

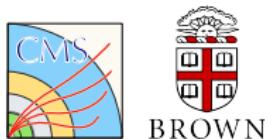
Measurements of the top quark mass at CMS

TQP@PF 2018, FNAL

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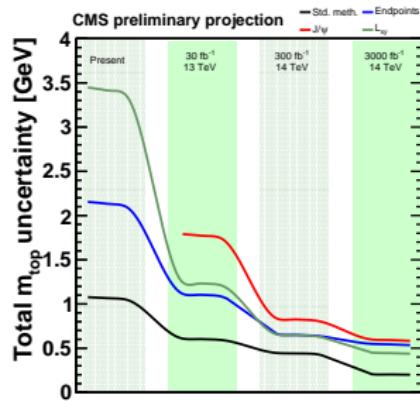


Overview

Central question:

How is CMS pushing top mass measurements to a new precision frontier?

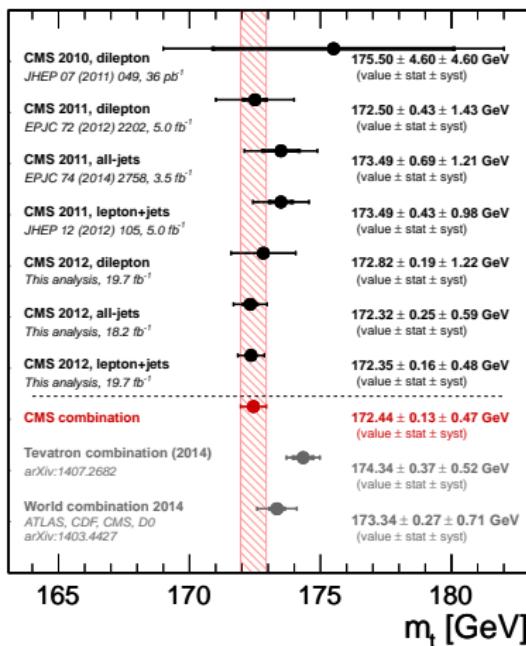
- ▶ Summary of the $\sqrt{s} = 8$ TeV results
 - ▶ Combinations and new results: the current precision frontier
 - ▶ Individual channels & where we push forward
- ▶ Discussion of Run 2 results
 - ▶ Kinematic fits, statistical strategies
 - ▶ Systematics breakdown
- ▶ Concluding remarks



CMS-PAS-FTR-13-017

Run 1 Results

CMS-PAS-TOP-14-022 Run 1 combination



- ▶ CMS combination: total uncertainty of 0.3% via pair production channels
- ▶ Most impacted by flavor corrections and QCD modeling uncertainties

In 2017, 4 top mass publications:

- ▶ Top jet mass, boosted $t\bar{t}$ events
[CMS-PAS-TOP-15-015](#)
- ▶ Pole mass via $t\bar{t}$ production cross section
[CMS-PAS-TOP-16-006](#)
- ▶ m_t in dilepton channel using $M_{bl}, M_{T2}, \text{MAOS}$
[CMS-PAS-TOP-15-008](#)
- ▶ m_t from single top events (!)
[CMS-PAS-TOP-15-001](#)

Channel-by-channel breakdown

All hadrons – 46% of pair prod.

- ▶ $4q \implies$ Multijets background
- ▶ Run 1 with Ideogram method:
[CMS-PAS-TOP-14-022](#)
- ▶ Opportunity to leverage substructure developments in q vs. g discrimination

$\ell + \text{jets}$ – 30% (**45%**) of pair prod.

- ▶ Clean signal, generally most precise channel
- ▶ Limited by b quark JEC's
- ▶ Run 1 with Ideogram method:
[CMS-PAS-TOP-14-022](#)
- ▶ Top jet mass measurement:
[CMS-PAS-TOP-15-015](#)

* Percentages in red include τ decays

Dilepton – 4% (**9%**) of pair prod.

