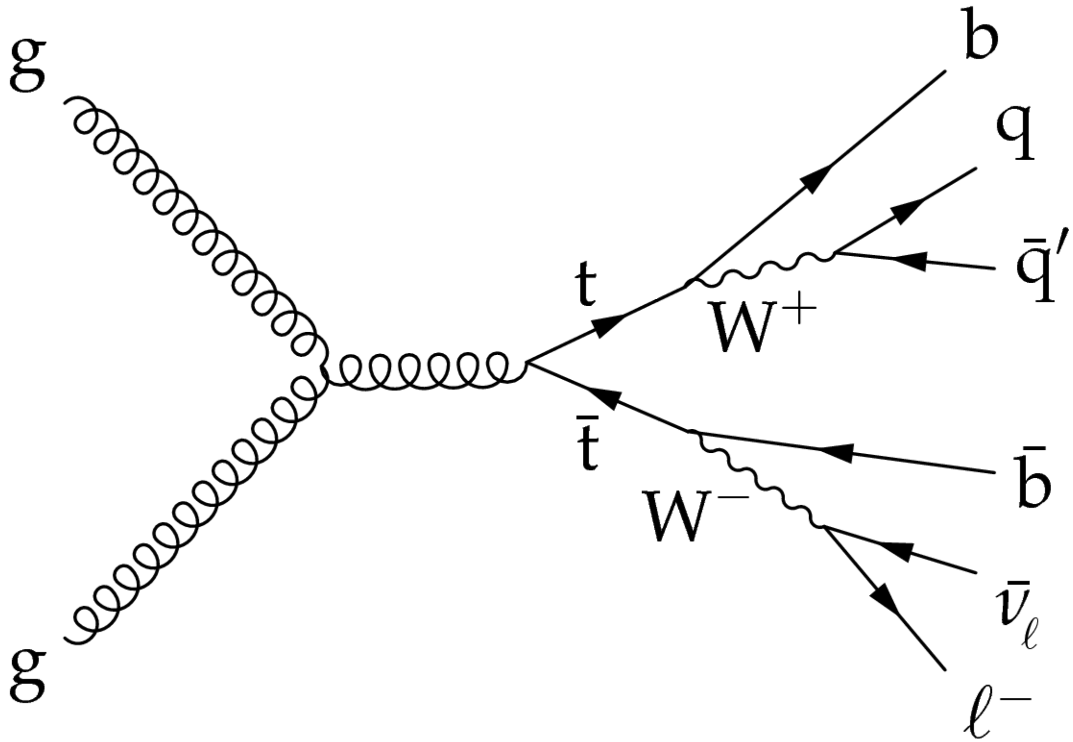


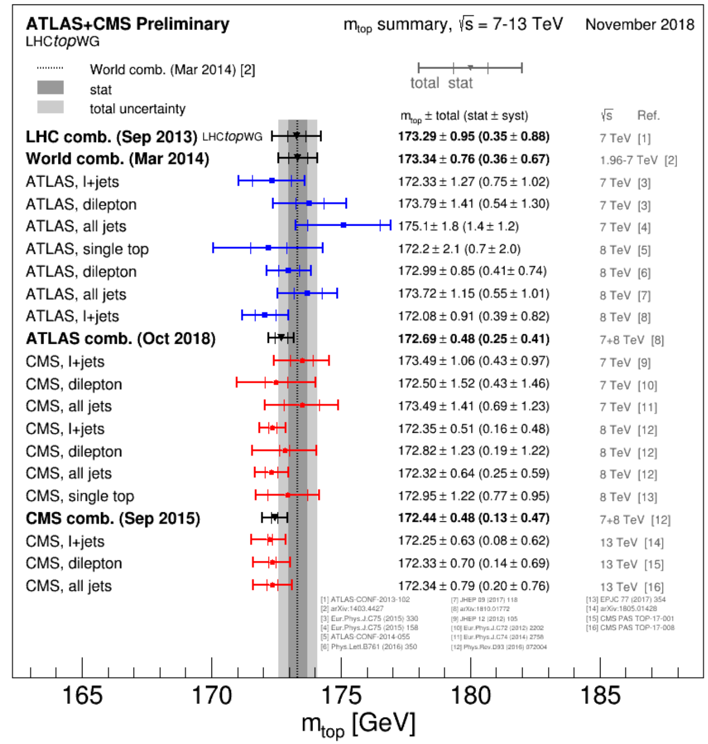
Recent measurements of top quark properties

Brent R. Yates

On behalf of the ATLAS and CMS Collaborations

Introduction

- The top quark
  - Elementary particle with largest mass $m_{\mathrm{t}} \approx 172.5\ \mathrm{GeV}$
  - Top quark mass is a leading uncertainty in determining vacuum stability
- Top quark production at the LHC
  - $\sqrt{s} = 13\ \mathrm{TeV}$ with peak instantaneous $\mathcal{L} = 2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ in 2018
  - Millions of $\mathrm{t\bar{t}}$ events produced
  - Precision tests of SM



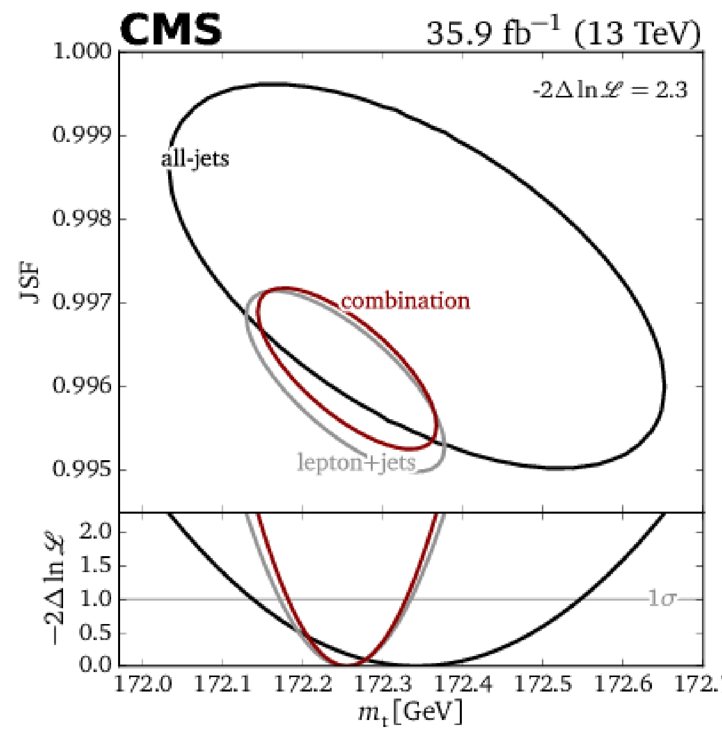
Overview

- New measurements of top quark properties in this talk
  - Pole mass (m_{t}) and modified minimal subtracted ($\overline{\mathrm{M}S}$ four loop level)
  - Strong coupling constant (α_{s}) and parton distribution functions
  - Spin correlation
  - Charge and spin asymmetry
  - Yukawa coupling (Y_{t})

- Many measurements rely on inclusive or differential cross section measurements to extract properties
  - See $\sigma_{\mathrm{t\bar{t}}}$ talk by J. Garcia for details on cross section measurements

Measurement of the top quark mass

- CMS combined all-jets and lepton + jets
  arxiv:1812.10534
  - $35.9\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV with additional jet energy scale factor (JSF)
- ATLAS lepton + jets and combination
  Eur. Phys. J. C (2019) 79: 290
  - $\sqrt{7}$ TeV and $\sqrt{8}$ TeV with JSF
  - Comparable precision with CMS at $\sqrt{7}$ TeV and $\sqrt{8}$ TeV



Results

CMS all-jets channel fit (JSF method)

- $m_t = 172.34 \pm 0.20(\mathrm{stat}+\mathrm{JSF}) \pm 0.43(\mathrm{CR}+\mathrm{ERD}) \pm 0.55(\mathrm{syst})\ \mathrm{GeV}$

  PYTHIA 8 – more color reconnection and early resonance decay models available than pervious versions

CMS combined channels fit (leptons + jets and all jets)

- $m_t = 172.26 \pm 0.07(\mathrm{stat}+\mathrm{JSF}) \pm 0.61(\mathrm{syst})\ \mathrm{GeV}$

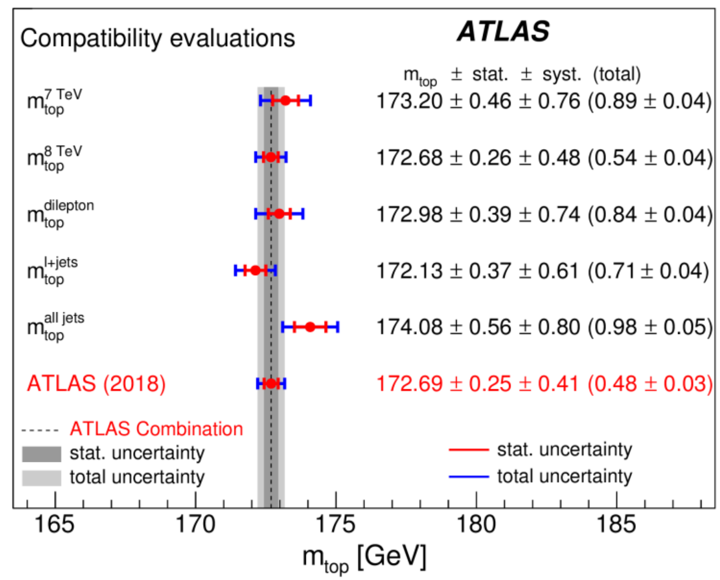
ATLAS lepton + jets channel fit (JSF method)

- $m_t = 172.08 \pm 0.39(\mathrm{stat}) \pm 0.82(\mathrm{syst})\ \mathrm{GeV}$

ATLAS combined channels fit

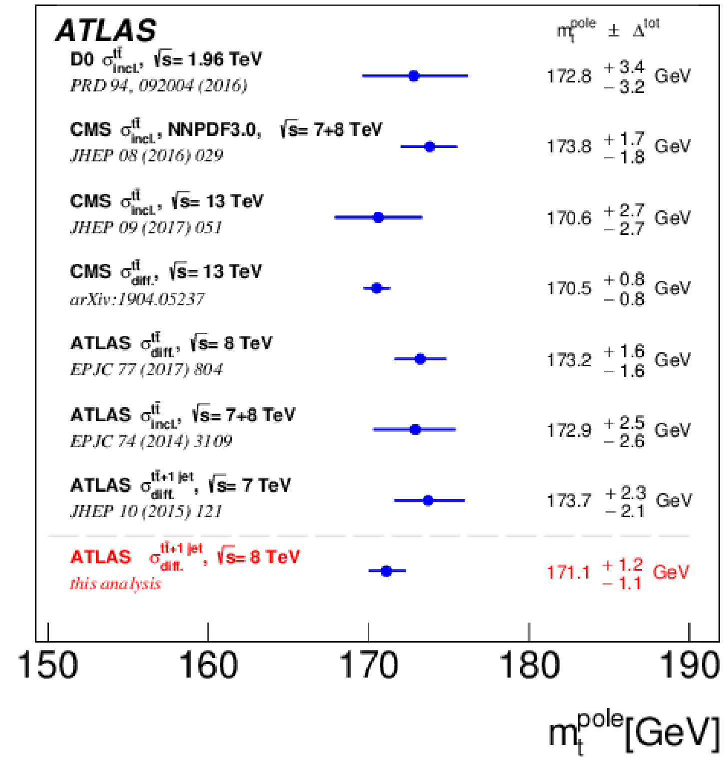
- $m_t = 172.69 \pm 0.25(\mathrm{stat}) \pm 0.41(\mathrm{syst})\ \mathrm{GeV}$

  Increase in precision reduces total error by half



Extraction of the top quark mass from $\sigma_{t\bar{t}}$

- Cross section measurement used to extract m_t^{pole} and $m_t^{\overline{\text{MS}}}$
- CMS dilepton final state Eur. Phys. J. C (2019) 79: 368
  - $35.9\ \text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV
  - Inclusive $\sigma_{t\bar{t}}$
- ATLAS lepton + jets final state arxiv:1905.02302 (JHEP)
  - $20.2\ \text{fb}^{-1}$ at $\sqrt{s} = 8$ TeV
  - $\frac{d\sigma_{t\bar{t}+1\text{jet}}}{d\rho_s}$ where $\rho_s = \frac{360\ \text{GeV}}{m_{t\bar{t}+1\text{jet}}}$



Results

CMS extraction of $m_{\mathrm{t}}^{\overline{\mathrm{MS}}}$ for various PDFs

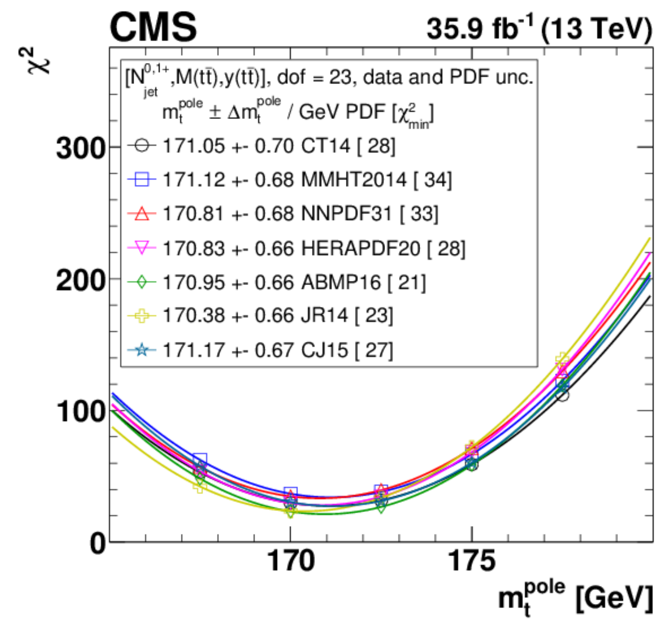
PDF set	$m_{\mathrm{t}}(m_{\mathrm{t}})$ [GeV]
ABMP16	$161.6 \pm 1.6\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.1}_{-1.0}\,(\text{scale})$
NNPDF3.1	$164.5 \pm 1.6\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.1}_{-1.0}\,(\text{scale})$
CT14	$165.0 \pm 1.8\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.1}_{-1.0}\,(\text{scale})$
MMHT14	$164.9 \pm 1.8\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.1}_{-1.1}\,(\text{scale})$

