Top quark mass measurements at CMS

Fred Stober

on behalf of the CMS Collaboration

QCD@LHC 2017, Debrecen

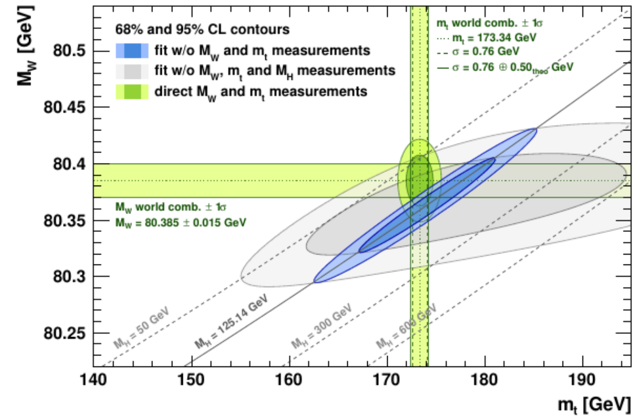
2017-08-28

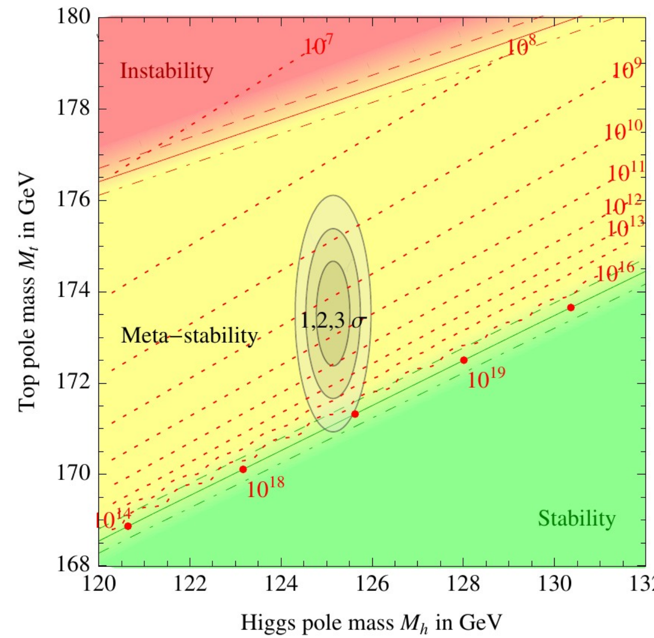
Motivation: Why measure m_t?

- Heaviest measured Standard Model particle
- τ(top decay) $\approx 5 \times 10^{-25}$ s < τ(hadronisation)

  $\Rightarrow$ spin correlation conserved
- Check self-consistency of SM through radiative corrections to M_W constraining M_h

  (EPJC 74 (2014) 3046, arXiv:1407.3792)
- M_t is related to the vacuum stability of the SM / our universe (arXiv:1307.3536)
- The top mass is very close to the EWSB scale, so the top might play a special role...

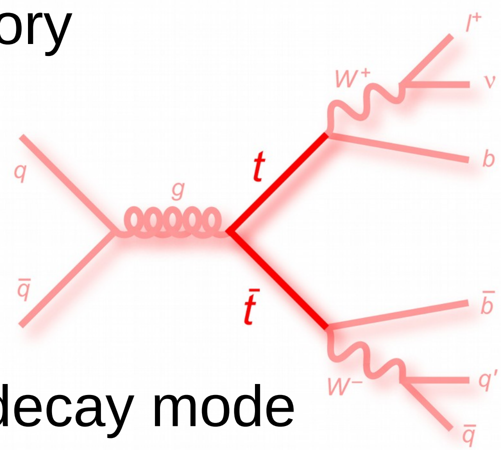




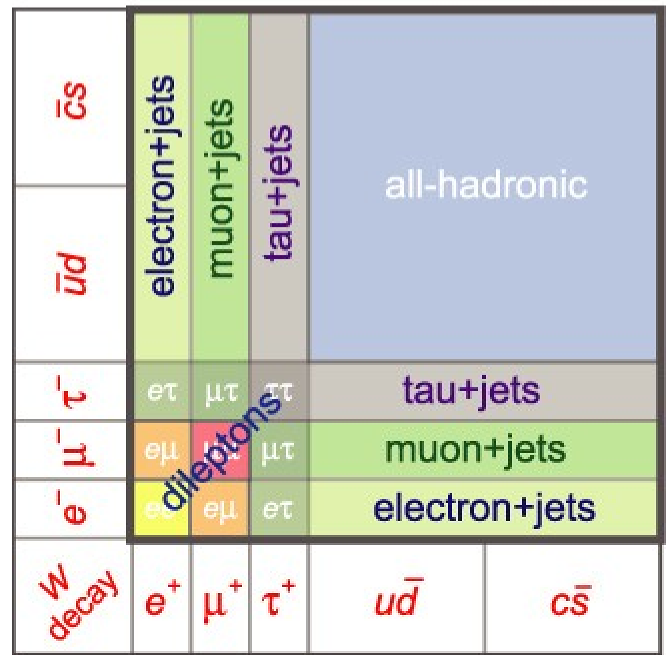
The Top Quark at the LHC

- Large cross section + huge integrated lumi

  ⇒ LHC is a Top Factory
- Top Pair Production:
  - 172 pb @ 7 TeV
  - 249 pb @ 8 TeV
  - 832 pb @ 13 TeV



Top Pair Decay Channels



- Characterized by W decay mode
  - all-jets: large yield, also large background
  - dilepton: low yield, high S/B
  - lepton+jet: good yield, good S/B, golden
- Important to measure in all channels, since some uncertainties are uncorrelated and can cancel in a combination.
- Single Top Production ($\sigma_t \sim \sigma_{tt}/3$)
- Many interesting different ways to study the top quark mass…

Uncertainties

- Statistical uncertainties become negligible due to high luminosity of the LHC and larger cross sections at higher energies
- Systematic uncertainties
  - Experimental sources: eg. (b-)JES, MET scale, PU, trigger, ...
  - Signal: eg. MC, hadronization, ISR/FSR, PDF, UE, CR, b quark modelling ...
  - Background: either data-driven or MC: normalization and shape
  - Methodology: eg. regularization through parameterization, calibration
- Im most cases, the systematic uncertainties are evaluated using pseudo experiments, where the change of M_t is studied for different well (?) defined input parameter sets

