Beyond Standard Model Top Quark Interactions
— Anomalous Couplings —

Top Workshop 2020
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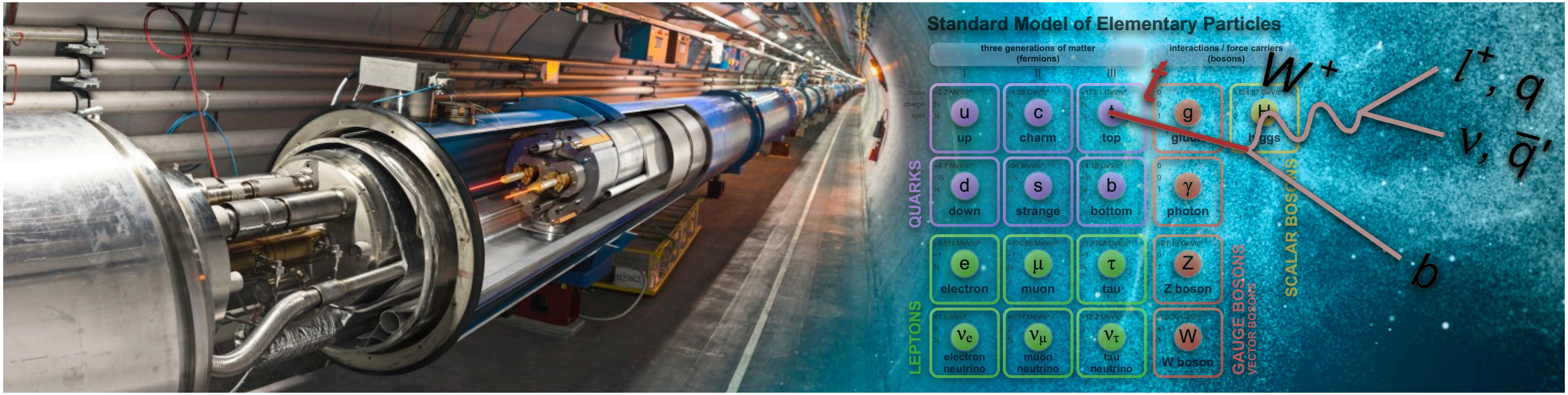
on behalf of the ATLAS and CMS collaborations



ATLAS EXPERIMENT

CMS

YORK UNIVERSITÉ UNIVERSITY

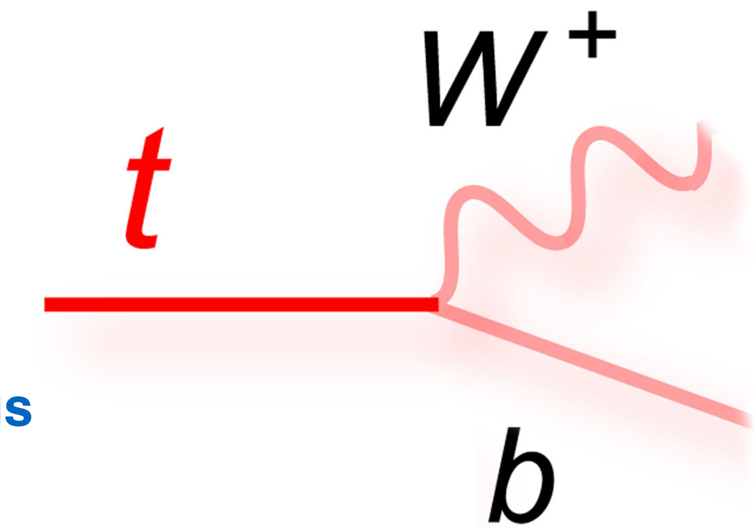
Outline

Top Quark Interactions

- Probing **Wtb** structure
  - W boson polarization
  - Triple-differential angular decay rate
- Searching for **new decay vertex** or modified **Wtb** structure
  - Polarization and spin correlation
- Probing **ttg** structure
  - Forward-backward Production Asymmetry
  - CP violating anomalous top quark couplings
- Probing **top - u/c quark** and **neutral boson** coupling (FCNC in top quark)
  - Search for $t \to q\gamma$
  - Search for $t \to qZ$
  - Search for $t \to qH$

The Wtb Vertex

- The top quark decay vertex Lagrangian with EFT generalization:



$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\overbrace{(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}})}^{\text{Vector couplings}}\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\overbrace{\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}})}^{\text{Tensor couplings}}\,t\,W_{\mu}^{-} + \mathrm{h.c.}\,,$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

(≈ 1 in SM)

Anomalous couplings (≈ 0 in SM at tree level)

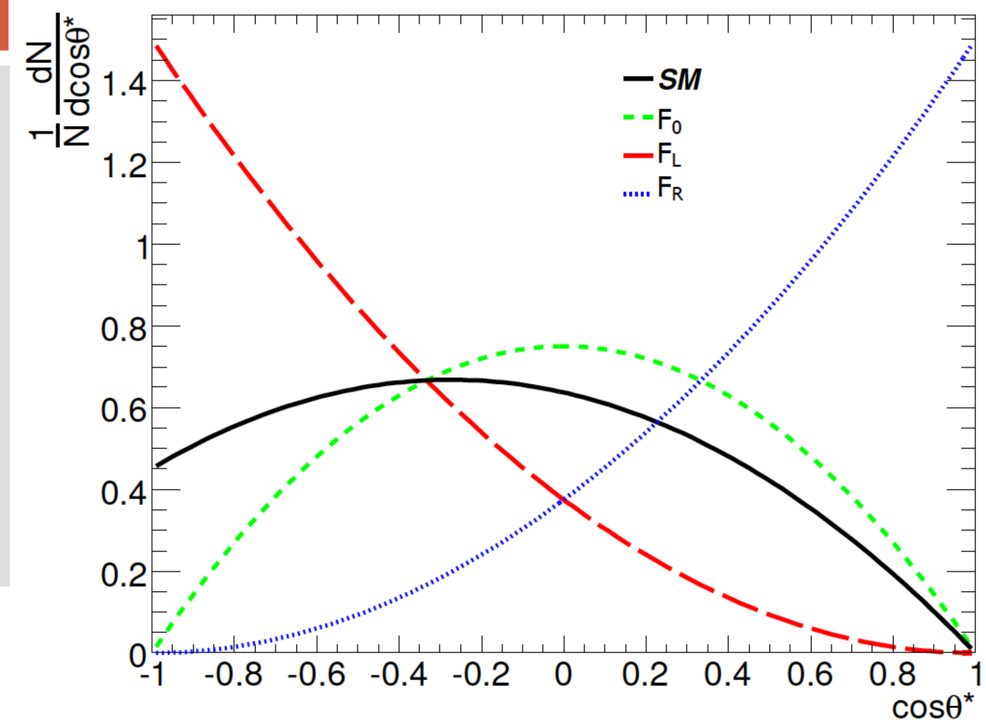
How to probe anomalous couplings in the *Wtb* vertex?

- Indirect limits from *B*-physics
- Single top production and decay
- Angular distributions of the **top quark** decay products
  - sensitive to *W* helicity fractions

Probing *Wtb* structure

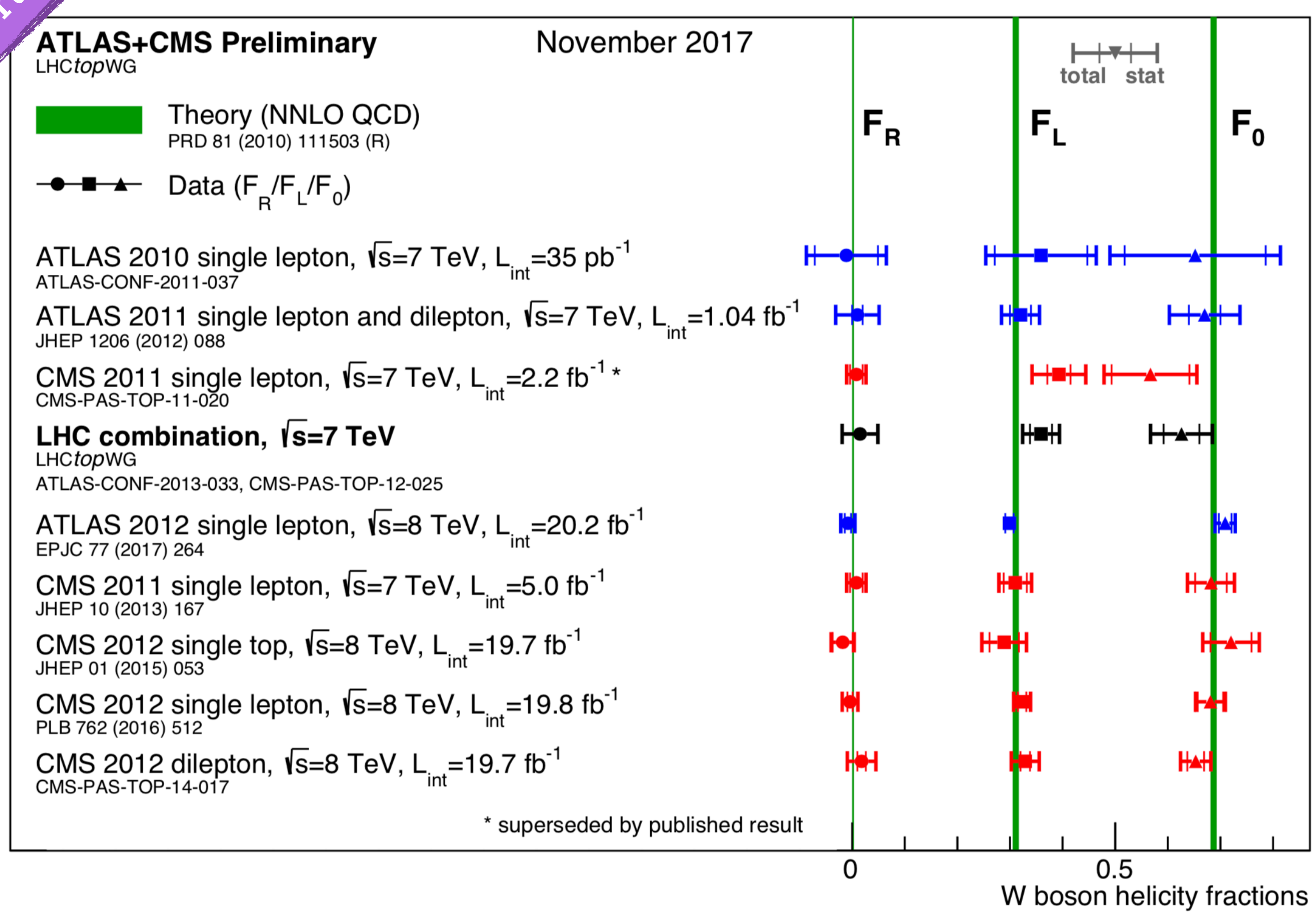
W boson polarization measurements @ LHC

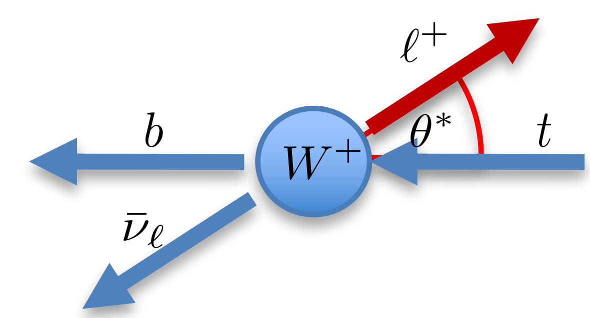
- Multiple measurements performed by ATLAS and CMS in **Run 1**
- Using **top pair and singe top events**
- The **lepton angular distribution** in W rest frame is sensitive to the W polarization
- All measurements so far are **compatible with SM** prediction at NNLO QCD

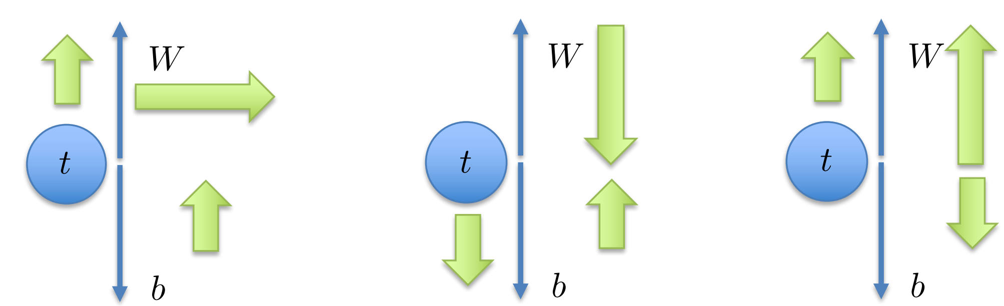


Run I data

#LHCTopWG







F_0=0.687±0.005 F_L=0.311±0.005 F_R0=0.0017±0.0001

SM NNLO calculation: Phys. Rev. D81, 111503 (2010)

W Boson Polarization Measurements

Combination of W boson polarization measurements @8TeV

New!

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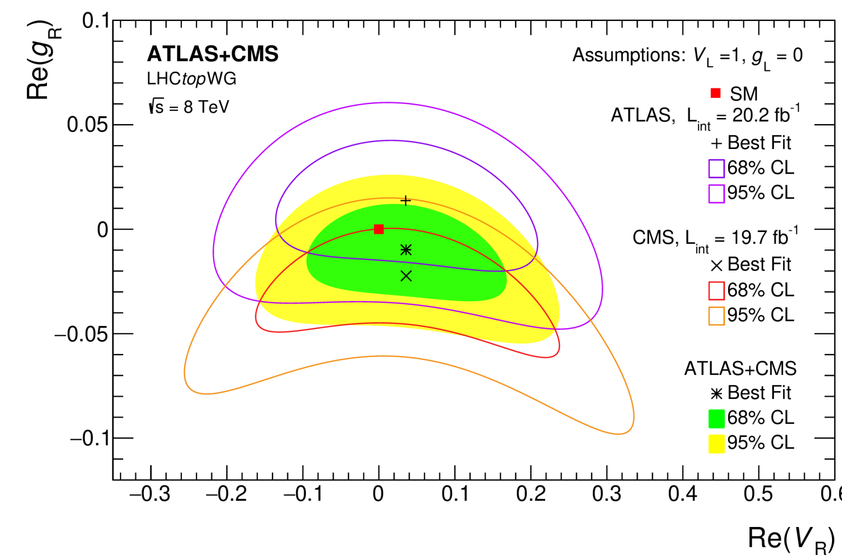
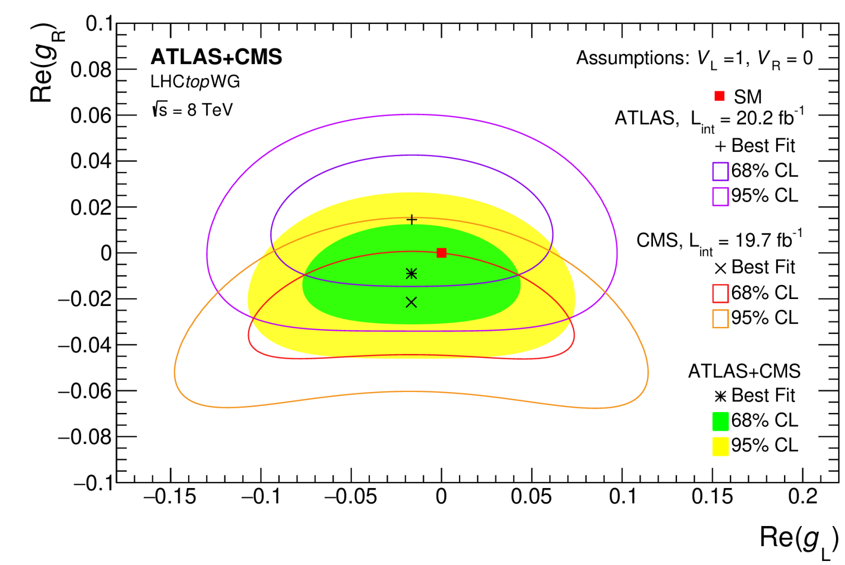
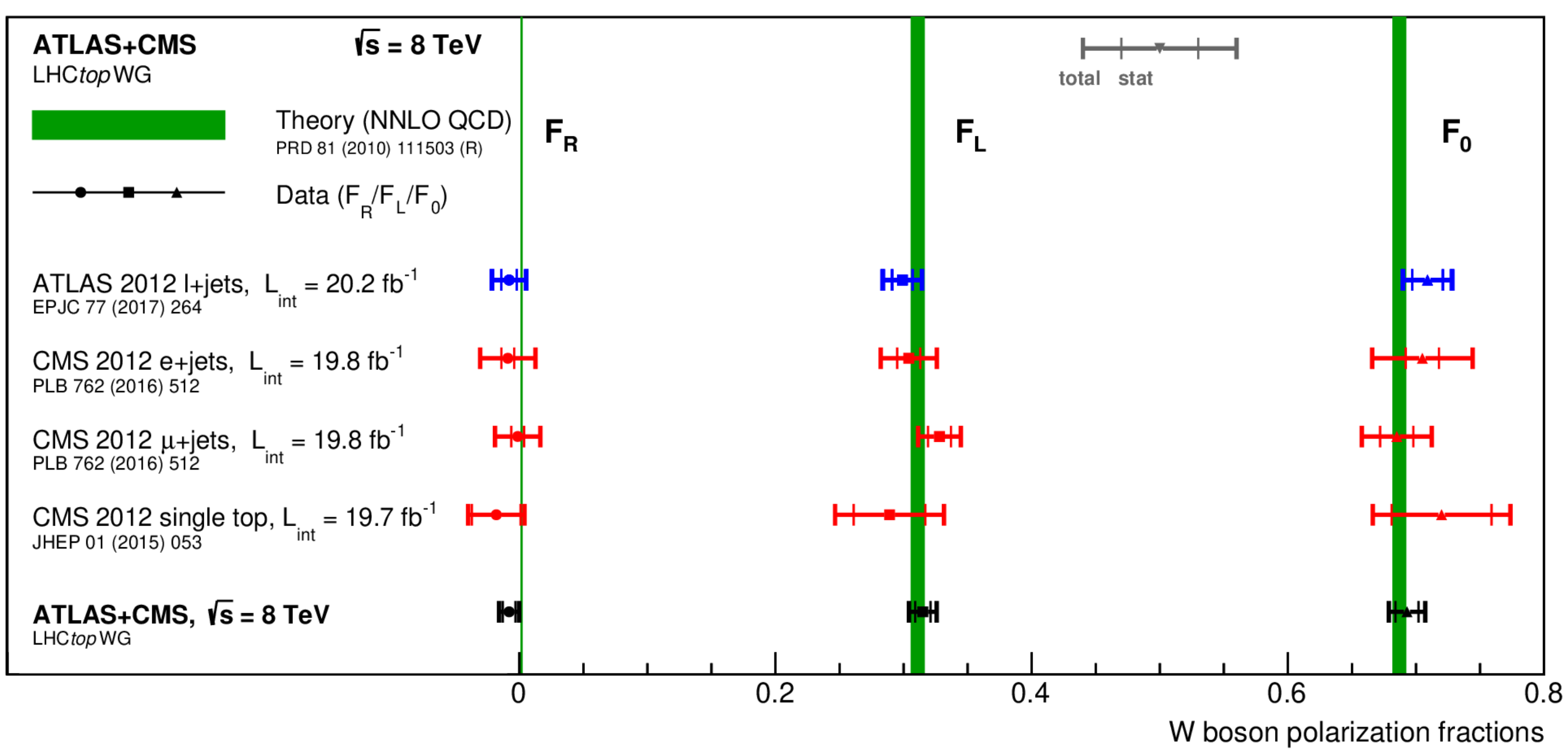
- Precision of **~ 2% in F_0, ~3.5% in F_L** is achieved
- Improvement w.r.t previous most precise individual measurements: ~25% in F_0 , ~29% in F_L

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

- Lead by stat+bkg, radiation&scales, MC stats
- Compatible with SM prediction at NNLO QCD
- Tightened the previous allowed regions of the Wtb anomalous couplings (assuming real coefficients → CP-conserving)







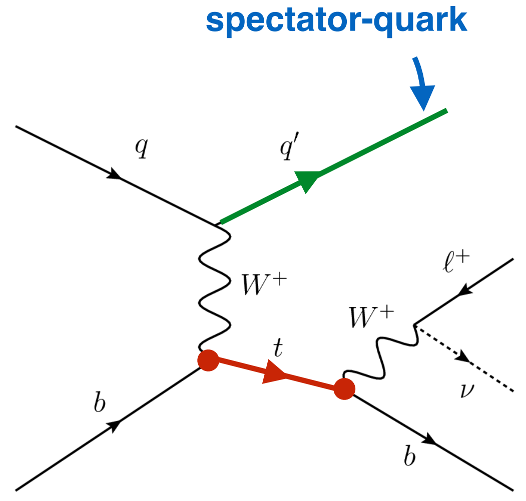
1D limits @ 95% CL interval

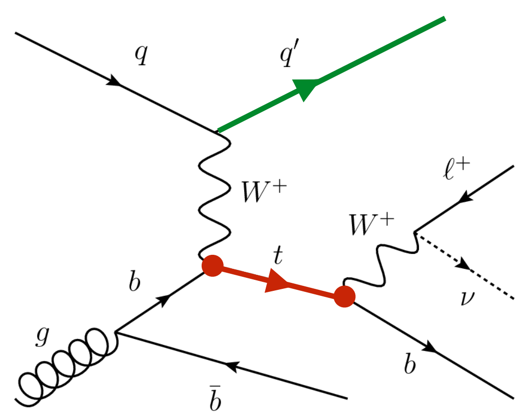
Coupling	ATLAS+CMS
$\mathrm{Re}(V_R)$	$[-0.11, 0.16]$
$\mathrm{Re}(g_L)$	$[-0.08, 0.05]$
$\mathrm{Re}(g_R)$	$[-0.04, 0.02]$

