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Top Quark Mass

On behalf of the CMS collaboration

The top quark mass at LHC

22 years after its discovery at Tevatron we are still measuring the top quark mass:

- exploiting different channels (for completeness)
- recurring to different techniques (with different systematics)
- exploring its connection to the theory

Taking advantage of:

- **LHC is a top factory**
  - ≈5 million pairs per experiment in 2012, ≈30 million in 2016, each **t** decays ≈100% to W+b
  - single top EWK production ($\sigma_t \sim \sigma_{tt}/3$)

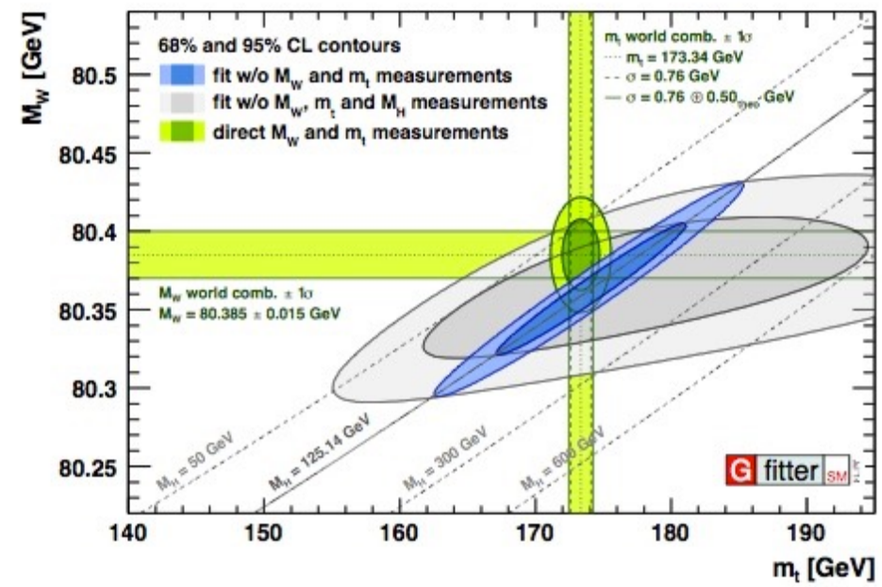
- **Physics objects**
  - isolated energetic e or μ
  - energetic jets
  - b-tagged jets
  - momentum imbalance (MET)
  - *boosted top jets*

Why measure M_t ?

1) free parameter of SM
   - **t** decays well before hadronizing ⇒ measure M_t directly from decay products
   - we usually compare to Monte Carlo expectations, so what we really measure is M_t^{MC} parameter
   - there are 'standard methods' and 'alternative methods' (based on specific features)
   - this is complemented by a pole mass measurement

Why measure M_t ?

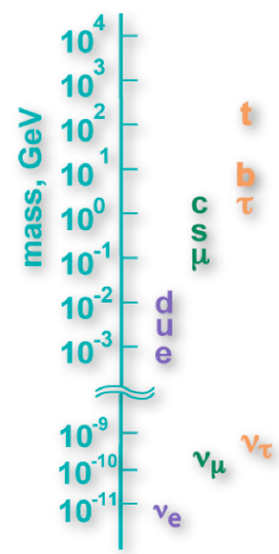
M_W vs M_t correlations not shown



EPJC 74 (2014) 3046, arXiv:1407.3792

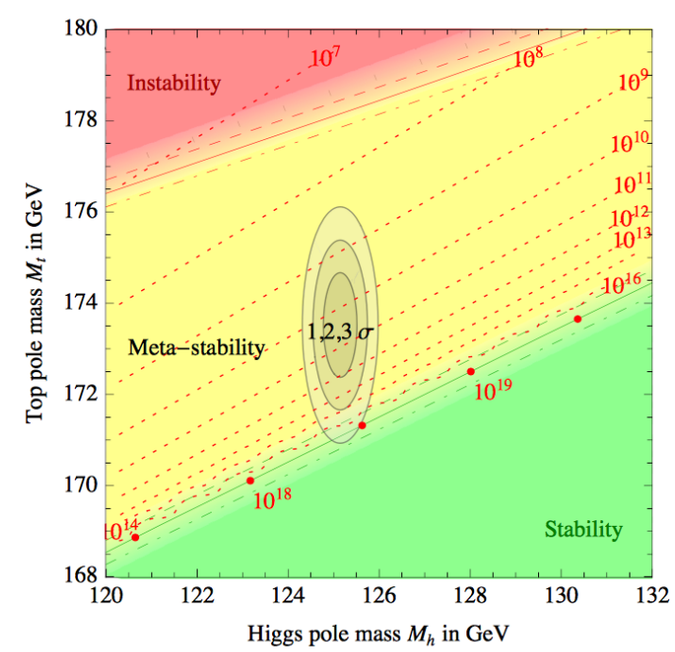
2) Participates in quantum loop radiative corrections to M_W constraining M_H
⇒ assessment of self-consistency within SM

3) M_t is close to scale of EWSB, so **t** might play a special role in it



4) M_t related with M_H and vacuum stability of SM (and of Universe): near criticality of M_H

arXiv:1307.3536



Latest results on M_t

There are several M_t measurements made so far by CMS at 7 and 8 TeV

We will discuss here only the most recent ones at 8 TeV (19.7 fb^{-1}):

- single top μ+jets
- boosted top
- pole mass
- “alternative” methods

Systematic uncertainties

Statistical uncertainties becoming smaller and smaller
⇒ systematic uncertainties become dominant

Different sources of systematics, related to:
- Experimental effects
- Signal modeling
- Background modeling
- Features of the method

For every source, measurements performed (usually with pseudo-experiments) with modified parameters:
change of M_t ⇒ syst. uncertainty

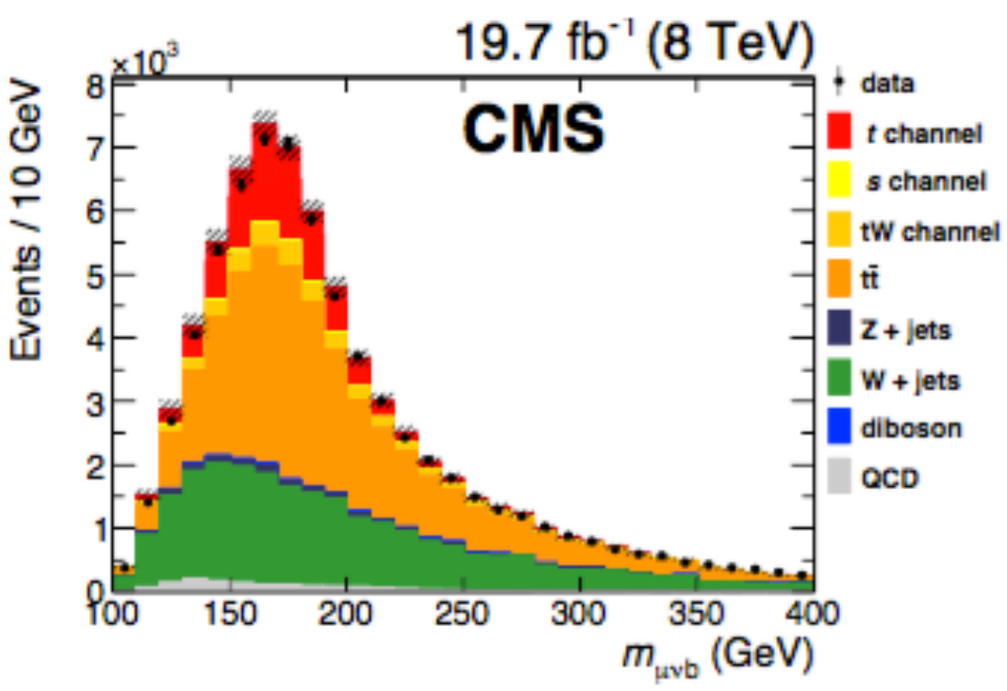
Single top: μ + jets

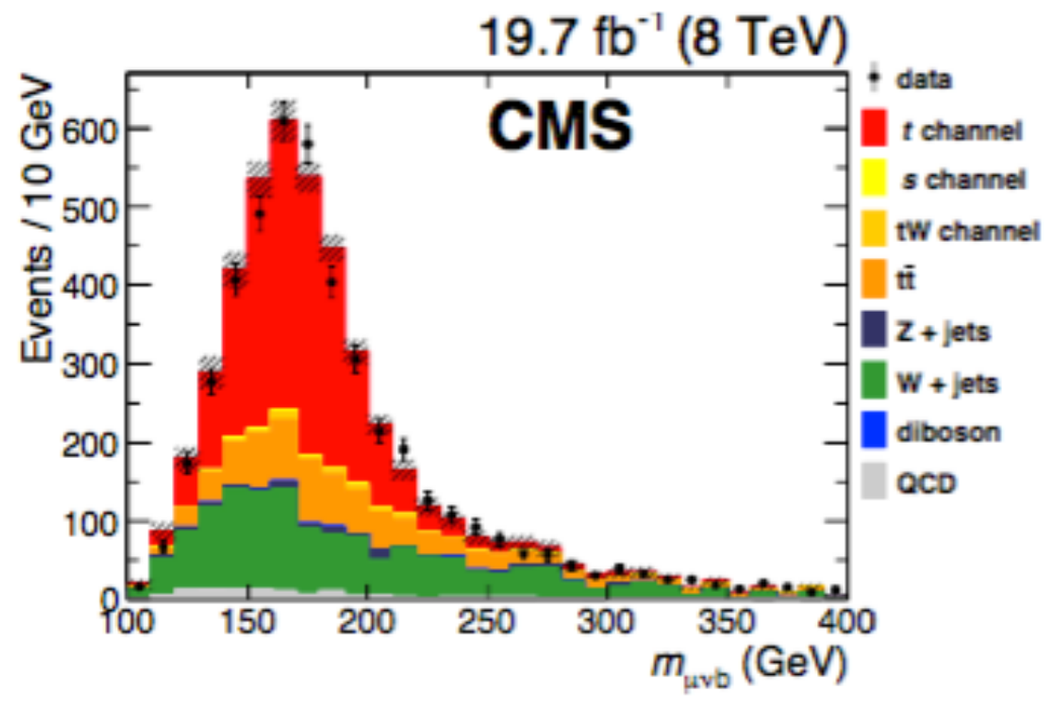
Template method ($m_{\mu\nu b}$)

