La Thuile, Aosta Valley (Italy) – Thursday, March 1st

Top-quark production at the LHC

Highlights on recent ATLAS and CMS top quark precision measurements

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On behalf of the ATLAS and CMS collaborations

The top quark

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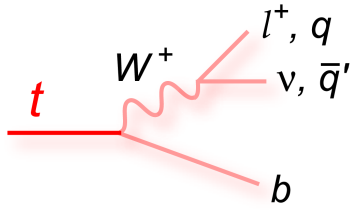
- A unique particle
  - Most massive elementary particle: $m_t \approx 175$ GeV
  - Large coupling to Higgs boson & special role in EWSB
  - Decays before hadronising, allowing study of bare quarks



- An important probe for testing SM & BSM Physics
  - Test pQCD at NNLO precision (fixed-order)
  - Constrain Parton Distribution Functions (PDFs)
  - Determine SM parameters (m_t, $|V_{tb}|$) and measure rare processes ($t\bar{t}$+W, $t\bar{t}$+Z, tZ, etc.)
  - Constrain New Physics: Anomalous couplings, direct searches ($t\bar{t}$ resonances, W′ → $t\bar{b}$)

A particle abundantly produced at the LHC

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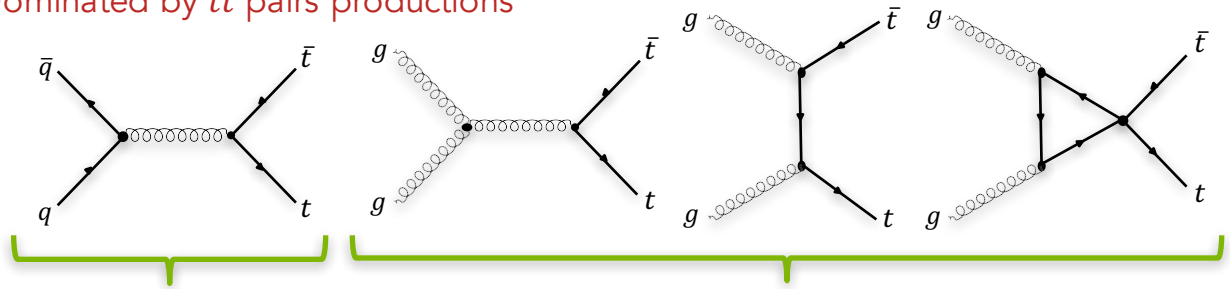
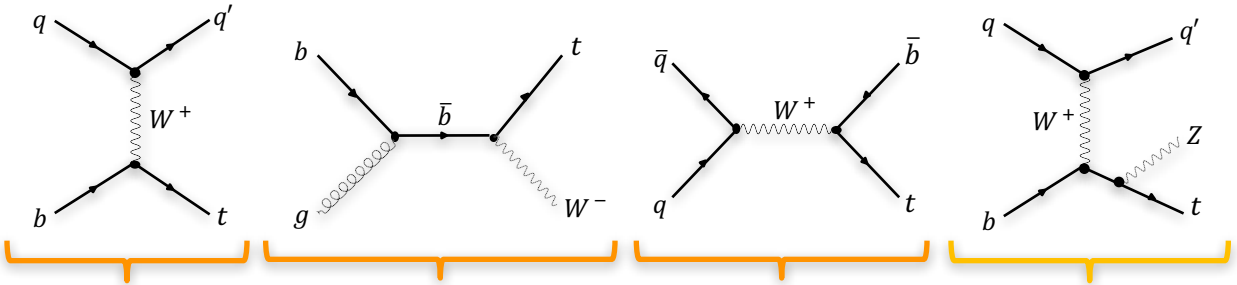
Dominated by $t\bar{t}$ pairs productions



quark-antiquark annihilation (~10%)

gluon-gluon fusions (~ 90%)

Single top-quark productions



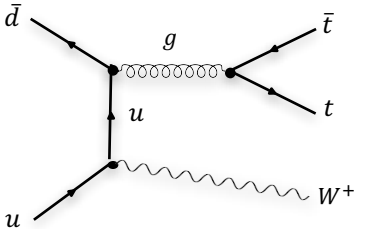
t-channel (~73%)

tW associated production (~24%)

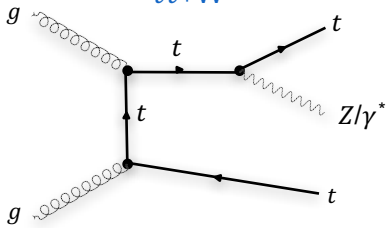
s-channel (~3%)

tZ production (<1%)

Other productions



$t\bar{t}$+W



$t\bar{t}$+Z/γ*

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Top-quark pair production

Overview of recent cross section measurements

State of the art of $t\bar{t}$ cross section measurements

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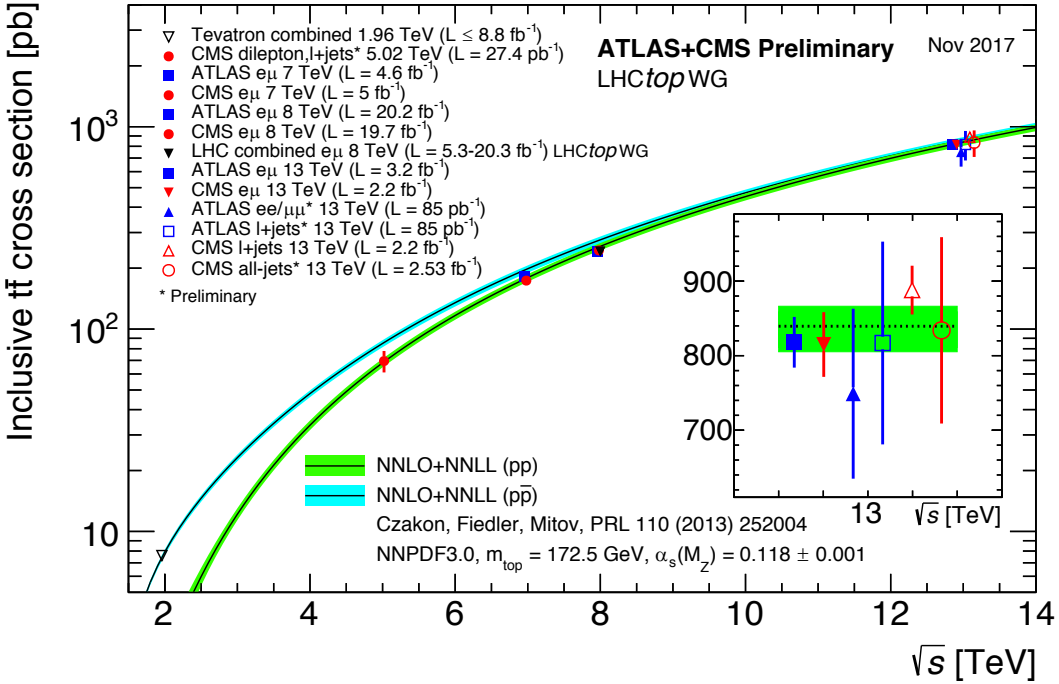
- Many measurements performed by the ATLAS and CMS collaborations at $\sqrt{s} = 7$, 8 and 13 TeV



Up to now, an impressive agreement between predictions and measurements

State of the art of $t\bar{t}$ cross section measurements

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Analysis channels

Dilepton

- *Most precise results*
- Wt, fake leptons, diboson, Z→ ττ bakgrounds
- *Limited constrains on modelling uncertainties*

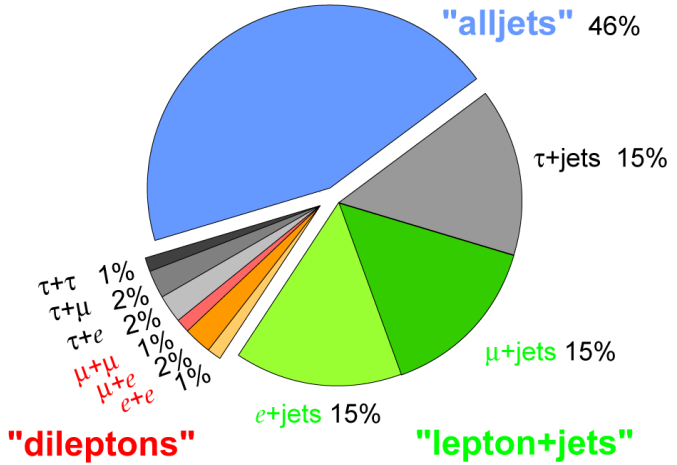
Lepton+jets

- *Infinite statistics*
- *Single top t-channel, W+jets, Multi-jet backgrounds*
- *Possibility to exploit multiple control regions*

All-hadronic

- *Significantly less precise*
- *Possibility to probe highly-boosted top quarks*

