Top-quark mass measurements at ATLAS and CMS

On behalf of the ATLAS and CMS collaborations

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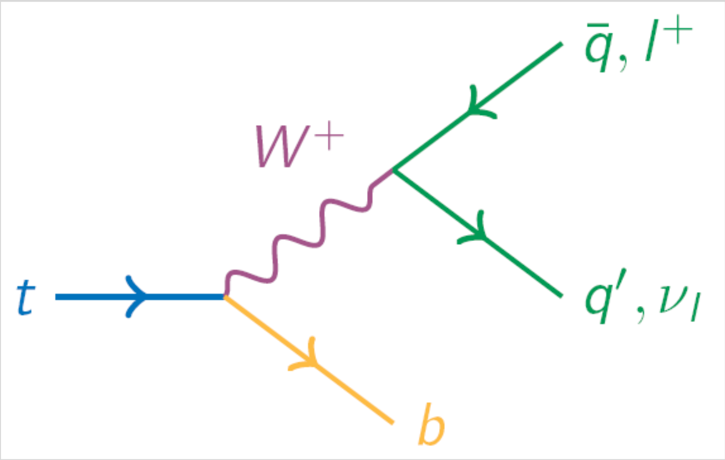
Top 2018, Bad Neuenahr, 16-21 Sep 2018

Topics in This Talk

- Motivation for the top-quark mass measurements
- Important top-quark mass issues
- Direct top-quark mass measurements
- Top-quark pole mass measurements
- Conclusions

Top-quark mass: motivation



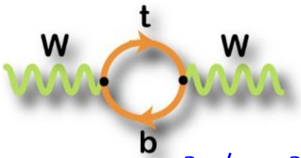
- The top-quark mass (m_{top}) is one of the fundamental SM parameters.
- Its precise value provides a key input to global EW fit $\Rightarrow$ test of internal consistency of the SM.
- Its value leads to a significant constraint on stability of the EW vacuum.
- it has a significant impact on cosmological models with inflation.

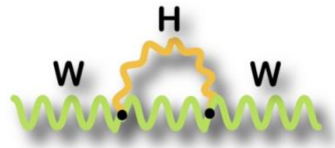
- Theoretical predictions use the top-quark pole mass $\Rightarrow$ a good understanding of the measured top-quark mass w.r.t. the top-quark pole mass or a mass with a well defined renormalization scheme is needed.

On some top-quark mass implications

SM consistency test

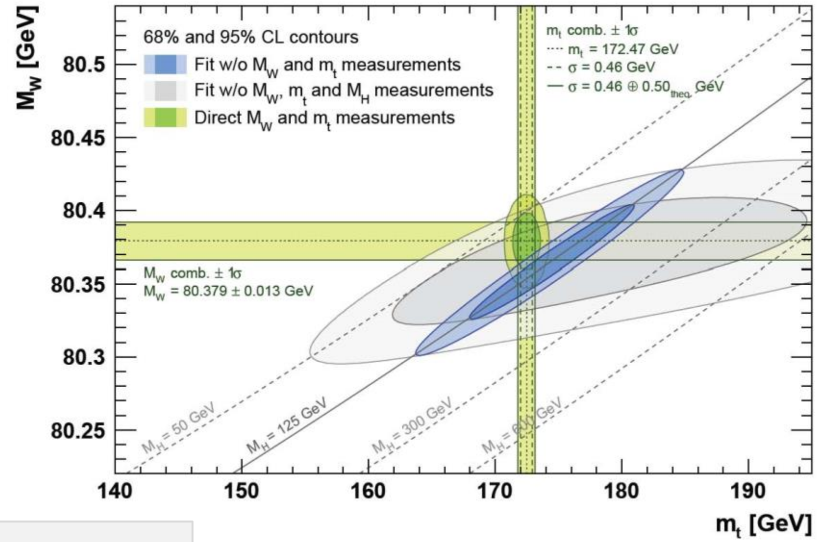
Radiative corrections to W-boson propagator:





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

$\Rightarrow$ Masses m_t , M_W and M_H are bounded



EW precision data: Gfitter used for the global fit (arXiv:1803.01853[pep-ph]) $\Rightarrow$ ΔM_H : 1.7σ

c.f. s.23

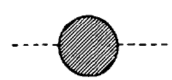
Stability of EW vacuum

Degrassi et al., arXiv:1405.6852

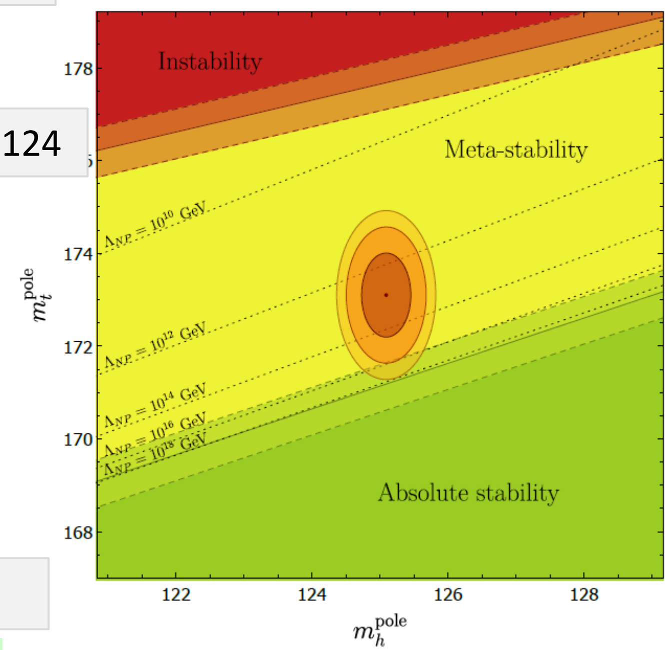
Andreassen et al., arXiv:1707.08124

Higgs quartic coupling λ scale evolution:

a decrease due to **top loop corrections**



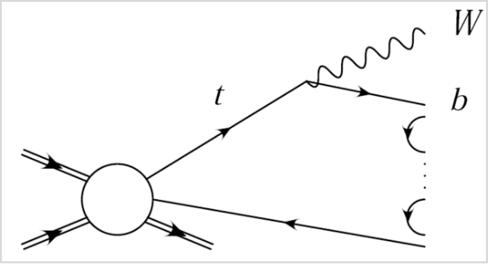
- slope of λ strongly depends on m_t
- change of λ sign at μ =10^{11}-10^{12} GeV
- $\lambda < 0 \equiv$ meta-stability of vacuum.



c.f. s.24

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: $m_{top} + i\Gamma_{top}$
- ✓ Top is colored object - due to confinement its mass uncertainty $\sim\Lambda_{QCD}$ (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-quark decay is trapped by *b*-quark.

Measured mass vs short-distance mass

A. Hoang, arXiv.1412.3649

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

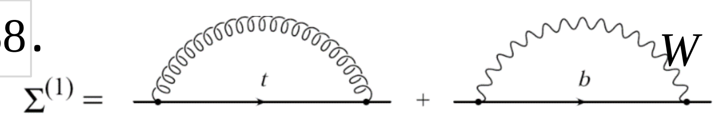
Pole mass vs short-distance mass ($\overline{\text{MS}}$ mass) non-perturb. corrections included:

PRL 114 (2015) 142002

$$m_{pole} = \bar{m}\left(\bar{m}\right)\left(1 + 0.4244\alpha_s + 0.8345\alpha_s^2 + 2.375\alpha_s^3 + \left(8.49 \pm 0.25\right)\alpha_s^4 + \ldots\right)$$

195±5 MeV

top self energy Σ pert. expanded in $\alpha_s \equiv \alpha_s^{(6)}\left(\bar{m}\right) = 0.1088$.



Top-quark mass reconstruction

How to extract top-quark mass?

