ATLAS & CMS combination of inclusive tt cross-section at 7 & 8 TeV

Extraction of top quark pole mass and α_s

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Introduction

ATLAS (EPJC 76 (2016) 642)

7TeV: 182.9±3.1(stat)±4.2(syst)±3.6(lumi) pb (3.5%)
8TeV: 242.9±1.7(stat)±5.5(syst)±5.1(lumi) pb (3.2%)

CMS (JHEP 08 (2016) 029)

7TeV: 173.6 ± 2.1 (stat) ± 4.5 (syst) ± 3.8 (lumi) pb (3.6%)
8TeV: 244.9 ± 1.4 (stat) ± 6.3 (syst) ± 6.4 (lumi) pb (3.7%)

- Precise ttbar cross sections give access to
  - Comparison and confirmation of high order QCD predictions
  - Mass in well defined renormalisation schemes
  - Strong coupling at high scales
- High precision Run 1 legacy results
- Same channel but different contributions from uncertainties
- Large gain is almost a guaranteed

The measurements in a nutshell

- ATLAS
  - Determine b-jet efficiency and cross section simultaneously to decrease JES and b-tag uncertainties
  - Evaluate for each uncertainty

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

- CMS
  - Use the equations (plus one more) to parametrise total signal contribution
  - Perform a simultaneous binned likelihood fit of the jet pT (and total event yield) in categories of b jets and additional light jets
  - As a result all fit parameters are potentially correlated

$$N_{0,\geq 3} = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} - (N_1 - N_1^{\text{bkg}}) - (N_2 - N_2^{\text{bkg}}) + N_{0,\geq 3}^{\text{bkg}},$$

Systematics in Detail

ATLAS Source	Merged uncertainty [%] 7 TeV	8 TeV
Trigger	0.2	0.2
Lepton (mis-)ID/isolation	0.9	0.8
Lepton energy scale	0.3	0.5
JES flavour composition/specific response	0.2	0.4
JES modelling	0.04	0.2
JES central/forward balance	0.03	0.1
JES pile-up	0.03	0.2
Other JES	0.03	0.2
Jet energy resolution	0.3	0.5
b-jet ID	0.4	0.4
b-jet mis-ID	0.02	0.02
tW background	0.8	0.8
Drell–Yan background	0.05	0.02
Diboson background	0.1	0.1
$t\bar{t}$ scale choice	0.3	0.3
$t\bar{t}$ generator modelling	1.4	1.2
PDF	1.0	1.1
Integrated luminosity	2.0	2.1
Statistical	1.7	0.7
Total uncertainty	**3.5**	**3.2**

CMS Source	Uncertainty [%] 7 TeV	8 TeV
Trigger	1.3	1.2
Lepton (mis-)ID/isolation	1.5	1.5
Lepton energy scale	0.2	0.1
JES total	0.8	0.9
Jet energy resolution	0.1	0.1
b-jet ID	0.5	0.5
b-jet mis-ID	0.2	0.1
Pile-up	0.3	0.3
tW background	1.0	0.6
Drell–Yan background	1.4	1.3
Non-$e\mu$ $t\bar{t}$	0.1	0.1
$t\bar{t}V$ background	0.1	0.1
Diboson background	0.2	0.6
W+jets/QCD background	0.1	0.2
$t\bar{t}$ scale choice	0.3	0.6
ME/PS matching	0.1	0.1
ME generator	0.4	0.5
Hadronisation (JES)	0.7	0.7
Top-quark p_{T} modelling	0.3	0.4
Colour reconnection	0.1	0.2
Underlying event	0.1	0.1
PDF	0.2	0.3
Integrated luminosity	2.2	2.6
Statistical	1.2	0.6
$t\bar{t}$ scale choice (extrapolation)	$^{+0.1}_{-0.4}$	$^{+0.2}_{-0.1}$
ME/PS matching (extrapolation)	$^{+0.1}_{-0.1}$	$^{+0.3}_{-0.3}$
Top-quark p_{T} (extrapolation)	$^{+0.5}_{-0.3}$	$^{+0.6}_{-0.3}$
PDF (extrapolation)	$^{+0.1}_{-0.1}$	$^{+0.1}_{-0.1}$
Total uncertainty	$^{\mathbf{+3.6}}_{\mathbf{-3.5}}$	$^{\mathbf{+3.7}}_{\mathbf{-3.5}}$

