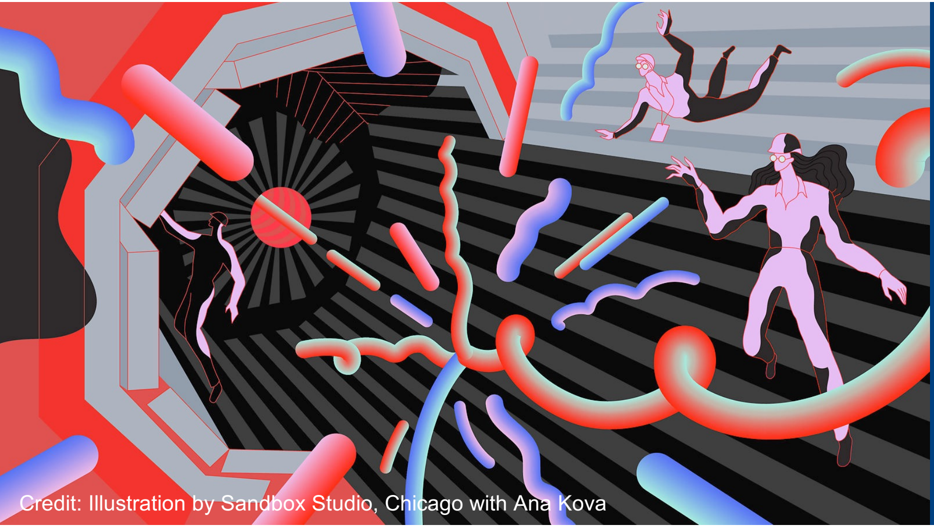
TAE 2023 – International Workshop on High Energy Physics
Benasque (Spain), 3-16 September 2023


Credit: Illustration by Sandbox Studio, Chicago with Ana Kova

Top Physics
(Lecture 2)

Aurelio Juste (ICREA/IFAE)

ICREA
IFAE
Institut de Física d'Altes Energies
BIST Barcelona Institute of Science and Technology

Next lecture

Lecture 1: Bread & butter Top Physics

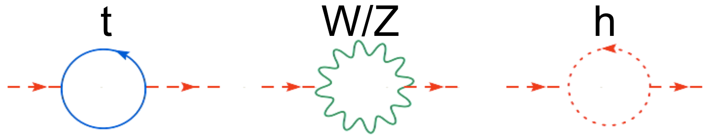
- Introduction
- Top pair production cross-section
- Top mass

Lecture 2: Top and New Physics

- Top couplings
- Exotic top production & decay

Top as a window to New Physics

- The top quark dramatically affects the stability of the Higgs mass. Consider the SM as an effective field theory valid up to scale Λ:

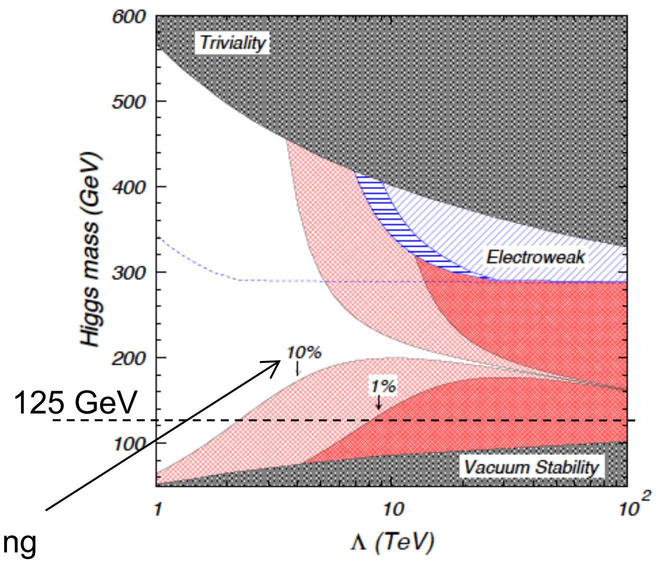


$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

Bare mass

Quantum corrections

Λ= New physics cutoff



Either New Physics appears at a scale Λ or there has to be a very delicate cancellation

If cut-off is at Λ=M_{Pl}=10^{19} GeV, need: $(125\ \mathrm{GeV})^2 \approx (10^{19}\ \mathrm{GeV})^2 - (10^{19}\ \mathrm{GeV})^2$

listening to your favorite radio needs the tuned frequency to match that of the radio channel:

```
radio freq. = 59.0587185209150109198128796234985761 2 kHz
tuned freq. = 59.0587185209150109198128796234985798 7 kHz
```

Proposed solutions

1. **Denial**:
   There is no problem. Naturalness is our problem, not Nature's.
   Con: there is no reason to expect new physics after the Higgs discovery.

Top is the only natural quark

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   Introduce new particles to cancel SM "divergences".

   → Top partners: new scalar/vectors possibly strongly coupled with top, exotic top decays

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   New strong dynamics enters at ~1 TeV.

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→ tt resonances, tt bound states, colorons, 4-top production,…

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KK excitations

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KK excitations

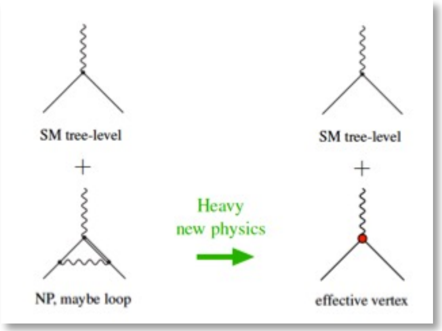
Strategy:
- Precision measurements of top quark properties.
- Searches for anomalous top production and decay.

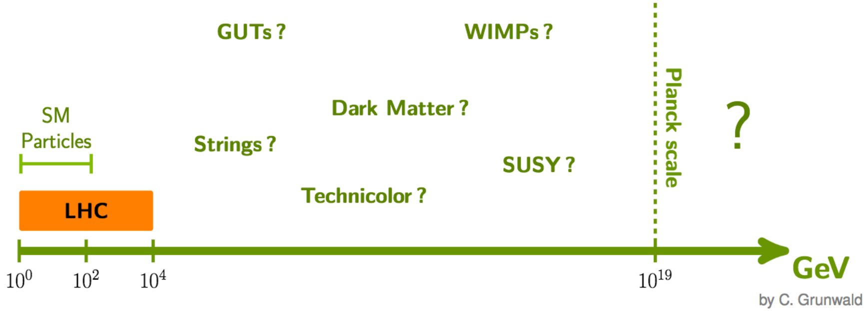
Top Couplings

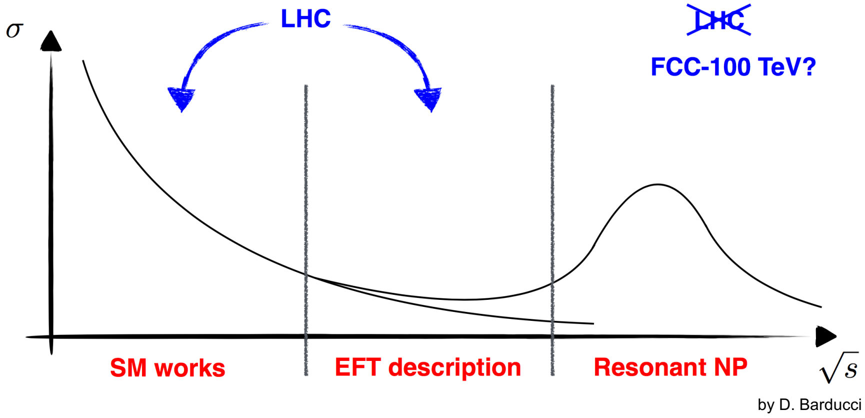
Motivation

- The experimental results so far point to a situation where $M_X >> \sqrt{s}$.
  ➔New states too heavy to be resonantly produced.

- Integrate out explicitly heavy mediator and have instead an effective interaction.

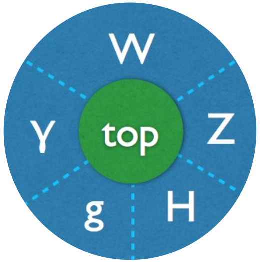






- Assume production & decay dominated by SM.
- Search for new physics indirectly through precision measurements of SM observables.

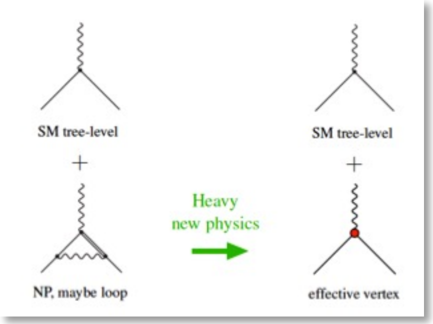
Top couplings in the SM and beyond



- The top quark couples to the other SM fields through its gauge and Yukawa interactions with well-defined Lorentz structure.

to W boson	$\frac{g_W}{\sqrt{2}} \sim 0.45$	$\frac{g_W}{\sqrt{2}} V_{tq} \bar{t}_L \gamma^\mu q_L \, W_\mu^-$
to Z boson	$g_Z = \frac{g_W}{4\cos\theta_W} \sim 0.14$	$g_Z t_L \left[(1-\frac{8}{3}\sin^2\theta_W)\gamma^\mu - \gamma^\mu\gamma_5\right] t_L \, Z_\mu$
to photon	$e_t = \frac{2}{3} e \sim 0.21$	$e_t \bar{t} \gamma^\mu t \, A_\mu$
to gluon	$g_s \sim 1.12$	$g_s \bar{t}_j \gamma^\mu \, T_{jk}^{SU(3)} t_k \, G_\mu$
to Higgs	$Y_t = \frac{g_W m_t}{\sqrt{2} M_W} \sim 1$	$\frac{Y_t}{\sqrt{2}} \bar{t} t \, H$

- New Physics contributions can lead to deviations from the SM prediction.



Effective Vf_if_j vertices, V=W, Z, γ, g:

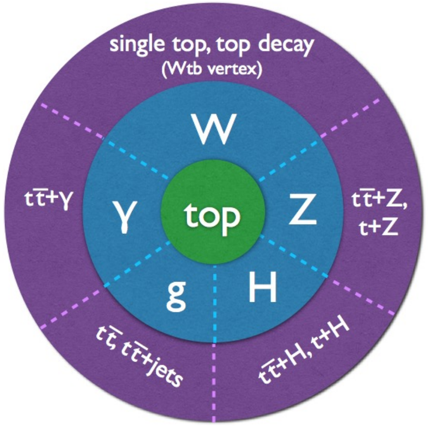
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t \, W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t \, W_\mu^- + \text{H.c.}\,.$$

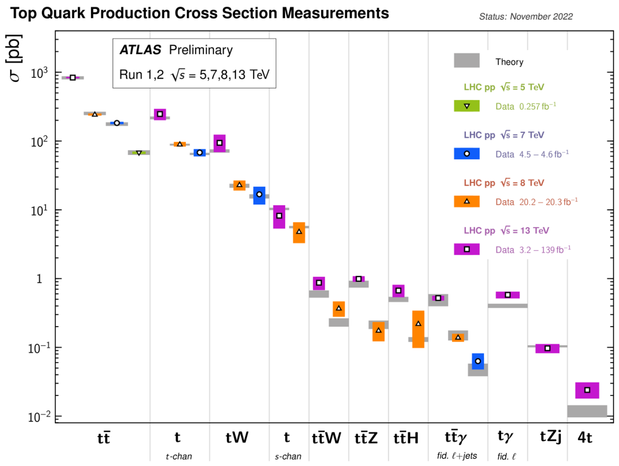
$$\mathcal{L}_{Ztt} = -\frac{g}{2c_W} \bar{t} \gamma^\mu \left(X_{tt}^L P_L + X_{tt}^R P_R - 2 s_W^2 Q_t\right) t \, Z_\mu - \frac{g}{2c_W} \bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{M_Z} (d_V^Z + i d_A^Z \gamma_5) t \, Z_\mu \,,$$

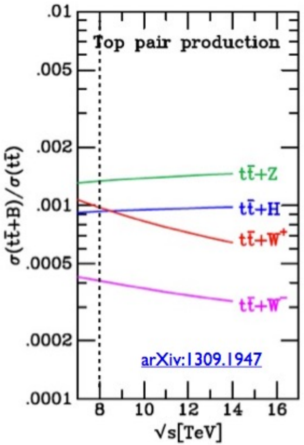
$$\mathcal{L}_{\gamma tt} = -e Q_t \bar{t} \gamma^\mu t \, A_\mu - e \bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (d_V^\gamma + i d_A^\gamma \gamma_5) t \, A_\mu$$

$$\mathcal{L}_{gtt} = -g_s \bar{t} \frac{\lambda^a}{2} \gamma^\mu t \, G_\mu^a - g_s \bar{t} \lambda^a \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (d_V^g + i d_A^g \gamma_5) t \, G_\mu^a$$

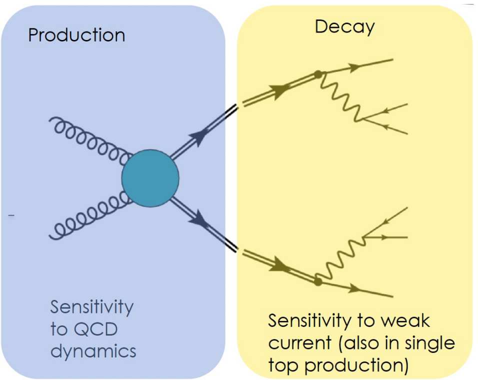
Probing top couplings at the LHC





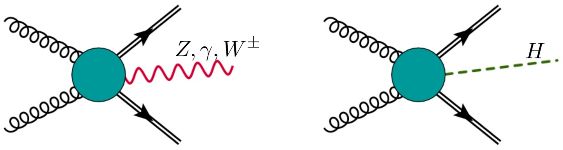


tt / single-top production & decay



The LHC is not only a top-quark factory, but it is opening the door to a whole new class of processes:

tt+X production



Associated production adds sensitivity to neutral currents (Z/γ) and Yukawa interactions (Higgs)

13 TeV	Run 2 (140 fb^{-1})
tt	~120 M
tt+γ	~400k
tt+Z	~140k
tt+H	~80k

The SM Effective Field Theory (SMEFT)

- The effects of new physics at a scale Λ can be described by an effective Lagrangian.
- Consider all higher-dimensional operators that can be built from SM fields and respecting the SM symmetries:

$$\mathcal{L}_{Eff} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

O_i = dim 6 gauge invariant operators

C_i=complex constants

Operators involving the top quark

$$O_{\varphi Q}^{(3)} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$
$$O_{\varphi Q}^{(1)} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$
$$O_{\varphi t} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$
$$O_{\varphi b} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{b}\gamma^\mu b)$$
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$
$$O_{bW} = y_b g_w (\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$
$$O_{t\varphi} = (\varphi^\dagger \varphi)(\bar{Q}t\tilde{\varphi})$$
$$O_{\varphi tb} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$
$$O_{\varphi G} = g_s^2 (\varphi^\dagger \varphi)\, G^A_{\mu\nu} G^{A\mu\nu}$$

4-fermion ops

- These operators can induce corrections to SM couplings (e.g. may originate anomalous couplings of the top quark to the gauge bosons).