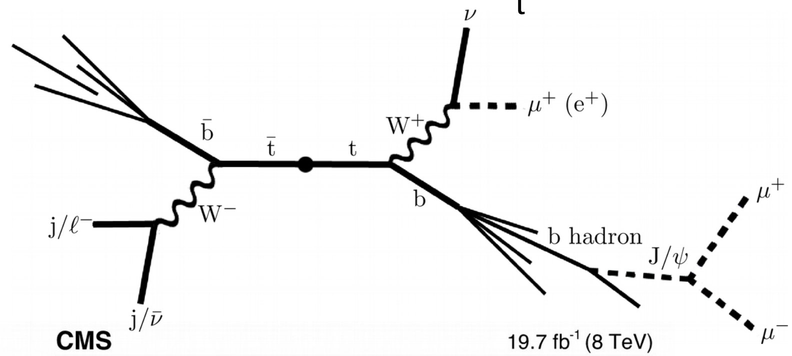
Measurements of m_t by CMS

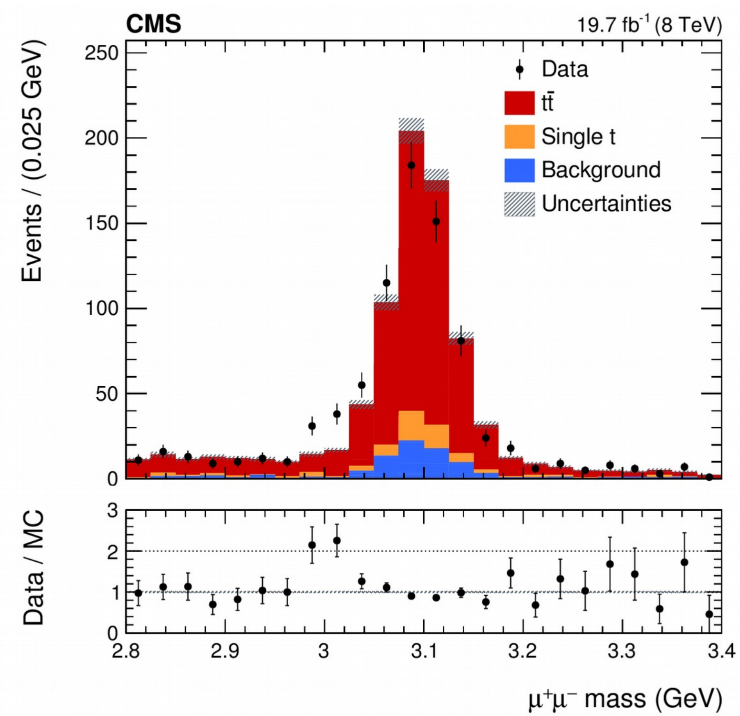
- Comprehensive set of top quark mass measurements by CMS

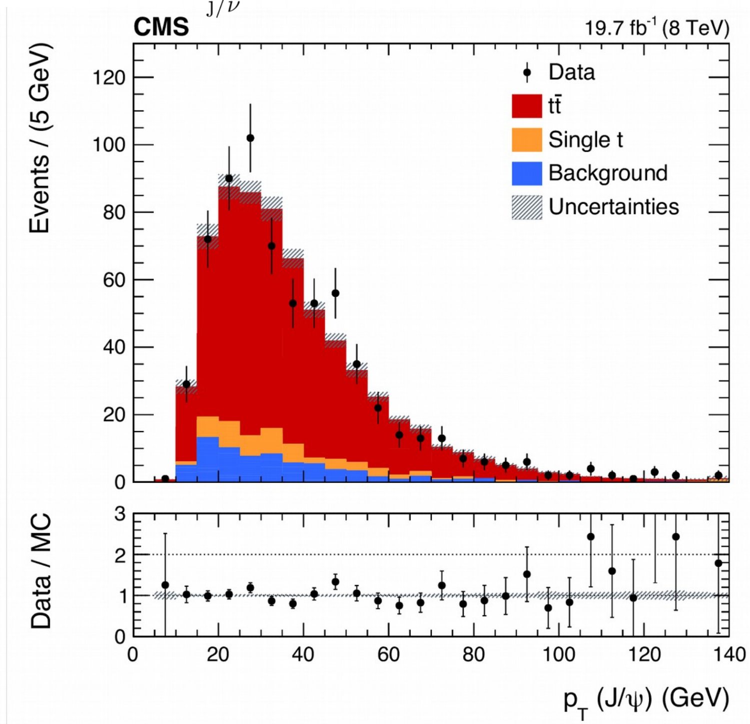
Top Physics Publications			Mass Measurements	
74	TOP-15-008	Measurement of the top quark mass in the dileptonic $t\bar{t}$ decay channel using the mass observables $M_{b\ell}$, M_{T2}, and $M_{b\ell\nu}$ in pp collisions at $\sqrt{s} = 8$ TeV	PRD 96 (2017) 032002	20 April 2017
73	TOP-15-015	Measurement of the jet mass in highly boosted $t\bar{t}$ events from pp collisions at $\sqrt{s} = 8$ TeV	EPJC 77 (2017) 467	18 March 2017
72	TOP-15-001	Measurement of the top quark mass using single top quark events in proton-proton collisions at $\sqrt{s} = 8$ TeV	EPJC 77 (2017) 354	7 March 2017
68	TOP-16-006	Measurement of the $t\bar{t}$ production cross section using events with one lepton and at least one jet in pp collisions at $\sqrt{s} = 13$ TeV	Submitted to JHEP	22 January 2017
60	TOP-15-014	Measurement of the mass of the top quark in decays with a J/ψ meson in pp collisions at 8 TeV	JHEP 12 (2016) 123	11 August 2016
56	TOP-12-030	Measurement of the top quark mass using charged particles in pp collisions at $\sqrt{s} = 8$ TeV	PRD 93 (2016) 092006	21 March 2016
53	TOP-13-004	Measurement of the $t\bar{t}$ production cross section in the $e\mu$ channel in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV	JHEP 08 (2016) 029	7 March 2016
43	TOP-14-022	Measurement of the top quark mass using proton-proton data at $\sqrt{s} = 7$ and 8 TeV	PRD 93 (2016) 072004	15 September 2015
36	TOP-12-022	Determination of the top-quark pole mass and strong coupling constant from the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s}$ = 7 TeV	PLB 728 (2014) 496 [Corr PLB 738 (2014) 526]	21 August 2014
24	TOP-11-017	Measurement of the top-quark mass in all-jets $t\bar{t}$ events in pp collisions at $\sqrt{s}$ = 7 TeV	EPJC 74 (2014) 2758	17 July 2013
23	TOP-11-027	Measurement of masses in the $t\bar{t}$ system by kinematic endpoints in pp collisions at $\sqrt{s}$ = 7 TeV	EPJC 73 (2013) 2494	21 April 2013
13	TOP-11-016	Measurement of the top-quark mass in $t\bar{t}$ events with dilepton final states in pp collisions at $\sqrt{s}$ = 7 TeV	EPJC 72 (2012) 2202	12 September 2012
12	TOP-11-015	Measurement of the top-quark mass in $t\bar{t}$ events with lepton+jets final states in pp collisions at $\sqrt{s}$ = 7 TeV	JHEP 12 (2012) 105	12 September 2012
2	TOP-11-002	Measurement of the $t\bar{t}$ production cross section and the top quark mass in the dilepton channel in pp collisions at $\sqrt{s}$ = 7 TeV	JHEP 07 (2011) 049	31 May 2011

