Recent top quark properties in CMS

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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:

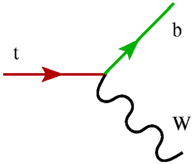
$$m_{\text{top}} = y_t \frac{v}{\sqrt{2}} \simeq 174\,\mathrm{GeV} \Longrightarrow y_t \sim 1$$

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

- Decay happens before hadronization can occur:

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

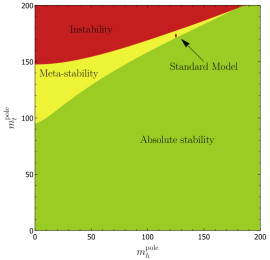
- Angular properties directly accessible through its decay products
- Weak interaction decay, dominantly in a W boson and a b quark



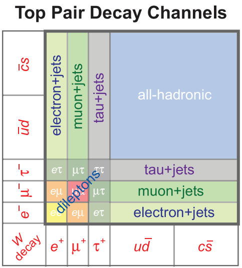
Top mass

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}



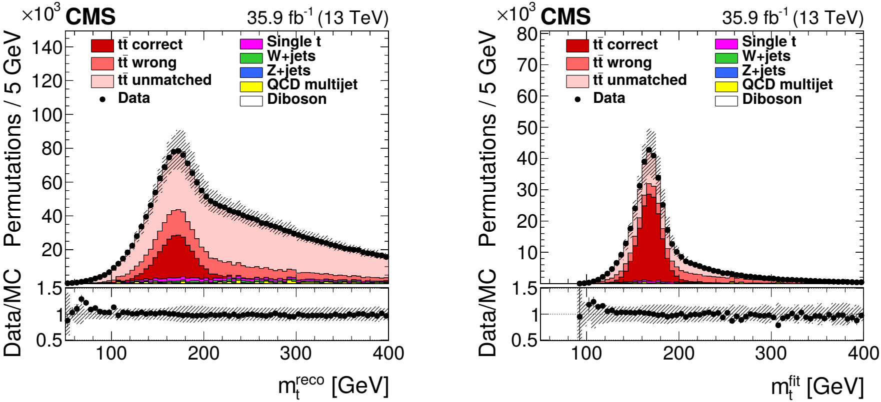
How it can be determined?



- 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: estimation of the jet energy scale factor (JSF) to reduce JES impact



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

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

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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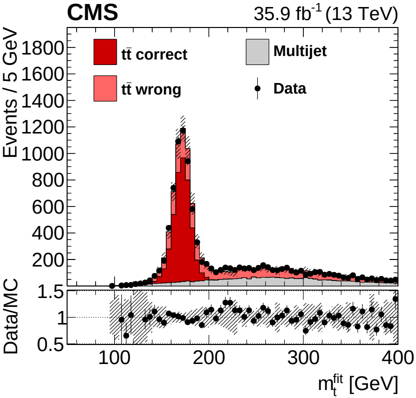
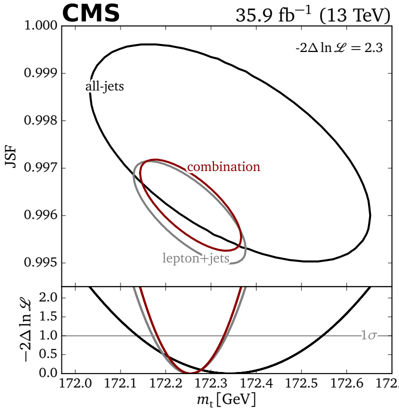




$m_t = 172.34 \pm 0.20(\text{stat}) \pm 0.70(\text{syst})$

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

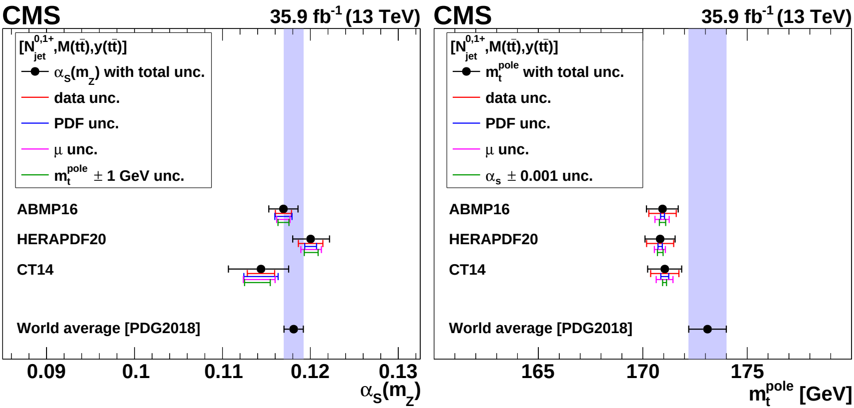
$m_t = 172.26 \pm 0.07(\text{stat}) \pm 0.61(\text{syst})$

