Top physics at LHC

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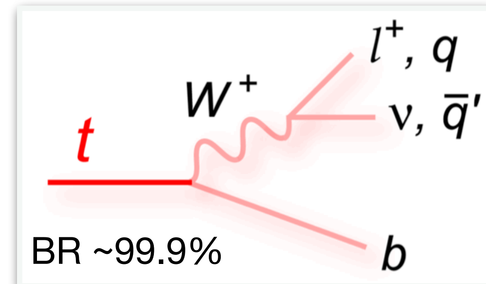
on behalf of the ATLAS and CMS Collaboration

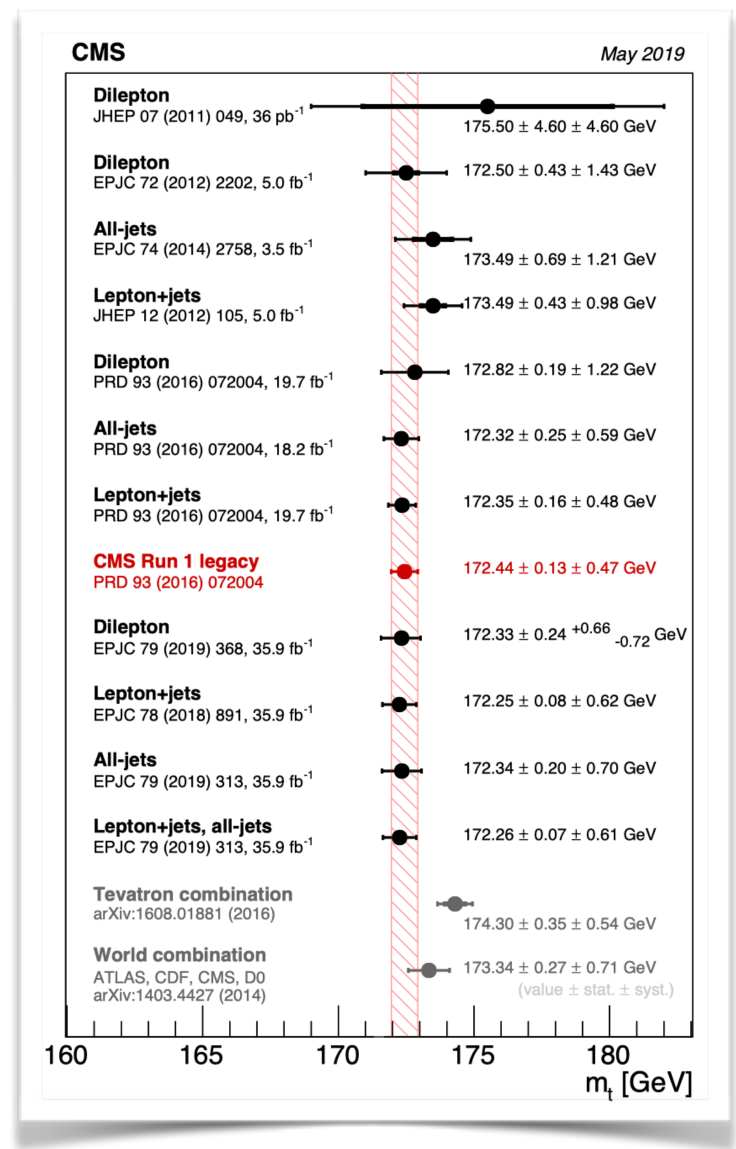
SIF2020
17 September 2020

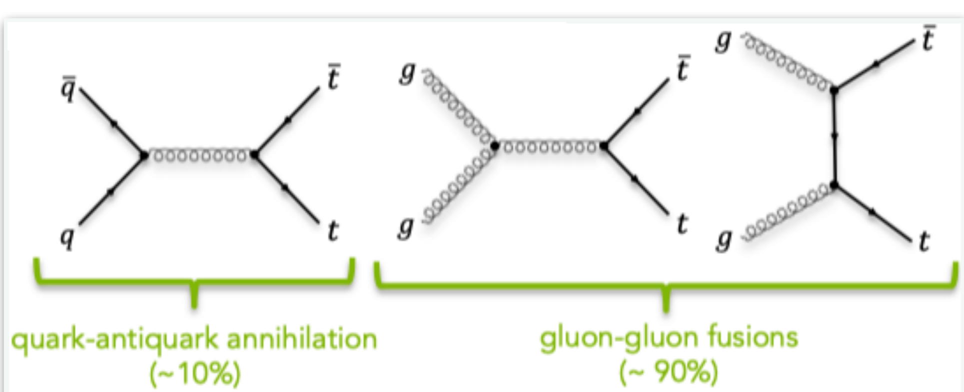
The Top Quark

- Heaviest elementary particle discovered so far
- Extremely short lifetime → bare quark properties
- Large Yukawa coupling to Higgs boson → important for EW symmetry breaking
- Spin information preserved in the angular distribution of its decay products → **ideal candidate for spin measurements**
- Studies of its properties provide crucial info to:
  - test internal consistency of SM
  - search for new phenomena (BSM physics)
- Top quark pairs production @LHC dominated by gluon fusion (~90%)
  - constraint of fundamental SM parameters (e.g. PDF, α_S, m_t^{pole})
- Single top production:
  - constraint of EWK sector of SM (direct sensitivity to V_{tb})



$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\ \text{s}}}$$

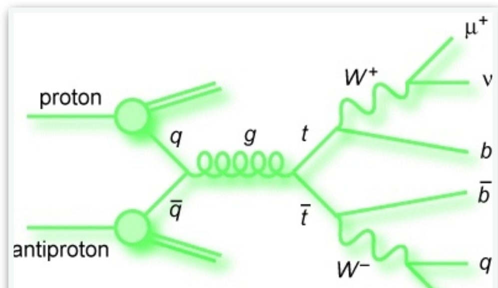




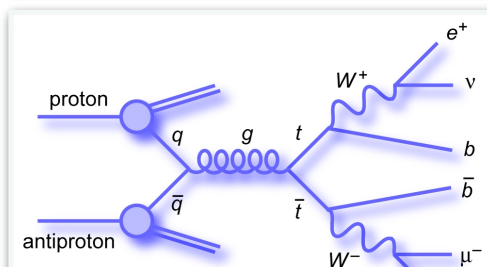
Top quark pair production

- Many measurements performed by the LHC collaborations at $\sqrt{s}$=7, 8 and 13 TeV
  - impressive agreement between predictions and measurements

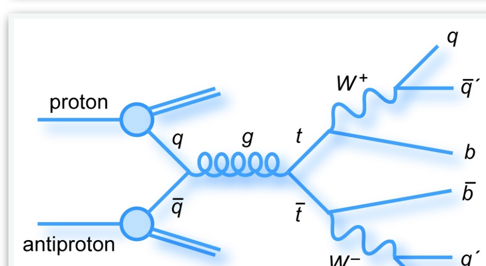
- 3 main investigation channels:
  - **lepton+jets**
    - compromise between signal statistic & bkg contamination
  - **dilepton**
    - cleanest signature but lower signal statistics
  - **full hadronic**
    - significantly less precise (large multijet bkg)



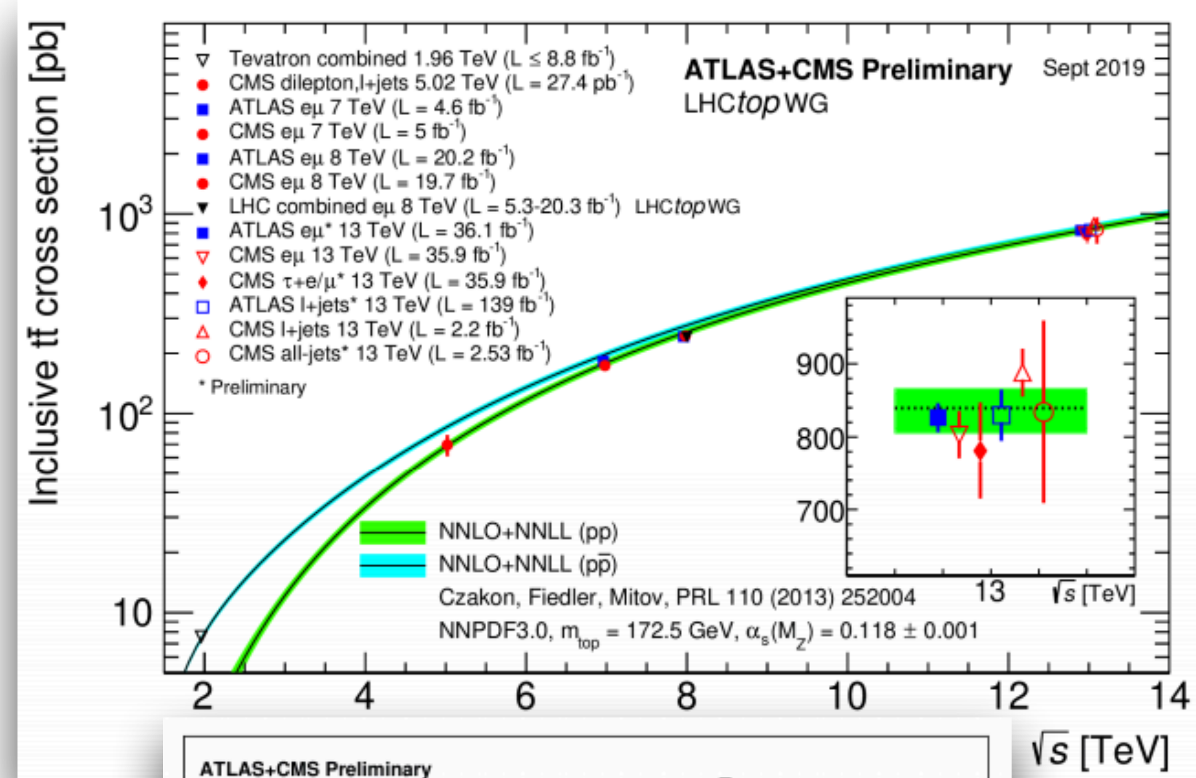
BR ~45%

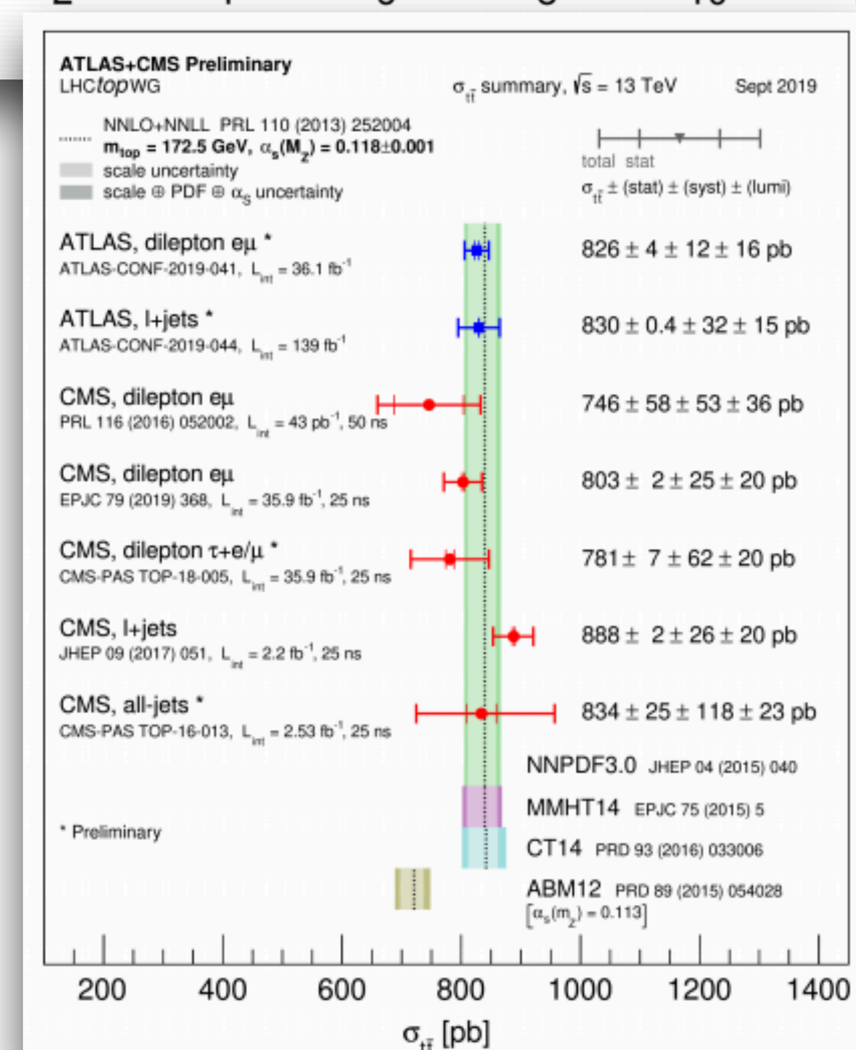


BR ~9%



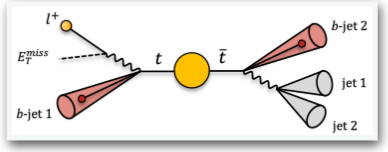
BR ~46%

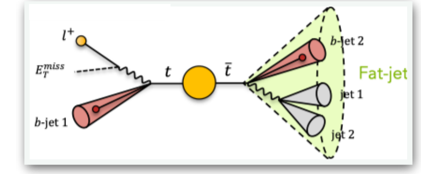




Dominant syst. unc.:
tt modeling, objects efficiencies and calibrations, bkg estimates, luminosity (~2%)

tt differential





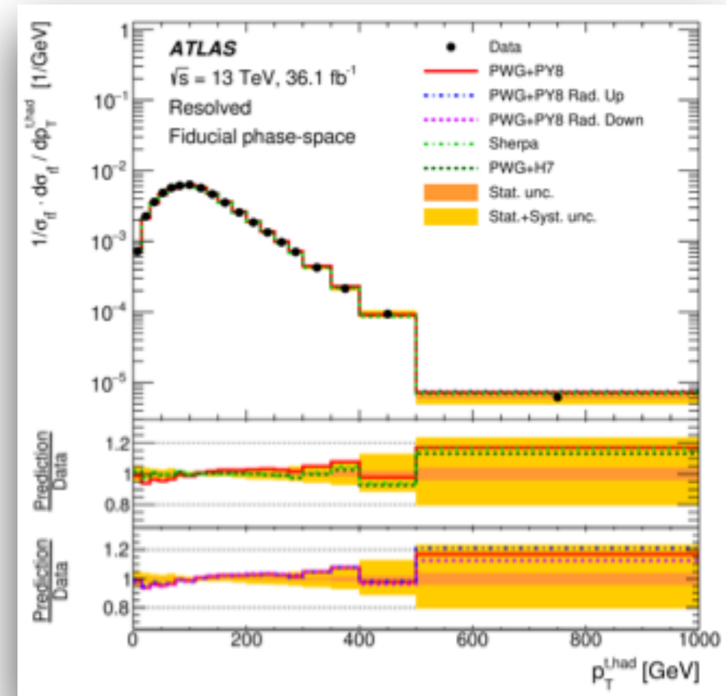
l+jets channel

EPJC 79 (2019) 1028

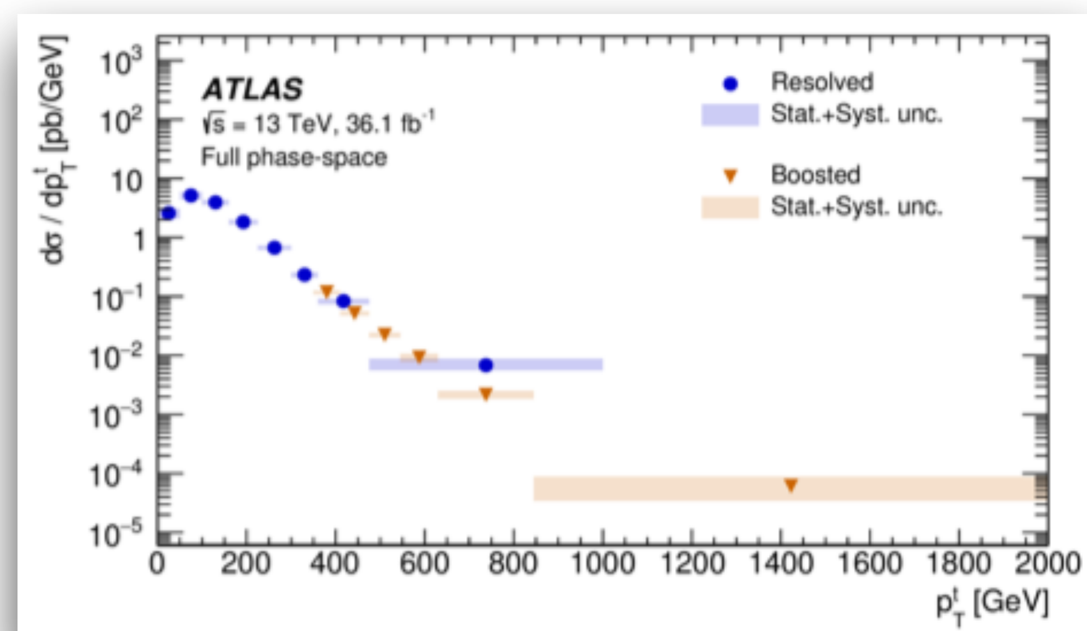
2015+2016 data
@13 TeV: 36 fb^{-1}

- Resolved and boosted analysis

Discrepancies between data and MC in top pt distribution: Powheg+Pythia8 best description



Good overlap between resolved and boosted regime



Full hadronic channel

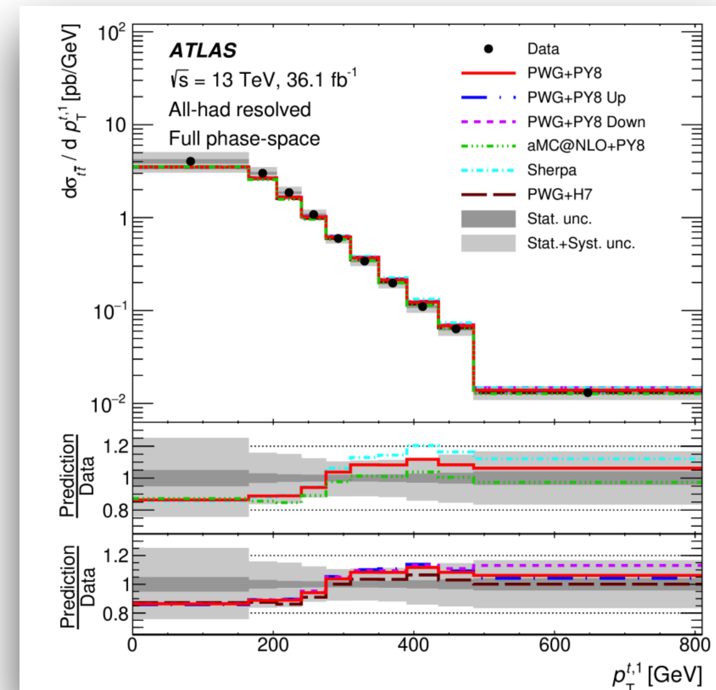
NEW

arXiv:2006.09274 submitted to JHEP

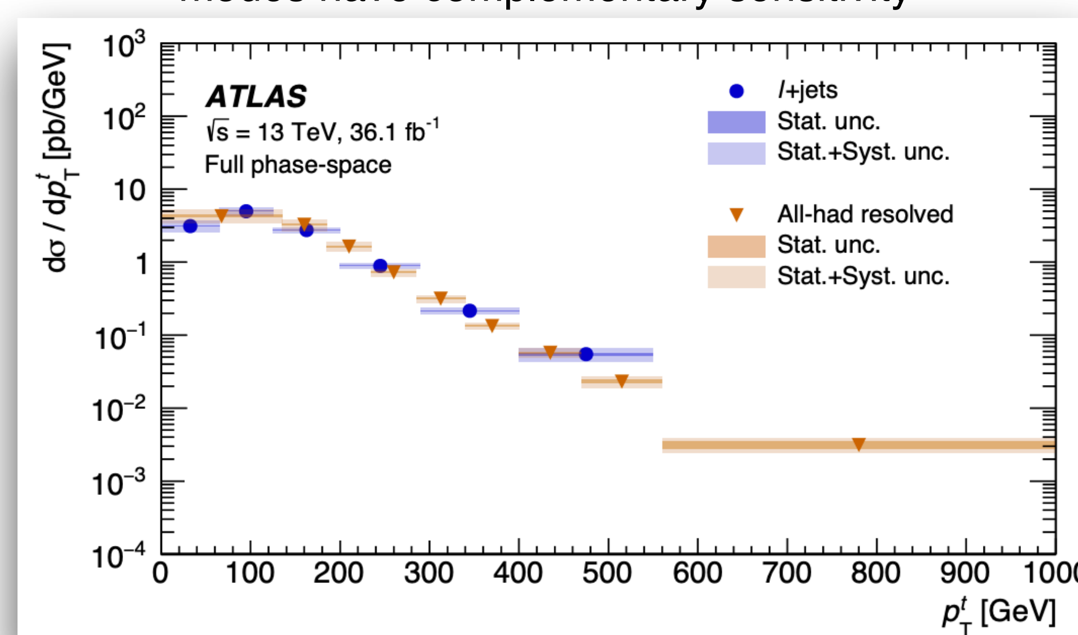
2015+2016 data
@13 TeV: 36.1 fb^{-1}

- Resolved analysis

Leading top pt and pt(tt) distributions incompatible with several theory predictions