EPJC 77 (2017) 354

Selection:
- 1 μ
- MET
- 2 jets (1 b-tagged)

- $m_{\mu\nu b}$ distributions as a proxy for m_t^{reco}
- μ charge >0 to improve S/B since $\sigma_t \sim 2\,\sigma_{/t}$
- light jet at large η expected from single top





~70%

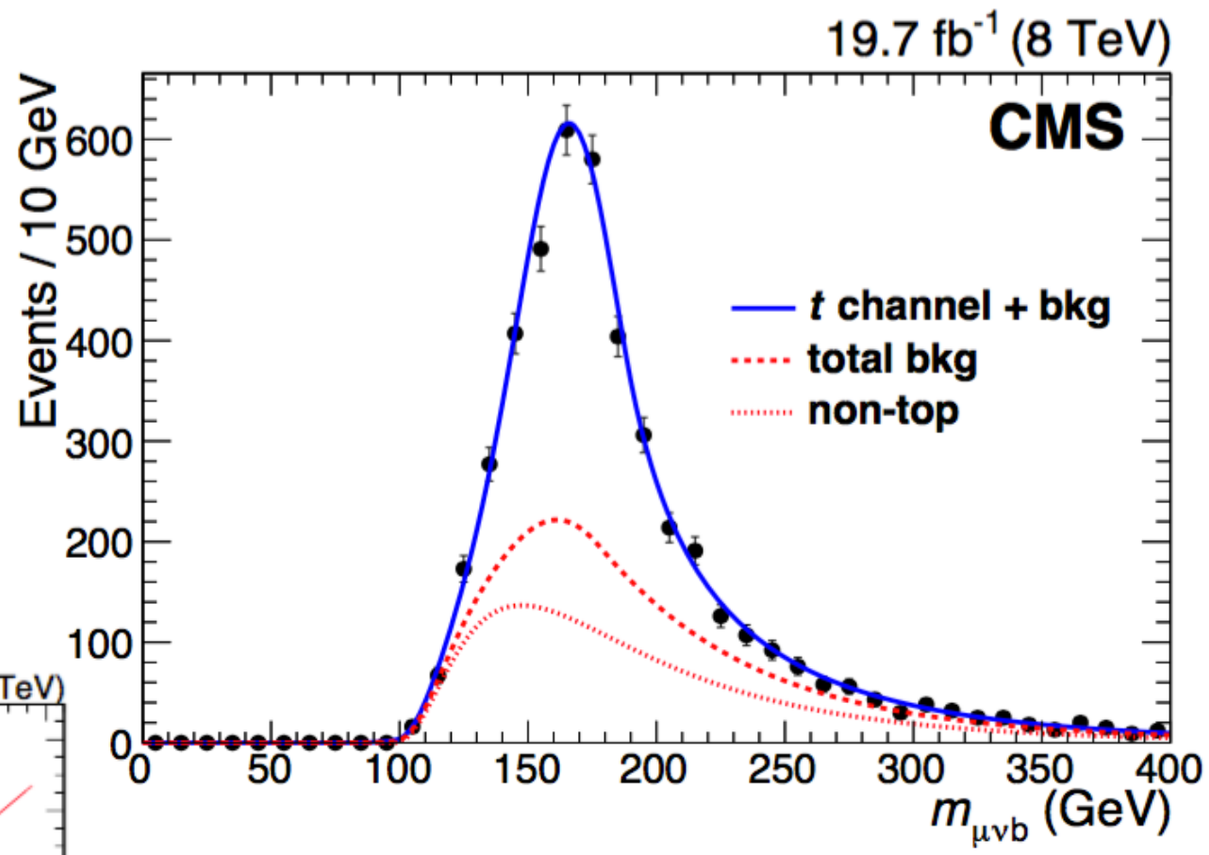
$q_\mu>0$ & $|\eta_j|>2.5 \Rightarrow$

Single top: μ + jets

Template method ($m_{\mu\nu b}$)

$m_{\mu\nu b}$ parametrization
Gaussian core (μ,σ)+ tails:
- t: Crystal Ball
- tt: Crystal Ball
- non-t: Novosibirsk

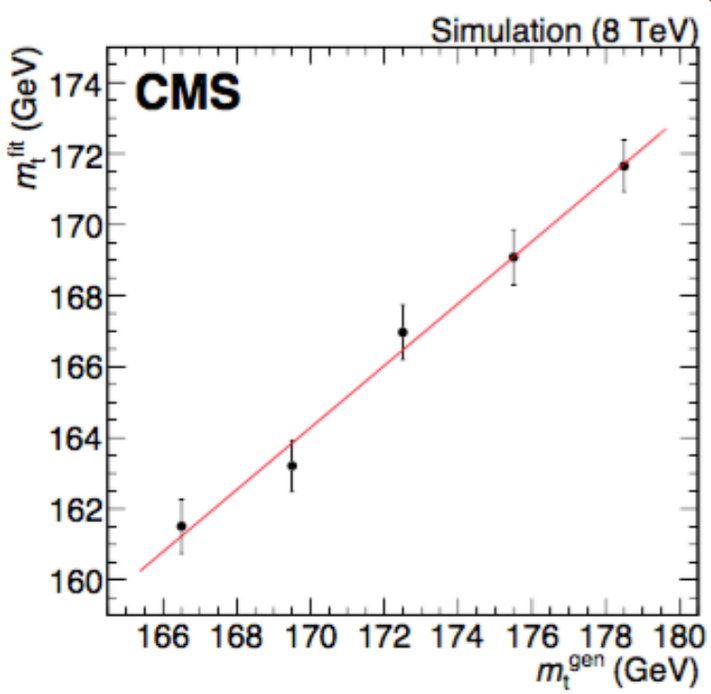
Calibration for the mass parameter μ



Main systematics

source	GeV
JES	0.68
bkgd	0.39
fit calibration	0.39

μ



Fit

M_t=172.95±0.77(stat)+0.97−0.93(syst) GeV

M_t=172.95±1.24 GeV (±0.72%)

TOP2017

Boosted top: e/μ + jets

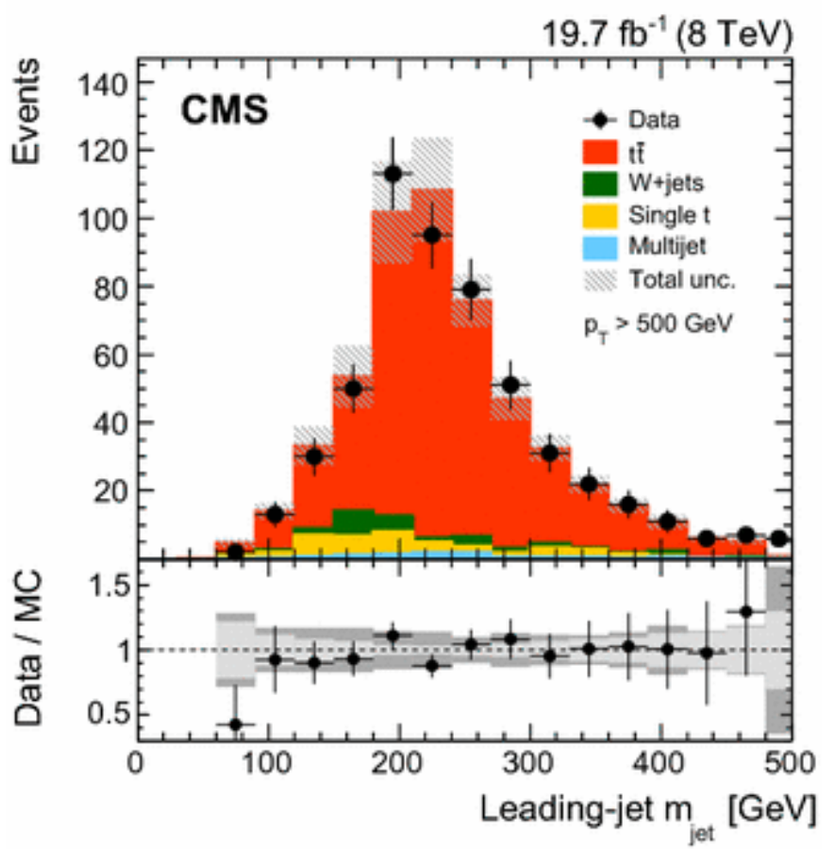
Template method (m_{jet})

EPJC 77 (2017) 467

Selection:

- 1 e or μ
- ≥2 narrow jets (≥1 b-tagged)
- ≥2 wide jets
- MET

The M_t-sensitive quantity is the leading-jet mass

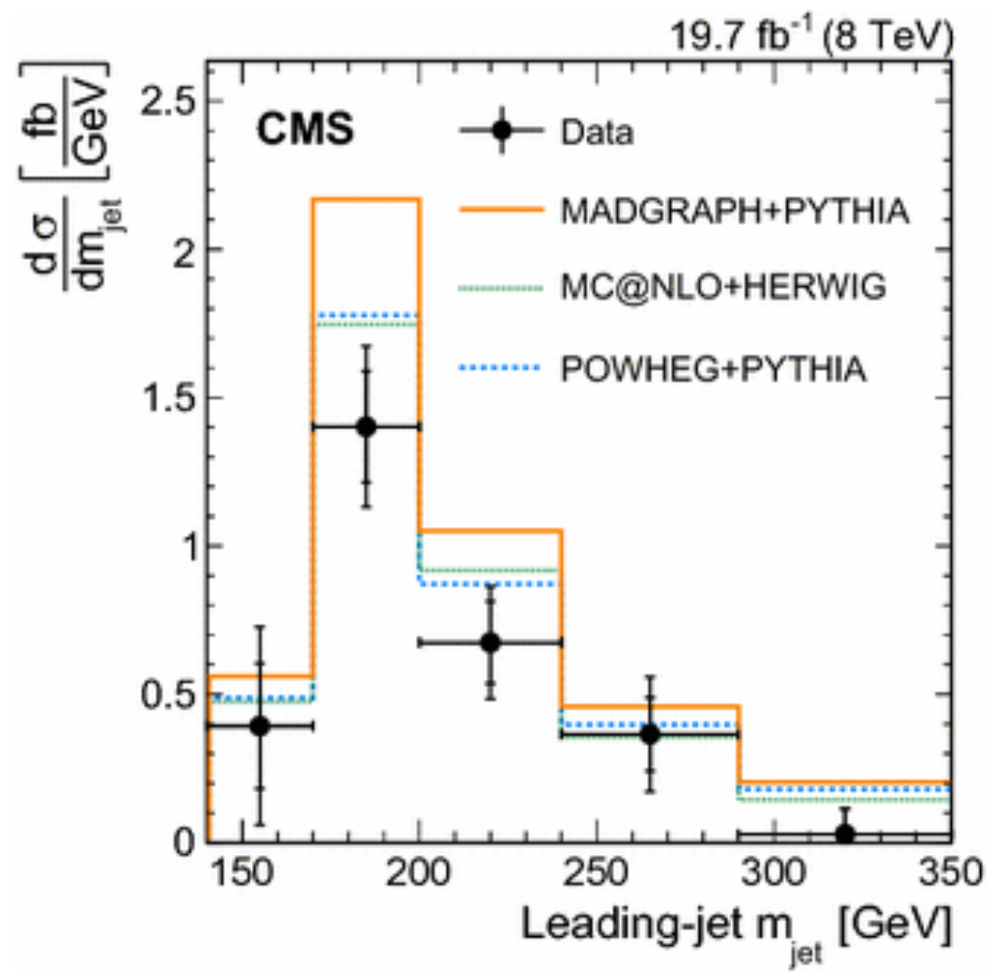


p_T>500 GeV

dσ/dM

⇒

Distributions are translated (unfolded) from reconstruction to particle-level (fiducial)