  E.g. Effective Lagrangian for Wtb interaction:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu (V_L P_L + V_R P_R)\, t\, W^-_\mu - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(g_L P_L + g_R P_R)\, t\, W^-_\mu + \text{H.c.}\,.$$

$$\delta V_L = C_{\phi q}^{(3,33)*}\frac{v^2}{\Lambda^2}, \qquad \delta g_L = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2}$$
$$\delta V_R = \frac{1}{2}C_{\phi\phi}^{33}\frac{v^2}{\Lambda^2}, \qquad \delta g_R = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}$$

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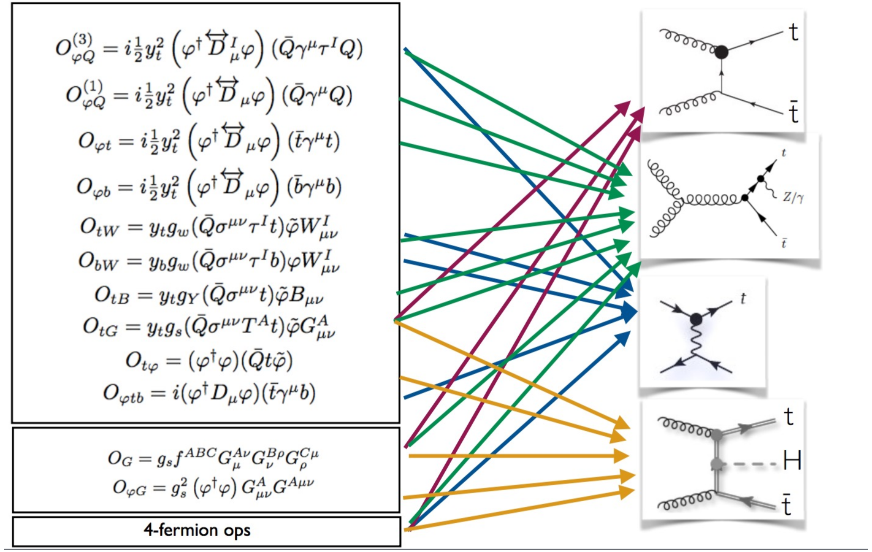
Operators involving the top quark



- But many operators to consider!
- Multiple measurements may be sensitive to the same operator and the vice-versa (i.e. ttZ cross section sensitive to the coupling to the gluon and to the Z boson).
- The ultimate goal is to find observables which are sensitive to the various possible EFT operators coefficients

$$\mathcal{O}^i = f(c_1^i, c_2^i, \ldots, c_n^i)$$

set of observables — Dependence with the parameters (anomalous couplings, effect. operators coefficients)

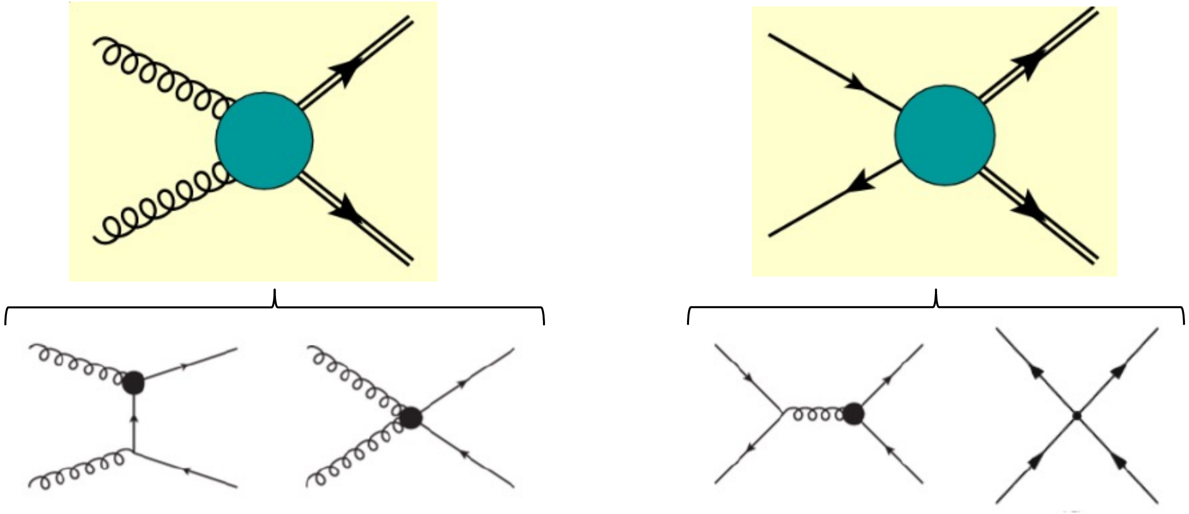
and then perform a global fit to all observables, considering proper correlations of statistical and systematic uncertainties.

- This requires a coordinated effort among theorists and experimentalists (being followed up within LHC TOPWG).

Top coupling to the gluon

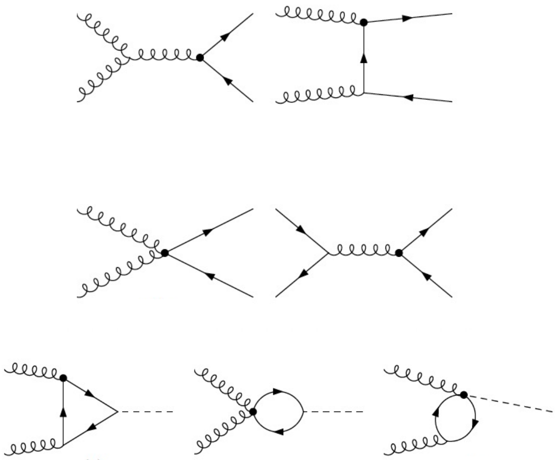
- Studied in tt production, including tt+jets processes.
- Exploit inclusive as well as differential cross-section measurements.
- Other observables:
  - Charge asymmetry
  - Top-quark spin correlations
- Can be affected also by 4-quark operators!

$gg \rightarrow t\bar{t}$ $\quad$ $q\bar{q} \rightarrow t\bar{t}$



Constraints on New Physics - EFT

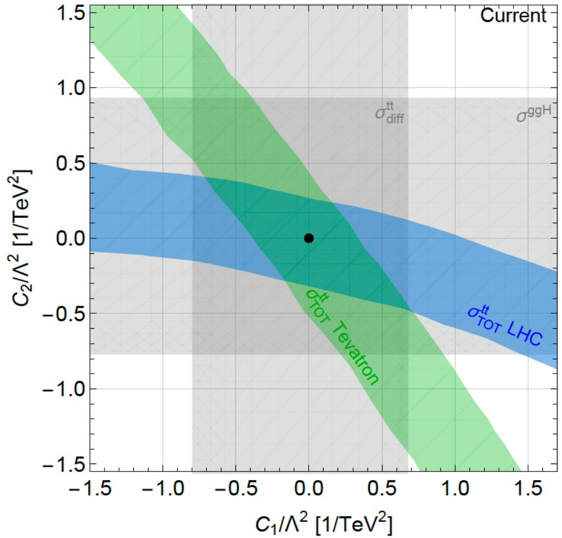
- Some of the inclusive tt and differential measurements have been used by theorists to constrain top anomalous couplings (or EFT Wilson coefficients).
- Top pair, together with Higgs measurements, provide independent observables to bound non-standard top-gluon interactions. Assumptions: CP even operators, flavour independence.

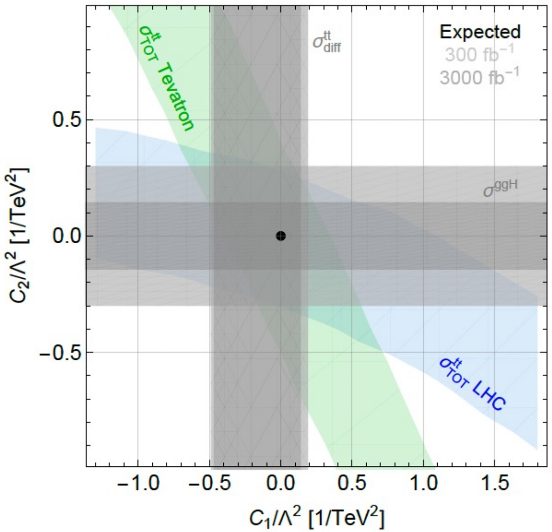


$$\mathcal{O}_1 = \frac{C_1}{\Lambda^2}\,\bar{t}\gamma^\mu T^a t\, D^\nu G^a_{\mu\nu}$$

$$\mathcal{O}_2 = \frac{C_2}{\Lambda^2}\,v\,\bar{t}\sigma^{\mu\nu} T^a t\, G^a_{\mu\nu}$$

arXiv:1704.05478





Constraints on New Physics - EFT

- ATLAS and CMS are also interpreting their own measurements in the context of the SMEFT.
- E.g. differential tt cross-section in the boosted regime ➔ particularly sensitive to 4-quark operators.

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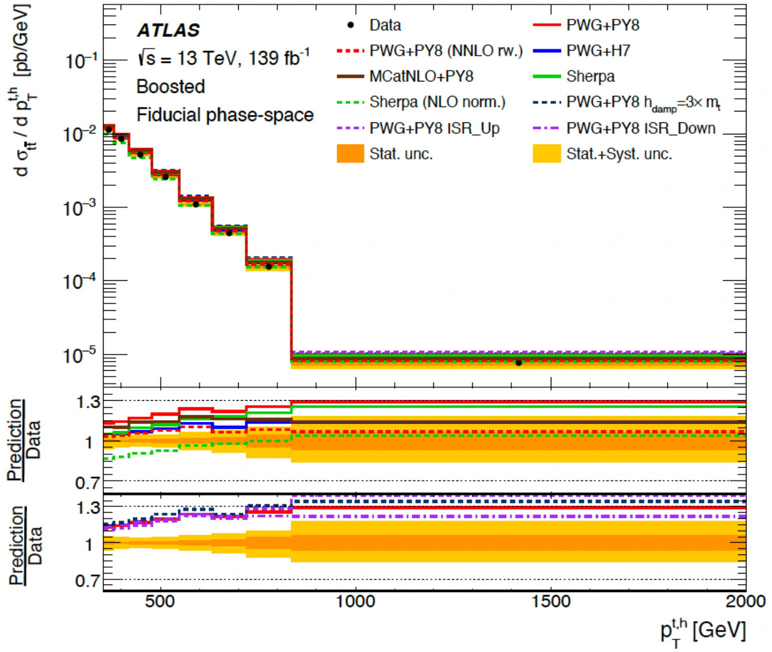
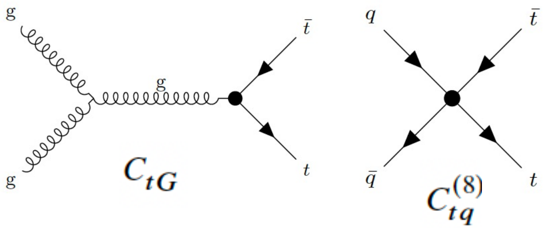
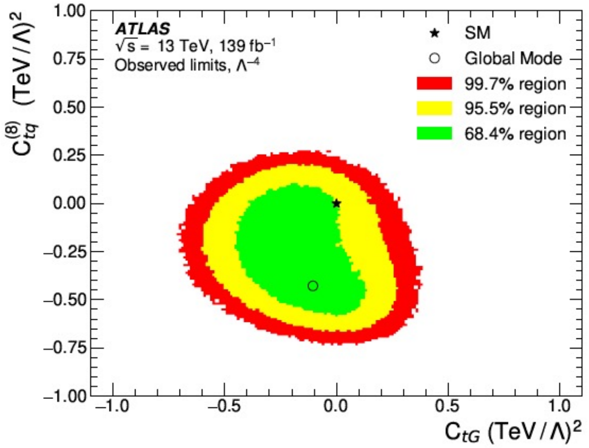


Use PWH+PY8 (NNLO rw.) prediction for EFT interpretation

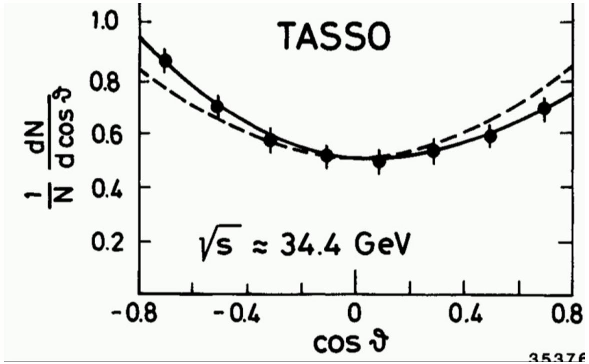


$$\sigma^j(C_{tG}, C_{tq}^{(8)}) = p_0^j + p_1^j \cdot C_{tG} + p_2^j \cdot C_{tq}^{(8)} + p_3^j \cdot (C_{tG})^2 + p_4^j \cdot (C_{tq}^{(8)})^2 + p_5^j \cdot C_{tG} \cdot C_{tq}^{(8)}$$



Charge asymmetry

- Precision measurements of forward-backward asymmetries are very powerful to uncover New Physics.
- Wisdom from the past: indications of Z boson in measured A_{FB} in $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s} << M_Z$.

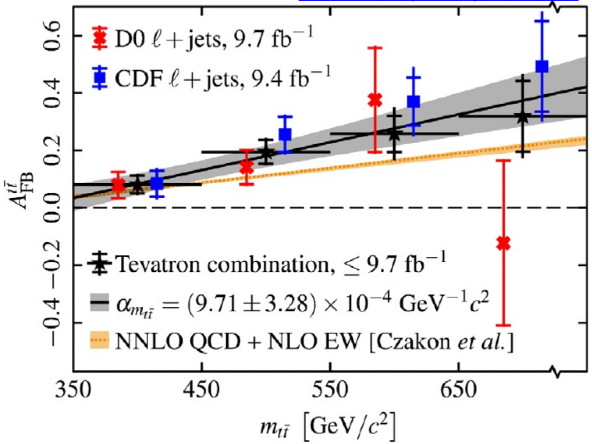


- What about in tt production? QCD predicts a non-zero forward-backward asymmetry beyond LO. Slightly enhanced by QED+EW corrections.

- Can be enhanced in BSM scenarios (axigluons, Z' bosons, KK gluons).

- The Tevatron was particularly well positioned to perform this measurement:
  - qq-dominated initial state (85%)
  - ppbar collisions give direction for incoming quark and antiquark

PRL 120 (2018) 042001



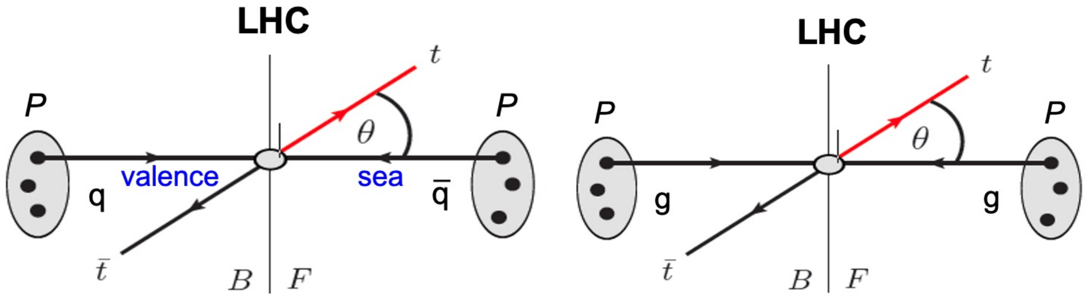
FB asymmetry = charge asymmetry

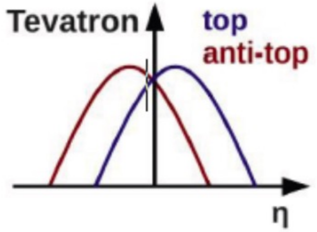
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

CP conservation

$$\Delta y = y_t - y_{\bar{t}}$$

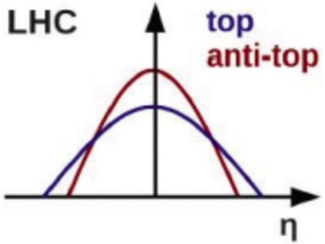
Charge asymmetry at the LHC





$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \sim 9\%(SM)$$

$$\Delta y = y_t - y_{\bar{t}}$$



$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \sim 1\%(SM)$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

In proton-proton collisions:

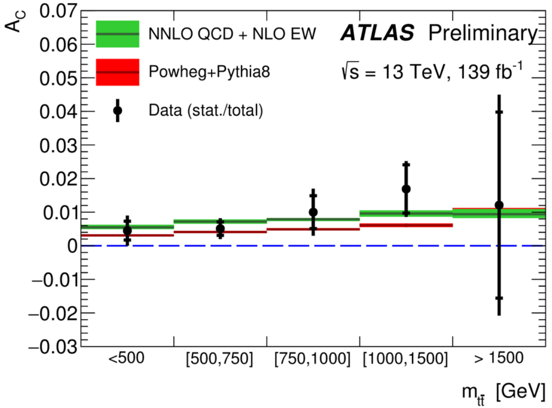
- no forward-backward asymmetry
- asymmetry can only arise from qq→tt process
- quarks have on average larger momentum than antiquarks
  ➔ rapidity distribution of top quark is wider than anti-top

A rather challenging measurement!

- less sensitive observable to start with
- initial state dominated by charge symmetric gg→tt process (90%)

Charge asymmetry measurements

- Measurements performed in the l+jets (including also boosted top dedicated analysis) and dilepton channels.
- Different methods to reconstruct the ttbar kinematics (e.g. likelihood fit in l+jets, specific technique to deal with boosted top decays in l+jets boosted, kinematic method in dilepton).
- Unfolding method used to correct to parton level or template method (CMS).
- Inclusive and differential measurements as a function of mass, p_T and longitudinal boost β_z of the ttbar system provided.



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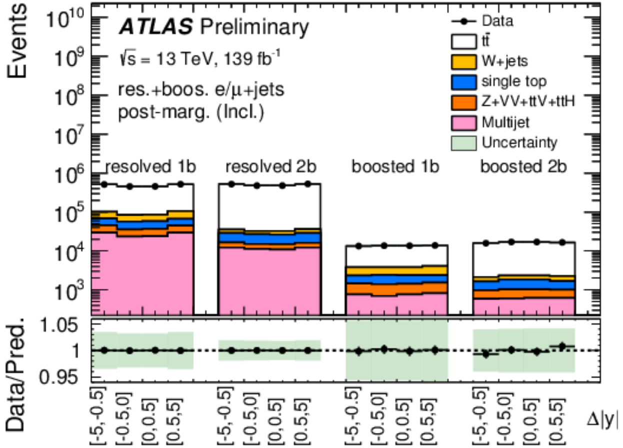
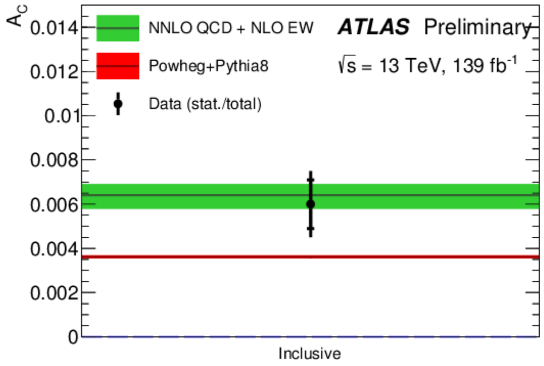
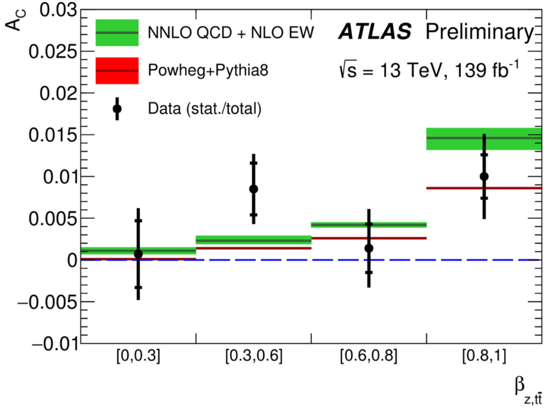




4σ evidence of non-zero A_C



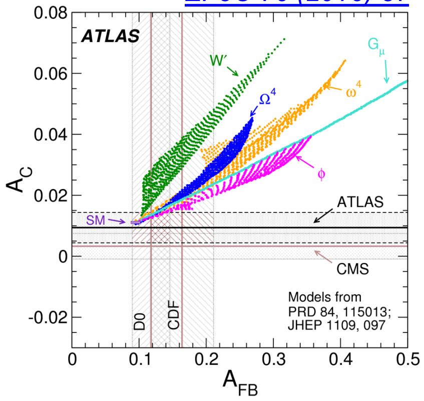
All compatible with SM predictions

Constraints on New Physics

- Measurements can be used to constrain specific BSM or EFT Wilson coefficients.