ATLAS extraction of $m_{\mathrm{t}}^{\mathrm{pole}}$ and $m_{\mathrm{t}}^{\overline{\mathrm{MS}}}$ for CT10 PDF

- $m_{\mathrm{t}}^{\mathrm{pole}} = 171.1 \pm 0.4(\text{stat}) \pm 0.9(\text{syst})^{+0.7}_{-0.3}(\text{theory})$ GeV
- $m_{\mathrm{t}}^{\overline{\mathrm{MS}}} = 162.9 \pm 0.5(\text{stat}) \pm 1.0(\text{syst})^{+2.1}_{-1.2}(\text{theory})$ GeV

Extraction of the top quark mass and α_s from $\sigma_{t\bar{t}}$

- Cross section measurement used to extract m_t^{pole} and α_s parton level
  - $35.9\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV



- CMS dilepton final state Eur. Phys. J. C (2019) 79: 368
  - Inclusive $\sigma_{t\bar{t}}$
- CMS lepton + jets final state arxiv:1904.05237 (EPJ C)
  - Differential $\sigma_{t\bar{t}}$ ($M(t\bar{t})$, $y(t\bar{t})$, and $N^{0,1+}{}_{jet}$)

Results

CMS extraction of m_t^{pole} and α_s for various PDFs (dilepton)

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	$173.6 \pm 1.9\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.9}_{-1.4}\,(\text{scale})$

PDF set	$\alpha_S(m_Z)$
ABMP16	$0.1139 \pm 0.0023\,(\text{fit} + \text{PDF})\,^{+0.0014}_{-0.0001}\,(\text{scale})$
NNPDF3.1	$0.1140 \pm 0.0033\,(\text{fit} + \text{PDF})\,^{+0.0021}_{-0.0002}\,(\text{scale})$
CT14	$0.1148 \pm 0.0032\,(\text{fit} + \text{PDF})\,^{+0.0018}_{-0.0002}\,(\text{scale})$
MMHT14	$0.1151 \pm 0.0035\,(\text{fit} + \text{PDF})\,^{+0.0020}_{-0.0002}\,(\text{scale})$

- $m_t = 172.33 \pm 0.14(\text{stat})^{+0.66}_{-0.72}(\text{syst})\ \text{GeV}$ for NNPDF3.0

CMS extraction of m_t^{pole} and α_s for NNPDF3.0 (lepton + jets)

- $\alpha_s = 0.1135^{+0.0021}_{-0.0017}$
- $m_t = 170.5 \pm 0.8\ \text{GeV}$

$t\bar{t}$ charge asymmetry

- Differential $\sigma_{t\bar{t}}$ ($M(t\bar{t})$ and $\Delta y(t\bar{t})$)
  - $35.9\ \text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV

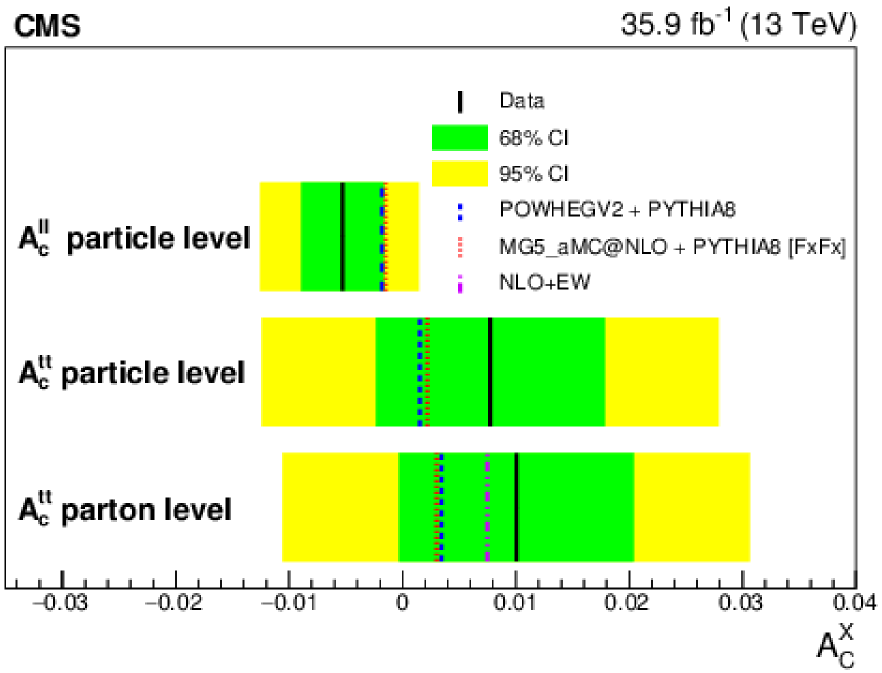
- CMS dilepton final state
  J. High Energ. Phys. (2019) 2019: 14

$t\bar{t}$ asymmetry

- $A_C^{t\bar{t}} = \frac{\sigma_{t\bar{t}}(\Delta|y|(t\bar{t})>0) - \sigma_{t\bar{t}}(\Delta|y|(t\bar{t})<0)}{\sigma_{t\bar{t}}(\Delta|y|(t\bar{t})>0) + \sigma_{t\bar{t}}(\Delta|y|(t\bar{t})<0)}$
  - $A_C^{t\bar{t}}(\text{parton level}) = 0.01 \pm 0.009$
  - $A_C^{t\bar{t}}(\text{particlelevel}) = 0.008 \pm 0.009$

Lepton asymmetry

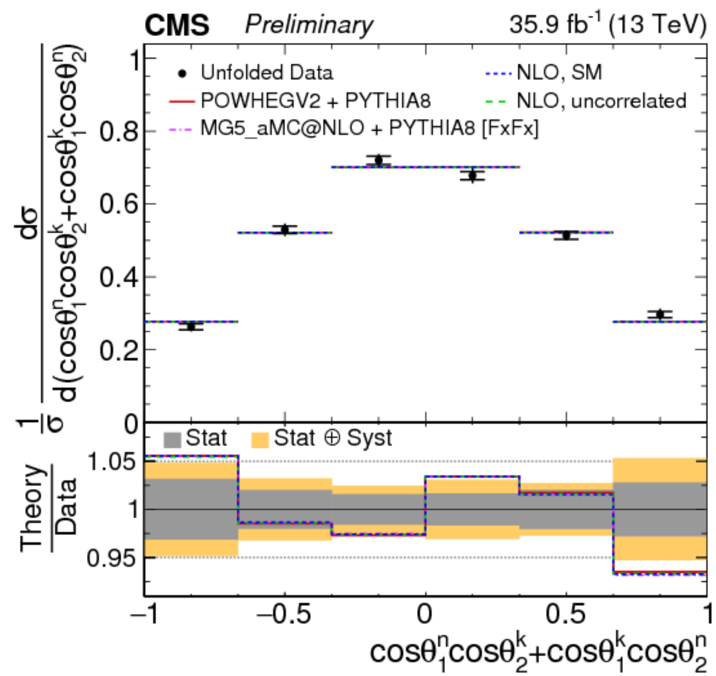
- $A_C^{\ell\bar{\ell}} = \frac{\sigma_{t\bar{t}}(\Delta\eta(\ell\bar{\ell})>0) - \sigma_{t\bar{t}}(\Delta\eta(\ell\bar{\ell})<0)}{\sigma_{t\bar{t}}(\Delta\eta(\ell\bar{\ell})>0) + \sigma_{t\bar{t}}(\Delta\eta(\ell\bar{\ell})<0)}$
  - $A_C^{\ell\bar{\ell}}(\text{particle level}) = -0.005 \pm 0.004$



Top quark pair spin correlations

- Differential $\sigma_{t\bar{t}}$
  - $35.9\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV (CMS)
  - $36.1\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV (ATLAS)

- CMS dilepton final state CMS-PAS-TOP-18-006
- ATLAS dilepton final state arxiv:1903.07570



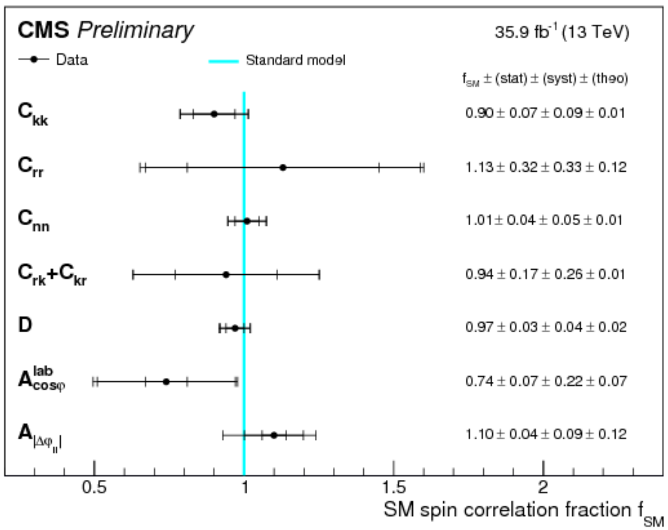
$$\frac{1}{\Gamma_t} < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda_{QCD}^2}$$

(top quark lifetime < hadronization time < spin decorrelation time)

- Leptons from $t\bar{t} \rightarrow b\ell\bar{b}\,\bar{\ell}$ retain top quark spin information

Results

- Fit wrt SM predictions
  - $f_{SM} = 1$ indicates full agreement
  - $f_{SM} = 0$ indicates uncorrelated events



ATLAS

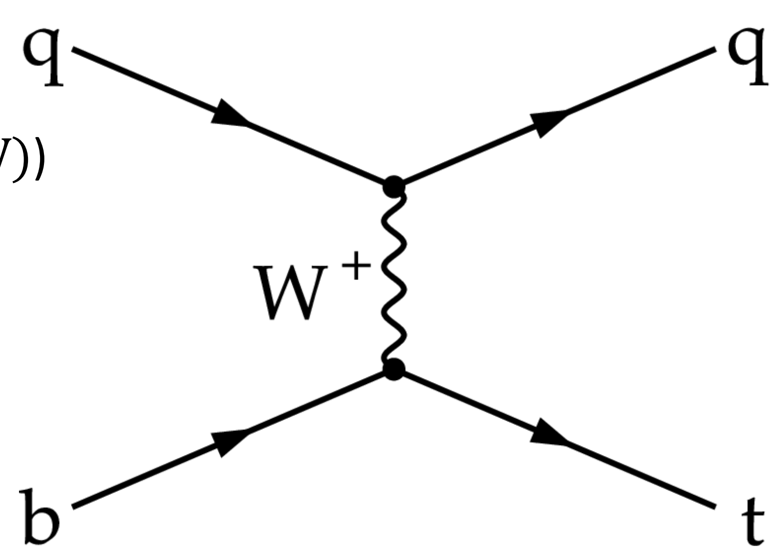
Region	$f_{SM} \pm$ (stat.,syst.,theory)	Significance (excl. theory uncertainties)
Inclusive	$1.249 \pm 0.024 \pm 0.061 \pm 0.040$	3.2 (3.8)
$m_{t\bar{t}} < 450$ GeV	$1.12 \pm 0.04\ ^{+0.12}_{-0.13} \pm 0.02$	0.86 (0.87)
$450 \leq m_{t\bar{t}} < 550$ GeV	$1.18 \pm 0.08\ ^{+0.13}_{-0.14} \pm 0.08$	1.0 (1.1)
$550 \leq m_{t\bar{t}} < 800$ GeV	$1.65 \pm 0.19\ ^{+0.31}_{-0.41} \pm 0.22$	1.3 (1.4)
$m_{t\bar{t}} \geq 800$ GeV	$2.2 \pm 0.9\ ^{+2.5}_{-1.7} \pm 0.7$	0.58 (0.61)

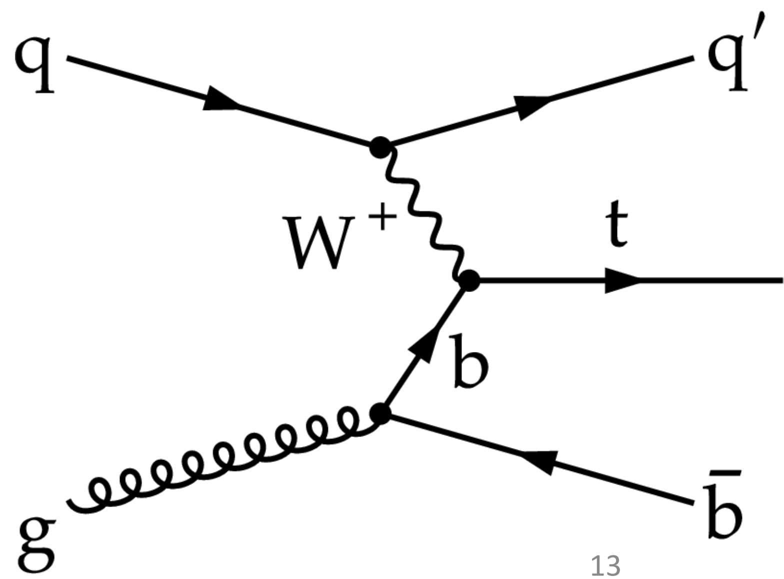
Generator	Inclusive	$m_{t\bar{t}} < 450$ GeV	$450 \leq m_{t\bar{t}} < 550$ GeV	$550 \leq m_{t\bar{t}} < 800$ GeV	$m_{t\bar{t}} \geq 800$ GeV
f_{SM} values					
POWHEG + PYTHIA 8	1.25	1.11	1.17	1.60	2.19
POWHEG + PYTHIA 8 (2.0 μ_F, 2.0 μ_R)	1.29	1.14	1.21	1.70	1.70
POWHEG + PYTHIA 8 (0.5 μ_F, 0.5 μ_R)	1.18	1.09	1.11	1.40	1.30
POWHEG + PYTHIA 8 (PDF variations)	1.26	1.12	1.24	1.69	2.19
POWHEG + PYTHIA 8 RadLo tune	1.29	1.14	1.21	1.40	1.70
POWHEG + HERWIG 7	1.32	1.16	1.23	1.70	1.70
MADGRAPH5_aMC@NLO + PYTHIA 8	1.20	1.06	1.17	1.40	0.70
NLO (QCD + EW expanded) [83,84,35]	1.07	-	-	-	-
NNLO QCD [82]	1.14	-	-	-	-

