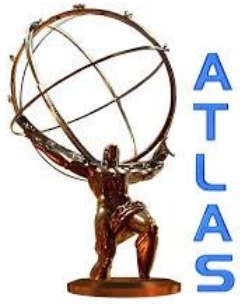
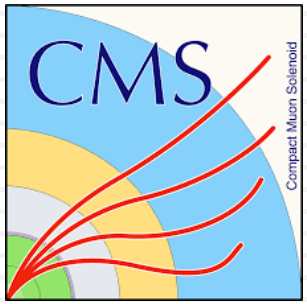
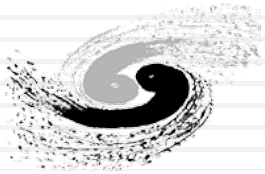
Status of Top Physics in CMS and ATLAS



Jin Wang (IHEP, CAS)

On behalf of CMS and ATLAS Collaborations





Institute of High Energy Physics
Chinese Academy of Sciences

Outline

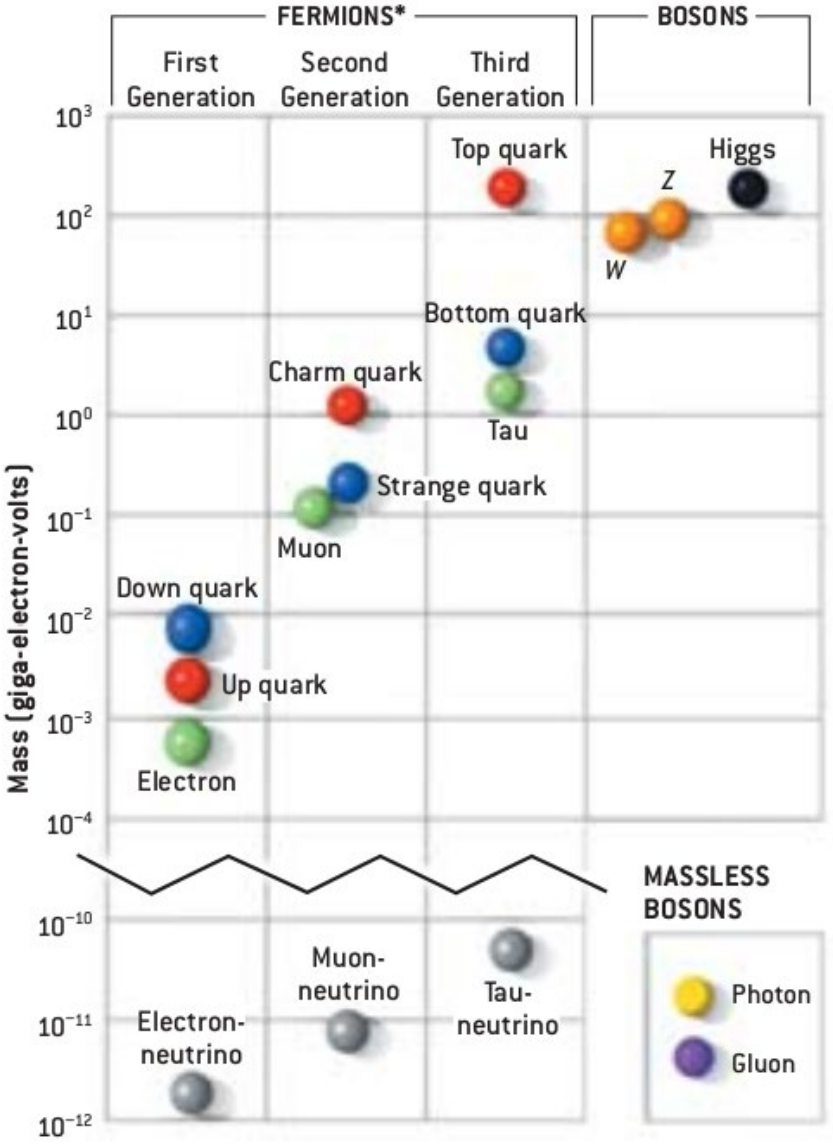
Focus on new results published in 2018

- Introduction
- Top quark production cross-section measurements
  - $t\bar{t}$ inclusive and differential cross sections
  - $t\bar{t} + X$ cross sections
  - Single top quark production cross sections
  - Four-top-quark production
- Top quark properties measurements
  - Top quark mass measurements
  - Top pair spin correlations
- New Physics searches
  - Flavour changing neutral currents from top-quark decays
  - Charged lepton-flavour violation in top-quark decays

Introduction

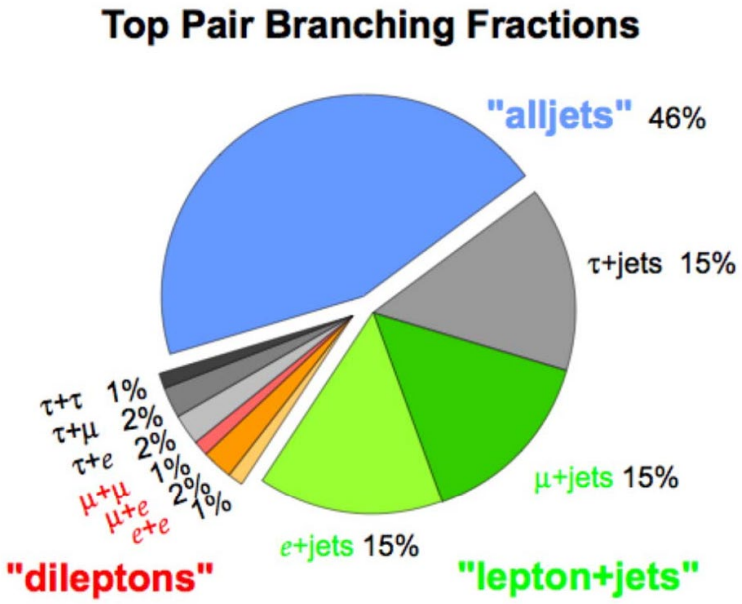
- The unique top quark
  - Most massive of known fundamental particles ~ 173 GeV
  - Mass is of order of the electroweak symmetry breaking scale
    - large couplings to new resonances predicted by New Physics models
    - large Yukawa coupling to Higgs boson
  - The only quark that decays before it can hadronise
    - opportunity to study a bare quark
    - access to its spin and polarization
  - Important backgrounds to many precision measurements and New Physics searches
- Huge top quark production cross sections at the LHC
  - >100 million top quarks produced in Run 2

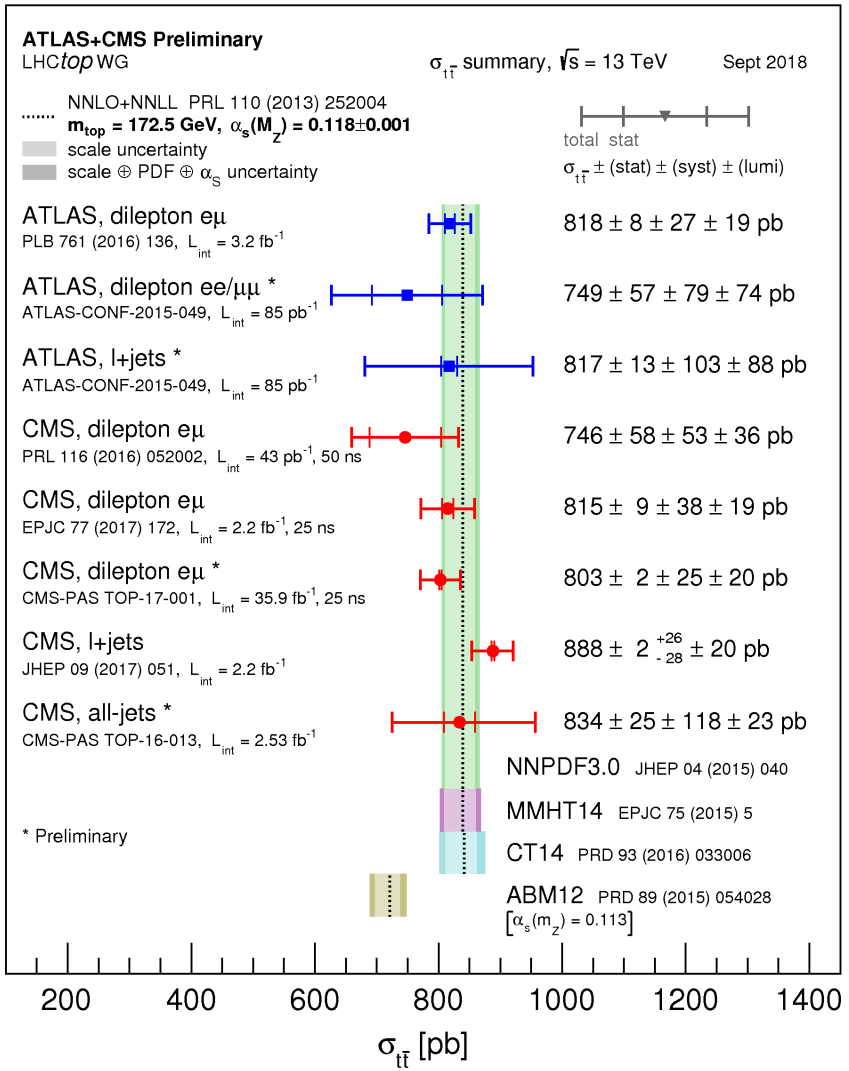
Very interesting and important at the LHC



