Summary of the Direct Top Quark Mass Measurements and New CMS Mass Combinations

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on behalf of the
ATLAS and CMS Collaboration

Disclaimer: topics not covered in this talk

There is a large body of work from ATLAS & CMS that targets the top quark mass.

In the interests of time I have been selective of the results that are covered and I will not cover:

- the indirect measurements from the production cross section

- the analyses that measure the pole or msbar mass using ttbar + jet events

These are in the additional material at the end of the talk.

My apologies if your favorite analysis isn't included!

Topics covered in this talk

- *Summary of ATLAS and CMS Measurements using 'standard analysis techniques/topologies'*
- *New ATLAS and CMS results at 8 and 13 TeV*
- *Mass measurements using 'alternative topologies and techniques'*
- *New CMS mass combinations*
- *Comments on the LHC and World Average combinations*

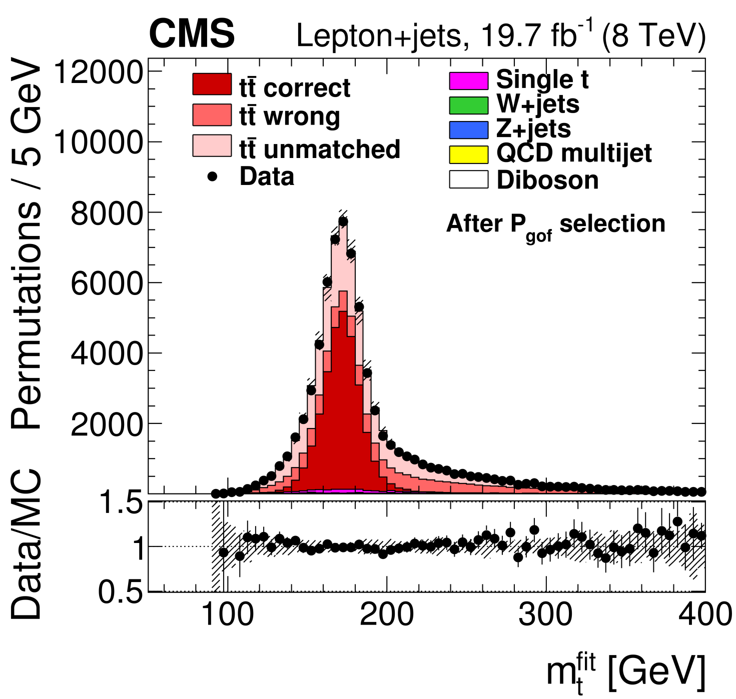
Top Quark Mass – Kinematic Reconstruction

CMS
√s = 8 (7) TeV

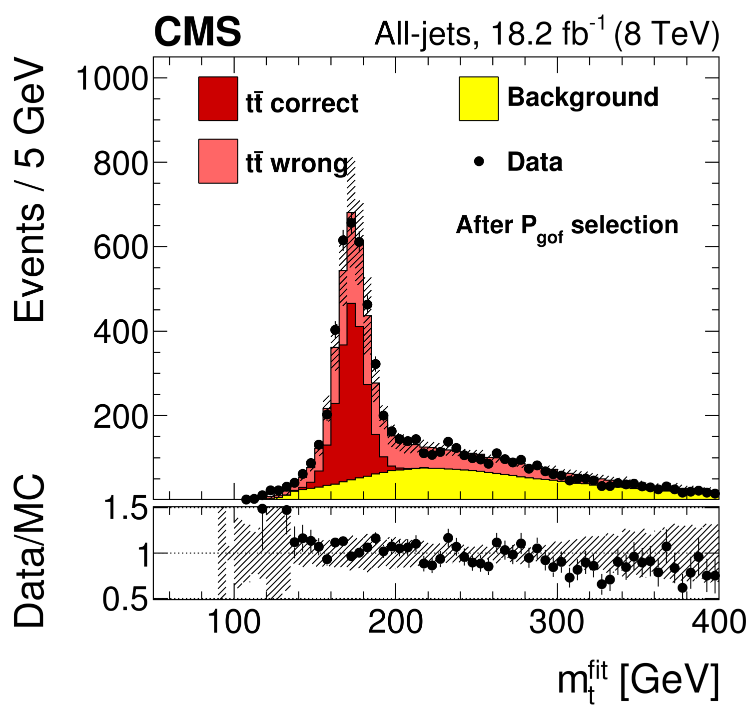
CMS Run I
Analysis

Phys. Rev. D93 (2016) 072004

Measurements based on kinematic reconstruction

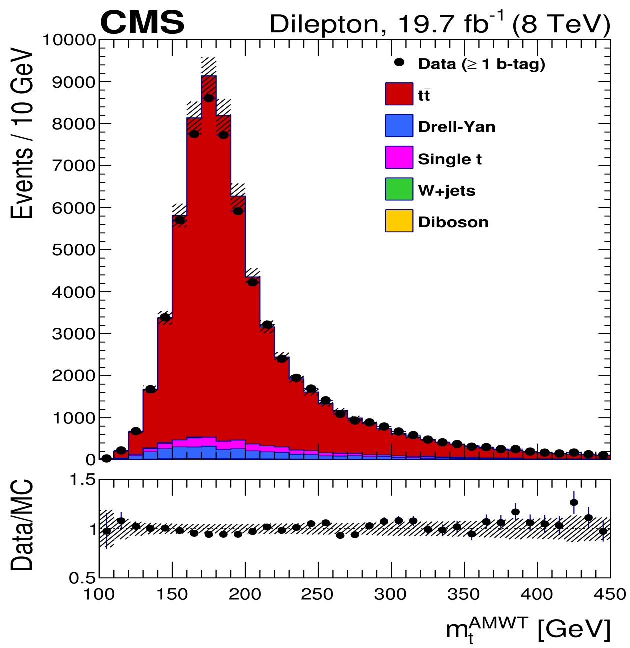


lepton+jets channel at 8 TeV



all-jets channel at 8 TeV

Top Quark Mass – Kinematic Reconstruction

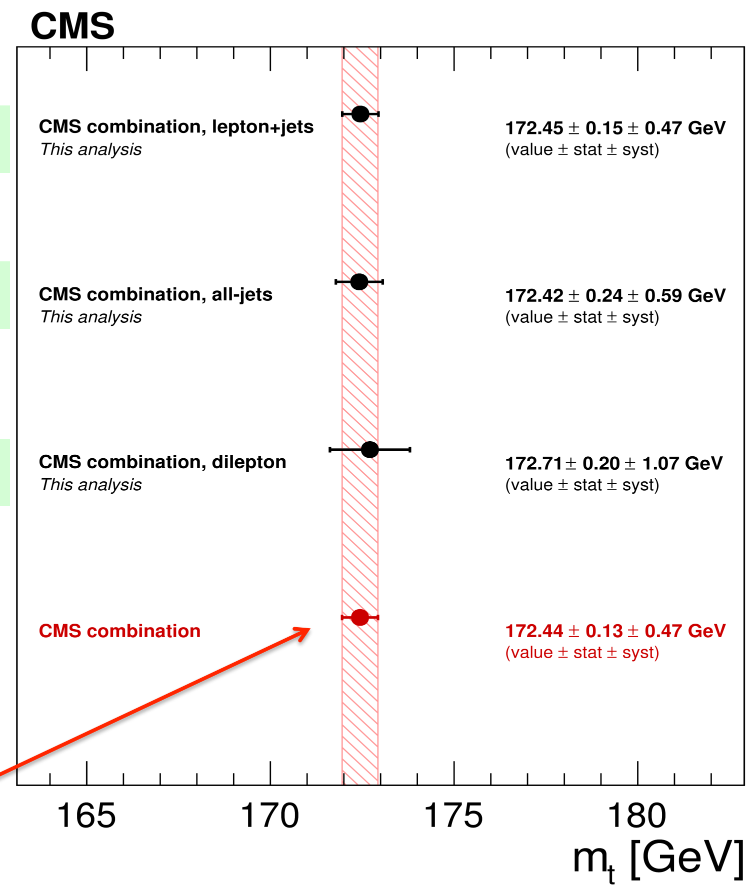


dilepton channel at 8 TeV

l+jets

all-jets

dilepton



Combined measurement

m_t = 172.44 ± 0.13 (stat) ± 0.47 (syst) GeV

Combined 7 and 8 TeV data channel-by-channel results

Precision ~ 480 MeV (0.3%)

limited by systematic uncertainties

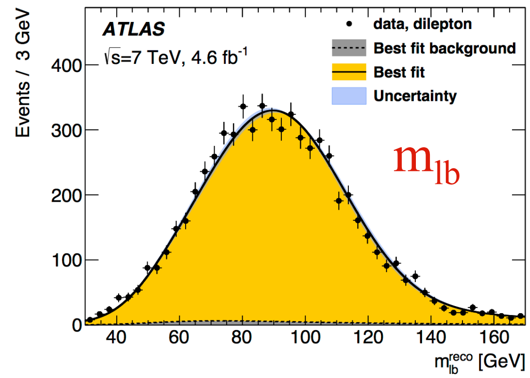
7 TeV Dilepton & Lepton+jets Measurements

dilepton channel

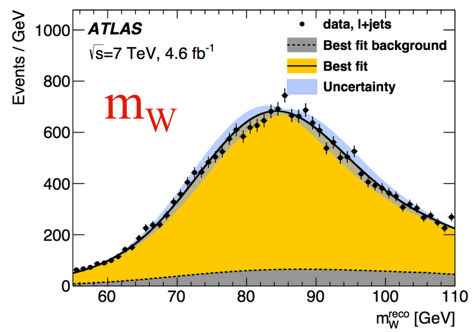
(Eur. Phys. J. C75 (2015) 330)

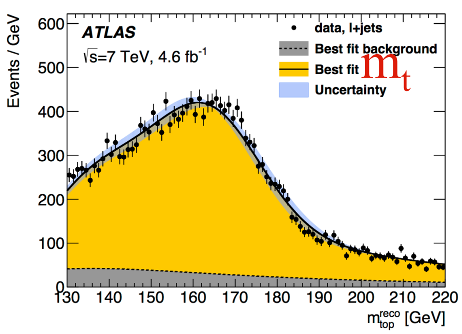
Partial kinematic reconstruction

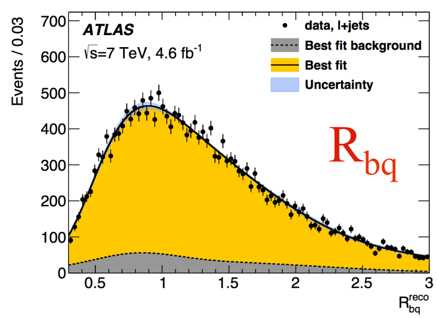
$m_t = 173.79 \pm 0.54$ (stat) ± 1.30 (syst) GeV



lepton+jets channel







Full kinematic reconstruction
3D fit (m_t, m_W, R_{bq})

