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Measurement of the Top-Quark Mass with CMS

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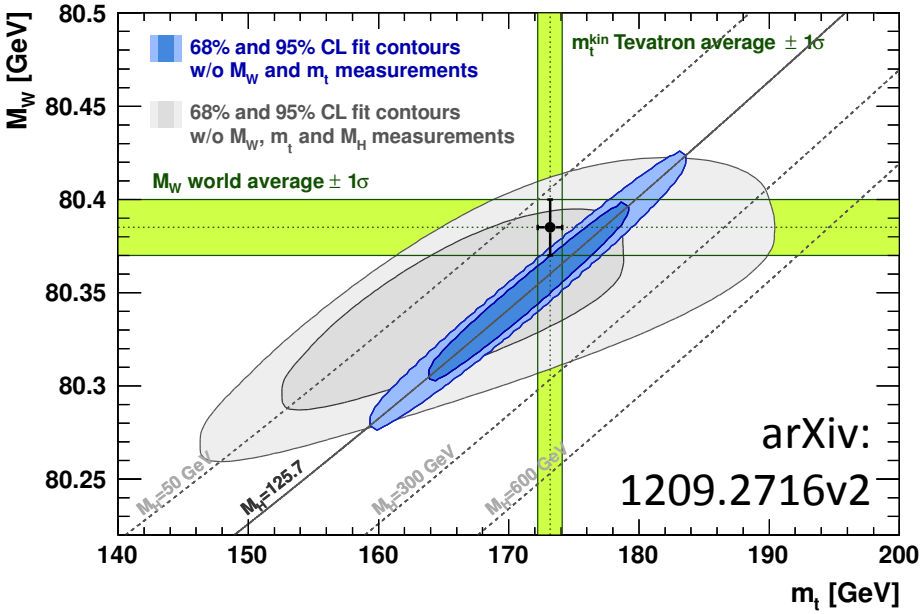
Universität Hamburg
on behalf of the CMS collaboration

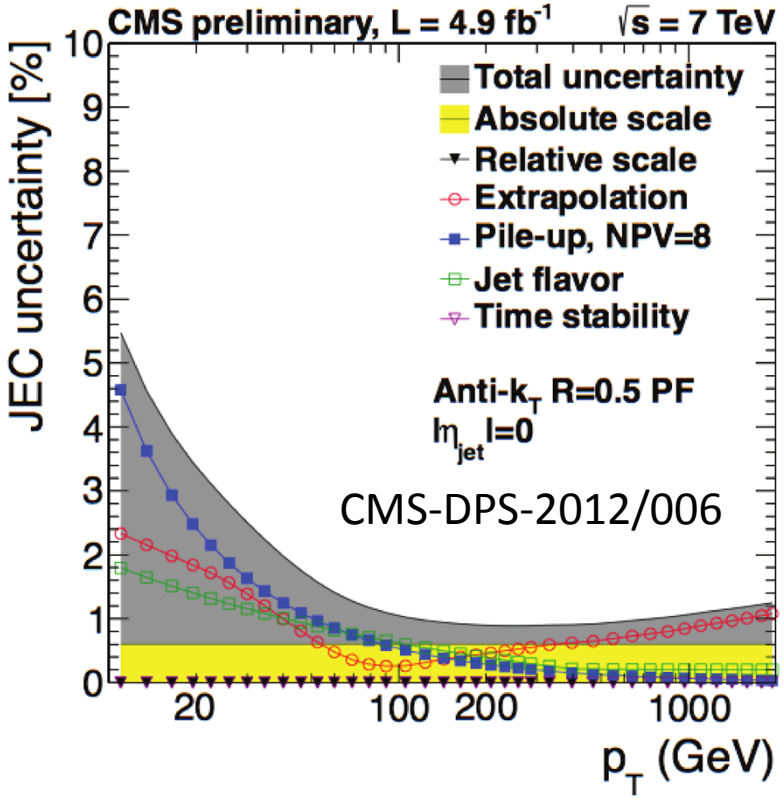
Motivation

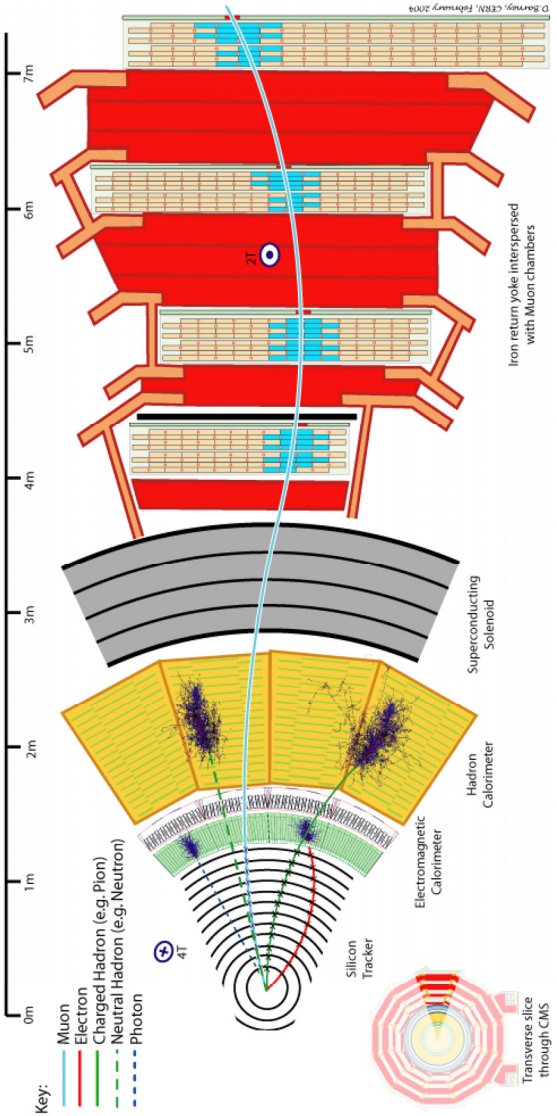
- Important parameter of SM → check consistency (esp. in combination with m_W and m_H)
- Number of top quark pair events:
  - 2011 @ 7 TeV: $N_{tt} = L \times \sigma = 800k$
  - 2012 @ 8 TeV: $N_{tt} = L \times \sigma = 4.8M$
- Tevatron combination:
  - $m_{top} = 173.20 \pm 0.87$ GeV **(5.0‰)**



