New approaches in determining m_t: alternative techniques and kinematic dependence

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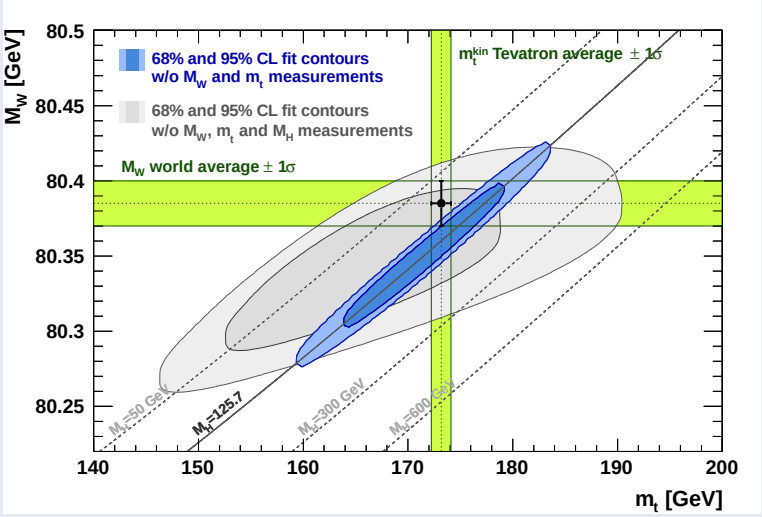
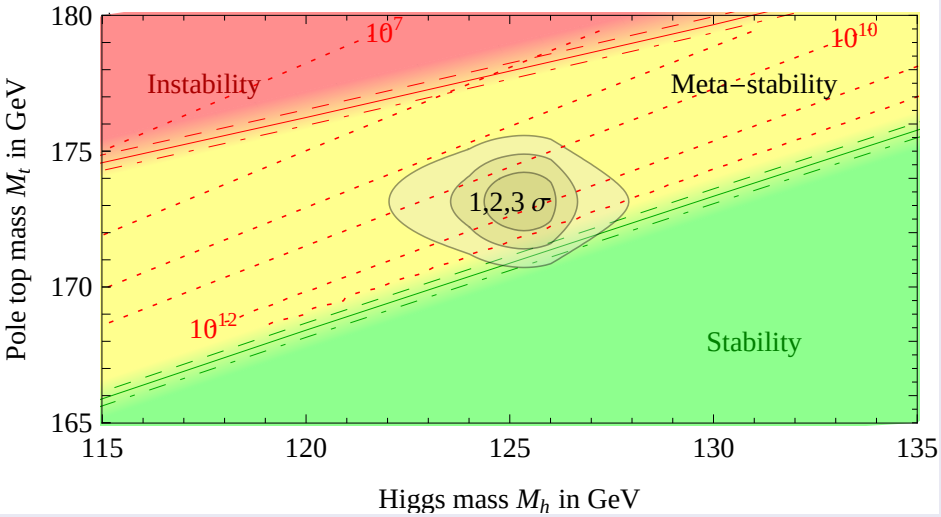
Physics motivation

Why measure M_t with high precision?





- Important for global EW fits (arXiv:1209.2716)
- Fate of universe depends on it! (arXiv:1205.6497)

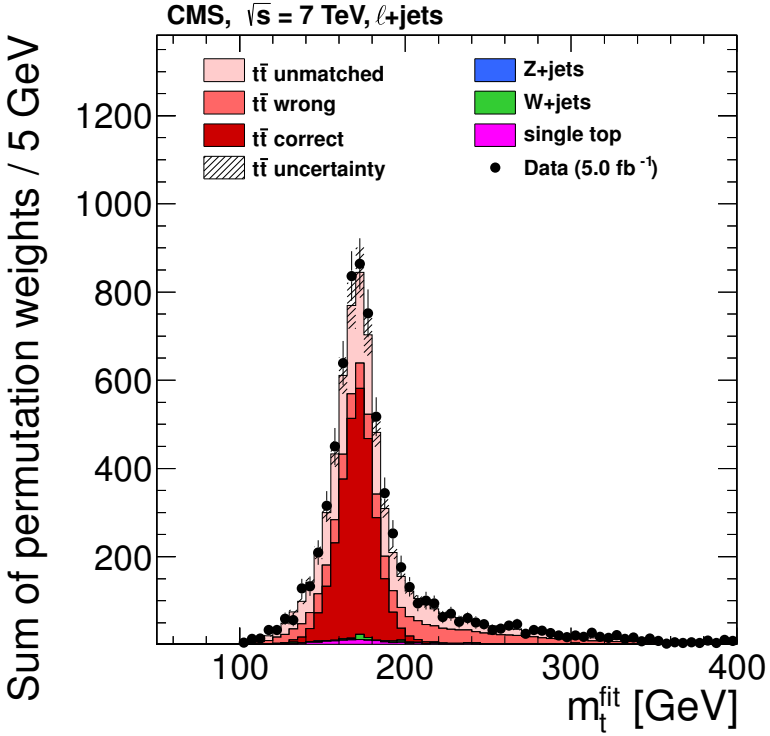
- How to improve $m_t^{observable}$ understanding?
  - Check current understanding of m_t^{obs} modelling in MC simulations
  - What is m_t^{MC} measured with standard techniques? $m_t^{MC} \stackrel{?}{=} m_t^{pole}$
  - Use non-standard techniques (different sensitivity to systematics)

