Top-quark properties at the LHC

($\sqrt{s} = 13$ TeV)

Jacob Kempster

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E-mail: jacob.julian.kempster@cern.ch

Introduction

- The top quark is the **heaviest** known fundamental particle. Could it play a special role in electroweak symmetry breaking?
- The top quark has a **very short lifetime**, and is the only quark that decays before forming **hadronic bound states**
- This leads to many **measureable properties** that we can test from its **decay products**, probing the **predictions of QCD**
- **Understanding $t\bar{t}$ production is crucial** for many searches for rare SM processes and **physics beyond the SM**
- **The LHC is a Top factory!**

Lots of interesting results!

- **ATLAS:**
  - **Spin Correlations** Eur. Phys. J. C 80 (2020) 754
  - **Charge Asymmetry** ATLAS-CONF-2019-026
  - **Energy Asymmetry – (Pending)**
  - **Top-quark Polarisation** ATLAS-CONF-2021-027
  - **Flavour-Changing Neutral-Currents**
    - $tq\gamma$ – Phys. Lett. B 800 (2020) 135082
  - **Lepton Flavour Universality** Nat. Phys. 17 813–818 (2021)

- **CMS:**
  - **Spin Correlations / Asymmetries**
    - $t\bar{t}$ - Phys. Red. D 100 (2019) 072002
    - tqZ - CMS-PAS-TOP-20-010
  - **CP Violation** CMS-PAS-TOP-20-005
  - **Flavour-Changing Neutral-Currents**
    - $tqH(\rightarrow \gamma\gamma)$ – CMS-PAS-TOP-20-007
    - $tqH(\rightarrow b\bar{b})$ – CMS-PAS-TOP-19-002
  - **Lepton Flavour Universality** CMS-PAS-SMP-18-011

This talk

- **ATLAS:**
  - **Charge Asymmetry** ATLAS-CONF-2019-026
  - **Energy Asymmetry – (Pending)**
  - **Top-quark Polarisation** ATLAS-CONF-2021-027

  - **Lepton Flavour Universality** Nat. Phys. 17 813–818 (2021)

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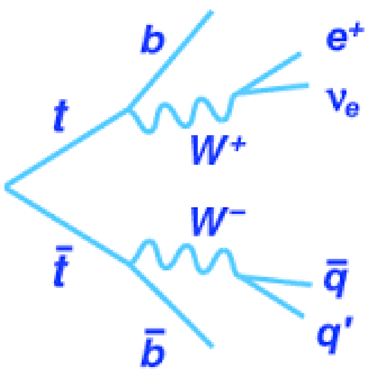
15min, 6 topics…

Asymmetries that probe CP violating interactions are measured in observables constructed from linearly independent four-moment vectors
Define T-odd operators using final state objects of top decays to build asymmetries (see backup for details) [2]



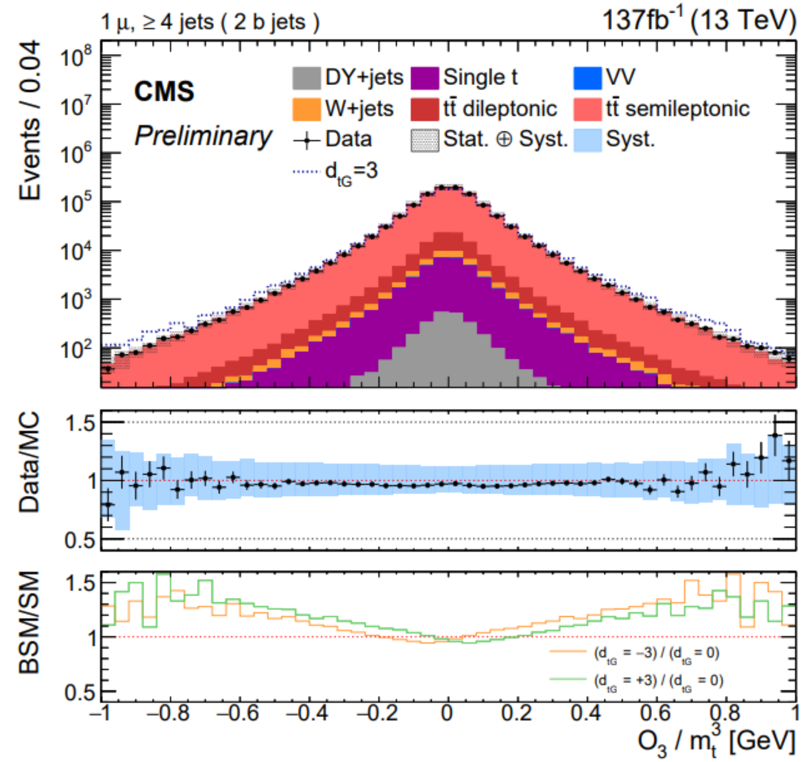
$t\bar{t}$ l+jets selection, 90% purity
- Backgrounds: ttbar dilepton, Single-top, W+jets, Drell-Yan+jets, Diboson…

χ^2-based Jet assignment for Top and W reconstruction, ~75% accuracy

Fit m_{lb} with CR for W+jets normalisation

$$O_3 = Q_\ell \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell \vec{p}'_b \cdot (\vec{p}'_\ell \times \vec{p}'_{j_1})$$
$$O_6 = Q_\ell \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$$
$$O_{12} = q \cdot (p_b - p_{\bar{b}}) \epsilon(P, q, p_b, p_{\bar{b}}) \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})_z$$
$$O_{14} = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}).$$

$$A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)}, i = 3, 6, 12, 14.$$



Note that green and yellow ratio bands are **not** symmetric

CPV

CMS-PAS-TOP-20-005
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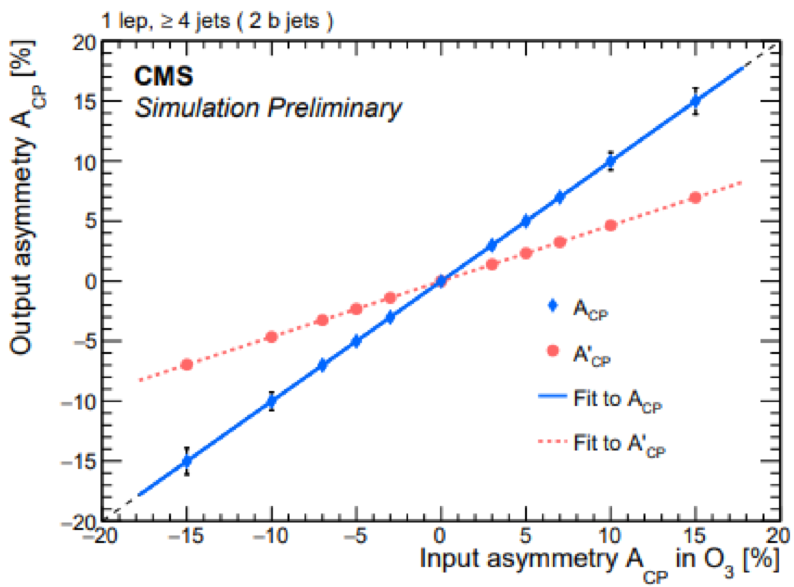
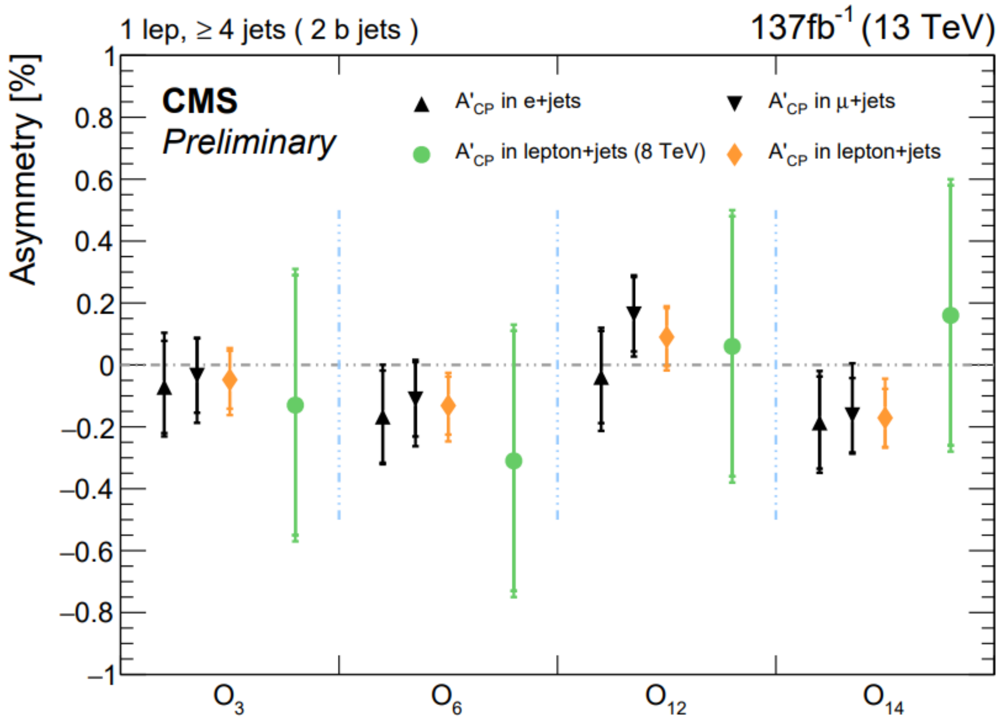
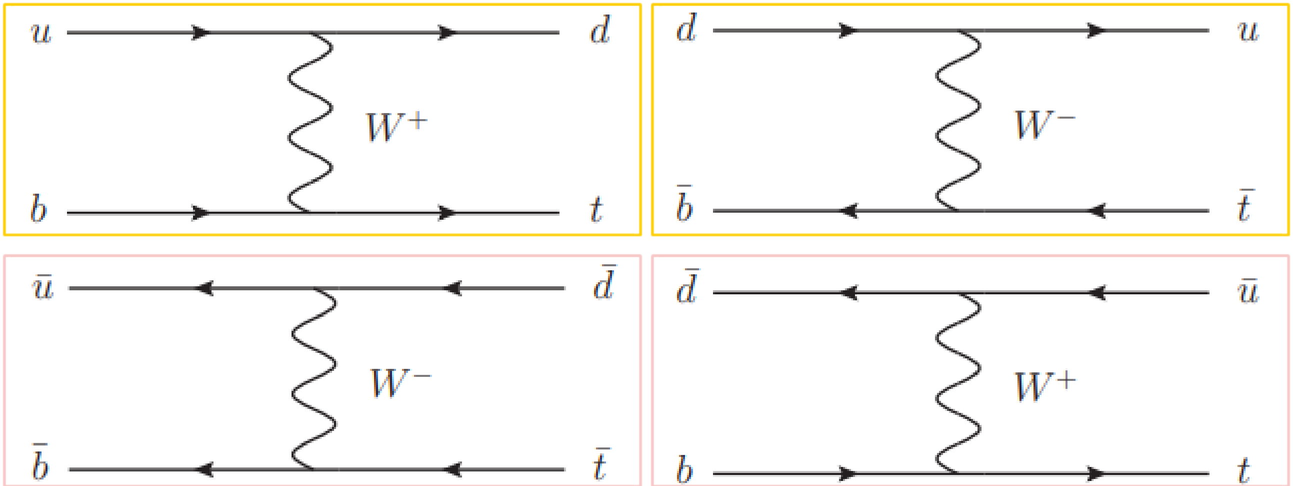
- Many sources of 'dilution' may affect the measured asymmetry A_{CP} (e.g. object mis-reconstruction) which can be corrected for
- BSM physics could be large enough to appear even in an uncorrected asymmetry A'_{CP}

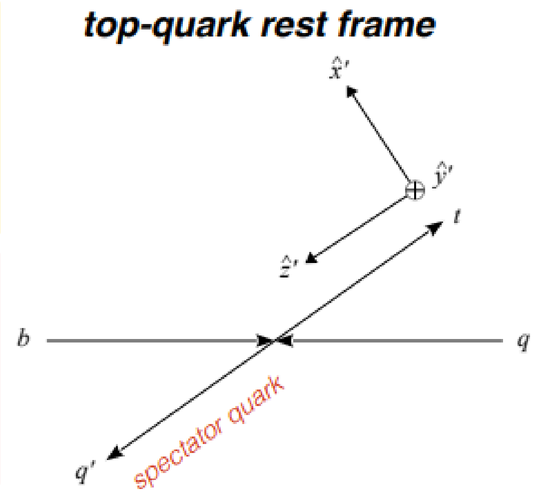




Precision of 10^{-3} achieved, no evidence for CP violating effects observed – consistent with SM expectation.
Results are stat dominated.
Largest systematics: Top Modelling (see backup)

Top Polarisation





$t\bar{t}$ produces unpolarised tops (parity conservation in QCD)

t-channel is dominant process for single-top production at LHC

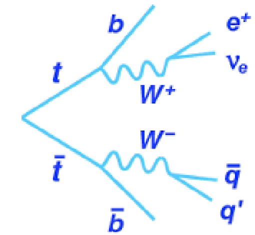
Single-top production (V-A coupling in Wtb vertex) leads to tops with their spin completely aligned along (or against) the direction of the down-type quark (the 'spectator' quark), depending on the dominant or subdominant process and the production of a t or $\bar{t}$

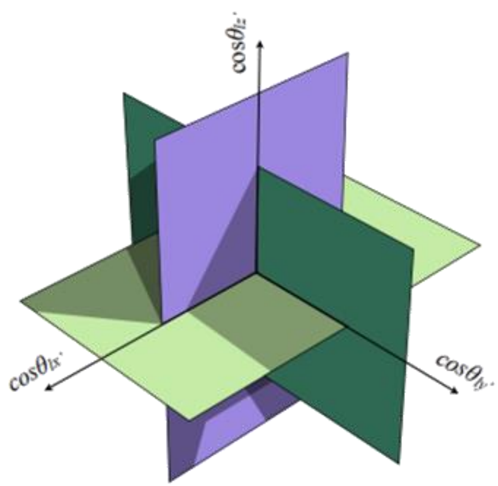
t = Aligned $\quad$ $\bar{t}$ = Anti Aligned $\quad$ $P_{z'}(t) \sim 0.90$

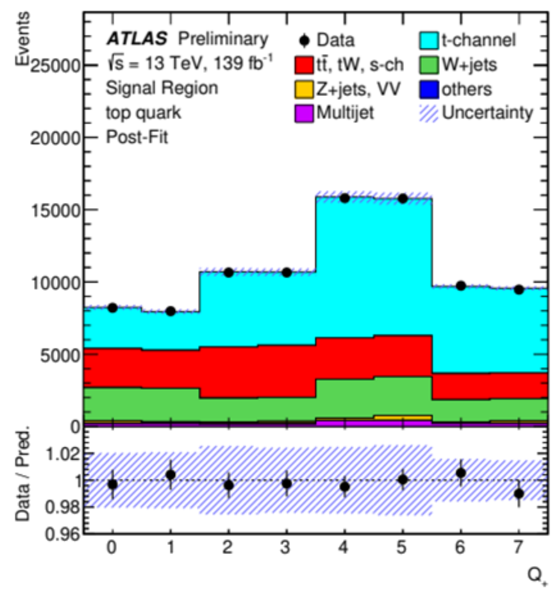
t = Anti Aligned $\quad$ $\bar{t}$ = Aligned $\quad$ $P_{z'}(\bar{t}) \sim -0.86$

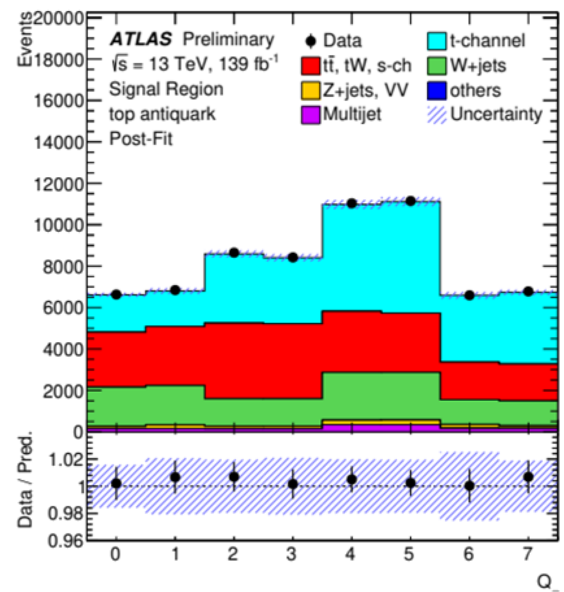
(Depend on $\sqrt{s}$, acceptance...)

- Top quark spin affects angular distributions of decay products
- MC Templates may be built between samples to represent any combination of valid polarisations $\{P_{x'}, P_{y'}, P_{z'}\}$
- Build angular distributions for the charged lepton with respect to each axis θ_{li}







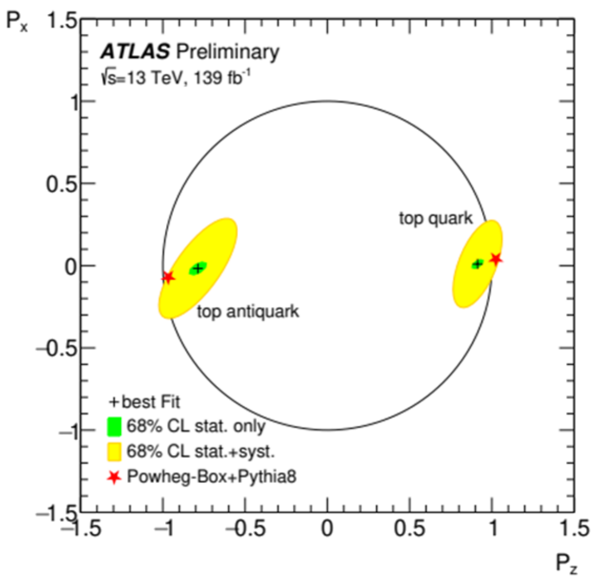


- *Octant Variable* Q defines all signal regions, broken by sign of $\cos\theta_{l\hat{\imath}}$ and q_l
- CRs are introduced for $t\bar{t}$, W+jets backgrounds

Profile likelihood fit over all regions simultaneously:

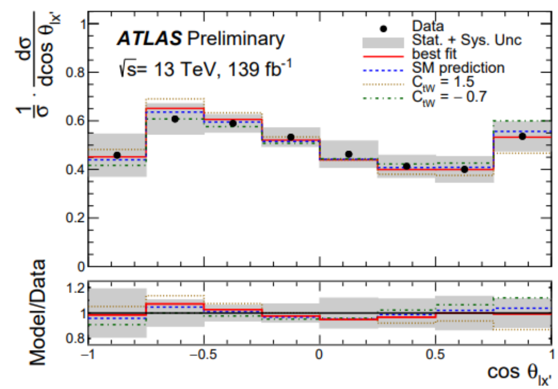
- 6 PoIs (polarisations split by top charge)
- Normalisation Factors for CRs
- Nuisance parameters associated to systematic uncertainties

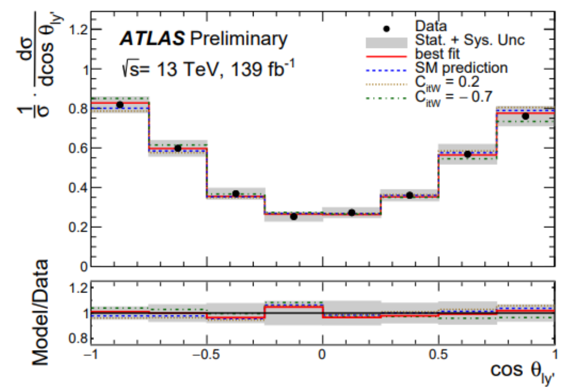
Polarisations in agreement with SM predictions to 1σ
(Powheg+Pythia8)

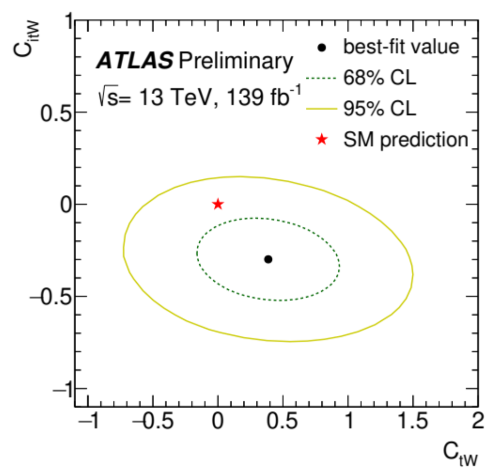


Uncertainties dominated by Jet Energy Resolution (JER)
- Polarisation depends on kinematic angles determined in top-quark rest frame
- JER is key to reconstruction of this frame

