# Top Quark Flavour Physics

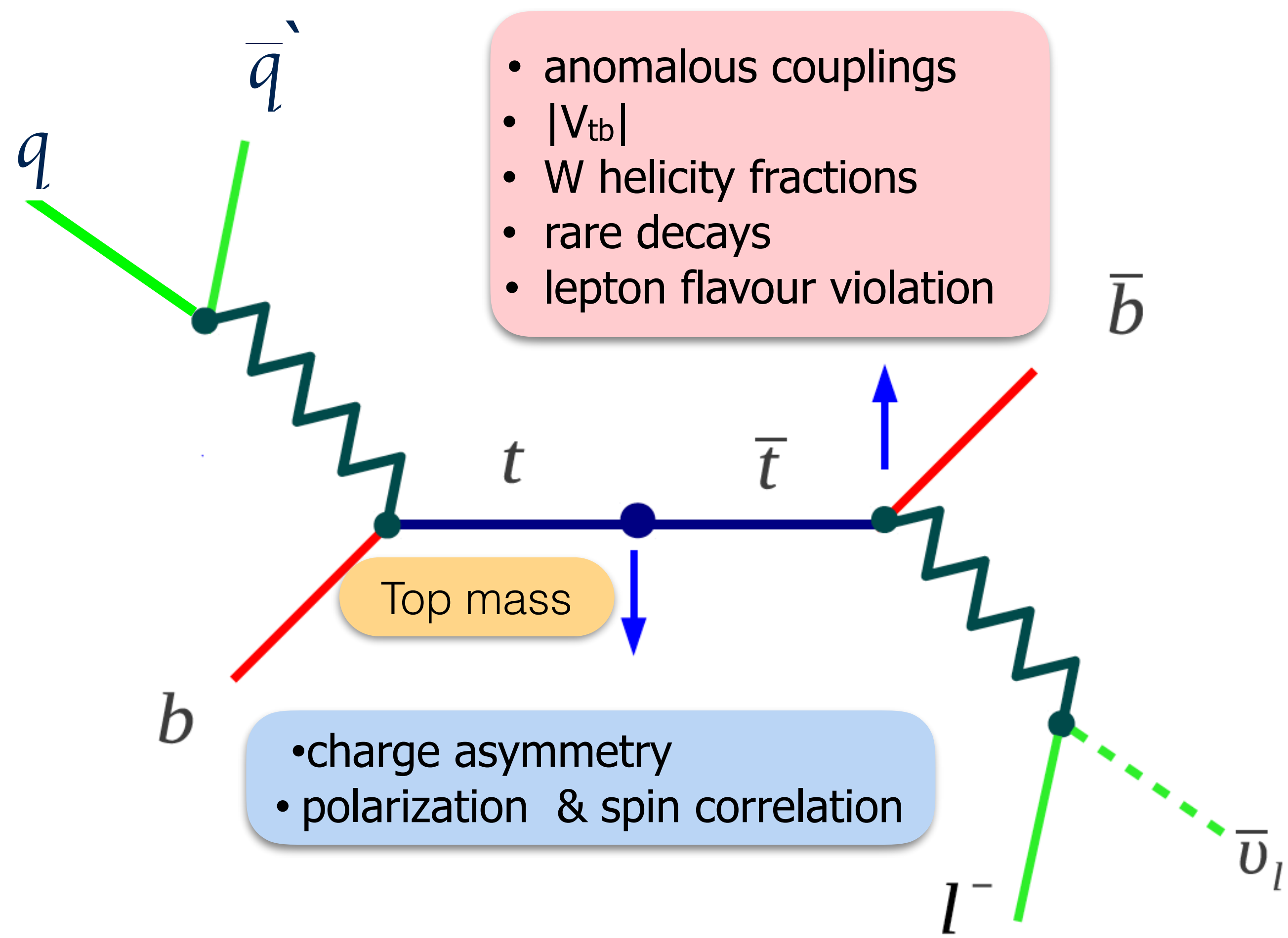
FPCP 2019
06-10 May, Victoria, Canada

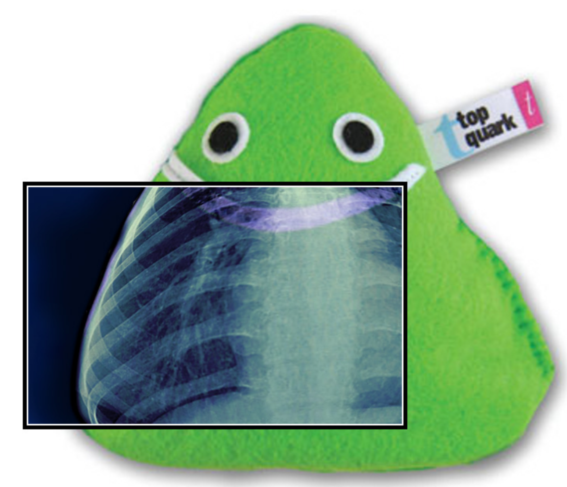
Mohammad J. Kareem
on behalf of the ATLAS and CMS collaborations

# Introduction & Motivation

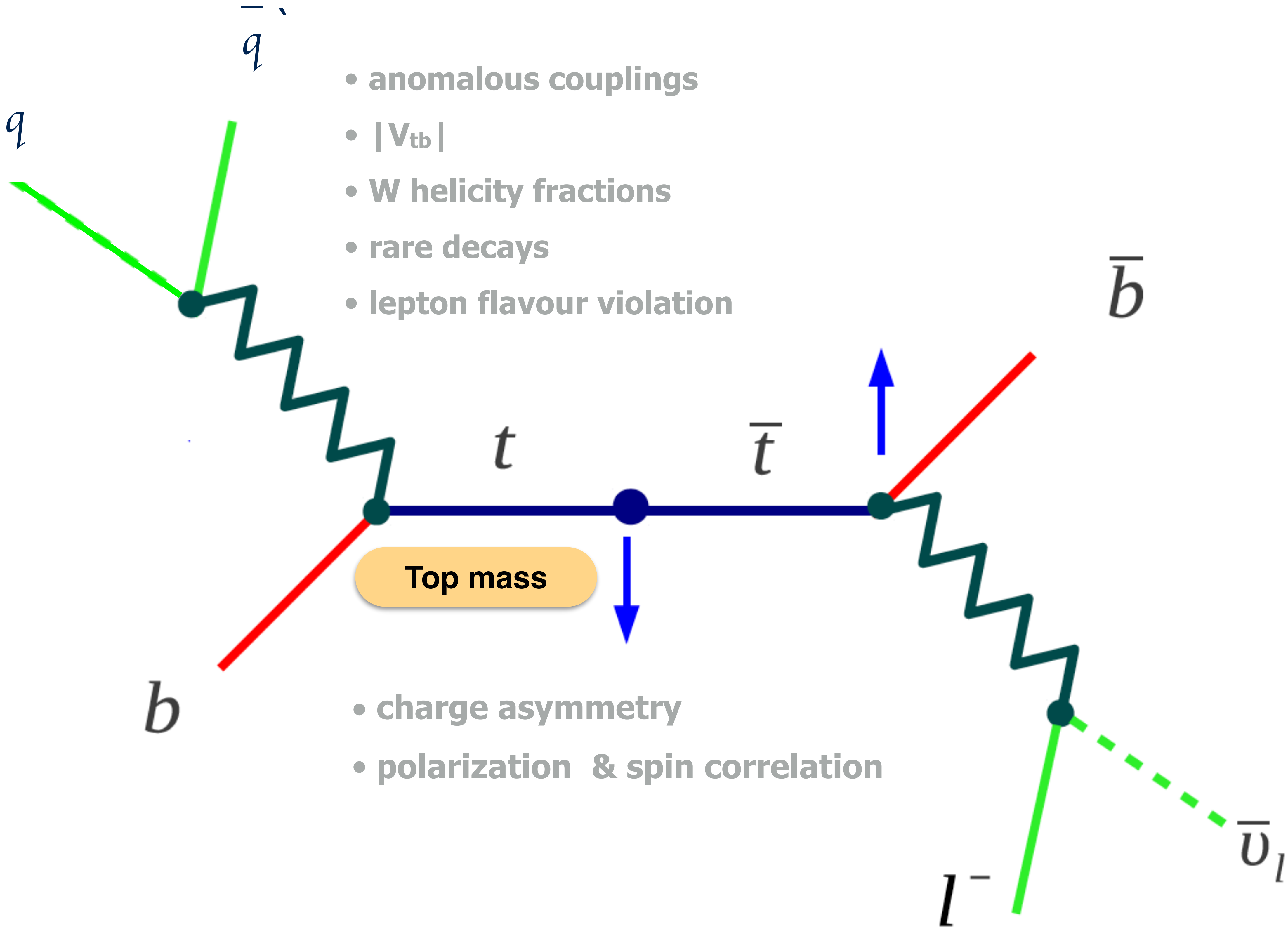
## Why Studying Top Quark Properties?

- **Heaviest fundamental particle discovered so far** → $m_t \approx 173$ GeV
- **Extremely short lifetime** → a unique opportunity to study a bare quark
- **Strong coupling to Higgs** → special role in the Standard Model
- **A portal to new physics?**
- **High production rate at the LHC** → precision measurements and detailed studies of properties



# Top Quark Properties




- anomalous couplings
- $|V_{tb}|$
- W helicity fractions
- rare decays
- lepton flavour violation

- charge asymmetry
- polarization & spin correlation

# Top Quark Mass Measurement

## Measurement strategies

- **Direct:** Using the decay products of the top quark
- **Indirect:** Using **cross sections** or unfolded distributions and compare with **theory predictions**

## Direct measurement @8TeV, Combination of 7 & 8 TeV

- top mass measurement in **l+jets channel @8TeV**
- Analysis technique: **three-dimensional template fit**
  - events are reconstructed via **kinematic likelihood fit**
  - $(m_{top})^{reco}$, $(m_W)^{reco}$, $(R_{bq})^{reco}$ =sum(pTb-jets)/sum(pT light-jets)
  - simultaneous fit for $m_{top}$ for and **energy scale factors** (**JSF**, **bJSF**) ➜ **reduces the total uncertainty in $m_{top}$**

$$m_{top} = 172.08 \pm 0.39(\text{stat}) \pm 0.82(\text{syst})\ \text{GeV}$$

- Dominant systematics: JES, b-tagging

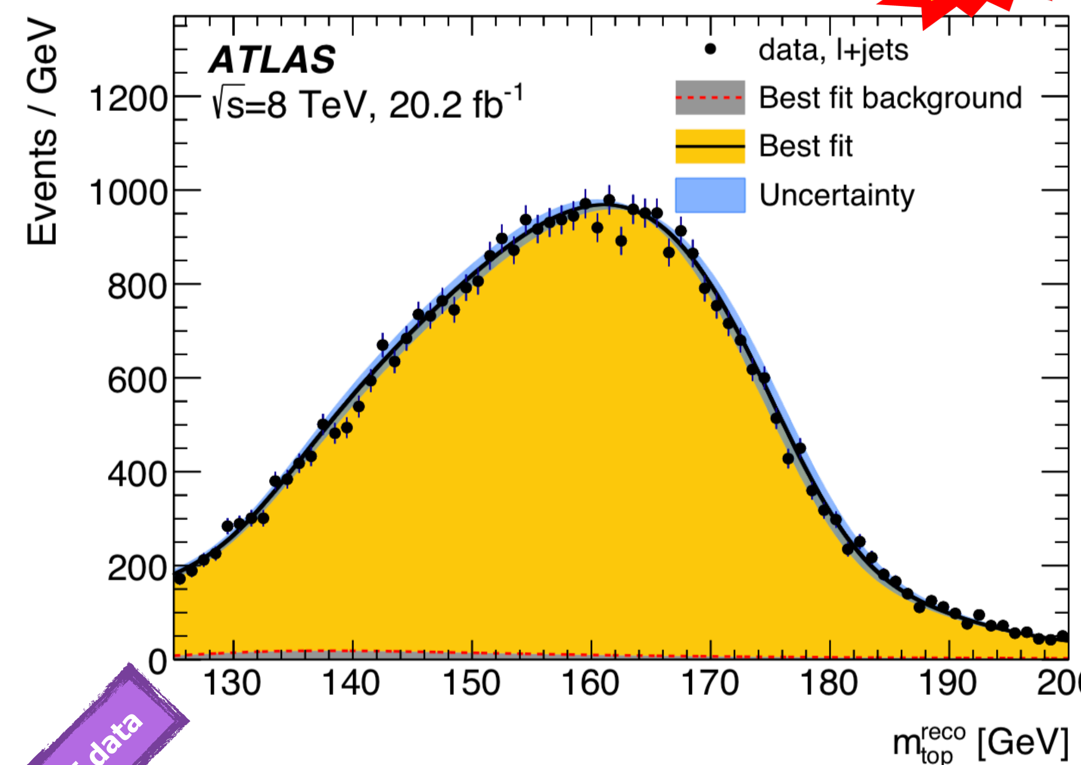
- Combination with **previous measurements:**

$$m_{top} = 172.69 \pm 0.25\ (\text{stat}) \pm 0.41\ (\text{syst})\ \text{GeV}$$

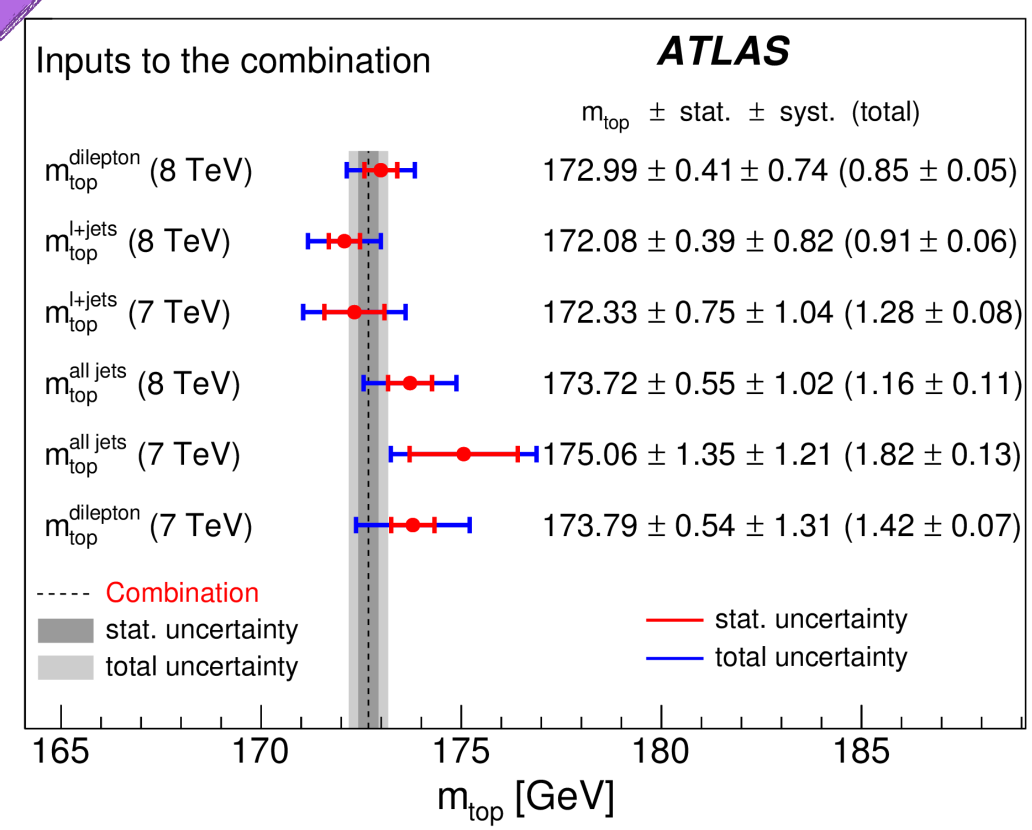
**Total uncertainty: 0.48 GeV (Δ = 0.28%)**

EPJC 79 (2019) 290

New!




Run I data



# Top Quark Mass Measurement

## Indirect measurements @13TeV

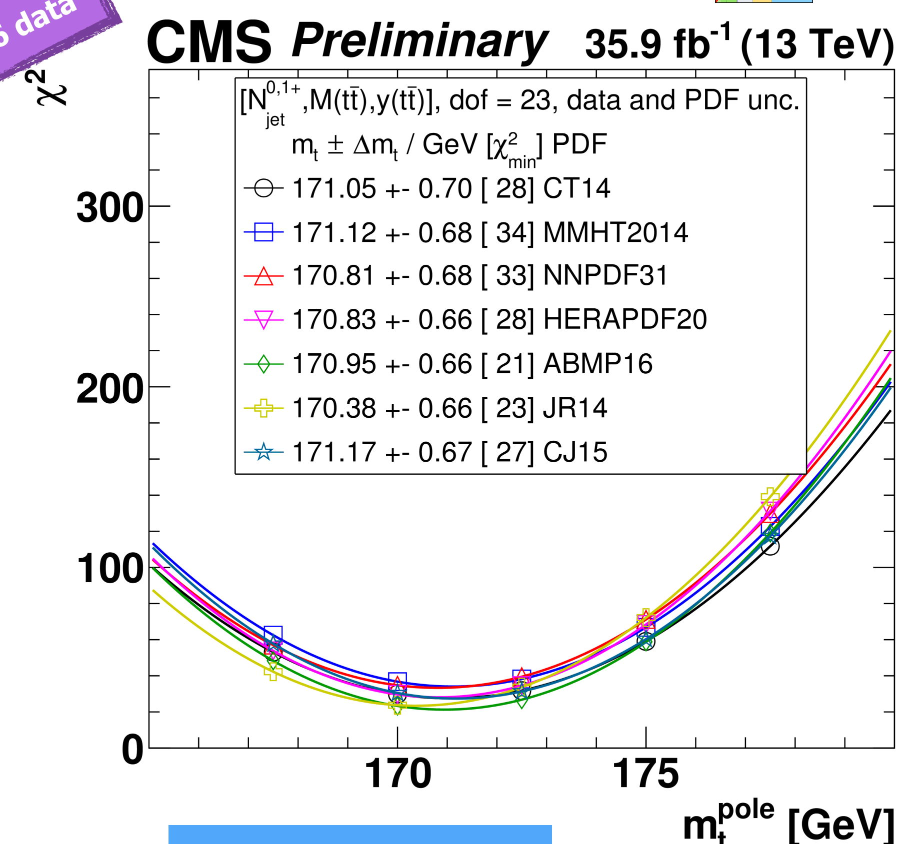
- Calculation of $t\bar{t}$ production depends on:
  - **Strong coupling ($\alpha_s$)**
  - **Top quark pole mass**
  - **Gluon PDF**
- Analysis method: **triple-differential cross section dilepton channel** to **simultaneously** determine all fit parameters:

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

**Total uncertainty: 0.8 GeV (Δ = 0.45%)**

2016 data

CMS-PAS-TOP-18-004

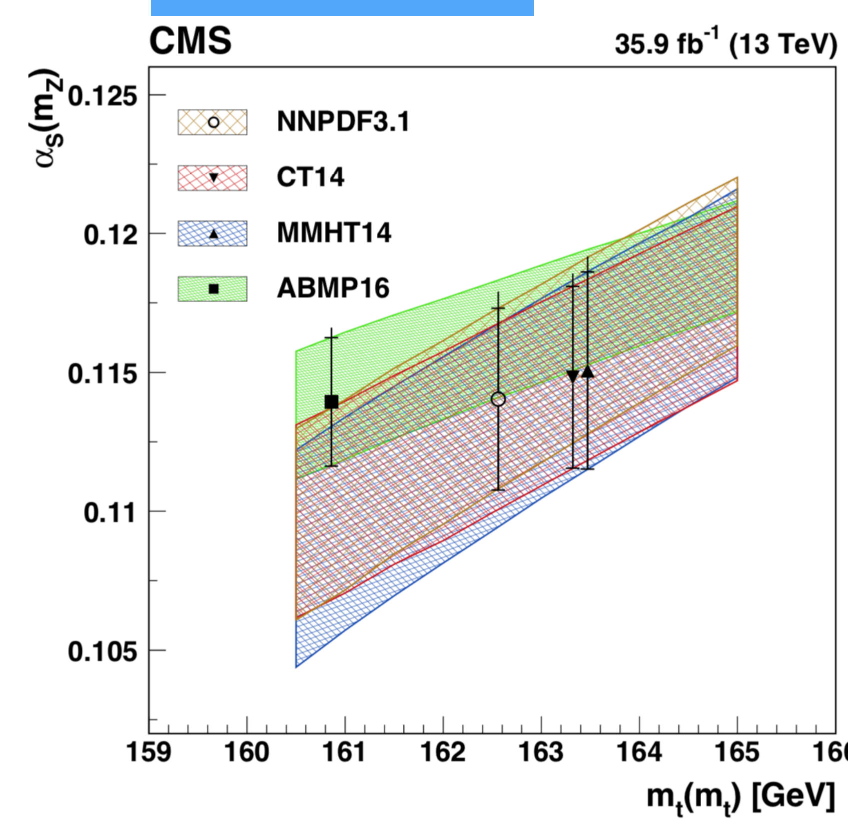



- **Inclusive cross section** measurement in **dilepton channel**
- extracting the pole mass and $\alpha_s$ by using theoretical prediction at NNLO with different PDF sets

