Top mass measurement.

A summary of Tevatron and LHC results

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On behalf of the ATLAS, CMS, D0, and CDF collaborations

Aspen DM, January 2014

HELMHOLTZ GEMEINSCHAFT

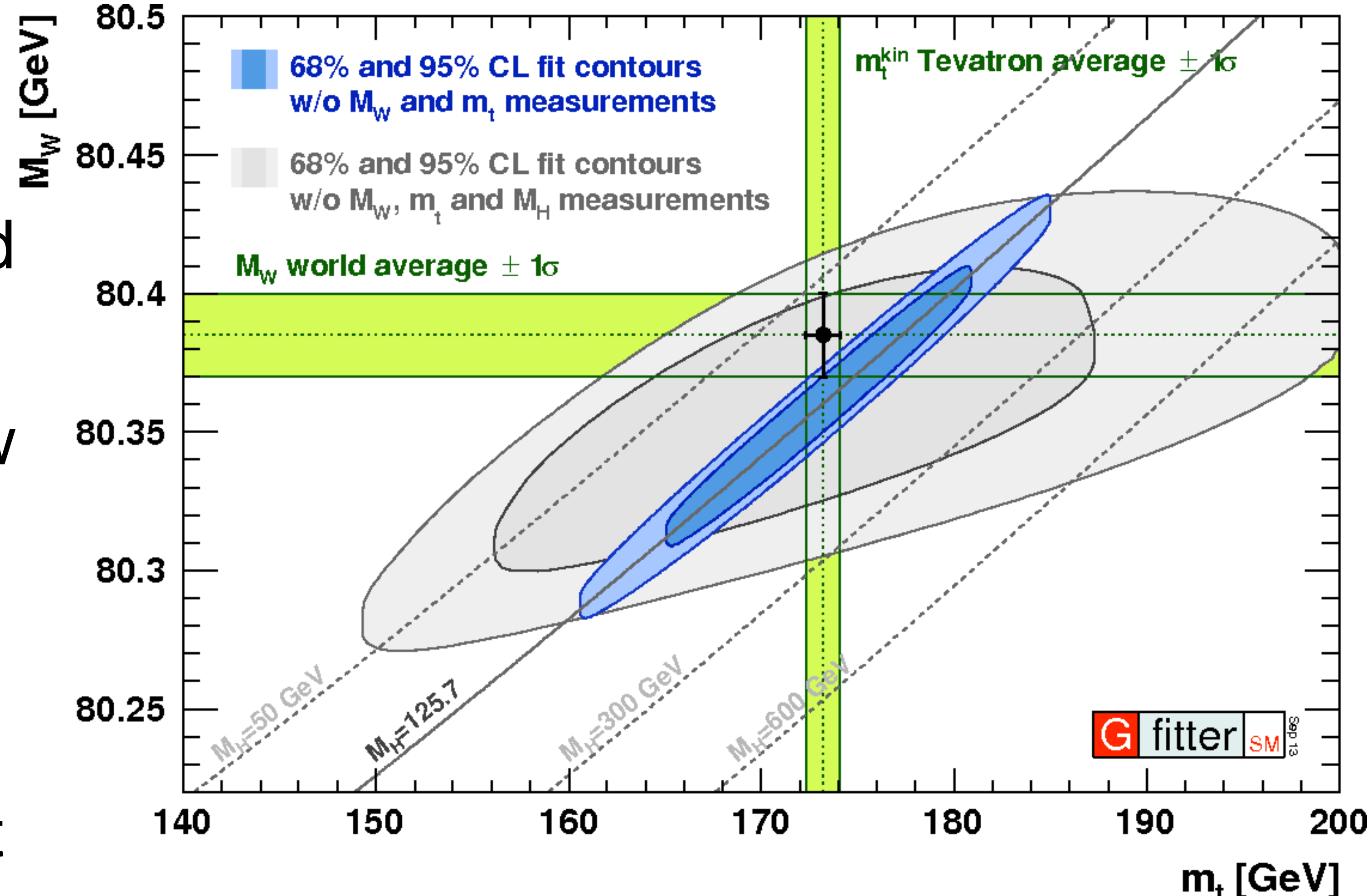
DESY

Outline

- Why top mass?
- What mass?
- Tevatron and LHC: standard measurements
- Tevatron and LHC: combinations
- Mass from cross section
- Alternative direct measurements
- Measurements of top–anti-top mass difference
- Conclusions

Why top mass?

- Fundamental parameter of the Standard Model.
- Relationship between top, W and Higgs masses predicted.
- With H mass known, we can now check internal consistency.
- Useful constraint for future calibrations.
- Mass difference top–anti-top test of CPT invariance.



http://gfitter.desy.de/Standard_Model/

What mass?

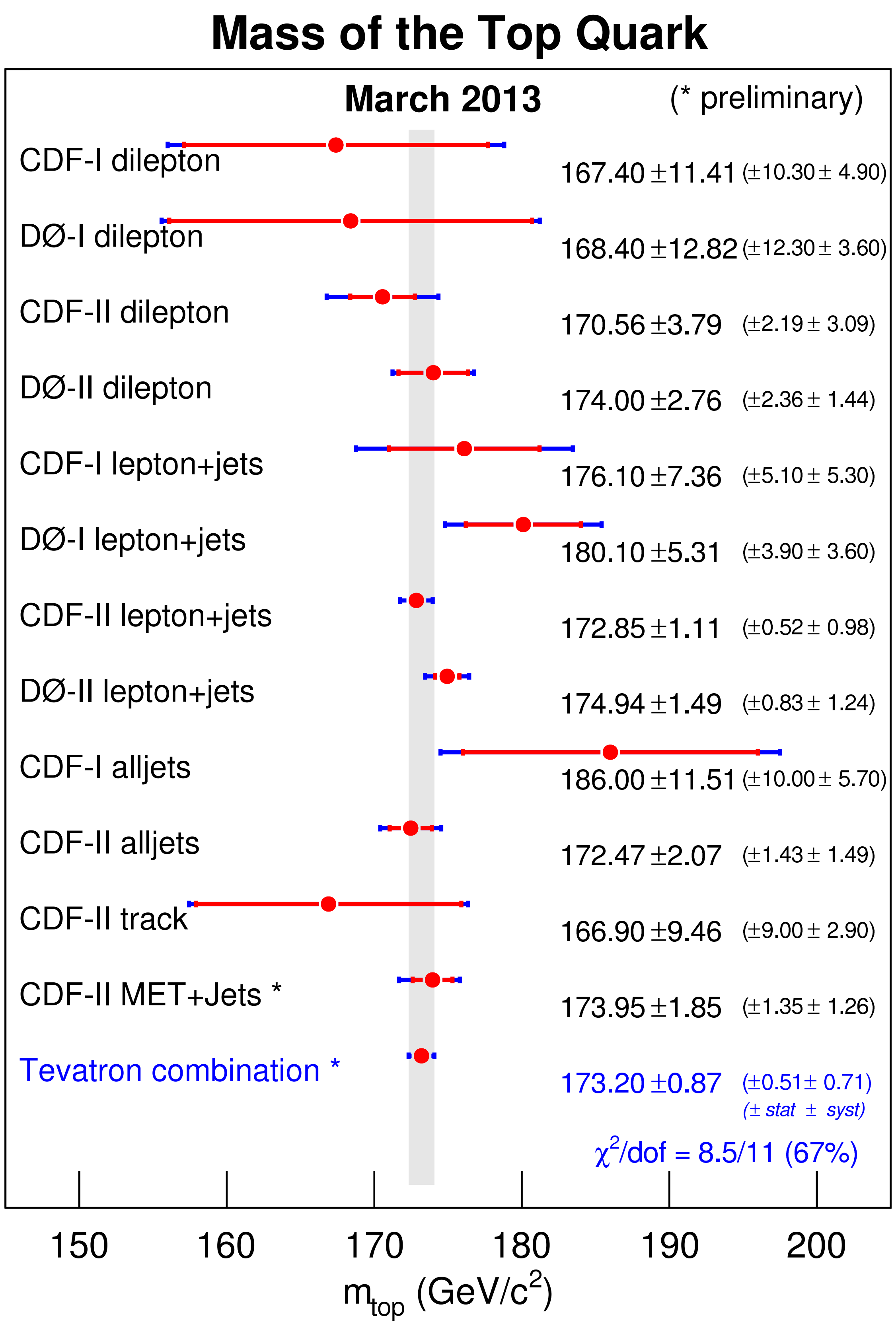
- Top mass not an observable, but a parameter.
- Value depends on chosen renormalization scheme.
- ”Conventional” measurements typically fit template distributions of Monte Carlo simulation to data.
- Measures a ”Monte Carlo mass”, which can be argued to be equivalent to the pole mass within 0.5~1 GeV.
- Alternative: Extract mass from from comparison of experimental measurements to full NLO or NNLO calculations.

Overview of measurements

- As usual for ttbar measurements, can be done in di-lepton, lepton+jets, and all-hadronic channels.
- Lepton+jets channel providing best accuracy in both LHC and Tevatron.
- Measurements (both Tevatron-II and LHC) generally limited by systematics.
- LHC measurements thus still mostly using 2011 data (up to 5.0 fb^{-1}).
- Tevatron
  - CDF-I — dilepton, lepton+jets, all hadronic
  - CDF-II — dilepton, lepton+jets, all hadronic, track, MET+jets
  - D0-I — dilepton, lepton+jets
  - D0-II — dilepton, lepton+jets
- LHC
  - ATLAS — dilepton, lepton+jets, all hadronic, delta m
  - CMS — dilepton, lepton+jets, all hadronic, delta m, kinematic endpoints, B hadron lifetime

Tevatron measurements and combination

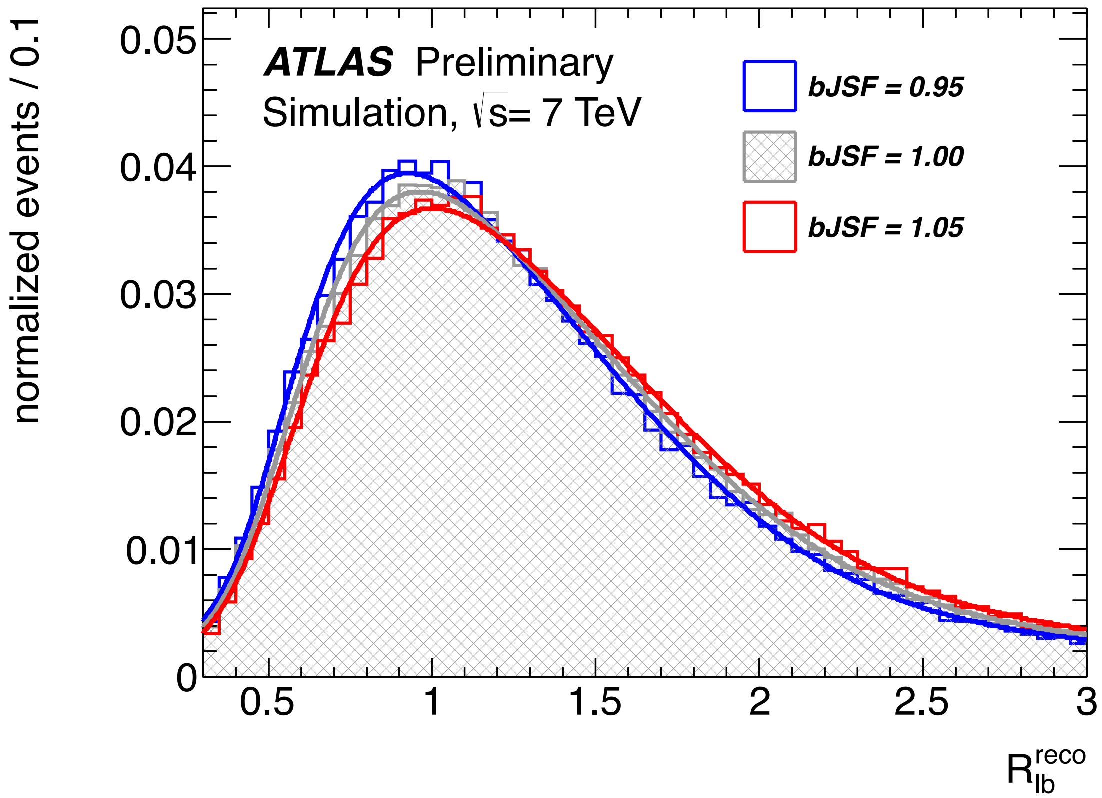
- Large number of measurements performed by D0 and CDF.
- Runs I and II.
- Up to 8.7 fb^{-1} per experiments.
- Most precise measurements in lepton +jets channel.
- Combined using BLUE method (details later).
- 2013 combination updated with respect to 2011: CDF-II l+jets and CDF-II MET +Jets using full 8.7 fb^{-1} data set.