First order dim6 EFT operators that contribute to t-channel production:
- O_{tW} - Operator to focus on
  - C_{tW} most affects $P_{x'}$
  - C_{itW} most affects $P_{y'}$
  - (Non-zero value could imply **CPV**)







- Morphing technique used to interpolate between different Wilson Coefficient values
- Both coefficients fitted simultaneously (does not assume other is zero)

Result compatible with SM within 2σ (MG5_aMC@NLO+Pythia8)

Top Spin Asymmetry

In single-top tZq events, a 'spin asymmetry' A_l may be defined using leptons from top-decays which can be used as a proxy for the Top polarisation:

$$A_l = \frac{1}{2} P a_l$$

P = Top polarisation
a_l= Spin analysing power of lepton

$$\cos(\theta^*_{\mathrm{pol}}) = \frac{\vec{p}(q'^*) \cdot \vec{p}(l^*_t)}{|\vec{p}(q'^*)||\vec{p}(l^*_t)|}$$

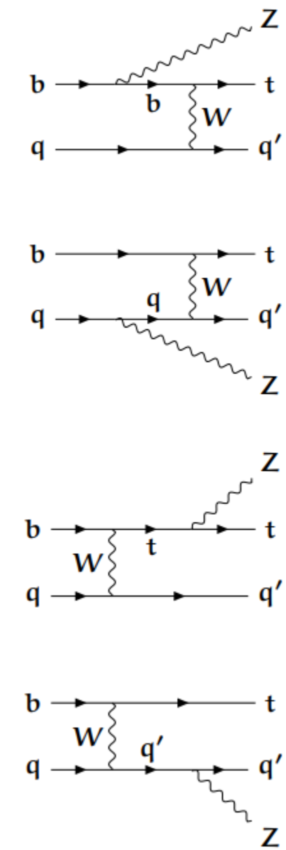
Momenta of spectator quark q' and lepton from top decay l_t in

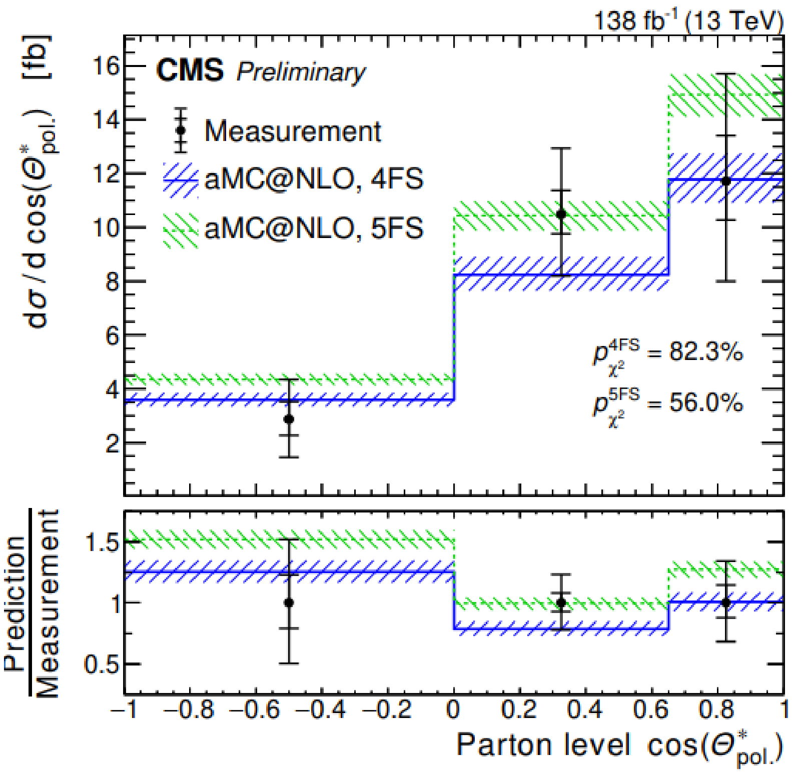
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos(\theta^*_{\mathrm{pol}})} = \sigma_{tZq}\left(\frac{1}{2} + A_l \cos(\theta^*_{\mathrm{pol}})\right)$$

Spin asymmetry may be related to differential cross-section using top quark polarisation angle

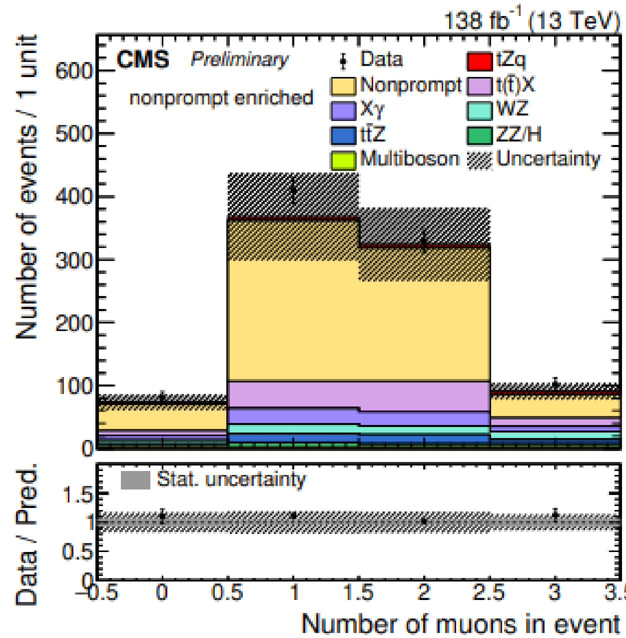
Top Spin Asymmetry

- **Measure tZq differential cross-sections using 3-lepton final states**
- Neural Network (NN) to separate signal tZq events from backgrounds: $t\bar{t}Z/X$, Diboson, Non-prompt leptons
- Many CRs defined with enhanced processes to check modelling in a **profile-likelihood fit**





Unfolded polarisation distribution at parton level



$$A_\ell = 0.58 \,^{+0.15}_{-0.16}\,\text{(stat)} \pm 0.06\,\text{(syst)}$$

$$A_l^{4FS,SM} = 0.437^{+0.004}_{-0.003}$$

$$A_l^{5FS,SM} = 0.454^{+0.004}_{-0.005}$$

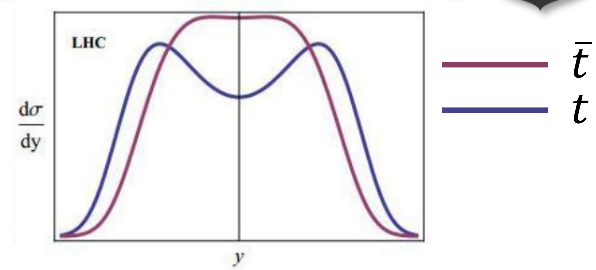
(ISR, FSR, PDFs, renormalisation + factorisation scales)

Charge Asymmetry

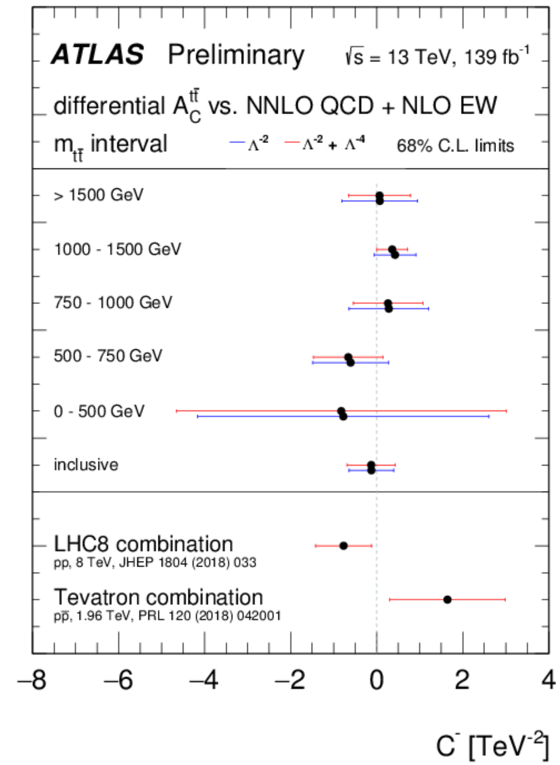
- LO $t\bar{t}$ production is symmetric
- Higher-order interferences between $q\bar{q}$ and qg create an asymmetric production
  - t is produced preferentially in direction of incoming q

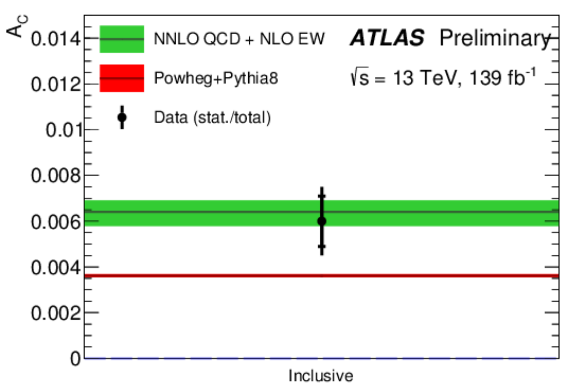
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

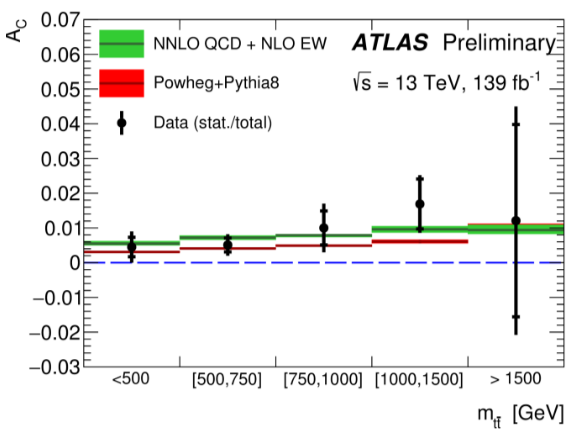
$\Delta|y| = |y_t| - |y_{\bar{t}}|$



- Charge symmetric gg production dilutes asymmetry
- Several BSM models predict alterations to A_C, especially with variation as a function of $m_{t\bar{t}}$ and $\beta_{z,t\bar{t}}$
  - Anomalous vector/axial couplings (e.g. axigluons)
  - Heavy Z' bosons





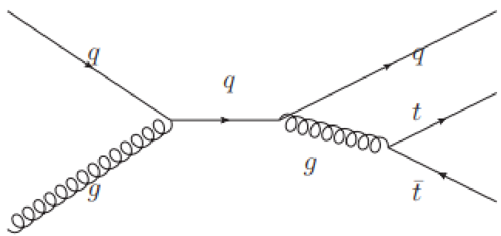


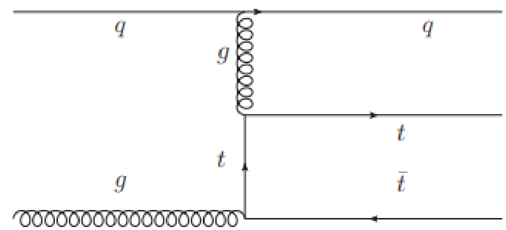
C^-/Λ^2 — C^- is linear combination of Wilson Coefficients. Λ is scale of new physics

EFT coefficient useful for many models (axigluons, kaluza-klein, randall-sundrum)

$A_C = 0.0060 \pm 0.0015$ (stat+syst.)

Energy Asymmetry

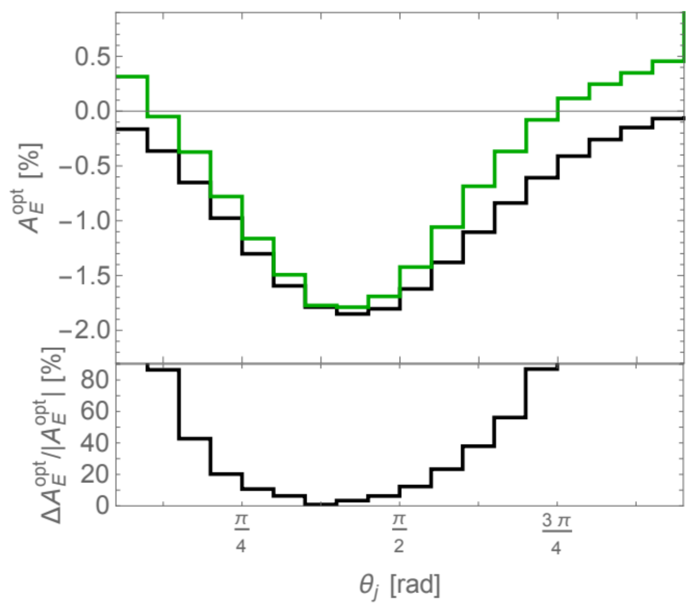




Asymmetry built in $t\bar{t}j$ production

- $\Delta E = E_t - E_{\bar{t}}$
- θ_j = Jet scattering angle w.r.t incoming parton
- ΔE , θ_j defined in $t\bar{t}j$ rest frame

$$A_E(\theta_j) \equiv \frac{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) - \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) + \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)} \equiv \frac{\sigma_A(\theta_j)}{\sigma_S(\theta_j)}$$



- Complementary measurement to charge (rapidity) asymmetry (CA) – probes new directions in SMEFT
- Potential for future combination with CA
- Many BSM models generate multiple four-quark operators simultaneously

S. Berge and S. Westhoff, Phys. Rev. D 95, 014035 (2017), arXiv:1608.00574 [hep-ph]

Energy Asymmetry

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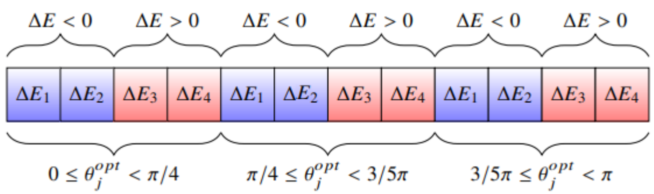
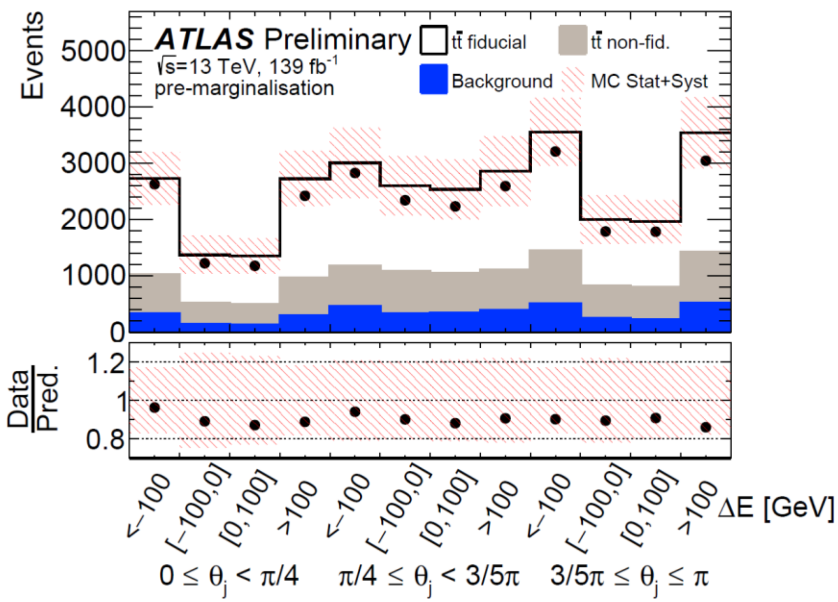
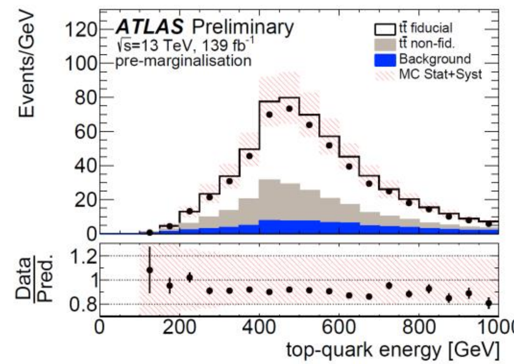
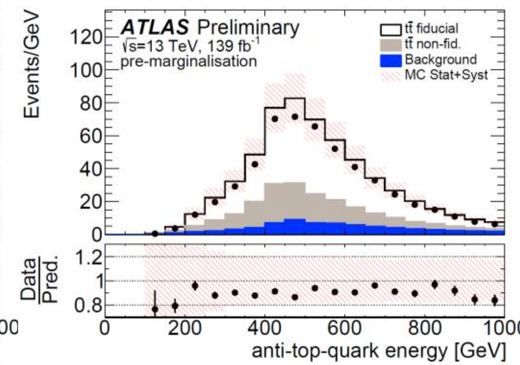
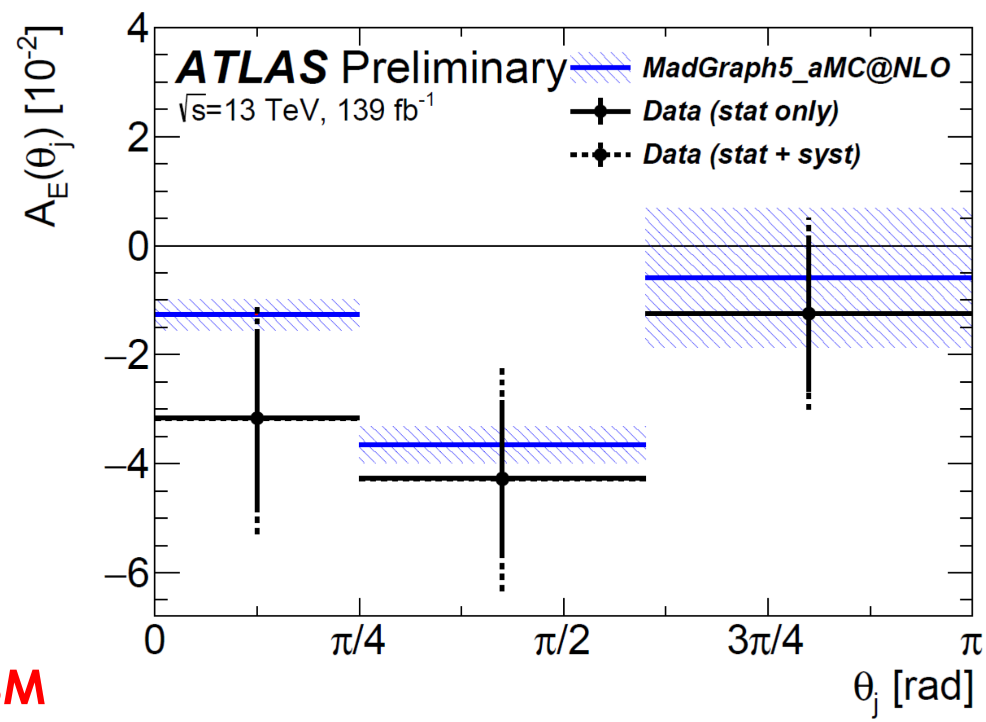
- $t\bar{t}$ lepton+jets boosted topology
- Fully Bayesian Unfolding to particle level
- Binned in θ_j to increase sensitivity











All asymmetry results agree with SM predictions (MG5_aMC@NLO+Pythia8, NLO QCD + PS)