- ✓ Kinematical approach: a top mass sensitive variable (invariant mass of top-decay products) is reconstructed *via* matrix element or template method ... ⇒ kinematic top-quark mass
- ✓ Approach based on measured $t\bar{t}$ production cross section (exponential decrease of $\sigma_{t\bar{t}}$ with m_t^{pole}) ⇒ top-quark pole mass

Observables sensitive to top-quark mass are reconstructed for $pp \to t\bar{t} + X$ and $pp \to t\bar{t} + 1\text{jet}$ in:

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

PRD 63, 032003 (2001)

Kinematicaly recostructed top-quark mass

- Template method (PRD 63, 032003 (2001)
- Ideogram method (Eur. Phys. J. C **2**,581 (1998))
- Matrix element methods (J.Phys.Soc.Jap. 57, 4126 (1988))
- Special methods (PRD 81, 032002 (2010))

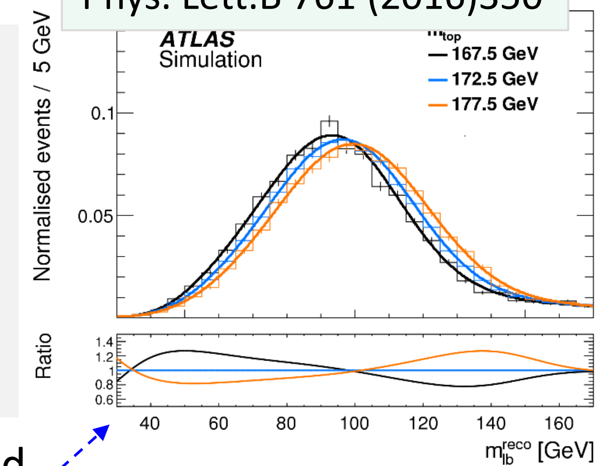
ATLAS: top mass in DiL channel at 8 TeV

Dilepton at 8 TeV: a template fit to observable $m_{\ell b}^{reco}$.

Phys. Lett.B 761 (2016)350

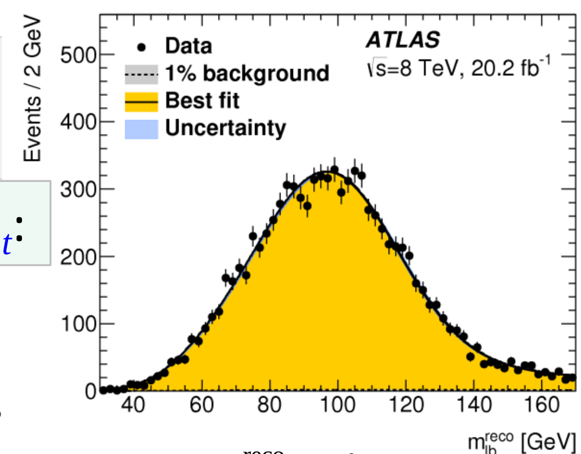
After preselection: a single-lepton (e, μ) trigger, 2 leptons ($\ell^+\ell^-$) ; $\geq$2 jets (p_T>25 GeV) ... $\Rightarrow$ **Selection optimisation:**

- ✓ events with 2 central b-jets ($|\eta| < 2.5$) are taken;
- ✓ The combination with the lowest average invariant mass of two ℓ-b-jet pairs is kept ($30\text{ GeV} < m_{lb}^{reco} < 170\text{ GeV}$);
- ✓ The average p_T of two ℓ-b pairs : $p_{T\ell b} > 120$ GeV.



Signal: single top (Wt) with the $\ell^+\ell^-$ lepton final states are included
Background <1% : fake leptons, Z+jets, dibosons

Signal $m_{\ell b}^{reco}$ templates (G+L) for 5 different input masses.
Event likelihood is based on the $m_{\ell b}^{reco}$ S+B templates (=$f(m_t,f_{bkg})$).



Fit to $m_{\ell b}^{reco}$ in data

Result: unbinned likelihood maximization gives the meas. m_t:

$$m_t^{2l} = 172.99 \pm 0.41(\text{stat}) \pm 0.74(\text{syst})\text{ GeV}, \quad \Delta = 0.49\%$$

Systematics: JES, Relative b-to-light JES, Hadronization, ISR/FSR.

Combination with 7 TeV ℓ +jets and 2ℓ (EPJC 75 (2015) 330)

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

ATLAS: top mass in all-jet channel at 8 TeV

- Minimum-χ^2 approach used to assign jets in fully hadronic $t\bar{t}$ events
- Top mass sensitive observable: $R_{3/2}=m_{jjj}/m_{jj}$ (to reduce the systematic effects common to reconstructed **top** (m_{jjj}) and W (m_{jj}) masses).
- Large multijet background → estimated from data (ABCD method).
- Template fit to $R_{3/2}$ with a binned minimum-χ^2 approach – output: m_t and $F_{\rm bkg}$.

Event selection

Jet-based trigger
Well-reconstructed PV(> 5 tracks) +no isol. e/μ
≥ 6 jets high p_T central jets (5 jets >60 GeV)
≥ 2 b-tagged jets among 6 leading jets
No jet overlap within $\Delta R(j_i, j_k) < 0.6$
Missing E_T <60 GeV (neutrinos removed)...

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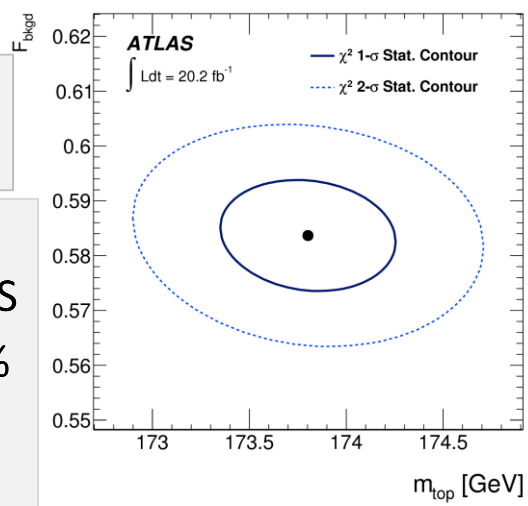
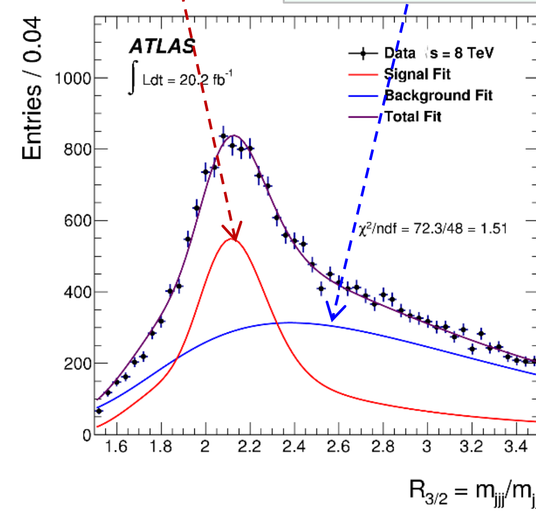
Signal template: for 5 input top masses (167.5-175 GeV)

- Main systematic uncertainties: hadronization modeling, JES and bJES
- Measurement precision: around 40% better w.r.t. m_t at 7 TeV (EPJC (2015) 75:158)



Novosibirsk +Landau

Gauss +Landau



$m_t = 173.72 \pm 0.55(\text{stat.}) \pm 1.01(\text{syst.})$ GeV ($\Delta = 0.66\%$).