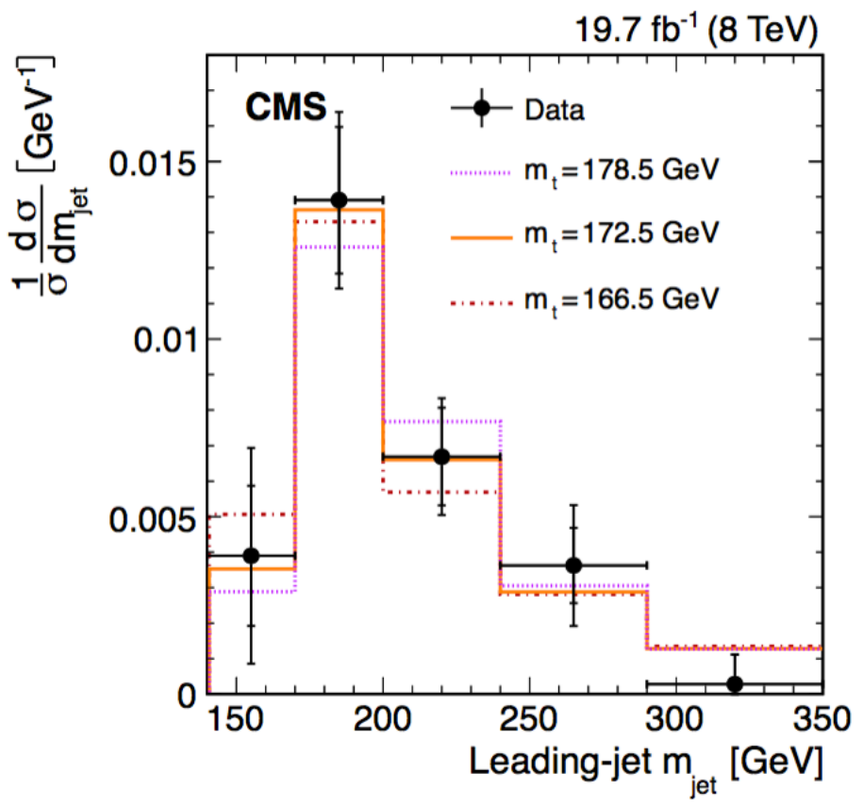
$\sigma_{fid}^{obs} \approx (0.7–0.8)\sigma_{fid}^{th}$

TOP2017

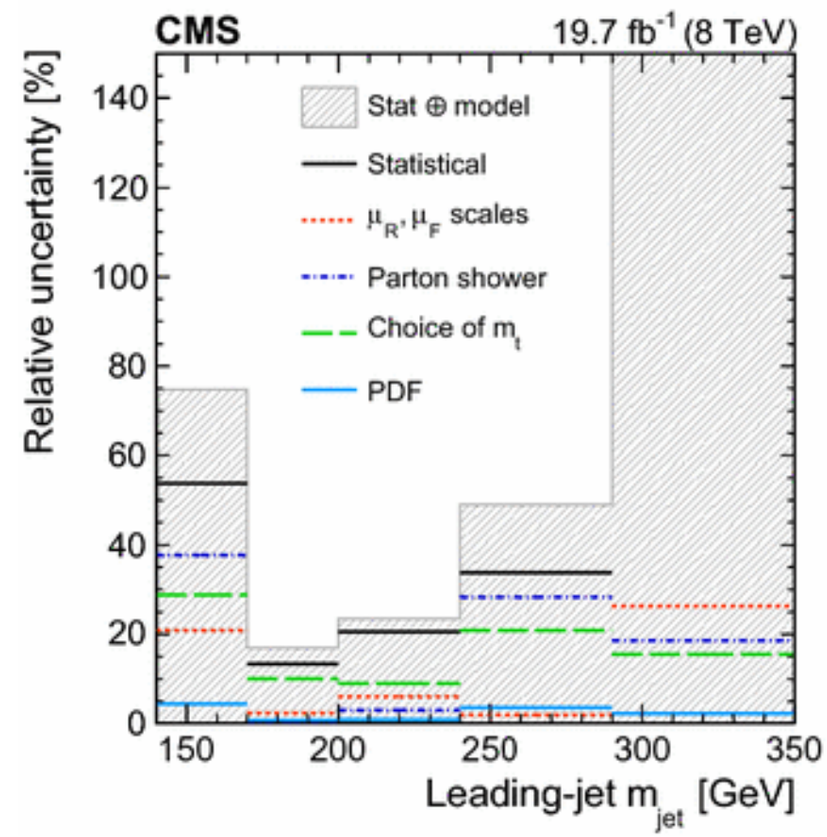
Boosted top: e/μ + jets

Template method (m_{jet})

Normalized differential cross section
(Madgraph+Pythia)



Uncertainties



Fit

M_t=170.8±6.0(stat)±2.8(syst)±4.6(model)±4.0(theory) GeV

M_t=170.8±9.0 GeV (±5.3%)

Method works but need more data, better modeling and higher-order calculations

What mass are we measuring?

The mass measured so far is the M_t^{MC} (typically LO or NLO) and is affected by perturbative/non-perturbative sub-1% uncertainties

The increasing level of accuracy requires to relate this to theory-based quantities like:

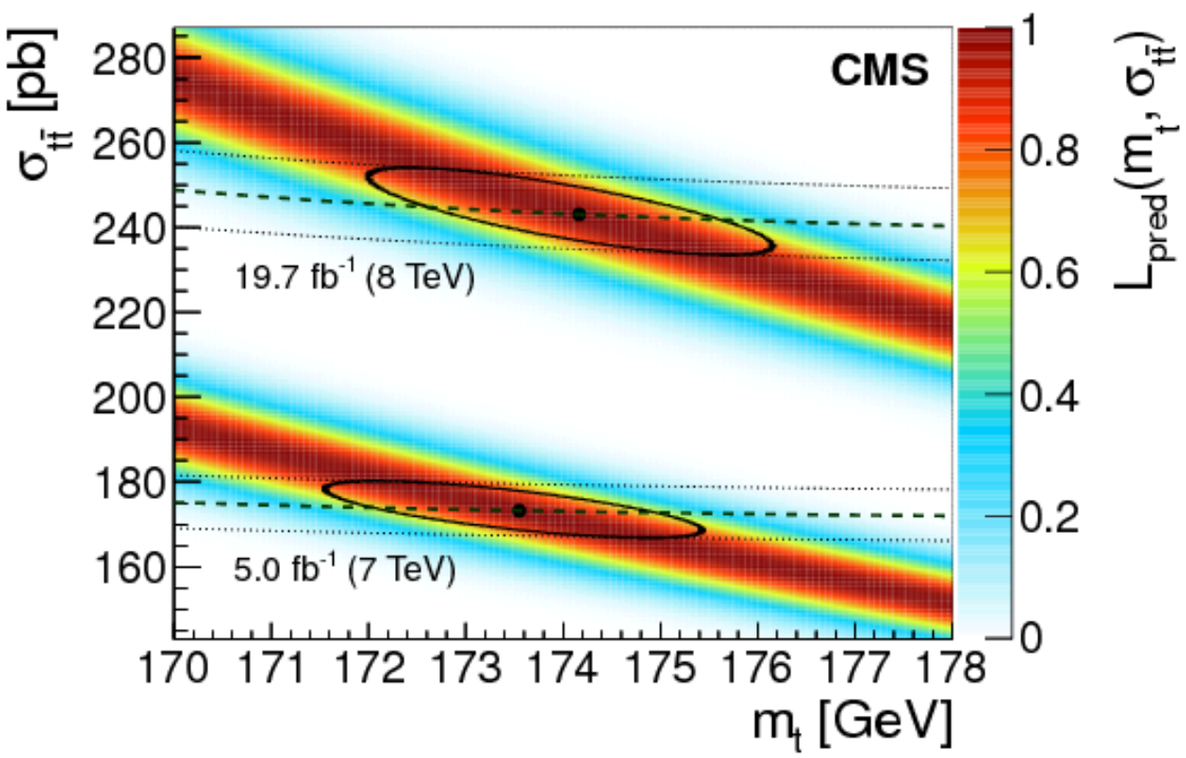
– the *pole mass*, universal but theoretically ambiguous by amounts $\mathbf{O}(\Lambda_{QCD})$ due to soft gluon radiation (*infrared renormalon problem*)