Heavily dominated by statistical uncertainties

Energy Asymmetry

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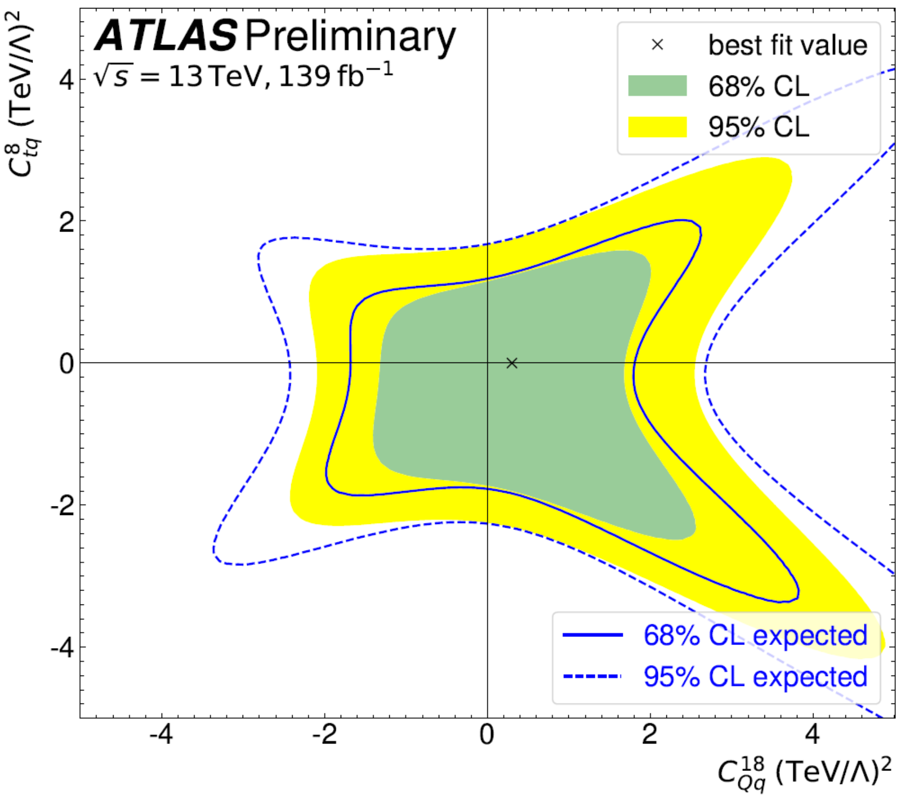
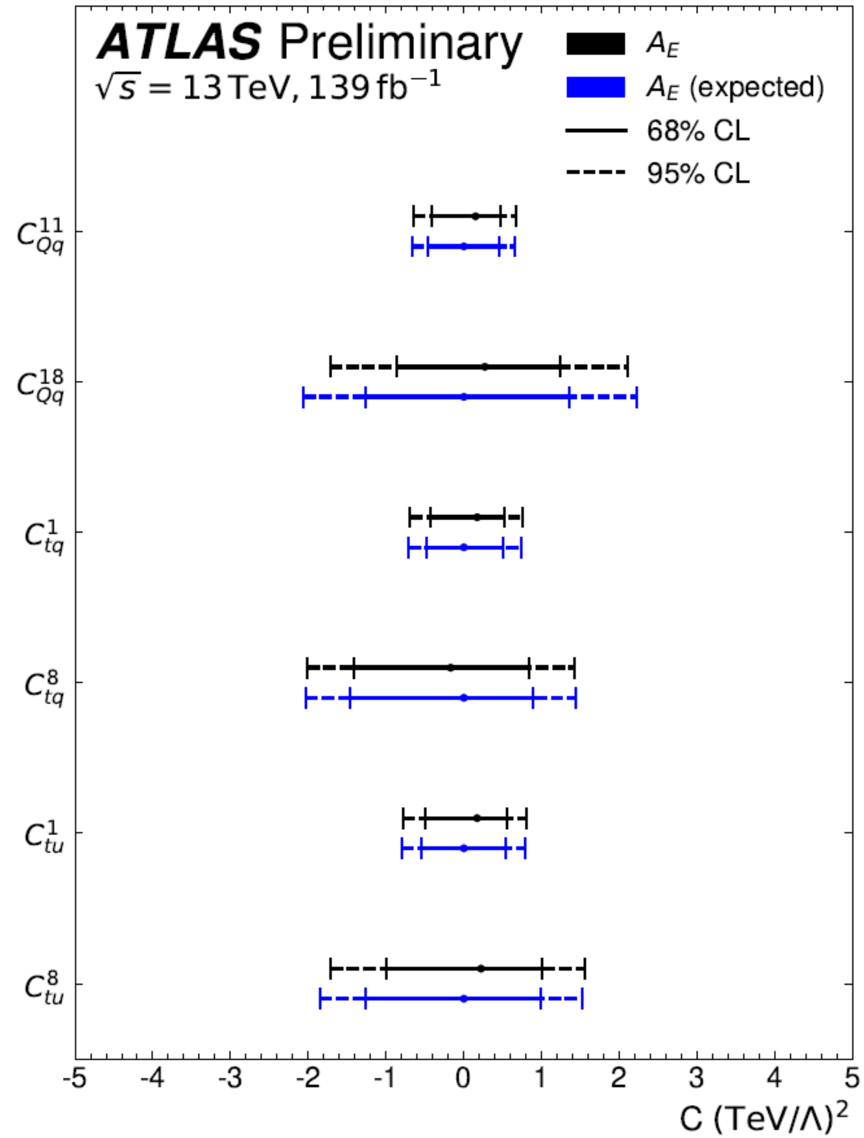




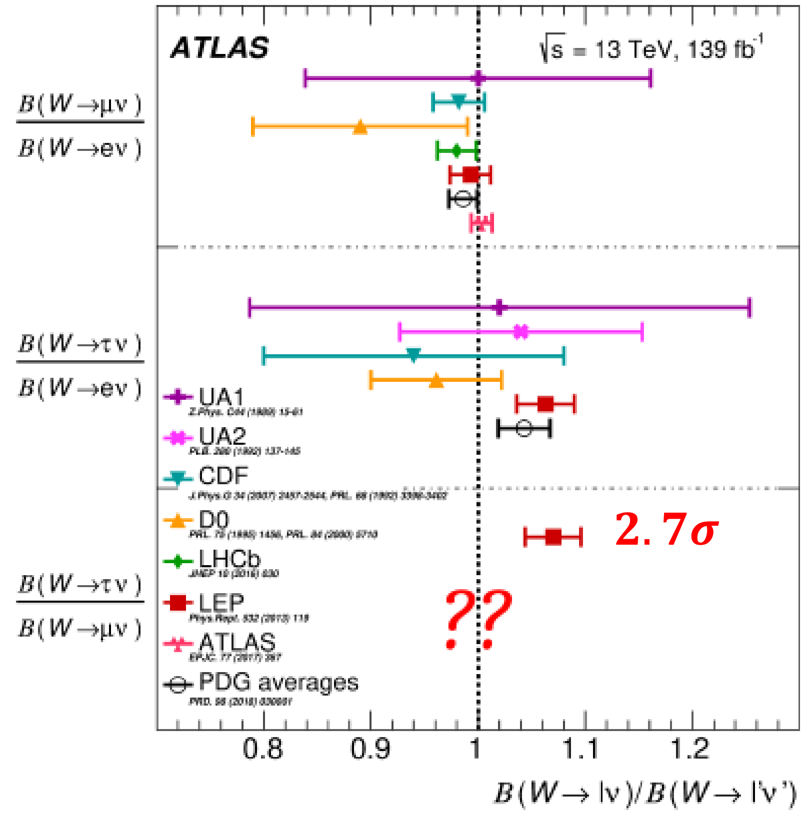
All EFT fits are consistent with zero

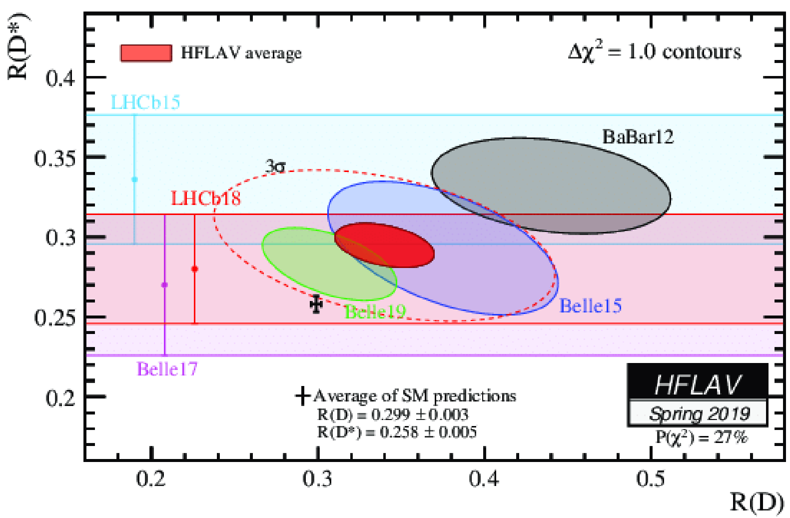
Lepton Flavour Universality (LFU)

- Fundamental axiom of SM
- Branching ratios of W and Z boson decays should be equal for all lepton flavours and charges $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$ - ratios can be used to check this!

LEP

$$\mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_{\mu}) \,/\, \mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_{\mathrm{e}}) = 0.993 \pm 0.019\,,$$
$$\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_{\tau}) \,/\, \mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_{\mathrm{e}}) = 1.063 \pm 0.027\,,$$
$$\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_{\tau}) \,/\, \mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_{\mu}) = \boxed{1.070 \pm 0.026}\,.$$



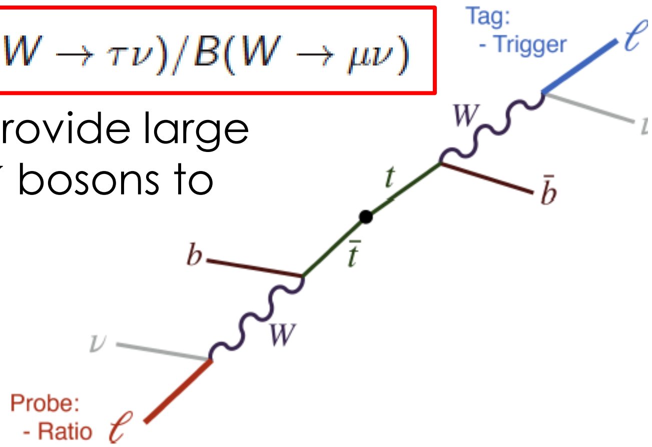


$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\mu\nu)}$$

3.1σ

$R(\tau/\mu) = B(W \to \tau\nu)/B(W \to \mu\nu)$

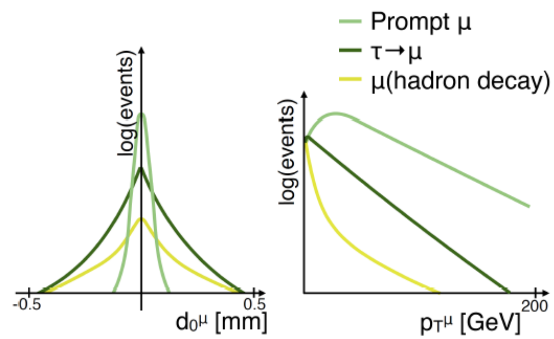
$t\bar{t}$ decays provide large source of W bosons to study



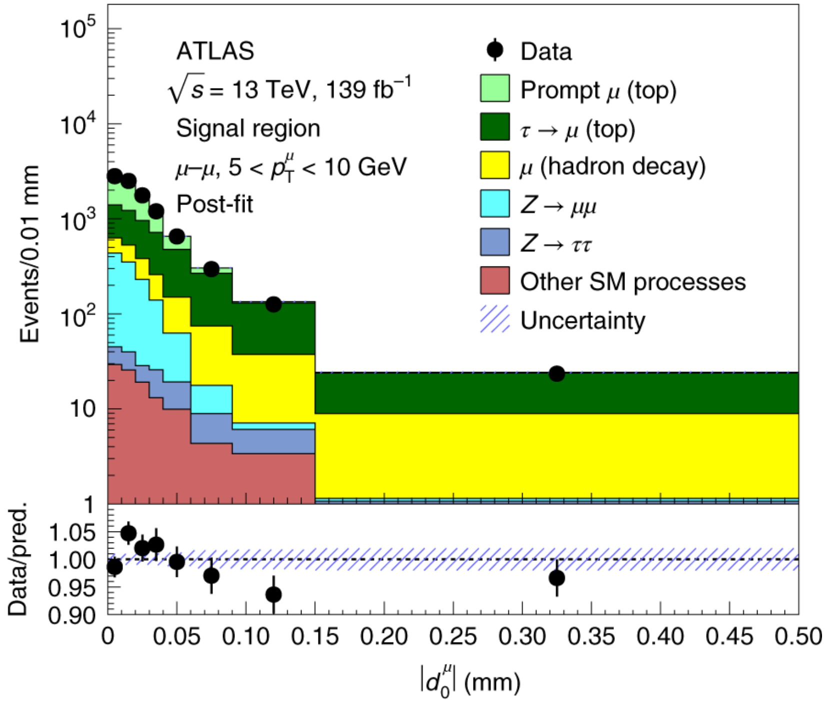
Focus on leptonic $\tau \to \mu$ decays, for a final state with opposite-sign $e\mu$, $\mu\mu$

Large background from $Z \to \mu\mu$, had $\to \mu$

- CRs for normalisation
- Focus on muons with low-p_T and large transverse-impact parameter $|d_0^\mu|$



Requires careful $|d_0^\mu|$ modelling – corrections for beamspot size, alignment and material interactions



$R(\tau/\mu) = 0.992 \pm 0.013\,[\pm 0.007\,(\text{stat}) \pm 0.011\,(\text{syst})]$

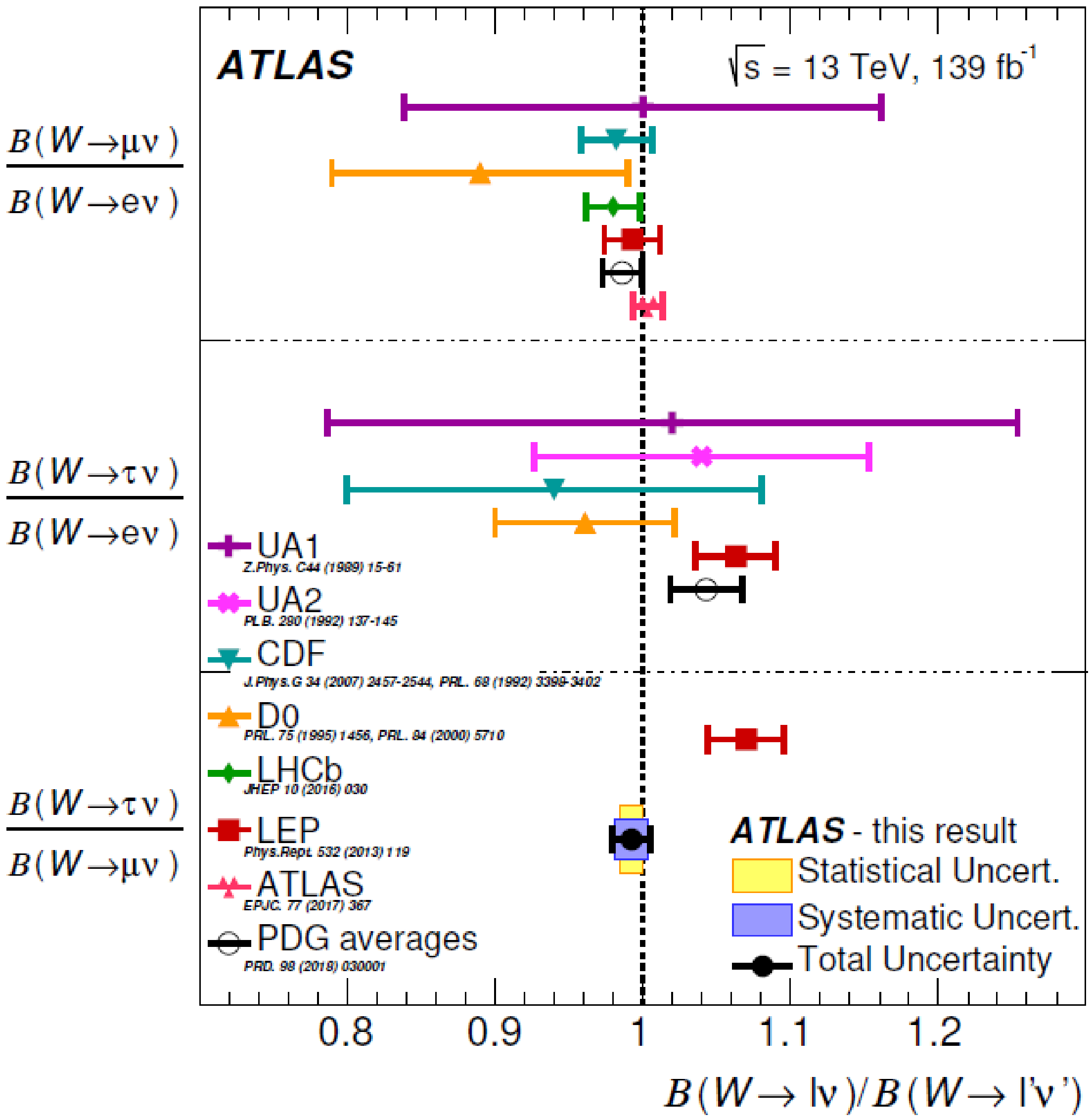
Consistent with SM expectation!

Largest systematic uncertainties:

- Prompt d_0^μ templates
- Parton shower variations
- Muon isolation efficiency

LFU

Nat. Phys. 17 813–818 (2021)
139 fb^{-1}



Precision tighter than LEP

LFU

[CMS-PAS-SMP-18-011](#)
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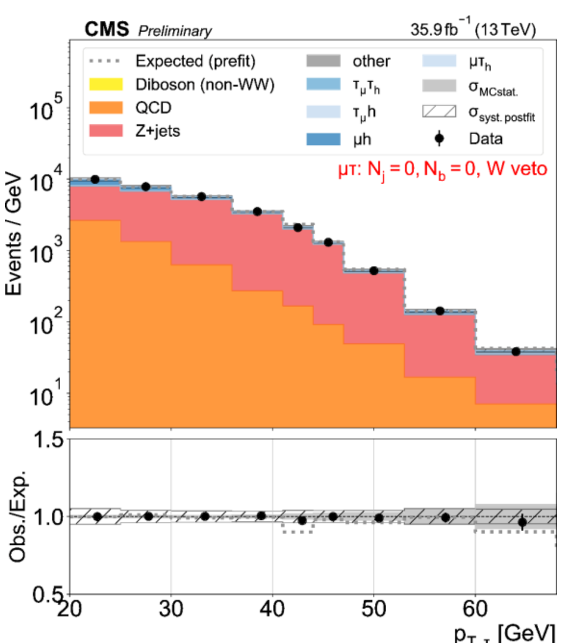
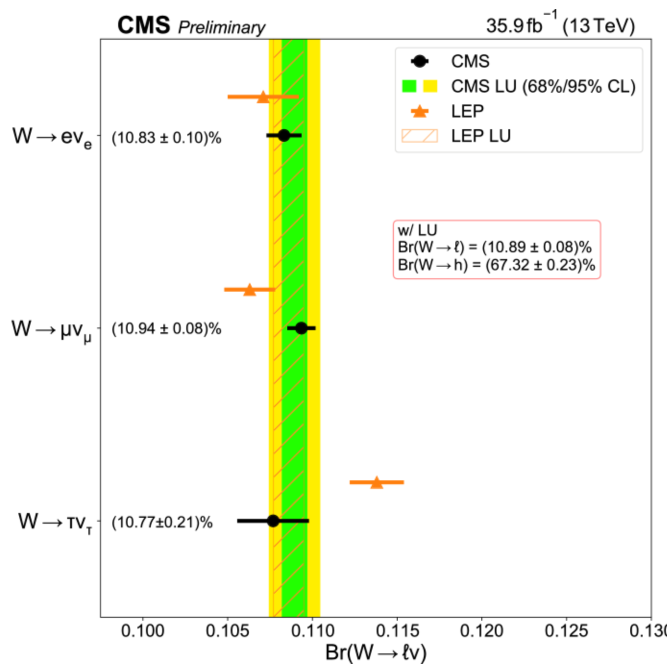
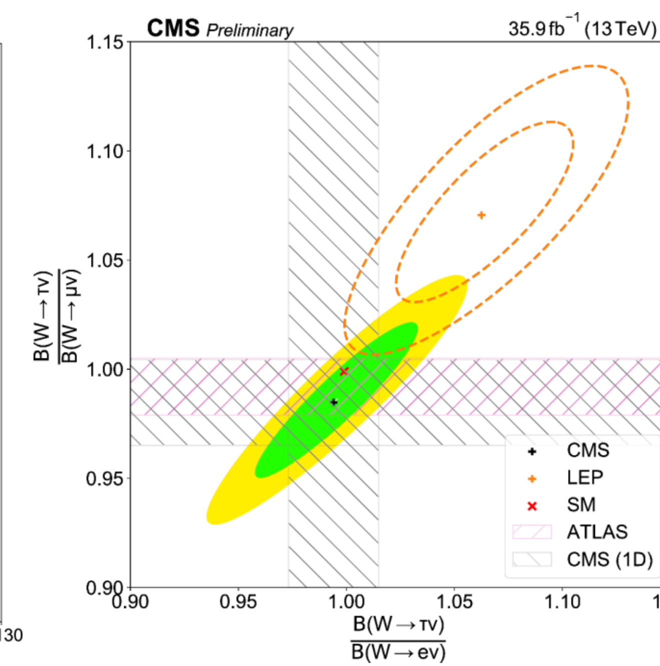
- Measuring each $W \to l\nu$ branching ratio using $t\bar{t}$, tW, WW and W+jets processes, including hadronic tau final states
- p_T spectrum used as primary distribution
- CRs for estimating non-prompt background SFs
- MLE approach using histogram templates

	$N_j = 0$	$N_j = 1$	$N_j = 2$	$N_j = 3$	$N_j \geq 4$
$N_b = 0$	$e\tau, \mu\tau, e\mu$	$e\tau, \mu\tau, e\mu$	$e\tau, \mu\tau$; $ee, \mu\mu, e\mu$		
$N_b = 1$		$e\tau, \mu\tau, e\mu$	$e\tau, \mu\tau$	$e\tau, \mu\tau$	
			$ee, \mu\mu, e\mu$		
					$eh, \mu h$
$N_b \geq 2$			$e\tau, \mu\tau$	$e\tau, \mu\tau$	
			$ee, \mu\mu, e\mu$		
					$eh, \mu h$

$R(\tau/\mu) = 0.985 \pm 0.020$ Agreement with SM!



