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Highlights on top quark physics with the ATLAS experiment at the LHC

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on behalf of the ATLAS Collaborations

8/29/2024

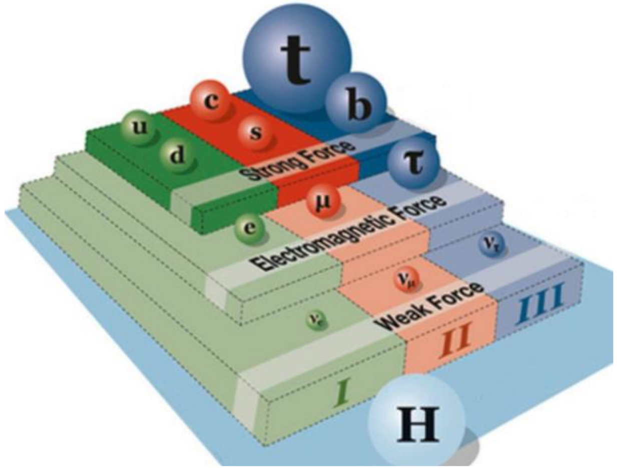
ATLAS EXPERIMENT

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

Introduction

Focus on ATLAS!

- Top quark is the heaviest fundamental particle discovered : m_t =172.52±0.33 GeV (LHC run1 combination)
- Precision measurements of top quark productions is important for the SM
  - Top-quark pair production (p+pb, arXiv:2405.05078 ; run3: Phys. Let. B 848 (2024) 138376)
  - Single top production in t-channel (arXiv:2405.05078)
  - Associated production of top quarks (ttW: JHEP05(2024)131; ttZ: JHEP07(2024)163; ttγ: arXiv:2403.09452)
- Any observation of deviations would indicate physics beyond the SM
  - Quantum entanglement in top-quark pairs (arXiv:2311.07288)
  - Charged Lepton Flavor Violation (Phys.Rev.D 110, 012014 (2024))
  - Test of Lepton-flavour universality in W decay (arXiv:2403.02133)
  - Search for flavour changing neutral currents (EPJC:84, 757 (2024)



Top-quark production

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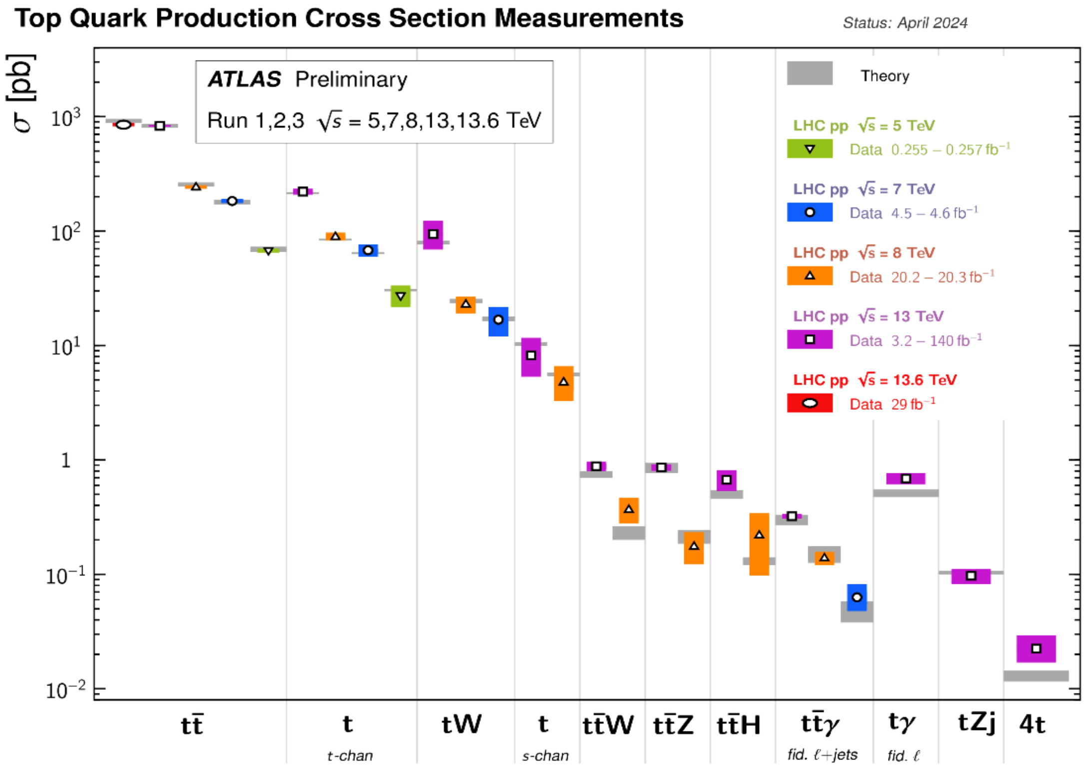
Top quark production Cross section measurement

- Dominant production modes at LHC: $t\bar{t}$, then electroweak single top
- Highly sensitive to EFT operators
- Important backgrounds for SM/BSM processes
- Multiple rare $t\bar{t}$X processes accessible at the LHC
- Window into top-quark yukawa couplings
- Increasingly precise measurements with growing LHC datasets

ATL-PHYS-PUB-2024-006



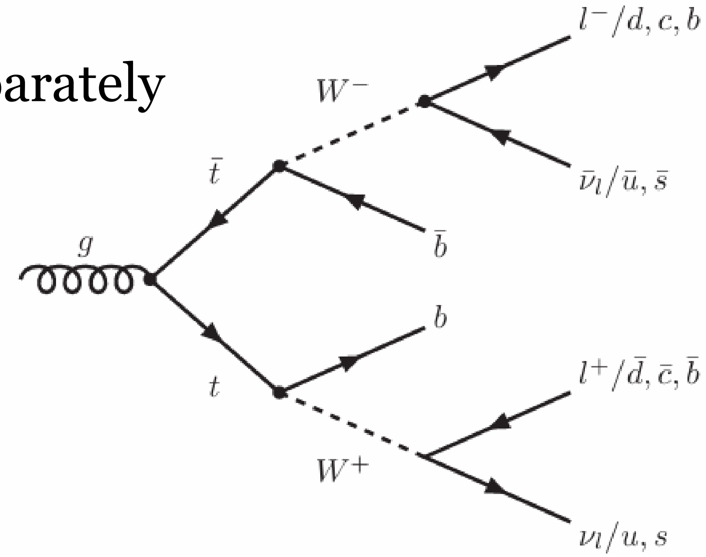
arXiv:2405.05078 Submitted to: JHEP

$t\bar{t}$ production in p+Pb collisions I

- p+Pb data collected in 2016 by ATLAS $\sqrt{S_{NN}}$ = 8.16TeV, 165 nb^{-1}

- Important probe for:
  - properties of the strongly interacting quark-gluon plasma (QGP)
  - nuclear parton distribution functions (nPDFs) in the kinematic region of high Bjorken-x

- Measure $t\bar{t}$ cross section in single-lepton and dilepton channels separately then combine:
  - ℓ+jets channel
  - dilepton channel (**firstly measured**)



$t\bar{t}$ production in p+Pb collisions II

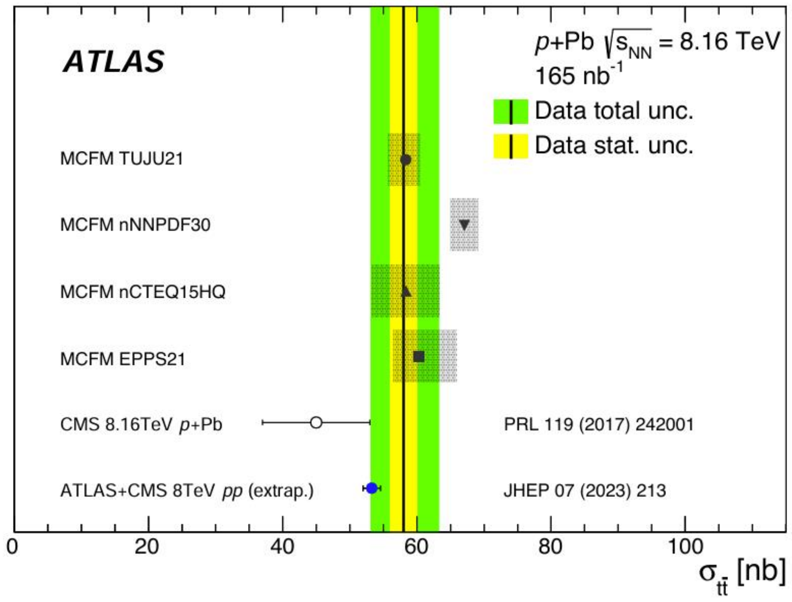
- The inclusive cross section is:
  - $\sigma(t\bar{t}) = \mathbf{58.1}^{+2}_{-2}\,(\text{stat.})^{+4.8}_{-4.4}(\text{syst.})\text{nb} = \mathbf{58.1}^{+5.2}_{-4.9}$ nb.
- Significance is above **5 σ** in both individual and inclusive channels(9% total uncertainty)

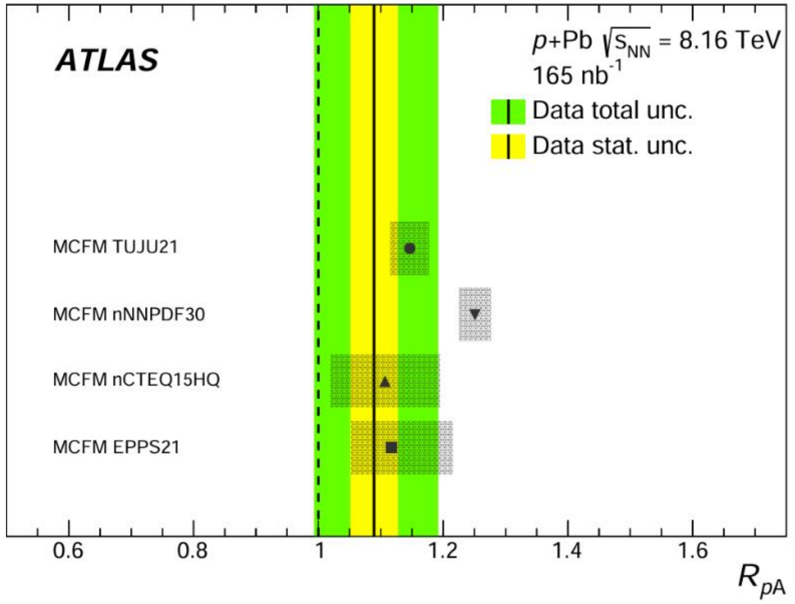
- The nuclear modification factor is defined as:

$$R_{pA} = \frac{\sigma_{t\bar{t}}^{p+\text{Pb}}}{A_{\text{Pb}} \cdot \sigma_{t\bar{t}}^{pp}}$$

  - $R_{pA} = 1.090^{+0.039}_{-0.039}\,(\text{stat.})^{+0.094}_{-0.087}(\text{syst.})$

- **First observation** of $t\bar{t}$ production on in p+Pb collisions with ATLAS.
- **Most precise** $t\bar{t}$ cross-section measurement in nuclear collisions.
- R_{pA} measurement has been done **first time** for $t\bar{t}$ at the LHC.



