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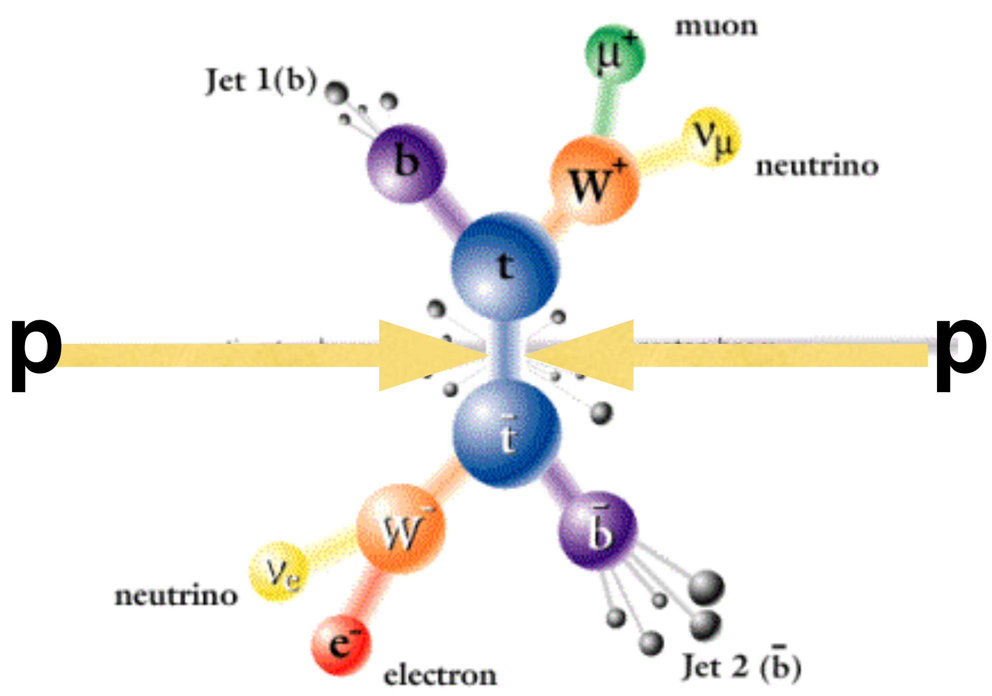
Top Mass measurements in ATLAS and CMS

On behalf of ATLAS and CMS collaborations

Blois2017

The top quark at LHC

$pp \rightarrow t\bar{t} \rightarrow W^{+}bW^{-}\bar{b}$



- **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 ($\sigma_t \sim \sigma_{tt}/3$)

- **Characterized by W decays**

  – dilepton (DIL, BR(DIL)≈5%, low yield, better S/B)

  – lepton + jets (LJ, BR(LJ)≈30%, golden channel, good yield and good S/B)

  – all-jets (AJ, BR(AJ)≈45%, max yield, large bkgd)

All of them useful for completeness and with (some) uncorrelated systematics

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

Why measure M_t ?

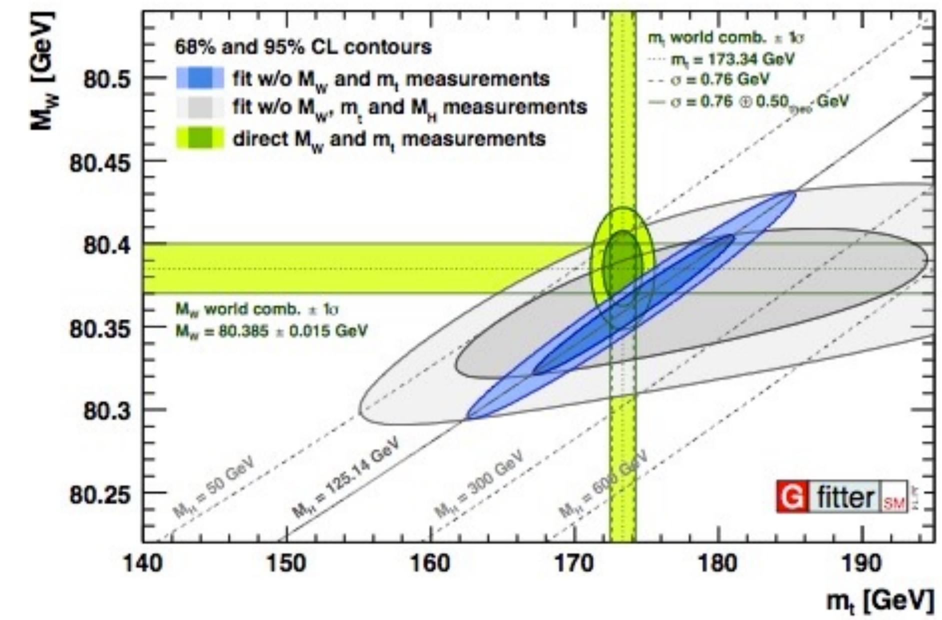
1) free parameter of SM

- **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 ?

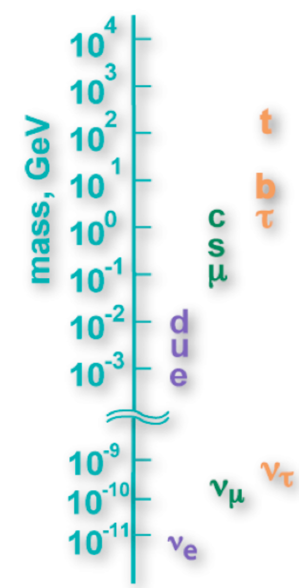
2) Participates in quantum loop radiative corrections to M_W constraining M_H
⇒ assessment of self-consistency within SM

M_W vs M_t correlations not shown



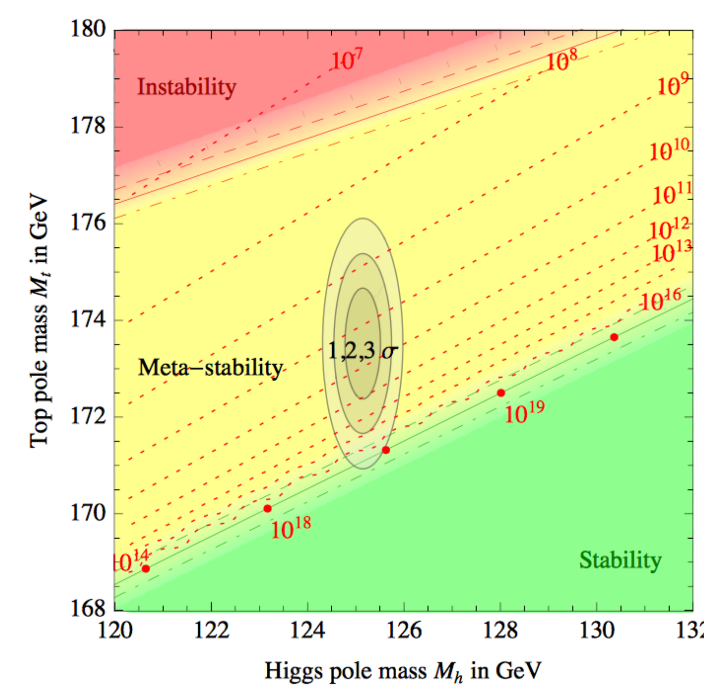
[EPJC 74 (2014) 3046, arXiv:1407.3792]

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]



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Latest results on M_t

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

We will discuss here only the most recent ones (2012, 8 TeV):

- ATLAS dilepton
- ATLAS all-had
- CMS single top μ+jets
- CMS boosted top
- pole mass

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

ATLAS dilepton

Template ($m_{\ell b}$)

(8 TeV, 20.2 fb^{-1})

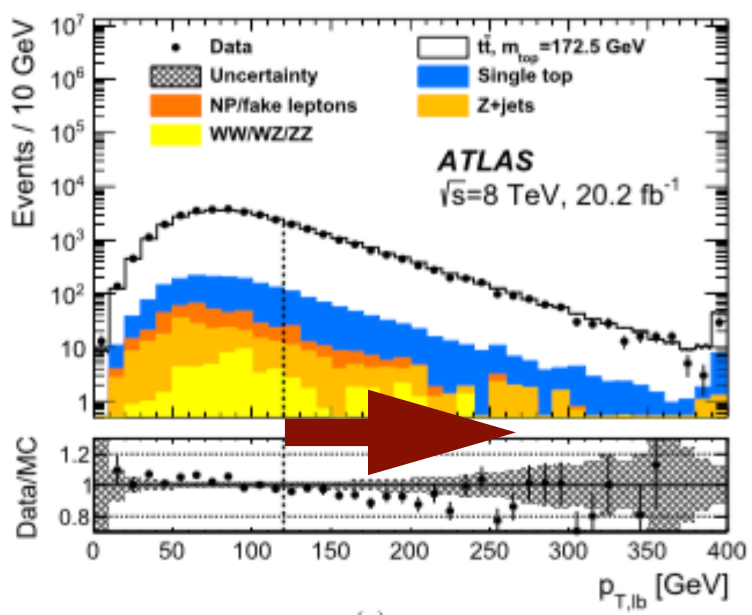
[PLB 761 (2016) 350](#)

