Top Quark Properties Measurement at the LHC (excluding EFT)

Standard Model at the LHC 2017

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New Phenomena at the TeV Scale With Top Quarks NPTEV-TQP2020

on behalf of the ATLAS and CMS Collaborations

ATLAS EXPERIMENT

CMS Compact Muon Solenoid

Physics of Top Quarks

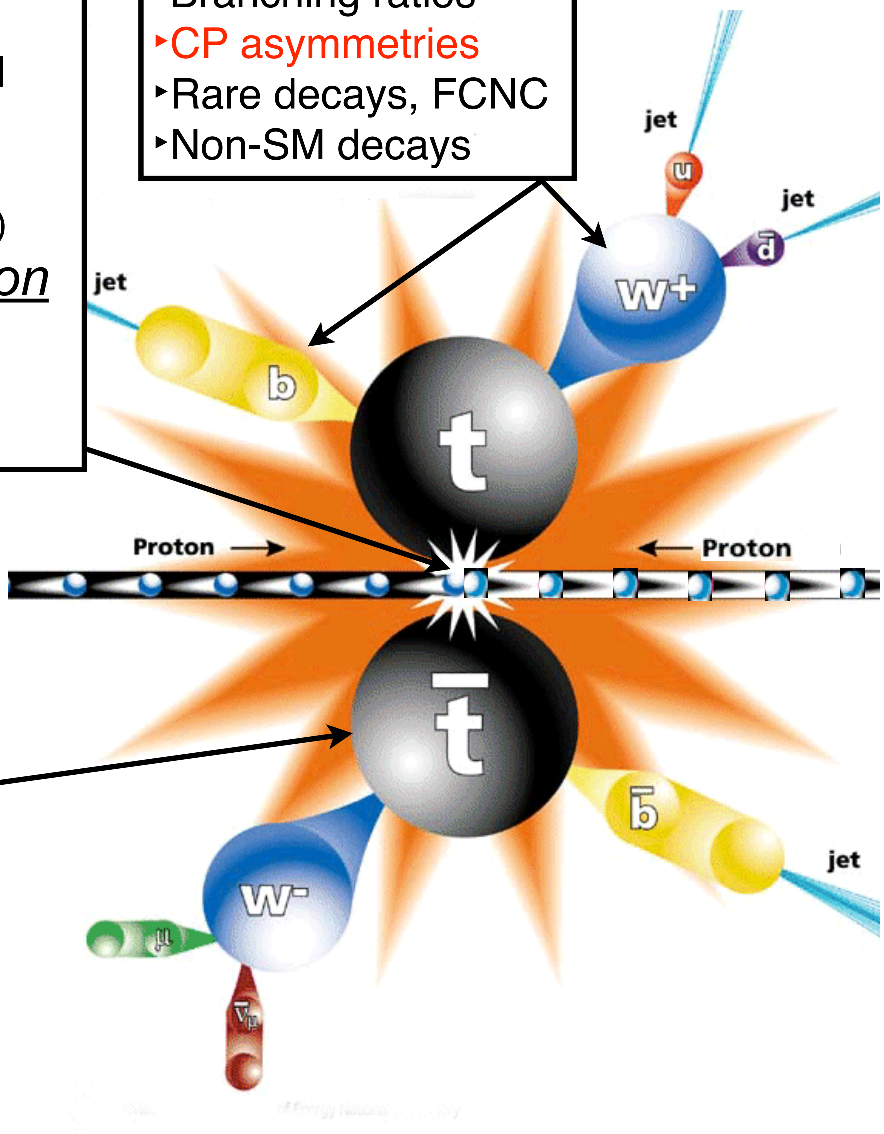
- Test of SM (production, decay, coupling....etc)
- Top quark does not hadronize: momentum and spin transferred to decay products
- Search for processes with similar signature (t', Z'...)
- Mass is a fundamental parameter of the SM, and crucial for SM constraints via loop diagrams

Production Rate
- Pair Production cross section
- Single (EWK) production, $|V_{tb}|$
- FCNC, anomalous couplings
- Differential cross sections
- Production mechanism (gg,qq)

New Physics in production
- Resonant production?
- Heavy Quark production?
- ...

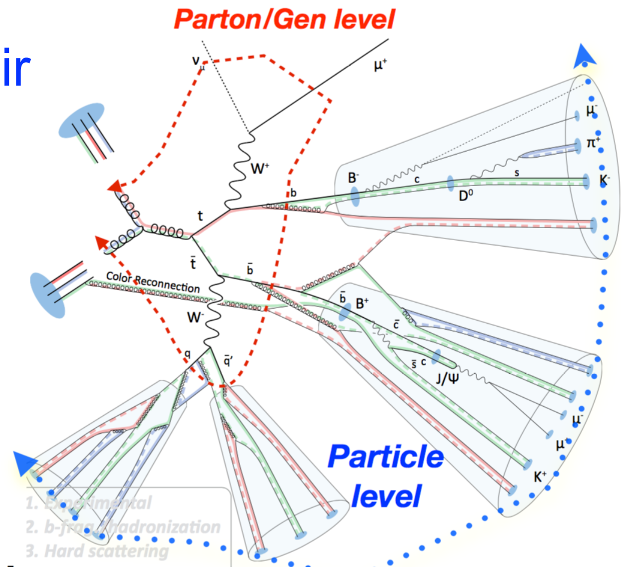
Decay
- Branching ratios
- CP asymmetries
- Rare decays, FCNC
- Non-SM decays

Properties
- Top mass
- Top charge
- Top width
- Spin correlation
- W helicity
- Charge asymmetry



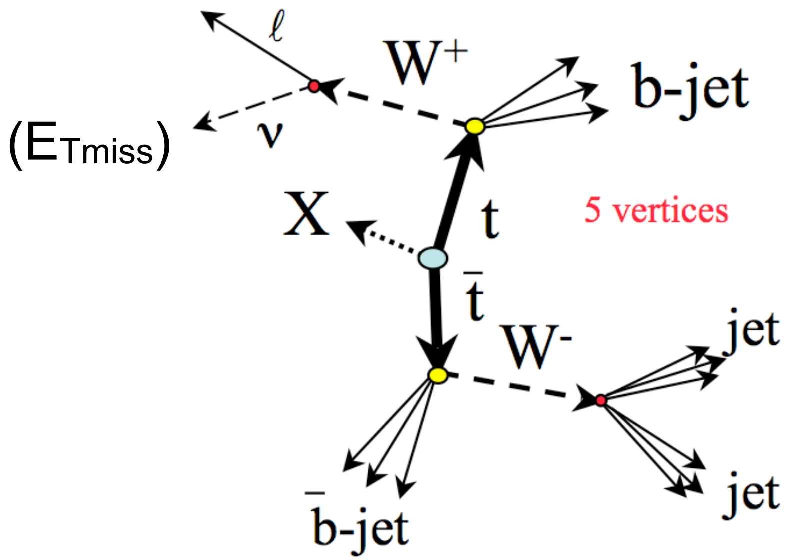
Top Events - Terminology

- Resolved: reconstructs well separated final state of top pair
- Boosted: hadronic top merged into one large-radius jet
- Particle Level: observable objects (stable leptons and jets clustered from stable particles)
- Fiducial phase space: close to detector acceptance
- Full phase space: full extrapolation

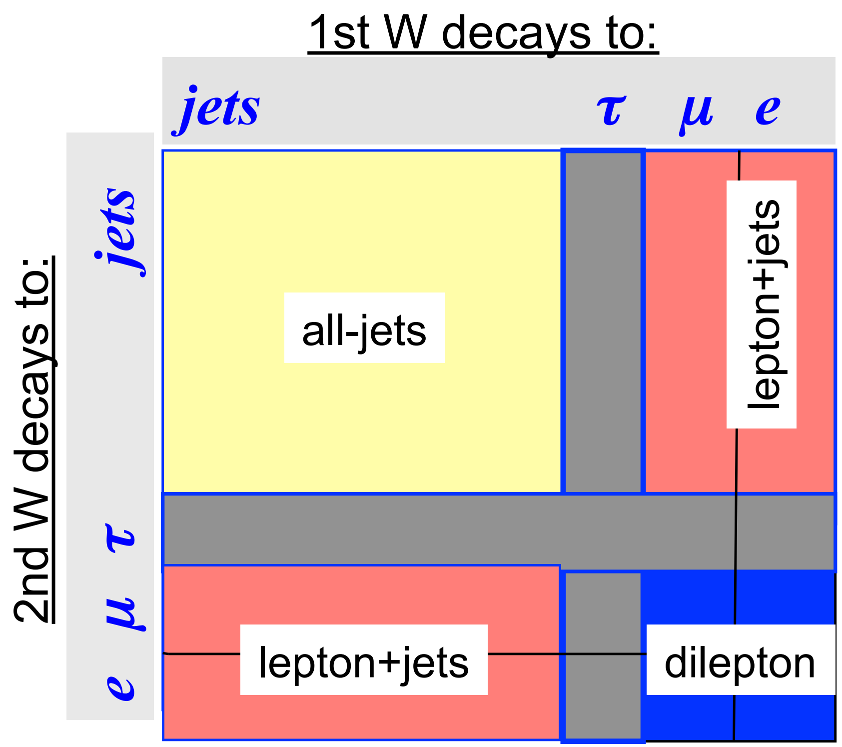


[Figure by B Stieger (CERN)]

$|V_{tb}| \sim 1$, and $M_t > M_W + M_b \Rightarrow t \rightarrow Wb$ (~100%)