$\int L\,dt = 20.2\,\text{fb}^{-1}$

See p.25

ATLAS: top mass in ℓ+jets at 8 TeV

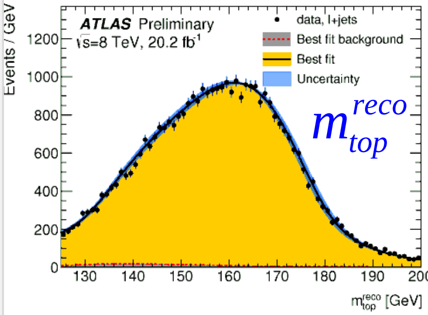
Top mass in ℓ+jets: 3D template method

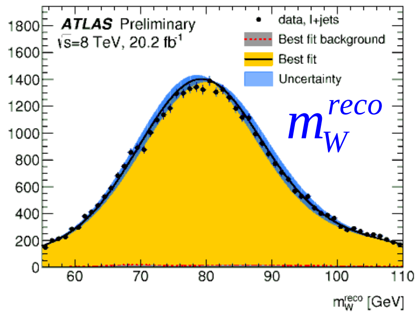
ATLAS-CONF-2017-071

$\int L\,dt = 20.2\,\text{fb}^{-1}$

Event selection:

- ✓ 1 lepton, ≥ 4 central jets (p_T >25 GeV, |η|<2.5), 2 of them b-tagged .
- ✓ In $t\bar{t} \to \mu + \text{jets}\ (\to e + \text{jets})$ events: $E_T^{miss} > 20\,(30)$ GeV and $E_T^{miss} + m_T^W > 60\,(30)$ GeV
- ✓ Optimization of the selection: BDT (13 inp. variables)

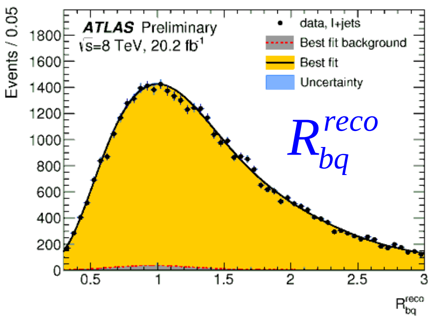




Background: Single top, NP/fake leptons (DD), W+jets (DD), Z+jets...

- Event kinematics reconstr. using KLFitter
- 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.
- Output of likelihood fit: m_t, JSF, bJSF, f_{bkg}
- Main systematic: JES, bJES

Due to BDT the expected f_{bkg}:
0.043±0.012
⇒
0.010±0.003



Data distributions of the 3 observables + best fit

See also p.27

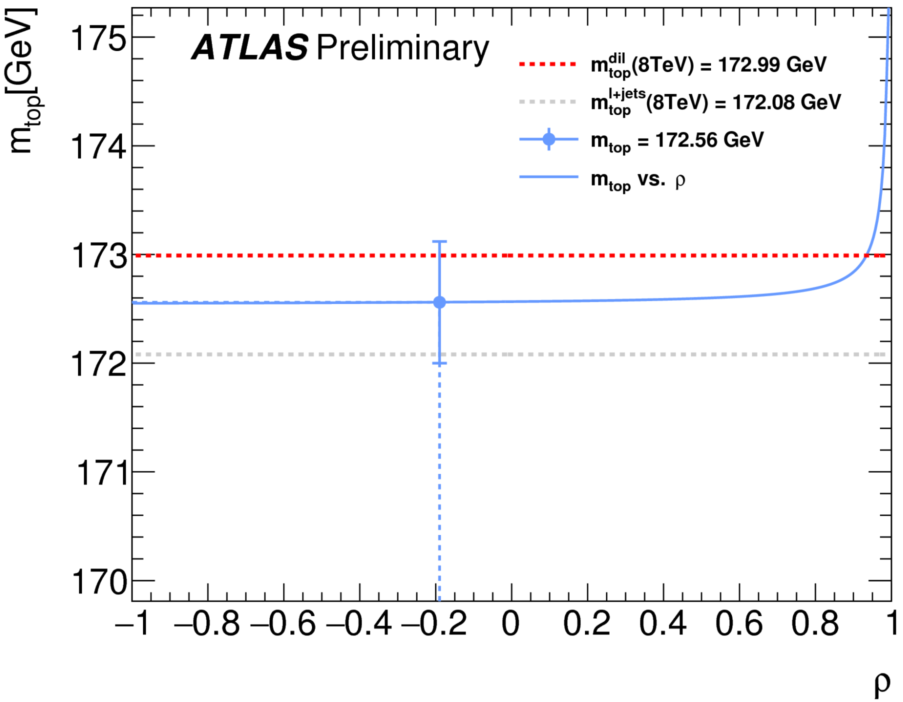
$$m_t^{\ell+\text{jets}} = 172.08 \pm 0.39(\text{stat}) \pm 0.82(\text{syst})\ \text{GeV}, \quad \Delta = 0.53\%$$

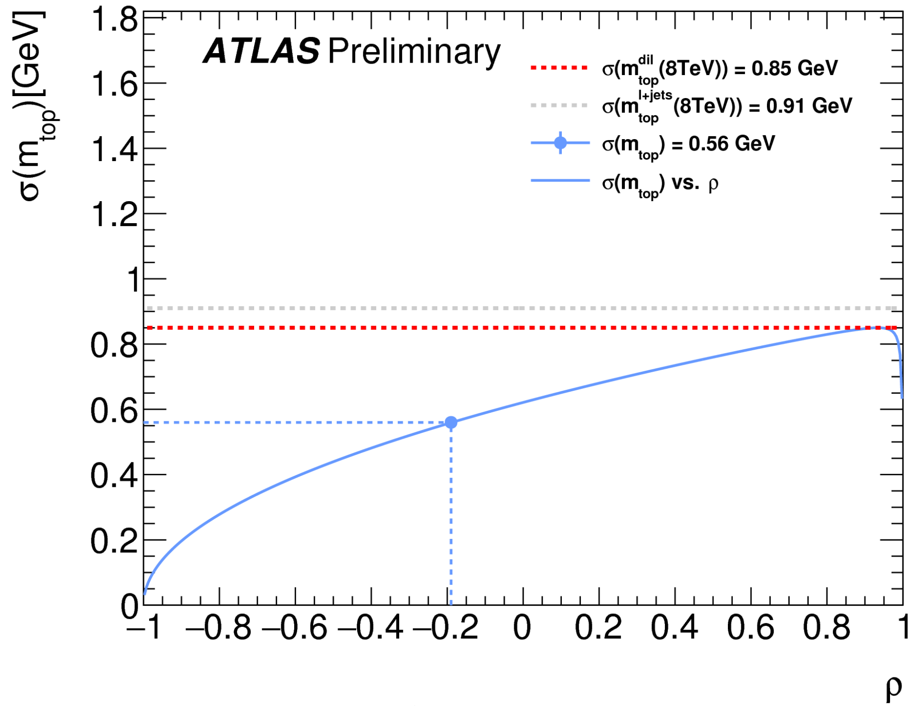
Combination of **this result** with ℓ+jets m_t at 7 TeV and the dilepton m_t at 7 and 8 TeV using BLUE technique:

$$m_{top} = 172.51 \pm 0.27(\text{stat}) \pm 0.42(\text{syst})\ \text{GeV}, \quad \Delta = 0.29\%$$

Correlations of the top mass combination

The combination of the two results from √s=8 TeV data.





The mass combination (two results) at 8 TeV vs their correlation. The blue point corresponds to the actual correlation. The corresponding values for the input measurements: grey and red dashed lines.

Uncertainty of the mass combination at 8 TeV vs their correlation. The blue point corresponds to the actual correlation. The corresponding values for the input measurements: grey and red dashed lines.

