

Systematic uncertainties in the top mass measurements

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Systematics in the top mass measurements

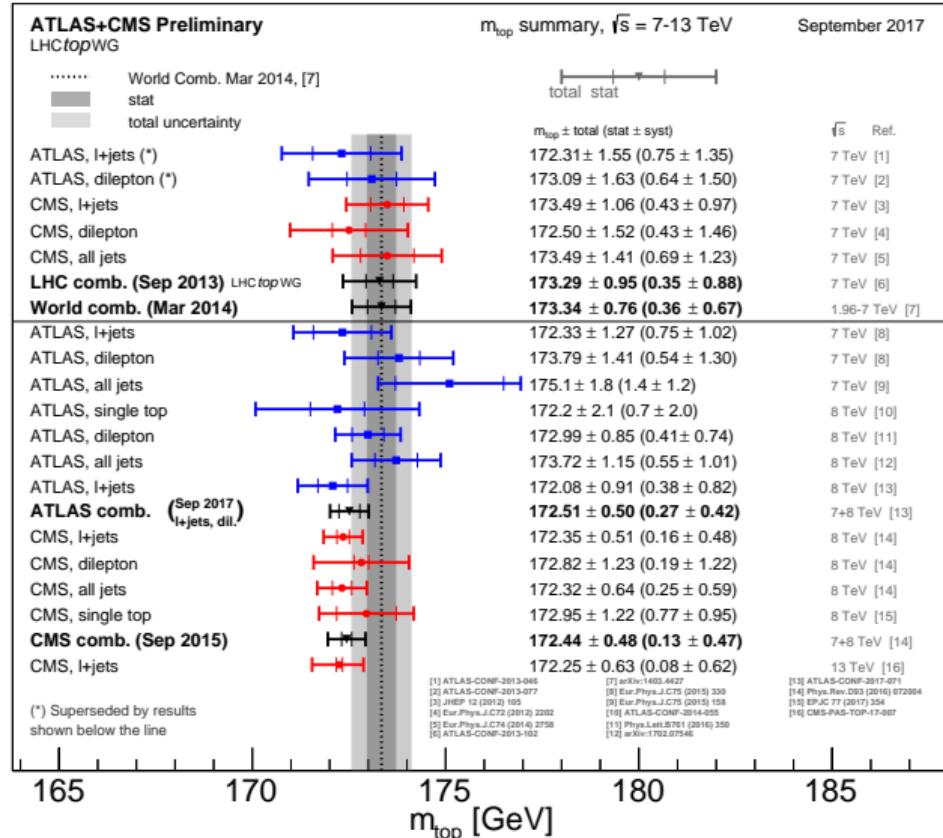
April 24-26, 2019



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Top mass measurements: current status

- Reducing the uncertainty further requires improving the systematical component
- Here we focus on the modelling systematics



Top mass measurements methods

Standard (direct)

- Template (ATLAS)
- Ideogram (CMS)

Alternative (indirect)

- Inclusive cross section
- Differential cross sections
- Leptonic observables, J/Ψ , ...