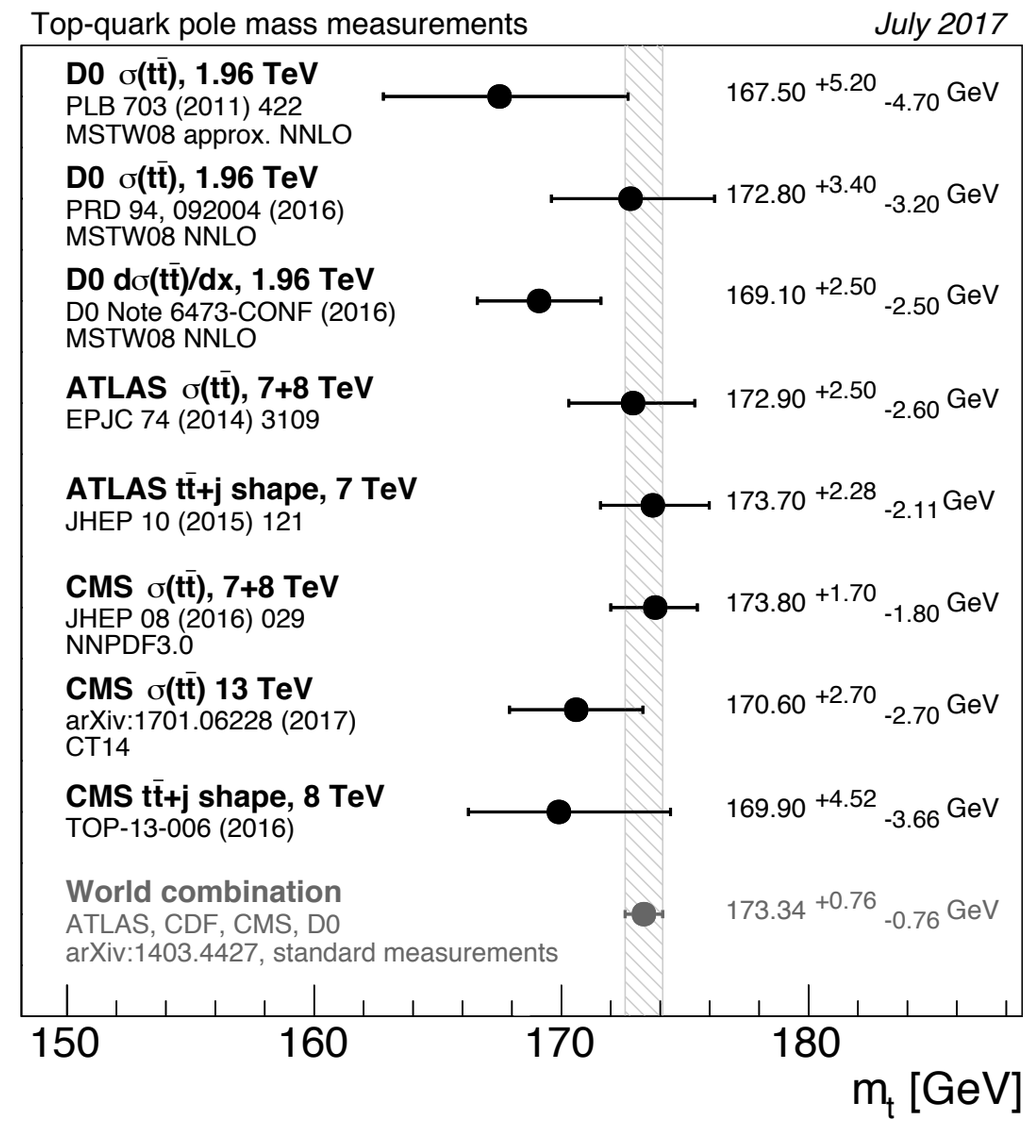
– *Lagrangian masses*, theoretically unambiguos but not universal, like the *MS mass* which is defined only in perturbation theory

Pole mass

JHEP 08 (2016) 029

M_t^{pole} can be derived from σ_{tt} cross section measurements compared to NNLO (but need to assume M_t^{MC})





Syst. dominated by PDF and lumi

1% precision, but could reach 0.5% (CMS-PAS-FTR-16-006)

M_t^{pole}=173.8+1.7−1.8 GeV

Alternative methods

The precision of the standard measurements depends strongly on the hadronization modeling

To improve it we can use cleaner observables, i.e. avoid jets

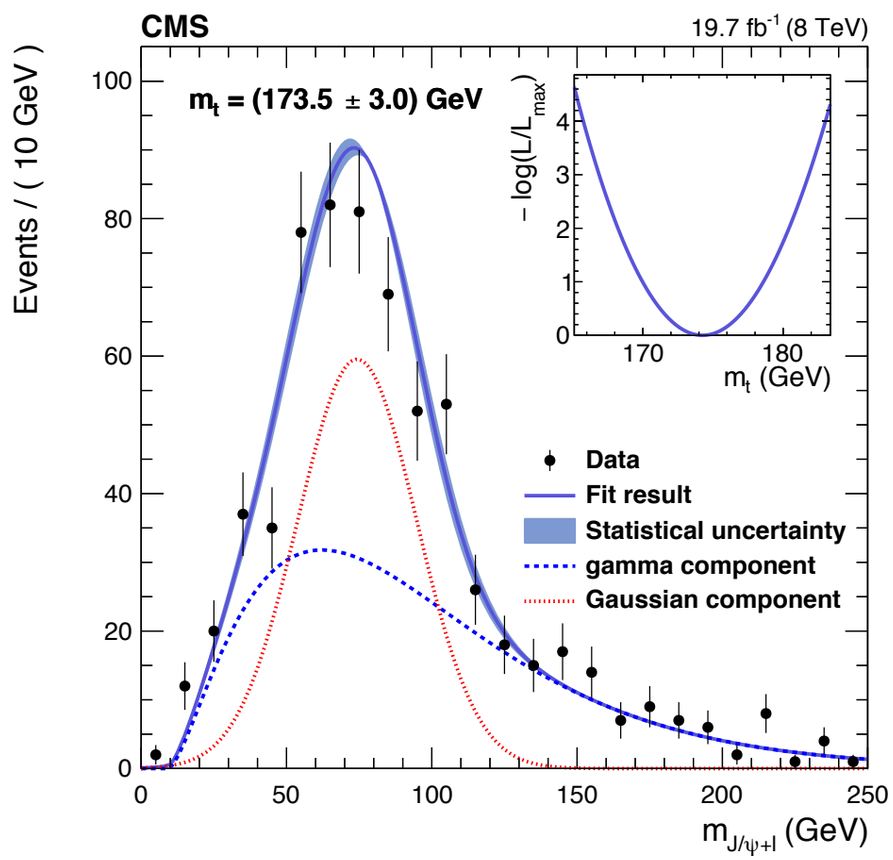
M_t can be derived from observables other than the reconstructed mass, like for instance:

- lepton + J/Ψ mass
- lepton + secondary vertex mass
- mass observables: $M_{b\ell}$, M^{bb}_{T2}, $M_{b\ell\nu}$

Lepton+J/Ψ

JHEP 12 (2016) 123

The M_t-sensitive quantity is the lepton+J/Ψ mass



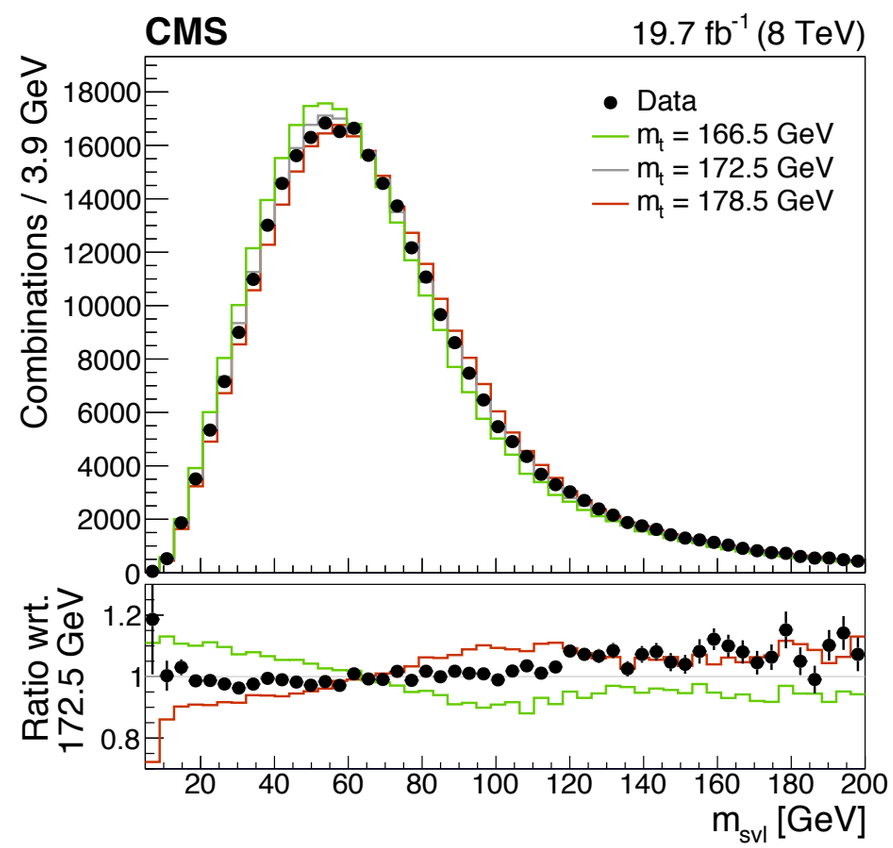
Limited by statistics, top p_T modeling and QCD scales

M_t=175.3±3.0(stat)±0.9(syst) GeV

Lepton+sec.vertex

PRD 93 (2016) 092006

The M_t-sensitive quantity is the lepton+S.V. mass in bins of track multiplicity



Limited by b-fragmentation and top p_T modeling

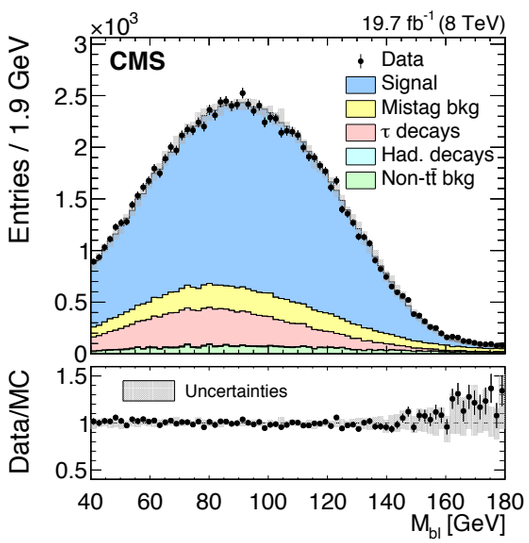
$M_t = 173.68 \pm 0.20\ (\text{stat})^{+1.58}_{-0.97}\ (\text{syst})$ GeV

