ATLAS EFT Results in the Top Quark Sector

TOP2024 | Saint-Malo, France

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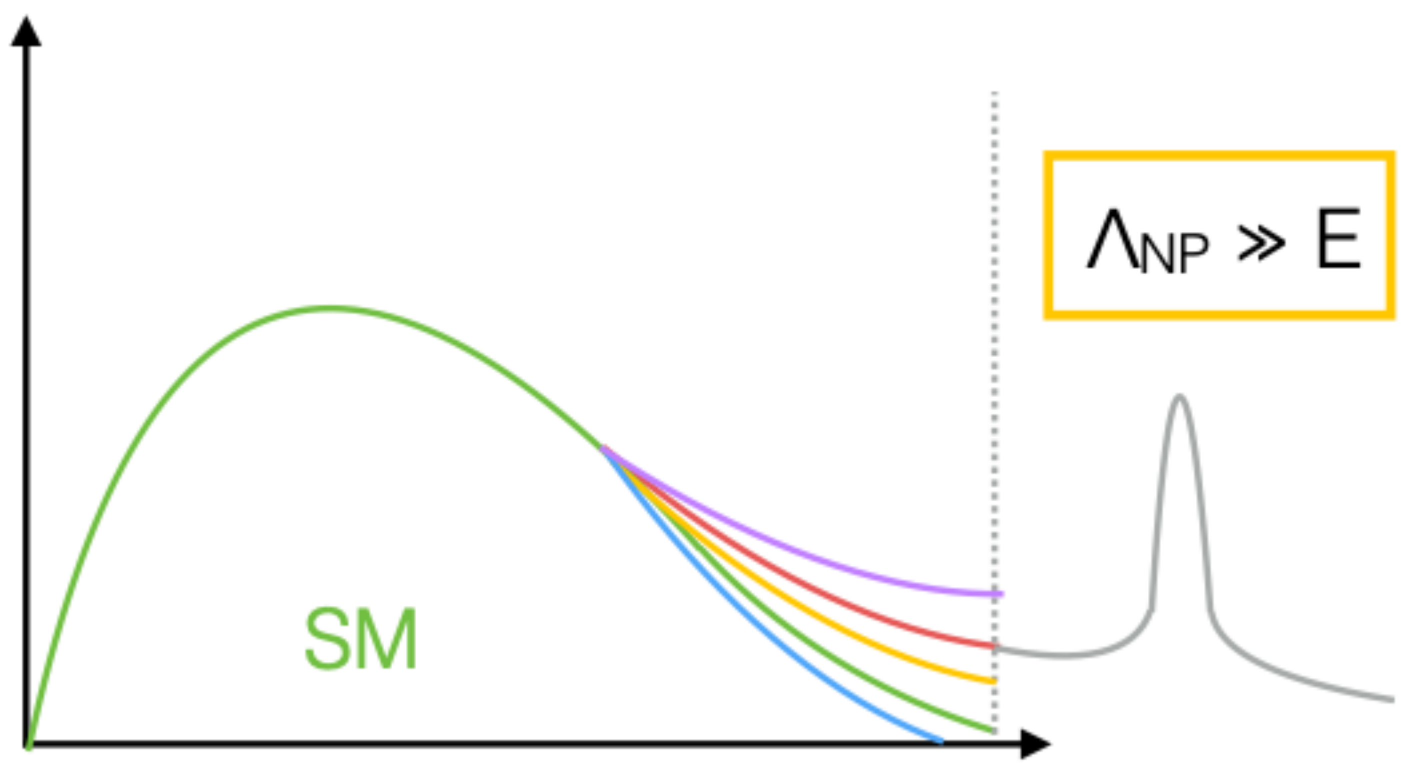
on behalf of the ATLAS Collaboration

Effective Field Theory (EFT)



Coupling Strength
Operators with new interactions

$$\mathscr{L}_{SMEFT} = \mathscr{L}^{SM}_{d\leq 4} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Standard Model

- Possibility for new physics to reside beyond the energy reach of the LHC
  - Still possible to observe the indirect effects of NP in the kinematic tails of distributions
- Framework choice: Standard Model Effective Field Theory (SMEFT)
- Integrated out heavy states (e.g. Fermi theory)
  - Only local operators from SM fields
  - Sensitive to heavy states via large momentum flows at effective vertices, esp. in tails of energy distributions
  - Truncated at dimension-6 (leading baryon number & lepton number preserving interactions)
- Complete, independent set of operators: Warsaw basis

The Importance of the Top Quark Sector

- Largest Yukawa couplings → Heaviest known particle

  - Top quark is possibly closest to new physics sectors

  - Sensitive probe in electroweak symmetry breaking (EWSB) (top mass - a crucial role in determining stability of Higgs potential in UV)

  - Probe for largest mixing with exotic states in non-linear EWSB sector (Composite Higgs and warped extra dimensions)

- A complementary picture to that of the Higgs boson.
- Significantly larger dataset compared to Higgs physics in LHC
- New physics can be found potentially as a deviation in any of the EFT parameters.
- ***Remark***: the EFT captures the full theory (as long as the EFT condition is satisfied), i.e. no need for new degrees of freedom

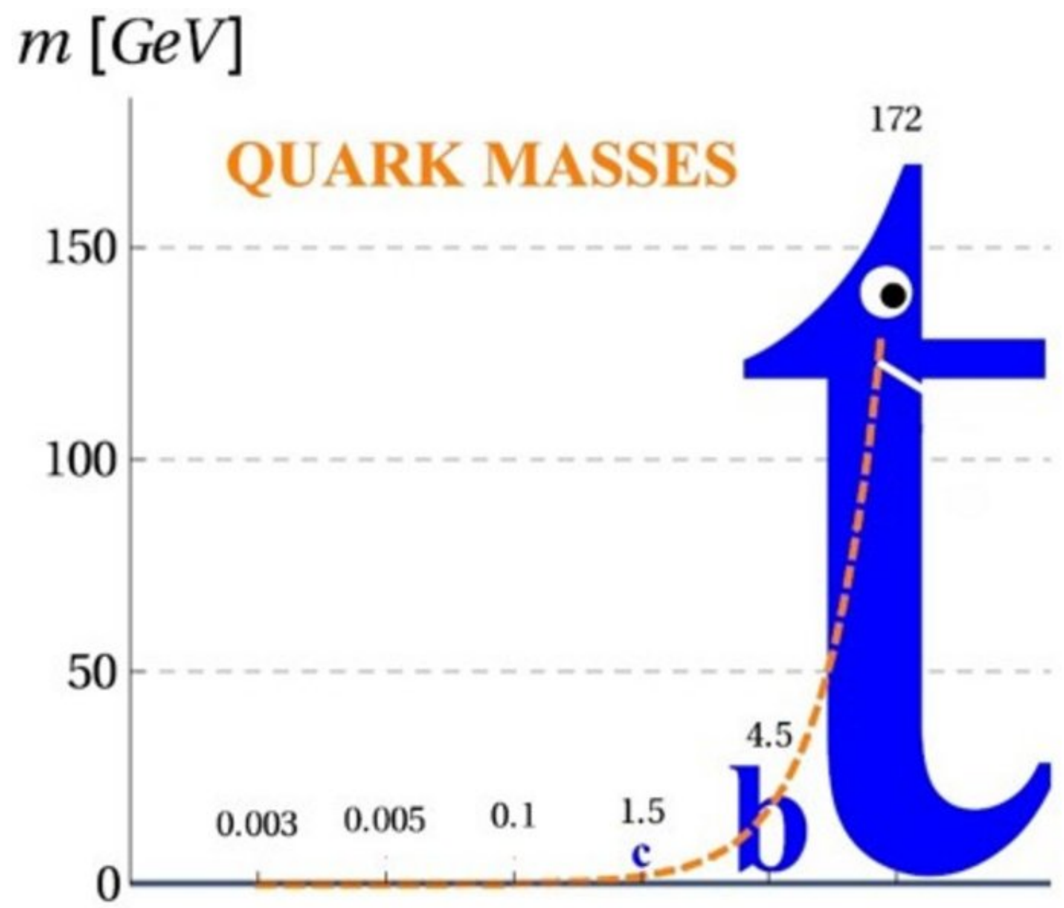
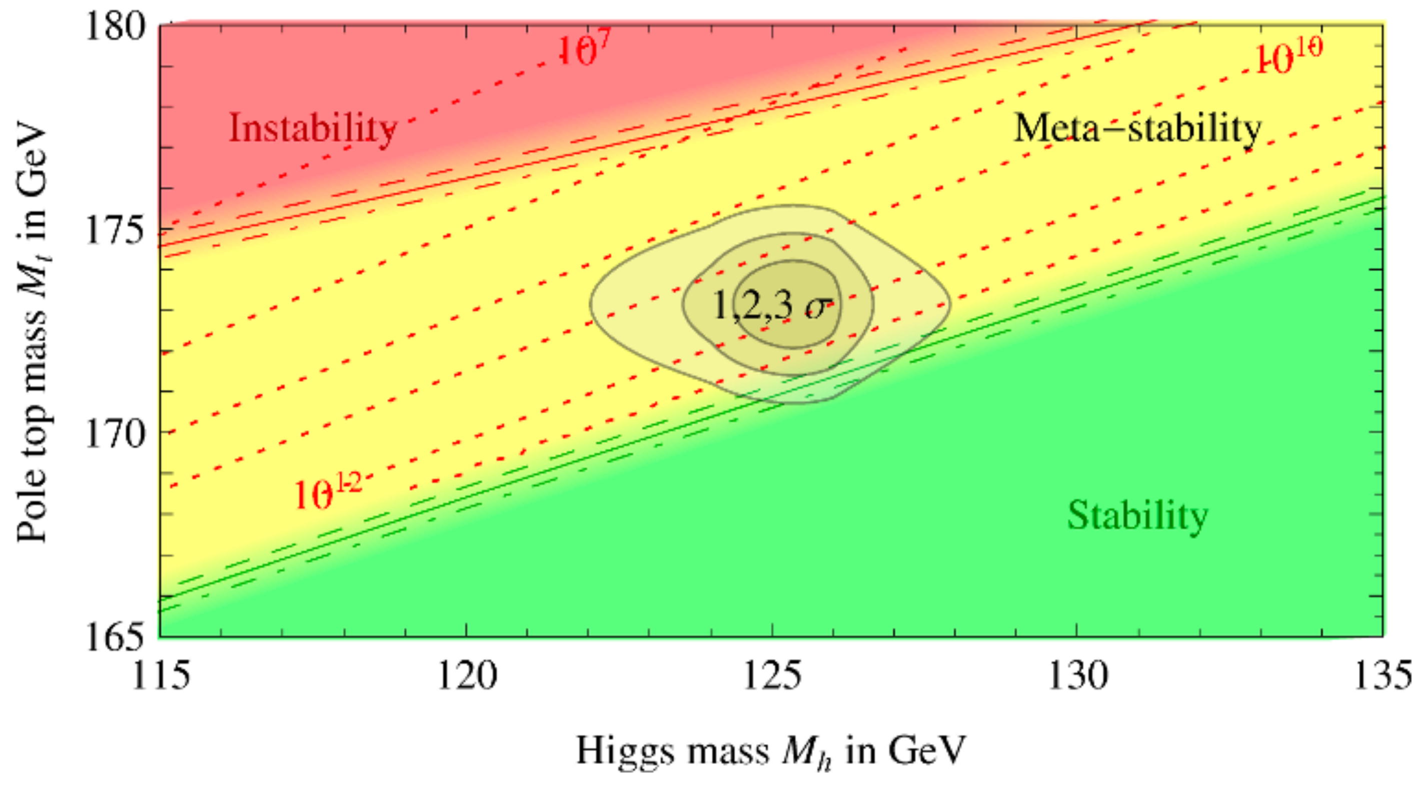


