Recent top quark measurements with the CMS experiment

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A. De Iorio

on behalf of the CMS Collaboration

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Top quark overview

Main properties

- Heaviest particle of SM: $\frac{1}{2}$ spin, $\frac{2}{3}e$, color charge
- Participates to all interactions
- "Natural" mass:

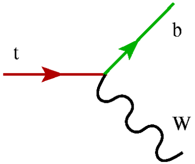
$$m_{\text{top}} = y_t \frac{v}{\sqrt{2}} \simeq 174\,\mathrm{GeV} \Longrightarrow y_t \sim 1$$

  - Privileged relationship with Higgs boson
  - Possible role in the EWSB mechanism

- Decay happens before hadronization can occur:

$$\tau_{top} = \frac{h}{\Gamma_{top}} \simeq \frac{h}{G_F m_{\text{top}}^3 |\mathrm{V_{tb}}| \frac{2}{8\pi\sqrt{2}}} \simeq 2 \times 10^{-25} s$$

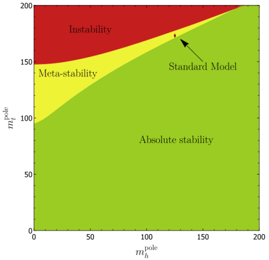
- Angular properties directly accessible through its decay products
- Weak interaction decay, dominantly to a W boson and a b quark



Top quark mass

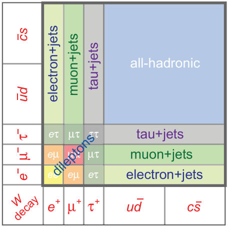
Why is it important?

- Key input for EW precision tests
- Crucial interplay with the Higgs and α_S
  - EW vacuum stability
- Cosmological consequences
- Challenging for experiments and theory
  - theory ambiguities on m_t^{MC} vs. m_t^{pole}



How can it be determined?

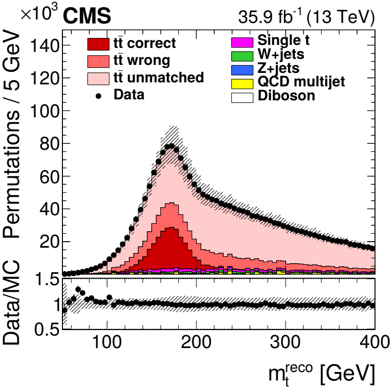
Top Pair Decay Channels

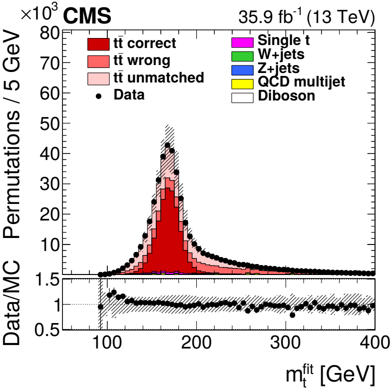


- Direct measurements:
  - observable dependent on m_t
- Indirect measurements:
  - property $f(m_t^{pole})$
- Many decay channels, many experimental observables $\rightarrow$ combination

Direct top mass in ℓ+jets final state

- 1 high-pt isolated e/μ, $N_{jets} \geq 4$, $N_{b-tags} = 2$
- Reconstruction using m_W constraint + kinematic fit $\rightarrow$ goodness of fit
- Ideogram method: joint likelihood for m_t and JSF to constraint JECs to reduce corresponding uncertainty





$$m_t = 172.25 \pm 0.08(\text{stat}) \pm 0.62(\text{syst}) \quad \epsilon_{m_t} = 3.6 ‰$$