Top-pair branching ratios

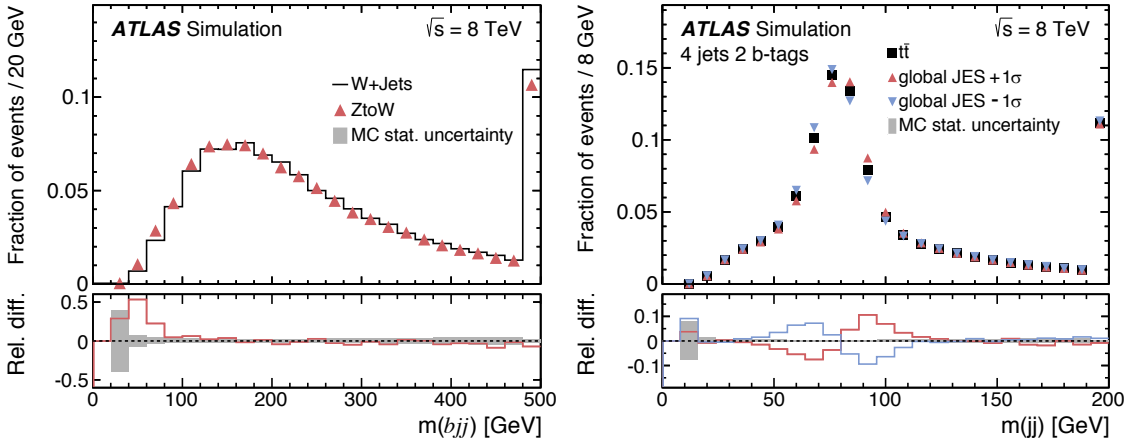


Main systematic uncertainties

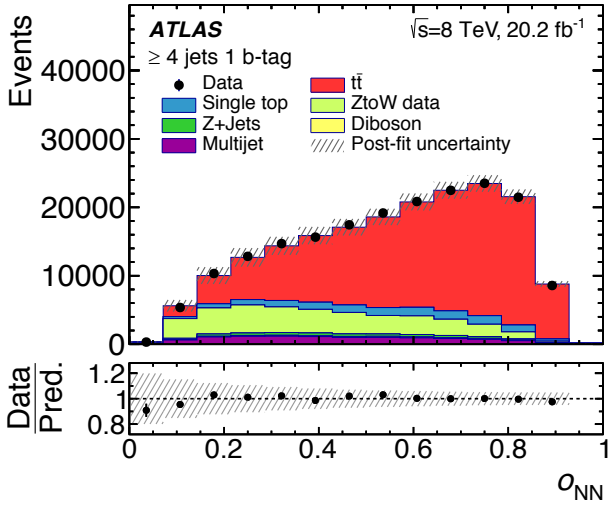
- *Signal modelling (generators, QCD scales, radiation, hadronisation)*
- *Object efficiencies & calibrations (leptons, jets, flavour-tagging)*
- *Background estimates* • *Luminosity (2-3%)*

Inclusive cross section measurements

- Inclusive and fiducial $t\bar{t}$ cross section in l+jets events at $\sqrt{s} = 8$ TeV by ATLAS
  arXiv:1712.06857 – submitted to EPJC



- *Maximum likelihood fit to NN output & m(jj) distributions*



- *Event categorization based on jet and b-tagged jet multiplicities*
- *W+jets background shape using data Z+jets*
- *Exploit $W \to q\bar{q}$ decay to constrain JES*

Results consistent with SM expectations

$$\sigma_{\text{inc}}(t\bar{t}) = 248.3 \pm 0.7\,(\text{stat.}) \pm 13.4\,(\text{syst.}) \pm 4.7\,(\text{lumi.})\ \text{pb}$$

$$\sigma_{\text{fid}}(t\bar{t}) = 48.8 \pm 0.1\,(\text{stat.}) \pm 2.0\,(\text{syst.}) \pm 0.9\,(\text{lumi.})\ \text{pb}$$

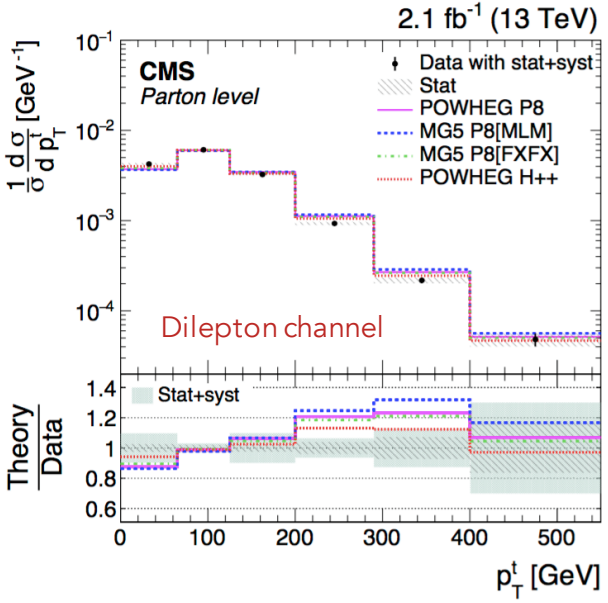
NB: Similar CMS results in Phys. Rev. D 93 (2016) 072004

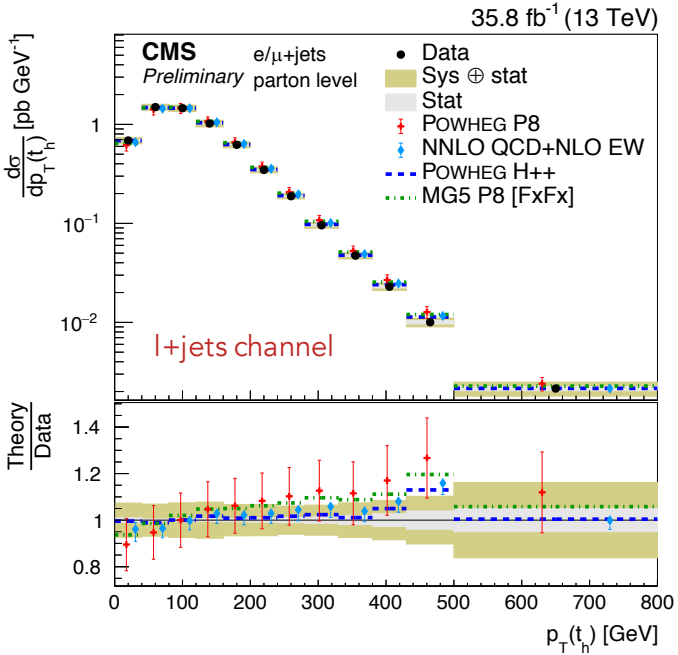
Differential cross section measurements

- Differential $t\bar{t}$ cross section in dilepton and l+jets events at $\sqrt{s}$ = 13 TeV by CMS
  arXiv:1708.07638 – submitted to JHEP, CMS PAS TOP-17-002

- *Measured as a function of several observables at particle level*
- *Parton level results extrapolated to full phase space using POWHEG+PYTHIA8 simulation*

General good agreement with predictions





NB: Similar ATLAS results in Eur. Phys. J. C77 (2017) 299

Confirm softer top-quark p_T in data than in MC predictions both at particle and parton levels
→ partially be explained by NNLO QCD+NLO EW calculations

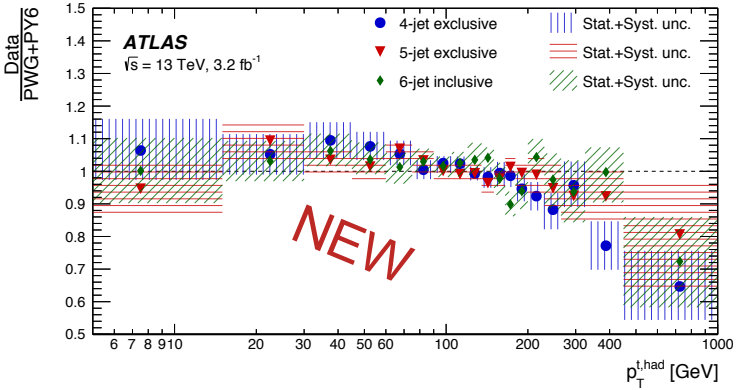
Differential cross section measurements

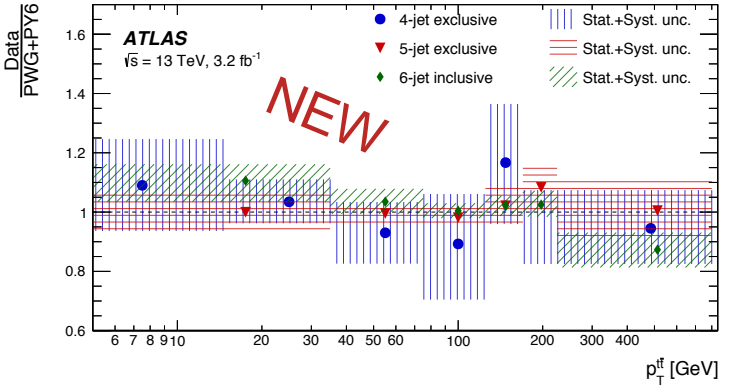
- Differential $t\bar{t}$ + jets cross section in l+jets events at $\sqrt{s}$ = 13 TeV by ATLAS
  arXiv:1802.06572 – submitted to JHEP

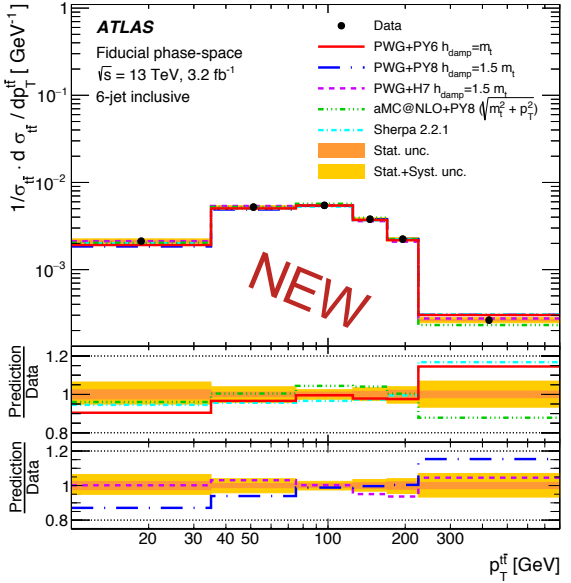
- *Study the effect of QCD radiation emission on top quark kinematic variables at particle level*
- *Measured as function of several observables at particle level*
- In *3 exclusive jet configurations*

