Top quark mass at Tevatron and LHC

On behalf of ATLAS, CDF, CMS and D0 collaborations

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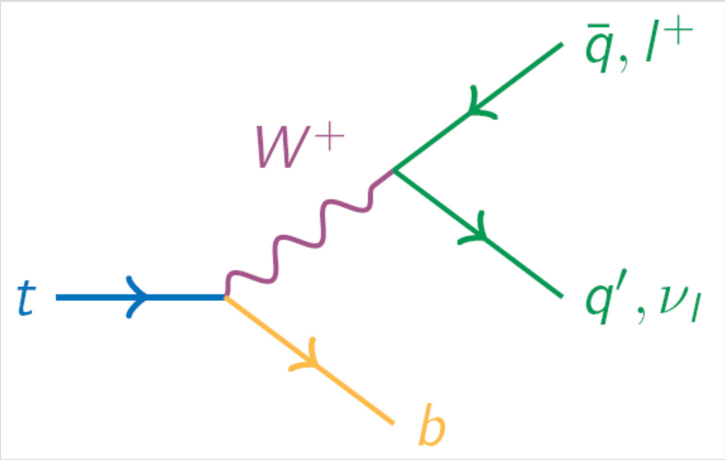
Topics in This Talk

- Motivation for the top quark mass measurements
- Some top quark mass implications
- Direct top mass measurements at Tevatron
- Direct top mass measurements at LHC
- Top quark pole mass measurements
- Alternative methods of top mass measurement

Top quark mass: Motivation

- The top quark mass (m_{top}) is one of the fundametal SM parameters.
- Its precise value provides a key input to global EW fit $\Rightarrow$ test of internal consistency of the SM.



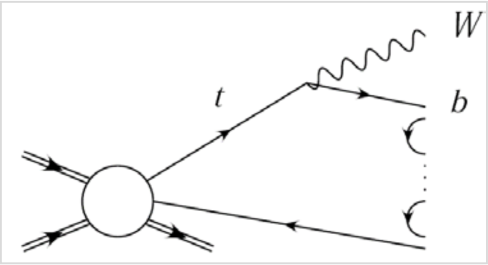
- Its value leads to a significant constraints on stability of the EW vacuum.
- it has a significant impact on cosmological models with inflation

- A better understanding between the measured top mass and a well defined renormalization scheme for the top mass is needed.

What is the Top Quark Mass ?

Top quark pole mass: corresponds to pole in the full top quark propagator –

- ✓ top is unstable – pole is complex: $\boldsymbol{m_{top} + i\Gamma_{top}}$
- ✓ Top is colored object - due to confinement its mass uncertainty $\sim\Lambda_{\mathrm{QCD}}$ (non-perturb. effects)



Pole mass is close to invariant mass of the top decay products.
Ambiguities: extra radiation, color reconnection and hadronization – at least one quark not coming from top decay is trapped by *b*-quark.

A. Hoang, arXiv.1412.3649

Measured mass vs short distance mass

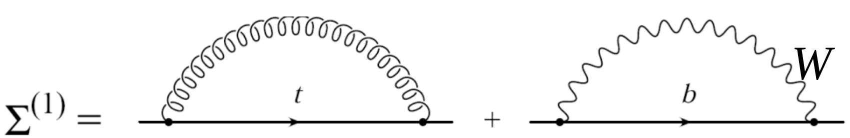
$$m_{t,MC} = m_{t,MSR}(R = 1\mathrm{GeV}) + \Delta_{t,MSR}(R = 1\mathrm{GeV}), \quad \Delta_{t,MSR}(1\mathrm{GeV}) \sim O(1\mathrm{GeV})$$

Pole mass vs short distance mass perturbatively (+ non-perturb. corrections):

$$\boldsymbol{m}_{pole} - \boldsymbol{m}_{MSR}(\boldsymbol{R}) = \boldsymbol{R}\Big[\underbrace{0.4244\,\boldsymbol{\alpha}_s(\boldsymbol{R}) + 0.8345\,\boldsymbol{\alpha}_s^2(\boldsymbol{R}) + 2.368\,\boldsymbol{\alpha}_s^3(\boldsymbol{R})}\cdots\Big]$$

Scale $R < \bar{m}, \gg \Lambda_{QCD}$

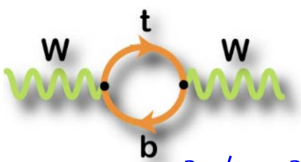
top self energy Σ pert. expanded in α_s

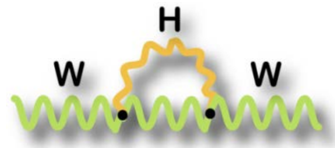


On some top quark mass implications

SM consistency test

Radiative corrections to W-boson propagator:

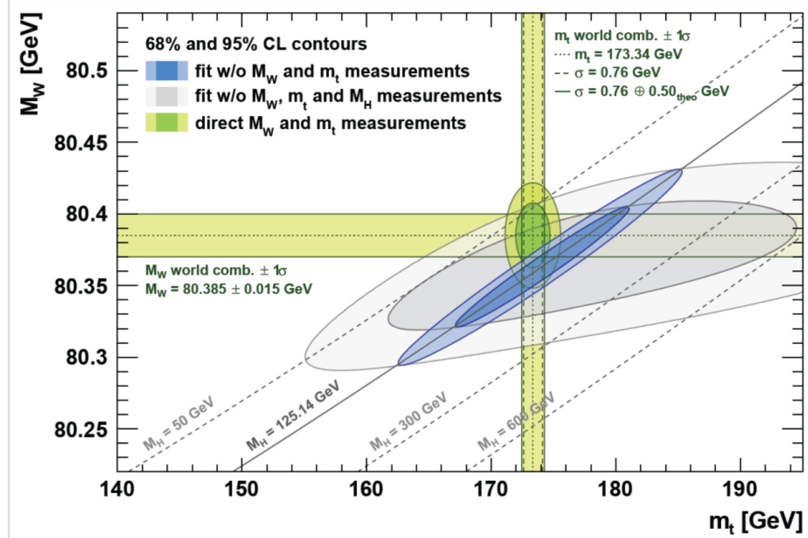




$\Delta\rho \sim m_t^2 / M_W^2$ $\qquad (\Delta r)_{nl} \propto \ln M_H^2 / M_Z^2$

$\Rightarrow$ Masses m_{top}, M_W and M_H are bounded

EW precision data: Gfitter used for the global fit (http://project-gfitter.web.cern.ch/project-gfitter/)

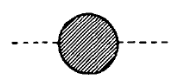


Stability of EW vacuum

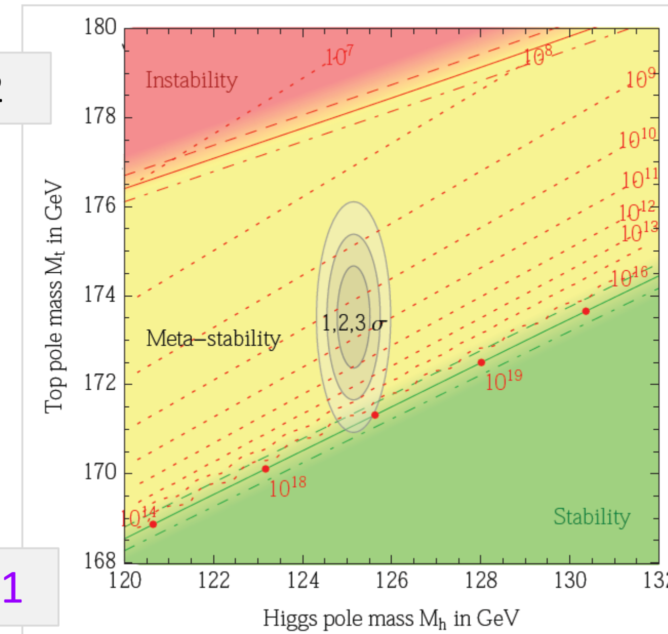
Degrassi et al., arXiv:1405.6852

Higgs quartic coupling λ scale evolution:

a decrease due to **top loop corrections**



- slope of λ strongly depends on m_{top}
- change of λ sign t $\mu = 10^{10}$-10^{11} GeV
- $\lambda < 0 \equiv$ meta-stability of vacuum.



c.f. s.31

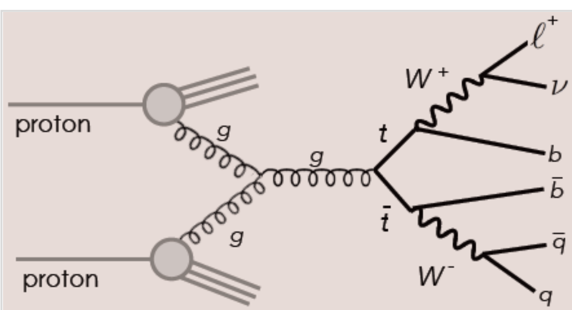
Top quark mass reconstruction

The top-quark mass is presently inferred:

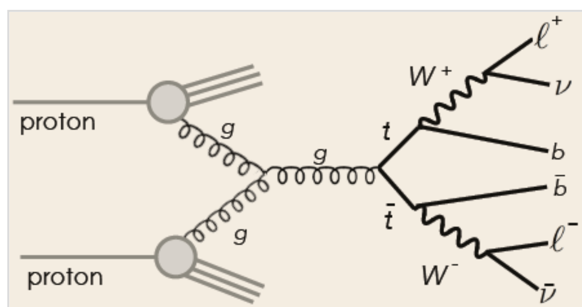
- ✓ by direct kinematical reconstruction of the invariant mass of its decay products *via* matrix element or template method ...
- ✓ by its relation to the top-quark pair production cross section

Observable sensitive on top quark mass is reconstructed in:

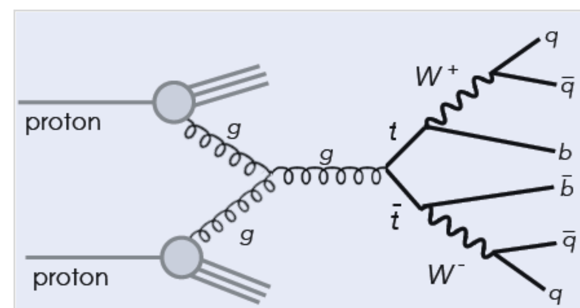
- Lepton + jets (semileptonic) channel
- Dileptonic channel
- All hadronic (all jets) channel



Lepton+jets channel



Dileptonic channel

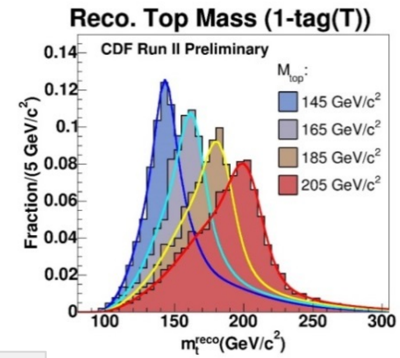


All hadronic channel

Top quark mass : different approaches

Template method:

PRD 63, 032003 (2001)



- ✓ uses **observable(s) sensitive to top quark mass** (e.g. reconstructed m_t from decay products)
- ✓ More than one observable can be used (to m_t also JES)
- ✓ likelihood fit to data based on templates for S + B.

