# Top physics in ATLAS and CMS

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# Outline



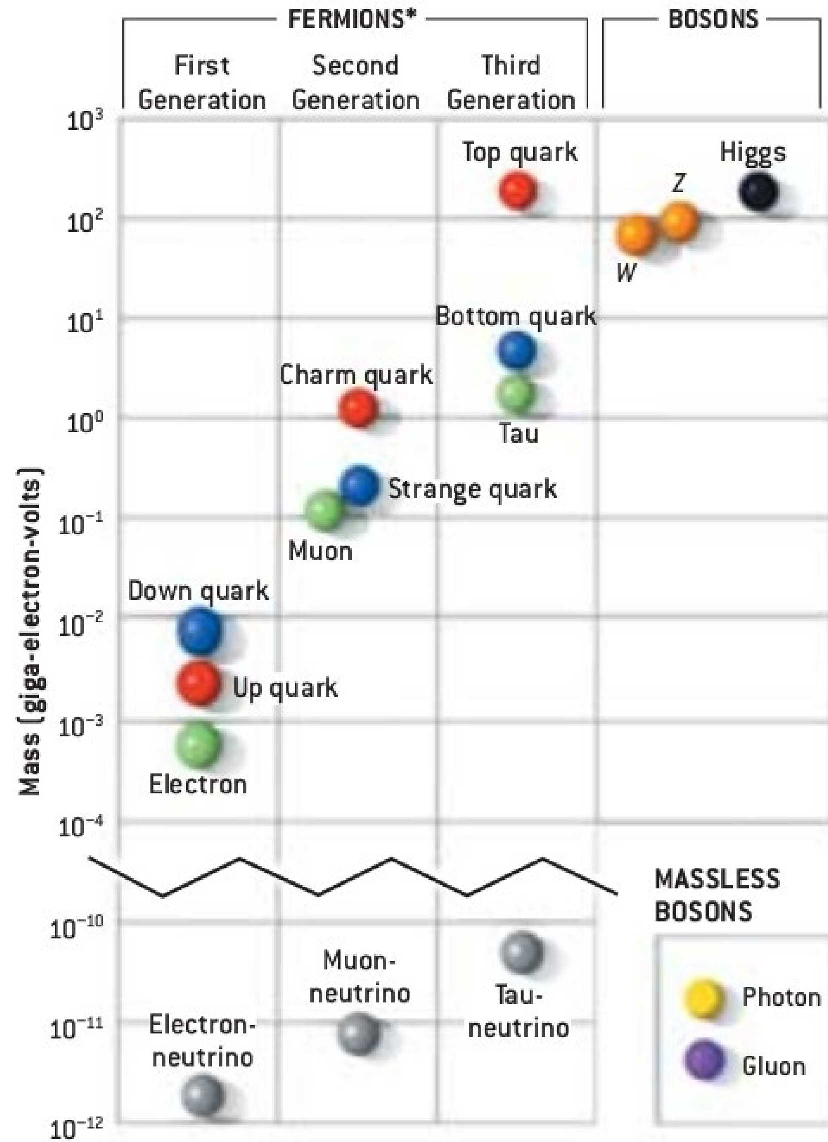
Focus on new results published in 2018 and 2019

- Introduction
- Top quark production cross-section measurements
  - $t\bar{t}$ inclusive and differential cross sections
  - Single top quark production cross sections
  - Top+X production measurements
- Top quark properties measurements
  - Top quark mass measurements, top decay width
  - Top pair spin correlations, charge asymmetry
- 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

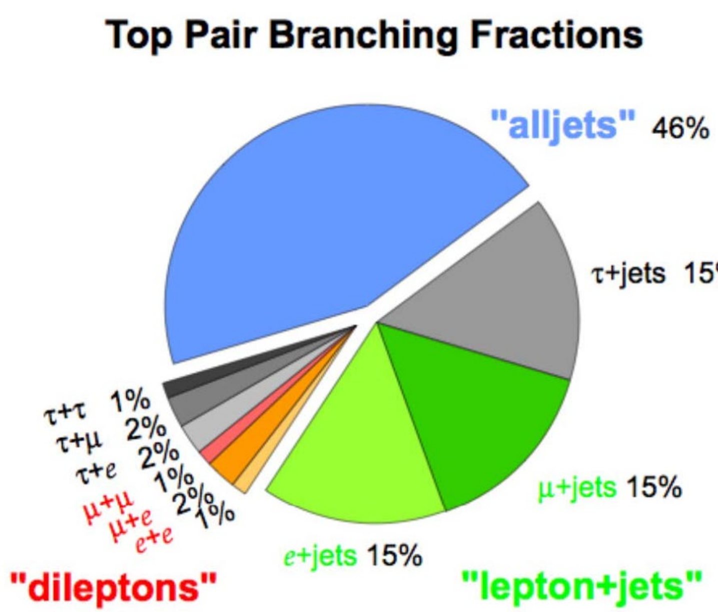
Very interesting and important at the LHC

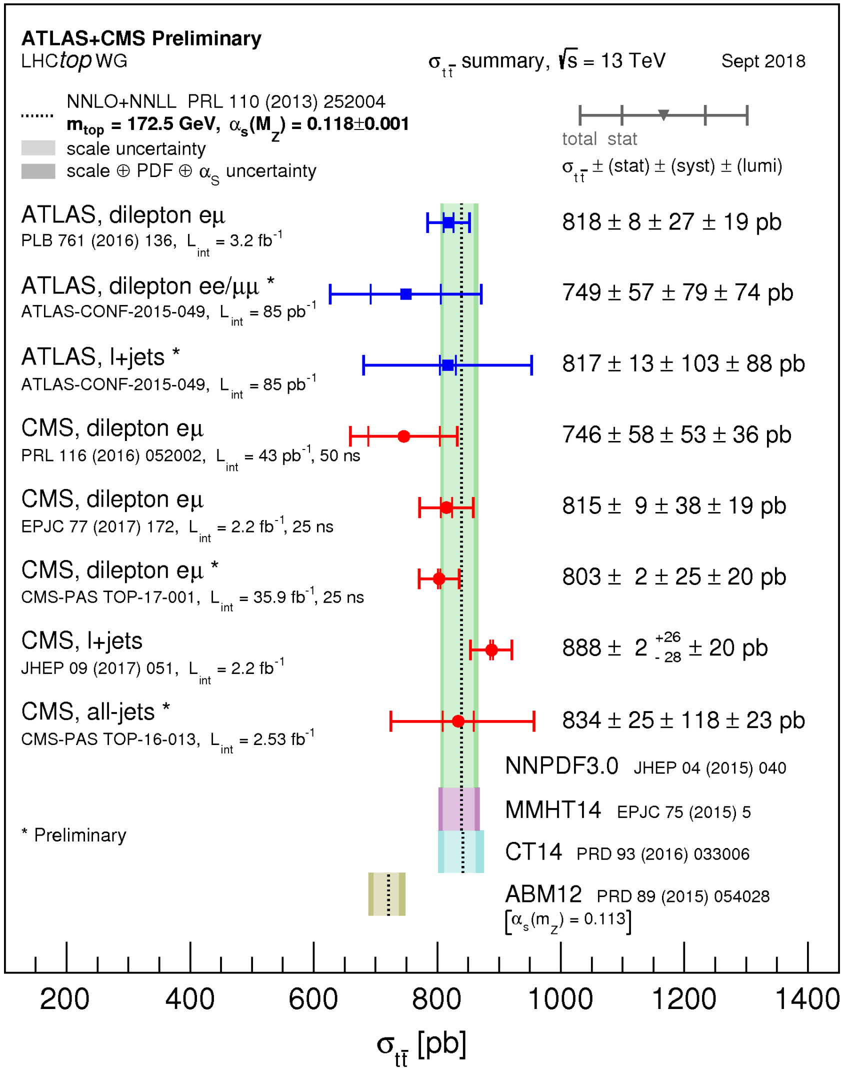
# $t\bar{t}$ inclusive and differential cross sections

# $t\bar{t}$ 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
  - Constraints on SM parameters ($m_t$, $\alpha_S$) and PDFs
  - Constraints on anomalous EFT terms
  - Background for many BSM and Higgs signals

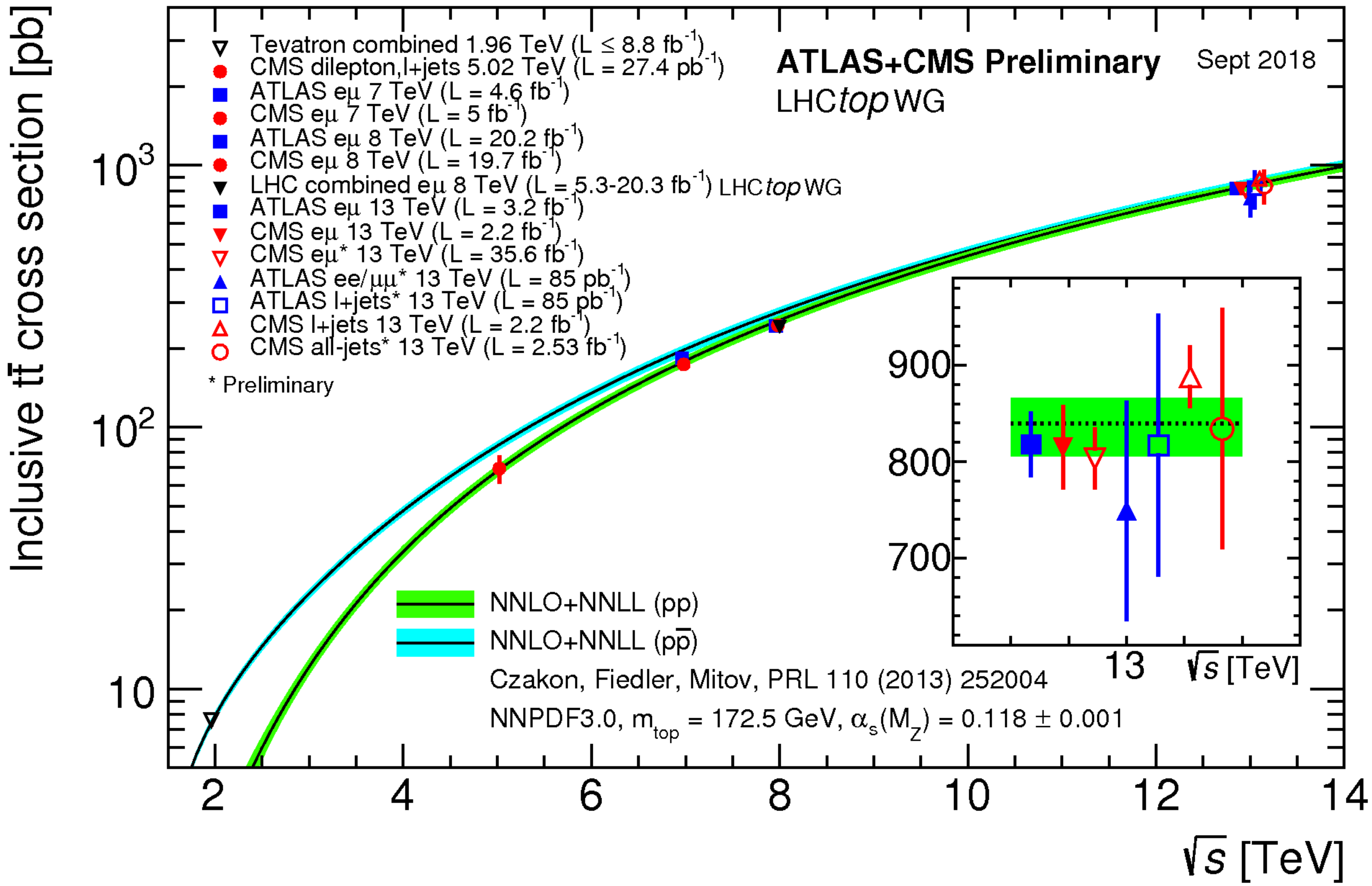



Good agreement between data and prediction

# $t\bar{t}$ inclusive cross sections





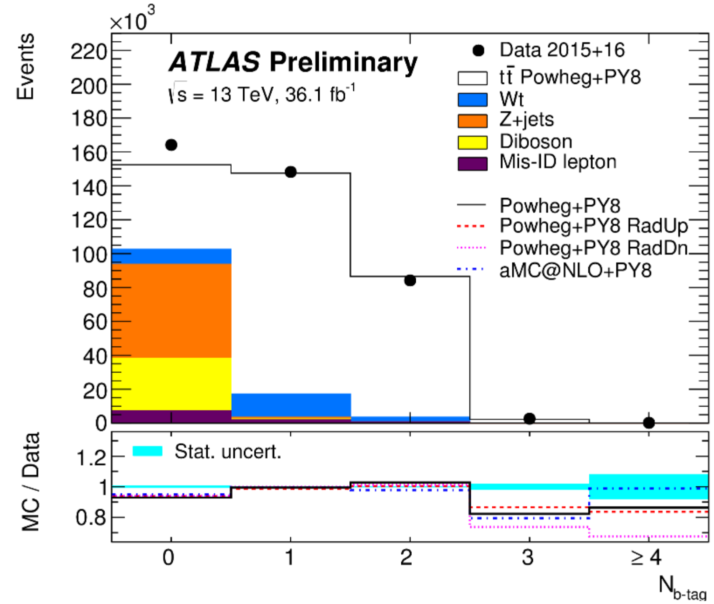

- Single measurement precision: ~3.5%
- Limited mainly by luminosity and signal model uncertainty.