- ATLAS: 'standard' quadratic sum
- CMS: Evaluate impact by fixing group of uncertainties, repeating the fit and recording difference in total uncertainty in quadrature

How the combination is done

- **ATLAS** (same analysis at 7 and 8 TeV)
  - uncorrelated uncertainties
  - group of individual uncertainties in the paper, adapted to correspond to CMS ones as closely as possible
- **CMS** simultaneous fit at 7 and 8 TeV
  - post-fit the uncertainties are correlated
  - can not be easily grouped together
- BLUE program can not be used due to this correlation of uncertainties within one of the measurement
- **Convino** program (approximate the measurement likelihood, introduce penalty terms for correlation assumptions, input central values and covariances, fit a Chi2)
  - Published paper: JK, EPJC (2017) 77: 792 (arXiv:1706.01681)

➡Approved by ATLAS & CMS Stats Committee/Forum

Combination Method

- Find approximation for initial measurement likelihood (Covariance/Hessian known)

$$\tilde{H}^{\alpha}_{\text{in}} = \begin{pmatrix} \tilde{D} & \kappa^T \\ \kappa & \tilde{M} \end{pmatrix}^{\alpha}$$

- Assume form:
  statistical + nuisance constraints + systematic penalty terms

$$\chi^2 = \sum_{\alpha} \left(\chi^2_{s,\alpha} + \chi^2_{u,\alpha} \right) + \chi^2_p$$

$$\chi^2_{s,\alpha} = \sum_{\mu\nu} M^{\alpha}_{\mu\nu} \frac{\xi^{\alpha}_{\mu} \xi^{\alpha}_{\nu}}{\tau^{\alpha}_{\mu} \tau^{\alpha}_{\nu}} \text{ and}$$

$$\chi^2_{u,\alpha} = \sum_{ij} \lambda_i D^{\alpha}_{ij} \lambda_j, \text{ with}$$

$$\xi^{\alpha}_{\mu} = x^{\alpha}_{\mu} - \bar{X}_{\mu} \text{ and}$$

$$\bar{X}_{\mu} = \bar{x}_{\mu} \prod_i (\lambda_i K^{\alpha}_{\mu i} / x^{\alpha}_{\mu} + 1) + \sum_i \lambda_i k^{\alpha}_{\mu i}.$$

- Derive terms through derivatives

- Expression for ‘data fit’ separate from nuisance penalty terms
- Just add input measurements and build one combined matrix with penalty terms containing correlation assumptions in the off-diagonal elements

Correlation assumptions

These assumptions are in line with previous combinations

- Define possible correlation values:
  - Full: 1, high: 0.75, half: 0.5, low: 0.25, no: 0
- For all (significant) uncertainties, scan assumption in the range of +- 0.25
  - Also includes unc. assumed to be uncorrelated
  - No significant effect except for luminosity
- Largest impact from choices of:
  - Lepton ID/Resolution: 0.5
  - Luminosity: 0.1

ATLAS merged uncertainties	Value	CMS uncertainties
Lepton ID and energy resolution	HALF	Lepton ID and energy resolution
JES flavour composition/specific response	HIGH	JES flavour composition
	–LOW	b-jet fragmentation tune
	LOW	b-jet neutrino decay fraction
JES modelling	HALF	JES: AbsoluteMPFBias 7 TeV
	HALF	JES: AbsoluteMPFBias 8 TeV
JES central/forward balance	HIGH	JES: RelativeFSR 7 TeV
	HIGH	JES: RelativeFSR 8 TeV
tW background	HIGH	tW single top quark correlated
	LOW	tW single top quark 7 TeV
	LOW	tW single top quark 8 TeV
Diboson	HIGH	Diboson correlated
	LOW	Diboson 7 TeV
	LOW	Diboson 8 TeV
$t\bar{t}$ scale choice	HALF	$t\bar{t}$ scale choice
	HALF	$t\bar{t}$ scale choice (extrapolation)
$t\bar{t}$ generator	LOW	Top-quark p_{T}
	LOW	Top-quark p_{T} (extrapolation)
	–LOW	ME generator
	LOW	ME/PS matching
	LOW	ME/PS matching (extrapolation)
	–LOW	Colour reconnection
	–LOW	Underlying-event tune
Each PDF CT10 eigenvector	FULL	Each PDF CT10 eigenvector
Integrated luminosity	0.1	Integrated luminosity