- ▶ $2\nu \implies$ Difficult reconstruction
 - ▶ Attempt to satisfy constraints: M_{T_2}
 - ▶ Give up on neutrinos: $M_{\ell b}$
 - ▶ Run 1: [CMS-PAS-TOP-15-008](#)
- ▶ Analytical Matrix Weighting
 - ▶ Run 1: [CMS-PAS-TOP-14-010](#)
- ▶ Limited by pQCD, b-jet modeling

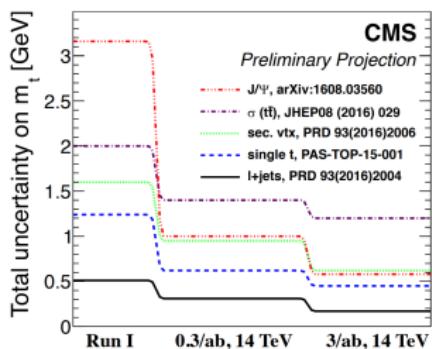
Single top

- ▶ Difficult to isolate from dominant $t\bar{t}$, smaller cross-section
- ▶ First result from CMS published:
[CMS-PAS-TOP-15-001](#)
- ▶ Limited by JES, matching scales

“Alternative measurements”

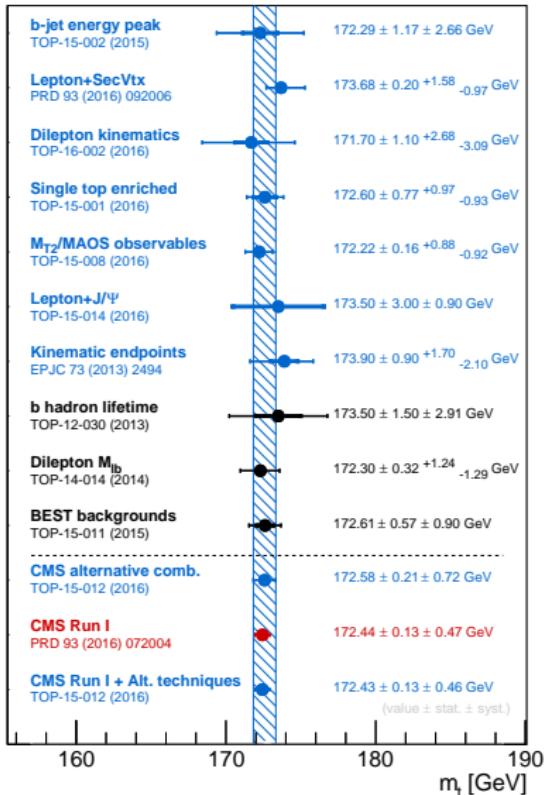
CMS-PAS-TOP-15-012

- ▶ CMS produces a diversity of top mass results
- ▶ Alternatives give 0.4% error
- ▶ Combination of all results yields only slight improvement
- ▶ But, demonstrates consistency of top mass measurements at CMS



CMS-DR-2016-064

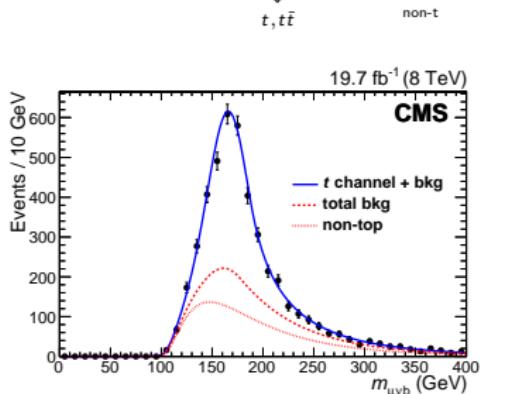
Run 1 Alternative Combination



“Alternative measurements”

Single-top: CMS-PAS-TOP-15-001

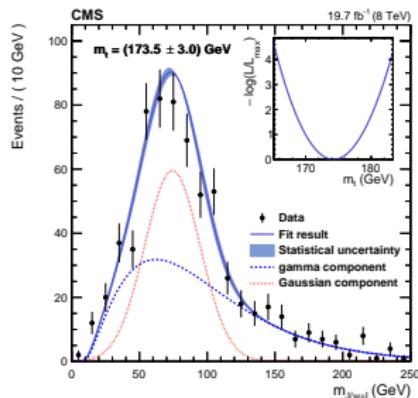
- Unbinned ML fit using $m_{\mu\nu b}$ with Gaussian core, $(2 \times \text{Crystal Ball}) + \text{Novosibirsk tail}$