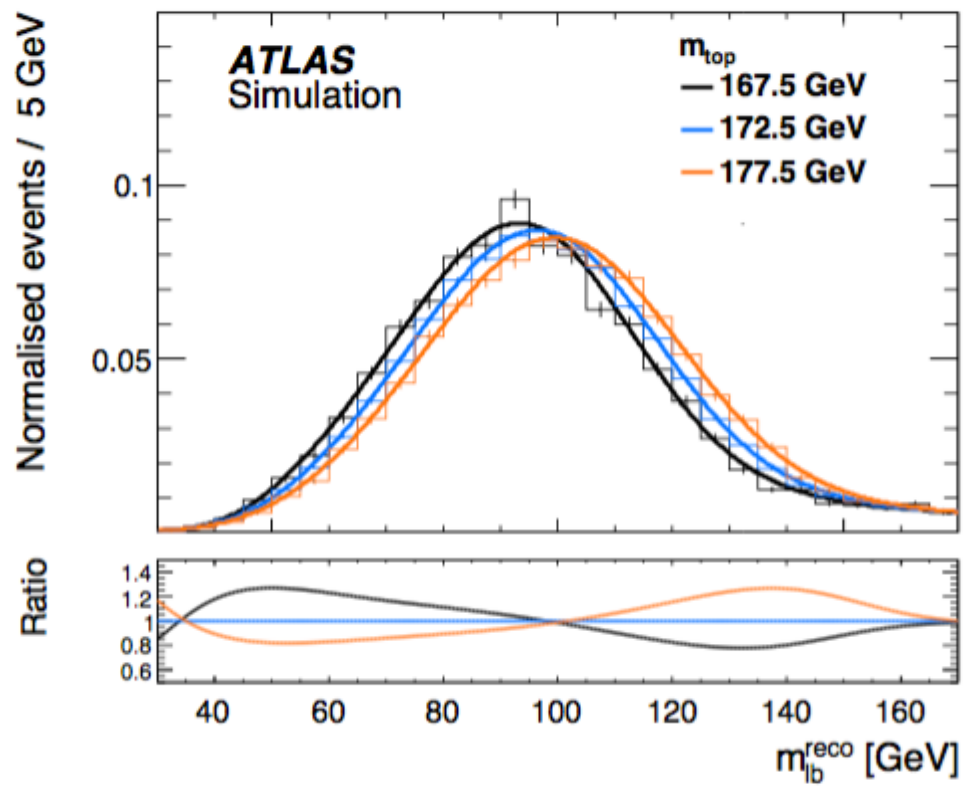
[arXiv:1606.02179](#)

m(top) cannot be reconstructed so the M_t-sensitive quantity is the average ℓ-b invariant mass $m_{\ell b}$

Selection:

- 2 e/μ
- ≥2 jets (≥1 b-tagged)
- select ℓb pair minimizing $m_{\ell b}$ (~70% purity)
- cut on $p_T^{\ell b}$ to reduce total uncertainties





MC templates fitted with Gaussian + Landau with parameters depending linearly on M_t

ATLAS dilepton

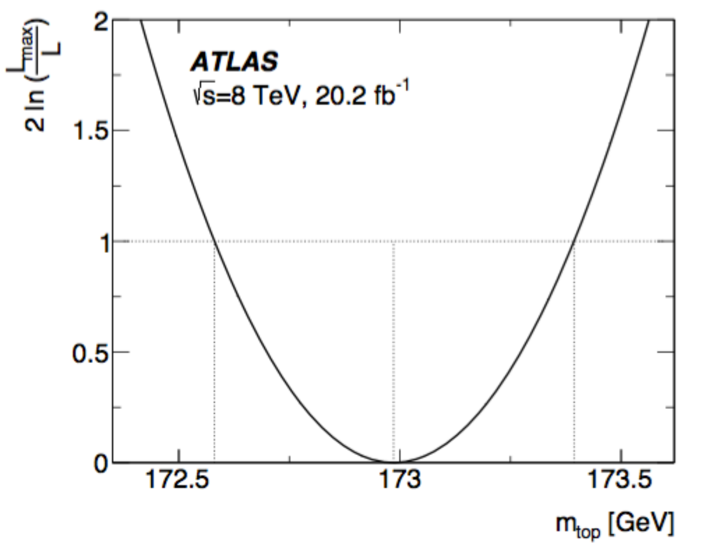
Template ($m_{\ell b}$)

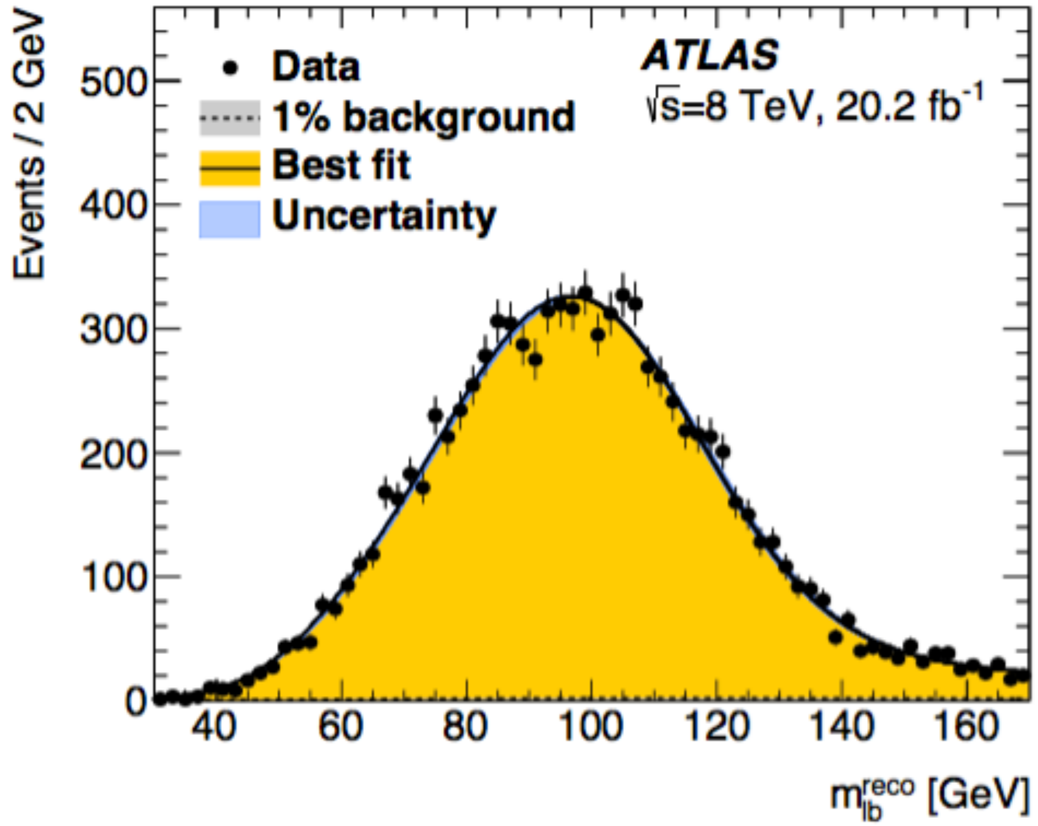
(8 TeV, 20.2 fb^{-1})

PLB 761 (2016) 350

arXiv:1606.02179

Best fit of the M_t parameter





Main systematics

source	GeV
JES	0.54
bJSF	0.30
ISR/FSR	0.23

M_t=172.99±0.41(stat)±0.74(syst) GeV

M_t=172.99±0.85 GeV (±0.49%)

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ATLAS all-jets

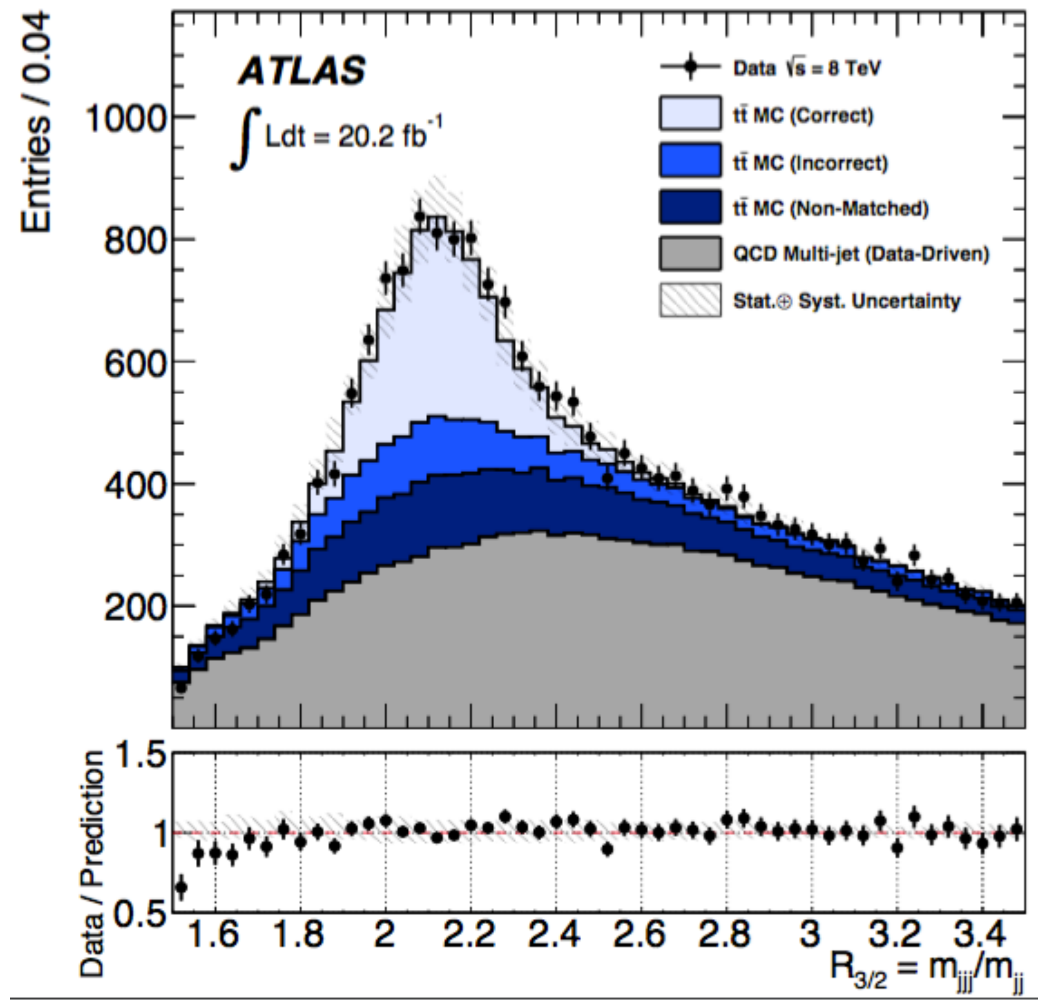
Template ($R_{3/2}$)
(8 TeV, 20.2 fb^{-1})

arXiv:1702.07546

Selection:

- ≥6 jets (≥2 b-tagged)
- lepton veto, MET
- select combination minimizing

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



The M_t-sensitive quantity is

$$R_{3/2} = \frac{m_{jjj}}{m_{jj}} = \frac{m_t^{reco}}{m_W^{reco}}$$

For $R_{3/2}$ significant cancellation of uncertainties on JES and hadronic modeling