arXiv:1305.3929, http://tevewwg.fnal.gov

ATLAS lepton+jets

- **World's first measurement constraining JES and *b*JES in simultaneous fit with m_t.**
- Full 2011 data set (4.7 fb^{-1}).
- Require:
  - 1 lepton
  - 4 jets, of which at least one *b*-tagged
  - $E_{T,miss}$
  - $m_{T,W}$ (el channel) or $m_{T,W} + E_{T,miss}$ (mu channel)
- Full event reconstruction through kinematic likelihood fit using parton-jet transfer functions.
- 3D template fit in
  - m^{reco}_{top}
  - m^{reco}_{W}
  - R^{reco}_{lb} ← constrains the relative ratio of the *b*JES and overall JES



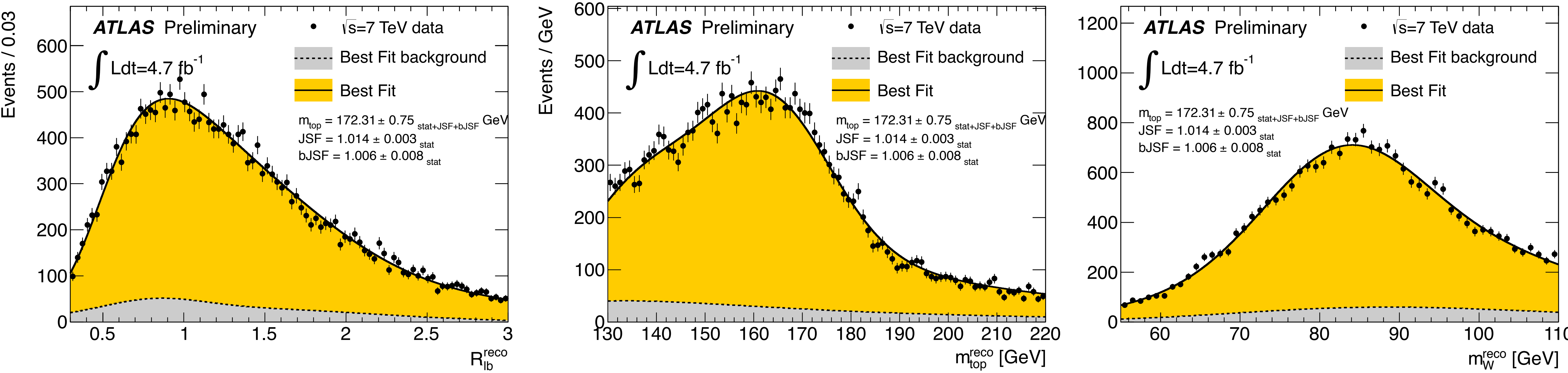
ATLAS-CONF-2013-046

$$R_{lb}^{reco,2b} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{W_{jet_1}} + p_T^{W_{jet_2}}},$$

$$R_{lb}^{reco,1b} = \frac{p_T^{b_{tag}}}{(p_T^{W_{jet_1}} + p_T^{W_{jet_2}})/2}$$

ATLAS lepton+jets (contd.)

Fitted distributions



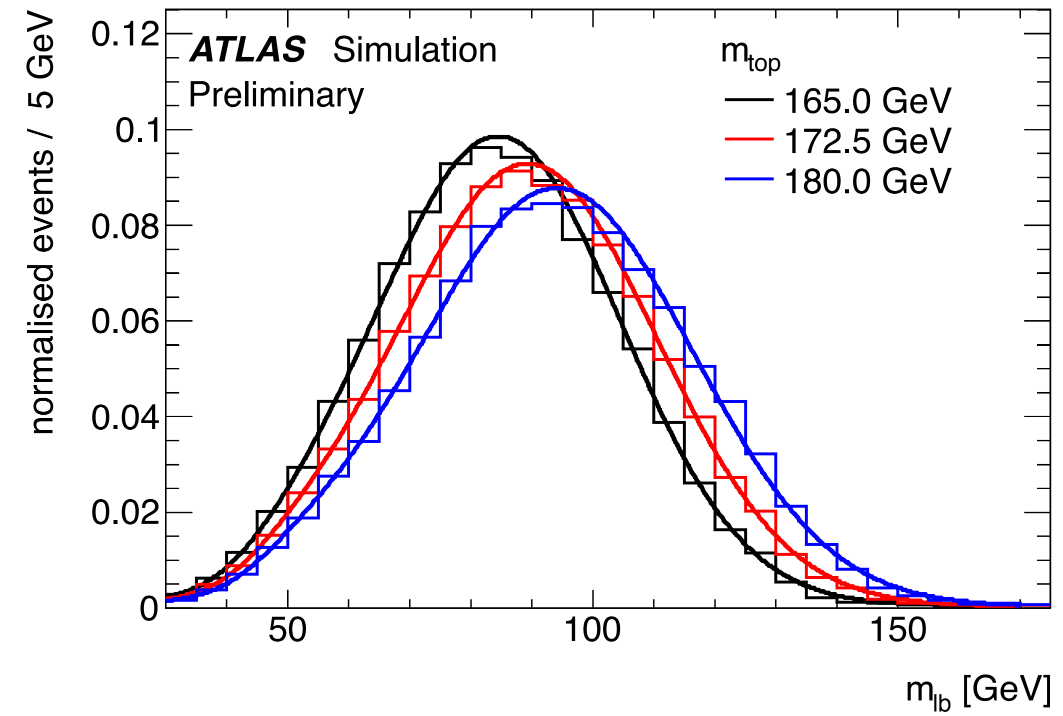
- Jet energy scale uncertainty considerably constrained (but still one of the largest)
- Other dominating uncertainties: modeling, b-tagging

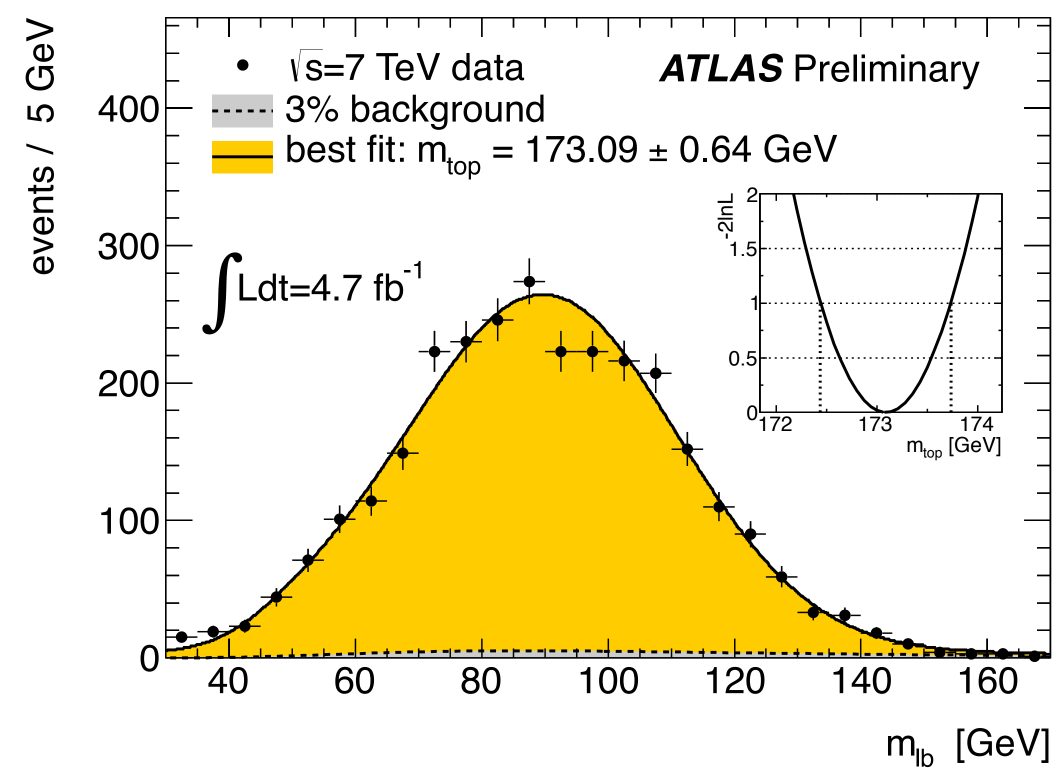
ATLAS-CONF-2013-046

172.31 ± 0.75 (stat + JSF + bJSF) ± 1.35 (syst) GeV, *or*
172.31 ± 0.23 (stat) ± 0.27 (JSF) ± 0.67 (bJSF) ± 1.35 (syst) GeV

- Full 2011 data set (4.7 fb^{-1}).
- Require:
  - 2 leptons
  - 2 b-tagged jets
  - Etmiss (ee/mumu) or HT (emu)
- Consider m_{lb} (lepton–b-jet invariant mass). Assignment with lowest average picked (77% correct).
- One-dimensional template fit.
- Very pure sample: only 3% background (almost only single top).
- Dominant systematics: JES, bJES, b-tagging.