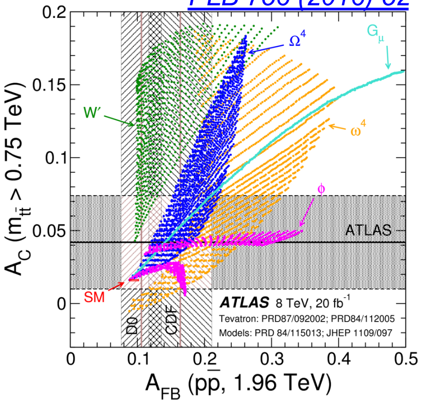
EPJC 76 (2016) 87

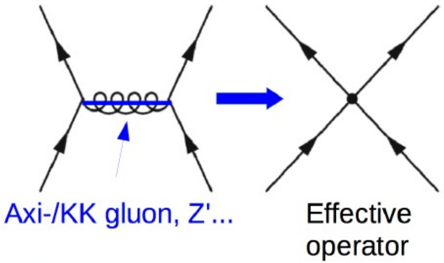
Resolved



PLB 756 (2016) 52

Boosted



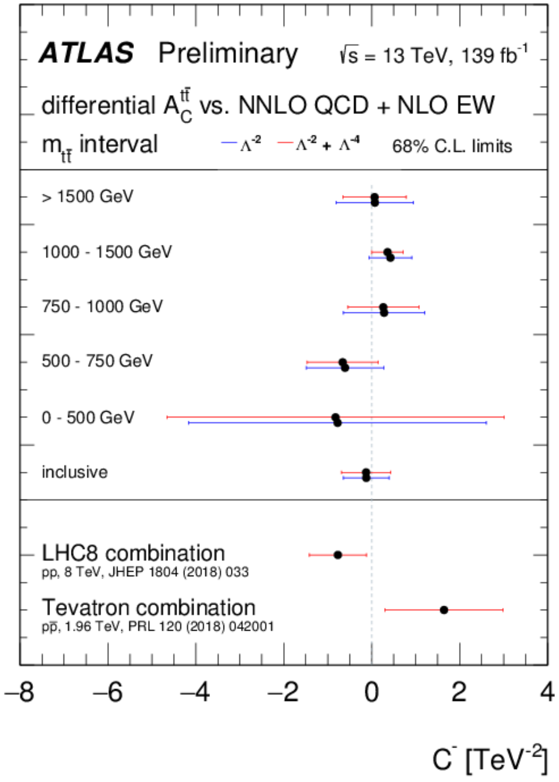


$$C_u^1 = C_{qq}^{(8,1)} + C_{qq}^{(8,3)} + C_{ut}^{(8)}$$
$$C_u^2 = C_{qu}^{(1)} + C_{qt}^{(1)}$$
$$C_d^1 = C_{qq}^{(8,1)} - C_{qq}^{(8,3)} + C_{dt}^{(8)}$$
$$C_d^2 = C_{qd}^{(1)} + C_{qt}^{(1)}$$

$$C_u^1 = C_d^1 = C^1 \text{ and } C_u^2 = C_d^2 = C^2$$

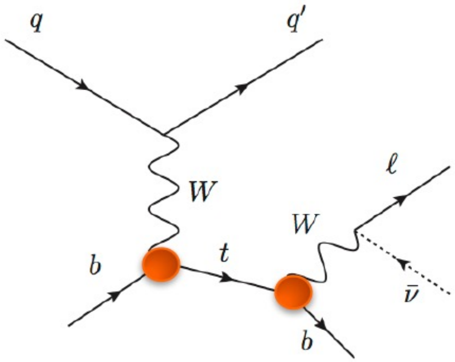
$$\frac{C^-}{\Lambda^2} = \frac{C_1 - C_2}{\Lambda^2} = -\frac{4g_s^2}{m_A^2}$$

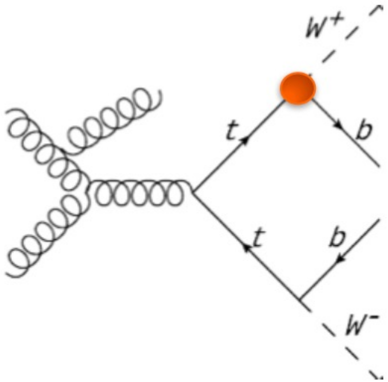
ATLAS-CONF-2019-026



Top coupling to the W boson

- Can we probed by studying single top production and top decays.





Many possible observables!

R = B(t→Wb)/B(t→Wq) in ttbar

Single top cross sections (t-channel, Wt-channel)

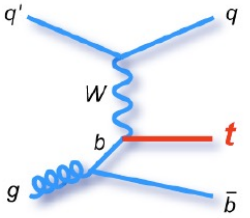
W helicity (ttbar, t-channel)
W spin observables in t-channel
Top polarisation in t-channel
Differential angular decay rates

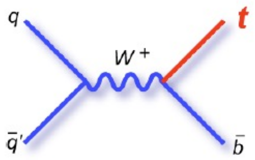
Vtb measurements

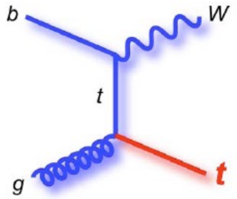
Constraints on Wtb anomalous couplings within EFT

Single top production

- Main production mechanisms for (SM-like) single top production:







$$\sigma \propto |V_{tb}|^2$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

	t-channel	s-channel	tW-channel
Tevatron	2.26 pb	1.04 pb	0.28 pb
LHC 8 TeV	84.7 pb	5.2 pb	22.7 pb
LHC 13 TeV	217 pb	10.3 pb	71.7 pb

$$V_{\rm CKM} = \begin{pmatrix} 0.97401 \pm 0.00011 & 0.22650 \pm 0.00048 & 0.00361^{+0.00011}_{-0.00009} \\ 0.22636 \pm 0.00048 & 0.97320 \pm 0.00011 & 0.04053^{+0.00083}_{-0.00061} \\ 0.00854^{+0.00023}_{-0.00016} & 0.03978^{+0.00082}_{-0.00060} & 0.999172^{+0.000024}_{-0.000035} \end{pmatrix}$$

Assuming 3-generations and unitary matrix

- Motivation:
  - Direct measurement of $|V_{tb}|$ (w/o assumptions on number of generations)
  - Anomalous couplings in Wtb vertex
  - Probes b-quark PDF
  - s- and t-channel processes sensitive to different BSM scenarios
  - Top spin physics (~100% polarized top quark)

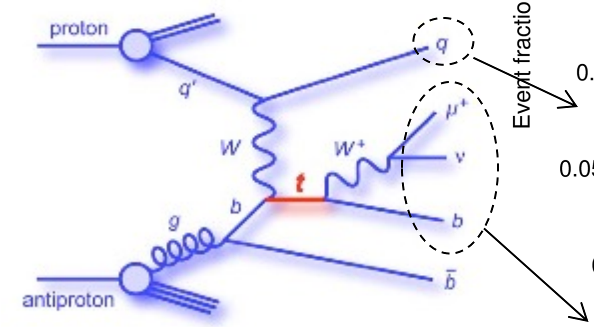
- Experimental extraction challenging due to large background from W+jets and tt production.

The golden single top (t-)channel

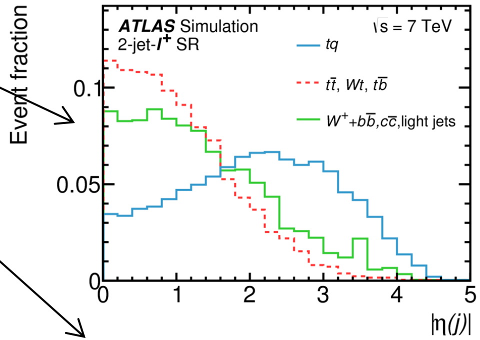
- Signature:
  - Single isolated electron or muon
  - Large E_T^{miss}
  - One central b jet from top decay
  - Possibly one additional b jet (mainly s-channel)
  - A light quark jet in the forward region (t-channel)

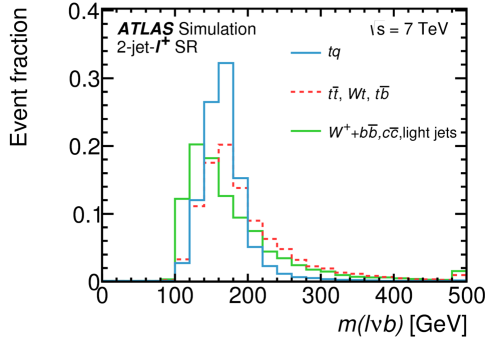
- Backgrounds: W+jets, tt

- Consider discriminant variables between single top and backgrounds:
  - Reconstructed top mass
  - Q(lepton)•η(untagged jet) (t-channel)
  - Energy-related variables
  - Top spin-related angular variables
  - ….
  - ➔ Best discrimination achieved using multivariate techniques (e.g. Neural Networs).



PRD 90 (2014) 112006





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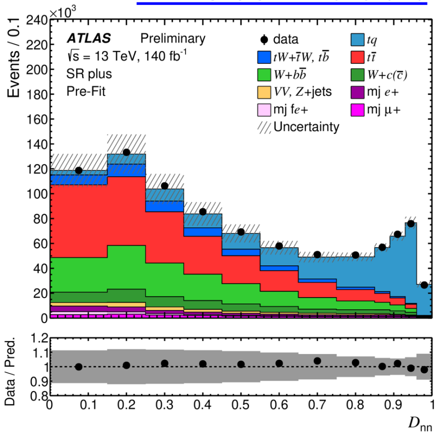
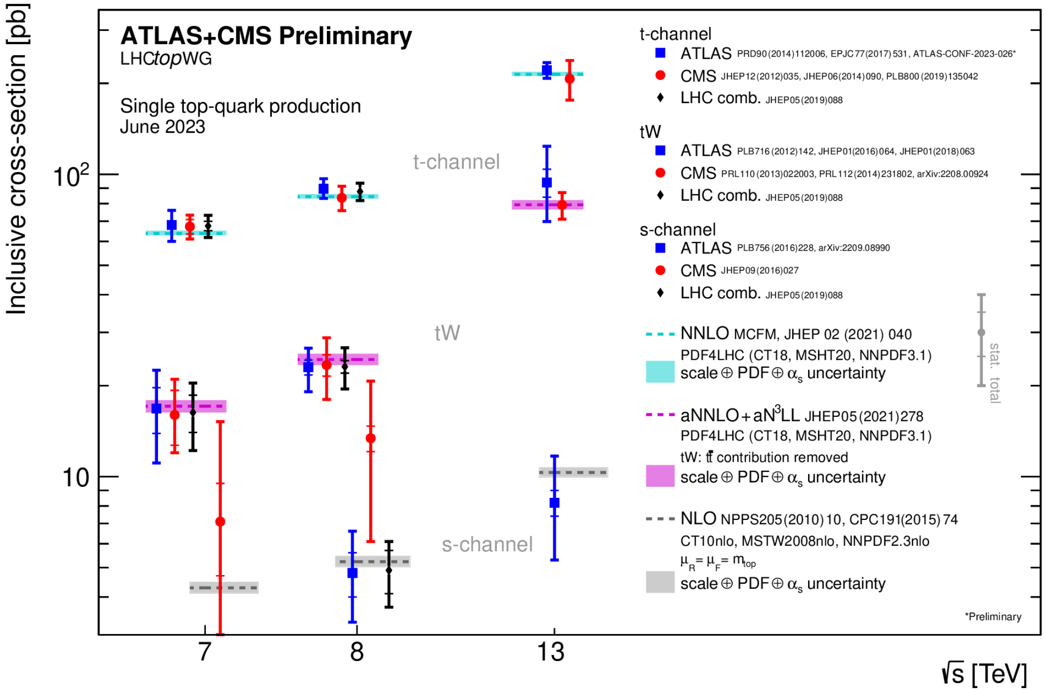
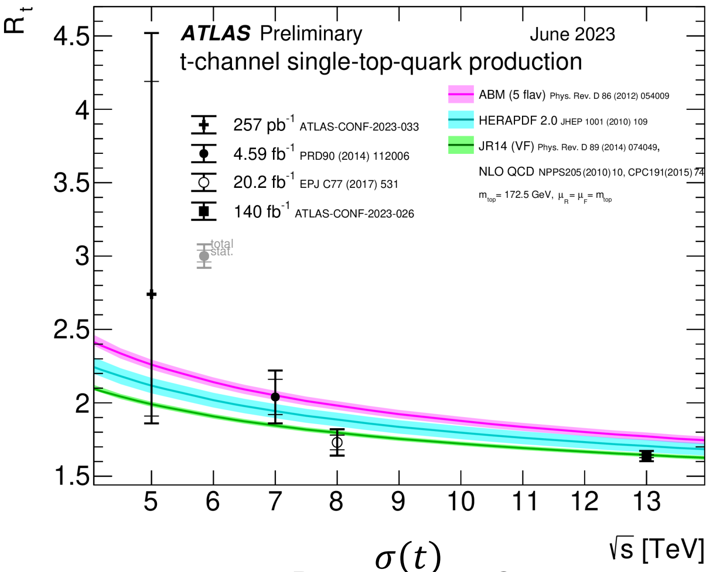
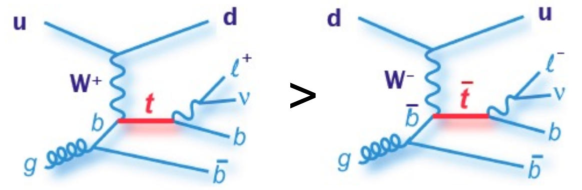


Single top cross section measurements



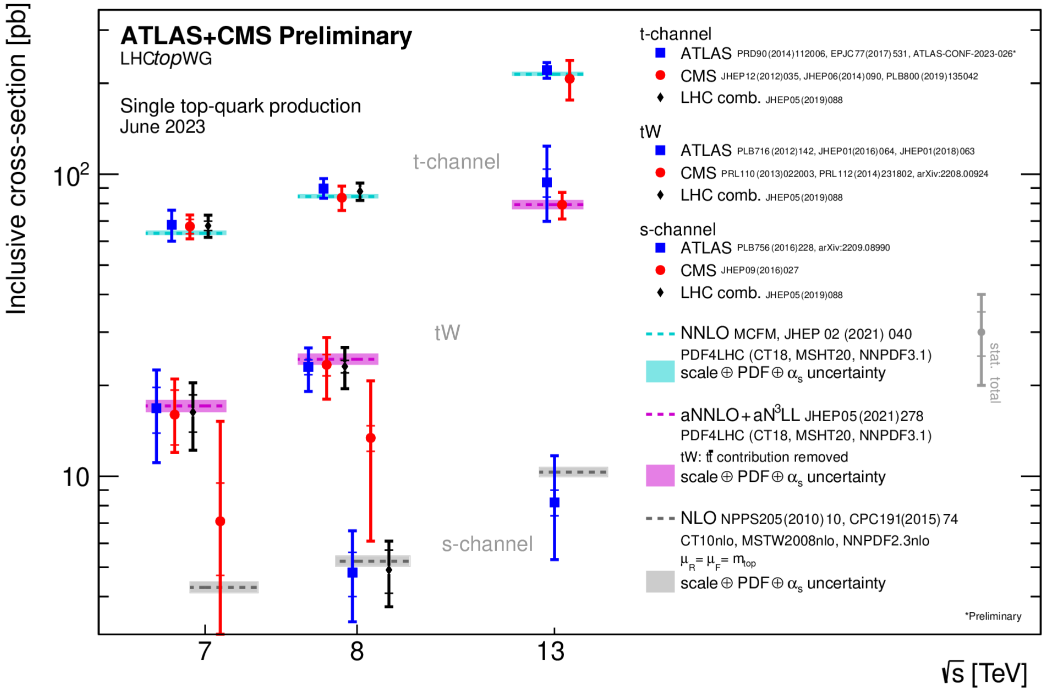


$$R_t = \frac{\sigma(t)}{\sigma(\bar{t})} \sim 2$$

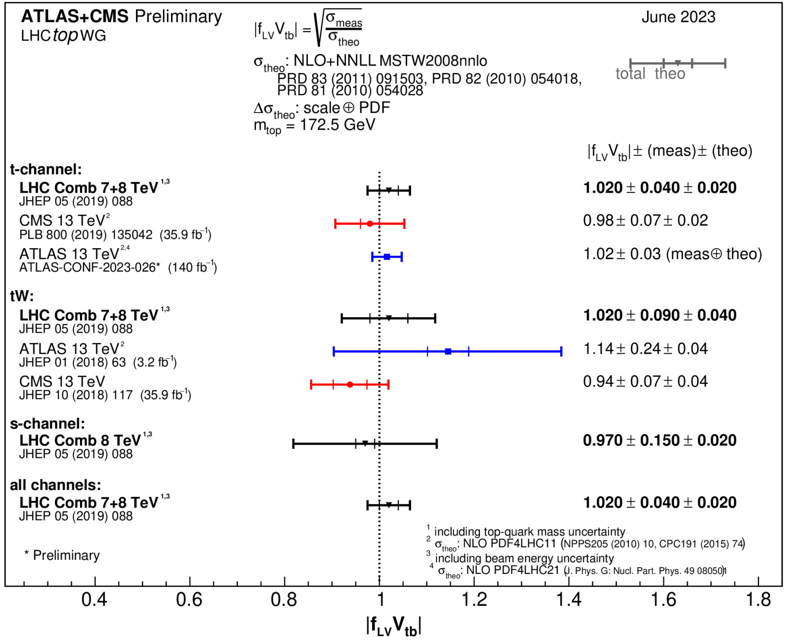


- Measurements in good agreement with SM predictions for all production modes.
- Charge asymmetry measurement helps constraint PDFs.

