$$d\sigma = d\sigma_{\rm LO} + \alpha_S\, d\sigma_{\rm NLO} + \alpha_S^2\, d\sigma_{\rm NNLO} + \alpha_S^3 d\sigma_{\rm N3LO} + \ldots$$

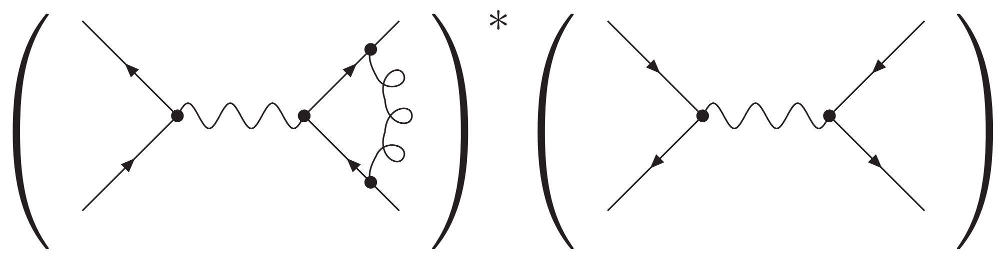
$$d\sigma_{\rm NLO} = \frac{1}{2s}\int d\Phi_n \left[|\mathcal{M}_{\rm LO}|^2 + 2{\rm Re}\{\mathcal{M}_{\rm LO}\mathcal{M}^*_{\rm NLO,V}\}\right] + \frac{1}{2s}\int d\Phi_{n+1}|\mathcal{M}_{\rm NLO,R}|^2$$

NLO = B + V + R

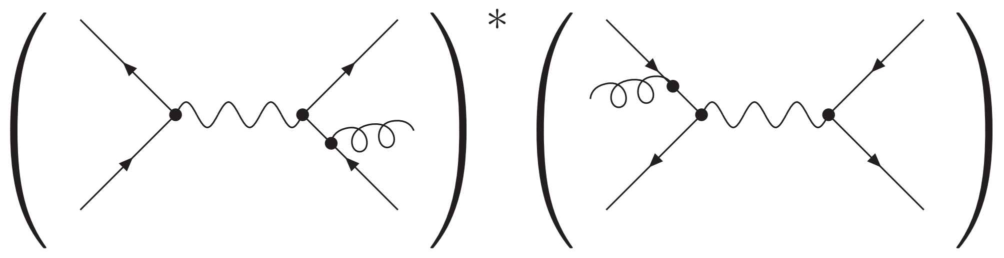
$\mathcal{M}_{\rm NLO,V}$ **virtual** one-loop matrix element

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

$\mathrm{Re}\{\mathcal{M}_{\rm LO}\mathcal{M}^*_{\rm NLO,V}\}$

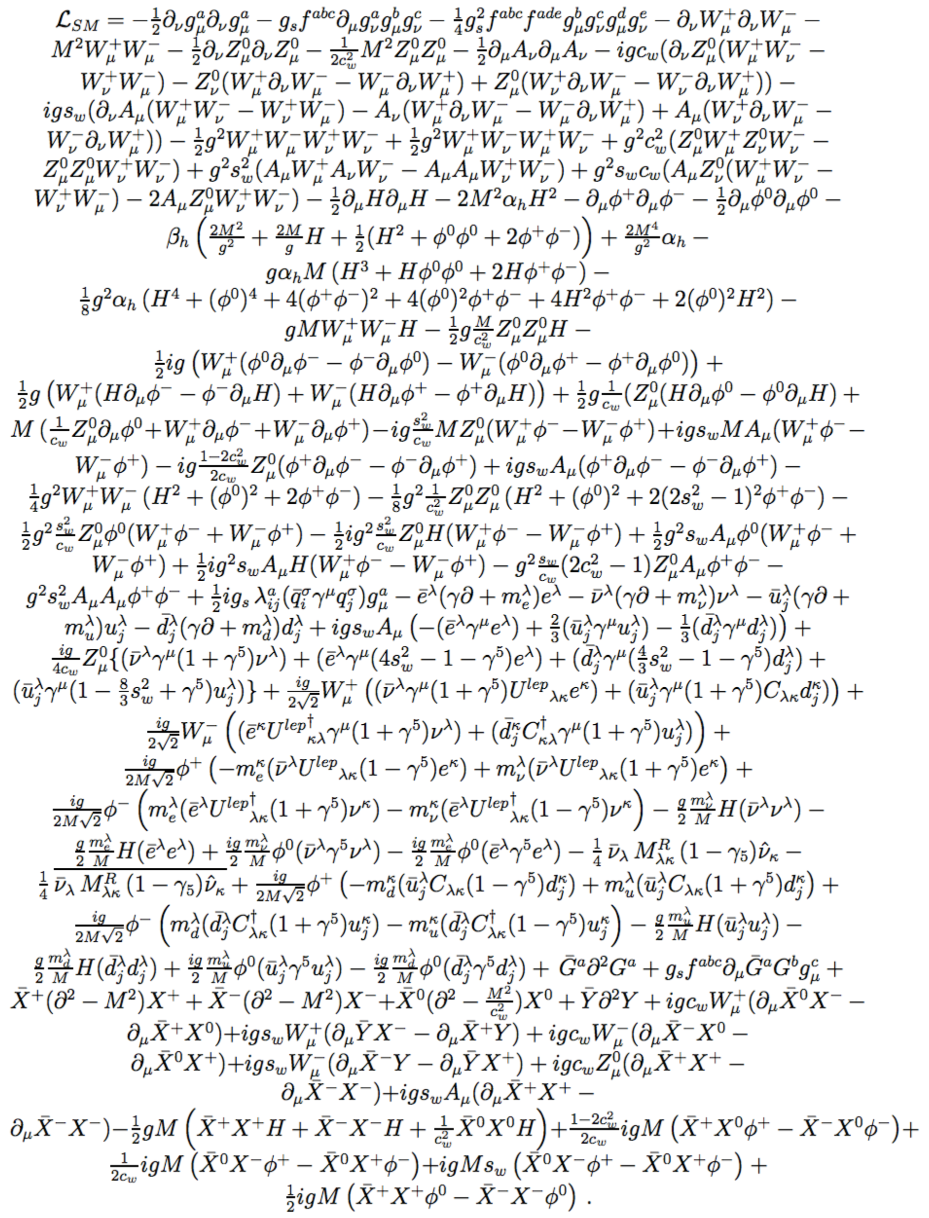


$|\mathcal{M}_{\rm NLO,R}|^2$



- UV renormalisation ⇒ reduction of **μ_R dependence**
- soft/collinear cancellations+PDF renormalisation ⇒ reduction of **μ_F dependence**

Theoretical Predictions for the LHC



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

Hard (perturbative) scattering process:

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

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

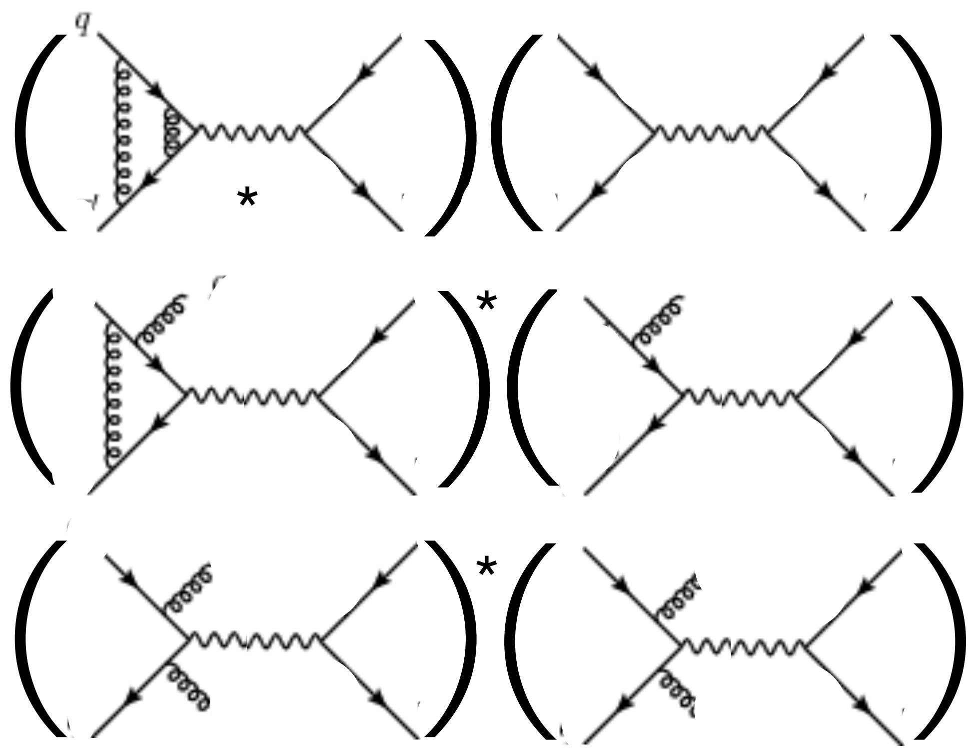
NNLO = B + V + V2 + …

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

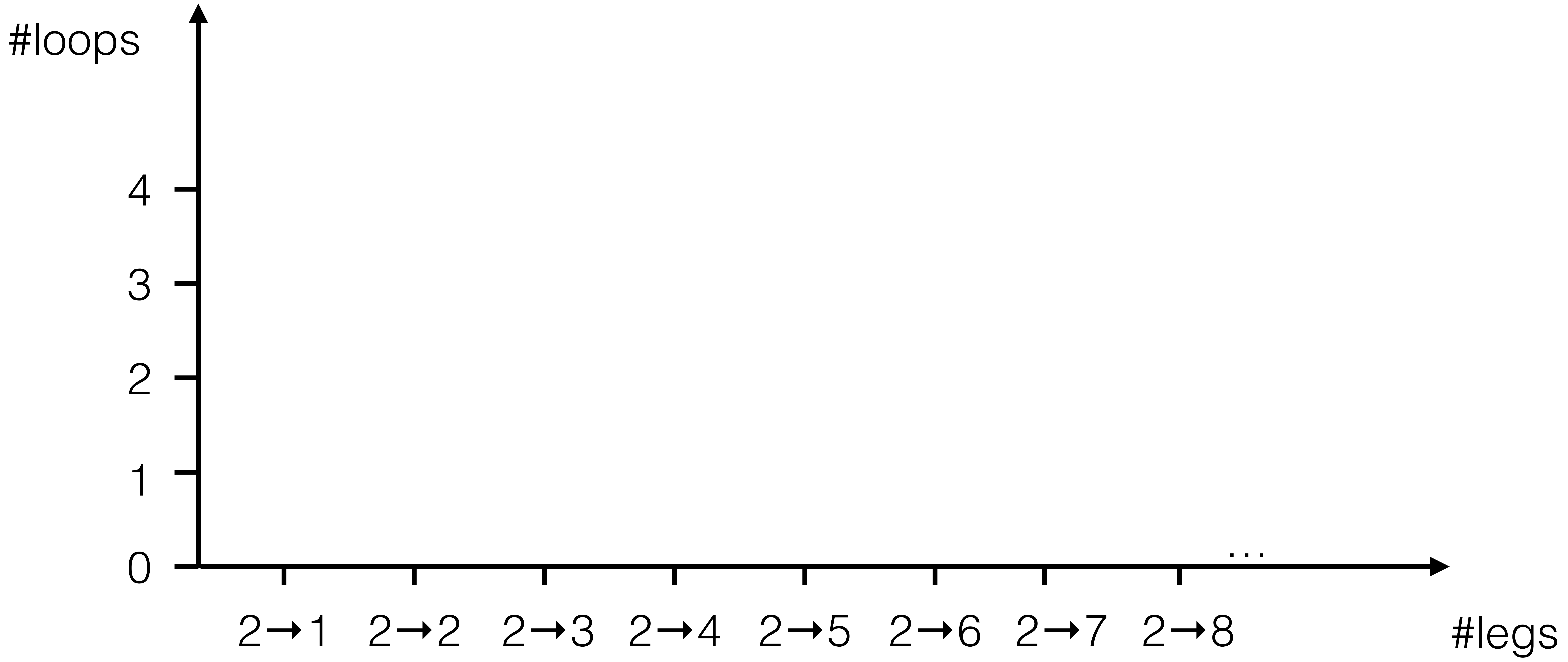
+ R + RV + RR

ΔNNLO $\propto \alpha^2$

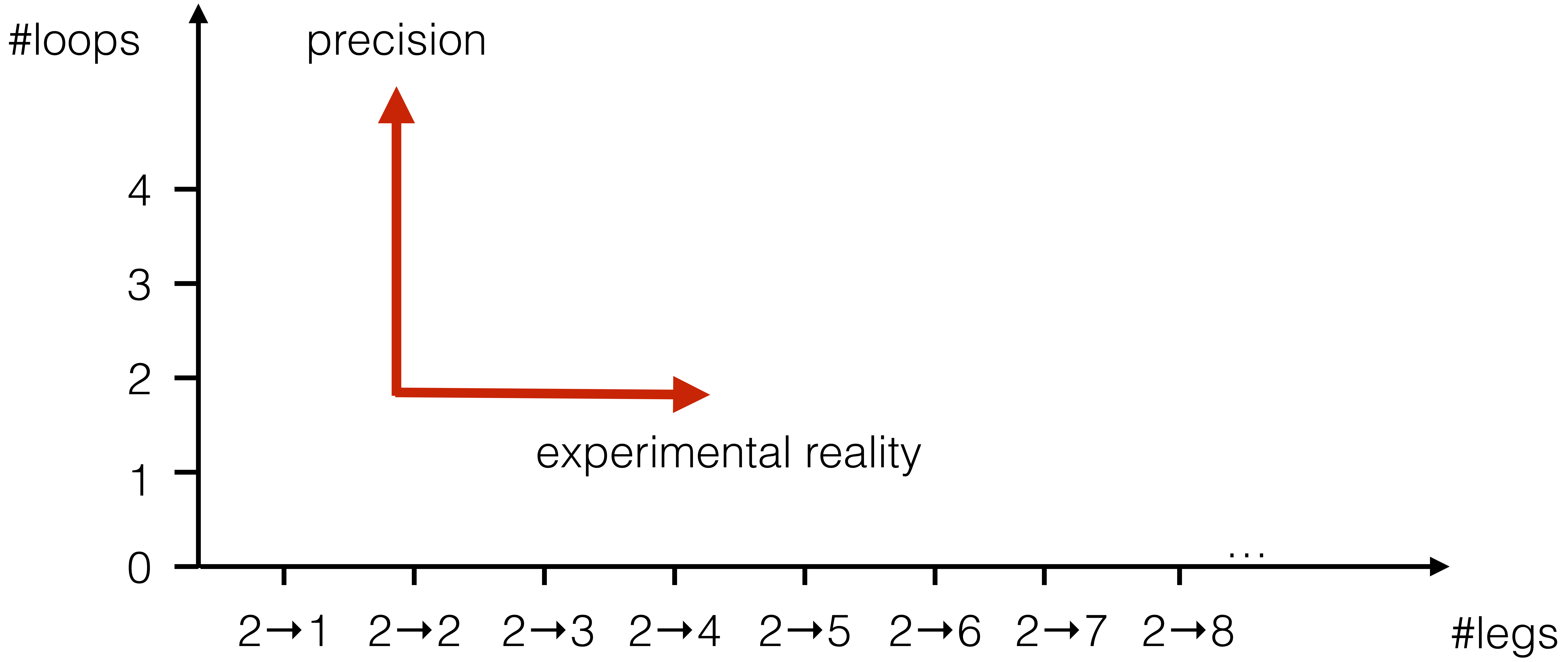
- $M_{NNLO,V}$ **double-virtual** two-loop matrix element
- $M_{NNLO,RV}$ **real-virtual** one-loop matrix element
- $\mathcal{M}_{NNLO,RR}$ **double-real** tree-level matrix element



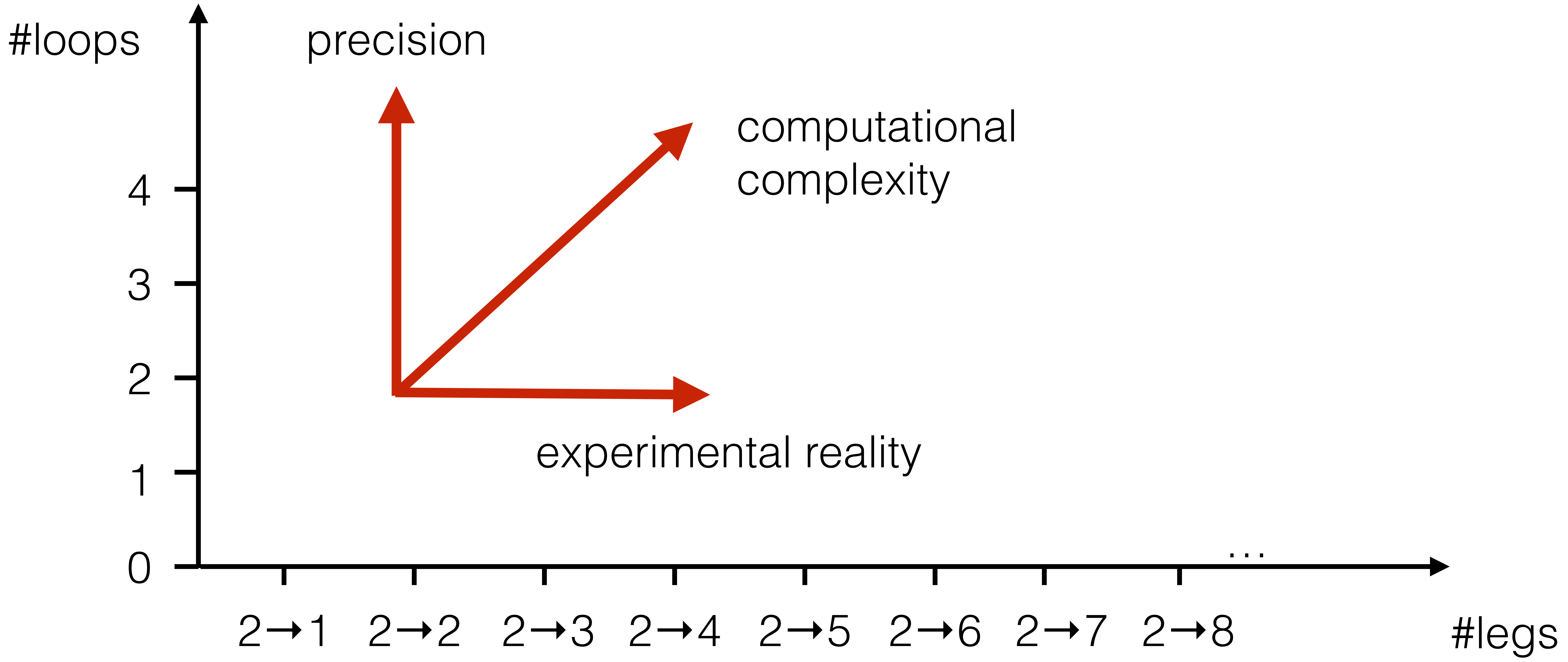
Theory frontier



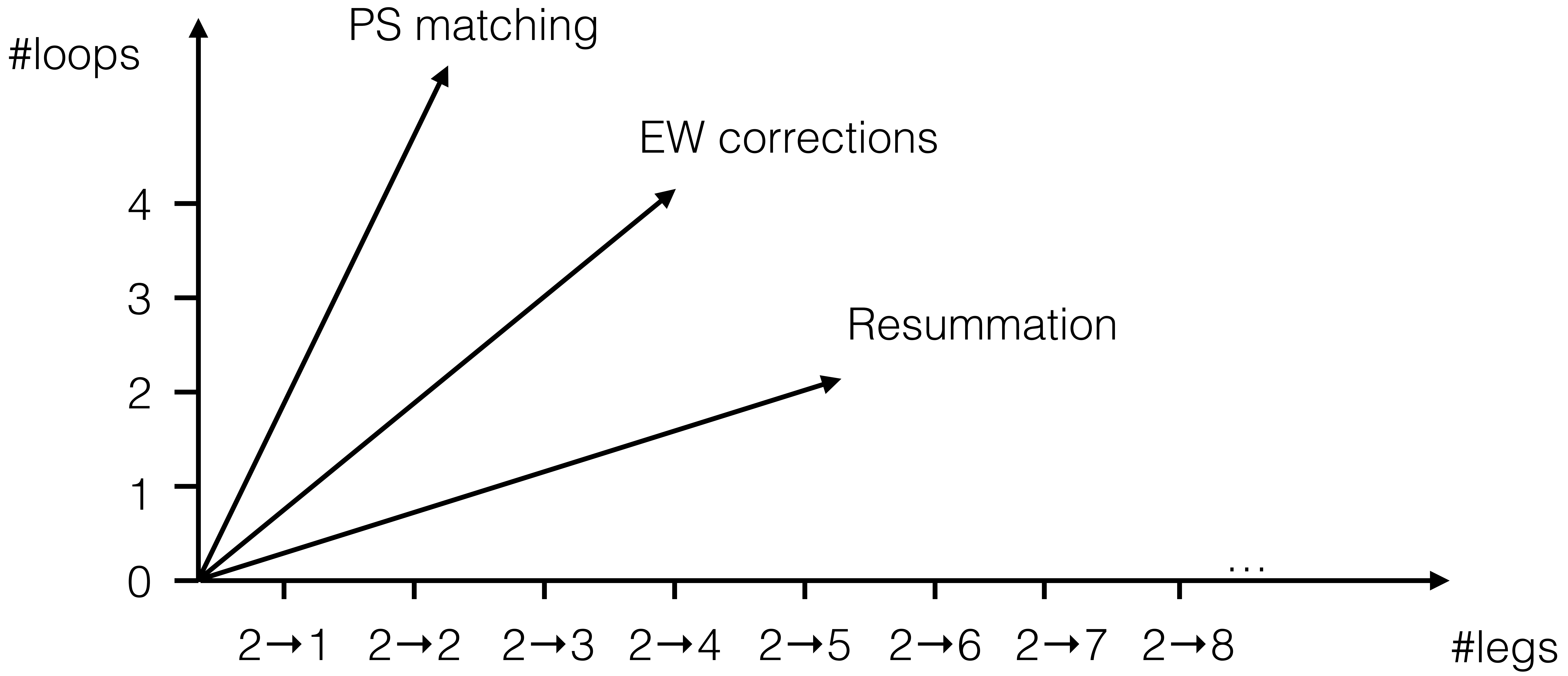
Theory frontier



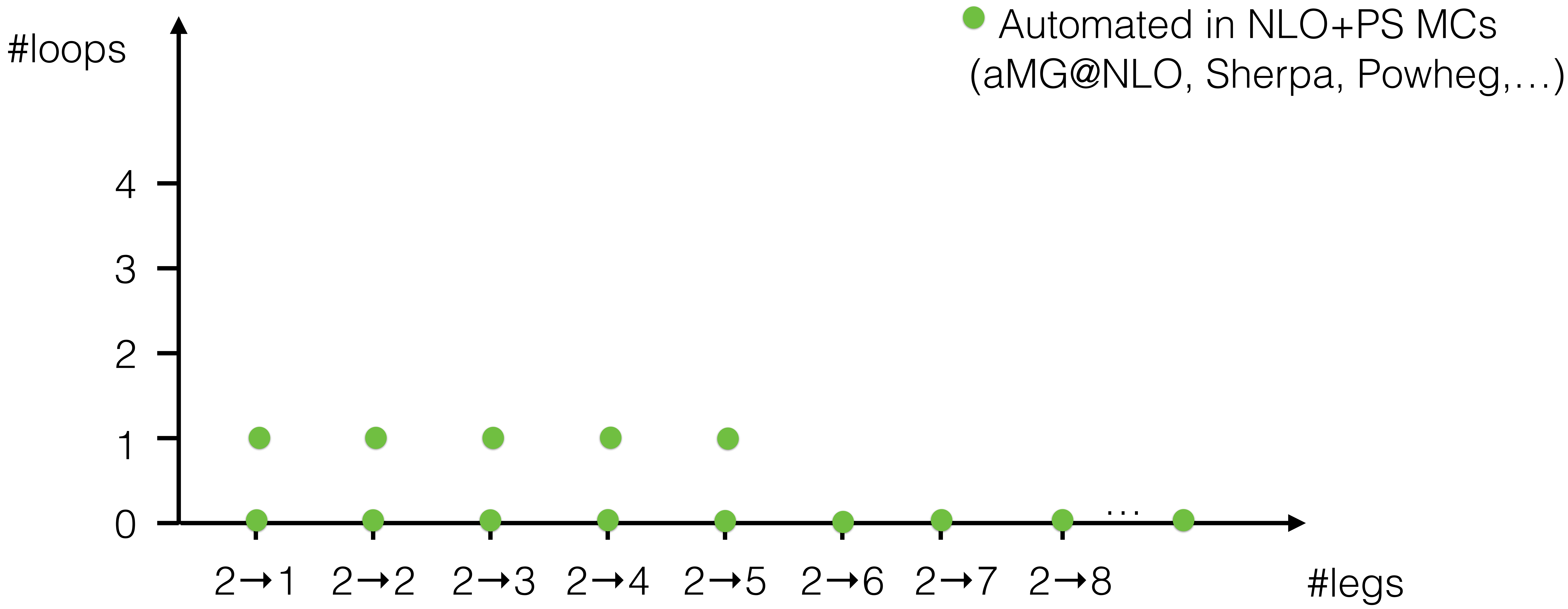
Theory frontier



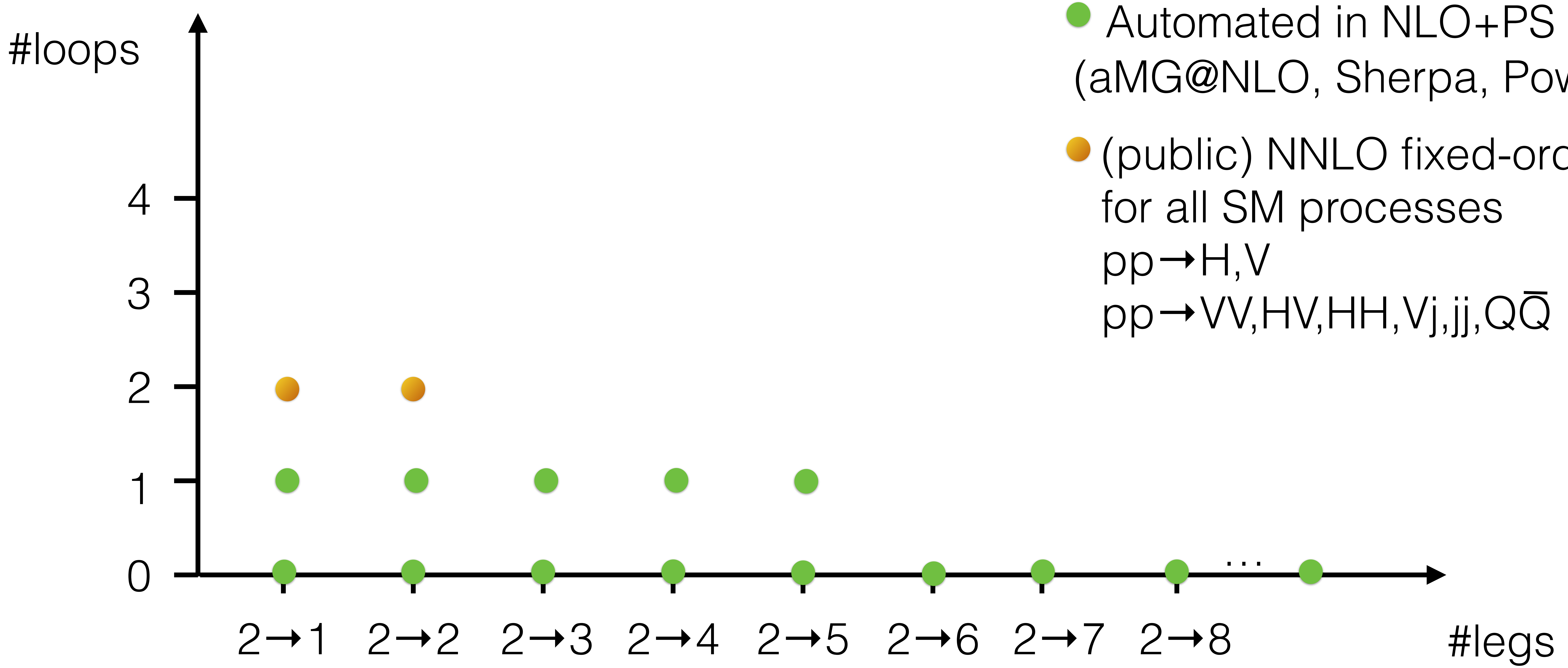
Theory frontier



Theory frontier

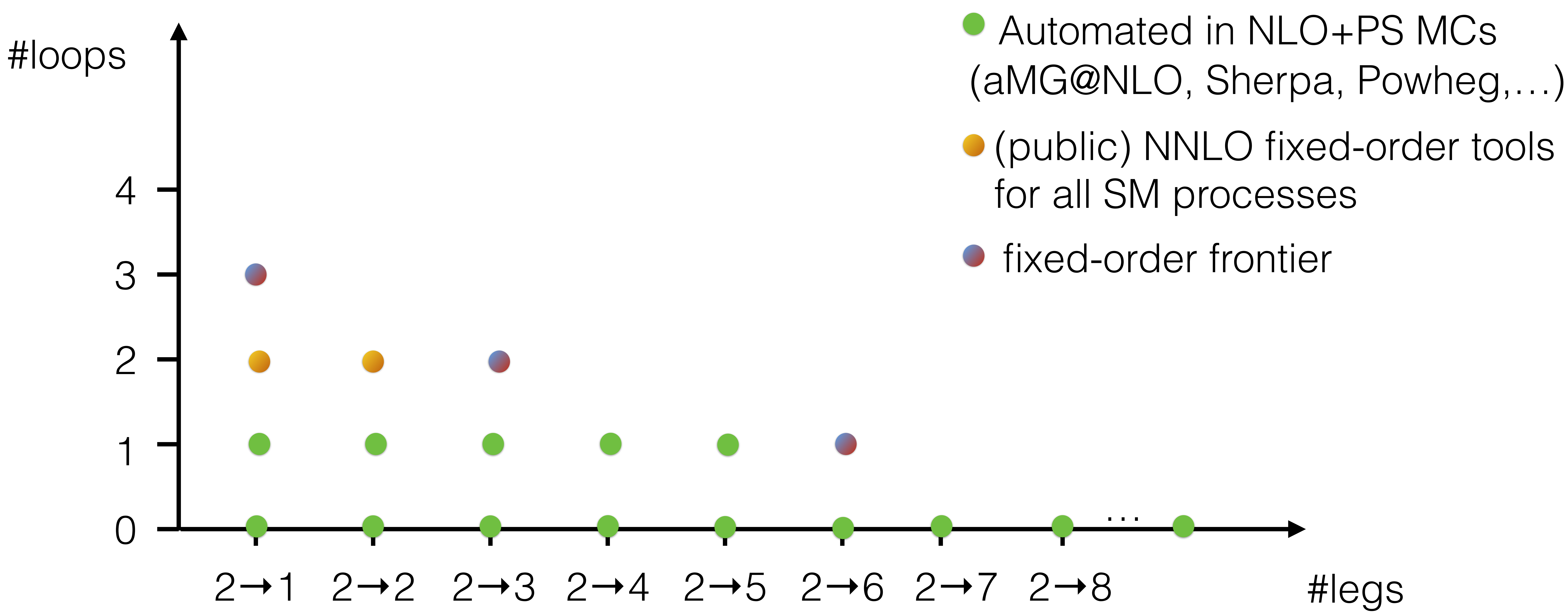


Theory frontier

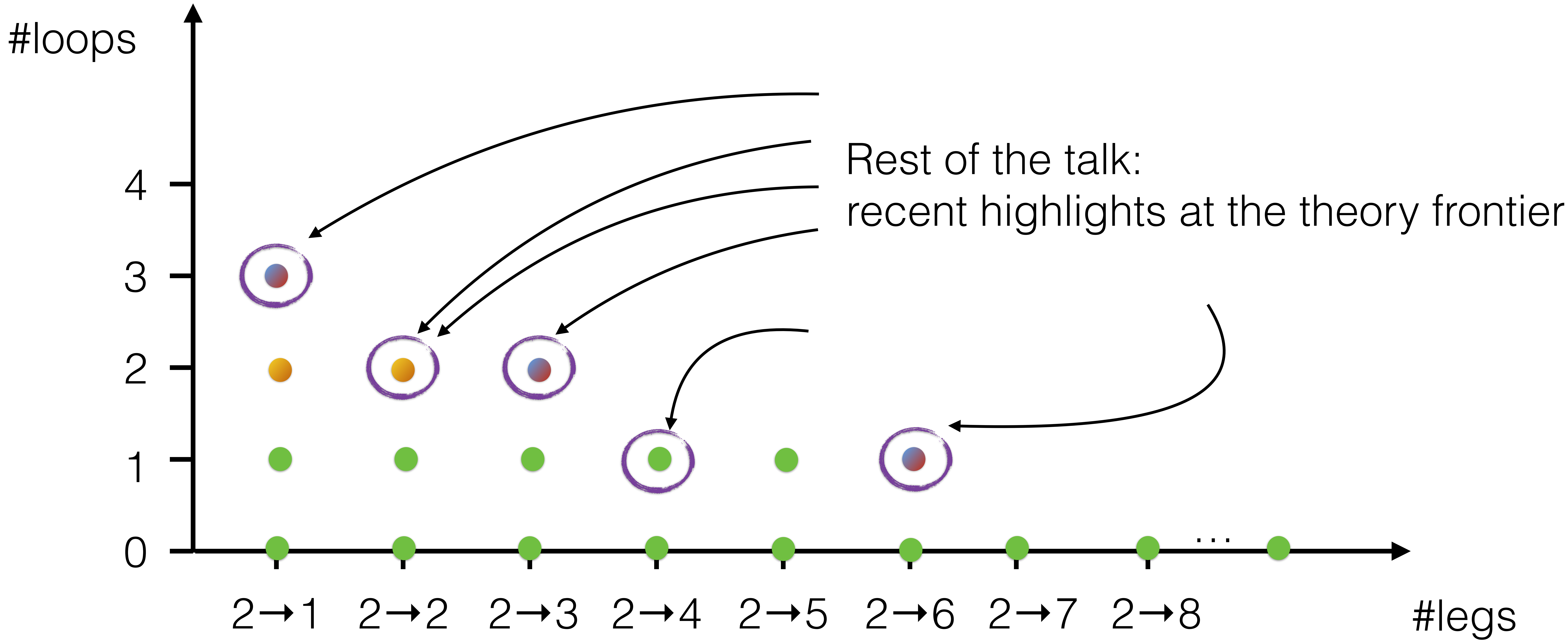


- Automated in NLO+PS MCs (aMG@NLO, Sherpa, Powheg,…)
- (public) NNLO fixed-order tools for all SM processes
  pp→H,V
  pp→VV,HV,HH,Vj,jj,$Q\bar{Q}$

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→γγγ

[Chawdhry, Czakon, Mitov, Poncelet '19]

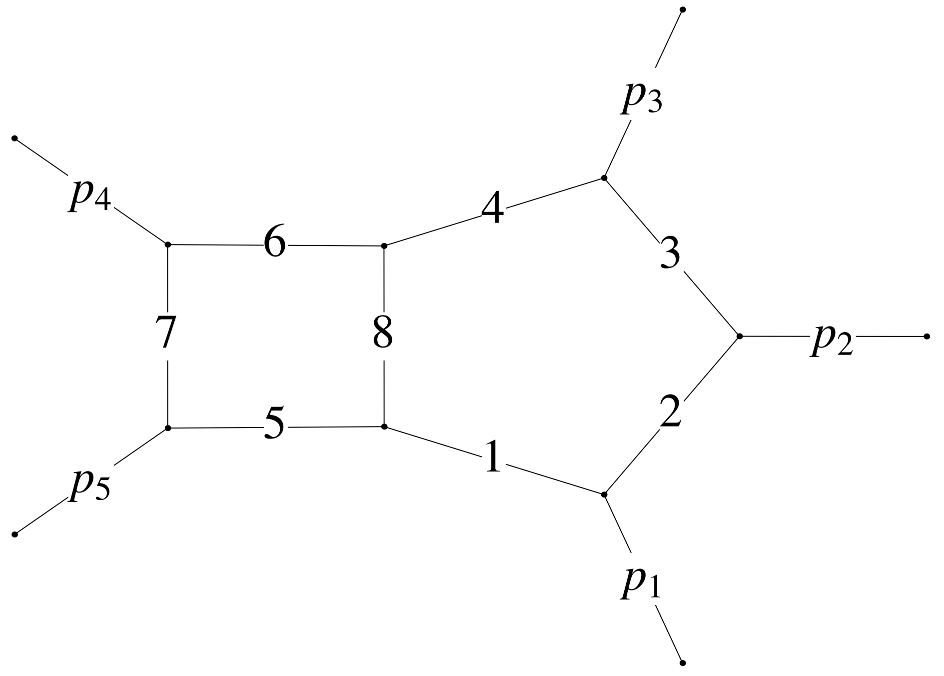
[Kallweit, Sotnikov, Wiesemann '20]

pp→γγj

[Chawdhry, Czakon, Mitov, Poncelet '21]

pp→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, Frebres Cordero, Ita, Page, Sotnikov '19]