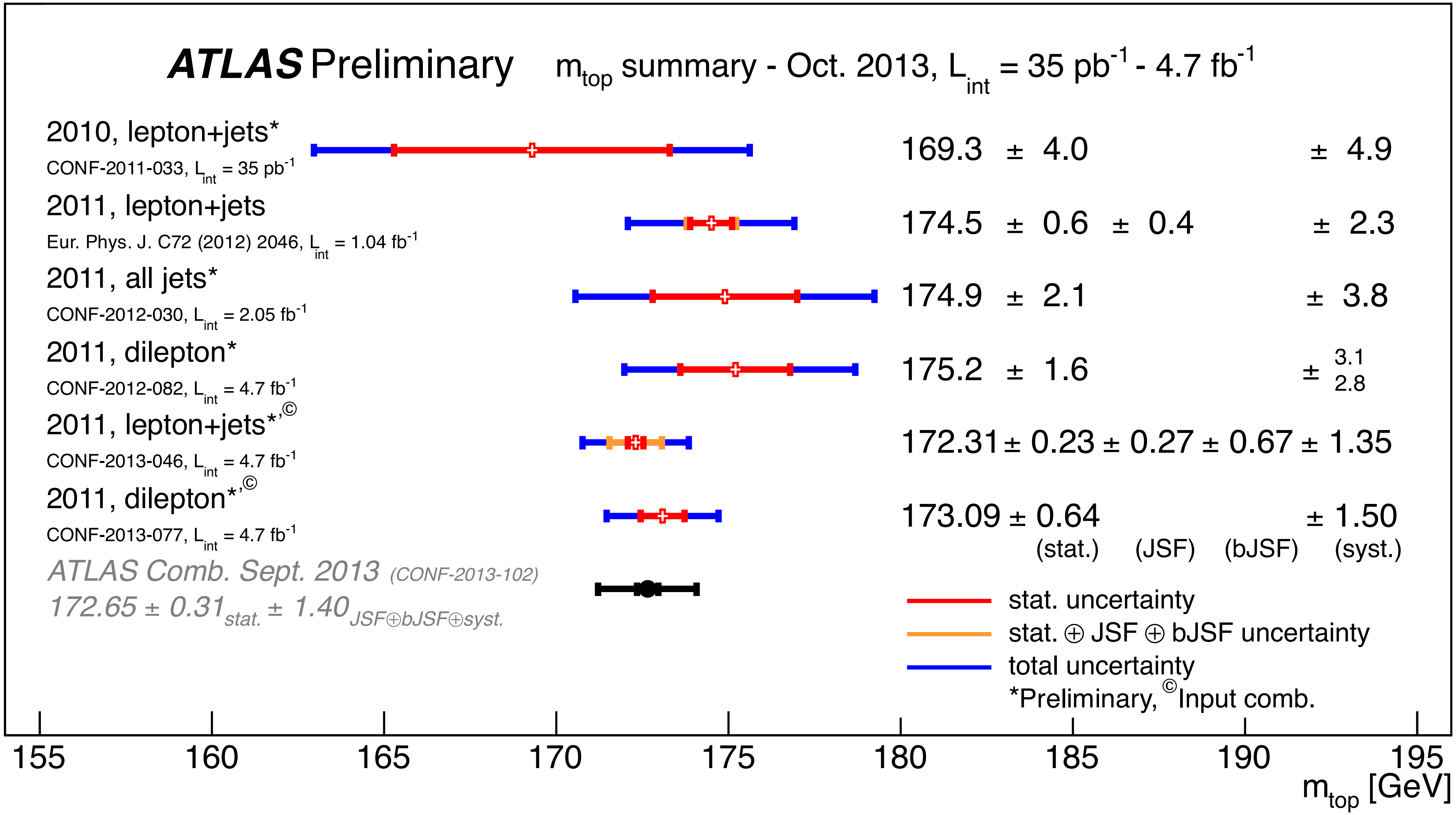
173.09 ± 0.64 (stat) ± 1.50 (syst) GeV





ATLAS-CONF-2013-077 (July 2013)

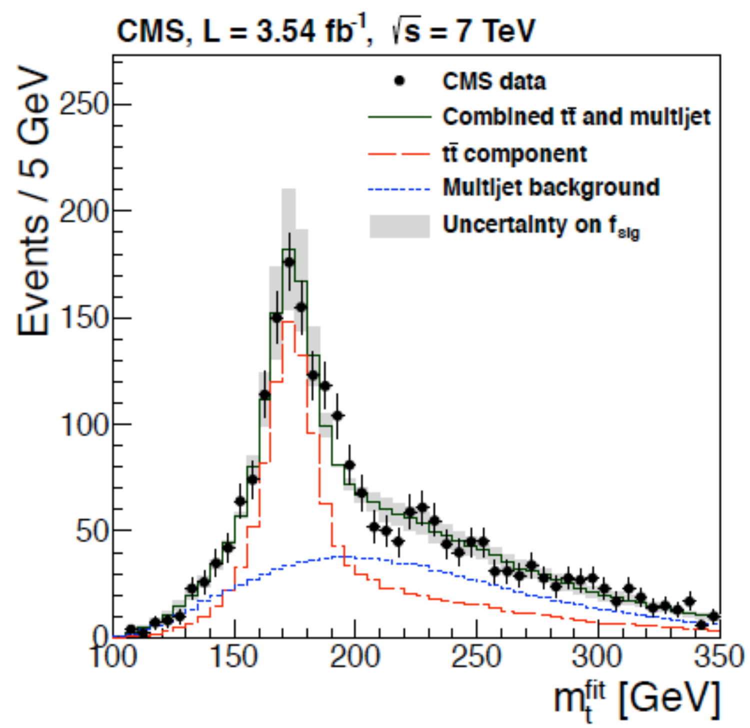
ATLAS summary

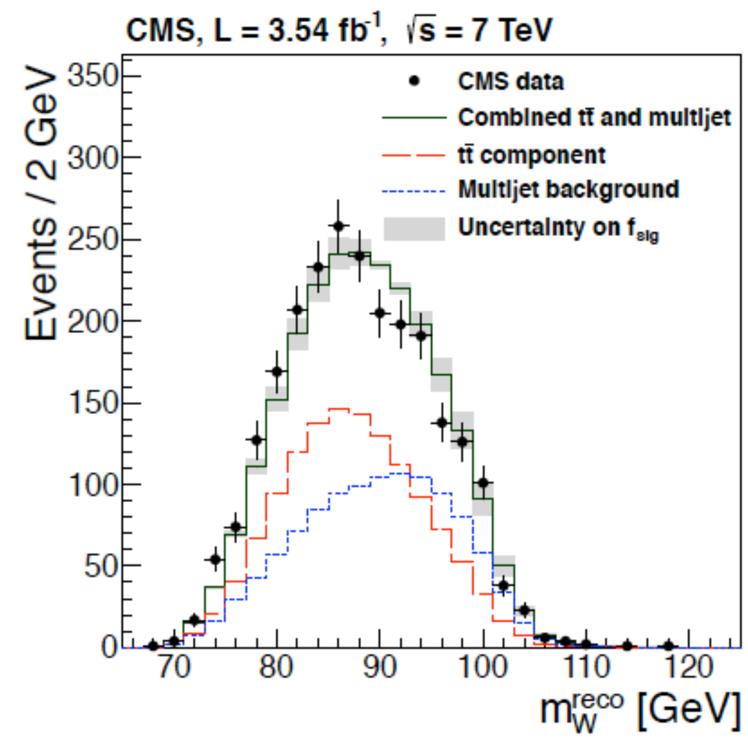


CMS all-hadronic

- 3.54 fb^{-1} from 2011.
- Require
  - 6 jets
  - 2 of which b-tagged.
- Multi-jet background obtained by mixing events.
- Top mass reconstructed directly through kinematic fit.
- Likelihood constructed with ideogram method.

$$\prod_{\text{events}} P\left(m_t^{\text{fit}}, m_W^{\text{reco}} | m_t, \text{JES}\right)^{w_{\text{event}}}$$





Dominant uncertainties: JES, bJES, modeling

174.28 ± 1.00 (stat+JES) ± 1.23 (syst) GeV, *or fixing JES*, 173.49 ± 0.69 (stat) ± 1.21 (syst) GeV

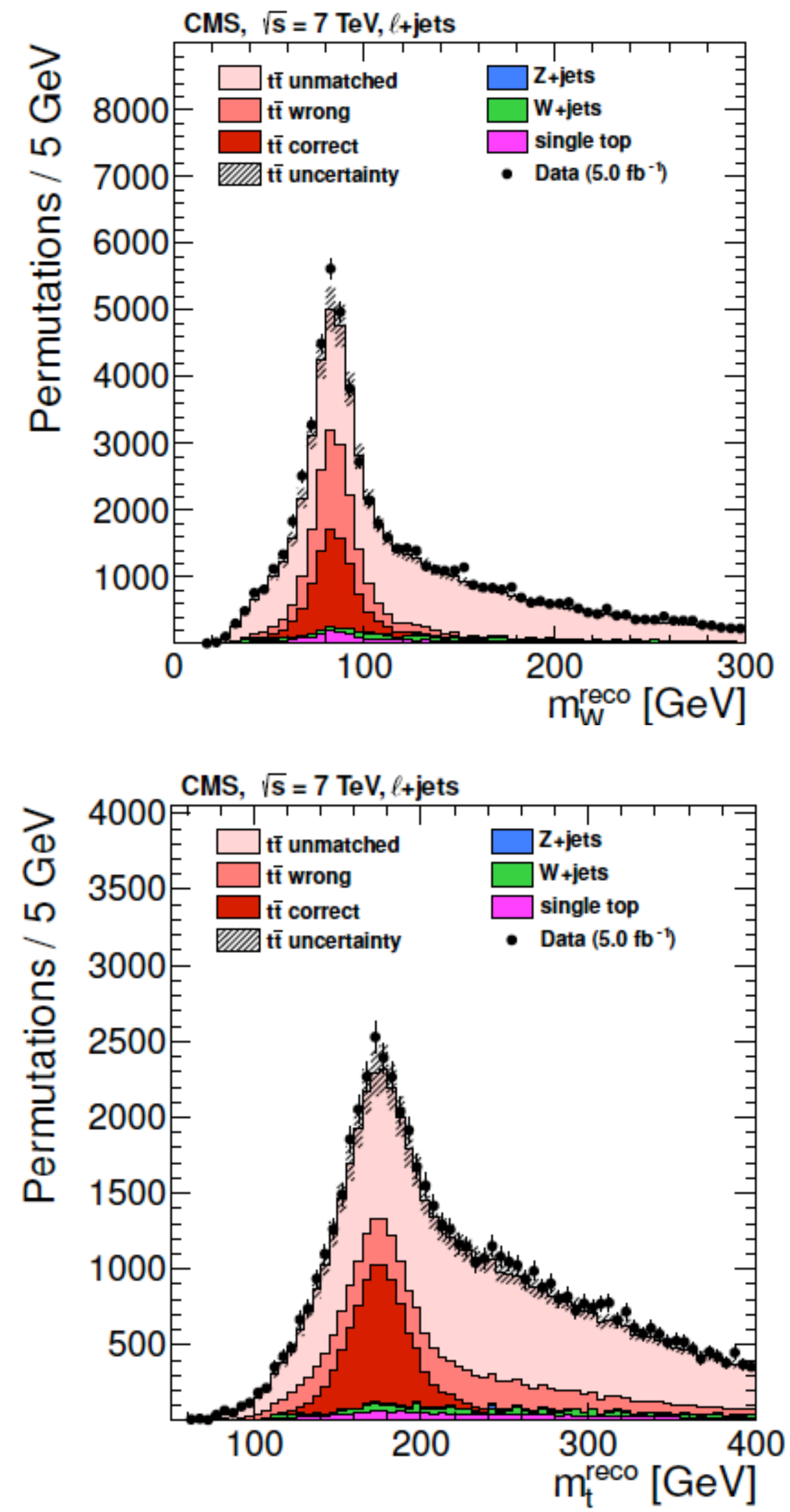
CMS-TOP-11-017, submitted to Eur. Phys. J. C, July 2013

CMS lepton+jets

- Full 2011 data set (5.0 fb-1).
- Require:
  - 1 lepton
  - 4 or more jets (2 or more b-tagged)
- Kinematic fit, cut on goodness of fit.
- Ideogram method, weighting with goodness of fit