- CMS results in good agreement with SM
- ATLAST results larger than SM, may be limitations in modeling

Top quark spin asymmetry

- Differential σ_{t} $(p_{\mathrm{T}}(\mathrm{t}), \mathrm{y}(\mathrm{t}), \theta_{\mathrm{pol.}}(\mathrm{t}), p_{\mathrm{T}}(\ell), \mathrm{y}(\ell), p_{\mathrm{T}}(\mathrm{W}))$
  - $35.9\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13\ \mathrm{TeV}$
- CMS lepton + jets final state CMS-PAS-TOP-17-023
- Charge ratio: $\frac{\sigma_{\mathrm{t}}}{\sigma_{\mathrm{t}+\bar{\mathrm{t}}}}$ good agreement with tested PDFs – NNPDF3.0, MMHT14, and CT10
- Spin asymmetry $\frac{d\sigma}{\sigma\, d\cos\theta^{\star}_{\mathrm{pol}}} = \frac{1}{2}\left(1 + 2A_{\ell}\cos\theta^{\star}_{\mathrm{pol}}\right)$
  - $\vec{p}^{\,\mathrm{top}}_{\mathrm{q'}} \cdot \vec{p}^{\,\mathrm{top}}_{\ell} = \left|\vec{p}^{\,\mathrm{top}}_{\mathrm{q'}}\right| \left|\vec{p}^{\,\mathrm{top}}_{\ell}\right| \cos\theta^{\star}_{\mathrm{pol}}$
- $A_{\mathrm{e}+\mu} = 0.439 \pm 0.032(\mathrm{stat}) \pm 0.053(\mathrm{syst})$

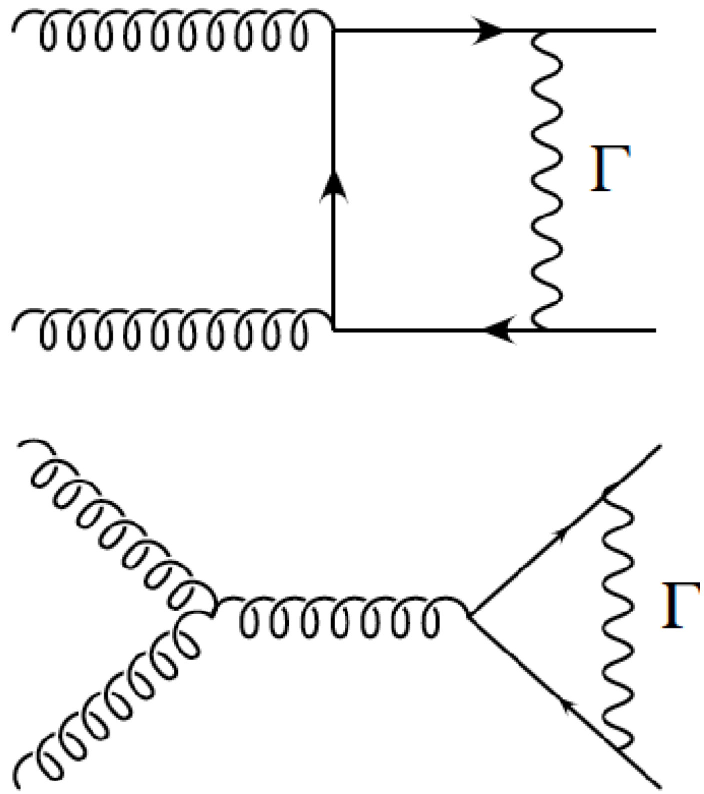




Constraining the top Yukawa coupling

- Differential $\sigma_{t\bar{t}}$ ($M(t\bar{t})$ and $y(t\bar{t})$)
  - $35.9\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13\ \mathrm{TeV}$

- CMS lepton + jets final state CMS-PAS-TOP-17-004
- Electroweak corrections (Γ)



Channel	Expected 95% CL	Observed 95% CL
3 jets	$Y_t < 2.17$	$Y_t < 2.59$
4 jets	$Y_t < 1.88$	$Y_t < 1.77$
5 jets	$Y_t < 2.03$	$Y_t < 2.23$
Combined	$Y_t < 1.62$	$Y_t < 1.67$

Summary

- Measurements presented from CMS at $\sqrt{13}$ TeV and ATLAS at $\sqrt{7}$ TeV, $\sqrt{8}$ TeV, $\sqrt{13}$ TeV
  - Combined ATLAS analyses give comparable precision to CMS
- Top pole mass — agreement between collaborations
- $\overline{\text{MS}}$ mass — agreement between collaborations
- Extraction of α_s — $\alpha_s = 0.1135^{+0.0021}_{-0.0017}$
- Charge and spin asymmetry — consistent with SM (CMS presented)
- Spin correlation — CMS consistent with SM, ATLAS shows 3.2σ deviation
- Yukawa coupling — consistent with SM (CMS presented)

Currently no evidence of deviations from the Standard Model at the level of precision available from the ATLAS and CMS detectors

Thank you to both collaborations for their hard work in producing these measurements

Backup

Top quark mass in the hadronic final state Combination with leptons + jets channel

arxiv:1812.10534

(Submitted to European Physical Journal C)

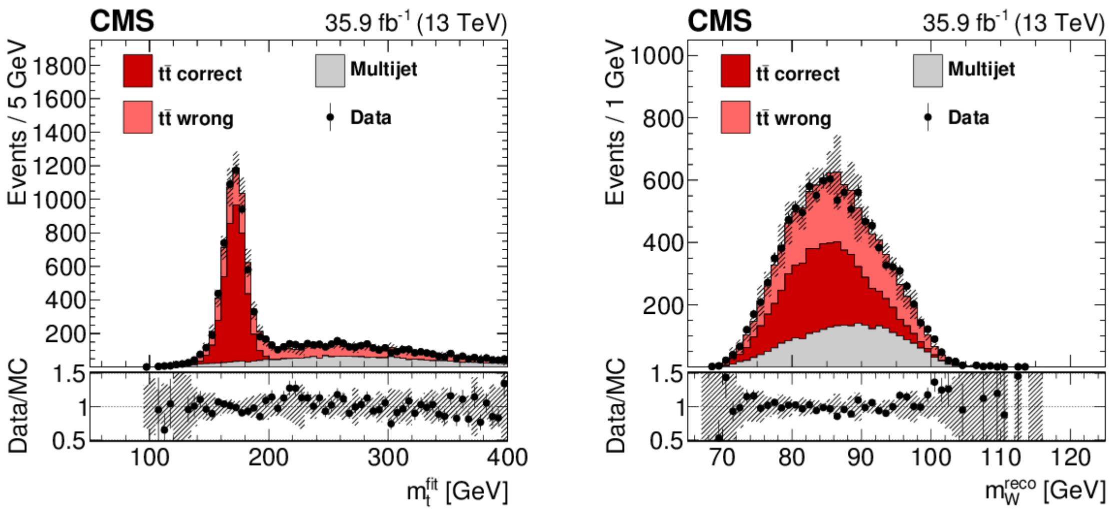
Event selection

- Jets
  - HLT with at least six particle flow jets, each $p_{\mathrm{T}} > 40$ GeV and $H_{\mathrm{T}} > 450$ GeV
    - At least one b-tagged
  - Anti-k_{T} $R = 0.4$ with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.4$
  - b-tagging with combined secondary vertex algorithm
  - Softest of the six jets must have $p_{\mathrm{T}} > 40$ GeV and $H_{\mathrm{T}} > 450$ GeV
  - $\Delta R\left(b\bar{b}\right) > 2.0$
  - Kinematic fit to minimize

$$\chi^2 = \sum_{j \in \mathrm{jets}} \left[\frac{\left(p_{\mathrm{T}j}^{\mathrm{reco}} - p_{\mathrm{T}j}^{\mathrm{fit}}\right)^2}{\sigma_{p_{\mathrm{T}j}}^2} + \frac{\left(\eta_j^{\mathrm{reco}} - \eta_j^{\mathrm{fit}}\right)^2}{\sigma_{\eta j}^2} + \frac{\left(\phi_j^{\mathrm{reco}} - \phi_j^{\mathrm{fit}}\right)^2}{\sigma_{\phi j}^2} \right]$$

  - Constrain $m_{\mathrm{W}} = 80.4$ GeV
  - $P_{\mathrm{gof}} = 1 - \mathrm{erf}\left(\sqrt{\frac{\chi^2}{2}}\right) + \sqrt{\frac{2\chi^2}{\pi}} e^{-\chi^2/2} > 0.1$

Ideogram method



- Simultaneous fit of m_{t} and jet energy scale factor (JSF)
- $m_{\mathrm{t}}^{\mathrm{fit}}$ from kinematic fit and $m_{\mathrm{W}}^{\mathrm{reco}}$ are used in a combined fit
- Likelihood fit maximized, yielding a best fit for m_{t} and JSF

$$\mathcal{L}(m_{\mathrm{t}}, \mathrm{JSF}) = P(\mathrm{sample}|m_{\mathrm{t}}, \mathrm{JSF}) \times \boxed{P(\mathrm{JSF})}$$

prior

$$P(\mathrm{sample}|m_{\mathrm{t}}, \mathrm{JSF}) = \prod\nolimits_{\mathrm{events}} P(m_{\mathrm{t}}^{\mathrm{fit}}, m_{\mathrm{W}}^{\mathrm{reco}}|m_{\mathrm{t}}, \mathrm{JSF})$$

Mass measurement

- $P\left(m_{\mathrm{t}}^{\mathrm{fit}}\,|m_{\mathrm{t}},\mathrm{JSF}\right)$ and $P(m_{\mathrm{W}}^{\mathrm{reco}}|m_{\mathrm{t}},\mathrm{JSF})$ are analytic functions of m_{t} and JSF
- Parameters are fit using templates for different $m_{\mathrm{t}}^{\mathrm{gen}}$ and JSF values in MC
- Three fit methods
    - 1D – JSF fixed to unity
    - 2D – JSF is a free parameter, possible compensation for systematic uncertainties
    - Hybrid – weighted combination of 1D and 2D methods, Gaussian constraint of JSF around unity (constraint is optimized to yield smallest total uncertainty)

- All-jets (A) and lepton + jets (L) are combined in a single likelihood function

$$\mathcal{L}(m_{\mathrm{t}},\mathrm{JSF}) = \mathcal{L}_{\mathrm{A}}(m_{\mathrm{t}},\mathrm{JSF}) \times \mathcal{L}_{\mathrm{L}}(m_{\mathrm{t}},\mathrm{JSF})$$

Systematic uncertainties

All-jets

	2D		1D	hybrid	
	δm_t^{2D} [GeV]	δJSF^{2D} [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	δJSF^{hyb} [%]
Experimental uncertainties					
Method calibration	0.06	0.2	0.06	0.06	0.2
JEC (quad. sum)	0.18	0.3	0.73	0.15	0.2
– Intercalibration	−0.04	−0.1	+0.12	−0.04	−0.1
– MPFInSitu	−0.03	0.0	+0.22	+0.08	+0.1
– Uncorrelated	−0.17	−0.3	+0.69	+0.12	+0.2
Jet energy resolution	−0.09	+0.2	+0.09	−0.04	+0.1
b tagging	0.02	0.0	0.01	0.02	0.0
Pileup	−0.06	+0.1	0.00	−0.04	+0.1
Background	0.10	0.1	0.03	0.07	0.1
Trigger	+0.04	−0.1	−0.04	+0.02	−0.1
Modeling uncertainties					
JEC flavor (linear sum)	−0.35	+0.1	−0.31	−0.34	0.0
– light quarks (uds)	+0.10	−0.1	−0.01	+0.07	−0.1
– charm	+0.03	0.0	−0.01	+0.02	0.0
– bottom	−0.29	0.0	−0.29	−0.29	0.0
– gluon	−0.19	+0.2	+0.03	−0.13	+0.2
b jet modeling (quad. sum)	0.09	0.0	0.09	0.09	0.0
– b frag. Bowler–Lund	−0.07	0.0	−0.07	−0.07	0.0
– b frag. Peterson	−0.05	0.0	−0.04	−0.05	0.0
– semileptonic b hadron decays	−0.03	0.0	−0.03	−0.03	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 ± 0.20	−0.3	−0.05 ± 0.14	+0.24 ± 0.18	−0.2
ISR PS scale	+0.17 ± 0.17	−0.2	+0.13 ± 0.12	+0.12 ± 0.14	−0.1
FSR PS scale	+0.22 ± 0.12	−0.2	+0.11 ± 0.08	+0.18 ± 0.11	−0.1
Top quark p_T	+0.03	0.0	+0.02	+0.03	0.0
Underlying event	+0.16 ± 0.19	−0.3	−0.07 ± 0.14	+0.10 ± 0.17	−0.2
Early resonance decays	+0.02 ± 0.28	+0.4	+0.38 ± 0.19	+0.13 ± 0.24	+0.3
CR modeling (max. shift)	+0.41 ± 0.29	−0.4	−0.43 ± 0.20	−0.36 ± 0.25	−0.3
– "gluon move" (ERD on)	+0.41 ± 0.29	−0.4	+0.10 ± 0.20	+0.32 ± 0.25	−0.3
– "QCD inspired" (ERD on)	−0.32 ± 0.29	−0.1	−0.43 ± 0.20	−0.36 ± 0.25	−0.1
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