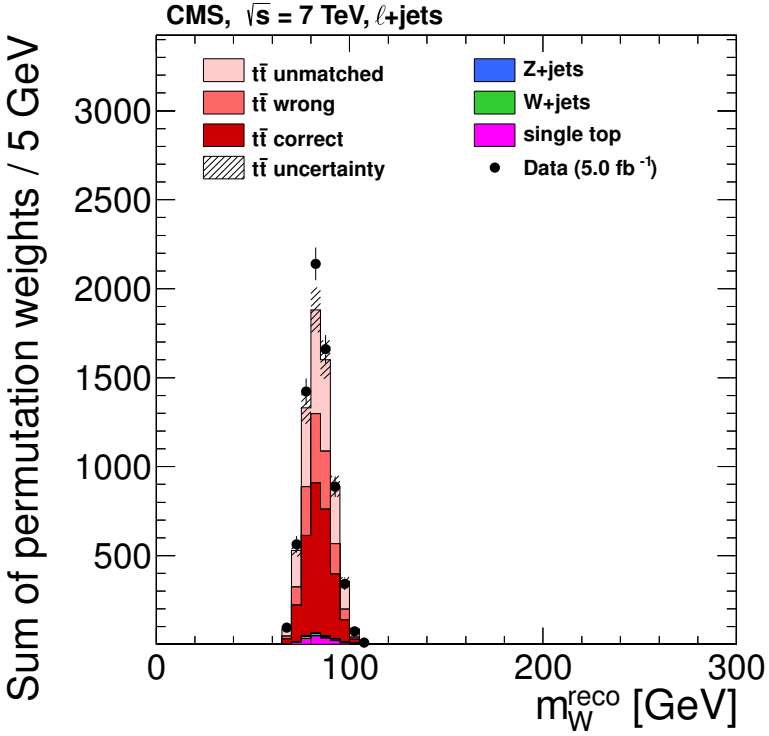
How to improve $m_t^{observable}$ understanding?

- Check current understanding of m_t^{obs} modelling in MC simulations
  - Dependence of m_t^{obs} on event kinematics
    - Increase confidence in current m_t^{obs} modelling in MC
      $\rightarrow$ compare MadGraph, PowHeg & MC@NLO
    - Sensitive to soft-QCD effects
      $\rightarrow$ underlying event, color reconnection, ...
- What is m_t^{MC} measured with standard techniques? $m_t^{MC} \stackrel{?}{=} m_t^{pole}$
- Use non-standard techniques (different sensitivity to systematics)

Dependence of m_t^{obs} on event kinematics (CMS-PAS-TOP-12-029)

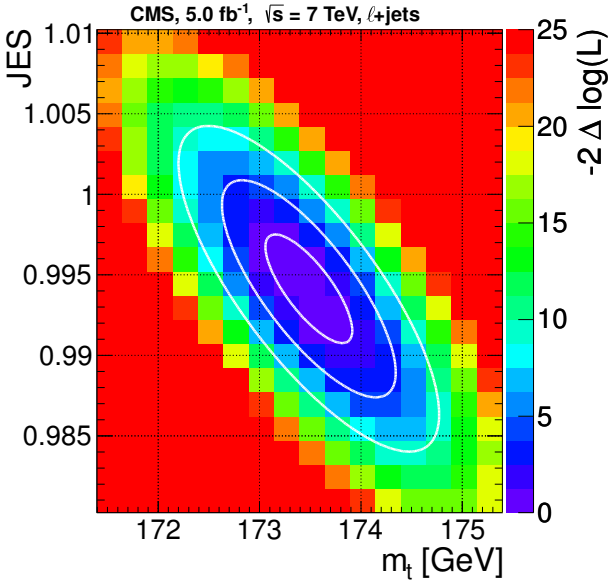
- Based on 2011 ℓ+jets combined m_t+JES
  - 2D-Ideogram method, `arXiv:1209.2319`
  - See presentation of H. Stadie
    $m_t^{2D} = 173.49 \pm 0.43_{\text{stat+JES}} \pm 0.98_{\text{syst}}$ GeV

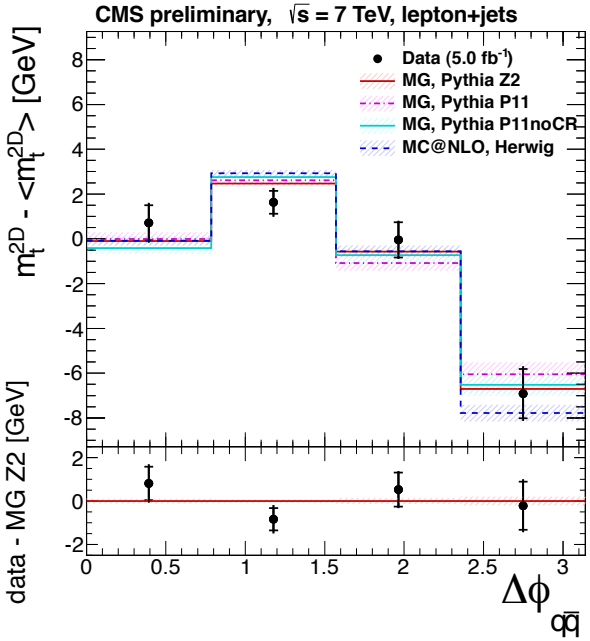


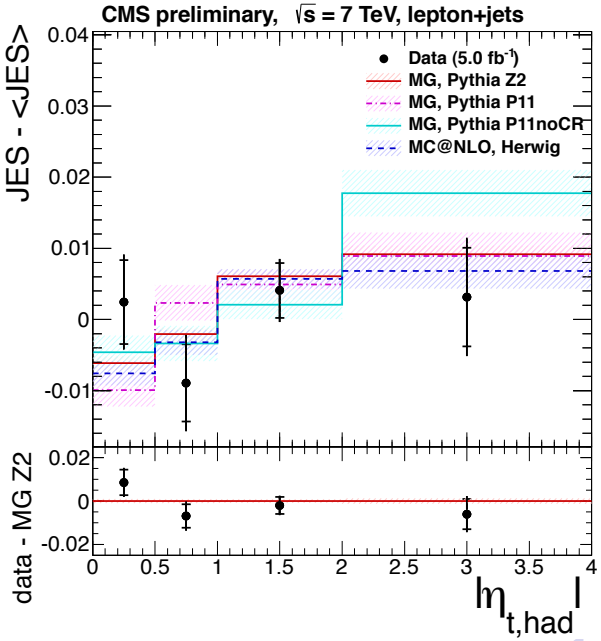


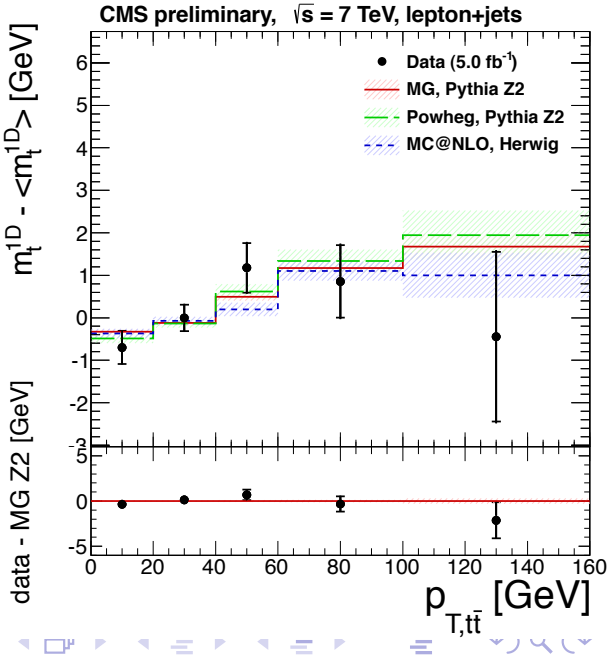
Dependence of m_t^{obs} on event kinematics (CMS-PAS-TOP-12-029)