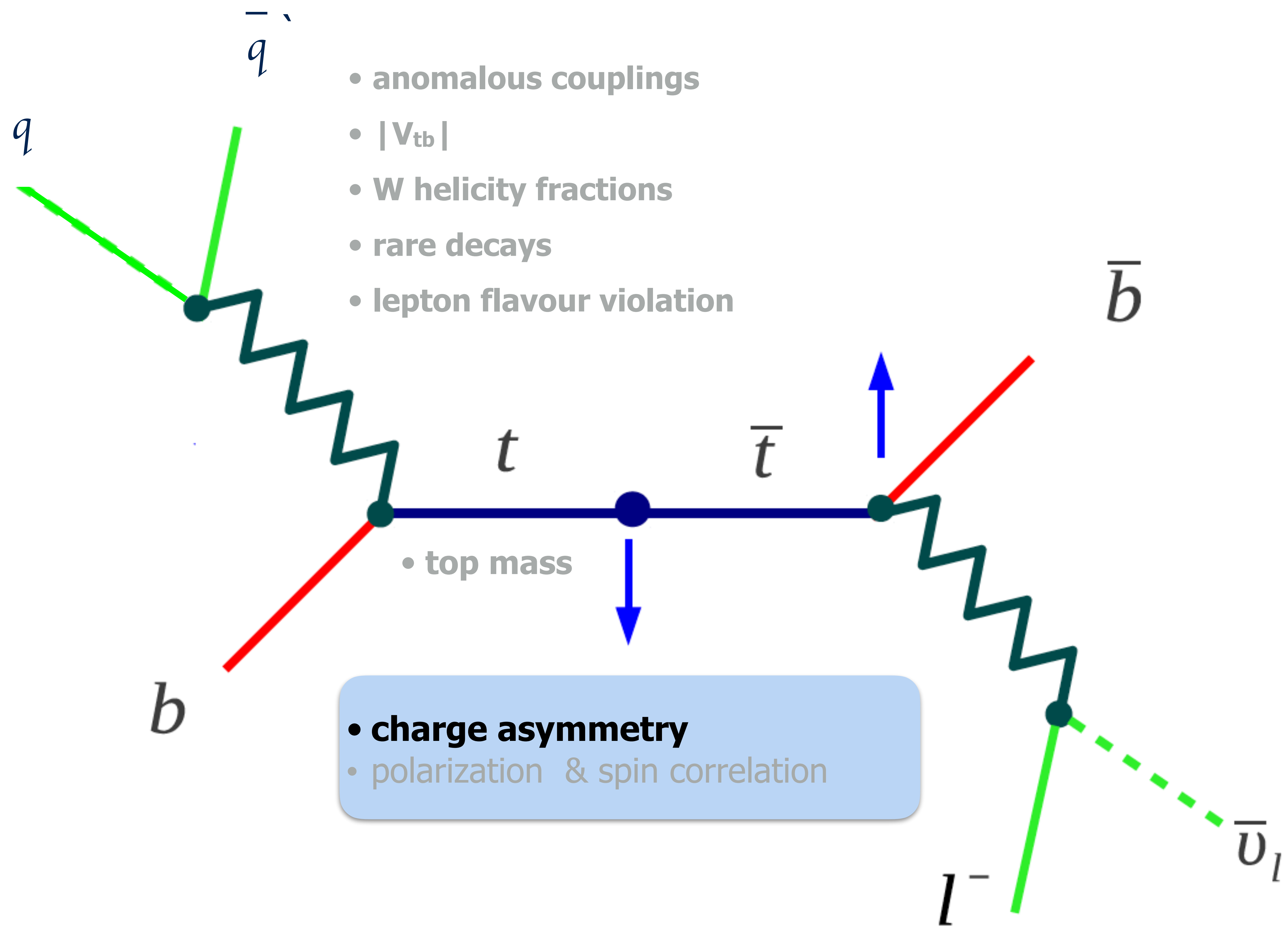
| PDF set | $m_t^{pole}$ [GeV] |
|---|---|
| ABMP16 | $169.9 \pm 1.8\ (\mathrm{fit} + \mathrm{PDF} + \alpha_S)\ ^{+0.8}_{-1.2}\ (\mathrm{scale})$ |
| NNPDF3.1 | $173.2 \pm 1.9\ (\mathrm{fit} + \mathrm{PDF} + \alpha_S)\ ^{+0.9}_{-1.3}\ (\mathrm{scale})$ |
| CT14 | $173.7 \pm 2.0\ (\mathrm{fit} + \mathrm{PDF}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

**Total uncertainty: 2.4 GeV (Δ = 1.4%)**

arXiv:1812.10505



# Top Quark Properties - Production



# Charge Asymmetry

## Where charge asymmetry comes from?

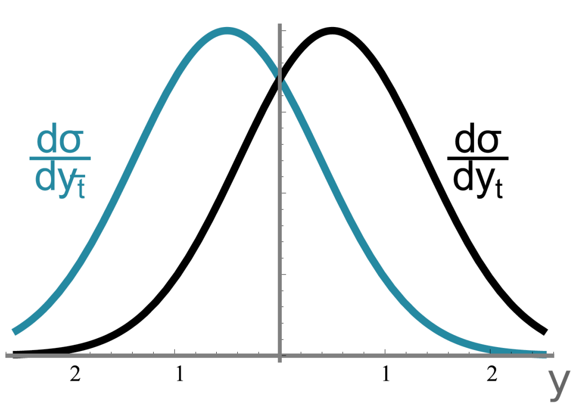
- **@LO:** Top quark and Top anti-quark are **symmetric** with respect to the angular distribution
- **@Higher orders:** $q\bar{q} \rightarrow t\bar{t}$ mainly causes an **asymmetry** in top quark and Top anti-quark **rapidity**

## $A_{FB}$ Forward-backward asymmetry

- ***pp̄* collisions @Tevatron** $q\bar{q} \rightarrow t\bar{t}$ **~ 85%**
- Direction of incoming quark almost always coincides with that of proton
- Allows to define a direct $A_{FB}$ measurement
- **SM: 8 - 9%**

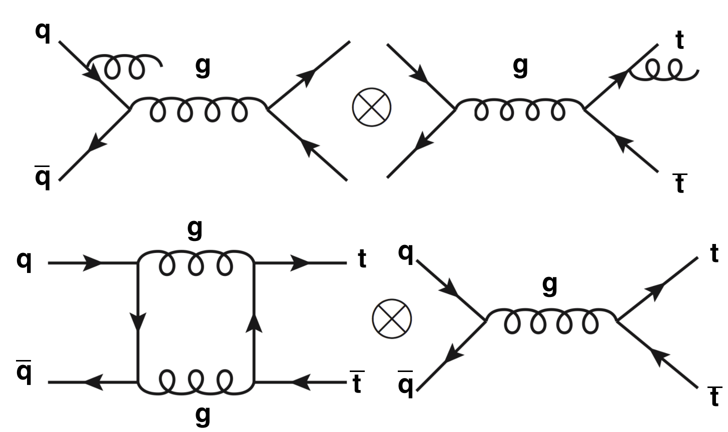
## $A_C$ Charge asymmetry

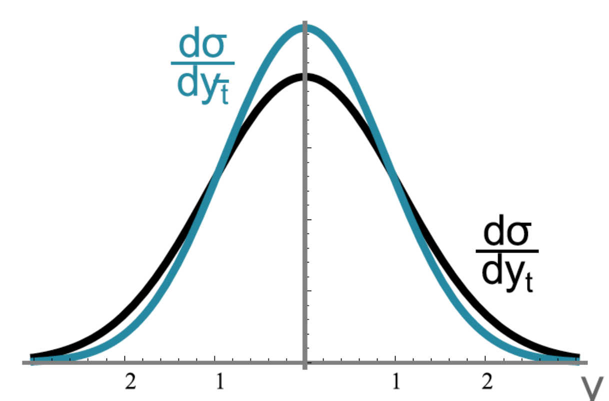
- ***pp* collisions @LHC** $q\bar{q} \rightarrow t\bar{t}$ **~ 10% @ 13 TeV**
- **Valence** quarks carry on average larger fraction of the proton momentum than the **sea** quarks
- **Top quarks** (**anti-quarks**) are more forward (central)
- **SM: ~1%**




$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

where: $\Delta y = y_t - y_{\bar{t}}$




$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

where: $\Delta|y| = |y_t| - |y_{\bar{t}}|$

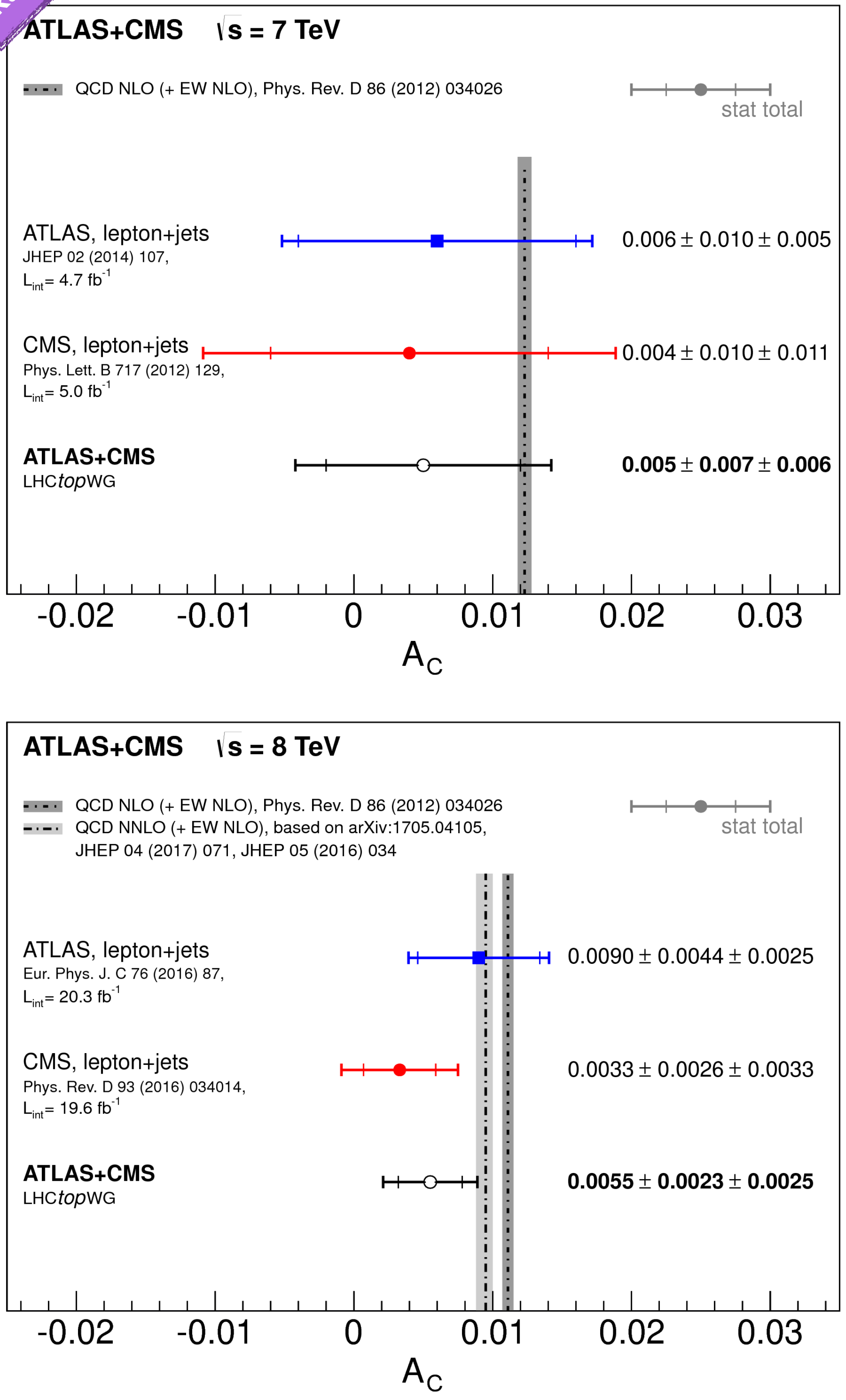
# Charge Asymmetry

## ATLAS+CMS Combination - inclusive @ 7 and 8 TeV

- **Three separate combinations** of ATLAS and CMS results
- **7 TeV inclusive combination:**
    - **18%** improvement over ATLAS alone (weight 0.65)
    - **40%** improvement over CMS alone (weight 0.35)
    - Uncertainty dominated by data statistics, detector modelling and W+jets background determination
- **8 TeV inclusive combination:**
    - **32%** improvement over ATLAS alone (weight 0.39)
    - **17%** improvement over CMS alone (weight 0.61)
    - Uncertainty dominated by data statistics, detector modelling and W+jets background determination

Run I data

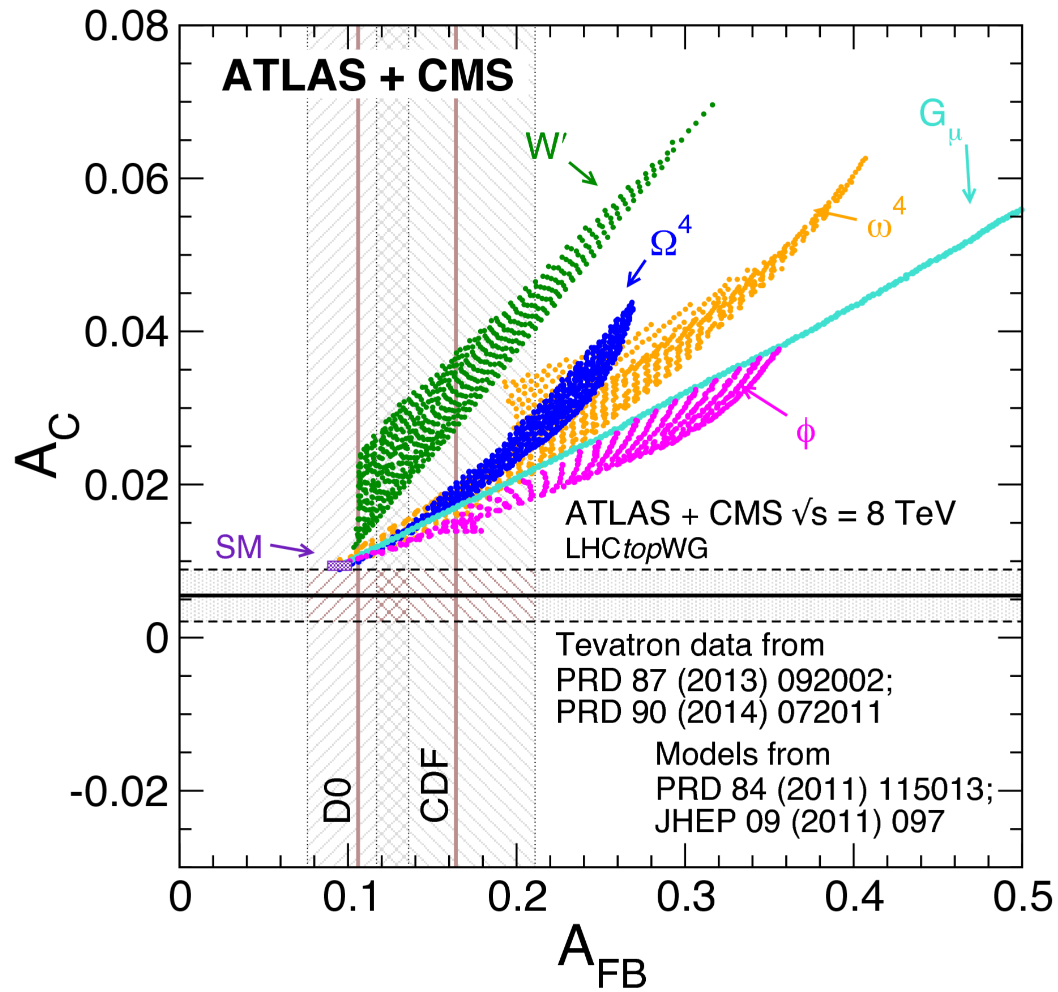
JHEP 04 (2018) 033



# Charge Asymmetry

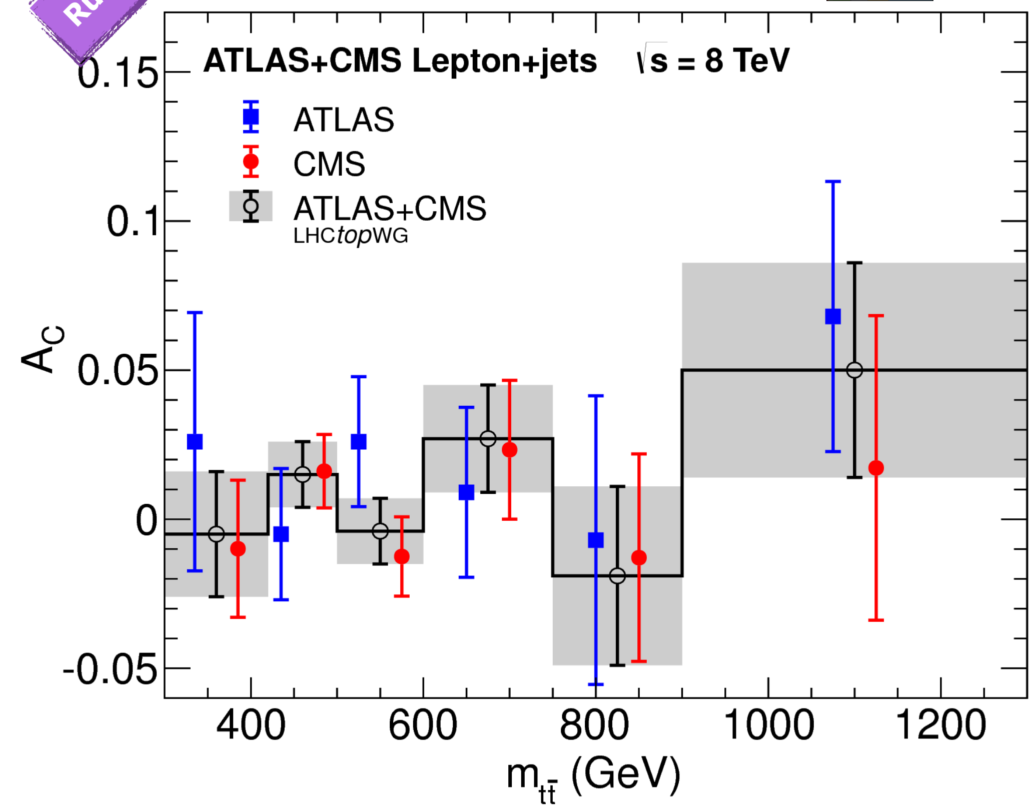
## ATLAS+CMS Combination - differential @ 8 TeV

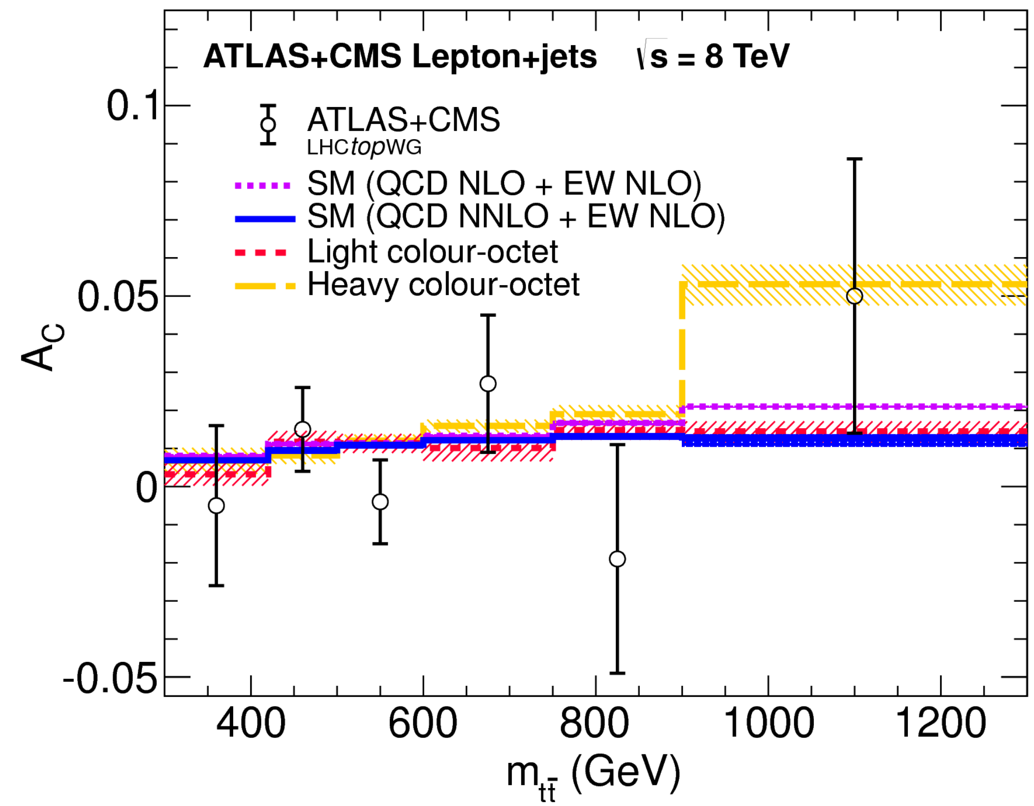
- bin-to-bin correlations for a particular source
- **20%** (last bin) to **52%** (first bin) improvement over ATLAS result
  - Weight: 0.22 (first bin) to 0.59 (last bin)
- **9%** (last bin) to **31%** (first bin) improvement over CMS result
  - Weight: 0.41 (first bin) to 0.78 (last bin)
- The result uniquely **restricts wide regions of the possible BSM parameter space**, e.g. for axigluon models