Modelling uncertainty estimation



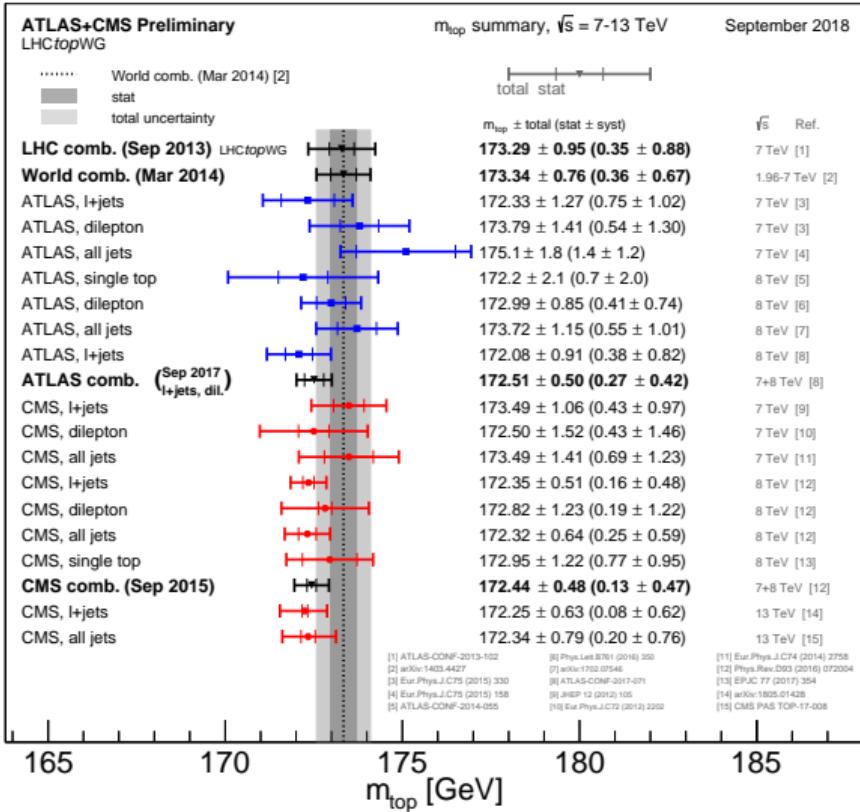
Matrix Element	Compare POWHEG vs MC@NLO	Compare POWHEG vs MC@NLO (not included in the latest analyses)
Parton Shower	Compare HERWIG vs PYTHIA	JEC flavor: HERWIG vs PYTHIA (in JES only); b jet modelling: vary the fragmentation functions + B^0/B^+ branching
Scales, radiation	ISF/FSR: comparing PYTHIA with two tunes with different h_{damp} (Perugia RadLo/RadHi tunes)	ME/PS matching: vary h_{damp} value in PYTHIA; μ_R/μ_F scales: vary the scales by factors of 0.5, 2 (in ME and ISR) or $1/\sqrt{2}, \sqrt{2}$ (in FSR); Early resonance decays: ERD on/off in PYTHIA8
CR	Vary the Colour Reconnection Strength in PYTHIA (Perugia tune with/w.o loCR)	Compare the default PYTHIA model to "QCD inspired" and "gluon move" models
Underlying event	Vary the number of Multi Parton Interactions in PYTHIA (Perugia tune with/w.o mpiHi)	Vary the tuned Underlying Event parameters in CUETP8M2T4
PDF	Compare CT10 vs MSTW2008 vs NNPDF or eigenvector variations or using CTEQ and CT10 reweighted to MSTW2008 and NNPDF	Using NNPDF replicas or CT10 or CT14 eigenvector variations

Standard (direct)

■ Template (ATLAS)

- Top reconstruction using a kinematic fit (in most analyses)
- Likelihood fit of one or several parameters using templates/ideograms (1D or 2D fit)
- Templates/ideograms are built using MC with several input m_{top} values (and other parameters if used)
- External constrain (from the jet energy scale uncertainty) could be added in the fit ("hybrid" method)

■ Ideogram (CMS)



All-hadronic channel



8 TeV

JHEP 09 (2017) 118

- Total uncertainty 1.15 GeV
- Hadronisation gives the largest contribution to the modelling uncertainty (0.64 GeV \sim 56% of the total uncertainty)

Source of uncertainty	Δm_{top} [GeV]
Monte Carlo generator	0.18 ± 0.21
Hadronisation modelling	0.64 ± 0.15
Parton distribution functions	0.04 ± 0.00
Initial/final-state radiation	0.10 ± 0.28
Underlying event	0.13 ± 0.16
Colour reconnection	0.12 ± 0.16
⋮	⋮
Total systematic uncertainty	1.01
Total statistical uncertainty	0.55
Total uncertainty	1.15



13 TeV

CMS-PAS-TOP-17-008

- Total uncertainty: 0.83 GeV (2D), 1.04 GeV (1D), 0.72 GeV (hyb.)