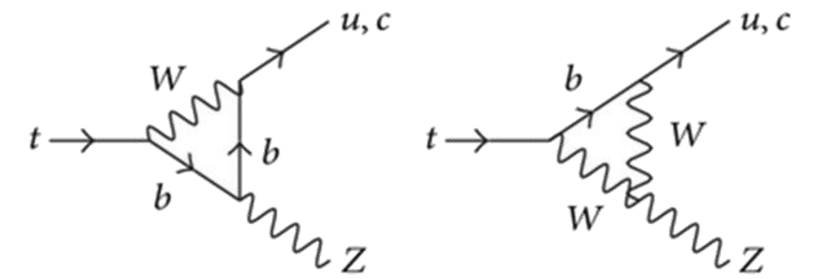




(Latest ATLAS result overlaid)

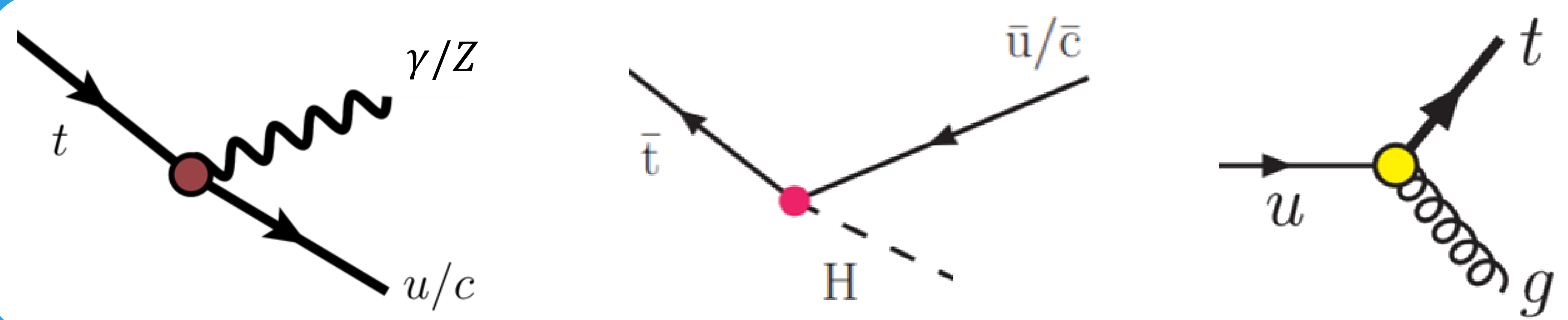
Flavour-changing neutral currents

FCNCs are forbidden in SM at tree level and strongly suppressed at higher orders via GIM mechanism ($BR{\sim}10^{-14}$)



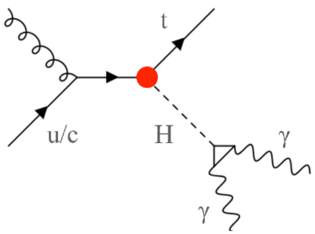
Some BSM models predict significantly larger branching ratios for FCNC processes ($BR{\sim}10^{-4}$), e.g. R-parity-violating SUSY [1], 2HDM [2], new exotic quarks [3]

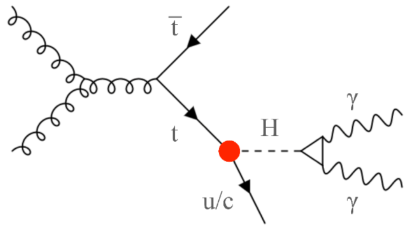
Top FCNCs may be studied in many channels:



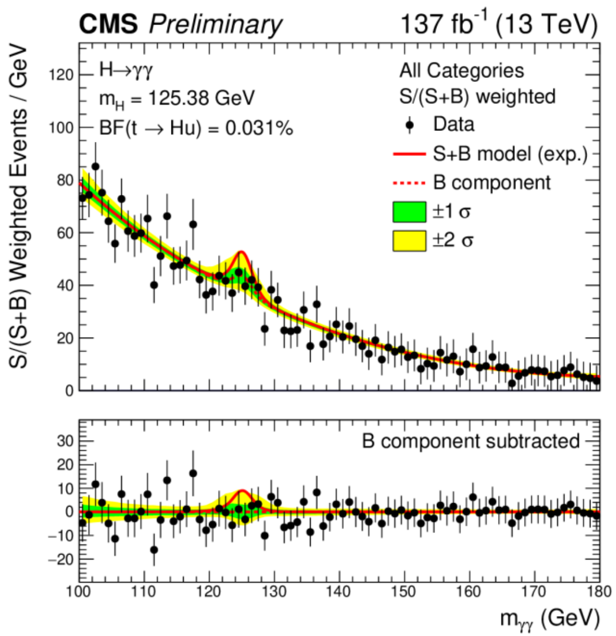
FCNC $tqH(\to \gamma\gamma)$

CMS-PAS-TOP-20-007
137 fb^{-1}

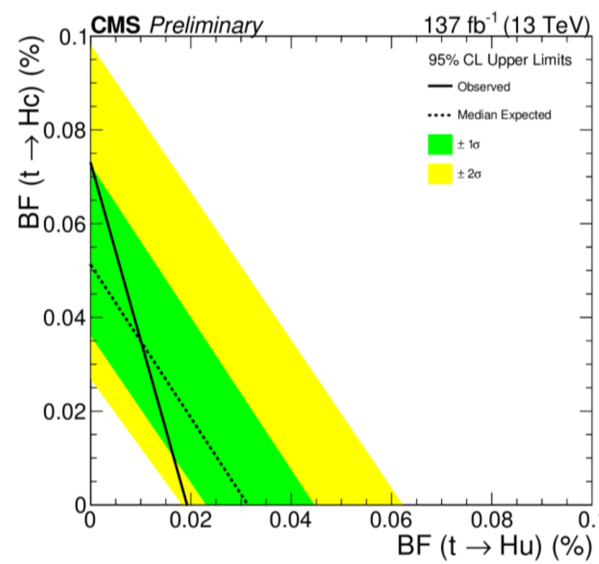




- Both production and decay modes
- Non-resonant background is modelled using data
- Resonant background is modelled using simulation
- 14 $m_{\gamma\gamma}$ distributions simultaneously fit to extract FCNC signal strength (breakdown by background-category BDT scores)



- **No evidence of new physics found**
- Observed limits are significant improvement on previous combined results
- Dominant uncertainties are from b-jet and photon identification

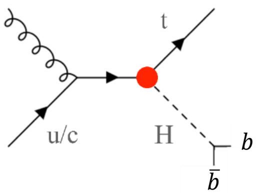


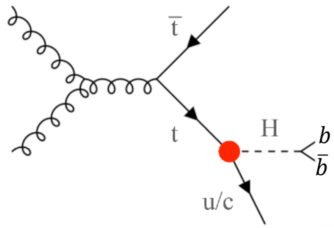
$$\boldsymbol{B(t \to Hu) \leq 1.9 \times 10^{-4}}$$

$$\boldsymbol{B(t \to Hc) \leq 7.3 \times 10^{-4}}$$

FCNC $tqH(\rightarrow b\bar{b})$

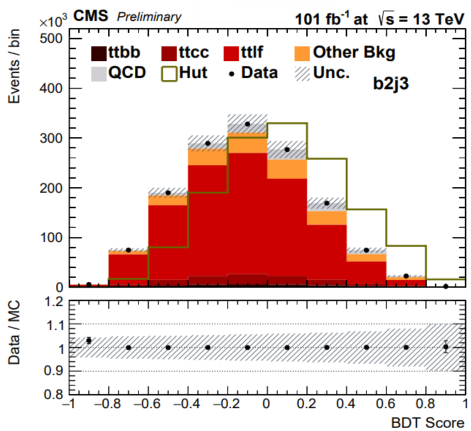
CMS-PAS-TOP-19-002
137 fb^{-1}



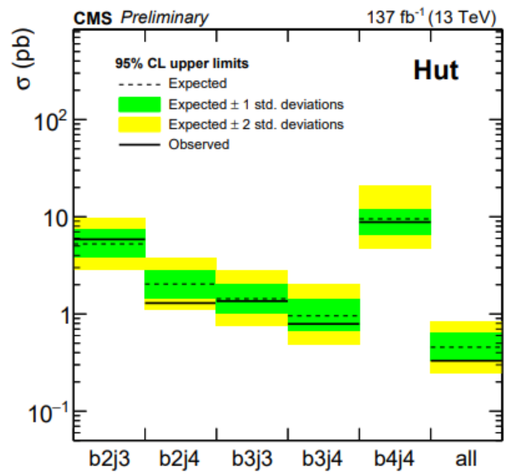


- Both production and decay modes

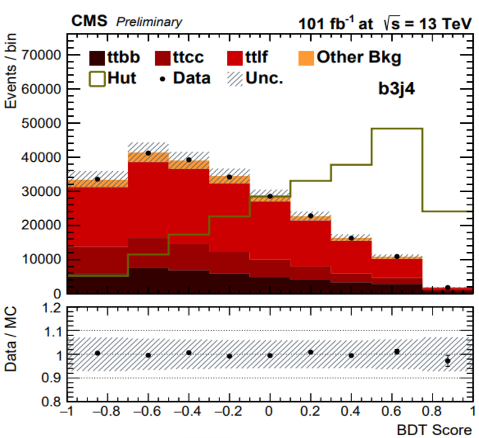
Events are categorised by jet and b-jet tag multiplicities



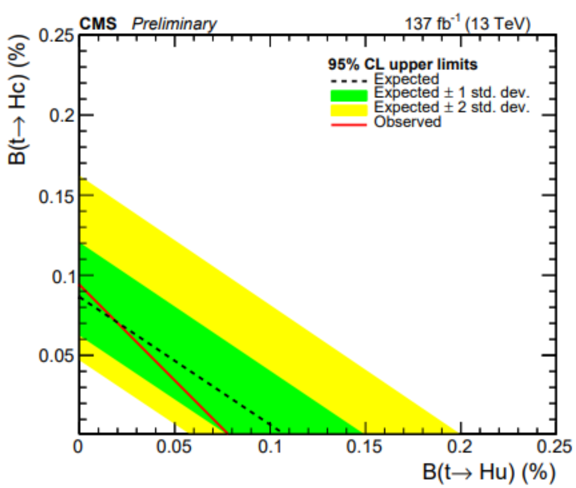
b2j3



- DNN used to reconstruct tops with jet permutations
- Resultant kinematic distributions input to BDT for signal-background separation
- **No evidence of new physics found**
- Observed limits are significant improvement on previous combined results
- Dominant uncertainties are from b-jet identification



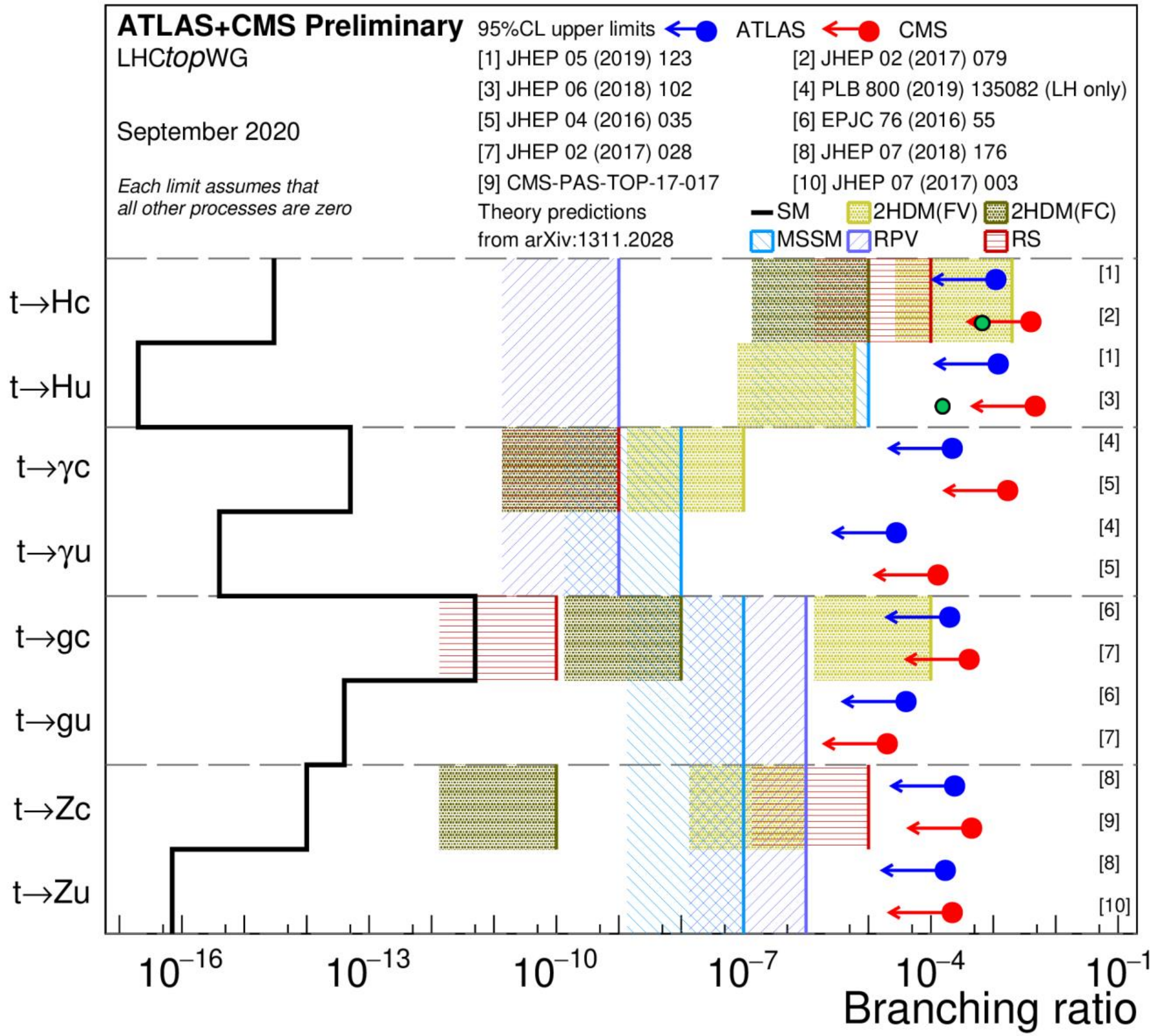
b3j4



$$B(t \rightarrow Hu) \leq 7.9 \times 10^{-4}$$

$$B(t \rightarrow Hc) \leq 9.4 \times 10^{-4}$$

Flavour-changing neutral currents



Approximate positions of new $t \to Hq$ result ($H \to \gamma\gamma$)

CMS-PAS-TOP-20-007

Summary

- There is a **lot** of very interesting physics being studied with respect to the properties of the top quark! (Far too much to cover in a single presentation)

- Novel analysis techniques are being created to probe new and interesting properties at increasing precision – aiming to answer fundamental universal questions
  - CPV limits set down to 10^{-3}
  - Top Polarisation / Spin Asymmetry / Energy Asymmetry in agreement with SM
  - LFU measurements more precise than LEP – agreement with SM
  - FCNC tHq limits set down to 10^{-4}

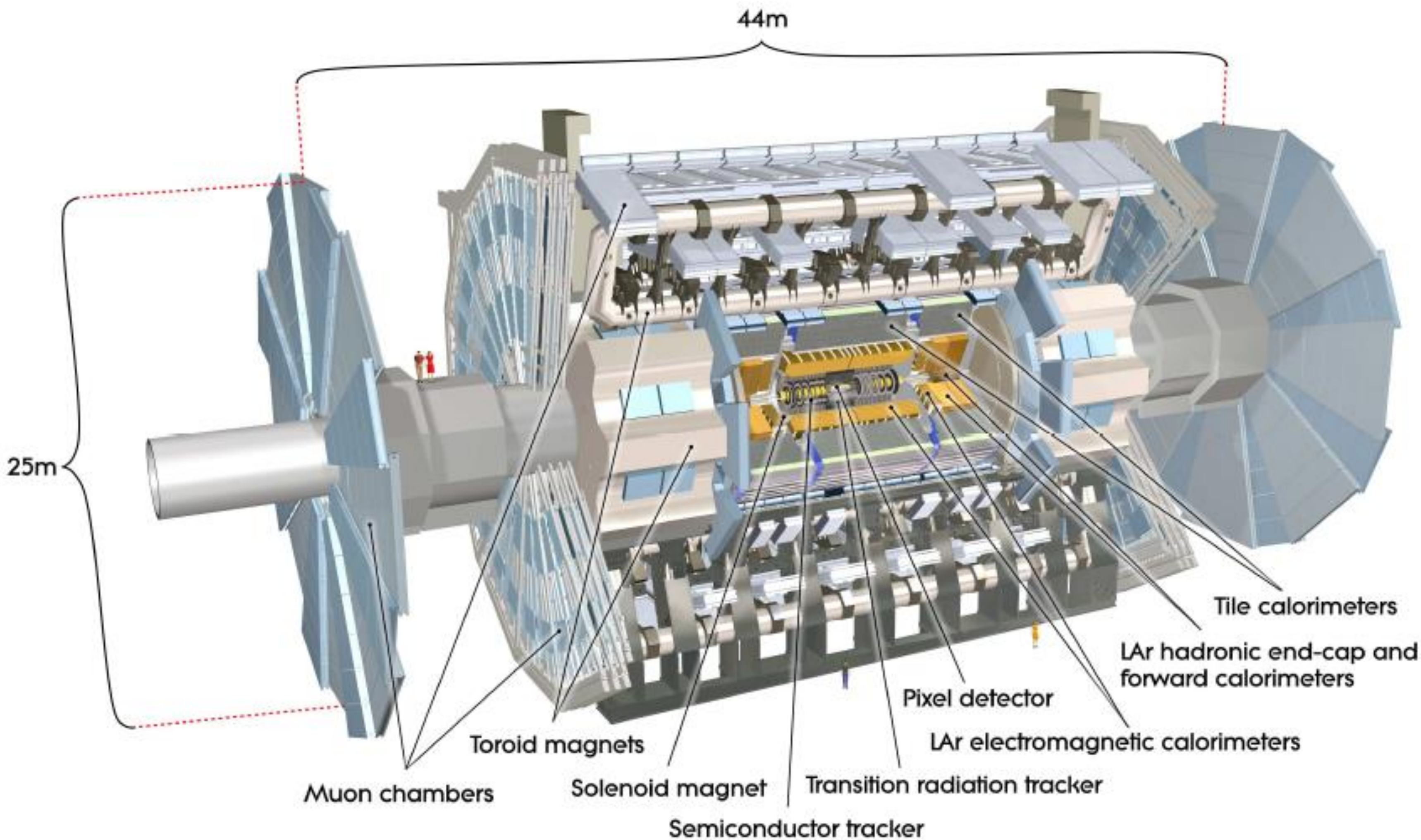
- FCNC analyses are beginning to take the next step forward using the full Run 2 dataset – these should make for tighter limits approaching BSM model sensitivities

ATLAS Top Public Results

CMS Top Public Results

LHC Top Working Group

BACKUP



44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

Top EFT

arXiv:1008.4484

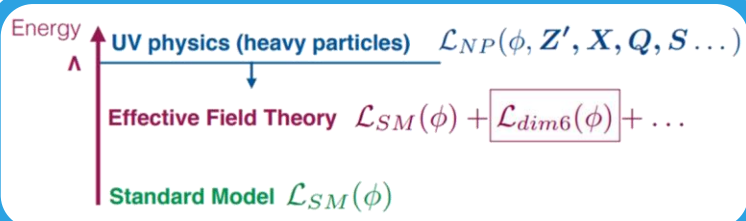
Effective Field Theories parameterise the effect of new physics via higher-dimension operators:

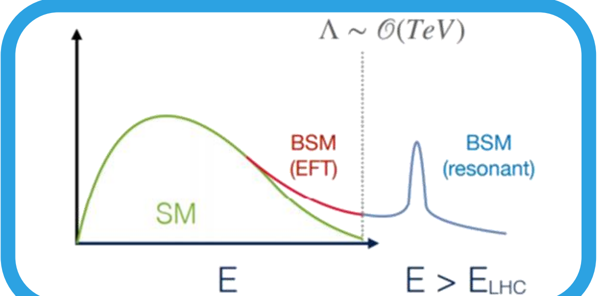
$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

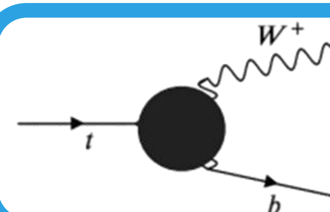
Wilson coefficients: Couplings of SM fields to NP

Gauge invariant operators

Higher terms supressed by increasing powers of Λ







- May induce corrections to the SM couplings.