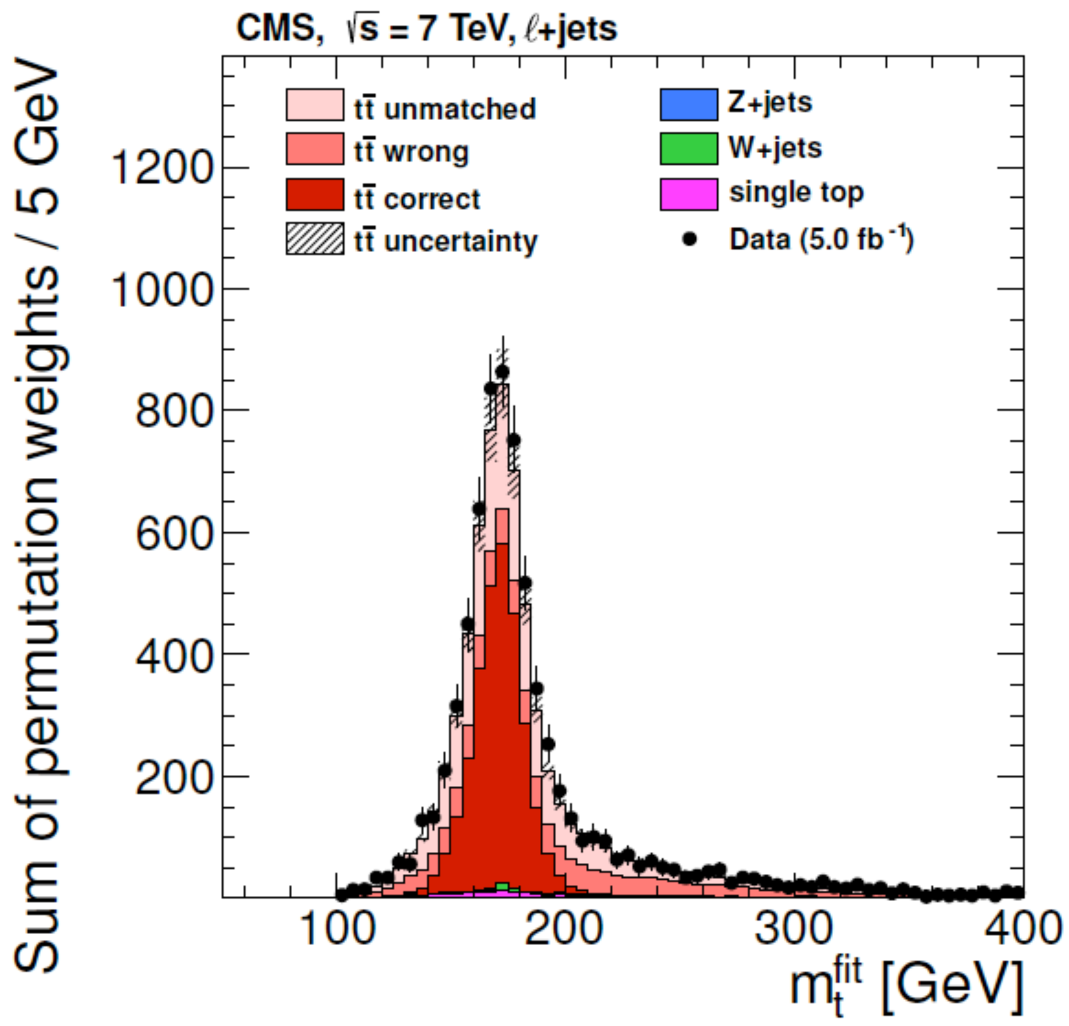
$$\prod_{\text{events}} \left(\sum_{i=1}^{n} c\, P_{\text{gof}}(i)\, P\left(m_{\text{t},i}^{\text{fit}}, m_{\text{W},i}^{\text{reco}} | m_{\text{t}}, \text{JES} \right) \right)^{w_{\text{event}}}$$

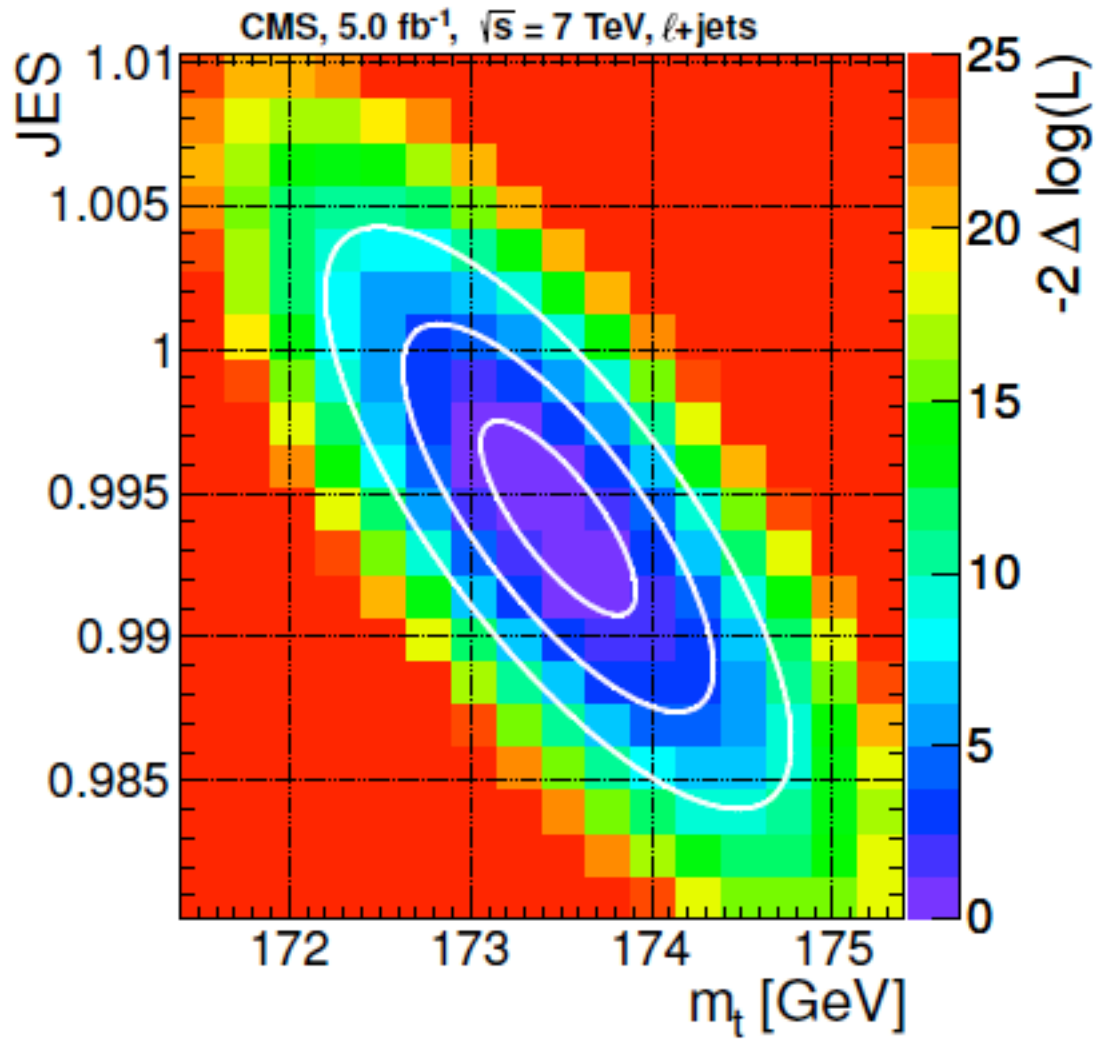
- Constraining JES.
- Most precise measurement to date.



