Inclusive $t\bar{t}$ cross section at ATLAS

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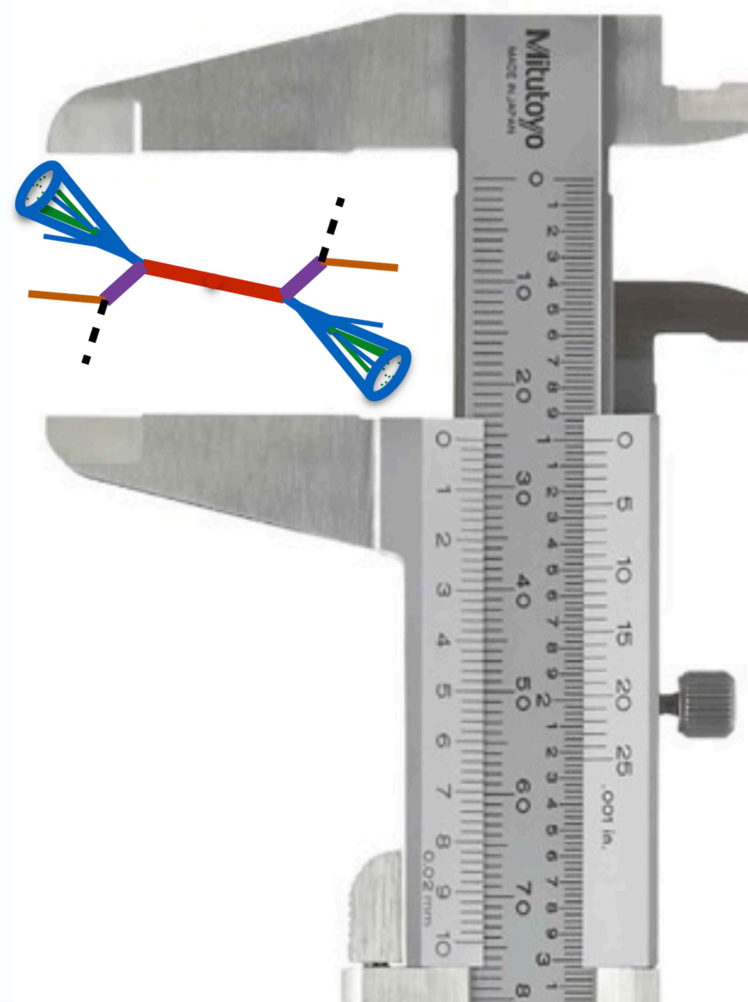


Top Quark Physics at the Precision Frontier

January 16-17, 2018

Fermilab

Outline

- Motivation
- Introduction and available measurements
- Selected measurements in detail
  - Dilepton measurements at 8 & 13 TeV
  - Lepton+jets measurement at 8 TeV
  - Comparison of uncertainties
  - Demise of the beam energy uncertainty
- Applications
  - Fiducial cross-sections
  - Cross section ratios
- Conclusions

This talk borrows heavily from Richard Hawking's excellent Top2017 talk which includes (& compares) ATLAS & CMS tt csec results:
https://indico.cern.ch/event/659310/contributions/2689370/attachments/1524910/2384065/RH_TTXSec_final.pdf

Motivation

- Why should we (still) care about measuring $\sigma_{t\bar{t}}$?

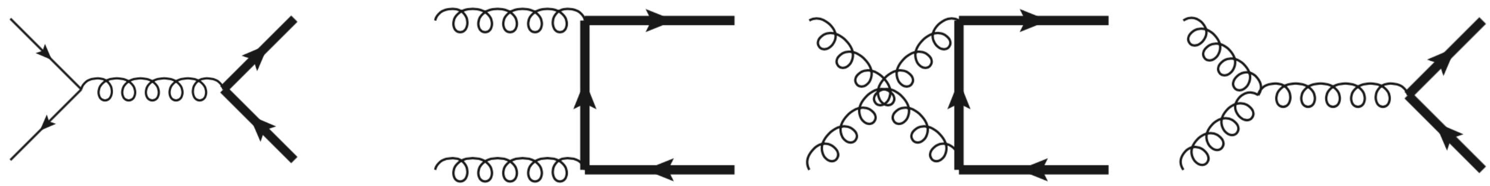
- LHC is a top factory
  - 8 TeV: 15 $t\bar{t}$ pairs/min, 5 million $t\bar{t}$ events in 20 fb^{-1}
  - 13 TeV: 500 $t\bar{t}$ pairs/min, 30 million $t\bar{t}$ events in 36 fb^{-1}

Unprecedented opportunity to look for deviations from the SM

- Test pQCD at NNLO precision (fixed order)
- Tune MC generators (recall that $t\bar{t}$ production is an irreducible background to many BSM processes)
  - NLO ME generators
  - (New) parton shower generators

Introduction

- $\sigma(t\bar{t})$ dominated by gluon fusion (qq/gg=10%/90%) at LHC



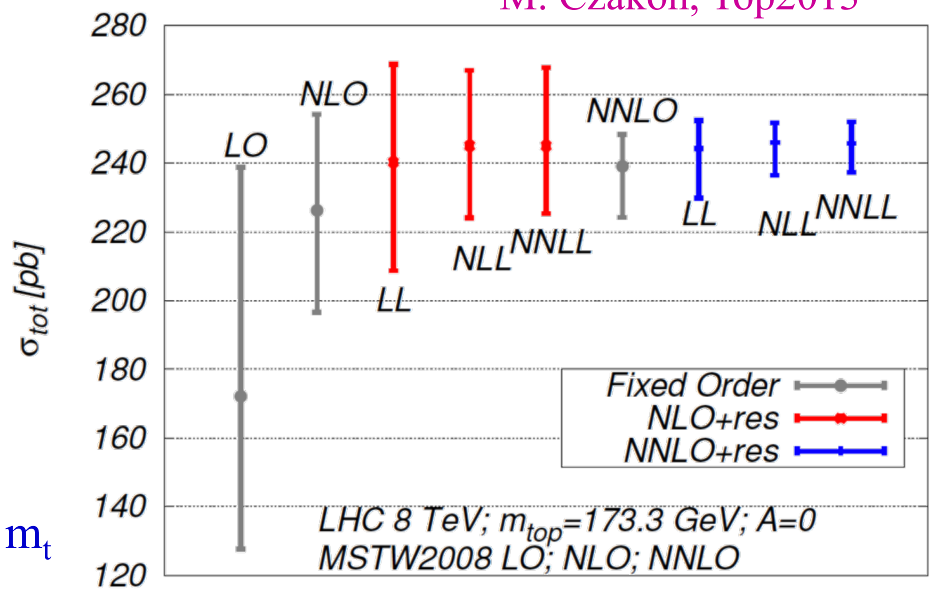
LO diagrams

- Challenging to calculate – NNLO and NNLL corrections are important
  - Uncertainties dominated by QCD scale choice and PDFs
- Cross-sections for m_t=172.5 GeV

√s (TeV)	σ(tt) ± PDF/α_s ± scale	Δσ/σ
7	177.3 ± 9.0 +4.6 -6.0 pb	6.1%
8	252.9 ± 11.7 +6.4 -8.6 pb	5.7%
13	832 ± 35 +20 -29 pb	5.5%

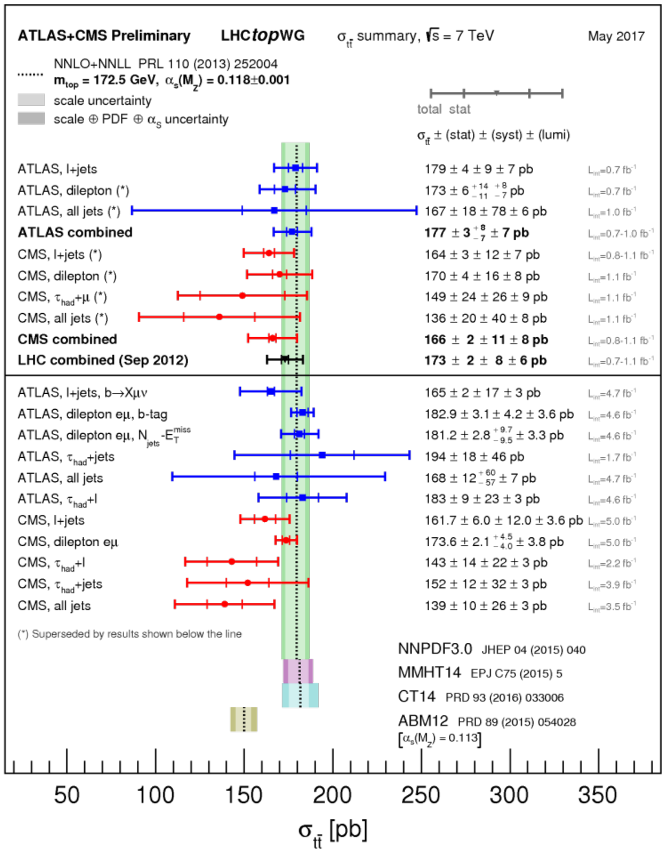
  - Calculated with Top++ 2.0
  - MSTW, CT10 and NNPDF 2.3 PDFs
  - Additional uncertainty of ∓3% for ±1 GeV on m_t