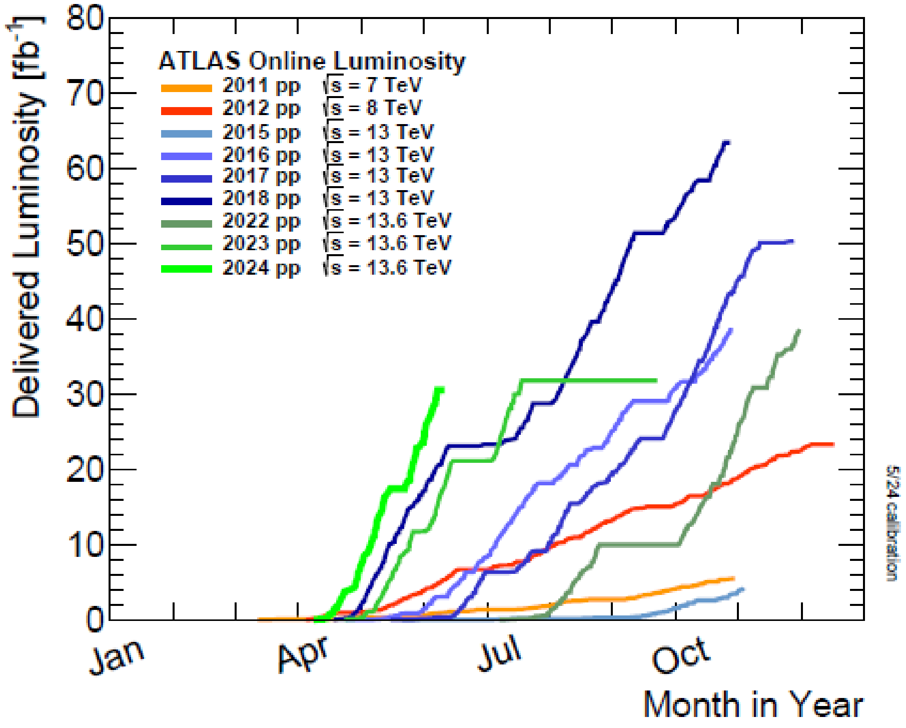


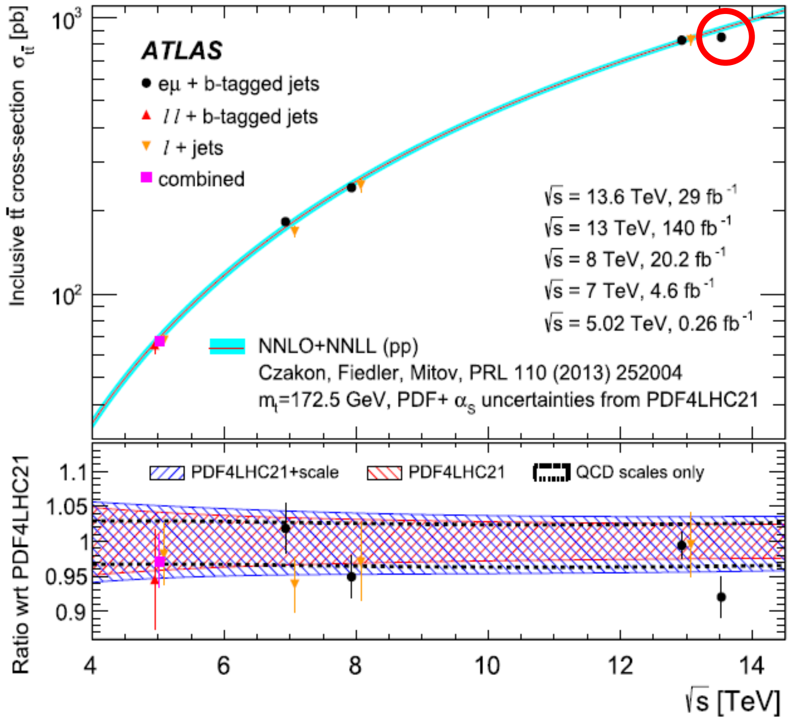
Phys. Let. B 848 (2024) 138376

Run3: $t\bar{t}$ and $t\bar{t}/Z$ cross-section ratio at 13.6 TeV I

- Dataset: Run3, 13.6 TeV, $29fb^{-1}$
- First Run 3 measurements of $t\bar{t}$ are shown

➢ Measured $\sigma(t\bar{t})$ = **850** ±3(stat.)±18(syst.)±20(lumi.) pb agree with SM prediction of $\mathbf{924}^{+32}_{-40}$ pb

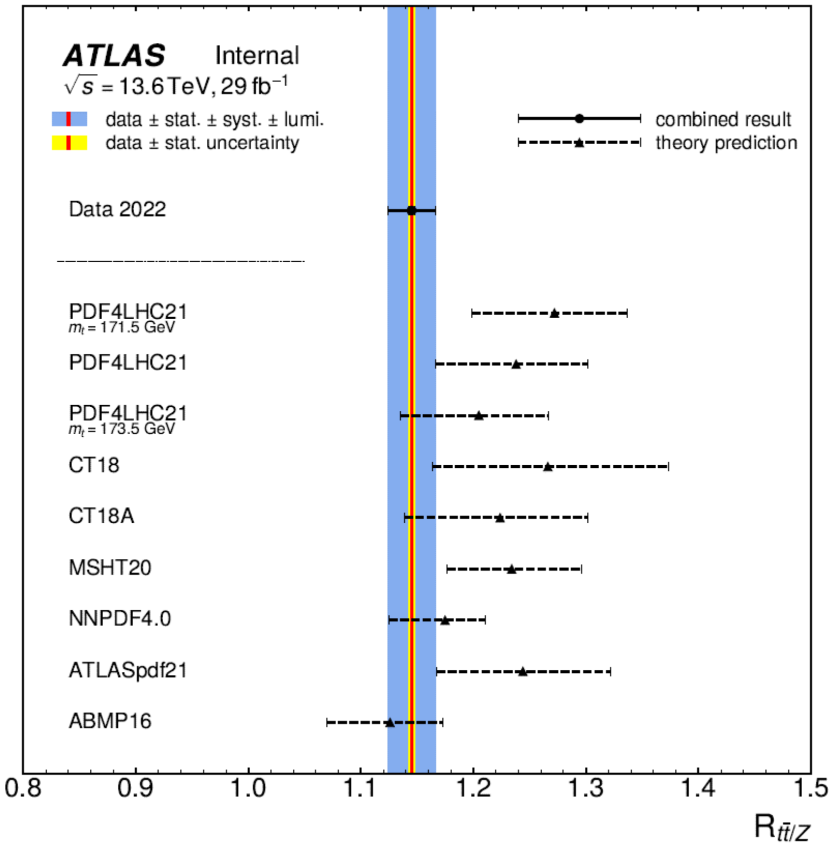




Run3: $t\bar{t}$ and $t\bar{t}/Z$ cross-section ratio at 13.6 TeV II

- **First** Run 3 measurements of $t\bar{t}/Z$ are shown
- Total uncertainty of about **1.9%**

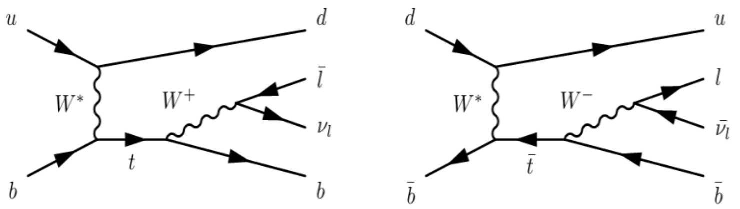
➢ Measured $R_{tt/Z}$ = **1.145** ± 0.003(stat.) ± 0.021(syst.) ± 0.002(lumi.) agree with SM prediction of $\mathbf{1.238}^{+0.063}_{-0.071}$ (scale+PDF+α_s)