CMS Experimental Tools

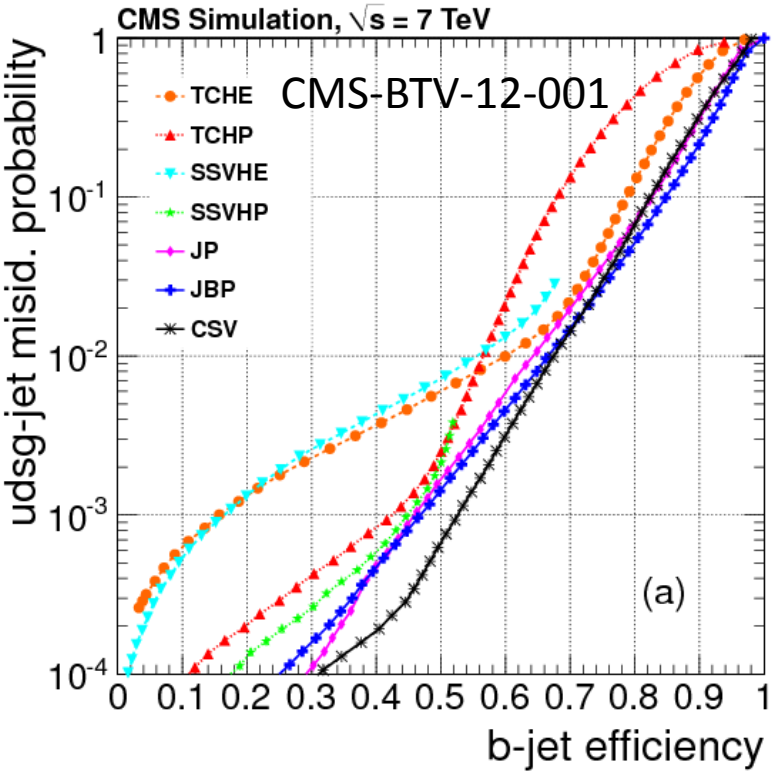
- Jets with Anti-k_t (R=0.5) algorithm
  - $p_T > 30$ GeV & $|\eta| < 2.4$
  - Particle Flow: combine all sub-detectors





CMS Experimental Tools

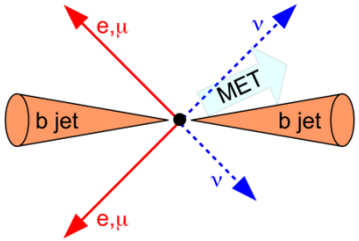
- b tagging
  - MVA algorithm exploiting lifetime of B mesons
- Isolated lepton (muon & electron)
  - Single lepton:
    - $p_T > 30$ GeV & $|\eta| < 2.1$
  - Double lepton:
    - $p_T > 20$ GeV & $|\eta| < 2.4$
- Missing transverse energy
  - From PF particles

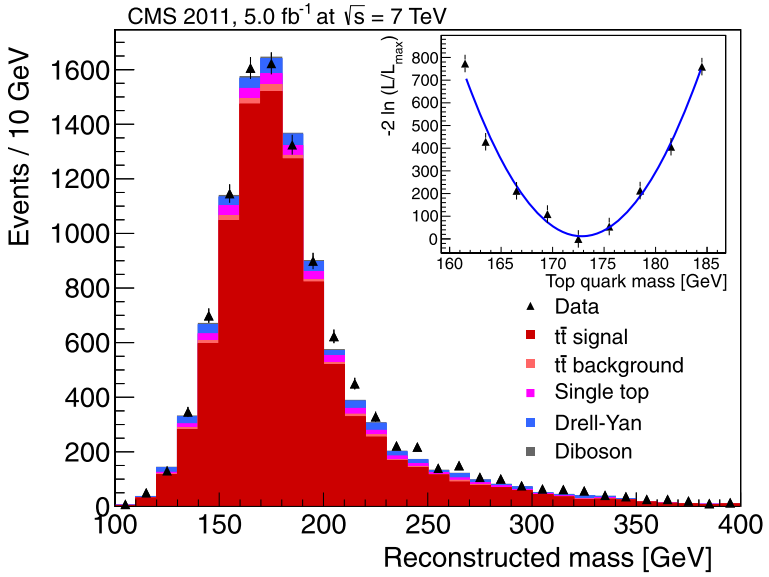


Dilepton Channel

CMS-PAS-TOP-11-016
arXiv: 1209.2393
Eur. Phys. J. C72 (2012) 2202

- Require: =2 isolated e/μ, ≥2 jets, ≥1 b tag
- After selection 9934 events (89% $t\bar{t}$ signal)
- Uses analytical matrix weighting
  - Scan for different m_t hypotheses
  - Solve kin. equations of $t\bar{t}$ system (under constrained)
  - Events weighted with PDF(lepton energy in top rest frame)
- Result on 5.0 fb^{-1} @ 7 TeV:
  - m_t = 172.5 ± 0.4 (stat.)
    ± 1.5 (syst.) GeV **(9.0‰)**
- Main uncertainties:
  - Jet energy scale (JES)
  - bJES