$m_t = 172.33 \pm 0.75$ (stat) ± 1.02 (syst) GeV

Precision limited by systematic uncertainties

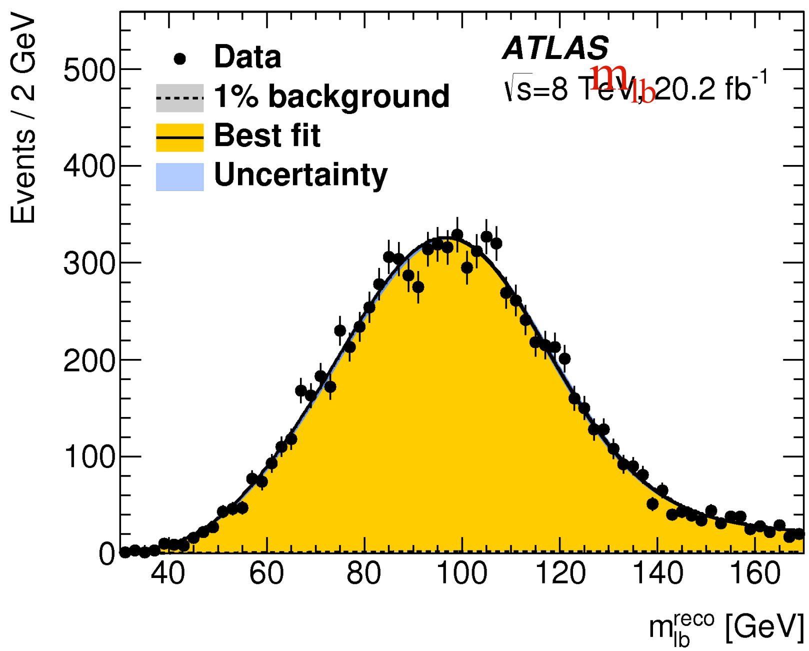
Top Quark Mass – Partial Kinematic Reconstruction

ATLAS
$\sqrt{s}$ = 8 TeV

Measurement based on
1D template fit to M_{lb} distribution

Phys. Lett. B761 (2016) 350

dilepton channel



$m_t = 172.99 \pm 0.41$ (stat) ± 0.74 (syst) GeV

Combined
7 TeV dilepton & lepton+jets
8 TeV dilepton
measurements

$m_t = 172.84 \pm 0.34$ (stat) ± 0.61 (syst) GeV

Precision ~ 700 MeV (0.4%)

limited by systematic uncertainties

ATLAS Combination Top Quark Mass Systematics

	m_{top}^{all} [GeV]
Results	172.84
Statistics	0.34
Method	0.05
Signal Monte Carlo generator	0.14
Hadronisation	0.23
Initial- and final-state QCD radiation	0.08
Underlying event	0.02
Colour reconnection	0.01
Parton distribution function	0.08
Background normalisation	0.04
W/Z+jets shape	0.09
Fake leptons shape	0.05
Jet energy scale	0.41
Relative b-to-light-jet energy scale	0.25
Jet energy resolution	0.08
Jet reconstruction efficiency	0.04
Jet vertex fraction	0.02
b-tagging	0.15
Leptons	0.09
E_T^{miss}	0.05
Pile-up	0.03
Total systematic uncertainty	0.61
Total	0.70

Phys. Lett. B761 (2016) 350

Combined
7 TeV dilepton & lepton+jets
8 TeV dilepton
measurements

Dominant uncertainties:
b JES
fragmentation

CMS Run I Combination Top Quark Mass Systematics

Combined m_t result	δm_t(GeV)
Experimental uncertainties	
Method calibration	0.03
Jet energy corrections	
– JEC: Intercalibration	0.01
– JEC: In situ calibration	0.12
– JEC: Uncorrelated non-pileup	0.10
Lepton energy scale	0.01
E_T^{miss} scale	0.03
Jet energy resolution	0.03
b tagging	0.05
Pileup	0.06
Backgrounds	0.04
Trigger	<0.01
Modeling of hadronization	
JEC: Flavor	0.33
b jet modeling	0.14
Modeling of perturbative QCD	
PDF	0.04
Ren. and fact. scales	0.10
ME-PS matching threshold	0.08
ME generator	0.11
Top quark p_T	0.02
Modeling of soft QCD	
Underlying event	0.11
Color reconnection modeling	0.10
Total systematic	0.47
Statistical	0.13
Total Uncertainty	0.48

Phys. Rev. D93 (2016) 072004

Combined 7 and 8 TeV

lepton+jets, dilepton & all jets measurements

Dominant uncertainties:
flavor dependent JEC: (u,d,s), c, b, g
b jet modeling: b-fragmentation + b-hadron decays

limited by same uncertainties as ATLAS but treatment is different

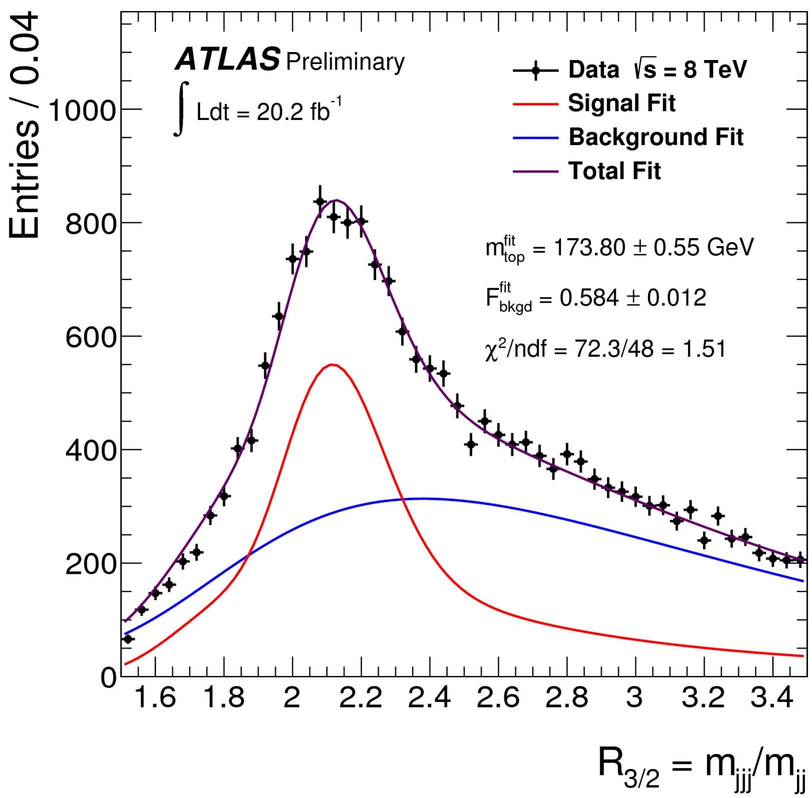
Top Quark Mass – Kinematic Reconstruction

ATLAS
$\sqrt{s}$ = 8 TeV

New Result

ATLAS Conf-2016-064
(to be submitted for publication)

all-jets channel



Fit to m_t dependence of m_{jjj}/m_{jj} ratio
→ reduces dependence on JES calibration

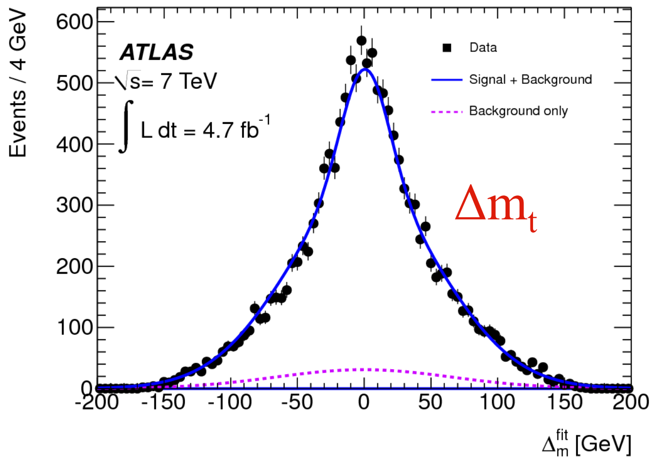
$m_t = 173.80 \pm 0.55$ (stat) ± 1.01 (syst) GeV

Precision ~ 1.15 GeV (0.7%)

limited by systematic uncertainties

Dominant uncertainties:
JES & hadronization modeling

Top-Antitop Mass Difference



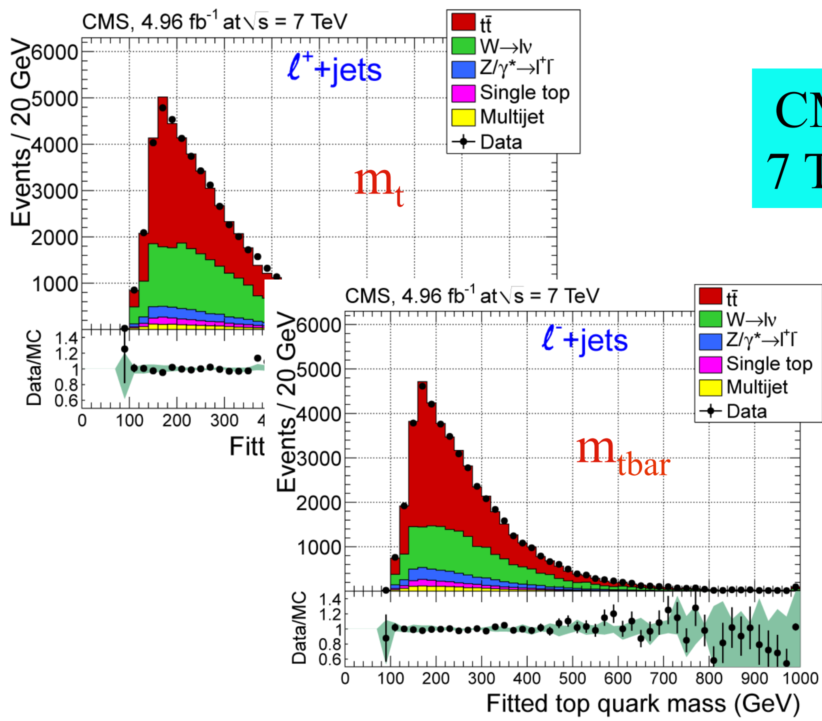
ATLAS 7 TeV

Phys. Lett. B728 (2014) 363

lepton+jets channel

Fit to the $m_t - m_{tbar}$ mass difference

$\Delta m_t = 0.67 \pm 0.61\ (stat) \pm 0.41\ (syst)$ GeV



CMS 7 TeV

JHEP 06 (2014) 109

lepton+jets channel

Difference between 1D fits to m_t and m_{tbar} separately

$\Delta m_t = -0.44 \pm 0.46\ (stat) \pm 0.27\ (syst)$ GeV

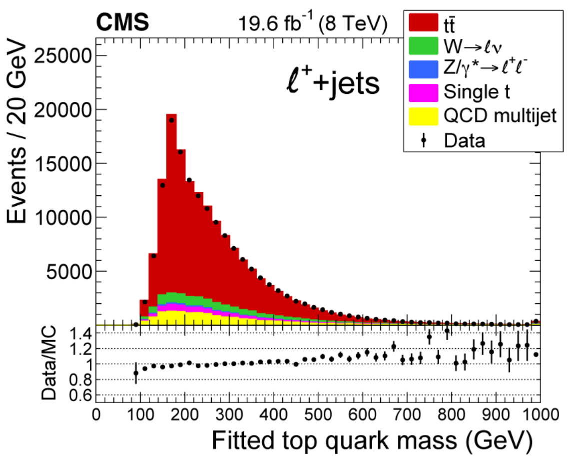
Top-Antitop Mass Difference

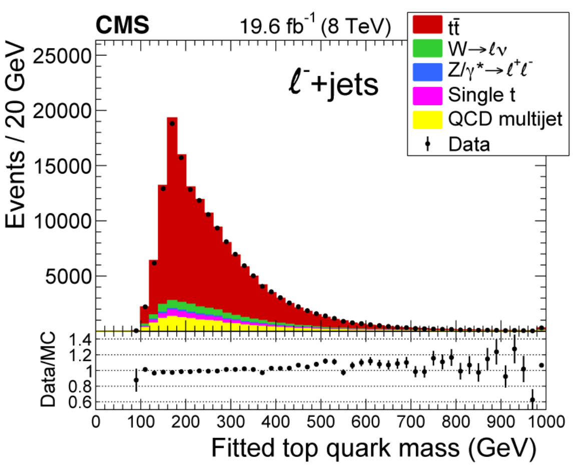
CMS
$\sqrt{s}$ = 8 TeV

lepton+jets channel

New Result

arXiv 1610.09551
(submitted to PLB)