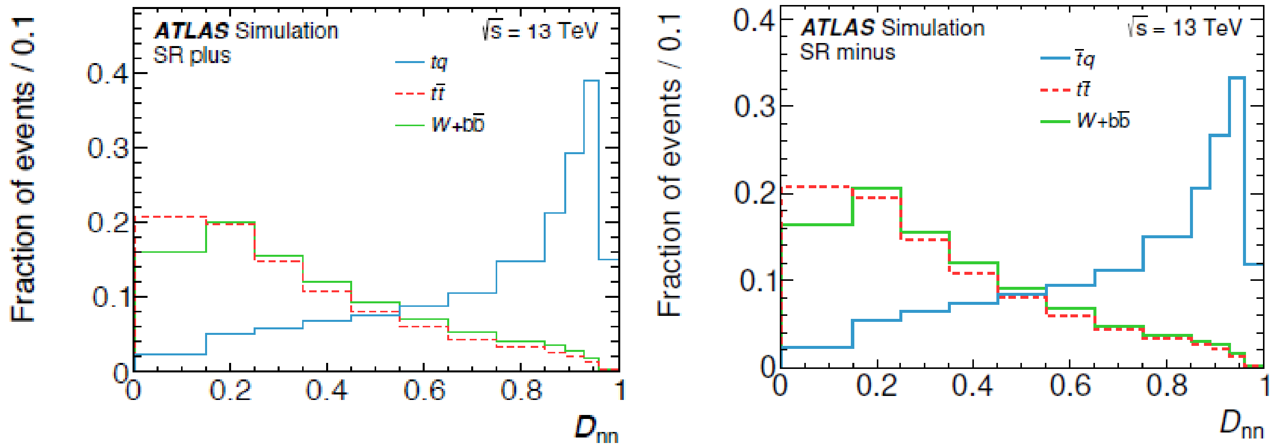


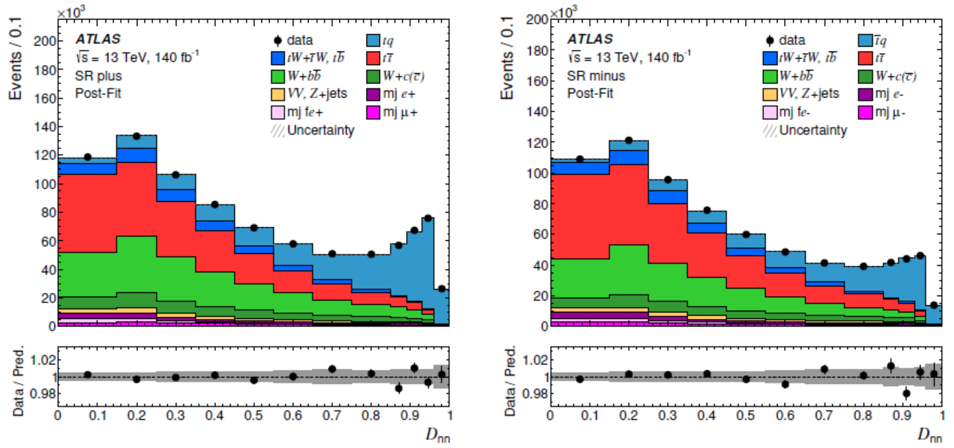
Single top cross section in t-channel I

JHEP 05 (2024) 305

- t-channel is the dominant single-top production in LHC [full run2 13TeV]
- Precision measurement provides SM test and energy-dependent non-SM couplings search
- Choose tq signal process and require final state has a charged lepton
  - 1 e/μ, 1 b-jet, 1 forward jet
  - Main background from $t\bar{t}$ and $Wb\bar{b}$
  - Use artificial neural network to separate signal and background







Single top cross section in t-channel II

- $\sigma(tq)$ = $\mathbf{137^{+8}_{-8}}$ and $\sigma(\bar{t}q)$ = $\mathbf{84^{+6}_{-5}}$ pb; $R_t = \sigma(tq)/\sigma(\bar{t}q) = \mathbf{1.636^{+0.036}_{-0.034}}$
- An EFT interpretation finds new limits on a four-quark point interaction:

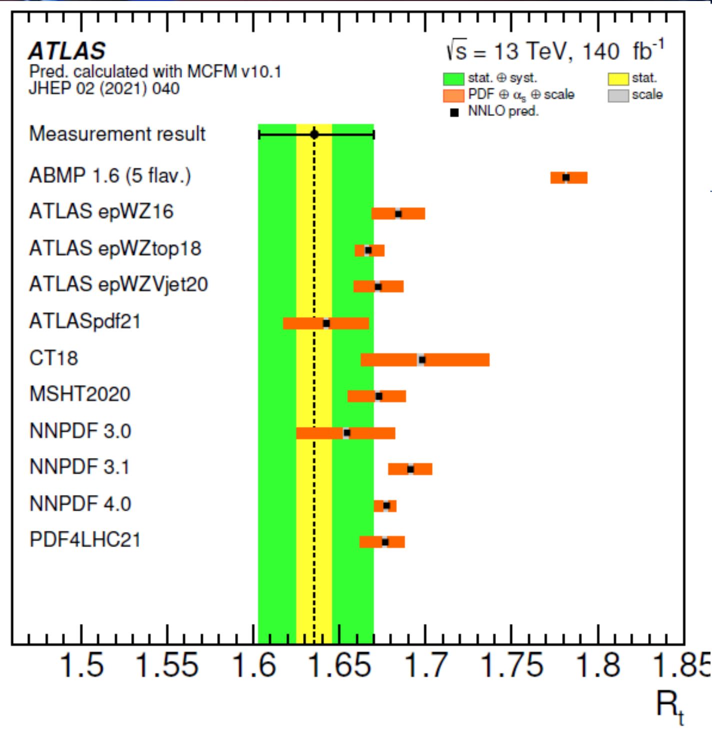
$$-0.37 < \frac{C^{3,1}_{Qq}}{\Lambda^2} < 0.06$$

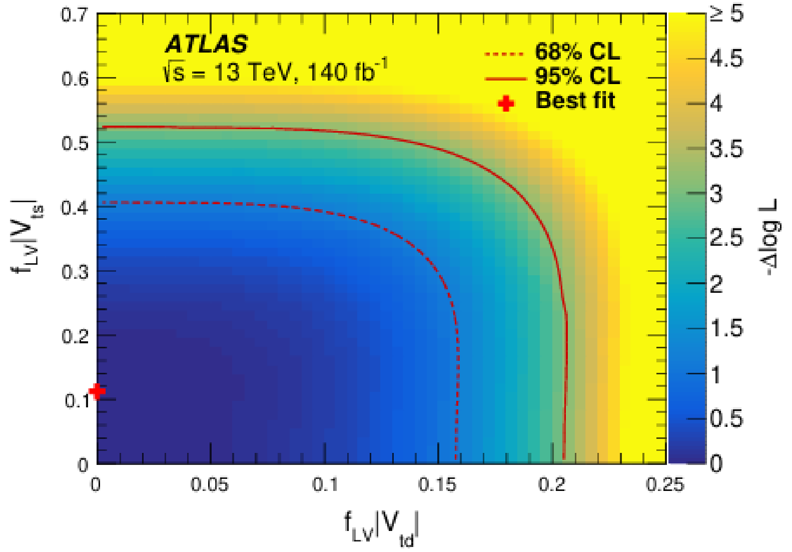
- New limits on anomalous tH coupling: $-0.87 < \frac{C^{3}_{Qq}}{\Lambda^2} < 1.42$
- Assuming CKM unitarity, from total cross section measurements :

$$f_{\rm LV} \cdot |V_{tb}| = 1.015 \pm 0.031$$

➢ The new results are in good agreement with predictions made at NNLO in perturbation theory.

➢ The **most precise** measurements of $\sigma(tq)$ and $\sigma(\bar{t}q)$





Associated production of top quarks

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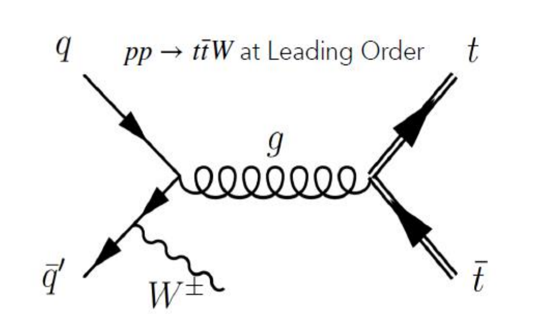
$t\bar{t}W$ production

JHEP05(2024)131

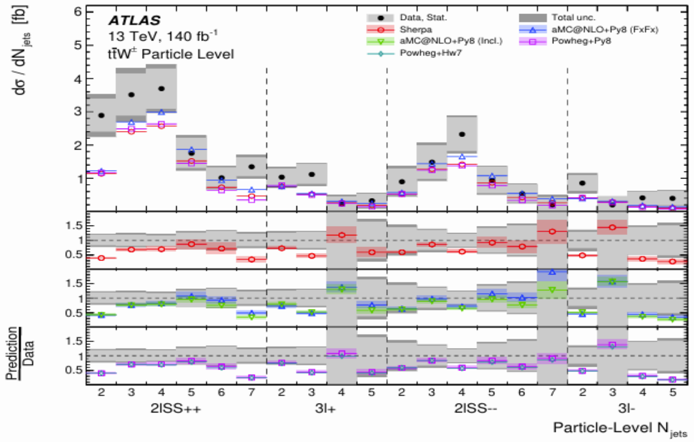


- ATLAS and CMS measure 20-50% larger inclusive cross section than SM NLO prediction.
- $t\bar{t}W$ can be the dominant background for $t\bar{t}H$, $t\bar{t}t\bar{t}$
- Rare top quark production is sensitive to BSM physics: like $t\bar{t}H$ and $t\bar{t}t\bar{t}$ production processes

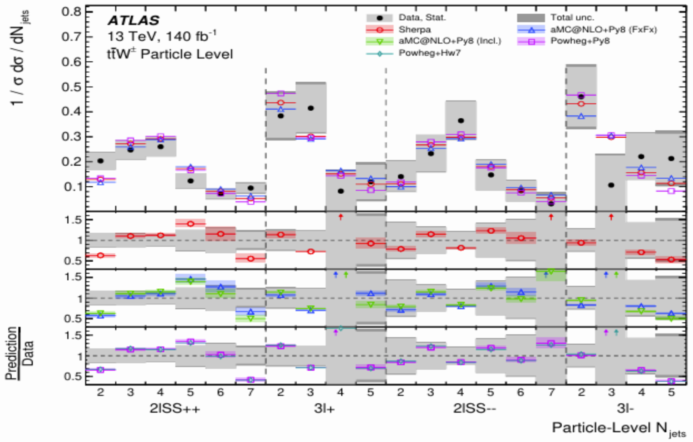
Differential $t\bar{t}W$ Cross Sections

- **First differential measurement** of $t\bar{t}W$ for 6 observables using profile likelihood unfolding
- All MC generators agree with unfolded data within uncertainties

Absolute Cross-section



Normalised Cross-section



Inclusive $t\bar{t}W$ Cross-Section

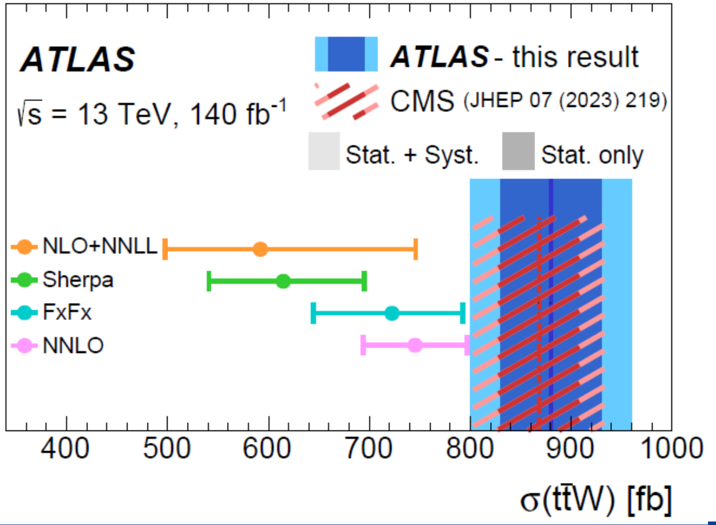
- $\sigma(t\bar{t}W)$ =**880±50**(stat.)±70(syst.) fb. is consistent at **1.4 σ** of the SM NNLO cross section **745**±50(scale)±13(2-loop approx.)± 19 (PDF, αs) fb.