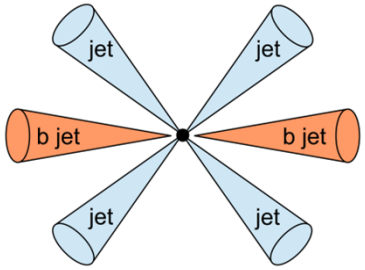


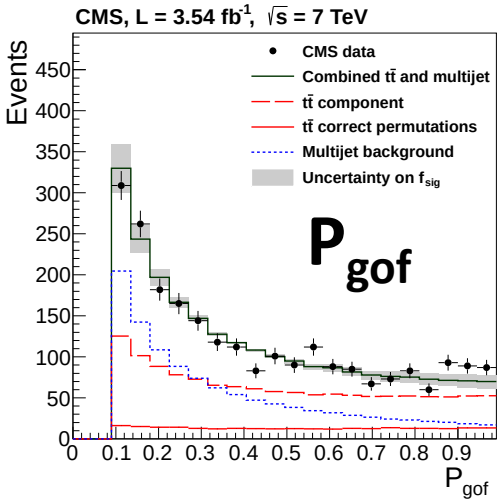


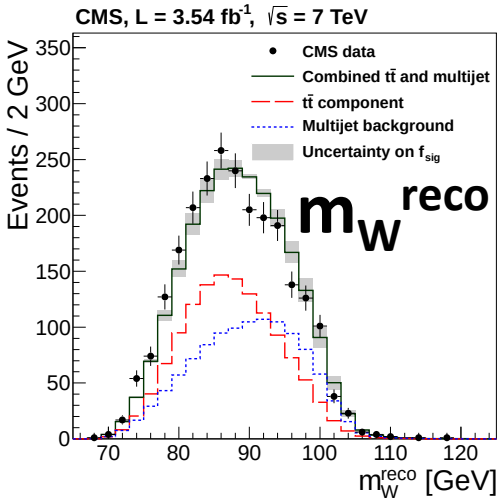
All-jets Channel

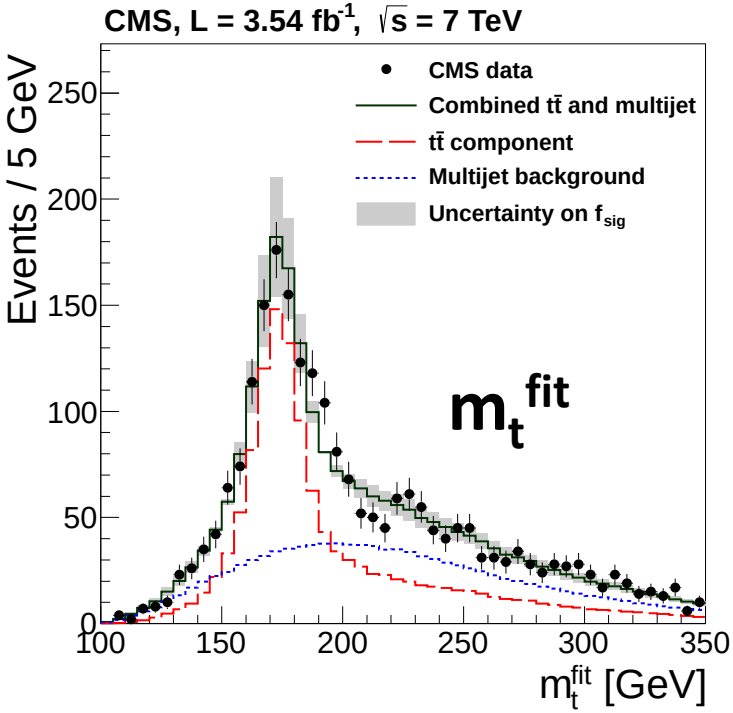
CMS-PAS-TOP-11-017
arXiv: 1307.4617
Submitted to EPJC

- Selection: ≥ 6 jets (>4x60/50/40 GeV), ≥ 2 b tags
- Kinematic fit:
  - 2 x 2 untagged jets: m_{jj} = 80.4 GeV
  - Combine with two b jets: $m_{jjb,1} = m_{jjb,2}$
- After final selection:
  - 2418 events, 51% $t\bar{t}$ signal



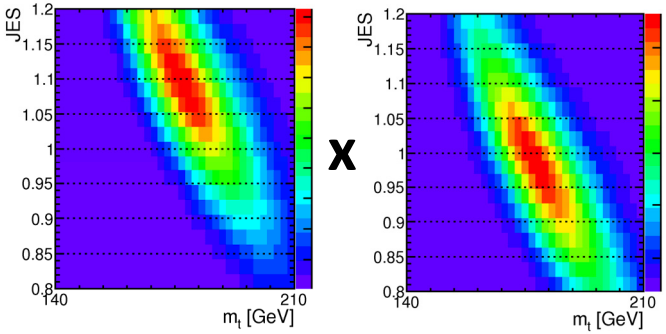
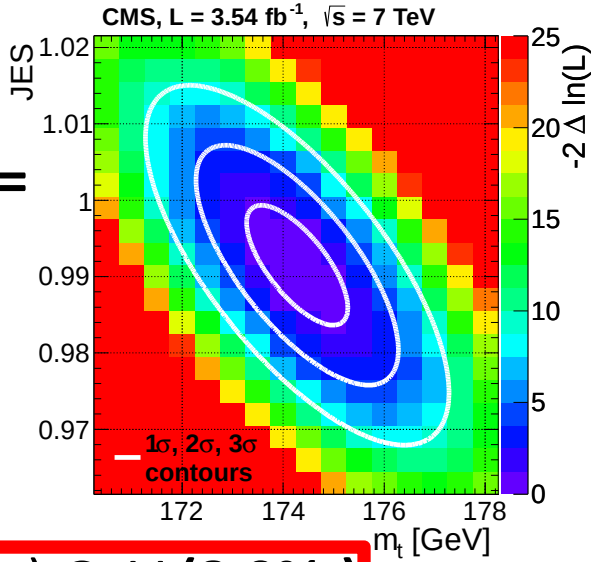