Resolved l+jets and hadronic decay modes have complementary sensitivity



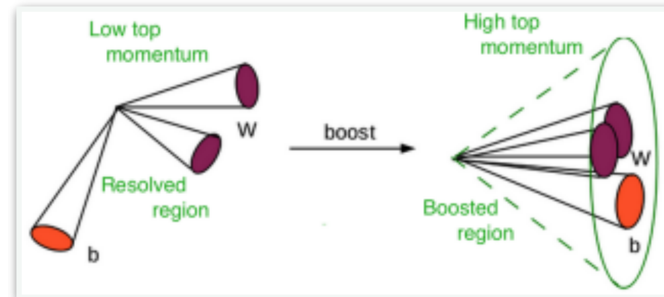
tt differential - high pT

CMS-PAS-TOP-18-013

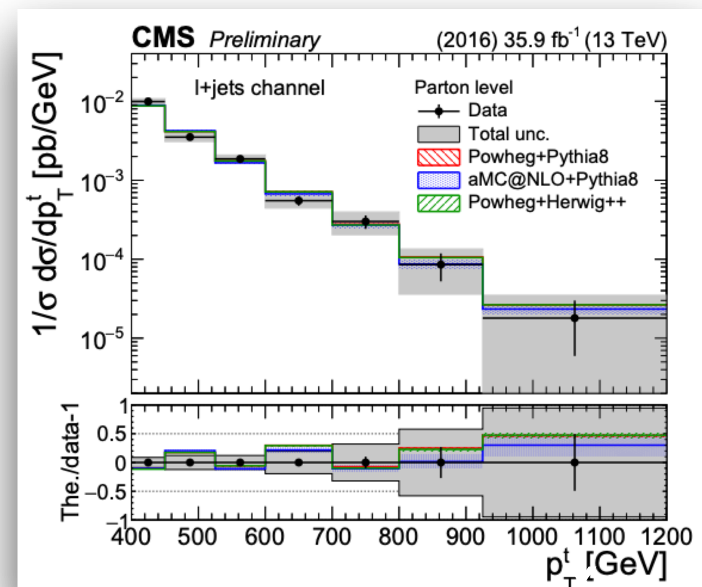
NEW

2016 data
@13 TeV: 35.9 fb^{-1}

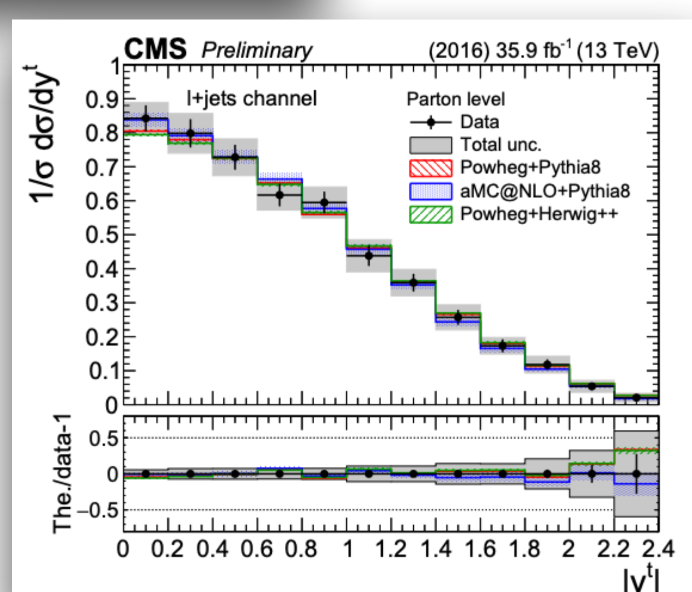
- Absolute and normalised differential cross section at parton and particle levels
  - distributions overall compatible with theory
  - all measurements consistent with SM expectations



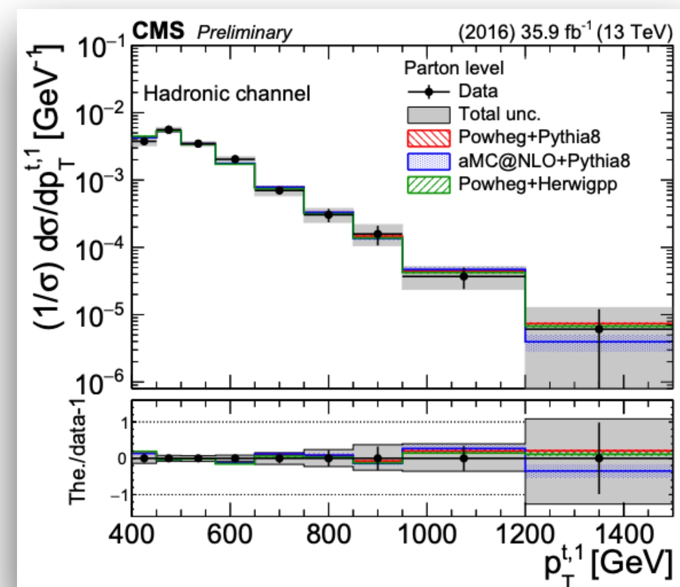
l+jets channel



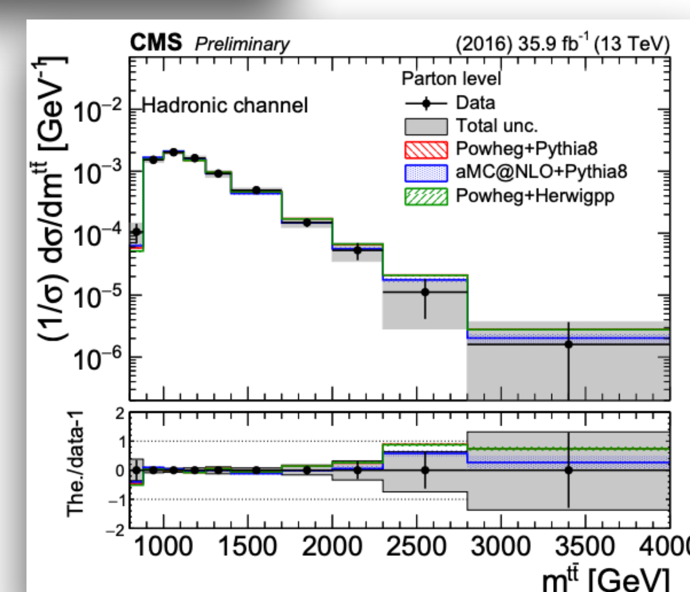
models overpredict absolute cross sections by 20%



Full hadronic channel

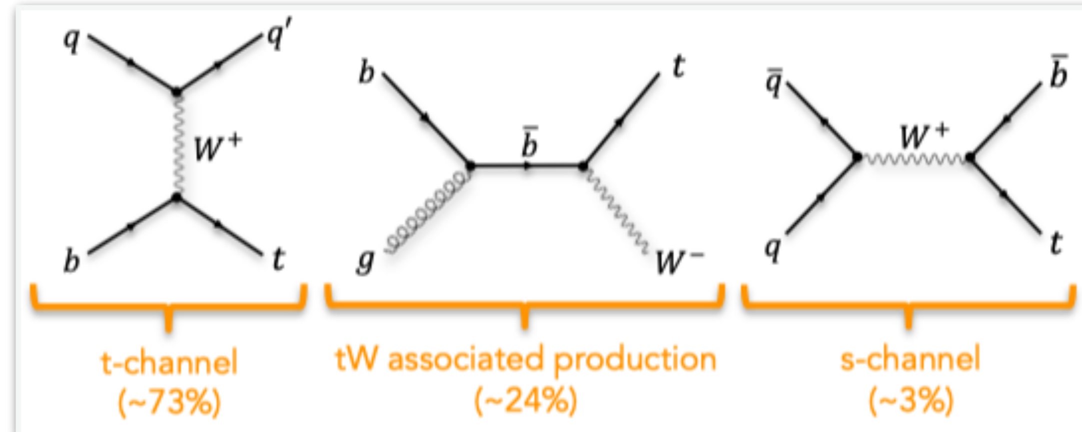


models overpredict absolute cross sections by 35%



Single top quark production

- Many measurements performed by the LHC collaborations at $\sqrt{s}$=7,8 and 13 TeV
  - as for tt, predictions impressively in agreement with measurements
- 3 main investigation channels
- Used to measure V_{tb}, charge ratio, spin asymmetry..



PLB 800 (2020) 135042

2016 data
@13 TeV: 35.9 fb^{-1}

- **t-channel inclusive** in l+jets
- Charge ratio

$$R_{t-ch} = 1.68 \pm 0.02(\text{stat.}) \pm 0.05(\text{syst.})$$

- improvement of $R_{t\text{-}ch}$ precision (3.0%) wrt 2015 analysis (12.9%)

- $|V_{tb}|$

$$\sigma^{\text{theo}}_{\text{t-ch}} = 217^{+7}_{-5}\,(\text{scale}) \pm 6\,(\text{PDF} + \alpha_S)\ \text{pb (NLO, HATHOR v2.1)}$$

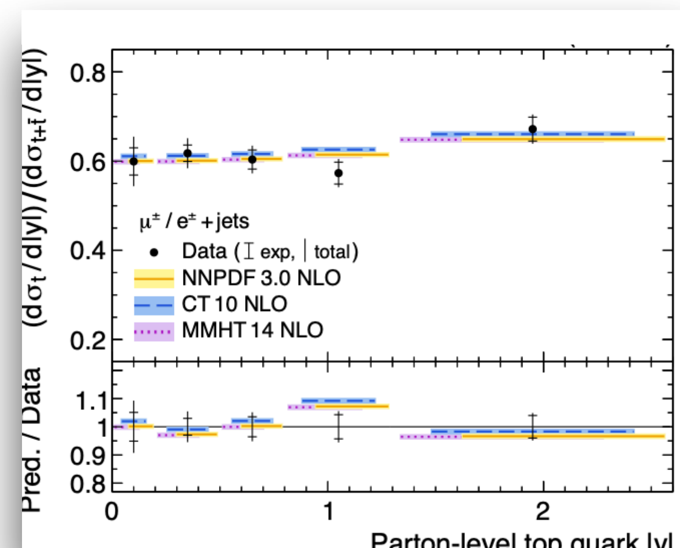
$$\sigma_{meas} = 207 \pm 2(\text{stat.}) \pm 31(\text{syst.})\text{pb}$$

$$|f_{LV}V_{tb}| = p\sigma_{meas}/\sigma_{theo} = 0.98 \pm 0.07(\text{exp.}) \pm 0.02(\text{theo.})$$

Eur. Phys. J. C 80, 370 (2020)

2016 data
@13 TeV: 35.9 fb^{-1}

- **t-channel differential** in l+jets
- Charge ratio
  - shapes overall compatible with theory



- Spin asymmetry:
  - estimated from differential distribution of polarisation angle at parton level
  - in agreement with SM (POWHEG@NLO) predictions: 0.436

	A_μ	A_e	$A_{\mu+e}$
Central values	0.403	0.446	0.440

ST Run1 combination

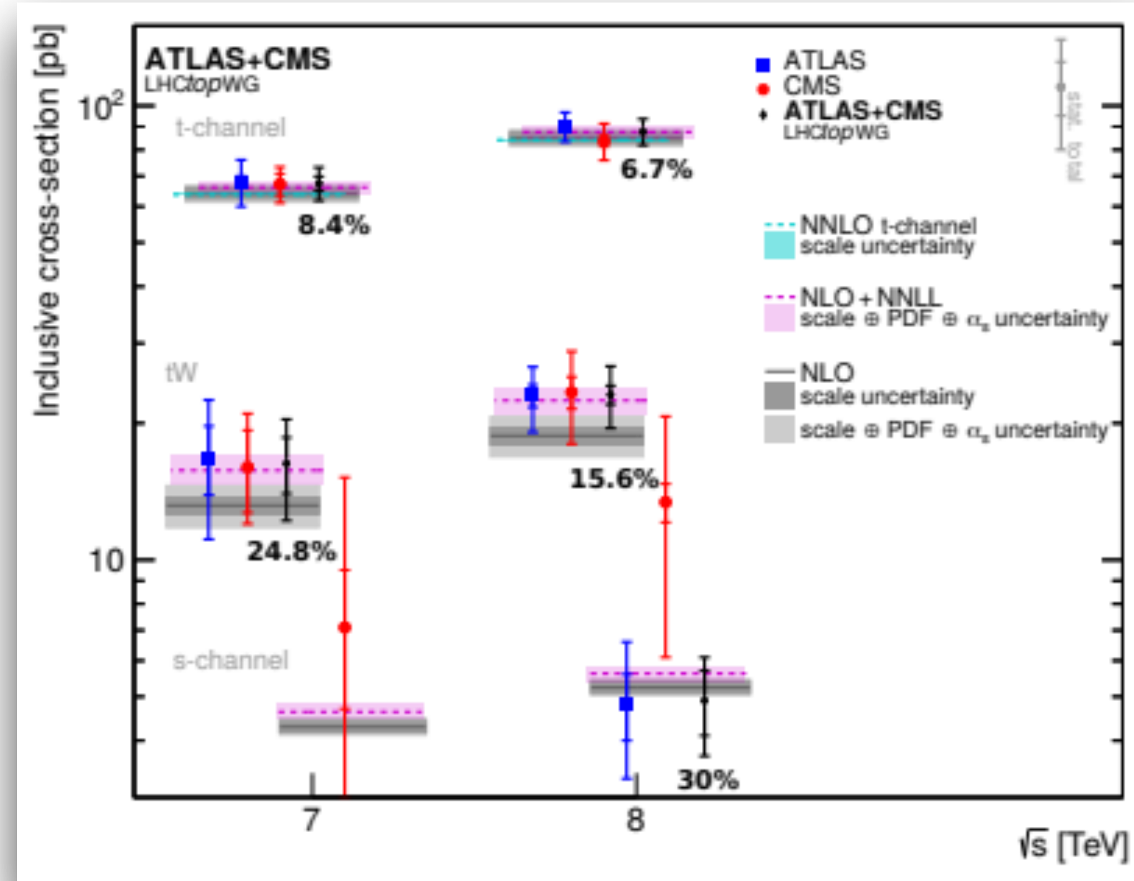
JHEP 05 (2019) 088

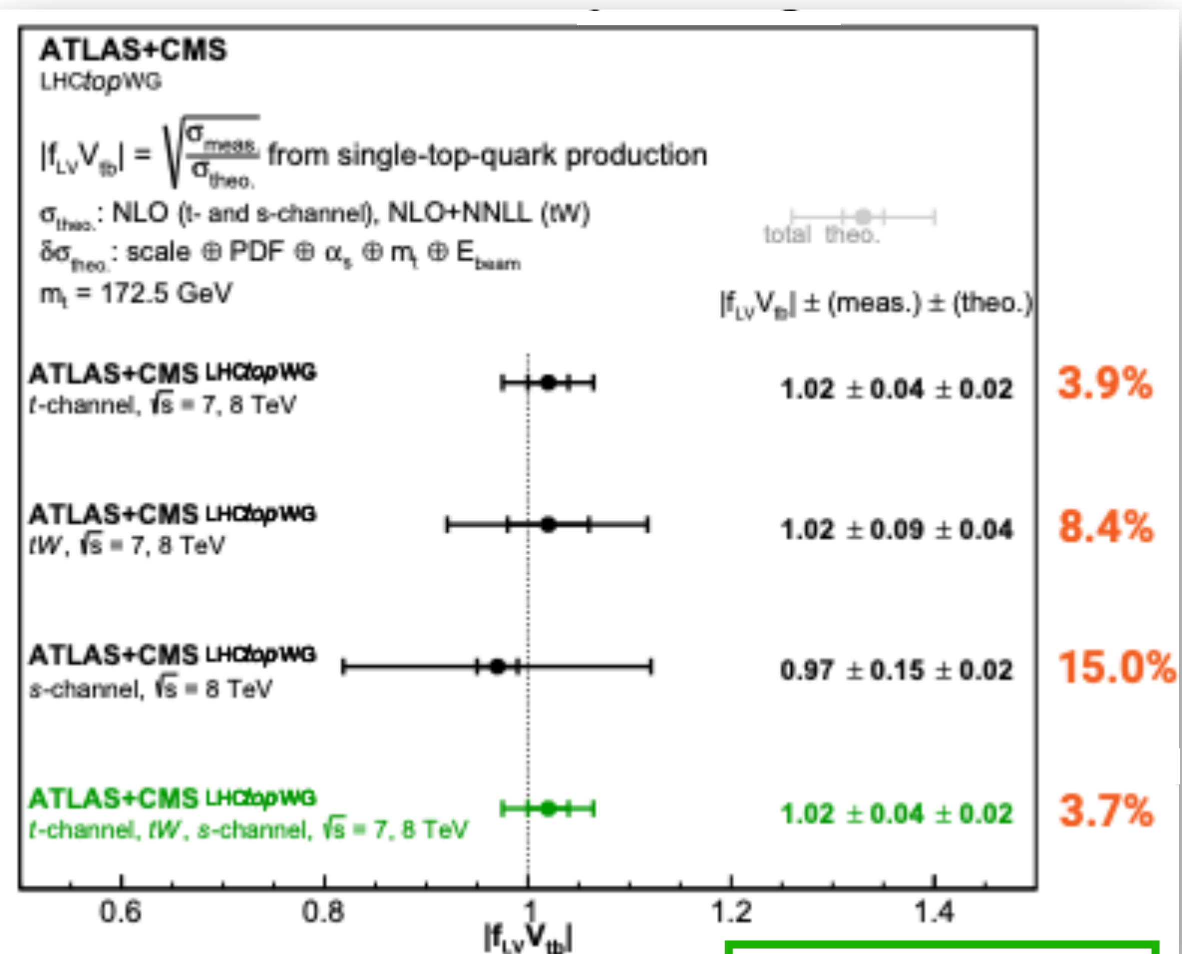
Run1 data @8 TeV:
20.3 fb^{-1} (ATLAS)
12.2 fb^{-1} (CMS)

Run1 data @7 TeV:
5.1 fb^{-1} (ATLAS)
1.17 fb^{-1} (CMS)

- **ATLAS+CMS combination** @7/8 TeV within *LHCtopWG*:
  - 10 inclusive cross section measurements (different production and center-of-mass energy)

Dominant syst. unc.:
theory modeling, detector modeling, jets reconstruction, data statistics for s-channel





Comparison with Tevatron: $1.02^{+0.06}_{-0.05}$ (5.4%)

- $$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{meas}}{\sigma_{theo}}}$$ extraction
  - determined for each production mode and full combination

Dominant syst. unc.:
theory modeling (4.5%), theoretical cross section (4.3%), jets reconstruction (2.4%)

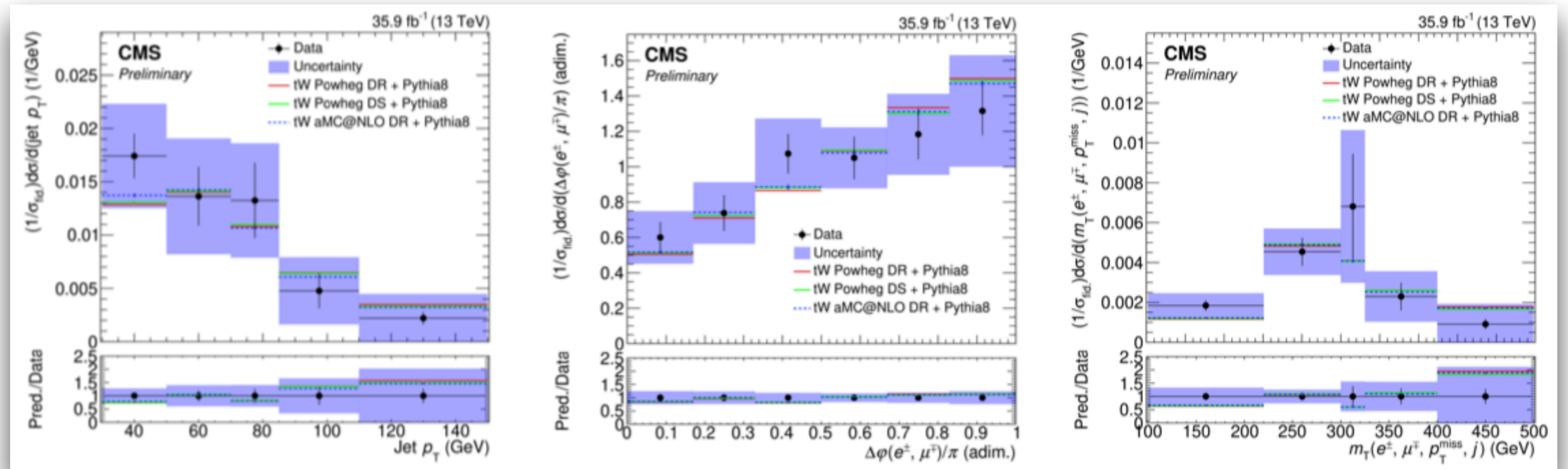
ST tW channel - differential

CMS-PAS-TOP-19-003

NEW

2016 data
@13 TeV: 35.9 fb -1

- **Dilepton events** ($e\mu$)
- Signal extraction performed by subtracting bkg, estimated through MC simulations
- Absolute and normalised results at particle level
    - fair agreement within the uncertainties with POWHEG and MADGRAPH5 aMC@NLO