Dominant modelling uncertainties:

- Colour reconnection (\sim 0.4 GeV, \sim 50% of the total)
- JEC flavor (0.3–0.35 GeV, \sim 30-40% of the total)
- ME/PS matching for 2D/hybrid (0.2–0.3 GeV, 30–40% of the tot.)
- ERD for 1D (0.38 GeV, \sim 40% of the total)

	δm_t^{2D} [GeV]	$\delta \text{JSF}^{\text{2D}}$ [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	$\delta \text{JSF}^{\text{hyb}}$ [%]
⋮	⋮	⋮	⋮	⋮	⋮
<i>Modeling uncertainties</i>					
JEC flavor (linear sum)	-0.35	+0.1	-0.31	-0.34	0.0
b jet modeling (quad. sum)	0.09	0.0	0.09	0.09	0.0
⋮	⋮	⋮	⋮	⋮	⋮
PDF	0.01	0.0	0.01	0.01	0.0
Ren. and fact. scales	0.05	0.0	0.04	0.04	0.0
ME/PS matching	$+0.32 \pm 0.20$	-0.3	-0.05 ± 0.14	$+0.24 \pm 0.18$	-0.2
ISR PS scale	$+0.17 \pm 0.17$	-0.2	$+0.13 \pm 0.12$	$+0.12 \pm 0.14$	-0.1
FSR PS scale	$+0.22 \pm 0.12$	-0.2	$+0.11 \pm 0.08$	$+0.18 \pm 0.11$	-0.1
Top quark p_T	$+0.03$	0.0	$+0.02$	$+0.03$	0.0
Underlying event	$+0.16 \pm 0.19$	-0.3	-0.07 ± 0.14	$+0.10 \pm 0.17$	-0.2
Early resonance decays	$+0.02 \pm 0.28$	+0.4	$+0.38 \pm 0.19$	$+0.13 \pm 0.24$	+0.3
CR modeling (max. shift)	$+0.41 \pm 0.29$	-0.4	-0.43 ± 0.20	-0.36 ± 0.25	-0.3
⋮	⋮	⋮	⋮	⋮	⋮
Total systematic	0.81	0.9	1.03	0.70	0.7
Statistical (expected)	0.21	0.2	0.16	0.20	0.1
Total (expected)	0.83	0.9	1.04	0.72	0.7

Lepton+jets channel



8 TeV, combination with
7 TeV measurements ▶ EPJC (2019) 79

- Total uncertainty for the BDT selection — 0.91 GeV

Dominant modelling for the BDT selection:

- Colour reconnection (0.19 GeV, 21% of the total)
- Signal MC generator (0.16 GeV, 18% of the total)
- Hadronisation (0.15 GeV, 18% of the total)

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	
Event selection	Standard	Standard	BDT
Signal Monte Carlo generator	0.22 ± 0.21	0.50 ± 0.17	0.16 ± 0.17
Hadronization	0.18 ± 0.12	0.05 ± 0.10	0.15 ± 0.10
Initial- and final-state QCD radiation	0.32 ± 0.06	0.28 ± 0.11	0.08 ± 0.11
Underlying event	0.15 ± 0.07	0.08 ± 0.15	0.08 ± 0.15
Colour reconnection	0.11 ± 0.07	0.37 ± 0.15	0.19 ± 0.15
Parton distribution function	0.25 ± 0.00	0.08 ± 0.00	0.09 ± 0.00
Total systematic uncertainty	1.04 ± 0.08	1.07 ± 0.10	0.82 ± 0.06
Total	1.28 ± 0.08	1.13 ± 0.10	0.91 ± 0.06



7–8 TeV ▶ PRD 93 (2016) 072004

- Total uncertainty: 0.6 GeV (1D/2D), 0.51 GeV (hyb.)

Dominant modelling uncertainties:

- JEC flavour (~ 0.3 GeV, $\sim 50\%$ of the total)
- μ_R/μ_F scales ($\sim 0.1\text{--}0.2$ GeV, $\sim 20\text{--}40\%$ of the total)