- Measure m_t^{1D}, m_t^{2D}, JES ($\oplus$ stat $\oplus$ syst) in bins of kinematic variables
  - 2D-Ideogram method, `arXiv:1209.2319`
    - m_t^{2D} & JES: 2D measurement
    - m_t^{1D}: no JES measured
  - Results for 12 kinematic variables
  - First binned m_t^{obs} measurement
    - Due to large $t\bar{t}$ dataset @ LHC

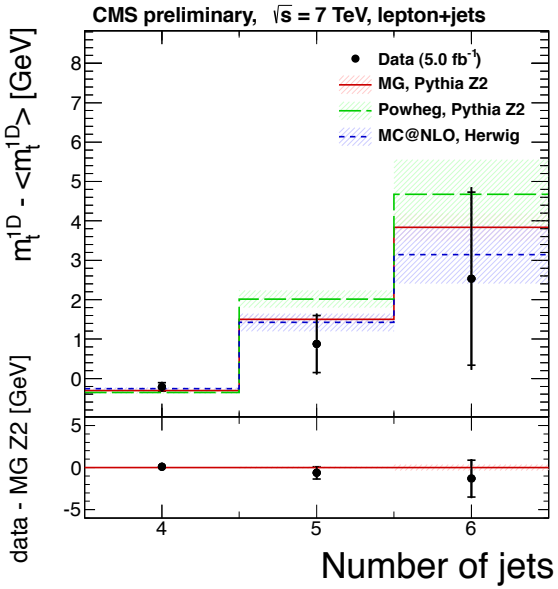


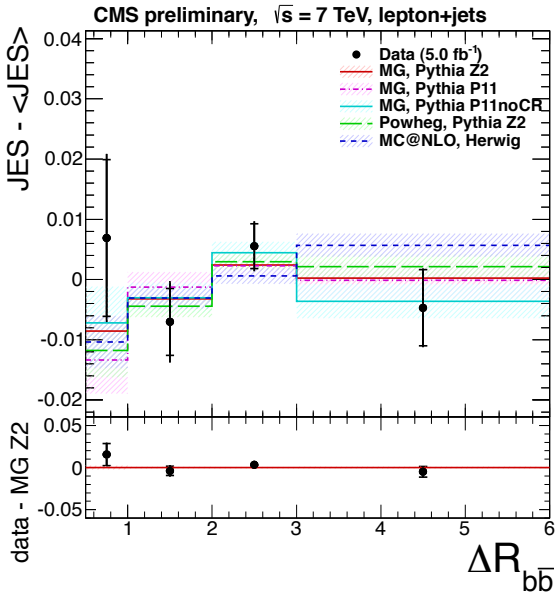






Dependence of m_t^{obs} on event kinematics (CMS-PAS-TOP-12-029)





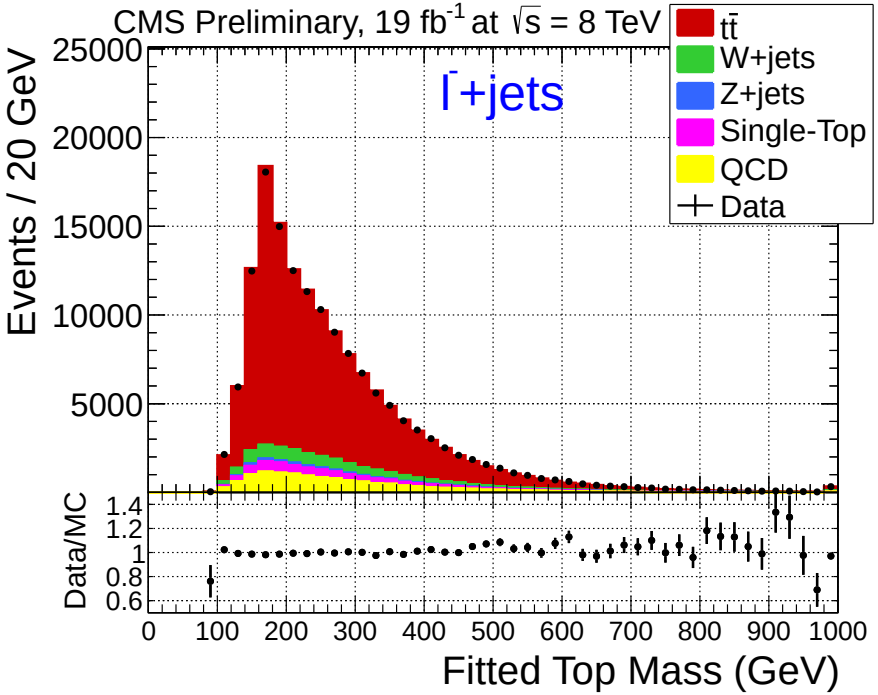
Data – Madgraph (Z2)