Top Mass from decays with a J/ψ meson at 8 TeV

- In leptonic final states that contain a J/ψ meson from a b hadron decay, the mass of the J/ψ + l system is correlated with M_t
- Low BR (1.5×10^{-4}) but clear, nearly background free signal due to three leptons in the event (JHEP 12 (2016) 123)





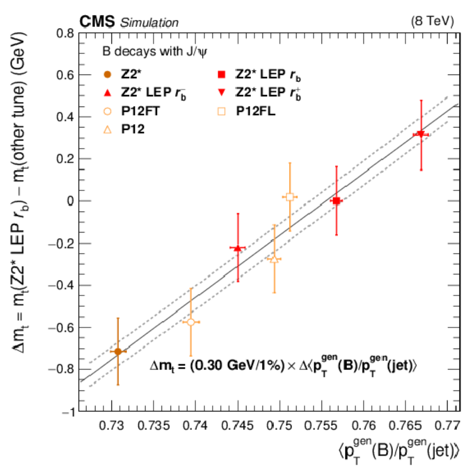


Top Mass from decays with a J/ψ meson at 8 TeV

- Fit of M_t with **template method**
  - PDFs are derived from MC with different input parameters M_{tMC} and parametrized as a function of M_t
  - The outcome is calibrated for biases (using the pull distributions in pseudo experiments)
  - Likelihood fit of PDFs to data gives the top quark mass
  - Method allows to include additional templates for in-situ calibrations
  - Simple and fast, but can be improved further (see later)
- Result of the fit:

$$M_t = 173.5 \pm 3.0 \pm 0.9 \text{ GeV}$$

- Also studied the dependence of the extracted mass on the average bottom fragmentation ratio

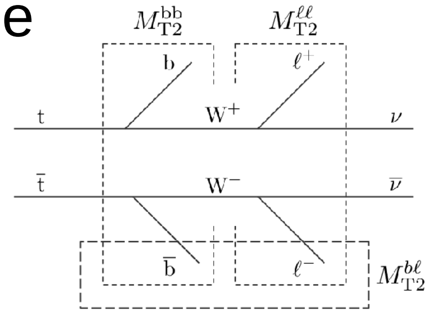


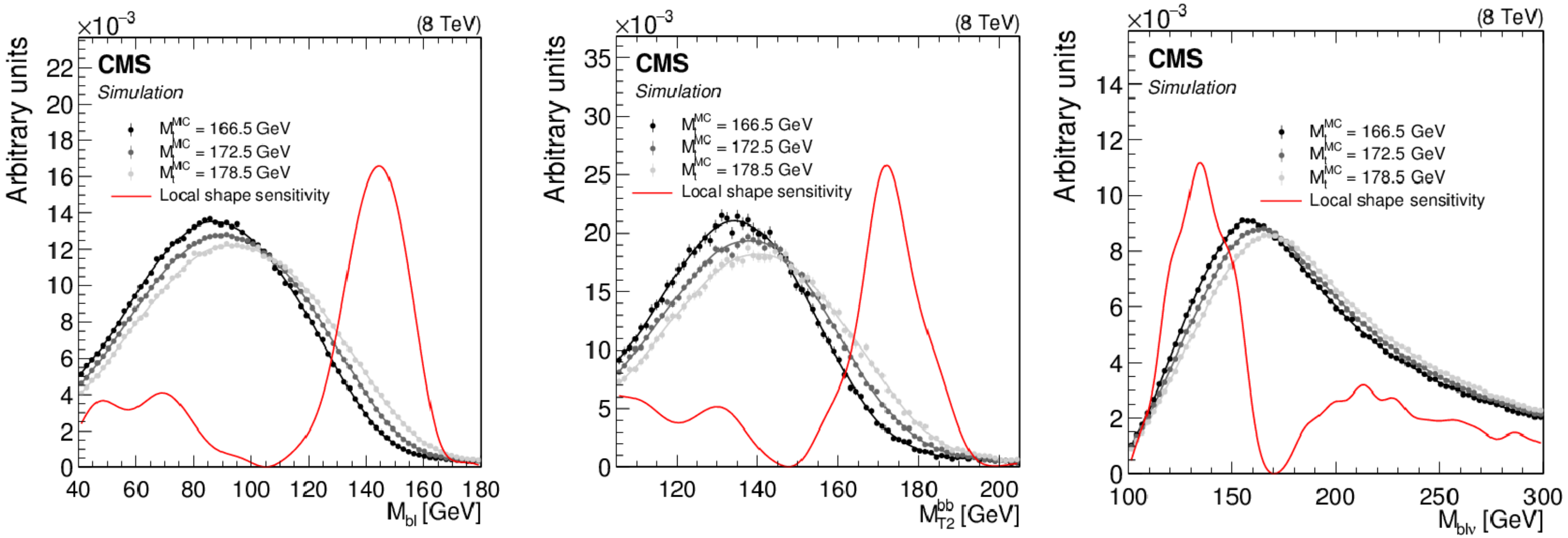
Source	Value (GeV)
Experimental uncertainties	
Limited size of the simulation samples	±0.22
Muon momentum scale	±0.09
Electron momentum scale	±0.11
Modeling of the J/ψ meson candidate mass distribution	+0.09
Jet energy scale	<0.01
Jet energy resolution	<0.01
Trigger efficiencies	±0.02
Pileup	±0.07
Theoretical uncertainties	
Background normalization	±0.01
Matrix-element generator	−0.37
Factorization and renormalization scales	+0.12, −0.46
Matching of matrix element and parton shower	+0.12, −0.58
Top quark transverse momentum	+0.64
b quark fragmentation	±0.30
Underlying event	±0.13
Modeling of color reconnection	+0.12
Parton distribution functions	+0.39, −0.11
Total (in quadrature)	+0.89, −0.94