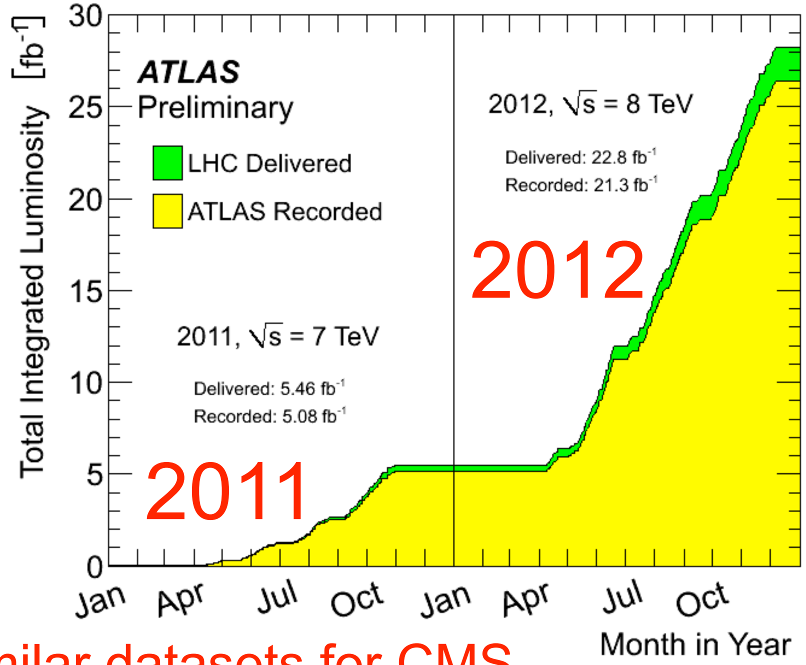


tt event classification:

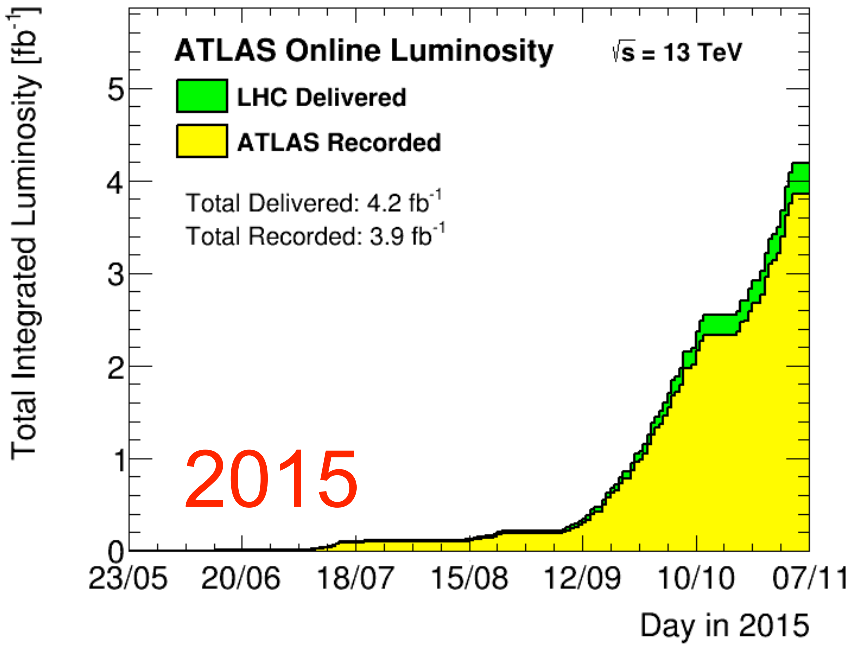


Outline and Datasets in this talk

- Top Quark Mass
  - hadronic channel, 8 TeV (ATLAS)
  - l+jets channel, 13 TeV (CMS)
  - dilepton channel, 8 TeV (CMS)
  - Alternative techniques combination (CMS)
- Charge Asymmetry (ATLAS, CMS)
- CPT, CP
  - Top-antitop mass difference, 8 TeV (CMS)
  - CPV in top production / decay, 8 TeV (CMS)
  - CP asymmetries in B from top, 8 TeV (ATLAS)



Similar datasets for CMS.



Top Quark Mass

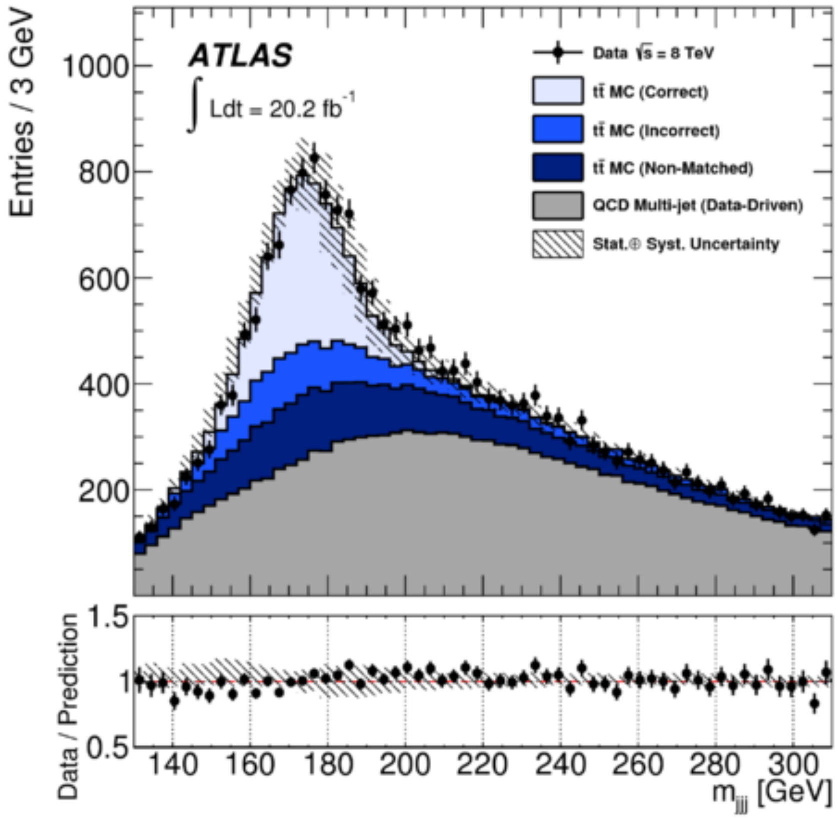
Signature: (all hadronic) ≥6 jets (≥2 *b*) & E_{Tmiss} <60 GeV

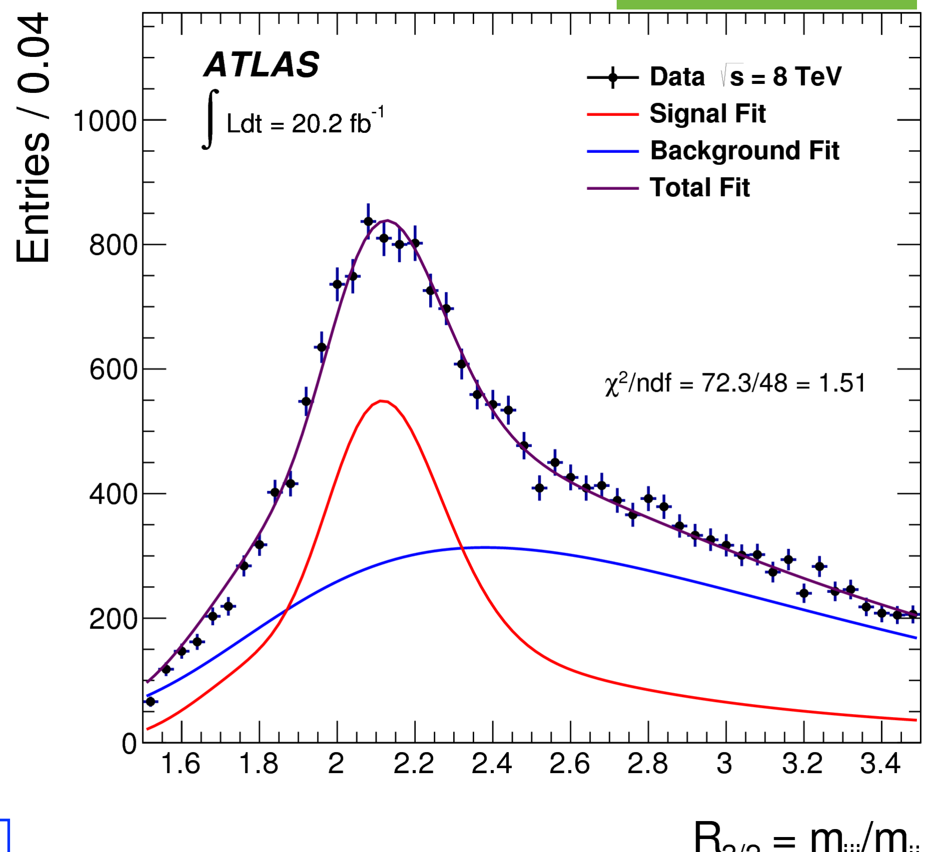
Method: Template fits to Ratio 3-jets (top) /2-jets (W) mass and F_{bkg}

NEW

- Minimised-χ^2 kinematic event reconstruction; POWHEG-PYTHIA tt modelling
- ±1.1 GeV total uncertainty
- Largest systematics from Had. modeling (PYTHIA vs. HERWIG 0.6 GeV), JES/bJES (0.6/0.3 GeV)

8 TeV, 20.2 fb^{-1}





m_{top}= 173.72±0.55 (stat.)±1.01 (syst.) GeV

[arXiv:1702.07546 (Feb 2017)]