1D Mass analysis performed separately for
l^+ + jets and l^- + jets
Result → difference between the
two measurements

Δm_t = - 0.15 ± 0.19 (stat) ± 0.09 (syst) GeV

Substantial cancellation of
systematic uncertainties in the mass difference

~ factor of 2 more precise than
previous measurements
dominant uncertainties: statistics,
b (bbar) jet and background modeling

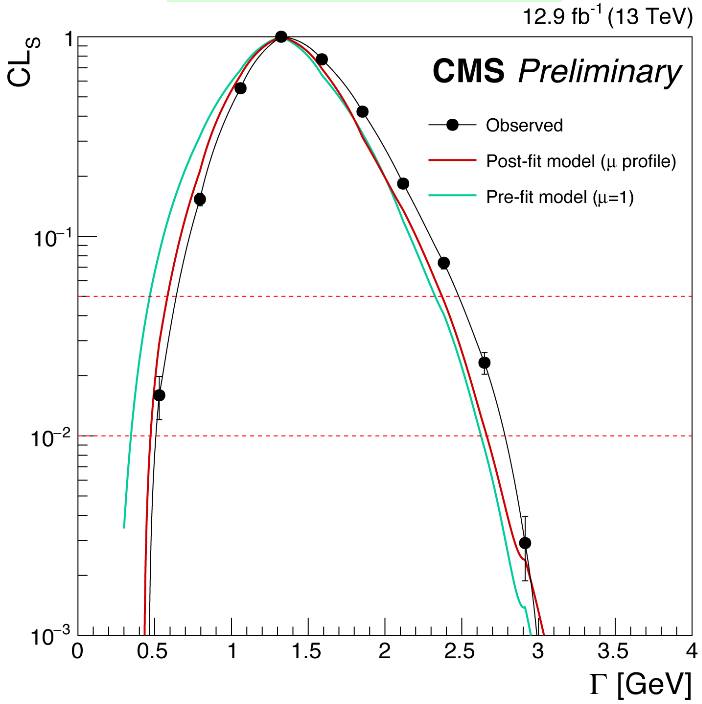
Limits on the Top Quark Width

CMS
$\sqrt{s}$ = 13 TeV

New Result

CMS PAS TOP-16-019

dilepton channel



First direct top width bounds from the LHC

Profile likelihood fit to shape of the M_{lb} spectrum for dilepton events
→ used to bound the top quark width

Fit is done in categories (# b-jets, p_T of lepton) to optimize sensitivity

Limits at 95% CL:

$0.6 \leq \Gamma_t \leq 2.5$ GeV observed
$0.6 \leq \Gamma_t \leq 2.4$ GeV expected

for m_t = 172.5 GeV

‘Standard’ Top Quark Mass Measurements

Analyses typically based on
kinematic reconstruction and template fitting

Significant uncertainties

Experimental:

- *Flavor – dependent jet energy corrections*
- *Jet energy corrections*
- *Pileup*

Further improvement
→ need improved theory input
and analysis methods that
constrain or marginalize
some of uncertainties

Modeling:

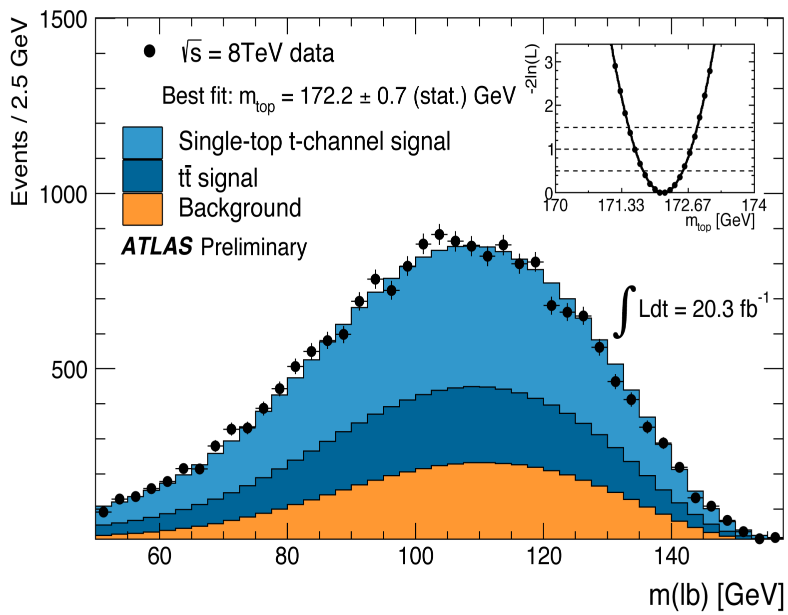
- *Hadronization: Flavor – dependent jet energy corrections**
  (string vs cluster fragmentation)
- *b-jet modeling (fragmentation and BR)*
- *Renormalization & factorization scales*
- *Matrix element generator*
- *Underlying event*

Example of an 'Alternative' Process

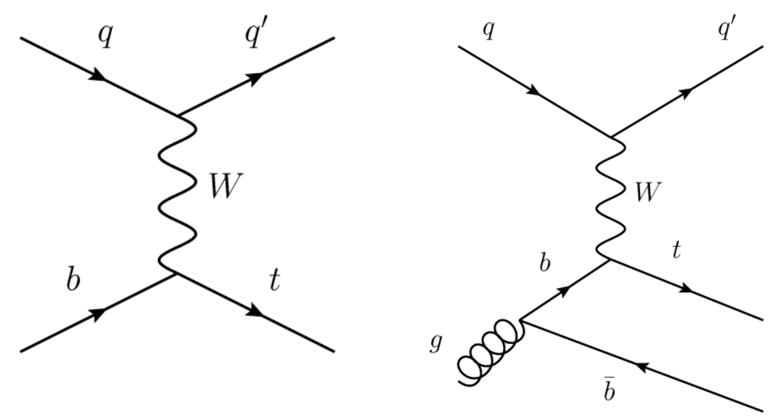
ATLAS
$\sqrt{s}$ = 8 TeV

lepton+jets analysis
in single top t-channel

ATLAS CONF-2014-055



fit to m(tb)



w.r.t. standard analyses:
- different CR, hard scattering, pdf's

m_t = 172.2 ± 0.7 (stat) ± 2.0 (syst) GeV

Dominant uncertainties: Jet energy scales & hadronization

Measurements not included in published Run I Combination

Dilepton Channel Analyses:

7 TeV	End Point analysis	(EPJC 73 (2013) 2494)
8 TeV	M_{T2}/MAOS analysis	(CMS PAS TOP-15-008)
8 TeV	M_{lb} analysis	(CMS PAS TOP-14-014)
8 TeV	b-jet energy peak (E_b)	(CMS PAS TOP-15-002)
8 TeV	Dilepton p_T distribution	(CMS PAS TOP-16-002)

Lepton + Jets Channel Analysis:

8 TeV	BEST analysis	(CMS PAS TOP-14-011)

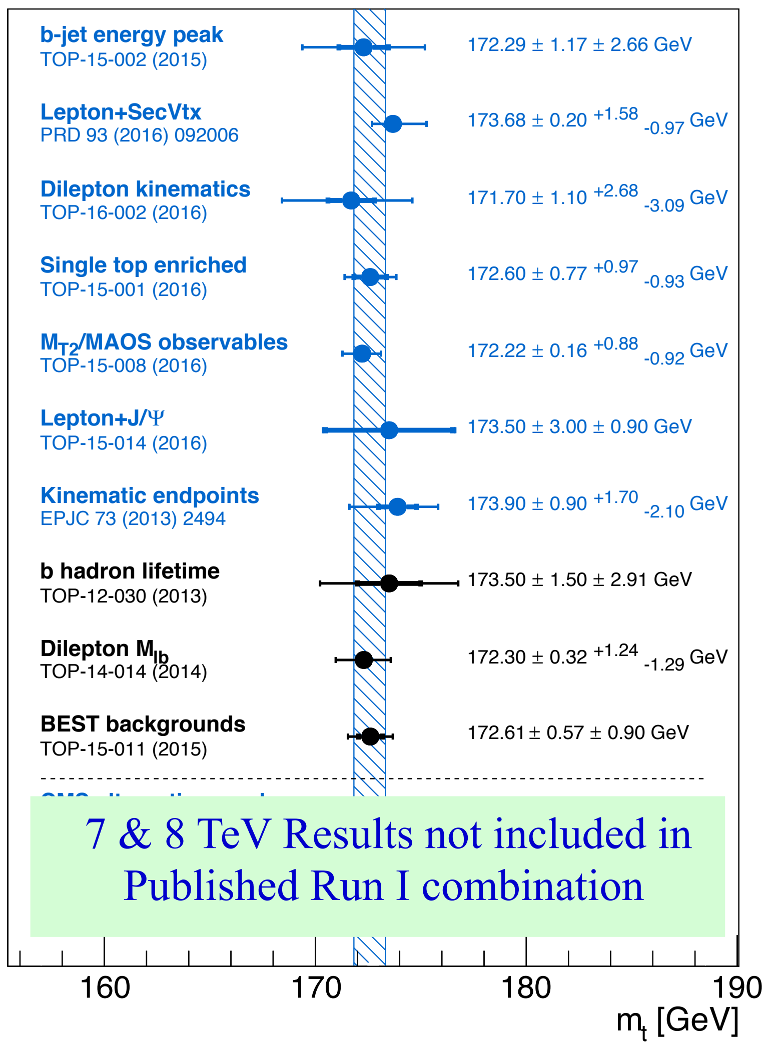
Dilepton + Lepton + Jets Channel Analyses:

8 TeV B-lifetime analysis	(CMS PAS TOP-12-030)
8 TeV Lepton+ Sec. Vtx. Mass	(CMS PAS TOP-12-030)
8 TeV Lepton + J/ψ analysis	(CMS PAS TOP-15-014)

Single Top Analysis:

8 TeV Single Top Enhanced	(CMS PAS TOP-15-001)

Alternative Event Topologies/Analysis Techniques



7 & 8 TeV Results not included in Published Run I combination

Results individually quite consistent with each other

Some of these are more alternative in approach than others

Significant overlap in the datasets and methods for some measurements

Can a combination provide useful new information?