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

Eur. Phys. J. C 78 (2018) 891

Direct top mass in all-had final state

- $N_{jets} = 6,\ N_{b-tags} = 2$
- Same strategy of ℓ+jets analysis

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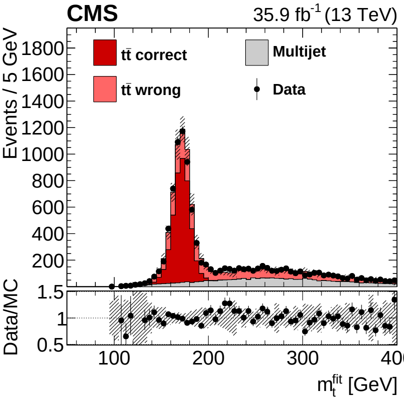
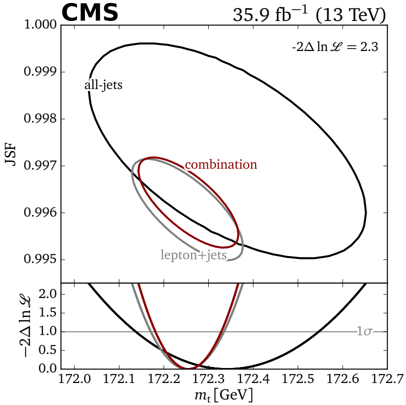




$m_t = 172.34 \pm 0.20(\text{stat}) \pm 0.70(\text{syst})$

$JSF = 0.997 \pm 0.002(\text{stat}) \pm 0.007(\text{syst})$

$m_t = 172.26 \pm 0.07(\text{stat}) \pm 0.61(\text{syst})$

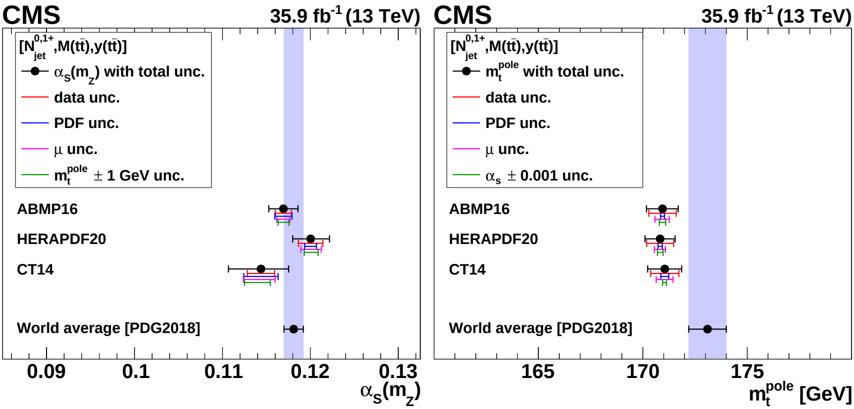
$JSF = 0.996 \pm 0.001(\text{stat}) \pm 0.007(\text{syst})$

Indirect top pole mass in dilepton final state

- 2 isolated leptons (e or μ)
- Triple-differential $\sigma(\mathrm{N_{jets}}, \mathrm{m(t\bar{t})}, \mathrm{y(t\bar{t})})$

arXiv:1904.05237

Submitted to JHEP



$$\alpha_S(m_Z) = 0.1135 \pm 0.0016(\mathrm{fit})^{+0.0002}_{-0.0004}(\mathrm{model})^{+0.0008}_{-0.0001}(\mathrm{param})^{+0.0011}_{-0.0005}(\mathrm{scale})$$

$$m_{\mathrm{t}}^{\mathrm{pole}} = 170.5 \pm 0.7(\mathrm{fit}) \pm 0.1(\mathrm{model})^{+0.0}_{-0.1}(\mathrm{param}) \pm 0.3(\mathrm{scale})\ \mathrm{GeV}$$

Direct top MC mass in dilepton final state

- Kinematic fit for full event reconstruction

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- $m_{\ell b}^{min}$ increases sensitivity to m_t
- 12 regions in N_{jets} and N_{b-jets}
- Simultaneous fit for cross section and mass extraction

$$\sigma_{t\bar{t}} = 815 \pm 2\,(\text{stat}) \pm 29\,(\text{syst}) \pm 20\,(\text{lumi})\,\text{pb}$$
$$m_t^{MC} = 172.33 \pm 0.14\,(\text{stat})\,^{+0.66}_{-0.72}\,(\text{syst})\,\text{GeV}$$