$t\bar{t}$ production cross sections

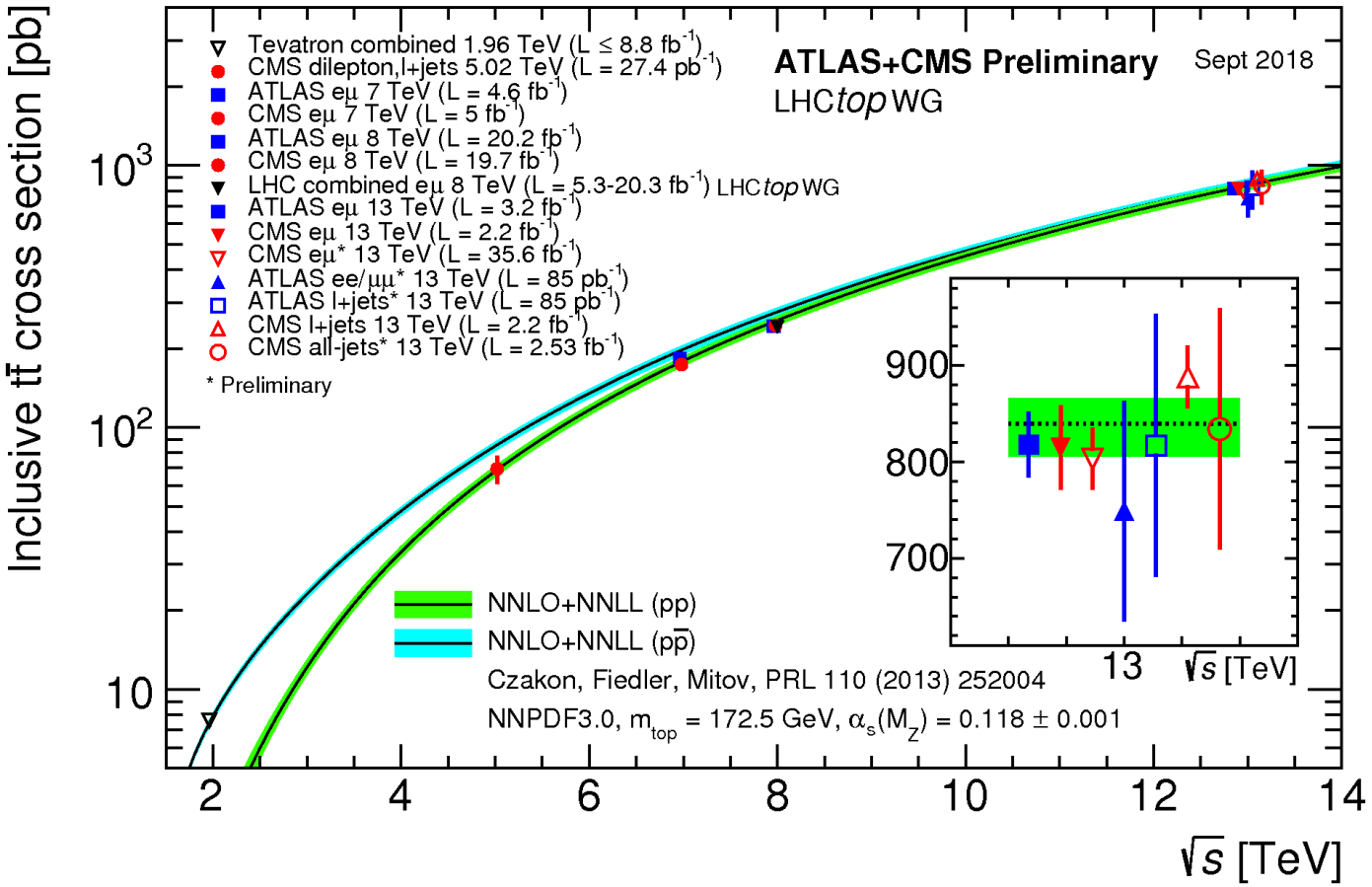
- Core physics delivery of the LHC with statistics O(1000) times Tevatron
  - Unique test of QCD with massive partons and constraints on QCD soft scale modelling
  - Indirect determination of m_t^{pole}
  - Constraints on anomalous EFT terms
  - Background for many BSM and Higgs signals





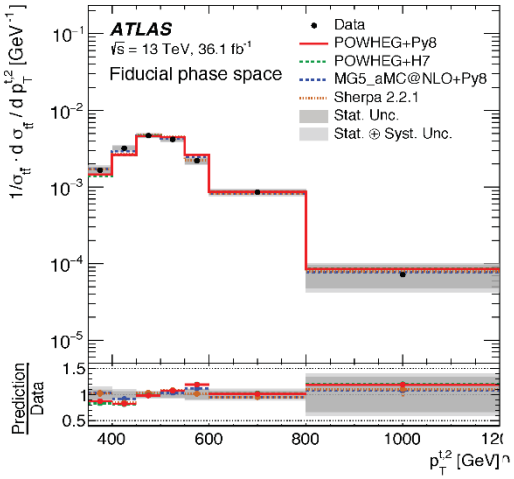
Good agreement between data and prediction

$t\bar{t}$ inclusive cross sections



- Single measurement precision: ~3.5%
- Limited mainly by luminosity and signal model uncertainty.

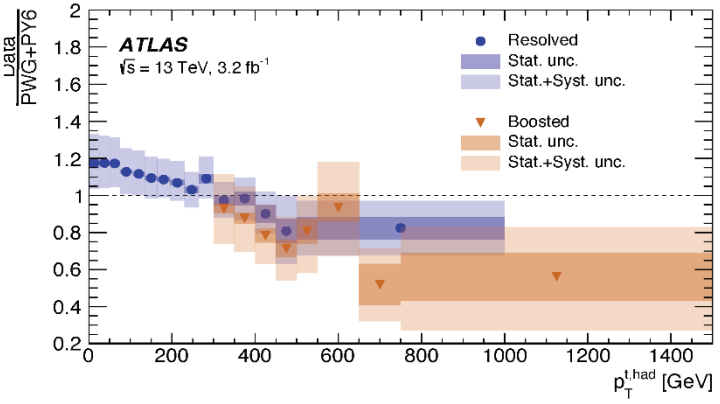
$t\bar{t}$ differential cross sections - ATLAS



All-jets 36.1 fb^{-1}

PRD 98 (2018) 012003

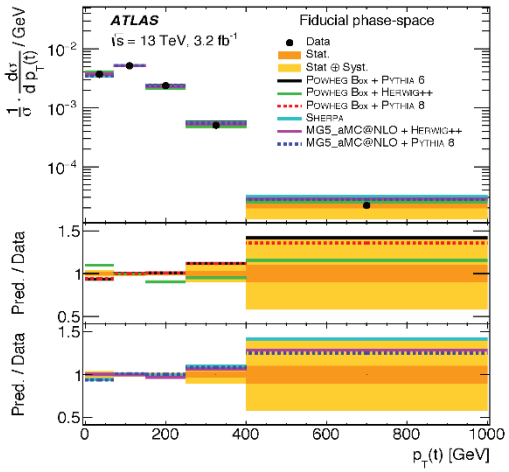
Boosted jet topologies



l+jets 3.2 fb^{-1}

JHEP 1711 (2017) 191

Both resolved and boosted jets



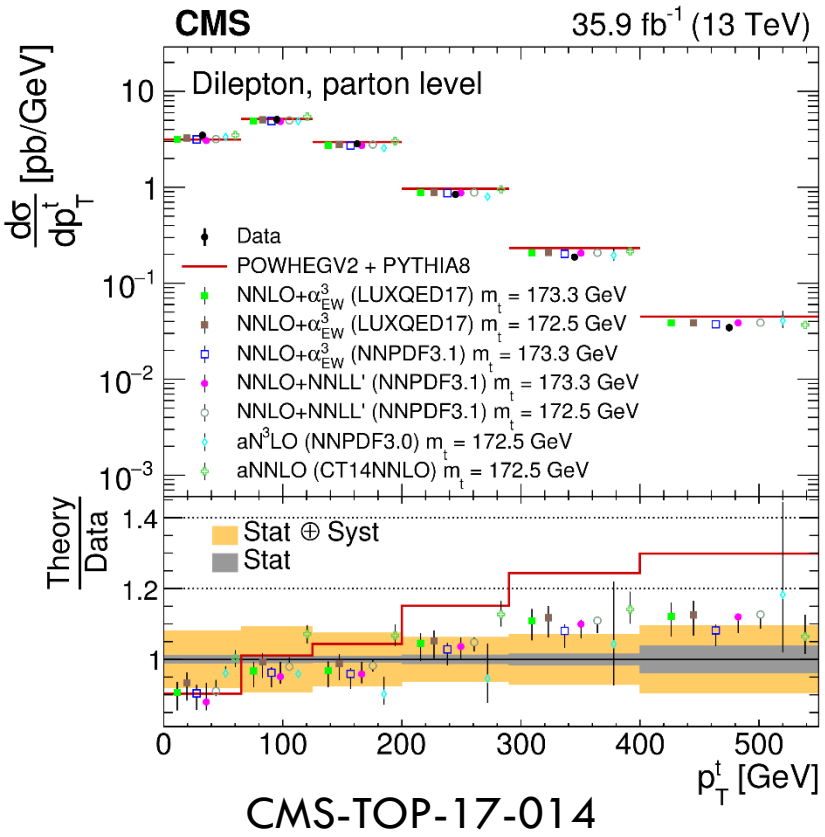
eμ channel 3.2 fb^{-1}

Eur. Phys. J C77 (2017) 299

Neutrino momenta from E_T^{miss} and mass constraints

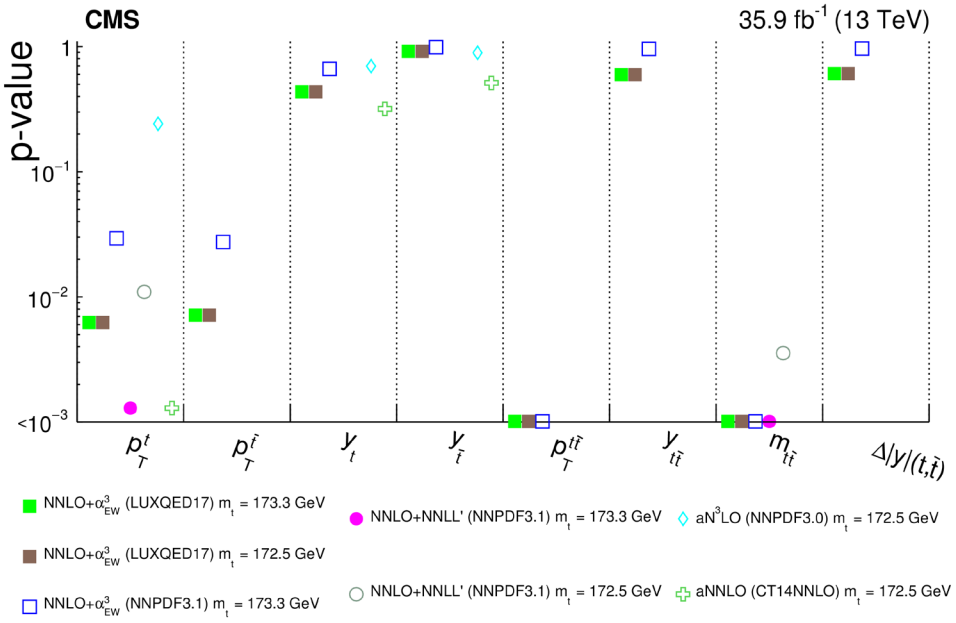
- Kinematic variables consistent with NLO QCD in general
- l+jets data have softer top p_T than predicted