# Latest $t\bar{t}$ inclusive cross sections

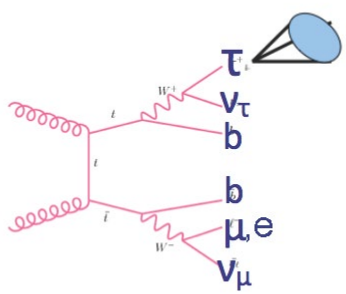


- ATLAS, ATLAS-CONF-2019-041
  - 13 TeV, 36.1 fb$^{-1}$ data
  - events with an opposite-charge eμ pair and one or two b-tagged jets
  - 2.4% precision

$$\sigma_{t\bar{t}} = 826.4 \pm 3.6\,(\mathrm{stat}) \pm 11.5\,(\mathrm{syst}) \pm 15.7\,(\mathrm{lumi}) \pm 1.9\,(\mathrm{beam})\ \mathrm{pb}$$



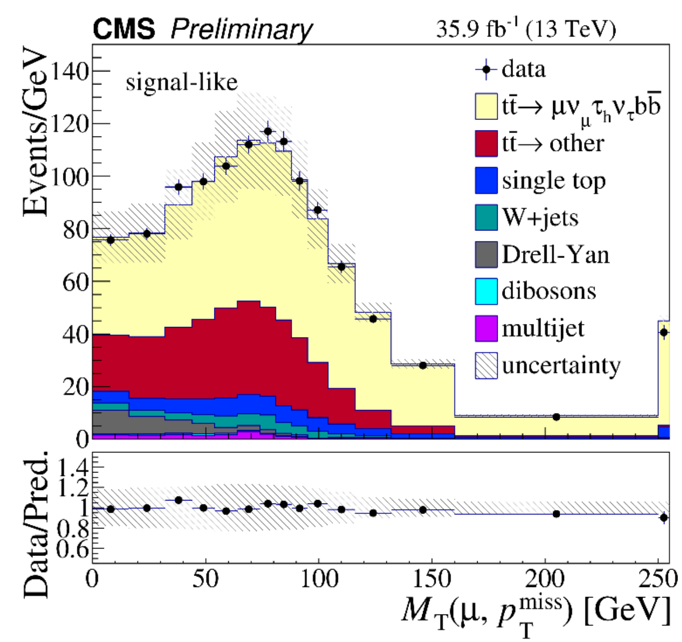

- CMS, CMS-PAS-TOP-18-005
  - 13 TeV, 35.9 fb$^{-1}$ data
  - events $t\bar{t} \to (l\nu_l)(\tau_h\nu_\tau)b\bar{b}$
  - measured cross section




$$\sigma_{t\bar{t}} = 781 \pm 7(stat) \pm 62(syst) \pm 20\ (lumi)\ pb$$

  - ratio of the partial width to the total width

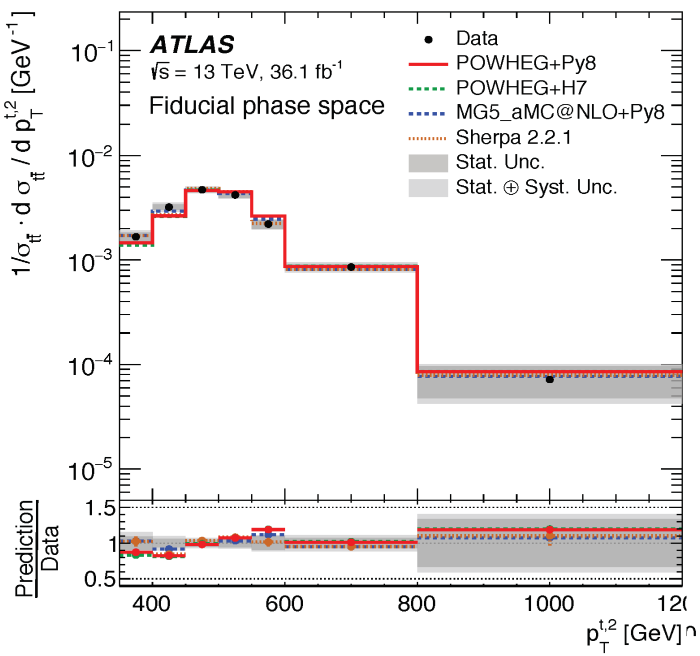
$$\Gamma(t \to \tau\nu_\tau b)/\ \Gamma_{total} = 0.1050 \pm 0.0009(stat) \pm 0.0071(syst)$$



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

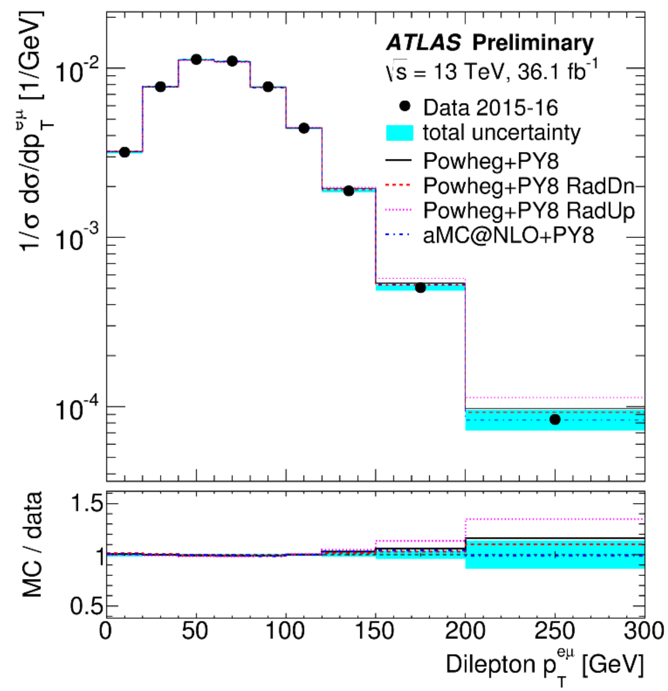


- Scrutinize tt production in many channels as a function of many observables
  - precision tests of QCD in different regions of phase space
  - sensitive to BSM physics




All-jets 36.1 fb$^{-1}$

PRD 98 (2018) 012003



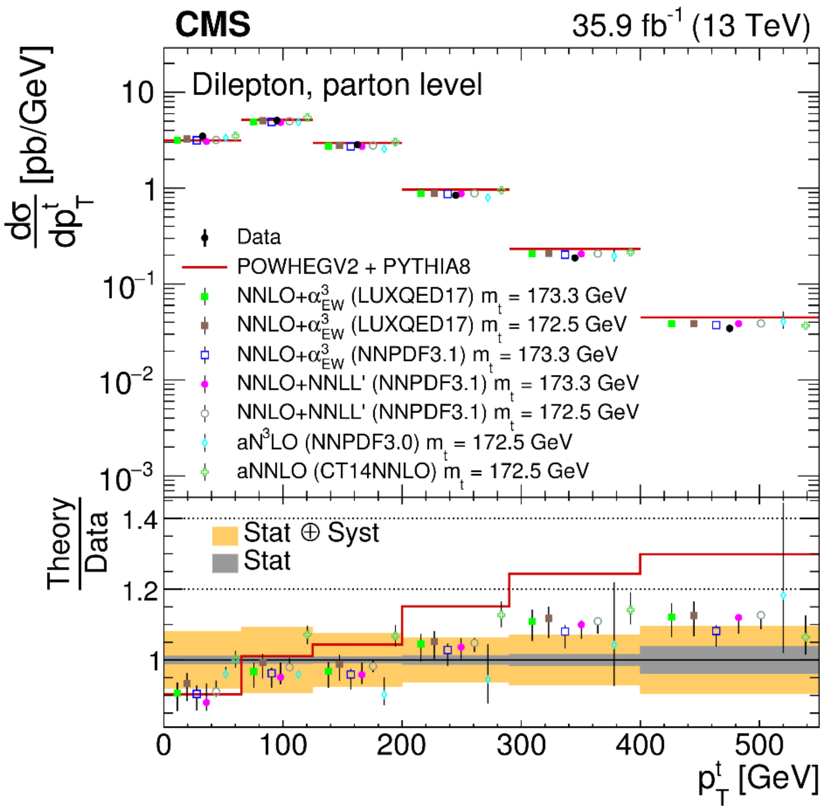

ATLAS-CONF-2019-041

- Kinematic variables consistent with NLO QCD in general

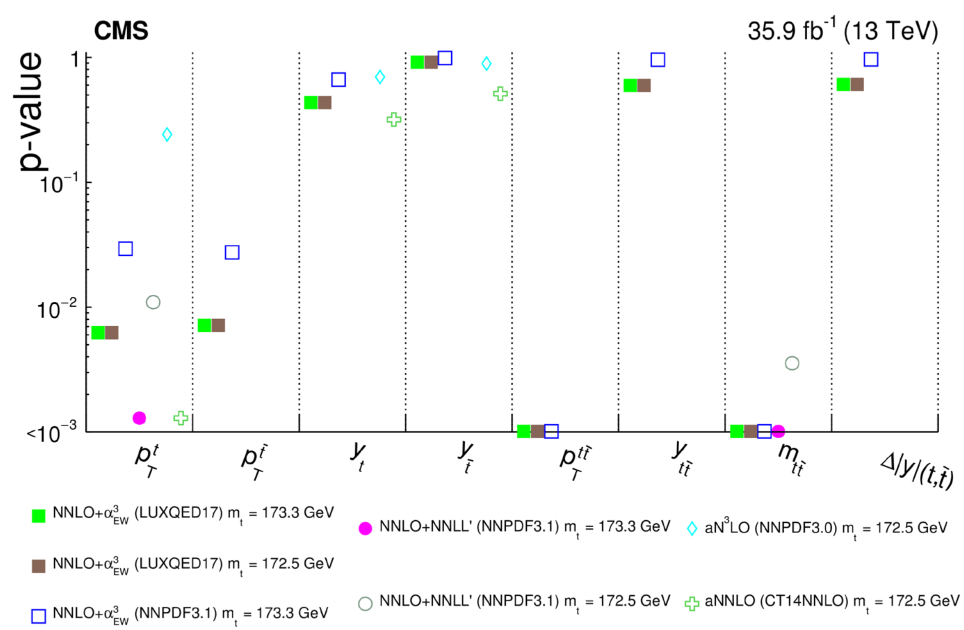
# $t\bar{t}$ differential cross sections - CMS



CMS-TOP-17-014, JHEP 02 (2019) 149




p-value agreement between theoretical prediction and data

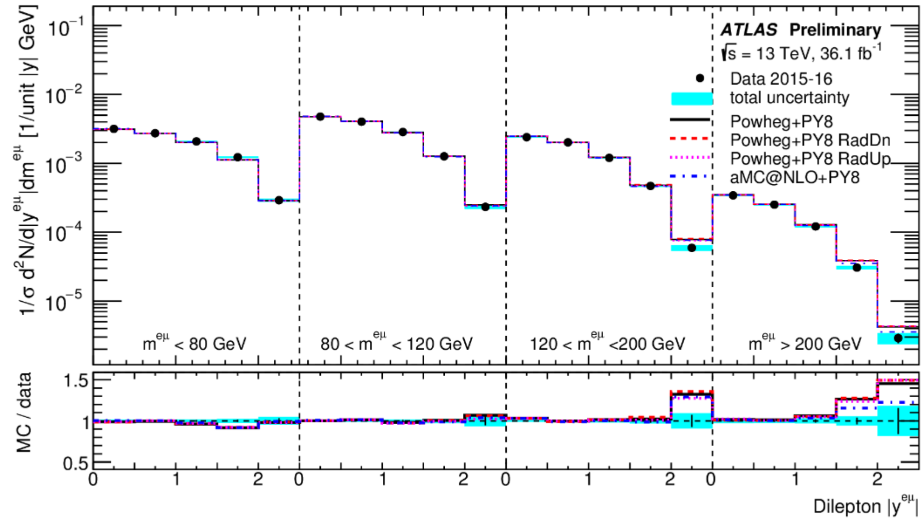



- Data shows softer top $p_T$ than POWHEG+PYTHIA predicted in dilepton channel
  - still see the trend with higher order QCD and EW corrections
- Other variables related to top $p_T$ are also in tension

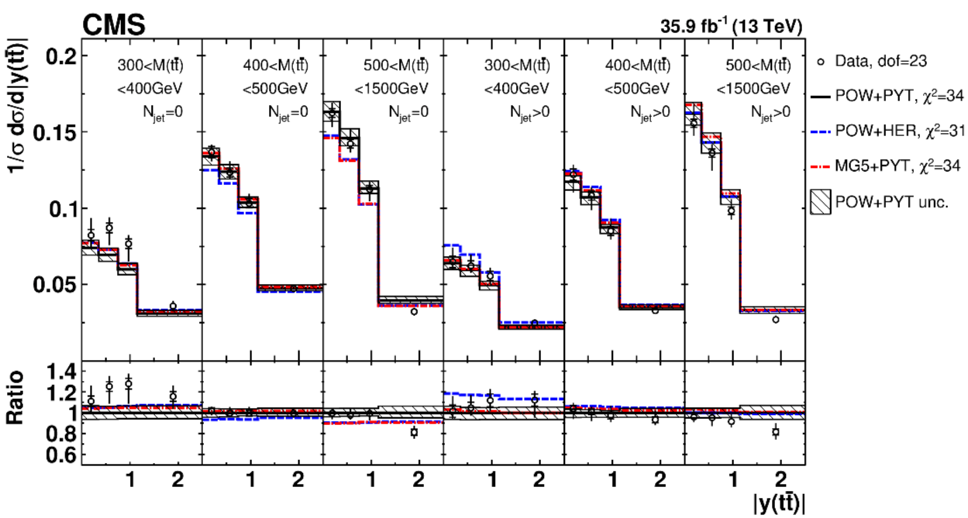
# $t\bar{t}$ differential cross sections - multidifferential

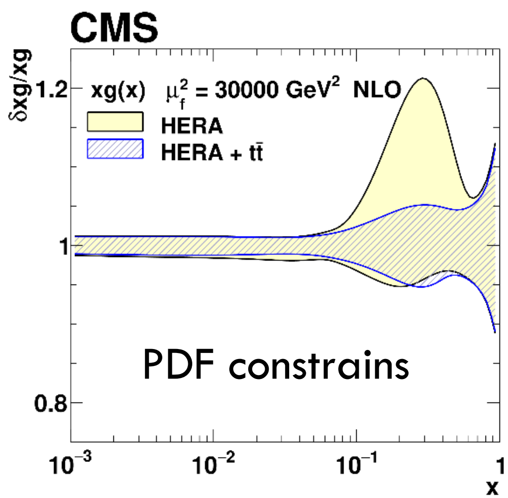


- ATLAS: 2D differential cross sections as a function of lepton and dilepton kinematics




- CMS: 2D, 3D differential cross sections vs. top, $t\bar{t}$ kinematics and Njets, extracted $m_t^{pole}$, $\alpha_s$, PDF



