Towards a Precision Measurement of the Top Quark Mass

Stephen Wimpenny
Dept. of Physics & Astronomy, UC Riverside

Disclaimer

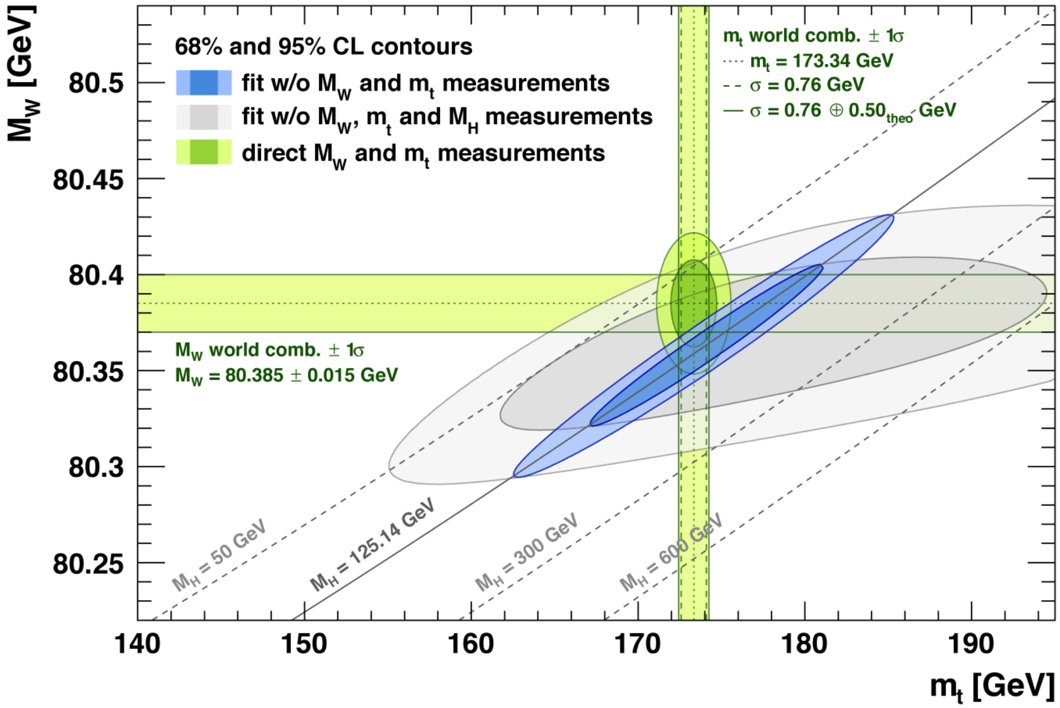
There is a large body of work from the Experiments at both the Tevatron and the LHC that targets the top quark mass.

CMS has recently completed the last of its Run 1 analyses so it is a good point to take stock of what we have learned so far.

In this talk I will focus on a select set of the CMS measurements and only comment briefly on those from the other experiments.

The CMS measurements provide the most extensive set of results and, in most cases, they are the most precise.

m_t 20 years after the top discovery



EPJC 74 (2014) 3046

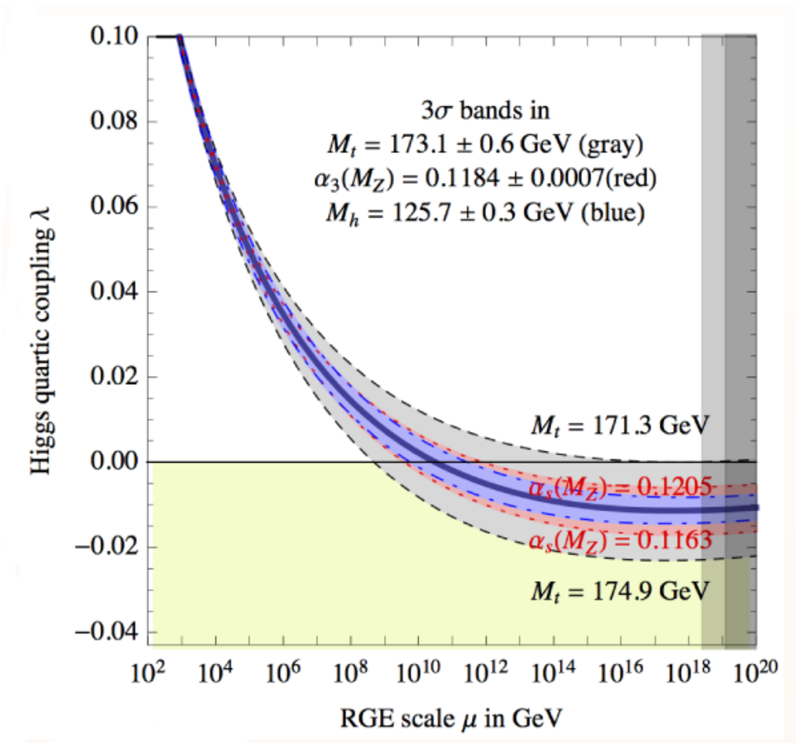
Indirect measurement of M_W (Electroweak fit) and direct measurements of m_t, M_W and M_H

m_t = 173.34 ± 0.27 (stat) ± 0.71 (syst) GeV *(arXiv:1403.4427, 2014)*

→ *heaviest known fundamental particle*

m_t enters the quantum loop corrections to the W boson mass
→ *an important ingredient in self-consistency tests of the Standard Model*

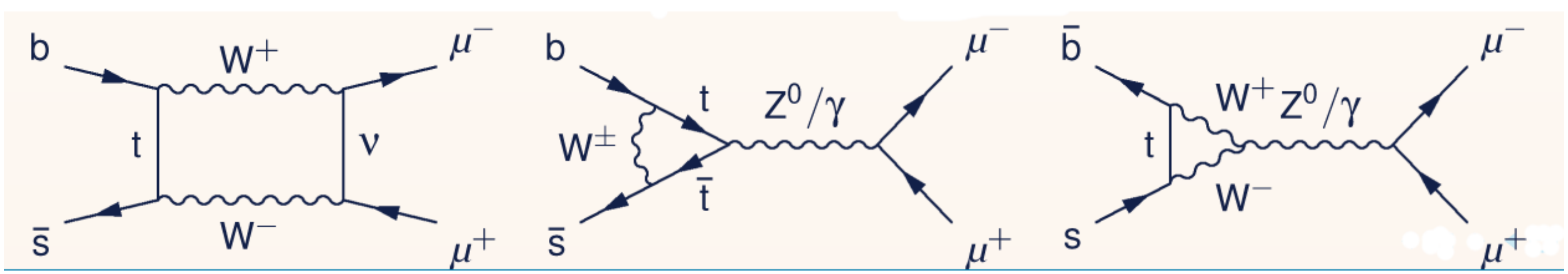
m_t 20 years after the top discovery



JHEP 1208 (2012) 098

If the Higgs quartic coupling is small at the Planck scale it depends on both M_H and m_t → information on stability of the Electroweak vacuum

m_t also important for the computation of rare decays, such as $B_s \rightarrow \mu^+\mu^-$



Top Mass and Related Measurements

Measurements using full reconstruction of the ttbar final states:

- *mass (m_t) measurements*
- $m_t - m_{tbar}$
- *direct bounds on Γ_t (13 TeV data)*

Analyses using partial reconstruction, alternative analysis strategies and the t-channel single top final state:

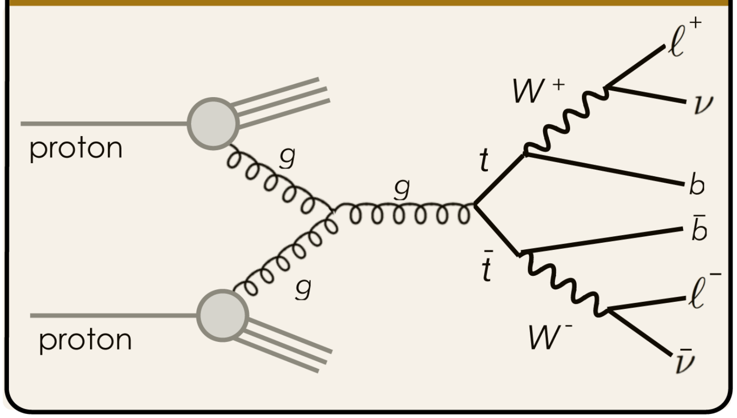
- *mass (m_t) measurements*

Indirect measurements of m_t^{pole} using theory input and the measured production cross section:

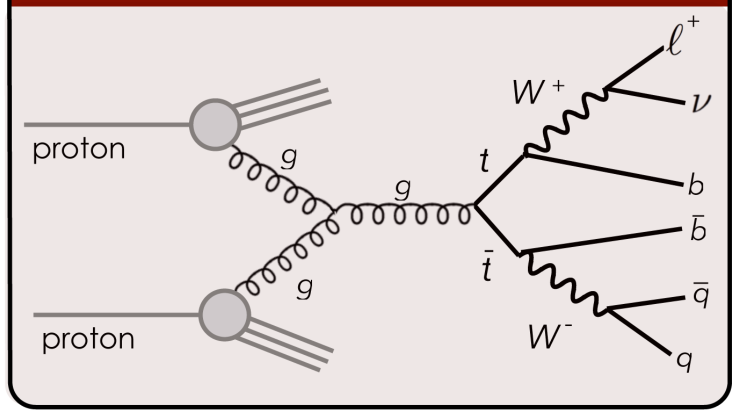
- *7, 8 and 13 TeV data*

Full Kinematic Reconstruction

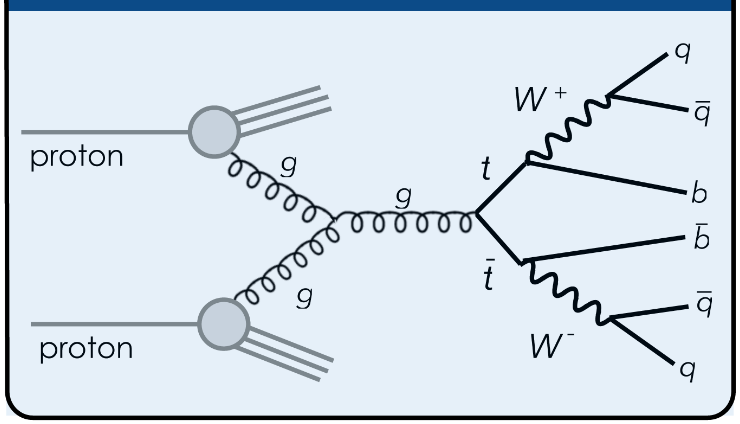
Dileptonic $t\bar{t}$ Channel



Semileptonic $t\bar{t}$ Channel



All-Hadronic (All-Jets) $t\bar{t}$ Channel



Top quarks decay before they have time to hadronize → measure m_t directly from the decay products