Mass Measurement in the dilepton channel

PRD 96 (2017) 032002

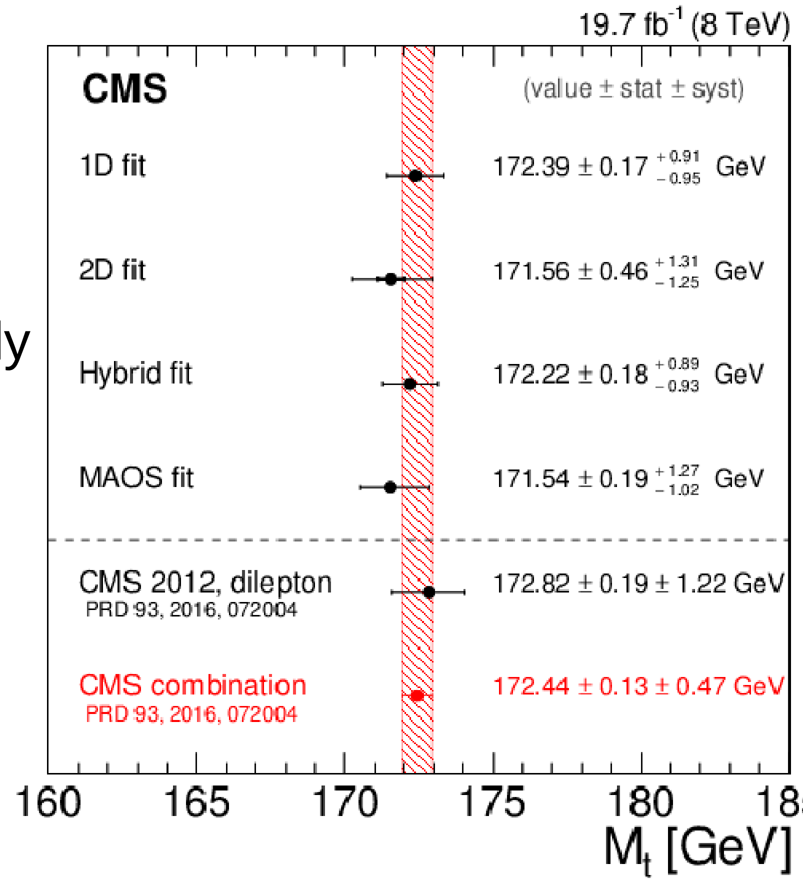
- In the dilepton channel, neutrinos prevent a full reconstruction.
- Latest analysis by CMS uses three kinematic observables, that are sensitive to the value of M_t and the jet energy scale
  - the invariant mass M_{bl} of a b system
  - the stransverse mass variable, M^{bb}_{T2}, constructed with the b and b daughters of the tt system
  - the M_{T2}-assisted on-shell (MAOS) reconstructed $M_{bl\nu}$





Mass Measurement in the dilepton channel

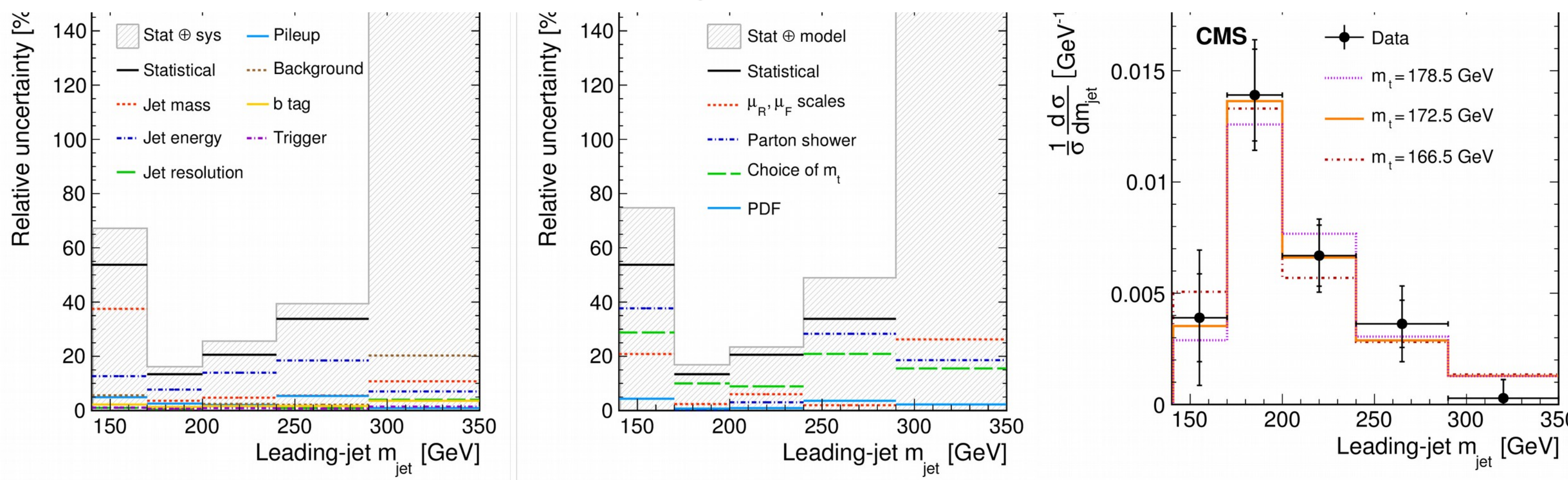
- To model the three observables, the nonparametric and thus largely model independent Gaussian process (GP) regression technique is used
- Several different fits are performed:
  - the 1D fit uses M_{bl} and M^{bb}_{T2}; JSF is constrained to be unity
  - the 2D fit also uses M_{bl} and M^{bb}_{T2}; determines M_t and JSF simultaneously
  - the MAOS fit uses M^{bb}_{T2} and $M_{bl\nu}$; JSF is constrained to be unity
  - The hybrid fit is a linear combination of the 1D and 2D fit to minimize the uncertainties



Top Mass from boosted top-pair events

- In the lepton+jets channel where the semi-leptonic decay is used as a tag, the products of the fully hadronic decay are reconstructed using a single Cambridge-Aachen jet with distance parameter R = 1.2, and pT > 400 GeV.
- The m_{jet} distribution is unfolded at the particle level and is used to test the modelling of highly boosted top quark production
- The peak position of the m_{jet} distribution is sensitive to the top quark mass M_t. The data are used to extract M_t and assess this sensitivity.