All-jets Channel

CMS-PAS-TOP-11-017
arXiv: 1307.4617
Submitted to EPJC

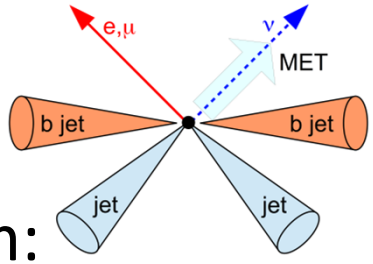
- Ideogram Method:
  - $\mathcal{L}(m_t, \mathrm{JES}|\mathrm{sample}) \sim \Pi_{\mathrm{events}} P\left(m_t{}^{fit}, m_W{}^{reco} \middle| m_t, \mathrm{JES}\right)^{P_{\mathrm{gof}}}$
  - **-2 ln (**  **x** **x …) =** 

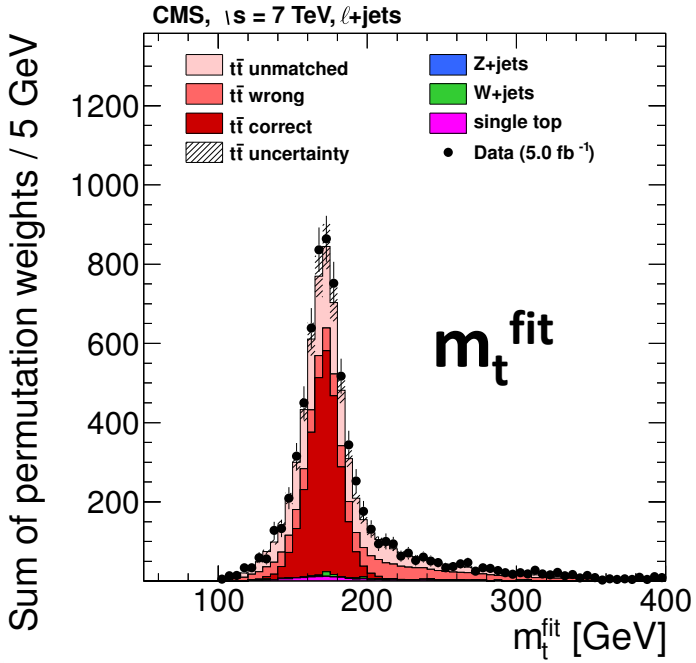
- Extract m_t (and JES) after calibration
- Result on 3.54 fb^{-1} @ 7 TeV:
  - m_t (1D) = 173.49 ± 0.69 (stat.) ± 1.21 (syst.) GeV **(8.0‰)**
  - m_t (2D) = 174.28 ± 1.00 (stat.+JES) ± 1.23 (syst.) GeV **(9.1‰)**
  - JES = 0.991 ± 0.008 (stat.) ± 0.013 (syst.)
- Main uncertainties: Jet energy scale (JES), bJES

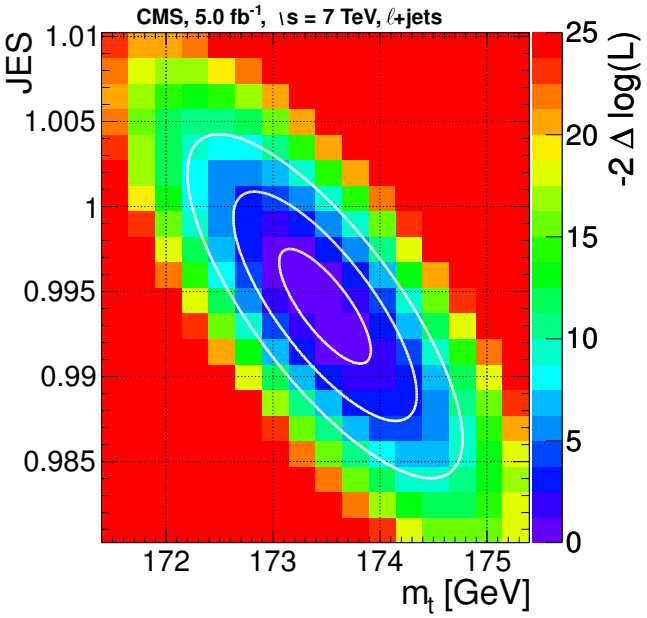
Lepton+Jets Channel

CMS-PAS-TOP-11-015
arXiv: 1209.2319
JHEP 12 (2012) 105

- Require: =1 isolated e/μ, ≥4 jets, ≥2 b tags
- After selection 5174 events (96% $t\bar{t}$ signal)
- Result on 5.0 fb^{-1} @ 7 TeV with 2D ideogram:
  - m_t = 173.49 ± 0.43 (stat.+JES) ± 0.98 (syst.) GeV **(6.2‰)**
  - JES = 0.994 ± 0.003 (stat.) ± 0.008 (syst.)