[Abreu, Page, Pascual, Sotnikov '20]

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

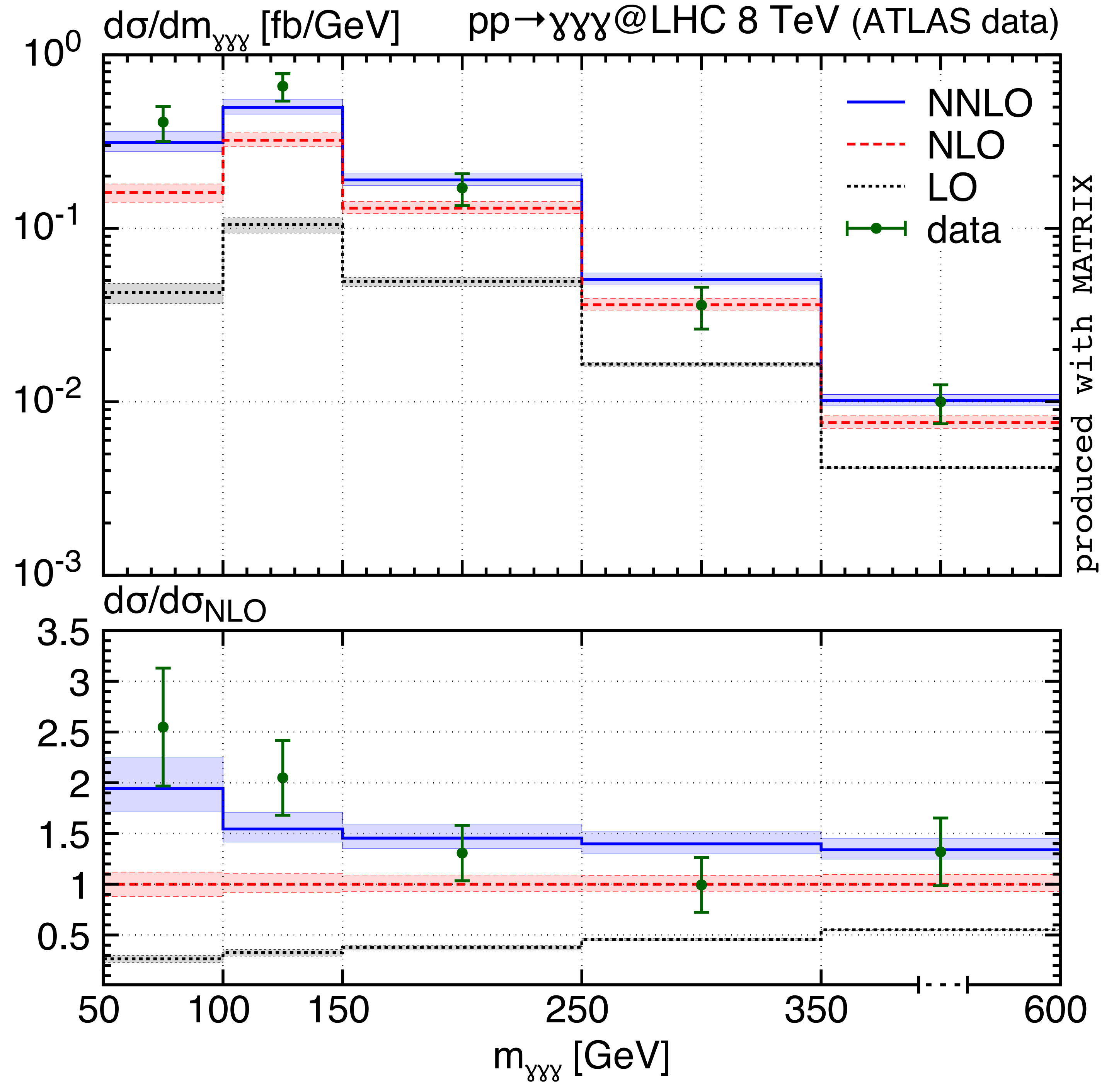
[Agarwal, Buccioni, v. Manteuffel, Tancredi '21]

2→3 at NNLO

pp→γγγ

[Chawdhry, Czakon, Mitov, Poncelet '19]

[Kallweit, Sotnikov, Wiesemann '20]



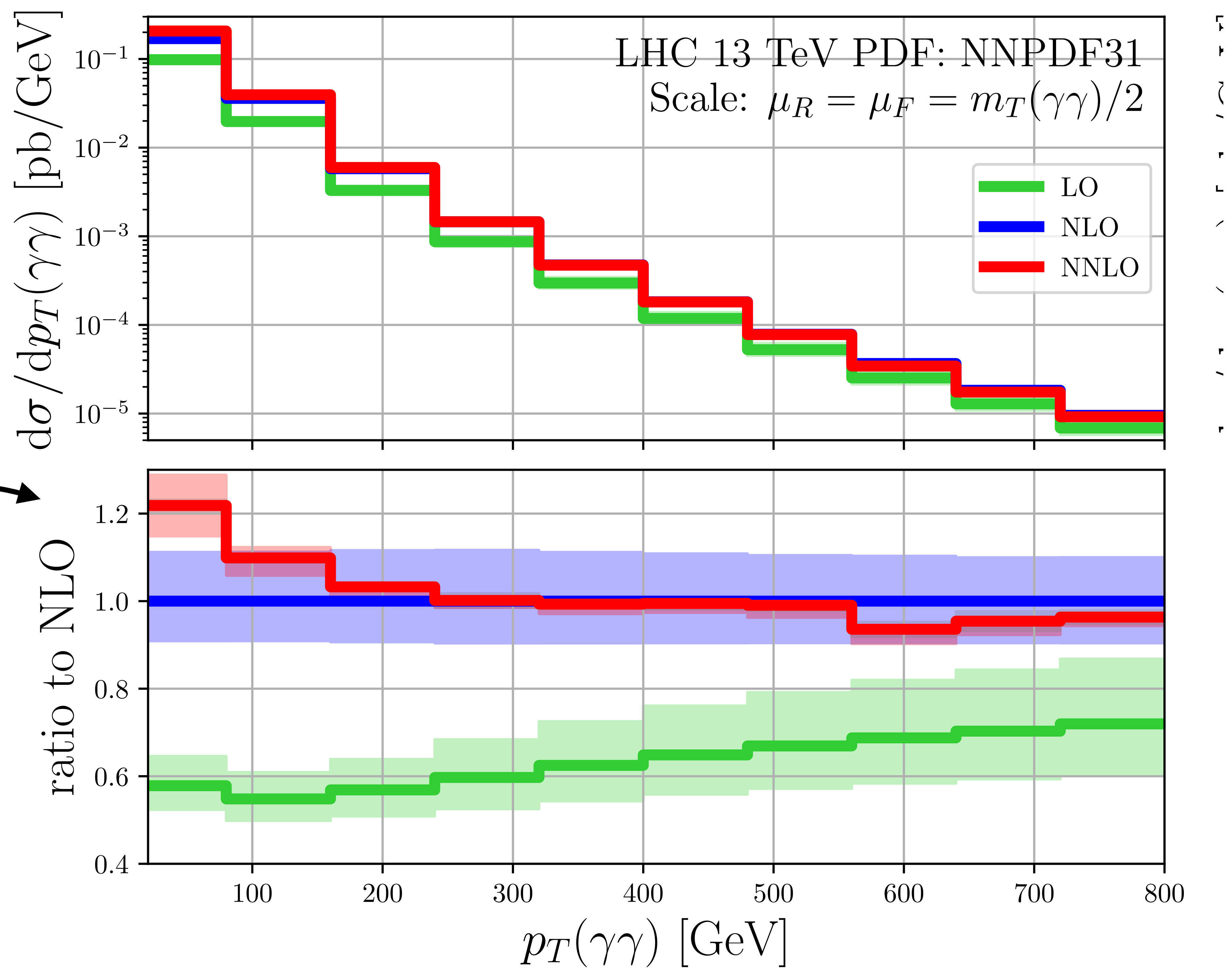
- significant NNLO/NLO corrections
- improved data/theory agreement at NNLO

gg→γγg

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

pp→γγj

[Chawdhry, Czakon, Mitov, Poncelet '21]



- NNLO mandatory due to large NLO/LO corrections

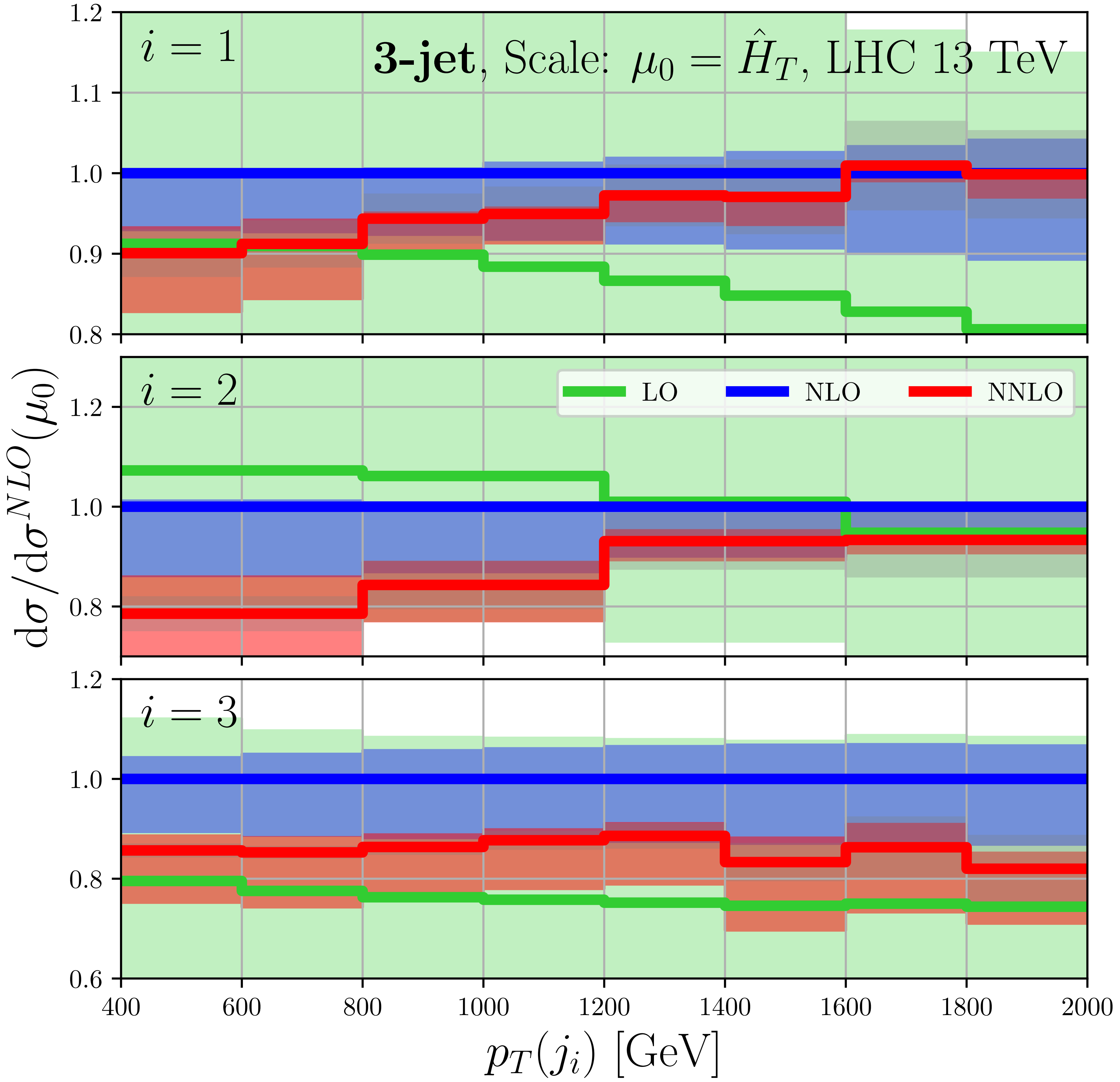
➡precision probes of QCD dynamics

pp→jjj at NNLO

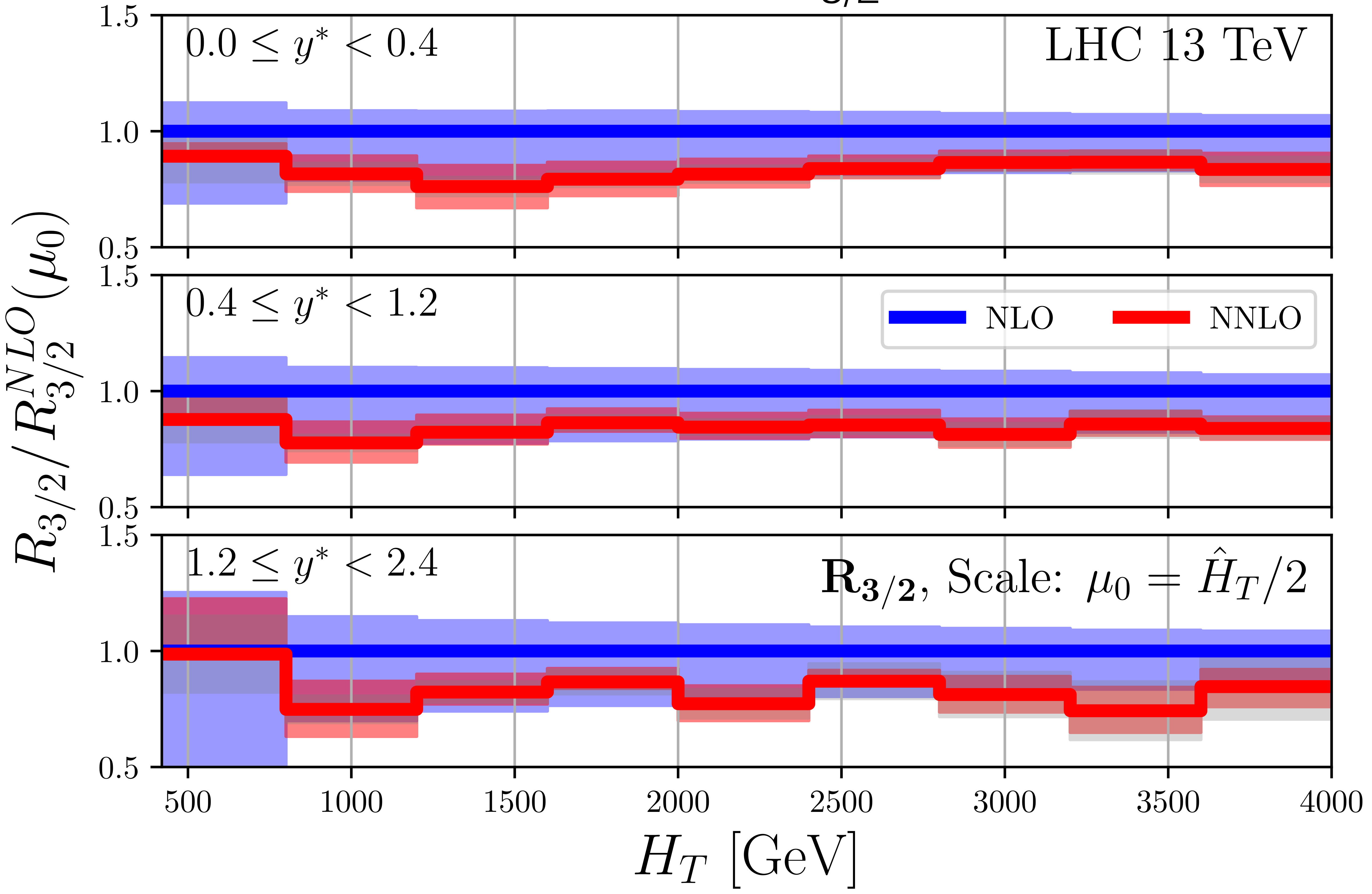
"Tour de force in Quantum Chromodynamics"

[Czakon, Mitov, Poncelet '21]

$p_{T,j}$

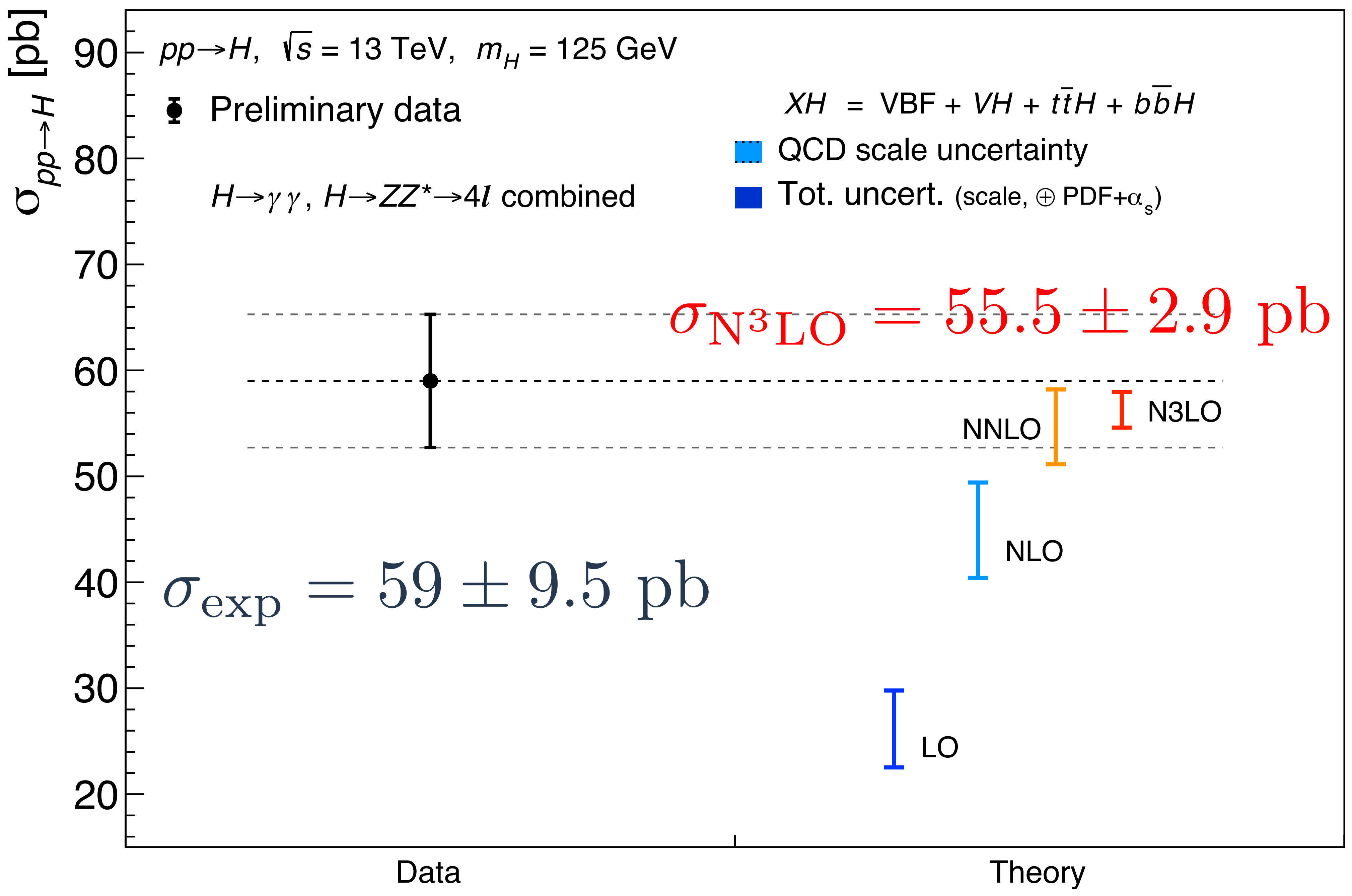


$R_{3/2}$



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

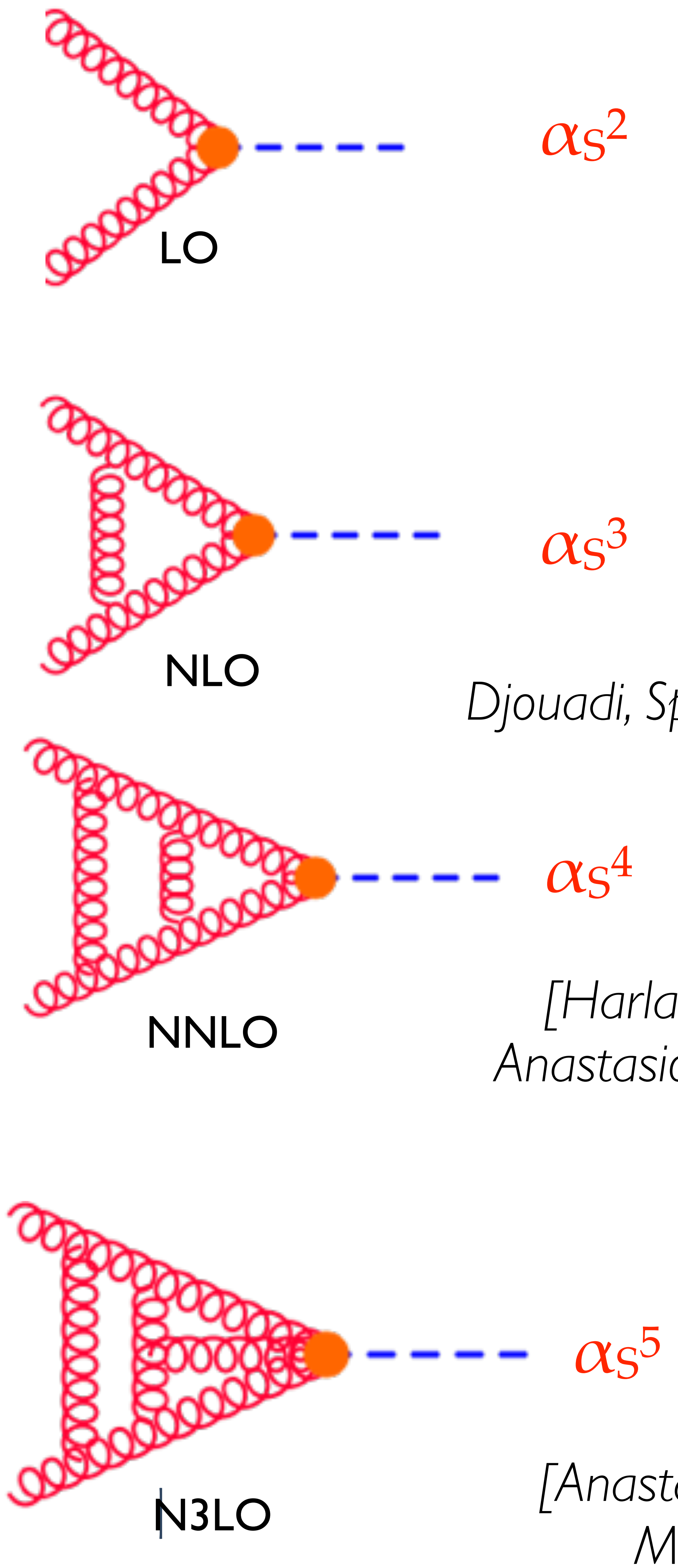
Convergence of the perturbative expansion: inclusive Higgs



➡ Error estimate at LO largely underestimated!

➡ N3LO ~ 2 LO

➡ Higher-orders are crucial for reliable predictions and precision tests of Higgs properties

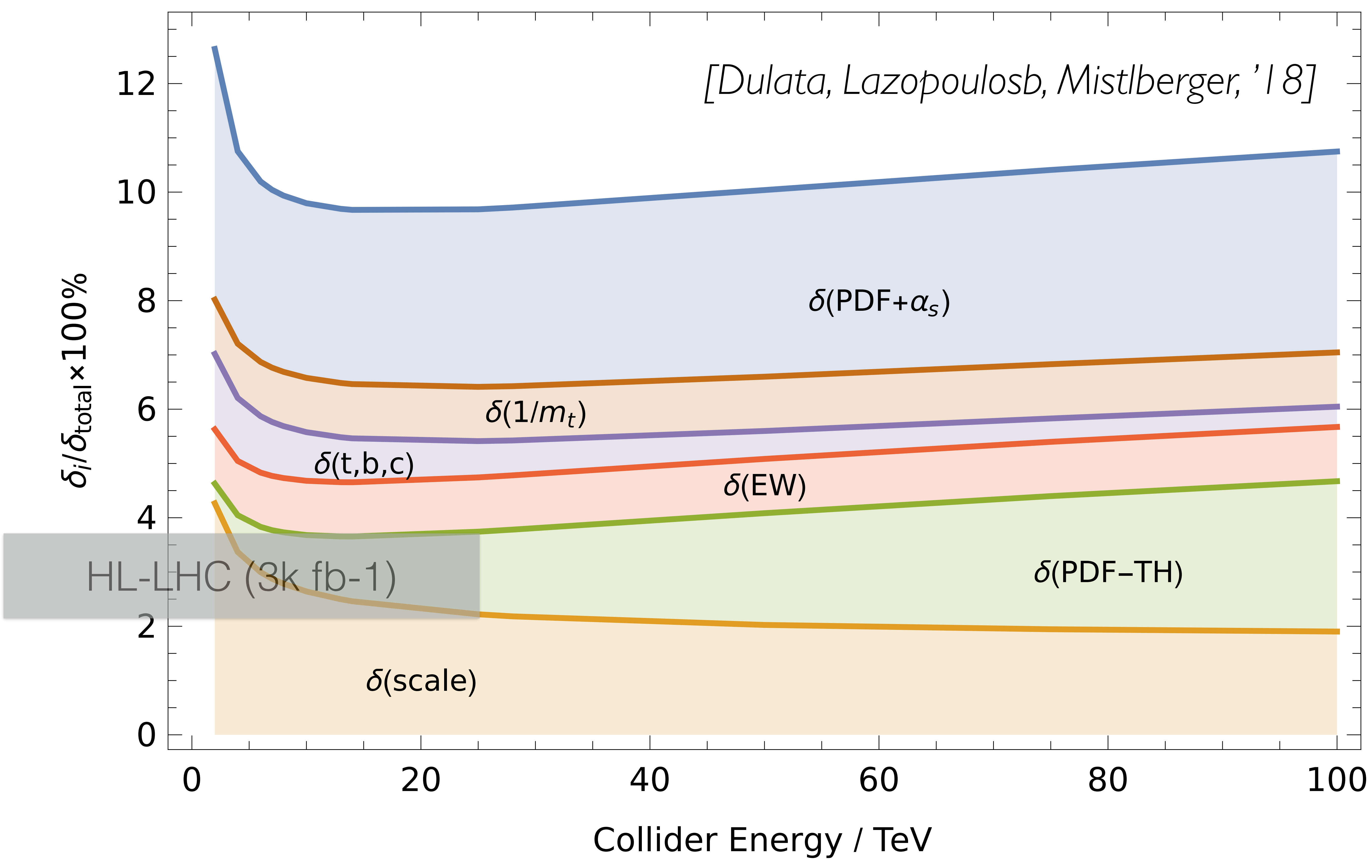


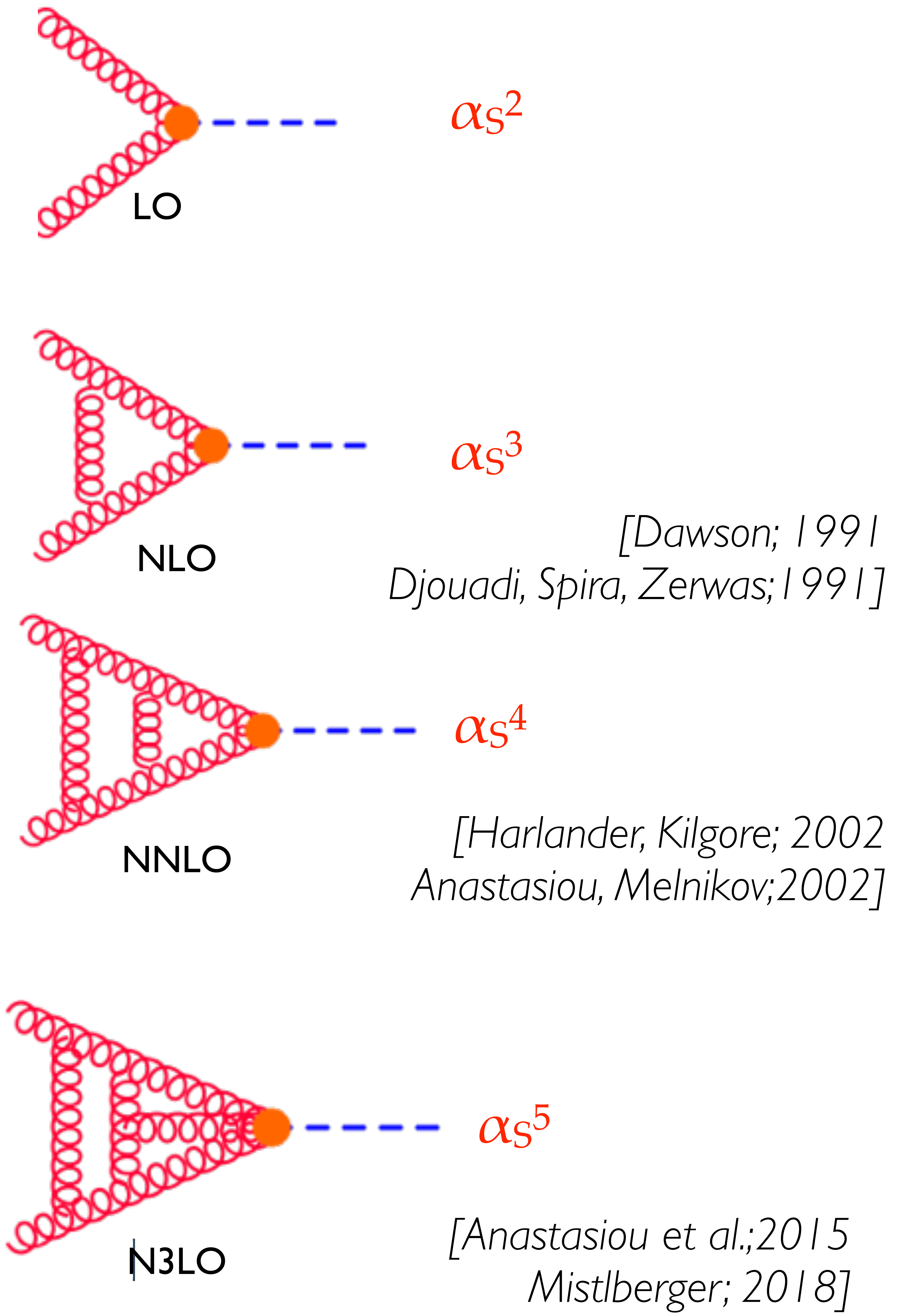
[Dawson; 1991
Djouadi, Spira, Zerwas; 1991]

[Harlander, Kilgore; 2002
Anastasiou, Melnikov; 2002]

[Anastasiou et al.; 2015
Mistlberger; 2018]

Convergence of the perturbative expansion: inclusive Higgs up to N3LO

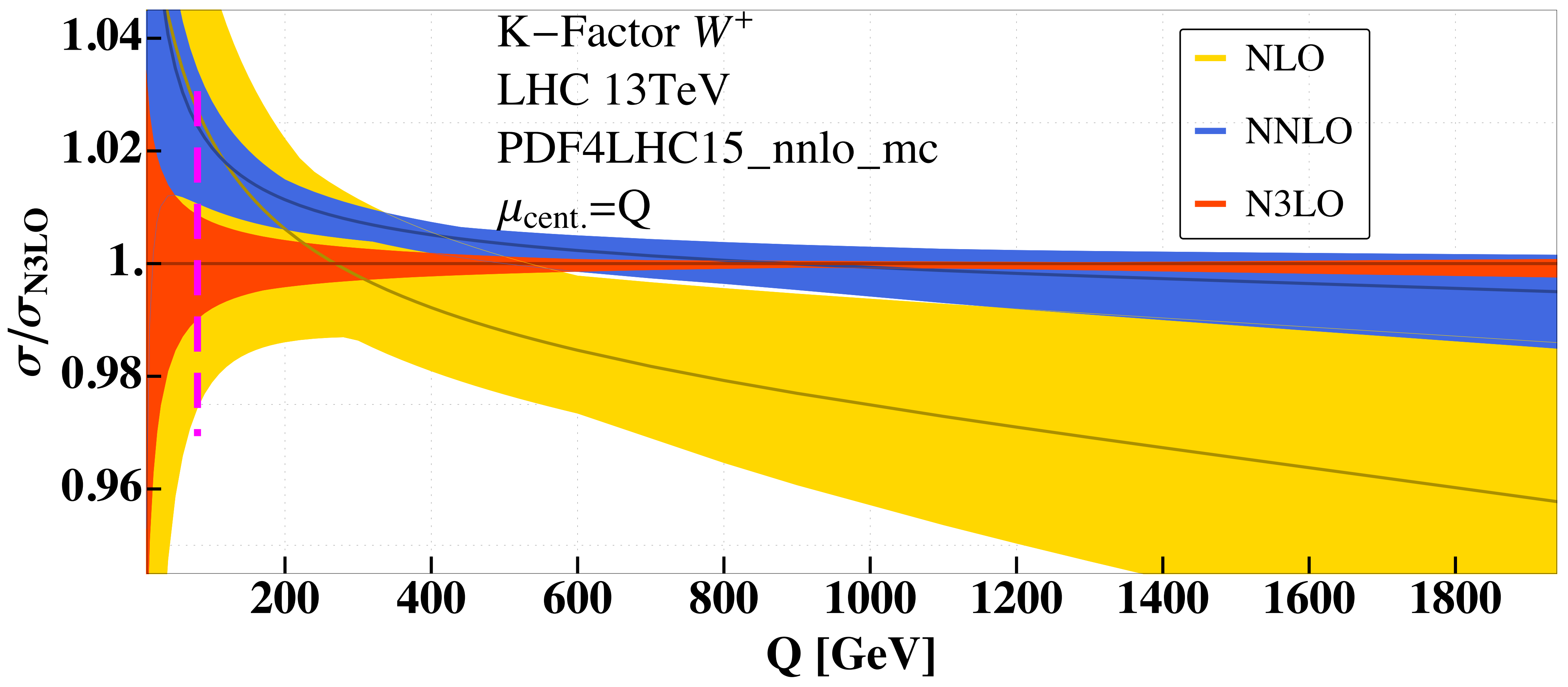




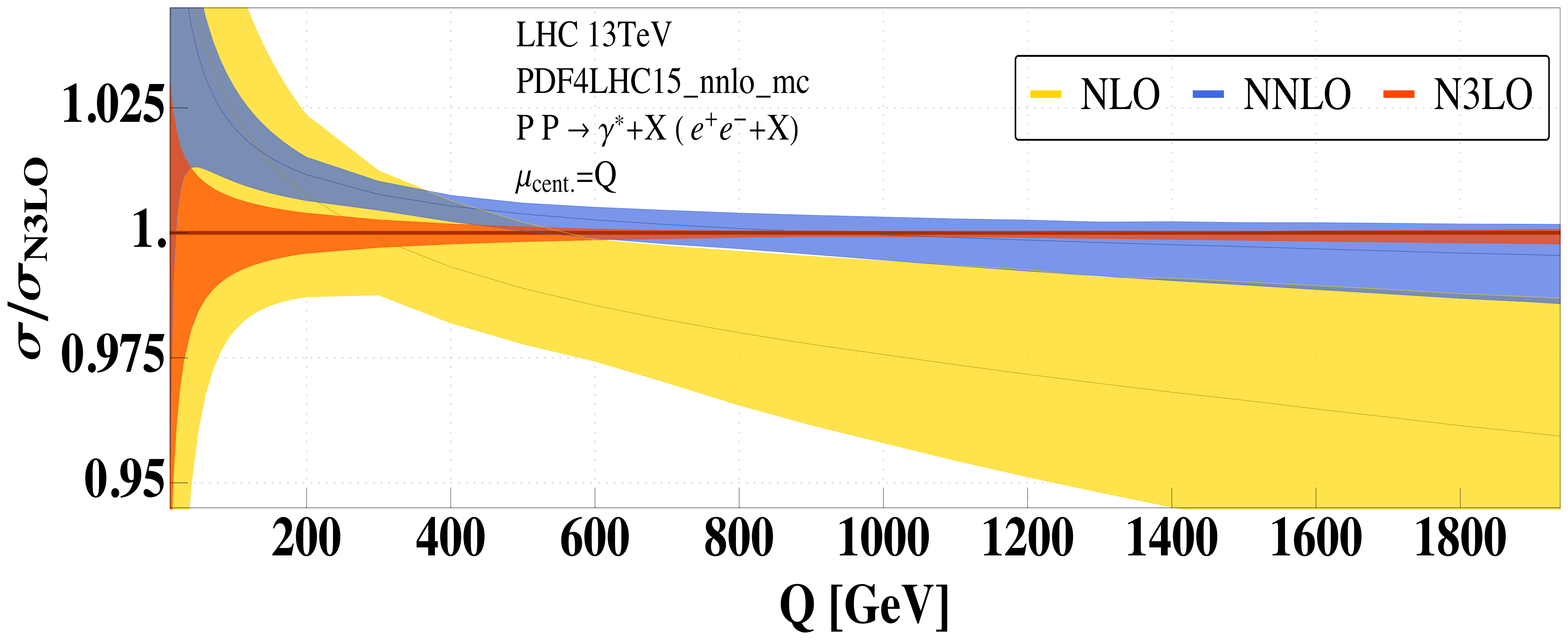
➡ At this level: crucial to investigate any possible uncertainty beyond naive scale variations

DY @ N3LO: inclusive

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



W+



γ*

➡ 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: **δ**N3LO~1-2%)

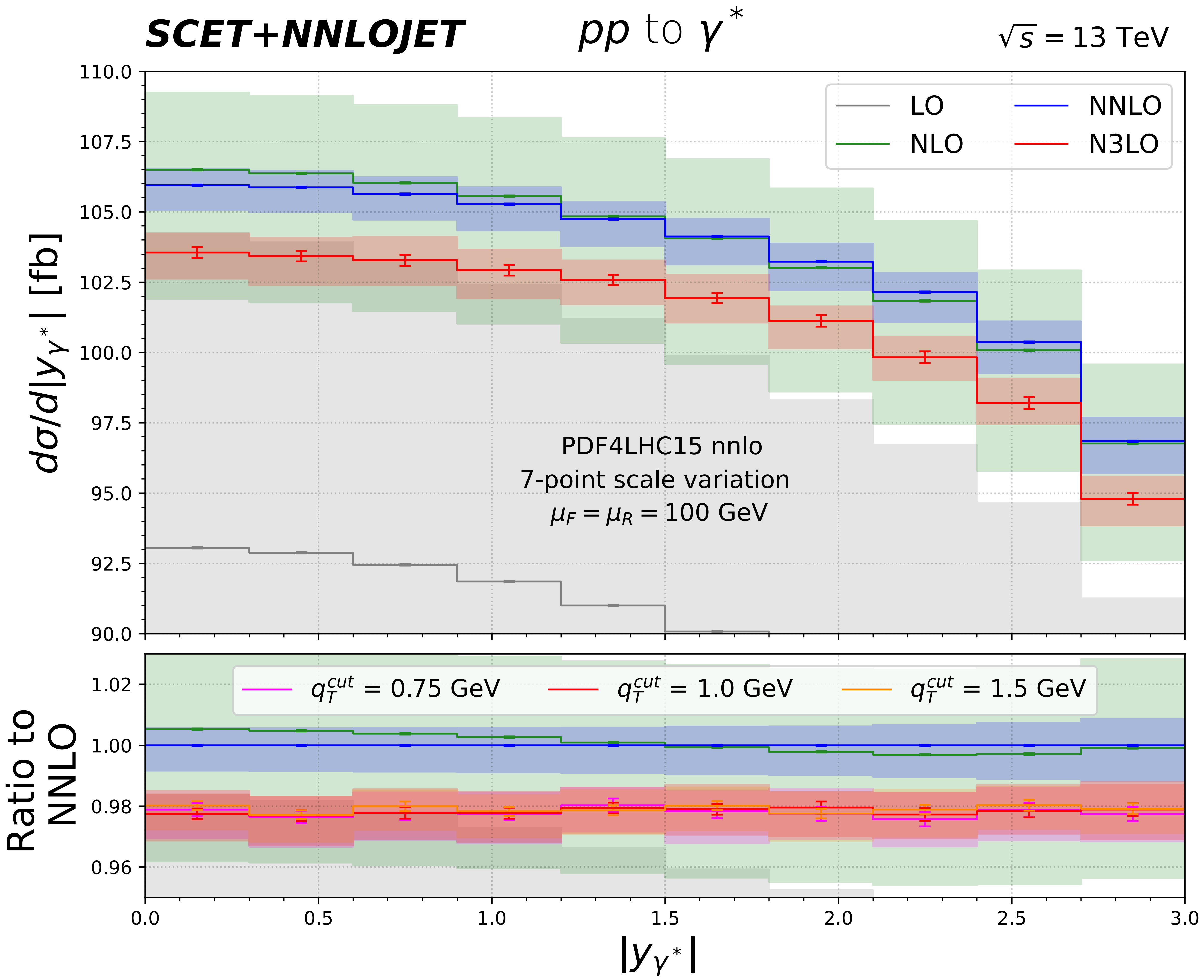
➡ Origin: quite large cancellation of quark and gluon initial state.

