Recent measurements of top quark properties in CMS

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on behalf of the CMS Collaboration

ICHEP2020
29 July 2020

Focus on: Top spin correlations
W boson polarization
Top Yukawa coupling
Top quark mass
Top CKM matrix elements
F-B asymmetry

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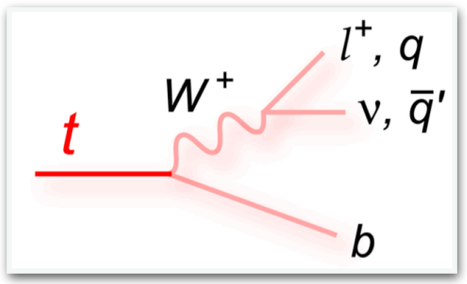
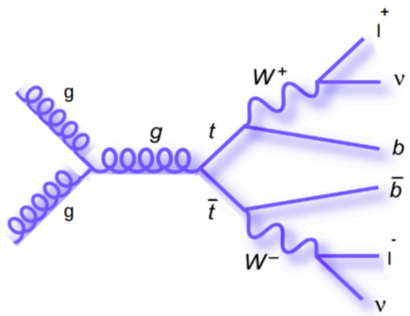
The Top Quark

- Heaviest elementary particle discovered so far
- Extremely short lifetime → bare quark properties
- Large Yukawa coupling to Higgs boson → important for EW symmetry breaking
- Spin information preserved in the angular distribution of its decay products → **ideal candidate for spin measurements**
- Studies of its properties provide crucial info to:
  - test internal consistency of SM
  - search for new phenomena (BSM physics)

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\ \text{s}}}$$



Other related talks @ICHEP:
D. Muller on *"Inclusive cross sections"*
G. Bakas on *"Differential cross sections"*
S. May on *"FCNC and EFT interpretations"*



Spin correlations

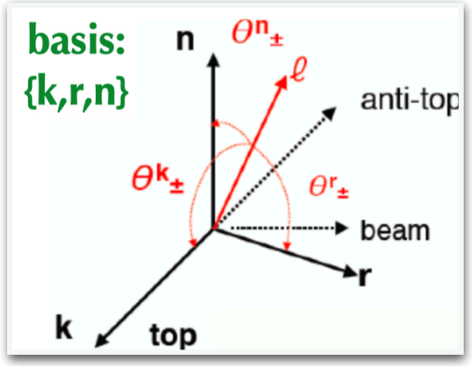
Phys. Rev. D 100 (2019) 072002

2016 data
@13 TeV: 35.9 fb^{-1}

- Measurement of full spin density production matrix in dilepton channel
- Angular distributions in $t\bar{t}$ rest frame (**direct measurement**):
  - full reconstruction of $t\bar{t}$ system required

$$\frac{1}{\sigma}\frac{d\sigma}{dcos\theta_1^i dcos\theta_2^i} = \frac{1}{4}(1 + B_1^i cos\theta_1^i + B_2^i cos\theta_2^i - C_{ii} cos\theta_1^i cos\theta_2^i)$$

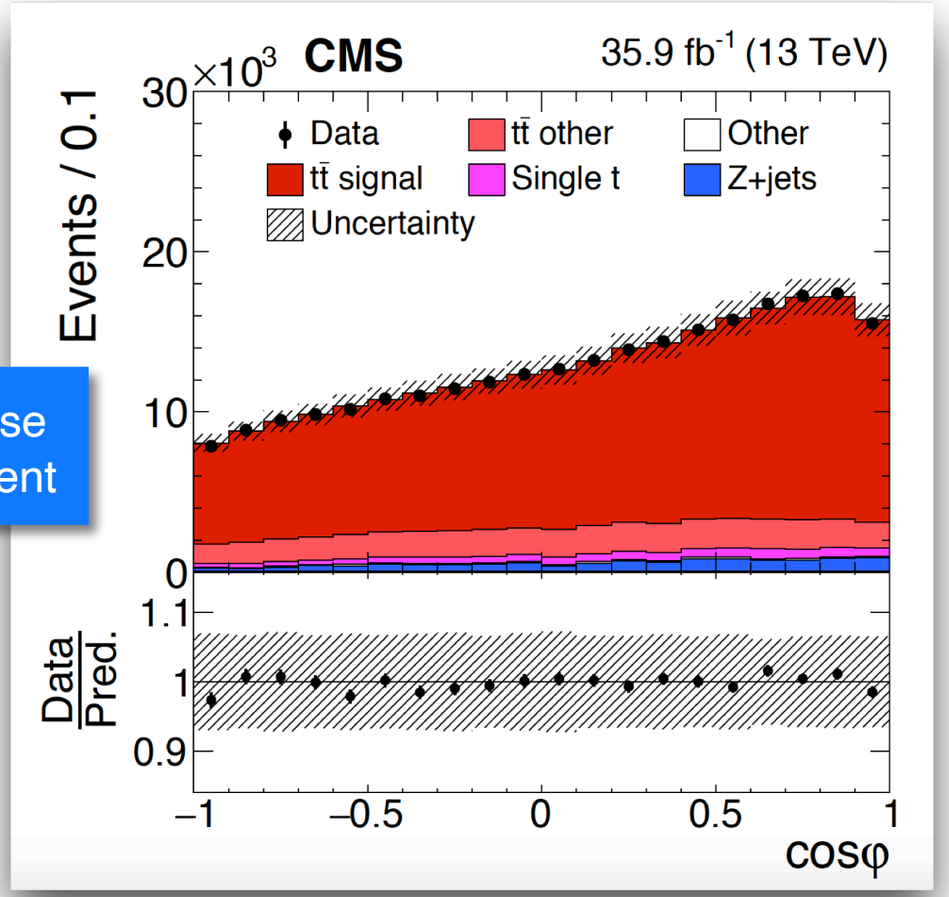
Polarizations Spin correlations

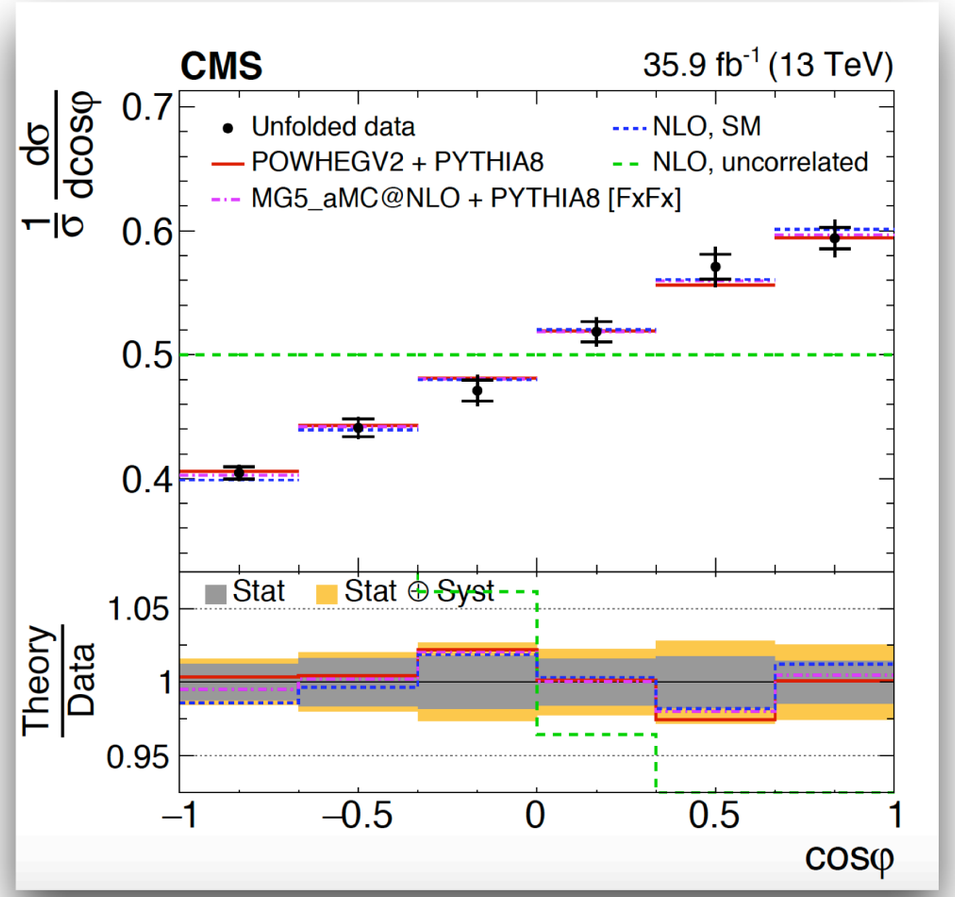


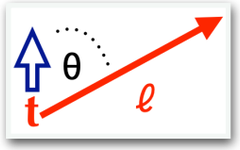
- Coefficients individually probed by 1D angular distribution
- Opening angle between leptons $cos\varphi = \hat{\ell}_1 \cdot \hat{\ell}_2$:

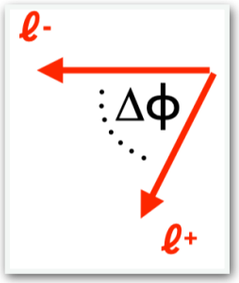
$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}(1 + [\text{Coef.}]\, x)\, f(x)$$

Most precise measurement





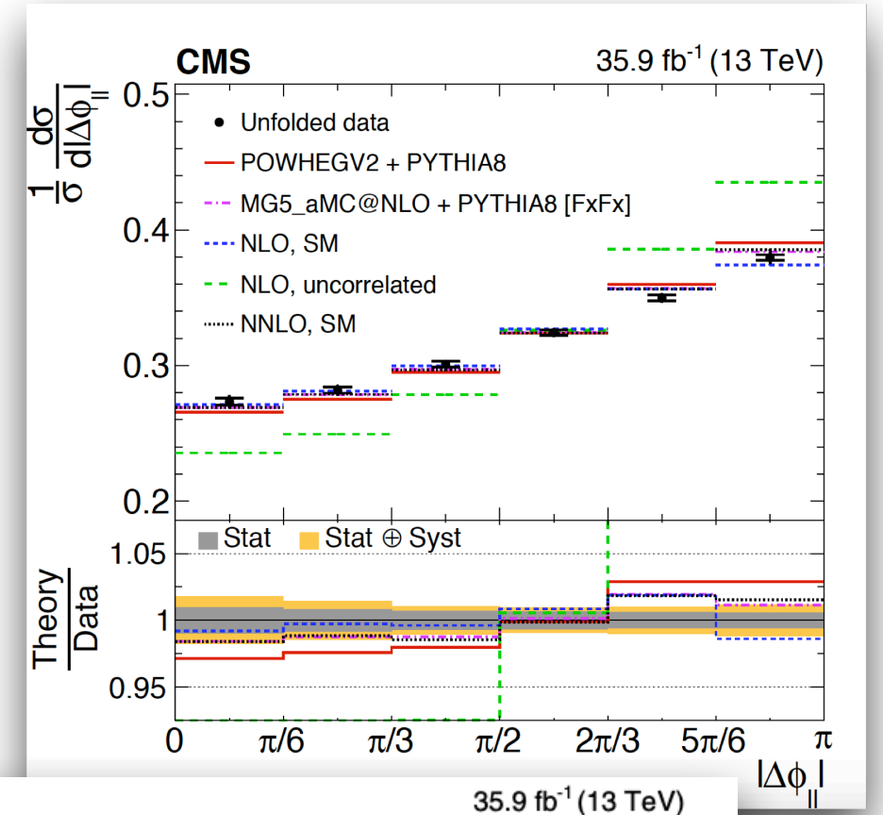


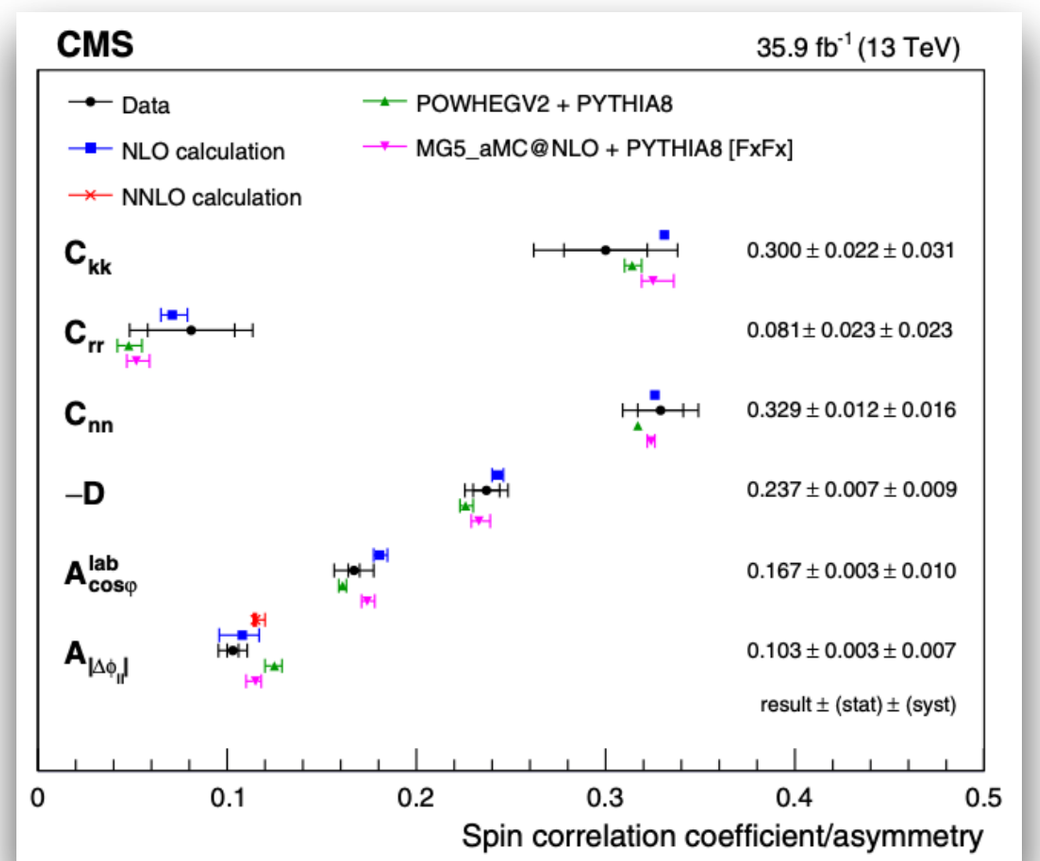


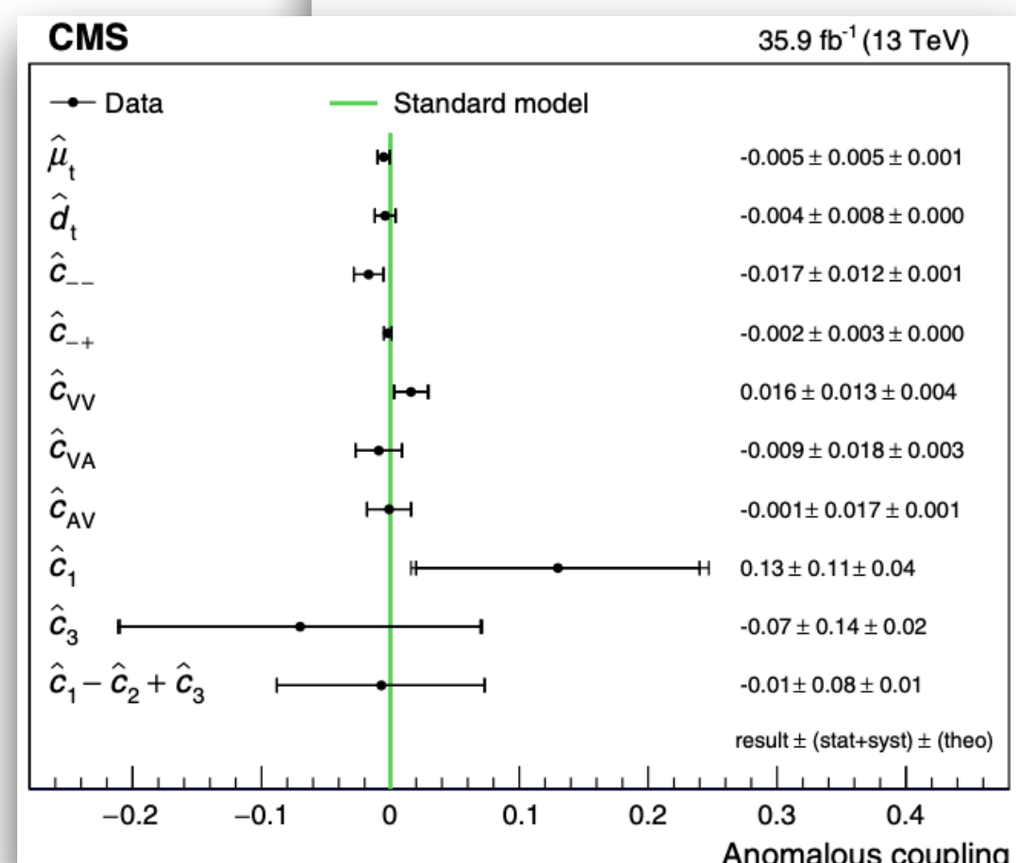
Spin correlations

Phys. Rev. D 100 (2019) 072002

- Lab-frame observables (**indirect measurement**):
  - $\ell^{\pm}$ angular distributions $\hat{\ell}_1^{lab} \cdot \hat{\ell}_2^{lab} = (1 \pm \cos\theta)/2$
  - angle between leptons in transverse plane = $|\Delta\phi_{\ell\ell}|$
- All distributions and extracted parameters in close agreement with SM predictions
- Unfolded results used to constrain anomalous couplings