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

Indirect top pole mass in dilepton final state

- Details on the analysis → see Otto's talk
- Triple-differential $\sigma(\mathrm{N_{jets}}, \mathrm{M(t\bar{t})}, \mathrm{y(t\bar{t})})$

arXiv:1904.05237



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

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

Direct top MC mass in dilepton final state

- Analysis strategy details → see Juan's talk

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- Simultaneous fit for cross section and mass extraction

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

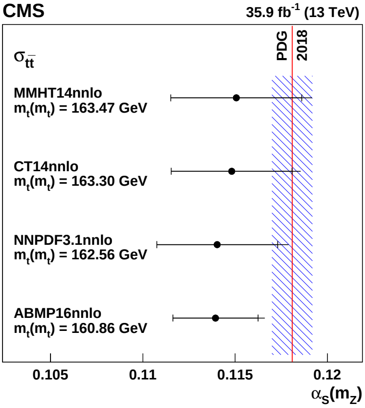
- Residual dependence of the cross section on m_t^{MC}
  → indirect measurement of m_t^{pole}

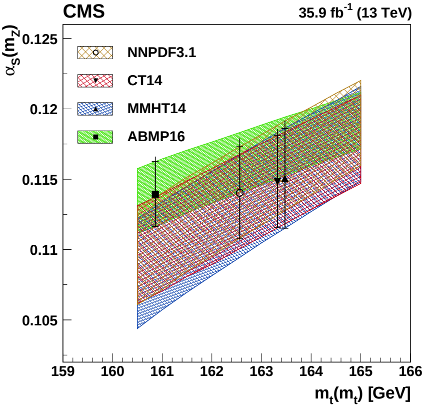
PDF set	m_t^{pole} [GeV]
ABMP16	$169.9 \pm 1.8(\text{fit} + \text{PDF} + \alpha_S)^{+0.8}_{-1.2}(\text{scale})$
NNPDF3.1	$173.2 \pm 1.9(\text{fit} + \text{PDF} + \alpha_S)^{+0.9}_{-1.3}(\text{scale})$
CT14	$173.7 \pm 2.0(\text{fit} + \text{PDF} + \alpha_S)^{+0.9}_{-1.4}(\text{scale})$
MMHT14	$173.6 \pm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

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





Top quark polarization

- By factorizing decay density matrices ρ and $\bar{\rho}$:

$$|\mathcal{M}(\mathrm{q\bar{q}}/gg \to \mathrm{t\bar{t}} \to (\ell^+ \nu b)(\ell^- \bar{\nu} \bar{b}))|^2 \sim Tr[\rho R \bar{\rho}]$$

- Study spin density matrix R using double-differential cross section:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i \, d\cos\theta_2^j} = \frac{1}{4}\left(1 + B_1^i \cos\theta_1^i + B_2^j \cos\theta_2^j - C_{ij}\cos\theta_1^i \cos\theta_2^j\right)$$

Top quark polarization

- By factorizing decay density matrices ρ and $\bar{\rho}$:

$$|\mathcal{M}(q\bar{q}/gg \to t\bar{t} \to (\ell^+ \nu b)(\ell^- \bar{\nu} \bar{b}))|^2 \sim Tr[\rho R \bar{\rho}]$$

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- Derive single-differential cross sections with respect to $\cos\theta_1^i$, $\cos\theta_2^j$, and $\cos\theta_1^i \cos\theta_2^j$:

Polarization

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta_1^i} = \frac{1}{2}\left(1 + B_1^i \cos\theta_1^i\right) \qquad \frac{1}{\sigma} \frac{d\sigma}{d\cos\theta_2^j} = \frac{1}{2}\left(1 + B_2^j \cos\theta_2^j\right)$$

