Istituto Nazionale di Fisica Nucleare

Università di Roma Tor Vergata

New Phenomena at the TeV Scale With Top Quarks

NPTEV-TQP2020

Top Mass (and Width) Measurements with the ATLAS experiment

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on behalf of the ATLAS Collaboration

DIS-2018

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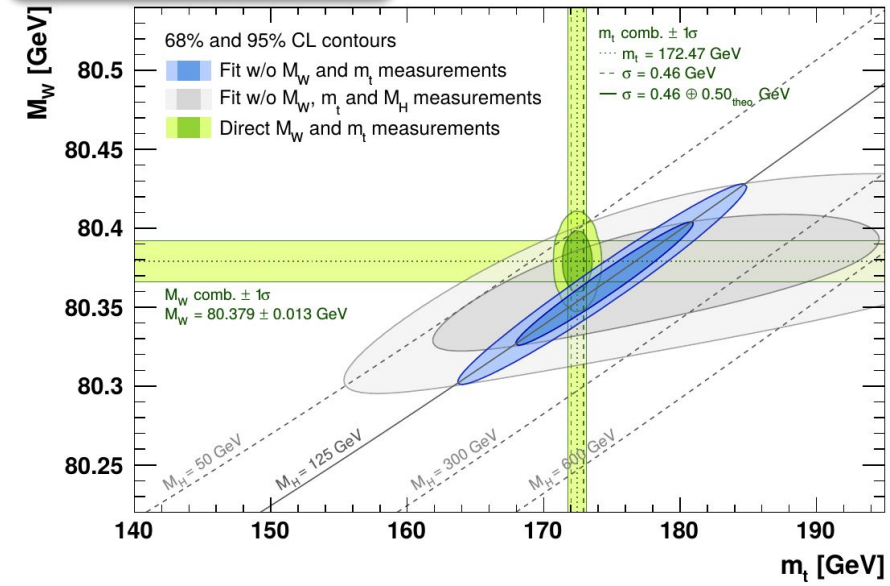
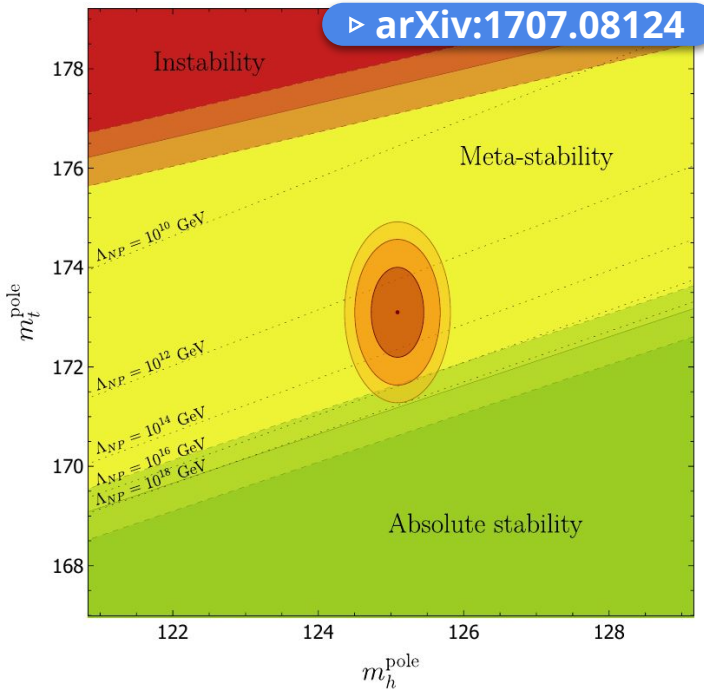
The Top Quark Mass

- Top quark: the **heaviest** known elementary particle
- $m_t + m_W + m_H$ measurements → over-constraints to SM fits
  - **direct measurements** can be compared to **indirect results** to probe validity of SM
  - m_t important to determine SM **vacuum stabilty**

▹ arXiv:1803.01853

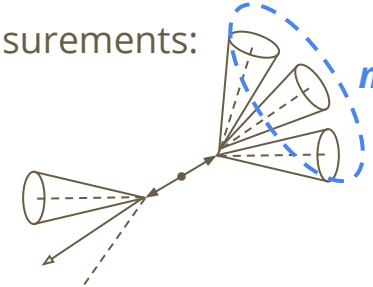


▹ arXiv:1707.08124



Methods to Measure the Top Mass

- **Direct** "m_t" measurements:



m_{top}^{reco} = *invariant mass of jets from top decay*

extraction from total or partial invariant mass of top decay products
⇒ **"Standard Method"**

  - data compared with MC simulation with different input values of m_t in MC
  - relying on jets, parton showers (LO), non-perturbative effects
    ⇒ measuring "m_t^{MC}"
    (still controversial arguments, see e.g. ▹ **CERN-TH-2017-266**)

- **Indirect** measurements of m_t from cross-sections (inclusive or differential)
  - in a well-defined renormalization scheme, e.g. m_t^{pole} (corresponding to definition of free particle mass)

$$\sigma^{theor.}(\alpha_s, \boxed{m_t}, \text{PDF}, \mu_F, \mu_R, \ldots) \text{ vs } \sigma^{meas.}$$

m_t = *parameter in the SM*

    - "O(1 GeV) difference" between m_t^{MC} and m_t^{pole}

Both types: precision measurements

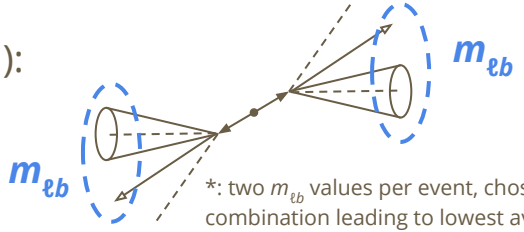
⇩

All the presented measurements based on LHC Run1 *pp*-data @7-8 TeV

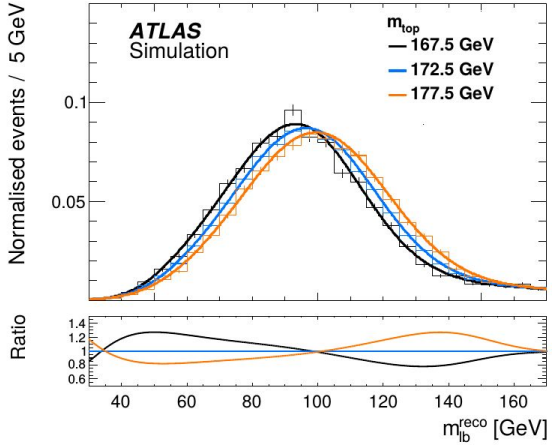
Standard Method - Dilepton Channel

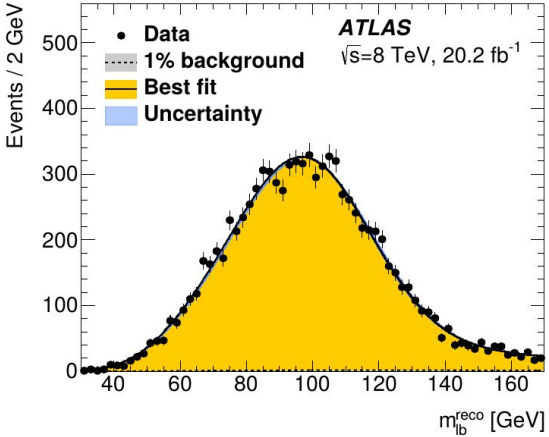
▹ PLB 761(2016)350

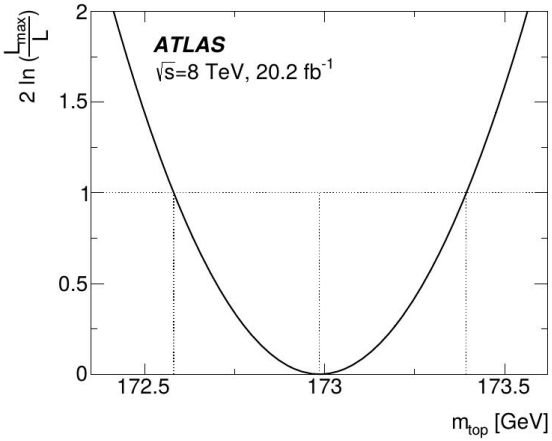
- Clean standard dilepton selection ($ee/e\mu/\mu\mu$ + 2 jets (≥1 b-tag)):
  - not possible to fully reconstruct top decay
    ⇒ use $m_{\ell b}$ (*) as observable sensitive to m_t
- **Template method**:
  - **analytical model** to describe $m_{\ell b}$ distribution
    as a function of m_t built with MC simulation as different m_t values:
    - for signal (tt+sing.top) → Gaussian+Landau with linear dependence of parameters vs m_t
  - unbinned maximum-likelihood fit to data



*: two $m_{\ell b}$ values per event, chosing combination leading to lowest average $m_{\ell b}$