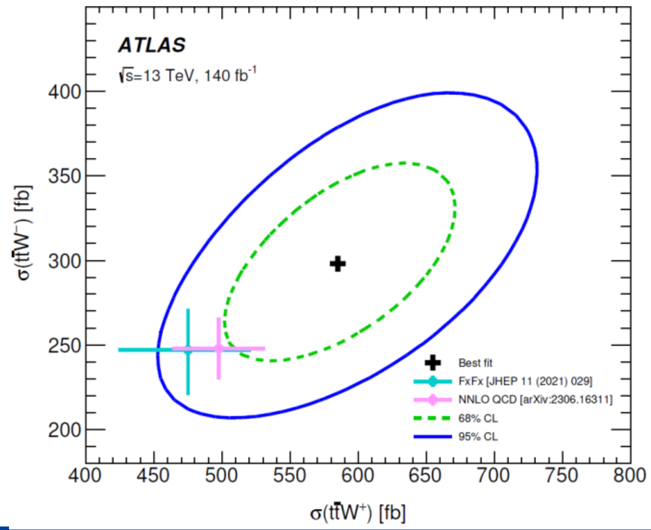
Leptonic Charge Asymmetry

- Ratio of $\sigma(t\bar{t}W^+)$ and $\sigma(t\bar{t}W^-)$ production rate is **consistent** with the MC prediction **0.322** ± 0.003(scale) ± 0.007(PDF) from Sherpa.

$$A_c^{rel} = \frac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)}$$

$$A_C^{\mathrm{rel}} = 0.33 \pm 0.05\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{syst.})$$

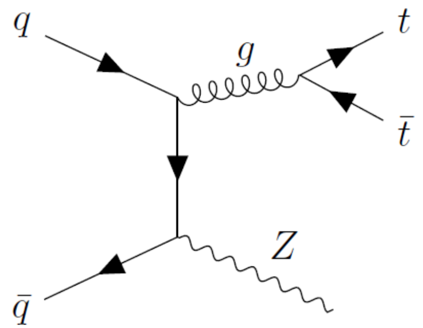




JHEP07(2024)163

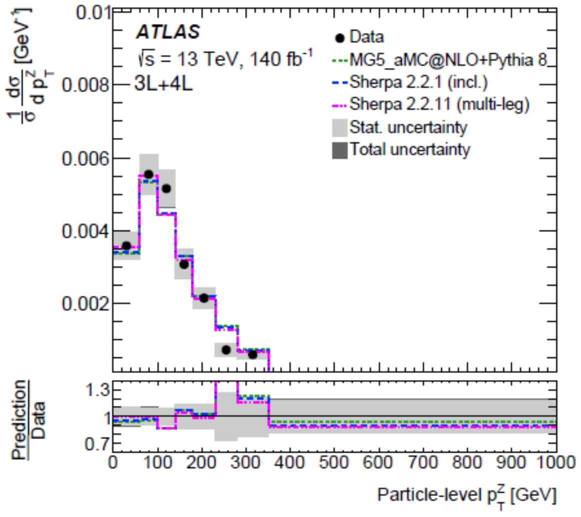
$t\bar{t}Z$ production including EFT and spin correlations

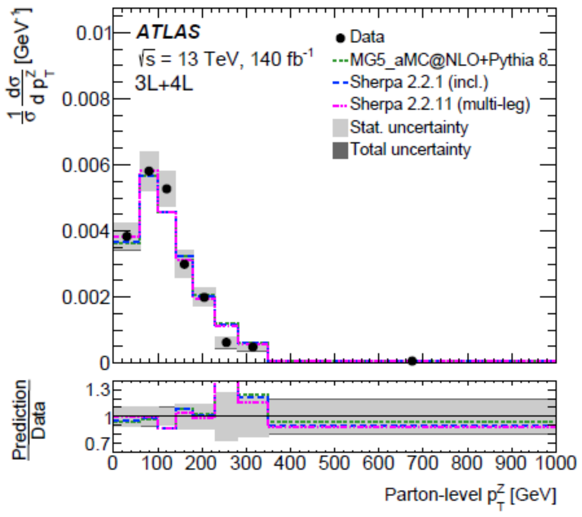
- The coupling of the top and Z is not yet well constrained and the value is significant altered by BSM
- Main background for $t\bar{t}H$, $t\bar{t}W$, tZq, etc.
- Probes the top-electroweak coupling (complementary to $t\bar{t}\gamma$)



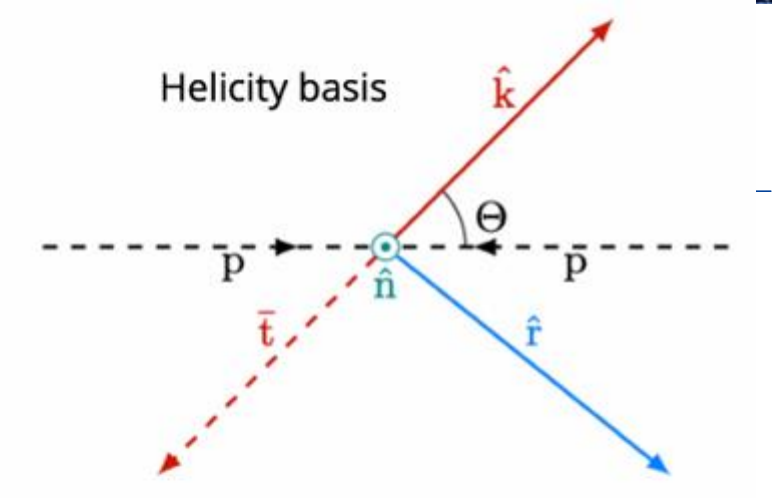
$t\bar{t}Z$ cross section

- Inclusive measurement σ_{ttZ}= 0.86±0.04 (stat) ±0.04 (syst)pb. agrees with SM prediction (**6.5% precision**)
- 17 differential cross section variables at parton and particle level
- Good agreement with NLO predictions across all variables





$t\bar{t}Z$ spin correlation



- **First measurement** of spin correlation at detector-level using template method

$$O = f_{\mathrm{SM}} \cdot O_{\text{spin-on}} + (1 - f_{\mathrm{SM}}) \cdot O_{\text{spin-off}}.$$

- $f_{SM}^{obs.}$ = 1.20±0.63(stat.)±0.25(syst.) = 1.20±0.68(tot.)
- Spin correlations observed with **1.8σ** significance
- Still need more statistics

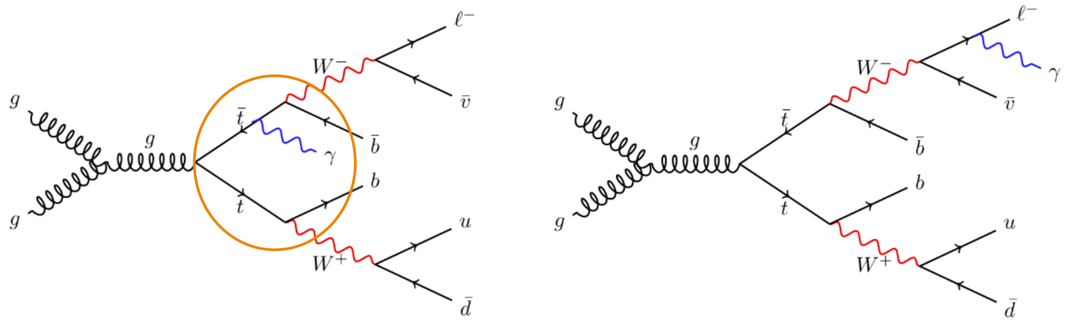
Distribution	Channel	Expected values	Observed values
$\cos\varphi$	$3\ell + 4\ell$	$1^{+1.39}_{-1.38}$	$-0.09^{+1.34}_{-1.28}$
$\cos\theta_r^+ \cdot \cos\theta_r^-$	$3\ell + 4\ell$	$1^{+1.83}_{-1.82}$	$1.17^{+1.80}_{-1.76}$
$\cos\theta_k^+ \cdot \cos\theta_k^-$	$3\ell + 4\ell$	$1^{+1.78}_{-1.78}$	$1.39^{+1.72}_{-1.73}$
$\cos\theta_n^+ \cdot \cos\theta_n^-$	$3\ell + 4\ell$	$1^{+1.87}_{-1.86}$	$-1.05^{+2.06}_{-1.96}$
$\cos\theta_r^+ \cdot \cos\theta_k^- + \cos\theta_r^- \cdot \cos\theta_k^+$	$3\ell + 4\ell$	$1^{+1.93}_{-1.93}$	$0.36^{+1.99}_{-1.93}$
$\cos\theta_r^+$	$3\ell + 4\ell$	$1^{+1.81}_{-1.80}$	$1.56^{+1.86}_{-1.98}$
$\cos\theta_r^-$	$3\ell + 4\ell$	$1^{+1.82}_{-1.78}$	$1.81^{+1.63}_{-1.68}$
$\cos\theta_k^+$	$3\ell + 4\ell$	$1^{+1.69}_{-1.67}$	$2.00^{+1.65}_{-1.70}$
$\cos\theta_k^-$	$3\ell + 4\ell$	$1^{+1.68}_{-1.68}$	$2.31^{+1.68}_{-1.68}$

$t\bar{t}\gamma$ production

arXiv:2403.09452 submit to JHEP

- Direct probe of tγ electroweak coupling
- Sensitive to EFT operators related to top to anomalous dipole (complementary to $t\bar{t}Z$)

- Measurement in the single lepton and dilepton $t\bar{t}$ decay channels
- Single-lepton: **4-class NN** to separate: $t\bar{t}\gamma$ production, $t\bar{t}\gamma$ decay, fake-photon, and prompt-photon backgrounds
- Dilepton: **2-class NN** to separate signal from background