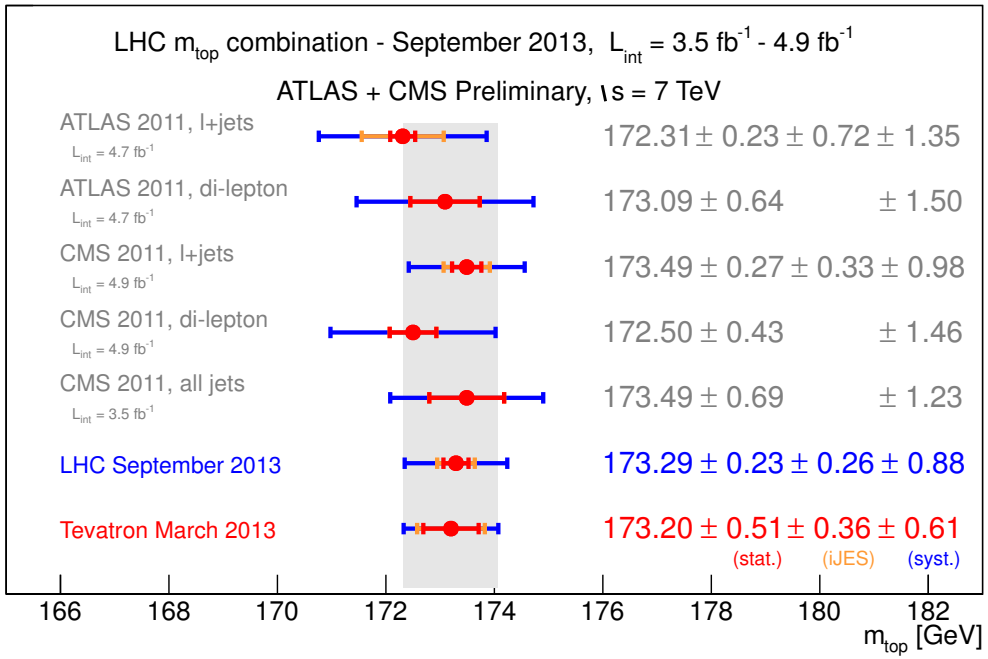






Combination

LHC Combination



CMS Combination

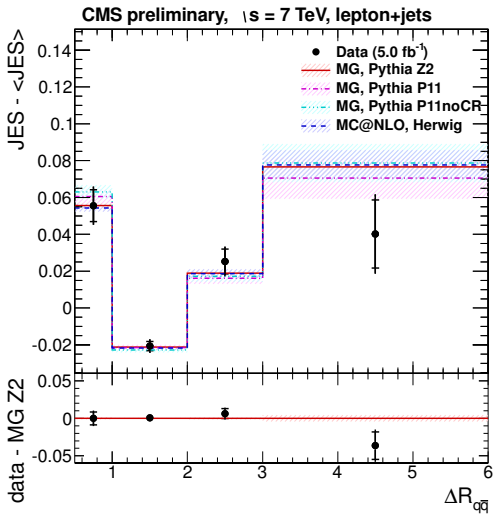
$$m_t^{CMS} = 173.59 \pm 1.03 \text{ GeV} \quad (5.9‰)$$

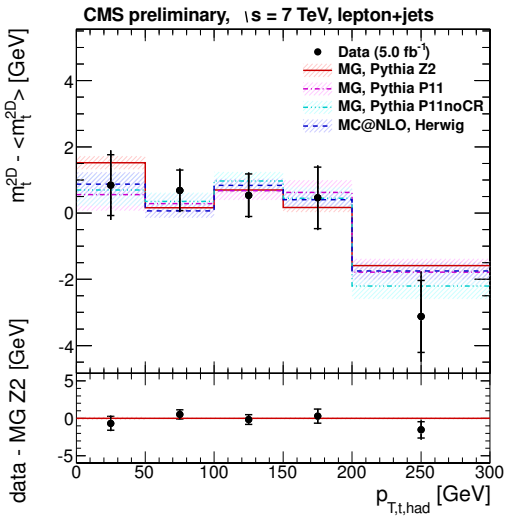
$$m_t^{LHC} = 173.29 \pm 0.95 \text{ GeV} \quad (5.5‰)$$

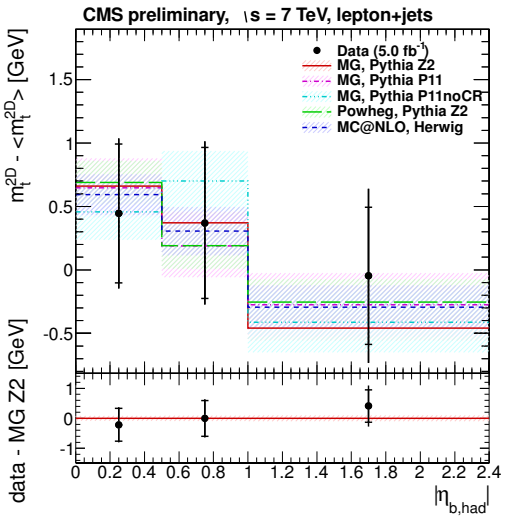
Main systematic uncertainties (both combinations): bJES & modeling

Differential Top-Quark Mass

- Based on lepton+jets analysis (JHEP 12 (2012) 105)
- Study color reconnection and radiations in details
- Results dm_t/dx available for 12 kinematic variables
- First binned m_t measurement
- Sensitivity limited by sample size → 20 fb^{-1} @ 8 TeV
- No mis-modeling observed: $\chi^2/ndf = 68/78 \rightarrow P = 0.77$