Combined

	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

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Top quark mass combination in lepton + jets final state
Combination with leptons + jets analyses

arxiv:1810.01772

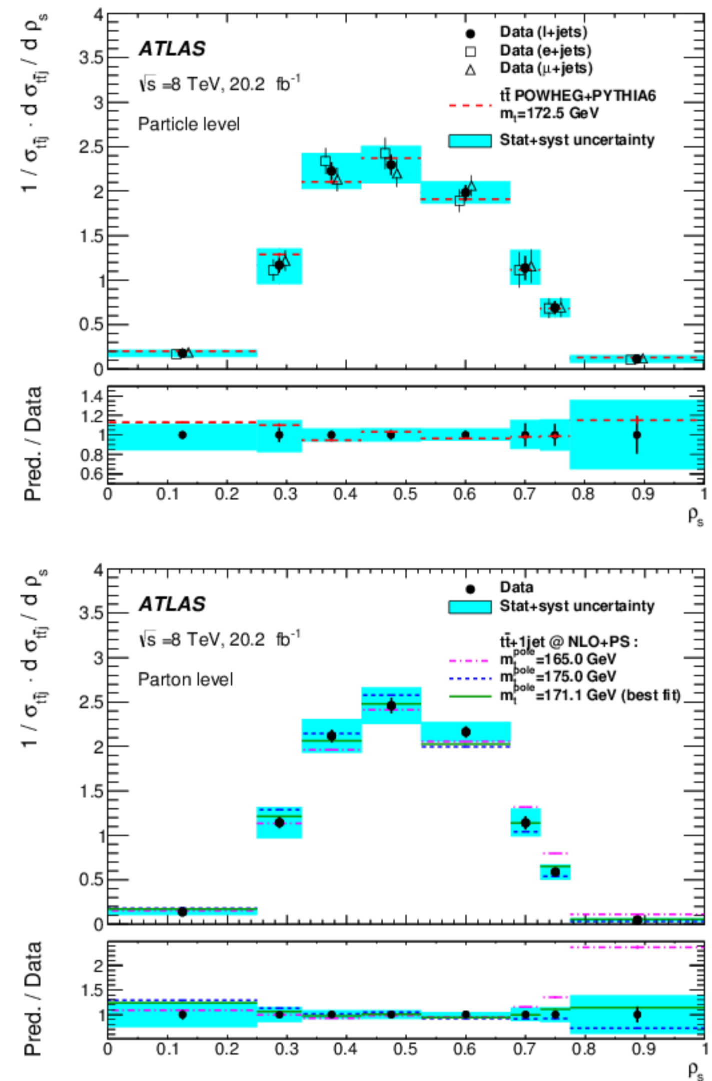
(Submitted to European Physical Journal C)

Overview

- Differential cross section used to extract m_t^{pole} and $m_t^{\overline{\text{MS}}}$
  - $20.2\ \text{fb}^{-1}$ at $\sqrt{s} = 8$ TeV (2012)
  - $\frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}$ where $\rho_s = \frac{360\ \text{GeV}}{m_{t\bar{t}+1\text{-jet}}}$

- Lepton + jets final state
  - Includes leading jet not used in identifying top quark candidates

- Particle and parton level measurements



Event selection

- Single lepton trigger
  - μ $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$, $p_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV, and $p_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{\mathrm{W}} > 60$ GeV
  - e $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.47$ (transition region$1.37 < |\eta| < 1.52$ is excluded), $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV, and $p_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{\mathrm{W}} > 30$ GeV
- Jets – anti-k_{T} $\Delta R = 0.4$, $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$
  - Exactly 2 b-tagged (neural network MV1) jets and at least additional jet
- $\vec{p}_{\ell} \cdot \vec{p}^{\mathrm{miss}} = m_{\mathrm{W}}$
- $\vec{p}_{\mathrm{t}} = \vec{p}_{\ell} + \vec{p}_{\mathrm{bjet}} + \vec{p}_{\nu}$

Inputs to BDT

Separation	Description
31%	Logarithm of the event likelihood of the best permutation, $\ln L$
13%	ΔR of the two untagged jets q_1 and q_2 from the hadronically decaying W boson, $\Delta R(q, q)$
5.0%	p_T of the hadronically decaying W boson
4.3%	p_T of the hadronically decaying top quark
4.2%	Relative event probability of the best permutation
2.0%	p_T of the reconstructed $t\bar{t}$ system
1.7%	p_T of the semi-leptonically decaying top quark
1.2%	Transverse mass of the leptonically decaying W boson
0.3%	p_T of the leptonically decaying W boson
0.3%	Number of jets
0.2%	ΔR of the reconstructed b-tagged jets
0.2%	Missing transverse momentum
0.1%	p_T of the lepton

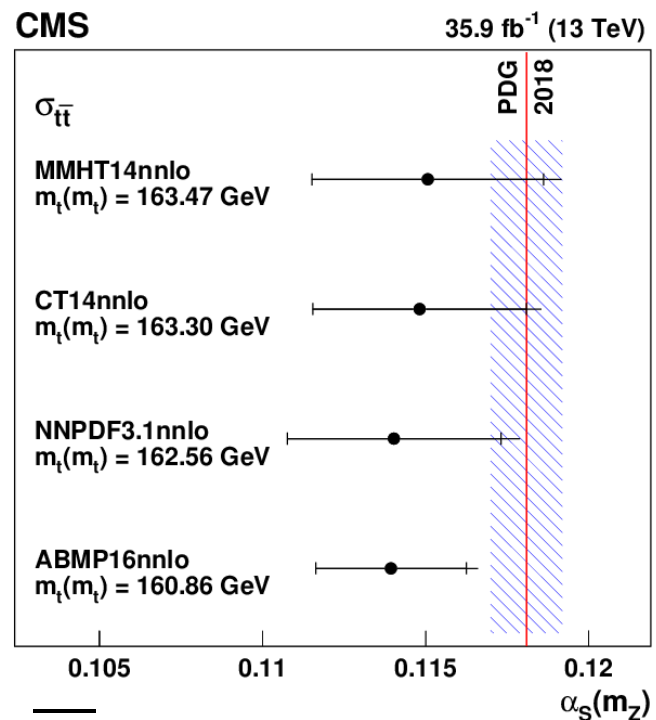
$t\bar{t}$ production cross section, top quark mass, and the strong coupling constant α_s

arxiv:1812.10505

(Submitted to European Physical Journal C)

Overview

- Measure $\sigma_{t\bar{t}}, m_t$, and α_s
  - $35.9\ \text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV
- Dilepton final state ($e^{\pm}\mu^{\pm}, \mu^{+}\mu^{-}, e^{+}e^{-}$)
- Maximum-likelihood fit to simultaneously fit $\sigma_{t\bar{t}}$ and m_t
  - $\sigma_{t\bar{t}}$ fit with $m_t = 172.5$ GeV, then m_t is treated as a free parameter for fitting
  - Systematic uncertainties treated as nuisance parameters



$\overline{\text{MS}}$ scheme α_s

- Fit for $\sigma_{t\bar{t}}$ is used to extract $\alpha_s(m_Z)$ for various PDFs
- Fit for $\sigma_{t\bar{t}}$ is used to extract $\overline{\text{MS}}$ m_t separately for various PDFs
  - Denoted as $m_t(m_t)$

Event selection

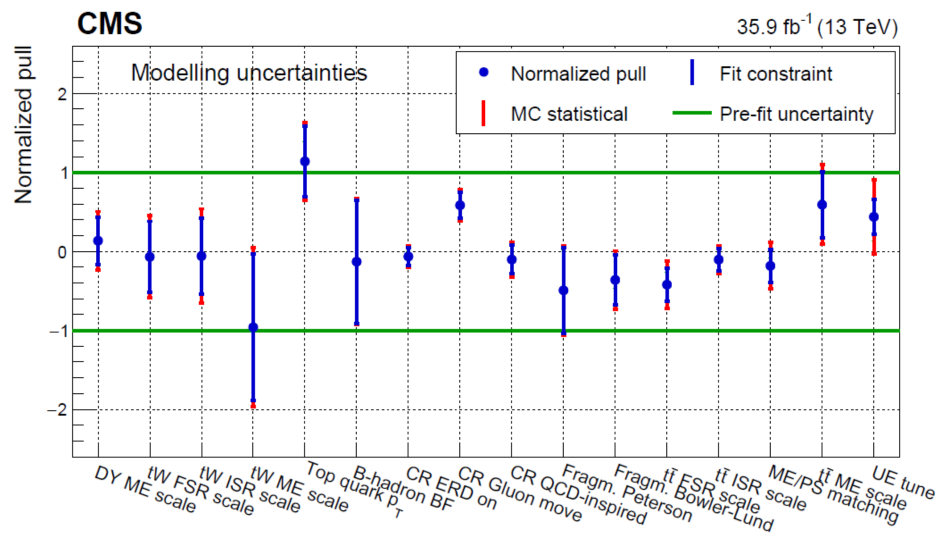
- All leptons $|\eta| < 2.4$
- $e^{\pm}\mu^{\mp}$ channel
  - e $p_T > 12$ GeV and μ $p_T > 23$ GeV or e $p_T > 23$ GeV and μ $p_T > 8$ GeV
- $\mu^{+}\mu^{-}$ channel
  - $p_T > 23$ GeV
- $e^{+}e^{-}$ channel
  - $p_T > 17$ GeV
- Single lepton trigger
  - μ $p_T > 27$ GeV and e $p_T > 24$ GeV
- PF leptons with leading $p_T > 25$ GeV an sub-leading $p_T > 20$ GeV
  - $m_{\ell\ell} < 20$ GeV and $76 < m_{\ell\ell} < 106$ GeV ($\ell = e, \mu$)
- Jets – anti-k_T $\Delta R = 0.4$, $p_T > 20$ GeV, $|\eta| < 2.4$
  - At lest 1 b-tagged (CSVv2) jet in $e^{+}e^{-}$ and $\mu^{+}\mu^{-}$ channels

Fit procedure

- Templates are fit to multi-differential distributions
    - Categorized by b-tagged jet multiplicity
    - Same-flavor channels categorized by 1 or 2 b-jets
    - $e^{\pm}\mu^{\mp}$ channel categorized by 1, 2, or 0 or 3+ b-jets
    - Then by the number of non—b-tagged jets
- Efficiency for selecting and identifying b-jets (ϵ_{b}) can be constrained
- $\sigma_{t\bar{t}}^{\mathrm{vis}}$ defined for fiducial volume
- $\sigma_{t\bar{t}} = \frac{\sigma_{t\bar{t}}^{\mathrm{vis}}}{A_{\ell\ell}}$ where $A_{\ell\ell}$ is the acceptance $\left(\frac{N_{t\bar{t}}^{\mathrm{vis}}}{N_{t\bar{t}}}\right)$
- Likelihood $L = \prod_i \frac{e^{v_i} v_i^{n_i}}{n_i!} \prod_j \pi(\lambda_j)$ where v_i and n_i are the expected and observed number of event in bin i
- $\vec{\lambda} = (\lambda_1, \lambda_2, \ldots, \lambda_j)$ correspond to the systematic uncertainties and $\pi(\lambda_j)$ is a penalty term
- $v_i = s_i\left(\sigma_{t\bar{t}}^{\mathrm{vis}}, \vec{\lambda}\right) + \sum_k b_{k,i}(\vec{\lambda})$ for the number of signal and background events

Systematic uncertainties ($\sigma_{t\bar{t}}$)

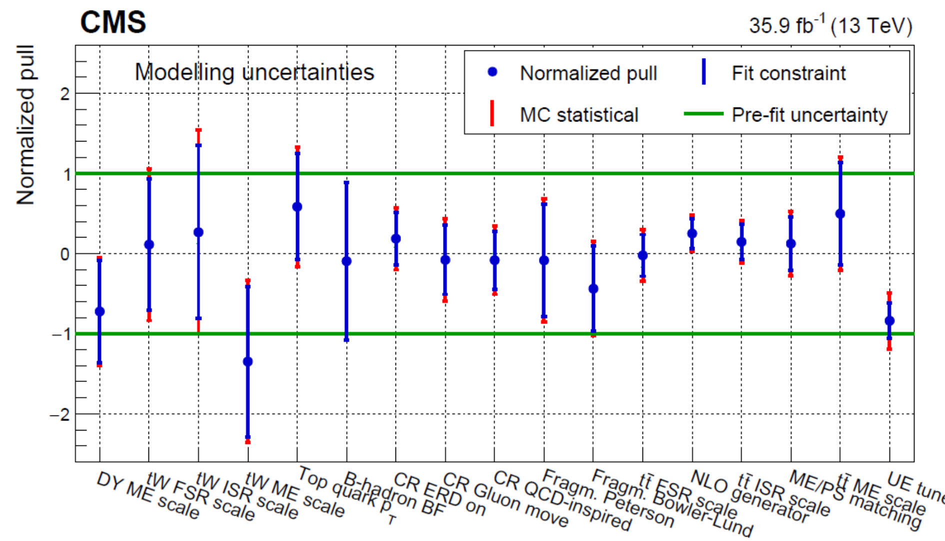
Source	Uncertainty [%]
Trigger	0.3
Lepton ident./isolation	2.0
Muon momentum scale	0.1
Electron momentum scale	0.1
Jet energy scale	0.4
Jet energy resolution	0.4
b tagging	0.4
Pileup	0.1
$t\bar{t}$ ME scale	0.2
tW ME scale	0.2
DY ME scale	0.1
PDF	1.1
Top quark p_T	0.5
ME/PS matching	0.2
UE tune	0.3
$t\bar{t}$ ISR scale	0.4
tW ISR scale	0.1
$t\bar{t}$ FSR scale	0.8
tW FSR scale	0.1
b quark fragmentation	0.7
b hadron BF	0.1
Colour reconnection	0.3
DY background	0.9
tW background	1.1
Diboson background	0.2
W+jets background	0.2
$t\bar{t}$ background	0.2
Statistical	0.2
Integrated luminosity	2.5
MC statistical	1.1
Total $\sigma_{t\bar{t}}^{vis}$ uncertainty	3.8