Spin correlation

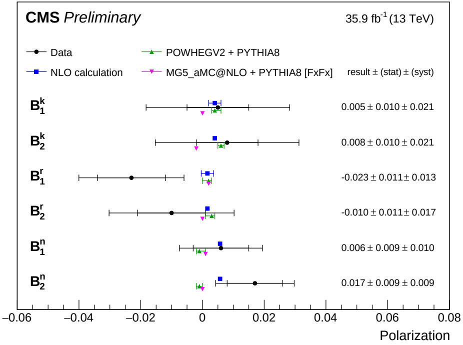
$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta_1^i \cos\theta_2^j} = \frac{1}{2}\left(1 - C_{ij} \cos\theta_1^i \cos\theta_2^j\right) \ln\left(\frac{1}{\cos\theta_1^i \cos\theta_2^j}\right)$$

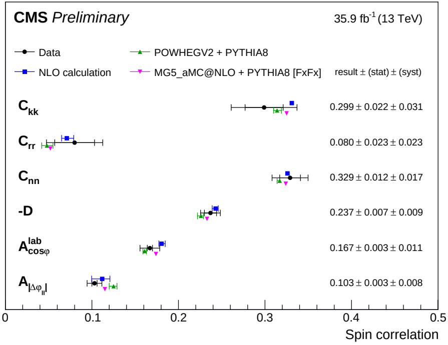
Measurement of the top quark polarization

- $t\bar{t} \rightarrow (\ell^+ \nu b)(\ell^- \bar{\nu} \bar{b})$ perfect for spin measurements: spin analyzing power of the lepton ~ 1

CMS-PAS-TOP-18-006

- Kinematic fit for full event reconstruction
- χ^2 minimization technique to unfold distributions
- 15 single-differential cross sections measured





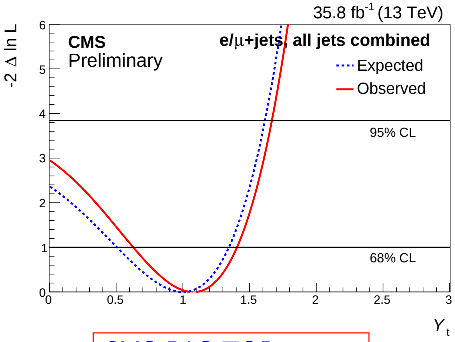
Yukawa coupling

- Weak force mediated corrections $\sim \mathcal{O}(\alpha^2 \alpha_{weak})$
- t and $\bar{\mathrm{t}}$ with small relative velocity, $\sigma_{\mathrm{t}\bar{\mathrm{t}}}$ sensitive to Yukawa coupling
- 1 high-pt isolated e/μ, $N_{jets} \geq 3$, $N_{b-tags} \geq 2$
- New kinematic reconstruction technique with one missing jet events
- Missing jet events favour low-$\mathrm{m}_{\mathrm{t}\bar{\mathrm{t}}}$ region $\rightarrow$ max sensitivity
- Extraction from $\mathrm{M}_{\mathrm{t}\bar{\mathrm{t}}}$ and $\Delta y = y_{\mathrm{t}} - y_{\bar{\mathrm{t}}}$ for different jet multiplicities.

Weak virtual corrections

Exclusion limit

Channel	Expected 95% CL	Observed 95% CL
3 jets	$Y_{\mathrm{t}} < 2.17$	$Y_{\mathrm{t}} < 2.59$
4 jets	$Y_{\mathrm{t}} < 1.88$	$Y_{\mathrm{t}} < 1.77$
5 jets	$Y_{\mathrm{t}} < 2.03$	$Y_{\mathrm{t}} < 2.23$
Combined	$Y_{\mathrm{t}} < 1.62$	$Y_{\mathrm{t}} < 1.67$