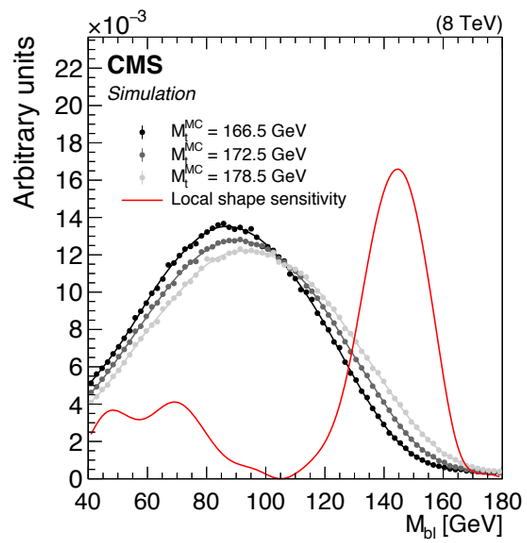
Mass observables: 2e/μ + jets

PRD 96 (2017) 032002

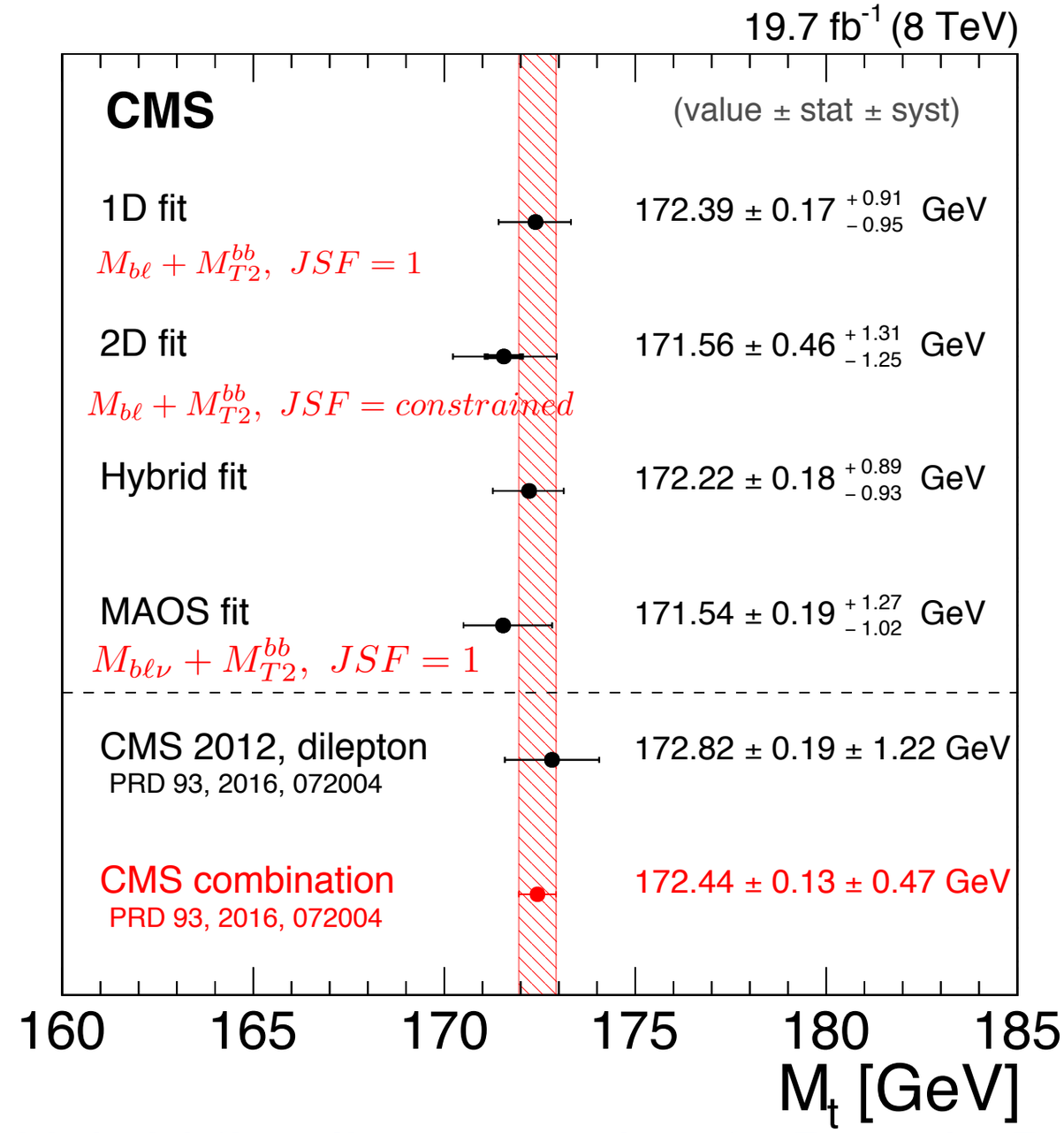
The M_t-sensitive quantities M_x are:

$$M_{b\ell} \qquad M_{T2}^{bb} \qquad M_{b\ell\nu}$$





3D (M_x, M_t,JSF) non-parametrical modeling of these distributions



Hybrid fit = linear comb. of 1D and 2D

Systematics dominated by JES, b fragmentation and top p_T reweighting

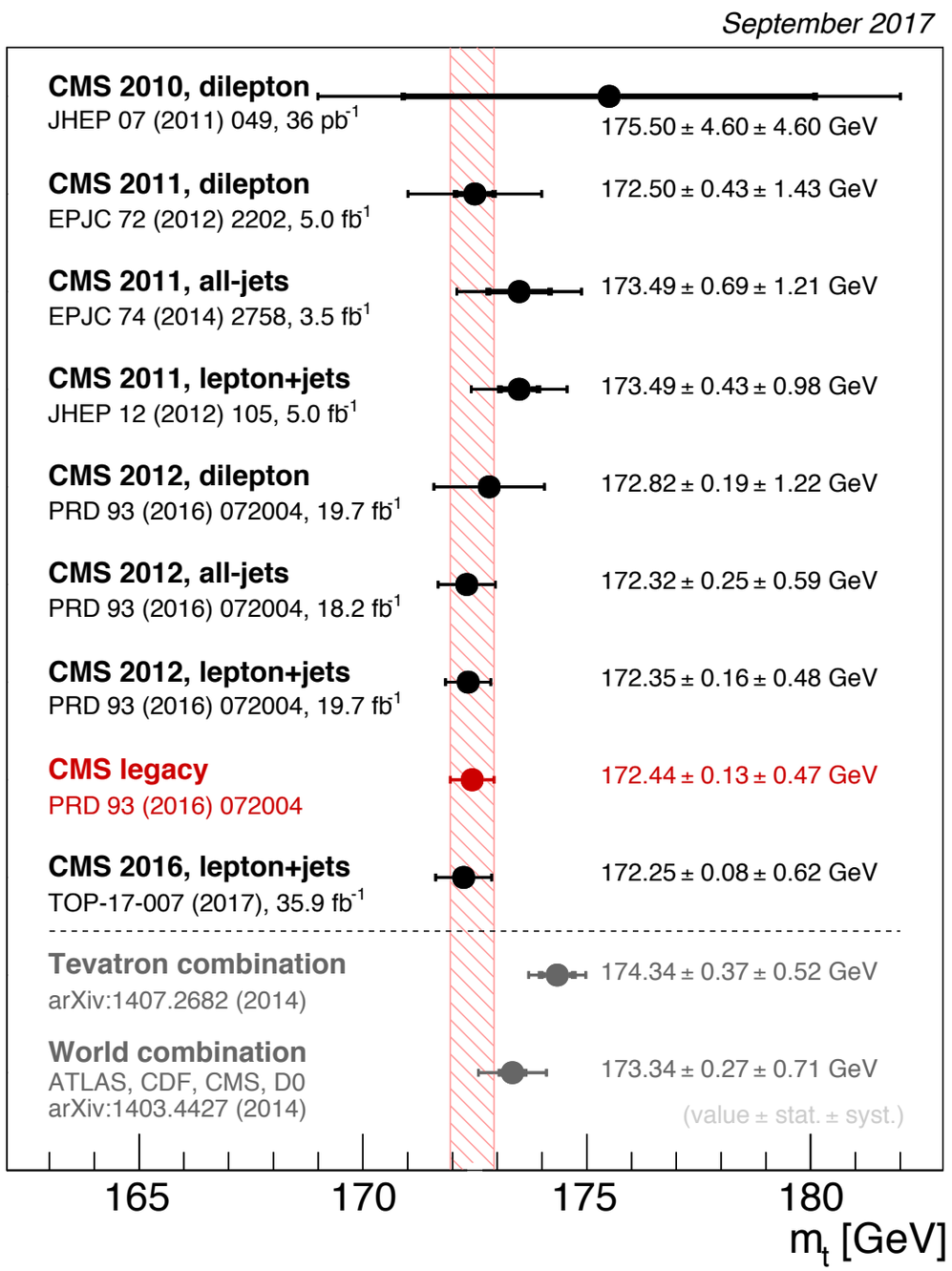
$M_t = 172.22 \pm 0.18\ (stat)^{+0.89}_{-0.93}\ (syst)$ GeV

M_t combinations

The individual measurements are then combined into experiment/world averages to gain in precision

Results computed with the Best Linear Unbiased Estimator, accounting for correlations ρ in the systematics (ρ signs are relevant for large systematics)