Dominant syst. unc.:
jet reconstruction and theoretical modeling, driven by overwhelming tt background

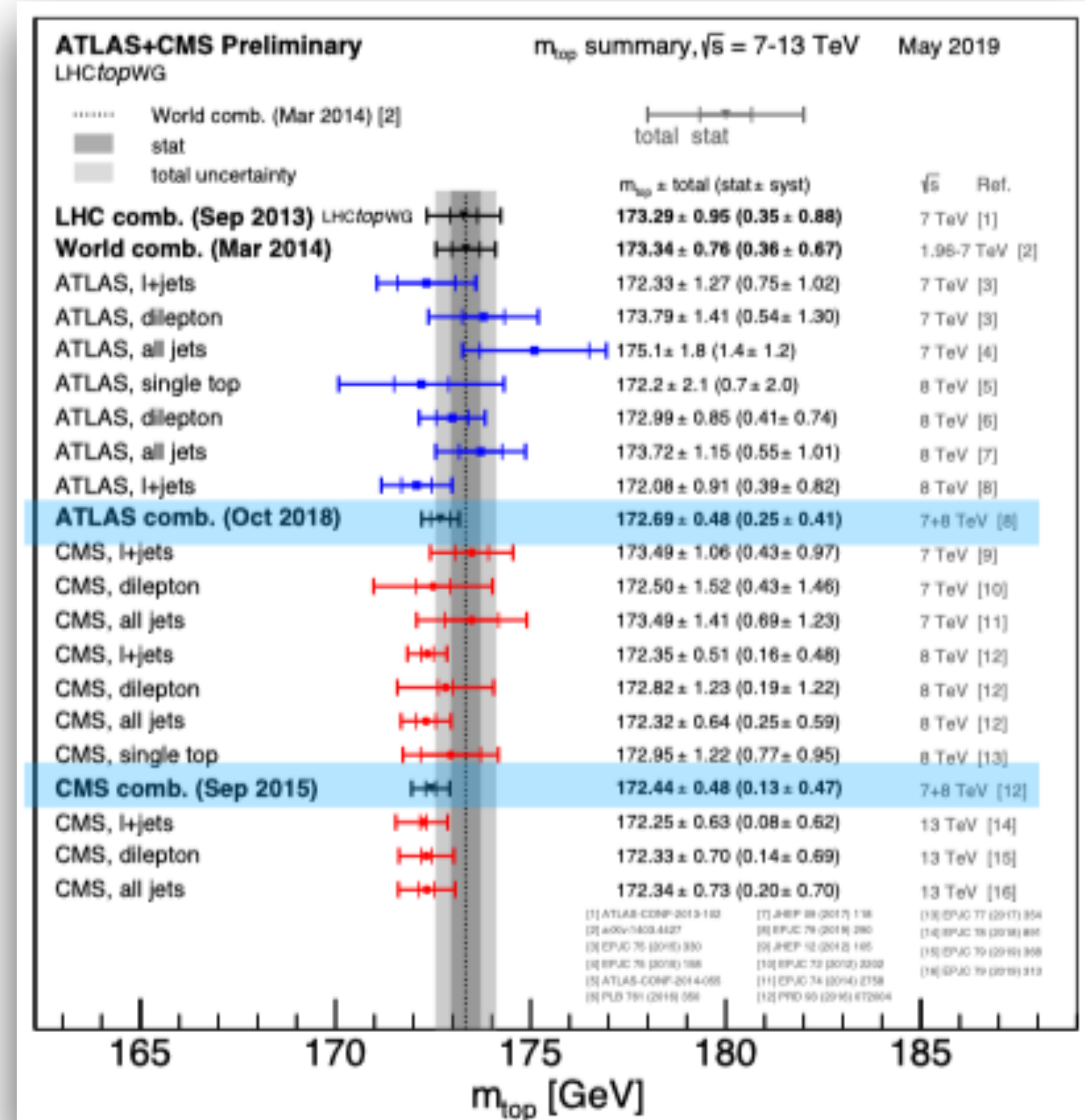
Similar result from ATLAS
EPJ C 78 (2018) 186

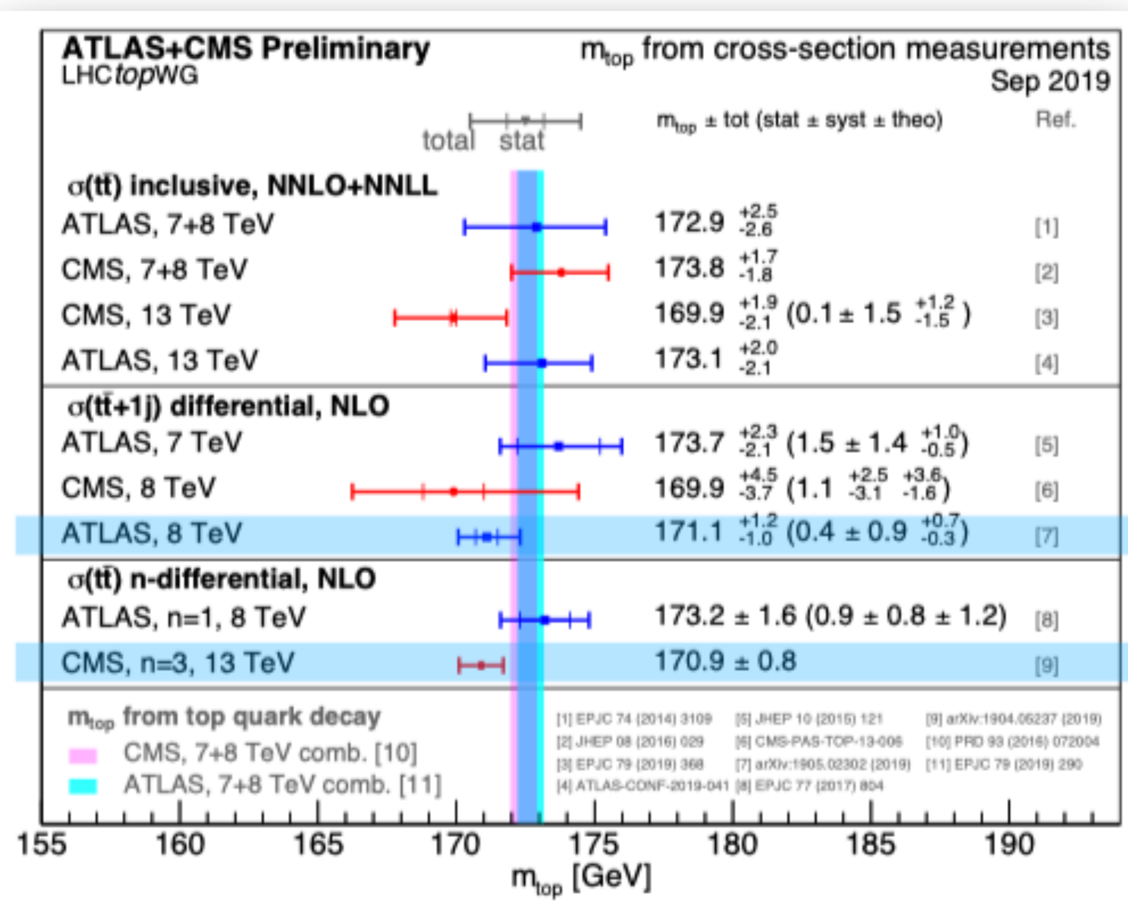
Methods to measure top mass

Direct measurement:

- extraction from kinematic reconstruction of invariant mass of top quark decay products
- data compared to MC simulations with different input values of m_t
- relying on jets, parton showers (LO), non-perturbative effects
- combined measurements precision ~ 500 MeV → 0.28% (ATLAS & CMS)

Dominant syst. unc.:
jet energy scale calibration, b-tagging and modeling

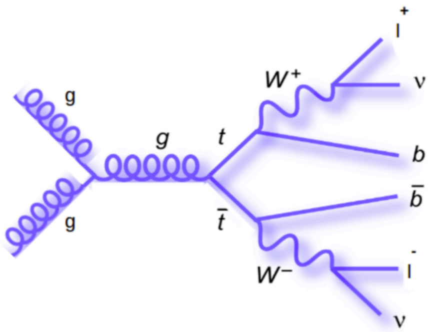




Indirect measurement:

- from inclusive/differential cross-sections in a well defined renormalization scheme, e.g. m_t^{pole}
- dominated by tt threshold production

Dominant syst. unc.:
PDFs and higher order corrections

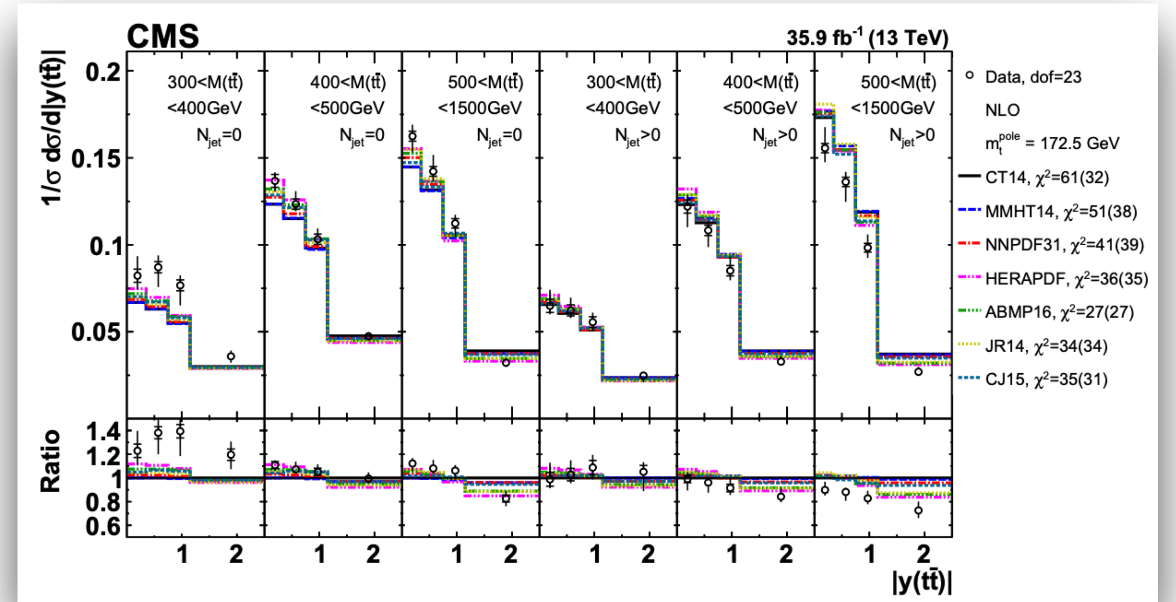


Mass from multidifferential

[arXiv:1904.05237 submitted to Eur. Phys. J.]

2016 data
@13 TeV: 35.9 fb^{-1}

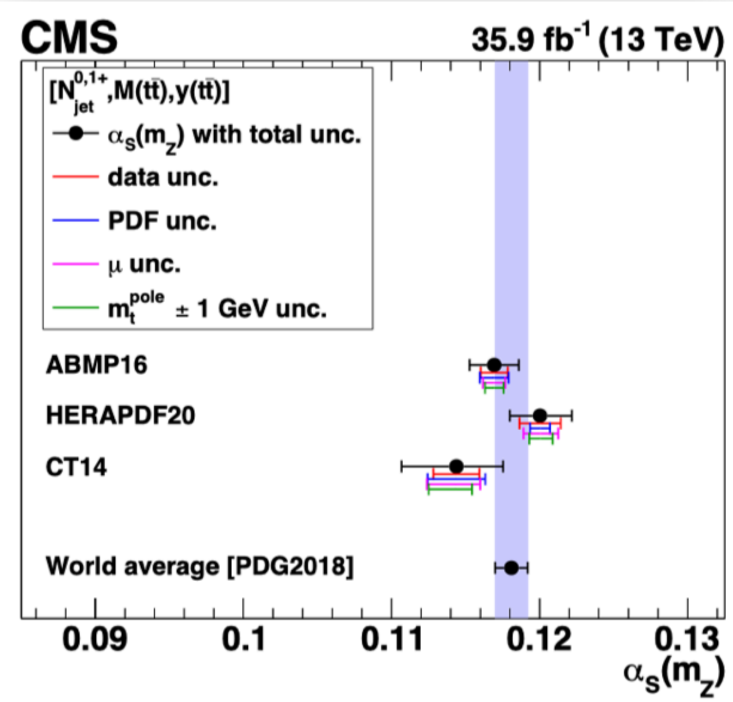
- **Normalized 3D cross sections** vs $m_{t\bar{t}}$, $y_{t\bar{t}}$, N(extra jets) in dilepton channel
- Extraction of α_S and m_t^{pole}:
  - cross sections compared to NLO predictions with different PDFs
  - simultaneous fit of PDF+α_S+m_t^{pole} at NLO + HERA DIS data

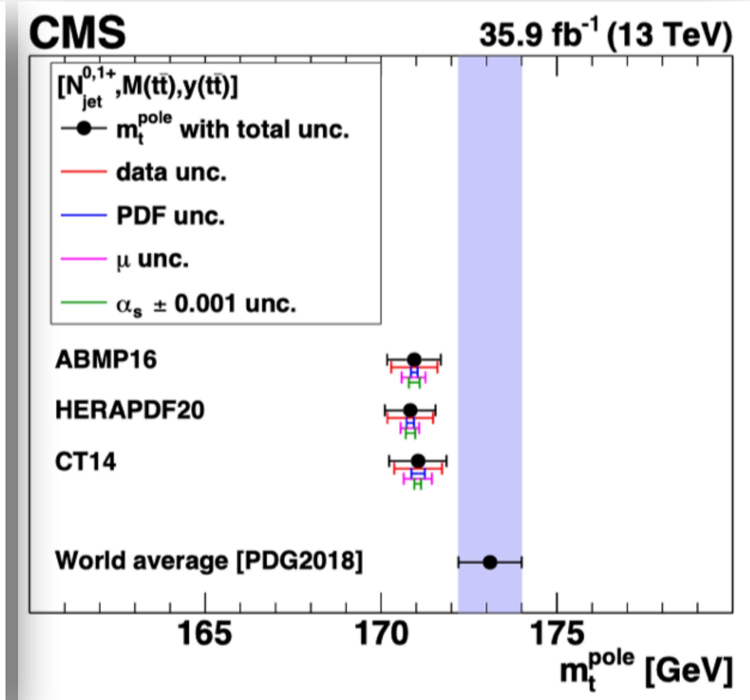


$$\alpha_S(m_Z) = 0.1135^{+0.0021}_{-0.0017}$$
$$= 0.1135 \pm 0.0016\,(\text{fit})^{+0.0002}_{-0.0004}\,(\text{model})^{+0.0008}_{-0.0001}\,(\text{param})^{+0.0011}_{-0.0005}\,(\text{scale})$$
$$m_t^{pole} = 170.5 \pm 0.8\,\text{GeV}$$
$$= 170.5 \pm 0.7\,(\text{fit}) \pm 0.1\,(\text{model})^{+0.0}_{-0.1}(\text{param}) \pm 0.3\,(\text{scale})\,\text{GeV}$$

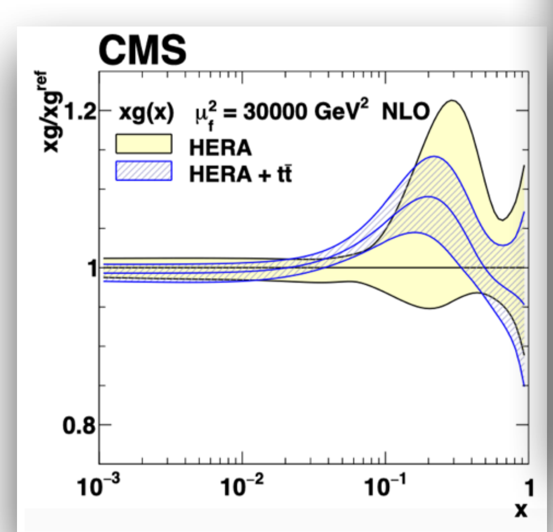
Most precise result on m_t^{pole} from single analysis!