$t\bar{t}$ differential cross sections - CMS



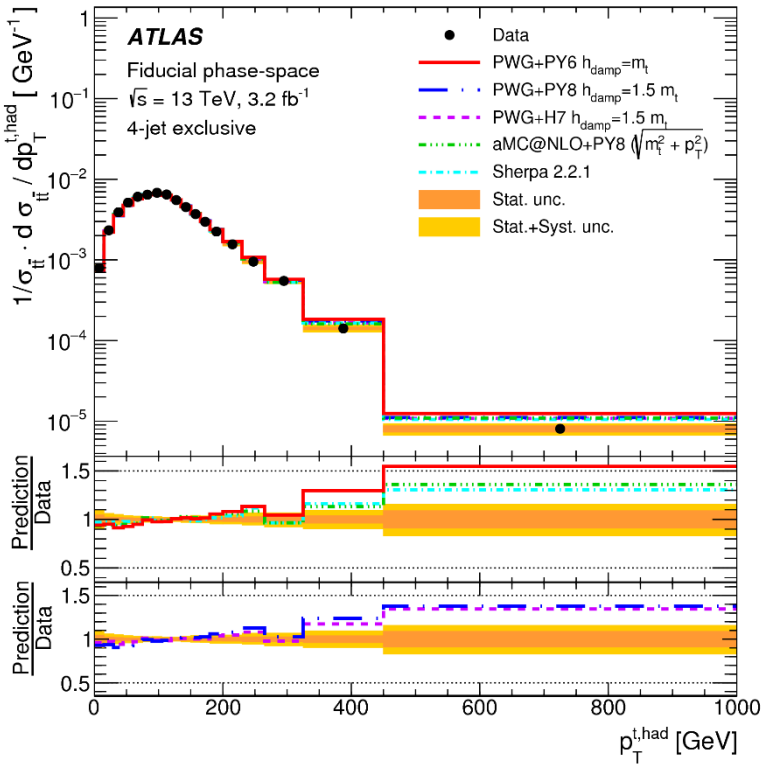
CMS-TOP-17-014

p-value agreement between theoretical prediction and data

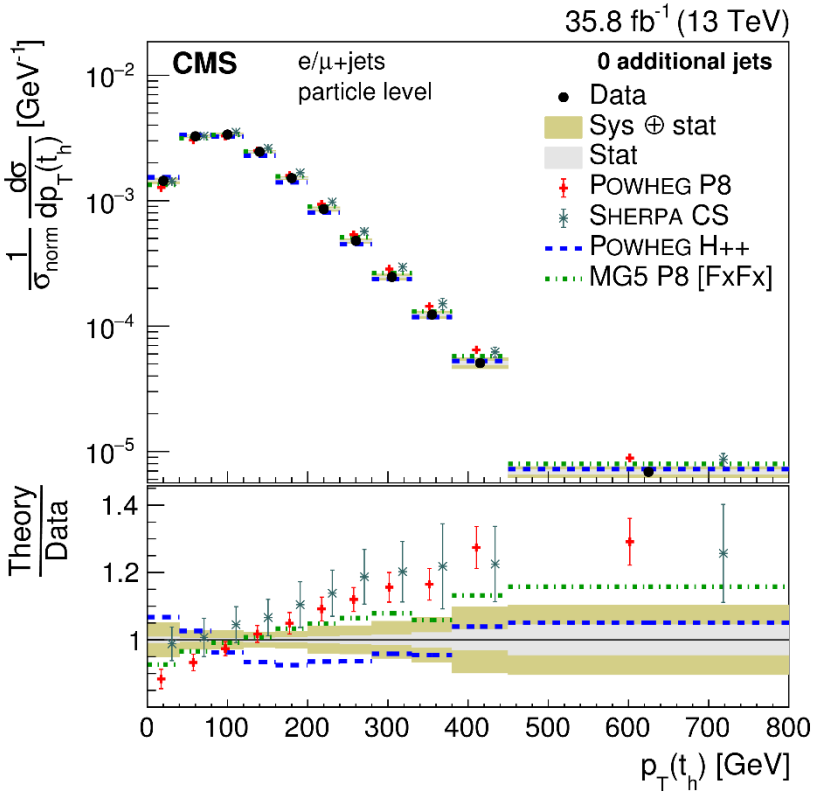


- Data shows softer top p_T than POWHEG+PYTHIA predicted in dilepton channel
  - still see the trend with higher order QCD and EW corrections
- Other variables related to top p_T are also in tension

$t\bar{t}$ + jets in leptop+jets channel



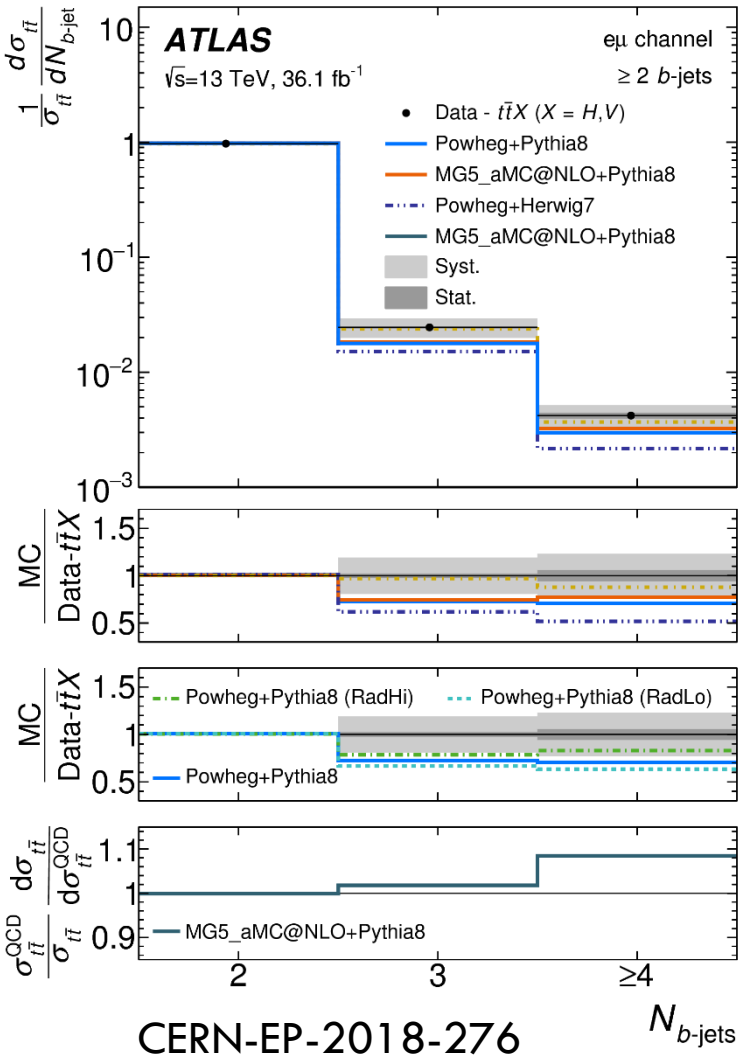
JHEP 10 (2018) 159



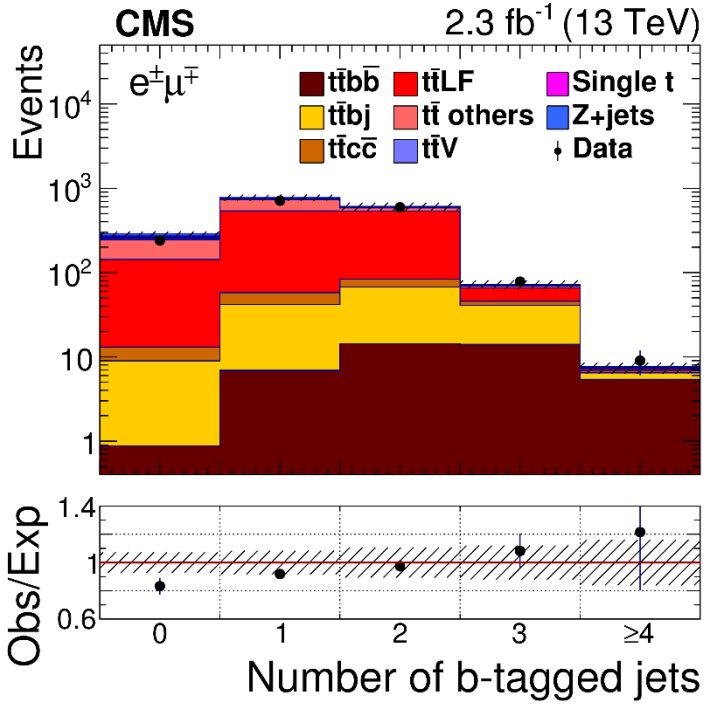
Phys. Rev. D 97 (2018) 112003

- Some tension found between data and prediction for reconstructed hadronical top p_T in 4-jet exclusive configuration in both ATLAS and CMS
- POWHEG+PYTHIA also has difficulties simultaneously reproducing Njets and $p_T(t\bar{t})$