Correlation assumptions (2)

- Trigger:
  - ATLAS and CMS use different triggers (single lepton and dilepton)
  - Efficiencies are measured differently (tag&probe versus MET monitoring triggers)
- B-tagging
  - Taken as uncorrelated, different methods in ATLAS and CMS, also not a significant source of uncertainties given the measurement techniques
- JES:
  - Following JES group guidelines and previous combinations
    - Exception: JES relFSR: should be 0.5-1.0, but is one uncertainty for 7 and 8 TeV in ATLAS, and uncorrelated between 7 and 8 TeV in CMS: poses logic issue: set to 0.7
    - Impact of JES relFSR very small for both measurements
    - Does not have a measurable impact

https://cds.cern.ch/record/1956734
https://cds.cern.ch/record/2103759

ATLAS Source	Uncertainty [%] 7 TeV	8 TeV
JES central/forward balance	0.03	0.1
Total uncertainty	3.5	3.2

Correlation assumptions (3)

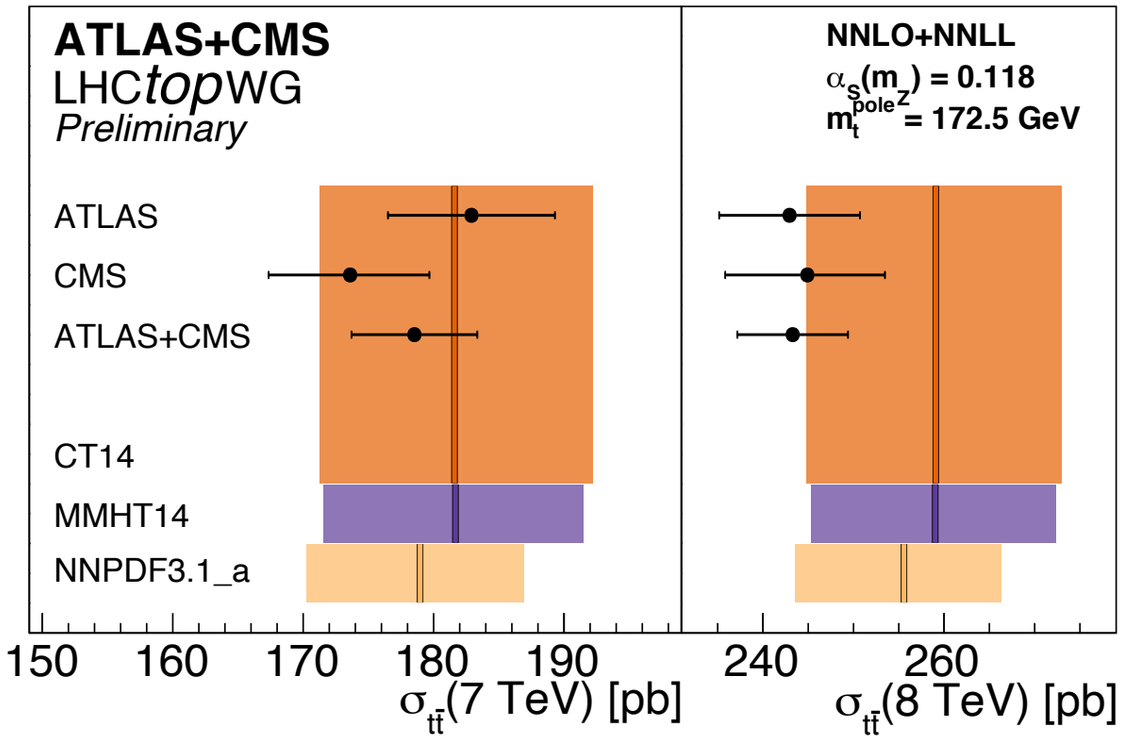
- Backgrounds:
  - CMS measurement uses slightly different tunes at 7 and 8 TeV, so that the backgrounds are only correlated to 90% between 7 and 8 TeV. This part is taken as mostly uncorrelated also to ATLAS, while the rest is taken as highly correlated
  - Different nominal scale choices and behaviour in MadGraph (CMS) versus POWHEG (ATLAS). Still it should describe a similar effect, therefore half correlated
- Other generator related uncertainties
  - A lot of CMS sources need to be mapped to the merged ATLAS group.
  - Scanned simultaneously
- PDF uncertainties correlated eigenvector by eigenvector

