Top mass, spin and decay properties

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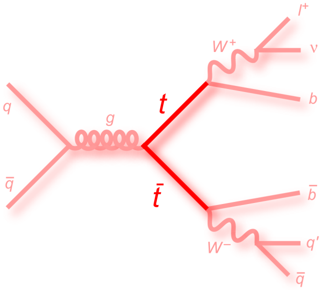
Introduction

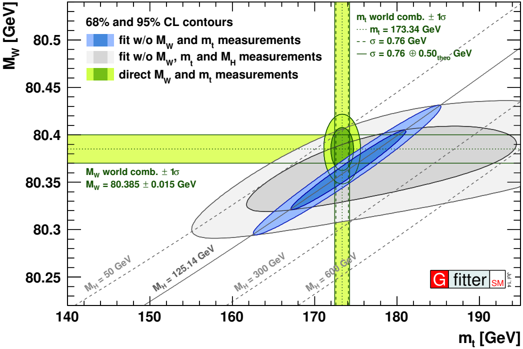
- The top decays before hadronising - behaves like a bare quark.
- Top spin at production transferred to its decay products - can measure spin correlations in $t\bar{t}$ events and probe $V-A$ structure of Wtb vertex
- $\implies$ top quark properties provide a powerful test of the predictions of perturbative QCD and a sensitive probe of BSM physics



Introduction

The top is the heaviest fundamental particle in the SM.

- Largest coupling to the Higgs ($y_t \approx 1$)
- The top, Higgs and W masses are related through radiative corrections
- $\implies$ precision measurements of m_{Top} are crucial self-consistency tests of the SM



Top spin and decay properties

Top spin observables in $t\bar{t}$ events (ATLAS)

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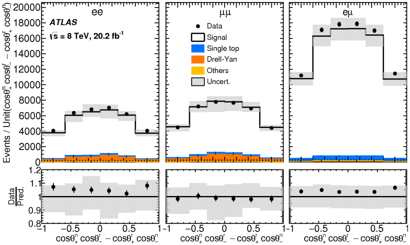
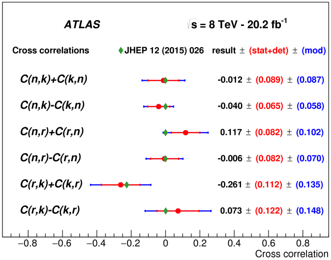
$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta_+^a\,\mathrm{d}\cos\theta_-^b} = \frac{1}{4}(1 + B_+^a\cos\theta_+^a + B_-^b\cos\theta_-^b - C(a,b)\cos\theta_+^a\cos\theta_-^b)$$

- Dilepton channel: measure angles θ between leptons and suitably defined axes
- Measurement of spin density matrix: polarisations and spin correlations
- Kinematic reconstruction of the $t\bar{t}$ system using *neutrino weighting method*





See talk by Tom Neep

W boson polarisation in $t\bar{t}$ events (ATLAS)

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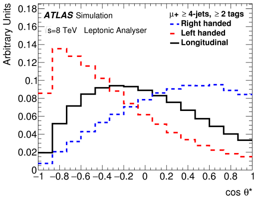
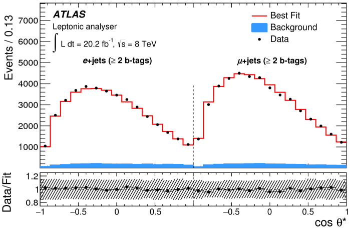
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_\mathrm{L} + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_\mathrm{R}$$

In the SM: $F_L = 0.311 \pm 0.005, F_R = 0.00117 \pm 0.0001, F_0 = 0.687 \pm 0.005.$

- Structure of Wtb vertex $\longrightarrow$ angular distribution of W decay products
- l+jets channel; kinematic likelihood reconstruction of the $t\bar{t}$ system
- Using two analysers: charged lepton from leptonic W and d-type quark from hadronic W (using b-tagging and jet p_T information)
- Template fit used to extract helicity fractions





See talk by Tom Neep

W boson polarisation in $t\bar{t}$ events (ATLAS)

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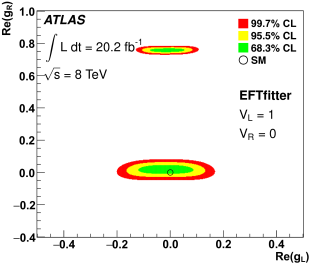
- Dominant uncertainty from jet energy scale and resolution