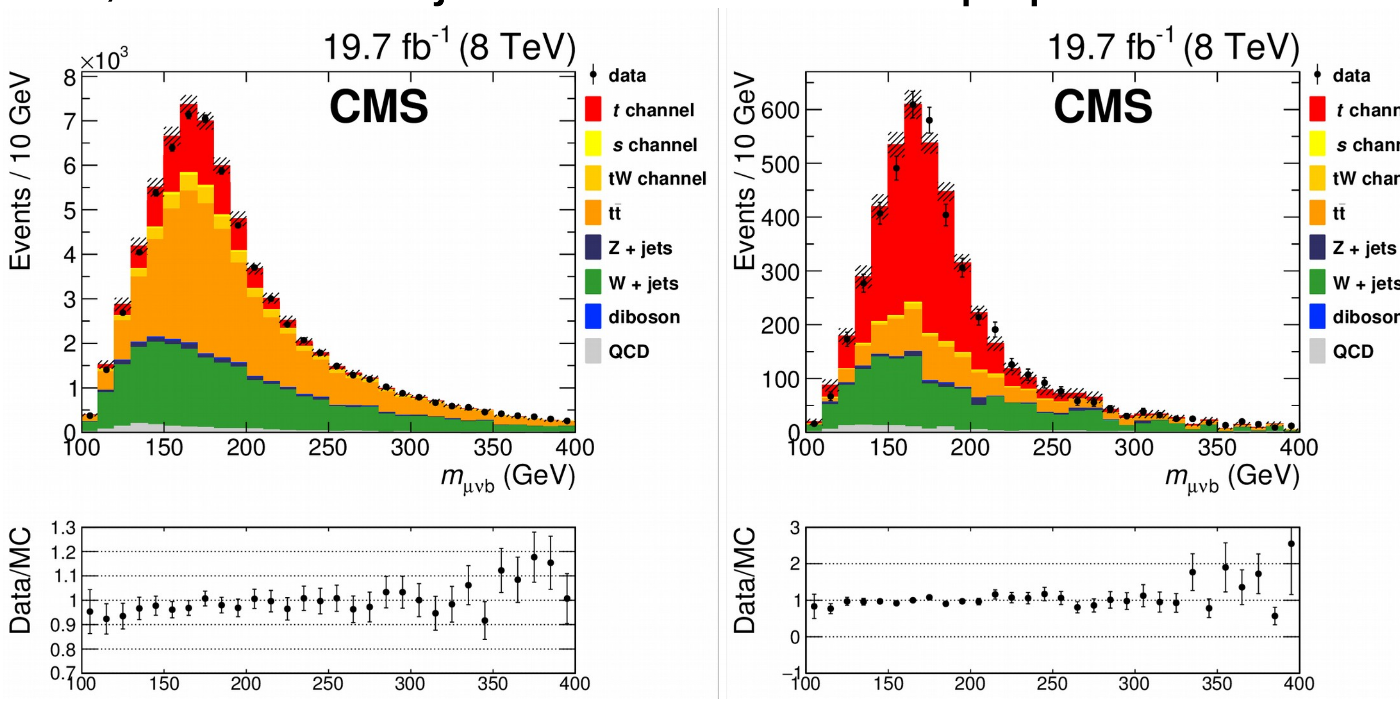
$$m_t = 170.8 \pm 6.0\,(\text{stat}) \pm 2.8\,(\text{syst}) \pm 4.6\,(\text{model}) \pm 4.0\,(\text{theo})\,\text{GeV}$$



Measurement using single top events

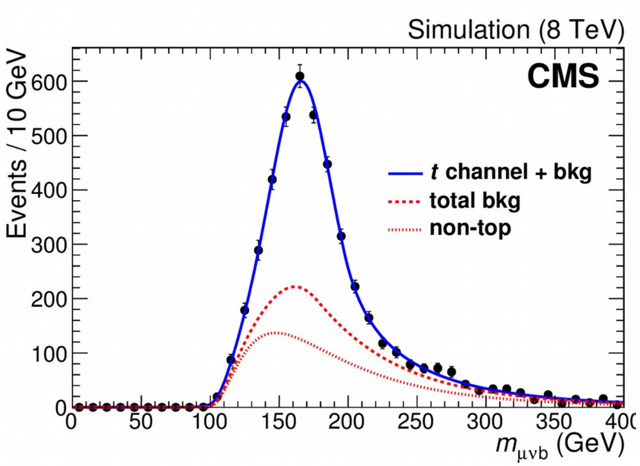
EPJC 77 (2017) 354

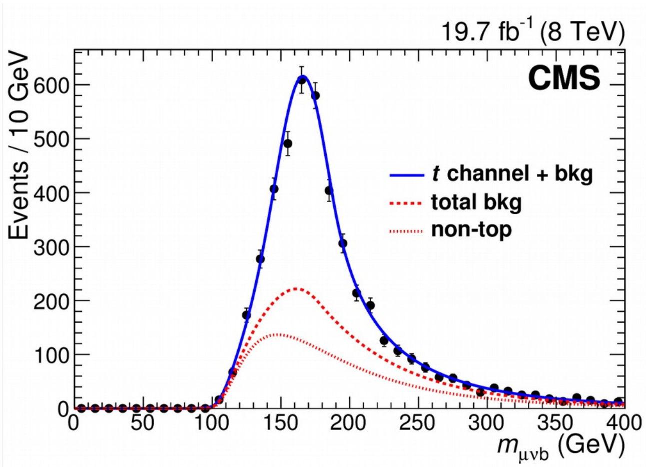
- Single top event selection:
  - 1 positively charged muon
    (S/B improved due to ~twice the higher cross section)
  - 2 jets (1 b jet, 1 forward jet || > 2.4)
- Reconstructed with the template method using the invariant mass of the muon, MET and b jet to estimate the top quark mass



Measurement using single top events

- Fit of the combined top-, top-pair-, and background contributions yields a top quark mass of $172.95 \pm 0.77\,(\text{stat})^{+0.97}_{-0.93}\,(\text{syst})$