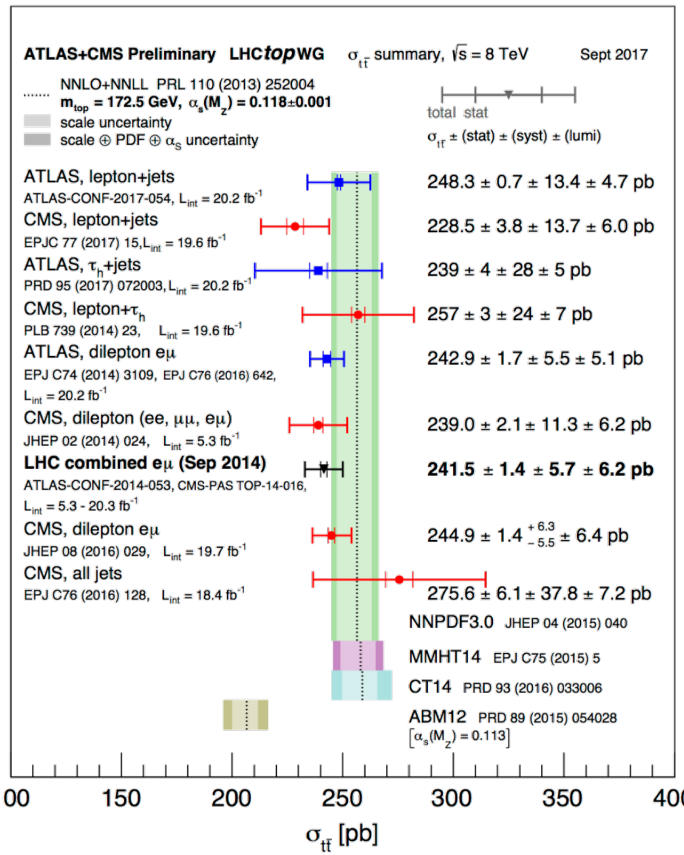
M. Czakon, Top2013

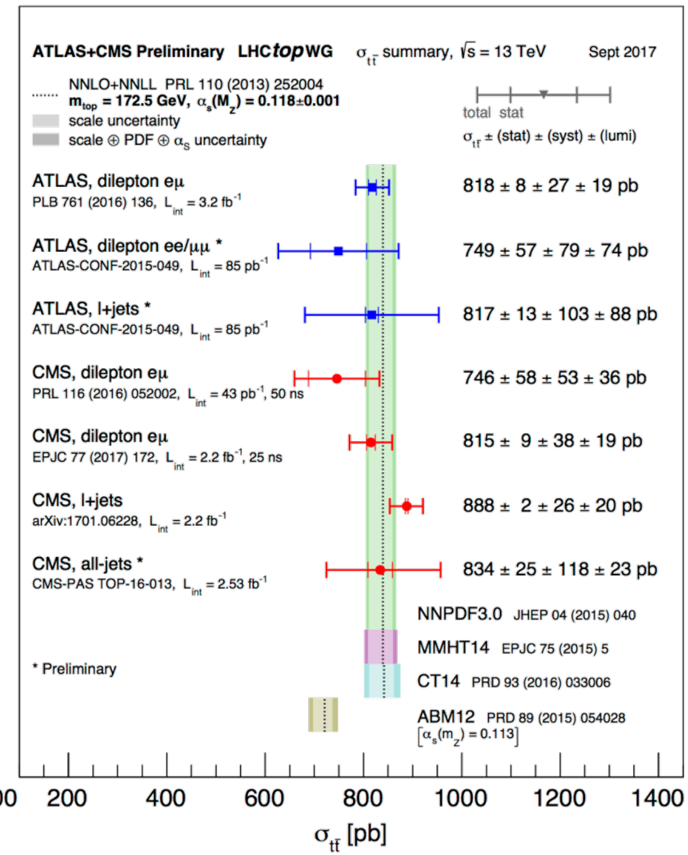


Some measurements

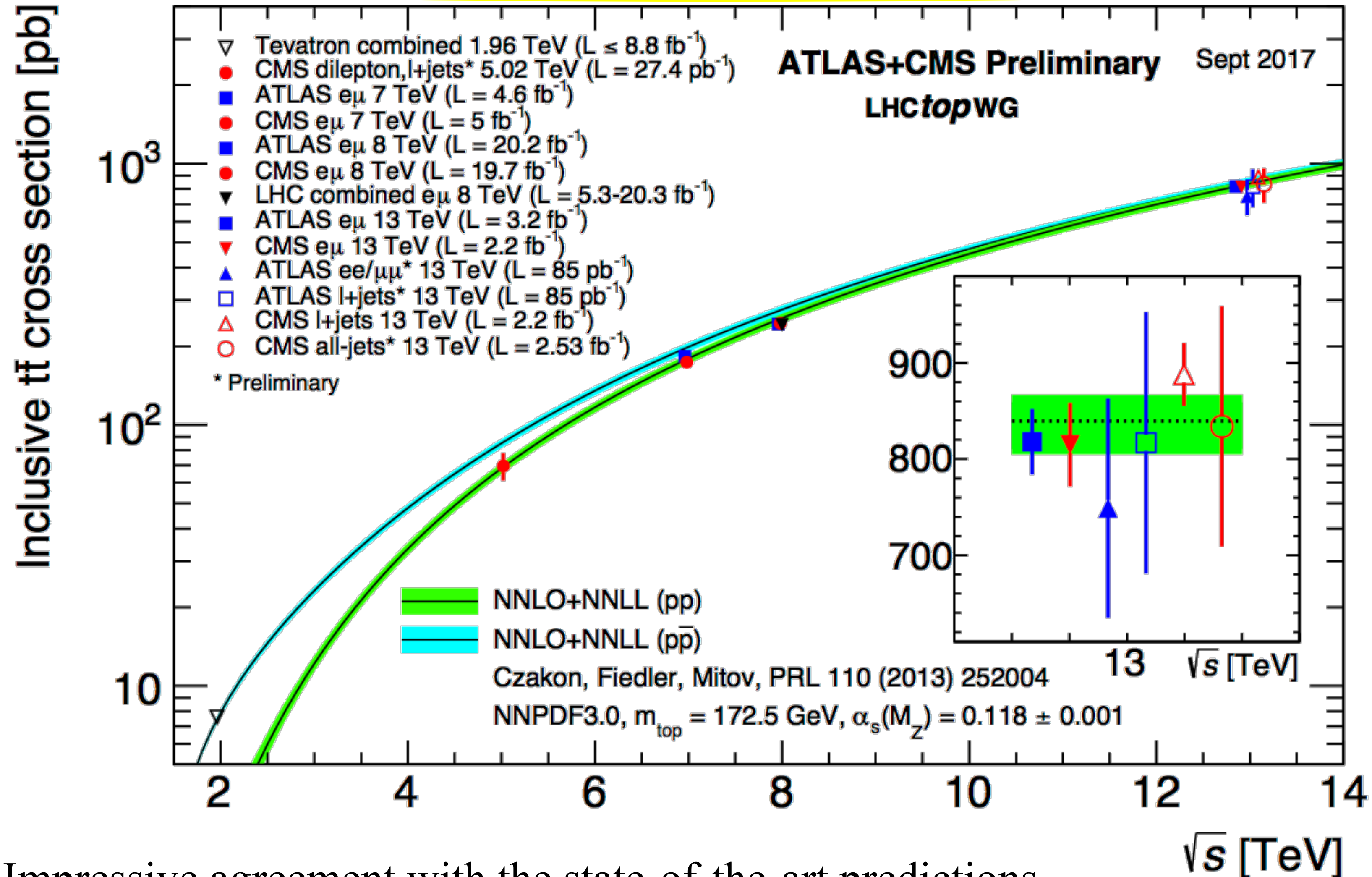
- 18+8+7=33 $t\bar{t}$ cross-section measurements at 7, 8, & 13 TeV – a mature field
  - Most precise measurements from eμ dilepton at 7+8 TeV, and l+jets at 13 TeV
    - Individual analyses with precision of 3-4%
  - All-hadronic and measurements with taus are significantly less precise







Measurements vs. energy



- Impressive agreement with the state-of-the-art predictions
  - Both at Tevatron and all LHC energies