Ambiguous signs

- In some cases, there is "some kind of correlation" but the sign is not clear
- E.g. ATLAS flavour composition and flavour dependent JES and CMS B fragmentation tune
- In general for uncertainties comparing some tune/generator A to B, where at least one of A or B is not the same for CMS and ATLAS
- Here, choose the sign that maximises the uncertainty on combined value

ATLAS merged uncertainties	Value	CMS uncertainties
Lepton ID and energy resolution	HALF	Lepton ID and energy resolution
JES flavour composition/specific response	HIGH	JES flavour composition
	–LOW	*b*-jet fragmentation tune
	LOW	*b*-jet neutrino decay fraction
JES modelling	HALF	JES: AbsoluteMPFBias 7 TeV
	HALF	JES: AbsoluteMPFBias 8 TeV
JES central/forward balance	HIGH	JES: RelativeFSR 7 TeV
	HIGH	JES: RelativeFSR 8 TeV
tW background	HIGH	tW single top quark correlated
	LOW	tW single top quark 7 TeV
	LOW	tW single top quark 8 TeV
Diboson	HIGH	Diboson correlated
	LOW	Diboson 7 TeV
	LOW	Diboson 8 TeV
$t\bar{t}$ scale choice	HALF	$t\bar{t}$ scale choice
	HALF	$t\bar{t}$ scale choice (extrapolation)
$t\bar{t}$ generator	LOW	Top-quark p_{T}
	LOW	Top-quark p_{T} (extrapolation)
	–LOW	ME generator
	LOW	ME/PS matching
	LOW	ME/PS matching (extrapolation)
	–LOW	Colour reconnection
	–LOW	Underlying-event tune
Each PDF CT10 eigenvector	FULL	Each PDF CT10 eigenvector
Integrated luminosity	0.1	Integrated luminosity

Results



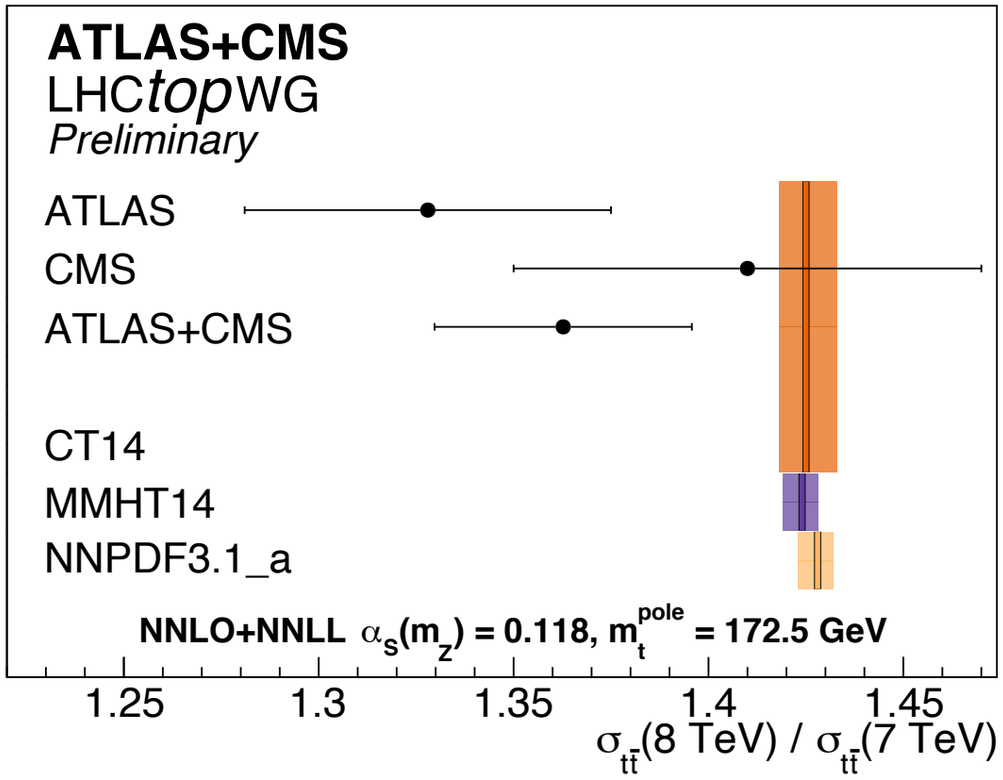
- Minimum chi2=1.6
- Very stable
- Correlation between 7 and 8 TeV: 0.41
- Uncertainty impact evaluated by freezing parameters and repeating the fit