Illustration by F. Goertz (MoriondEW2019)

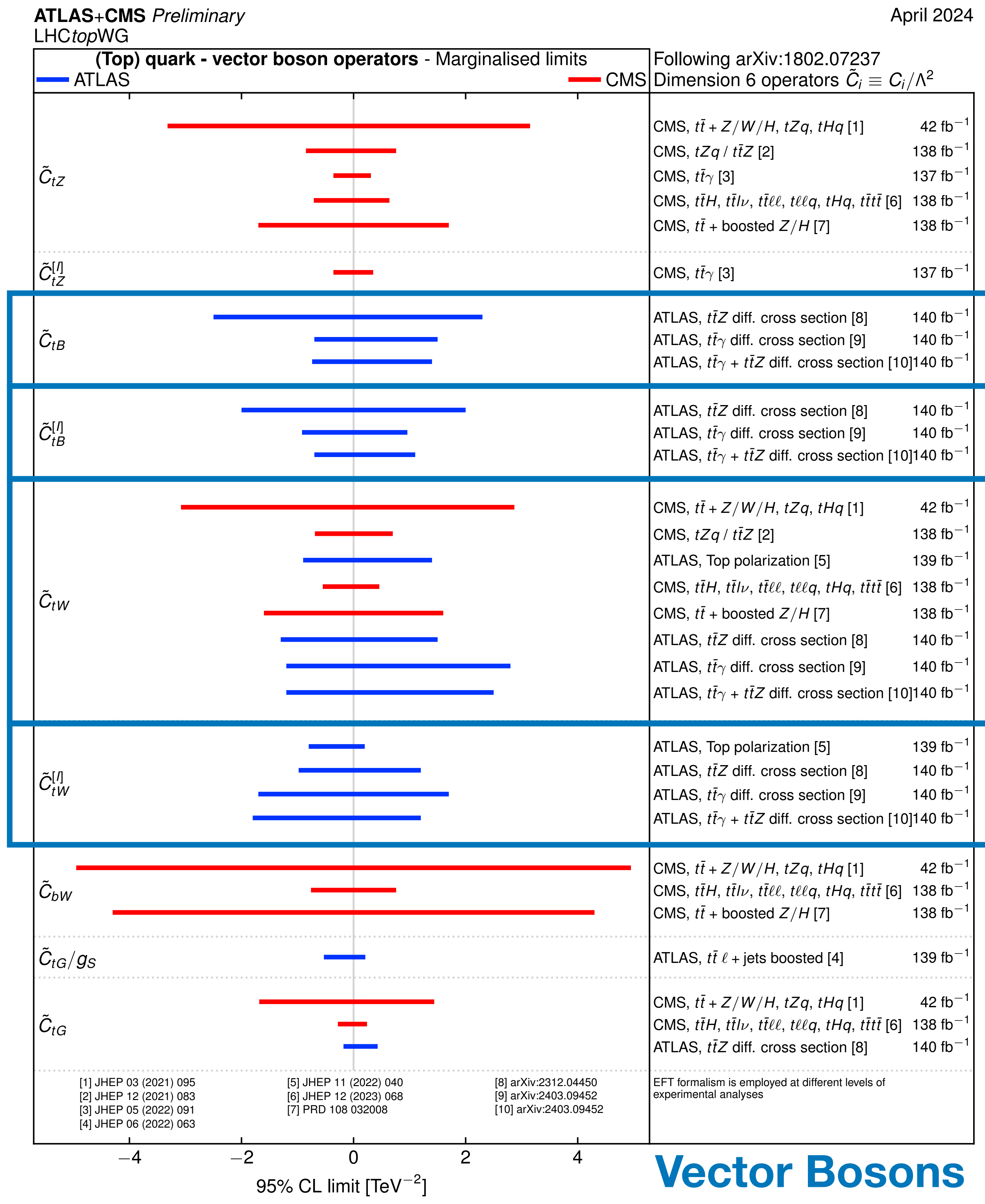


JHEP 08 (2012) 098

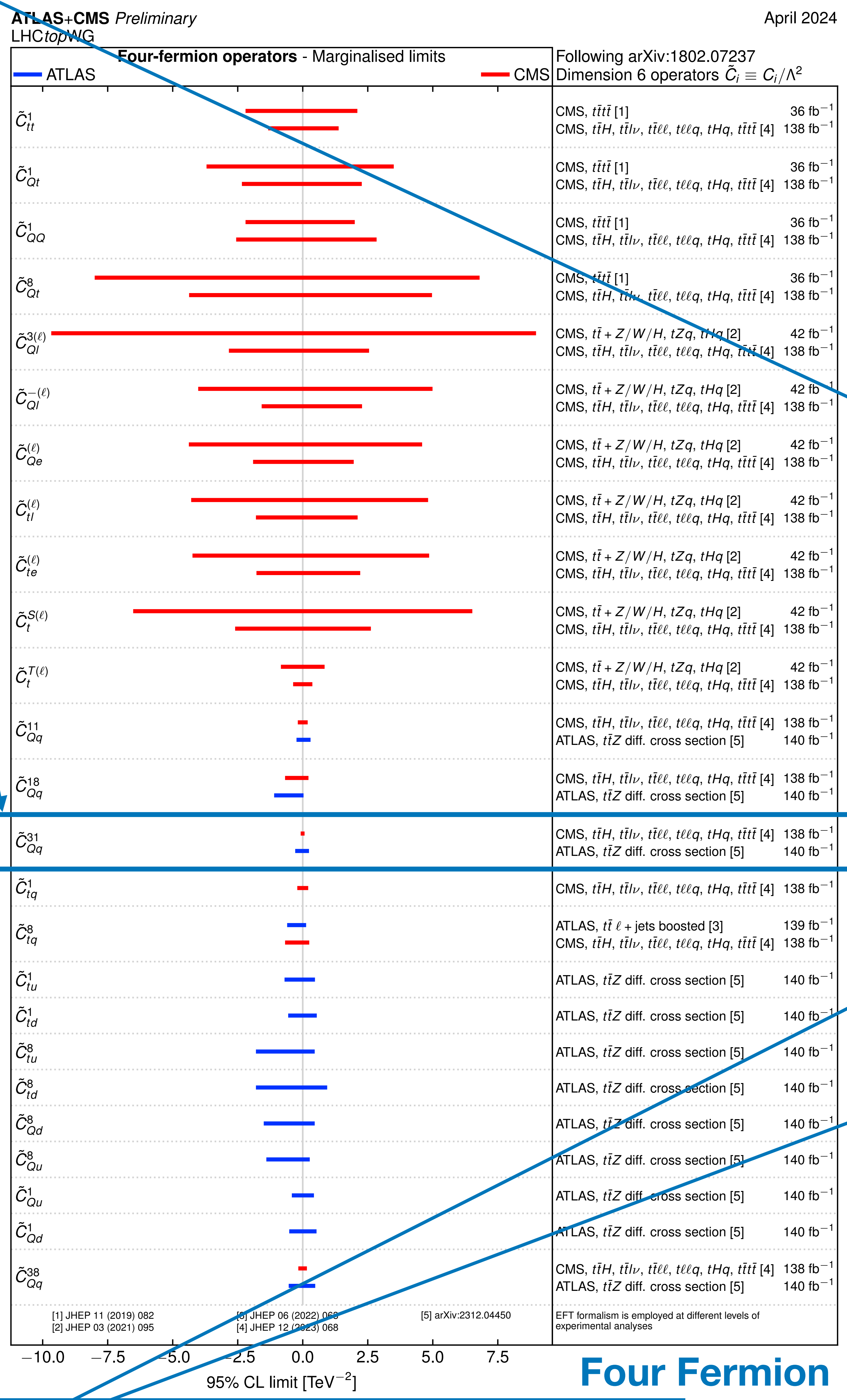
EFT Overview of the Top Sector in ATLAS + CMS

- Summary of 95% confidence interval observed limits on EFT Wilson coefficient of dim-6 operators

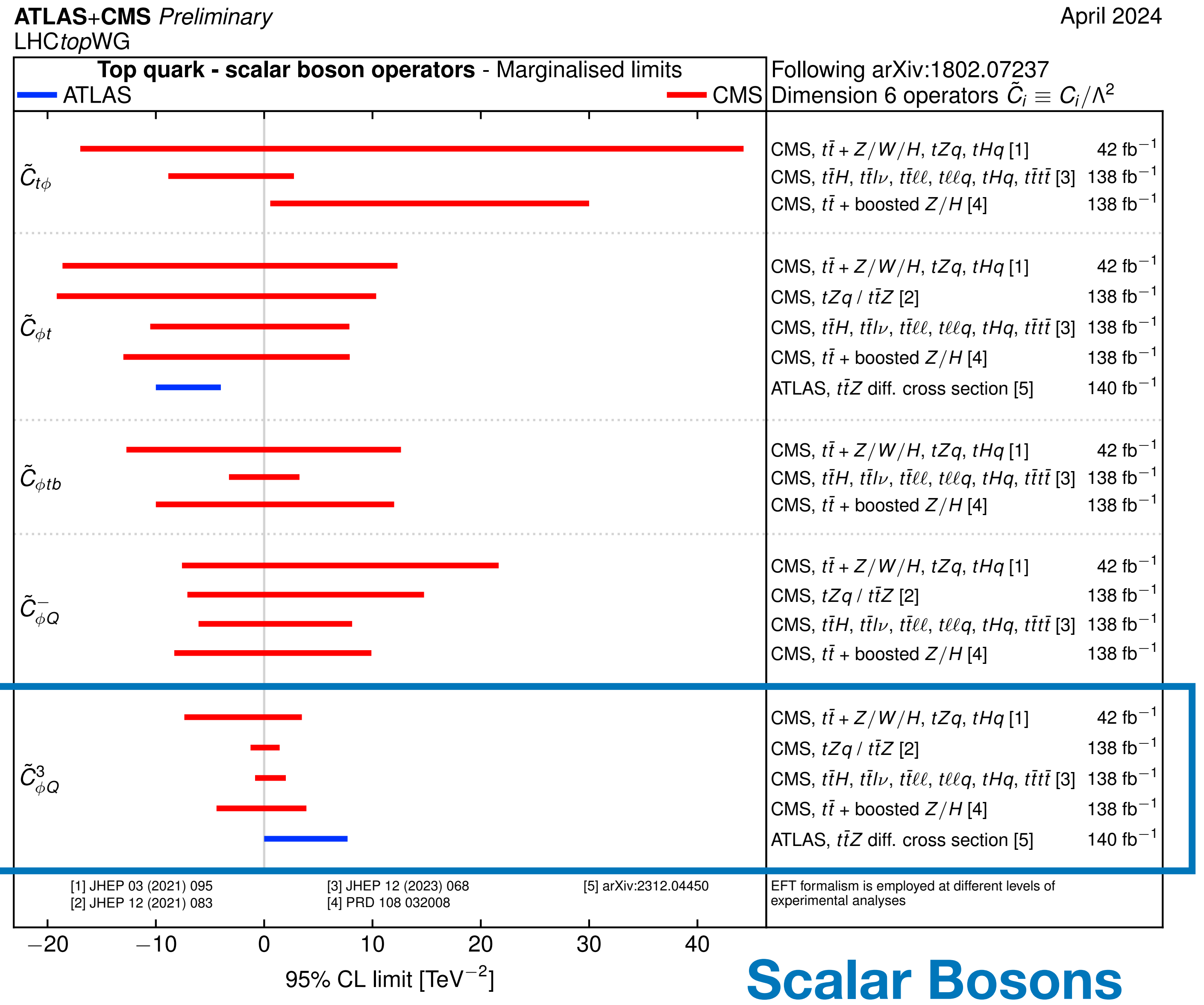
$C^{31}_{Qq}, C^{3}_{\phi Q}$ - Single top (t-channel)