$p_T^{t,had}$ in 4-jet config.
Underestimated by prediction at low value & overestimated at high values

p_T^{tt} in 6-jet config.
Disfavour several predictions







Lepton differential distributions

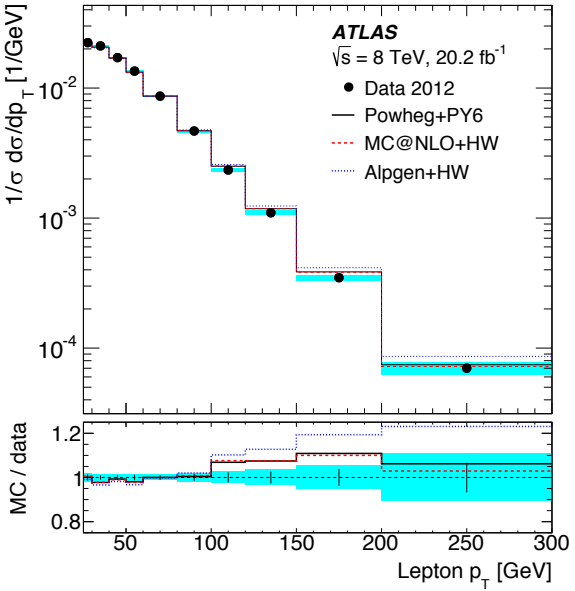
- $\sqrt{s}$ = 8 TeV measurements in OS eμ pairs with 2 jets events by ATLAS
  Eur. Phys J. C 77 (2017) 804

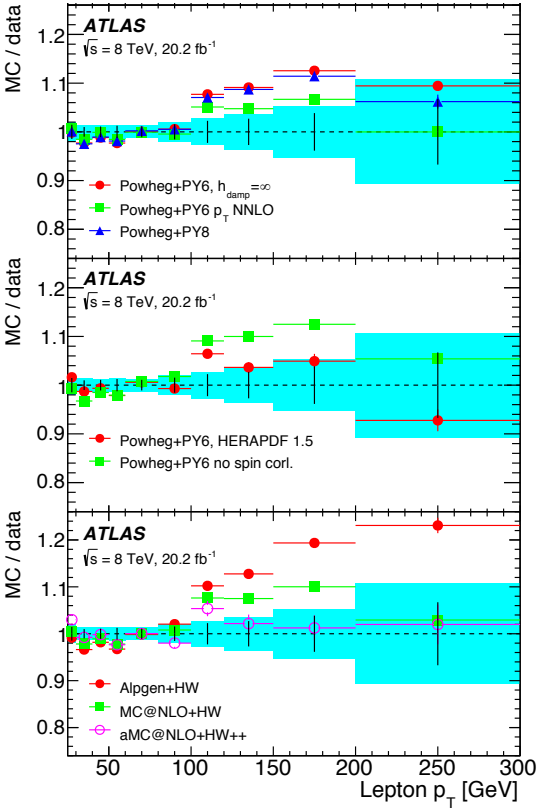
- *Cross section extracted bin-by-bin from*

$$N_1^i = L\sigma_{t\bar{t}}^i G_{e\mu}^i 2\epsilon_b^i(1 - C_b^i\epsilon_b^i) + N_1^{i,\mathrm{bkg}},$$
$$N_2^i = L\sigma_{t\bar{t}}^i G_{e\mu}^i C_b^i(\epsilon_b^i)^2 + N_2^{i,\mathrm{bkg}},$$

$G_{e\mu}^i$: binned eff. & mig. corr. from MC
ε_b^i : *b-tagging eff. extracted*

- *Measured as a function of several observables at particle level*





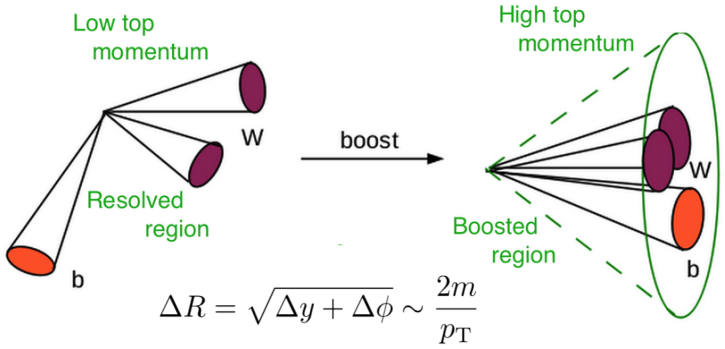
m_t extraction from sensitive kinematics
fits to fixed-order NLO QCD predictions

m_t^{pole} = 173.2 ± 0.9 (stat.) ± 0.9 (syst.) ± 0.9 (th.) GeV

Good agreements with SM predictions
Dependence to lepton p_T improved using HERAPDF and NNLO predictions

Probing boosted all-hadronic final states

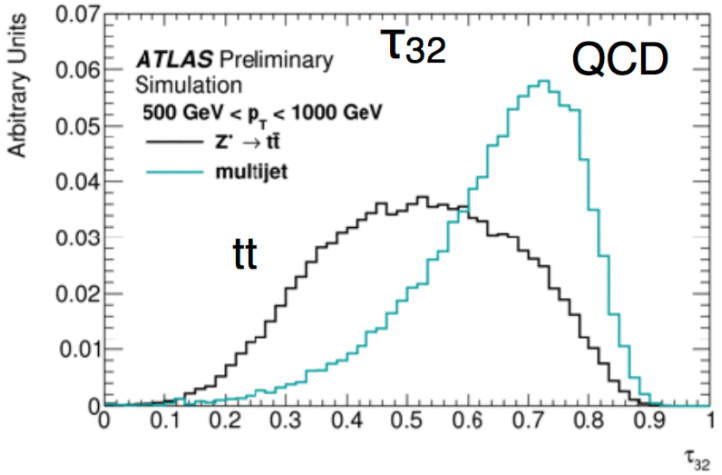
- Challenges
  - High-p_T hadronic top-quark decay reconstruction
  - Systematic uncertainties and modelling of boosted kinematics
  - Limited statistics compared to resolved analysis



$$\Delta R = \sqrt{\Delta y + \Delta \phi} \sim \frac{2m}{p_{\mathrm{T}}}$$

- Distinguish boosted top-quark from QCD background
  - Jet mass peaks near m_t
  - Using flavour-tagging on boosted top quark
  - Exploit large-R jet expected substructures

e.g. Using τ_{32} ratio of 3- to 2-subjetiness, discriminating jets containing 3- and 2-prong sub-structures



Probing boosted all-hadronic final states

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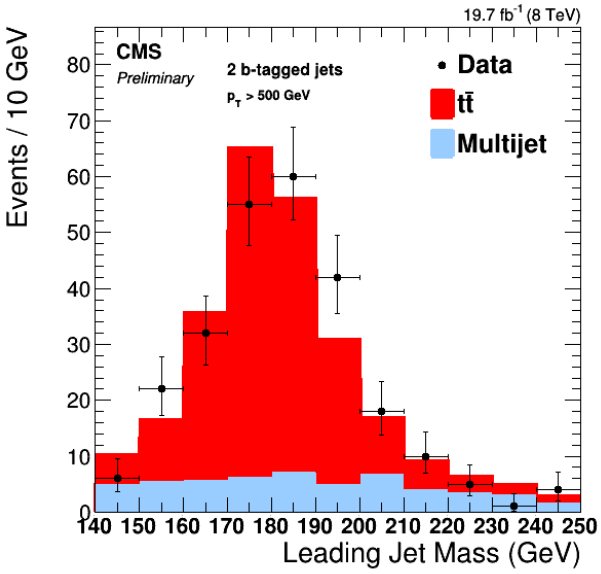
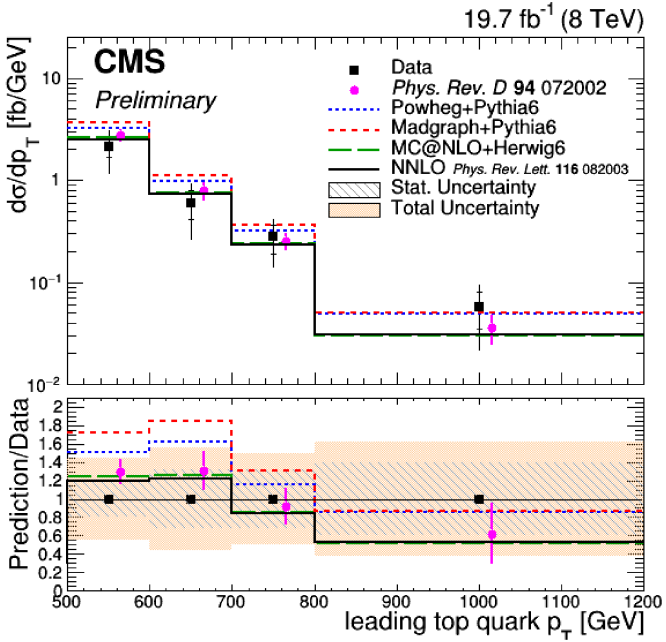
- Differential cross-section using highly-boosted top quarks at $\sqrt{s}$ = 8 TeV by CMS
  CMS PAS TOP-16-018

- *Selecting 2 large R=0.8 C/A jets with p_T>400 GeV*
- *Top-tagging using jet-substructure observables, large-R jet mass and b-tagged sub-jets*
- *$t\bar{t}$ yield extracted using binned likelihood fit of Leading jet mass*





Inclusive cross section
(for jets with p_T>500 GeV jets)

$\sigma(t\bar{t})$ = 404 ± 23 (stat.) ± 140 (syst.) fb

Results in agreement with NLO+PS simulation calculations with large experimental uncertainties