Run I data

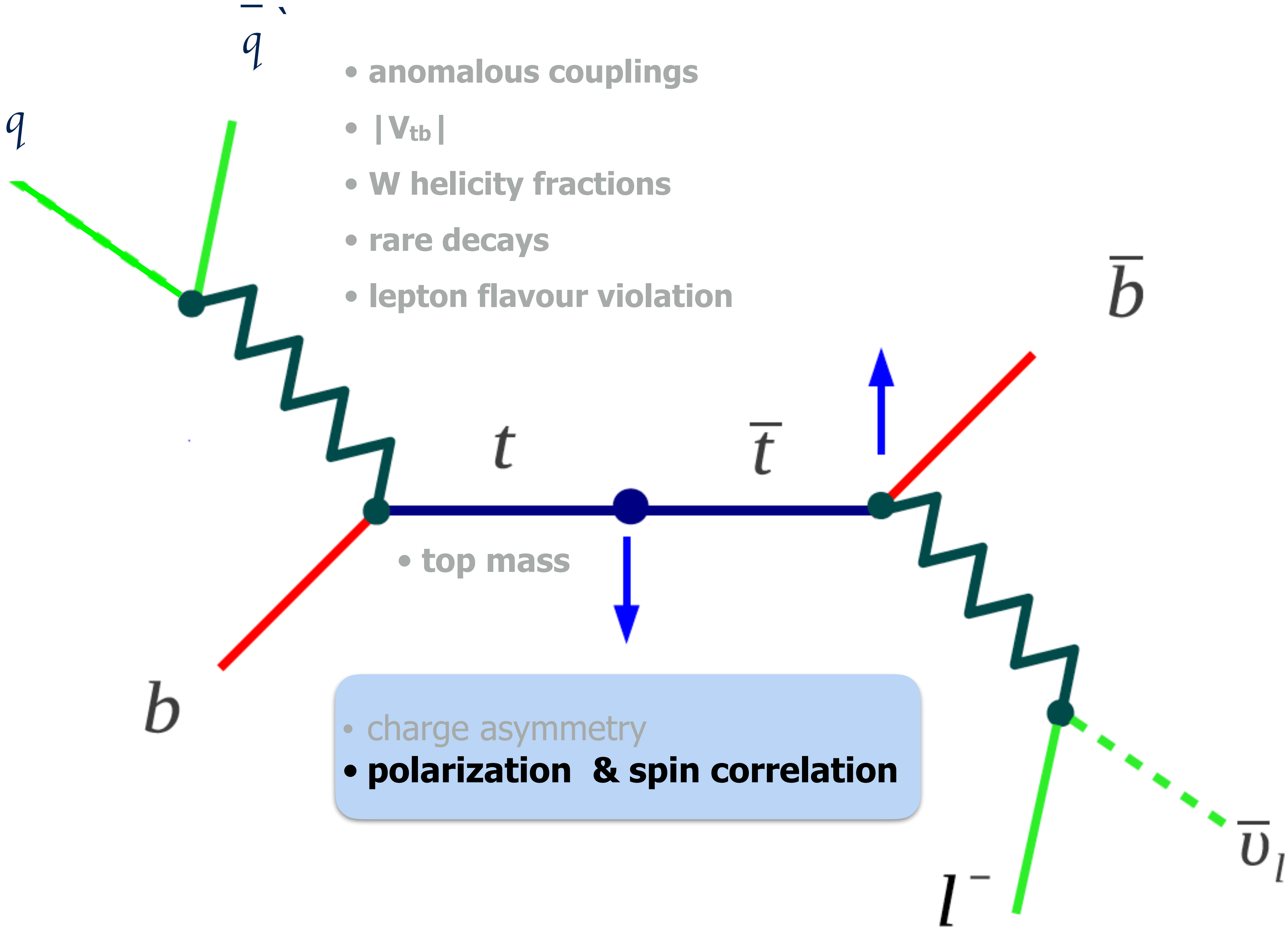
JHEP 04 (2018) 033



# Top Quark Properties - Production

- anomalous couplings
- $|V_{tb}|$
- W helicity fractions
- rare decays
- lepton flavour violation
- top mass

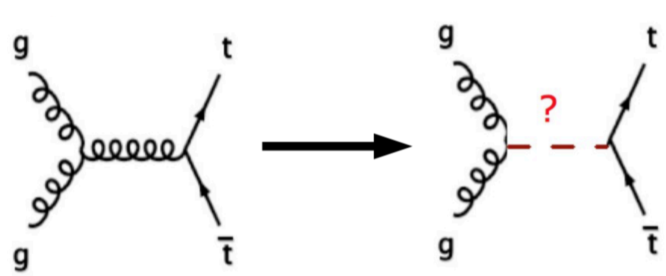


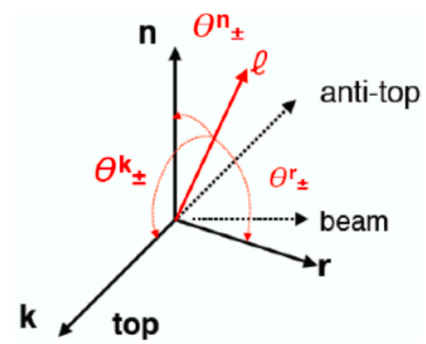

- charge asymmetry
- **polarization & spin correlation**

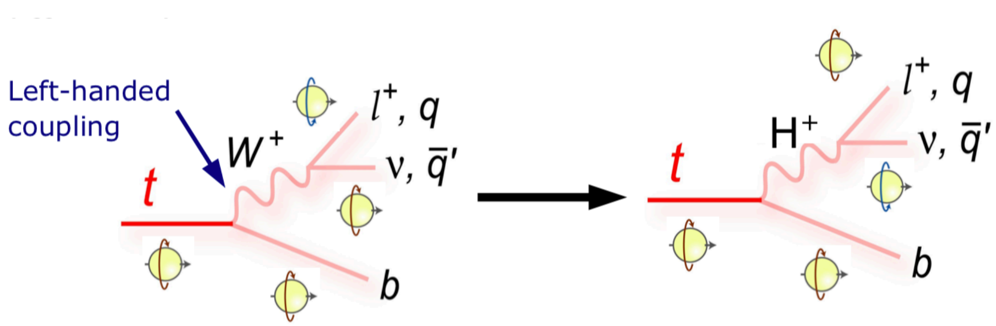
# Polarization & Spin Correlation

## Where the top polarization comes from?

- Top quarks decay before fragmentation
  - **spin information is transferred** to daughter particles
- In SM, top quarks produced **un-polarized**, and **spins are 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
  - **charge 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:

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

- Can find 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

## ATLAS: Indirect 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

  **$f_{SM}$= 1.25 ±0.08  ≈ 3.2σ**

  - 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

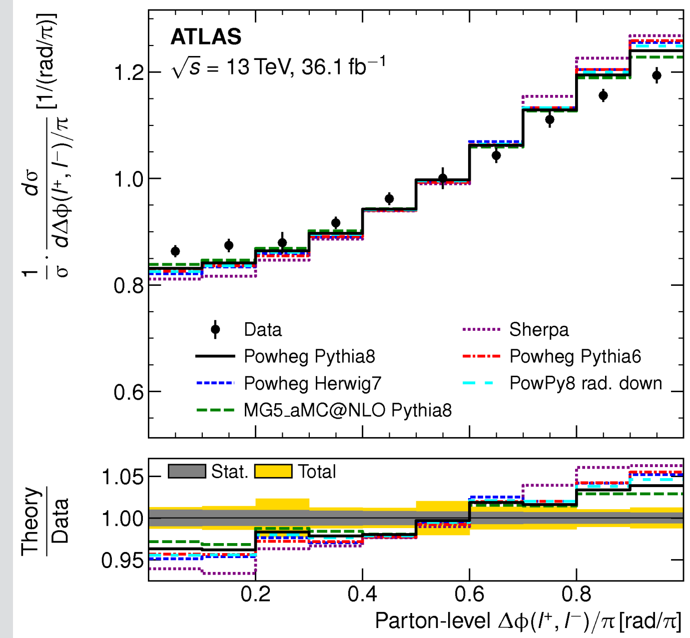
**SUSY**: search for **top squarks** production:
Excluded top squark mass: **[170 - 230 GeV]**

2015+2016 data

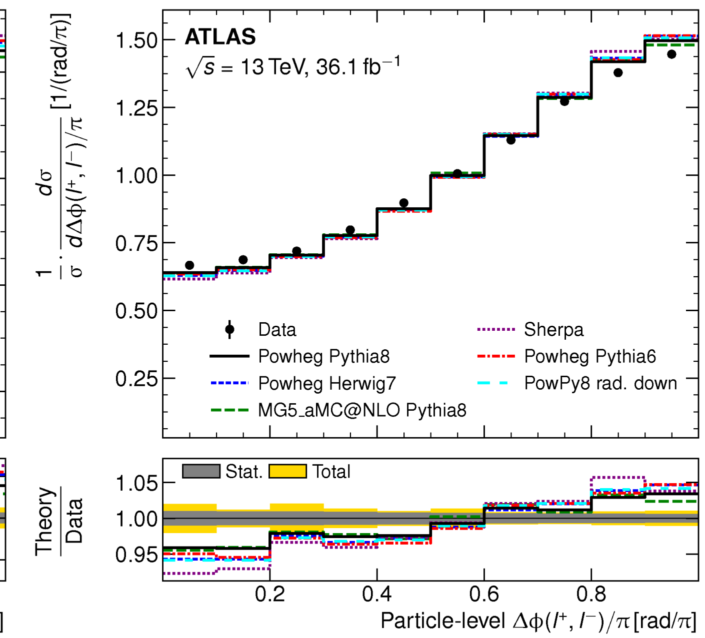
arXiv:1903.07570

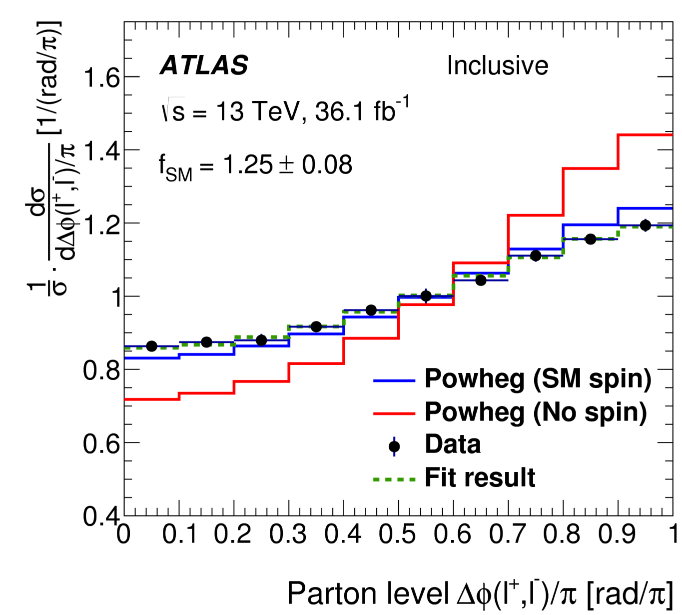
New!

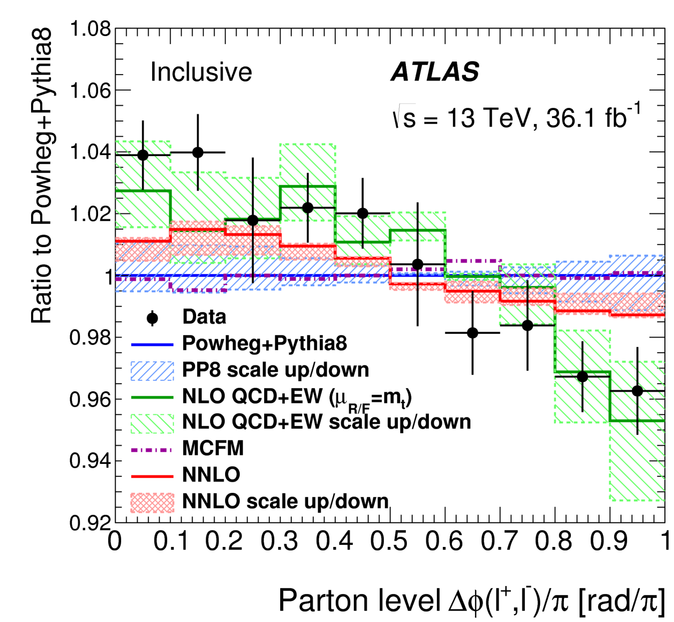
parton level, full phase space




particle level, fiducial phase space



# Polarization & Spin Correlation

## CMS: direct measurement

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

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

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

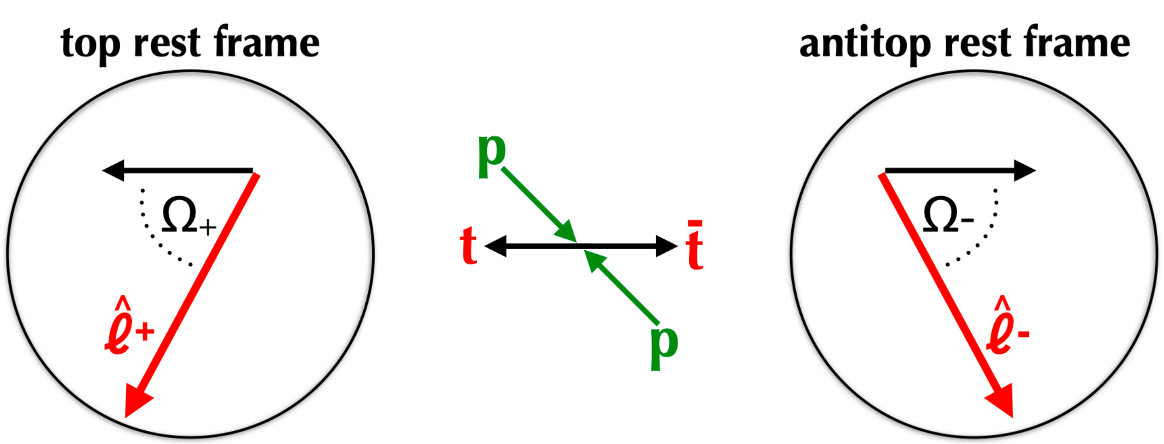
CMS-PAS-TOP-18-006

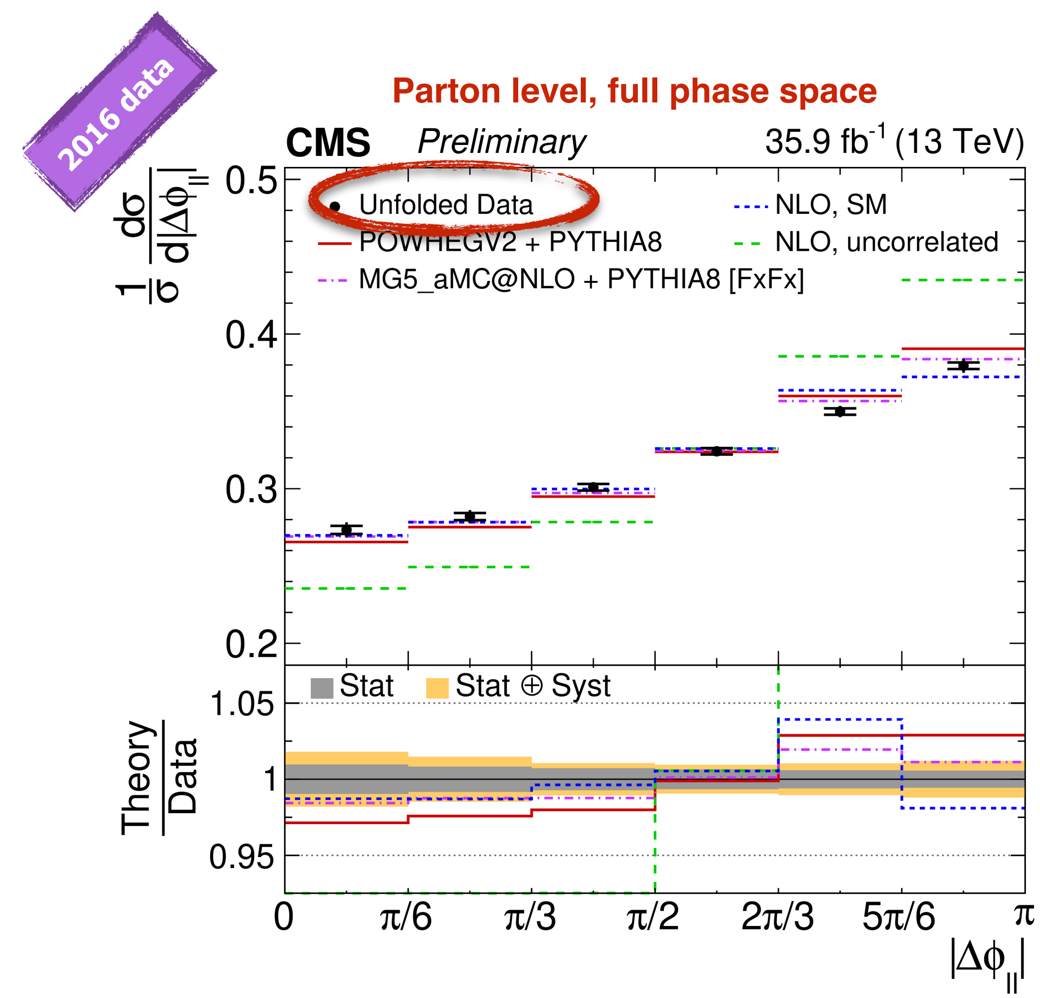
R: Spin Density Matrix

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ \Omega_-} = \frac{1}{(4\pi)^2}\left(1 + B^+ . \hat{\ell}^+ + B^- . \hat{\ell}^- - \hat{\ell}^+ . \mathbb{C} . \hat{\ell}^-\right)$$