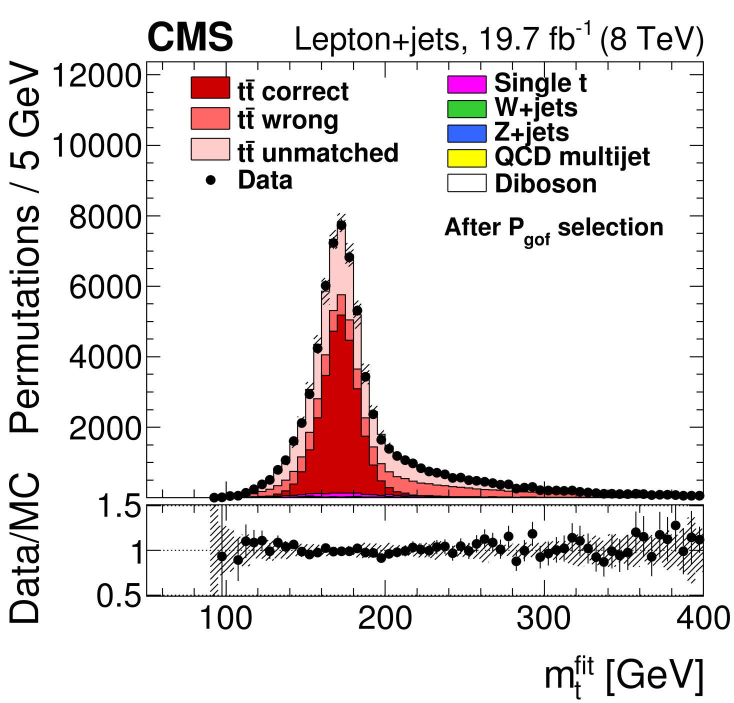
Full ttbar reconstruction analyses focus on these three ttbar decay channels ($l = e$ *or* μ)

Lepton+jets and All-jets channels

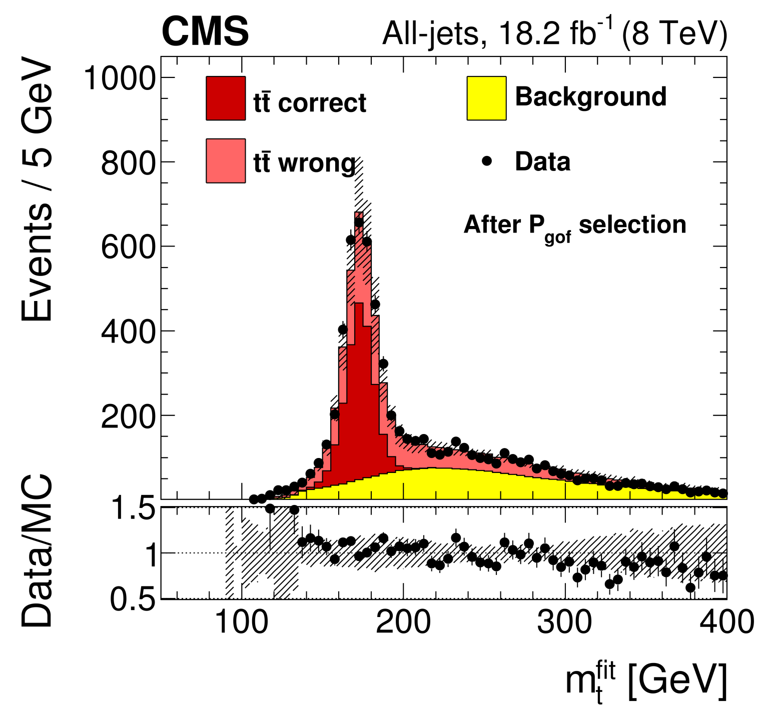
CMS
$\sqrt{s}$ = 8 TeV

CMS Legacy Analysis

Phys. Rev. D93 (2016) 072004



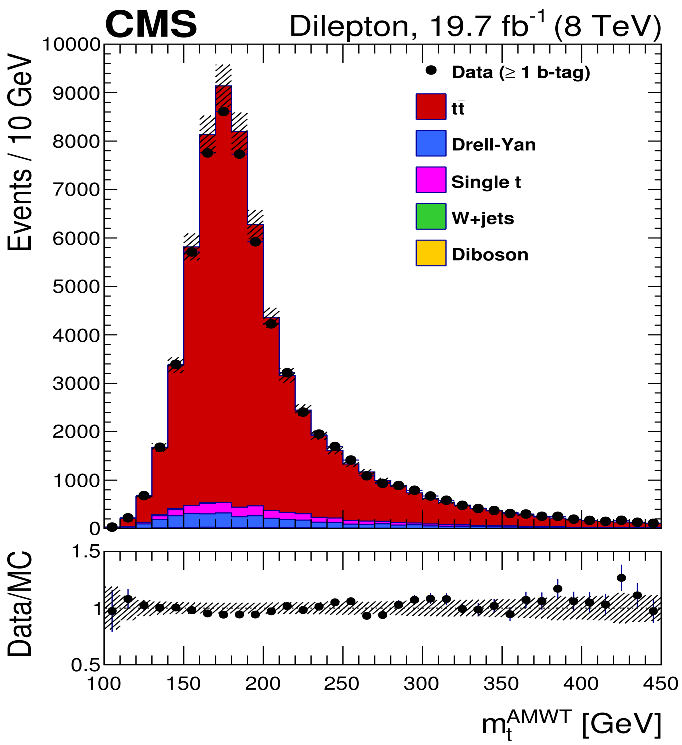
lepton+jets channel



all-jets channel

Analyses use 1D (m_t) and 2D ideogram techniques (m_t and JSF) combined with a kinematic fit