Matrix element method:

K. Kondo, J. Phys. Soc. Jap. 57, 4126 (1988).

evaluates **event-by-event probability** based on the full event kinematics

- ✓ signal probability:

measured 4-momenta

Matrix el.

partonic final-state 4-momenta

$$P_{t\bar{t}}\left(\vec{x}; m_t\right) = \frac{1}{\sigma_{t\bar{t}}\left(m_t\right)} \sum_{\text{flavors}} \int dq_1 dq_2 d\vec{y} \, \frac{d\sigma\left(p\bar{p} \to tt \to \vec{y}\right)}{d\vec{y}} \cdot f\left(q_1\right) f\left(q_2\right) \cdot W\left(\vec{x}, \vec{y}\right)$$

PDFs resolution

- ✓ Top mass extracted from global likelihood fit to data based on P_{tt} and P_{bkg}

Ideogram method:

Eur. Phys. J. C **2**,581 (1998) PRL **98,** 142001 (2007)

Combines ME and template approaches – based on event-by event likelihood – using top mass templates and including all parton jet assignements with corresponding weights.

Methods based on Mellin moments:

PRD 81, 032002 (2010) TOP-16-002

uses b-decay transverse distance, Lxy, lepton kinematics,... without calorimetric info.

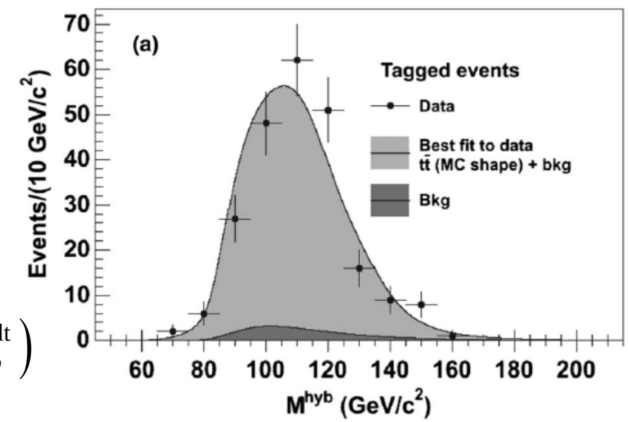
CDF: top quark mass in dilepton channel

Measurement of m_{top} in dilepton channel,

$$p\bar{p}, \quad \sqrt{s} = 1.96\ \text{TeV}, \quad \int L dt = 9.1\ \text{fb}^{-1}$$

Template technique applied using two observables:

- ✓ $M_t^{reco} \equiv$ top decay product inv. mass ($\ell\nu b$) - ϕ-scan over both ν momenta; a weight added to each value of M_t^{reco} to find preferred M_t^{reco} value.
- ✓ „alternative" mass: $M_{lb}^{alt} = \sqrt{(l_1 \cdot b_1)(l_2 \cdot b_2)/E_{b_1} \cdot E_{b_2}}$ jet energies in denominator „cancels" JES-dependence
- ✓ Signal and background templates of $M^{hyb} \left(= wM_t^{reco} + (1-w)M_{lb}^{alt}\right)$ used (function of m_{top}, n_s and n_b – # of signal and bkg evnts)



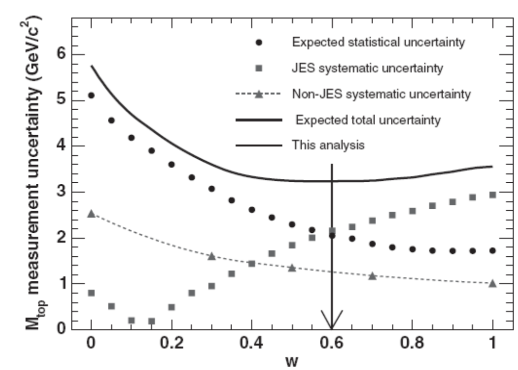
Likelihood fit to data events, based on M^{hyb} templates with w = 0.6, gives:

$m_{top} = 171.5 \pm 1.9_{stat} \pm 2.5_{syst}$

An improvement over the previous result (m_{top}=170.3 $\pm$ 2.0$_{stat}$ $\pm$3.1$_{syst}$)

Source	Uncertainty (GeV/c^2)
Jet-energy scale	2.2
NLO effects	0.7
Monte Carlo generators	0.5
Lepton-energy scale	0.4
Background modeling	0.4
Initial- and final-state radiation	0.4
gg fraction	0.3
b-jet-energy scale	0.3
Luminosity profile	0.3
Color reconnection	0.2
MC sample size	0.2
Parton distribution functions	0.2
b-tagging	0.1
Total systematic uncertainty	2.5
Statistical uncertainty	1.9
Total	3.2

Weight w found by minim. of the total uncertainty



PRD92, 032003(2015)

CDF: top quark mass summary

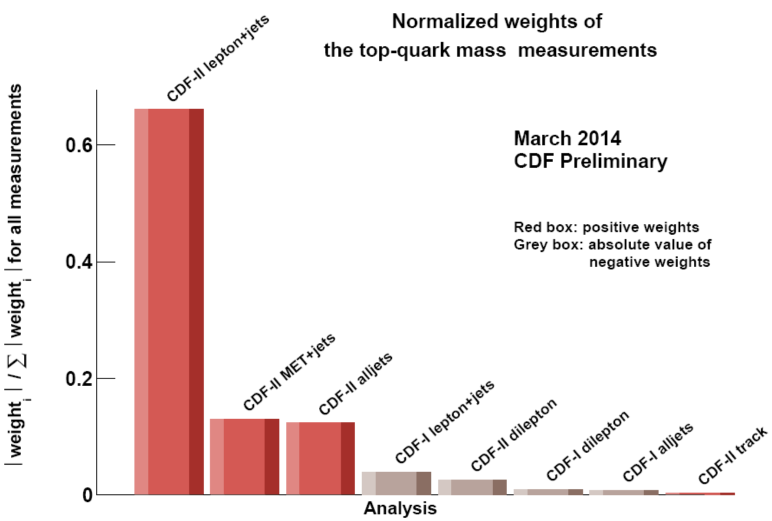
- Run I and Run II top mass measurements based on datasets of 8.7-9.3 fb^{-1}
- Correlations of the uncertainties taken into account.

Conf-note-11080

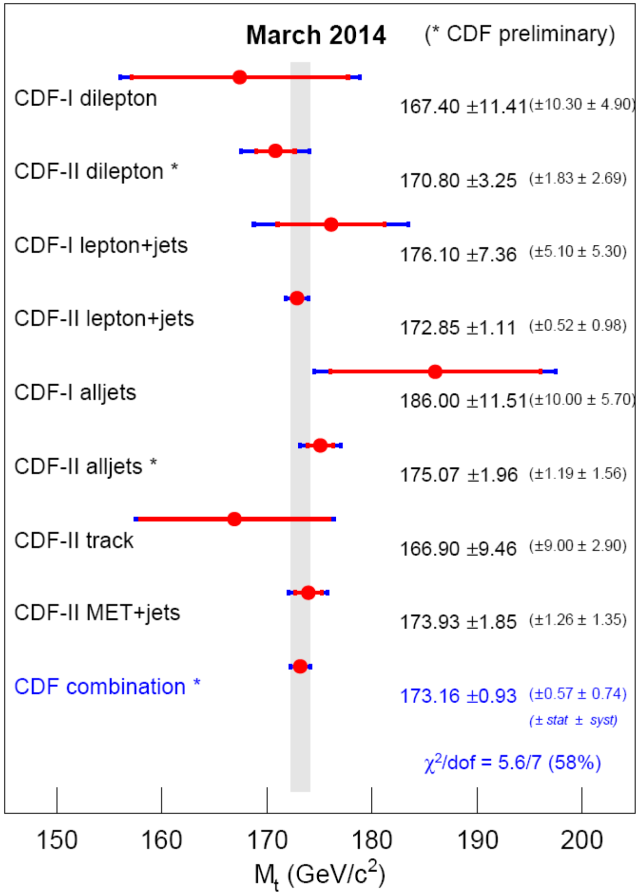
$M_t^{\ell\ell}$: PRD92, 032003(2015) not included !

CDF Preliminary

Final State	M_t [GeV/c^2]	Correlations			
		$M_t^{\ell+\mathrm{jets}}$	$M_t^{\ell\ell}$	M_t^{alljets}	M_t^{MET}
$M_t^{\ell+\mathrm{jets}}$	172.51 ± 1.02	1.00			
$M_t^{\ell\ell}$	169.40 ± 2.76	0.40	1.00		
M_t^{alljets}	174.99 ± 1.90	0.25	0.26	1.00	
M_t^{MET}	173.64 ± 1.79	0.25	0.20	0.13	1.00



Mass of the Top Quark



CDF average: $m_{top} = 173.16 \pm 0.93$ GeV

Rel. precision = 0.54%

D0 top quark mass in dilepton channel

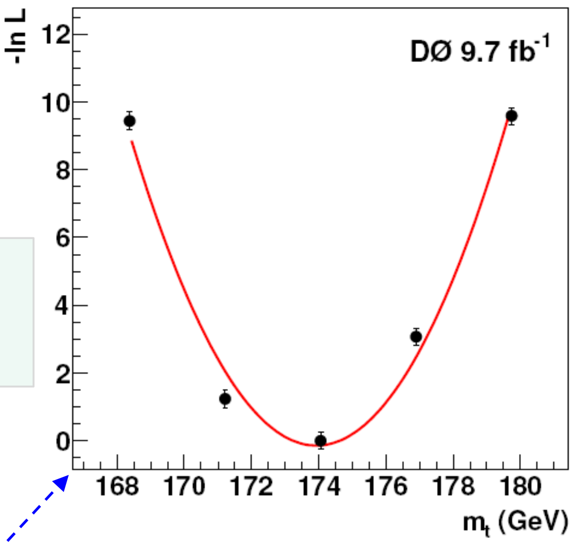
- Top mass measurement in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV corresp. to 9.7 fb^{-1}
- Matrix element technique applied to dilepton $t\bar{t}$ events

ArXiv:1606.02814

- ME technique associates to each event a probability

$$P(x, f_{t\bar{t}}, m_t) = f_{t\bar{t}} P_{t\bar{t}}(x, m_t) + (1 - f_{t\bar{t}}) P_{\text{bkg}}(x)$$

$\boldsymbol{x} \equiv$ set of observables: p_T, η, and ϕ for jets and leptons
$f_{t\bar{t}} \equiv$ fraction of $t\bar{t}$ events in data



- To extract m_t and $f_{t\bar{t}}$: likelihood fit to data, based on P

Negative log-likelihood ratio for the combined $\ell\ell$ data, after calibration, as a function of the input MC m_t.