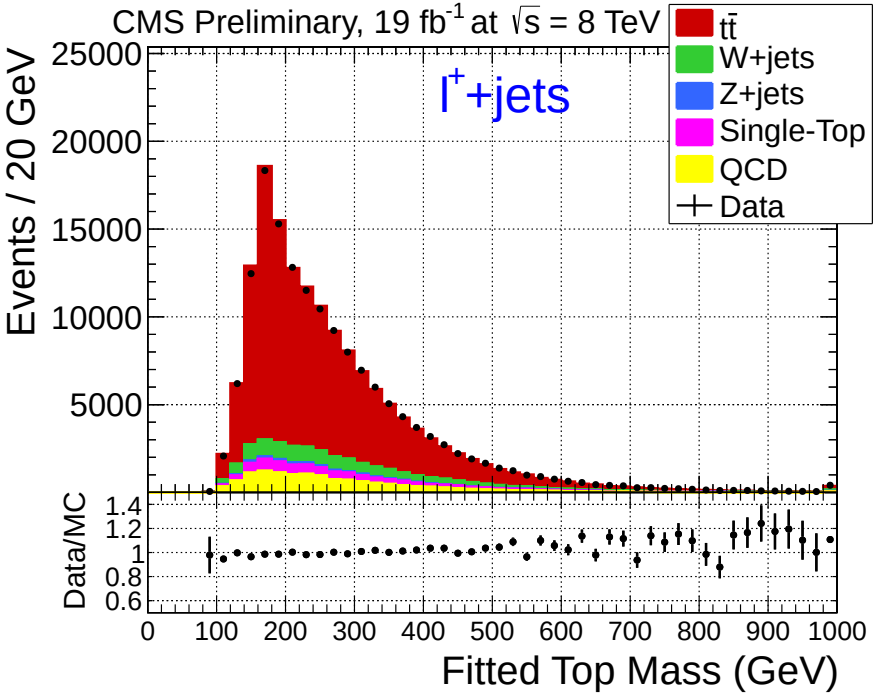
Observable	m_t^{1D} χ^2	JES χ^2	m_t^{2D} χ^2	Ndf
$\Delta R_{q\bar{q}}$	1.01	3.41	1.49	3
$\Delta\phi_{q\bar{q}}$	2.31	2.18	2.89	3
$p_{T,t,had}$	9.40	7.83	2.41	4
$\lvert\eta_{t,had}\rvert$	0.41	3.33	3.17	3
H_T	3.18	1.19	2.24	4
$m_{t\bar{t}}$	2.52	2.98	2.25	4
$p_{T,t\bar{t}}$	3.39	1.67	2.18	4
Jet multiplicity	1.47	2.00	1.56	2
$p_{T,b,had}$	0.81	2.35	2.17	4
$\lvert\eta_{b,had}\rvert$	2.64	0.30	0.48	2
$\Delta R_{b\bar{b}}$	4.87	2.61	8.01	3
$\Delta\phi_{b\bar{b}}$	2.87	3.85	6.86	3

- Good agreement between Data and 'standard' MadGraph TuneZ2
- m_t^{obs} not heavily affected by different tunes / generators
- Sensitivity limited by data statistics
  - 20 fb^{-1} @ 8 TeV will help

Δm_t in the ℓ+jets channel (CMS-PAS-TOP-12-031)

- Check of CPT invariance in top sector: $m_t \stackrel{?}{=} m_{\bar{t}}$
- lepton charge: split data in 2 samples: $\Delta m_t = m_{t,\text{hadronic}} - m_{\bar{t},\text{hadronic}}$
  - Measure m_t in each sample with 1D Ideogram method
    - m_t measurement differential in lepton charge
  - Using entire 2012 dataset @ 8 TeV





Δm_t in the ℓ+jets channel (CMS-PAS-TOP-12-031)

Result with 19 fb^{-1} @ 8 TeV

$$\Delta m_t = -272 \pm 196_{\text{stat}} \pm 122_{\text{syst}} \text{ MeV}$$

- Uncertainty statistics dominated
  - Systematics reduce in the difference
- Compatible with zero (CPT conservation)

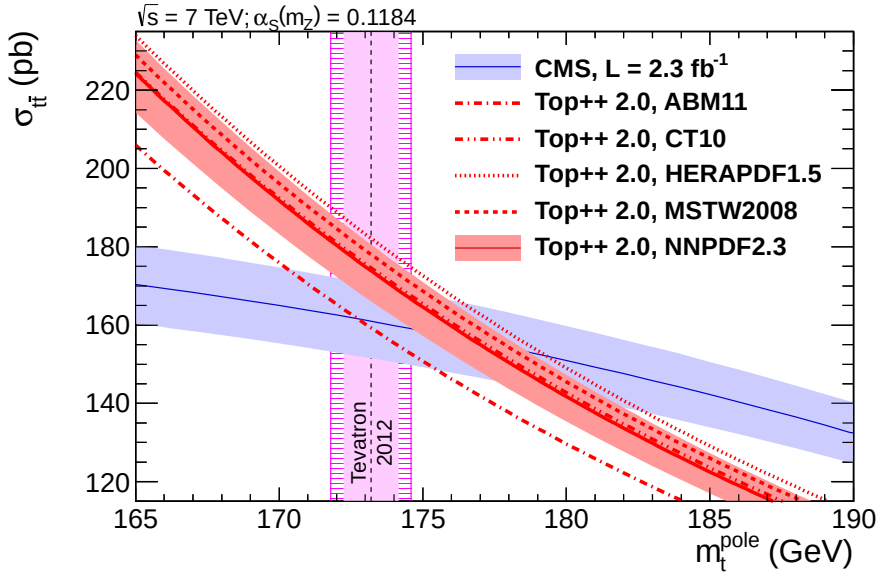
Source	Estimated effect (MeV)
Jet energy scale	$\mathbf{17} \pm 15$
Jet energy resolution	$8 \pm \mathbf{11}$
b vs. $\bar{\text{b}}$ jet response	$\mathbf{64} \pm 7$
Signal fraction	$\mathbf{45} \pm 2$
Background charge asymmetry	$\mathbf{12.43} \pm 0.03$
Background composition	$\mathbf{50} \pm 1$
Pileup	$\mathbf{17.4} \pm 0.4$
b-tagging efficiency	$\mathbf{20} \pm 8$
b vs. $\bar{\text{b}}$ tagging efficiency	$\mathbf{43} \pm 6$
Method calibration	$15 \pm \mathbf{54}$
Parton distribution functions	$\mathbf{12} \pm 3$
Total	122