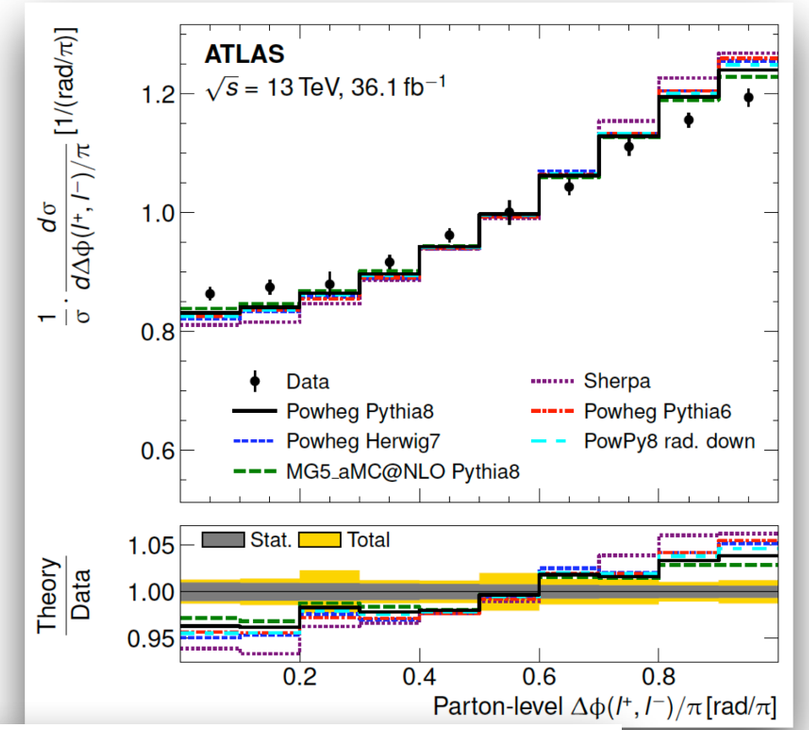




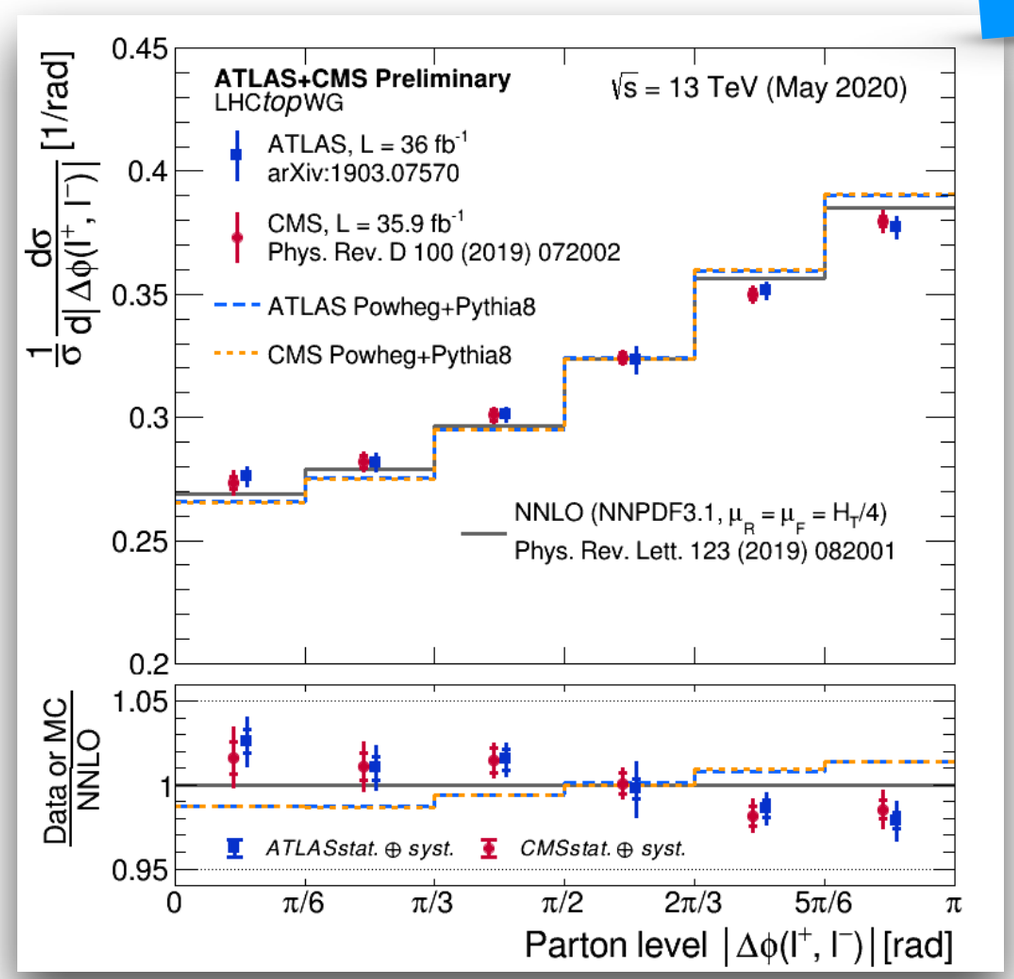


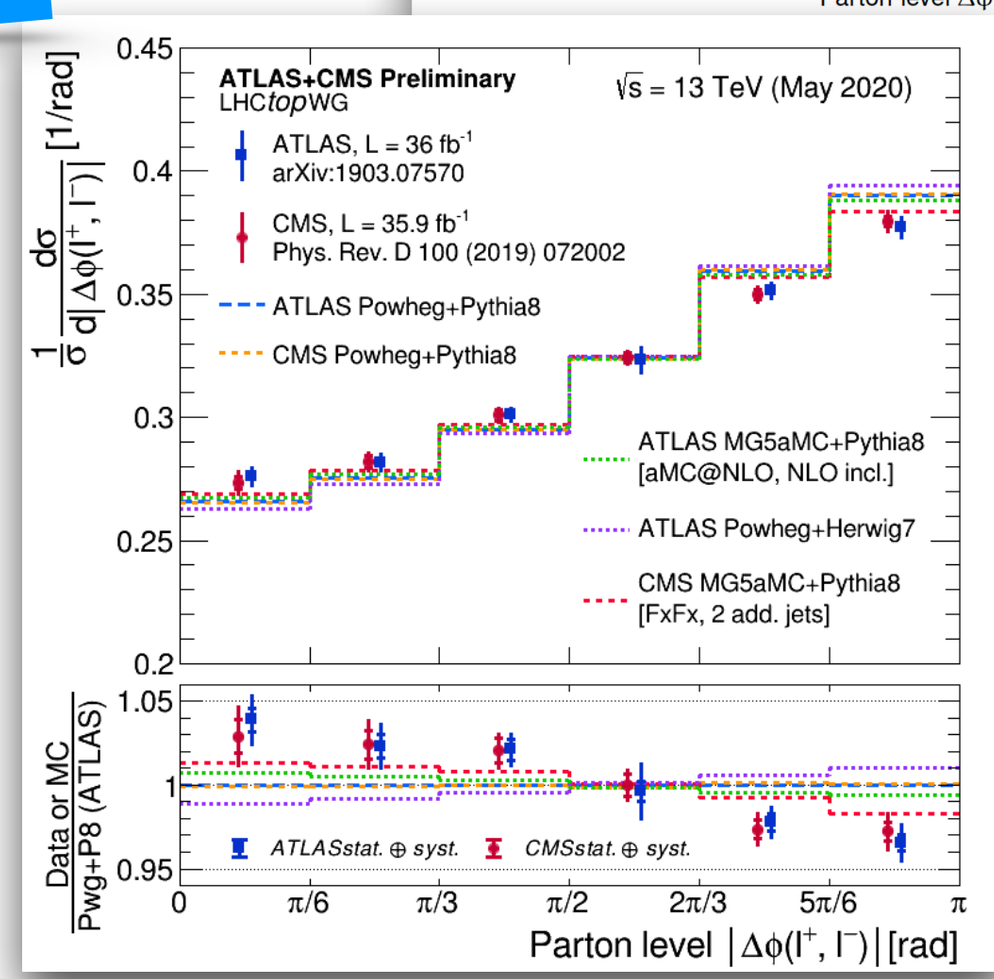
Δϕ distribution

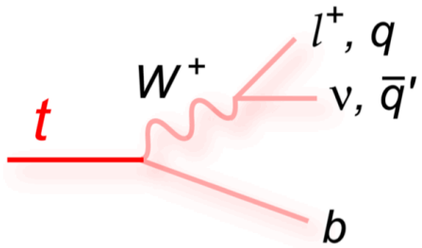
- Tension between data and predictions in both ATLAS and CMS
- First **ATLAS+CMS comparison** @13 TeV within *LHCtopWG*:
  - normalized cross sections at parton level
  - very good agreement between ATLAS and CMS data and between ATLAS and CMS main MC predictions
  - fair agreement with NNLO calculation



NEW







W polarization

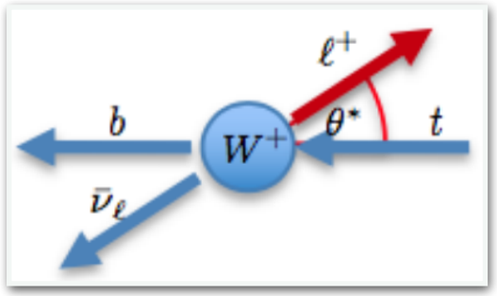
arXiv:2005.03799
submitted to JHEP

NEW

Run1 data @8 TeV:
20.2 fb^{-1} (ATLAS)
19.7 fb^{-1} (CMS)

- Fractions of W bosons polarization determined by V-A structure of tWb vertex
  - in SM unitarity constraint $F_0 + F_L + F_R = 1$
  - anomalous contributions to tWb vertex can change probabilities of W helicity states
- Distribution of $cos\theta^*$ particularly sensitive to polarization fractions

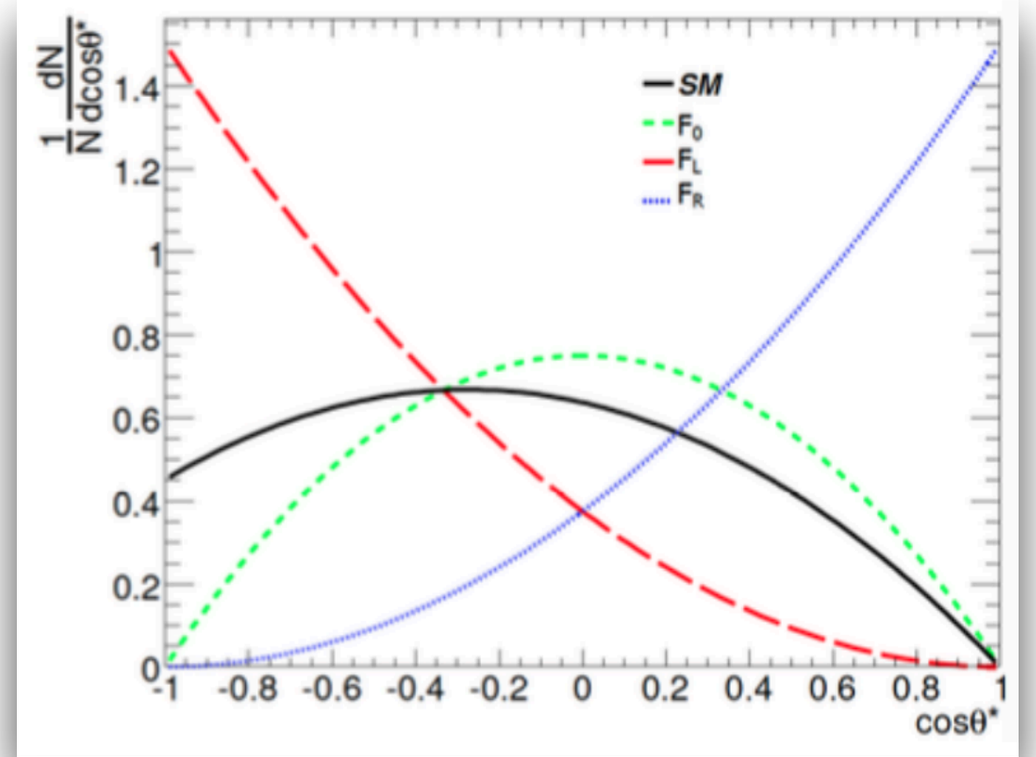
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)F_0 + \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R$$



In SM: ~70% ~30% ~0%

- **ATLAS + CMS combination** with Run1 data
  - ATLAS: l+jets
  - CMS: e/mu+jets, single top t-channel

Measurement	F_0	F_L	F_R
ATLAS (ℓ+jets)	$0.709 \pm 0.012 \pm 0.015$	$0.299 \pm 0.008 \pm 0.013$	$-0.008 \pm 0.006 \pm 0.012$
CMS (e+jets)	$0.705 \pm 0.013 \pm 0.037$	$0.304 \pm 0.009 \pm 0.020$	$-0.009 \pm 0.005 \pm 0.021$
CMS (μ+jets)	$0.685 \pm 0.013 \pm 0.024$	$0.328 \pm 0.009 \pm 0.014$	$-0.013 \pm 0.005 \pm 0.017$
CMS (single top)	$0.720 \pm 0.039 \pm 0.037$	$0.298 \pm 0.028 \pm 0.032$	$-0.018 \pm 0.019 \pm 0.011$

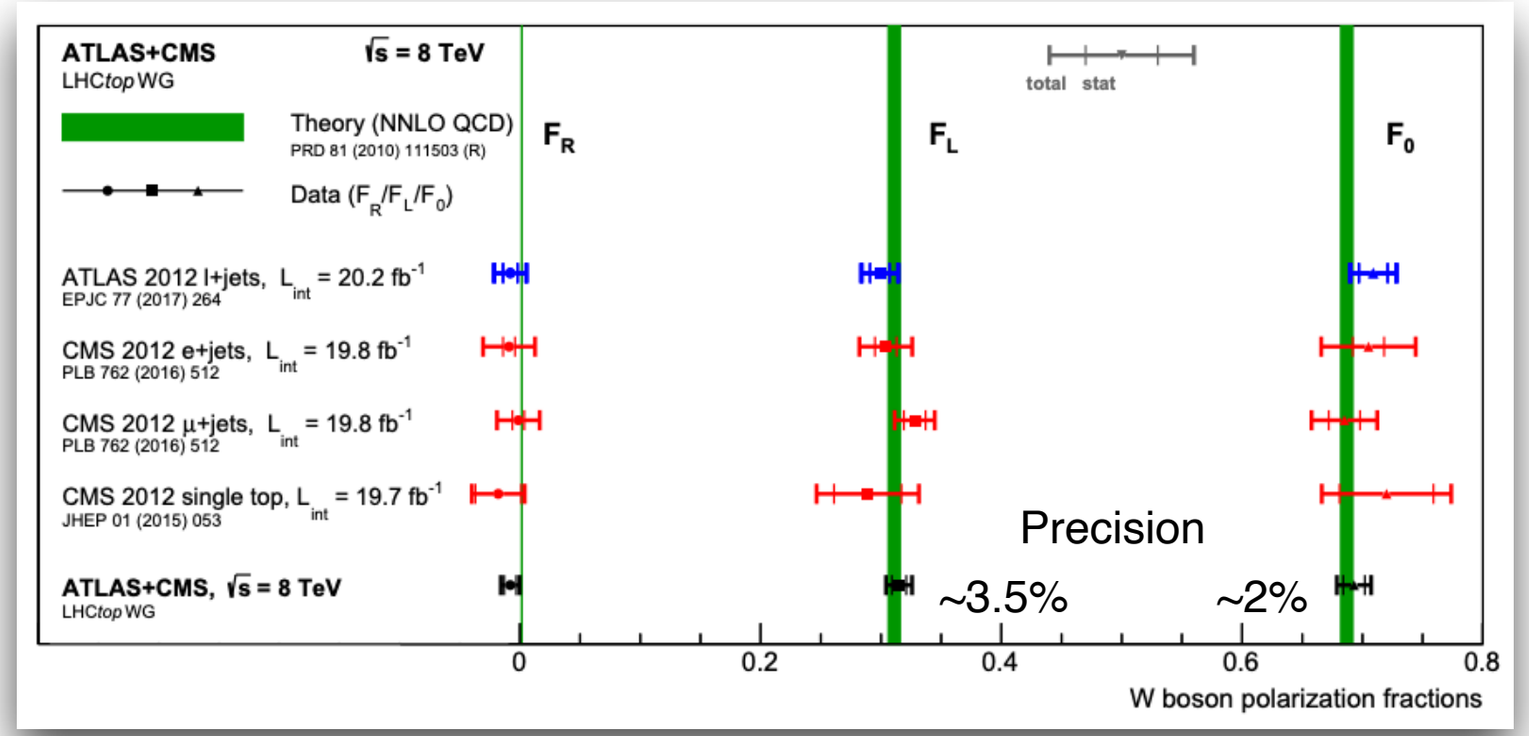


W polarization

arXiv:2005.03799
submitted to JHEP

- Results in agreement with NNLO QCD
- Improvement wrt most precise single measurement:
  - $F_0 \sim 25\,\%$
  - $F_L \sim 29\,\%$

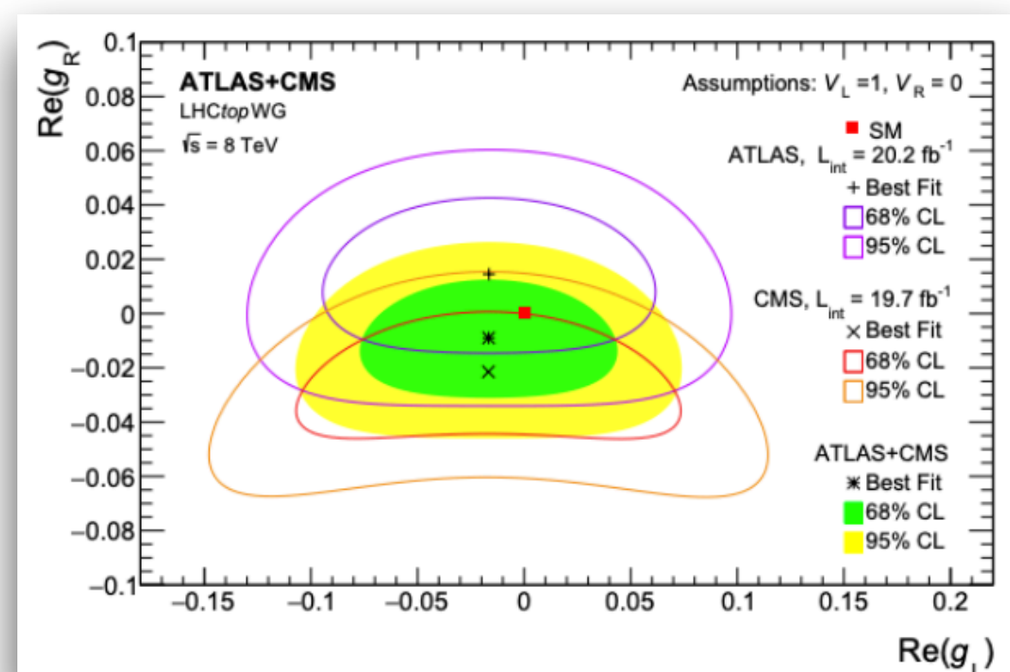
$$
\begin{aligned}
F_0 &= 0.693 \pm 0.009\,(\text{stat+bkg}) \pm 0.011\,(\text{syst}) \\
F_L &= 0.315 \pm 0.006\,(\text{stat+bkg}) \pm 0.009\,(\text{syst}) \\
F_R &= -0.008 \pm 0.005\,(\text{stat+bkg}) \pm 0.006\,(\text{syst})
\end{aligned}
$$



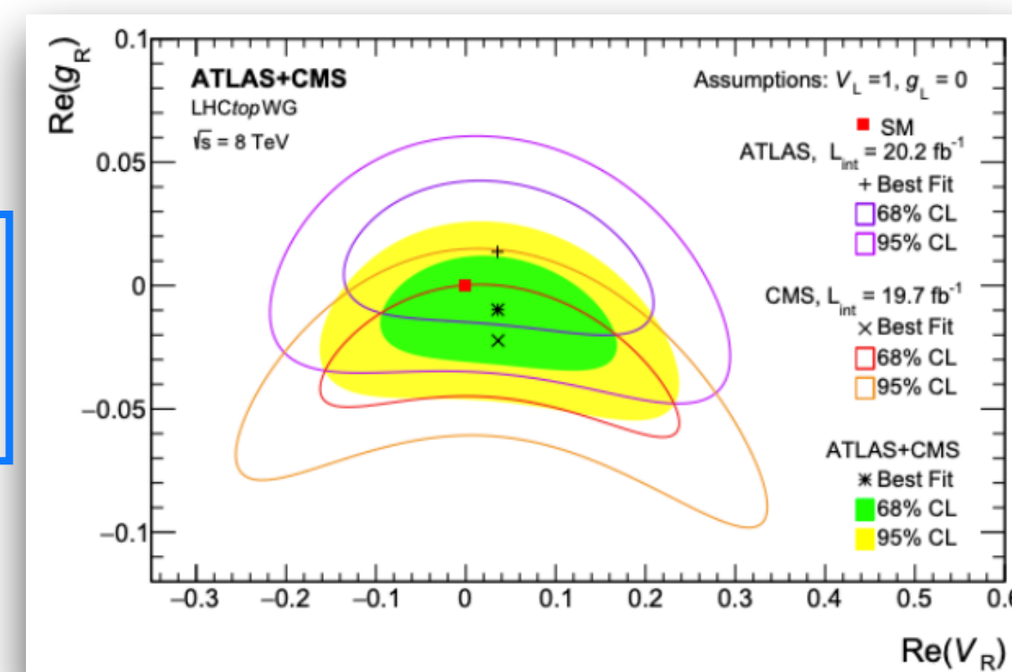
- Limits on tWb anomalous couplings

$$
\mathcal{L}_{\text{tWb}} = -\frac{g}{\sqrt{2}}\bar{\text{b}}\,\gamma^{\mu}\,(V_L P_L + V_R P_R)\,\text{t}\,\text{W}^-_{\mu} - \frac{g}{\sqrt{2}}\bar{\text{b}}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\,(g_L P_L + g_R P_R)\,\text{t}\,\text{W}^-_{\mu} + \text{h.c.}
$$

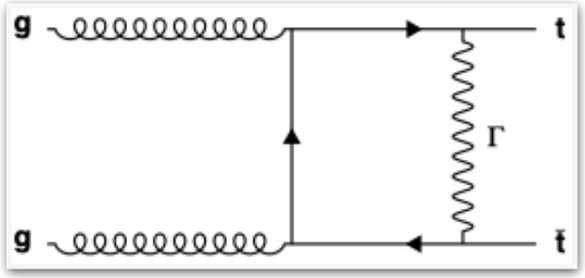
0 in SM

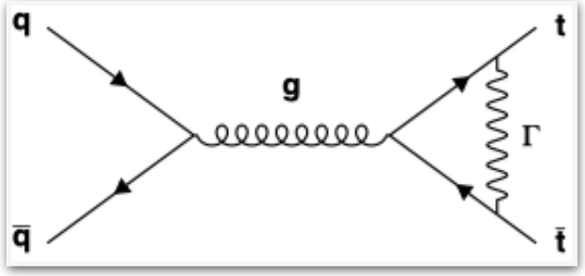


Coupling	ATLAS+CMS
$\text{Re}(V_R)$	$[-0.11, 0.16]$
$\text{Re}(g_L)$	$[-0.08, 0.05]$
$\text{Re}(g_R)$	$[-0.04, 0.02]$



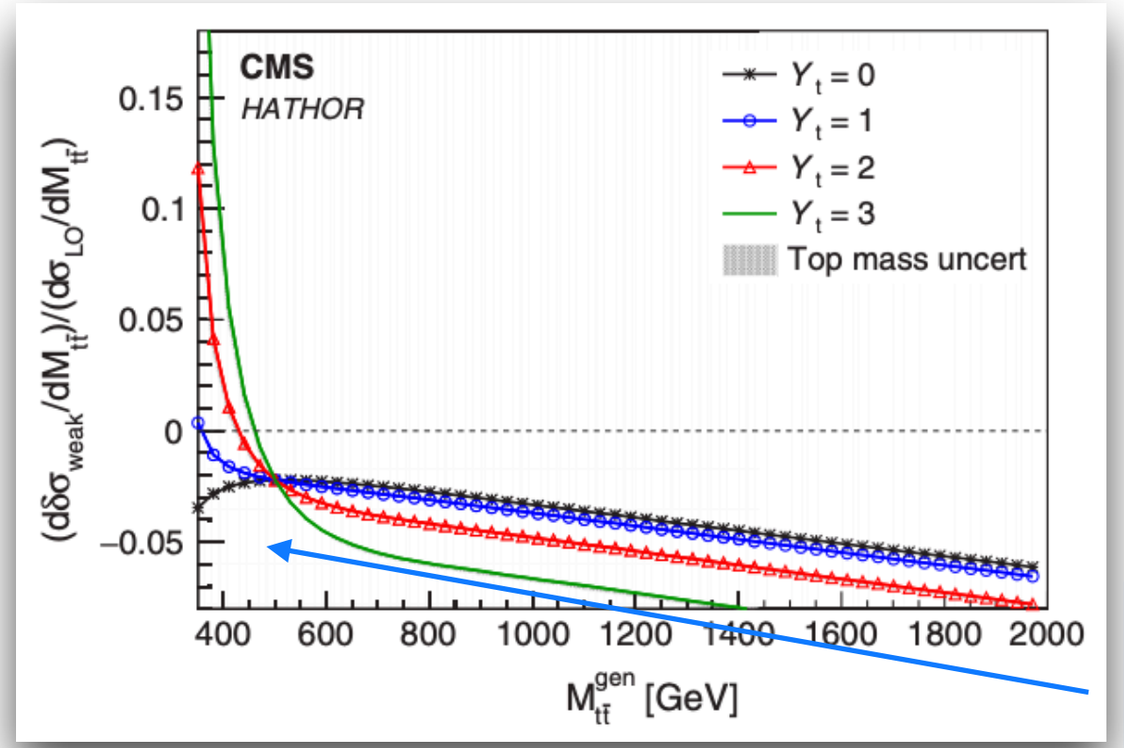
Top Yukawa coupling



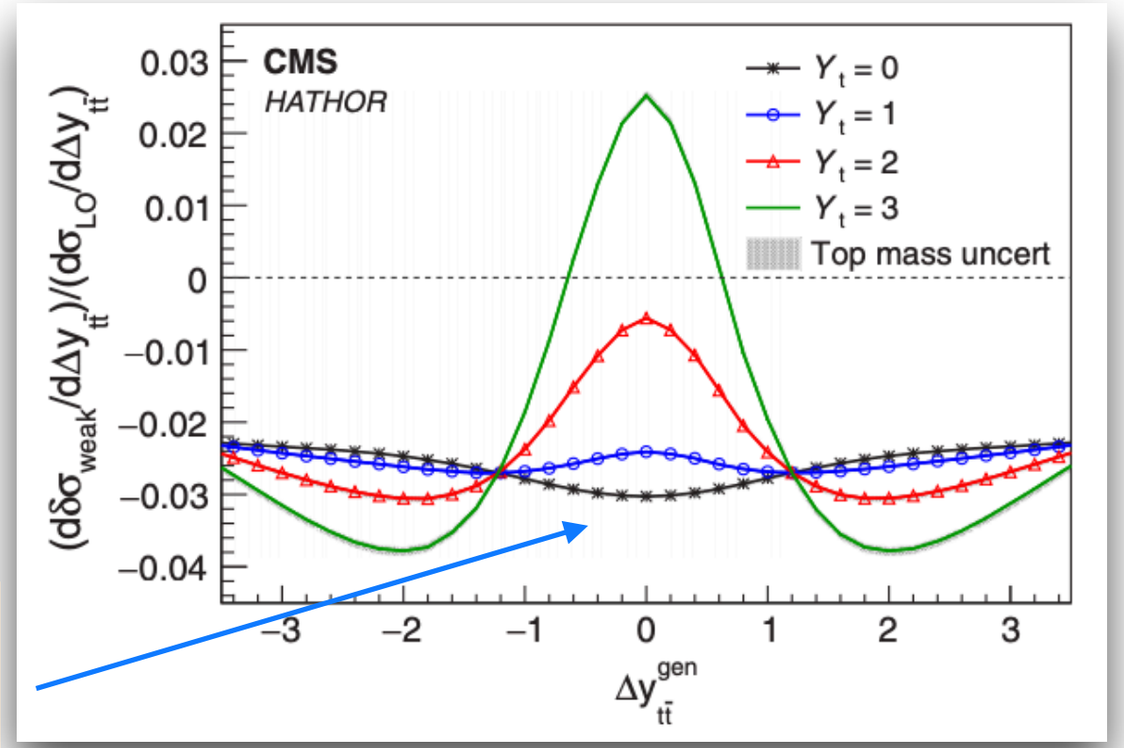


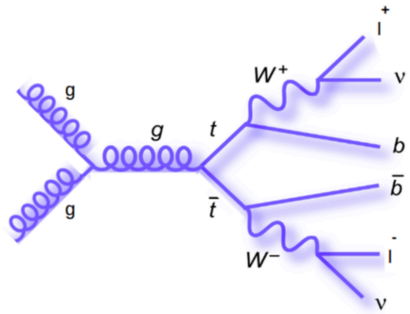
- **Weak corrections** from virtual exchange of a vector/scalar boson Γ affect cross sections only at $\alpha_S^2 \alpha_w$ order
  - small contribution to inclusive $t\bar{t}$ cross section
  - may lead to large distortions of $t\bar{t}$ differential distributions near the production threshold region
- Virtual Higgs exchange depends on the top-Higgs Yukawa coupling g_t → quadratic dependence of cross sections on g_t
- Corrections to differential cross-sections generated for different values of Y_t as function of $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$
- Multiplicative corrections applied to gen-level $t\bar{t}$ events