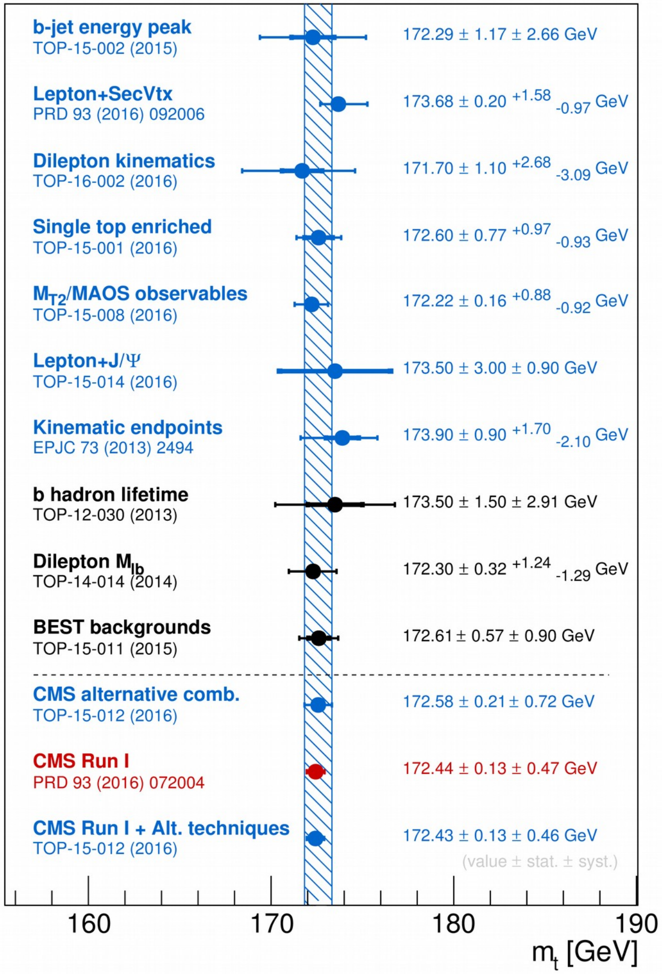




Source	Subcategory	Uncertainty (GeV)
Jet energy scale	In-situ correlation group	$+0.20, -0.21$
	Inter-calibration group	± 0.05
	Flavour-correlation group	± 0.40
	Pileup p_T uncertainty	$+0.18, -0.10$
	Uncorrelated group	$+0.48, -0.40$
	Total	$+0.68, -0.61$
b quark JES and hadronisation model		± 0.15
Jet energy resolution		± 0.05
Muon momentum scale		± 0.05
p_T^{miss}		± 0.15
Pileup		± 0.10
b tagging efficiency		± 0.10
Fit calibration		± 0.39
Background estimate	Shape	± 0.10
	Normalisation	± 0.14
	μ_R and μ_F scales	± 0.18
	Matching scales	± 0.30
	Total	± 0.39
Generator model		± 0.10
Signal μ_R and μ_F scales		± 0.23
Underlying event		± 0.20
Colour reconnection		± 0.05
Parton distribution functions		± 0.05
Total		$+0.97, -0.93$

Combination of measurements using alternative techniques

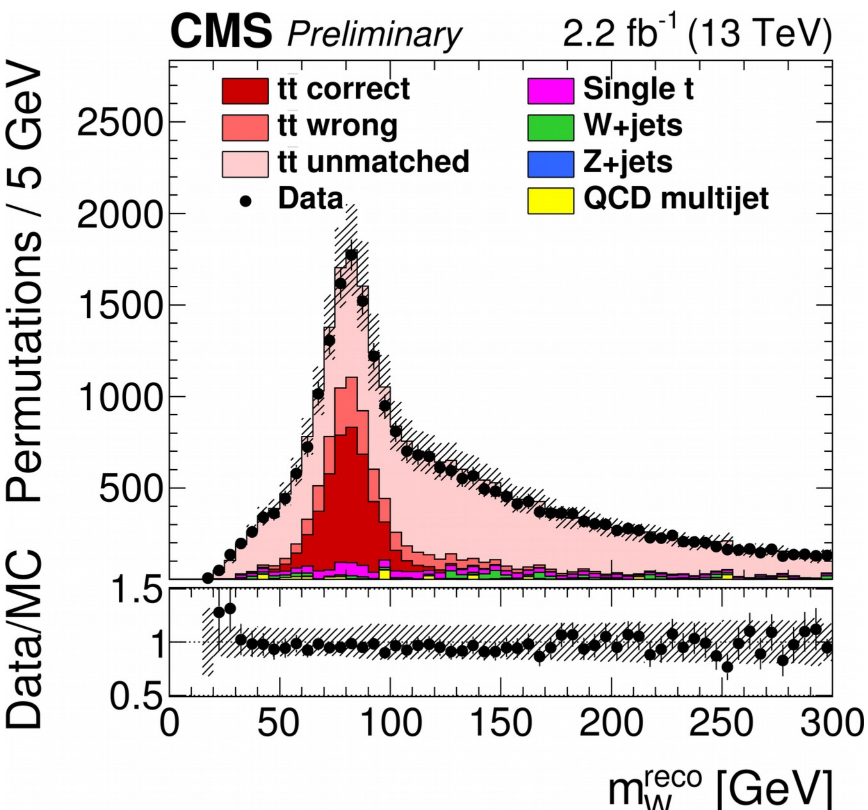
- The combination of the alternative top quark mass measurements results in m_t = 172.58 ± 0.21 (stat) ± 0.72 (syst) GeV with a precision of 0.4%
- This is in very good agreement with the published CMS Run I combination and gives an independent confirmation (CMS-PAS-TOP-15-012)

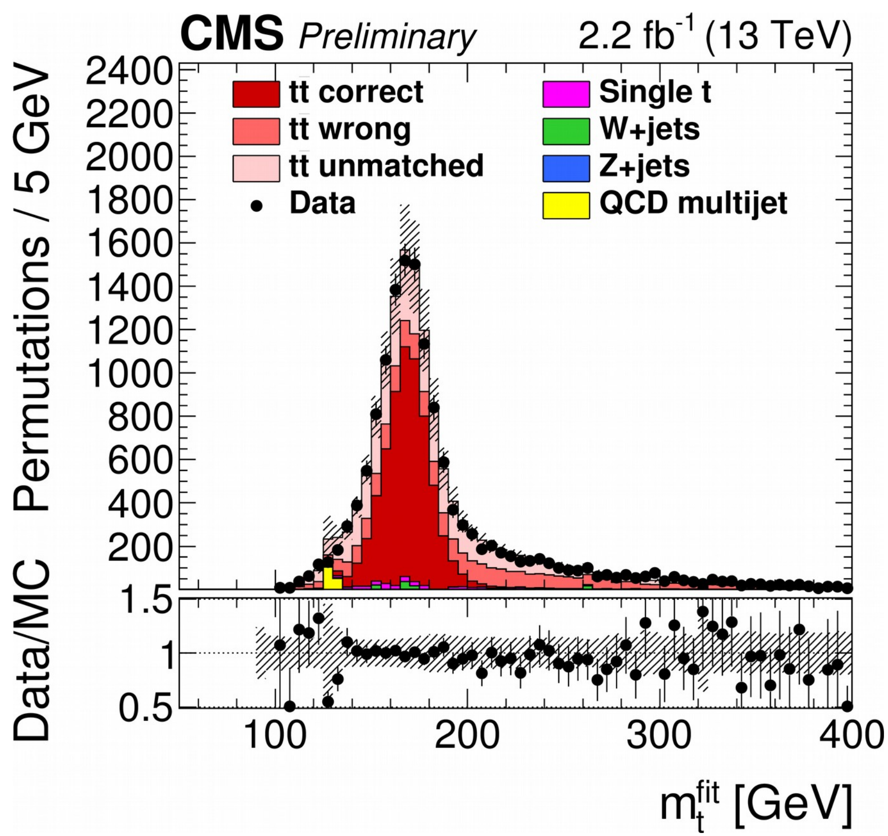


Top quark mass from muon+jets at 13 TeV

Preliminary 13 TeV result: CMS-PAS-TOP-16-022

- Kinematic fit to the top-quark-pair hypothesis
  Permutations are weighted according to P_{gof}





