Top Mass at ATLAS and CMS

Moriond / La Thuile
26th March - 1st April 2017

Niels Bohr Institute
University of Copenhagen

James Monk
On Behalf of ATLAS & CMS

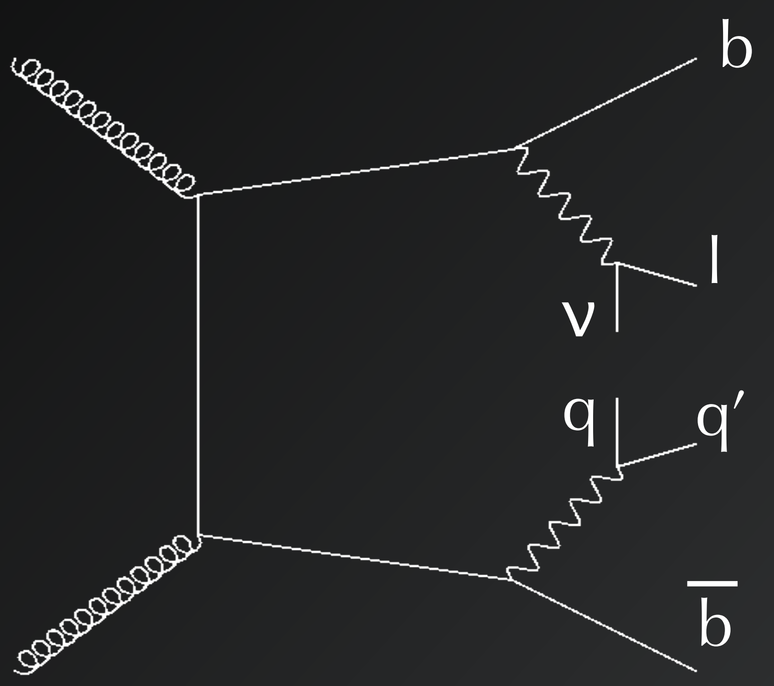
Why, and how, to Measure the Top Quark Mass?

- Fundamental parameter of the Standard Model
- Largest scale in the Standard Model
  - 5 orders of magnitude between up quark and top quark mass

    (not dissimilar to neutrino: electron hierarchy)
  - Large effect on the running of the Higgs coupling and stability of the SM vacuum
- Only quark that decays prior to hadronisation
  - probe of QCD and heavy flavour behaviour

Why, and how, to Measure the Top Quark Mass?

Decays can be either fully hadronic, semi-leptonic, or fully leptonic



Fully hadronic
-> all top decay products are seen, incl. 1 or 2 b-jets, **but**, larger QCD effects/background

Boosted hadronic
-> high pT tops boost decay products into a single (fat) jet
-> reduced background (searches), but needs special jet treatment

semi-leptonic
-> One top decays to b-jet + hadronically decaying W, the other to a b-jet + leptonically decaying W
-> Generally most precise, still relies on template fit modelling

fully-leptonic
-> Both tops decay to b-jet + leptonically decaying W
-> Less dependent on jet modelling, but not all decay products can be reconstructed (MET)

Outline

- Will show most **recent** results from LHC representing overview of these channels
  - di-lepton + b-jets at ATLAS
  - (one) Muon + 4 jets at CMS
  - 3/2 jet ratio in hadronic top decays at ATLAS
  - Boosted top jets at CMS
  - Measurement of mass in single top events

There are a large number of measurements and methods, too many to show them all in this talk.

ATLAS

http://inspirehep.net/record/1094859 - lepton + jets template @ 7 TeV
http://inspirehep.net/record/1261966 - t-tbar mass difference @ 7TeV
http://inspirehep.net/record/1353391 - lepton + jets and di-lepton @ 7 TeV
http://inspirehep.net/record/1313597 - Fully hadronic @ 7 TeV
http://inspirehep.net/record/1381766 - Pole mass in ttbar + 1 jet
http://inspirehep.net/record/1515025 - Fully hadronic @ 8 TeV (this talk)
http://inspirehep.net/record/1468064 - Di-lepton @ 8 TeV (this talk)

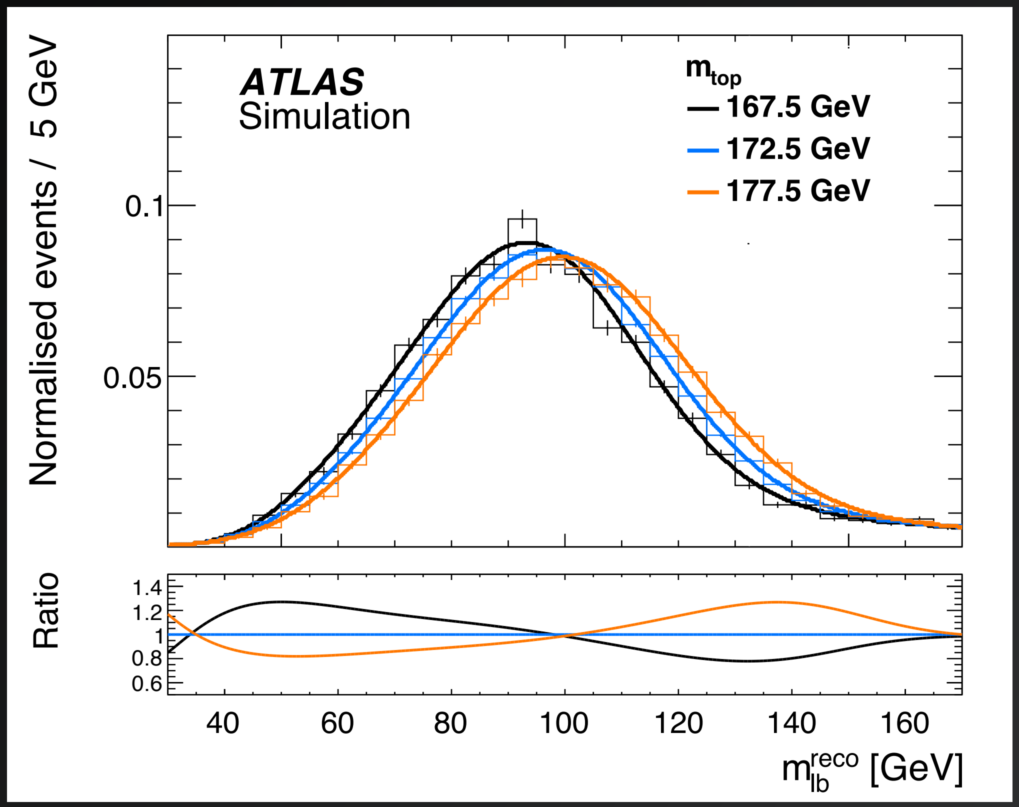
CMS

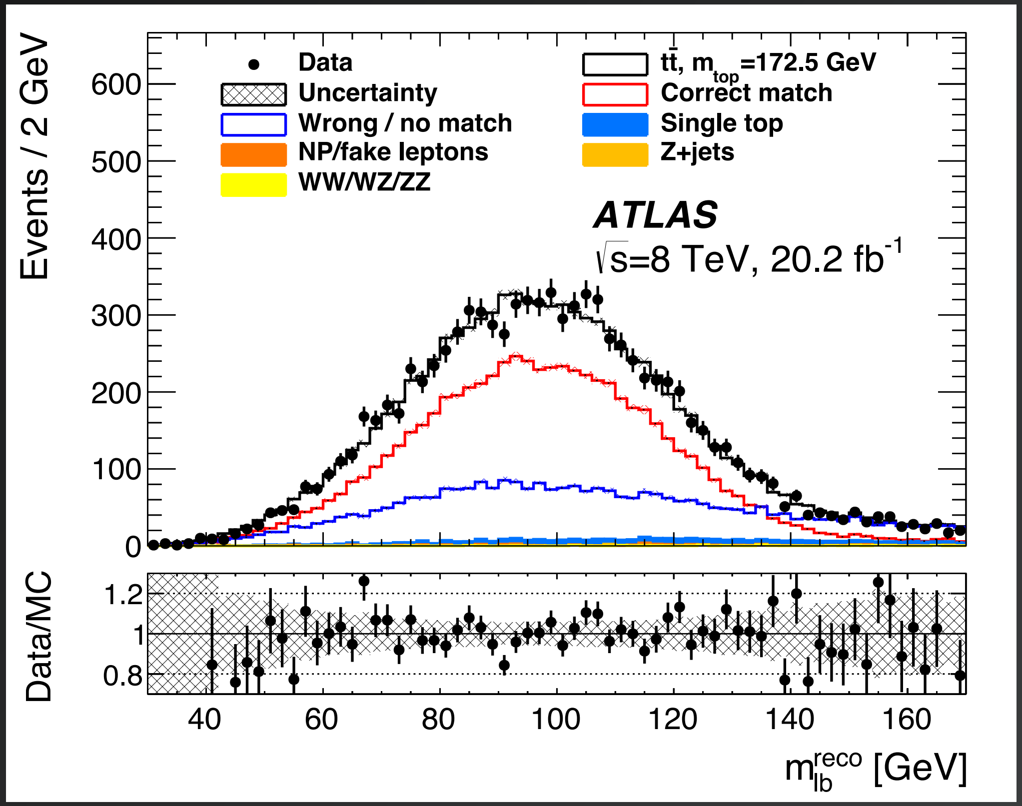
http://inspirehep.net/record/901829 - di-lepton @ 7 TeV
http://inspirehep.net/record/1185101 - lepton + jets @ 7 TeV
http://inspirehep.net/record/1185104 - di-lepton @ 7 TeV
http://inspirehep.net/record/1229333 - di-lepton kinematics @ 7 TeV
http://inspirehep.net/record/1243161 - fully hadronic @ 7 TeV
http://inspirehep.net/record/1241819 - pole mass from cross section @ 7 TeV
http://inspirehep.net/record/1393269 - combination @ 7 & 8 TeV
http://inspirehep.net/record/1430902 - using track jets @ 8 TeV
https://arxiv.org/abs/1701.06228 - single lepton + jets @ 13 TeV (this talk)
https://arxiv.org/abs/1703.02530 - single top events @ 13 TeV (this talk)

Best precision is reached when combining all of them across all experiments

Di-lepton + b-jets with ATLAS

http://inspirehep.net/record/1468064



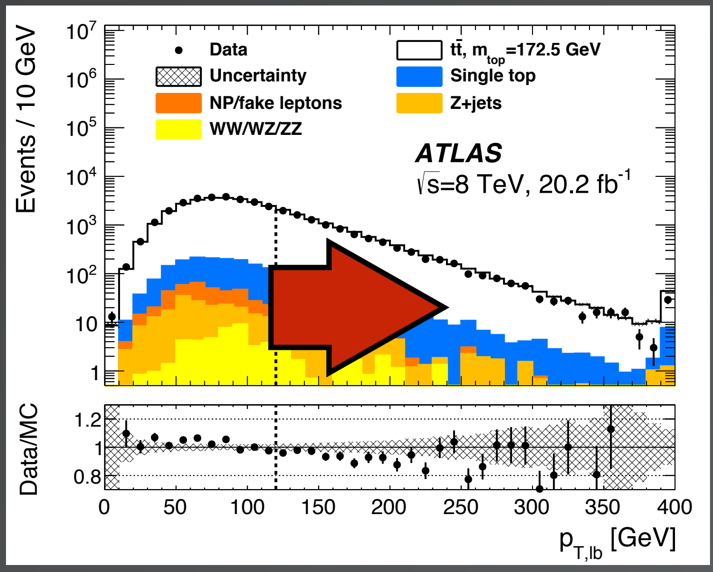


20.2 fb^{-1} @ 8 TeV

- Electrons, ET > 25 GeV
- Muons, pT > 25 GeV
- Exactly two oppositely charged isolated leptons
- If both leptons same flavour, missing ET > 60 GeV and di-lepton mass outside Z window
- At least two anti-Kt R=0.4 jets with pT > 25 GeV
- At least one of the jets must be b-tagged

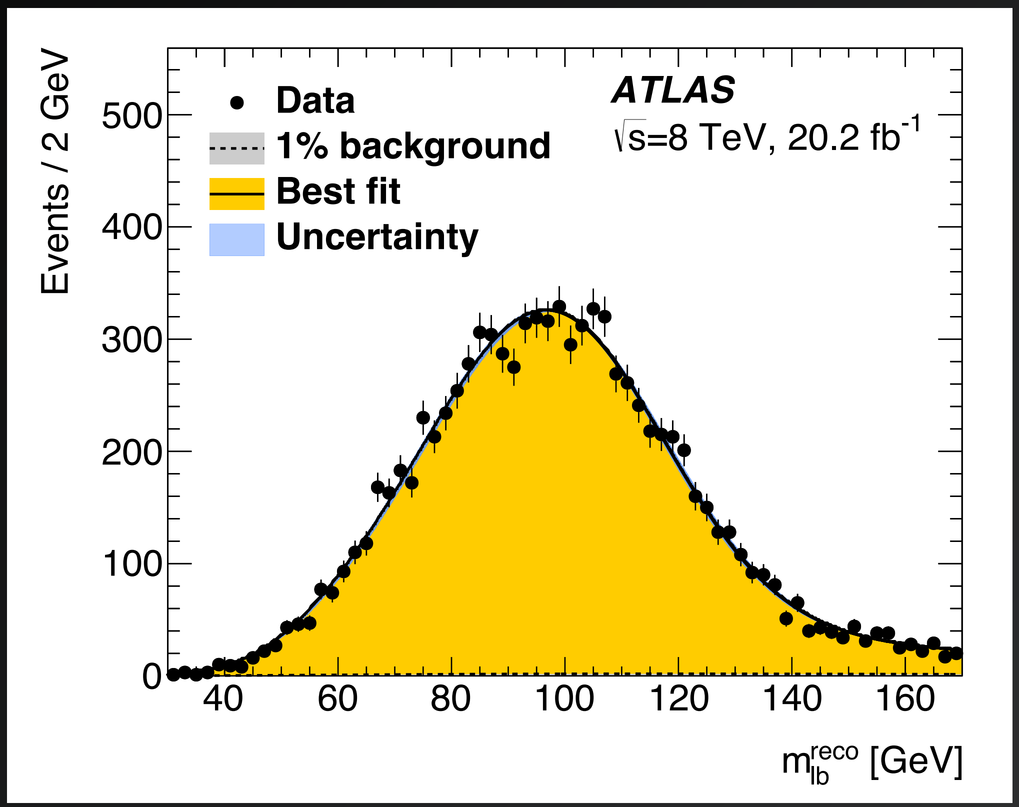
Take the lepton-b-jet pairs that minimise the mean mass for the pair in the event

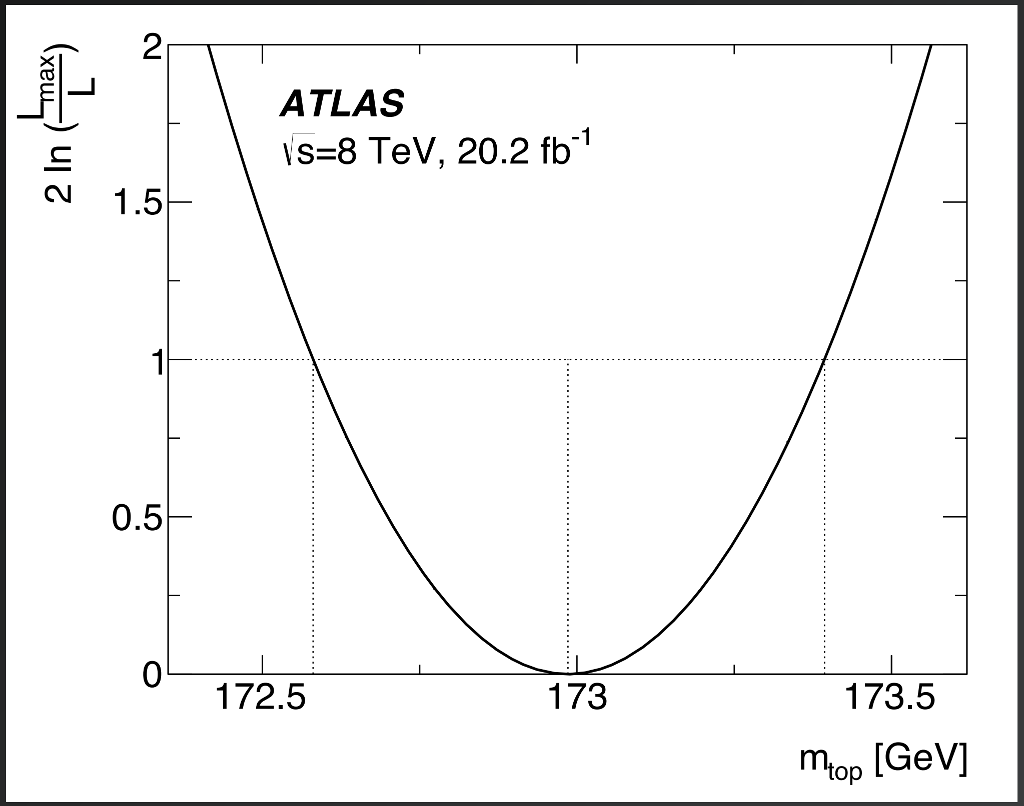
Select events for which the mean l-b-jet pT is above 120 GeV



Di-lepton + b-jets with ATLAS

http://inspirehep.net/record/1468064





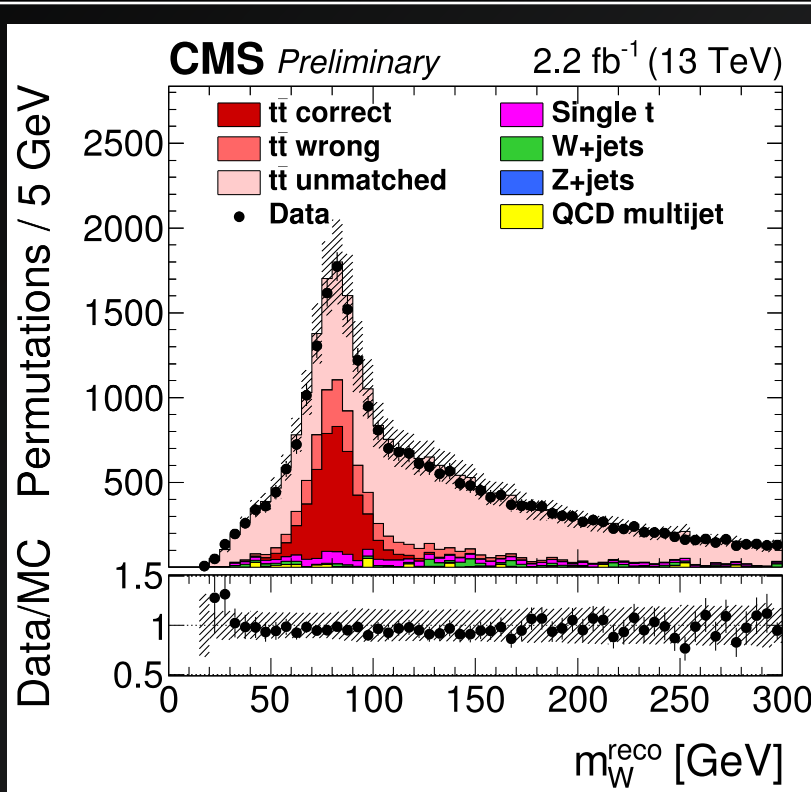
- MC templates produced with Powheg + Pythia 6 (P2011).
  - (Alpgen + Pythia or Herwig also used for bg, and MC variations use MC@NLO + Herwig)
- Signal and bg lepton-b-jet masses fitted with Landau curve -> only free param is mt
- Systematic uncertainties are dominated by QCD MC modelling and jet energy scale

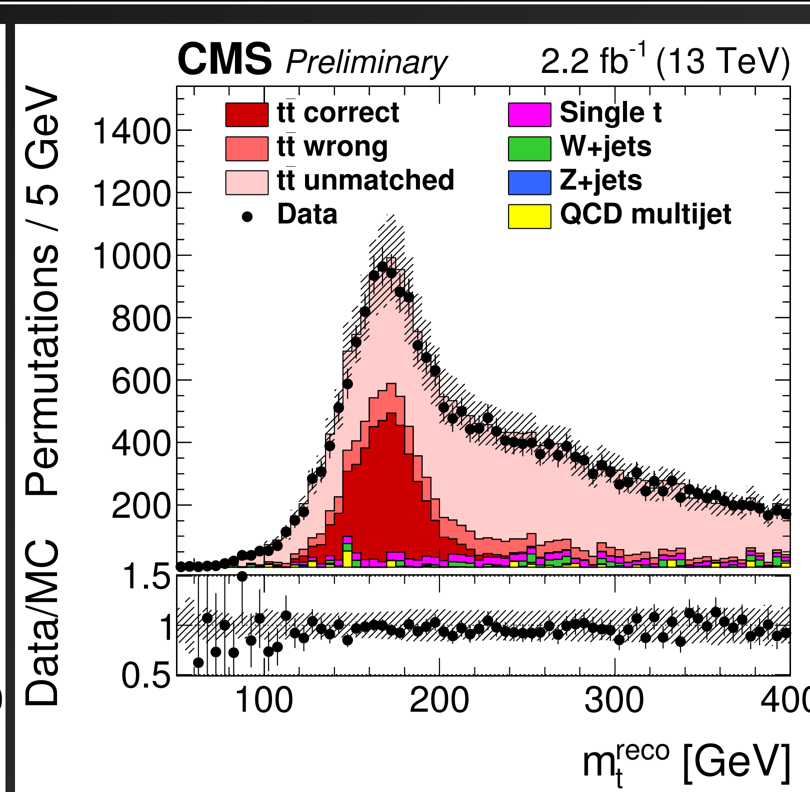
Source	Approach	Contribution
Hadronisation	Pythia Vs. Herwig	0.22 ± 0.09GeV
Shower & QCD	Matching scale & hdamp variations	0.23 ± 0.07 GeV
ME	MC@NLO Vs. Powheg	0.09 ± 0.15 GeV
Jet Energy Scale	25 up/down variations	0.54 ± 0.04 GeV
B-jet calibration	Additional jet energy uncertainty	0.3 ± 0.1 GeV

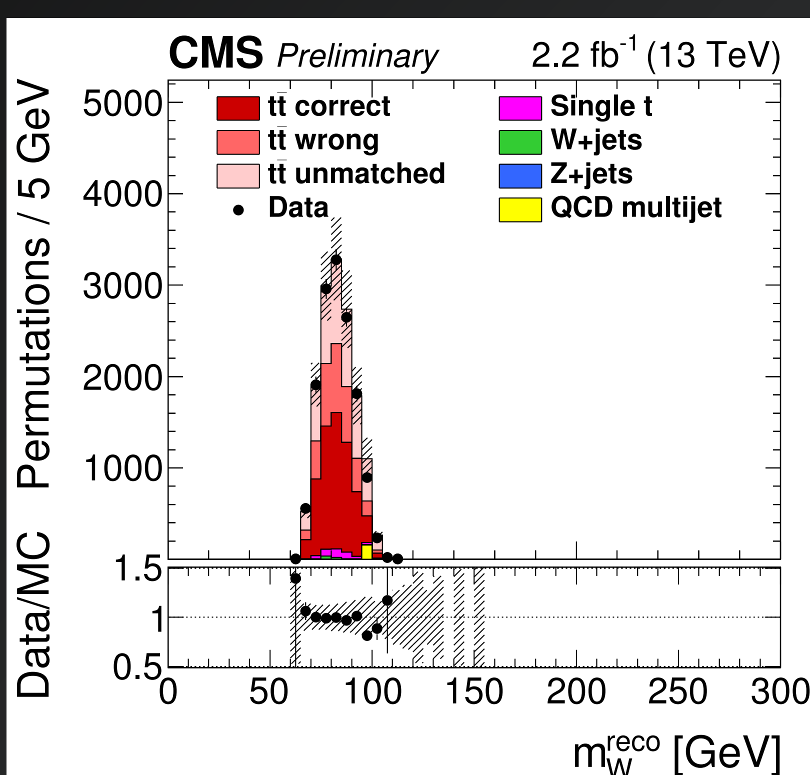
Best fit value is m_t = 172.99 ± 0.41 (stat) ± 0.74 (syst) GeV

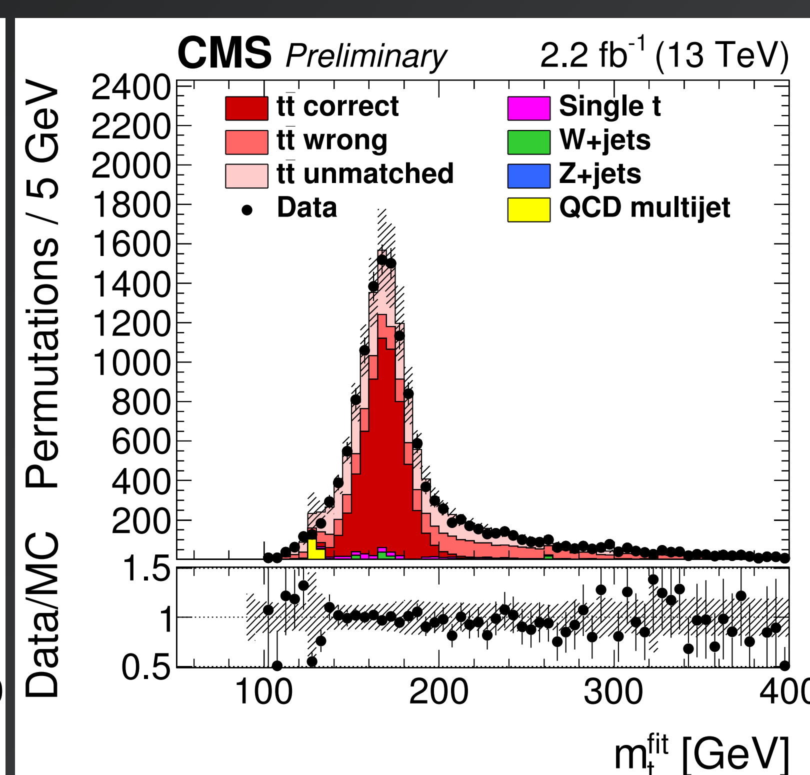
Muon + 4 Jets with CMS

https://inspirehep.net/record/1517829









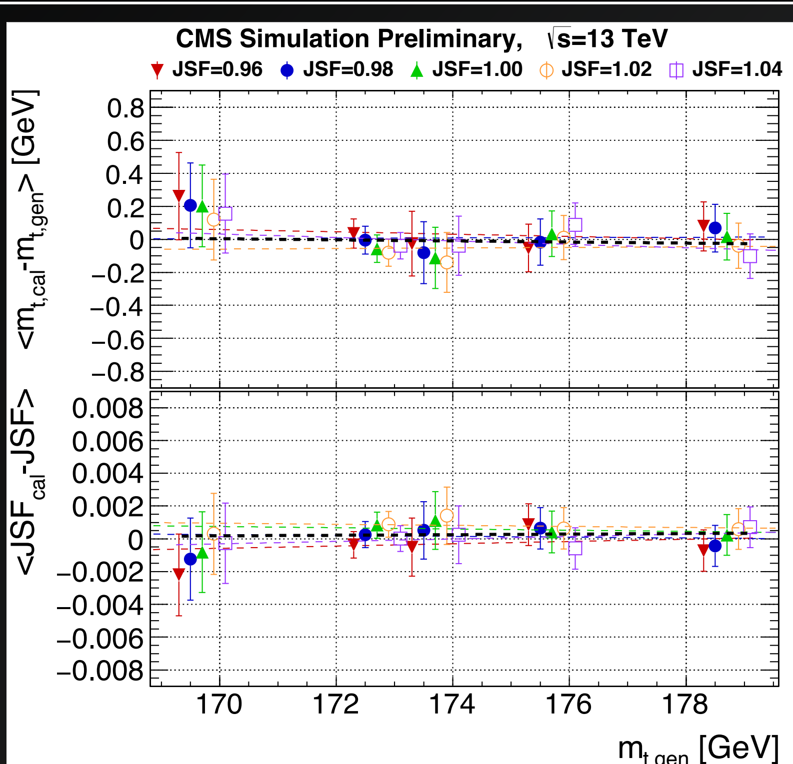
2.2 fb^{-1} @ 13 TeV

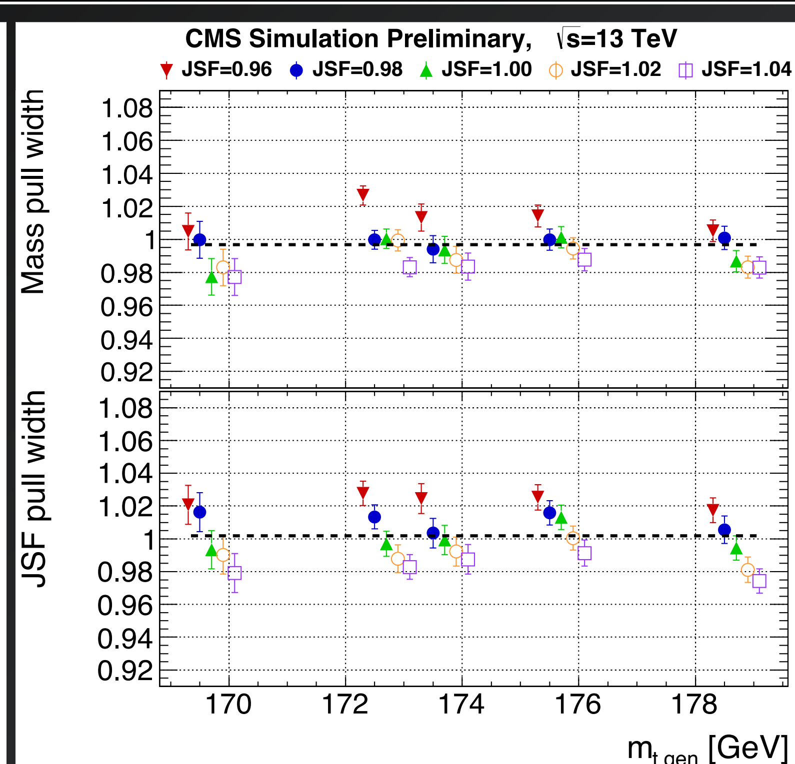
Selection:

- Exactly 1 muon, pT > 25 GeV
- At least 4 anti-Kt R=0.4 jets, pT > 30 GeV
- Exactly 2 of the leading 4 jets must be b-tagged
- Combine W-candidate with **both** b-jets (will give wrong combinations)
- Refine the selection by applying a fit to the 4 jets, muon and missing ET -> reject t candidates where implied P(top) is less than 0.2

Muon + 4 Jets with CMS

https://inspirehep.net/record/1517829



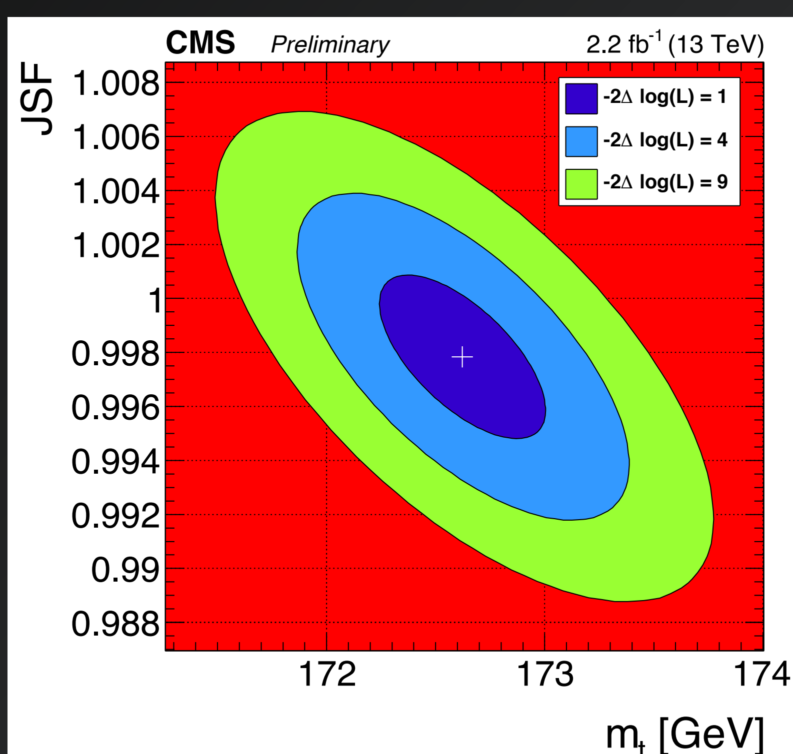


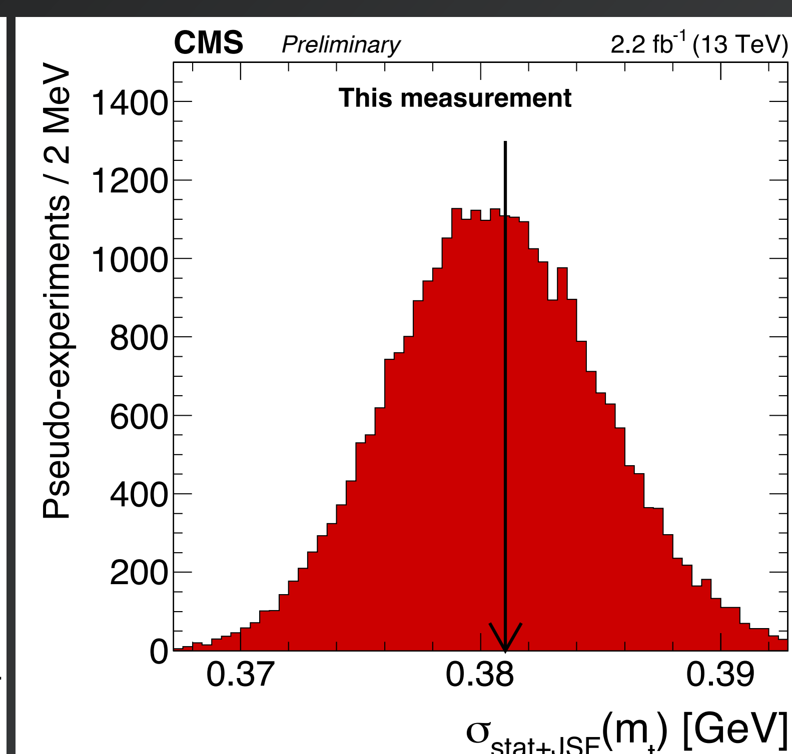
"Ideogram" fit method (also used at 7 TeV)

lepton, 4-jets and MET. Different permutations give different fit masses -> take the one with lowest X^2

JES calibrated in same events using W-mass in fit

Systematic uncertainties are dominated by jet energy calibration and QCD modelling



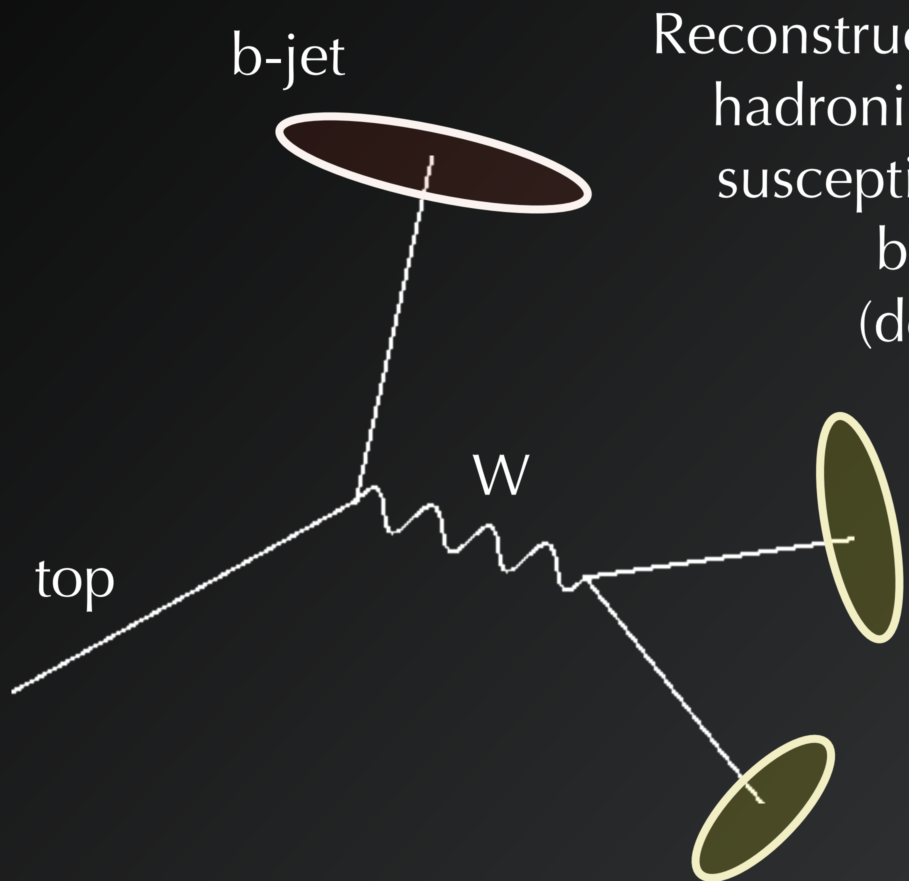


Source	Approach	Contribution
Jet calibration	Up / down variations	0.3 GeV
B-jet modelling	Pythia Vs. Herwig	0.41 GeV
Shower matching	Scale variations	0.23 GeV
Soft QCD	Tune and colour reconnection variations	0.18GeV 0.22 GeV

172.62 ± 0.38 (stat) ± 0.7 (syst) GeV

R3/2 Jet Ratio with ATLAS

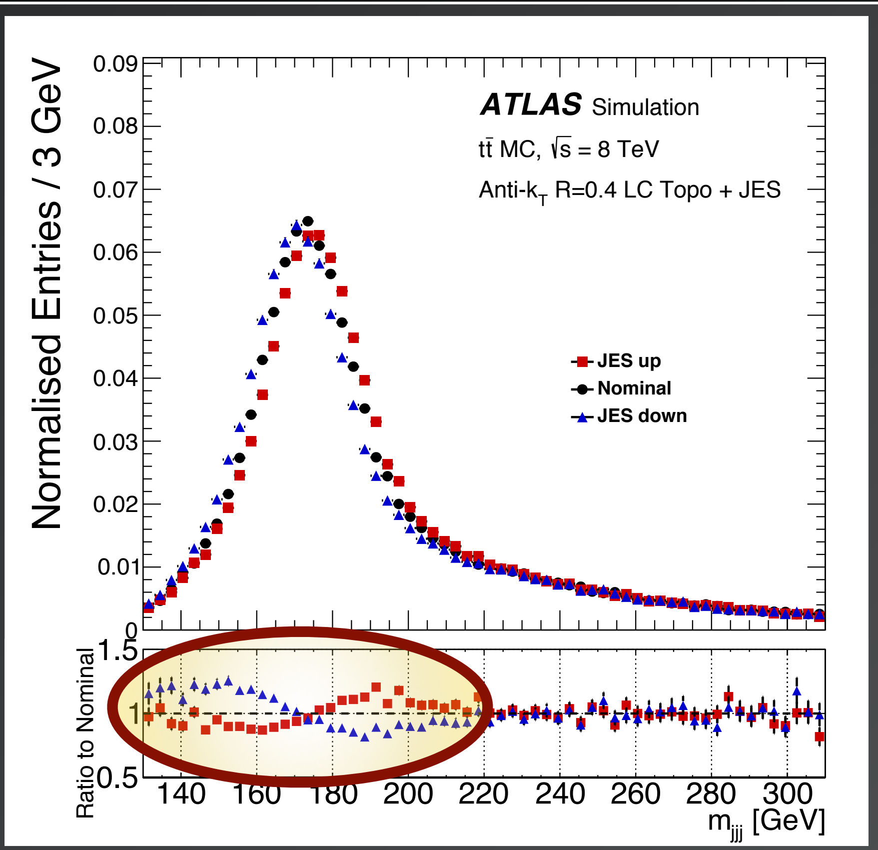
http://inspirehep.net/record/1515025

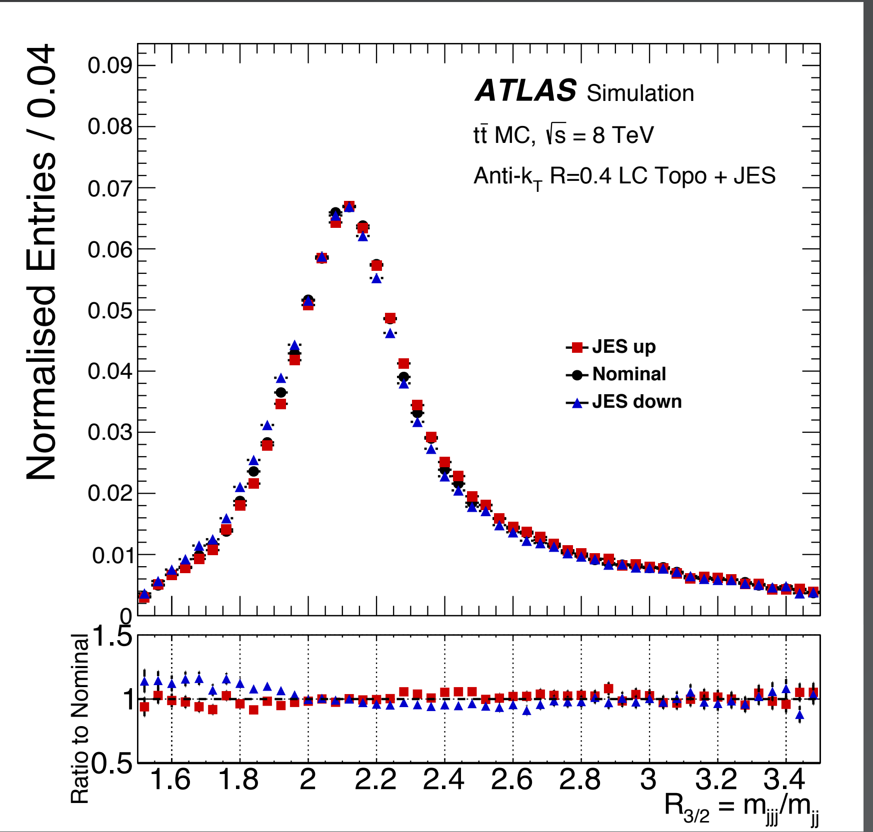


Reconstructing the top mass from hadronic top decays to 3 jets is susceptible to corrections from both the jet energy scale (detector calibration) and hadronic corrections

The jets themselves are intrinsically sensitive to QCD modelling - depend on jet R param, out of cone radiation, non-perturbative effects etc.

But, these things affect the W-candidate as well as the top -> there is a significant degree of cancellation in the ratio of the 3-jet top-candidate mass (M_{jjj}) to the 2-jet W-candidate mass (M_{jj})

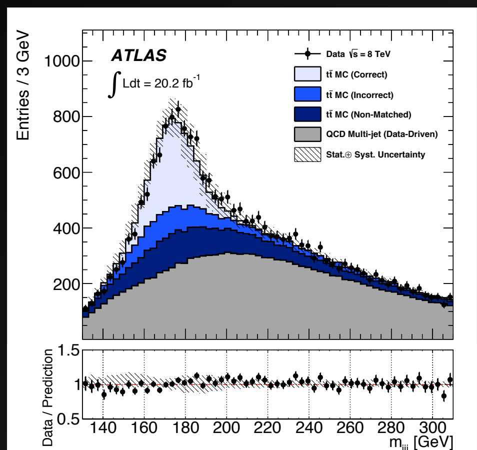




R3/2 Measurement

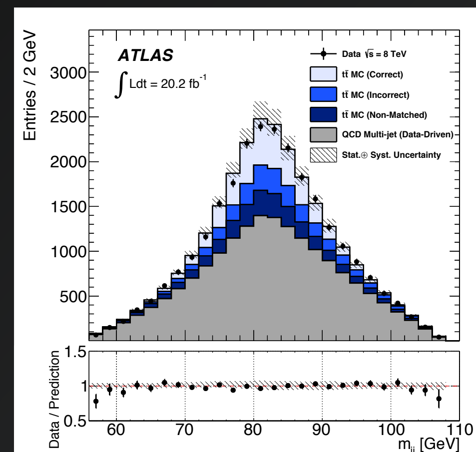
http://inspirehep.net/record/1515025

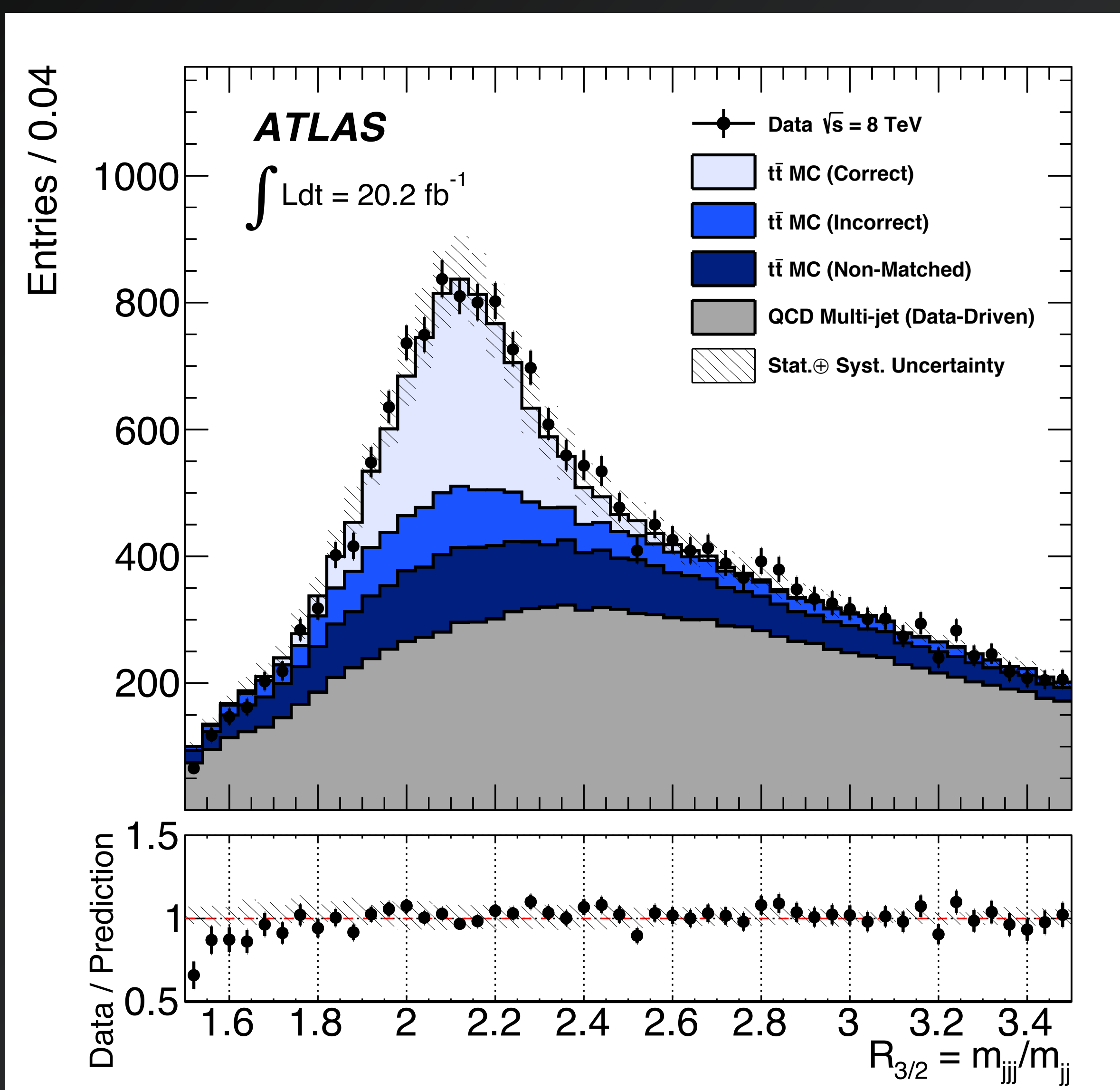
top candidate



÷

W candidate





20.2 fb^{-1} @ 8 TeV

Selection:

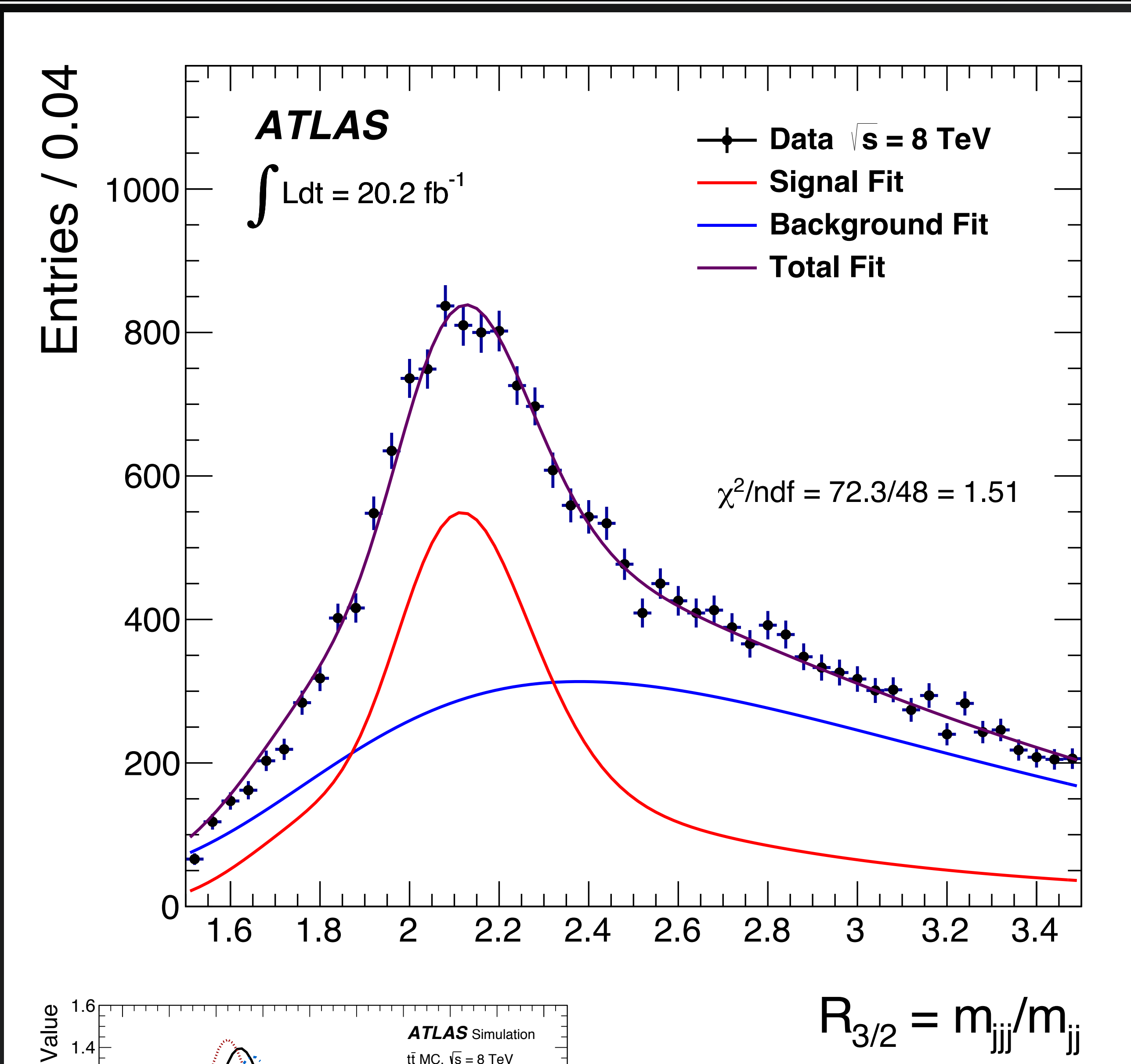
- At least 5 jets, pT > 60 GeV. Any additional “lead” jets pT > 25 GeV
- Jets must be separated by ΔR > 0.6
- Missing ET < 60 GeV (no neutrinos)
- Muon veto (pT > 20 GeV) and electron veto (ET > 25 GeV)
- 2 of the lead jets must be b-tagged
- Highest two b-weight jets must satisfy **Δφ** > 1.5
- W-candidate and associated b-jet satisfy **Δφ** > 2

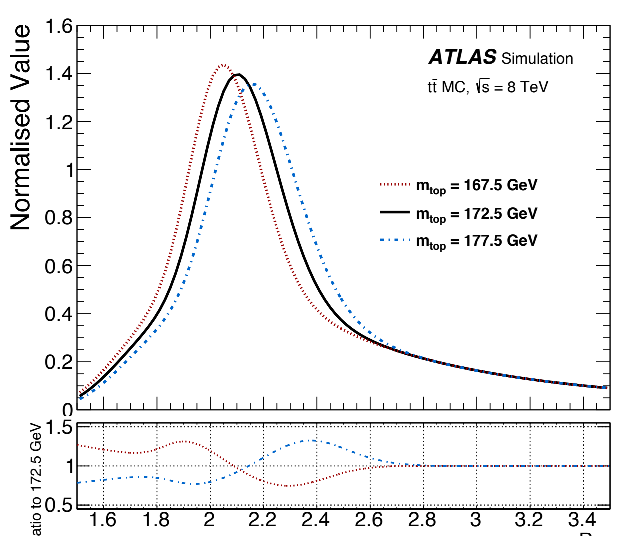
Top candidate combinations selected by minimising

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

Fits to Data

http://inspirehep.net/record/1515025





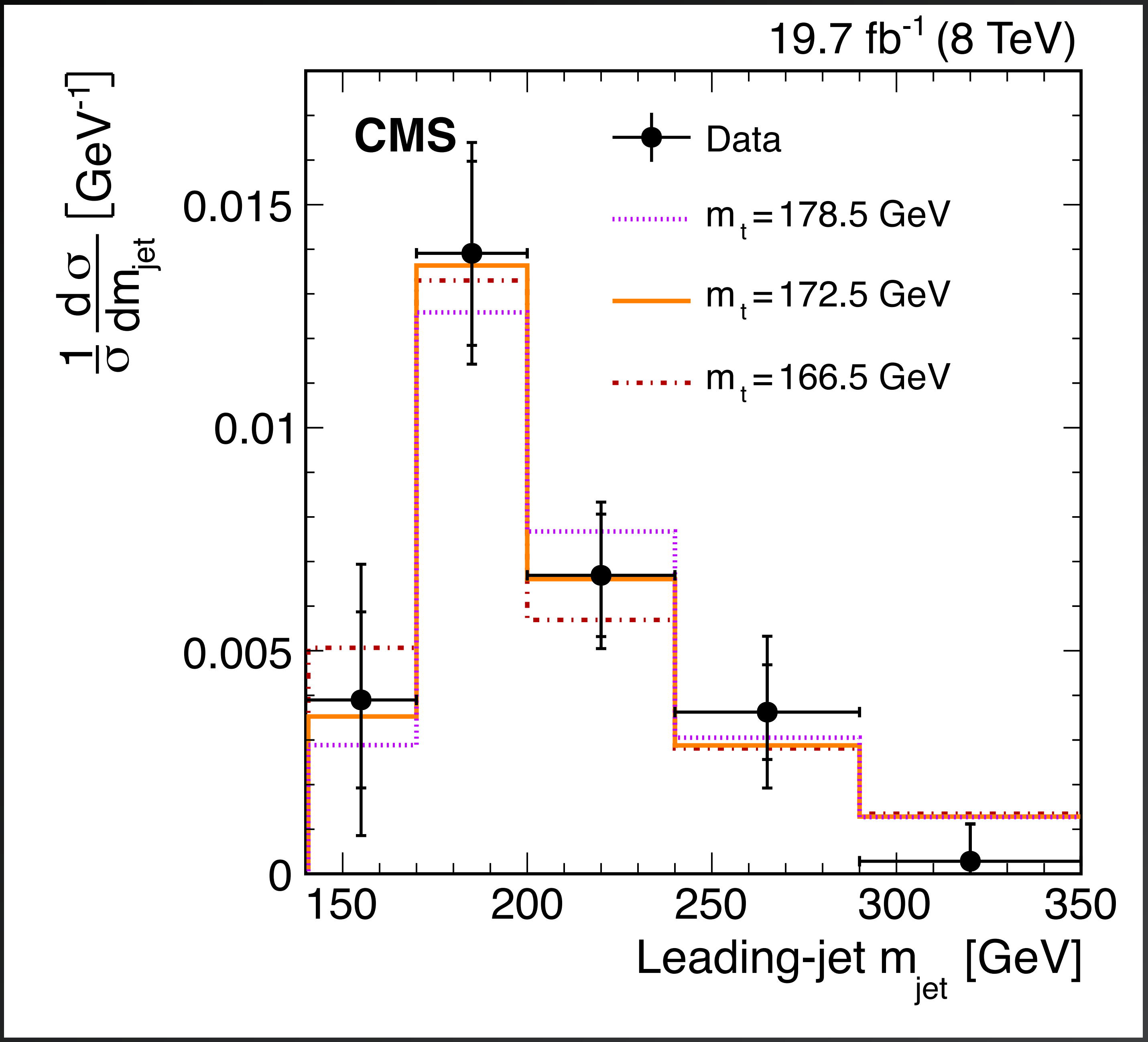
- 5 Powheg + Pythia samples at mass points 167.5, 170, 172.5, 175 and 177.5 are fitted by a Landau + Novosibirsk curve -> 6 params per curve, but they are linear in generated mass
- Systematics are (surprise!) dominated by QCD modelling and jet energy scale. Main ones are

Source	Approach	Contribution
Hadronisation	Pythia Vs. Herwig	0.64 GeV
ME	MC@NLO Vs. Powheg	0.18 GeV
Jet Energy Scale	25 up/down variations	0.6 GeV
B-jet calibration	Additional up/down jet variations	0.34 GeV

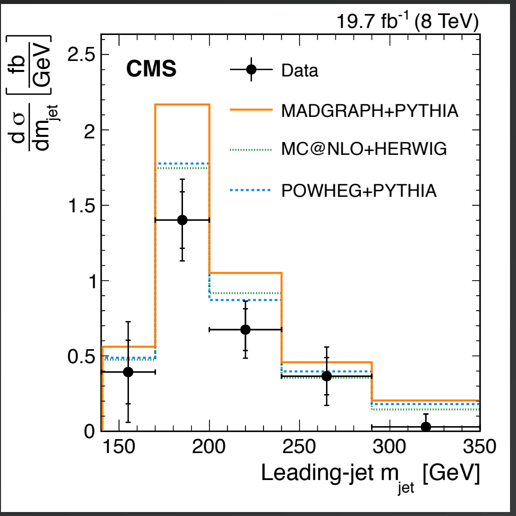
173.72 ± 0.55 (statistical) ± 1.01 (systematic) GeV

Boosted Top Jet Mass with CMS

https://inspirehep.net/record/1487491



Unfolded R=1.2 CA jets, pT > 400 GeV, |η|< 2.5

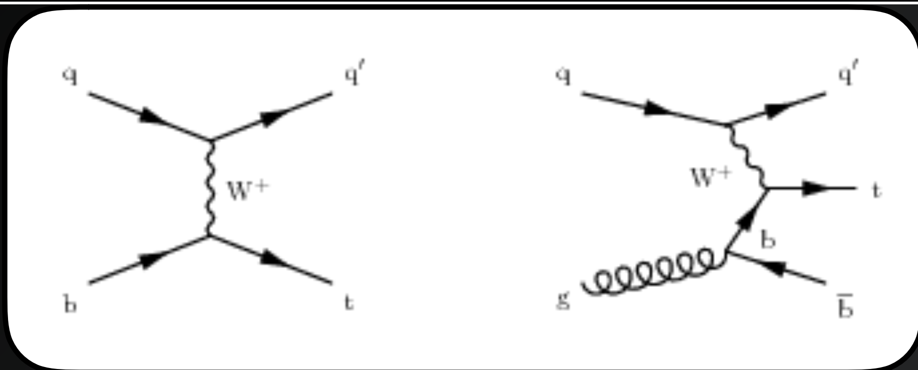


- Constrains modelling and improves understanding of boosted jets
- When appropriate calculations become available, can be used to extract the top mass in a theoretically well defined way -
- lepton + jets channel, one muon or electron with pT > 45 GeV and |η| < 2.1
- Exactly one additional jet, pT > 150 GeV. Second jet and lepton must satisfy Δr < 1.2
- Largest uncertainties are statistical. More data will allow a better unfolding (more finely binned, more correlations)
- Modelling of ttbar production also affects the unfolding and contributes to the uncertainty.

170.8 ± 6 (stat) ± 2.8 (syst) ± 4.6 (MC) ± 4 (theory) GeV

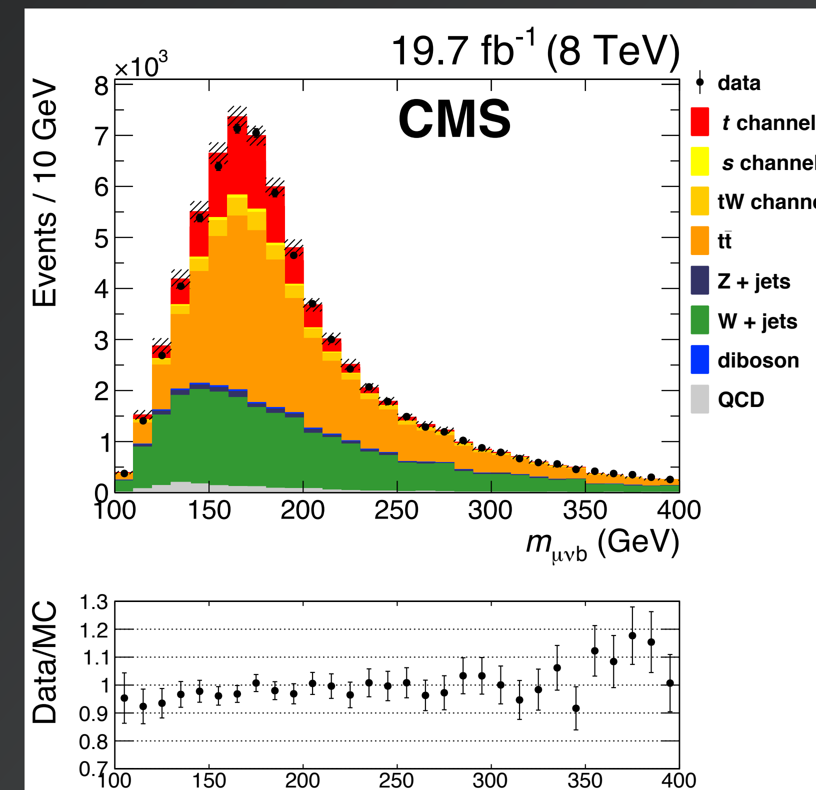
Top Mass in Single Top Events with CMS

https://inspirehep.net/record/1516412

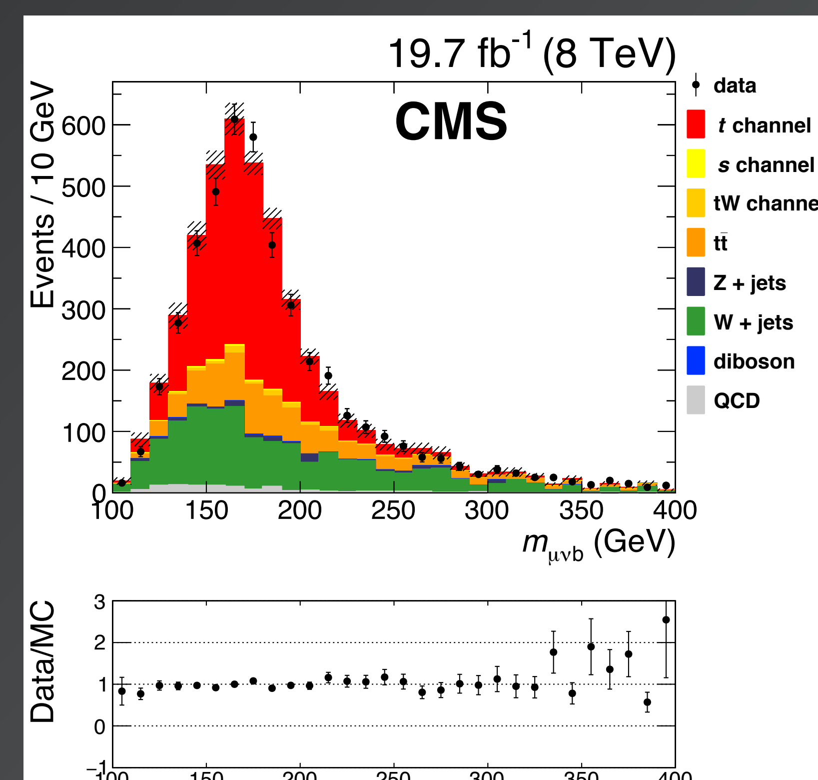


19.7 fb^{-1} @ 8 TeV

- Single top is produced at LHC via electroweak exchange.
- Interesting because
  - Different production means different QCD background to ttbar pair production -> different colour topology could help constrain QCD uncertainty
  - Theoretical grey area (difference between ttbar and t + highly off-shell t = W +b)
- Event selection:
  - 1 isolated muon with pT > 26 GeV (no additional muons above 10 GeV or electron above 20 GeV)
  - Two AKt R=0.5 jets, pT > 40 GeV. Exactly one b-tag (selects t-channel W EW exchange above)
  - Missing transverse pT > 50 GeV
  - Transverse mass of the W (μ + pTMiss) > 50 GeV

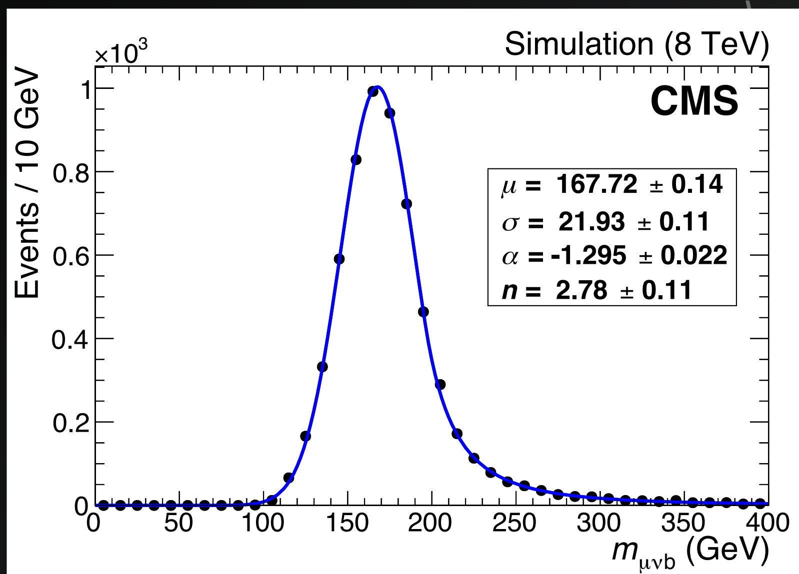


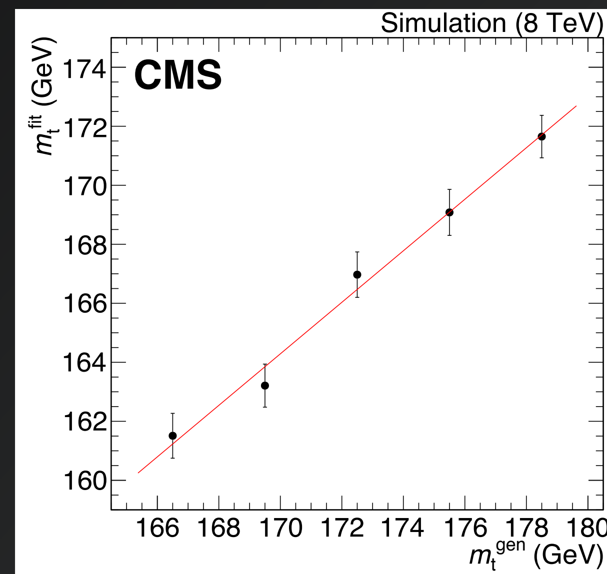
After final selection requires light jet |η| > 2.5 and muon charge is positive

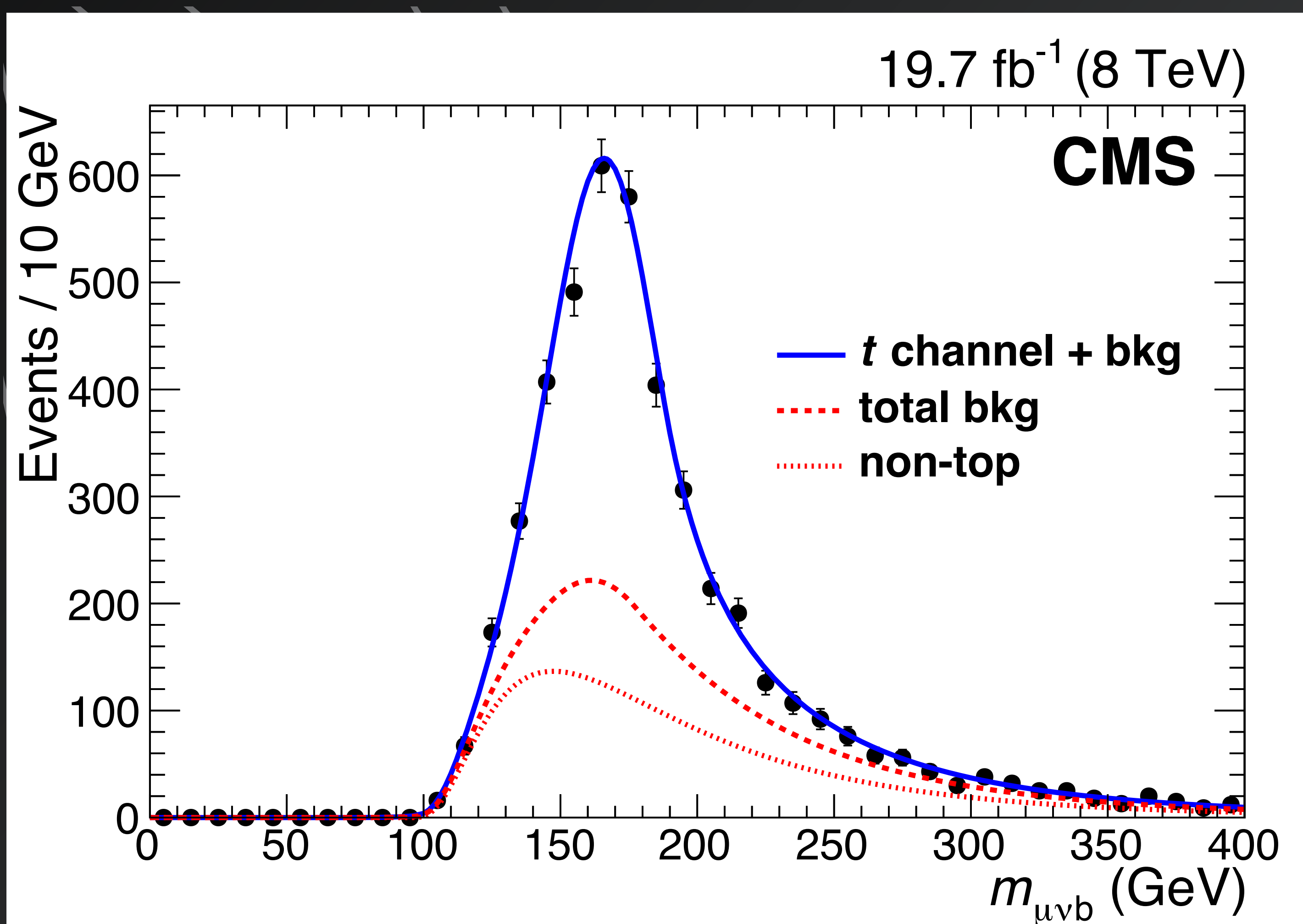


Top Mass in Single Top Events with CMS

https://inspirehep.net/record/1516412







- Fit μνb mass with crystal ball function
- Needs calibration of fitted mean Vs. generated mass - 5 MC samples
- Largest uncertainties are jet calibration, background fit and fit calibration

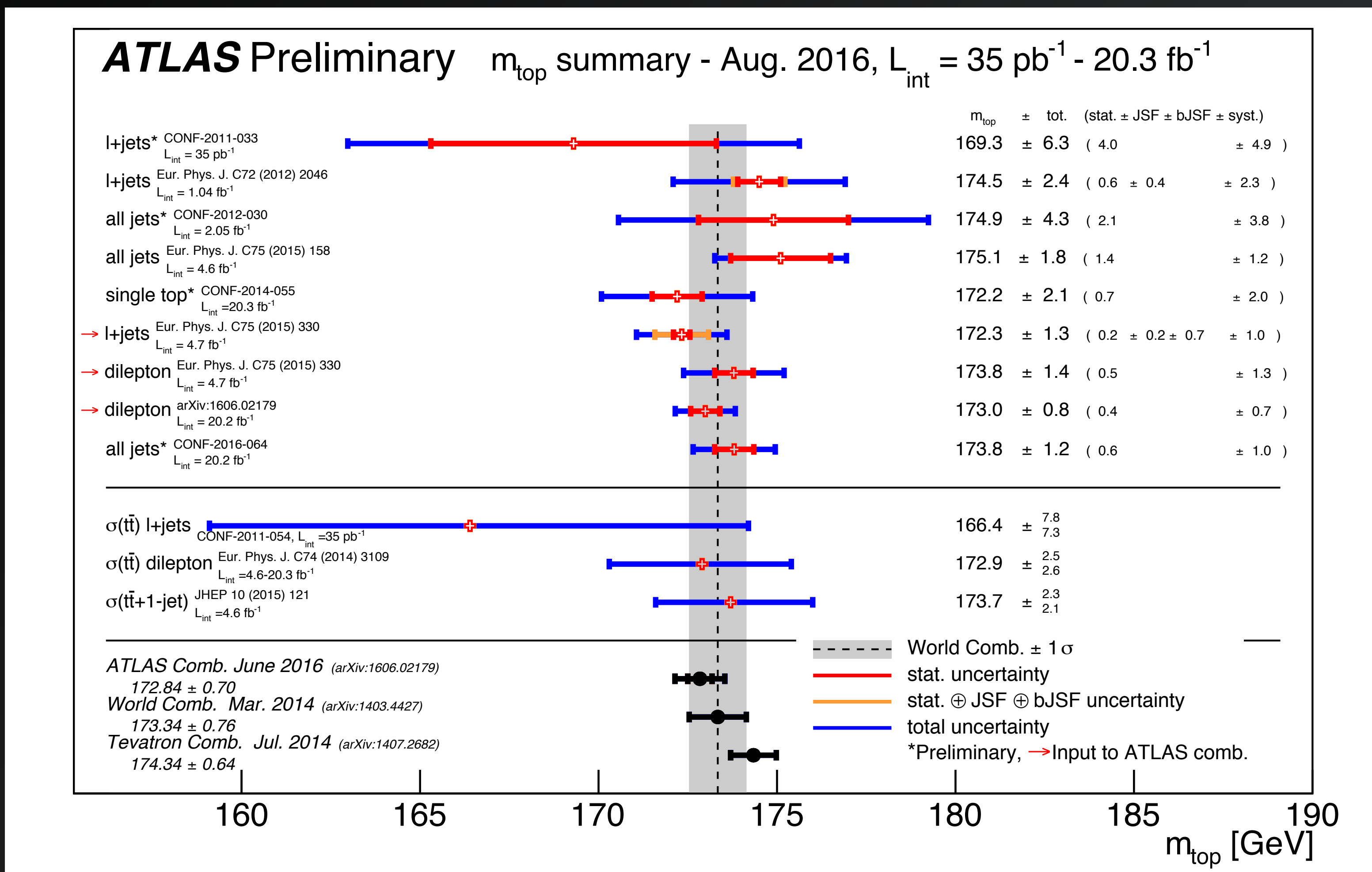
Source	Contribution
Up / down jet energy scale variations	+0.68 / -0.61 GeV
Mass calibration curve statistical uncertainty	0.39 GeV
MC scale variations	0.23 GeV

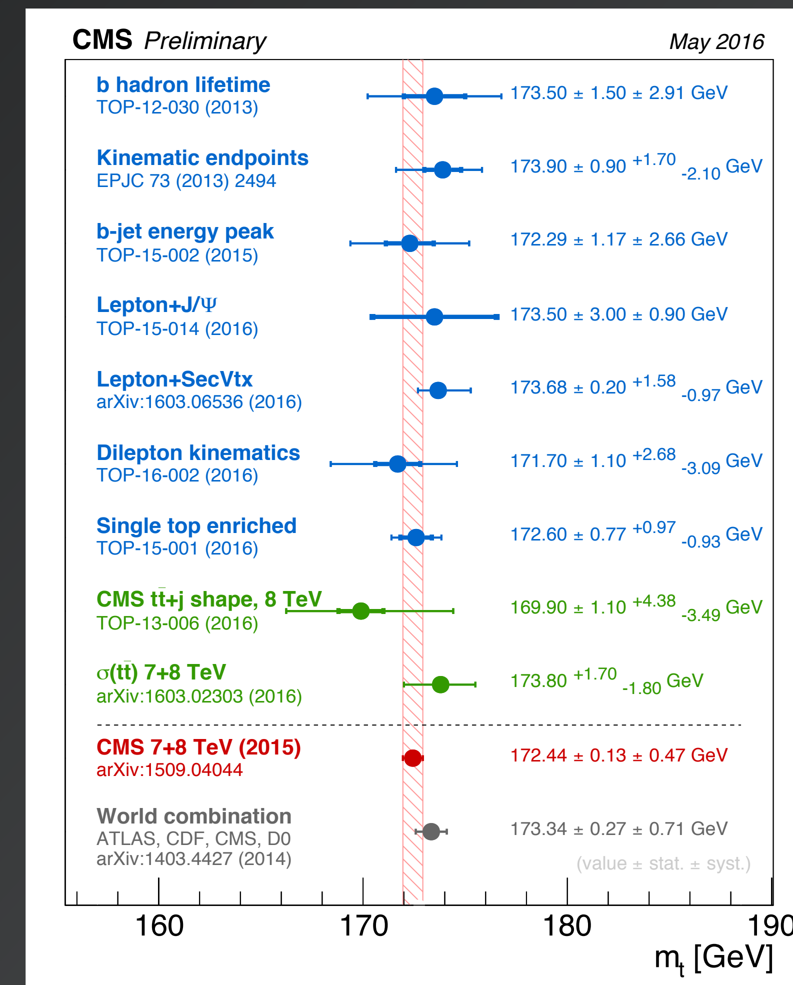
- BG is dominated by ttbar and W+jets (MadGraph + Pythia 6). BG normalisation is varied up and down by 1 σ, and the BG fit params are also varied by the same. BG scale variations add 0.18 (fact + renorm) and 0.3 (shower matching) GeV

172.95 ± 0.77 (stat)
+ 0.97 / -0.93 (syst) GeV

Combinations

Combined results from the individual experiments

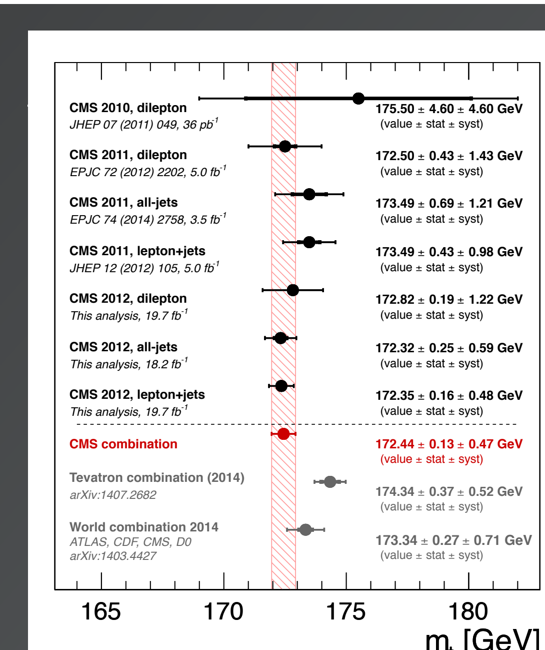




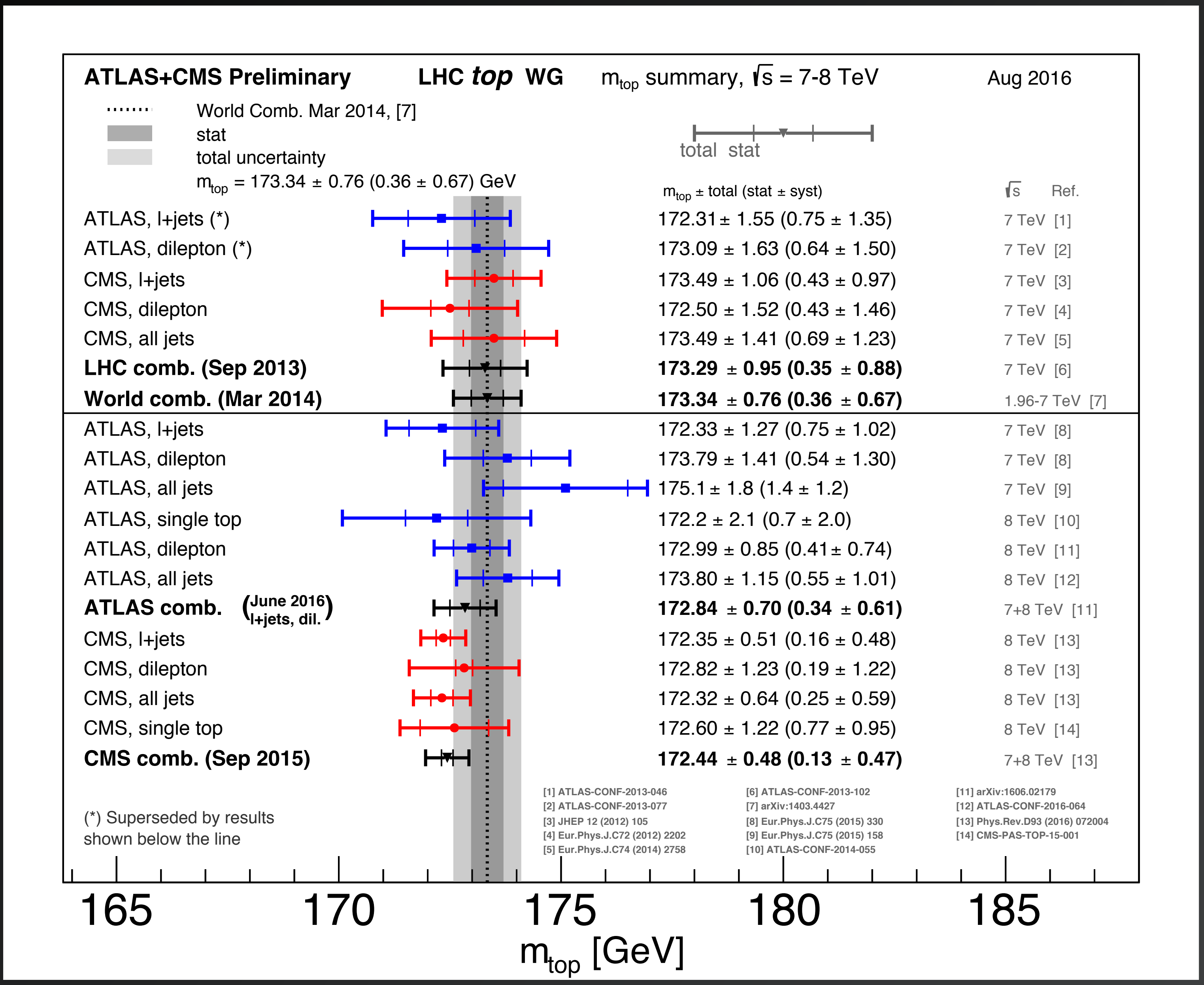
Combinations are a bit old and will need to be re-done once the full set of 8 and 13 TeV results are available

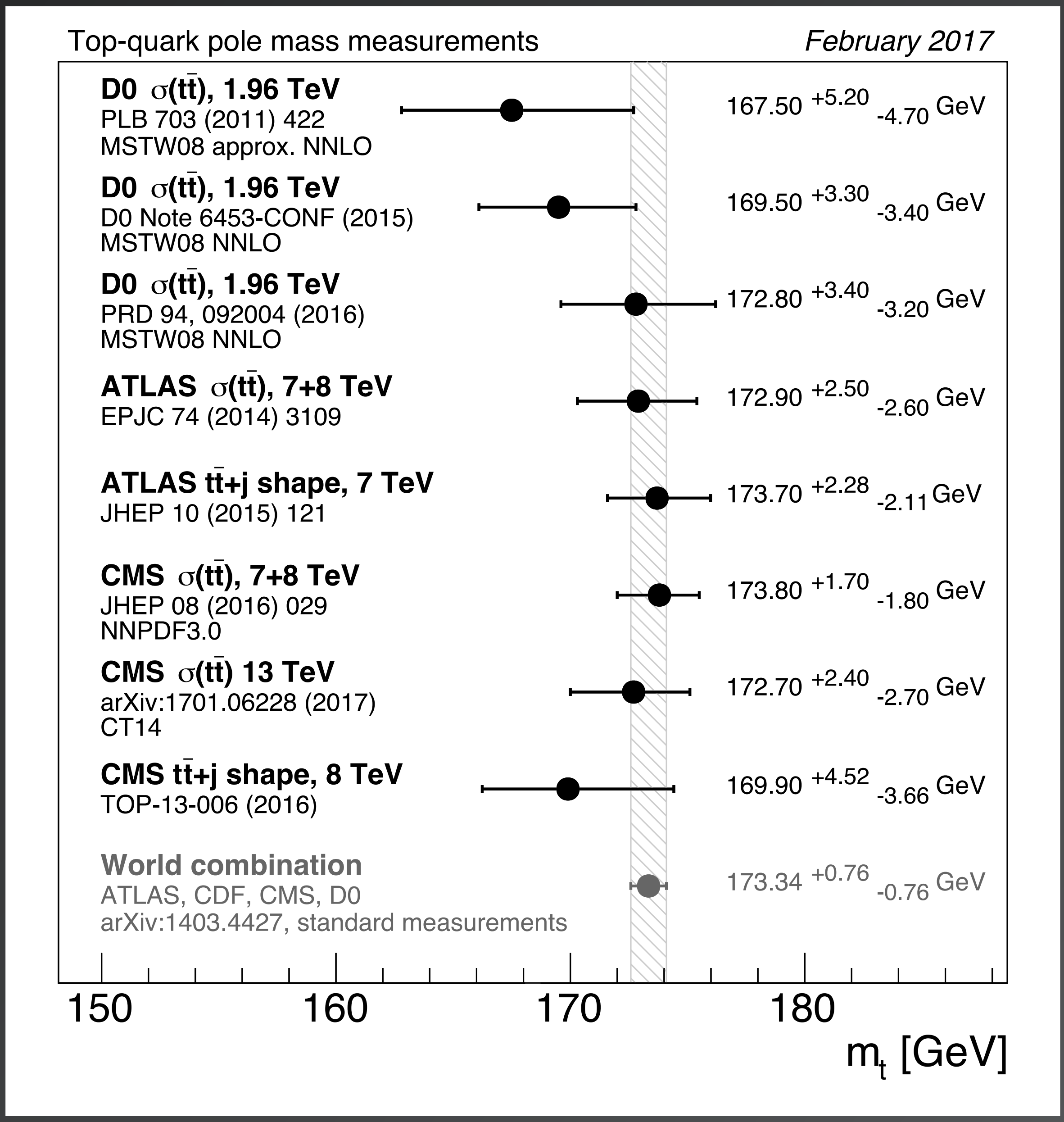
Most recent ATLAS combination: 172.84 ± 0.7 GeV (June 2016)

Most recent CMS combination: 172.44 ± 0.13 ± 0.47 GeV (Sept 2015)



Combinations





The most recent world combination (incl. Tevatron) is 173.34 ± 0.76 GeV (March 2014). Only includes 7 TeV LHC results -> to be updated!

Any pole mass discrepancy with the world average would be **very** interesting (mass definition dependence)

Summary

- Have shown recent results representing the range of LHC top mass measurements
- Di-lepton channel at ATLAS and muon + 4 jets at CMS
    - Channels with the best experimental precision
- Hadronic channel at ATLAS
    - 3/2 ratio reduces QCD and jet uncertainties
- Single top at CMS
    - Complementary channel with different QCD dependence
- Boosted fat top jets at CMS
    - Demonstration of feasibility, opportunity for well defined theory and QCD constraints