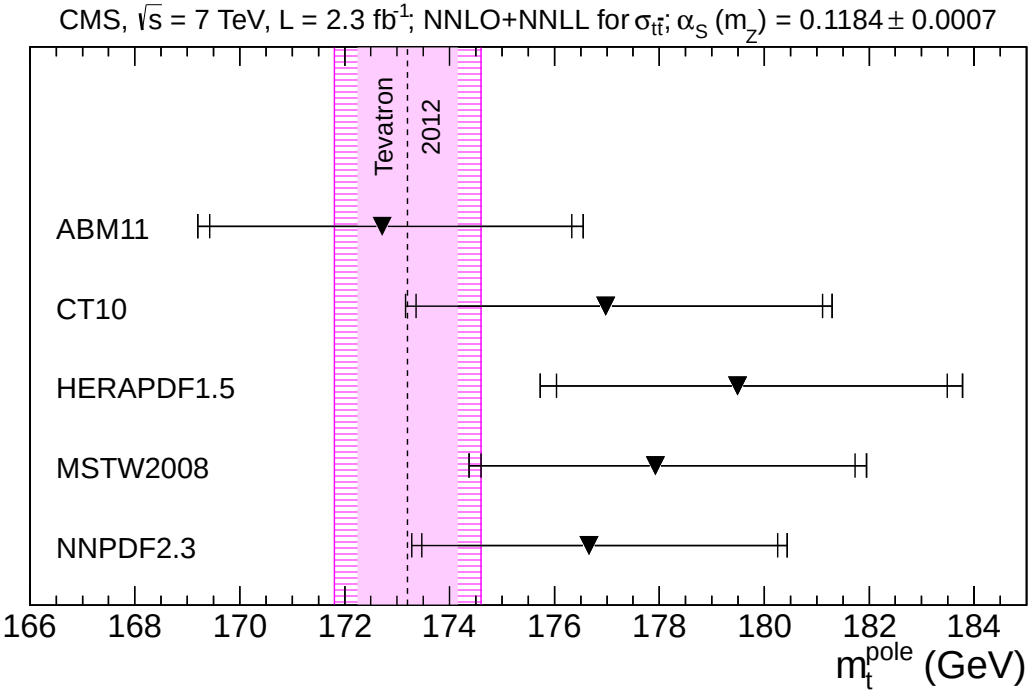
How to improve $m_t^{observable}$ understanding?

- Check current understanding of m_t^{obs} modelling in MC simulations
- What is m_t^{MC} measured with standard techniques? $m_t^{MC} \stackrel{?}{=} m_t^{pole}$
  - Perform measurements less dependent on m_t^{MC}
    - Extract mass from other measured quantities (e.g. $\sigma_{t\bar{t}}$)
    - Fully data-driven measurements
- Use non-standard techniques (different sensitivity to systematics)

m_t^{pole} from $t\bar{t}$ cross section (arXiv:1307.1907)

- Based on most precise $\sigma_{t\bar{t}}$ @ 7 TeV (CMS dilepton, arXiv:1208.2671)
- Measure $\sigma_{t\bar{t}}$ for different m_t
- Compare with theoretical $\sigma_{t\bar{t}}(m_t^{pole})$
  - Using latest NNLO calculation
  - α_s fixed to PDG value





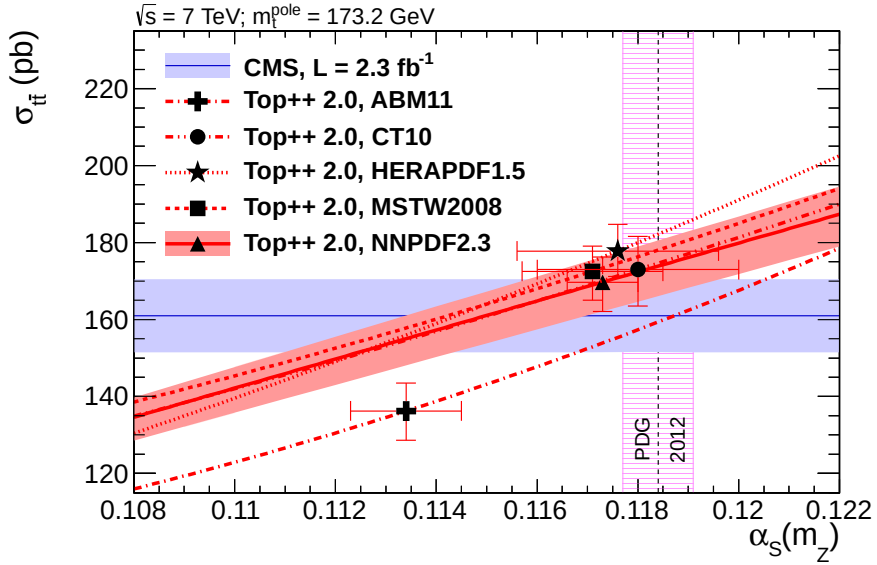
Result with NNPDF

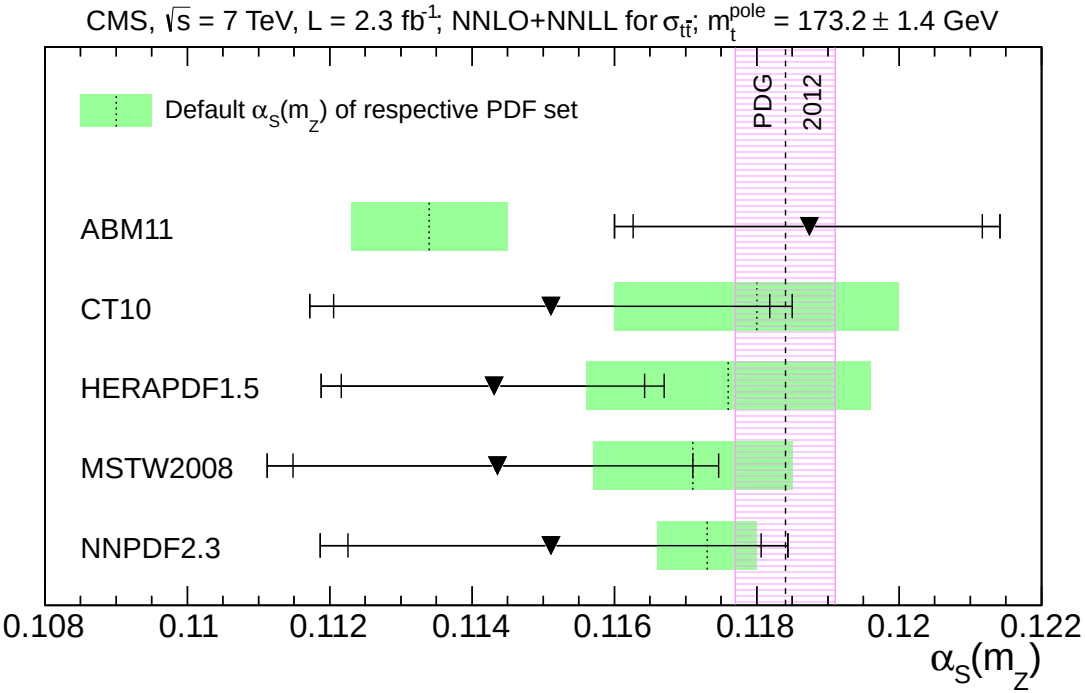
$$m_t^{pole} = 176.7^{+3.8}_{-3.4} \text{ GeV}$$