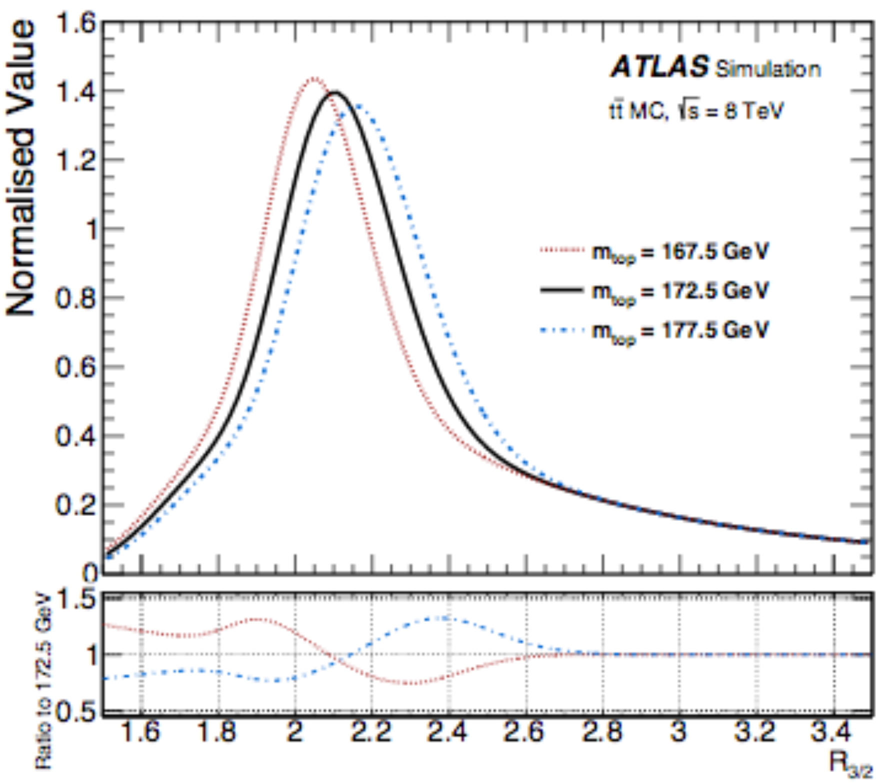
Data-driven bckgd using control regions in $<\Delta\phi_{bW}>$ and N_{btag}

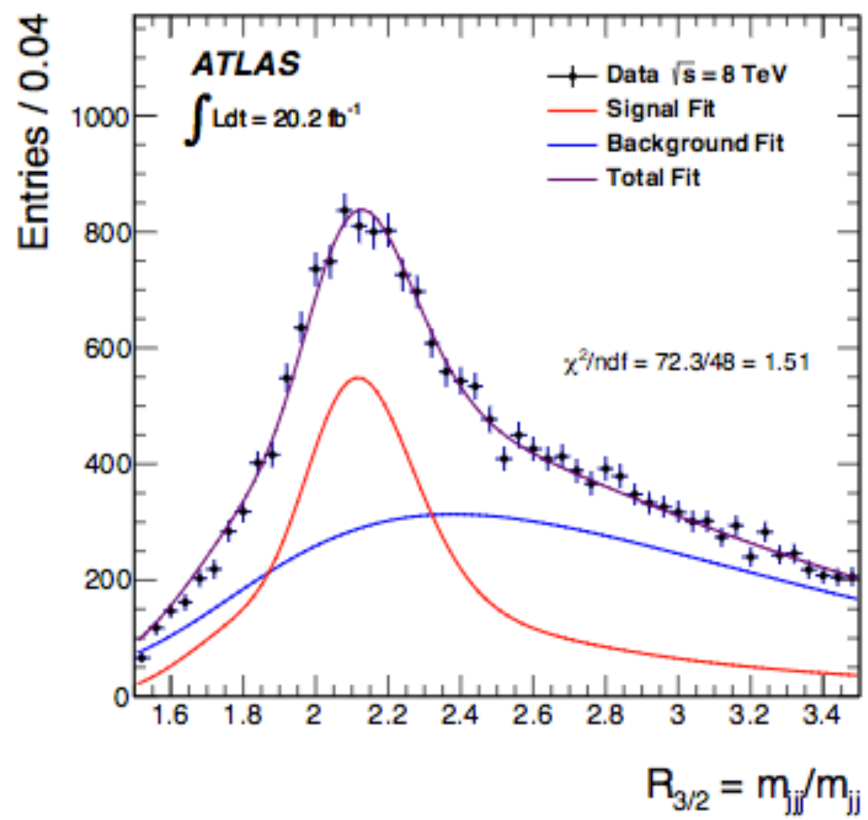
ATLAS all-jets

Template ($R_{3/2}$)

(8 TeV, 20.2 fb^{-1})

arXiv:1702.07546





Main systematics

source	GeV
hadronization	0.64
JES	0.60
bJES	0.34

$R_{3/2}=m_t^{reco}/m_W^{reco}$ templates:

- Novosibirsk for correct combinations
- Landau for combinatorial bckgd
- parameters depend linearly on M_t

2 $R_{3/2}$ entries per event, accounting for correlations

M_t=173.72±0.55(stat)±1.01(syst) GeV

M_t=173.72±1.15 GeV (±0.66%)

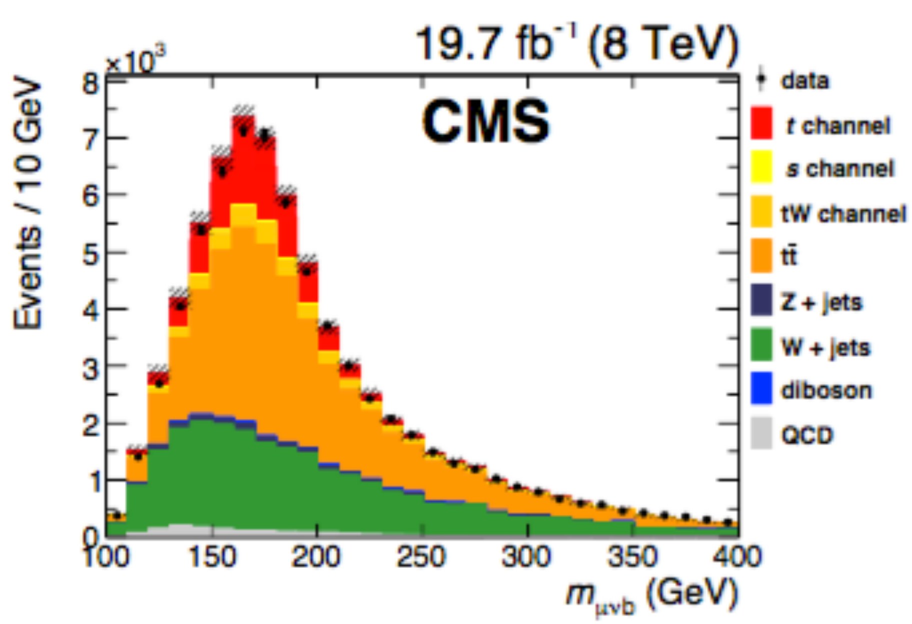
CMS single top: μ + jets

Template method ($m_{\mu\nu b}$) (8 TeV, 19.7 fb^{-1})

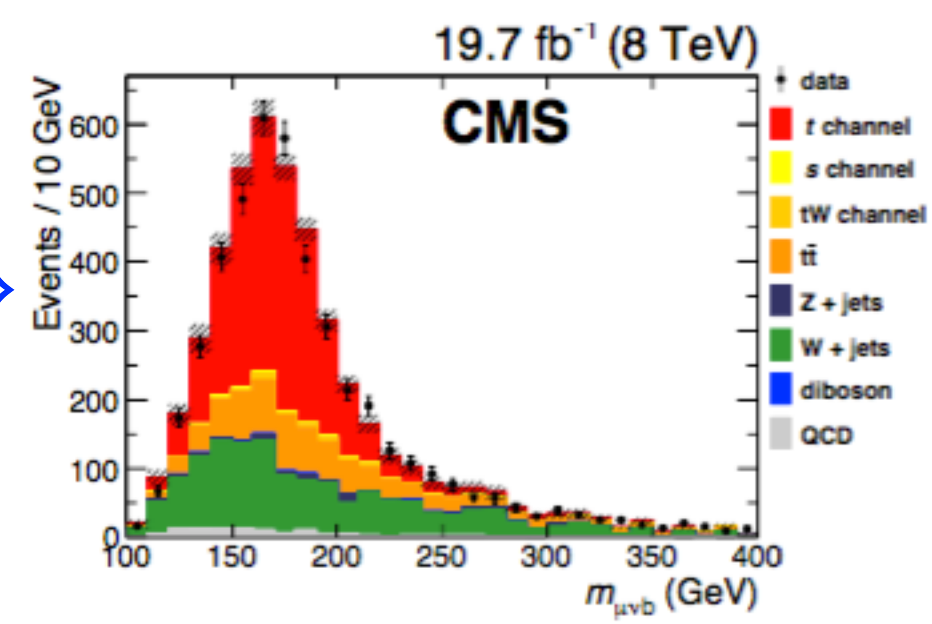
https://inspirehep.net/record/1516412

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 $\sigma_t \sim 2\,\sigma_{\bar{t}}$
- light jet at large η expected from single top



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



~70%

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CMS single top: μ + jets

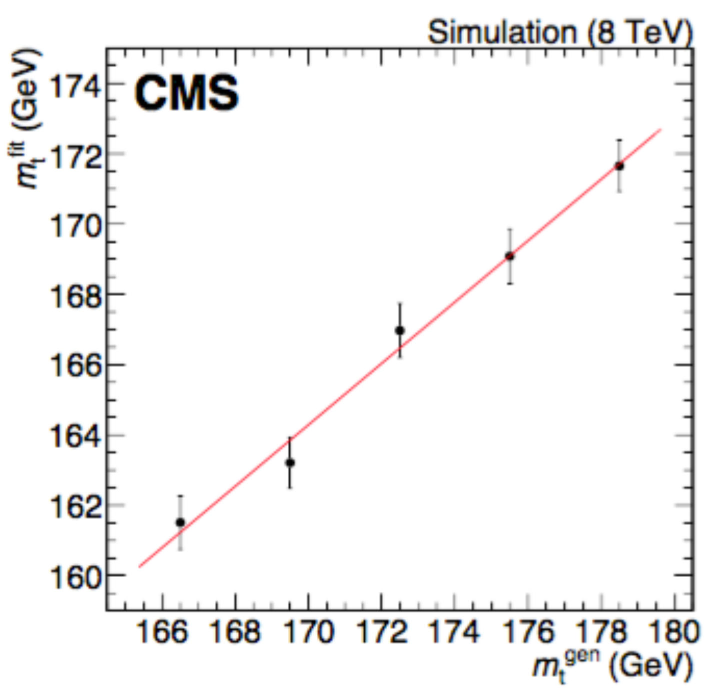
Template method ($m_{\mu\nu b}$) (8 TeV, 19.7 fb^{-1})