$$\frac{m_t}{\Delta m_t} < 0.5\,\%$$





- Constraint on PDFs:
  - significant impact on gluon PDF at large values of x



Dominant syst. unc.:
JES and signal modeling

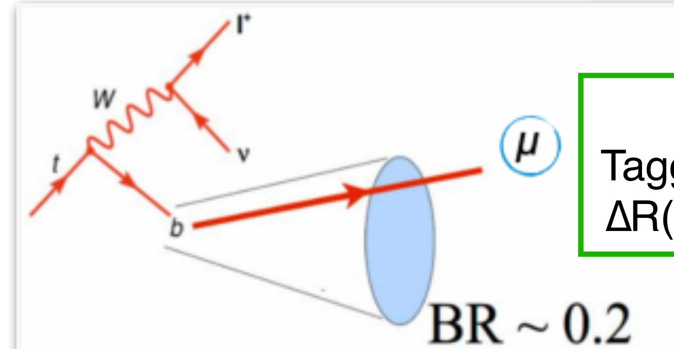
Mass from soft muon tags

ATLAS-CONF-2019-046

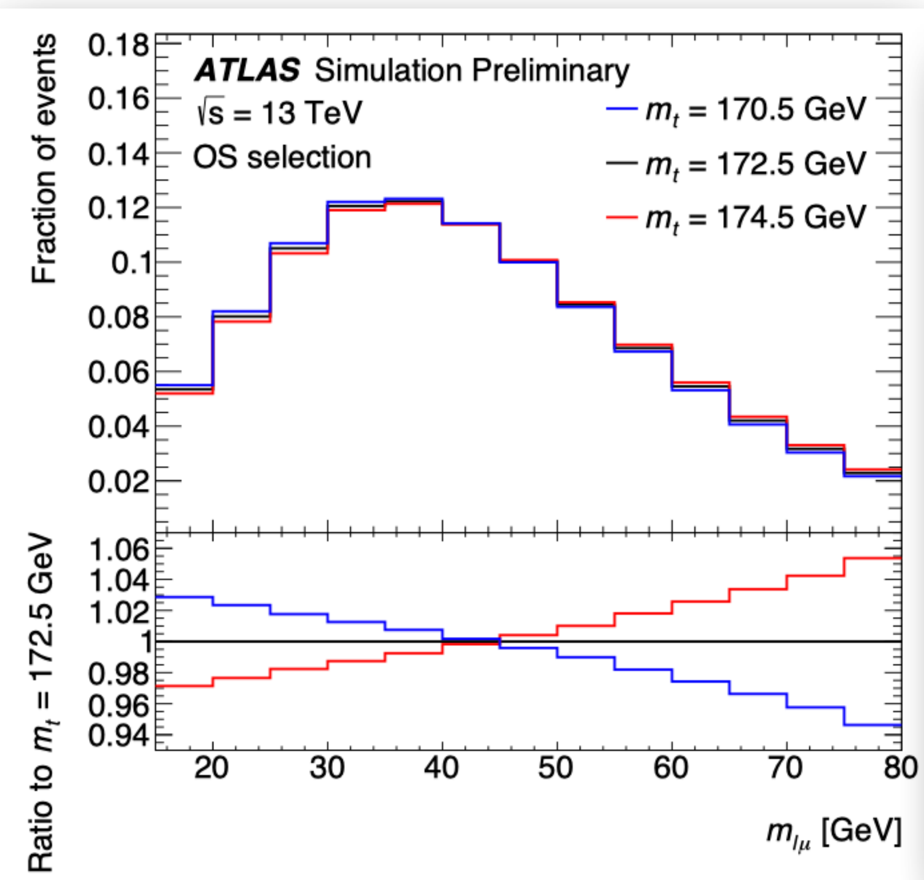
NEW

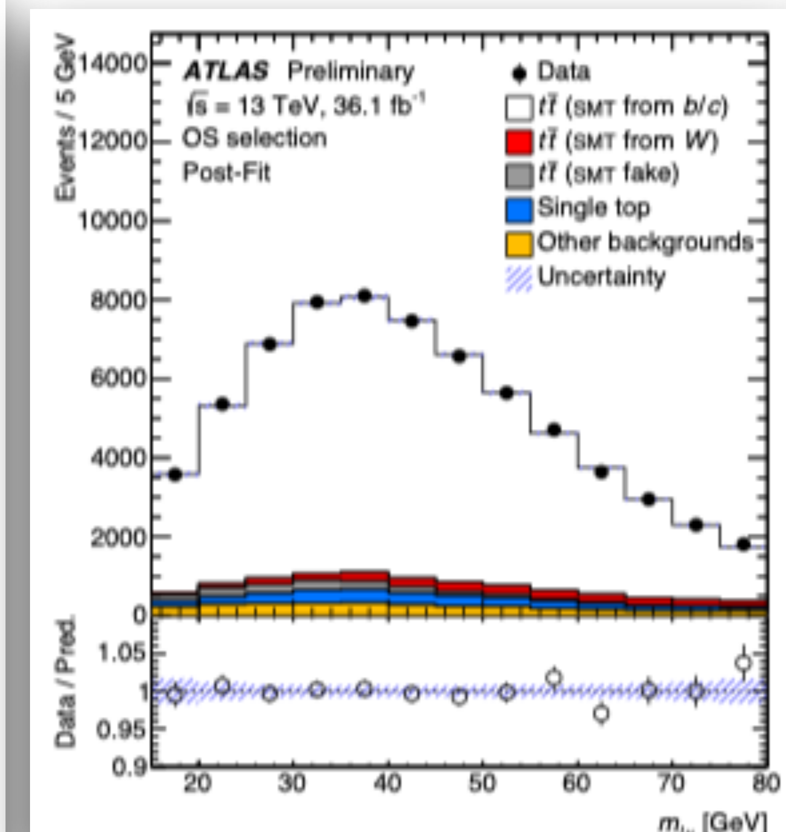
2016 data
@13 TeV: 36.1 fb^{-1}

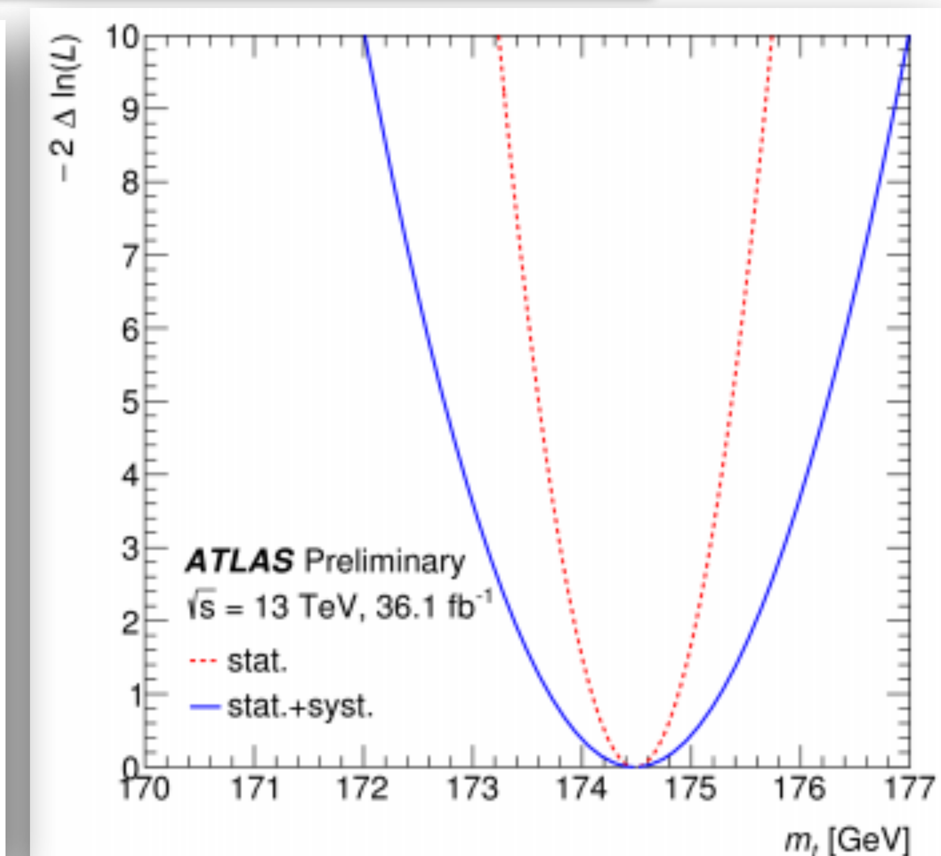
- **l+jets channel**
  - ≥ 2 b-tagged jets: 1 with displaced vertex, 1 with soft muon tag
- Simultaneous template fit to $m_{l\mu}$ distributions from same-sign (SS) and opposite-sign (OS) samples
  - purely leptonic, less sensitive to jets uncertainty



Soft Muon Tagging for b-jets: ΔR(muon,jet)<0.4







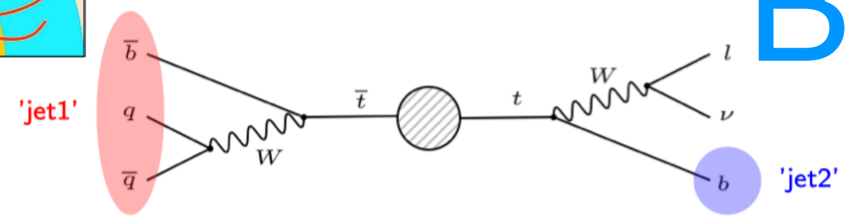
$$m_t = 174.48 \pm 0.40(stat) \pm 0.67(syst)\,\text{GeV} = 174.48 \pm 0.78\,\text{GeV}$$

~0.45%

Dominant syst. unc.:
signal modeling (b fragmentation and decay, tt production)

Boosted mass

Phys. Rev. Lett. 124, 202001 (2020)



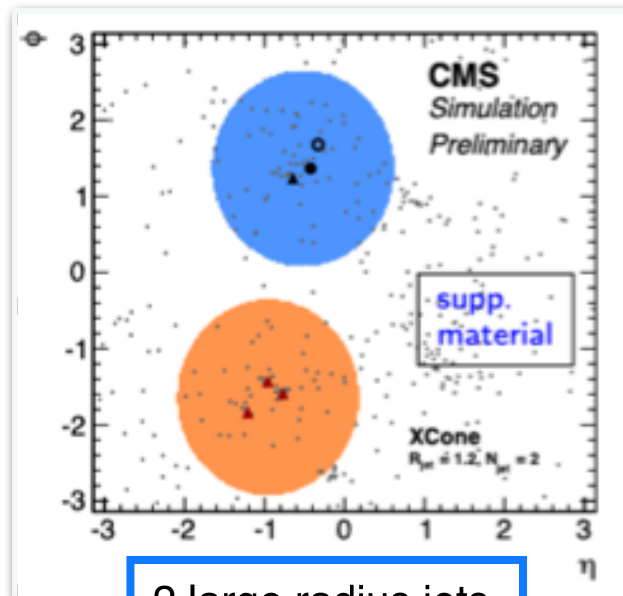
2016 data
@13 TeV: 35.9 fb^{-1}

- Measurement of top quark mass in hadronic decays of boosted top quarks in **lepton+jets** channel
- Novel jet reconstruction technique, XCone:
  - excellent m_{jet} resolution
- m_t extracted from normalized $t\bar{t}$ cross section as function of m_{jet} unfolded at particle level:

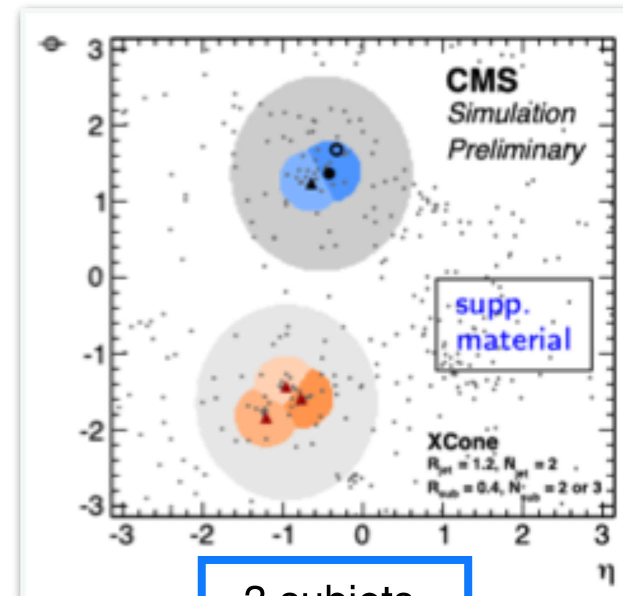
$$m_t = 172.6 \pm 2.5\,\text{GeV}$$
$$= 172.6 \pm 0.4\,(\text{stat}) \pm 1.6\,(\text{exp}) \pm 1.5\,(\text{model}) \pm 1.0\,(\text{theo})\ \text{GeV}$$

$$\frac{m_t}{\Delta m_t} \sim 0.7\,\%$$

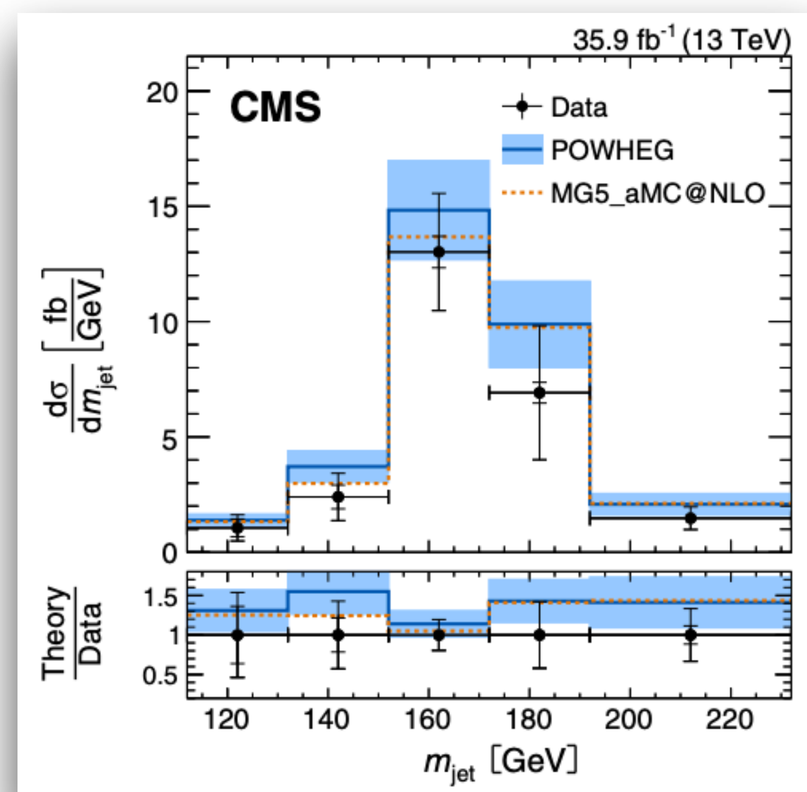
Dominant syst. unc.:
JES, JER, XCone jet energy correction, signal modeling FSR, color reconnection, UE tune, top mass value)

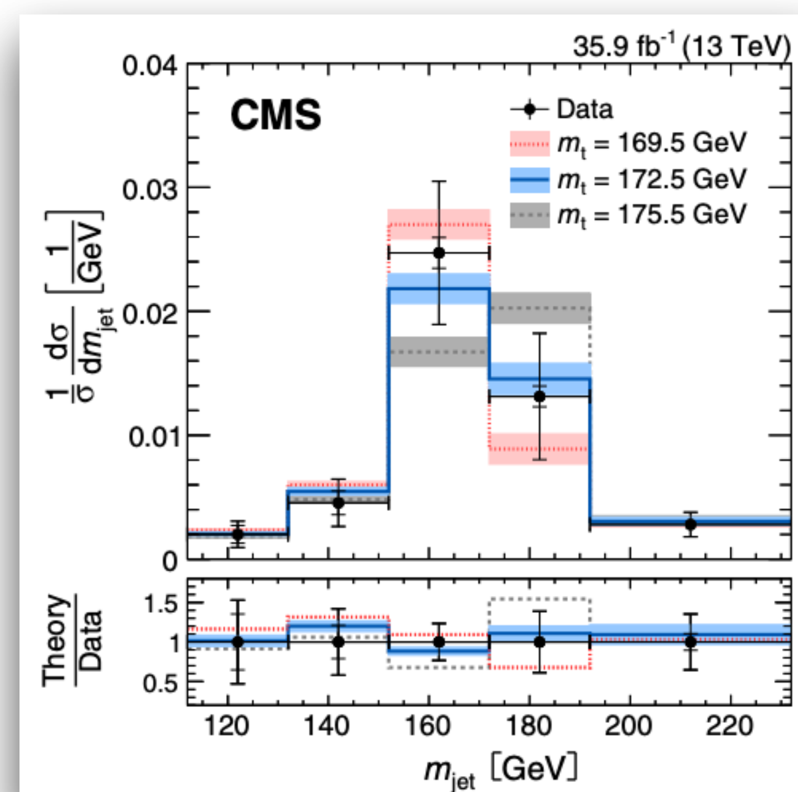


2 large radius jets, $p_T > 400$ GeV



3 subjets, $p_T > 30$ GeV





Running of top mass

First experimental investigation!

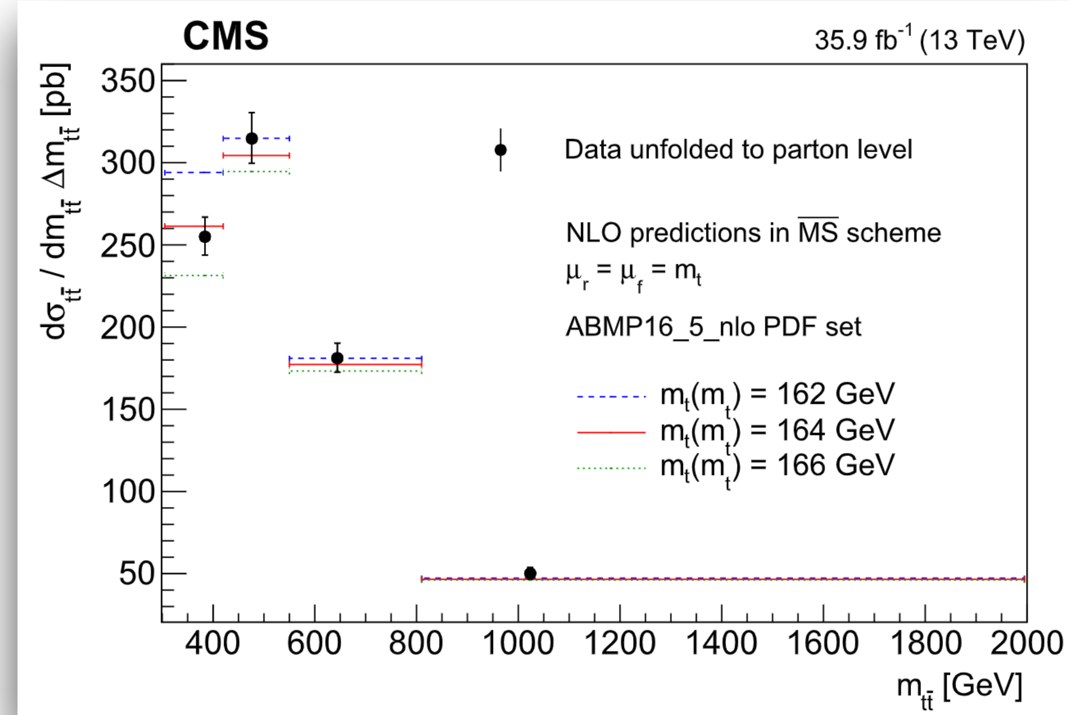
Phys. Lett. B 803 (2020) 135263

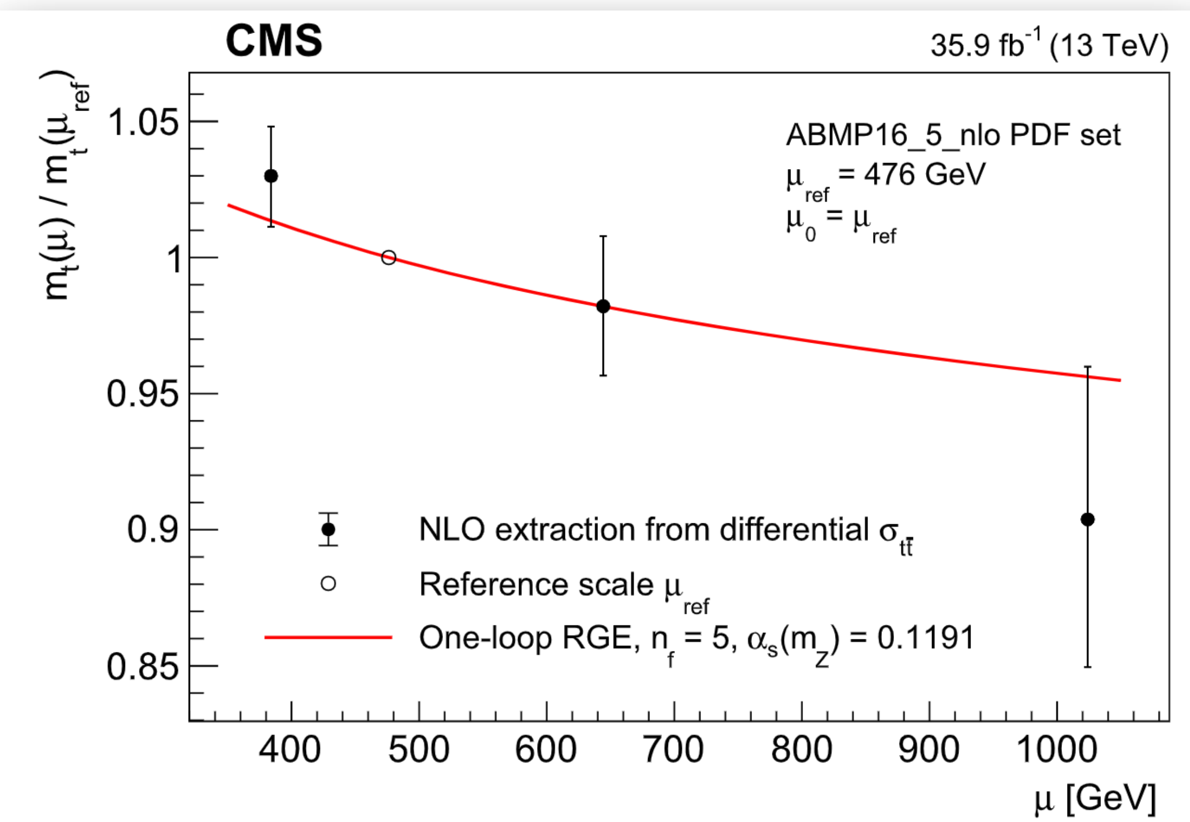
2016 data
@13 TeV: 35.9 fb^{-1}

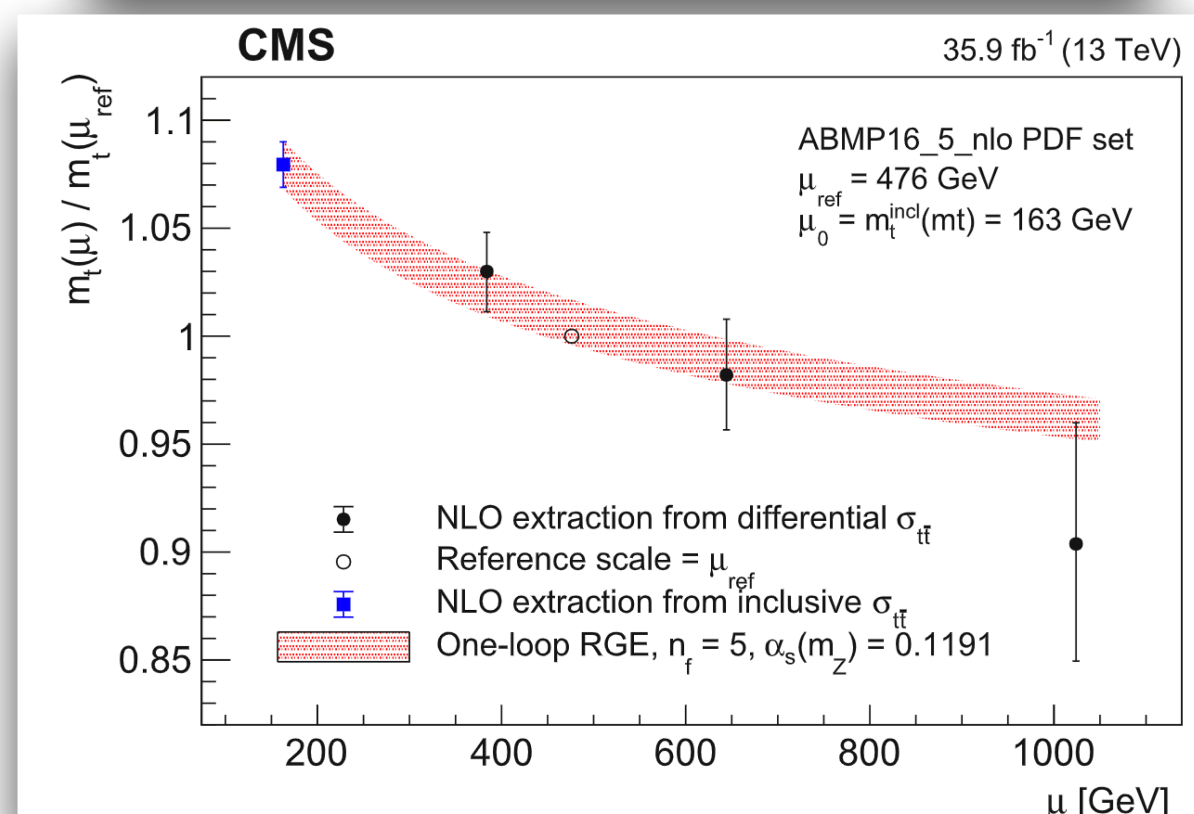
- Extracted by comparing NLO predictions to differential cross section measured vs $m_{t\bar{t}}$ in ***eμ* channel**
- Simultaneous measurement of $d\sigma_{t\bar{t}}/dm_{t\bar{t}}$ and m_t^{MC} by means of maximum-likelihood fit to multi-differential distributions
- Running of m_t in agreement with prediction of corresponding RGE within 1.1 σ
- No-running scenario excluded at above 95% C.L.