Measurement basics

- Dilepton measurements
  - Most precise results use only eμ final state to avoid $Z/\gamma^* \to ee$ / μμ background
  - Remaining backgrounds from Wt, fake leptons, and residual $Z \to \tau\tau$ and $VV \to e\mu$
  - Limited opportunity for profiling and constraining modeling uncertainties
- Lepton+jets
  - Huge statistics, but backgrounds from t-channel single top, W+jets, and multijets
  - Multiple control regions with different jet and b-tag multiplicities
    - Can constrain JES from $W \to qq$ as in top mass analyses
- Main systematics
  - $t\bar{t}$ modeling (generator choice, QCD scales, radiation, hadronization)
    - Influences efficiencies and acceptances – some gain from fiducial cross-sections
  - Detector calibration – lepton, jet and b-tagging efficiencies, and energy calibration
  - Backgrounds – model using data wherever possible
    - Irreducible Wt background modeled using simulation
  - Luminosity – generally 2-3%, benefitting from precise van der Meer scans
    - No need to normalize to Z cross-section, as sometimes done at Tevatron

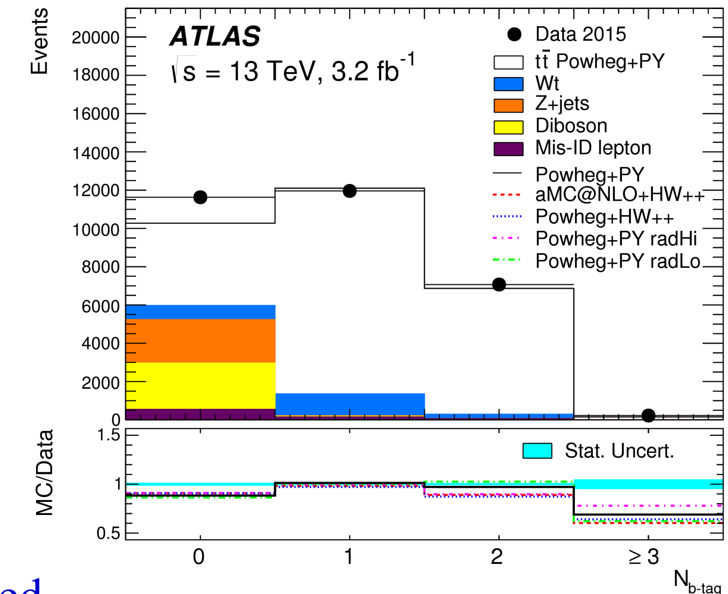
Dilepton eμ measurements

- Avoid systematics due to jet and b-tag modeling
  - Count number of eμ events with 1 & 2 b-tagged jets
    - Ignore light jets – reduces radiation uncertainty
  - Assume two top quarks decay independently

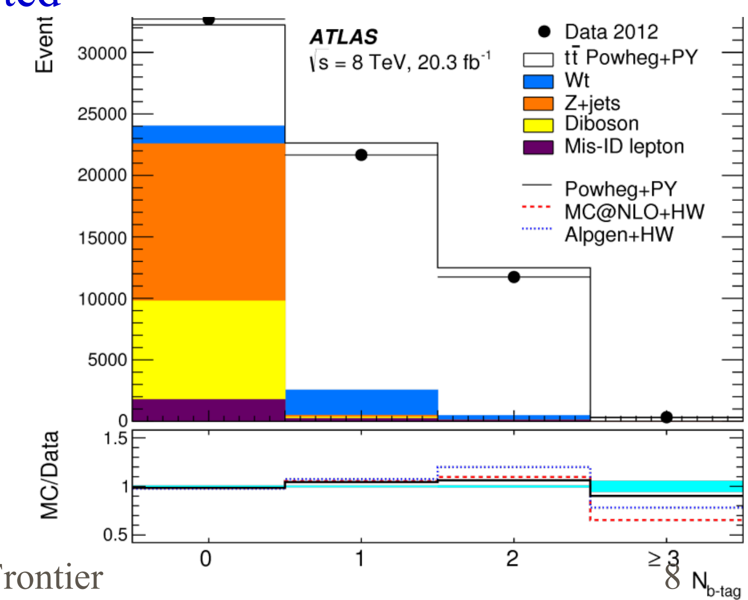
1 b-tag: $$N_1 = L\sigma_{t\bar{t}}\, \epsilon_{e\mu} 2\epsilon_b (1 - C_b \epsilon_b) + N_1^{\mathrm{bkg}}$$

2 b-tag: $$N_2 = L\sigma_{t\bar{t}}\, \epsilon_{e\mu} C_b {\epsilon_b}^2 + N_2^{\mathrm{bkg}}$$

  - $\varepsilon_{e\mu}$: fraction of $t\bar{t}$ with reconstructed $e\mu$ pair
  - ε_b: probability for b-jet from top decay to be reconstructed within acceptance and b-tagged
  - $C_b \approx 1$ accounts for correlations between b-jets
  - N_1^{bkg} and N_2^{bkg} from Wt, $Z \rightarrow \tau\tau$+jets, diboson, fakes
- Fit $\sigma_{t\bar{t}}$ and ε_b; $\varepsilon_{e\mu}$, C_b, Wt and diboson b/g from MC
  - $Z \rightarrow \tau\tau$+1,2 b-tags from $Z \rightarrow ee/\mu\mu$+jets control region
  - Fake leptons from same-sign control region
- Same analysis at 7, 8 and 13 TeV



Phys. Lett. B761 (2016) 136



Eur. Phys. J C74 (2014) 3109

Dilepton eμ measurements – continued

- Largest systematics from modeling $\varepsilon_{e\mu}$
  - Different $t\bar{t}$ models, Pythia vs Herwig parton shower, PDFs
    - 13 TeV models not yet mature
  - Lepton efficiencies/scales from Z→ll
    - Only single lepton triggers to reduce systematic uncertainties
    - Isolation efficiencies measured in-situ in $t\bar{t}$ samples by relaxing cuts
- Background modeling dominated by Wt x-sec uncertainty and $t\bar{t}$/Wt interference
  - Jets, b-tagging and fake leptons <1%
- 8 TeV analysis now updated with final 2012 luminosity uncertainty
  - Beam energy uncertainty can now also be neglected

Uncertainty $\sqrt{s}$	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%) 7 TeV	8 TeV	13 TeV
Data statistics	1.69	0.71	0.9
$t\bar{t}$ modelling and QCD scale	1.46	1.26	3.0
Parton distribution functions	1.04	1.13	0.5
Background modelling	0.83	0.83	0.9
Lepton efficiencies	0.87	0.88	0.8
Jets and b-tagging	0.58	0.82	0.5
Misidentified leptons	0.41	0.34	0.6
Analysis systematics ($\sigma_{t\bar{t}}$)	2.27	2.26	3.3
Integrated luminosity	1.98	2.1	2.3
LHC beam energy	1.79	1.72	1.5
Total uncertainty	3.89	3.6	4.4

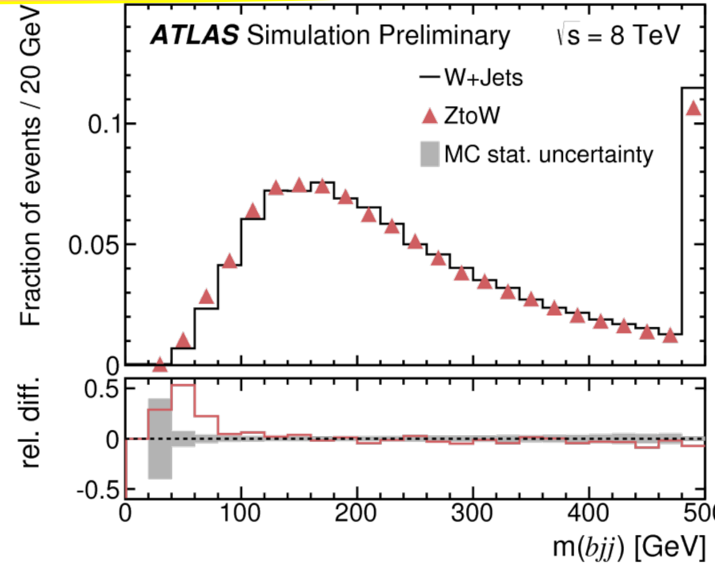
$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\text{pb}\ (\sqrt{s} = 7\,\text{TeV})$$