- $m_t = 172.60 \pm 0.77^{+0.97}_{-0.93} \text{ GeV}$
- Limitations: JES, matching scales
- First top mass result to use single-top-enriched samples in CMS

Lepton+ J/ψ : CMS-PAS-TOP-15-014

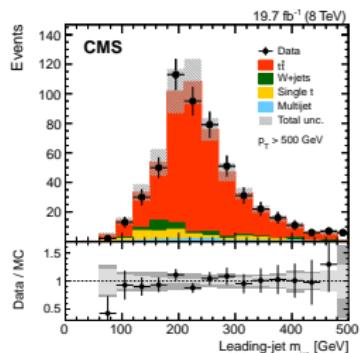
- Decay process within $t\bar{t}$:
 $t \rightarrow (W \rightarrow \ell\nu)(b \rightarrow J/\psi + X \rightarrow \mu^+\mu^- + X)$



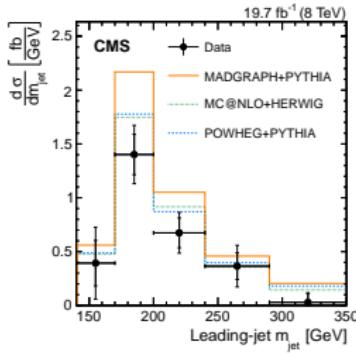
- $m_t = 173.50 \pm 3.00 \pm 0.90 \text{ GeV}$
- Unbinned ML fit: Gaussian+Gamma
- Limitations: μ_F, μ_R , top p_T , matrix element generator/PS matching

$\ell + \text{jets}$ channel:

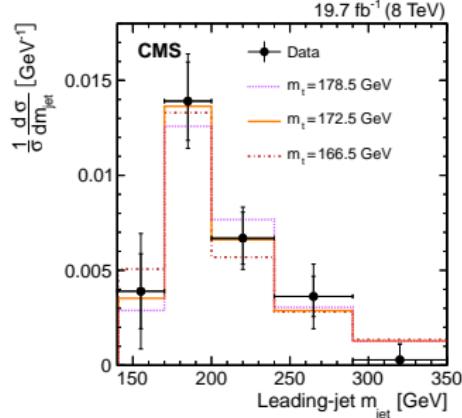
- ▶ Idea: Compute differential $t\bar{t}$ cross section with (1) leading-jet p_T for events with highly-boosted top jets
- ▶ “Unfold” to move from reconstruction to particle level (2)
- ▶ After unfolding, leading-jet p_T peak is sensitive to m_t (3)
- ▶ After a χ^2 fit to data: $m_t = 170.8 \pm 9.0$ GeV
 - ▶ Statistical uncertainty: 6.0 GeV
 - ▶ Modeling uncertainty: 4.6 GeV



(1)



(2)



(3)

Run 2: Pushing the precision frontier

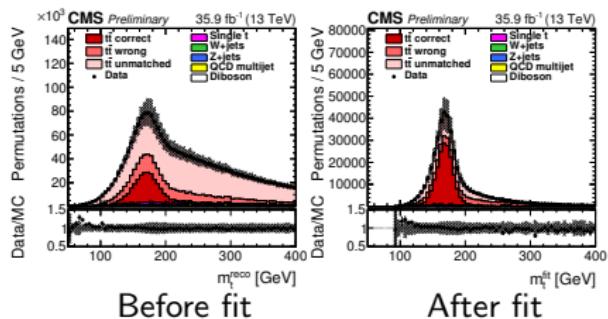
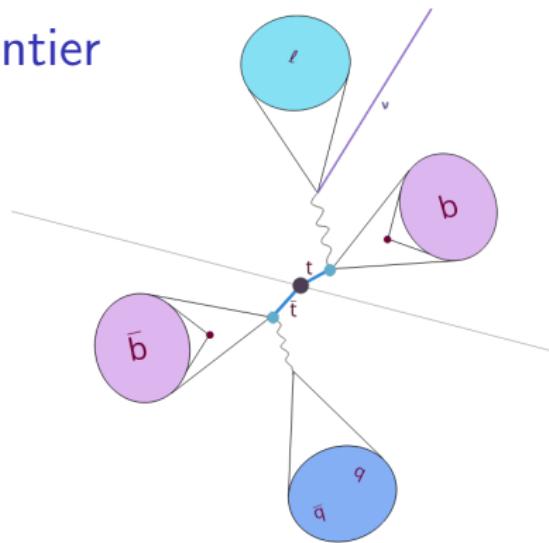
$\ell + \text{jets}$ channel CMS-PAS-TOP-17-007