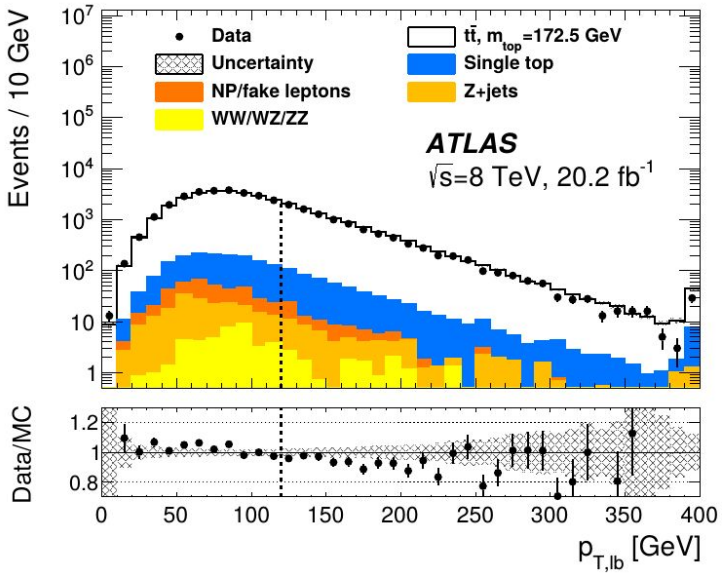


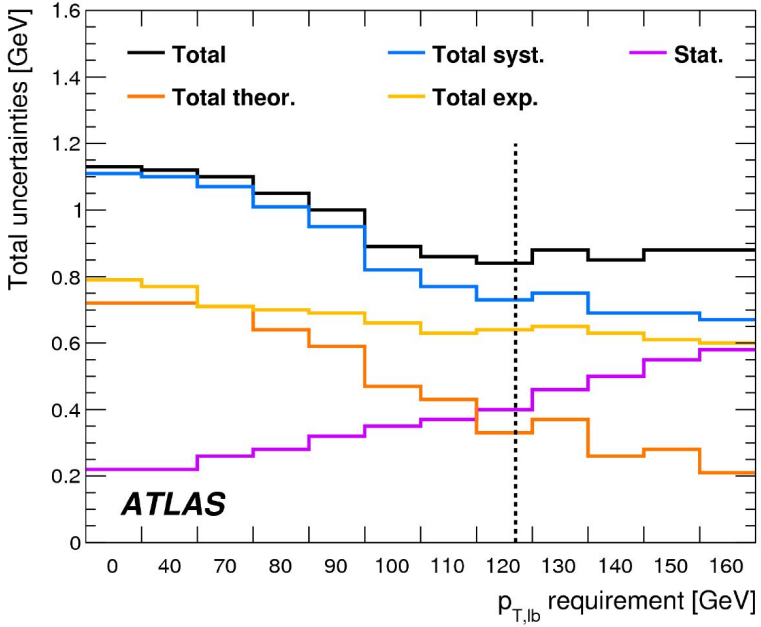




Standard Method - Dilepton Channel

- **Optimization**:
  - cut on $p_{T,\ell b}$ to increase purity of correctly matched ℓb pairs
    ⇒ minimize total uncertainty





JES (0.54)
b-JES (0.30)

ISR/FSR (0.23)
PS & had. (0.22)
ME gen. (0.10)

$$m_{\text{top}} = 172.99 \pm 0.41\ (\text{stat}) \pm 0.74\ (\text{syst})\ \text{GeV}$$

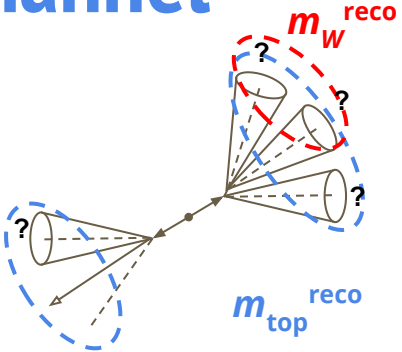
± 0.85 GeV

Standard Method - ℓ+jets Channel

▹ ATLAS-CONF-2017-071

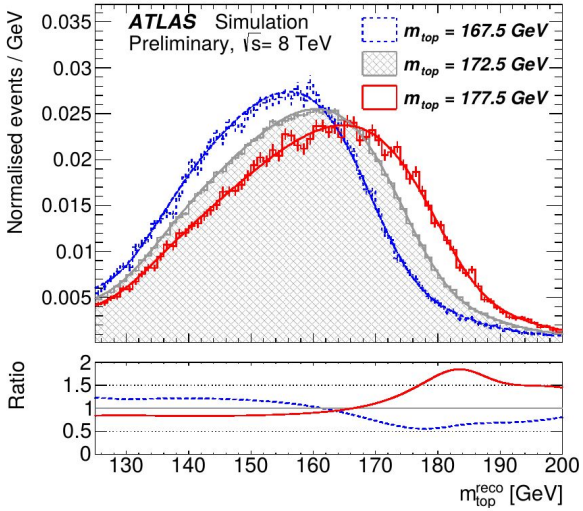
- **"3D" template method**:
  - symultaneous fit to **3 distributions**:
    - m_{top}^{reco}, m_W^{reco}, $R_{bq}^{reco} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{q_1} + p_T^{q_2}}$

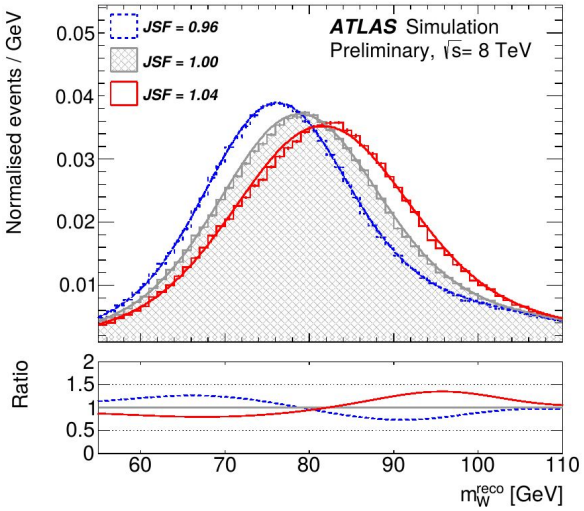
    (q_1 and q_2 light jets assigned to W)
  - **3 free parameters** in the template fit:
    - m_t, JSF^*, $bJSF^*$ (*: *(b-)Jet-energy-Scale-Factor*)

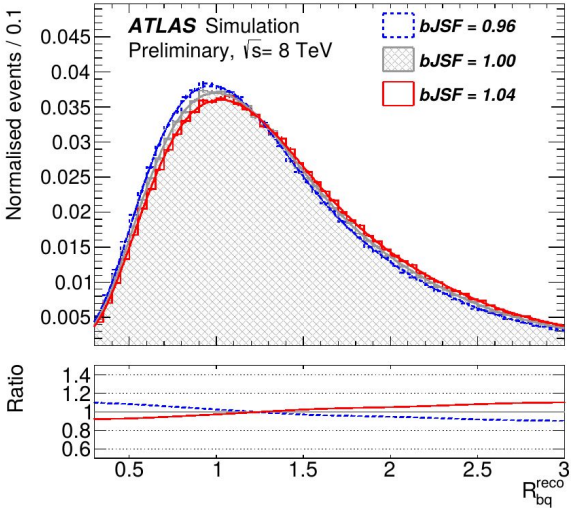


- **KLFitter*** to reconstruct *tt* system (for jet-parton assignment and m_{top}^{reco})

  *: kinematical likelihood fit in each event
- m_W^{reco} and R_{bq}^{reco} use chosen jet permutation, but with original jet 4-momenta (to retain the maximum sensitivity to *JES* and *b-JES*)

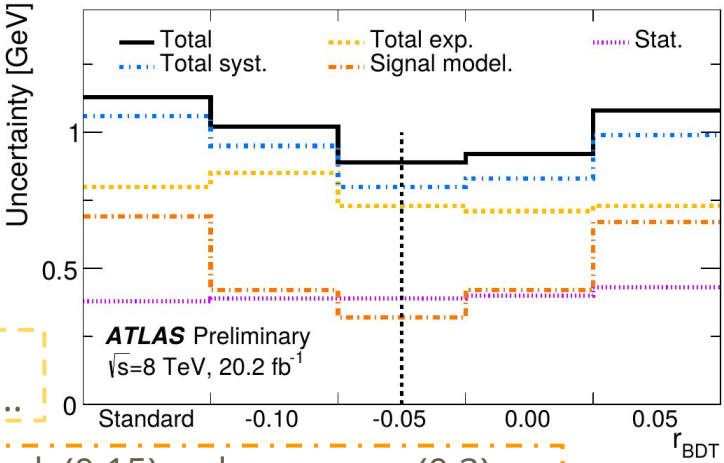






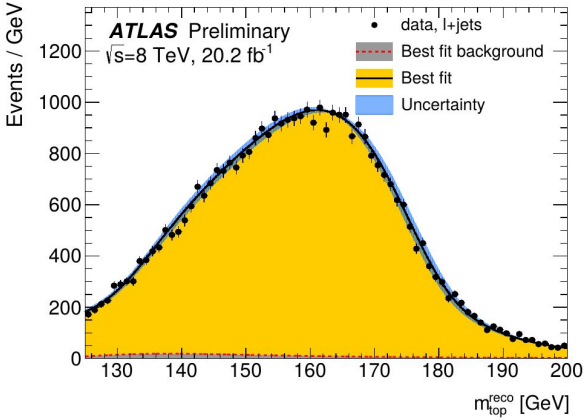
Standard Method - ℓ+jets Channel

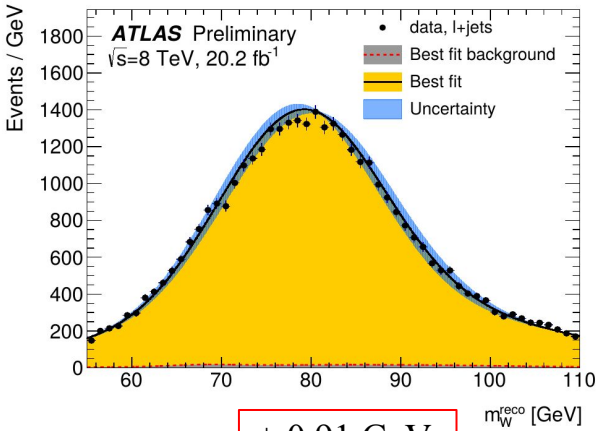
- **Optimization**:
  - cut on **BDT** built to remove **wrongly assigned events**
    ⇒ reduce systematics
  - BDT trained with 13 variables
    (best ones: KLFitter likelihood of best permutation and ΔR_{qq})

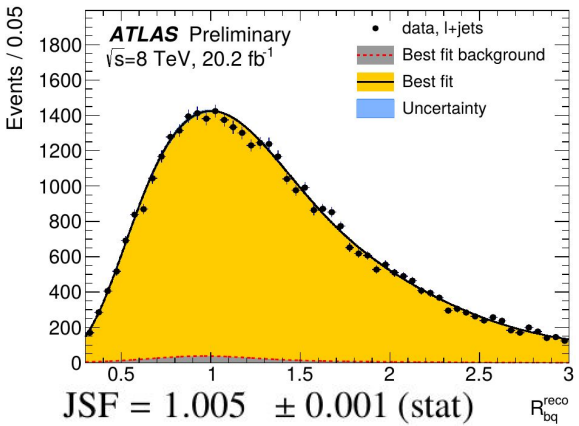


JES (0.54), *b*-JES, JER, *b*-tagging (0.38) ...

ME gen. (0.16), PS&had. (0.15), color reconn. (0.2) ...







$m_{\text{top}} = 172.08 \pm 0.39\,(\text{stat}) \pm 0.82\,(\text{syst})$ GeV $\boxed{\pm\, 0.91 \text{ GeV}}$

JSF = 1.005 ± 0.001 (stat)

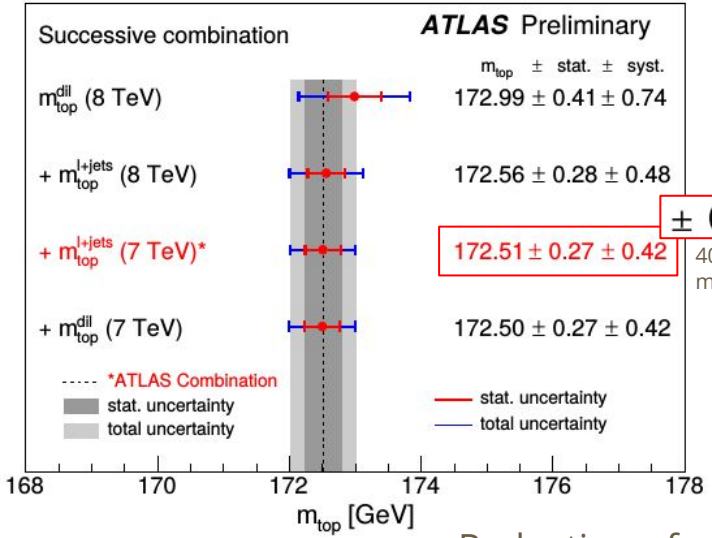
bJSF = 1.008 ± 0.005 (stat)

Std. Method - Combination

▹ ATLAS-CONF-2017-071

- 7 TeV + 8 TeV, ℓ+jets + dilepton:
  - **successive combination** from most sensitive to less sensitive
  - 7 TeV dilep. excluded because of no significant(*) gain

*: considering statistical precision of systematic uncertainties



± 0.50 GeV

40% improvement w.r.t. most sensitive single channel

	dilep.@8TeV	ℓ+jets@8TeV	comb.@7+8TeV
Statistics	0.41	0.39	0.27
Method	0.05 ± 0.07	0.13 ± 0.11	0.06
Signal Monte Carlo generator	0.09 ± 0.15	0.16 ± 0.17	0.14
Hadronisation	0.22 ± 0.09	0.15 ± 0.10	0.07
Initial- and final-state QCD radiation	0.23 ± 0.07	0.08 ± 0.11	0.07
Underlying event	0.10 ± 0.14	0.08 ± 0.15	0.05
Colour reconnection	0.03 ± 0.14	0.19 ± 0.15	0.08
Parton distribution function	0.05 ± 0.00	0.09 ± 0.00	0.07
Background normalisation	0.03 ± 0.00	0.08 ± 0.00	0.03
W/Z+jets shape	0	0.11 ± 0.00	0.07
Fake leptons shape	0.07 ± 0.00	0	0.03
Jet energy scale	0.54 ± 0.04	0.54 ± 0.02	0.21
Relative b-to-light-jet energy scale	0.30 ± 0.01	0.03 ± 0.01	0.15
Jet energy resolution	0.09 ± 0.05	0.20 ± 0.04	0.10
Jet reconstruction efficiency	0.01 ± 0.00	0.02 ± 0.01	0.03
Jet vertex fraction	0.02 ± 0.00	0.09 ± 0.01	0.05
b-tagging	0.04 ± 0.02	0.38 ± 0.00	0.17
Leptons	0.14 ± 0.01	0.16 ± 0.01	0.09
E_T^{miss}	0.01 ± 0.01	0.05 ± 0.01	0.04
Pile-up	0.05 ± 0.01	0.15 ± 0.01	0.06
Total systematic uncertainty	0.74 ± 0.05	0.82 ± 0.06	0.42
Total	0.85 ± 0.05	0.91 ± 0.06	0.50

Correlations	m_{top}^{dil} (7 TeV)	m_{top}^{l+jets} (7 TeV)	m_{top}^{dil} (8 TeV)	m_{top}^{l+jets} (8 TeV)
m_{top}^{dil} (7 TeV)	1.00			
m_{top}^{l+jets} (7 TeV)	−0.07	1.00		
m_{top}^{dil} (8 TeV)	0.52	0.00	1.00	
m_{top}^{l+jets} (8 TeV)	0.06	−0.07	−0.19	1.00
BLUE weight (m_{top})	-	0.17	0.43	0.40

- Reduction of uncertainties thanks to **complementarity** and **anti-correlations**

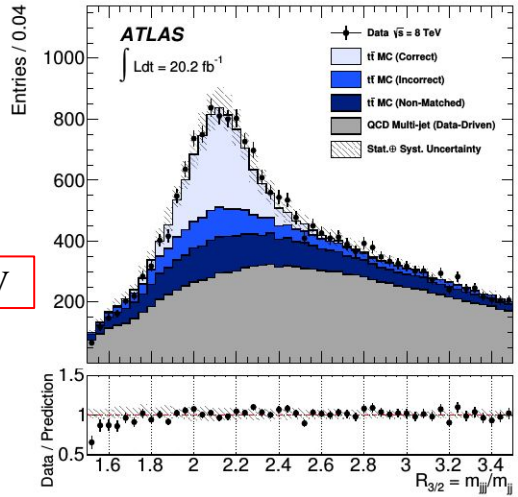
Standard Method - All-had. and single-top

▹ **JHEP09 (2017) 118**

- **All-hadronic channel:**
  - multi-jet from ABCD method
  - **system reconstruction** with χ^2
  - fit variable $R = m_{jjj}/m_{jj}$

$m_{\text{top}} = 173.72 \pm 0.55\ (\text{stat.}) \pm 1.01\ (\text{syst.})\ \text{GeV}$ $\boxed{\pm 1.2\ \text{GeV}}$

  - dominant systematitcs from:
    - PS & had., JES and *b*-JES



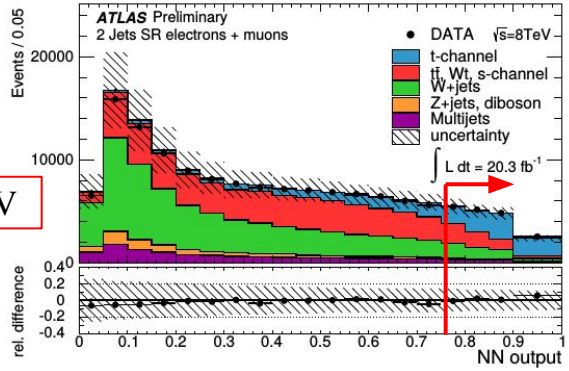
In both channels, **backgroud determination** via symultaneous fit with m_t

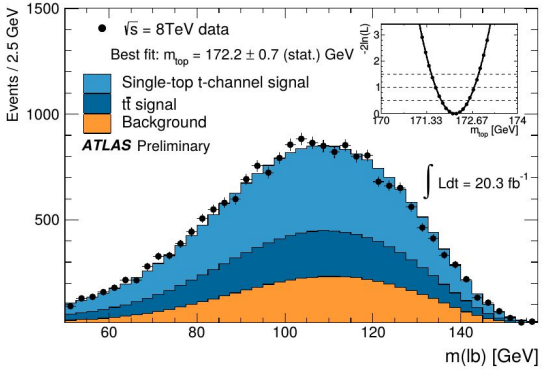
▹ **ATLAS-CONF-2014-055**

- **Single-top-enriched selection:**
  - cut on **NN** to enrich sample in t-channel single top
  - fit $m_{\ell b}$ like in dilepton *tt*
    (unambiguous ℓb choice)

$m_{\text{top}} = 172.2 \pm 0.7\ (\text{stat.}) \pm 2.0\ (\text{syst.})\ \text{GeV}$ $\boxed{\pm 2.1\ \text{GeV}}$

  - dominant systematics from:
    - JES, PS & had., *W*+jets

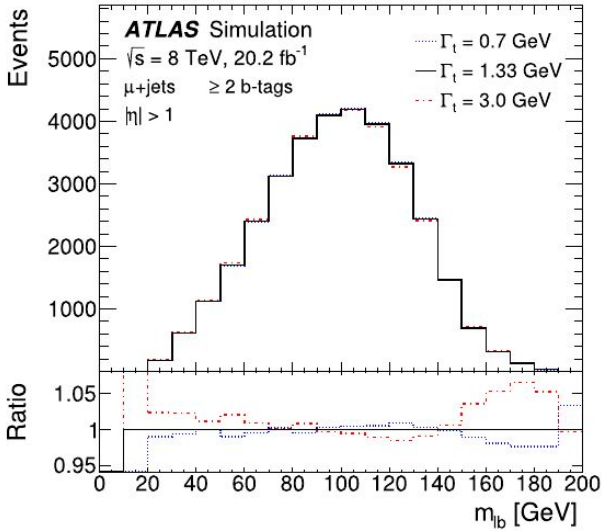


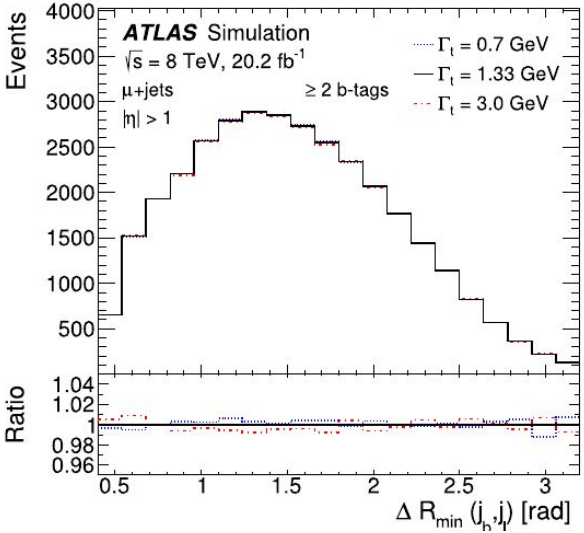


Top width measurement

▹ EPJC 78 (2018) 129

- ℓ+jets channel
- Symultaneous fit to **two distributions**:
  - $m_{\ell b}$
  - $\Delta R(\text{jet}_b\,\text{jet}_{light})$



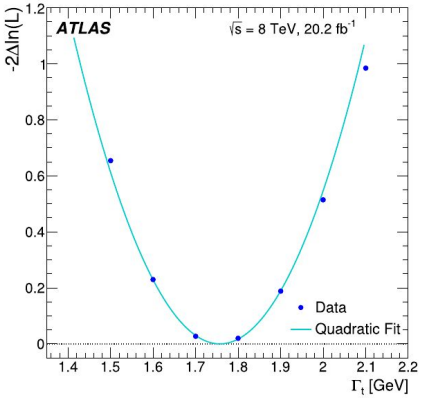


- **Binned template fit** with **constrained background** norm. parametersin several categories (lep. flavor, N *b*-tags, $|\eta(\text{lep.})|$)
  - result extracted from min. of -Δlog(L) value vs Γ_t hypothesis
    (templates derived through reweighting, quadratic interpolation of -Δlog(L))

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

(NNLO → 1.322 GeV)

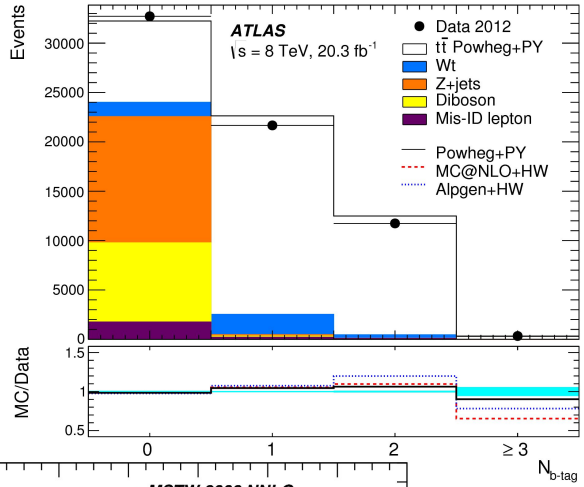
- Systematic uncertaity mostly from JES, *b*-tagging and *tt* ME generator



Top Mass from *tt* cross-section

▹ EPJC 74 (2014) 3109

- Theory calculations for σ_{tt} use m_t^{pole}
- Most precise **total σ_{tt} measurements** at 7 and 8 TeV compared with theory with different PDF sets
  - **small dependency on m_t^{MC}** through acceptance

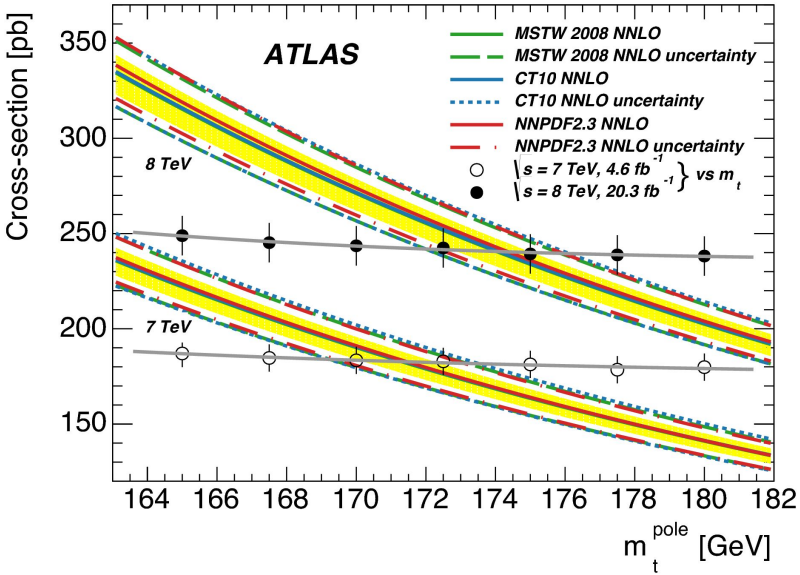


- Combined value:

$$m_t^{pole} = 172.9^{+2.5}_{-2.6}\ \text{GeV}$$

  - uncertainty mostly from **theory**
    ⇒ not gaining much combining

Δm_t^{pole} (GeV)	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
Data statistics	0.6	0.3
Analysis systematics	0.8	0.9
Integrated luminosity	0.7	1.2
LHC beam energy	0.7	0.6
PDF+α_s	1.8	1.7
QCD scale choice	$^{+0.9}_{-1.2}$	$^{+0.9}_{-1.3}$



Top Mass from *tt* +1-jet

▹ JHEP 10 (2015) 121

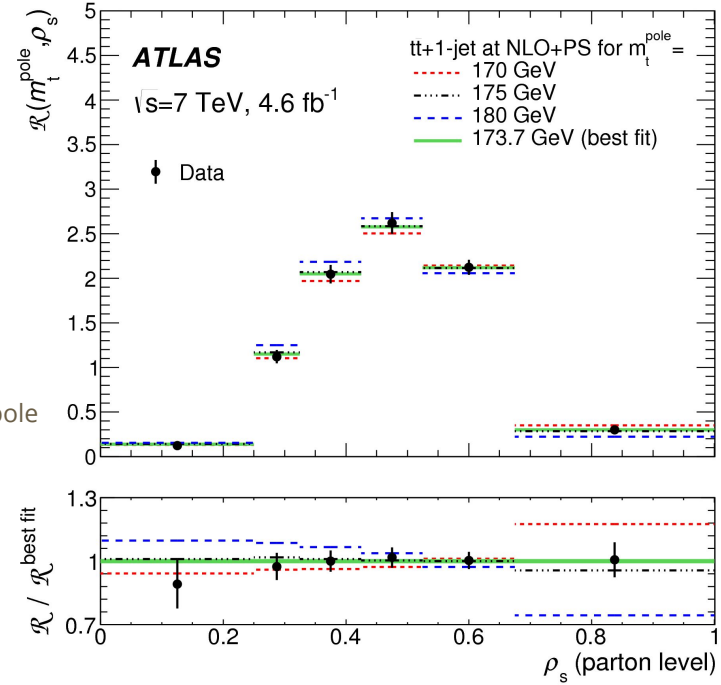
- m_t^{pole} extractd from **normalized differential cross-section** of inverse of ***tt*+1j invariant mass**:

$$\mathcal{R}(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{pole}, \rho_s)$$

$$\rho_s = \frac{2m_0^*}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$$

*: m_0 = 170 GeV

  - sensitive because amount of **gluon radiation depends on m_t**, with large effects in phase-space region near threshold
- 7 TeV data-set, *tt* ℓ+jets selection:
  - ***tt* system reconstructed**, **additional** leading **jet** required p_T> 50 GeV
  - parton-level **unfolded distribution** compared to NLO+PS *tt* +1jet calculation vs m_t^{pole}



$$m_t^{pole} = 173.7 \pm 1.5\,(\text{stat.}) \pm 1.4\,(\text{syst.})^{+1.0}_{-0.5}\,(\text{theory})\ \text{GeV}$$

± 2.2 GeV

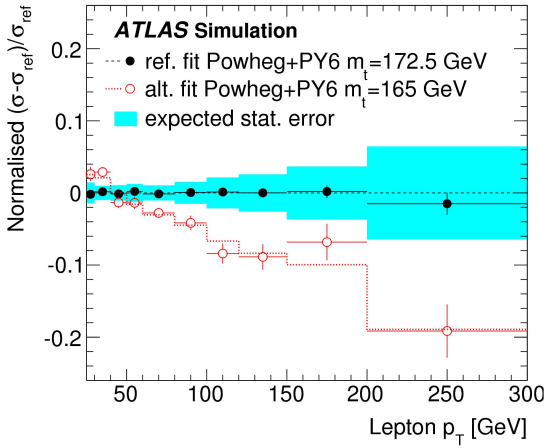
  - dominant systematic uncertainties:
    - JES and ISR/FSR

Top Mass from leptonic differential distributions

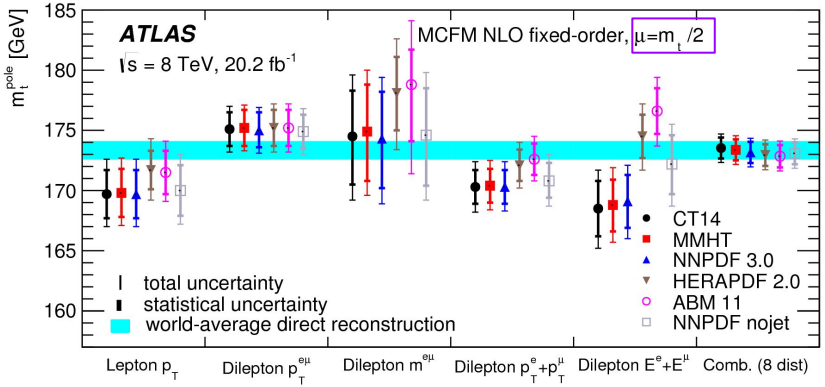
▹ EPJC 77 (2017) 804 *(see J. E. Garcia Navarro talk)*

*: lepton p_T^{ℓ} and dilepton $p_T^{e\mu}$, $m^{e\mu}$, $p_T^{e} + p_T^{\mu}$ and $E^{e} + E^{\mu}$

- **Normalized differential σ_{tt} vs lepton kinematics**(*) sensitive to m_t compared to:
  - NLO+PS → extraction of m_t^{MC} (Poweg+Pythia 6, CT10 PDFs)
  - **QCD fixed order calc.** → m_t^{pole} (MCFM, various PDFs)
    - template fit method, parametrizing predictions vs m_t and fitting value that minimizes χ^2



- Modeling of top kinematics (e.g. **top p_T**) is the key aspect



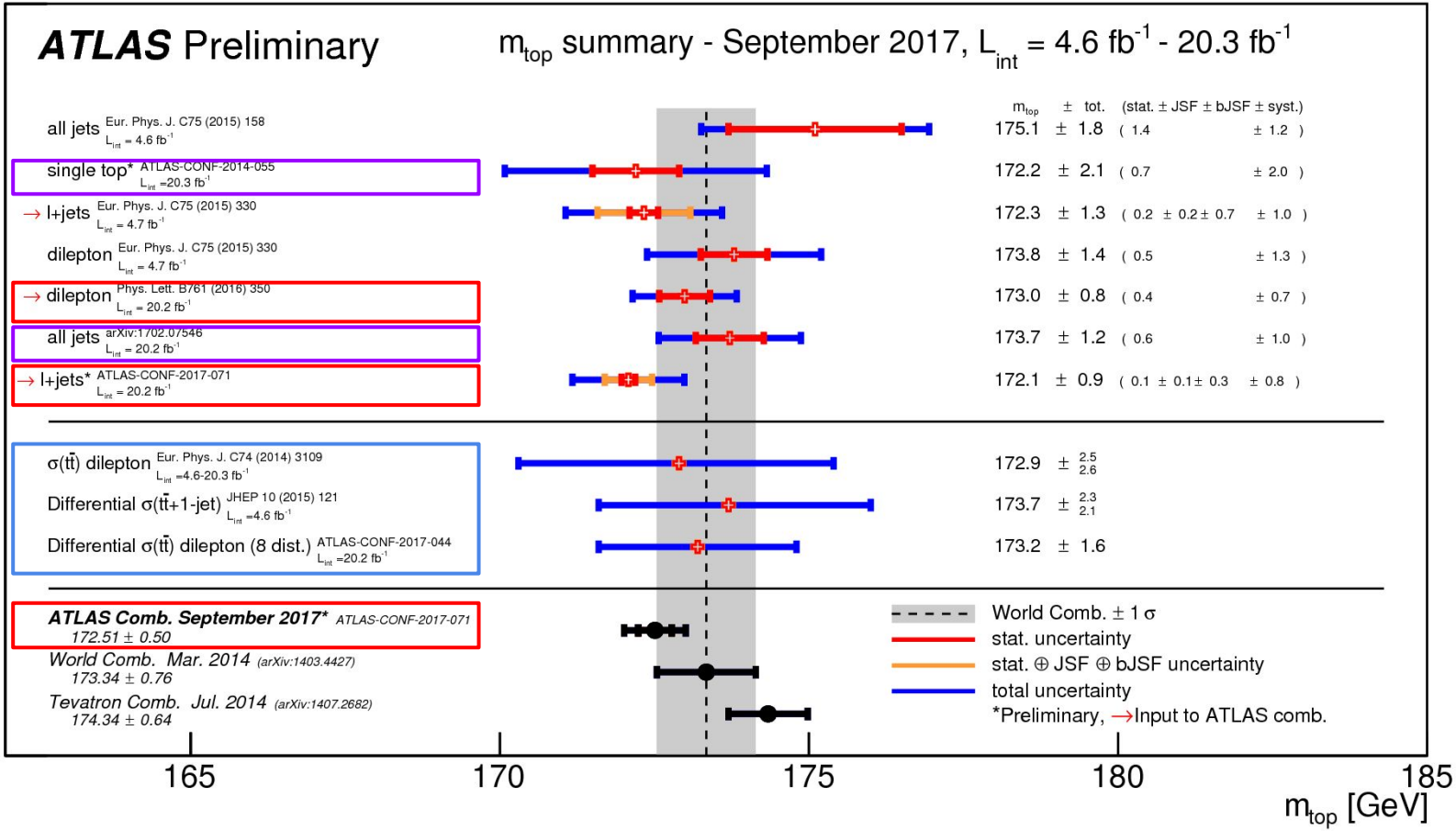
- **Combination** of different observables for m_t^{pole} reduces theoretical uncertainties significantly:
  - constraint on variations of QCD scales that control modeling of top kinematics
  - **choice of functional form for scales**: $\mu = m_t/2\ H_T/4$...
    ⇒ still ~1 GeV uncertainty

$$m_t^{pole} = 173.2 \pm 0.9\,(\text{stat}) \pm 0.8\,(\text{exp}) \pm 1.2\,(\text{theory})\ \text{GeV}$$

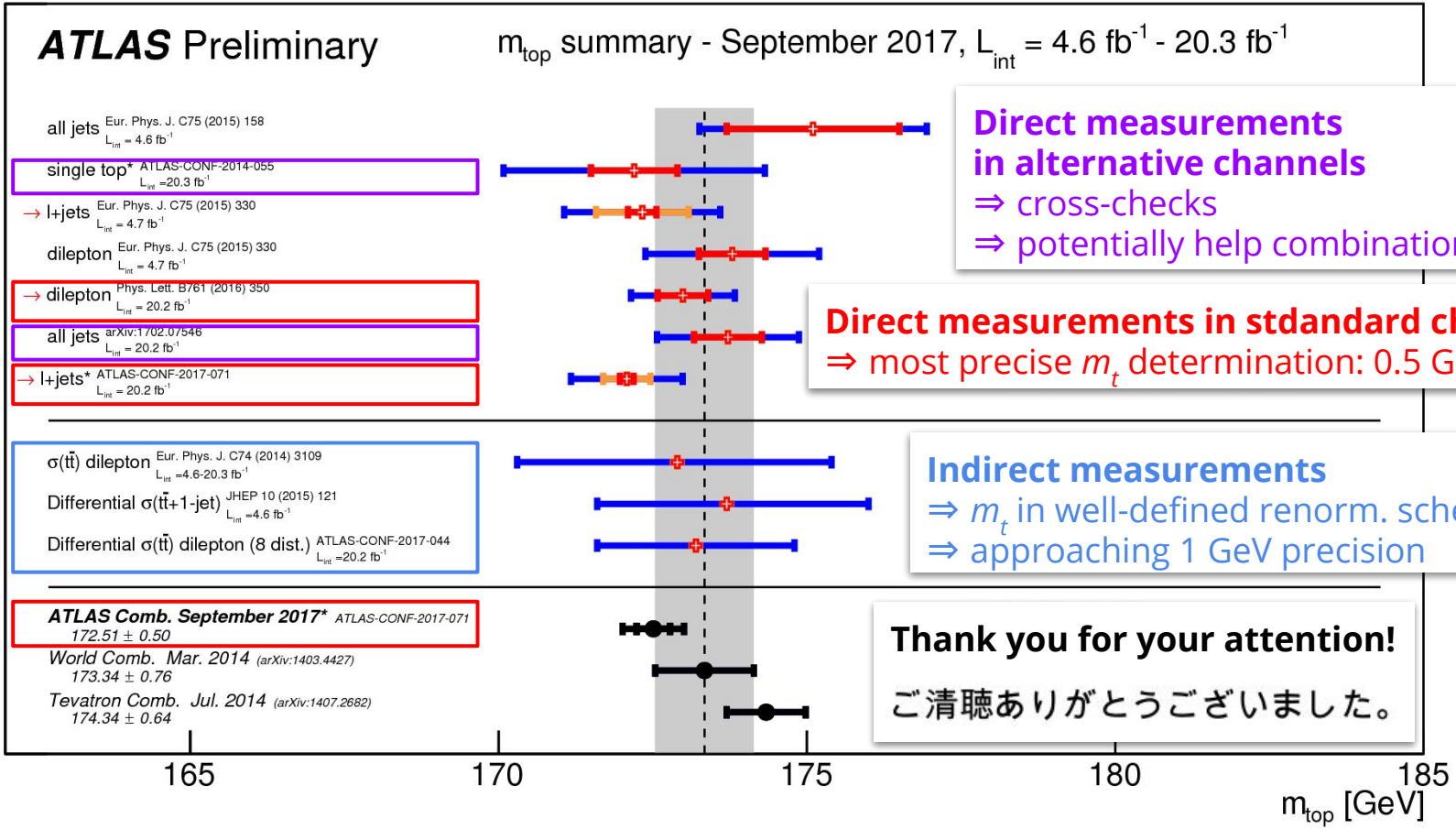
$\pm$ 1.6 GeV

most precise m_t^{pole} measurement at present!

Top Quark Mass Measurements at ATLAS - Summary



Top Quark Mass Measurements at ATLAS - Summary



Direct measurements in alternative channels
⇒ cross-checks
⇒ potentially help combination

Direct measurements in stdandard channels
⇒ most precise m_t determination: 0.5 GeV

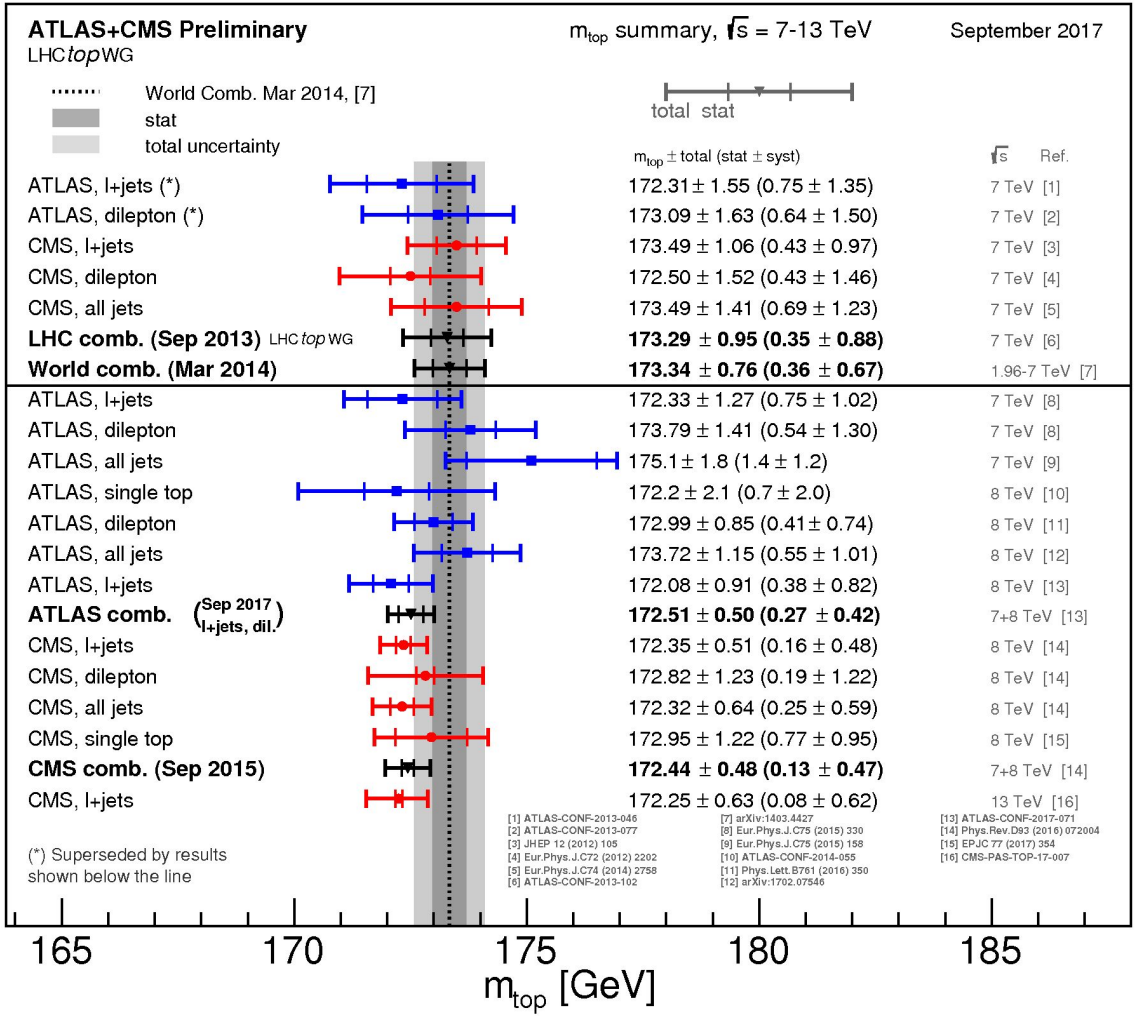
Indirect measurements
⇒ m_t in well-defined renorm. scheme
⇒ approaching 1 GeV precision

Thank you for your attention!

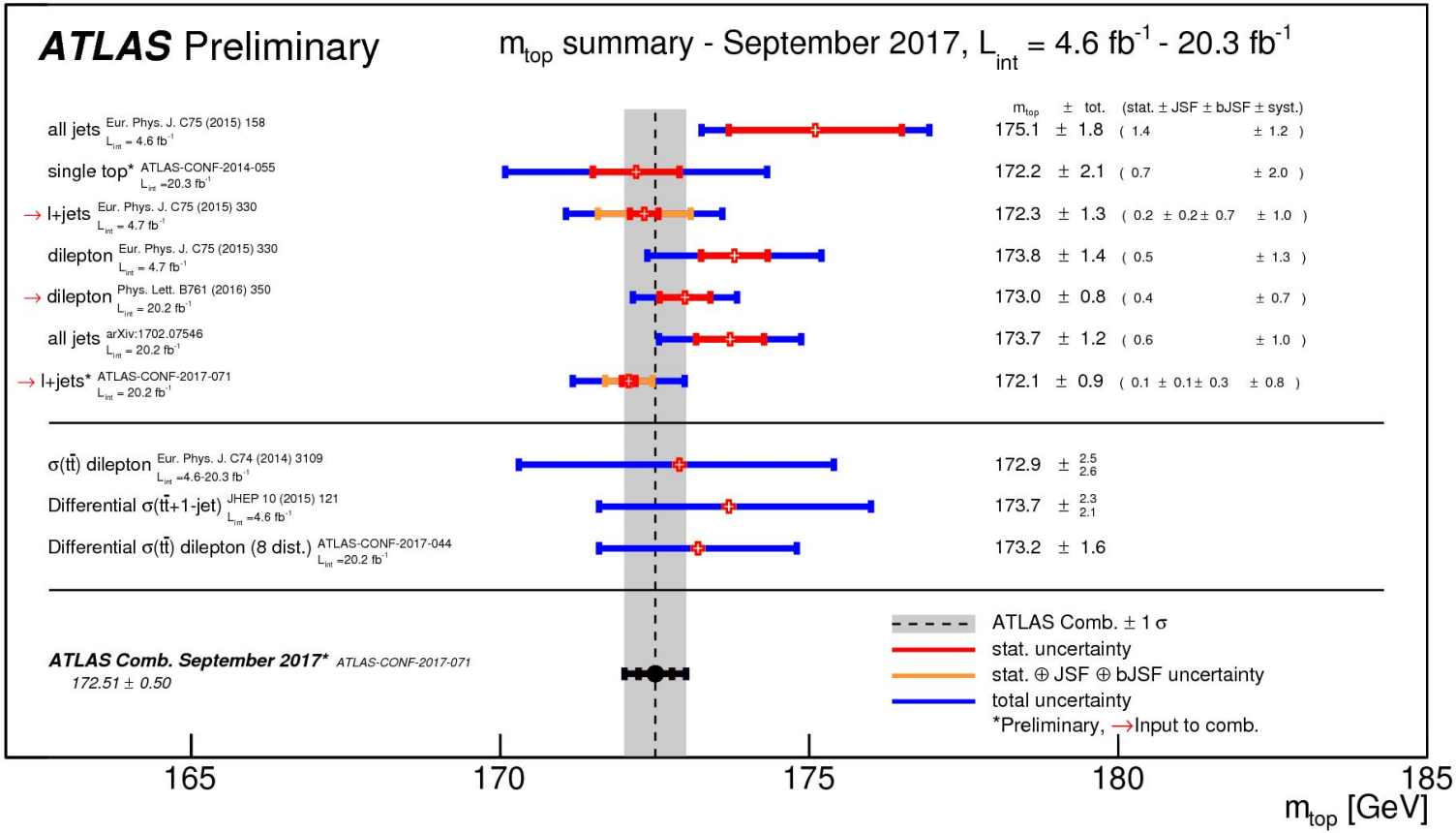
ご清聴ありがとうございました。

Backup

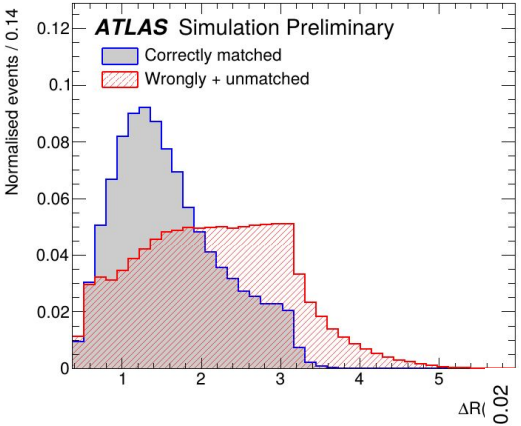
ATLAS vs CMS

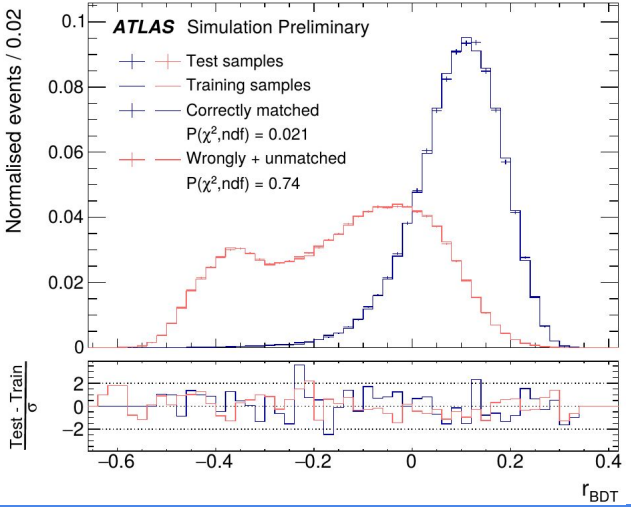

ATLAS+CMS Preliminary
LHC top WG
m_{top} summary, $\sqrt{s}$ = 7-13 TeV
September 2017
World Comb. Mar 2014, [7]
stat
total uncertainty
total stat
m_{top} ± total (stat ± syst)
$\sqrt{s}$ Ref.
ATLAS, l+jets (*) 172.31 ± 1.55 (0.75 ± 1.35) 7 TeV [1]
ATLAS, dilepton (*) 173.09 ± 1.63 (0.64 ± 1.50) 7 TeV [2]
CMS, l+jets 173.49 ± 1.06 (0.43 ± 0.97) 7 TeV [3]
CMS, dilepton 172.50 ± 1.52 (0.43 ± 1.46) 7 TeV [4]
CMS, all jets 173.49 ± 1.41 (0.69 ± 1.23) 7 TeV [5]
LHC comb. (Sep 2013) LHC top WG 173.29 ± 0.95 (0.35 ± 0.88) 7 TeV [6]
World comb. (Mar 2014) 173.34 ± 0.76 (0.36 ± 0.67) 1.96-7 TeV [7]
ATLAS, l+jets 172.33 ± 1.27 (0.75 ± 1.02) 7 TeV [8]
ATLAS, dilepton 173.79 ± 1.41 (0.54 ± 1.30) 7 TeV [8]
ATLAS, all jets 175.1 ± 1.8 (1.4 ± 1.2) 7 TeV [9]
ATLAS, single top 172.2 ± 2.1 (0.7 ± 2.0) 8 TeV [10]
ATLAS, dilepton 172.99 ± 0.85 (0.41 ± 0.74) 8 TeV [11]
ATLAS, all jets 173.72 ± 1.15 (0.55 ± 1.01) 8 TeV [12]
ATLAS, l+jets 172.08 ± 0.91 (0.38 ± 0.82) 8 TeV [13]
ATLAS comb. (Sep 2017 l+jets, dil.) 172.51 ± 0.50 (0.27 ± 0.42) 7+8 TeV [13]
CMS, l+jets 172.35 ± 0.51 (0.16 ± 0.48) 8 TeV [14]
CMS, dilepton 172.82 ± 1.23 (0.19 ± 1.22) 8 TeV [14]
CMS, all jets 172.32 ± 0.64 (0.25 ± 0.59) 8 TeV [14]
CMS, single top 172.95 ± 1.22 (0.77 ± 0.95) 8 TeV [15]
CMS comb. (Sep 2015) 172.44 ± 0.48 (0.13 ± 0.47) 7+8 TeV [14]
CMS, l+jets 172.25 ± 0.63 (0.08 ± 0.62) 13 TeV [16]
(*) Superseded by results shown below the line
[1] ATLAS-CONF-2013-046
[2] ATLAS-CONF-2013-077
[3] JHEP 12 (2012) 105
[4] Eur.Phys.J.C72 (2012) 2202
[5] Eur.Phys.J.C74 (2014) 2758
[6] ATLAS-CONF-2013-102
[7] arXiv:1403.4427
[8] Eur.Phys.J.C75 (2015) 330
[9] Eur.Phys.J.C75 (2015) 158
[10] ATLAS-CONF-2014-055
[11] Phys.Lett.B761 (2016) 350
[12] arXiv:1702.07546
[13] ATLAS-CONF-2017-071
[14] Phys.Rev.D93 (2016) 072004
[15] EPJC 77 (2017) 354
[16] CMS-PAS-TOP-17-007
165
170
175
180
185
m_{top} [GeV]

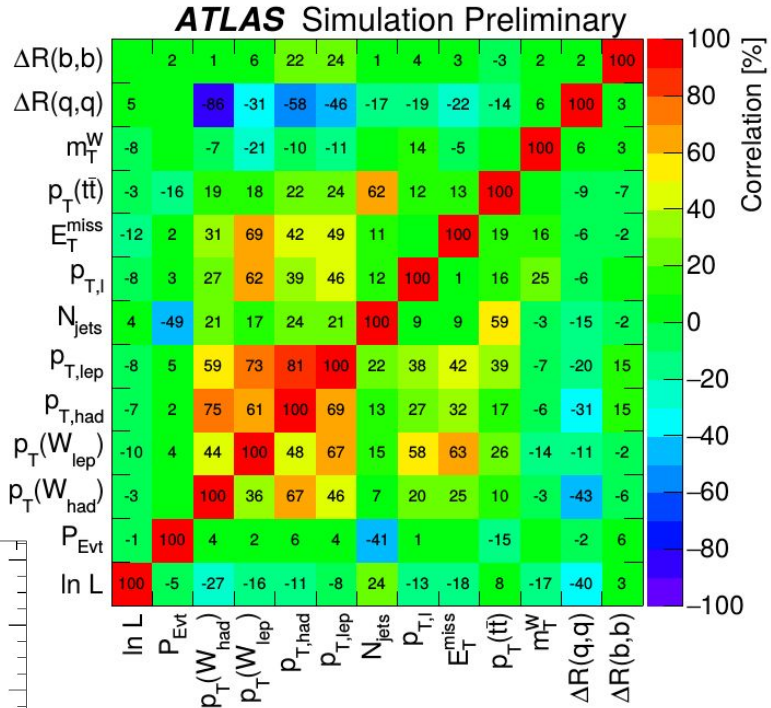
Measurements compared to ATLAS combination



Single lepton BDT



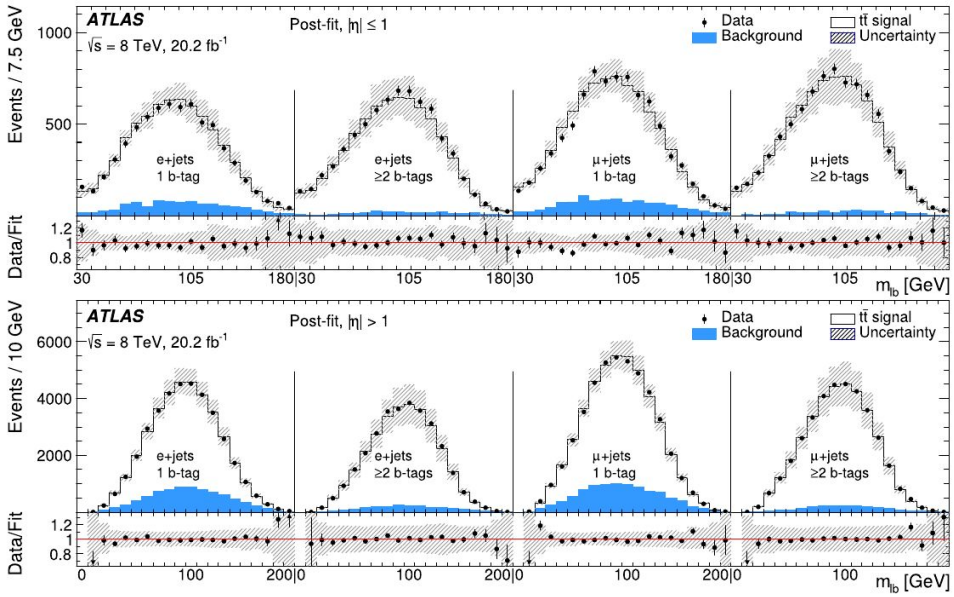


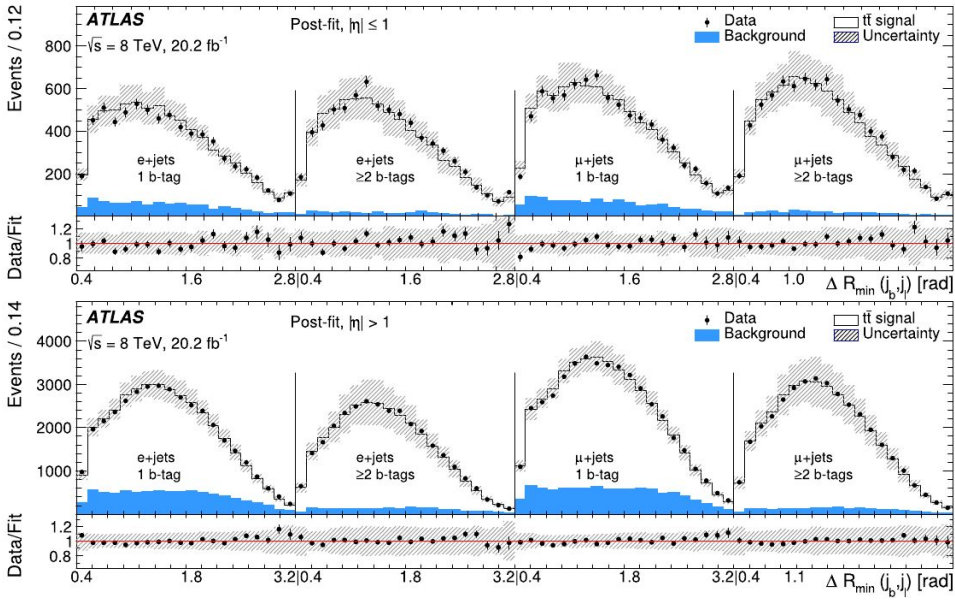


Systematics

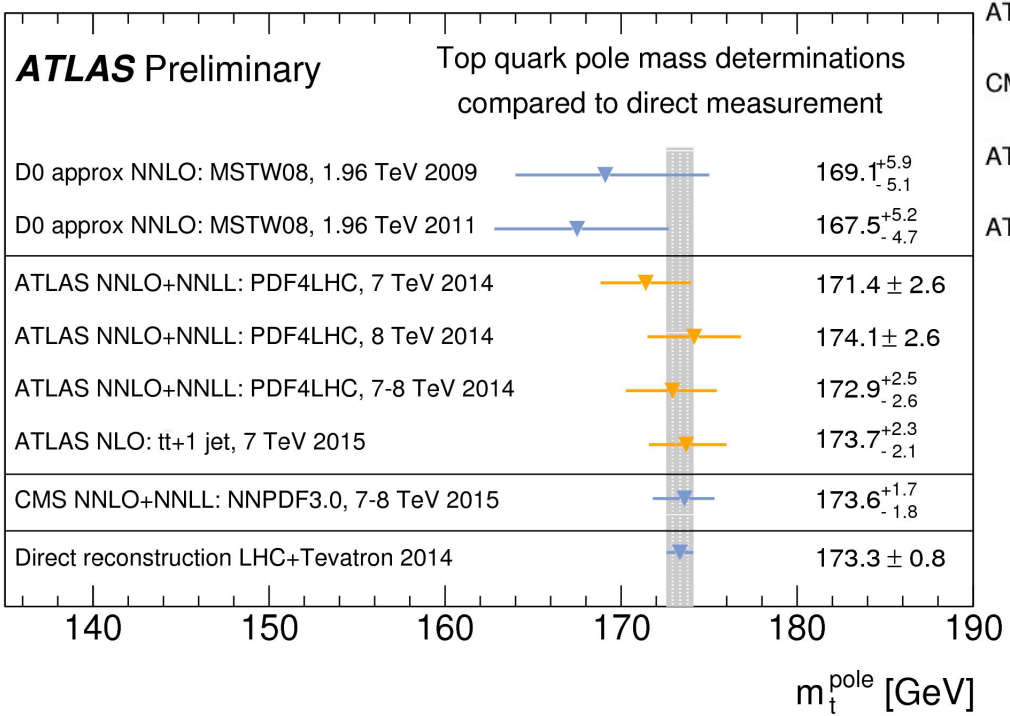
	$\sqrt{s}$ = 7 TeV		$\sqrt{s}$ = 8 TeV		Correlations		
	m_{top}^{dil} [GeV]	m_{top}^{l+jets} [GeV]	m_{top}^{dil} [GeV]	m_{top}^{l+jets} [GeV]	ρ_{03}	ρ_{13}	ρ_{23}
Results	173.79	172.33	172.99	172.08			
Statistics	0.54	0.75	0.41	0.39	0	0	0
– *Stat. comp.* (m_{top})		0.23		0.11			
– *Stat. comp.* (JSF)		0.25		0.11			
– *Stat. comp.* (bJSF)		0.67		0.35			
Method	0.09 ± 0.07	0.11 ± 0.10	0.05 ± 0.07	0.13 ± 0.11	0	0	0
Signal Monte Carlo generator	0.26 ± 0.16	0.22 ± 0.21	0.09 ± 0.15	0.16 ± 0.17	+1.00	+1.00	+1.00
Hadronisation	0.53 ± 0.09	0.18 ± 0.12	0.22 ± 0.09	0.15 ± 0.10	−1.00	−1.00	−1.00
Initial- and final-state QCD radiation	0.47 ± 0.05	0.32 ± 0.06	0.23 ± 0.07	0.08 ± 0.11	+1.00	−1.00	+1.00
Underlying event	0.05 ± 0.05	0.15 ± 0.07	0.10 ± 0.14	0.08 ± 0.15	+1.00	−1.00	+1.00
Colour reconnection	0.14 ± 0.05	0.11 ± 0.07	0.03 ± 0.14	0.19 ± 0.15	−1.00	+1.00	−1.00
Parton distribution function	0.11 ± 0.00	0.25 ± 0.00	0.05 ± 0.00	0.09 ± 0.00	+0.72	+0.72	−0.48
Background normalisation	0.04 ± 0.00	0.10 ± 0.00	0.03 ± 0.00	0.08 ± 0.00	−0.77	−0.74	−0.06
W/Z+jets shape	0.00 ± 0.00	0.29 ± 0.00	0	0.11 ± 0.00	0	0	0
Fake leptons shape	0.01 ± 0.00	0.05 ± 0.00	0.07 ± 0.00	0	0	0	0
Jet energy scale	0.75 ± 0.08	0.58 ± 0.11	0.54 ± 0.04	0.54 ± 0.02	+0.18	−0.29	−0.54
Relative b-to-light-jet energy scale	0.68 ± 0.02	0.06 ± 0.03	0.30 ± 0.01	0.03 ± 0.01	+1.00	+1.00	+1.00
Jet energy resolution	0.19 ± 0.04	0.22 ± 0.11	0.09 ± 0.05	0.20 ± 0.04	0	0	+0.22
Jet reconstruction efficiency	0.07 ± 0.00	0.12 ± 0.00	0.01 ± 0.00	0.02 ± 0.01	+1.00	+1.00	+1.00
Jet vertex fraction	0.00 ± 0.00	0.01 ± 0.00	0.02 ± 0.00	0.09 ± 0.01	−1.00	+1.00	+1.00
b-tagging	0.07 ± 0.00	0.50 ± 0.00	0.04 ± 0.02	0.38 ± 0.00	0	0	−0.23
Leptons	0.13 ± 0.00	0.04 ± 0.00	0.14 ± 0.01	0.16 ± 0.01	−0.08	−0.17	+0.11
E_T^{miss}	0.04 ± 0.03	0.15 ± 0.04	0.01 ± 0.01	0.05 ± 0.01	−0.12	+0.22	+0.97
Pile-up	0.01 ± 0.00	0.02 ± 0.01	0.05 ± 0.01	0.15 ± 0.01	0	0	0
Total systematic uncertainty	1.31 ± 0.07	1.03 ± 0.08	0.74 ± 0.05	0.82 ± 0.06			
Total	1.41 ± 0.07	1.27 ± 0.08	0.85 ± 0.05	0.91 ± 0.06	0.06	−0.07	−0.19

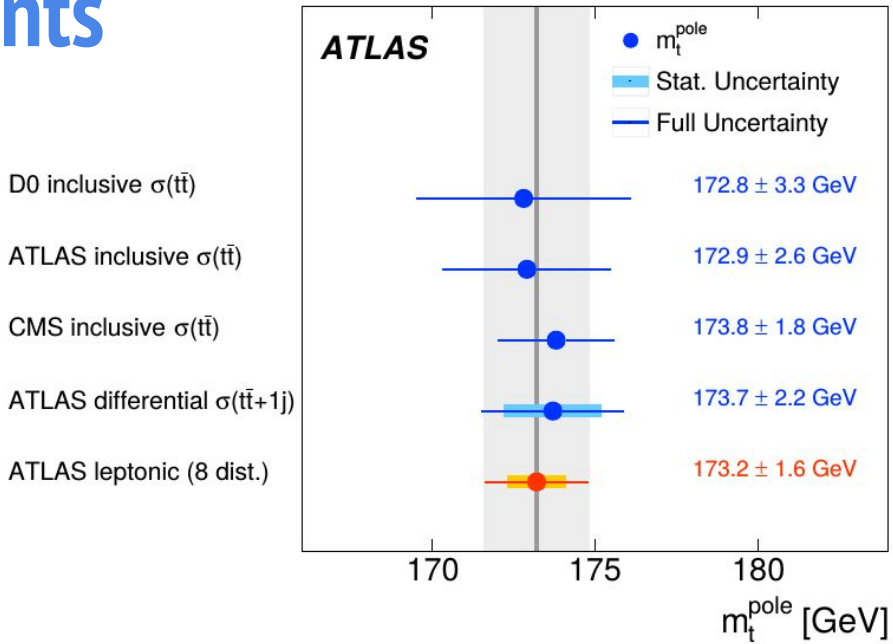
Top width categories





Indirect top mass measurements





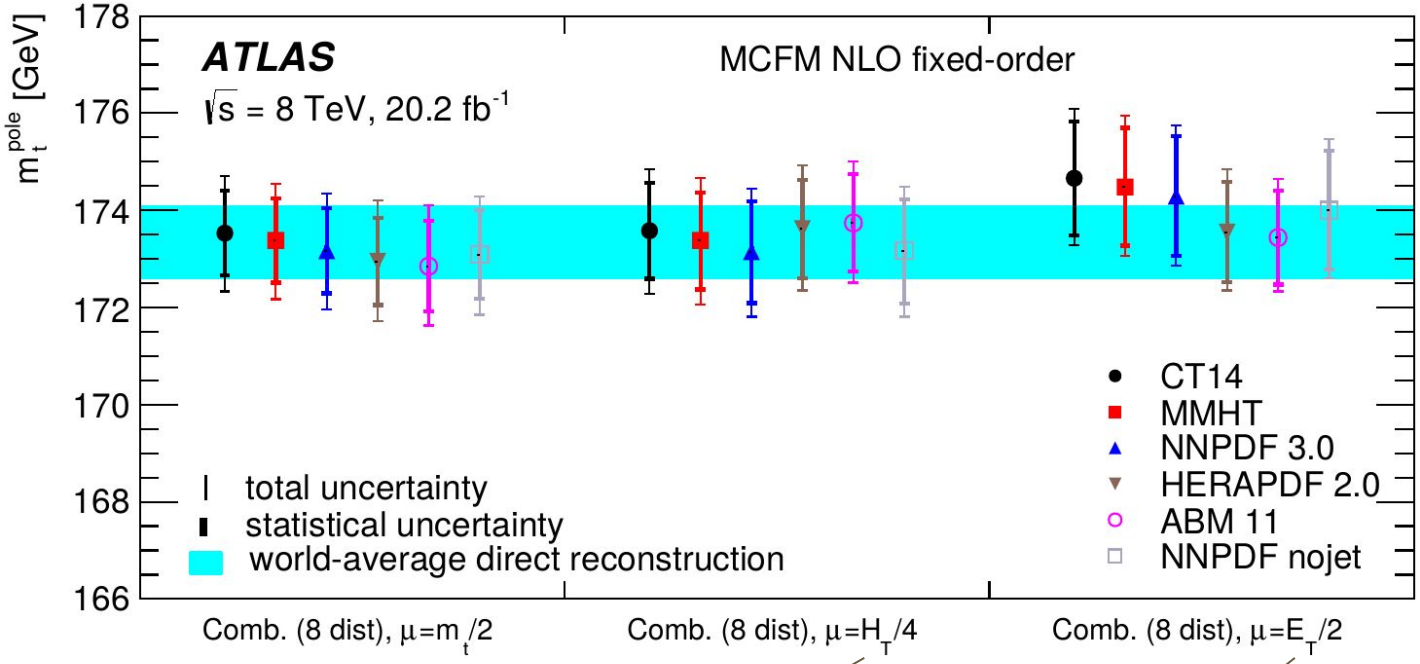
Systematics in top mass from dilep. kinematics

- Dependence on top pT
  (from comparison with NLO+PS)

Mass shift [GeV]	m_t^{MC}	p_T^{ℓ}	$p_T^{e\mu}$	$m^{e\mu}$	$p_T^{e} + p_T^{\mu}$	$E^{e} + E^{\mu}$
POWHEG ($h_{damp} = \infty$) $\rightarrow$ ($h_{damp} = m_t$)		0.9	3.0	-1.3	0.9	0.5
Top p_T NNLO reweighting		1.8	0.3	2.2	1.3	1.3

- On comparison with fNLO:
  - PDFs: 0.3 GeV from envelope of different PDF sets (considering also PDFs without LHC and Tevatron jet data in region relevant for *tt* production)
  - uncertainty from α_s: 0.01 GeV
  - dependency on m_t^{MC} (acceptance effects): 0.1 GeV from 5 GeV variation of m_t^{MC}

Dependence on scale functional form



$$\sqrt{m_t^2 + p_T(t)^2} + \sqrt{m_t^2 + p_T(\bar{t})^2}$$

$$\sqrt{m_t^2 + p_T(t\bar{t})^2}$$