$t\bar{t}$ + bjets



CERN-EP-2018-276

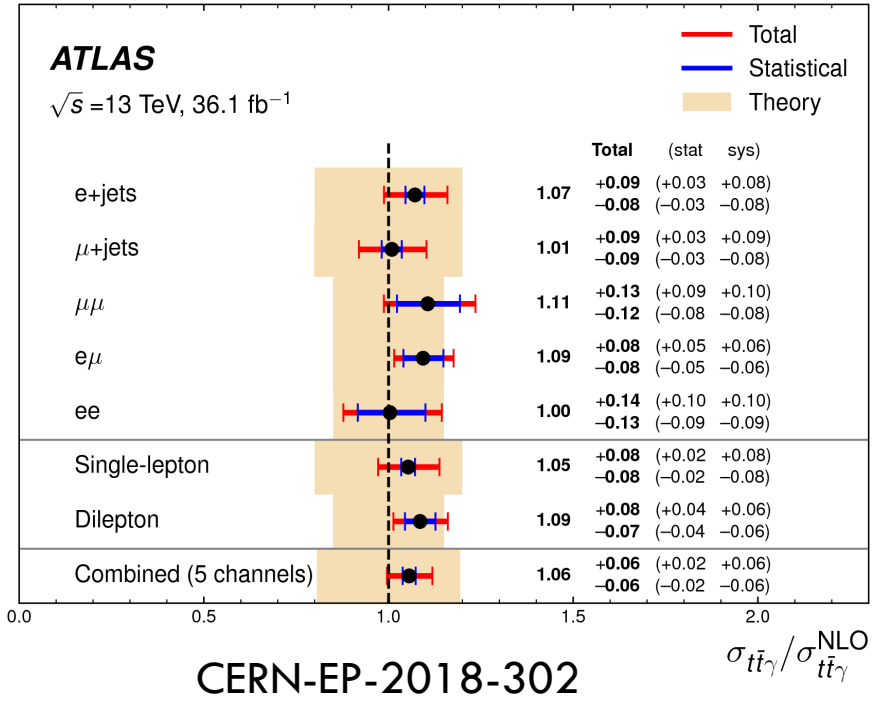


Phys. Lett. B 776 (2018) 355

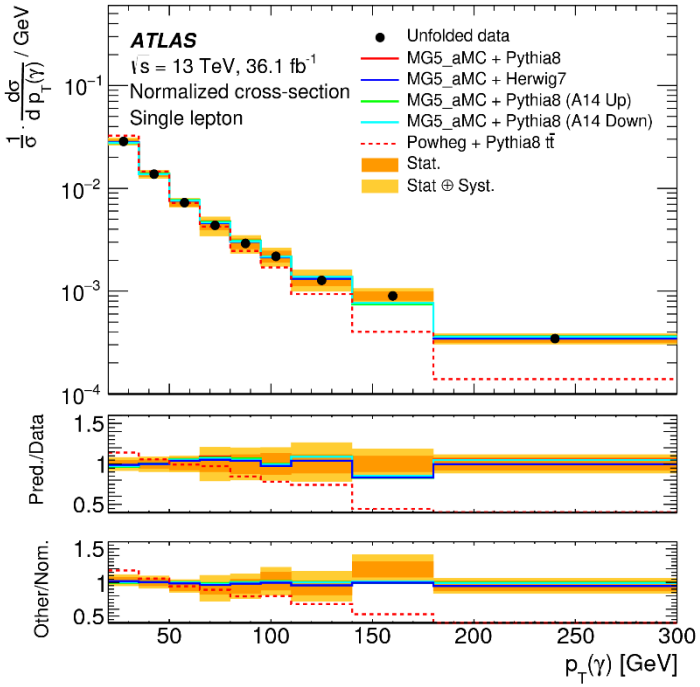
- Important background to ttH(bb) production
- In some cases data exceeds the predictions but within 2σ uncertainties.

$t\bar{t}$ + γ

- Photon emitted by ISR, FSR from top quark
- Important background to ttH(γγ) production or BSM processes
- Probe tγ EW coupling



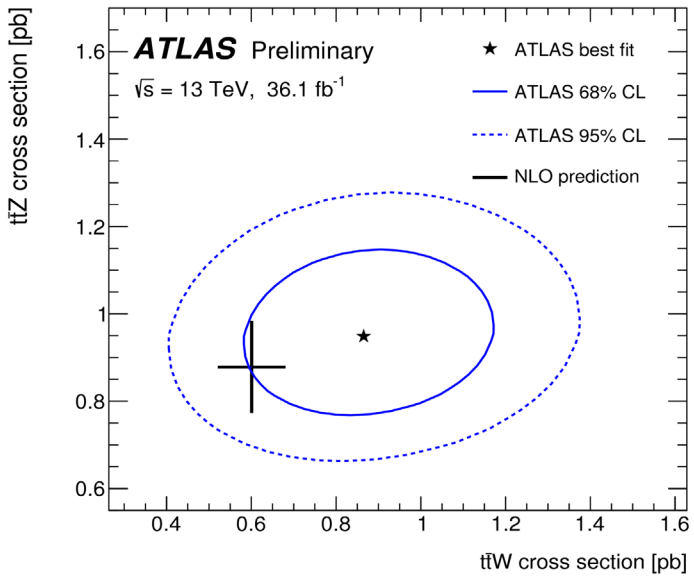
CERN-EP-2018-302



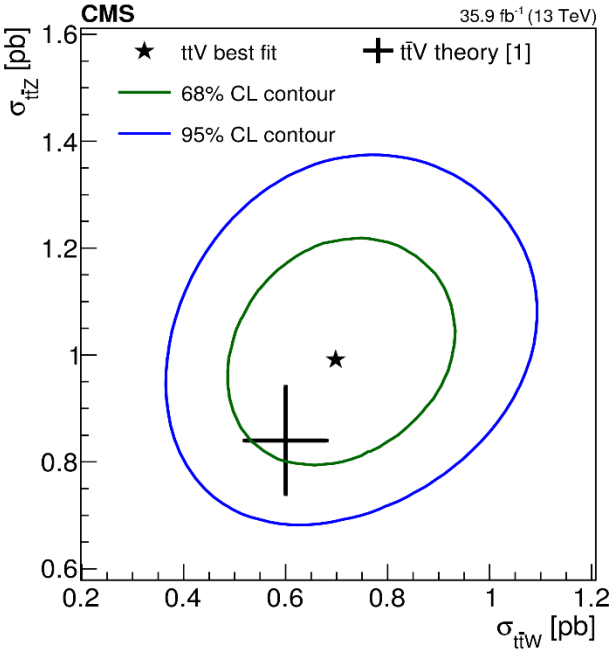
- ATLAS updated 13TeV results of inclusive and differential cross-sections for $t\bar{t}$ + γ with 2015+2016 data, recently submitted to EPJC
- All measurements are in agreement with the theoretical predictions.

$t\bar{t} + W/Z$

- Important background to ttH production or BSM processes
- Could be increased by BSM effects



ATLAS-CONF-2018-047

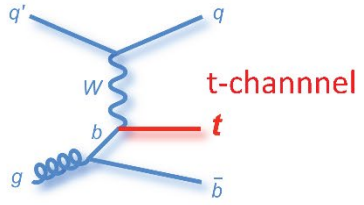


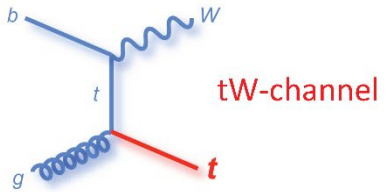
JHEP 08 (2018) 011

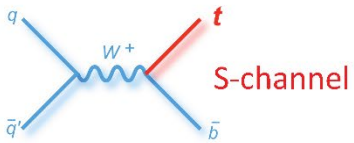
- Results are in agreement with the standard model.
- Constrained the anomalous EFT operators

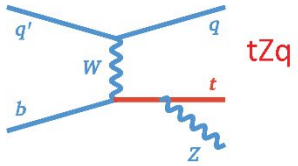
Single top quark production measurements

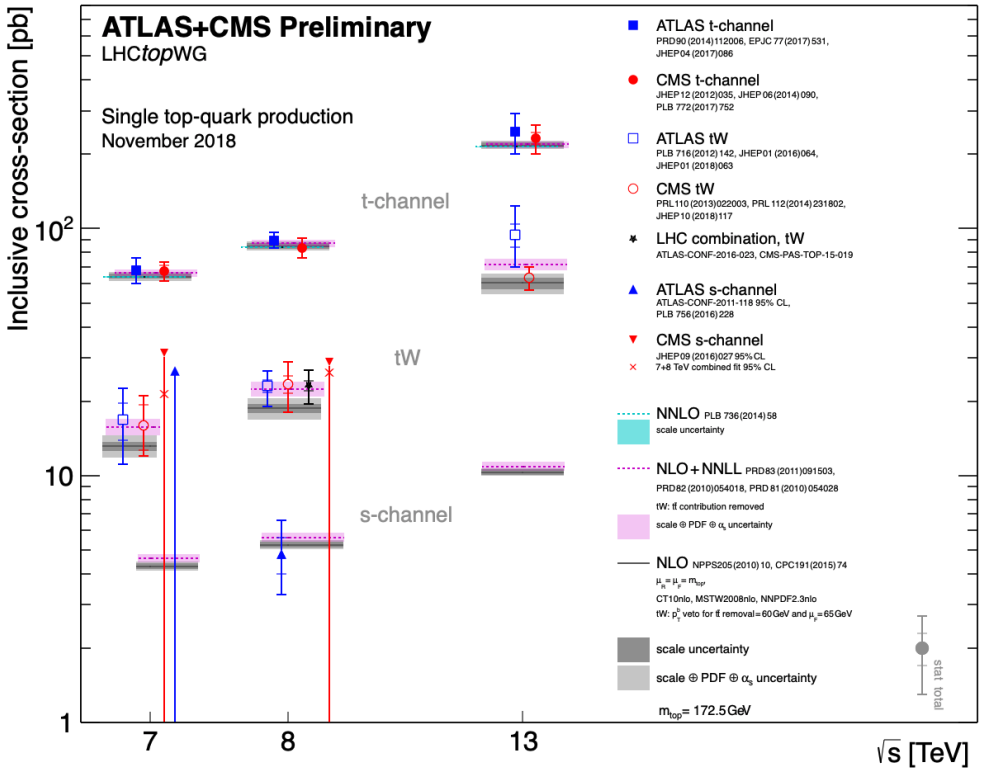
- Top quark electroweak production @ 13 TeV
  - t-channel: 216.99 pb, tW channel: 71.7 pb, s-channel: 10.32 pb, rare tZq production: ~ 1 pb











2018 updates

ATLAS tW:

Eur. Phys. J. C 78 (2018) 186

CMS tW:

JHEP 10 (2018) 117

and tZq observation

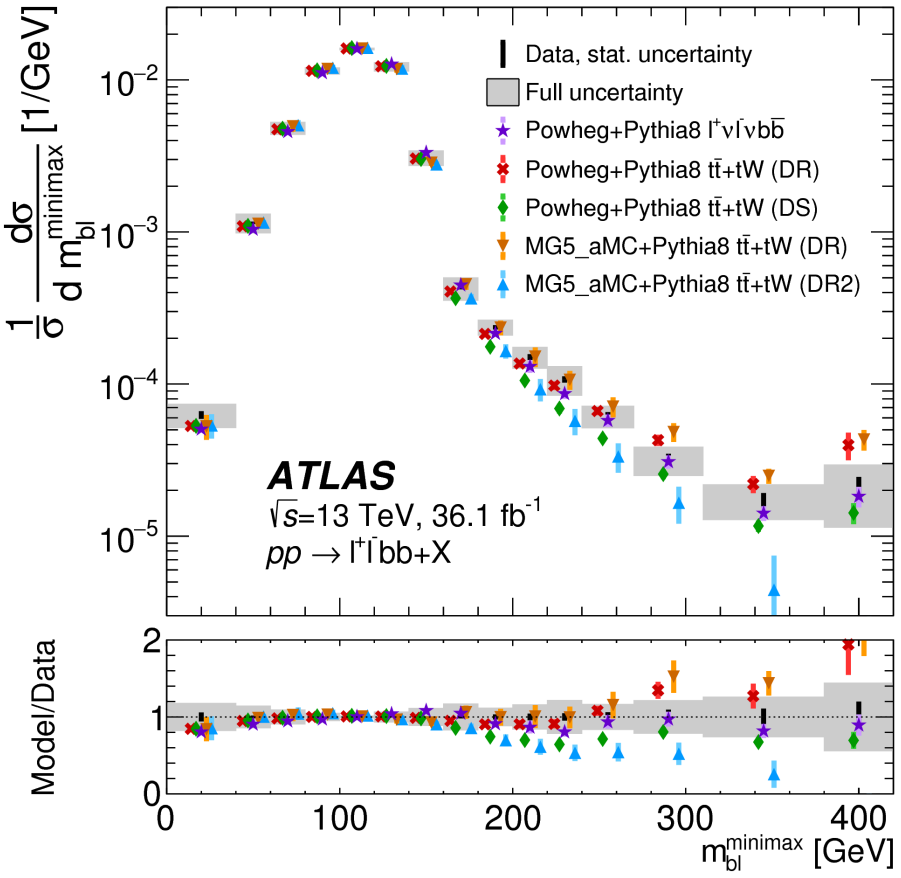
Probing interference between tW and $t\bar{t}$ production

- Treatments of the tW and $t\bar{t}$ NLO interference effects:
  - **Diagram removal** (**DR**): remove doubly resonant diagrams from Wtb matrix element
  - **Diagram subtraction** (**DS**): subtract gauge-invariant term from Wtb matrix element
  - arXiv:1607.05862 for details

- New study from ATLAS testing different models
  - Phys. Rev. Lett. 121, 152002 (2018)
- Use variable sensitive to interference effects

$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

- Results provide an important constraint on interference models and will guide future model development and tuning.



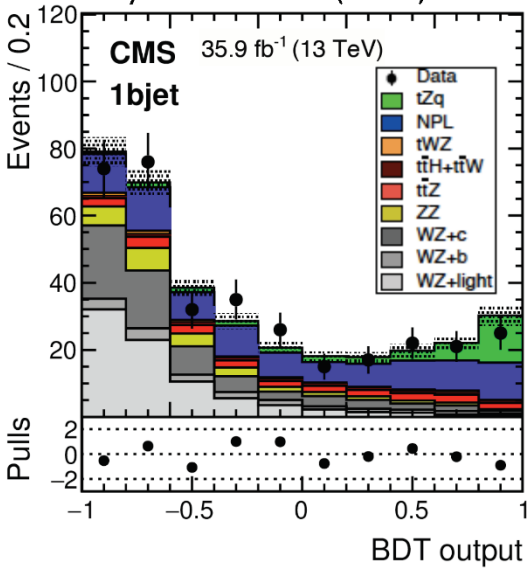
tZq measurements

- tZq rare production
  - unique sensitivity to some EFT operators due to $Wb \rightarrow tZ$ vertex
  - Challenging large SM backgrounds

- Previous results

CMS result with 2016 data

Phys. Lett. B 779 (2018) 358

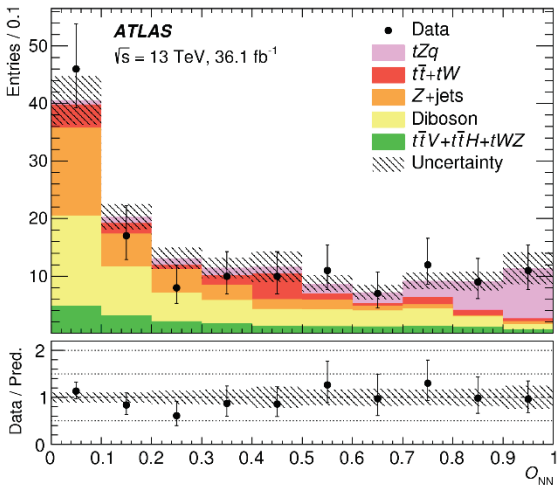


$\mu = 1.31^{+0.35}_{-0.33}(\text{stat})\ ^{+0.31}_{-0.25}(\text{sys})$

3.7 (3.1) σ Obs.(Exp.)

ATLAS result with 2016 data

Phys. Lett. B 780 (2018) 557



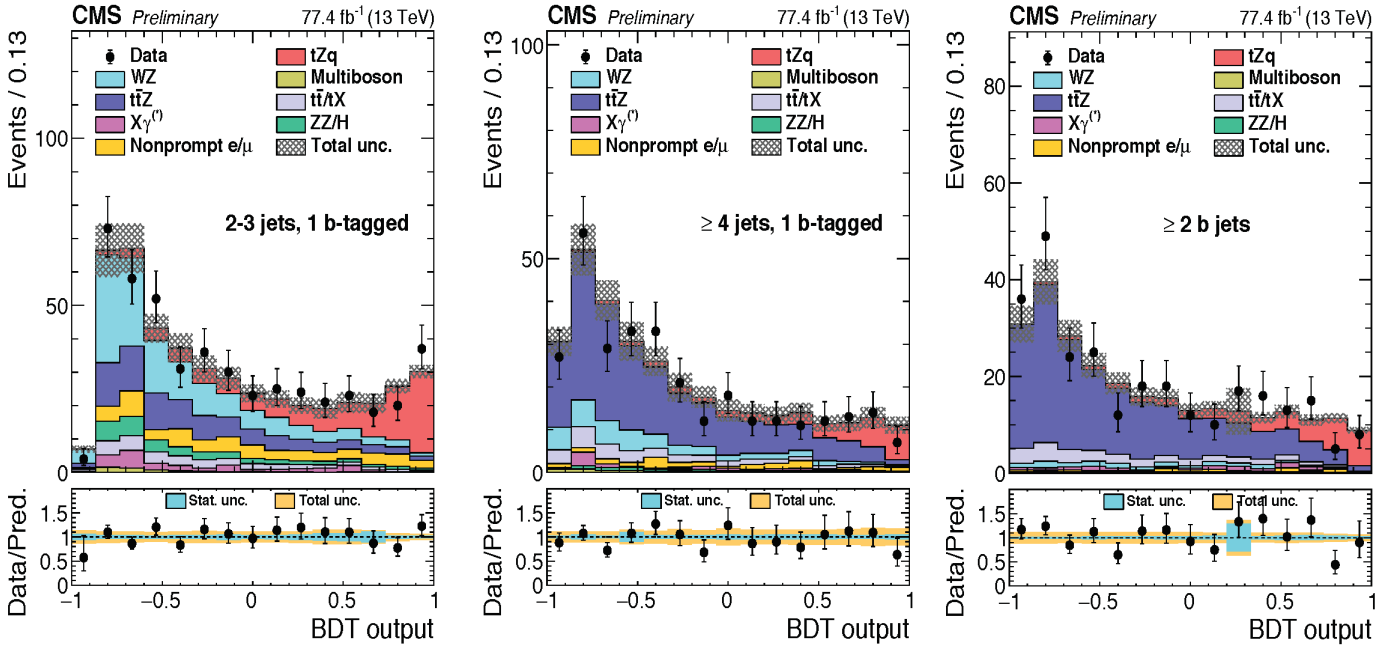
$\mu = 0.75 \pm 0.21(\text{stat}) \pm 0.17(\text{sys})$

4.2 (5.4)σ Obs.(Exp.)

Both measurements with about 35% uncertainty

tZq observation

- Updates from CMS with 77.4 fb^{-1} data from 2016 and 2017
- Binned maximum likelihood fit to BDTs of three signal regions and the WZ/ZZ control regions



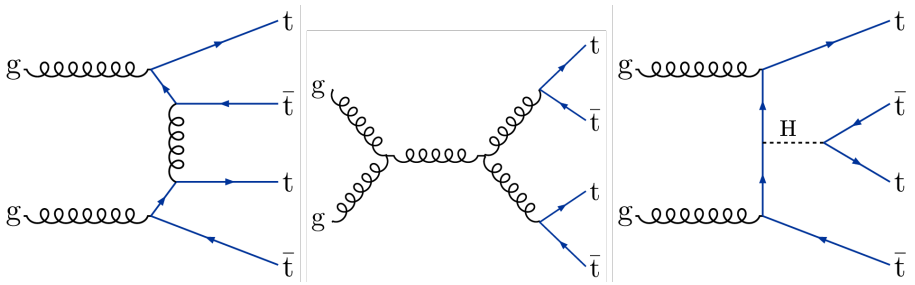
- Measured cross section with 15% precision:

$$\sigma(tZq \to t\ell^+\ell^- q) = 111 \pm 13(stat)^{+11}_{-9}(syst)\ \text{fb}$$

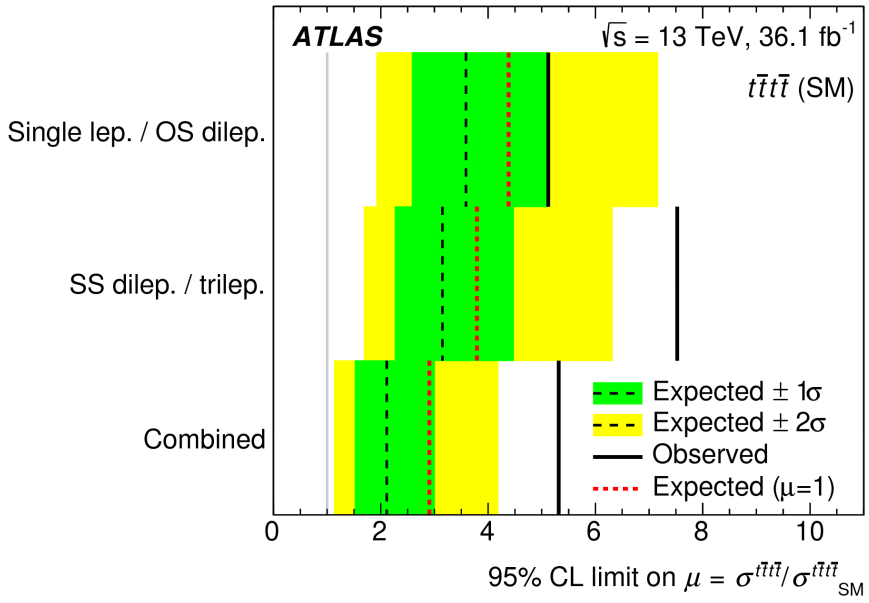
- First observation with observed (expected) significance 8.2 (7.7) σ.