Result: m_t = 173.93 ± 1.61 (stat) ± 0.88 (syst) GeV

Neutrino weighting dilepton [Phys. Lett. B **757**, 199 (2016)]

m_t = 173.32 ± 1.36(stat) ± 0.85(syst) GeV

Main systematics

H.O. Corrections	±0.16
ISR/FSR	±0.16
Hadronization & UE	+0.31
b-jet modelling	+0.21
PDF uncertainty	±0.20
kJES factor	∓0.46
Flavor jet response	∓0.30
b-tagging efficiency	∓0.28
…	

Top quark mass in lepton+jets channel

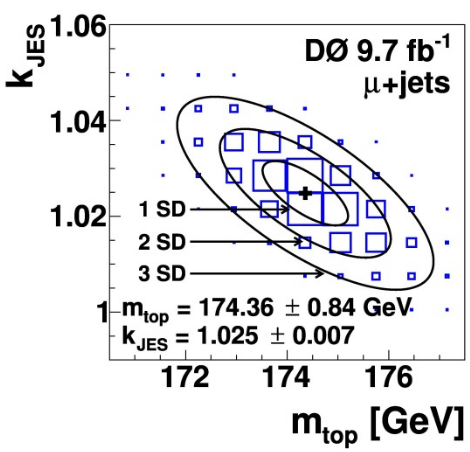
Top mass in ℓ+jets channel using $p\bar{p}$ collision data $\left(\sqrt{s} = 1.96\ \text{TeV}, \int L\,dt = 9.7\ \text{fb}^{-1}\right)$

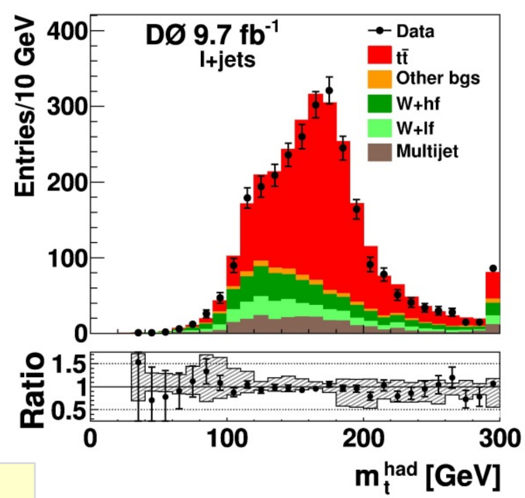
Phys. Rev. D **91**, 112003 (2015)

Matrix element technique used $\Rightarrow$
extraction of m_t through likelihood technique using signal and bkg probability densities (via ME) for each event.
Extracted also signal fraction (f_{sig}) and k_{JES}

Selection:

- = 4 jets $p_T > 20$ GeV, $|\eta| < 2.5$, leading jet $p_T > 40$ GeV
- 1 iso. lepton (*e* or μ) $p_T > 20$ GeV and $|\eta| < 1.1$ or $|\eta| < 2$
- Imbalance of $p_T > 20$ GeV





Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher-order corrections	+0.15
Initial/final state radiation	$\mp$0.06
Transverse momentum of the $t\bar{t}$ system	−0.07
Hadronization and underlying event	+0.26
Color reconnection	+0.10
Multiple $p\bar{p}$ interactions	−0.06
Heavy-flavor scale factor	$\mp$0.06
Modeling of b-quark jet	+0.09
Parton distribution functions	±0.11
Detector modeling:	
Residual jet energy scale	±0.21
Flavor-dependent response to jets	$\mp$0.16
Tagging of b jets	$\mp$0.10
Trigger	±0.01
Lepton momentum scale	±0.01
Jet energy resolution	±0.07
Jet identification efficiency	−0.01
Method:	
Modeling of multijet events	+0.04
Signal fraction	±0.08
MC calibration	±0.07
Total systematic uncertainty	±0.49
Statistical uncertainty	±0.58
Total uncertainty	±0.76

The measured top mass:

$$m_t = 174.98 \pm 0.58(\text{stat+JES}) \pm 0.49(\text{syst})\ \text{GeV}$$

$\varepsilon = 0.43\%$

Top mass – Tevatron combination

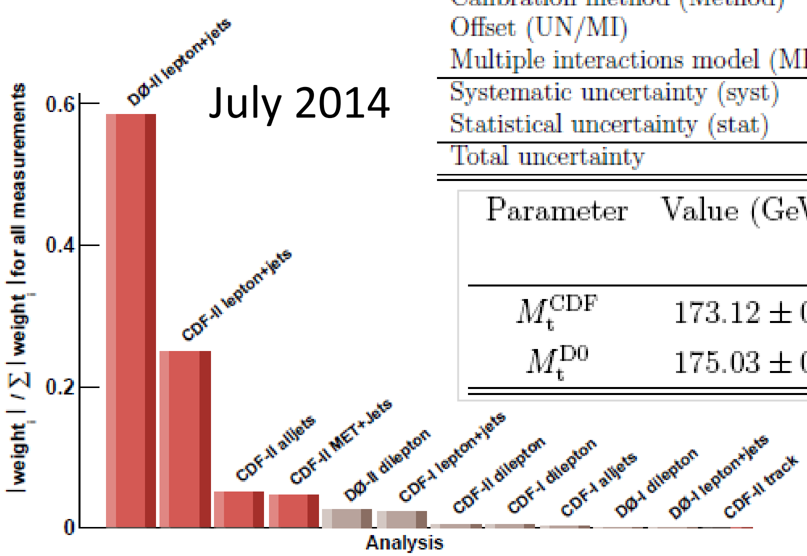
arXiv:1407.2682

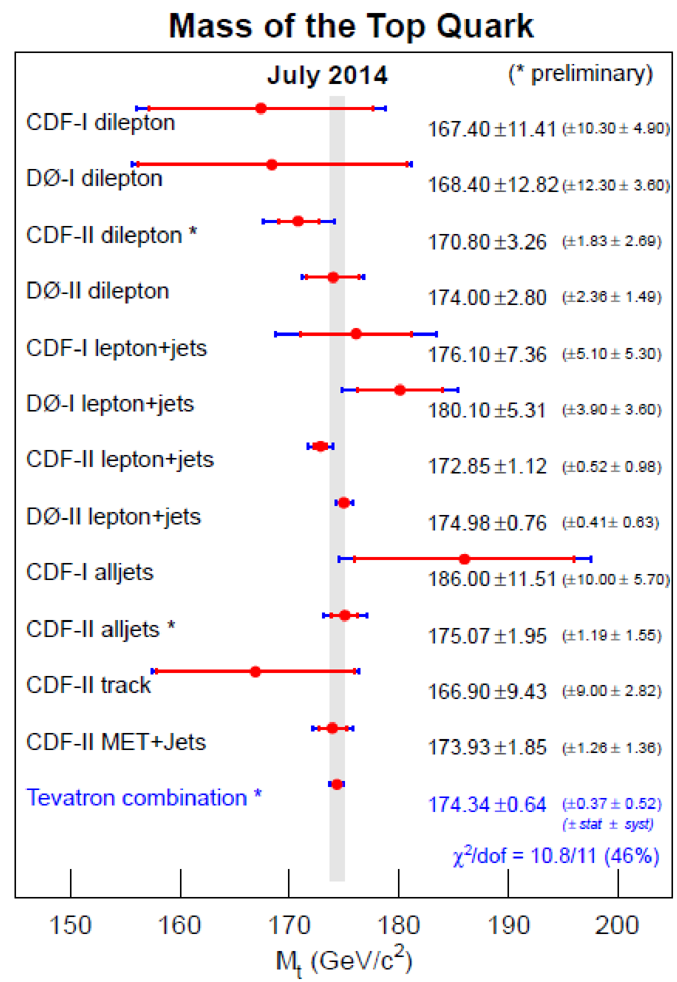
- Run I and Run II results included
- BLUE method used

Correlation between sources of uncertainty taken into account

	Tevatron combined values
M_t	174.34
In situ light-jet calibration (iJES)	0.31
Response to $b/q/g$ jets (aJES)	0.10
Model for b jets (bJES)	0.10
Out-of-cone correction (cJES)	0.02
Light-jet response (1) (rJES)	0.05
Light-jet response (2) (dJES)	0.13
Lepton modeling (LepPt)	0.07
Signal modeling (Signal)	0.34
Jet modeling (DetMod)	0.03
b-tag modeling (b-tag)	0.07
Background from theory (BGMC)	0.04
Background based on data (BGData)	0.08
Calibration method (Method)	0.07
Offset (UN/MI)	0.00
Multiple interactions model (MHI)	0.06
Systematic uncertainty (syst)	0.52
Statistical uncertainty (stat)	0.37
Total uncertainty	0.64

