Top quark measurements at the LHC

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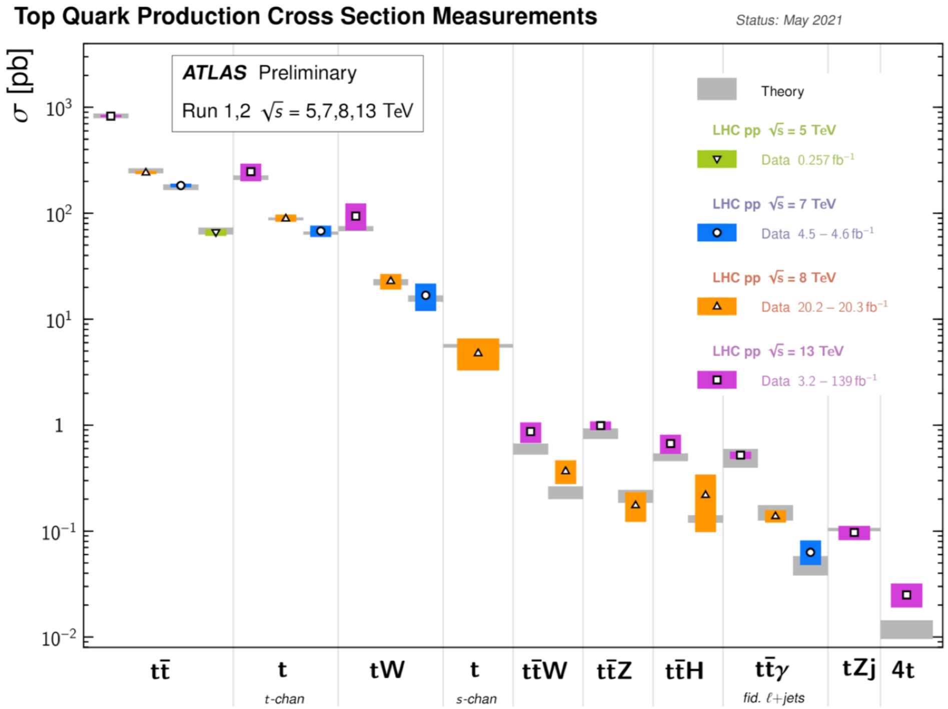
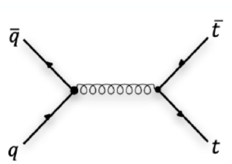
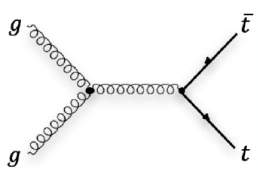
Introduction

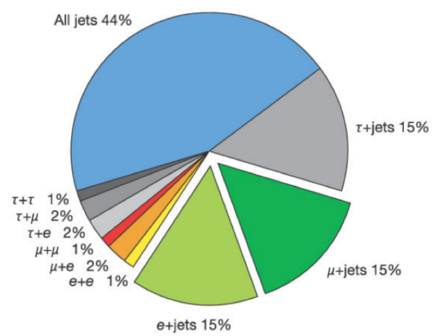


- Top quark is abundantly produced at the LHC. The process cross sections range from ~800 pb to ~20 fb.
- More data makes possible differential measurements, such as EFT.
- It decays before hadronization. Can gain deep understanding of its properties such as mass, CP and polarizations.

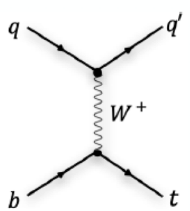
Pair production and decay:

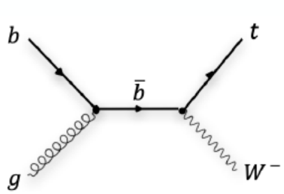




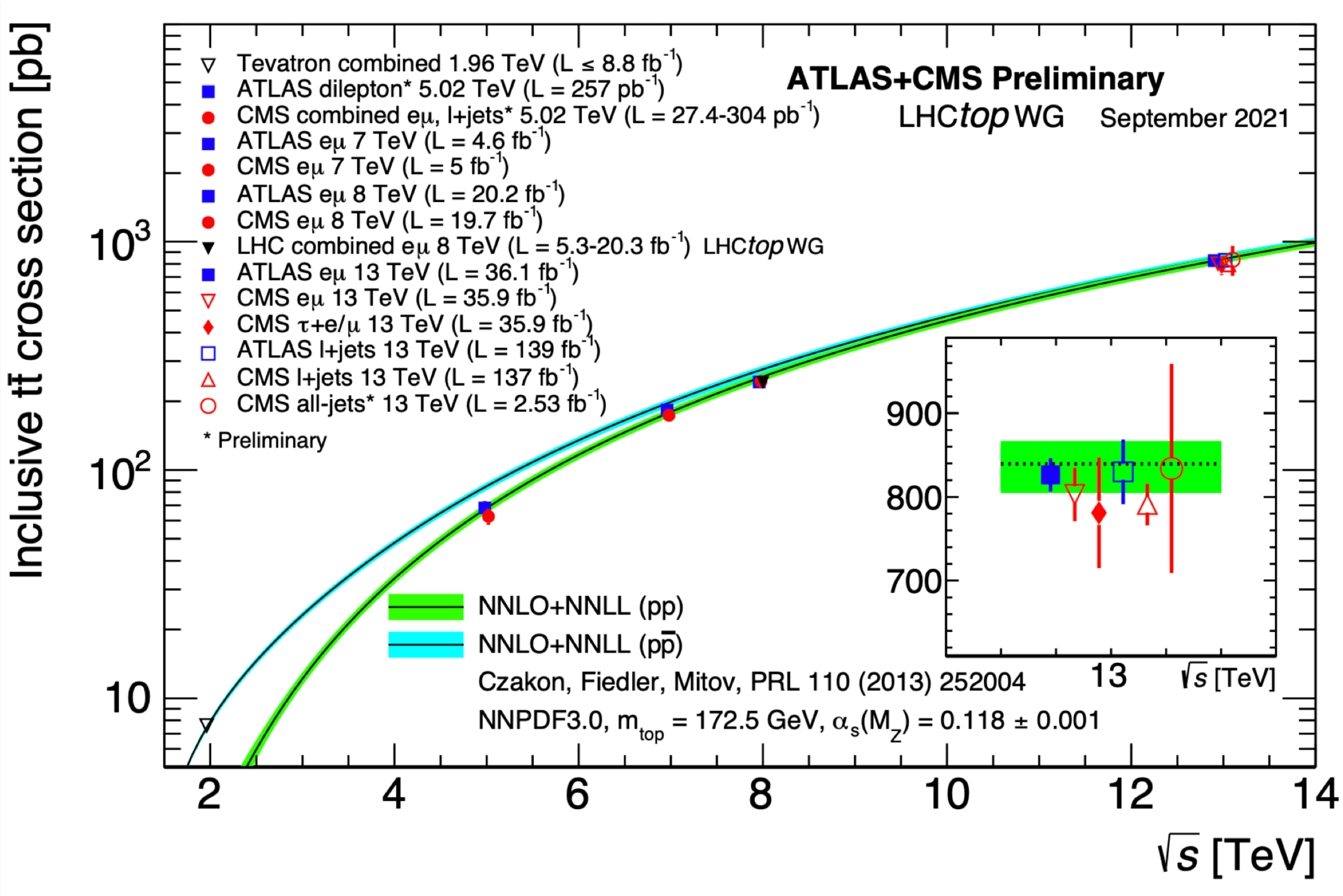


Single production:



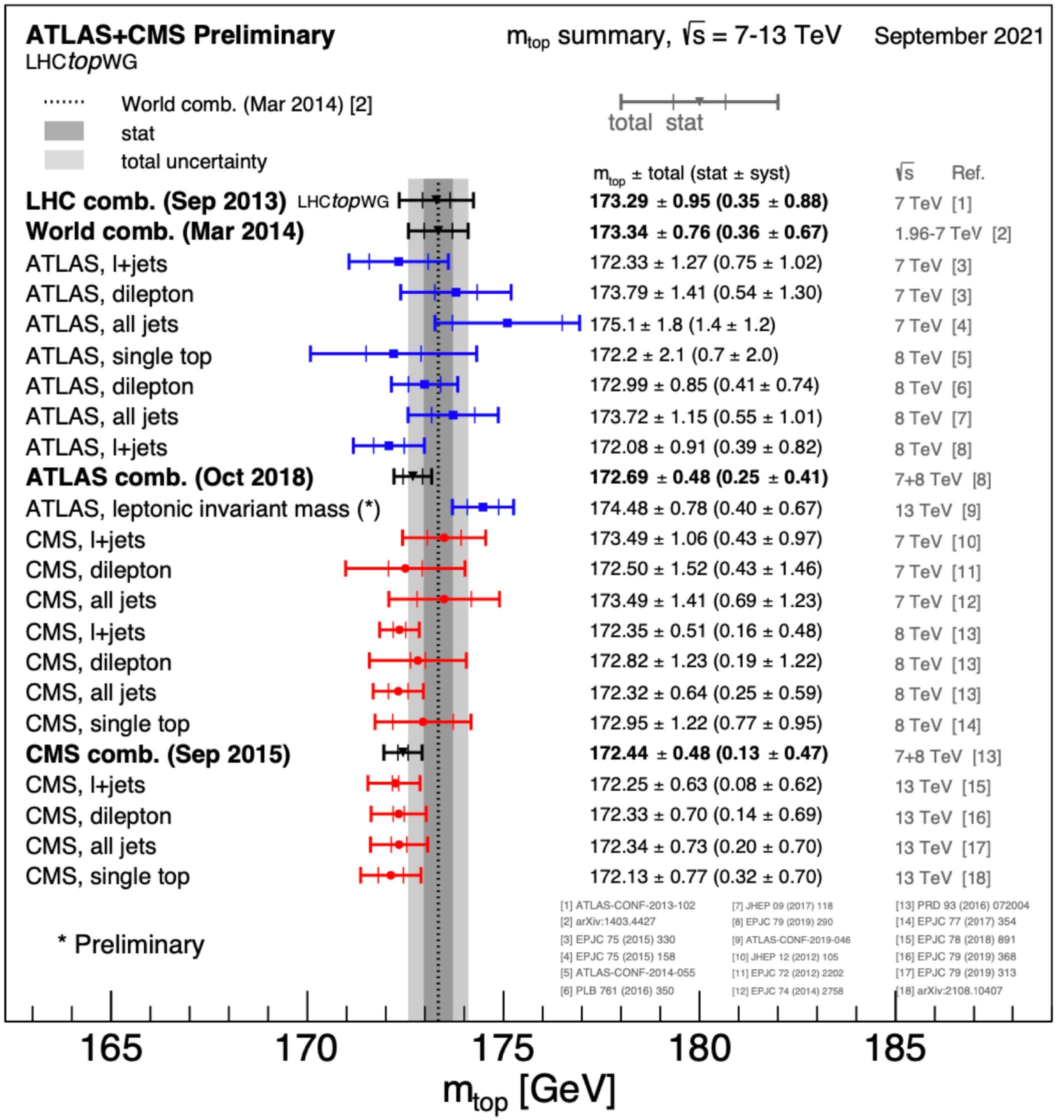


Top pair production



Measurements from ATLAS and CMS at 5, 7, 8 and 13 TeV. Good agreement between measurements and theory (NNLO+NNLL QCD).

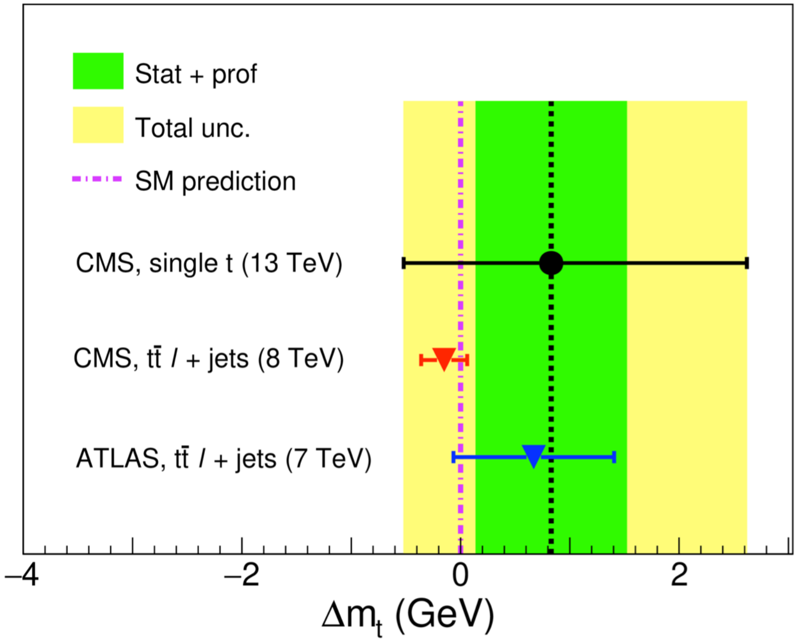
Top mass



- Monte Carlo mass is close to the pole mass, but non-perturbative effects etc. introduce theory systematics.
- Direct (reconstruction of top decay) and indirect (inclusive or differential cross sections) top quark mass measurements are carried out at LHC, with uncertainty at ~0.5 GeV (systematics dominated)

Top mass

[CMS-TOP-19-009]



$$m_t = 172.62 \pm 0.37(\text{stat+prof})^{+0.97}_{-0.65}(\text{ext})\,\text{GeV} = 172.62^{+1.04}_{-0.75}\,\text{GeV},$$

$$m_{\bar{t}} = 171.79 \pm 0.58(\text{stat+prof})^{+1.32}_{-1.39}(\text{ext})\,\text{GeV} = 171.79^{+1.44}_{-1.51}\,\text{GeV}.$$

$$m_t = 172.13 \pm 0.32(\text{stat+prof})^{+0.69}_{-0.70}(\text{ext})\,\text{GeV} = 172.13^{+0.76}_{-0.77}\,\text{GeV}$$

$$\Delta m_t = m_t - m_{\bar{t}} = 0.83 \pm 0.69(\text{stat+prof})^{+1.65}_{-1.16}(\text{ext})\,\text{GeV} = 0.83^{+1.79}_{-1.35}\,\text{GeV}$$

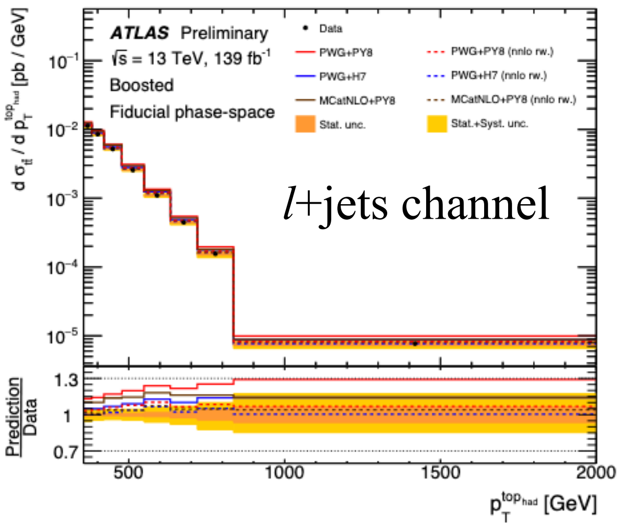
CMS measured the top and anti-top masses independently using 2015-2016 data.

