Top mass at the LHC

Miho Yamada, KEK
on behalf of the ATLAS and the CMS collaborations

Higgs and Beyond 2013

June 5-9, 2013, Sendai Japan

Introduction

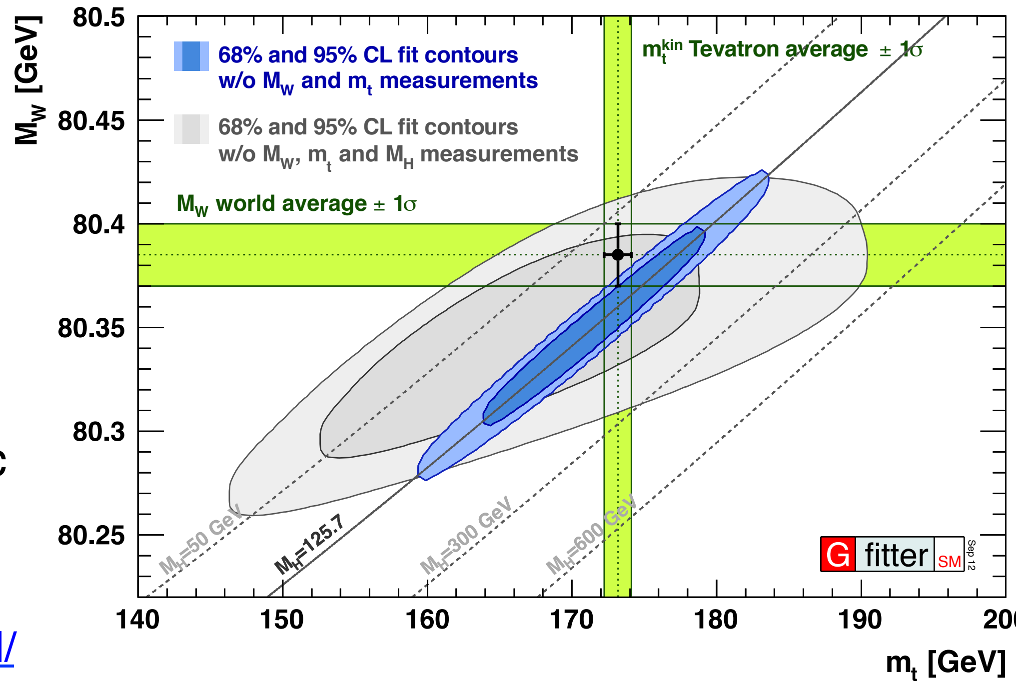
The W and top quark masses are important observables of the Standard Models.
Predicted Higgs mass from W and top masses is consistent with measured Higgs mass at LHC.
The top quark has high sensitivity to physics beyond the Standard Model.
The most precise measurement of W and top masses are done by CDF and DØ at Tevatron.

W mass $$80385 \pm 15 \text{ (stat.+syst.) MeV}$$

top mass $$173.20 \pm 0.51 \text{ (stat.)} \pm 0.71 \text{ (syst.) GeV}$$

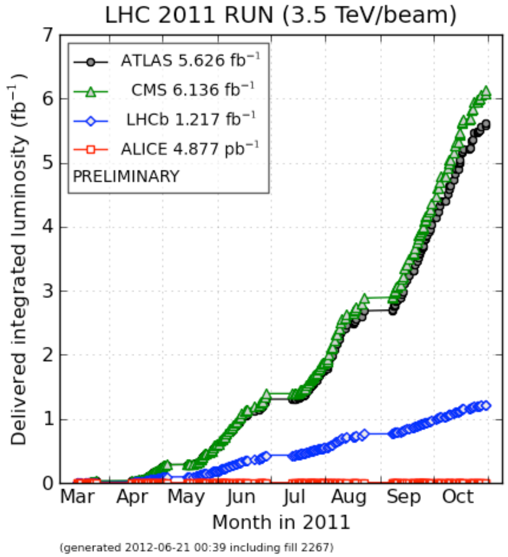
Also at the LHC, a lot of measurements of top quark mass are available.
➡ This talk

The W mass measurement at the LHC is now work in progress
➡ Focus on reducing the systematic uncertainties of PDF and W recoil modeling etc…



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

LHC and Detectors



2011: $\sqrt{s}$ = 7 TeV

Collected collision data of ~5 fb^{-1}

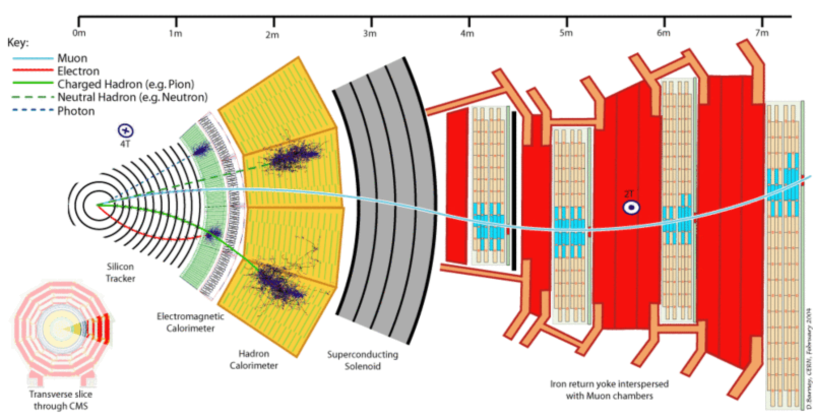
➡ ~1 million of top quark pairs produced

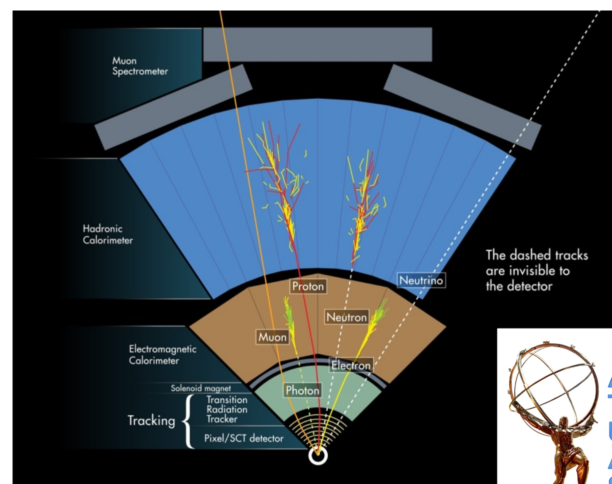
(This talk mainly covers analyses on this data sample)

2012: $\sqrt{s}$ = 8 TeV

Collected collision data of ~22 fb^{-1}

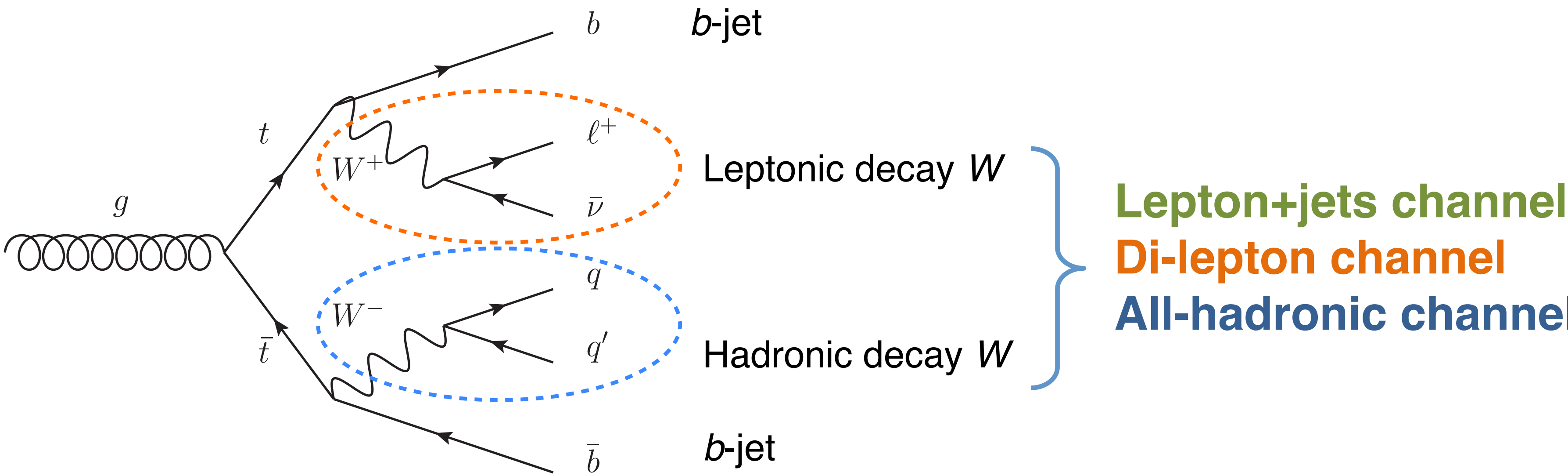
ATLAS and CMS detectors are the general purpose detectors consisting of inner tracker, EM and hadronic calorimeters, muon detectors and magnet system.