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_{\rm L}P_{\rm L} + V_{\rm R}P_{\rm R})\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\,(g_{\rm L}P_{\rm L} + g_{\rm R}P_{\rm R})\,t\,W_{\mu}^{-} + \text{h.c.}$$

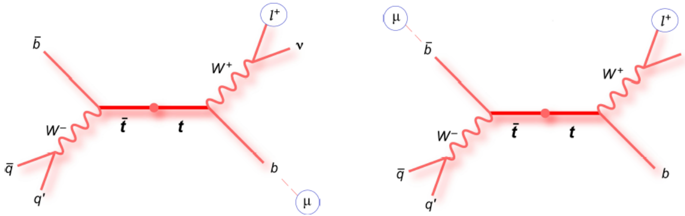
Leptonic analyser (≥2 b-tags)
$F_0 = 0.709 \pm 0.012$ (stat.+bkg. norm.) $^{+0.015}_{-0.014}$ (syst.)
$F_{\rm L} = 0.299 \pm 0.008$ (stat.+bkg. norm.) $^{+0.013}_{-0.012}$ (syst.)
$F_{\rm R} = -0.008 \pm 0.006$ (stat.+bkg. norm.) ± 0.012 (syst.)



CP asymmetries in b-hadron decays using $t\bar{t}$ (ATLAS)

JHEP 02 (2017) 071

- $t\bar{t}$ production excellent source of b-hadrons, where the hadron charge can be measured at production and decay
- Soft muon tagging (SMT) used to reconstruct the charge at decay



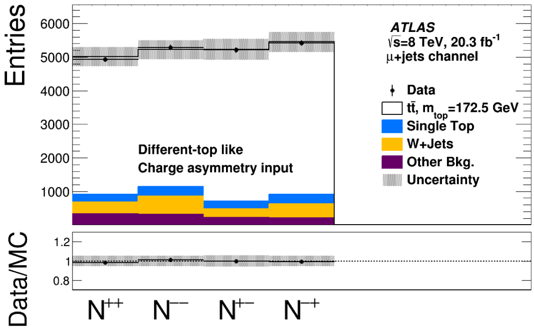
$$A^{ss} = \frac{P(b \to \ell^+) - P(\bar{b} \to \ell^-)}{P(b \to \ell^+) + P(\bar{b} \to \ell^-)}, \quad A^{os} = \frac{P(b \to \ell^-) - P(\bar{b} \to \ell^+)}{P(b \to \ell^-) + P(\bar{b} \to \ell^+)},$$

$$A^{ss} = \frac{\left(\frac{N^{++}}{N^+} - \frac{N^{--}}{N^-}\right)}{\left(\frac{N^{++}}{N^+} + \frac{N^{--}}{N^-}\right)}, \quad A^{os} = \frac{\left(\frac{N^{+-}}{N^+} - \frac{N^{-+}}{N^-}\right)}{\left(\frac{N^{+-}}{N^+} + \frac{N^{-+}}{N^-}\right)}.$$

See talk by Tom Neep

CP asymmetries in b-hadron decays using $t\bar{t}$ (ATLAS)

- Obtain constraints on CP violation parameters $A^{bl}_{\mathrm{dir}}, A^{cl}_{\mathrm{dir}}, A^{bc}_{\mathrm{dir}}$.



	Data (10^{-2})		Existing limits (2σ) (10^{-2})		SM prediction (10^{-2})	
A^{ss}	-0.7	± 0.8	-		$< 10^{-2}$	[19]
A^{os}	0.4	± 0.5	-		$< 10^{-2}$	[19]
A^{b}_{mix}	-2.5	± 2.8	< 0.1	[95]	$< 10^{-3}$	[96] [95]
$A^{b\ell}_{\mathrm{dir}}$	0.5	± 0.5	< 1.2	[94]	$< 10^{-5}$	[19] [94]
$A^{c\ell}_{\mathrm{dir}}$	1.0	± 1.0	< 6.0	[94]	$< 10^{-9}$	[19] [94]
A^{bc}_{dir}	-1.0	± 1.1	-		$< 10^{-7}$	[97]

Dominated by statistical uncertainties $\Longrightarrow$ will improve with 13 TeV data.