‘Alternative’ Measurement Combination

CMS
$\sqrt{s}$ = 7 & 8 TeV

New Result

CMS PAS TOP-15-012

Alternative Measurements

B-lifetime, M_{lb} measurements dropped - overlap and/or strong correlation with other measurements

BEST measurement dropped as it is a template fit method and too similar in style to the published results

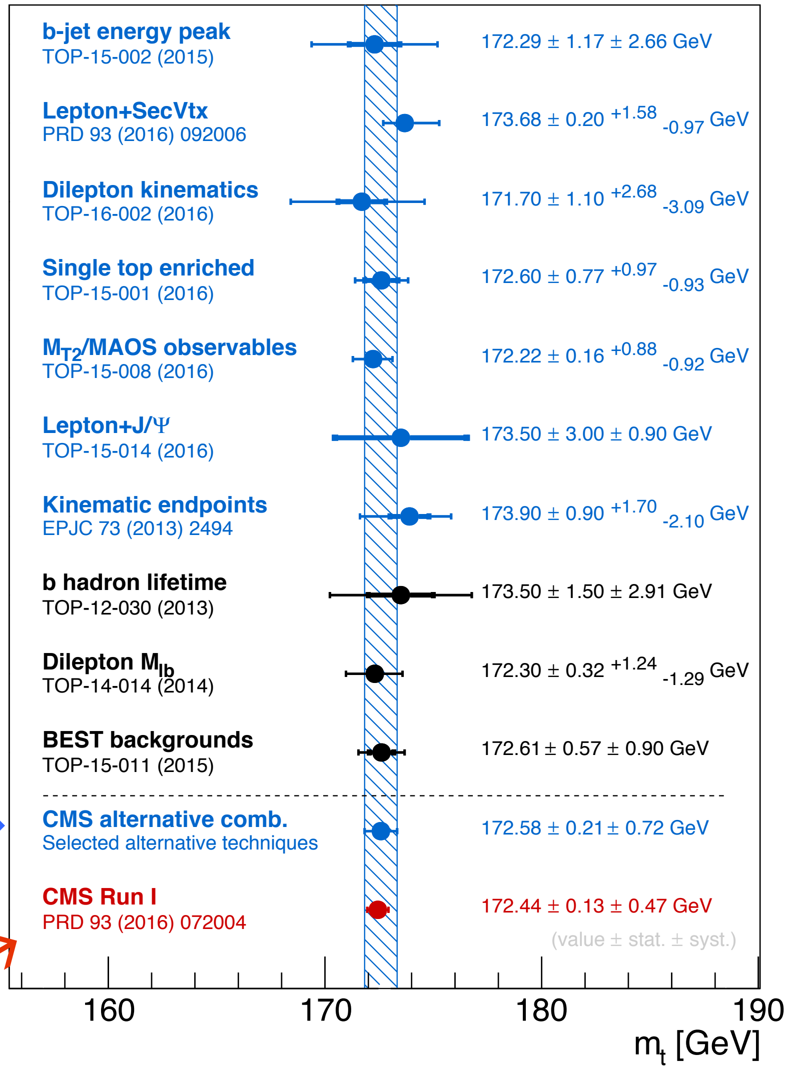
→ 7 measurements to be combined

Measurements combined using BLUE

m_t = 172.58 ± 0.21 (stat) ± 0.72 (syst) GeV

χ^2 = 1.6/7 dof, Prob = 95 %

'Alternative' Measurement Combination



Precision 0.4 %

Precision 0.3 %

Alternative technique measurements

CMS Run I and Alternative combinations

New combination agrees very well with CMS Run I result

CMS Run I and Alternative Combination Systematics

Combined m_t results	Run I δm_t(GeV)	Alternative δm_t(GeV)	Combined δm_t(GeV)
Experimental uncertainties			
Method calibration	0.03	0.08	0.04
Jet energy corrections			
– JEC: Intercalibration	0.01	0.06	0.02
– JEC: In situ calibration	0.12	0.16	0.12
– JEC: Uncorrelated non-pileup	0.10	0.26	0.10
Lepton energy scale	0.01	0.14	0.01
E_T^{miss} scale	0.03	0.04	0.04
Jet energy resolution	0.03	0.03	0.03
b tagging	0.05	0.02	0.05
Pileup	0.06	0.07	0.06
Secondary vertex mass	n/a	0.04	$<$0.01
Backgrounds	0.04	0.08	0.04
Trigger	$<$0.01	$<$0.01	$<$0.01
Modeling of hadronization			
JEC: Flavor	0.33	0.33	0.31
b jet modeling	0.14	0.22	0.14
Modeling of perturbative QCD			
PDF	0.04	0.11	0.04
Ren. and fact. scales	0.10	0.30	0.10
ME-PS matching threshold	0.08	0.21	0.08
ME generator	0.11	0.07	0.11
Single top modeling	n/a	0.04	0.01
Top quark p_T	0.02	0.21	0.02
Modeling of soft QCD			
Underlying event	0.11	0.10	0.11
Color reconnection modeling	0.10	0.11	0.10
Uncertainties (GeV)			
Total systematic	0.47	0.72	0.46
Statistical	0.13	0.21	0.13
Total Uncertainty	0.48	0.75	0.48

Alternative combination:

- *distribution of uncertainties very similar to the Run I*
- *dominant uncertainties:*
  → hadronization modeling (comparable to Run I)
- *other significant contributions*
  → QCD modeling PDF, Q^2, ME-PS, Top
  → LES (larger than Run I)

Mass Combination Summary

a.) CMS

Run 1 combination: 0.3%

172.47 ± 0.48 GeV — Phys. Rev. D93 (2016) 072994

Alternative combination: 0.4%

172.58 ± 0.75 GeV — CMS PAS TOP-15-012

b.) ATLAS

Current ATLAS combination: 0.4%

172.84 ± 0.70 GeV — Phys. Lett. B761 (2016) 350

c.) Tevatron

New Tevatron combination: 0.4%

174.34 ± 0.64 GeV — Fermilab-Conf-16-298

Four independent combined results with precision at the sub 0.5% level

CMS Full Run I Combination

Combine the 7 published measurements and the 7 alternative measurements to produce a new Run I combination

Measurements combined using BLUE

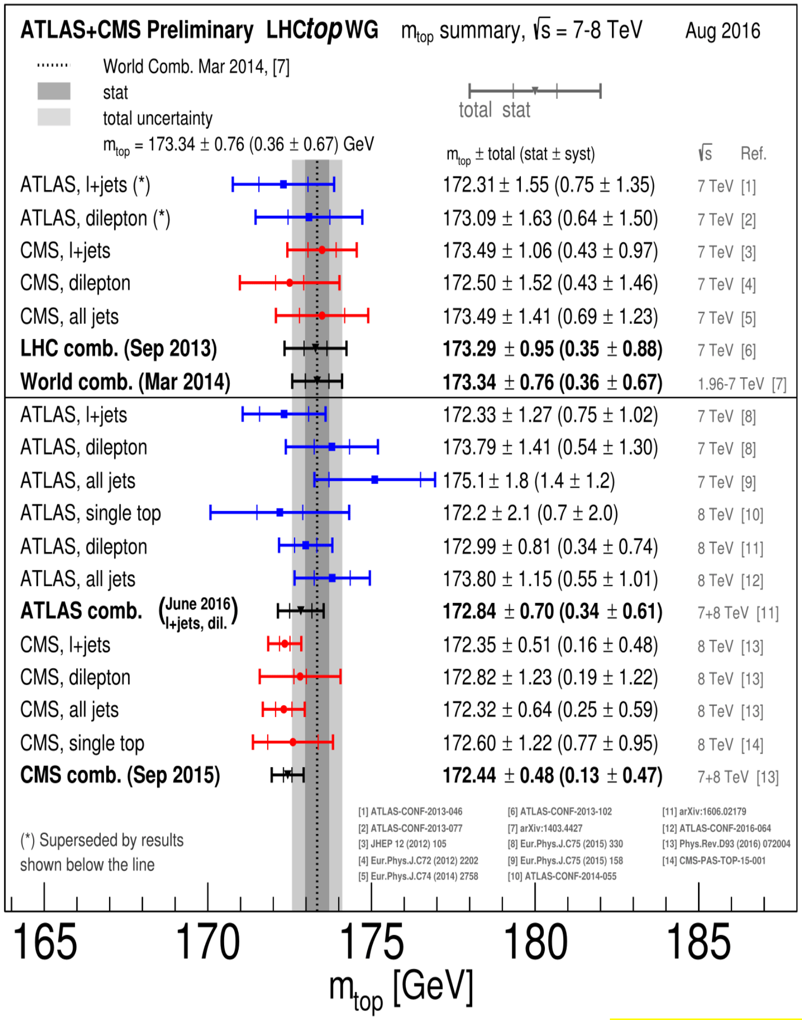
$m_t = 172.43 \pm 0.13$ (stat) ± 0.46 GeV (syst) $\chi^2 = 4.4/13$ dof, Prob = 98 %

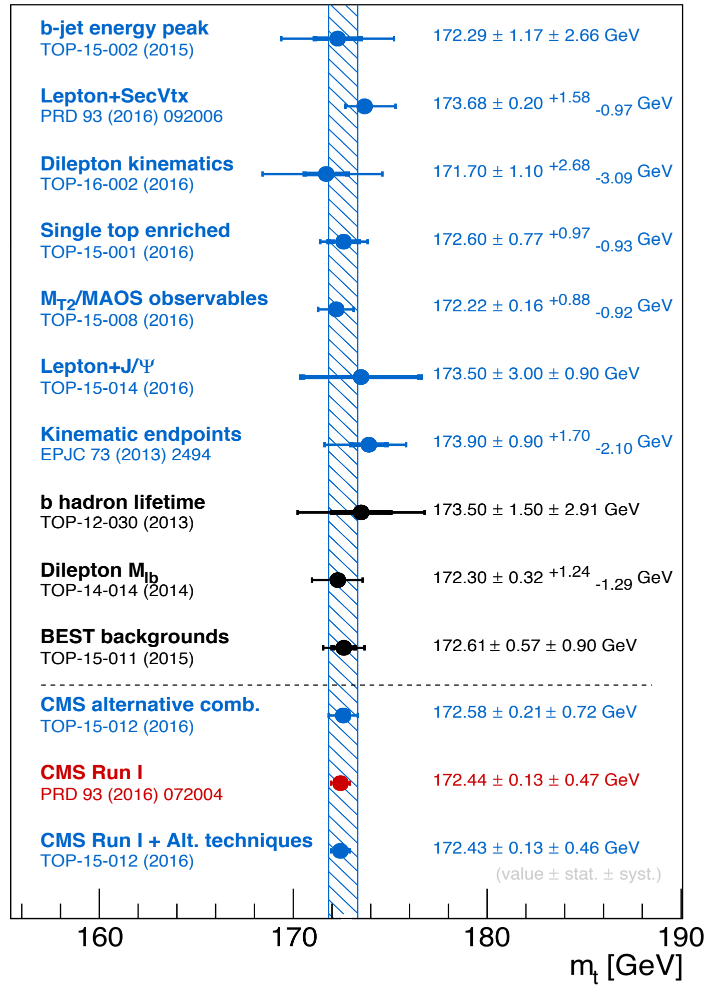
Precision 0.3 %

$m_t = 172.44 \pm 0.13$ (stat) ± 0.47 GeV (syst)   Phys. Rev. D93 (2016) 072994

no significant improvement in precision → new results have a systematic uncertainty distribution too similar to the published combination

Measurement & Combination Summary





Very consistent picture

Summary – Run I Measurements

Both collaborations have produced very accurate measurements measurements of the top quark mass using 7 and 8 TeV LHC data using 'standard analysis techniques'

There is a growing set of additional measurements using 'alternative topologies', such as the single top t-channel and a variety of 'different analysis techniques'.

The precision of the results from these hasn't yet matched that of the 'standard measurements'.

CMS has presented a new analysis of its 'alternative' measurements and obtains a mass in good agreement with and comparable precision to its published Run I result based on a 'standard technique' combination

Both the individual measurements and the ATLAS and CMS combinations are in good agreement

Is it time to update the LHC and world average results?

Logic

LHC*top*WG

World and LHC Average Results → make use of reduction of systematical uncertainties by combining measurements measurements with different sensitivity to the systematic uncertainties
Data from the LHC (ATLAS & CMS) and the Tevatron (CDF & D0)

Last Update : 2014 (arXiv:1403.4427)

This is seriously out-of-date !

Does not include the most precise results from ATLAS, CMS and D0

CMS Run I mass analyses are completed

Work on D0:CMS lepton+jets studies has not found any problems on either side → both measurements look OK

Results are compatible at ~ 3 σ level

Can we agree on resuming the update of the LHC and World Average results?