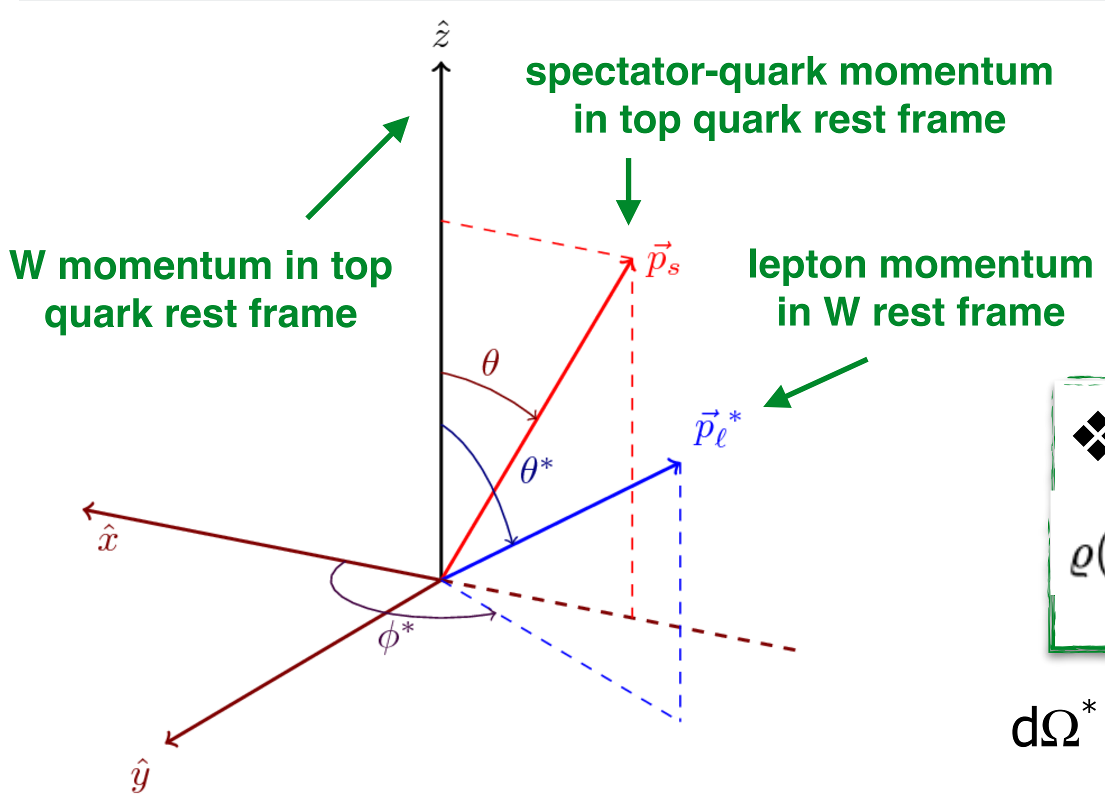
Probing *Wtb* structure

Triple-differential angular decay rates in t-channel single-top-quark

- In hadron colliders top quarks are produced predominantly in pairs (tt).
- Unlike $t\bar{t}$, single top is produced **polarized**.
- In the t-channel single-top-quark production, both production and decay proceed through the Wtb vertex
- BSM in production or decay can modify angular distributions of the decay products of polarized top quarks
- Direct searches for anomalous couplings in t-channel single-top-quark events set limits simultaneously on **Real** and **Imaginary** part of anomalous couplings
- **Degree of polarization:** $P \equiv \hat{p}_s.\vec{s}_t / |\vec{s}_t|$ ~ 90% at 8 TeV for SM couplings







Angular coefficients

❖ t-channel cross section:

$$\varrho(\theta, \theta^*, \phi^*; P) = \frac{1}{N}\frac{\mathrm{d}^3N}{\mathrm{d}(\cos\theta)\mathrm{d}\Omega^*} = \sum_{k=0}^{1}\sum_{l=0}^{2}\sum_{m=-k}^{k} a_{k,l,m} M_{k,l}^{m}(\theta, \theta^*, \phi^*)$$

Orthonormal functions over the three angles

$$\mathrm{d}\Omega^* \equiv \mathrm{d}(\cos\theta^*)\mathrm{d}\varphi^*$$

Triple-differential angular decay rates

Analysis

- Analyzed data: **20.2 fb^{-1} at 8 TeV**
- Selection: exactly one lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$, and two jets (1b-jet + 1untagged jet)
  - transverse mass $m_T(\ell E_{\mathrm{T}}^{\mathrm{miss}}) > 50\mathrm{GeV}$
  - untagged jet must be in the forward region
- W boson and Top quark are **fully reconstructed** from the final state objets four-momenta, to obtain **q**, $\mathbf{p_s}$ and $\mathbf{p_\ell}$ vectors
- Largest backgrounds: $t\bar{t}$, W+jets events
- signal and backgrounds normalizations estimated via simultaneous maximum-likelihood fit to the data

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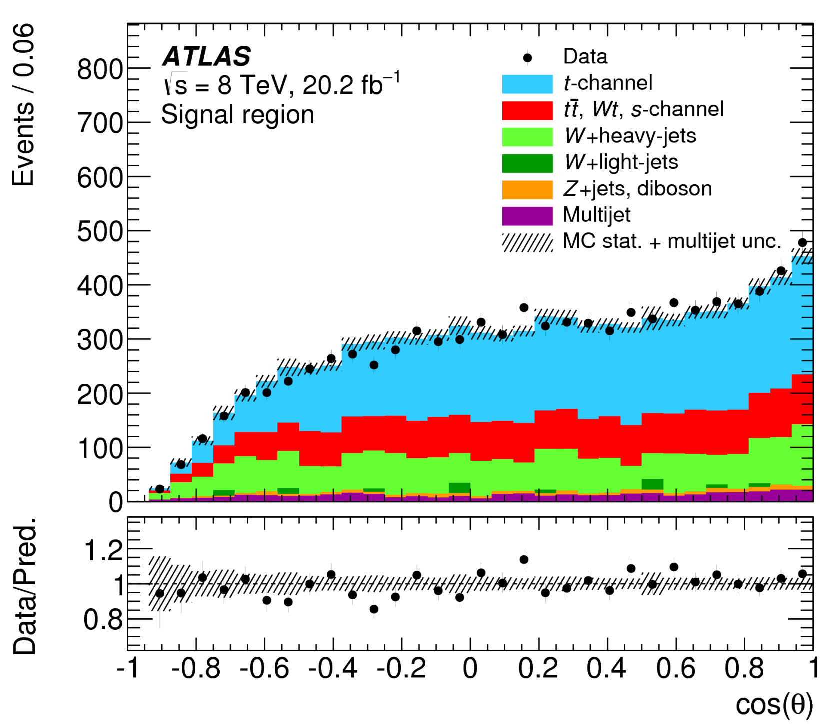
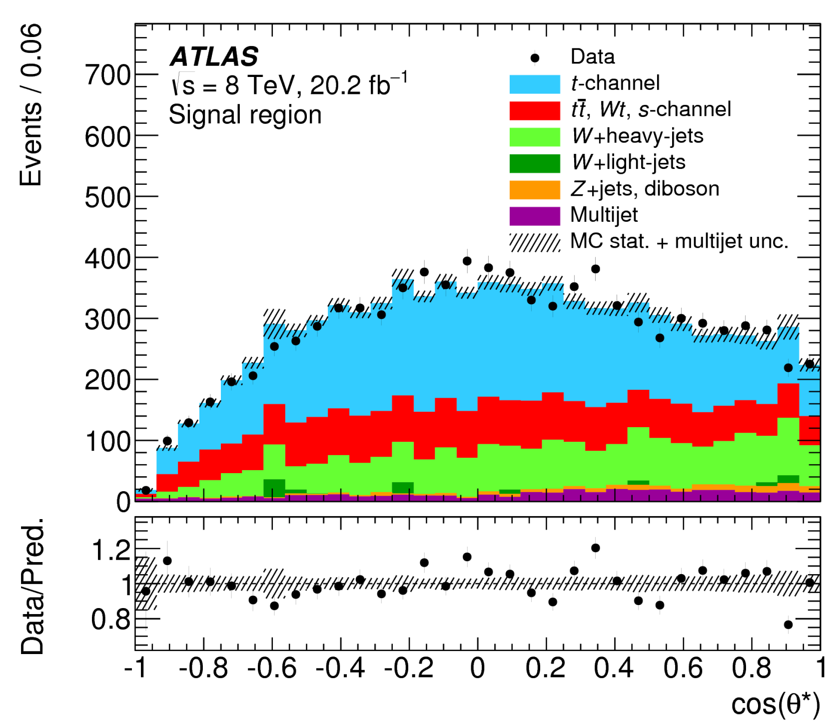
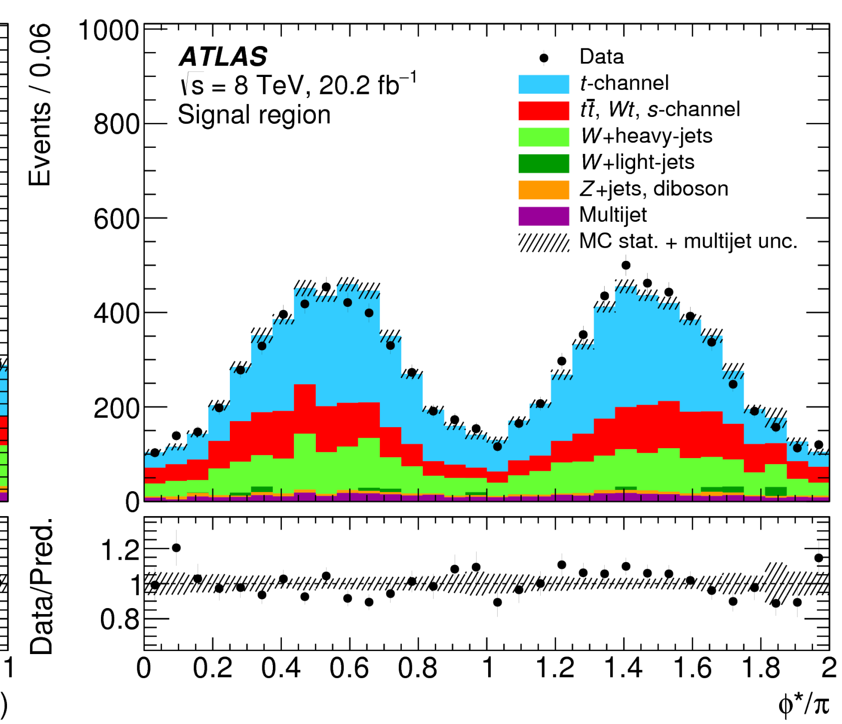
- The model is based on the three angles θ, θ^*, and φ^*
- to determine:
  - generalized helicity fractions
  - phases
  - top quark polarization







Triple-differential angular decay rates

Results

- The **angular coefficients** measurement is compatible with SM
- Limits obtained in the space of the **generalized helicity fractions** and **phases** and **polarization (P)**, and translated to Wtb anomalous **couplings ratios** and **P** (no external constraints or assumptions)

$$|V_R/V_L| < 0.37 \quad (95\%\ \mathrm{CL})$$
$$|g_R/V_L| < 0.29 \quad (95\%\ \mathrm{CL})$$
$$P > 0.72 \quad (95\%\ \mathrm{CL})$$

$$\mathrm{Re}[\frac{g_R}{V_L}] \in [-0.12, 0.17] \quad \text{and} \quad \mathrm{Im}[\frac{g_R}{V_L}] \in [-0.07, 0.06]$$

CMS results in [JHEP02 (2017) 028], obtained in single top t-channle assuming real couplings: $|f_V^R| < 0.16, |f_T^L| < 0.057,$ and $-0.049 < |f_T^R| < 0.048$

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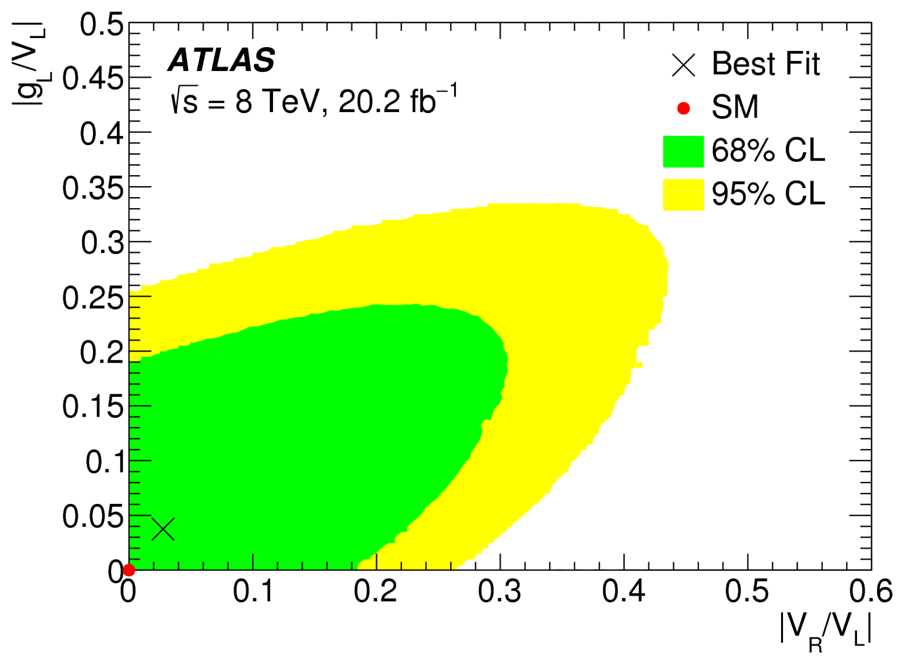
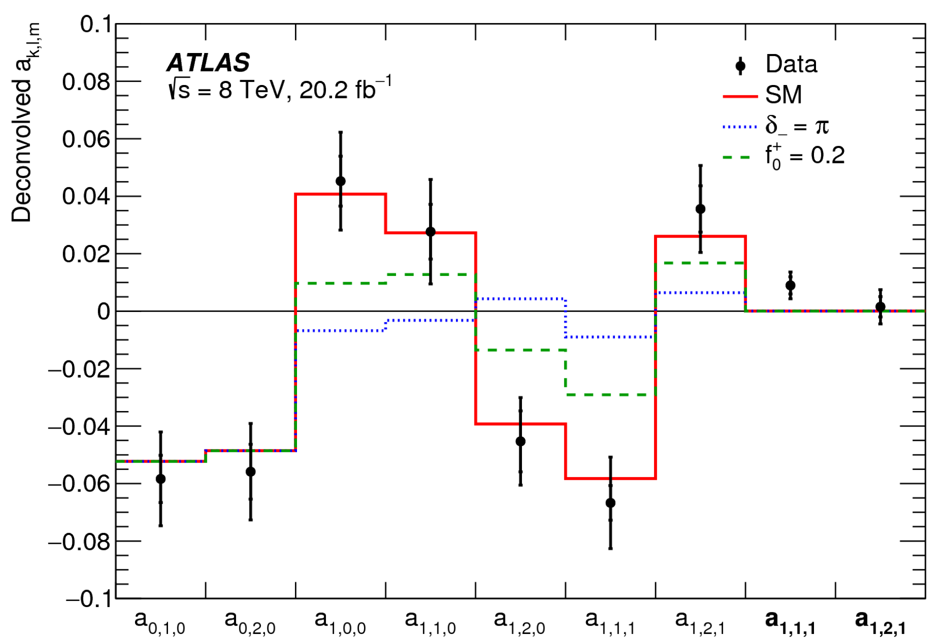
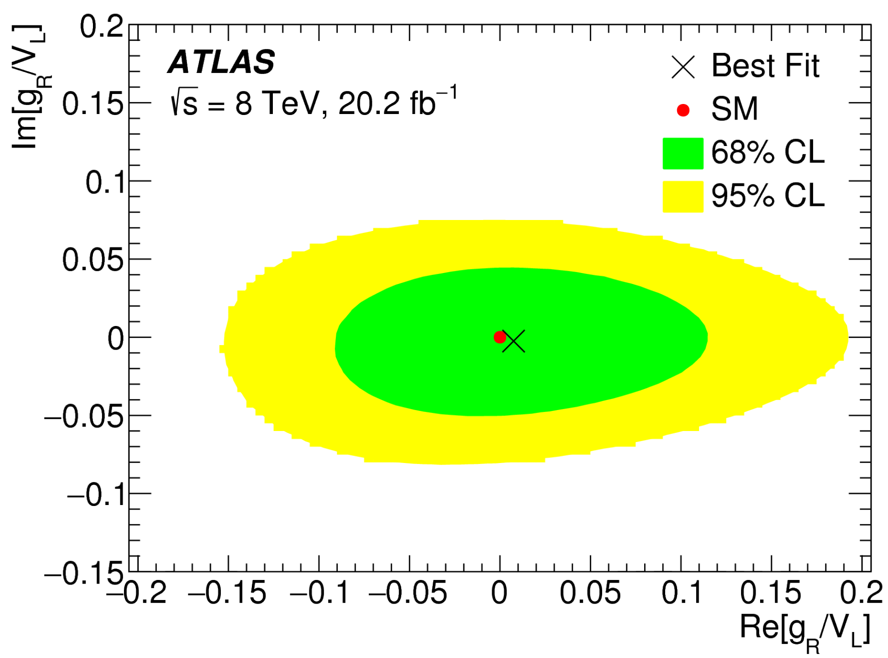


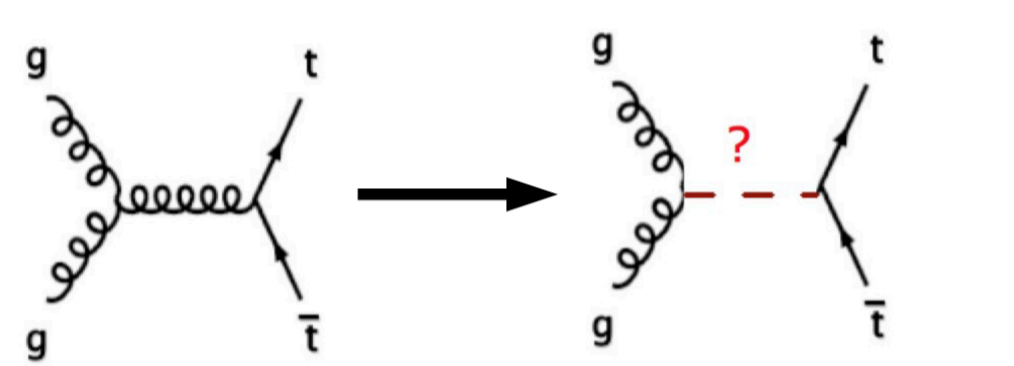


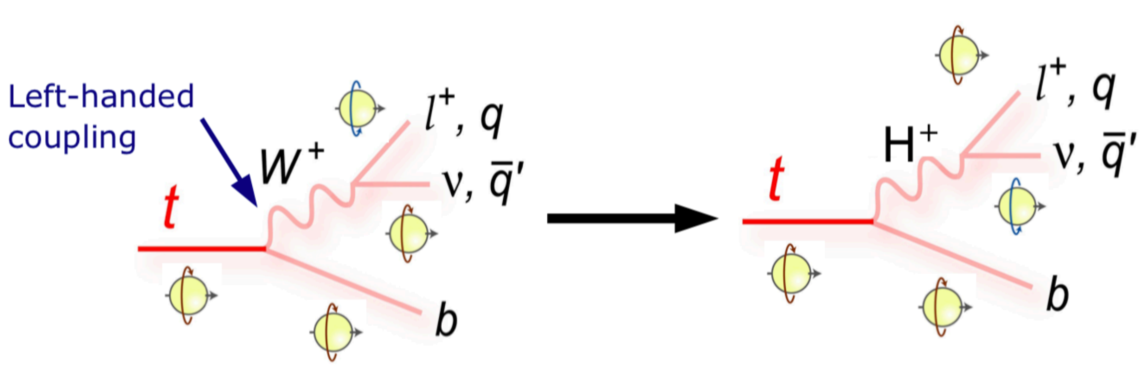


Polarization & Spin Correlation

Where it comes from?