CMS: top mass in ℓ+jets at 8 and 13 TeV

8 TeV: Phys. Rev. D93, 072004 (2016)

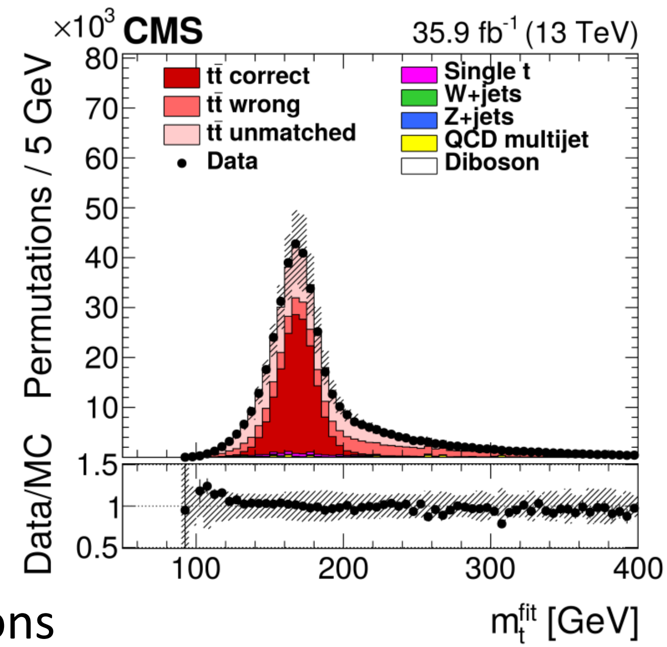
13 TeV: arXiv.1805.01428

Ideogram technique used (see also s.28):

- It is a joint maximum likelihood fit to selected data – the fit output is the top mass m_t and (optionally) JSF.
- Observables for measuring m_t and JSF, the masses m_t^{fit} and m_W^{reco}, are estimated by a kinematic fit for each event and for different parton-jet assignments ($P_{\rm gof} = e^{-\chi^2/2}$).
- The likelihood fit is based on event likelihood created using m_t^{fit} and m_W^{reco} templates obtained from simulation for 7 different m_t and 5 JSF.

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 corrections $\Rightarrow$ JSF = 1)
- ***Hybrid approach***: prior knowledge about JES used but Gaussian constraint is applied centered at 1 with variance depending on JES uncertainty.



Background: Single top, W+jets, Z+jets, multijets, dibosons

Observable m_t^{fit} (weighted by P_{gof})

CMS: top mass in ℓ+ jets at 13TeV

Results at 13TeV, L = 35.9 fb^{-1}:

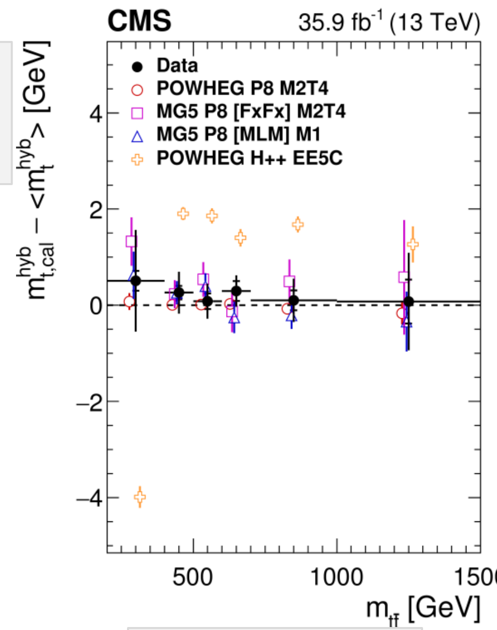
Selection: exactly 1 isolated μ (e) with p_T >26 (34) GeV, $|\eta|$<2.4 (2.1)
$\geq$ 4 jets with p_T > 30 GeV, $|\eta|$<2.4, P_{gof} > 0.2

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

$$m_t^{2D} = 172.40 \pm 0.09(\text{stat+JSF}) \pm 0.72(\text{syst})\ \text{GeV},$$
$$\text{JSF}^{2D} = 0.995 \pm 0.001\ (\text{stat}) \pm 0.010(\text{syst}).$$

1D and hybrid analyses:

$$m_t^{1D} = 171.93 \pm 0.06\ (\text{stat}) \pm 1.09\ (\text{syst})\,\text{GeV},$$
$$m_t^{hyb} = 172.25 \pm 0.08\ (\text{stat+JSF}) \pm 0.62\ (\text{syst})\,\text{GeV},$$
$$\text{JSF}^{hyb} = 0.996 \pm 0.001\ (\text{stat}) \pm 0.008(\text{syst}).$$



m_t pull vs m_{tt}

Most precise is hybrid approach – total uncertainty of 0.63 GeV (Δ = 0.37%).
Main systematics: JEC (exp.+ model.), color reconnection, ME generator

Comparison with the 8 TeV (L=19.7 fb^{-1}) ℓ+jets result:

1D and hybrid analyses:

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

Total uncertainty of 0.51 GeV (Δ = 0.29%).

Top mass in all-jets channel at 13 TeV

CMS-PAS-TOP-17-008

Ideogram method applied to all-jets channel (13 TeV, L=35.9 fb^{-1}) using 2D, 1D and hybrid approaches.

Selection: $\geq$ 6 jets, exactly 2b-tagged, $\Delta R_{b\bar{b}} > 2$.

Background estimation: Multijet $\Rightarrow$ data-driven technique using 0 b-tagged events

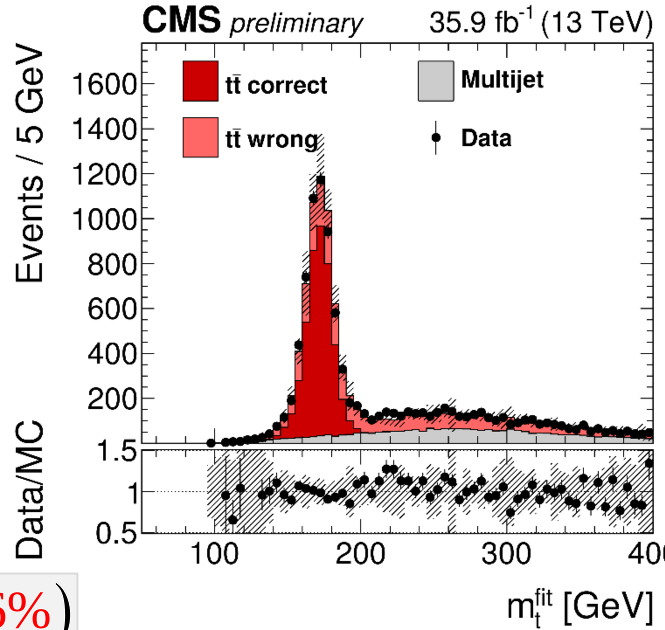
Kinematic fit: $m_t = m_{\bar{t}}$, $m_W = 80.4$ GeV, $P_{\text{gof}} > 0.1$

Dominant systematics: Jet energy corrections, color reconnections, ME generator

The most precise result: hybrid approach:

$$m_t^{\text{hyb}} = 172.34 \pm 0.20(\text{stat+JSF}) \pm 0.76(\text{syst})\,\text{GeV}\ (\Delta = 0.46\%)$$

$$\text{JSF}^{\text{hyb}} = 0.997 \pm 0.002(\text{stat}) \pm 0.007\ (\text{syst})\,\text{GeV}.$$



m_t^{fit} after weighted by P_{gof}

Comparison with the 8 TeV all-jets result: PRD 93, 072004 (2016)