Final Summary – Top Mass Measurements

There is an impressive collection of measurements from the LHC (and the Tevatron)

The results show very good consistency

Work on the Run I data is beginning to come to an end and preliminary results from Run II will begin to appear in the next few months

Progress is being made towards understanding what these 'MC' mass measurements mean in relation to a theoretically well-defined masses (not covered in this talk)

It's probably time to think about re-starting the work on LHC Run I combination and an update of world average value (my personal view)

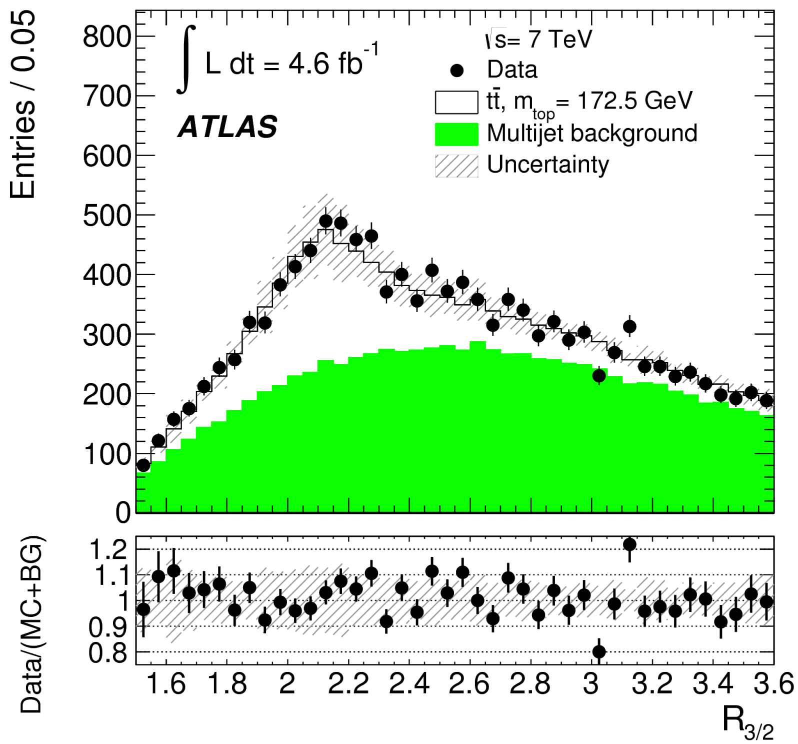
Additional Material

Top Quark Mass – Kinematic Reconstruction

ATLAS
$\sqrt{s}$ = 7 TeV

(Eur. Phys. J. C75 (2015) 158)

all-jets channel



Fit to m_t dependence of m_{jjj}/m_{jj} ratio
→ reduces dependence on JES calibration

m_t = 175.1 ± 1.4 (stat) ± 1.2 (syst) GeV

Precision ~ 1.8 GeV (1.1%)

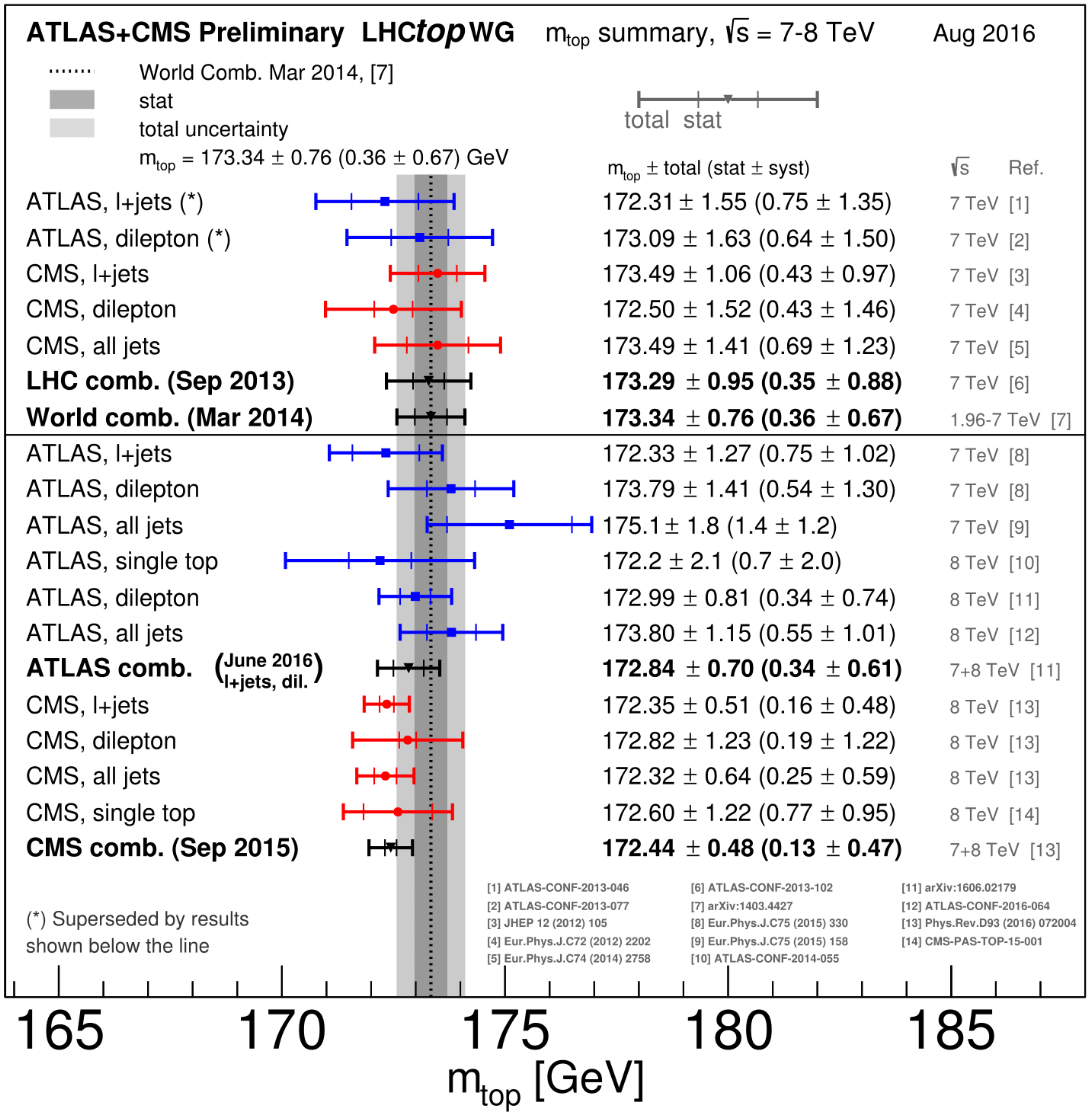
limited by systematic uncertainties

Alternative Event Topologies/Analysis Techniques

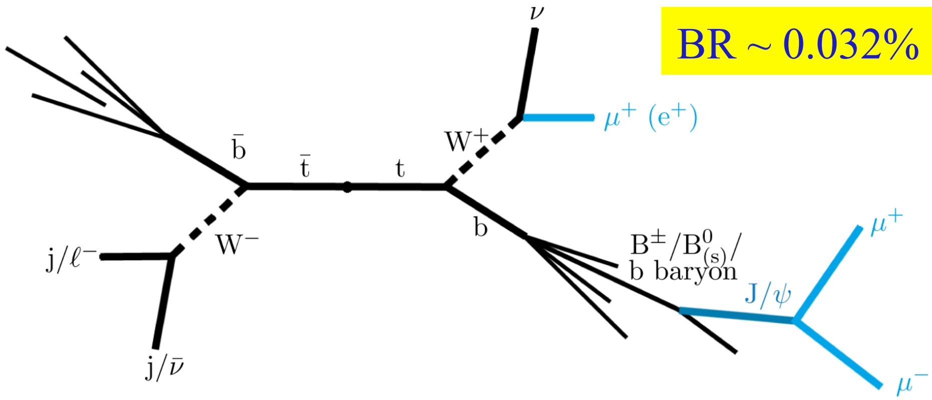
Analysis	Channel	Dataset	Reference	m_t (GeV)	Stat. Uncertainty	Syst. Uncertainty
End Point	Dilepton	7 TeV	[2]	173.90	0.90	$^{+1.70}_{-2.10}$
B-lifetime	Dilepton and Lepton+jets	8 TeV	[7]	173.50	1.50	± 2.91
Lepton + J/ψ Mass	Dilepton and Lepton+jets	8 TeV	[8]	173.50	3.00	± 0.90
Lepton + SVX Mass	Dilepton and Lepton+jets	8 TeV	[9]	173.68	0.20	$^{+1.58}_{-0.97}$
BEST	Lepton+jets	8 TeV	[11]	172.61	0.57	± 0.90
E_b	Dilepton	8 TeV	[3]	172.29	1.17	± 2.66
Single Top Enriched	Lepton+jets	8 TeV	[10]	172.60	0.77	$^{+0.97}_{-0.93}$
Dilepton p_T	Dilepton	8 TeV	[4]	171.70	1.10	$^{+2.68}_{-3.09}$
M_{T2}/MAOS	Dilepton	8 TeV	[5]	172.22	0.16	$^{+0.88}_{-0.92}$
M_{lb}	Dilepton	8 TeV	[6]	172.30	$^{+0.32}_{-0.31}$	$^{+1.24}_{-1.29}$

10 additional measurements using a variety of techniques,
some more 'alternative' in approach than others
and some with
significant overlap in both dataset and analysis method

LHCtopWG Measurement Summary: August 2016



Marginalizing Uncertainties: *l + J/ψ Mass*

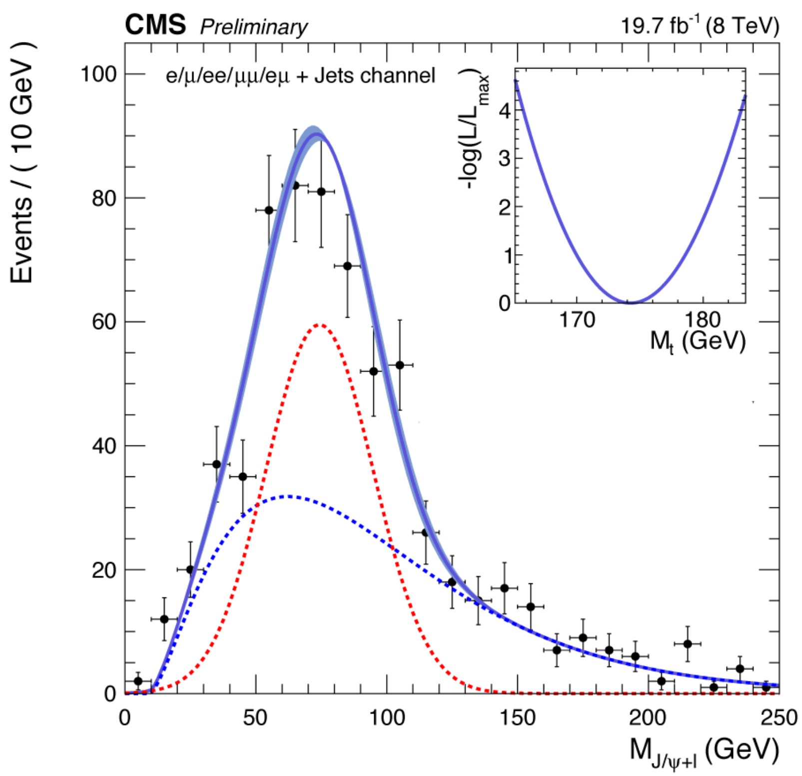


BR ~ 0.032%

CMS-PAS-TOP-15-014

8 TeV: lepton+jets & dilepton channels

Fit m_t dependence of the $l + J/\psi$ mass distribution



marginal sensitivity to JES and light quark/gluon fragmentation uncertainties

m_t = 173.5 ± 3.0 (stat) ± 0.9 (syst) GeV

dominant systematics:

b-fragmentation, top p_T distribution
Q^2 and matching scales

measurement limited by statistics

Marginalizing Uncertainties: *Secondary Vertex Mass*

CMS-PAS-TOP-12-030

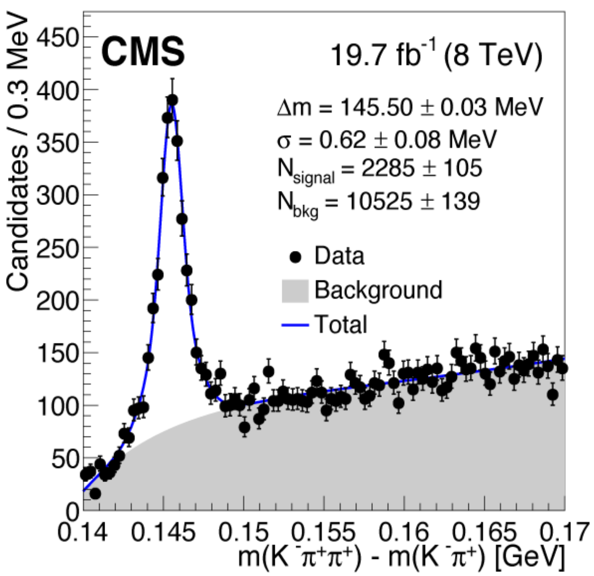
8 TeV: lepton+jets & dilepton channels

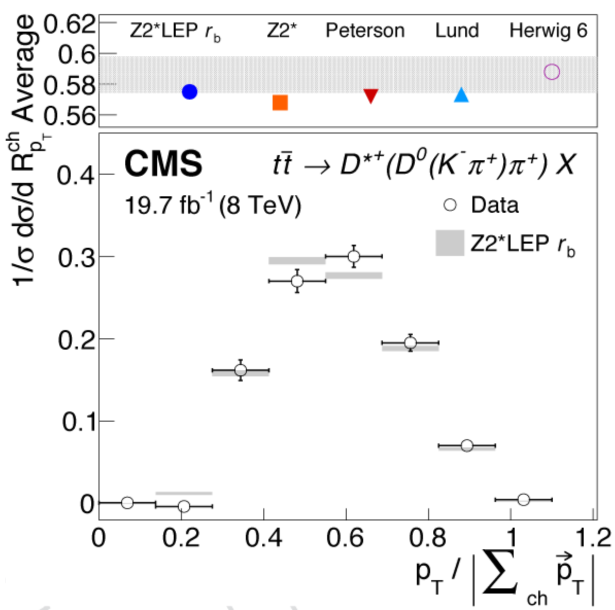
Fit m_t dependence of the mass formed from the charged tracks associated with the displaced vertex from the b-decay

$m_t = 173.7 \pm 0.2$ (stat) $^{+1.6}_{-1.0}$ (syst) GeV

dominant systematics:

b-fragmentation, top p_T distribution
Q^2 and matching scales





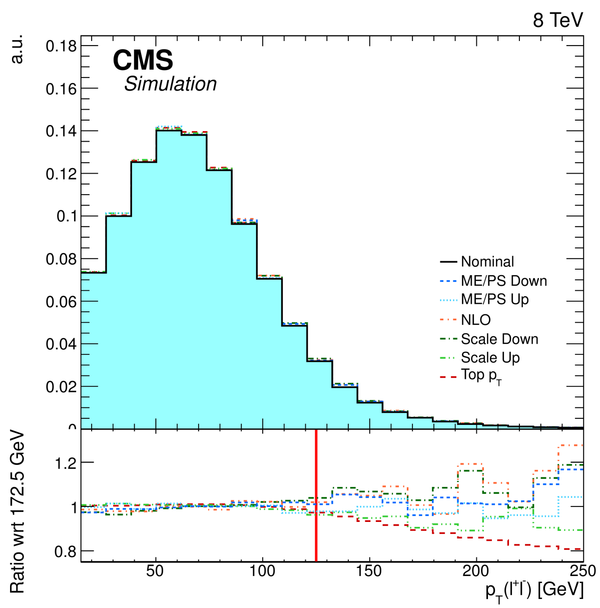
Reconstruction of J/ψ, D0 and D$^{\pm}$ in these events → check of b-fragmentation modeling for ttbar events*

Marginalizing Uncertainties: *Dilepton Kinematics*

CMS-PAS-TOP-16-002

motivation → Frixione & Mitov JHEP 09 (2014) 012

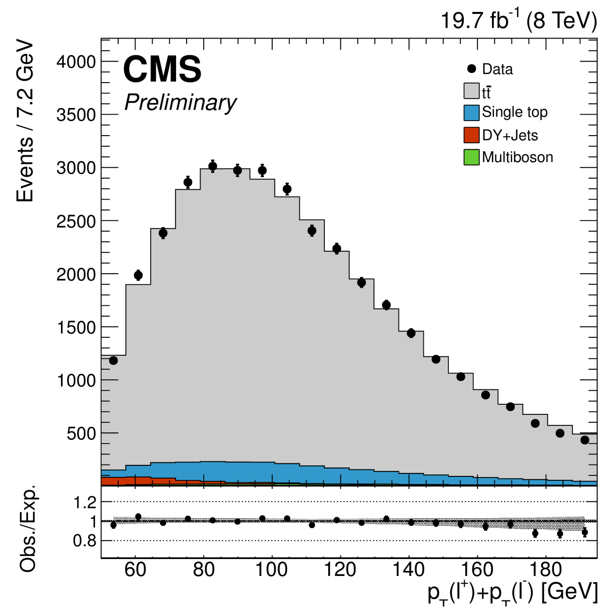
8 TeV: dilepton eμ channel



Look for experimentally clean variable that is theoretically calculable

most sensitive:
$p_T(l^+l^-)$

Expt. limitation: lepton momentum scale (well controlled)



$m_t = 171.7 \pm 1.1\ (\text{stat}) \pm 0.5\ (\text{expt})\ ^{+3.1}_{-2.5}\ (\text{thy})\ ^{+0.8}\ (\text{top } p_T)$ GeV

dominant systematics: QCD scale uncertainty, top quark p_T modeling

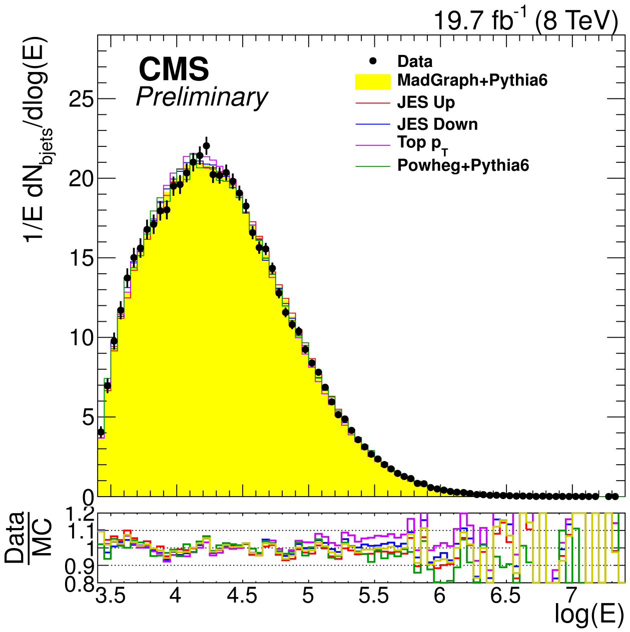
Caveat: analysis done only using LO multileg MC

Marginalizing Uncertainties: *b-jet Energy Spectrum*

CMS-PAS-TOP-15-002

motivation → Agashe, Franchesini, Kim
Phys. Rev. D988 (2013) 057701
arXiv:1603.03445

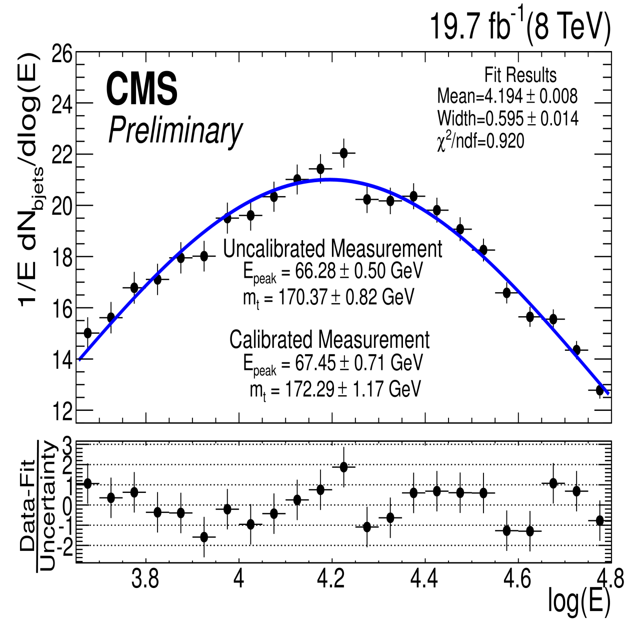
8 TeV: dilepton eμ channel



fit m_t dependence of b-quark energy spectrum in the lab frame, E

(unpolarized t approx)

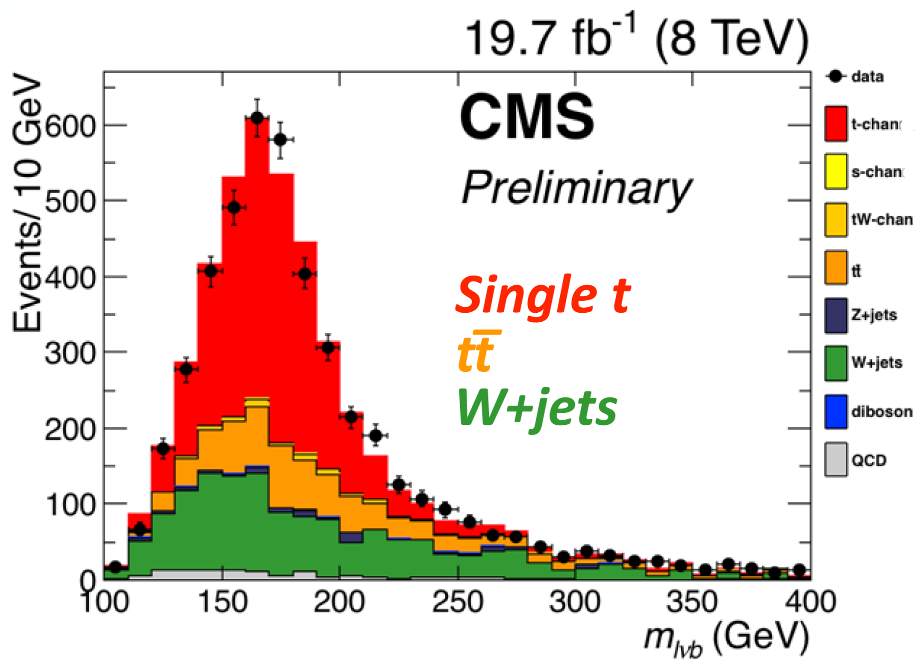
peak of spectrum approx. symmetric in log(E)