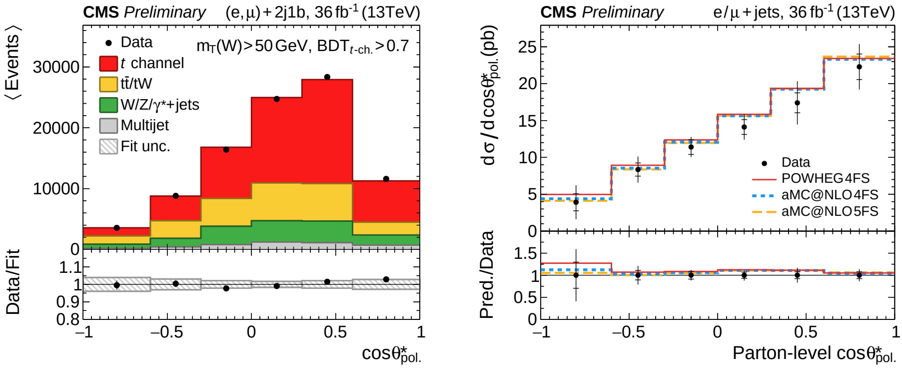
CMS-PAS-TOP-17-004

Top quark spin asymmetry

- Spin asymmetry from differential t-channel single-top cross section

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_X^*} = \frac{1}{2}\left(1 + P_{\mathrm{t}}^{(\vec{s})}\alpha_X\cos\theta_X^*\right) = \left(\frac{1}{2} + A_X\cos\theta_X^*\right)$$

- 1 ℓ with $p_{\mathrm{T}} > 35(26)$ for e(μ), $N_{jets} = 2$–3, $N_{b-tags} = 0$–2
- Differential measurement with χ^2 minimization technique

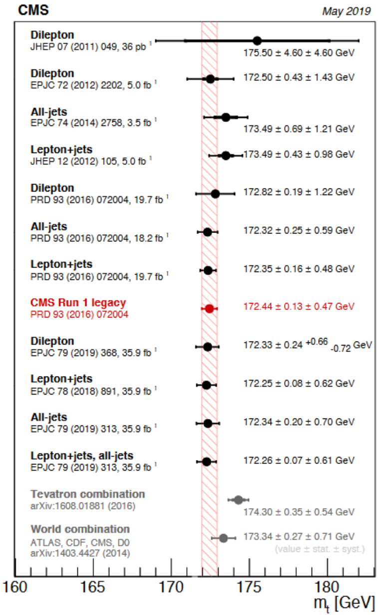


$A_{e/\mu} = 0.439 \pm 0.032(\text{stat}) \pm 0.053(\text{syst})$

CMS-PAS-TOP-17-023

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
- High quantity of data allows measurements of rare processes to test the SM predictions
- Many BSM models can be tested with differential and multi-differential measurements
- No deviation from the SM predictions are observed but the top quark sector is one of the most interesting for BSM physics manifestation



Thank you

BACKUP

Production processes

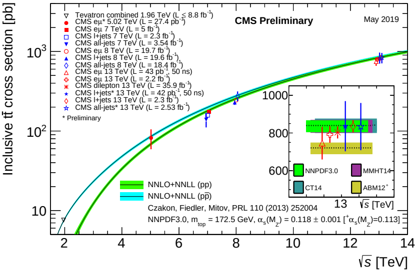
Top quark can be produced by:

Strong interaction

$t\bar{t}$ pairs

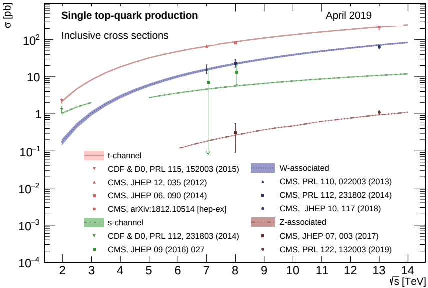
$q\bar{q} \rightarrow t\bar{t}$ (15%) $\quad gg \rightarrow t\bar{t}$ (85%)

$\sigma_{t\bar{t}} = 816^{+19.4+34.4}_{-28.6-34.4}$ pb



Weak interaction

- *s*-channel
- tW associate production
- *t*-channel
- tZ associate production



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:

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

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:

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

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

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

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 0.32 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**

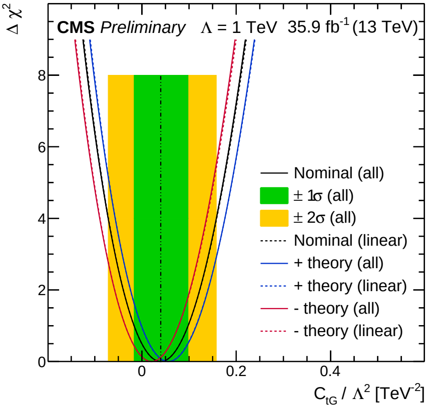
Direct top mass in all-had final state details