Based on EPJC 79 (2019) 368's strategy

Dominant syst. unc.: luminosity, lepton id, JES/JER and signal modeling







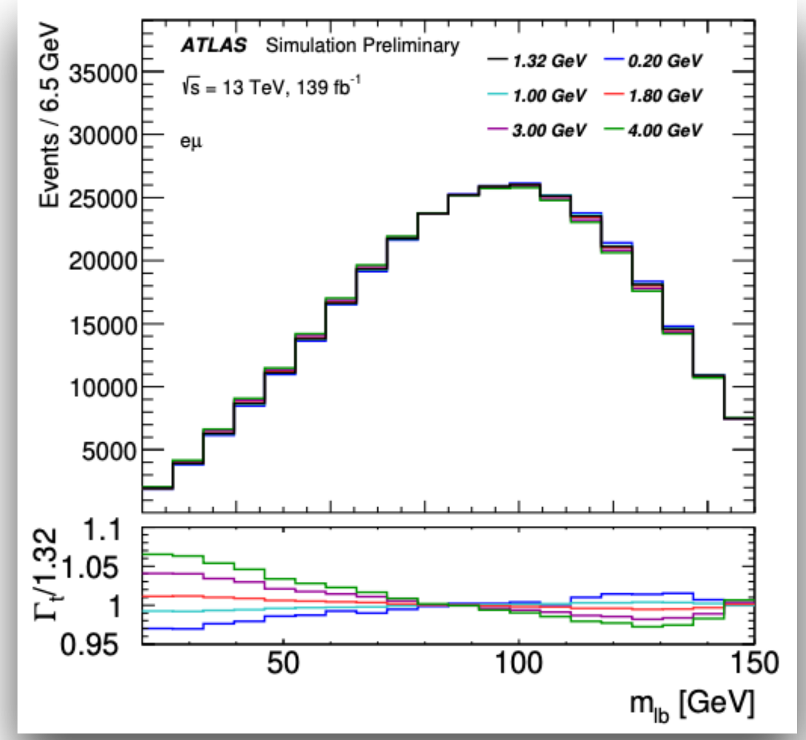
Top decay width

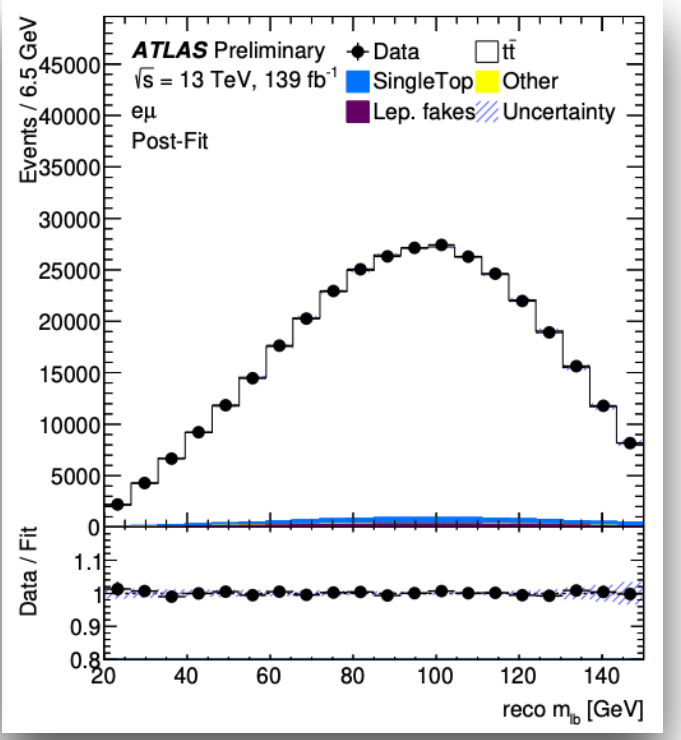
ATLAS-CONF-2019-038

NEW

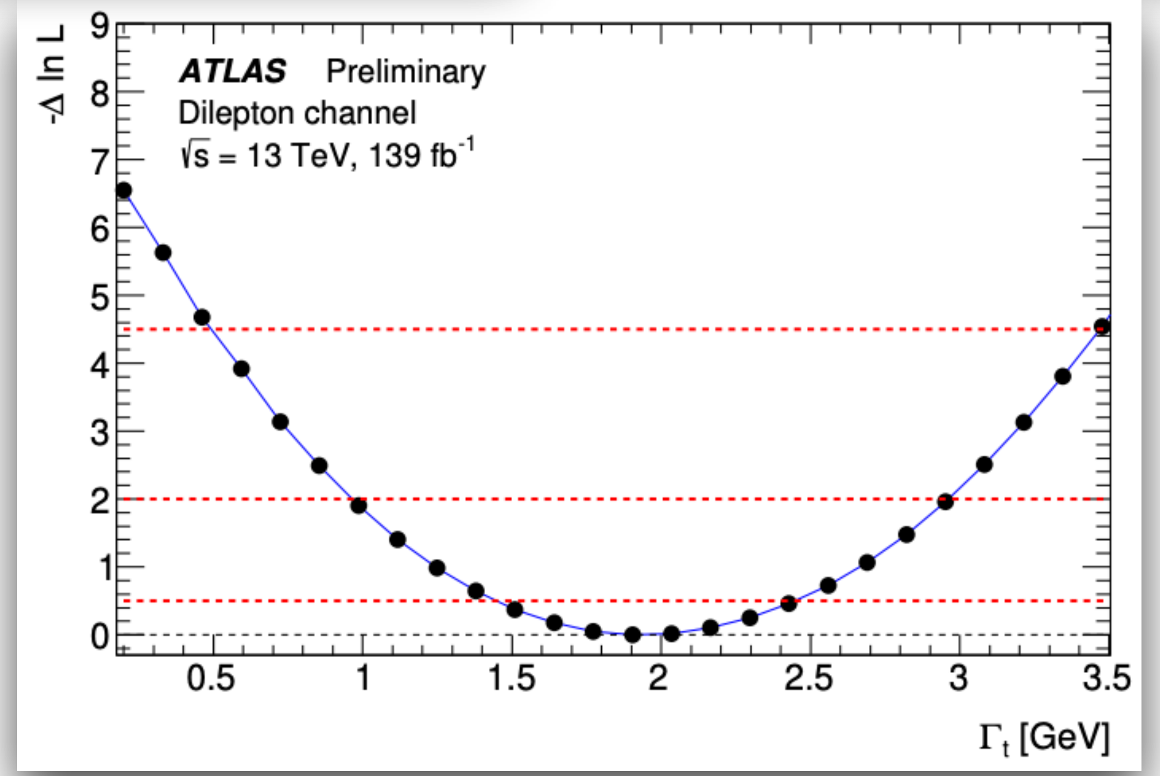
Full Run2 data
@13 TeV: 139 fb^{-1}

- Direct measurement in **dilepton channel**
- Profile-likelihood template fit to m(l,b) distribution
  - templates with different underlying top-quark decay widths
  - simultaneous fit in 3 channels
- Due to its large mass the decay width is expected to be very large:
  - in agreement with NNLO prediction



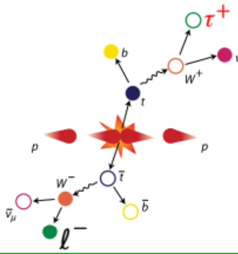


	m_t = 172 GeV		m_t = 172.5 GeV		m_t = 173 GeV	
	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]
Measured	2.01	+0.53 −0.50	1.94	+0.52 −0.49	1.90	+0.52 −0.48
Theory	1.306	< 1%	1.322	< 1%	1.333	< 1%



Dominant syst. unc.:
jet calibration, bkg model, MC statistics, b-tagging

Lepton universality



NEW

[arXiv2007.14040 - submitted to Nature Physics]

Full Run2 data
@13 TeV: 139 fb^{-1}

- $W \to \tau\nu_\tau \to \mu\nu_\mu\nu_\tau\nu_\tau$ process in **dilepton channel**
- BR of leptonic W decay used to measure universality of lepton couplings to the EW gauge boson

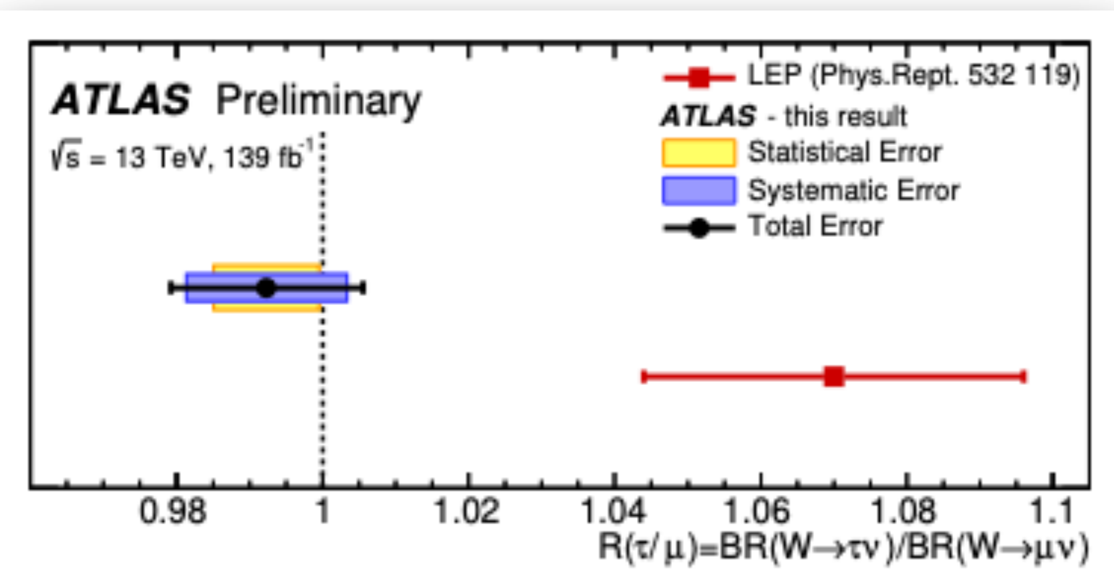
$$R(\tau/\mu) = BR(W \to \tau\nu_\tau)/BR(W \to \mu\nu_\mu)$$

- Extraction of $R(\tau/\mu)$ from profile likelihood fit in each $e\mu$ and $\mu\mu$ channels

$$R(\tau/\mu) = 0.992 \pm 0.013\ [\pm 0.007\ (\text{stat}) \pm 0.011\ (\text{syst})]$$

  - measurement in good agreement with SM
  - more precise than LEP measurement

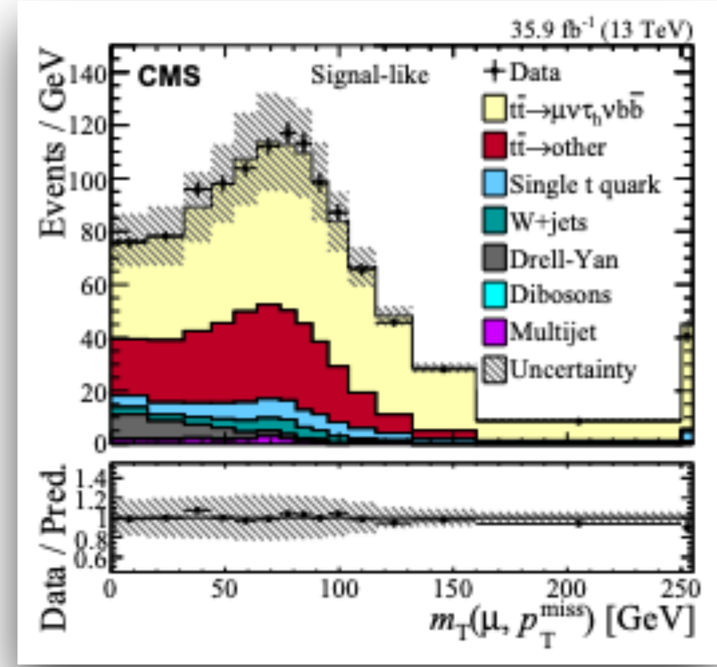
    $R(\tau/\mu)$ = 1.070 ± 0.026 @ LEP



[JHEP 02 (2020) 191]

2016 data
@13 TeV: 35.9 fb^{-1}

- ***τ+e/μ* channel**
- Cross section extraction from profile likelihood fit to transverse mass $m_T(l, p_T^{miss})$, separately for $e\tau$ and $\mu\tau$ final state



$$\sigma_{tt}(l\tau_h) = 781 \pm 7(stat) \pm 62(syst) \pm 20(lumi)\ pb$$

  - 8.3% precision
  - in agreement with NNLO+NNLL predictions

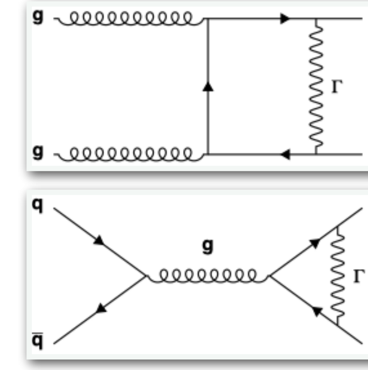
- Using tt dilepton result [EPJC 79 (2019) 368]

$$R(l\tau_h/ll) = 0.973 \pm 0.009(\text{stat.}) \pm 0.066(\text{syst.})$$

  - compatible to unity → lepton universality conserved

Dominant syst. unc.:
tau_had jet id. (4.5%), luminosity (2.5%), tt background norm. (2.3%) and pile-up (2.3%)

Top Yukawa coupling



$$Y_t = \frac{g_t}{g_t^{SM}}$$

- **Weak corrections** affect cross sections at $\alpha_S^2\alpha_w$ order → may lead to large distortions of $t\bar{t}$ differential distributions near the production threshold region
- Virtual Higgs exchange depends on the top-Higgs Yukawa coupling g_t

NEW

Phys. Rev. D 100 (2019) 072007

2016 data
@13 TeV: 35.8 fb^{-1}

- Full kinematic reconstruction in **lepton+jets** channel
- 2D likelihood fit in $(M_{t\bar{t}}, \Delta y_{t\bar{t}})$ to constrain Y_t

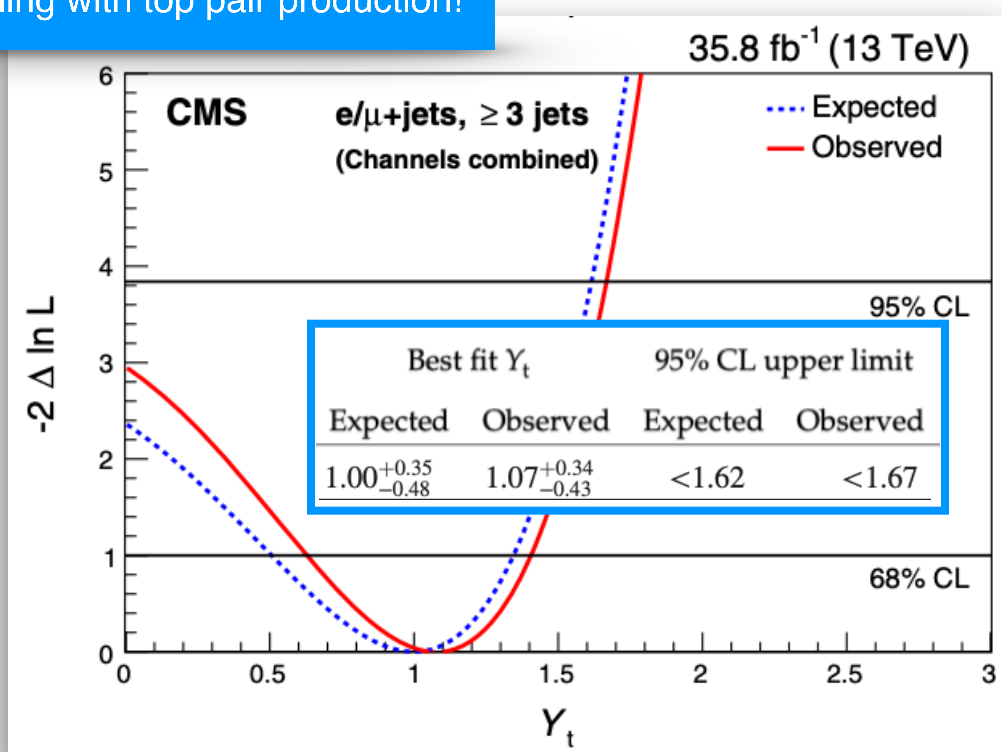
First analysis to measure Yukawa coupling with top pair production!