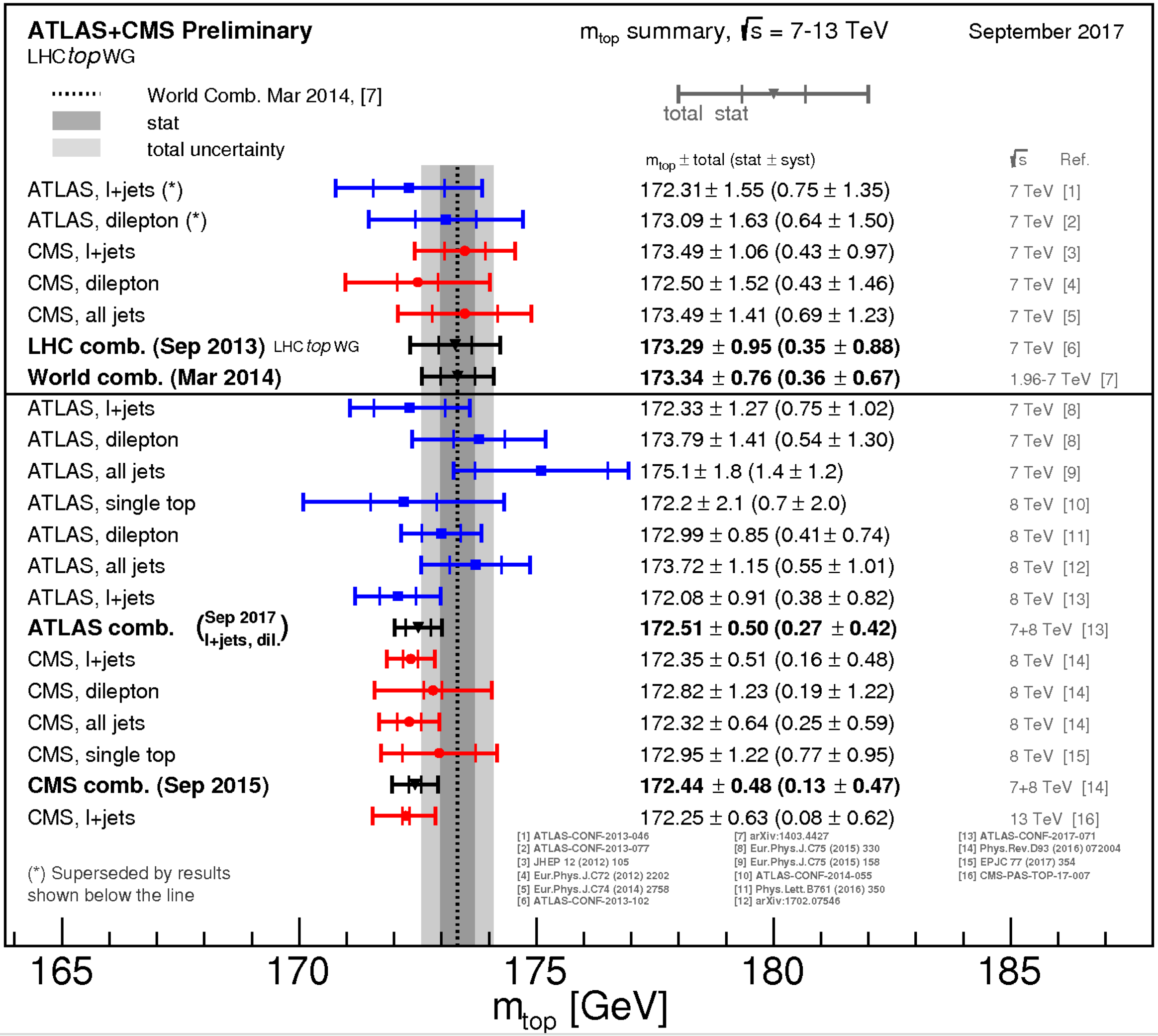
$$m_t^{\text{hyb}} = 172.32 \pm 0.25(\text{stat+JSF}) \pm 0.64(\text{syst})\,\text{GeV}\quad (\Delta = 0.40\%).$$

CMS DiL result at 8 TeV - an example of matrix element approach - see s.31:

$$m_t = 172.82 \pm 0.19(\text{stat}) \pm 1.22\ (\text{syst})\,\text{GeV}\ \ (\Delta = 0.71\%)$$

Main syst: scales μ_F, μ_R

LHC top-quark mass summary



Summary of the ATLAS and CMS direct m_{top} measurements. The results are compared with the LHC and Tevatron+LHC m_{top} combinations.

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
- Well-defined mass scheme

Top-quark pole mass from differential $t\bar{t}$ cross section

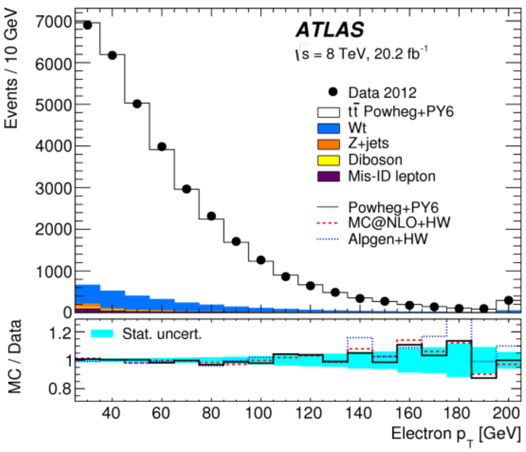
EPJC77(2017) 804

Top-pole mass from $\sigma_{t\bar{t}}$ measurements at 8 TeV; L= 20.3 fb^{-1}

Dilepton channel with oppositely charged $e\mu$ as W decay products $\left(t\bar{t} \to \mu e \nu \bar{\nu} b \bar{b}\right)$

✓ 8 diff. cross sections measured:

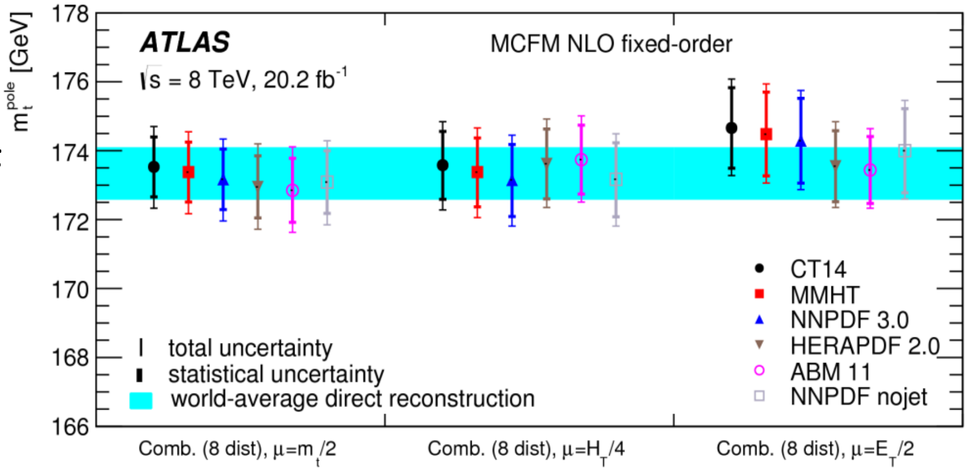
$\sigma_{t\bar{t}}$ vs. p_T^{ℓ}, $|\eta^{\ell}|$, $p_T^{e\mu}$, $m^{e\mu}$, $|\eta^{e\mu}|$, $\Delta\phi^{e\mu}$, $p_T^{e} + p_T^{\mu}$, and $E^e + E^e$.



Mass extraction: Normalized measured diff. Xsections vs theoretical predictions:

- NLO generator POWHEG + PYTHIA6 + CT10 - template fits and Mellin moments within minimum χ^2 approach
- NLO fixed order MCFM + various PDFs – data vs prediction: χ^2-approach with PDF and scale uncertainties as nuisance parameters.