Polarization 3+3

Correlation 3x3



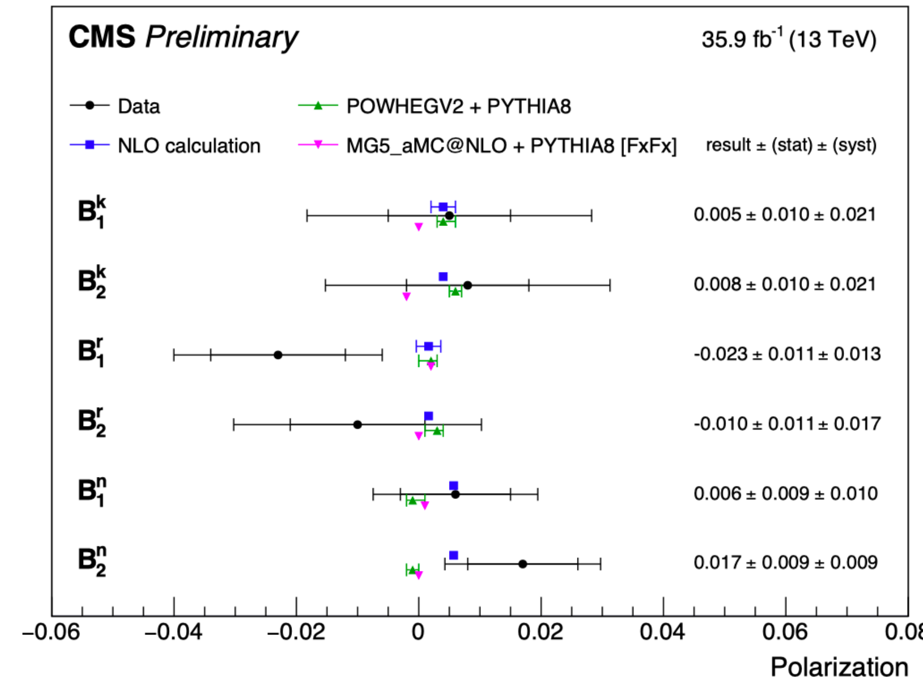



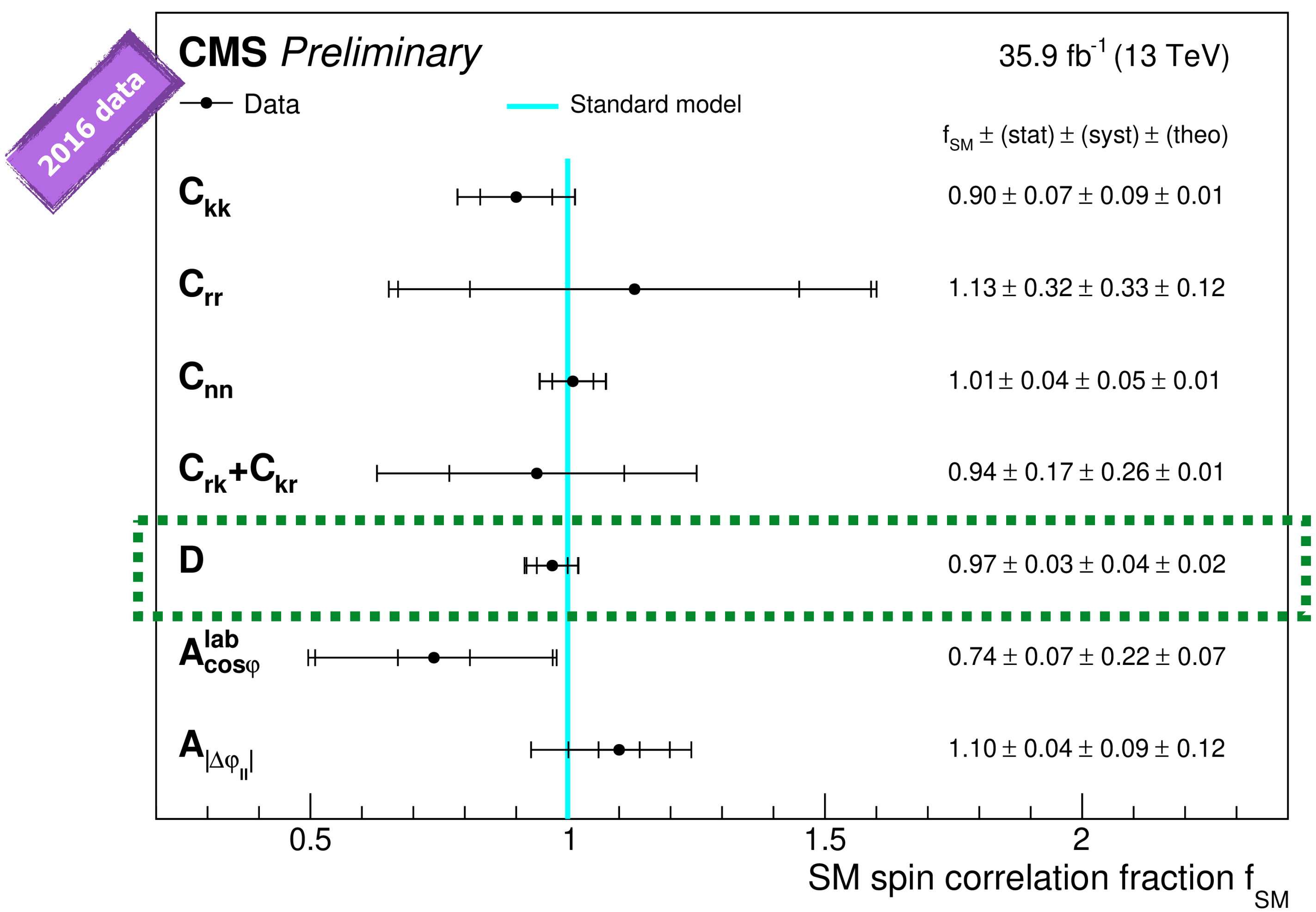
# Polarization & Spin Correlation

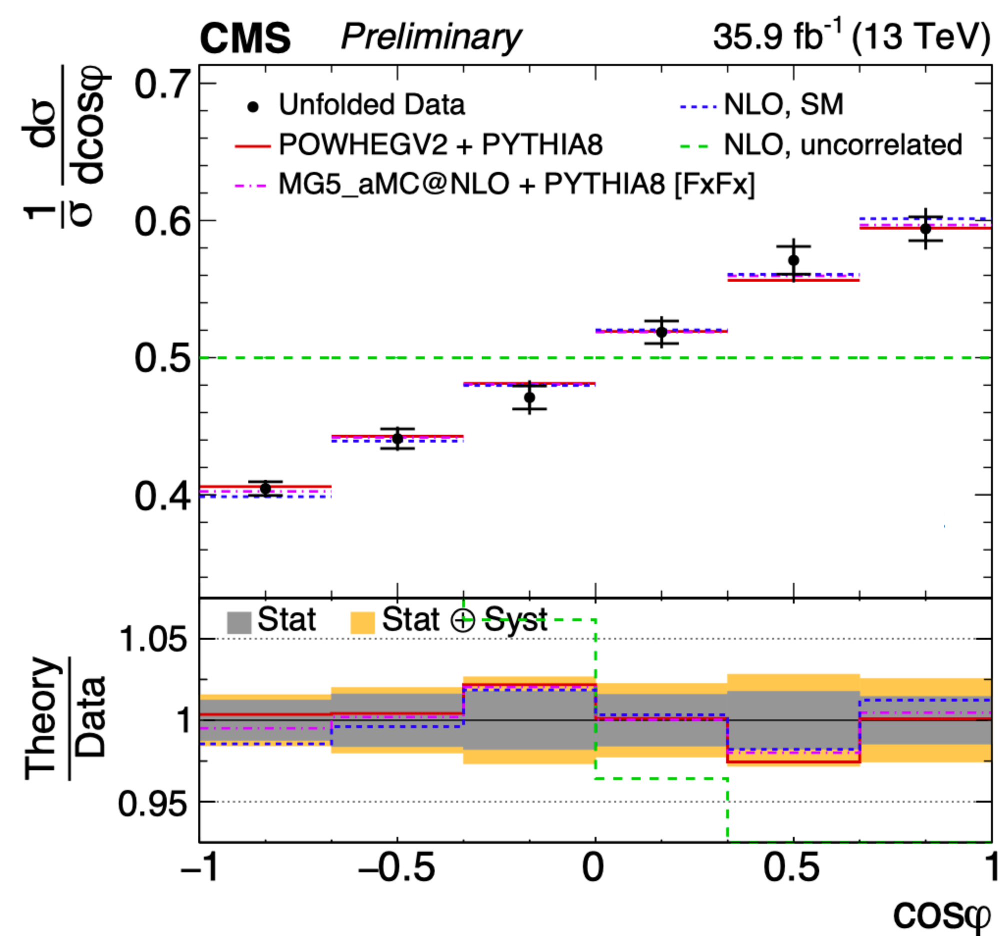
## CMS: <u>direct</u> measurement

CMS-PAS-TOP-18-006

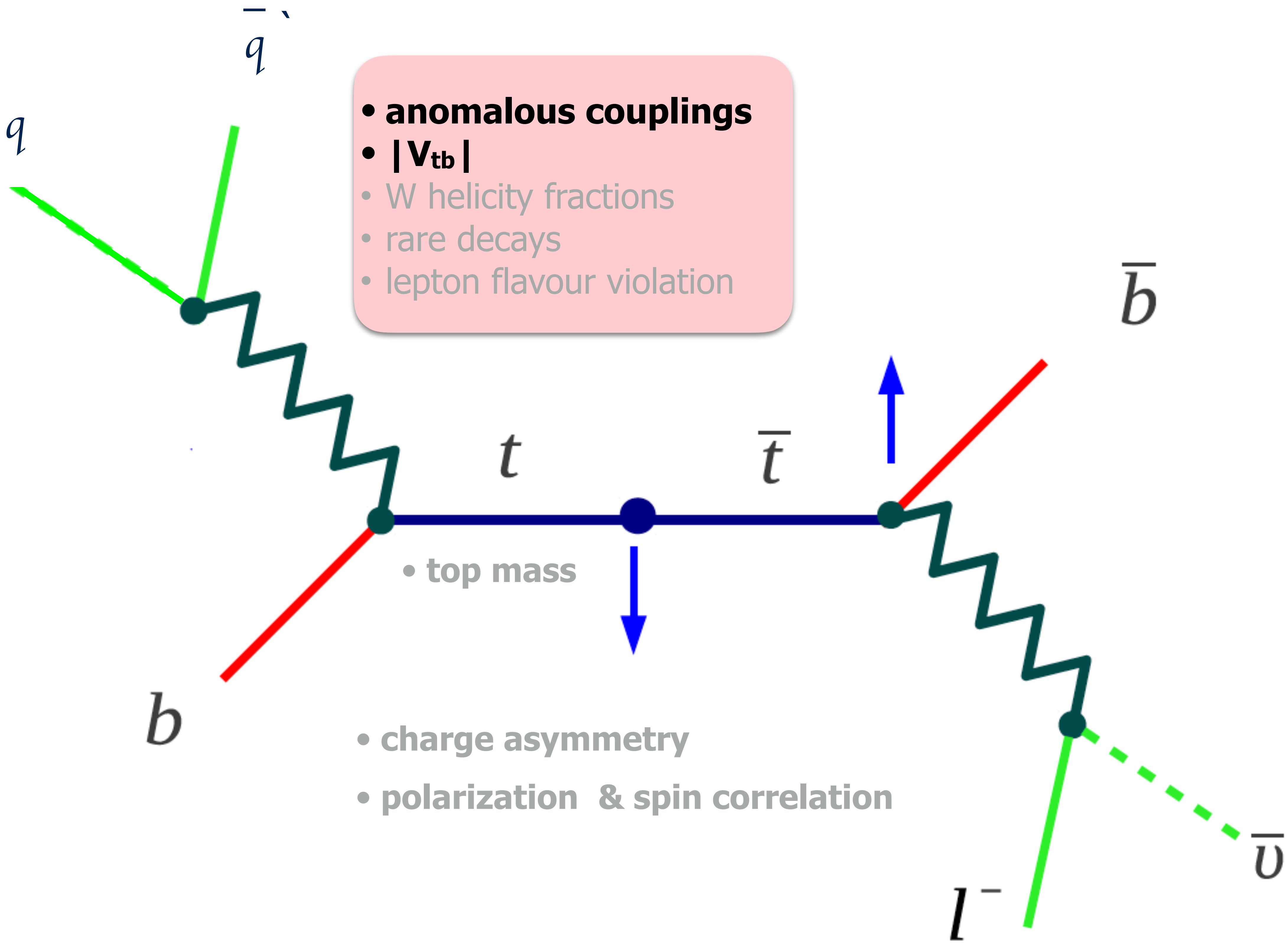
- Measured top quark **polarization**: **consistent with zero**
- Opening angle between the leptons (in parent top rest frames) has **maximal sensitivity** to the alignment of the top quark spins:
  - **D= -0.237± 0.007±0.009**
  - **$f_{SM}$ =0.97± 0.05** (most precise measurement to date)



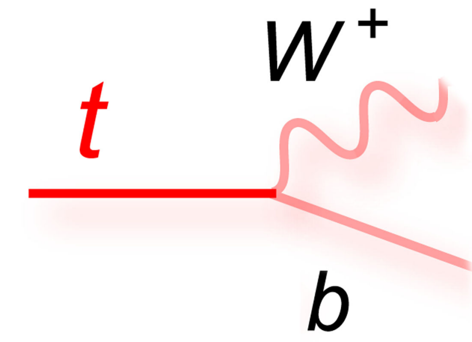
# Top Quark Properties - Decay



# Anomalous Couplings & $|V_{tb}|$

## Most general *Wtb* vertex

- The ***Wtb* vertex** Lagrangian with minimum generalization in **EFT** includes **anomalous couplings** (≈ 0 in SM at tree level)
- New physics can modify the structure of the *Wtb*




**Vector couplings** — **Tensor couplings**

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_{\rm L}P_{\rm L} + V_{\rm R}P_{\rm R}\right) t\, W^{-}_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_{\rm L}P_{\rm L} + g_{\rm R}P_{\rm R}\right) t\, W^{-}_{\mu} + \text{h.c.}\,,$$

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

(≈ 1 in SM)

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

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

# Anomalous Couplings & $|V_{tb}|$

## Combination of Single Top quark x-sec. @7 and 8 TeV

Run I data

arXiv:1902.07158

New!

- **Single-top-quark** production rate is **proportional to $V_L$** in *Wtb* vertex
  - SM: $\mathbf{V_L \rightarrow V_{tb}}$ (CKM matrix element)
- **Direct $V_{tb}$ measurement** from Single-top-quark production:

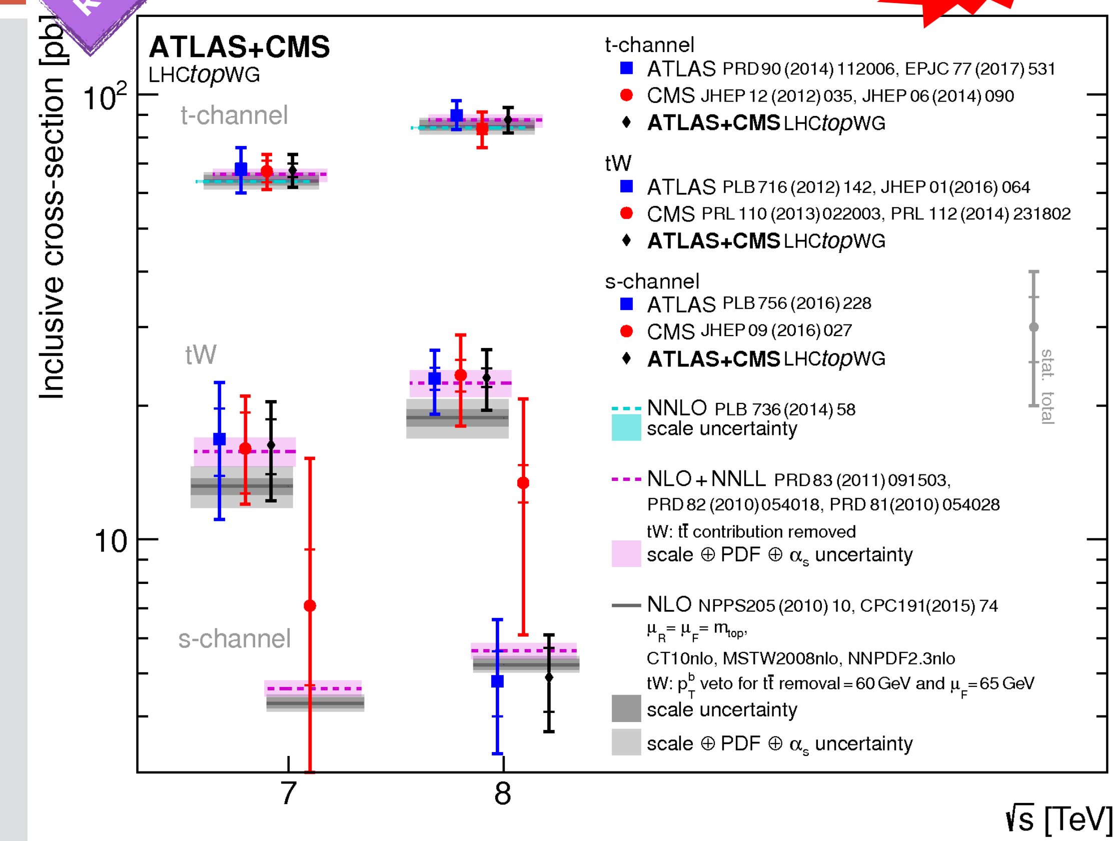
$$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{meas.}}{\sigma_{theo.(V_{tb}=1)}}}$$

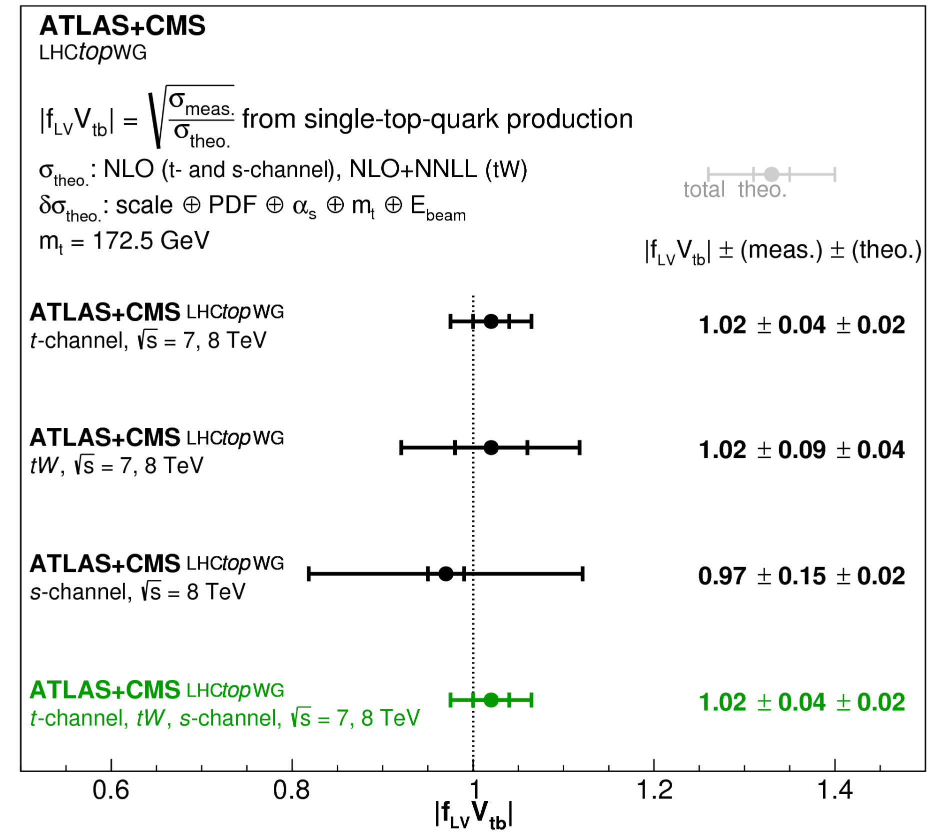
- **Model independent** measurement
- measurements at **√s= 7 and 8 TeV** by ATLAS and CMS are combined per √**s** and **production modes**
- Theoretical predictions:
  - **NLO** (t- and s-channel) and **NLO+NNLL** (tW)

$$|f_{LV}V_{tb}| = 1.02 \pm 0.04\ (exp) \pm 0.02\ (theo)$$

➥ **most precise direct measurement of $V_{tb}$**

**Uncertainty improved from 4.7% to 3.7% w.r.t the most precise single measurement (ATLAS @8 TeV)**



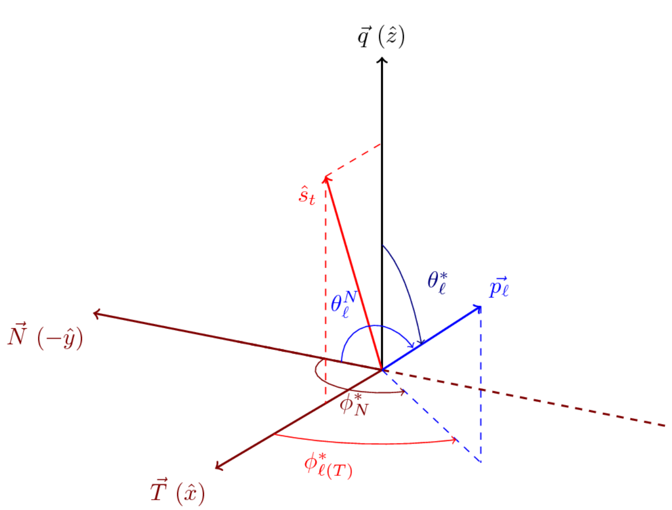



# Anomalous Couplings & $|V_{tb}|$

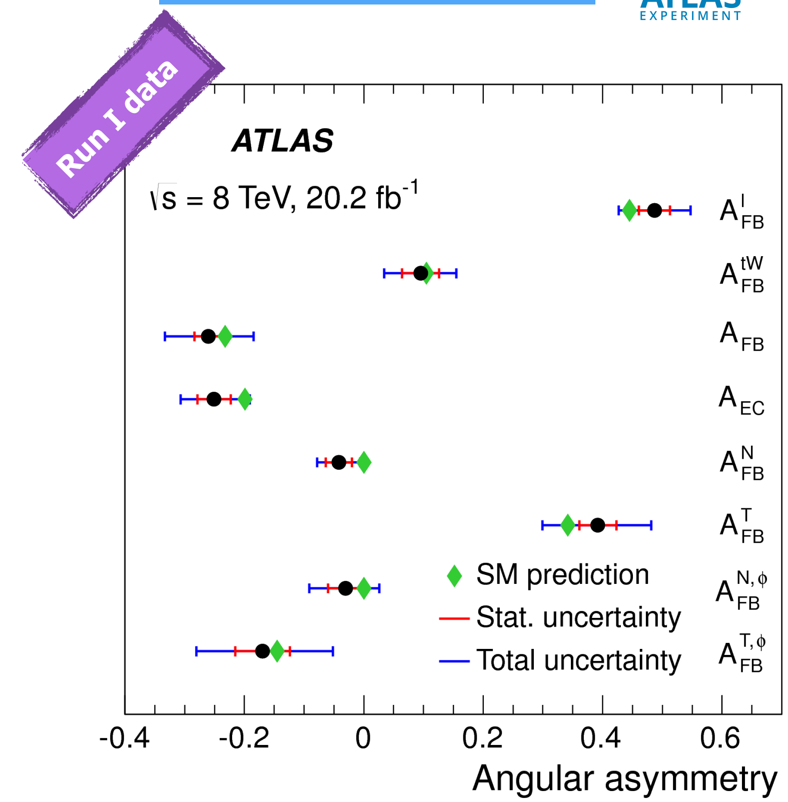
## Probing *Wtb* structure in t-channel single-top-quark @ 8TeV