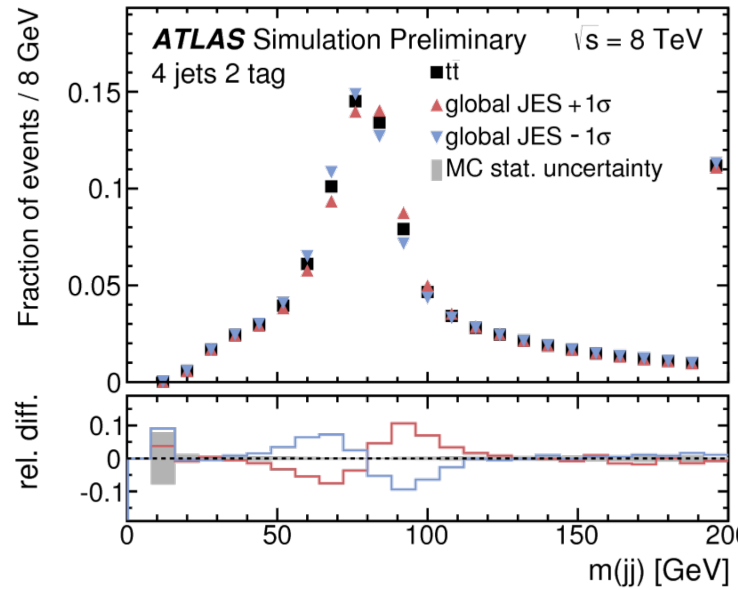
$$\sigma_{t\bar{t}} = 242.9 \pm 1.7 \pm 5.5 \pm 5.1 \pm 4.2\,\text{pb}\ \ (\sqrt{s} = 8\,\text{TeV})$$

($\pm$stat, $\pm$syst, $\pm$lumi, $\pm E_{beam}$)

Lepton+jets measurement – at 8 TeV

- Lepton+jets channel: $t\bar{t} \rightarrow l\nu b\ qqb$
  - Select lepton+E_T^{miss} + ≥4 jets, 1-2 b-tags
  - Significant backgrounds from W+jets and t-channel single top, QCD multijet with fake lepton
  - More complex event selection with more jets
    - Typically larger uncertainties on acceptance
- New ATLAS l+jets analysis at 8 TeV
  - Model W+jets background shape using **data** Z+jets
    - Scale lepton momenta to account for $m_W \neq m_Z$
    - Convert one lepton to a neutrino (E_T^{miss})
  - Provides a good model of W+jets kinematics
    - Normalization of W+jets background floated in fit
  - Exploit $W \rightarrow qq$ decay to constrain jet energy scale with an overall scale factor ($\pm 1\sigma$ of JES syst.)
    - Reduces systematics on jet energy scale





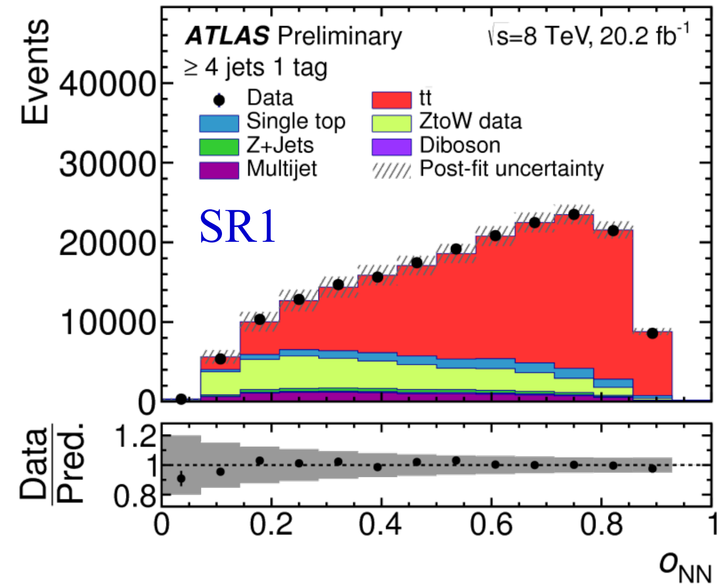
arXiv:1712.06857

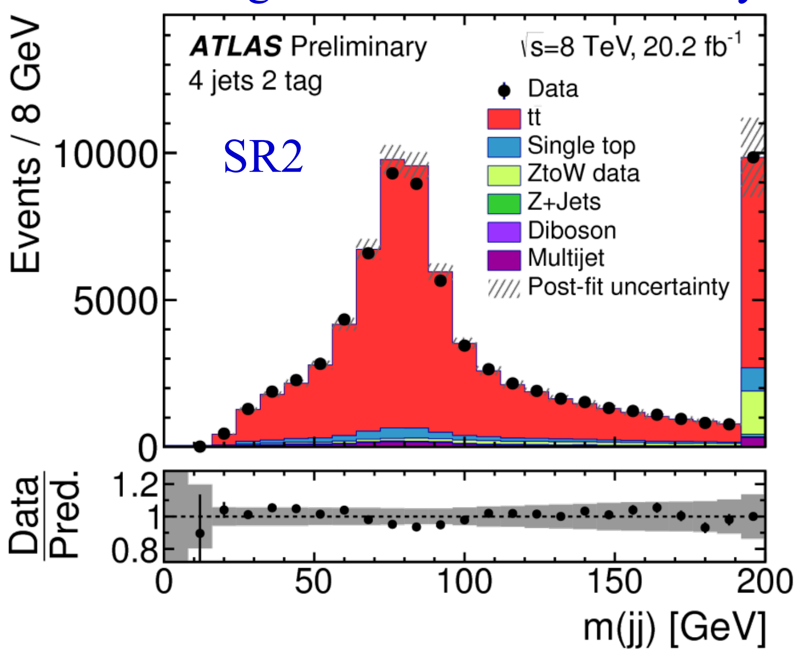
Lepton+jets at 8 TeV – continued

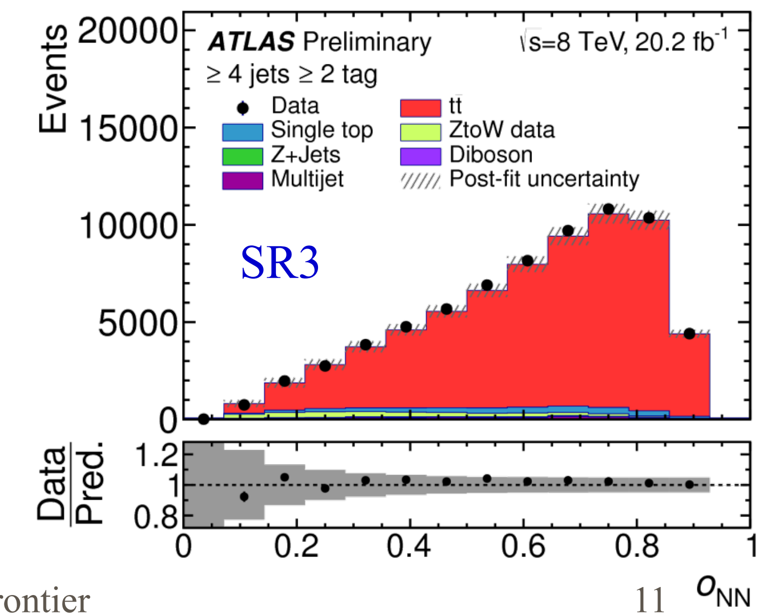
- Final fit to 3 signal regions depending on N_{jet},$N_{b\text{-}tag}$

	Selection	Fit variable
SR1	≥4 jets, 1 b-tag	NN discriminant
SR2	4 jets, 2 b-tags	m(jj)
SR3	≥4 jets, ≥2 b-tags, not SR2	NN discriminant

  - Discriminating variable in each region to separate signal and background and/or constrain systematics







Lepton+jets at 8 TeV – continued

- Simultaneous fit for several parameters
  - $t\bar{t}$ signal strength, W+jets background normalisation in SR1 and SR2+SR3
  - Correction factors for b-tagging efficiency and jet energy scale
- Final result:

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

  - Total uncertainty of 5.7%, systematics dominated
- Largest systematics
  - MC modelling, including scale variations and PDFs
  - Lepton trigger and identification efficiencies
  - Jet energy scale (reduced by 60% due to in-situ W→qq constraint)
    - Residual b-tagging efficiency systematic is small

Source	$\frac{\Delta\sigma}{\sigma}$ [%]
Data statistics	±0.3
Detector	
Jet energy scale	±1.1
Jet energy resolution	±0.1
Jet reconstruction efficiency	<0.1
E_T^{miss} scale	±0.1
E_T^{miss} resolution	<0.1
Muon momentum scale	<0.1
Muon momentum resolution	<0.1
Electron energy scale	±0.1
Electron energy resolution	<0.1
Lepton identification	±1.4
Lepton reconstruction	±0.3
Lepton trigger	±1.3
Flavour tagging	
b-tagging efficiency	±0.3
c-tagging efficiency	±0.5
Mistag rate	±0.3
Background normalisation	
Multijet	±0.6
Single top	±0.3
Z+jets	±0.2
Diboson	±0.1
MC modelling	
NLO matching	±1.1
Scale variations	±2.2
Parton shower	±1.3
PDF	±3.0
$Z$to$W$ modelling	±1.1
Luminosity	±1.9
Total(sys)	±5.7
Total(sys+stat)	±5.7