Dilepton channel and consistency between channels



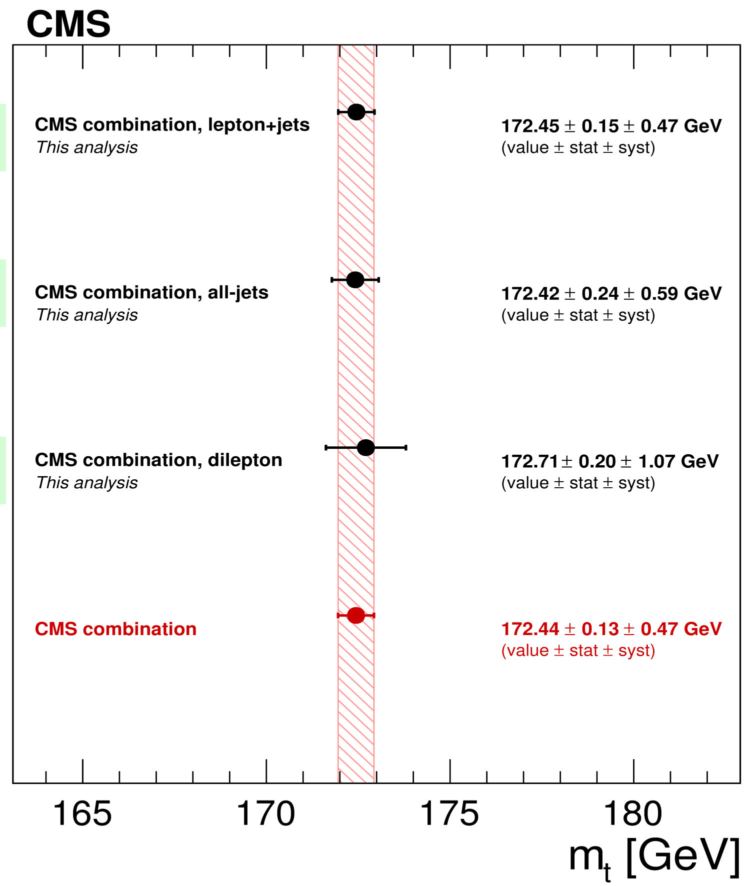
dilepton channel at 8 TeV

1D (m_t) AMWT analysis

l+jets

all-jets

dilepton



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

Run I Combined (Legacy) Result

Phys. Rev. D93 (2016) 072004

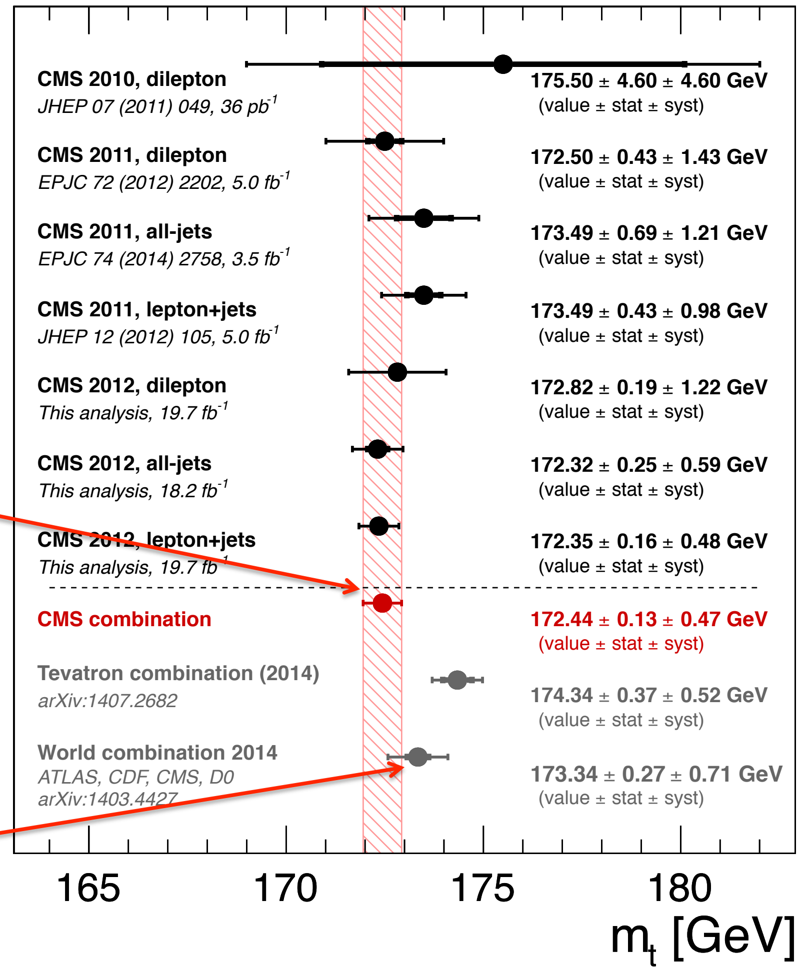
Measurements combined using Best Linear Unbiased Estimate (BLUE) method

Combined result

$m_t = 172.44 \pm 0.13$ (stat) ± 0.47 (syst) GeV

Precision ~ 480 MeV (0.3%)

2014 World Average value



Systematic Uncertainties

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

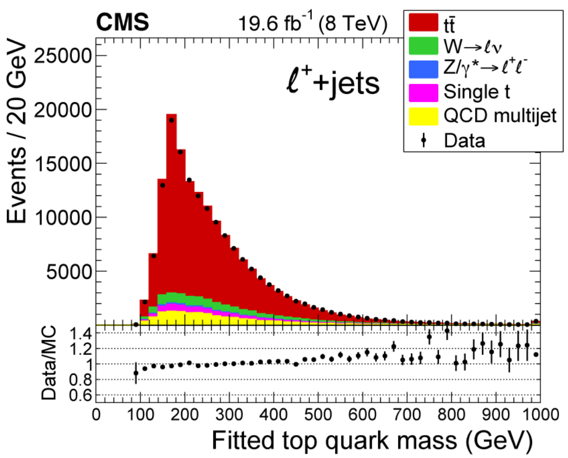
Dominant uncertainties:
flavor dependent JEC:
(u,d,s), c, b, g
b jet modeling:
b-fragmentation
+ b-hadron decays

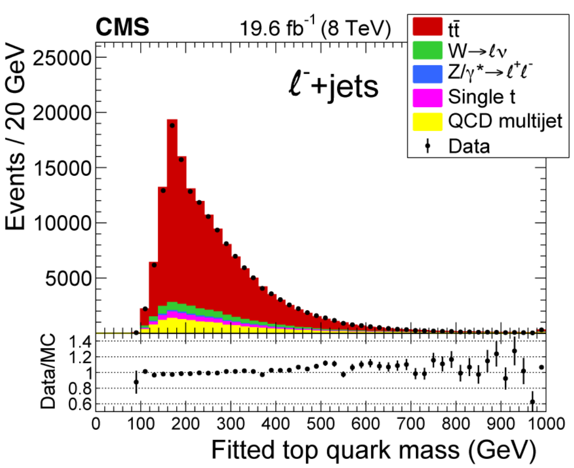
Top-Antitop Mass Difference: 8 TeV Data

CMS
$\sqrt{s}$ = 8 TeV

lepton+jets channel

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

Limited by statistics. Substantial cancellation of systematic uncertainties in the mass difference

~ factor of 2 more precise than CMS and ATLAS 7 TeV measurements
dominant uncertainties: statistics, b (bbar) jet and background modeling

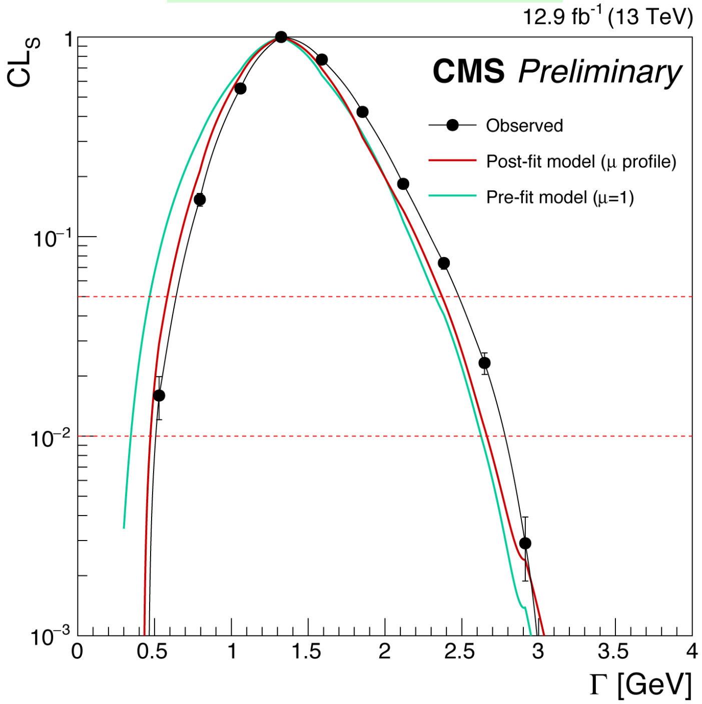
Limits on the Top Quark Width

CMS
$\sqrt{s}$ = 13 TeV

1^{st} Run II 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:

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

for m_t = 172.5 GeV

Limiting Factors – Full Reconstruction

Experimental:

- *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*

Investigate 'Alternative' analysis strategies and different event topologies

Alternative Analysis Strategies

Dilepton channel

7 TeV End Point analysis	(EPJC 73 (2013) 2494)
8 TeV M_{T2}/MAOS analysis	(arXiv:1704.06142)
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

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

Dilepton + lepton + jets channels

8 TeV B-lifetime analysis	(CMS PAS TOP-12-030)
8 TeV Lepton+ Sec. Vtx. Mass	(Phys. Rev. D93 (2016) 092006)
8 TeV Lepton + J/ψ analysis	(JHEP 12 (2016) 123)

Single top analysis

8 TeV t-channel single top enhanced	(arXiv:1703.02530)

Alternative Observables: M_{bl} and M_{T2}^{bb}

arXiv:1704.06142

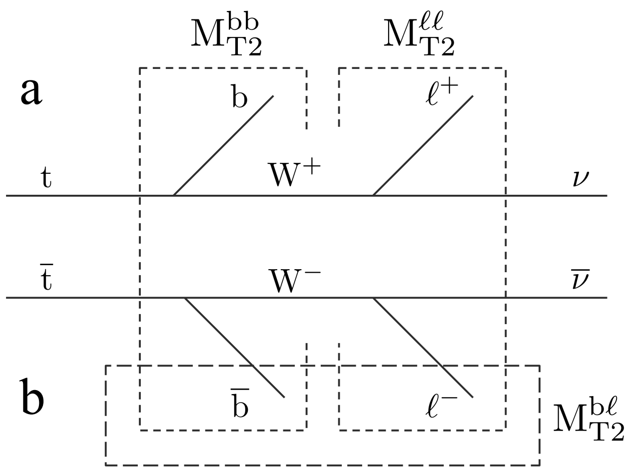
8 TeV: dilepton channel

Analysis concept taken from BSM searches

2 identical decay branches (a and b)

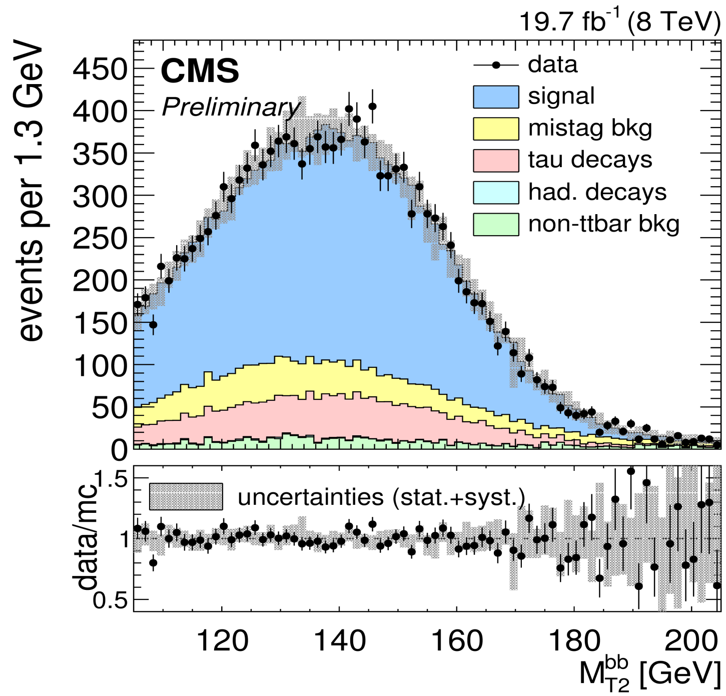
m_t extracted from M_{bl} and M_{T2}^{bb} using the combination of 1D (m_t) and 2D (m_t, JSF) fits

(similar to the standard lepton+jets analysis)