- Compatible with direct measurements

Also: α_s from $t\bar{t}$ cross section (arXiv:1307.1907)

- Revert logic of m_t^{pole} extraction
  - Fix m_t^{pole} to direct $m_t^{Tevatron}$
- Compare measured $\sigma_{t\bar{t}}$ with theoretical $\sigma_{t\bar{t}}(\alpha_s)$
  - Using latest NNLO calculation





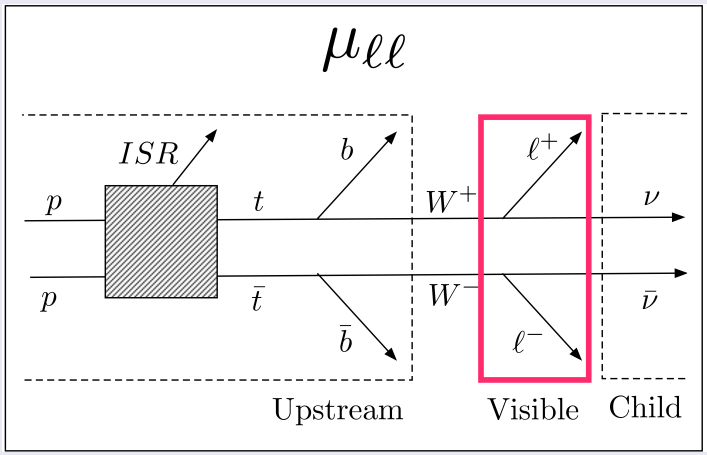
Result with NNPDF

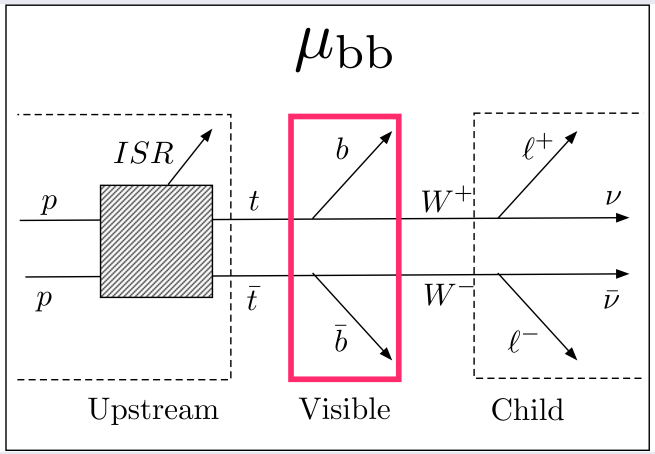
$$\alpha_s(m_Z) = 0.1151^{+0.0033}_{-0.0032}$$

- First α_s at NNLO from hadron collider

Measuring $m_t^{endpoint}$ via kinematic endpoints (arXiv:1304.5783)

- Endpoint of 'transverse mass' variables sensitive to masses
  - m_W measurement via $m_T(\ell,\ E_T^{miss})$
- M_{T2}-type variables designed to measure SUSY masses via endpoints.
  - Exploit analytic relations between $M_{T2}^{endpoint}$ and underlying masses





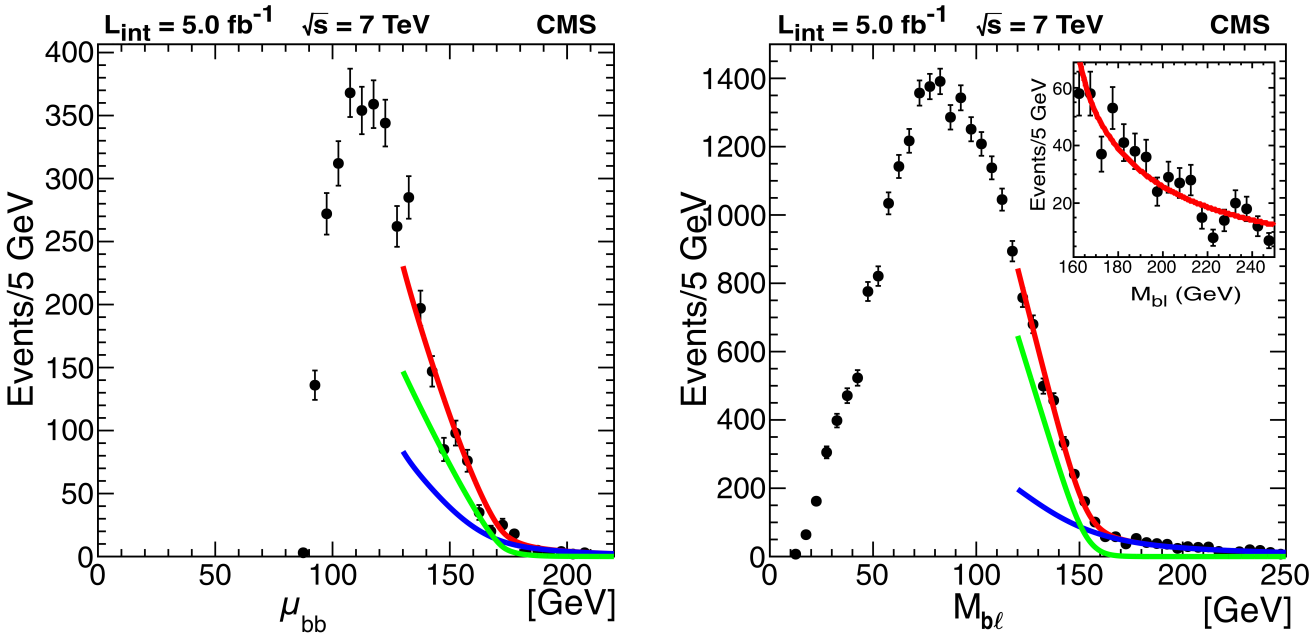
$\mu_{\ell\ell} = M_{T2\perp}^{210}$
$\rightarrow\ m_\nu$ & m_W