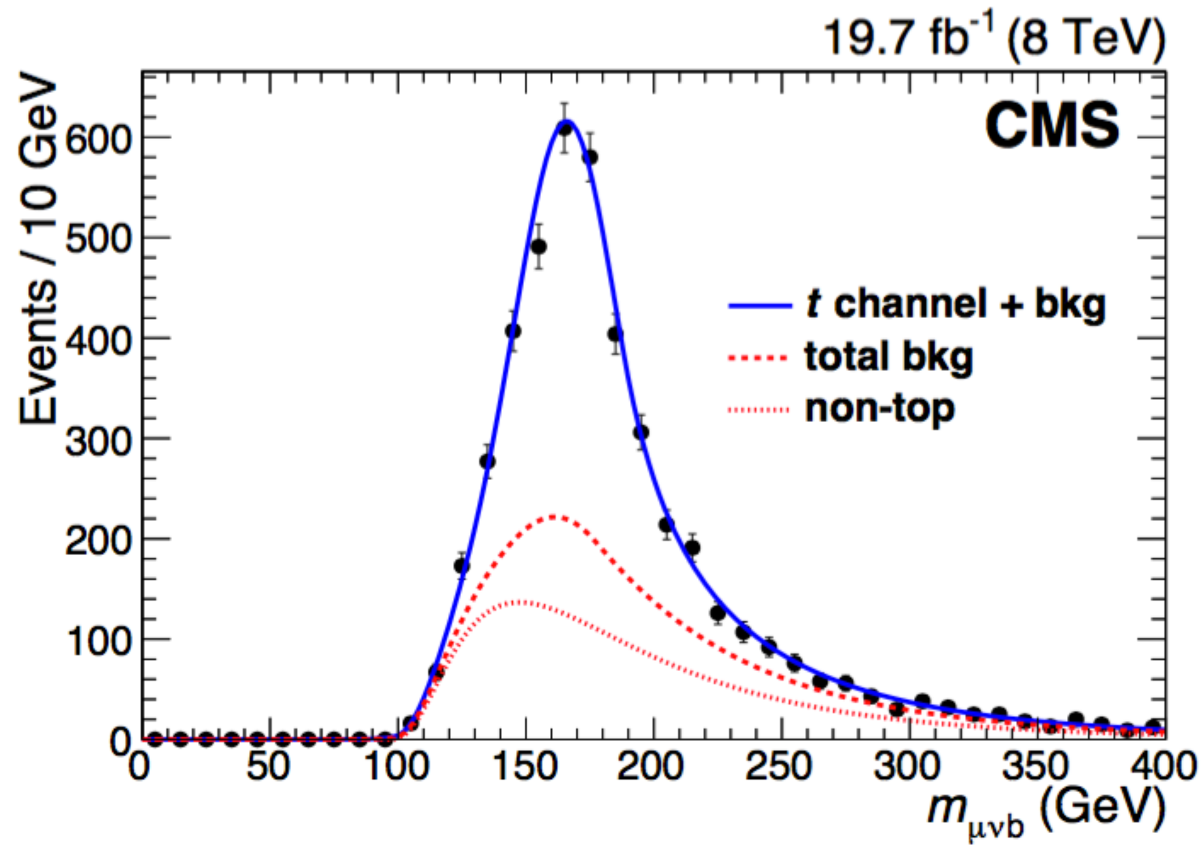
https://inspirehep.net/record/1516412

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

Calibration for the mass parameter μ

μ





Main systematics

source	GeV
JES	0.68
bkgd	0.39
fit calibration	0.39

Fit

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

M_t=172.95±1.24 GeV (±0.72%)

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CMS boosted top

Template method (m_{jet}) (8 TeV, 19.7 fb^{-1})

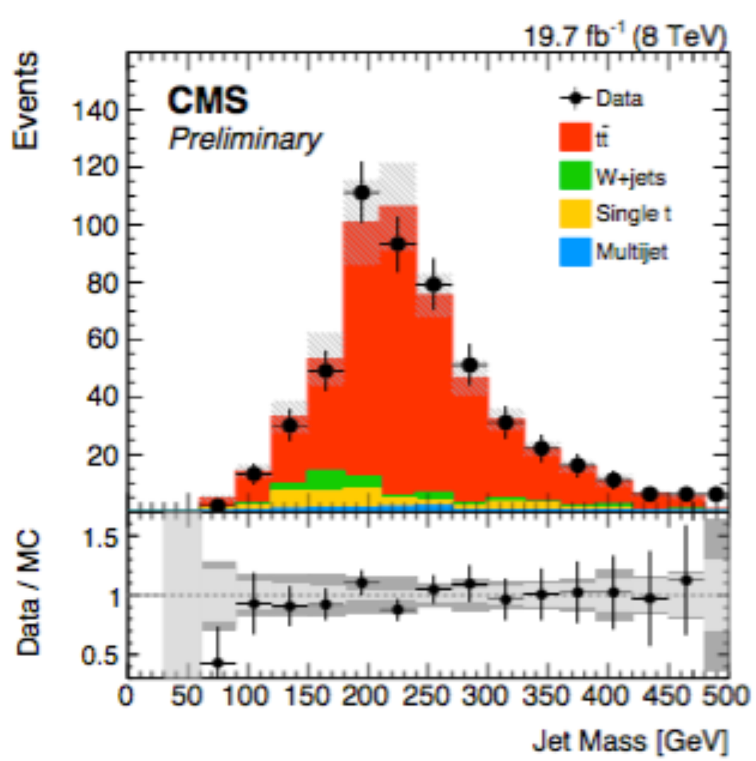
Selection:

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

https://inspirehep.net/record/1487491

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

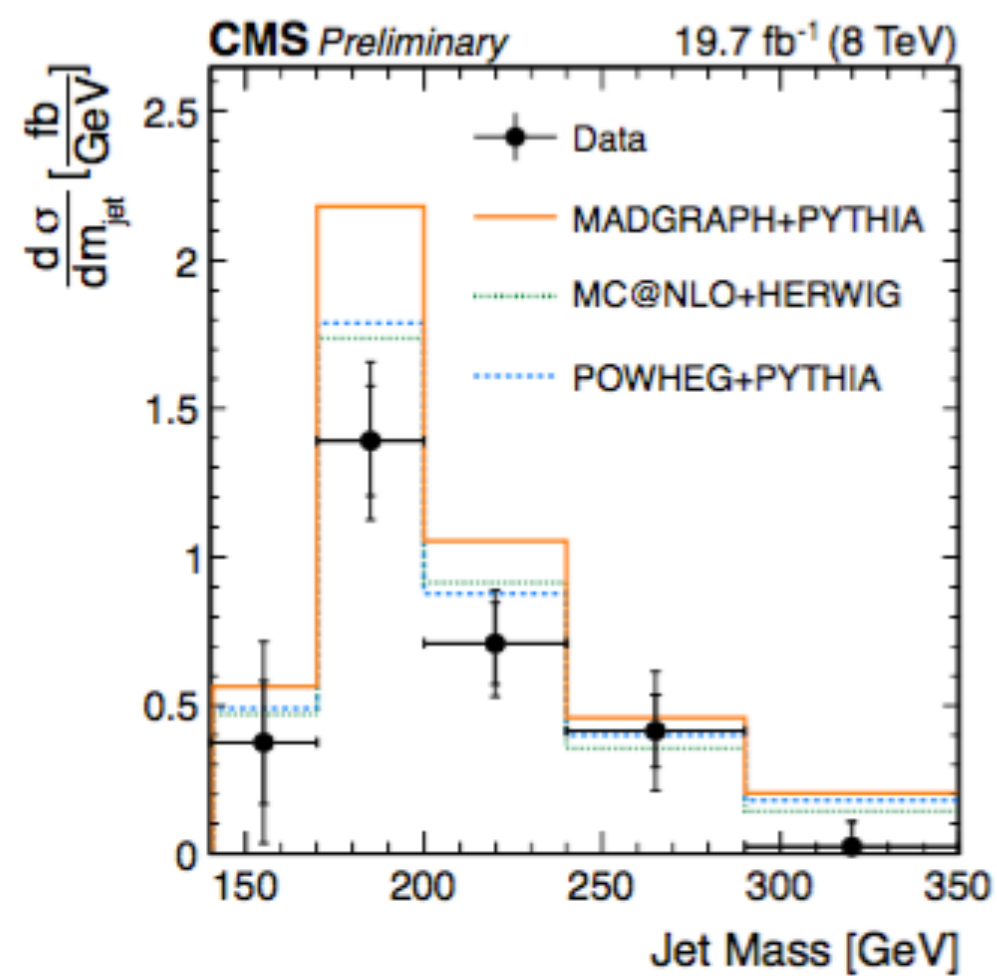
The M_t-sensitive quantity is the leading-jet mass



p_T>500 GeV

dσ/dM

⇒



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

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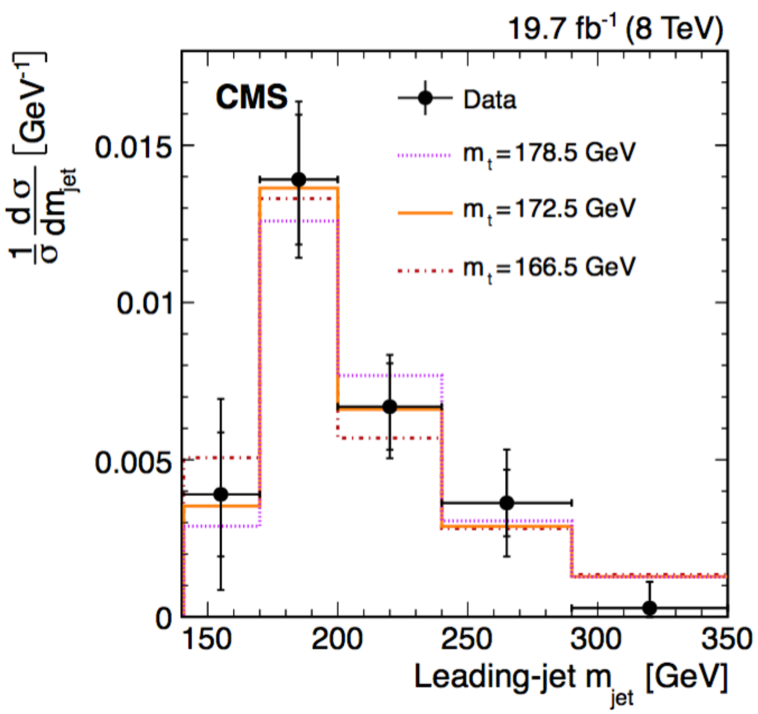
CMS boosted top