- Top quarks decay before fragmentation
  - **spin information is preserved in the final state**
- In SM, top quarks from $t\bar{t}$ produced **un-polarized**, and **spins are strongly correlated** but …
  - **New physics** could induce polarization
  - change spin structure via new mediator or change the *Wtb* vertex structure





Indirect vs. direct measurements

Indirect:

- Top spins determine the preferred lepton directions
  - **charged lepton** is **perfect spin analyzer**
  - **Δφ:** angle between leptons in transverse plan
  - large Δφ preferred: tops are produced back to back
  - We can **indirectly probe** the spin correlations using Δφ in the lab frame!
  - **experimentally very precise** because lepton angles have **excellent resolution**

Direct:

- Requires full tt reconstruction
- Spin density matrix (R) ➜ Matrix Element:

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

- Can define observables sensitive to the coefficients of the **decomposed matrix R**.
- Measurements: **differential cross section** of $t\bar{t}$ production: $\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}(1+[\text{Coef.}]x)f(x)$

Polarization & Spin Correlation

Analysis

- Top quark 4-momenta is fully reconstructed
- Probe **spin in 3D** (**15 observables**):
  - related to independent coefficients of spin-dependent parts of the $t\bar{t}$ **production density matrix**
  - Each coefficient is extracted from a measured normalized differential tt cross section

Indirect result using Δφ(ll): $F_{SM}(\Delta\varphi) = 1.10^{+0.14}_{-0.17}$

- **Fully consistent with SM**

Top quark anomalous **chromomagnetic dipole moment** (**CMDM**) constrain: $-0.07 < C_{tG}/\Lambda^2 < 0.16\ \mathrm{TeV}^{-2}$ at 95% CL

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$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2}\overbrace{(1 + B^+.\hat{\ell}^+ + B^-.\hat{\ell}^- - \hat{\ell}^+.\mathbb{C}.\hat{\ell}^-)}^{\text{R: Spin Density Matrix}}$$

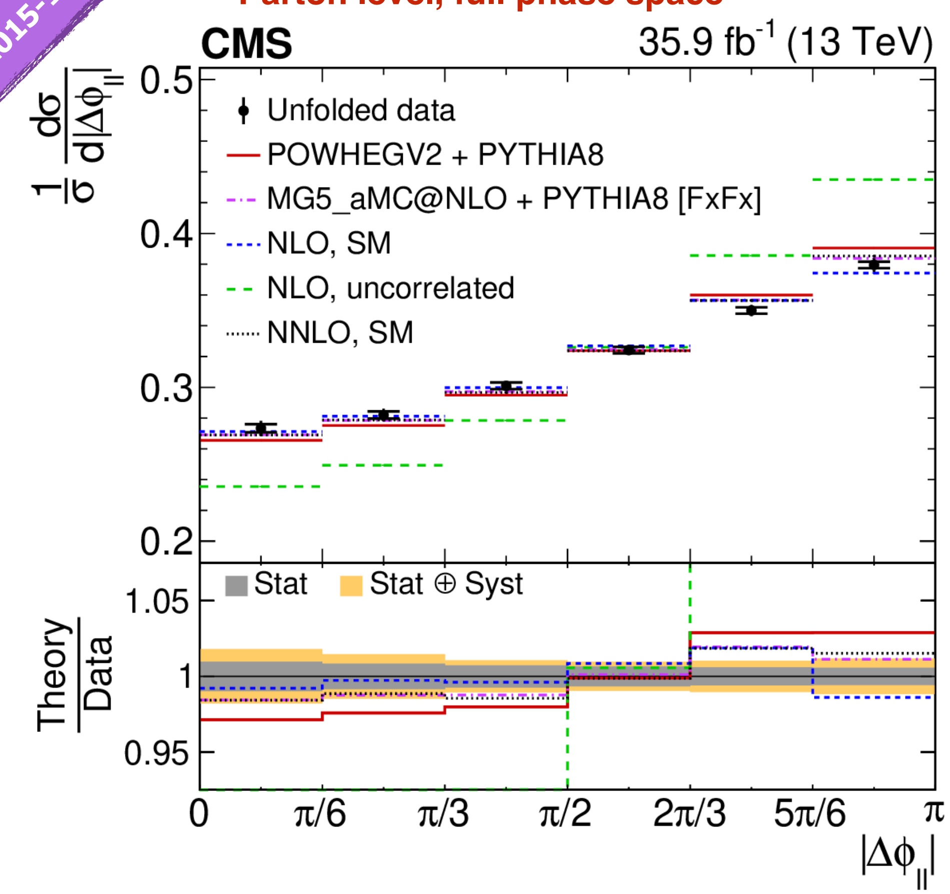
15 observables = Polarization 3+3 + Correlation 3x3

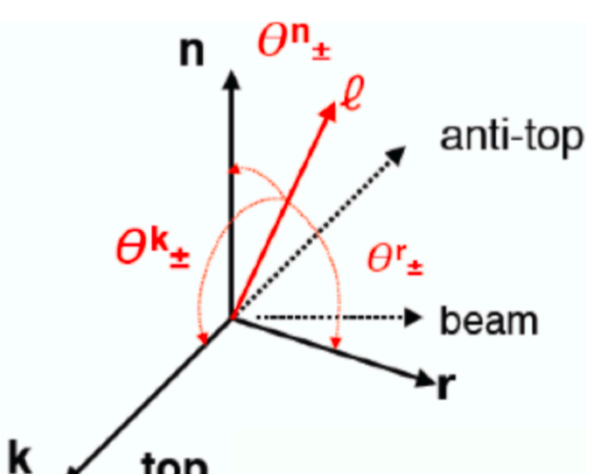
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i} = \frac{1}{2}(1 + B_1^i\cos\theta_1^i),$$
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_2^i} = \frac{1}{2}(1 + B_2^i\cos\theta_2^i),$$

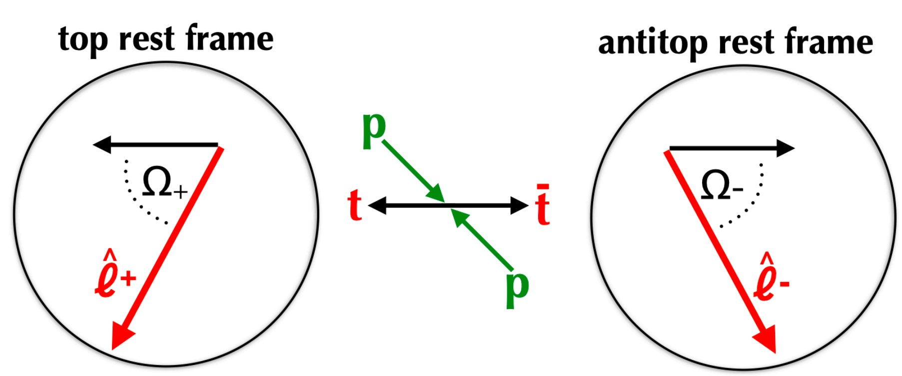
$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}(1 - C_{ij}x)\ln\left(\frac{1}{|x|}\right)$$
$$x = \cos\theta_1^i\cos\theta_2^j.$$

2015-16 data

Parton level, full phase space







Polarization & Spin Correlation

Results

- Measured top quark **polarization**: **consistent with zero**
- opening angle between the leptons (in parent top rest frames) has **maximal sensitivity** to the alignment of the top quark spins: $$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$
  - **D= -0.237± 0.007±0.009**
  - **f_{SM} =0.97± 0.05**
- Results are consistent with unity → measured spin correlation strengths are in agreement with SM prediction

2015-16 data

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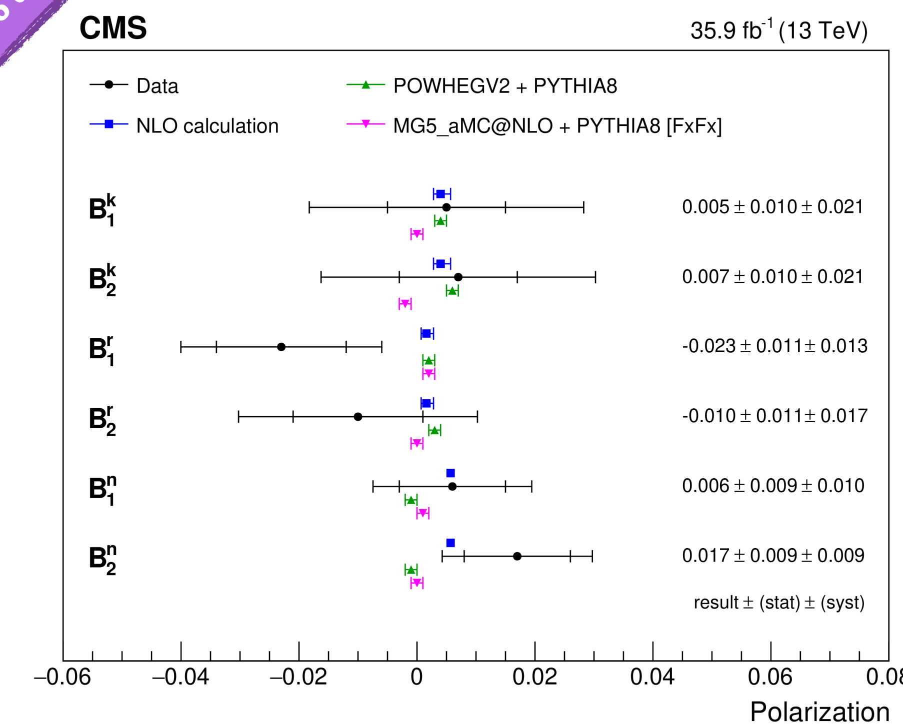
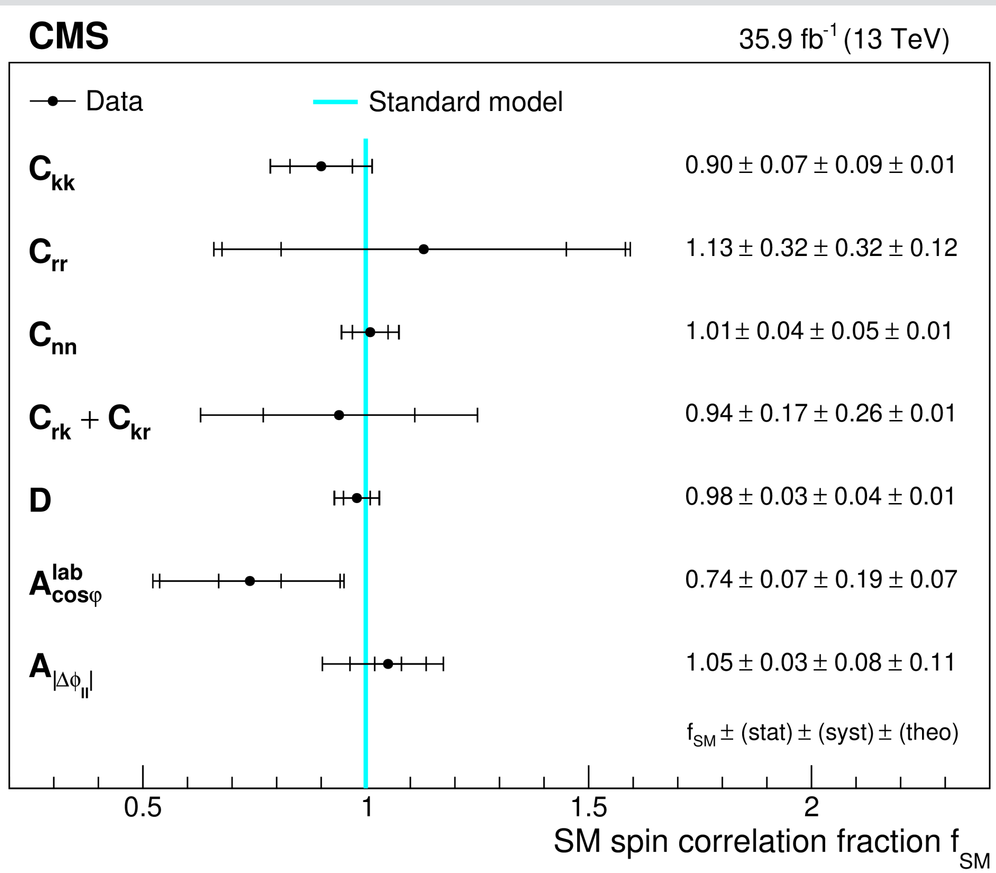
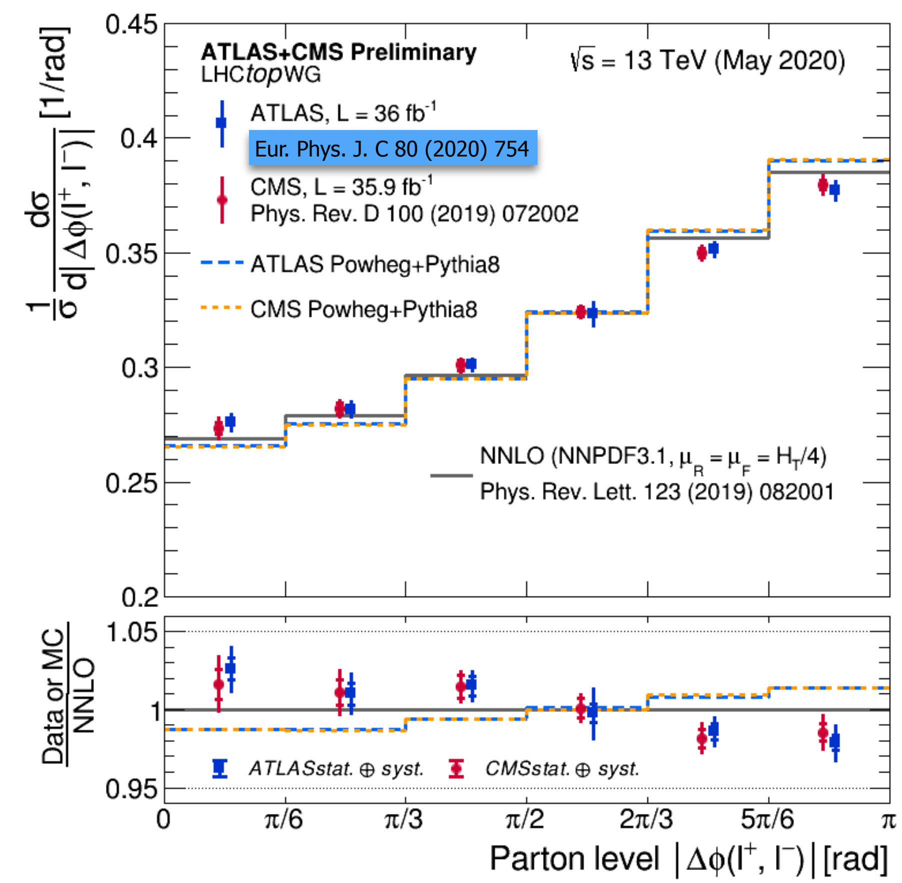






Forward-backward Production Asymmetry

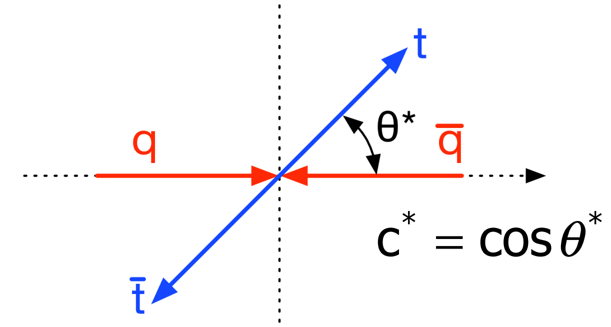
Where it comes from?

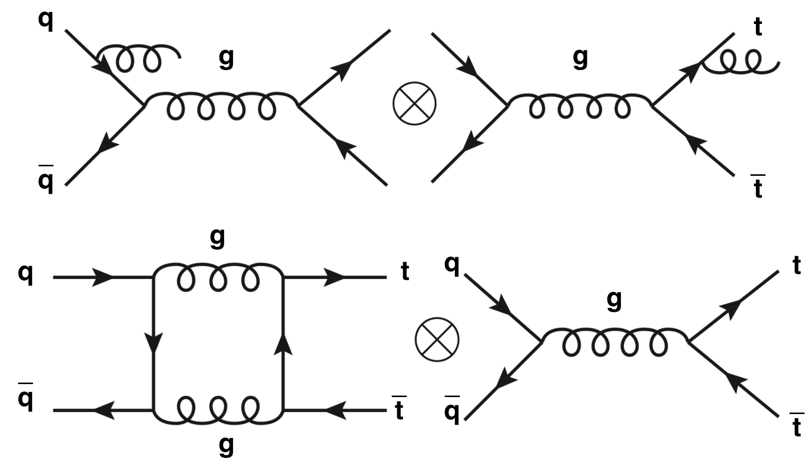
- **@LO:** top quark and top anti-quark are **symmetric** with respect to the angular distribution
- **@Higher orders:** interference terms between between $q\bar{q} \to t\bar{t}$ causes an **asymmetry:**

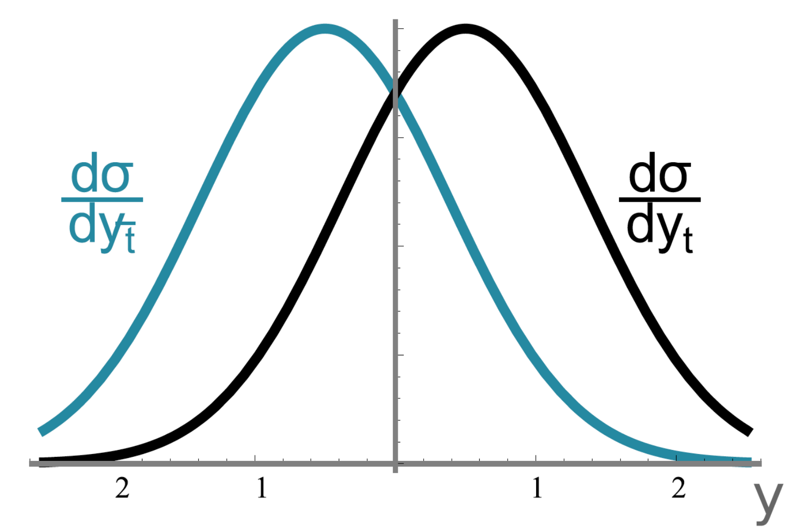
$$A_{FB} = \frac{\sigma(c^* > 0) - \sigma(c^* < 0)}{\sigma(c^* > 0) + \sigma(c^* < 0)}$$

- **BSM causes Angular distribution anomalies:**
  - impose modification to the **ttg** vertex,
  - introduce high-mass resonances coupled to top

- tt production @LHC is dominated by $gg \to t\bar{t}$ (~ 90% @13TeV)







Forward-backward Production Asymmetry

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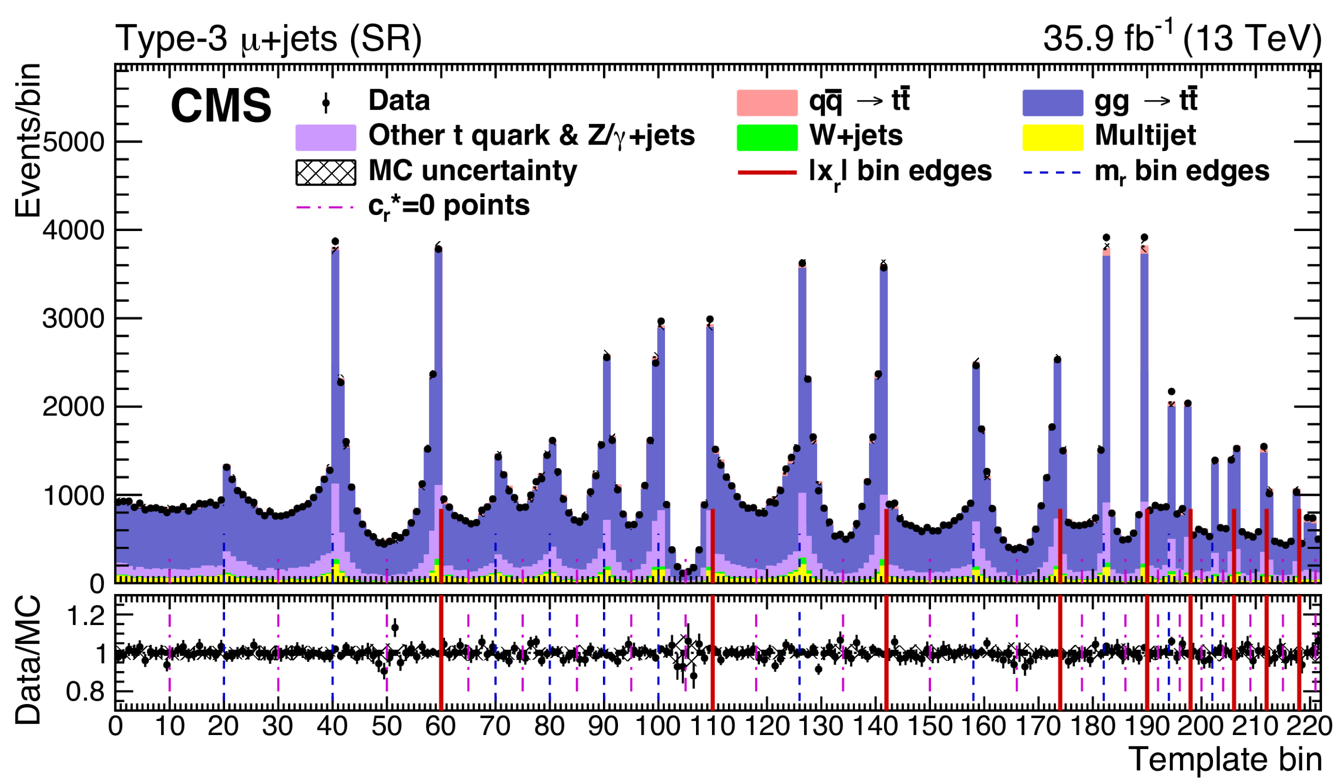
Analysis