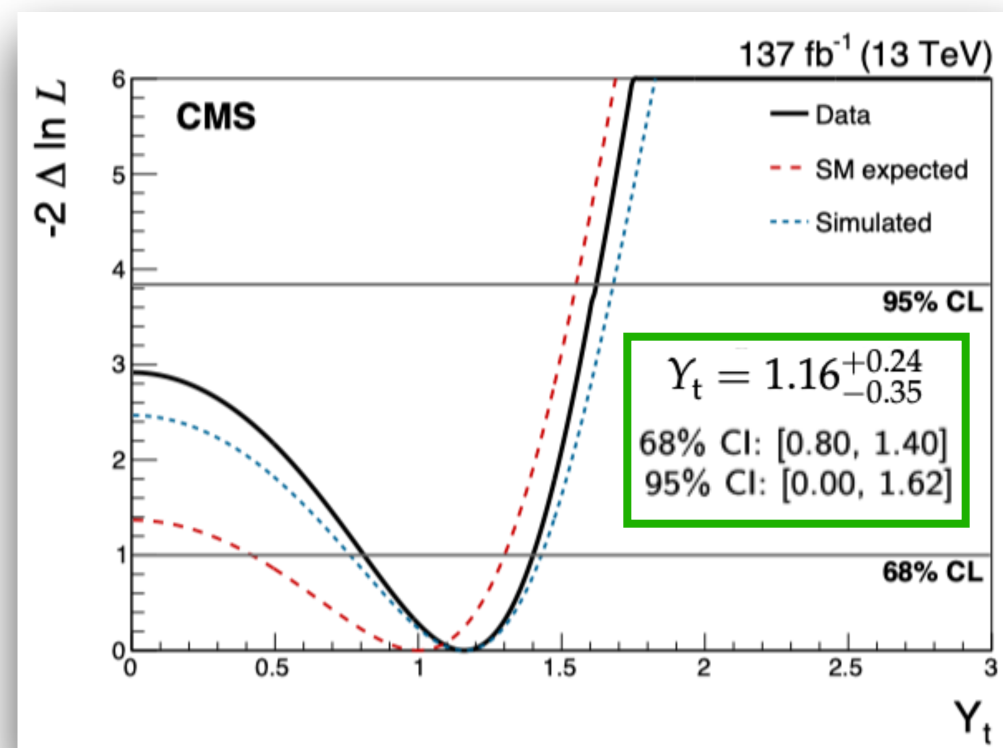
CMS-PAS-TOP-19-008

Full Run2 data
@13 TeV: 137 fb^{-1}

- Partial kinematic reconstruction in **dilepton** channel
- 2D likelihood fit in $(M_{b\ell}, \Delta y_{b\ell})$ to constrain Y_t

Upper limit extraction on top quark Yukawa coupling





Results in agreement between 2 channels

- More sensitive than 4t production: $Y_t < 1.7$ @ 95% C.L.
- Less sensitive than model-dependent Higgs combination: $Y_t = 0.98 \pm 0.14$

Top CKM elements

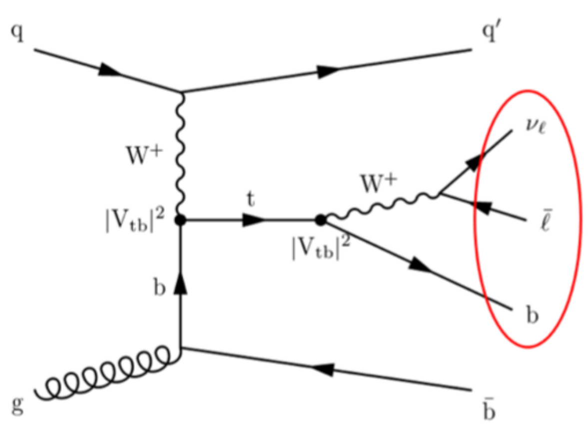
Phys. Lett. B 808 (2020) 135609

NEW

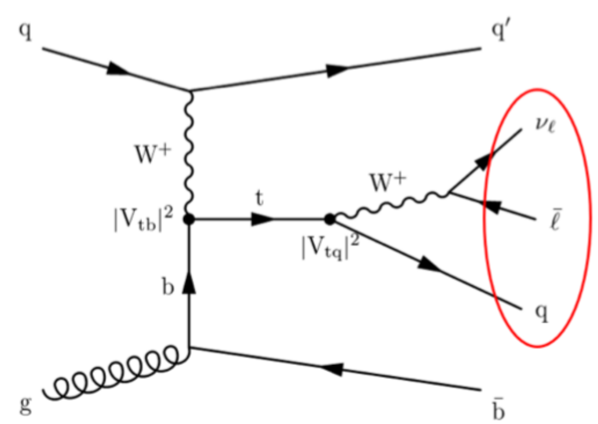
2016 data
@13 TeV: 35.9 fb^{-1}

- Processes directly sensitive to $|V_{tb}|$, $|V_{td}|$, and $|V_{ts}|$ are considered at both the production and decay vertices of the top quark:

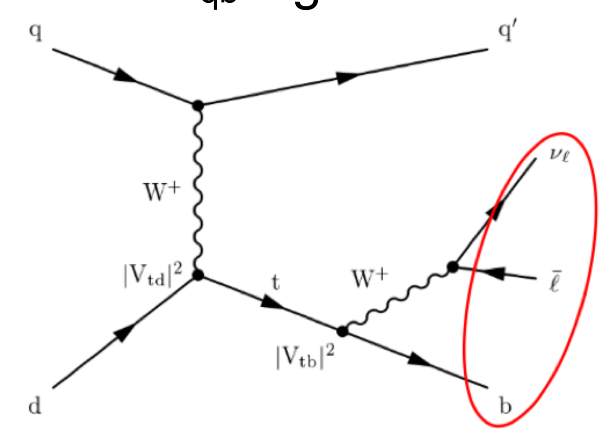
ST_{bb} signal



ST_{bq} signal



ST_{qb} signal



- BDT discriminant trained for each category to separate signal and background processes
- Multivariate discriminators used in a simultaneous fit to the 3 event categories to discriminate between ST_{bb}, ST_{bq}, and ST_{qb}

Category	Enriched in
2j1t	$ST_{b,b}$
3j1t	$ST_{b,q}$, $ST_{q,b}$
3j2t	$ST_{b,b}$

- CKM matrix elements extracted by signal strengths
  - **in SM** assuming CKM unitarity (@ 95% C.L.):
  - also **BSM scenarios** are probed

$$|V_{tb}| > 0.970$$
$$|V_{td}|^2 + |V_{ts}|^2 < 0.057$$

- All results are consistent with each other
- Best determination of these parameters w.r.t. latest measurements of single top quark in Run2

Dominant syst. unc.: modeling

First direct model-independent measurement in single top t-channel events

Asymmetries

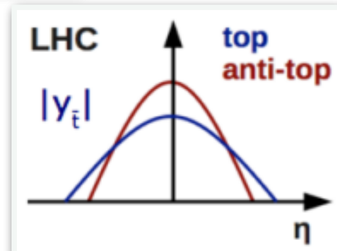
NEW

ATLAS-CONF-2019-026

Full Run2 data @13 TeV: 139 fb^{-1}

- **Charge asymmetry**
- Lepton+jets combining resolved and boosted topologies

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



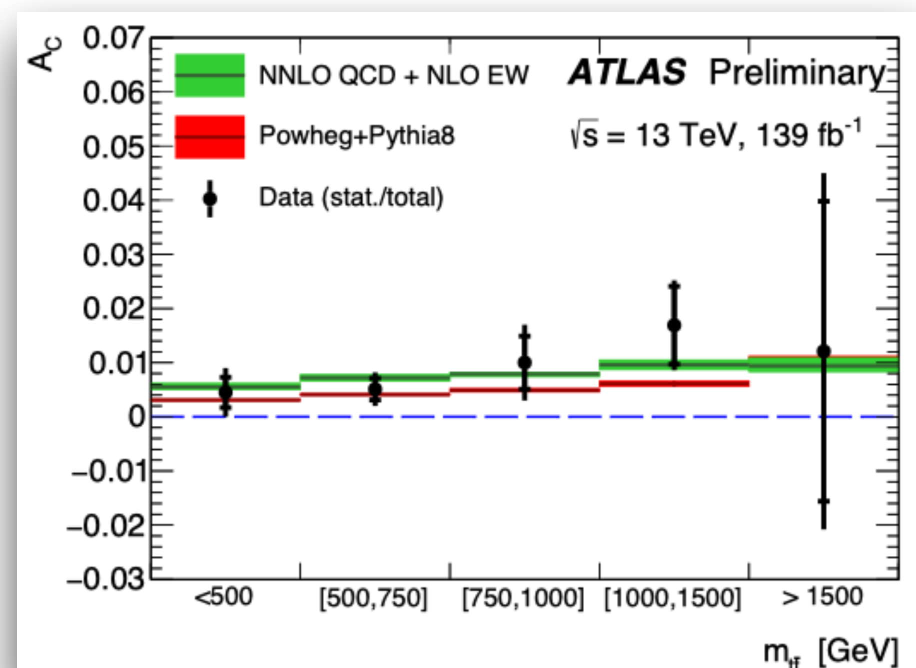
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

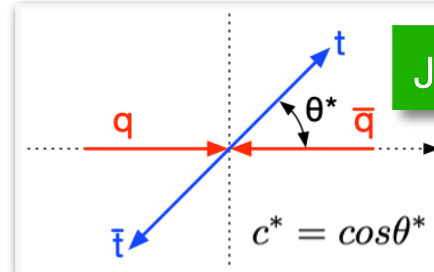
- Inclusive and differential measurements:
  - consistent with QCD NNLO + EWK NLO predictions
  - differs 4σ from zero

First evidence in pp collisions!

$$A_C = 0.0060 \pm 0.0015$$

$$A_C^{NNLO} = 0.0064^{+0.0005}_{-0.0006}$$





JHEP 06 (2020) 146

2016 data @13 TeV: 35.9 fb^{-1}

First measurement @LHC !

- **Top Forward-Backward asymmetry**
- Lepton+jets events with boosted and resolved topologies
- Search for anomalies in the angular distribution of produced $t\bar{t}$ pairs:

$$\frac{d\sigma}{dc^*}(q\bar{q}) \approx f_{\rm sym}(c^*) + \left[\int_{-1}^{1} f_{\rm sym}(x)dx\right] c^* A_{\rm FB}^{(1)}(m_{t\bar{t}})$$

anomalous chromoelectric (d_t) + chromomagnetic (μ_t) dipole moments

$$A_{\rm FB} = \frac{\sigma(c^*>0) - \sigma(c^*<0)}{\sigma(c^*>0) + \sigma(c^*<0)}$$

- Values consistent with SM expectations and in good agreement with previous measurements

$$A_{\rm FB}^{(1)} = 0.048^{+0.095}_{-0.087}\,({\rm stat})^{+0.020}_{-0.029}\,({\rm syst})$$

$$\hat{\mu}_t = -0.024^{+0.013}_{-0.009}\,({\rm stat})^{+0.016}_{-0.011}\,({\rm syst})$$

$$|\hat{d}_t| < 0.03 \text{ at } 95\% \text{ C.L.}$$

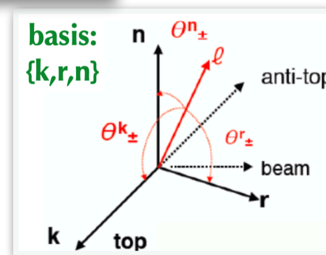
Spin correlations

CMS

Phys. Rev. D 100 (2019) 072002

2016 data
@13 TeV: 35.9 fb^{-1}

- Measurement of full spin density production matrix in dilepton channel
- Angular distributions in $t\bar{t}$ rest frame (**direct measurement**)



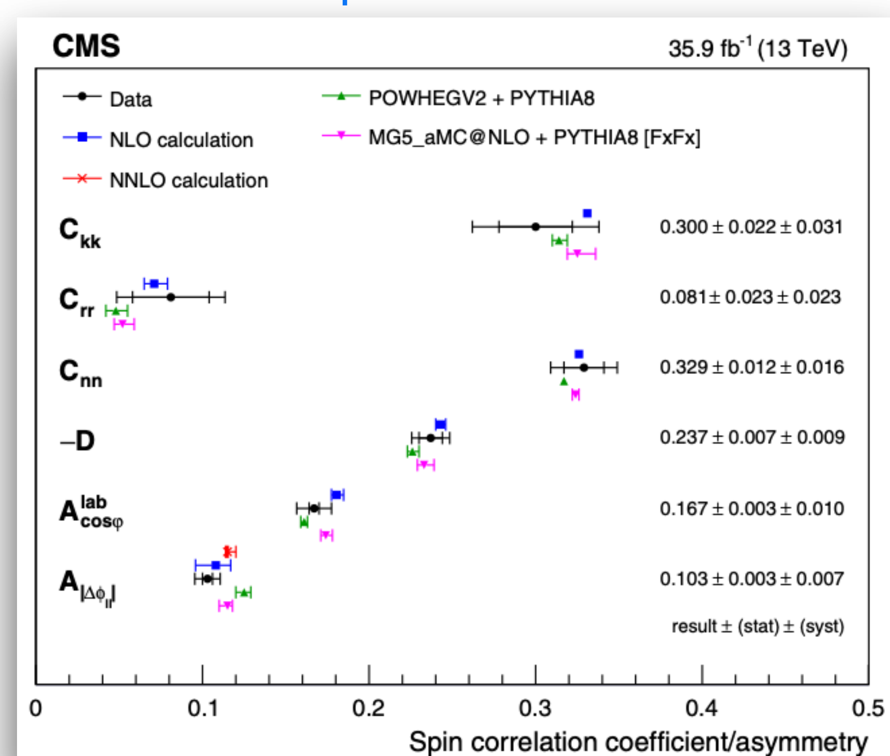
$$\frac{1}{\sigma}\frac{d\sigma}{dcos\theta_1^i dcos\theta_2^j} = \frac{1}{4}(1 + B_1^i cos\theta_1^i + B_2^j cos\theta_2^j - C_{ij} cos\theta_1^i cos\theta_2^j)$$

Polarizations — Spin correlations

- Lab-frame observables (**indirect measurement**)
- Coefficients individually probed by 1D angular distribution

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}(1 + [\mathbf{Coef.}]\, x)\, f(x)$$

- All distributions and extracted parameters in close agreement with SM predictions



ATLAS

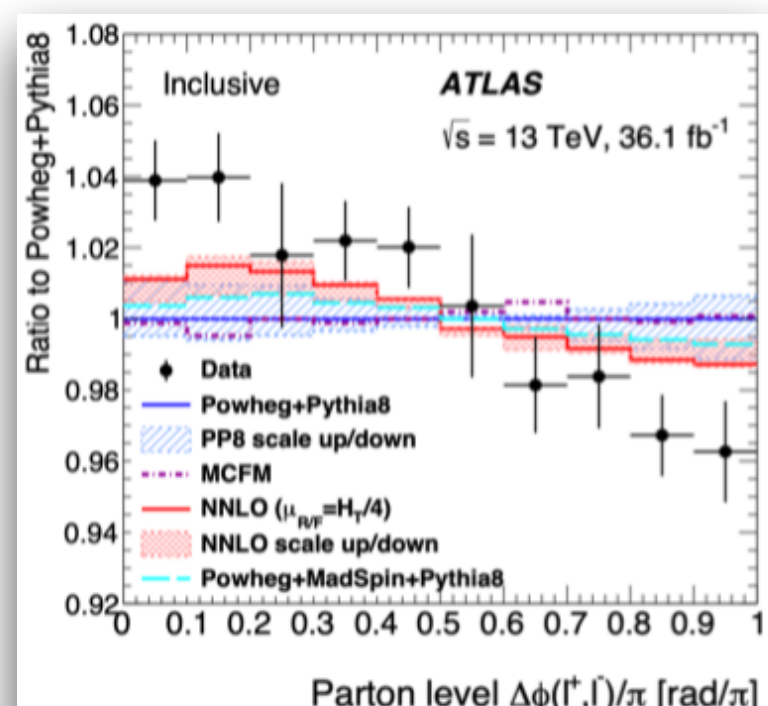
Eur. Phys. J. C 80 (2020) 754

2016 data
@13 TeV: 36.1 fb^{-1}

- Δϕ, Δη, and Δϕ vs m(tt) in ***eμ* channel**
- Fraction of SM-like spin correlation extracted with templates fit
  - 2.2σ difference between POWHEG + PYTHIA8 prediction and data

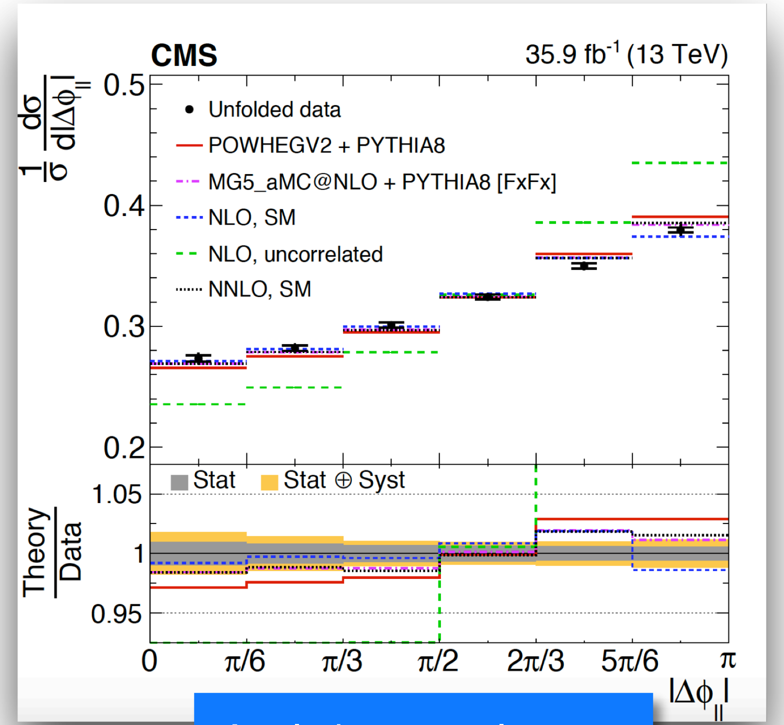
$$f_{SM} = 1.249 \pm 0.024(\text{stat.}) \pm 0.061(\text{syst.})^{+0.067}_{-0.090}(\text{theo.})$$

- Comparison with various SM predictions:
  - higher order calculations reduce the tension but still do not agree fully
  - NLO in strong and weak gauge couplings agrees better with data but large scale uncertainties

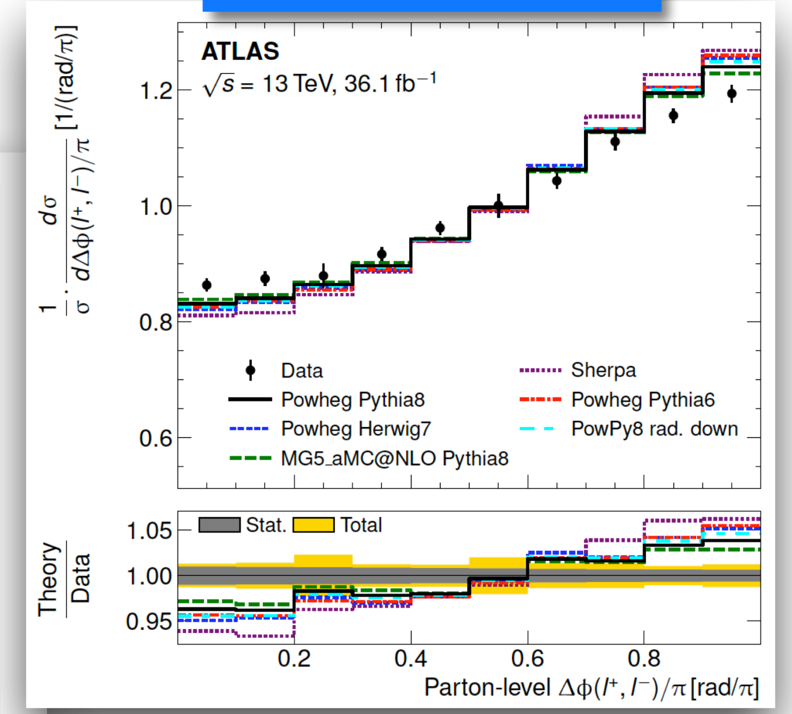


Δϕ distribution

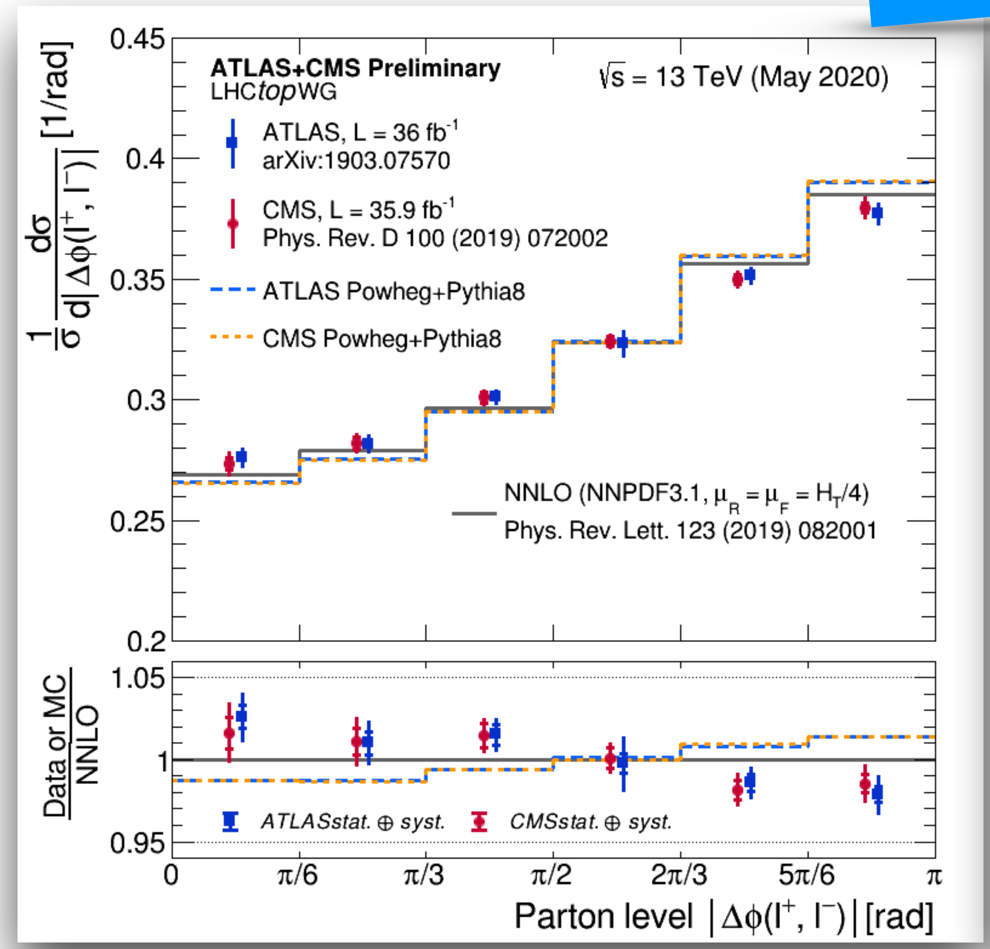
- Tension between data and predictions in both ATLAS (3.2σ) and CMS (1σ)
- First **ATLAS+CMS comparison** @13 TeV within *LHCtopWG*:
  - normalized cross sections at parton level
  - very good agreement between ATLAS and CMS data and between ATLAS and CMS main MC predictions
  - good agreement between data and MG5_aMC@NLO with FXFX merging (2 additional jets from the matrix element)
  - fair agreement with NNLO calculation