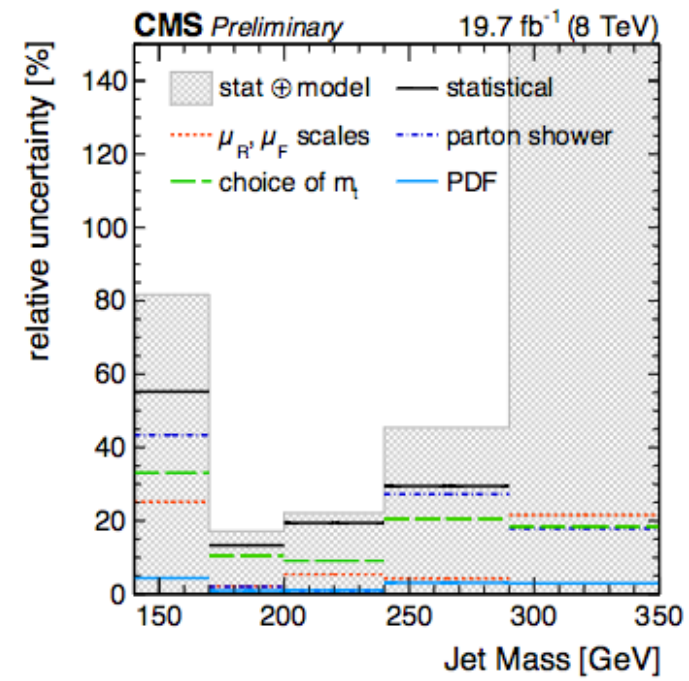
Template method (m_{jet}) (8 TeV, 19.7 fb^{-1})

https://inspirehep.net/record/1487491

Normalized differential cross section
(Madgraph+Pythia)



Uncertainties



Fit

M_t=171.8±5.4(stat)±3.0(syst)±5.5(model)±4.6(theory) GeV

M_t=171.8±9.5 GeV (±5.5%)

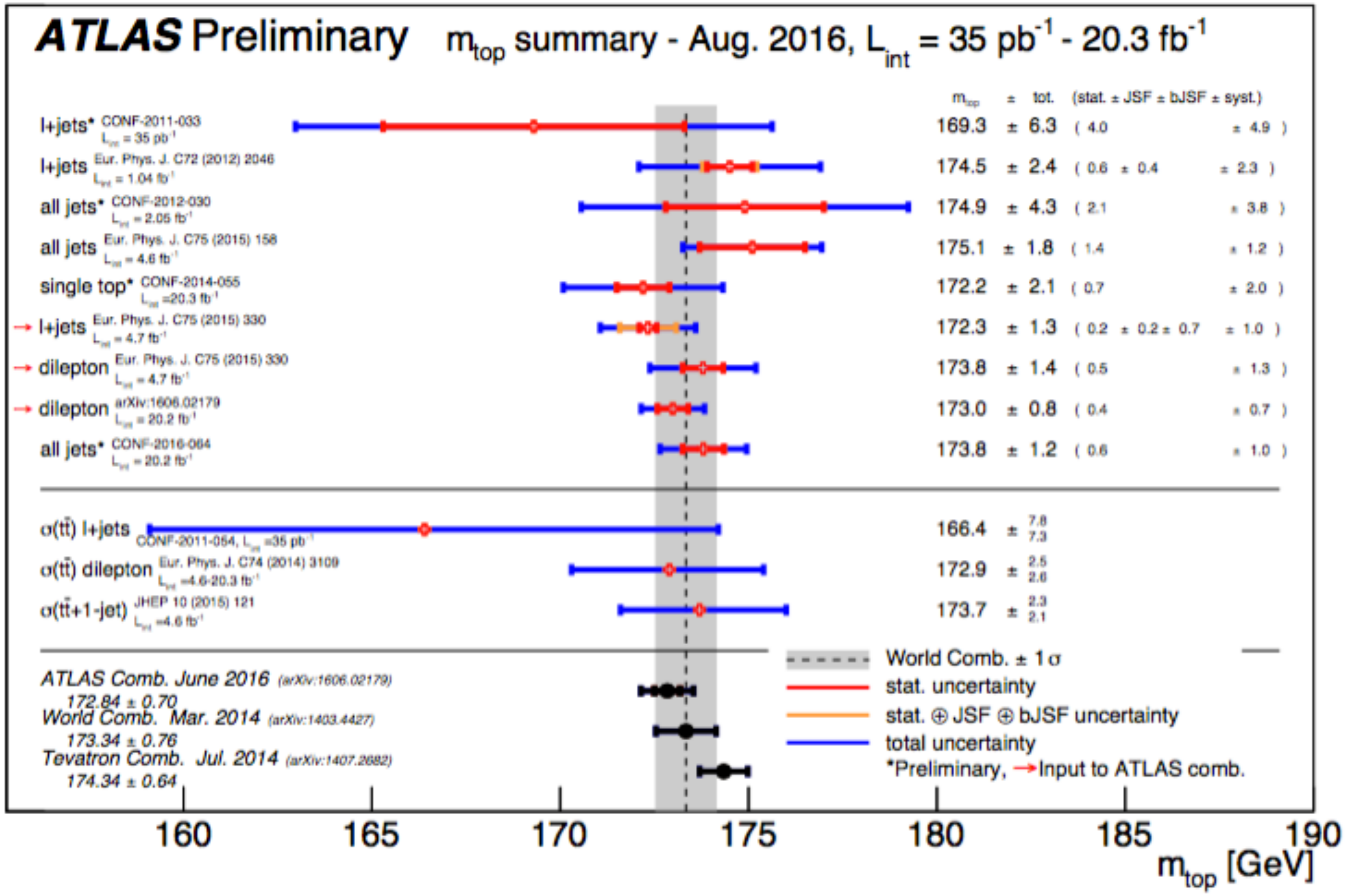
Method works but need more data, better modeling and higher-order calculations

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)

ATLAS 7+8 TeV combination



Combination of DIL(8 TeV) + LJ+DIL(7 TeV) results

PLB 761 (2016) 350

arXiv:1606.02179

June 2016 value:

M_t=172.84±0.34(stat)±0.61(syst) GeV

M_t=172.84±0.70 GeV (±0.41%)

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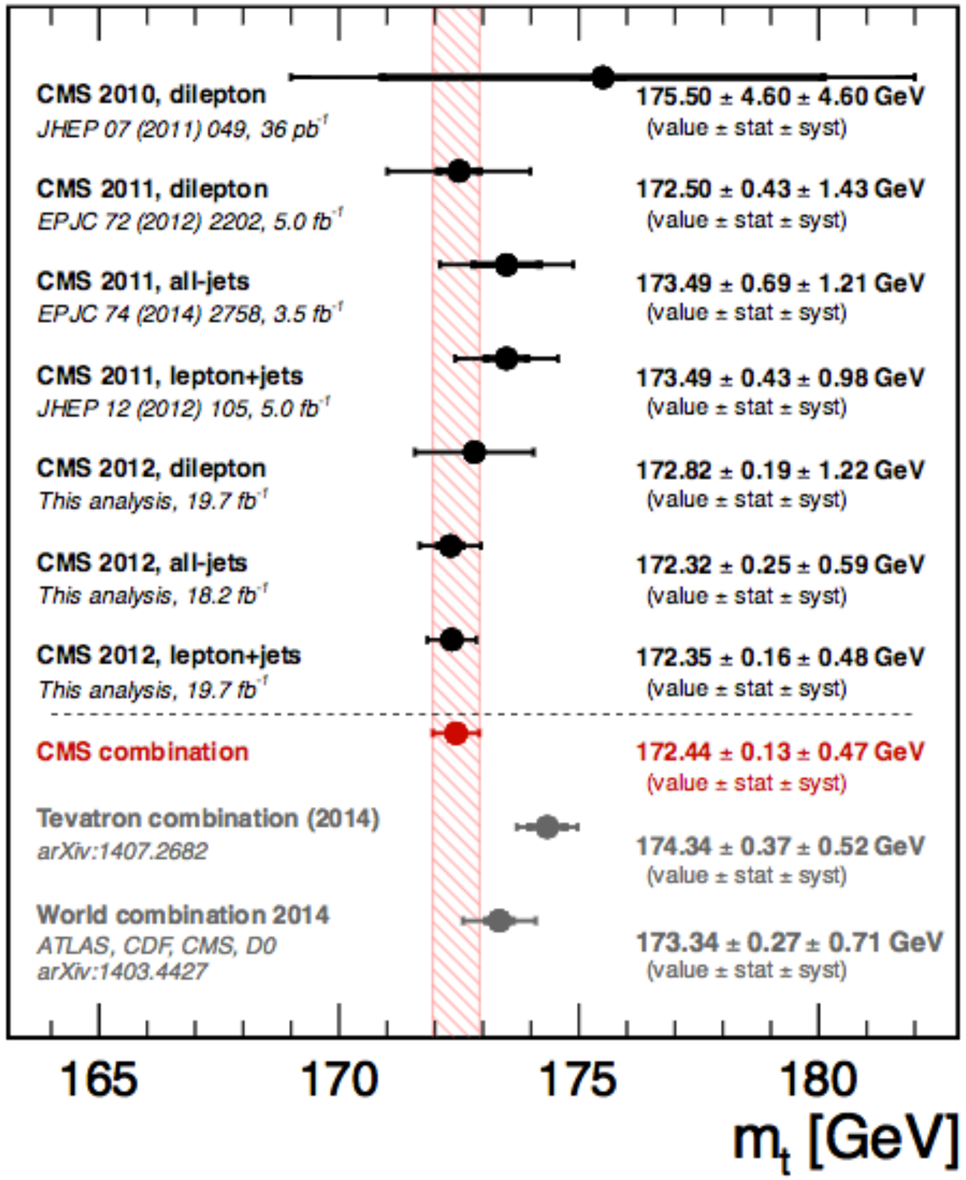
CMS 7+8 TeV combination