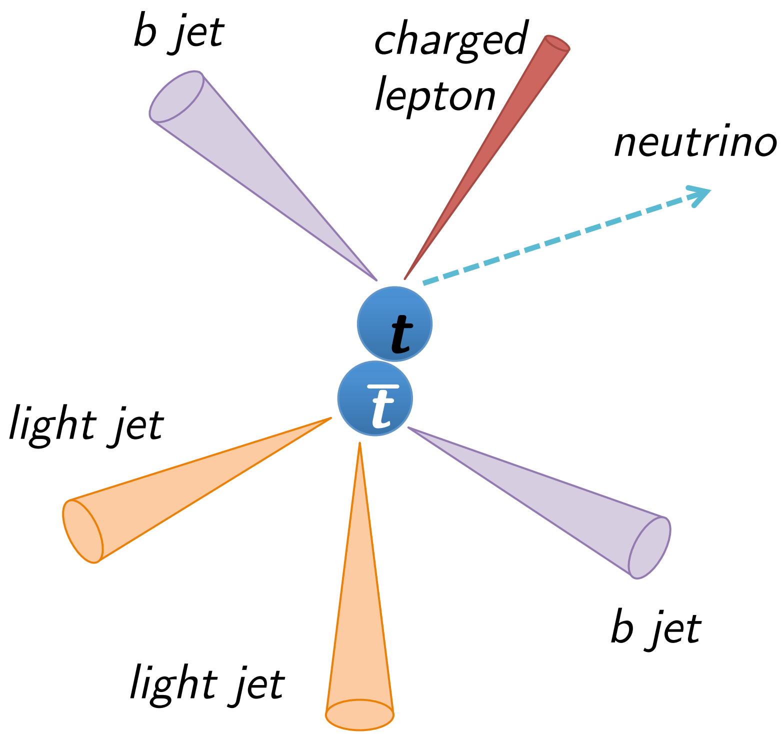
Top Quark Pair Decay Channel and Analyses

Top quark pair decay channel is categorized according to the combination of decay modes of two *W* bosons in the final state.

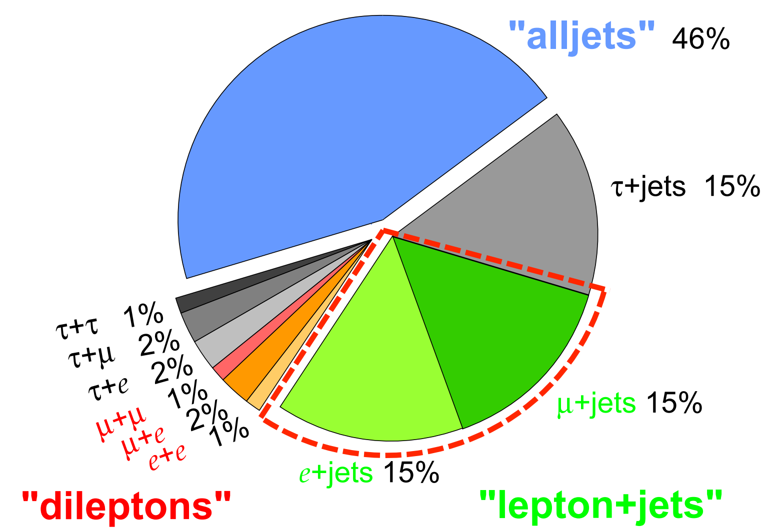


Channel	ATLAS	CMS
Lepton + Jets	Template Method (1, 2 and 3D)	Ideogram Method
	Mass from Cross Section	Top Mass Difference (Ideogram Method)
Di - Lepton	m_{T2} Method	Endpoints Method
		Analytical Matrix Weighting Technique
		Mass from Cross Section
All - hadronic	Template Method	Ideogram Method

Lepton+Jets Channel



- Large branching ratio (30% for *e* and *μ* channel)
- Good S/N due to the existence of isolated lepton and missing E_T
- One neutrino →ttbar reconstruction is easier than di-lepton channel



Lepton + Jets: Template Method

Event Selection

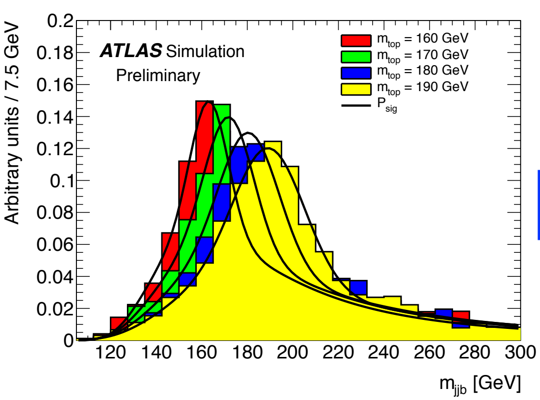
- Exactly 1 isolated charged lepton

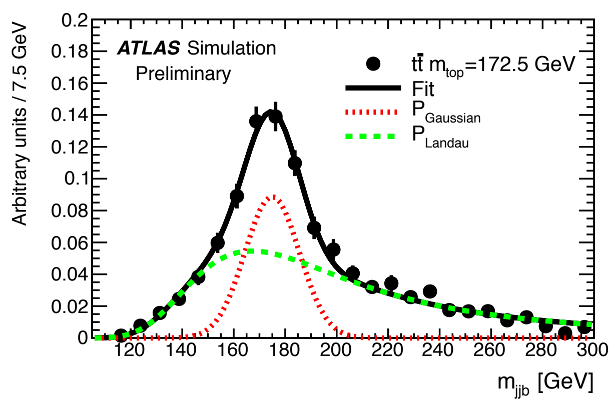
Electron
$E_T > 25$ GeV, $|\eta_{cluster}| < 2.47$
$E_T^{miss} > 35$ GeV, $m_T > 25$ GeV

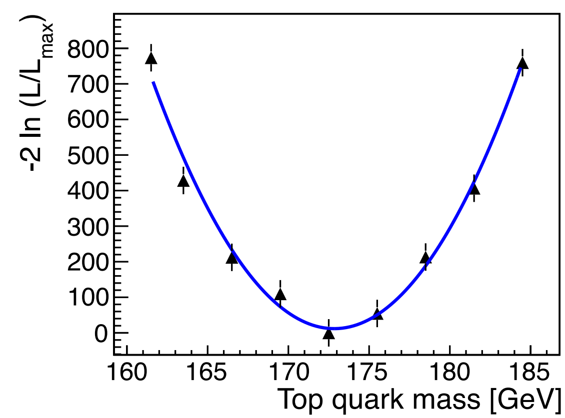
Muon
$p_T > 20$ GeV, $|\eta| < 2.5$
$E_T^{miss} > 20$ GeV, $E_T^{miss} + m_T > 60$ GeV

- At least 4 jets with $p_T > 25$ GeV, $|\eta| < 2.5$
- At least 1 jet of these jets is tagged as *b*-jet

Template Method







Derive some template of kinematic distributions from MC.
➔varying variables (***m*~top~** etc.)

Parameterize templates to obtain probability density function (pdf) distribution for signal and background.

Determine $\boldsymbol{m_{top}}$ (and other variables) by likelihood fit using the estimated pdf distribution.

Lepton + Jets: Template Method

3D Template Analysis

- Jets permutations are obtained from Kinematic Likelihood Fitting
- $55 < m_W^{reco} < 110$ GeV
- $0.3 < R_{1b}^{reco} < 3.0$
- $125 < m_{top}^{reco} < 225$ GeV (1 *b*-tagged jet)
- $130 < m_{top}^{reco} < 220$ GeV (2 *b*-tagged jet)

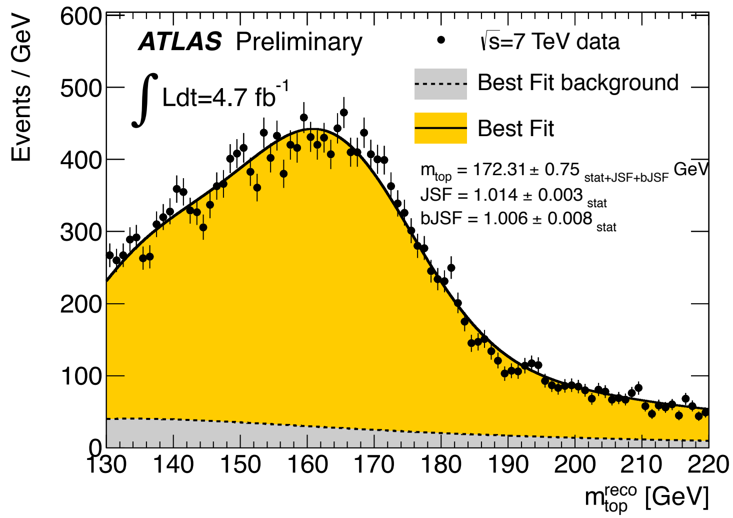
$$R_{1b}^{\mathrm{reco,2b}} = \frac{p_T^{b_{\mathrm{had}}} + p_T^{b_{\mathrm{lep}}}}{p_T^{W_{\mathrm{jet}_1}} + p_T^{W_{\mathrm{jet}_2}}}$$

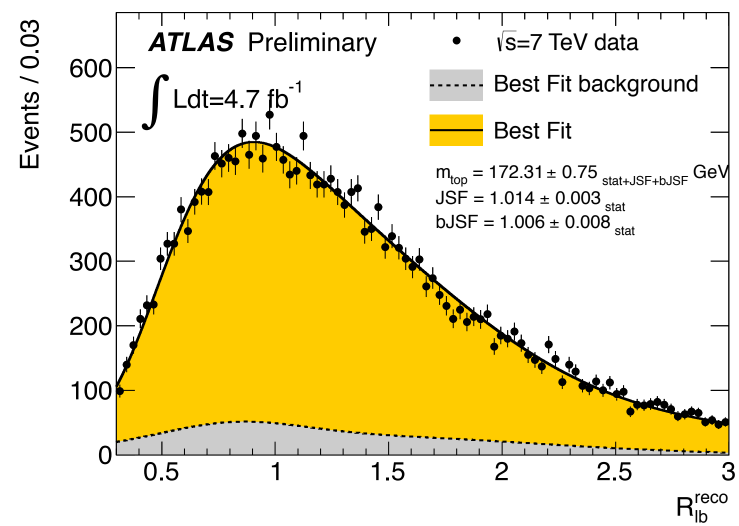
$$R_{1b}^{\mathrm{reco,1b}} = \frac{p_T^{b_{\mathrm{tag}}}}{\left(p_T^{W_{\mathrm{jet}_1}} + p_T^{W_{\mathrm{jet}_2}}\right)/2}$$

Derived templates

Global Jet Energy Scale Factor (JSF) ➡ correct energy **parton** → **particle** level

R_{1b}^{reco}, m_W^{reco} and m_{top}^{reco} as function of input m_{top}, assumed JSF and *b*-JSF.