	δm_t^{2D} (GeV)	δJSF	δm_t^{1D} (GeV)	δm_t^{hyb} (GeV)
⋮	⋮	⋮	⋮	⋮
Modeling of hadronization				
JEC: Flavor-dependent				
- light quarks (u d s)	+0.11	-0.002	-0.02	+0.05
- charm	+0.03	<0.001	-0.01	+0.01
- bottom	-0.32	<0.001	-0.31	-0.32
- gluon	-0.22	+0.003	+0.05	-0.08
b jet modeling				
- b fragmentation	+0.06	-0.001	-0.06	<0.01
- Semileptonic b hadron decays	-0.16	<0.001	-0.15	-0.16
Modeling of perturbative QCD				
PDF	0.09	0.001	0.06	0.04
Ren. and fact. scales	$+0.17 \pm 0.08$	-0.004 ± 0.001	-0.24 ± 0.06	-0.09 ± 0.07
ME-PS matching threshold	$+0.11 \pm 0.09$	-0.002 ± 0.001	-0.07 ± 0.06	$+0.03 \pm 0.07$
ME generator	-0.07 ± 0.11	-0.001 ± 0.001	-0.16 ± 0.07	-0.12 ± 0.08
Top quark p_T	+0.16	-0.003	-0.11	+0.02
Modeling of soft QCD				
Underlying event	$+0.15 \pm 0.15$	-0.002 ± 0.001	$+0.07 \pm 0.09$	$+0.08 \pm 0.11$
Color reconnection modeling	$+0.11 \pm 0.13$	-0.002 ± 0.001	-0.09 ± 0.08	$+0.01 \pm 0.09$
Total systematic	0.59	0.007	0.62	0.48
Statistical	0.20	0.002	0.12	0.16
Total	0.62	0.007	0.63	0.51



7–8 TeV ▶ PRD 93 (2016) 072004

- Total uncertainty: 0.6 GeV (1D/2D), 0.51 GeV (hyb.)

Dominant modelling uncertainties:

- JEC flavour (~ 0.3 GeV, $\sim 50\%$ of the total)
- μ_R/μ_F scales (~ 0.1 – 0.2 GeV, ~ 20 – 40% of the total)

	δm_t^{2D} (GeV)	δJSF	δm_t^{1D} (GeV)	δm_t^{hyb} (GeV)
⋮	⋮	⋮	⋮	⋮
Modeling of hadronization				
JEC: Flavor-dependent				
- light quarks (u d s)	+0.11	-0.002	-0.02	+0.05
- charm	+0.03	<0.001	-0.01	+0.01
- bottom	-0.32	<0.001	-0.31	-0.32
- gluon	-0.22	+0.003	+0.05	-0.08
b jet modeling				
- b fragmentation	+0.06	-0.001	-0.06	<0.01
- Semileptonic b hadron decays	-0.16	<0.001	-0.15	-0.16
Modeling of perturbative QCD				
PDF	0.09	0.001	0.06	0.04
Ren. and fact. scales	+0.17 ± 0.08	-0.004 ± 0.001	-0.24 ± 0.06	-0.09 ± 0.07
ME-PS matching threshold	+0.11 ± 0.09	-0.002 ± 0.001	-0.07 ± 0.06	+0.03 ± 0.07
ME generator	-0.07 ± 0.11	-0.001 ± 0.001	-0.16 ± 0.07	-0.12 ± 0.08
Top quark p_T	+0.16	-0.003	-0.11	+0.02
Modeling of soft QCD				
Underlying event	+0.15 ± 0.15	-0.002 ± 0.001	+0.07 ± 0.09	+0.08 ± 0.11
Color reconnection modeling	+0.11 ± 0.13	-0.002 ± 0.001	-0.09 ± 0.08	+0.01 ± 0.09
Total systematic	0.59	0.007	0.62	0.48
Statistical	0.20	0.002	0.12	0.16
Total	0.62	0.007	0.63	0.51

13 TeV ▶ EPJC 78 (2018) 891

- Total unc.: 0.7 GeV (2D), 1 GeV (1D), 0.5 GeV (hyb.)