➡ Might be compensated by currently missing N3LO PDFs

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

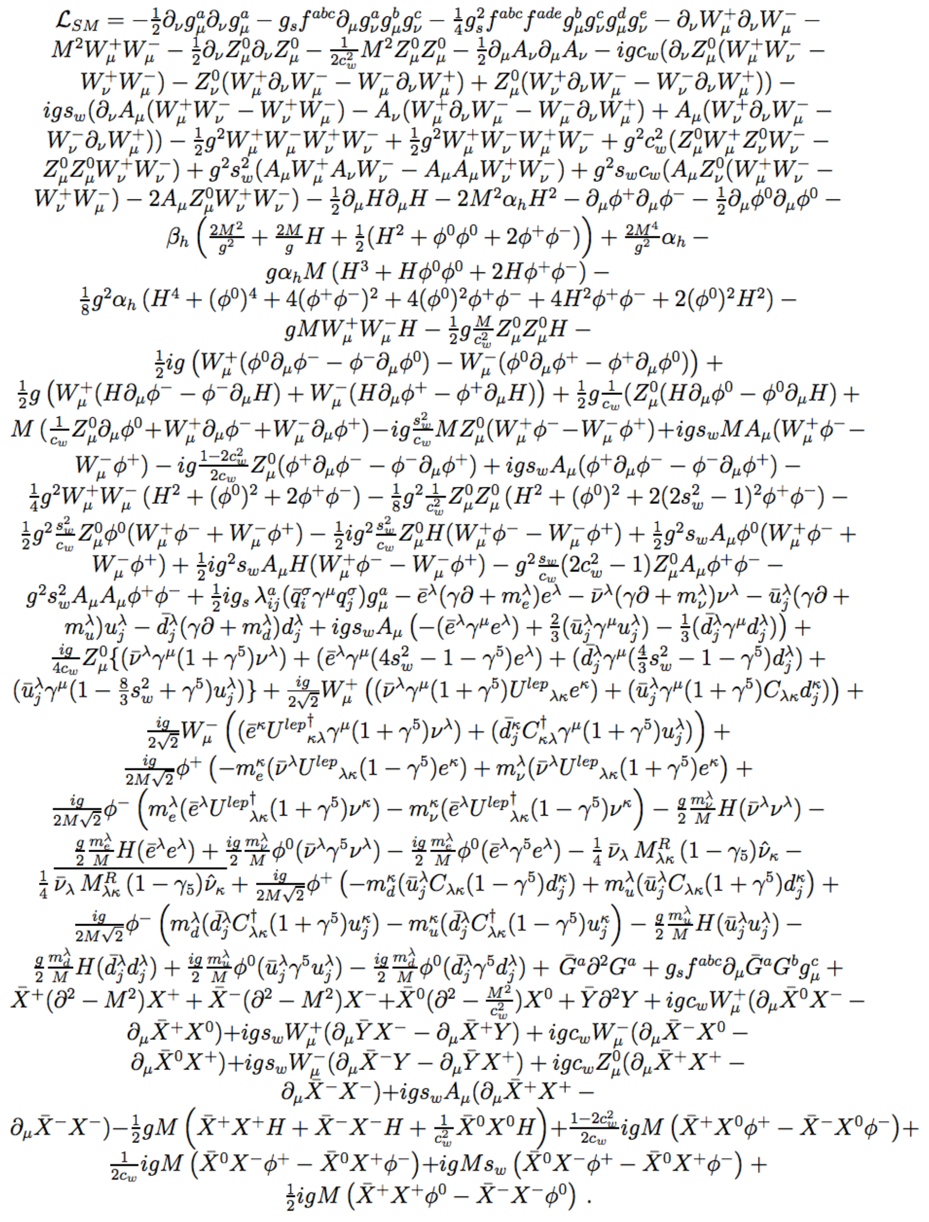
DY @ N3LO: differential

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



- method: qT 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



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

Hard (perturbative) scattering process:

→ aMC@NLO, POWHEG, Sherpa, MATRIX, …

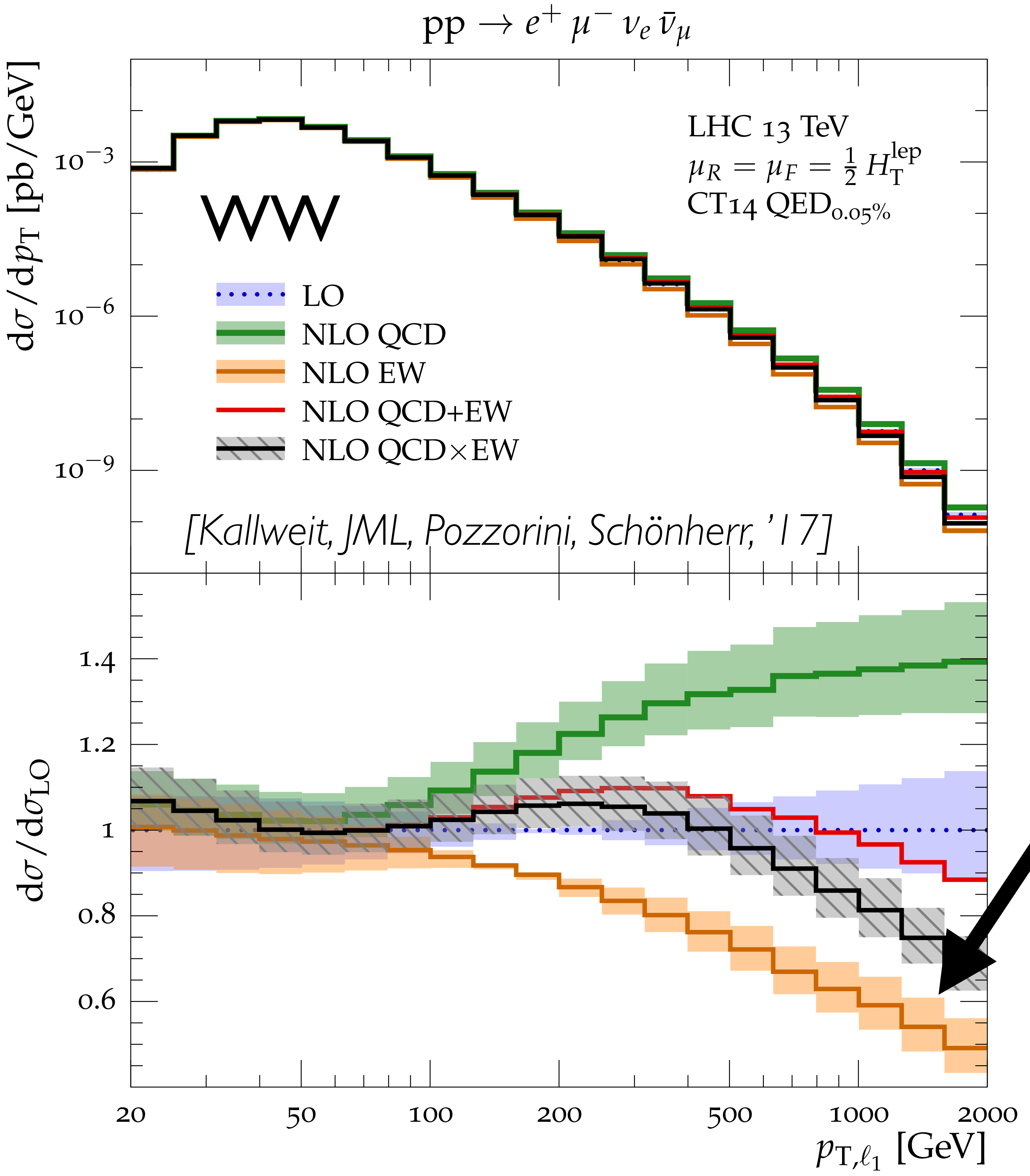
$$d\sigma = d\sigma_{\mathrm{LO}} + \alpha_S\, d\sigma_{\mathrm{NLO}} + \alpha_{\mathrm{EW}}\, d\sigma_{\mathrm{NLO\,EW}}$$

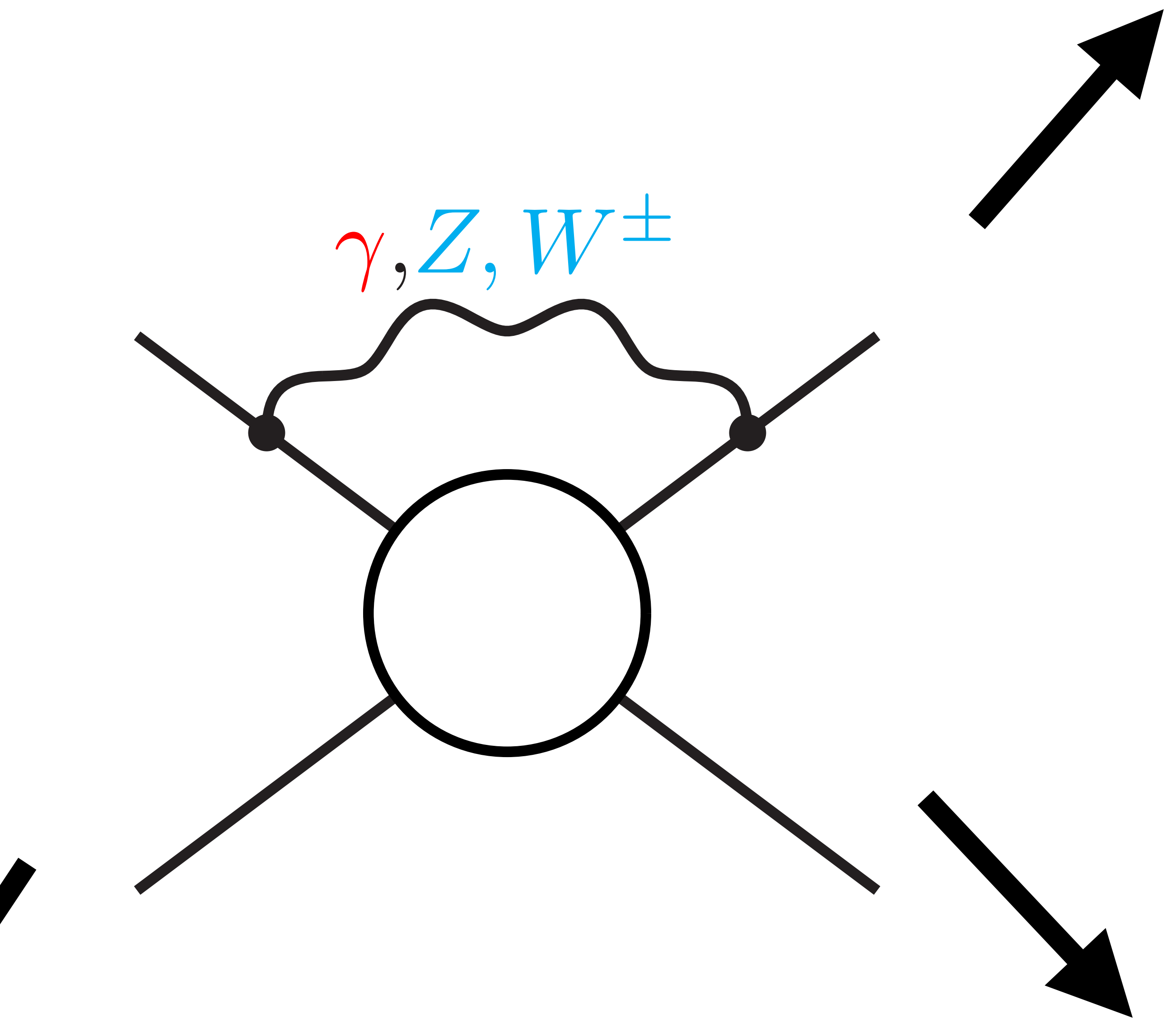
$$+\alpha_S^2\, d\sigma_{\mathrm{NNLO}} + \alpha_{\mathrm{EW}}^2\, d\sigma_{\mathrm{NNLO\,EW}} + \alpha_S\alpha_{\mathrm{EW}}\, d\sigma_{\mathrm{NNLO\,QCDxEW}}$$

? ?

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]

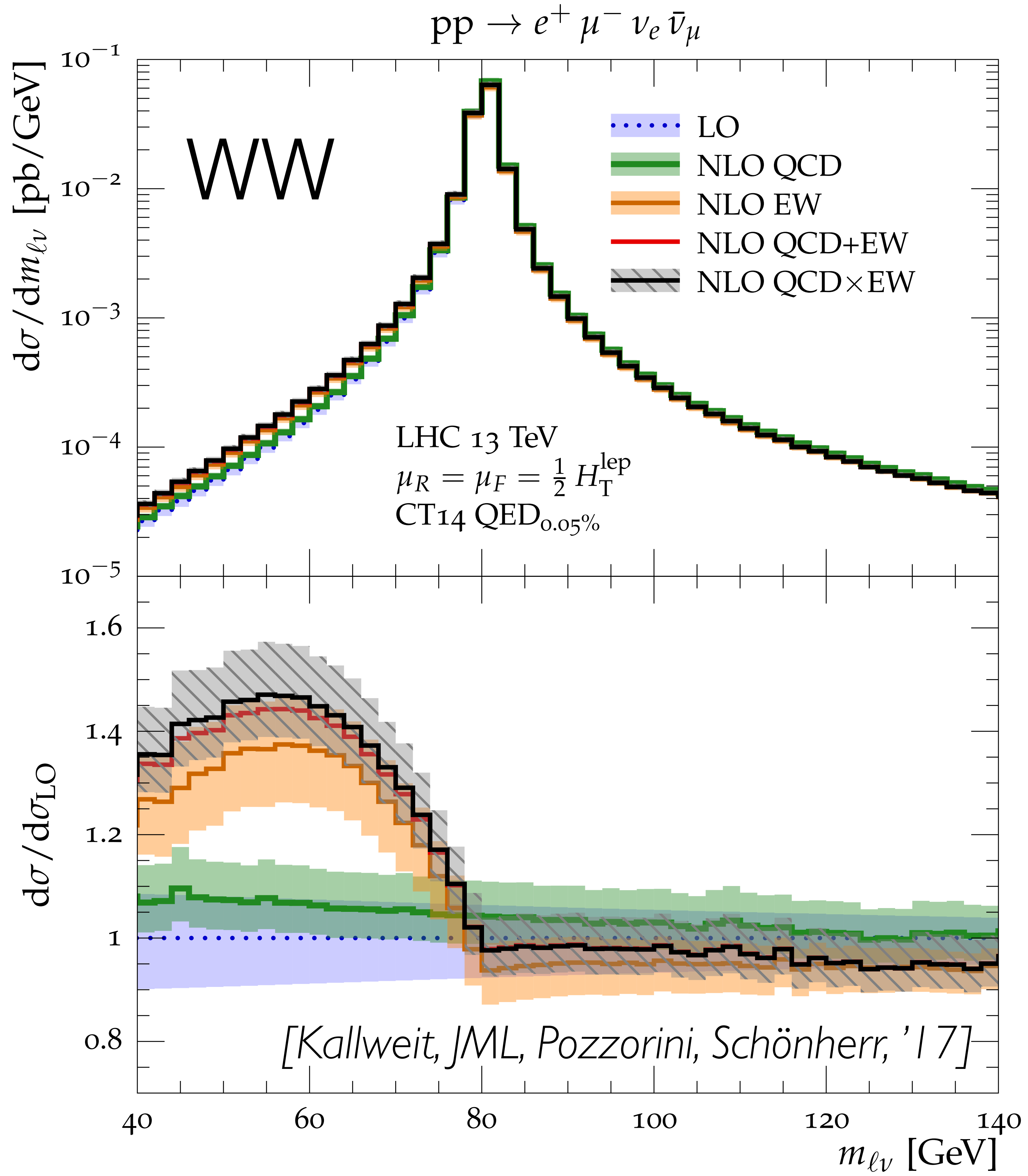
Universality and factorisation: *[Denner, Pozzorini; '01]*

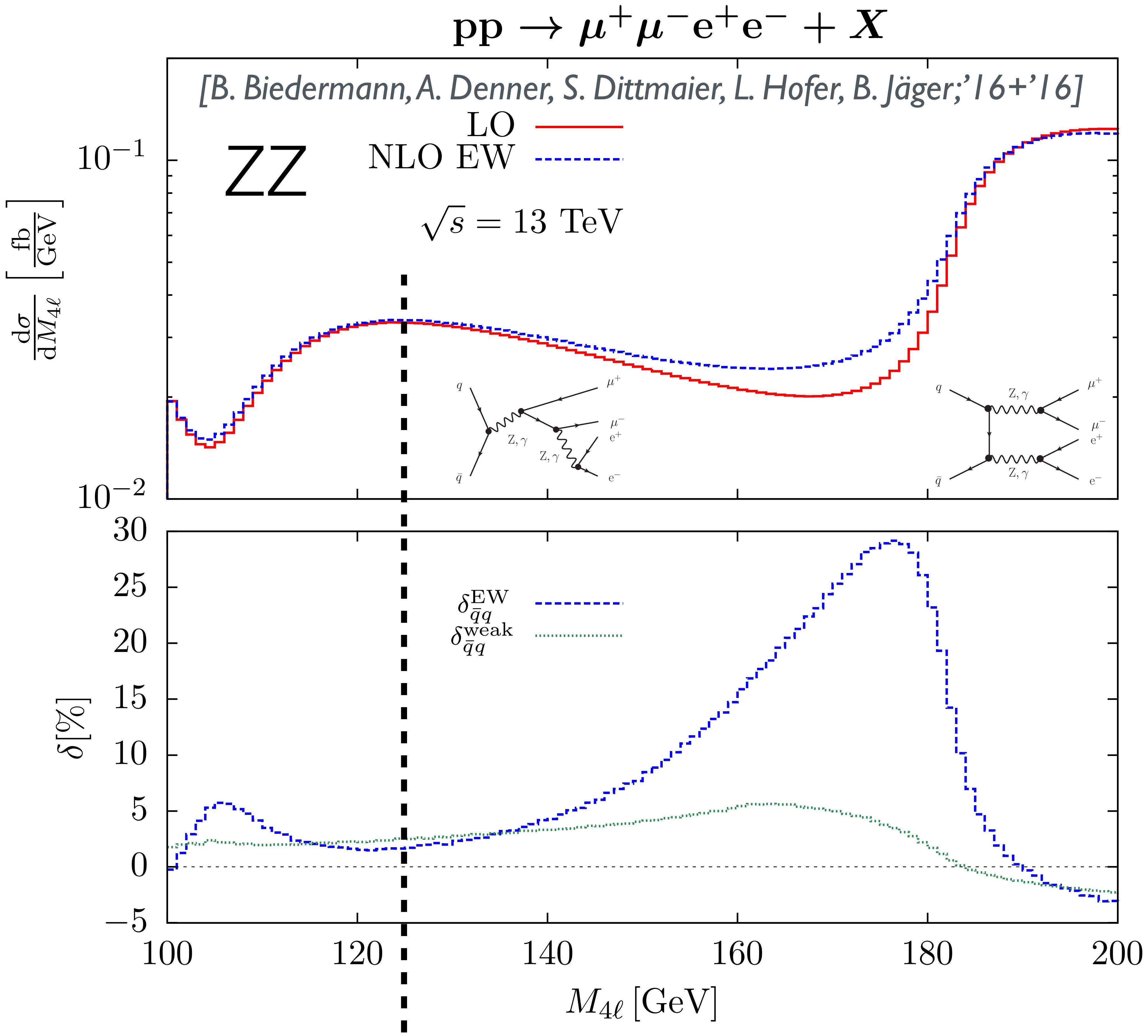
$$\delta\mathcal{M}^{1-\text{loop}}_{\text{LL+NLL}} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left\{\frac{1}{2}\sum_{l\neq k}\sum_{a=\gamma,Z,W^\pm} I^a(k)I^{\bar{a}}(l)\ln^2\frac{\hat{s}_{kl}}{M^2} + \gamma^{\text{ew}}(k)\ln\frac{\hat{s}}{M^2}\right\}\mathcal{M}_0$$

➜ overall large (negative) effect in the tails of distributions: p_T, m_{inv}, H_T, … (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 ~ $\alpha \log\left(\frac{m_f^2}{Q^2}\right)$ in sufficiently exclusive observables.





$M_{4\ell} \sim M_{\rm H}$

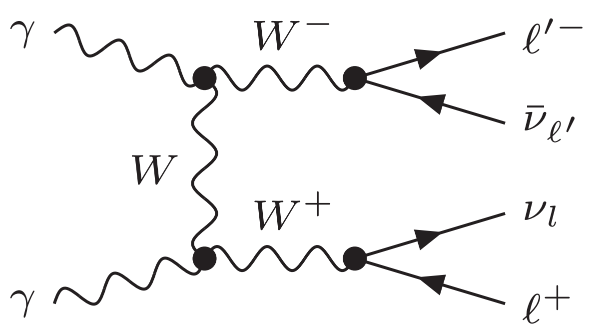
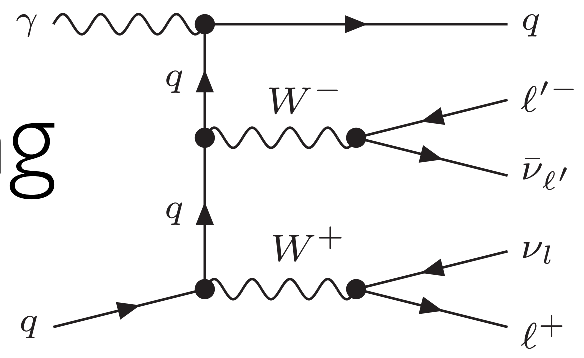
➜ important for radiative tails, Higgs backgrounds etc.

➜ typically considered via QED PS (PHOTOS / YFS)

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

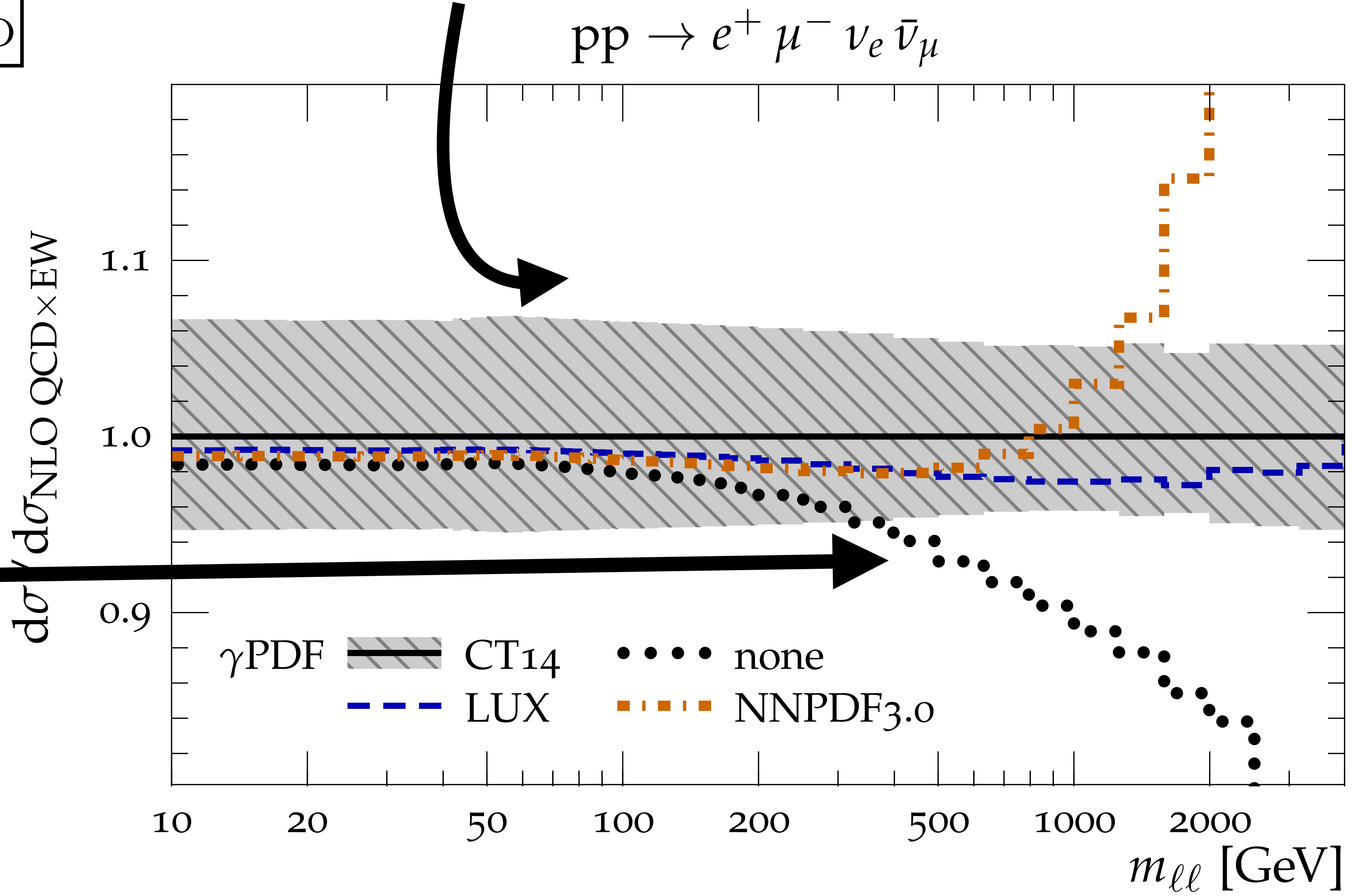
III. QED factorisation and thus photon luminosities needed to absorb IS photon singularities.

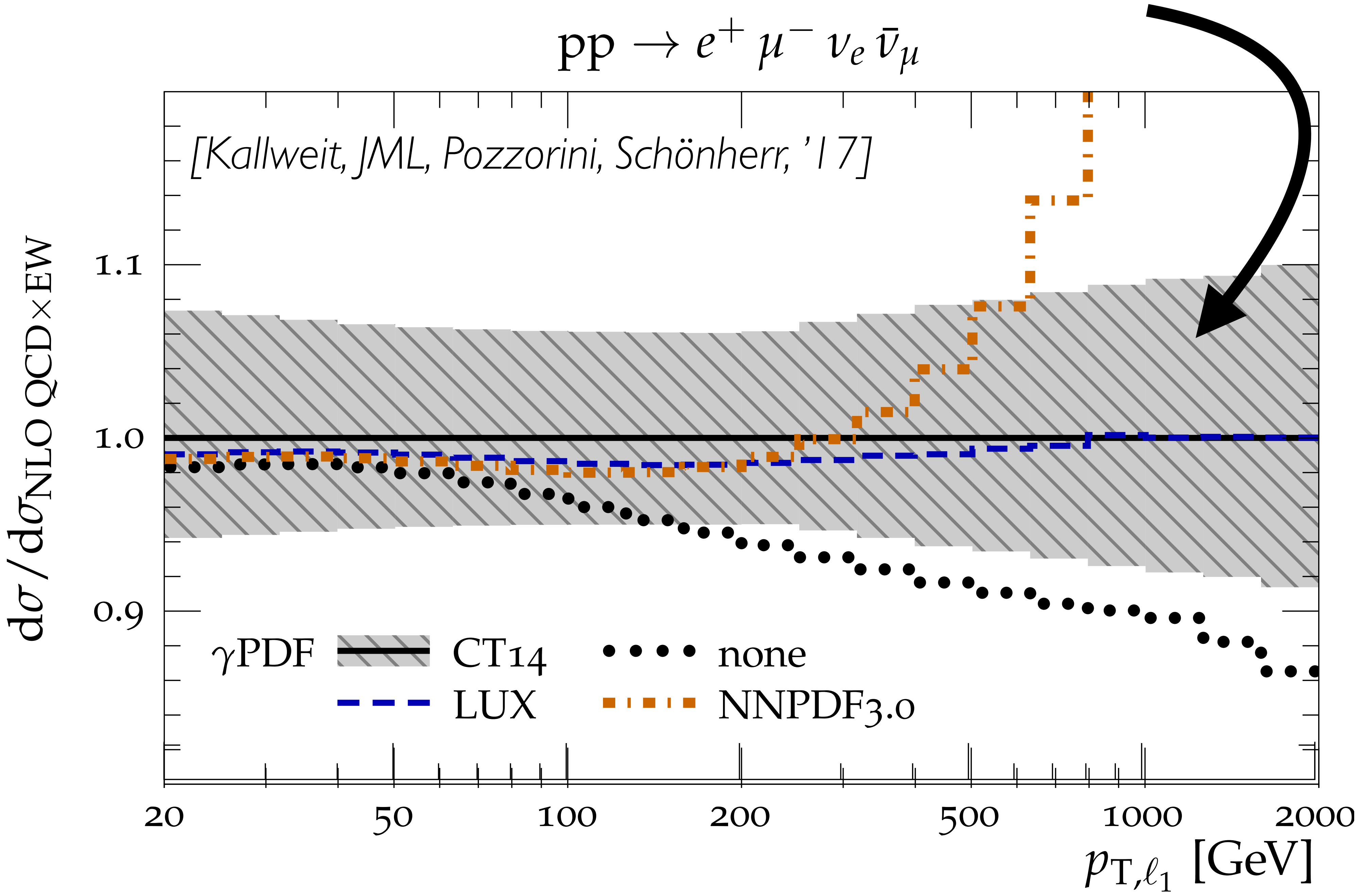
➜ Possible large enhancement due to photon-induced channels in the tails of kinematic distributions,

in particular in WW:  (t-channel enhancement), but also in Bremsstrahlung 

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

no γ

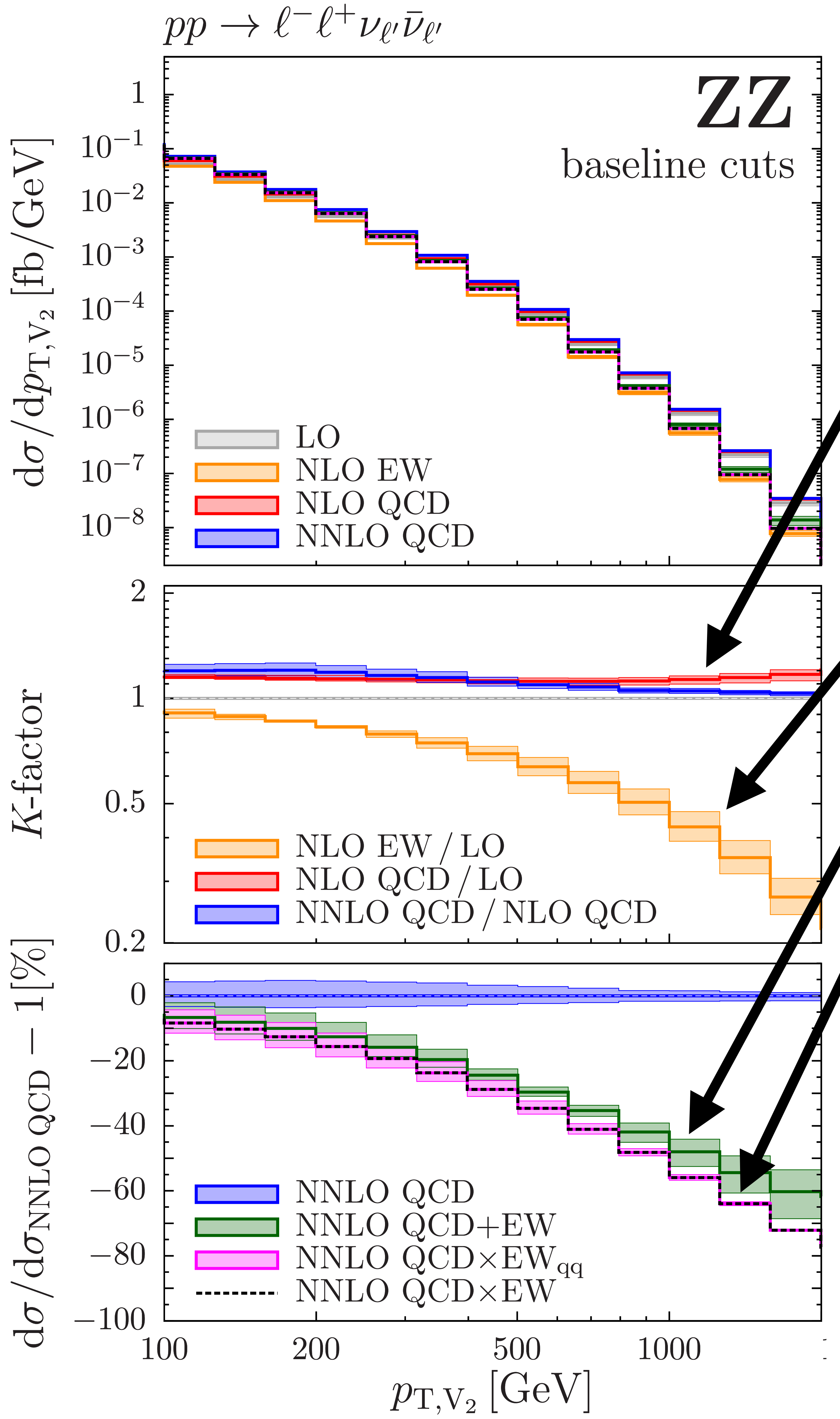




➜ O(10%) contributions from photon-induced channels

NNLO QCD + NLO EW for dibosons: pTV2

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



pTV2

- 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	$pp \to \ell^+\ell^-\ell^+\ell^-$	ZZ
4l-DF-ZZ	$pp \to \ell^+\ell^-\ell'^+\ell'^-$	ZZ
3l-SF-WZ	$pp \to \ell^+\ell^-\ell\nu_\ell$	WZ
3l-DF-WZ	$pp \to \ell^+\ell^-\ell'\nu_{\ell'}$	WZ
2l-SF-ZZ	$pp \to \ell^+\ell^-\nu_{\ell'}\bar{\nu}_{\ell'}$	ZZ
2l-SF-ZZWW	$pp \to \ell^+\ell^-\nu_\ell\bar{\nu}_\ell$	ZZ,WW
2l-DF-WW	$pp \to \ell^+\ell'^-\nu_\ell\bar{\nu}_{\ell'}$	WW