✓ Dominant systematics: QCD scale



Extracted mass:

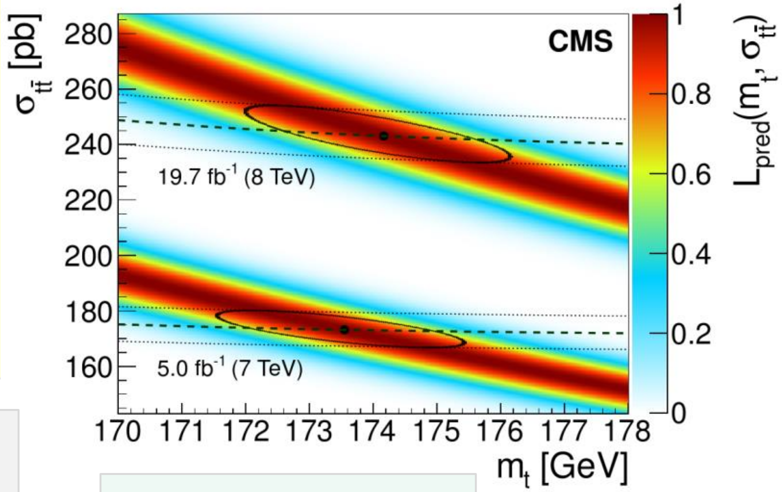
$$m_t^{\text{pole}} = 173.2 \pm 0.9(\text{stat}) \pm 0.8(\text{syst}) \pm 1.2(\text{theo})\,\text{GeV}$$

$\Delta = 0.98\%$

Top-quark pole mass from inclusive $t\bar{t}$ cross section

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

- Extended binned likelihood fit used to determine $\sigma_{t\bar{t}}$ in addition from fit: bkgd normalizations and systematic uncertainties (nuisance parameters)
- Measurement of $\sigma_{t\bar{t}}$ is based on PDF set NNPDF3.0 and α_S=0.118 ± 0.001
- PDFs CT14 and MMHT2014 give consistent results



JHEP 08 (2016) 029

Event selection ~ ATLAS → dilepton $e\mu$ pairs (op. ch.)
Leptons: p_T>20 GeV, |η|<2.4, *b-jets*: p_T>30 GeV, |η|<2.4

Main systematics: Luminosity, lepton id/isolation, trigger efficiency and DY

- ❑ 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):

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

Δ = 1.0%

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

Phys. Lett. B **728** (2014) 496

Top-quark pole mass 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 enhanced:

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

The pole mass can be extracted from: the normalized 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

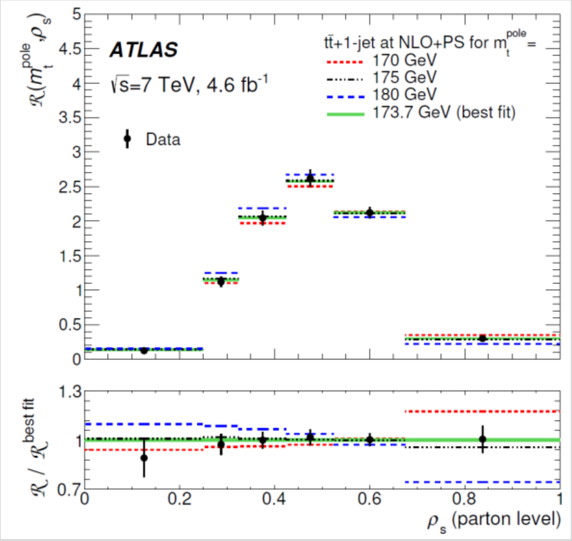
A template technique is used to extract m_t^{pole}.

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

Selection: ℓ+jets (ℓ= e or μ) with two b-tags
Background: Single top, W/Z+jet, fake leptons,...

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

Systematics: μ_R, μ_F variation, JES, ISR/FSR, PDF



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

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

Systematics: μ_R, μ_F variation, jet-parton matching, hadronization, color reconnection

Not shown in this talk

- ✓ New CMS top mass measurement – the top mass is simultaneously extracted with the tt cross section - it will be presented by Matteo Defranchis on Wednesday
- ✓ Alternative top mass measurement methods: top mass from single top, use of b-decay transverse distance, L_{xy}, lepton kinematics,... without calorimetric info – moved to Backup s.22

Conclusions

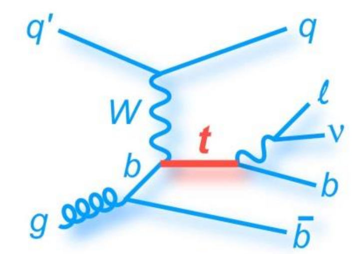
- The top quark mass is a key parameter with a big impact on many important issues of the SM and BSM physics.
- In the ATLAS and CMS experiments the top mass is investigated within a variety of approaches giving compatible results between them.
- Top mass uncertainties are now below 1 GeV and approach to Λ_{QCD}
- Effort on both the experimental and theoretical side continues to move us to a better understanding of what the meas. top mass is.
- We are looking forward to the 13 TeV top mass measurements on full statistics of Run II at LHC and to the update of the top quark mass world combination.

Thank you!

Alternative top-quark mass measurements

Top-quark mass from single-top production: $t \to W\,b$ and $W \to \ell\nu$.

Observables: $M_{\ell b}$ or $M_{\ell\nu b}$ mass - alternative event topology (different color flow), partially uncorrelated with $t\bar{t}$ systematics.



ATLAS (8 TeV, 20.2 fb^{-1}) using observable $\boldsymbol{M_{\ell b}}$:

$$m_t = 172.2 \pm 0.7(\text{stat.}) \pm 2.0(\text{syst.})\ \text{GeV}$$

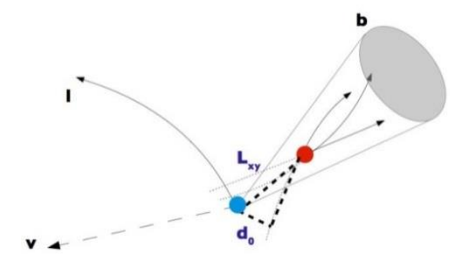
ATLAS-CONF-2014-055

CMS (8 TeV, 19.7fb^{-1}) using observable: $M_{\ell\nu b}$:

$$m_t = 172.60 \pm 0.77(\text{stat.})\,^{+0.97}_{-0.93}(\text{syst.})\ \text{GeV}$$

TOP-15-001

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



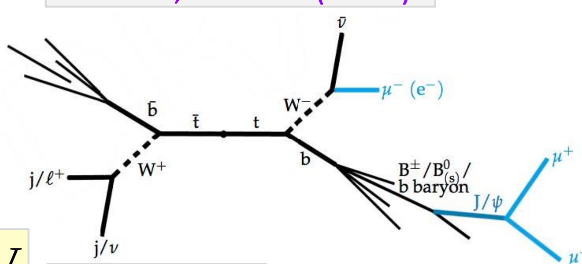
Pros: minimal sensitivity to JES, ***cons***: dependence on b-fragment.

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

$$t \to (W \to \ell\nu)\ (b \to J/\psi + X \to \mu^+\mu^- + X).$$



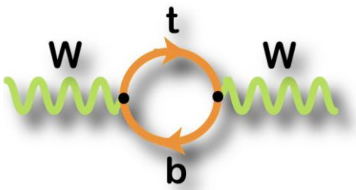
Observable: $J/\psi + \ell$ invariant mass .

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

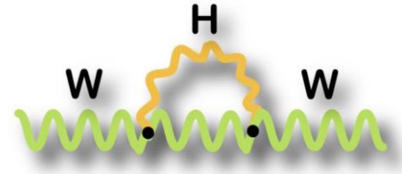
TOP-15-014

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 ⇒ Masses m_{top}, M_W and M_H are bounded by

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

Measuring precisely masses m_t and M_W
⇒ M_H can be extracted!