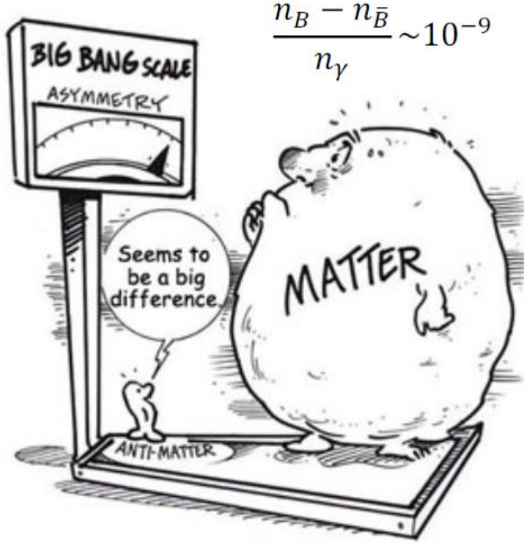
CP Violation (CPV)

- CPV originates from complex phase in CKM matrix
- Detailed measurements frequent in b, c, s-quark sectors
  - Consistent with SM expectation
  - Insufficient to explain matter-antimatter asymmetry in universe

1. *Baryon number violating interactions;*
2. *CP violation;*
3. *Departure from thermal equilibrium;*

Sakharov

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$$



- CPV in top decays is expected to be very small [1]
  - Any observation would imply BSM physics (e.g. chromo-electric dipole moments (CEDM)

CMS CP violation

$$O_3 = Q_\ell \epsilon(p_{\mathrm{b}}, p_{\bar{\mathrm{b}}}, p_\ell, p_{j_1}) \propto Q_\ell \vec{p}'_{\mathrm{b}} \cdot (\vec{p}'_\ell \times \vec{p}'_{j_1}) \quad (3)$$

$$O_6 = Q_\ell \epsilon(P, p_{\mathrm{b}} - p_{\bar{\mathrm{b}}}, p_\ell, p_{j_1}) \propto Q_\ell (\vec{p}_{\mathrm{b}} - \vec{p}_{\bar{\mathrm{b}}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}) \quad (4)$$

$$O_{12} = q \cdot (p_{\mathrm{b}} - p_{\bar{\mathrm{b}}}) \epsilon(P, q, p_{\mathrm{b}}, p_{\bar{\mathrm{b}}}) \propto (\vec{p}_{\mathrm{b}} - \vec{p}_{\bar{\mathrm{b}}})_z \cdot (\vec{p}_{\mathrm{b}} \times \vec{p}_{\bar{\mathrm{b}}})_z \quad (5)$$

$$O_{14} = \epsilon(P, p_{\mathrm{b}} + p_{\bar{\mathrm{b}}}, p_\ell, p_{j_1}) \propto (\vec{p}_{\mathrm{b}} + \vec{p}_{\bar{\mathrm{b}}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}). \quad (6)$$

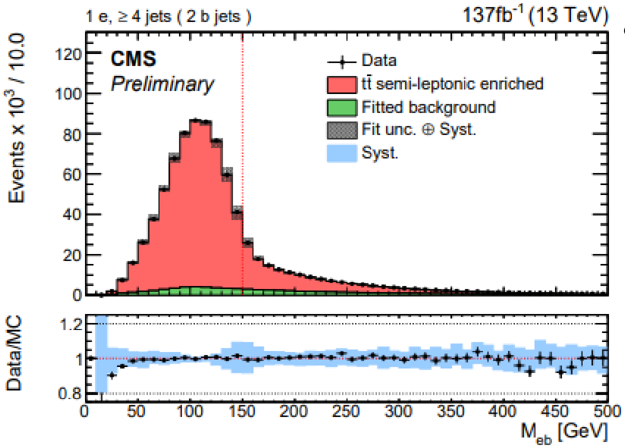
The symbol $\propto$ indicates a simplification of the observable value by only considering the sign of the triple product; ϵ is the Levi-Civita tensor, which is contracted with four vector $\epsilon(a, b, c, d) \equiv \epsilon_{\mu\nu\alpha\beta} a^\mu b^\nu c^\alpha d^\beta$ and $\epsilon_{0123} = 1$; P is the sum of the incoming protons' four-momenta; q is the difference of the incoming protons' four-momenta; p_{b} and $p_{\bar{\mathrm{b}}}$ refers to the b jet momenta; p_ℓ refers to the momentum of an isolated lepton that decays from a W boson; p_{j_1} is the momentum of the highest transverse momentum (p_{T}) jet assigned to the hadronically decaying W; and Q_ℓ is the charge of isolated lepton. The z subscript indicates a projection along the beam axis (z-axis) of the CMS coordinate system. The $\mathrm{b\bar{b}}$ CM represents transformation to the centre-of-mass frame of $\mathrm{b\bar{b}}$. The $'$ sign represents the quantity measured in the centre-of-mass frame of the $\mathrm{b\bar{b}}$ pair. The performance and sometimes the exact definition of these observables are different between the lepton+jets and dilepton decay channels. Therefore, the measured asymmetries may not be directly compared. This is in particular true for O_3 which is measured here and in Ref [7].

$$A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)}, i = 3, 6, 12, 14.$$

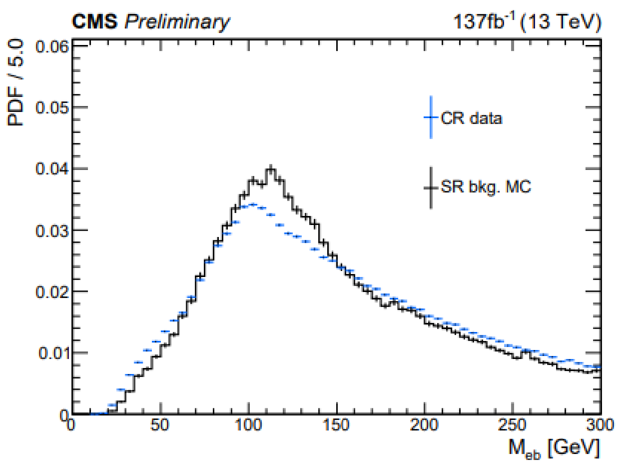
CPV

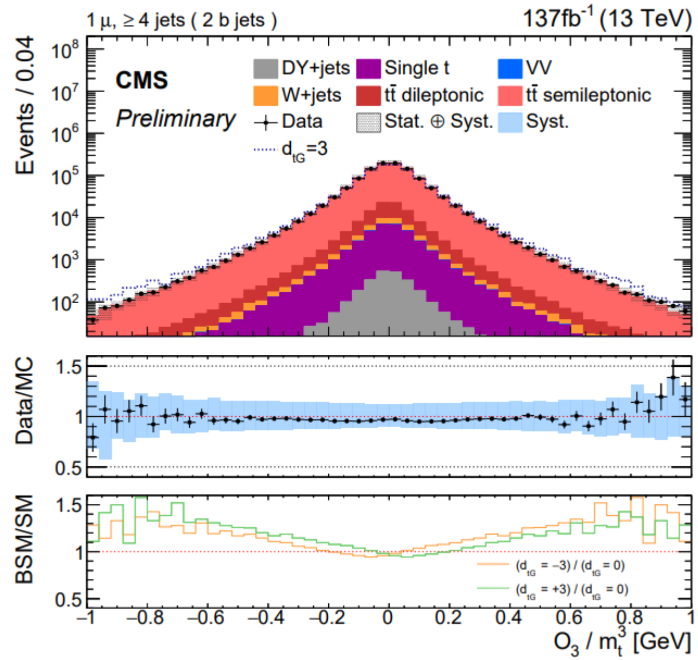
CMS-PAS-TOP-20-005
$137\ \text{fb}^{-1}$

- $t\bar{t}\ l$+jets selection, 90% purity
  - Backgrounds: ttbar dilepton, Single-top, W+jets, Drell-Yan+jets, Diboson…
- χ^2-based Jet assignment for Top+W reconstruction, ~75% accuracy



- W+jets control region (CR) for data-driven background estimation
  - CR composition differs to SR background, but kinematic shapes are similar (+ systematic)





- M_{lb} distribution used for template fit in signal region (SR) and CR, split by the sign of the relevant observable

CMS CP violation

Syst. source		$A'_{CP}(\%)$ O_3	O_6	O_{12}	O_{14}
Experimental uncertainties					
PU re-weight	$+1\sigma$	-0.0008	-0.0003	$+0.0023$	$+0.0040$
	-1σ	$+0.0010$	$+0.0007$	-0.0017	-0.0044
b-tag scale factor (b and c quark)	$+1\sigma$	$+0.0002$	$+0.0001$	$+0.0000$	$+0.0000$
	-1σ	-0.0002	-0.0003	-0.0000	-0.0002
b-tag scale factor (light quark)	$+1\sigma$	-0.0003	-0.0003	-0.0009	-0.0007
	-1σ	$+0.0004$	-0.0000	$+0.0007$	$+0.0005$
Lepton	$+1\sigma$	-0.0002	-0.0001	-0.0001	-0.0004
	-1σ	$+0.0002$	-0.0001	$+0.0000$	$+0.0001$
JER	$+1\sigma$	-0.0028	-0.0069	-0.0024	-0.0070
	-1σ	-0.0029	$+0.0032$	-0.0021	$+0.0026$
JEC	$+1\sigma$	-0.0051	-0.0046	-0.0046	-0.0062
	-1σ	-0.0018	$+0.0065$	$+0.0011$	$+0.0041$
Bkg. template	-	$+0.0061$	$+0.0050$	$+0.0139$	$+0.0016$

CMS CP violation

Syst. source		$A'_{CP}(\%)$ O_3	O_6	O_{12}	O_{14}
Theoretical uncertainties					
PDF	$+1\sigma$	$+0.0008$	-0.0008	$+0.0003$	$+0.0003$
	-1σ	-0.0008	$+0.0006$	-0.0004	-0.0006
μ_R and μ_F	$+1\sigma$	$+0.0008$	$+0.0008$	$+0.0013$	$+0.0007$
	-1σ	$+0.0012$	-0.0002	-0.0033	-0.0004
ISR	$+1\sigma$	$+0.0006$	-0.0005	$+0.0017$	$+0.0024$
	-1σ	-0.0004	$+0.0004$	-0.0015	-0.0021
FSR	$+1\sigma$	-0.0001	-0.0215	$+0.0053$	-0.0129
	-1σ	-0.0008	$+0.0122$	-0.0017	$+0.0060$
Color reconnection	CR1	-0.0162	$+0.0186$	$+0.0091$	$+0.0384$
	CR2	$+0.0000$	-0.0206	-0.0464	$+0.0304$
ME-PS matching	$+1\sigma$	-0.0235	-0.0043	-0.0185	$+0.0352$
	-1σ	$+0.0399$	$+0.0177$	$+0.0139$	$+0.0376$
Underlying event	$+1\sigma$	-0.0515	-0.0576	-0.0082	$+0.0116$
	-1σ	-0.0099	$+0.0355$	$+0.0218$	$+0.0424$
Flavour response	$+1\sigma$	-0.0017	-0.0007	-0.0033	-0.0105
	-1σ	-0.0024	$+0.0024$	-0.0004	$+0.0070$
Top mass variation	$+1$ GeV	$+0.0049$	$+0.0152$	$+0.0119$	$+0.0082$
	-1 GeV	-0.0179	-0.0118	-0.0097	-0.0046
Per event resolution	$+10\%$	-0.0027	-0.0022	$+0.0023$	-0.0005
	-10%	-0.0004	$+0.0040$	$+0.0014$	$+0.0048$
W+HF enriched	-	-0.0174	-0.0132	-0.0102	-0.0098
w/o Top p_T reweighting	-	-0.0008	-0.0005	-0.0000	-0.0000

Top Polarisation

Top polarisation is sensitive to NP that affects the tWb vertex

First order dim6 EFT operators that contribute to t-channel production:

- $O_{\phi q}$ - Affects cross-section only
- $O_{\phi q}$ - Four-fermion operator, negligible effect on angular distributions
- O_{tW} - Operator to focus on

C_{tW} most affects $P_{x'}$

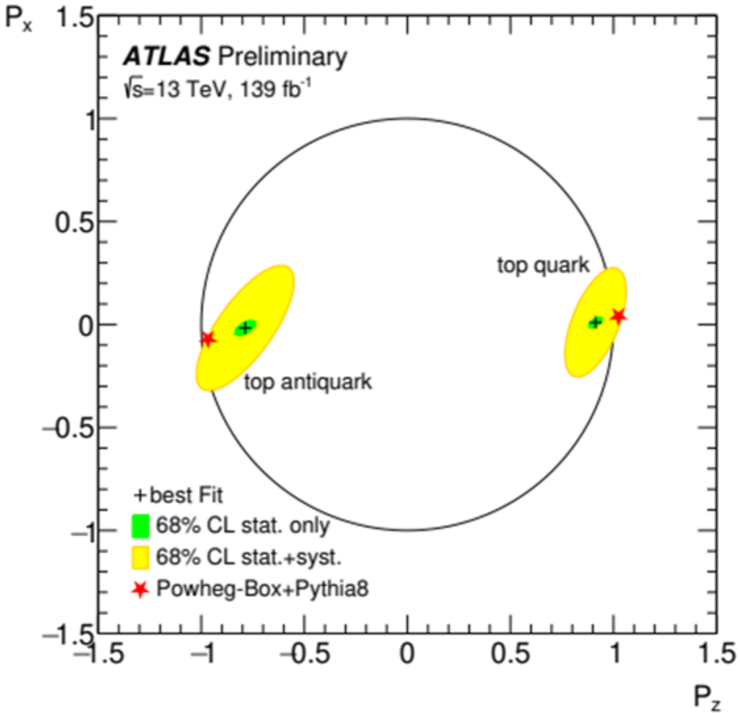
$P_{z'}$ less sensitive as ~1

C_{itW} most affects $P_{y'}$
(Non-zero value could imply **CPV**)

Top Polarisation

ATLAS-CONF-2021-027
139 fb^{-1}

Polarisations in agreement with SM predictions to 1σ (Powheg+Pythia8)



Parameter	Extracted value	(stat.)
t-channel norm.	$+1.045 \pm 0.022$	(± 0.006)
W+jets norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P^{t}_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^{t}_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$	-0.007 ± 0.051	(± 0.017)
$P^{t}_{z'}$	$+0.91 \pm 0.10$	(± 0.02)
$P^{\bar{t}}_{z'}$	-0.79 ± 0.16	(± 0.03)

Uncertainties dominated by Jet Energy Resolution (JER)

- Polarisation depends on kinematic angles determined in top-quark rest frame
- JER is key to reconstruction of this frame

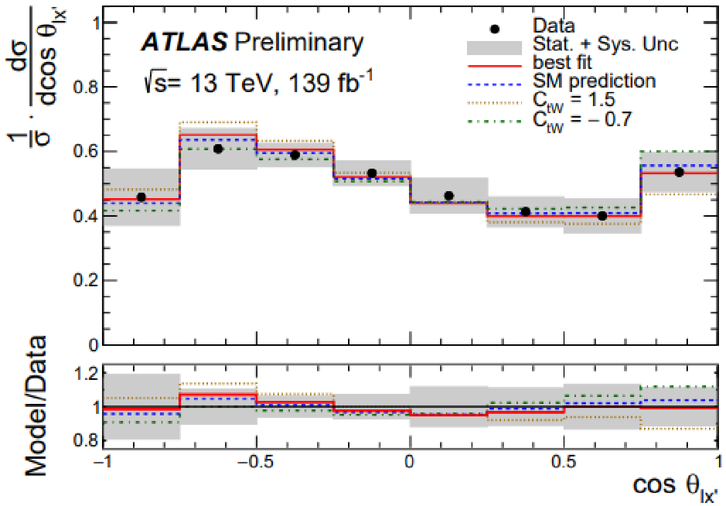
First order dim6 EFT operators that contribute to t-channel production:

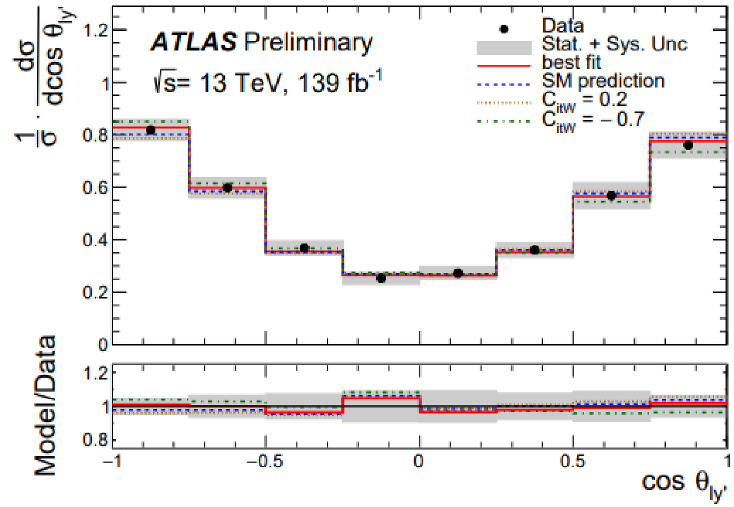
- O_{tW} - Operator to focus on → C_{tW} most affects $P_{x'}$; C_{itW} most affects $P_{y'}$

(Non-zero value could imply **CPV**)

Top Polarisation

ATLAS-CONF-2021-027
139 fb^{-1}





Unfolded to particle level fiducial region

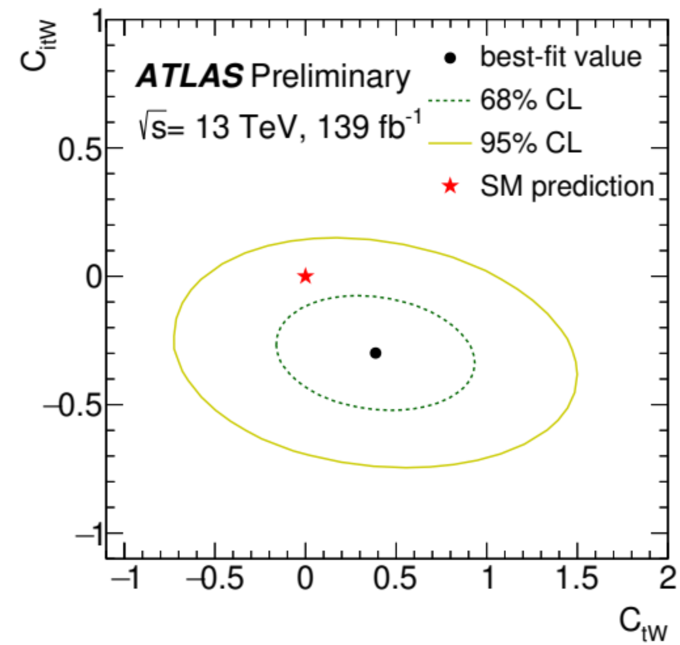
$$\sigma(C_{tW}, C_{itW}) \propto \left| O_{\rm SM} + \frac{C_{tW}}{\Lambda^2} \cdot O_{tW} + \frac{C_{itW}}{\Lambda^2} \cdot O_{itW} \right|^2_{\rm production} \cdot \left| O_{\rm SM} + \frac{C_{tW}}{\Lambda^2} \cdot O_{tW} + \frac{C_{itW}}{\Lambda^2} \cdot O_{itW} \right|^2_{\rm decay}$$