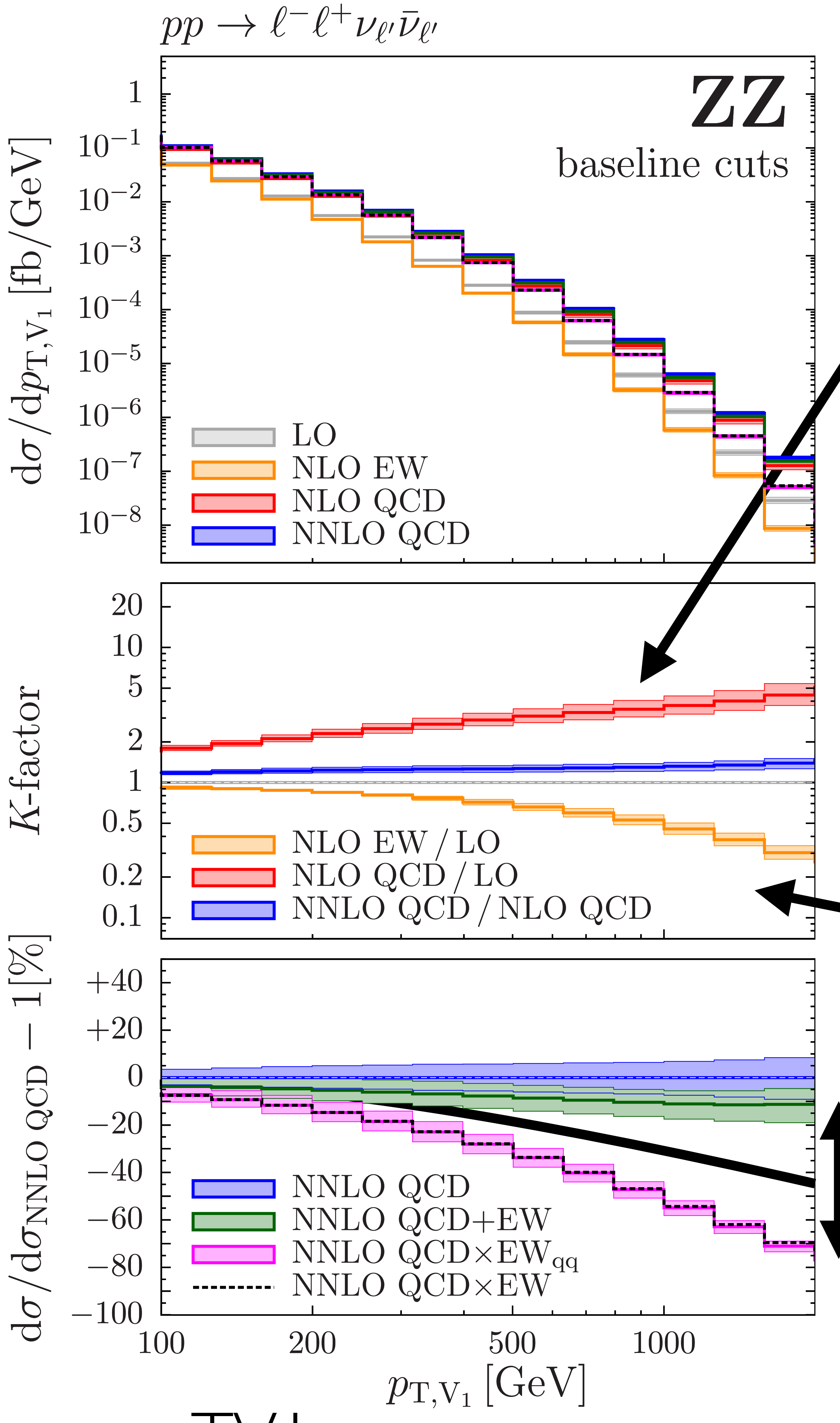
$$\begin{aligned} d\sigma_{\rm NNLO\,QCD+EW} &= d\sigma_{\rm LO}\left(1+\delta_{\rm QCD}+\delta_{\rm EW}\right)+d\sigma^{gg}_{\rm LO} \\ d\sigma_{\rm NNLO\,QCD\times EW} &= d\sigma_{\rm LO}\left(1+\delta_{\rm QCD}\right)\left(1+\delta_{\rm EW}\right)+d\sigma^{gg}_{\rm LO} \\ &= d\sigma_{\rm NNLO\,QCD+EW}+d\sigma_{\rm LO}\delta_{\rm QCD}\,\delta_{\rm EW} \end{aligned}$$

- 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: $\frac{1}{2}\delta^2_{\rm EW}$

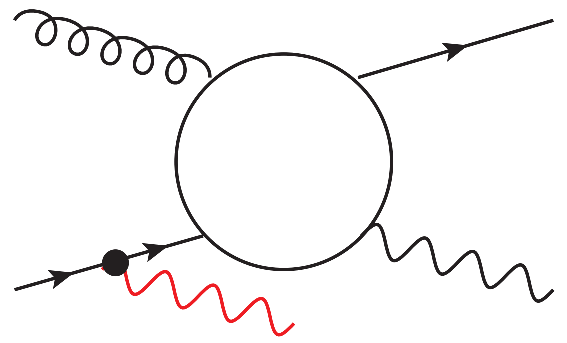
Giant QCD K-factors and EW corrections: pTV1

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



pTV1

- NLO QCD/LO=2-5! ("giant K-factor")
- at large pTV1: VV phase-space is dominated by V+jet (w/ soft V radiation)

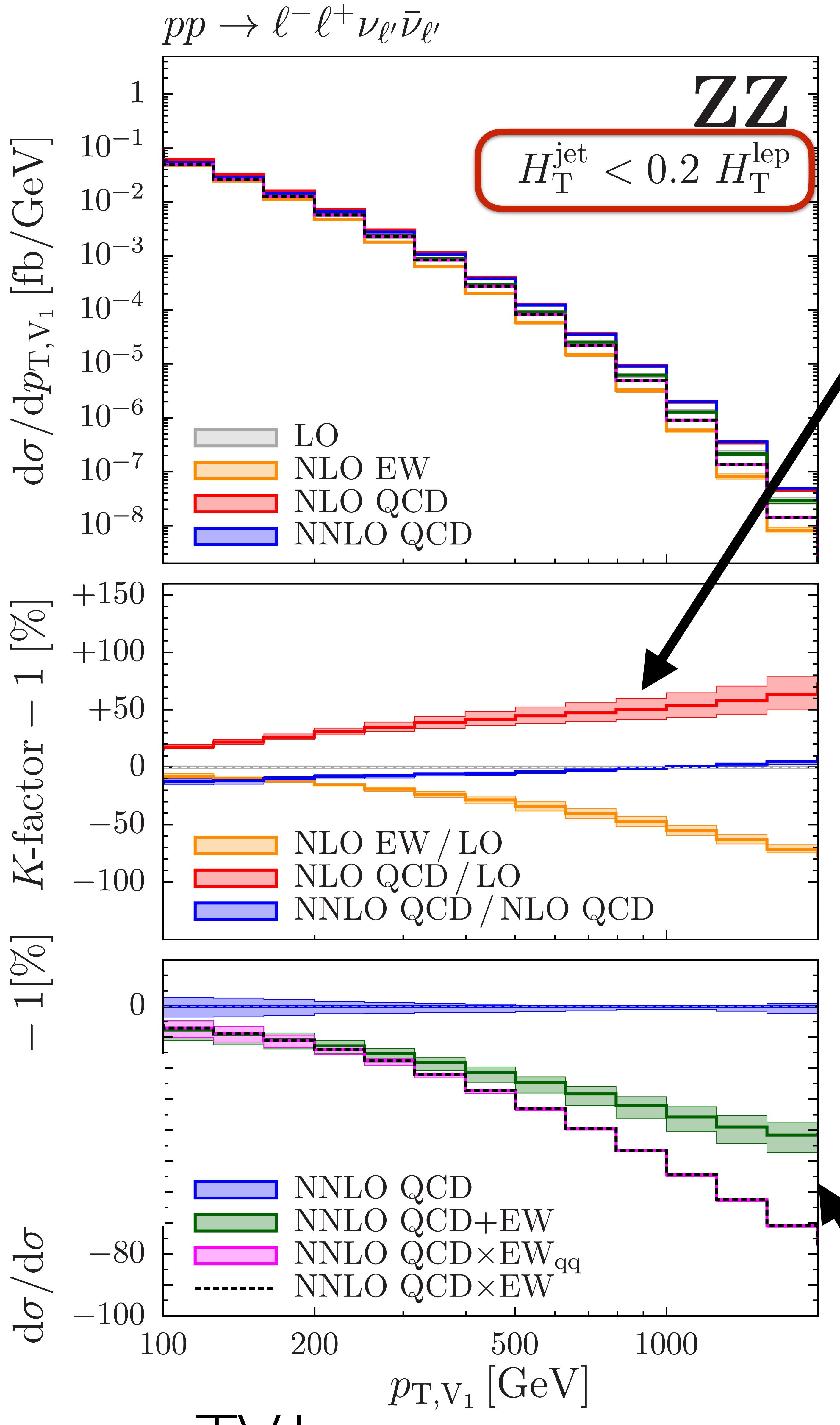


$$\frac{d\sigma^{V(V)j}}{d\sigma^{LO}_{VV}} \propto \alpha_S \log^2\left(\frac{Q^2}{M_W^2}\right) \simeq 3 \qquad \text{at} \quad Q = 1\,\text{TeV}$$

- NNLO / NLO QCD moderate and NNLO uncert. 5-10%
- NLO EW/LO=-(40-50)%
- Very large difference $d\sigma_{NNLO\,QCD+EW}$ vs. $d\sigma_{NNLO\,QCD\times EW}$
- 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 toplogoies**
- Rigorous solution: **merge VVj incl. EW corrections with VV** retaining NNLO QCD + EW

Giant QCD K-factors and EW corrections: pTV1

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



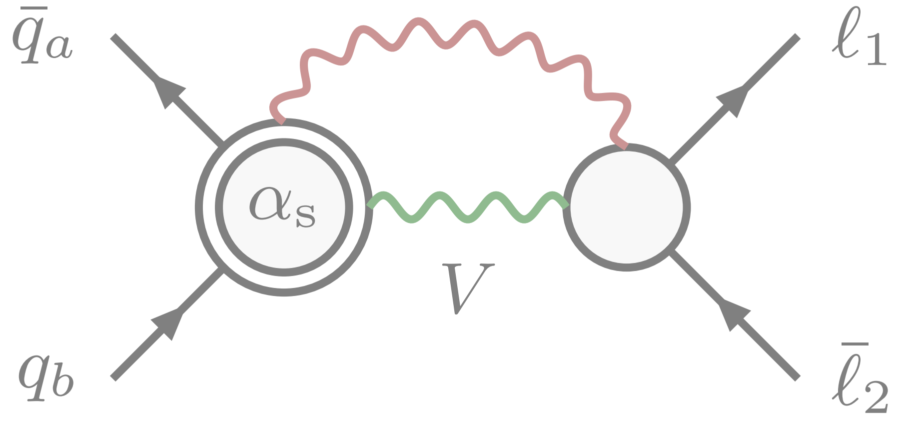
pTV1

- NLO QCD/LO=~<1.5 ("normal K-factor")
- very small NNLO / NLO QCD corrections and ~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 toplogoies**
- Rigorous solution: **merge VVj incl. EW corrections with VV** retaining NNLO QCD + EW

Mixed QCD-EW corrections to DY production: NC

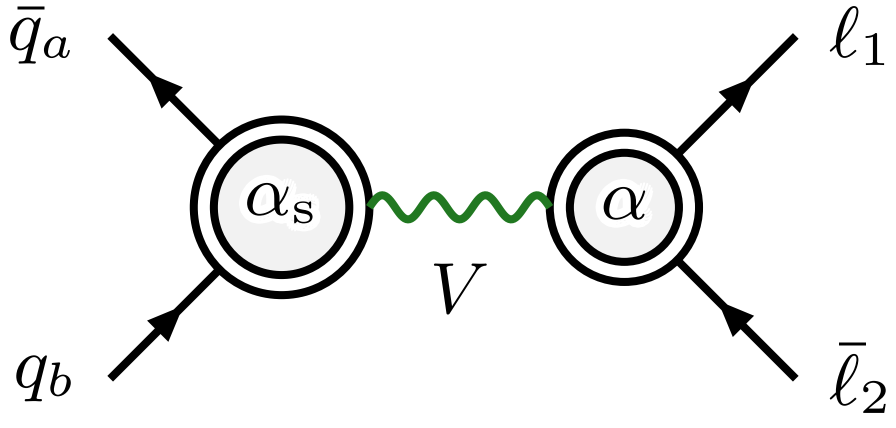
- Complete O(αs α) corrections still beyond currently technology
- For precision in resonant region: expand around M^2



non-factorizable

[Dittmaier, Huss, Schwinn, '14]

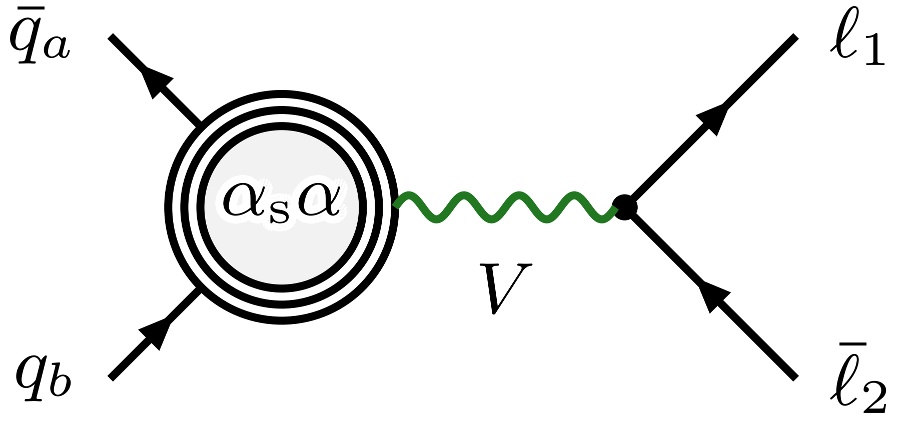
negligible



prod x decay

[Dittmaier, Huss, Schwinn, '15]

dominant



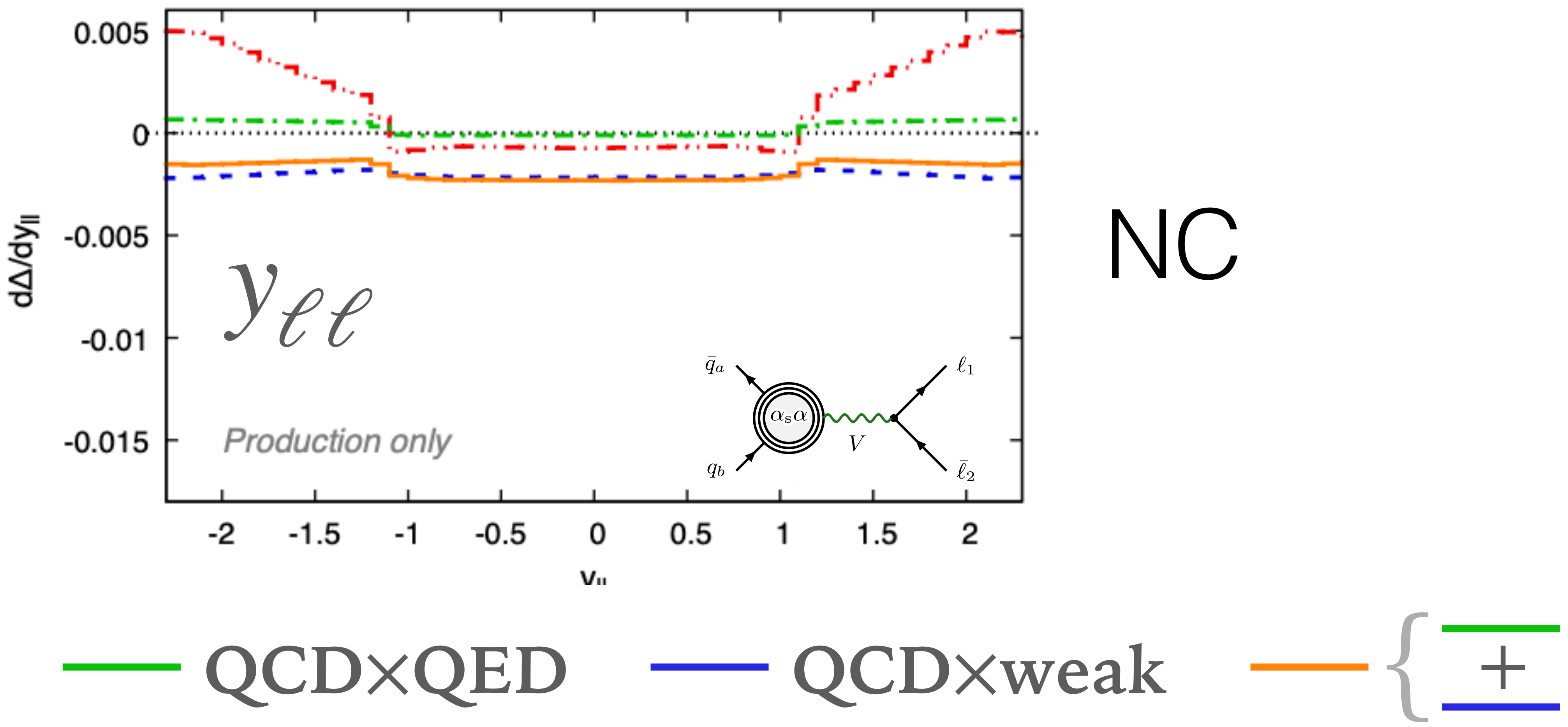
genuine QCD-EW in prod

[Buccioni, Caola, Delto, Jaquier, Melnikov, Röntsch, '20]
[Behring, Buccioni, Caola, et. al. '20]

last missing piece

For production only

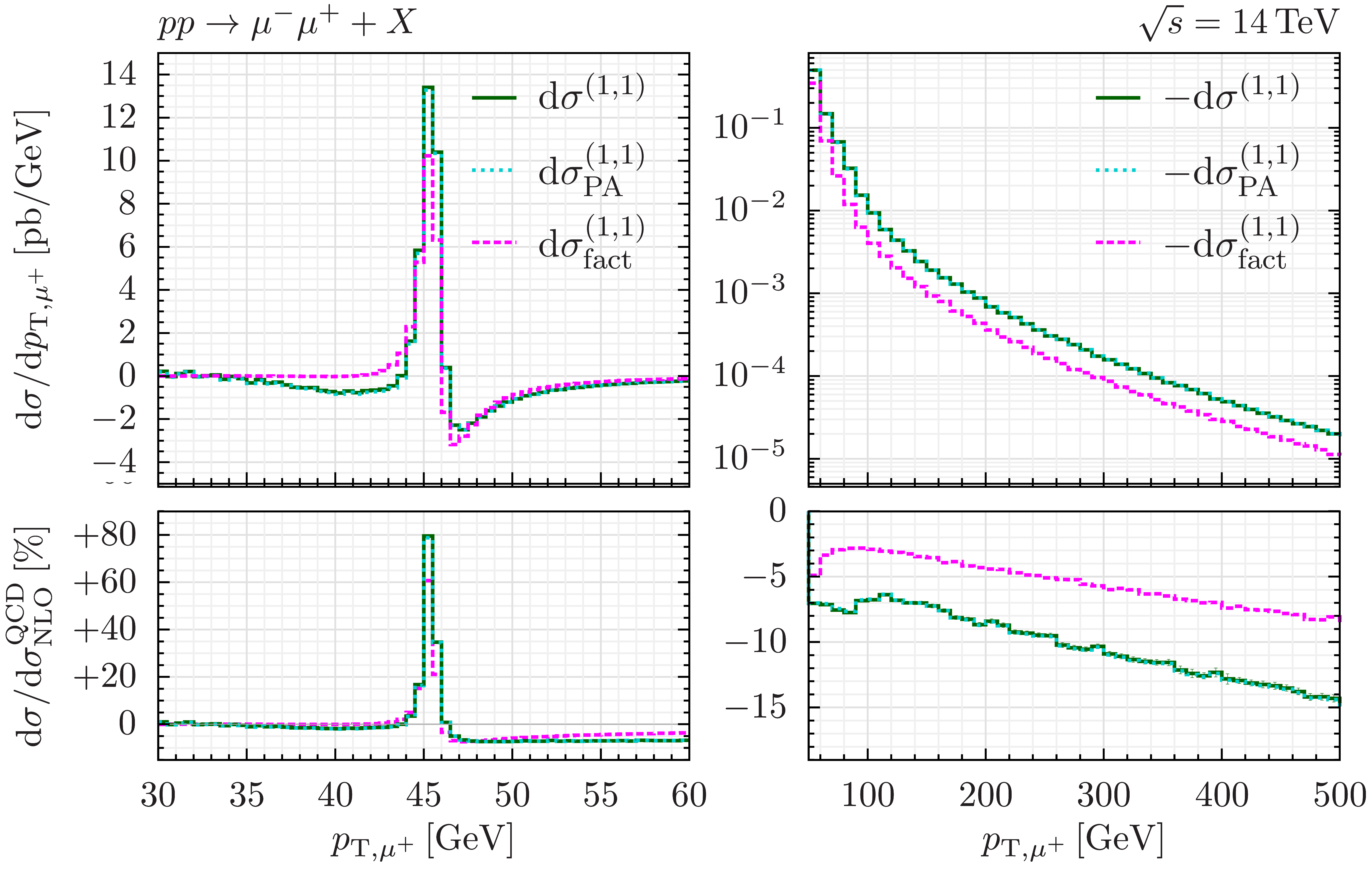
- QCD×weak dominant over QCD×QED
- net effect: few per-mille



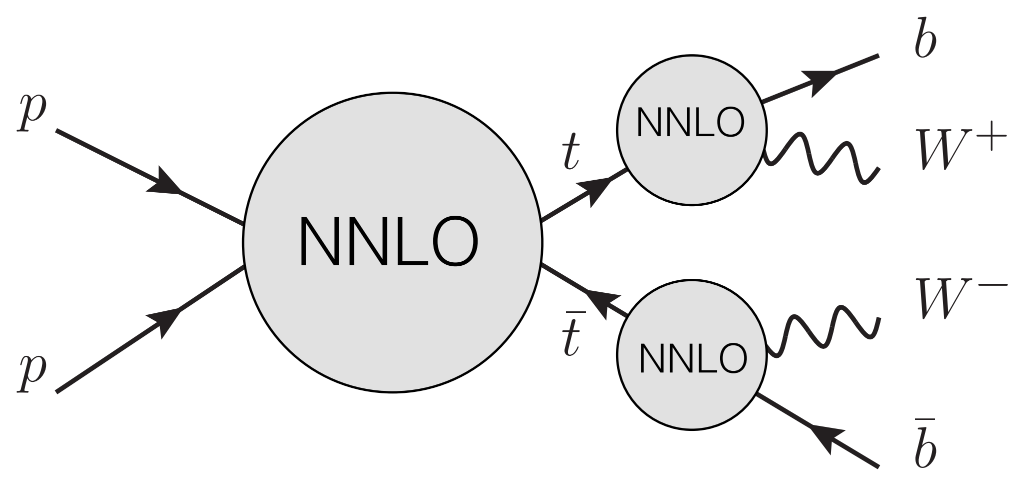
NC

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

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



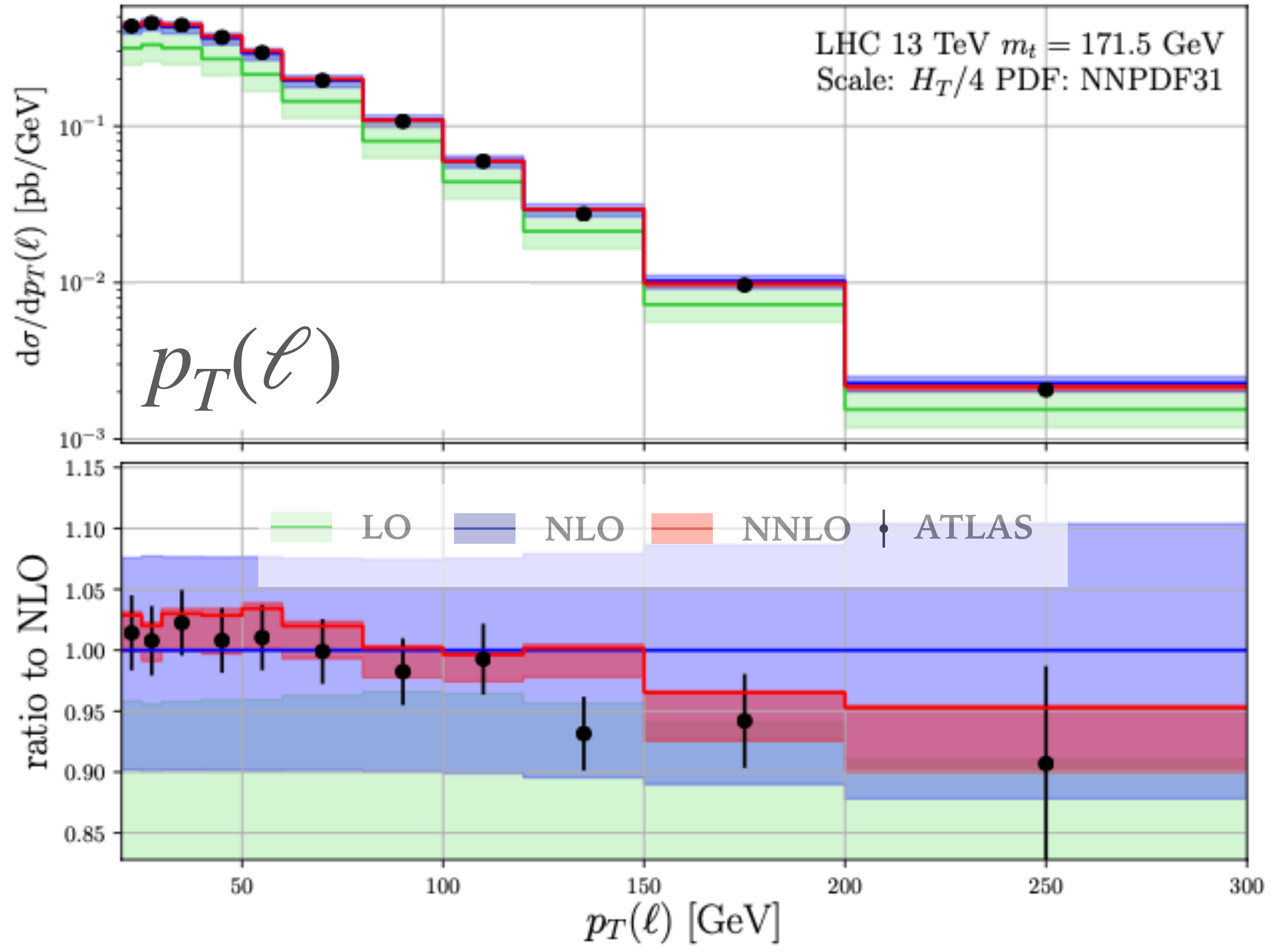
- Comparison against naive factorised NLO QCD x NLO EW ansatz: fail at the 5-10% level
- pole approximation vs. full computation: agree below the percent level

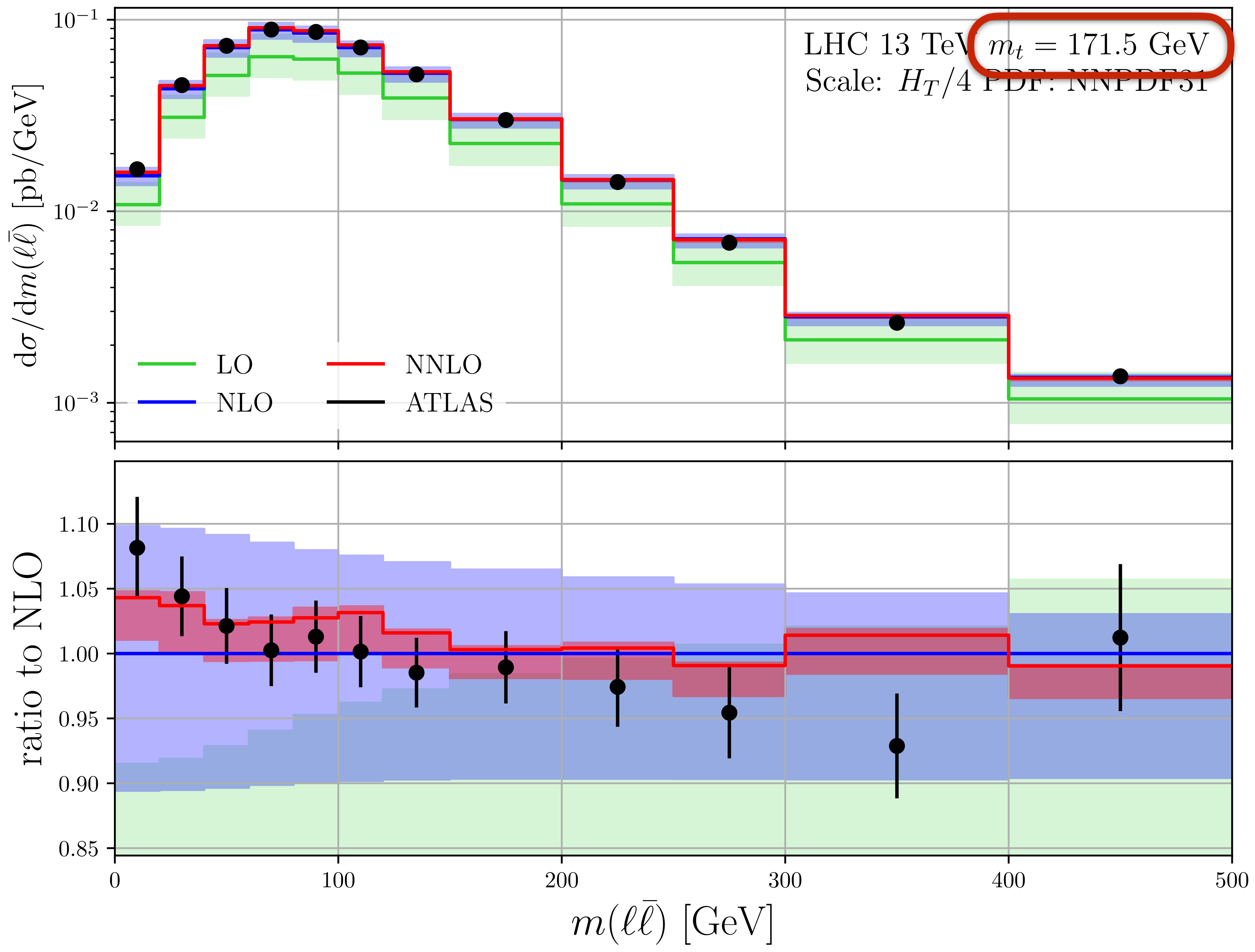


Top-quark spin correlations at NNLO

[Czakon, Mitov, Poncelet `20]

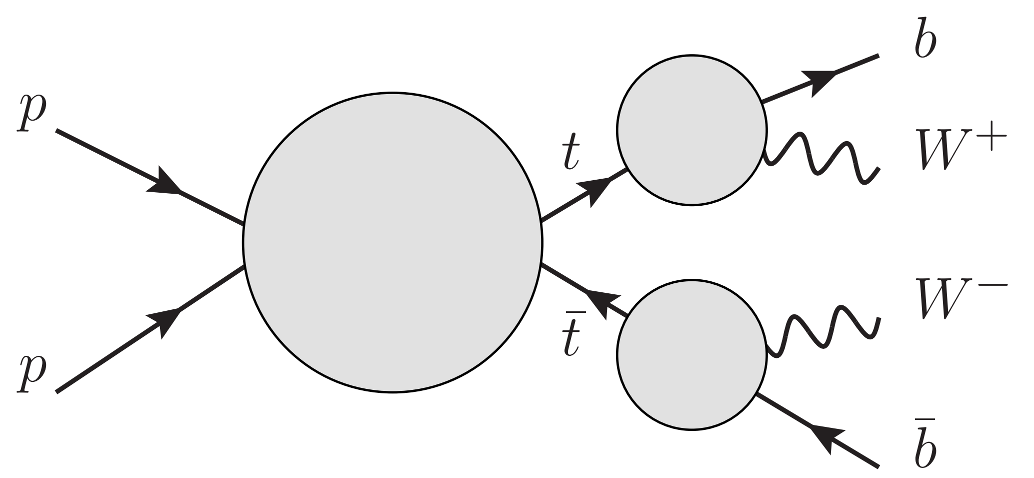
$$pp \to t\bar{t} \to 2\ell 2\nu b\bar{b}$$





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

- Might allow for an additional handle on Mtop
- Need to understand systematics at small mll (EW corrections, finite width effects, …)



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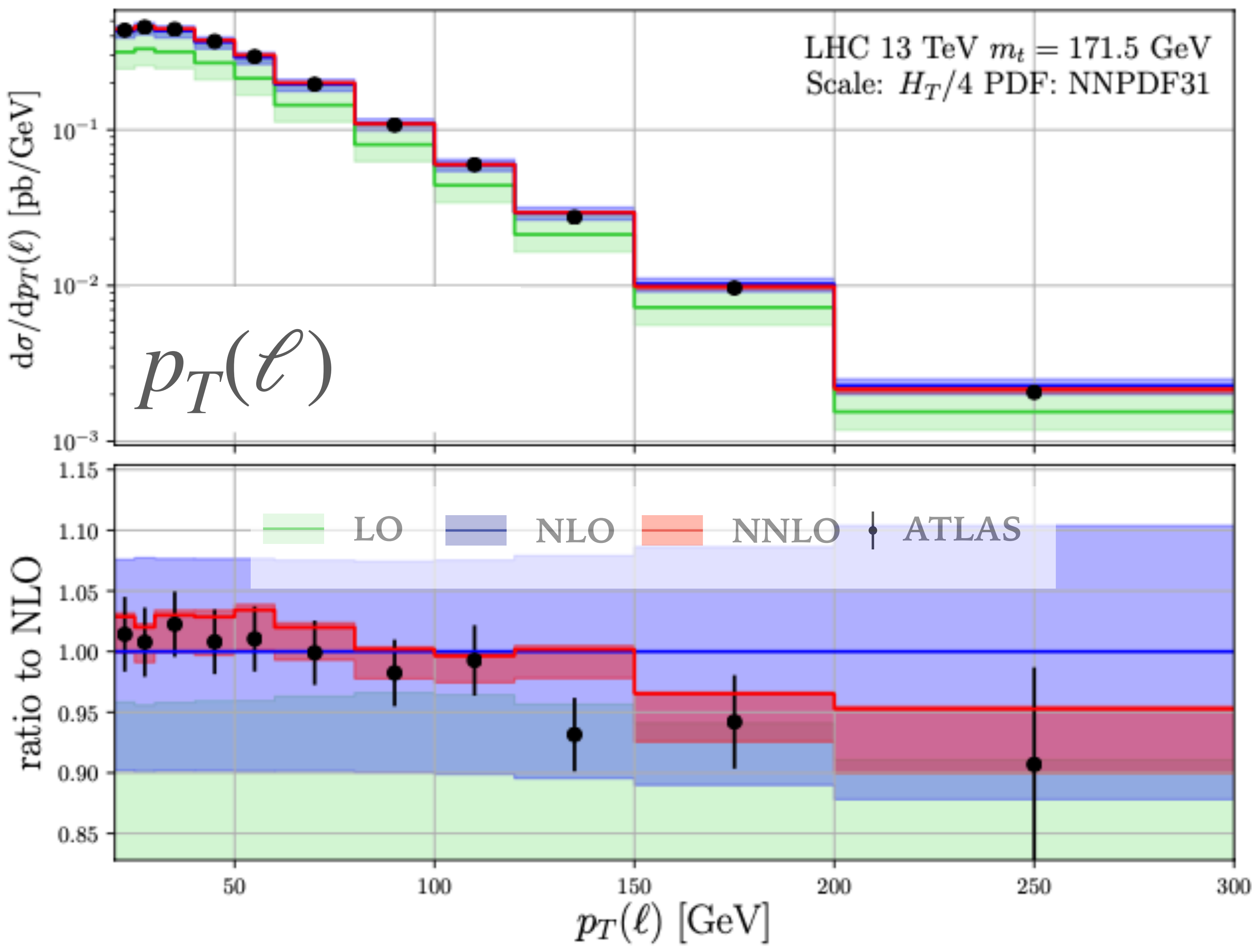