- ▶ 2j2b events with 1ℓ (e/μ)
 - ▶ AK4 jets, b-tagging uses SV+tracks+MVA (69% eff.)
- ▶ Kinematic fits generate m_t , m_W distributions, improve signal purity

$$\chi^2 = (x^f - x^m)^T \cdot \mathbb{G} \cdot (x^f - x^m)$$

$$P_{gof} = e^{-\frac{1}{2}\chi^2} \geq 0.2$$

- ▶ Weighting by P_{gof} improves probability of correct parton-jet assignment



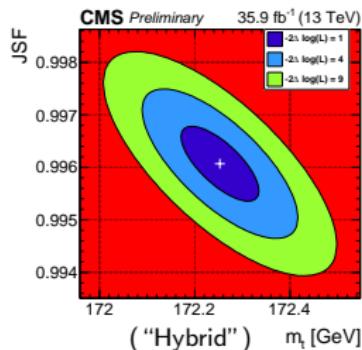
Perform ML fit to data:

- **Ideogram method** constrains mass, jet energy scale factor (JSF)

$$\mathcal{L}(\text{sample}|m_t, JSF) = P(JSF) \prod_{\text{events}} \left(\sum_{i=1}^n P_{gof}(i) \left(\sum_j f_j P_j(m_{t,i}^{\text{fit}}|m_t, JSF) \times P_j(m_{W,i}^{\text{reco}}|m_t, JSF) \right)^{w_i} \right)$$

- $n = \#$ parton-jet permutations (perm.)
- j -sum runs over correct/wrong/unmatched perm.
- w_i = event weight emphasizes events with correct perm.

- Presents 1D fit, 2D fit, and “Hybrid” fit ($P(JSF)$ as Gaussian)



Effects on results:

- Benefit: syst. impact of JEC reduced (0.74 GeV 1D $\rightarrow \sim 0.15$ GeV 2D)
- In 2D options, have to balance uncertainties on JSF

Run 2: $\ell + \text{jets}$

CMS-PAS-TOP-17-007

Result:

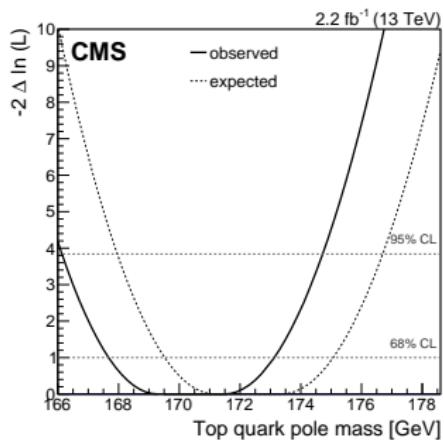
$$m_t^{\text{hyb}} = 172.25 \pm 0.08(\text{stat.} + \text{JSF}) \pm 0.62(\text{syst.}) \text{ GeV}$$

$$\text{JSF}^{\text{hyb}} = 0.996 \pm 0.001(\text{stat.}) \pm 0.008(\text{syst.})$$

Systematic breakdown →

- ▶ Key: Affects all / Affects some
- ▶ First Run 2 measurement with NLO generator setups.
- ▶ bJEC impacts persist
- ▶ Color reconnection modeling more rigorous than in Run 1
 - ▶ Constraints will tighten
- ▶ Factor of 2 improvement on stat. unc. relative to Run 1