NNPDF3.1_a: special NNPDF3.1 entirely without top data

Uncertainty	$\Delta\sigma_{t\bar{t}}$(7 TeV) [%]	$\Delta\sigma_{t\bar{t}}$(8 TeV) [%]
Trigger	0.6	0.5
Lepton (mis-)ID, isolation and energy	1.0	0.9
JES flavour composition	0.4	0.4
JES modelling	< 0.1	0.1
JES central/forward balance	0.2	0.2
b-jet (mis-)ID	0.4	0.4
Pile-up	0.2	0.2
tW background	0.8	0.6
Drell–Yan background	0.7	0.4
Diboson background	0.2	0.4
$t\bar{t}$ generator	0.8	0.8
$t\bar{t}$ scale choice	0.4	0.4
PDF	0.4	0.3
Integrated luminosity	1.7	1.7
Statistical	1.0	0.4
Total uncertainty	$^{+2.7}_{-2.6}$	$^{+2.5}_{-2.4}$

$$\sigma_{t\bar{t}}\,(\sqrt{s} = 7\ \text{TeV}) = 178.5 \pm 4.7\ \text{pb}$$
$$\sigma_{t\bar{t}}\,(\sqrt{s} = 8\ \text{TeV}) = 243.3^{+6.0}_{-5.9}\ \text{pb},$$

Ratio



- Ratio not affected strongly by the choice of mt, alpha_s
- Determine ratio from results and correlation coefficient
- Predictions calculated correlating the corresponding individual PDF eigenvectors and scale choices
- Both the individual cross-sections and their ratio are in agreement with the SM prediction
  - 0.3 (7 TeV) , 1.0 (8 TeV) and 1.9 (ratio) sigma