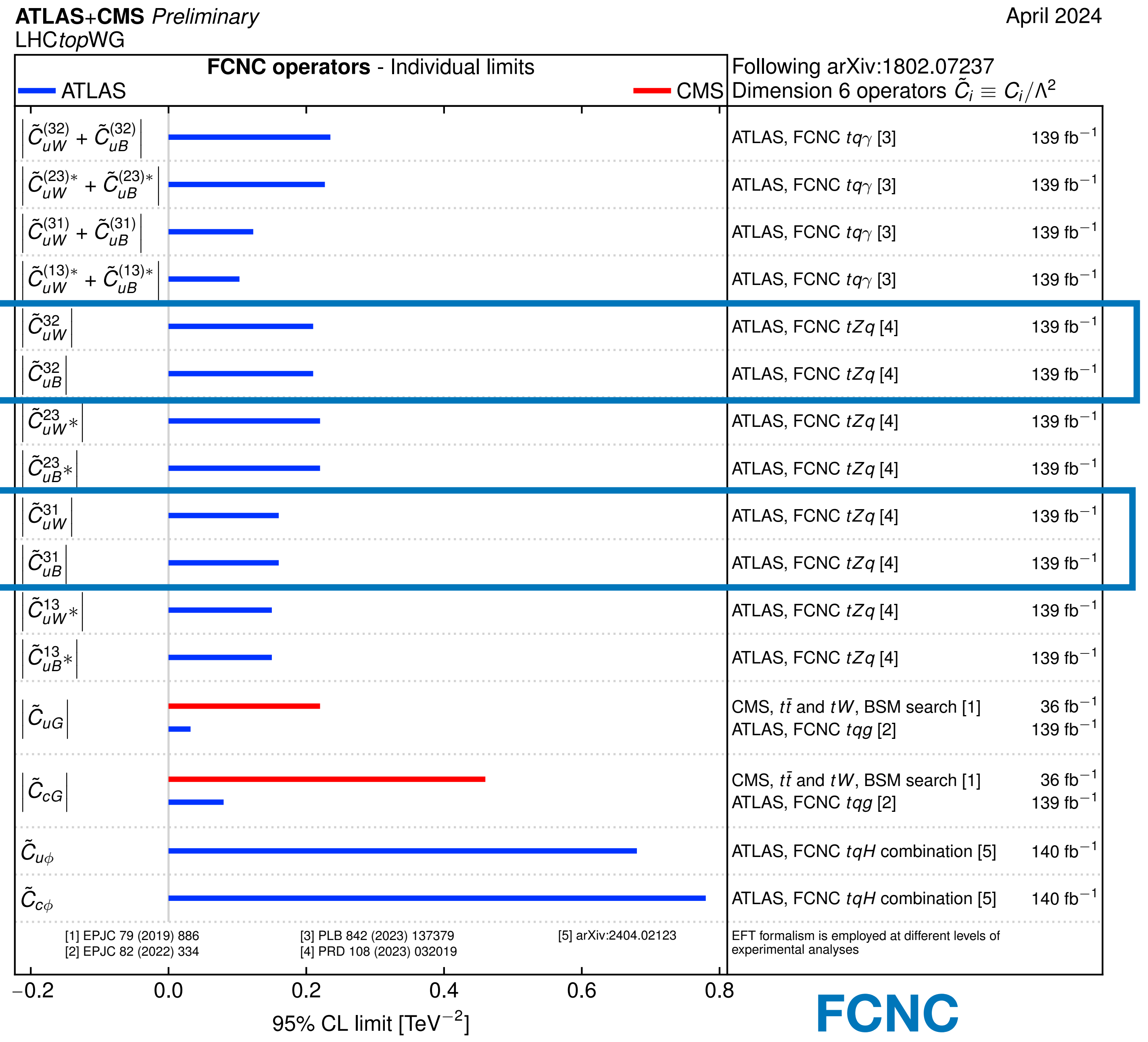
Vector Bosons



Four Fermion



Scalar Bosons



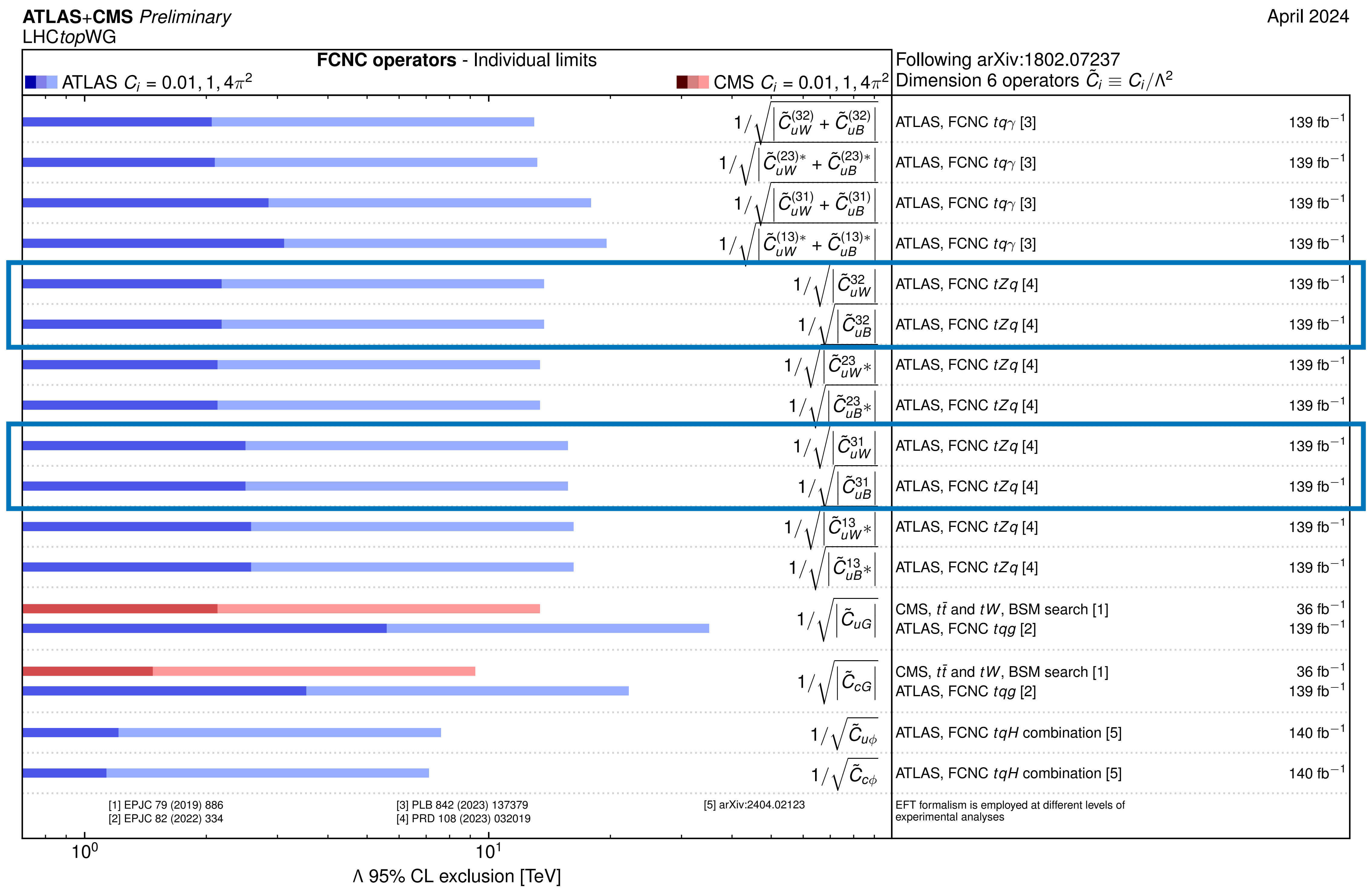
FCNC

C_{tB}, C_{tW} - $t\bar{t}\gamma$ Cross Section

$c^{32,31}_{uB,uW}$ - cLFV (re-interpretation of FCNC)