Comparison of uncertainties for 13 and 8 TeV

- Uncertainties (%) on total cross-section classified into various components
  - Statistics, $t\bar{t}$ modeling, detector, background, luminosity
    - Beam energy uncertainty neglected if quoted

$\sqrt{s}$ (TeV)	$\int L$ (fb^{-1})	Measurement	Stat.	$t\bar{t}$ model	Det.	Bkg	Lumi	Total
13	3.2	dilepton	0.9	3.0	1.1	0.9	2.3	4.2
8	20.2	dilepton	0.7	1.7	1.2	0.9	2.1	3.2
8	20.2	l+jets	0.3	4.1	2.3	1.3	1.9	5.7

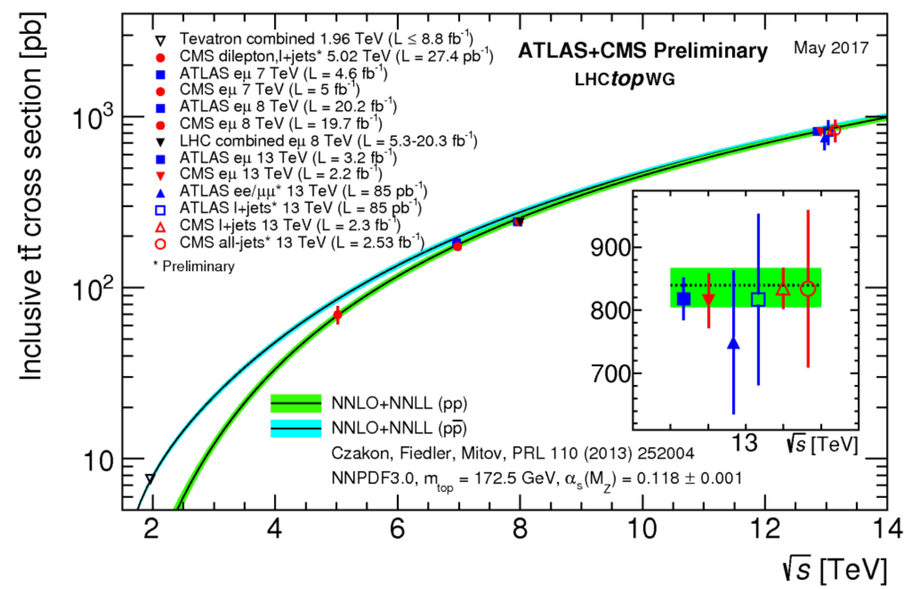
- 13 TeV dilepton result not as precise as 8 TeV
  - Modeling uncertainties significantly larger for l+jets at 8 TeV
- 13 TeV not yet mature – larger $t\bar{t}$ modeling uncertainties
  - Still potential for improvement in 13 TeV dilepton analyses

Demise of the beam energy uncertainty

- Cross-section is a steep function of √s
  - At √s=8 TeV, 2.6% change in $\sigma(t\bar{t})$ **prediction** for 1% change in √s
    - Not negligible compared to experimental precision
- How well do we know √s at LHC?
  - First estimates from revolution frequency difference of protons and Pb in LHC
  - 2013 p+Pb run → 0.66% in √s, giving 1.7% in $\sigma(t\bar{t})$ – significant uncertainty
- New estimates based on magnetic model

$$P = \frac{Ze}{2\pi} \oint B(s)ds$$

  - LHC magnets and transfer functions understood to 0.1%
    - Other sources negligible
- Now, 0.2-0.3% on $\sigma(t\bar{t})$ – can neglect it ☺



LHC beam energy uncertainty

Contribution	Error (%)
PC calibration	0.001
Slow radial changes	0.005
Earth tides	0.005
Orbit correctors	0.03
Transfer function	0.1
Sum	0.1

Phys. Rev. Accel. Beams 20 081003

Fiducial cross-sections

- Analyses also quote fiducial cross-sections
  - Fiducial predictions with NNLO corrections for production/decay now available

ATLAS setup, $e^{\pm}\mu^{\mp}$ channel [24]						
energy	fiducial volume	LO [pb]	NLO [pb]	$\hat{\text{N}}$NLO [pb]	$\delta_{\text{dec.}}$	ATLAS [pb]
7 TeV	$p_T(l^{\pm}) > 25$ GeV, $\lvert\eta(l^{\pm})\rvert < 2.5$	$1.592^{+39.2\%}_{-26.0\%}$	$2.007^{+11.9\%}_{-13.2\%}$	$2.210^{+2.2\%}_{-6.0\%}$	-0.3%	$2.305^{+3.8\%}_{-3.8\%}$
7 TeV	$p_T(l^{\pm}) > 30$ GeV, $\lvert\eta(l^{\pm})\rvert < 2.4$	$1.265^{+39.3\%}_{-26.1\%}$	$1.585^{+11.8\%}_{-13.1\%}$	$1.736^{+2.2\%}_{-6.0\%}$	-0.8%	$1.817^{+3.8\%}_{-3.8\%}$
8 TeV	$p_T(l^{\pm}) > 25$ GeV, $\lvert\eta(l^{\pm})\rvert < 2.5$	$2.249^{+37.9\%}_{-25.5\%}$	$2.855^{+11.9\%}_{-12.9\%}$	$3.130^{+2.3\%}_{-6.0\%}$	-0.3%	$3.036^{+4.1\%}_{-4.1\%}$
8 TeV	$p_T(l^{\pm}) > 30$ GeV, $\lvert\eta(l^{\pm})\rvert < 2.4$	$1.788^{+38.0\%}_{-25.5\%}$	$2.256^{+11.7\%}_{-12.9\%}$	$2.461^{+2.3\%}_{-6.1\%}$	-0.7%	$2.380^{+4.1\%}_{-4.1\%}$

Gao and Papanastasiou, arXiv:1705.08903

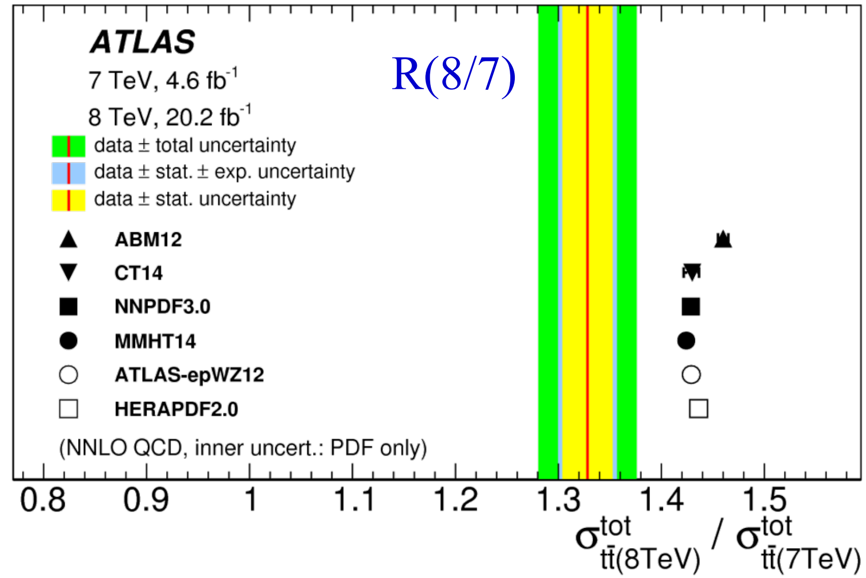
  - Good agreement with experiment after incorporating NNLO corrections

$t\bar{t}$ cross-section ratios at different $\sqrt{s}$

- Some systematics cancel in ratio of cross-sections at different energies
  - Especially for analyses using the same technique, consistent MC, etc.