Parameter	Value (GeV/c^2)	Correlations M_t^{CDF}	Correlations M_t^{D0}
M_t^{CDF}	173.12 ± 0.92	1.00	
M_t^{D0}	175.03 ± 0.74	0.25	1.00





m_t = 174.34 ±0.37 (stat) ±0.52 (syst) GeV

ε = 0.37%

ATLAS: m_{top} in ℓ+jets + dilepton at 7 TeV

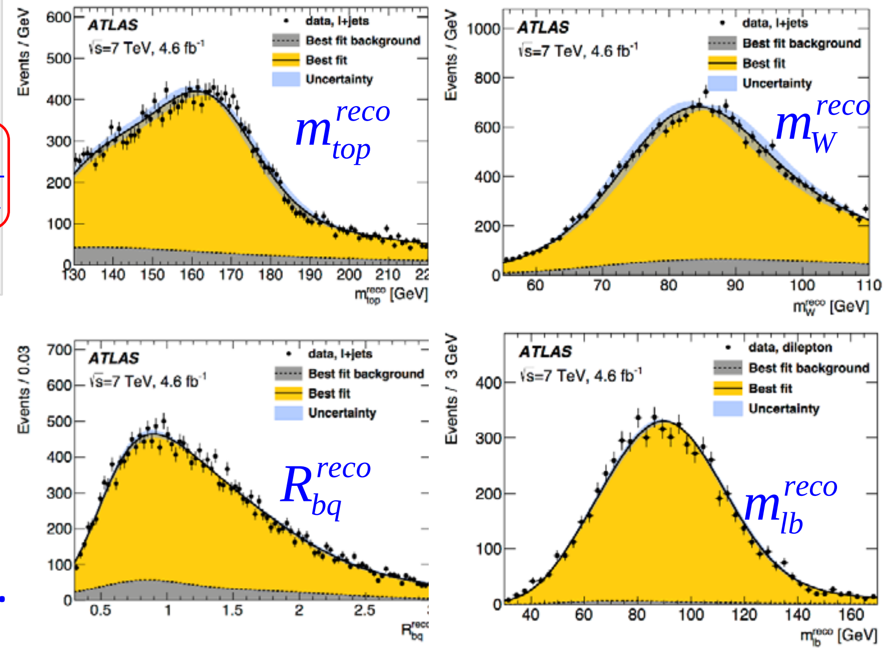
ℓ+jets: 3D template method

- $t\bar{t}$ events reconstructed by kinematic fit
- S+B templates of m_{top}^{reco}, m_{W}^{reco} and $R_{bq}^{reco} = \frac{\langle p_T^b \rangle}{\langle p_T^{light} \rangle}$ used in unbinned likelihood fit to data.

Sensitive to m_{top}, JSF and bJSF

Output of likelihood fit: $\boldsymbol{m_{top}}$, JSF, bJSF, $\boldsymbol{f_{bkg}}$

JSF and bJSF: to improve systematics on (b)JES.



$$m_{top}^{\ell+jets} = 172.33 \pm 0.75(\text{stat+JSF+bJSF}) \pm 1.02(\text{syst})\ \text{GeV}$$

$$\int L\,dt = 4.6\,\text{fb}^{-1}$$

EPJC (2015)75:330

dilepton: 1D template method

- m_{top} sensitive observable: m_{lb}^{reco} (ℓ - b-jets invariant mass)
- unbinned likelihood fit to data based on m_{lb}^{reco} S+B distributions
- Output of the likelihood fit: $\boldsymbol{m_{top}}$, $\boldsymbol{f_{bkg}}$

$$m_{top}^{diL} = 173.79 \pm 0.54(\text{stat}) \pm 1.30(\text{syst})\ \text{GeV}$$

Combination (BLUE method)

$$m_{top}^{comb} = 172.99 \pm 0.91\ \text{GeV}$$

ATLAS: m_{top} in dilepton channel at 8 TeV

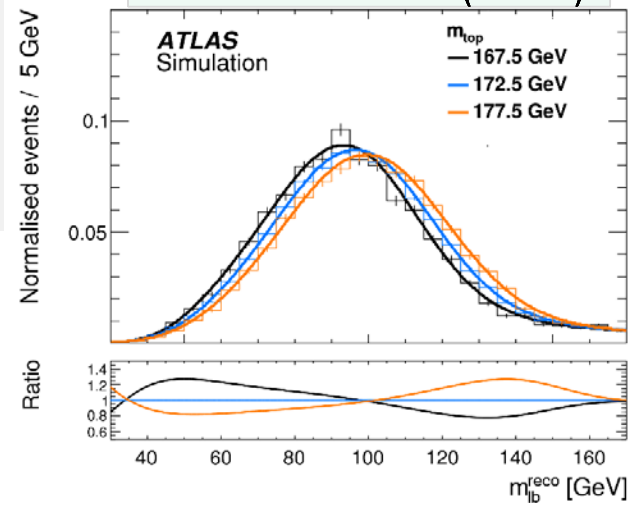
Dilepton at 8 TeV: the same strategy and template method as at 7 TeV with the observable m_{lb}^{reco} used.

- Refined event selection
- Single top with the same lepton final states included

Signal m_{lb}^{reco} templates for different input m_{top} →

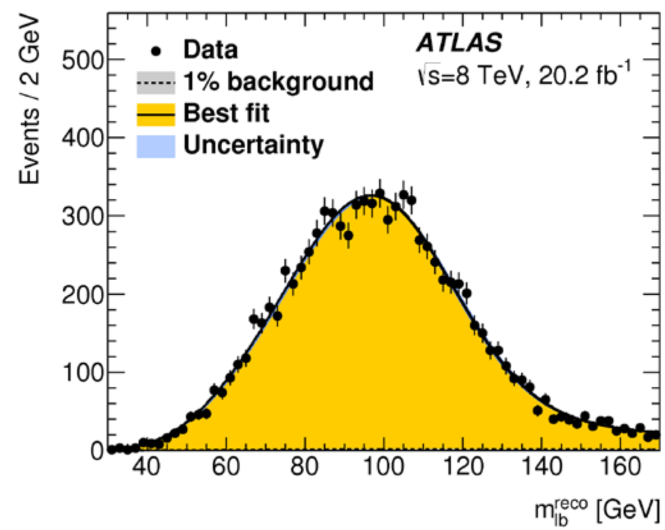
Output of the likelihood fit to data: $\boldsymbol{m_{top}}$, $\boldsymbol{f_{bkg}}$

arXiv:1606.02179 (toPLB)



Main systematics (GeV):

✓ Hadronization	0.22
✓ ISR/FSR	0.23
✓ JES	0.54
✓ Relative b-to-light JES	0.30



Dilepton channel $\boldsymbol{m}_{top}$ measurement (8 TeV, 20.2fb^{-1}):

$$m_t^{2l} = 172.99 \pm 0.41(\text{stat}) \pm 0.74(\text{syst}) \text{ GeV}$$

Combination with 7 TeV ℓ +jets and 2ℓ:

$$m_t = 172.84 \pm 0.34(\text{stat}) \pm 0.61(\text{syst}) \text{ GeV} = 172.84 \pm 0.70 \text{ GeV}, \quad \sigma(m_t)/m_t = 0.40\%$$

ATLAS: m_{top} in all-jet channel at 7 TeV

- Template method with kinematic fit used to reconstruct fully hadronic $t\bar{t}$ events
- Top mass sensitive observable: $R_{3/2}=m_{jjj}/m_{jj}$

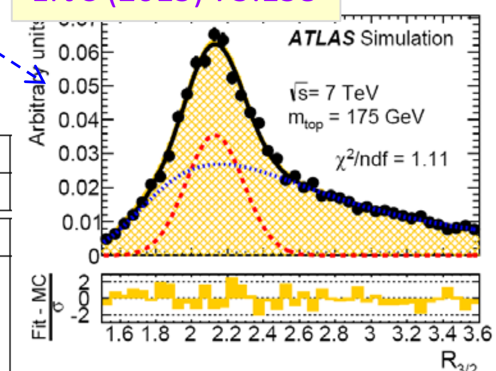
$R_{3/2}$ is used rather than recon. top mass (m_{jjj}) to reduce the systematic effects common to reconstructed top and W (m_{jj}) masses.

- Large multijet background → estimated from data (ABCD method).
- Binned Likelihood fit output: m_t and f_{bkg}

Event selection

Jet-based trigger
≥ 6 jets with p_T > 30 GeV and $|\eta|$ < 2.5
≥ 5 jets with p_T > 55 GeV and $|\eta|$ < 2.5
R > 0.6 for jet pairs with p_T > 30 GeV
Jet vertex fraction JVF> 0.75
Reject events w. isol. Electrons, E_T > 25 GeV
Reject events w. isol. muons with p_T > 20 GeV
Exactly 2 b-tagged jets among 4 leading jets
Missing E_T significance $E_T^{miss}[\mathrm{GeV}]/\sqrt{H_T[\mathrm{GeV}]} < 3$
Centrality C > 0.6

EPJC (2015) 75:158



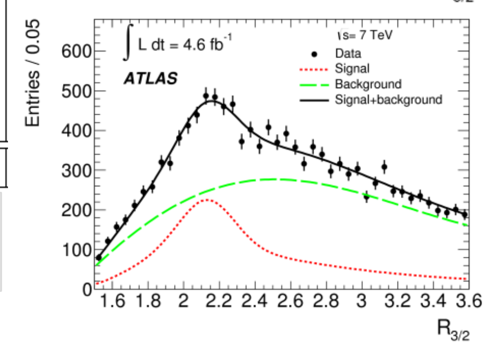
Systematics

Signal modelling:	Δm_t [GeV]
Method calibration	0.42
Trigger	0.01
Signal MC generator	0.30
Hadronisation	0.50
Fast simulation	0.24
Colour reconnection	0.22
Underlying event	0.08
ISR and FSR	0.22
Proton PDF	0.09
Pile-up	0.02

Background modelling:	Δm_t [GeV]
Multijet background	0.35
Jet measurements:	Δm_t [GeV]
Jet energy scale (see Table ??)	0.51
b-jet energy scale	0.62
Jet energy resolution	0.01
Jet reconstruction efficiency	0.01
b-tag efficiency and mistag rate	0.17
Soft contributions to missing energy	0.02
JVF scale factors	0.02
Total systematic uncertainty	1.22

$$m_t = 175.1 \pm 1.4\ (\mathrm{stat.}) \pm 1.2\ (\mathrm{syst.})\ \mathrm{GeV}$$

$$\int L\,dt = 4.6\,\mathrm{fb}^{-1}$$

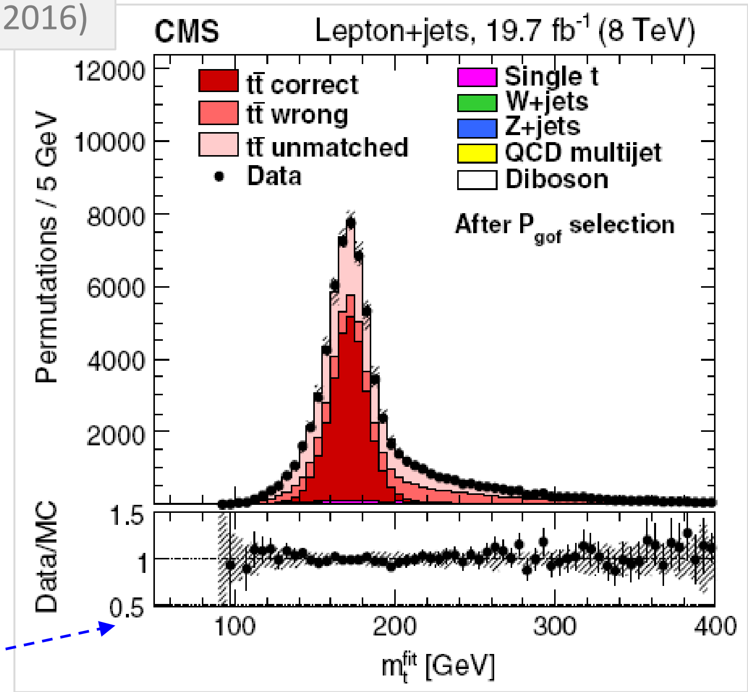


CMS: top mass in lepton+jets at 8 TeV

Phys. Rev. D93, 072004 (2016)

Ideogram technique used:

- It is a joint maximum likelihood fit to data – the fit output is the top mass m_t and (optionally) JSF.
- The likelihood fit is based on event likelihood created using m_t^{fit} and m_W^{reco} templates obtained from simulation for different m_t and JSF.
- Observables for measuring m_t and JSF, masses m_t^{fit} and m_W^{reco}, are estimated by a kinematic fit for each event and different parton-jet assignement



The reconstructed fitted top quark masses taking into account the goodness-of-fit for each parton-jet assignement.