Top Quark Mass

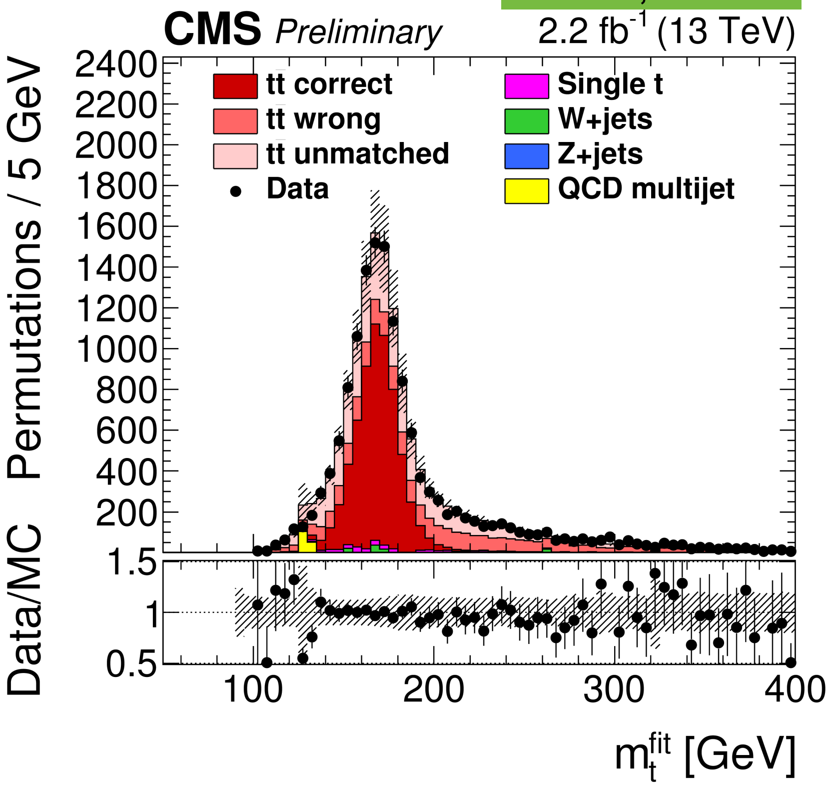
Signature: (l+jets) 1 isolated μ & ≥4 jets (≥2 *b*).

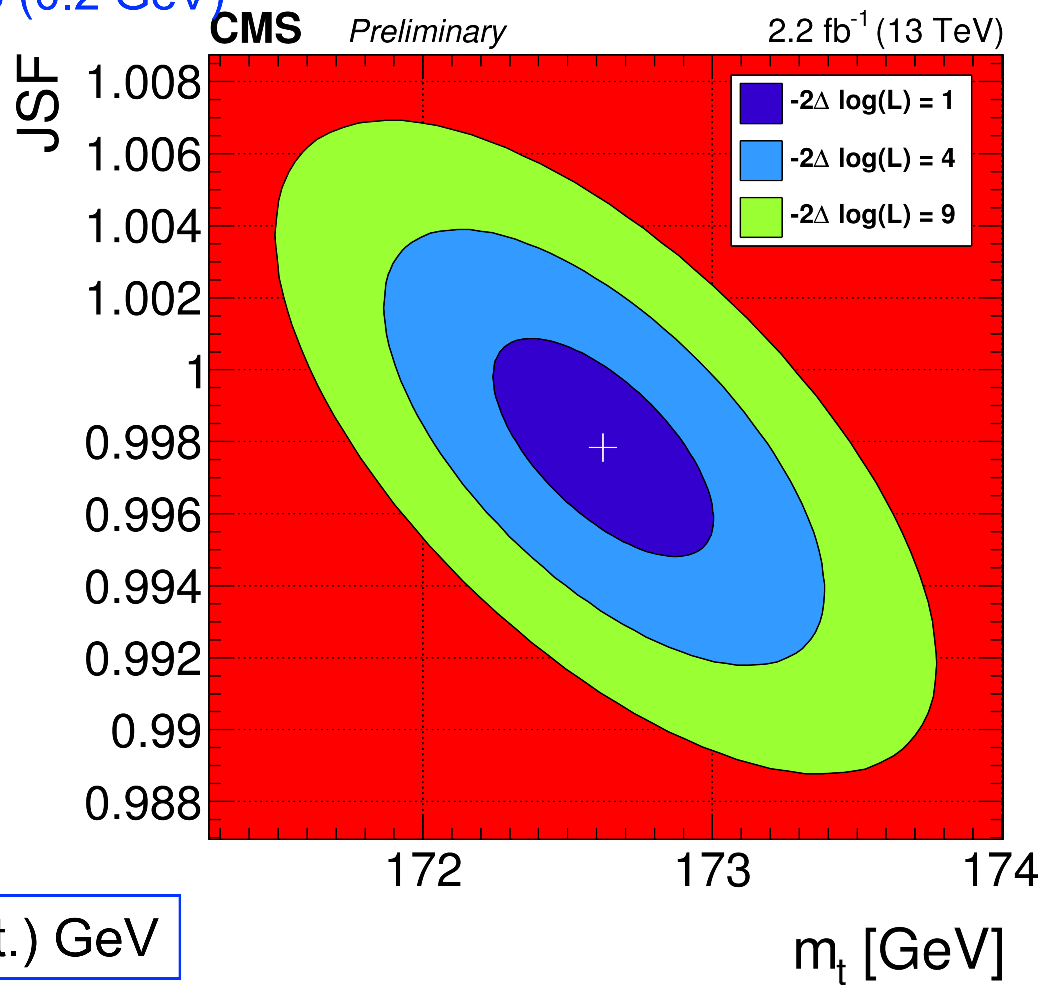
Method: Likelihood fit (ideogram) to m_t^{reco} and JES (2 parameter)

- χ^2 kinematic event reconstruction; POWHEG-PYTHIA tt modelling
- ± 0.8 GeV total uncertainty
- Largest systematics from Hadronisation modeling (PHYTHIA vs. HERWIG 0.4 GeV) and *b*-fragmentation, PS (0.2 GeV)

[CMS-PAS-TOP-16-022 (March 2017)]

13 TeV, 2.2 fb^{-1}





m_{top}= 172.62 ± 0.38 (stat.+JSF) ± 0.70 (syst.) GeV

Top Quark Mass

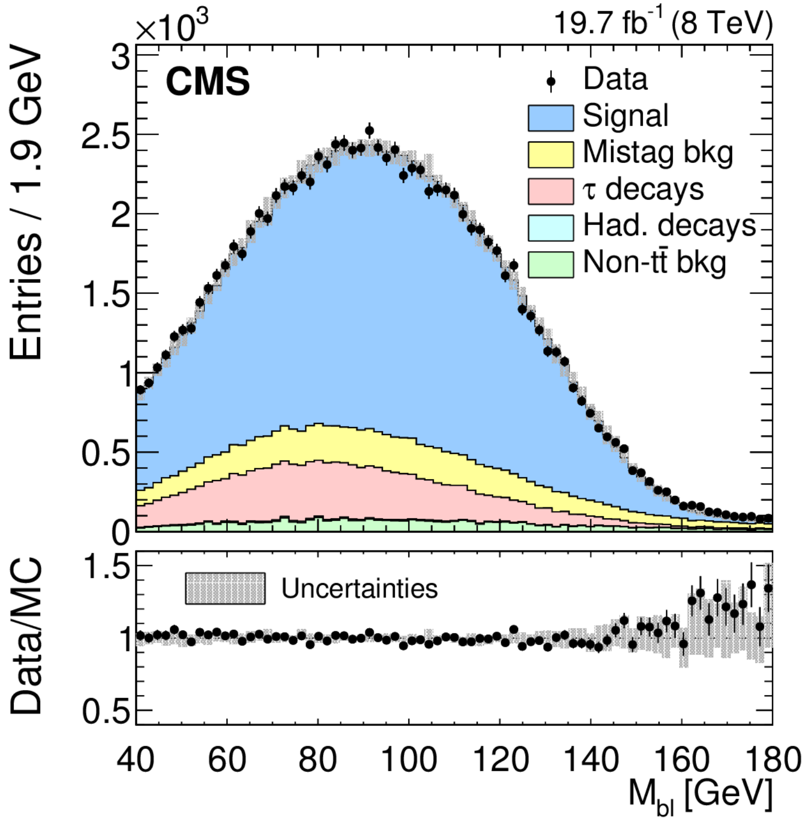
Signature: (dilepton) 2 isolated OS e/μ & E_{Tmiss} >40 GeV & ≥2 *b* jets.

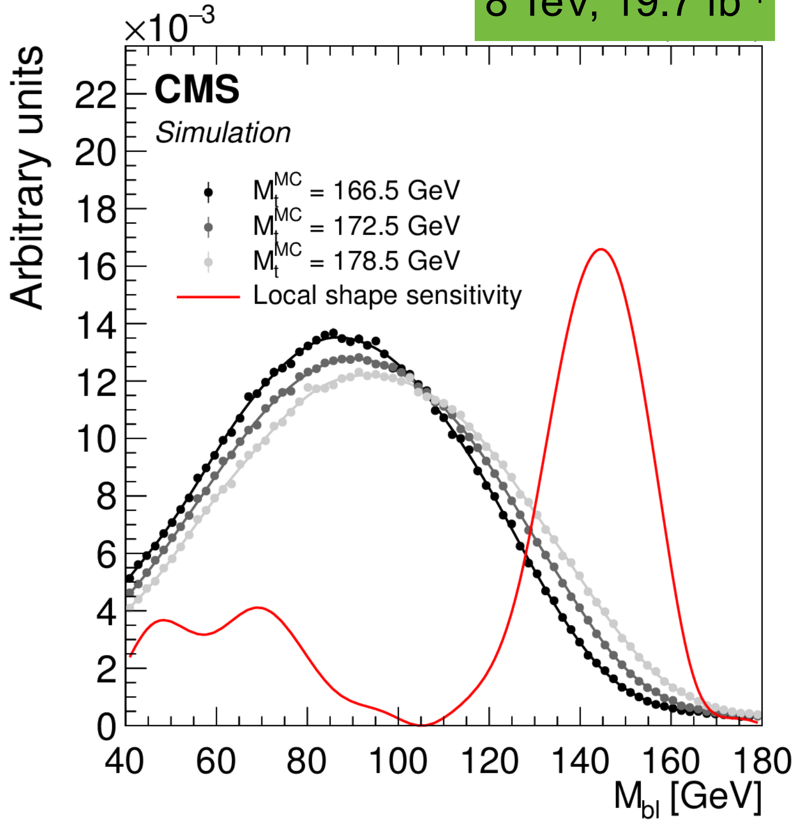
Method: Template fits of $M_{l\text{-}b}$ (mass of lepton and b-jet), M_{T2}^{bb}, $M_{l\text{-}b\nu}$ to m_t, JES