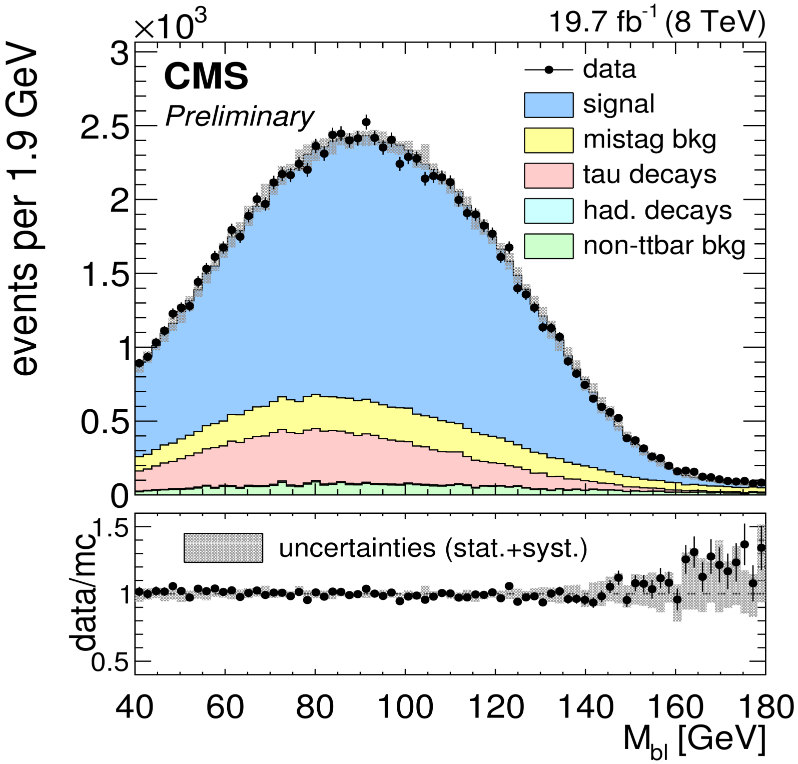


$$M_{T2} = \min_{\vec{p}_T^{\,a}+\vec{p}_T^{\,b}=\vec{p}_T^{\,miss}} \left[\max\{M_T^a, M_T^b\}\right]$$

M_{T2}^{bb} is the M_{T2} variable built using the two b-jets



Alternative Observables: $M_{bl\nu}$ and M_{T2}^{bb}



Mass is determined from simultaneous fits to the distribution shapes using MC templates and Gaussian Process regression techniques

$m_t = 172.22 \pm 0.18\,(\text{stat})\,^{+0.89}_{-0.93}\,(\text{syst})$ GeV

(most precise 'non-standard' result)

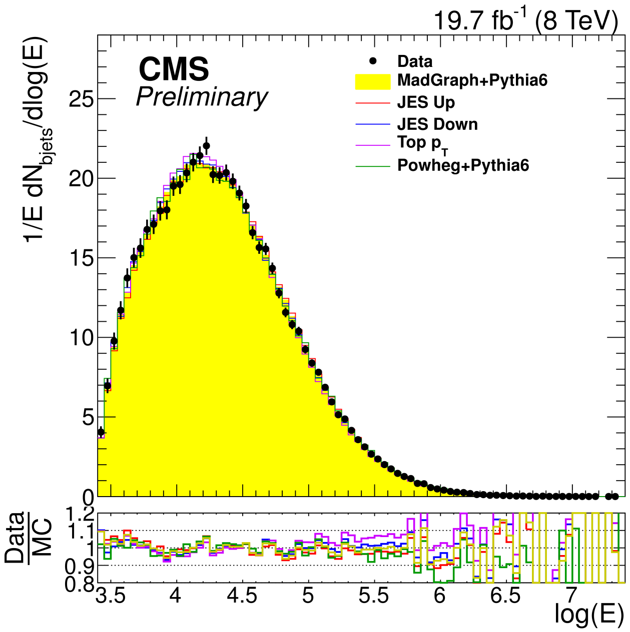
dominant systematics: top quark p_T modeling, jet energy corrections b-fragmentation, Q^2 scale uncertainties

Alternative Observable: *b-jet Energy Spectrum*

CMS-PAS-TOP-15-002

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

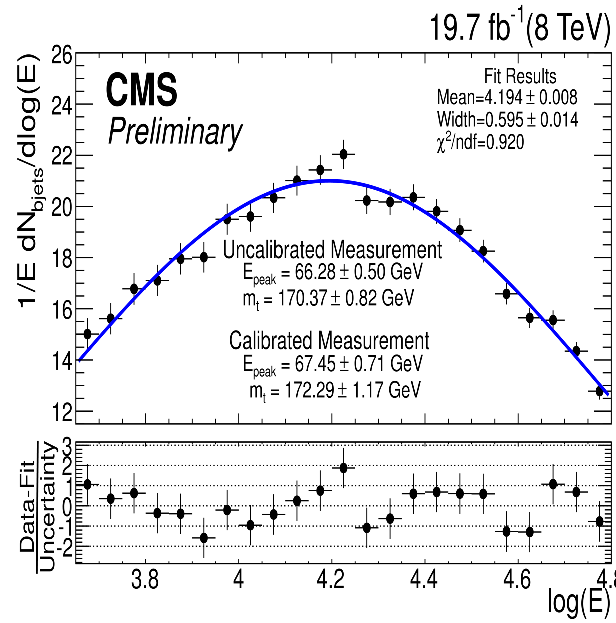
8 TeV: dilepton eμ channel



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

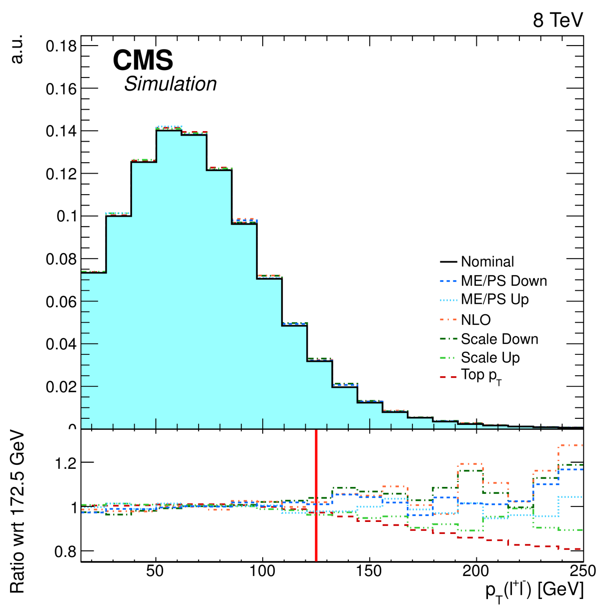
dominant systematics: jet energy scale, generator modeling, top quark p_T modeling

Alternative Observable: *Dilepton Kinematics*

CMS-PAS-TOP-16-002

motivation → Frixione & Mitov JHEP 09 (2014) 012

8 TeV: dilepton eμ channel

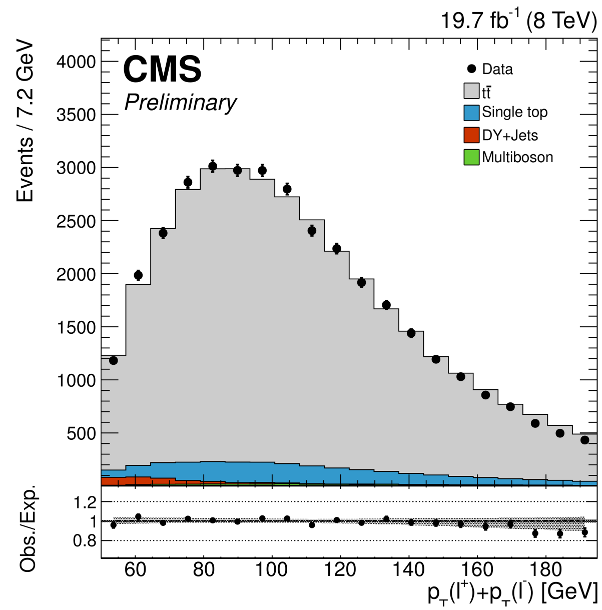


Look for experimentally clean variable that is theoretically calculable

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: Q^2 scale uncertainties, top quark p_T modeling

Caveat: analysis done only using LO multileg MC

Marginalizing Uncertainties: *l + Secondary Vertex Mass*

Phys. Rev. D93 (2016) 092006

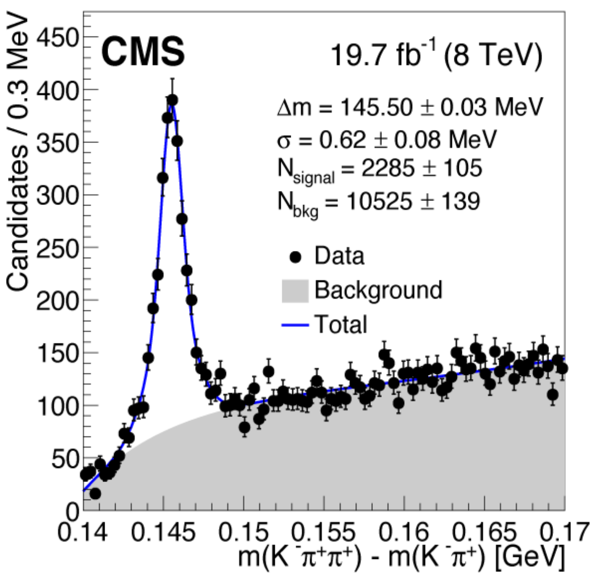
8 TeV: lepton+jets & dilepton channels

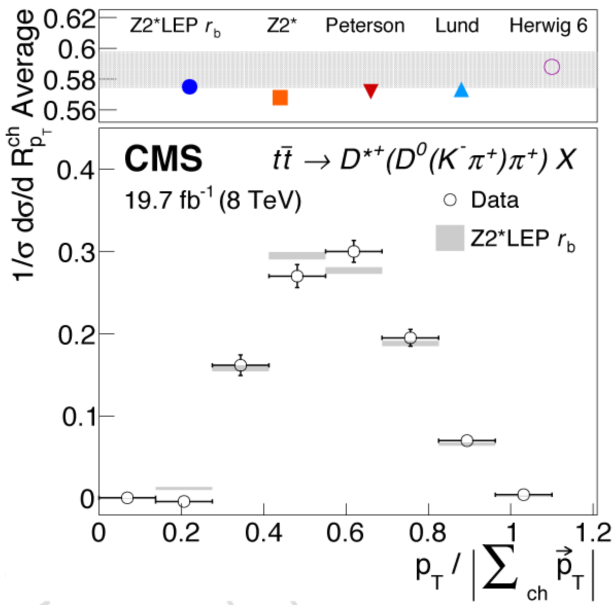
$m_t = 173.7 \pm 0.2\ (stat)\ ^{+1.6}_{-1.0}\ (syst)$ GeV