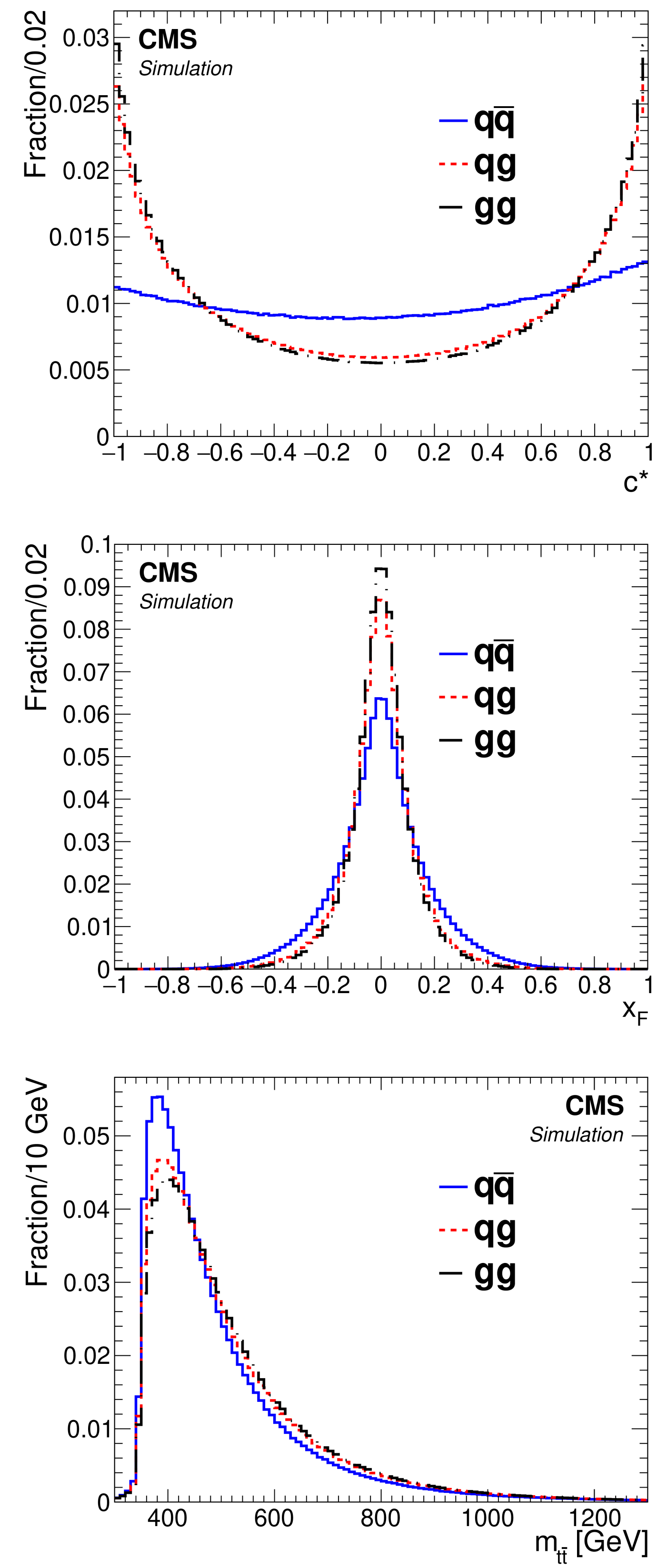
- Analyzed data: 35.9 fb^{-1} at 13 TeV
- Selection: Lepton+jets events with “boosted” and “resolved” topologies
- $t\bar{t}$ events fully reconstructed via kinematic fit
- The $q\bar{q}$ subprocess is approximated as a linear function of c*

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

- **Templates** are built using $m_{t\bar{t}}$, c* and X_F scaled longitudinal momentum
- Anomalous chromoelectric (**d_t**) + chromomagnetic (**μ_t**) dipole moments are probed from the symmetric term



⇦ Template observables ⇨



Forward-backward Production Asymmetry

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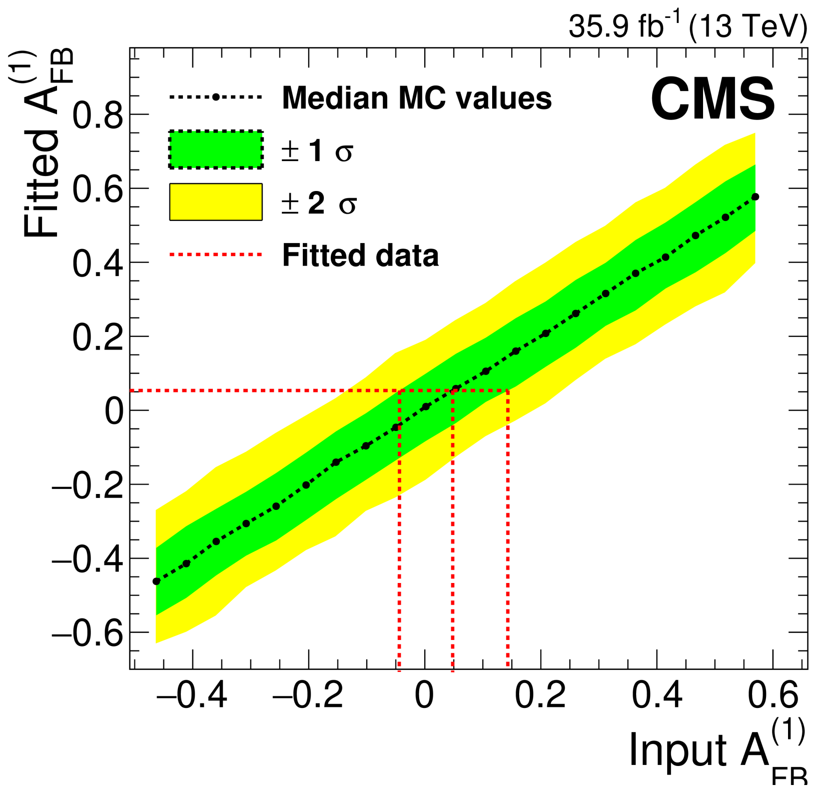
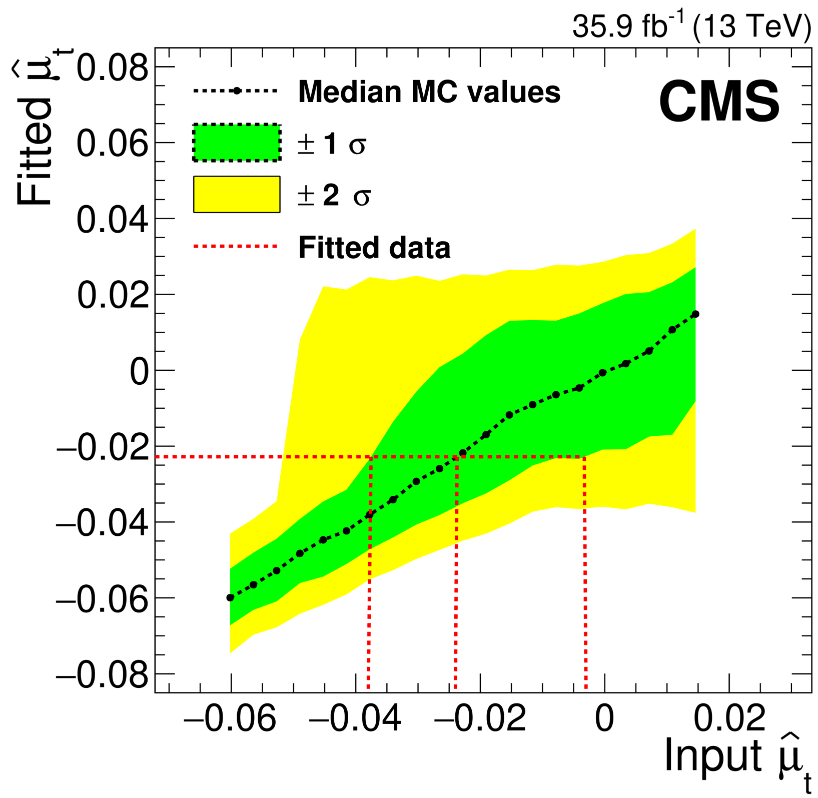
Result

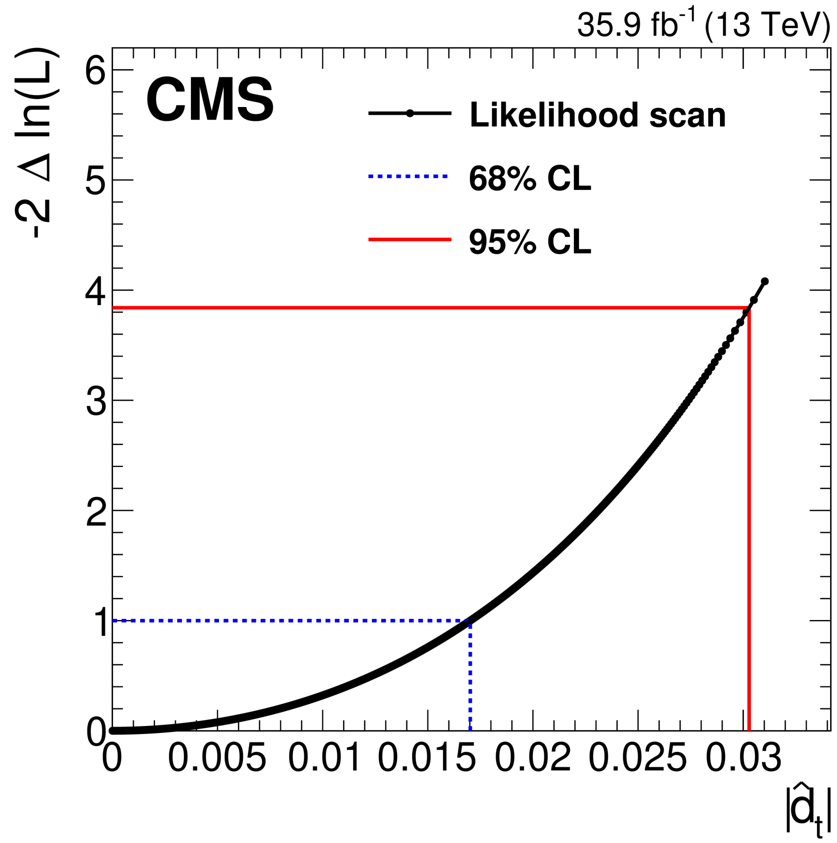
- A linear combination of the 3D templates fitted to data for each topology, lepton flavour and charge
- Values are consistent with SM expectations



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



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



$|\hat{d}_t| < 0.03$ at 95% C.L.

CP violating anomalous top quark couplings

Where it comes from?

- The CP symmetry is violated in the SM, although not large enough to explain the matter-antimatter asymmetry
- Search for new sources of CP violation is ongoing in many sectors
- Large CP violation is proposed in BSM via **chromoelectric dipole moment** (CEDM) interaction of top quark
- The CP-odd physics observable with **largest sensitivity**: Levi-Civita tensors

$$\mathcal{O}_1 = \varepsilon(p_t, p_{\bar{t}}, p_\ell, p_{\bar{\ell}})$$

$$\mathcal{O}_3 = \varepsilon(p_b, p_{\bar{b}}, p_\ell, p_{\bar{\ell}})$$

- Asymmetry **(A_i)**: number of produced events, N, with a positive and negative value of the observable $\mathcal{O}_i$ in top quark pairs
- Some BSM models [1] predict an asymmetry as large as **15%** and **9%** for $\mathcal{O}_1$ and $\mathcal{O}_3$
- Asymmetry **(A_i)** is **linearly** proportional to the **CEDM**

top - gluon dipole couplings

$$\mathcal{L} = \frac{g_S}{2}\bar{t}T^a\sigma^{\mu\nu}(a_t^g + i\gamma_5 d_t^g)tG^{\mu\nu}$$

CP-odd CEDM

Asymmetry

$$A_i = \frac{N(\mathcal{O}_i > 0) - N(\mathcal{O}_i < 0)}{N(\mathcal{O}_i > 0) + N(\mathcal{O}_i < 0)}$$

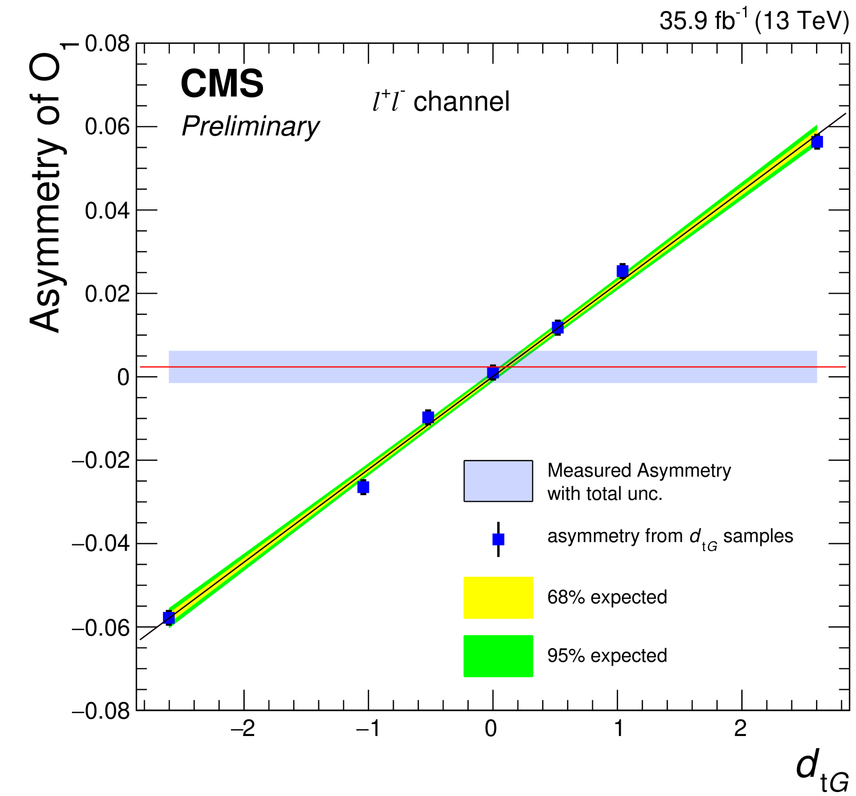
[1] Phys. Rev. D 93 (Jan, 2016) 014020

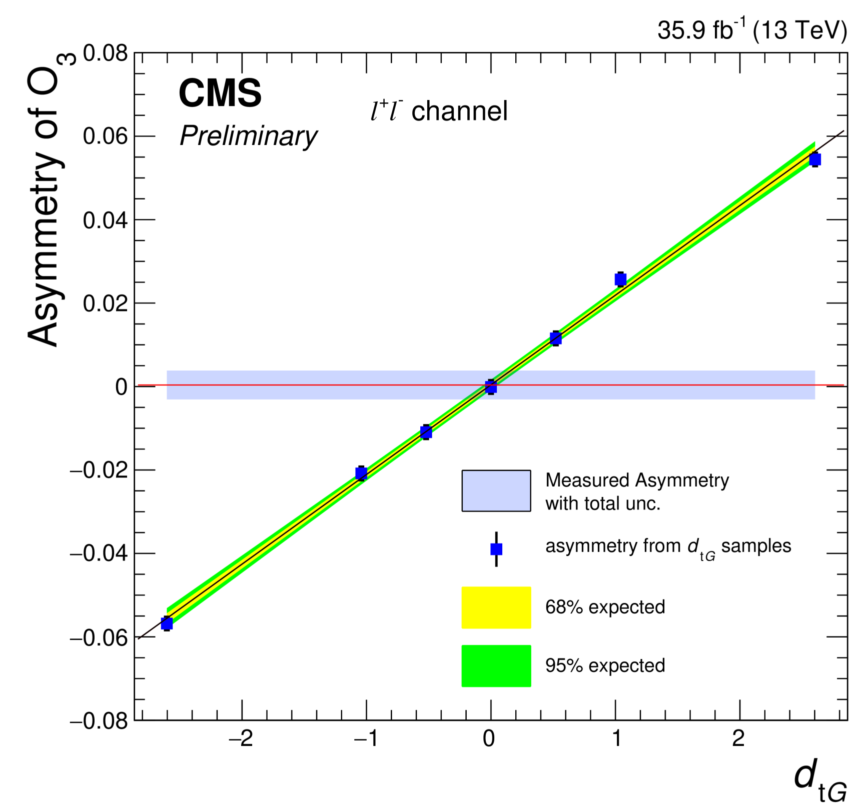
CP violating anomalous top quark couplings

New! CMS-PAS-18-007

Analysis

- Analyzed data: 35.9 fb^{-1} at 13 TeV
- Selection: dilepton $t\bar{t}$ events in **ee**, ***eμ***, ***μμ*** channels
- kinematic event reconstruction applied
- Main backgrounds: $t\bar{t}$ (other channels), single top
- Maximum likelihood fit used to extract **A**$_i$, $\mathcal{O}_i$, and $\sigma_{t\bar{t}}$
- Measurement is limited by signal modelling (color reconnection, underlying event)
- CEDM is extracted from linear fit to the Asymmetry distribution
- Results are in agreement with SM





Results

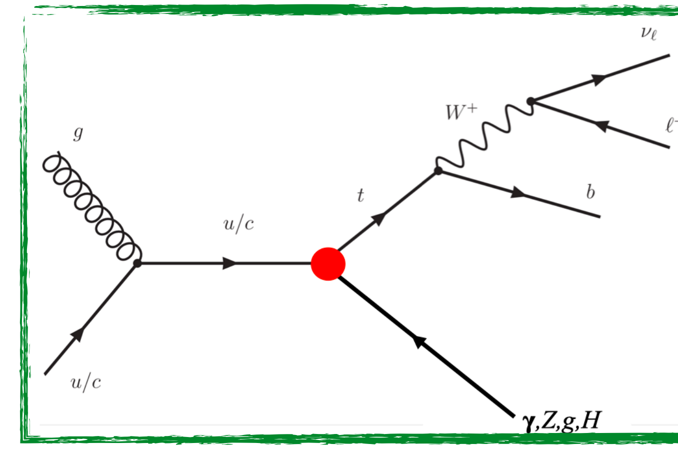
	Asymmetry and uncertainty ($\times 10^{-3}$)			
Physics observable	$e^{\pm}\mu^{\mp}$	e^+e^-	$\mu^+\mu^-$	Combined
$\mathcal{O}_1$	6.9 ± 5.3	8.8 ± 7.5	0.6 ± 3.4	2.4 ± 2.8
$\mathcal{O}_3$	6.1 ± 5.3	4.1 ± 7.5	-1.7 ± 3.4	0.4 ± 2.8

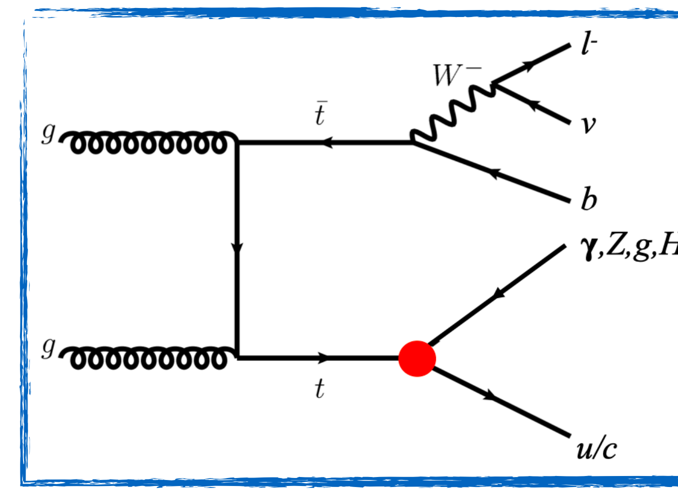
Physics observable	d_{tG}	CEDM (10^{-18} $g_s \cdot$ cm)
$\mathcal{O}_1$	$0.10 \pm 0.12(\text{stat}) \pm 0.12(\text{syst})$	$0.58 \pm 0.69(\text{stat}) \pm 0.70(\text{syst})$
$\mathcal{O}_3$	$0.00 \pm 0.13(\text{stat}) \pm 0.10(\text{syst})$	$-0.01 \pm 0.72(\text{stat}) \pm 0.58(\text{syst})$

Top Quark Rare Decays

Flavour Changing Neutral Current in top quark

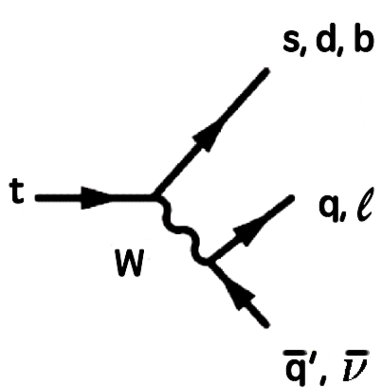
- Top quark couples to an **up-type quark** (u or c) and a **neutral boson** (γ,Z,H,g)
- Forbidden at tree-level in SM
- Heavily suppressed at higher orders via GIM suppression (rate is not observable with current dataset)
- **BSM can enhance FCNC up to ~ 10^{-4}**
  - Any observation of FCNC can indicate new physics
- FCNC probe can be done in both top quark production, and decay



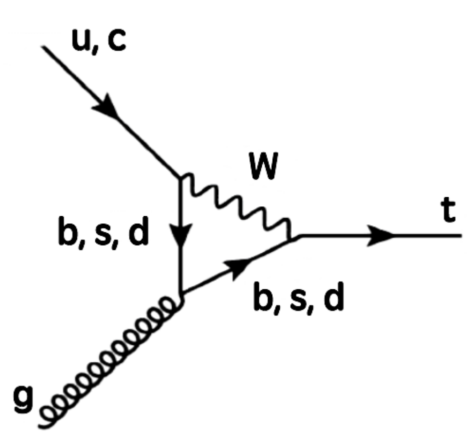


[K. Agashe et al., arXiv:1311.2028]