R(8/7)	R ± stat ± syst ± lumi	ΔR/R
ATLAS eμ	1.328±0.024±0.015±0.038	3.5%

  - NNLO+NNLL prediction 1.430±0.013
    - Uncertainty dominated by PDFs
- 8/7 TeV result 2.1σ below prediction …
- ATLAS has also calculated ratios from eμ analysis at 13/7 and 13/8 TeV
  - Results in agreement with predictions, but lower precision (4.8% and 4.7%)
- ATLAS has also calculated ratios $t\bar{t}$/Z
  - Luminosity uncertainty cancels
  - Good agreement with expectations



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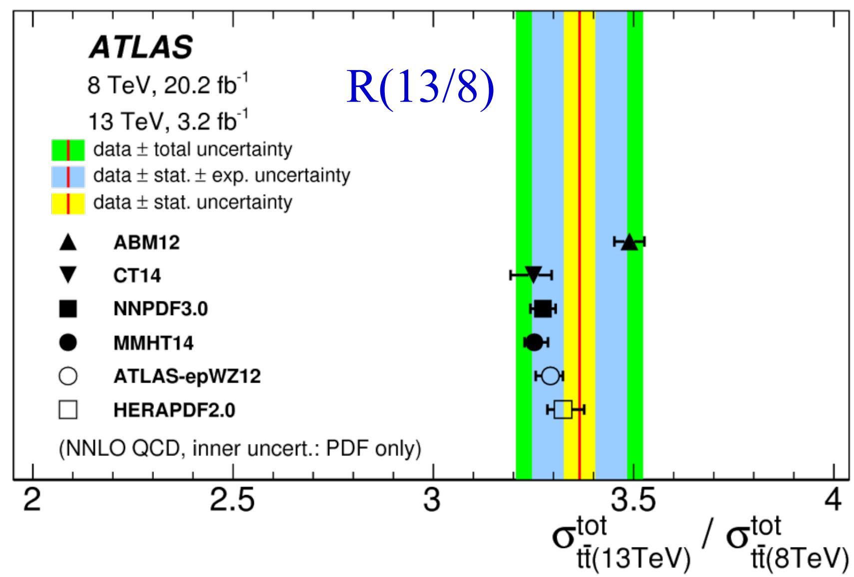


Conclusions

- Inclusive $t\bar{t}$ cross-sections from LHC are now quite mature
  - Most precise measurements from dilepton and lepton+jets channels
  - 7-8 TeV individual channel results with precision of 3-4%
    - Slightly less precise at 13 TeV, but only relatively 'early' analyses so far, and no use of 2016 data yet
- Total x-sec results consistent with NNLO+NNLL predictions for all energies
  - First comparisons with NNLO **fiducial** cross-section predictions
    - Important to model the decays at NNLO, as well as production
- Various applications
  - Constraints on gluon PDF
- Can we do better?
  - Refine analysis of 13 TeV data, profiting from $t\bar{t}$ modelling studies at 13 TeV
  - Improved predictions – since more LHC data in PDFs, but beware of circularity …

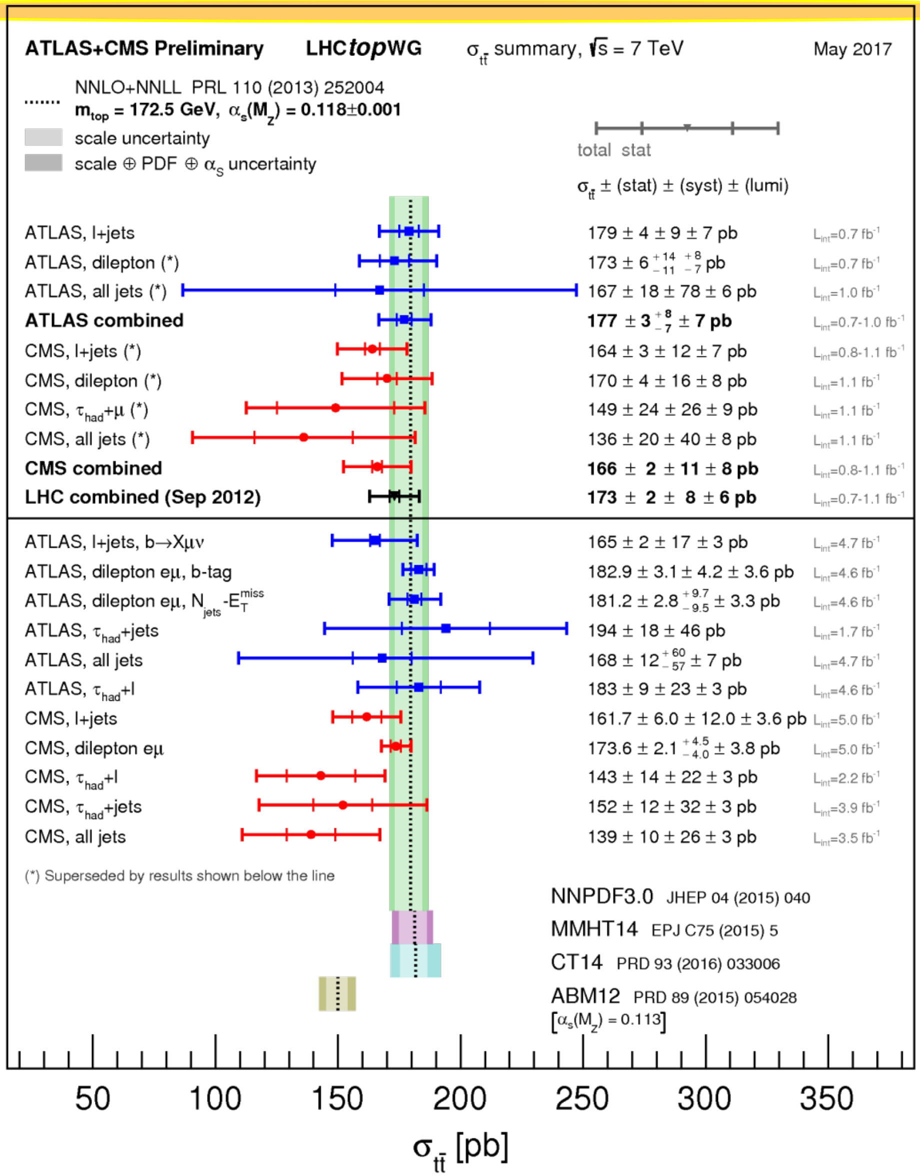
References

- Dilepton analyses
  - ATLAS 13 TeV: Phys. Lett. B761 (2016) 136
  - ATLAS 7+8 TeV: Eur. Phys. J C74 (2014) 3109 + addendum C76 (2016) 642
- Lepton+jet analyses
  - ATLAS 8 TeV: arXiv:1712.06857
- Others
  - ATLAS tt/Z ratios: JHEP 02 (2017) 117
  - ATLAS 8 TeV τ+jets: Phys. Rev. D 95 (2017) 072003
  - LHC beam energy: Phys. Rev. Accel. Beams 20 081003
  - Combined summary plots