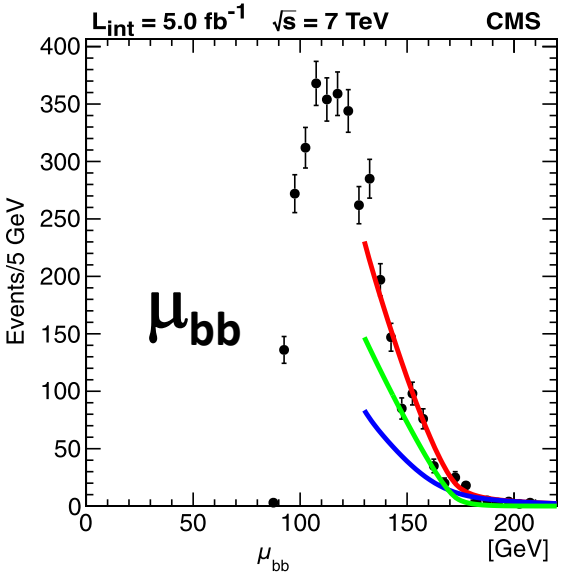


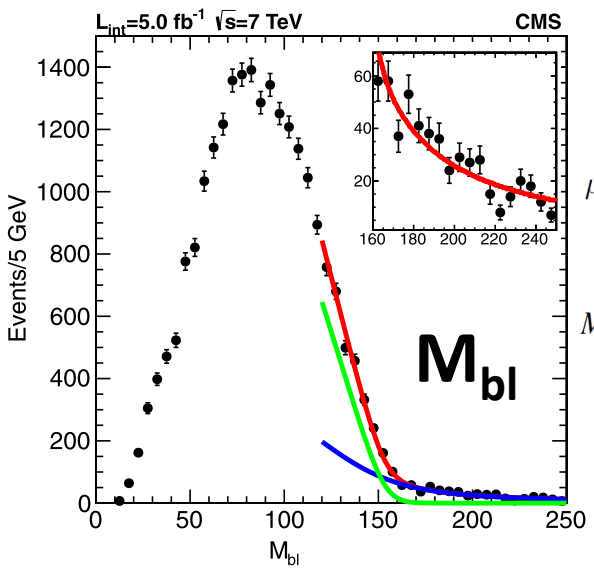


Kinematic Endpoint

CMS-PAS-TOP-11-027
arXiv: 1304.5783
Eur. Phys. J. C73 (2013) 2494

- Endpoints of invariant/transverse mass sensitive to mass
- Require: =2 isolated e/μ, ≥2 b tagged jets
- Endpoints are fitted with MC independent shapes
- Result on 5.0 fb^{-1} @ 7 TeV:
  - $m_t = 173.9 \pm 0.9\ (\text{stat.})\ ^{+1.7}_{-2.1}\ (\text{syst.})$ GeV **(13.1‰)**





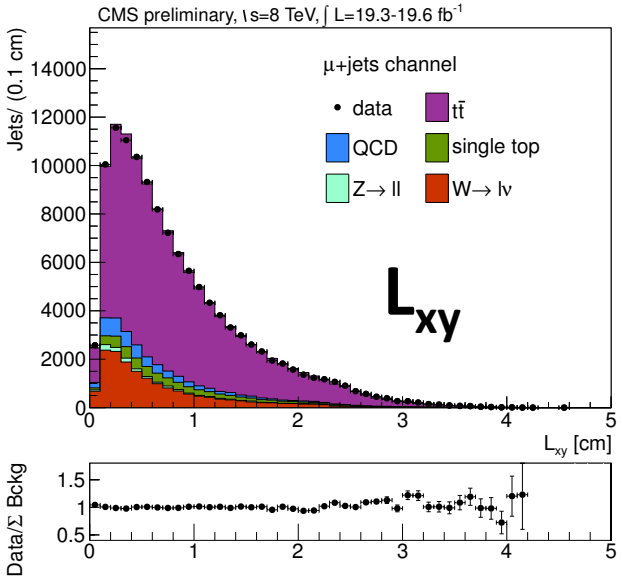
$$\mu_{bb} = \frac{M_t}{2}\left(1 - \frac{M_W^2}{M_t^2}\right) + \sqrt{\frac{M_t^2}{4}\left(1 - \frac{M_W^2}{M_t^2}\right)^2 + \tilde{M}_W^2}$$

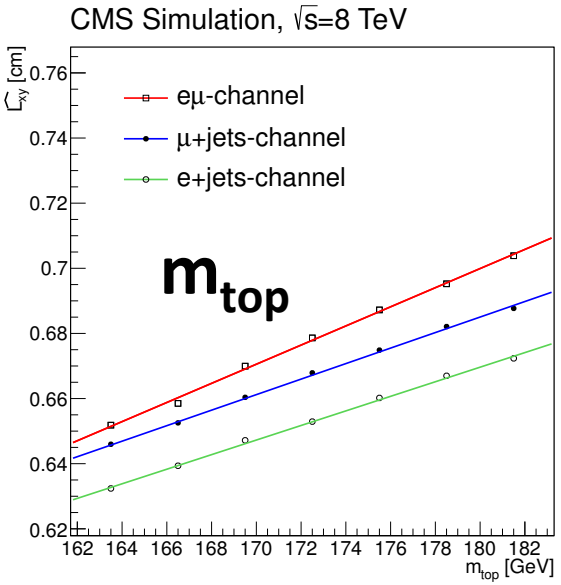
$$M_{b\ell} = \sqrt{m_b^2 + \left(1 - \frac{m_\nu^2}{M_W^2}\right)(E_W^* + p^*)(E_b^* + p^*)}$$

B-Hadron Lifetime

- Boost of B hadron correlated with m_t
- Selection: e/μ+jets, eμ dilepton
- Track-based → reduced JES uncertainty
- Result on 19.0 fb^{-1} @ 8 TeV:
  - m_t = 173.5 ± 1.5 (stat.) ± 1.3 (syst.) ± 2.6 (p_T^{top}) GeV **(18.9‰)**