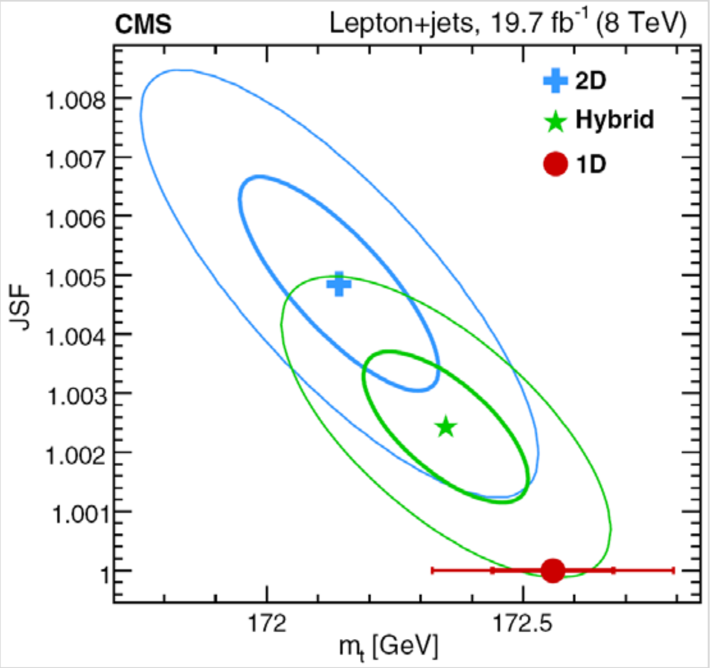
Systematics:

- ✓ Experimental effects: the uncertainties arising from calibration and resolution of the CMS detector (JES, lepton energy scale, JER, trigger efficiency, pileup, background).
- ✓ Theoretical and modelling uncertainties: PDFs, renormalization and factorization scales, ME-PS matching threshold, ME generator, top p_T uncertainty.

CMS: top mass in lepton+jets

Approaches used in l+jets channel:

- 2D approach: simultaneous fit to m_t and JSF.
- 1D approach: fit only to m_t (JES determined from jet energy correction $\Rightarrow$ JSF = 1)
- Hybrid approach: prior knowledge about JES used but Gaussian costraint applied centered at 1 with variance depending on JES uncertainty.



Results at 8TeV, integrated luminosity of 19.7 fb^{-1}

2D ideogram fit (combined e + μ channels):

$$m_t^{2D} = 172.14 \pm 0.19(\text{stat+JSF}) \pm 0.59(\text{syst})\ \text{GeV},$$
$$JSF^{2D} = 1.005 \pm 0.002\ (\text{stat}) \pm 0.007(\text{syst})\ .$$

1D and hybrid analyses:

$$m_t^{1D} = 172.56 \pm 0.12\ (\text{stat}) \pm 0.62\ (\text{syst})\text{GeV},$$
$$m_t^{hyb} = 172.35 \pm 0.16\ (\text{stat+JSF}) \pm 0.48\ (\text{syst})\text{GeV},$$

Most precise results: hybrid approach – total uncertainty of 0.51 GeV.

ε = 0.30%

Top mass in all-jets and dilepton at 8 TeV

PRD 93, 072004 (2016)

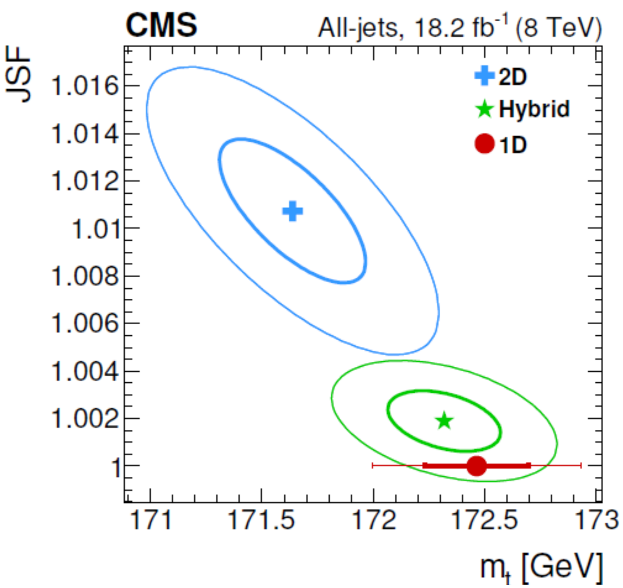
All jet channel (8 TeV, L=19.7 fb^{-1})

2D ideogram analysis:

$$m_t^{2D} = 171.64 \pm 0.32(\text{stat+JSF}) \pm 0.95(\text{syst})\,\text{GeV},$$
$$\text{JSF}^{2D} = 1.011 \pm 0.003(\text{stat}) \pm 0.011(\text{syst}).$$

1D and hybrid analyses:

$$m_t^{1D} = 172.46 \pm 0.23(\text{stat}) \pm 0.62\ (\text{syst})\,\text{GeV},$$
$$m_t^{hyb} = 172.32 \pm 0.25(\text{stat+JSF}) \pm 0.59(\text{syst})\,\text{GeV}.$$



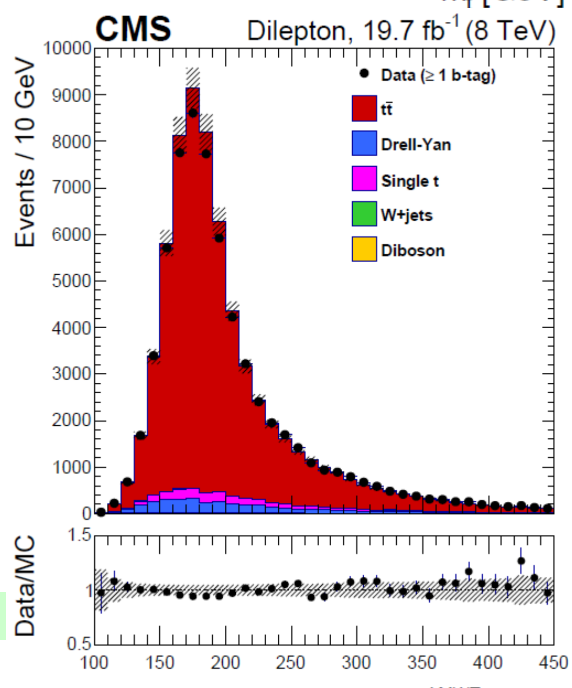
Dilepton channel (8 TeV, L=19.7 fb^{-1})

Analytical matrix weighting technique used

Dominant systematics: the factorization and renormalization scale.

Very small bacground

$$m_t = 172.82 \pm 0.19(\text{stat}) \pm 1.22\ (\text{syst})\,\text{GeV}.$$



CMS top mass summary at 7 and 8 TeV

PRD 93, 072004 (2016)

Correlations between input measurements

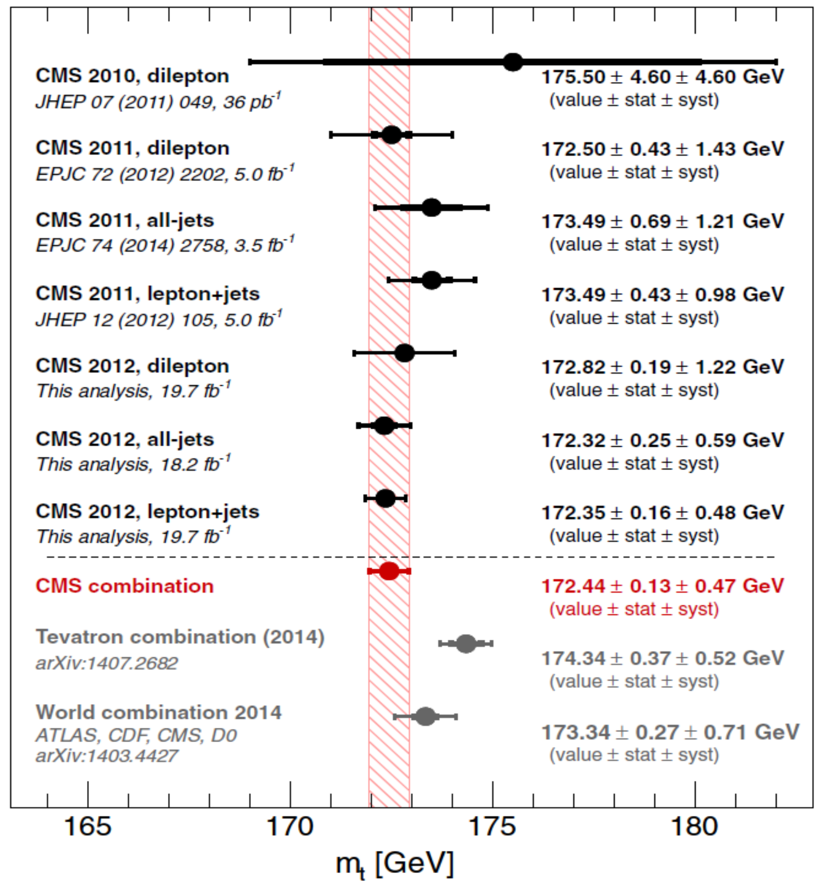
		2010	2011			2012		
		dilepton	dilepton	lepton+jets	all-jets	dilepton	lepton+jets	all-jets
2010	dilepton	1.00						
2011	dilepton	0.15	1.00					
	lepton+jets	0.09	0.37	1.00				
	all-jets	0.10	0.62	0.31	1.00			
2012	dilepton	0.09	0.26	0.17	0.17	1.00		
	lepton+jets	0.05	0.21	0.30	0.26	0.26	1.00	
	all-jets	0.06	0.20	0.27	0.28	0.32	0.61	1.00

Combined 7 and 8 TeV result:

$$m_t = 172.44 \pm 0.13(\mathrm{stat}) \pm 0.47(\mathrm{syst})\,\mathrm{GeV}$$
$$= 172.44 \pm 0.48\,\mathrm{GeV}$$

Rel. Precision = 0.28%

The most precise measurement to date, the result is better than the 2014 world summary !!!