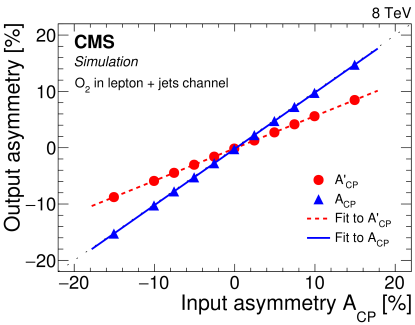
- Provides the first constraint on A^{bc}_{dir} and an improved limit on A^{cl}_{dir}

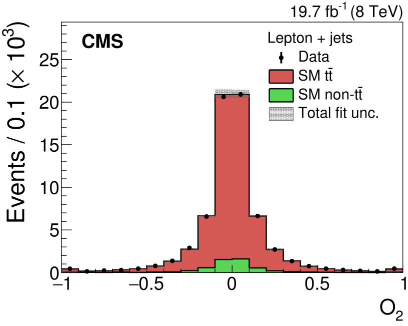
See talk by Tom Neep

CP violation in $t\bar{t}$ production and decay (CMS)

JHEP 03 (2017) 101

- Construct T-odd observables of the form $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$ from momentum and spin vectors
- e.g. $(\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_l \times \vec{p}_{j_1})$ and $Q_l \; \vec{p}_b \cdot (\vec{p}_l \times \vec{p}_{j_1})$
- CP violation manifests as an asymmetry in $\mathcal{O}_i$ (> 0 versus < 0)
- Diluted by $35 - 73\%$, mainly due to incorrectly assigned b-jets
- Measured values consistent with 0, with %-level uncertainties





See talk by Tom Neep

Top quark width

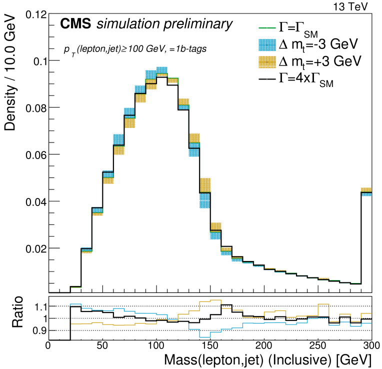
CMS-PAS-TOP-16-019

Predicted to be $\Gamma_t^{\text{NLO}} = 1.35$ GeV.

- Strong indirect constraints exist, but direct measurements (from Tevatron) limited by statistics and jet resolution systematics
- Uses the m_{lb} distribution in the dilepton channel: the shape is sensitive to both m_t and Γ_t

Extract $0.6 \leq \Gamma_t \leq 2.5$ GeV @ 95% CL, for $m_t = 172.5$ GeV.

LO decays of the top $\implies$ looking forward to having the full $b\bar{b}4l$ @NLO description (see talk by J. Lindert).



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Top mass measurements

Overview

The top quark mass is a fundamental parameter of the SM.

Different approaches to measuring it.

Direct measurements in $t\bar{t}$ events:

- dilepton, l+jets and all-hadronic channels can be used
- Template method often used
- $\mathcal{O}(1)$ GeV theoretical uncertainties in relating the extracted value to the desired pole mass

Alternative methods:

- Using single top events, top decays to b-jets containing J/ψ's, etc

Measurements of the pole mass:

- E.g. from $t\bar{t}$ cross section or $t\bar{t}$+1 jet events $\longrightarrow$ 1% precision, not (yet) competitive with direct methods

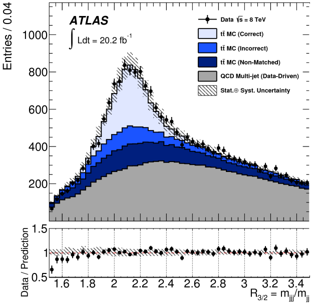
Most measurements dominated by systematic uncertainties; significant gains from combinations of different methods.

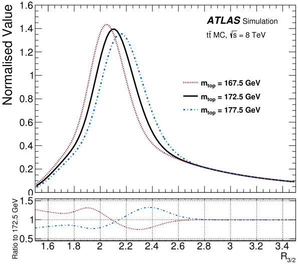
Top mass in the all-hadronic $t\bar{t}$ channel (ATLAS)

arXiv:1702.07546

- Large BR (46%) but suffers from QCD and combinatorial background
- Reconstruct $t\bar{t}$ system using χ^2 procedure
- Observable used is $R_{3/2} = m_{jjj}/m_{jj}$: the ratio helps reduce the impact of the jet energy scale uncertainty