More details in the talk of Silvia Costantini, next-to-next talk

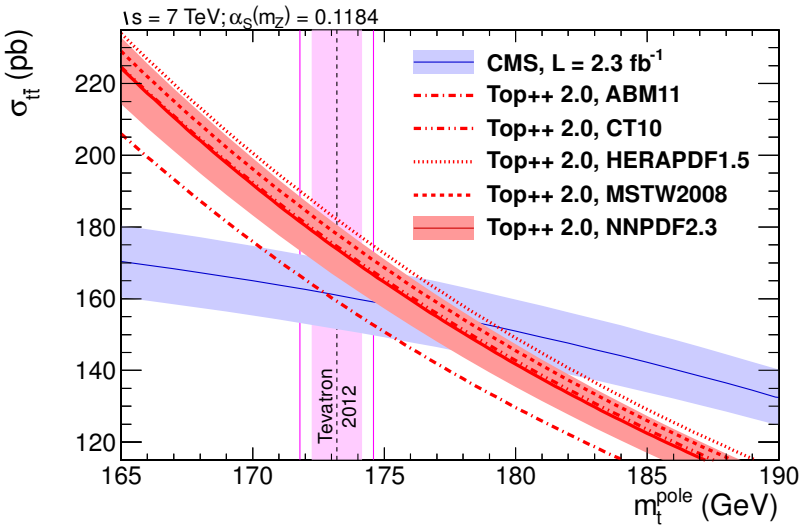


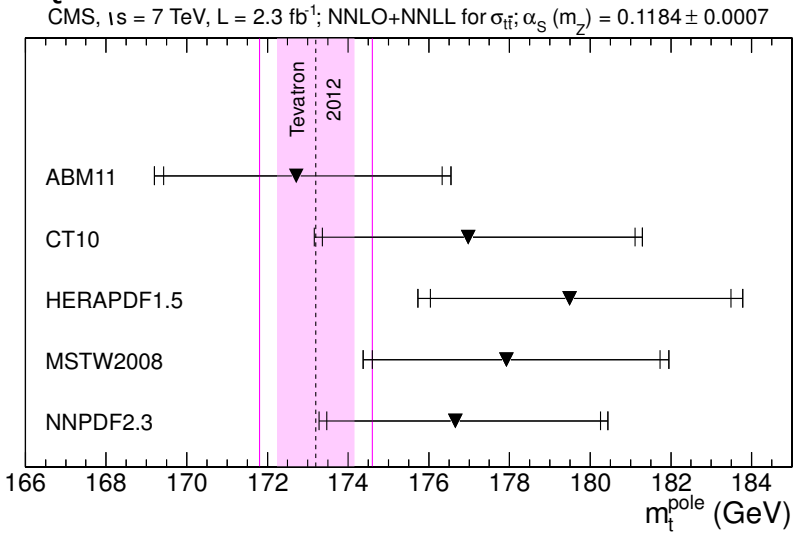


Mass from Cross Section

CMS-PAS-TOP-12-022
arXiv: 1307.1907

- Measure m_t^{pole}, theoretical well understood/motivated
- Based on most precise single $\sigma_{t\bar{t}}$ (JHEP 11 (2012) 067)
- Constrain with theoretical $\sigma_{t\bar{t}}(m_t^{pole}, \alpha_s)$ @ NNLO
- Results with NNPDF2.3:
  - $m_t^{pole} = 176.7\ ^{+3.8}_{-3.4}$ GeV **(21.5‰)** (PDG value for α_s: 0.1184)
  - $\alpha_s(m_Z) = 0.1151\ ^{+0.0033}_{-0.0032}$ ($m_t^{pole} = m_t^{Tevatron} = 173.2$ GeV)





Conclusion

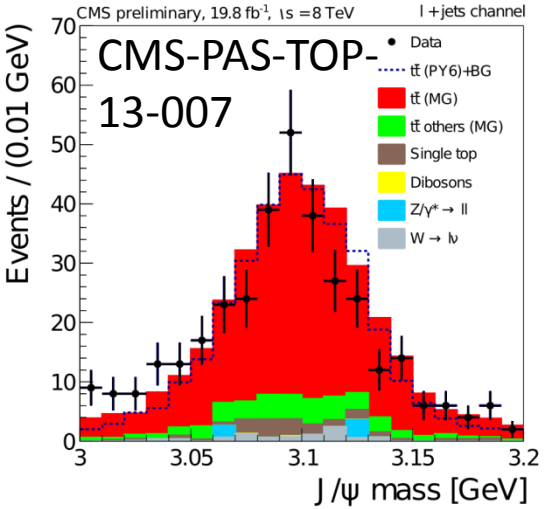
- Use several techniques to improve understanding of m_t
  - Direct measurements (most precise in each channel)
  - Lifetime based
  - Measurement independent of m_t^{MC}
- All measurements in agreement
- Everything well modeled by simulations

- Tevatron combination: **m_t = 173.20 ± 0.87 GeV (5.0‰)**
- CMS combination: **m_t = 173.59 ± 1.03 GeV (5.9‰)**
- LHC combination: **m_t = 173.29 ± 0.95 GeV (5.5‰)**

Outlook

- Larger 2012 dataset @ 8 TeV
  - Even more non-standard techniques become available (J/Ψ)
- Possibility to constrain model uncertainties with data
- Expected uncertainties (CMS-PAS-FTR-13-017):

  L_{int} @ √s : standard / endpoint / lifetime / J/Ψ
  - 30 fb^{-1} @13 TeV: 0.6 GeV / 1.1 GeV / 1.3 GeV / 1.8 GeV
  - 3000 fb^{-1} @14 TeV: 0.2 GeV / 0.5 GeV / 0.4 GeV / 0.6 GeV



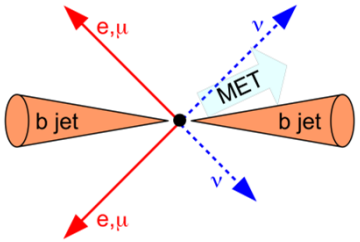
Use $m_{l,J/\Psi}$ to extract m_{top}
arXiv:hep-ph/9912320

Back Up

Dilepton Channel

CMS-PAS-TOP-11-016
arXiv: 1209.2393
Eur. Phys. J. C72 (2012) 2202

- Result on 5.0 fb^{-1} @ 7 TeV:
  - m_t = 172.5 ± 0.4 (stat.) ± 1.5 (syst.) GeV **(9.0‰)**

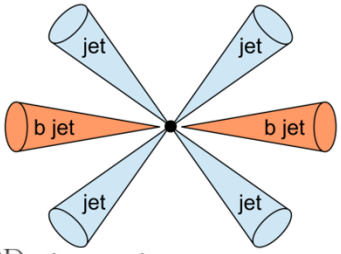


Source	δ_{m_t} (GeV)
Fit calibration	±0.40
Jet energy scale	$^{+0.90}_{-0.97}$
b-JES	$^{+0.76}_{-0.66}$
Lepton energy scale	±0.14
Unclustered E_T	±0.12
Jet energy resolution	±0.14
b tagging	±0.09
Pileup	±0.11
Background normalization	±0.05
Parton distribution functions	±0.09
μ_R and μ_F scales	±0.55
ME-PS matching threshold	±0.19
Underlying event	±0.26
Color reconnection effects	±0.13
Monte Carlo generator	±0.04
Total	±1.48