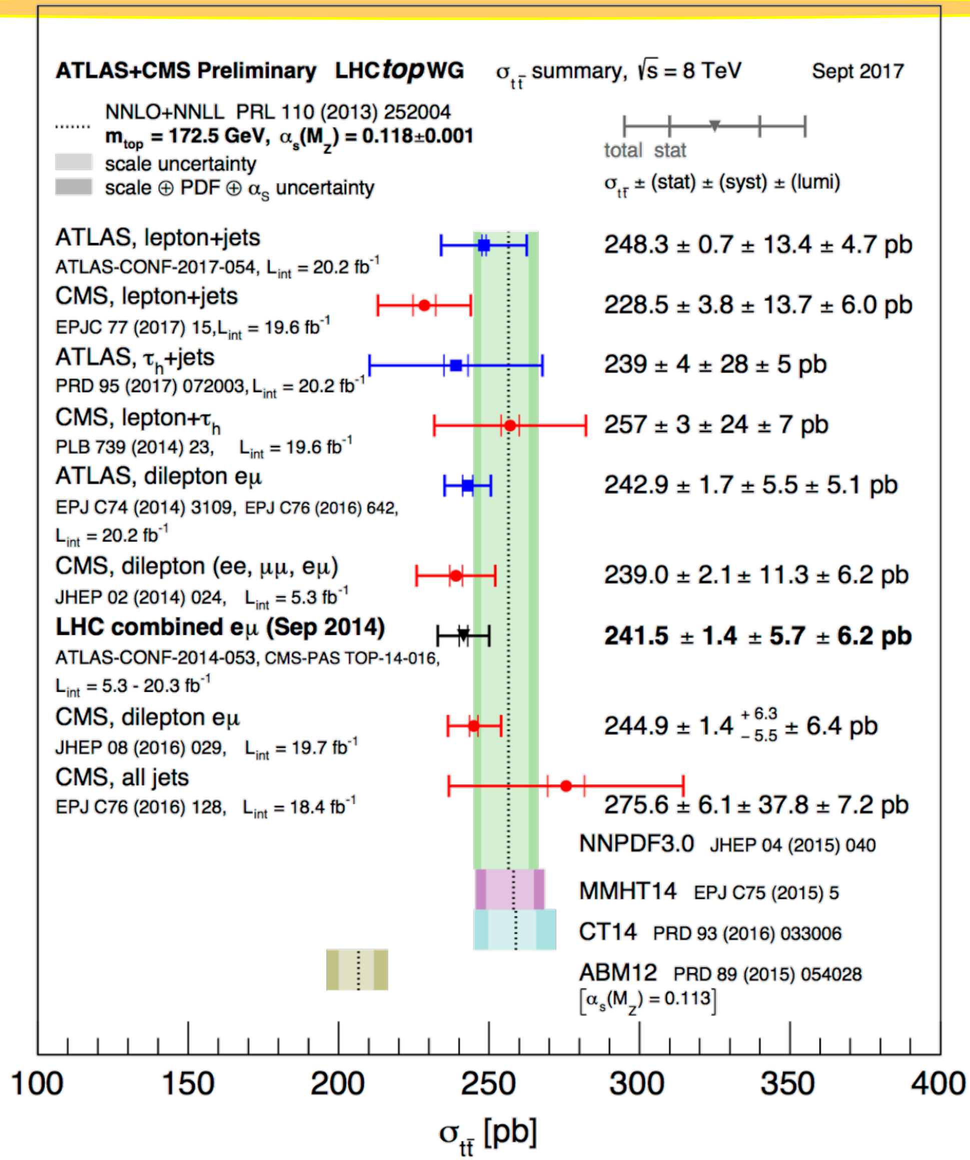
Backup

- Backup slides

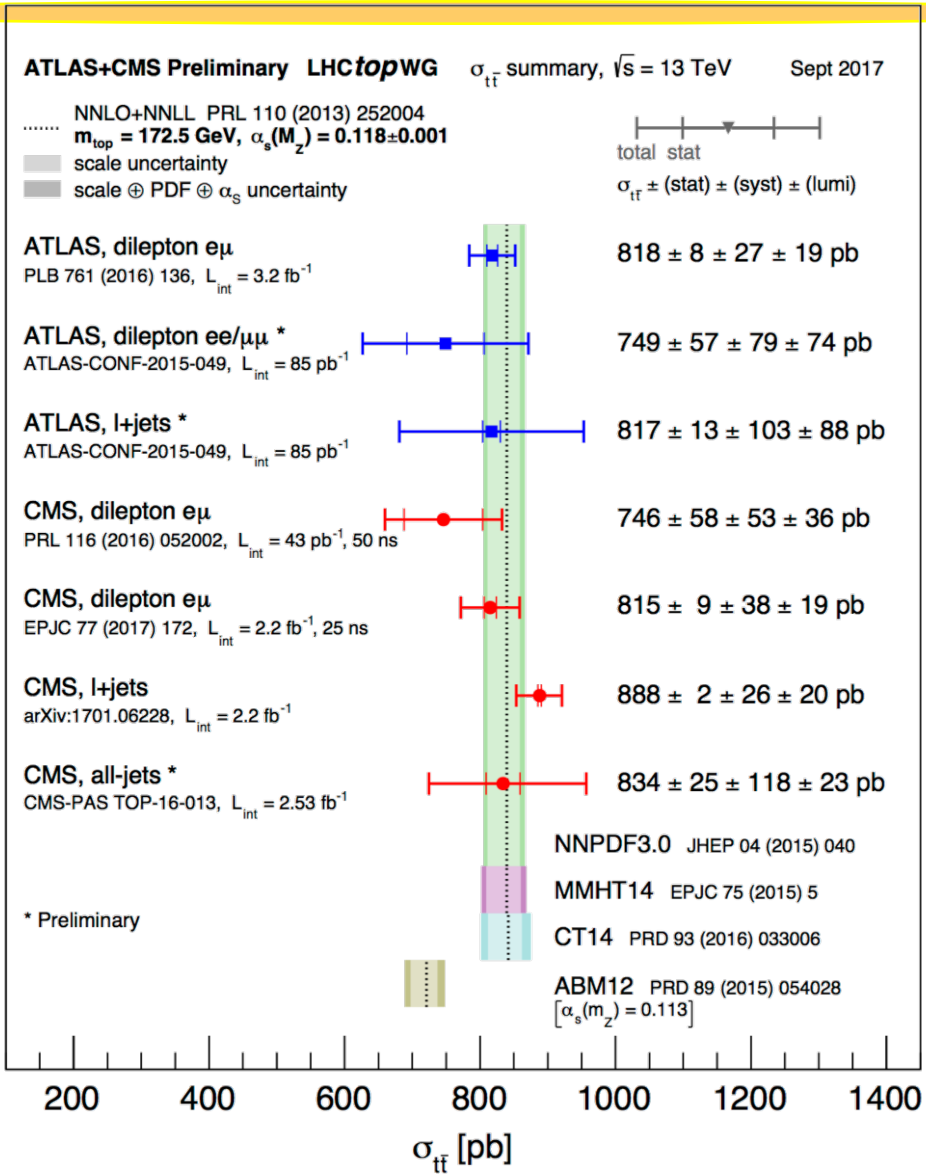
Cross-section measurements at 7 TeV



Cross-section measurements at 8 TeV



Cross-section measurements at 13 TeV

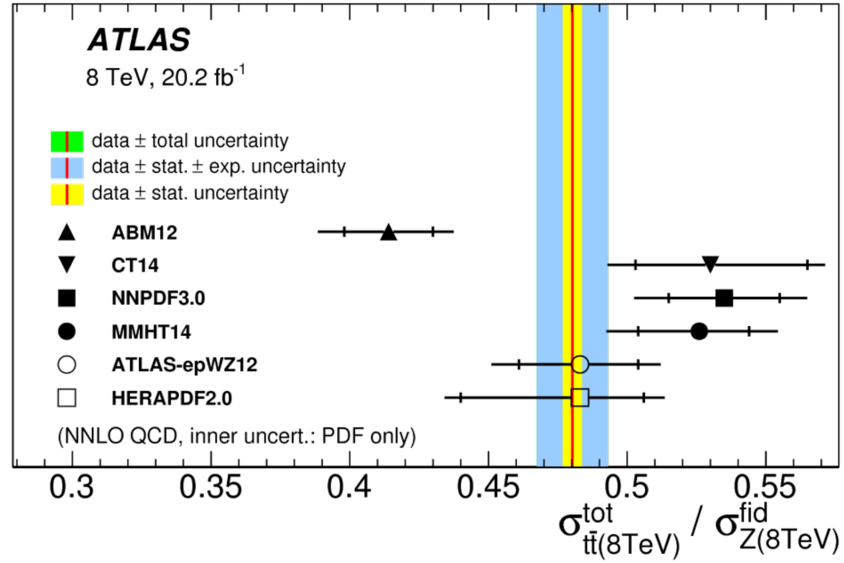


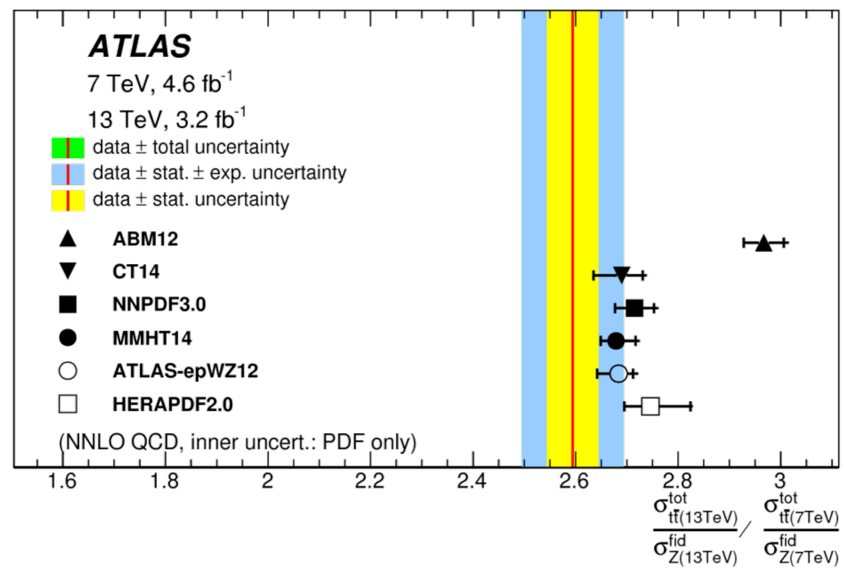
tt/Z cross-section ratios

- Luminosity uncertainty removed by considering $t\bar{t}$/Z cross-section ratio

$$R_{t\bar{t}/Z} = \frac{\sigma_{t\bar{t}}}{0.5\left(\sigma_{Z\to ee} + \sigma_{Z\to\mu\mu}\right)}$$