Top quark in SM



BR~ 100%



GIM

BR~ 10^{-12} - 10^{-17}

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\le 10^{-7}$	$\le 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\le 10^{-6}$	$\le 10^{-10}$	$\le 10^{-7}$	$\le 10^{-6}$	$\le 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\le 10^{-7}$	$\le 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\le 10^{-4}$	$\le 10^{-8}$	$\le 10^{-7}$	$\le 10^{-6}$	$\le 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\le 10^{-8}$	$\le 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\le 10^{-7}$	$\le 10^{-9}$	$\le 10^{-8}$	$\le 10^{-9}$	$\le 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\le 10^{-5}$	$\le 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\le 10^{-5}$	$\le 10^{-5}$	$\le 10^{-9}$	$\le 10^{-4}$

FCNC in Top Quark

Search for t → u /c γ

- Analyzed data: 81 fb^{-1} at 13 TeV
- Selection: exactly 1 photon, lepton and b-tagged jet and E_T^{miss}
- Only leptonic top quark decay is considered
- Models with left-handed (LH) and right-handed (RH) couplings are considered
- Neural Network (NN) classifier trained for each model using kinematics of the final state objects
- Dominating backgrounds: **e → γ fake** and **V+ γ +jets**
  - Data driven normalization estimate
  - Data driven estimate for photons misidentification

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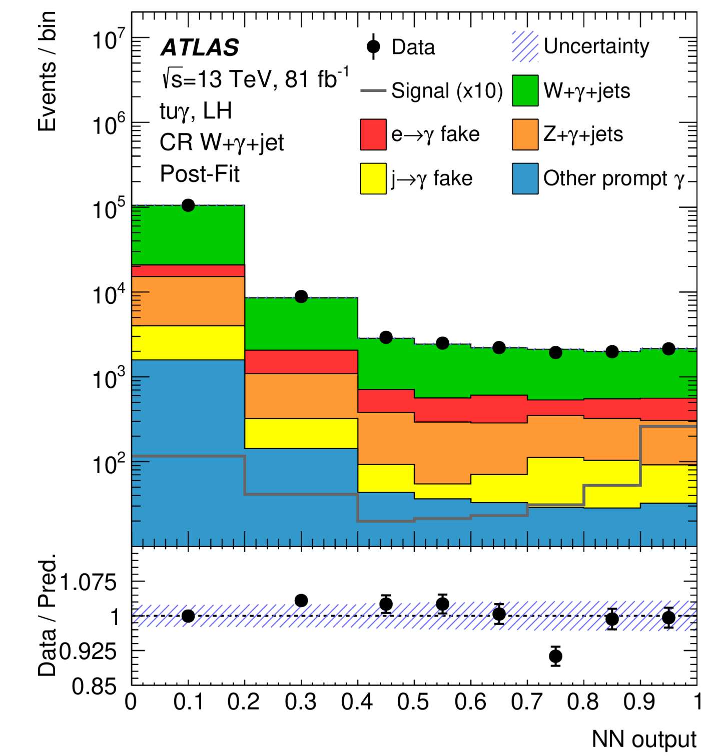
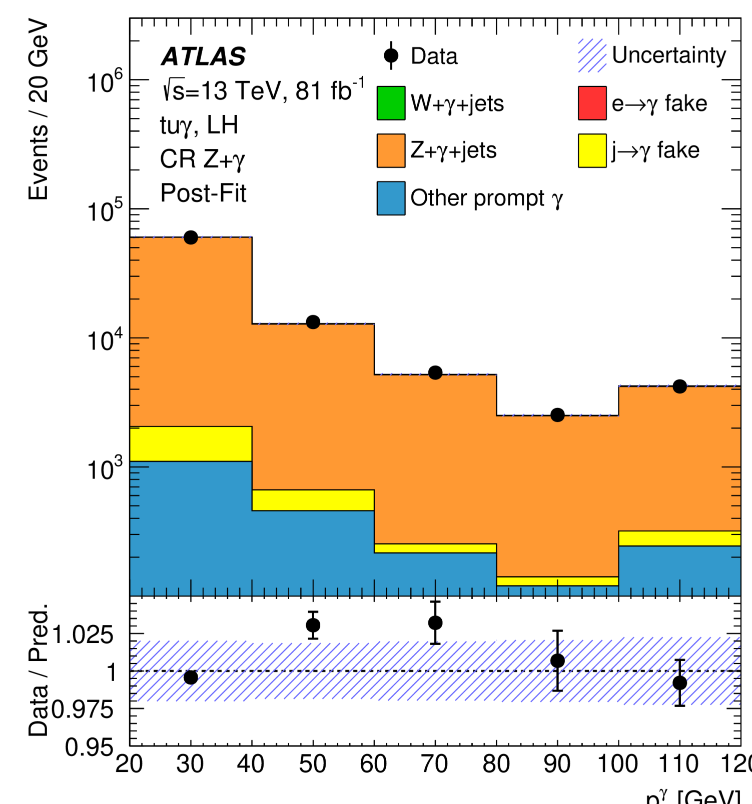
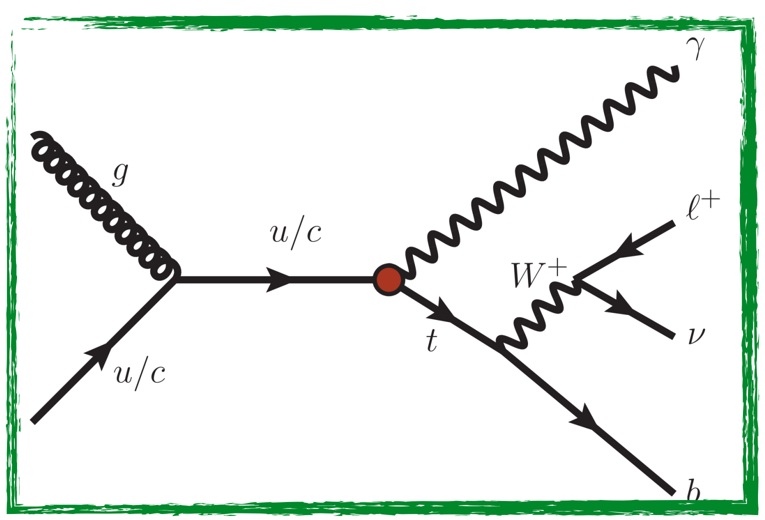
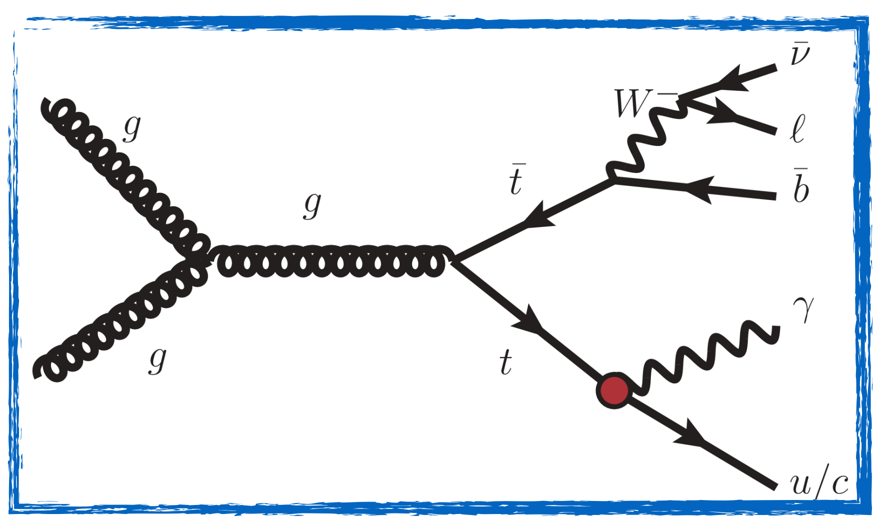








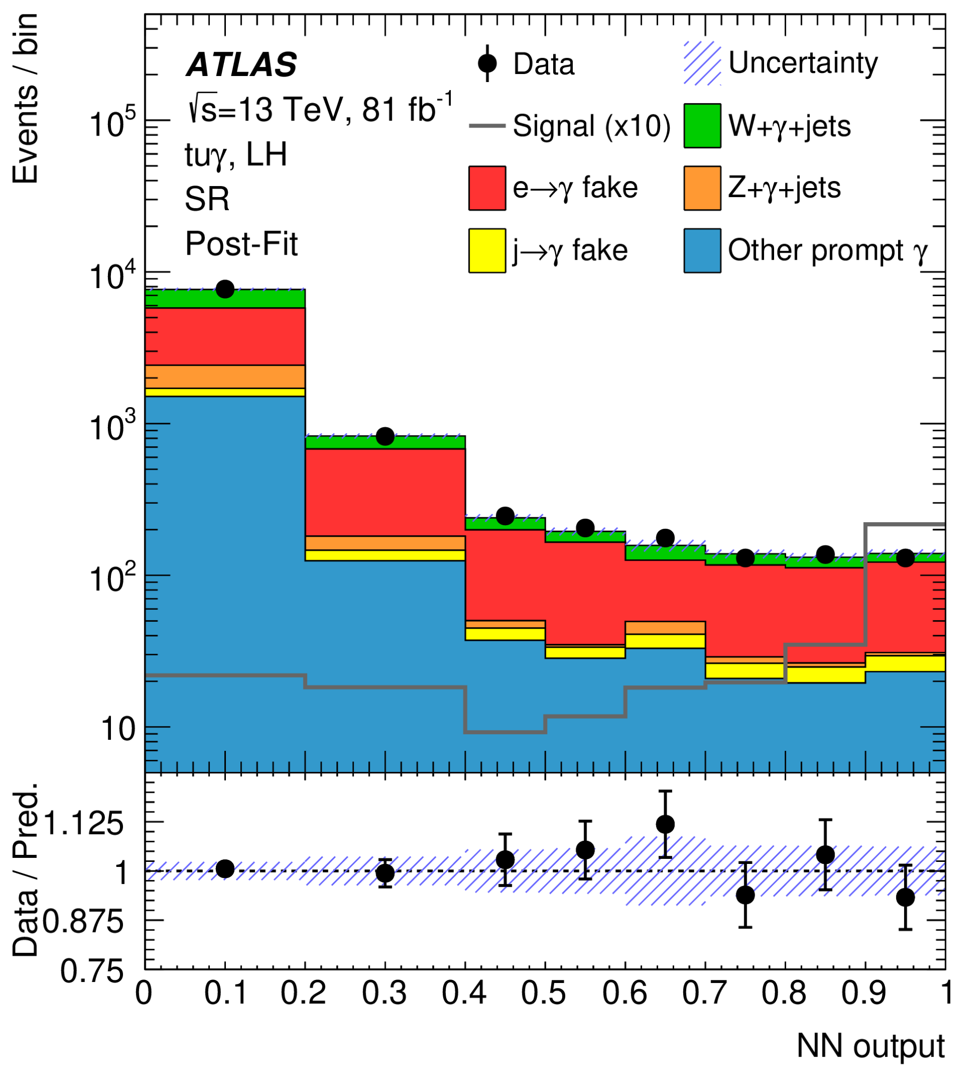
FCNC in Top Quark

Results

- The results are consistent with the background-only hypothesis
- Limits are set on the LH and RH flavour-changing tqγ **coupling** along with production **cross section** and **branching ratio**

Observable	Vertex	Coupling	Obs.	Exp.
$\lvert C_{\mathrm{uW}}^{(13)*} + C_{\mathrm{uB}}^{(13)*}\rvert$	$tu\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$\lvert C_{\mathrm{uW}}^{(31)} + C_{\mathrm{uB}}^{(31)}\rvert$	$tu\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
$\lvert C_{\mathrm{uW}}^{(23)*} + C_{\mathrm{uB}}^{(23)*}\rvert$	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
$\lvert C_{\mathrm{uW}}^{(32)} + C_{\mathrm{uB}}^{(32)}\rvert$	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	LH	36	52^{+21}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	RH	78	75^{+31}_{-21}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}

ATLAS EXPERIMENT Phys. Lett. B 800 (2019) 135082



FCNC in Top Quark

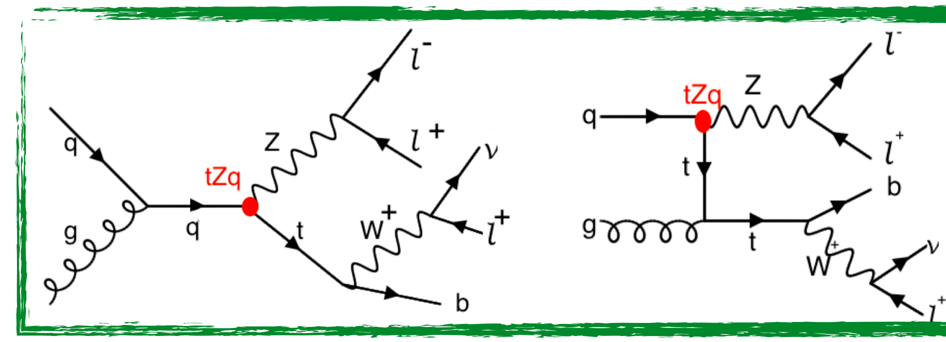
Search for t → qZ

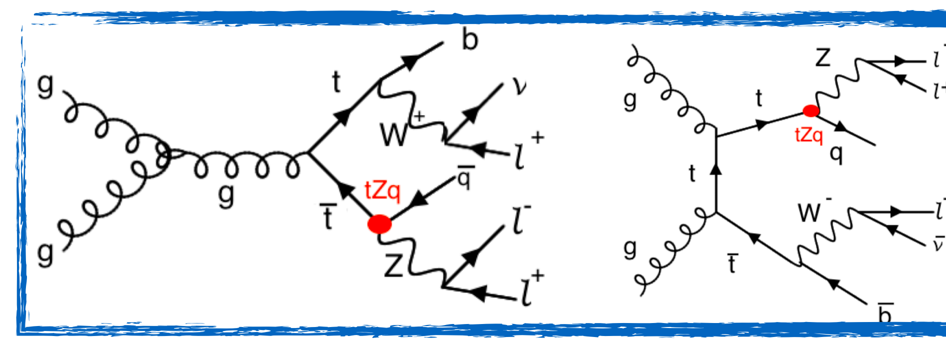
CMS-PAS-TOP-17-017

- Two channels are considered:
  - single top quark **FCNC production** (pp → tZ)
  - top quark pair production with **FCNC decay** (t → qZ)
- Looking for events with:
  - exactly 3 leptons= one opposite sign + same flavour pair
  - 1≤ jet(s) ≤ 3 & W transverse mass < 300 GeV
- Dedicated BDT discriminants for each of 3 signal regions
- Set observed (expected) 95% CL limits on the branching ratio t → qZ:

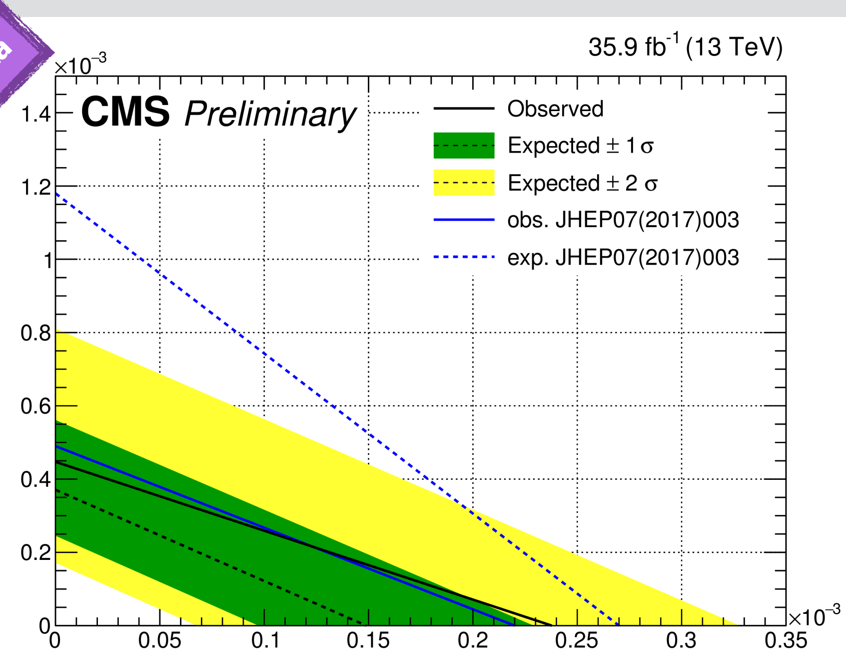
$\mathcal{B}$(t → uZ) < 0.024% (0.015%)

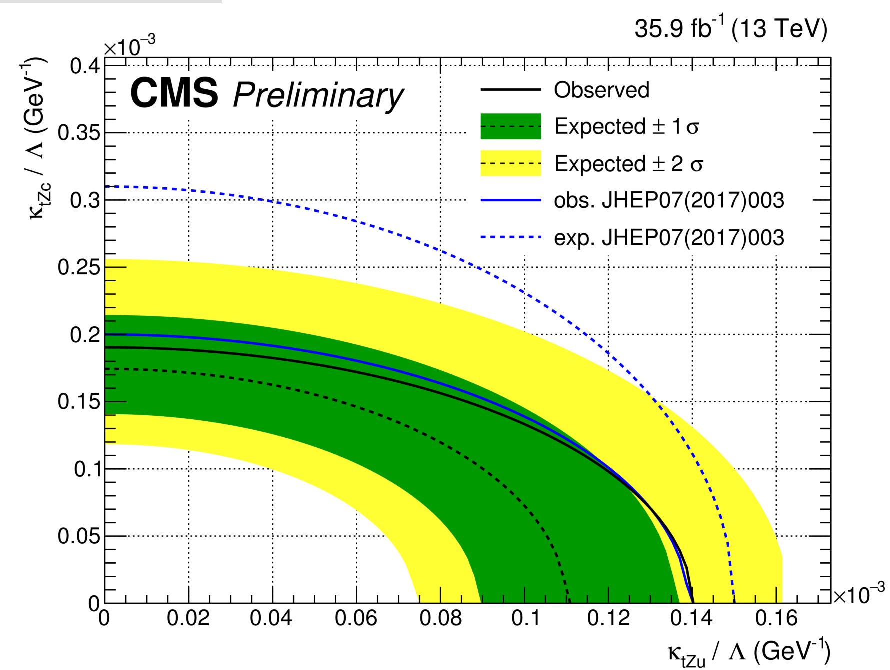
$\mathcal{B}$(t → cZ) < 0.045% (0.037%)





2015-16 data





FCNC in Top Quark

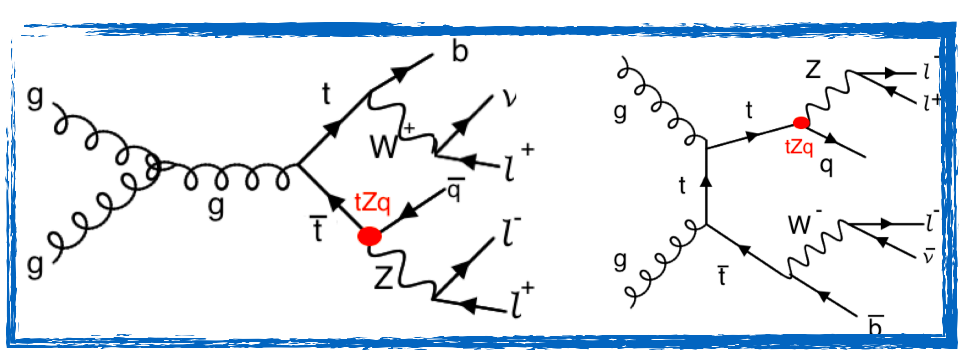
Search for t → qZ

- Looking in **top-quark pair events** for one FCNC and one SM top quark decay:
  - three isolated leptons (e, μ)
  - at least two jets, (one b-tagged) and MET
- Only **Z boson** decays **into charged leptons** and **leptonic W boson decays** are considered as signal
- Events are reconstructed via χ^2 minimization of the kinematic properties of the final state objects
- The data are **consistent with SM background contributions**

Set observed (expected) 95% CL limits on the branching ratio t → qZ:

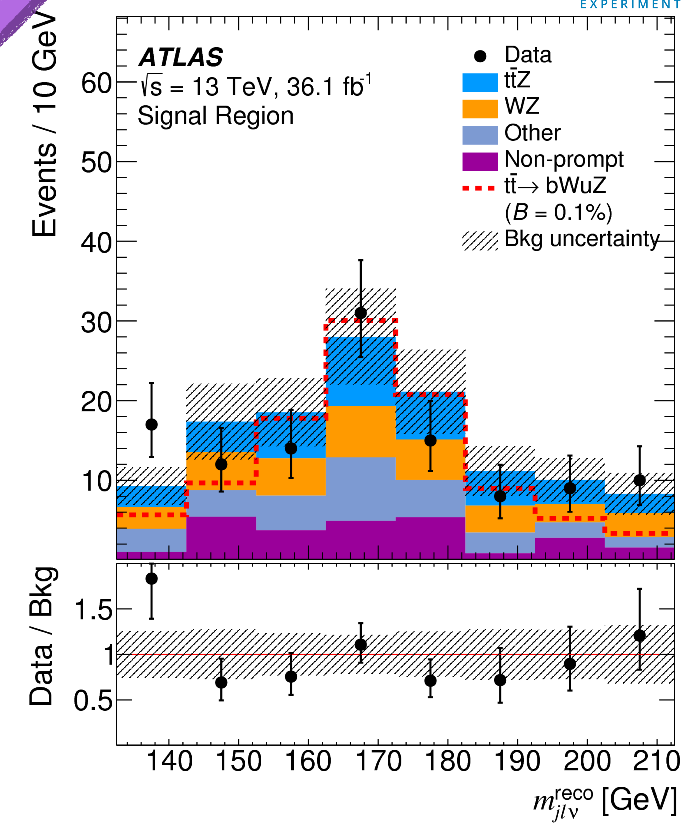
$$\mathcal{B}(t \to uZ) < 0.017\%\ (0.024\%)$$

