Top physics at the LHC

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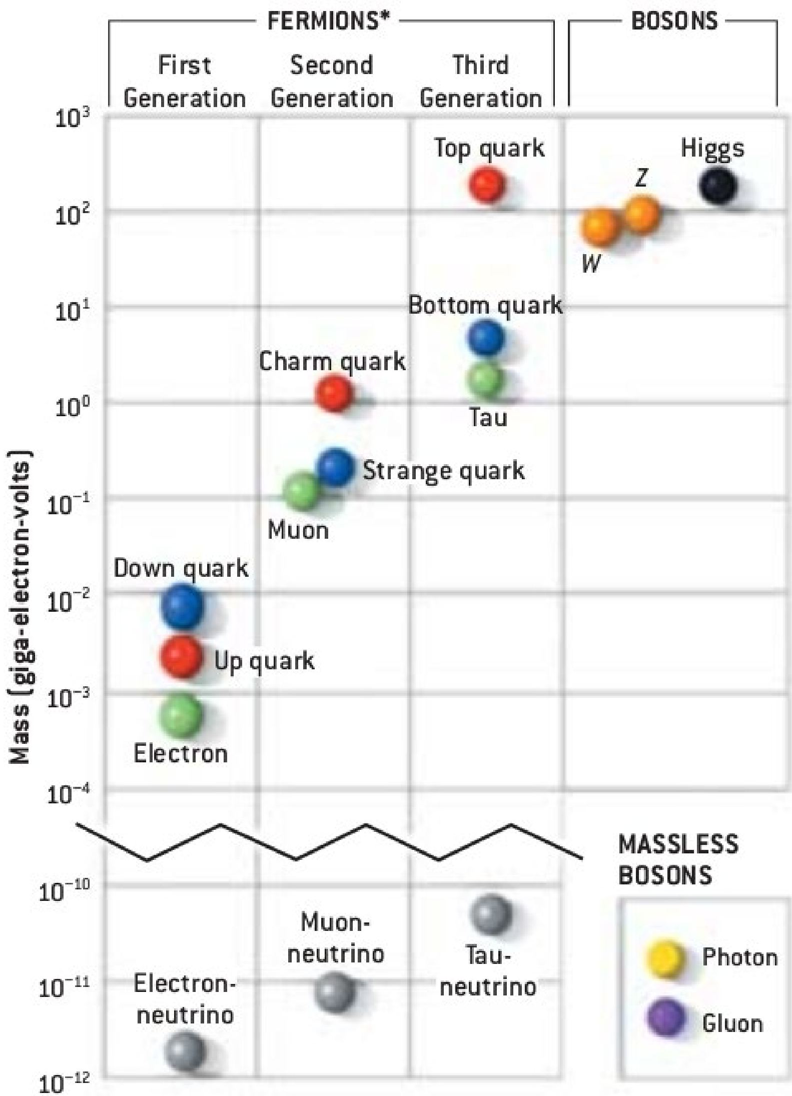
CEPC Meeting

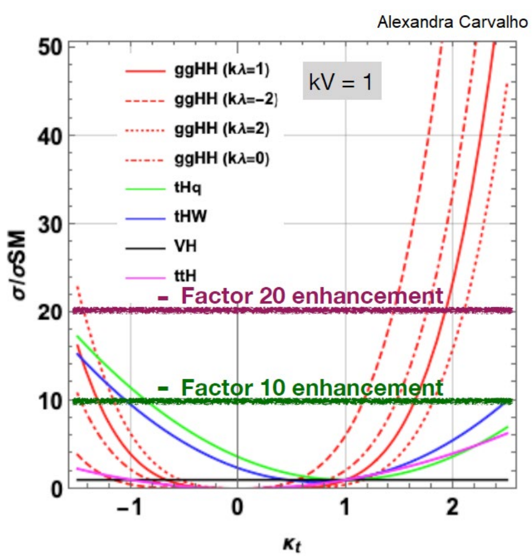
Top quark

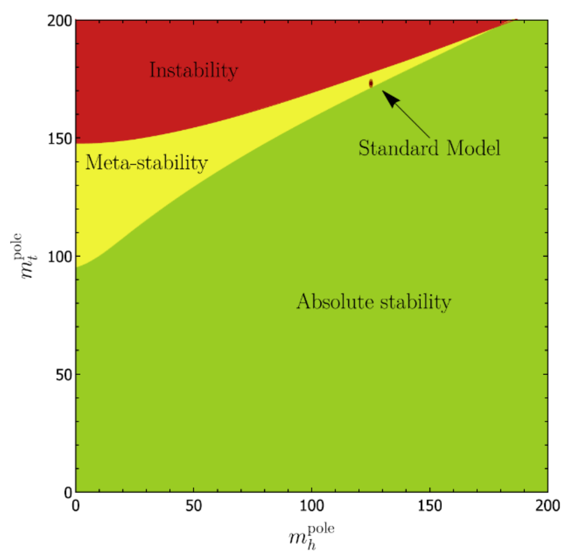
- The unique top quark
  - Most massive of known fundamental particles ~ 173 GeV
  - Mass is of order of the electroweak symmetry breaking scale
    - large Yukawa coupling to Higgs boson
    - large couplings to new resonances predicted by New Physics models
  - The only quark that decays before it can hadronise
    - opportunity to study a bare quark
    - access to its spin and polarization
- Important in many precision measurements and New Physics searches
    - SM parameters: couplings, top quark properties
    - tuning underlying events models, color flow
    - important backgrounds of many physics
    - EFT interpretation with BSM
    - related to naturaless/hierarchy problem, universe lifetime etc.

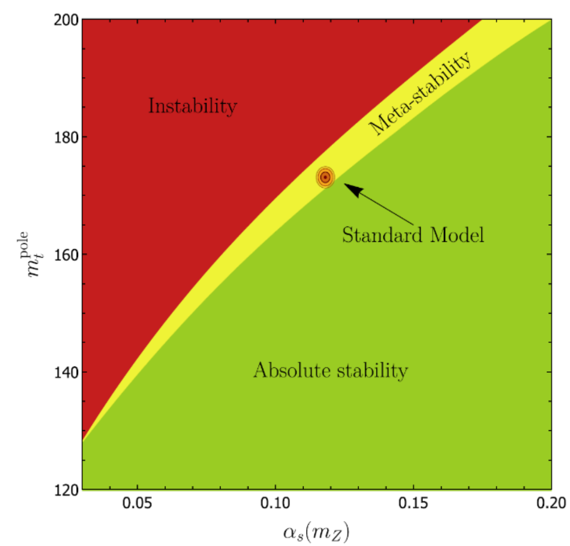


Top and Higgs

- SM measurements:
  - effect of top coupling on rates of associated production of Higgs with top(s)
  - effect of top loops on Higgs couplings, arXiv:1804.09766
  - effect of top loops on production rates and kinematics of multi-Higgs
- BSM searches for new particles or interactions:
  - extensions of the Higgs sector (H±, A, etc.) with top quarks in their decays
  - flavour changing neutral currents (FCNC) in top-Higgs sector
  - CP violation in Higgs-top interactions
- Cosmological consequences, stability (PhysRevD.97.056006), inflation (PRL)

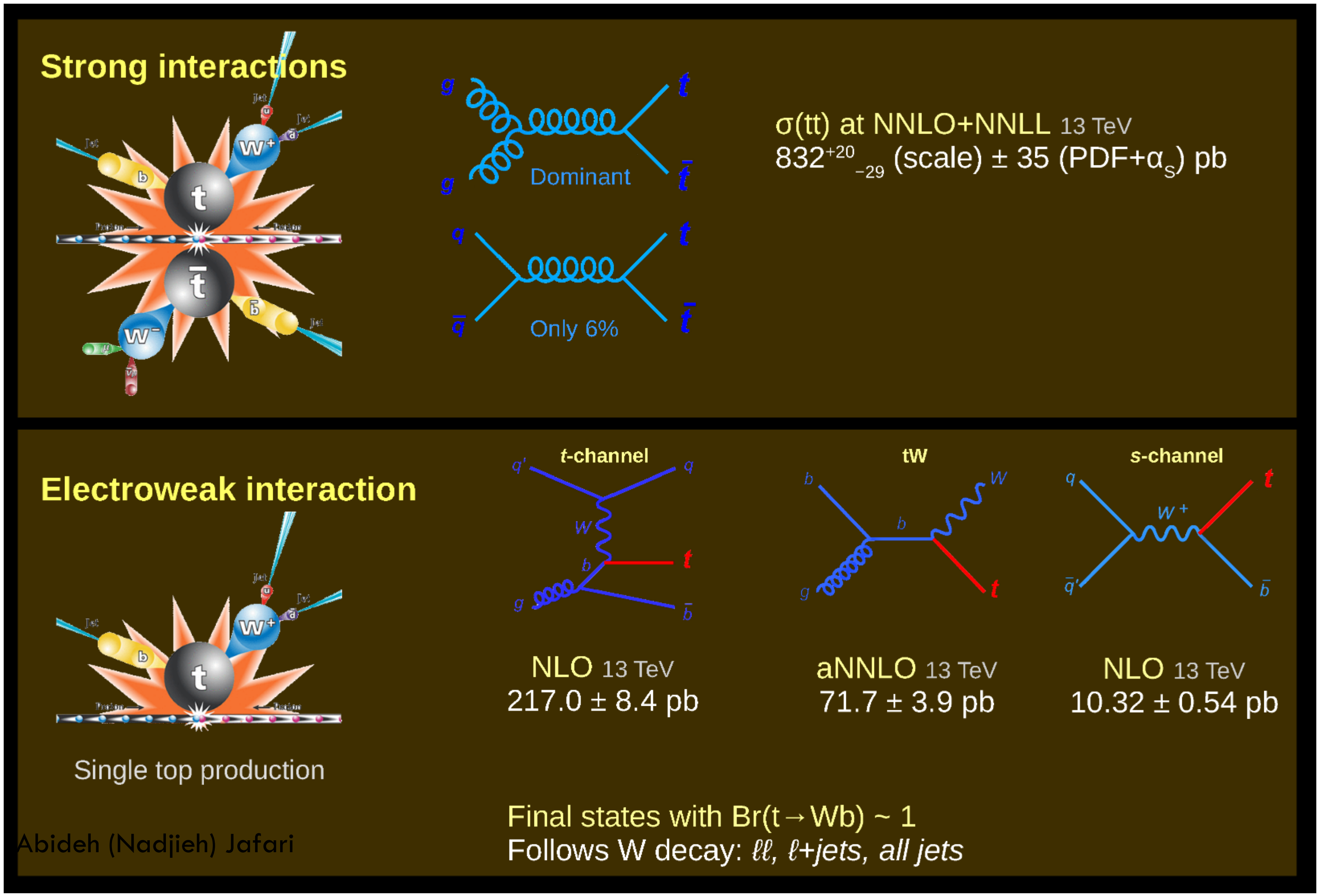






Top pair and single top production at the LHC

- Huge top quark production cross sections at the LHC
  - >100 times cross section of Tevatron
  - >100 million top quarks produced in Run 2



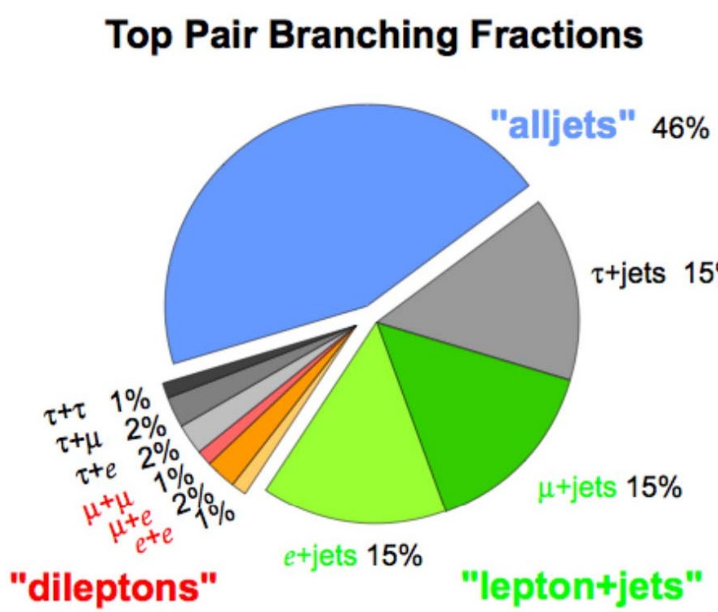
Outline

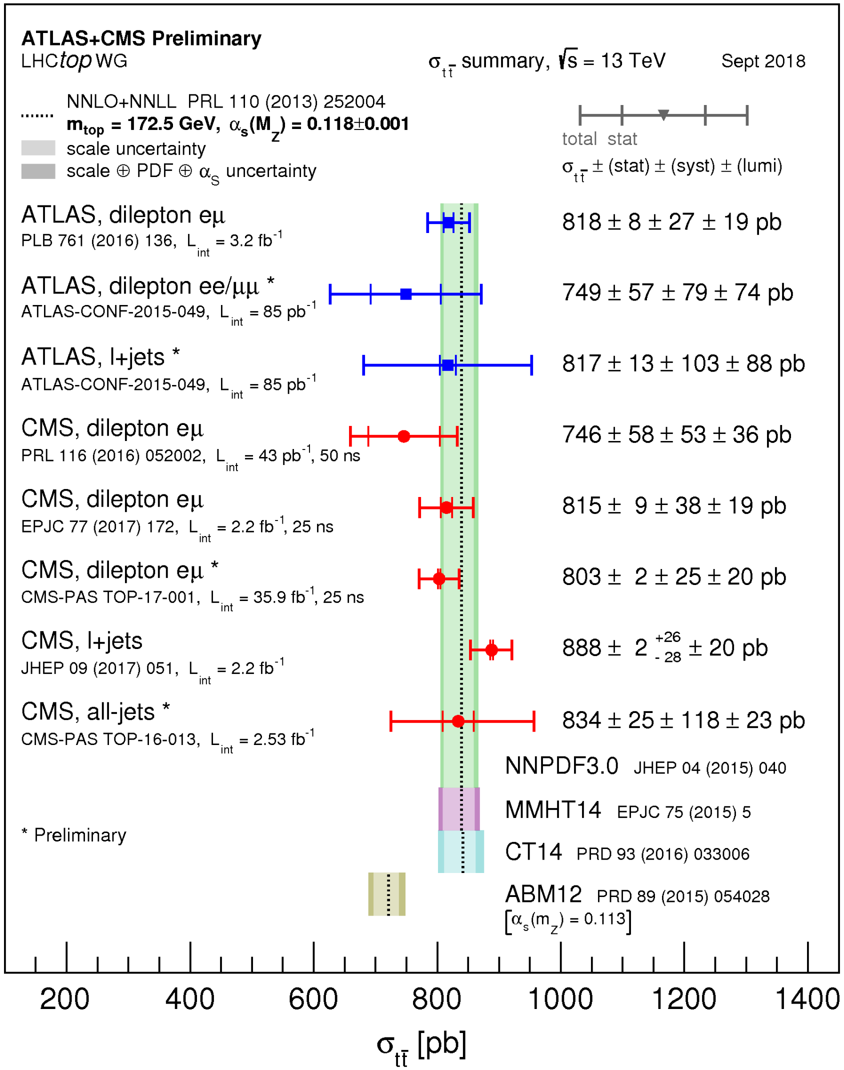
- Top quark production cross-section measurements
  - $t\bar{t}$ inclusive and differential cross sections
  - Single top quark production cross sections
  - Top+X production measurements
- Top quark properties measurements
  - Top quark mass measurements, top decay width
  - Top pair spin correlations,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

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

$t\bar{t}$ production cross sections

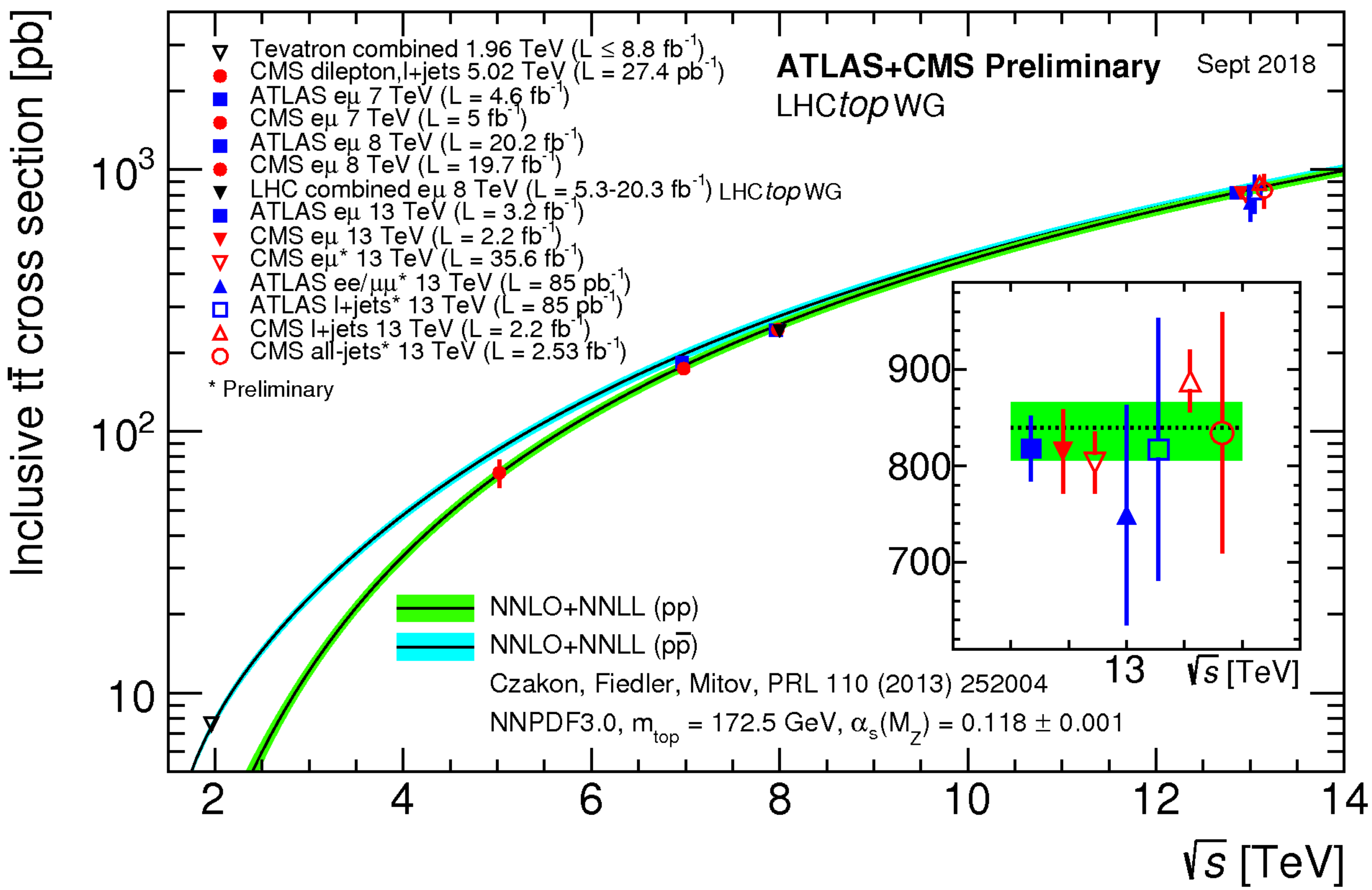
- Core physics delivery of the LHC with statistics O(1000) times Tevatron
  - Unique test of QCD with massive partons and constraints on QCD soft scale modelling
  - Constraints on SM parameters (m_t, α_S) and PDFs
  - Constraints on anomalous EFT terms
  - Background for many BSM and Higgs signals





Good agreement between data and prediction

$t\bar{t}$ inclusive cross sections

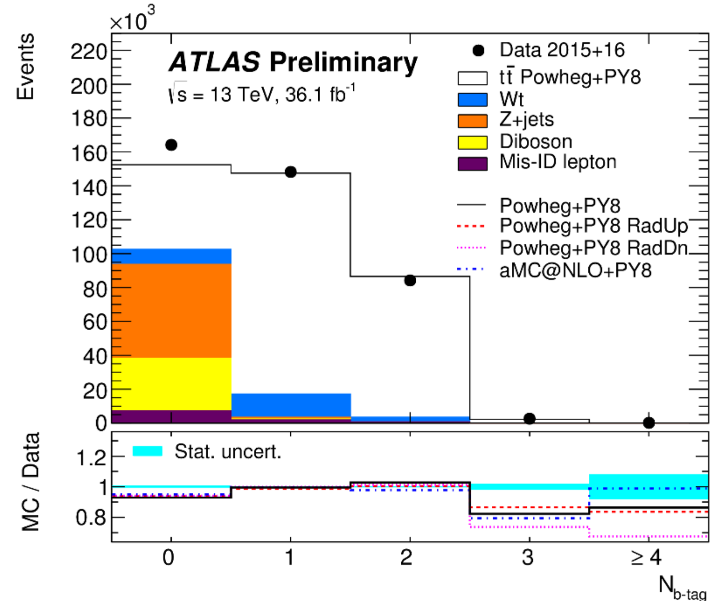


- Single measurement precision: ~3.5%
- Limited mainly by luminosity and signal model uncertainty.

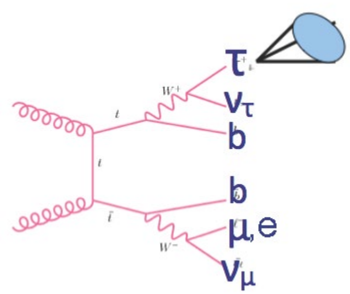
Latest $t\bar{t}$ inclusive cross sections

- 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

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



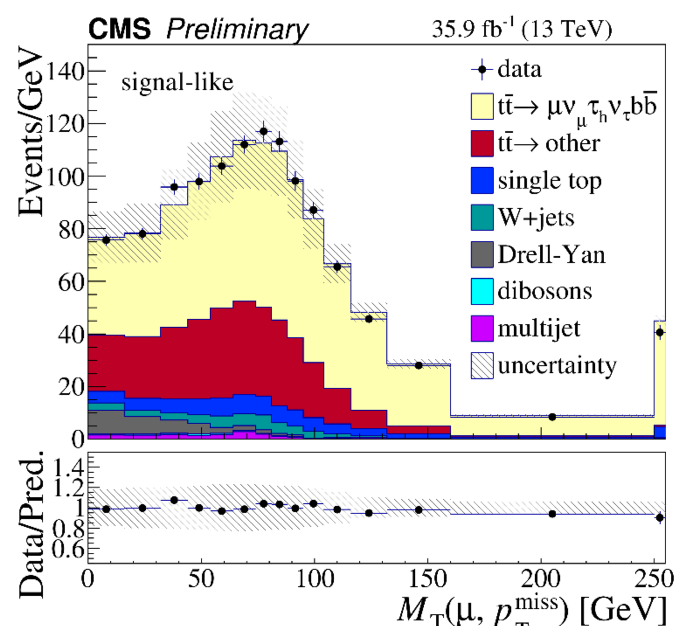
- CMS, CMS-PAS-TOP-18-005
  - 13 TeV, 35.9 fb^{-1} data
  - events $t\bar{t} \to (l\nu_l)(\tau_h\nu_\tau)b\bar{b}$
  - measured cross section



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

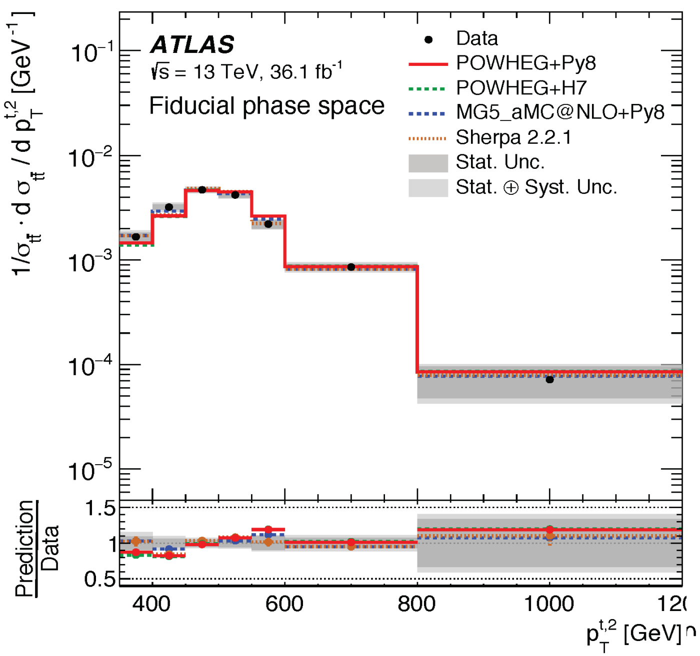
- ratio of the partial width to the total width

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



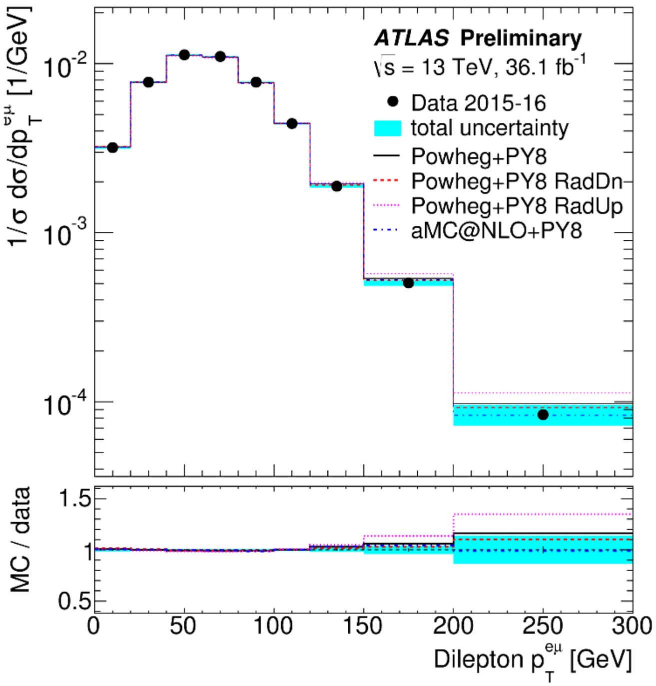
$t\bar{t}$ differential cross sections - ATLAS

- 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

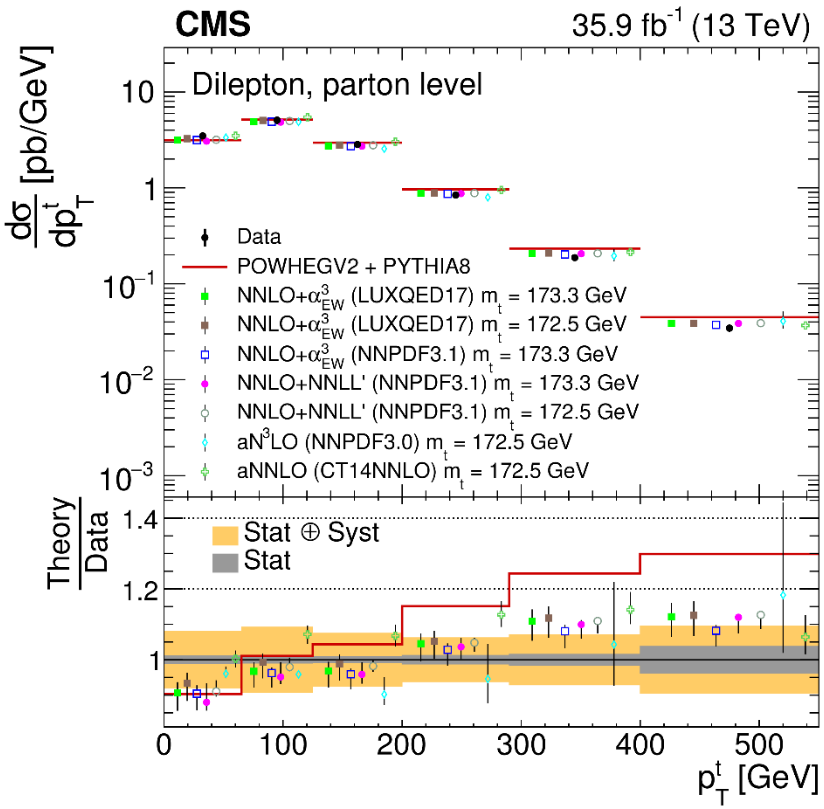


ATLAS-CONF-2019-041

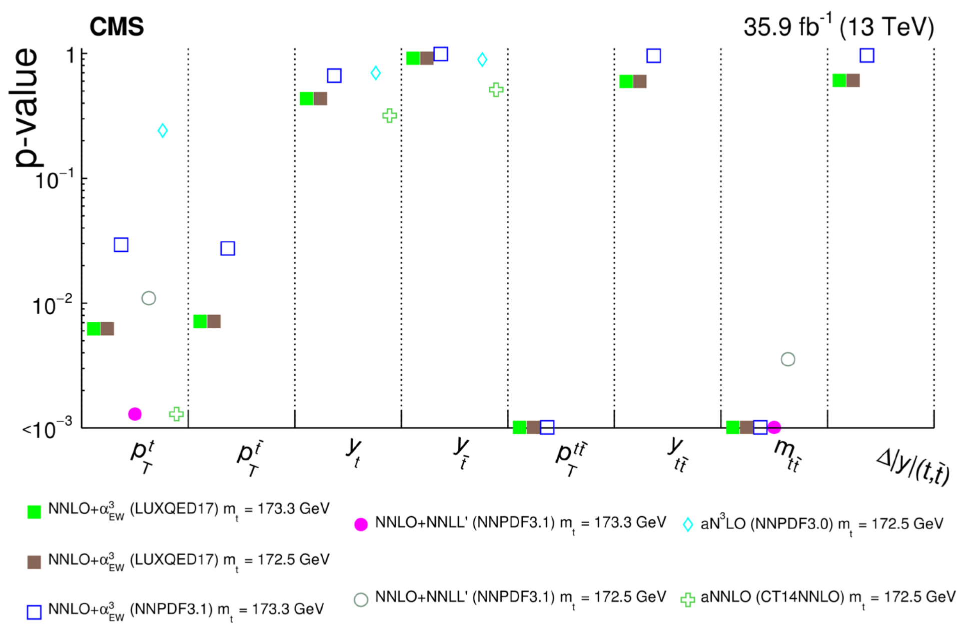
- Kinematic variables consistent with NLO QCD in general

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

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



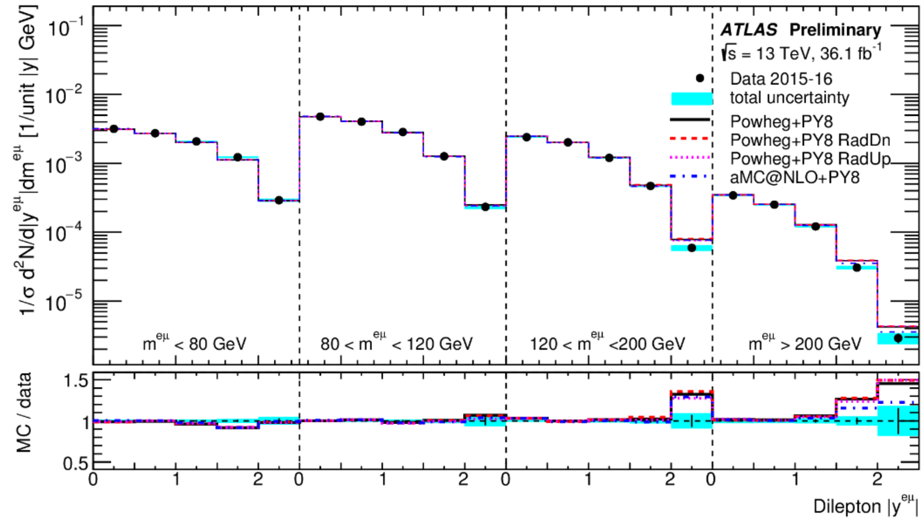
p-value agreement between theoretical prediction and data



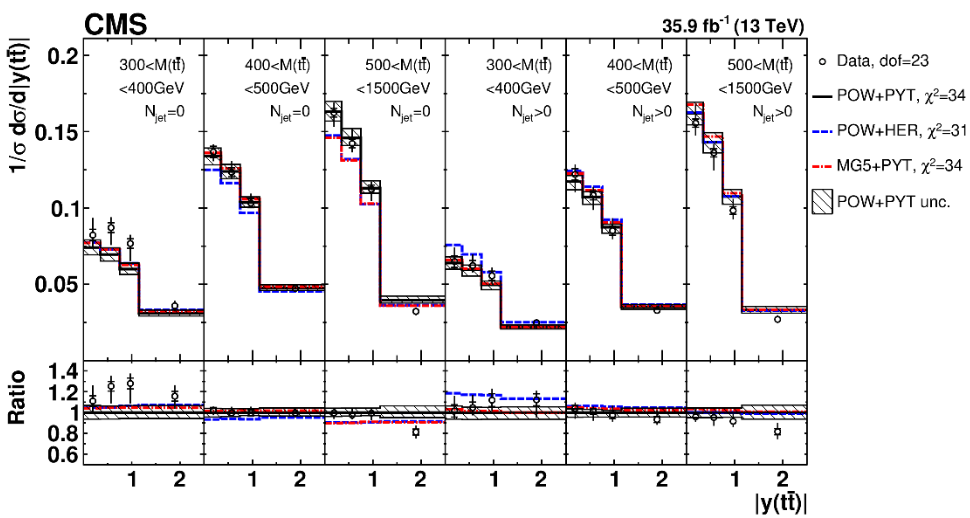
- Data shows softer top p_T than POWHEG+PYTHIA predicted in dilepton channel
  - still see the trend with higher order QCD and EW corrections
- Other variables related to top p_T are also in tension

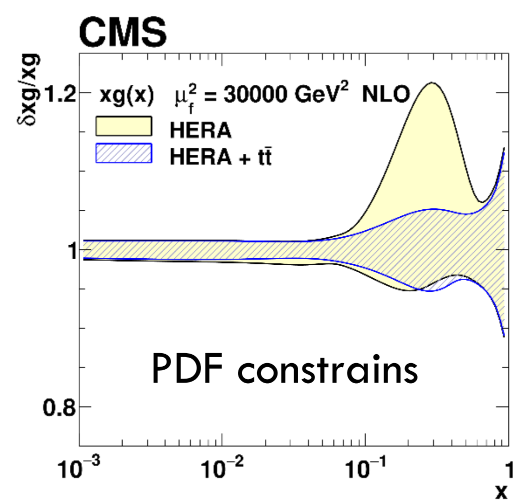
$t\bar{t}$ differential cross sections - multidifferential

- 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}, α_s, PDF

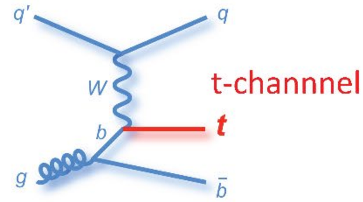


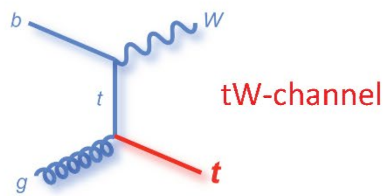


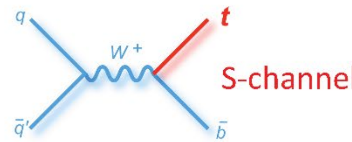
Single top quark production cross sections

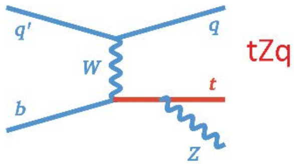
Single top quark production measurements

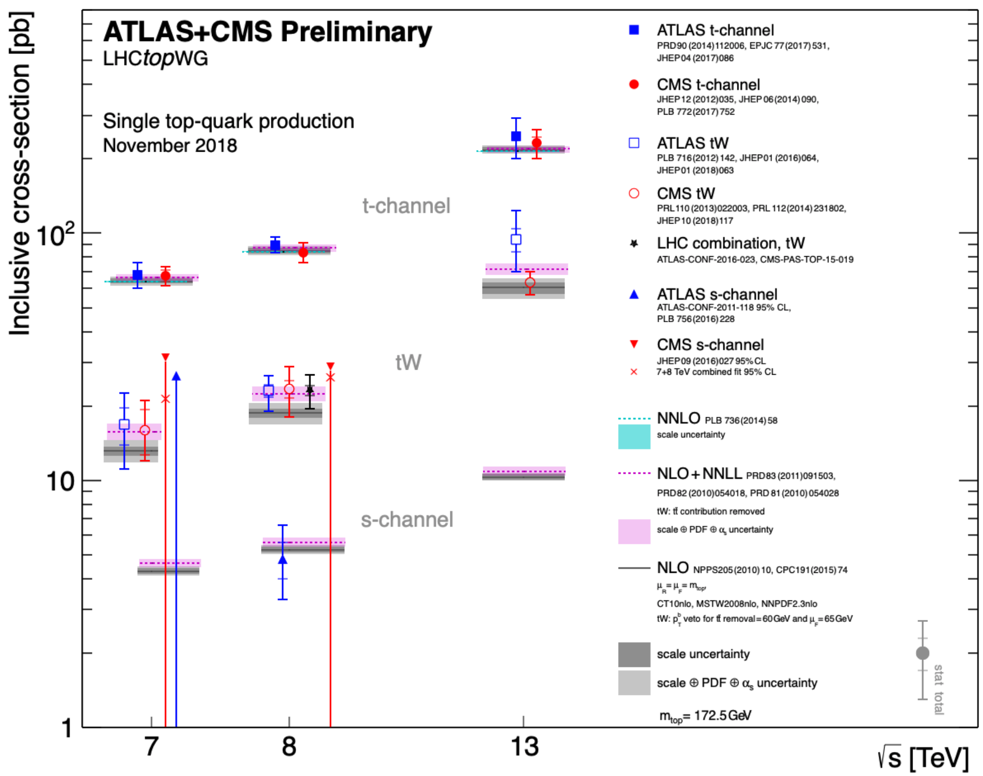
- Top quark electroweak production @ 13 TeV
  - t-channel: 216.99 pb, tW channel: 71.7 pb, s-channel: 10.32 pb, rare tZq production: ~ 1 pb











2018 updates

ATLAS tW:

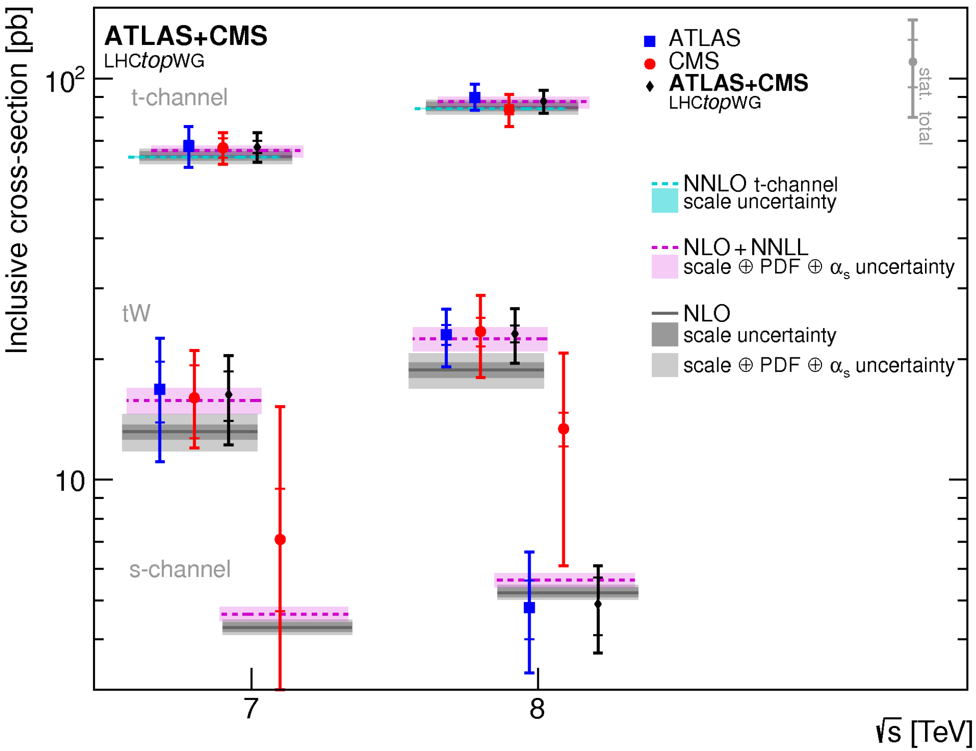
[Eur. Phys. J. C 78 (2018) 186]

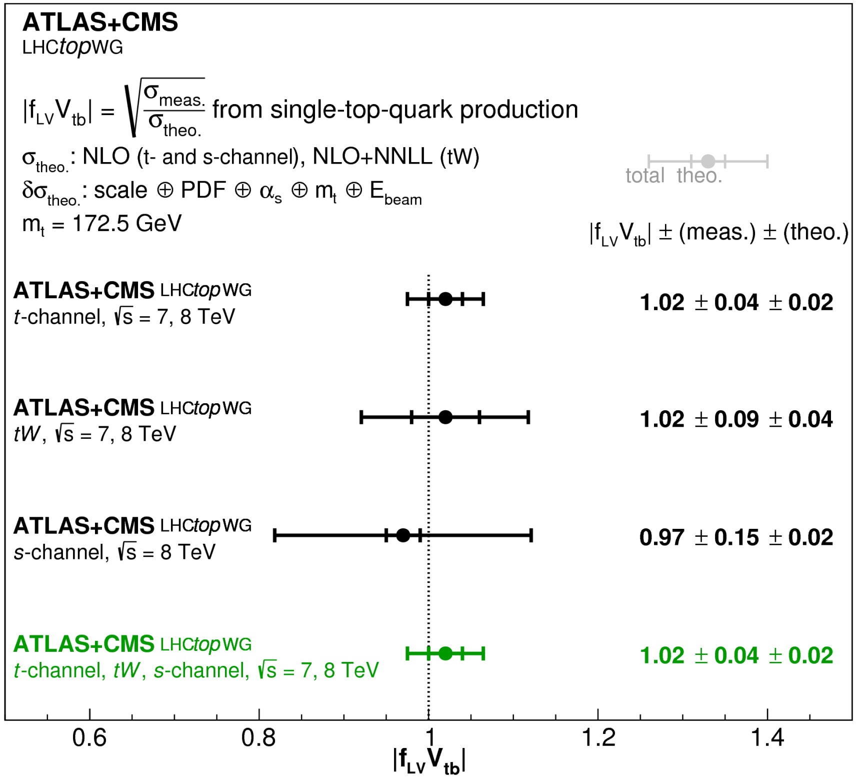
CMS tW:

[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*]



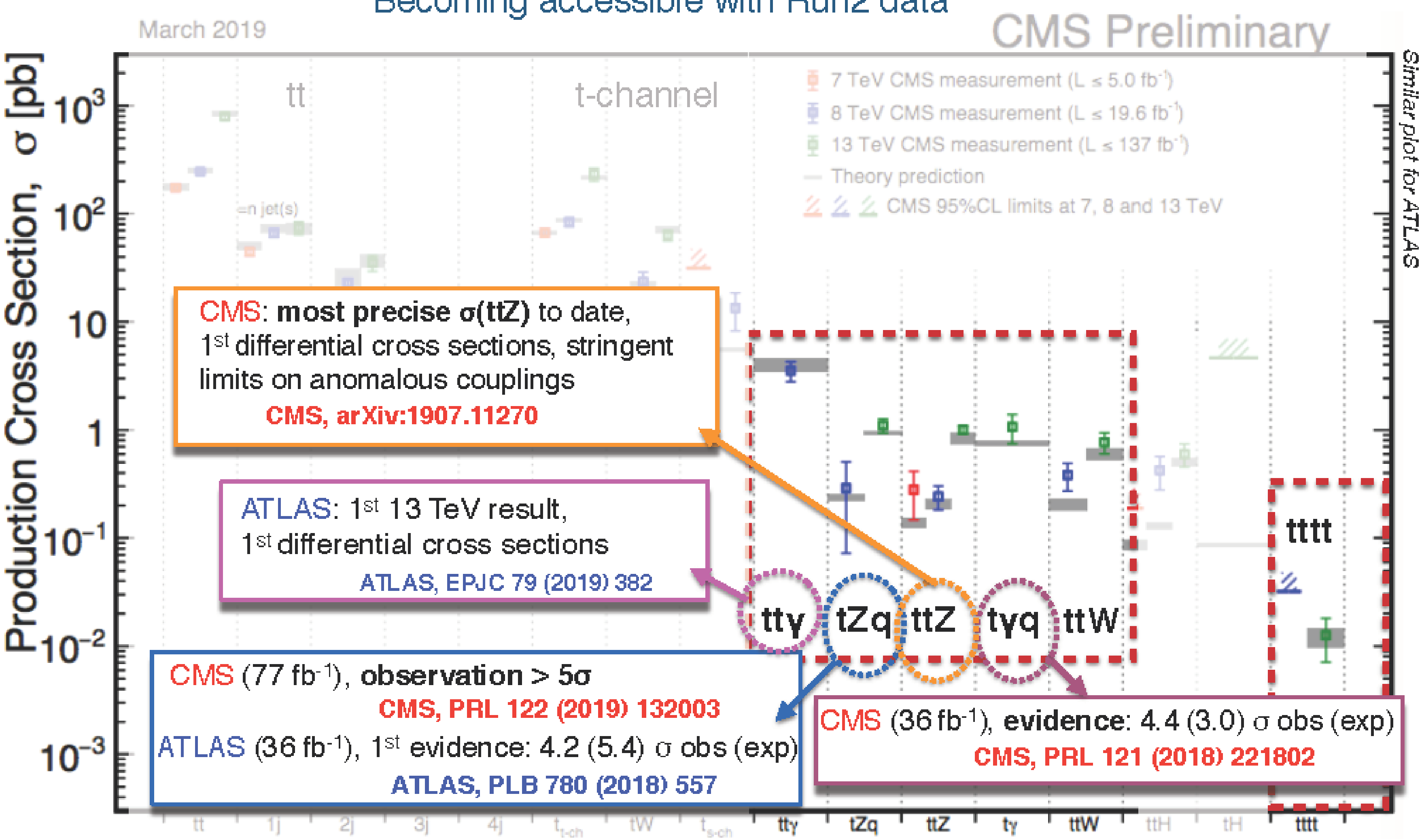


Best V_{tb} direct determination to date!

Top+X production measurements

Top+X production in a nutshell

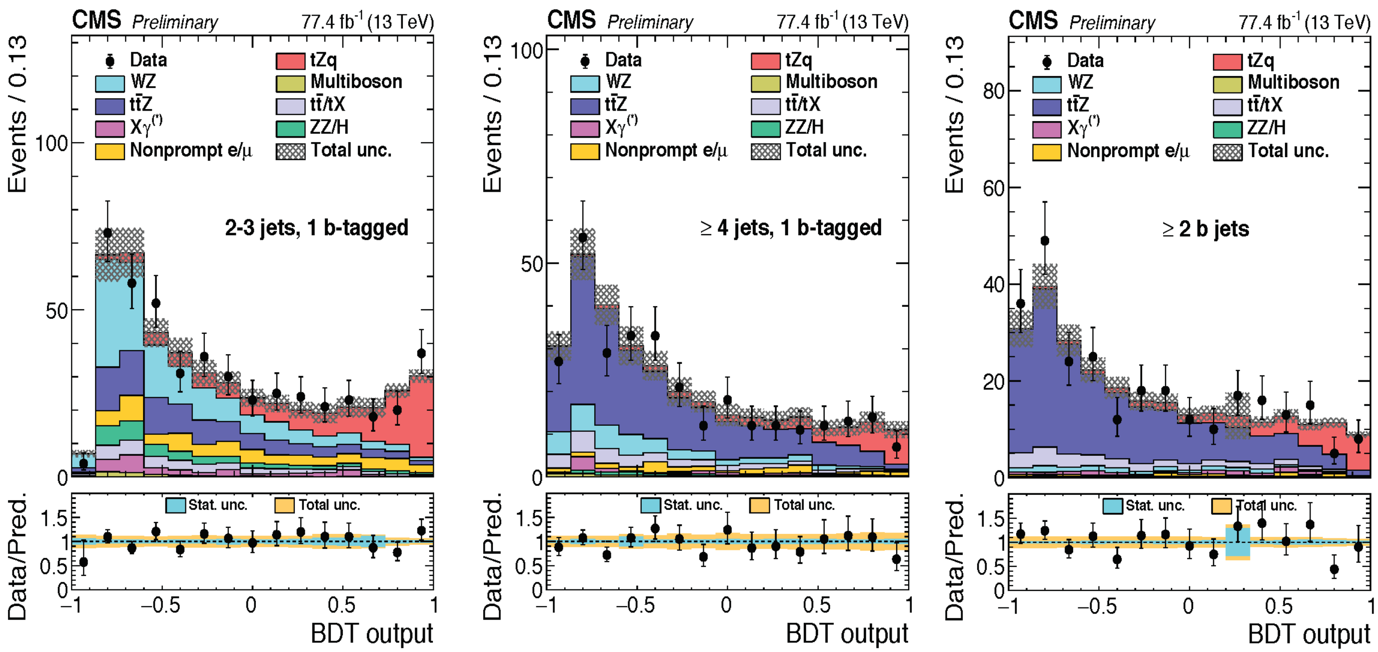
Becoming accessible with Run2 data



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



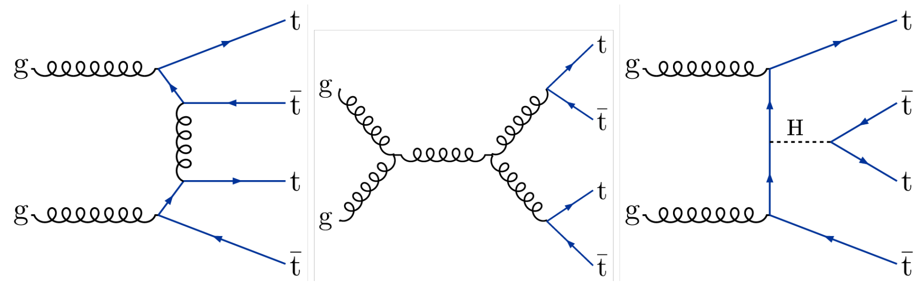
- Measured cross section with 15% precision:

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

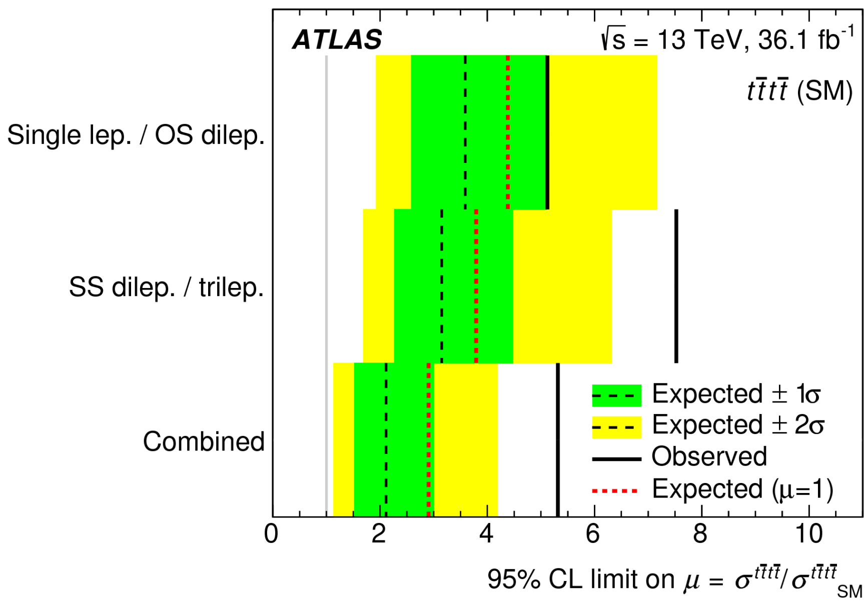
- First observation with observed (expected) significance 8.2 (7.7) σ.

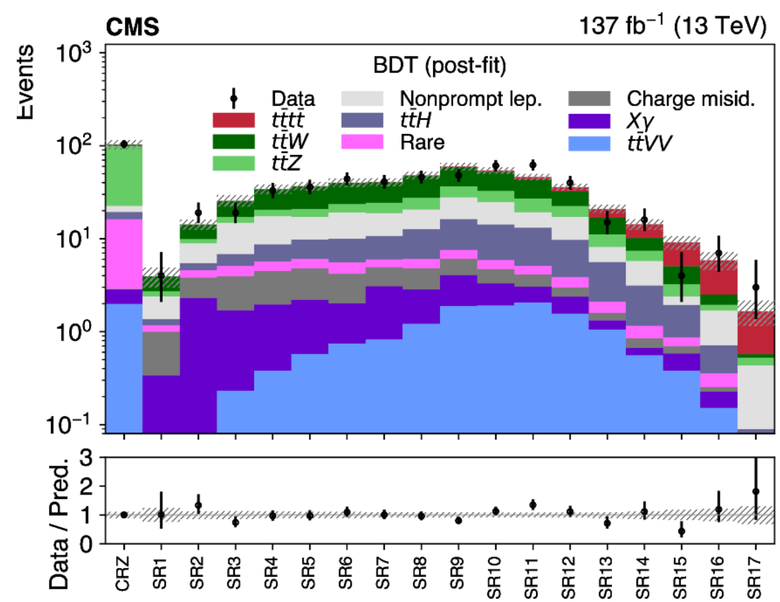
Searches for standard model production of four top quarks

- 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**

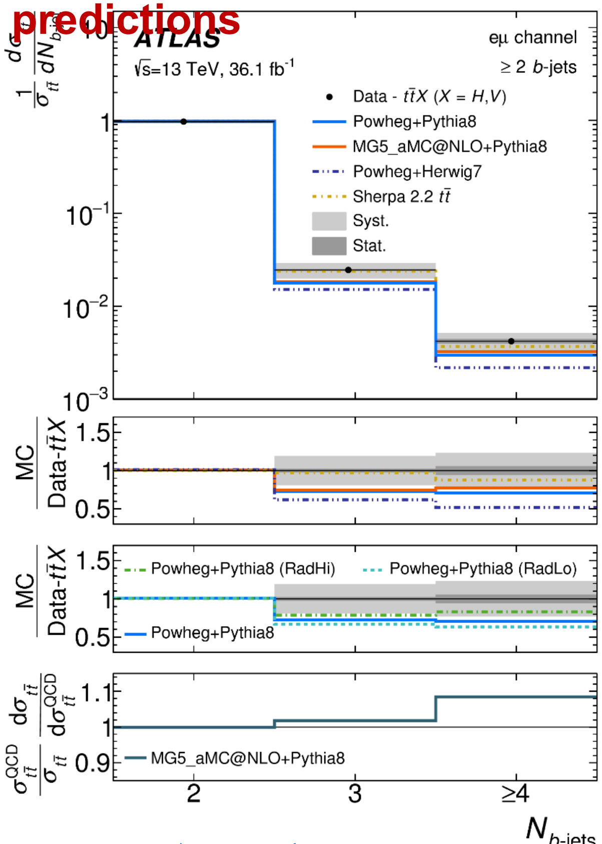




Significance: 2.6 (2.7) σ obs (exp)

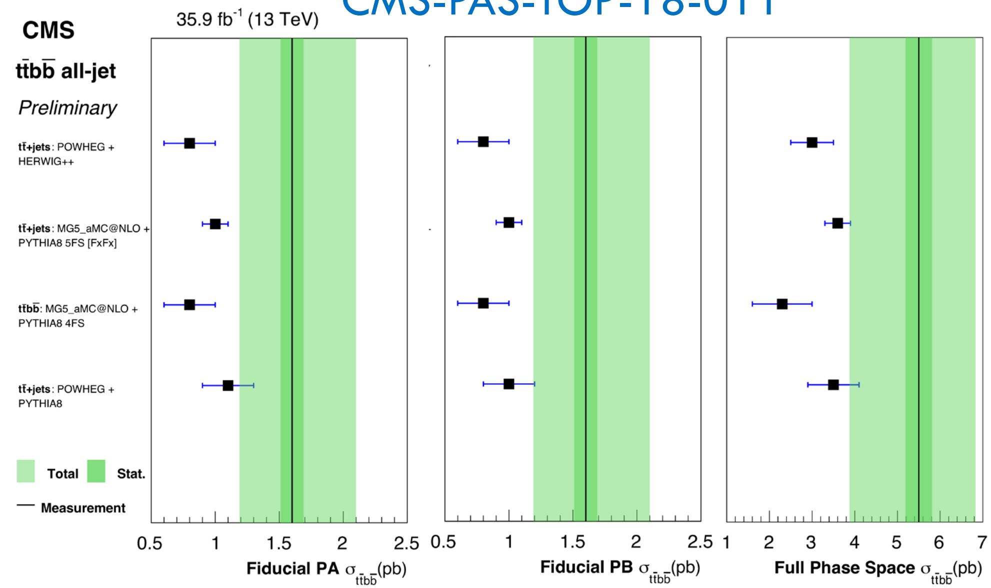
$t\bar{t} + b\bar{b}$

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

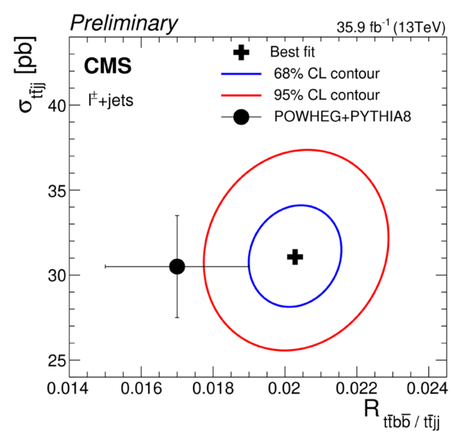


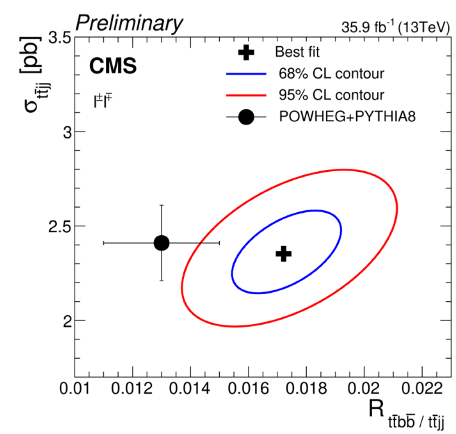
[JHEP 04 (2019) 046]

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 σ^{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

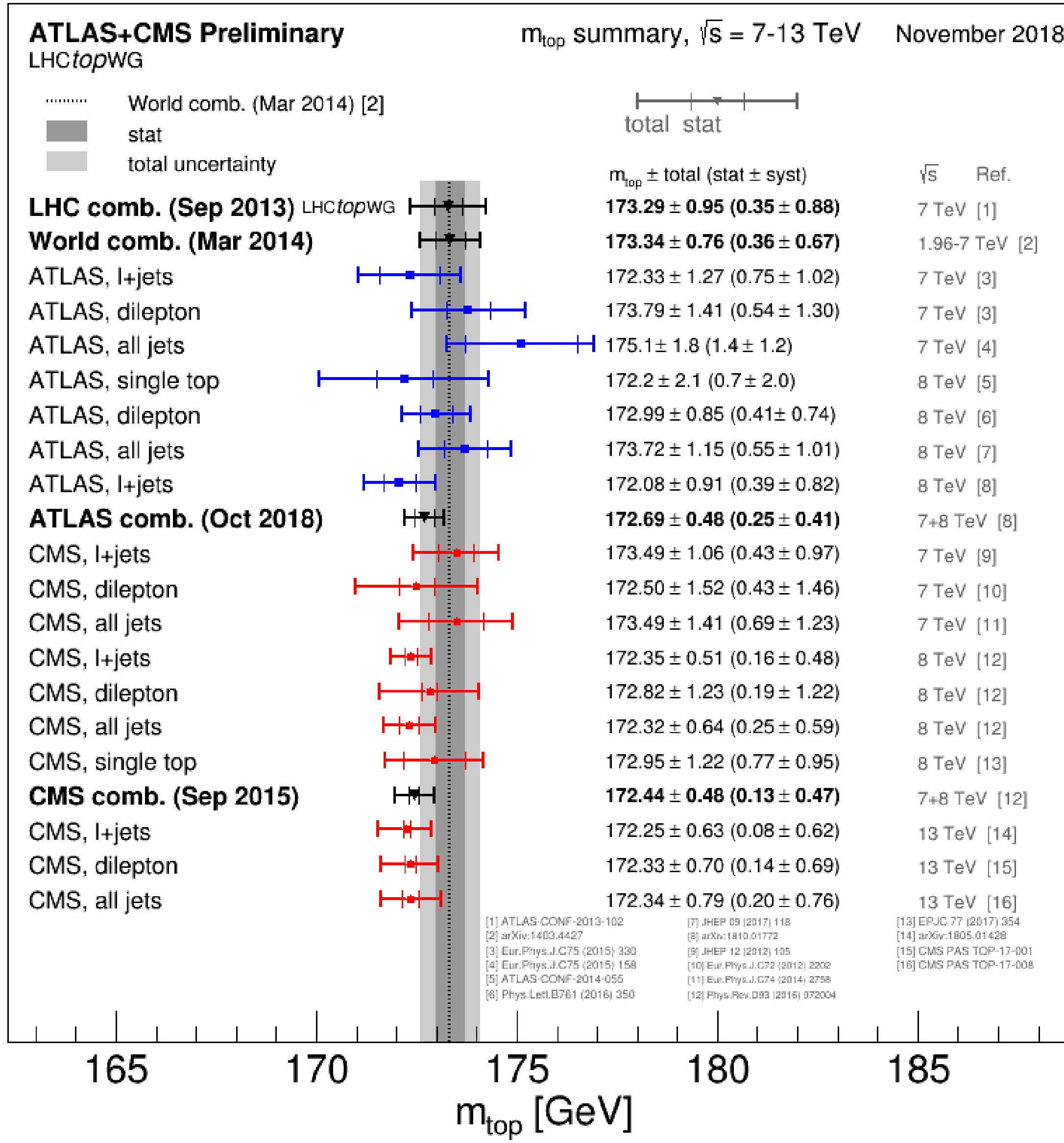
Lepton+jets channel 8TeV 20.2 fb^{-1} data

172.08±0.39(stat)±0.82(syst)

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

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

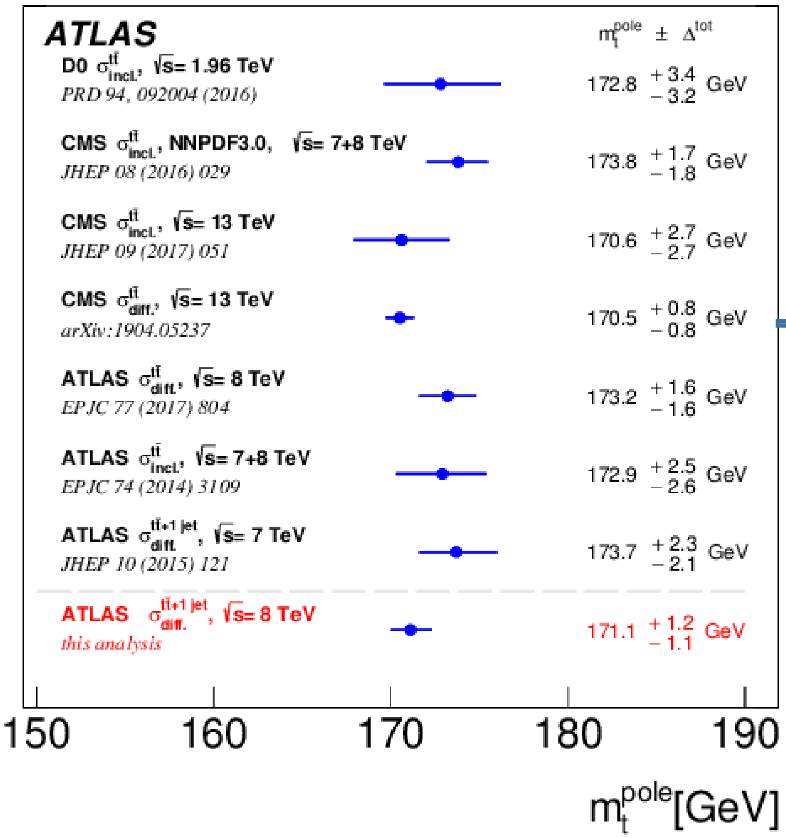
172.25 ± 0.08 (stat+JSF) ± 0.62 (syst GeV

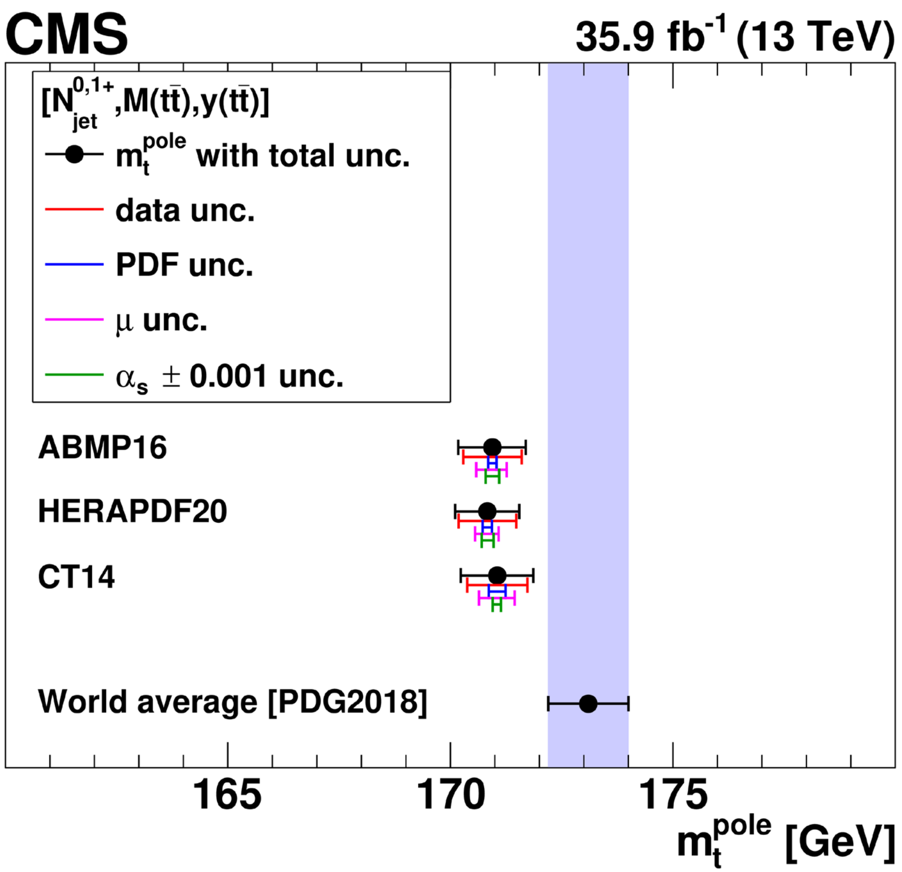


reached ~0.5 GeV precision

Indirect measurement of the m_t^{pole}

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

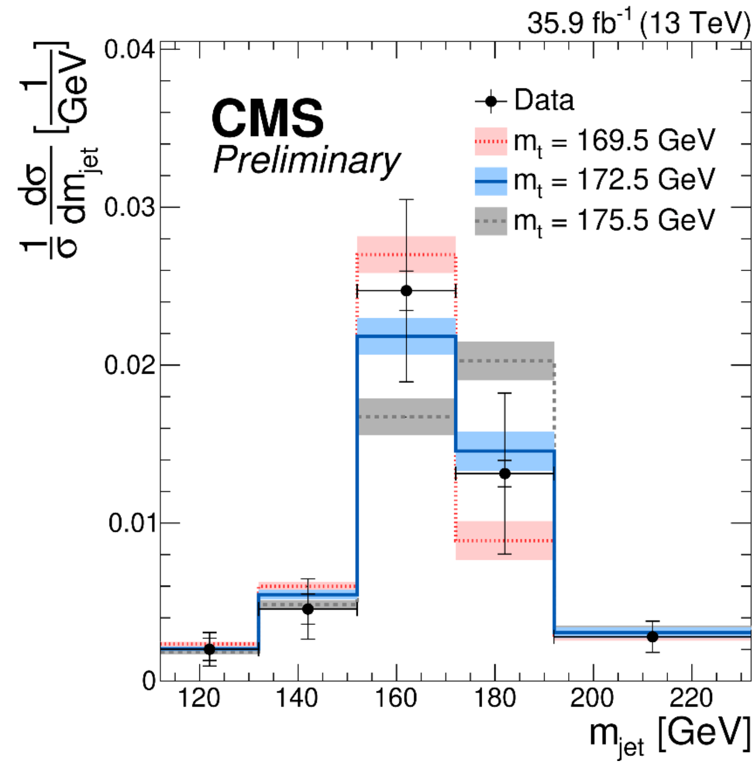




most precise result so far

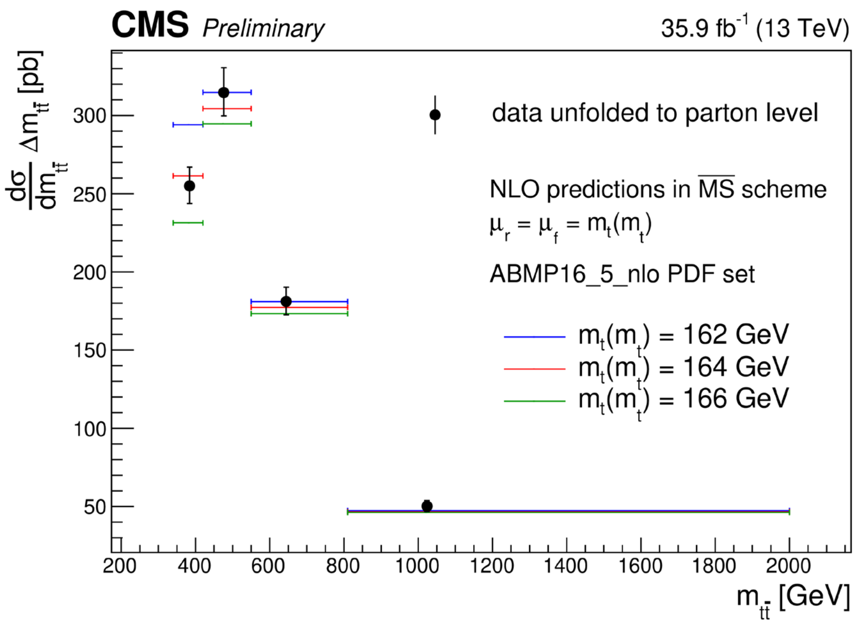
Latest top mass measurement in CMS

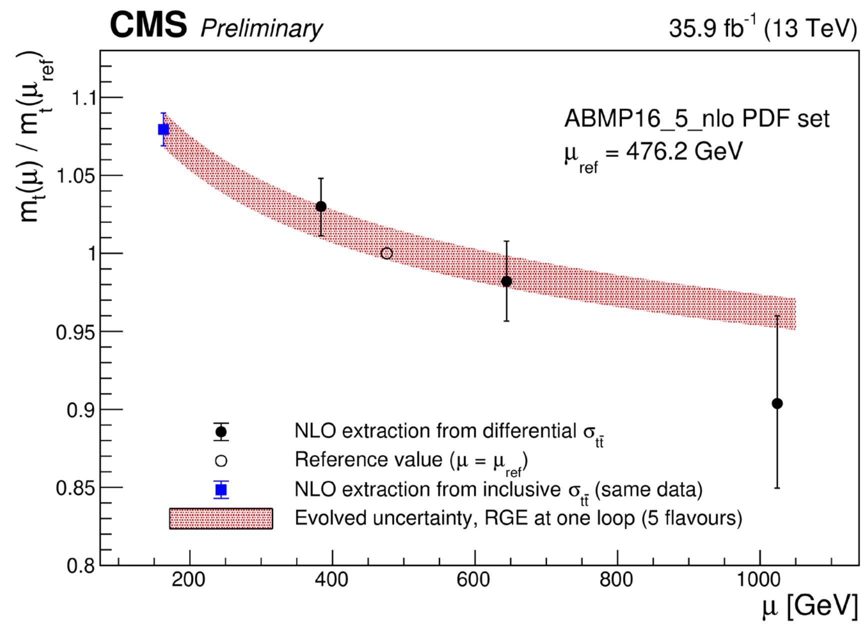
- Measure top mass m_t from boosted jet mass (mjet) observable
  - CMS-PAS-TOP-19-005
  - using highly boosted hadronic top quark decays produced in $t\bar{t}$ events
  - reconstruct highly-boosted top quark decays with a novel XCone jet algorithm JHEP11(2015)072
  - the normalized differential cross 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

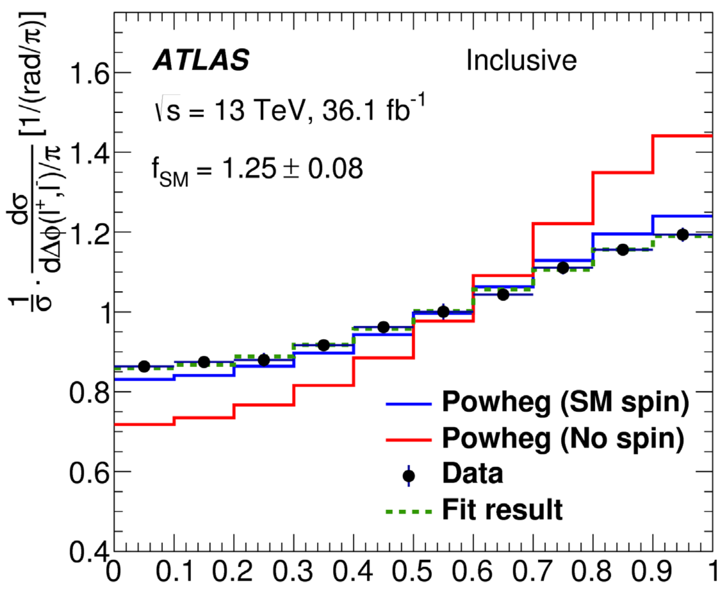




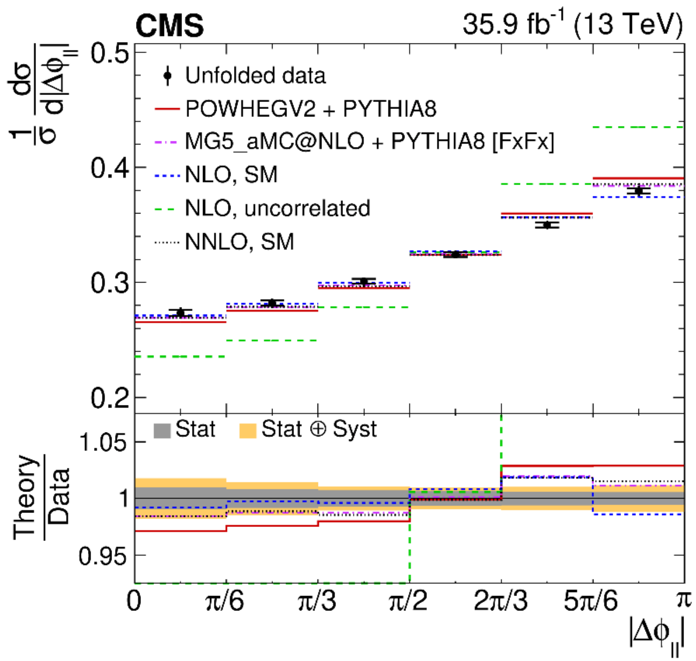
- differential $t\bar{t}$ production cross section as a function of $m_{t\bar{t}}$ at the parton level, compared to NLO predictions in the $\overline{MS}$ scheme obtained with different values of m_t
- extract the running of the top quark mass (evolution of the top quark mass as a function of the scale), 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

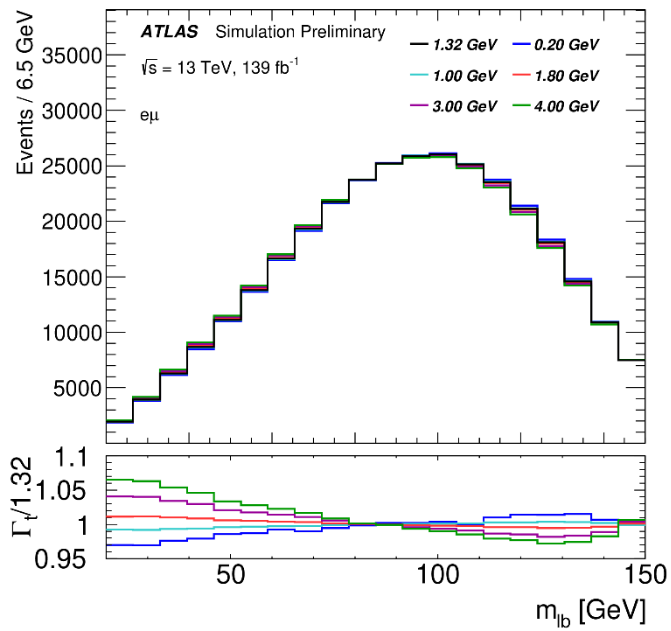


arXiv:1907.03729

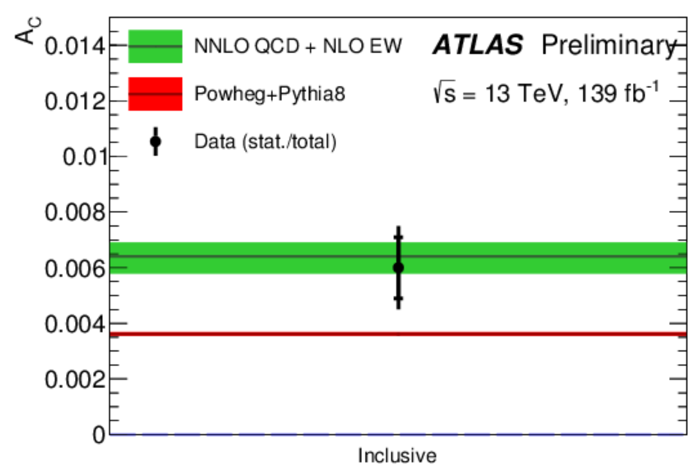
stronger spin correlation in data comparing to NLO prediction

Top decay width and top pair charge asymmetry

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



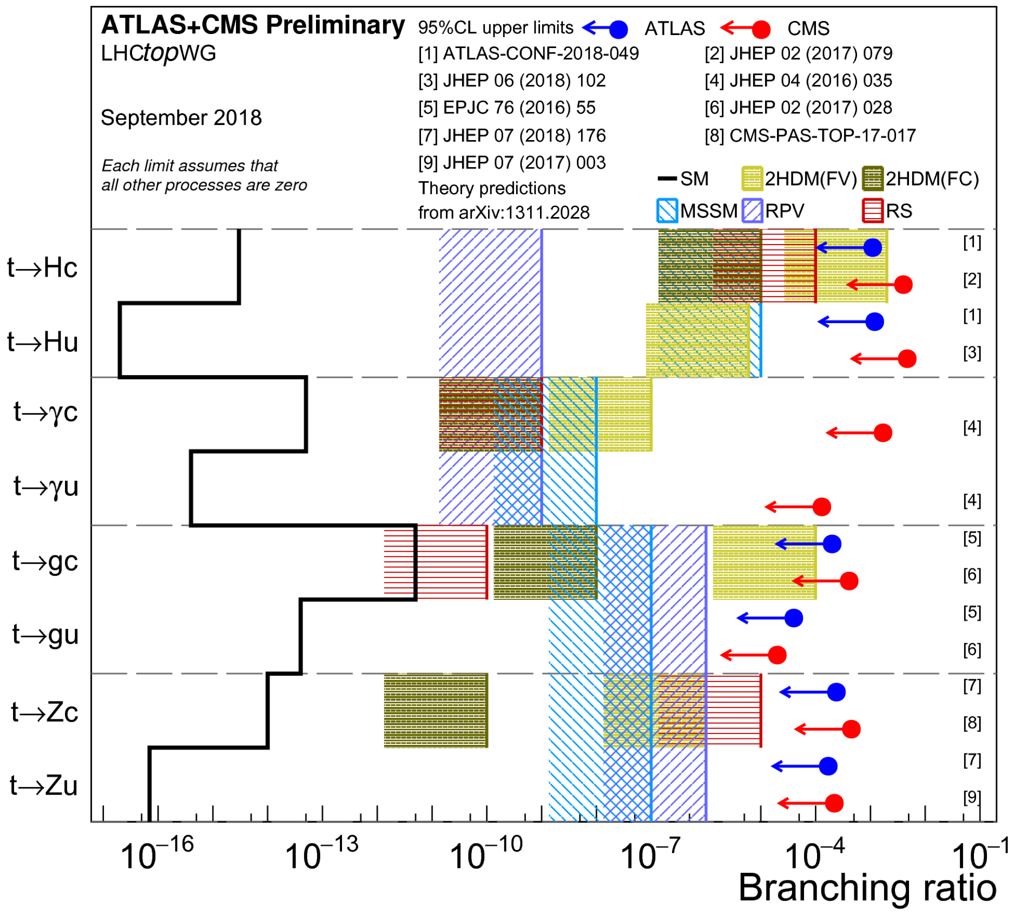
- Top pair charge asymmetry is measured in ATLAS using full Run2 data
  - asymmetry introduced by high order interference effects from qqbar, qg
  - The inclusive $t\bar{t}$ charge asymmetry is measured as A_C=0.0060±0.0015(stat+syst.)
  - 4 σ significance ATLAS-CONF-2019-026



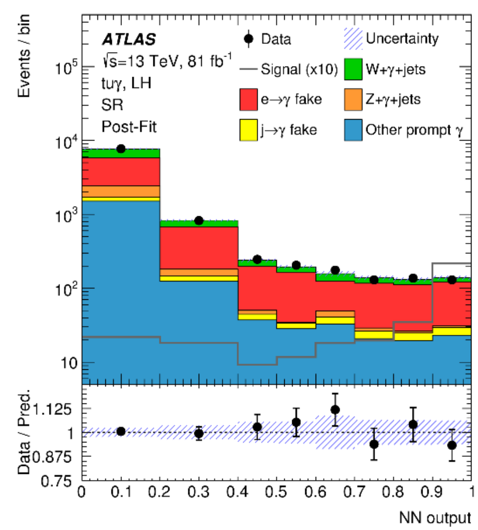
New Physics searches

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

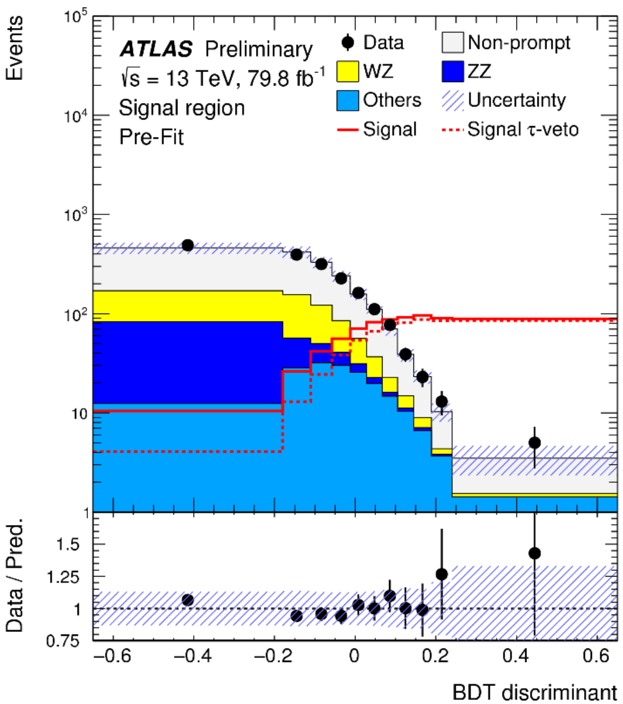


- $B(t \to u\gamma) < 2.8 \times 10^{-5}$ obs
  4.0×10^{-5} exp
- $B(t \to c\gamma) < 22 \times 10^{-5}$ obs
  27×10^{-5} exp

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 $t \to l^{\pm} l'^{\mp} q$ 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

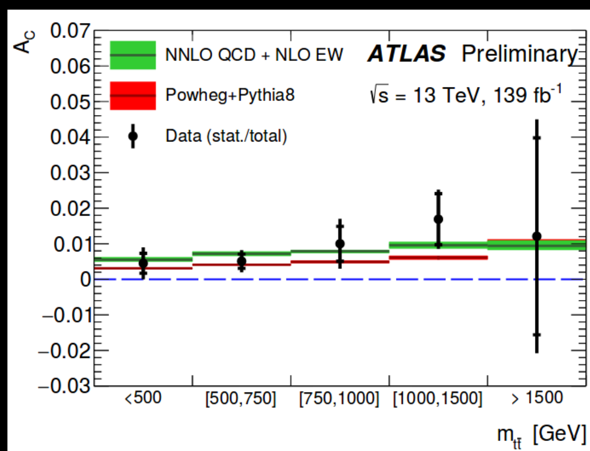
$$\mathcal{B}(t \to \ell\ell' q) < 1.86 \times 10^{-5} \quad \text{(observed)}.$$

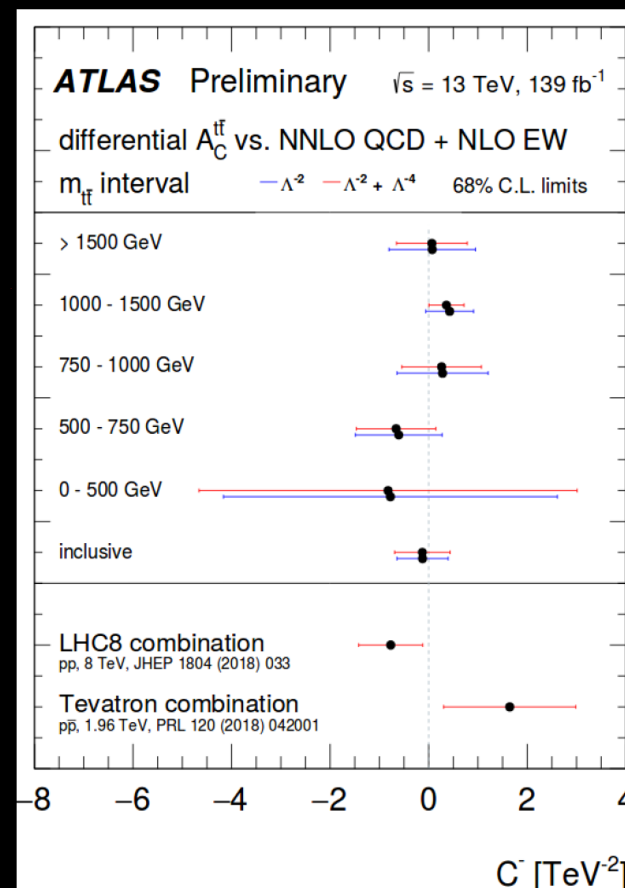


Generic Top Interpretations: Effective Field Theory

Generic Top Interpretations: Effective Field Theory

- EFT Interpretation is becoming a natural part of many top physics analyses
  - *encodes the effect of new physics phenomena at a scale beyond the direct reach of the experiment*



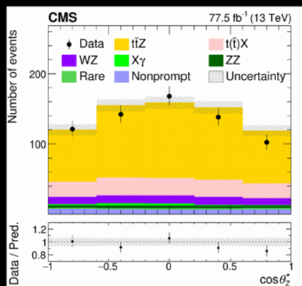


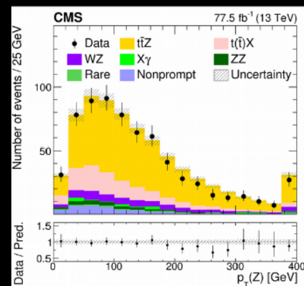
- **C^{-} :** a combination of 4-fermion operators
- Limit can be recast as bound on coupling and mass of massive new states in many BSM scenarios

Abideh (Nadjieh) Jafari

Generic Top Interpretations: Effective Field Theory

Exploiting more and more our *privileged access to data*

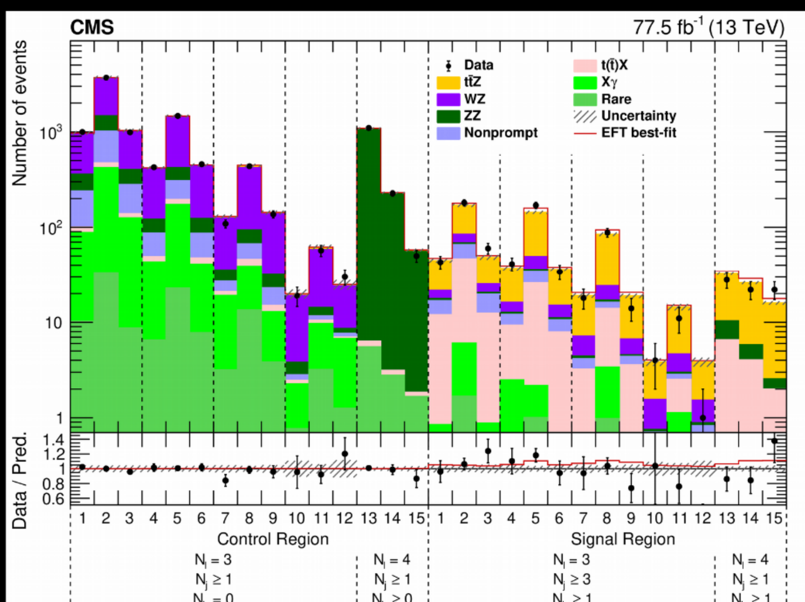


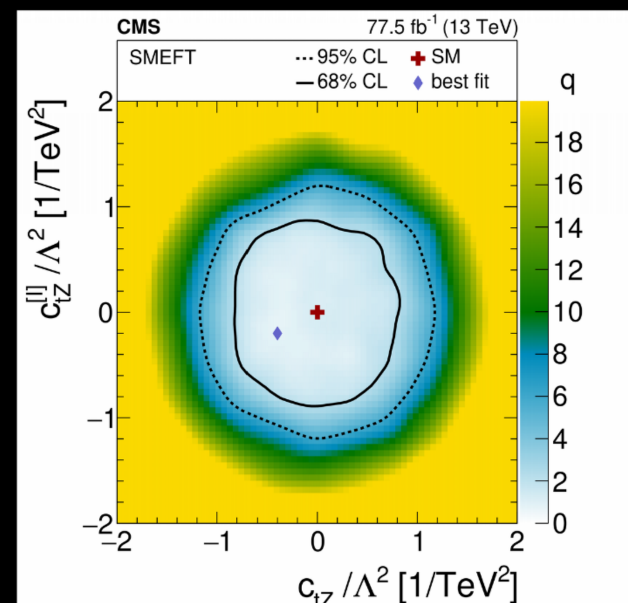


Sensitive to BSM in top-Z couplings

- Reweighting using EFT MC and fit to data at the detector level
- Account for systematics and correlations

arXiv:1907.11270
Submitted to JHEP





Abideh (Nadjieh) Jafari

Summary

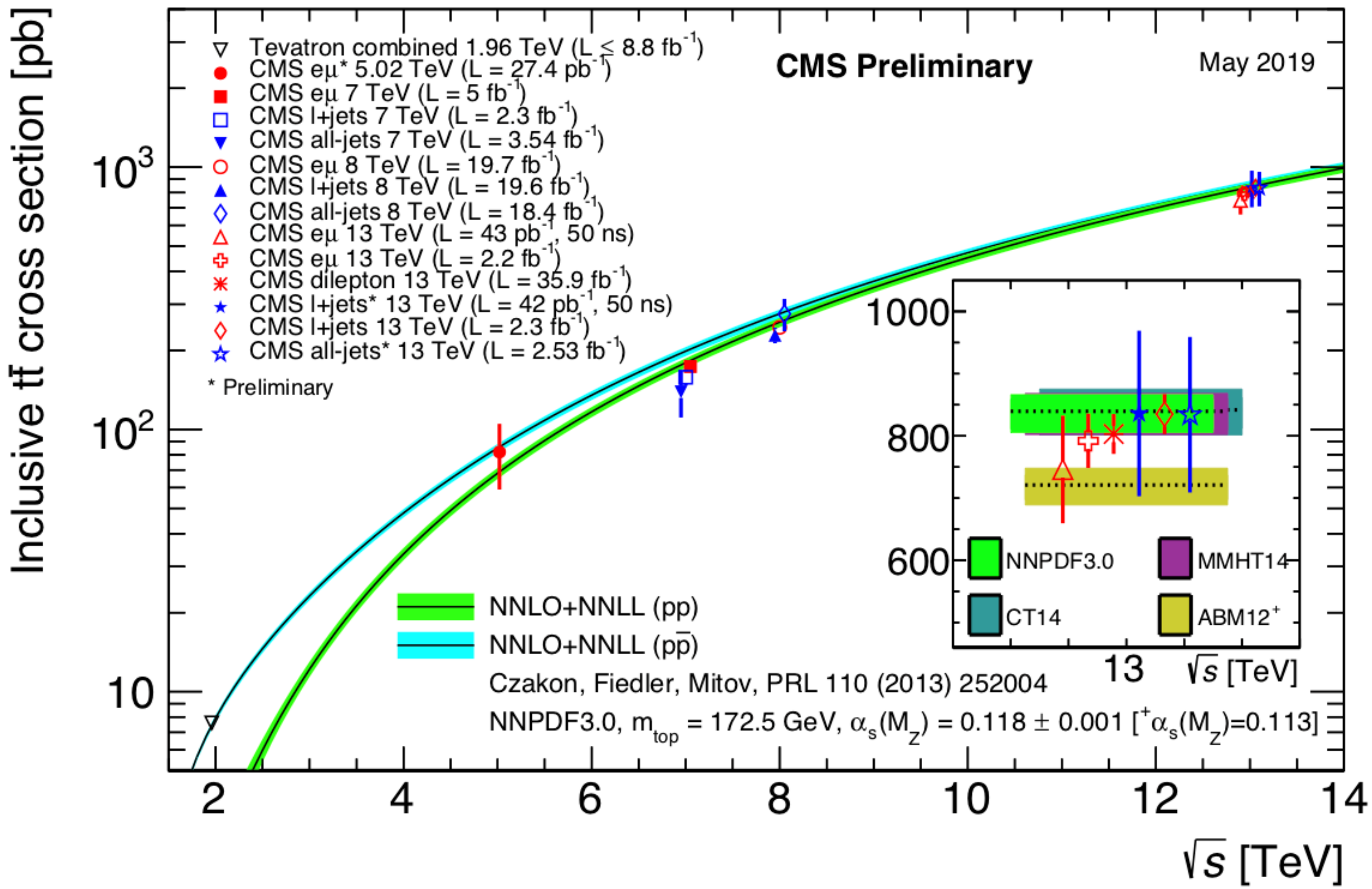
Summary

- Top quark is unique and important to SM, BSM, Cosmology physics
- Rich physics in top with LHC
  - precision measurements of top production and decay, top quark properties, constraining models
    - $t\bar{t}$, 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
    - running of top mass, tW and $t\bar{t}$ interference models, EFT interpretation
  - various new physic searches
    - FCNC, cLFV, etc.
- LHC data are generally consistent with theoretical predictions on top physics 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 top quark physics results with full Run 2 data from LHC
  - 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



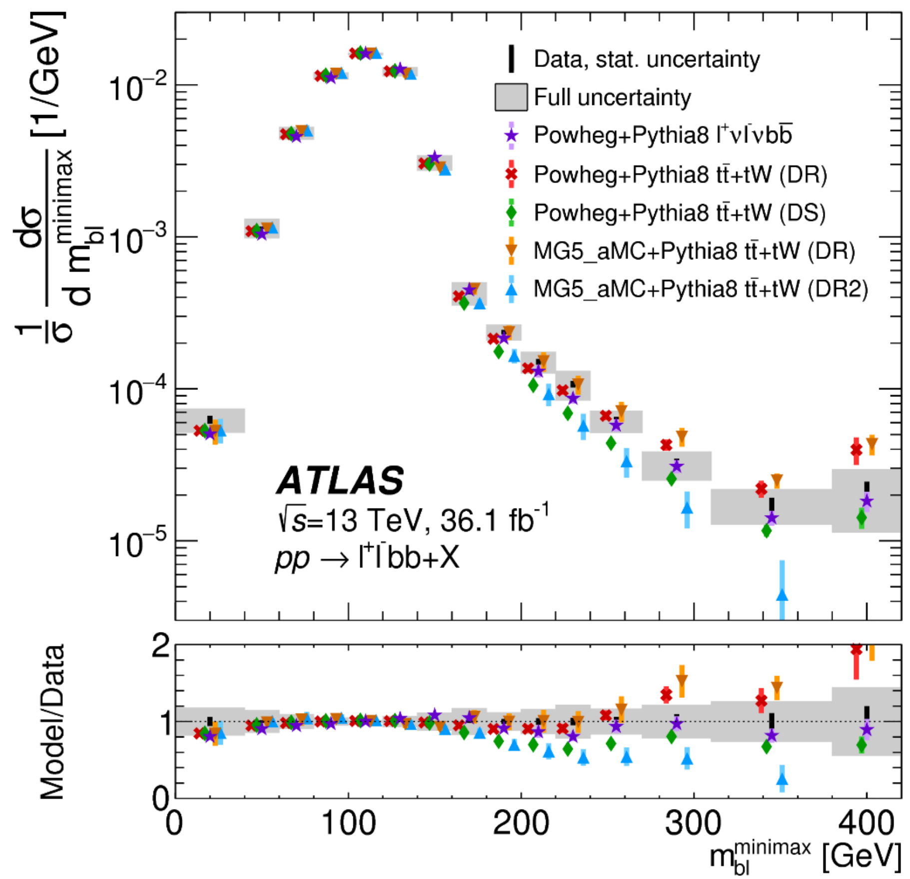
- Single measurement precision: ~3.5%
- Limited mainly by luminosity and signal model uncertainty.

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

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

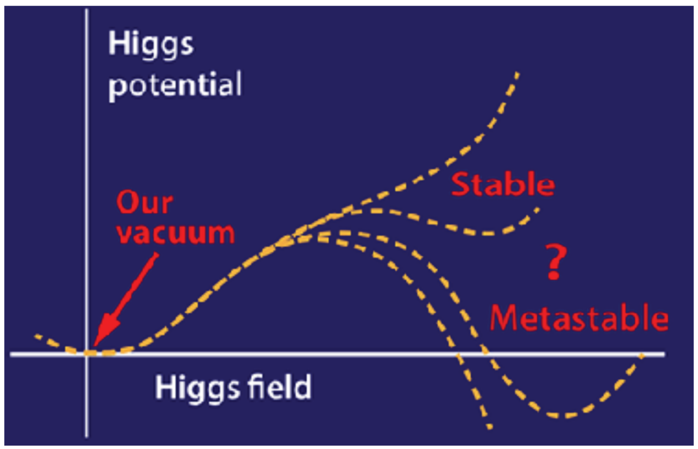
- Results provide an important constraint on interference models and will guide future model development and tuning.



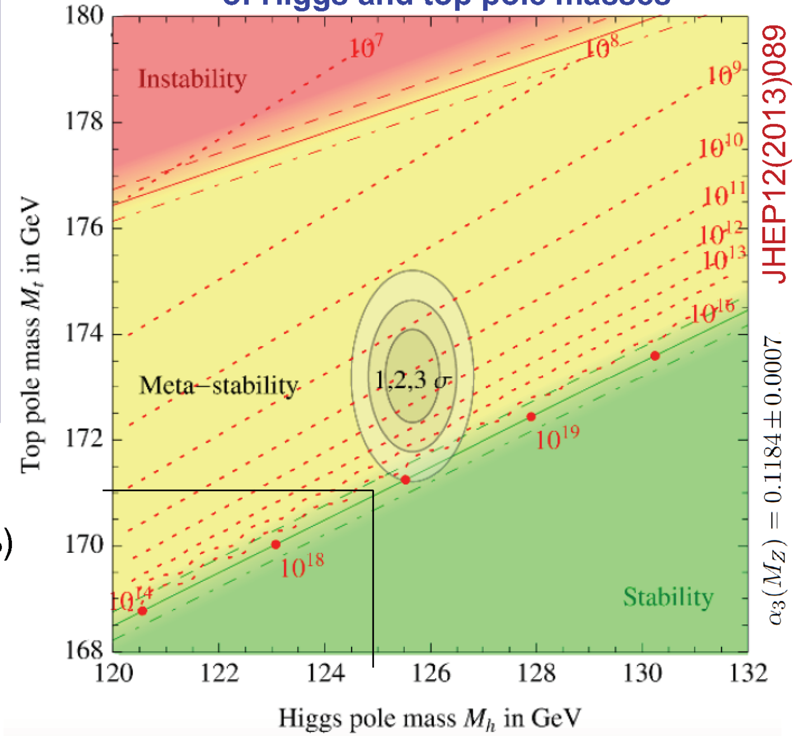
Stability

Is our world stable?

The answer is strongly connected to the top and Higgs properties !



SM phase diagram in terms of Higgs and top pole masses



Direct (MC)
ATLAS: m_{top}=172.69±0.48 GeV (δ~0.28%)
Pole mass
CMS: m_{top}=170.9±0.8 GeV (δ~0.47%)

Precise determination of m_t, m_H, m_W and y_t are crucial to understand where we live !!

CMS: m_H=125.35±0.15 GeV
ATLAS: m_H=124.97±0.24 GeV

δ~0.12% (stat. unc. >~ syst. unc.)

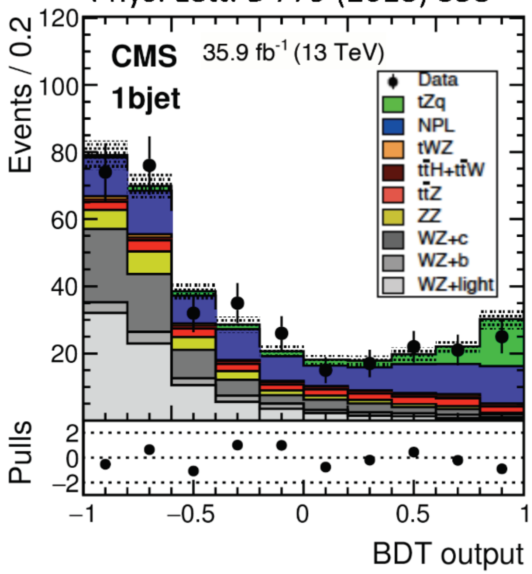
tZq measurements

- 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

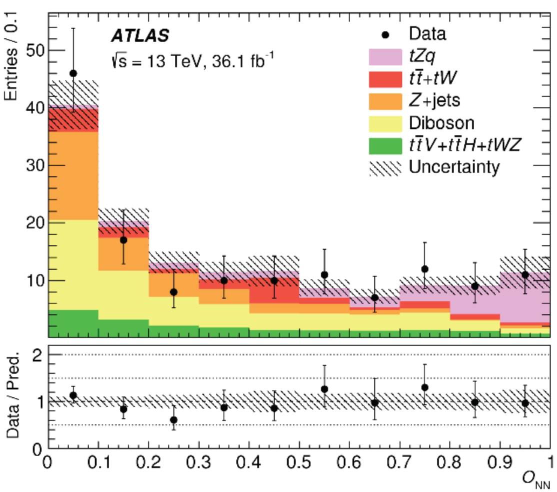


$\mu = 1.31^{+0.35}_{-0.33}(\text{stat})\ ^{+0.31}_{-0.25}(\text{sys})$

3.7 (3.1) σ Obs.(Exp.)

ATLAS result with 2016 data

Phys. Lett. B 780 (2018) 557

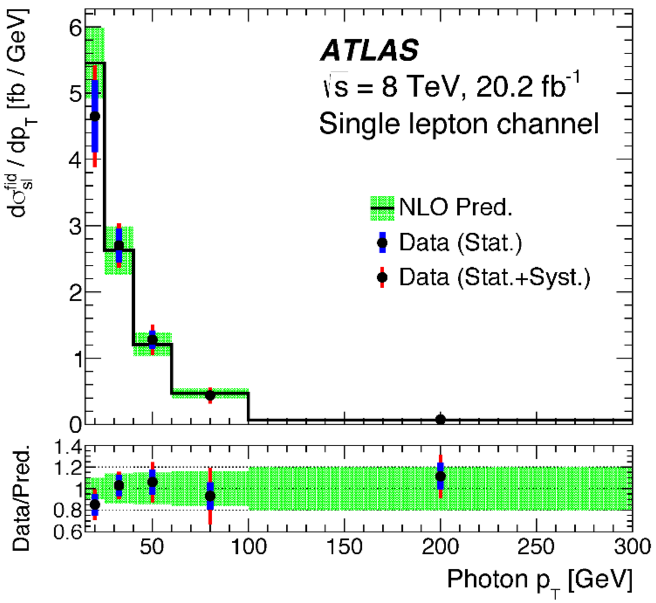


$\mu = 0.75 \pm 0.21(\text{stat}) \pm 0.17(\text{sys})$

4.2 (5.4)σ Obs.(Exp.)

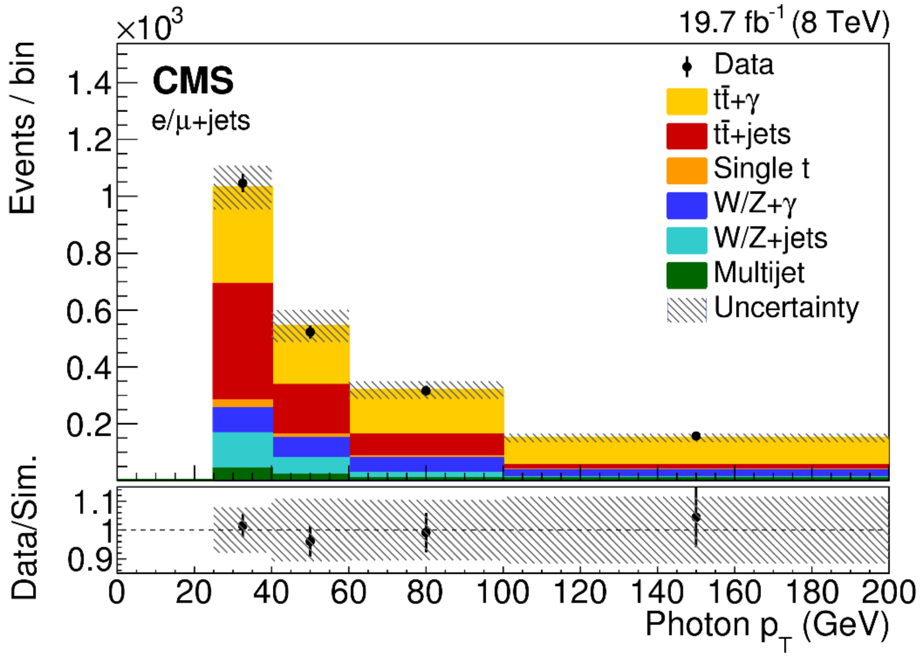
Both measurements with about 35% uncertainty

$t\bar{t} + \gamma$



JHEP 11 (2017) 086

$\sigma_{tt\gamma}$=139 ± 18pb

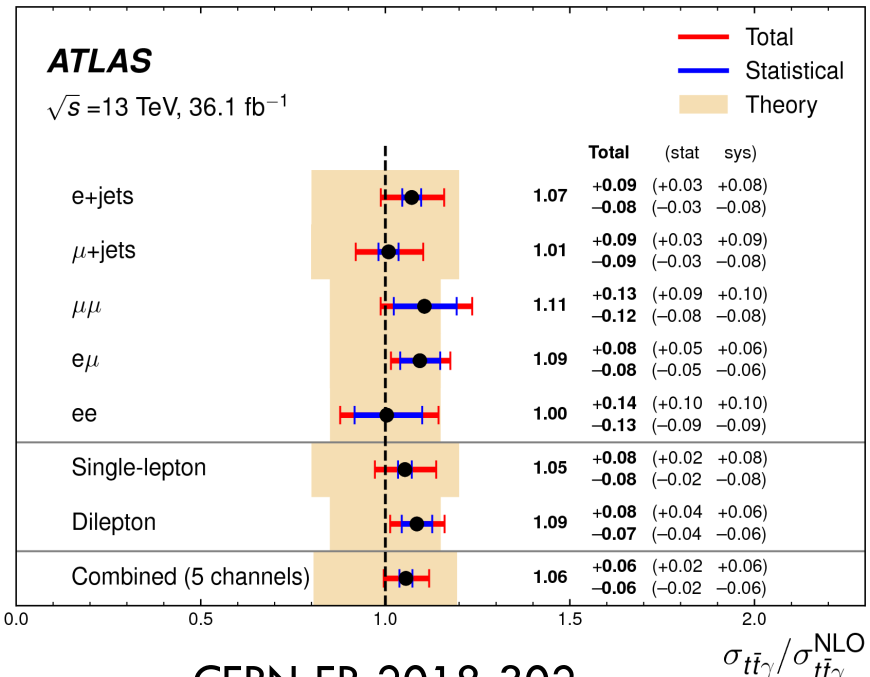


JHEP 10 (2017) 006

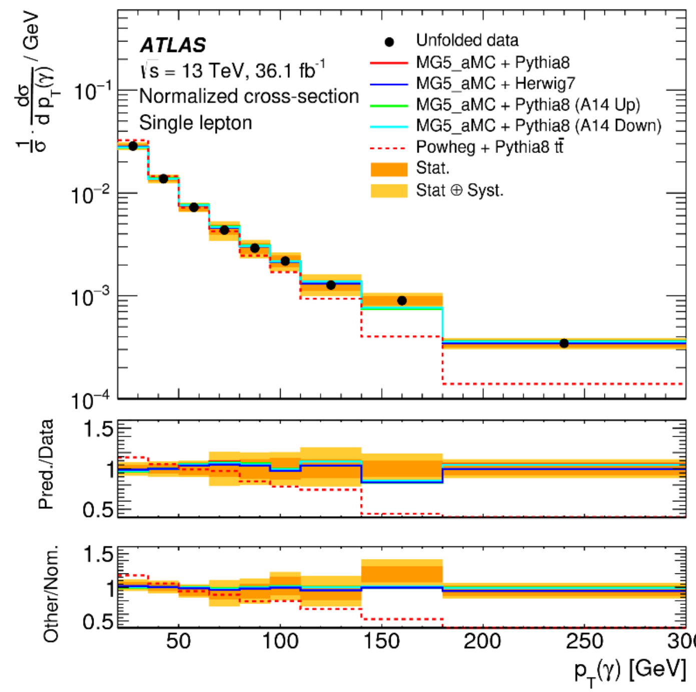
$\sigma_{tt\gamma}$=127 ± 27pb

$t\bar{t} + \gamma$

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

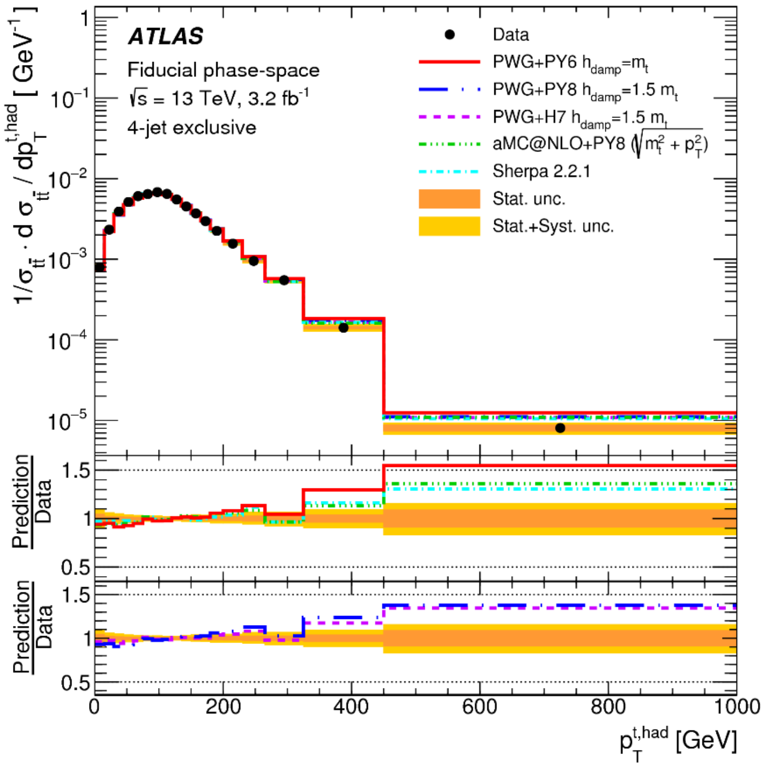


CERN-EP-2018-302

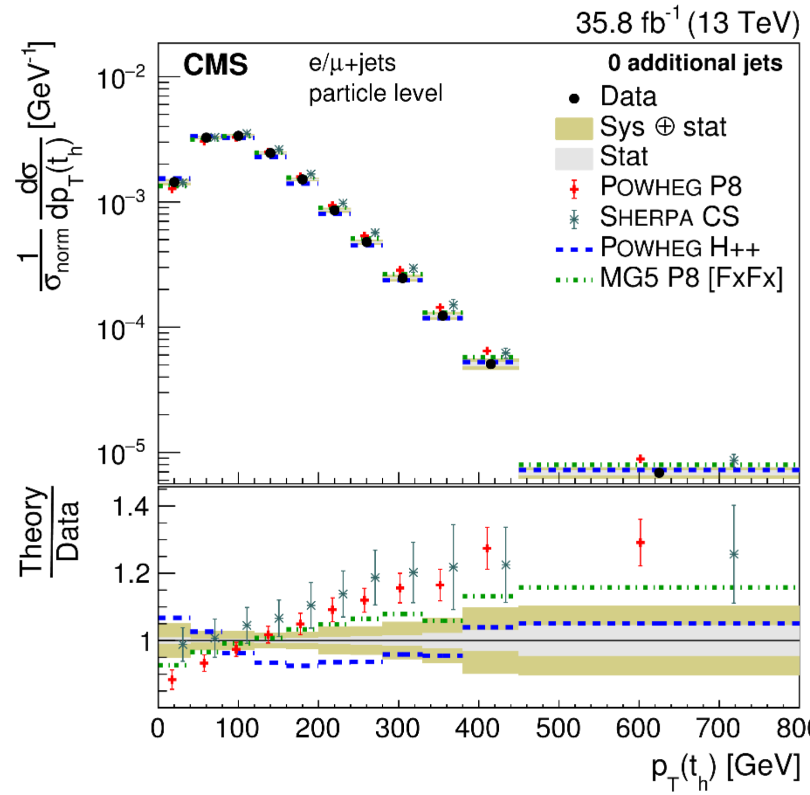


- ATLAS updated 13TeV results of inclusive and differential cross-sections for $t\bar{t}$ + γ with 2015+2016 data, recently submitted to EPJC
- All measurements are in agreement with the theoretical predictions.