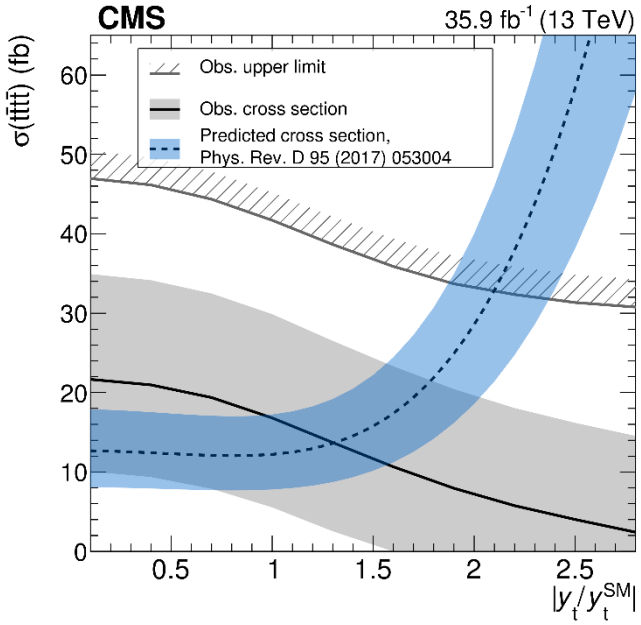
Searches for standard model production of four top quarks

- Tiny cross section in SM ~9fb @13 TeV
- Many BSM models probes an increase



- Searches performed in LHC with 36 pb^{-1} data
  - ATLAS: single lepton and opposite-sign dilepton channels arXiv:1811.02305
  - CMS: same sign and multilepton final states *Eur. Phys. J. C 78 (2018) 140*





Top quark mass measurement

- Top quark mass is a key parameter of the Standard Model, important for electroweak vacuum stability

- Direct measurement of "Monte Carlo mass" m_t^{MC}
  - Extracted from invariant mass of decay products
  - Results updated in 2018 for both ATLAS and CMS

- Indirect measurement of the pole mass m_t^{pole} from observables depending on m_t
  - E.g. inclusive or differential cross section $\sigma^{measure}$ compared to σ^{theory}
  - Measurement made in a given renormalization scheme
  - No updates in 2018, results from previous years can be found in backup

- Difference between m_t^{MC} and m_t^{pole} could be ~ GeV

Direct top mass measurement

2018 updates

ATLAS: arxiv 1810.01772

Lepton+jets channel 8TeV 20.2 fb^{-1} data

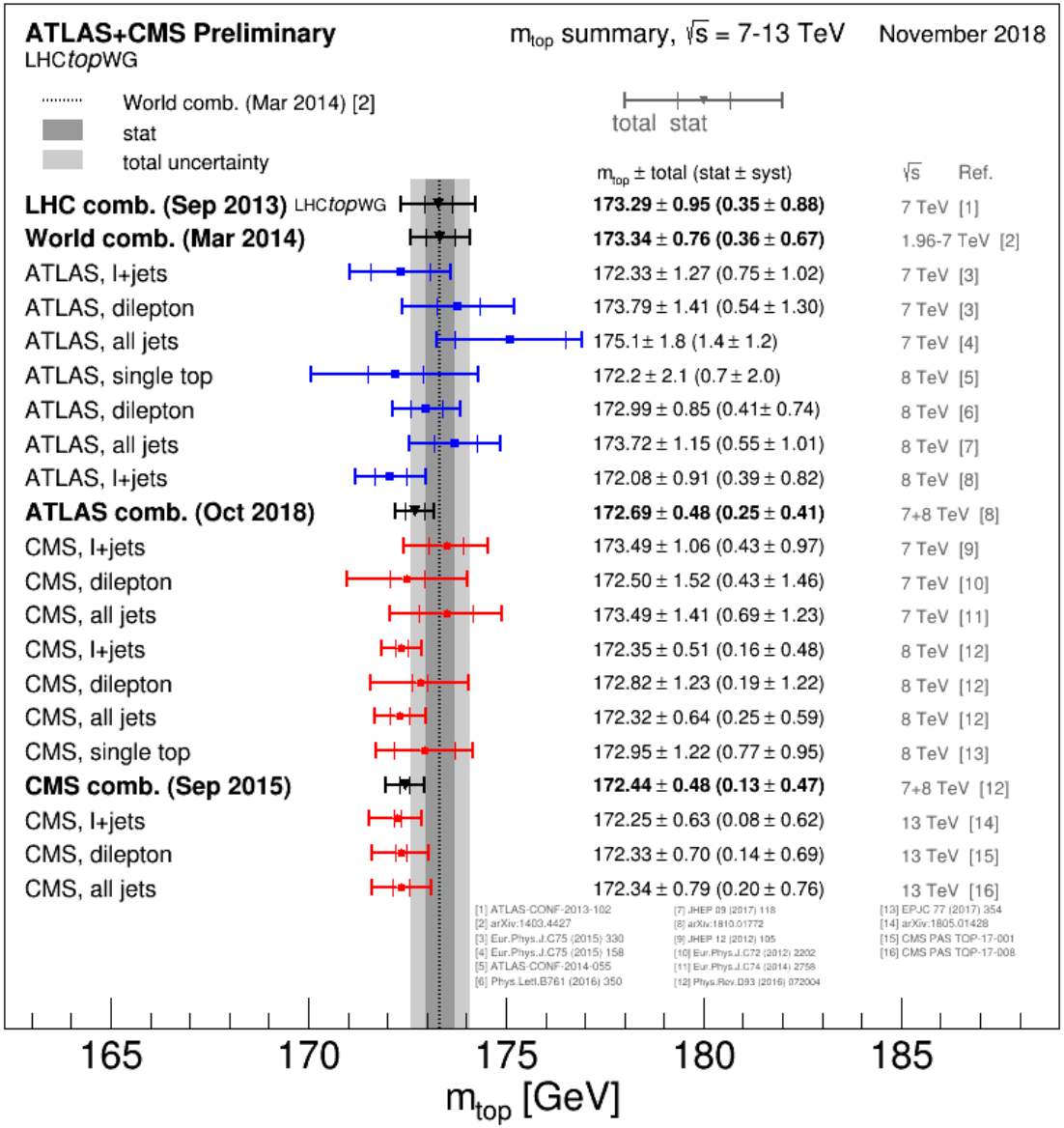
172.08±0.39(stat)±0.82(syst)

CMS: *Eur. Phys. J. C 78 (2018) 891*

Lepton+jets channel 2016 36 fb^{-1}data

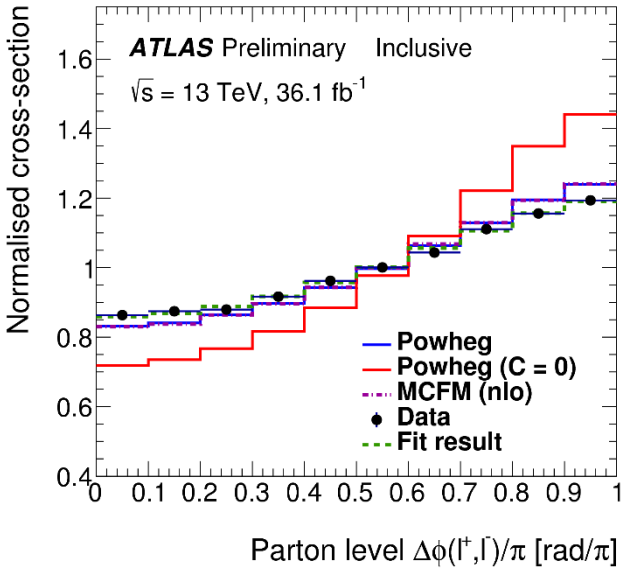
172.25 ± 0.08 (stat+JSF) ± 0.62 (syst GeV

reached ~0.5 GeV precision

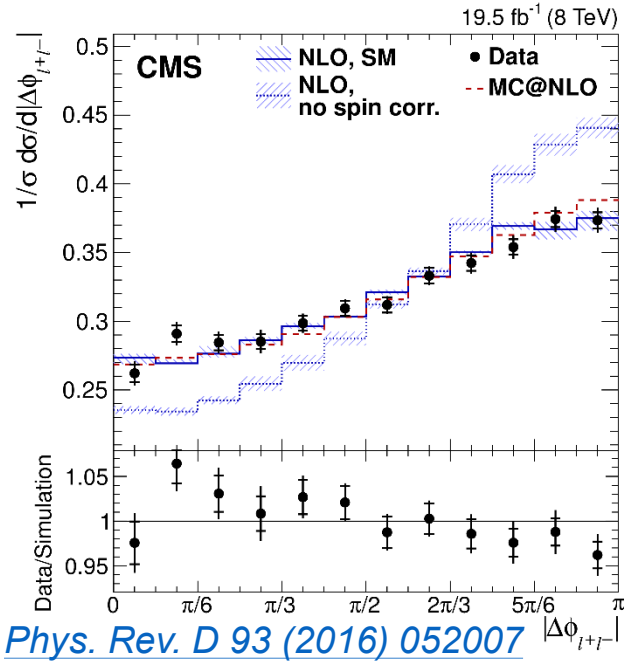


Top pair spin correlations

- Top quarks in $t\bar{t}$ production are mainly unpolarized, but the top pairs are strongly correlated
- Some BSM scenarios would lead to different top spin correlation
- Leptons from top decay carry the most spin information of the parent top
  - The easiest observable is the azimuthal opening angle Δφ between l^+l^-
- In ATLAS and CMS, unfolded parton-level differential cross sections for $\Delta\varphi(l^+l^-)$ are compared to different generator predictions



ATLAS-CONF-2018-027



Phys. Rev. D 93 (2016) 052007

- Latest ATLAS results show stronger spin correlation in data comparing to NLO prediction (tension ~3.2σ).

Flavour changing neutral currents from top-quark decays

- In SM, quark flavours can only change at tree level via charged currents (W+/- bosons)
- FCNC processes occur via loops in the SM, highly suppressed by GIM mechanism
- An observation of FCNC would be unambiguous evidence of BSM.

Current summary of 95% C.L. observed limits on the branching ratios of the top quark decays via FCNC in ATLAS and CMS.