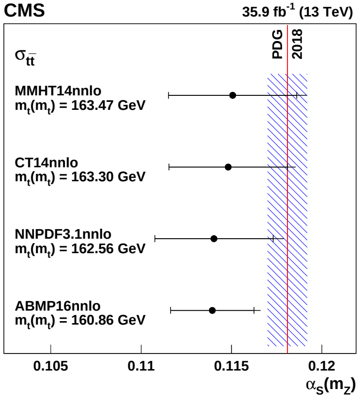
- Residual dependence of the cross section on m_t^{MC}
  $\rightarrow$ indirect measurement of m_t^{pole}

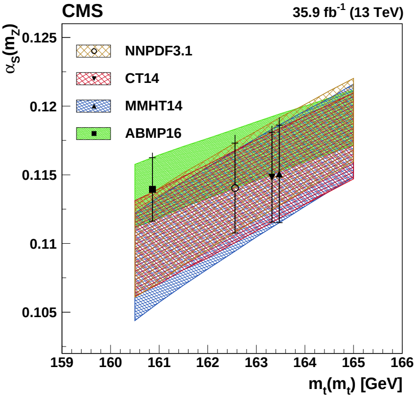
PDF set	m_t^{pole} [GeV]
ABMP16	$169.9 \pm 1.8(\text{fit} + \text{PDF} + \alpha_S)^{+0.8}_{-1.2}(\text{scale})$
NNPDF3.1	$173.2 \pm 1.9(\text{fit} + \text{PDF} + \alpha_S)^{+0.9}_{-1.3}(\text{scale})$
CT14	$173.7 \pm 2.0(\text{fit} + \text{PDF} + \alpha_S)^{+0.9}_{-1.4}(\text{scale})$
MMHT14	$173.6 \pm 1.9(\text{fit} + \text{PDF} + \alpha_S)^{+0.9}_{-1.4}(\text{scale})$

Indirect $\overline{\mathrm{MS}}$ top mass in dilepton final state

$$\sigma_{t\bar{t}} = 815 \pm 2\,(\text{stat}) \pm 29\,(\text{syst}) \pm 20\,(\text{lumi})\ \text{pb}$$
$$m_t^{\mathrm{MC}} = 172.33 \pm 0.14\,(\text{stat})\ ^{+0.66}_{-0.72}\,(\text{syst})\ \text{GeV}$$

- Residual dependence of the cross section on m_t^{MC}
  $\rightarrow$ indirect $m_t(m_t)$ and α_S determination: Eur. Phys. J. C 79 (2019) 368





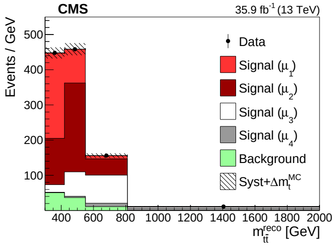
Running top mass

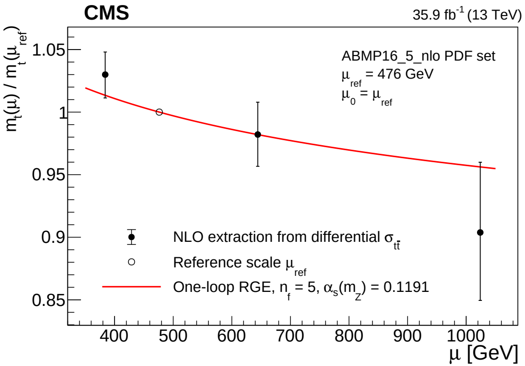
NEW

- Running mass equation: $\mu^2 \frac{dm(\mu)}{d\mu^2} = -\gamma(\alpha_S(\mu))m(\mu)$
- 2 opposite flavour leptons final states
- m_t extracted from $d\sigma/dm_{\mathrm{t\bar{t}}}$ at parton level

4 bins in $m_{\mathrm{t\bar{t}}}$

Bin	$m_{\mathrm{t\bar{t}}}$ [GeV]	Fraction [%]	μ_k [GeV]
1	<420	30	384
2	420–550	39	476
3	550–810	24	644
4	>810	7	1024