NB: Similar CMS results at $\sqrt{s}$ = 13 TeV in Top-16-013

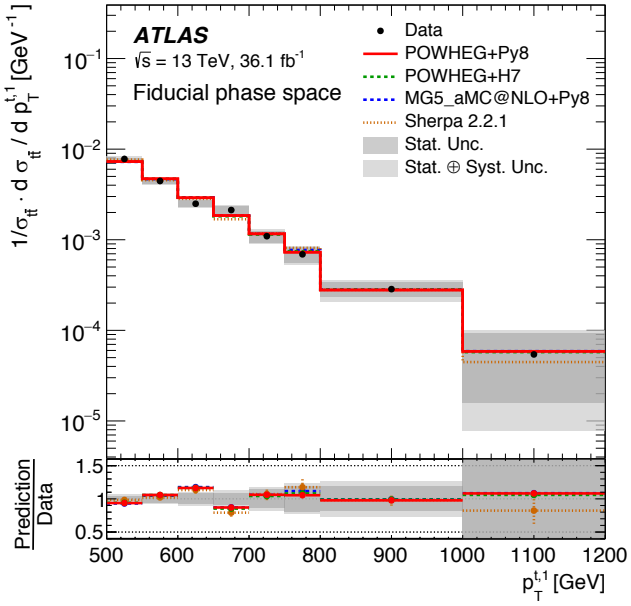
Probing boosted all-hadronic final states

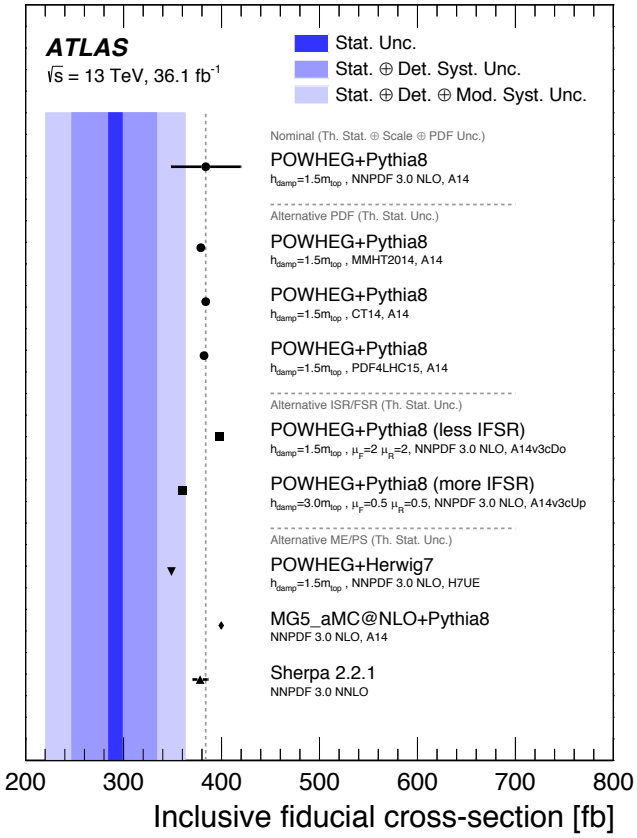
- Similar measurements at $\sqrt{s}$ = 13 TeV by ATLAS
  arXiv:1801.02052 – submitted to PRD

- *Selecting 2 large R=1.0 anti-kt jets with p_T>500 (350) GeV*
- *Top-tagging using only jet-substructure and Large-R jet mass*
- *Iterative Bayesian unfolding to particle-level observables*

Measured particle-level fiducial xs

$\sigma(t\bar{t}) = 292 \pm 7$ (stat.) ± 76 (syst.) fb





Generally good agreement between measured diff. cross-sections & predictions
(good p_T modelling at parton-level and particle-level)

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

More details in Illia Khvastunov's talk

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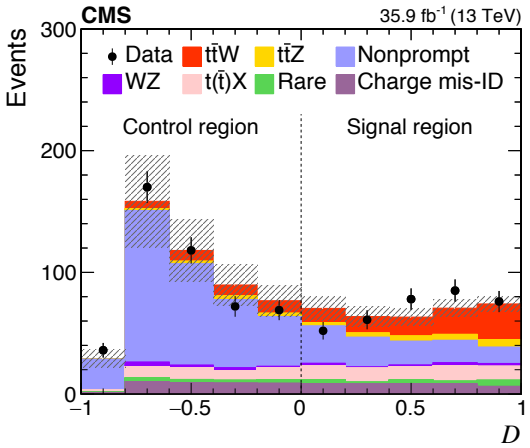
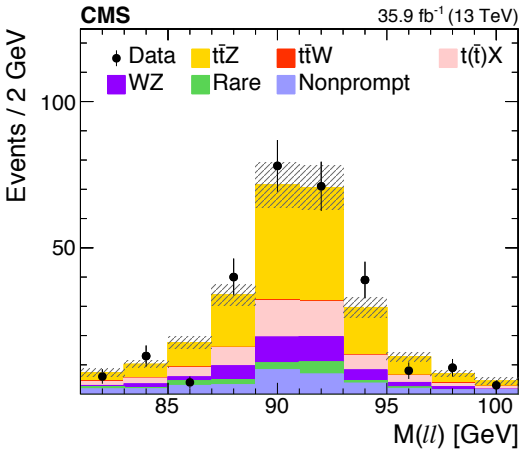
- Motivations
  - Access to top-quark EW coupling - test of pQCD - Important background for BSM searches
- $\sqrt{s} = 13$ TeV measurements by CMS
  arXiv:1711.02547 – submitted to JHEP

• *ttW: Same sign dilepton channel*



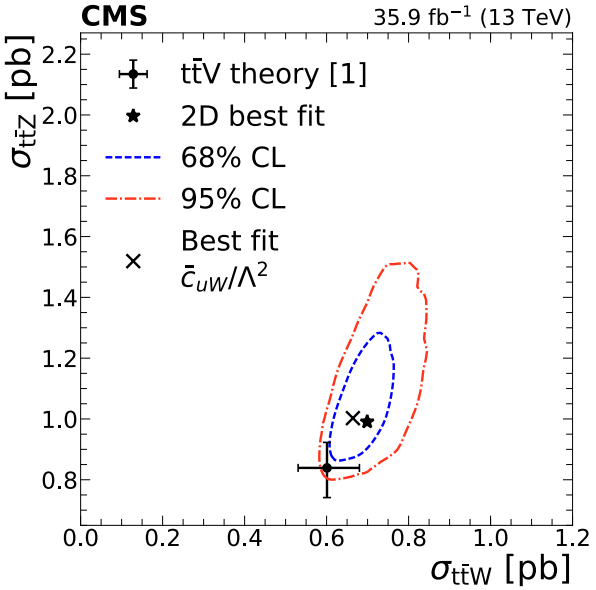
• *ttZ: 3 or 4 lepton channels*



Simultaneous fit of ttW and ttZ consisted with ~30 sub-channel 1D fits

$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}W}) = 0.77^{+0.12}_{-0.11}\,(\mathrm{stat})^{+0.13}_{-0.12}\,(\mathrm{syst})\,\mathrm{pb}$ $\sigma(\mathrm{pp} \to \mathrm{t\bar{t}Z}) = 0.99^{+0.09}_{-0.08}\,(\mathrm{stat})^{+0.12}_{-0.10}\,(\mathrm{syst})\,\mathrm{pb}$

EFT Interpretation



NB: Similar ATLAS results in Eur. Phys. J. C77 (2017) 40

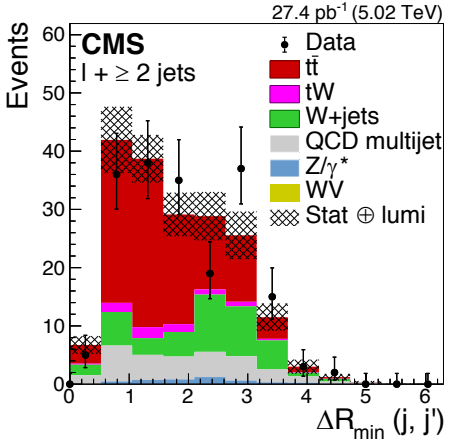
Inclusive $t\bar{t}$ cross-section $\sqrt{s} = 5$TeV

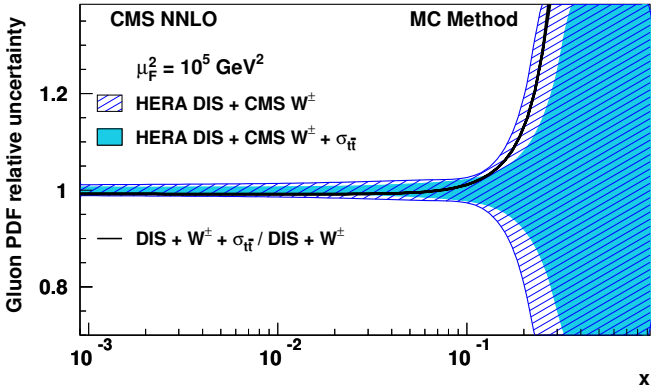
- Complementary data measured by CMS, offering a reference for future Pb-Pb and p-Pb measurements
  - e.g. Lower gluon-gluon initiated $t\bar{t}$ event fraction compared to higher energy samples

arXiv:1711.03143 – submitted to JHEP

- *l+jets analysis: Fit to ΔR non-b-tagged jets in samples with 0, 1, 2 b-tags*
- *Dilepton analyses: Counting measurements*

Channels	$\sigma(t\bar{t})$ result ± stat. ± syst. ± lumi.	$\Delta\sigma/\sigma$
l+jets	68.9 ± 6.5 ± 6.1 ± 1.6 pb	13%
eμ+jets	77 ± 19 ± 4 ± 2 pb	25%
$\mu\mu$+jets	59 ± 29 ± 11 ± 1 pb	52%
Combined	69.5 ± 6.1 ± 5.6 ± 1.6 pb	12%