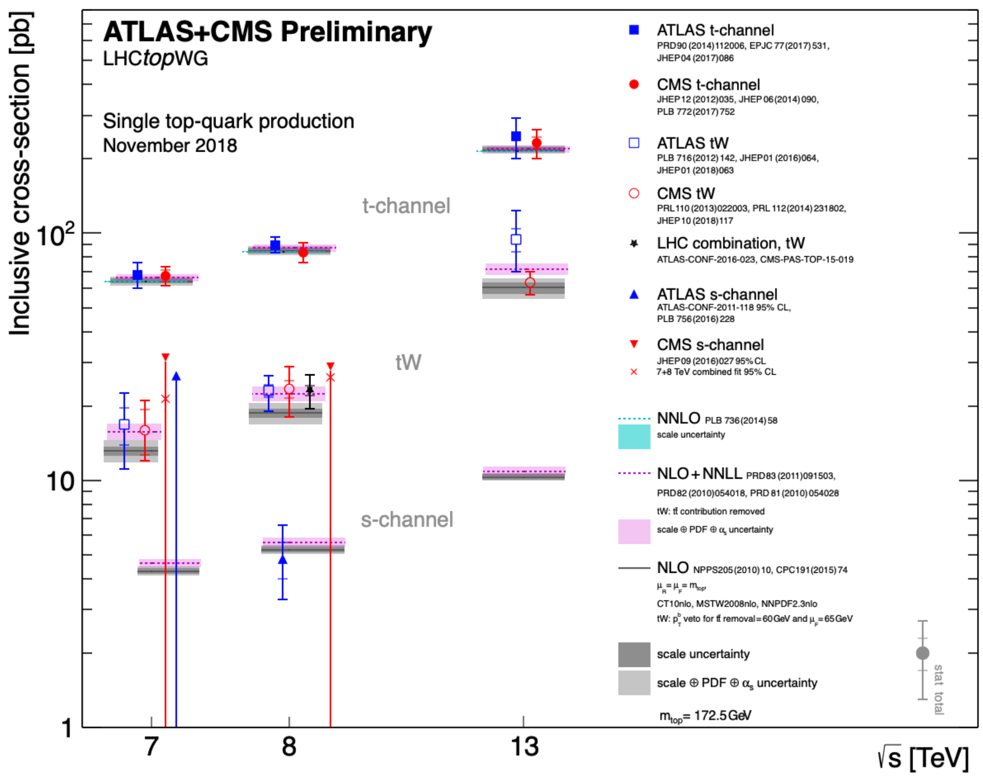



# Single top quark production cross sections

# 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]

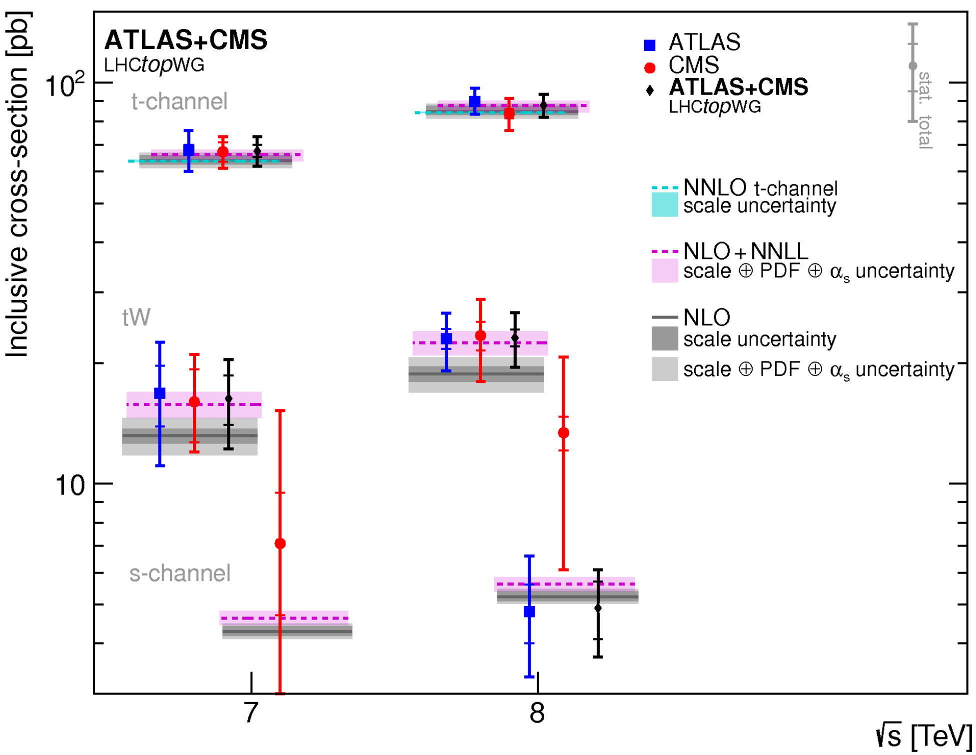
CMS tW:

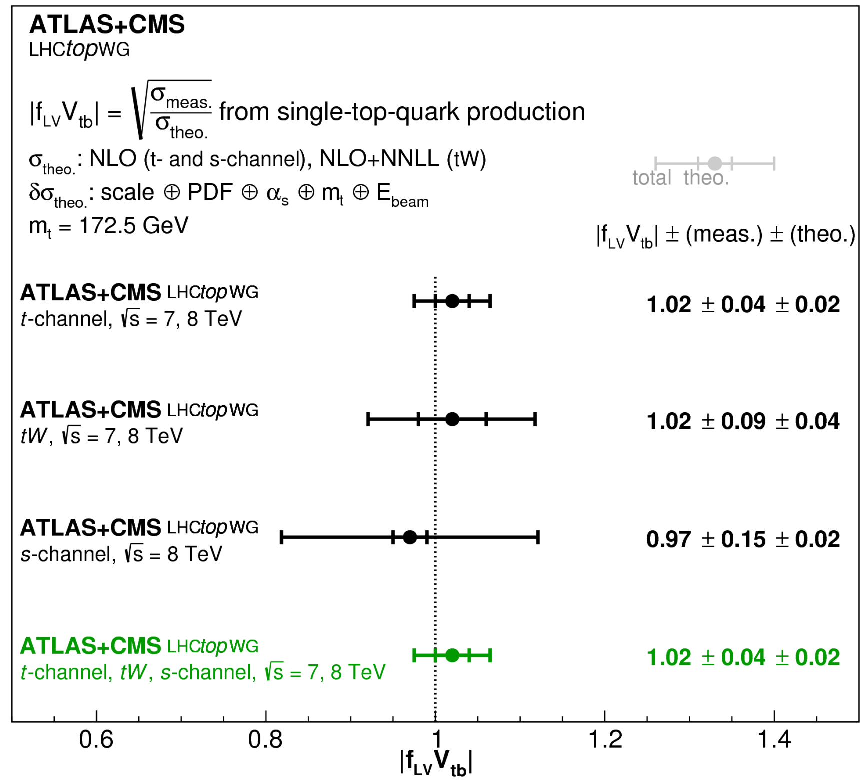
*[JHEP 10 (2018) 117]*

# ATLAS and CMS Run1 Combination



- Run1 ATLAS+CMS combinations on single-top-quark cross sections and Vtb
  - *JHEP 05 (2019) 088*



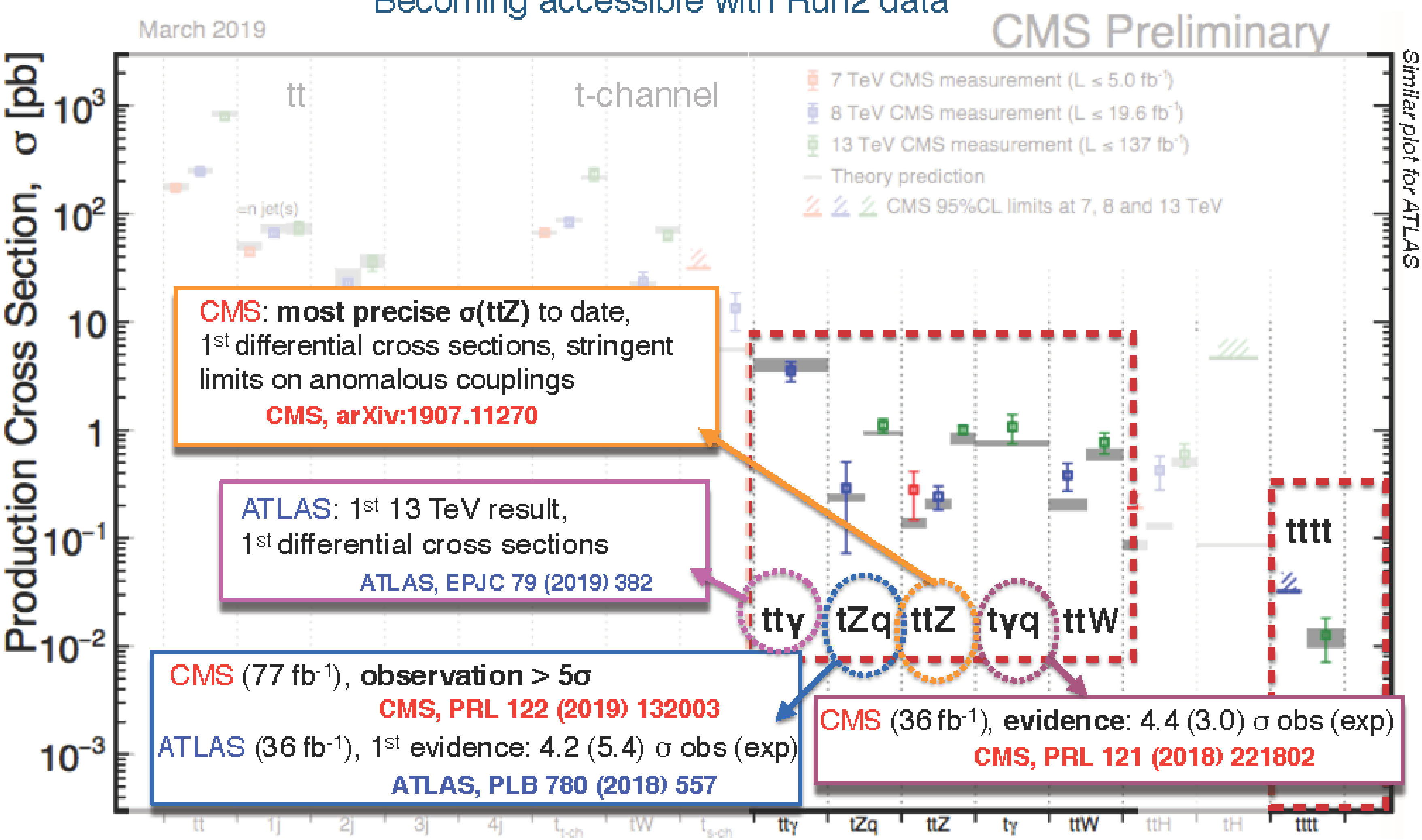

**Best $V_{tb}$ direct determination to date!**

# Top+X production measurements

# Top+X production in a nutshell



Becoming accessible with Run2 data

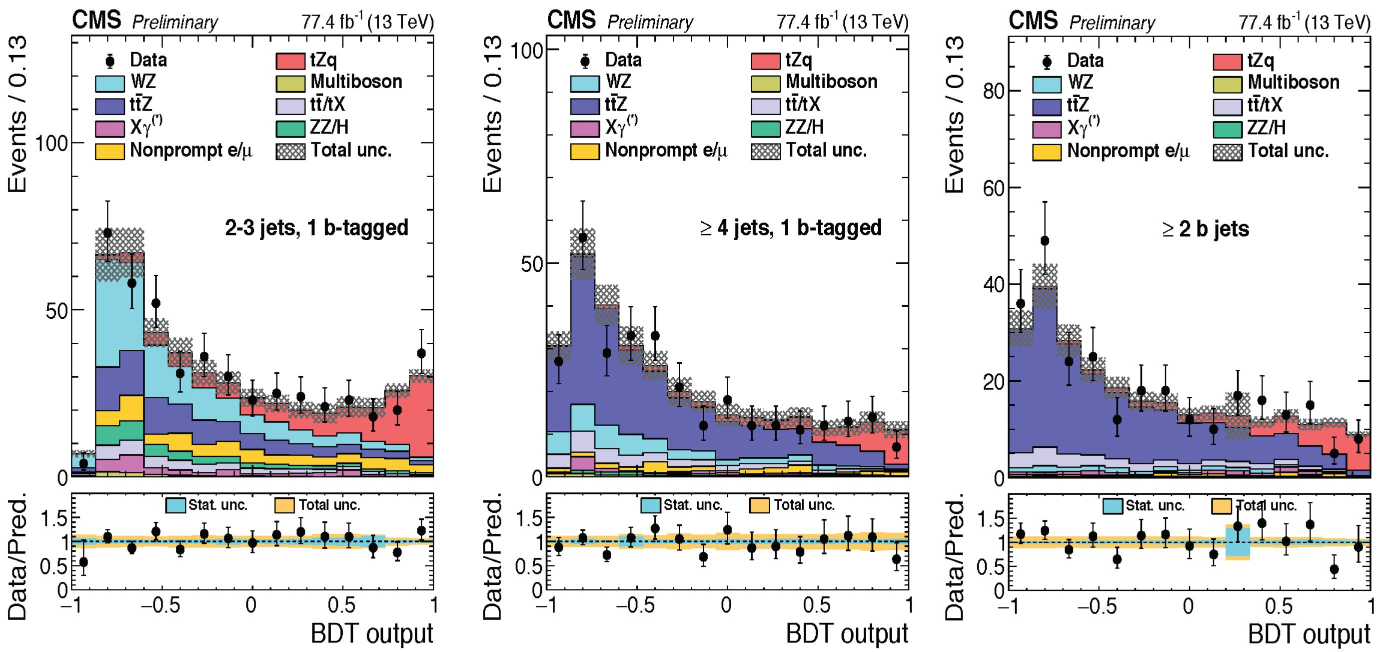



M. Aldaya

# 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:

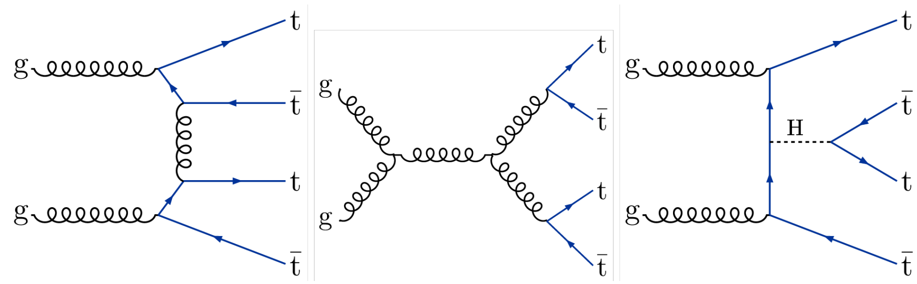
$$\sigma(tZq \to t\ell^+\ell^-q) = 111 \pm 13(stat)^{+11}_{-9}(syst)\,\text{fb}$$