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

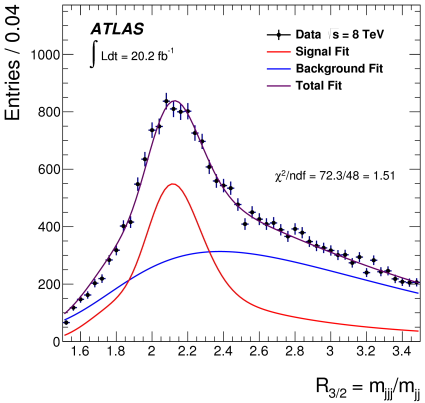




Top mass in the all-hadronic $t\bar{t}$ channel (ATLAS)

arXiv:1702.07546

Template fit in $R_{3/2} = m_{jjj}/m_{jj}$ used to extract m_{top}.



Measure $m_{\text{Top}} = 173.72 \pm 0.55$ (stat.) $\pm$ 1.01 (syst.). Dominant systematics are jet energy scale and hadronisation modelling.

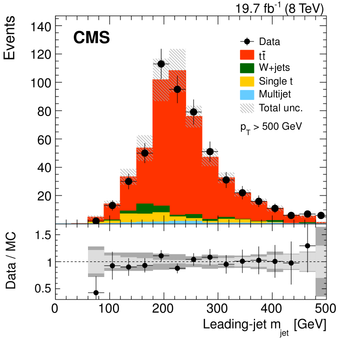
T Barillari

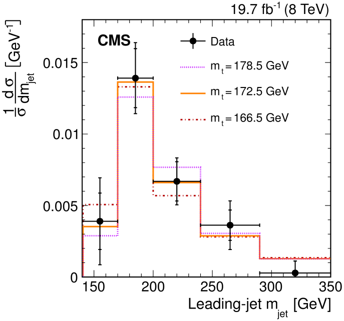
Jet mass in boosted $t\bar{t}$ events (CMS)

arXiv:1703.06330

Mass of boosted jets: $m_{\mathrm{Top}}^{\mathrm{meas}} \leftrightarrow m_{\mathrm{Top}}^{\mathrm{pole}}$ appears tractable (see talk by M. Preisser).

- Select highly boosted $t\bar{t} \to (bjj)(bl\nu)$ events and measure fat jet mass
- Using $R = 1.2$ jets with $p_{\mathrm{T}} > 400$ GeV





- Cross section measured as a function of $d\sigma/dm_{\mathrm{jet}}$ and unfolded to particle level
- Extract (using MadGraph+Pythia8 predictions) $m_t = 170.8 \pm 6.0$ (stat) ± 2.8 (syst) ± 4.6 (model) ± 2.8 (theo) GeV

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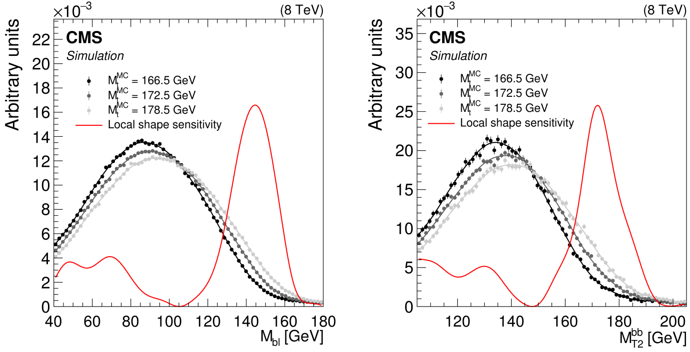
Top mass in dileptonic $t\bar{t}$ events (CMS)

arXiv:1704.06142

Uses the M_{bl} and M_{T2}^{bb} observables.

- Both of these have endpoints at m_{Top}-dependent values
- Only sensitive to overall energy scale since only b-jets are used
- Extract jet energy scale factor (JSF) together with m_{Top} by fitting the M_{bl} and M_{T2}^{bb} shapes simultaneously



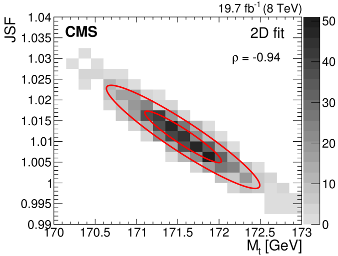
"Local shape sensitivity" function shows regions most sensitive to m_{Top}.