All-jets Channel

CMS-PAS-TOP-11-017
arXiv: 1307.4617
Submitted to EPJC

- Result on 3.54 fb^{-1} @ 7 TeV:
  - m_t = 173.49 ± 0.69 (stat.) ± 1.21 (syst.) GeV **(8.0‰)**



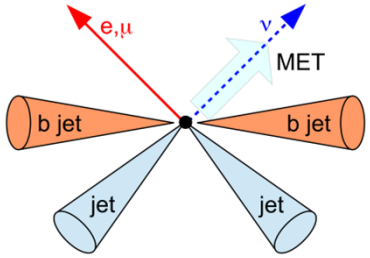
Source	Description	$\delta^{1D}_{m_t}$ (GeV)	$\delta^{2D}_{m_t}$ (GeV)
Fit Calibration	Propagate statistical uncertainty	0.13	0.14
Jet energy scale	Scale all jet energies $\pm\sigma$	0.97	0.10
b-JES	Scale b-jet energies $\pm\sigma_{\text{flavor}}$	0.49	0.52
Jet energy resolution	Scale jet energy resolution $\pm\sigma$	0.15	0.13
b tagging	Shift b-tag working point	0.06	0.10
Trigger	Shift offline p_T cut + 2 GeV	0.24	0.26
Pileup	Number of pile-up events $\pm 5\%$	0.06	0.10
PDF	Uncertainty on CTEQ 6.6 PDF	0.06	0.10
Q^2 scale	Vary by factors of 0.5 and 2	0.22	0.34
ME-PS matching scale	Vary by factors of 0.5 and 2	0.24	0.34
Underlying event	Pythia Tune P11, P11mpiHi, P11TeV	0.20	0.42
Color reconnection	Pythia Tune P11 and P11noCR	0.15	0.58
Multijet background	Vary $f_{\text{sig}} \pm 5\%$ and shape	0.13	0.60
Total	Quadratic sum of syst. uncertainties	1.21	1.23

Lepton+Jets Channel

CMS-PAS-TOP-11-015
arXiv: 1209.2319
JHEP 12 (2012) 105

- Result on 5.0 fb^{-1} @ 7 TeV with 2D ideogram:
  - m_t = 173.49 ± 0.43 (stat.+JES) ± 0.98 (syst.) GeV **(6.2‰)**
  - JES = 0.994 ± 0.003 (stat.) ± 0.008 (syst.)

	δ_{m_t} (GeV)	δ_{JES}
Fit calibration	0.06	0.001
Jet energy scale	0.28	0.001
b-JES	**0.61**	0.000
Lepton energy scale	0.02	0.000
Unclustered E_T	0.06	0.000
Jet energy resolution	0.23	0.004
b tagging	0.12	0.001
Pileup	0.07	0.001
Non-$t\bar{t}$ background	0.13	0.001
Parton distribution functions	0.07	0.001
μ_R and μ_F scales	0.24	0.004
ME-PS matching threshold	0.18	0.001
Underlying event	0.15	0.002
Color reconnection effects	**0.54**	0.004
Total	0.98	0.008



Kinematic Endpoint

CMS-PAS-TOP-11-027
arXiv: 1304.5783
Eur. Phys. J. C73 (2013) 2494

- Result on 5.0 fb^{-1} @ 7 TeV:
  - m_t = 173.9 ± 0.9 (stat.) $^{+1.7}_{-2.1}$ (syst.) GeV **(13.1‰)**

Source	δM_t (GeV)
Jet energy scale	$^{+1.3}_{-1.8}$
Jet energy resolution	± 0.5
Lepton energy scale	$^{+0.3}_{-0.4}$
Fit range	± 0.6
Background shape	± 0.5
Jet and lepton efficiencies	$^{+0.1}_{-0.2}$
Pileup	<0.1
QCD effects	± 0.6
Total	$^{+1.7}_{-2.1}$

B-Hadron Lifetime

- Result on 19.0 fb^{-1} @ 8 TeV:
  - m_t = 173.5 ± 1.5 (stat.) ± 1.3 (syst.) ± 2.6 (p_T^{top}) GeV **(18.9‰)**

Source		Δm_t[GeV]		
		μ+jets	e+jets	$e\mu$
Statistical		1.0	1.0	2.0
Experimental	Jet energy scale	0.30 ± 0.01	0.30 ± 0.01	0.30 ± 0.01
	Multijet normalization (ℓ+jets)	0.50 ± 0.01	0.67 ± 0.01	-
	W+jets normalization (ℓ+jets)	1.42 ± 0.01	1.33 ± 0.01	-
	DY normalization ($\ell\ell$)	-	-	0.38 ± 0.06
	Other backgrounds normalization	0.05 ± 0.01	0.05 ± 0.01	0.15 ± 0.07
	W+jets background shapes (ℓ+jets)	0.40 ± 0.01	0.20 ± 0.01	-
	Single top background shapes	0.20 ± 0.01	0.20 ± 0.01	0.30 ± 0.06
	DY background shapes ($\ell\ell$)	-	-	0.04 ± 0.06
	Calibration	0.42 ± 0.01	0.50 ± 0.01	0.21 ± 0.01
Theory	Q^2-scale	0.47 ± 0.13	0.20 ± 0.03	0.11 ± 0.08
	ME-PS matching scale	0.73 ± 0.01	0.87 ± 0.03	0.44 ± 0.08
	PDF	0.26 ± 0.15	0.26 ± 0.15	0.26 ± 0.15
	Hadronization model	0.95 ± 0.13	0.95 ± 0.13	0.67 ± 0.10
	B hadron composition	0.39 ± 0.01	0.39 ± 0.01	0.39 ± 0.01
	B hadron lifetime	0.29 ± 0.18	0.29 ± 0.18	0.29 ± 0.18
	Top quark p_T modeling	3.27 ± 0.48	3.07 ± 0.45	2.36 ± 0.35
	Underlying event	0.27 ± 0.51	0.25 ± 0.48	0.19 ± 0.37
	Colour reconnection	0.36 ± 0.51	0.34 ± 0.48	0.26 ± 0.37