Top quark pole mass vs. $t\bar{t}$ cross section

- Dependence of $t\bar{t}$ cross section on top pole mass (m_t^{pole}) is used to infer m_t^{pole}
- NNLO inclusive $t\bar{t}$ cross section including NNLL soft gluon resummations is used
- Well-defined mass scheme

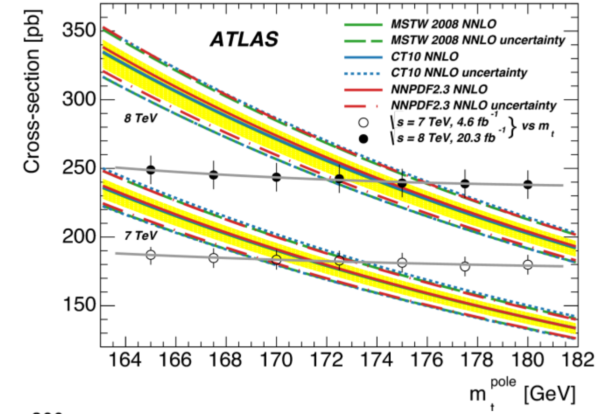
ATLAS: top pole mass from inclusive $t\bar{t}$ cross section

ATLAS: $\sigma_{t\bar{t}}$ measurements at 7 and 8 TeV with lumi 4.6 and 20.3 fb^{-1}, resp.

Theory: $\sigma_{t\bar{t}}$ available at NNLO in α_S including the NNLL soft gluon resummations.
Dependence of $\sigma_{t\bar{t}}$ on top pole mass is used to extract the mass

[EPJC74(2014)3109]

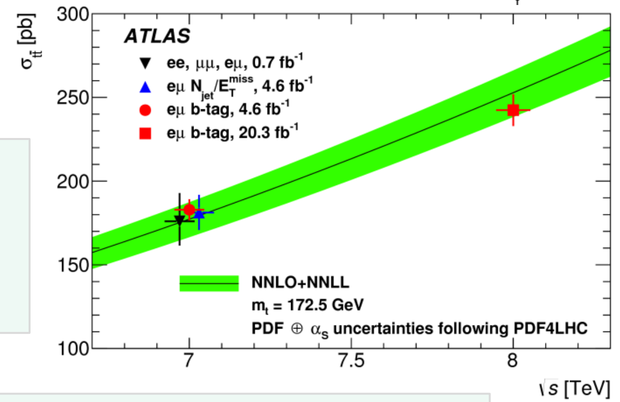
Dilepton channel with e-μ as decay products



Uncertainty	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	
$\sqrt{s}$	7 TeV	8 TeV
Data statistics	1.69	0.71
$t\bar{t}$ modelling and QCD scale	1.46	1.26
Parton distribution functions	1.04	1.13
Background modelling	0.83	0.83
Lepton efficiencies	0.87	0.88
Jets and b-tagging	0.58	0.82
Misidentified leptons	0.41	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	2.27	2.26
Integrated luminosity	1.98	3.10
LHC beam energy	1.79	1.72
Total uncertainty	3.89	4.27

PDFs: MSTW2008, CT10 and NNPDF2.3

The measured $t\bar{t}$ cross sections at √s=7 and 8 TeV for m_t^{ref} = 172.5:



$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3 \text{ pb } \left(\sqrt{s} = 7 \text{ TeV}\right)$$

$$\sigma_{t\bar{t}} = 242.9 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2 \text{ pb } \left(\sqrt{s} = 8 \text{ TeV}\right)$$

Extracted top pole mass: $m_t^{pole} = 172.9^{+2.5}_{-2.6}$ GeV

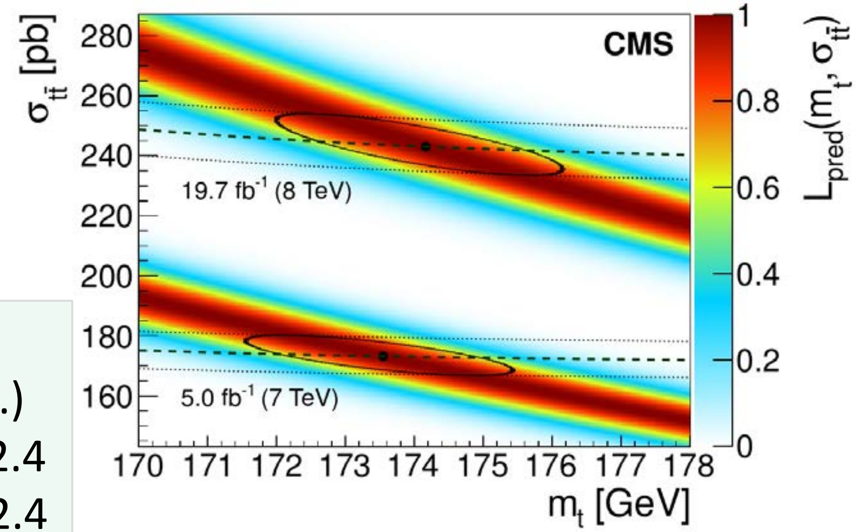
ε = 1.45%

CMS: top pole mass from inclusive $t\bar{t}$ cross section

[arXiv:1603.02303]

CMS: m_t^{pole} extracted from $\sigma_{t\bar{t}}$ measurements at 7 and 8 TeV, 5.0 and 19.7 fb^{-1} resp.

- Measurement of $\sigma_{t\bar{t}}$ based on PDF set NNPDF3.0 and α_S=0.118 ± 0.001
- PDFs CT14 and MMHT2014 gives consistent results



Source	Uncertainty [%] 7 TeV	8 TeV
Trigger	1.3	1.2
Lepton ID/isolation	1.5	1.5
Lepton energy scale	0.2	0.1
Jet energy scale	0.8	0.9
Jet energy resolution	0.1	0.1
tW/$\bar{t}$W	1.0	0.6
DY	1.4	1.3
$t\bar{t}$ bkg.	0.1	0.1
$t\bar{t}$V	0.1	0.1
Diboson	0.2	0.6
W+jets/QCD	0.1	0.2
b-tag	0.5	0.5
Mistag	0.2	0.1
Pileup	0.3	0.3
μ_R, μ_F scales	0.3	0.6
ME/PS matching	0.1	0.1
MADGRAPH vs POWHEG	0.4	0.5
Hadronisation (JES)	0.7	0.7
Top quark p_T modelling	0.3	0.4
Colour reconnection	0.1	0.2
Underlying event	0.1	0.1
PDF	0.2	0.3
Integrated luminosity	2.2	2.6
Statistical	1.2	0.6

Event selection ~ ATLAS dilepton eμ pairs (op. ch.)
Leptons: p_T>20 GeV, |η|<2.4
b-jets: p_T>30 GeV, |η|<2.4

- Measured $t\bar{t}$ cross sections:

$$\sigma_{t\bar{t}} = 173.9 \pm 2.1(\text{stat.})^{+4.5}_{-4.0}(\text{syst.}) \pm 3.8(\text{lumi})\ \text{pb}\ \left(\sqrt{s} = 7\ \text{TeV}\right)$$

$$\sigma_{t\bar{t}} = 244.9 \pm 1.4(\text{stat.})^{+6.3}_{-5.5}(\text{syst.}) \pm 6.4(\text{lumi.})\ \text{pb}\ \left(\sqrt{s} = 8\ \text{TeV}\right)$$

- Extracted top pole mass (combining 7 and 8 TeV results):

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

ε = 1.0%

Previous results: $m_t^{pole} = 176.8^{+3.0}_{-2.8}$ GeV

Top pole mass from D0

The m_t^{pole}: from the inclusive $t\bar{t}$ cros section of the RUN II data based on ℓ+jets and dilepton channels at √s=1.96 TeV, L=9.7 fb^{-1} [arXiv:1605.06168].

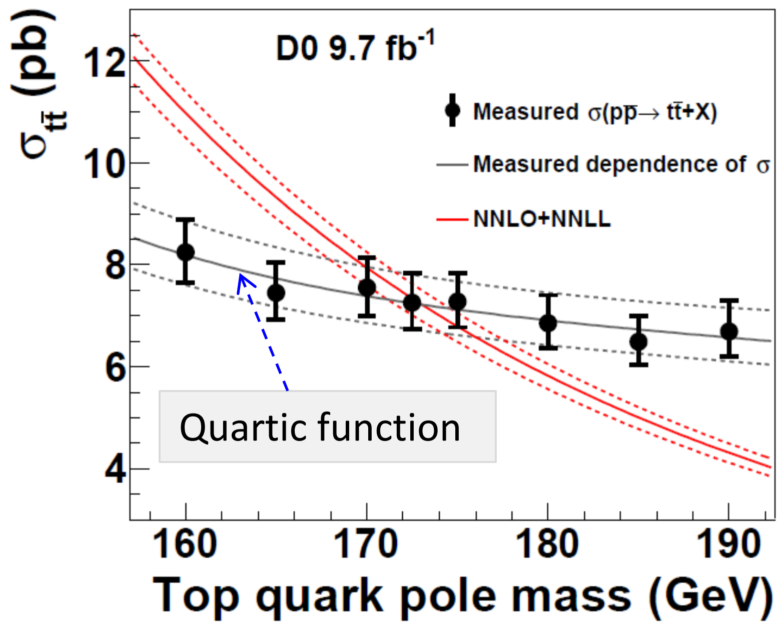
To determine the inclusive $t\bar{t}$ cross section a simultaneous log-likelihood fit to ℓ+jets and dilepton channel MVA discriminants performed.