Morphing technique used to interpolate between MC templates using difference Wilson Coefficient values

Both coefficients fitted simultaneously (does not assume other is zero)

Result compatible with SM within 2σ

(MG5_aMC@NLO+Pythia8)

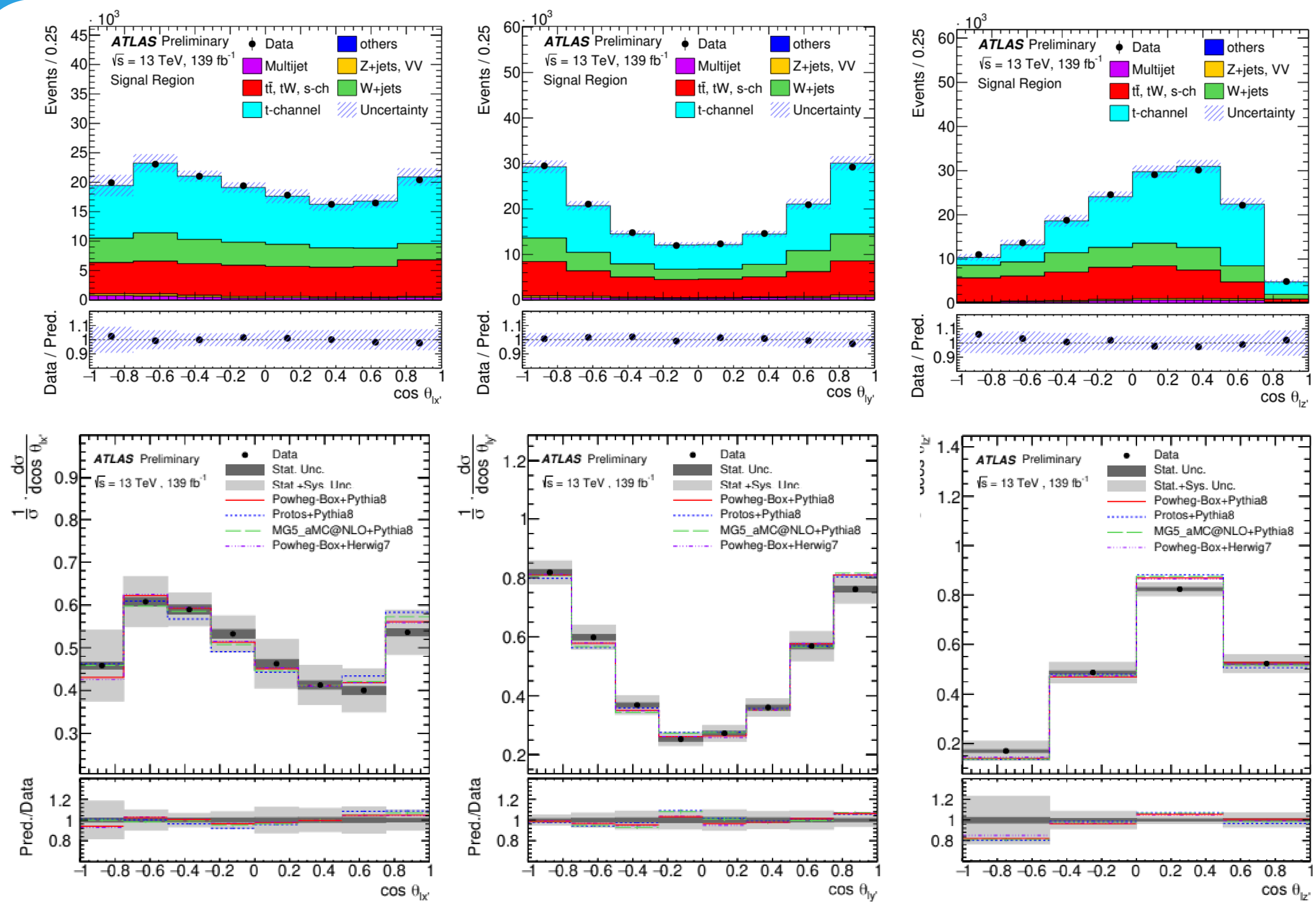


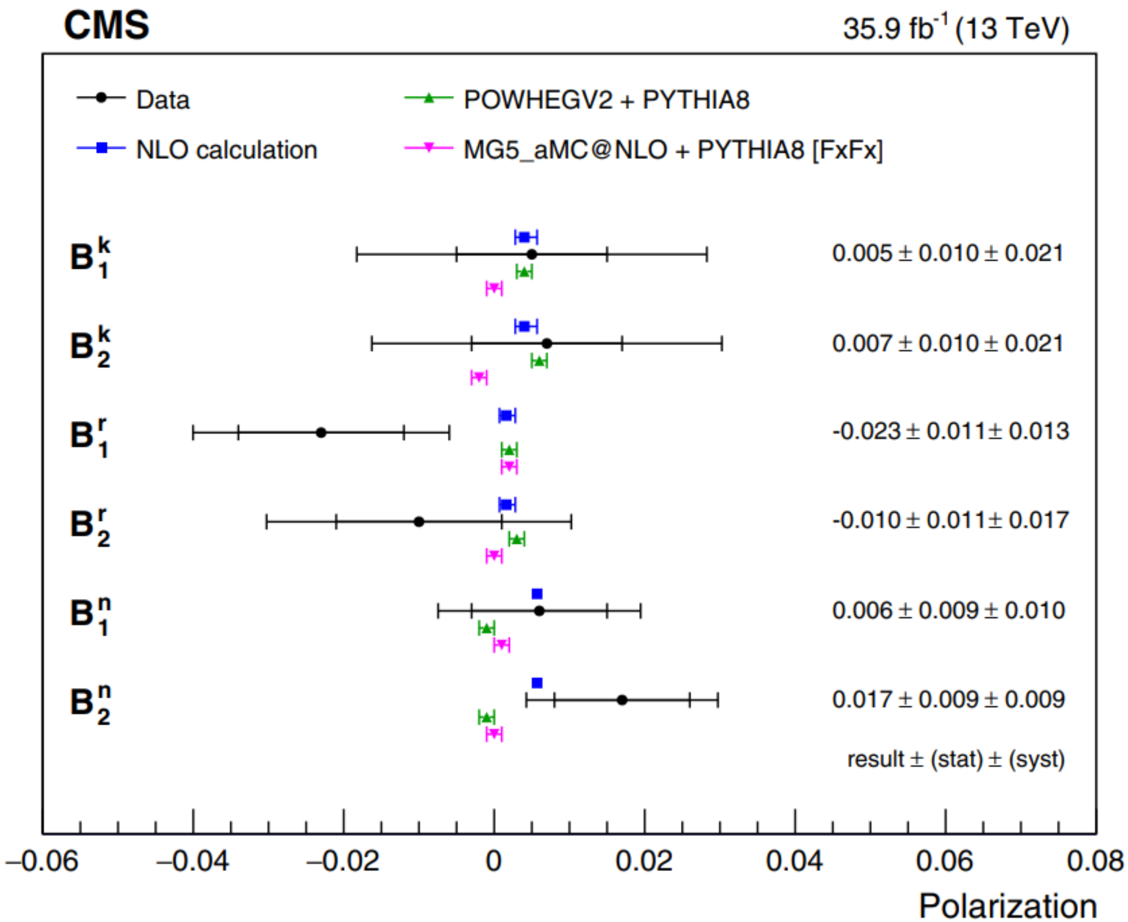
Measurement of Top Polarisation

ATLAS-CONF-2021-027

$\sqrt{s} = 13$ TeV, 139 fb^{-1}

June 2021





Polarisation — Spin correlation

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+^a\, d\cos\theta_-^b} = \frac{1}{4}(1 + \boxed{B_+^a}\cos\theta_+^a + \boxed{B_-^b}\cos\theta_-^b - \boxed{C(a,b)}\cos\theta_+^a\cos\theta_-^b)$$

The top quark polarization is linked to the polarization of the lepton from its decay and can be measured in respect to the axis of the spectator quark. The top quark polarization angle $\cos(\theta^{\star}_{\mathrm{pol}})$ is defined similarly to Ref. [4] as:

$$\cos(\theta^{\star}_{\mathrm{pol}}) = \frac{\vec{p}(\mathrm{q}'^{\star}) \cdot \vec{p}(\ell^{\star}_{\mathrm{t}})}{|\vec{p}(\mathrm{q}'^{\star})||\vec{p}(\ell^{\star}_{\mathrm{t}})|}, \tag{2}$$

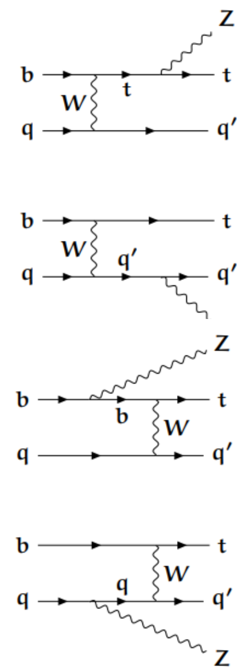
where $\vec{p}(\mathrm{q}'^{\star})$ and $\vec{p}(\ell^{\star}_{\mathrm{t}})$ are the three-momenta of the spectator quark and the lepton from the top quark decay, respectively. The asterisk indicates that the three-momentum is measured in the top quark candidate rest frame. The polarization P of the top quark is related to the spin asymmetry as $A_{\ell} = \frac{1}{2} P a_{\ell}$, where a_{ℓ} refers to the the spin-analyzing power of the lepton associated with the top quark decay and is equal to unity in LO calculations [42, 43]. The spin asymmetry A_{ℓ} is related to the cross section as a function of $\cos(\theta^{\star}_{\mathrm{pol}})$ by:

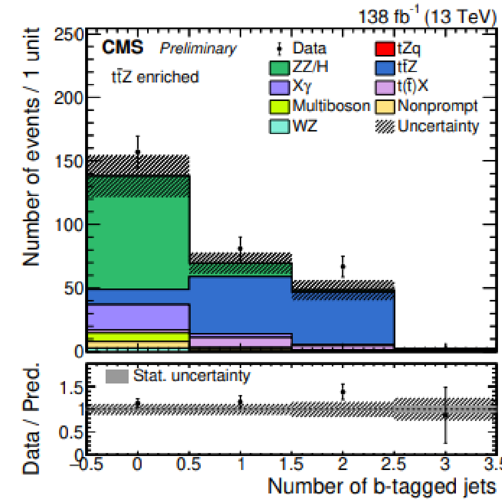
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos(\theta^{\star}_{\mathrm{pol}})} = \sigma_{\mathrm{tZq}} \left(\frac{1}{2} + A_{\ell} \cos(\theta^{\star}_{\mathrm{pol}}) \right). \tag{3}$$

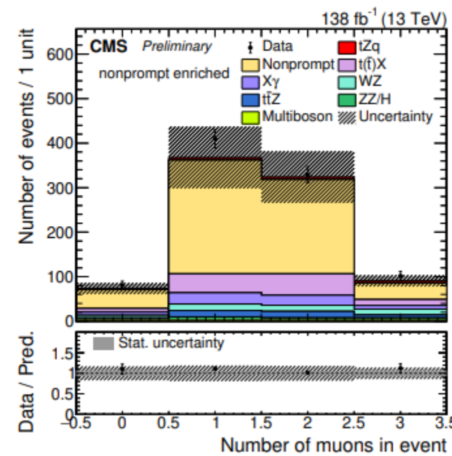
Top Spin Asymmetry

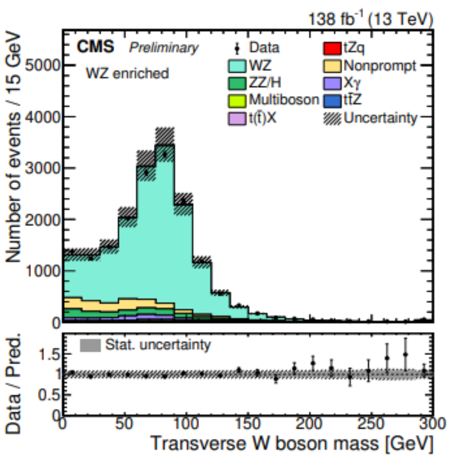
CMS-PAS-TOP-20-010
138 fb^{-1}

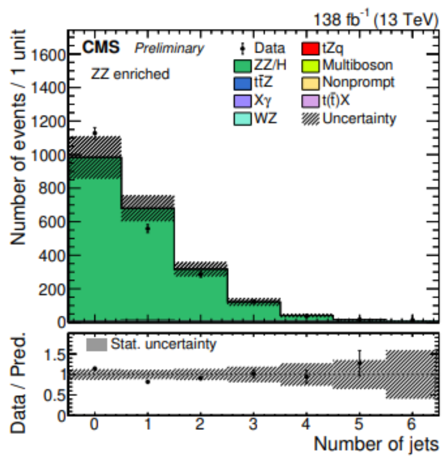
- **Measure tZq differential cross-sections using 3-lepton final states**
- Lepton opposite-sign same-flavour pair Z-mass requirement provides reconstruction ambiguity resolution
- Neural Network (NN) used to separate signal tZq events from backgrounds: $t\bar{t}Z/X$, Diboson, Non-prompt leptons
- Many CRs defined with enhanced processes to check modelling in a **profile-likelihood fit**

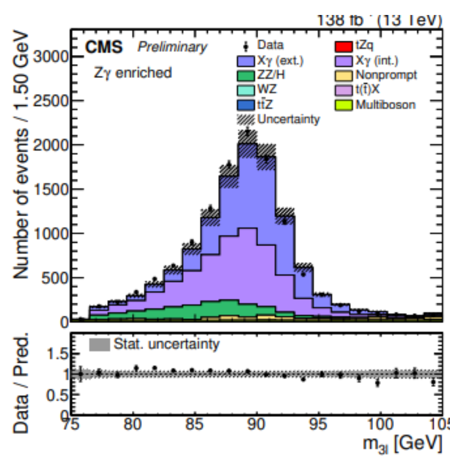








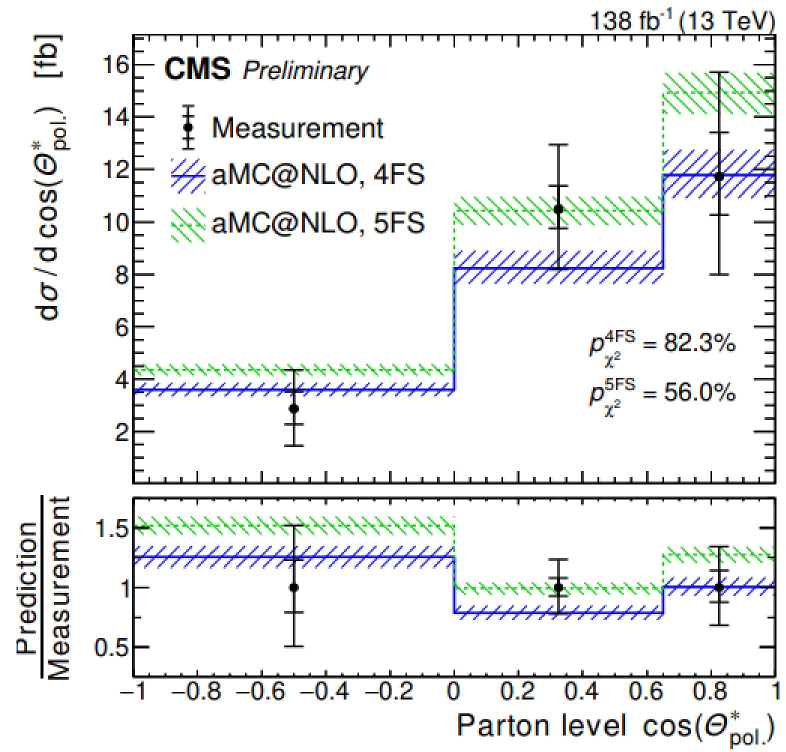




Top Spin Asymmetry

CMS-PAS-TOP-20-010
138 fb^{-1}

- Unfolded polarisation distribution at parton level
- Spin asymmetry is left as a free-parameter in the fit
- Comparisons are made using two schemes:
  - Four-flavour scheme (4FS); preferred for the kinematic modelling of final state particles, which the b-quark is explicitly required to be associated with the gluon-splitting process at the Matrix Element level. However, larger renormalisation and factorisation uncertainties.
  - Five-flavour scheme (5FS); preferred for the calculation of the total production cross-section



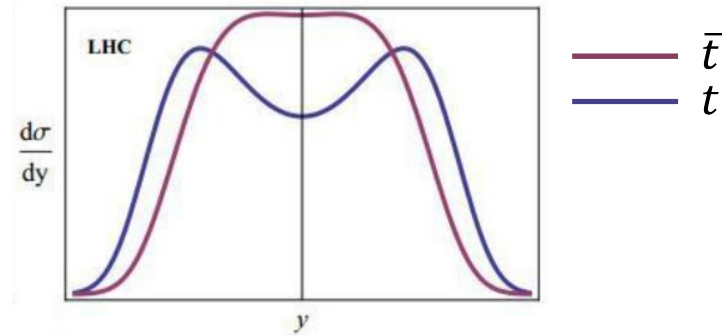
$$A_\ell = 0.58\ ^{+0.15}_{-0.16}\ \text{(stat)} \pm 0.06\ \text{(syst)}$$

$$A_l^{4FS,SM} = 0.417^{+0.004}_{-0.003}$$

$$A_l^{5FS,SM} = 0.454^{+0.004}_{-0.005}$$

Charge Asymmetry

- LO $t\bar{t}$ production is symmetric
- Higher-order interferences between $q\bar{q}$ and qg create an asymmetric production
  - t is produced preferentially in the direction of the incoming q

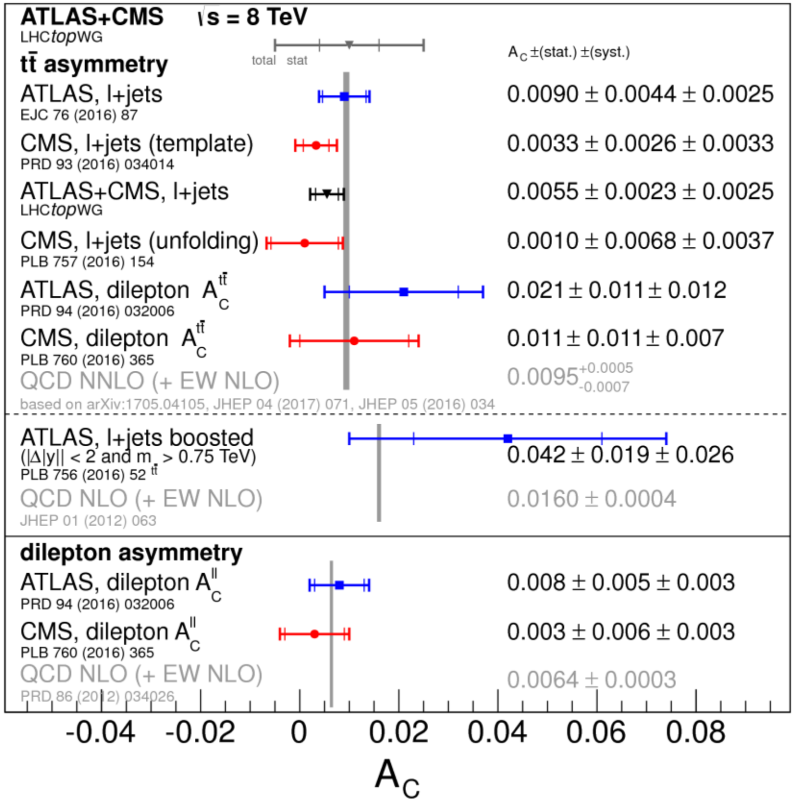


- At the LHC, this produces a central-forward charge asymmetry:

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

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

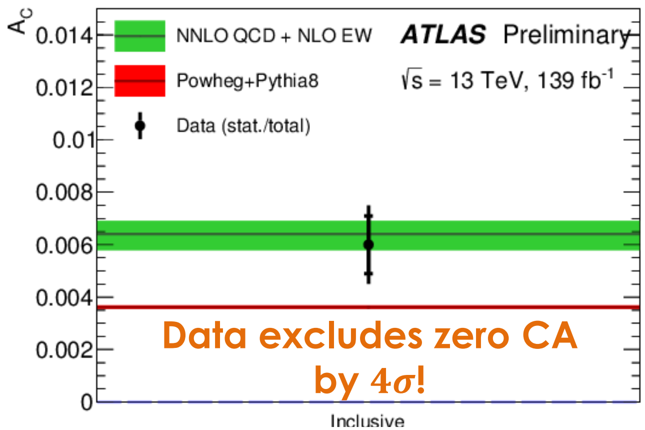
- Charge symmetric gg production dilutes measurable asymmetry
- Several BSM models predict alterations to A_C especially with variation as a function of $m_{t\bar{t}}$ and $\beta_{z,t\bar{t}}$
  - Anomalous vector/axial couplings (e.g. axigluons)
  - Heavy Z' bosons

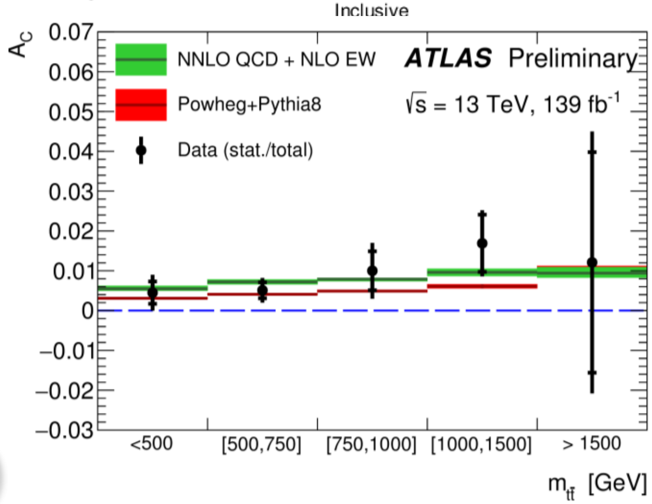


Possible to do an EFT interpretation to test many models!