$$Y_t = \frac{g_t}{g_t^{SM}}$$



Most sensitive region





Top Yukawa coupling

CMS-PAS-TOP-19-008

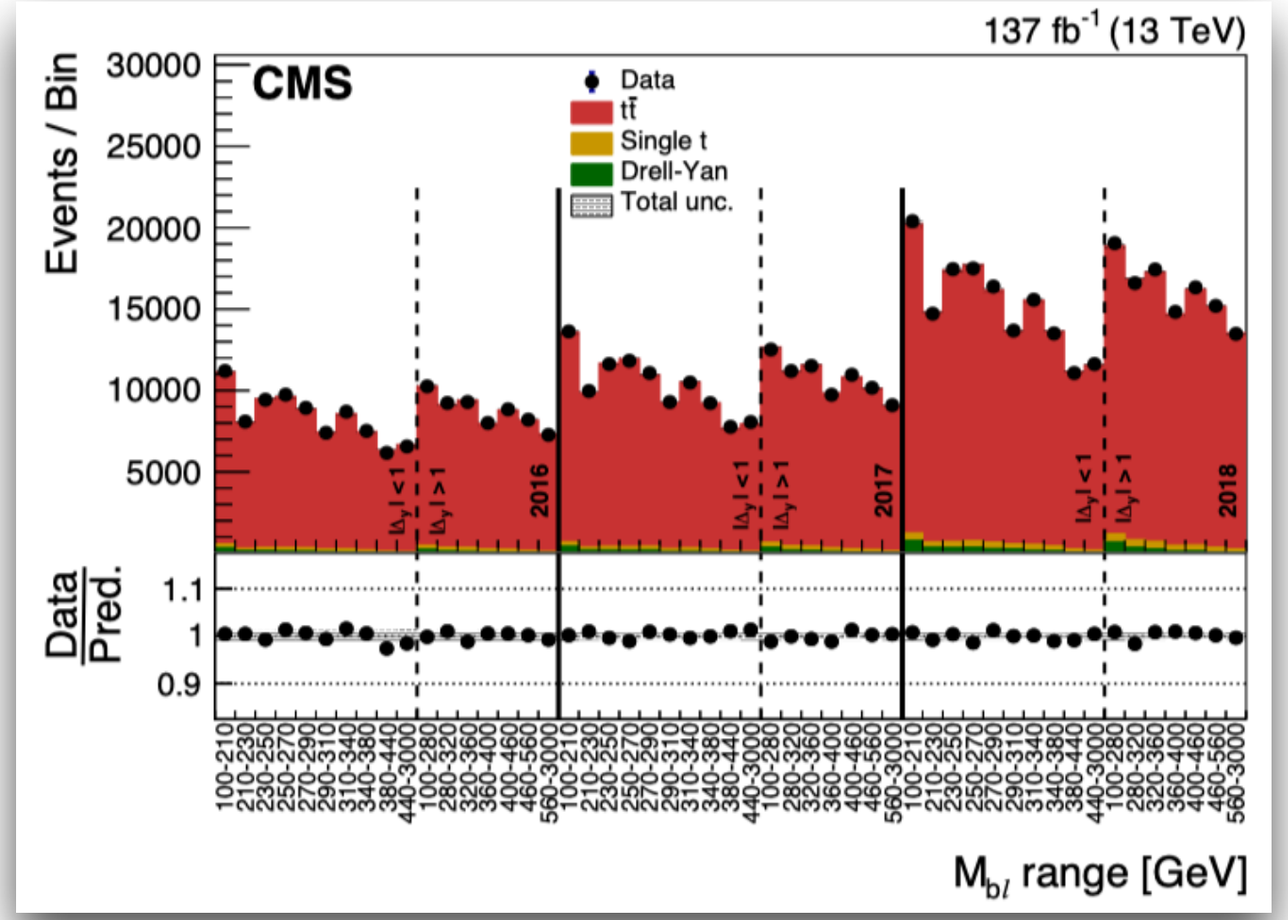
NEW

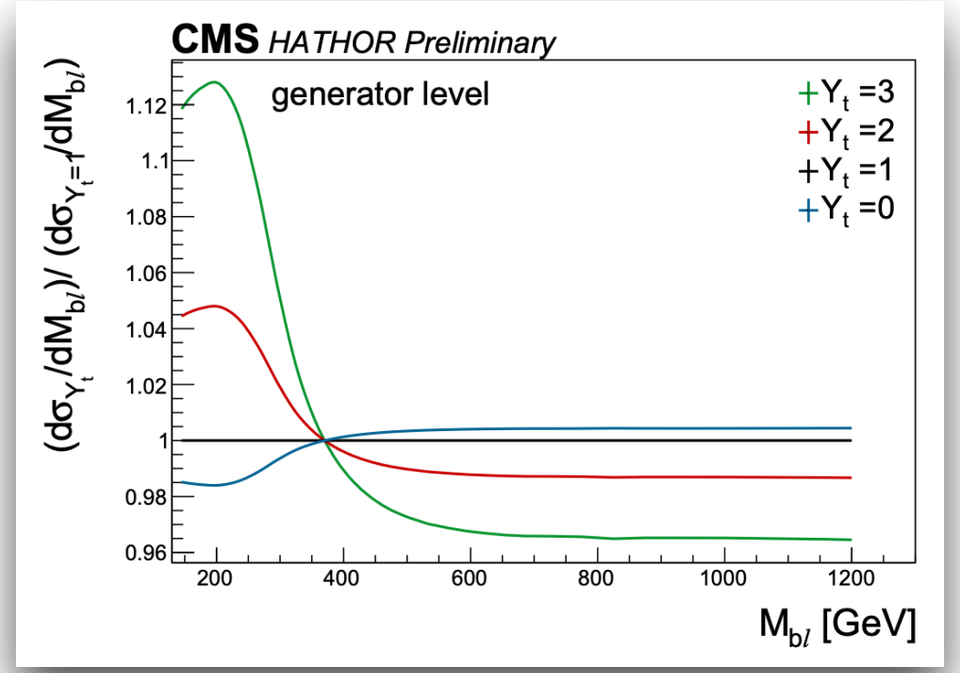
Full Run2 data
@13 TeV: 137 fb^{-1}

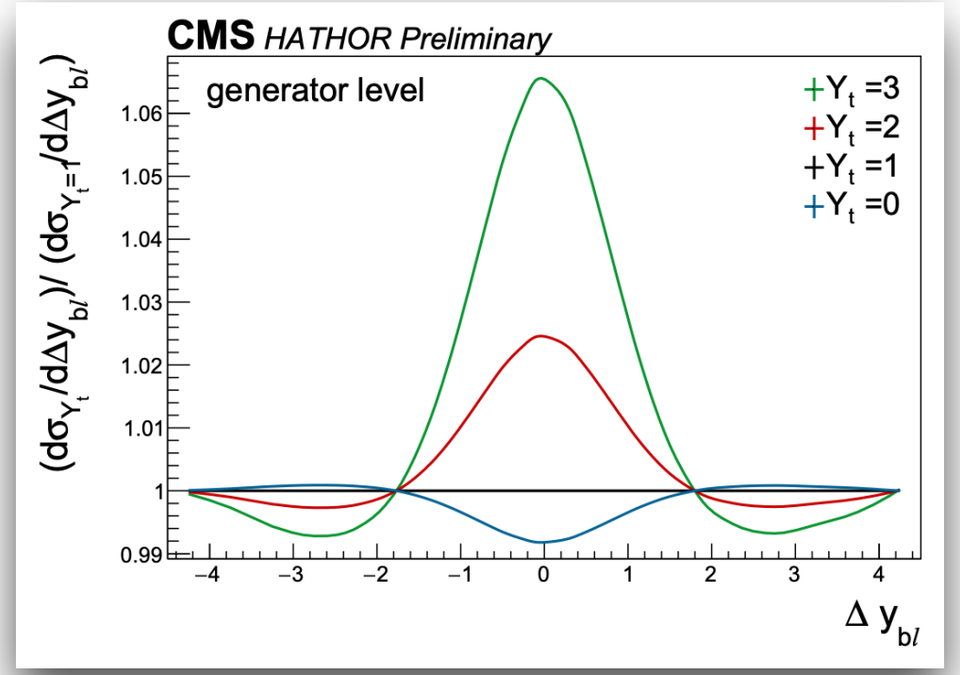
- Partial kinematic reconstruction in dilepton channel
- Improved sensitivity achieved with proxy variables:

$$\begin{aligned} M_{b\ell} &= M(b+\bar{b}+\ell+\bar{\ell}) \\ |\Delta y|_{b\ell} &= |y(b+\bar{\ell}) - y(\bar{b}+\ell)| \end{aligned}$$

- 2D likelihood fit in $(M_{b\ell}, \Delta y_{b\ell})$ to constrain Y_t
  - expected yield extrapolated as a function of Y_t with quadratic fit



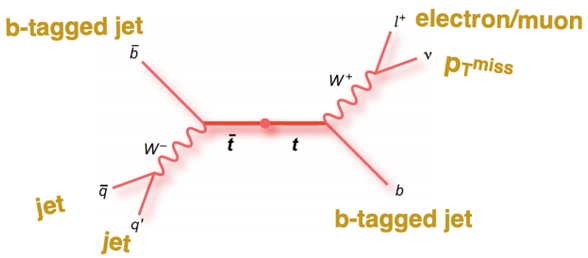




Top Yukawa coupling

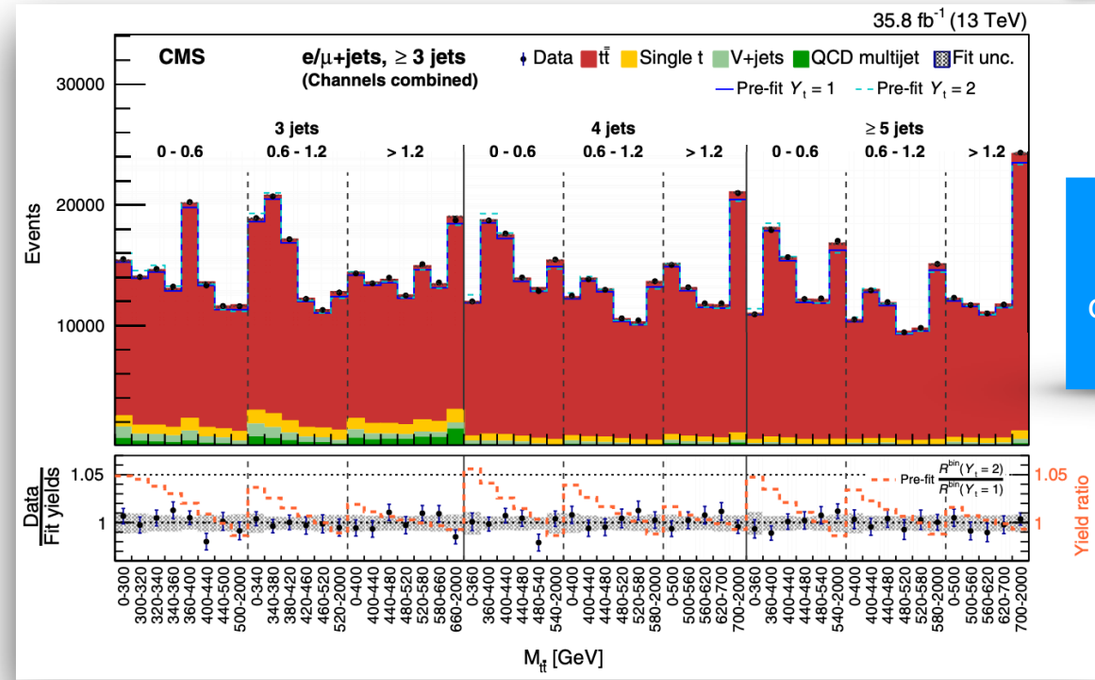
Phys. Rev. D 100 (2019) 072007

2016 data
@13 TeV: 35.8 fb^{-1}



- Full kinematic reconstruction in lepton+jets channel
  - novel technique for events with 1 missing jet → experimental sensitivity enhanced in low invariant mass region
- 2D likelihood fit in ($M_{t\bar{t}}$, $\Delta y_{t\bar{t}}$) to constrain Y_t

- Upper limit extraction on top quark Yukawa coupling

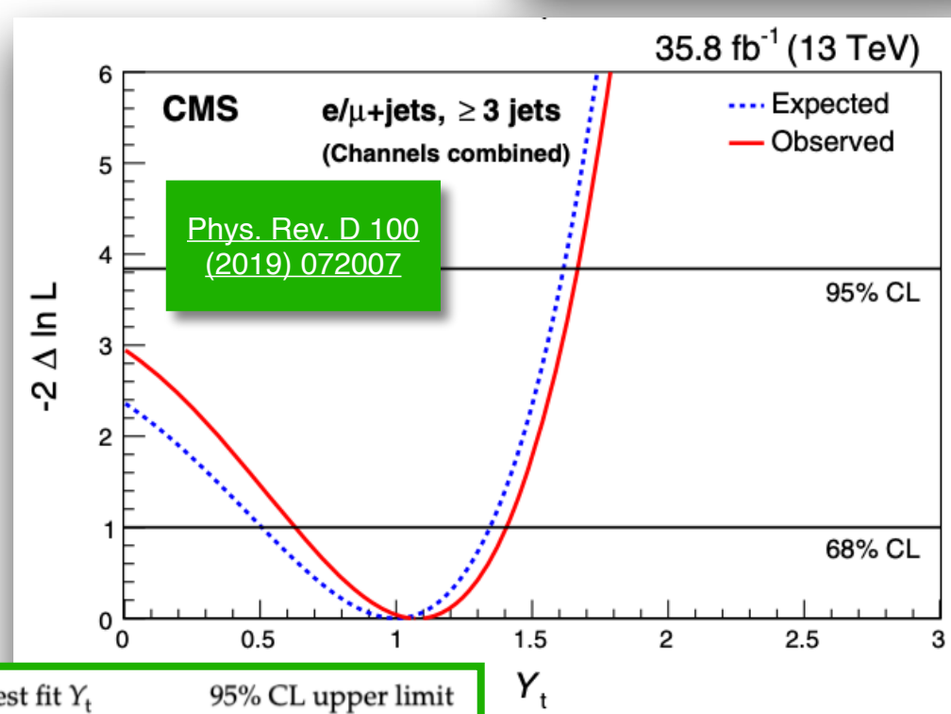


First analysis to measure Yukawa coupling with top pair production!

- Results in agreement between 2 channels

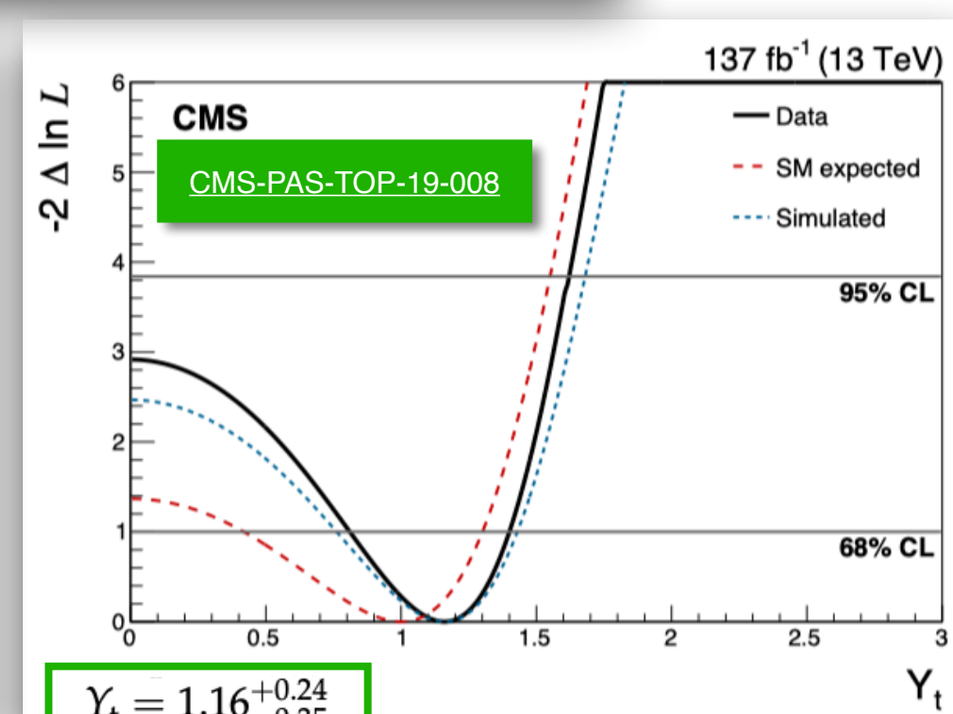
- More sensitive than 4t production: $Y_t < 1.7$ @ 95% C.L.

- Less sensitive than model-dependent Higgs combination: $Y_t = 0.98 \pm 0.14$



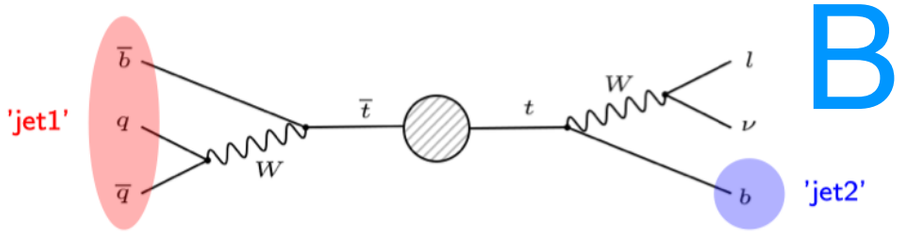
Phys. Rev. D 100 (2019) 072007

Best fit Y_t		95% CL upper limit	
Expected	Observed	Expected	Observed
$1.00^{+0.35}_{-0.48}$	$1.07^{+0.34}_{-0.43}$	<1.62	<1.67



CMS-PAS-TOP-19-008

$Y_t = 1.16^{+0.24}_{-0.35}$
68% CI: [0.80, 1.40]
95% CI: [0.00, 1.62]



Boosted mass

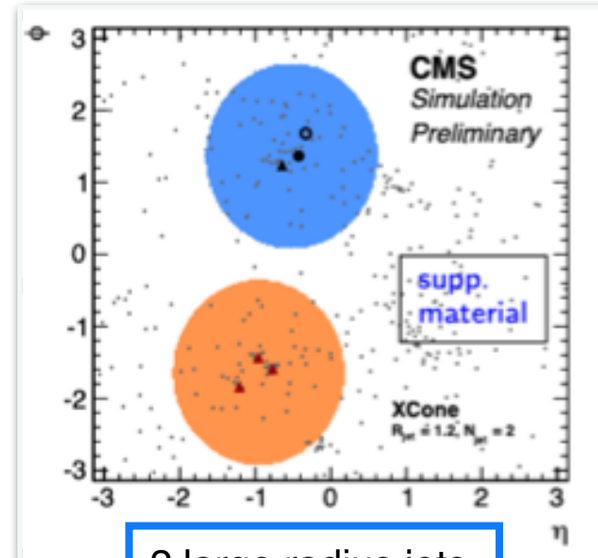
Phys. Rev. Lett. 124, 202001 (2020)

2016 data
@13 TeV: 35.9 fb^{-1}

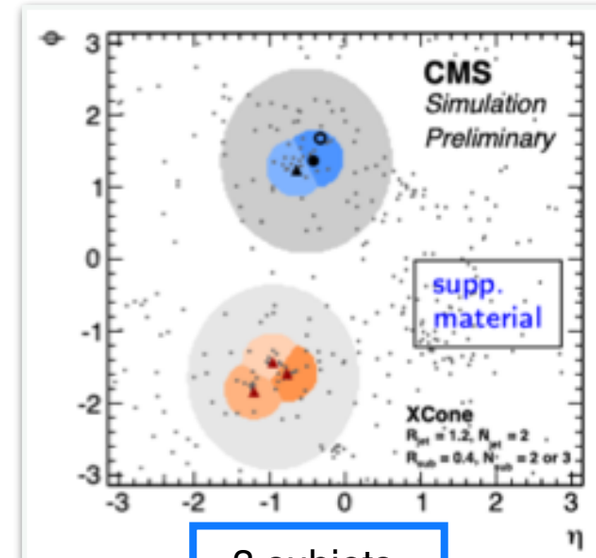
- Measurement of top quark mass in hadronic decays of boosted top quarks in lepton+jets channel
- Novel jet reconstruction technique, XCone:
  - excellent m_{jet} resolution
- m_t extracted from normalized $t\bar{t}$ cross section as function of m_{jet} unfolded at particle level:

$$m_t = 172.6 \pm 2.5\,\text{GeV}$$
$$= 172.6 \pm 0.4\,(\text{stat}) \pm 1.6\,(\text{exp}) \pm 1.5\,(\text{model}) \pm 1.0\,(\text{theo})\ \text{GeV}$$