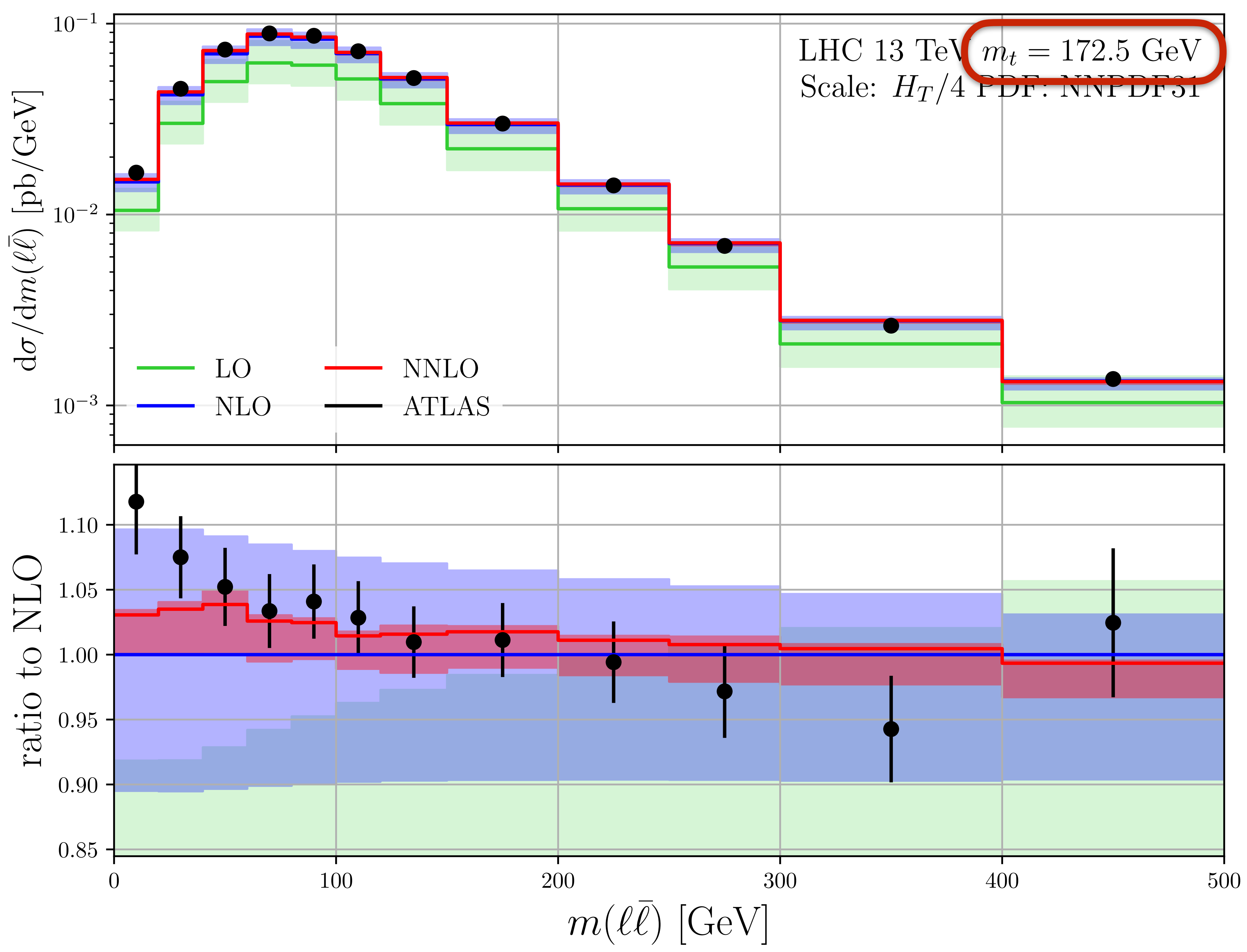

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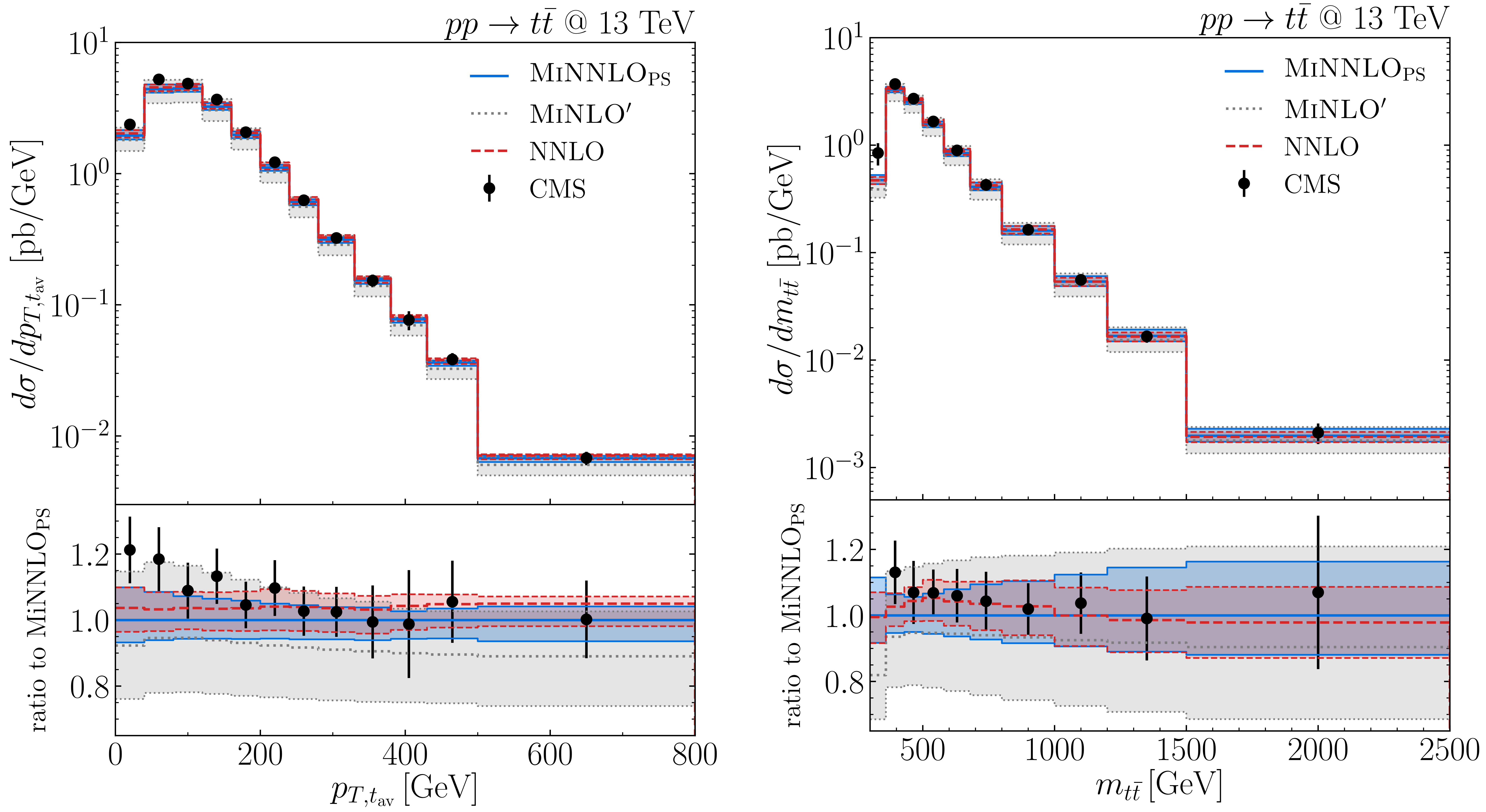
Top-quark pair production at NNLO+PS

[Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi `20]

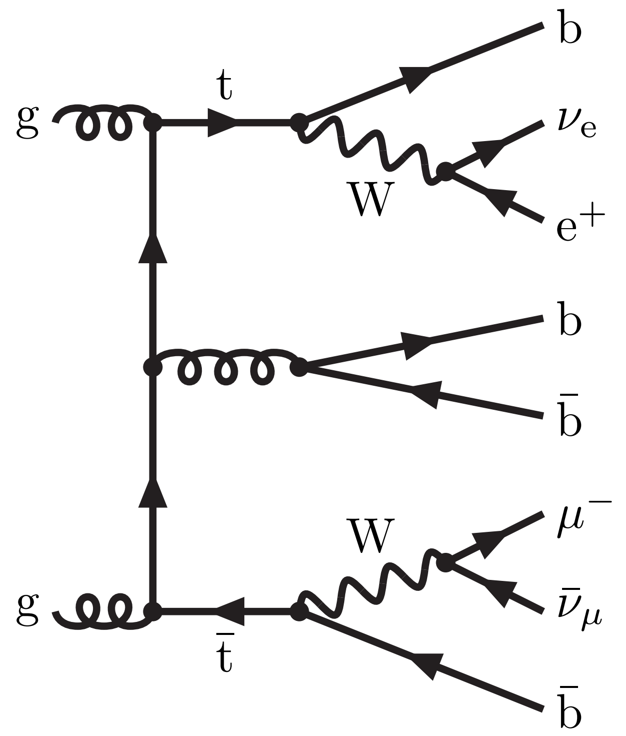


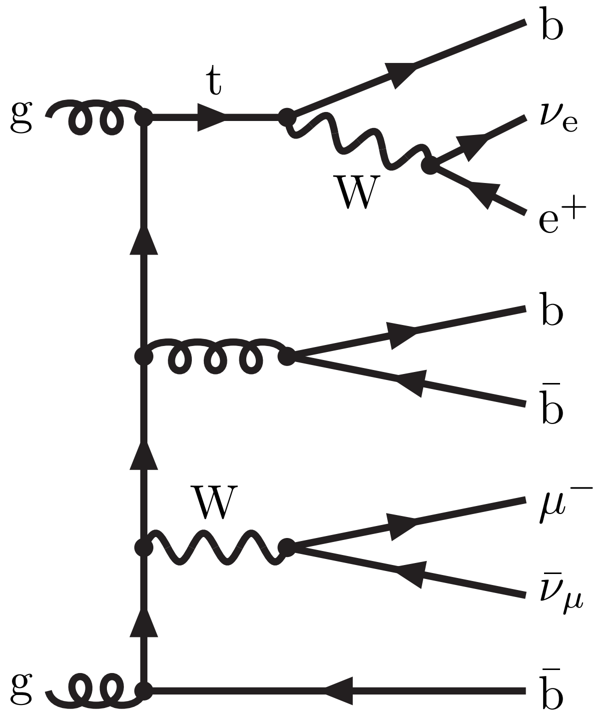
- Requires highly non-trivial extension of MiNNLOPS method to final state radiation
- NNLO accuracy mandatory given data accuracy
- Allows for NNLO top-pair production at detector level

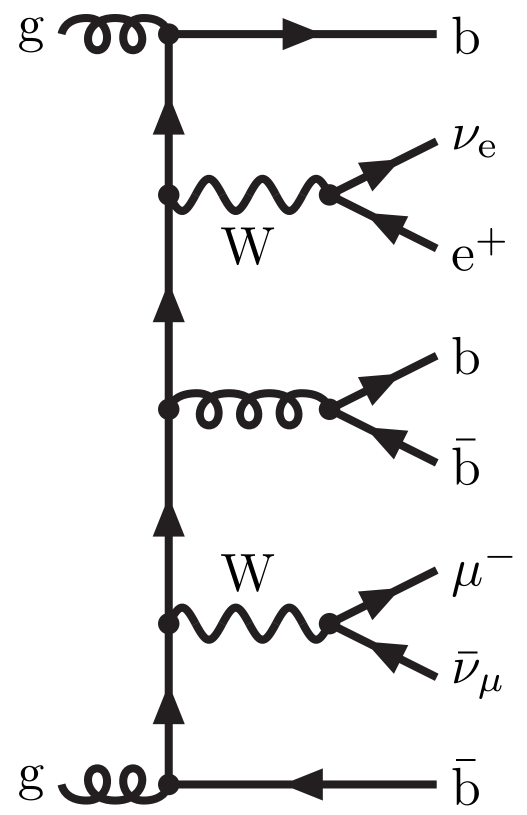
$t\bar{t}b\bar{b}$ x decays @ NLO: precision for the highest multiplicities

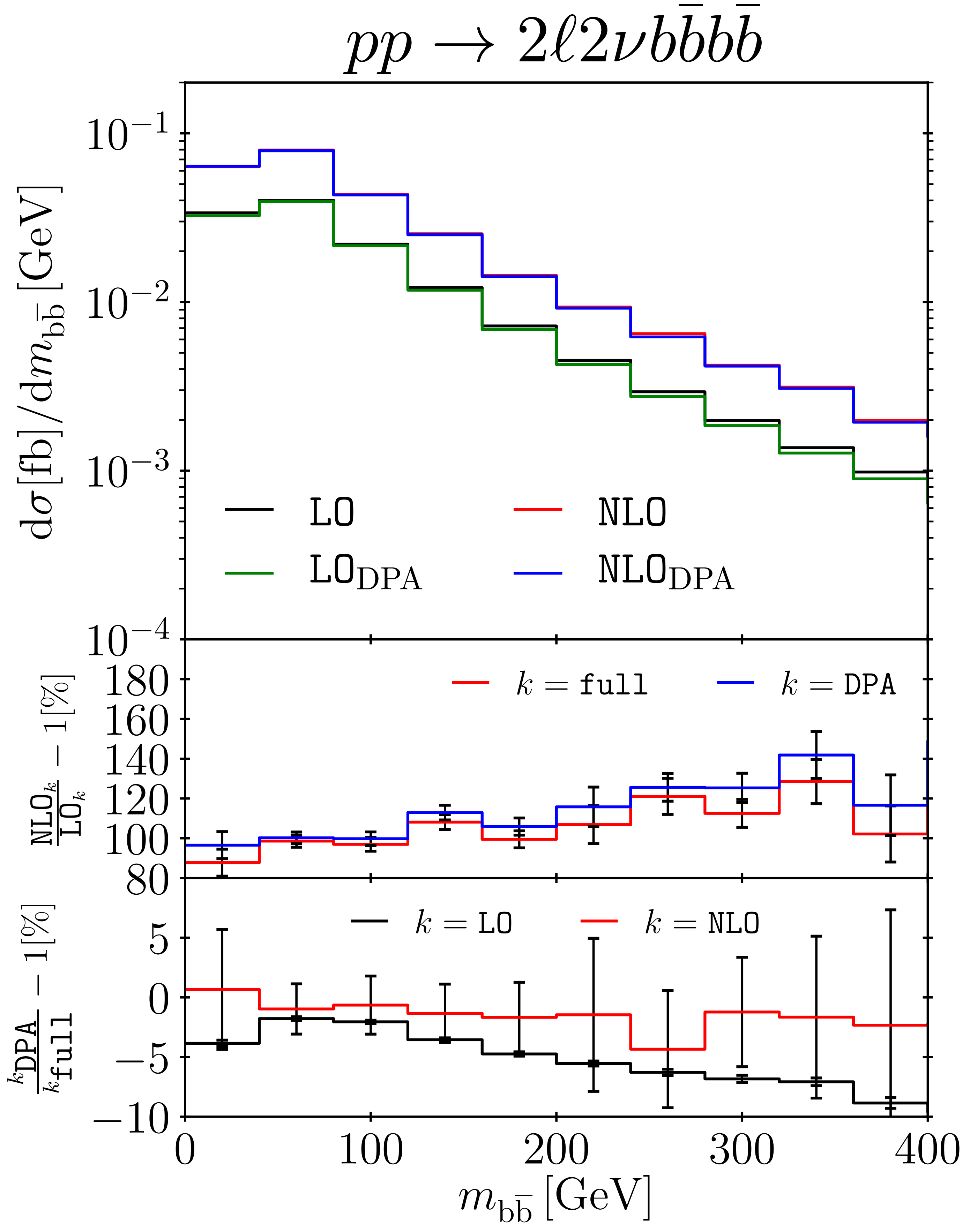
[Denner, Lang, Pellen `20]

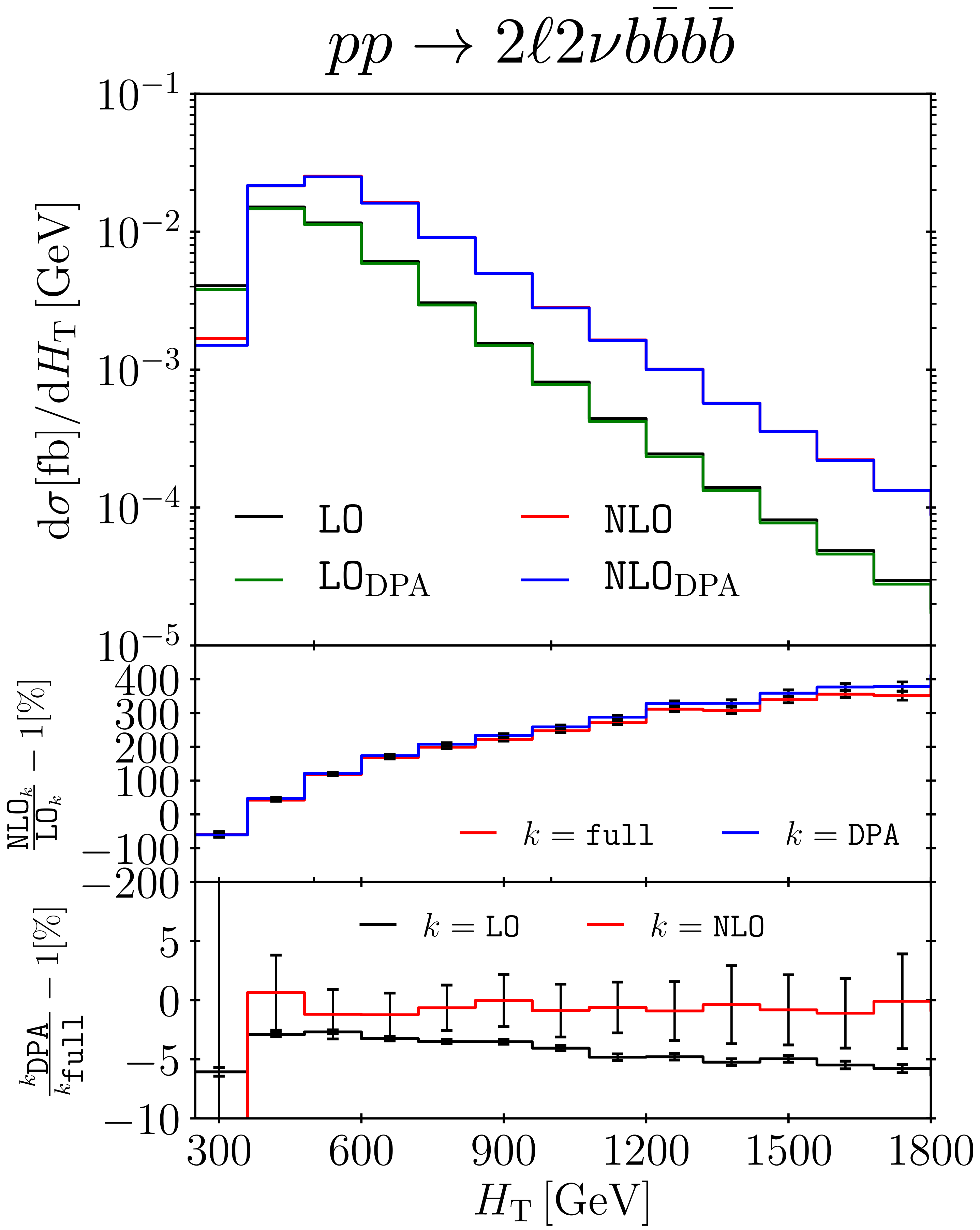
[Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, '21]







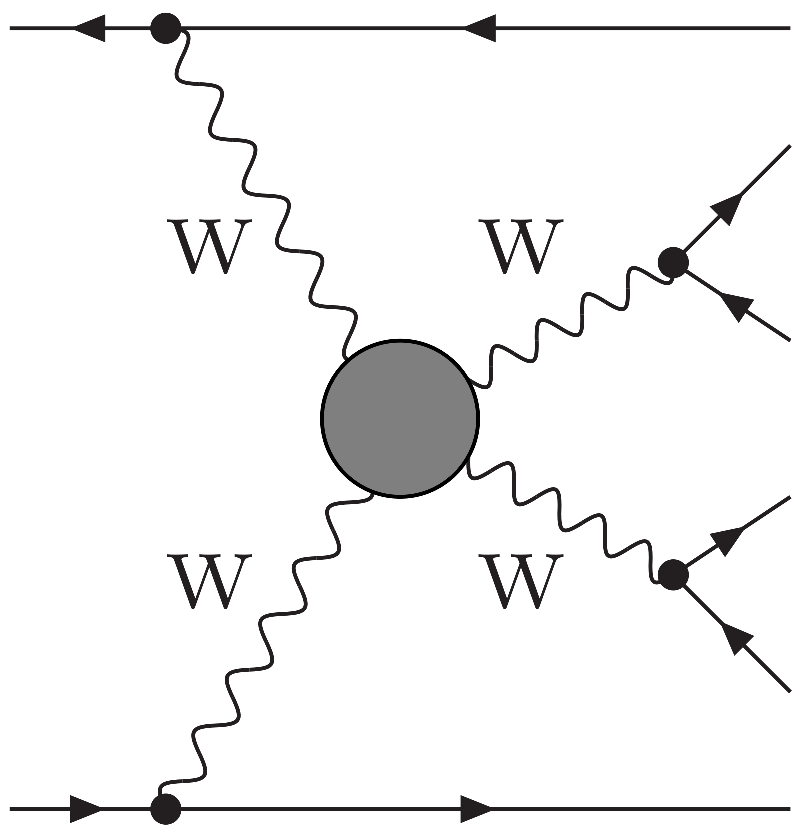


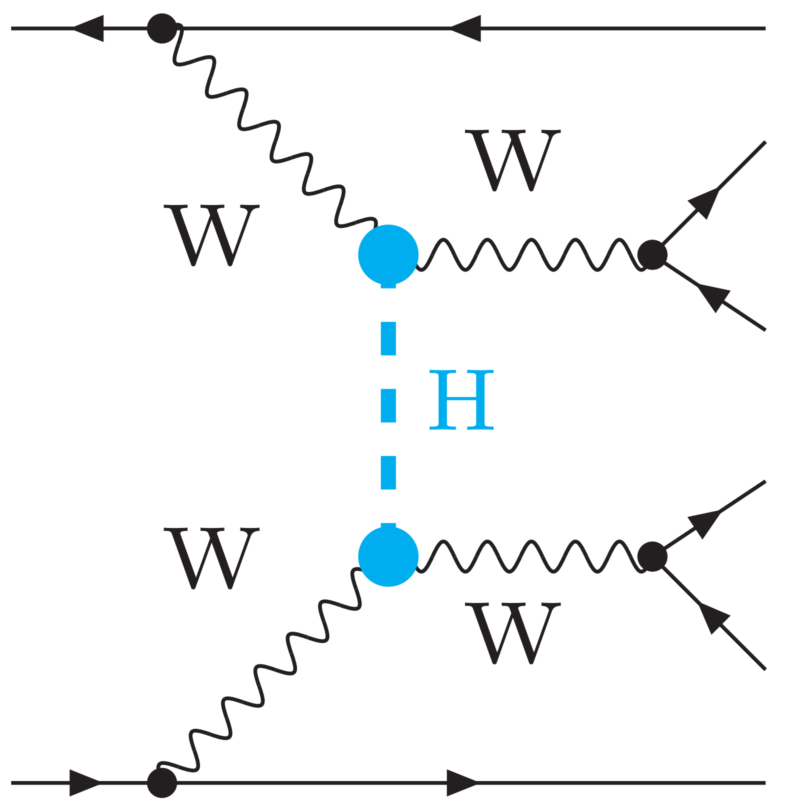


- Thorough understanding of theory systematics in this channel crucial for ttH measurements where H→bb
- $t\bar{t}b\bar{b}$ receives sizeable QCD corrections
- Very important confirmation of (ttbb) double pole approximation

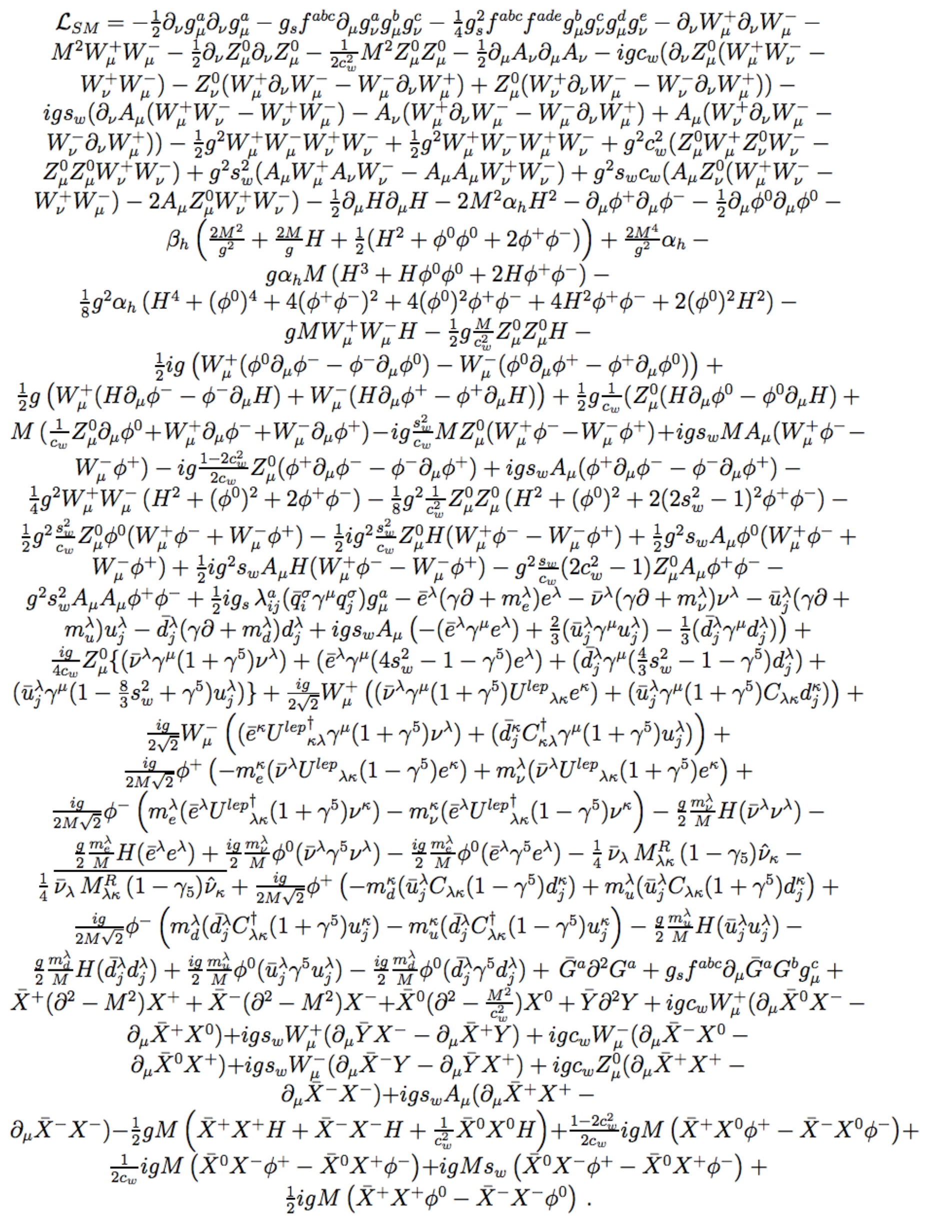
Vector-boson scattering

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

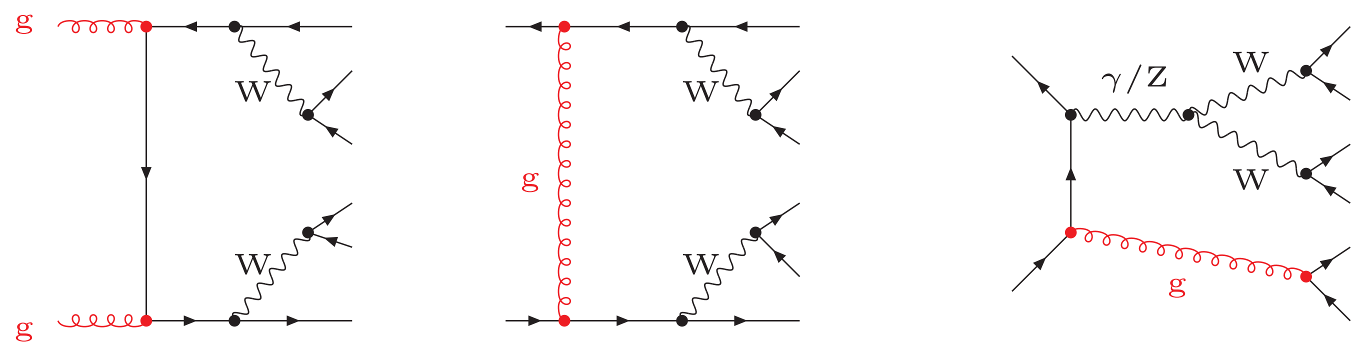




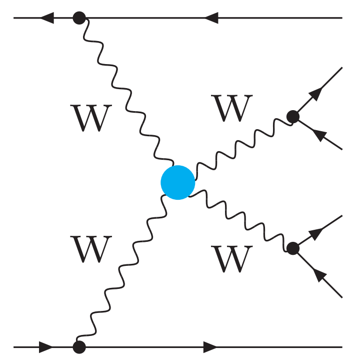
Perturbative expansion revised: VBF-V, VBS-VV



Example: WW+2jets



vs.

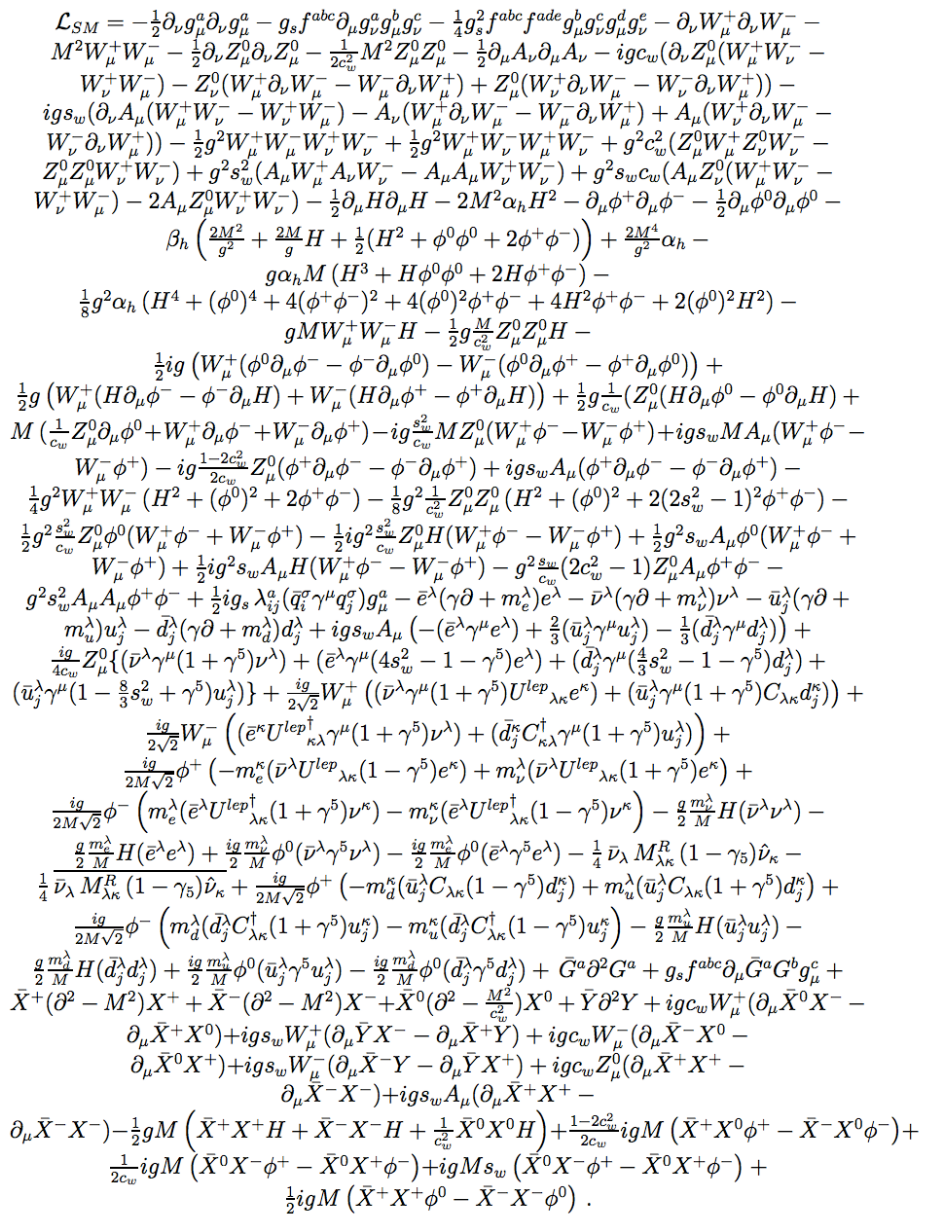


$$d\sigma = d\sigma(\alpha_S^2\alpha^4) + d\sigma(\alpha_S\alpha^5) + d\sigma(\alpha^6) + \ldots$$

QCD-background | interference | VBS-signal

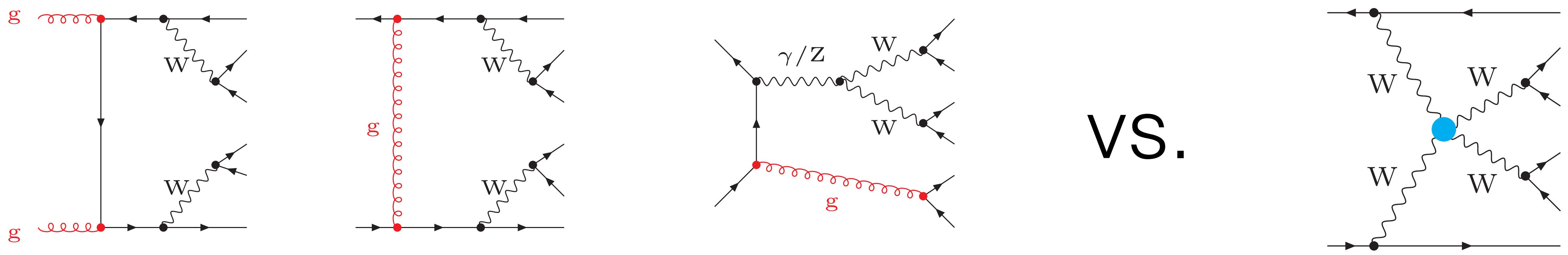
$$\hookrightarrow |\mathcal{M}|^2 \to \sigma$$

Perturbative expansion revised: VBF-V, VBS-VV



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

Example: WW+2jets



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

QCD-background | interference | VBS-signal

$\mathcal{O}(\alpha_s)$ | $\mathcal{O}(\alpha)$

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

"NLO QCD" "NLO EW" "NLO QCD" "NLO EW"