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

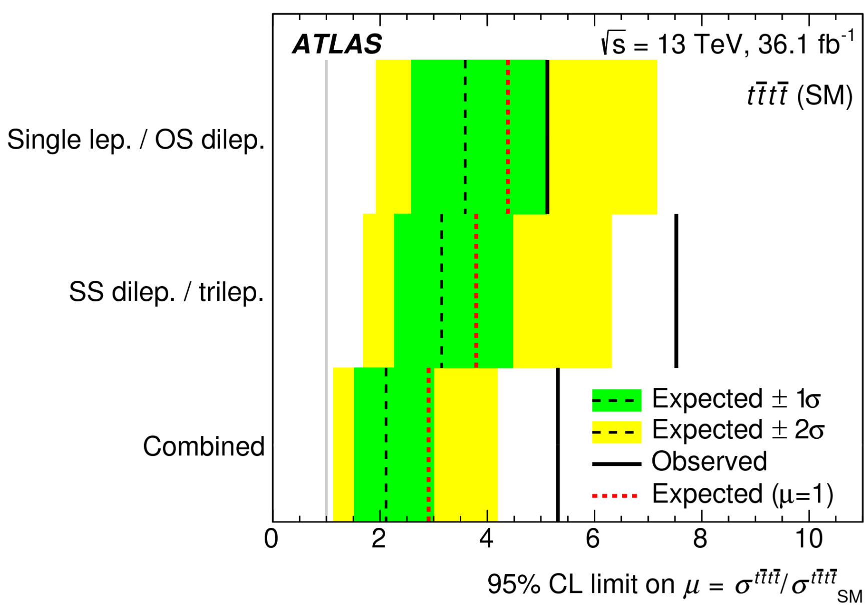
# Searches for standard model production of four top quarks

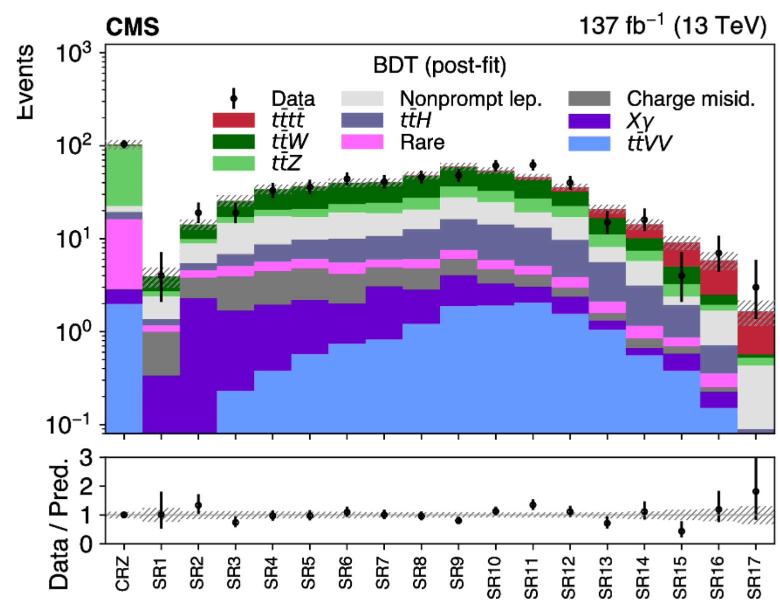


- Tiny cross section in SM ~9fb @13 TeV
- Many BSM models probes an increase




- Searches performed in LHC with Run2 data
  - ATLAS/CMS: single lepton and opposite-sign dilepton channels arXiv:1811.02305, CMS-TOP-17-019
  - CMS: same sign and multilepton final states CMS-TOP-18-003, **using full Run2 data**

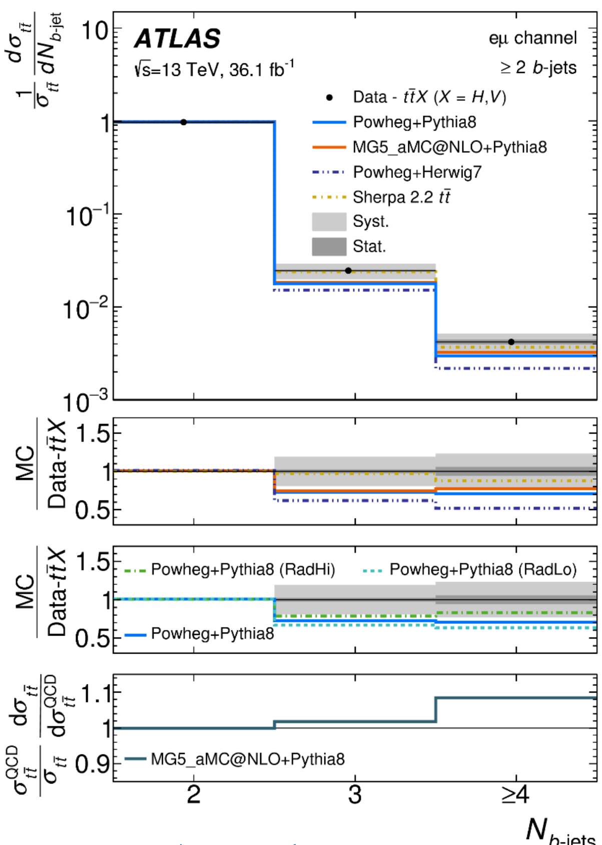



**Significance: 2.6 (2.7) σ obs (exp)**

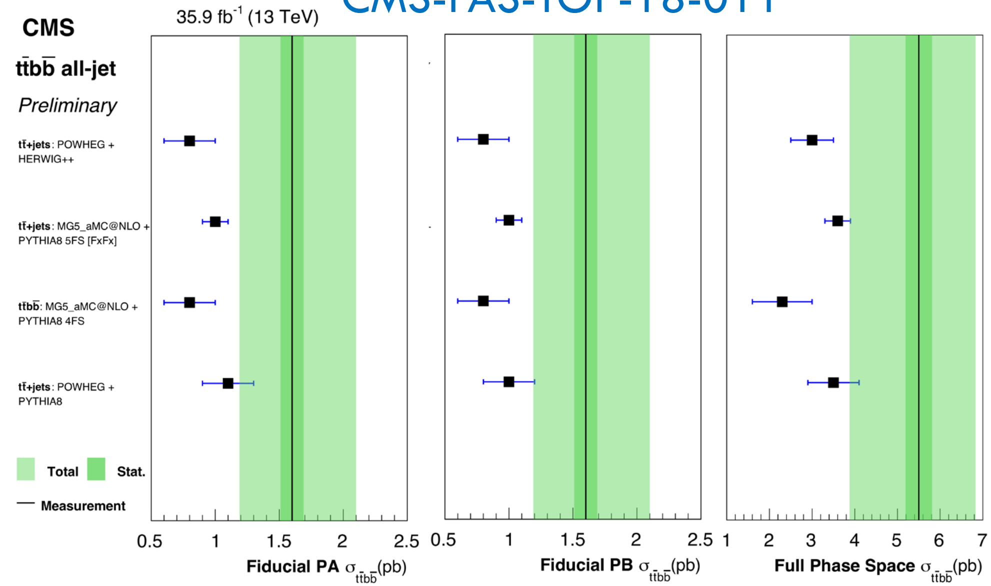
# $t\bar{t} + b\bar{b}$

- Important background to ttH(bb) production
- Different phase spaces compared to NLO MC simulations
- **In general data exceeds the predictions**

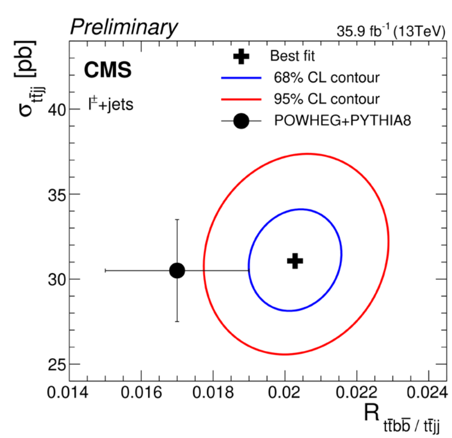


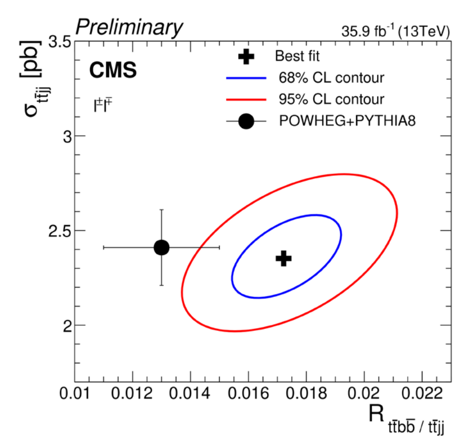

JHEP 04 (2019) 046

CMS-PAS-TOP-18-011




fresh results from CMS-PAS-TOP-18-002



# Top quark properties measurements

# Top quark mass measurement



- Top quark mass is a key parameter of the Standard Model, important for electroweak vacuum stability
  - Need to measure the top mass in all possible ways with highest possible precision

- Direct measurement of “Monte Carlo mass” $m_t^{MC}$
  - Extracted from invariant mass of decay products

- 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 $\sigma^{theory}$
  - Measurement made in a given renormalization scheme

- 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

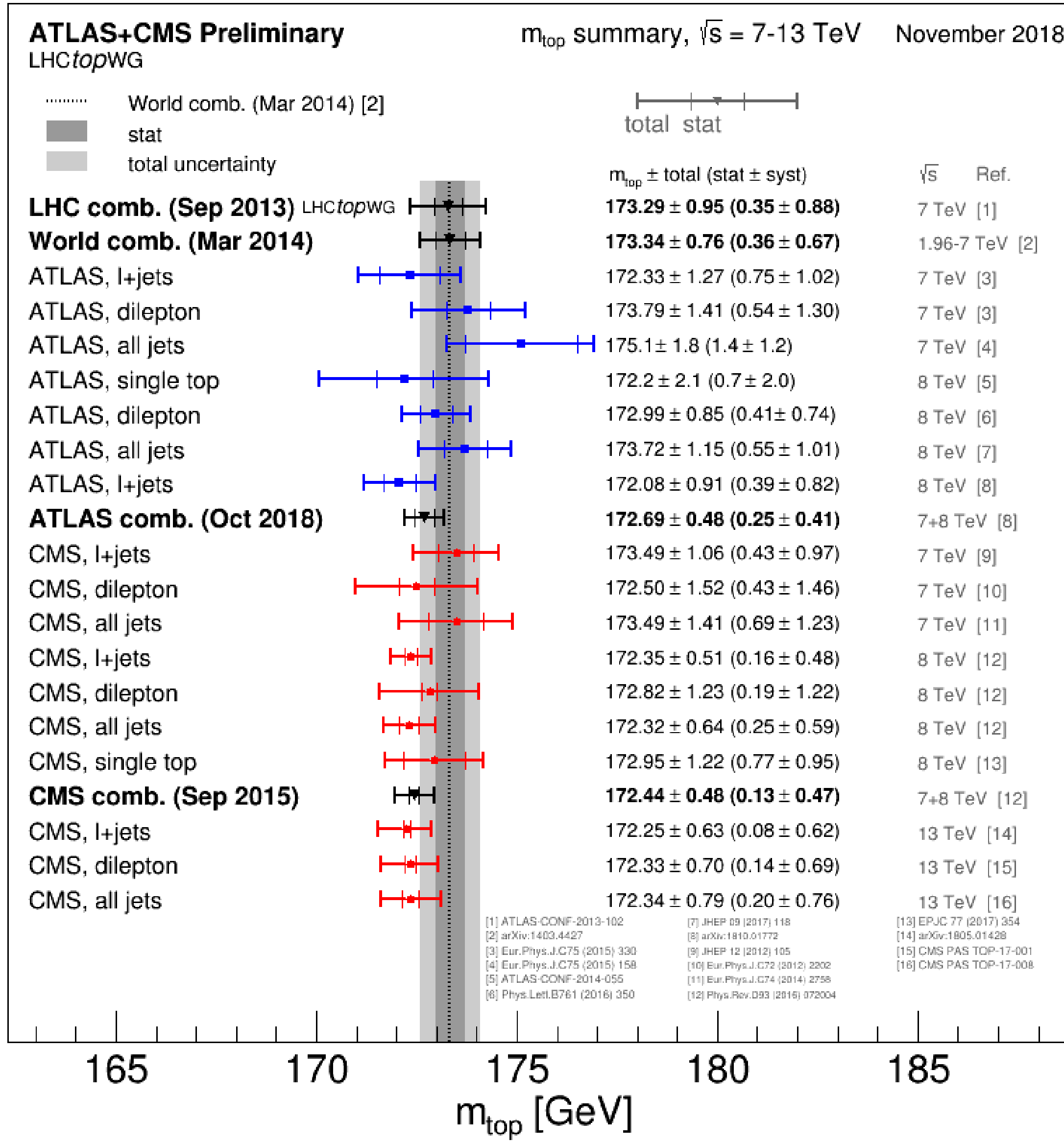
172.08±0.39(stat)±0.82(syst)

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

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

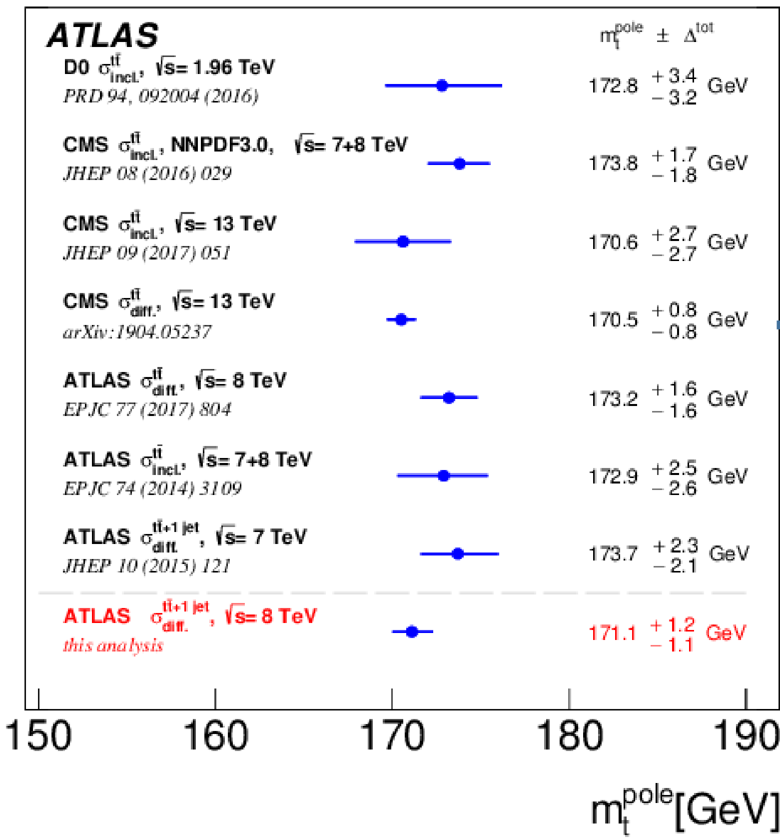
172.25 ± 0.08 (stat+JSF) ± 0.62 (syst GeV