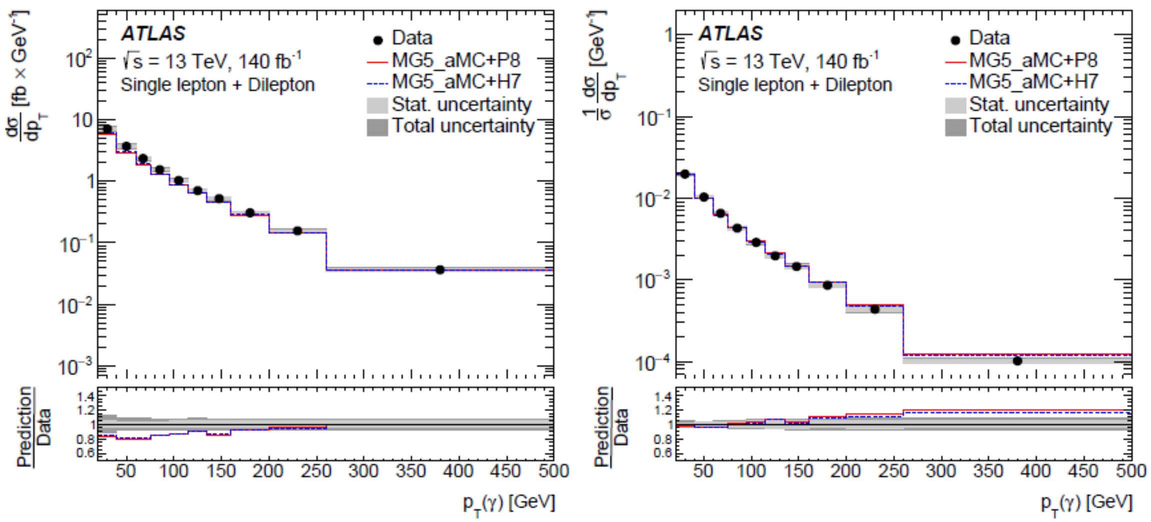


$t\bar{t}\gamma$ production cross section

- Fiducial cross section at particle level from a combined fit to the signal and control regions in both channels
- Dominant systematics uncertainties are modeling of $t\bar{t}\gamma$ production and the normalization of $t\bar{t}\gamma$ decay

- $\sigma_{fid}(t\bar{t}\gamma\ \text{production}) = 322 \pm 5\ (\text{stat}) \pm 15\ (\text{syst})\ \text{fb}$
- $\sigma_{SM}^{NLO}(t\bar{t}\gamma\ \text{production}) = 299^{+29}_{-30}\ (\text{scale})^{+7}_{-4}\ (\text{PDF})\ \text{fb}$

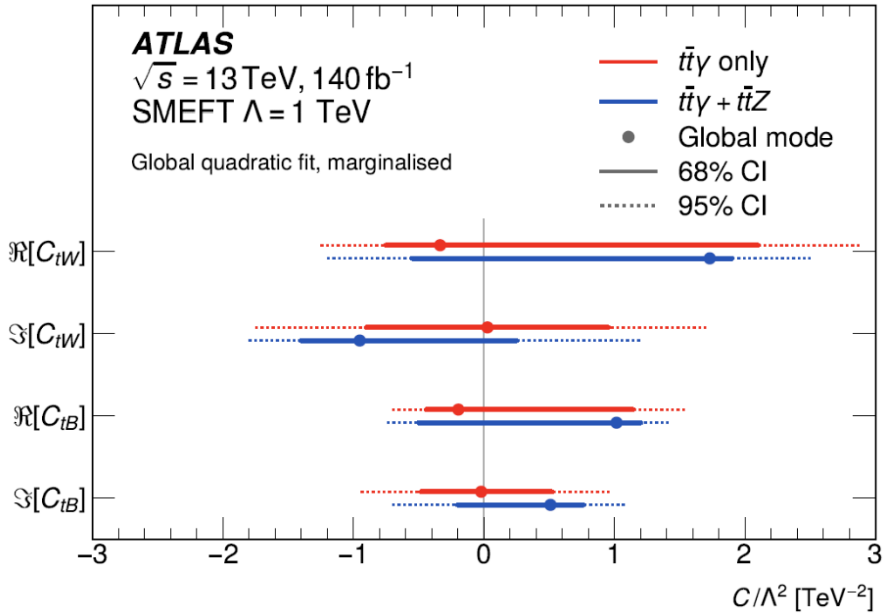
- The inclusive cross section measurement is **agreement with MC** prediction within uncertainties.
- Up to 11 variables are measured and the shape of measured cross sections are compatible with MC generators
- The total $t\bar{t}\gamma$ (production and decay) cross sections are measured

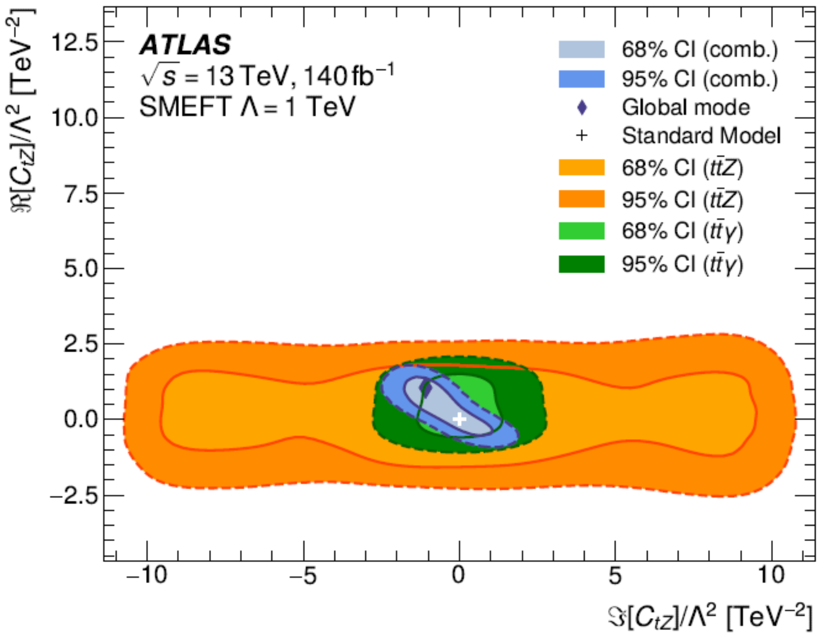


$t\bar{t}\gamma + t\bar{t}Z$ EFT interpretation

- Relevant dim-6 Wilson coefficients: C_{tB} and C_{tW}
- Rotate basis to extract C_{tZ} and $C_{t\gamma}$
- Combined limits obtained from simultaneous unfolding of the p_T of photon and Z
- $t\bar{t}Z$ shows degenerated structure in combination

$$C_{tZ} = c_w \cdot C_{tW} - s_w \cdot C_{tB}$$
$$C_{t\gamma} = s_w \cdot C_{tW} + c_w \cdot C_{tB}$$





Top quark properties

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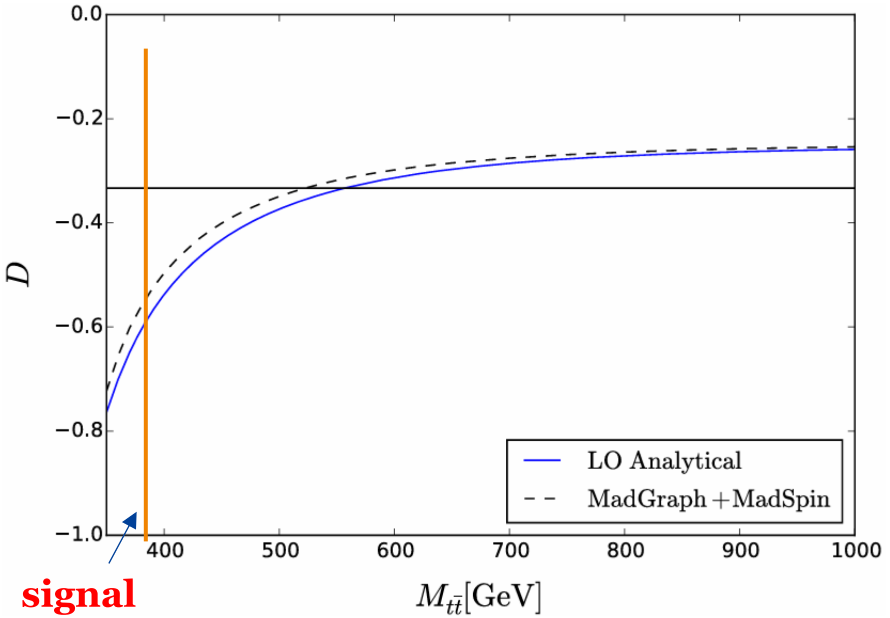
arXiv:2311.07288
Accepted by nature

Entanglement Measurements I

Observation of quantum entanglement in **top-quark pairs!**

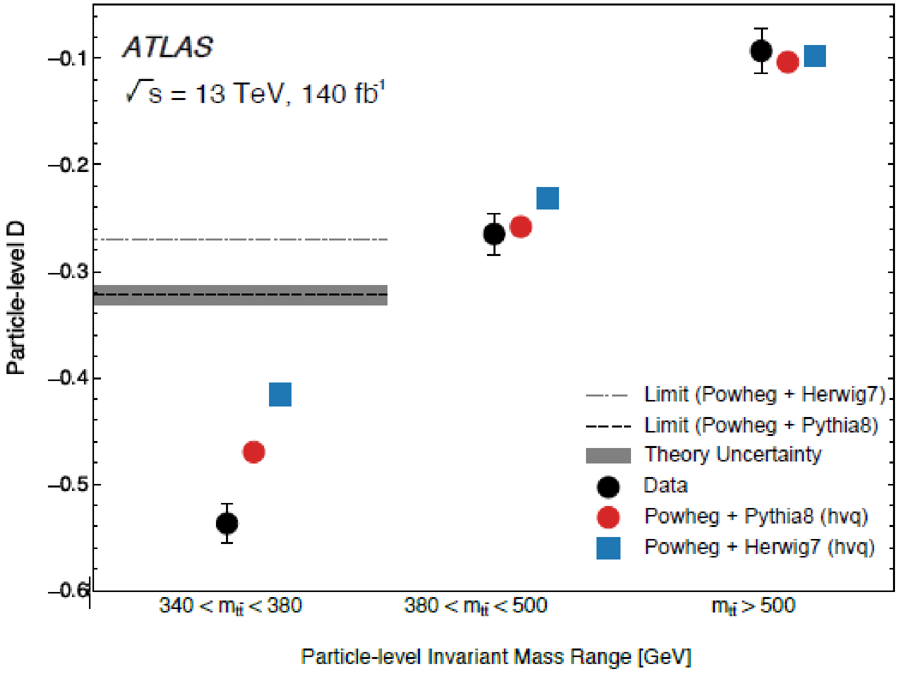
- the top quantum numbers (spin) are transferred to the decay products via the maximally parity-violating Wtb vertex
- By measuring decay angles of decay products, can determine top polarization and spin-correlation between top quarks
- Split the phase space in bins of $M_{t\bar{t}}$, and expect that entanglement can only be observed near threshold
  - 340< $M_{t\bar{t}}$<380 GeV: entanglement **signal region**
  - 380< $M_{t\bar{t}}$<500 GeV: validation region
  - 500 GeV < $M_{t\bar{t}}$: no entanglement validation region



Entanglement Measurements II

- D = -3.<cosφ> (φ angle between the lepton directions in each one of the parent top and anti-top rest frames)
- D < -1/3 is the existence of entangled state

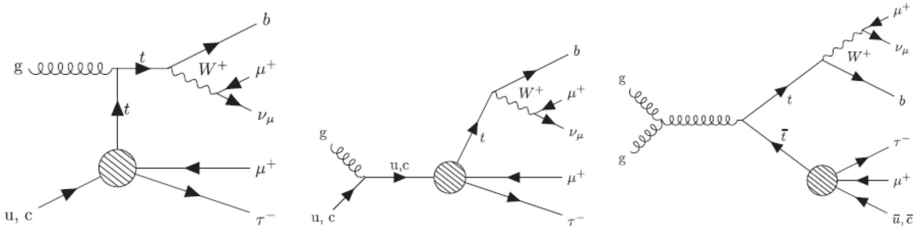
- Observed: D = -0.537 ±0.002 (stat.)± 0.019 (syst.) for 340 < $m_{t\bar{t}}$ < 380 GeV
- Measured D greater than **5σ** away from scenario with no entanglement
- **First observation** of entanglement in top quark pairs !