Moderate constraint on gluon PDF at high x

Studying top-quark production in p-Pb collisions

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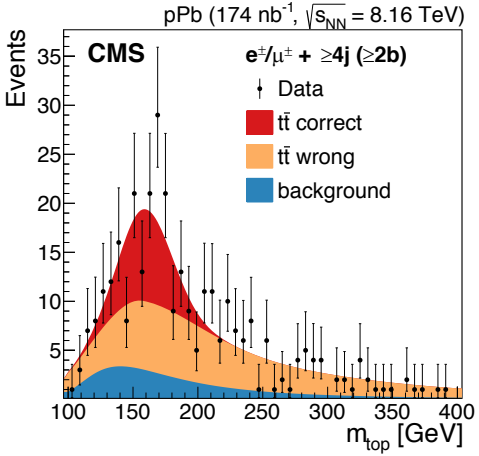
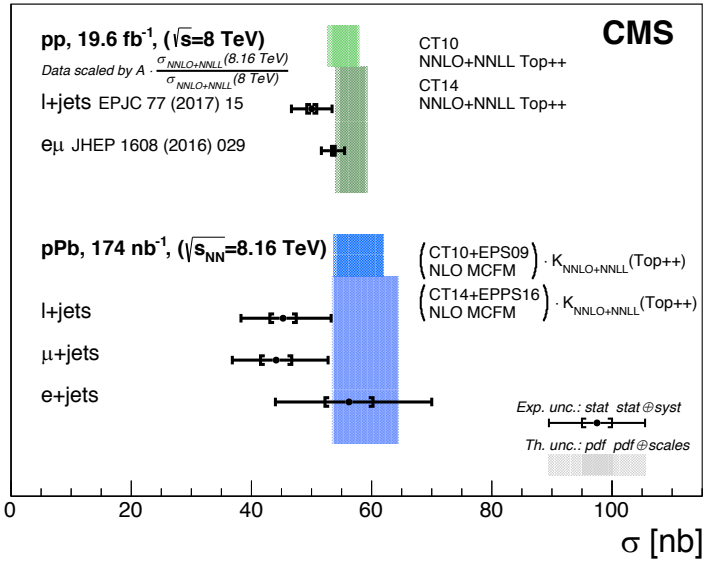
- Motivations
  - Precise probe of nuclear gluon density at high virtualities $Q^2 \approx m_t^2$
  - Provides information on nuclear parton distribution functions (nPDF)
  - Study parton energy loss using top quarks in QGP

- First observation of top quark production in proton-nucleus collisions by CMS
  Phys. Rev. Lett. 119, 242001 (2017)

• *Considering different event categories with 0, 1, ≥ 2 b-tagged jets*

• *$t\bar{t}$ cross section extracted from comb. unbinned max. likelihood fit of $m_{jj'}$ (with jj' the di-jet pairs from W decay)*





$$\sigma_{t\bar{t}}^{\mu+\text{jets}} = 44 \pm 3\,(\text{stat}) \pm 8\,(\text{syst})\,\text{nb},$$
$$\sigma_{t\bar{t}}^{\text{e}+\text{jets}} = 56 \pm 4\,(\text{stat}) \pm 13\,(\text{syst})\,\text{nb},$$

Combined fit →

$$\sigma_{t\bar{t}} = 45 \pm 8\,(\text{total})\,\text{nb}$$

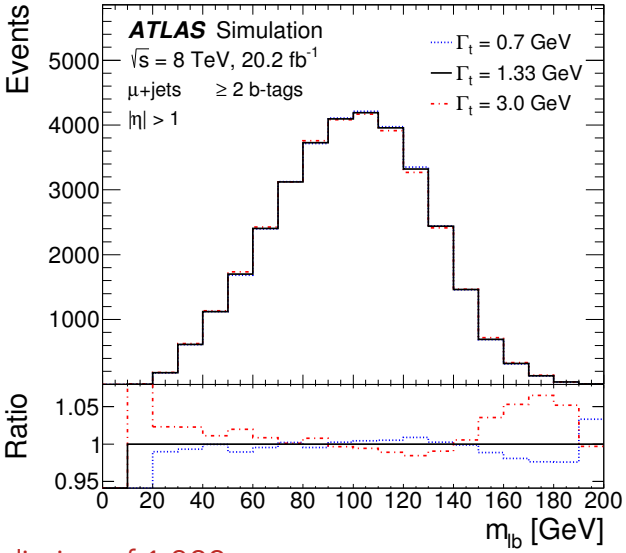
Further top-quark properties measurements

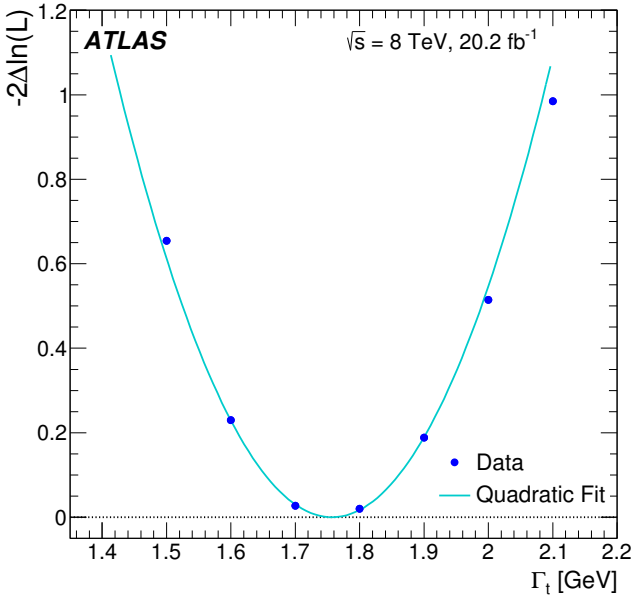
Decay width, mass, charge asymmetry combination

Top-quark decay width measurement

- First direct measurement at $\sqrt{s} = 8$ TeV by ATLAS
  arXiv:1709.04207 – submitted to JHEP

- *Avoid assumptions on top decay branching ratios*
- *Width extracting using l+jets events*
- *$t\bar{t}$ pairs reconstructed using kinematic likelihood fit method*
- *Template method using Γ_t sensitive observables : m_{bl}, $\Delta R\,(j_b, j_l)$*





In good agreement with NNLO prediction of 1.322
⟶ *but less precise than indirect measurements*

$$\Gamma_t = 1.76 \pm 0.33\ (\text{stat.})\ ^{+0.79}_{-0.68}\ (\text{syst.})\ \text{GeV} = 1.76^{+0.86}_{-0.76}\ \text{GeV}$$

⟶ *Assuming $m_t = 172.5$ GeV*
(m_t change by ±0.5 GeV leading up to 0.2 GeV shift on width)

NB: Similar CMS results in CMS-PAS-TOP-16-019

Top-quark mass measurements

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- Some recent measurements with lepton+jets final states at $\sqrt{s}$ = 8 / 13 TeV by ATLAS and CMS
  ATLAS-CONF-2017-071, CMS PAS TOP-17-007

ATLAS (8TeV)

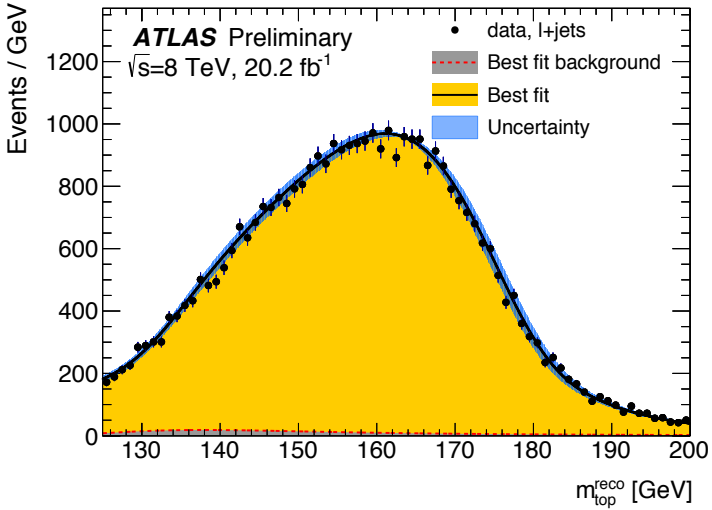
- *3-D template method*: $m_{top}^{reco}, m_W^{reco}, R_{bq}^{reco}$
- *Kinematic fit for jet-parton assignment*
- m_t, *JSF & bJSF extracted simultaneously from unbinned max. likelihood fit to data*

m_{top} = 172.08 ± 0.39 (stat) ± 0.82 (syst) GeV

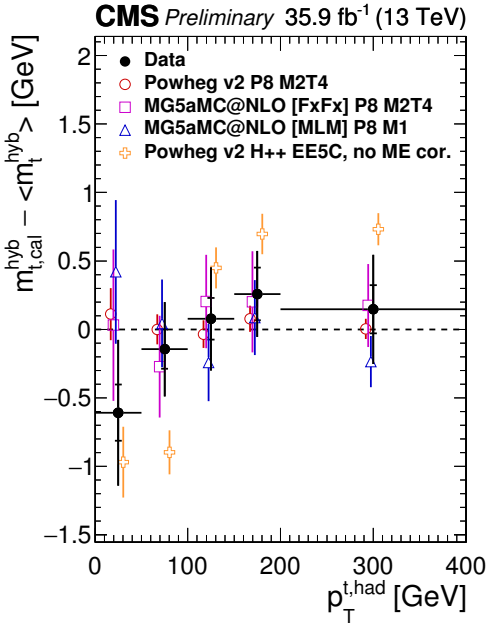
CMS (13 TeV)

- *Ideogram method*: $(m_{top}^{reco}, m_W^{reco})$ *2D fit*
- *In situ JSF extraction & Kinematic fit for jet-parton assignment*
- *Measure as function of several kinematics*

m_{top} = 172.25 ± 0.08 (stat+JSF) ± 0.22(syst) GeV



→ *Latest ATLAS combination*
m_{top} = 172.51 ± 0.50 GeV (29%)