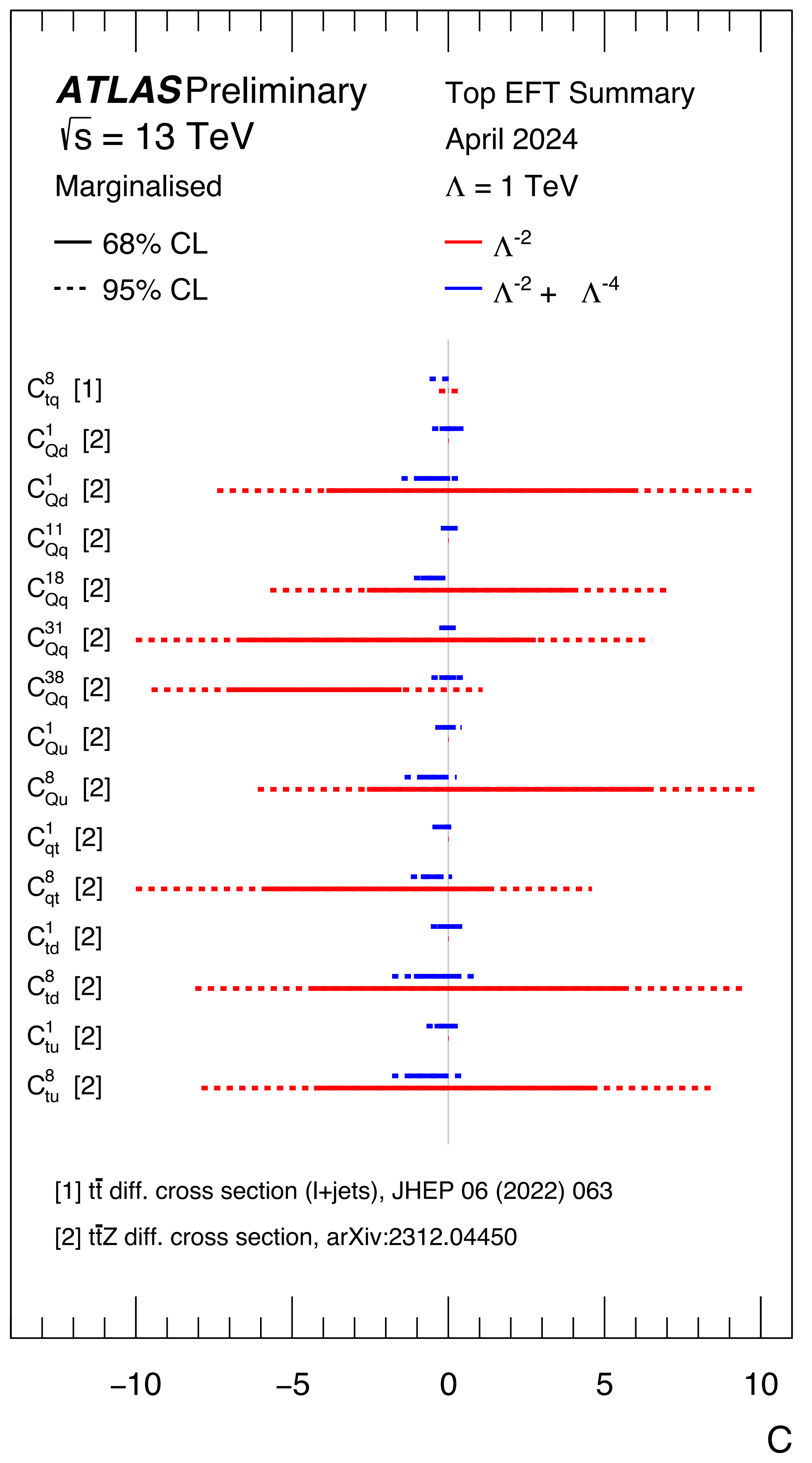
Source: LHCTopWGSummaryPlots

EFT Overview of the Top Sector in ATLAS + CMS



Constraints on scale of new physics Λ

- 95% confidence level observed limits on EFT Wilson coefficients are set assuming $\Lambda = 1$ TeV → processes studied can be already at this energy scale
- Started to set limits on Λ that can be reached (with variations in $c_i = 0.01, 1, 4\pi^2$)



Constraints on four-fermion SMEFT operators

- Effect of quadratic terms in extracting bounds on Wilson coefficient depends on analyses.

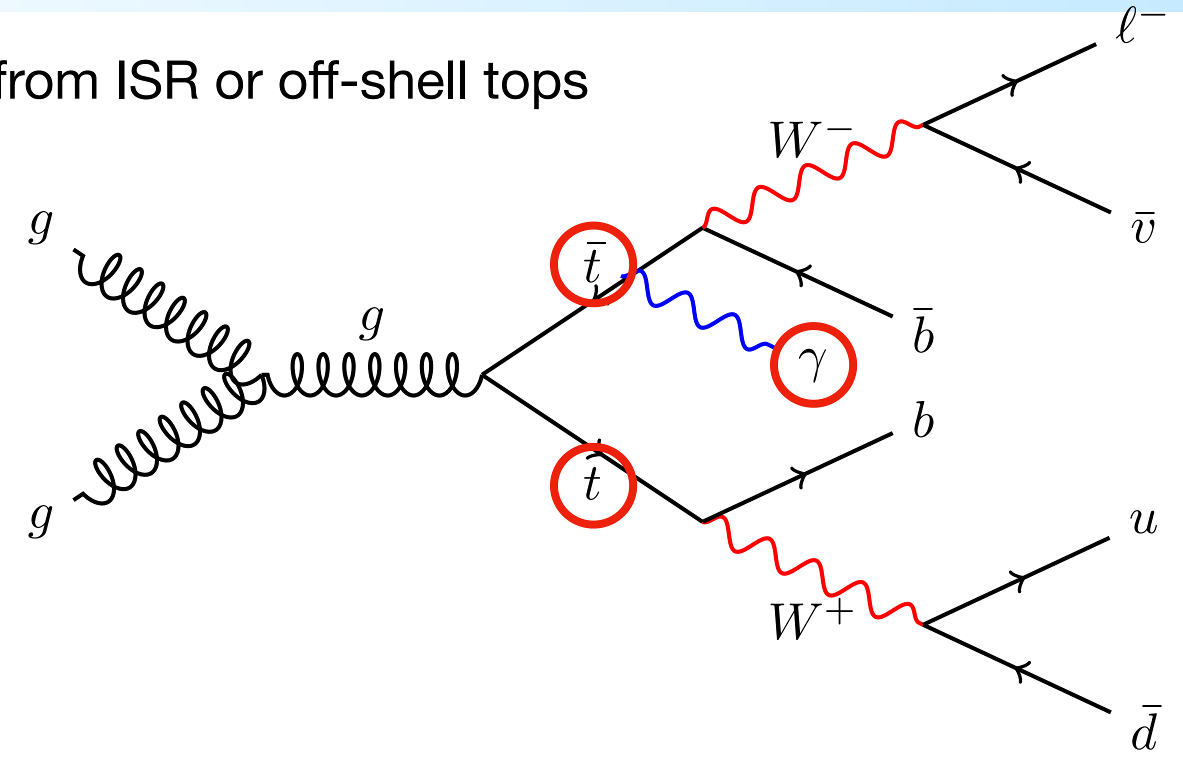
Inclusive/Differential $t\bar{t}\gamma$ Cross Section

Source: arXiv:2403.09452 (Accepted by JHEP)

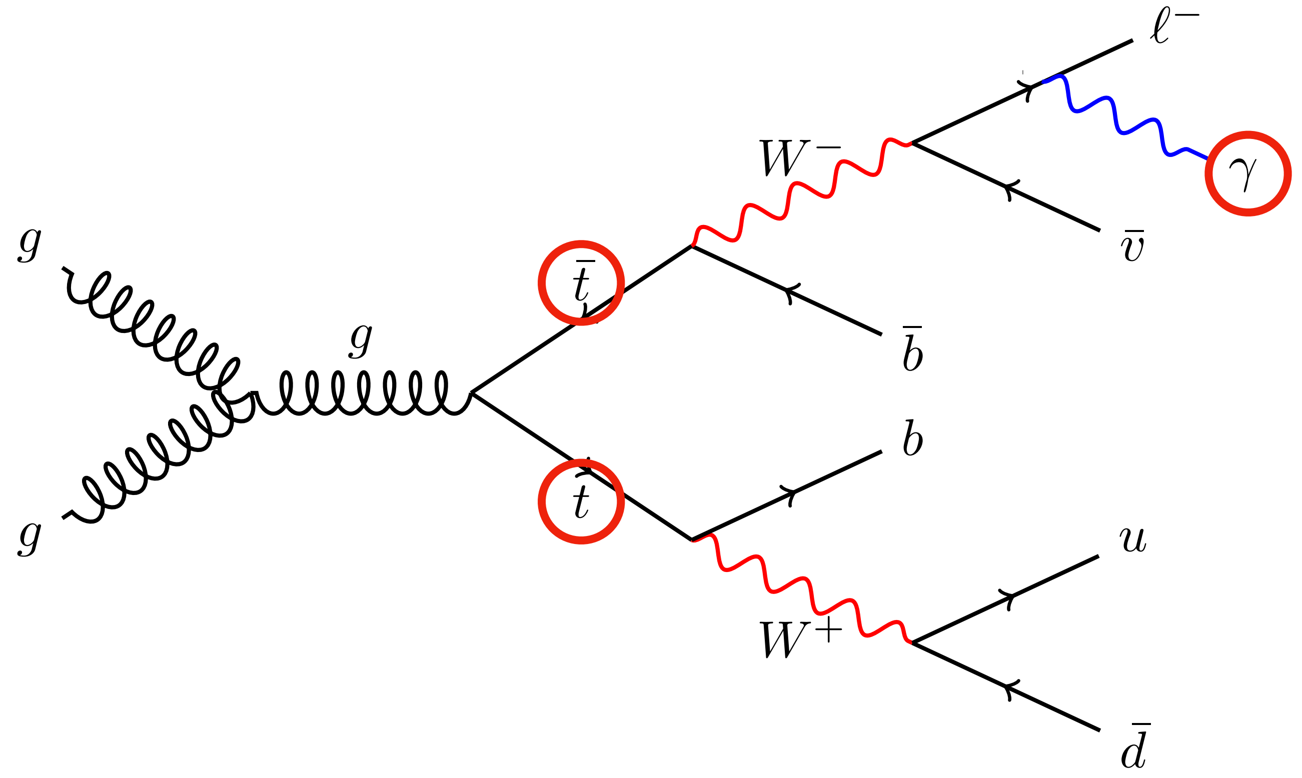
Poster Session: Measurements of inclusive and differential cross-sections of ttgamma production in ATLAS by Carmen