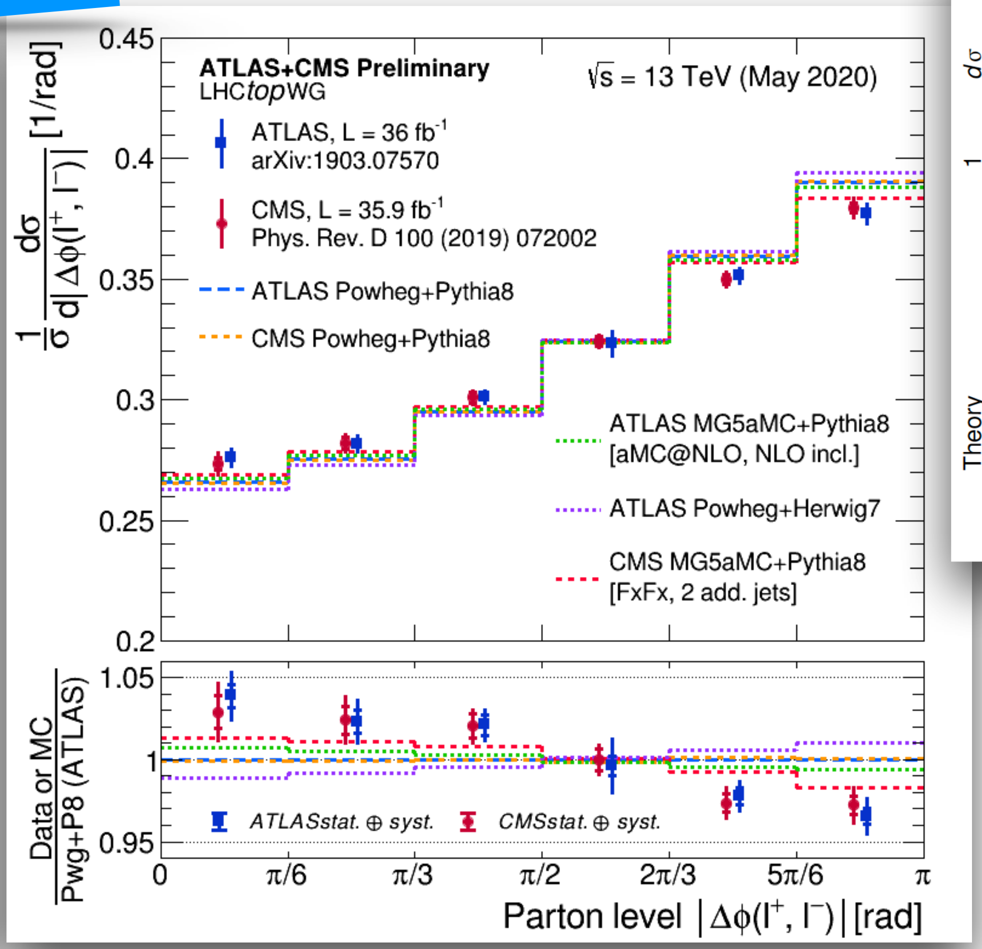


Angle between leptons in transverse plane



NEW





W polarization

arXiv:2005.03799 submitted to JHEP

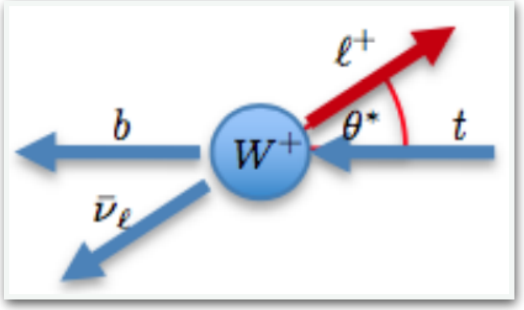
NEW

Run1 data @8 TeV:
20.2 fb^{-1} (ATLAS)
19.7 fb^{-1} (CMS)

- Fractions of W bosons polarization determined by V-A structure of tWb vertex
  - in SM unitarity constraint $F_0 + F_L + F_R = 1$
  - anomalous contributions to tWb vertex can change probabilities of W helicity states
- Distribution of $cos\theta^*$ particularly sensitive to polarization fractions

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

In SM: ~70% ~30% ~0%



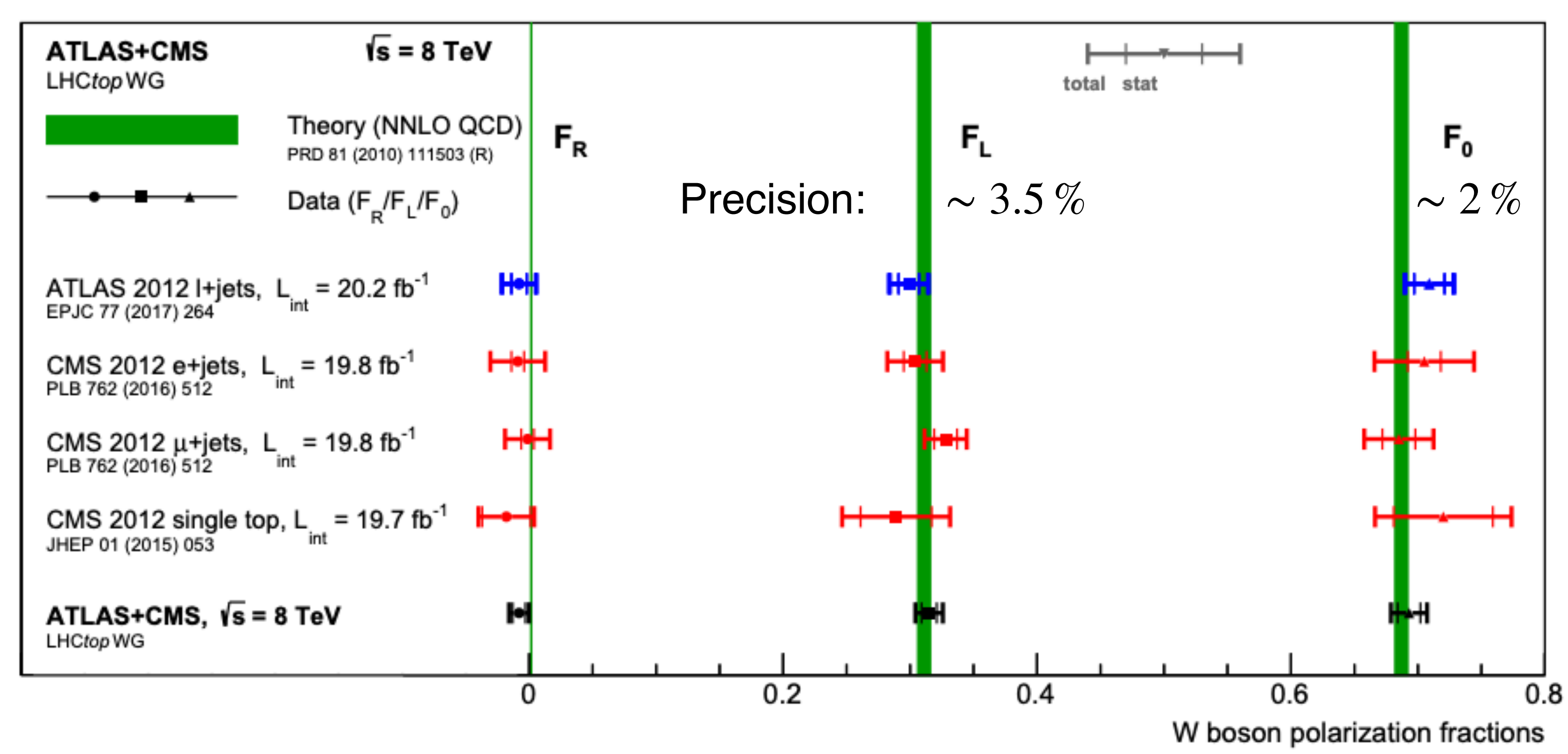
- **ATLAS + CMS combination** with Run1 data

Measurement	F_0	F_L	F_R
ATLAS (ℓ+jets)	$0.709 \pm 0.012 \pm 0.015$	$0.299 \pm 0.008 \pm 0.013$	$-0.008 \pm 0.006 \pm 0.012$
CMS (e+jets)	$0.705 \pm 0.013 \pm 0.037$	$0.304 \pm 0.009 \pm 0.020$	$-0.009 \pm 0.005 \pm 0.021$
CMS (μ+jets)	$0.685 \pm 0.013 \pm 0.024$	$0.328 \pm 0.009 \pm 0.014$	$-0.013 \pm 0.005 \pm 0.017$
CMS (single top)	$0.720 \pm 0.039 \pm 0.037$	$0.298 \pm 0.028 \pm 0.032$	$-0.018 \pm 0.019 \pm 0.011$

Improvement wrt most precise single measurement: $\sim 29\,\%$ $\sim 25\,\%$

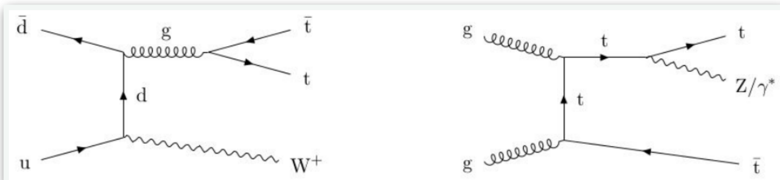
- Results in agreement with NNLO QCD

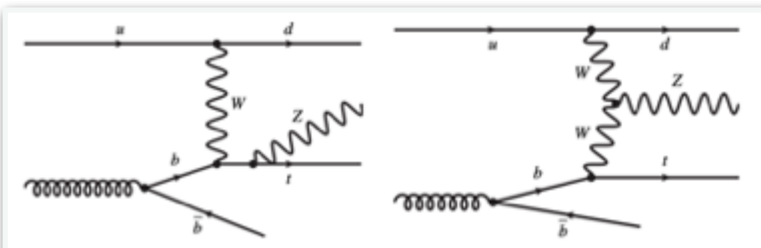
$$F_0 = 0.693 \pm 0.009\,(\text{stat+bkg}) \pm 0.011\,(\text{syst})$$
$$F_L = 0.315 \pm 0.006\,(\text{stat+bkg}) \pm 0.009\,(\text{syst})$$
$$F_R = -0.008 \pm 0.005\,(\text{stat+bkg}) \pm 0.006\,(\text{syst})$$

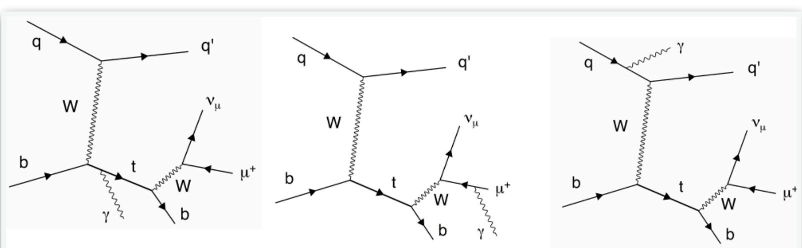


Top quark rare production

- Rare top production modes become fully accessible with Run2 data

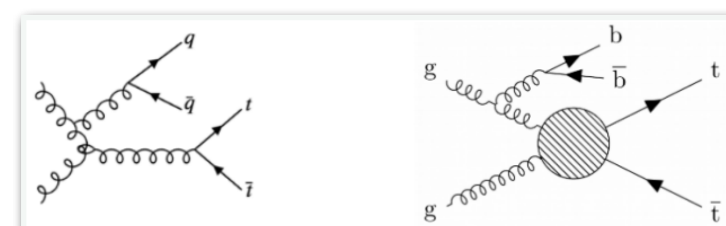


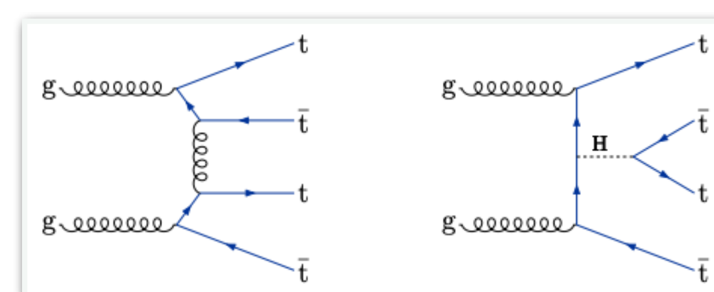




- **ttW/ttZ/ttγ production**:
  - among the most massive signatures that can be studied with high precision
  - important backgrounds for searches and measurements such as ttH in multilepton final states
  - ttZ production most sensitive process for directly measuring the coupling of the top quark to the Z boson
- **tZq production**:
  - sensitive to top-Z and triple gauge boson WWZ couplings
- **tγq production**:
  - sensitive to top quark charge and top quark electric and magnetic dipole moments

- **ttjj, ttbb**:
  - important background for ttH and for BSM events
  - precise measurements needed to improve tt+jets MC simulation
  - NLO calculations are affected by large uncertainties associated to μ_R/μ_F scales
- **tttt**:
  - not observed yet, but expected in SM with a NLO cross section of ≈ 12 fb
  - allows to constrain t-H Yukawa coupling (but less precisely than ttH)
  - Very tiny cross section in SM
    - σ_{NLO}(tttt) = 11.97 fb at NLO QCD + NLO QED at 13 TeV





ttZ production

NEW

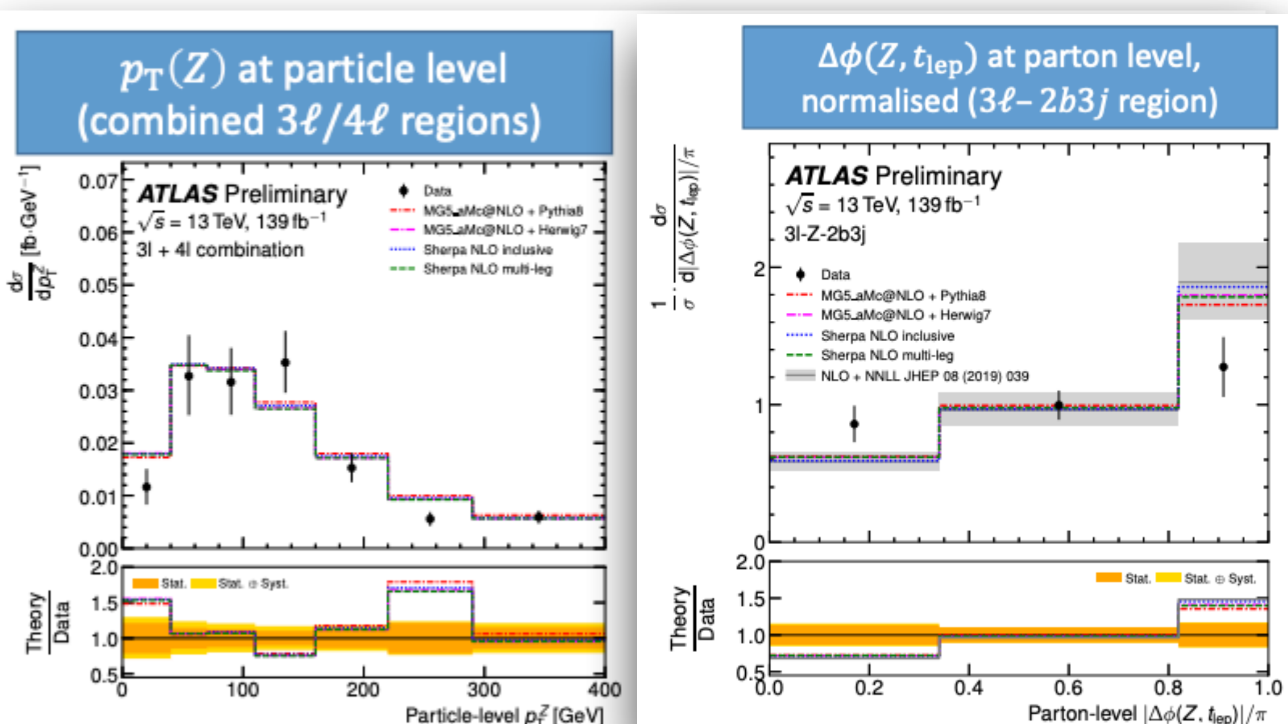
ATLAS-CONF-2020-028

Full Run2 data
@13 TeV: 139 fb^{-1}

- **3l/4l final states**
- Inclusive & differential measurements at parton and particle level
- Simultaneous profile likelihood fit of all trilepton and tetralepton signal regions + control regions
- Measured inclusive cross-section in agreement with NLO+NNLL prediction

$$\sigma(pp \to t\bar{t}Z) = 1.05 \pm 0.05(\text{stat.}) \pm 0.09(\text{syst.})\text{pb}$$ 10%

$$\sigma_{t\bar{t}Z}^{\text{NLO+NNLL}} = 0.86^{+0.07}_{-0.09}(\text{scale}) \pm 0.03(\text{PDF} + \alpha_S)\text{pb}$$ 11%



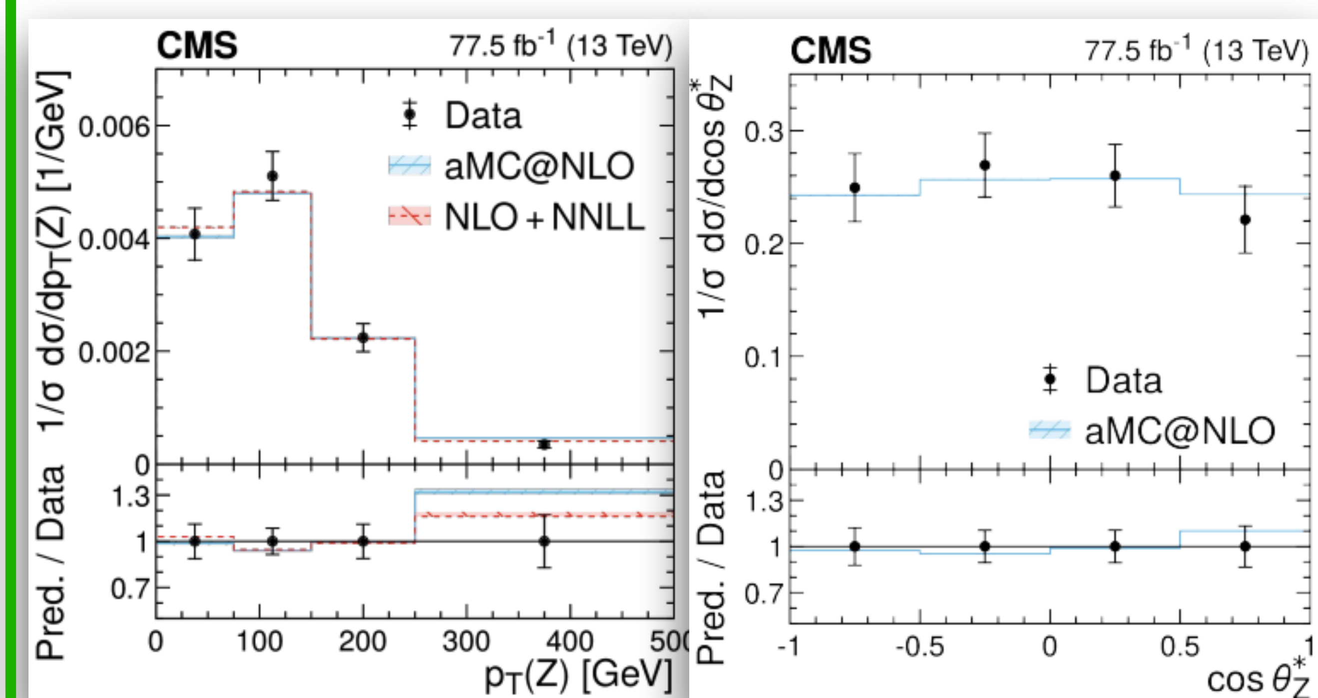
JHEP 03 (2020) 056

2016+2017 data
@13 TeV: 77.5 fb^{-1}

- **3/4 leptons**
- Differential cross sections in agreement with aMC@NLO prediction
  - 8% precision