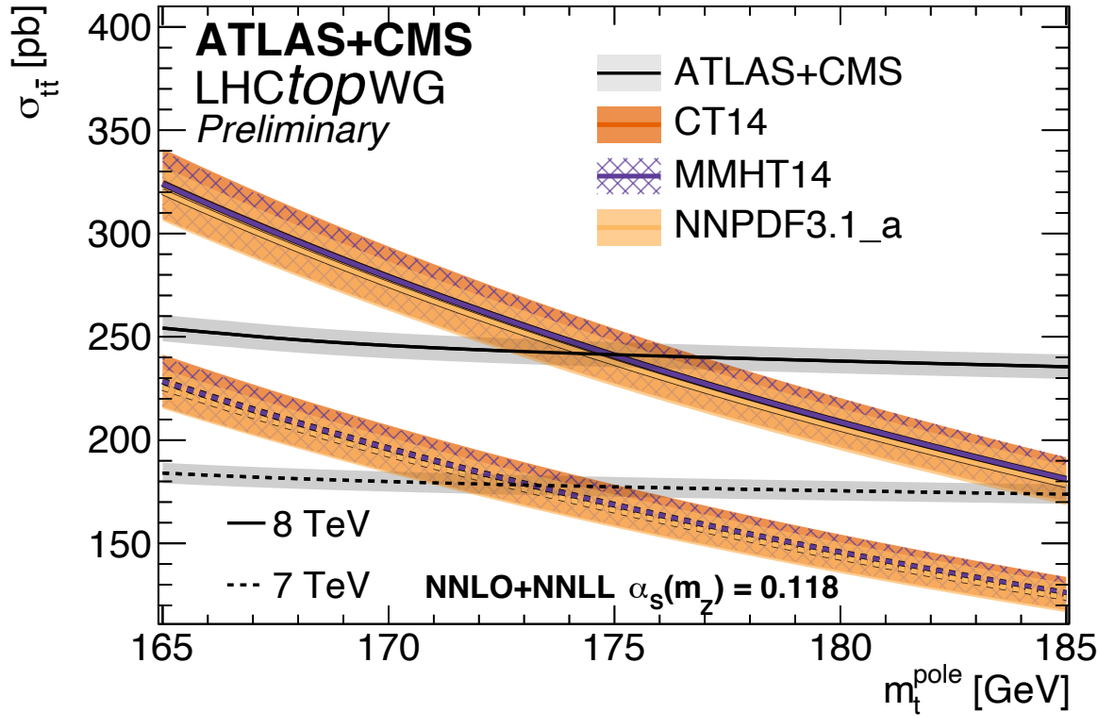
Top pole mass and α_S

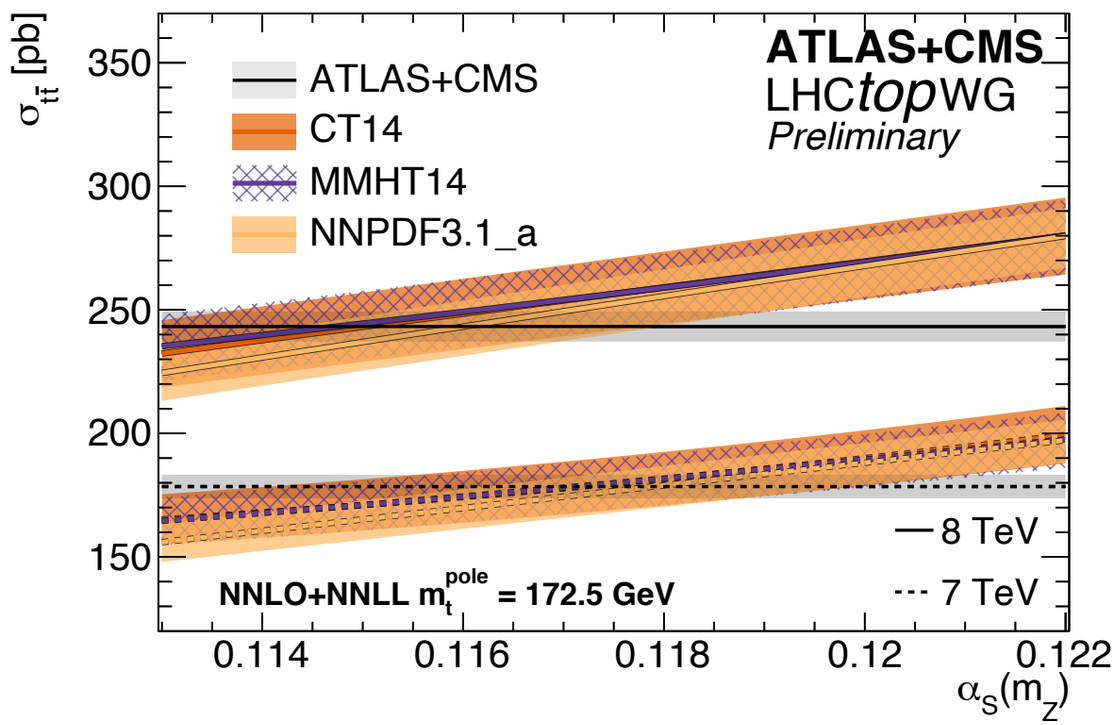
- Predicted cross-section depends strongly on top mass and α_S. The experimental dependence is mild.
- Dependence on m_t is different for ATLAS and CMS so fit 3 points (166.5 GeV, 172.5 GeV and 178.5 GeV) and get weight at each point. Interpolate in between.
- Theory dependence obtained from running top++ with various PDF sets for 10 mass points (at alpha_s = 0.118) and 5 α_S variations (at m_t = 172.5), using 4th order polynomial
- Chi2 method

$$\chi^2 = \frac{1}{1-\rho^2}\left(\Delta(7\text{ TeV})^2 + \Delta(8\text{ TeV})^2 - 2\rho\Delta(7\text{ TeV})\Delta(8\text{ TeV})\right), \text{ with}$$

$$\Delta = \frac{\sigma_{t\bar{t}}(m_t^{\text{pole}}) - \sigma_{t\bar{t}}^{\text{p}}(m_t^{\text{pole}}, \alpha_S(m_Z))}{\delta},$$