7+8 TeV combination



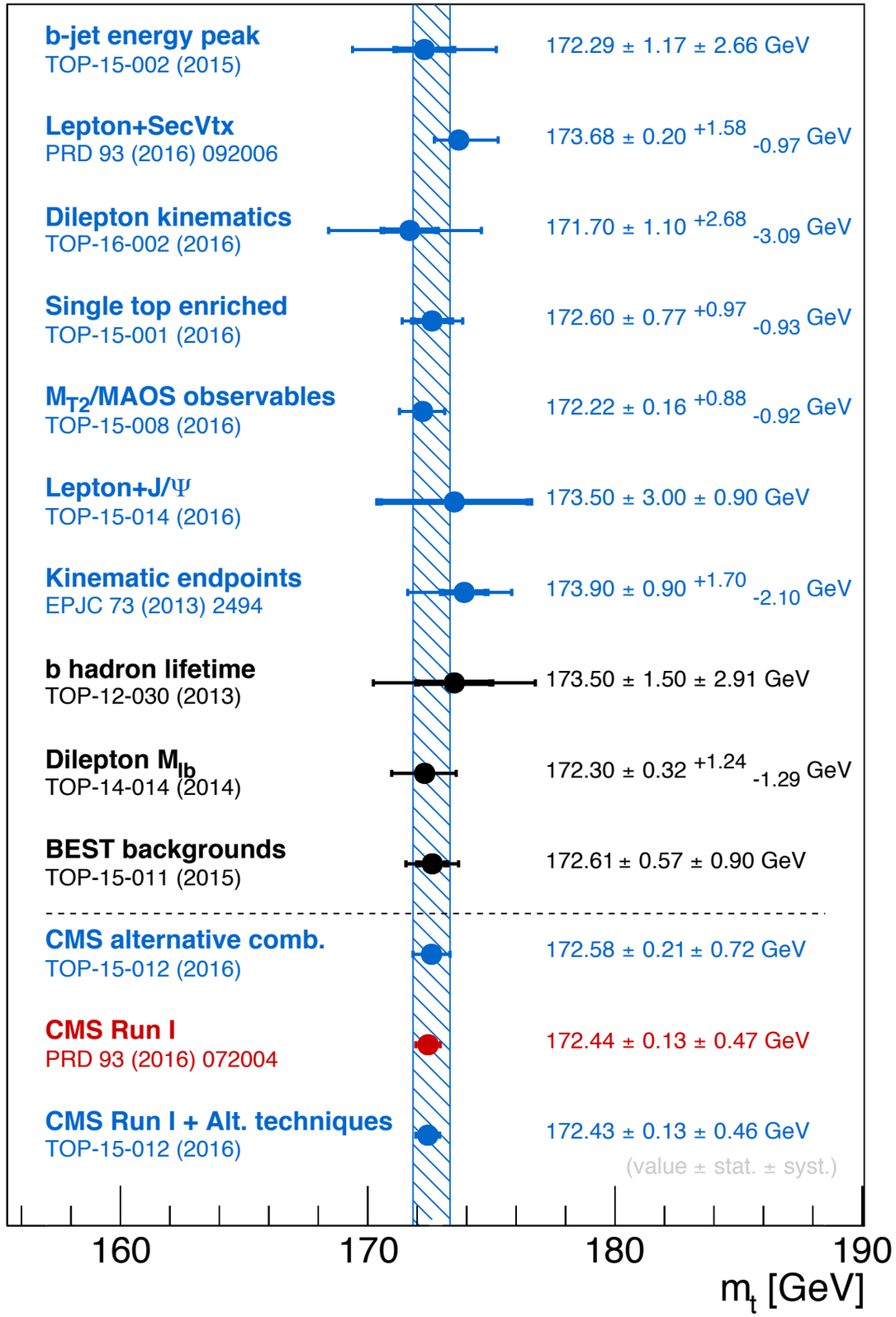
PRD 93 (2016) 072004

- Several decay channels pursued (some with in situ JSF)
- Different main systematics
- Combination to check consistency and increase precision

September 2015 value:

M_t=172.44±0.13(stat)±0.47(syst) GeV

M_t=172.44±0.49 GeV (±0.28%)



7+8 TeV alternative methods

CMS-PAS-TOP-15-012

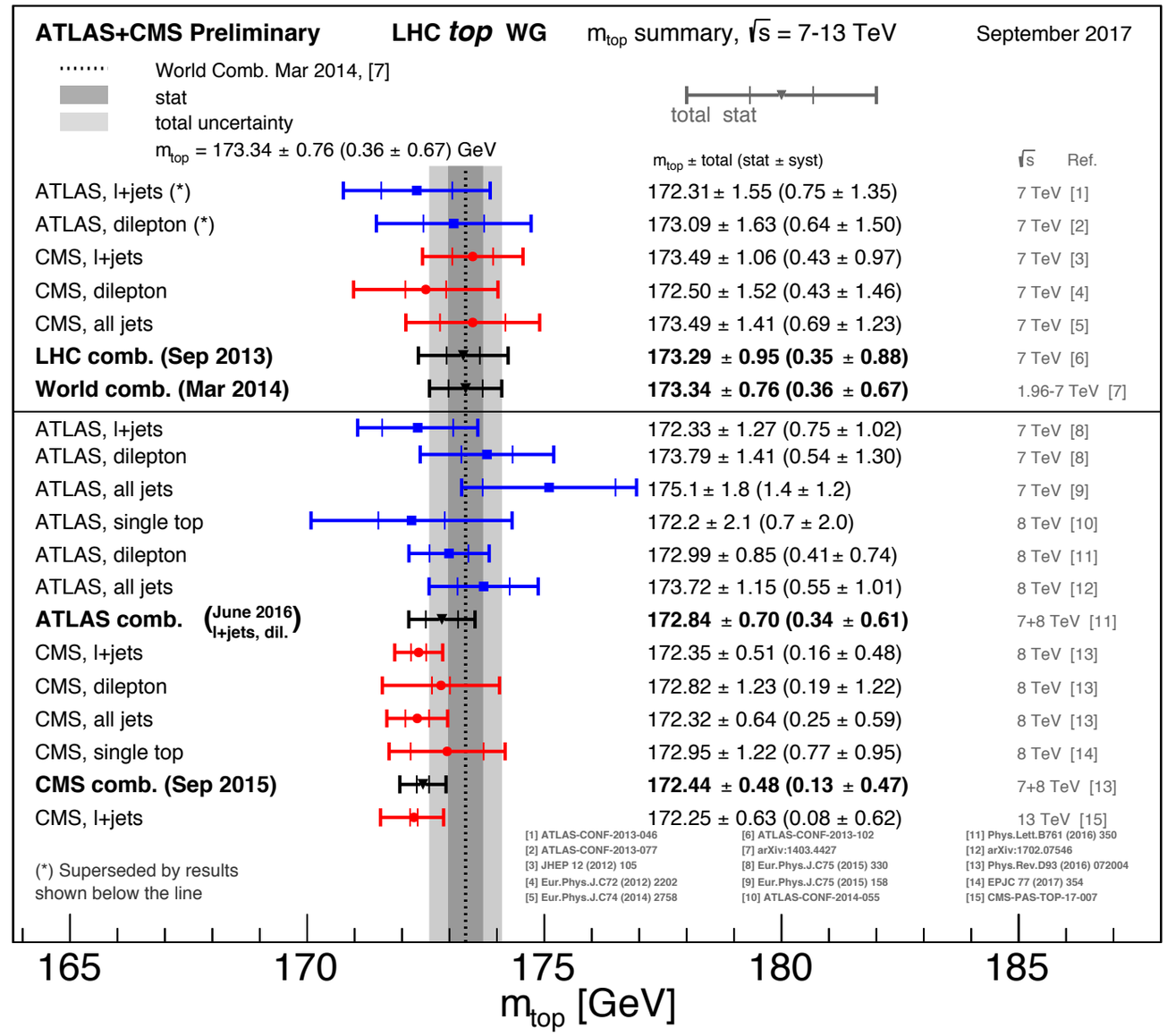
Slightly less precise (0.4%) than the standard measurements

Independent verification with different systematics

$M_t = 172.58 \pm 0.21\ (\text{stat}) \pm 0.72\ (\text{syst})$ GeV

World combination

Combination of all ATLAS+CMS (7+8 TeV) + Tevatron results computed accounting for correlations in the systematics



March 2014 value:
arXiv:1403.4427

M_t=173.34±0.36(stat)±0.67(syst) GeV
M_t=173.34±0.76 GeV (±0.44%)

Tevatron 2016 combination
174.30±0.65 GeV
arXiv:1608.01881

@13 TeV: e/μ + 4 jets

Ideogram method

2D fit (m_t^{reco}, m_W^{reco})

w. in situ JSF (35.9 fb^{-1})

CMS-PAS-TOP-17-007

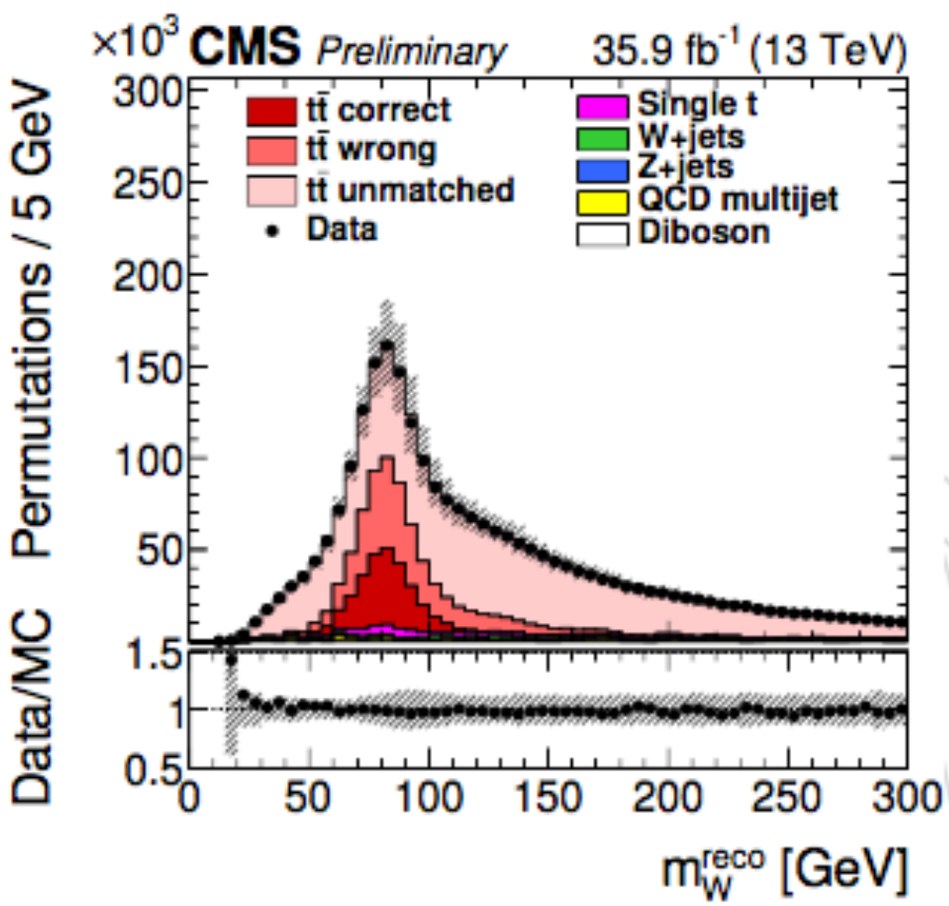
Selection:

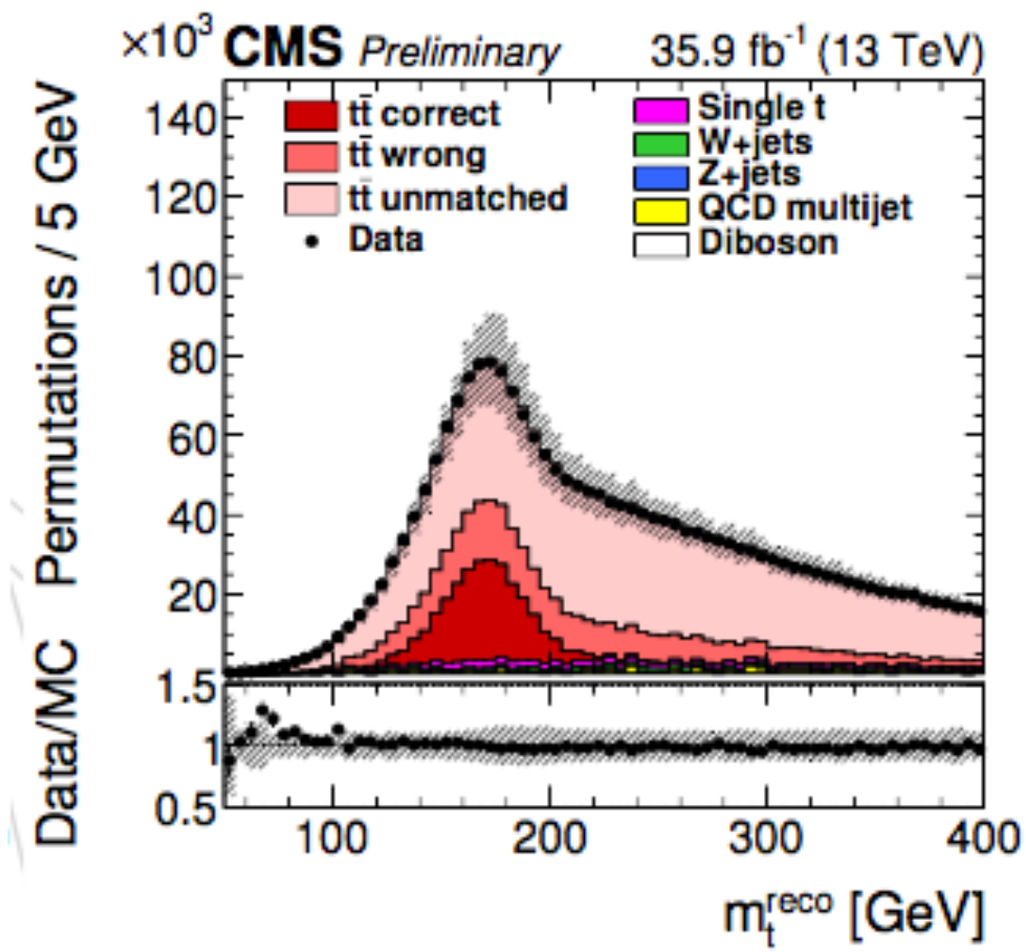
- 1 e or μ
- ≥4 jets (2 b-tagged)

Kinematic fit to the tt→WbWb hypothesis

Possible combinations treated separately:

- correct:
- wrong:
- unmatched

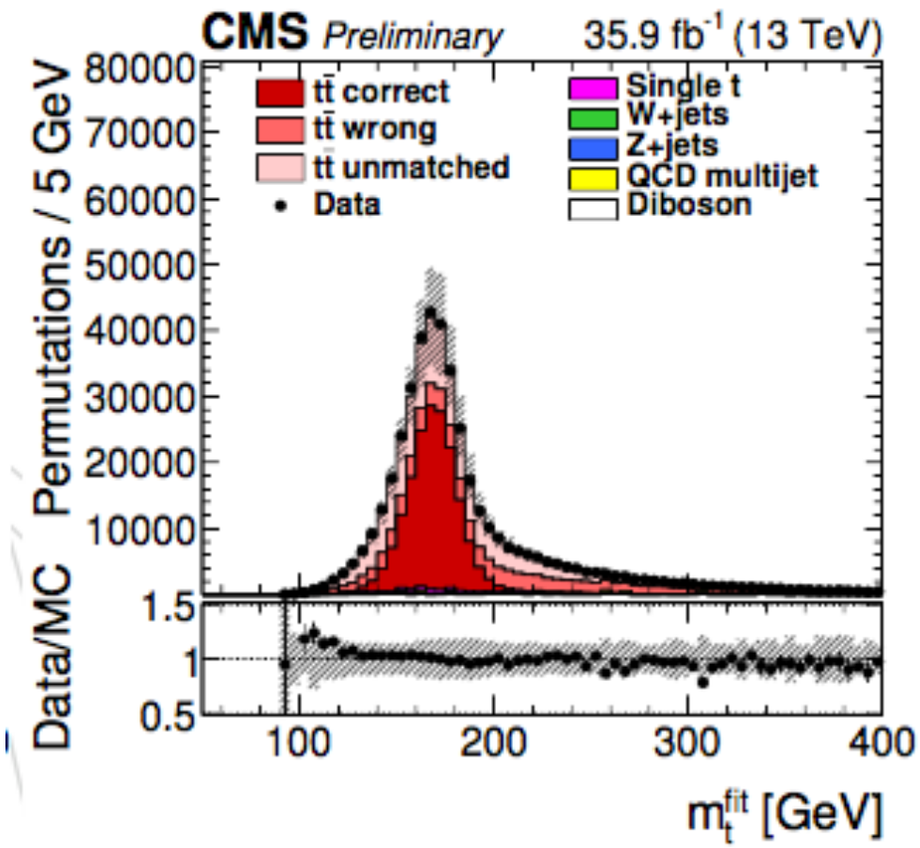


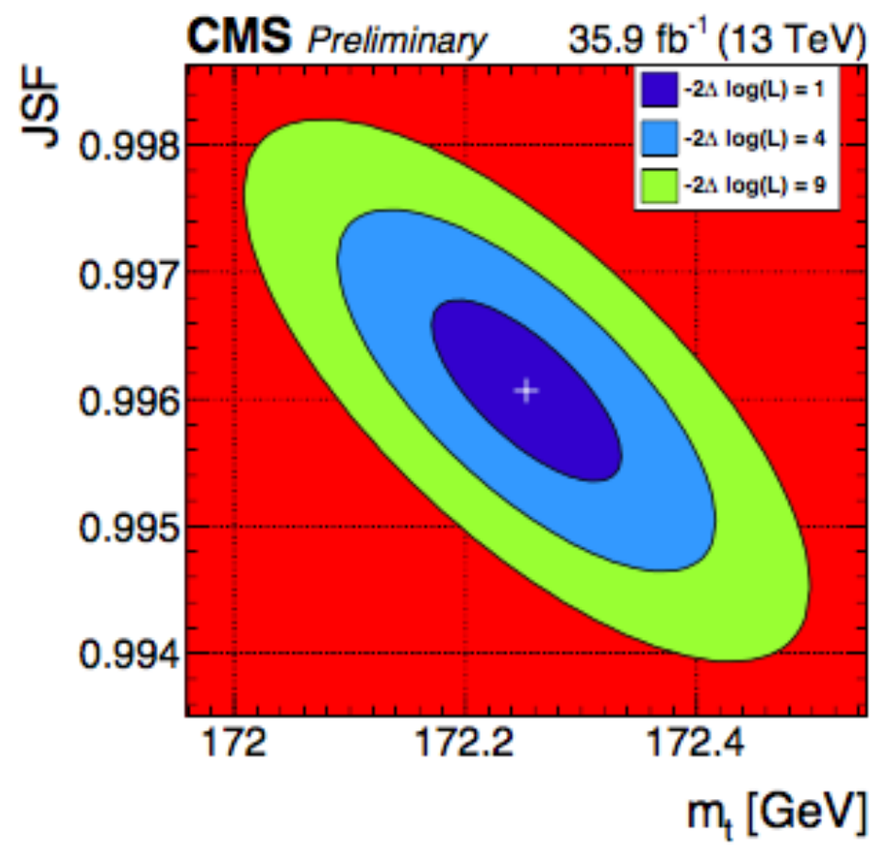


@13 TeV: μ + 4 jets

Ideogram method (m_t^{reco}, m_W^{reco})
w. in situ JSF

See E. Yazgan's talk





Main systematics

source	GeV
flavor JEC	0,39
color reconn.	0,31
ME generator	0,22

Multiple permutations weighted by $P_{gof}=\exp(-\chi^2/2)$

$P_{gof}=\exp(-\chi^2/2)>0.2$
to favor the correct combin.