Dominant modelling uncertainties:

- JEC flavor (~ 0.4 GeV, $\sim 60\%$ of the total)
- CR (~ 0.3 GeV, $\sim 50\%$ of the total)
- ERD for 1D (0.42 GeV, $\sim 40\%$ of the total)

	δm_t^{2D} [GeV]	δJSF^{2D} [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	$\delta \text{JSF}^{\text{hyb}}$ [%]
⋮	⋮	⋮	⋮	⋮	⋮
Modeling uncertainties					
JEC Flavor (linear sum)	0.42	0.1	0.31	0.39	<0.1
⋮	⋮	⋮	⋮	⋮	⋮
b jet modeling (quad. sum)	0.13	0.1	0.09	0.12	<0.1
⋮	⋮	⋮	⋮	⋮	⋮
PDF	0.02	<0.1	0.02	0.02	<0.1
Ren. and fact. scales	0.02	0.1	0.02	0.01	<0.1
ME/PS matching	-0.08	+0.1	+0.03	-0.05	+0.1
ME generator	+0.19 ± 0.14	+0.1	+0.29 ± 0.08	+0.22 ± 0.11	+0.1
ISR PS scale	+0.07 ± 0.09	+0.1	+0.10 ± 0.05	+0.06 ± 0.07	<0.1
FSR PS scale	+0.24 ± 0.06	-0.4	-0.22 ± 0.04	+0.13 ± 0.05	-0.3
Top quark p_T	+0.02	-0.1	-0.06	-0.01	-0.1
Underlying event	-0.10 ± 0.08	+0.1	+0.01 ± 0.05	-0.07 ± 0.07	+0.1
Early resonance decays	-0.22 ± 0.09	+0.8	+0.42 ± 0.05	-0.03 ± 0.07	+0.5
Color reconnection	+0.34 ± 0.09	-0.1	+0.23 ± 0.06	+0.31 ± 0.08	-0.1
Total systematic	0.72	1.0	1.09	0.62	0.8
Statistical (expected)	0.09	0.1	0.06	0.08	0.1
Total (expected)	0.72	1.0	1.09	0.62	0.8

Dilepton channel



8 TeV; combination with 7 TeV
measurements ▶ PLB 761 (2016) 350

- Total uncertainty at 8 TeV — 0.84 GeV

Dominant modelling uncertainties at 8 TeV:

- ISR/FSR (0.23 GeV, 27% of the total)
- Hadronisation (0.22 GeV, 26% of the total)

	$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 8 \text{ TeV}$	
	$m_{\text{top}}^{\ell+\text{jets}}$ [GeV]	$m_{\text{top}}^{\text{dil}}$ [GeV]	$m_{\text{top}}^{\text{dil}}$ [GeV]
Results	172.33	173.79	172.99
Statistics	0.75	0.54	0.41
Method	0.11 ± 0.10	0.09 ± 0.07	0.05 ± 0.07
Signal Monte Carlo generator	0.22 ± 0.21	0.26 ± 0.16	0.09 ± 0.15
Hadronisation	0.18 ± 0.12	0.53 ± 0.09	0.22 ± 0.09
Initial- and final-state QCD radiation	0.32 ± 0.06	0.47 ± 0.05	0.23 ± 0.07
Underlying event	0.15 ± 0.07	0.05 ± 0.05	0.10 ± 0.14
Colour reconnection	0.11 ± 0.07	0.14 ± 0.05	0.03 ± 0.14
Parton distribution function	0.25 ± 0.00	0.11 ± 0.00	0.05 ± 0.00
⋮	⋮	⋮	⋮
Total systematic uncertainty	1.03 ± 0.31	1.31 ± 0.23	0.74 ± 0.29
Total	1.27 ± 0.33	1.41 ± 0.24	0.84 ± 0.29



13 TeV ▶ PRD 96 (2017) 032002

- Total unc.: 1.3 GeV (2D/MAOS), 1 GeV (1D/hyb.)

Dominant modelling uncertainties:

- Matching scale (${}^{+0.86}_{-0.30}$ GeV for 2D, $\sim 45\%$ of total)
- Hard scat. scale (~ 0.3 GeV, $\sim 20\text{--}40\%$ of the total)
- Underlying event tunes ($\sim 45\%$ for 2D)