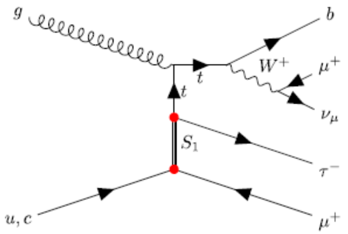
Phys.Rev.D 110, 012014 (2024)

Charged Lepton Flavor Violation (cLFV)

- Direct probe of the existence of many BSM models

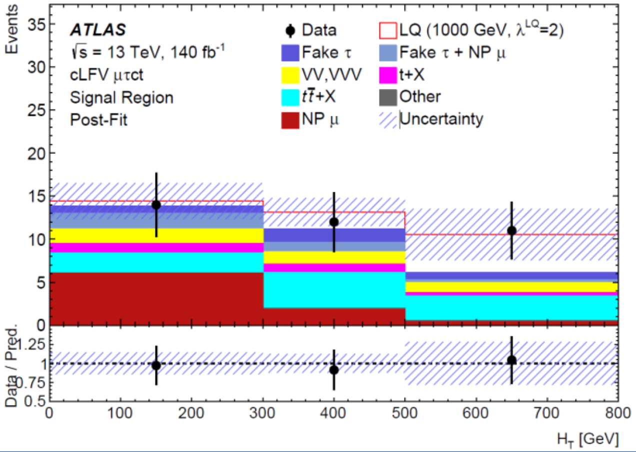


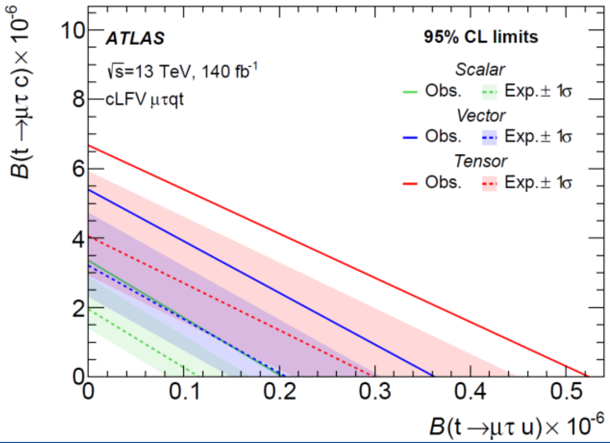
hatched circle represents the cLFV vertex

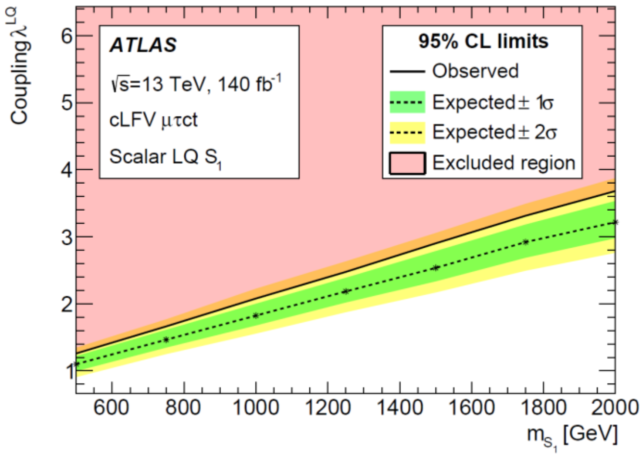


Scalar LFV leptoquarks

- The SM prediction is found to agree with the data to within **1.6σ**
- The limit of Br(t→ μτq) < 8.7 × 10^{-7} at 95% CL are set
- Leptoquark coupling strengths between 1.3 < λ^{LQ} < 3.7 are excluded for masses between 0.5 and 2.0 TeV



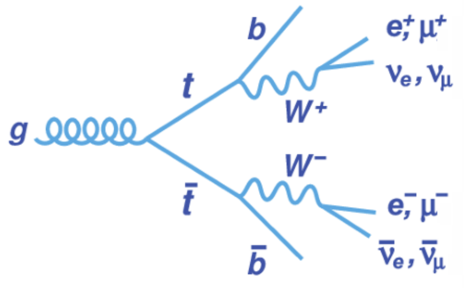




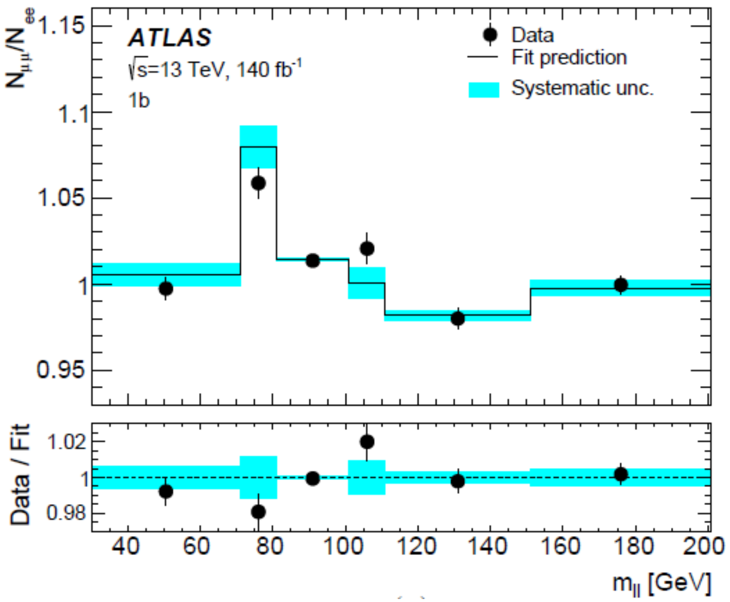
arXiv:2403.02133 Accepted by EPJC

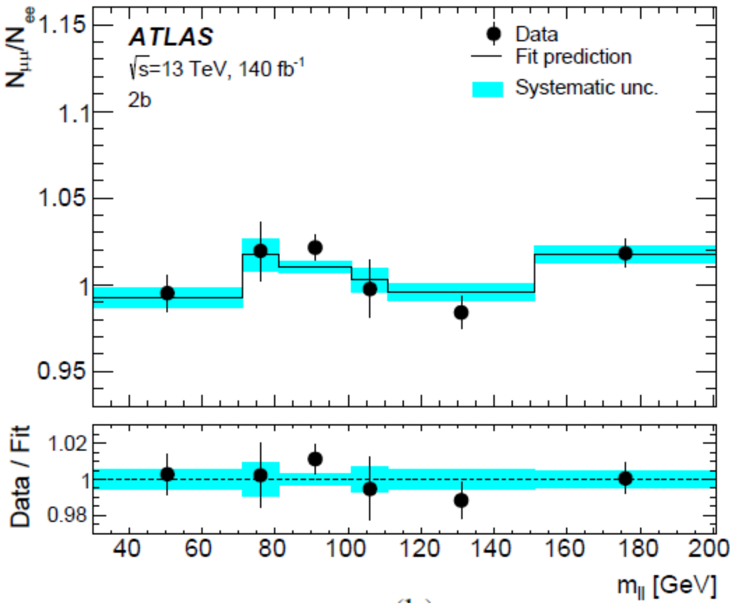
Test of lepton flavor universality in W decays

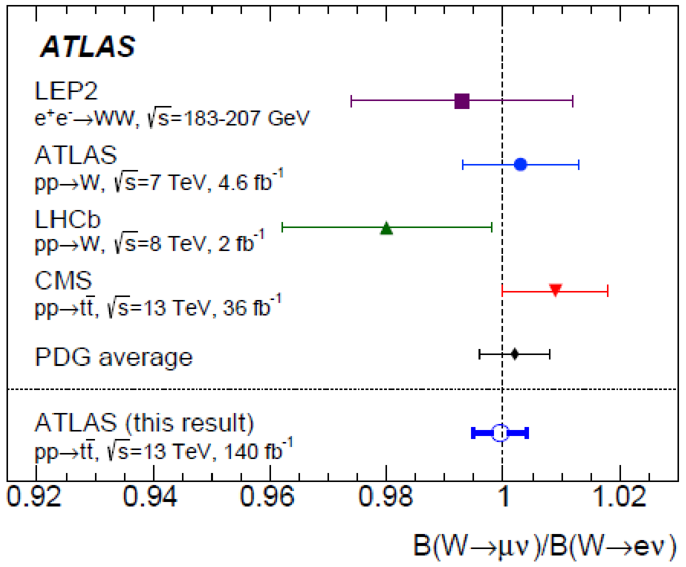
- Fundamental axiom of the SM that the couplings of W and Z-bosons to the charged leptons are independent of their mass
- **Most precise** measurement of $R_W^{\mu/e}$, achieve **0.45%** precision
- Consistent with the assumption of lepton flavor universality



$$R_W^{\mu/e} = R_{WZ}^{\mu/e}\sqrt{R_{Z-\text{ext}}^{\mu\mu/ee}} = 0.9995 \pm 0.0022\,(\text{stat}) \pm 0.0036\,(\text{syst}) \pm 0.0014\,(\text{ext})$$