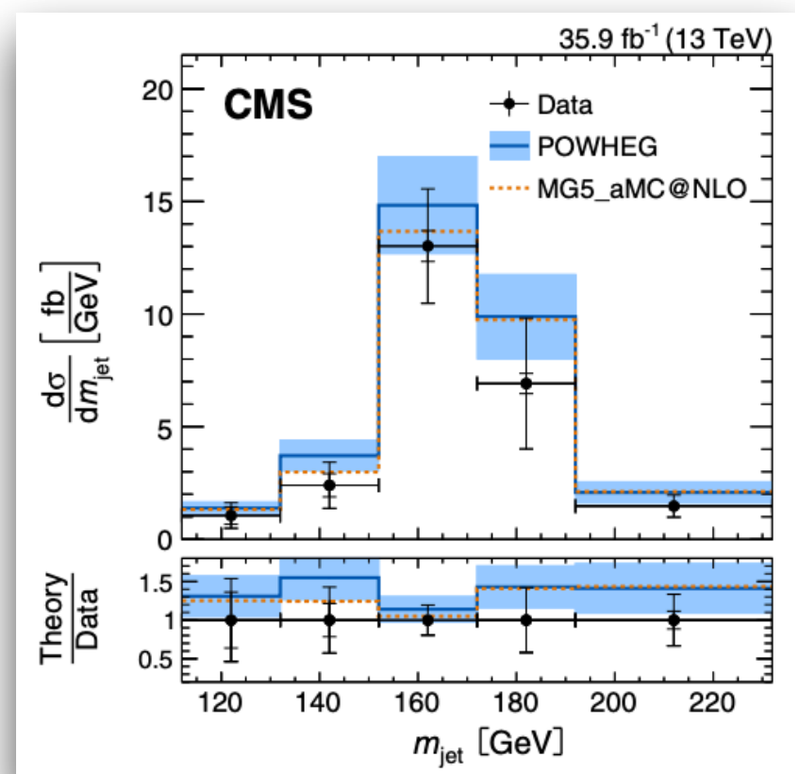
$$\frac{m_t}{\Delta m_t} \sim 0.7\,\%$$

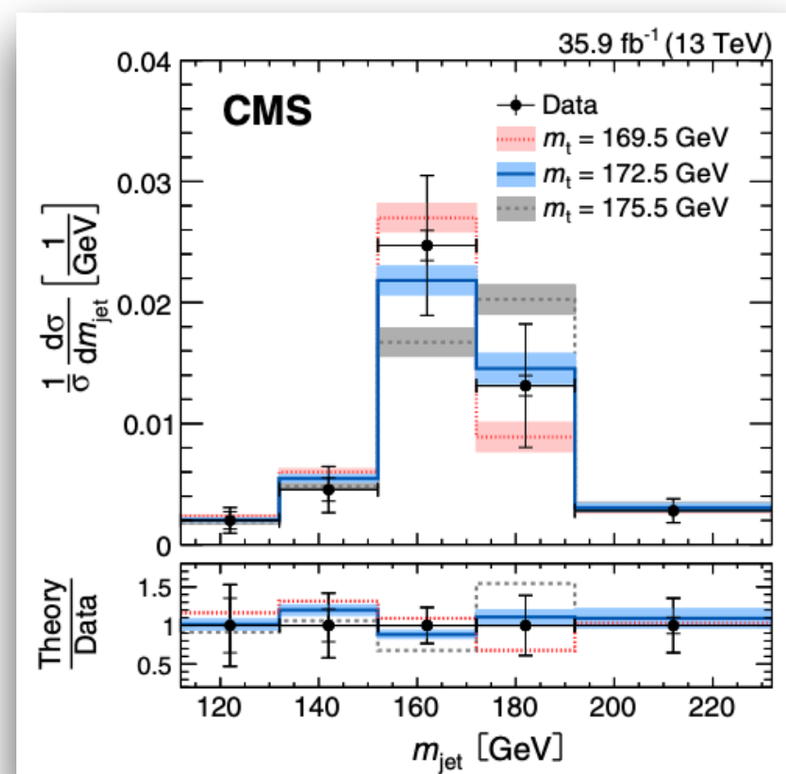


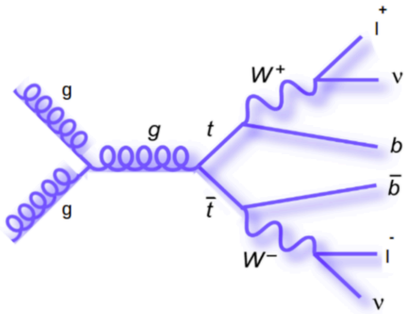
2 large radius jets, $p_T > 400$ GeV



3 subjets, $p_T > 30$ GeV







Mass from multidifferential

arXiv:1904.05237
submitted to Eur. Phys. J.

2016 data @13 TeV: 35.9 fb^{-1}

- Normalized 3D cross sections vs $m_{t\bar{t}}$, $y_{t\bar{t}}$, N(extra jets) in dilepton channel
- Extraction of α_S and m_t^{pole}:
  - cross sections compared to NLO predictions with different PDFs
  - simultaneous fit of PDF+α_S+m_t^{pole} at NLO + HERA DIS data

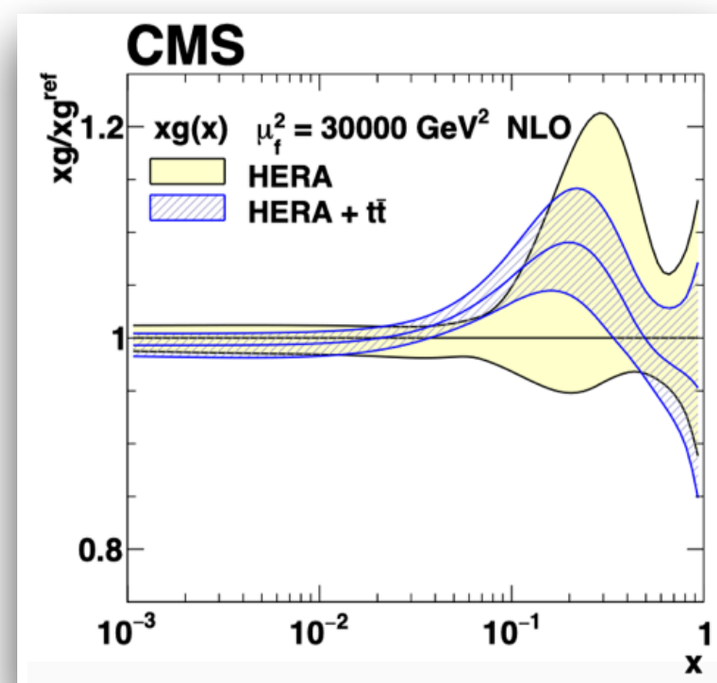
See G. Bakas's talk for details on analysis

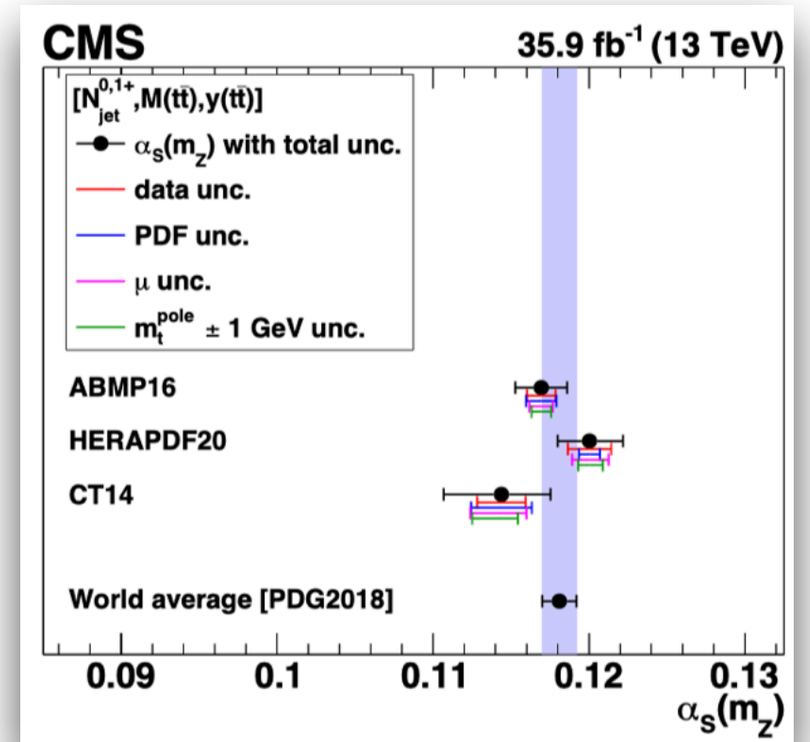
$$\alpha_S(m_Z) = 0.1135^{+0.0021}_{-0.0017}$$
$$= 0.1135 \pm 0.0016\,(\text{fit})^{+0.0002}_{-0.0004}\,(\text{model})^{+0.0008}_{-0.0001}\,(\text{param})^{+0.0011}_{-0.0005}\,(\text{scale})$$
$$m_t^{pole} = 170.5 \pm 0.8\,\text{GeV}$$
$$= 170.5 \pm 0.7\,(\text{fit}) \pm 0.1\,(\text{model})^{+0.0}_{-0.1}(\text{param}) \pm 0.3\,(\text{scale})\,\text{GeV}$$

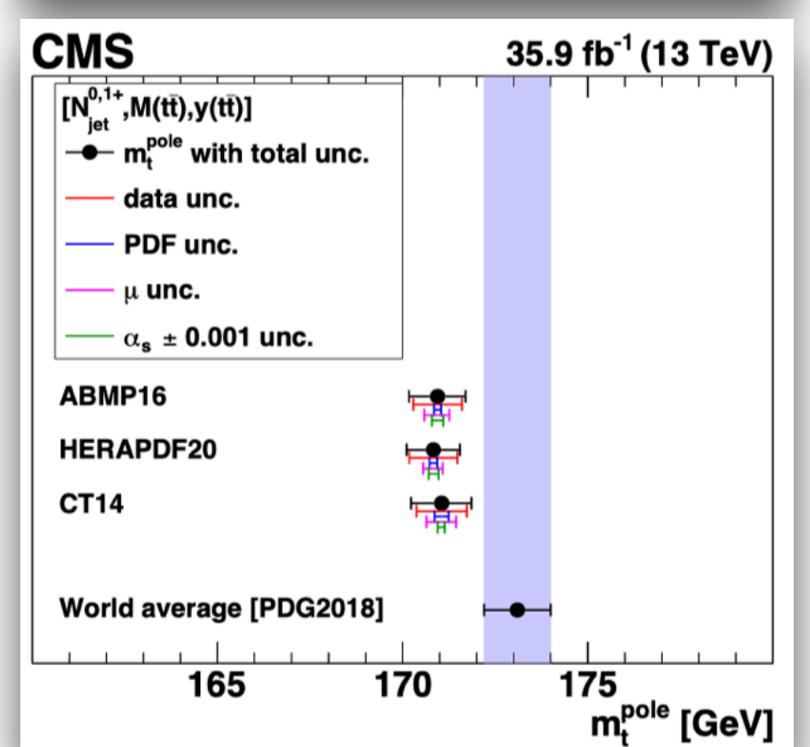
Most precise result on m_t^{pole} from single analysis!

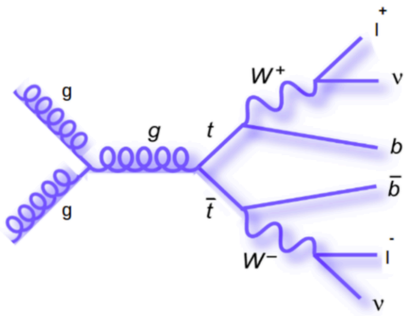
$$\frac{m_t}{\Delta m_t} < 0.5\,\%$$

- PDFs:
  - significant impact on gluon PDF at large values of x









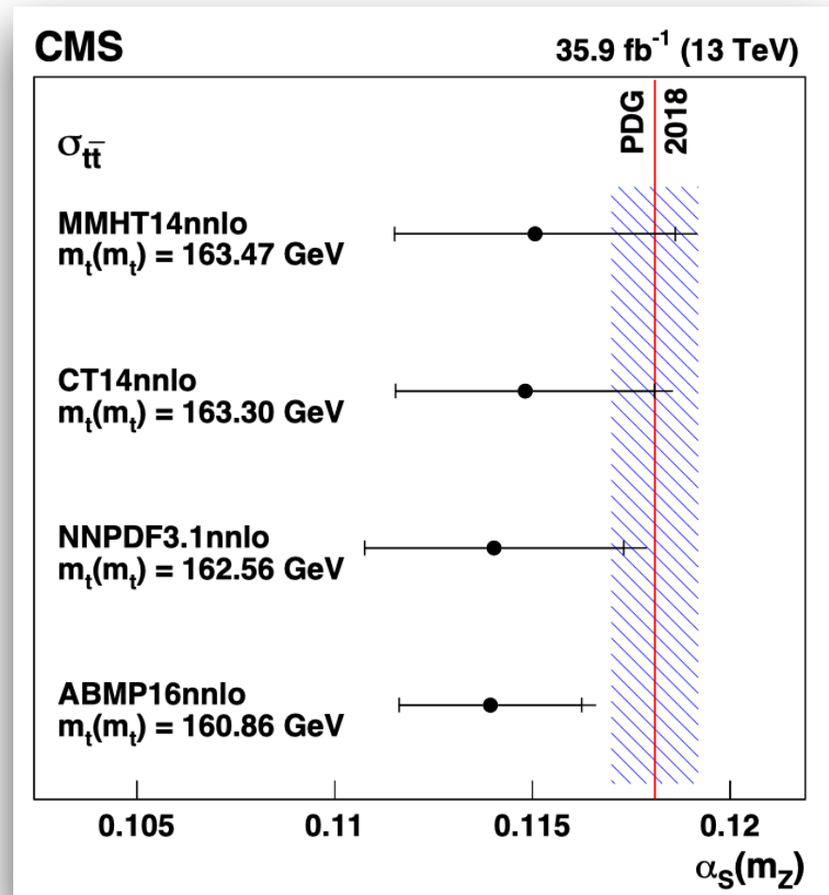
Mass from inclusive measurement

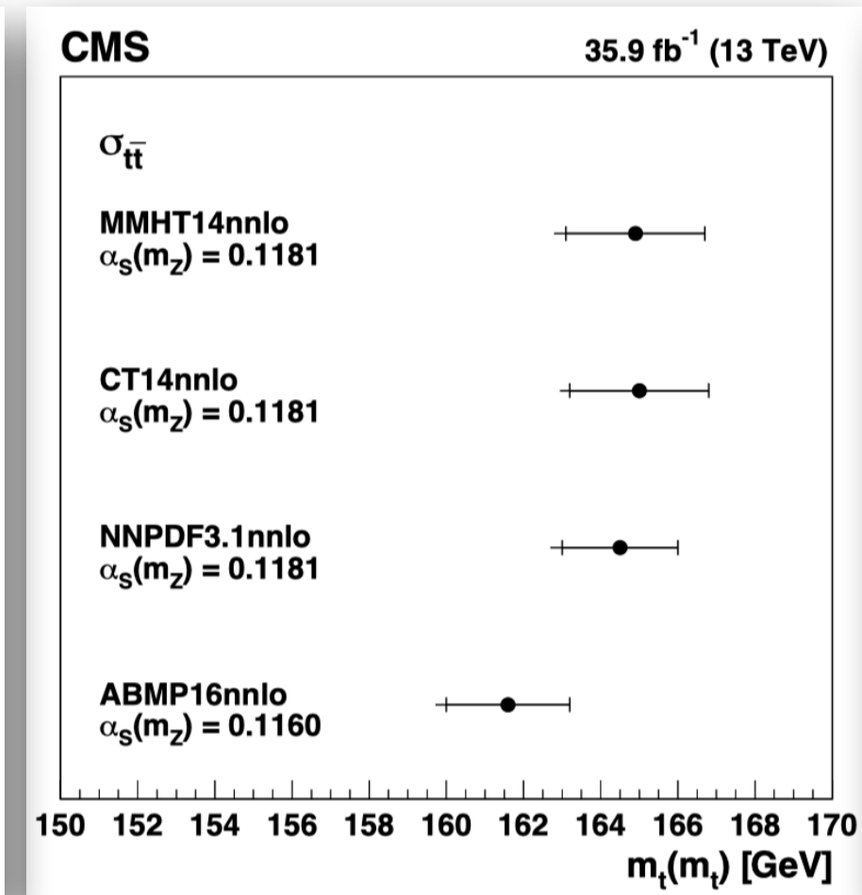
EPJC 79 (2019) 368

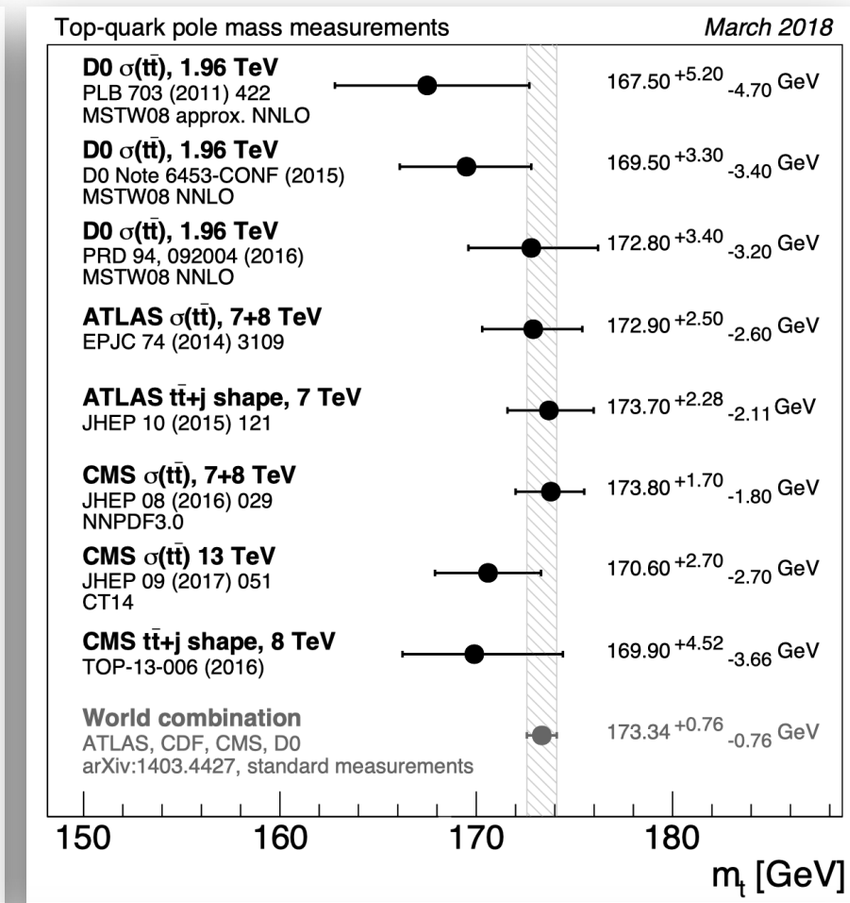
2016 data
@13 TeV: 35.9 fb^{-1}

See D. Muller's talk for details on analysis

- Inclusive cross section in emu channel
- Extraction of $\alpha_S(m_Z)$, m_t in MS scheme, and m_t in pole mass scheme:
  - simultaneous fit of $\sigma_{t\bar{t}} + m_t^{MC}$







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

PDF set	$m_t(m_t)$ [GeV]
ABMP16	161.6 ± 1.6 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
NNPDF3.1	164.5 ± 1.6 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
CT14	165.0 ± 1.8 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
MMHT14	164.9 ± 1.8 (fit + PDF + α_S) $^{+0.1}_{-1.1}$ (scale)

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

First experimental investigation!