$A_C = 0.0060 \pm 0.0015$ **(stat+syst.)**

Both **inclusive and differential** measurements are found to be **compatible with SM** predictions, at NNLO in perturbation theory with NLO electroweak corrections

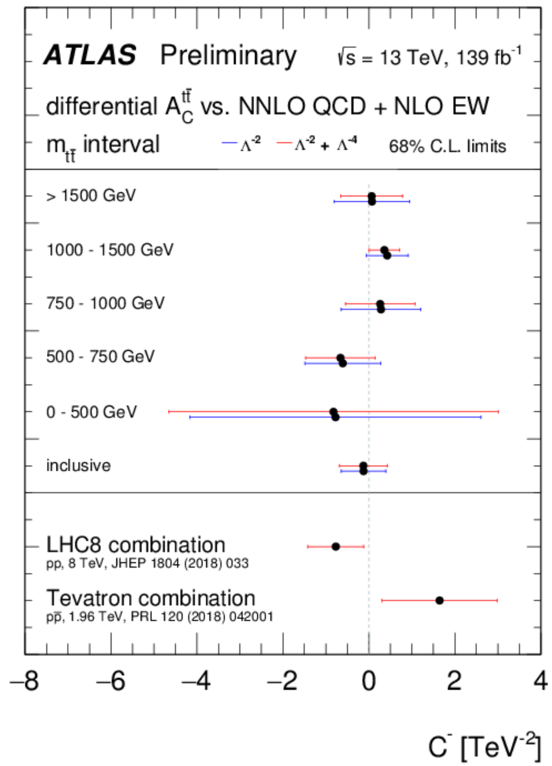




EFT interpretation probes single important parameter in the Warsaw basis (see CONF note!): C^-/Λ^2

C^- is linear combination of Wilson Coefficients

Λ is scale of new physics



This is valid for many models (axigluons, kaluza-klein, randall-sundrum), for example:

$$C^-/\Lambda^2 = -4g_s^2/m_A^2$$

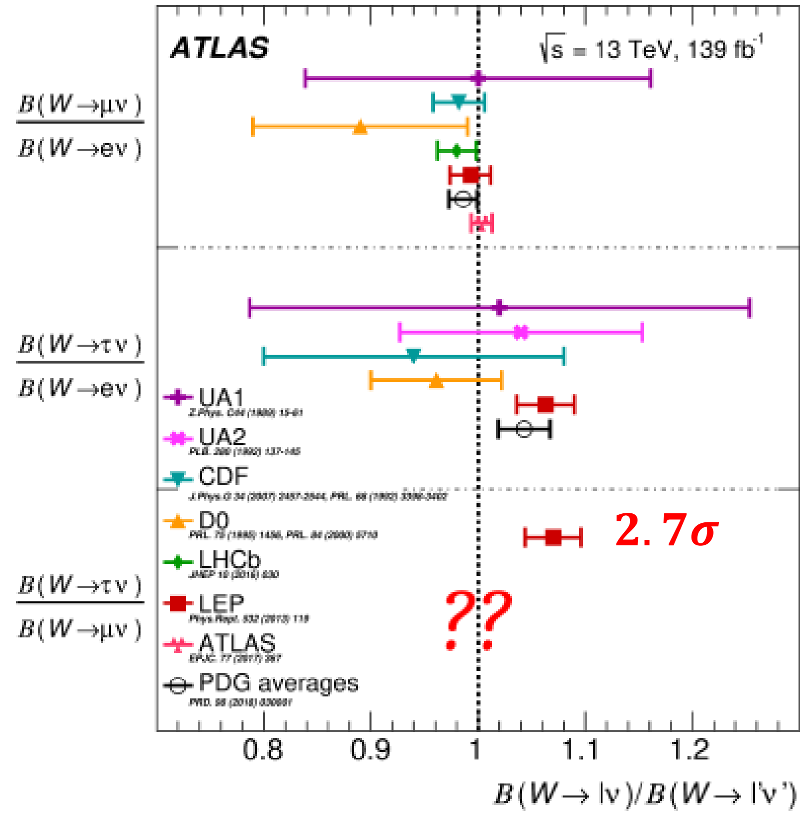
Tighter bounds achieved than for previous LHC 8 TeV combination!

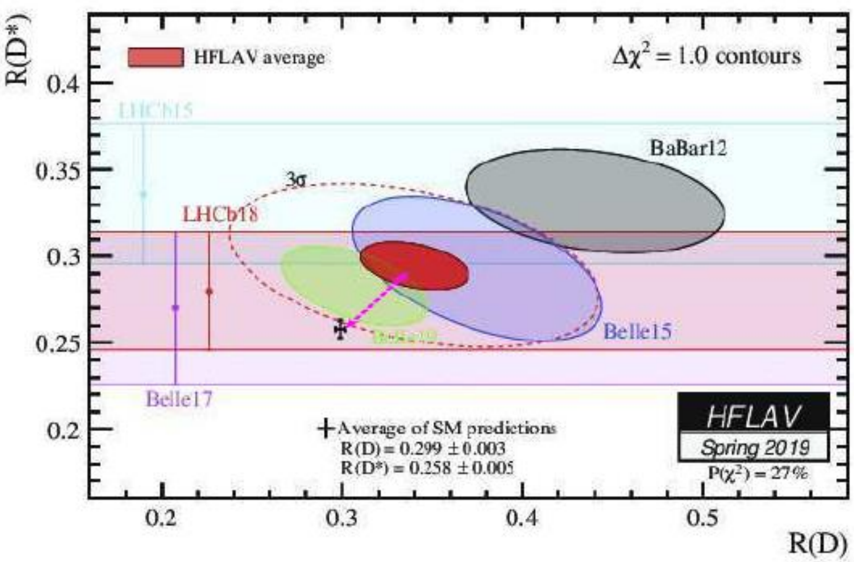
Lepton Flavour Universality (LFU)

- Fundamental axiom of SM
- Branching ratios of W and Z boson decays should be equal for all lepton flavours and charges $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$ - ratios can be used to check this!

LEP

$$\mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_\mu) \,/\, \mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}) = 0.993 \pm 0.019 \,,$$
$$\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_\tau) \,/\, \mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}) = 1.063 \pm 0.027 \,,$$
$$\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_\tau) \,/\, \mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_\mu) = \boxed{1.070 \pm 0.026} \,.$$





$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\mu\nu)}$$

3.1σ

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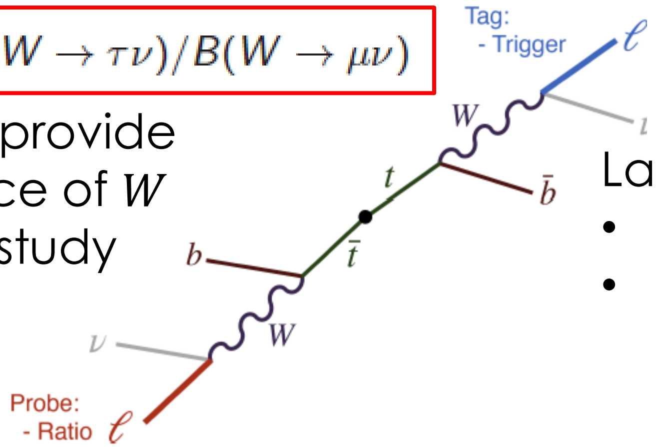
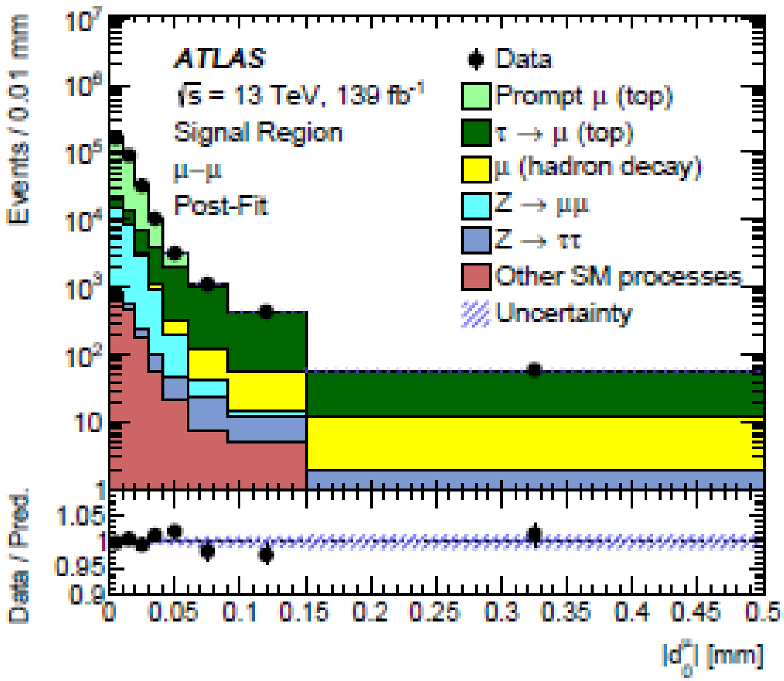
$$R(\tau/\mu) = B(W \to \tau\nu)/B(W \to \mu\nu)$$

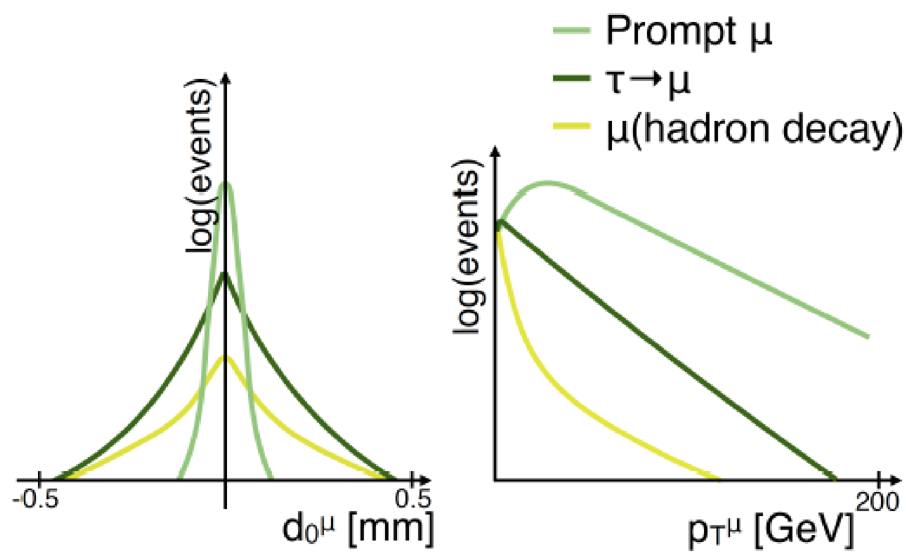
$t\bar{t}$ decays provide large source of W bosons to study



Focus on leptonic $\tau \to \mu$ decays, for a final state with opposite-sign $e\mu$, $\mu\mu$

Large background from $Z \to \mu\mu$, had $\to \mu$
- Veto Z window
- Focus on muons with low-p_T and large transverse-impact parameter $|d_0^\mu|$





Requires careful $|d_0^\mu|$ modelling – corrections for beamspot size, alignment and material interactions

[Nat. Phys. 17 813–818 (2021)](#)
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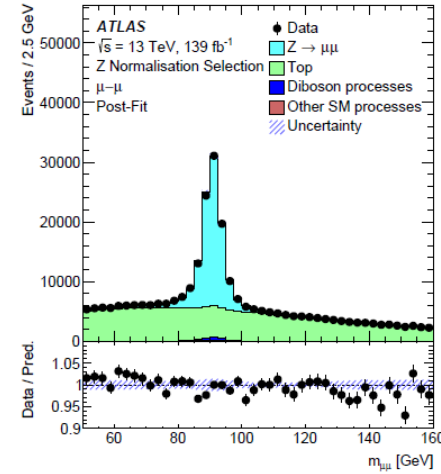
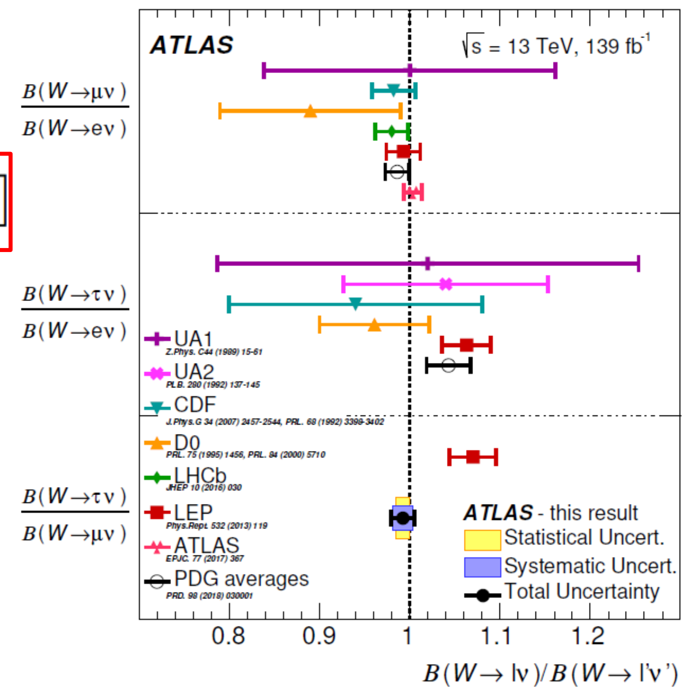
- Fit to Z mass peak in CR to extract normalisation
- Heavy-flavour normalisation extracted from SS lepton CR
- 2D profile-likelihood fit (p_T, d_0^{μ}) utilised, with two free-floating parameters
  - $R(\tau/\mu)$
  - $\kappa(t\bar{t})$ – total normalisation
- Normalisations from CRs are extracted prior to fit

$$R(\tau/\mu) = 0.992 \pm 0.013\ [\pm 0.007\ (\text{stat})\ \pm\ 0.011\ (\text{syst})]$$

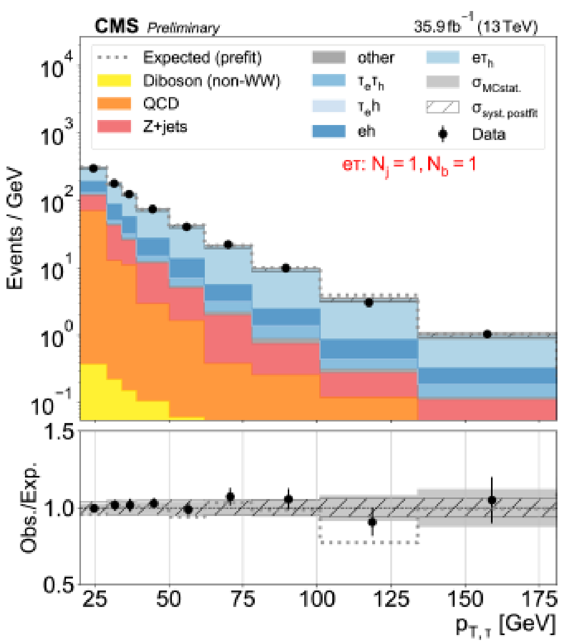
Consistent with SM expectation!

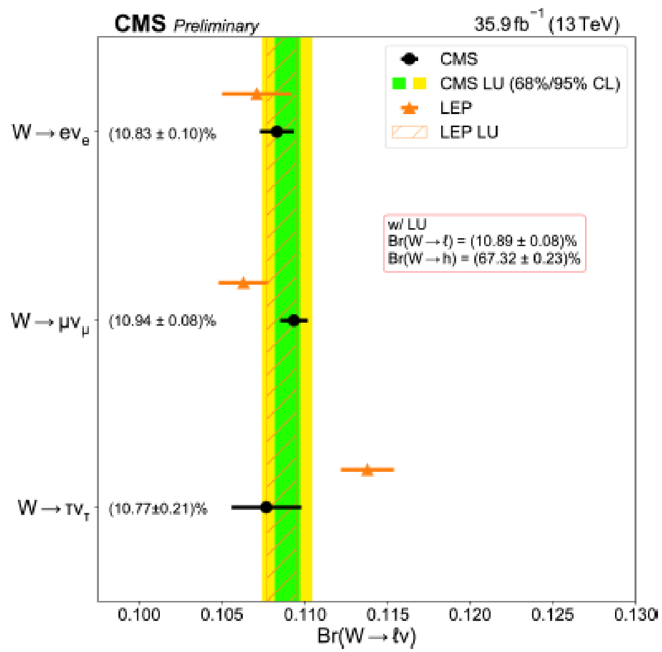
Largest systematic uncertainties:
- Prompt d_0^{μ} templates
- Parton shower variations
- Muon isolation efficiency