- MADGRAPH-PYTHIA *tt* modelling
- Largest systematics from JES (0.45 GeV) and b quark fragmentation (0.4 GeV)

NEW

8 TeV, 19.7 fb^{-1}

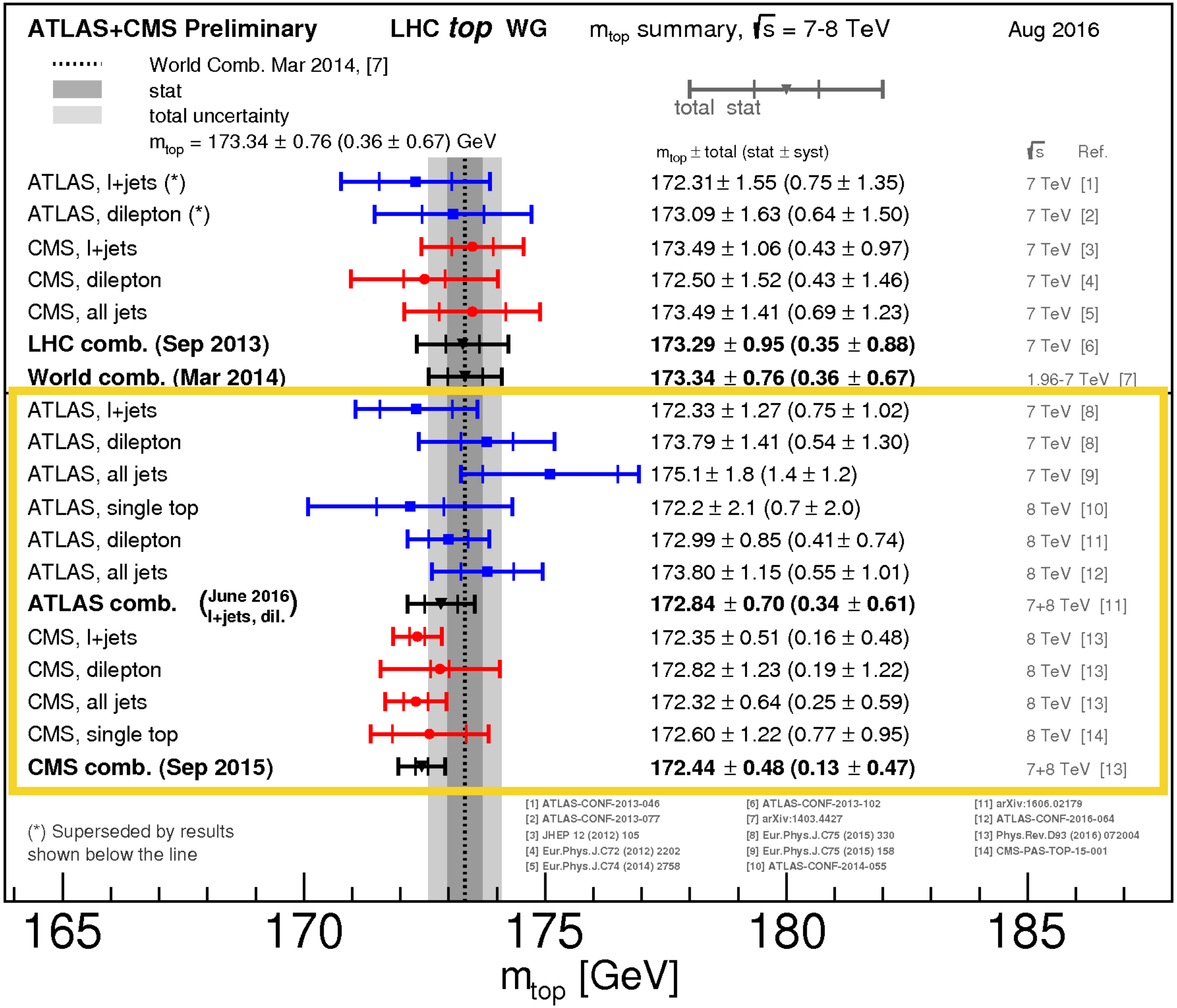




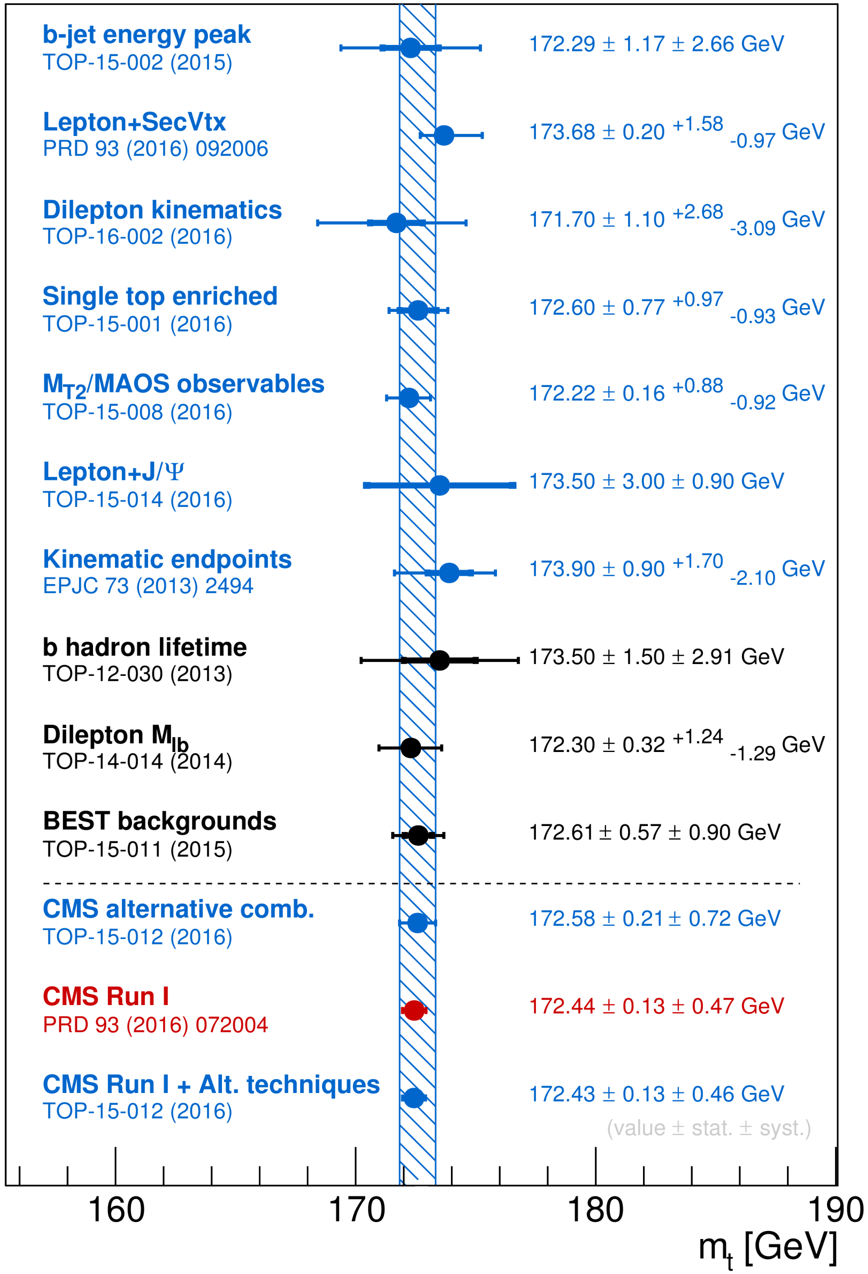
[CMS-TOP-15-008 (April 2017)]

m_{top}= 172.22 ± 0.18 (stat.) + 0.89/-0.93 (syst.) GeV

Top Quark Mass: combination



Top Mass: Alternative techniques



[CMS-PAS-TOP-15-012 (November 2016)]

NEW

- Cross-check and support "standard techniques" of l+j, dil., had. channels
- 0.75 GeV precision
- Further combination does not improve yet on CMS Run I "standard" (0.48 GeV)
- Will improve with 13 TeV data

Combined m_t results	Legacy δm_t (GeV)	Alternative δm_t (GeV)	Combined δm_t (GeV)
Experimental uncertainties			
Method calibration	0.03	0.08	0.04
Jet energy corrections			
– JEC: Intercalibration	0.01	0.06	0.02
– JEC: In situ calibration	0.12	0.16	0.12
– JEC: Uncorrelated non-pileup	0.10	0.26	0.10
Lepton energy scale	0.01	0.13	0.01
E_T^{miss} scale	0.03	0.04	0.04
Jet energy resolution	0.03	0.03	0.03
b tagging	0.05	0.02	0.05
Pileup	0.06	0.07	0.06
Secondary vertex mass	n/a	0.04	<0.01
Backgrounds	0.04	0.08	0.04
Trigger	<0.01	<0.01	<0.01
Modeling of hadronization			
JEC: Flavor	0.33	0.33	0.31
b jet modeling	0.14	0.22	0.14
Modeling of perturbative QCD			
PDF	0.04	0.11	0.04
Ren. and fact. scales	0.10	0.31	0.10
ME-PS matching threshold	0.08	0.22	0.08
ME generator	0.11	0.08	0.11
Single top modeling	n/a	0.04	0.01
Top quark p_T	0.02	0.23	0.02
Modeling of soft QCD			
Underlying event	0.11	0.11	0.11
Color reconnection modeling	0.10	0.10	0.10
Uncertainties (GeV)			
Total systematic	0.47	0.72	0.46
Statistical	0.13	0.21	0.13
Total Uncertainty	0.48	0.75	0.48