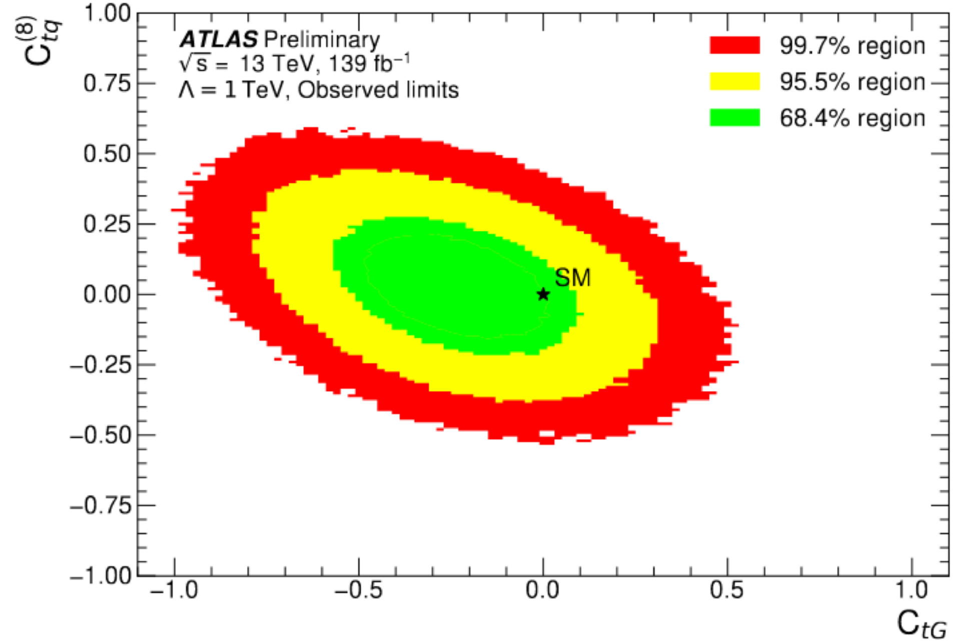
- A data sample enriched with leptonic t-channel single top: 1 e/μ, 2 jets, 1 b-jet@55%, M_T>50 GeV.
- MVA approach with 2 BDTs trained.
- Estimate QCD background from fit to M_T and subtract from data.
- Derive mass calibration to correct fitted mass.

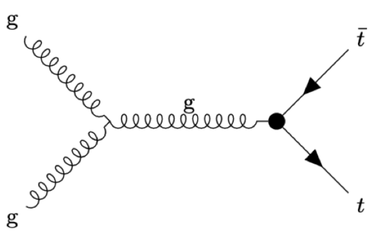
Results consistent with the conservation of CPT

Top pair differential search

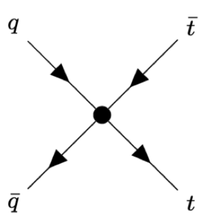
[ATL-CONF-2021-031]







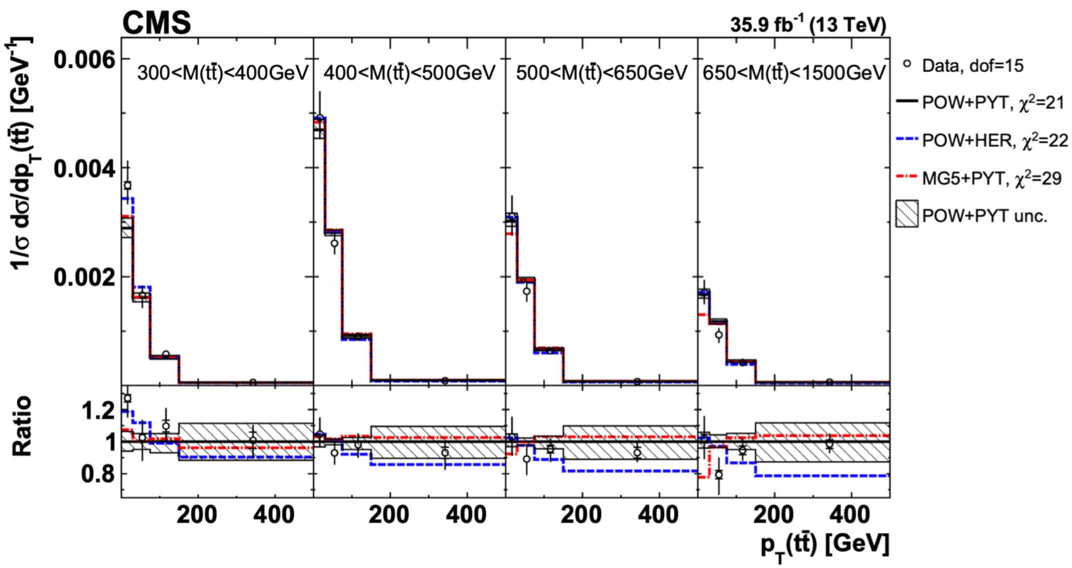
C_{tG}

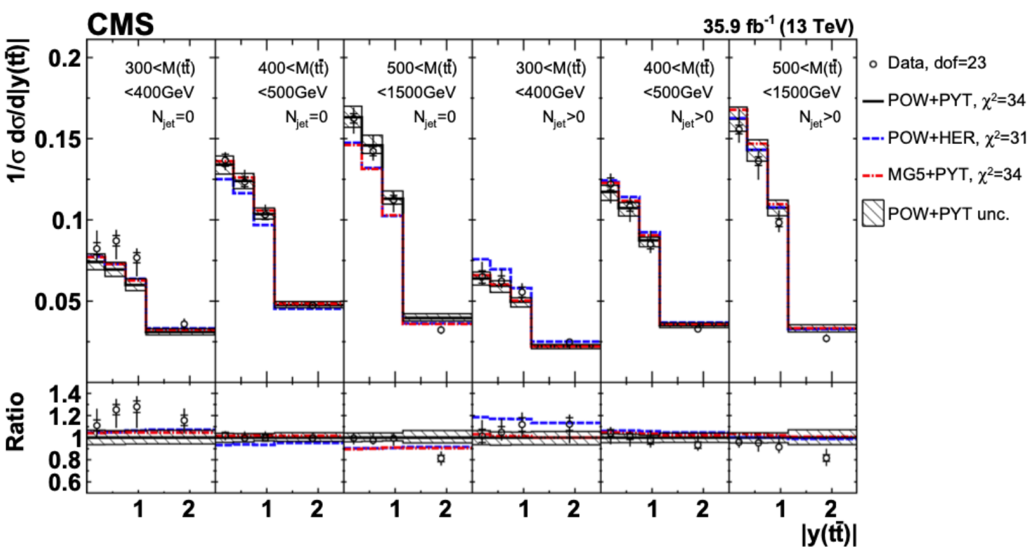


$C_{tq}^{(8)}$

- Reweighting MC to NNLO leads to better agreement.
- Top quark p_T relevant for differential EFT search.
- Limits on Wilson coefficients of dim-6 EFT operators C_{tG} and $C_{tq}^{(8)}$.