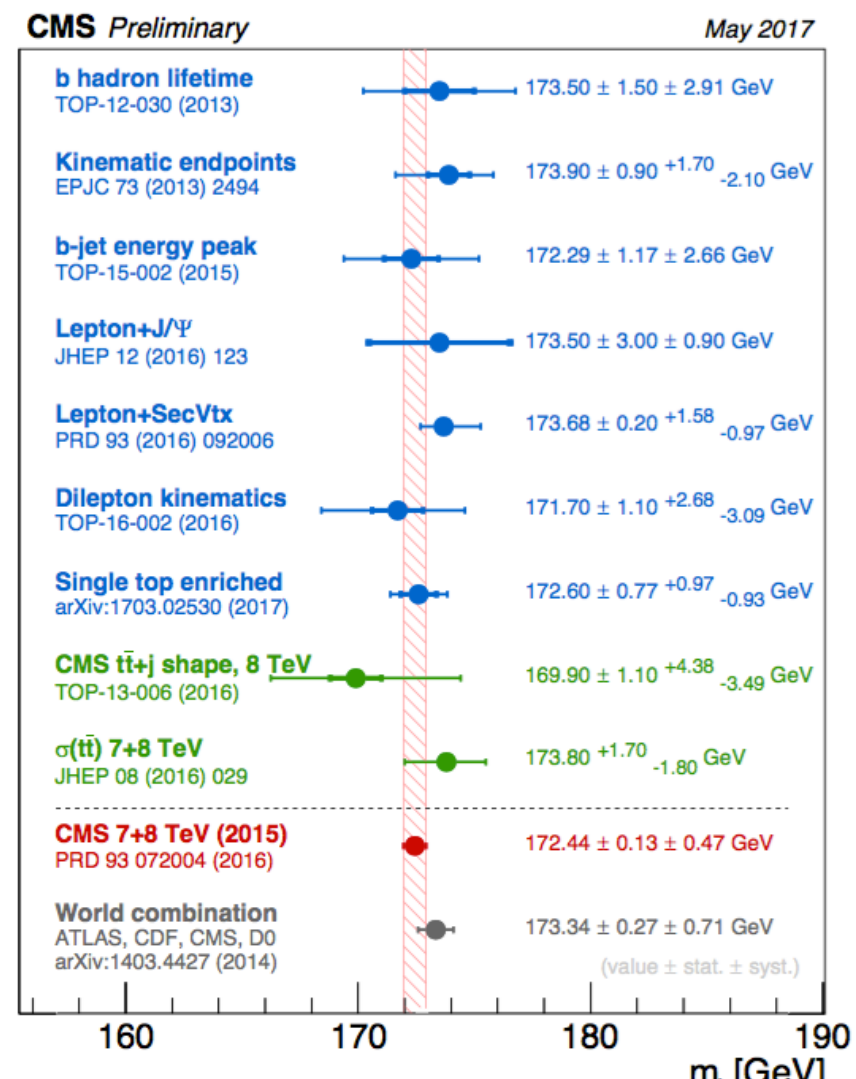


[PRD 93 (2016) 072004](PRD 93 (2016) 072004)

arXiv:1509.04044

... and then there are alternative methods

https://inspirehep.net/record/1500083



September 2015 value:

M_t=172.44±0.13(stat)±0.47(syst) GeV

M_t=172.44±0.49 GeV (±0.28%)

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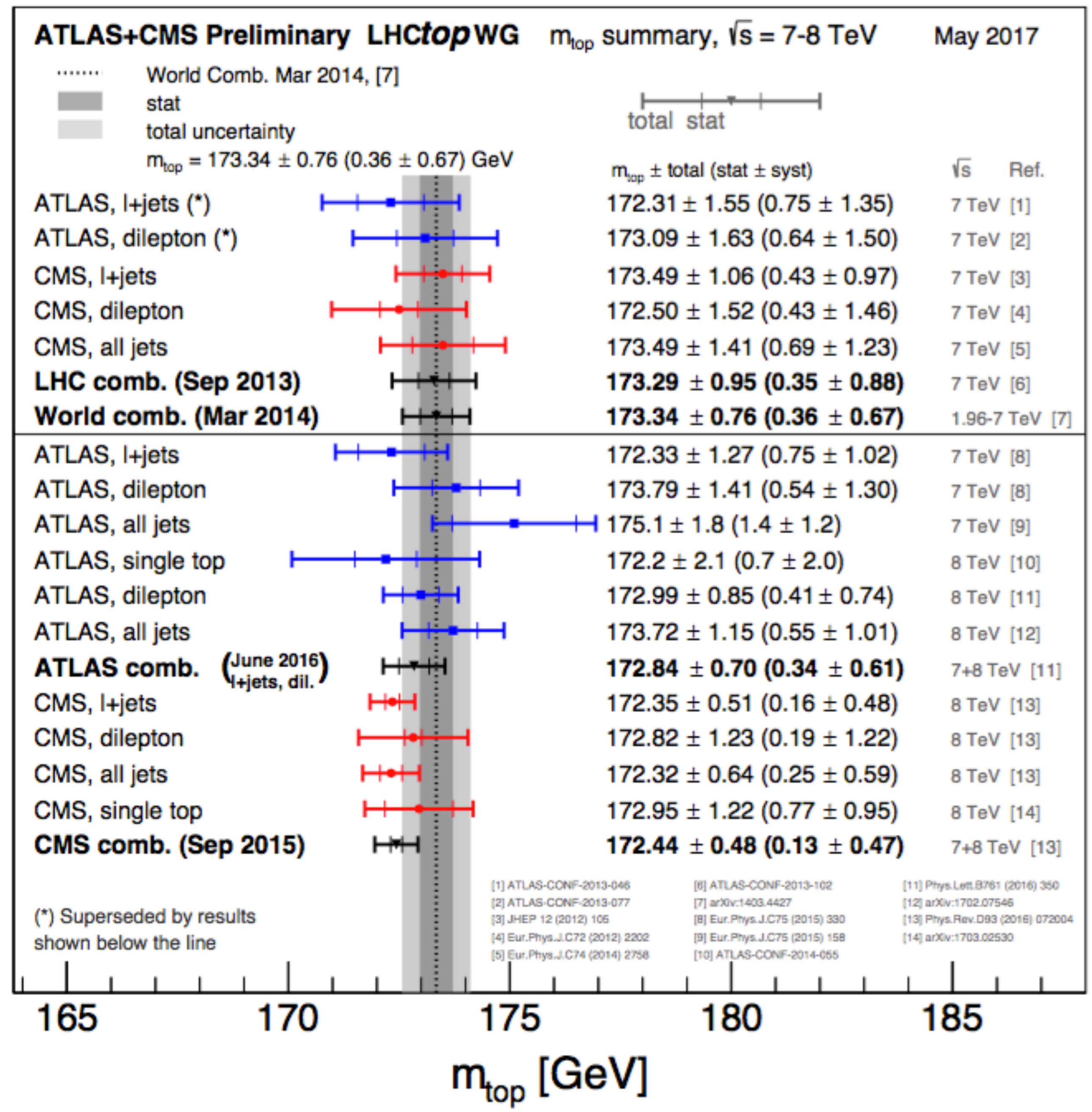
World combination

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

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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

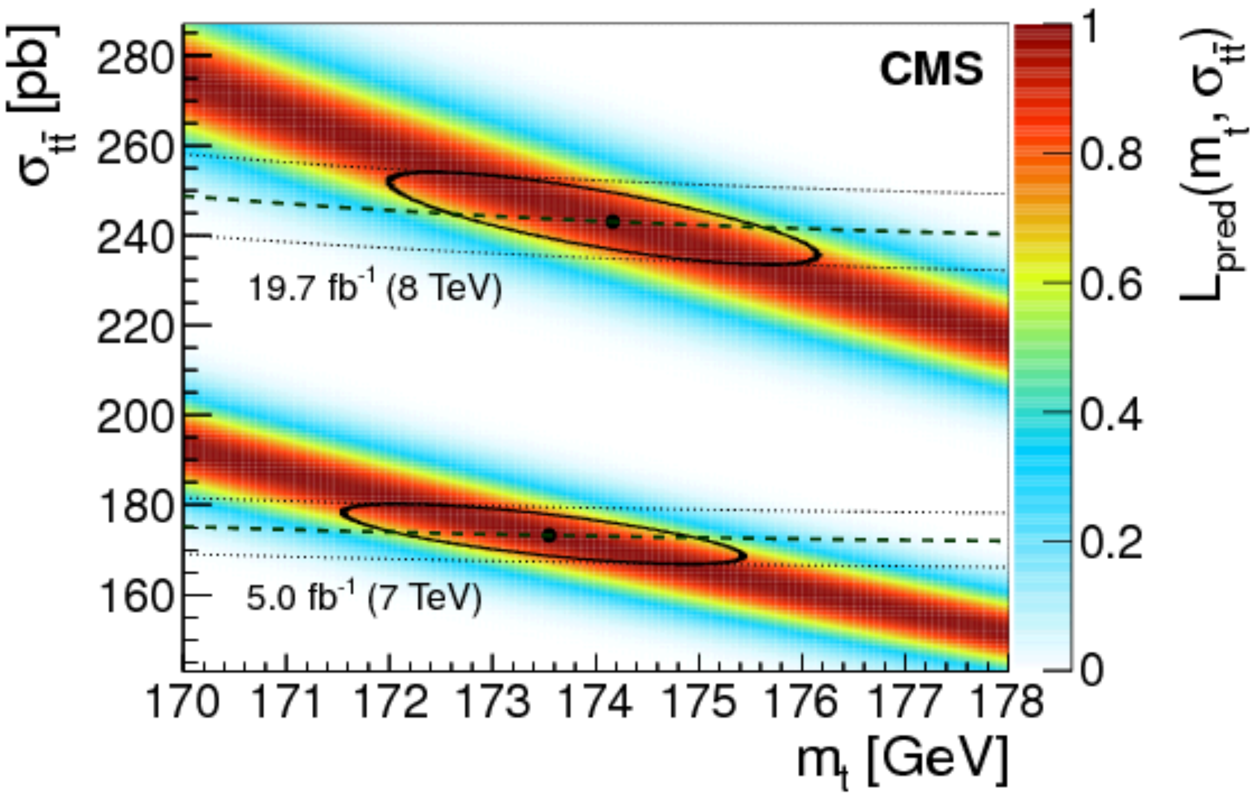
The increasing level of accuracy requires to relate this to theory-based quantities like:

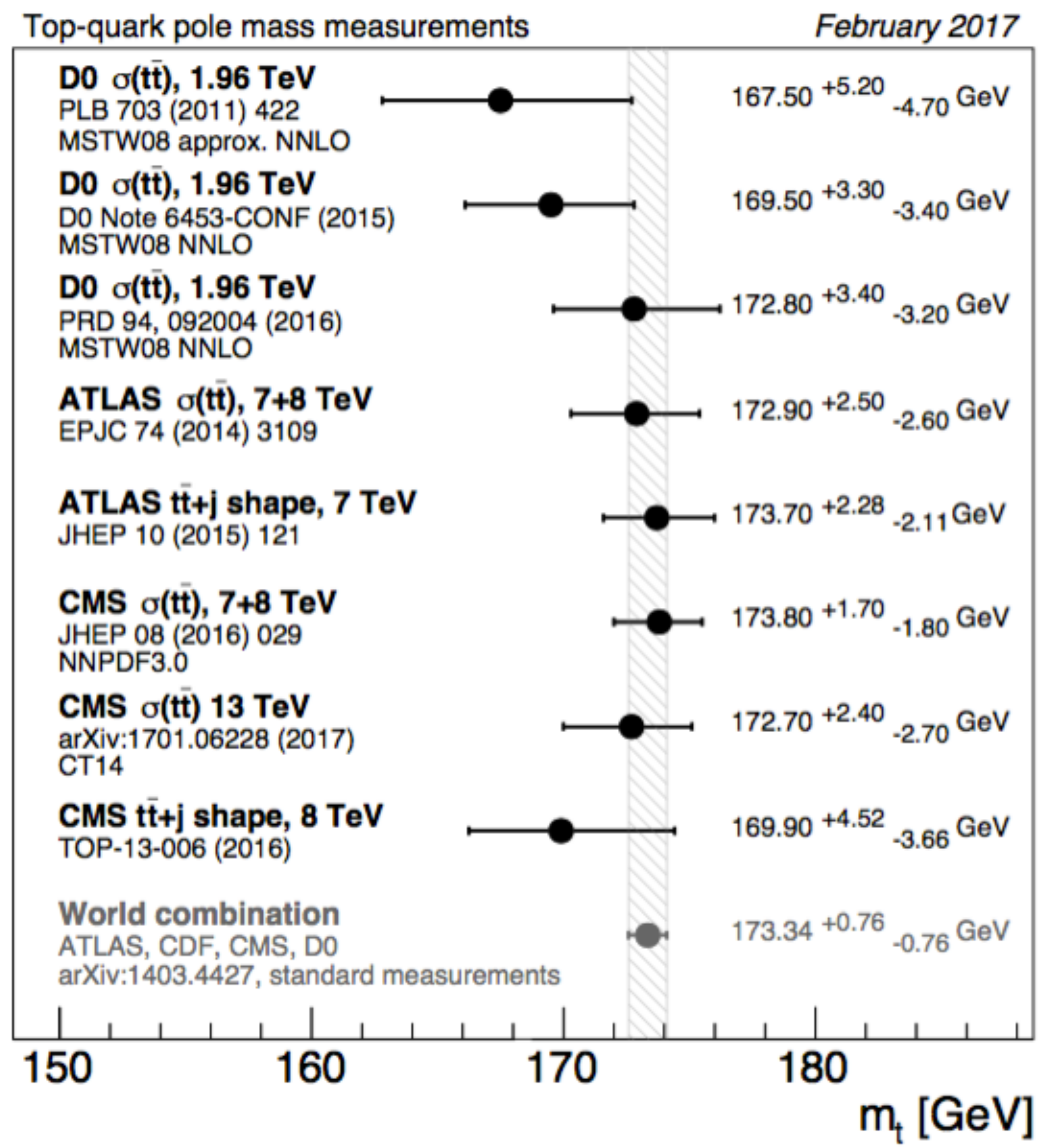
– the *pole mass*, universal but theoretically ambiguous by amounts **O**(Λ_{QCD}) due to soft gluon radiation (*infrared renormalon problem*)

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

Pole mass

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





Discrepancies w.r.t. the average M_t can be interesting

13 TeV results on M_t

There is also a new M_t measurements made at 13 TeV (2015 data):

- CMS μ+jets

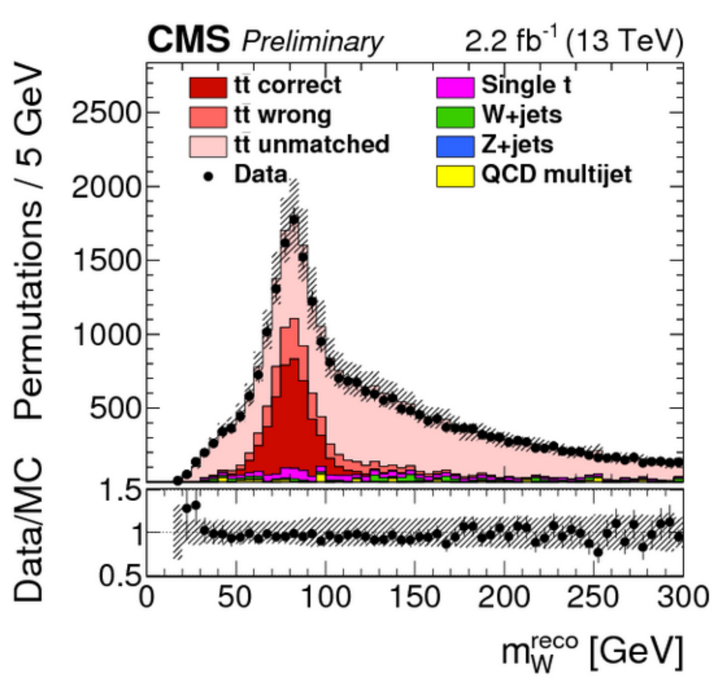
CMS μ + 4 jets

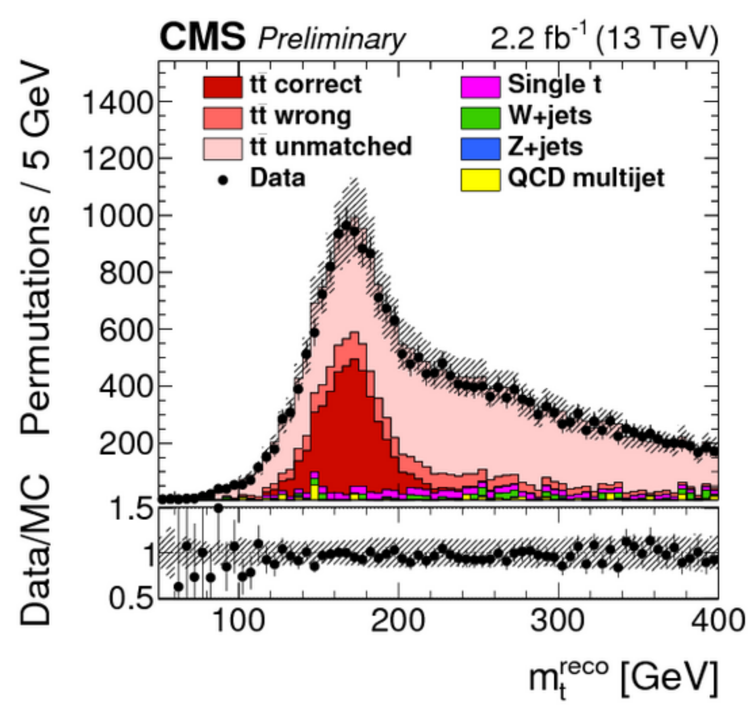
Ideogram method
2D fit (m_t^{reco}, m_W^{reco})
w. in situ JSF (13 TeV, 2.2 fb^{-1})

https://inspirehep.net/record/1517829

Selection:
- 1 μ
- ≥4 jets (2 b-tagged)

Kinematic fit to the tt→WbWb hypothesis
Possible combinations treated separately:
- correct:
- wrong:
- unmatched





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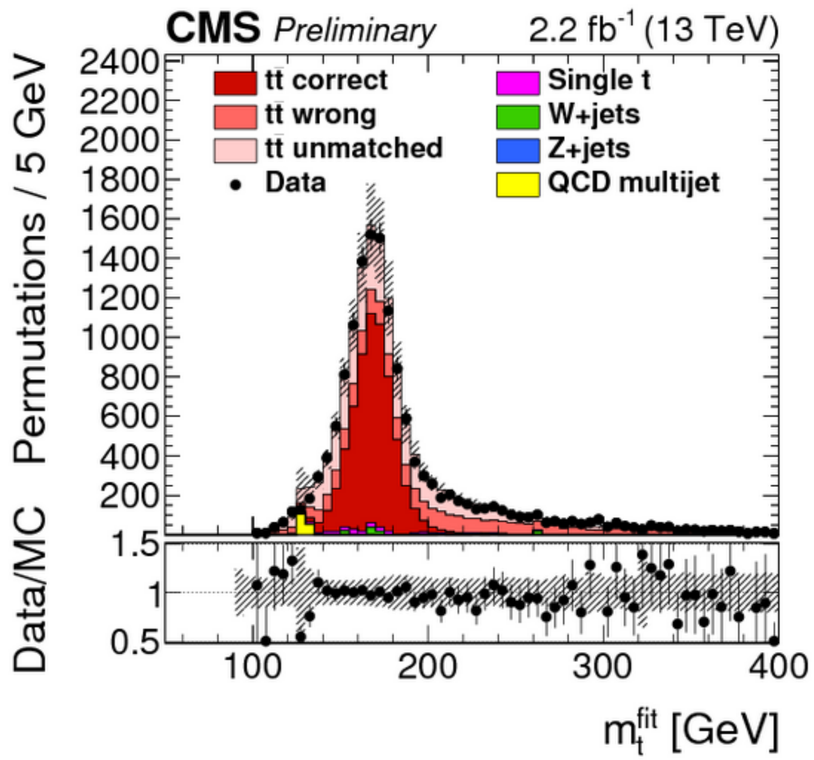
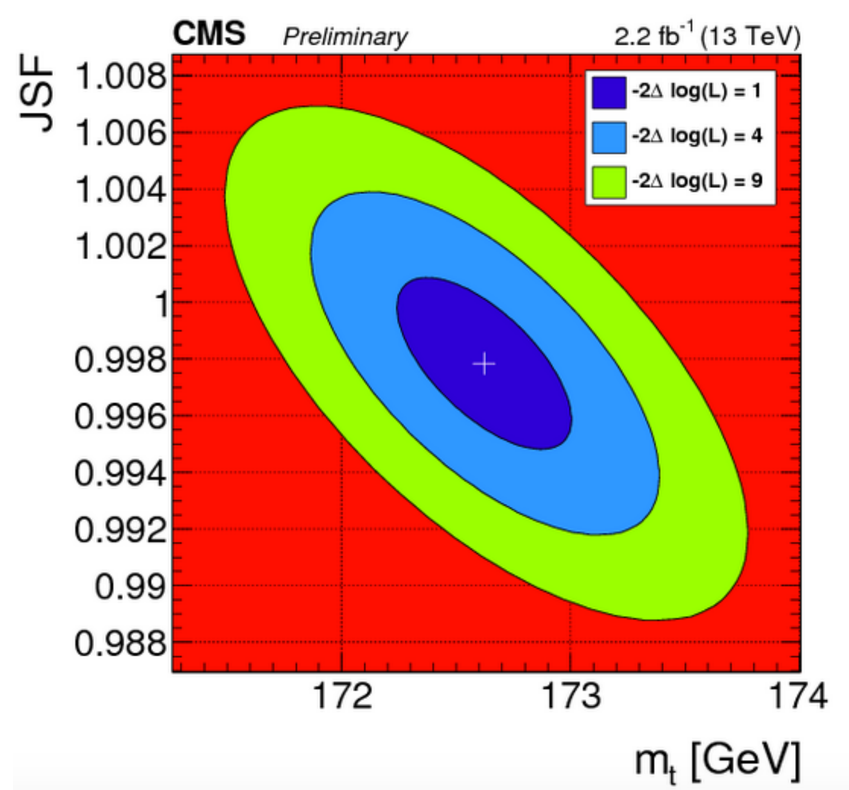
M_t with CMS: μ + 4 jets