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

dominant systematics:

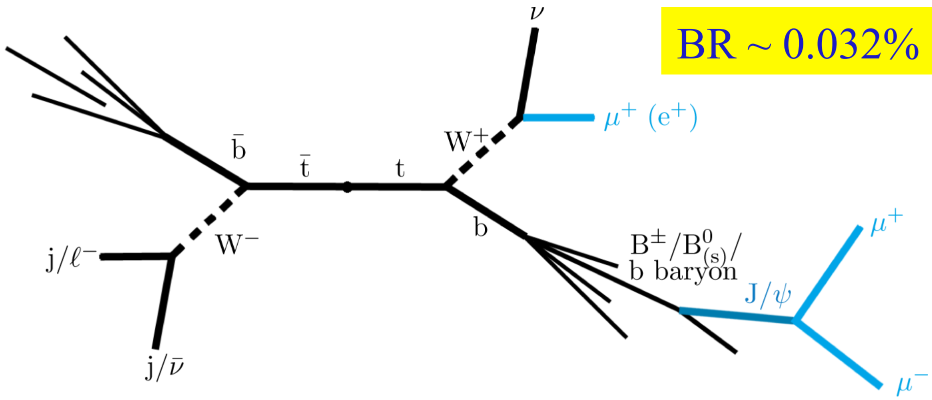
b-fragmentation, top p_T distribution
Q^2 and matching scales



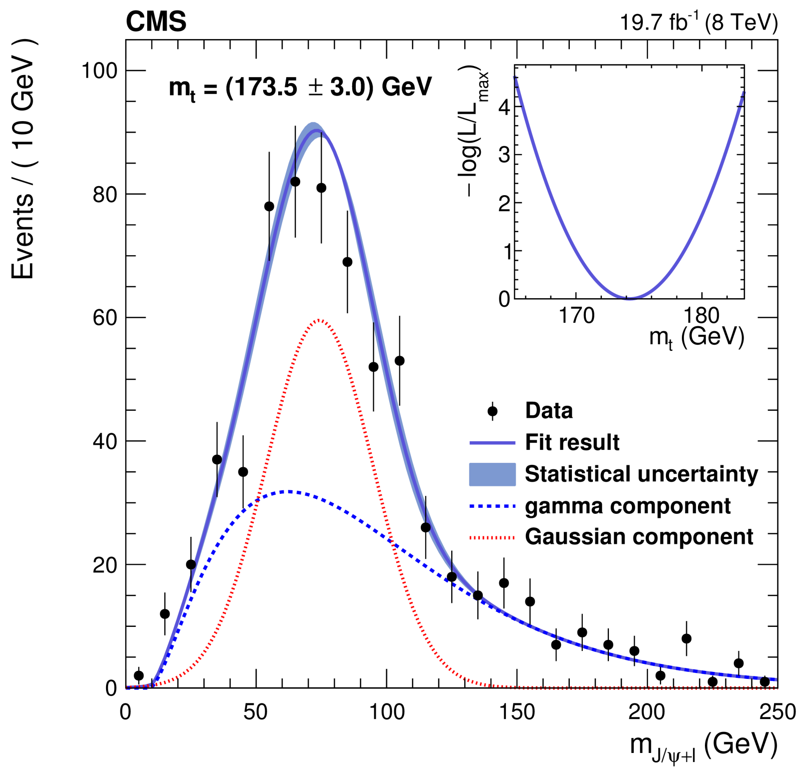


Reconstruction of J/ψ, D0 and D± in these events → check of b-fragmentation modeling for ttbar events*

Marginalizing Uncertainties: $l + J/\psi$ Mass



BR ~ 0.032%



JHEP 12 (2016) 123

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

$m_t = 173.5 \pm 3.0$ (stat) ± 0.9 (syst) GeV

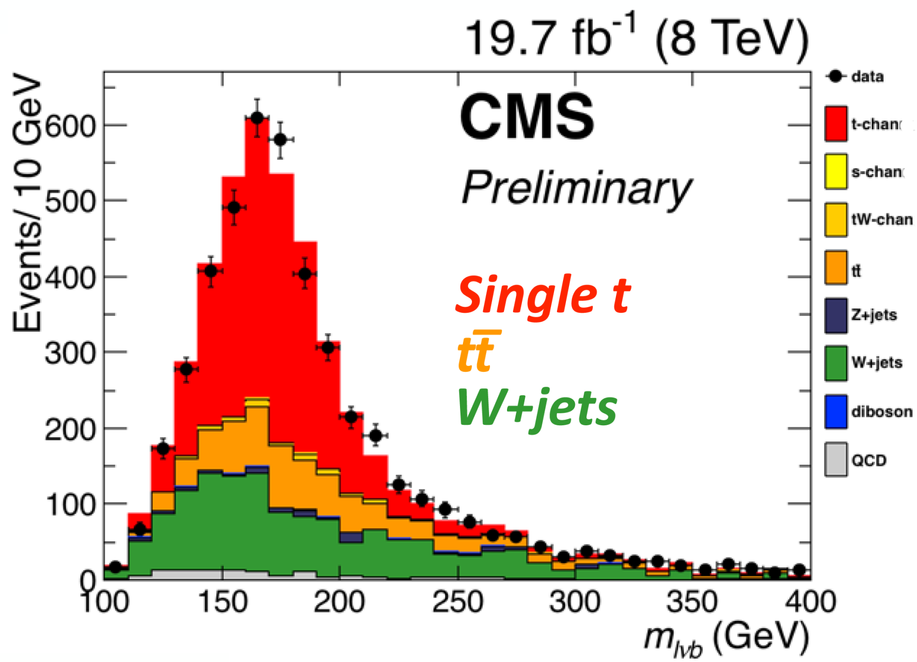
limited by statistics

dominant systematics:

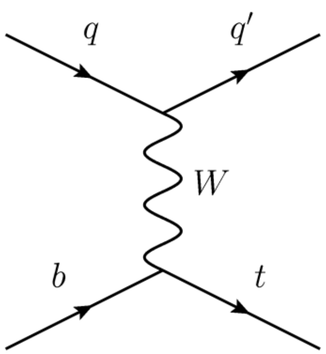
b-fragmentation, top p_T distribution
Q^2 and matching scales

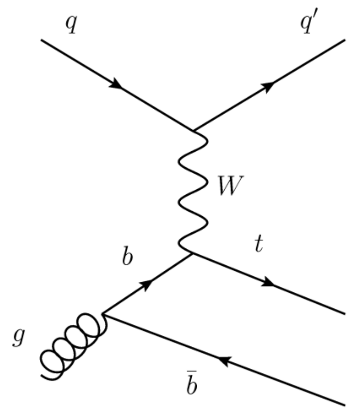
Alternative Topologies: *t-channel single top*