EW precision data:

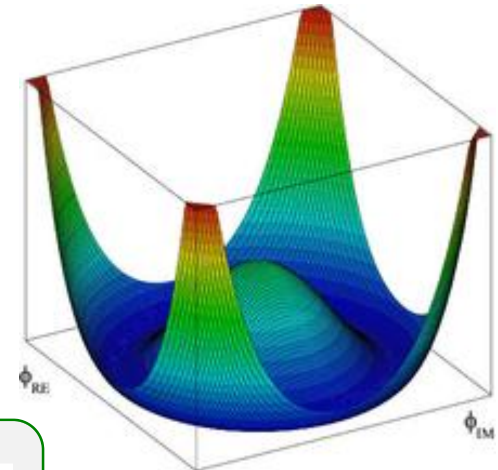
Gfitter package used for the global fit (arXiv:1803.01853)

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

Parameter	Input value	Free in fit	Fit Result	Fit w/o exp. input in line	Fit w/o exp. input in line, no theo. unc.
M_H [GeV]	125.1 ± 0.2	yes	125.1 ± 0.2	90^{+21}_{-18}	89^{+20}_{-17}
M_W [GeV]	80.379 ± 0.013	–	80.359 ± 0.006	80.354 ± 0.007	80.354 ± 0.005
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1882 ± 0.0020	91.2013 ± 0.0095	91.2017 ± 0.0089
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4947 ± 0.0014	2.4941 ± 0.0016	2.4940 ± 0.0016
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.484 ± 0.015	41.475 ± 0.016	41.475 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.742 ± 0.017	20.721 ± 0.026	20.719 ± 0.025
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01620 ± 0.0001	0.01619 ± 0.0001	0.01619 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1470 ± 0.0005	0.1470 ± 0.0005	0.1469 ± 0.0003
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23153 ± 0.00006	0.23153 ± 0.00006	0.23153 ± 0.00004
$\sin^2\theta^\ell_{\rm eff}(\rm Tevt.)$	0.23148 ± 0.00033	–	0.23153 ± 0.00006	0.23153 ± 0.00006	0.23153 ± 0.00004
A_c	0.670 ± 0.027	–	0.6679 ± 0.00021	0.6679 ± 0.00021	0.6679 ± 0.00014
A_b	0.923 ± 0.020	–	0.93475 ± 0.00004	0.93475 ± 0.00004	0.93475 ± 0.00002
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0736 ± 0.0003	0.0736 ± 0.0003	0.0736 ± 0.0002
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1030 ± 0.0003	0.1032 ± 0.0003	0.1031 ± 0.0002
R^0_c	0.1721 ± 0.0030	–	0.17224 ± 0.00008	0.17224 ± 0.00008	0.17224 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21582 ± 0.00011	0.21581 ± 0.00011	0.21581 ± 0.00004
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	–	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	–	–
m_t [GeV]$^{(\nabla)}$	172.47 ± 0.68	yes	172.83 ± 0.65	176.4 ± 2.1	176.4 ± 2.0
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2760 ± 9	yes	2758 ± 9	2716 ± 39	2715 ± 37
$\alpha_s(M_Z^2)$	–	yes	0.1194 ± 0.0029	0.1194 ± 0.0029	0.1194 ± 0.0028

Higgs quartic coupling

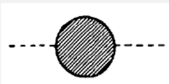
Higgs boson looks to be firmly established by LHC ⇒ Vacuum has nonzero Higgs field component (Higgs condensate). What can be said about its stability?



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 $\lambda>0$

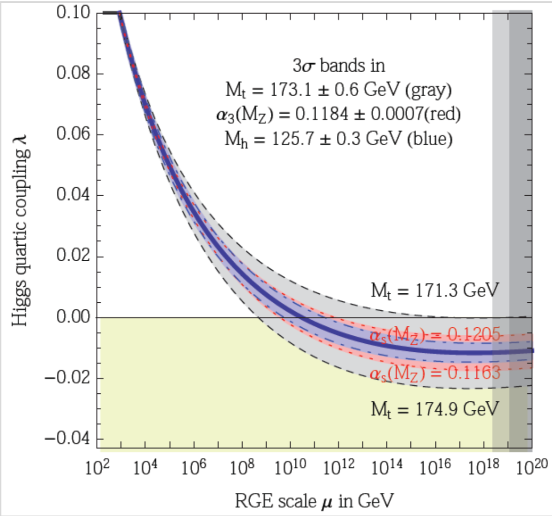
Top loops mainly 

λ vs Higgs mass and Fermi constant

⇒ 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.



⇒ 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 ***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”.

Template method for top mass in *all*-jets

$t\bar{t}$ reconstruction: the $t\bar{t}$ final state is reconstructed using the decay chain:

$$t\bar{t} \to bWbW \to b_1 j_1 j_2 b_2 j_3 j_4$$

A minimum -χ^2 used with χ^2 defined as:

$$\chi^2 = \frac{\left(m_{b_1 j_1 j_2} - m_{b_2 j_3 j_4}\right)^2}{\sigma^2_{\Delta m_{bjj}}} + \frac{\left(m_{j_1 j_2} - m_W^{\mathrm{MC}}\right)^2}{\sigma^2_{\Delta m_W^{\mathrm{MC}}}} + \frac{\left(m_{j_3 j_4} - m_W^{\mathrm{MC}}\right)^2}{\sigma^2_{\Delta m_W^{\mathrm{MC}}}}$$

All possible permutations of the six or more reconstructed jets in each event are considered.

Final χ^2 fit:

$$\chi^2 = \sum_{i=1}^{N_{\mathrm{bin}}} \sum_{k=1}^{N_{\mathrm{bin}}} \left(n_i - \mu_i\right)\left(n_k - \mu_k\right)\left[V_{\mathrm{data}} + V_{\mathrm{signal}}\left(m_t, F_{\mathrm{bkg}}\right) + V_{\mathrm{bkg}}\left(F_{\mathrm{bkg}}\right)\right]^{-1}_{ik}$$

Here m_{t} and F_{bkg} are fit parameters.
$\mathbf{V}_{\mathrm{data}}$ is the $N_{\mathrm{bin}} \times N_{\mathrm{bin}}$ diagonal covariance matrix with $V_{ik} = \delta_{ik} n_i$ - statistical uncertainty in bin i.
$\mathbf{V}_{\mathrm{signal}}$ and $\mathbf{V}_{\mathrm{bkgd}}$ are $N_{\mathrm{bin}} \times N_{\mathrm{bin}}$ non-diagonal covariance matrices which account for the signal and background shape parametrisation uncertainties and their correlations.
In the $R_{3/2}$ distribution (a total number of data entries N_{d}, and a bin width w_{bin}), estimated entries in bin i, μ_i, is given by:

$$\mu_i\left(m,\ F_{\mathrm{bkg}}\right) = w_{\mathrm{bin}} N_{\mathrm{d}} \left[\left(1 - F_{\mathrm{bkg}}\right) P_{\mathrm{S}}\left(R_{3/2,i} \middle| m_t\right) + F_{\mathrm{bkg}} P_{\mathrm{B}}\left(R_{3/2,i}\right)\right]$$

Where P_S and P_B are the probability density functions for the signal and background, resp.