Running of top mass

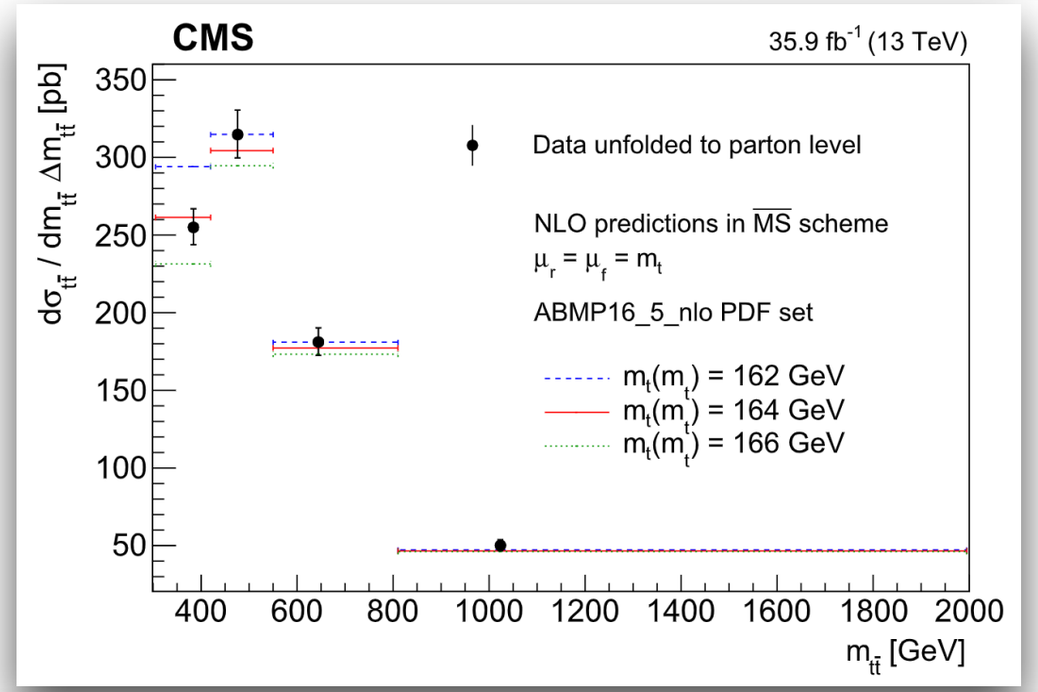
Phys. Lett. B 803 (2020) 135263

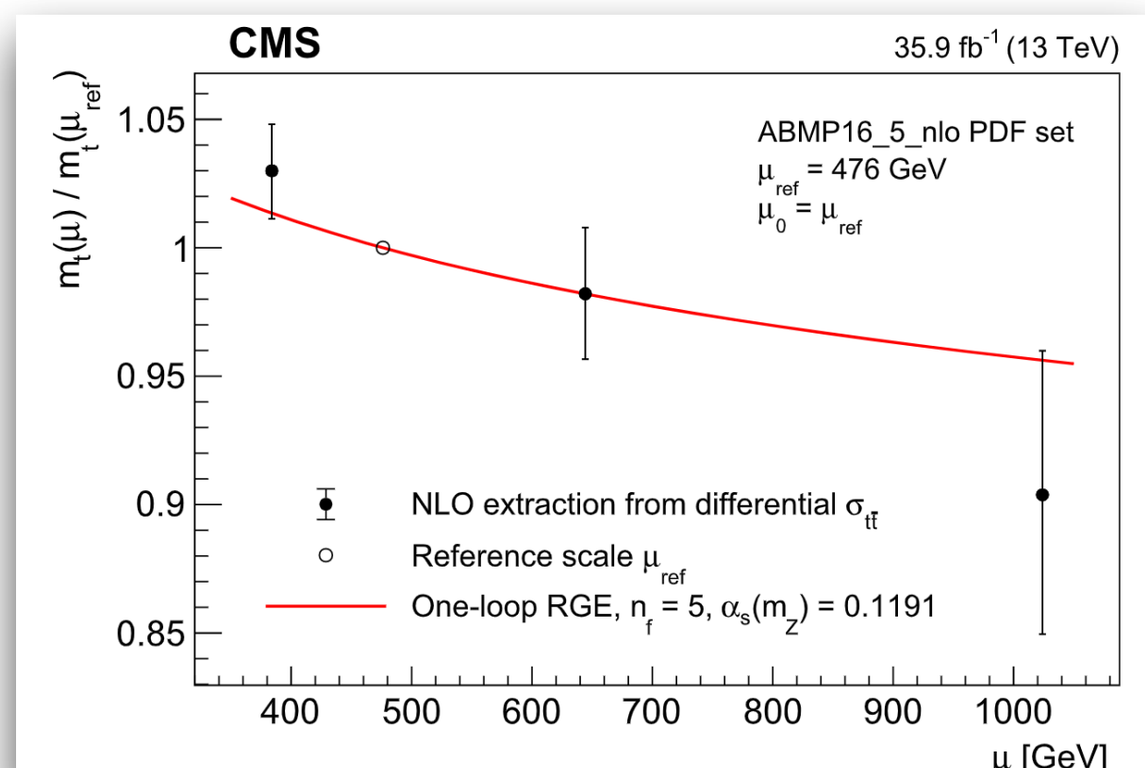
2016 data
@13 TeV: 35.9 fb^{-1}

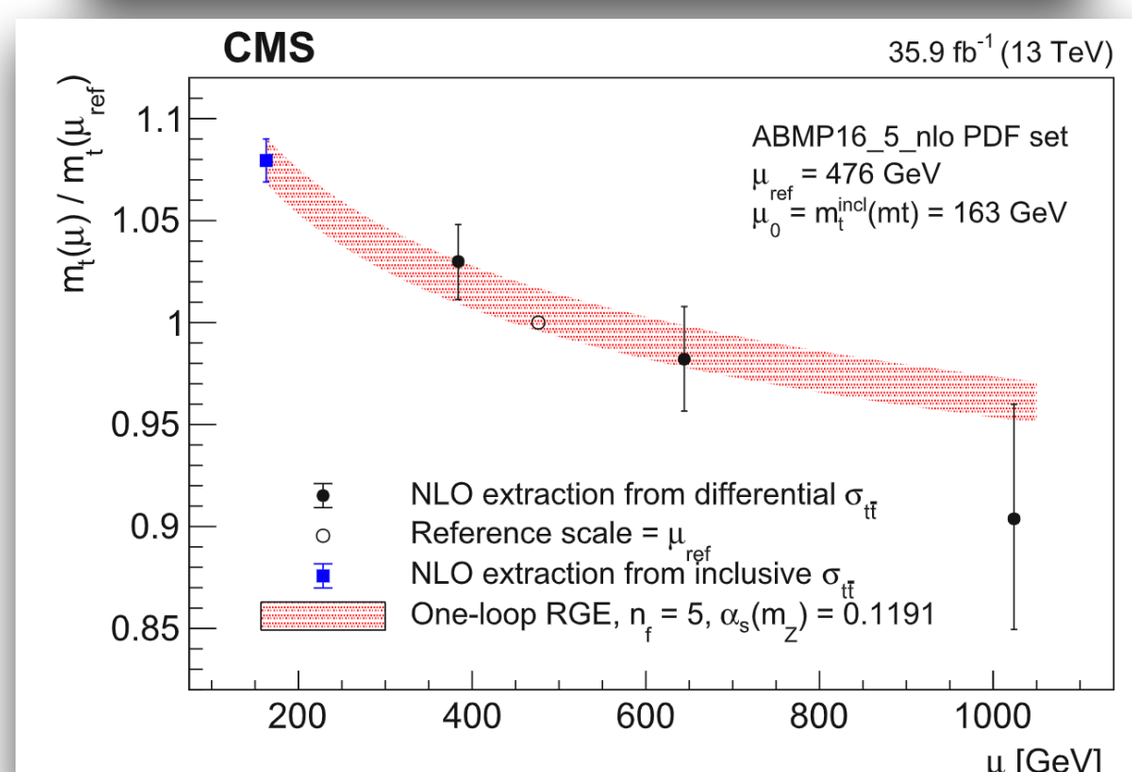
- Extracted by comparing NLO predictions to differential cross section measured vs $m_{t\bar{t}}$ in emu channel
- Simultaneous measurement of $d\sigma_{t\bar{t}}/dm_{t\bar{t}}$ and m_t^{MC} by means of maximum-likelihood fit to multi-differential distributions

Based on EPJC 79 (2019) 368's strategy (see D. Muller's talk)

- Running of m_t in agreement with prediction of corresponding RGE within 1.1 σ
- No-running scenario excluded at above 95% C.L.







First direct model-independent measurement in single top t-channel events

Top CKM elements

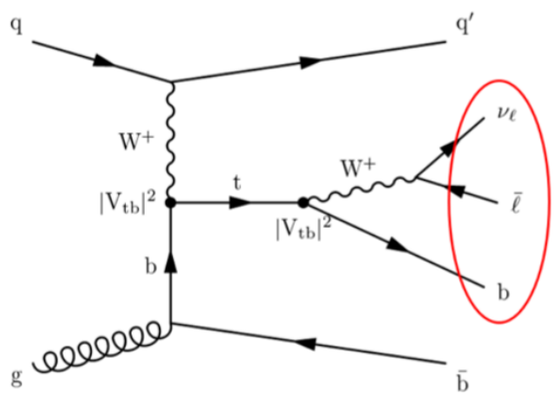
Phys. Lett. B 808 (2020) 135609

NEW

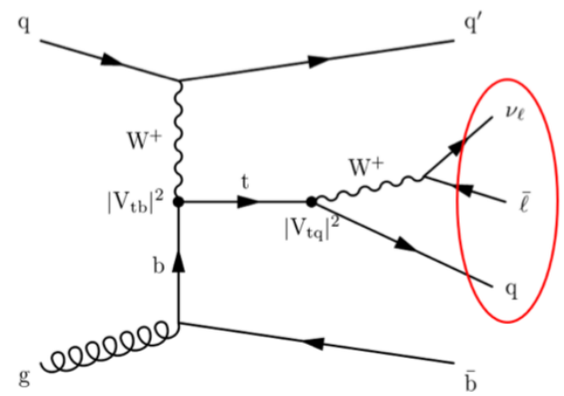
2016 data
@13 TeV: 35.9 fb^{-1}

- Processes directly sensitive to $|V_{tb}|$, $|V_{td}|$, and $|V_{ts}|$ are considered at both the production and decay vertices of the top quark:

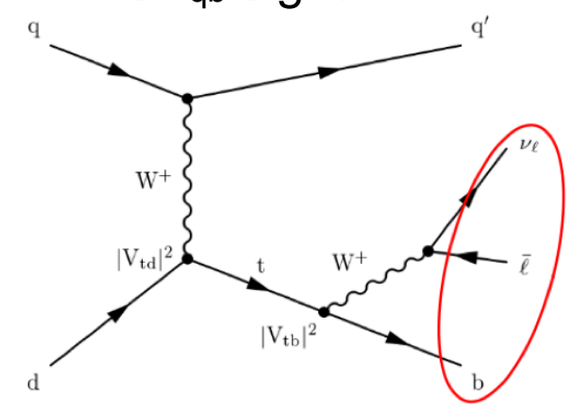
ST_{bb} signal



ST_{bq} signal

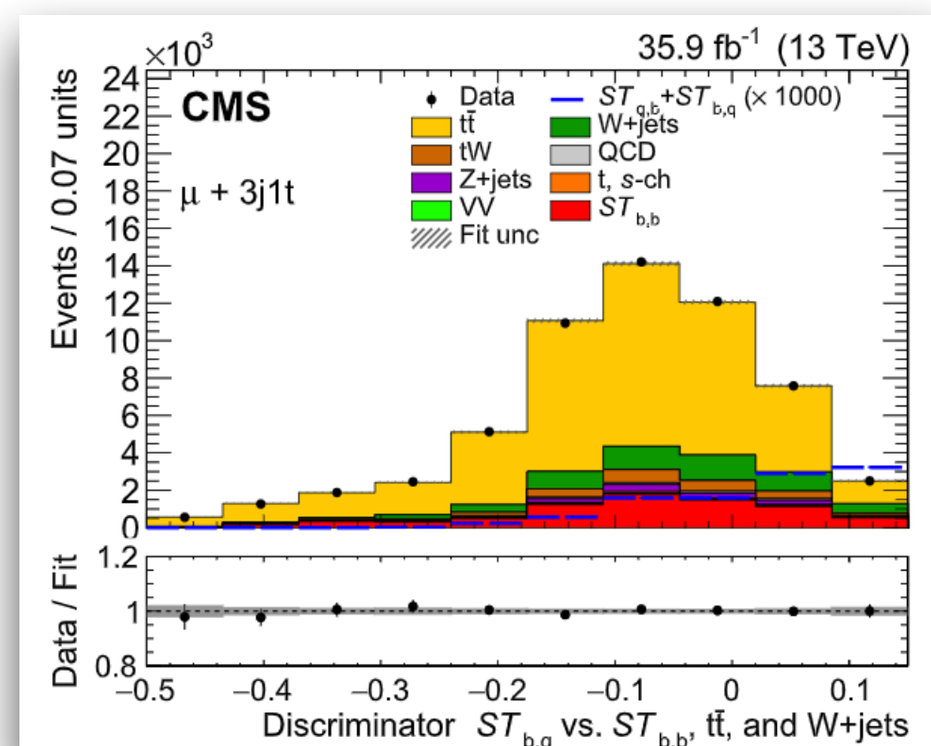


ST_{qb} signal



Category	Enriched in
2j1t	$ST_{b,b}$
3j1t	$ST_{b,q}$, $ST_{q,b}$
3j2t	$ST_{b,b}$

- BDT discriminant trained for each category to separate signal and background processes
- Multivariate discriminators used in a simultaneous fit to the 3 event categories to discriminate between ST_{bb}, ST_{bq}, and ST_{qb}



Top CKM elements

Phys. Lett. B 808 (2020) 135609

- CKM matrix elements extracted by signal strengths:

$$\mu_b = \frac{\sigma^{\text{obs}}_{t-\text{ch.,b}} \times (\text{BR}(\text{t} \to \text{Wb}))^{\text{obs}}}{\sigma_{t-\text{ch.,b}} \times (\text{BR}(\text{t} \to \text{Wb}))} = \frac{|\text{V}_{\text{tb}}|^{4\,\text{obs}} \cdot \Gamma^{\text{obs}}_q \cdot \Gamma_{\text{top}}}{|\text{V}_{\text{tb}}|^4 \cdot \Gamma_q \cdot \Gamma^{\text{obs}}_{\text{top}}}$$

$$\mu_{sd} = \frac{\sigma^{\text{obs}}_{t-\text{ch.,b}} \times (\text{BR}(\text{t} \to \text{Wd,s}))^{\text{obs}} + \sigma^{\text{obs}}_{t-\text{ch.,s,d}} \times (\text{BR}(\text{t} \to \text{Wb}))^{\text{obs}}}{\sigma_{t-\text{ch.,b}} \times (\text{BR}(\text{t} \to \text{Wd,s})) + \sigma_{t-\text{ch.,s,d}} \times (\text{BR}(\text{t} \to \text{Wb}))} = \frac{|\text{V}_{\text{tb}}|^{2\,\text{obs}} \cdot (|\text{V}_{\text{ts}}|^2 + |\text{V}_{\text{td}}|^2)^{\text{obs}} \cdot \Gamma^{\text{obs}}_q \cdot \Gamma_{\text{top}}}{|\text{V}_{\text{tb}}|^2 \cdot (|\text{V}_{\text{ts}}|^2 + |\text{V}_{\text{td}}|^2) \cdot \Gamma_q \cdot \Gamma^{\text{obs}}_{\text{top}}}$$

- **In SM**:
  - assuming CKM unitarity (@ 95% C.L.):

$$|V_{\text{tb}}| > 0.970$$
$$|V_{\text{td}}|^2 + |V_{\text{ts}}|^2 < 0.057$$

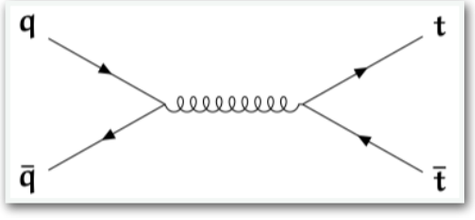
- **BSM scenario 1**:
  - additional quark families with m > mt
  - no CKM unitarity

$$|V_{\text{tb}}| = 0.988 \pm 0.027\ (\text{stat+prof}) \pm 0.043\ (\text{nonprof})$$
$$|V_{\text{td}}|^2 + |V_{\text{ts}}|^2 = 0.06 \pm 0.05\ (\text{stat+prof})\ ^{+0.04}_{-0.03}\ (\text{nonprof})$$

- **BSM scenario 2**:
  - additional, undetected decays

$$|V_{\text{tb}}| = 0.988 \pm 0.011\ (\text{stat+prof}) \pm 0.021\ (\text{nonprof})$$
$$|V_{\text{td}}|^2 + |V_{\text{ts}}|^2 = 0.06 \pm 0.05\ (\text{stat+prof}) \pm 0.04\ (\text{nonprof})$$
$$R_\Gamma = 0.99 \pm 0.42\ (\text{stat+prof}) \pm 0.03\ (\text{nonprof}).$$

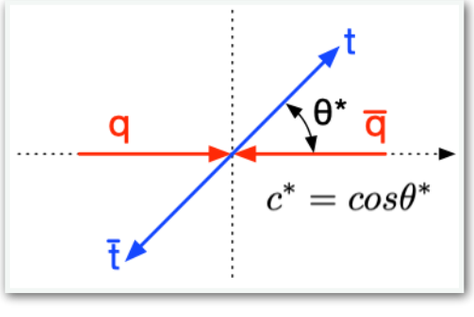
- All results are consistent with each other
- Best determination of these parameters w.r.t. latest measurements of single top quark in Run2



Top Forward-Backward Asymmetry

JHEP 06 (2020) 146

2016 data @13 TeV: 35.9 fb^{-1}



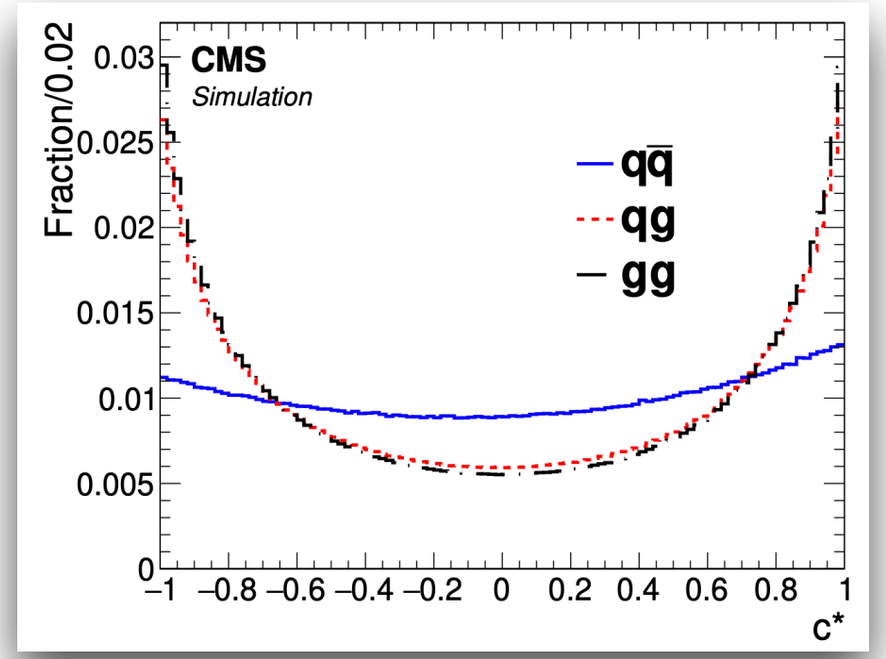
- Asymmetry in $t\bar{t}$ production due to NLO interference terms between $q\bar{q}$ initial states
- Search for anomalies in the angular distribution of produced $t\bar{t}$ pairs:

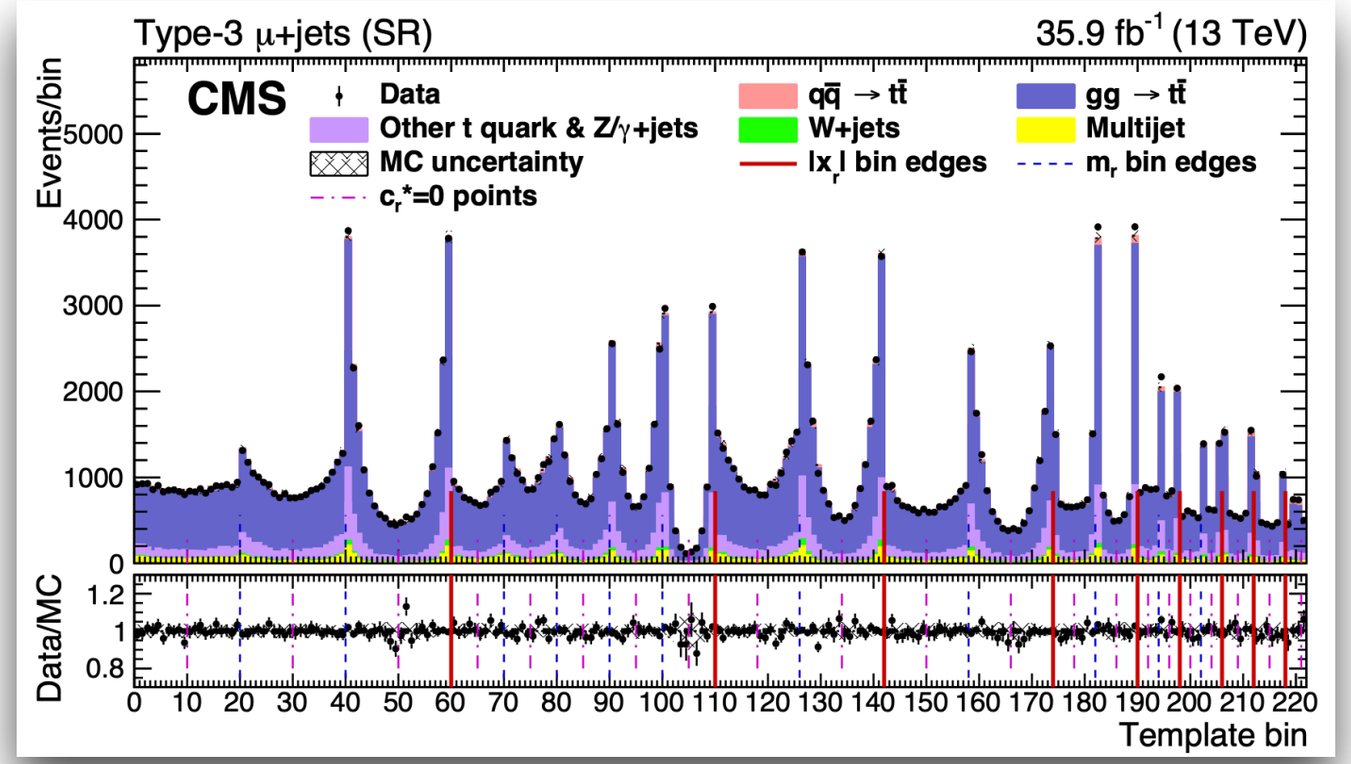
$$\frac{d\sigma}{dc^*}(q\bar{q}) \approx f_{sym}(c^*) + \left[\int_{-1}^{1} f_{sym}(x)dx\right] c^* A_{FB}^{(1)}(m_{t\bar{t}})$$

anomalous chromoelectric (d_t) + chromomagnetic (μ_t) dipole moments

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

- Lepton+jets events with "boosted" and "resolved" topologies
- Multi-dimensional template fit for each category, lepton flavour and charge to $c^*, m_{t\bar{t}}, x_F = 2p_L/\sqrt{s}$



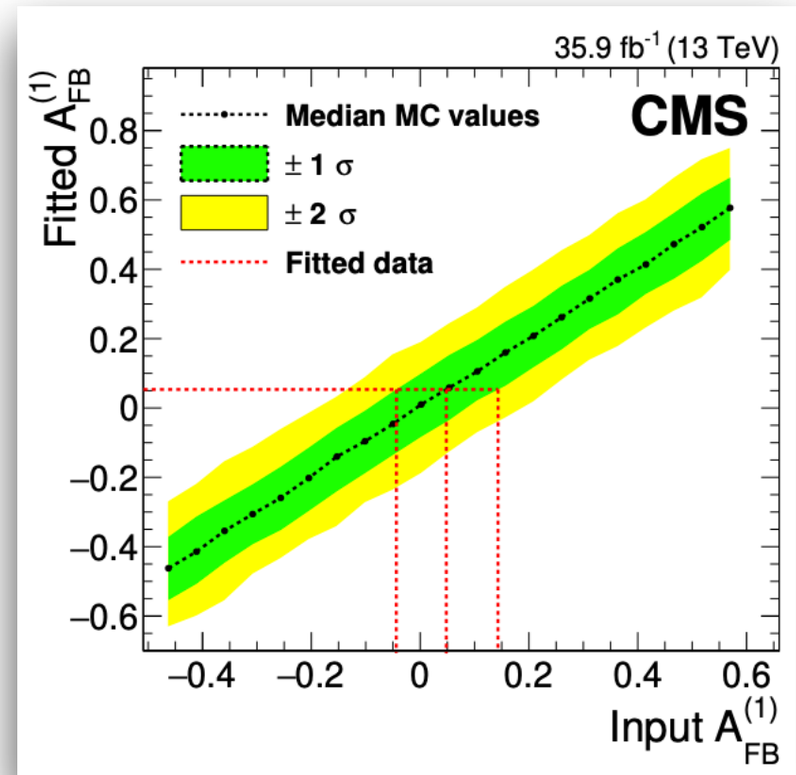


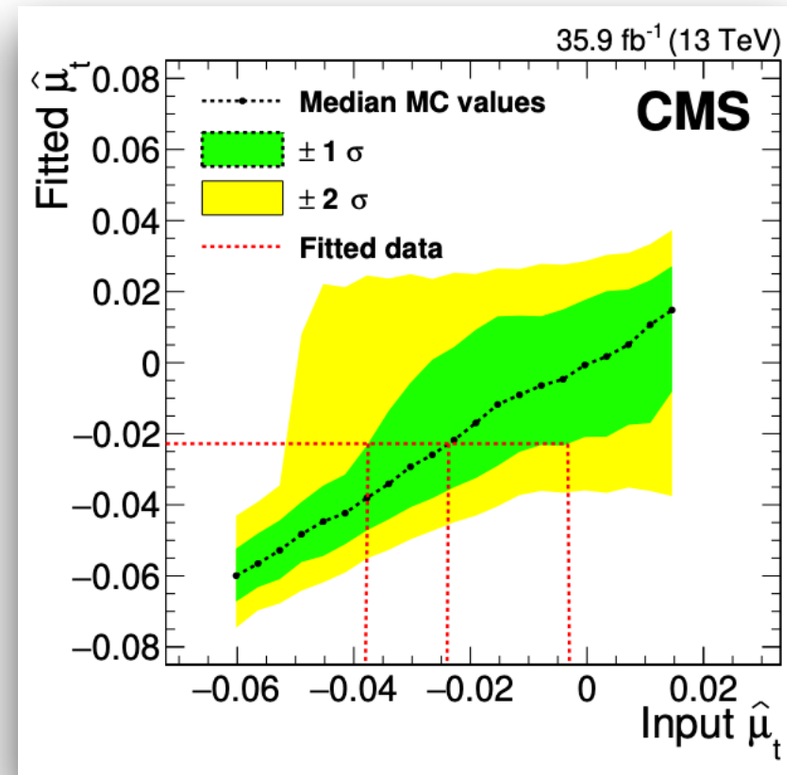
First measurement @LHC !