Hybrid Fit

M_t=172.25±0.08(stat+JSF)±0.62(syst) GeV

M_t=172.25±0.63 GeV (±0.36%)

JSF = 0.996±0.008

Conclusions

- Level of precision reached (<0.3%) in measuring M_t impressive but comes from 22 years of continuous improvements
- Even better precision expected from Run2; single top events and boosted top can contribute
- Inclusion of alternative methods will improve precision
- Test of the consistency of the SM, vacuum stability and new physics

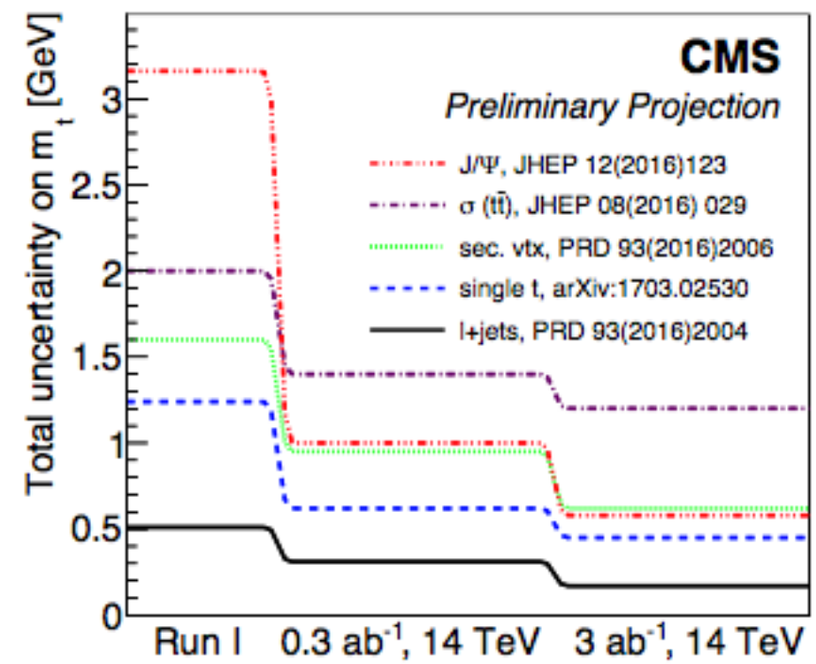
Important to work on reducing systematics
e.g. those related to theory and signal modeling

Outlook

Run1 legacy measurements of M_t being completed
⇒ published soon

CMS-PAS-FTR-16-006

Ultimate precision of few hundreds MeV expected merging measurements/experiments, accounting for correlations and taking advantage of improvements in MC modelling



Differences between M_t^{MC} and theoretical definitions (pole mass, Lagrangian mass): important issue to deal with

Backup

Methods for measuring M_t

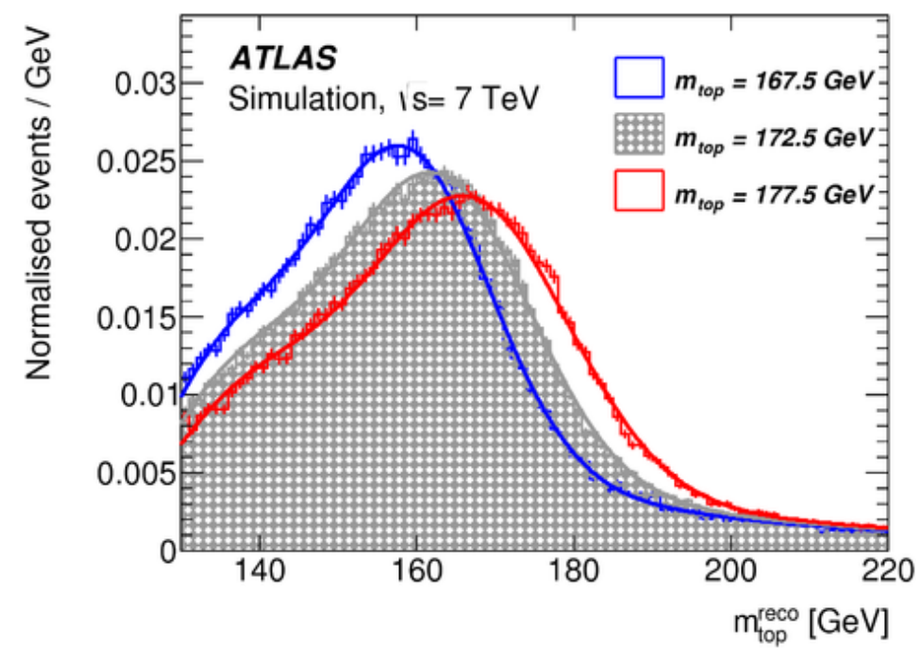
1) *Template method:* distributions of variables sensitive to M_t, e.g., reconstructed M_t^{reco} from χ^2 fit to WbWb

Pdf's derived for MC events assuming different M_t^{MC}; parametrized vs M_t

Likelihood from pdf's; outcome calibrated for biases (pull-mean and pull-width of pseudo-experiments)

M_W templates for in-situ calibration of JES

Possible to add constraints on b-jet JES



Relatively simple, fast, but non optimal statistical uncertainty

Methods for measuring M_t

2) *Ideogram method:* modification of template method using multiple permutations with different weights

Starts from kinematical reconstruction, then computes event likelihood as a function of M_t

Different pdf's used for different jet-quark assignments

Event likelihoods (ideograms) are given by

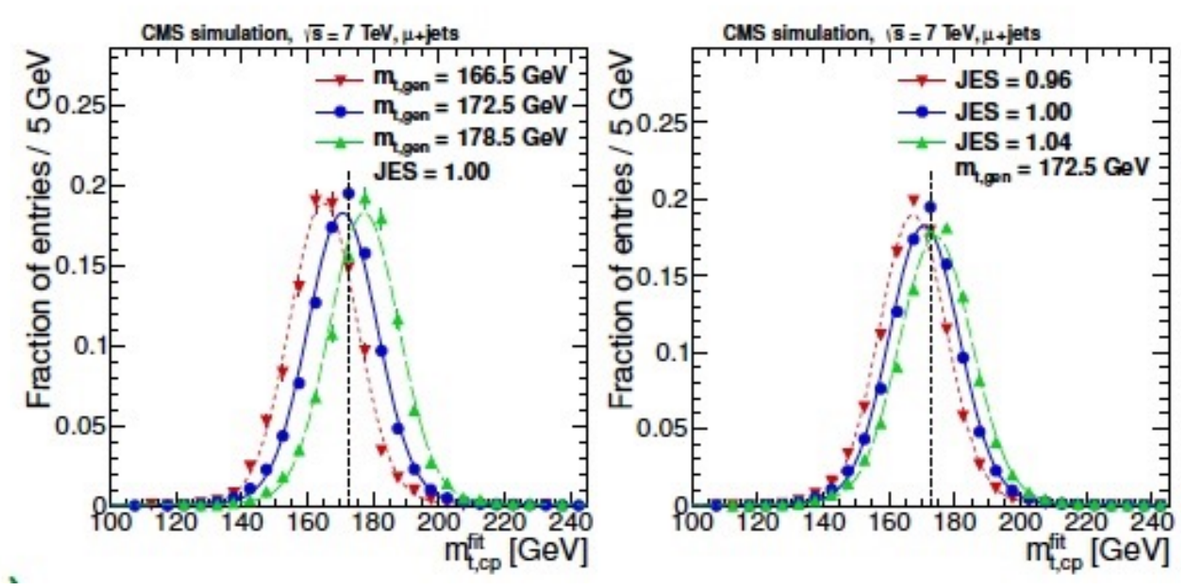
$$\mathcal{L}\left(\text{event}|m_t,\text{JSF}\right) = \sum_{i=1}^{n} P_{\text{gof}}(i)\left\{f_{\text{sig}}P_{\text{sig}}\left(m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}}|m_t,\text{JSF}\right) + \left(1-f_{\text{sig}}\right)P_{\text{bkg}}\left(m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}}\right)\right\}$$

$P_{gof}=\exp(-\chi^2/2)$

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

$w_{event}=\sum P_{gof}(i)$

$P_{sig}^{cp}(m_t^{fit}|M_t,JSF)$



Gaussian process regression technique

GP shape determined by:

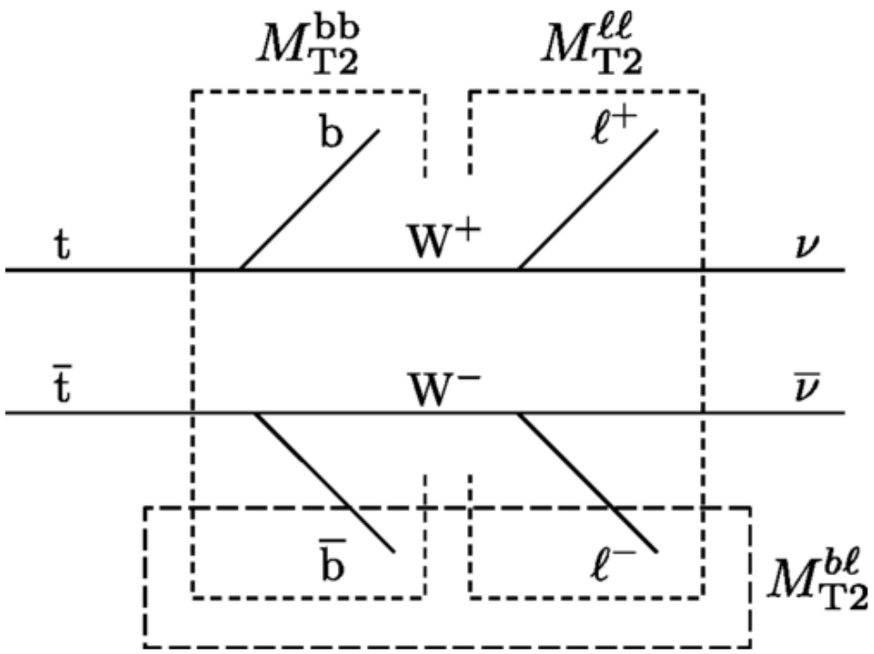
- a set of training points
- smoothing parameters
- 35 binned distributions (7 bins for M_t, 5 for JSF, 75 for M_x)
- Gaussian = values in each point are Gaussian distributions

Mass observables: M_{T2}^{bb}

$$M_{\mathrm{T}} = \sqrt{m_\ell^2 + m_\nu^2 + 2(E_{\mathrm{T}\ell}E_{\mathrm{T}\nu} - \vec{p}_{\mathrm{T}\ell}\cdot\vec{p}_{\mathrm{T}\nu})},$$

$$M_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\mathrm{a}}+\vec{p}_{\mathrm{T}}^{\mathrm{b}}=\vec{p}_{\mathrm{T}}^{\mathrm{miss}}}[\max\{M_{\mathrm{T}}^{\mathrm{a}}, M_{\mathrm{T}}^{\mathrm{b}}\}],$$

Impose the constraint on the invisible particle momenta + preserve the kinematic endpoint



Systematic uncertainties

Experimental *(i.e. imperfect knowledge of)*:
- Jet Energy Scale (JES)
- b-Jet Energy Scale (bJES)
- jet energy resolution and reconstruction
- MET scale
- b-tagging scale factor
- lepton energy scale and reconstruction
- pileup
- trigger

Signal modeling *(i.e. imperfect knowledge of theory regarding)*:
- MC generator
- hadronization
- amount of ISR/FSR
- flavor-dependent hadronization
- b-quark fragmentation and BRs
- renormaliz./factoriz. scales
- PDF's
- Color reconnection
- Underlying event

Background modeling *(i.e. uncertainty on)*:
- MC normalization and shape
- normalization and shapes of data-driven backgrounds

Features of the method *(i.e. dependence on)*:
- parametrization of pdf's
- calibration
- MC statistics

Agreement between ATLAS and CMS is essential