	2D approach δm_t^{2D} (GeV)	1D approach δm_t^{1D} (GeV)	Hybrid δm_t^{hyb} (GeV)	$\delta \text{JSF}^{\text{hyb}}$ (GeV)
Experimental uncertainties				
Method calibration	0.05	<0.001	0.05	0.05 <0.001
Jet energy corrections (quad. sum)	(0.13)	(0.002)	(0.85)	(0.19) (0.003)
- JEC: InterCalibration	0.02	<0.001	0.16	0.04 <0.001
- JEC: MPFInSitu	0.01	<0.001	0.23	0.07 <0.001
- JEC: Uncorrelated	0.13	0.002	0.78	0.16 0.003
Jet energy resolution	0.08	0.001	0.04	0.04 0.001
b tagging	0.03	<0.001	0.01	0.03 <0.001
Pileup	0.08	0.001	0.02	0.05 0.001
Non- $t\bar{t}$ background	0.04	0.001	0.02	0.02 0.001
Modeling of hadronization				
JEC: Flavor (linear sum)	(0.42)	(0.001)	(0.31)	(0.39) (<0.001)
- light quarks (uds)	0.12	-0.001	-0.01	+0.07 0.001
- charm	0.03	<0.001	-0.01	0.02 <0.001
- bottom	-0.31	<0.001	-0.31	-0.31 <0.001
- gluon	-0.23	0.003	0.02	-0.15 0.002
b-jet modeling (quad. sum)	(0.13)	(0.001)	(0.09)	(0.12) (<0.001)
- b fragmentation Bowler-Lund	0.07	<0.001	0.01	0.05 0.001
- b fragmentation Peterson	0.04	<0.001	0.05	0.04 <0.001
- semileptonic B hadron decays	0.11	<0.001	0.08	0.10 <0.001
Modeling of perturbative QCD				
PDF	0.02	<0.001	0.02	0.02 <0.001
Ren. and fact. scale	0.02	0.001	0.02	0.01 <0.001
ME/PS matching threshold	0.08	0.001	0.03	0.05 0.001
ME generator	0.19	0.001	0.29	0.22 0.001
ISR PS scale	0.07	0.001	0.10	0.06 <0.001
FSR PS scale	0.24	0.004	0.22	0.13 0.003
Top-quark transverse momentum	<0.01	<0.001	<0.01	<0.01 <0.001
Modeling of soft QCD				
Underlying event	0.07	0.001	0.10	0.06 <0.001
Early resonance decays	0.22	0.008	0.42	0.03 0.005
Color reconnection modeling	0.34	0.001	0.23	0.31 0.001
Total systematic	0.71	0.010	1.09	0.62 0.008
Statistical (expected)	0.09	0.001	0.05	0.07 0.001
Total (expected)	0.72	0.010	1.09	0.62 0.008



Source	Δm_t [GeV]
Uncertainties from the fit in the fiducial region	-2.2 / +2.5
Extrapolation to the full phase space	-0.7 / +1.1
Beam energy	-0.08 / +0.12
μ_R/μ_F and PDF+ α_S	-0.9 / +1.1
Total	± 2.7

Extract m_t given parametric dependence of production cross-section, $\sigma_{t\bar{t}}$, on mass

$\ell+\text{jets}$ channel:

$$m_t = 170.6 \pm 2.7 \text{ GeV}$$

- ▶ On 2.2 fb⁻¹ of Run 2 data
- ▶ Categorize by jet/b multiplicity, lepton charge/flavor
 - ▶ 44 categories in total
- ▶ Limited by uncertainties on $\sigma_{t\bar{t}}$
- ▶ Previous World Combination:

$$173.34 \pm 0.27 \text{ (stat.)} \pm 0.71 \text{ (syst.)} \text{ GeV}$$

In summary & the path ahead

- ▶ In Run 1, CMS reached a precision of 0.3% on m_t
- ▶ Our public Run 2 result demonstrates improvements thanks to the increased luminosity and center-of-mass energy at the LHC
- ▶ Top mass *distribution* is replete with physical information
 - ▶ Repeating measurement procedures... for now
 - ▶ "While we have data, we have hope"
- ▶ More results to come + future combinations and collaboration.