arXiv:1703.02530



8 TeV: lepton+jets analysis in t-channel





fit to $m_{l\nu b}$

$m_t = 172.6 \pm 0.8\ (\text{stat})\ ^{+1.0}_{-0.9}\ (\text{syst})\ \text{GeV}$

Dominant uncertainties: Jet energy scales & hadronization

‘Alternative’ Measurement Combination

CMS
√s = 7 & 8 TeV

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

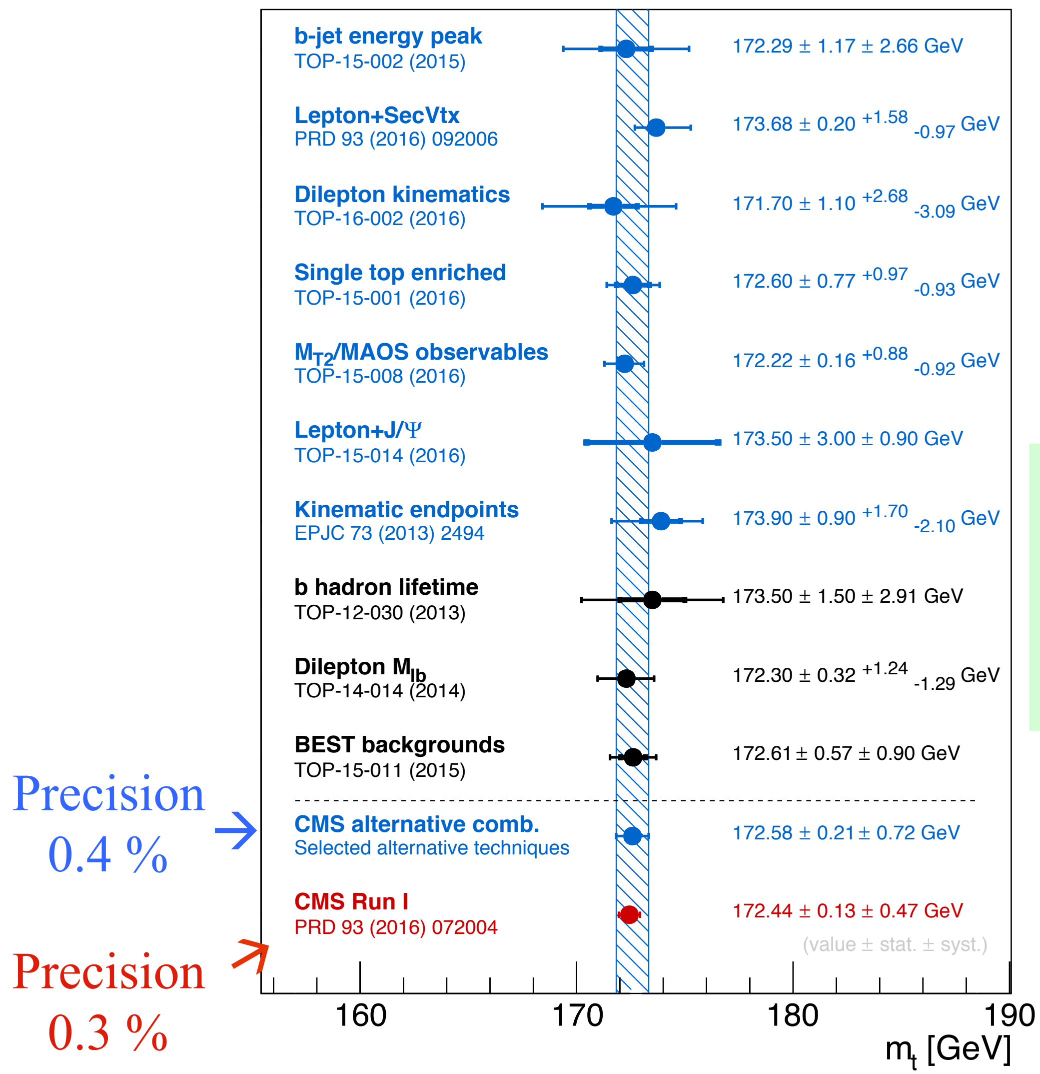
→ 7 measurements to be combined

Measurements combined using BLUE

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

Precision 0.4 %

CMS 'Alternative' Measurements



Alternative Measurement Summary

Results with varying systematic sensitivities are very consistent with each other

Some of these are more alternative in approach than others

Significant overlap in the datasets and methods for some measurements

New combination agrees very well with CMS legacy result and has comparable precision.

Comparison of Systematic Uncertainties

Combined m_t results	Legacy δm_t(GeV)	Alternative δm_t(GeV)
Experimental uncertainties		
Method calibration	0.03	0.08
Jet energy corrections		
– JEC: Intercalibration	0.01	0.06
– JEC: In situ calibration	0.12	0.16
– JEC: Uncorrelated non-pileup	0.10	0.26
Lepton energy scale	0.01	0.13
E_T^{miss} scale	0.03	0.04
Jet energy resolution	0.03	0.03
b tagging	0.05	0.02
Pileup	0.06	0.07
Secondary vertex mass	n/a	0.04
Backgrounds	0.04	0.08
Trigger	<0.01	<0.01
Modeling of hadronization		
JEC: Flavor	0.33	0.33
b jet modeling	0.14	0.22
Modeling of perturbative QCD		
PDF	0.04	0.11
Ren. and fact. scales	0.10	0.31
ME-PS matching threshold	0.08	0.22
ME generator	0.11	0.08
Single top modeling	n/a	0.04
Top quark p_T	0.02	0.23
Modeling of soft QCD		
Underlying event	0.11	0.11
Color reconnection modeling	0.10	0.10
Uncertainties (GeV)		
Total systematic	0.47	0.72
Statistical	0.13	0.21
Total Uncertainty	0.48	0.75

Alternative Combination

Uncertainty distribution very similar to the legacy result

Dominant terms:

hadronization modeling

Other significant contributions:

PDF, Q^2, ME-PS, top p_T, LES

(larger than Run I result)

Note:

Legacy + Alternative combination is in the additional material section of this talk.