Phys. Lett. B 803 (2020) 135263

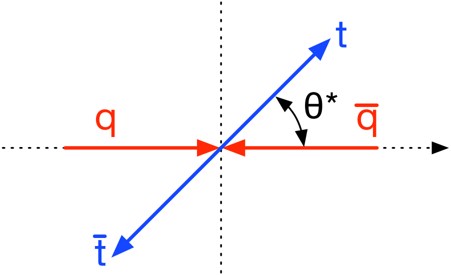
Forward-backward asymmetry

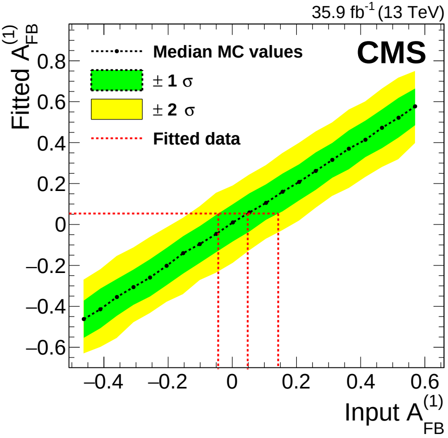
NEW

JHEP 06 (2020) 146

- 1 isolated lepton (μ or e)
- Several variables simultaneously fitted to distinguish between $q\bar{q}$ and gg or qg productions

$$A_{\rm FB} = \frac{\sigma(\cos\theta^* > 0) - \sigma(\cos\theta^* < 0)}{\sigma(\cos\theta^* > 0) + \sigma(\cos\theta^* < 0)}$$



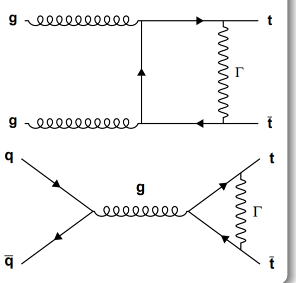


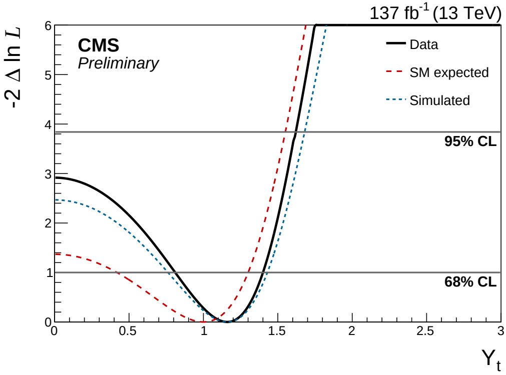
$$A_{\rm FB}^{(1)} = 0.048^{+0.095}_{-0.087}\,(\mathrm{stat})^{+0.020}_{-0.029}\,(\mathrm{syst})$$

CMS-PAS-TOP-17-004

- Weak force mediated corrections $\sim \mathcal{O}(\alpha^2 \alpha_{weak})$
- t and $\bar{\mathrm{t}}$ with small relative velocity, $\sigma_{\mathrm{t\bar{t}}}$ sensitive to Yukawa coupling
- 2 high-pt isolated e/μ, $N_{b-tags} \geq 2$
- No full kinematic reconstruction due to the presence of 2 neutrinos
- Proxy variables $M_{b\ell} = M(b + \bar{\ell} + b + \ell)$ and $|\Delta y|_{b\ell} = |y(b + \bar{\ell}) + y(b + \ell)|$

Weak virtual corrections

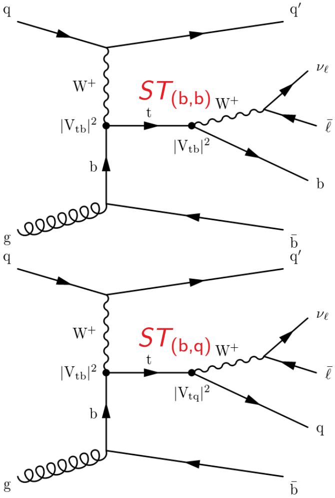




CKM matrix elements

NEW

- Single top events indicated for CKM matrix elements measurements
- 1 high-pt isolated e/μ, $N_{jets} \geq 2$, $N_{b-tags} \geq 1$
- Several BDTs to discriminate signals $ST_{(b,b)}$ and $ST_{(b,q)}$