$m_t = 172.3 \pm 1.2$ (stat) ± 2.6 (syst) GeV

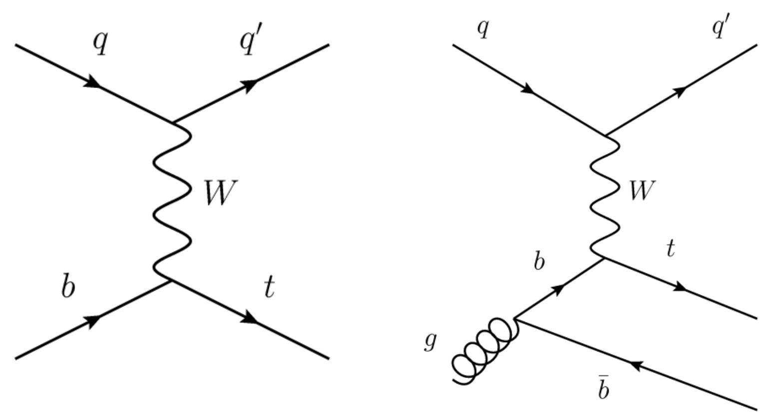
dominant systematics: jet energy scale, generator modeling, top quark p_T modeling

Alternative Event Topologies: *t-channel single top*



CMS-PAS-TOP-15-001

8 TeV: lepton+jets analysis in t-channel



fit to m(tb) $m_t = 172.6 \pm 0.8\,(stat)\ ^{+1.0}_{-0.9}\,(syst)$ GeV

Dominant uncertainties: Jet energy scales & hadronization

Alternative Measurement Combination

Combination coefficients

Analysis	Combination Coefficient (%)
Lepton + J/ψ Mass	1.9
Lepton + SVX Mass	12.0
Single Top Enriched	21.0
M_{T2}/MAOS	59.0
Dilepton p_T	2.0
E_b	-1.4
End Point	5.5

dominant contributions:

M_{T2}/MAOS
single top enriched
lepton + SVX

Correlation coefficients

	J/ψ	SVX	Sin.Top	M_{T2}/MAOS	Dil. p_T	E_b	End Pt.
Lepton + J/ψ Mass	1.00						
Lepton + SVX Mass	0.17	1.00					
Single Top	0.07	0.11	1.00				
M_{T2}/MAOS	0.13	0.32	0.38	1.00			
Dilepton p_T	0.09	0.22	0.07	0.13	1.00		
E_b	0.09	0.24	0.15	0.20	0.44	1.00	
End Point	0.02	0.19	0.06	0.14	0.06	0.13	1.00

Full Run I Combination

dominant contributions:

legacy 2012 l+jets
legacy 2012 alljets
legacy 2011 l+jets

8 TeV single top enriched

M_{T2}/MAOS, lepton + SVX have small contributions because of strong correlations with Run I measurements

Analysis	Combination Coefficient (%)
2010 Dilepton	-0.1
2011 Dilepton	1.2
2011 Lepton+jets	5.9
2011 Alljets	-0.1
2012 Dilepton	1.1
2012 Lepton+jets	70.2
2012 Alljets	15.1
Lepton + J/ψ Mass	0.7
Lepton + SVX Mass	-0.5
Single Top Enriched	6.7
M_{T2}/MAOS	-1.2
Dilepton p_T	1.5
E_b	-0.6
End Point	0.3

Full Run I Combination

	10 dil.	11 dil.	11 l+jets	11 all-jets	12 dil.	12 l+jets	12 all-jets	J/ψ	SVX	Sin.Top	M_{T2}/MAOS	Dil. p_T	E_b	End Point
2010 Dilepton	1.00													
2011 Dilepton	0.15	1.00												
2011 Lepton+jets	0.09	0.37	1.00											
2011 Alljets	0.10	0.62	0.31	1.00										
2012 Dilepton	0.09	0.26	0.17	0.17	1.00									
2012 Lepton+jets	0.05	0.21	0.30	0.26	0.26	1.00								
2012 Alljets	0.06	0.20	0.27	0.28	0.32	0.61	1.00							
Lepton + J/ψ Mass	0.03	0.05	0.07	0.06	0.09	0.09	0.08	1.00						
Lepon + SVX Mass	0.11	0.33	0.32	0.19	0.20	0.28	0.23	0.17	1.00					
Single Top	0.05	0.13	0.14	0.14	0.34	0.21	0.24	0.07	0.11	1.00				
M_{T2}/MAOS	0.08	0.30	0.31	0.28	0.52	0.48	0.46	0.13	0.32	0.38	1.00			
Dilepton p_T	0.10	0.08	0.11	0.05	0.23	0.04	0.06	0.09	0.22	0.07	0.13	1.00		
E_b	0.07	0.07	0.16	0.10	0.27	0.10	0.13	0.09	0.24	0.15	0.20	0.44	1.00	
End Point	0.12	0.49	0.34	0.39	0.07	0.13	0.13	0.02	0.19	0.06	0.14	0.06	0.13	1.00

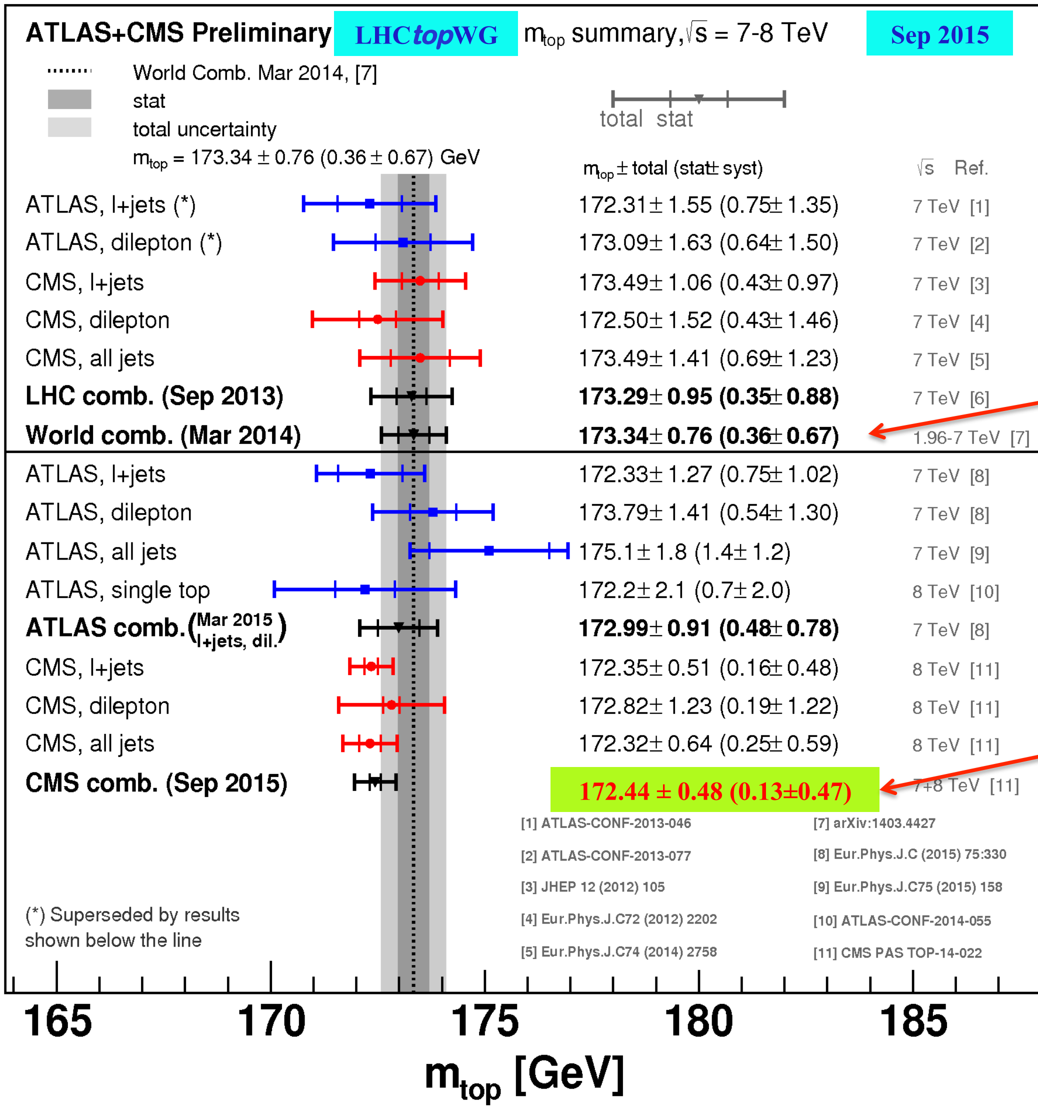
Note:

correlations between MT2/MAOS (SVX) and legacy values

CMS Run I Combination: Systematic Uncertainties

Combined m_t results	Run I δm_t (GeV)	Alternative δm_t (GeV)	Combined δm_t (GeV)
Experimental uncertainties			
Method calibration	0.03	0.08	0.04
Jet energy corrections			
– JEC: Intercalibration	0.01	0.06	0.02
– JEC: In situ calibration	0.12	0.16	0.12
– JEC: Uncorrelated non-pileup	0.10	0.26	0.10
Lepton energy scale	0.01	0.14	0.01
E_T^{miss} scale	0.03	0.04	0.04
Jet energy resolution	0.03	0.03	0.03
b tagging	0.05	0.02	0.05
Pileup	0.06	0.07	0.06
Secondary vertex mass	n/a	0.04	<0.01
Backgrounds	0.04	0.08	0.04
Trigger	<0.01	<0.01	<0.01
Modeling of hadronization			
JEC: Flavor	0.33	0.33	0.31
b jet modeling	0.14	0.22	0.14
Modeling of perturbative QCD			
PDF	0.04	0.11	0.04
Ren. and fact. scales	0.10	0.30	0.10
ME-PS matching threshold	0.08	0.21	0.08
ME generator	0.11	0.07	0.11
Single top modeling	n/a	0.04	0.01
Top quark p_T	0.02	0.21	0.02
Modeling of soft QCD			
Underlying event	0.11	0.10	0.11
Color reconnection modeling	0.10	0.11	0.10
Uncertainties (GeV)			
Total systematic	0.47	0.72	0.46
Statistical	0.13	0.21	0.13
Total Uncertainty	0.48	0.75	0.48