(1) Inclusive/Differential $t\bar{t}\gamma$ Cross Section

$t\bar{t}\gamma$ production - γ from ISR or off-shell tops



$t\bar{t}\gamma$ decay

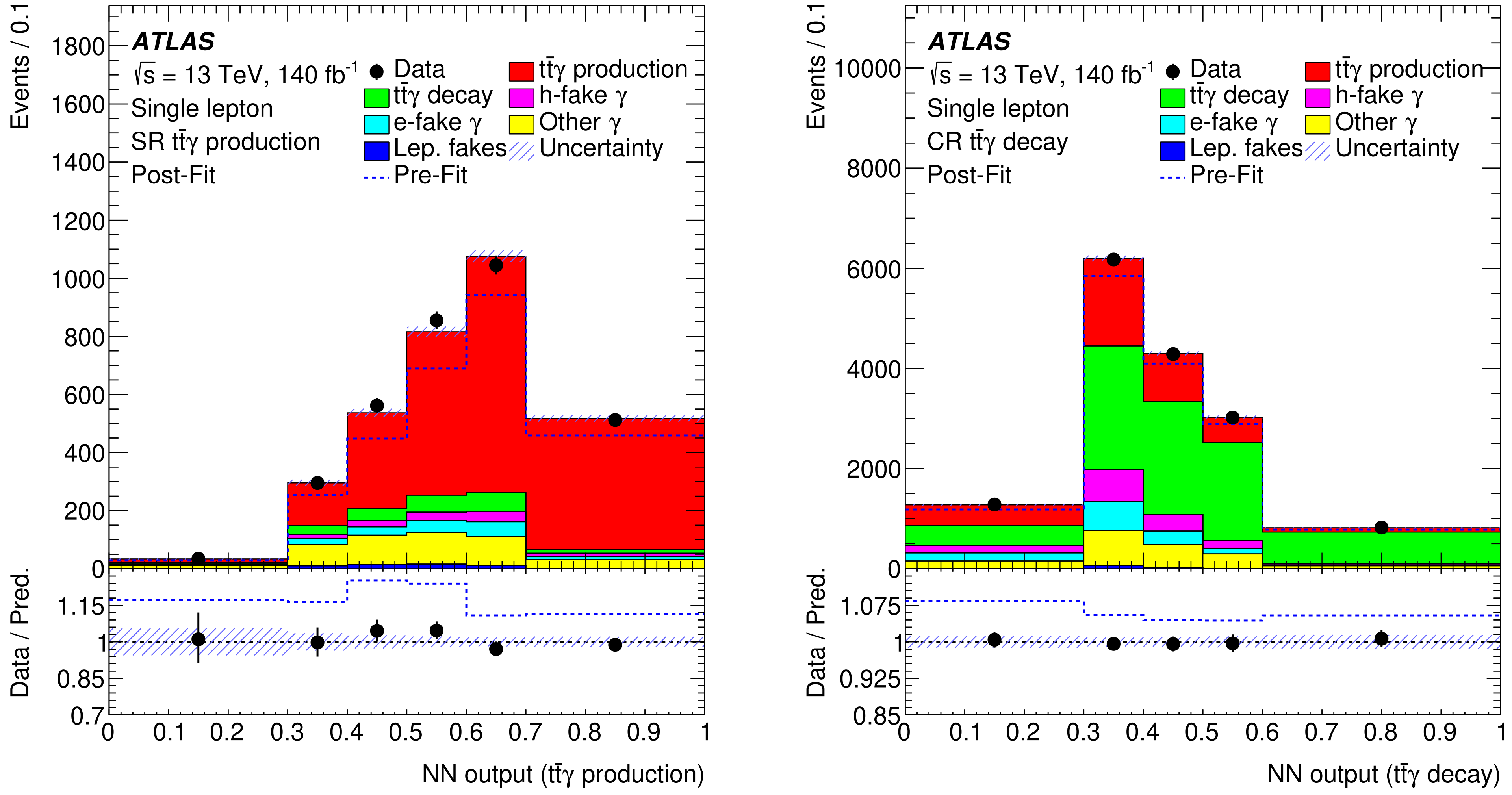


Negligible Interference under NWA (JHEP 03 (2020) 154)

- **Motivation**

  - Sensitive to t-γ electroweak coupling

  - Sensitive to new physics via anomalous dipole moments of the top quark and interpretation in SMEFT (C_{tB}, C_{tW})



- **Analysis Strategy: $t\bar{t}$ in single-lepton or di-lepton channel with exactly one photon**
  - single-lepton channel (see NN score plots above)

    > 4 class NN - $t\bar{t}\gamma$ production, $t\bar{t}\gamma$ decay, photon fakes, other γ → SR and 3 CRs.
  - dilepton channel

    > binary classification

    ($t\bar{t}\gamma$ production vs. all backgrounds)

    > NN output distribution as input for fit + definition of 2 regions for the differential σ

(1) EFT interpretation - $t\bar{t}\gamma$ production

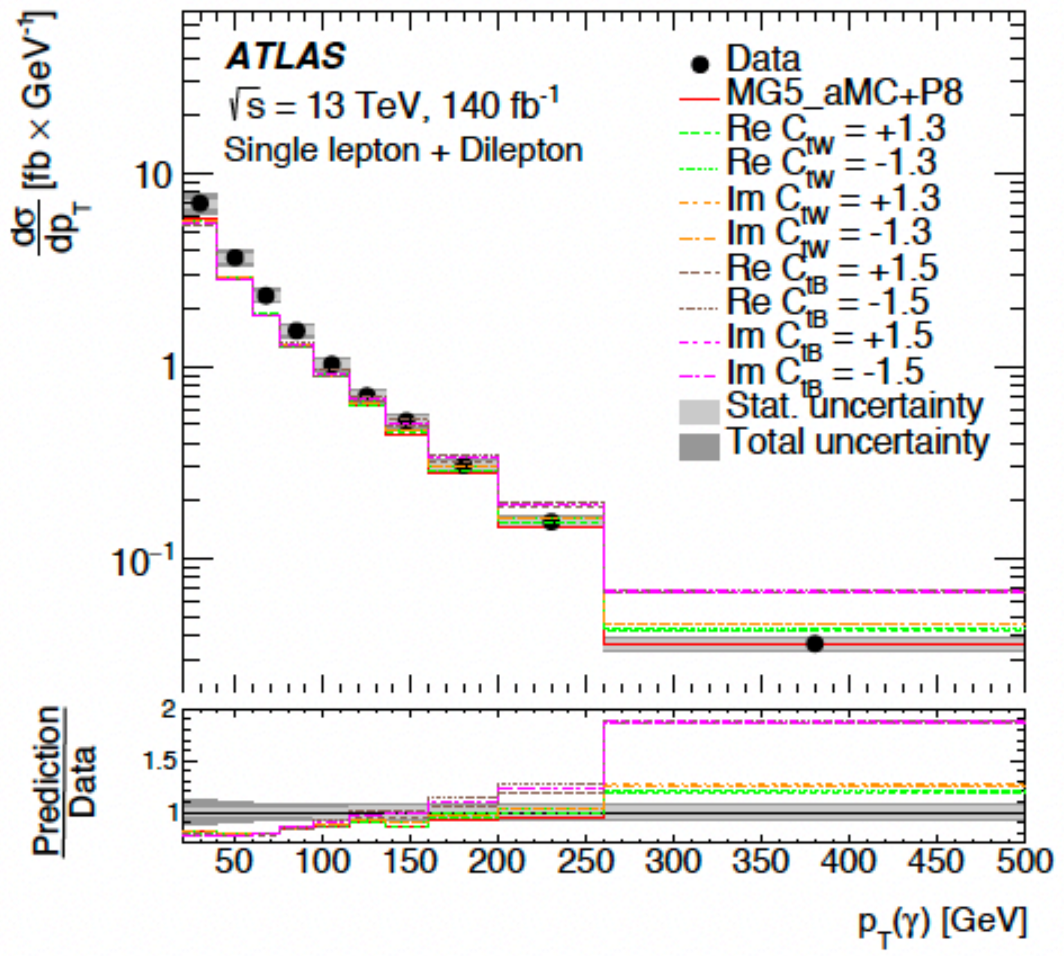
- Sensitive to new physics through anomalous dipole moments of the top quark: C_{tB}, C_{tW}

$$\mathcal{L}_{t\bar{t}X} = e\bar{t}\left[\gamma^{\mu}\left(C^{X}_{1,\mathrm{V}} + \gamma_5 C^{X}_{1,\mathrm{A}}\right) + \frac{i\sigma^{\mu\nu}q_{\nu}}{m_t}\left(C^{X}_{2,\mathrm{V}} + \gamma_5 C^{X}_{2,\mathrm{A}}\right)\right] tX_{\mu}$$

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

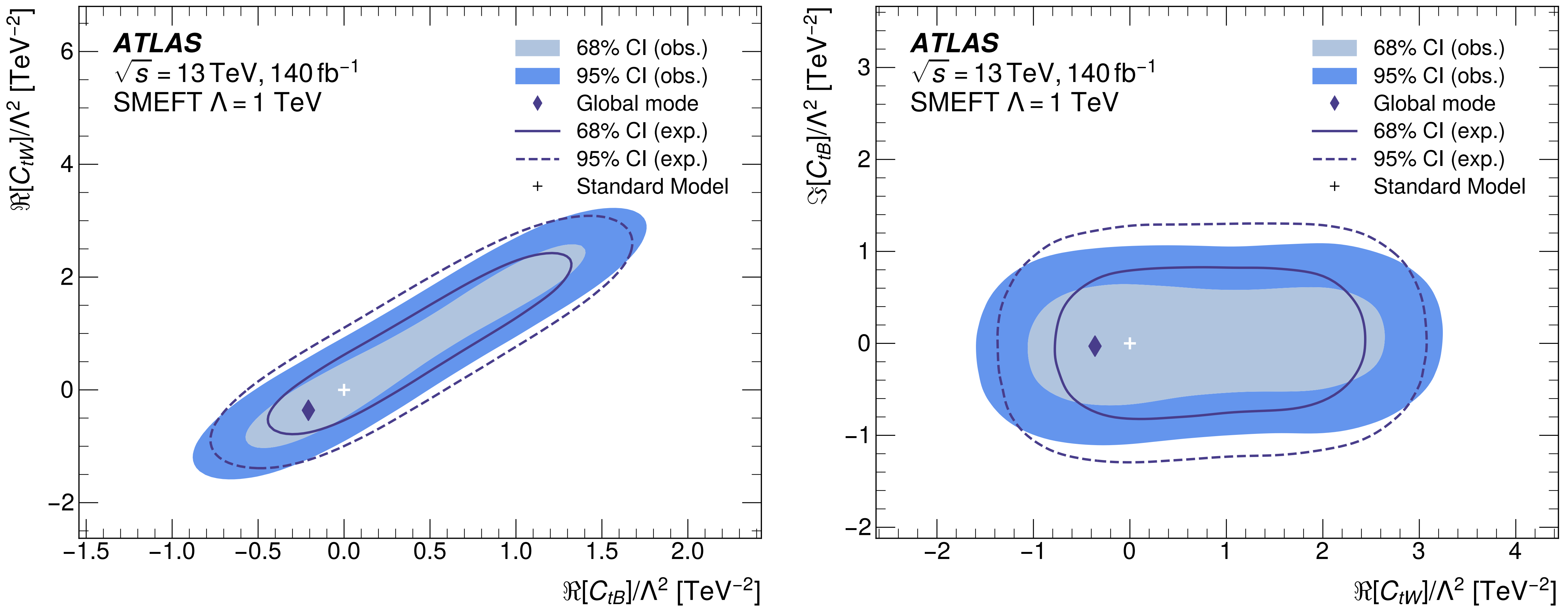
$$C^{Z}_{2,\mathrm{V}} = \frac{v^2 m_t}{\sqrt{2} c_w s_w m_Z \Lambda^2} \Re\left[C_{tZ}\right] \qquad C^{Z}_{2,\mathrm{A}} = \frac{v^2 m_t}{\sqrt{2} c_w s_w m_Z \Lambda^2} \Im\left[C_{tZ}\right]$$
$$C^{\gamma}_{2,\mathrm{V}} = \frac{\sqrt{2} v m_t}{e\Lambda^2} \Re\left[C_{t\gamma}\right], \qquad C^{\gamma}_{2,\mathrm{A}} = \frac{\sqrt{2} v m_t}{e\Lambda^2} \Im\left[C_{t\gamma}\right],$$