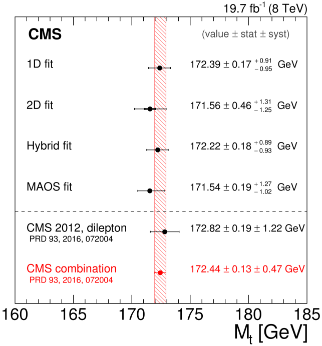
Top mass in dileptonic $t\bar{t}$ events (CMS)

arXiv:1704.06142

m_{Top} extracted using an unbinned maximum likelihood fit, together with JSF.

- Distribution shapes modelled using a non-parametric Gaussian process regression technique
- Captures the smooth evolution of shapes as m_{Top} and JSF are varied



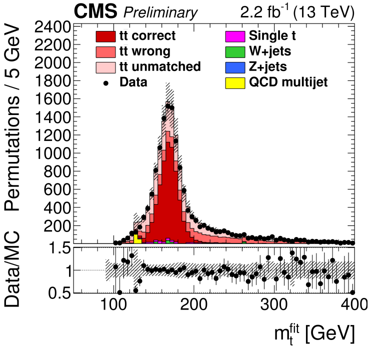


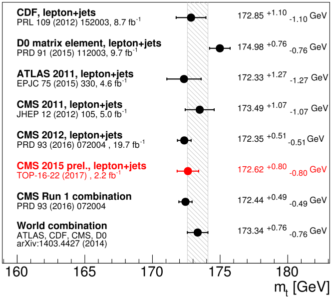
Extracted value $m_{\mathrm{Top}} = 172.22\pm$ 0.18 (stat) $^{+0.89}_{-0.93}$ (syst) GeV. Modelling, jet energy scale and b-quark fragmentation uncertainties dominate.

Top mass in μ+jets final states (CMS)

PAS TOP-16-022

- First measurement at $\sqrt{s} = 13$ TeV, using a new MC setup (Powheg+Pythia8 instead of MadGraph+Pythia6 used for $t\bar{t}$)
- Reconstruct events with a χ^2 kinematic fit; m_W used as an input
- 2D fit using reconstructed $m_{\rm Top}$ and m_W to extract JSF in situ





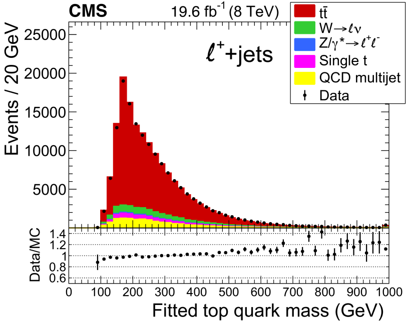
Consistent with most precise Run I CMS measurement, $m_{\rm Top} = 172.35 \pm 0.51$ GeV.

- Still some tension with Tevatron measurement, $m_{\rm Top} = 174.98 \pm 0.76$ GeV

Measurement of $m_t - m_{\bar{t}}$ (CMS)

arXiv:1610.09551

- Check of CPT invariance
- Performed in l+jets channel at 8 TeV; dataset split into l^+ and l^- components
- Mass measured separately for $l^\pm$ categories



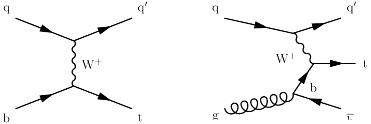
Source	Uncertainty in Δm_t (MeV)
Jet energy scale	$7 \pm \mathbf{16}$
Jet energy resolution	$7 \pm \mathbf{11}$
b vs. $\bar{\text{b}}$ jet response	$\mathbf{51} \pm 1$
Signal fraction	$\mathbf{27} \pm 2$
Background charge asymmetry	$\mathbf{11.9} \pm 0.1$
Background composition	$\mathbf{28} \pm 1$
Pileup	$\mathbf{9.1} \pm 0.3$
b tagging efficiency	$\mathbf{24} \pm 7$
b vs. $\bar{\text{b}}$ tagging efficiency	$\mathbf{11} \pm 7$
Method calibration	$3 \pm \mathbf{53}$
Parton distribution functions	$\mathbf{9} \pm 3$
Total	91

Measure $\Delta m_{\text{Top}} = -0.15 \pm 0.19$ (stat) ± 0.09 (syst) GeV.