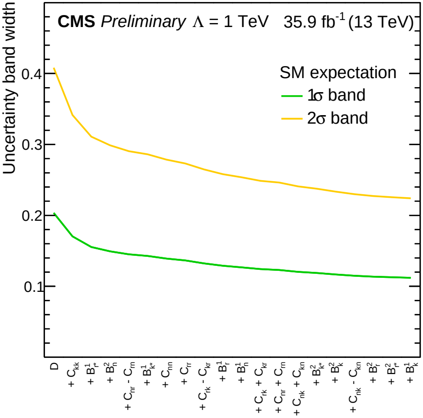
	2D		1D	hybrid	
	δm_t^{2D} [GeV]	δJSF^{2D} [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	δJSF^{hyb} [%]
Experimental uncertainties					
Method calibration	0.03	0.0	0.03	0.03	0.0
JEC (quad. sum)	0.12	0.2	0.82	0.17	0.3
– Intercalibration	−0.01	0.0	+0.16	+0.04	+0.1
– MPFInSitu	−0.01	0.0	+0.23	+0.07	+0.1
– Uncorrelated	−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	$+0.02 \pm 0.05$	$+0.07 \pm 0.07$	+0.1
ME generator	$+0.16 \pm 0.21$	+0.2	$+0.32 \pm 0.13$	$+0.21 \pm 0.18$	+0.1
ISR PS scale	$+0.07 \pm 0.08$	+0.1	$+0.10 \pm 0.05$	$+0.07 \pm 0.07$	0.1
FSR PS scale	$+0.23 \pm 0.07$	−0.4	-0.19 ± 0.04	$+0.12 \pm 0.06$	−0.3
Top quark p_T	+0.01	−0.1	−0.06	−0.01	−0.1
Underlying event	-0.06 ± 0.07	+0.1	$+0.00 \pm 0.05$	-0.04 ± 0.06	+0.1
Early resonance decays	-0.20 ± 0.08	+0.7	$+0.42 \pm 0.05$	-0.01 ± 0.07	+0.5
CR modeling (max. shift)	$+0.37 \pm 0.09$	−0.2	$+0.22 \pm 0.06$	$+0.33 \pm 0.07$	−0.1
– "gluon move" (ERD on)	$+0.37 \pm 0.09$	−0.2	$+0.22 \pm 0.06$	$+0.33 \pm 0.07$	−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

Top quark chromomagnetic dipole moment

- CMDM is for a colour-charged particle the analogous to the magnetic dipole for electrically charged particle
- Top quark CMDM small due to intrinsic top spin and colour charge
- BSM predict anomalous CMDM, parametrizable in dim-6 EFT
- C_{Gt} sensitivity improved by 50% w.r.t. previous 13 TeV results



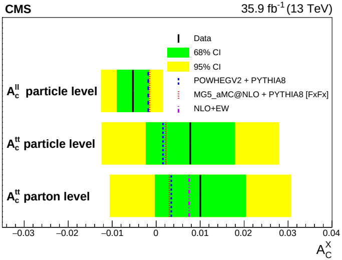


Top charge asymmetry

- Signals of BSM physics could also appear in $\mathrm{t\bar{t}}$ production as anomalous top quark or leptonic charge asymmetries

$$A_c^{\mathrm{t\bar{t}}} = \frac{\sigma_{\mathrm{t\bar{t}}}(\Delta|y|(\mathrm{t},\mathrm{\bar{t}}) > 0) - \sigma_{\mathrm{t\bar{t}}}(\Delta|y|(\mathrm{t},\mathrm{\bar{t}}) < 0)}{\sigma_{\mathrm{t\bar{t}}}(\Delta|y|(\mathrm{t},\mathrm{\bar{t}}) > 0) + \sigma_{\mathrm{t\bar{t}}}(\Delta|y|(\mathrm{t},\mathrm{\bar{t}}) < 0)}$$

$$A_c^{\ell\bar{\ell}} = \frac{\sigma_{\mathrm{t\bar{t}}}(\Delta\eta(\ell,\bar{\ell}) > 0) - \sigma_{\mathrm{t\bar{t}}}(\Delta\eta(\ell,\bar{\ell}) < 0)}{\sigma_{\mathrm{t\bar{t}}}(\Delta\eta(\ell,\bar{\ell}) > 0) + \sigma_{\mathrm{t\bar{t}}}(\Delta\eta(\ell,\bar{\ell}) < 0)}$$



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