Latest results since Dec. 2017:

ATLAS with 2015+2016 36 fb^{-1} data

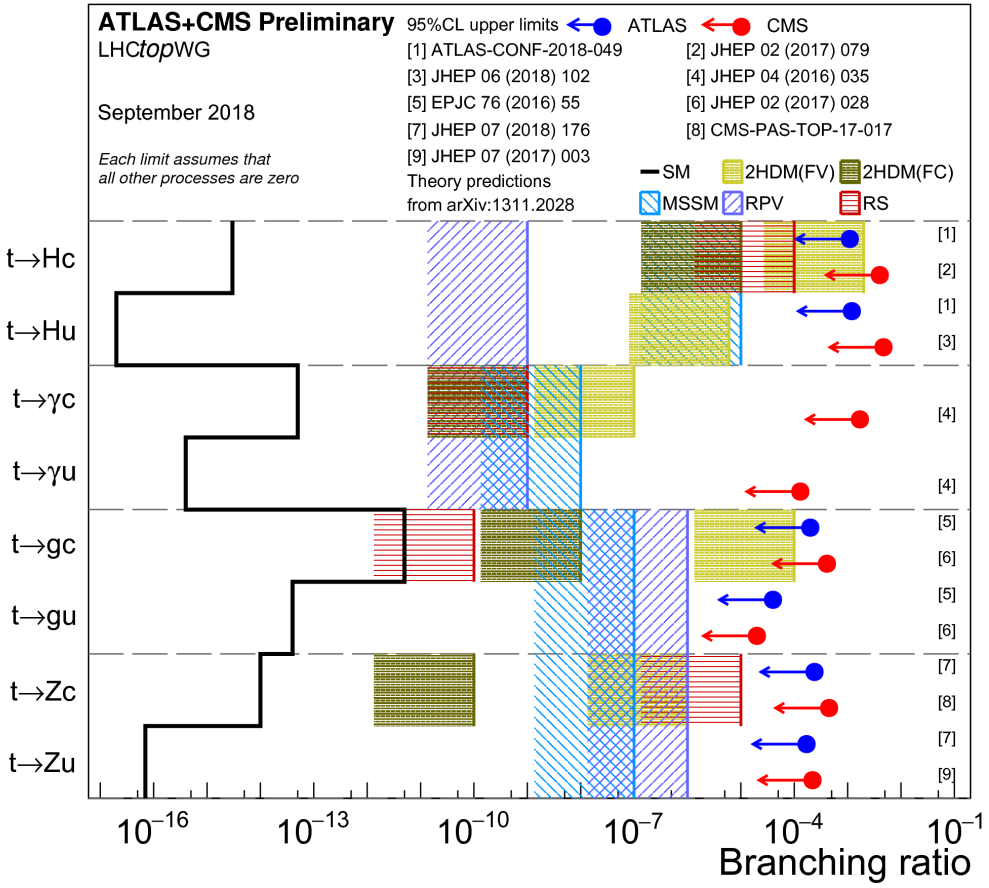
JHEP 07 (2018) 176 $t \to qZ$ (q=u, c)

Phys. Rev. D 98 (2018) 032002 $t \to Hq$ with $H \to multilepton$

ATLAS-CONF-2018-049 $t \to Hq$ with $H \to b\bar{b}, \tau\tau$

CMS with 35.9 fb^{-1} 2016 data

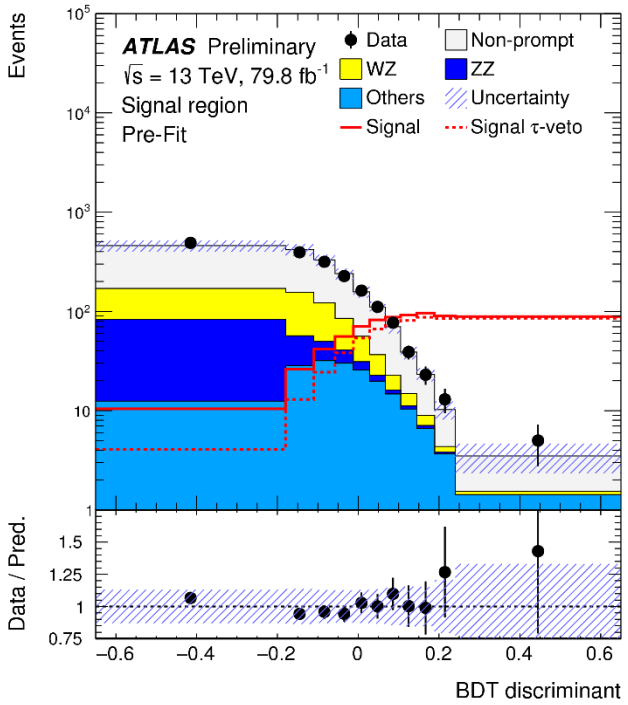
JHEP 06 (2018) 102 $t \to Hq$ with $H \to b\bar{b}$



Search for charged lepton-flavour violation in top-quark decays

- Test BSM models that allow the local non-conservation of charged lepton flavor
  - E.g. minimal extension of the SM explaining neutrino mass
- Latest results ATLAS-CONF-2018-044 from ATLAS use 79.8 fb^{-1} data collected from 2015 to 2017
  - Search for $t \to l^{\pm} l'^{\mp} q$ decay in $t\bar{t}$ with the other top decays semileptonically
  - Use binned maximum-likelihood fit on BDT discriminant to test for the presence of the signal events
- The observed exclusion on cLFV decay branching ratio is

$$\mathcal{B}(t \to \ell\ell' q) < 1.86 \times 10^{-5} \quad \text{(observed)}.$$

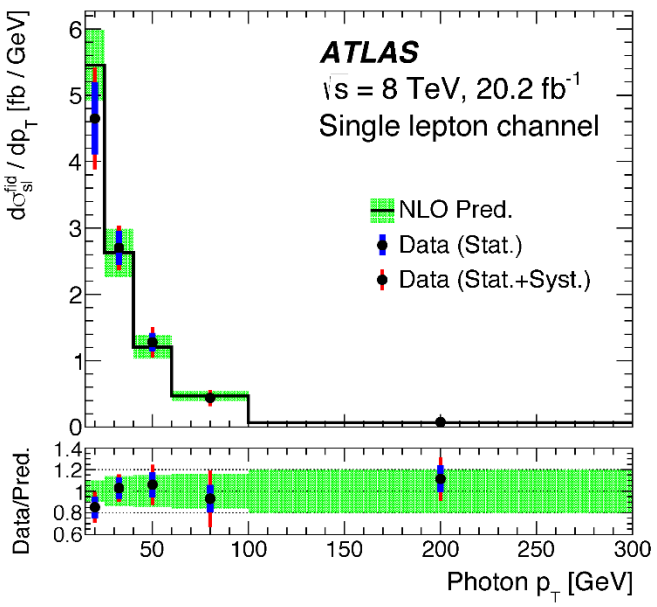


Summary

- LHC Run-2 data is taking a central stage in top physics studies, a broad range of new results were updated in 2018 by ATLAS and CMS
  - precision measurements of top production and decay, top quark properties
    - $t\bar{t}$, $t\bar{t}$+jets, $t\bar{t}$+bjets, single top tW cross sections
    - top quark mass and top pair spin correlations
  - challenging and rare production and decay modes are exploited
    - four-top-quark production, tZq observation
  - improved limits on various new physic searches
    - FCNC, cLFV
  - new study on tW and $t\bar{t}$ interference models
- Data results are generally consistent with theoretical predictions with a few exceptions that need further investigation
  - some differential distribution in $t\bar{t}$, $t\bar{t}$+jets, $t\bar{t}$+bjets
  - top pair spin correlations
- The total Run 2 data will be a factor of up to 4 times larger than currently investigated and offer many new exciting opportunities.

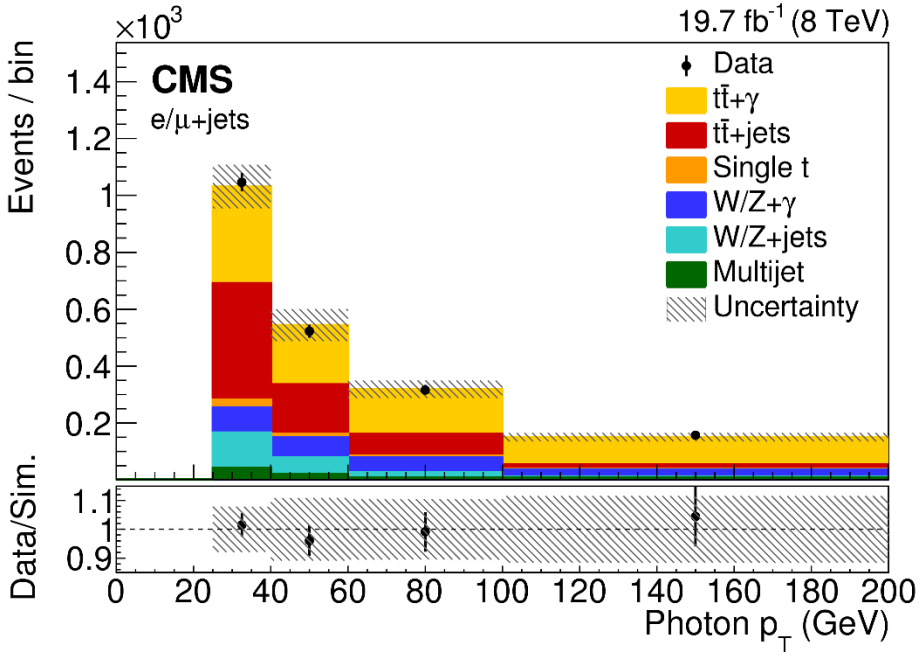
Backup

$t\bar{t}$ + γ



JHEP 11 (2017) 086

$\sigma_{tt\gamma}$=139 ± 18pb



JHEP 10 (2017) 006

$\sigma_{tt\gamma}$=127 ± 27pb

Indirect top mass measurement

CMS: 13 TeV data, L = 2.2 fb^{-1}; lepton+jets final state

- Measure differential cross section wrt min(m_{lb}) in categories of N_{jet} and $N_{b\text{-}jet}$:
  σ = 888 ± 2 (stat) ± 27(sys) ± 20 (lumi) pb
- Extract pole mass from cross section:
  m_t^{pole} = 170.6 ± 2.7 (tot) ± 1.01 (syst.) GeV