Extrapolation uncertainties	
$t\bar{t}$ ME scale	$\mp^{0.3}_{0.1}$
PDF	$\pm^{0.8}_{0.6}$
Top quark p_T	$\mp^{0.5}_{<0.1}$
$t\bar{t}$ ISR scale	$\mp^{0.1}_{<0.1}$
$t\bar{t}$ FSR scale	$\pm^{0.1}_{<0.1}$
UE tune	<0.1
Total $\sigma_{t\bar{t}}$ uncertainty	4.0

Systematic uncertainties ($\sigma_{t\bar{t}}$ and m_t)

Source	Uncertainty [%]
Trigger	0.4
Lepton ident./isolation	2.2
Muon momentum scale	0.2
Electron momentum scale	0.2
Jet energy scale	0.7
Jet energy resolution	0.5
b tagging	0.3
Pileup	0.3
$t\bar{t}$ ME scale	0.5
tW ME scale	0.7
DY ME scale	0.2
NLO generator	1.2
PDF	1.1
m_t^{MC}	0.4
Top quark p_T	0.5
ME/PS matching	0.2
UE tune	0.3
$t\bar{t}$ ISR scale	0.4
tW ISR scale	0.4
$t\bar{t}$ FSR scale	1.1
tW FSR scale	0.2
b quark fragmentation	1.0
b hadron BF	0.2
Colour reconnection	0.4
DY background	0.8
tW background	1.1
Diboson background	0.3
W+jets background	0.3
$t\bar{t}$ background	0.2
Statistical	0.2
Integrated luminosity	2.5
MC statistical	1.2
Total $\sigma_{t\bar{t}}^{vis}$ uncertainty	4.2



Extrapolation uncertainties	
$t\bar{t}$ ME scale	$\mp^{0.4}_{<0.1}$
PDF	$\pm^{0.8}_{0.6}$
Top quark p_T	$\pm^{0.2}_{0.3}$
$t\bar{t}$ ISR scale	$\mp^{0.2}_{<0.1}$
$t\bar{t}$ FSR scale	± 0.1
UE tune	<0.1
m_t^{MC}	$\mp^{0.2}_{0.3}$
Total $\sigma_{t\bar{t}}$ uncertainty	$^{+4.3}_{-4.2}$

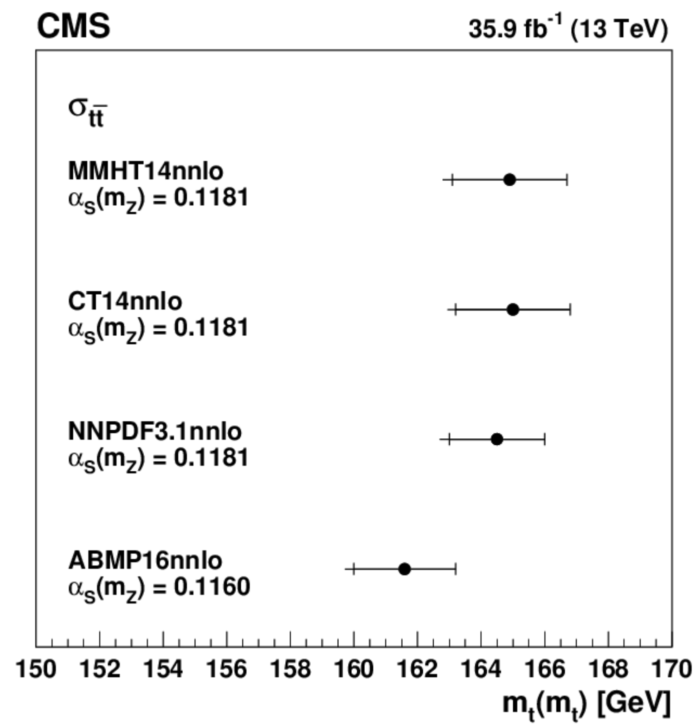
Results

$m_t^{MC} = 172.5$ GeV fixed

- $\sigma_{t\bar{t}}^{vis} = 25.61 \pm 0.05(\mathrm{stat}) \pm 0.75(\mathrm{syst}) \pm 0.64(\mathrm{lumi})$ pb
- $\sigma_{t\bar{t}} = 803 \pm 2(\mathrm{stat}) \pm 25(\mathrm{syst}) \pm 20(\mathrm{lumi})$ pb

Mass fit

- Also minimize m_{lb} invariant mass of leptons and b-jets in $e^{\pm}\mu^{\mp}$ events
- Templates are generated with $m_t = 172.5 \pm 3$ GeV
- $\sigma_{t\bar{t}} = 815 \pm 2(\mathrm{stat}) \pm 29(\mathrm{syst}) \pm 20(\mathrm{lumi})$ pb
- $m_t = 172.33 \pm 0.14(\mathrm{stat})^{+0.66}_{-0.72}(\mathrm{syst})$ GeV



Top quark pole mass and $\overline{\mathrm{MS}}$ mass in lepton + jets final states

arxiv:1905.02302

(Submitted to Journal of High Energy Physics)

Event selection

- Single lepton trigger
  - μ $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$
  - e $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.47$ (transition region$1.37 < |\eta| < 1.52$ is excluded)
  - Trigger matching $\Delta R = 0.15$
- Jets – anti-k_{T} $\Delta R = 0.4$, $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$
  - Exactly 2 b-tagged (MV1) jets and at least three additional jet
- $m_{\mathrm{T}}(\mathrm{W}) > 30$ GeV and $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV
- $\mathrm{t\bar{t}} + 1$-jet system
  - Reduce multijet and combinatorial background
  - $0.9 < m_{\mathrm{W}}/m_{ij} < 1.25$ where ij are pairs of non b-tagged jets
  - $\min\left(p_{\mathrm{T}}^{i}, p_{\mathrm{T}}^{j}\right) \cdot \Delta R_{ij} < 90$ GeV
  - $p_{\mathrm{T}}(\nu) = \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$, infer $p_{z}(\nu)$ by constraining m_{W}
  - $\min\left(\frac{\left|m_{\mathrm{t}}^{\mathrm{lep}} - m_{\mathrm{t}}^{\mathrm{had}}\right|}{m_{\mathrm{t}}^{\mathrm{lep}} + m_{\mathrm{t}}^{\mathrm{had}}}\right)$ for pairs of leptonic and hadronic top candidates
  - $\frac{m_{\mathrm{t}}^{\mathrm{lep}}}{m_{\mathrm{t}}^{\mathrm{had}}} > 0.9$
- Leading jet ($p_{\mathrm{T}} > 50$ GeV) not used in in top quark candidates is assumed to be produced in association with the top quark, before decay

Systematic uncertainties

Mass scheme	m_t^{pole} [GeV]	$m_t(m_t)$ [GeV]
Value	**171.1**	**162.9**
Statistical uncertainty	**0.4**	**0.5**
Simulation uncertainties		
Shower and hadronisation	0.4	0.3
Colour reconnection	0.4	0.4
Underlying event	0.3	0.2
Signal Monte Carlo generator	0.2	0.2
Proton PDF	0.2	0.2
Initial- and final-state radiation	0.2	0.2
Monte Carlo statistics	0.2	0.2
Background	<0.1	<0.1
Detector response uncertainties		
Jet energy scale (including b-jets)	0.4	0.4
Jet energy resolution	0.2	0.2
Missing transverse momentum	0.1	0.1
b-tagging efficiency and mistag	0.1	0.1
Jet reconstruction efficiency	<0.1	<0.1
Lepton	<0.1	<0.1
Method uncertainties		
Unfolding modelling	0.2	0.2
Fit parameterisation	0.2	0.2
Total experimental systematic	**0.9**	**1.0**
Scale variations	(+0.6, −0.2)	(+2.1, −1.2)
Theory PDF$\oplus\alpha_s$	0.2	0.4
Total theory uncertainty	**(+0.7, −0.3)**	**(+2.1, −1.2)**
Total uncertainty	**(+1.2, −1.1)**	**(+2.3, −1.6)**

$t\bar{t}$ differential cross sections, top quark pole mass, the strong coupling constant α_s, and parton distribution functions

arxiv:1904.05237

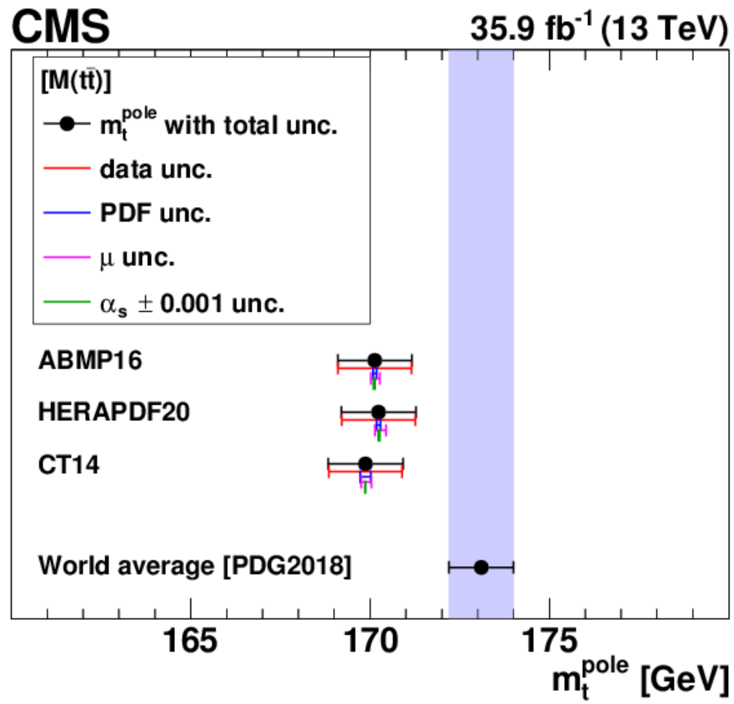
(Submitted to European Physical Journal C)

Overview

- Measure multi-differential $\sigma_{t\bar{t}}, m_t$, and α_s at parton level
  - $35.9\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV
- Single lepton ($e^{\pm}$ + jets and $\mu^{\pm}$ + jets) and ii-lepton ($e^{\pm}\mu^{\pm}, \mu^{+}\mu^{-}, e^{+}e^{-}$) final state
- Double-differential cross section for observables:

$$p_T(t), p_T(t\bar{t}), y(t\bar{t}), m(t\bar{t}), \Delta\eta(t,\bar{t}), \Delta\phi(t,\bar{t})$$

  where t is the to quark only to avoid double counting
- Triple-differential c ross-section for observables: $m(t\bar{t}), y(t\bar{t})$, and N_{jet}
- Triple-differential cross section is used to extract $\alpha_s(m_Z)$ and m_t
- Fit for $\sigma_{t\bar{t}}$ is used to extract m_t and $\alpha_s(m_z)$
- Simultaneous fit for $m_t, \alpha_s(m_z)$, and PDFs



Event selection

- All leptons $|\eta| < 2.4$
- $\mathrm{e}^{\pm}\mu^{\mp}$ channel
  - leading $p_{\mathrm{T}} > 23$ GeV and sub-leading $p_{\mathrm{T}} > 8$ GeV
- $\mu^{+}\mu^{-}$ channel
  - $p_{\mathrm{T}} > 17$ GeV and $p_{\mathrm{T}} > 8$ GeV
- $\mathrm{e}^{+}\mathrm{e}^{-}$ channel
  - $p_{\mathrm{T}} > 23$ GeV and $p_{\mathrm{T}} > 17$ GeV
- Single lepton trigger
  - $\mu\ p_{\mathrm{T}} > 27$ GeV and e $p_{\mathrm{T}} > 24$ GeV
- PF leptons with leading $p_{\mathrm{T}} > 25$ GeV an sub-leading $p_{\mathrm{T}} > 20$ GeV
  - $\mathrm{I}_{\mathrm{rel}} < 0.03$ for e and $\mathrm{I}_{\mathrm{rel}} < 0.15$ for μ
  - $m_{\ell\ell} < 20$ GeV and $76 < m_{\ell\ell} < 106$ GeV ($\ell = \mathrm{e}, \mu$)
  - $p_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV for same-signed Dileptons
- Jets – anti-k_{T} $\Delta R = 0.4$, $p_{\mathrm{T}} > 30$ GeV, $|\eta| < 2.4$
  - At lest 1 b-tagged (CSVv2) jet in $\mathrm{e}^{+}\mathrm{e}^{-}$ and $\mu^{+}\mu^{-}$ channels