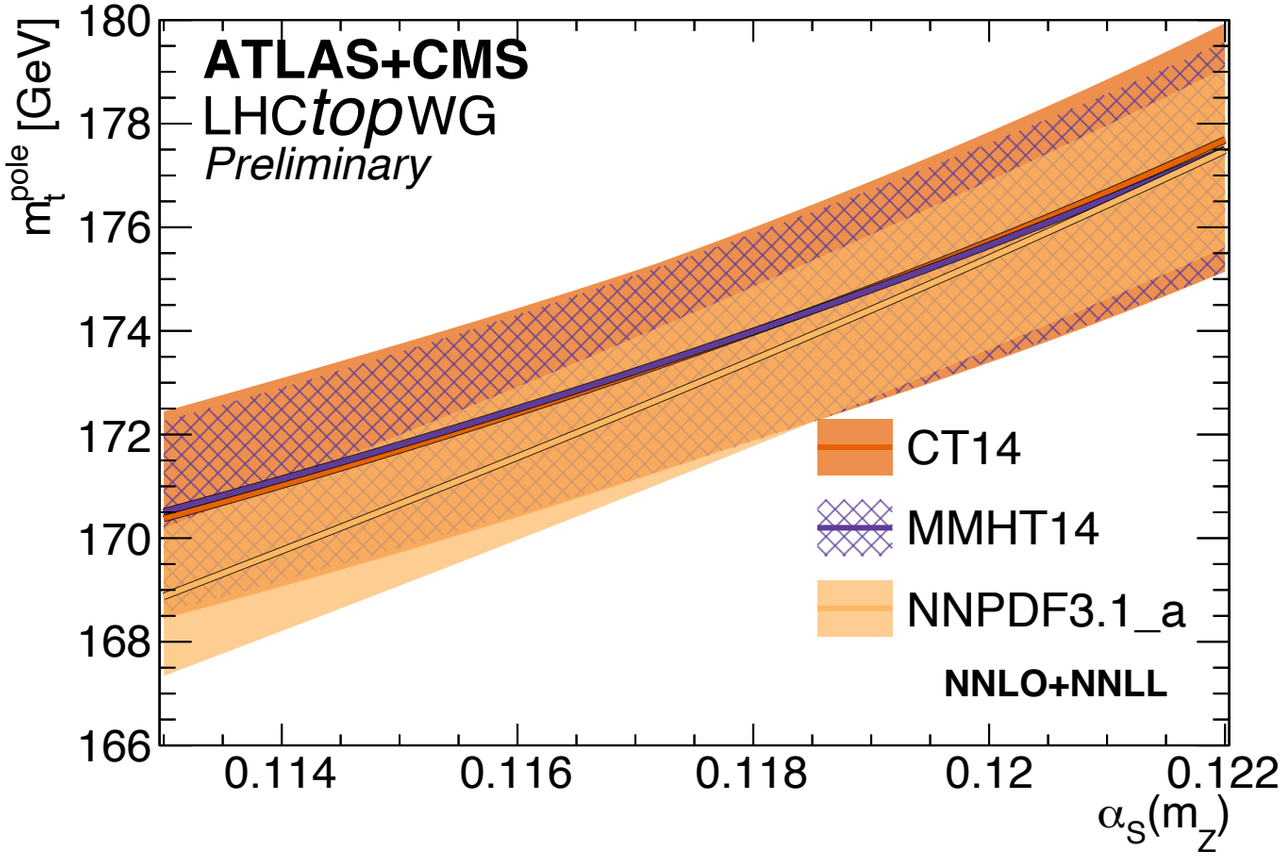
- Repeat extraction for each PDF eigenvector/scale choice and determine final uncertainty using the prescription of corresponding PDF set





Final extraction result

- Not possible to extract m_t and α_S from one number at the same time
- But: measurement can give constraints on compatible choices
  - Scan one against the other
- NB: the plot is designed to be read both ways

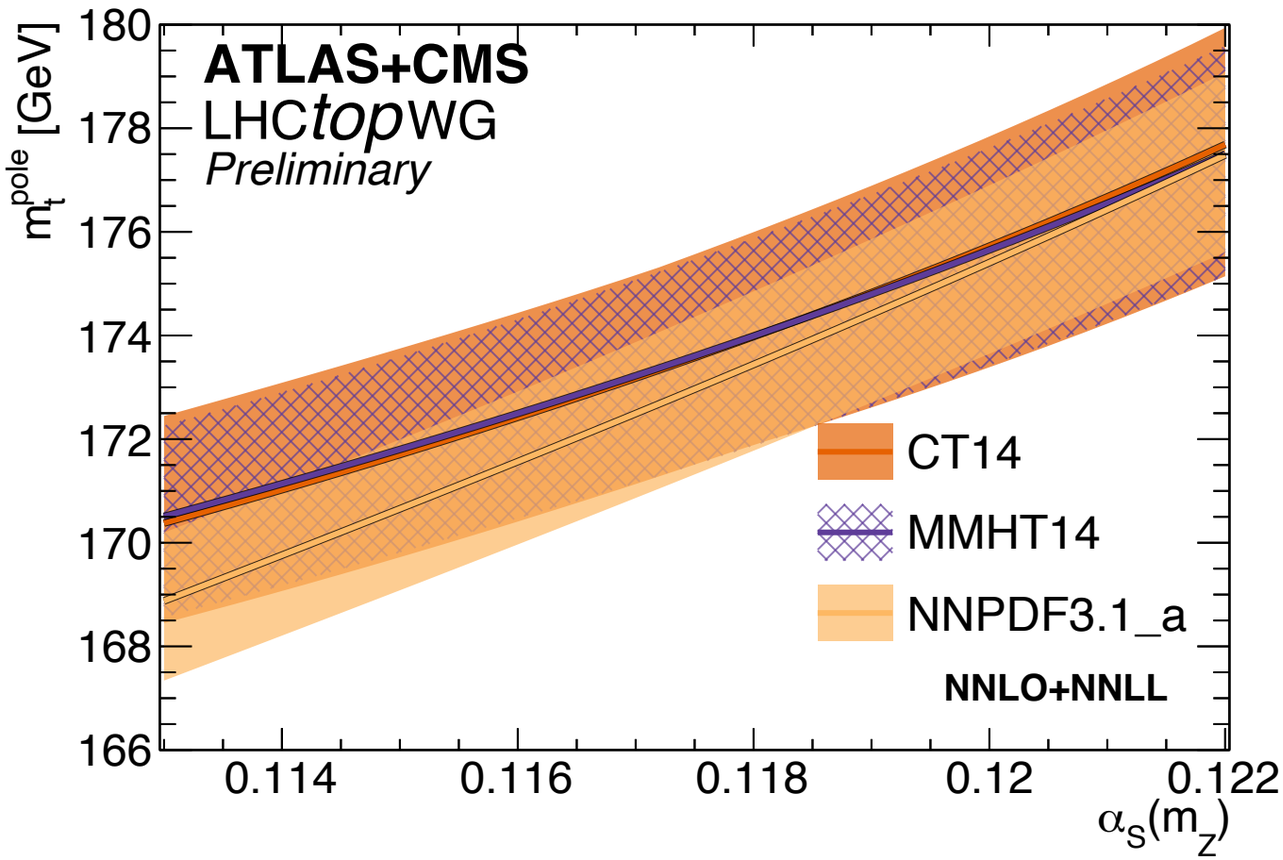


PDF set	m_t^{pole} ($\alpha_S = 0.118 \pm 0.001$)	$\alpha_S(m_Z)$ ($m_t = 172.5 \pm 1.0$ GeV)
CT14	$174.0 \pm^{2.3}_{2.3}$ GeV	$0.1161 \pm^{0.0030}_{0.0033}$
MMHT2014	$174.0 \pm^{2.1}_{2.3}$ GeV	$0.1160 \pm^{0.0031}_{0.0030}$
NNPDF3.1_a	$173.4 \pm^{1.8}_{2.0}$ GeV	$0.1170 \pm^{0.0021}_{0.0018}$

Summary

- Finalised ATLAS+CMS combination of inclusive LHC run 1 top quark pair cross section measurements

- Combined results have about ~2.5% uncertainty; world's most precise:
  - 25% improvement for 7 TeV
  - 28% for 8 TeV and
  - 45% improvement for the ratio



- Top pole mass is competitive with other pole mass uncertainties (1.2%)

- Extracted α_S competitive with other measurements at top scales

Backup