Combined ℓ+jets and $\ell\ell$ result (for m_t =172.5) GeV:

$$\sigma_{t\bar{t}} = 7.26 \pm 0.13(\text{stat.})\,^{+0.57}_{-0.50}(\text{syst.})\text{ pb}$$

Measured vs theoretical dependence of $\sigma_{t\bar{t}}\left(m_t^{pole}\right)$

Top quark mass [GeV]	Cross section $\sigma(t\bar{t})$ [pb]
150	$9.70 \pm 0.16\,(\text{stat.})^{+0.73}_{-0.67}\,(\text{syst.})$
160	$8.25 \pm 0.14\,(\text{stat.})^{+0.63}_{-0.57}\,(\text{syst.})$
165	$7.46 \pm 0.13\,(\text{stat.})^{+0.58}_{-0.51}\,(\text{syst.})$
170	$7.55 \pm 0.13\,(\text{stat.})^{+0.58}_{-0.55}\,(\text{syst.})$
172.5	$7.26 \pm 0.12\,(\text{stat.})^{+0.57}_{-0.50}\,(\text{syst.})$
175	$7.28 \pm 0.12\,(\text{stat.})^{+0.54}_{-0.49}\,(\text{syst.})$
180	$6.86 \pm 0.12\,(\text{stat.})^{+0.53}_{-0.47}\,(\text{syst.})$
185	$6.50 \pm 0.11\,(\text{stat.})^{+0.50}_{-0.43}\,(\text{syst.})$
190	$6.70 \pm 0.11\,(\text{stat.})^{+0.60}_{-0.47}\,(\text{syst.})$



Previous D0 meas.: PLB 703, 422 (2011)

The measured top-quark pole mass is:

$$m_t^{pole} = 172.8 \pm 1.1(\text{theo.})\,^{+3.4}_{-3.5}(\text{exp.})\text{ GeV} = 172.8\,^{+3.4}_{-3.5}(\text{tot.})\text{ GeV}$$

Precision: 1.8%

Previous one: 3%

Top pole mass (m_t^{pole}) from tt-bar+1 jet

The m_t^{pole} dependence of the $t\bar{t}+1$-jet cross section ($\sigma_{t\bar{t}+1\,\text{jet}}$) is inhanced:

$$\frac{\Delta\sigma_{t\bar{t}+1\text{-jet+X}}}{\sigma_{t\bar{t}+1\text{-jet+X}}} \approx -5\frac{\Delta m_t^{pole}}{m_t^{pole}}$$ $\Rightarrow$ from NLO calculations [JHEP 10 (2015) 121]

The pole mass can be extracted from: the normalised differential distribution

$$R\left(m_t^{pole},\rho_s\right) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet+X}}}\frac{d\sigma_{t\bar{t}+1\text{-jet+X}}}{d\rho_s}\left(m_t^{pole},\rho_s\right), \quad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}$$

m_0 → 170 GeV

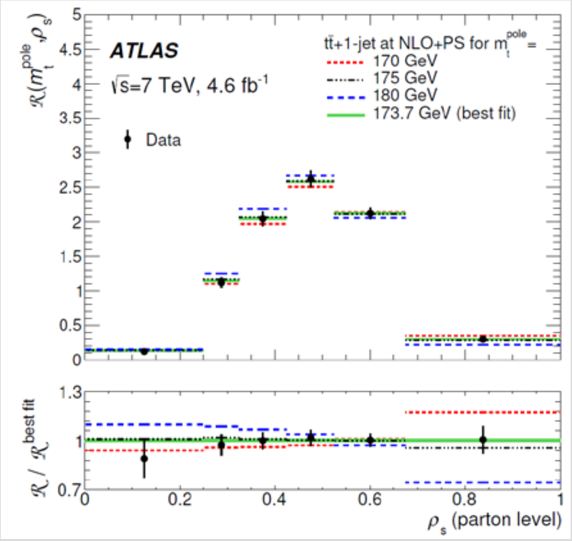
Due to the normalization many exp. and theo. uncertainties cancel.

Selection: ℓ+jets ($\ell = e$ or μ)

Background: Single top, W/Z+jet, fake leptons,...

ATLAS: measured top-quark pole mass (7 TeV, L=4.6fb^{-1}):

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



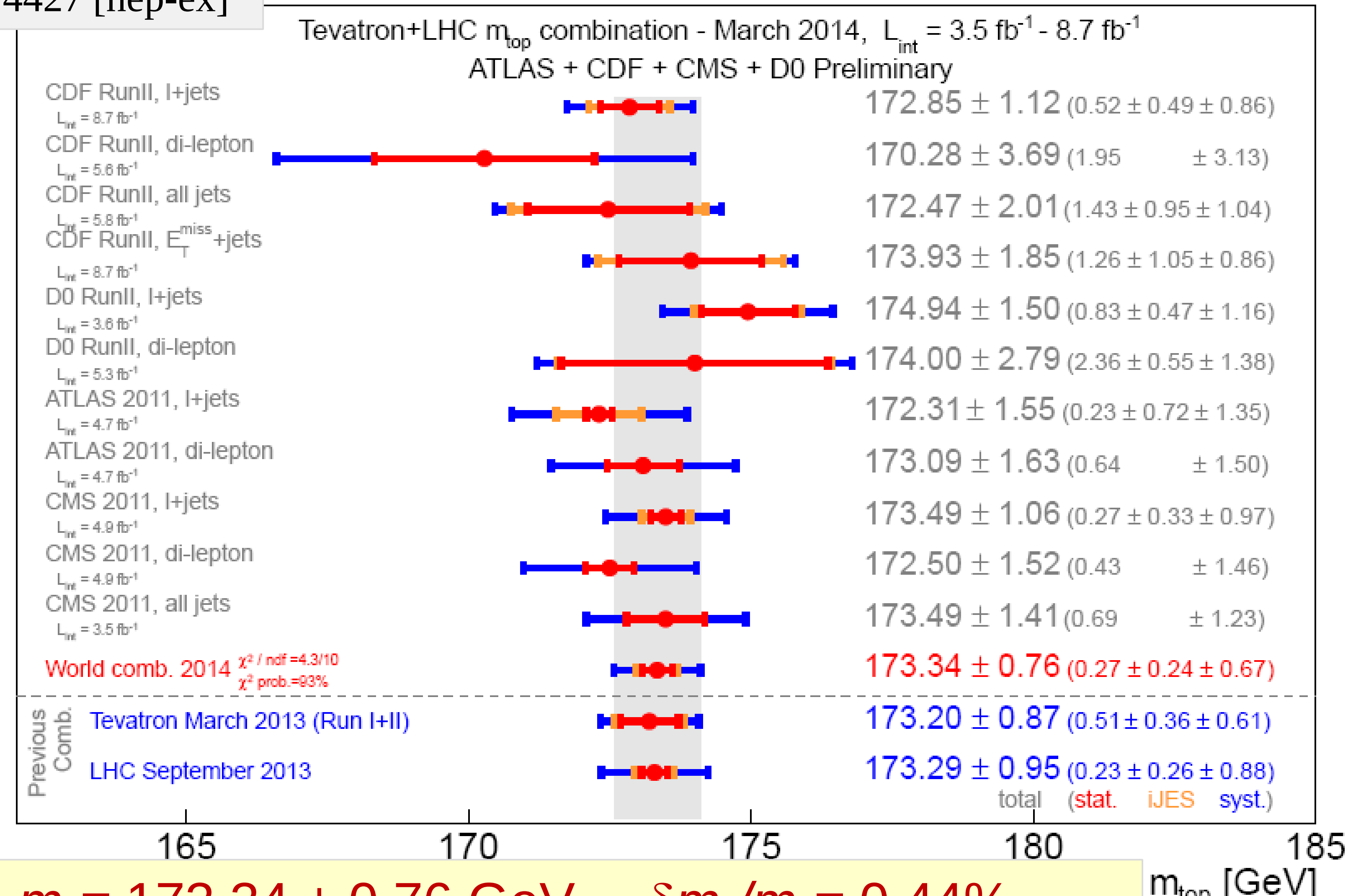
CMS: similar analysis based on observable ρ_s in *dilepton channel* at 8 TeV, L=19.7fb^{-1} [TOP-13 -006]:

$$m_t^{\text{pole}} = 169.9 \pm 1.1(\text{stat.})\,^{+2.5}_{-3.1}(\text{syst.})\,^{+3.6}_{-1.6}(\text{theory})\ \text{GeV}$$

The systematic uncertainties arise from modelling of bkg and detector effects, and the theory uncertainties from the POWHEG tt+jet modelling.

Top mass – world combination

arXiv:1403.4427 [hep-ex]



m_t = 173.34 ± 0.76 GeV, $\delta m_t / m_t$ = 0.44%

χ^2 = 4.3/10 ndf (93%)

Top mass measurements using alternative topologies

Mainly to cope with (b-)jet energy uncertainties

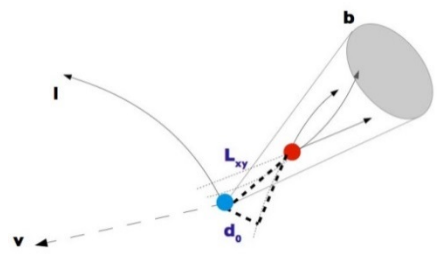
(see also s.34)

Alternative top quark mass measurements

Top mass measurement exploiting the transverse decay length of b-jets (Lxy) and isolated lepton p_T – both Lxy and p_T depend approximately linearly on top mass.

CDF (1.96 TeV, 1.9fb^{-1}): $m_t = 170.7 \pm 6.3(\text{stat.}) \pm 2.6(\text{syst.})\ \text{GeV}$ PRD 81, 032002 (2010)

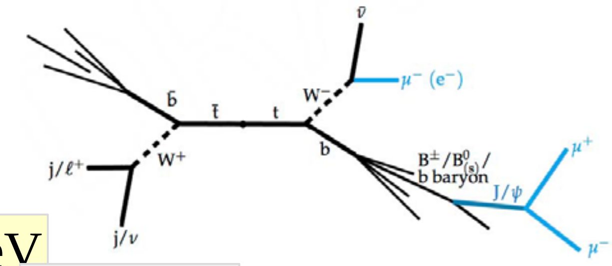
Top mass from invariant mass of the secondary b-vertex + lepton from W decay. **Observable**: invariant mass of SVTX +lepton.



Pros: minimal sensitivity to JES, *cons*: dependence on b-fragment.