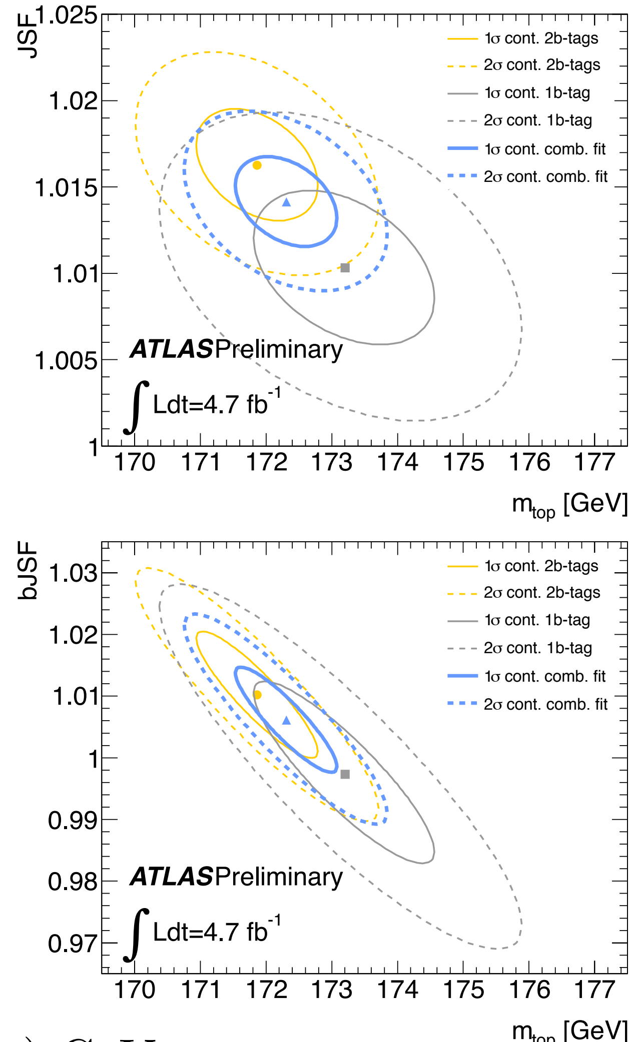




Measurement of the Top Quark Mass from √s = 7 TeV ATLAS Data using a 3-dimensional Template Fit
ATLAS-CONF-2013-046

Systematic Uncertainties

Systematic Uncertainty	Δm_{top} (GeV)
Jet energy scale factor	0.27
b-Jet energy scale factor	0.67
Method calibration	0.13
Signal MC generator	0.19
Hadronization	0.27
Underlying event	0.12
Color reconnection	0.32
ISR and FSR (signal only)	0.45
Proton PDF	0.17
W+jets background	0.03
QCD multijet background	0.10
Jet energy scale	0.79
b-jet energy scale	0.08
Jet energy resolution	0.22
Jet reconstruction efficiency	0.05
b-tagging efficiency	0.81
Lepton energy scale	0.04
Missing transverse momentum	0.03
Pile-up	0.03
Total	**1.35**



$$\text{1D:} \quad 174.4 \pm 0.9 \text{ (stat.)} \pm 2.5 \text{ (syst.) GeV}$$

$$\text{2D:} \quad 174.5 \pm 0.8 \text{ (stat.+JSF)} \pm 2.3 \text{ (syst.) GeV}$$

$$\text{3D:} \quad 172.31 \pm 0.75 \text{ (stat.+JSF+bJSF)} \pm 1.35 \text{ (syst.) GeV}$$

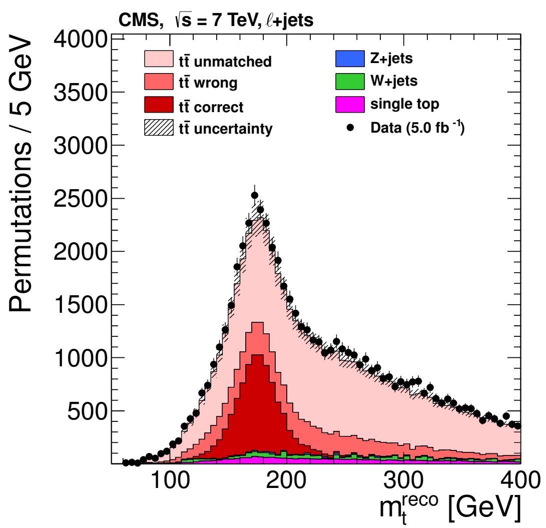
Lepton + Jets: Ideogram Method

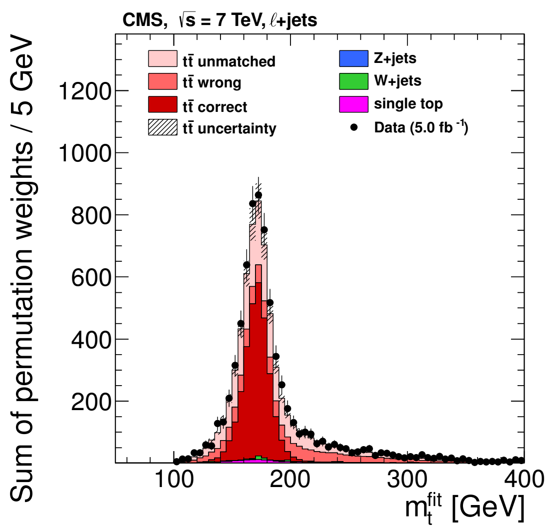
Event Selection

- Exactly 1 isolated electron / muon with pT > 30 GeV and $|\eta| < 2.1$
- At least 4 jets with pT > 30 GeV and $|\eta| < 2.4$
- At least 2 jets of these jets are tagged as *b*-jet

ttbar Reconstruction by Kinematic Fitting

- Use 4 leading jets
  (assigned *b*-tagged jets to *b*-quarks, untagged jets to light quarks)
- Constraints: $m_W = 80.4$ GeV, $m_{top} = m_{anti\text{-}top}$
- Require $P_{\rm gof}(\chi^2) = \exp\left(-\frac{1}{2}\chi^2\right) > 0.2$ and weight all permutations





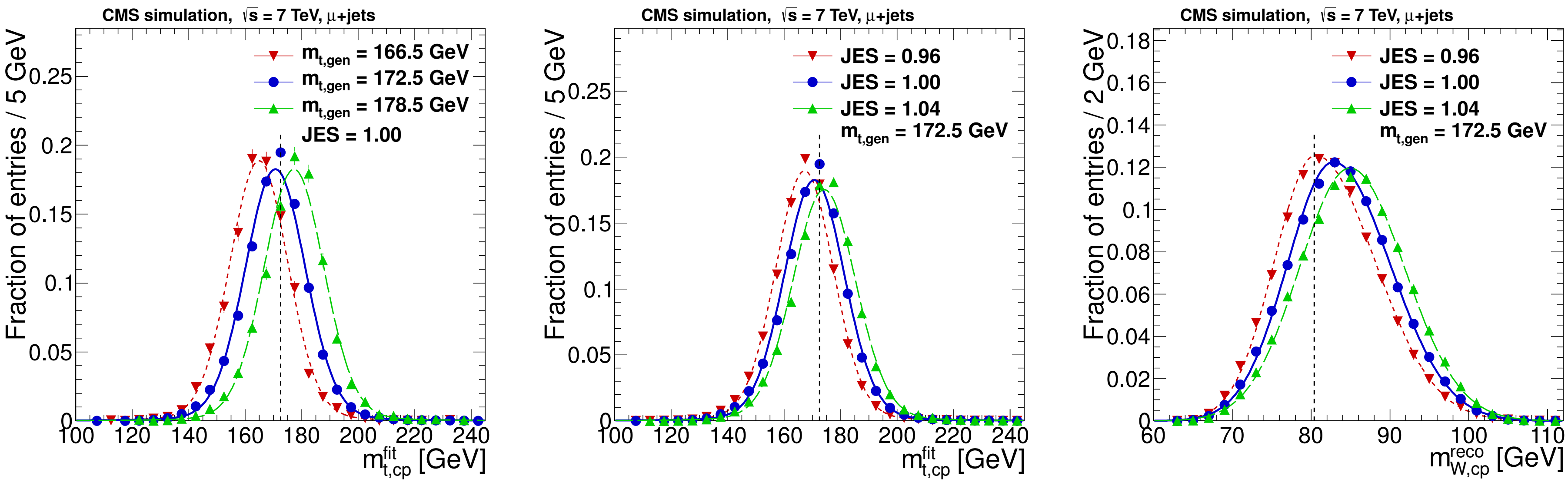
Measurement of the top-quark mass in t t-bar events with lepton+jets final states in pp collisions at sqrt(s)=7 TeV
[JHEP 12 (2012) 105]

Lepton + Jets: Ideogram Method

Top quark mass (m_t) and JES are determined simultaneously in a joint likelihood fit.

j representing ***correct***, ***wrong*** and ***unmatched*** permutation of parton-jet assignment.