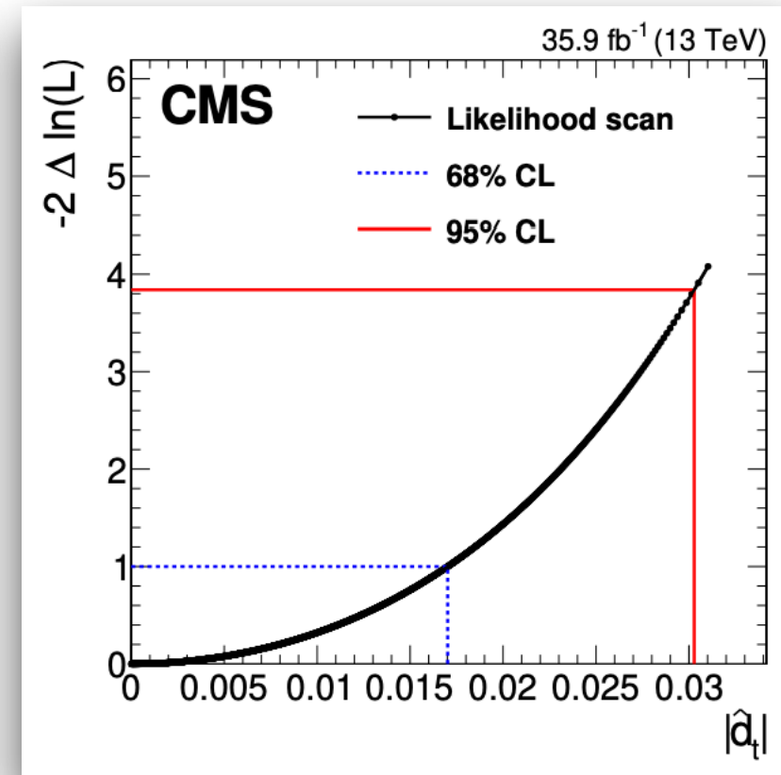
Top Forward-Backward Asymmetry

JHEP 06 (2020) 146

- Parameters independently extracted from a linear combination of the 3D templates fitted to data







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

$$\hat{\mu}_{\mathrm{t}} = -0.024^{+0.013}_{-0.009}\,(\mathrm{stat})^{+0.016}_{-0.011}\,(\mathrm{syst})$$

$$|\hat{d}_{\mathrm{t}}| < 0.03 \text{ at } 95\%\,\mathrm{C.L.}$$

- Values consistent with SM expectations and in good agreement with previous measurements like CMS spin correlation measurements in dilepton channel

Summary

- Several measurements of top quark properties with new Run2 data presented:
  - Spin correlations in $t\bar{t}$ production
    - new ATLAS+CMS comparison @13 TeV
  - ATLAS+CMS Run1 combination of W polarization
  - Top quark Yukawa coupling with full Run2 dataset
    - new decay channel + new reconstruction technique
  - Top quark mass:
    - from boosted quarks
      - new jet clustering technique
    - from multi differential cross sections
    - from inclusive cross sections
  - First investigation of top quark mass running
  - First direct measurement of CKM elements in single-top production and decay
  - First Forward-Backward asymmetry measurement in $t\bar{t}$

- Increased precision (up to NNLO+NLO EWK level) allowed by huge number of produced top quark events:
  - better understanding of top quark properties
  - constraints on new physics

- New results with full Run2 data coming soon!

Focus on a selection of recent results..
for other CMS results you can look here

BACKUP

Spin correlations: basis of spin quantization axes

Phys. Rev. D 100 (2019) 072002

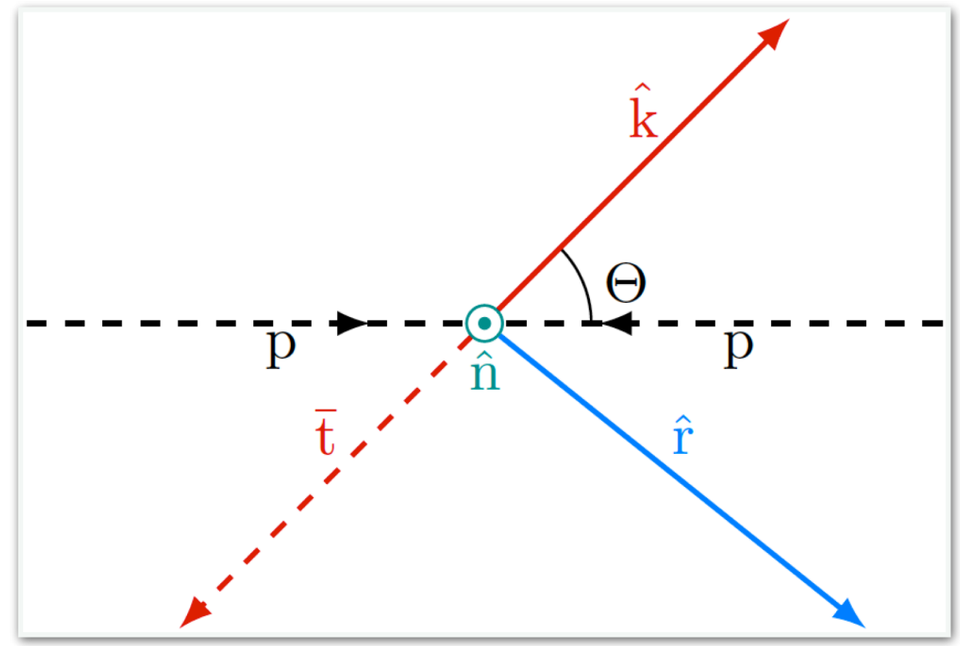
- B and C coefficients:
  - functions of $\sqrt{s}$ and of the top quark scattering angle
  - written in terms of **orthonormal basis** $\{\hat{k}, \hat{r}, \hat{n}\}$:
    - helicity $\hat{k}$-axis: top quark direction in ttbar rest frame
    - transverse $\hat{n}$-axis: transverse to production (ttbar scattering) plane

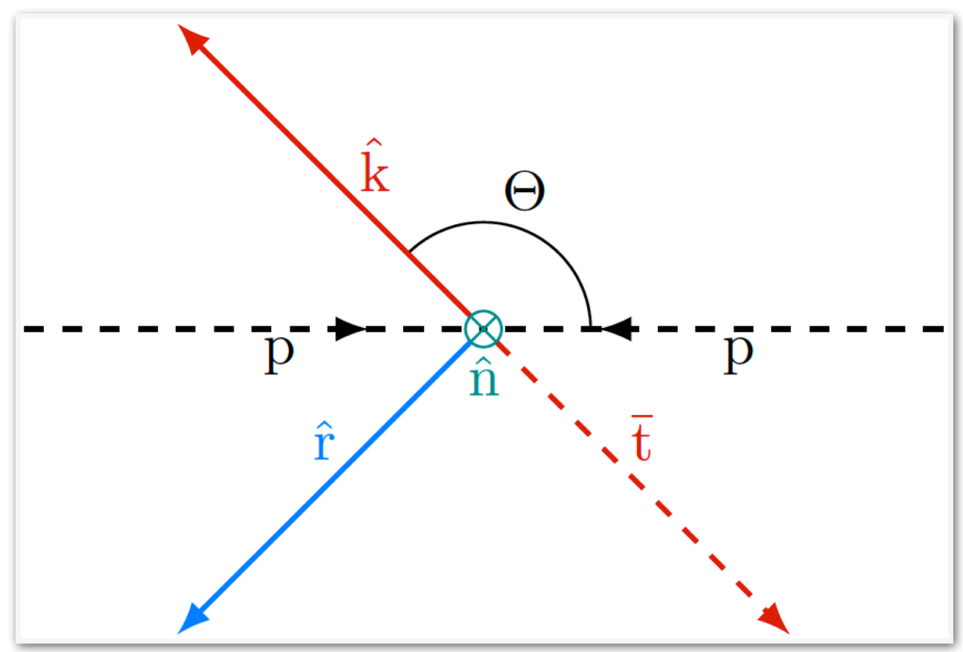
$$\hat{n} = \frac{sign(cos\Theta)}{sin\Theta}(\hat{p} \times \hat{k})$$

- $\hat{r}$-axis: orthogonal to the other 2 axes (normal to k in ttbar scattering plane)

$$\hat{r} = \frac{sign(cos\Theta)}{sin\Theta}(\hat{p} - \hat{k}cos\Theta)$$

- $\hat{p}$ = direction of the incoming parton, i.e. direction of the proton beam (z-direction in the laboratory frame)
- Θ = top quark scattering angle in ttbar rest frame



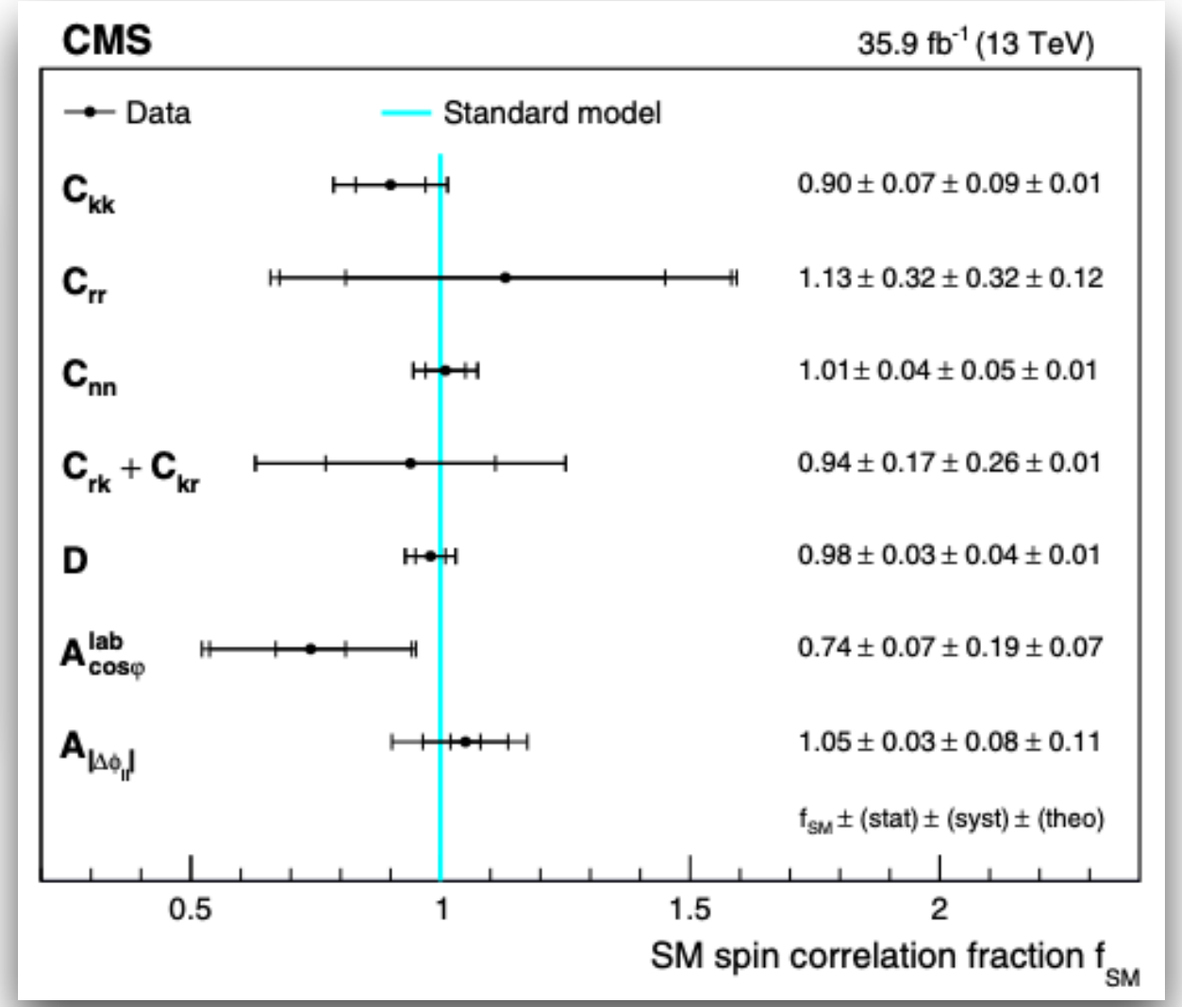


Spin correlations: extraction of f_{SM}

Phys. Rev. D 100 (2019) 072002

- f_{SM} = strength of the measured spin correlation relative to the SM prediction
  - f_{SM} = 1 for SM, 0 for uncorrelated events
  - values derived using the measured coefficients and NLO calculations
  - allows easy comparison of results between different variables (and between different experiments)

Coefficient	$f_{SM} \pm$ (stat) $\pm$ (syst) $\pm$ (theor)	Total uncertainty
C_{kk}	$0.90 \pm 0.07 \pm 0.09 \pm 0.01$	± 0.12
C_{rr}	$1.13 \pm 0.32 \pm 0.33^{+0.10}_{-0.13}$	$^{+0.47}_{-0.48}$
C_{nn}	$1.01 \pm 0.04 \pm 0.05 \pm 0.01$	± 0.06
$C_{rk} + C_{kr}$	$0.94 \pm 0.17 \pm 0.26 \pm 0.01$	± 0.31
D	$0.97 \pm 0.03 \pm 0.04^{+0.01}_{-0.02}$	± 0.05
$A^{\text{lab}}_{\cos\varphi}$	$0.74 \pm 0.07 \pm 0.22^{+0.06}_{-0.08}$	$^{+0.24}_{-0.25}$
$A_{\lvert\Delta\phi_{\ell\ell}\rvert}$	$1.10 \pm 0.04 \pm 0.09^{+0.10}_{-0.14}$	$^{+0.14}_{-0.17}$



D coefficient: most precise measurement to date (5% uncertainty)

Spin correlations: uncertainties

Phys. Rev. D 100 (2019) 072002

Table 3: Summary of the systematic uncertainties in the extracted top quark polarization coefficients.

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

Spin correlations: uncertainties

Phys. Rev. D 100 (2019) 072002

Table 4: Summary of the systematic uncertainties in the extracted $t\bar{t}$ spin correlation coefficients.

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

W polarization

arXiv:2005.03799
submitted to JHEP

- Limits on anomalous right-handed vector (VR), and left- and right-handed tensor (gL, gR) tWb couplings set while fixing all others to their SM values:

$$\mathcal{L}_{\mathrm{tWb}} = -\frac{g}{\sqrt{2}}\bar{\mathrm{b}}\,\gamma^{\mu}\,(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}})\,\mathrm{t}\,\mathrm{W}^{-}_{\mu} - \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\,\frac{i\sigma^{\mu\nu}\mathrm{q}_{\nu}}{m_{\mathrm{W}}}\,(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}})\,\mathrm{t}\,\mathrm{W}^{-}_{\mu} + \mathrm{h.c.}$$

0 in SM

	95% CL interval		
Coupling	ATLAS	CMS	ATLAS+CMS combination
$\mathrm{Re}(V_{\mathrm{R}})$	$[-0.17, 0.25]$	$[-0.12, 0.16]$	$[-0.11, 0.16]$
$\mathrm{Re}(g_{\mathrm{L}})$	$[-0.11, 0.08]$	$[-0.09, 0.06]$	$[-0.08, 0.05]$
$\mathrm{Re}(g_{\mathrm{R}})$	$[-0.03, 0.06]$	$[-0.06, 0.01]$	$[-0.04, 0.02]$

- Limits on corresponding Wilson coefficients:

$$-L^{\mathrm{eff}} = \mathcal{L}^{\mathrm{SM}} + \Sigma_x \frac{C_x}{\Lambda^2} O_x + \mathcal{O}\left(\frac{1}{\Lambda^3}\right) + \cdots$$

	95% CL interval		
Coefficient	ATLAS	CMS	ATLAS+CMS combination
$C^{*}_{\phi\phi}$	$[-5.64, 7.68]$	$[-3.84, 4.92]$	$[-3.48, 5.16]$
C^{*}_{bW}	$[-1.30, 0.96]$	$[-1.06, 0.72]$	$[-0.96, 0.67]$
C_{tW}	$[-0.34, 0.67]$	$[-0.62, 0.19]$	$[-0.48, 0.29]$

W polarization: uncertainties

- Uncertainty treatment harmonized between 2 collaborations
- Correlations between observables and between CMS & ATLAS studied in detail
  - drastic variation of correlation assumptions resulting in deviations covered by uncertainties of combined measurement

arXiv:2005.03799
submitted to JHEP

	ATLAS+CMS combination	
	F_0	F_L
Fractions	0.693	0.315
Uncertainty category		
Samples size and background determination		
Stat+bkg	0.009	0.006
Size of simulated samples	0.005	0.003
Detector modelling		
JES	0.004	0.002
JER	0.004	0.002
b tagging	0.001	0.001
JVF	0.001	0.001
Jet reconstruction	<0.001	<0.001
Lepton efficiency	0.002	0.001
Pileup	<0.001	<0.001
Signal modelling		
Top quark mass	0.003	0.004
Simulation model choice	0.006	0.005
Radiation and scales	0.005	0.004
Top quark p_T	0.001	0.002
PDF	0.001	0.001
Single top method	0.001	<0.001
Total uncertainty	0.014	0.011

Correlations within the same measurement

- ATLAS: from covariance matrix of each systematic uncertainty category
- CMS: $\rho(F_0, F_L) = \frac{\sigma^2[F_R] - \sigma^2[F_0] - \sigma^2[F_L]}{2\sigma[F_0]\sigma[F_L]}$

Correlations between the ATLAS and CMS experiments $\rho_{LHC}(F_i,F_j)$

- Assuming: $\rho_{LHC}(F_0,F_0) = \rho_{LHC}(F_L,F_L)$ and $\rho_{LHC}(F_0,F_L) = -\rho_{LHC}(F_0,F_0)$
- Detector modelling, JER, data-driven background estimation and method-specific uncertainty ➜ uncorrelated, $\rho_{LHC}(F_0,F_0)= 0$
- Radiation & scales, JES ➜ partially correlated, $\rho_{LHC}(F_0,F_0)= 0.5, 0.2$
- All other sources ➜ fully correlated, $\rho_{LHC}(F_0,F_0)= +1$

Correlations between measurements within the CMS experiment

- Assuming $\rho_{CMS}(F_i,F_j)_{(st,\ e+jets)} = \rho_{CMS}(F_i,F_j)_{(st,\ mu+jets)} = \rho_{CMS}(F_i,F_j)_{(st,\ l+jets)}$
- In all cases: assuming $\rho_{CMS}(F_0,F_0) = \rho_{CMS}(F_L,F_L)$ and $\rho_{CMS}(F_0,F_L) = -\rho_{CMS}(F_0,F_0)$
- Data statistics, background estimation, lepton efficiency, MC statistics ➜ uncorrelated
- All other sources ➜ fully correlated

Top Yukawa coupling: multiplicative corrections

CMS-PAS-TOP-19-008

- The full expression for the EW multiplier R_{EW} used in the fit, including the associated uncertainty, it

$$R_{\mathrm{EW}}^{\mathrm{bin}}(Y_{\mathrm{t}}, \phi) = (1 + \delta_{\mathrm{EW}}^{\mathrm{bin}}(Y_{\mathrm{t}})) \times (1 + \delta_{\mathrm{QCD}}^{\mathrm{bin}} \delta_{\mathrm{EW}}^{\mathrm{bin}}(Y_{\mathrm{t}}))^{\phi},$$

where $\delta_{\mathrm{QCD}}^{\mathrm{bin}} \delta_{\mathrm{EW}}^{\mathrm{bin}}$ represents the cross term arising from the difference in multiplicative and additive approaches. Specifically,

$$\delta_{\mathrm{EW}} = (K_{\mathrm{EW}}^{\mathrm{NLO}}(Y_{\mathrm{t}}) - 1) \longrightarrow \delta_{\mathrm{EW}}^{\mathrm{bin}} = \frac{n_{\mathrm{HATHOR}}^{\mathrm{bin}} - n_{\mathrm{LO}}^{\mathrm{bin}}}{n_{\mathrm{LO}}^{\mathrm{bin}}}$$

$$\delta_{\mathrm{QCD}} = \frac{\Sigma_{\mathrm{POWHEG}} - \Sigma_{\mathrm{LO\ QCD}}}{\Sigma_{\mathrm{POWHEG}}} \longrightarrow \delta_{\mathrm{QCD}}^{\mathrm{bin}} = \frac{n_{\mathrm{POWHEG}}^{\mathrm{bin}} - n_{\mathrm{LO}}^{\mathrm{bin}}}{n_{\mathrm{POWHEG}}^{\mathrm{bin}}}$$

- The uncertainty term is included only in the sensitive region where virtual Higgs exchange enhances $\mathrm{t\bar{t}}$ production.