Lepton requirement	Measured cross section
3ℓ	$0.97 \pm 0.06\,(\text{stat}) \pm 0.06\,(\text{syst})$ pb
4ℓ	$0.91 \pm 0.14\,(\text{stat}) \pm 0.08\,(\text{syst})$ pb
Total	$0.95 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})$ pb

Dominant syst. unc.:
lepton identification (4%), WZ (3%) and t(t)X (3%)



$t\bar{t}\gamma$ production

arXiv:2007.06946 submitted to JHEP

Full Run2 data @13 TeV: 139 fb^{-1}

- Inclusive and differential cross-sections in ***eμ* channel**
- Cross section extraction from binned profile likelihood fit

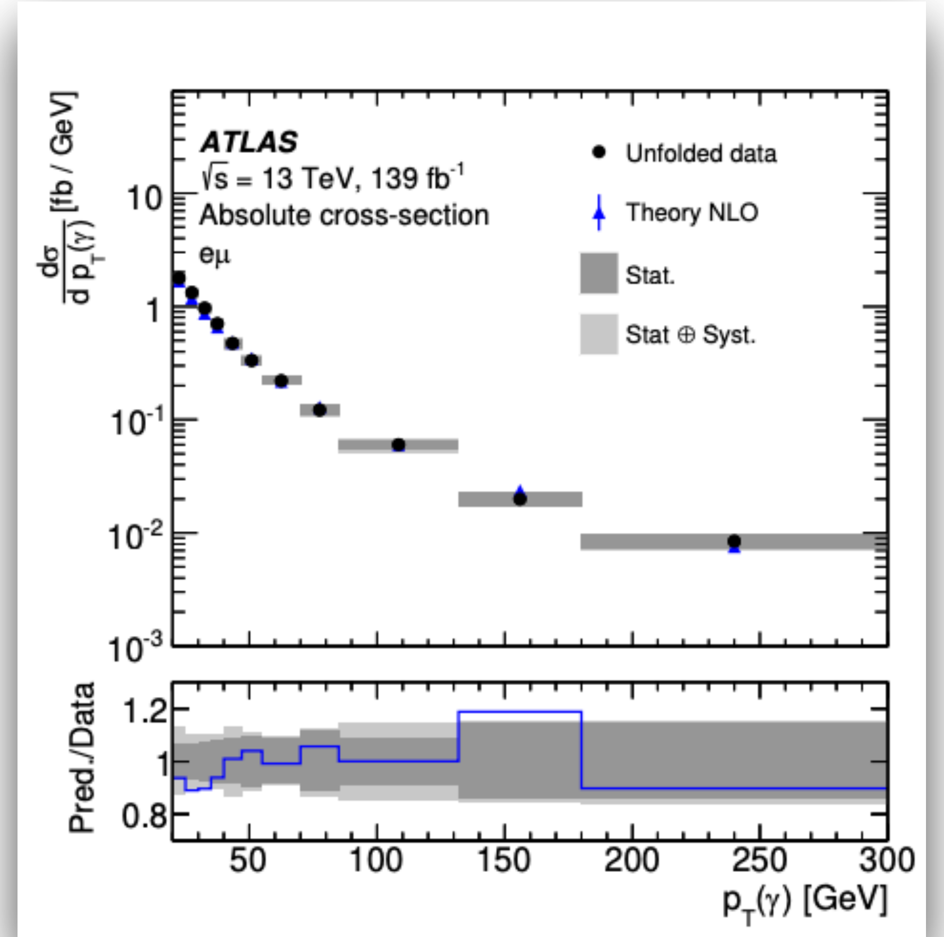
$$\sigma = 39.6 \pm 0.8(\text{stat.})^{+2.6}_{-2.2}(\text{syst.})\text{fb} = 39.6^{+2.7}_{-2.3}\text{fb}$$ 6.3%

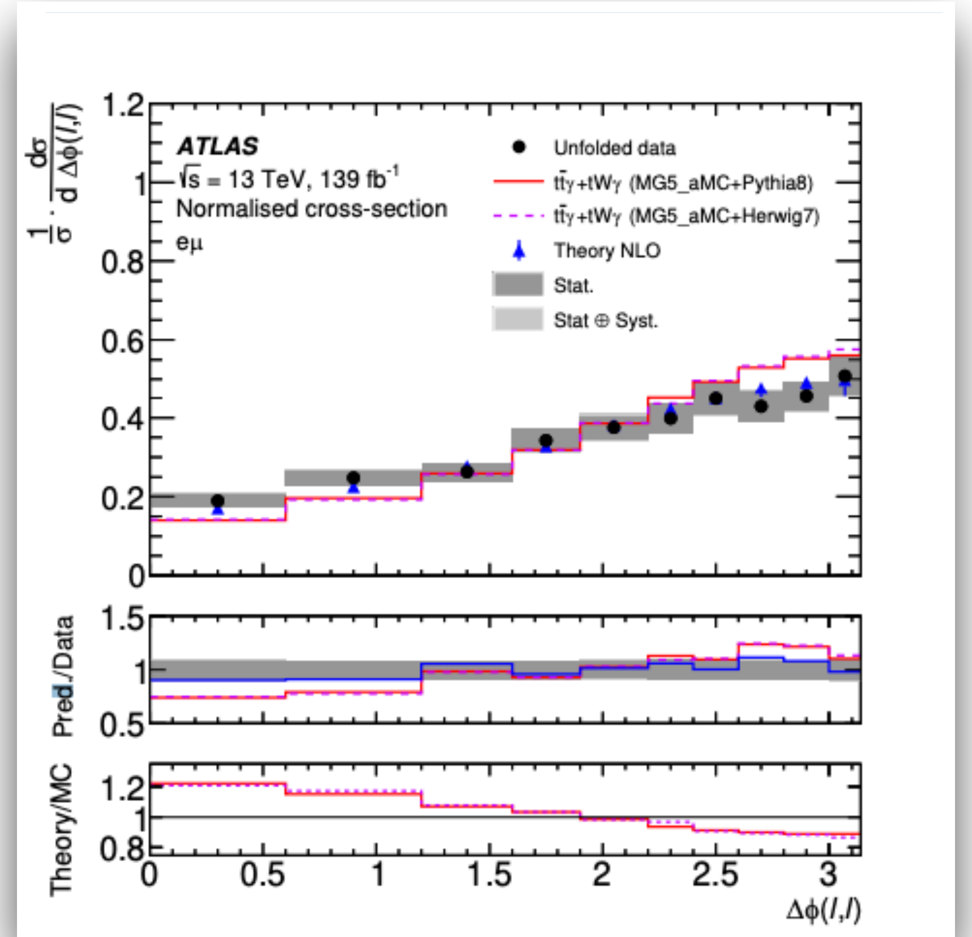
- Theory value:

$$\sigma = 38.50^{+0.56}_{-2.18}(\text{scale})^{+1.04}_{-1.18}(\text{PDF})\text{fb}$$ 6.4%

Dominant syst. unc.: MC modeling of Eγ and Wtγ (3.4%)

- Compared against fixed-order NLO calculation in QCD and LO+PS simulation
  - NLO theory in good agreement with data
  - LO+PS simulation has difficulties to describe some of the observables





tZq/tγq production

Observation of tZq production

arXiv:2002.07546 submitted to JHEP

Full Run2 data @13 TeV: 139 fb^{-1}

- Trilepton channel (best signal significance)
- Simultaneous profile-likelihood fit of all signal and control regions

$$\sigma_{tZq} = 97 \pm 13(\text{stat.}) \pm 7(\text{syst.})\text{fb}$$

PRL 122 (2019) 132003

2016+2017 data @13 TeV: 77.4 fb^{-1}

- 3 isolated high-pT leptons
- Simultaneous template fit to BDT outputs and yields of control regions

$$\sigma(pp \to tZq \to t\ell^+\ell^-q) = 111 \pm 13(\text{stat})^{+11}_{-9}(\text{syst})\ \text{fb}$$
$$\sigma^{\text{SM}}(pp \to tZq \to t\ell^+\ell^-q) = 94.2 \pm 3.1\ \text{fb}$$

Observation 8.2σ (7.7σ expected)

Dominant syst. unc.: non-prompt bkg, jet energy scale, lepton efficiency, FSR, QCD scale uncertainty

Evidence of tγq production

PRL 121 (2018) 221802

2016 data @13 TeV: 35.9 fb^{-1}

- t-channel: 1μ, 1γ, MET, ≥ 2 jets, 1 b-tagged jet
- Binned likelihood fit performed to the BDT in the SR and the tt+γ CR (2 b-tagged jets)

$$\sigma(pp \to t\gamma j)\mathcal{B}(t \to \mu\nu b) = 115 \pm 17(\text{stat}) \pm 30(\text{syst})\ \text{fb}$$

$\sigma_{t\gamma}$(NLO) = 81 ± 4(scale+PDF) fb

Fiducial region: $p_{T,\gamma}$ > 25 GeV, $|\eta_\gamma|$ < 1.44 and ΔR({μ, b, j}, γ) > 0.5

Observation 4.4σ (3.0σ expected)

First evidence of this process !

Dominant syst. unc.: JES (12%), b-tagging, tγq modeling (9%)

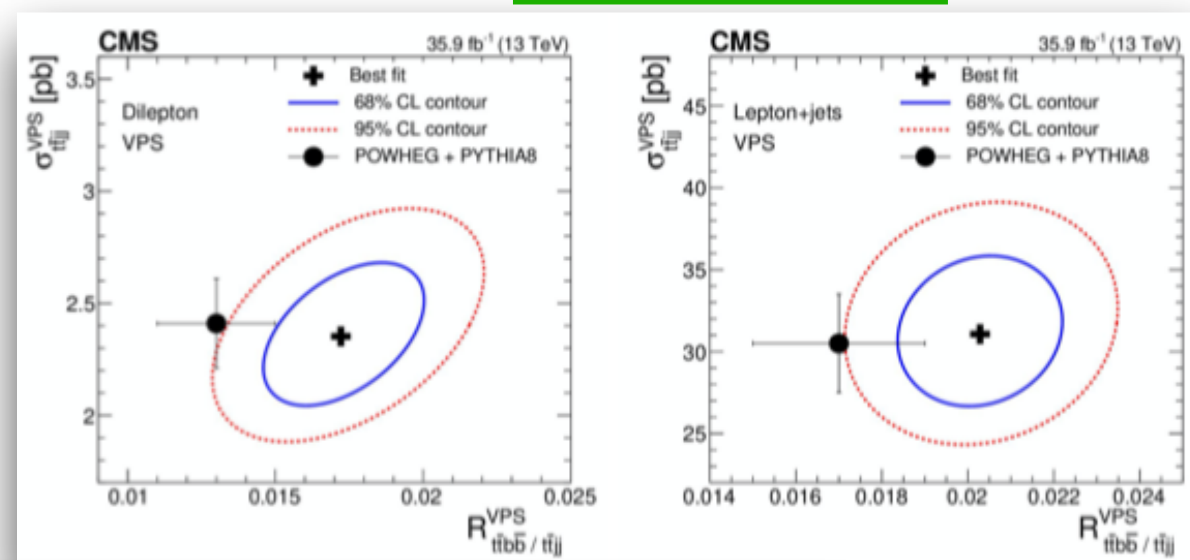
All results consistent with SM predictions

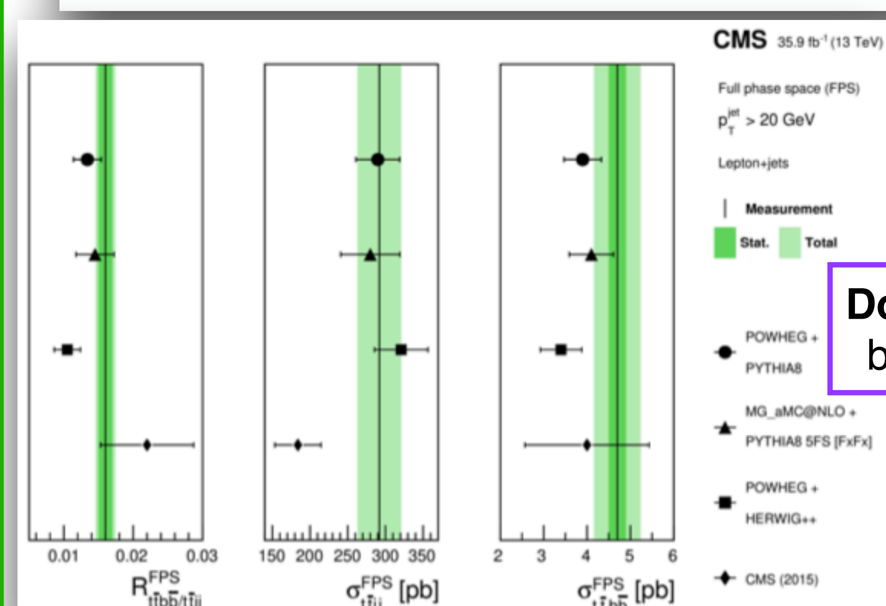
ttjj+ttbb production

JHEP 07 (2020) 125

2016 data
@13 TeV: 35.8 fb^{-1}

- **Dilepton**: 2 e/μ + ≥4 jets (≥2 b-jets)
- **Single lepton**: 1 e/μ + ≥6 jets (≥2 b-jets)
- Extraction of cross sections / ratio from max likelihood binned fit in VPS independently for the 2 channels
  - extrapolated to FPS using acceptances from MC
  - σ_{obs}(ttjj) and R_{obs} higher but consistent with different MCs $\sigma_{obs}(ttjj) \simeq \sigma_{SM}(ttjj)$





Dominant syst. unc.:
b-tagging, JES, ISR

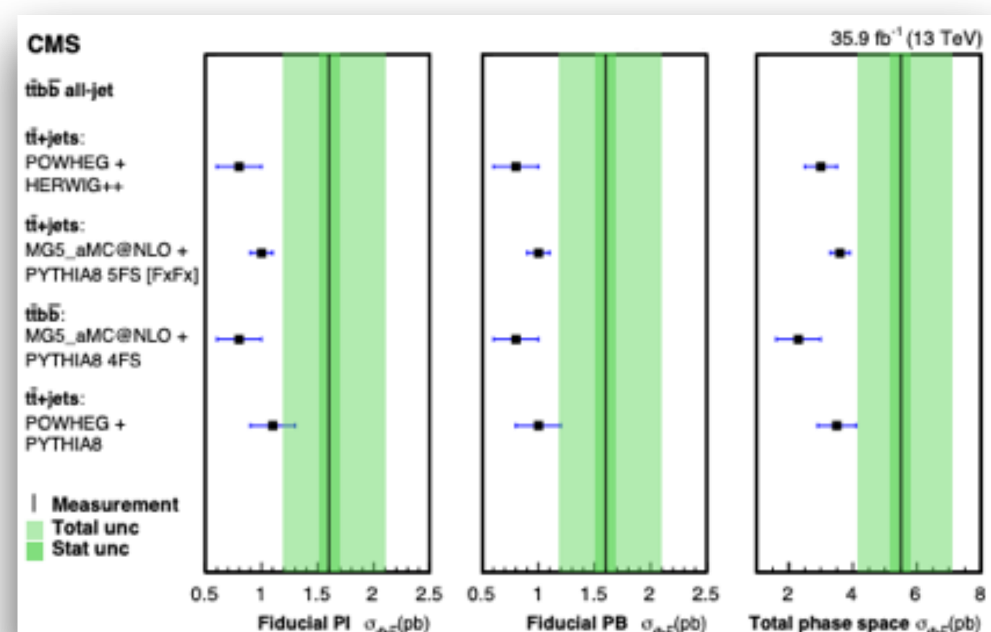
PLB 803 (2020) 135285

2016 data
@13 TeV: 35.9 fb^{-1}

- **Full hadronic**: ≥8 jets (≥4 b-jets)
- Data fitted with profiled ML technique
- Predictions underestimate measurements by a 1.5-2.4 factor (1-2 σ)
- Consistent with previous results

	FPS PI (pb)	FPS PB (pb)	TPS (pb)
Measurement	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$5.5 \pm 0.3^{+1.6}_{-1.3}$
POWHEG ($t\bar{t}$)	1.1 ± 0.2	1.0 ± 0.2	3.5 ± 0.6
POWHEG ($t\bar{t}$) + HERWIG++	0.8 ± 0.2	0.8 ± 0.2	3.0 ± 0.5
MADGRAPH5_aMC@NLO (4FS $t\bar{t}b\bar{b}$)	0.8 ± 0.2	0.8 ± 0.2	2.3 ± 0.7
MADGRAPH5_aMC@NLO (5FS $t\bar{t}$+jets, FxFx)	1.0 ± 0.1	1.0 ± 0.1	3.6 ± 0.3

Dominant syst. unc.:
b-tagging, quark/gluon likelihood, renorm. and fact. scales, MC stat.



4t production

SS dilepton or trilepton

EPJC 80 (2020) 75

Full Run2 data
@13 TeV: 137 fb^{-1}

- Cut-based and BDT approach
  - consistent results
- Cross section extraction from profiled ML fit to observed and predicted yields

$$\sigma_{tttt}^{cut} = 9.4^{+6.2}_{-5.6}\,\text{fb}$$
$$\sigma_{tttt}^{BDT} = 12.6^{+5.8}_{-5.2}\,\text{fb}$$

Significance: 2.6σ (2.7σ) observed (expected)

Dominant syst. unc.:
modeling of additional b-jets (11%), JES (9%), JER (6%), b-tagging (6%)

$$\sigma_{t\bar{t}t\bar{t}}^{\text{NLO QCD + EW}} = 12.0 \pm 2.4\ \text{fb}$$

arXiv:2007.14858 - submitted to EPJC

Full Run2 data
@13 TeV: 139 fb^{-1}

- Cross section extraction from binned likelihood fit to BDT output in signal region and control regions
- Strong evidence:

$$\sigma_{tttt} = 24 \pm 5(\text{stat.})^{+5}_{-4}(\text{syst.})\text{fb}$$

Significance: 4.3σ (2.4σ) observed (expected)

$$\mu = 2.0^{+0.8}_{-0.6} = 2.0^{+0.4}_{-0.4}(\text{stat.})^{+0.7}_{-0.5}(\text{syst.})$$

Single lepton or OS dilepton

JHEP 11 (2019) 082

2016 data
@13 TeV: 35.8 fb^{-1}

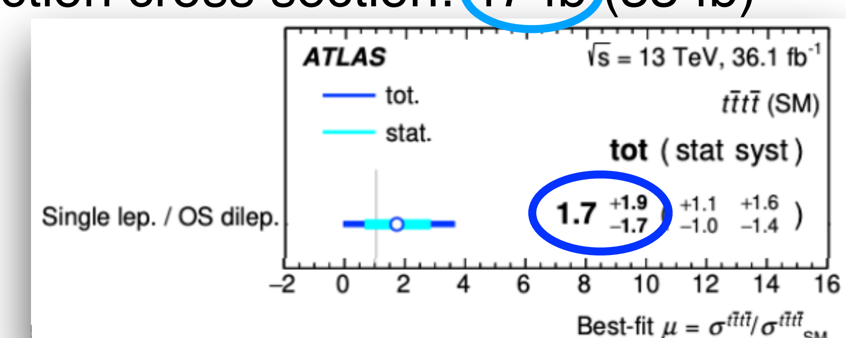
- 95% CL upper limits on cross section extracted from simultaneous binned ML template fit

Channel	Expected limit, μ	Observed limit, μ	Expected limit (fb)	Observed limit (fb)
Single-lepton	$9.4^{+4.4}_{-2.9}$	10.6	86^{+40}_{-26}	97
Dilepton	$7.3^{+4.5}_{-2.5}$	6.9	67^{+41}_{-23}	64
Combined (this analysis)	$5.7^{+2.9}_{-1.8}$	5.2	52^{+26}_{-17}	48

PRD 99 (2019) 052009

2015+2016 data
@13 TeV: 36.1 fb^{-1}

- Simultaneous fit to HT in multiple signal regions
- Observed (expected) 95% C.L. upper limit on the production cross section: 47 fb (33 fb)



Summary

- LHC Run1 and Run2 provided huge number of produced top quark events
- Several measurements with new Run2 data presented
  - confirm good agreements with SM expectations
  - allow to explore parameters of EFT and other BSM models
- Increased precision up to NNLO+NLO EWK level
  - allowed by large statistics and via ATLAS+CMS combinations
  - better understanding of top quark properties and physics modeling
  - constraints on new physics

Focus only on a selection of recent measurements.. for more results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP