Alternative top quark mass determinations in ATLAS and CMS

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On behalf of the ATLAS and CMS collaborations

Top2015, Ischia, September 2015

Prospects for precision

Today's **direct measurements reach 0.5% precision**, limited by statistics (still ~0.17%), detector systematics (few JES-related sources of order 0.1%) and modeling (few sources of 0.15%)
see talk by Andrea Castro, Andreas Maier

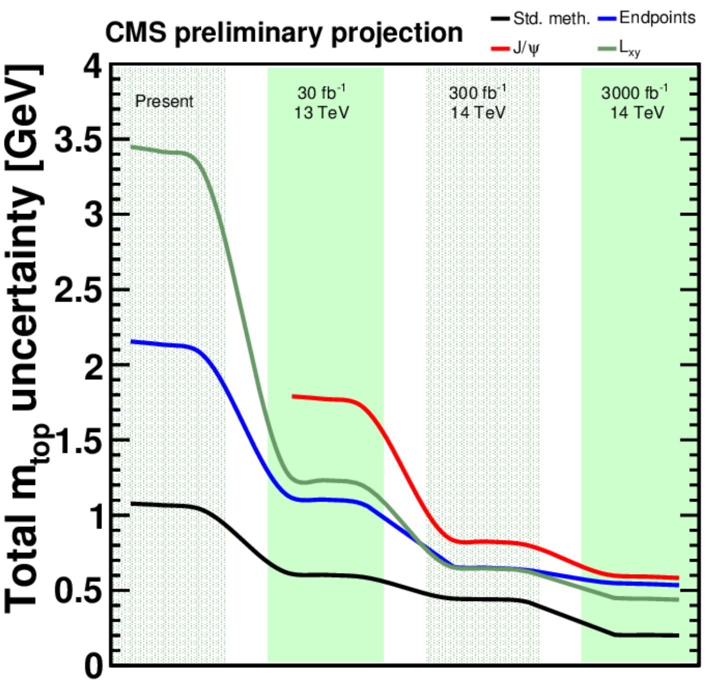
For a long time the LHC claimed it would reach 1 GeV, but we can be a bit more ambitious now
Pessimistic (EPJ C74, 2014):

"a top mass extraction with uncertainty as low as 500-600 MeV"

Optimistic (CMS-FTR-13-017-PAS):

"[the ultimate reach of the] *conventional method is 200 MeV",*
based on "assumptions [that] are optimistic but not unrealistic."

Alternative determinations help with a different "systematics mix":
- reveal systematic bias, or
- reduce overall uncertainty



Prospects for precision: alternatives

The MC mass is not the pole mass

Ask me after the talk, or (better still) Gennaro Corcella in the next session

Literature: Juste et al.,EPJ C74 (2014), Hoang, arXiv:1412.3649

The top quark mass measurements need a theory uncertainty

Like any other quantity inferred from the data. Truncated perturbative series, parametric uncertainties, intrinsic limitations of mass definition.

A precise & universal relation between the MC and pole mass may exist, and numerically this difference may even be vanishing, but currently this relation is unknown

Related uncertainties have long been negligible, but we're embarking on an attempt to perform a per-mil level quark mass measurement now!

Alternative determinations may provide a clear interpretation in terms of a well-defined scheme and a more robust basis for estimating theory uncertainties

Top quark mass - alternatives

Change final state

- single top, 2.1 GeV, ATLAS-CONF-2014-055

Change observable

- J/psi spectra t → Wb → lvb → lvJ/ψ → lvll → CMS-PAS-TOP-13-007
  – ATLAS-CONF-2015-040
- Endpoint, 2 GeV, CMS, arXiv:1304.5783
- B-hadron L_{xy}, lepton p_T
  → CDF 8 GeV, PLB698
  → CMS 3 GeV, CMS-PAS-TOP-12-030
- m_{bl}, 1.3 GeV, CMS-PAS-TOP-14-014
- b-jet energy spectrum, 3 GeV, CMS-PAS-TOP-15-002

Extraction from cross-section

Connect theory prediction with measurement

Traditionally inclusive cross-section, but...

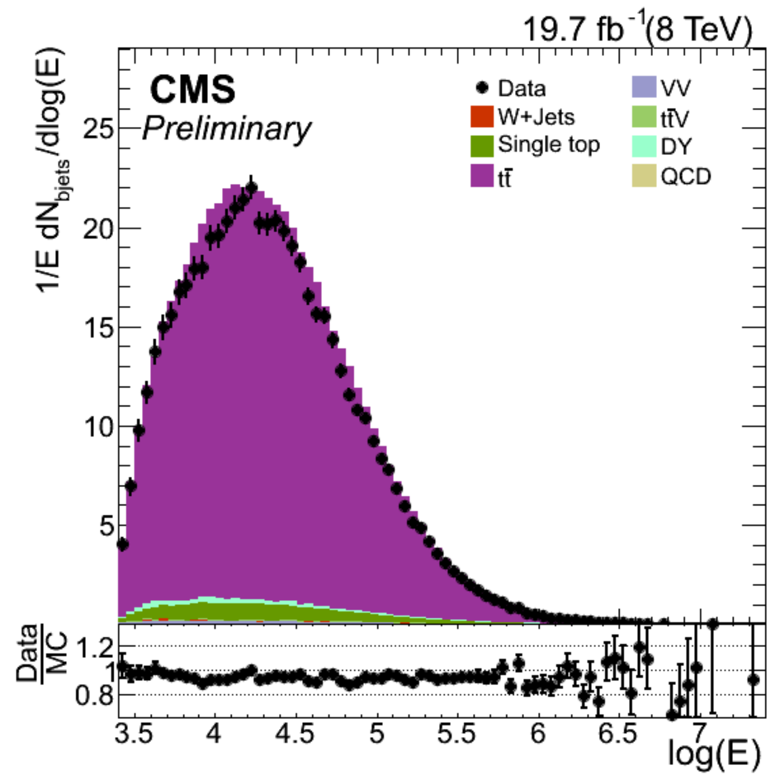
This talk

See excellent summary by Stefanie Adomeit and Benjamin Stieger on behalf of CDF, D0, ATLAS, CMS at TOP2014

Meaurement of the b-jet energy spectrum

Based on following observations for products of 2-body decay:
- the peak of the energy distribution in the parent rest frame is related to the parent mass
- for unpolarized parent and massless daughter the relation holds also in the laboratory frame
K. Agashe, R. Franceschini, D. Kim, PRD88

CMS PAS TOP-15-002
- Measures b-jet energy distribution in eμ events
- Peak energy extracted from Gaussian fit to 1/E log(E) distribution
- Calibration to b-quark energy peak using pseudo-experiments isnumerically small: 171.0 GeV → 172.3 GeV

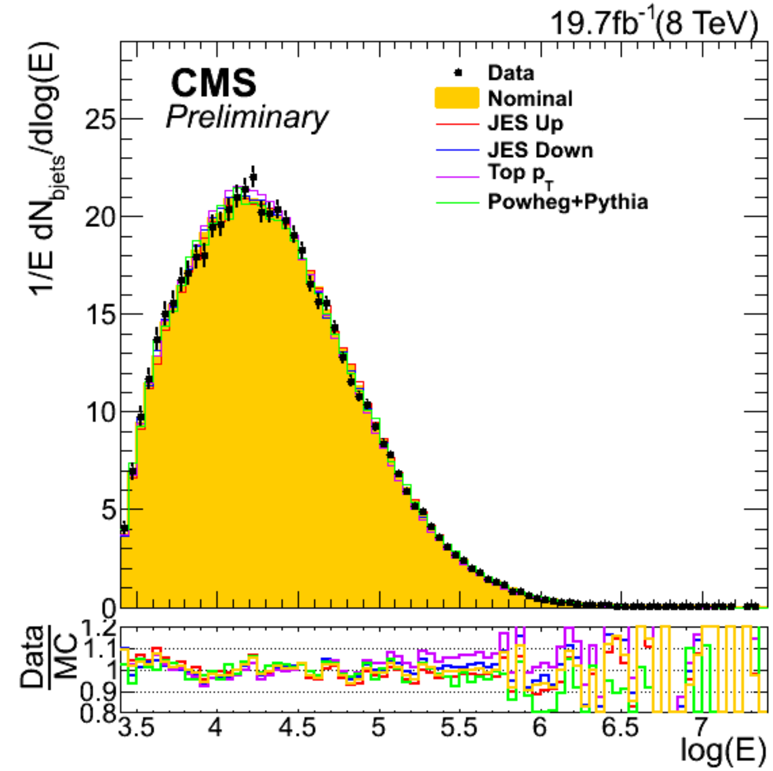


Measurement from b-jet energy measurement

Top boost indeed found to change the tail, but to leave the peak position ~ unchanged

Dominant systematics:

- JES (1.2 GeV)
- ME (1.5 GeV)
- top p_T spectrum (1.5 GeV)



NEW

Mass extracted using simple kinematical relation:

M_t=172.3 ± 1.2 (stat.) ± 2.7 (syst.) GeV

Promising result for determination of the mass of new particles (authors of PRD88 expected 2.5 GeV for 5/fb at 7 TeV)

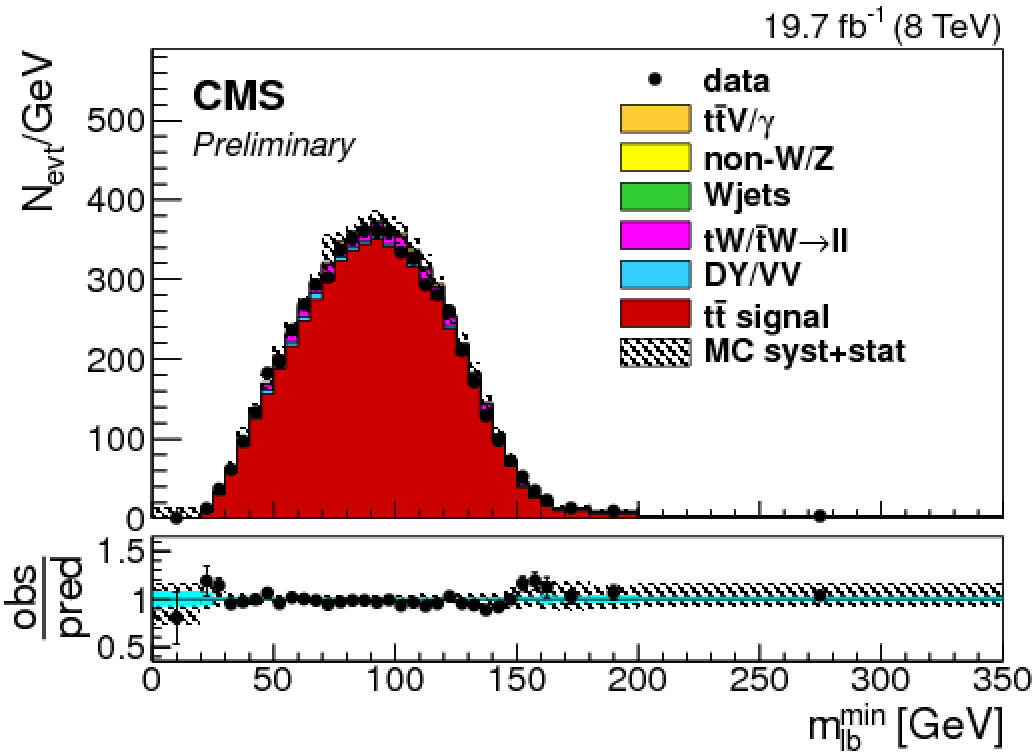
Measurement from m_{lb} distribution

S. Biswas, K. Melnikhov, M. Schulze, JHEP 1008 (2010) 048

Observable is boost-invariant → little sensitivity to production

CMS-TOP14-014

Full 2012 data set
Clean selection based on opposite-sign eμ events
Minimal invariant mass between charged lepton and b-jet

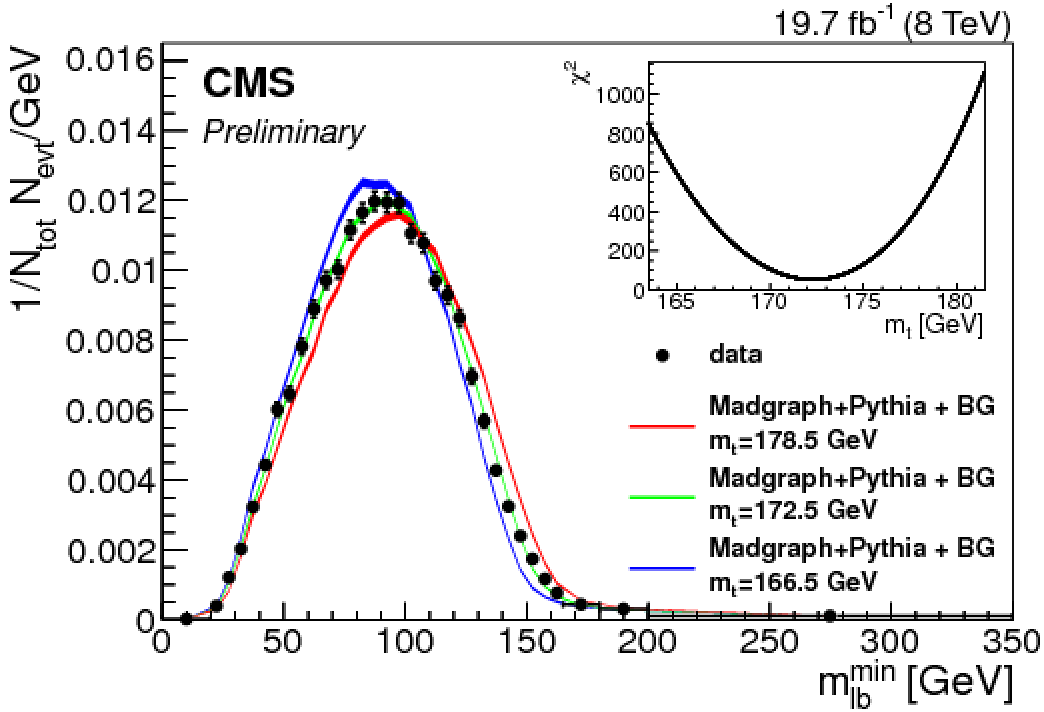


Results from m_{lb}

CMS-TOP14-014-PAS

Observable is very sensitive to m_t

Experimental systematics and modelling uncertainty are under control



Prediction	Fit method	Fitted m_t [GeV] from m_{lb}^{min}
MADGRAPH+PYTHIA	shape+rate	$173.1^{+1.9}_{-1.8}$
MADGRAPH+PYTHIA	rate	$173.7^{+3.5}_{-3.4}$
MADGRAPH+PYTHIA	shape	$172.3^{+1.3}_{-1.3}$
MCFM (LO)	shape	$171.5^{+1.1}_{-1.1}$
MCFM (NLO)	shape	$171.4^{+1.0}_{-1.1}$

Shape information more effective than absolute rate. MCFM fixed-order predictions are folded to account for detector effects.

Interpretation of m_{lb} mass

Currently, the mass is calibrated to MC. A reliable extraction of (pole) mass is possible, but requires a more sophisticated description of decay to fix the renormalization scheme and estimate theory uncertainty

LO scale variations are small < 100 MeV

→ scale variations known to underestimate error at LO

LO << NLO << WbWb*, see Heinrich et al., JHEP06 (2014)*

→ large difference between LO and NLO in decay found by CMS

MCFM (NLO prod. + LO decay)	171.4 ± 1.1 GeV
MCFM (NLO prod. + NLO decay)	172.3 ± ? GeV

Top quark mass extraction: mass schemes

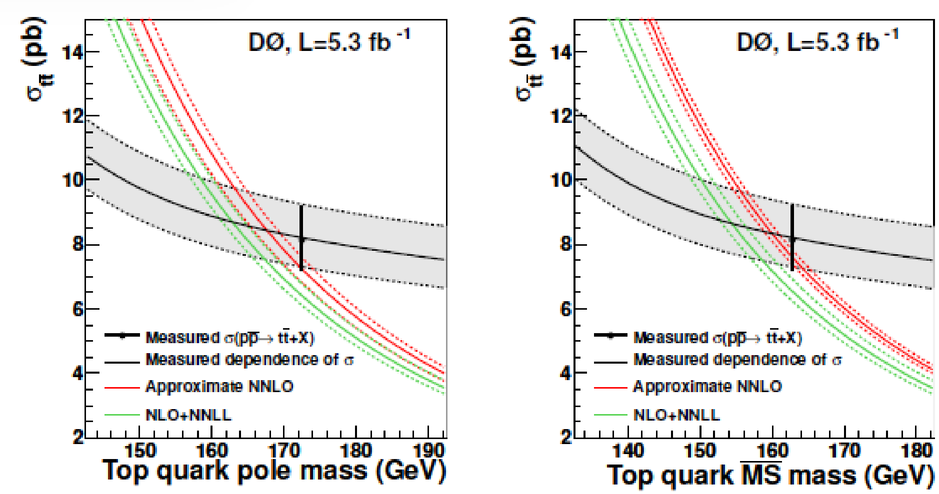
The scheme makes a difference:
For a top quark pole mass of 173 GeV,
the $\overline{MS}$ mass at the top mass ~167 GeV

We need the mass as input to calculations:
Pole mass → ultimately limited by $O(\Lambda_{QCD})$ ambiguity?
Running mass → hopes of faster convergence?

Tentatively, for O(1 GeV):
whichever can be extracted most precisely
Ultimately, for O(100 MeV):
$\overline{MS}$ mass?

Conversion between schemes can be made very precise
Marquard et al., PRL 114 (2015)

D0, extraction of the the pole and running mass from the inclusive cross section using approximate NNLO calculation, PLB 703 , 422 (2011)



$m_t^{pole} = 167.5^{+5.2}_{-4.7}$ GeV $\quad m_t^{\overline{MS}} = 160.0^{+4.8}_{-4.2}$ GeV

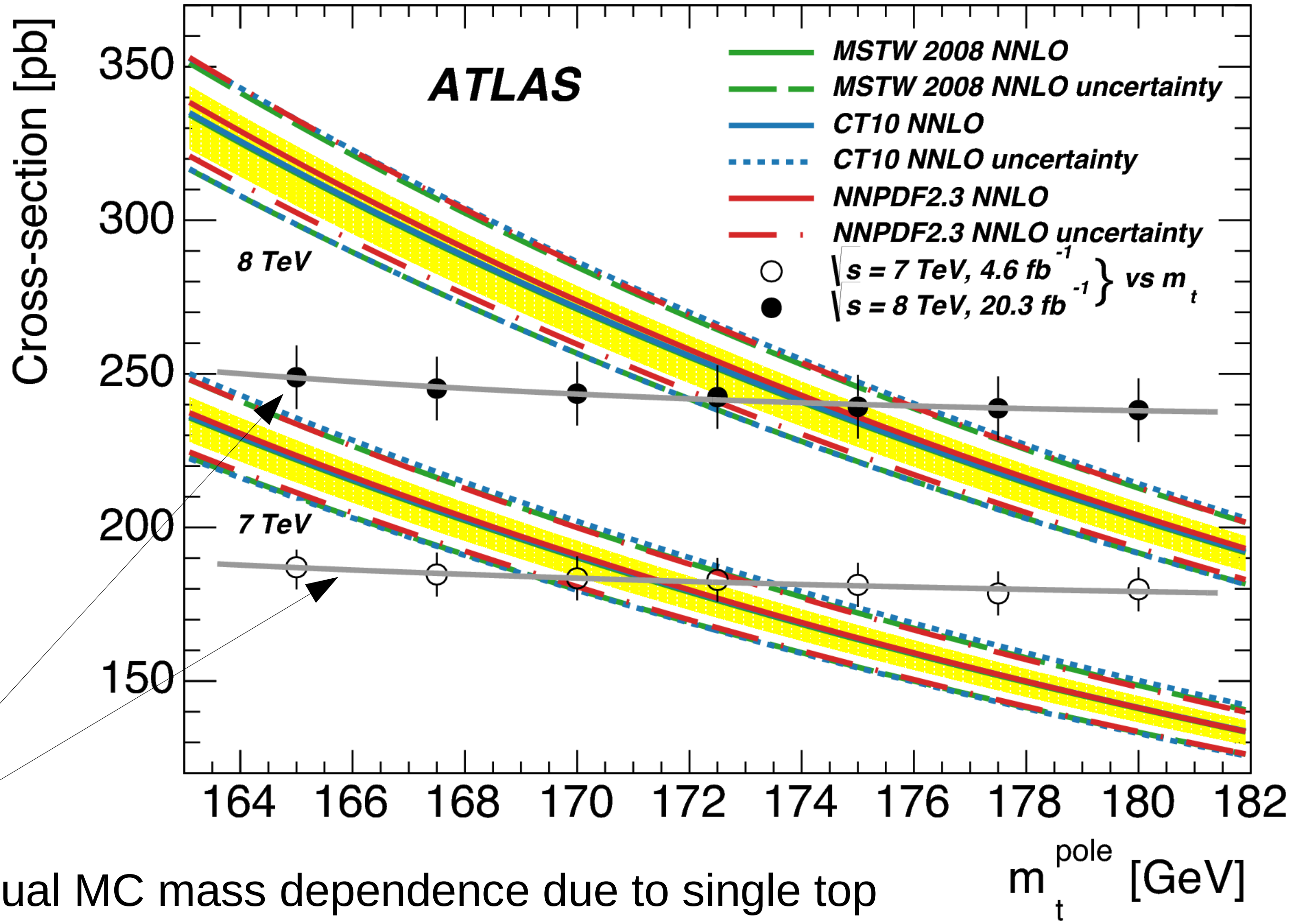
Alternative: top quark pole mass from cross-section

$\sigma_{tt}(7\,TeV) = 182.9 \pm 3.1(stat.) \pm 4.2(syst.) \pm 3.6(lumi.) \pm 3.3(energy)\,pb$

$\sigma_{tt}(8\,TeV) = 242.4 \pm 1.7(stat.) \pm 5.5(syst.) \pm 7.5(lumi.) \pm 4.2(energy)\,pb$

Precision on cross-section: 3.9 – 4.3%

Δm_t^{pole} = 2.5 GeV



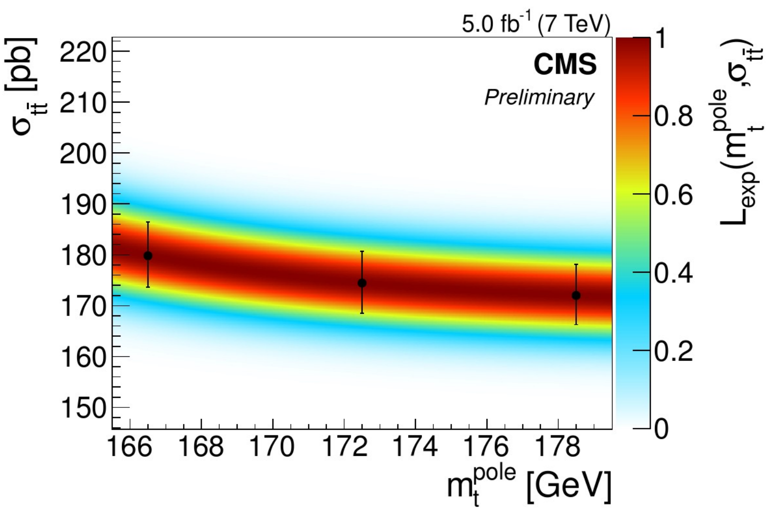
Nearly flat, small residual MC mass dependence due to single top

Cross-section measurement in eμ channel

CMS TOP-13-004

- Full run I samples: 5/fb @ 7 TeV, 19.7/fb @ 8 TeV
- analyze eμ channel only → very clean $t\bar{t}$ sample
- template fit in several bins of (b-) jet multiplicity
- extract visible cross-section
- correct to parton-level

$$\sigma_{tot} = \frac{\sigma_{vis}}{A_{e\mu}}$$

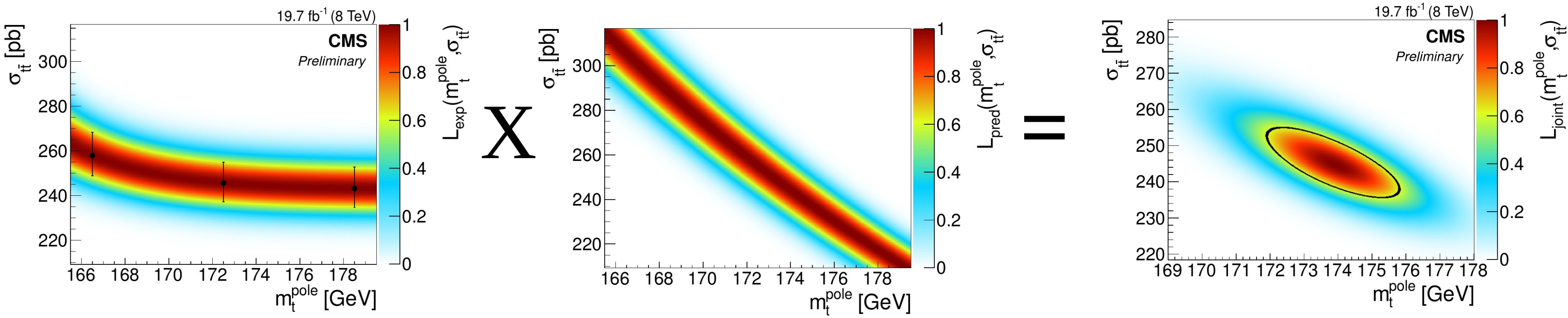


Source	Uncertainty [%]	
	7 TeV	8 TeV
Trigger	1.2	1.2
Lepton ID/isolation	1.4	1.5
Lepton energy scale	0.1	0.1
Jet energy scale	0.7	0.9
Jet energy resolution	0.1	0.1
Single top	0.9	0.6
DY	1.2	1.2
$t\bar{t}$ other	0.1	0.1
$t\bar{t}+V$	0.0	0.1
Diboson	0.2	0.6
W+jets	0.0	0.0
QCD	0.0	0.0
B-tag	0.5	0.5
Mistag	0.2	0.1
Pileup	0.3	0.3
Q^2 scale	0.3	0.3
ME/PS matching	0.2	0.1
MG+PY → PH+PY	0.2	0.4
Hadronization (JES)	0.6	0.8
Top p_T	0.3	0.3
Color reconnection	0.1	0.0
Underlying event	0.0	0.1
PDF	0.2	0.7
Luminosity	2.2	2.6
Statistical	1.2	0.6

Total uncertainty on visible cross-section: 3.4%

Source	Uncertainty [%]	
	7 TeV	8 TeV
Total (vis)	$\pm^{3.5}_{3.4}$	$\pm^{3.7}_{3.4}$
Q^2 scale (extrapol.)	$\pm^{0.4}_{0.0}$	$\pm^{0.2}_{0.1}$
ME/PS matching (extrapol.)	$\mp^{0.1}_{0.1}$	$\pm^{0.3}_{0.3}$
Top p_T (extrapol.)	$\pm^{0.4}_{0.2}$	$\pm^{0.8}_{0.4}$
PDF (extrapol.)	$\mp^{0.2}_{0.1}$	$\mp^{0.1}_{0.2}$
Total	$\pm^{3.6}_{3.4}$	$\pm^{3.8}_{3.5}$

Pole mass extraction



Extract top quark pole mass by minizing product of experimental and theoretical likelihood distribusions

Theory likelihood includes:
- uncertainties NNLO + NNLL scale variations
- PDF uncertainties from one PDF set at a time
- 1 GeV shift for relation MC and pole masses
- 1.7-1.8% uncertainty to account for uncertaint beam energy

NEW

M_t^{pole}=173.6 ± 1.8 GeV (CMS-PAS-TOP-13-004)
assuming NNPDF3.0 and α_s = 0.118 ± 0.001

Pole mass extraction, PDFs and uncertainties

ATLAS EPJC :

$\Delta\sigma$ = 3.9% (7 TeV) – 4.3% (8 TeV)

Δm_t^{pole} = 2.5 GeV, using "PDF4LHC" envelope of CT10, MSTW, NNPDF2.3

CMS PAS TOP 13-004:

$\Delta\sigma$ = 3.6% (7 TeV) – 3.8% (8 TeV)

Δm_t^{pole} = 1.8 GeV, assuming NNPDF3.0 and $\alpha_s = 0.118 \pm 0.001$

Full "PDF4LHC" uncertainty is more conservative than single PDF

New PDFs have smaller uncertainties than previous generation, thanks to the inclusion in the fit of LHC data

At 13 TeV the uncertainties due to PDFs are smaller than a 7/8 TeV, as we probe gluon content at lower x. ($\Delta\sigma$ (PDF) ~ 2.8% at 7 TeV, 1.8% at 14 TeV)

PDFs or top mass? Or both?

NNPDF3.0 includes pair production cross-section: *"Finally, we include six independent measurements of the total top quark pair production cross-section from ATLAS and CMS, both at 7 TeV and at 8 TeV. " (Parton distributions for the LHC Run II, JHEP1504 (2015) 040).*

	m_t
NNPDF30	$173.6 \pm^{1.7}_{1.8}$ GeV
MMHT2014	$173.9 \pm^{1.8}_{1.9}$ GeV
CT14	$174.1 \pm^{2.1}_{2.2}$ GeV

Same is true for MMHT14
See Robert Thorne's talk on Thursday

However, not for CT14:
"[$t\bar{t}$ data] are not included into our fit, as the differential NNLO $t\bar{t}$ cross section predictions for the LHC are not yet complete. In addition, constraints on the PDFs from $t\bar{t}$ cross sections are mutually correlated with the values of QCD coupling and top quark mass." (arXiv:1506:07443)

Avoid a circular exercise:
Extracting the mass from the inclusive cross-section after using the x-sec to constrain the PDFs leads to a bias

Can PDF fitter collaboration provide a separate set excluding just the $t\bar{t}$ cross-section data?

Can we use only $d\sigma/dp_T$ shape information for PDFs?

Extraction from differential cross-section

Alioli, Moch, Uwer, Fuster, Irles, Vos, EPJC73 (2013) 2438, arXiv:1303.6415

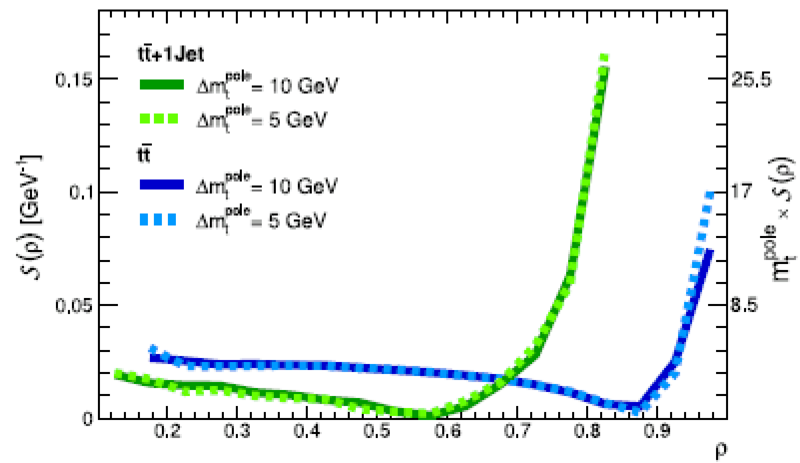
Extraction from total cross section

Precision limited by poor sensitivity: $\Delta m/m \sim 0.2\ \Delta\sigma/\sigma$

$t\bar{t}$ threshold offers better sensitivity, but:

→ is limited to a very narrow region

→ requires description of bound state effects



ρ µ 1/m($t\bar{t}$) for top quark pairs

Now consider the $t\bar{t}j$ cross-section

Sensitivity enhanced by mass-dependent radiation

Threshold effect spreads over large region

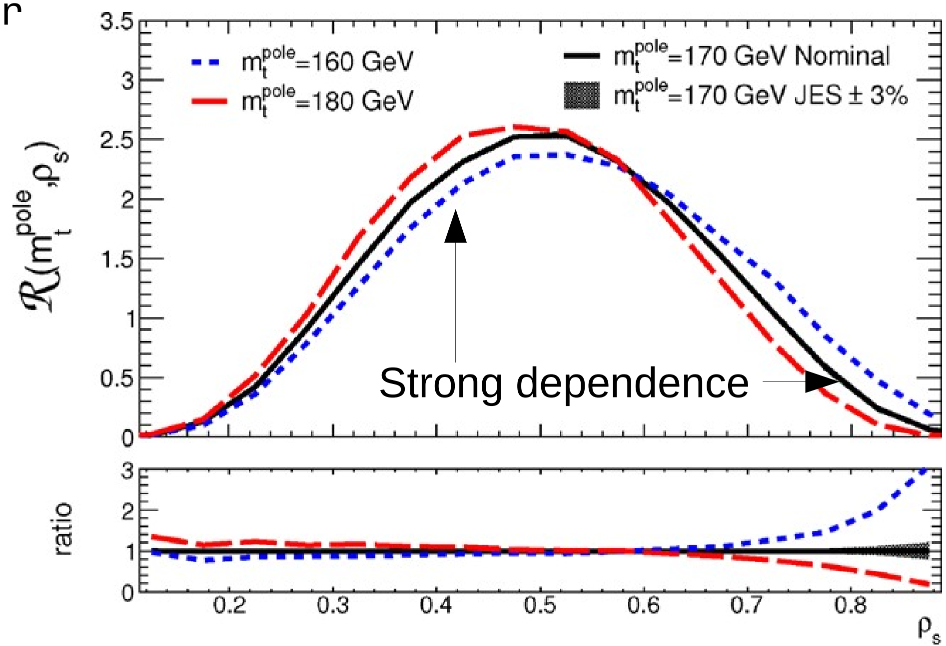
Infer mass from (normalized) shape

of ρ = 1/m(ttj) distribution

ρ µ 1/m($t\bar{t}j$) for associated $t\bar{t}j$ production

→ *1 at threshold*

→ *0 for boosted production*



ATLAS: Top quark mass from tt + 1 jet events

ATLAS, arXiv:1507.01769

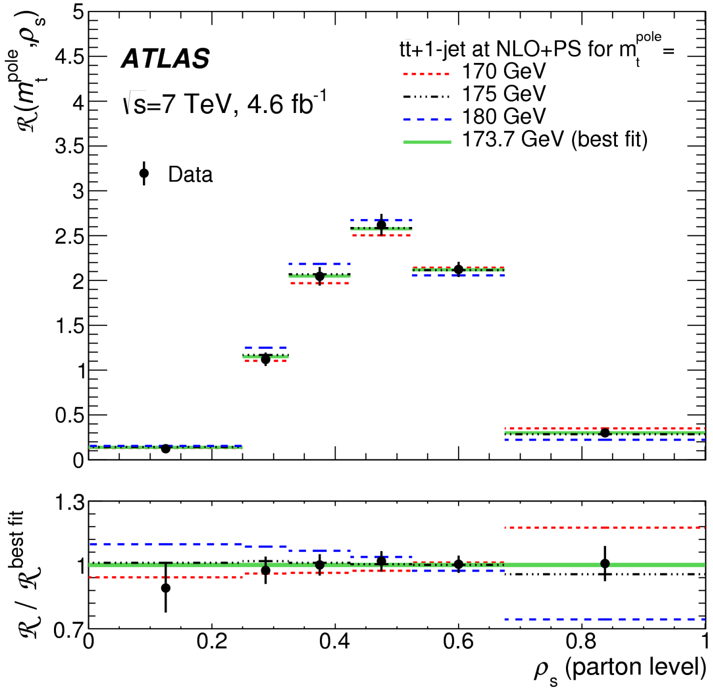
Unfold normalized differential cross-section at 7 TeV to parton-level