SM assumption

By assuming: $|V_{tb}|^2 + |V_{td}|^2 + |V_{ts}|^2 = 1$

$$|V_{tb}|^2 > 0.970$$

$$|V_{td}|^2 + |V_{ts}|^2 < 0.057$$

BSM scenario

Presence of additional quark families:

$$|V_{tb}|^2 = 0.988 \pm 0.051$$

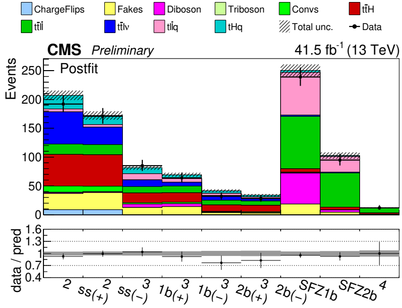
$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$$

Phys. Lett. B 808 (2020) 135609

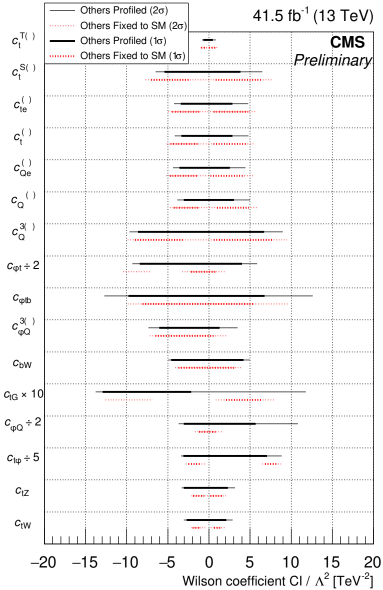
New physics with EFT approach

NEW

- Associated top quark production with a H, W or Z boson
- 16 dimension-six operators simultaneously studied
- Detector-level observables to enhance sensitivity to all operators

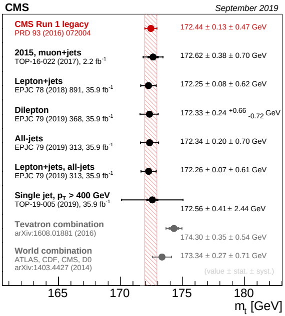


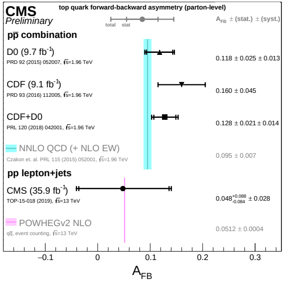
CMS-PAS-TOP-19-001



Conclusions

- Many properties of the top quark measured with high precision
- Top mass is one of the most important: direct and indirect measurements with uncertainties below 1 GeV
- Large amount of collision data allows measurements of rare processes to test the SM predictions for the first time:
  - Running top quark mass
  - Direct measurement of $|V_{td}|^2 + |V_{ts}|^2$
- Many BSM models can be tested with differential and multi-differential measurements
- No deviation from the SM predictions is observed but the top quark sector is one of the most interesting for BSM physics manifestation





BACKUP

On top mass definition

In the on-shell (o.s.) and $\overline{\mathrm{MS}}$ schemes $S^R(p)$ can then be expressed in terms of pole and $\overline{\mathrm{MS}}$ masses, respectively, as follows:

$$S^R_{\text{o.s.}}(p) \simeq \frac{i}{\not{p} - m_{\text{pole}}} \qquad S^R_{\overline{\mathrm{MS}}}(p,\mu) \simeq \frac{i}{\not{p} - m_{\overline{\mathrm{MS}}}(\mu) - (A-B)m_{\overline{\mathrm{MS}}}(\mu)}$$

The relation between top-quark pole ($m_{\mathrm{t}}^{\mathrm{pole}}$) and $\overline{\mathrm{MS}}$ ($m_{\mathrm{t}}(m_{\mathrm{t}})$) masses was calculated up to four loops in and reads:

$$\begin{aligned} m_{t,\text{pole}} &= \bar{m}_t(\bar{m}_t)\left[1 + 0.4244\,\alpha_S + 0.8345\,\alpha_S^2 + 2.375\,\alpha_S^3 + (8.615 \pm 0.017)\,\alpha_S^4 + \mathcal{O}(\alpha_S^5)\right] \\ &= [163.508 + 7.529 + 1.606 + 0.496 + (0.195 \pm 0.0004)]\ \text{GeV}. \end{aligned}$$