$|V_{tb}|$ from single top cross section



$$|V_{tb}| = \sqrt{\frac{\sigma_{meas}}{\sigma_{theo}}}$$



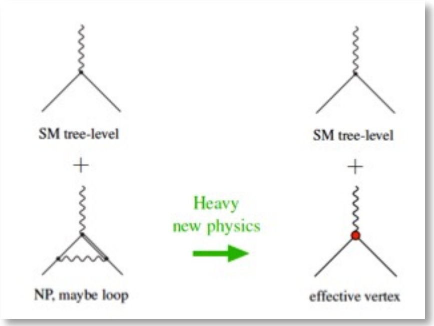
- Most precise measurement from ATLAS at 13 TeV (3% total uncertainty).
  - Dominated by signal modeling uncertainties

Wtb anomalous couplings

- New physics can be parametrised in terms of an effective Lagrangian:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \text{h.c.}$$

SM at tree level: $V_L = V_{tb} \simeq 1 \text{ and } V_R = g_L = g_R = 0$



- New physics can affect:
  - Total single top cross section:

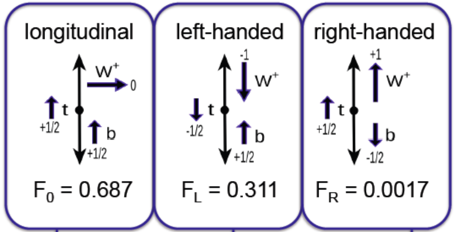
$$\sigma = \sigma_{\rm SM}\left(V_L^2 + \kappa^{V_R}\, V_R^2 + \kappa^{V_L V_R}\, V_L V_R + \kappa^{g_L}\, g_L^2 + \kappa^{g_R}\, g_R^2 + \kappa^{g_L g_R}\, g_L g_R + \ldots\right)$$

  - Top polarisation in single top production (via asymmetries)
  - W polarisation observables (via asymmetries)
  - Differential angular decay rates

W helicity fractions from ttbar decays

- Top quarks are not polarised → measure W helicity fractions.

W polarization states

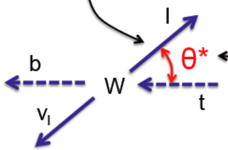


SM (NNLO, ~% rel. uncert.)

PRD 81 (2010) 111503

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)\,F_0 + \frac{3}{8}(1-\cos\theta^*)^2\,F_L + \frac{3}{8}(1+\cos\theta^*)^2\,F_R$$

$F_0 + F_L + F_R = 1$



angle between the charged lepton in the W rest frame and W momentum in top rest frame.

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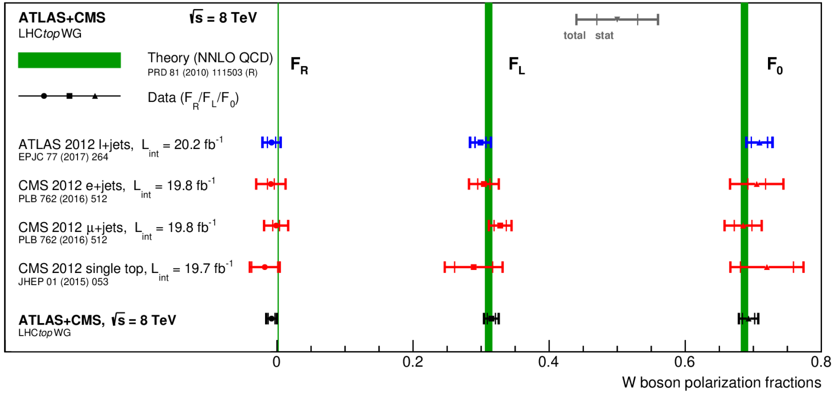
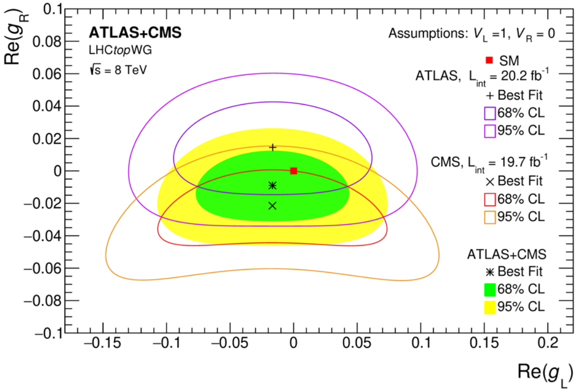
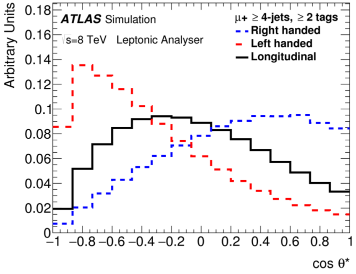
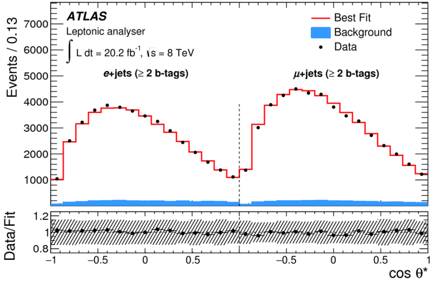




EPJC 77 (2017) 264





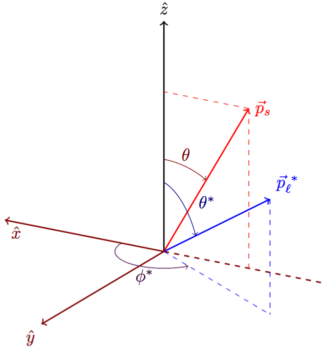
Couplings assumed to be real.
Need to make assumptions about the other couplings.

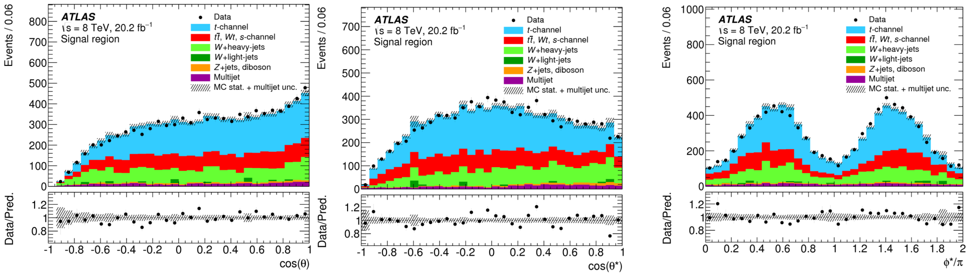
Triple differential angular decay rate

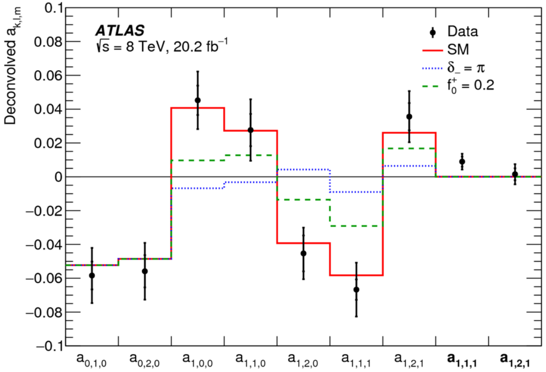
[JHEP 12 (2017) 017](https://doi.org/)

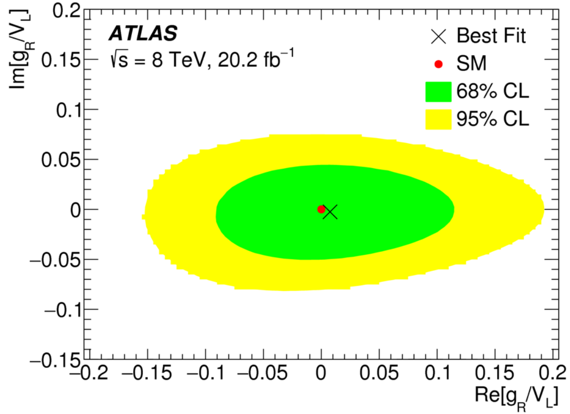
- A more complete approach was proposed in arXiv:1304.5639 to simultaneously constrain the full Wtb parameter space by measuring the triple-differential decay rate.
- Using single top events.

$$
\begin{aligned}
\varrho(\theta,\theta^*,\phi^*;P) = \frac{1}{N}\frac{d^3N}{d(\cos\theta)d\Omega^*} &= \frac{1}{8\pi}\Bigg\{\frac{3}{4}\left|A_{1,\frac{1}{2}}\right|^2(1+P\cos\theta)(1+\cos\theta^*)^2 \\
&+ \frac{3}{4}\left|A_{-1,-\frac{1}{2}}\right|^2(1-P\cos\theta)(1-\cos\theta^*)^2 \\
&+ \frac{3}{2}\left(\left|A_{0,\frac{1}{2}}\right|^2(1-P\cos\theta)+\left|A_{0,-\frac{1}{2}}\right|^2(1+P\cos\theta)\right)\sin^2\theta^* \\
&- \frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1+\cos\theta^*)\,\mathrm{Re}\left[e^{i\phi^*}A_{1,\frac{1}{2}}A^*_{0,\frac{1}{2}}\right] \\
&- \frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1-\cos\theta^*)\,\mathrm{Re}\left[e^{-i\phi^*}A_{-1,-\frac{1}{2}}A^*_{0,-\frac{1}{2}}\right]\Bigg\} \\
&= \sum_{k=0}^{1}\sum_{l=0}^{2}\sum_{m=-k}^{k} a_{k,l,m}M^m_{k,l}(\theta,\theta^*,\phi^*)\,,
\end{aligned}
$$



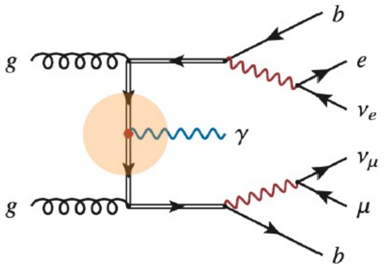


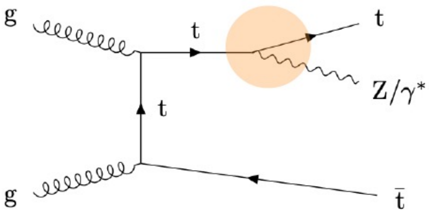


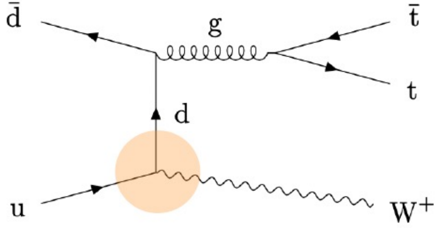


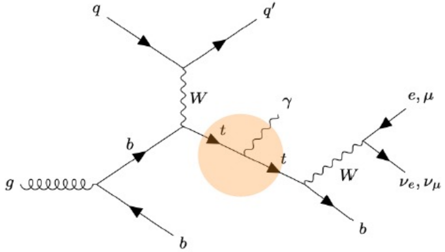
Couplings allowed to be complex.
No assumptions about the other couplings.

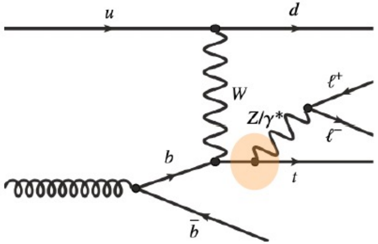
Associated production of top with γ, W, Z











Rare processes that

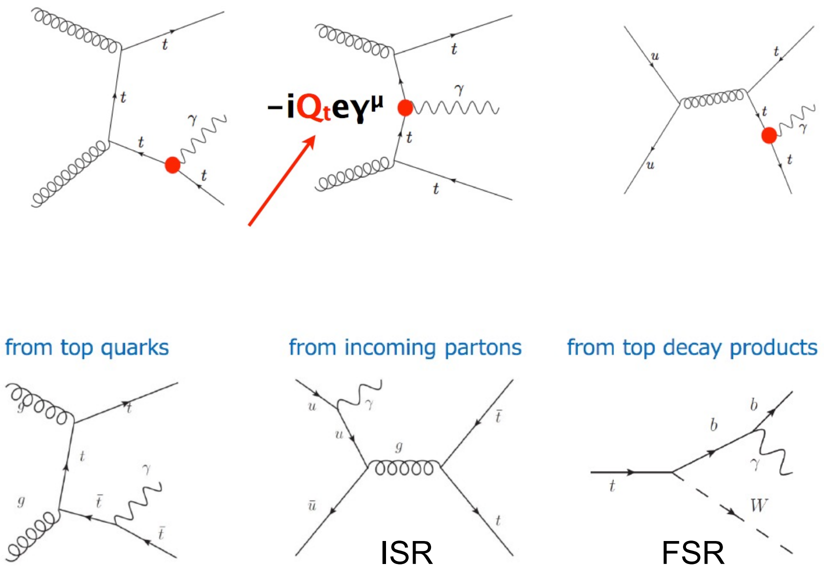
- **test electroweak couplings** of top quarks with bosons as predicted by SM,
- **probe anomalous couplings** for potential signs of new physics,
- **test higher-order calculations and Monte Carlo simulations** for better modelling,
- are **irreducible background** to many BSM searches and to important SM measurements (e.g. ttH or 4-top).

Top coupling to the photon

- Measurements of ttɣ/tɣ production allow to directly measure the top-quark charge, and more generally probe the tɣ electroweak coupling.
- Deviations from SM could point to new physics through anomalous dipole moments of the top quark.

$$\mathcal{L}_{\gamma tt} = -eQ_t\bar{t}\,\gamma^\mu t\; A_\mu - e\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\,(d_V^\gamma + i d_A^\gamma\gamma_5)\,t\; A_\mu$$

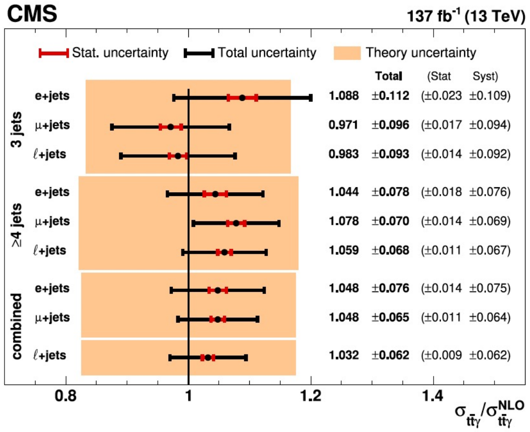
- Photons can be emitted from the top quark, incoming quarks (initial-state radiation, ISR) or top-quark decay products (final-state radiation, FSR).
  ➔ Need event selection that enhaces photons emitted by top quarks.



Measurements of $t\bar{t}\gamma$ production

JHEP 12 (2021) 180

- Measurements performed at 7 TeV, 8 TeV and 13 TeV.
- Most recent measurements exploit ttbar l+jets and dilepton final states, and include both inclusive fiducial cross-sections and differential cross-sections.
- Good agreement with the theoretical predictions. Sensitivity to EFT operators in the tail of the photon p_T distribution.