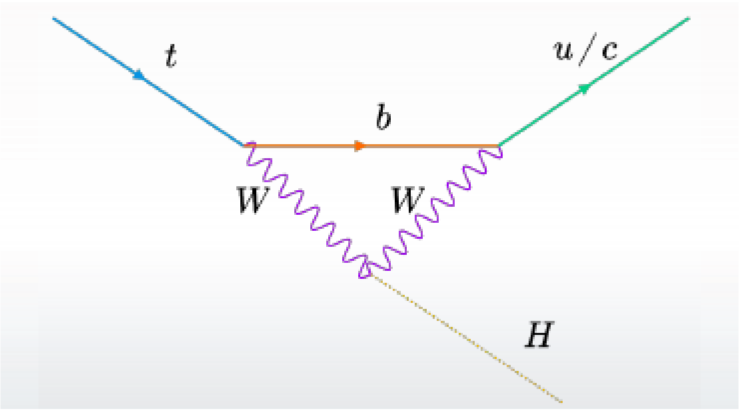


EPJC:84, 757 (2024)

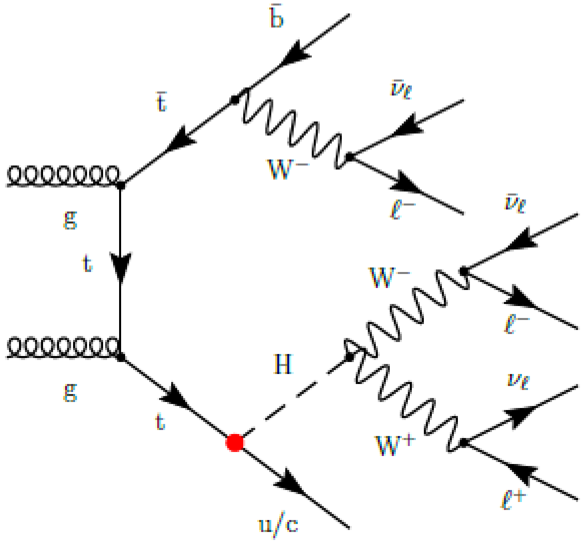
FCNC interactions with the top quark I

Flavour-Changing Neutral-Current interactions (FCNC)
- Tree-level FCNC couplings forbidden in SM
- Higher-order interactions suppressed due to GIM mechanism

➢ Observing FCNC interactions at the LHC would be a clear sign of physics beyond the SM

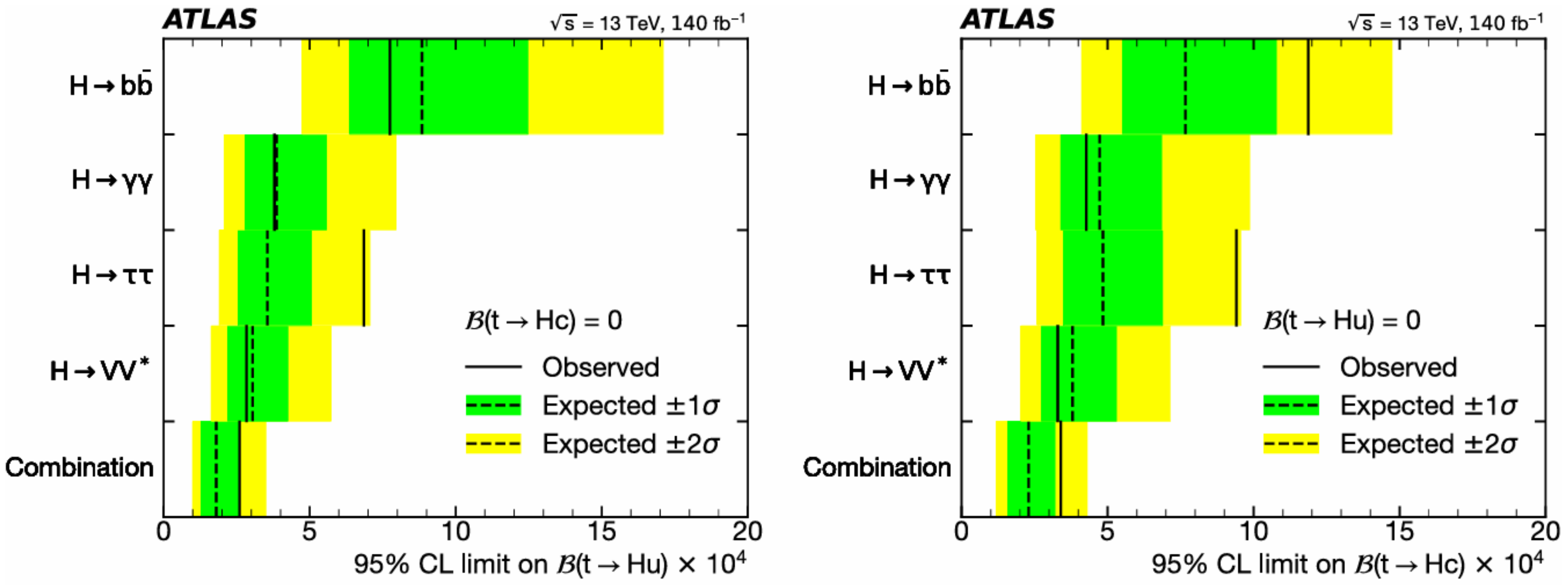


- Consider tH and $t\bar{t}$(t->Hq) processes
- Focus on 2lSS and 3l channels final states
- Several previous searches are combined



FCNC interactions with the top quark II

- Improvements w.r.t. previous analysis mainly coming from improved techniques(MVA) and inclusion of single top quark production signal
- The results are **compatible with the SM** and no evidence of FCNC couplings is observed
- The observed upper limits on the branching ratio are $B(t \rightarrow Hu) < 2.8\times10^{-4}$ and $B(t \rightarrow Hc) < 3.3\times10^{-4}$.



Summary

- The full Run 2 Highlights:
  - Precision Cross Sections: Achieved **more precise** measurements of the top quark production cross section.
  - Quantum Entanglement: **Observed quantum entanglement** in top quarks for the first time!
- Outlook for Run 3:
  - Increased Precision: Expect further refinement in measurements with higher data statistics.
  - Potential for New Discoveries: Improved technologies and analysis methods may reveal new insights of top quark

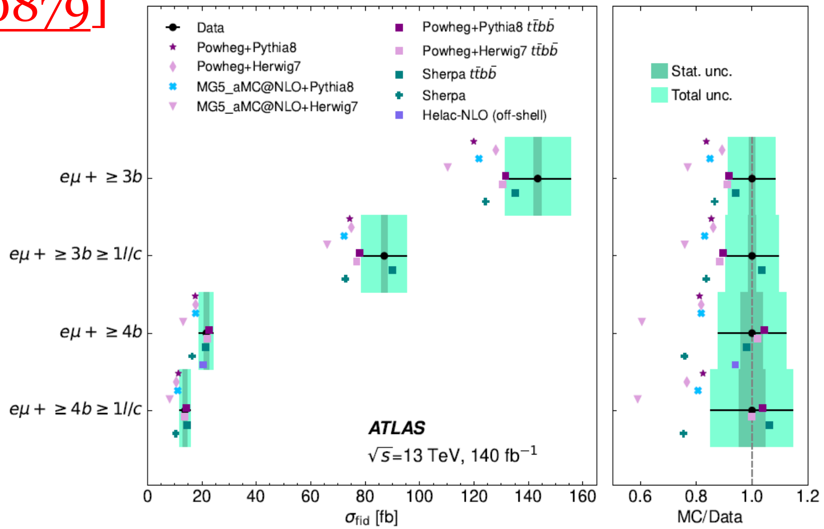
Thanks for your attention!

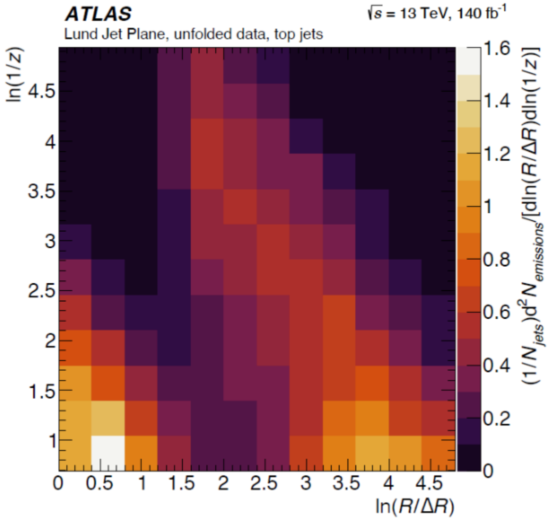
Other latest measurements

- ***$t\bar{t}$* +b-jets:** [arXiv:2407.13473]
  - The measured fiducial cross-sections are compared with various theoretical predictions with best precision
  - Variety of observables are measured for differential cross section