- C_{tB}, C_{tW} also modify $t\bar{t}Z$ production
- Most sensitive observable: photon p_T (single lepton + dilepton combined)
- EFT samples at LO (NLO k-factor applied)



- **Limits on C_{tB}, C_{tW} from $t\bar{t}\gamma$ production**
  - Linear + quadratic + cross-terms
  - Bayesian statistical framework
  - Simultaneous extraction of real and imaginary part of C_{tB}, C_{tW}
  - Stronger constraints on C_{tB} than on C_{tW}
  - In good agreement with SM

2-dim. marginalised posteriors for C_{tW} and C_{tB} operators



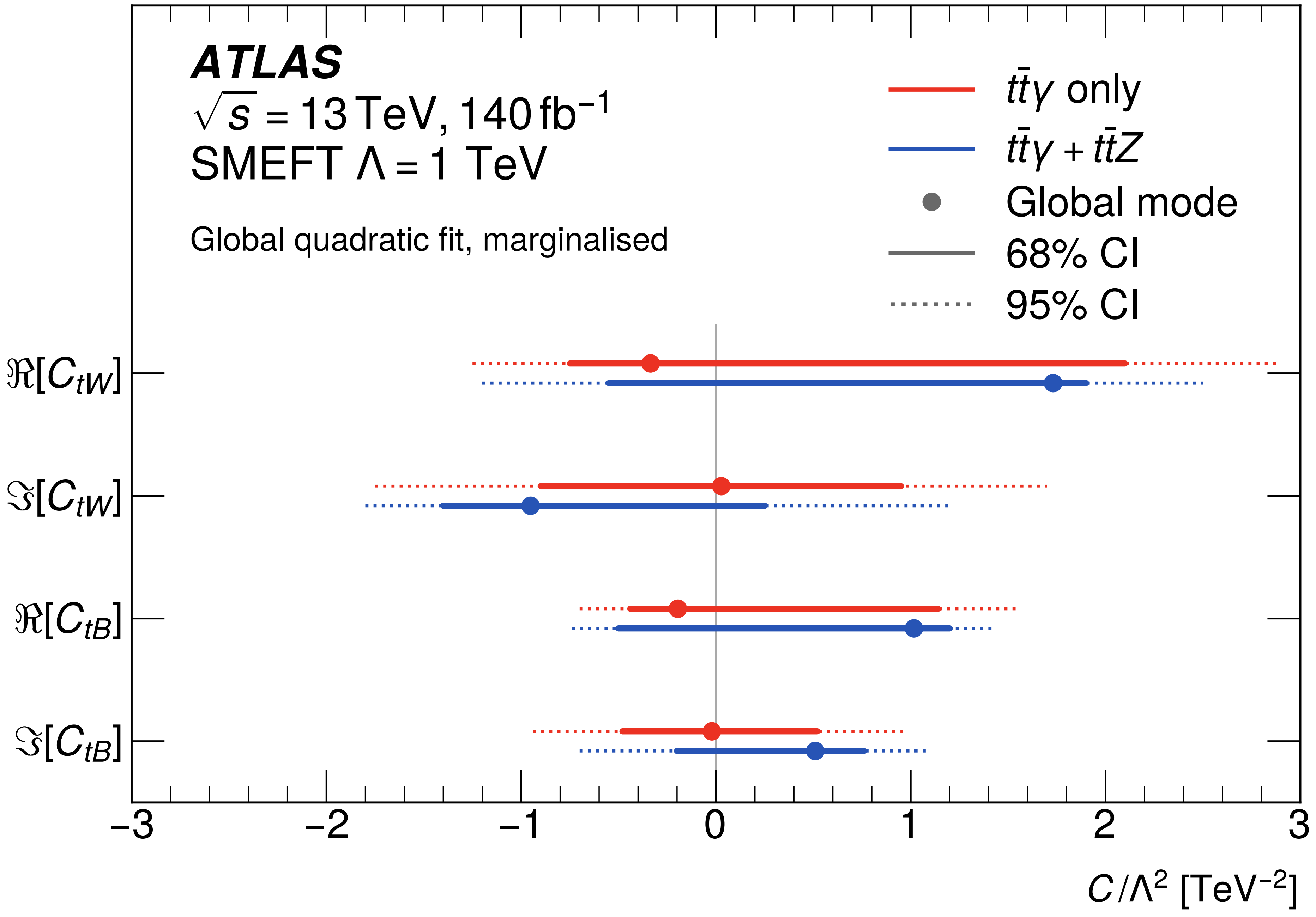
(1) EFT interpretation - $t\bar{t}\gamma$ production

- **Combination of $t\bar{t}\gamma$ and $t\bar{t}Z$**

  - $t\bar{t}Z$: complementary constraining power

  - limits from simultaneous profile-likelihood unfolding of photon p_T and Z boson p_T (separately) in all SRs and CRs of the analysis

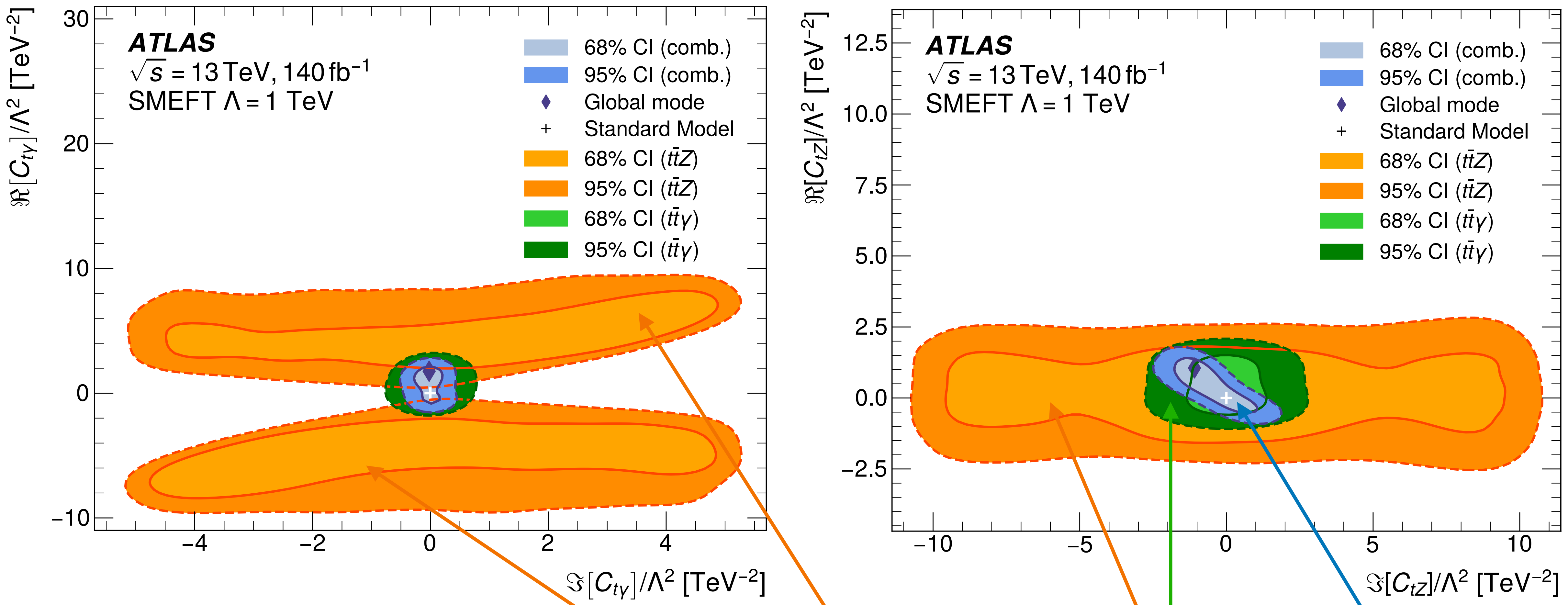
  - tighter limits, especially in C_{tW}



- **Limits on C_{tZ}, $C_{t\gamma}$ from $t\bar{t}\gamma$ and $t\bar{t}Z$ combination**

  - Provides information about the modifications of $t\gamma$ and tZ vertices (using quadratic fits)

2-dim. marginalised posteriors for $C_{t\gamma}$ and C_{tZ} operators



Same contour shape ($t\bar{t}Z$,$t\bar{t}\gamma$)

Different structure ($t\bar{t}Z + t\bar{t}\gamma$) !

  - $t\bar{t}\gamma$ measurement resolves degeneracies from $t\bar{t}Z$ measurement alone