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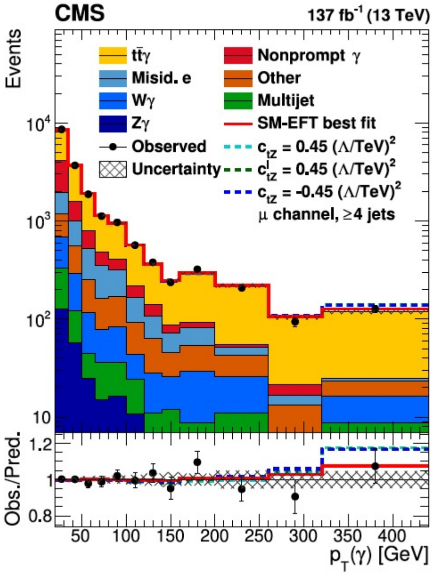
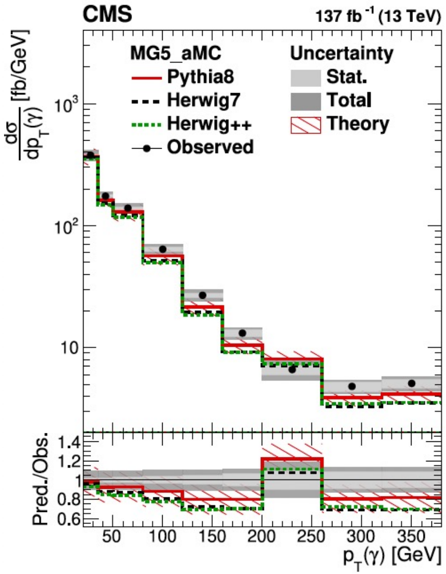
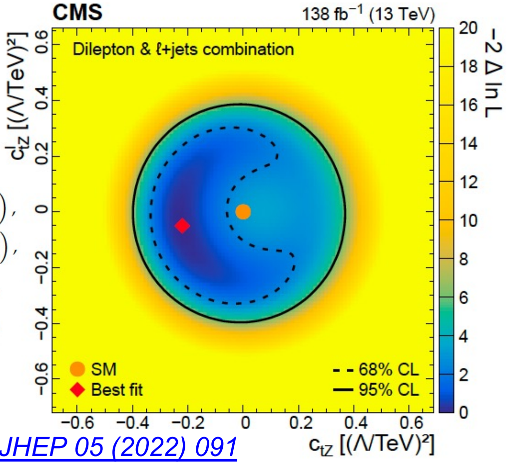




$$c_{tZ} = \mathrm{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right),$$
$$c_{tZ}^{I} = \mathrm{Im}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right),$$
$$c_{t\gamma} = \mathrm{Re}\left(\cos\theta_W C_{uB}^{(33)} + \sin\theta_W C_{uW}^{(33)}\right),$$
$$c_{t\gamma}^{I} = \mathrm{Im}\left(\cos\theta_W C_{uB}^{(33)} + \sin\theta_W C_{uW}^{(33)}\right),$$



JHEP 05 (2022) 091

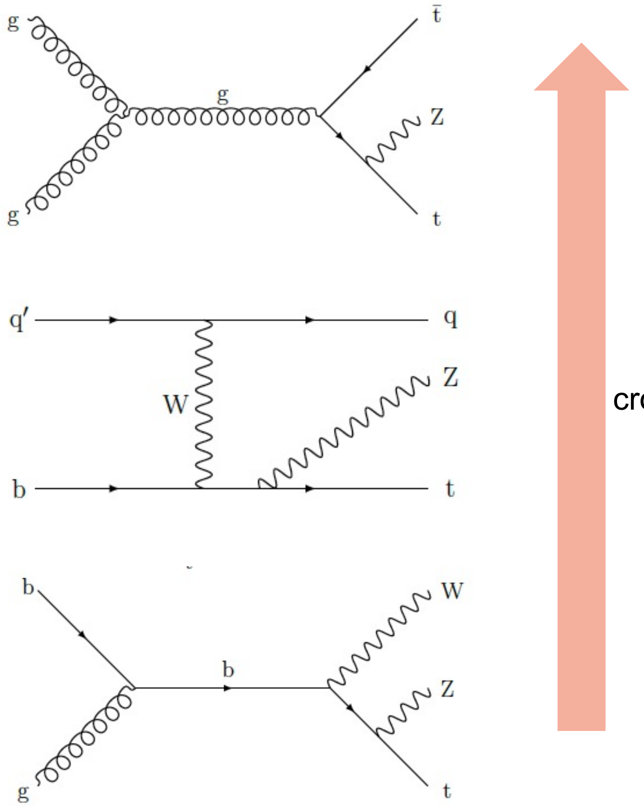
Top coupling to the Z boson

- Several processes provide sensitivity to the tZ coupling.
- Deviations can be parameterized via EFT operators:

$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \mathcal{M}_{\mathrm{EFT}} = \mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{M}_i,$$

Operator	WC	Mapping to Warsaw-basis coefficients
$\mathcal{O}_{\mathrm{tZ}}$	c_{tZ}	$\mathrm{Re}\{-s_{\mathrm{W}} c_{\mathrm{uB}}^{(33)} + c_{\mathrm{W}} c_{\mathrm{uW}}^{(33)}\}$
$\mathcal{O}_{\mathrm{tW}}$	c_{tW}	$\mathrm{Re}\{c_{\mathrm{uW}}^{(33)}\}$
$\mathcal{O}_{\varphi\mathrm{Q}}^{3}$	$c_{\varphi\mathrm{Q}}^{3}$	$c_{\varphi\mathrm{q}}^{3(33)}$
$\mathcal{O}_{\varphi\mathrm{Q}}^{-}$	$c_{\varphi\mathrm{Q}}^{-}$	$c_{\varphi\mathrm{q}}^{1(33)} - c_{\varphi\mathrm{q}}^{3(33)}$
$\mathcal{O}_{\varphi\mathrm{t}}$	$c_{\varphi\mathrm{t}}$	$c_{\varphi\mathrm{u}}^{(33)}$

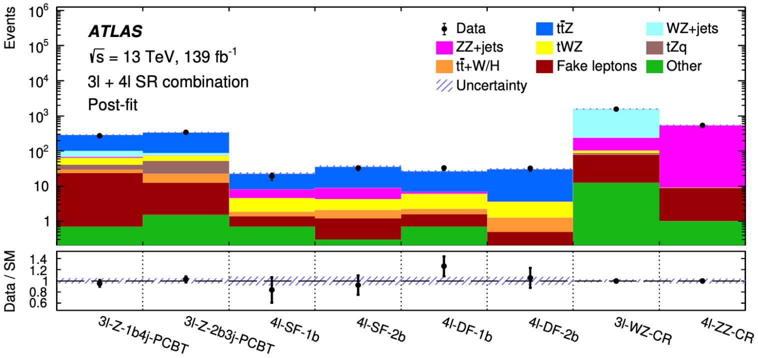
- The definitions of the relevant Warsaw-basis operators can be found in arXiv:1802.07237.



Higher cross-section

Measurements of ttZ production

- Measurements target 3l and 4l final states to reduce backgrounds (with Z→ll).
- Both inclusive cross-sections and differential cross-section in particle and parton level in a fiducial phase space.

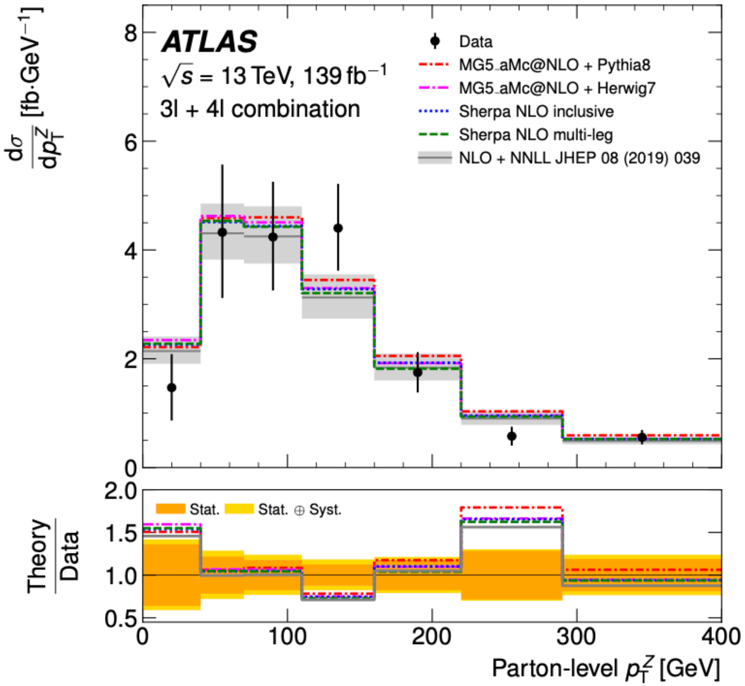


$$\sigma_{t\bar{t}Z}^{incl} = 0.99 \pm 0.05(stat) \pm 0.08(syst)\ pb$$

$$\sigma_{t\bar{t}Z}^{SM} = 863^{+8.5\%}_{-9.9\%}(scale)^{+3.2\%}_{-3.2\%}(PDF + \alpha_s)\ fb$$

(@ NLO QCD + NNLL soft-gluon resummation)

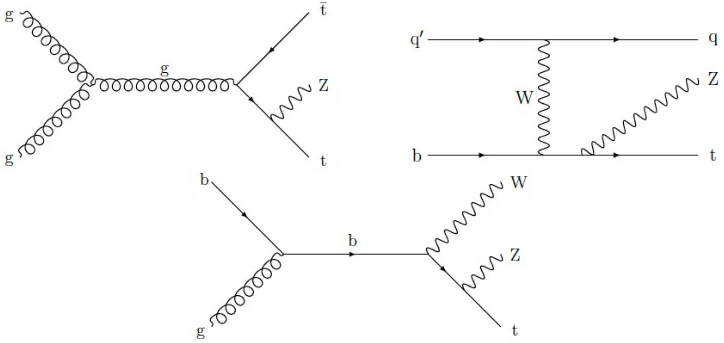
EPJC 81 (2021) 737



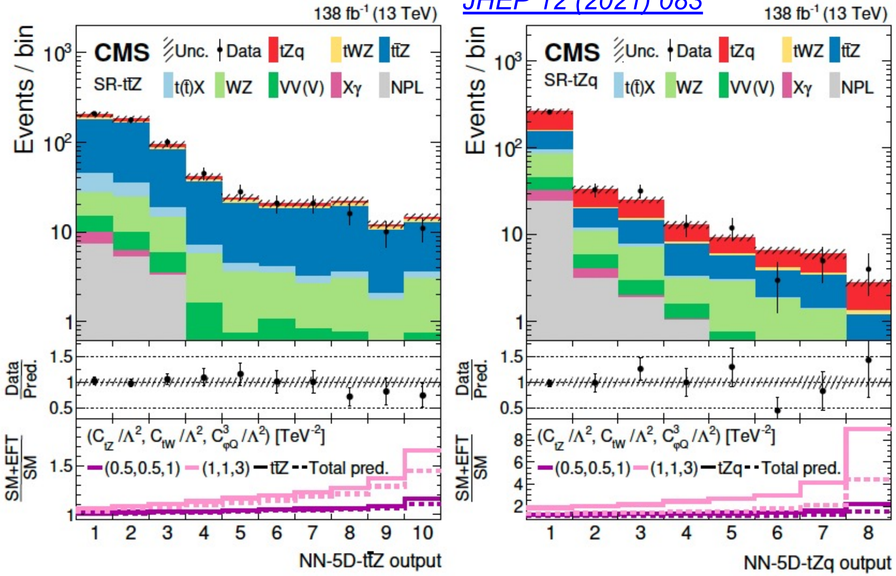
All measurements in agreement with SM
Dominant uncertainties: ttZ parton shower, modelling of tWZ

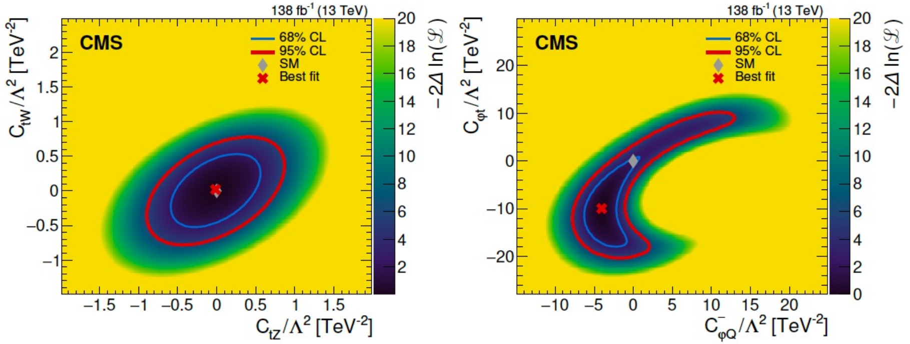
Constraints on ttZ anomalous couplings

- Consider all relevant production modes with one or two tops and a Z boson, in 3l and 4l final states.
- In 3l events use NNs to categorize events into ttZ, tZq and Other, and to discriminate between SM and SM+EFT hypotheses.



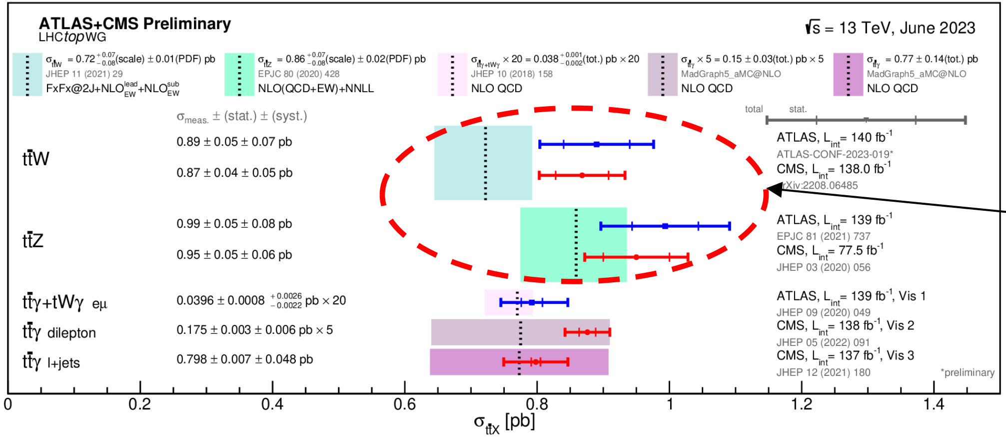
JHEP 12 (2021) 083



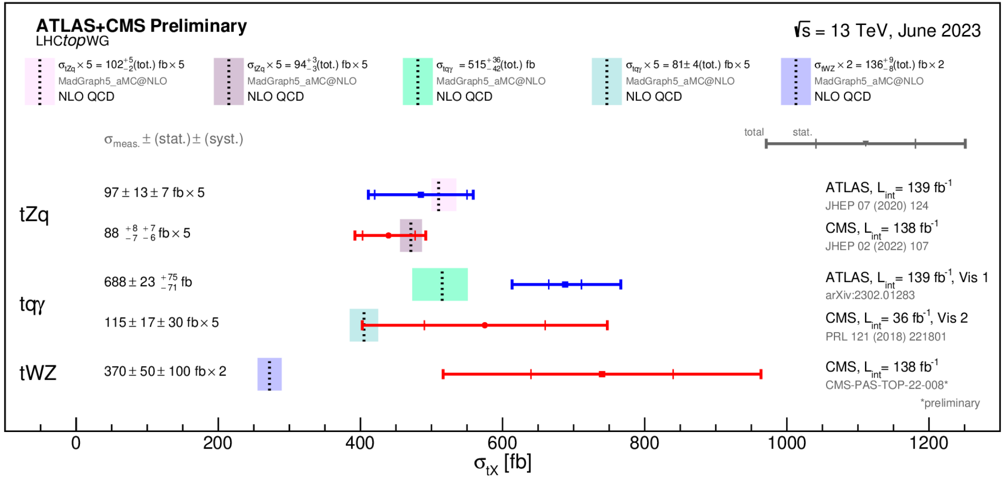


Results in agreement with SM

Summary of tt(t)+X measurements

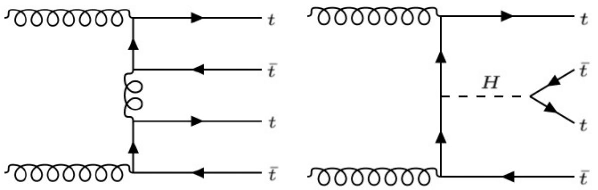


Looking forward to improved measurements in Run 3!



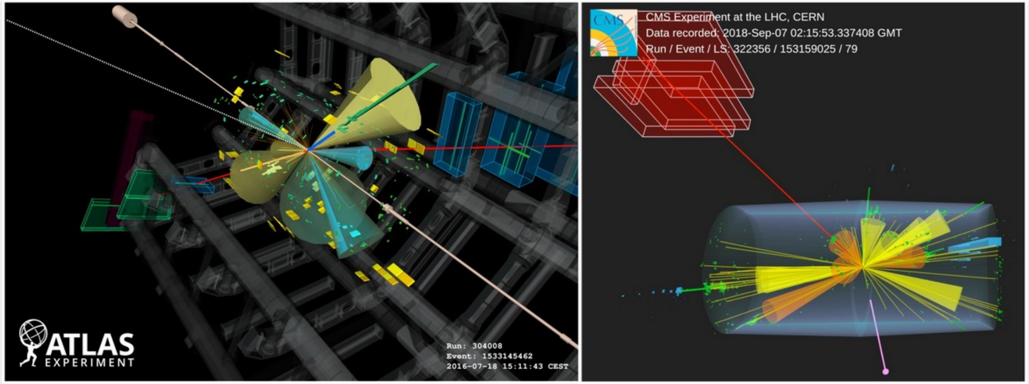
Observation of 4-top production

ATLAS and CMS observe simultaneous production of four top quarks



The ATLAS and CMS collaborations have both observed the simultaneous production of four top quarks, a rare phenomenon that could hold the key to physics beyond the Standard Model

24 MARCH, 2023 | By Naomi Dinmore



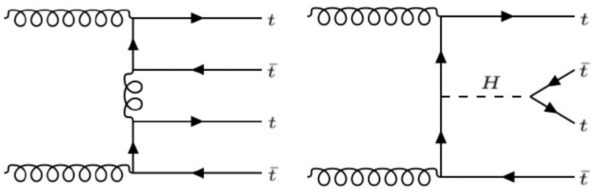
Event displays of four-top-quark production from ATLAS (left) and CMS (right).

https://home.cern/news/news/physics/atlas-and-cms-observe-simultaneous-production-four-top-quarks

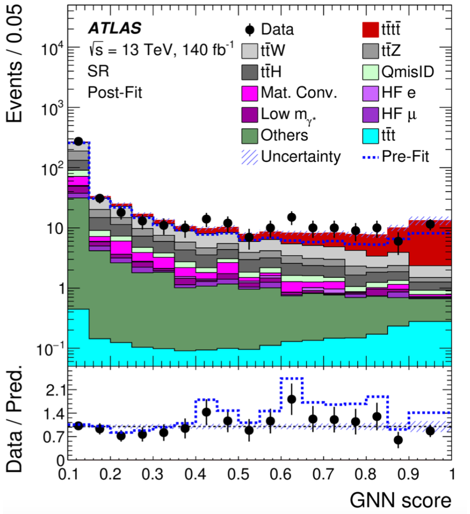
Observation of 4-top production

- One of the most-massive SM processes that can be probed at the LHC.
- σ~12 fb @NLO in SM; can be enhanced in BSM coupled to top quark.