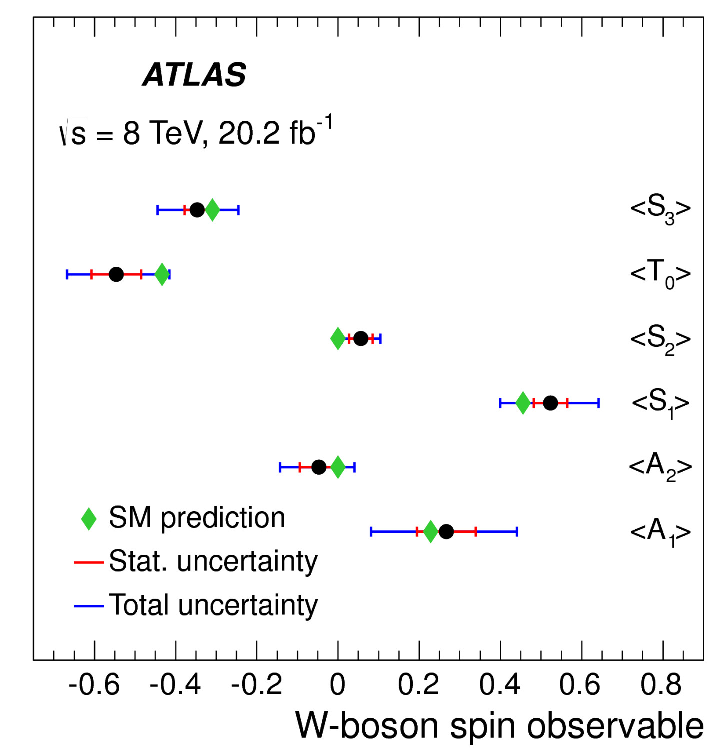
- **Looking for single top events with:**
  - one isolated electron or muon, large missing transverse momentum
  - exactly two jets (one to be b-tagged)
- The polarization observables are extracted from asymmetries in angular distributions w.r.t. spin quantization axes
- Set limits: **$\text{Im}[g_R] \in [-0.18, 0.06]$ @ 95 CL**
  - assuming $V_L = 1$ and $\text{Re}[V_R] = \text{Re}[g_L] = \text{Re}[g_R] = 0$
- Dominant systematics: **$t\bar{t}$ modelling, JES, MC statistics**
- **In agreement with SM predictions**

JHEP 04 (2017) 124

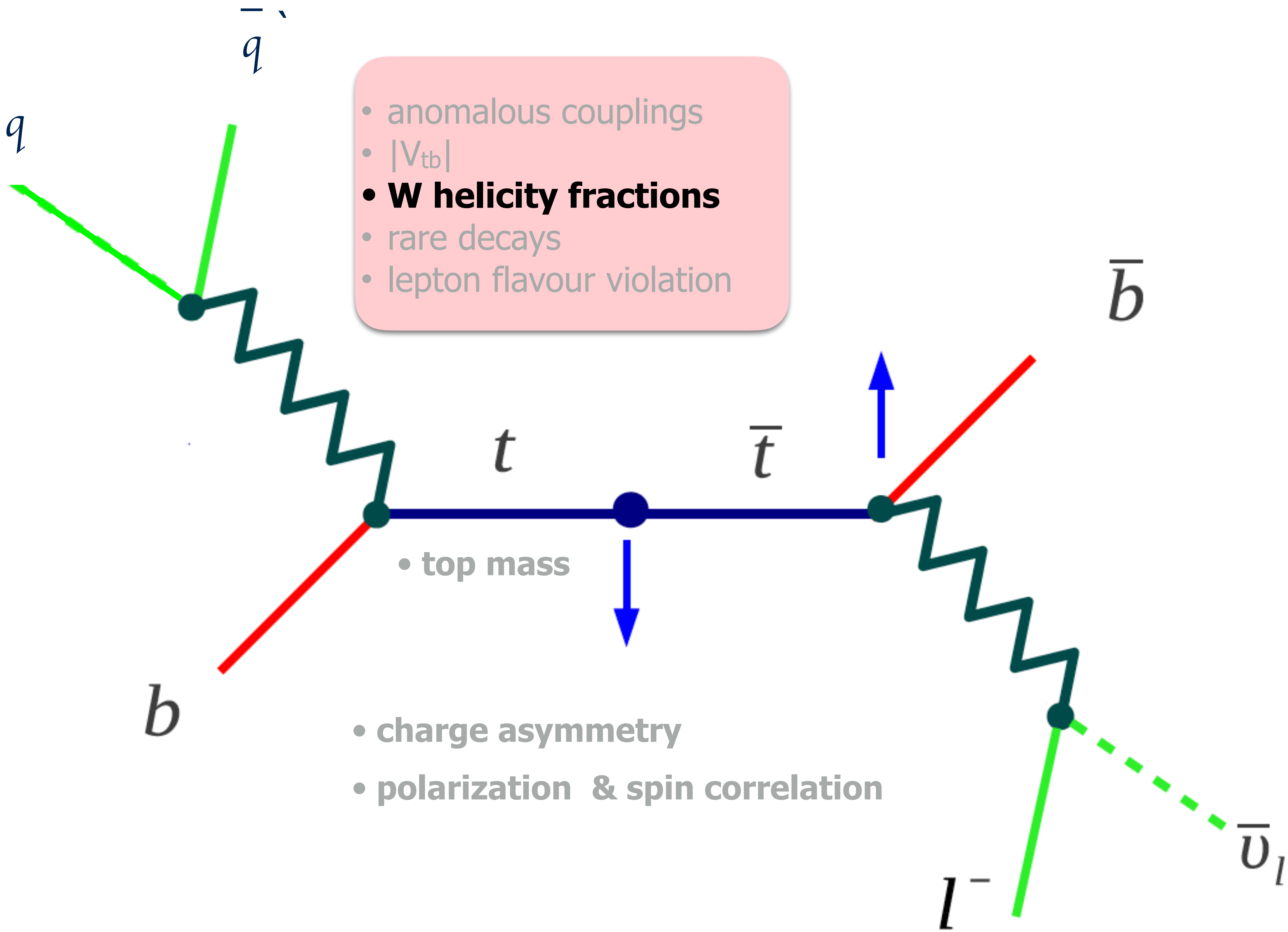



| Asymmetry | Angular observable | Polarisation observable | SM prediction |
|---|---|---|---|
| $A^{\ell}_{\rm FB}$ | $\cos\theta_\ell$ | $\frac{1}{2}\alpha_\ell P$ | 0.45 |
| $A^{tW}_{\rm FB}$ | $\cos\theta_W \cos\theta^*_\ell$ | $\frac{3}{8}P(F_{\rm R}+F_{\rm L})$ | 0.10 |
| $A_{\rm FB}$ | $\cos\theta^*_\ell$ | $\frac{3}{4}\langle S_3\rangle = \frac{3}{4}(F_{\rm R}-F_{\rm L})$ | −0.23 |
| $A_{\rm EC}$ | $\cos\theta^*_\ell$ | $\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}(1-3F_0)$ | −0.20 |
| $A^{T}_{\rm FB}$ | $\cos\theta^T_\ell$ | $\frac{3}{4}\langle S_1\rangle$ | 0.34 |
| $A^{N}_{\rm FB}$ | $\cos\theta^N_\ell$ | $-\frac{3}{4}\langle S_2\rangle$ | 0 |
| $A^{T,\phi}_{\rm FB}$ | $\cos\theta^*_\ell \cos\phi^*_T$ | $-\frac{2}{\pi}\langle A_1\rangle$ | −0.14 |
| $A^{N,\phi}_{\rm FB}$ | $\cos\theta^*_\ell \cos\phi^*_N$ | $\frac{2}{\pi}\langle A_2\rangle$ | 0 |



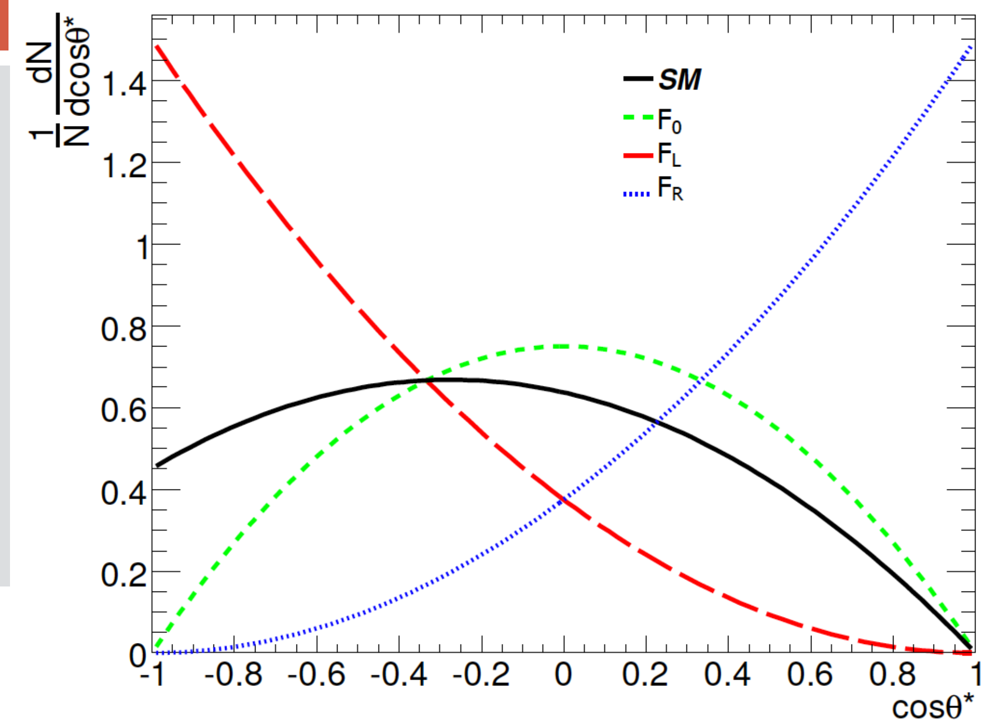
# Top Quark Properties - Decay



# W Helicity Fraction Measurements

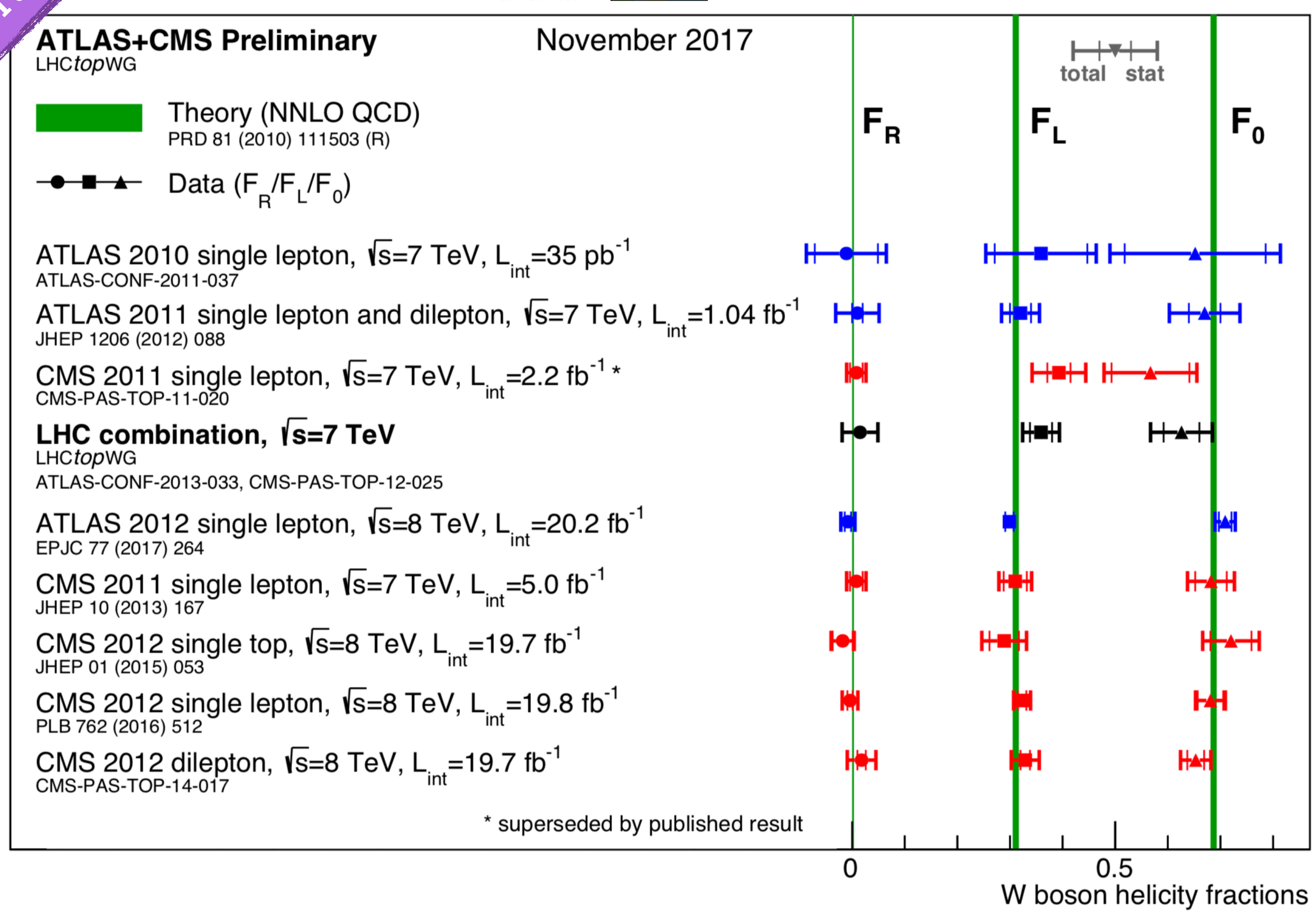
## W helicity fraction measurements @ LHC

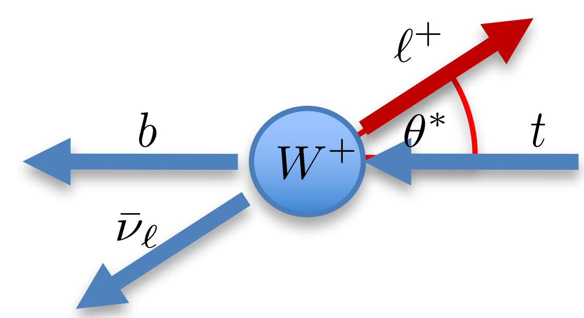
- Multiple measurements performed by ATLAS and CMS in **Run 1**
- Using **top pair and singe top events**
- The **lepton angular distribution** in W rest frame is sensitive to the W helicity
- All measurements so far are **compatible with SM** prediction at NNLO QCD