Probability density distributions P_j are determined different $m_{t,\mathrm{gen}}$ and JES variation



$$\mathcal{L}\left(\mathrm{event}|m_t,\mathrm{JES}\right) = \sum_{i=1}^{n} cP_{\mathrm{gof}}(i)P\left(m_{t,i}^{\mathrm{fit}}, m_{W,i}^{\mathrm{reco}}|m_t,\mathrm{JES}\right)$$

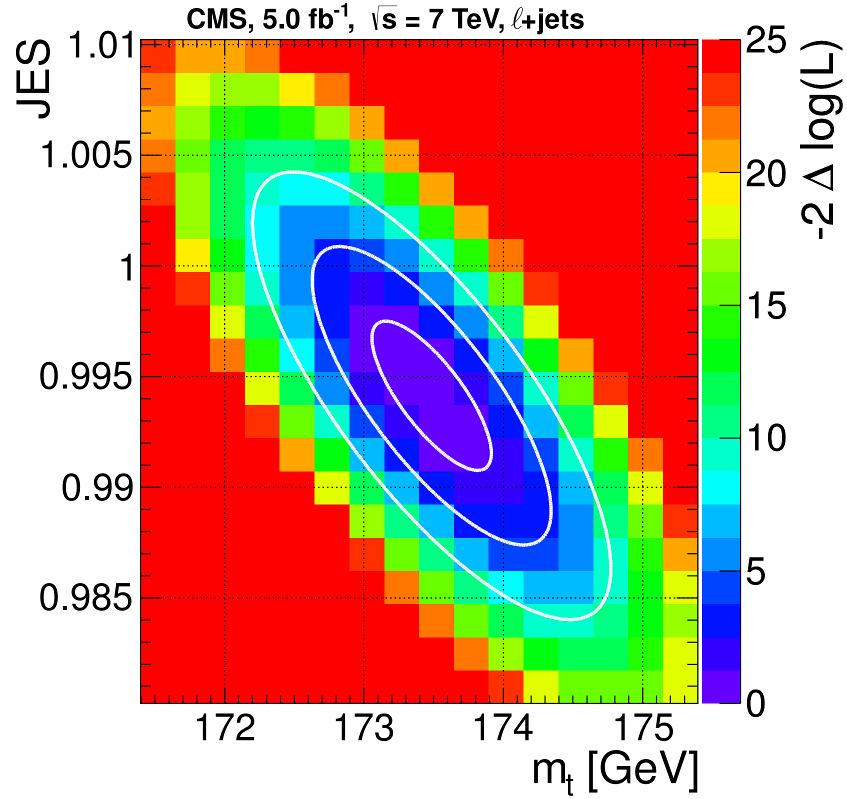
$$P(m_{\mathrm{t},i}^{\mathrm{fit}}, m_{W,i}^{\mathrm{reco}}|m_{\mathrm{t}},\mathrm{JES}) = \sum_j f_j P_j\left(m_{\mathrm{t},i}^{\mathrm{fit}}|m_{\mathrm{t}},\mathrm{JES}\right) \times P_j(m_{W,i}^{\mathrm{reco}}|m_{\mathrm{t}},\mathrm{JES})$$

The most likely m_t and JES are obtained by maximizing

$$\mathcal{L}(m_t,\mathrm{JES}|\mathrm{sample}) \sim \prod_{\mathrm{event}} \mathcal{L}\left(\mathrm{event}|m_t,\mathrm{JES}\right)^{w_{\mathrm{event}}}$$

Systematic Uncertainties

Systematic Uncertainty	Δm_{top} (GeV)
Fit calibration	0.06
b-JES	0.61
p_T- and η-dependent JES	0.28
Lepton energy scale	0.02
Missing transverse momentum	0.06
Jet energy resolution	0.23
b-tagging	0.12
Pileup	0.07
Non-ttbar background	0.13
PDF	0.07
μ_R and μ_F scale	0.24
ME-PS matching threshold	0.18
Underlying event	0.15
Color reconnection effects	0.54
Total	**0.98**



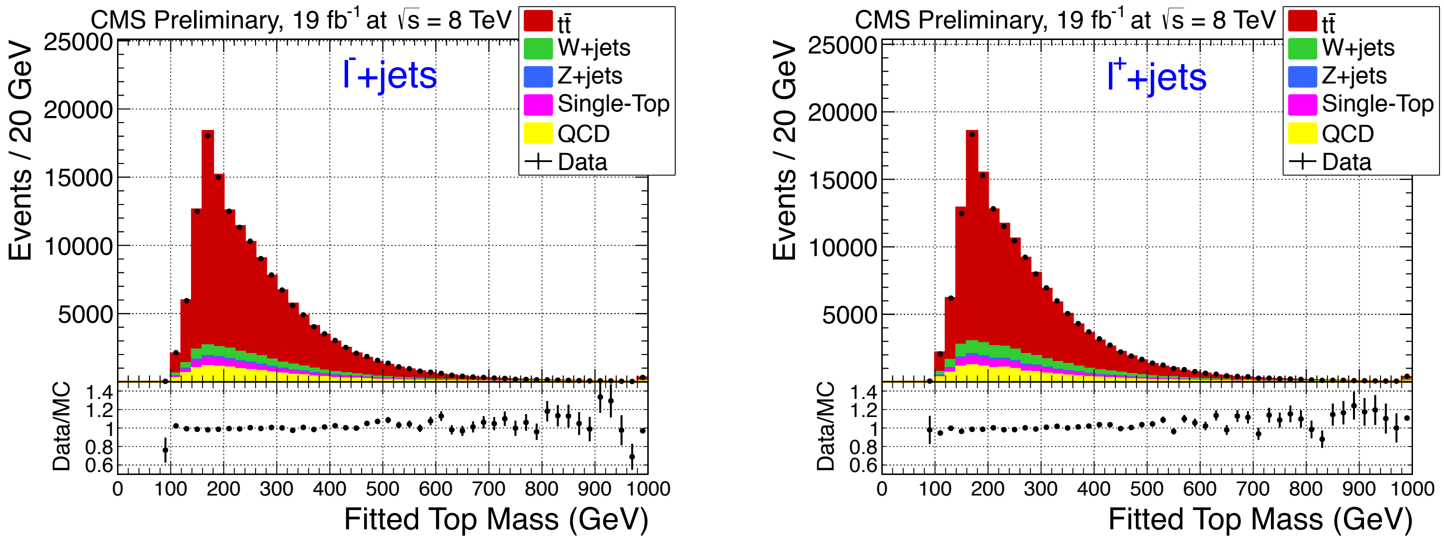
$$173.49 \pm 0.43\ (\text{stat.+JES}) \pm 0.98\ (\text{syst.})\ \text{GeV}$$

Top mass difference

The invariance of the SM under the CPT transformation predicts equality of top and anti-top quark masses

Data are split into ℓ^- and ℓ^+ samples
Ideogram Method (lepton+jets analysis) is used to measure the masses
➡Compare the hadronically decaying top and anti-top mass

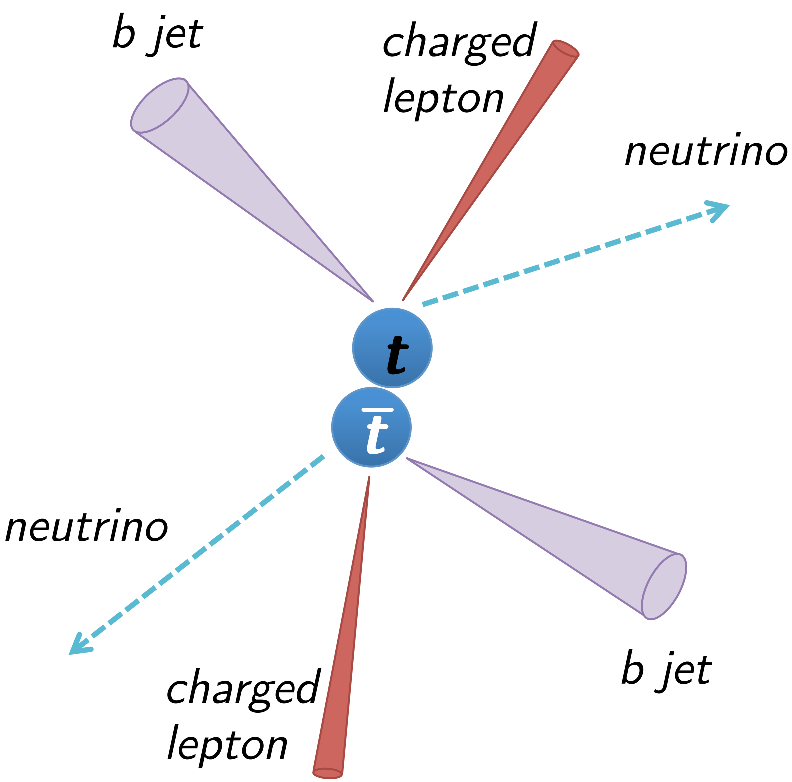
$$\Delta m_t = m_t^{\text{had}} - m_{\bar{t}}^{\text{had}}$$



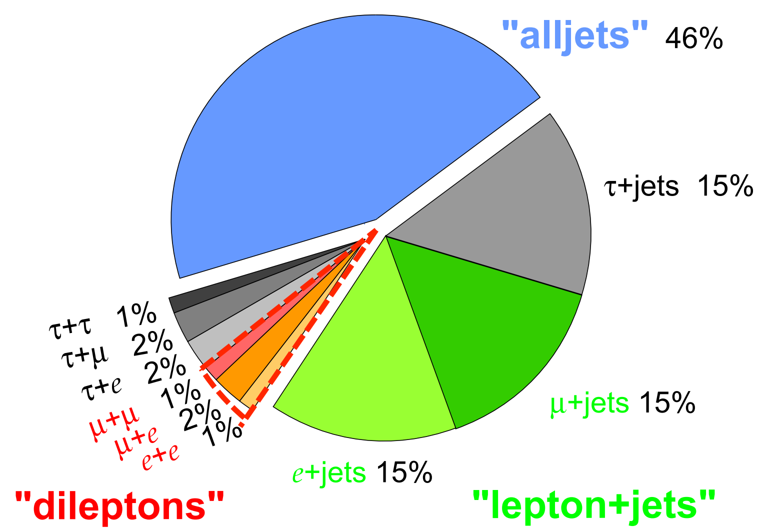
$$\Delta m_t = -272 \pm 196(\text{stat.}) \pm 122(\text{syst.})\text{MeV}$$

Measurement of the top/antitop mass difference
CMS PAS TOP-12-031

Di-Lepton Channel



- Small branching ratio (10%)
- Very good S/N
- Energies of two neutrino are merged to a missing E_T
  →Full reconstruction of ttbar is difficult



Di-Lepton: $\bar{m}_{T2}$ method

m_{T2} represents a lower bound of the parent particle mass.

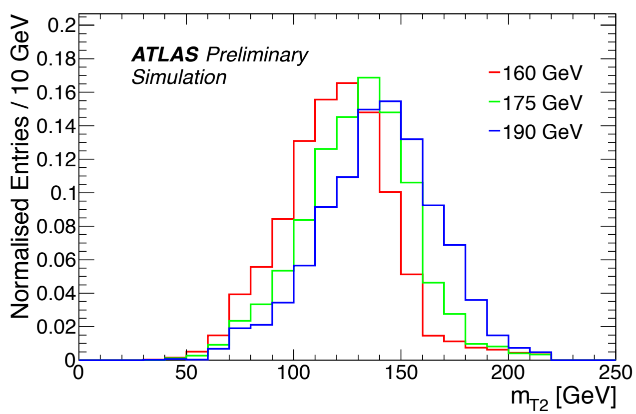
$\vec{p}_T^{(i)}$: kinematically allowed trial values of the invisible particles' p_T (neutrino)

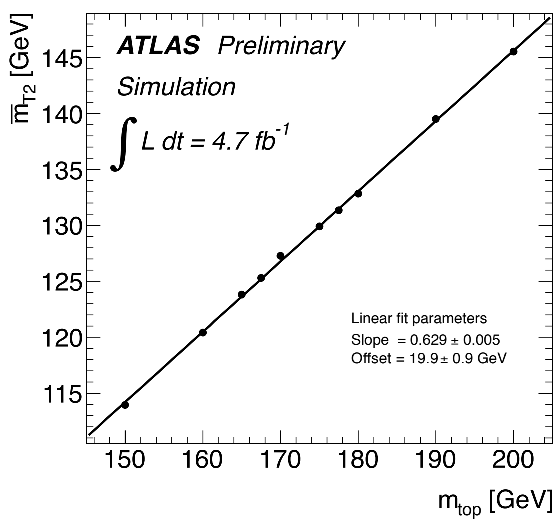
$$\vec{p}_T^{(1)} + \vec{p}_T^{(2)} = \vec{p}_T^{miss} \qquad \vec{p}_{vis}^{(i)} = \vec{p}_{lepton}^{(i)} + \vec{p}_{b-jet}^{(i)}$$

$$m_{T2}(m_{invis}) = \min_{\vec{p}_T^{(1)}, \vec{p}_T^{(2)}} \{\max[m_T(m_{invis}, \vec{p}_T^{(1)}), m_T(m_{invis}, \vec{p}_T^{(2)})]\}$$

$$m_T(m_{invis}, \vec{p}_T^{(i)}) = \sqrt{m_{vis}^2 + m_{invis}^2 + 2\left(E_T^{vis} E_T^{invis} - \vec{p}_T^{vis} \vec{p}_T^{(i)}\right)}$$

Pairing of lepton-jet that returns the smallest m_{T2} value is taken





Systematics	Δm_{top} (GeV)
Signal MC generator	1.3
Parton shower	0.9
Color Reconnection	1.2
Jet energy scale	-1.4/+1.6
b-jet energy scale	-1.2/+1.5
...	

m_{T2} depends on the top quark mass
➡Mean value of m_{T2}, $\bar{m}_{T2}$, gives an estimator of top mass

$m_{top} = 175.2 \pm 1.6\ (stat.)\ ^{+3.1}_{-2.8}\ (syst.)$ GeV

Top-quark mass measurement in the eμ channel using the m_{T2} variable at ATLAS
ATLAS-CONF-2012-082

Di-Lepton: Endpoints Method

$M_{\mathrm{T2}\perp}^{221}$: the visible particles are the two b-jets.

Endpoint: $M_{\mathrm{T2}\perp}^{\max}(221) = M_{\mathrm{t}}$

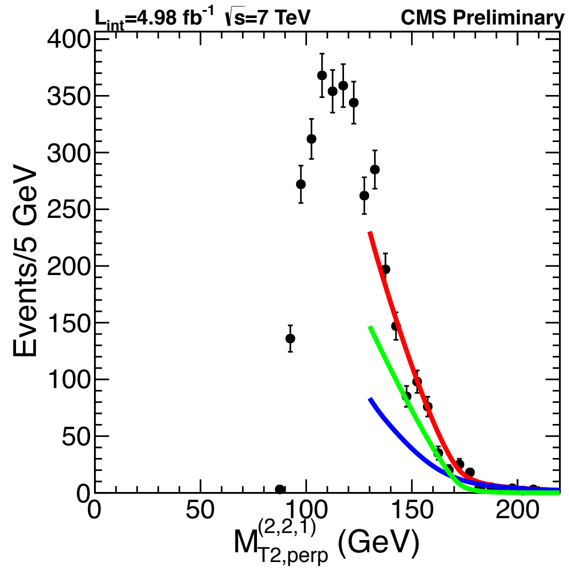
$M_{\mathrm{T2}\perp}^{210}$: the visible particles are the two charged leptons.

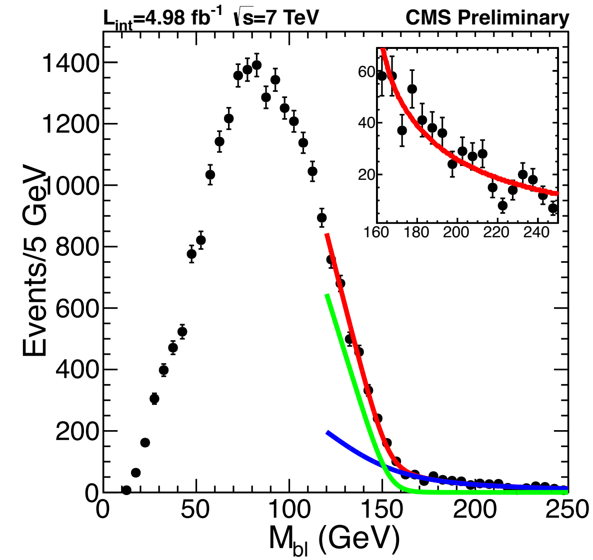
Endpoint: $M_{\mathrm{T2}\perp}^{\max}(210) = M_{W}$

$M_{b\ell}$: Endpoint: $\sqrt{M_{\mathrm{t}}^2 - M_W^2}$

Double constrained fit (m_ν=0 and m_W = 80.4 GeV) to the three endpoint distributions.

Systematics	**Δm_{top} (GeV)**
Jet energy scale	-1.4/+0.5
Jet energy resolution	0.5
Fit range	0.6
Background modeling	0.5
Color reconnection	0.6
…	





Top mass with the kinematic endpoints method
CMS PAS TOP-11-027

$$m_t = 173.9 \pm 0.9(\mathrm{stat.})^{+1.2}_{-1.8}(\mathrm{syst.})\ \mathrm{GeV}$$

Di-Lepton: Analytical Matrix Weighting Technique

Two neutrino momenta are solved analytically

➡Up to 8 solutions for the neutrino momenta for a given m_t hypothesis

Weight w is assigned to each solution in order to determine a preferred mass hypothesis

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

Sum over the possible LO initial-state partons with PDFs $f(x_i)$

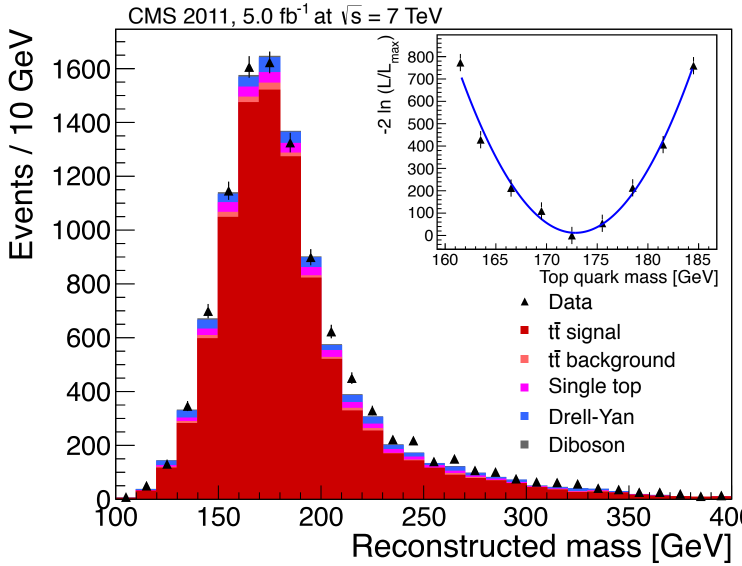
Probability density of observing a massless charged lepton of energy E^* for given m_t

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

Vary the jets p_T, η and ϕ within detector resolution in 1000 times repeating for each event
➡The top quark mass hypothesis with the maximum weitht is taken as reconstructed top mass m_{AMWT}

Compute a likelihood of m_{AMWT} distribution obtained from data for $161.5 < m_t < 184.5$ GeV

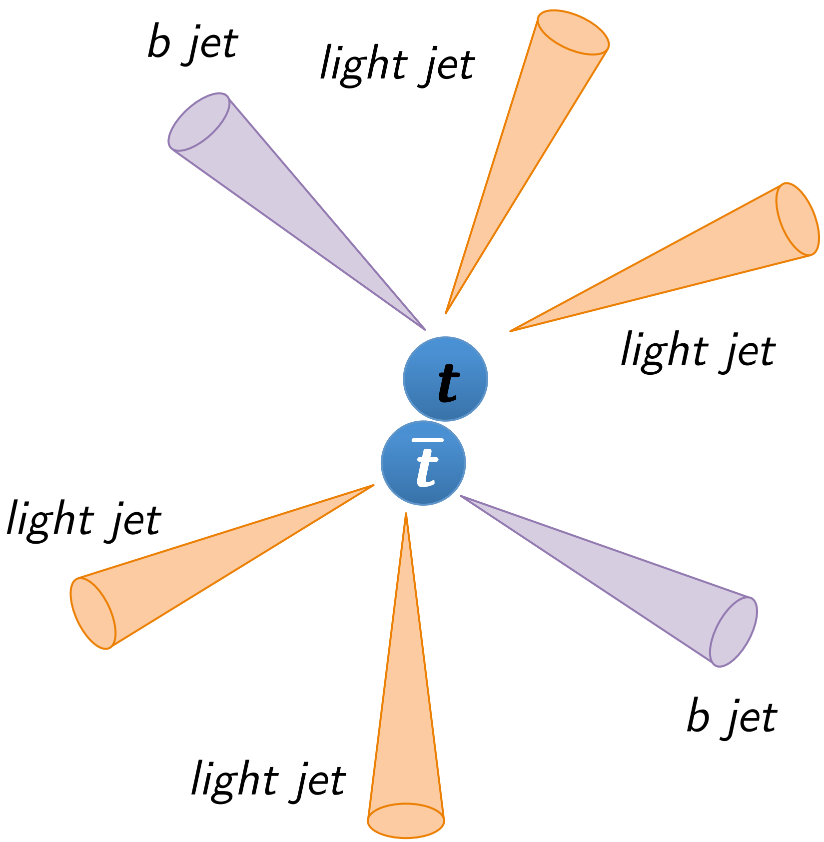
Systematics	Δm_{top} (GeV)
Jet energy scale	-0.97/+0.90
b-jet energy scale	+0.76/-0.66
μ_R and μ_F	0.55
...	



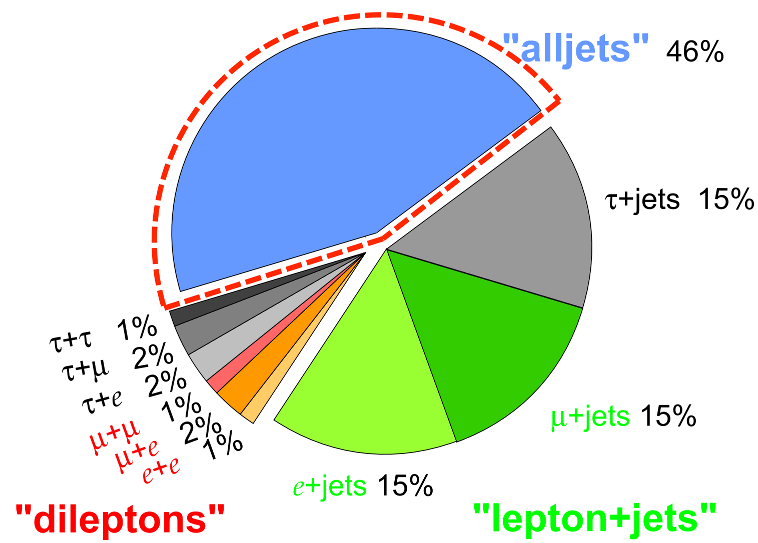
m_{top} = 175.2 ± 0.4 (stat.) ±1.5 (syst.) GeV

Measurement of the top-quark mass in t t-bar events with dilepton final states in pp collisions at sqrt(s)=7 TeV
[Eur. Phys. J. C72 (2012) 2202]

All-Hadronic Channel



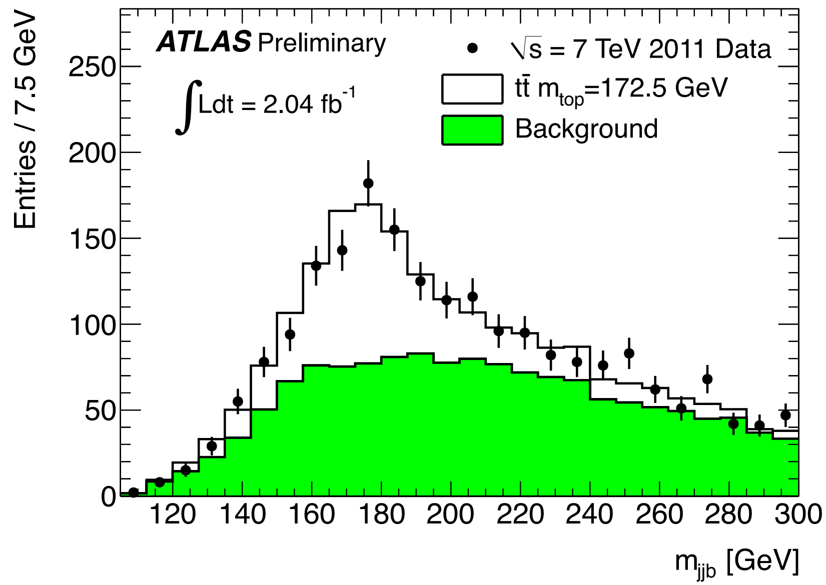
- Large branching ratio (46 %)
- Suffer from large QCD multi-jet background
- No neutrino →constrained kinematics



All - Hadronic: Template Method

Event Selection

- 5 jets $p_T > 55$ GeV,
  6th jet $p_T > 30$ GeV with $|\eta| < 4.5$
  (motivated by trigger condition)
- 2 jets with $p_T > 55$ GeV, $|\eta| < 2.5$
  tagged as b-jets ($\Delta R(b,b) > 1.2$)
- $E_T^{miss}/\sqrt{H_T} < 3$



Reconstruction

χ^2 is minimized as a function of m_W (20 - 420 GeV) and m_t (100 - 800 GeV)

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

Events with $50 < m_{jj} < 110$ GeV and $\chi^2 < 8$ are used for top mass determination

Light jets are rescaled by the energy scale of m_W / m_{jj} (m_W=80.4 GeV)
Two values of m_{jjb} from each event contribute for measurement

Determination of the Top Quark Mass with a Template Method in the All-Hadronic Decay Channel using 2.04 fb^{-1} of ATLAS Data
ATLAS-CONF-2012-030

All - Hadronic: Template Method

Background Template (QCD multi-jet event)

Event Mixing Algorithm

Use events with exactly 5 jets

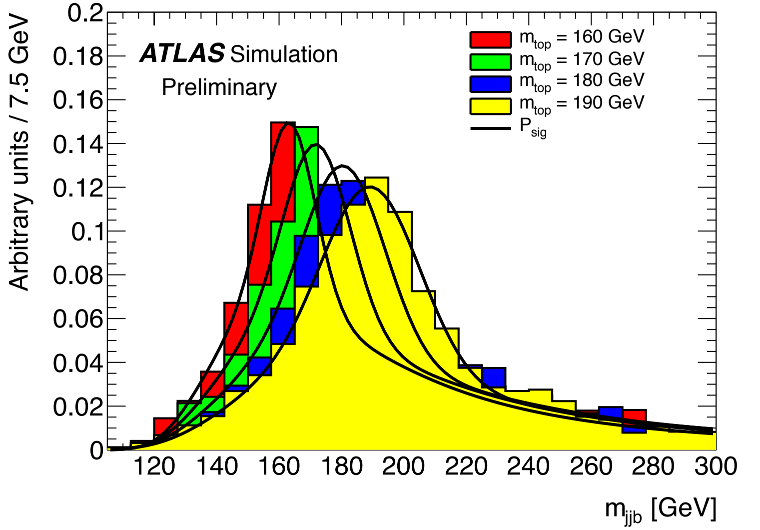
➡Add jet from events with ≥ 6 jets

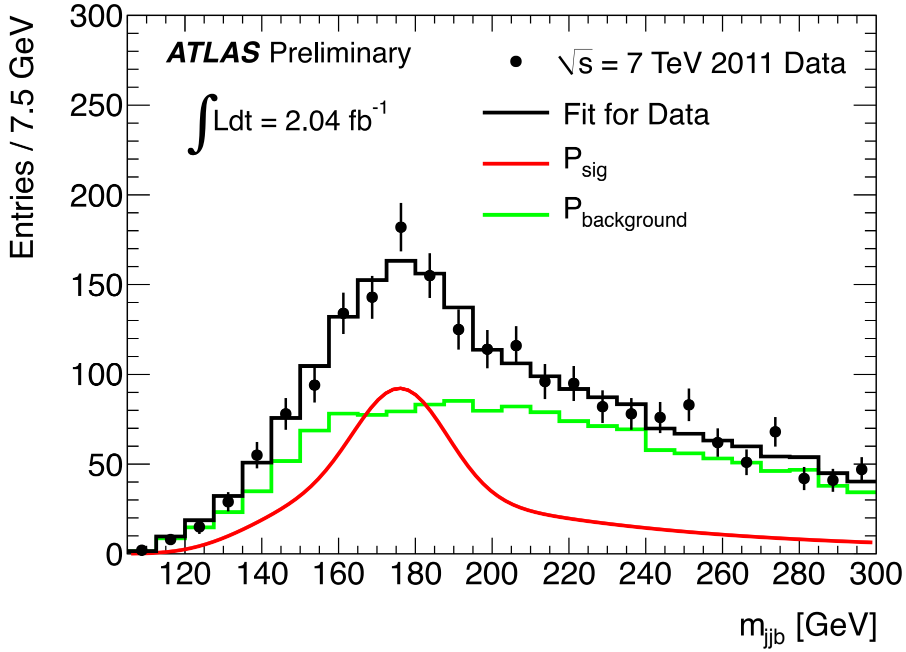
Signal Template (Signal + Combinatorial bkg)

Generate m_{jjb} template using MC as function of input m_t (160 - 190 GeV)

Mass Determination

Fit m_{jjb} templates to data using binned likelihood





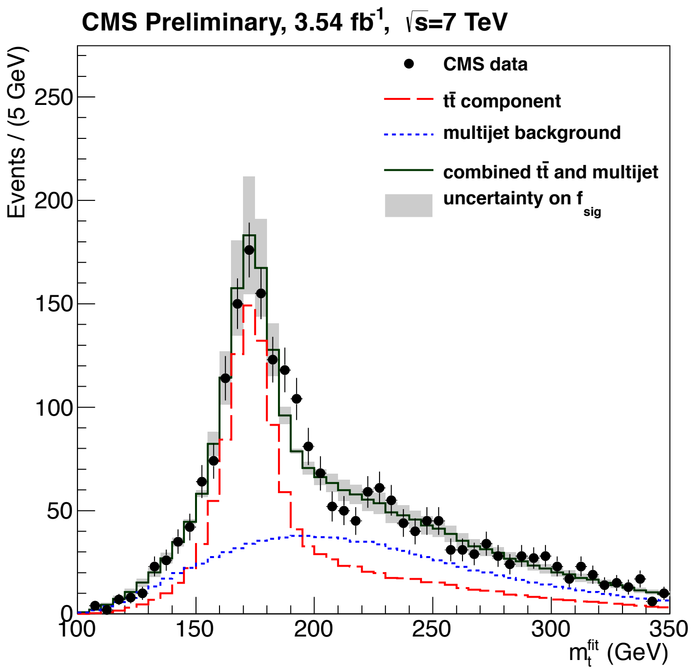
Systematics	Δm_{top} (GeV)
Jet energy scale	2.1
b-jet energy scale	1.4
Background modeling	1.9
ISR/FSR	1.7
…	

m_{top} = 174.9 ± 2.1 (stat.) ± 3.8(syst.) GeV

All - Hadronic: Ideogram Method

Event Selection

- ≥ 4jets with pT > 60 GeV, 5th jet with pT > 50 GeV, 6th jet > 40 GeV Iηl < 2.4 (Additional jets are considered if $p_T > 30$ GeV)
- At least 2 jets are tagged as *b*-jet



Kinematic Fit

- Constraints: $m_{top} = m_{anti\text{-}top}$, $m_W = 80.4$ GeV
- b-tagged jets are assigned as *b*-quarks
  →Remaining jets are assigned as light quarks
- The smallest χ^2 jet permutation is chosen
- Require $P_{gof} > 0.09$
- $\Delta R(b,b) > 1.5$

Background Modeling (Event Mixing Technique)

Jets are mixed between the different events based on the p_T-order in the original events

At least 2 *b*-tagged jets are found in every new event

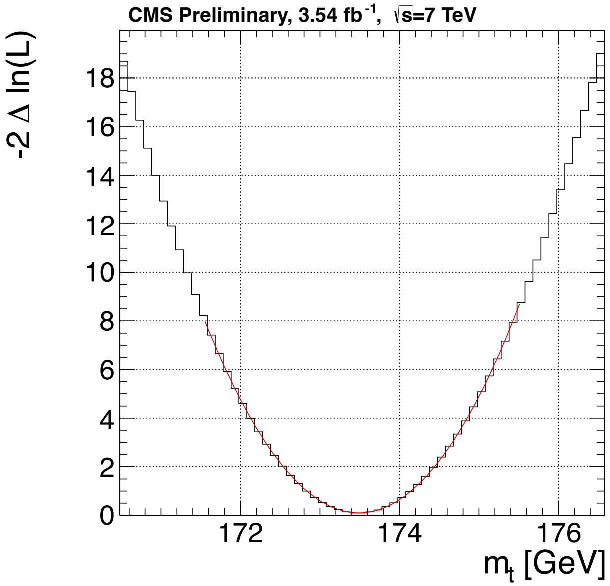
Measurement of the top-quark mass in all-jets final states

CMS PAS TOP-11-017

All - Hadronic: Ideogram Method

Ideogram Method (used for lepton+jets analysis)
Determine JES and top mass simultaneously
Create template for different $m_{t,\mathrm{gen}}$ and JES variation

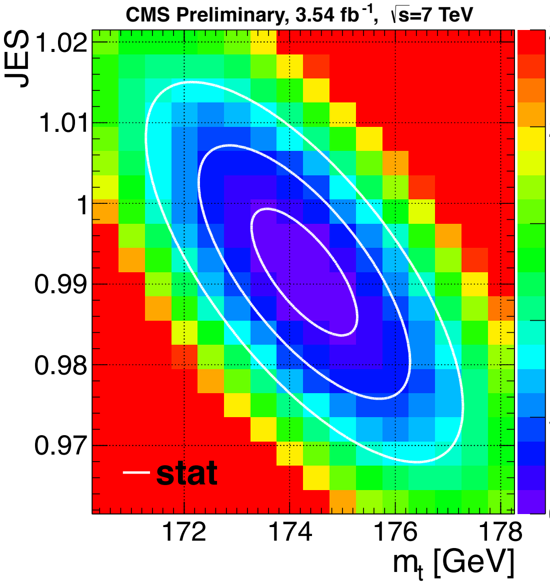
$$-2\ln\{\mathcal{L}\,(m_t, \mathrm{JES}=1|\mathrm{sample})\}$$



m_{top} = 173.49 ± 0.69 (stat.) ± 1.25(syst.) GeV

Systematics	Δm_{top} (GeV)
Jet energy scale	0.97
b-jet energy scale	0.49
…	

$$-2\ln\{\mathcal{L}\,(m_t, \mathrm{JES}|\mathrm{sample})\}$$



m_{top} = 174.28 ± 1.00 (stat.+JES) ± 1.46(syst.) GeV
JES = 0.991 ± 0.008 (stat.) ± 0.015 (syst.)

Systematics	Δm_{top} (GeV)
b-jet energy scale	0.52
Underlying event	0.88
Color reconnection	0.58
Background modeling	0.62
…	

Mass from Cross Section

Predicted and experimentally measured cross section as function of top mass
Experimental cross section: Lepton+jets channel with 35 pb^{-1} at ATLAS
Di-lepton channel with 1.14 fb^{-1} at CMS

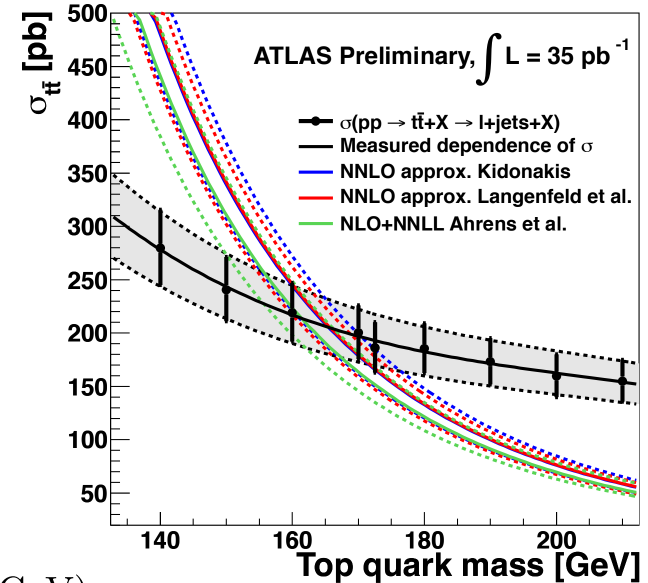
Top quark mass extraction

Combined theoretical and experimental likelihood

$$f(m_{\rm top}) \propto \int f_{\rm th}(\sigma|m_{\rm top}) \cdot f_{\rm exp}(\sigma|m_{\rm top})$$

Uncertainties

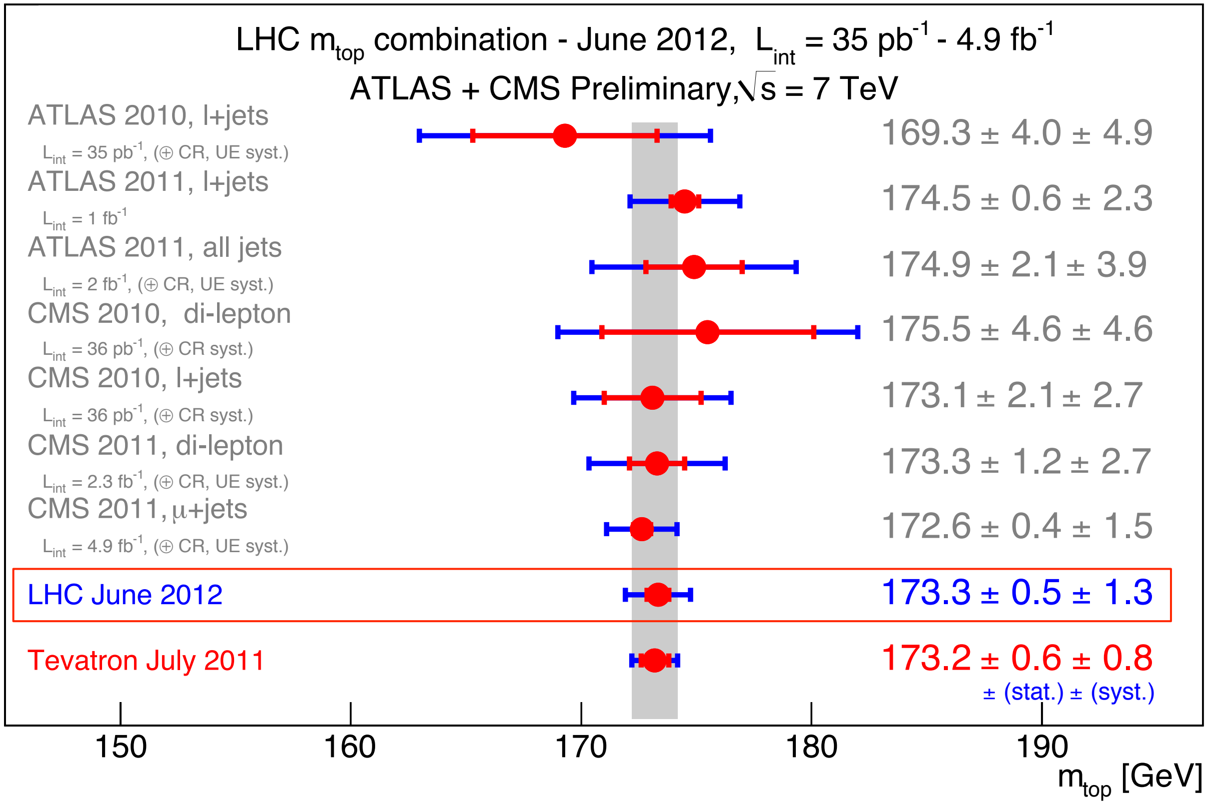
- Experimental
- Variation of $\mu_{\text{renormalization}}$ and $\mu_{\text{factorization}}$
- PDF (MSTW2008NNLO)



	ATLAS	CMS	
approx. NNLO	$m_t^{\rm Pole}$ (GeV)	$m_t^{\rm Pole}$ (GeV)	$m_t^{\overline{\rm MS}}$ (GeV)
Langenfeld	$166.4^{+7.8}_{-7.3}$	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis	$166.2^{+7.8}_{-7.4}$	$170.0^{+7.6}_{-7.1}$	—
Ahrens	$162.2^{+8.0}_{-7.6}$	$167.6^{+7.6}_{-7.1}$	$159.8^{+7.3}_{-6.8}$

Determination of the Top-Quark Mass from the ttbar Cross Section Measurement in pp Collisions at √s = 7 TeV with the ATLAS detector
ATLAS-CONF-2011-054
Top mass from the cross section in dileptons
CMS PAS TOP-11-008

Combination of ATLAS and CMS



Measurement of the top quark mass at the LHC reached a great precision. Some results are not included in this combination and succeeded to reduce systematic uncertainty.

➔Expect to obtain much better combined result in the future.

Combination of ATLAS and CMS results on the mass of the top quark using up to 4.9 fb^{-1} of data
ATLAS-CONF-2012-095

Backup

Lepton + Jets: Template Method

Event Selection

Common Selection

- Exactly 1 isolated charged lepton

Electron
$E_T > 25$ GeV, $|\eta_{cluster}| < 2.47$
$E_T^{miss} > 35$ GeV, $m_T > 25$ GeV

Muon
$p_T > 20$ GeV, $|\eta| < 2.5$
$E_T^{miss} > 20$ GeV, $E_T^{miss} + m_T > 60$ GeV

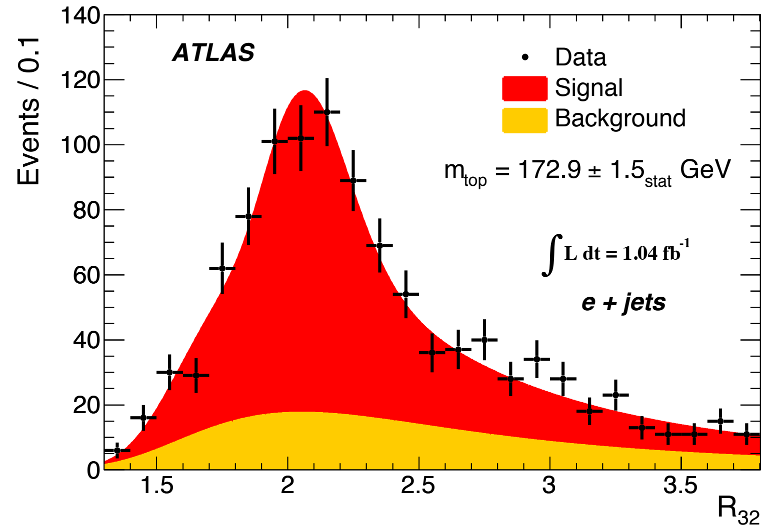
- At least 4 jets with $p_T > 25$ GeV, $|\eta| < 2.5$
- At least 1 jet of these jets is tagged as *b*-jet

1D Template Analysis

- Kinematic Likelihood Fit with ln L > -50
  → Jets permutations are obtained from KLFitting
- Constructed m_{jjb} with jets $p_T > 40$ GeV
- $60 < m_W^{reco} < 100$ GeV

Systematic Uncertainty	Δm_{top} (GeV)
Signal MC generator	0.74
Hadronization	0.43
Color Reconnection	0.62
ISR/FSR	1.42
Jet energy scale	1.23
b-jet energy scale	1.16
…	

Derive templates for $\mathbf{R_{32}} \equiv m_{top}^{reco} / m_W^{reco}$ as a function of m_{top} (160-190 GeV)



$m_{top} = 174.5 \pm 0.9$ (stat.) ± 2.5 (syst.) GeV

Measurement of the Top Quark Mass with the Template Method in the ttbar -> lepton+jets Channel using ATLAS Data
Eur.Phys.J. C72 (2012) 2046

Lepton + Jets: Template Method

2D Template Analysis

- Light jet pairs with $50 < m_{jj} < 110$ GeV
- Jet triplet (jjb) with maximum p_T is chosen
- Constructed m_{top}^{reco} to constrain $m_{jj} = m_W$ within Γ_W

Systematic Uncertainty	Δm_{top} (GeV)
Underlying event	0.59
Color Reconnection	0.55
ISR/FSR	1.01
Jet energy scale	0.66
b-jet energy scale	1.58
…	

Derived templates

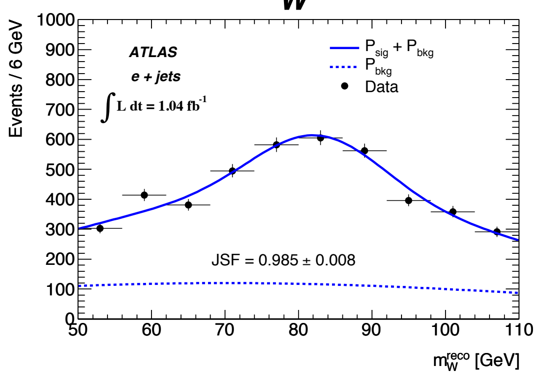
Global Jet Energy Scale Factor (JSF)

➡correct energy **parton** → **particle** level

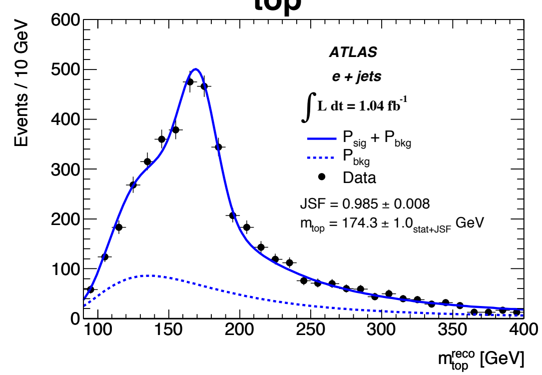
- for m_W^{reco} as function of assumed global jet energy scale factor (JSF)
- for m_{top}^{reco} as function of input m_{top} (160-190 GeV) and assumed JSF

Parameters of m_{top}, n_{bkg} and JSF are determined by unbinned likelihood fit

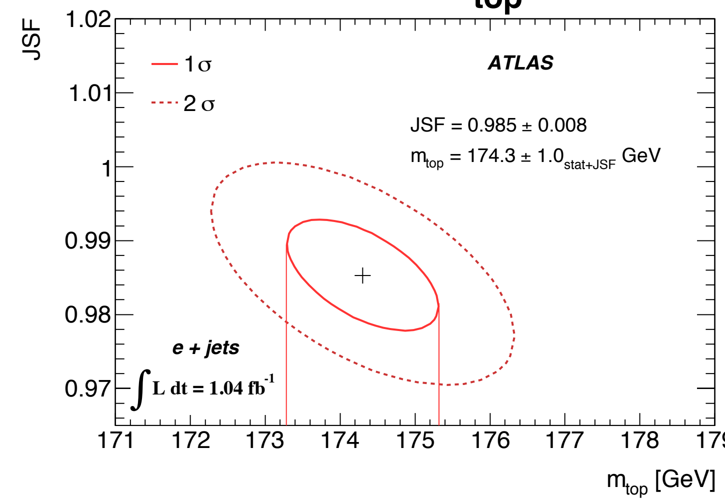
m_W^{reco}



m_{top}^{reco}



JSF - m_{top}



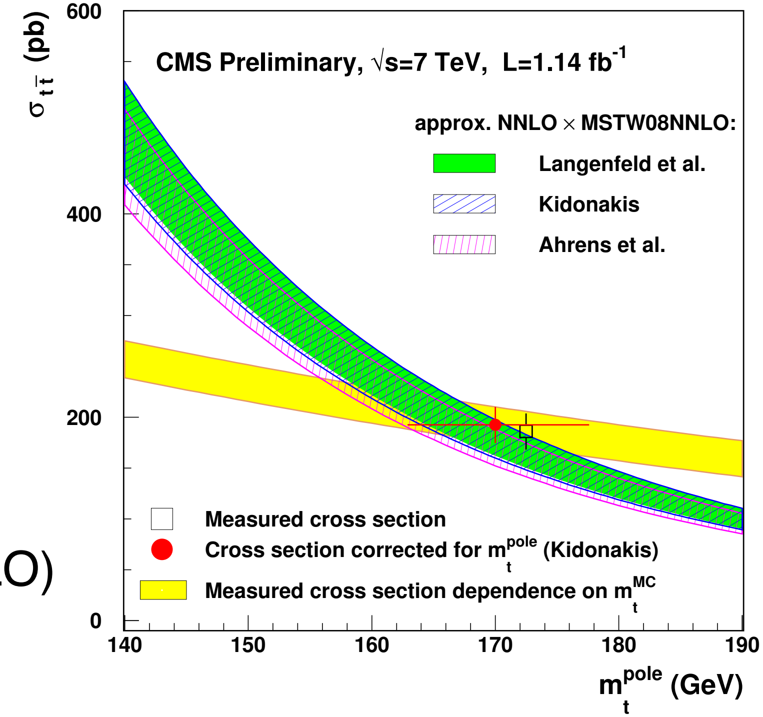
$m_{top} = 174.5 \pm 0.6$ (stat.) ± 2.3 (syst.) GeV

Mass from Cross Section

Predicted and experimentally measured cross section as function of top mass
Experimental cross section: Di-lepton channel with 1.14 fb^{-1}

Top quark mass extraction
Combined theoretical and experimental likelihood

$$f(m_{\rm top}) \propto \int f_{\rm th}(\sigma|m_{\rm top}) \cdot f_{\rm exp}(\sigma|m_{\rm top})$$



Uncertainties
- Experimental
- Variation of μ_{ren} and μ_{fac}
- PDF (MSTW2008NNLO, HERAPDF15NNLO)
- $\alpha_s(M_Z)$

Approx. NNLO × MSTW08NNLO	$m_t^{\rm pole}$ / GeV	$m_t^{\overline{\rm MS}}$ / GeV
Langenfeld et al. [7]	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis [8]	$170.0^{+7.6}_{-7.1}$	–
Ahrens et al. [9]	$167.6^{+7.6}_{-7.1}$	$159.8^{+7.3}_{-6.8}$

Top mass from the cross section in dileptons
CMS PAS TOP-11-008