Top Yukawa coupling: systematic uncertainties

Phys. Rev. D 100 (2019) 072007

- JEC split into 19 independent sources → dominant experimental uncertainty
- QCD shape uncertainty derived by b-tagging inversion → larger and higher impact uncertainties for 3 jets channel

Uncertainty	$t\bar{t}$	Single t	V + jets	QCD multijet
Integrated luminosity	2.5%	2.5%	2.5%	2.5%
Pileup	0–1%	0–1%	···	···
Lepton identification/trigger	1.9%	1.9%	1.9%	···
JEC	0–5%	0–5%	···	···
JER	0–0.6%	···	···	···
b tag scale factor	3%	3%	2–3%	···
b mistag scale factor	0.5%	1%	3–6%	···
Background normalization	···	15%	30%	30%
QCD multijet CR definition	···	···	···	0–60%
Factorization and renormalization scales	0–6%	2–5%	0–15%	···
PDF	0.5–1.5%	0.5–1.5%	···	···
$\alpha_S(m_Z)$ in PDFs	1%	1.5%	···	···
Top quark mass	1–5%	···	···	···
Top quark p_T modeling	0–0.5%	···	···	···
Parton shower				
-NLO shower matching	1.5–5%	···	···	···
-ISR	2–3%	···	···	···
-FSR	0–9%	0–12%	···	···
-Color reconnection	0–3%	···	···	···
-b jet fragmentation	0–3%	0–5%	···	···
-b hadron branching fraction	3%	2.5–3%	···	···
Weak correction $\delta_{QCD}\delta_W$	0–0.2% ($Y_t = 2$)	···	···	···

Top Yukawa coupling: systematic uncertainties

CMS-PAS-TOP-19-008

- Very similar to those of previous measurement
- Main differences:
  - lack of QCD multijet background
  - use of full Run 2 data

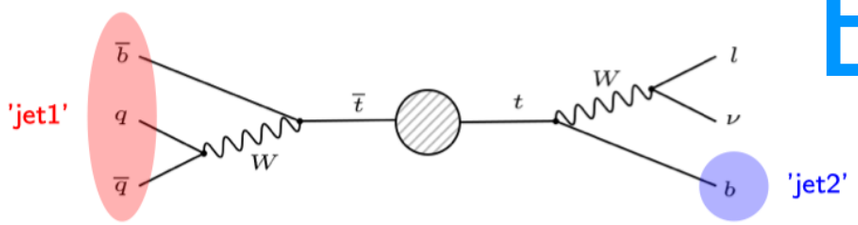
- Correlations
  - full or partial correlations are imposed on nuisance parameters between data-taking periods where appropriate

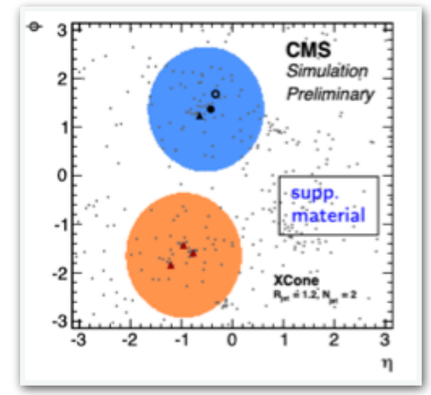
- Dominant uncertainties:
  - EW correction uncertainty
  - ISR, FSR
  - ME scale variations (RS, FS)
  - JES

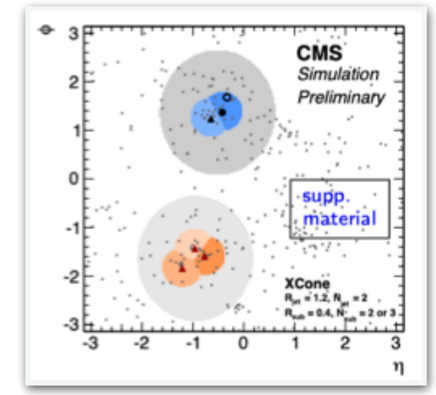
Uncertainty:	type
EW correction uncertainty	signal shape modifier
signal & background cross sections	normalization
ME scale variations	shape
b fragmentation, b decay	shape
pdf uncertainties	mostly shape
ISR, FSR	shape
top mass	shape
hdamp, MC tune	normalization*
btag SFs, lepton SFs	shape
lumi	shape
pileup	shape
prefire corrections	shape
JER	shape
JES	mostly shape

Boosted mass

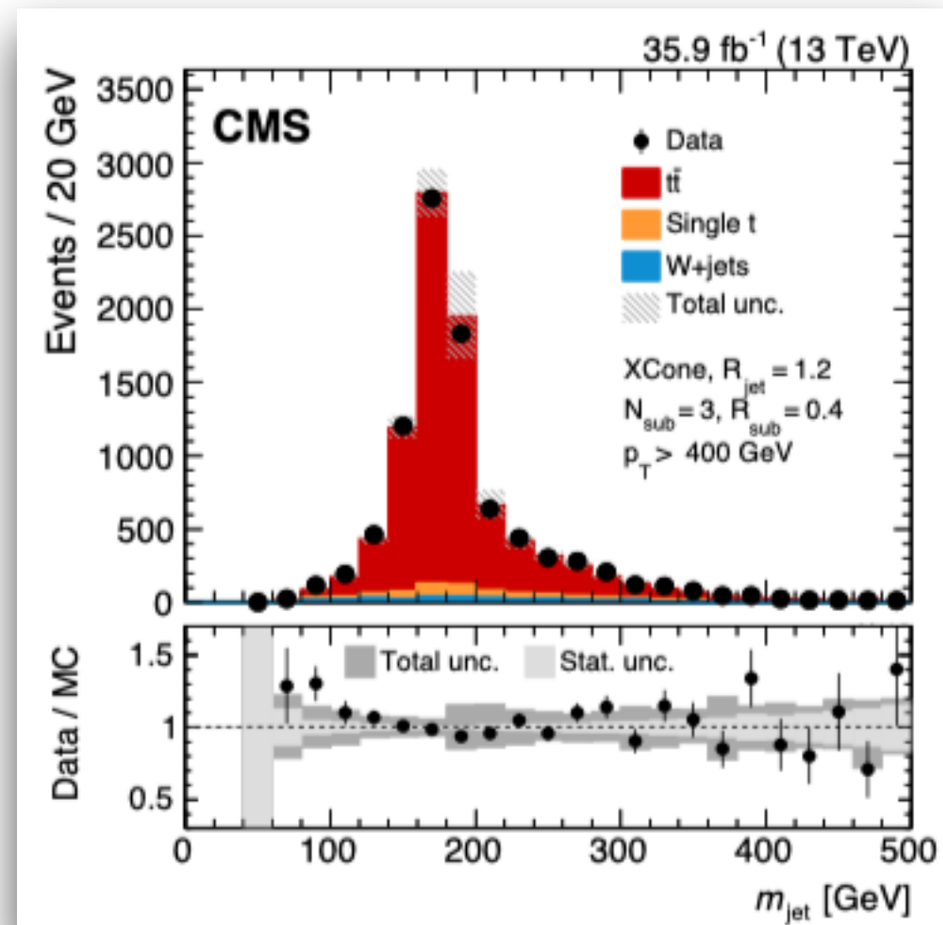
Phys. Rev. Lett. 124, 202001 (2020)







- Novel jet reconstruction technique, 2-step XCone jet clustering procedure:
  - find 2 jets with large radius R=1.2 (corresponding to 2 boosted top quarks)
    - calculate ΔR(lep, jet) for both jets
    - lowest ΔR → leptonic jet; other → hadronic jet
  - find subjets using R=0.4
    - four-momenta of subjets combined to form final jet
- Procedure results in:
  - 2 large-radius XCone jets (pT > 400 GeV) with 3 XCone subjets each (pT > 30 GeV)
  - narrow particle-level width and excellent mjet resolution
  - high performance reconstructing the top quark decay
- XCone on detector level:
  - no JEC for XCone available
  - derive additional correction on top of AK4 JEC in all had t ¯t
  - correction applied dependent on pT and η of subjets
  - improvement:
    - better statistics
    - no mass shift (peak around mt)
    - less pile-up effects (mjet stable against PU)
    - better mass resolution (~6%)



Boosted mass: uncertainties

Phys. Rev. Lett. 124, 202001 (2020)

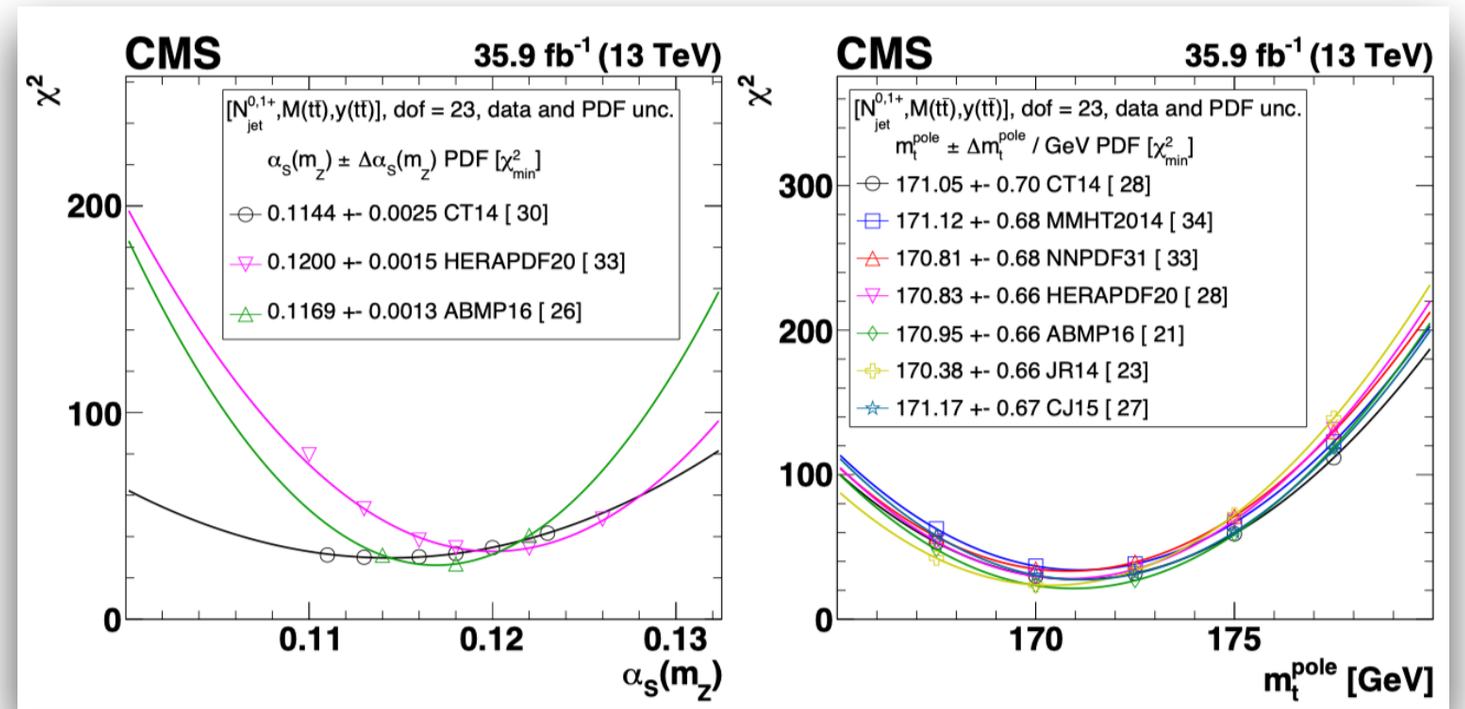
- Experimental uncertainties:
  - JEC, JER, XCone additional correction, lepton ID, lepton Trigger, b-tagging, PU
- Model uncertainties: scales μr, μf, ISR, FSR, hdamp, UE, choice of mtop, pdf
- Other uncertainties:
  - statistics
  - background rates
  - luminosity 2.5% on every bin
- Limiting uncertainty: jet mass scale

source	uncertainty [GeV]
Total uncertainty	2.47
Statistical uncertainty	0.44
Experimental uncertainty	1.57
jet energy scale	1.52
jet energy resolution	0.48
XCone jet correction	0.45
Model uncertainty	1.55
FSR	1.17
CR	0.66
UE tune	0.51
choice of mtop	0.48
Theoretical uncertainty	1.02
CR	0.74
FSR	0.51

Mass from multidifferential

arXiv:1904.05237
submitted to Eur. Phys. J.

- Simultaneous fit of PDF+αS+mtpole at NLO + HERA DIS data
  - extraction of αS, mtpole as minimum of parabola modelling χ2 between data and NLO predictions as a function of the input αS(mZ) or mtpole value using different PDF sets and scale values
  - uncertainty estimated from the Δχ2 =1 variation



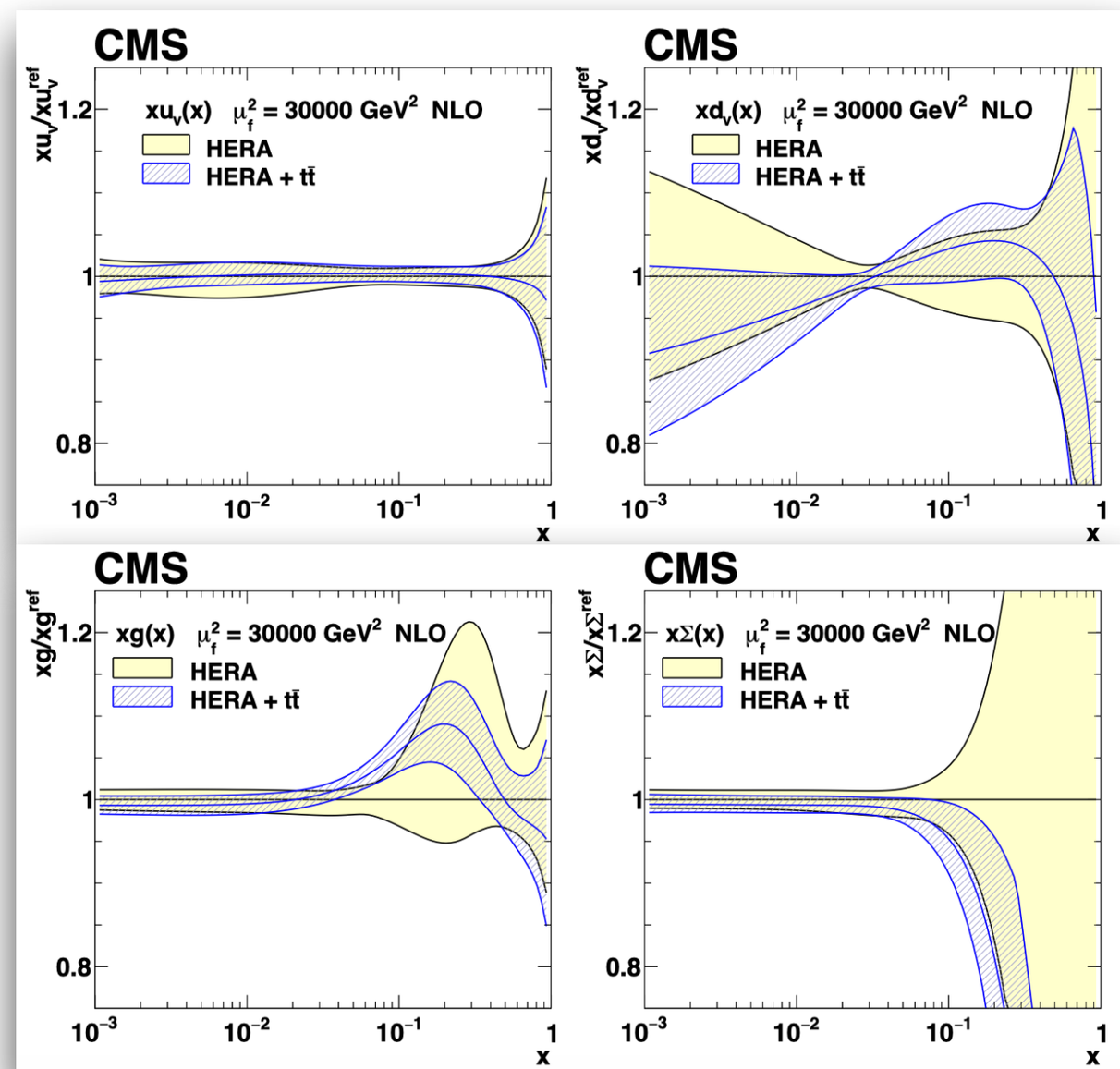
PDF set	$\alpha_S(m_Z)$
CT14	$0.1144 \pm 0.0016(\text{fit}) \pm 0.0019(\text{PDF})^{+0.0020}_{-0.0016}(\mu)^{+0.0019}_{-0.0011}(m_t^{\text{pole}})$
HERAPDF2.0	$0.1200 \pm 0.0014(\text{fit}) \pm 0.0007(\text{PDF})^{+0.0011}_{-0.0012}(\mu)^{+0.0007}_{-0.0009}(m_t^{\text{pole}})$
ABMP16	$0.1169 \pm 0.0009(\text{fit}) \pm 0.0010(\text{PDF})^{+0.0008}_{-0.0007}(\mu)^{+0.0006}_{-0.0006}(m_t^{\text{pole}})$

PDF set	m_t^{pole} [GeV]
CT14	$171.1 \pm 0.7(\text{fit}) \pm 0.2(\text{PDF})^{+0.4}_{-0.4}(\mu)^{+0.1}_{-0.1}(\alpha_S)$
HERAPDF2.0	$170.8 \pm 0.6(\text{fit}) \pm 0.1(\text{PDF})^{+0.3}_{-0.3}(\mu)^{+0.1}_{-0.1}(\alpha_S)$
ABMP16	$170.9 \pm 0.7(\text{fit}) \pm 0.1(\text{PDF})^{+0.4}_{-0.3}(\mu)^{+0.2}_{-0.2}(\alpha_S)$

Mass from multidifferential

arXiv:1904.05237
submitted to Eur. Phys. J.

- Impact on PDFs:
  - significant on gluon PDF at large values of x
  - a reduction of uncertainties is observed for the gluon distribution, especially at x ~ 0.1 where the included tt data are expected to provide constraints, while the improvement at x . 0.1 originates mainly from the reduced correlation between αS (mZ) and the gluon PDF



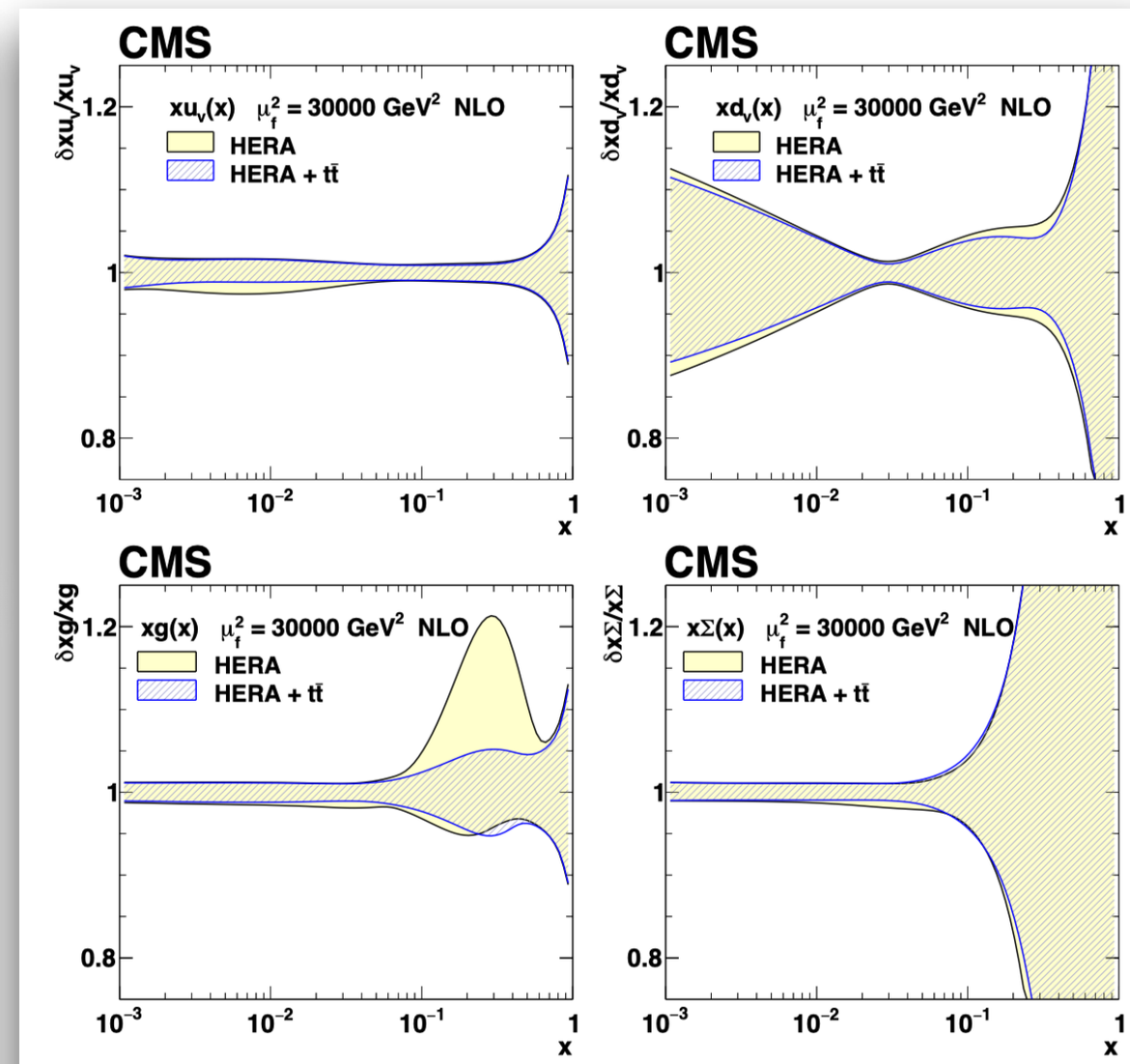


Figure 23: The relative total PDF uncertainties in the fit using the HERA DIS data only, and the HERA DIS and $t\bar{t}$ data.