Top Mass: Pole and MC mass

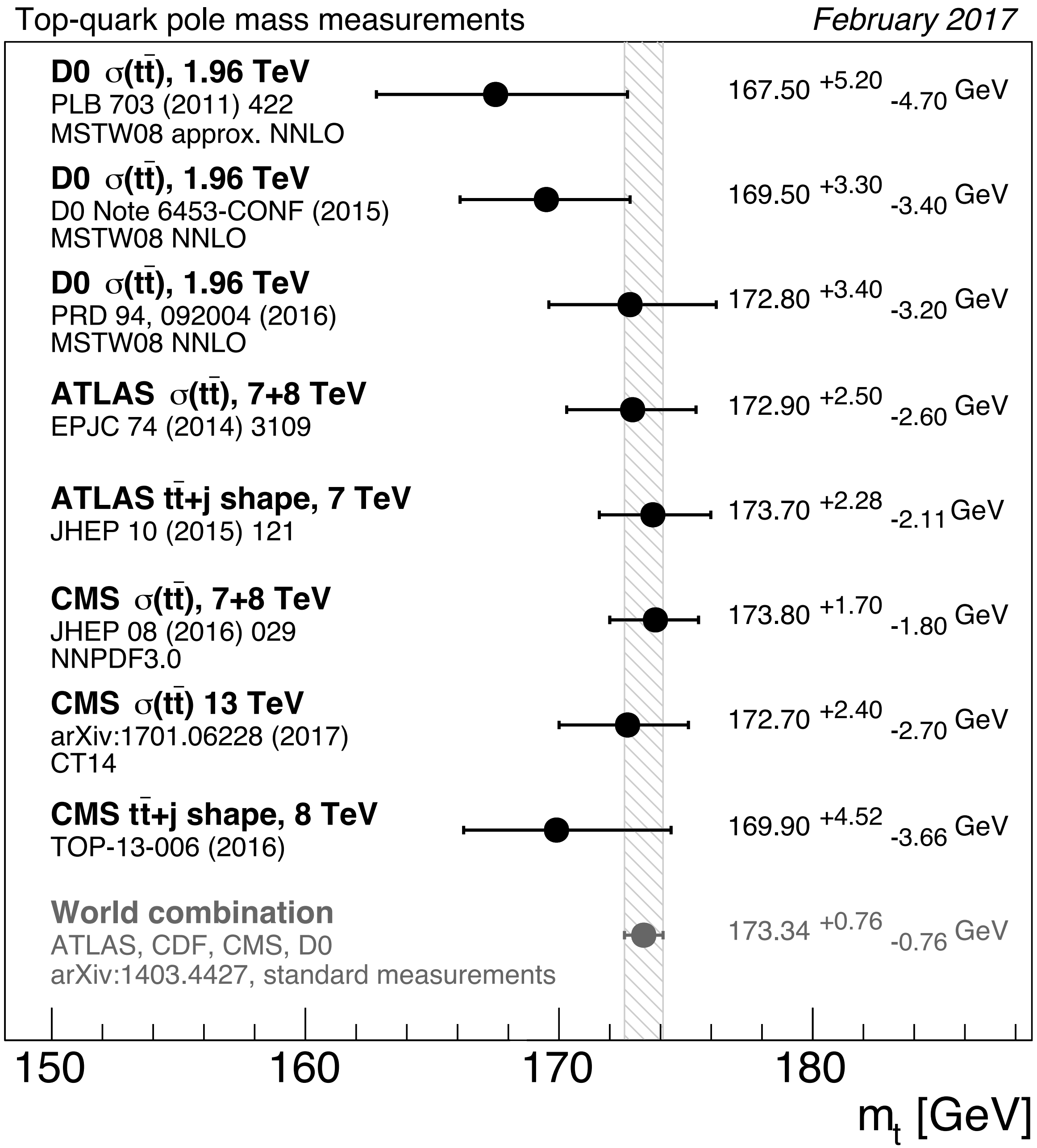
Pole Mass determination:

- Pair production cross section
- Gluon radiation (tt+j)

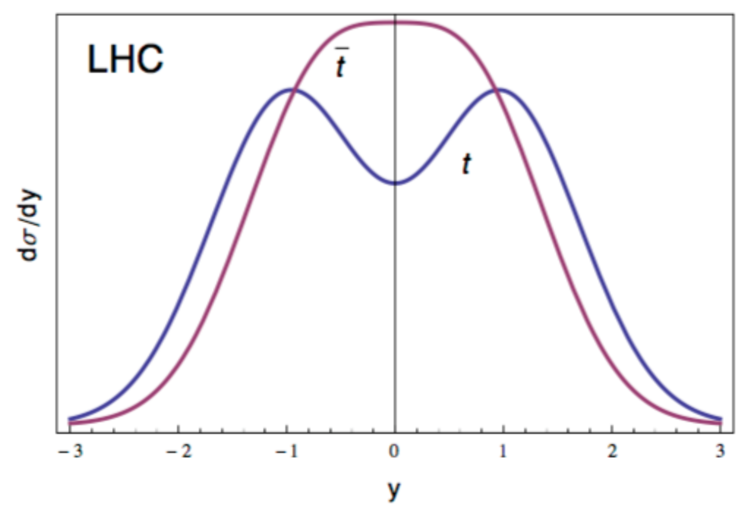
$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s),$$

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}, \qquad m_0 = 170 \text{ GeV}$$

NEW



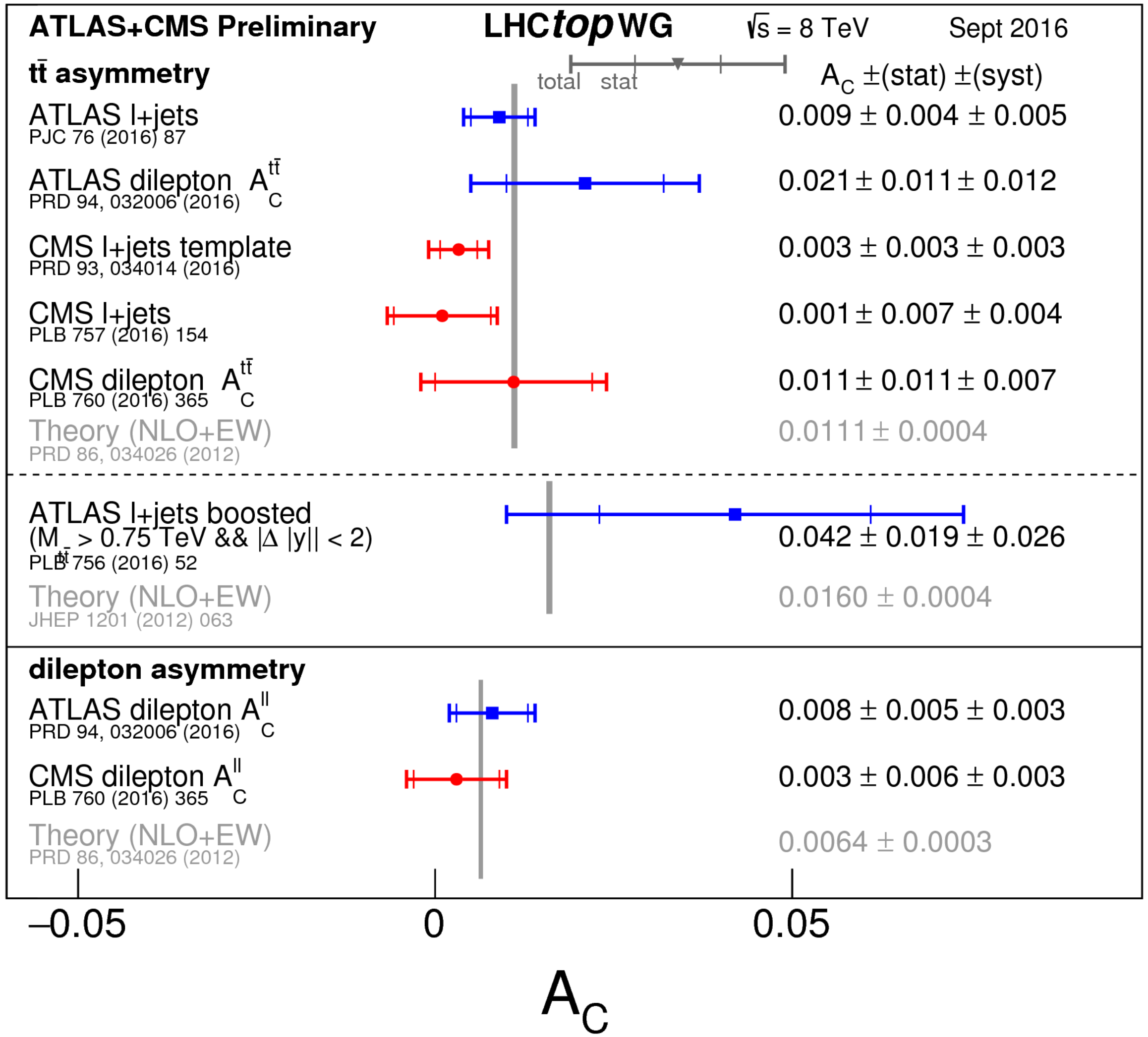
Charge Asymmetry



Arises at higher than tree-level order in the $qq \to tt$ process (NLO)

[Khun, Rodrigo, PRD 59 054017; Rodrigo, arXiv:1207.0331v1 (2012)]

$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)} \quad \Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$



- Analyses use boosted and resolved final states
- Probed at low and high m_{tt} and p_{tt}
- Precision at the level of 0.5%, with sizeable systematic uncertainties