For further details see arXiv:1903.06574v2

Ideogram method

- PDFs from samples with 7 different mt and 5 different JSF values
- Method bias estimated with pseudo-experiments and corrected

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

where:

- i=i-th permutation in one event
- j=correct permutation, uncorrect permutation, unmatched

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Direct top mass in ℓ+jets final state details

- Main systematic uncertainty: JEC 0.18 GeV (experimental) JEC 0.39 GeV (model)

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	2D approach		1D approach	Hybrid	
	δm_t^{2D} [GeV]	δJSF^{2D} [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	δJSF^{hyb} [%]
Experimental uncertainties					
Method calibration	0.05	<0.1	0.05	0.05	<0.1
JEC (quad. sum)	0.13	0.2	0.83	0.18	0.3
– InterCalibration	(−0.02)	(<0.1)	(+0.16)	(+0.04)	(<0.1)
– MPFInSitu	(−0.01)	(<0.1)	(+0.23)	(+0.07)	(<0.1)
– Uncorrelated	(−0.13)	(+0.2)	(+0.78)	(+0.16)	(+0.3)
Jet energy resolution	−0.08	+0.1	+0.04	−0.04	+0.1
b tagging	+0.03	<0.1	+0.01	+0.03	<0.1
Pileup	−0.08	+0.1	+0.02	−0.05	+0.1
Non-$t\bar{t}$ background	+0.04	−0.1	−0.02	+0.02	−0.1
Modeling uncertainties					
JEC Flavor (linear sum)	0.42	0.1	0.31	0.39	<0.1
– light quarks (uds)	(+0.10)	(−0.1)	(−0.01)	(+0.06)	(−0.1)
– charm	(+0.02)	(<0.1)	(−0.01)	(+0.01)	(<0.1)
– bottom	(−0.32)	(<0.1)	(−0.31)	(−0.32)	(<0.1)
– gluon	(−0.22)	(+0.3)	(+0.02)	(−0.15)	(+0.2)
b jet modeling (quad. sum)	0.13	0.1	0.09	0.12	<0.1
– b frag. Bowler–Lund	(−0.07)	(+0.1)	(−0.01)	(−0.05)	(<0.1)
– b frag. Peterson	(+0.04)	(<0.1)	(+0.05)	(+0.04)	(<0.1)
– semileptonic B decays	(+0.11)	(<0.1)	(+0.08)	(+0.10)	(<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**