- Most sensitive channels: 2lSS, 3l ➔ spectacular final state!
- Use ML techniques for signal-to-background discrimination.
  Main backgrounds: ttW, ttZ, ttH.

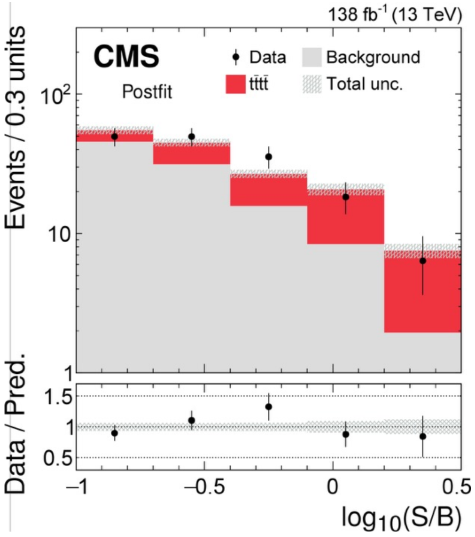


arXiv:2303.15061

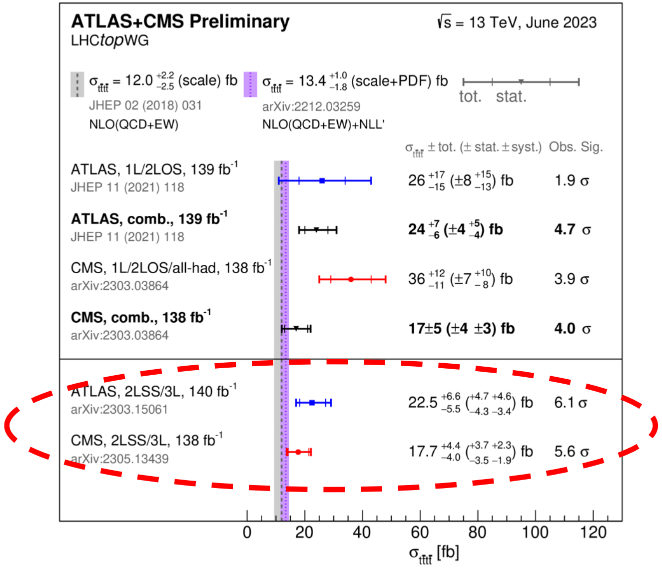


Obs. Significance: 6.1σ

arXiv:2305.13439



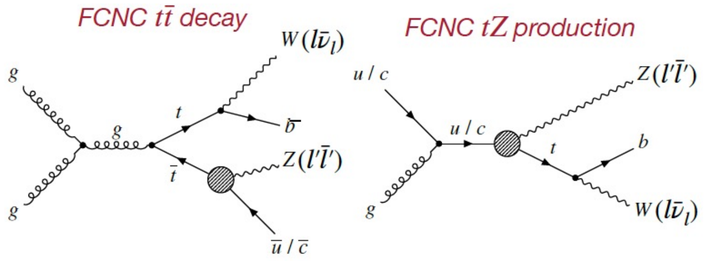
Obs. Significance: 5.6σ



In agreement w/ SM, but on the "high side"

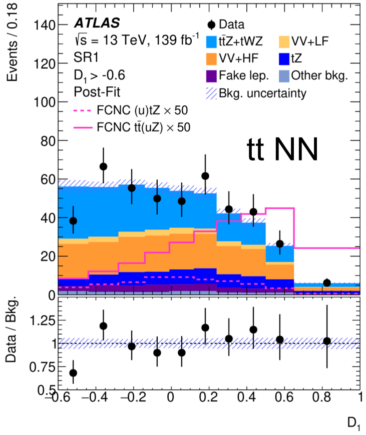
FCNC top interactions

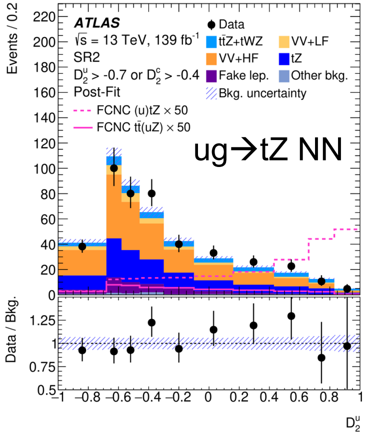
- Within the SM, neutral-current (NC) interactions are flavor-diagonal at tree level.
  Flavor-changing NC (FCNC) interactions are loop-induced and tiny: BR(t→cg)~10^{-10}, BR(t→cg)~10^{-12}, BR(t→cZ)~10^{-12}, BR(t-→cH)~10^{-7}
  Significantly enhanced in models beyond the SM (~x10^3-10^4)!



Example: Search for FCNC uZt and cZt interactions with single-top production and decay

- Consider events with =3l and =1 b-jet, consistent with signal topology.
- Main backgrounds: VV+heavy-flavor, ttZ and tZ.
- Use NNs for S/B discrimination.

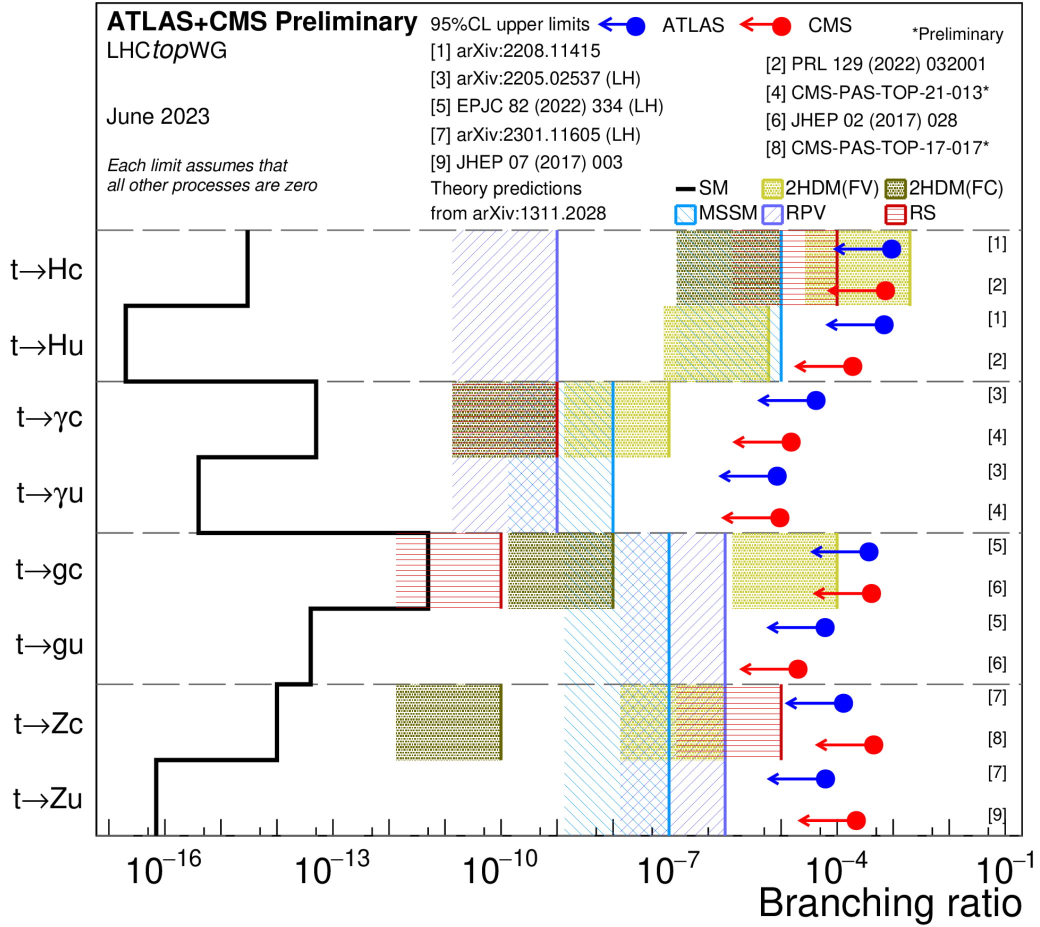




arXiv:2301.11605

Observable	Vertex	Coupling	Observed	Expected
	SRs+CRs			
$\mathcal{B}(t \to Zq)$	tZu	LH	6.2×10^{-5}	$4.9\,^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	6.6×10^{-5}	$5.1\,^{+2.1}_{-1.4} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	LH	13×10^{-5}	$11\,^{+5}_{-3} \times 10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	RH	12×10^{-5}	$10\,^{+4}_{-3} \times 10^{-5}$
$\lvert C_{uW}^{(13)*}\rvert$ and $\lvert C_{uB}^{(13)*}\rvert$	tZu	LH	0.15	$0.13\,^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert$ and $\lvert C_{uB}^{(31)}\rvert$	tZu	RH	0.16	$0.14\,^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert$ and $\lvert C_{uB}^{(23)*}\rvert$	tZc	LH	0.22	$0.20\,^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert$ and $\lvert C_{uB}^{(32)}\rvert$	tZc	RH	0.21	$0.19\,^{+0.04}_{-0.03}$

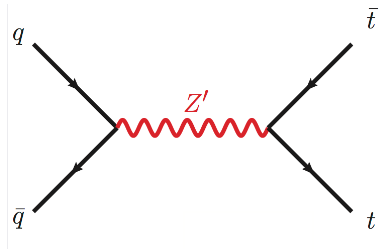
Summary of limits on FCNC top decays

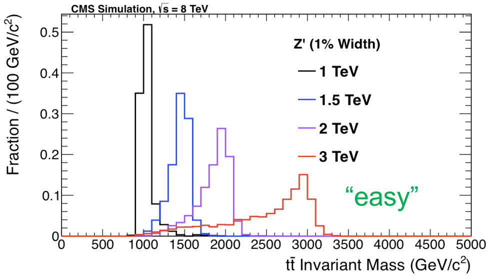


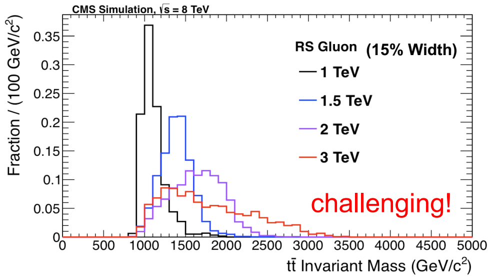
Exotic Top Production & Decay

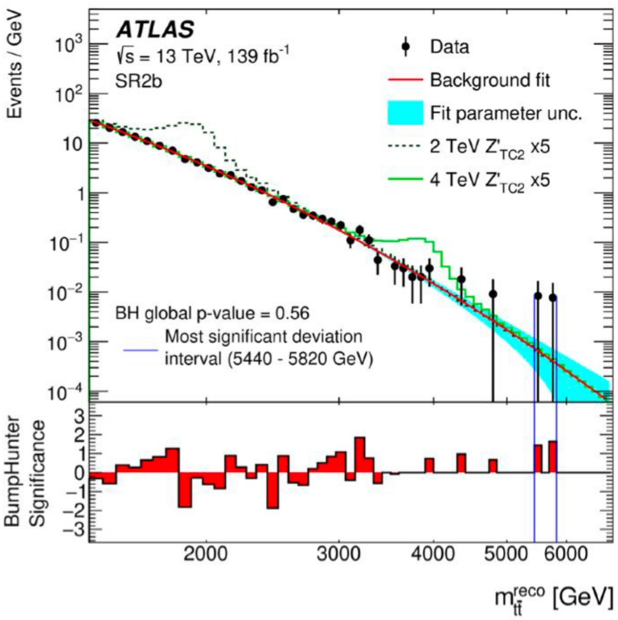
Top-philic heavy resonances: W', Z'

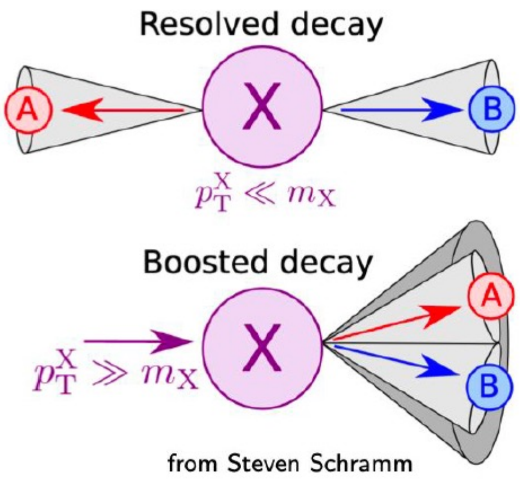
- Many BSM scenarios include heavy W' and Z' preferentially coupled to 3rd generation fermions.
- The signal can be searched for as a peak in the invariant mass distribution (small Γ/M) or a tail enhancement (large Γ/M).
- At high mass top/W decay products merge into a large-R jet. Need dedicated boosted-object tagging!



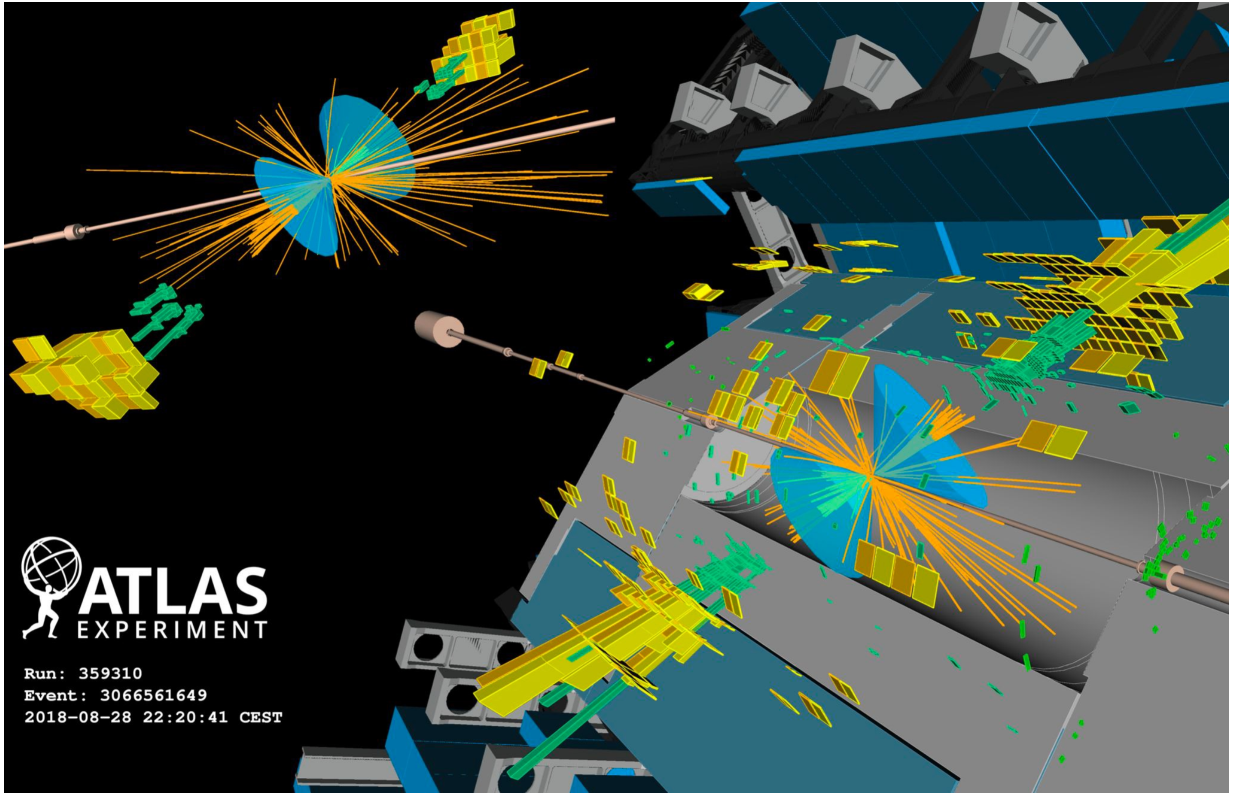


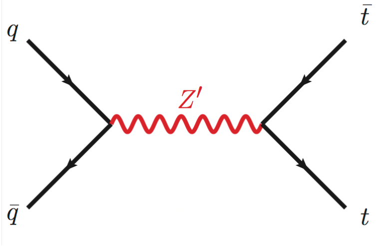


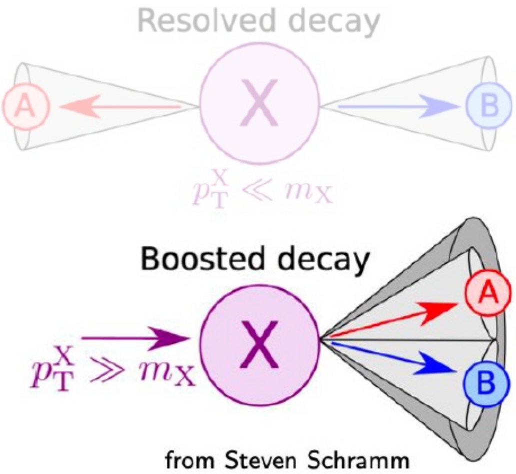




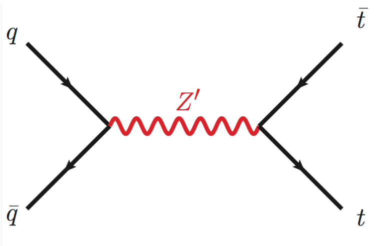
Top-philic heavy resonances: W', Z'

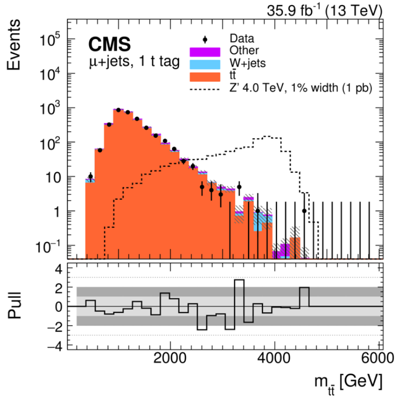


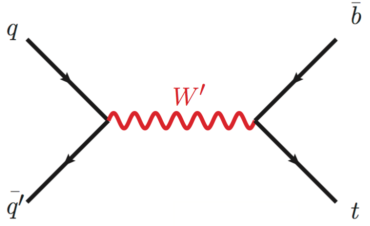


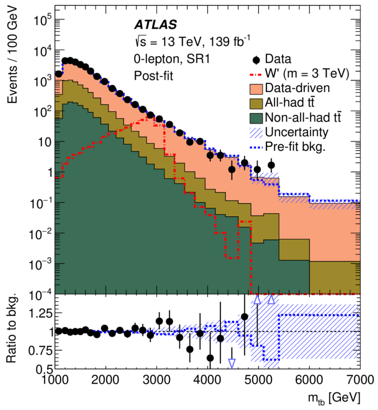


Top-philic heavy resonances: W', Z'

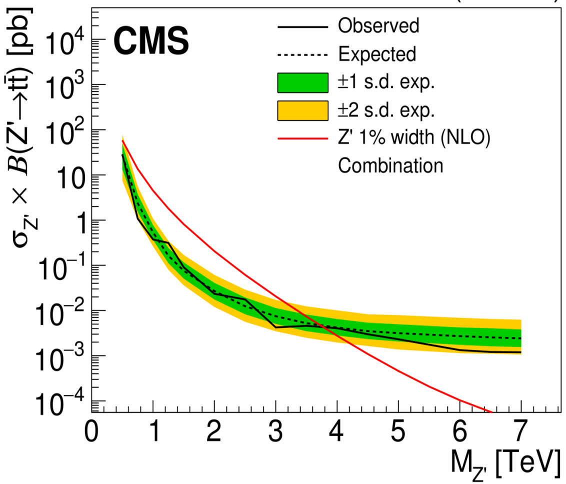




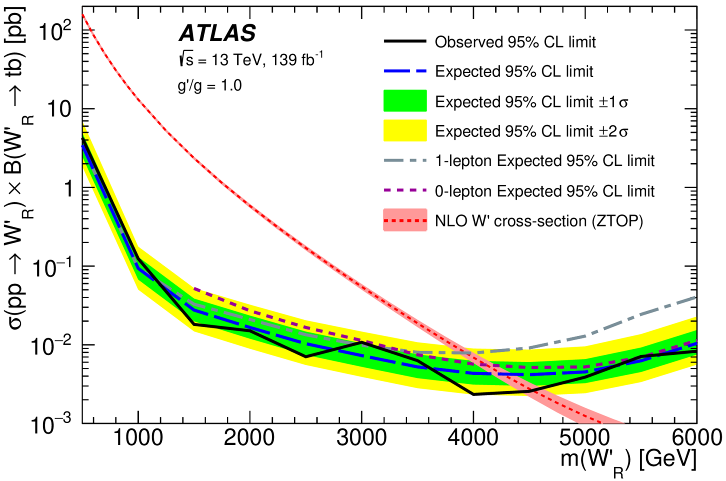




JHEP 04 (2019) 031

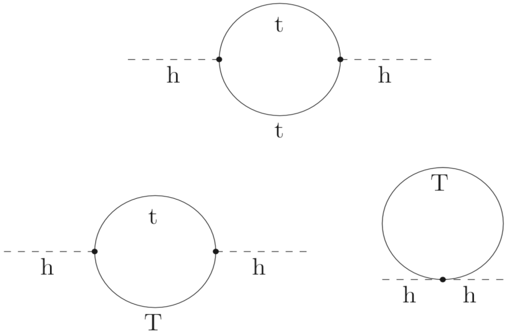


arXiv:2308.08521



Vector-like quarks

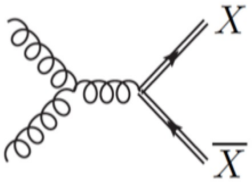
- Colored spin-1/2 fermions whose left and right components transform the same under $SU(2)_L$.
- Present in many BSM extensions: e.g. Composite Higgs, extra dimensions.
- Can mix with their SM counterparts and regulate the Higgs mass-squared divergence ➔ attractive solution to the Hierarchy Problem.

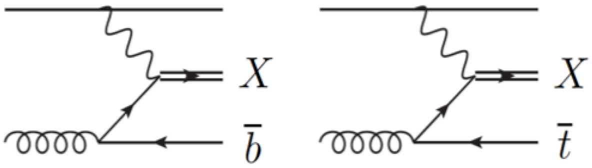


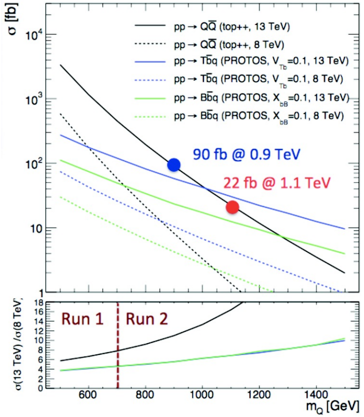
Production:

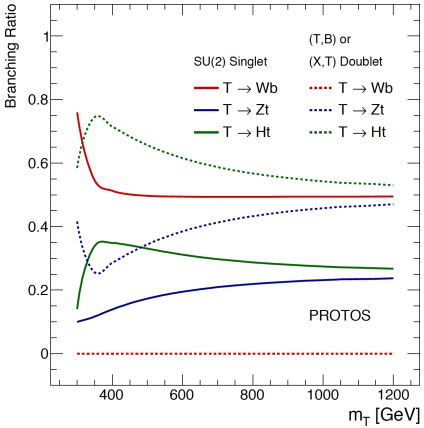
- Pair production: via QCD, "universal" production mode (just depends on m_Q).
- Single production: via EW interaction, depends on coupling strength, but potentially important at high m_Q.

Decay: T→Wb, Zt, Ht, all with sizable BR

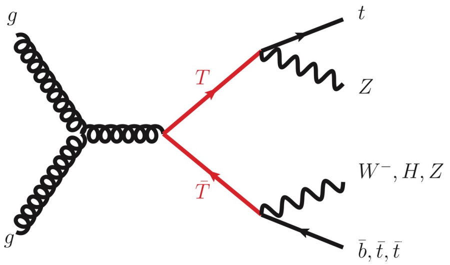




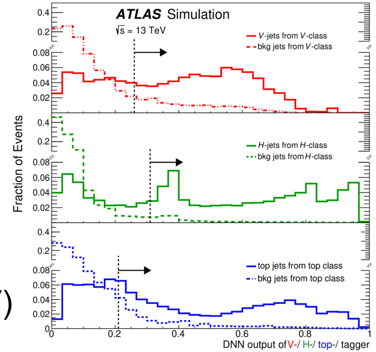


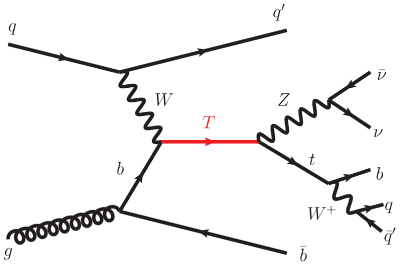


Vector-like quarks (and beyond)

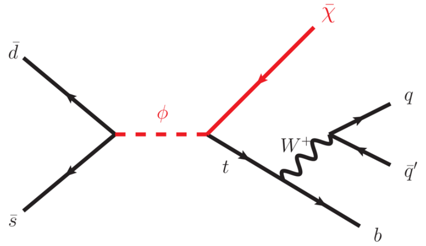


Signature: Z(→ll)+Multiple tags (t/H/V)



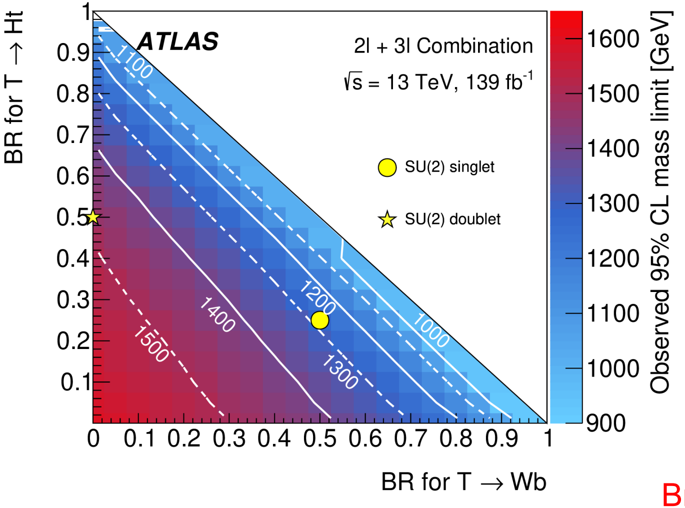


Signature: top+ETmiss

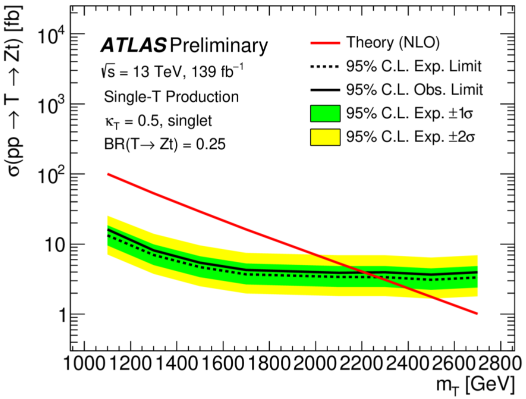


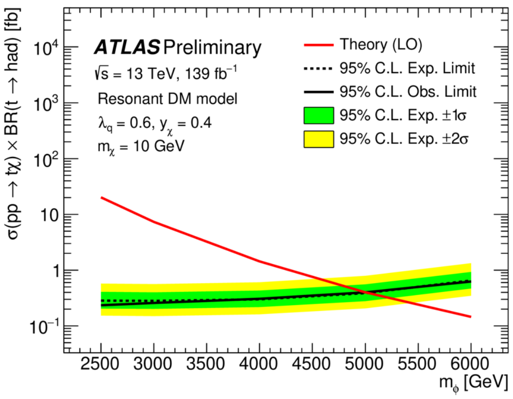
Also sensitive to models of top+DM production!

[PLB 843 (2023) 138019]



[ATLAS-CONF-2022-036]



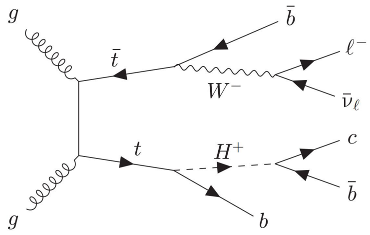


Broad program of searches underway

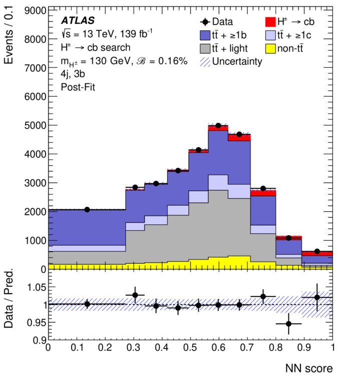
Top decaying into new light scalars

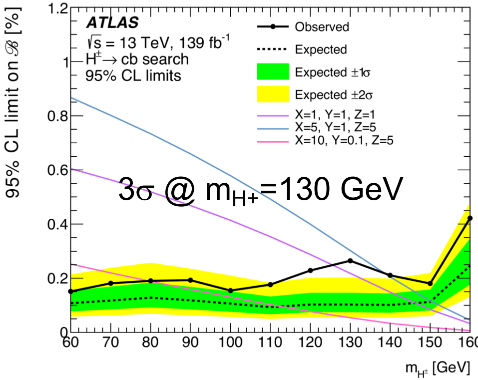
- Both searches target top quark decays into a light charged or neutral scalar.
- Final state: 1 lepton, 4-6 jets, 3 b-jets.
- Using NNs to suppress main background from tt+jets.

Search for t→H⁺b, H⁺→cb

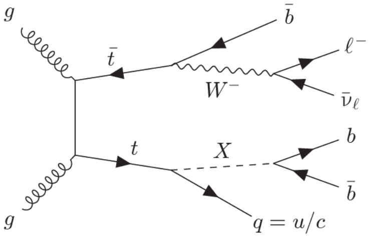


arXiv:2302.11739





Search for t→Xq, X→bb



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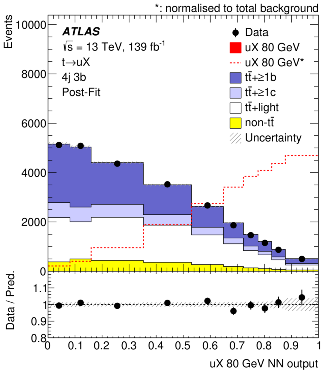
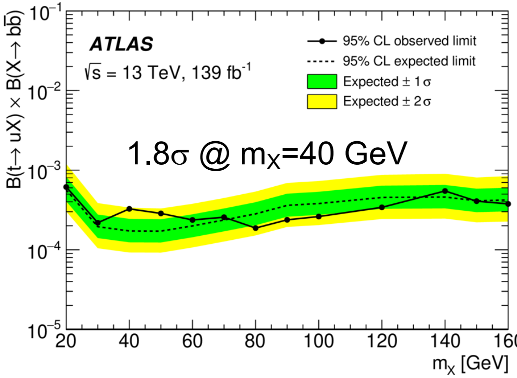




Searches being further pursued in Run 3

Conclusions

- Top quark physics is rich and exciting, and a central part the LHC physics program.
- Precise measurements of top quark production and properties allow for stringent tests of the SM, being at the same time sensitive to New Physics.
  - Many of the top measurements performed at the LHC are already dominated by systematics (e.g. jet energy scale, b-tagging, physics modelling). Reaching the ultimate precision requires a lot of effort and time from both experimentalists and theory community,
  - Some rare processes become accessible with the increase of statistics in Run 2 and beyond.

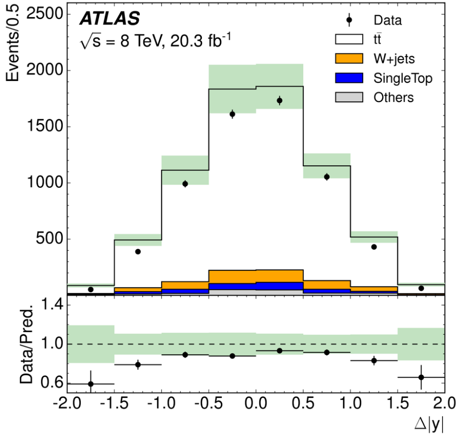
- A broad program of direct searches for New Physics in top quark final states is underway and offers one of the most compelling opportunities for discovery of new particles within kinematic reach of the LHC.
  - Many require developing new reconstruction techniques and/or analysis strategies.

- So far, all results are compatible with the SM but we are barely scratching the surface, with x20 more integrated to be cumulated by the end of the LHC!