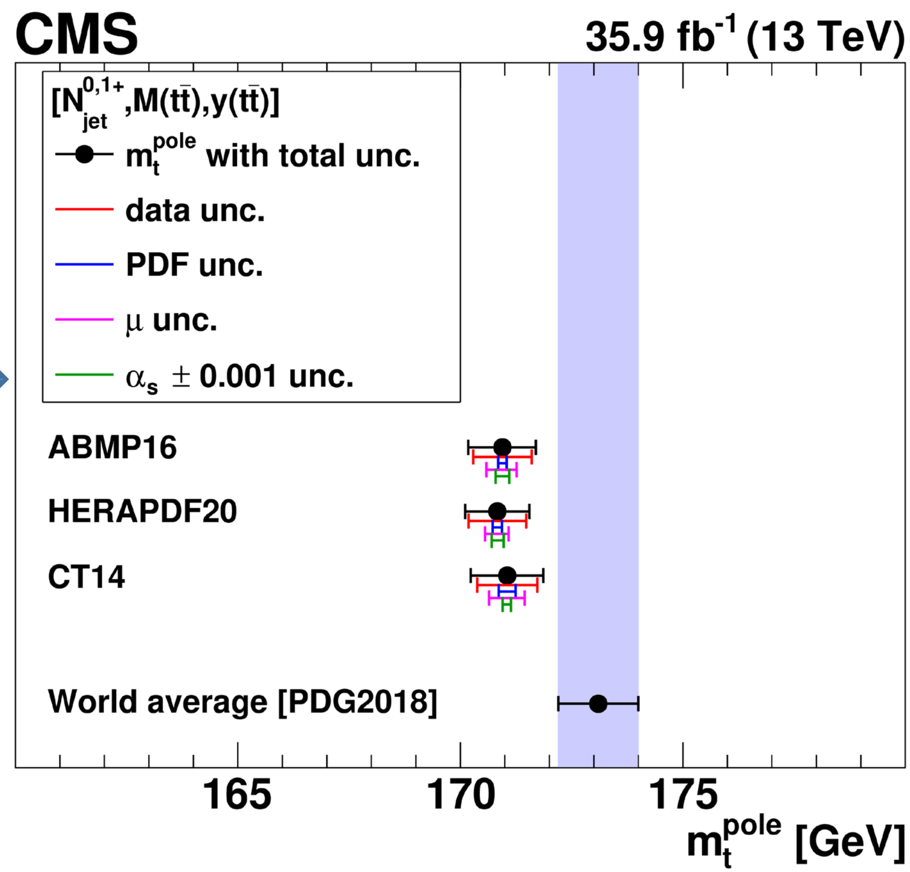
reached ~0.5 GeV precision



# Indirect measurement of the $m_t^{pole}$ in ATLAS

- Recent indirect measurement of the pole mass $m_t^{pole}$ extracted from differential measurement in ATLAS arXiv:1905.02302 and CMS arXiv:1904.05237



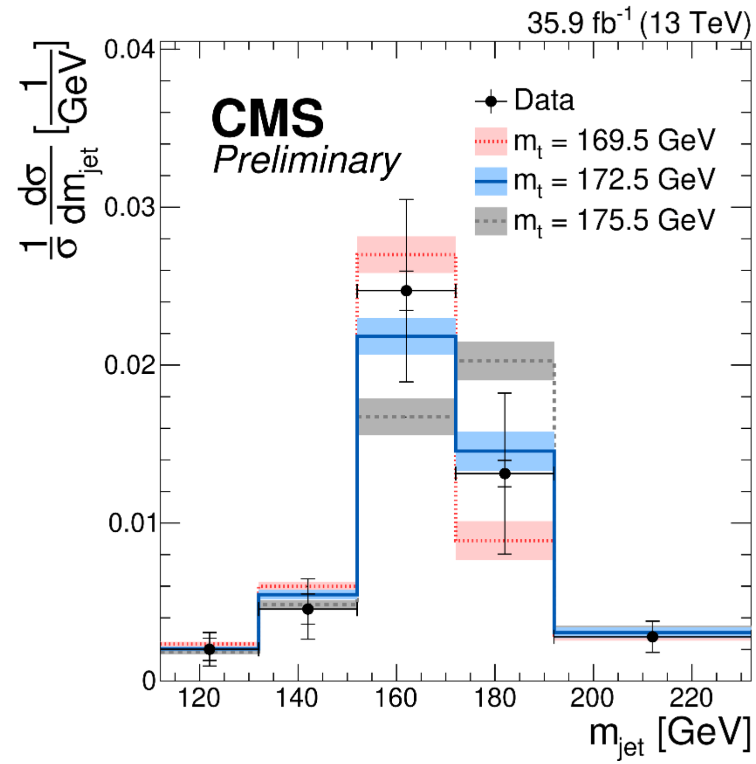




most precise result so far

# Latest top mass measurement in CMS



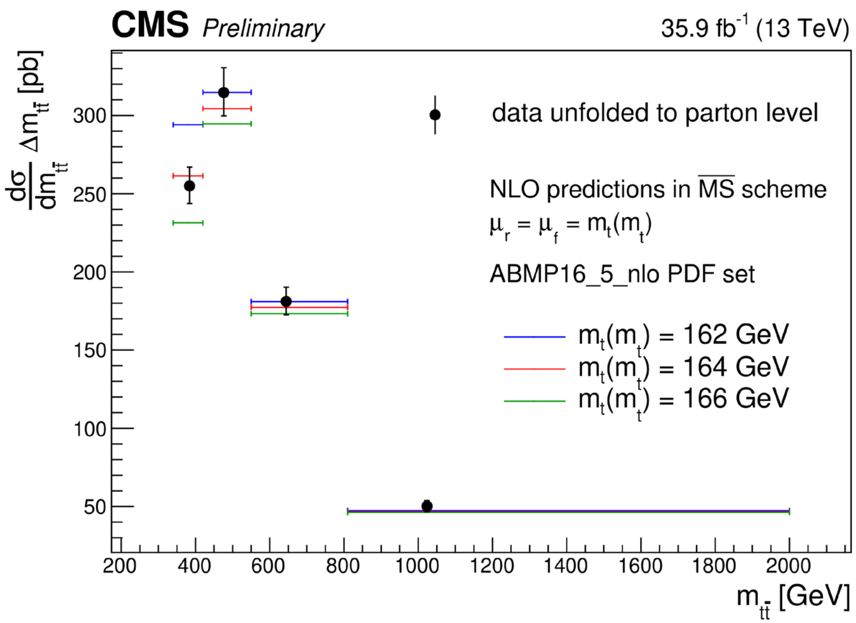
- Measure top mass $m_t$ from boosted jet mass (mjet) observable
  - CMS-PAS-TOP-19-005
  - using highly boosted hadronic top quark decays produced in $t\bar{t}$ events
  - reconstruct highly-boosted top quark decays with a novel XCone jet algorithm JHEP11(2015)072
  - the normalized differential cross section as a function of jet mass is compared to predictions from POWHEG with different values of $m_t$
  - extract a value of the top quark mass of 172.56 ± 2.47 GeV

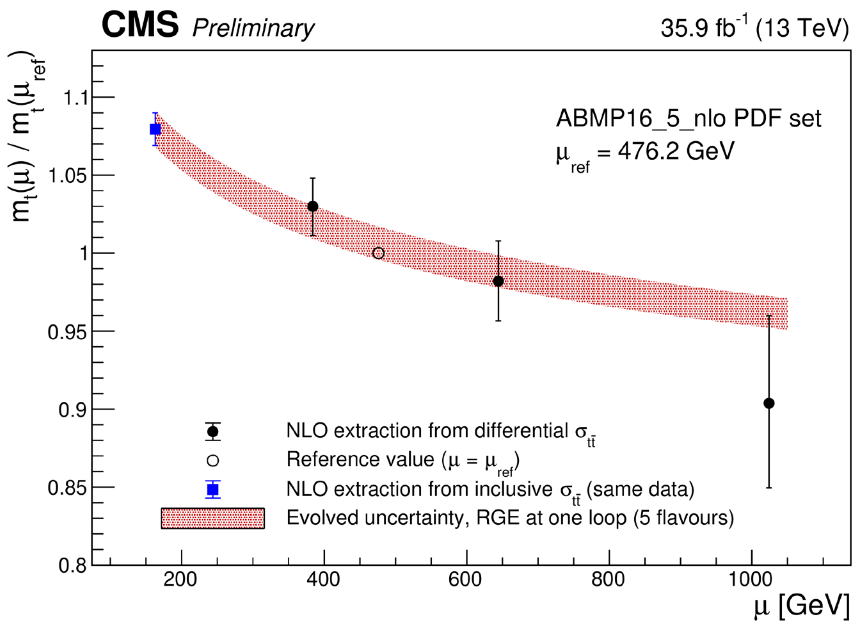


# The running of top mass measurement in CMS



- **First measurement of the running of the top quark mass from CMS**
  - CMS-PAS-TOP-19-007



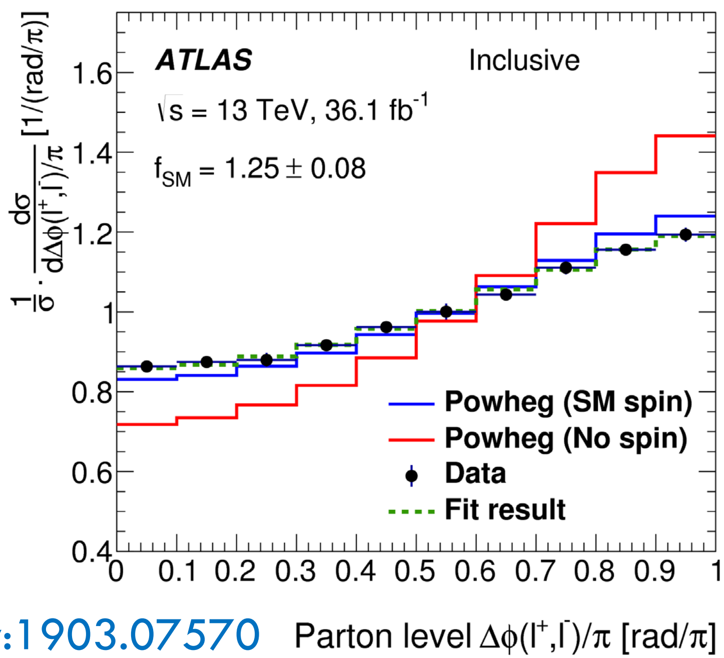



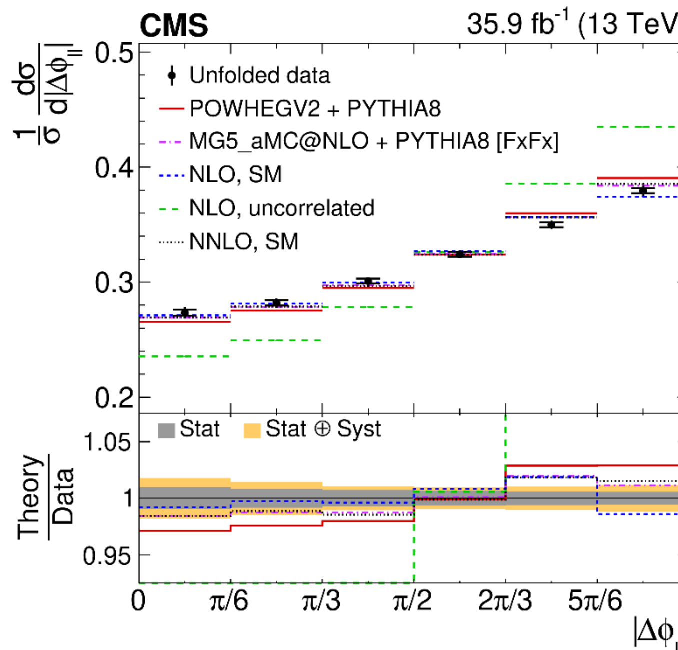

- differential $t\bar{t}$ production cross section as a function of $m_{t\bar{t}}$ at the parton level, compared to NLO predictions in the $\overline{MS}$ scheme obtained with different values of $m_t$
- extract the running of the top quark mass (evolution of the top quark mass as a function of the scale), compared to the prediction from renormalization group equations (RGE) solved with one-loop precision assuming five active flavours.