CMS-TOP-11-017, J. High Energy Phys. 12 (2012) 105, December 2012

CMS lepton+jets

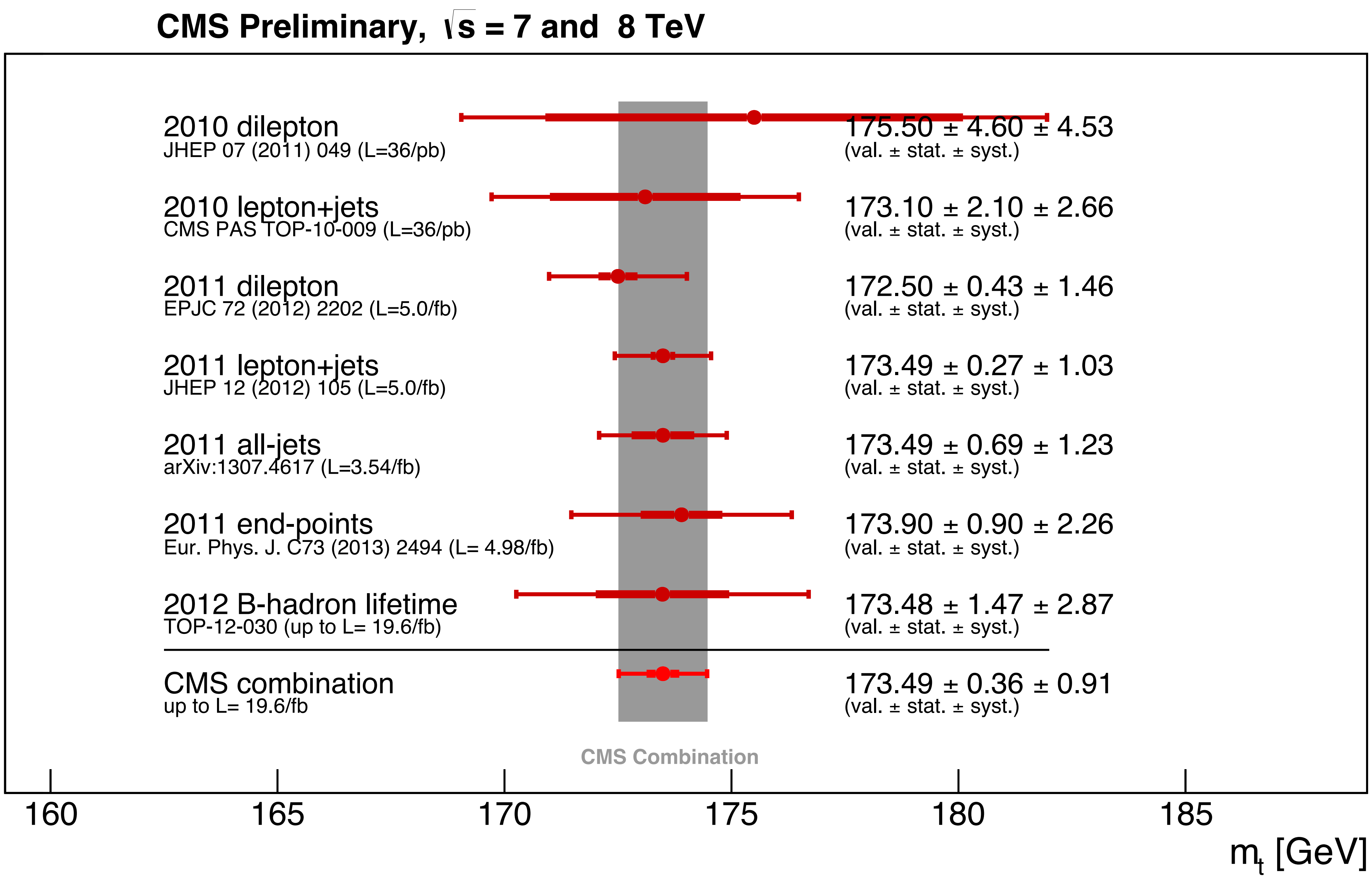




173.49 ± 0.43 (stat+JES) ± 0.98 (syst) GeV

CMS-TOP-11-017, J. High Energy Phys. 12 (2012) 105, December 2012

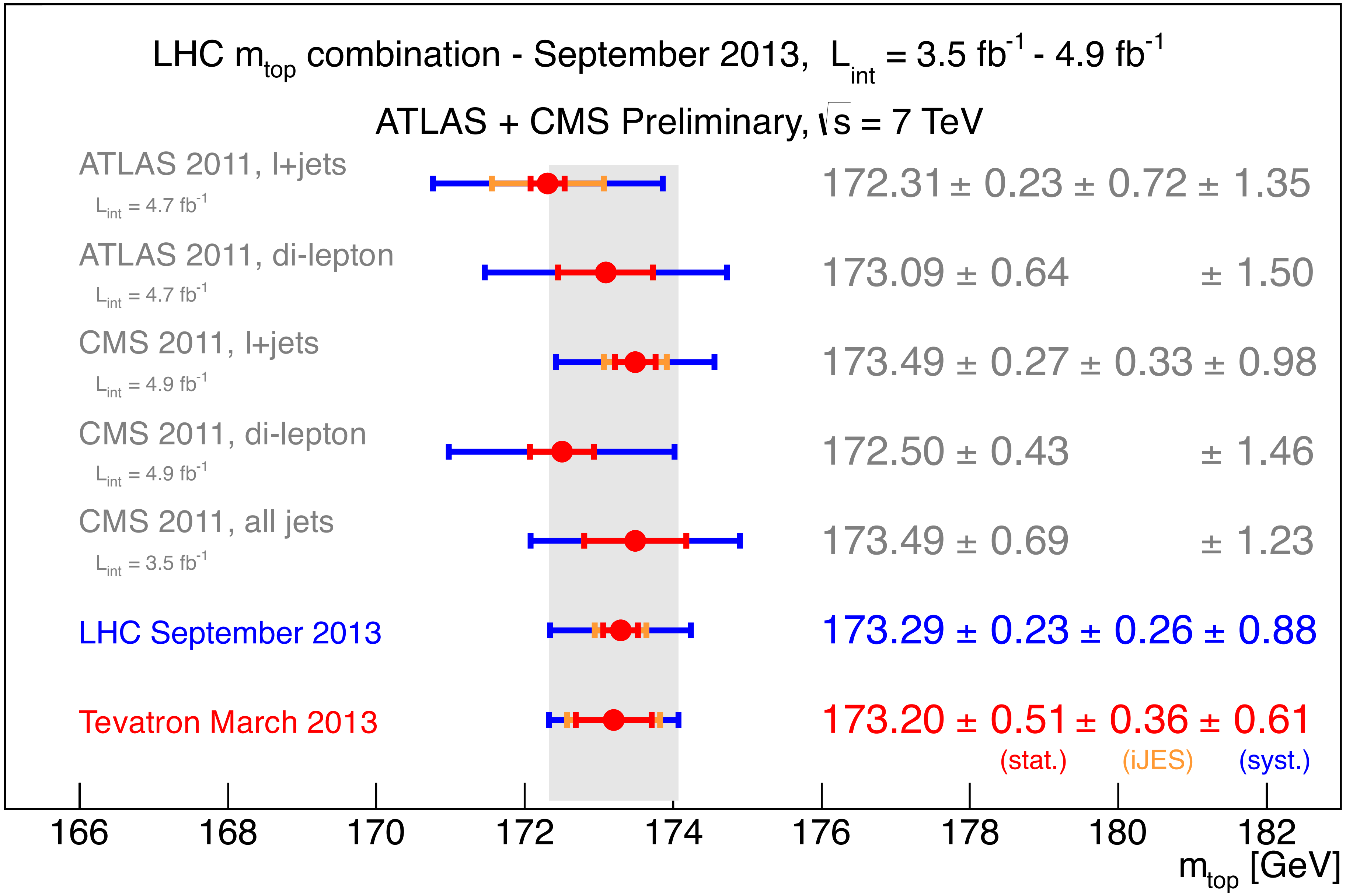
CMS summary



CMS-TOP-13-002, September 2013

Combination – BLUE

- **B**est **L**inear **U**nbiased **E**stimate.
- Used for both Tevatron and LHC combinations.
- Linear combination of measurements; weights optimized to minimize uncertainty on combined result.
- Correlations between systematic uncertainty sources taken into account.
  - Careful categorization of, e.g., JES uncertainties.
  - Coordinated through top LHC working group.
- Tested varying assumptions on correlations, found to be stable.
- Further study needed: ATLAS takes explicit hadronization systematic uncertainty (difference between Herwig and Pythia) into account, which CMS doesn't.



ATLAS-CONF-2013-102
CMS PAS TOP-13-005

Summary of best values

Single most precise measurements, per experiment

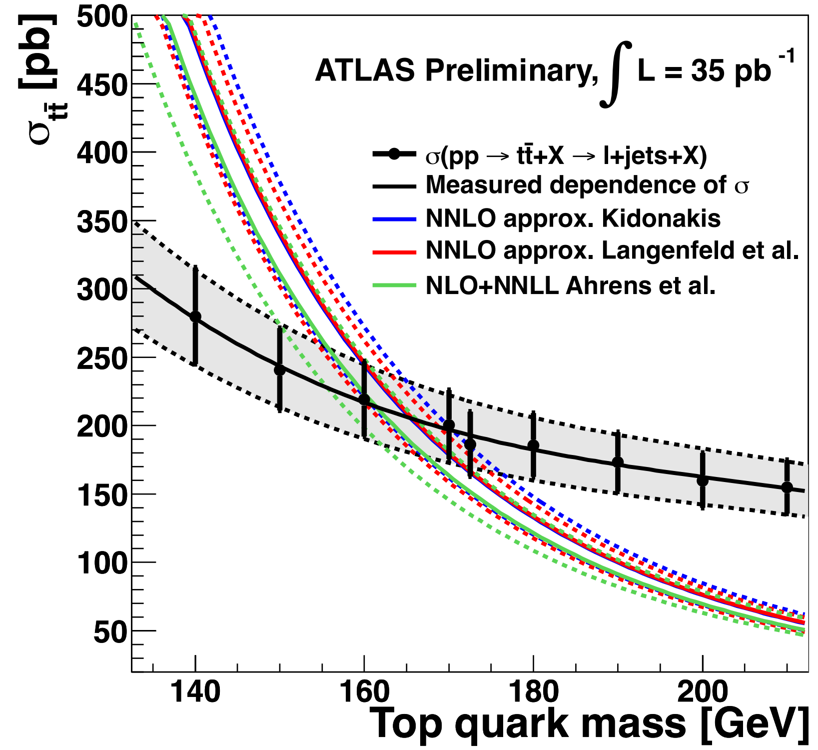
CDF-II (l+jets)	172.85	± 0.52 (stat)	± 0.98 (syst)	GeV
D0-II (l+jets)	174.94	± 0.83 (stat)	± 1.24 (syst)	GeV
ATLAS (2011, l+jets)	172.31	± 0.23 (stat)	± 1.53 (syst)	GeV
CMS (2011, l+jets)	173.49	± 0.27 (stat)	± 1.03 (syst)	GeV

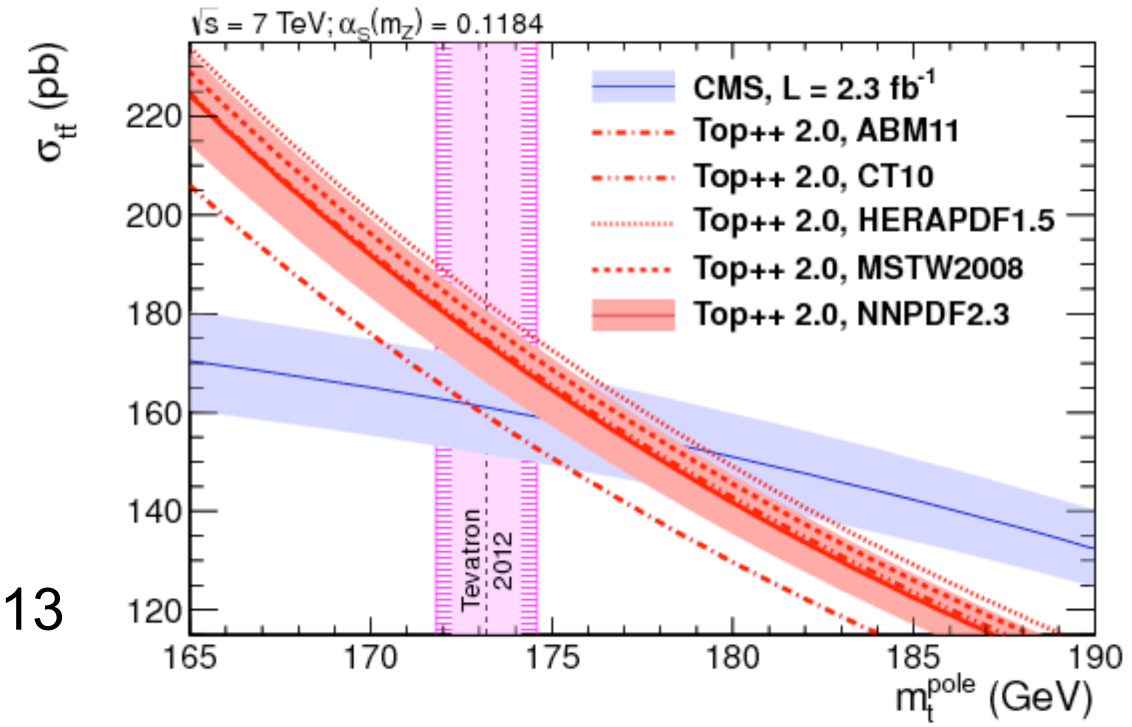
Combinations

Tevatron (Aug 2013)	173.20	± 0.51 (stat)	± 0.71 (syst)	GeV
ATLAS (Sep 2013)	172.65	± 0.31 (stat)	± 1.40 (syst)	GeV
CMS (Sep 2013)	173.49	± 0.36 (stat)	± 0.41 (syst)	GeV
LHC (Sep 2013)	173.29	± 0.51 (stat)	± 0.92 (syst)	GeV

Mass from cross section

- Extract mass from comparison of dependence of cross section on top mass in experiment and in NLO or NNLO calculations. Alternative to direct measurement.
- Advantage: Extract mass in well-defined renormalization scheme.
- Disadvantage: Less precise.
- Values of $m_{t,pole}$
  - D0 167.5 +5.4 -4.9 GeV (~3 %, 5.3 fb^{-1})
  - ATLAS 166.4 +7.8 -7.3 GeV (~5 %, 35 pb^{-1})
  - CMS 176.7 +3.8 -3.4 GeV (~2 %, 2.3 fb^{-1})

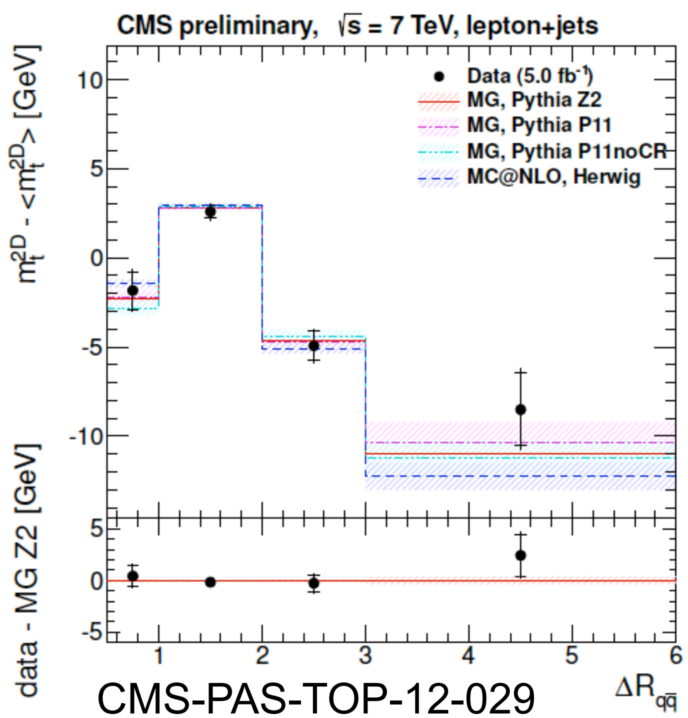




ATLAS-CONF-2011-054 March 2011
CMS TOP-12-022, Phys. Lett. B 728 (2013) 496, July 2013
D0 PLB 703, 422 (2011)

Alternative methods for direct measurement (I)

- Study of dependence on kinematic variables (CMS)
  - Study the dependence of reconstructed mass on kinematic variables, e.g., related to ISR/FSR and color reconnection.
  - Data results well described by simulation.
  - Within available statistics, models cannot be distinguished.



CMS-PAS-TOP-12-029

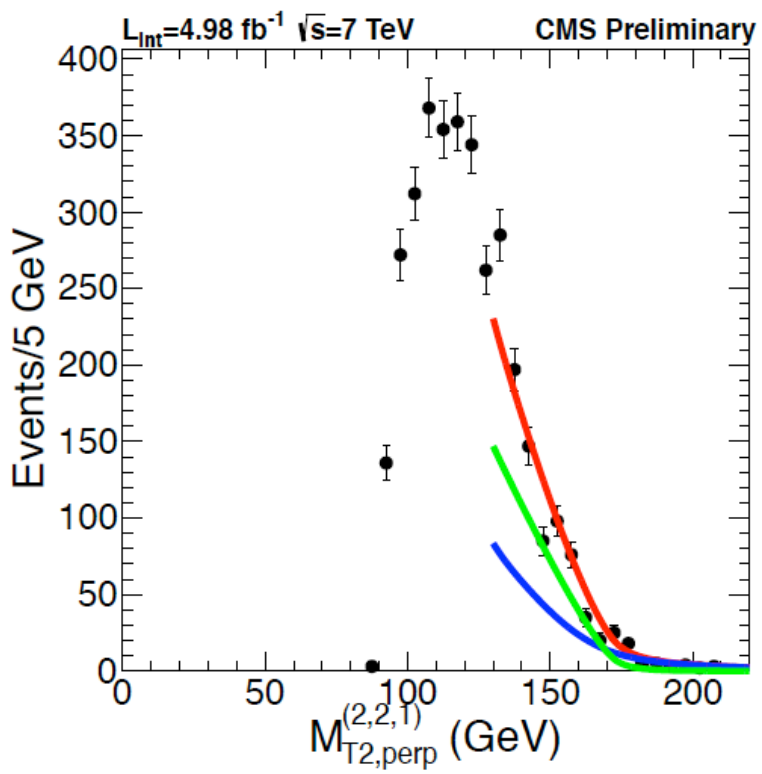
- Kinematic endpoint method (CMS)
  - Use endpoint distribution of M_{T2}: minimum parent mass consistent with the observed kinematics

$$M_{T2} \equiv \min_{\mathbf{p}_T^a + \mathbf{p}_T^b = \not{\mathbf{E}}_T} \left\{ \max(M_T^a, M_T^b) \right\}$$

  - Dominating systematics: JES
  - Performance comparable to di-lepton standard measurements.

173.9 ± 0.9 (stat) + 1.2 - 1.8 (syst) GeV

CMS-TOP-11-027



Alternative methods for direct measurement (II)

> B hadron lifetime

- Lifetime and decay length depends directly on top quark mass.
- Advantage: Low dependence on jet energy scale, instead on tracking.
- Disadvantage: Sensitive to b fragmentation modeling.
- Measured by CDF-II and CMS.

20 fb^{-1} 2012 data! CMS-PAS-TOP-12-030

Channel	m_t [GeV]
muon+jets	$173.2 \pm 1.0_{stat} \pm 1.6_{syst} \pm 3.3_{p_T(t)}$
electron+jets	$172.8 \pm 1.0_{stat} \pm 1.7_{syst} \pm 3.1_{p_T(t)}$
electron-muon	$173.7 \pm 2.0_{stat} \pm 1.4_{syst} \pm 2.4_{p_T(t)}$

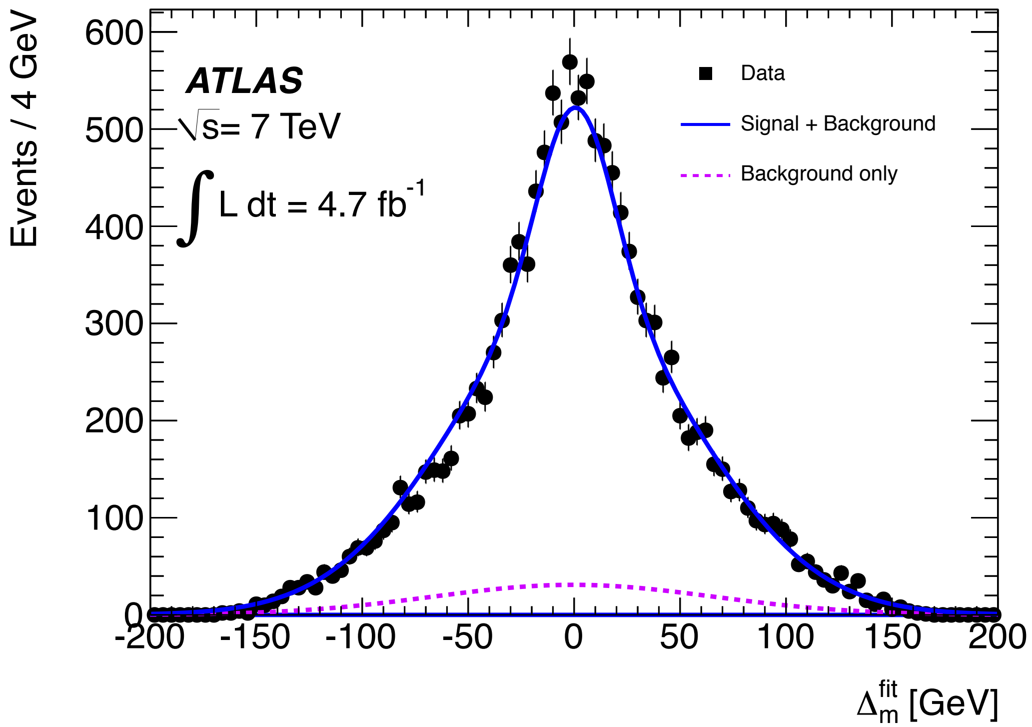
$m_t = 173.5 \pm 1.5_{stat} \pm 1.3_{syst} \pm 2.6_{pt(t)}$ GeV,

> Other proposed alternative measurements

- *J/ψ*+jets: Use invariant mass of leptons from W and *J/ψ* (from b fragmentation) -> μμ. Experimentally clean, but low branching ratio.
- ttbar+jets

Top–anti-top mass difference: test of CPT invariance

- ATLAS: Recently published!
- 2011 data, lepton+jets channel
- Template fit.



delta m = 0.67 ± 0.61 (stat) ± 0.41 (syst) GeV

Physics Letters B 728C (2014), pp. 363-379

- CMS: 2011 (5.0 fb-1) and 2012 (18.9 fb-1) data.
- lepton+jets channel.
- Ideogram method.

delta m = -0.44 ± 0.46 (stat) ± 0.27 (syst) GeV (2011)

delta m = -0.27 ± 0.20 (stat) ± 0.12 (syst) GeV (2012)

2011: TOP-11-019, JHEP 06 (2012) 109
2012: TOP-12-031

No significant deviation from zero observed.

Conclusions

- LHC and Tevatron measurements/combinations compatible and have equivalent accuracy (both ~0.5 %).
- Systematics limited already with full 2011 data set.
  Some potential for improvement in even better understanding of detectors and modeling. Central is understanding and constraining of jet energy scale. b-tagging.
- Alternative methods with different systematics are being investigated.
- No mass difference observed between top and anti-top.
- Considerable ongoing work on refining combinations. Understanding correlations between experiments. Moving towards Tevatron+LHC world average.

BACKUP

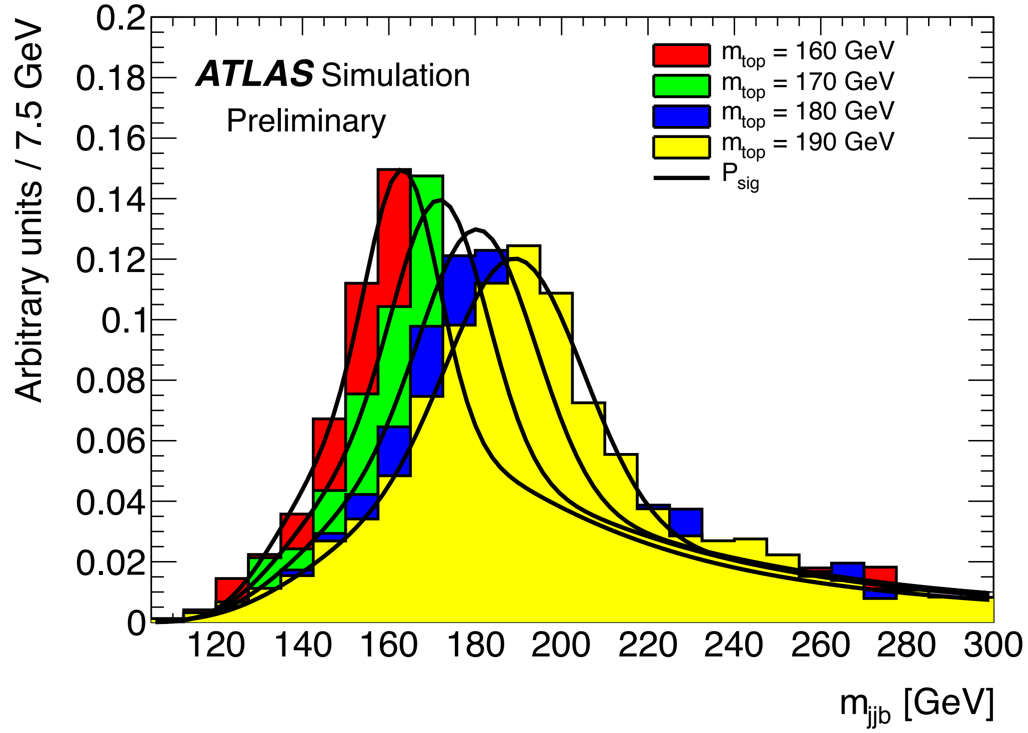
ATLAS all-hadronic

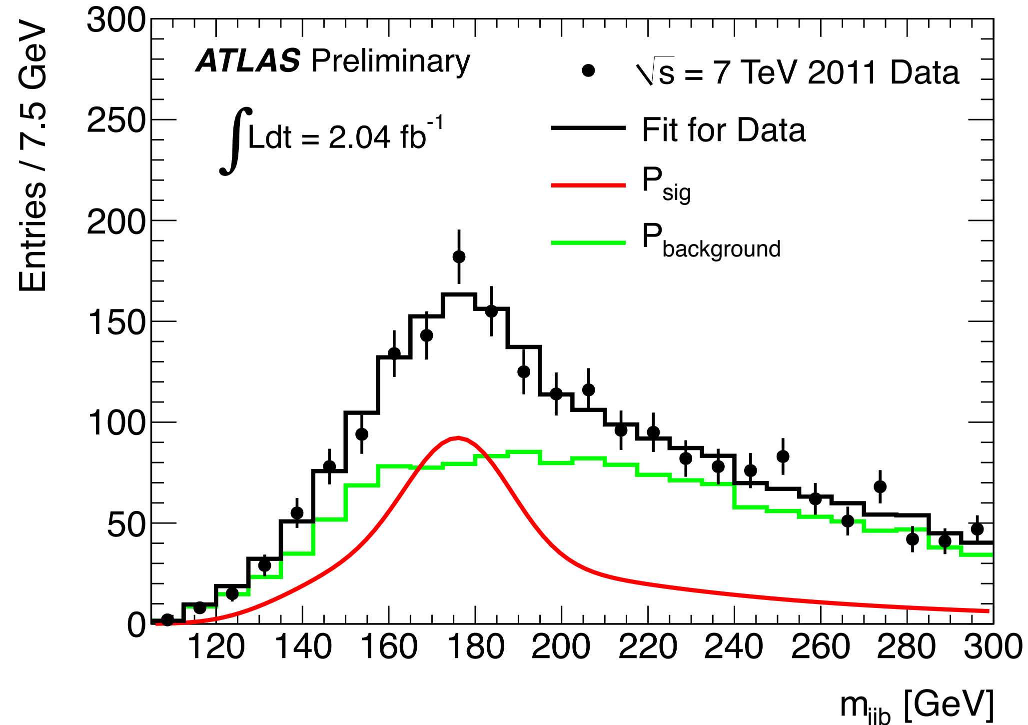
- 2.04 fb-1 from 2011.
- Require
  - 6 jets
  - 2 of which b-tagged.
- Multi-jet background obtained by mixing events.
- Jets assigned to top decay products by minimizing ”mass chi2”.

$$\chi^2 = \frac{(m_{j_1,j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_1,j_2,b_1} - m_t)^2}{\sigma_t^2} + \frac{(m_{j_3,j_4} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_3,j_4,b_2} - m_t)^2}{\sigma_t^2}$$

- One-dimensional template fit in mjjb.

174.9 ± 2.1 (stat) ± 3.8 (syst) GeV

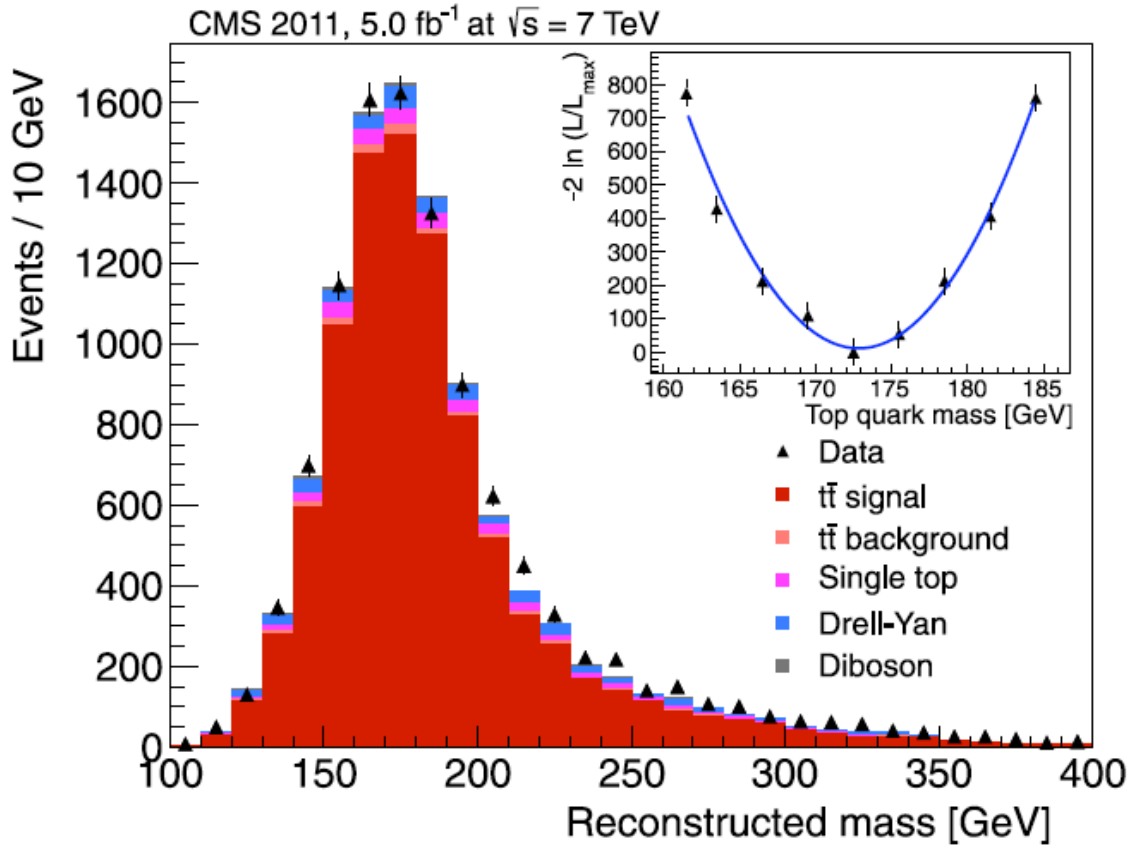




ATLAS-CONF-2012-030 (March 2012)

CMS di-leptons

- Full 2011 data set (5.0 fb-1).
- Require:
  - 2 leptons
  - 2 or more jets, of which 1 b-tagged
  - Etmiss
- Analytical matrix weighting technique (AMWT):
  - Kinematic equations for neutrino momenta solved for different top mass hypotheses.
  - Repeated 1000 times for each hypothesis with smeared jets.
  - Weights assigned to each solution based on prob. to observe charged lepton.
  - For each event, mass hypothesis with maximum weight is reconstructed top mass.



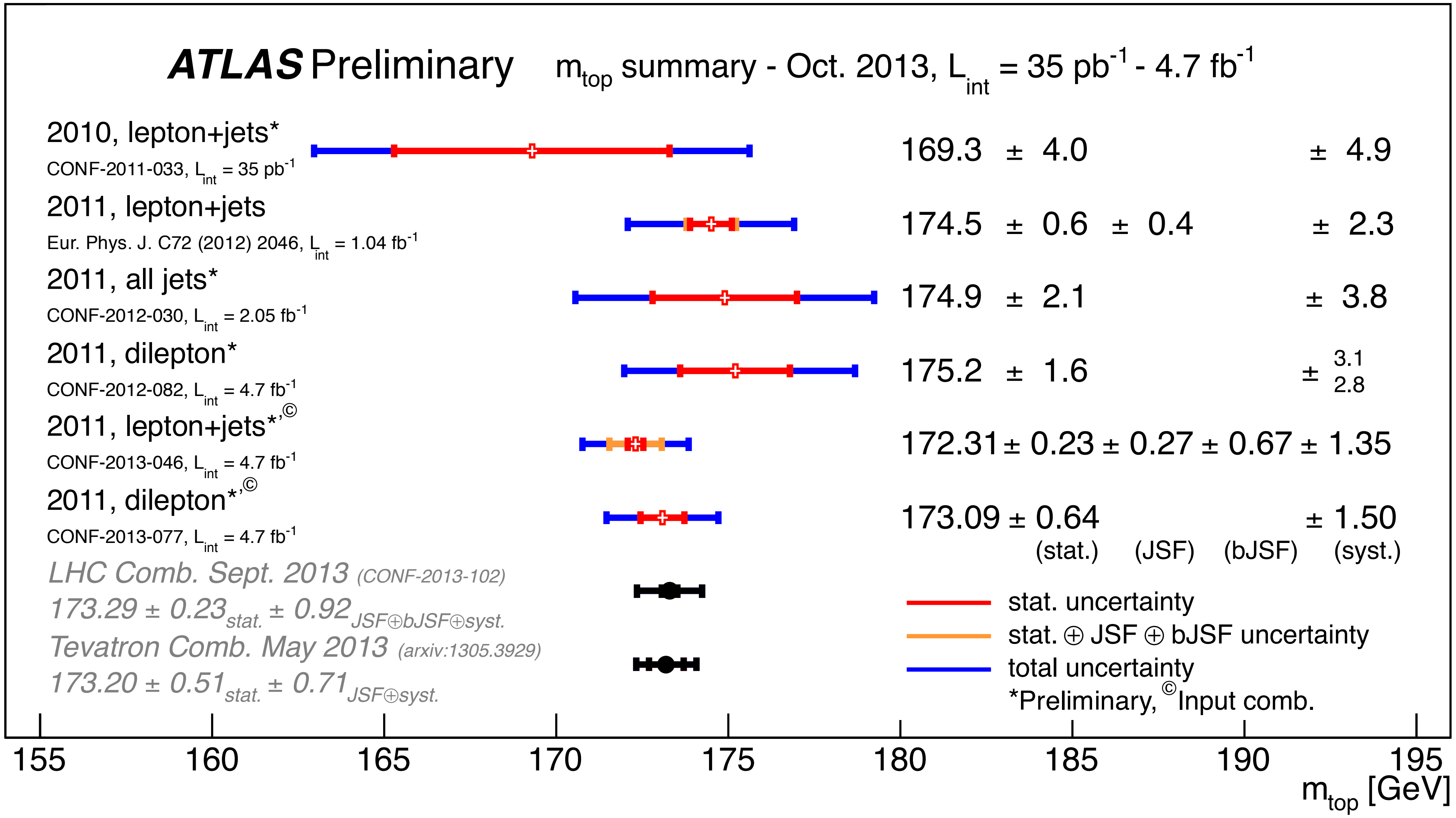
$$w = \left\{ \sum f(x_1) f(x_2) \right\} p(E^*_{\ell+} | m_t) p(E^*_{\ell-} | m_t),$$

$$p(E^* | m_t) = \frac{4 m_t E^* (m_t^2 - m_b^2 - 2 m_t E^*)}{(m_t^2 - m_b^2)^2 + M_W^2 (m_t^2 - m_b^2) - 2 M_W^4}.$$

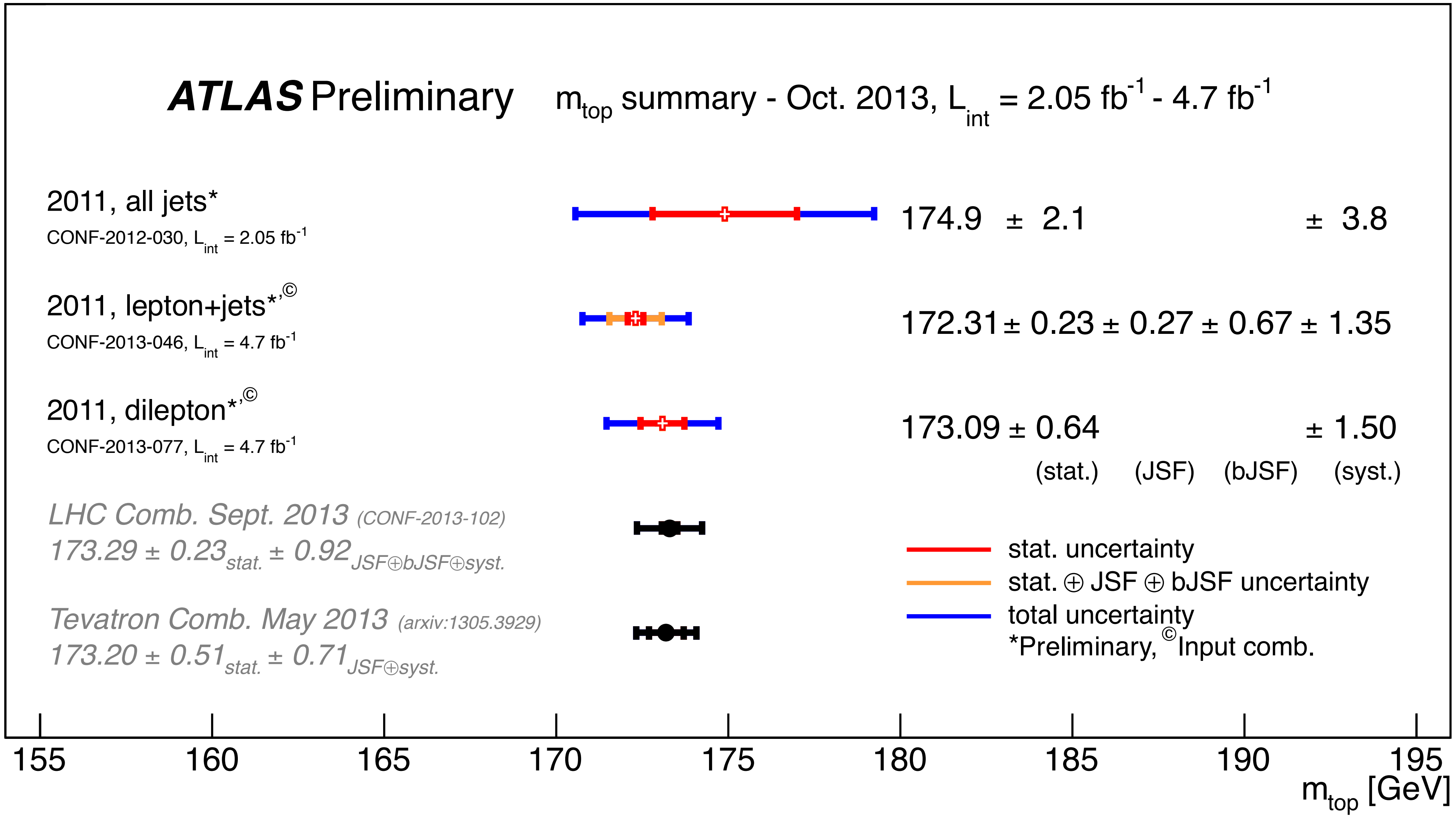
EPJ C 72 (2012) 2202 (Sep 2012)

172.5 ± 0.4 (stat) ± 1.5 (syst) GeV

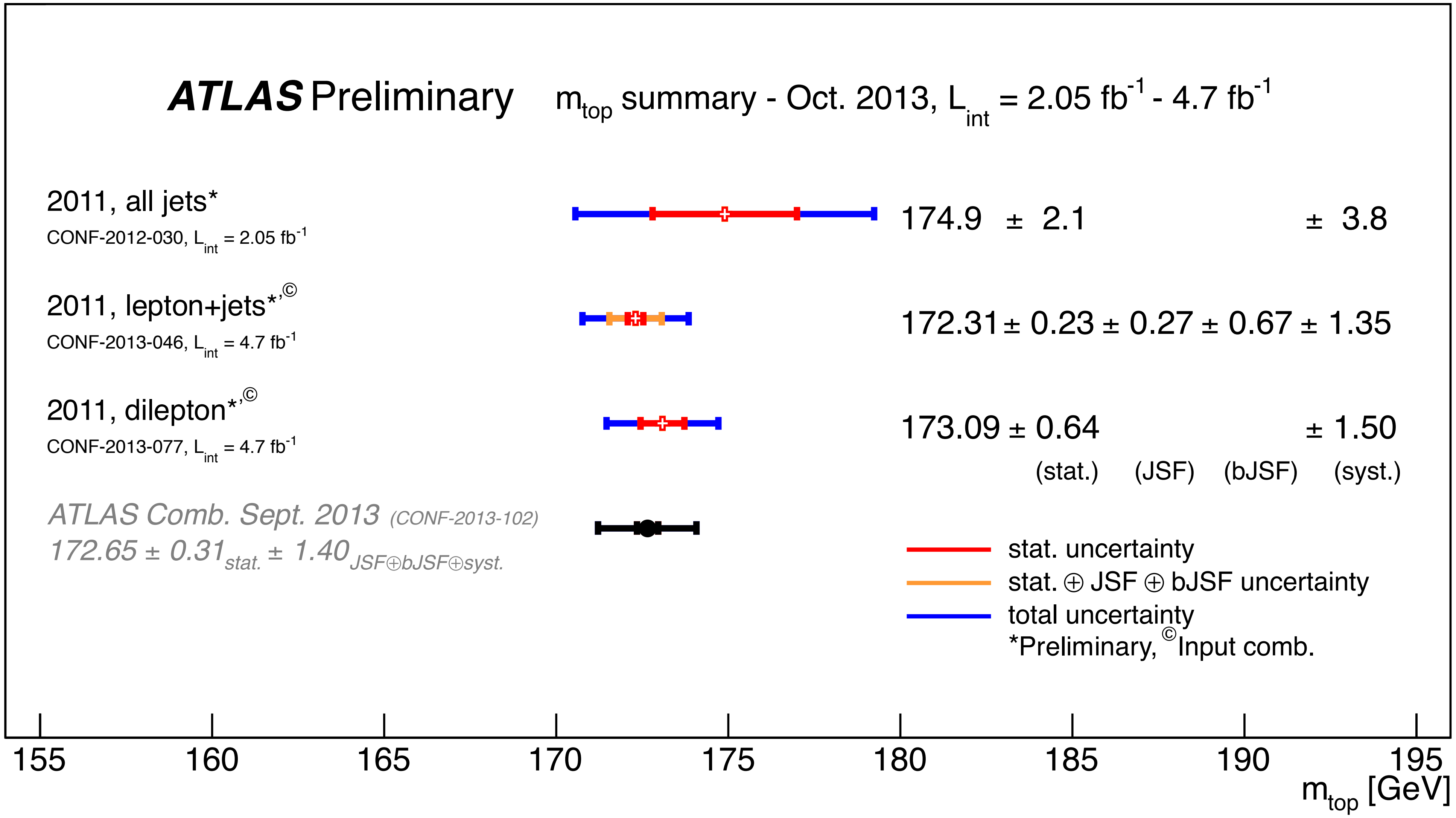
ATLAS combination



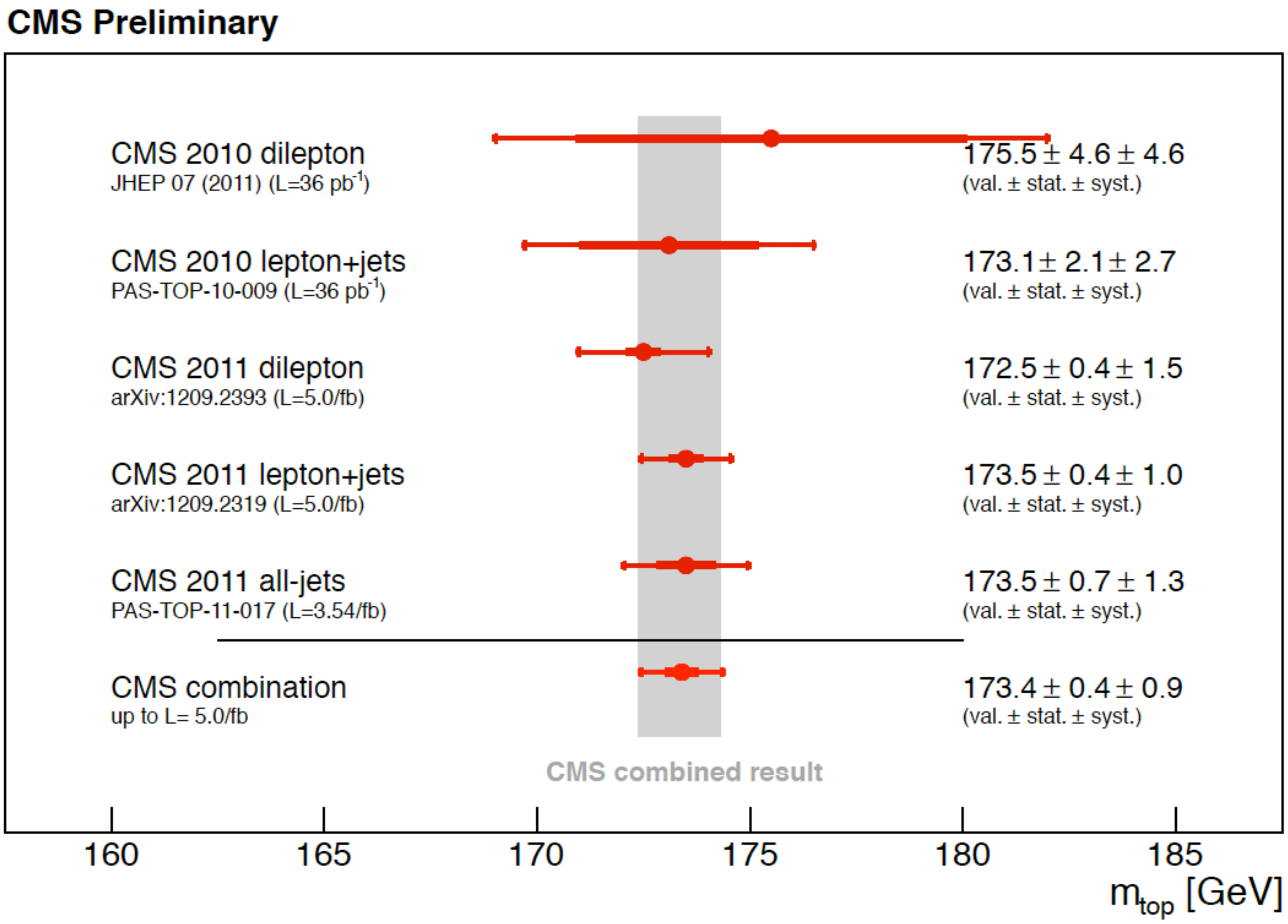
ATLAS combination



ATLAS combination



CMS summary


CMS Preliminary
CMS 2010 dilepton
JHEP 07 (2011) (L=36 pb-1)
175.5 ± 4.6 ± 4.6
(val. ± stat. ± syst.)
CMS 2010 lepton+jets
PAS-TOP-10-009 (L=36 pb-1)
173.1 ± 2.1 ± 2.7
(val. ± stat. ± syst.)
CMS 2011 dilepton
arXiv:1209.2393 (L=5.0/fb)
172.5 ± 0.4 ± 1.5
(val. ± stat. ± syst.)
CMS 2011 lepton+jets
arXiv:1209.2319 (L=5.0/fb)
173.5 ± 0.4 ± 1.0
(val. ± stat. ± syst.)
CMS 2011 all-jets
PAS-TOP-11-017 (L=3.54/fb)
173.5 ± 0.7 ± 1.3
(val. ± stat. ± syst.)
CMS combination
up to L= 5.0/fb
173.4 ± 0.4 ± 0.9
(val. ± stat. ± syst.)
CMS combined result
160
165
170
175
180
185
m_top [GeV]