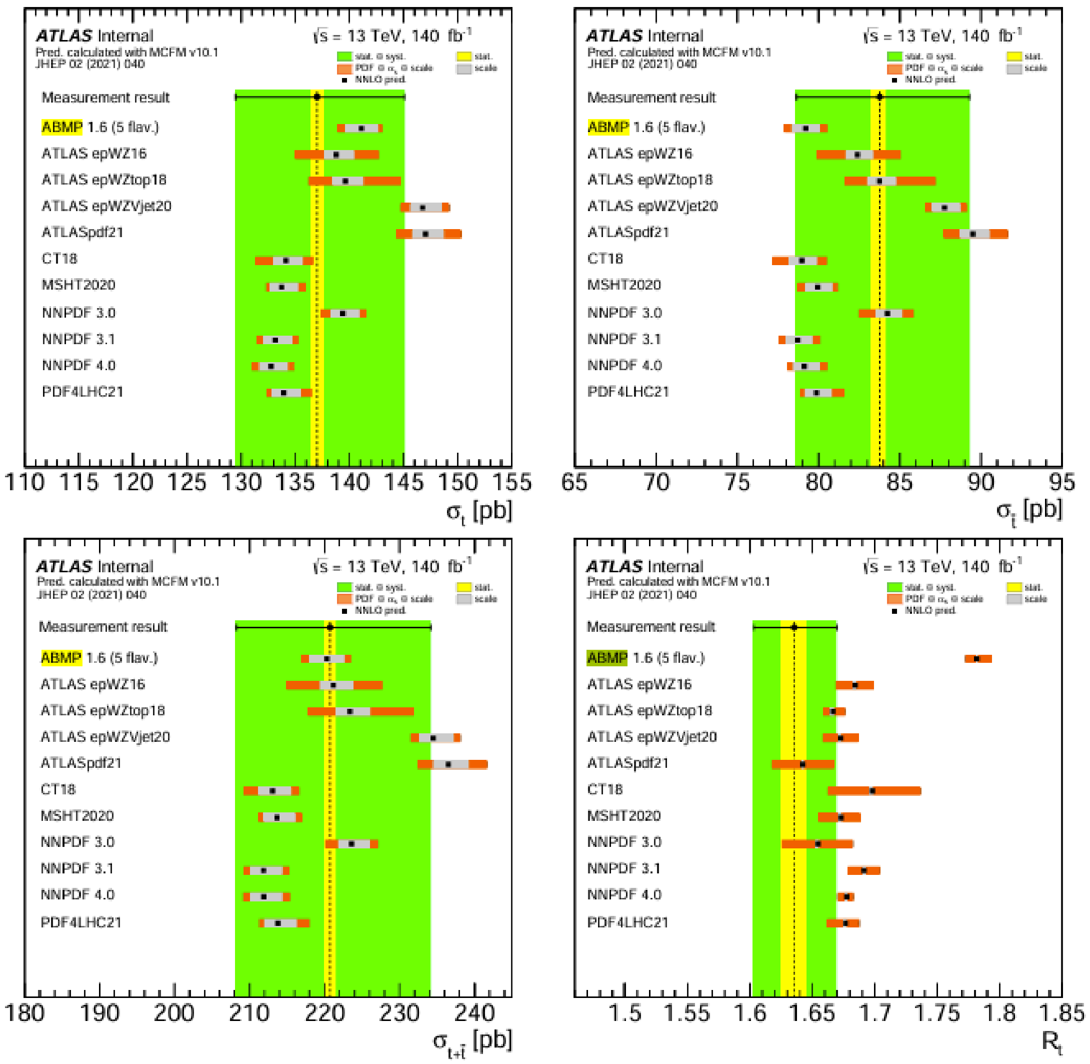
- Single top **Wt**: [arXiv:2407.15594]
  - Inclusive cross section $\sigma(tW) = 75^{+15}_{-14}$ pb is in good agreement with $\sigma^{theory}_{ttW} = 79^{+1.9}_{-1.8}$ (scale)±2.2(PDF)pb.
  - Constrains on CKM matrix element V_{tb} : $|f_{LV}V_{tb}| = 0.97 \pm 0.10$.

- **Lund Jet Plane for tops** (LJP): [arXiv:2407.10879]
  - First measurement in $t\bar{t}$
  - Lack of overall compatibility between the measurement and the MC predictions, particularly in the W jets.





Single top t-channel

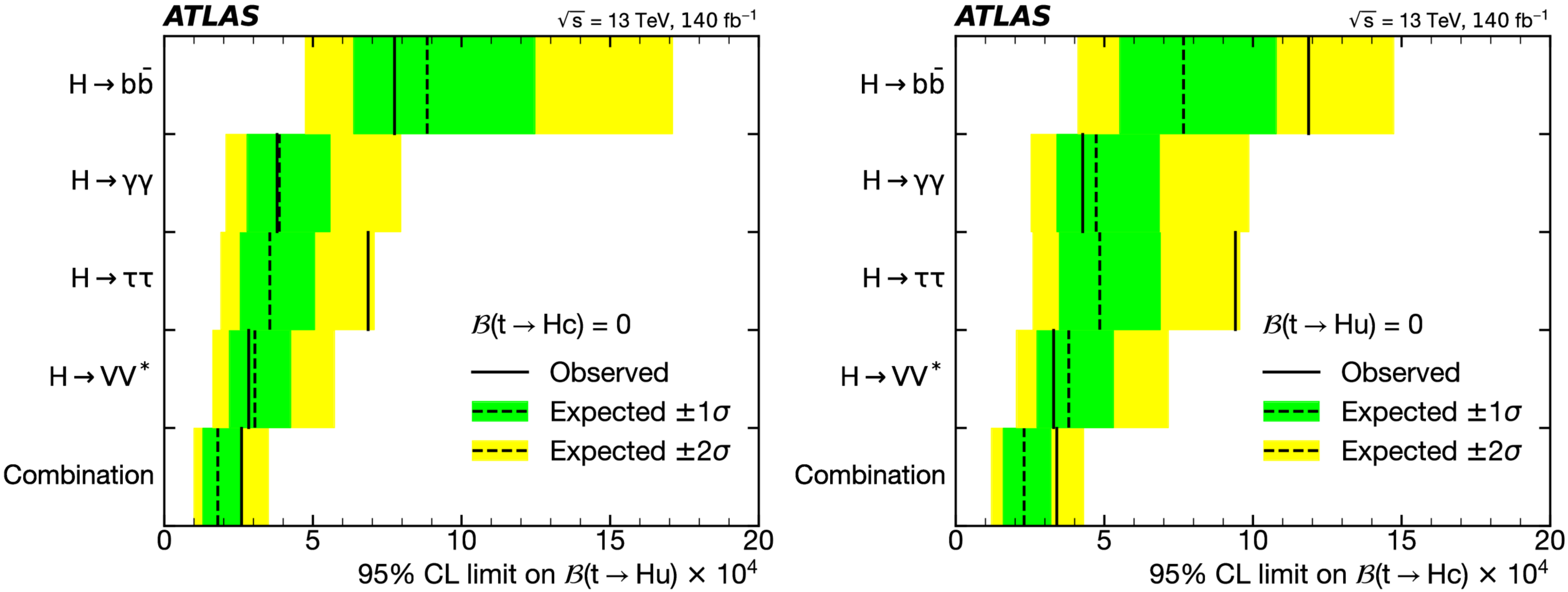


Entanglement Measurements

- the CMS collaboration has already measured D = -0.237 ±0.011 inclusively, showing no signal of entanglement Phys. Rev. D **100** (2019) 072002

Source of uncertainty	$\Delta D_{\text{observed}}(D = -0.537)$	ΔD [%]	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD [%]
Signal modeling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.2	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b-tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.002	0.4	0.002	0.4
Backgrounds	0.005	0.9	0.005	1.1
Total statistical uncertainty	0.002	0.3	0.002	0.4
Total systematic uncertainty	0.019	3.5	0.017	3.6
Total uncertainty	0.019	3.5	0.017	3.6

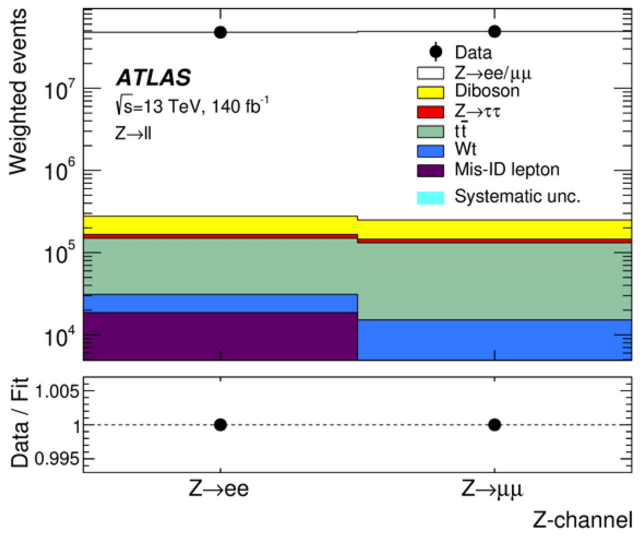
FCNC combination



Test of lepton flavour universality in W decays from $t\bar{t}$

- Final states: 2LOS, 1 or 2 b-jets
- Measurement would be limited by electron and muon efficiency uncertainties:
  - ➢ normalize to precise $R_Z^{\mu/e}$ measurement via a $Z \to \ell\ell$ events

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}} = \frac{B(W \to \mu\nu)}{B(W \to e\nu)} \cdot \sqrt{\frac{B(Z \to ee)}{B(Z \to \mu\mu)}}$$



Uncertainty [%]	$\sigma_{t\bar{t}}$	$\sigma_{Z\to\ell\ell}$	$R_{WZ}^{\mu/e}$	$R_Z^{\mu\mu/ee}$
Data statistics	0.13	0.01	0.22	0.02
$t\bar{t}$ modelling	1.68	0.03	0.10	0.00
Top-quark p_T modelling	1.42	0.00	0.06	0.00
Parton distribution functions	0.67	0.68	0.15	0.03
Single-top modelling	0.65	0.00	0.05	0.00
Single-top/$t\bar{t}$ interference	0.54	0.00	0.09	0.00
Z(+jets) modelling	0.06	0.73	0.13	0.20
Diboson modelling	0.05	0.04	0.01	0.00
Electron energy scale/resolution	0.05	0.06	0.10	0.11
Electron identification	0.10	0.07	0.04	0.13
Electron charge misidentification	0.06	0.06	0.01	0.13
Electron isolation	0.09	0.02	0.08	0.04
Muon momentum scale/resolution	0.04	0.02	0.06	0.04
Muon identification	0.18	0.12	0.11	0.23
Muon isolation	0.09	0.01	0.07	0.01
Lepton trigger	0.09	0.12	0.01	0.23
Jet energy scale/resolution	0.08	0.00	0.03	0.00
b-tagging efficiency/mistag	0.14	0.00	0.00	0.00
Misidentified leptons	0.17	0.02	0.15	0.05
Simulation statistics	0.04	0.00	0.06	0.00
Integrated luminosity	0.93	0.83	0.00	0.00
Beam energy	0.23	0.09	0.00	0.00
Total uncertainty	2.66	1.32	0.42	0.45

Universality

- Measurement would be limited by electron and muon efficiency uncertainties
  - Instead, normalise using ratio $R_Z=B(Z\to\mu\mu)/B(Z\to ee)$ measured from $Z\to ll$ sel^n

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}} = \frac{B(W\to\mu\nu)}{B(W\to e\nu)} \cdot \sqrt{\frac{B(Z\to ee)}{B(Z\to\mu\mu)}}$$

$$\Delta_Z = (R_Z^{\mu\mu/ee} - 1)/(R_Z^{\mu\mu/ee} + 1)$$

  - Determine $R^{\mu/e}_W$ from ttbar selection
    - Determine auxillary parameter R_Z in parallel $Z\to ll$ analysis with similar selections
  - Take $R^{\mu/e}_{WZ}$ as output from analysis – reduced lepton efficiency uncertanties
  - Convert to $R^{\mu/e}_W$ using $R^{\mu\mu/ee}_Z = 1.0009\pm0.0028$ from LEP/SLD as external input