# 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




arXiv:1903.07570

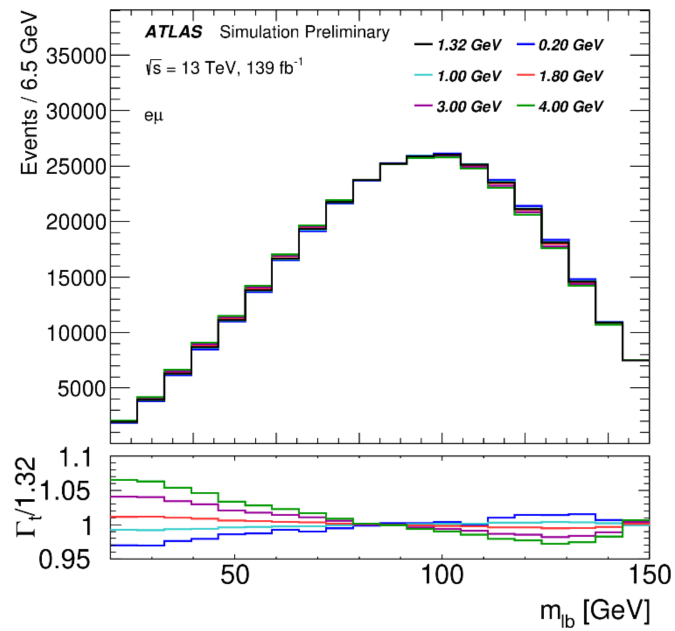
arXiv:1907.03729

stronger spin correlation in data comparing to NLO prediction

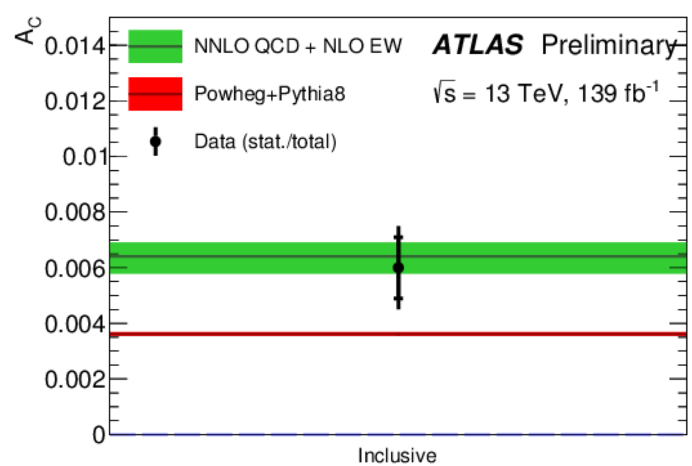
# Top decay width and top pair charge asymmetry



- Direct measurement of the top decay width $\Gamma_t$ in dilepton events in ATLAS with full Run2 data
  - ATLAS-CONF-2019-038
  - Compare data to MC templates with different $\Gamma_t$ assumptions
  - The measured width is $\Gamma_t$=1.9±0.5 GeV




- Top pair charge asymmetry is measured in ATLAS using full Run2 data
  - ATLAS-CONF-2019-026
  - The inclusive $t\bar{t}$ charge asymmetry is measured as $A_C$=0.0060±0.0015(stat+syst.)
  - 4 σ deviation from zero

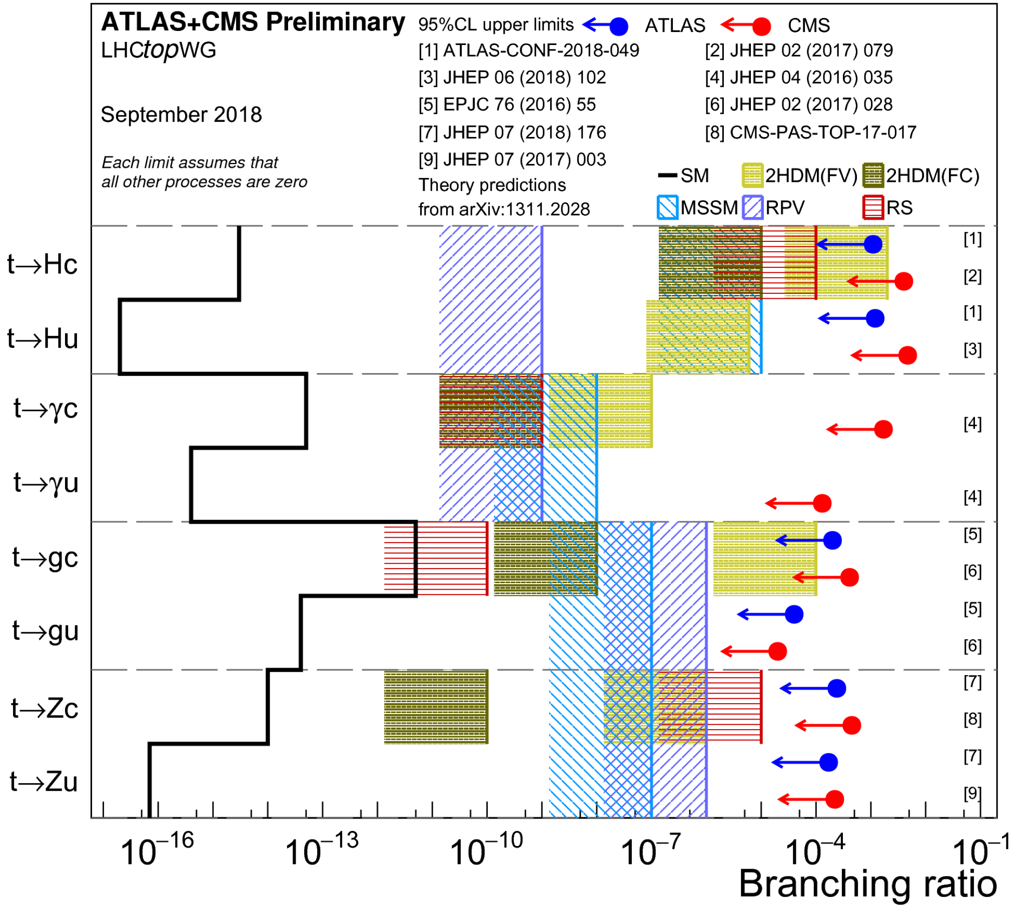


# New Physics searches

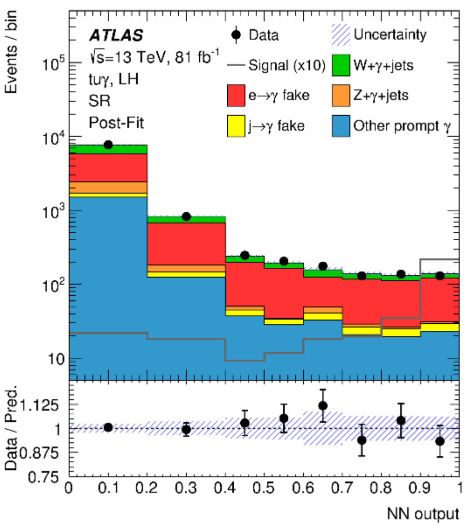
# Flavour changing neutral currents from top-quark decays



- 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.




- Latest update from ATLAS gives improved limits
  - Search for tqγ FCNC in single top + γ events using 81 fb$^{-1}$ 13TeV data
  - arXiv:1908.08461

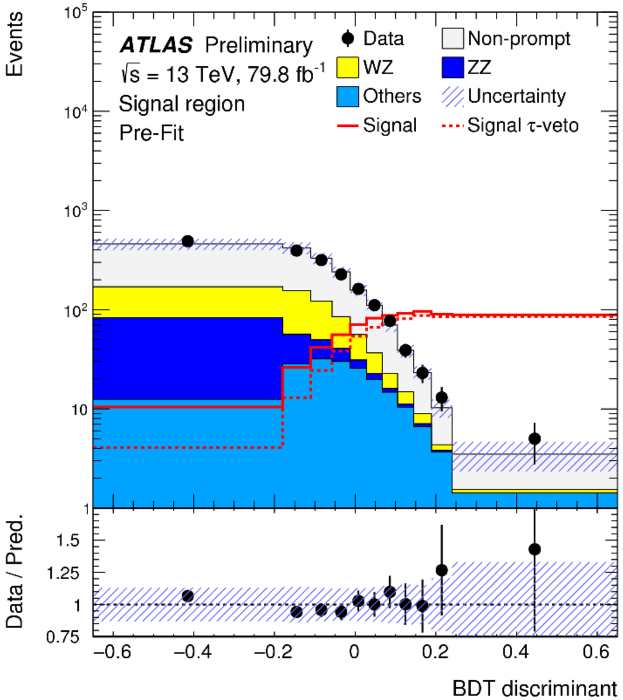



- B(t—>uγ) < 2.8 x 10$^{-5}$ obs
  4.0 x 10$^{-5}$ exp
- B(t—>cγ) < 22 x 10$^{-5}$ obs
  27 x 10$^{-5}$ exp

# 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 $t \rightarrow l^{\pm}l'^{\mp}q$ 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

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

# Summary

# Summary



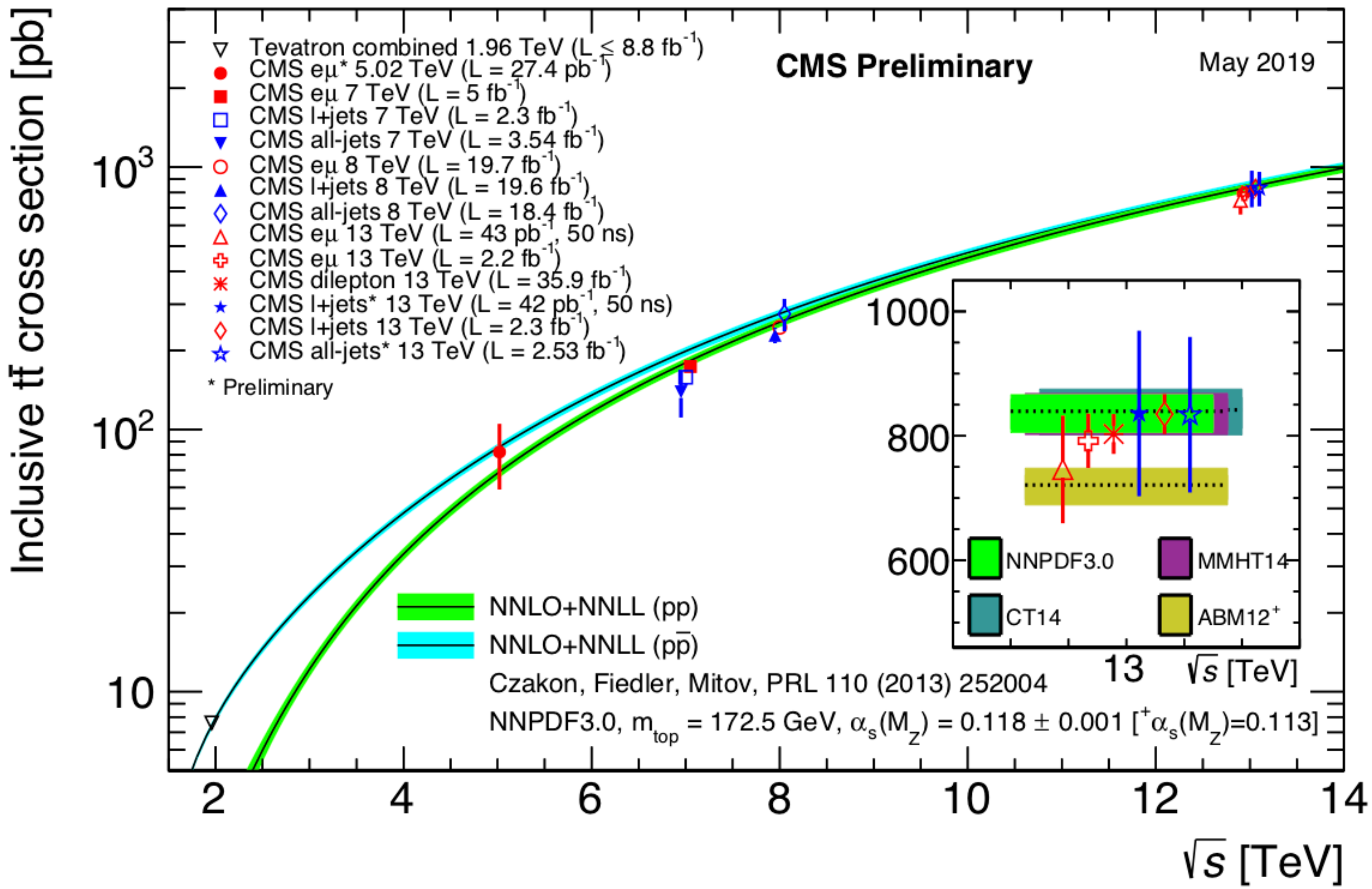
- LHC Run-2 data is taking a central stage in top physics studies, a broad range of new results were updated by ATLAS and CMS
  - precision measurements of top production and decay, top quark properties
    - $t\bar{t}$, single top, top+X cross sections
    - top quark mass, decay width, top pair spin correlations, charge asymmetries
  - challenging and rare production/decay modes are exploited
    - four-top-quark production, tZq observation
  - improved limits on various new physic searches
    - FCNC, cLFV
  - new studies on running of top mass, tW and $t\bar{t}$ interference models, jet shapes etc.
  - data results are generally consistent with theoretical predictions with a few exceptions that need further investigation
    - some differential distribution in $t\bar{t}$, $t\bar{t}$+ $b\bar{b}$, top pair spin correlations

- More potential and excitement for top quark physics with the upcoming results using full Run 2 data
  - larger statistics ~150 $fb^{-1}$, improved MC models and theoretical calculations
  - new BSM interpretations, access to rare processes, new physics searches etc.

# Backup

# $t\bar{t}$ inclusive cross sections






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

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

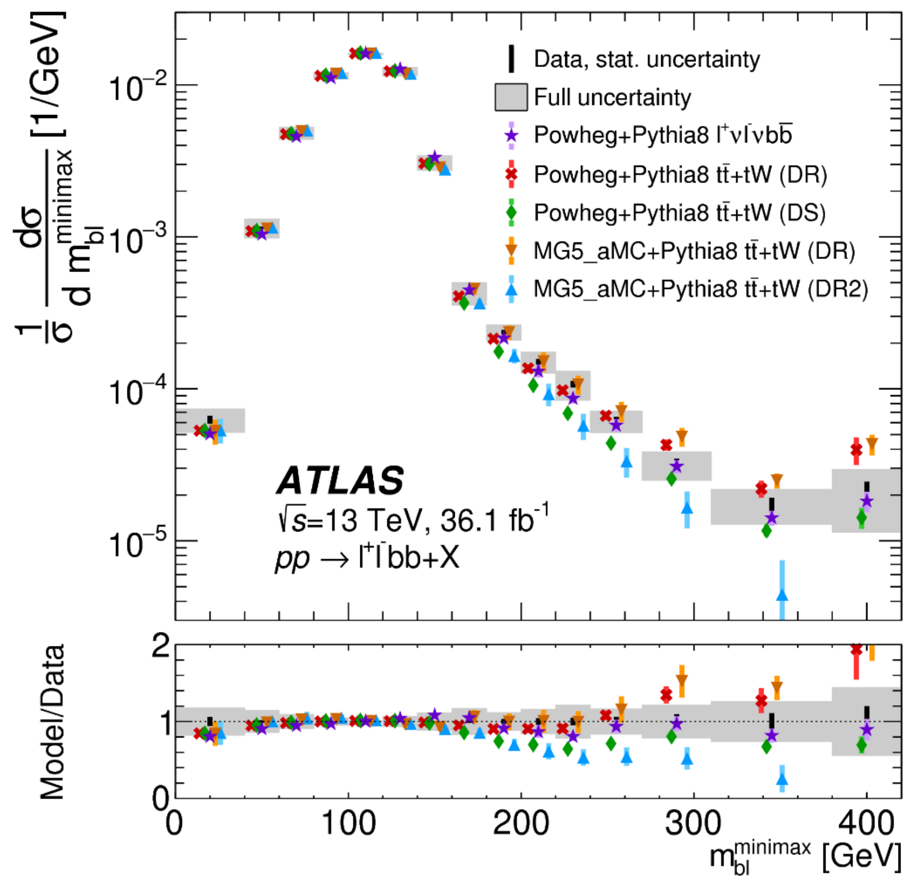


- Treatments of the tW and $t\bar{t}$ NLO interference effects:
  - **Diagram removal** (**DR**): remove doubly resonant diagrams from Wtb matrix element
  - **Diagram subtraction** (**DS**): subtract gauge-invariant term from Wtb matrix element
  - arXiv:1607.05862 for details