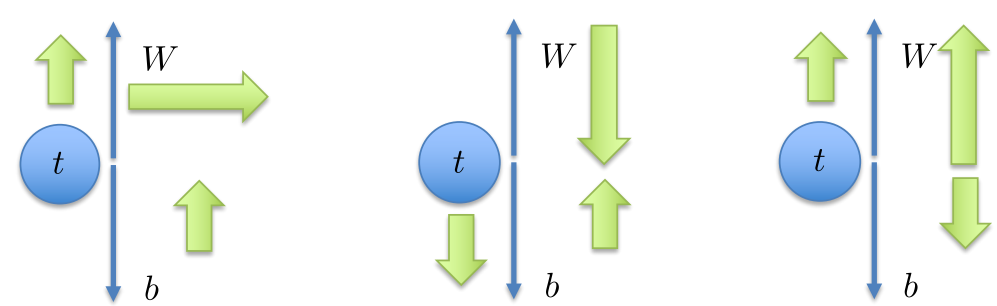



Run I data

#LHCTopWG



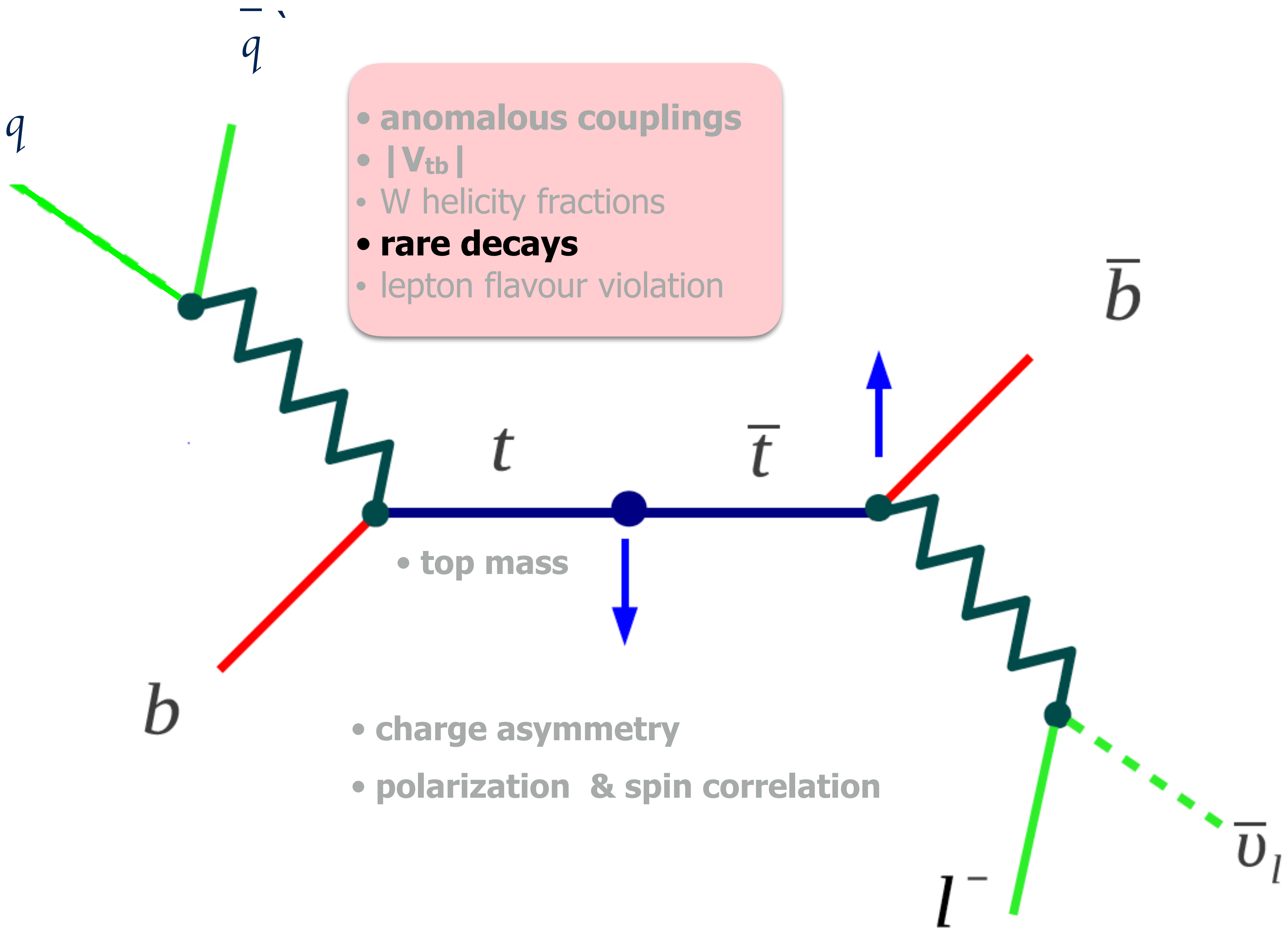




$F_0$=0.687±0.005 $F_L$=0.311±0.005 $F_R$0=0.0017±0.0001

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

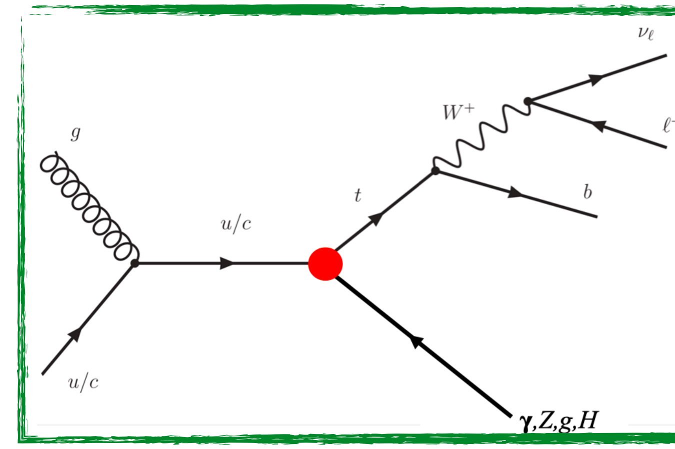
# Top Quark Properties - Decay

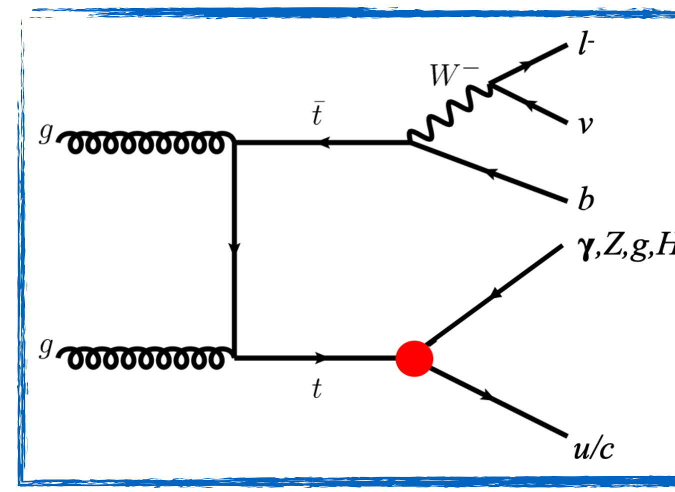


# FCNC in Top Quark

## Flavour changing neutral current in top qaaurk

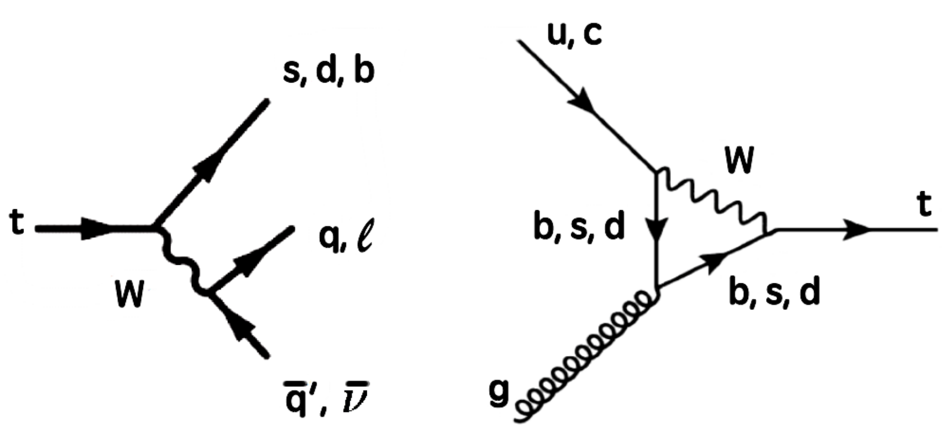
- Top quark couples to an **up-type quark** (u or c) and a **neutral boson** (γ,Z,H,g)
- Forbidden at tree-level in SM
- Heavily suppressed at higher orders via GIM suppression (rate is not observable with current dataset)
- **BSM can enhance FCNC up to ~ $10^{-4}$**
    - Any observation of FCNC can 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~ $10^{-13}$ - $10^{-14}$

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

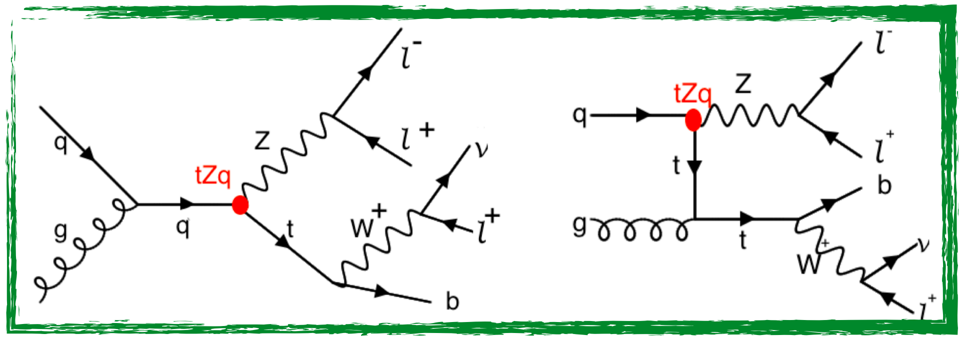
# FCNC in Top Quark

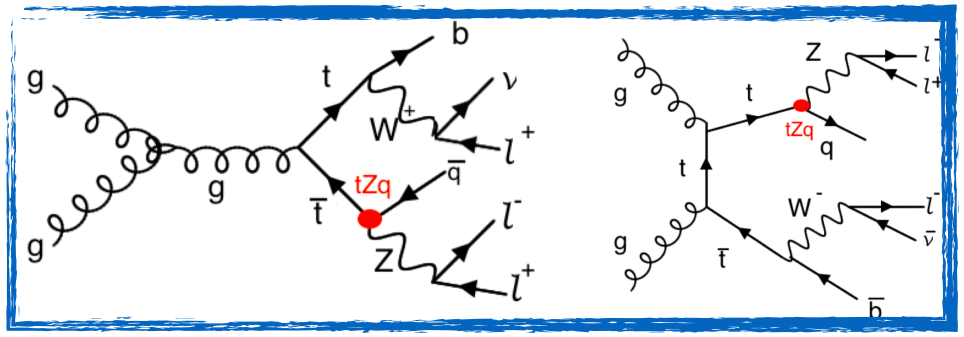
YORK UNIVERSITÉ UNIVERSITY

## Search for t → qZ

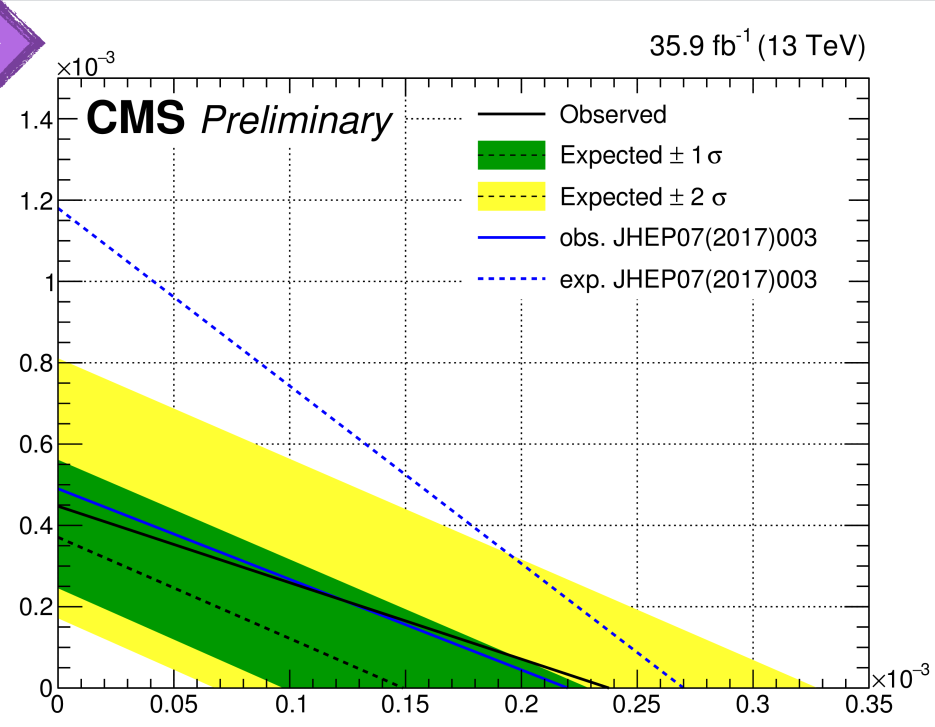
CMS-PAS-TOP-17-017

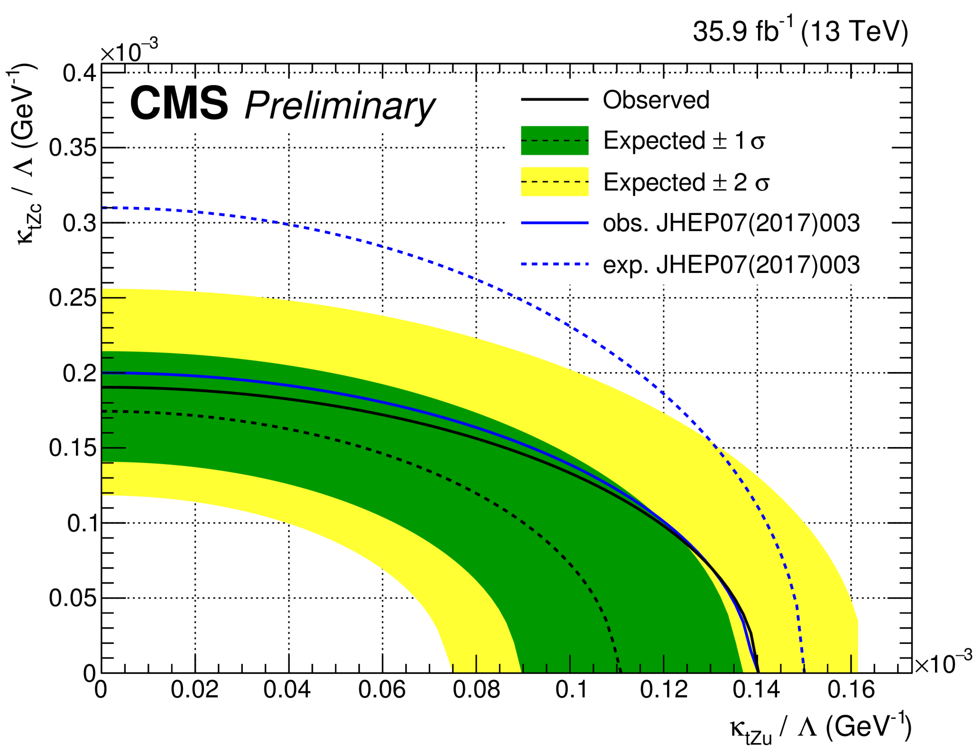
- Two channels are considered:
  - single top quark **FCNC production** (pp → tZ)
  - top quark pair production with **FCNC decay** (t → qZ)
- Looking for events with:
  - exactly 3 leptons= one opposite sign + same flavour pair
  - 1≤ jet(s) ≤ 3 & W transverse mass < 300 GeV
- Dedicated BDT discriminants for each of 3 signal regions
- Set observed (expected) limits on the branching ratio t → qZ:
  - **$\mathcal{B}$(t → uZ) < 0.024% (0.015%)**
  - **$\mathcal{B}$(t → cZ) < 0.045% (0.037%)**




2016 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 $\chi^2$ minimization of the kinematic properties of the to quarks
- The data are **consistent with SM background contributions**

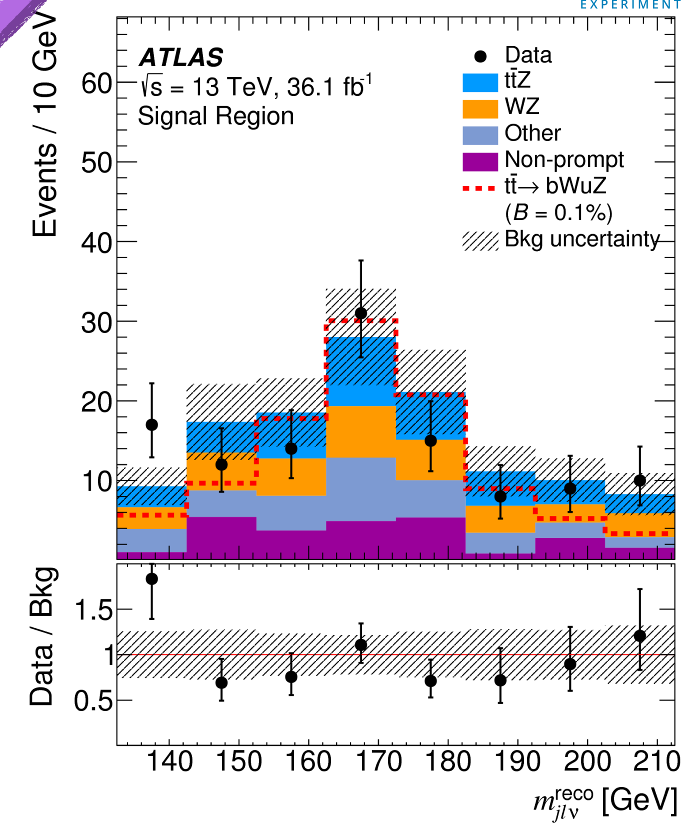
Set observed (expected) limits on the branching ratio t → qZ:

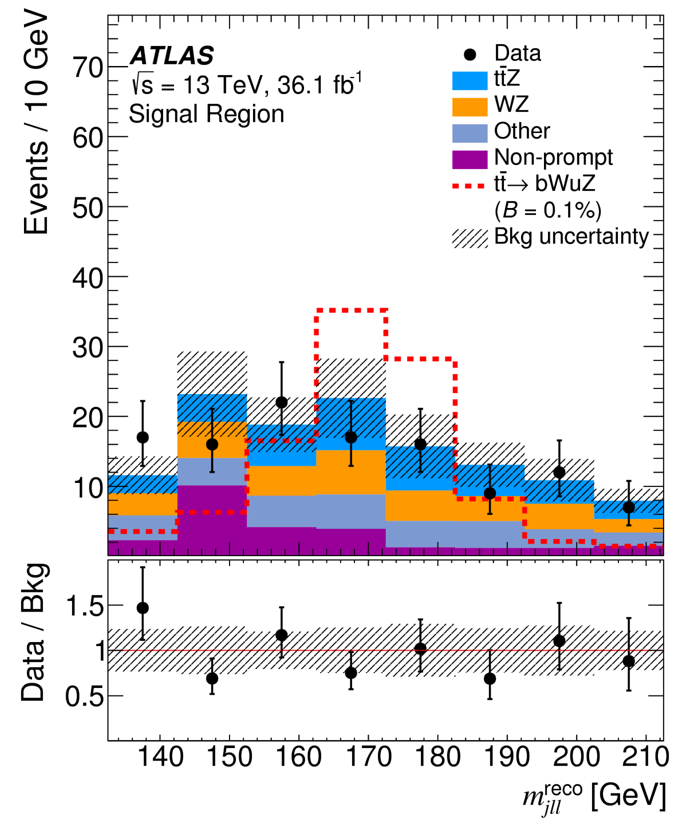
$$\mathcal{B}(t \rightarrow uZ) < 0.017\% \ (0.024\%)$$

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

2015+2016 data

JHEP 07 (2018) 176



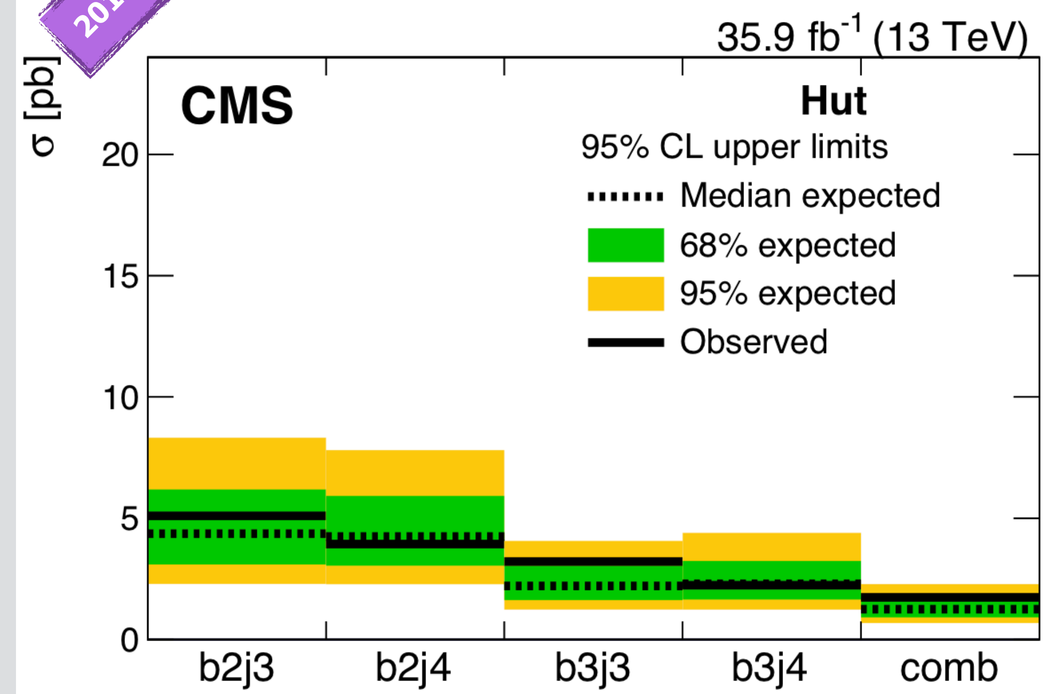
# FCNC in Top Quark

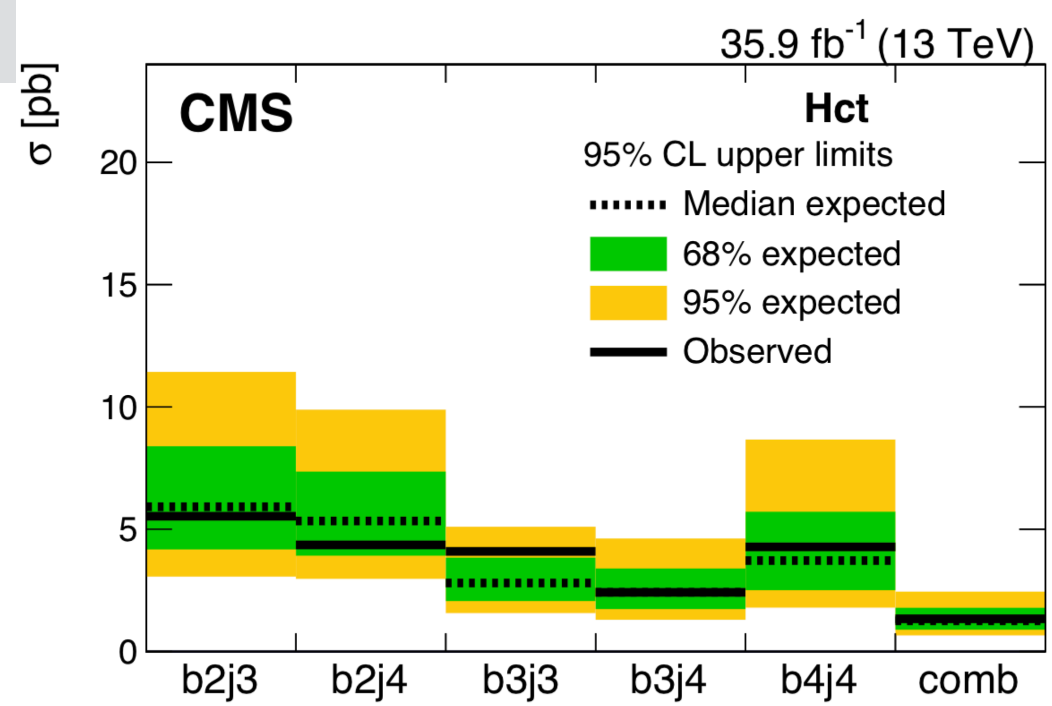
JHEP 06 (2018) 102

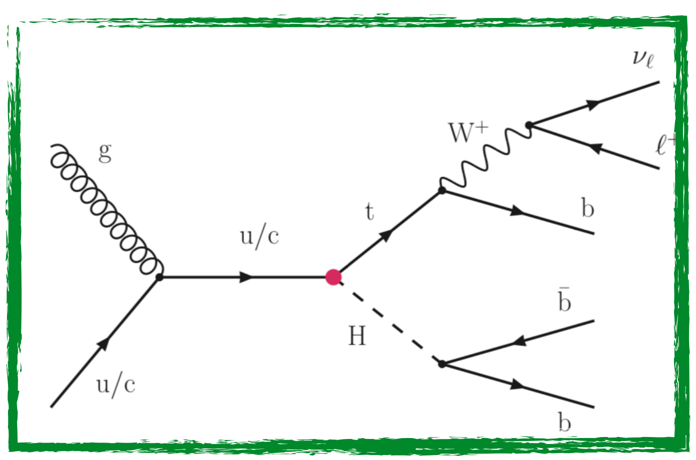
2016 data

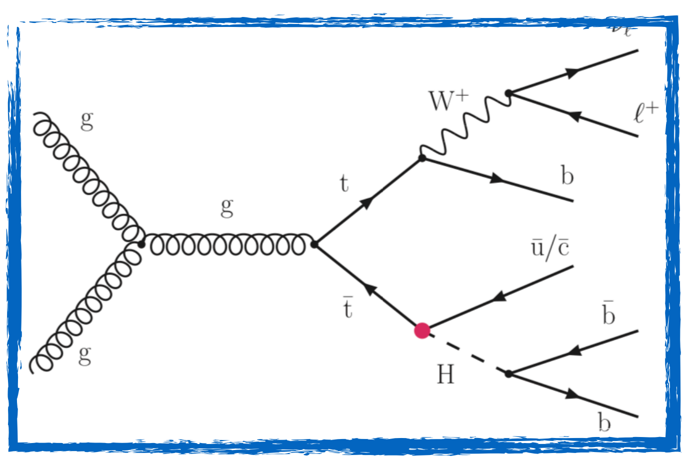
## Search for t → qH(bb)