Running of top mass

Phys. Lett. B 803 (2020) 135263

- Beyond leading order in perturbation theory, the fundamental parameters of the quantum chromodynamics (QCD) Lagrangian, i.e. the strong coupling constant αS and the quark masses, are subject to renormalization
- As a result, these parameters depend on the scale at which they are evaluated

- Numerical values of extracted masses:
  - experimental uncertainty only

scale μ [GeV]	$m_t(m_t)$ [GeV]	$m_t(\mu)$ [GeV]
384.0	$164.41^{+0.75}_{-0.77}$	$155.44^{+0.75}_{-0.78}$
476.2	$161.9^{+3.0}_{-3.0}$	$150.9^{+2.9}_{-3.0}$
644.3	$162.0^{+4.7}_{-4.8}$	$148.2^{+4.6}_{-4.7}$
1024	$153.6^{+9.7}_{-9.3}$	$136.4^{+9.2}_{-8.8}$

running of α_S is described by renormalization group equation (RGE)

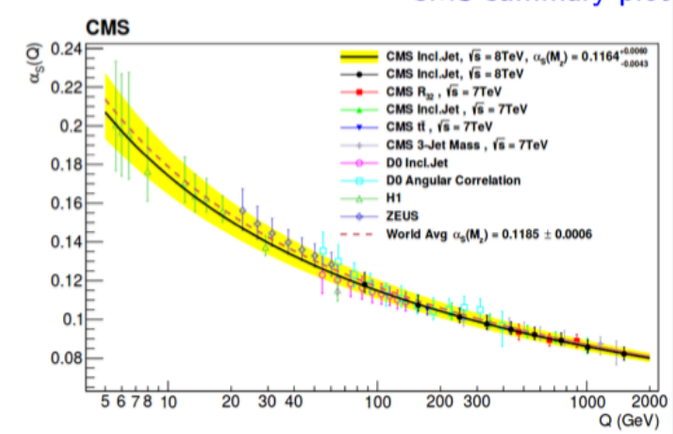
$$\alpha_S(\mu) = \frac{\alpha_S(\mu_0)}{\alpha_S(\mu_0)\frac{11N_c-2N_f}{12\pi}\ln\frac{\mu^2}{\mu_0^2}} \quad \text{(NLO)}$$

typical procedure to measure α_S running:

- extract $\alpha_S(m_Z)$ from some final state observable in limited scale range (e.g. μ = jet p_T)
- convert $\alpha_S(m_Z)$ to $\alpha_S(\mu)$ using RGE, w. appropriate choice of μ in each bin

N.B. this is equivalent to extracting $\alpha_S(\mu)$ directly (RGE implicitly assumed)

CMS summary plot



- **well-established procedure**
- experimentally verified on a very wide range of scales, at different experiments

Phys. Lett. B775 (2017)

- similar procedure can be used to extract running of heavy quark masses

short distance $\overline{\text{MS}}$ mass can be expressed in terms of pole mass

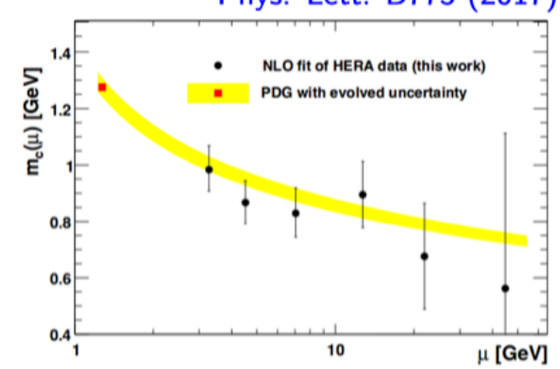
$$m_q(m_q) = m_q^{\text{pole}}\left[1 - \tfrac{4}{3\pi}\alpha_S(m_q) + \mathcal{O}(\alpha_S^2)\right]$$

and evolved to an arbitrary scale μ

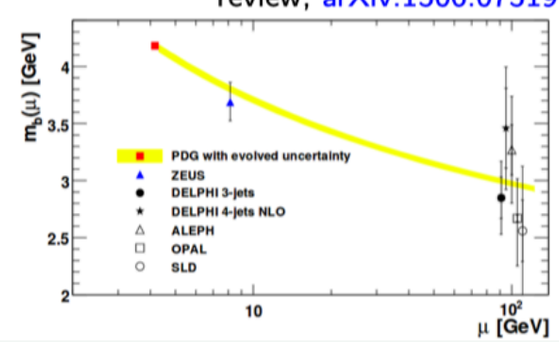
$$m_q(\mu) = m_q(m_q)\left[1 - \frac{\alpha_S(\mu)}{\pi}\ln\frac{\mu^2}{m_q^2} + \mathcal{O}(\alpha_S^2)\right]$$

- running of m_c has been experimentally determined at HERA experiments
- running of m_b determined with data from different experiments

→ **goal: determine running of m_t** using LHC data at 13 TeV



review, arXiv:1506.07519



Running of top mass

Phys. Lett. B 803 (2020) 135263

- Dominant uncertainties in the measured σ tt μ k are associated with the integrated luminosity, the lepton identification efficiencies, the jet energy scales and, at large mtt, the modelling of the top quark pT
- Additional uncertainty (≃ 1%) due to statistical fluctuations in templates
- Total uncertainty ~4-5%

Source	Uncertainty [%]
Jet energy scale	1.0
PDF	1.1
Lepton ID/isolation	2.2
Electron energy	0.5
b quark fragmentation	1.1
b tagging	0.2
Colour reconnection	0.7
Kinematic reconstruction	0.4
DY ME scale	0.4
Jet energy resolution	0.2
Muon energy scale	0.1
Pile-up	0.5
tW FSR scale	0.2
tW ISR scale	0.2
tW ME scale	0.2
m_t^{MC}	0.5
Top quark p_T	0.7
Trigger	0.3
b hadron BF	0.1
$t\bar{t}$ FSR scale	0.7
$t\bar{t}$ ISR scale	0.3
ME/PS matching	0.2
$t\bar{t}$ ME scale	0.3
UE tune	0.3
DY background	0.9
tW background	0.6
W+jets background	0.1
Diboson background	0.6
$t\bar{t}$ background	0.3
Integrated luminosity	2.6
Statistical	0.7
MC statistical	1.5
Extrapolation uncertainties	
$t\bar{t}$ ISR scale	± 0.2
$t\bar{t}$ FSR scale	± 0.1
$t\bar{t}$ ME scale	± 0.1
UE tune	$\mp^{<0.1}_{0.1}$
PDF	$\pm^{0.8}_{0.5}$
Top quark p_T	$\pm^{<0.1}_{0.1}$
Total $\sigma_{t\bar{t}}^{(\mu_1)}$ uncertainty	$^{+4.7}_{-4.4}$

Top CKM elements

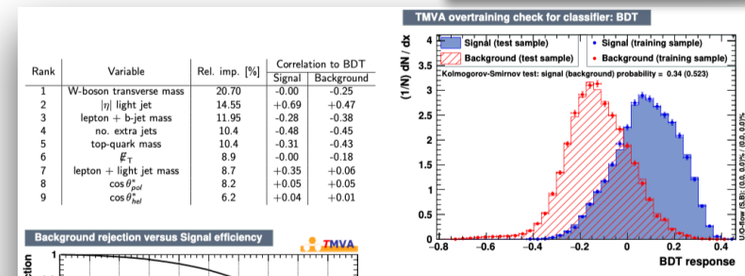
Phys. Lett. B 808 (2020) 135609

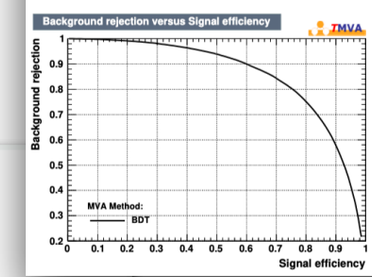
- Multivariate discrimination between signal and background processes
  - BDT discriminant trained for each category

2-jets–1-tag

- j' defined as the non b-tagged jet
- QCD sample depleted with $m_{\mathrm{T}}^{\mathrm{W}} > 50$ GeV requirement
- BDT training: single top t-channel ($ST_{(\mathrm{b,b})}$) vs $\mathrm{t\bar{t}}$ and $\mathrm{W}+\mathrm{jets}$

Rank	Variable	Rel. imp. [%]	Correlation to BDT Signal	Correlation to BDT Background
1	W-boson transverse mass	20.70	-0.00	-0.25
2	$\lvert\eta\rvert$ light jet	14.55	+0.69	+0.47
3	lepton + b-jet mass	11.95	-0.28	-0.38
4	no. extra jets	10.4	-0.48	-0.45
5	top-quark mass	10.4	-0.31	-0.43
6	$\not{E}_{\mathrm{T}}$	8.9	-0.00	-0.18
7	lepton + light jet mass	8.7	+0.35	+0.06
8	$\cos\theta^*_{pol}$	8.2	+0.05	+0.05
9	$\cos\theta^*_{hel}$	6.2	+0.04	+0.01





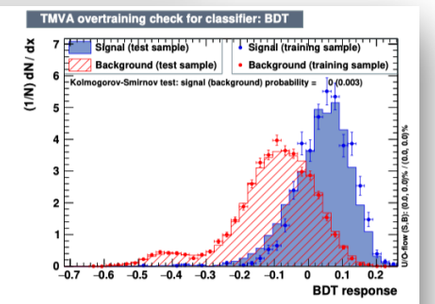
Summary

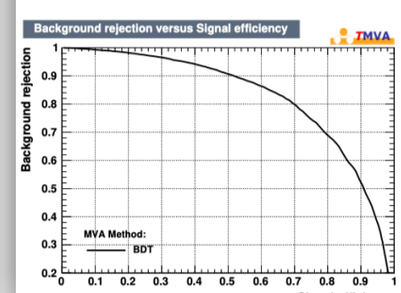
Sample	Training
t-channel	40000
$\mathrm{t\bar{t}}$	40000
$\mathrm{W}+\mathrm{jets}$ (W+2jets)	20000
ROC-Integral	0.856

3-jets-1-tag

- j' defined as the most forward non b-tagged jet
- signal region $m_{\mathrm{T}}^{\mathrm{W}} > 50$ GeV & $|\eta_{j'}| > 2.5$
- BDT training: single top t-channel with $|\mathrm{V_{tq}}|^2$ vertex in decay ($ST_{(\mathrm{b,q})}$) vs single top t-channel ($ST_{(\mathrm{b,b})}$), standard $\mathrm{t\bar{t}}$ and $\mathrm{W}+\mathrm{jets}$

Rank	Variable	Rel. imp. [%]	Correlation to BDT Signal	Correlation to BDT Background
1	CMVA extra jet	9.2	-0.41	-0.61
2	W-boson transverse mass	8.6	-0.06	-0.15
3	$\not{E}_{\mathrm{T}}$	8.4	-0.15	-0.11
4	$\cos\theta^*_{hel}$	8.3	+0.17	+0.05
5	$\lvert\eta\rvert$ light jet	7.6	+0.33	+0.08
6	top-quark mass extra	7.1	-0.29	-0.18
7	no. extra jets	7.1	-0.39	-0.21
8	$\cos\theta^*_{pol}$	6.9	+0.16	+0.14
9	lepton + extra jet mass	6.9	-0.23	-0.19
10	$\cos\theta^*_{pol}$ extra	6.6	+0.09	+0.22
11	lepton + light jet mass	6.0	+0.15	-0.07
12	lepton + b-jet mass	6.0	+0.10	+0.07
13	$\cos\theta^*_{hel}$ extra	5.9	+0.01	-0.06
14	top-quark mas	5.4	+0.04	+0.07





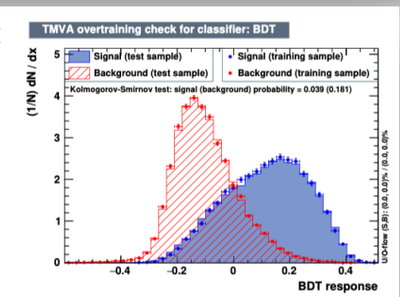
Summary

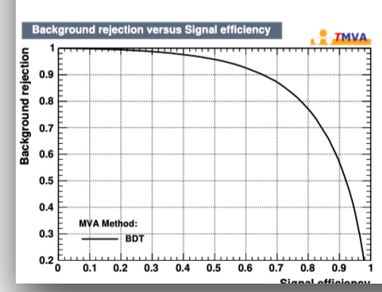
Sample	Training
t-channel sd decay	4000
t-channel	30000
$\mathrm{t\bar{t}}$	40000
$\mathrm{W}+\mathrm{jets}$ (W+2jets)	8000
ROC-Integral	0.827

3-jets–2-tags

- j' defined as the non b-tagged jet
- BDT training: single top t-channel ($ST_{(\mathrm{b,b})}$) vs $\mathrm{t\bar{t}}$

Rank	Variable	Rel. imp. [%]	Correlation to BDT Signal	Correlation to BDT Background
1	$\lvert\eta\rvert$ light jet	12.0	+0.77	+0.66
3	lepton + light jet mass	9.3	+0.38	+0.26
2	W-boson transverse mass	9.2	-0.06	+0.26
4	no. extra jets	9.1	-0.47	-0.43
5	$\cos\theta^*_{pol}$ second	7.0	+0.20	+0.14
6	$\lvert\Delta\eta_{b-b}\rvert$	6.9	+0.02	-0.02
7	$\cos\theta^*_{hel}$ leading	6.7	+0.11	+0.06
8	top-quark mass leading	6.6	-0.04	+0.01
9	lepton + second b-jet mass	6.6	-0.00	-0.13
10	lepton + leading b-jet mass	6.4	+0.01	-0.00
11	top-quark mass second	5.2	-0.03	-0.06
12	$\cos\theta^*_{pol}$ leading	5.2	+0.11	+0.11
13	$\cos\theta^*_{hel}$ second	5.0	-0.07	+0.03
14	$\not{E}_{\mathrm{T}}$	4.9	-0.036	-0.10





Summary

Sample	Training
t-channel	20000
$\mathrm{t\bar{t}}$	40000
ROC-Integral	0.863

Top CKM elements

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- Systematic uncertainties
  - Profiled = treated as nuisance parameters and profiled in the fit procedure
  - Nonprofiled = estimated as the difference between the result of the fit procedure by varying the systematic scenario

Table 4: The sources and relative values in percent of the systematic uncertainty in the measurement of the $ST_{b,b}$ cross section. The uncertainties are broken up into profiled and nonprofiled sources.

Treatment	Uncertainty	$\Delta\sigma_{ST_{b,b}}/\sigma$ (%)
Profiled	Lepton trigger and reconstruction	0.50
	Limited size of simulated event samples	3.13
	$t\bar{t}$ modelling	0.66
	Pileup	0.35
	QCD background normalisation	0.08
	W+jets composition	0.13
	Other backgrounds μ_R/μ_F	0.44
	PDF for background processes	0.42
	b tagging	0.73
	Total profiled	3.4
Nonprofiled	Integrated luminosity	2.5
	JER	2.8
	JES	8.0
	PDF for signal process	3.8
	Signal μ_R/μ_F	2.4
	ME-PS matching	3.7
	Parton shower scale	6.1
	Total nonprofiled	11.5
Total uncertainty		12.0

Top Forward-Backward Asymmetry: event type

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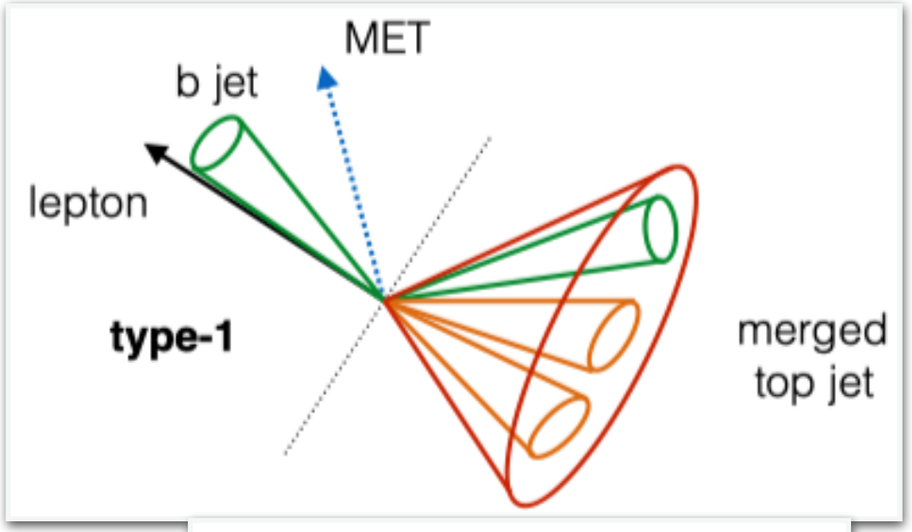
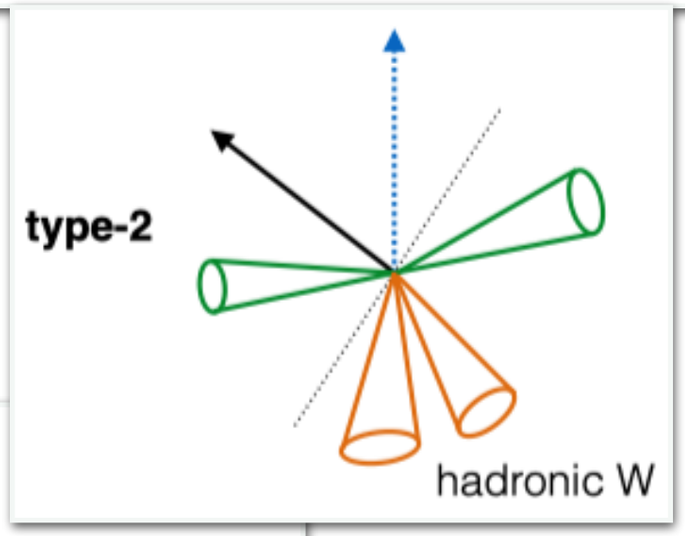
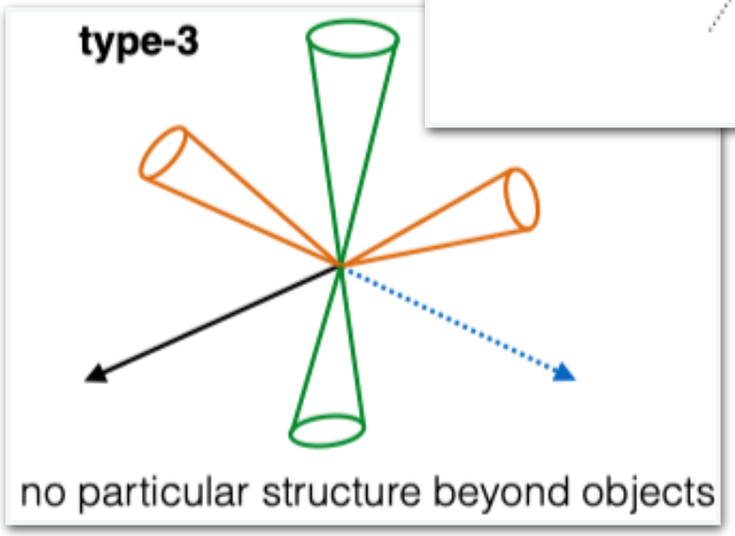
- Semileptonic top pair decays:
  - use lepton charge to tag top vs. antitop direction
  - greater sensitivity and higher qqbar fraction at higher momentum (large |xF|)
- Type-1: boosted, fully merged
  - non-isolated leptons
  - 1 fat top-tagged jet (high Lorentz boost in which the decay products of the hadronic top quark are fully merged into a single jet)
  - hemispheric separation
- Type-2: boosted, untagged
  - non-isolated leptons
  - untagged (but heavy) fat jet
  - reconstruction only uses small jets
- Type-3: resolved
  - isolated leptons
  - no hemispherical separation
  - only small (low-mass) jets
- In total 20 analysis channels:
  - 2 lepton flavors, both split based on charge
  - 3 decay topologies with orthogonal selections
  - 2 boosted topologies include background CRs







Top Forward-Backward Asymmetry: uncertainties

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Source	Uncertainty in	Type	Size	Affects
Jet energy scale	$\pm 1\sigma(p_T, \eta, A)$	N & S	7.6%	All
Jet energy resolution	$\pm 1\sigma(\lvert\eta\rvert)$	N & S	3.2%	All
Pileup	$\pm 1\sigma(n_{PV})$	N & S	2.9%	All
Boosted μ+jets trigger eff.	$\pm 1\sigma(p_T, \eta)$	N & S	0.4%	Type-1/2 μ+jets
Resolved μ+jets trigger eff.	$\pm 1\sigma(p_T, \eta)$	N & S	0.1%	Type-3 μ+jets
Boosted e+jets trigger eff.	$\pm 1\sigma(p_T, \lvert\eta\rvert)$	N & S	18.6%	Type-1/2 e+jets
Resolved e+jets trigger eff.	$\pm 1\sigma(p_T, \eta)$	N & S	2.5%	Type-3 e+jets
Muon ident. eff.	$\pm 1\sigma(p_T, \lvert\eta\rvert, n_{PV})$	N & S	0.4%	All μ+jets
Muon PF isolation eff.	$\pm 1\sigma(p_T, \lvert\eta\rvert, n_{PV})$	N & S	0.2%	Type-3 μ+jets
Electron ident. eff.	$\pm 1\sigma(p_T, \lvert\eta\rvert)$	N & S	1.0%	All e+jets
b tag eff., b jets (loose)	$\pm 1\sigma(p_T, \eta)$	N & S	2.5%	Type-1/2
b tag eff., c jets (loose)	$\pm 1\sigma(p_T, \eta)$	N & S	1.2%	Type-1/2
b tag eff., light jets (loose)	$\pm 1\sigma(p_T, \eta)$	N & S	6.3%	Type-1/2
b tag eff., b jets (medium)	$\pm 1\sigma(p_T, \eta)$	N & S	1.9%	Type-3
b tag eff., c jets (medium)	$\pm 1\sigma(p_T, \eta)$	N & S	0.8%	Type-3
b tag eff., light jets (medium)	$\pm 1\sigma(p_T, \eta)$	N & S	1.2%	Type-3
t tag eff. (merged)	$\pm 1\sigma(p_T)$	N & S	1.6%	Type-1
t tag eff. (semimerged)	$\pm 1\sigma(p_T)$	N & S	2.2%	Type-1
t tag eff. (not merged)	$\pm 1\sigma(p_T)$	N & S	2.8%	Type-1
ISR scale	$\pm 1\sigma$	N & S	2.2%	$t\bar{t}$
FSR scale	$\pm 1\sigma$	N & S	2.6%	$t\bar{t}$
ME-PS matching (h_{damp})	$\pm 1\sigma$	N & S	2.5%	$t\bar{t}$
CUETP8M2T4 tune	$\pm 1\sigma$	N & S	2.4%	$t\bar{t}$
Color reconnection	$\pm 1\sigma$	S	2.8%	$t\bar{t}$
b fragmentation	$\pm 1\sigma(x_b)$	N & S	3.7%	$t\bar{t}$
b branching fraction	$\pm 1\sigma$	N & S	1.0%	$t\bar{t}$
Top quark p_T reweighting	$\pm 1\sigma(p_T^{gen,t}, p_T^{gen,\bar{t}})$	S	2.5%	$t\bar{t}$
PDF/α_S variation	NNPDF 3.0	S	1.5%	$t\bar{t}$
Renormalization scale μ_R	$\frac{1}{2}\mu_R \to 2\mu_R$	S	2.6%	$t\bar{t}$
Factorization scale μ_F	$\frac{1}{2}\mu_F \to 2\mu_F$	S	1.5%	$t\bar{t}$
Combined μ_R/μ_F scale	$\frac{1}{2} \to 2(\mu_R$ and $\mu_F)$	S	3.8%	$t\bar{t}$ MC
Integrated luminosity	$\pm 2.5\%$	N	—	All
$R_{q\bar{q}}$	$\pm 1\%$	N & S	—	All f_{qp*}/f_{qm*}
R_{W+jets}	$\pm 10\%$	N	—	All W+jets MC
$R_{QCD}^{t/C/R}$ (20 params total)	$\pm 1\sigma$ (stat)	N	—	Multijet