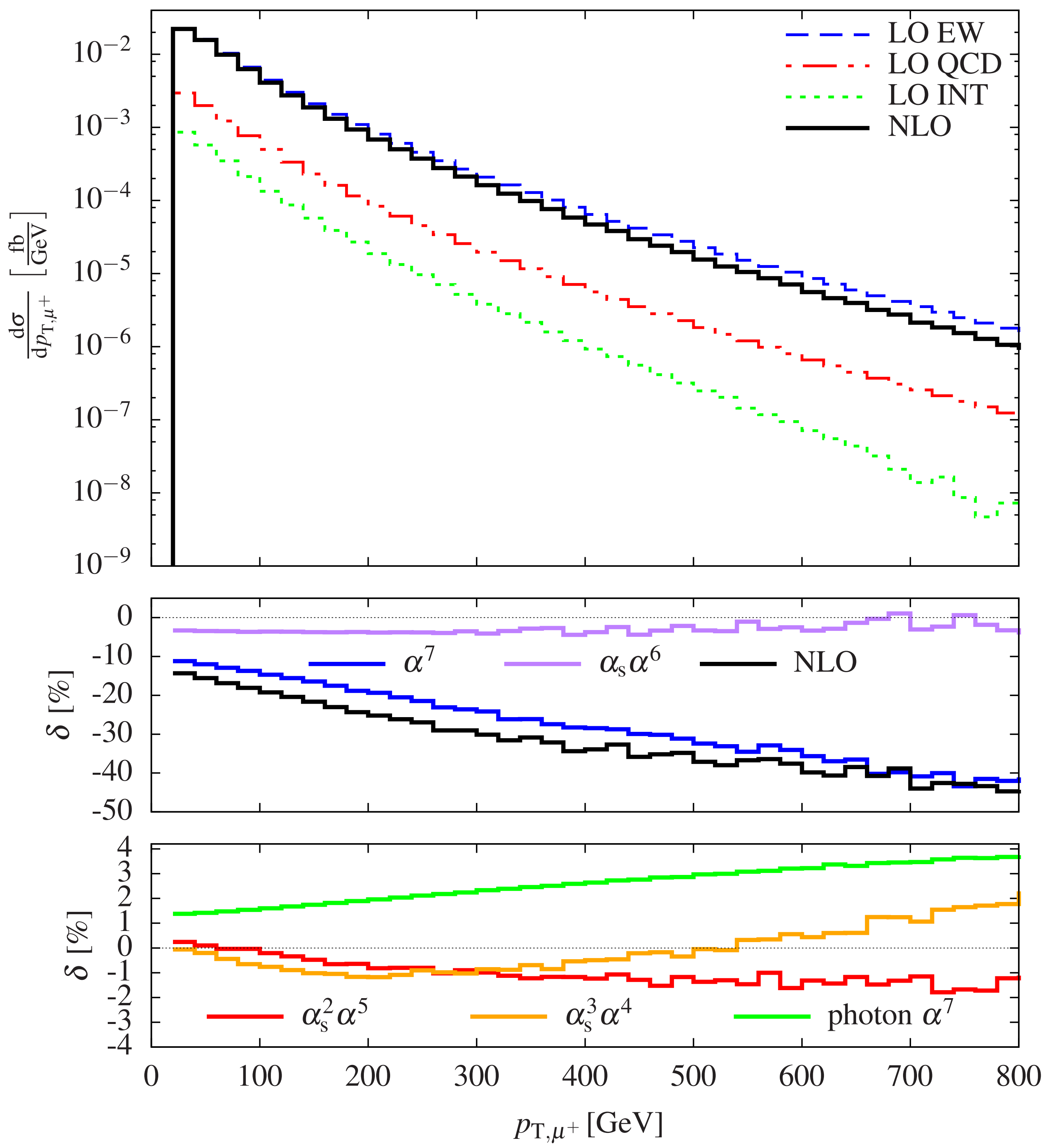
➡ separation formally meaningless at NLO
➡ strictly well defined measurements: fiducial cross sections

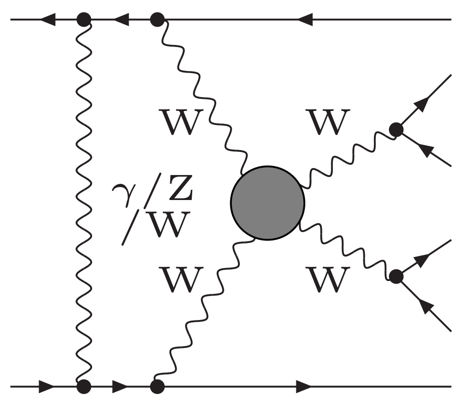
VBS-@ full NLO

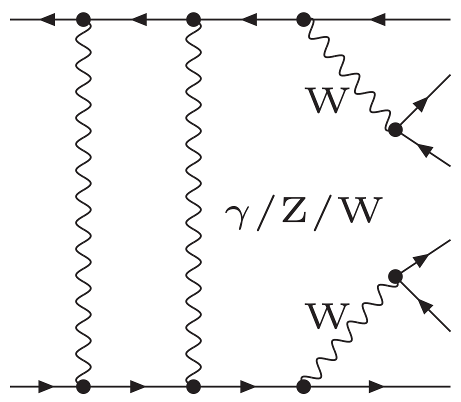
WW full NLO: *[Biedermann, Denner, Pellen '16+'17]*

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 α^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
$\delta\sigma_{NLO}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{NLO}/\sigma_{LO}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

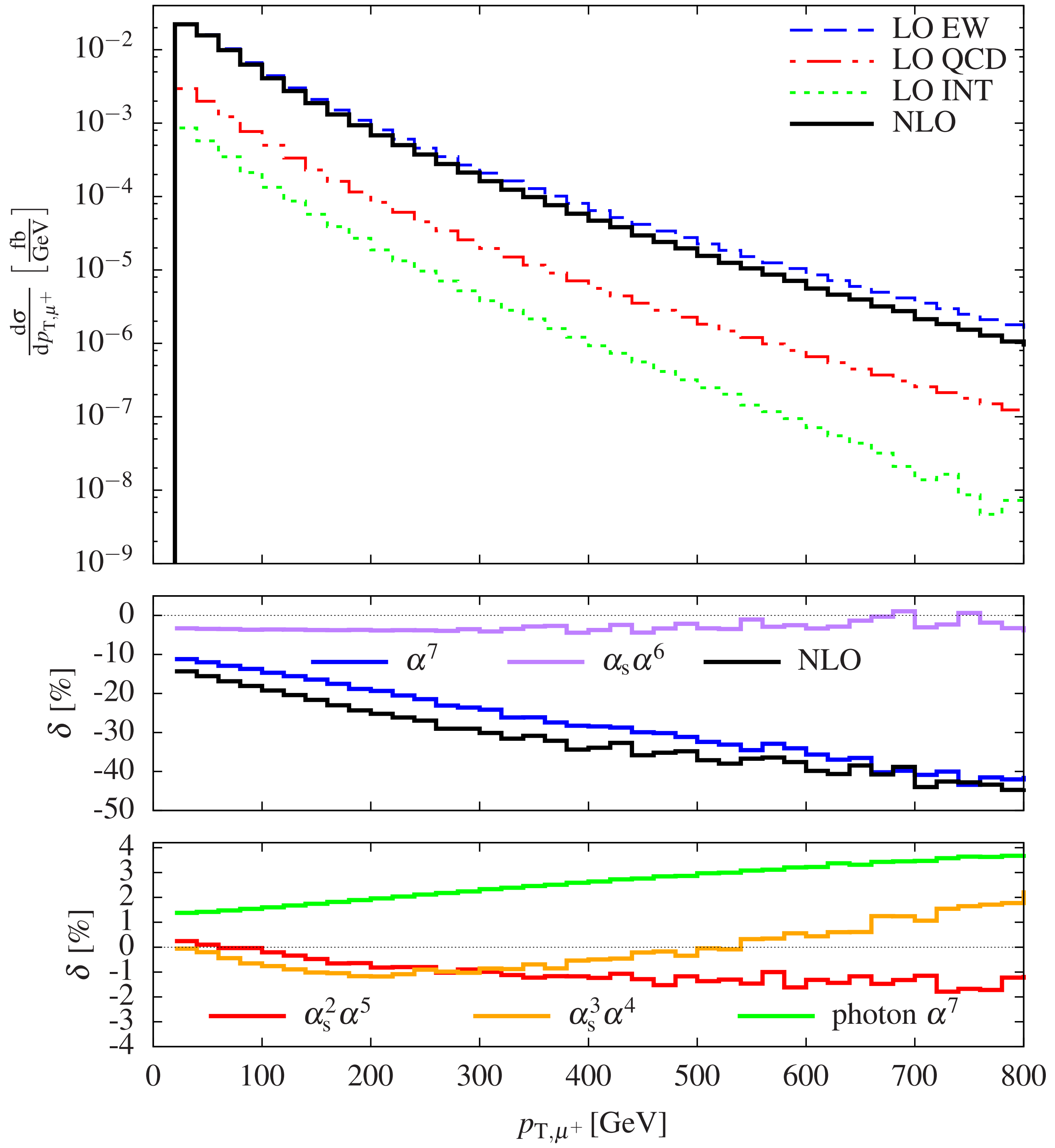
with $M_{jj} > 500\,\text{GeV},\ p_{T,j} > 30\,\text{GeV},\ p_{T,\ell} > 20\,\text{GeV},$

	σ^{LO} [fb]	σ^{NLO}_{EW} [fb]	δ_{EW} [%]
LO: $\mathcal{O}(\alpha^6)$ 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: $\mathcal{O}(\alpha^6)$
NLO: $\mathcal{O}(\alpha^7)$

$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}_{\rm EW}$ [fb]	$\delta_{\rm EW}$ [%]
1.5348(2)	1.2895(6)	−16.0

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

$$\sigma_{\rm LL} = \sigma_{\rm LO}\left[1 - \frac{\alpha}{4\pi}4C_{\rm W}^{\rm ew}\log^2\left(\frac{Q^2}{M_{\rm W}^2}\right) + \frac{\alpha}{4\pi}2b_{\rm W}^{\rm ew}\log\left(\frac{Q^2}{M_{\rm W}^2}\right)\right]$$

$= -16\%$ (!)

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

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

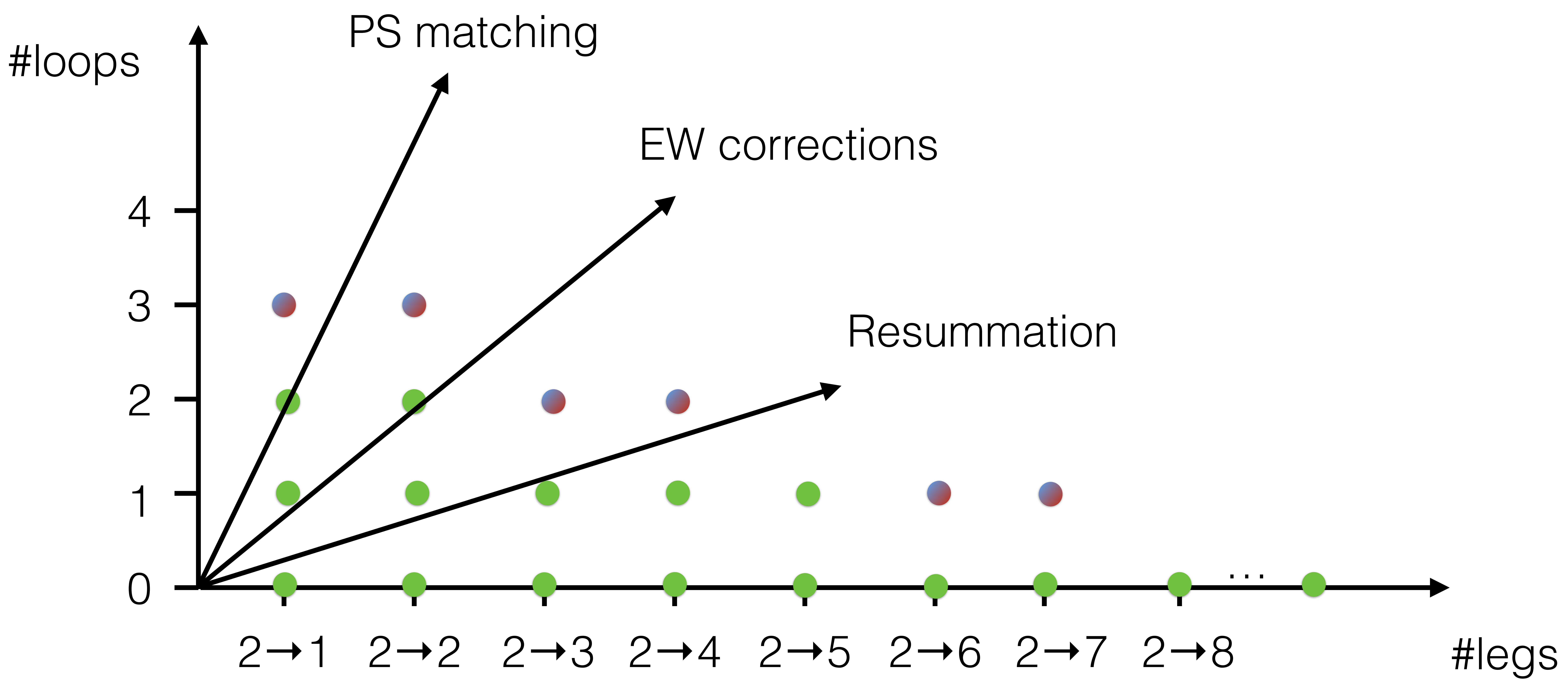
➡Large NLO EW corrections: intrinsic feature of VBS at the LHC

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➞3 NNLO results are becoming available.
- N3LO for some 2➞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!

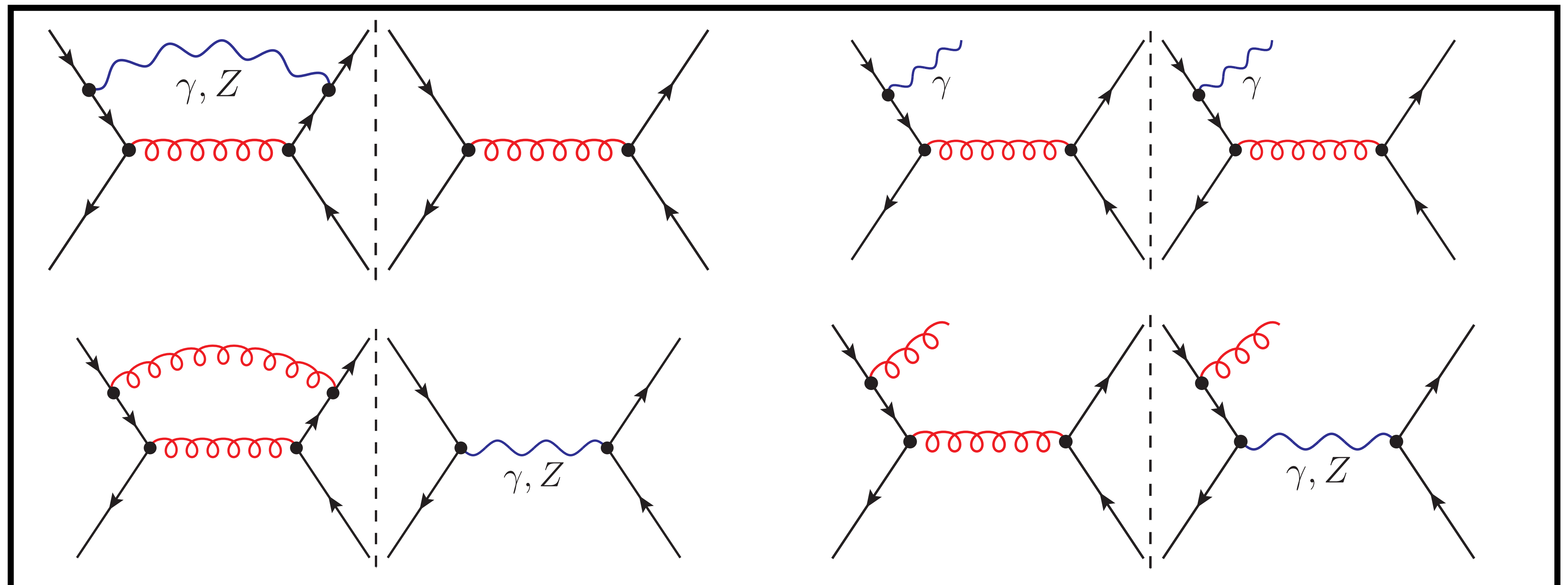
Theory frontier



BACKUP

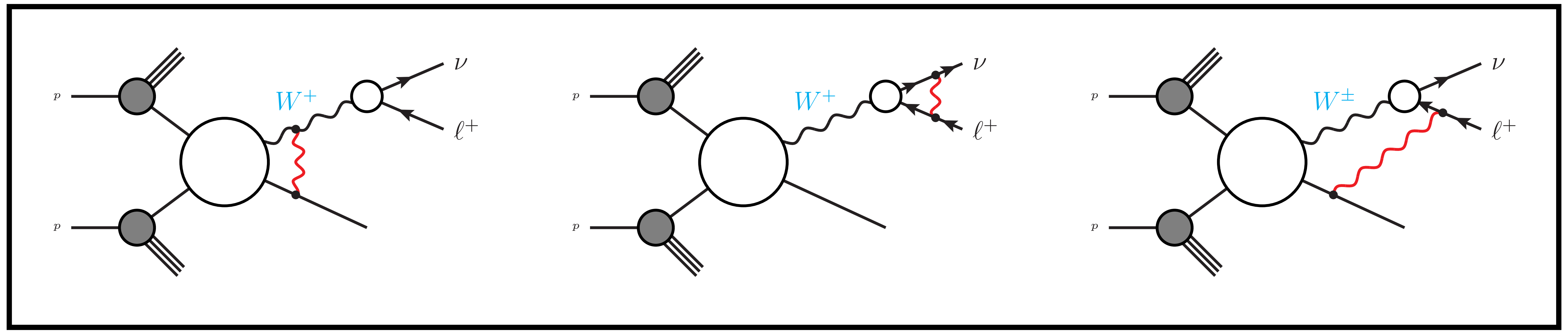
Nontrivial features in NLO QCD → NLO EW

1. **QCD-EW interplay**

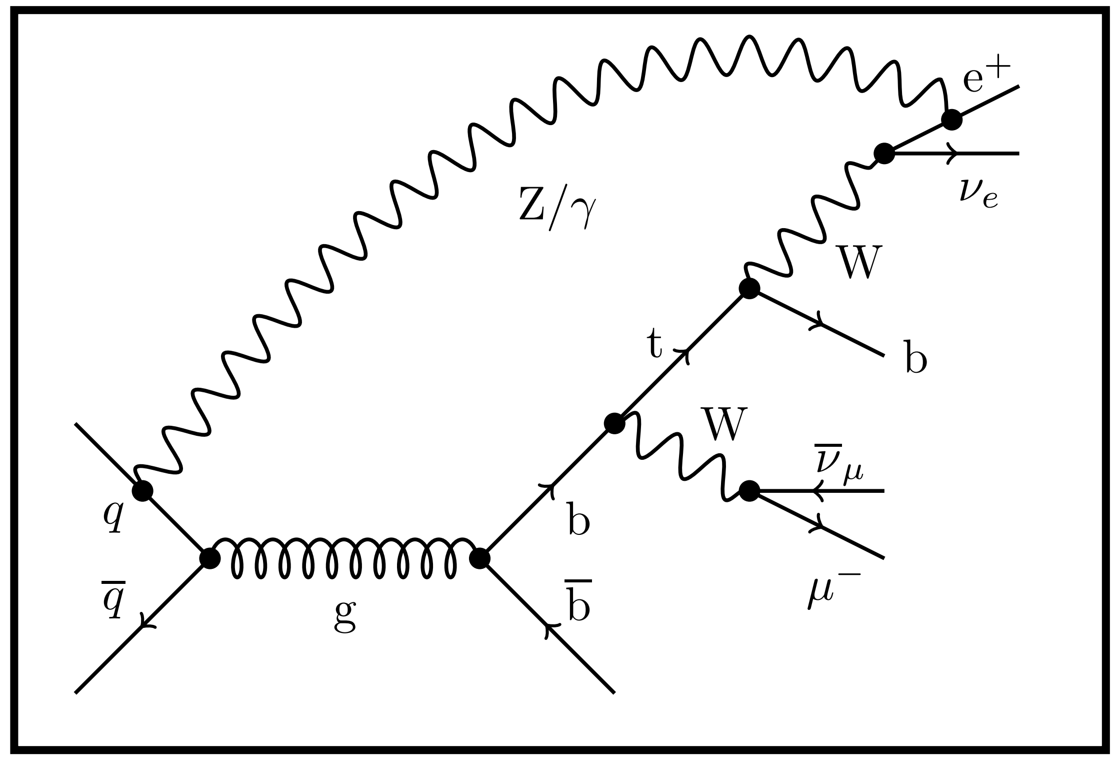


$O(\alpha_S^2\alpha)$

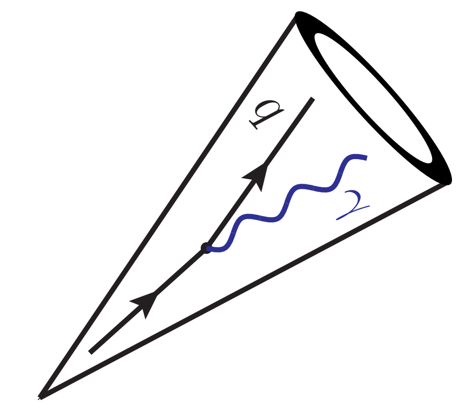
2. At NLO EW corrections in production, decay and non-factorizable contributions for V decays
→ **complex-mass-scheme**



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



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



collinear q → qγ singularities

The motivation for BSM searches are as compelling as ever

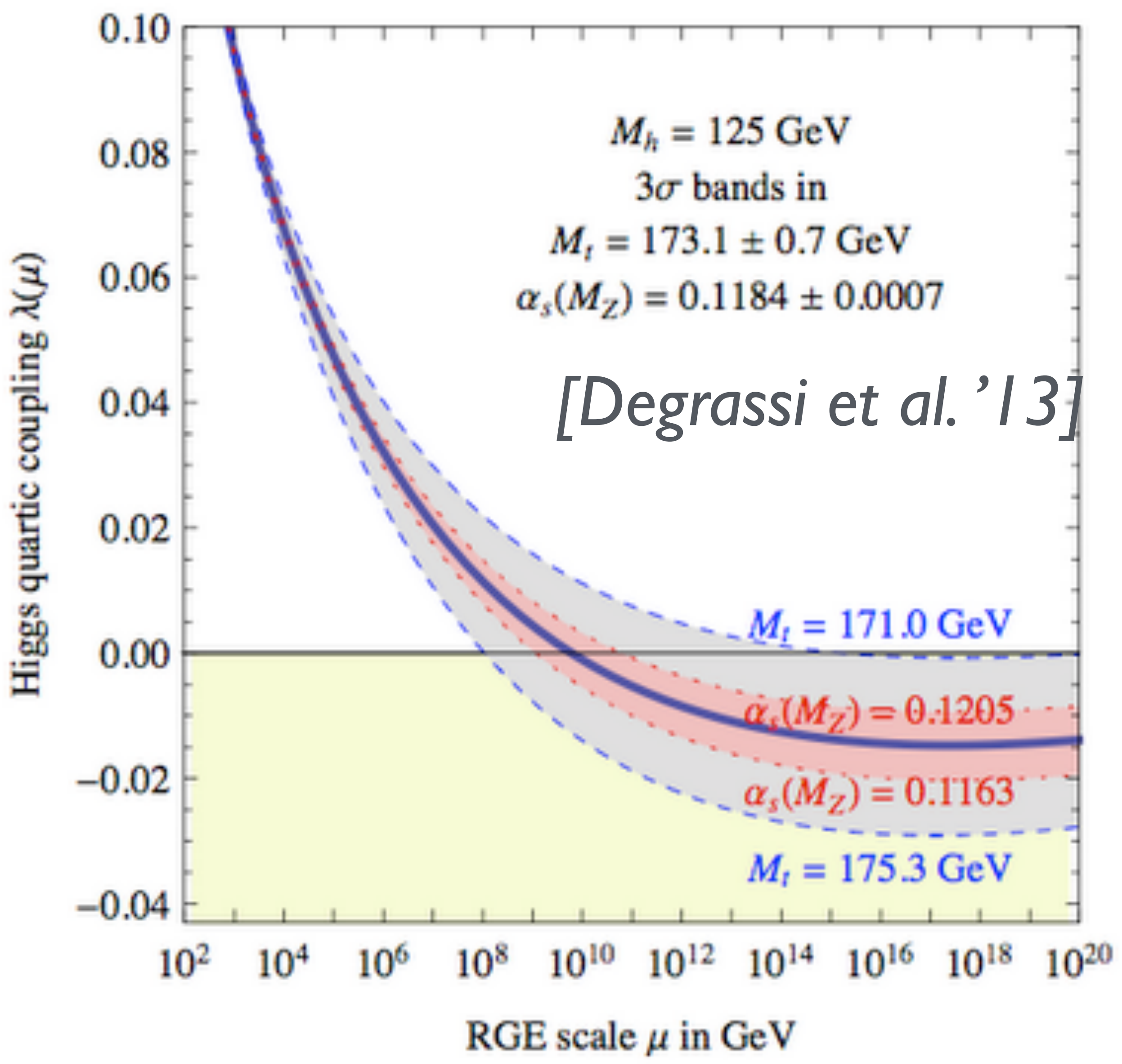
EW vacuum stability

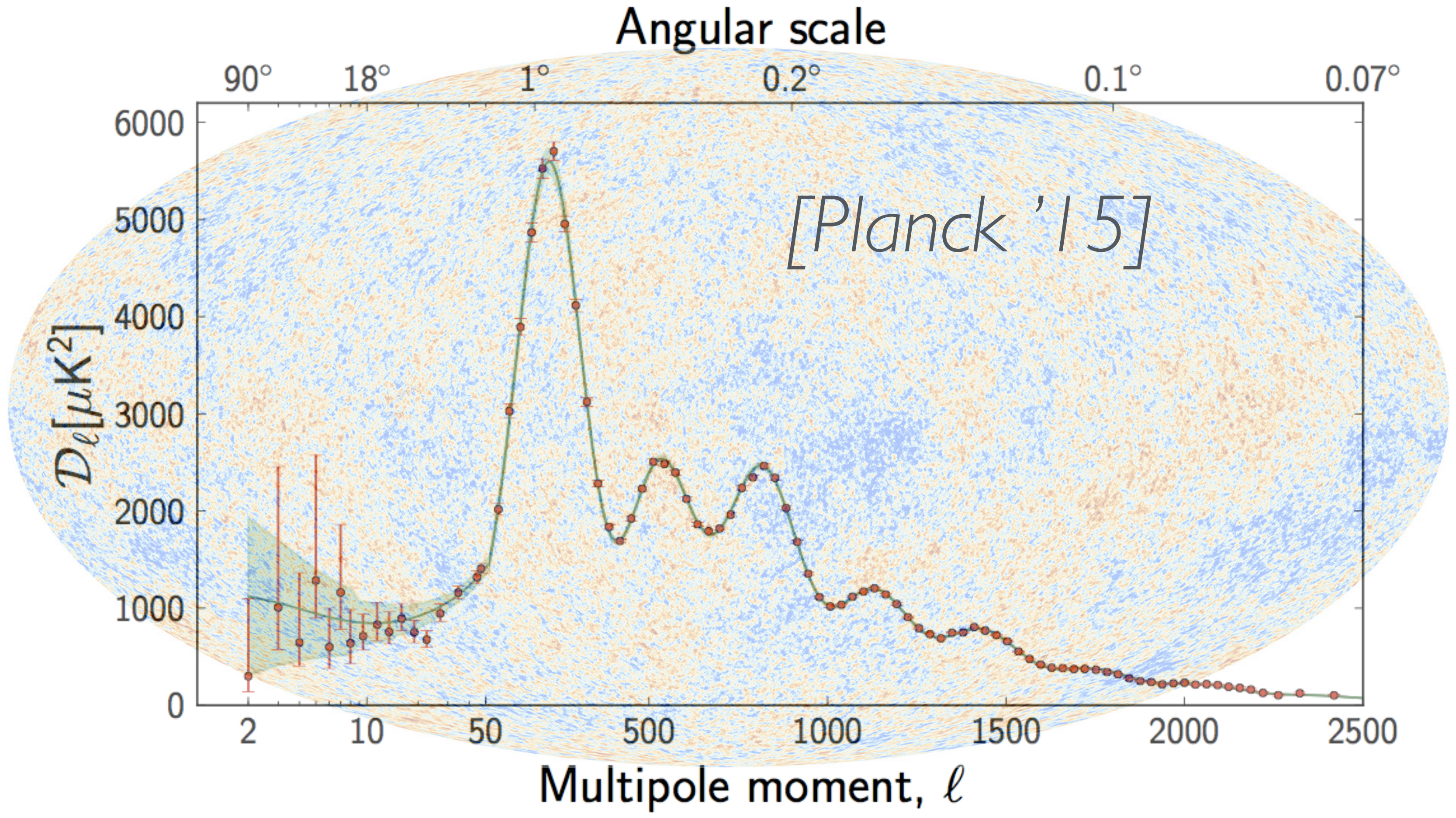
Dark Matter

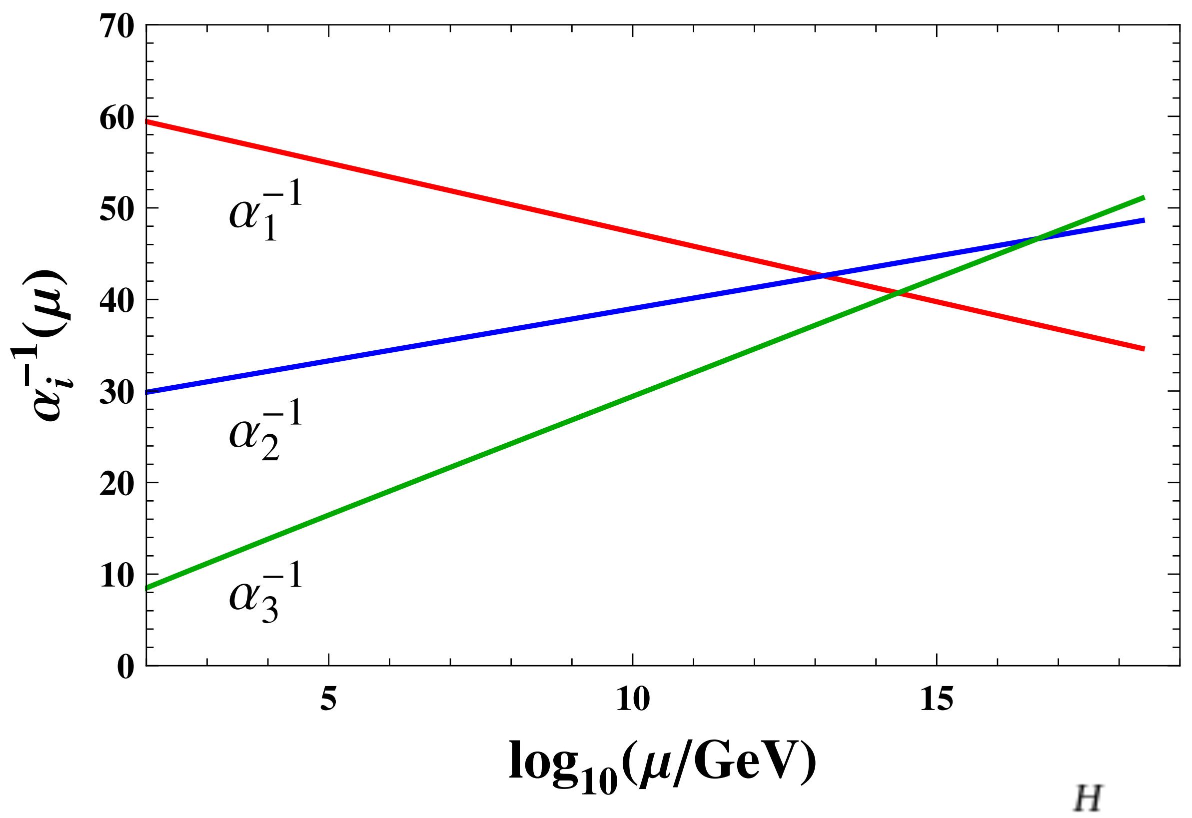
GUT unification

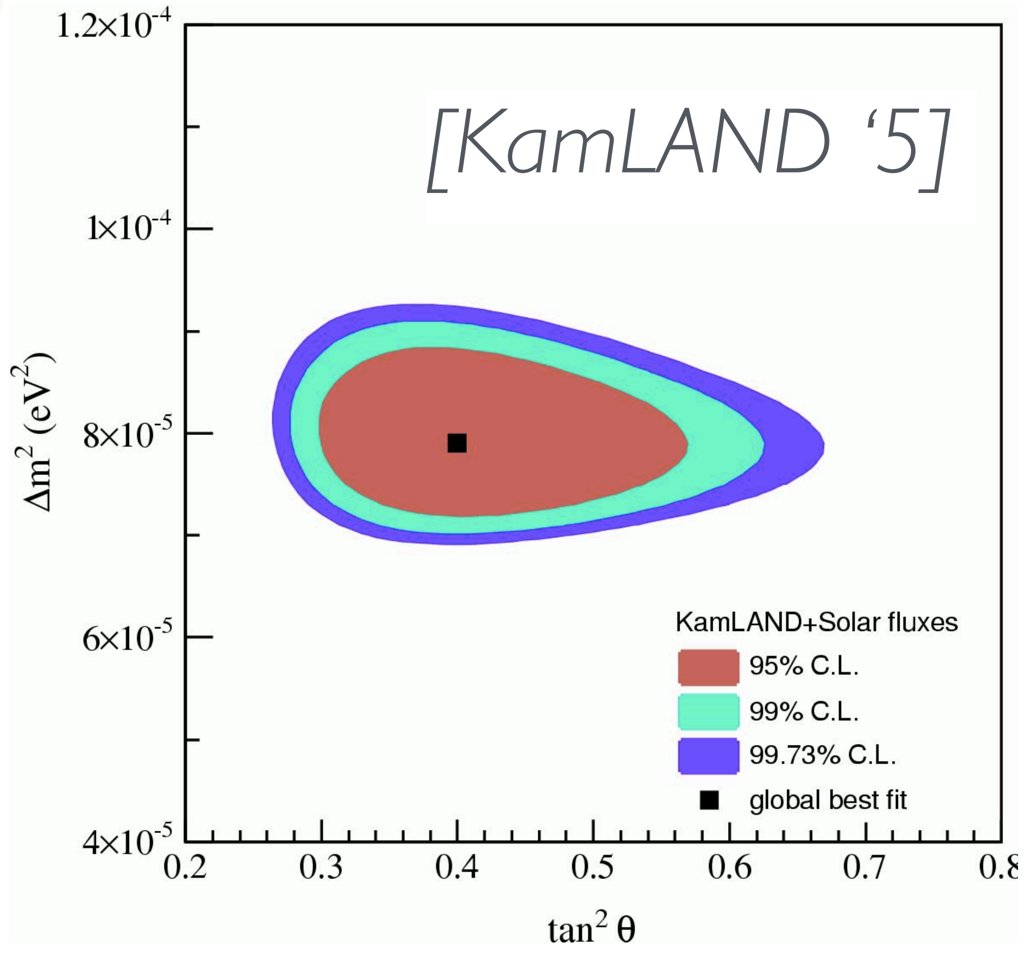
Neutrino masses

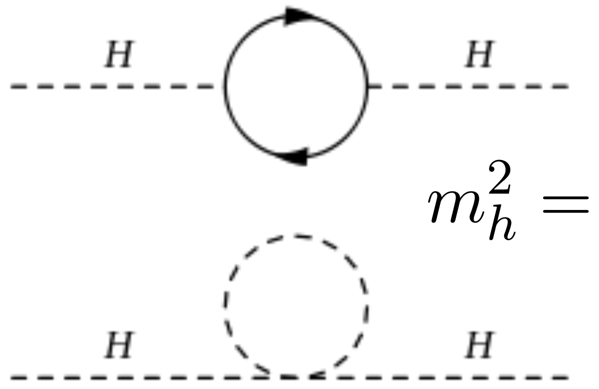
Hierarchy problem





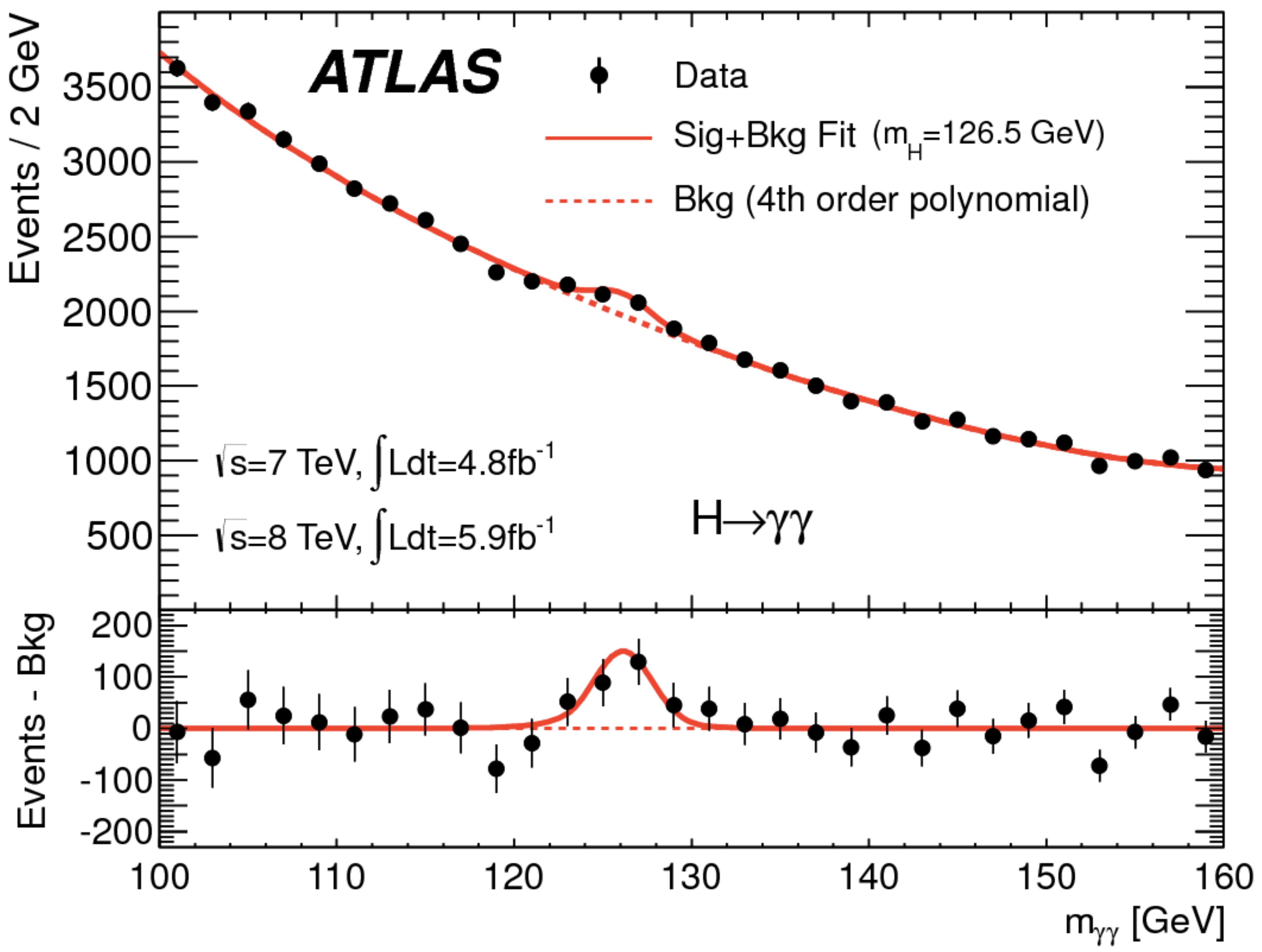


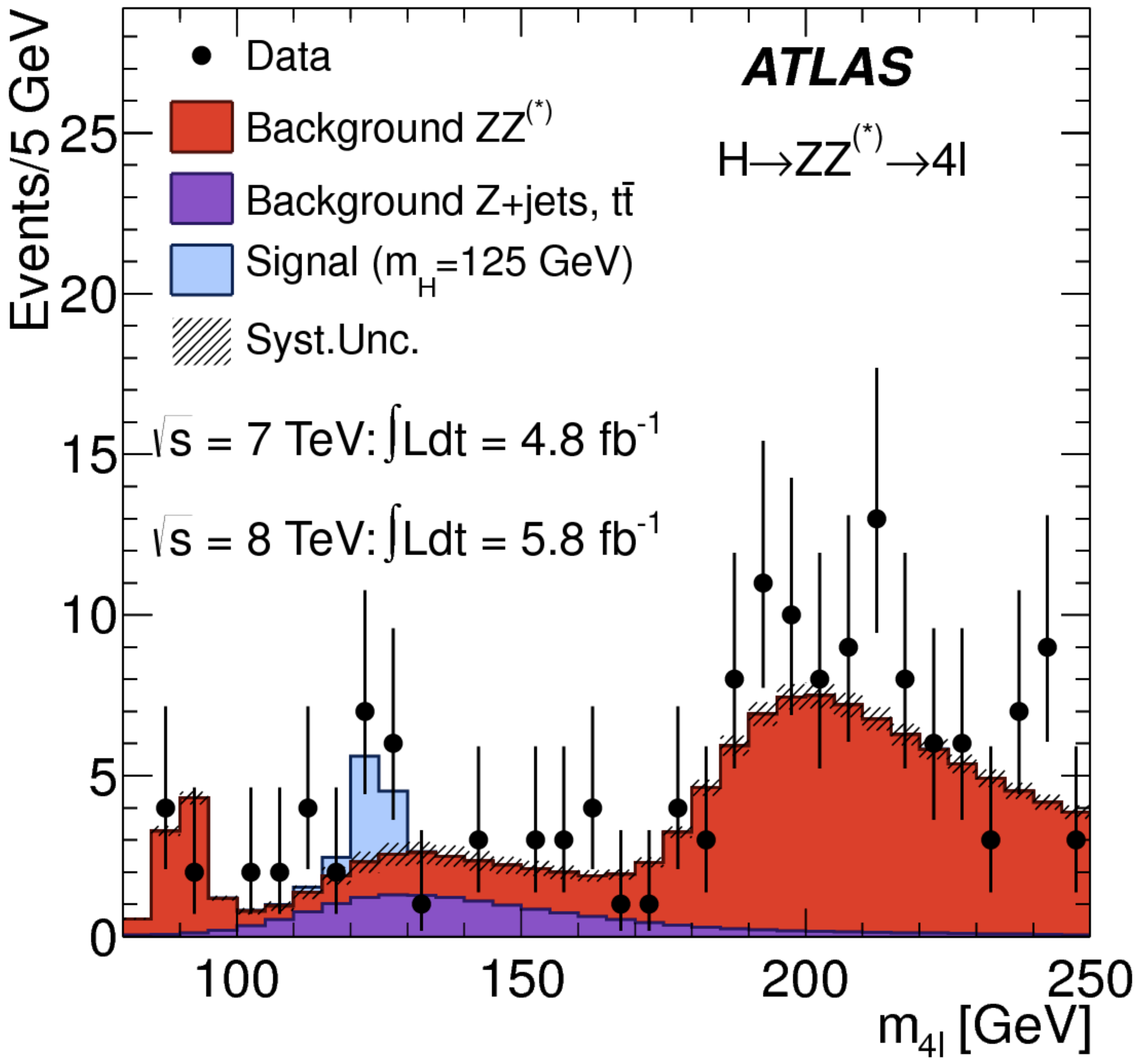




$$m_h^2 = (m_h^0)^2 + \frac{3\Lambda_{\rm UV}^2}{8\pi v^2}(m_h^2 + 2m_W^2 + m_Z^2 - 4m_t^2)$$

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.