Template method for top mass in ℓ+jets

Signal and background probability density functions P_{sig} and P_{bkg} for m_{top}^{reco}, m_W^{reco} and $R_{bq}^{\text{reco}} = \frac{\langle p_T^b \rangle}{\langle p_T^{\text{light}} \rangle}$ (templates) are used in an unbinned likelihood fit to the data for all events, i =1, . . . N.
The likelihood function maximized is:

$$L_{\text{shape}}^{\ell+\text{jets}}\left(m_{\text{top}},\ \text{JSF, bJSF}, f_{\text{bkg}}\right) =$$

$$= \prod_{i=1}^{N} P_{\text{top}}\left(m_{\text{top}}^{\text{reco},i} \middle| m_{\text{top}},\ \text{JSF, bJSF}, f_{\text{bkg}}\right) \times P_W\left(m_W^{\text{reco},i} \middle|\ \text{JSF}, f_{\text{bkg}}\right) \times P_{bq}\left(R_{bq}^{\text{reco},i} \middle| m_{\text{top}}, \text{bJSF}, f_{\text{bkg}}\right)$$

With

$$P_{\text{top}}\left(m_{\text{top}}^{\text{reco},i} \middle| m_t,\ \text{JSF, bJSF}, f_{\text{bkg}}\right) = \left(1 - f_{\text{bkg}}\right) P_{\text{top}}^{\text{sig}}\left(m_{\text{top}}^{\text{reco},i} \middle| m_t,\ \text{JSF, bJSF}\right) + f_{\text{bkg}} P_{\text{top}}^{\text{bkg}}\left(m_{\text{top}}^{\text{reco},i} \middle| \text{JSF, bJSF}\right)$$

$$P_W\left(m_{\text{top}}^{\text{reco},i} \middle| \text{JSF},\ f_{\text{bkg}}\right) = \left(1 - f_{\text{bkg}}\right) P_W^{\text{sig}}\left(m_W^{\text{reco},i} \middle| \text{JSF}\right) + f_{\text{bkg}} P_{\text{top}}^{\text{bkg}}\left(m_W^{\text{reco},i} \middle| \text{JSF}\right)$$

$$P_{bq}\left(R_{bq}^{\text{reco},i} \middle| m_t,\ \text{bJSF}, f_{\text{bkg}}\right) = \left(1 - f_{\text{bkg}}\right) P_{bq}^{\text{sig}}\left(m_{\text{top}}^{\text{reco},i} \middle| m_t,\ \text{JSF, bJSF}\right) + f_{\text{bkg}} P_{bq}^{\text{bkg}}\left(R_{bq}^{\text{reco},i} \middle| \text{bJSF}\right)$$

$f_{\text{bkg}} \equiv$ the fraction of background events;

The parameters to be determined by the fit are m_{top}, JSF, bJSF and f_{bkg}, where f_{bkg} is determined separately for the +jets data sets with exactly one or at least two b-tagged jets.

Top mass using ideogram method

PRD 93, 072004 (2016)

Ideogram method is a joint maximum likelihood fit that determines $\boldsymbol{m_t}$ (opt. also JSF) from a sample of selected $t\bar{t}$ candidate events in: ℓ+jets or all-jets channels. The observable used for measuring $\boldsymbol{m_t}$ is the mass m_t^{fit} estimated by a kinematic fit.

Kinematic fit constraints: $m_t = m_{\bar{t}}$, $m_W = 80.4$ GeV, $P_{\text{gof}} > 0.1$ (goodness-of-fit probab.) JSF is a multiplicative factor applied to JES extracted from m_W^{reco} (di-jet invariant mass associated with W).

Sensitive variables $m_t^{\text{fit}}, m_W^{\text{reco}}$ templates are from simulation for different values of m_t and JSF – for signal and background.
The signal templates: $P\left(m_t^{\text{fit}} \middle| m_t, \text{JSF}\right)$ and $P\left(m_W^{\text{reco}} \middle| m_t, \text{JSF}\right)$

Likelighood for measuring $\boldsymbol{m_t}$ and **JSF** in data sample:

$$L\left(\text{sample} \middle| m_t, \text{JSF}\right) = \prod_{\text{events}} L\left(\text{event} \middle| m_t, \text{JSF}\right)^{w_{event}},$$

For ℓ+jets (all-jets) $w_{\text{event}} = c\sum_{i=1}^{n} P_{\text{gof}}(i)$ ($w_{\text{event}} = 1$), P_{gof} is probability of jets permutation.

$$L\left(\text{event} \middle| m_t, \text{JSF}\right) = \sum_{i=1}^{n} P_{\text{gof}}(i)\left\{ f_{\text{sig}} P_{\text{sig}}\left(m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}} \middle| m_t, \text{JFS}\right)\right\} + \left(1 - f_{\text{sig}}\right) P_{\text{bkg}}\left(m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}}\right)$$

The index i runs over the n selected permutations, f_{sig} = 1 for ℓ+jets and free parameter for all-jets channel.

Top mass using ideogram method (2)

W boson mass is fixed in fit $\Rightarrow$ the observables m_t^{fit} and m_W^{reco} exhibit a low correlation (5%) and P can be parametrized:

$$P\left(m_t^{\text{fit}}, m_W^{reco} \middle| m_t, \text{JSF}\right) = \sum_j f_j P_j\left(m_t^{\text{fit}} \middle| m_t, \text{JSF}\right) P_j\left(m_W^{\text{reco}} \middle| m_t, \text{JSF}\right)$$

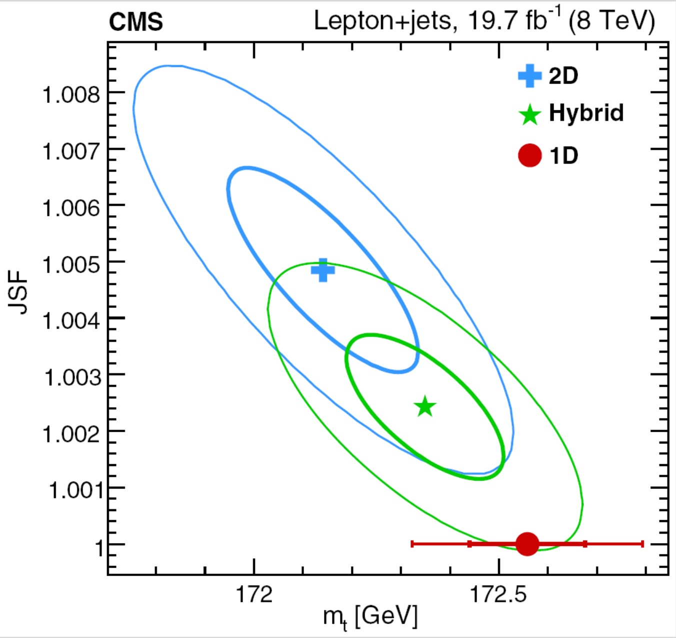
The index $\boldsymbol{j}$ denotes jet-parton permutation, $\boldsymbol{f_j}$ ≡relative fraction of $\boldsymbol{j}^{\mathbf{th}}$ jet permutation.

The $\boldsymbol{m_t}$ and $\mathbf{JSF}$ values are obtained by minimizing $-2\ln L\left(\text{event}\middle| m_t, \text{JSF}\right)$ for the 2D and hybrid
analyses. For the 1D analyses only mt is determined and the JSF is set to unity during the minimization.

CMS: top mass in lepton+jets at 8 TeV

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 ⇒ JSF = 1)
- *Hybrid approach*: prior knowledge about JES used but Gaussian constraint applied centered at 1 with variance depending on JES uncertainty.



Results at 8TeV, L = 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.

Δ= 0.30%

Top mass in all-jets and dilepton at 8 TeV

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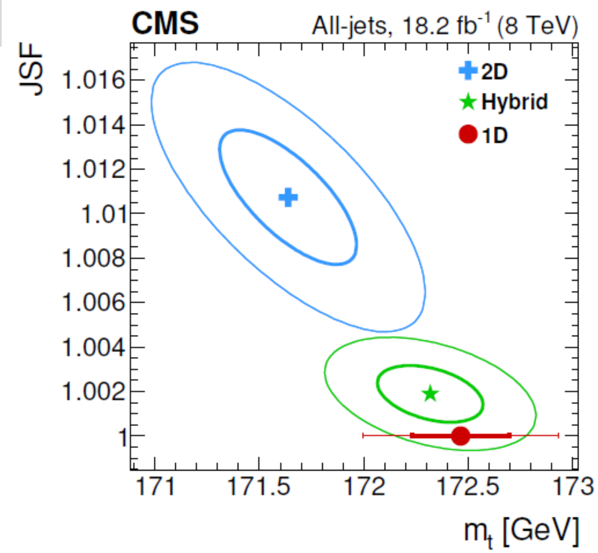
All jet channel (8 TeV, L=19.7 fb^{-1})

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

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