Top pair differential search

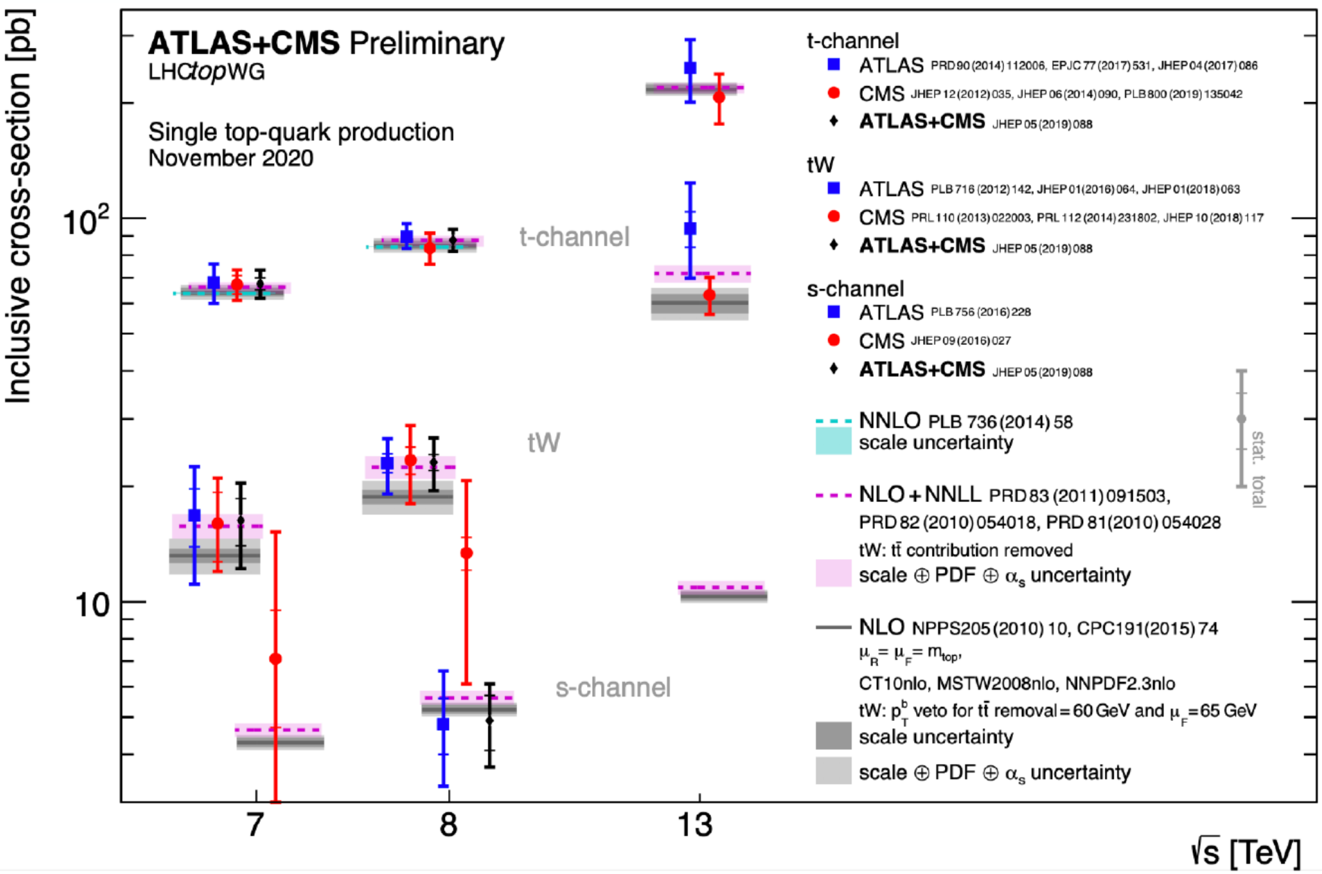


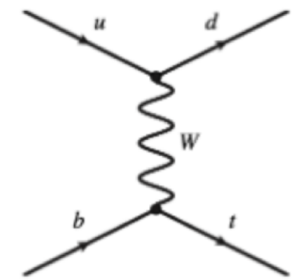


[Eur. Phys. J. C 80 (2020) 658]

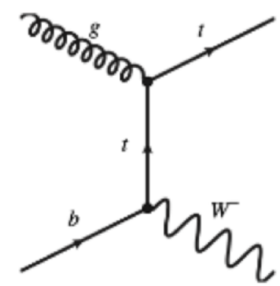
- Combined OS ee, eμ and $\mu\mu$ channels
- Unfolded kinematic variables in bins of top pair mass
- Double-differential and triple-differential measurement are made
- Triple-differential measurement is used to extract values of the strong coupling strength α_S and the top quark pole mass

Single top production

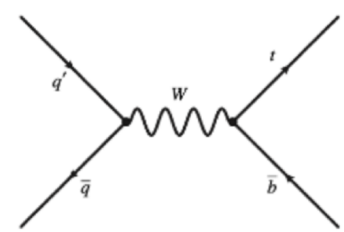




t-channel



tW-channel



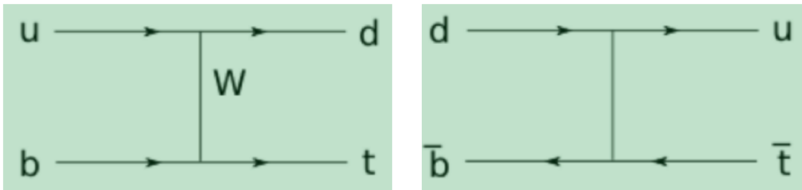
s-channel

- Single top production is dominated by t-channel (~200 pb @13 TeV).
- Theory and data agree within errors. Single top EW production allows to probe the Wtb vertex for new physics

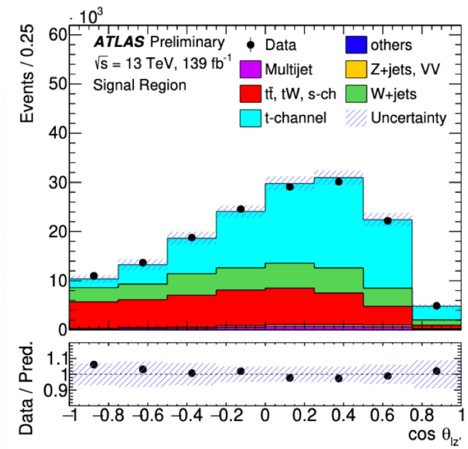
Top polarization

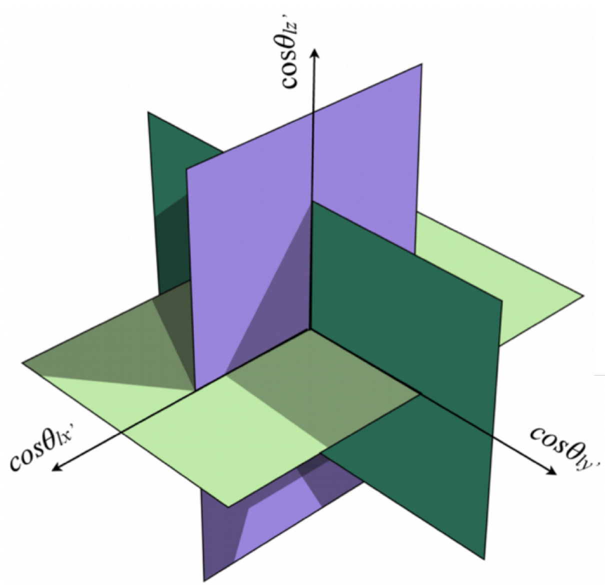
[ATL-CONF-2021-027]

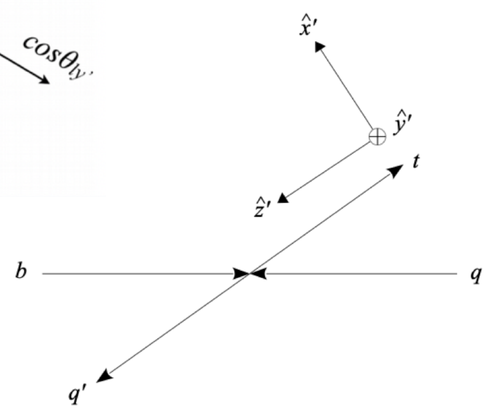
Dominant process (t-channel single top):



As opposed to top-pair production, top quarks are expected to be polarized in single top production.