LHC and Tevatron Combinations

a.) CMS

Legacy 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

ATLAS combination: 0.4%

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

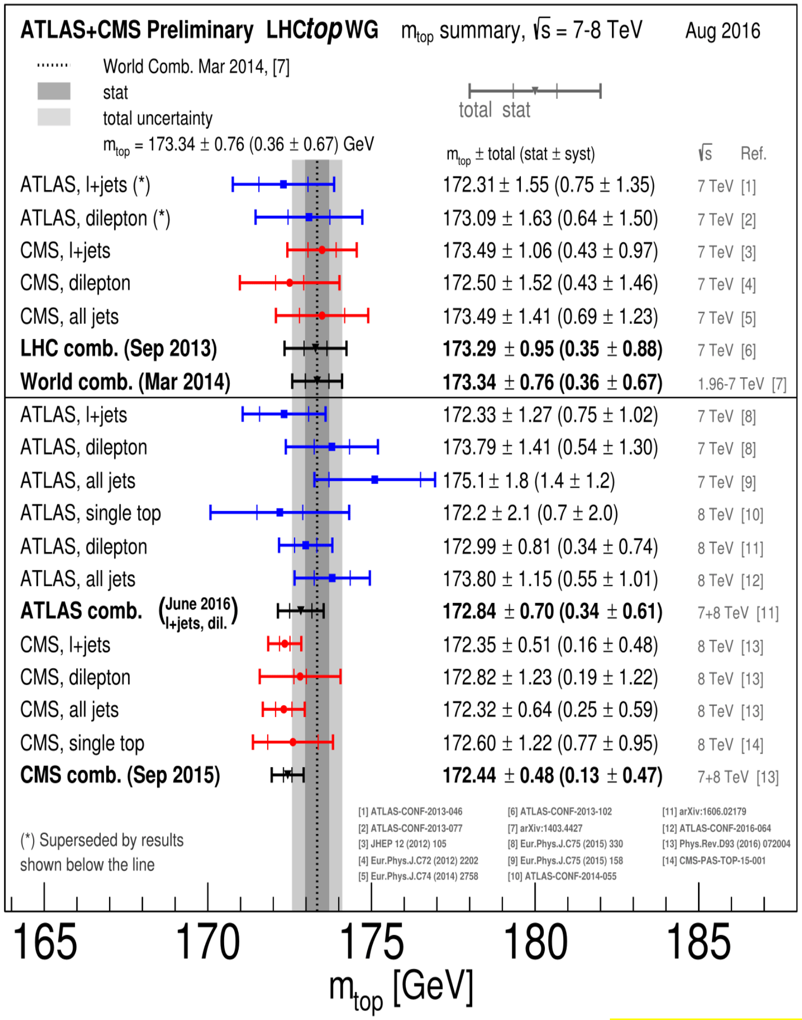
c.) Tevatron

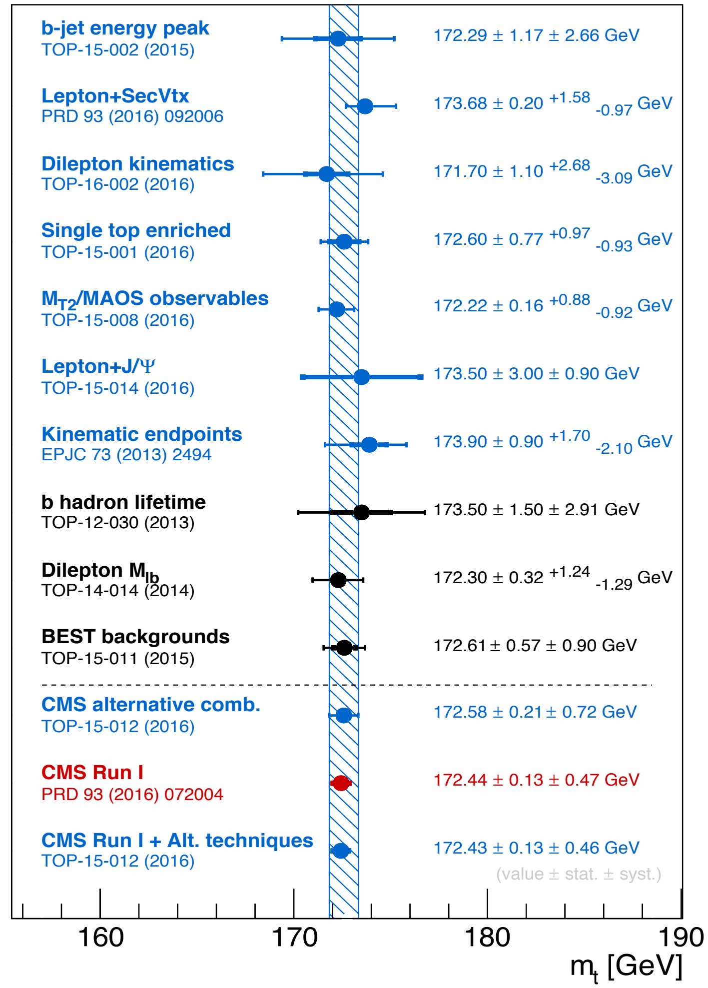
Tevatron combination: 0.4%

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

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

LHC Run I Measurements





Very consistent picture

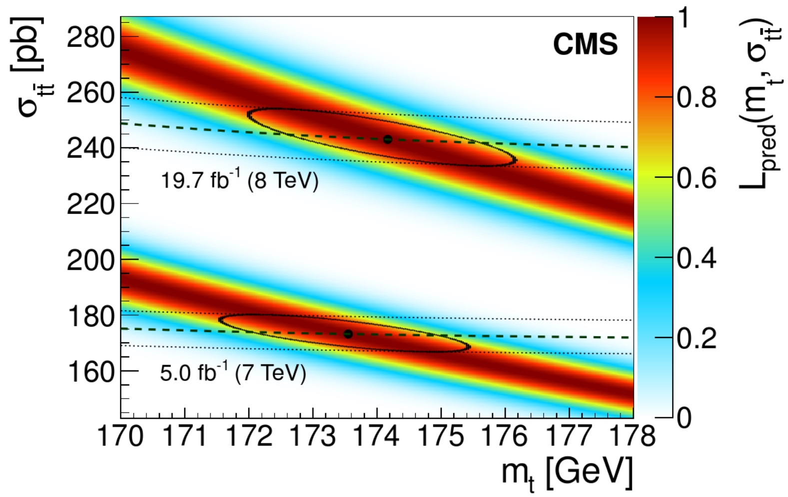
Summary of LHC Measurements

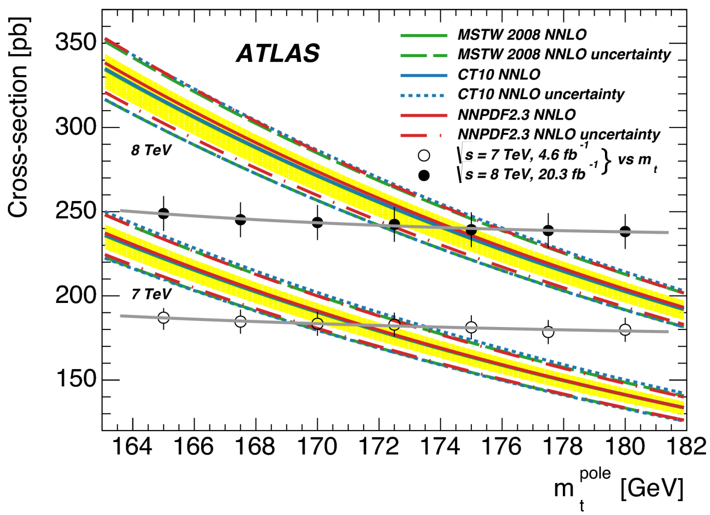
CMS and ATLAS have produced very accurate measurements measurements of the top quark mass using 7 and 8 TeV LHC data using 'standard analysis techniques'

CMS has a significant set of additional measurements using 'alternative' analysis strategies. These have varying systematic uncertainty sensitivities. However, the precision of the results from these hasn't yet matched that of the 'standard measurements'.

The combination of these 'alternative' measurements gives a mass in good agreement with, and of comparable precision to, its published Run I combination.

The individual Run I measurements and the ATLAS and CMS combinations are in good agreement