- 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) limits on the branching ratio t → qH:
  - **$\mathcal{B}$(t → uH) < 0.47% (0.34%)**
  - **$\mathcal{B}$(t → cH) < 0.47% (0.44%)**



# FCNC in Top Quark

## Search for t → qH (H → $b\bar{b}$, $\tau^+\tau^-$)

- Looking in **top-quark pair events** for one FCNC and one SM top quark decay:
  - ***tqH($b\bar{b}$)***: one isolated electron or muon, multiple jets (several b-tagged jets)
  - ***tqH($\tau^+\tau^-$)***: events with two τ-lepton candidates (at least one decays hadronically), multiple jets
- Background is dominated by **top-quark pair production**
- **likelihood discriminant (Multivariate technique)** used to separate signal from background H → $b\bar{b}$ (H → $\tau^+\tau^-$)
- The data are **consistent with SM background contributions**
- combined with searches in **diphoton** and **multilepton** final states (same dataset)

Set observed (expected) limits on the branching ratio t → qH:

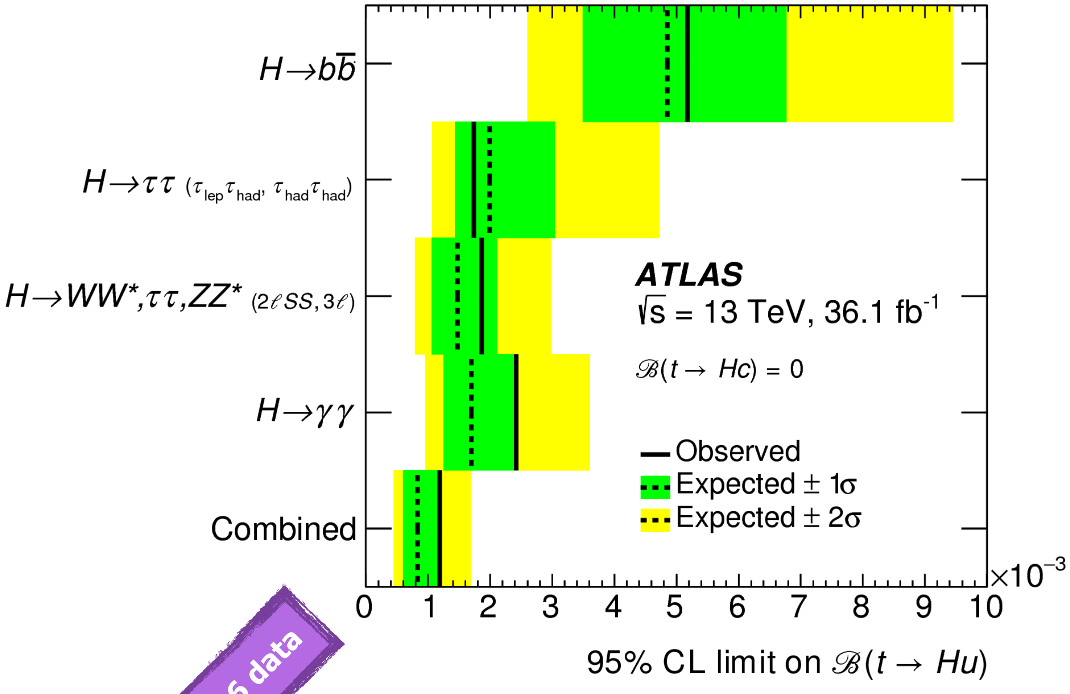
**$\mathcal{B}$(t → uH) < 0.11% (0.083%)**

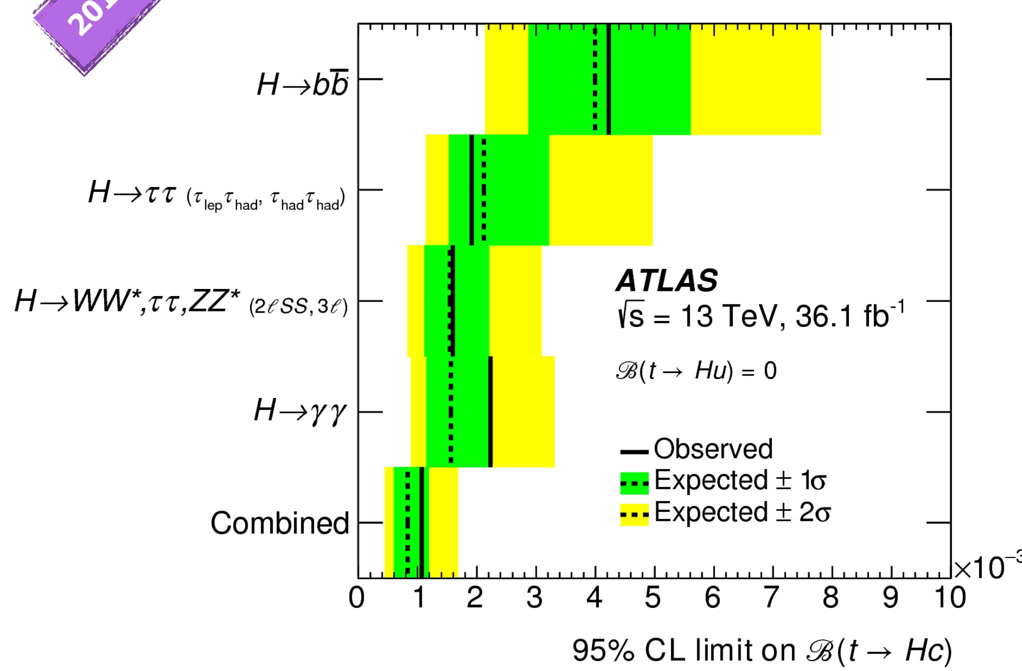
**$\mathcal{B}$(t → cH) < 0.12% (0.083%)**

arXiv:1812.11568

New!

2015+2016 data

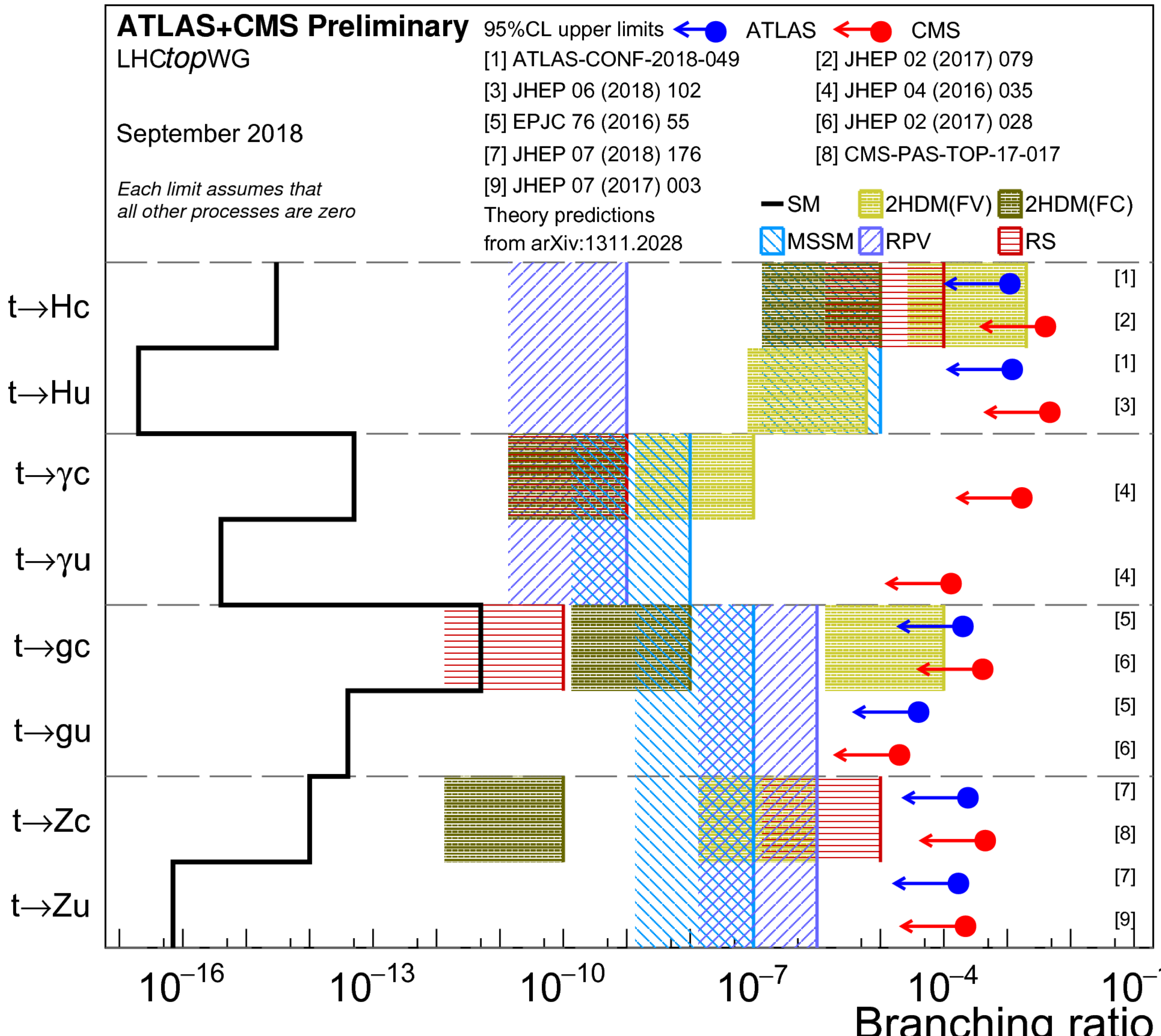


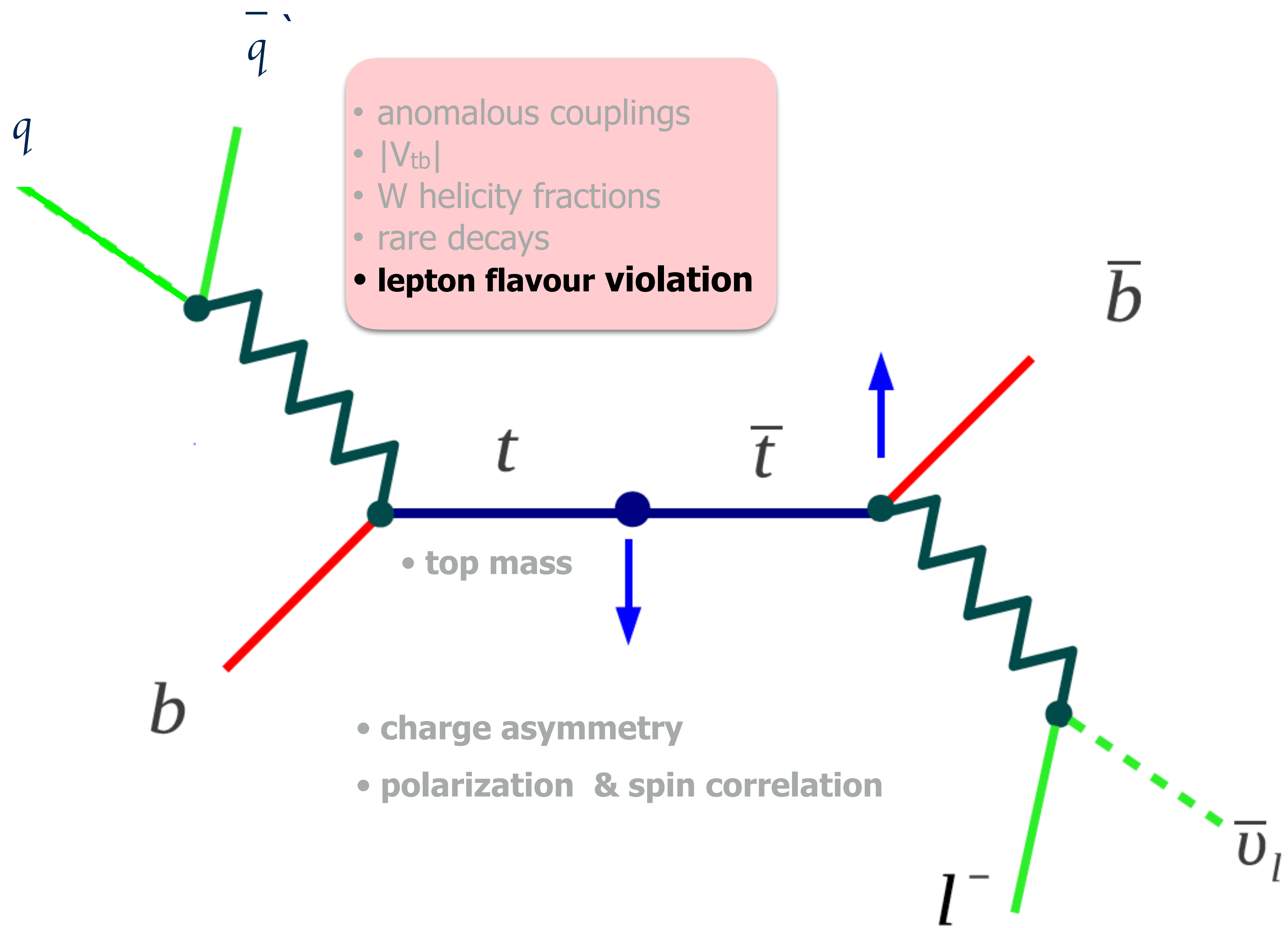
# FCNC in Top Quark

## 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!**



# Top Quark Properties - Decay



# Charged Lepton Flavour Violation

## Search for cLFV in top quark decays

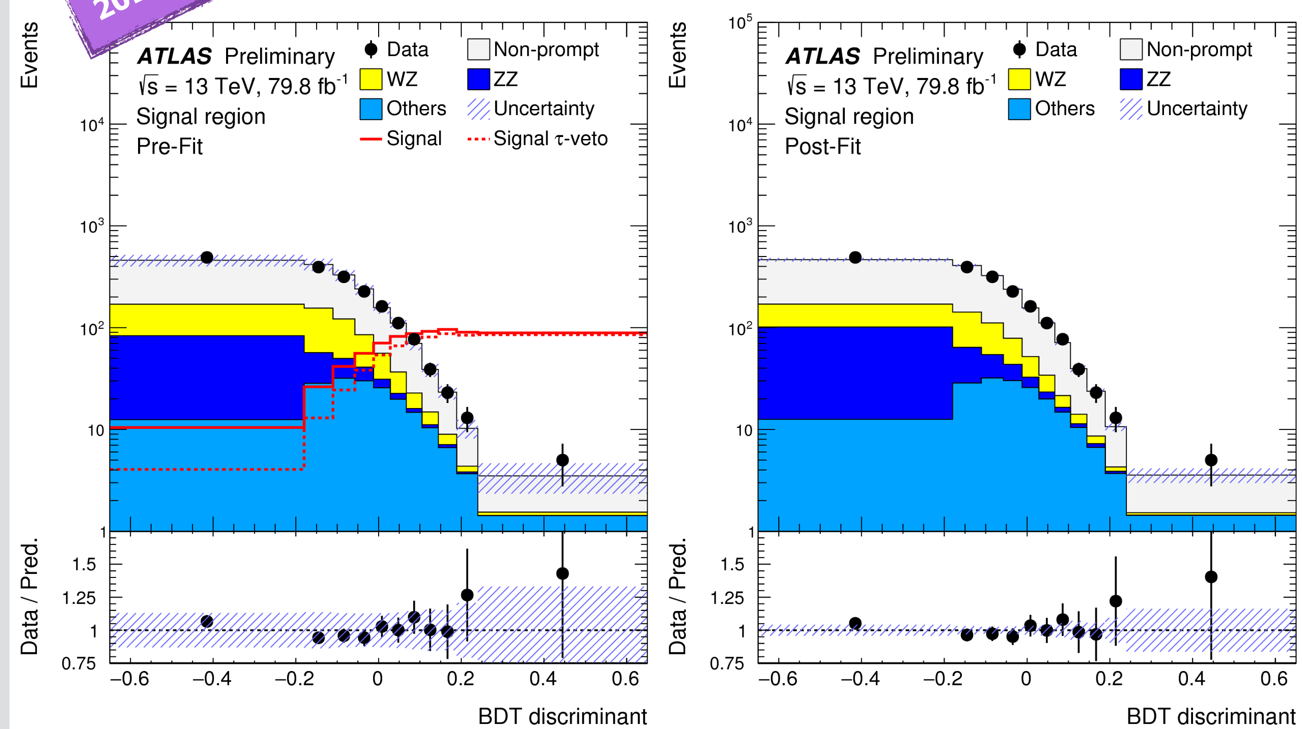
- **cLFV**: local interactions that change the flavour of charged leptons
- Heavily suppressed in SM, e.g. $\mathcal{B}(\mu \to e\gamma) \approx 10^{-55}$
- Analyzed data: 2015-2017 (79.8 fb$^{-1}$) @13TeV
- Model-independent **direct search**
- Looking for $t\bar{t}$ events with:
  - **three charged leptons**
  - **one light jet** and **one b-tagged jet**
- cLFV top quark reconstruction:
  - looking for ($\ell\ell$`q) system of mass close to $\mathbf{m_t}$
- **BDT discriminant** used to separate sig. and bkg.
- Dominant background: non-prompt leptons

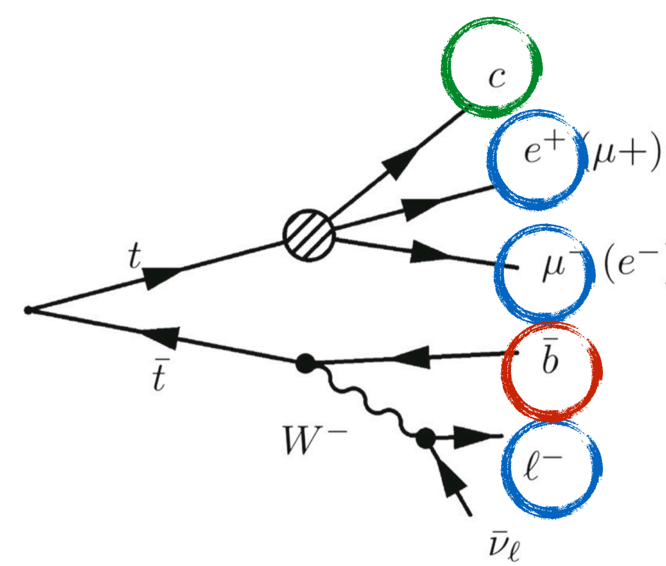
$$\mathcal{B}(t \to \ell\ell' q) < 1.36^{+0.61}_{-0.37} \times 10^{-5} \quad \text{(expected)}.$$

$$\mathcal{B}(t \to \ell\ell' q) < 1.86 \times 10^{-5} \quad \text{(observed)}$$

2015-2017 data

ATLAS-CONF-2018-044



# Summary & Conclusion

- **ATLAS** and **CMS** performed a large number of analyses with top quarks in LHC run 2 - Not enough time to cover them all in any detail
  - More **ATLAS** top results: **#TopPublicResults**, **#TopSummaryPlots**
  - More **CMS** top results: **#TopPhysicsPublications** , **#TopPhysicsPreliminaryResults**
- Large data volume enables us to do precise measurements with top quarks, and probe rare processes
- **Single top-quark** measurements have entered the **precision era** at the LHC!
- most results used **≈ 25%** of available data
- All measurements are so far **consistent** with the SM predictions
- Measurements dominated by **systematic uncertainties**
- No sign of new physics has been found yet, but…