CMS (8 TeV, 19.7fb^{-1}): $m_t = 173.68 \pm 0.20(\text{stat.})\,^{+1.58}_{-0.97}(\text{syst.})\ \text{GeV}$ PRD 93, 092005 (2016)

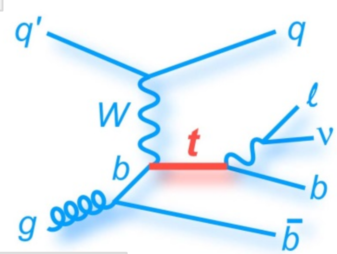
Top quark mass using the exclusive decay channel $t \to (W \to \ell\nu)\ (b \to J/\psi + X \to \mu^+\mu^- + X)$.



Observable: $J/\psi + \ell$ invariant mass .

CMS(8 TeV, 19.7fb^{-1}): $m_t = 173.5 \pm 3.0(\text{stat.}) \pm 0.9(\text{syst.})\ \text{GeV}$ TOP-15-014

Top quark mass from single-top production: $t \to W\,b$ and $W \to \ell\nu$. **Observable**: $M_{\ell\nu b}$ mass - alternative event topology (different color flow), partially uncorrelated with tt systematics.



CMS (8 TeV, 19.7fb^{-1}): $m_t = 172.60 \pm 0.77(\text{stat.})\,^{+0.97}_{-0.93}(\text{syst.})\ \text{GeV}$ TOP-15-001

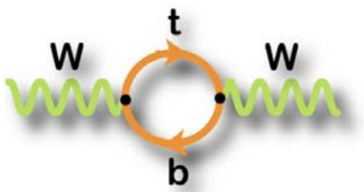
Conclusions

- The top quark mass is a key parameter with a big impact on many important issues of the SM and BSM physics
- Tevatron experiments (CDF and D0) have finalized their top quark mass analyses with excellent results
- Top mass investigated within a variety of approaches giving compatible results between Tevatron and LHC experiments
- Top mass uncertainties are now below 1 GeV and approach to Λ_{QCD}
- Effort on both the experimental and theoretical side continues to move us to better understanding of what the meas. top mass is.
- Time is up to update the top quark mass world combination.
- We are looking forward to 13 TeV top mass measurements at LHC.

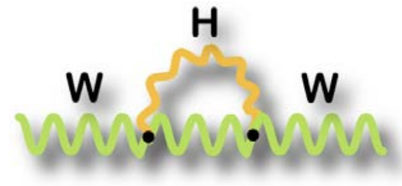
Thank you!

SM self-consitency tests and vacuum stability top mass

Processes with W boson: radiative corrections to W-boson propagator:



$$\Delta\rho \sim m_t^2 / M_W^2$$



$$(\Delta r)_{nl} \propto \ln M_H^2 / M_Z^2$$

It depends also on m_{top} and M_H $\Rightarrow$ Masses m_{top}, M_W and M_H are bounded by

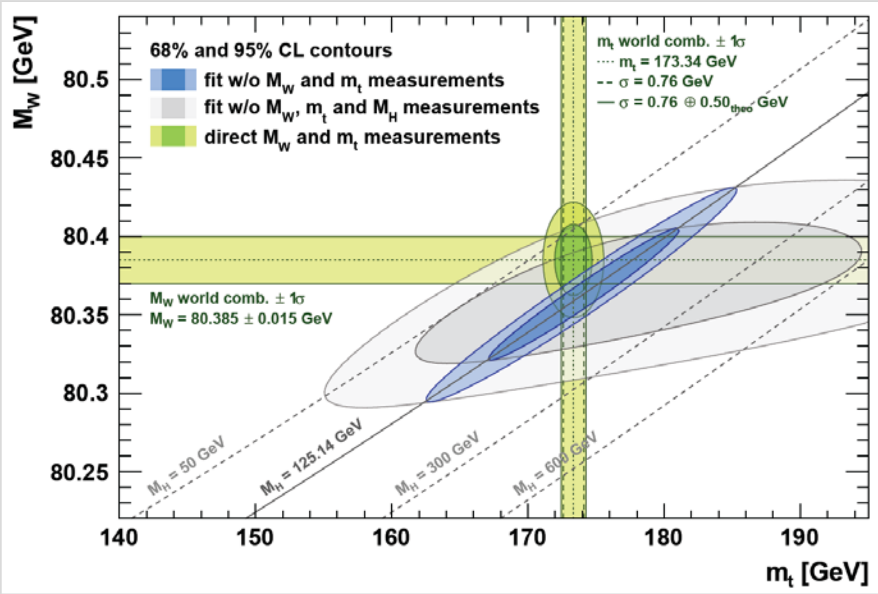
$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r),\qquad \Delta r=\Delta\alpha+\frac{s_W}{c_W}\Delta\rho+(\Delta r)_{nl}$$

Measuring precisely masses m_t and M_W $\Rightarrow$ M_H can be extracted!

EW precision data:

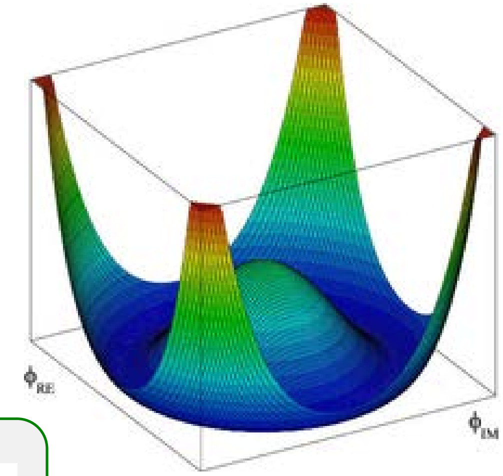
Gfitter package used for the global fit (http://project-gfitter.web.cern.ch/project-gfitter/)

Set of N_{ex} precisely measured observables described by N_{ex} theoretical expressions – functions of N_{mod} model parameters



Higgs quartic coupling

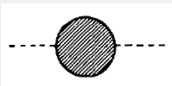
Higgs boson looks to be firmly established by LHC $\Rightarrow$ Vacuum has nonzero Higgs field component (Higgs condensate). What can be said about its stability?



Higgs potential:

$$V(\phi) = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2 , \quad \phi = \frac{\phi_1 + i\phi_2}{\sqrt{2}}$$

For $\mu^2 < 0$ and $\lambda > 0$

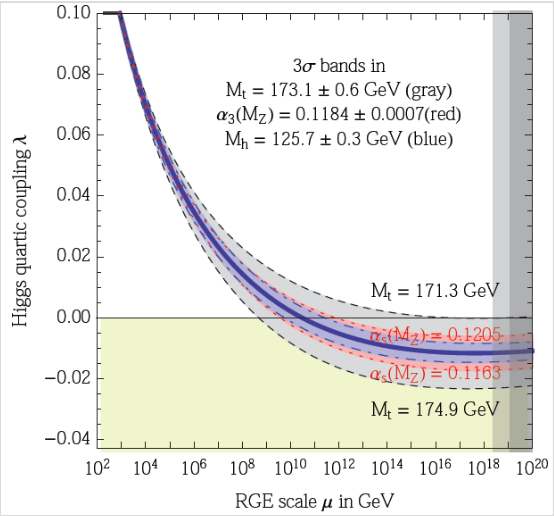
Top loops mainly 

λ vs Higgs mass and Fermi constant

$\Rightarrow$ due to interactions λ is running constant – scale dependent (as mass):

$$\lambda(\mu_R) = \frac{G_F M_H}{\sqrt{2}} + \Delta\lambda(\mu_R)$$

$\Delta\lambda$ is calculated in two loop approximation – the most important contribution: due to QCD and top Yukawa interactions.



$\Rightarrow$ What will happen if $\lambda < 0$?

Implication for the inflation

Fluctuations in Higgs field during inflation are set by Hubble scale H:

$$\delta h = \frac{H}{2\pi}, \qquad H^2 = \frac{\pi}{16} M_P^2 \Delta_R^2 r$$

$\Delta_R \equiv$ amplitude of curvature perturbations measured by Planck ($\Delta_R^2 = 2.21\times10^{-9}$)
$r \equiv$ tensor-scalar ratio measured by BICEP2

– measurement of BICEP2 [*arXiv:1403.3985*] indicates:

$$H \simeq 1.0\times10^{14}\,\text{GeV}\sqrt{\frac{r}{0.16}}, \quad r \approx 0.2$$

When $H > \Lambda_I$ (instability scale), the likelihood that $\boldsymbol{h}$ fluctuates to the unstable region of the potential during inflation will be sizable [*arXiv:1404.5953*].

Fate of universe: different scenarios of the post-inflationary vacuum evolution – from “our universe is extremely improbable” to “the additional vacuum does not appear to preclude existence of our universe”.

Top pole mass (m_t^{pole}) from tt-bar+1jet

ATLAS vs. CMS systematics

ATLAS systematics (ℓ+jets, 7 TeV, L =4.6 fb^{-1})

[JHEP 10 (2015) 121]

- ✓ Theory systematics (scale, PDF, α_S) (+0.95, -0.49)
- ✓ Jet energy scale (bJES included) 0.94
- ✓ ISR/FSR 0.72
- ✓ Proton PDFs (experimental) 0.54
- ✓ Hadronization 0.33
- ✓ Total experimental uncertainty 1.44

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

CMS systematics ($\ell\ell$, 8 TeV, L =19.7 fb^{-1})

Source	Δm_t [GeV]
POWHEG $t\bar{t}$+jet modelling	$^{-1.6}_{+3.6}$
Jet-Parton Matching	$^{-0.1}_{+1.6}$
Q^2 Scale	$^{+1.0}_{-2.8}$
ME/Showering	± 0.4
Color Reconnection	± 0.7
Underlying Event	± 0.3
PDF	$^{+0.9}_{-0.1}$
Background	± 1.0
Jet Energy Scale	± 0.1
Jet Energy Resolution	± 0.1
Pile-Up	± 0.3
Trigger Eff.	< 0.1
Kinematic Reconstruction	< 0.1
Lepton Eff.	± 0.1
B-Tagging	± 0.3
Syst. uncertainty	$^{+2.5}_{-3.1}$
Stat. untertainty	± 1.1

CMS top-quark pole mass:

$$m_t^{pole} = 169.9 \pm 1.1(\text{stat.})\,^{+2.5}_{-3.1}(\text{syst.})\,^{+3.6}_{-1.6}(\text{theory})\ \text{GeV}$$

Summary of Alternative Top Mass Measurements

CMS: many different techniques and observables have been explored at 8 TeV in all channels.

The reconstructed top masses are consistent within uncertainEes