Top mass and CPT

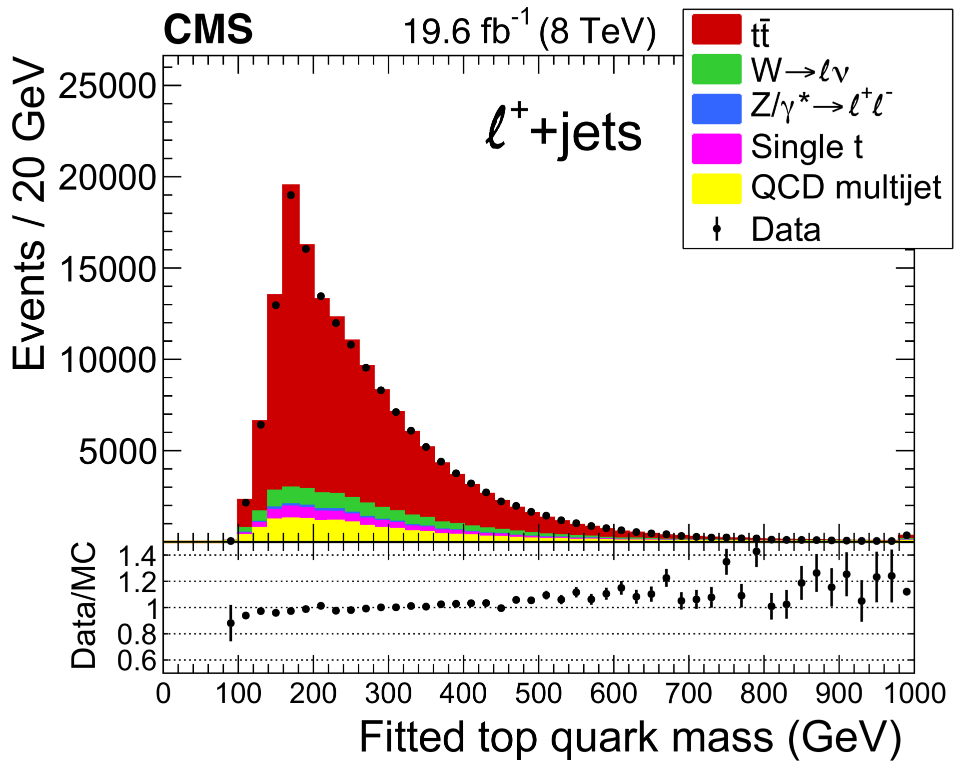
Signature: (l+jets) 1 isolated e/μ & ≥4 jets (≥1 *b*).

Method: Mass difference between top and anti-top, Likelihood fit (ideogram)

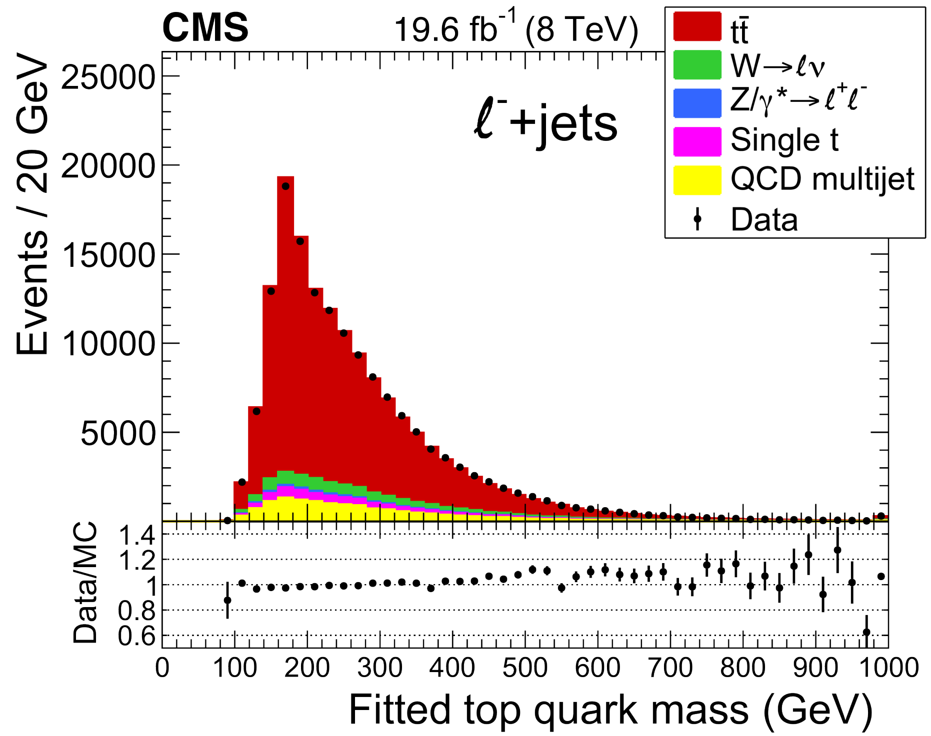
NEW

- χ^2 kinematic event reconstruction
- 0.2 GeV precision
- Statistically dominated, syst. at ±0.09 GeV (mainly *b-bbar* JES and *b* tagging)

8 TeV, 19.6 fb^{-1}



8 TeV, 19.6 fb^{-1}



$\Delta m_t = -0.15 \pm 0.19(\text{stat}) \pm 0.09\ (\text{syst})$ GeV

[CMS-TOP-12-031 (October 2016)]

CP violation in top

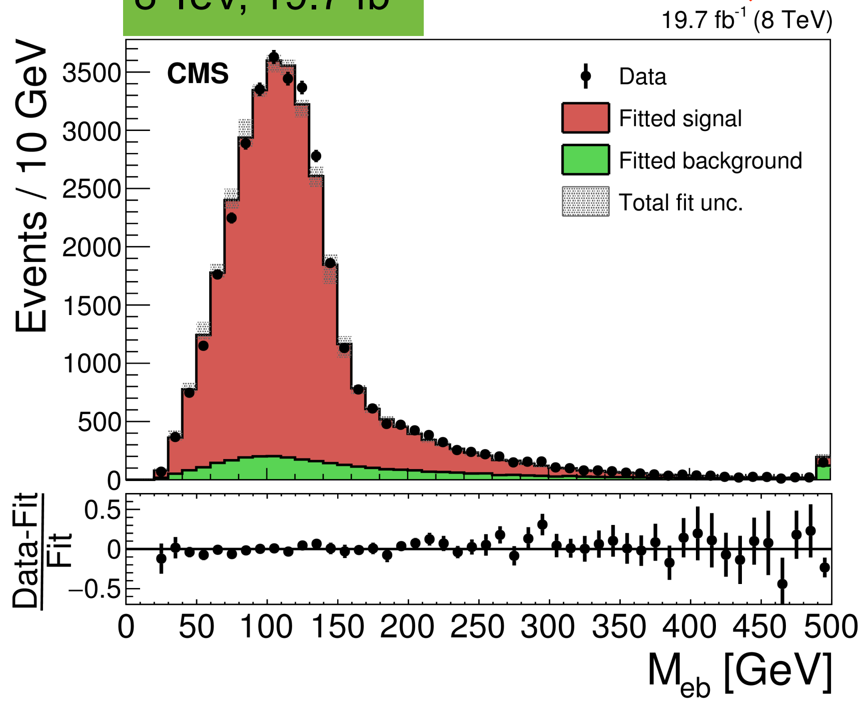
NEW

Signature: (l+jets) 1 isolated e/μ & ≥4 jets (≥2 *b*).

Method: T-odd triple product correlations from momentum vectors

- Minimised-χ^2 kinematic event reconstruction
- Likelihood fit for signal and background

8 TeV, 19.7 fb^{-1}



[JHEP 03 (2017) 101 (November 2016)]

$$A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)} \, .$$

$$O_2 = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$

$$O_3 = Q_\ell \, \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{b\bar{b}\,\text{CM}} \propto Q_\ell \, \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$

$$O_4 = Q_\ell \, \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto Q_\ell \, (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$

$$O_7 = q \cdot (p_b - p_{\bar{b}}) \, \epsilon(P, q, p_b, p_{\bar{b}}) \xrightarrow{\text{lab}} \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z (\vec{p}_b \times \vec{p}_{\bar{b}})_z.$$

	A'_{CP} (%)			A_{CP} (%)
	e + jets	μ + jets	ℓ + jets	ℓ + jets
O_2	$-0.19 \pm 0.61 \pm 0.59$	$+0.46 \pm 0.57 \pm 0.65$	$+0.16 \pm 0.42 \pm 0.44$	$+0.3 \pm 1.1$
O_3	$+0.02 \pm 0.61 \pm 0.59$	$-0.59 \pm 0.57 \pm 0.65$	$-0.31 \pm 0.42 \pm 0.44$	-0.8 ± 1.6
O_4	$-0.17 \pm 0.61 \pm 0.59$	$-0.10 \pm 0.57 \pm 0.65$	$-0.13 \pm 0.42 \pm 0.44$	-0.4 ± 1.7
O_7	$-0.38 \pm 0.61 \pm 0.59$	$+0.43 \pm 0.57 \pm 0.65$	$+0.06 \pm 0.42 \pm 0.44$	$+0.1 \pm 0.8$

un-corrected / corrected - for detector effects

CP asymmetries in *b* from top

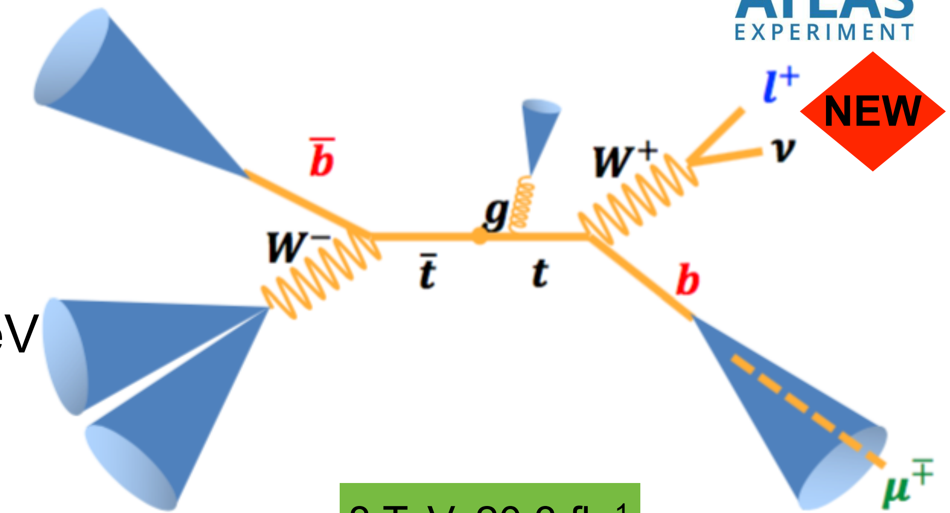
Top pairs: a.k.a. "**a new B factory**" !