Backup

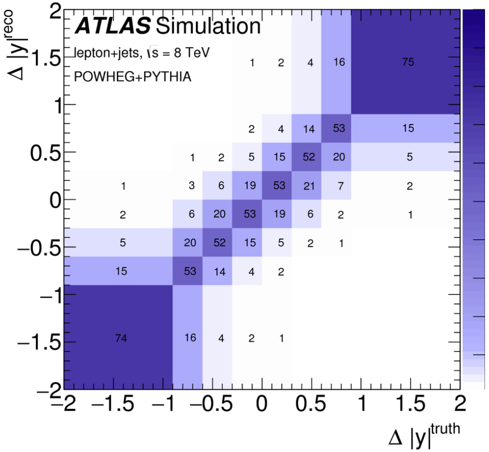
Charge asymmetry measurements

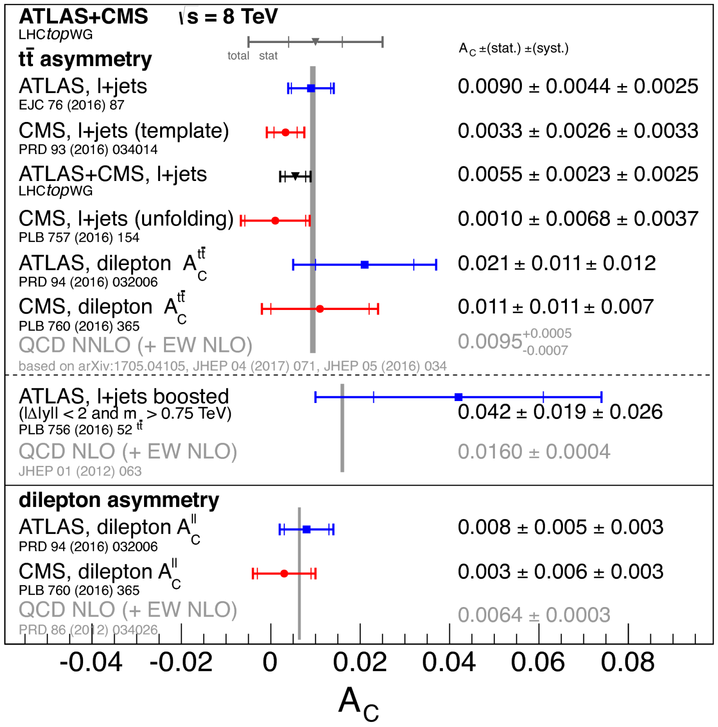
- Measurements performed in the l+jets (including also boosted top dedicated analysis) and dilepton channels.
- Different methods to reconstruct the ttbar kinematics (e.g. likelihood fit in l+jets, specific technique to deal with boosted top decays in l+jets boosted, kinematic method in dilepton).
- Unfolding method used to correct to parton level or template method (CMS).
- Inclusive and differential measurements as a function of mass, p_T and longitudinal boost β_Z of the ttbar system provided.



PLB 756 (2016) 52

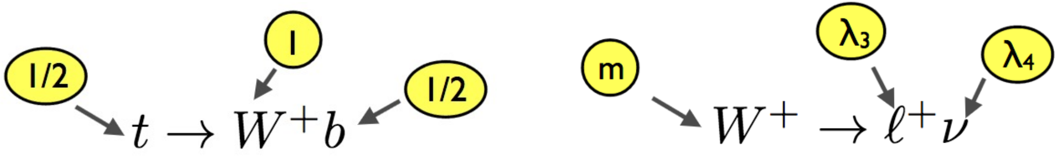
l+jets boosted

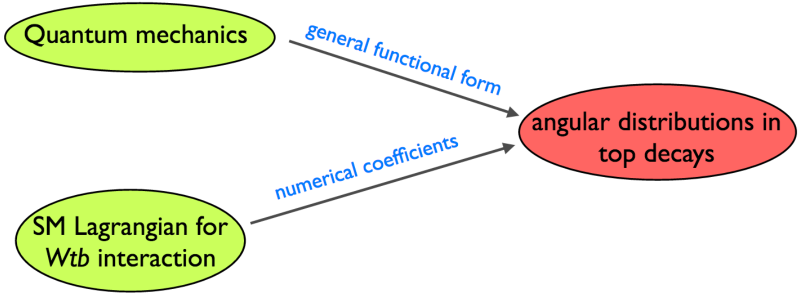


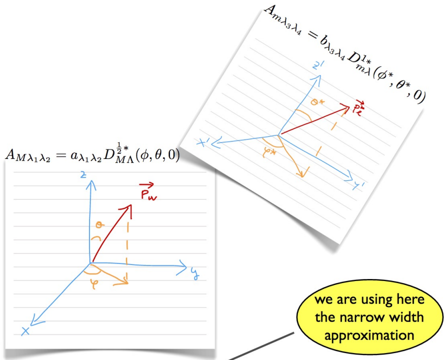


All compatible with SM predictions

Top decay within the SM







Using the helicity formalism of Jacob and Wick

we are using here the narrow width approximation

$$A_{M\lambda_2\lambda_3\lambda_4} = \sum_{\lambda_1} a_{\lambda_1\lambda_2} b_{\lambda_3\lambda_4} D^{\frac{1}{2}*}_{M\Lambda}(\phi,\theta,0) D^{1*}_{\lambda_1\lambda}(\phi^*,\theta^*,0)$$

global phase space factor — *b* helicities summed — common factor

$$\frac{d\Gamma}{d\phi\, d\cos\theta\, d\phi^*\, d\cos\theta^*} = C \sum_{MM'\lambda_1\lambda_1'\lambda_2} \rho_{MM'} a_{\lambda_1\lambda_2} a^*_{\lambda_1'\lambda_2} |b_{\lambda_3\lambda_4}|^2$$
$$\times D^{\frac{1}{2}*}_{M\lambda}(\phi,\theta,0) D^{\frac{1}{2}}_{M'\lambda'}(\phi,\theta,0)$$
$$\times D^{1*}_{\lambda_1\lambda}(\phi^*,\theta^*,0) D^{1}_{\lambda_1'\lambda}(\phi^*,\theta^*,0)$$

- The angular dependence is given by the well known Wigner D-functions.
- BSM corrections to the Wtb vertex will modify the t→Wb→lν angular distributions.
- 2 approaches: Measure asymmetries of angular distributions or measure the differential angular decay rate.

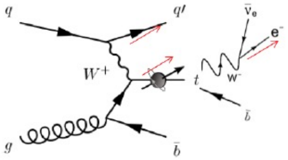
See J.A. Aguilar-Saavedra's lecture at TAE 2013:
http://benasque.org/2013tae/talks_contr/231_top.pdf

Top polarization in single top production

[JHEP 04 (2016) 073]

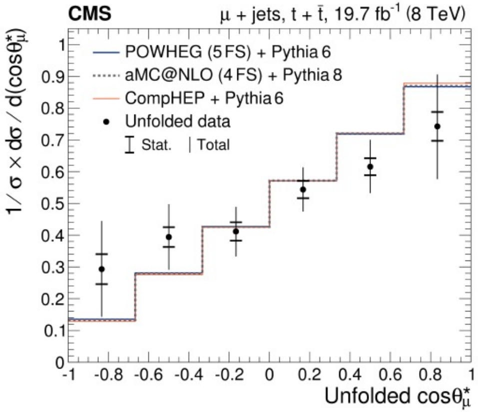
- In the t-channel, top quark is produced with a large degree of polarisation in the direction of spectator quark momentum [PRD 55 (1997) 7249].
- This direction is used to define the top quark spin axis.
- The top polarization can be measured from angular distributions of the decay products reconstructed in the top-quark rest frame.

$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_X)} = \frac{1}{2}(1 + \alpha_X P \cos\theta_X)$$

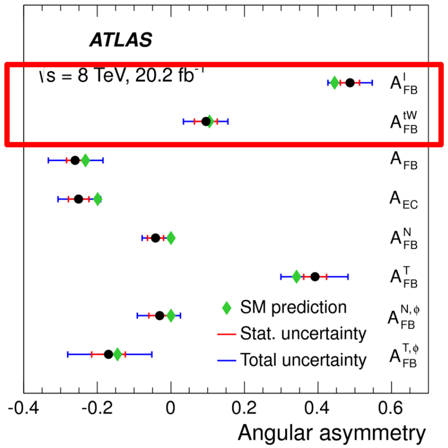


$\theta^* \equiv \measuredangle(l, q')$ in top rest frame

$$\alpha_{\ell^\pm} = \pm 0.998$$



[JHEP 04 (2017) 124]



$$A^{\ell}_{FB} = \frac{1}{N}[N(\cos\theta_\ell > 0) - N(\cos\theta_\ell < 0)] = \frac{1}{2}\alpha_\ell P$$

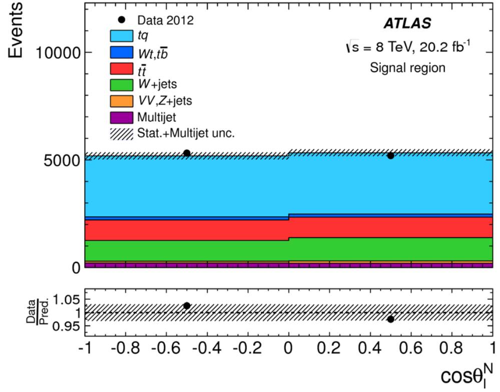
- Other asymmetries also proposed in Phys. Rev. Lett. B 718 (2013) 983, arXiv1404.1585.

- CMS has measured one asymmetry and finds some tension with the SM prediction (2σ). $A_\mu(t+\bar{t}) = 0.28 \pm 0.03\,(\text{stat}) \pm 0.1\,(\text{syst}) = 0.28 \pm 0.12$
- ATLAS measured more precisely two asymmetries sensitive to P and finds results compatible with SM.

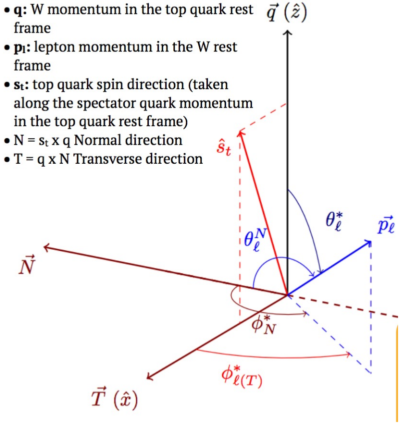
W-boson spin observables

JHEP 04 (2017) 124

- They can be determined from angular distributions of the charged lepton reconstructed in the W rest frame.
- The spin density matrix elements for the W components 0, +1-1 from the decay of polarised top quarks can be parametrised in terms of 6 independent observables $<S_{1,2,3}>$, $<T_0>$, $<A_{1,2}>$ which can be measured via asymmetries.
- For un-polarised top quark decays, the only meaningful direction in the top quark rest frame is the one of the W boson momentum → $\cos\theta_l^*$ → Helicity fractions F_0, F_R, F_L.

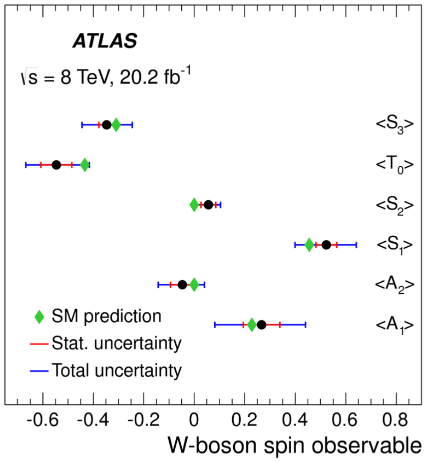


- **q**: W momentum in the top quark rest frame
- **p$_l$**: lepton momentum in the W rest frame
- **s$_t$**: top quark spin direction (taken along the spectator quark momentum in the top quark rest frame)
- N = s$_t$ x q Normal direction
- T = q x N Transverse direction



Asymmetry	Angular observable	Polarisation observable	SM prediction
$A_{\rm FB}^{\ell}$	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
$A_{\rm FB}^{tW}$	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P(F_{\rm R}+F_{\rm L})$	0.10
$A_{\rm FB}$	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}(F_{\rm R}-F_{\rm L})$	−0.23
$A_{\rm EC}$	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}(1-3F_0)$	−0.20
$A_{\rm FB}^{T}$	$\cos\theta_\ell^T$	$\frac{3}{4}\langle S_1\rangle$	0.34
$A_{\rm FB}^{N}$	$\cos\theta_\ell^N$	$-\frac{3}{4}\langle S_2\rangle$	0
$A_{\rm FB}^{T,\phi}$	$\cos\theta_\ell^* \cos\phi_T^*$	$-\frac{2}{\pi}\langle A_1\rangle$	−0.14
$A_{\rm FB}^{N,\phi}$	$\cos\theta_\ell^* \cos\phi_N^*$	$\frac{2}{\pi}\langle A_2\rangle$	0

$$\left.\begin{aligned} A^N_{FB} &\approx 0.64 P \,\mathrm{Im}\, g_R \\ A^l_{FB} &= \frac{1}{2}\alpha_l P \end{aligned}\right\} \mathrm{Im}\, g_R \in [-0.18,\ 0.06] \text{ at 95\% CL.}$$



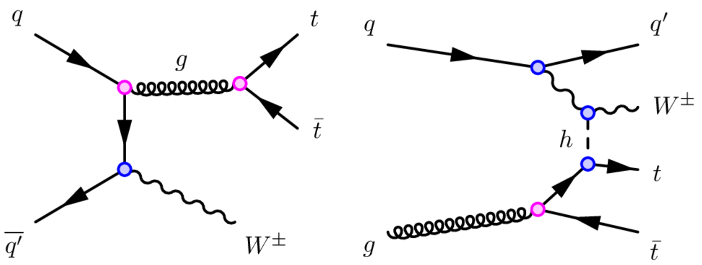
All measurements in agreement with SM predictions. First constraints on imaginary part of g_R (assuming SM values for all other couplings).

Measurements of ttW production

- ttW cross-section measured 20%-50% larger than prediction (consistently by both ATLAS and CMS).

- Inclusive and differential cross section (and charge asymmetry) measurements in 2lSS and 3l final states.
- Main backgrounds ttZ/γ*/H, VV and fake leptons.

- Inclusive cross section remains larger than theory predictions.
- Fist differential measurement in 9 observables.



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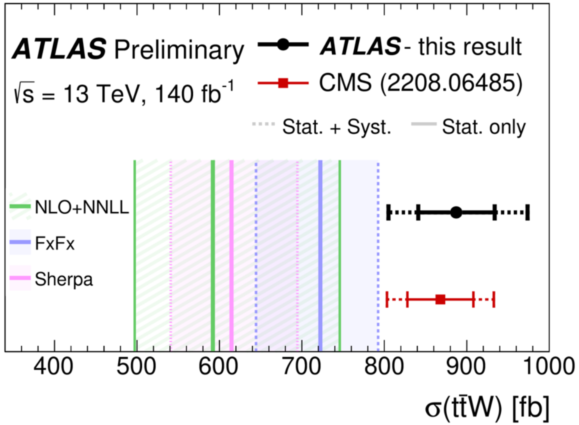
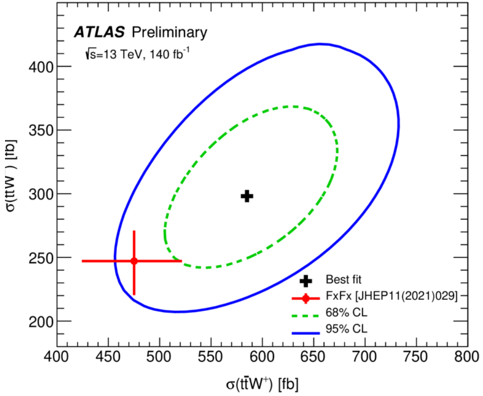
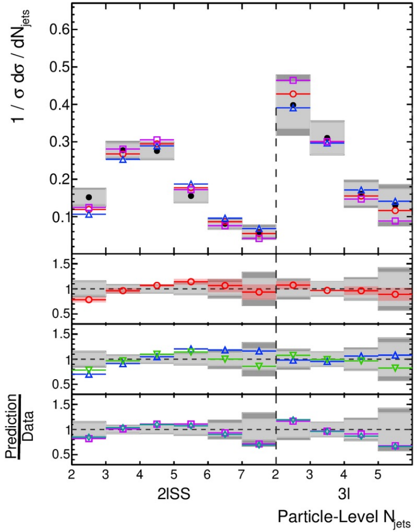




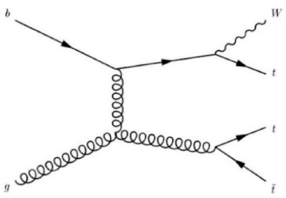
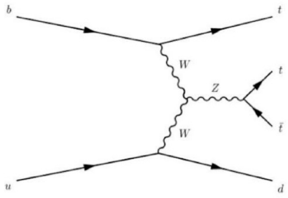


Shapes consistent between various MC and data

4-top interpretations by ATLAS

arXiv:2303.15061

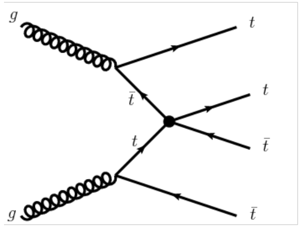
First limits on 3-top production

SM (NLO): σ(tttW) = 1.02 fb   σ(tttq) = 0.65 fb

Processes	95% CL cross section interval [fb]	
	$\mu_{t\bar{t}t\bar{t}} = 1$	$\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]

Limits on qqtt EFT operators



$$\sigma_{t\bar{t}t\bar{t}} = \sigma^{SM}_{t\bar{t}t\bar{t}} + \frac{1}{\Lambda^2}\sum_i C_i\sigma_i^{(1)} + \frac{1}{\Lambda^4}\sum_{i\leq j} C_iC_j\sigma_{i,j}^{(2)}$$

Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
O^1_{QQ}	[-2.4, 3.0]	[-3.5, 4.1]
O^1_{Qt}	[-2.5, 2.0]	[-3.5, 3.0]
O^1_{tt}	[-1.1, 1.3]	[-1.7, 1.9]
O^8_{Qt}	[-4.2, 4.8]	[-6.2, 6.9]

Also, bounds on CP structure of top-Higgs Yukawa coupling and Higgs oblique parameter.