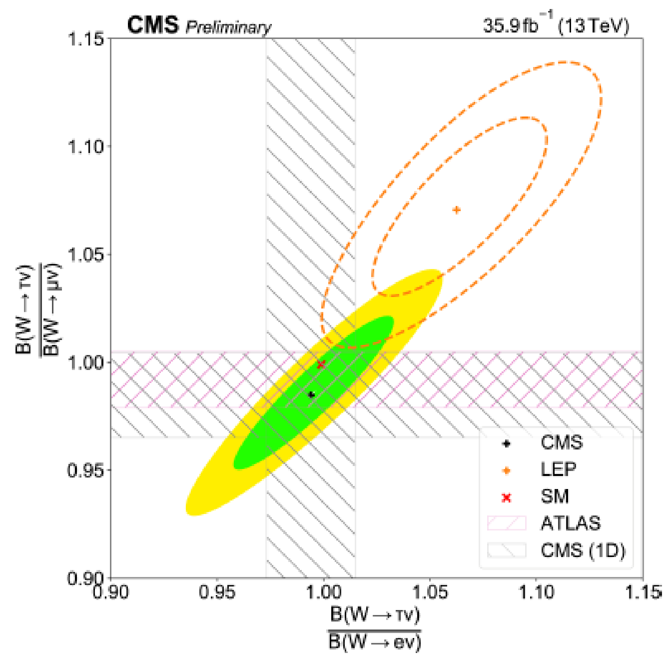




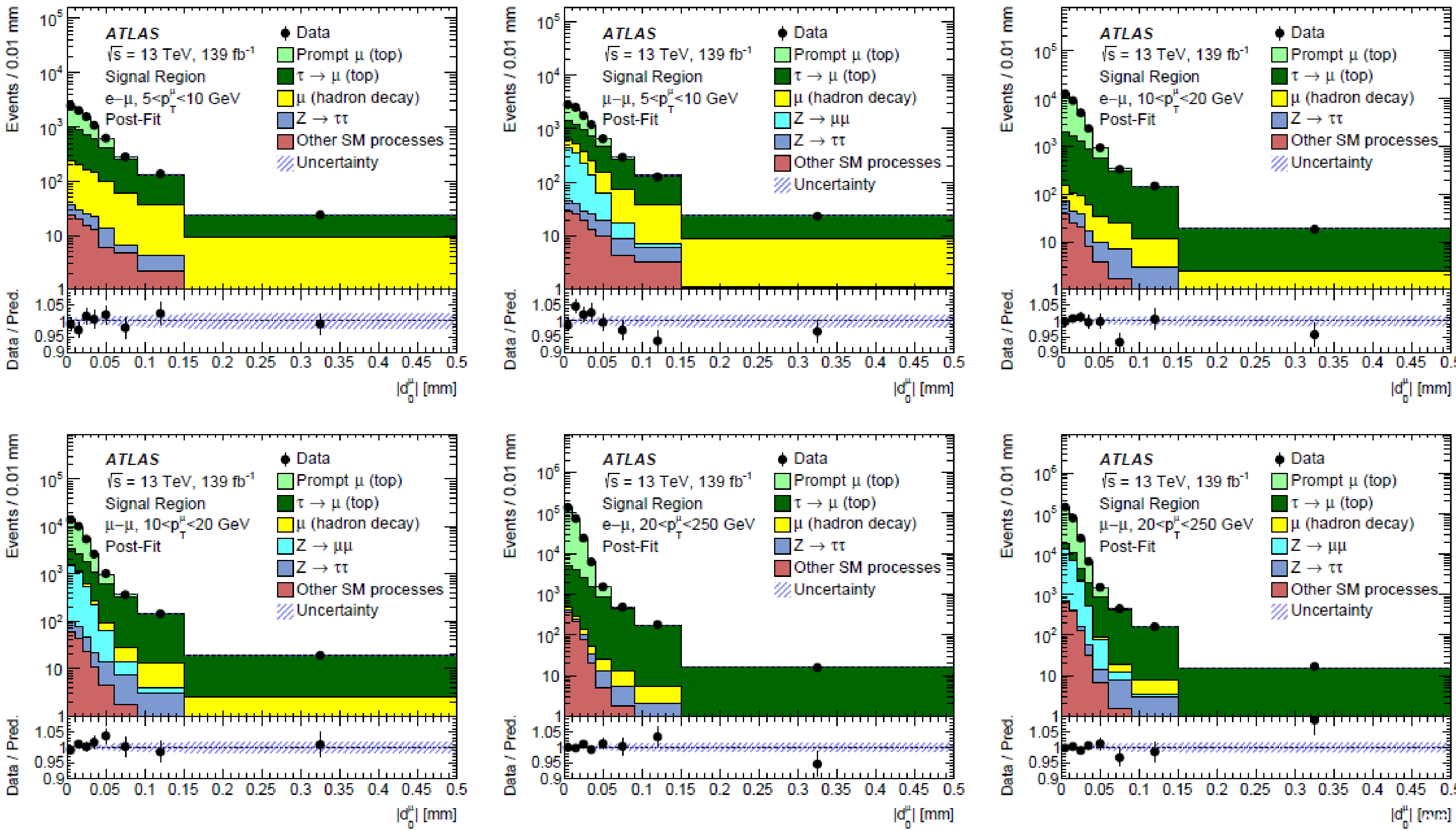
- CMS have a preliminary result on LFU using $t\bar{t}$ dilepton and single-lepton channels, also with hadronic τ decays
- p_T spectrum used as primary distribution
- All branching ratios extracted
- $R(\tau/\mu) = 0.985 \pm 0.020$ Also in agreement with SM!

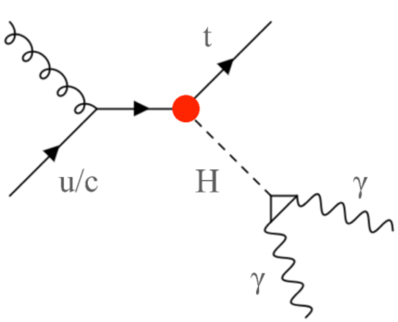


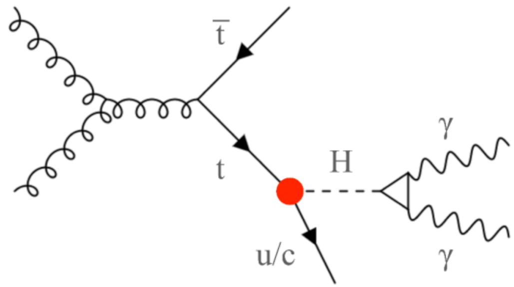


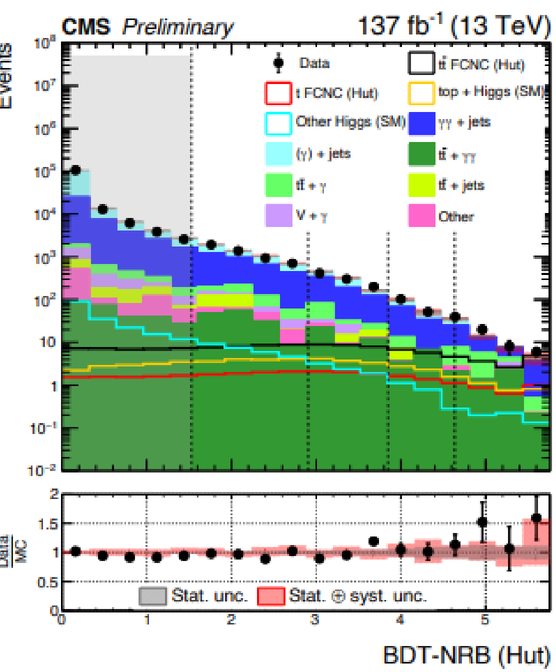


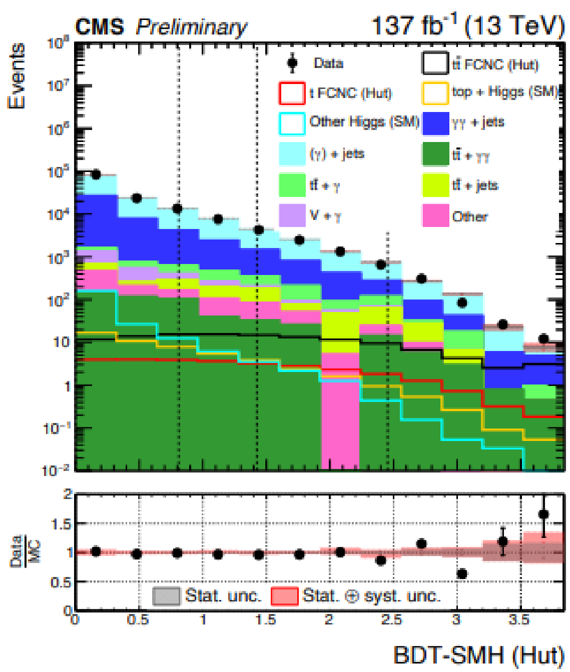
Lepton Flavour Universality



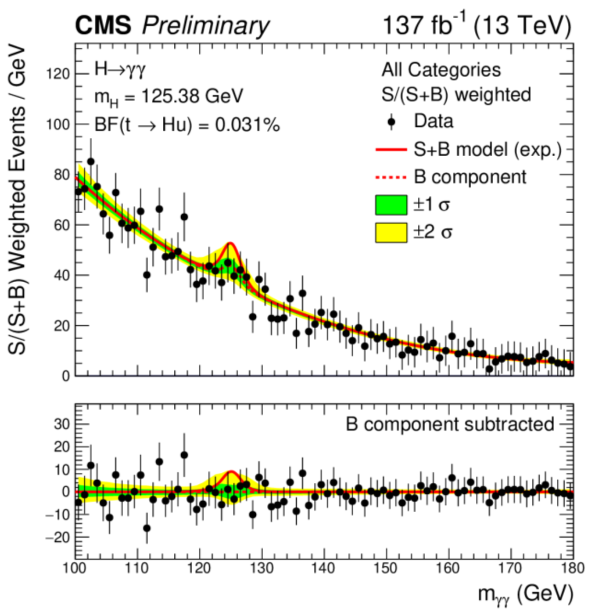


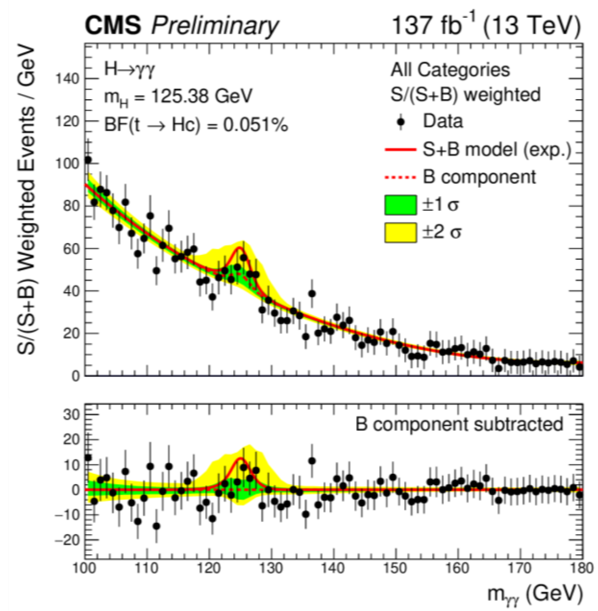






- Both production and decay modes considered
- Events are categorised according to two BDT scores
  - NRB = Non-Resonant background
  - SMH = SM Resonant Higgs
- 14 $m_{\gamma\gamma}$ distributions simultaneously fit to extract FCNC signal strength (CrystalBall+Gaussian)
- Non-resonant background is modelled using data
- Resonant background is modelled using simulation

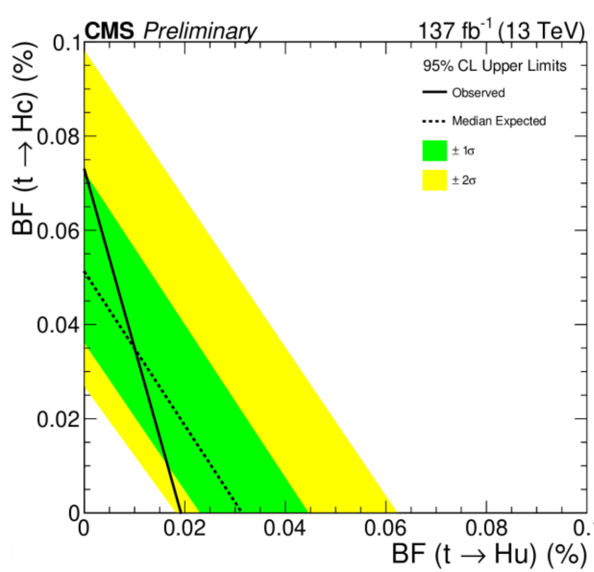


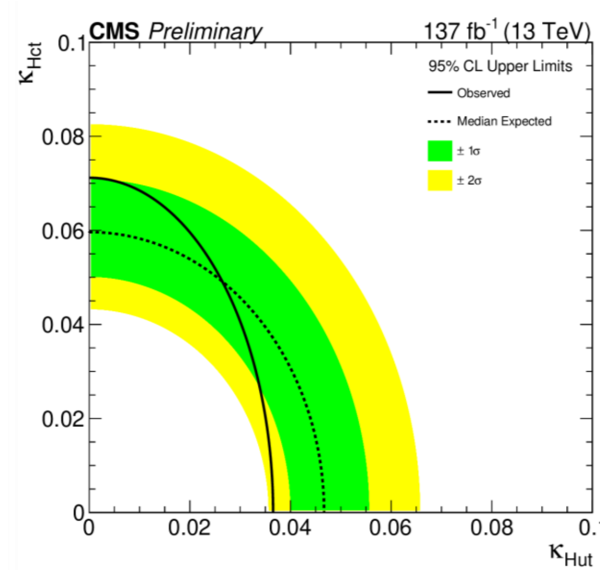


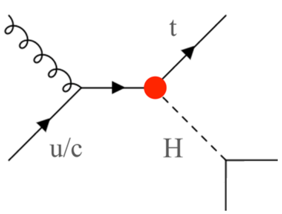
- No evidence of new physics found
- Observed limits are significant improvement on previous combined results
- Dominant uncertainties are from b-jet and photon identification

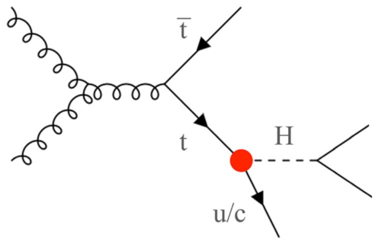
$$B(t \to Hu) \leq 1.9 \times 10^{-4}$$

$$B(t \to Hc) \leq 7.3 \times 10^{-4}$$

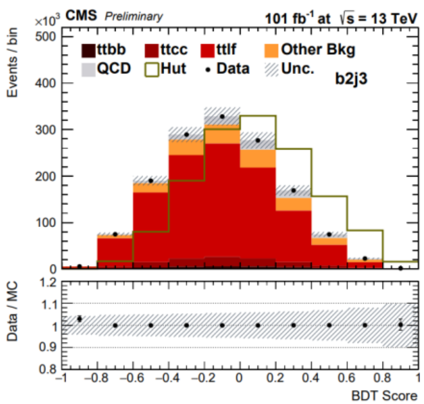




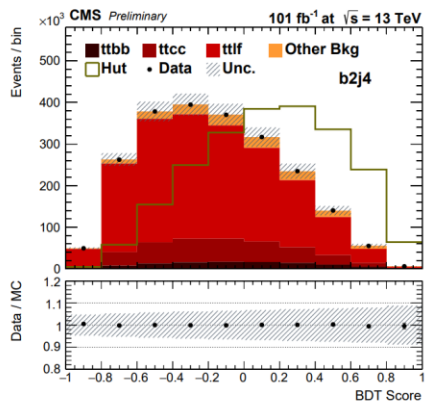




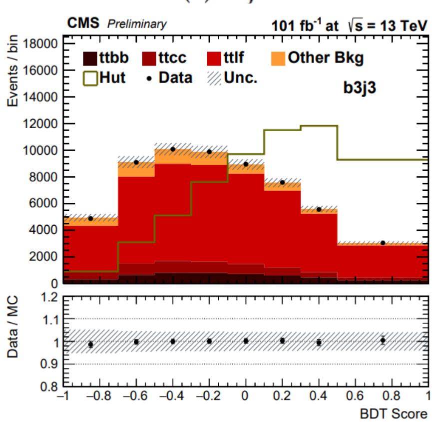
- Both production and decay modes considered
- Events are categorised by jet and b-tag multiplicities
- DNN used to reconstruct tops with jet permutations, label as FCNC production or decay signal-like, or background-like (including SM $t\bar{t}$)
- ~80% process efficiency



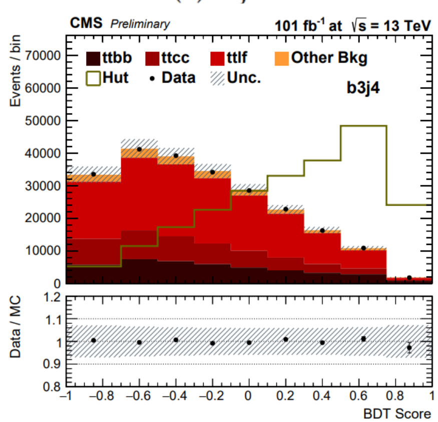
(a) b2j3



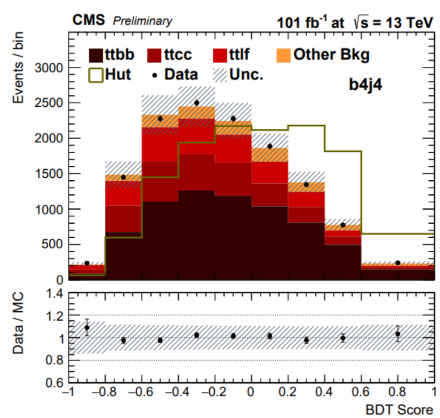
(b) b2j4



(c) b3j3



(d) b3j4



(e) b4j4

Resultant kinematic distributions input to BDT for signal-background separation

Asymptotic CLs method used to set 95% CLs

FCNC $tqH(\rightarrow b\bar{b})$

CMS-PAS-TOP-19-002
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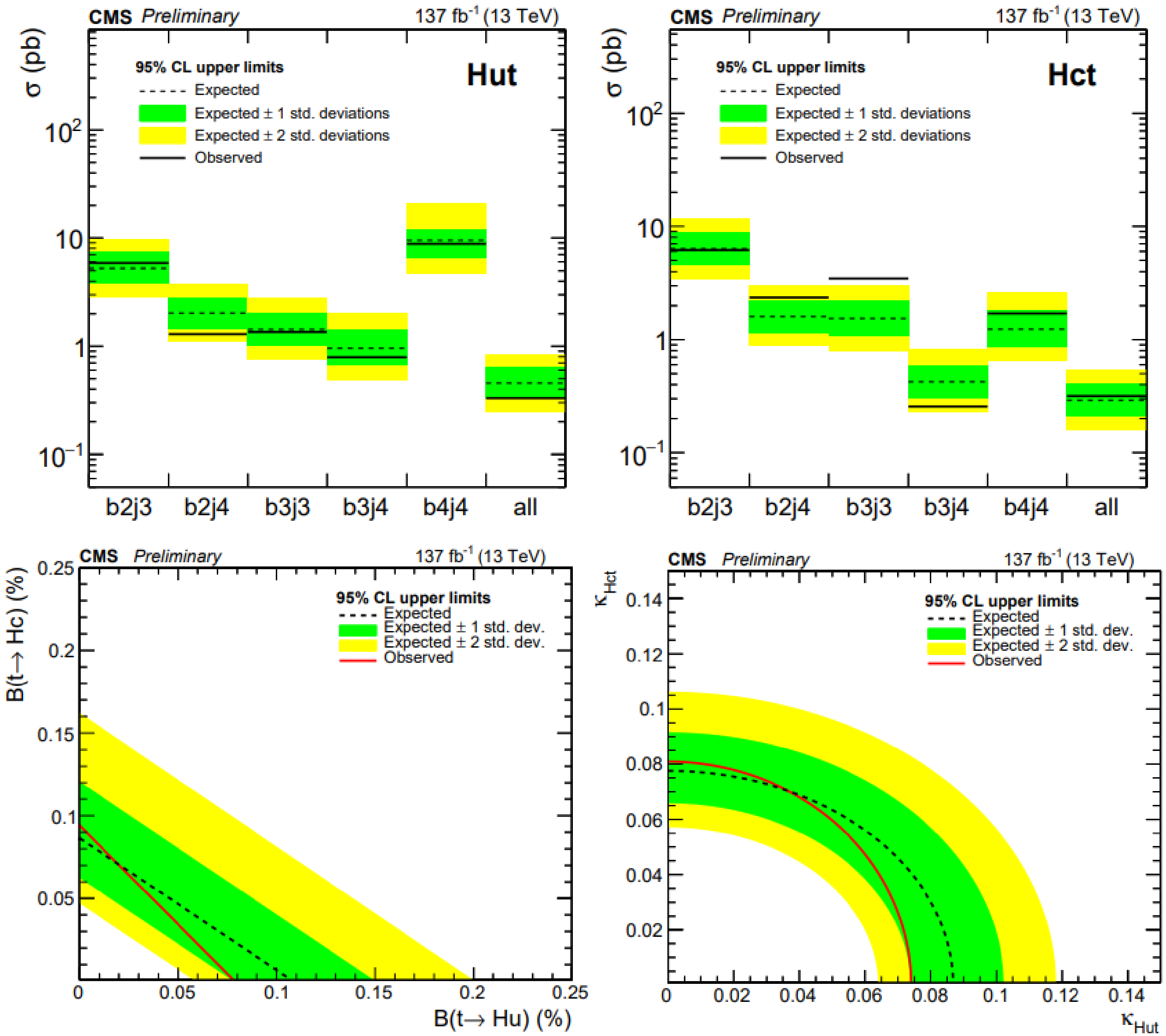

- No evidence of new physics found
- Observed limits are significant improvement on previous combined results
- Dominant uncertainties are from b-jet identification

$$B(t \rightarrow Hu) \leq 7.9 \times 10^{-4}$$

$$B(t \rightarrow Hc) \leq 9.4 \times 10^{-4}$$

Thanks for your attention

Jacob Kempster

8 September 2021