Can probe the D0 single/di-muon anomaly

$A_{dir}^{b} \simeq 0.3\%$ $A_{dir}^{c} \simeq 1\%$ PRD 89, (2014) 012002

Signature: (l+jets) 1 isolated e/μ & E_{Tmiss} >25 GeV & ≥4 jets (≥1 *b*).

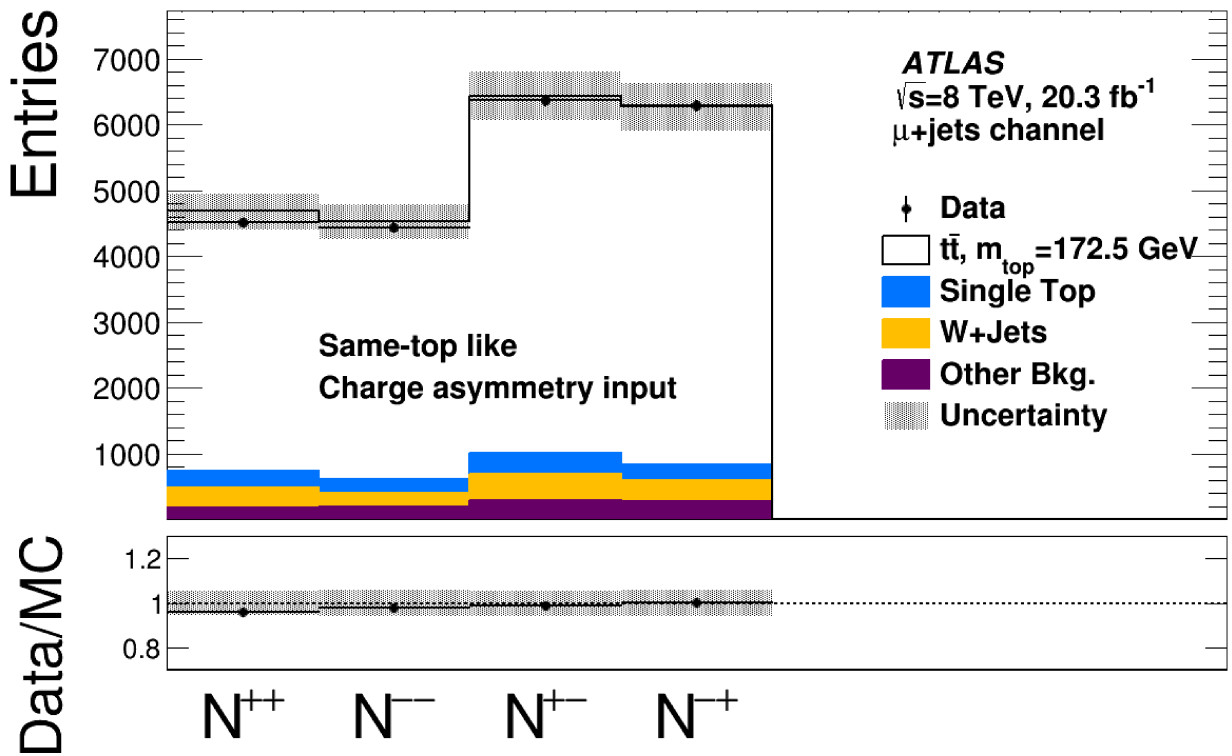
Method: Soft muon-*b*, Likelihood fit, Unfolded



8 TeV, 20.3 fb^{-1}

$$A_{SS} = \frac{\left(\frac{N^{++}}{N^{+}}\right) - \left(\frac{N^{--}}{N^{-}}\right)}{\left(\frac{N^{++}}{N^{+}}\right) + \left(\frac{N^{--}}{N^{-}}\right)}$$

$$A_{OS} = \frac{\left(\frac{N^{+-}}{N^{+}}\right) - \left(\frac{N^{-+}}{N^{-}}\right)}{\left(\frac{N^{+-}}{N^{+}}\right) + \left(\frac{N^{-+}}{N^{-}}\right)}$$



[JHEP 02 (2017) 071 (October 2016)]

CP asymmetries in b from top

NEW

- **Opposite Sign (OS)**
- $t \to l^+ \nu\, b \to l^+ l^- X$ ~55%
- $t \to l^+ \nu\, (b \to \bar{b} \to \bar{c}) \to l^+ l^- X$ ~4%
- $t \to l^+ \nu\, (b \to c\bar{c}) \to l^+ l^- X$ ~3%

- **Same Sign (SS)**
- $t \to l^+ \nu\, (b \to \bar{b}) \to l^+ l^+ X$ ~7%
- $t \to l^+ \nu\, (b \to c) \to l^+ l^+ X$ ~28%
- $t \to l^+ \nu\, (b \to \bar{b} \to c\bar{c}) \to l^+ l^+ X$ ~3%

$$A^{ss} = r_b A^{bl}_{\mathrm{mix}} + r_{c\bar{c}} A^{bc}_{\mathrm{mix}} + r_c A^{bc}_{\mathrm{dir}} - (r_c + r_{c\bar{c}}) A^{cl}_{\mathrm{dir}}$$

$$A^{os} = \tilde{r}_c A^{bc}_{\mathrm{mix}} + \tilde{r}_b A^{bl}_{\mathrm{dir}} + (\tilde{r}_c + \tilde{r}_{c\bar{c}}) A^{cl}_{\mathrm{dir}}$$

[JHEP 02 (2017) 071 (October 2016)]

Results	Data (10^{-2})	Existing limits (2σ) (10^{-2})	SM (10^{-2})
A^{ss}	-0.7 ± 0.8	–	$< 10^{-2}$ [1]
A^{os}	0.4 ± 0.5	–	$< 10^{-2}$ [1]
A^{b}_{mix}	-2.5 ± 2.8	< 0.1 [3]	$< 10^{-3}$ [2,3]
A^{bl}_{dir}	0.5 ± 0.5	< 1.2 [4]	$< 10^{-5}$ [1]
A^{cl}_{dir}	1.0 ± 1.0	< 6.0 [4]	$< 10^{-9}$ [1]
A^{bc}_{dir}	-1.0 ± 1.1	–	$< 10^{-7}$ [5]

[1] PRL 110, 232002 (2013) [2] arXiv:1511.09466v1 [3] arXiv:1412.7515v1 (HFAG) [4] PRD 87, 074036 (2015) [5] PLB 694, 374 (2011)

- Competitive direct CP limits. The first limit on direct *b*-to-*c*
- $\mathcal{O}$ (1%) precision reached (stat. limited), comparable to the D0 anomaly effect.

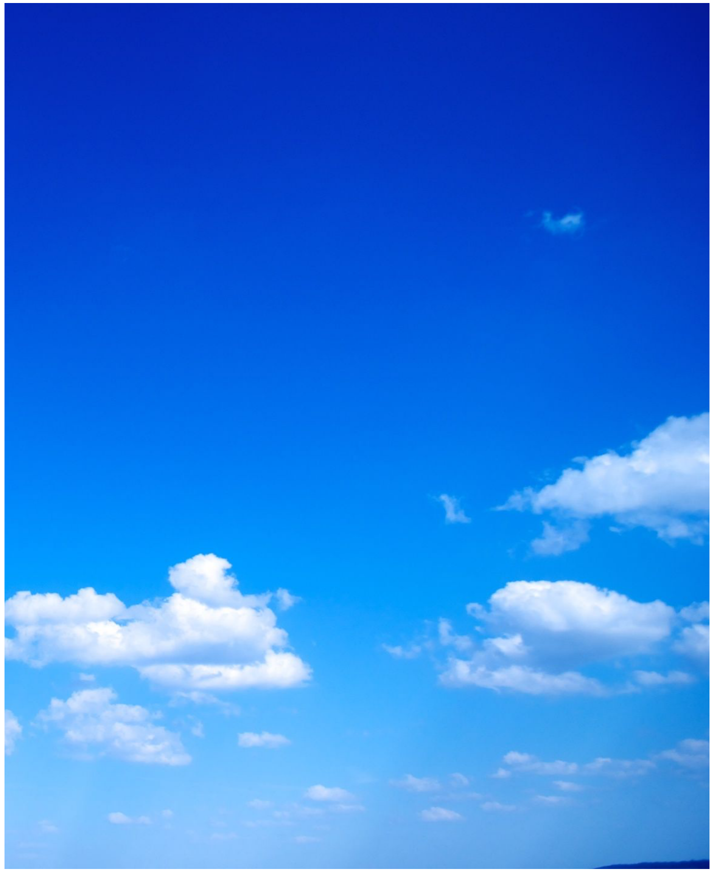
Summary

- Dramatic improvements on top mass precision in the last few years, now well below 1 GeV
  → b fragmentation and hadronisation modelling becoming a significant limitation

- The large top datasets allow for the first time to perform *precision* measurements of charge and CP asymmetries. Currently to 0.5% —1.0%.

- First measurements of B properties from top decay.