ATLAS: 8 TeV data, L = 20.2 fb^{-1}, dilepton with 1 or 2 b-jets

- 8 differential fiductial cross sections measured:
  p_T^l, |η|, $p^{eμ}$, $m^{eμ}$, $|y^{eμ}|$, $Δφ^{eμ}$, $p_T^e+p_T^μ$, $E^e+E^μ$
- m_t^{pole} extracted from combined fit to templates or distribution moments
  - m_t^{pole}= 173.2 ± 0.9 (stat) ± 0.8 (syst) ± 1.2 (theo) GeV

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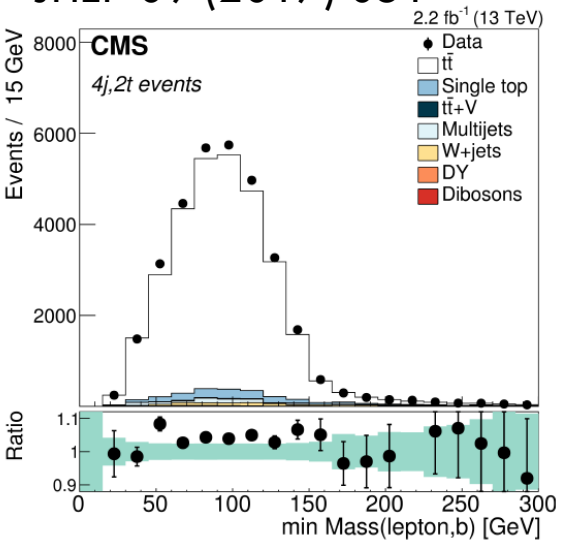
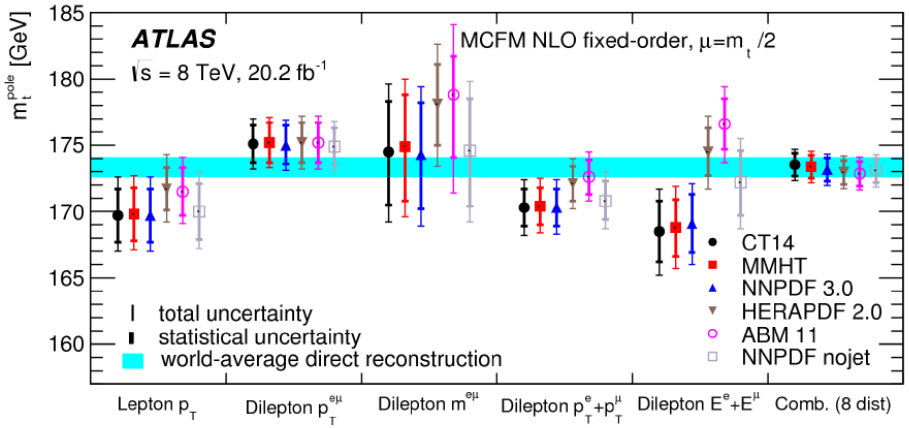
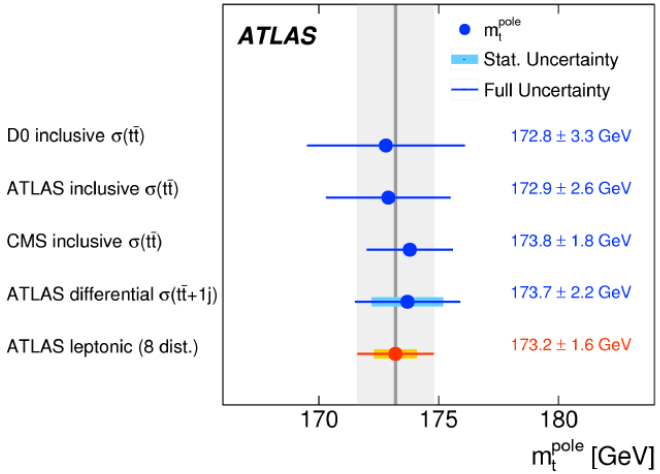




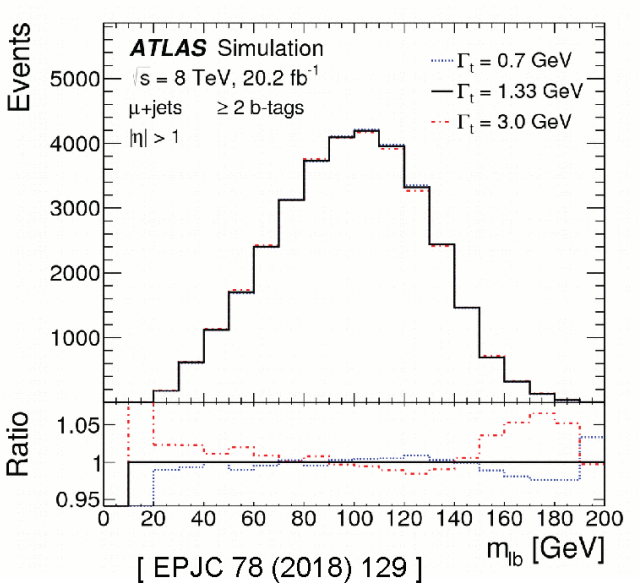


EPJC 77 (2017) 804

Top Width measurements

ATLAS: direct measurements from a partial kinematic reconstruction of the top decay

- Fit to m(lb) and $\Delta R_{min}(j,b)$
- Width extracted assuming m_{top}=172.5 GeV



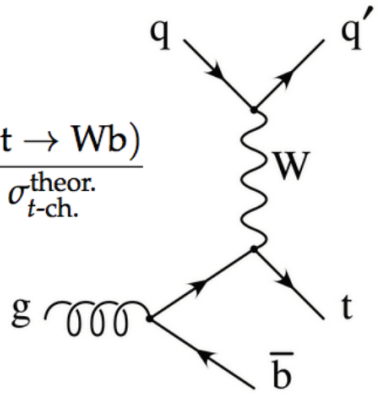
[EPJC 78 (2018) 129]

$$\Gamma_t = 1.76 \pm 0.33(\text{stat})^{+0.79}_{-0.68}(\text{sys})$$

CMS: direct measurement gives 0.6 GeV< Γ_t <2.5 GeV at 95% CL
[TOP-PAS-16-019]

CMS also derived Γ_t from t-channel single top production

$$\Gamma_t = \frac{\sigma_{t\text{-ch.}}}{\mathcal{B}(t \to Wb)} \cdot \frac{\Gamma(t \to Wb)}{\sigma^{\text{theor.}}_{t\text{-ch.}}}$$



B(t→Wb) is separately measured:
[PLB 736 (2014) 33]

$$\frac{B(t \to Wb)}{B(t \to Wq)} = 1.014 \pm 0.003(\text{stat}) \pm 0.032(\text{sys})$$

Finally, combined with previous CMS t-channel single-top-quark cross section:

$$\Gamma_t = 1.36 \pm 0.02(\text{stat})^{+0.14}_{-0.11}(\text{sys})$$

Top charge asymmetry

[JHEP 04 (2018) 033]

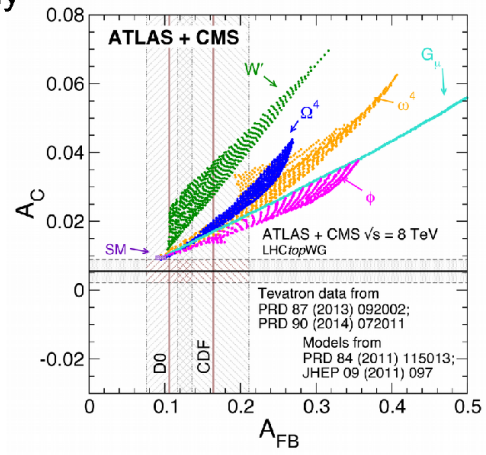
At Tevatron, measure A_{FB}. At LHC, measure A_C:

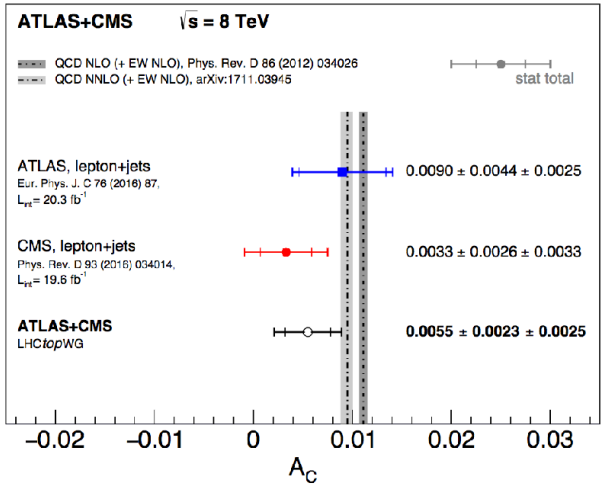
$$A_C = \frac{N^{\Delta|y|>0} - N^{\Delta|y|<0}}{N^{\Delta|y|>0} + N^{\Delta|y|<0}}$$

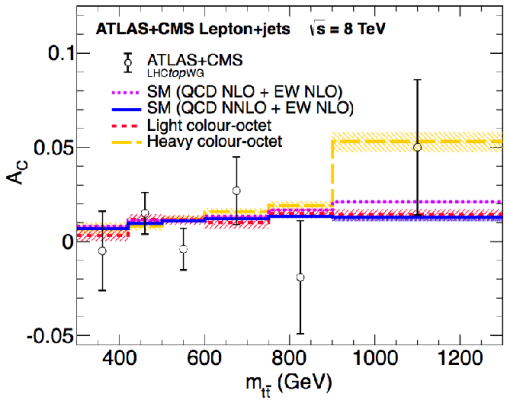
Non-zero A_C in SM due to higher order effects in $q\bar{q}$ annihilation

Use lep+jets events. Reconstruct $t\bar{t}$ events and unfold

LHC A_C measurements ruled out a number of theories explaining the Tevatron A_{FB} anomaly







High $t\bar{t}$ mass region has higher fraction of quark initiated production – A_C is more sensitive to BSM

Variables used in the multivariate analysis, sorted according to the method-specific ranking.

Variable	Separation (%)
OSSF lepton pair invariant mass	11
cLFV top mass	10
p_{T} of the electron associated to the cLFV decay	9.1
p_{T} of the muon associated to the cLFV decay	8.5
p_{T} of the lepton associated to the SM decay	8.3
Scalar mass of all jets and leptons in the event	7.6
Same-sign electron pair invariant mass	6.9
Missing transverse momentum	6.8
Number of b-jets	6.7
W transverse mass associated to the SM top lepton	6.6
ΔR between the cLFV electron and the cLFV light jet	6.5
SM top mass	6.4
ΔR between the cLFV muon and the cLFV light jet	6.3
BDT discriminant	44