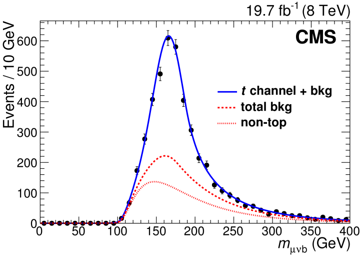
Top mass in single top events (CMS)

arXiv:1703.02530

- First measurement of $m_{\rm Top}$ in non-$t\bar{t}$ topology
- Different production mechanisms $\implies$ theoretical systematics partially uncorrelated



Using the reconstructed $\mu\nu b$ mass to extract $m_{\rm Top}$.



$m_{\rm Top} = 172.95 \pm$ 0.77 (stat) $^{+0.97}_{-0.93}$ (syst) GeV $\longrightarrow$ dominated by JES and background modelling uncertainties.

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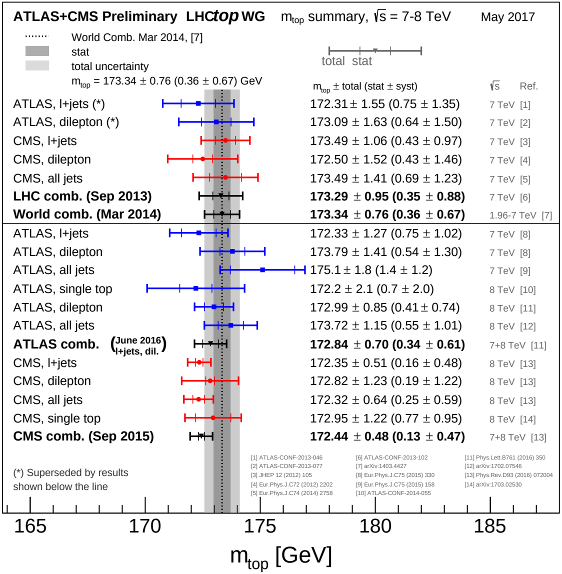
Top mass measurement combinations



Conclusions

Top spin and decays:

- Very precise constraints of the Wtb vertex and spin density matrix from $t\bar{t}$ events
- Studies of CP violation in production and decay of $t\bar{t}$ events - nearing per mil precision
- All measurements in agreement with the SM; typically jet and $t\bar{t}$ modelling systematics dominate the uncertainties

Top mass:

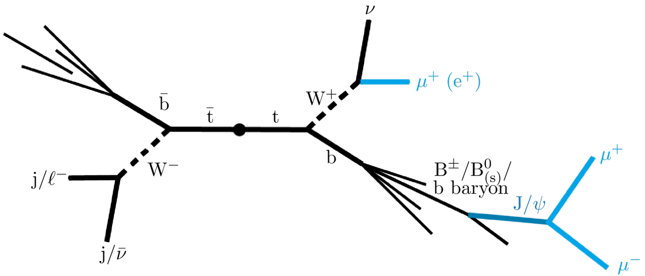
- ATLAS and CMS 8 TeV measurements in good agreement: 172.84 $\pm$ 0.70 GeV (ATLAS) vs 172.44 $\pm$ 0.48 GeV (CMS)
- First top mass measurements with 13 TeV data
- New methods being explored: using single top events, boosted topologies, J/ψ (see backup)

Many measurements statistically limited and yet to be done with 13 TeV data.

Lots of improvements to look forward to in the future!

Backup

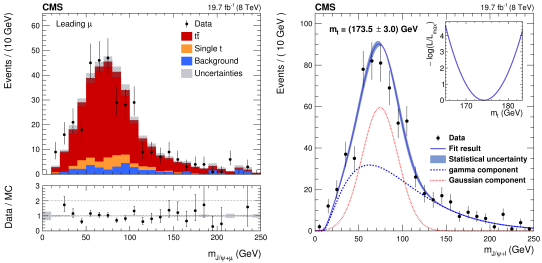
Top mass in decays with a J/ψ meson (CMS)



- Rely on $t \to (W \to l\nu)b(\to J/\psi(\to \mu\mu) + X)$ decays
- Uses leptons only $\implies$ not sensitive to b-jet energy scale
- Both lepton+jets and dilepton $t\bar{t}$ events exploited; J/ψ candidates from non-isolated muons with $p_\mathrm{T} > 4$ GeV

Top mass in decays with a J/ψ meson (CMS)

$m_{J/\psi+l}$ distribution fitted using a functional form with coefficients dependent on m_t.



- Measure $m_{\text{Top}} = 173.5\pm$ 3.0 (stat) $\pm$ 0.9 (syst) GeV.
- Dominated by top transverse momentum and b-quark fragmentation modelling uncertainties

Alternative m_{Top} measurements in CMS