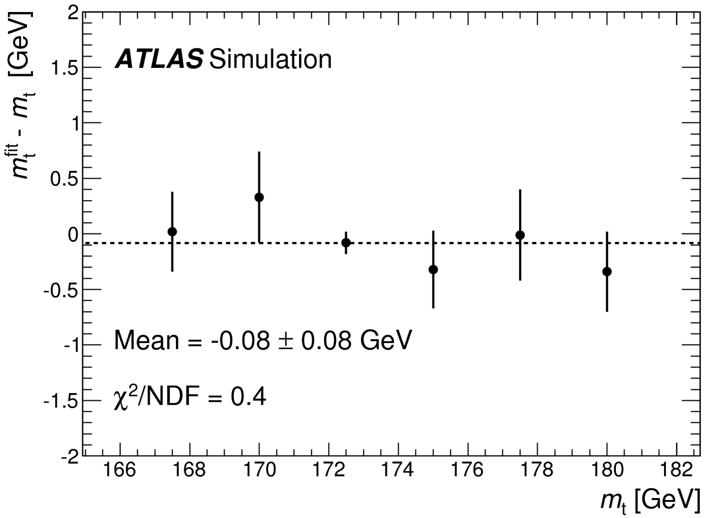
Fit with $t\bar{t}$ + 1 jet NLO+PS theory

Mass scheme fixed in NLO calculation (difference NLO vs. NLO+PS ~ 300 MeV)

Negligible MC mass dependence in the correction of the normalized differential cross-section

$$M_t^{pole} = 173.7 \pm 2.2 \text{ GeV}$$





Top quark pole mass

ATLAS pole mass extractions;

M_t^{pole}=172.9 ± 2.5 GeV
7 + 8 TeV inclusive cross-section

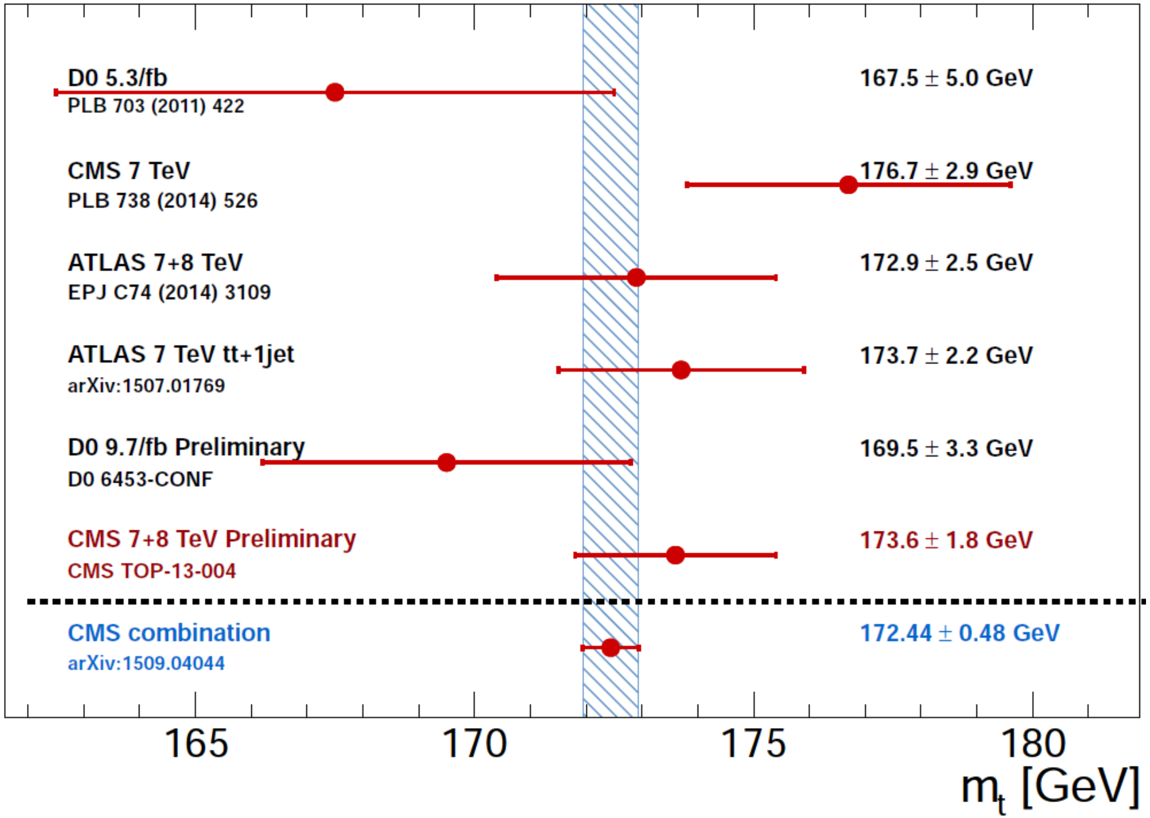
M_t^{pole}=173.7 ± 2.2 GeV
7 TeV tt+jet differential,

Reaching 2 GeV
Potential to reach 1 GeV

CMS pole mass extractions;

M_t^{pole}=176.7 ± 2.9 GeV
7 TeV inclusive cross-section

M_t^{pole}=173.6 ± 1.8 GeV for NNPDF3.0
7 + 8 TeV inclusive cross sections



Top quark mass: the alternative programme

With increasing precision, a healthy systematics mix, rigorous interpretation and quantifiable theory uncertainties are mandatory

Alternative mass extraction methods may provide these

Many new methods are being deployed:

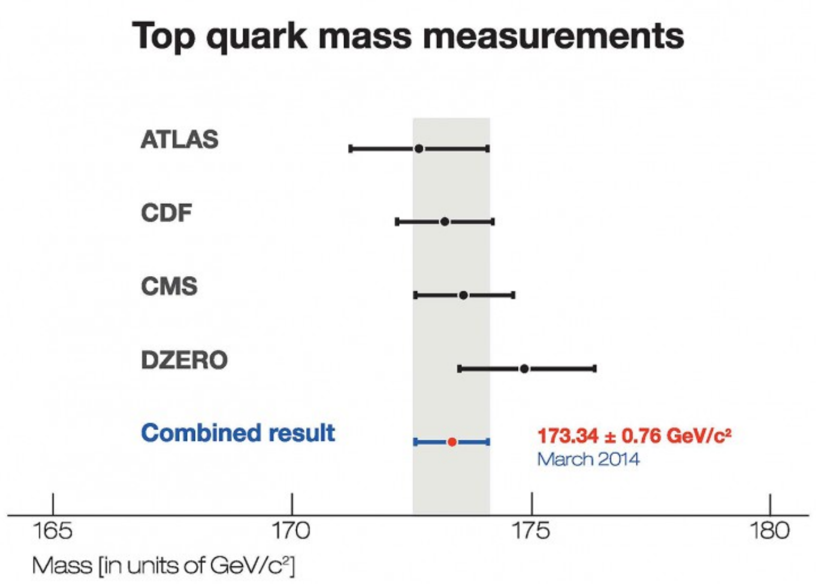
- *B hadron decay length, lepton $p_{T,}$ J/ψ, endpoints...*
- *b-jet energy spectrum, CMS: m_t = 172.3 ± 1.2 (stat.) ± 2.7 (syst.) GeV*
- *m_{bl} has demonstrated great potential, CMS: m_t = 172.3 ± 1.3 GeV*

Extraction of top pole mass from cross-section

- *Has achieved 1% precision, with a rigorous interpretation*
- *Improve PDFs without biasing the pole mass extraction*
- *Increase sensitivity: differential tt+jet x-section can yield ~GeV precision*

Top quark mass - today

LHC/Tevatron combination of direct measurements *(arXiv:1403.4427)* provides a quark mass measurement to better than 0.5%



Consistent result in different experiments, continents, initial and final states and kinematic regimes See talk by Andrea Castro, Andreas Maier

Break-down of uncertainties on March '14 world average:

Statistics:

already < 300 MeV

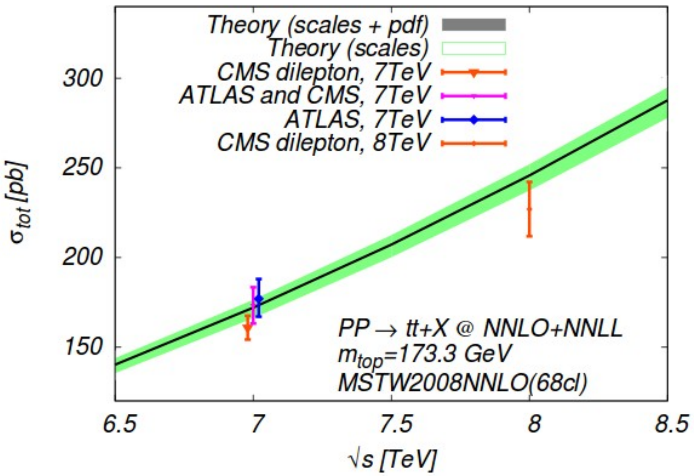
Jet energy scale:

in situ JES (240 MeV),
standardJES (200 MeV),
flavourJES (120 MeV)
and b-JES (250 MeV)

Modelling:

(strongly correlated even between experiments):
Monte Carlo (380 MeV)
radiation (210 MeV)
colour reconnection (310 MeV)

Theory milestone



Theory milestone:

full NNLO and NNLL result for top quark pair production at hadron colliders

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	+0.259(3.7%) −0.374(5.3%)	+0.169(2.4%) −0.121(1.7%)
LHC 7 TeV	167.0	+6.7(4.0%) −10.7(6.4%)	+4.6(2.8%) −4.7(2.8%)
LHC 8 TeV	239.1	+9.2(3.9%) −14.8(6.2%)	+6.1(2.5%) −6.2(2.6%)
LHC 14 TeV	933.0	+31.8(3.4%) −51.0(5.5%)	+16.1(1.7%) −17.6(1.9%)

cf. CMS PAS TOP-13-004 & ATLAS EPJC (2014)

8 TeV: s = $252.9^{+6.4}_{-8.6}$ (scales) +/- 11.7 (α_s + PDF)

7 TeV: s = $177.3^{+4.7}_{-6.0}$ (scales) +/- 9.0 (α_s + PDF)

(Top++ 2.0, PDF4LHC)

Systematics

1-2% variations in data/MC SF

27 sources

Conservative 30%

17 sources

5-8% variation in σ_{inel}

MG scales for LO matrix element and ME-PS matching
MG vs. Powheg
Pythia vs. Herwig++, b-frag reweighting
P11, noCR vs. CR
P11, MPIHi vs. TeV
CT10, 90%

Source	Uncertainty [%]	
	7 TeV	8 TeV
Trigger	1.2	1.2
Lepton ID/isolation	1.4	1.5
Lepton energy scale	0.1	0.1
Jet energy scale	0.7	0.9
Jet energy resolution	0.1	0.1
Single top	0.9	0.6
DY	1.2	1.2
$t\bar{t}$ other	0.1	0.1
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Mistag	0.2	0.1
Pileup	0.3	0.3
Q^2 scale	0.3	0.3
ME/PS matching	0.2	0.1
MG+PY $\rightarrow$ PH+PY	0.2	0.4
Hadronization (JES)	0.6	0.8
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Color reconnection	0.1	0.0
Underlying event	0.0	0.1
PDF	0.2	0.7
Luminosity	2.2	2.6
Statistical	1.2	0.6

Extrapolation to full phase space

Extrapolation to full phase space:

$$\sigma_{tot} = \frac{\sigma_{vis}}{A_{e\mu}}$$

Uncertainties:

Q^2 scale in Matrix Element
ME/PS matching
Top quark p_T modelling
Parton Density Functions

Source	Uncertainty [%]	
	7 TeV	8 TeV
Total (vis)	$\pm^{3.5}_{3.4}$	$\pm^{3.7}_{3.4}$
Q^2 scale (extrapol.)	$\pm^{0.4}_{0.0}$	$\pm^{0.2}_{0.1}$
ME/PS matching (extrapol.)	$\mp^{0.1}_{0.1}$	$\pm^{0.3}_{0.3}$
Top p_T (extrapol.)	$\pm^{0.4}_{0.2}$	$\pm^{0.8}_{0.4}$
PDF (extrapol.)	$\mp^{0.2}_{0.1}$	$\mp^{0.1}_{0.2}$
Total	$\pm^{3.6}_{3.4}$	$\pm^{3.8}_{3.5}$