Ideogram method (m_t^{reco}, m_W^{reco})
w. in situ JSF (13 TeV, 2.2 fb^{-1})

https://inspirehep.net/record/1517829





Main systematics

source	GeV
flavor JEC	0.41
JES	0.30
parton shower	0.23

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

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

2D Fit

$M_t=172.62\pm0.38(\text{stat+JSF})\pm0.70(\text{syst})$ GeV

$M_t=172.62\pm0.80$ GeV (±0.46%)

JSF = 0.998±0.010

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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
- Merge better with theory comparing M_t^{MC} to M_t^{pole}
- Help to explore fundamental issues like:
  – cosmological models for inflation
  – vacuum stability of SM
  – physics beyond SM

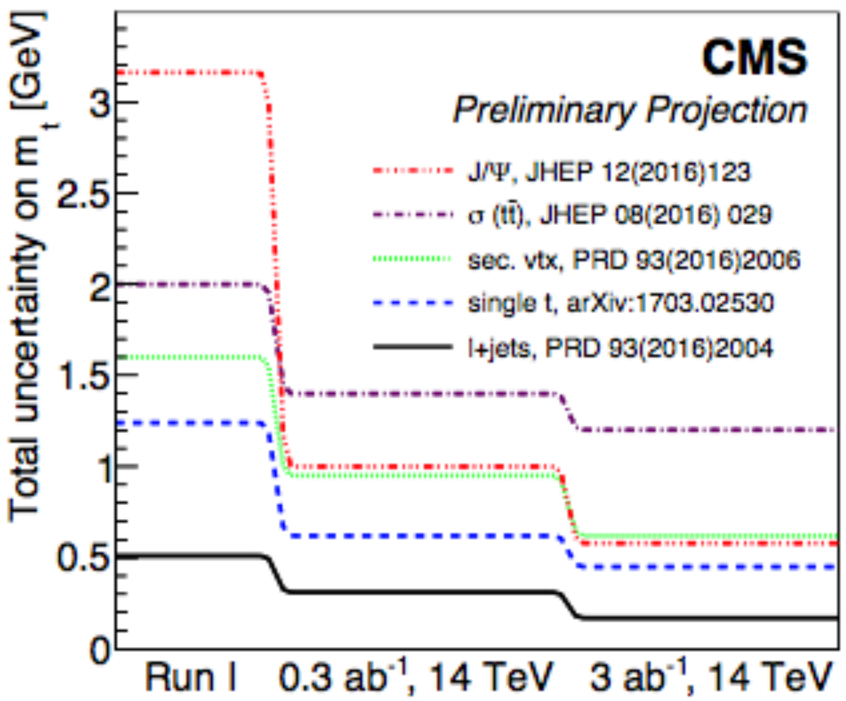
Important to work on reducing systematics
e.g. those related to theory and signal modeling

Outlook

Run1 legacy measurements of M_t being completed
⇒ published soon

https://inspirehep.net/record/1598338

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

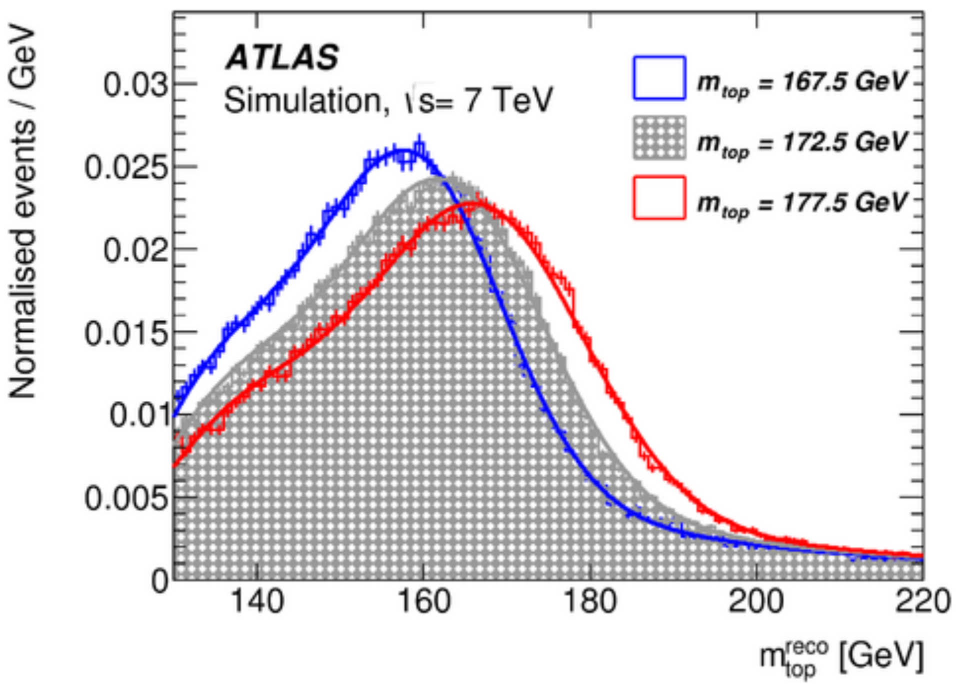
1) *Template method:* distributions of variables sensitive to M_t, e.g., reconstructed M_t^{reco} from χ^2 fit to WbWb

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

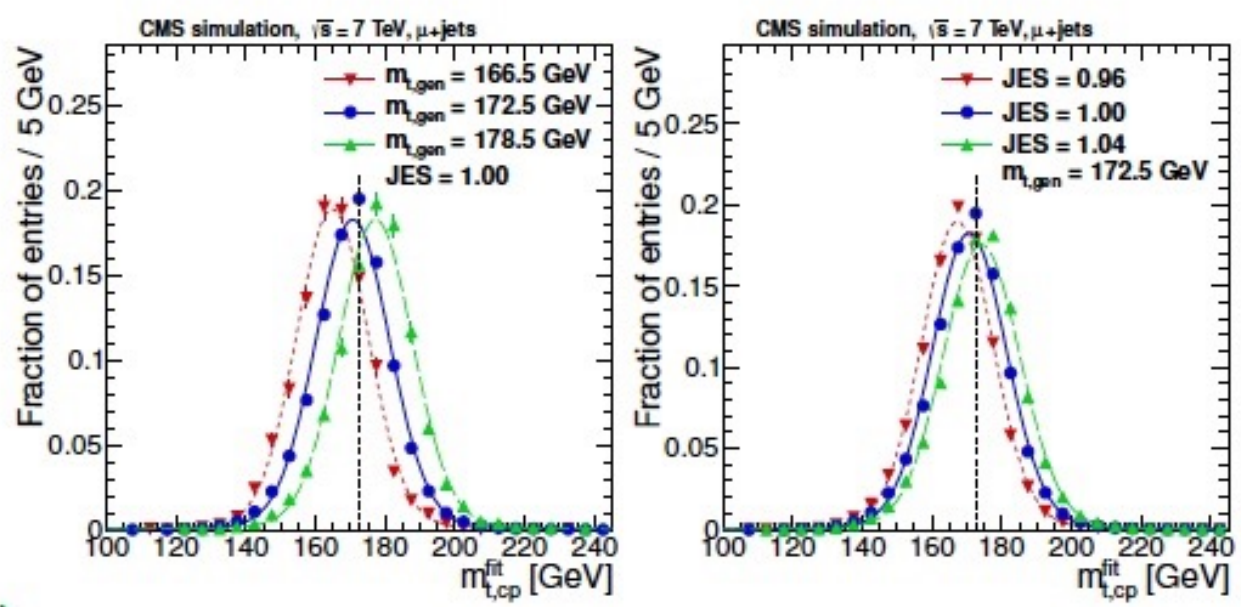
$$\mathcal{L}\left(\text{event}|m_t,\text{JSF}\right) = \sum_{i=1}^{n} P_{\text{gof}}(i)\left\{f_{\text{sig}}P_{\text{sig}}\left(m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}}|m_t,\text{JSF}\right) + \left(1-f_{\text{sig}}\right)P_{\text{bkg}}\left(m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}}\right)\right\}$$

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

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

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

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



Methods for measuring M_t

3) *Analytical Matrix Weighting technique:* (used for DIL)
- a given M_t used to constrain the $t\bar{t}$ system (1 GeV increments in range 100-600 GeV)
- inferring p^{ν} from MET and assuming values for unobserved quantities
- multiple solutions for each assignment, and weights assigned to solutions

The mass with highest sum weight becomes the mass estimator (AMWT mass)

Templates are built from the AMWT mass

... and then there are alternative methods

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