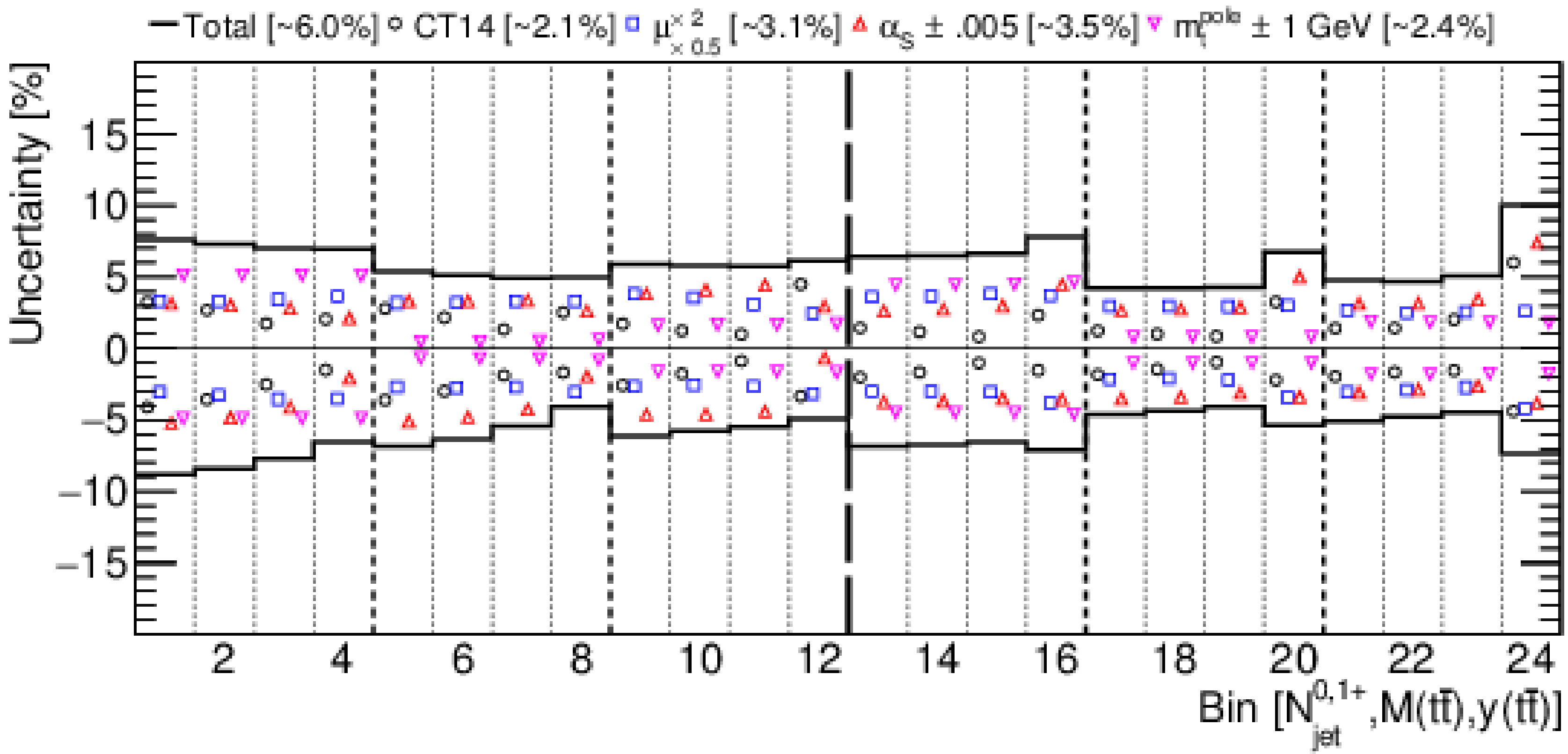
Reconstructing the ν

- $\vec{p}_{\mathrm{T}}^{\mathrm{tot}}$ conserved
- Constrain $m_{\mathrm{t}}, m_{\bar{t}}, m_{\mathrm{W}}$
- $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ assumed to be only from ν and $\bar{\nu}$
- Reconstruct 100 times, randomly smear particles with measured uncertainty
- $\vec{p}_{\mathrm{T}}^{\nu}$ is weighted average of all reconstructions
- All lepton-jet combinations with $m_{\ell\mathrm{b}} < 180\ \mathrm{GeV}$ are considered
    - b-jets are preferred

Kinematic reconstruction

- $\mathrm{t\bar{t}}$ kinematics found from $\sum p^{\mu}$ assuming $m_{\mathrm{t}} = m_{\bar{\mathrm{t}}} = 172.5\ \mathrm{GeV}$
- "Loose kinematic reconstruction" uses $\nu\bar{\nu}$ system without m_{t} constraint
  - Reconstructs entire $\mathrm{t\bar{t}}$ system
  - $\vec{p}_{\mathrm{T}}(\nu\bar{\nu}) = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}$
  - $p_z(\nu\bar{\nu}) = p_z(\ell\bar{\ell})$
  - $\mathrm{E}(\nu\bar{\nu}) = \mathrm{E}\left(\ell\bar{\ell}\right)$
  - $M(\nu\bar{\nu}) > 0, M(\mathrm{W^+W^-}) \geq 2m_{\mathrm{W}}$

Systematic uncertainties



Charge asymmetry from differential $\sigma_{t\bar{t}}$

arxiv:1811.06625

(Submitted to Journal of High Energy Physics)

Event selection

- All leptons $|\eta| < 2.4$
- $e^{\pm}\mu^{\mp}$ channel
  - leading e $p_T > 23$ GeV and sub-leading μ $p_T > 8$ GeV
  - Leading μ $p_T > 23$ GeV and sub-leading e $p_T > 12$ GeV
- $\mu^{+}\mu^{-}$ channel
  - $p_T > 17$ GeV and $p_T > 8$ GeV
- $e^{+}e^{-}$ channel
  - $p_T > 23$ GeV and $p_T > 17$ GeV
- Single lepton trigger
  - μ $p_T > 27$ GeV and e $p_T > 24$ GeV
- PF leptons with leading $p_T > 25$ GeV an sub-leading $p_T > 20$ GeV
  - $I_{rel} < 0.0588$ for e in barrel, $I_{rel} < 0.0571$ for e in endcap, $I_{rel} < 0.15$ for μ
  - $m_{\ell\ell} < 20$ GeV and $76 < m_{\ell\ell} < 106$ GeV ($\ell = e, \mu$)
  - $p_T^{miss} > 40$ GeV for same-signed Dileptons
- Jets – anti-k_T $\Delta R = 0.4$, $p_T > 30$ GeV, $|\eta| < 2.4$
  - At lest 1 b-tagged (CSVv2) jet and one additional jet

Reconstructing the ν

- $\vec{p}_{\mathrm{T}}^{\mathrm{tot}}$ conserved
- Constrain $m_{\mathrm{t}}, m_{\bar{t}}, m_{\mathrm{W}}$
- $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ assumed to be only from ν and $\bar{\nu}$
- Reconstruct 100 times, randomly smear particles with measured uncertainty
- m_{W} smeared with Breit–Wigner distribution
- $\vec{p}_{\mathrm{T}}^{\nu}$ is weighted average of all reconstructions
- Solution with most b-tagged jets is associated with top p_{T}
    - Maximum sum of weights if multiple solutions exist

Systematic uncertainties for polarization

Source	Uncertainty									
	B_1^k	B_2^k	B_1^r	B_2^r	B_1^n	B_2^n	B_1^{k*}	B_2^{k*}	B_1^{r*}	B_2^{r*}
JER	0.001	0.002	0.001	0.001	0.001	0.001	0.000	0.001	0.001	0.001
JES	0.011	0.012	0.007	0.009	0.003	0.003	0.009	0.008	0.007	0.007
Unclustered energy	0.001	0.002	0.001	0.001	0.000	0.001	0.001	0.000	0.001	0.002
Pileup	0.000	0.000	0.002	0.002	0.000	0.001	0.001	0.001	0.000	0.000
Trigger	0.001	0.001	0.001	0.001	0.000	0.000	0.001	0.001	0.002	0.002
Lepton ID/isolation	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Kinematic reconstruction	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
b tagging	0.003	0.004	0.003	0.003	0.000	0.000	0.002	0.002	0.001	0.001
Background	0.008	0.008	0.005	0.008	0.001	0.001	0.004	0.005	0.002	0.002
Scale	0.005	0.004	0.004	0.009	0.003	0.004	0.003	0.004	0.006	0.005
B-fragmentation	0.009	0.009	0.004	0.005	0.000	0.001	0.001	0.001	0.001	0.001
B-hadron semi-lep. BF	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Color reconnection	0.005	0.003	0.003	0.004	0.008	0.005	0.006	0.008	0.006	0.008
Underlying event	0.001	0.003	0.001	0.003	0.002	0.003	0.003	0.002	0.004	0.004
ME/PS matching	0.006	0.006	0.004	0.001	0.003	0.004	0.003	0.003	0.004	0.004
Top quark mass	0.006	0.007	0.000	0.001	0.001	0.002	0.002	0.001	0.002	0.002
PDF	0.002	0.002	0.000	0.000	0.000	0.000	0.004	0.004	0.002	0.002
Top quark p_T	0.003	0.003	0.001	0.001	0.000	0.000	0.001	0.001	0.000	0.000
Total systematic	0.021	0.021	0.013	0.017	0.010	0.009	0.014	0.014	0.013	0.014
Data statistics	0.009	0.008	0.009	0.009	0.007	0.008	0.010	0.010	0.010	0.009
MC statistics	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.004	0.004	0.003
Background MC statistics	0.005	0.005	0.005	0.005	0.004	0.004	0.006	0.006	0.005	0.005
Total statistical	0.010	0.010	0.011	0.011	0.009	0.009	0.012	0.012	0.012	0.011
Total	0.023	0.024	0.017	0.020	0.013	0.013	0.018	0.019	0.018	0.017

Systematic uncertainties for spin correlation

Source	Uncertainty											
	C_{kk}	C_{rr}	C_{nn}	$C_{rk}+C_{kr}$	$C_{rk}-C_{kr}$	$C_{nr}+C_{rn}$	$C_{nr}-C_{rn}$	$C_{nk}+C_{kn}$	$C_{nk}-C_{kn}$	D	$A^{\text{lab}}_{\cos\varphi}$	$A_{\lvert\Delta\phi_{\ell\ell}\rvert}$
JER	0.001	0.001	0.001	0.004	0.002	0.001	0.001	0.003	0.001	0.000	0.000	0.000
JES	0.012	0.009	0.005	0.022	0.011	0.011	0.009	0.012	0.007	0.002	0.000	0.001
Unclustered energy	0.001	0.001	0.001	0.004	0.001	0.001	0.002	0.001	0.001	0.000	0.000	0.001
Pileup	0.002	0.000	0.001	0.004	0.001	0.001	0.002	0.001	0.001	0.001	0.000	0.001
Trigger	0.001	0.001	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Lepton ID/isolation	0.001	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Kinematic reconstruction	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
b tagging	0.004	0.001	0.002	0.005	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000
Background	0.017	0.009	0.008	0.025	0.006	0.004	0.004	0.007	0.003	0.004	0.008	0.002
Scale	0.012	0.006	0.007	0.026	0.011	0.007	0.014	0.011	0.007	0.003	0.002	0.003
B-fragmentation	0.014	0.002	0.005	0.017	0.001	0.001	0.001	0.002	0.001	0.003	0.000	0.001
B-hadron semi-lep. BF	0.000	0.001	0.001	0.002	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000
Color reconnection	0.005	0.013	0.006	0.013	0.011	0.014	0.017	0.009	0.008	0.002	0.001	0.001
Underlying event	0.008	0.002	0.002	0.004	0.010	0.007	0.005	0.007	0.002	0.003	0.001	0.001
ME/PS matching	0.004	0.003	0.001	0.009	0.016	0.011	0.001	0.012	0.009	0.002	0.002	0.004
Top quark mass	0.001	0.002	0.006	0.006	0.009	0.002	0.002	0.009	0.001	0.002	0.001	0.000
PDF	0.005	0.005	0.001	0.004	0.001	0.001	0.001	0.001	0.001	0.002	0.007	0.002
Top quark p_T	0.008	0.010	0.005	0.019	0.000	0.001	0.000	0.001	0.000	0.004	0.003	0.005
Total systematic	0.031	0.023	0.017	0.053	0.029	0.024	0.025	0.026	0.016	0.009	0.011	0.008
Data statistics	0.018	0.019	0.010	0.029	0.029	0.024	0.025	0.025	0.020	0.006	0.003	0.003
MC statistics	0.007	0.007	0.004	0.011	0.011	0.009	0.009	0.010	0.008	0.002	0.001	0.001
Background MC statistics	0.011	0.010	0.005	0.018	0.017	0.012	0.010	0.015	0.012	0.003	0.002	0.002
Total statistical	0.022	0.023	0.012	0.035	0.035	0.028	0.028	0.031	0.025	0.007	0.003	0.003
Total	0.038	0.033	0.020	0.064	0.046	0.037	0.038	0.041	0.029	0.011	0.012	0.008

Top quark polarization and $t\bar{t}$ spin correlation from differential $\sigma_{t\bar{t}}$

CMS-PAS-TOP-18-006

Formalism

$$R \propto \tilde{A}\mathbb{1} \otimes \mathbb{1} + \tilde{B}_i^{+}\sigma^i \otimes \mathbb{1} + \tilde{B}_i^{-}\mathbb{1} \otimes \sigma^i + \tilde{C}_{ij}\sigma^i \otimes \sigma^j$$

- Spin density matrix decomposed into top (B^+), anti-top (B^-), and Pauli spin
  - $\tilde{A}$ total $t\bar{t}$ production cross section and the top quark kinematic distributions
  - $\tilde{\boldsymbol{B}}$ 3-vectors of functions that characterize the degree of top quark or antiquark polarization along each of the axes
  - $\tilde{C}$ 3×3 matrix of functions that characterize the correlation between the top quark and antiquark spins along each pair of axes
- Leptons ($1 =$ from t, $2 =$ from $\bar{\text{t}}$) from $\text{t} \rightarrow \text{bW}$ are used, θ is the angle wrt the reference axes i, j