Direct top mass in all-had final state details

	2D		1D	hybrid	
	δm_t^{2D} [GeV]	δJSF^{2D} [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	δJSF^{hyb} [%]
Experimental uncertainties					
Method calibration	0.03	0.0	0.03	0.03	0.0
JEC (quad. sum)	0.12	0.2	0.82	0.17	0.3
– Intercalibration	−0.01	0.0	+0.16	+0.04	+0.1
– MPFInSitu	−0.01	0.0	+0.23	+0.07	+0.1
– Uncorrelated	−0.12	−0.2	+0.77	+0.15	+0.3
Jet energy resolution	−0.18	+0.3	+0.09	−0.10	+0.2
b tagging	0.03	0.0	0.01	0.02	0.0
Pileup	−0.07	+0.1	+0.02	−0.05	+0.1
All-jets background	0.01	0.0	0.00	0.01	0.0
All-jets trigger	+0.01	0.0	0.00	+0.01	0.0
ℓ+jets Background	−0.02	0.0	+0.01	−0.01	0.0
ℓ+jets Trigger	0.00	0.0	0.00	0.00	0.0
Lepton isolation	0.00	0.0	0.00	0.00	0.0
Lepton identification	0.00	0.0	0.00	0.00	0.0
Modeling uncertainties					
JEC flavor (linear sum)	−0.39	+0.1	−0.31	−0.37	+0.1
– light quarks (uds)	+0.11	−0.1	−0.01	+0.07	−0.1
– charm	+0.03	0.0	−0.01	+0.02	0.0
– bottom	−0.31	0.0	−0.31	−0.31	0.0
– gluon	−0.22	+0.3	+0.02	−0.15	+0.2
b jet modeling (quad. sum)	0.08	0.1	0.04	0.06	0.1
– b frag. Bowler–Lund	−0.06	+0.1	−0.01	−0.05	0.0
– b frag. Peterson	−0.03	0.0	0.00	−0.02	0.0
– semileptonic b hadron decays	−0.04	0.0	−0.04	−0.04	0.0
PDF	0.01	0.0	0.01	0.01	0.0
Ren. and fact. scales	0.01	0.0	0.02	0.01	0.0
ME/PS matching	−0.10 ± 0.08	+0.1	+0.02 ± 0.05	+0.07 ± 0.07	+0.1
ME generator	+0.16 ± 0.21	+0.2	+0.32 ± 0.13	+0.21 ± 0.18	+0.1
ISR PS scale	+0.07 ± 0.08	+0.1	+0.10 ± 0.05	+0.07 ± 0.07	0.1
FSR PS scale	+0.23 ± 0.07	−0.4	−0.19 ± 0.04	+0.12 ± 0.06	−0.3
Top quark p_T	+0.01	−0.1	−0.06	−0.01	−0.1
Underlying event	−0.06 ± 0.07	+0.1	+0.00 ± 0.05	−0.04 ± 0.06	+0.1
Early resonance decays	−0.20 ± 0.08	+0.7	+0.42 ± 0.05	−0.01 ± 0.07	+0.5
CR modeling (max. shift)	+0.37 ± 0.09	−0.2	+0.22 ± 0.06	+0.33 ± 0.07	−0.1
– “gluon move” (ERD on)	+0.37 ± 0.09	−0.2	+0.22 ± 0.06	+0.33 ± 0.07	−0.1
– “QCD inspired” (ERD on)	−0.11 ± 0.09	−0.1	−0.21 ± 0.06	−0.14 ± 0.07	−0.1
Total systematic	0.71	1.0	1.07	0.61	0.7
Statistical (expected)	0.08	0.1	0.05	0.07	0.1
Total (expected)	0.72	1.0	1.08	0.61	0.7

	δm_t^{hyb} [GeV]		
	all-jets	ℓ+jets	combination
Experimental uncertainties			
Method calibration	0.06	0.05	0.03
JEC (quad. sum)	0.15	0.18	0.17
– Intercalibration	−0.04	+0.04	+0.04
– MPFInSitu	+0.08	+0.07	+0.07
– Uncorrelated	+0.12	+0.16	+0.15
Jet energy resolution	−0.04	−0.12	−0.10
b tagging	0.02	0.03	0.02
Pileup	−0.04	−0.05	−0.05
All-jets background	0.07	–	0.01
All-jets trigger	+0.02	–	+0.01
ℓ+jets background	–	+0.02	−0.01
Modeling uncertainties			
JEC flavor (linear sum)	−0.34	−0.39	−0.37
– light quarks (uds)	+0.07	+0.06	+0.07
– charm	+0.02	+0.01	+0.02
– bottom	−0.29	−0.32	−0.31
– gluon	−0.13	−0.15	−0.15
b jet modeling (quad. sum)	0.09	0.12	0.06
– b frag. Bowler–Lund	−0.07	−0.05	−0.05
– b frag. Peterson	−0.05	+0.04	−0.02
– semileptonic b hadron decays	−0.03	+0.10	−0.04
PDF	0.01	0.02	0.01
Ren. and fact. scales	0.04	0.01	0.01
ME/PS matching	+0.24	−0.07	+0.07
ME generator	–	+0.20	+0.21
ISR PS scale	+0.14	+0.07	+0.07
FSR PS scale	+0.18	+0.13	+0.12
Top quark p_T	+0.03	−0.01	−0.01
Underlying event	+0.17	−0.07	−0.06
Early resonance decays	+0.24	−0.07	−0.07
CR modeling (max. shift)	−0.36	+0.31	+0.33
– “gluon move” (ERD on)	+0.32	+0.31	+0.33
– “QCD inspired” (ERD on)	−0.36	−0.13	−0.14
Total systematic	0.70	0.62	0.61
Statistical (expected)	0.20	0.08	0.07
Total (expected)	0.72	0.63	0.61