Top Mass Measurements at the LHC

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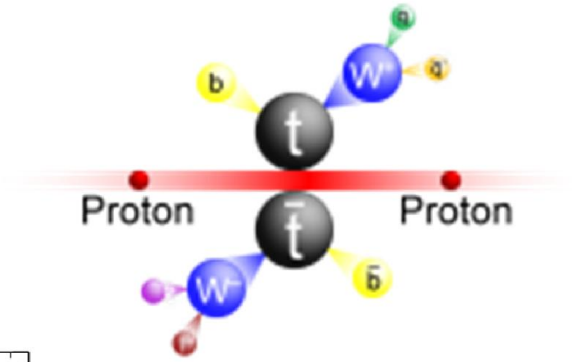
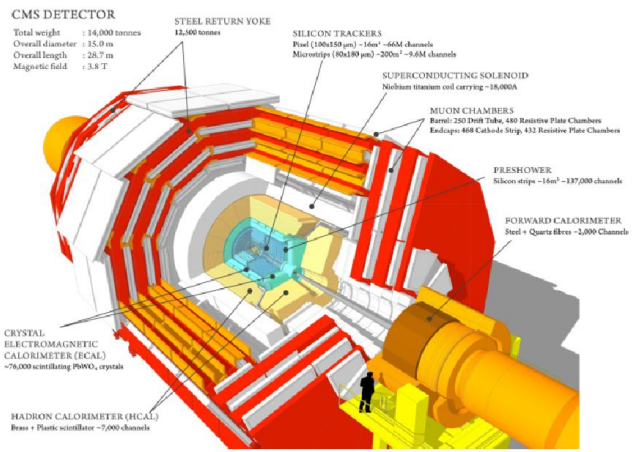
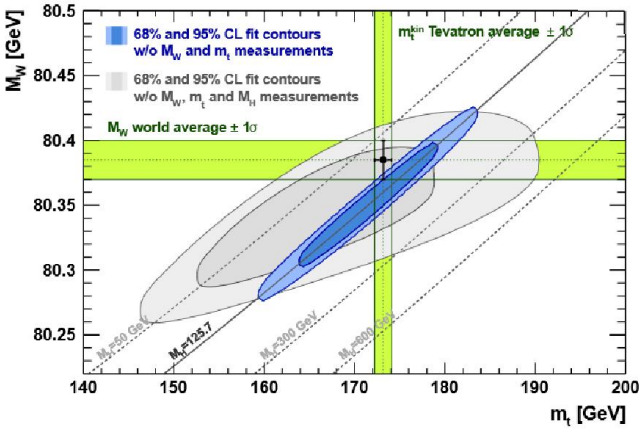
Ghent University
On behalf of the ATLAS and CMS collaborations

Standard Model at LHC
April 9, 2014

Top Quarks at the LHC







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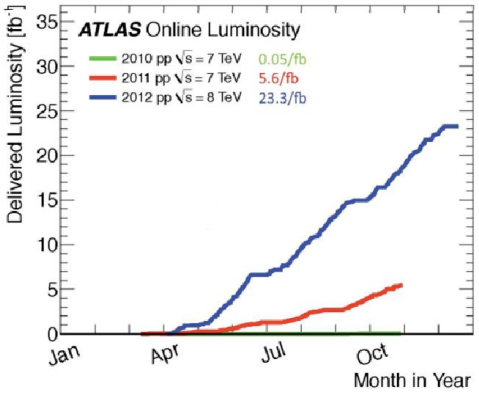
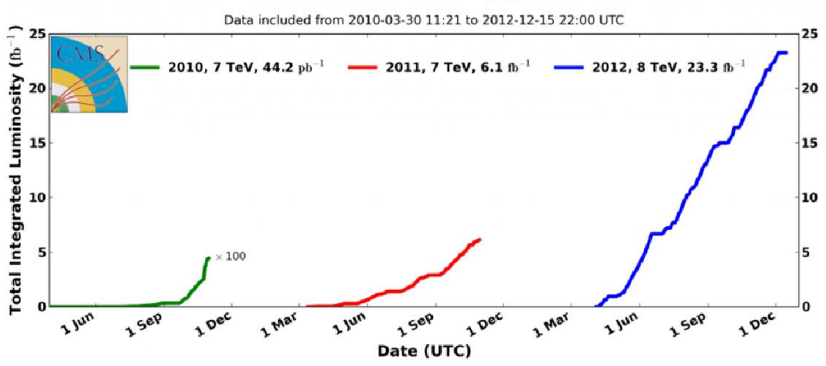
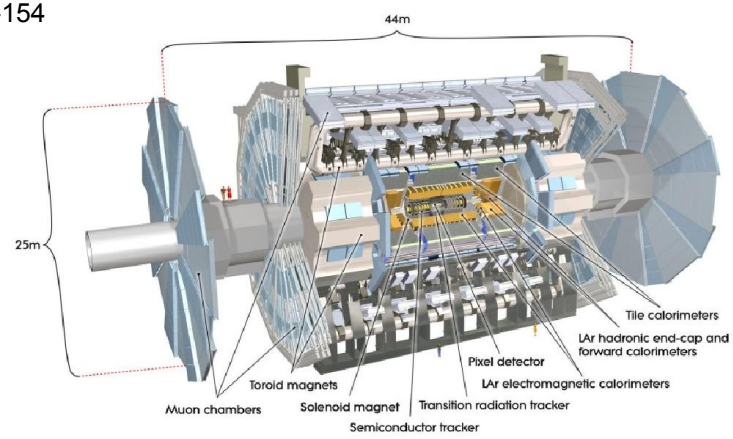


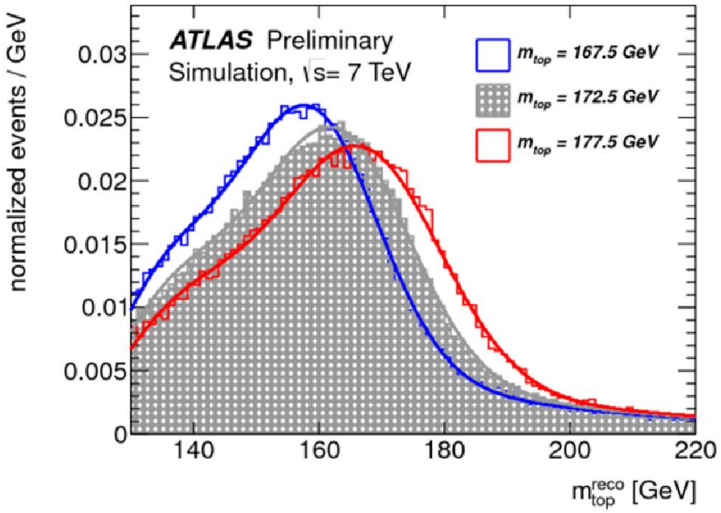


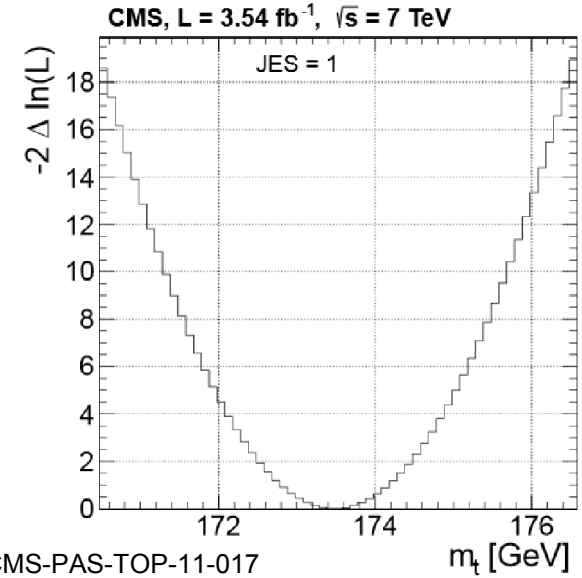


A Standard Analysis

1. **Select $t\bar{t}$ events.**
2. **Reconstruct an estimator:**
   - Examples: m_{lb} in template, m_{AMWT} in AMWT, m_t^{fit} in template or ideogram
   - Kinematic fits fix jet-parton assignment and can reduce backgrounds
3. **Parameterize distributions of estimator:**
   - Template: distributions are fit to analytic functions
   - Ideogram: Create PDFs from distributions, then calculate likelihoods
   - Analytic Matrix Weighting Technique: Take distributions as templates.
4. **Calibrate using pseudoexperiments on MC.**
5. **Fit to data.**

ATLAS_CONF-2013-046

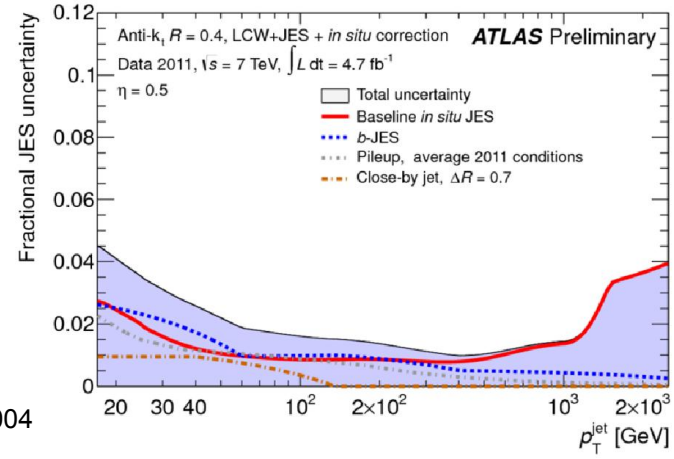




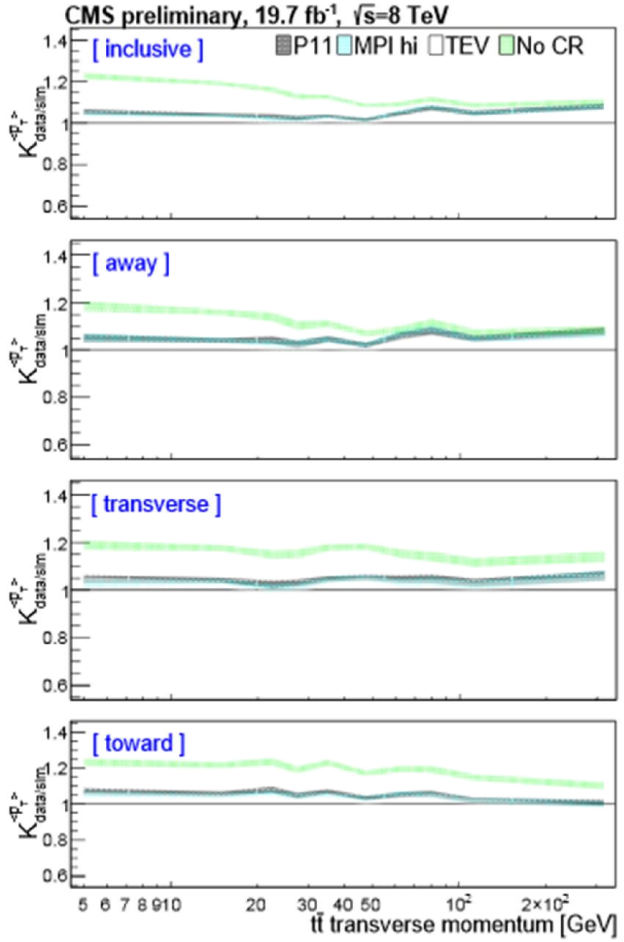
CMS-PAS-TOP-11-017

Systematic Uncertainties

- Jet Energy Scale
  - Corrections for energy loss, variations in response, calorimeter irregularities
  - JES Uncertainties < 5%→Δ_m=1-1.25 GeV
  - Solution: measure jet energy scale factor *in-situ*
- Signal Modelling
  - Includes: MC generator (ATLAS: Powheg+Pythia; CMS: MadGraph+Pythia), hadronization model, QCD radiation model, color reconnection effects, PDF uncertainties . . .
  - Some could be constrained by underlying event studies



ATLAS-CONF-2013-004



CMS-PAS-TOP-13-007

(Some) Top Mass Measurements

Standard Measurements					
ATLAS	Template Method	ℓ+jets	7 TeV	4.7 fb^{-1}	ATLAS-CONF-2013-046
CMS	Ideogram Method	ℓ+jets	8 TeV	19.7 fb^{-1}	CMS-PAS-TOP-2014-001
ATLAS	Template Method	dilepton	7 TeV	4.7 fb^{-1}	ATLAS-CONF-2013-077
CMS	AMWT-m_t	dilepton	7 TeV	5.0 fb^{-1}	Eur. Phys. J C72 (2012) 2202
Δm_t Measurement					
ATLAS	Template Method	ℓ+jets	7 TeV	4.7 fb^{-1}	Phys. Let. B 728C (2014) 363
Alternate Method					
CMS	B-hadron Lifetime	ℓ+jets/ dilepton	8 TeV	19.7 fb^{-1}	CMS-PAS-TOP-12-030

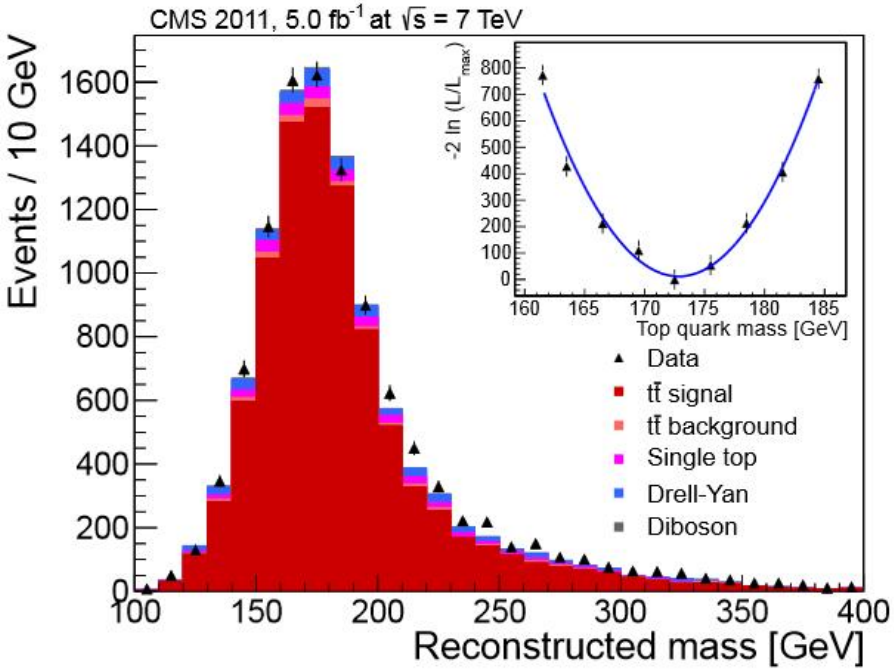
Combinations			
LHC	BLUE Method	7 TeV	ATLAS-CONF-2013-102/CMS-PAS-TOP-13-005
LHC + Tevatron	BLUE Method		CMS-PAS-TOP-13-014/ATLAS-CONF-2014-008/CDF Note 11071/D0 Note 6416

CMS—Dilepton

7 TeV

- Signature:
  - 2 OC high p_T leptons; ≥ 2 jets, ≥ 1 b-jet; E_t^{miss} →11627 events.
- AMWT: m_{AMWT}
- Likelihoods calculated per templates
- Drell-Yan estimated from data; others from MC
- Precision comparable to results of leptons+jets channel

m_t=172.5±0.4(stat.)±1.50(syst.) GeV



Eur. Phys. J. C72 (2012) 2202

Dominant Systematics (GeV)

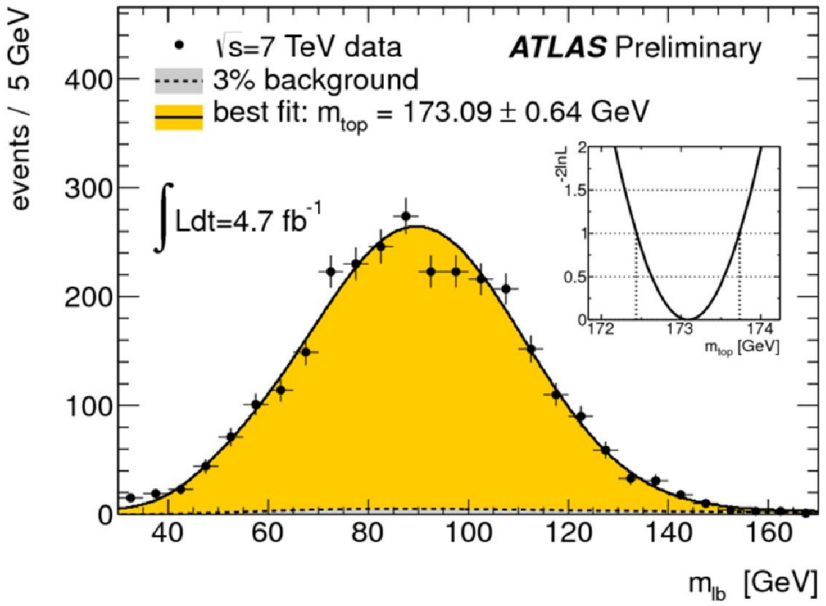
b-Jet Energy Scale	+0.9,-0.97
Jet energy scale	+0.76,-0.66
Renormalization/Factorization	0.55

ATLAS—Dilepton

7 TeV

- Signature:
  - 2 OC high p_T leptons, ≥ 2 jets, 2 b-tags, E_t^{miss} /H_T and $m_{\ell\ell}$ →2913 events
- Template Method: m_{lb}
  - m_{lb} : average invariant mass of lepton+b-jet system
  - less sensitive to systematics then previous m_{T2}+calibration curve method (ATLAS-CONF-2012-082)
- Background from fake leptons estimated in data to be zero; others estimated from MC

m_t=173.09±0.64(stat.)±1.50(syst.) GeV



ATLAS-CONF-2013-077

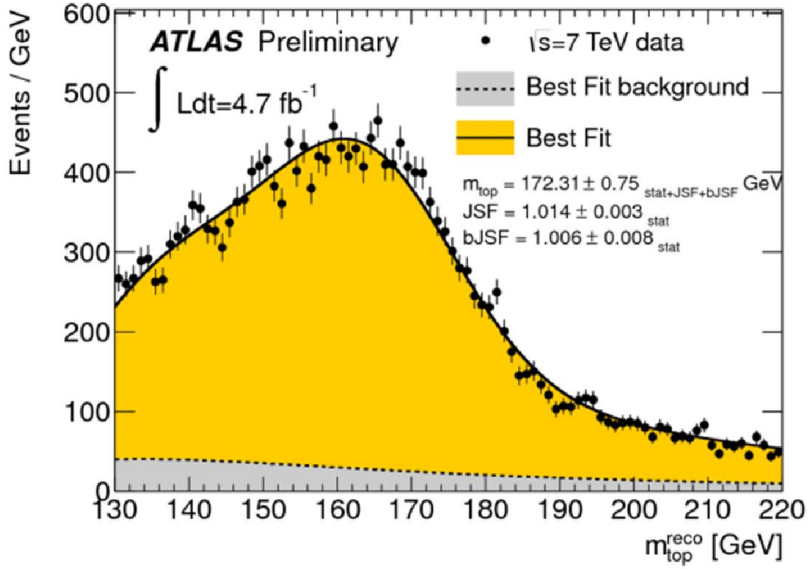
Dominant Systematics (GeV)

Jet Energy Scale	0.89
b-Jet energy scale	0.71
b-tagging efficiency/mistag rate	0.46

ATLAS—Lepton+Jets

7 TeV

- Signature:
  - 1 high p_T lepton, E_T^{miss}, ≥ 4 jets, ≥ 1 b-tag $m^W \rightarrow$ 22878 events
- Backgrounds:
  - Data-driven: w+jets normalization and QCD multijet
  - MC: all others
- Template Method: m_t^{reco} , m_W^{reco} , R_{lb}^{rec}
  - $R_{lb} = \frac{{p_T}^{b_{had}} + {p_T}^{b_{lep}}}{{p_T}^{W_{jet1}} + {p_T}^{W_{jet2}}}$ or $\frac{{p_T}^{b_{tag}}}{({p_T}^{W_{jet1}} + {p_T}^{W_{jet2}})/2}$
- 3 dimensional unbinned likelihood fit→ m_t, JSF, and bJSF.
  - 0.08 GeV bjes uncertainty (3D) from 0.92 GeV (2D)



ATLAS-CONF-2013-046

Dominant Systematics (GeV)

b-tagging efficiency	0.81
Jet energy scale	0.79
ISR/FSR	0.45

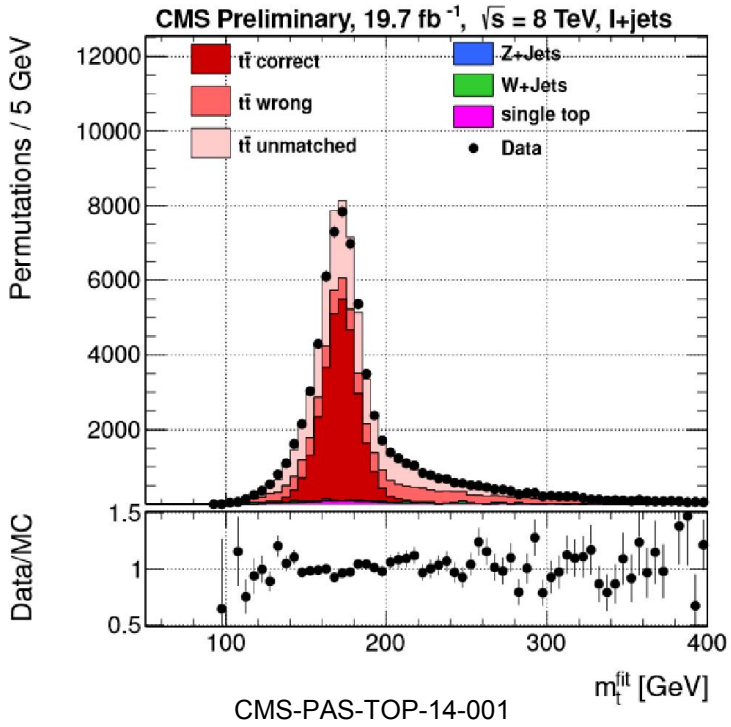
m_t=172.31±0.75(stat.+JSF+bJSF)±1.35(syst.) GeV

CMS—Lepton+Jets

8 TeV

- Signature:
  - 1 high p_T lepton, ≥ 4 jets, 2 b-tags, P_{gof} ≥ 0.2→28750 events .
- Sample ~96% pure $t\bar{t}$
  - Method assumes no background
- Ideogram Method: m_t^{fit}, m_W^{reco}
- Perform 2 dimensional likelihood fit→ m_t and JES.
- Uncertainties:
  - Flavor-dependent JES: Lund string fragmentation (Pythia 6) vs. cluster fragmentation (Herwig++) by jet flavor
  - Pileup: variations in pp cross-section and rescaling of JES

m_t=172.04±0.19(stat.+JSF)±0.75(syst.)



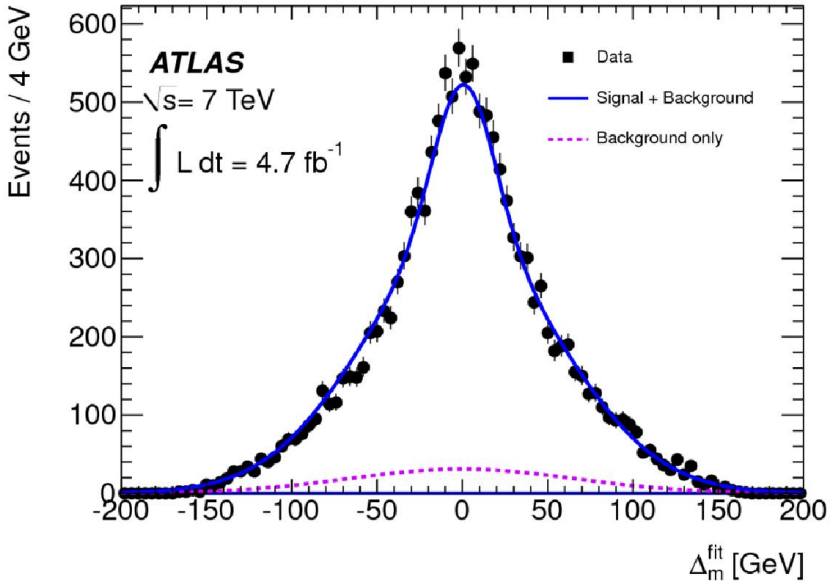
Dominant Systematics (GeV)	
Flavor-dependent JES	0.41
Pileup	0.27
Jet energy Resolution	0.26

ATLAS—Lepton+Jets, Δm

7 TeV

- Test of CPT invariance
- Signature:
  - 1 high p_T lepton, ≥ 4 jets, ≥ 2 b-tags, E_T^{miss} and $m_T(\ell, E_T^{miss})$→13450 events
- Template: $\Delta_m^{fit} = m_t - \bar{m}_t$ (per event)
- Unbinned extended likelihood fit to data
- Uncertainty dominated by signal modelling
  - Evaluated by comparing hadron decay models (Pythia vs. Evtgen) and hadron shower simulation models

Δm_t=0.67±0.61(stat.)±0.41(syst.) GeV



Phys. Let. B 728 C (2014)

Dominant Systematic (GeV)	
b fragmentation model	0.34
K^+/K^- response asymmetry	0.08
Residual b vs. $\bar{b}$ differences	0.08

CMS—B Hadron Lifetime

8 TeV

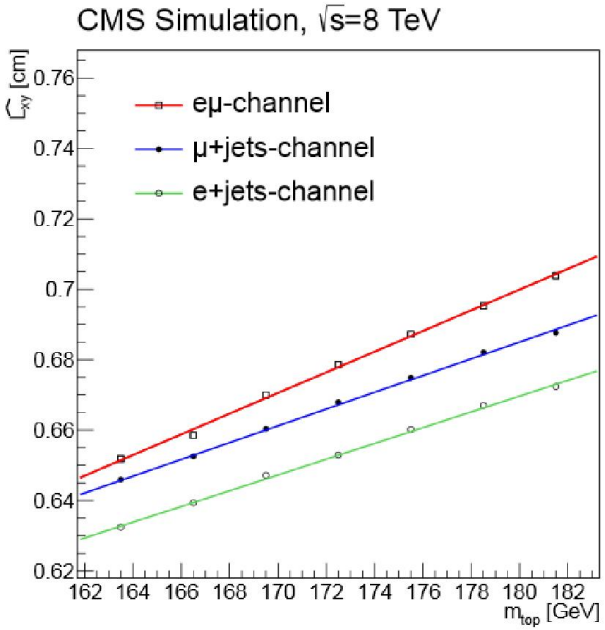
- Alternate technique: use B hadron decay length

$$L_{xy} \approx 0.4 \frac{m_t}{m_b} \beta_b \tau_b$$

→requires minimal knowledge of JES

  - L_{xy} not Lorentz-invariant—correlation taken from MC.
- Result combination of lepton+jets and eμ channel →456282 events
- Hadronization model:
  - default Pythia Z2* is compared to two others; cross-check by Pythia vs. Herwig

m_t=173.5±1.5(stat.)±1.3(syst.)±2.6(p_T(t)) GeV



CMS-PAS-TOP-12-030

Dominant Systematics (GeV)

Top quark p_T modelling	2.36-3.27
W+jets normalization (l+jets)	1.33-1.42
Hadronization model	0.67-0.95

Combinations: LHC and World

- Performed using the Best Linear Unbiased Estimate (BLUE) Method

Jet Energy Scale
- From jet energy corrections
- Traditionally dominate measurements

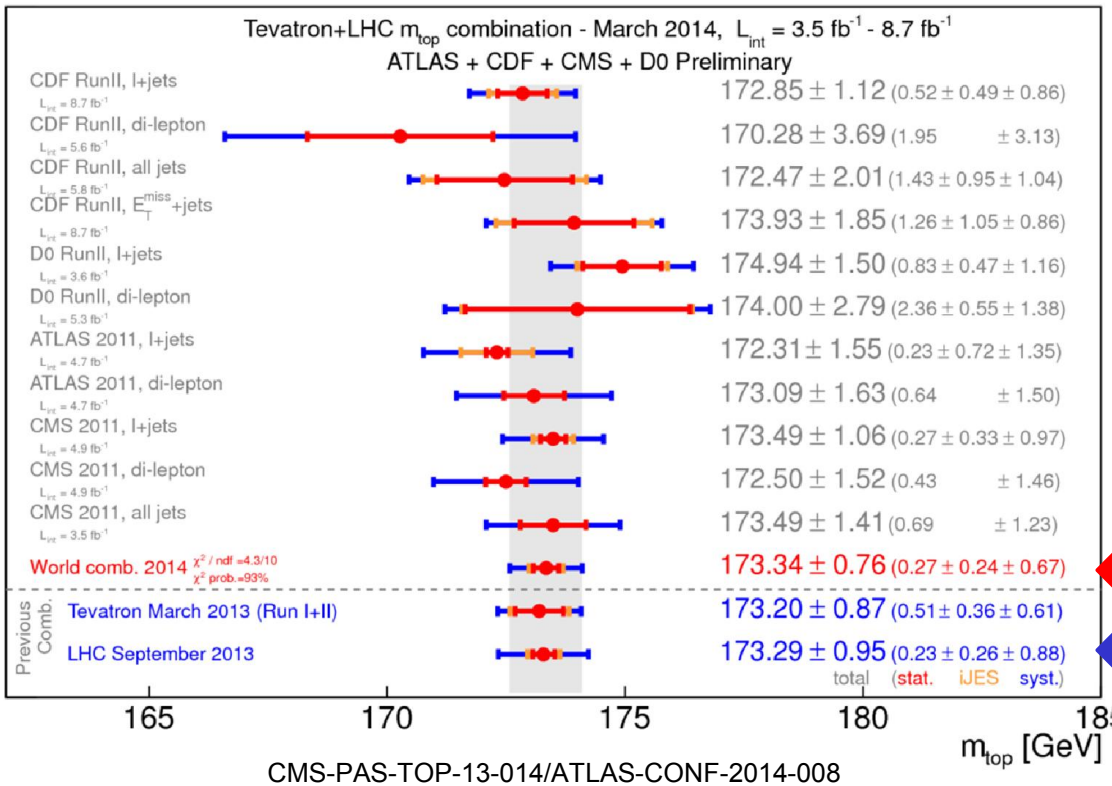
Signal Theory/Modelling
- Includes choice of generator, hadronization scheme, QCD radiation, color reconnection . . .

Detector, Method, & Environment
- Includes effects of pile-up, object reconstruction, background treatment, etc.

	ATLAS		CMS		
Uncertainty	*l*+jets	di-*l*	*l*+jets	di-*l*	all jet
m_{top}	172.31	173.09	173.49	172.50	173.49
Stat	0.23	0.64	0.27	0.43	0.69
iJES	0.72	n.a.	0.33	n.a.	n.a.
stdJES	0.70	0.89	0.24	0.78	0.78
flavourJES	0.36	0.02	0.11	0.58	0.58
bJES	0.08	0.71	0.61	0.76	0.49
MC	0.35	0.64	0.15	0.06	0.28
Rad	0.45	0.37	0.30	0.58	0.33
CR	0.32	0.29	0.54	0.13	0.15
PDF	0.17	0.12	0.07	0.09	0.06
DetMod	0.23	0.22	0.24	0.18	0.28
b-tag	0.81	0.46	0.12	0.09	0.06
LepPt	0.04	0.12	0.02	0.14	n.a.
BGMC	n.a.	0.14	0.13	0.05	n.a.
BGData	0.10	n.a.	n.a.	n.a.	0.13
Meth	0.13	0.07	0.06	0.40	0.13
MHI	0.03	0.01	0.07	0.11	0.06
Total Syst	1.53	1.50	1.03	1.46	1.23
Total	1.55	1.63	1.06	1.52	1.41

Uncertainties are in GeV.
CMS-PAS-TOP-13-014/ATLAS-CONF-2014-008

LHC and World Combination



CMS-PAS-TOP-13-014/ATLAS-CONF-2014-008

- First LHC+Tevatron result!
- Total uncertainty on top quark mass <1 GeV for combinations.

m_t=173.34±0.27(stat.)±0.71(syst.) GeV

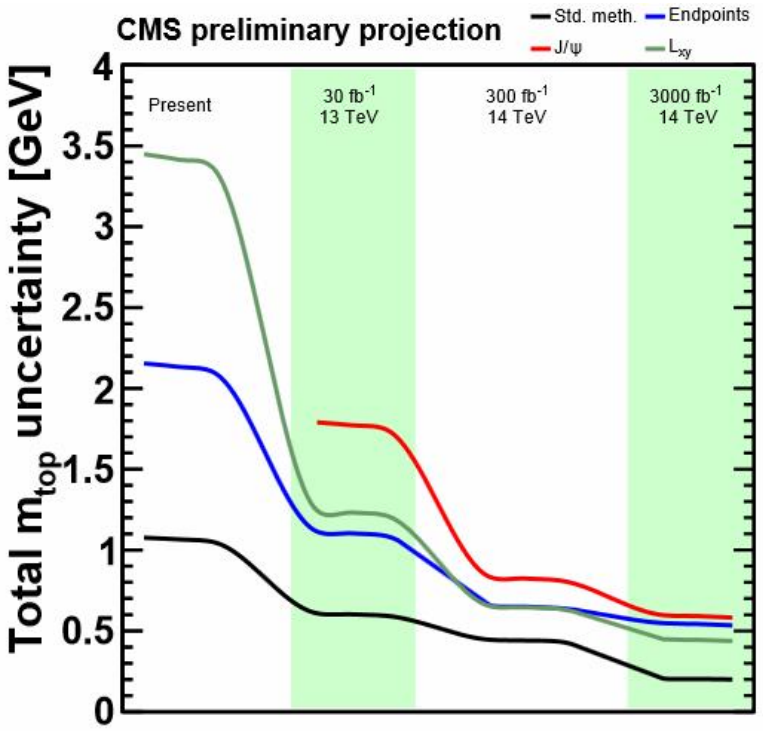
m_t=173.29±0.23(stat.)±0.92(syst.) GeV

- Stability of assumed correlations checked by fluctuating correlations →0.1-0.2 GeV.
- ATLAS reports an explicit hadronization uncertainty, while CMS reports this only in context of JES →0-0.15 GeV

Conclusions

- Top mass measurements at the LHC:
  - Standard measurements at 1-1.6 GeV precision
  - Dominance of jet energy scale reduced
  - Alternate methods have compatible results and uncorrelated uncertainties
- Looking forward:
  - New results using 8 TeV dataset
  - Improved systematic treatment, i.e. remove double-counting, use data-driven constraints.
  - LHC's increased energy and high luminosity→more advanced techniques possible

➢ Higher precisions to come!

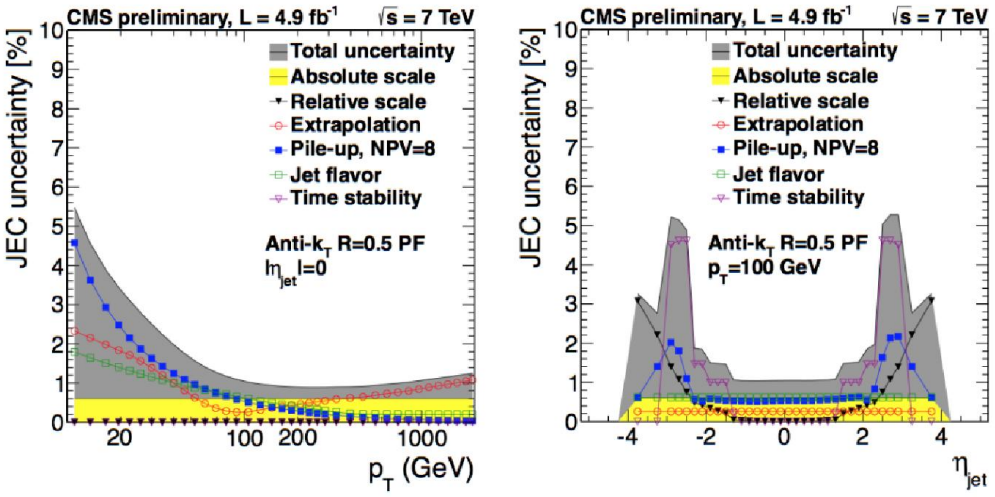


CMS-PAS-FTR-13-017

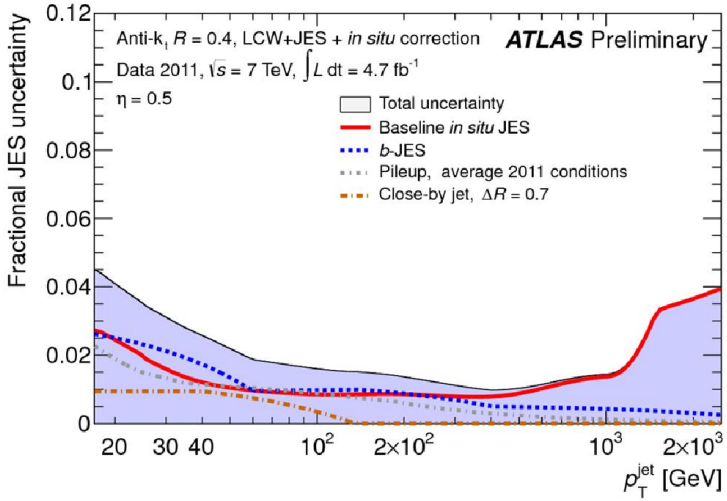
Thank you!

Uncertainties: Jet Energy Scale

- Jet energies are corrected to account for energy loss, differing response to electromagnetically and hadronically interacting particles, and irregularities in the calorimeters. Corrections are calibrated using gamma/Z+jet and dijet events.
- Uncertainties on jet energy corrections are typically 5% or less, but dominate systematic uncertainties of measurements→1.0-1.25 GeV.
- One solution: constrain JES in-situ with W boson mass or perform a simultaneous measurement—still have residual JES uncertainties due to any assumptions made on JES.



CMS-DP-2012-006

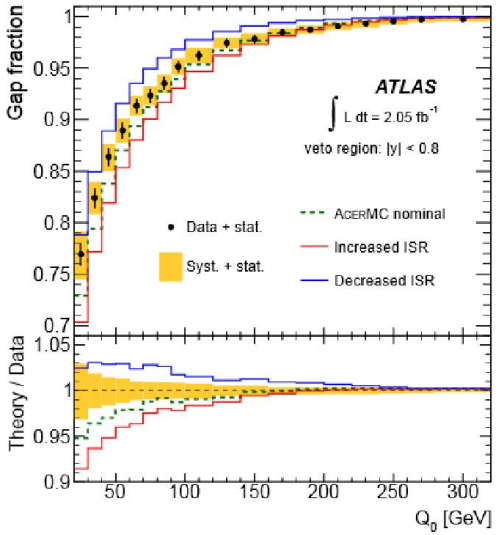


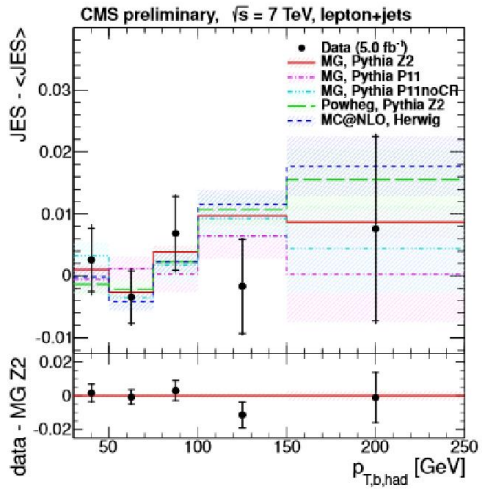
ATLAS-CONF-2013-004

Uncertainties: Theory and Modelling

CERN-HE-EP-2012-062

- **Choice of MC generator/hadronization model**
  - ATLAS: Default is Powheg+Pythia
    - Powheg vs. MC@NLO→0.35-0.64 GeV
  - CMS: Default is MadGraph+Pythia
    - MadGraph vs. Powheg→0.61-0.78 GeV
- **QCD radiation in $t\bar{t}$ events**
  - ATLAS: varied ISR/FSR within Pythia →0.37-0.45 GeV
  - CMS: varied factorization and renormalization scales, p_T threshold for MLM matching→0.3-0.58 GeV
- **Color reconnection effects**→0.13-0.54 GeV
  - ATLAS and CMS: compare Perugia2011 and Perugia2011noCR
- **Parton Distribution Functions** →0.06-0.17 GeV
  - ATLAS: CT10 with Perugia2011C
  - CMS: CTEQ6.6L with Z2





CMS-PAS-TOP-2012-029

Systematic Categories

- JES: uncertainty from limited understanding of detector response to and modeling of jets.
- iJES: JES uncertainty of analyses that measure JES in-situ.
- stdJES: standard, non-flavor dependent part of JES uncertainty
- flavorJES: uncertainty originating from differences in jet energy response between jet flavors.
- bJES: uncertainty arising from uncertainty in modelling response of b-jets (separate from flavorJES)
- Theory and Modelling: uncertainties related to MC modelling of $t\bar{t}$ signal.
- MC: uncertainty from choice of MC generator, hadronization model, and underlying event model.
- Rad: uncertainties in modelling of QCD radiation
- CR: uncertainties related to modelling of color reconnection effects.
- PDF: uncertainties stemming from the proton PDF.

Systematic Categories

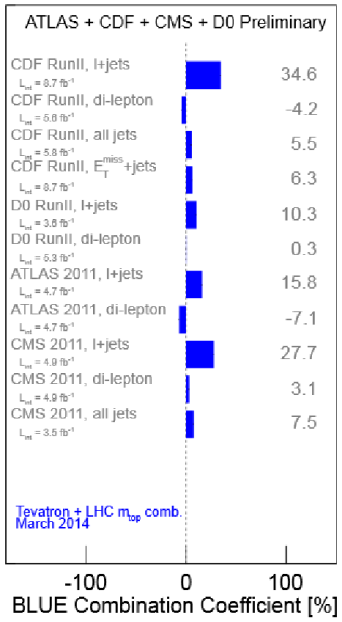
- Detector modelling, background contamination, environment: includes uncertainties from detector resolution effects, object reconstruction, b-tagging performance, normalization and shapes of backgrounds, and the modelling of data-taking conditions.
  - DetMod: uncertainties from lack of knowledge in modelling detector effects.
  - b-tag: uncertainty from modelling of b-tagging efficiency and light-quark rejection.
  - LepPt: uncertainties in efficiency of trigger, reconstruction of leptons, and possible miscalibration of lepton energy.
  - BGMC: uncertainty in modelling of background processes in MC.
  - BGData: uncertainties in modelling of background processes taken from data.
  - Meth: uncertainties related to mt extraction technique.
  - MHI: uncertainties related to modelling of pile-up conditions in simulation

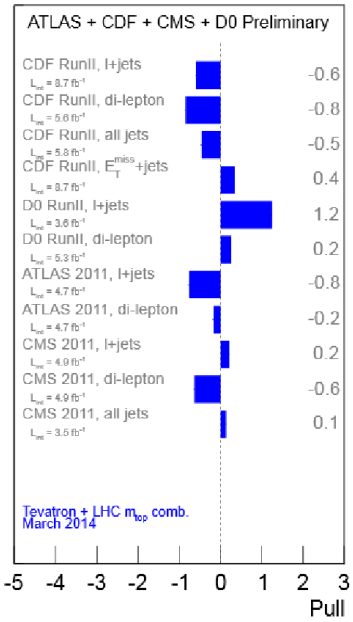
World Combination

CMS-PAS-TOP-13-014/ATLAS-CONF-2014-008

	Input measurements and uncertainties in GeV											
	CDF				D0		ATLAS		CMS			World
Uncertainty	*l*+jets	di-*l*	all jet	E_T^{miss}	*l*+jets	di-*l*	*l*+jets	di-*l*	*l*+jets	di-*l*	all jet	Combination
m_{top}	172.85	170.28	172.47	173.93	174.94	174.00	172.31	173.09	173.49	172.50	173.49	173.34
Stat	0.52	1.95	1.43	1.26	0.83	2.36	0.23	0.64	0.27	0.43	0.69	0.27
iJES	0.49	n.a.	0.95	1.05	0.47	0.55	0.72	n.a.	0.33	n.a.	n.a.	0.24
stdJES	0.53	2.99	0.45	0.44	0.63	0.56	0.70	0.89	0.24	0.78	0.78	0.20
flavourJES	0.09	0.14	0.03	0.10	0.26	0.40	0.36	0.02	0.11	0.58	0.58	0.12
bJES	0.16	0.33	0.15	0.17	0.07	0.20	0.08	0.71	0.61	0.76	0.49	0.25
MC	0.56	0.36	0.49	0.48	0.63	0.50	0.35	0.64	0.15	0.06	0.28	0.38
Rad	0.06	0.22	0.10	0.28	0.26	0.30	0.45	0.37	0.30	0.58	0.33	0.21
CR	0.21	0.51	0.32	0.28	0.28	0.55	0.32	0.29	0.54	0.13	0.15	0.31
PDF	0.08	0.31	0.19	0.16	0.21	0.30	0.17	0.12	0.07	0.09	0.06	0.09
DetMod	< 0.01	<0.01	<0.01	<0.01	0.36	0.50	0.23	0.22	0.24	0.18	0.28	0.10
b-tag	0.03	n.e.	0.10	n.e.	0.10	<0.01	0.81	0.46	0.12	0.09	0.06	0.11
LepPt	0.03	0.27	n.a.	n.a.	0.18	0.35	0.04	0.12	0.02	0.14	n.a.	0.02
BGMC	0.12	0.24	n.a.	n.a.	0.18	n.a.	n.a.	0.14	0.13	0.05	n.a.	0.10
BGData	0.16	0.14	0.56	0.15	0.21	0.20	0.10	n.a.	n.a.	n.a.	0.13	0.07
Meth	0.05	0.12	0.38	0.21	0.16	0.51	0.13	0.07	0.06	0.40	0.13	0.05
MHI	0.07	0.23	0.08	0.18	0.05	<0.01	0.03	0.01	0.07	0.11	0.06	0.04
Total Syst	0.99	3.13	1.41	1.36	1.25	1.49	1.53	1.50	1.03	1.46	1.23	
Total	1.12	3.69	2.01	1.85	1.50	2.79	1.55	1.63	1.06	1.52	1.41	

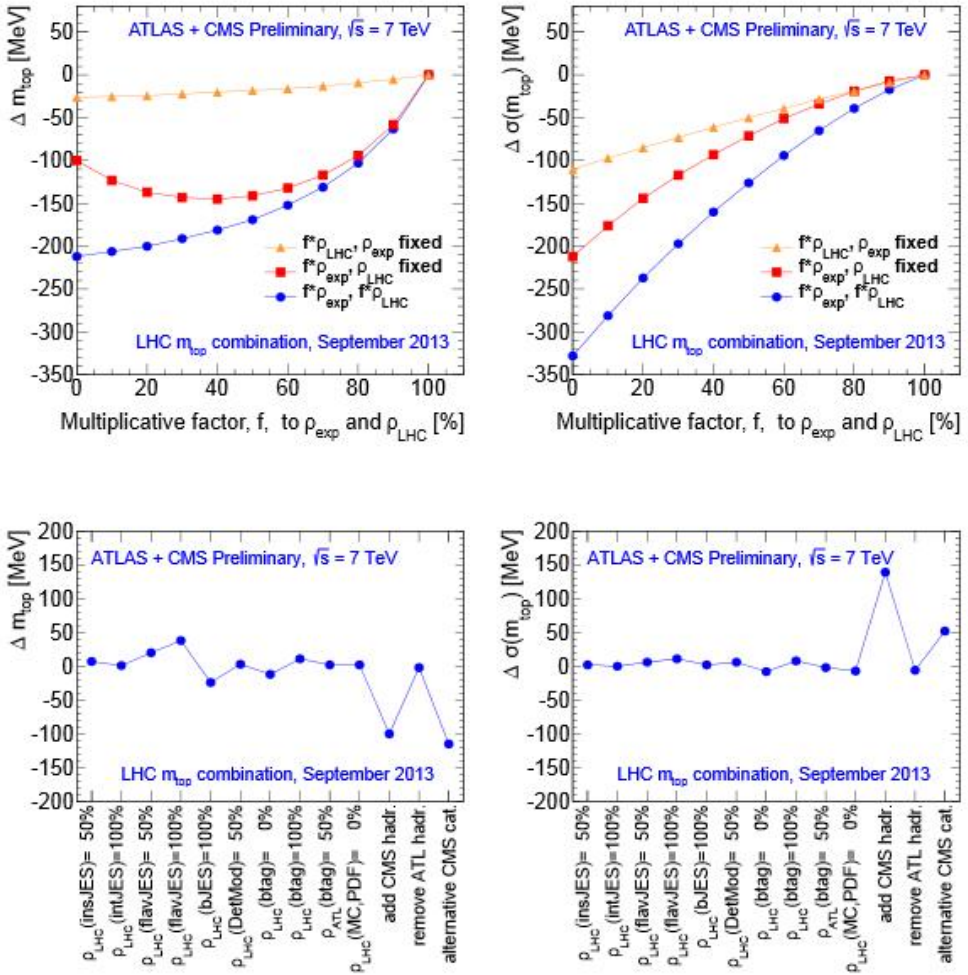
	ρ_{EXP}				ρ_{LHC}	ρ_{TEV}	ρ_{COL}	
	ρ_{CDF}	ρ_{D0}	ρ_{ATL}	ρ_{CMS}			$\rho_{\text{ATL-TEV}}$	$\rho_{\text{CMS-TEV}}$
Stat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
iJES	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
stdJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
flavourJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
bJES	1.0	1.0	1.0	1.0	0.5	1.0	1.0	0.5
MC	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Rad	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
CR	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PDF	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
DetMod	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
b-tag	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
LepPt	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
BGMC†	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
BGData	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Meth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MHI	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0





LHC Combination--Stability

- Upper plots show the change in measured mass and total uncertainty due to varying the correlations assumed between experiments.
- Lower plots show the changes for variations in correlation amongst some uncertainty sources.



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

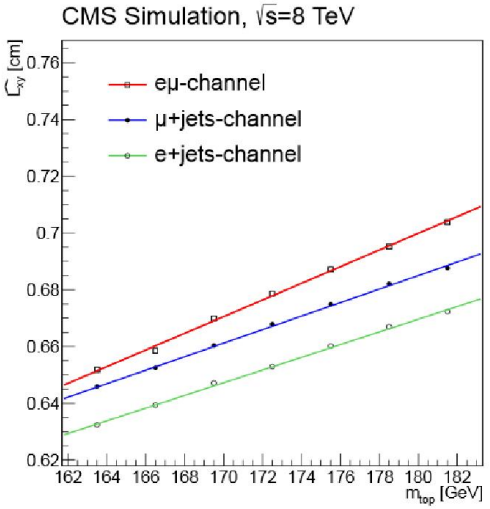
Non-Standard Analyses

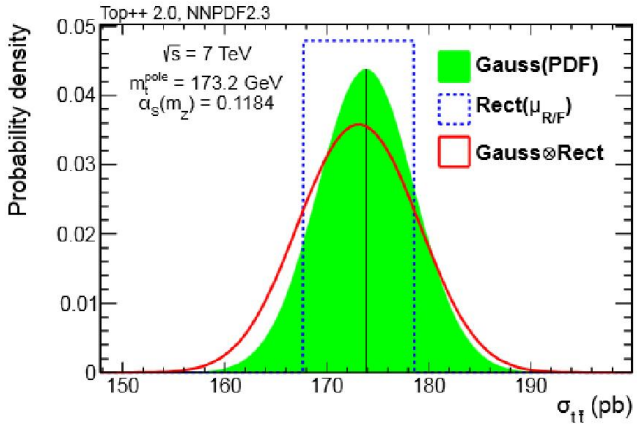
Alternative methods seek to:

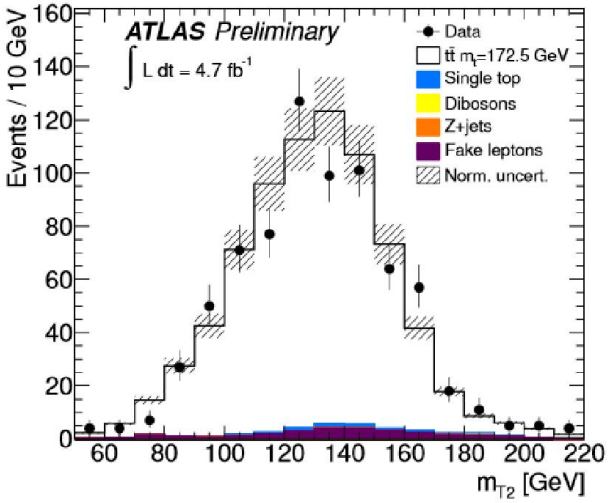
- avoid a limiting systematic uncertainty
- measure a different definition of top quark mass

Examples:

- B-hadron lifetime: CMS-PAS-TOP-12-030
- Top quark pole mass: CERN-PH-EP-2013-121
- mT2 variable: ATLAS-CONF-2012-082
- Kinematic Endpoints: CERN-PH-EP-2013-059







ATLAS—Template—Lepton+Jets

Process	Number of events after requiring		
	= 1 b-tagged jet	≥ 2 b-tagged jets	≥ 1 b-tagged jet
$t\bar{t}$ signal	10700 ± 1100	6980 ± 780	17700 ± 1800
single top (signal)	816 ± 47	253 ± 48	1070 ± 84
W+jets (data)	1640 ± 500	124 ± 40	1770 ± 540
Z+jets	211 ± 65	17.5 ± 5.7	229 ± 70
$ZZ/WZ/WW$	34.6 ± 2.2	3.25 ± 0.38	37.9 ± 2.3
QCD multijet (data)	780 ± 390	71 ± 37	851 ± 430
Signal+background	14200 ± 1200	7450 ± 780	21600 ± 1900
Data	14358	8520	22878

- Requires: 1 high p_T lepton, MET, ≥ 4 jets, ≥ 1 b-tag
- Normalization of w+jets background and QCD multijet background are taken from data; other backgrounds are taken from MC.
- Closure tests and calibration are performed through pseudoexperiments.

ATLAS-CONF-2013-046

	2d-analysis		3d-analysis		
	m_{top} [GeV]	JSF	m_{top} [GeV]	JSF	bJSF
Measured value	172.80	1.014	172.31	1.014	1.006
Data statistics	0.23	0.003	0.23	0.003	0.008
Jet energy scale factor (stat. comp.)	0.27	n/a	0.27	n/a	n/a
bJet energy scale factor (stat. comp.)	n/a	n/a	0.67	n/a	n/a
Method calibration	0.13	0.002	0.13	0.002	0.003
Signal MC generator	0.36	0.005	0.19	0.005	0.002
Hadronisation	1.30	0.008	0.27	0.008	0.013
Underlying event	0.02	0.001	0.12	0.001	0.002
Colour reconnection	0.03	0.001	0.32	0.001	0.004
ISR and FSR (signal only)	0.96	0.017	0.45	0.017	0.006
Proton PDF	0.09	0.000	0.17	0.000	0.001
single top normalisation	0.00	0.000	0.00	0.000	0.000
W+jets background	0.02	0.000	0.03	0.000	0.000
QCD multijet background	0.04	0.000	0.10	0.000	0.001
Jet energy scale	0.60	0.005	0.79	0.004	0.007
b-jet energy scale	0.92	0.000	0.08	0.000	0.002
Jet energy resolution	0.22	0.006	0.22	0.006	0.000
Jet reconstruction efficiency	0.03	0.000	0.05	0.000	0.000
b-tagging efficiency and mistag rate	0.17	0.001	0.81	0.001	0.011
Lepton energy scale	0.03	0.000	0.04	0.000	0.000
Missing transverse momentum	0.01	0.000	0.03	0.000	0.000
Pile-up	0.03	0.000	0.03	0.000	0.001
Total systematic uncertainty	2.02	0.021	1.35	0.021	0.020
Total uncertainty	2.05	0.021	1.55	0.021	0.022

ATLAS—Template—L+Jets—Δm

- Requires: 1 high p_T lepton, ≥ 4 jets, ≥ 2 b-tags, MET and m_T(lep,MET)
- Multijet background is estimated in data; others are taken from MC.
- Calibration is done by pseudoexperiments.

Channel	Muon	Electron
Data	8854	4941
SM $t\bar{t} \to W^+bW^-\bar{b}$	7700^{+1600}_{-1700}	4500^{+900}_{-1000}
W/Z + jets	320 ± 90	160 ± 40
Single top	300 ± 50	170 ± 30
Diboson	5 ± 1	3 ± 1
Multi-jet	220 ± 110	110 ± 60
Total expected (SM)	8550^{+1600}_{-1700}	4900^{+900}_{-1000}

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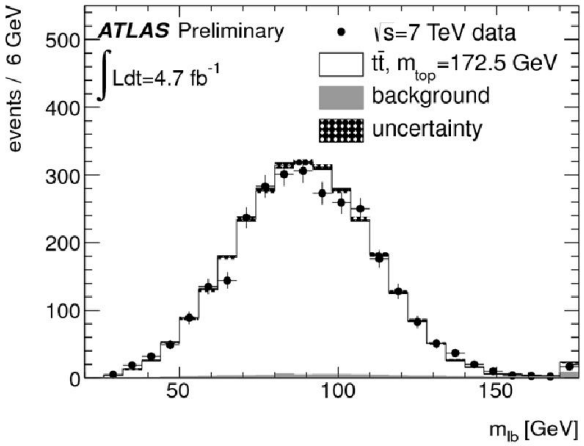
Systematic Uncertainty	$\Delta(\Delta m)$ [GeV]
$b/\bar{b}$ decay uncertainties	0.34
K^+/K^- calorimeter response asymmetry	0.08
Residual b vs $\bar{b}$ differences	0.08
b-tagging	0.08
Mis-tagging as a b-quark jet	0.05
Jet energy scale	0.04
b-jet energy scale	0.05
Jet energy resolution	0.03
Parton shower	0.08
MC generator	0.08
ISR/FSR	0.07
Calibration method	0.05
Non-$t\bar{t}$ normalization	0.04
Non-$t\bar{t}$ shape	0.04
Parton distribution function	0.02
Lepton energy scale asymmetry	< 0.01
Electron reconstruction & identification	0.02
Muon reconstruction & identification	0.04
Top mass input	0.04
Total	0.41

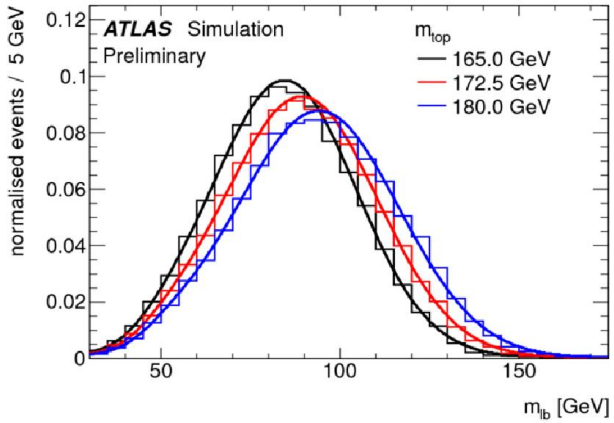
ATLAS—Template—Dilepton

- Requires: 2 OC high p_T leptons, ≥ 2 jets with exactly b-tags, MET/HT and mll
- m_{lb} is based on invariant mass of lepton+b-jet system—assignment that produces smallest average m_{lb} is selected (correct in 77% of cases).
- Calibrated via pseudoexperiments on MC.

	All channels		
$t\bar{t}$ signal	2400	±	400
Fake leptons	-4	±	7
Single top quark	73	±	15
Drell-Yan	3.1	±	1.3
Diboson	0.75	±	0.29
Total expected	2500	±	400
Total observed	2913		



ATLAS-CONF-2013-077



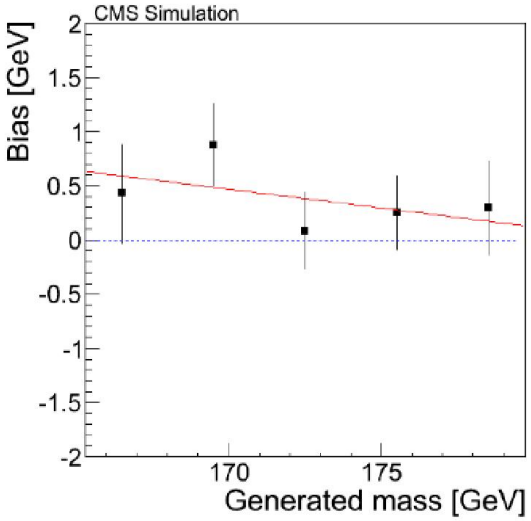
Description	Value [GeV]
Measured value	173.09
Statistical uncertainty	0.64
Method calibration	0.07
Signal MC generator	0.20
Hadronisation	0.44
Underlying event	0.42
Colour reconnection	0.29
ISR/FSR	0.37
Proton PDF	0.12
Background	0.14
Jet energy scale	0.89
b-jet energy scale	0.71
b-tagging efficiency and mistag rate	0.46
Jet energy resolution	0.21
Missing transverse momentum	0.05
Pile-up	0.01
Electron uncertainties	0.11
Muon uncertainties	0.05
Total systematic uncertainty	1.50
Total uncertainty	1.63

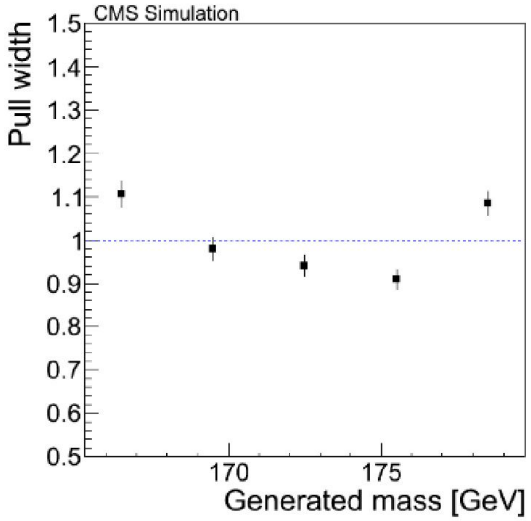
CMS—AMWT—Dilepton

Eur. Phys. J. C72 (2012) 2202

Processes	ee	eμ	μμ
1 b-tagged jet			
$t\bar{t}$ signal	598 ± 18	2359 ± 71	770 ± 23
$t\bar{t}$ background	10.6 ± 0.3	101.8 ± 3.1	15.7 ± 0.5
Single top	40.7 ± 1.2	172.2 ± 5.2	53.3 ± 1.6
Drell–Yan	107 ± 24	241 ± 27	143 ± 31
Dibosons	11.4 ± 0.3	39.7 ± 1.2	13.0 ± 0.4
Total prediction	767 ± 30	2914 ± 76	995 ± 39
Data	817	2788	1032
≥ 2 b-tagged jets			
$t\bar{t}$ signal	1057 ± 32	4312 ± 129	1393 ± 42
$t\bar{t}$ background	4.6 ± 0.3	37.6 ± 1.1	5.5 ± 0.5
Single top	36.8 ± 1.1	140.6 ± 4.2	48.2 ± 1.4
Drell–Yan	38 ± 11	38.9 ± 4.3	32 ± 12
Dibosons	2.9 ± 0.1	9.1 ± 0.3	2.5 ± 0.1
Total prediction	1139 ± 34	4539 ± 130	1481 ± 43
Data	1151	4365	1474

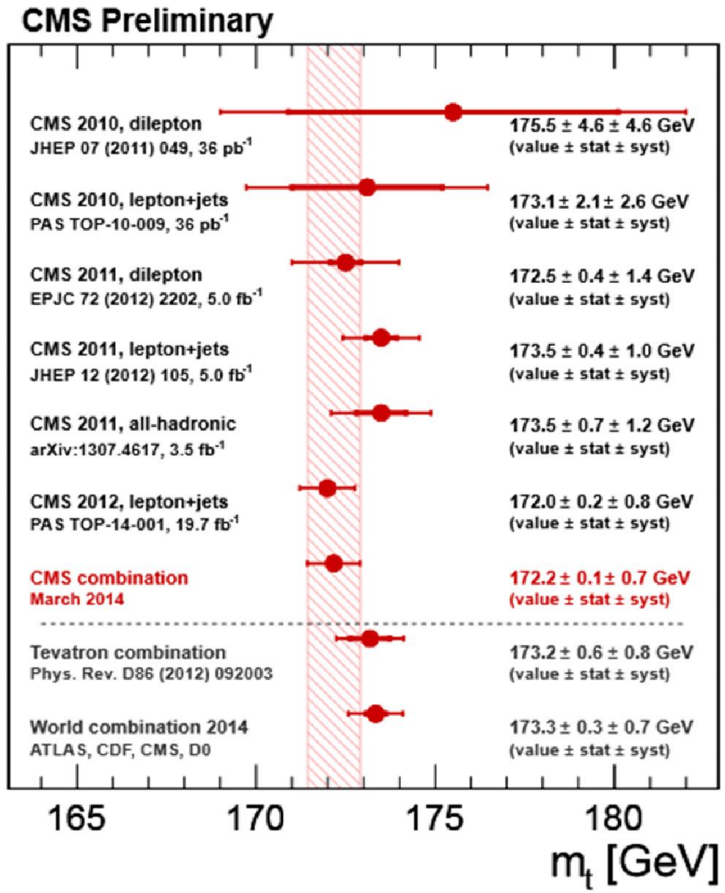
- Requires: 2 OC high p_T, isolated leptons; ≥ 1 b-jet, MET—final sample 89% $t\bar{t}$
- DY background is estimated from $R_{out/in}$ method (ee/μμ) and a fit to dilepton invariant mass distribution (eμ)
- Solve kinematic equations of system for neutrino momenta given $t\bar{t}$ mass hypothesis and summing weights of solutions (detector resolution effects are also varied)—9934 events have valid solutions.
- Calculate likelihoods by comparing template distributions of m_{AMWT} to data, than maximize.

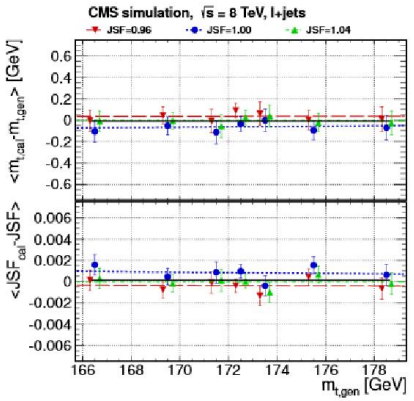
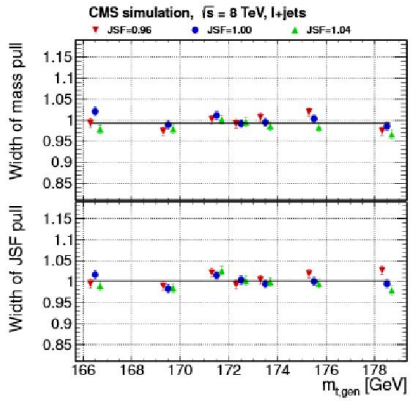




Source	Δm_t (GeV)
Jet energy scale	$^{+0.90}_{-0.97}$
b-jet energy scale	$^{+0.76}_{-0.66}$
Jet energy resolution	±0.14
Lepton energy scale	±0.14
Unclustered E_T^{miss}	±0.12
b-tagging efficiency	±0.05
Mistag rate	±0.08
Fit calibration	±0.40
Background normalization	±0.05
Matching scale	±0.19
Renormalisation and factorisation scale	±0.55
Pileup	±0.11
PDFs	±0.09
Underlying event	±0.26
Colour reconnection	±0.13
Monte Carlo generator	±0.04
Total	±1.48

CMS—Ideogram—Lepton+Jets—8 TeV



CMS-PAS-TOP-14-001

	δm_t^{2D} (GeV)	δJSF	δm_t^{1D} (GeV)
Experimental uncertainties			
Fit calibration	0.10	0.001	0.06
p_T- and η-dependent JES	0.18	0.007	1.17
Lepton energy scale	0.03	<0.001	0.03
MET	0.09	0.001	0.01
Jet energy resolution	0.26	0.004	0.07
b tagging	0.02	<0.001	0.01
Pileup	0.27	0.005	0.17
Non-$t\bar{t}$ background	0.11	0.001	0.01
Modeling of hadronization			
Flavor-dependent JSF	0.41	0.004	0.32
b fragmentation	0.06	0.001	0.04
Semi-leptonic B hadron decays	0.16	<0.001	0.15
Modeling of the hard scattering process			
PDF	0.09	0.001	0.05
Renormalization and factorization scales	0.12±0.13	0.004±0.001	0.25±0.08
ME-PS matching threshold	0.15±0.13	0.003±0.001	0.07±0.08
ME generator	0.23±0.14	0.003±0.001	0.20±0.08
Modeling of non-perturbative QCD			
Underlying event	0.14±0.17	0.002±0.002	0.06±0.10
Color reconnection modeling	0.08±0.15	0.002±0.001	0.07±0.09
Total	0.75	0.012	1.29