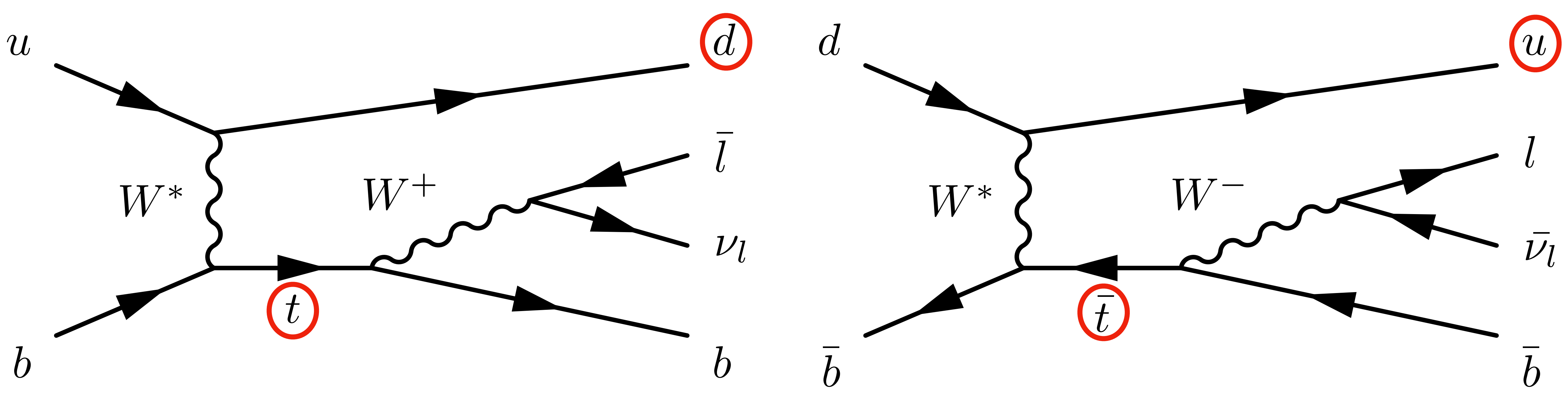
  - In good agreement with SM

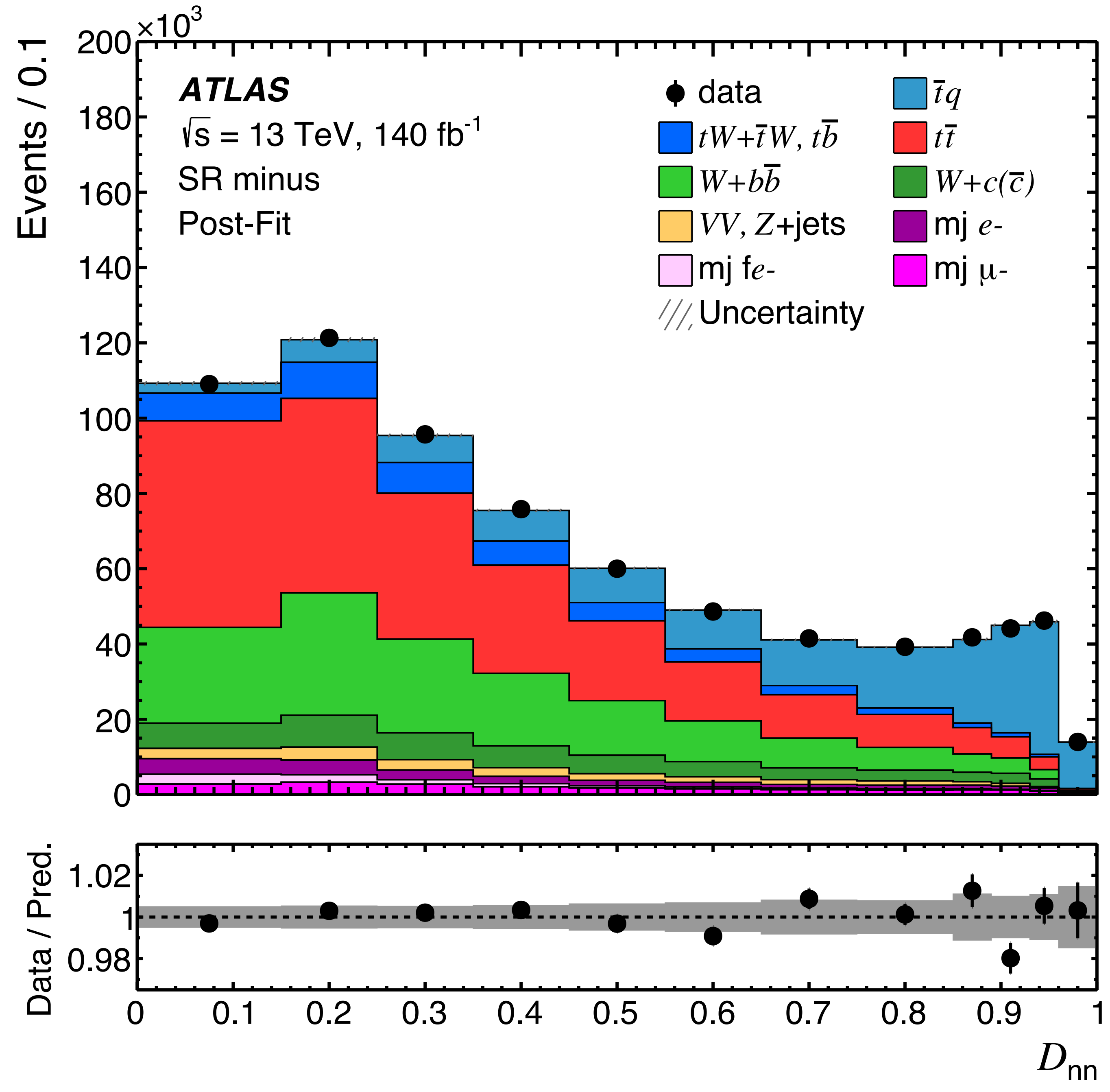
Single top in t-channel

Source: JHEP 05 (2024) 305

YSF: Measurements of t-channel production of single top quarks and top antiquarks in ATLAS by Maren

(2) Single top in t-channel

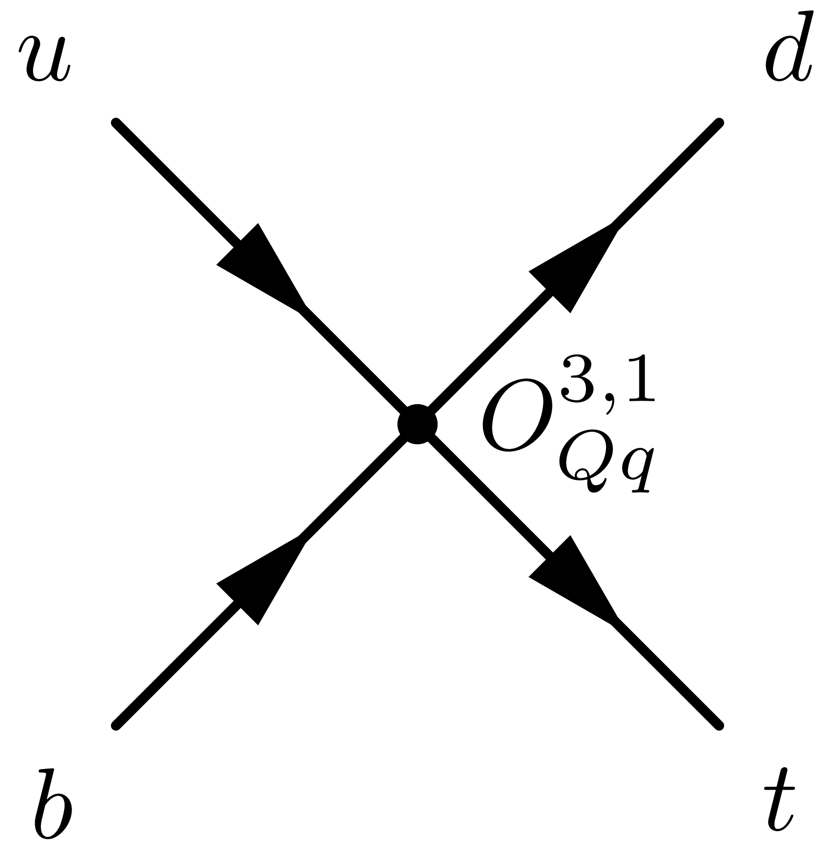




- **Motivation**
  - Precision measurement of dominant single top production channel with a virtual W boson
  - Directly constrain $|V_{tx}|$ CKM matrix element
  - Sensitive to new physics

- **Analysis Strategy**
  - Signal: tq, $\bar{t}q$ events + leptonically decaying W bosons
  - Rate of multijet background from 6 CRs (data-driven + included in fit)
  - Separation of signal from backgrounds: optimised NN discriminant D_{nn}

(2) Single top in t-channel



- **EFT operators**
  - $\mathcal{O}^{1(ijkl)}_{qq} = (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l)$ i,j,k = quark generation indices
  - $\mathcal{O}^{3(ijkl)}_{qq} = (\bar{q}_i \gamma^\mu \tau^I q_j)(\bar{q}_k \gamma_\mu \tau^I q_l)$ q = weak-isospin doublet
  - $\mathcal{O}^{3}_{\phi Q} = i(\Phi^+ \tau^I D_\mu \Phi)(\bar{Q}\gamma^\mu \tau^I Q)$ Q = third quark doublet
- $\mathcal{O}^{3,1}_{Qq} : C^{3,1}_{Qq} = \sum_{1,2} C^{3(ii33)}_{qq} + \frac{1}{6} C^{1(i33i)}_{qq} - \frac{1}{6} C^{3(i33i)}_{qq}$
  - Fully captures four-quark interaction
  - Set limits on coupling strengths of Wtq vertices - $f_{LV} \times V_{tb}, V_{ts}, V_{td}$

solely from the four-quark operator

SM

$$\nu_j = \nu_{0j} + a_{1j}\frac{C^{3,1}_{Qq}}{\Lambda^2} + a_{2j}\frac{(C^{3,1}_{Qq})^2}{\Lambda^4}$$

interference between SM and non-SM

- Single top-quark event yield in j^{th} bin -

- $\mathcal{O}^{3}_{\phi Q}$
  - same Lorentz structure as Wtb vertex in SM
  - nonzero contribution: only affect vertex strength (rescaling) → Δ in a total σ
  - no effect on kinematics

(2) EFT Interpretation - Single top in t-channel

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

- Includes reconstruction(detector) effects on EFT signal events (for simulated samples)
- Comparison to the previous measurements in ATLAS:

  - Charge asymmetry in $t\bar{t}$: [-0.70,0.75] JHEP 08 (2023) 077

  - Cross-section measurement from $t\bar{t}Z$: [-0.34,0.23] JHEP 05 (2019) 088

  - Global EFT fits including Λ^{-4} [-0.088,0.166] JHEP 11 (2021) 089

$$-0.87 < \frac{C_{\phi Q}^{3}}{\Lambda^2} < 1.42$$

- Quadratic contribution negligible
- Derived from the $\sigma(tq + \bar{t}q)$ measurement
- Comparison to the previous measurements in ATLAS:

  - $t\bar{t}Z$: [-0.95,2.0] JHEP 07 (2024) 163

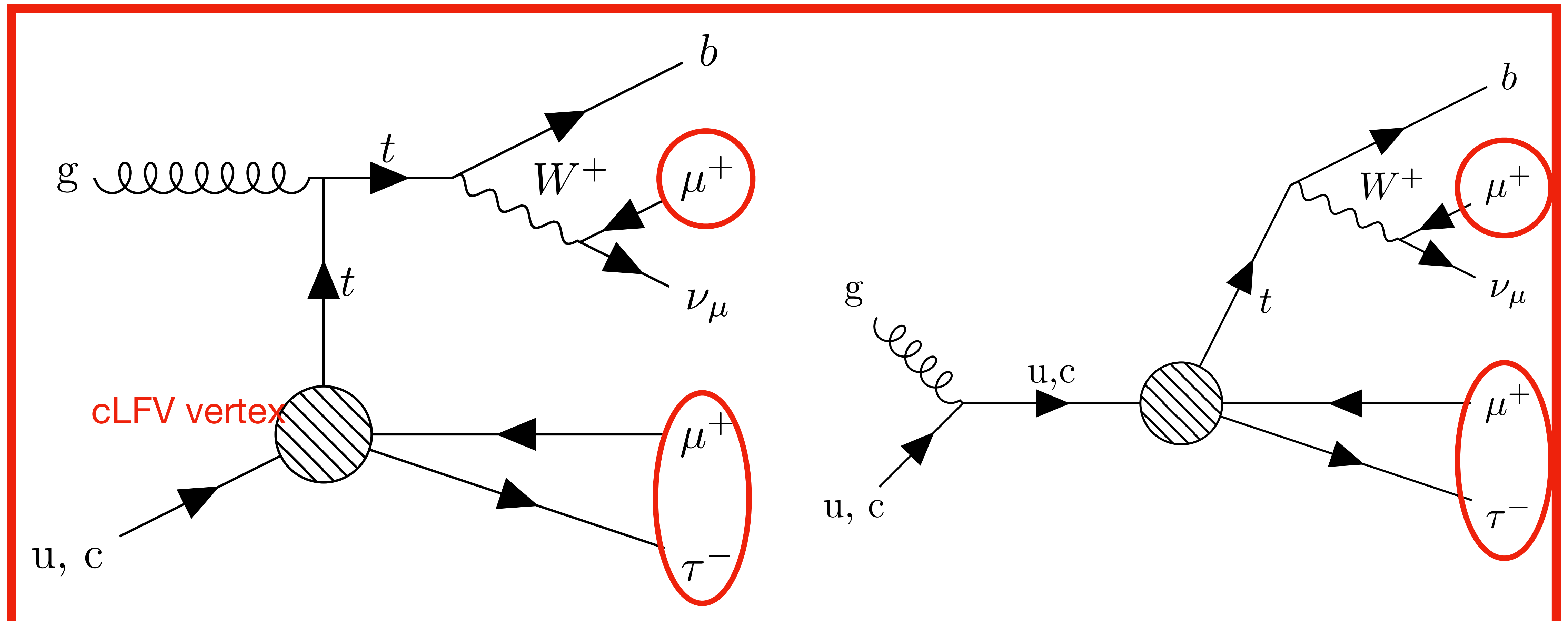
  - Combination of Higgs, VV, top: [-0.375,0.344] JHEP 11 (2021) 089