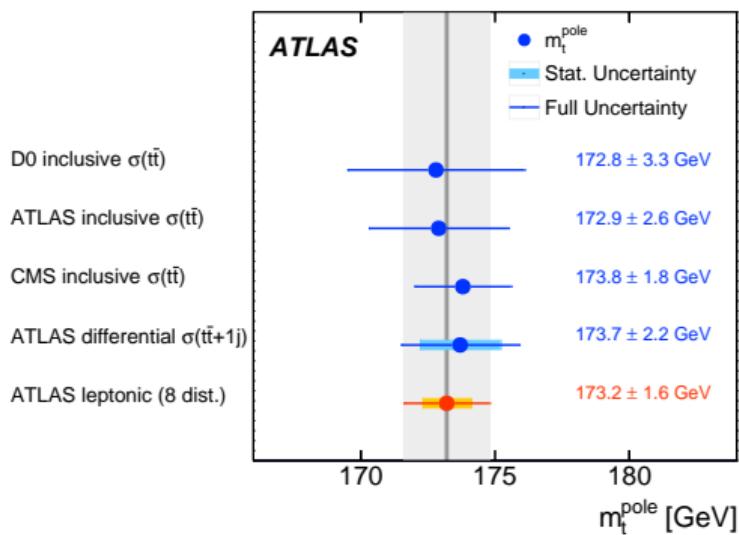
	δM_t^{2D} [GeV]	$\delta \text{JSF}^{\text{2D}}$ [GeV]	δM_t^{1D} [GeV]	δM_t^{hyb} [GeV]	δM_t^{MAOS} [GeV]
⋮	⋮	⋮	⋮	⋮	⋮
Hard scattering scale	⊗ $+0.36$ $+0.20$	$+0.007$ -0.003	$+0.31$ -0.49	$+0.21$ -0.47	$+0.33$ -0.08
Matching scale	⊗ -0.86 $+0.30$	-0.004 $+0.008$	-0.25 $+0.11$	-0.37 $+0.12$	$+0.12$ -0.12
Underlying event tunes	⊗ $+0.56$ -0.56	$+0.007$ -0.007	$+0.08$ -0.08	$+0.11$ -0.11	$+0.09$ -0.09
Color reconnection	$+0.06$ -0.06	$+0.001$ -0.001	$+0.15$ -0.15	$+0.13$ -0.13	$+0.16$ -0.16
ME Generator	$+0.18$ -0.18	-0.004 $+0.002$	-0.19 $+0.07$	-0.13 $+0.07$	$+0.11$ -0.07
PDFs	$+0.14$ -0.14	$+0.001$ -0.001	$+0.17$ -0.16	$+0.17$ -0.15	$+0.17$ -0.16
Total	$+1.31$ -1.25	$+0.015$ -0.014	$+0.91$ -0.95	$+0.89$ -0.93	$+1.27$ -1.02

Quick summary on the modelling uncertainties in direct methods

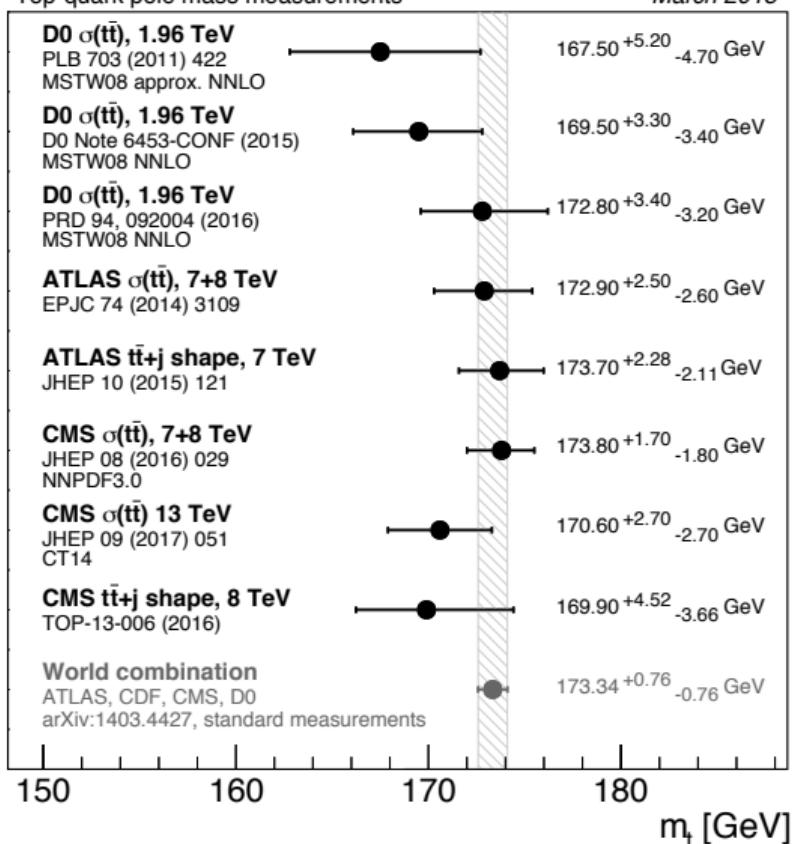
- Hadronisation/JEC flavour is most significant in all-hadronic channel, similar or less in lepton+jets, small in dilepton
- Colour reconnection: large contribution in all-hadronic/lepton+jets, small in dilepton
- The uncertainties related to the scales (μ_R, μ_F, h_{damp}) become important in dilepton/lepton+jets channel