- 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

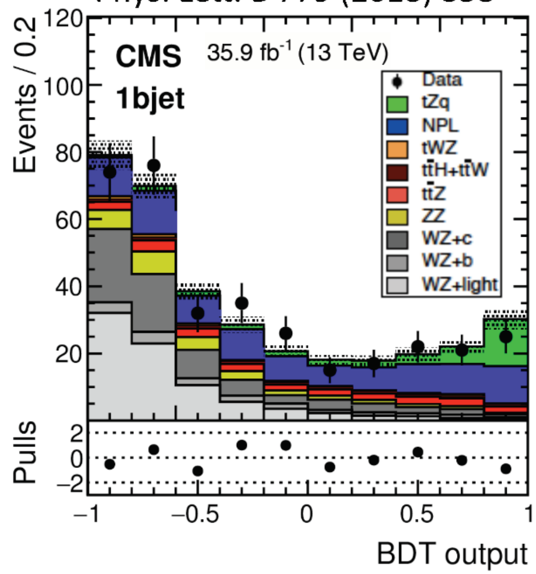


- tZq rare production
  - unique sensitivity to some EFT operators due to $Wb \rightarrow tZ$ vertex
  - Challenging large SM backgrounds

- Previous results

CMS result with 2016 data

Phys. Lett. B 779 (2018) 358

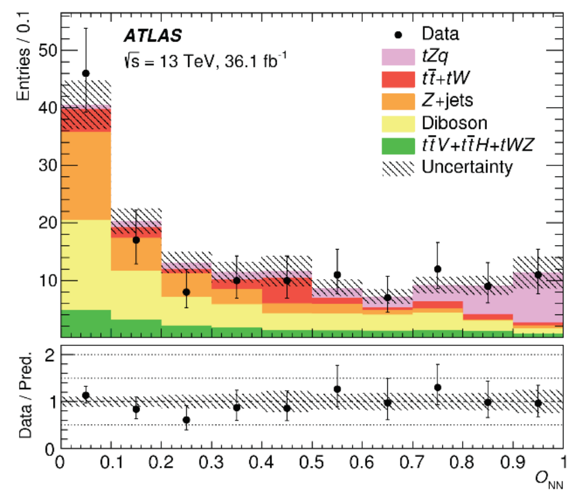



$\mu = 1.31^{+0.35}_{-0.33}(\text{stat})\ ^{+0.31}_{-0.25}(\text{sys})$

3.7 (3.1) σ Obs.(Exp.)

ATLAS result with 2016 data

Phys. Lett. B 780 (2018) 557



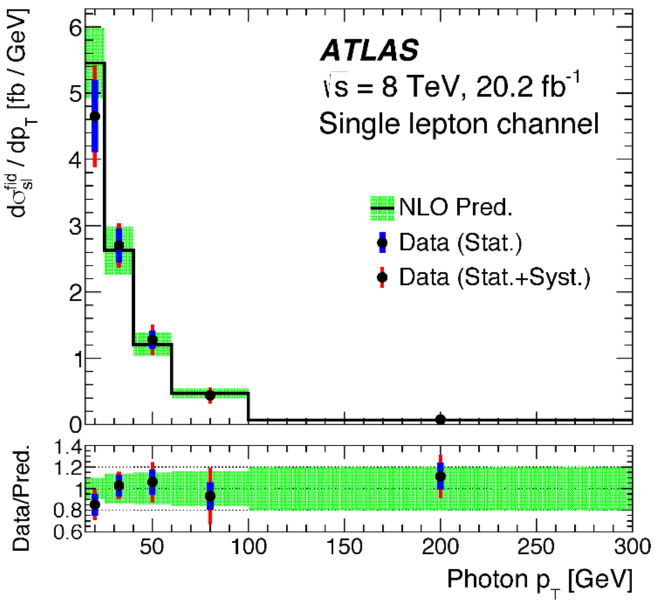

$\mu = 0.75 \pm 0.21(\text{stat}) \pm 0.17(\text{sys})$

4.2 (5.4)σ Obs.(Exp.)

Both measurements with about 35% uncertainty

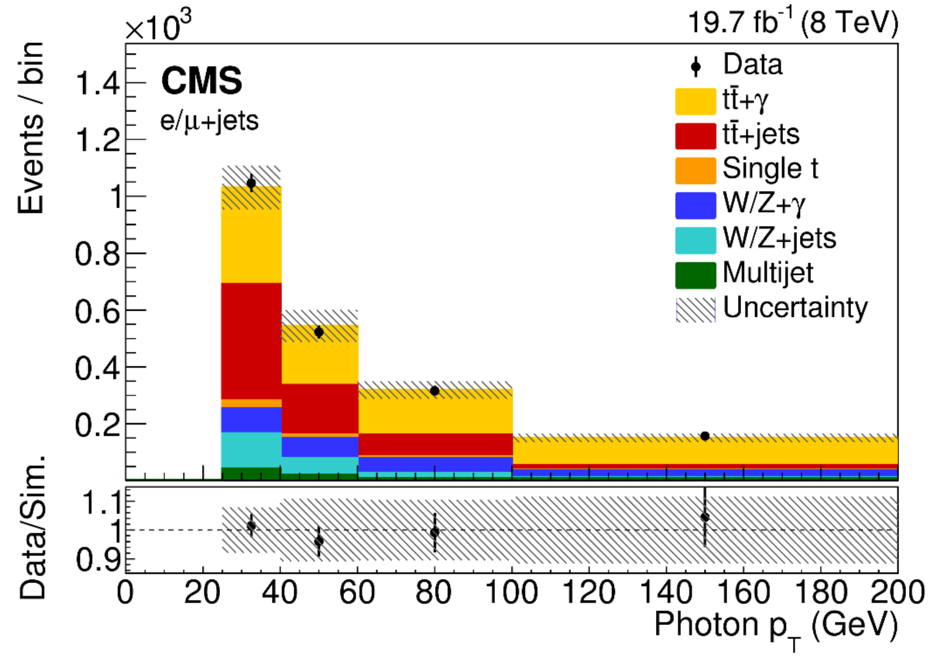
# $t\bar{t} + \gamma$






JHEP 11 (2017) 086

$\sigma_{tt\gamma}$=139 ± 18pb

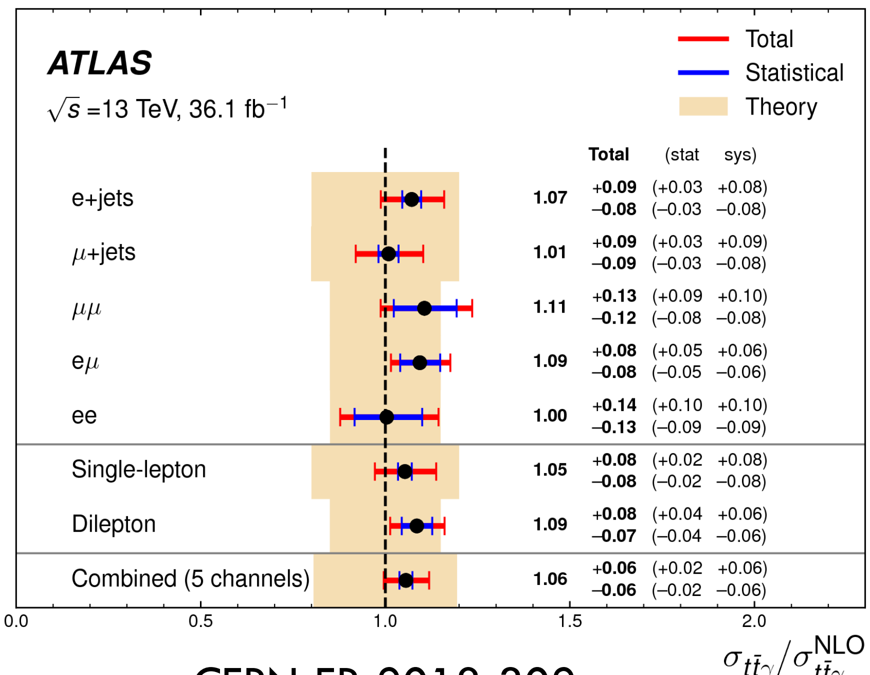



JHEP 10 (2017) 006

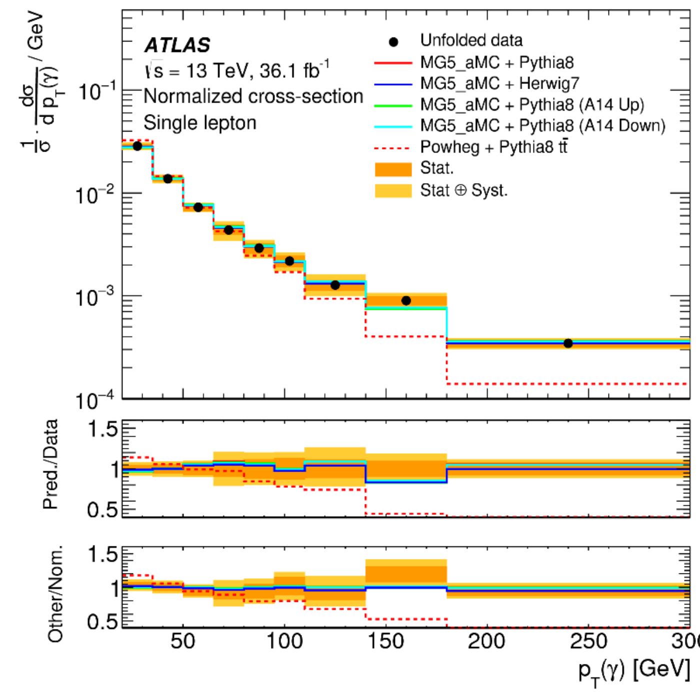
$\sigma_{tt\gamma}$=127 ± 27pb

# $t\bar{t} + \gamma$

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

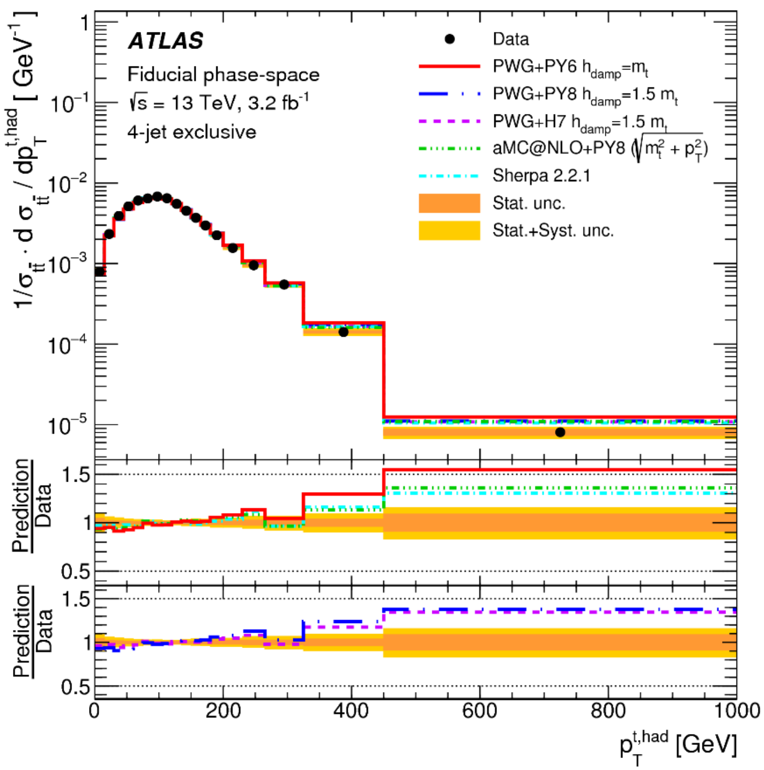


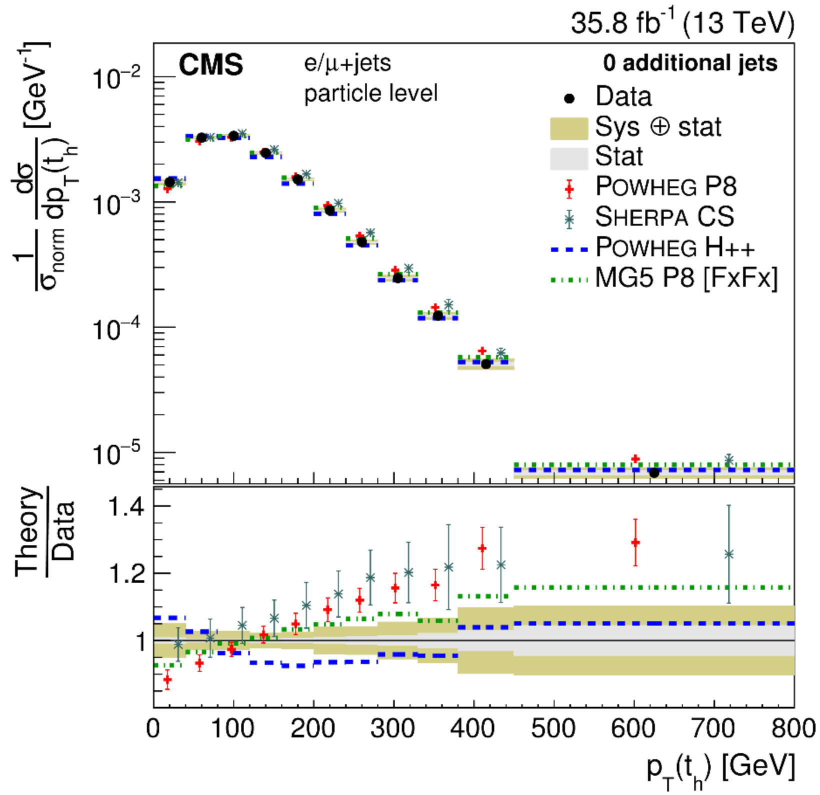

CERN-EP-2018-302




- 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.