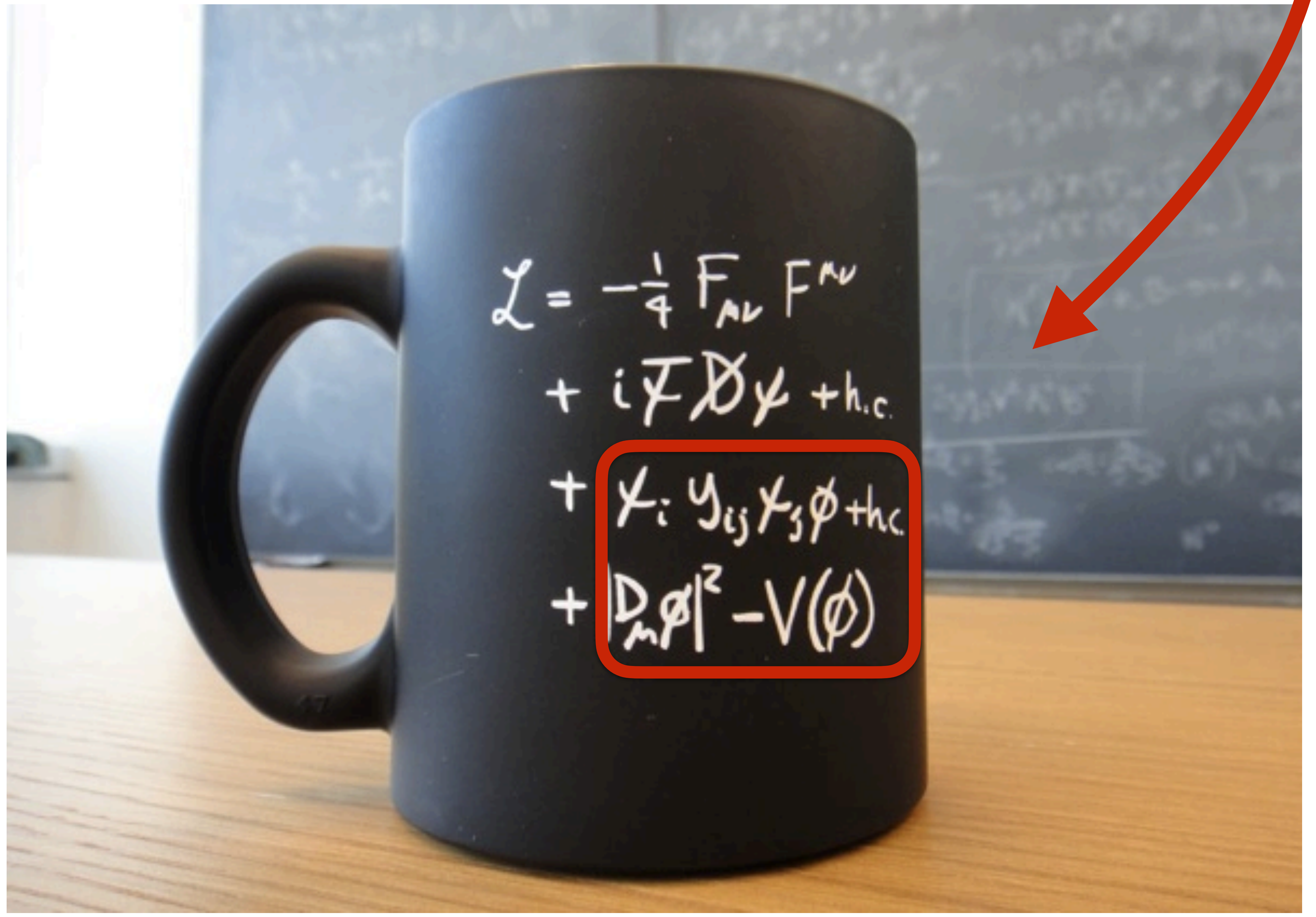
…understanding the Higgs and its properties is tough!

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

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

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 → 4,5,6)

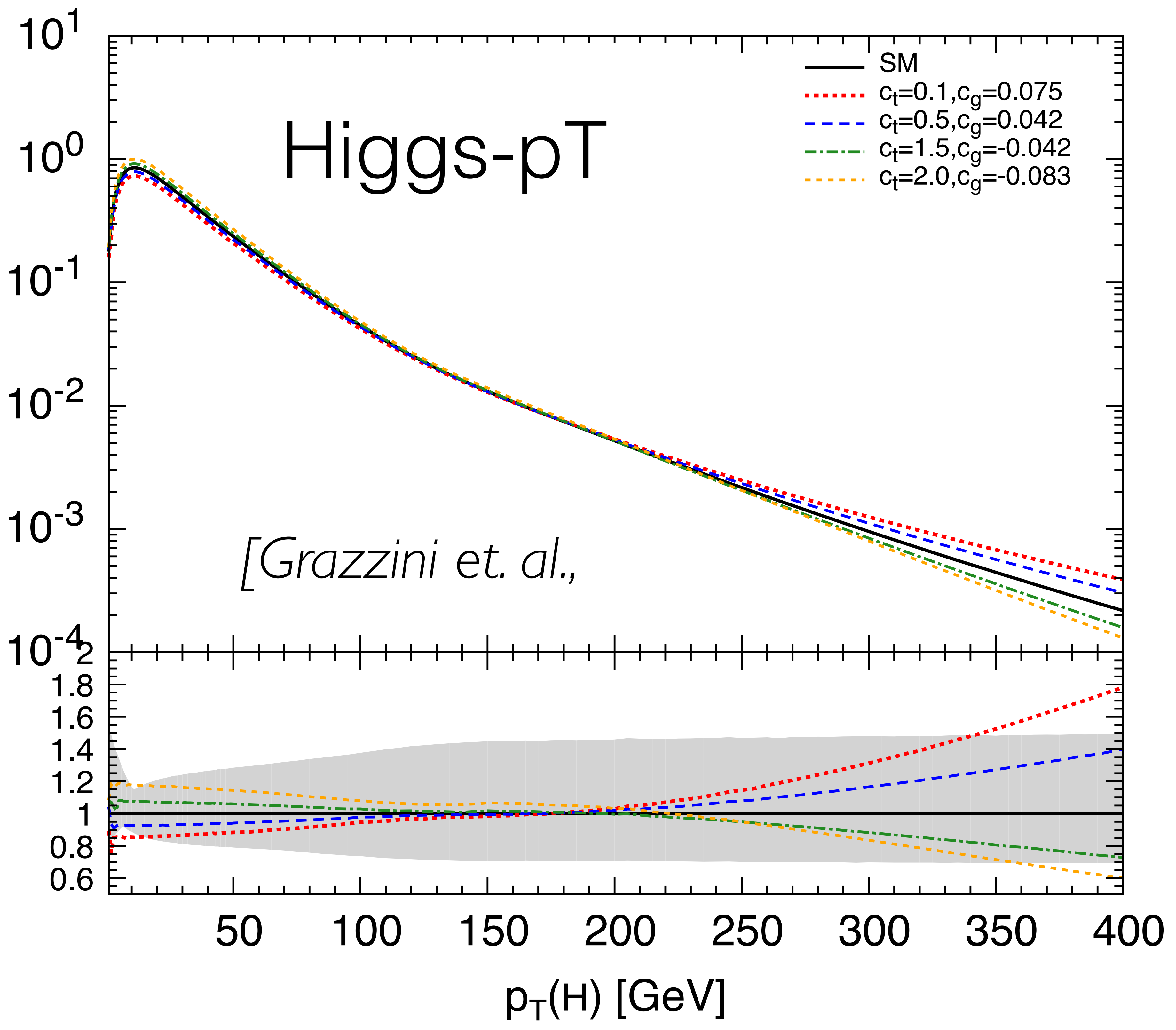
NLO Revolution (last ~20years):

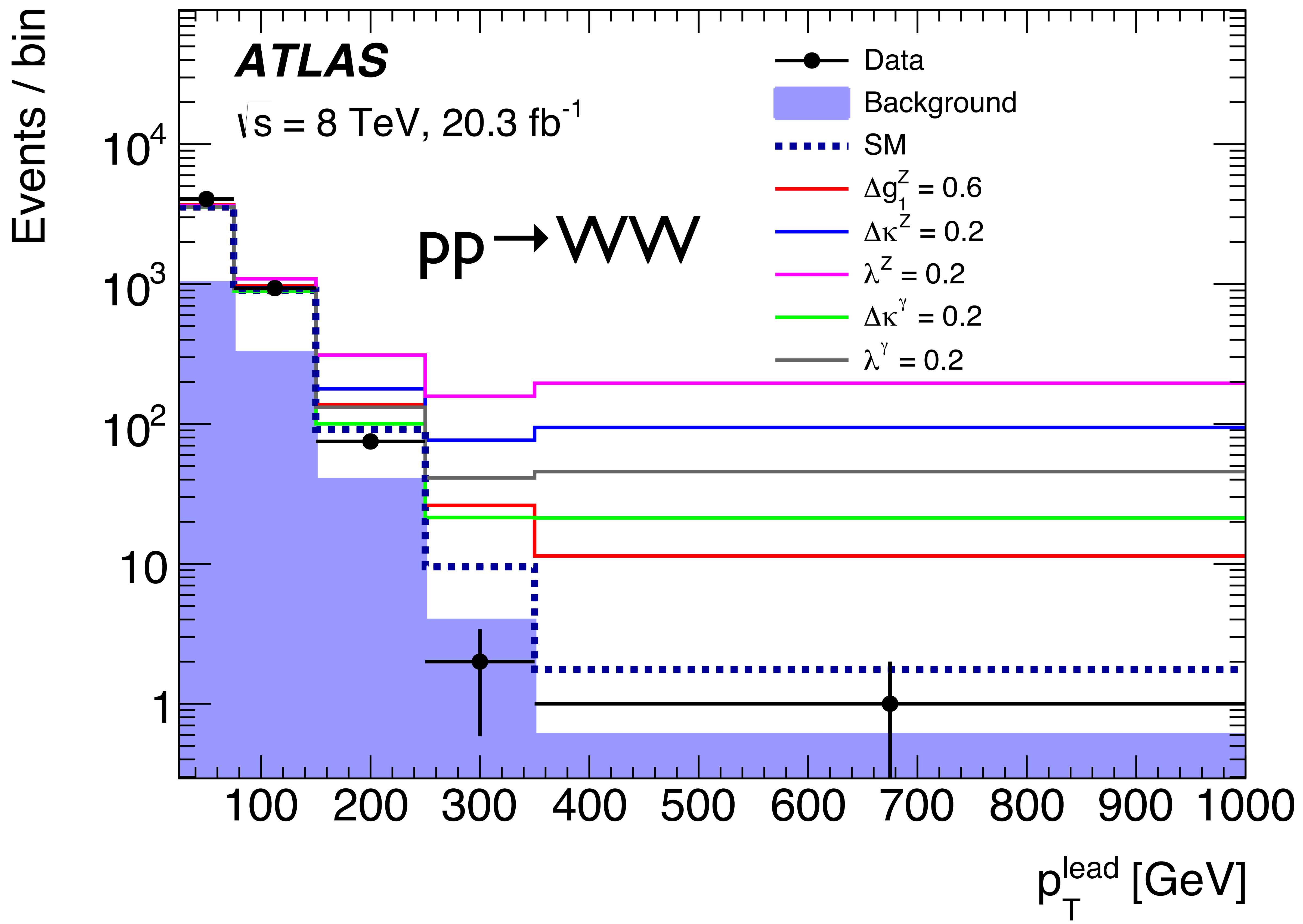
- radically new approaches: on-shell methods, OPP reduction, recursion-relations at NLO. . .
- automation of one-loop algorithms (BlackHat, CutTools, Collier, GoSam, HELAC 1-loop, MadLoop, NGluon, **OpenLoops**, Recola, Samurai, Ninja,. . .) and NLO MCs (MadGraph_aMC@NLO, Sherpa, POWHEG,. . .)
- vast range of multi-particle NLO predictions at LHC (pp → 5j, W + 5j, H + 3j, WWjj, WZjj, **γγ** + 3j, W**γγ**j, WWbb(+jet), bbbb, ttbb, ttjjj, tttt, ...)
- 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



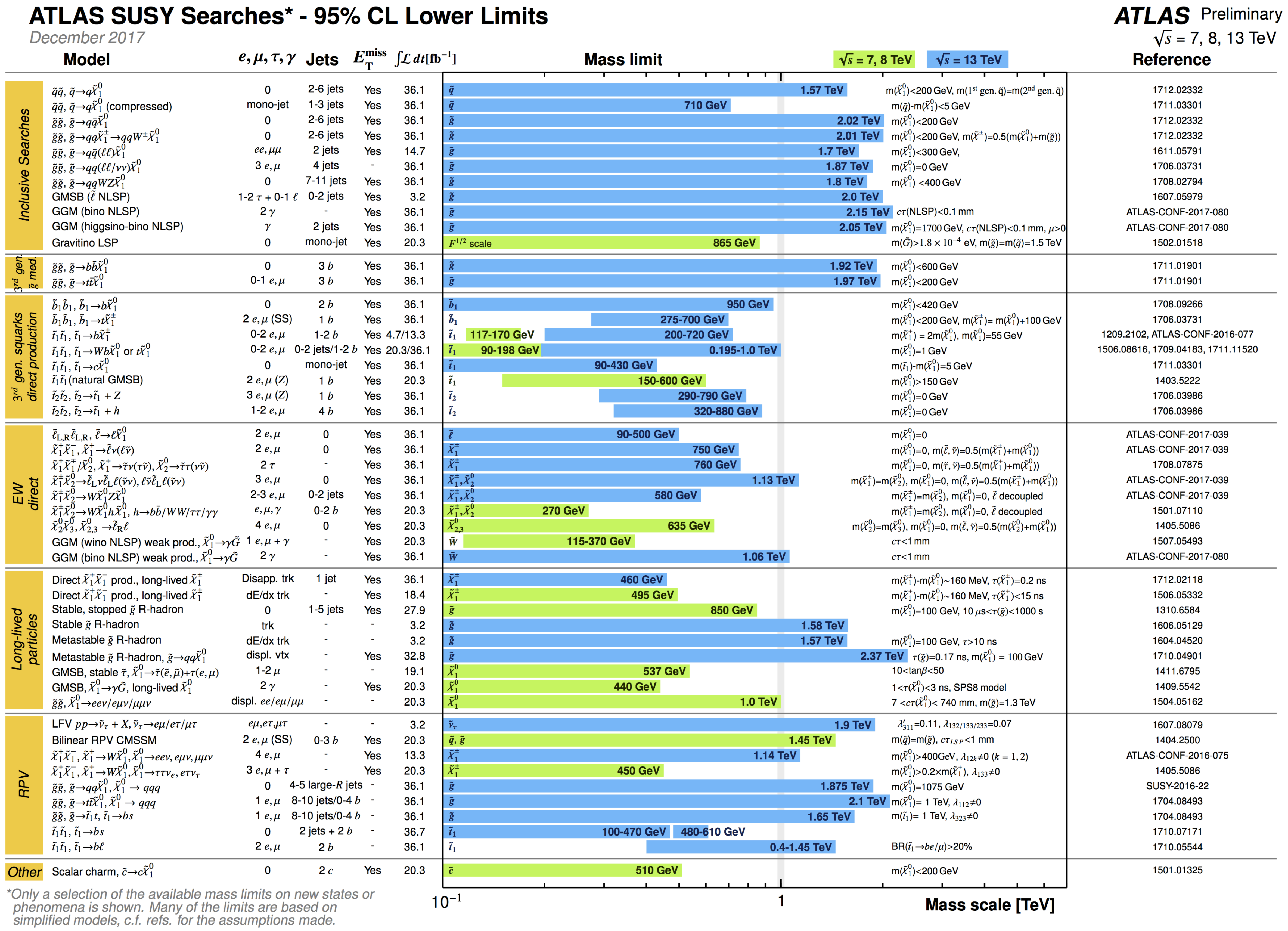


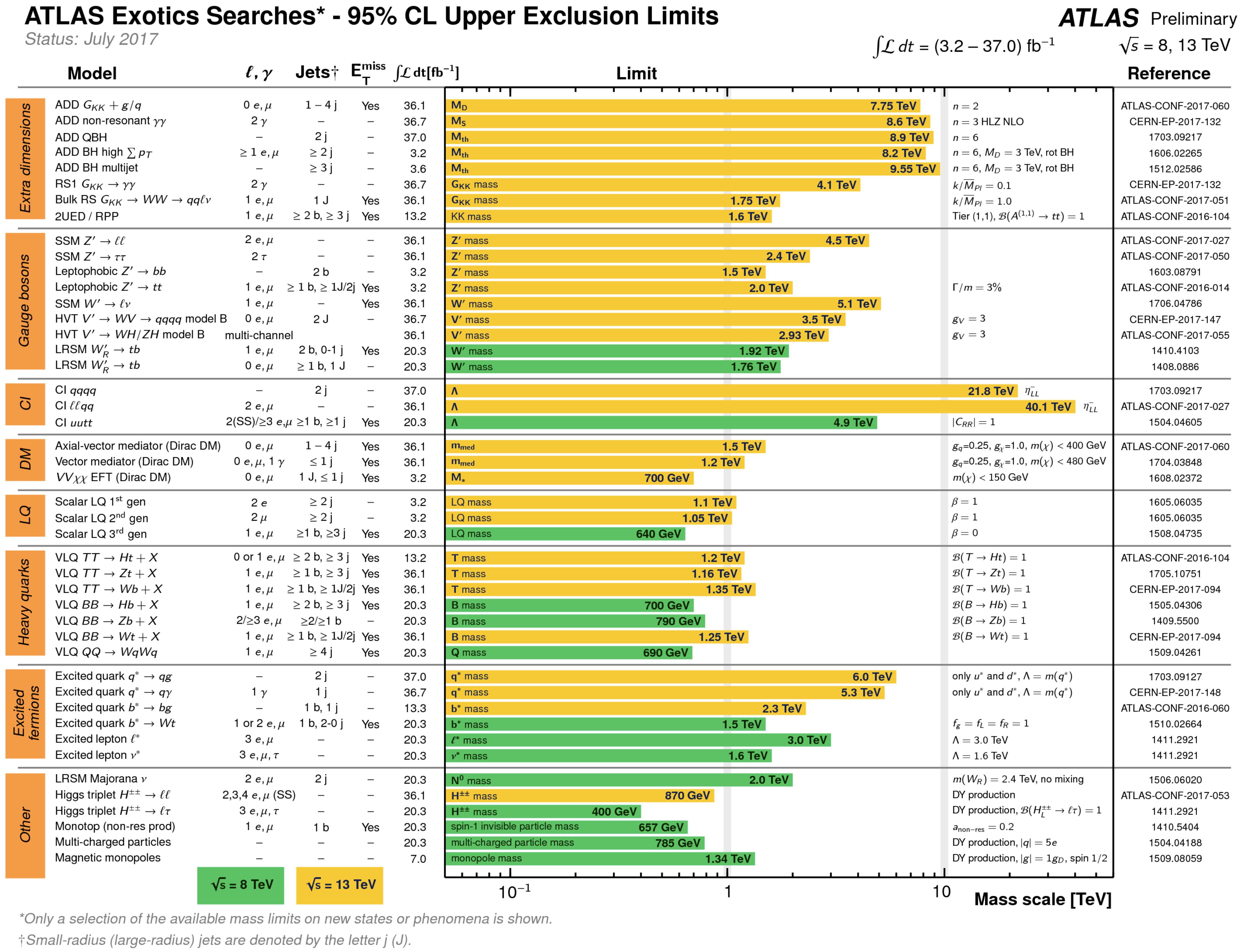
- many effective BSM operators yield growth with energy

  → expect small deviations in high energy shapes of distributions

  → **very good control on SM predictions necessary!**

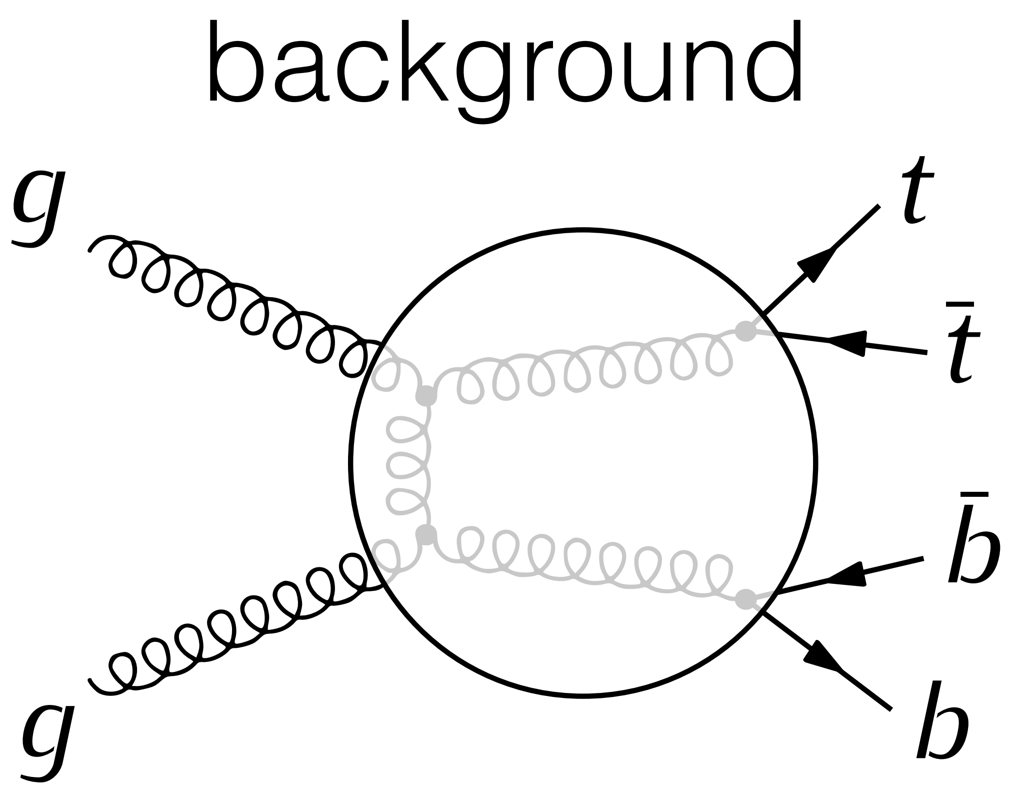
Search limits





- ➡ BSM certainly not 'around the corner'
- ➡ Leave no stone unturned
- ➡ Push towards smaller couplings / exotic signatures

Taming tt̄H backgrounds



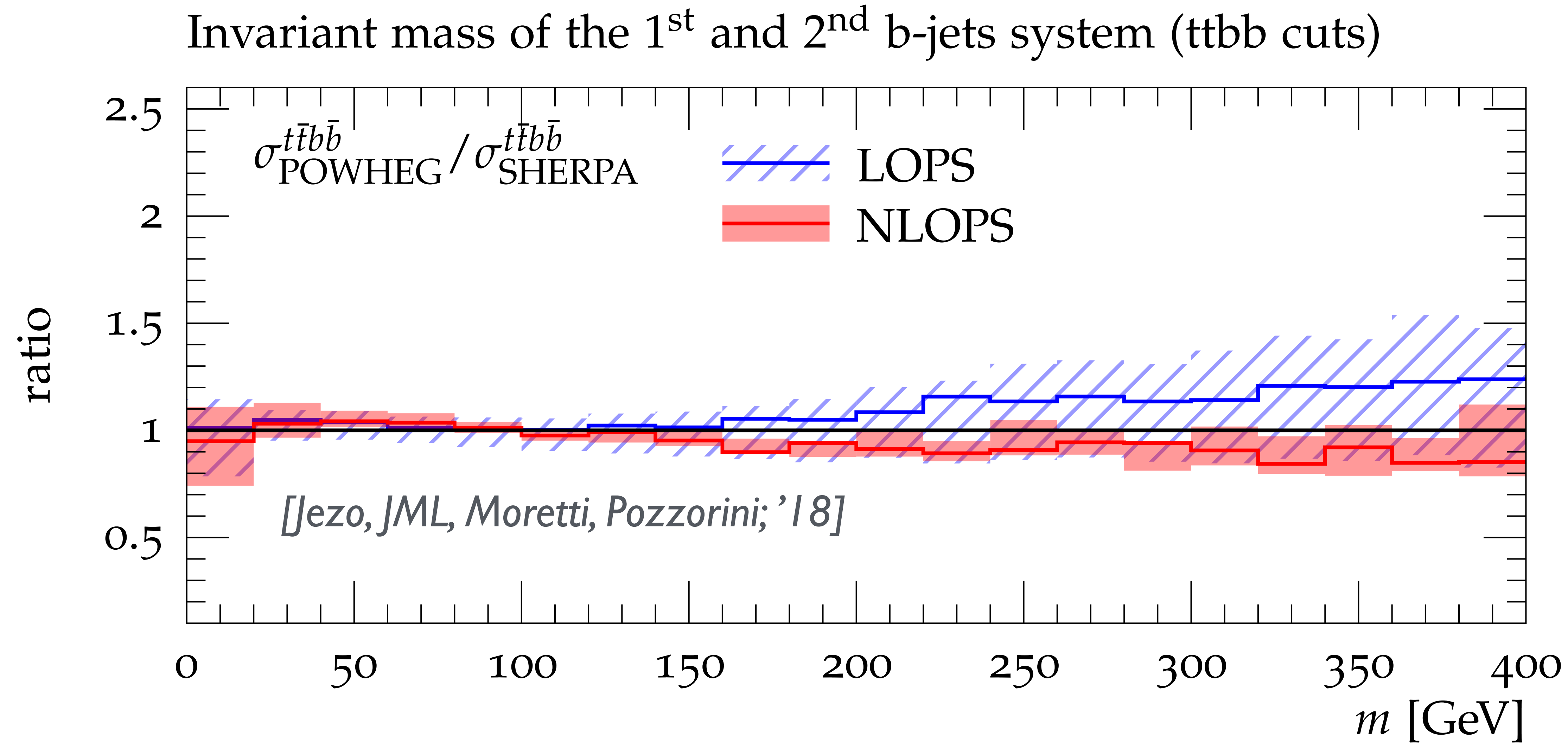
➡ in principle this process can be calculated out of the box at NLO+PS: NLO reduces scale uncertainties from 80% to 20-30%

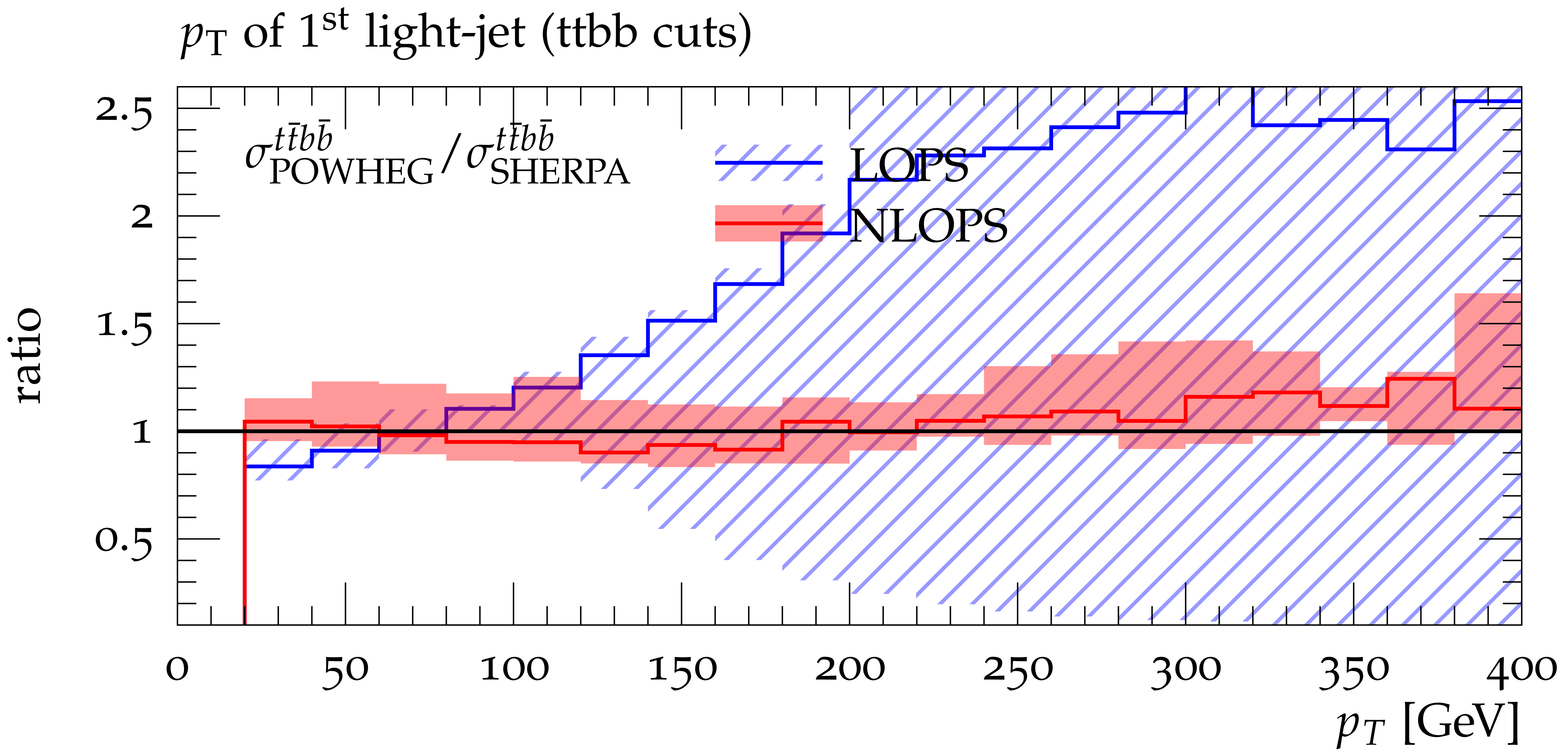
➡ However: notoriously difficult multi-scale problem: ET_t, $ET_{\bar{t}}$, ET_b, $ET_{\bar{b}}$