No indications of kinematical bias

A_C combination at $\sqrt{s}$ = 7/8TeV

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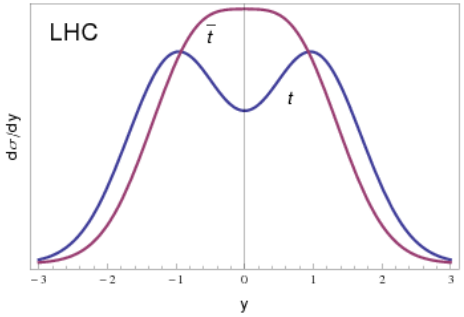
arXiv:1709.05327 - submitted to JHEP

In pp collisions: asymmetry appears as a central-forward asymmetry

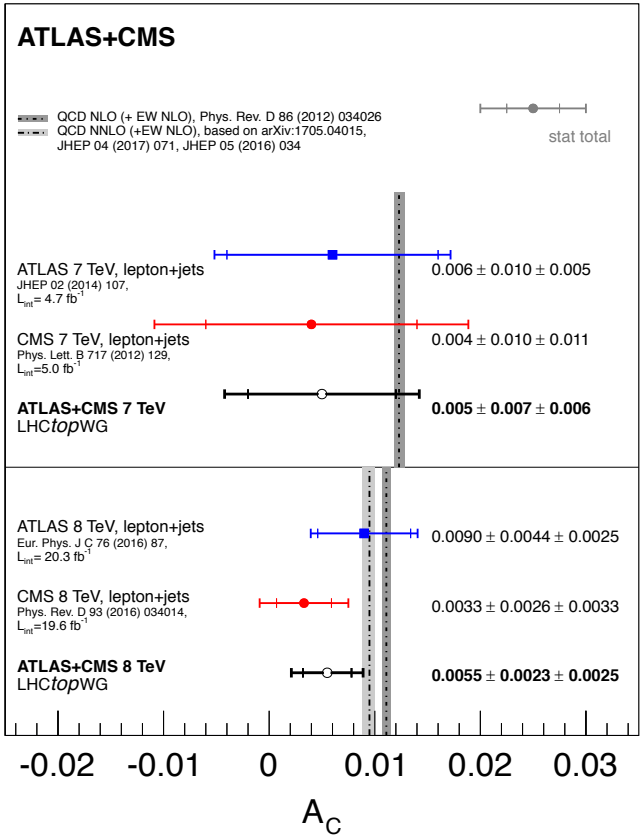
$$A_C = \frac{N^{\Delta|y|>0} - N^{\Delta|y|<0}}{N^{\Delta|y|>0} + N^{\Delta|y|<0}}$$

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



- Inputs extracted from fully reconstructed $t\bar{t}$ system in l+jets channel
  - ATLAS: $|\Delta y|$ corrected to parton level using Fully Bayesian Unfolding (FBU)
  - CMS: $|\Delta y|$ distribution unfolded to parton level with template fits (8TeV) or regularised matrix inversion (7TeV)
- Combination with Best Linear Unbiased Estimate - BLUE method
  - Coarser model (7TeV) or detailed systematic mapping (8TeV)

Significant precision improvement with respect to individual measurements



A_C combination at $\sqrt{s}$ = 7/8TeV

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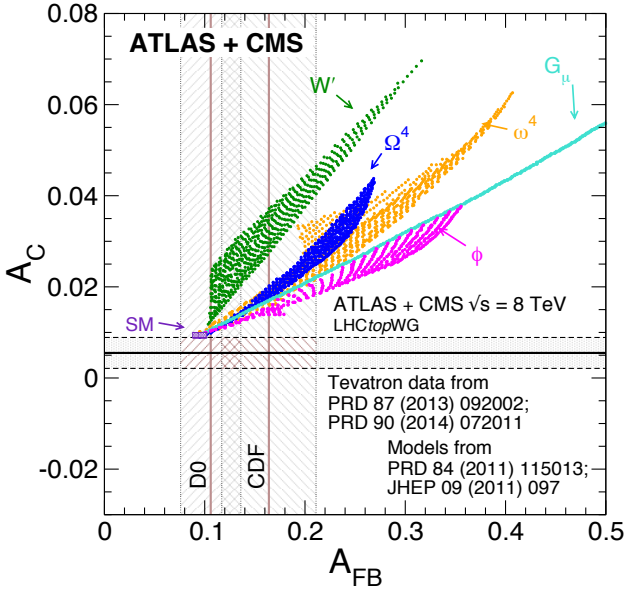
arXiv:1709.05327 - submitted to JHEP

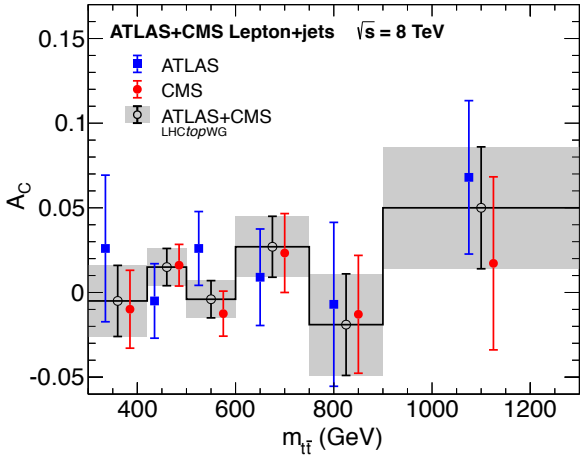
- Interpretation

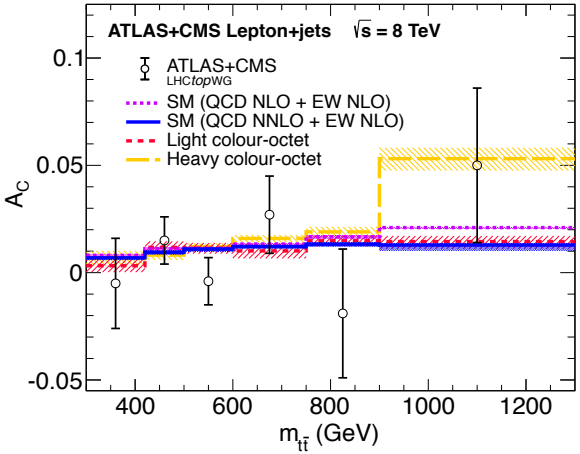


Uniquely restrict phase space of possible new physics phenomena

- Differential A_C combination at $\sqrt{s}$ = 8TeV

- *Main challenge: treatment of bin correlations for each uncertainty source*





In agreement with SM NLO/NNLO calculations
→ compatible with zero asymmetry

Studying colour flow in $t\bar{t}$ events

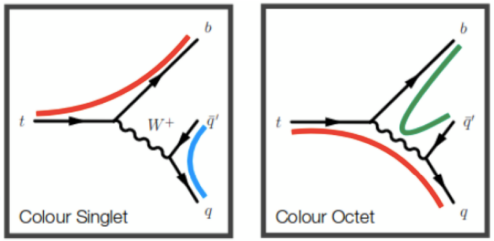
- Measurements by ATLAS, exploring l+jets events at $\sqrt{s} = 13$TeV
  ATLAS-CONF-2017-069

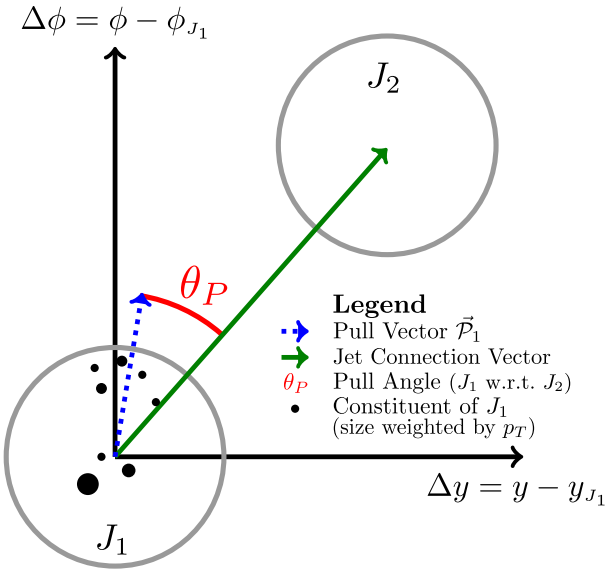
- Colour connections affect the energy distribution between & inside jets

  - *Jet pull: A p_T weighted radial moment of the jet*

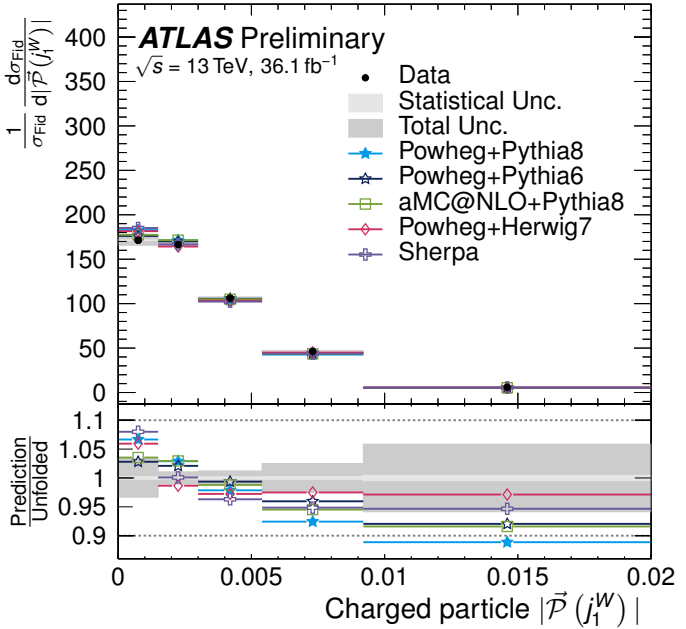
$$\vec{\mathcal{P}}(J) = \sum_{i \in J} \frac{\left|\vec{\Delta r}_i\right| \cdot p_{\mathrm{T}}^i}{p_{\mathrm{T}}^J} \vec{\Delta r}_i$$