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



JHEP 10 (2018) 159



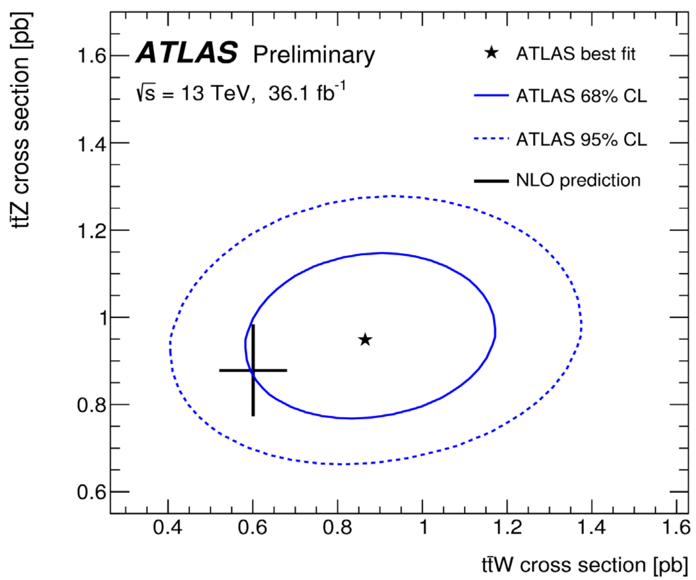
Phys. Rev. D 97 (2018) 112003

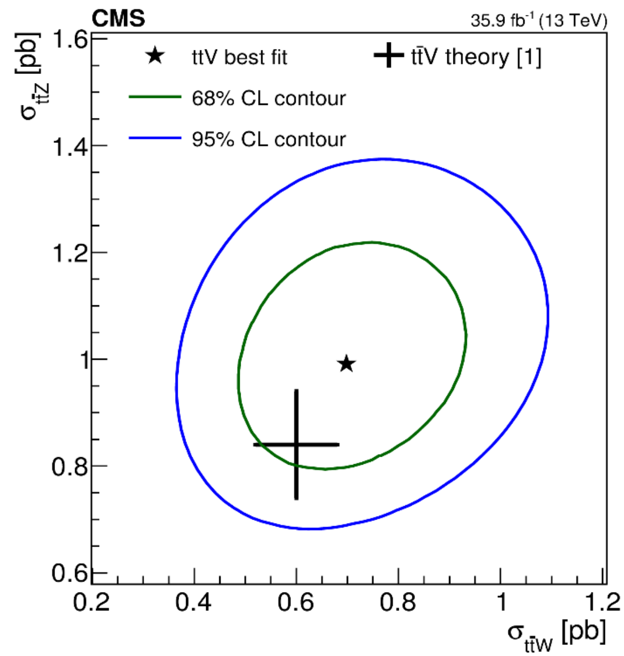
- Some tension found between data and prediction for reconstructed hadronical top p_T in 4-jet exclusive configuration in both ATLAS and CMS
- POWHEG+PYTHIA also has difficulties simultaneously reproducing Njets and $p_T(t\bar{t})$

- Two definitions for ttbb events in the visible phase space (VPS) are considered: one that is based exclusively on stable generated particles after hadronisation (parton-agnostic, PA), and one that also uses parton-level information after radiation emission (parton-based, PB).
  - The former facilitates comparisons with predictions from event generators
  - the latter is closer to the approach taken by searches for ttH production to define the contribution due to the ttbb process.
  - The cross section is reported for the full phase space (FPS) by correcting the cross section in the VPS by the experimental acceptance.

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

- 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

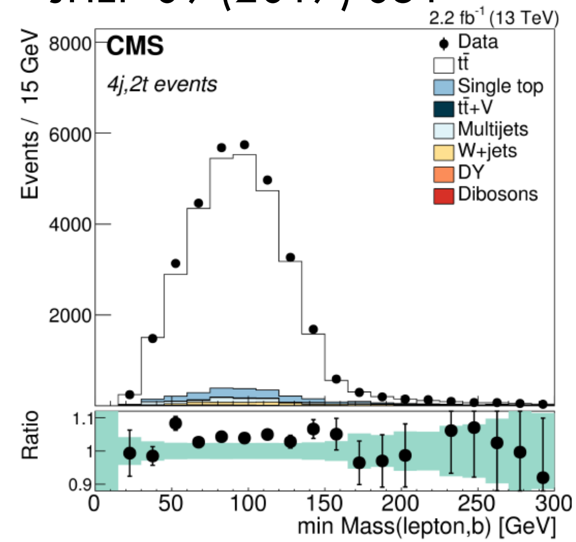
JHEP 09 (2017) 051

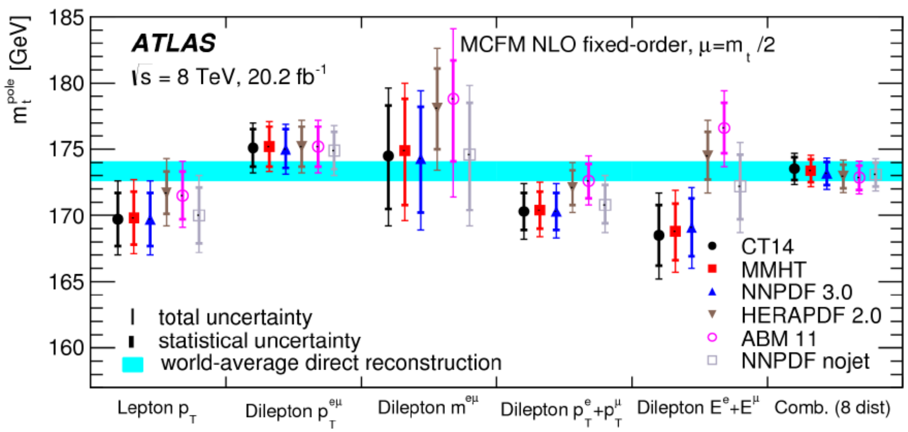
CMS: 13 TeV data, L = 2.2 fb^{-1}; lepton+jets final state

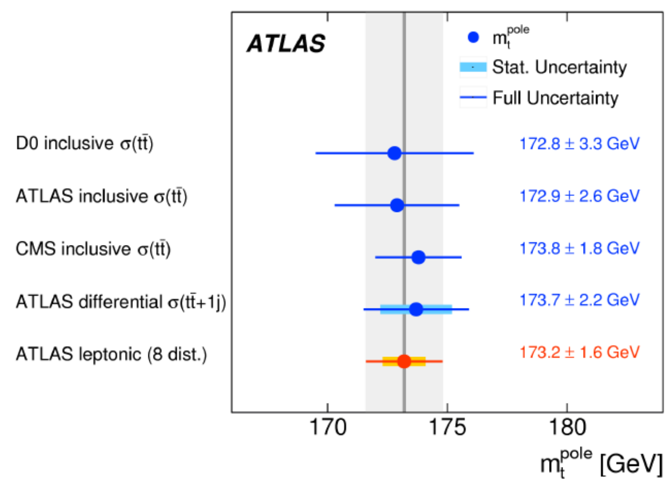
- Measure differential cross section wrt min(m_{lb}) in categories of N_{jet} and $N_{b\text{-}jet}$:
  σ = 888 ± 2 (stat) ± 27(sys) ± 20 (lumi) pb
- Extract pole mass from cross section:
  m_t^{pole} = 170.6 ± 2.7 (tot) ± 1.01 (syst.) GeV

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

- 8 differential 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^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





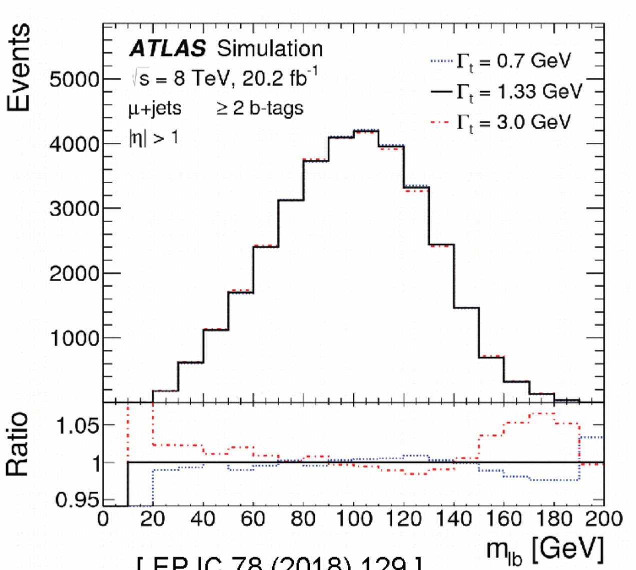


EPJC 77 (2017) 804

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



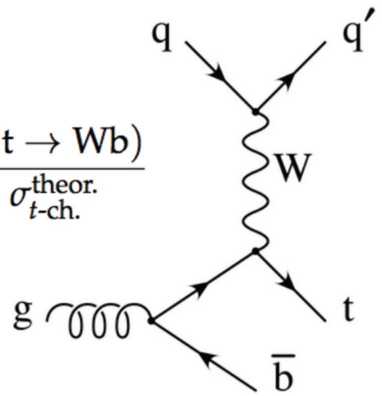
[EPJC 78 (2018) 129]

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

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]

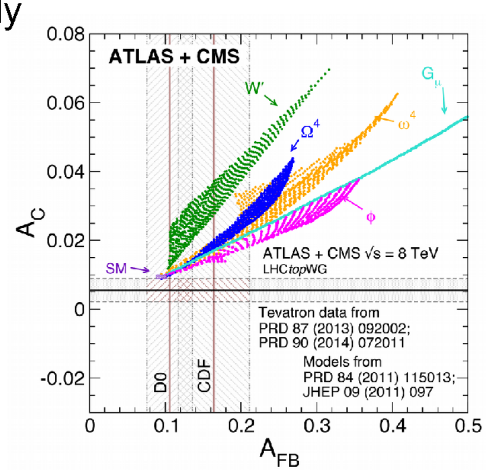
At Tevatron, measure A_{FB}. At LHC, measure A_C:

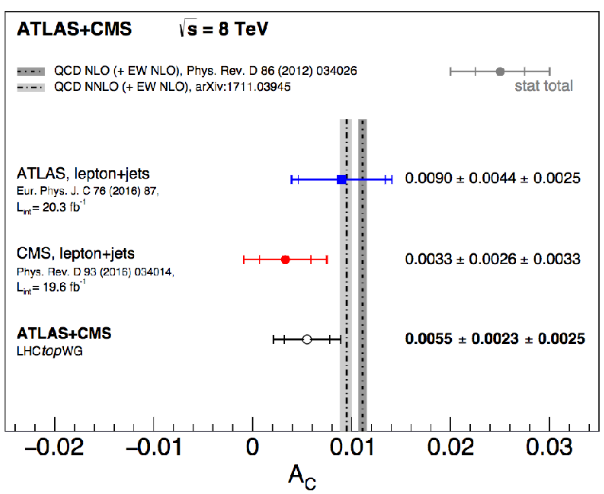
$$A_C = \frac{N^{\Delta|y|>0} - N^{\Delta|y|<0}}{N^{\Delta|y|>0} + N^{\Delta|y|<0}}$$

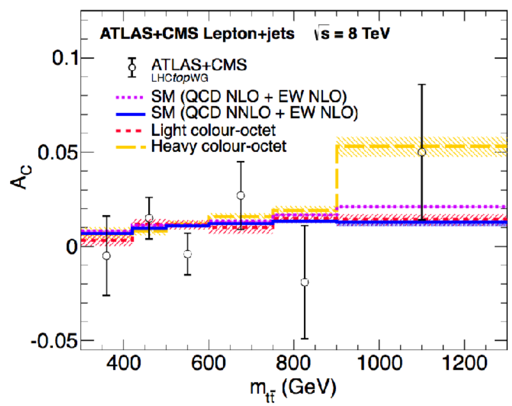
Non-zero A_C in SM due to higher order effects in $q\bar{q}$ annihilation

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

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

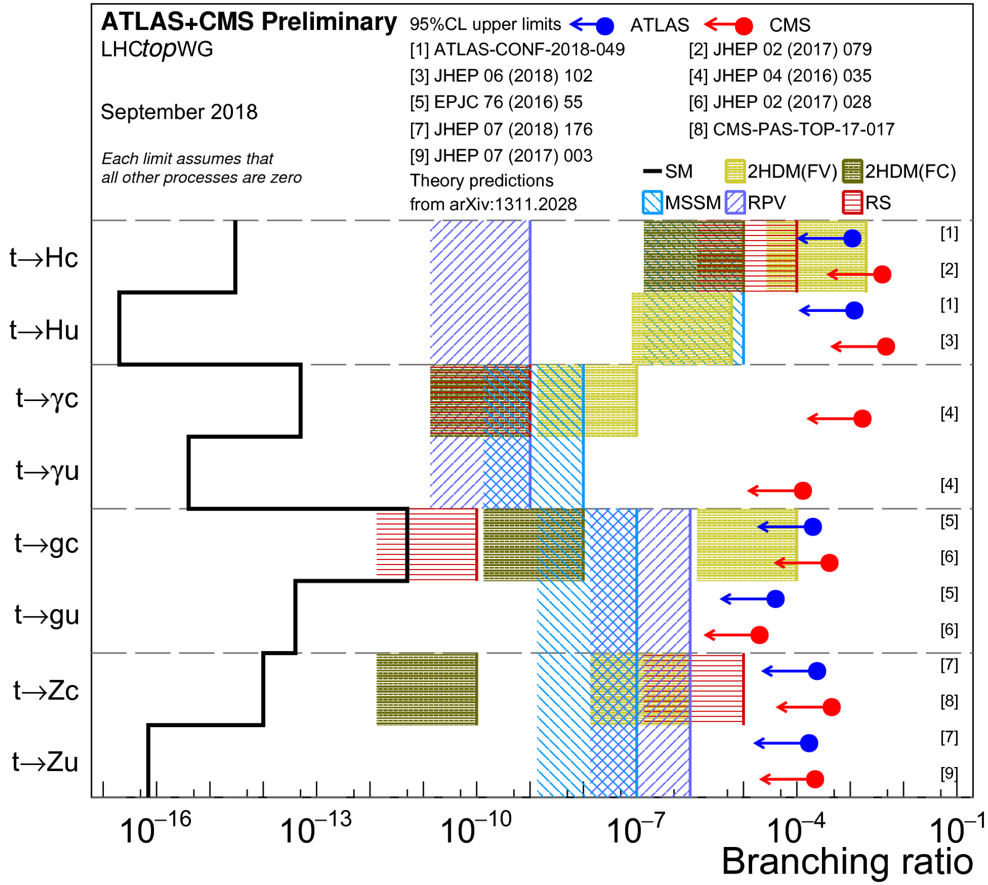
JHEP 07 (2018) 176 $t \to qZ$ (q=u, c)

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 $\mathrm{H} \to b\bar{b}$



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

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