Alternative (indirect)

- Inclusive cross section
- Differential cross sections
- Leptonic observables, J/Ψ , ...



Top-quark pole mass measurements March 2018



Inclusive cross section

Determine the m_T^{pole} by comparing the $\sigma_{t\bar{t}}^{inclusive}$ measurement with the theoretically-predicted cross section vs top mass



7-8 TeV, $e\mu$ events

► EPJC 74 (2014) 3109

- Total uncertainty 2.6 GeV
- Dominant modelling: $t\bar{t}$ modelling and QCD scale (0.8–1 GeV, 30–40% of the total)

Uncertainty breakdown for $\sigma_{t\bar{t}}$:

Uncertainty	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	
\sqrt{s}	7 TeV	8 TeV
Data statistics	1.69	0.71
$t\bar{t}$ modelling and QCD scale	1.46	1.26
Parton distribution functions	1.04	1.13
Background modelling	0.83	0.83
Lepton efficiencies	0.87	0.88
Jets and b -tagging	0.58	0.82
Misidentified leptons	0.41	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	2.27	2.26
Integrated luminosity	1.98	3.10
LHC beam energy	1.79	1.72
Total uncertainty	3.89	4.27



13 TeV, dilepton channel

► CMS-PAS-TOP-17-001

- Total uncertainty ~ 0.7 GeV
- Dominant modelling uncertainties:
 - $t\bar{t}$ ME scale (0.18 GeV, 26% of total)
 - Colour reconnection (0.17 GeV, 24% of total)
 - ISR scale, ME/PS matching (0.16 GeV, 23% of tot.)

Source	Uncertainty [GeV]
$t\bar{t}$ ME scale	0.18
tW ME scale	0.02
DY ME scale	0.06
NLO generator	0.14
PDF	0.05
$\sigma_{t\bar{t}}$	0.09
Top quark p_T	0.04
ME/PS matching	0.16
UE tune	0.03
$t\bar{t}$ ISR scale	0.16
tW ISR scale	0.02
$t\bar{t}$ FSR scale	0.07
tW FSR scale	0.02
b quark fragmentation	0.11
b hadron BF	0.07
Colour reconnection	0.17
Total m_t^{MC} uncertainty	± 0.68 ± 0.73

$t\bar{t}$ +jet differential cross section



7 TeV, lepton+jets channel

JHEP 10 (2015) 121

- Top mass is extracted from the inverse of the invariant mass of the $t\bar{t}$ +jet system
- Total uncertainty $^{+2.29}_{-2.14}$ GeV

Dominant modelling uncertainties:

- ISR/FSR (0.72 GeV, ~30% of the total)
- PDF (0.54 GeV, ~25% of the total)

Description	Value [GeV]	%
m_t^{pole}	173.71	
Statistical uncertainty	1.50	0.9
:	:	:
Signal MC generator	0.28	0.2
Hadronization	0.33	0.2
ISR/FSR	0.72	0.4
Colour reconnection	0.14	0.1
Underlying event	0.25	0.1
Proton PDF (experimental)	0.54	0.3
Background	0.20	0.1
Total experimental systematic uncertainty	1.44	0.8
Total uncertainty	(+2.29, -2.14)	(+1.3, -1.2)