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

CMS JHEP 08 (2016) 029

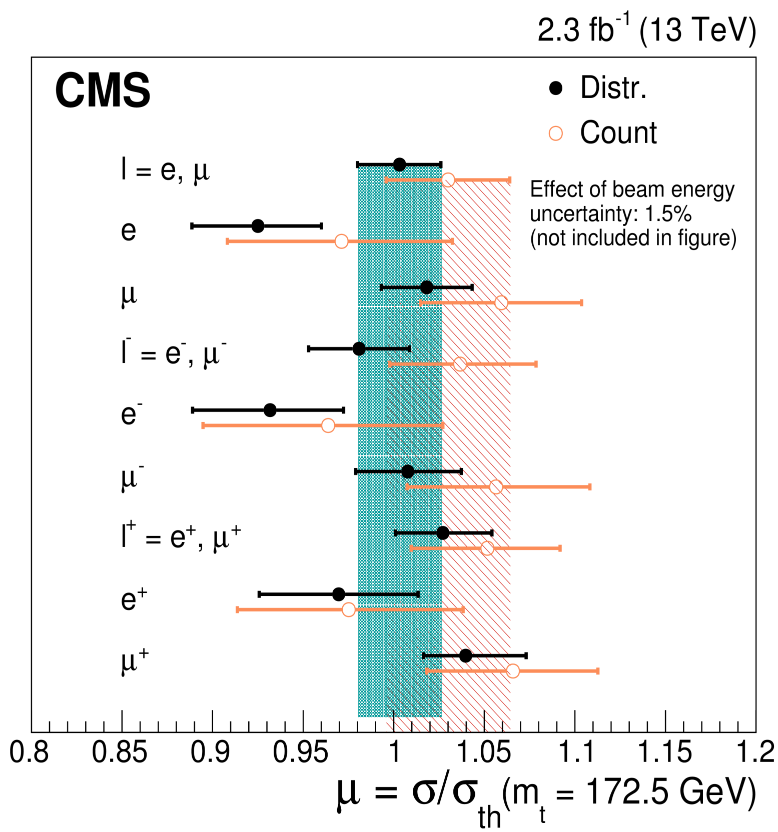
$m_t^{pole} = 173.8^{+1.7}_{-1.8}$ GeV

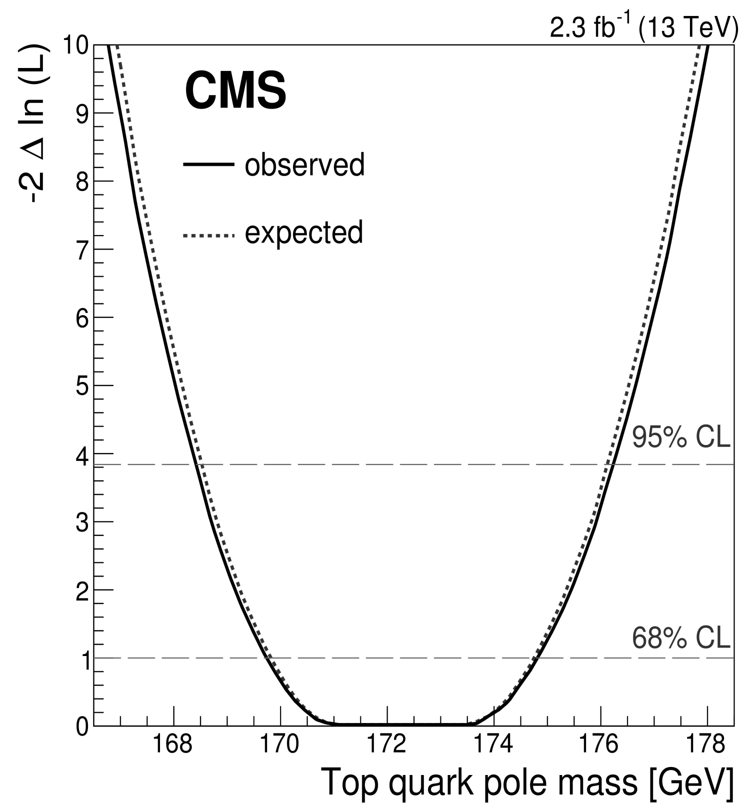
ATLAS EPJC 74 (2014) 3109

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

Results from combined fit to 7 and 8 TeV Cross Sections

CMS PAS TOP-16-006

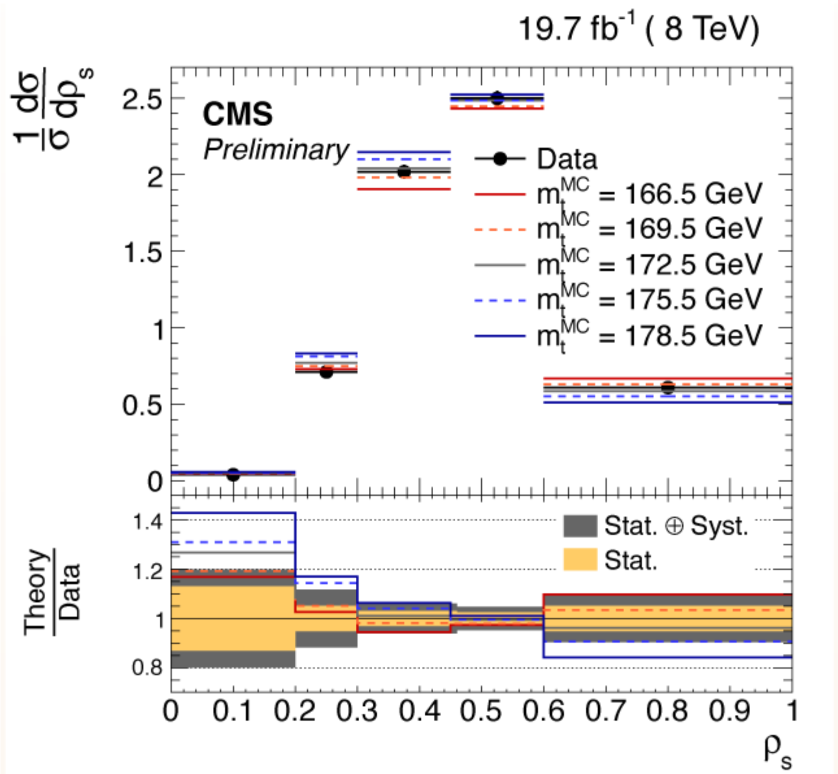




$m_t^{pole} = 172.7\ ^{+2.4}_{-2.7}$ GeV

Result from fit to
2.3 fb^{-1} of 13 TeV data

Indirect Measurements: Top Quark Pole Mass



CMS PAS TOP-13-006

8 TeV: dilepton channel analysis

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

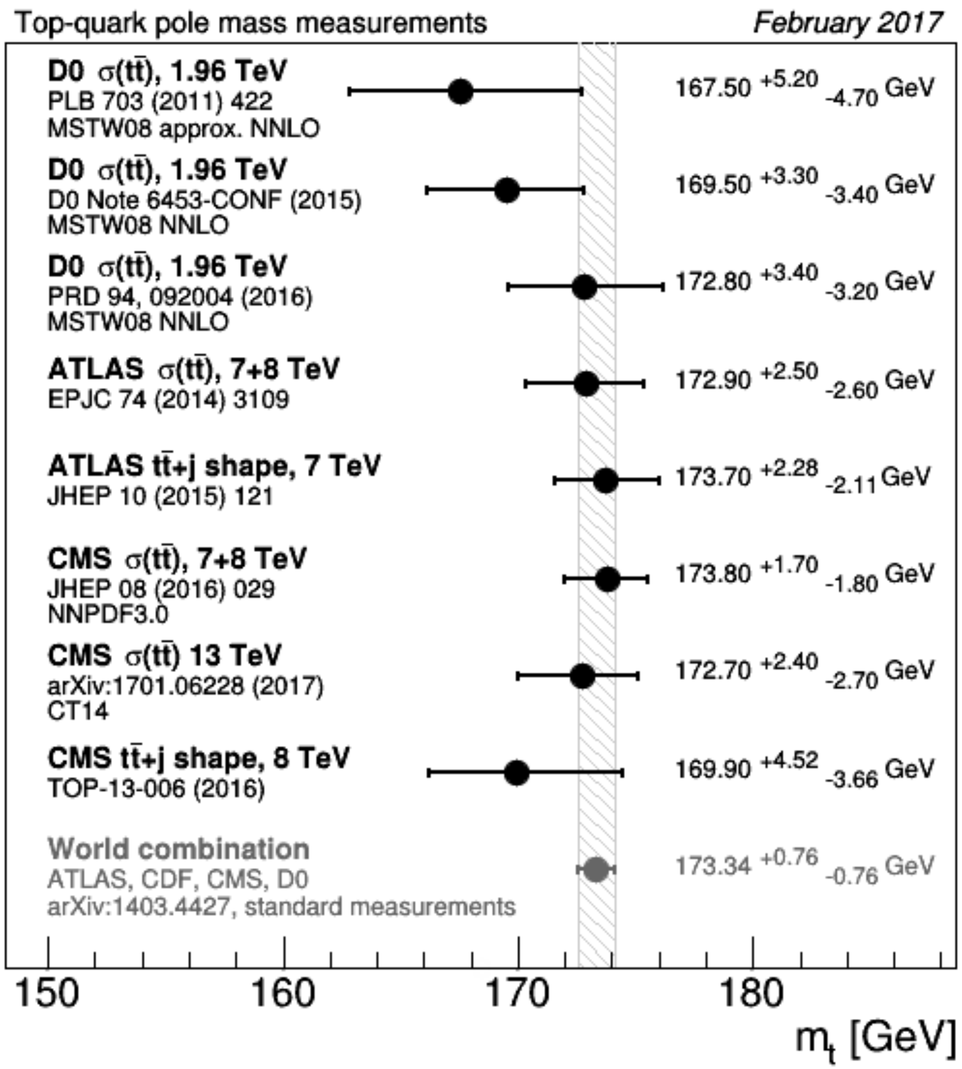
$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}} \qquad m_0 = 170 \text{ GeV}$$

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

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

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

Pole Mass Measurements



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 reconstruction analyses but they do yield a theoretically simpler mass observable

Summary: Direct and Indirect Measurements

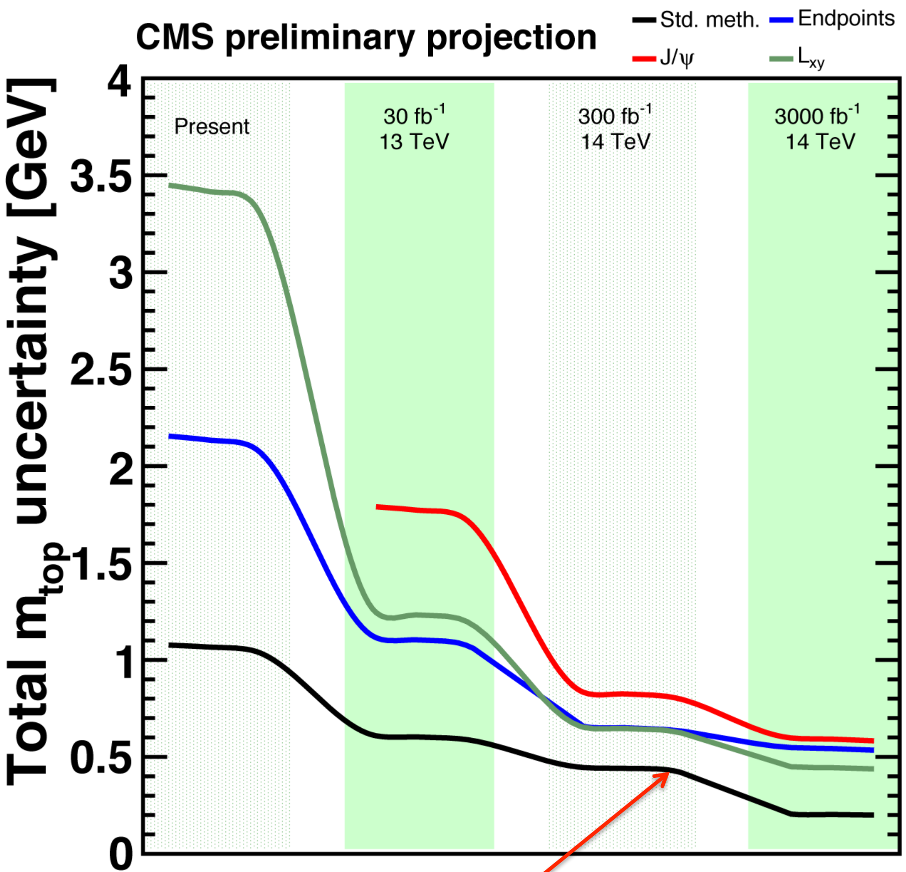
Significant improvement in precision achieved over the last 2 years.

Improved understanding of the limitations of the hard and soft QCD modeling are critical to future progress. New analyses using the data from Run 2 and the use of differential and double differential studies may help here.

It is not expected that the gain from combining the LHC and Tevatron results will be as significant as was obtained from the first LHC and World Average analyses in 2014.
Work on updating these analyses is in progress.

Indirect measurements of the pole mass have reached a precision of ~1.8 GeV. These are limited by beam, pdf and α_s uncertainties.
They should benefit from the higher statistics provided by Run 2.

Future Prospects (2013)



2013 ECFA
HL LHC Study

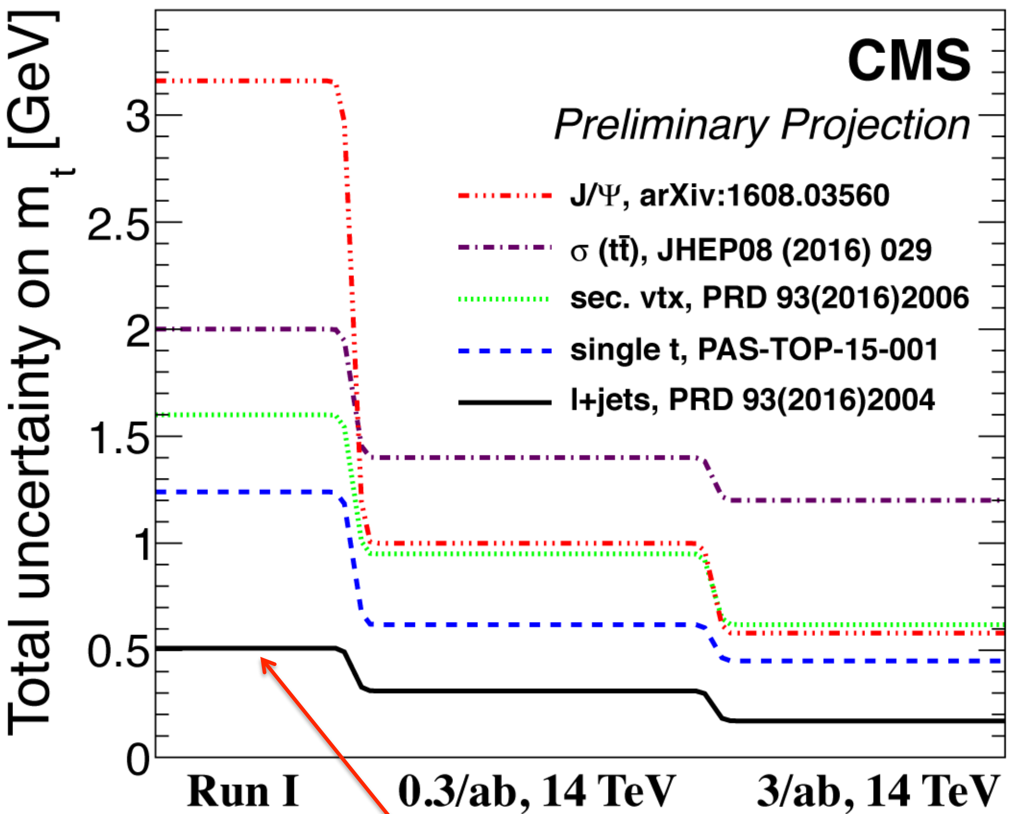
CMS PAS FTR-13-017

Curves are for single measurements using different techniques

today we are here

Integrated Luminosity ~ 20 fb^{-1} at 8 TeV

Future Prospects (2016)



2016 ECFA
HL LHC Study

CMS PAS FTR-16-006

Curves are for single measurements using different techniques

today we are here

'Standard Analysis' techniques → may be able to reach a precision ~ Λ_{QCD} using 3 ab^{-1} of data

Summary: Future Prospects

Precision of 500 MeV was the sensitivity expected for the end of Run II.
We have already achieved this using significantly less data.

From the current CMS projections it looks possible to achieve a
precision of ~ 300 MeV
for the experimental measureable, m_t at the LHC
(~ 0.3 ab^{-1} of data at 14 TeV).

The projections use current knowledge, based on the completed Run 1 analyses,
and preliminary studies using the 13 TeV data from Run 2.
These also assume the ability to start constraining some of the theory
uncertainties by using the data.

At the HL LHC with ~ 3 ab^{-1} this could be improved to
~ 100-200 MeV

This assumes further improvements both from theory and experiment.

Conclusions

A lot of progress has been made.

There is an impressive collection of top quark mass measurements from both the LHC and the Tevatron. A precision O(500 MeV) has been achieved, and the measurements show very good consistency.

For CMS, work on the Run I analyses is completed and preliminary results from Run II will be available soon. However, it will probably be some time before they are competitive with the Run I results.

On the longer term, an update of the LHC combined result is in progress and further significant improvements in precision may be possible using data from the LHC and HL LHC.

CMS Run 1 Legacy Result

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