Ideogram Method

$$\mathcal{L}(\mathrm{event}|\mathrm{m_t},\mathrm{JSF}) = \sum_{\mathrm{j}=1}^{\mathrm{n}} \mathrm{P_{gof}}(\mathrm{j})\mathrm{P}(\mathrm{m_{t,j}^{fit}},\mathrm{m_{W,j}^{reco}}|\mathrm{m_t},\mathrm{JSF}),\ j \text{ permutation}$$

$$\boxed{\mathcal{L}(\mathrm{sample}|\mathrm{m_t},\mathrm{JSF})} \sim \prod_{\mathrm{events}} \mathcal{L}(\mathrm{event}|\mathrm{m_t},\mathrm{JSF})$$

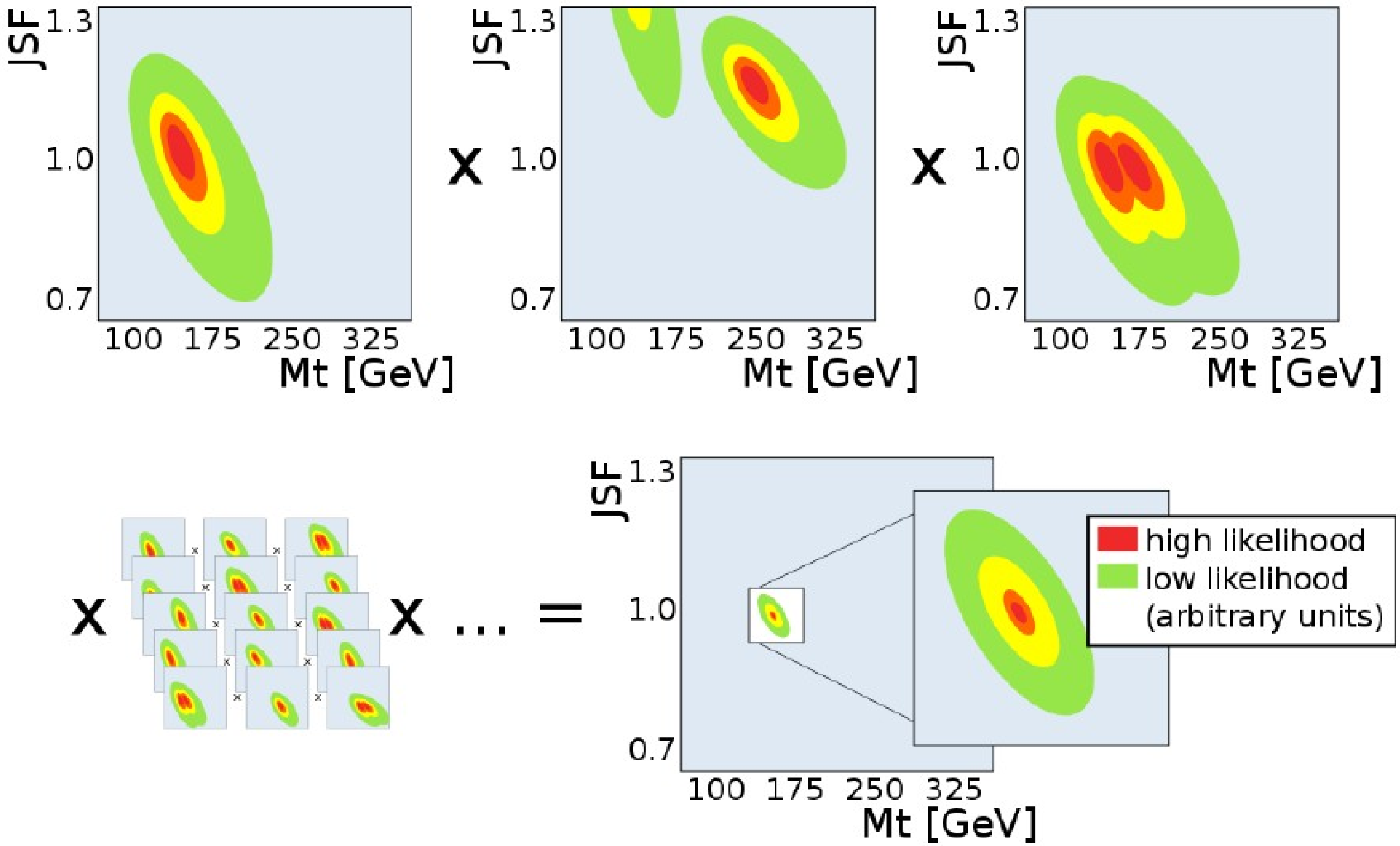
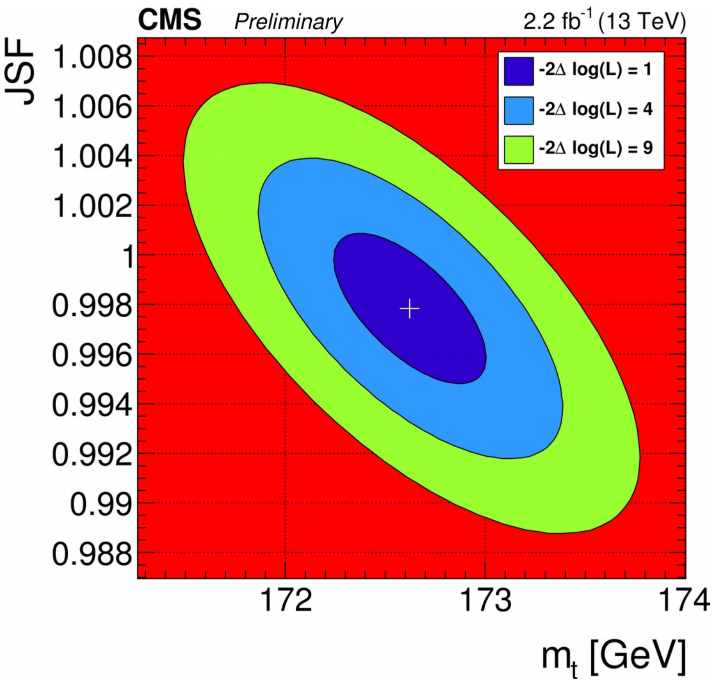
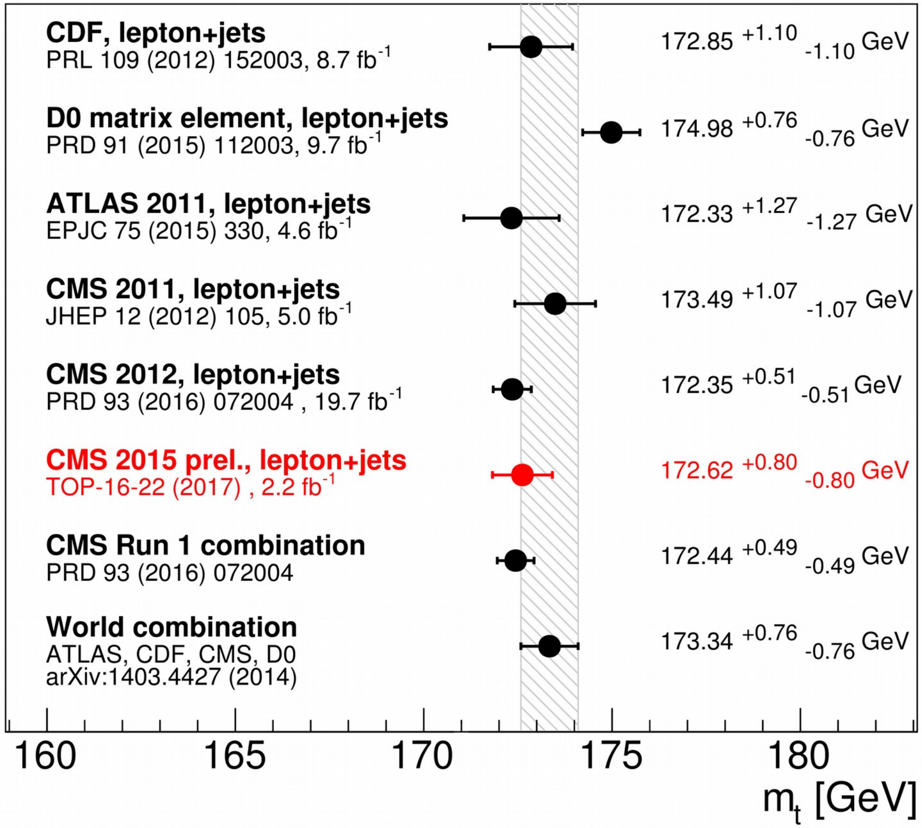