13 TeV, dilepton channel

CMS-PAS-TOP-13-006

- Top mass is extracted from the normalised $t\bar{t}$ +jet invariant mass + normalised differential cross section
- Total uncertainty $^{+2.2}_{-2.5}$ GeV
- Dominant modelling uncertainty:** μ_R/μ_F scales (2 GeV, 80-90% of the total)

Source	Δm_t [GeV]
Jet-Parton Matching	$^{-1.3}_{+0.1}$
Q^2 Scale	± 2.0
ME/Showering	$^{+0.2}_{-0.3}$
Color Reconnection	< 0.1
Underlying Event	± 0.1
PDF	± 0.1
:	:
Total syst.	$^{+2.0}_{-2.3}$
Stat.	± 1.0
Total unc.	$^{+2.2}_{-2.5}$

- Single lepton and dilepton kinematic differential distributions
- Combined fit of the NLO fixed-order predictions to all the measured distributions
- Total uncertainty 2–4 GeV

Largest modelling contributions:

- Parton distribution functions — dominant for all except $p_T^{e\mu}$
 - . for $p_T^l, m^{e\mu}, p_T^e + p_T^\mu$: 1–2 GeV, 30–40% of total
 - . for $E^e + E^\mu$: 3.4 GeV, 85% of total
- QCD radiation — dominant for $p_T^{e\mu}$ (1.4 GeV, 67% of total)
- $t\bar{t}$ generator for $p_T^l, p_T^{e\mu}$ (0.7–0.8 GeV, 30–40% of total)

Template	p_T^l	$p_T^{e\mu}$	$m^{e\mu}$	$p_T^e + p_T^\mu$	$E^e + E^\mu$
χ^2/N_{dof}	8.1/8	7.5/7	13.9/10	8.0/6	12.5/8
m_t [GeV]	168.4 ± 2.3	173.0 ± 2.1	170.6 ± 4.2	169.4 ± 2.0	166.9 ± 4.0
Data statistics	± 1.0	± 0.9	± 2.0	± 0.9	± 1.3
Expt. systematic	± 1.6	± 1.0	± 3.1	± 1.6	± 1.5
PDF uncertainty	± 1.0	± 0.2	± 1.6	± 0.6	± 3.4
$t\bar{t}$ generator	± 0.4	± 1.4	± 1.4	± 0.4	± 1.1
QCD radiation	± 0.7	± 0.8	± 0.5	± 0.2	± 0.2



- Normalised 2D/3D differential cross section
- Simultaneous fit of PDF, α_S and m_t^{pole} to NLO+PS predictions is performed
- Total uncertainty 0.8 GeV
- Dominant modelling uncertainty comes from μ_r/μ_F scales (0.3 GeV, 38% of the total)

Parameter	Variation	$\alpha_S(m_Z)$	m_t^{pole} [GeV]
Fit uncertainty			
Total	$\Delta\chi^2 = 1$	± 0.0016	± 0.7
Model uncertainty			
Total		$+0.0002$ -0.0004	$+0.1$ -0.1
PDF parametrisation uncertainty			
Total		$+0.0008$ -0.0001	$+0.1$ -0.1
Scale uncertainty			
Total		$+0.0011$ -0.0005	$+0.3$ -0.3

Quick summary on the modelling uncertainties in indirect methods

- The uncertainties related to the various scales are large for all the methods in both ATLAS and CMS
 - As in the standard methods in the corresponding channels
- PDF uncertainty is relatively large in ATLAS in all the methods
- Hadronisation modelling: not significant anymore comparing to the standard methods
- Colour reconnection modelling: not significant except in CMS in the inclusive cross section method

How to reduce the modelling?

- Use the recent generator versions
- Compute the modelling systematics within one generator using a well-defined variation scheme (instead of taking the difference between 2 generators)
- Update and improve the generator tunes
- Do the dedicated measurements to constrain the modelling systematics through tuning
- Go from NLO to NNLO where possible (e.g. in the decays for the leptonic obersvables)

- Try leptonic observables
- Try 2D/3D differential distributions