$\mu_{bb} = M_{T2\perp}^{221}$
$\rightarrow\ m_W$ & m_t

M_{bl} also used
$\rightarrow m_\nu,\ m_W$ & m_t

- Endpoints are fitted using shapes independent of MC
  - Measurement independent of m_t^{MC}

Measuring $m_t^{endpoint}$ via kinematic endpoints (arXiv:1304.5783)



Background
Data-driven

Signal
Kinked-line $\otimes$ resolution

Sum
Signal + Background

Source	Syst
Jet energy resolution	0.5
Jet energy scale	$^{+1.3}_{-1.8}$
Fit range	0.6
Background shape	0.5
B-tag & ℓ efficiency	$^{+0.1}_{-0.2}$
QCD effects	0.6

- Doubly-constrained fit ($m_\nu = 0, m_W = 80.4$ GeV)

$$m_t^{endpoint} = 173.9 \pm 0.9(\text{stat})^{+1.6}_{-2.0}(\text{syst})\ \text{GeV}$$

- In agreement with other measurements

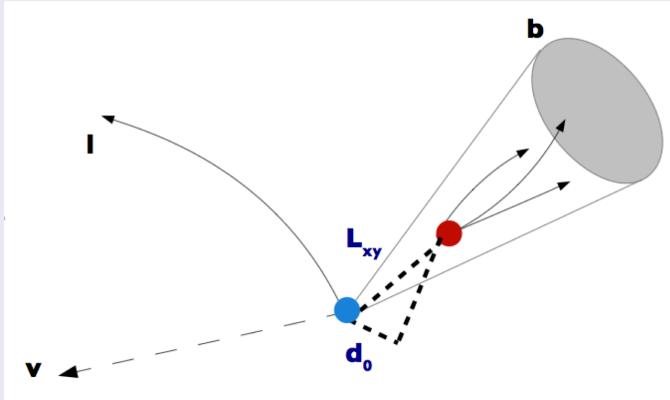
How to improve $m_t^{observable}$ understanding?

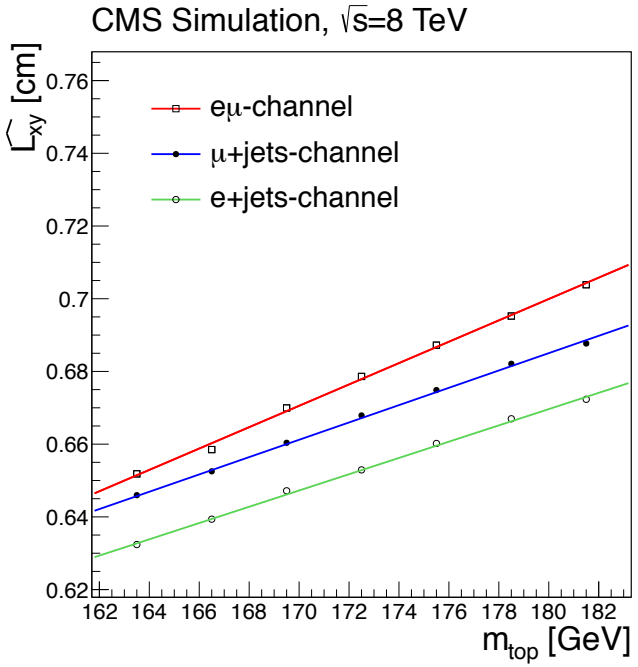
- Check current understanding of m_t^{obs} modelling in MC simulations
- What is m_t^{MC} measured with standard techniques? $m_t^{MC} \stackrel{?}{=} m_t^{pole}$
- Use non-standard techniques (different sensitivity to systematics)

Measure m_t^{MC} via b-hadron lifetime (CMS-PAS-TOP-12-030)

$t \to bW$ decay

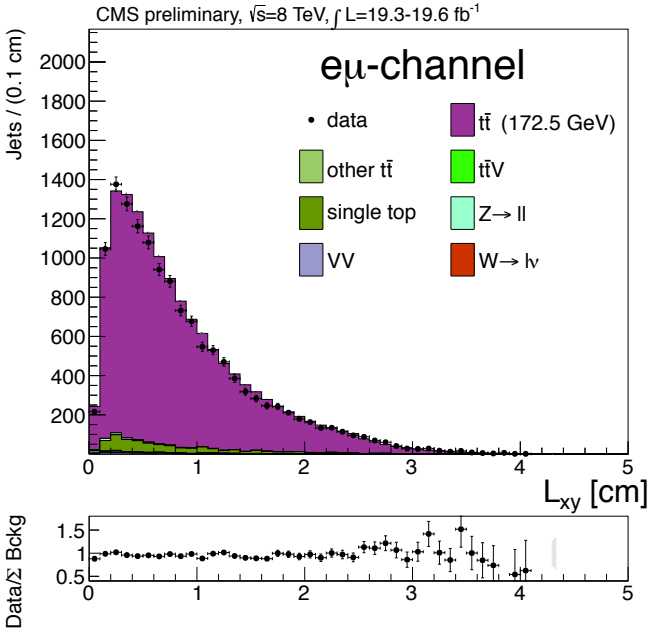
- Boost of b-quark correlated with m_t
- Decay length $L_{b-hadron}$ correlated with m_t
  - Use L_{xy}: transverse decay length of secondary vertex
- Same technique as CDF (arXiv:hep-ex/0612061)