Different colour model tested





e.g. $\theta_P \sim 0$ exhibits 2 colour-connected jets



Observed data favour larger values (i.e. wider jets)

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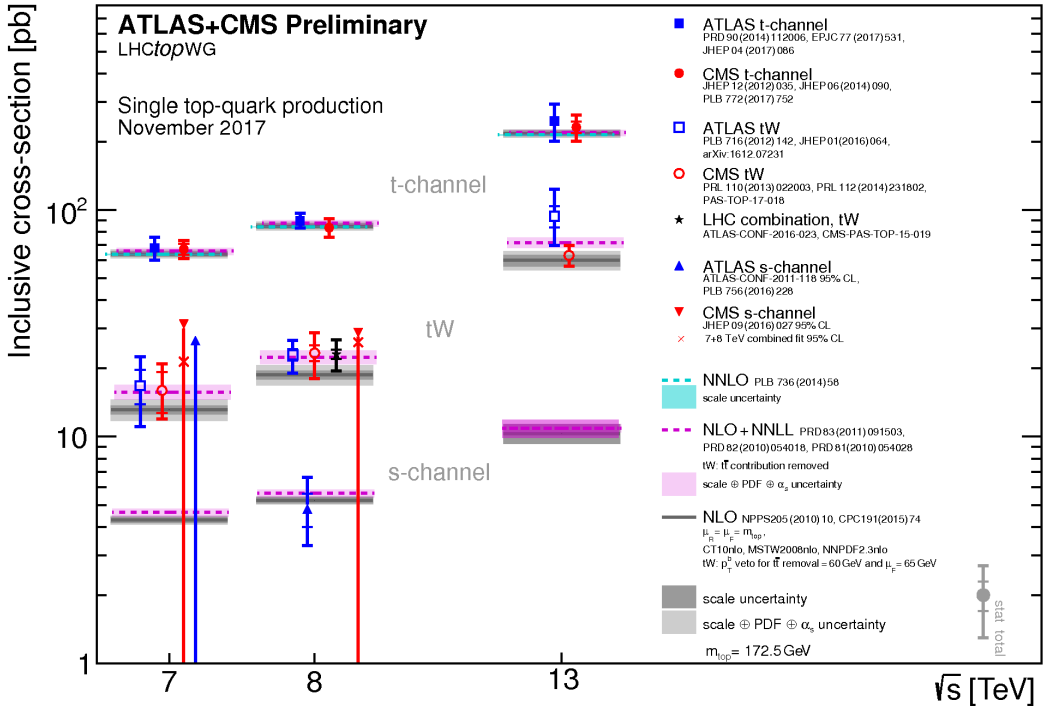
Single top-quark productions

Single top-quark production

- Many measurements performed by the ATLAS and CMS collaborations at $\sqrt{s} = 7$, 8 and 13 TeV

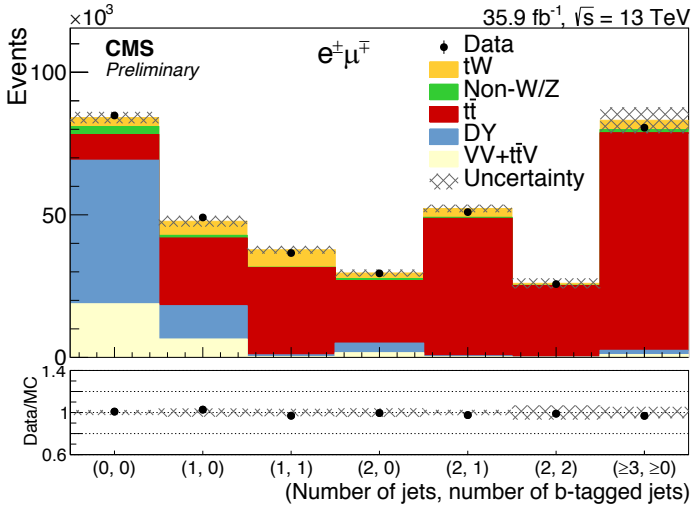


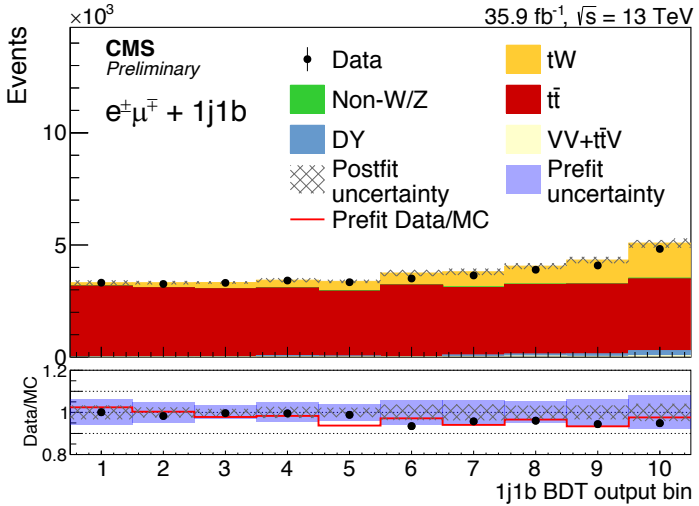
Here as well, predictions impressively in agreement measurements

tW production cross section

- Recent inclusive measurement $\sqrt{s} = 13$ TeV by CMS in di-lepton ($e^{\pm}\mu^{\pm}$) final state
  CMS PAS TOP-17-018

- *Event categorization*
- *BDT used to separate tW signal from $t\bar{t}$ background*
- *Max. likelihood fit to BDT output or $p_T(j)$ distributions to extract tW signal strength*





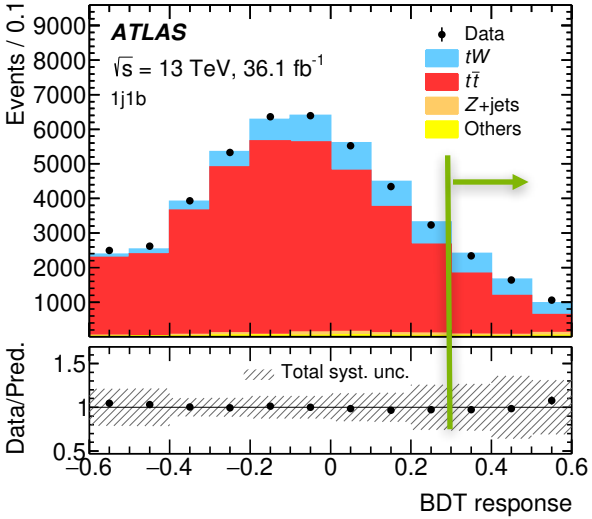
Measured cross section *consistent with SM expectations*

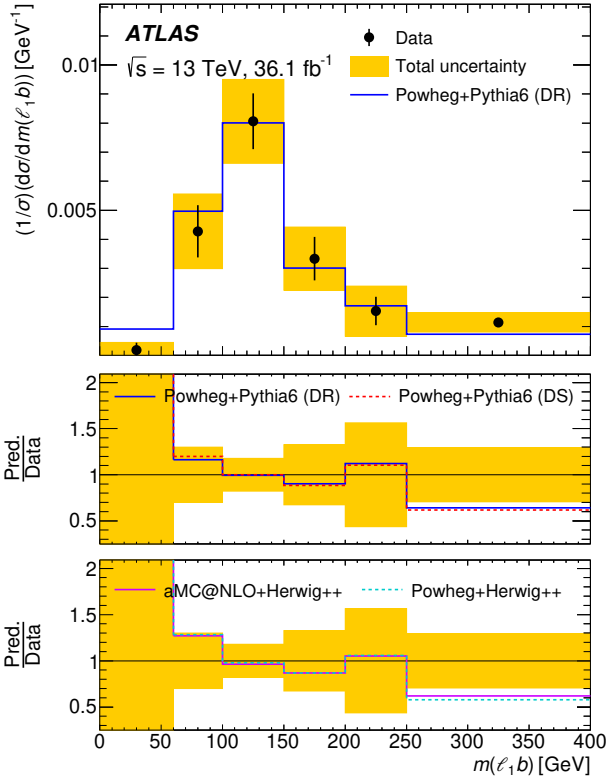
$\sigma = 63.1 \pm 1.8$ (stat.) $\pm$ 6.0 (syst.) $\pm$ 2.1 (lumi.) pb

Differential *tW* cross-section measurements

- Challenges
  - Difficult accurate estimates of rates & kinematics at higher α_s order
  - Interferences with $t\bar{t}$ production
- First differential measurement ever at $\sqrt{s} = 13$ TeV by ATLAS
  arXiv:1712.01602 – submitted to EPJC

- *In a 2l+ 1b-jet fiducial phase space*
- *BDT to separate tW from $t\bar{t}$*
- *Measured as function of several observables at particle-level, normalized with fiducial cross section*