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



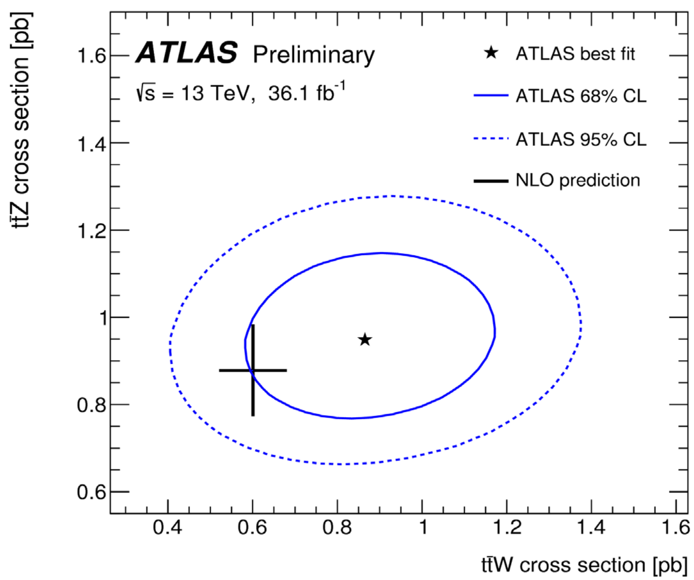

[JHEP 10 (2018) 159](#)

[*Phys. Rev. D 97 (2018) 112003*](#)

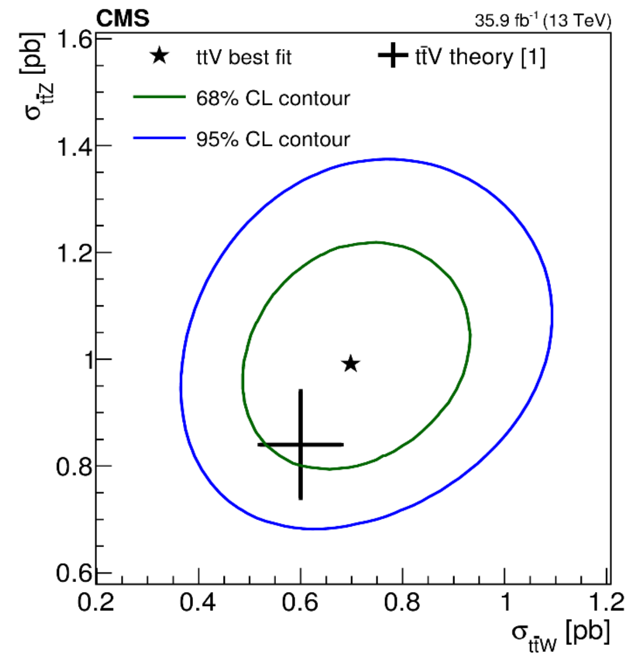
- Some tension found between data and prediction for reconstructed hadronical top $p_T$ in 4-jet exclusive configuration in both ATLAS and CMS
- POWHEG+PYTHIA also has difficulties simultaneously reproducing Njets and $p_T(t\bar{t})$

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

- 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

# Indirect top mass measurement

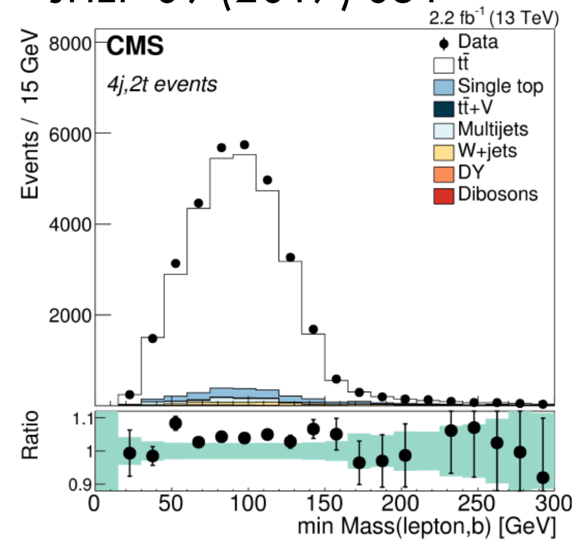
**CMS**: 13 TeV data, L = 2.2 $fb^{-1}$; lepton+jets final state

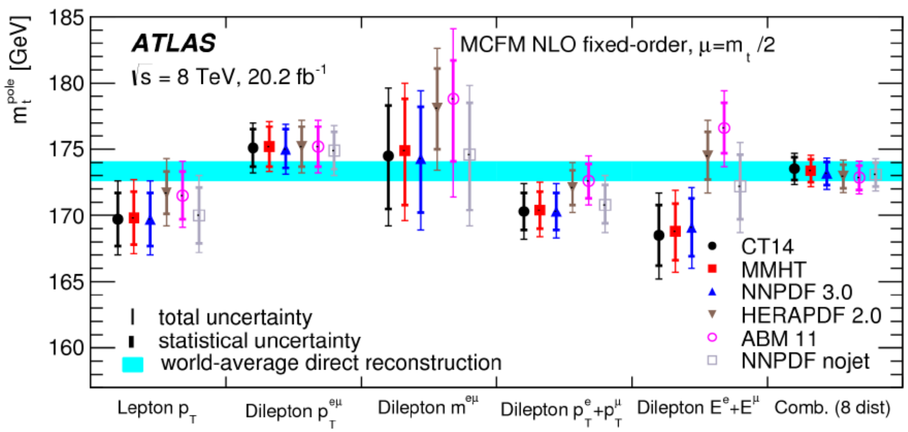
- Measure differential cross section wrt min($m_{lb}$) in categories of $N_{jet}$ and $N_{b\text{-}jet}$:
  $\sigma$ = 888 ± 2 (stat) ± 27(sys) ± 20 (lumi) pb
- Extract pole mass from cross section:
  $m_t^{pole}$ = 170.6 ± 2.7 (tot) ± 1.01 (syst.) GeV

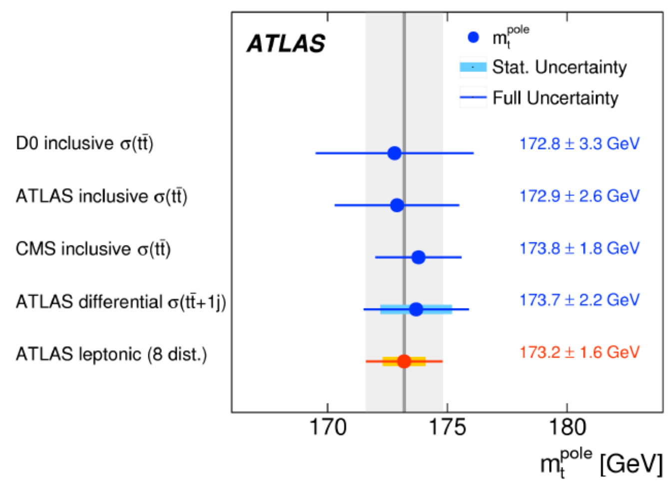
**ATLAS**: 8 TeV data, L = 20.2 $fb^{-1}$, dilepton with 1 or 2 b-jets

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

JHEP 09 (2017) 051



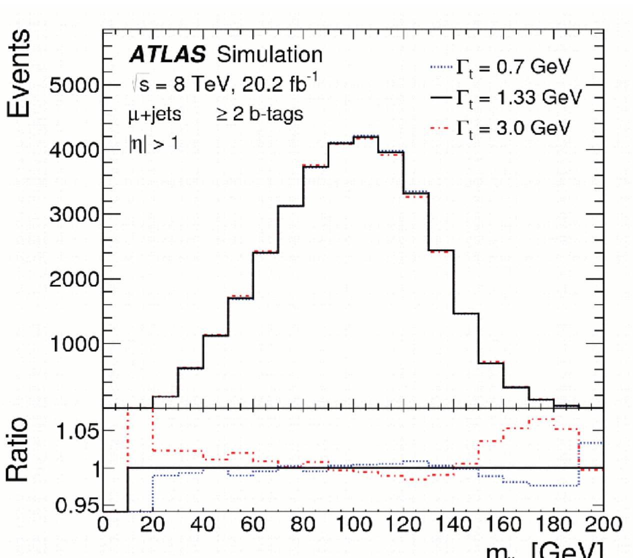




EPJC 77 (2017) 804

# 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



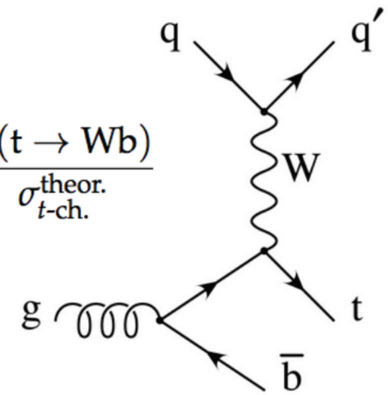

[ EPJC 78 (2018) 129 ]

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

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

CMS also derived $\Gamma_t$ 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



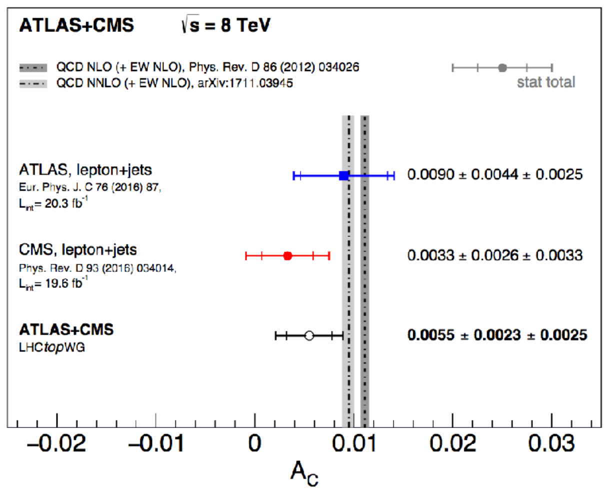
[ JHEP 04 (2018) 033 ]

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

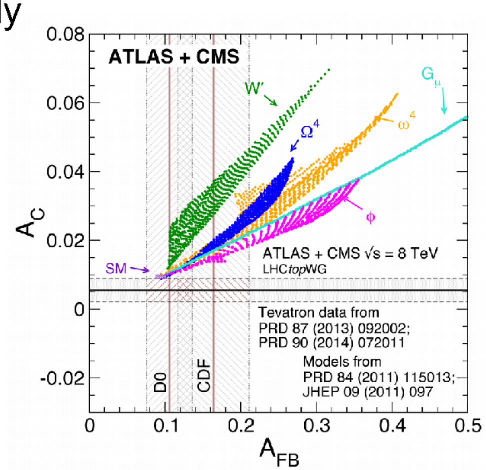
$$A_C = \frac{N^{\Delta|y|>0} - N^{\Delta|y|<0}}{N^{\Delta|y|>0} + N^{\Delta|y|<0}}$$

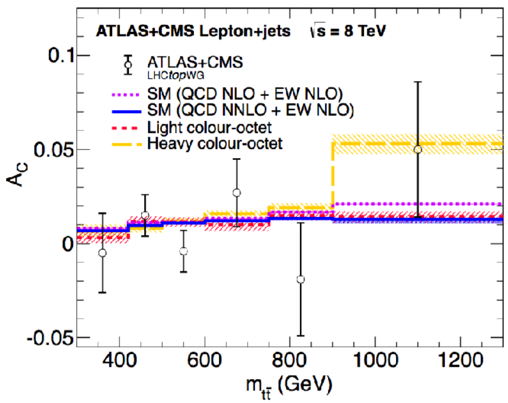
Non-zero $A_C$ in SM due to higher order effects in $q\bar{q}$ annihilation

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

# 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 updates since Dec. 2017:

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

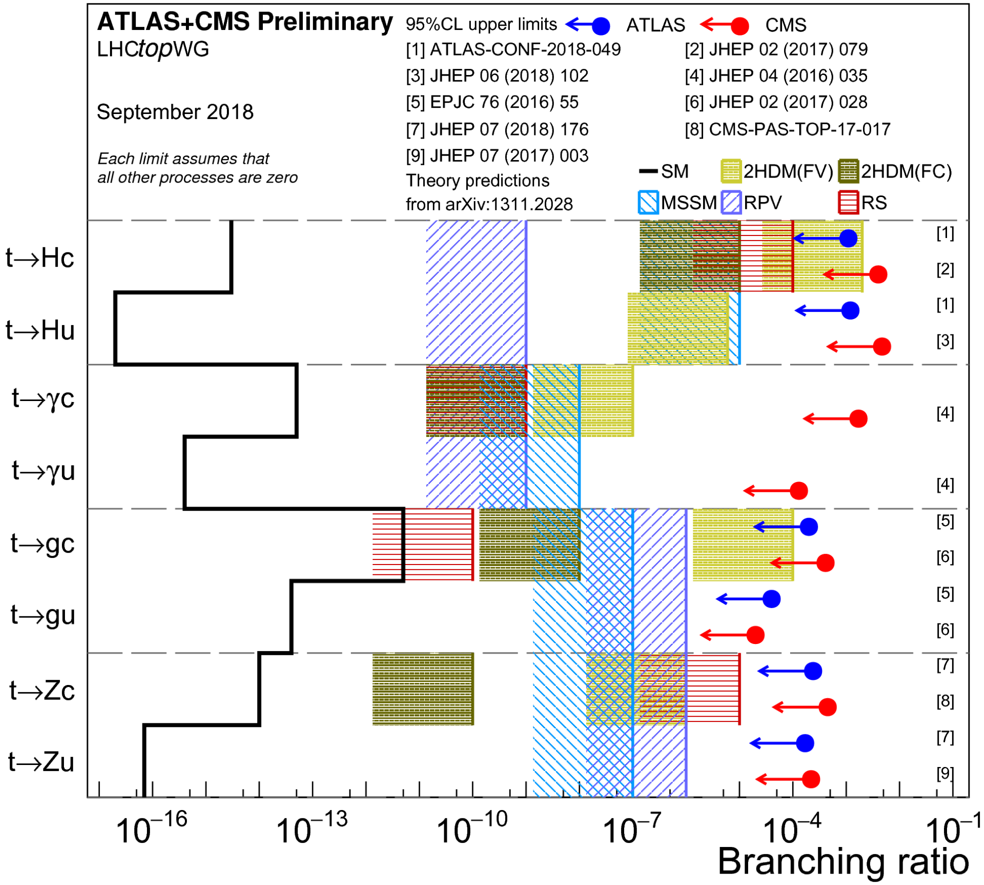
JHEP 07 (2018) 176 $t \to qZ$ (q=u, c)

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

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

CMS with 35.9 fb$^{-1}$ 2016 data

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



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 |
| $p_{\mathrm{T}}$ of the electron associated to the cLFV decay | 9.1 |
| $p_{\mathrm{T}}$ of the muon associated to the cLFV decay | 8.5 |
| $p_{\mathrm{T}}$ 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 |
| $\Delta R$ between the cLFV electron and the cLFV light jet | 6.5 |
| SM top mass | 6.4 |
| $\Delta R$ between the cLFV muon and the cLFV light jet | 6.3 |
| BDT discriminant | 44 |