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

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}\left(1 - \frac{C_{ij} \pm C_{ji}}{2}x\right)\cos^{-1}|x|$$

$$x = \cos\theta_1^i\cos\theta_2^j \pm \cos\theta_1^j\cos\theta_2^i.$$

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

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

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

Formalism

$$\tilde{B}_i^{\pm} = b_k^{\pm}\hat{k}_i + b_r^{\pm}\hat{r}_i + b_n^{\pm}\hat{n}_i$$

$$\begin{aligned}\tilde{C}_{ij} &= c_{kk}\hat{k}_i\hat{k}_j + c_{rr}\hat{r}_i\hat{r}_j + c_{nn}\hat{n}_i\hat{n}_j \\ &+ c_{rk}(\hat{r}_i\hat{k}_j + \hat{k}_i\hat{r}_j) + c_{nr}(\hat{n}_i\hat{r}_j + \hat{r}_i\hat{n}_j) + c_{kn}(\hat{k}_i\hat{n}_j + \hat{n}_i\hat{k}_j) \\ &+ c_n(\hat{r}_i\hat{k}_j - \hat{k}_i\hat{r}_j) + c_k(\hat{n}_i\hat{r}_j - \hat{r}_i\hat{n}_j) + c_r(\hat{k}_i\hat{n}_j - \hat{n}_i\hat{k}_j).\end{aligned}$$

- $\hat{k}$ direction of top quark
- $\hat{p}$ direction of incoming parton
- $\hat{r} = \frac{1}{r}(\hat{p} - y\hat{k}), \hat{n} = \frac{1}{r}(\hat{p} \times \hat{k}), y = \hat{k} \cdot \hat{p}, r = \sqrt{1 - y^2}$
- Direction of top quark

- Observables ($\hat{\ell}$ are the two leptons from leptonic top quark decays)

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B_1} \cdot \hat{\ell}_1 + \mathbf{B_2} \cdot \hat{\ell}_2 - \hat{\ell}_1 \cdot \mathrm{C} \cdot \hat{\ell}_2\right)$$

  - B_1^i and B_2^i are the top and anti-top polarization coefficients wrt reference axis i
  - C_{ii} diagonal spin coefficient for each reference axis i
  - $C_{ij} \pm C_{ji}$ “cross” spin correlation for each pair of axes i, j

Relation of observables and coefficients

Observable	Measured coefficient	Coefficient function
$\cos\theta_1^k$	B_1^k	b_k^+
$\cos\theta_2^k$	B_2^k	b_k^-
$\cos\theta_1^r$	B_1^r	b_r^+
$\cos\theta_2^r$	B_2^r	b_r^-
$\cos\theta_1^n$	B_1^n	b_n^+
$\cos\theta_2^n$	B_2^n	b_n^-
$\cos\theta_1^{k*}$	B_1^{k*}	b_k^+
$\cos\theta_2^{k*}$	B_2^{k*}	b_k^-
$\cos\theta_1^{r*}$	B_1^{r*}	b_r^+
$\cos\theta_2^{r*}$	B_2^{r*}	b_r^-
$\cos\theta_1^k \cos\theta_2^k$	C_{kk}	c_{kk}
$\cos\theta_1^r \cos\theta_2^r$	C_{rr}	c_{rr}
$\cos\theta_1^n \cos\theta_2^n$	C_{nn}	c_{nn}
$\cos\theta_1^r \cos\theta_2^k + \cos\theta_1^k \cos\theta_2^r$	$C_{rk} + C_{kr}$	c_{rk}
$\cos\theta_1^r \cos\theta_2^k - \cos\theta_1^k \cos\theta_2^r$	$C_{rk} - C_{kr}$	c_n
$\cos\theta_1^n \cos\theta_2^r + \cos\theta_1^r \cos\theta_2^n$	$C_{nr} + C_{rn}$	c_{nr}
$\cos\theta_1^n \cos\theta_2^r - \cos\theta_1^r \cos\theta_2^n$	$C_{nr} - C_{rn}$	c_k
$\cos\theta_1^n \cos\theta_2^k + \cos\theta_1^k \cos\theta_2^n$	$C_{nk} + C_{kn}$	c_{kn}
$\cos\theta_1^n \cos\theta_2^k - \cos\theta_1^k \cos\theta_2^n$	$C_{nk} - C_{kn}$	$-c_r$
$\cos\varphi$	D	$-(c_{kk} + c_{rr} + c_{nn})/3$
$\cos\varphi_{\text{lab}}$	$A^{\text{lab}}_{\cos\varphi}$	N/A
$\lvert\Delta\phi_{\ell\ell}\rvert$	$A_{\lvert\Delta\phi_{\ell\ell}\rvert}$	N/A

Top quark pair spin correlations in the different flavor dilepton final state

arxiv:1903.07570

(Submitted to European Physical Journal C)

Event selection

- Single lepton trigger
  - μ $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$
  - e $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.47$ (transition region$1.37 < |\eta| < 1.52$ is excluded)
- Jets – anti-k_{T} $\Delta R = 0.4$, $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$
  - Exactly 2 b-tagged (MV2c10) jets and at least one additional jet
- "Inclusive selection" – 93% $\mathrm{t\bar{t}}$
  - Used for $\Delta\phi$ and $\Delta\eta$
  - Exactly one e and μ, at least one $p_{\mathrm{T}} > 27$ GeV
  - At least one b-jet, and at least one additional jet
- "Reconstructed selection" – 96% $\mathrm{t\bar{t}}$
  - Used for $\Delta\phi\left(\mathrm{M(t\bar{t})}\right)$
  - At least two b-jets
  - Reconstructed $\mathrm{t\bar{t}}$ system

Reconstructing the ν

- Neutrino Weighting algorithm
- $\left(\vec{p}(\ell_{1,2}) + \vec{p}(\nu_{1,2}) + \vec{p}(\mathrm{b}_{1,2})\right)^2 = m_\mathrm{t}^2$
  - $\ell_{1,2}$ are the two leptons, $\mathrm{b}_{1,2}$ are the b-quarks
- $\eta(\nu)$ scanned between $[-5, 5]$ in steps of 0.2
- m_t scanned between $[171\ \mathrm{GeV}, 174\ \mathrm{GeV}]$ in steps of 0.5
  - p_T smeared with Gaussian function
- Inferred $\mathrm{E}_\mathrm{T}^\mathrm{miss}$ compared to actual $\mathrm{E}_\mathrm{T}^\mathrm{miss}$
- $w = \exp\left(\frac{-\Delta \mathrm{E}_x^2}{2\sigma_x^2}\right) \cdot \exp\left(\frac{-\Delta \mathrm{E}_y^2}{2\sigma_y^2}\right)$
  - $\Delta \mathrm{E}_x^2$ is the difference of the x component between computed and observed $\mathrm{E}_\mathrm{T}^\mathrm{miss}$
  - σ_x is related to the resolution of $\mathrm{E}_\mathrm{T}^\mathrm{miss}$ based on Z boson events
- b-jets with highest w are used to reconstruct $\mathrm{t}, \bar{\mathrm{t}}$
- Events with $w < 0$ or $M(\mathrm{t}\bar{\mathrm{t}}) < 300\ \mathrm{GeV}$ are rejected

Systematic uncertainties

Systematic	Inclusive	$m_{t\bar{t}}$ range [GeV] $m_{t\bar{t}} < 450$	$450 \leq m_{t\bar{t}} < 550$	$550 \leq m_{t\bar{t}} < 800$	$m_{t\bar{t}} \geq 800$
Matrix element	± 0.006	± 0.11	± 0.064	± 0.01	± 0.3
Parton shower and hadronisation	± 0.010	± 0.02	± 0.005	± 0.01	± 1.4
Radiation and scale settings	± 0.055	± 0.05	± 0.061	± 0.23	< 0.1
PDF	± 0.002	< 0.01	± 0.003	± 0.01	< 0.1
Background modelling	± 0.009	± 0.01	$^{+0.014}_{-0.015}$	± 0.01	± 0.1
Lepton ID and reconstruction	± 0.008	± 0.01	$^{+0.030}_{-0.036}$	$^{+0.03}_{-0.10}$	$^{+0.5}_{-0.2}$
b-tagging	$^{+0.004}_{-0.003}$	± 0.01	± 0.025	$^{+0.04}_{-0.02}$	$^{+0.1}_{-0.2}$
Jet ID and reconstruction	$^{+0.014}_{-0.017}$	$^{+0.02}_{-0.05}$	$^{+0.076}_{-0.093}$	$^{+0.17}_{-0.26}$	$^{+1.7}_{-0.6}$
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	< 0.001	$^{+0.01}_{-0.02}$	$^{+0.042}_{-0.034}$	$^{+0.12}_{-0.14}$	$^{+0.9}_{-0.7}$
Pile-up effects	$^{+0.013}_{-0.010}$	< 0.01	$^{+0.015}_{-0.019}$	$^{+0.07}_{-0.04}$	$^{+0.2}_{-0.4}$
Luminosity	± 0.001	< 0.01	$^{+0.002}_{-0.000}$	< 0.01	< 0.1
MC statistical uncertainty	± 0.005	< 0.01	± 0.007	± 0.03	± 0.05
Total systematics	± 0.061	$^{+0.12}_{-0.13}$	$^{+0.13}_{-0.14}$	$^{+0.31}_{-0.41}$	$^{+2.5}_{-1.7}$

Top quark charge ratio from differential single top cross section (σ_t)

CMS-PAS-TOP-18-006

Event selection

- Single lepton trigger
  - μ $p_{\mathrm{T}} > 27$ GeV, $|\eta| < 2.4$
  - e $p_{\mathrm{T}} > 35$ GeV, $|\eta| < 1.479$
- PF leptons with leading $p_{\mathrm{T}} > 25$ GeV an sub-leading $p_{\mathrm{T}} > 20$ GeV
  - $\mathrm{I_{rel}} < 0.0588$ for e in barrel, $\mathrm{I_{rel}} < 0.06$ for μ
- Jets – anti-k_{T} $\Delta R = 0.4$, $p_{\mathrm{T}} > 40$ GeV, $|\eta| < 4.7$
  - $p_{\mathrm{T}} > 50$ GeV in HCAL-HF transition $(2.7|\eta| < 3.0)$
  - 2 b-tagged (cMVA) jet and one additional jet
- $\vec{p}_{\ell} \cdot \vec{p}^{\mathrm{miss}} = m_{\mathrm{W}}$
- $\vec{p}_{\mathrm{t}} = \vec{p}_{\ell} + \vec{p}_{\mathrm{bjet}} + \vec{p}_{\nu}$

Top quark spin asymmetry from differential single top cross section (σ_t)

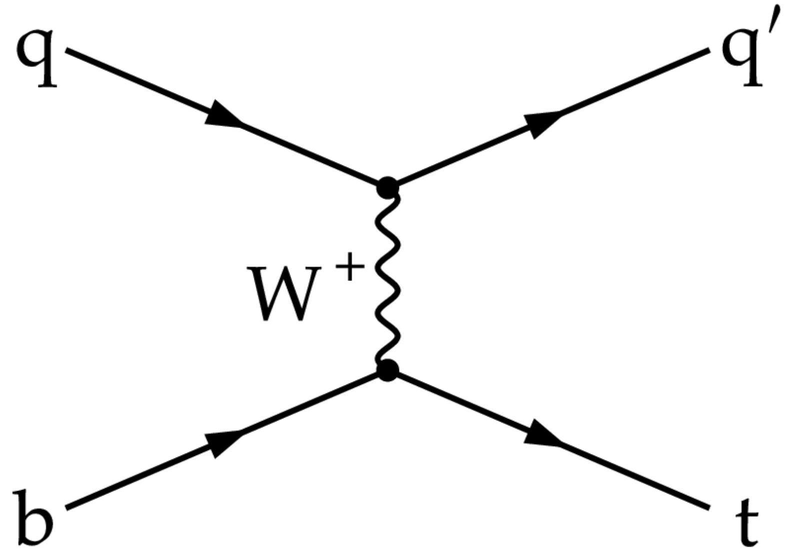
CMS-PAS-TOP-17-023

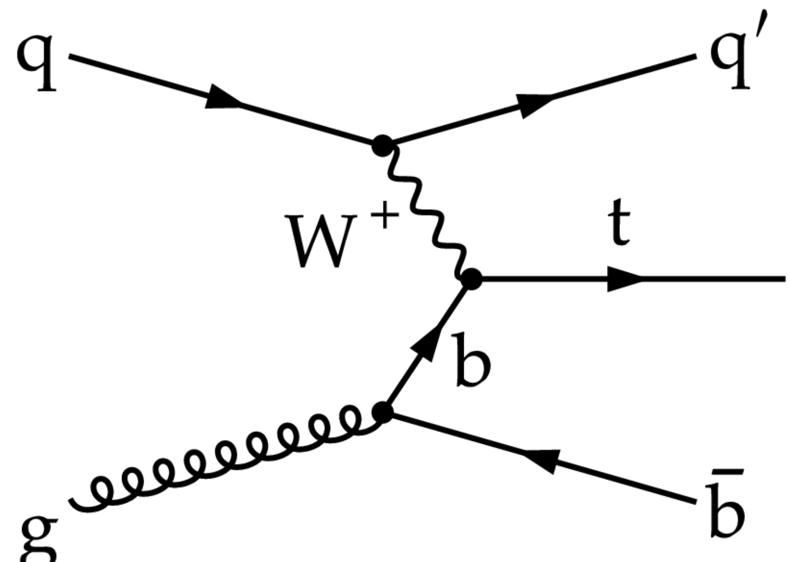
Overview

- Measure differential σ_t
  - $p_T(t), y(t), \theta_{pol.}(t), p_T(\ell), y(\ell), p_T(W)$
  - $35.9\ fb^{-1}$ at $\sqrt{s} = 13$ TeV (2016)

- Single lepton ($e^{\pm}$ + jets and $\mu^{\pm}$ + jets) final state

- $\cos\theta^{\star}_{pol.} = \frac{\vec{p}^{(top)}_{q'} \cdot \vec{p}^{(top)}_{\ell}}{\left|\vec{p}^{(top)}_{q'}\right|\left|\vec{p}^{(top)}_{\ell}\right|}$
- $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^{\star}_{pol.}} = \frac{1}{2}\left(1 + A_{\ell}\cos\theta^{\star}_{pol.}\right)$
- $A_{\ell} = \frac{1}{2}P \cdot \alpha_{\ell}$ is the spin asymmetry where α_{ℓ} is the spin-analyzing power of the lepton