➡ Large shower effects, in particular from double $g \to b\bar{b}$ splittings

➡ Large systematic uncertainties from parton shower matching

➡ Careful study required to understand these systematics

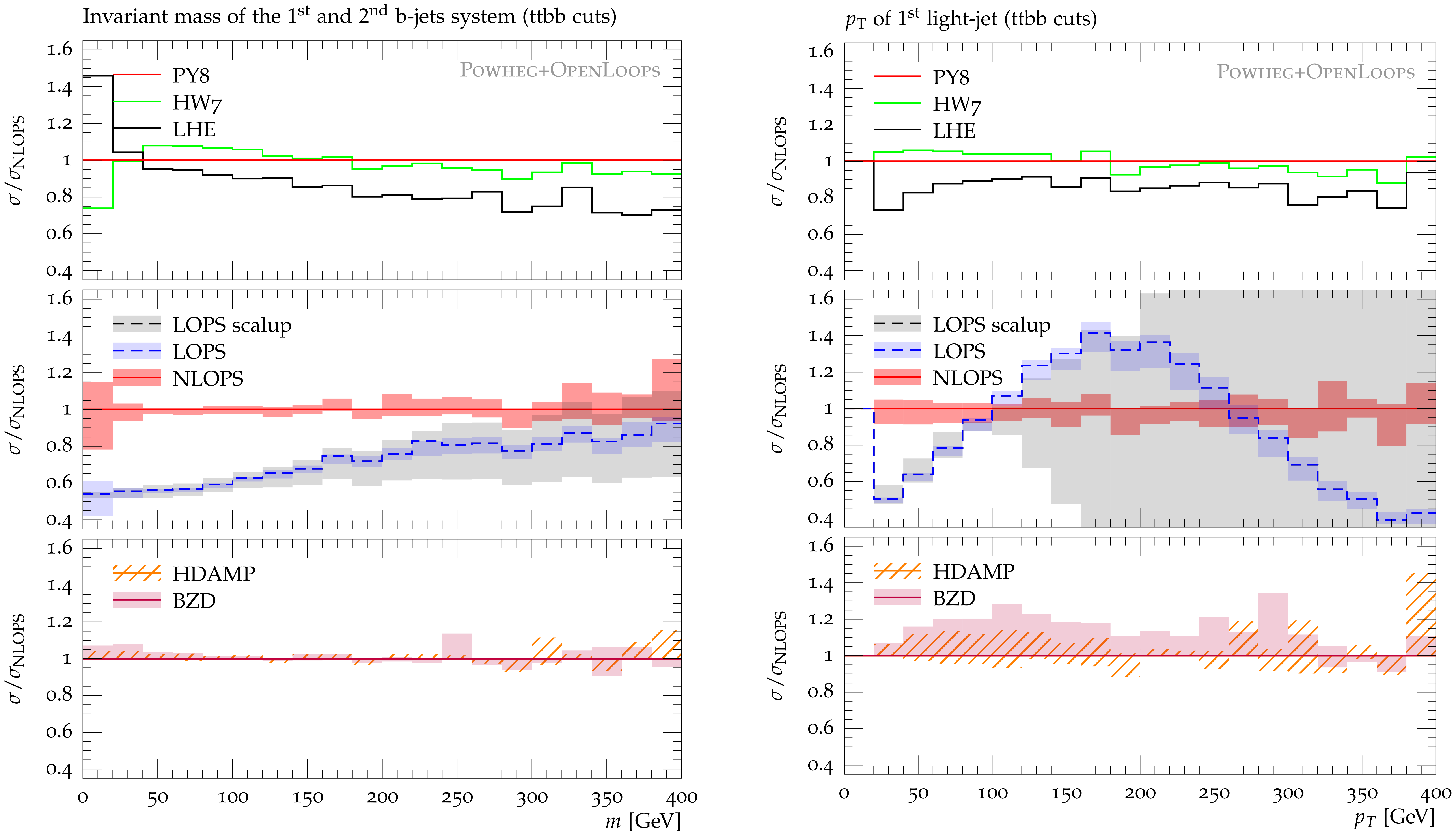




➡Sherpa vs. POWHEG+PY8 (both in 4-FS) in very good agreement

Taming t$\bar{t}$H backgrounds

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

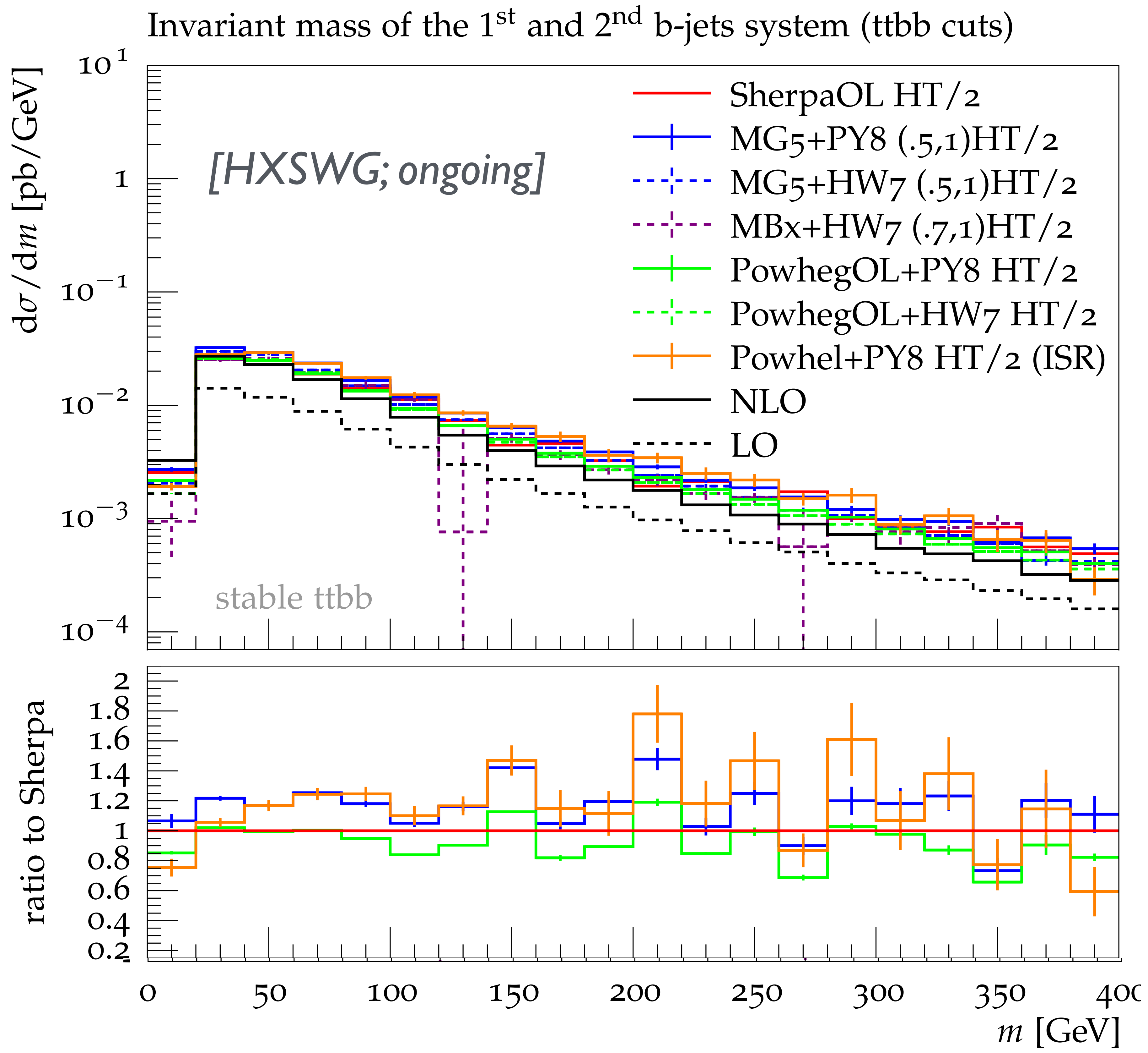


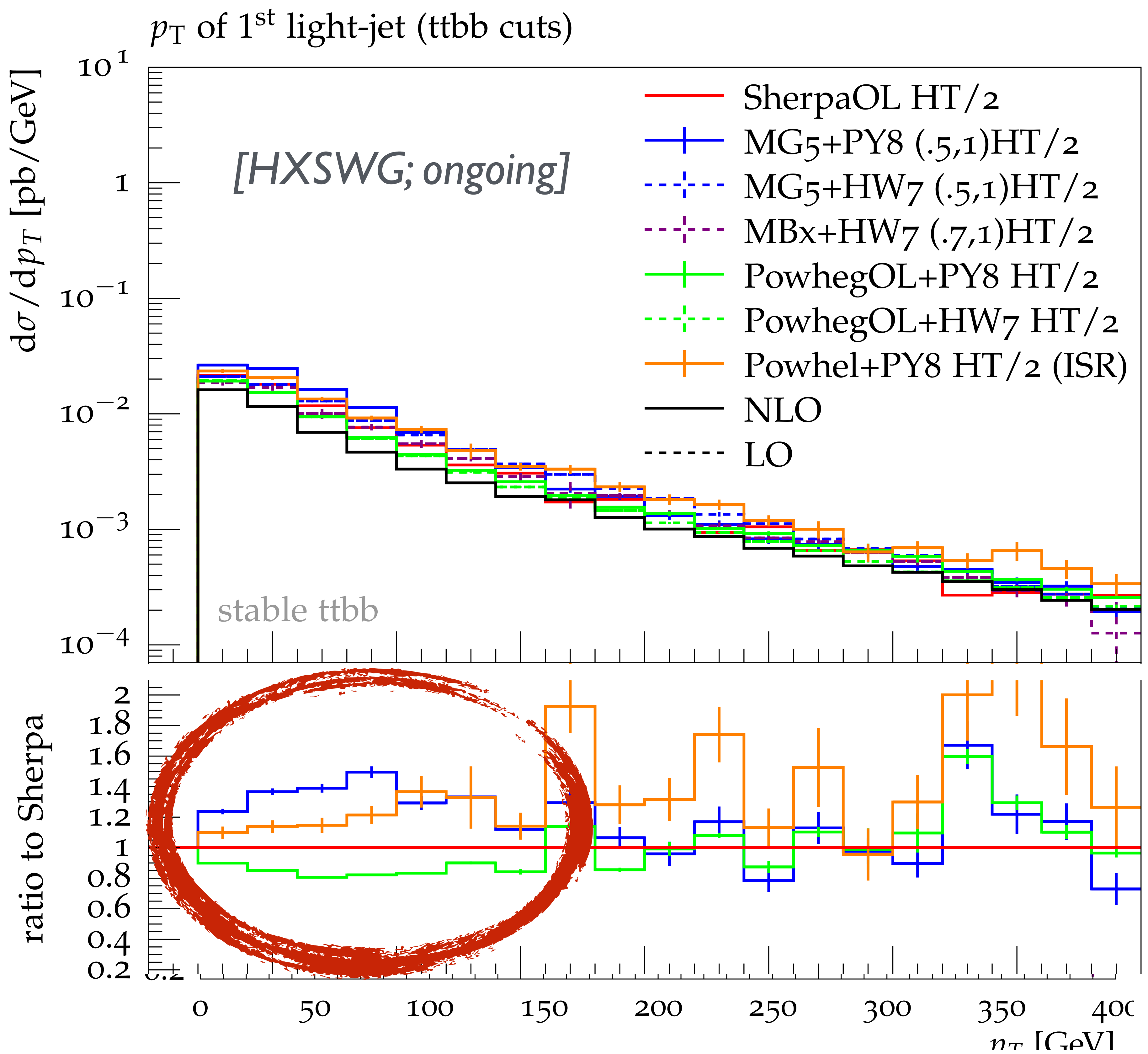
- Shower variations
- α_S & $g \to b\bar{b}$ variations
- hdamp & bzd variations

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

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

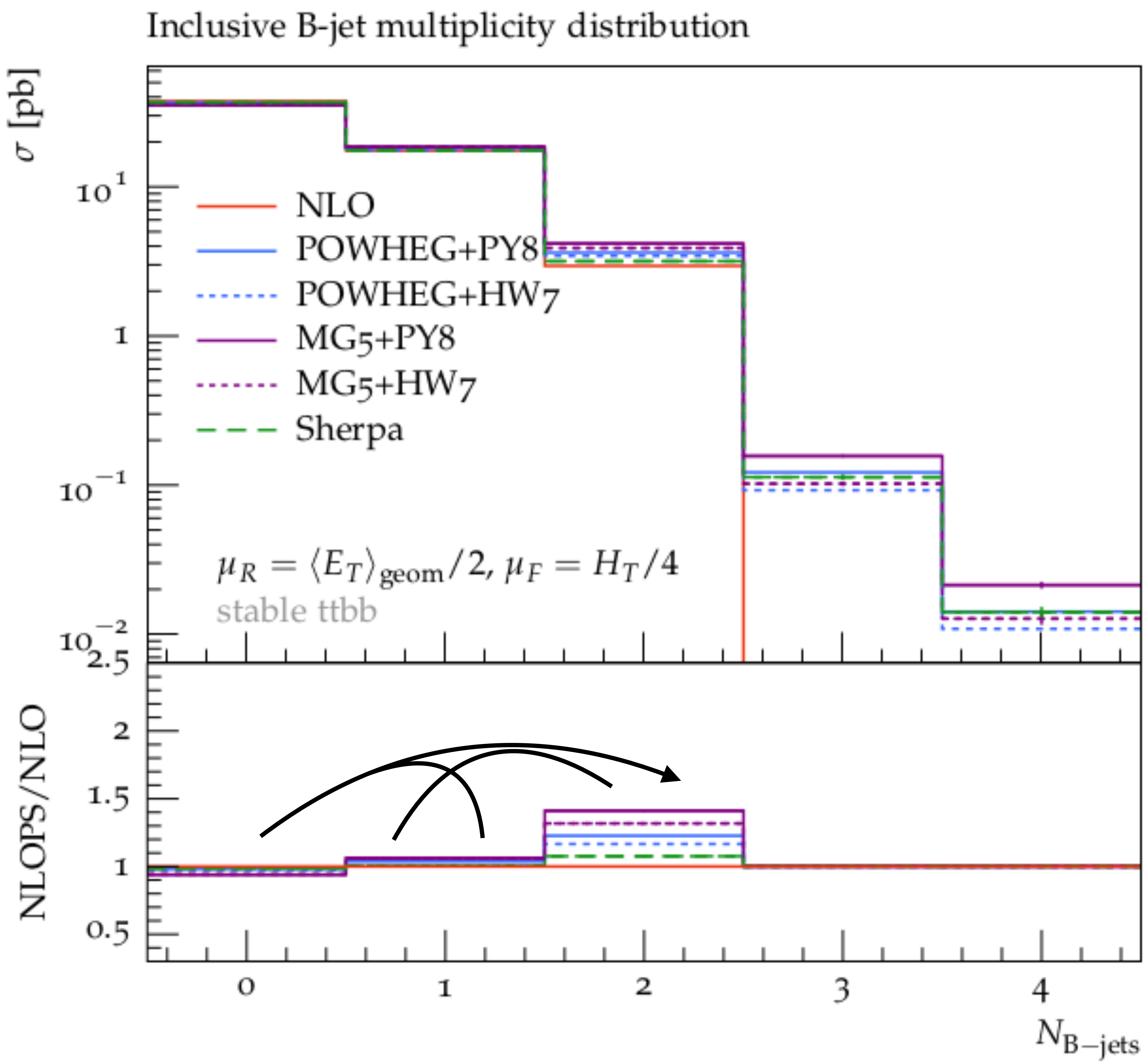
Taming $t\bar{t}H$ backgrounds





- ➡ 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

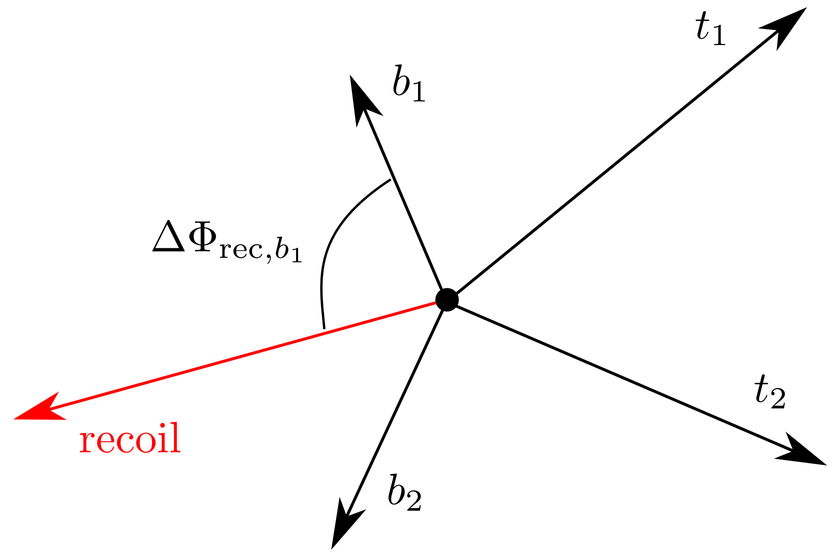


- origin: different shower-induced bins migrations across b-jets cuts

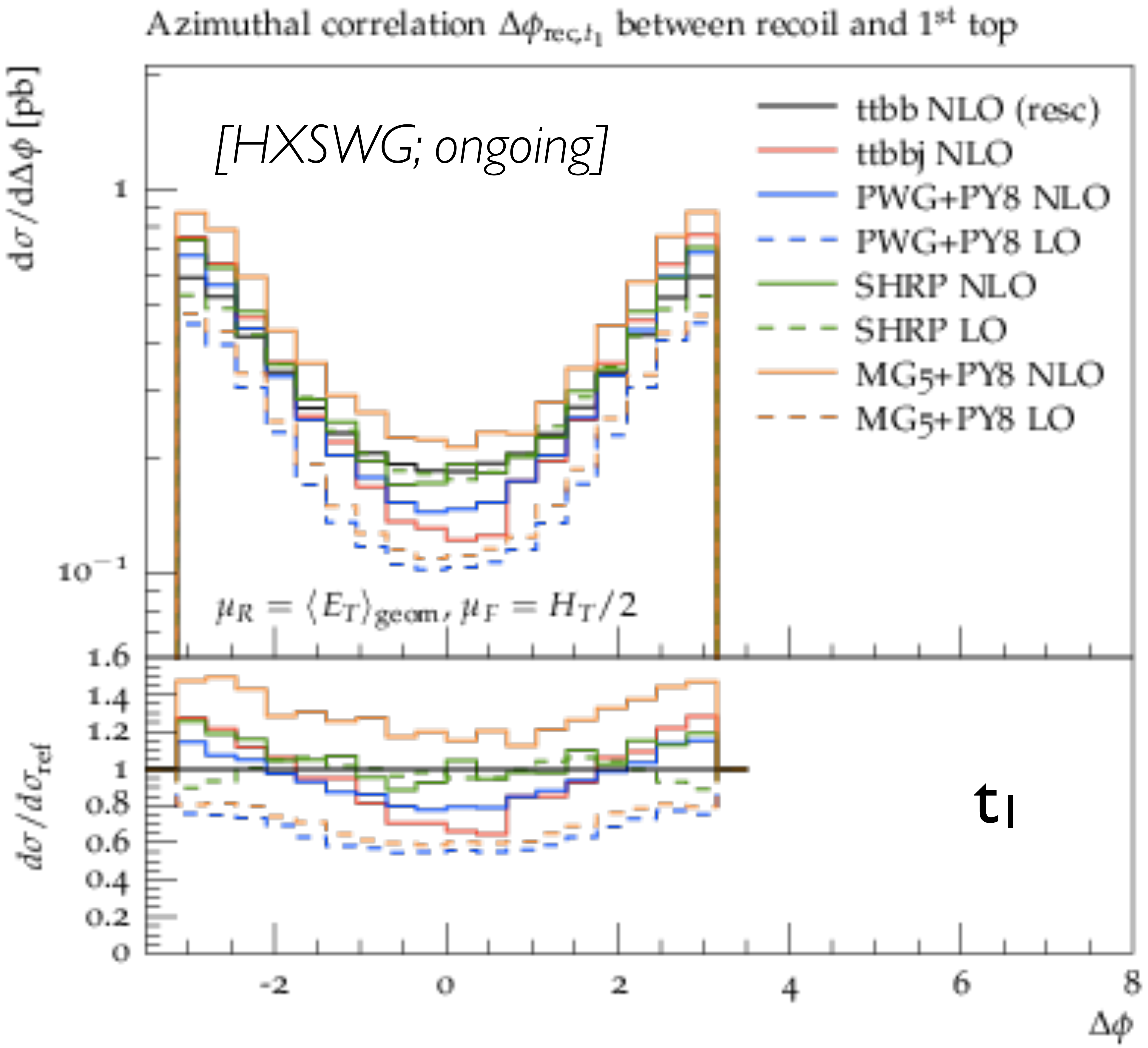
anti-k_t, $R = 0.4$

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

The smoking gun



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



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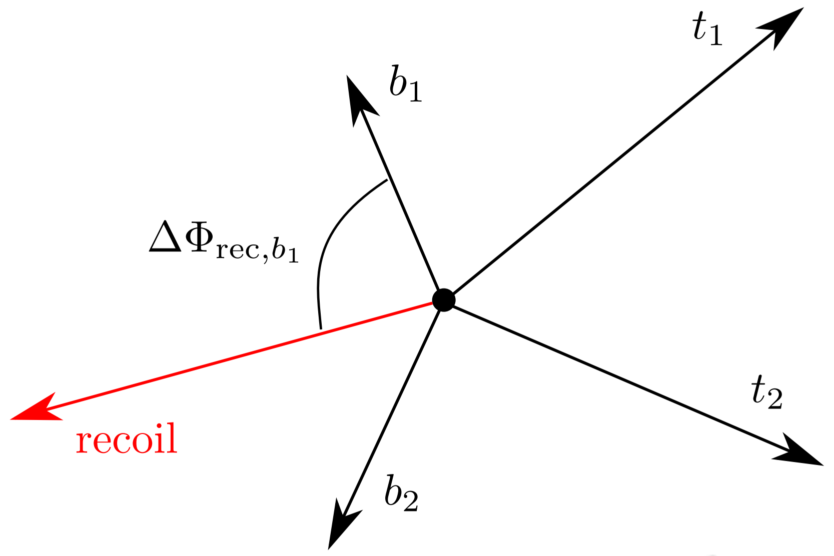
[Buccioni, Pozzorini, Zoller, 1907.13624]

The smoking gun



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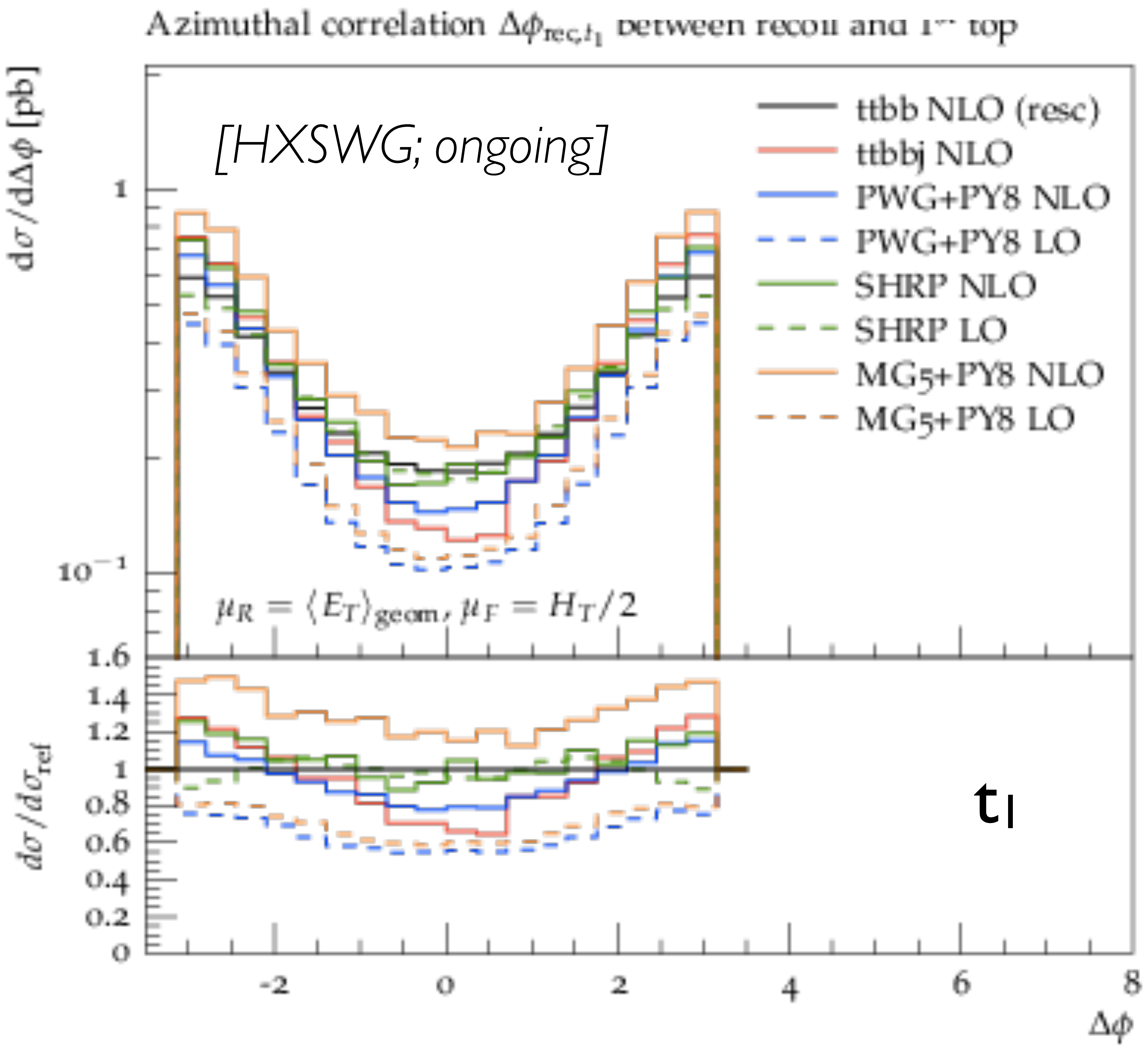

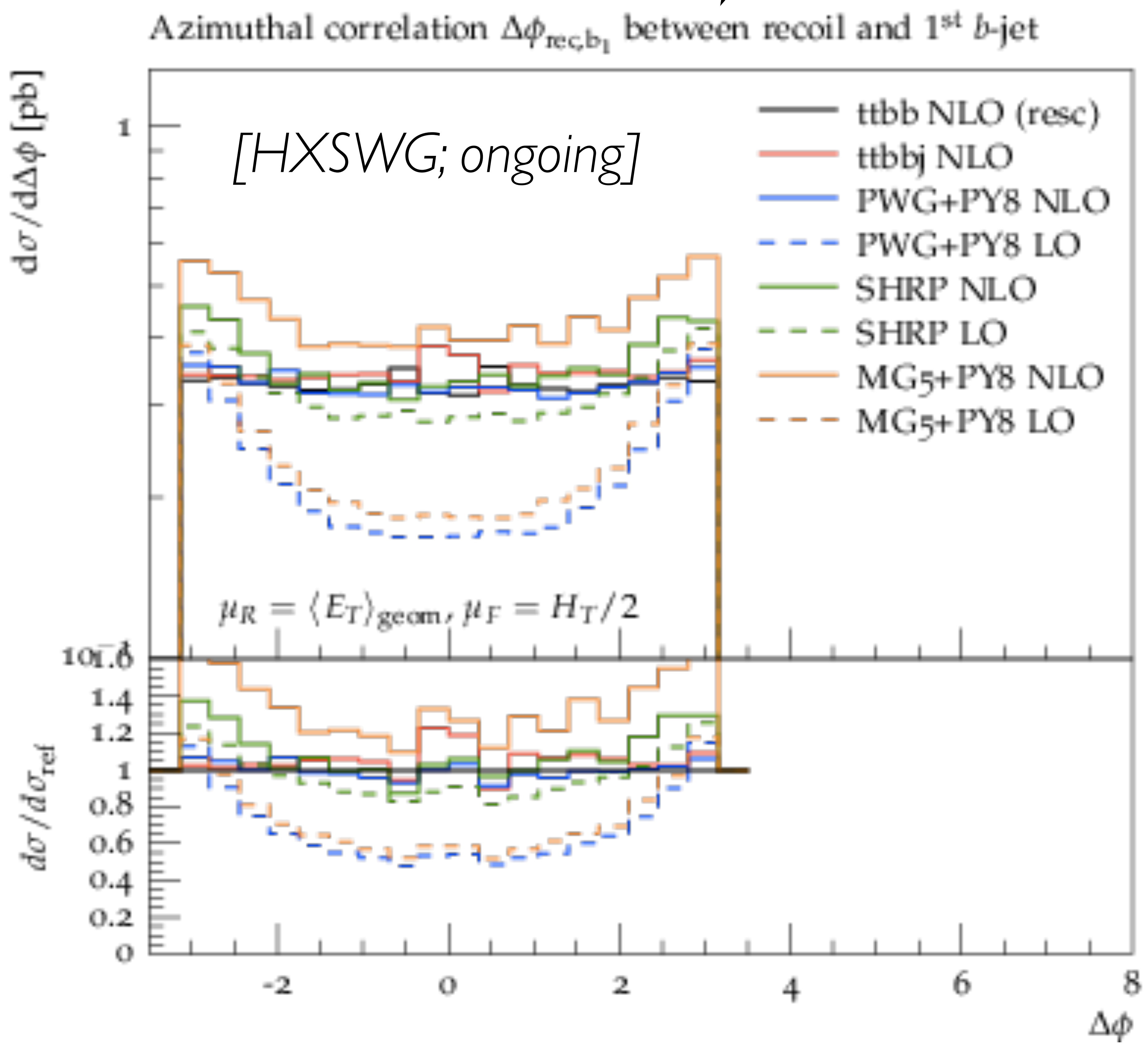

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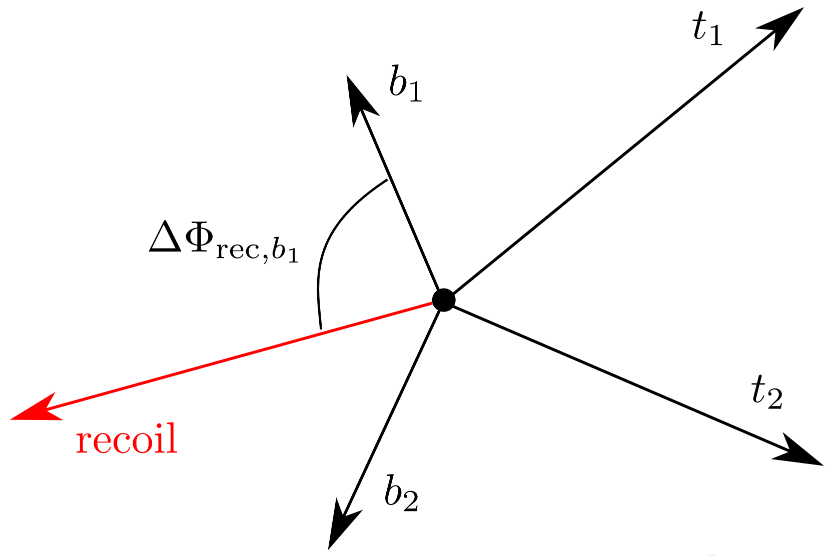
- unphysical since no evidence of recoil in ttbb, ttbbj, or PWG+PY8 at NLO
- unphysical recoil strongly suppressed only by Powheg / attenuated by MC@NLO matching (MG and Sherpa)

The smoking gun



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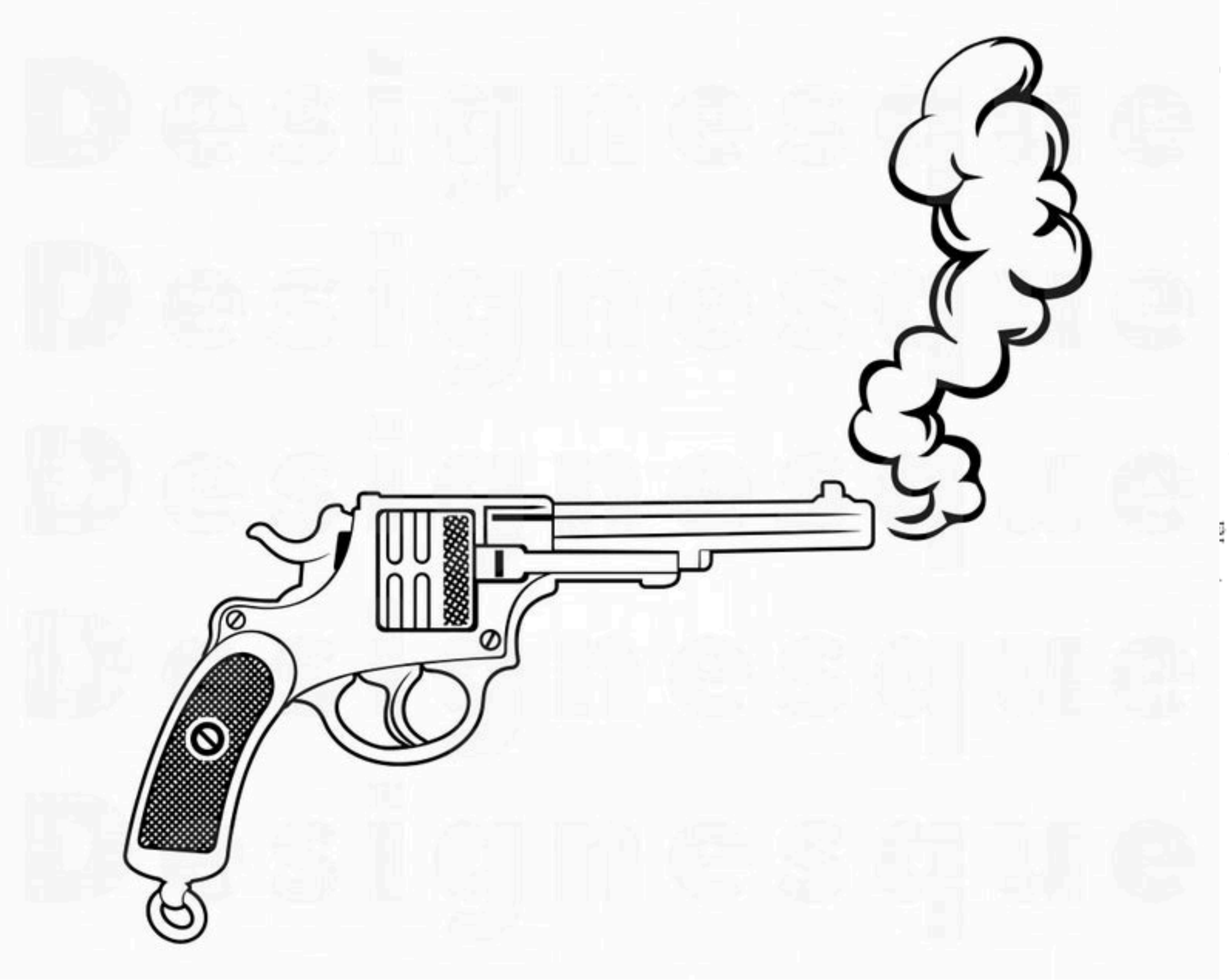

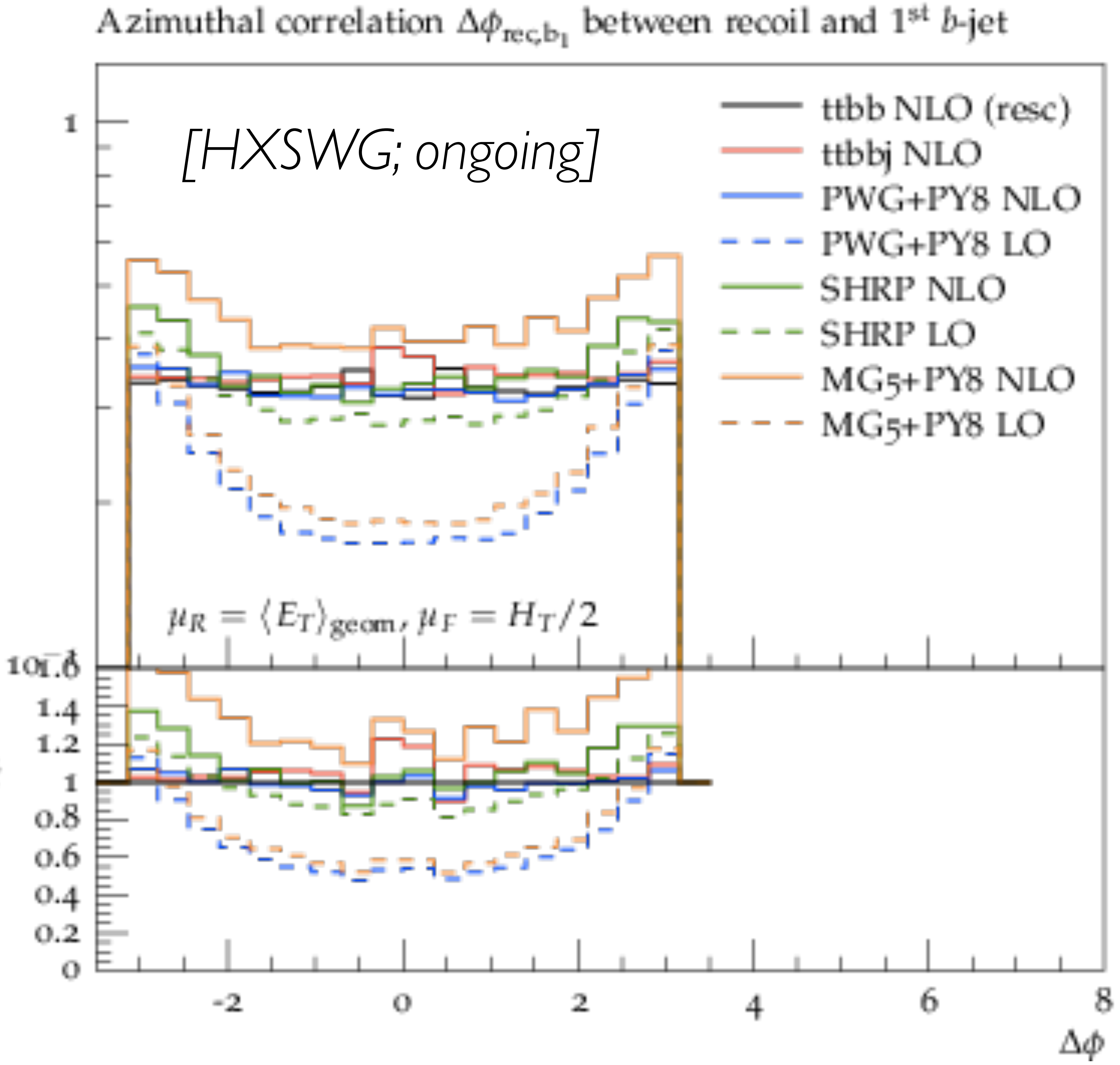

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