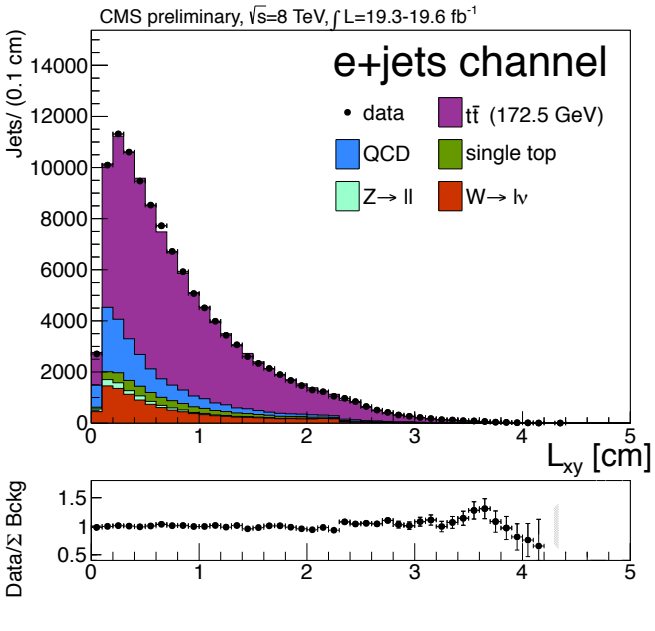


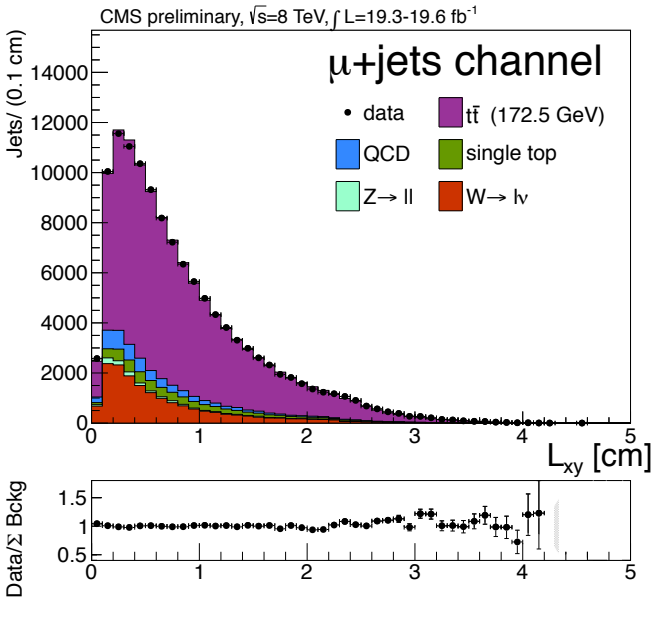


- e+jets, μ+jets and dilepton $e\mu$ $t\bar{t}$ events
  - Per event, use max L_{xy} of jets ($|\eta| < 1.1$, $\frac{L_{xy}}{\sigma_{L_{xy}}} > 3$)
  - Median L_{xy} $\left(\widehat{L_{xy}}\right)$ used to estimate m_t^{MC}
- Different sensitivity to systematics
  - Track-based
    $\to$ reduced jet energy scale uncertainty
  - Kinematics in lab frame
    $\to$ dependence on production model

Measure m_t^{MC} via b-hadron lifetime (CMS-PAS-TOP-12-030)







Data results

$\widehat{L_{xy}} = 0.682 \pm 0.004\ cm$	$\widehat{L_{xy}} = 0.6536 \pm 0.0013\ cm$	$\widehat{L_{xy}} = 0.6690 \pm 0.0013\ cm$
$m_t^{MC} = 173.7 \pm 2.0$ GeV	$m_t^{MC} = 172.8 \pm 1.0$ GeV	$m_t^{MC} = 173.2 \pm 1.0$ GeV

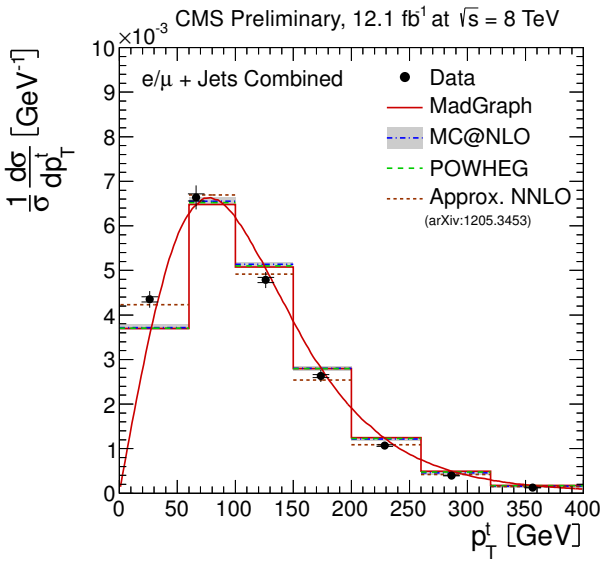
- Only statistical uncertainties

Measure m_t^{MC} via b-hadron lifetime (CMS-PAS-TOP-12-030)

NEW

		μ+jets	e+jets	$e\mu$
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

- Leading systematic: p_T^{top} modeling



Final results

Channel	m_t [GeV]
muon+jets	$173.2 \pm 1.0_{stat} \pm 1.6_{syst} \pm 3.3_{p_T(t)}$
electron+jets	$172.8 \pm 1.0_{stat} \pm 1.7_{syst} \pm 3.1_{p_T(t)}$
electron-muon	$173.7 \pm 2.0_{stat} \pm 1.4_{syst} \pm 2.4_{p_T(t)}$

Combination of all channels

$$m_t^{MC} = 173.5 \pm 1.5_{stat} \pm 1.3_{syst} \pm 2.6_{p_T^{top}}$$

Conclusion

- Several techniques explored to improve our m_t understanding
  - Cross-checks of m_t^{obs} modelling in MC
    - Kinematic dependence of m_t^{obs}
    - Also: very precise Δm_t measurement
  - Measurements independent of m_t^{MC}
    - From $\sigma_{t\bar{t}}$ and kinematic endpoints
  - Conducted alternative measurements of m_t^{MC}
    - Different sensitivity to systematics

  $\rightarrow$ Everything in agreement with standard m_t^{obs} measurements, and modelled well by MC simulations

- Outlook
  - Large 2012 dataset
    - Improvement of differential m_t^{obs} studies
    - Non-standard techniques become possible
  - Stay tuned!

Back-up

Endpoint method

Full results, with/without constraints

	Constraint		
Fit quantity	None	$m_\nu = 0$	$m_\nu = 0$ and $M_W = 80.4\,\mathrm{GeV}$
m_ν^2 (GeV^2)	$-556 \pm 473 \pm 622$	(0)	(0)
M_W (GeV)	$72 \pm 7 \pm 9$	$80.7 \pm 1.1 \pm 0.6$	(80.4)
M_t (GeV)	$163 \pm 10 \pm 11$	$174.0 \pm 0.9^{+1.5}_{-2.0}$	$173.9 \pm 0.9^{+1.6}_{-2.0}$