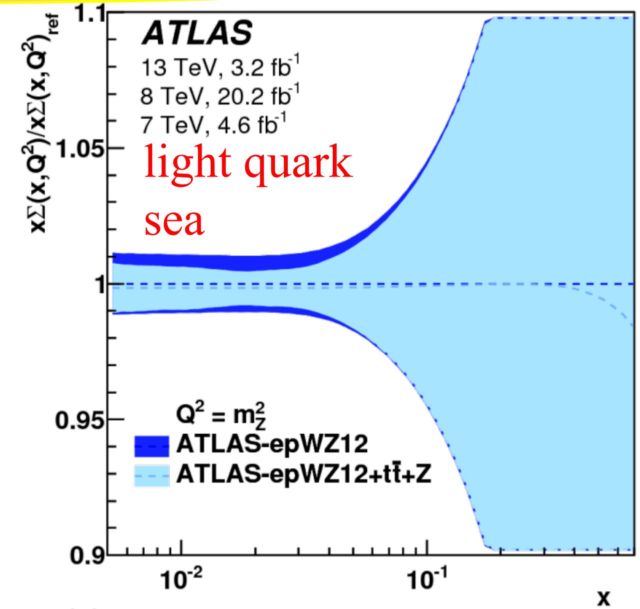
  - Use of Z→ee+μμ average cancels lepton efficiency systematics with $t\bar{t}$→eμ
    - Common selections for Z and $t\bar{t}$ analyses
- Ratio of $t\bar{t}$/Z at one energy sensitive to ratio of gluon vs quark PDF
  - 'Global' PDF sets a bit high
  - HERAPDF 2.0 and ATLAS epWZ (HERA DIS+ATLAS W/Z data) do well
- Double ratio with two energies
  - Reduces PDF, scale and m_t uncertainties
  - 13/8 TeV data agrees well with most PDFs
    - 8/7 $t\bar{t}$ ratio tension is increased to ~3σ

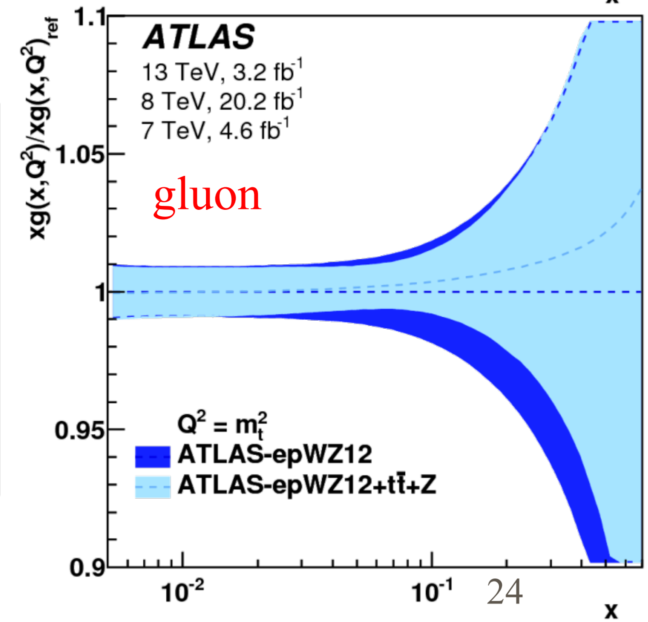


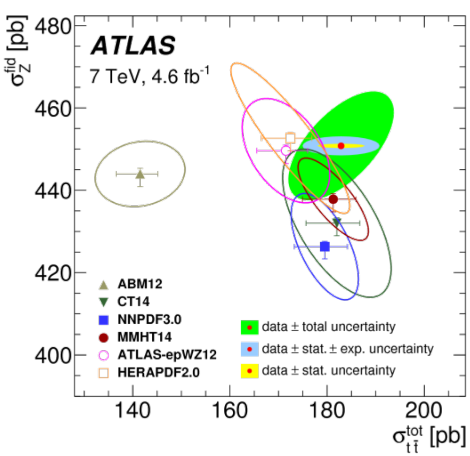


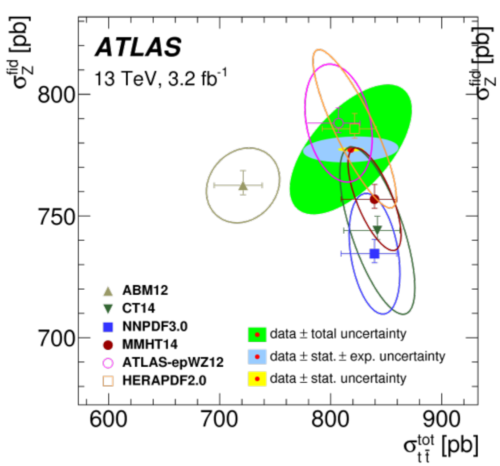
ATLAS tt/Z - ratio data in PDF fits

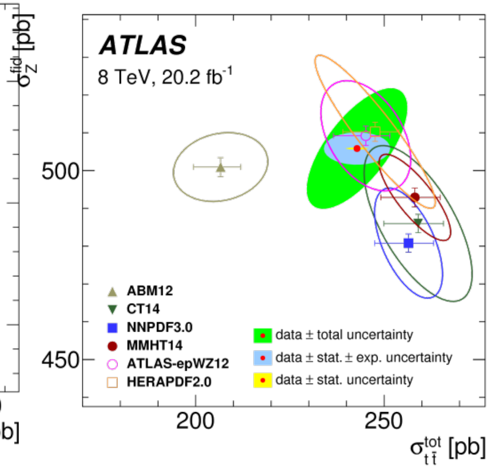
- Combined fit to all 6 measurements (tt and Z at 3 √s)
  - Fit cross-sections to predictions using ATLAS-epWZ12 PDF and profile uncertainties
  - Demonstrates impact of this data on PDF fits
    - Light quark sea is constrained around x≈0.02 – particularly significant effect on the strange sea from Z data
    - Gluon PDF constrained around 0.1 due to tt data









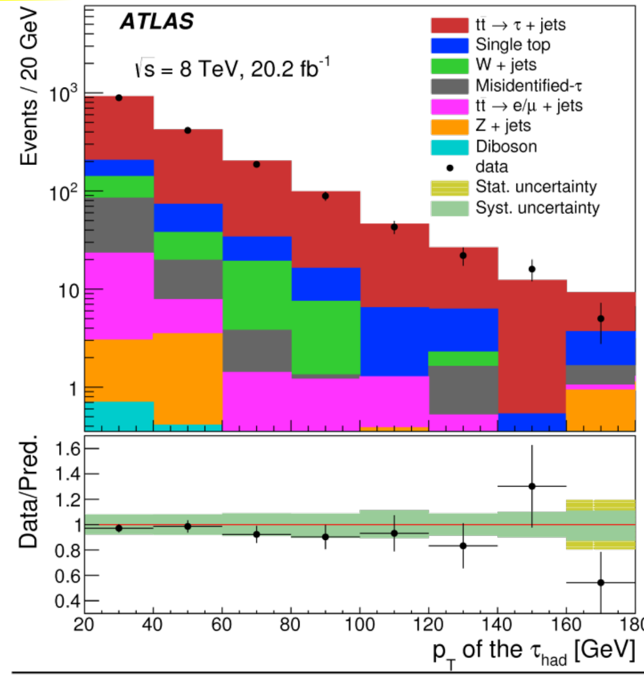


8 TeV τ_{had}+jets

- $t\bar{t}$ decays with τ used to probe BSM contributions
  - E.g. $t \to H^+b \to \tau\nu b$ in 2HDM – excess of τ vs e/μ
- Leptonic $\tau \to$ e/μ hard to separate from direct e/μ
- Hadronic τ decays give rise to narrow jet
  - Dedicated τ-ID, separate analysis for $\tau \to$ 1 or 3 tracks
- Require E_T^{miss}>150 GeV, 1/3 prong τ_{had} and ≥2 b-jets
  - Trigger based on E_T^{miss}
  - Veto isolated e/μ to reduce $t\bar{t} \to$ e/μ+jets contamination
  - Backgrounds with real τ (single top, W+jets) from MC
  - Fake τ background from data control samples with inverted τ identification requirements
- Final result

$$\sigma_{t\bar{t}} = 239 \pm 4(\text{stat}) \pm 28(\text{syst}) \pm 5(\text{lumi})\ \text{pb}$$

  - Total uncertainty of 12%
    - Main systematics from JES, b-tag and $t\bar{t}$ modelling
  - Limit of 22 fb on BSM contrib. to visible cross-section



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Event counts	$\tau_{1\text{-prong}}$	$\tau_{3\text{-prong}}$	τ_{had}
$t\bar{t} \to e/\mu + \text{jets}$	21.8 ± 4.7	6.8 ± 2.5	28.3 ± 5.3
Single top	107 ± 10	33.9 ± 5.8	141 ± 12
$W + \text{jets}$	71.7 ± 8.5	27.1 ± 5.2	99 ± 10
$Z + \text{jets}$	7.2 ± 2.7	1.6 ± 1.3	8.7 ± 3.0
Diboson	1.0 ± 1.0	0.4 ± 0.6	1.5 ± 1.2
Misidentified-τ_{had}	46.6 ± 6.8	24.9 ± 5.0	74.9 ± 8.7
Expected $t\bar{t} \to \tau + \text{jets}$	1084 ± 33	312 ± 18	1398 ± 37
Total Expected	1339 ± 37	407 ± 20	1751 ± 42
Data	1278	395	1678