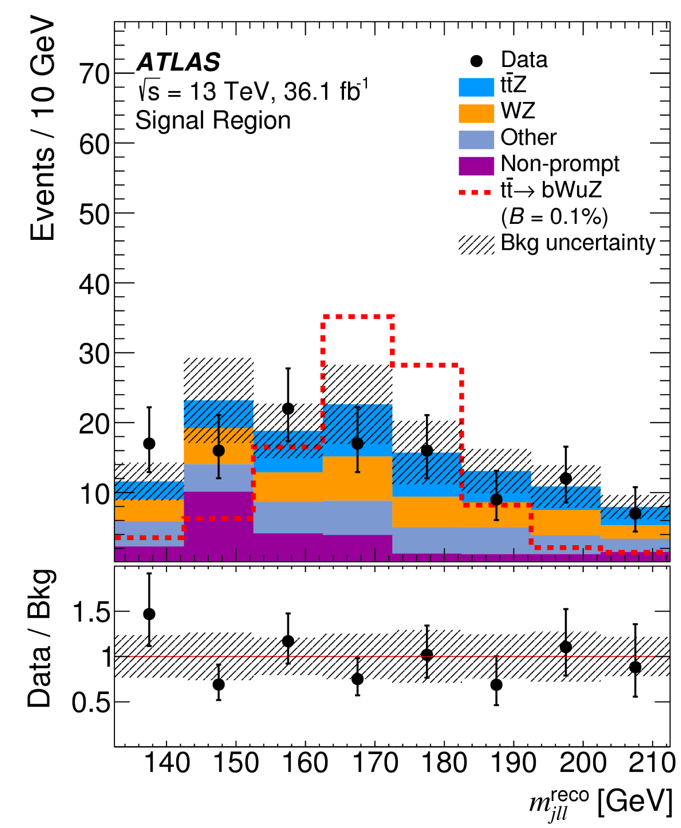
$$\mathcal{B}(t \to cZ) < 0.024\%\ (0.032\%)$$



2015+2016 data

JHEP 07 (2018) 176





FCNC in Top Quark

Search for t → qH(bb)

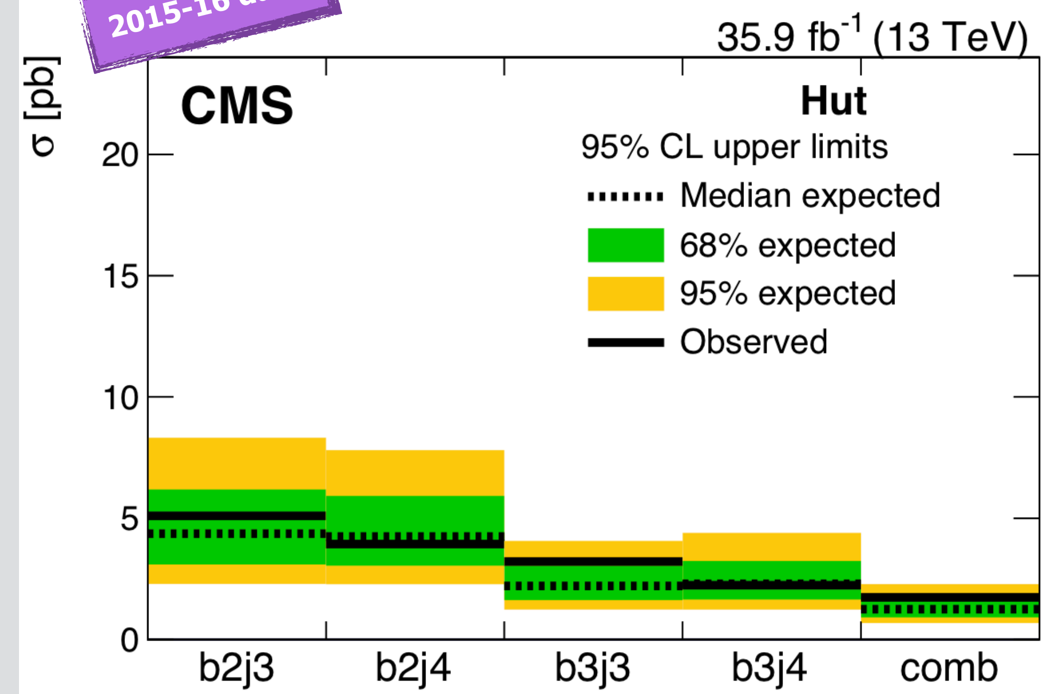
- Two channels are considered:
  - single top quark **FCNC production** (pp → tH)
  - top quark pair production with **FCNC decay** (t → qH)
- Looking for events with:
  - **one isolated lepton** (e, μ) and **at least 3 jets** (at least **2 of which are b-tagged**)
- Dedicated **BDT discriminants** for **5 signal regions**
- Set observed (expected) 95% CL limits on the branching ratio

t → qH: $\mathcal{B}(t \to uH) < 0.47\%\ (0.34\%)$

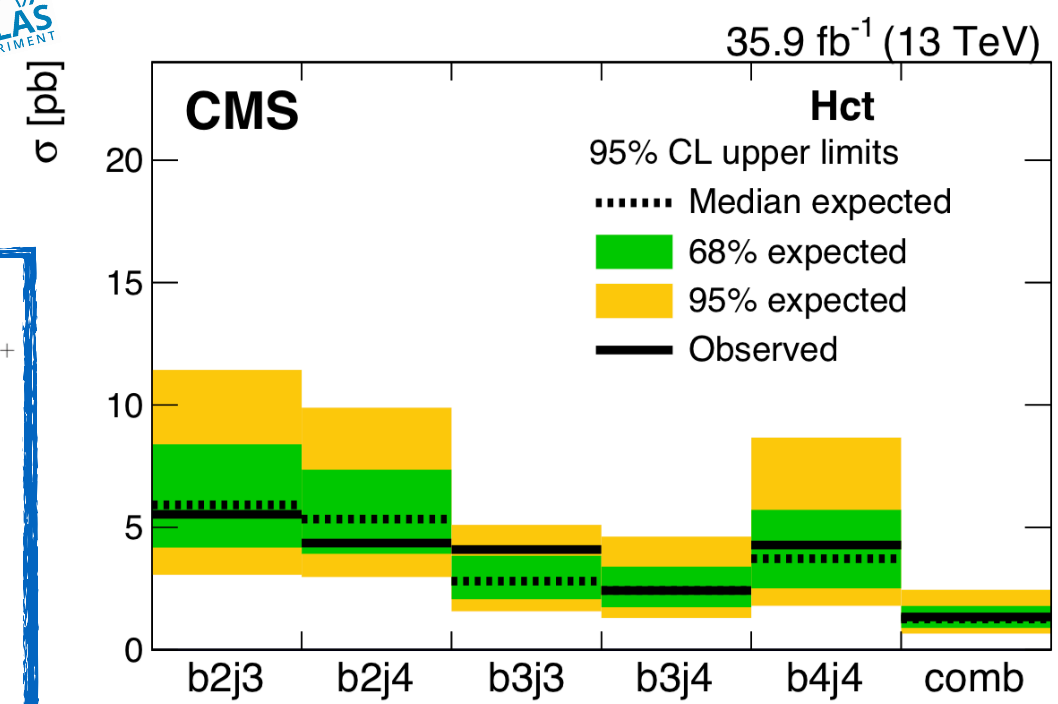
$\mathcal{B}(t \to cH) < 0.47\%\ (0.44\%)$

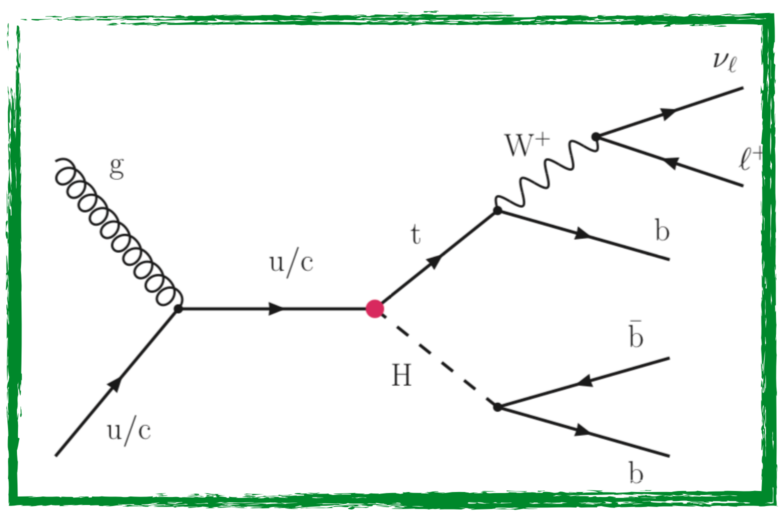
JHEP 06 (2018) 102

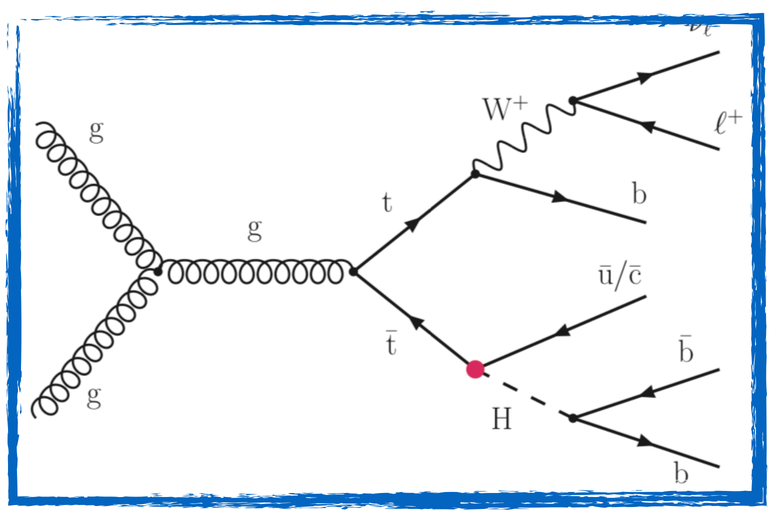
2015-16 data



Similar measurement JHEP 05 (2019) 123



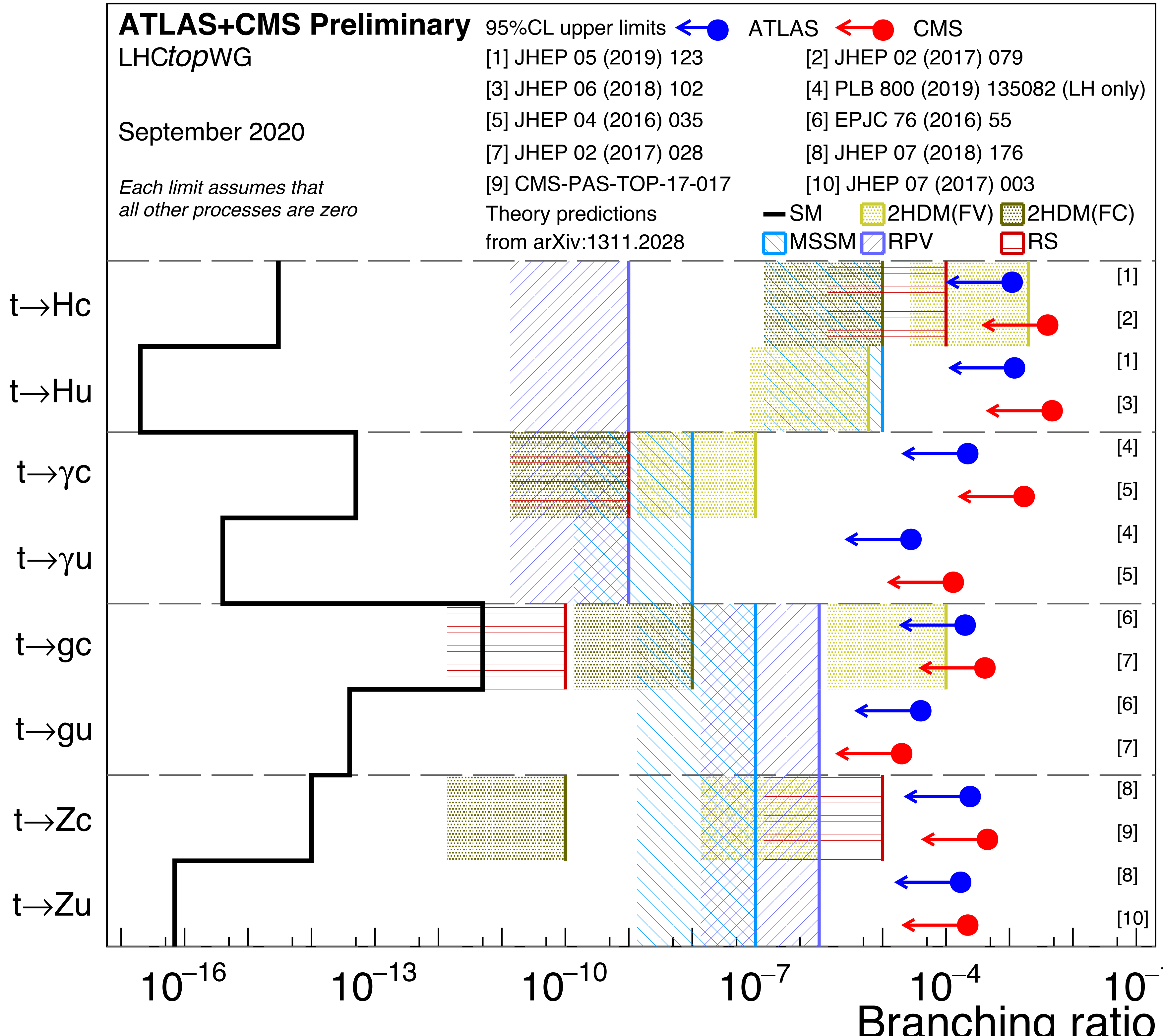




FCNC in Top Quark

FCNC @LHC in summary

- **ATLAS** and **CMS** limits on: t → q(H/γ/g/Z) branching rations comparison to **BSM** physics
- **The full Run 2 dataset is still to be analyzed**
- **More interesting results to come, stay tuned!**



Summary & Conclusion

- New W boson polarization measurements combination at 8 TeV
  - Improved polarization precision, tighter limits on the Wtb anomalous couplings
- Triple-differential angular decay rates in t-channel single top events
  - All angular coefficients are compatible with SM, limits set on anomalous couplings ratios and Polarization with no external constraints/ assumptions
- Top polarization and spin correlation is measured at 13 TeV (2016 data only)
  - Polarization is consistent with zero, spin correlation strengths are in agreement with SM prediction
- Forward-backward Asymmetry (A_{FB}) and CP violation are studied in top quark pair production
  - Results in agreement with SM expectation
- FCNC measurements are reaching some BSM effects sensitivity, no evidence found yet (but …)
- Most measurements are limited by **systematic uncertainties**
  - Measurements with full run 2 data to improve the current precision and probe rare processes
- All measurements are so far **consistent** with the SM predictions

Stay tuned for more full Run2 analyses!

Backup

W Boson Polarization Measurements

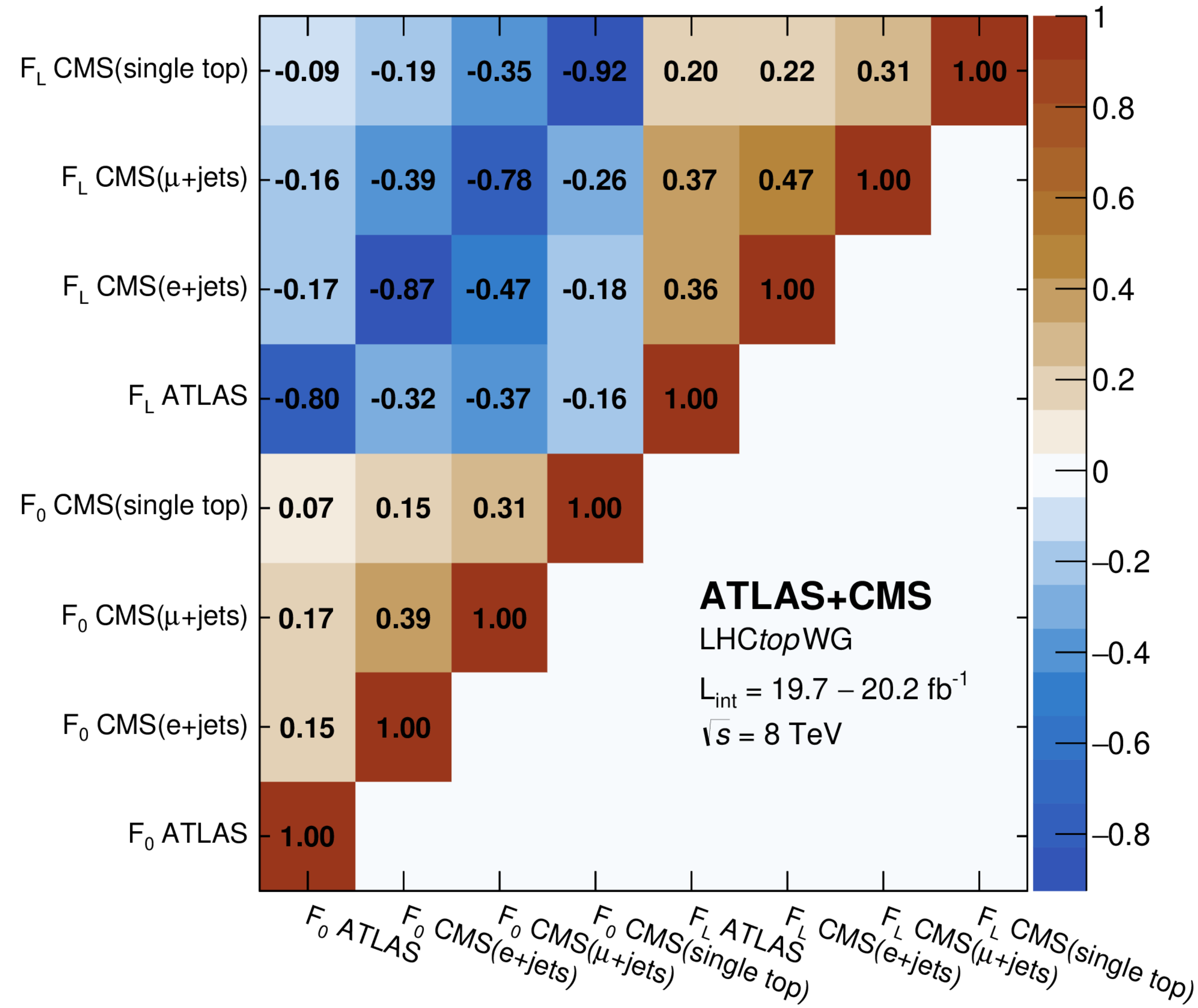
Input measurements

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)	$0.720 \pm 0.039 \pm 0.037$	$0.298 \pm 0.028 \pm 0.032$	$-0.018 \pm 0.019 \pm 0.011$