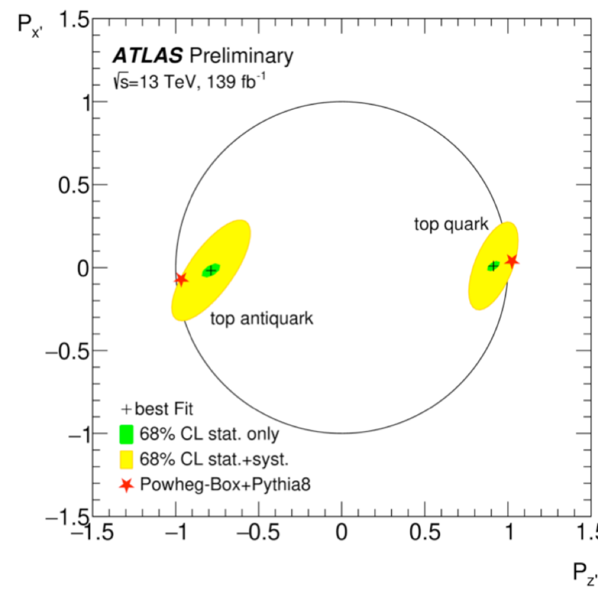






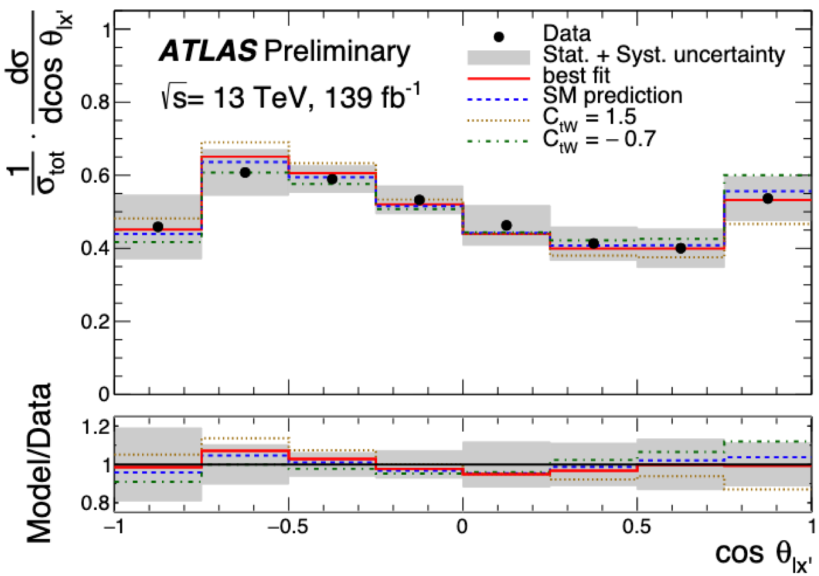
Signal region: octant variable Q depending on the signs of $\cos\theta_i$

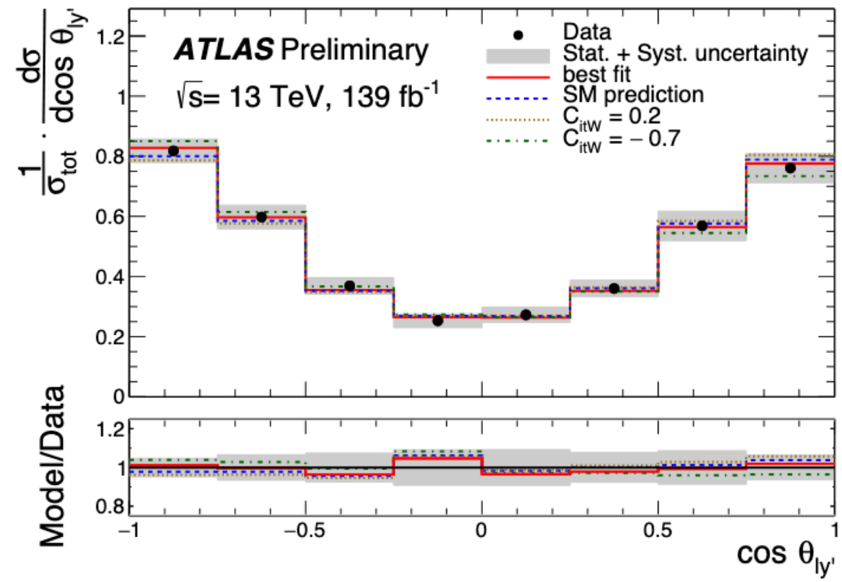
Templates simulated with fully polarized states ($P_{x',y',z'} = \pm 1$)



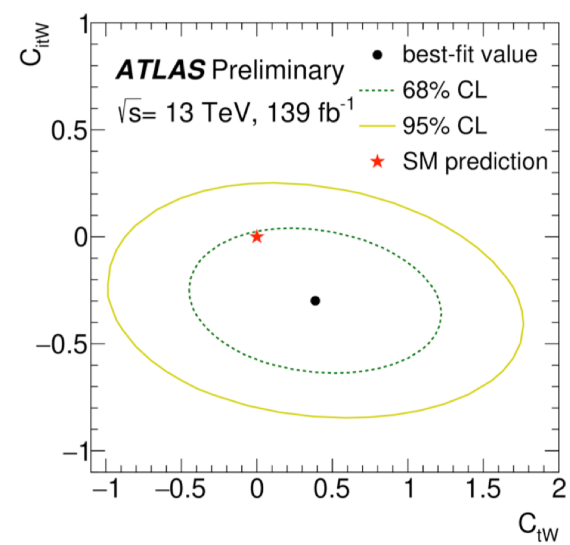
Top polarization for EFT

[ATL-CONF-2021-027]





- Normalized differential cross section as a function of the angular variables unfolded to particle level in a fiducial region.
- A profile LH fit to $\cos\theta_{lx'}$ and $\cos\theta_{ly'}$ to describe the cross sections as a function of EFT coefficients C_{tW}, C_{itW}.
- Stringent bounds obtained on the real and imaginary coefficients of the tWb dipole operator.



b-fragmentation parameter

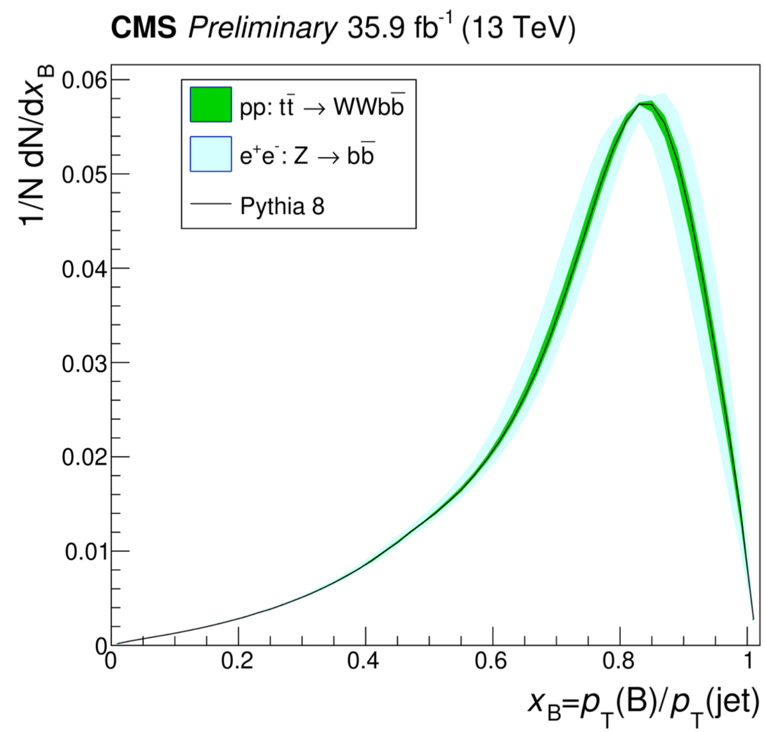
[CMS-PAS-TOP-18-012]

- Determine the shape parameter r_b of the Lund-Bowler b-fragmentation function, using c-mesons (D_0 & J/ψ) inside b-jets from ttbar decays.

- Use single and dilepton ttbar selections, search for displaced vertices from D_0 and J/ψ.

- Measure x_b, the fraction of p_T carried by c-meson inside jet, and fit to analytical expression to extract r_b.

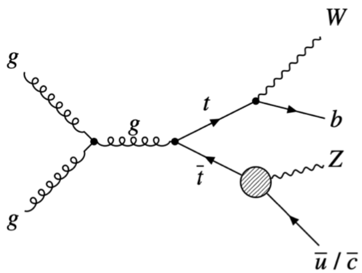
$$r_b = 0.858 \pm 0.037\,(\text{stat}) \pm 0.031\,(\text{syst})$$

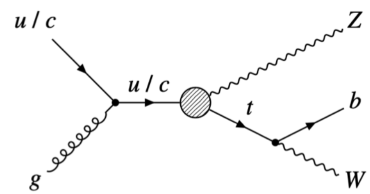


compare functional forms and uncertainties from pp to e^+e^- result

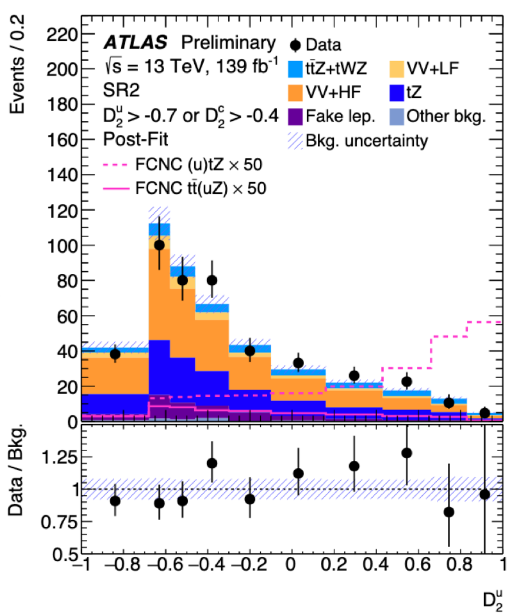
Top FCNC

[ATL-CONF-2021-049]





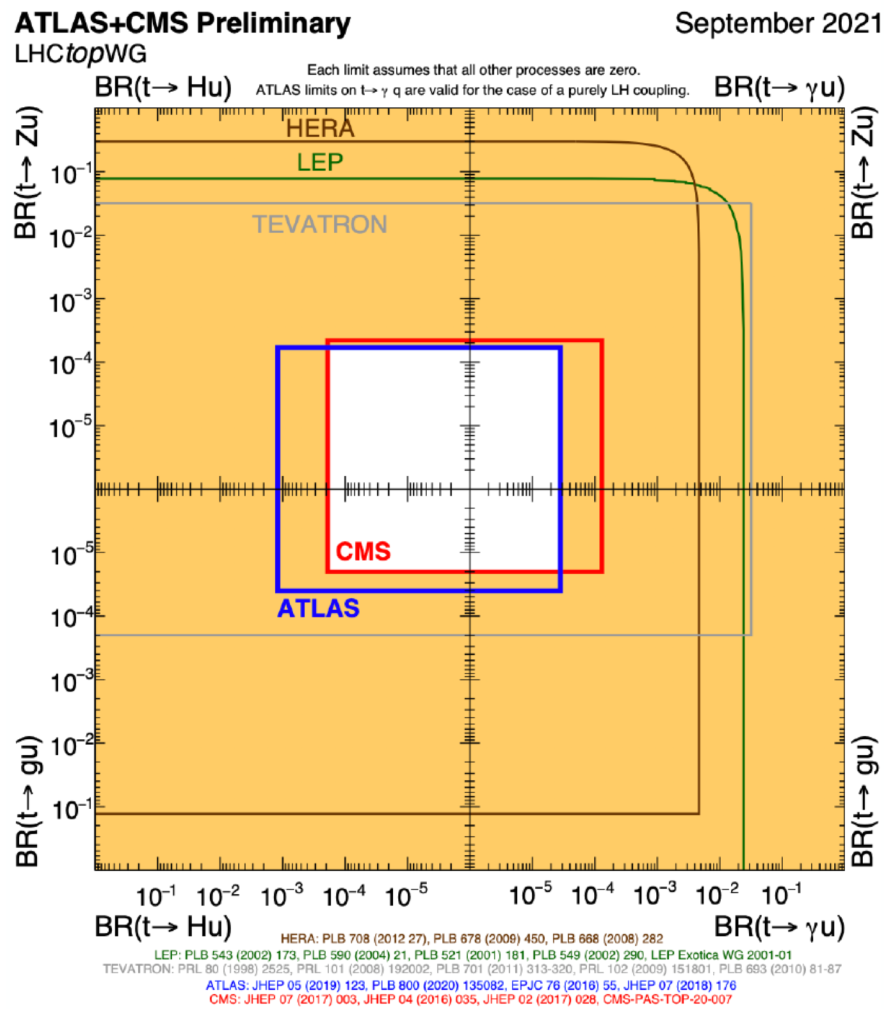
FCNC is forbidden in SM at tree level and suppressed at NLO.
FCNCs active at production and top decay are both explored.



Upper limits on top FCNC BRs:

$$6.2 \times 10^{-5} \text{ for } t \to Zu$$

$$13 \times 10^{-5} \text{ for } t \to Zc$$



Energy asymmetry

[TOPQ-2019-28]

Use energy asymmetry A_E in ttbar+jet (driven by gq channel) to probe the EFT parameters

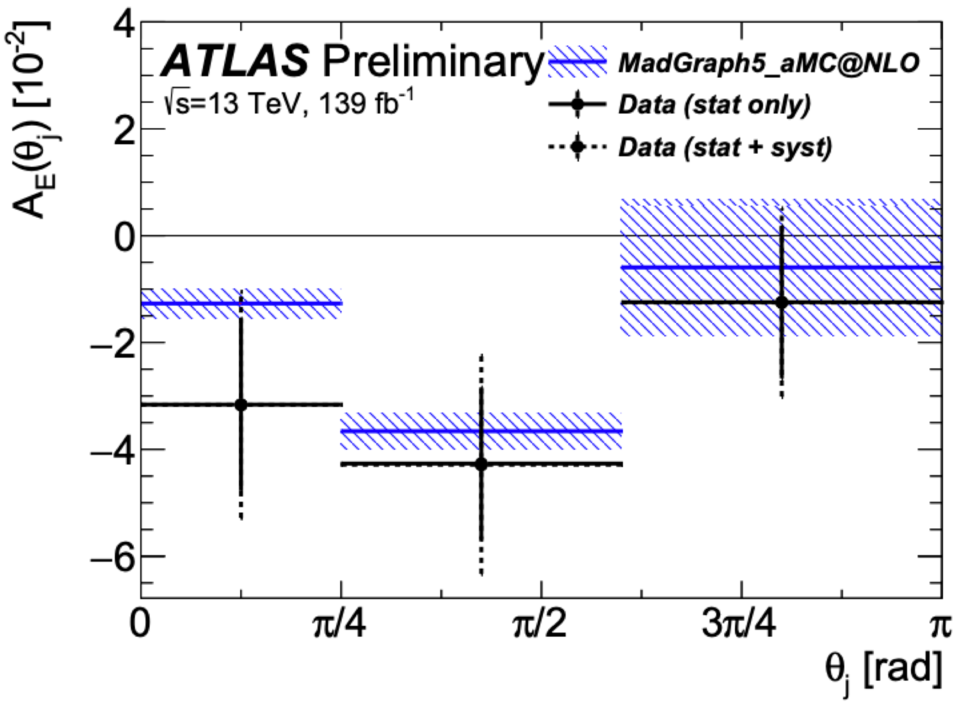
$$A_E(\theta_j) \equiv \frac{\sigma^{\mathrm{opt}}(\theta_j|\Delta E > 0) - \sigma^{\mathrm{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\mathrm{opt}}(\theta_j|\Delta E > 0) + \sigma^{\mathrm{opt}}(\theta_j|\Delta E < 0)} \qquad (\Delta E = E_t - E_{\bar{t}})$$

$$\sigma^{\mathrm{opt}}(\theta_j) = \sigma(\theta_j|y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j|y_{t\bar{t}j} < 0)\,, \qquad \theta_j \in [0, \pi]$$

- θ_j is the angle between the jet and the positive z-axis. Both ΔE and θ_j are defined in $t\bar{t}j$ rest frame.
- Results unfolded to particle level in bins of ΔE and θ_j .
- Event selection in l+jets final state:
  1e/μ, MET>20 GeV, MET+MT>60 GeV, ≥1 b-jet@85%, 1 ΔR=0.4 jet with p_T>100 GeV, 1 DNN top-tagged ΔR=1 jet with p_T>350 GeV.
- Sensitive to 4-quark operators, complementary to A_y.

Energy asymmetry

[TOPQ-2019-28]



Scenario	$A_E \pm \Delta A_E\,[10^{-2}]$		
	$0 \le \theta_j \le \frac{\pi}{4}$	$\frac{\pi}{4} \le \theta_j \le \frac{3\pi}{5}$	$\frac{3\pi}{5} \le \theta_j \le \pi$
Data	-3.17 ± 2.11	-4.29 ± 2.04	-1.25 ± 1.76
SM prediction	-1.27 ± 0.28	-3.66 ± 0.33	-0.59 ± 1.28
SM expectation	-1.27 ± 2.05	-3.66 ± 1.95	-0.59 ± 1.61

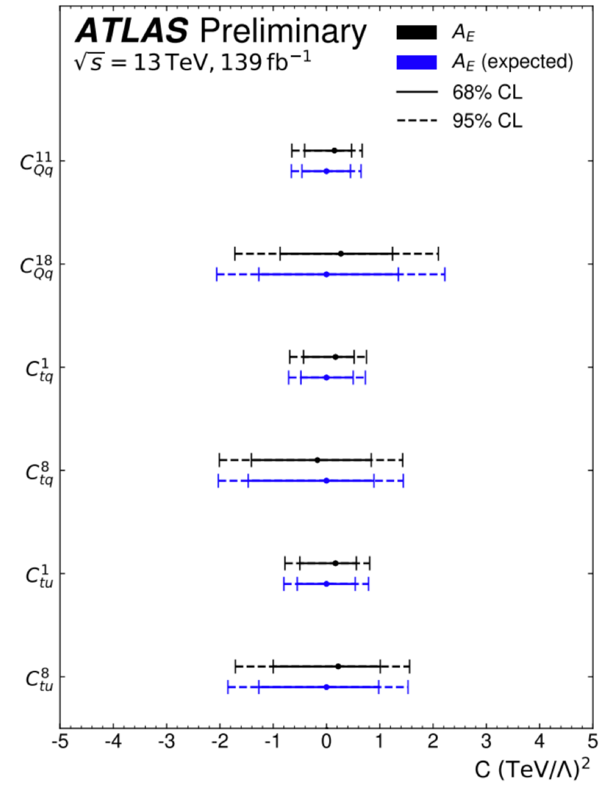
- High-purity region: 87% ttbar for A_E measurement, 5% W+jets, <2% fakes+QCD.
- Energy asymmetry shows good agreement with SM.
- Dominant sources of uncertainty are data statistics, followed by ttbar modelling.
- Inclusive energy asymmetry $A_E^2 = -0.043 \pm 0.020$ agrees with SM prediction of -0.037 ± 0.003.

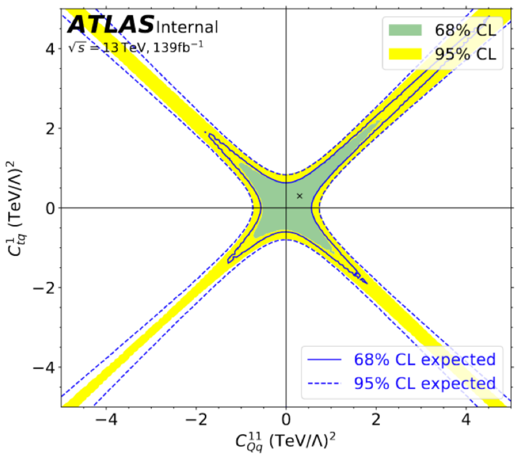
Energy asymmetry

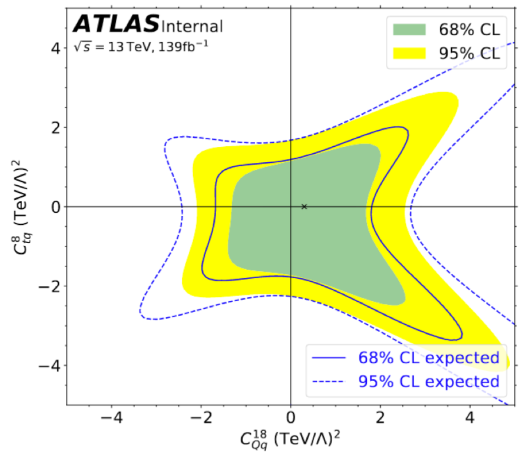
[TOPQ-2019-28]

Six four-quark EFT operators are studied

$$O_{Qq}^{1,8} = (\bar{Q}_L \gamma_\mu T^A Q_L)(\bar{q}_L \gamma^\mu T^A q_L)$$
$$O_{tu}^{8} = (\bar{t}_R \gamma_\mu T^A t_R)(\bar{u}_R \gamma^\mu T^A u_R)$$
$$O_{tq}^{8} = (\bar{q}_L \gamma_\mu T^A q_L)(\bar{t}_R \gamma^\mu T^A t_R)$$
$$O_{Qq}^{1,1} = (\bar{Q}_L \gamma_\mu Q_L)(\bar{q}_L \gamma^\mu q_L)$$
$$O_{tu}^{1} = (\bar{t}_R \gamma_\mu t_R)(\bar{u}_R \gamma^\mu u_R)$$
$$O_{tq}^{1} = (\bar{q}_L \gamma_\mu q_L)(\bar{t}_R \gamma^\mu t_R)\,.$$







Tighter bounds for color singlets, because of color factors in the amplitude

CP violation in top pairs

[CMS-PAS-TOP-20-005]

- Choose T-odd observables that are odd under CP transformation if CPT is conserved.

$$O_3 = Q_\ell \epsilon(p_\mathrm{b}, p_{\bar{\mathrm{b}}}, p_\ell, p_{j_1}) \propto Q_\ell \vec{p'}_\mathrm{b} \cdot (\vec{p'}_\ell \times \vec{p'}_{j_1})$$
$$O_6 = Q_\ell \epsilon(P, p_\mathrm{b} - p_{\bar{\mathrm{b}}}, p_\ell, p_{j_1}) \propto Q_\ell (\vec{p}_\mathrm{b} - \vec{p}_{\bar{\mathrm{b}}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$$
$$O_{12} = q \cdot (p_\mathrm{b} - p_{\bar{\mathrm{b}}}) \epsilon(P, q, p_\mathrm{b}, p_{\bar{\mathrm{b}}}) \propto (\vec{p}_\mathrm{b} - \vec{p}_{\bar{\mathrm{b}}})_z \cdot (\vec{p}_\mathrm{b} \times \vec{p}_{\bar{\mathrm{b}}})_z$$
$$O_{14} = \epsilon(P, p_\mathrm{b} + p_{\bar{\mathrm{b}}}, p_\ell, p_{j_1}) \propto (\vec{p}_\mathrm{b} + \vec{p}_{\bar{\mathrm{b}}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}).$$

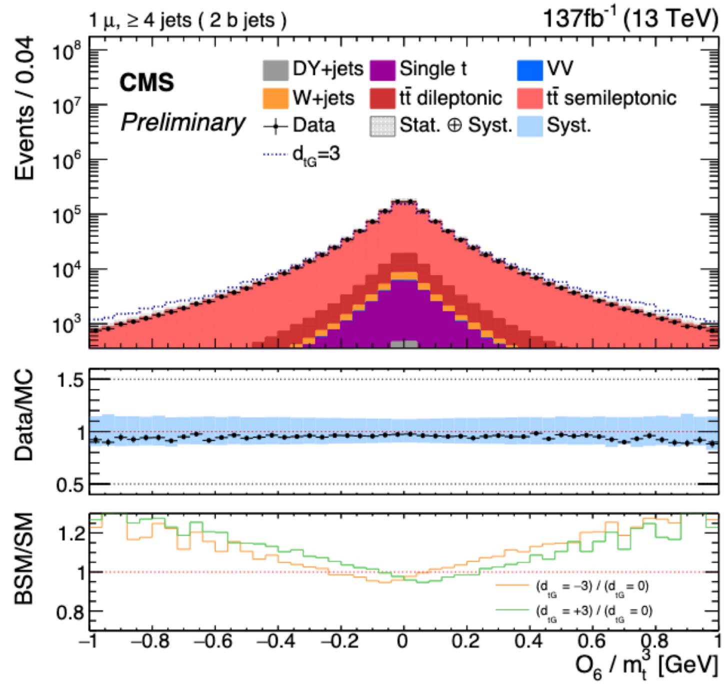
- CPV is manifested by a non-zero value of the asymmetry

$$A_{CP}(O_i) = \frac{N_\mathrm{events}(O_i > 0) - N_\mathrm{events}(O_i < 0)}{N_\mathrm{events}(O_i > 0) + N_\mathrm{events}(O_i < 0)}$$

- CP phase in CKM matrix too small to produce visible SM CP violation in ttbar decay, so any asymmetry is a sign of BSM.

Chromo-electric dipole moment (CEDM):

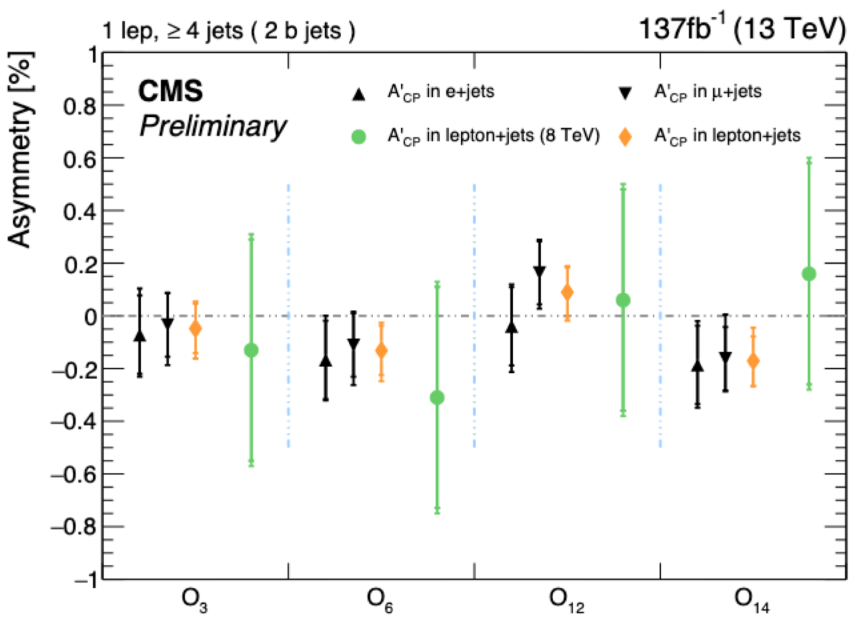
$$\mathcal{L} = \frac{g_s}{2} \bar{\mathrm{t}} T^a \sigma^{\mu\nu} (a_t^g + i\gamma_5 d_t^g) \mathrm{t} G^a_{\mu\nu}.$$



CP violation in top pairs

[CMS-PAS-TOP-20-005]

- *l+jets selection:* 1e/μ p_T>30/38 GeV, ≥4 jets p_T>30 GeV, 2 b-jets@68%.
- Use χ^2-based top reconstruction + M(lb)<150 GeV to minimize incorrect l-b pairing.
- Template fit to M(lb) to measure signal and background normalizations. Extract A_{CP} by counting signal events.



- Correct A_{CP} with dilution factor D to account for migration from detector and top reconstruction effects.
- No discrepancy within 2σ. A factor 3 improvement from 8 TeV measurement.

Summary

- LHC is a top factory. With more data accumulated, precision measurements such as differential EFT search, rare production (single and associated) and decay modes, top quark polarizations, can be probed.
- Some analyses are systematics dominated, precision measurements would benefit from improvement on jet energy scale uncertainty on the experimental side, and higher order as well non-perturbative uncertainty on the theory side. Non-perturbative parameters can be tuned to match data.
- Currently, all measurements of top showed good agreement with SM predictions, constraining BSM tighter with more data.
- Not all top measurements results are included in this talk, and focus is given to new results from ATLAS/CMS in the last year or so.

谢谢大家！

Thanks!