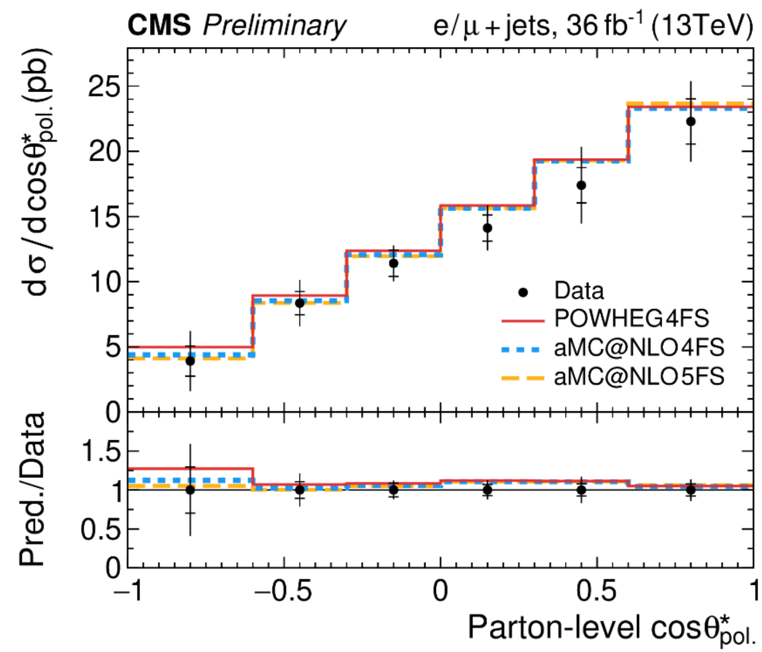




Results

- Linear χ^2 used to fit asymmetry
- $A_{\mathrm{e}} \quad = 0.443 \pm 0.048(\mathrm{stat}) \pm 0.068(\mathrm{syst})$
- $A_{\mu} \quad = 0.398 \pm 0.042(\mathrm{stat}) \pm 0.047(\mathrm{syst})$
- $A_{\mathrm{e}+\mu} = 0.439 \pm 0.032(\mathrm{stat}) \pm 0.053(\mathrm{syst})$

- Good agreement with SM predictions

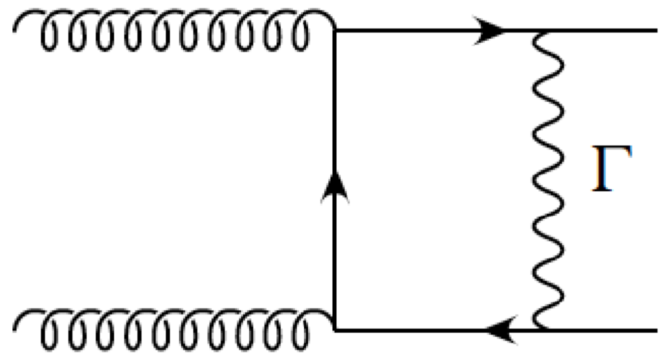


Constraining the top quark Yukawa coupling from differential $\sigma_{t\bar{t}}$

CMS-PAS-TOP-17-004

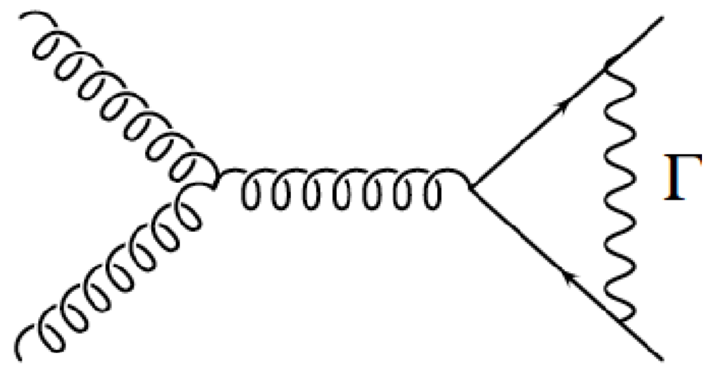
Overview

- Measure differential $\sigma_{t\bar{t}}$
  - $M(t\bar{t})$ and $\Delta y(t\bar{t})$
  - $35.9\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV (2016)



- Single lepton ($e^{\pm}$ + jets and $\mu^{\pm}$ + jets) final state

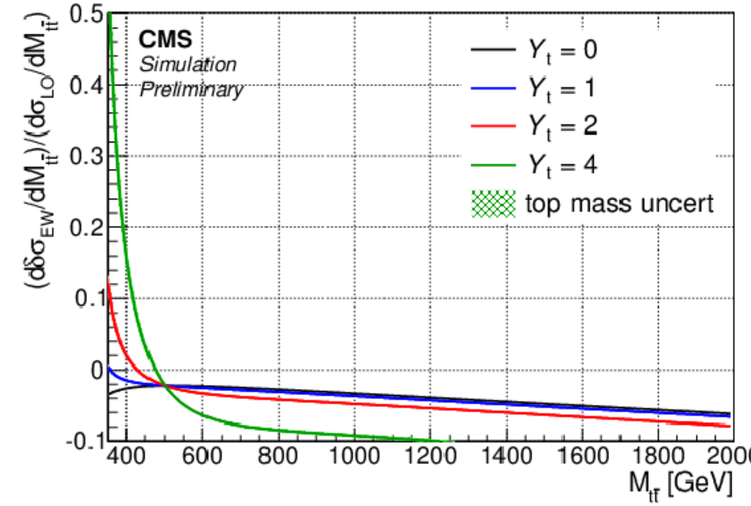
- Electroweak corrections affect $\frac{d\sigma_{t\bar{t}}}{dM(t\bar{t})}$ and $\frac{d\sigma_{t\bar{t}}}{d\Delta y(t\bar{t})}$

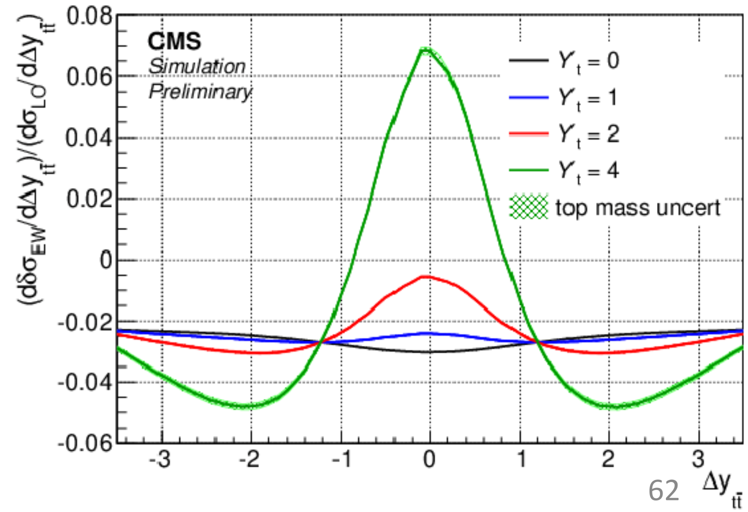


- Differential $\sigma_{t\bar{t}}$ is used to extract Y_t
  - Top quark Yukawa / SM prediction

Electroweak corrections

- Two $t\bar{t}$H vertices give $\sigma_{t\bar{t}}(Y_t^2)$
- $m_t = 172.5$ GeV fixed
  - Source of systematic uncertainty
- Corrections applied at parton level in POWHEG



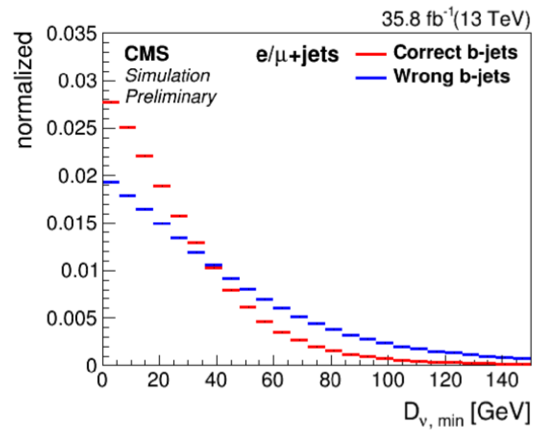


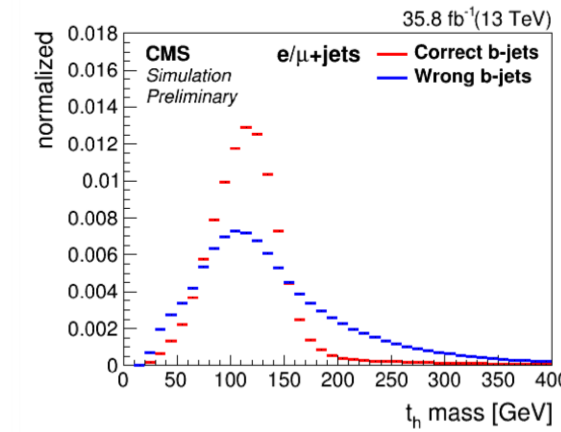
Event selection

- All leptons $|\eta| < 2.4$
- Single lepton trigger
  - $p_{\mathrm{T}} > 30\ \mathrm{GeV}$
- $M_{\mathrm{T}}^2 = 2\left(\mathrm{E}_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} - \vec{p}_{\mathrm{T}}^{\ell} \cdot \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right) < 140\ \mathrm{GeV}$
- Jets – anti-k_{T} $\Delta R = 0.4$, $p_{\mathrm{T}} > 30\ \mathrm{GeV}$, $|\eta| < 2.4$
  - At lest 1 b-tagged (CSVv2) jet in $\mathrm{e}^+\mathrm{e}^-$ and $\mu^+\mu^-$ channels
  - $p_{\mathrm{t}} > 50\ \mathrm{GeV}$ if $\mathrm{N}_{\mathrm{b-jets}} = 3$

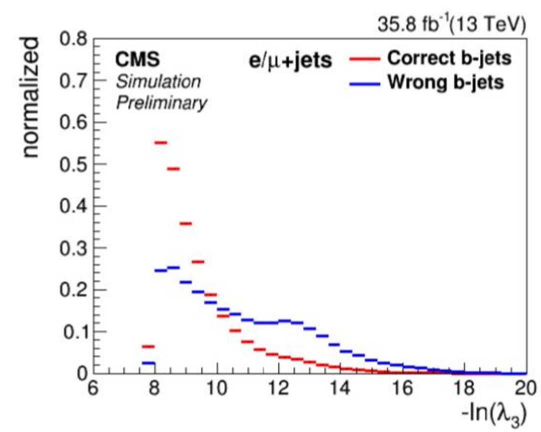
Event reconstruction

- Neutrino solver
  - $(p_\nu + p_\ell)^2 = m_{\mathrm{W}}^2$
  - $(p_\nu + p_\ell + p_{\mathrm{b}\ell})^2 = m_{\mathrm{t}}^2$
  - Select p_ν at $\mathrm{D}_{\nu,\min}$ distance between ellipses in transverse plane of momentum space





- $\mathrm{N_{jets}} \geq 4$
  - Minimize $\mathrm{D}_{\nu,\min}$ while constraining m_{W} and m_{t}
- One jet missing ($\mathrm{t\bar{t}}$ production threshold)
  - $\mathrm{N_{jets}} = 3$ with at least 2bi-tagged jets
  - Missing jet from W decay comprice 93% of events
  - Ambiguity in b-jet assigned to t or $\mathrm{\bar{t}}$
  - Neutrino Solver with no solutions is discarded
  - NLL used to find best assignment



Background estimation

- QCD multi-jet samples too small after event selection
- Events from control region (CR) used instead
  - CSVv2 working point < 0.6
- CR normalized to residual data signal region (SR) after other background is subtracted

$$N_{QCD}^{SR} = N_{resDATA}^{SR} \times \frac{N_{QCDMC}^{SR}}{N_{QCDMC}^{CR}}$$

Systematic uncertainties

Uncertainty	$t\bar{t}$	single t	V+jets	QCD
Luminosity	2.5%	2.5%	2.5%	2.5%
Pileup	shape	shape	-	-
Lepton ID/trigger	shape	shape	shape	-
JEC (19 independent variations)	shape	shape	-	-
JER	shape	-	-	-
b tagging scale factor	shape	shape	shape	-
b-mistag scale factor	shape	shape	shape	-
Background normalization	-	15%	30%	30%
CSV inversion on QCD template	-	-	-	shape
Factorization & renormalization scale	shape	shape	shape	-
PDF	shape	shape	-	-
$\alpha_s(M_Z)$ in PDFs	shape	shape	-	-
Top quark mass	shape	-	-	-
Top quark p_T modeling	shape	-	-	-
Parton Shower				
-NLO shower matching	shape	-	-	-
-ISR	2%/2%/3%	-	-	-
-FSR	shape	shape	-	-
-Color reconnection	shape	-	-	-
-b-jet fragmentation	shape	shape	-	-
-B hadron branching fraction	shape	shape	-	-
Weak correction $\delta_{QCD}\delta_{EW}$	shape	-	-	-

Results

- Binned likelihood function used to construct profile likelihood
  - $q(\mathrm{Y_t}) = -2\ln\left[\mathcal{L}\left(\mathrm{Y_t}, \hat{\hat{\theta}}\right) / \mathcal{L}(\mathrm{Y_t}, \hat{\theta})\right]$
  - $\hat{\hat{\theta}}$ is the estimator for $\theta(\mathrm{Y_t})$
  - $\mathcal{L}(\mathrm{Y_t}, \hat{\theta})$ is the unconditional likelihood

Channel	Expected 95% CL	Observed 95% CL
3 jets	$Y_t < 2.17$	$Y_t < 2.59$
4 jets	$Y_t < 1.88$	$Y_t < 1.77$
5 jets	$Y_t < 2.03$	$Y_t < 2.23$
Combined	$Y_t < 1.62$	$Y_t < 1.67$