Total Correlation

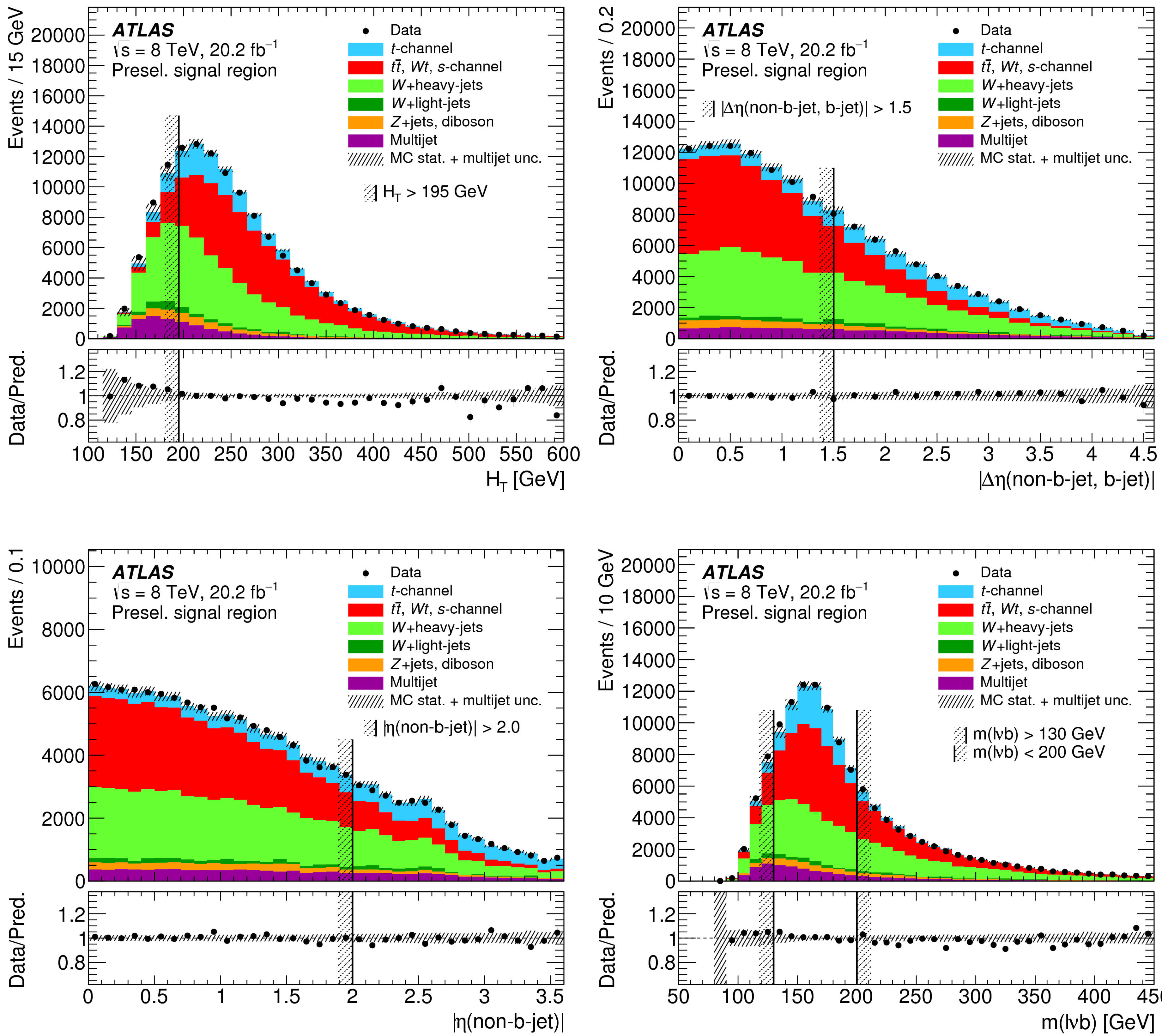
	ATLAS+CMS combination	
	F_0	F_L
Fractions	0.693	0.315
Uncertainty category		
Samples size and background determination		
Stat+bkg	0.009	0.006
Size of simulated samples	0.005	0.003
Detector modelling		
JES	0.004	0.002
JER	0.004	0.002
b tagging	0.001	0.001
JVF	0.001	0.001
Jet reconstruction	< 0.001	< 0.001
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

Total Correlation



Triple-differential angular decay rates

JHEP 12 (2017) 017



Triple-differential angular decay rates

JHEP 12 (2017) 017

Source	Helicity parameters		Coupling ratios	
	$\sigma(f_1)$	$\sigma(\delta_-)/\pi$	$\sigma(\mathrm{Re}\,[g_R/V_L])$	$\sigma(\mathrm{Im}\,[g_R/V_L])$
Statistical	0.022	0.013	0.030	0.027
Jets	0.029	0.007	0.039	0.009
Leptons	0.014	0.002	0.017	<0.001
E_T^{miss}	<0.001	<0.001	<0.001	<0.001
Generator	0.027	0.006	0.030	0.010
Parton shower and hadronisation	0.004	0.003	<0.001	0.003
PDF variations	0.008	0.004	<0.001	<0.001
Background normalisation	<0.001	<0.001	<0.001	<0.001
Multijet normalisation	<0.001	<0.001	<0.001	<0.001
W+jets shape	0.015	0.005	0.007	0.009
Luminosity	<0.001	<0.001	<0.001	<0.001
MC sample sizes	0.009	0.006	<0.001	0.013
Other	<0.001	<0.001	<0.001	<0.001
Total systematic uncertainty	0.044	0.010	0.061	0.017
Total	0.049	0.017	0.068	0.032

Angular coefficients

$$a_{0,0,0} = \frac{1}{\sqrt{8\pi}} ,$$

$$a_{0,1,0} = \frac{\sqrt{3}}{\sqrt{8\pi}} f_1 \left(f_1^+ - \frac{1}{2} \right) ,$$

$$a_{0,2,0} = \frac{1}{\sqrt{40\pi}} \left(\frac{3}{2} f_1 - 1 \right) ,$$

$$a_{1,0,0} = +P \frac{1}{\sqrt{24\pi}} \left(f_1 (2f_1^+ - 1) + (1 - f_1)(1 - 2f_0^+) \right) ,$$

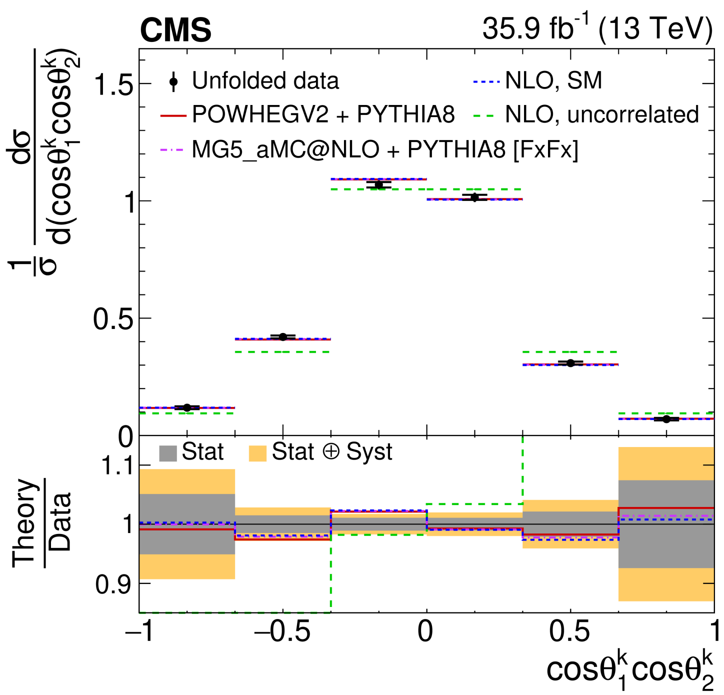
$$a_{1,1,0} = +P \frac{1}{\sqrt{32\pi}} f_1 ,$$

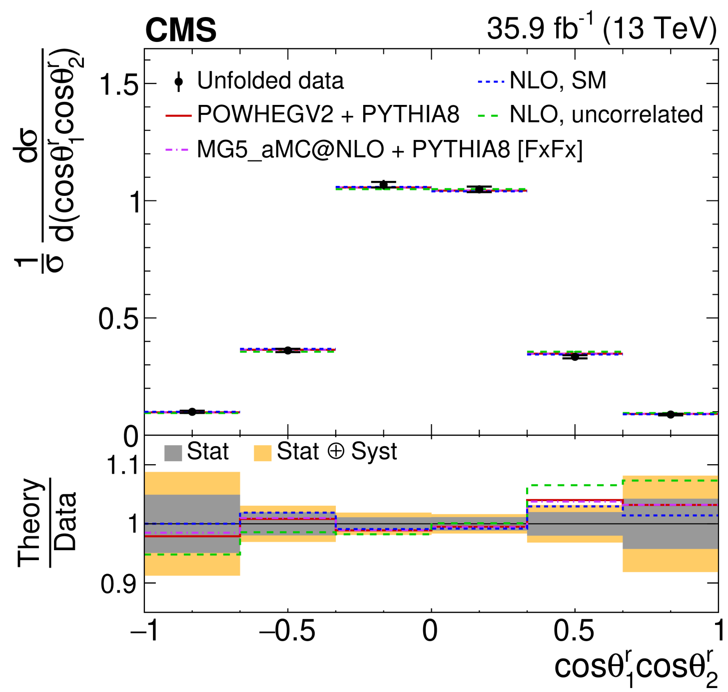
$$a_{1,2,0} = +P \frac{1}{\sqrt{480\pi}} \left(f_1 (2f_1^+ - 1) - 2(1 - f_1)(1 - 2f_0^+) \right) ,$$

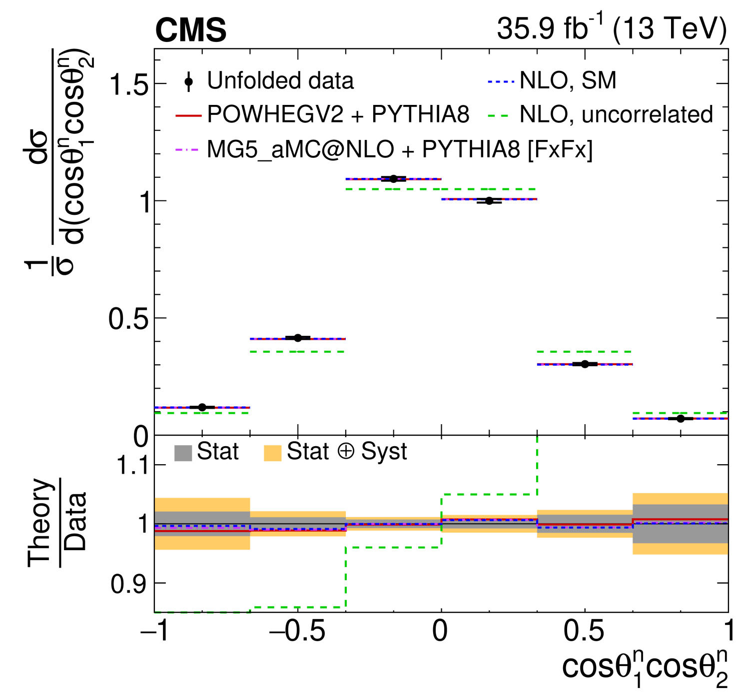
$$a_{1,1,1} = (a_{1,1,-1})^* = -P \frac{1}{\sqrt{16\pi}} \sqrt{f_1(1-f_1)} \left\{ \sqrt{f_1^+ f_0^+}\, \mathrm{e}^{i\delta_+} + \sqrt{(1-f_1^+)(1-f_0^+)}\, \mathrm{e}^{-i\delta_-} \right\}$$

$$a_{1,2,1} = (a_{1,2,-1})^* = -P \frac{1}{\sqrt{80\pi}} \sqrt{f_1(1-f_1)} \left\{ \sqrt{f_1^+ f_0^+}\, \mathrm{e}^{i\delta_+} - \sqrt{(1-f_1^+)(1-f_0^+)}\, \mathrm{e}^{-i\delta_-} \right\}$$

Polarization & Spin Correlation



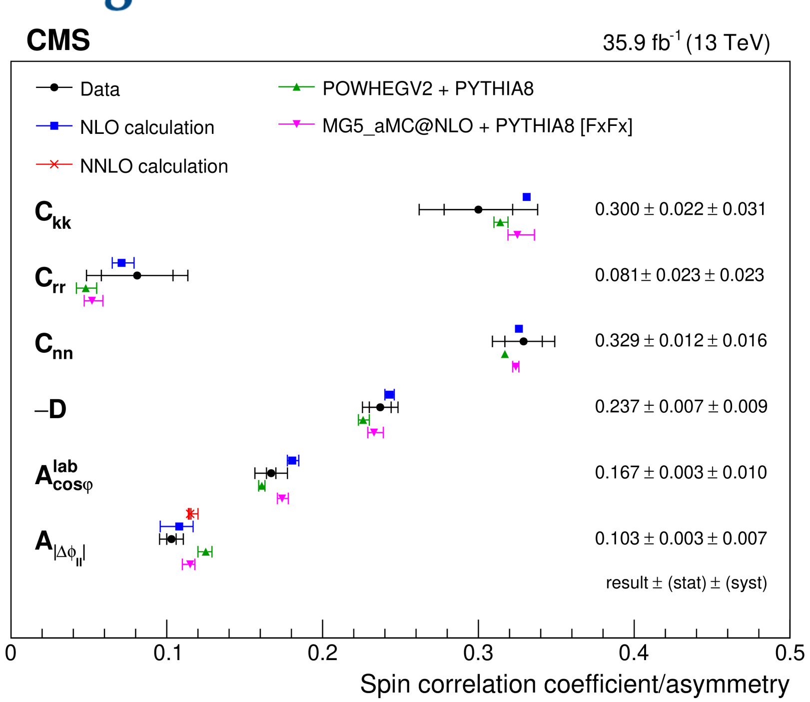




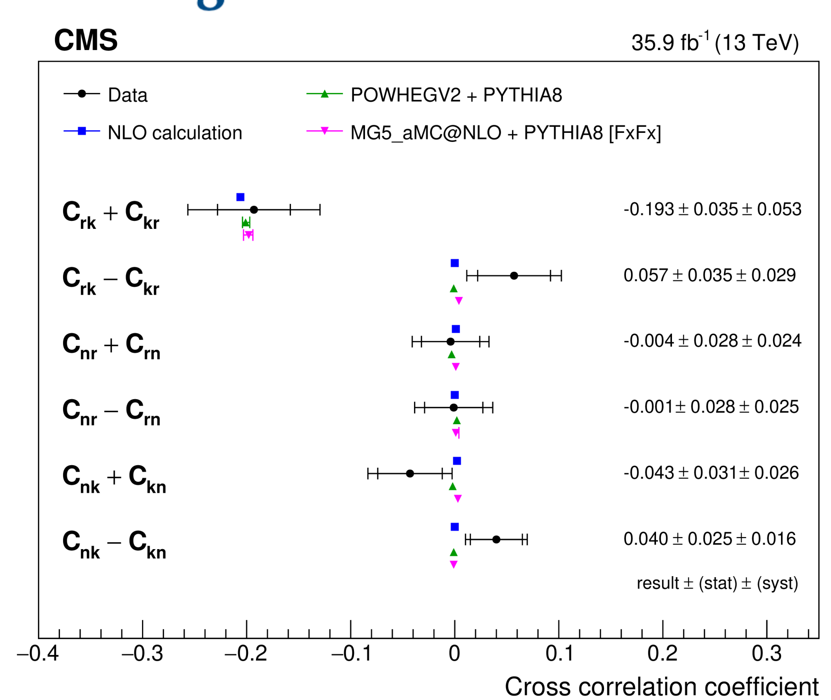
Phys. Rev. D 100 (2019) 072002

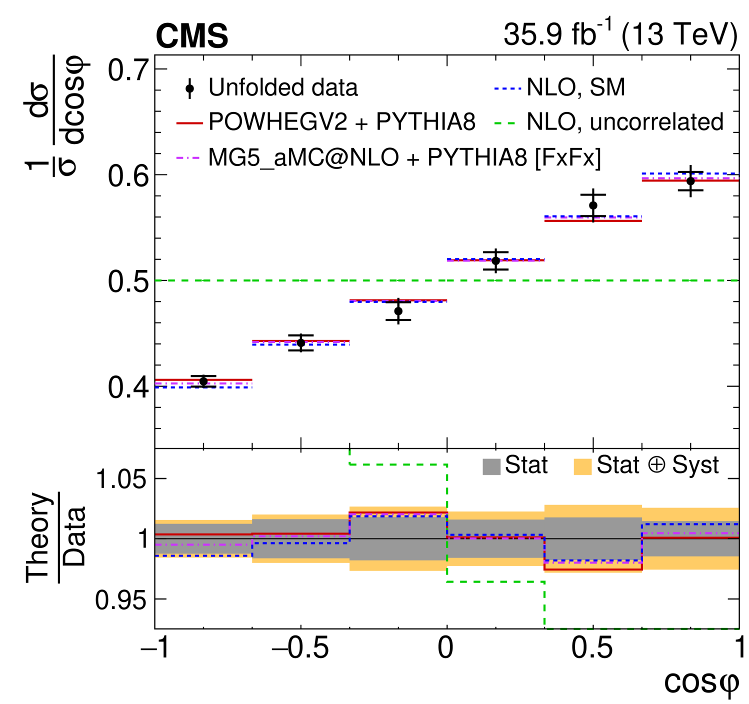
- C_{kk} =0.30±0.02±0.03
  SM: 0.33
- C_{rr} =0.08±0.02±0.02
  SM: 0.07
- C_{nn} =0.33±0.01±0.02
  SM: 0.33

Diagonal elements of ℂ matrix



Off-diagonal elements of ℂ matrix





Polarization & Spin Correlation

Eur. Phys. J. C 80 (2020) 754

2015+2016 data

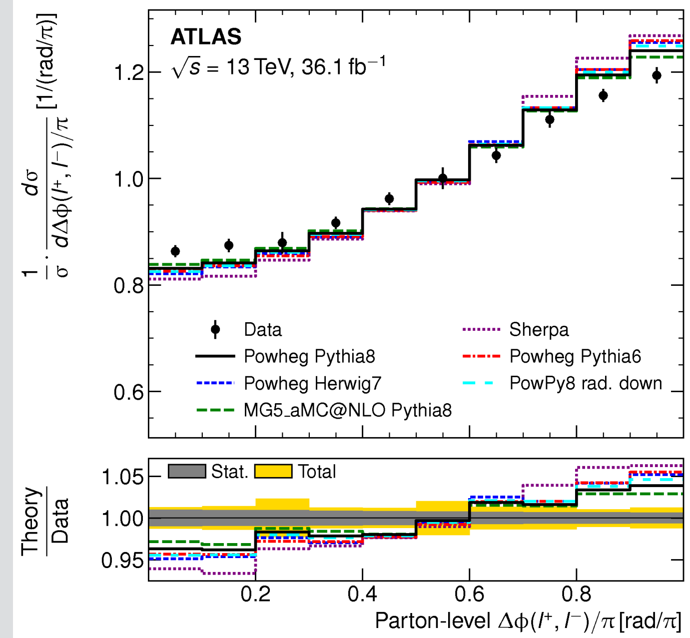
<u>Indirect</u> measurement

- Δφ distribution measured in ***eμ* channel**
  - corrected in data for acceptance effect
- **Data vs NLO discrepancy** in both full and fiducial phase space is observed

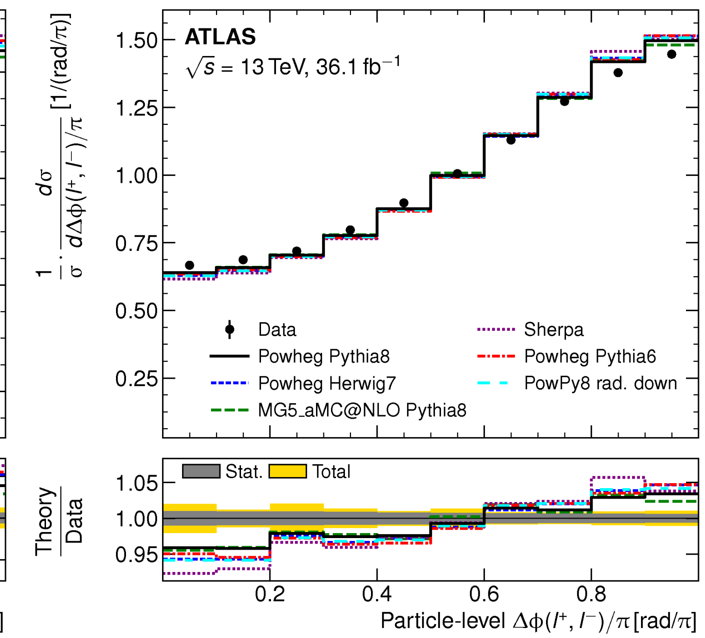
  $\mathbf{f_{SM} = 1.25 \pm 0.08 \;\approx 3.2\sigma}$
  - Due to Missmodelling of top quark kinematics
- Dominant systematics uncertainty: generator radiation and scale settings
- None of the studied MC generators are able to reproduce the normalized Δφ distribution within the experimental errors
- **NNLO**: reduced discrepancy
- **NNLO+EW**: compatible within (large) uncertainty

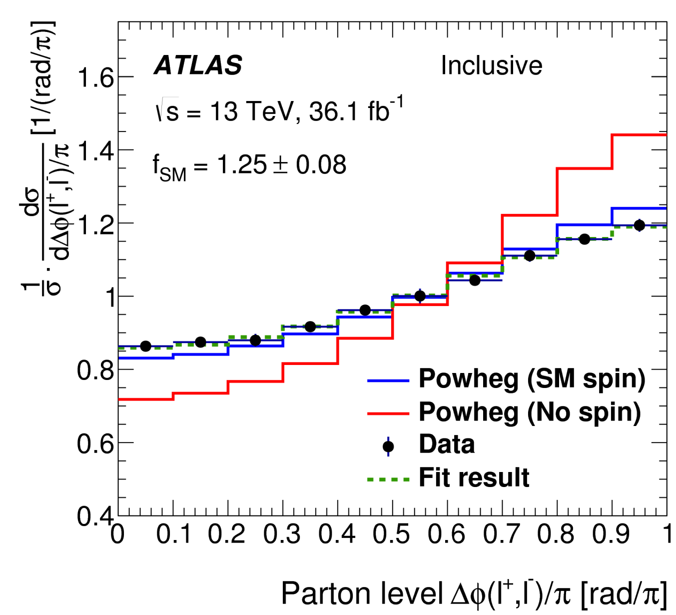
SUSY: search for **top squarks** production:
Excluded top squark mass: **[170 - 230 GeV]**