**The full Run 2 dataset is still to be analyzed, stay tuned!**

# Backup

# Lepton Flavour Violation

YORK UNIVERSITÉ UNIVERSITY

## Used Variables in the Multivariate Analysis

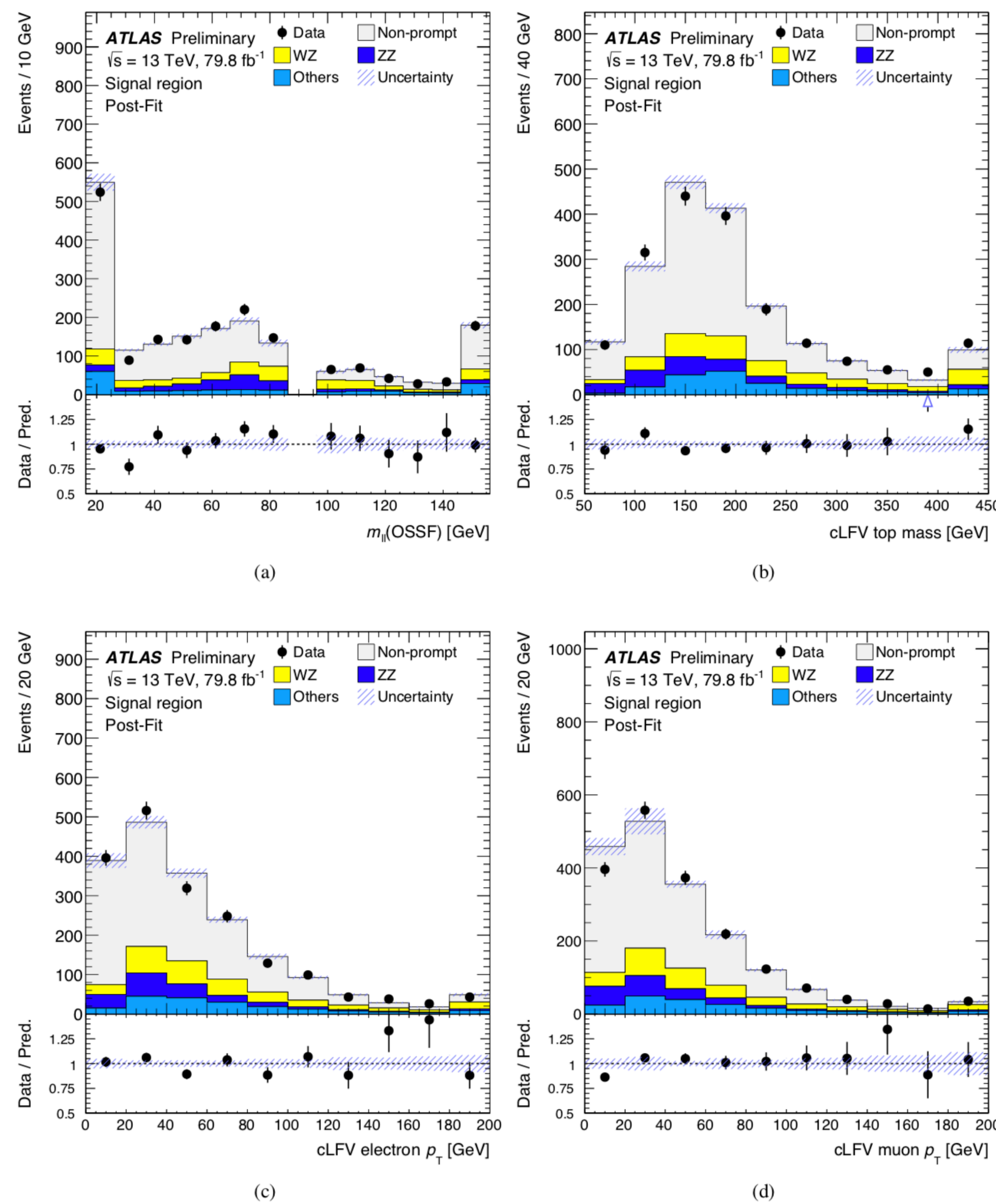
ATLAS-CONF-2018-044

Table 2: Variables used in the multivariate analysis, sorted according to the method-specific ranking.

| Variable | Separation (%) |
|---|---|
| OSSF lepton pair invariant mass | 11 |
| cLFV top mass | 10 |
| $p_T$ of the electron associated to the cLFV decay | 9.1 |
| $p_T$ of the muon associated to the cLFV decay | 8.5 |
| $p_T$ of the lepton associated to the SM decay | 8.3 |
| Scalar mass of all jets and leptons in the event | 7.6 |
| Same-sign electron pair invariant mass | 6.9 |
| Missing transverse momentum | 6.8 |
| Number of $b$-jets | 6.7 |
| $W$ transverse mass associated to the SM top lepton | 6.6 |
| $\Delta R$ between the cLFV electron and the cLFV light jet | 6.5 |
| SM top mass | 6.4 |
| $\Delta R$ between the cLFV muon and the cLFV light jet | 6.3 |
| BDT discriminant | 44 |

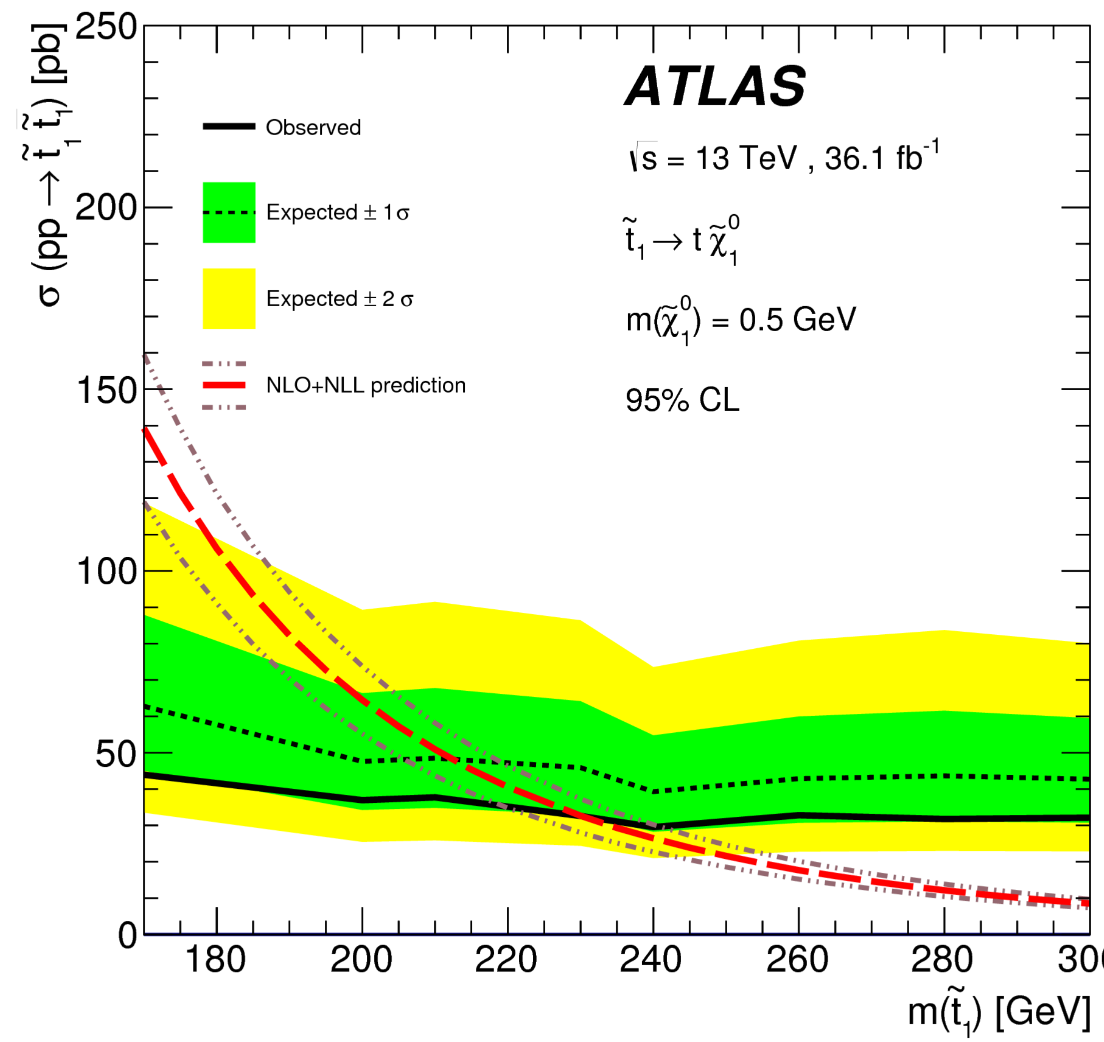
Table 3: Pre- and post-fit yields for the background-only fit in the signal region. The post-fit uncertainties account for correlations among the nuisance parameters.

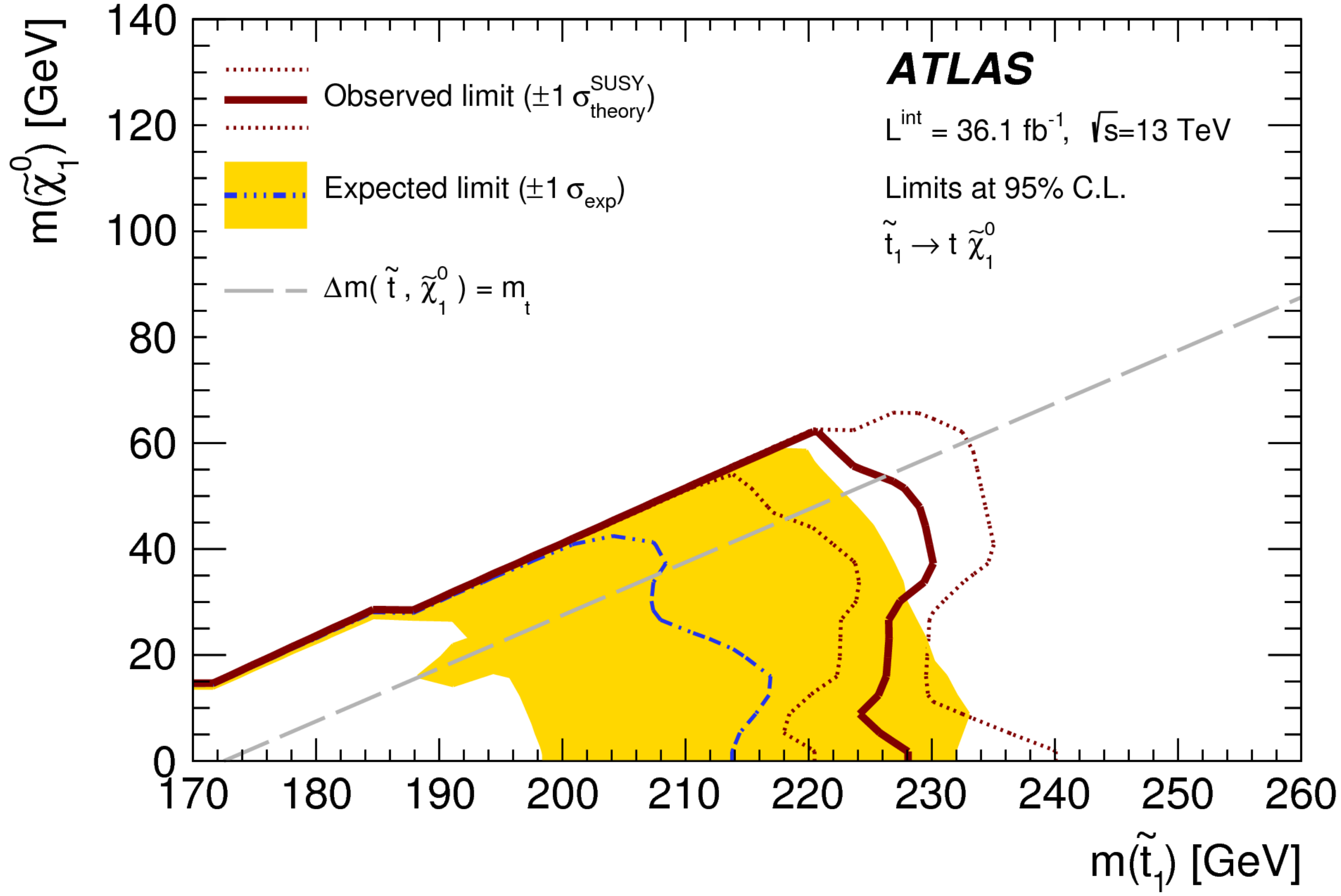
| Category | Non-prompt leptons | $WZ$ | $ZZ$ | $t\bar{t}V$ | Other prompt SM | Number of events |
|---|---|---|---|---|---|---|
| Pre-fit | 1190 ± 180 | 350 ± 140 | 140 ± 52 | 108 ± 10 | 76 ± 10 | 1860 ± 230 |
| Post-fit | 1220 ± 100 | 278 ± 86 | 170 ± 52 | 108 ± 10 | 78 ± 10 | 1854 ± 46 |
| Data | | | | | | 1857 |



# Polarization & Spin Correlation

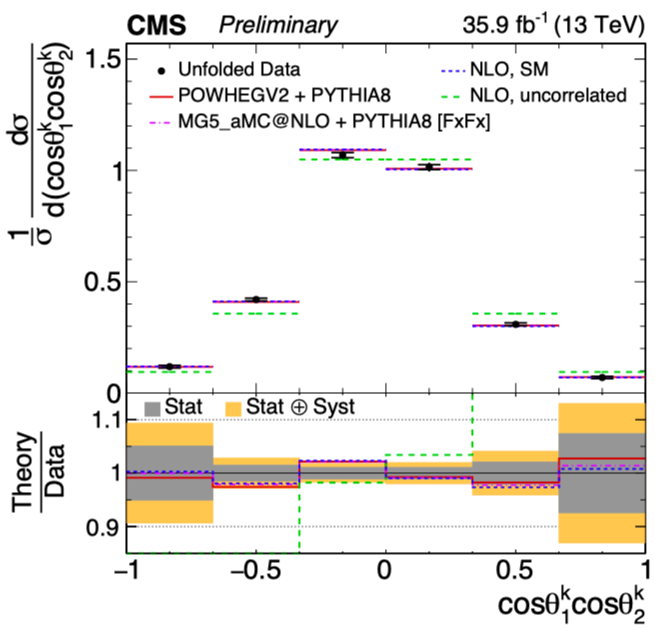
arXiv:1903.07570

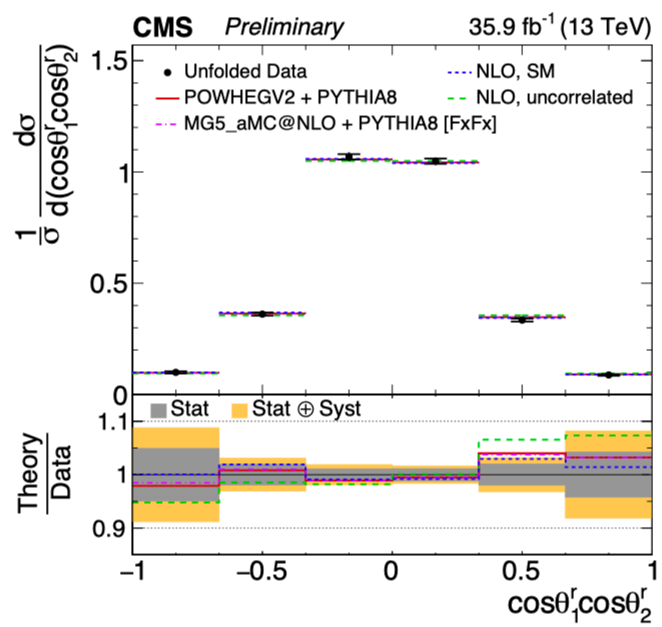


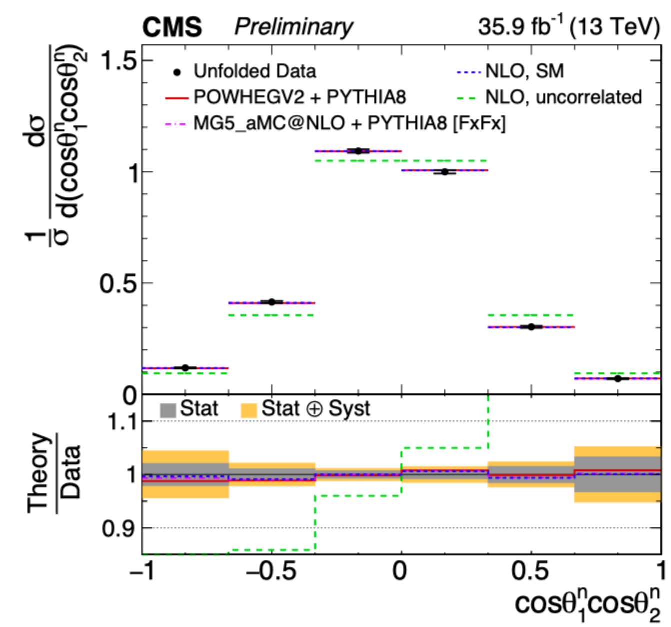



# Polarization & Spin Correlation

CMS-PAS-TOP-18-006

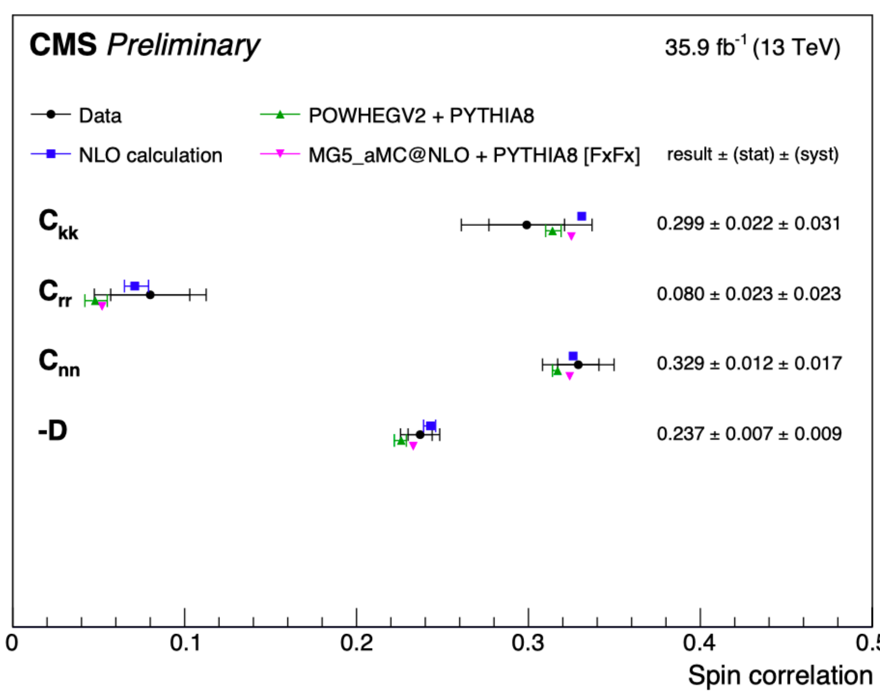


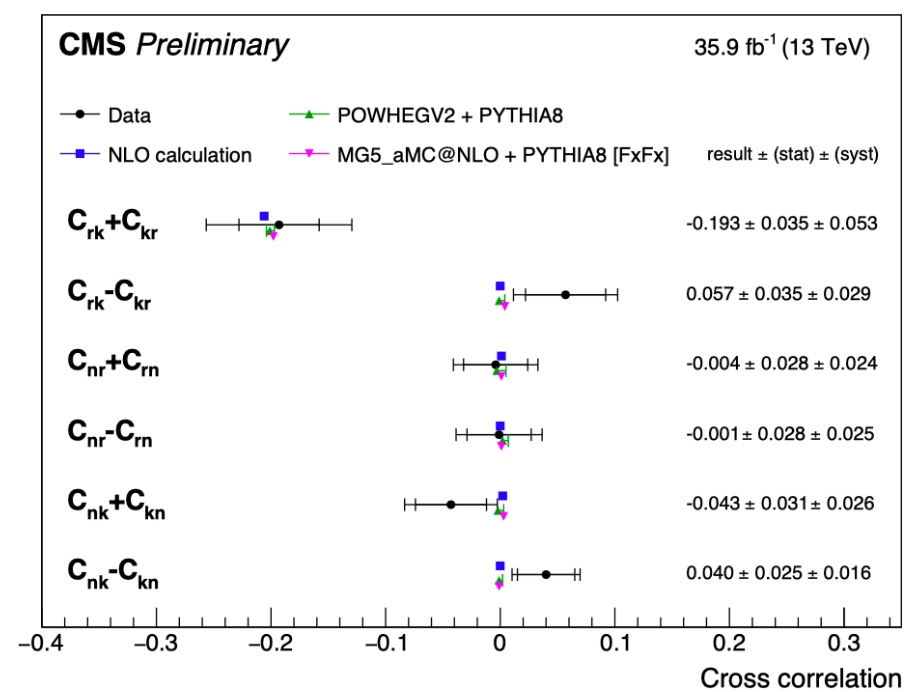




- $C_{kk} = 0.30 \pm 0.02 \pm 0.03$
  SM: 0.33
- $C_{rr} = 0.08 \pm 0.02 \pm 0.02$
  SM: 0.07
- $C_{nn} = 0.33 \pm 0.01 \pm 0.02$
  SM: 0.33

## Diagonal elements of $\mathbb{C}$ matrix




## Off-diagonal elements of $\mathbb{C}$ matrix



# ATLAS and CMS measurements of the single top production cross-sections

ATL-PHYS-PUB-2018-034