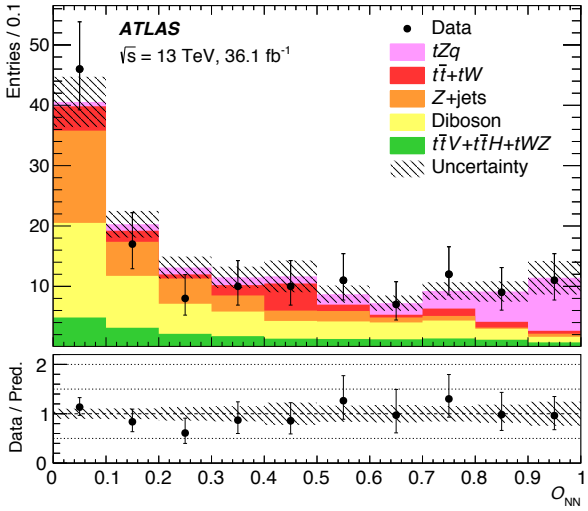


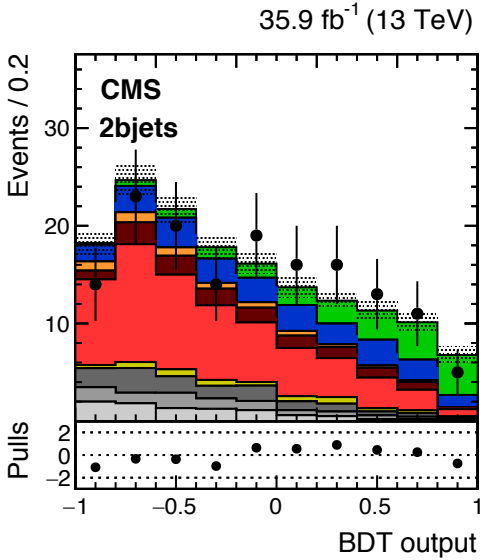


In good agreement with prediction from several MC event generators

First evidences of tZ production

- Motivations
  - Ability to study rare single top quark production with increase of LHC energy and integrated luminosity
  - $pp \rightarrow tZq$ process allows to probe tZ and WWZ couplings
- $\sqrt{s} = 13$ TeV measurements by ATLAS and CMS, exploring tri-lepton final states
  arXiv:1710.03659, arXiv:1712.02825 – both submitted to PLB





- *Max. likelihood fit to extract tZq signal strength on MVA discriminants*
- *Observed (expected) sig. of extracted signal*
  ATLAS: ***4.2σ*** *(5.4σ) vs. CMS:* ***3.7σ*** *(3.1σ)*

Measured cross-sections → $\sigma(tZq) = 600 \pm 170\ (stat.) \pm 140\ (syst.)$ fb

$\sigma(tl^+l^-q) = 123\ ^{+33}_{-31}(stat.)\ ^{+29}_{-23}\ (syst.)$ fb

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Summary

Summary

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- LHC Run I and II provided high statistics top-quark data
  - Many precision measurements performed
- Recent measurements confirm good agreements with SM expectations
  - Probing new kinematic regimes (e.g. in highly-boosted top quark final states)
  - Rare production modes now accessible with the increased LHC energy (e.g. tZ)
  - Improving precisions (e.g. via ATLAS+CMS combinations)
- Better understanding of detector effects and physics modelling
  - Largest experimental uncertainties from jet calibration and *b*-jet energy scales
  - Largest modelling uncertainties from Parton shower and hadronisation

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Back up

State of the art of $t\bar{t}$ cross section measurements

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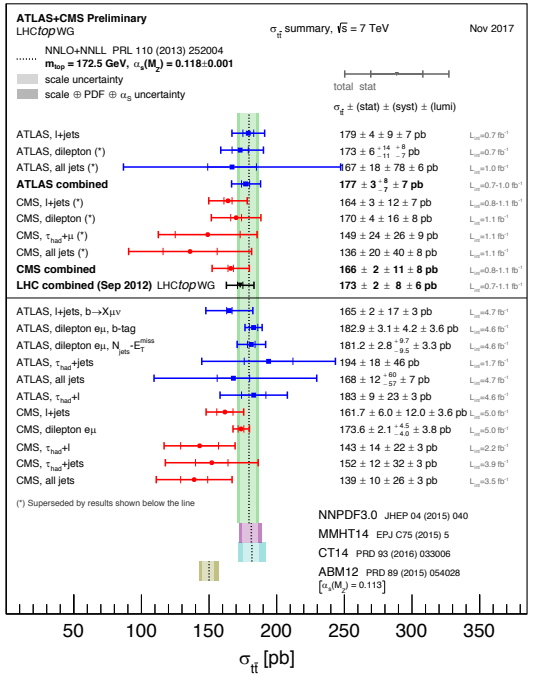
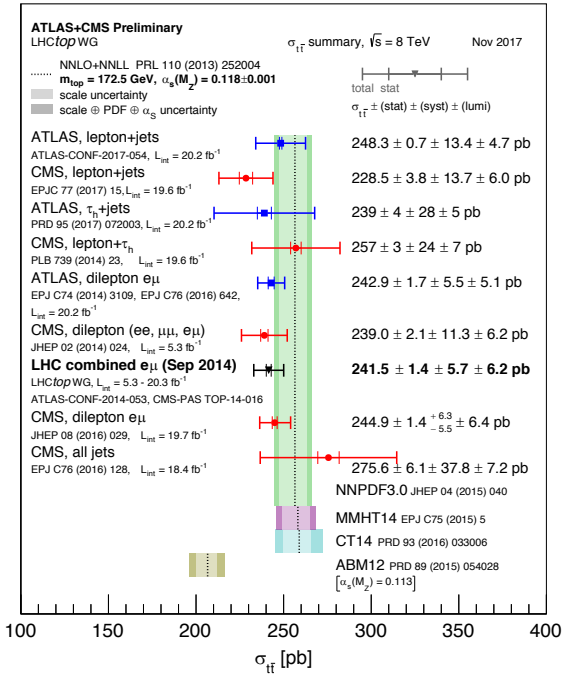
- Many measurements performed by the ATLAS and CMS collaborations at $\sqrt{s} = 7$, 8 and 13 TeV

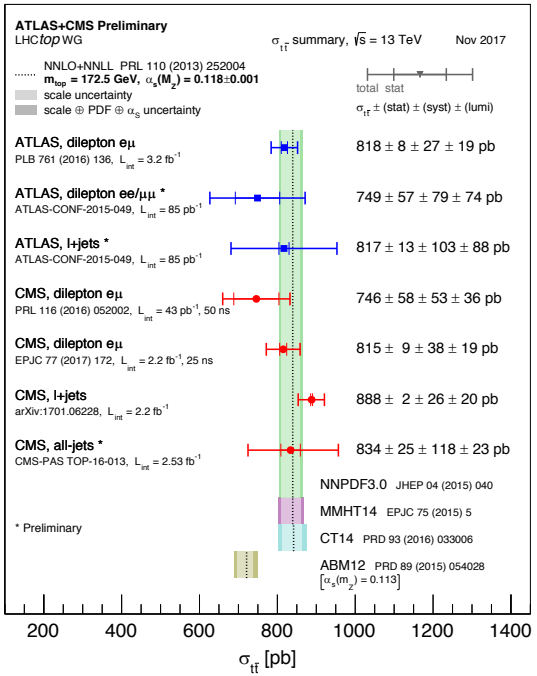
$\sqrt{s} = 7$ TeV



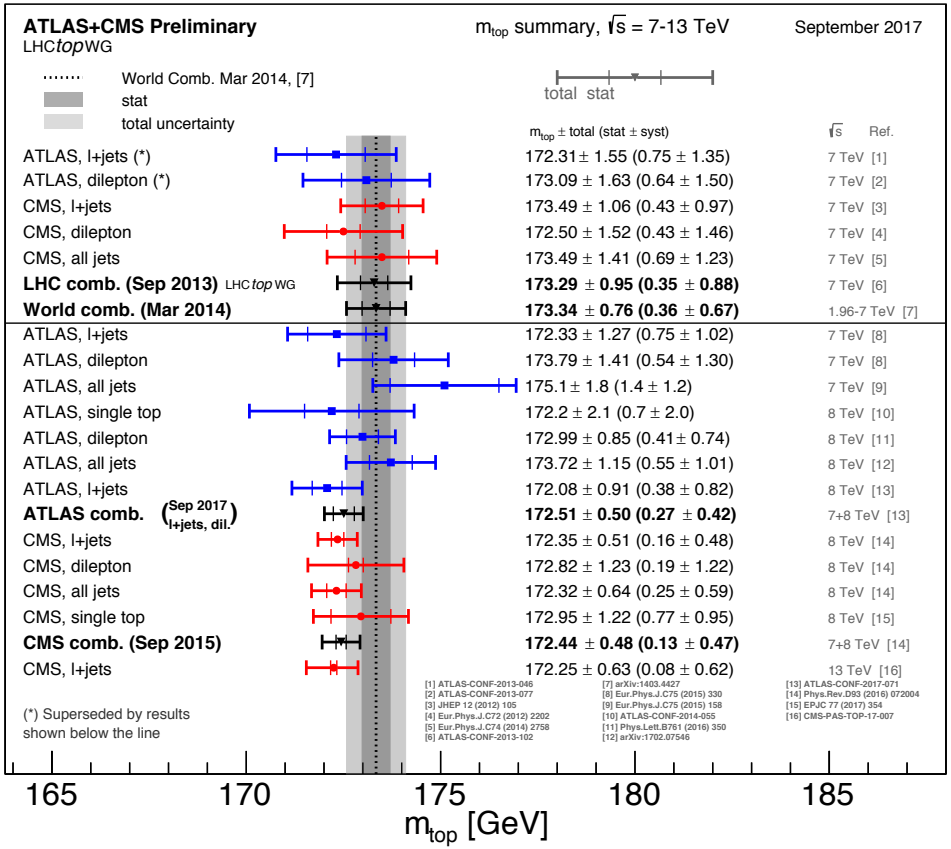
$\sqrt{s} = 8$ TeV



$\sqrt{s} = 13$ TeV



Summary of ATLAS & CMS direct m_{top} measurements



Abstract

Top-quark production at the LHC
(including properties, but not searches)

The top quark is the heaviest known fundamental particle. As it is the only quark that decays before it hadronizes, it gives us the unique opportunity to probe the properties of bare quarks at the Large Hadron Collider. This talk will present highlights of a few recent precision measurements of the top quark using 13 TeV and 8 TeV collision data: top-quark pair and single top production cross sections, including differential distributions and production in association with bosons, will be presented alongside top quark properties measurements. These measurements, including results using boosted top quarks, probe our understanding of top quark production in the TeV regime. Measurements of the top quark mass are also presented.