- Most measurements have yet to use the large 13 TeV dataset, benefitting from the increased top cross section and the exceptional LHC performance.
  Expect very significant advances by Summer 2017



- Find out more at:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP/index.html

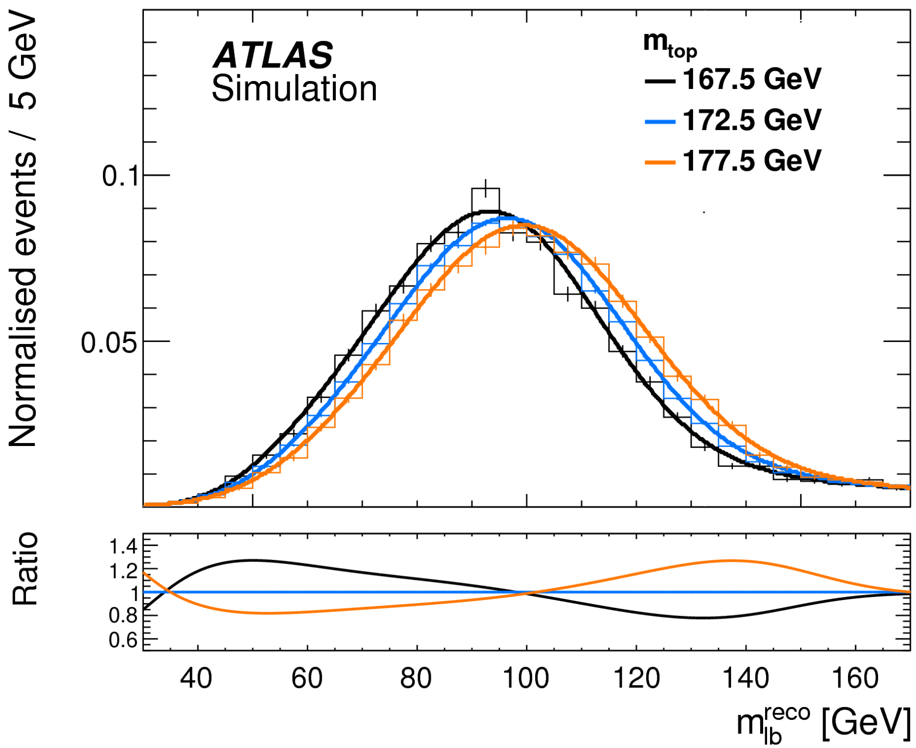
Additional Information

Top Quark Mass

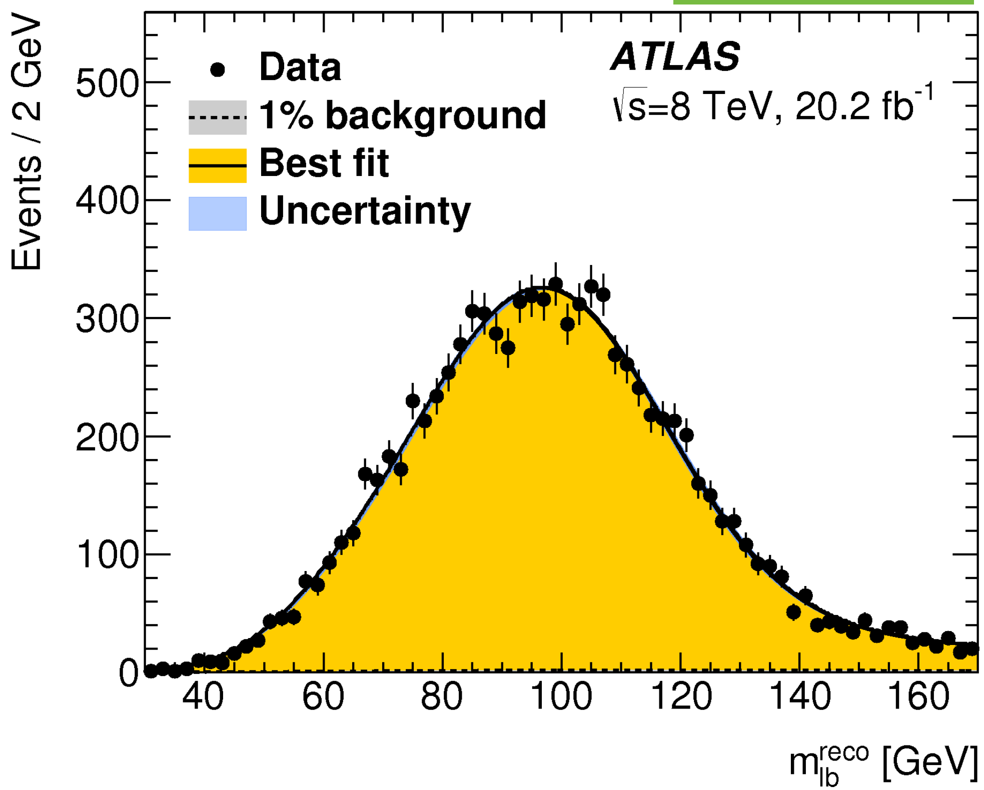
Signature: (dilepton) 2 isolated OS e/μ & E_{Tmiss} >25 GeV & ≥2 jets (≥1 *b*).

Method: Template fits to Reco. $m_{l\text{-}b}$ (mass of lepton and b-jet)

- Minimum $\langle p_T \rangle_{l\text{-}b}$ optimises reconstruction of the event
- ± 0.8 GeV total uncertainty, most precise in dilepton channel to date
- Largest systematics from JES/bJES (0.5/0.3 GeV) and from Had. modeling/IFSR (0.2 GeV)



8 TeV, 20.2 fb^{-1}



m_{top}= 172.99 ± 0.41(stat) ±0.74 (syst) GeV

[Phys Lett B 761 350 (June 2016)]

Top Width

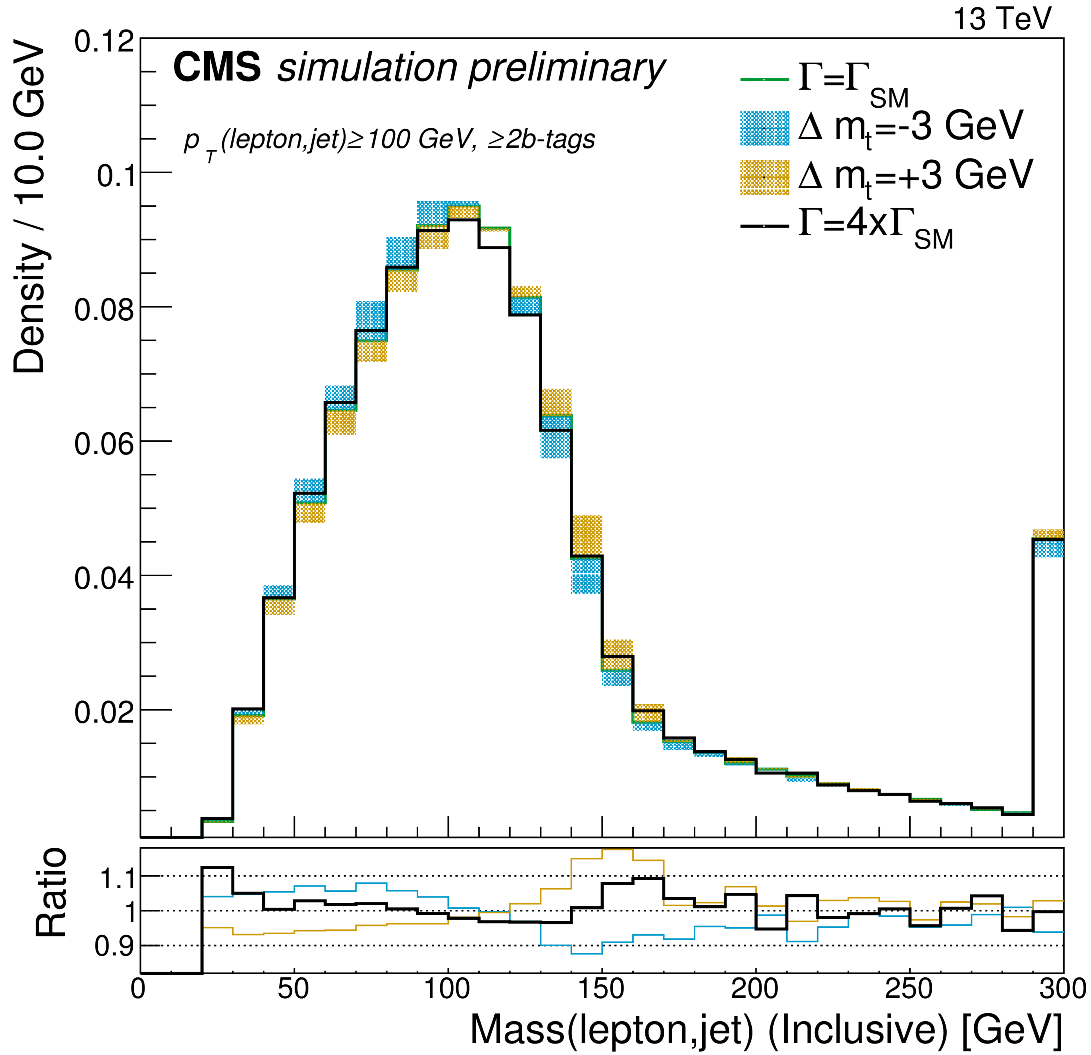
Indirect determinations use $R_b = B(t \to Wb)/B(t \to Wq)$ or the single top (t-ch) cross section. Precision of $\mathcal{O}(0.1\ \text{GeV})$

Direct determination focuses on mass lineshape.

SM: $\Gamma^{NLO} = 1.35 \pm \mathcal{O}(1\%)$ GeV (m_t = 173.3 GeV and α_S = 0.118)

Signature: (dilepton) 2 isolated OS e/μ & ≥2 jets (≥1 *b*).

Method: M_{lb} inclusive spectrum, with sensitivity at low M_{lb}; 2-D fit to signal and width



- First direct bound on Γ_t at the LHC
- Most precise direct bound on Γ_t

$0.6 < \Gamma_{top} < 2.5$ GeV (95% C.L.)

[CMS-PAS-TOP-16-019 (September 2016)]