Illustration by M. Seidel

Top quark mass from muon+jets at 13 TeV

- Fit result is consistent with the Run I results.



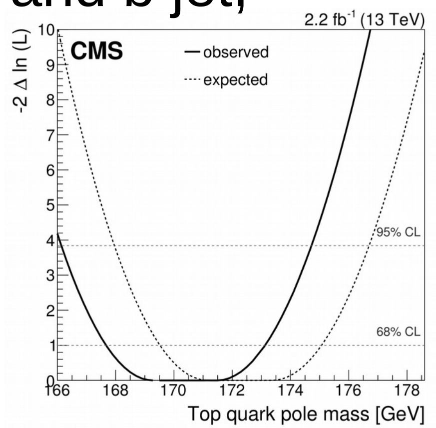


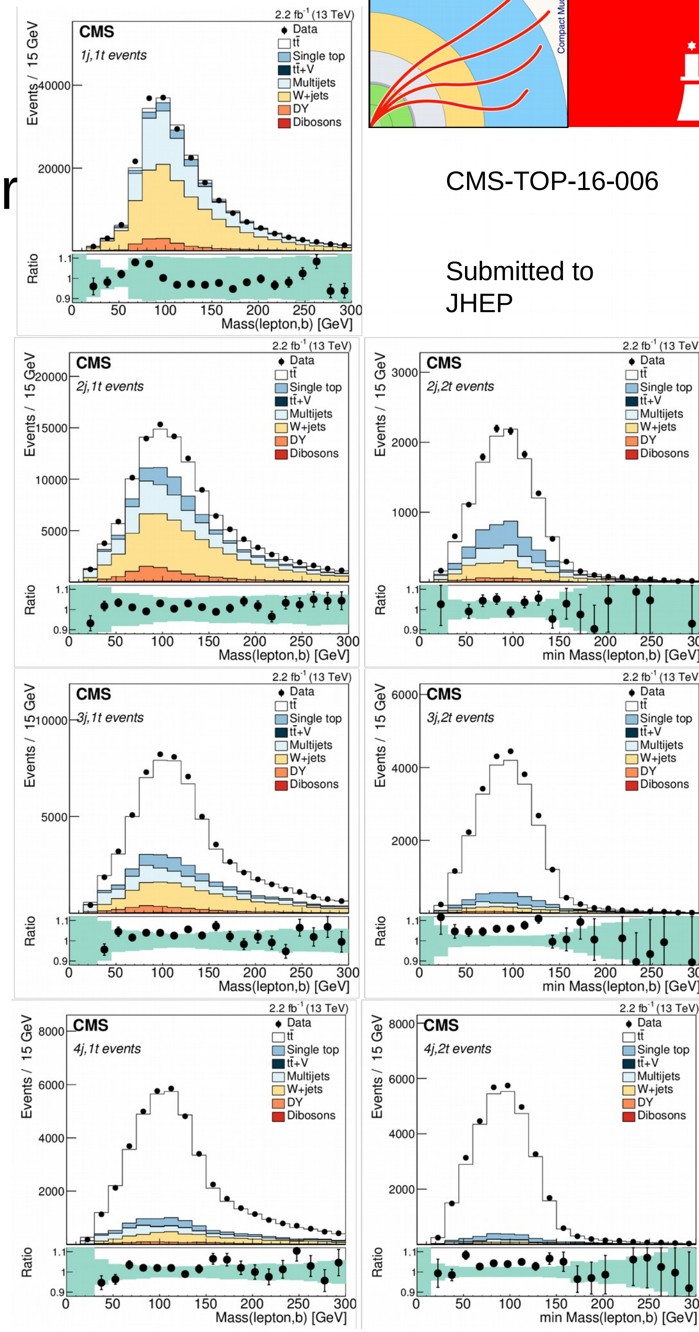
Top pole mass measurement

CMS-TOP-16-006

Submitted to JHEP

- The precise measurement of the top-pair production cross section allows to determine the top-quark pole mass
- In final states with one isolated electron or muon and at least one jet are selected and categorized according jet multiplicity
- From the invariant mass distribution of the isolated lepton and b jet, the cross section is measured.
- Using the expected dependence of the cross section on the pole mass of the top quark M_t is found to be 170.6 GeV





Conclusions

- CMS top quark mass precision has reached an impressive level
- The 13 TeV data set will decrease the statistical uncertainties further
- Systematic effects need to be better understood
  - Correlations between different analysis methods
  - Improvements in the theoretical uncertainties are needed
- More work on mass calibration needed
- Interesting 13 TeV results are incoming for TOP 2017