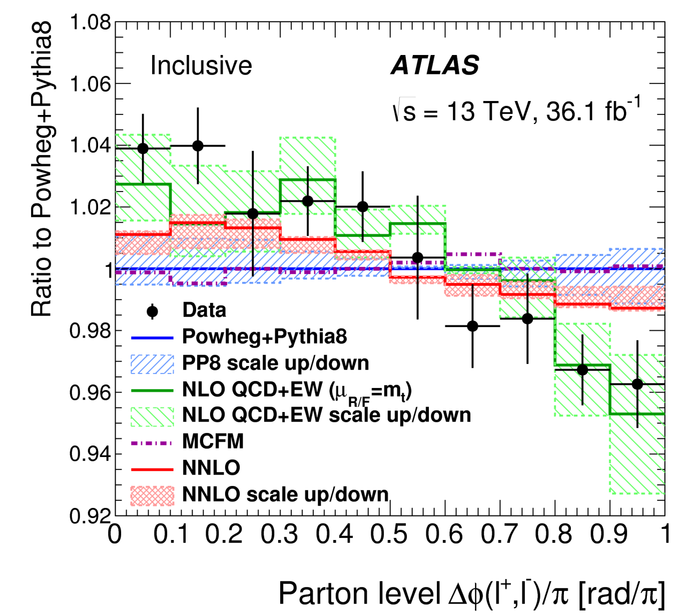
parton level, full phase space



particle level, fiducial phase space



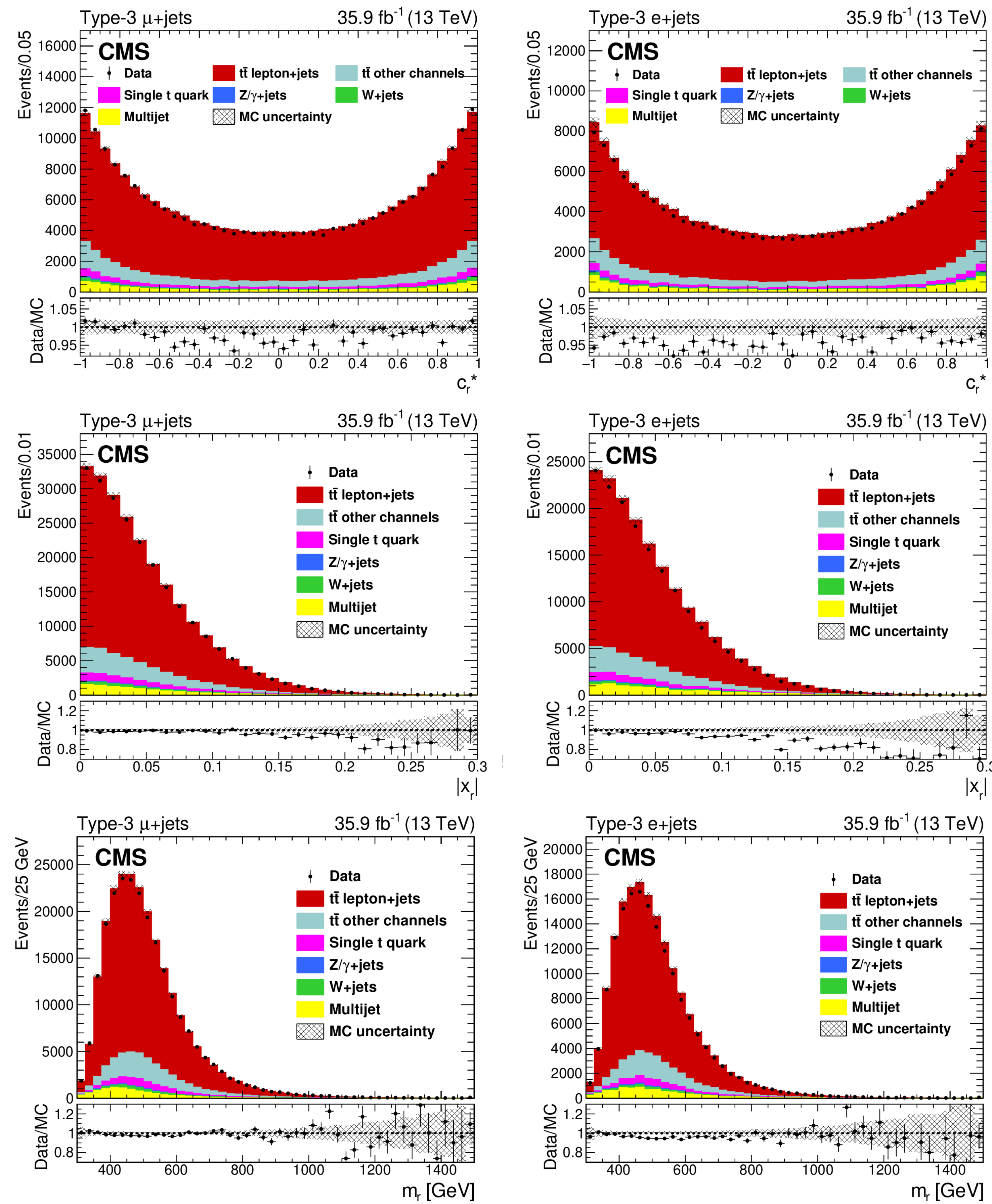




Forward-backward Production Asymmetry

JHEP 06 (2020) 146

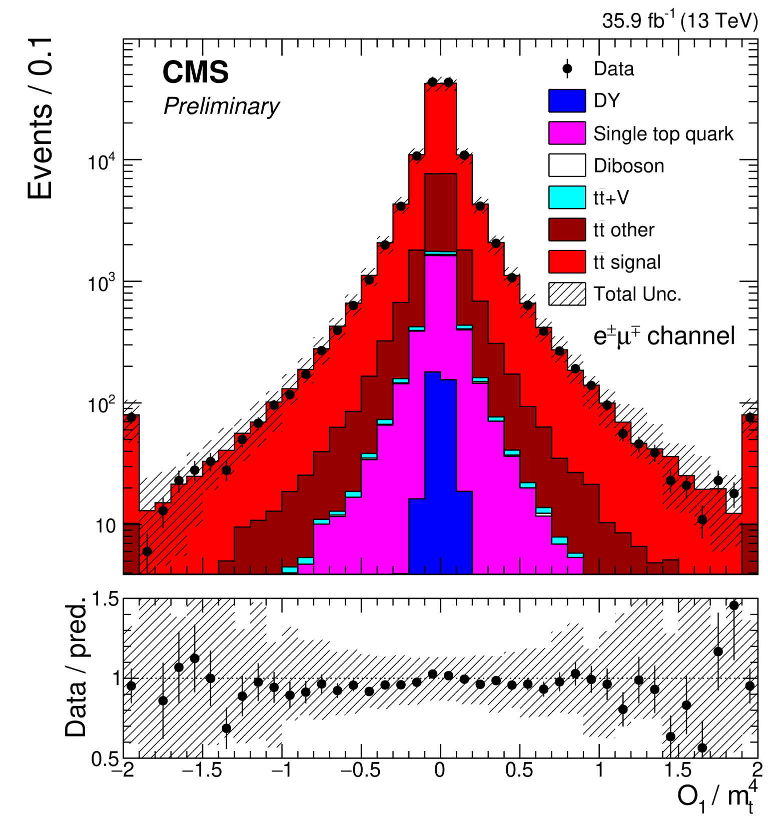
Source	Uncertainty in	Type	Size	Affects
Jet energy scale	$\pm 1\sigma(p_T, \eta, A)$	N & S	7.6%	All
Jet energy resolution	$\pm 1\sigma(\lvert\eta\rvert)$	N & S	3.2%	All
Pileup	$\pm 1\sigma(n_{PV})$	N & S	2.9%	All
Boosted μ+jets trigger eff.	$\pm 1\sigma(p_T, \eta)$	N & S	0.4%	Type-1/2 μ+jets
Resolved 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



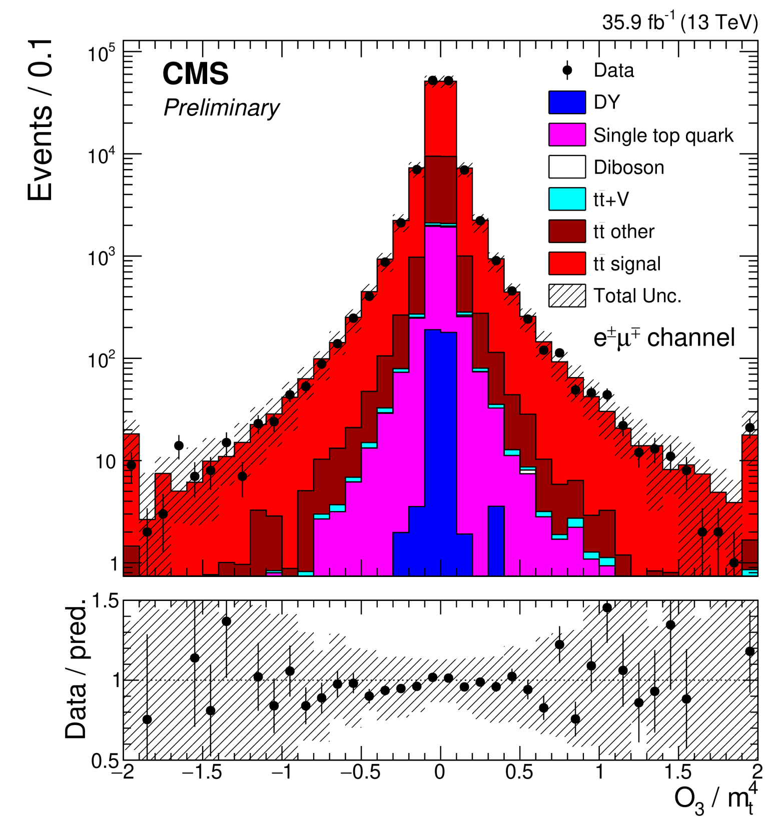
CP violating anomalous top quark couplings

CMS-PAS-18-007

Source	$\mu^+\mu^-$ up	$\mu^+\mu^-$ down	e^+e^- up	e^+e^- down	$e^\pm\mu^\mp$ up	$e^\pm\mu^\mp$ down	Combined up	Combined down
	Uncertainty ($\times10^{-3}$)							
Muon energy	2.3	−2.3	–	–	0.1	−0.1	0.5	−0.5
Electron scale and smearing	–	–	1.2	−1.2	0.2	−0.2	0.3	−0.3
JES	2.3	−2.3	1.9	−1.9	0.1	−0.1	0.7	−0.7
JER	1.2	−1.2	2.0	−2.0	0.3	−0.3	0.6	−0.6
Limited number of simulated BG events	2.3	−2.3	2.9	−2.9	0.6	−0.6	0.7	−0.7
ME–PS matching	0.8	−0.8	0.8	−0.8	0.3	−0.3	0.4	−0.4
Color reconnection	1.0	−1.0	1.9	−1.9	1.6	−1.6	1.5	−1.5
Underlying event	1.4	−1.4	0.6	−0.6	1.4	−1.4	1.4	−1.4
ISR	0.3	−0.3	1.5	−1.5	0.2	−0.2	0.3	−0.3
FSR	0.6	−0.6	1.0	−1.0	0.8	−0.8	0.7	−0.7
Hadronization	1.7	−1.7	2.0	−2.0	0.6	−0.6	0.9	−0.9
Charge misidentification	0.1	−0.1	0.8	−0.8	0.4	−0.4	0.3	−0.3
Total systematic uncertainty	5.0	−5.0	5.6	−5.6	2.6	−2.6	2.8	−2.8



Source	$\mu^+\mu^-$ up	$\mu^+\mu^-$ down	e^+e^- up	e^+e^- down	$e^\pm\mu^\mp$ up	$e^\pm\mu^\mp$ down	Combined up	Combined down
	Uncertainty ($\times10^{-3}$)							
Muon energy	1.0	−1.0	–	–	0.2	−0.2	0.3	−0.3
Electron scale and smearing	–	–	1.1	−1.1	0.2	−0.2	0.2	−0.2
JES	0.7	−0.7	0.6	−0.6	0.2	−0.2	0.3	−0.3
JER	0.3	−0.3	0.7	−0.7	0.2	−0.2	0.2	−0.2
Limited number of simulated BG events	2.3	−2.3	2.9	−2.9	0.6	−0.6	0.7	−0.7
ME–PS matching	1.5	−1.5	1.4	−1.4	0.7	−0.7	0.9	−0.9
Color reconnection	0.9	−0.9	3.8	−3.8	1.0	−1.0	1.1	−1.1
Underlying event	1.0	−1.0	0.9	−0.9	1.1	−1.1	1.0	−1.0
ISR	0.5	−0.5	1.8	−1.8	0.2	−0.2	0.3	−0.3
FSR	0.3	−0.3	1.9	−1.9	0.6	−0.6	0.6	−0.6
Hadronization	0.2	−0.2	0.5	−0.5	0.3	−0.3	0.3	−0.3
Charge misidentification	0.1	−0.1	0.8	−0.8	0.4	−0.4	0.3	−0.3
Total systematic uncertainty	3.5	−3.5	6.0	−6.0	2.0	−2.0	2.2	−2.2

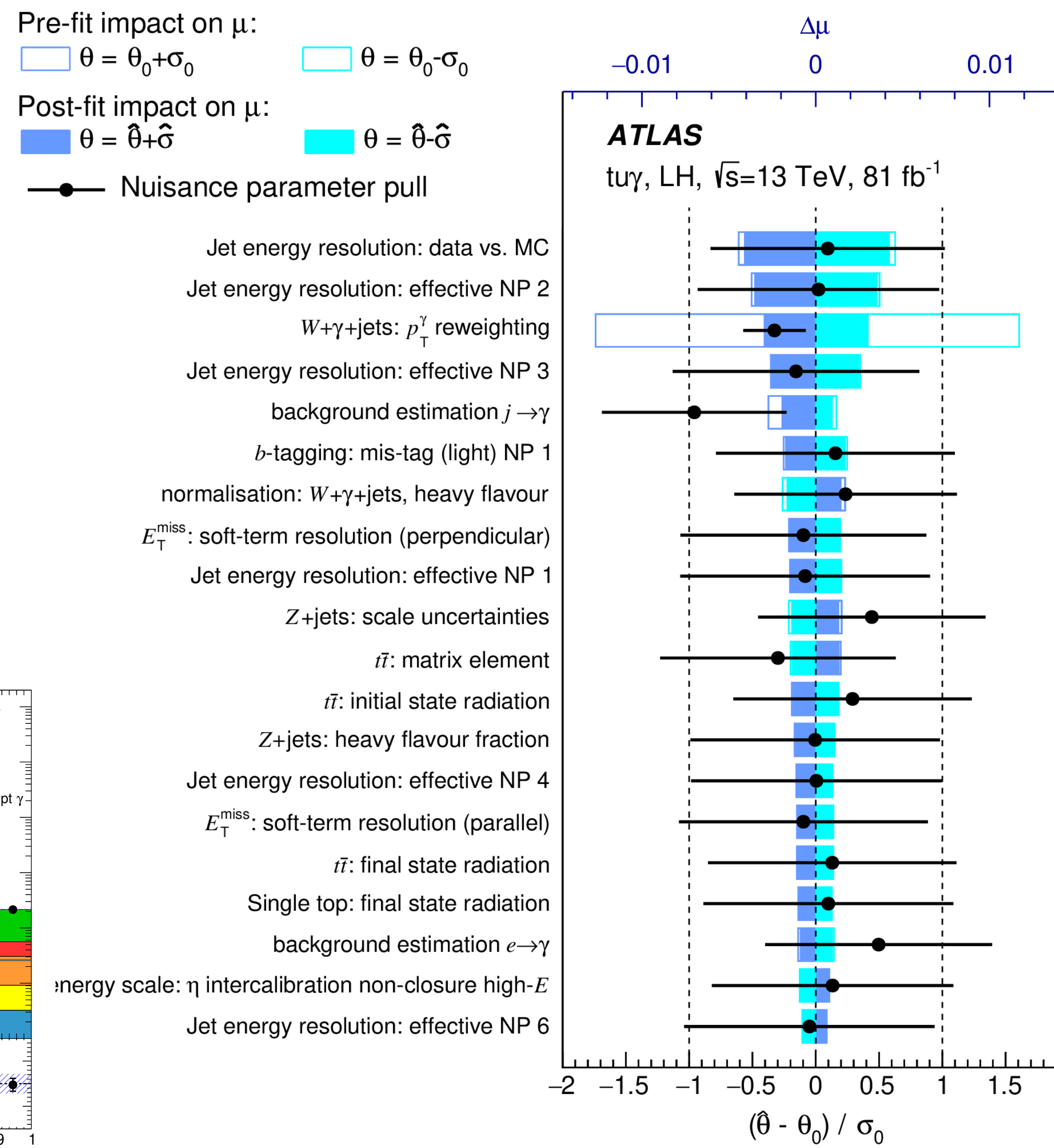


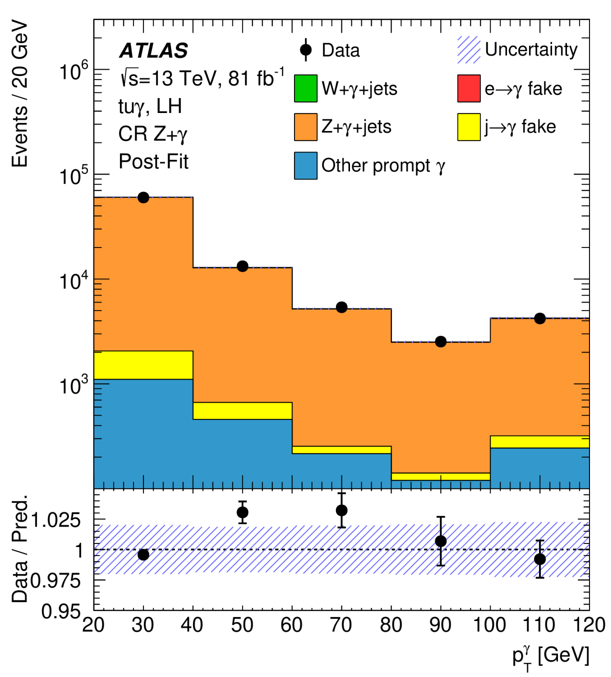
FCNC in Top Quark

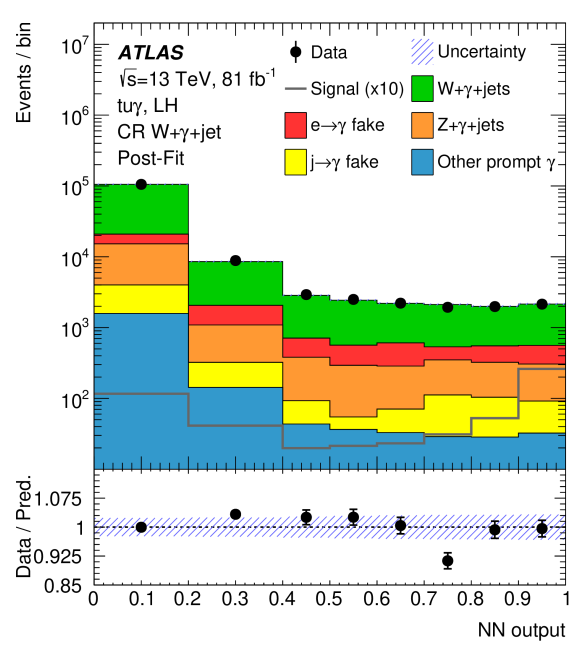
Search for t → qɣ

Phys. Lett. B 800 (2019) 135082

Observable	Vertex	Coupling	Obs.	Exp.
$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*} \rvert$	$tu\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(31)} + C_{uB}^{(31)} \rvert$	$tu\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
$\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*} \rvert$	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
$\lvert C_{uW}^{(32)} + C_{uB}^{(32)} \rvert$	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	LH	36	52^{+21}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	RH	78	75^{+31}_{-21}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}
$\mathcal{B}(t \to q\gamma)\ [10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)\ [10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)\ [10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)\ [10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}







Polarization & Spin Correlation

ATLAS: Indirect measurement

- $\Delta\varphi$ distribution measured in ***eμ* channel**
  - corrected in data for acceptance effect
- **Data vs NLO discrepancy** in both full and fiducial phase space is observed

  $$f_{SM} = 1.25 \pm 0.08 \approx 3.2\sigma$$

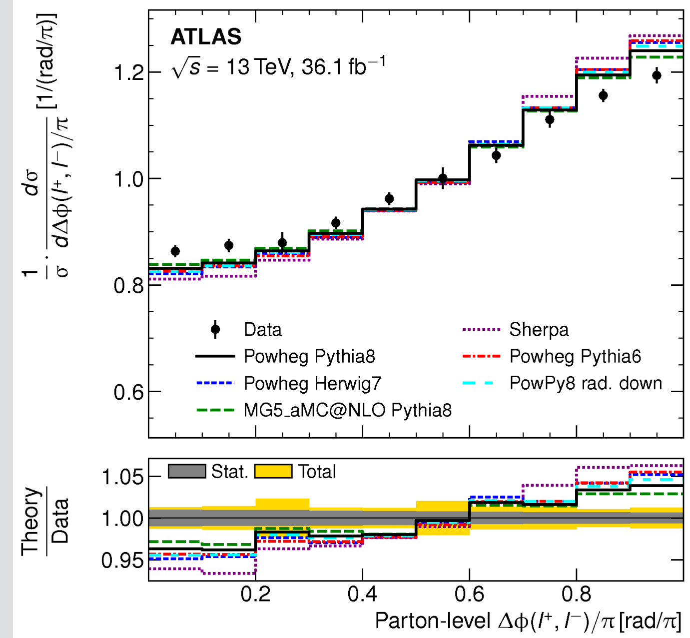
  - Due to Missmodelling of top quark kinematics
- Dominant systematics uncertainty: generator radiation and scale settings
- None of the studied MC generators are able to reproduce the normalized $\Delta\varphi$ distribution within the experimental errors
- **NNLO**: reduced discrepancy
- **NNLO+EW**: compatible within (large) uncertainty

SUSY: search for **top squarks** production:
Excluded top squark mass: **[170 - 230 GeV]**

2015+2016 data

Eur. Phys. J. C 80 (2020) 754

parton level, full phase space



particle level, fiducial phase space