Top Quark Mass – LHC Summary



LHC Summary

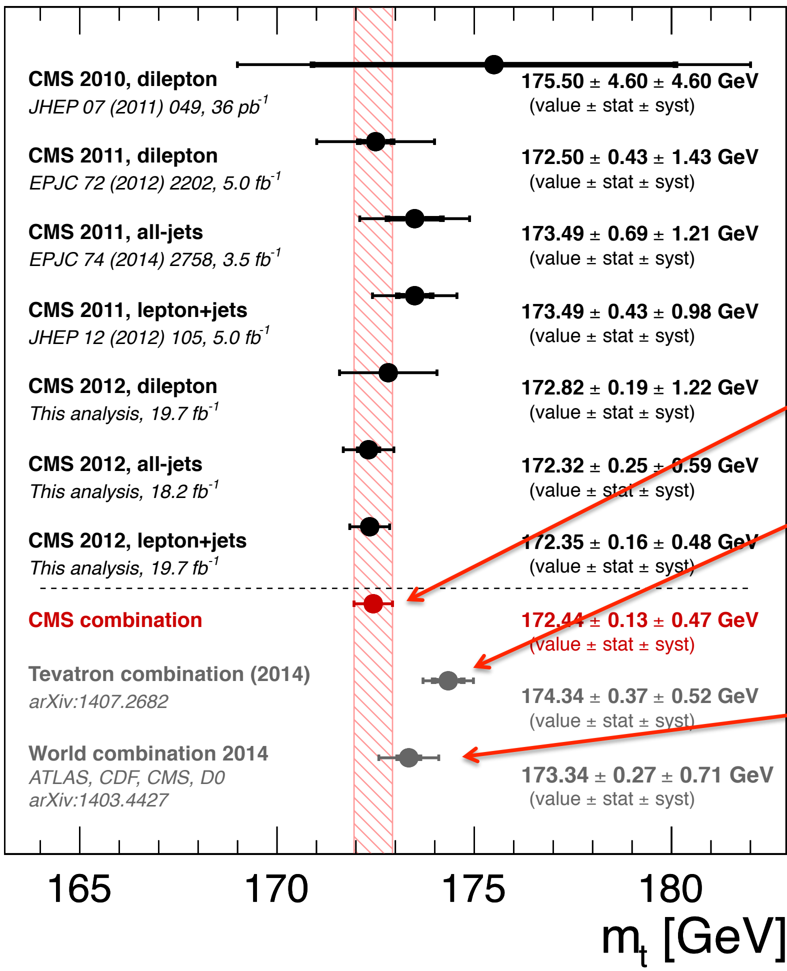
2014 World Combination Result

CMS Run I Result

CMS Run I Combination : Tevatron (D0) Results

CMS: Phys. Rev. D93 (2016) 072004

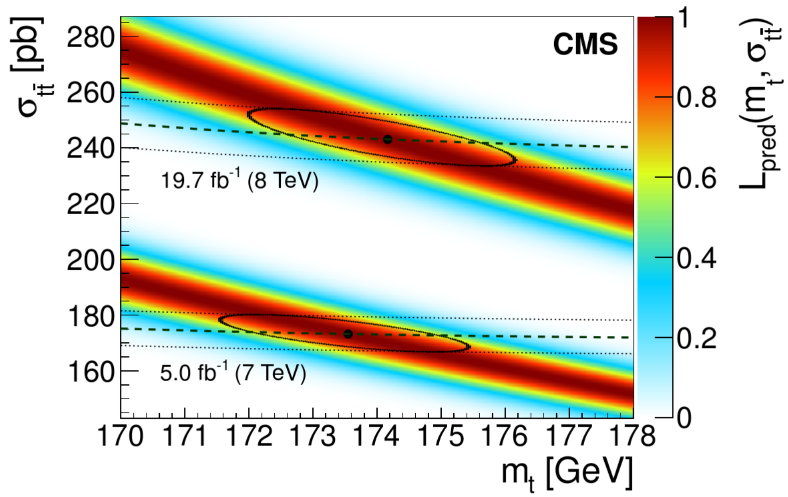
LHC*top*WG
+ Tevatron top groups

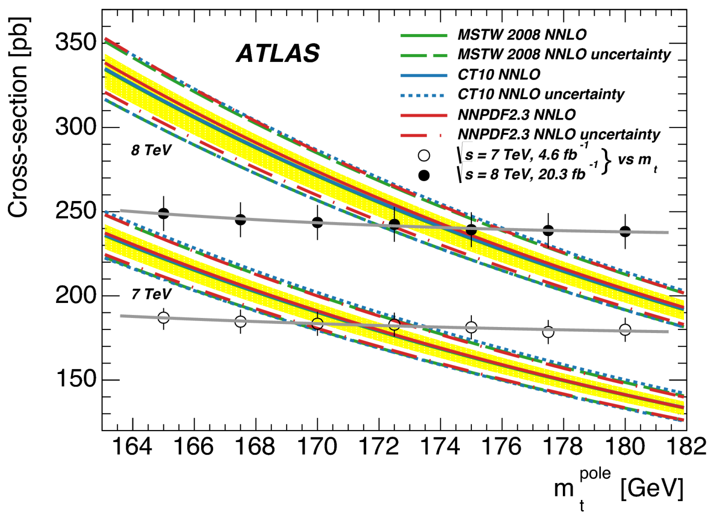


CMS-D0 studies:
CMS and Tevatron (D0) measurements in lepton+jets channel

2013 World Average value

Top Quark Pole Mass – from Production Cross Section





use mass dependence of measured cross section and NNLO prediction to find m_t^{pole}

CMS arXiv:1603.02303

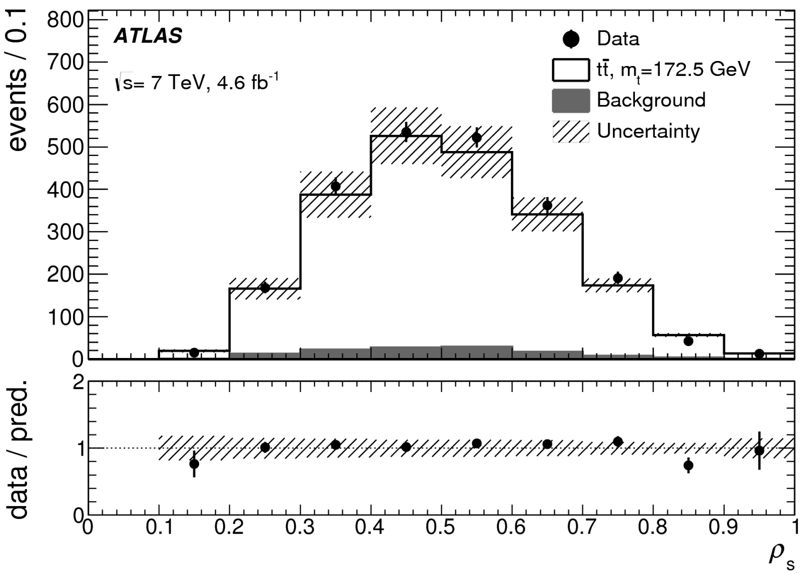
$m_t^{pole} = 173.8\,^{+1.7}_{-1.8}$ GeV

ATLAS EPJC 74 (2014) 3109

$m_t^{pole} = 172.9\,^{+2.8}_{-2.6}$ GeV

Results from combined fit to 7 and 8 TeV Cross Sections

Top Quark Pole Mass – *(lepton+jets) + 1 jet*



JHEP 10 (2015) 121

motivation → Alioli & Collaborators
arXiv:1303.6415

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

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}} \qquad m_0 = 170 \text{ GeV}$$

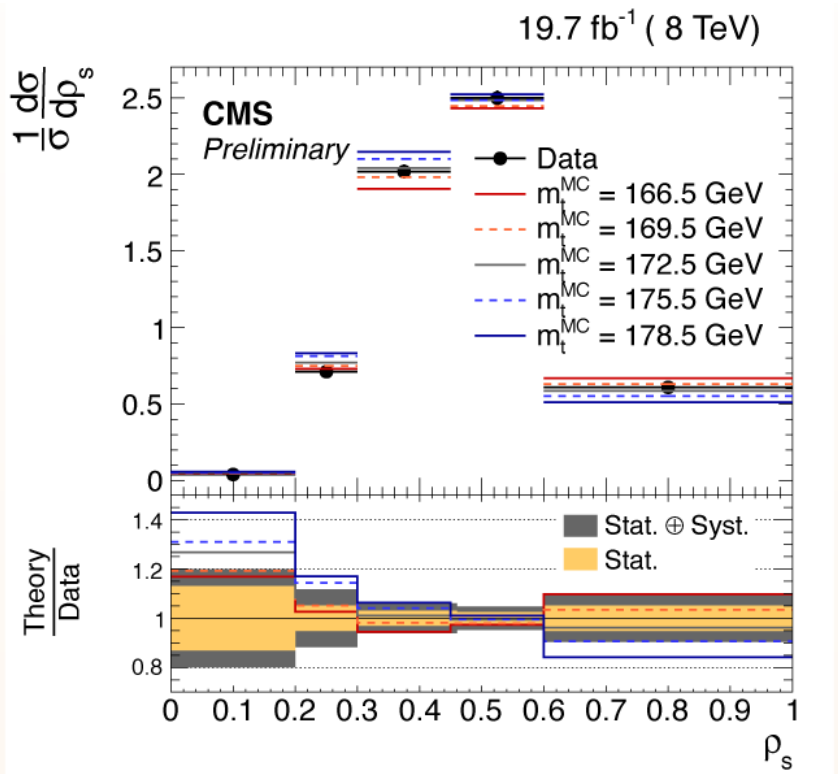
Normalized ttbar + 1 jet differential cross section → top quark pole mass

Dominant uncertainties: statistics (only 7 TeV data),
Jet energy scales & knowledge ISR/FSR and Q^2 scale

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

Top Quark Pole Mass – *(lepton+jets) + 1 jet*

CMS PAS TOP-13-006



8 TeV: dilepton channel analysis

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

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

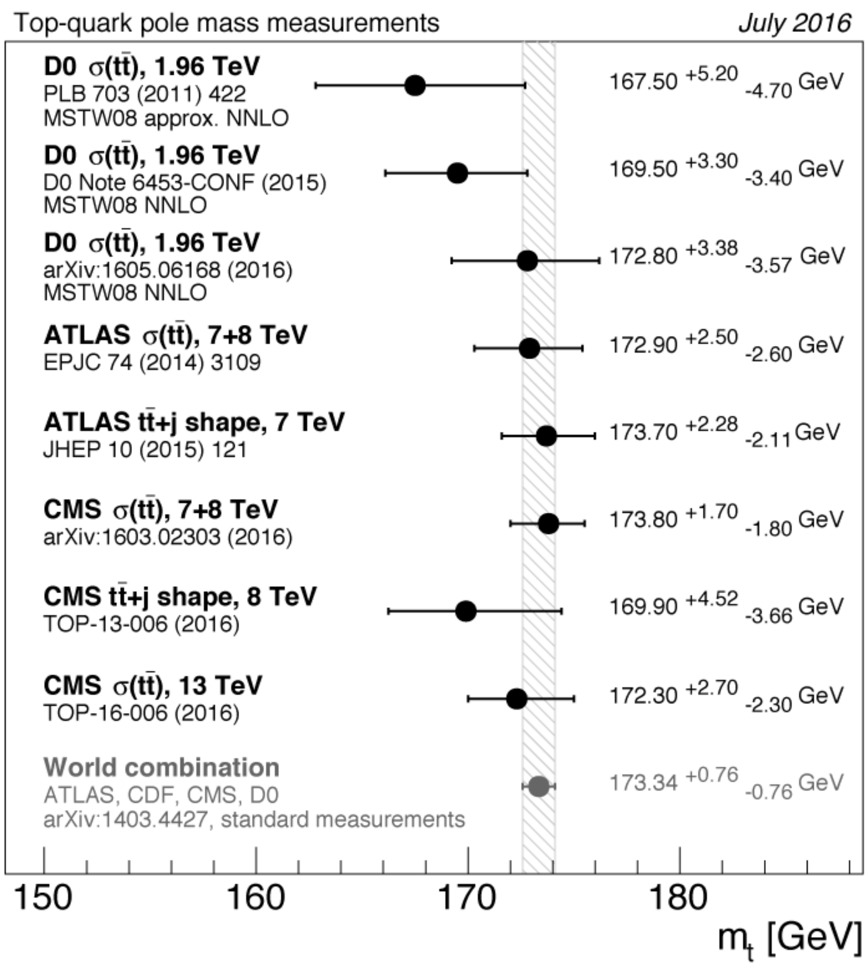
m_0 = 170 GeV

Normalized ttbar + 1 jet differential cross section → top quark pole mass

Dominant uncertainties: ttbar + jet modeling (POWHEG) ME/PS matching & knowledge of Q^2 scale

$m_t^{\mathrm{pole}} = 169.9 \pm 1.1\ (\mathrm{stat})\ ^{+2.5}_{-3.1}\ (\mathrm{syst})\ ^{+3.6}_{-1.6}\ (\mathrm{thy})$ GeV

Top Quark Pole Mass – Summary



Precision limited by knowledge of:

a.) Cross Sections:

LHC beam energy & luminosity, pdf's & α_s

b.) ttbar+1 jet:

Jet Energy Scales, ISR/FSR modeling and Q^2 scale

Not competitive in precision with kinematic mass reconstruction but it does produce a theoretically simpler mass observable