Charged Lepton Flavour Violation (cLFV) - $\mu\tau qt$

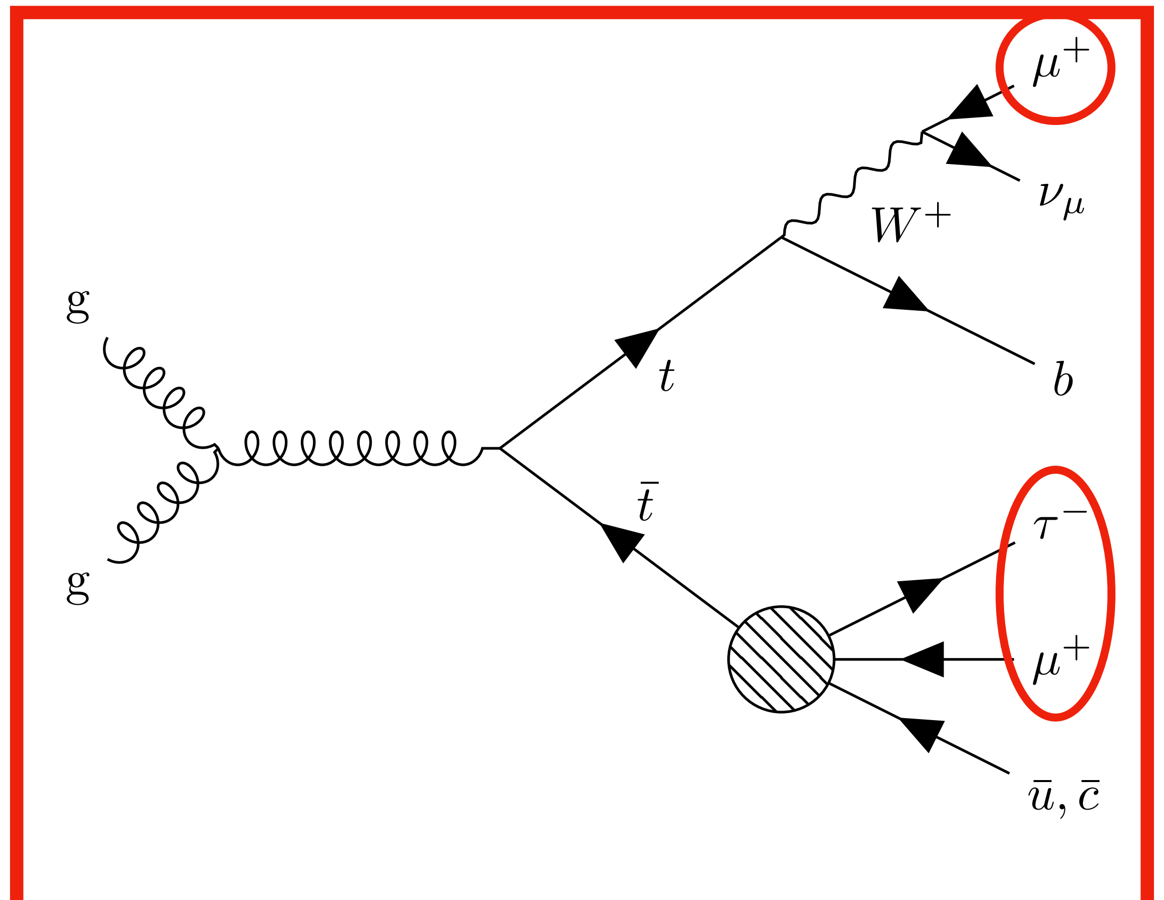
Source: PRD 110 (2024) 012014

Probes of Flavor Symmetry and Violation with Top Quarks in ATLAS and CMS by Miriam

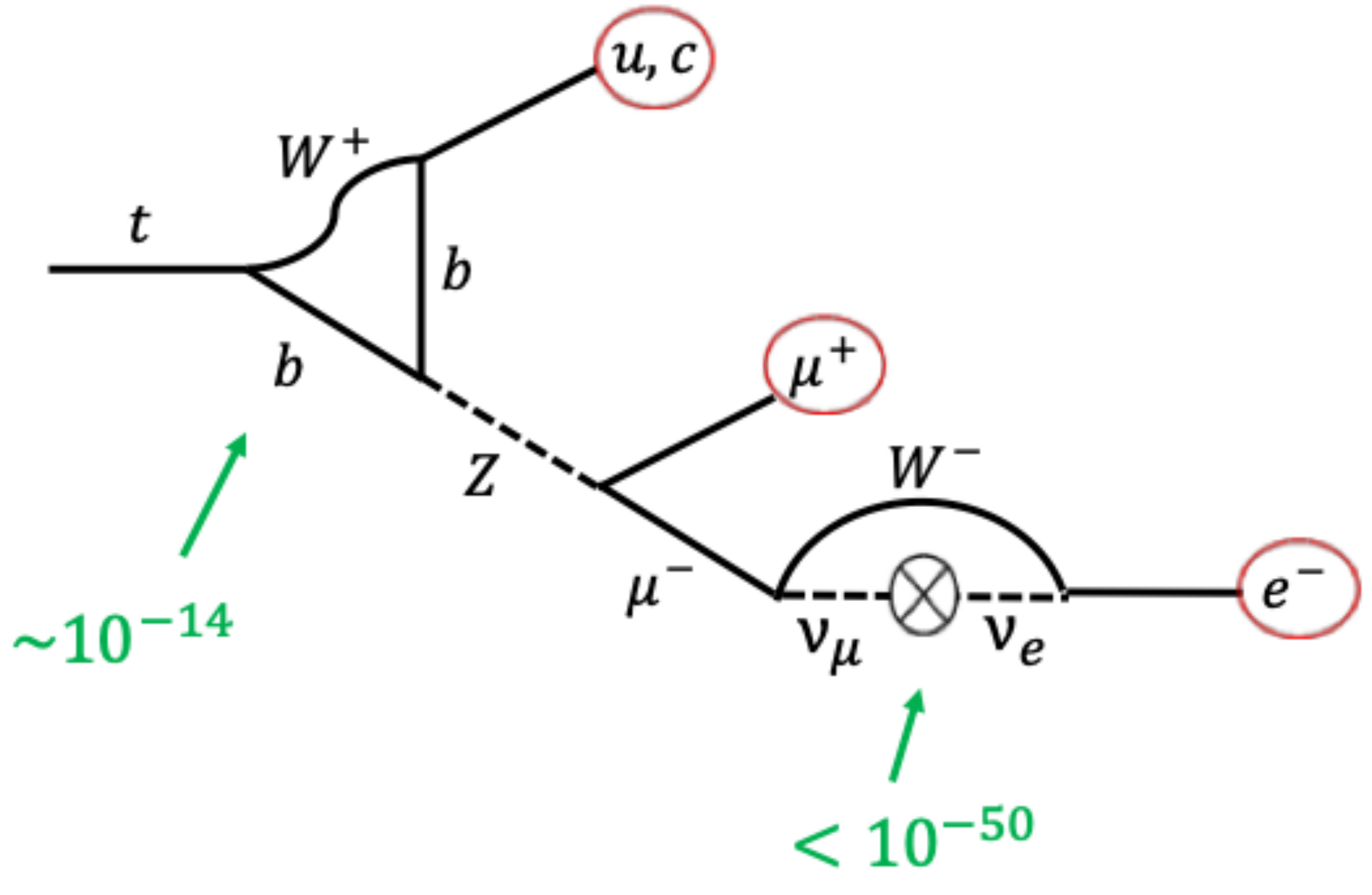
(3) Charged Lepton Flavour Violation - $\mu\tau q(u,c)t$



$q(u,c)g \rightarrow tll'(e\mu/\mu e)$ production



$t\bar{t} \rightarrow (ll'q)(l\nu b)$ decay



- **Motivation**

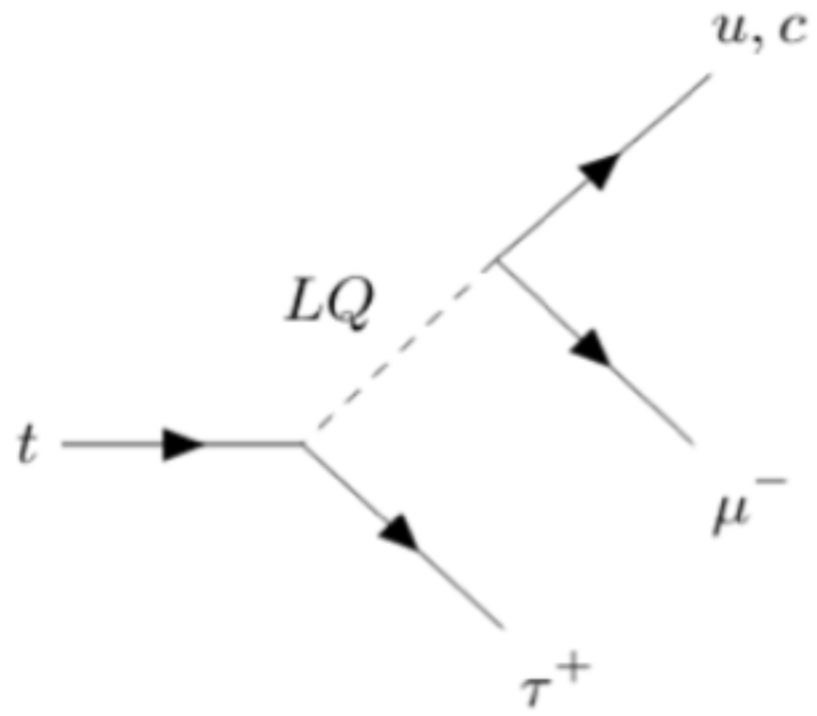
  - any observation → strong evidence for new physics

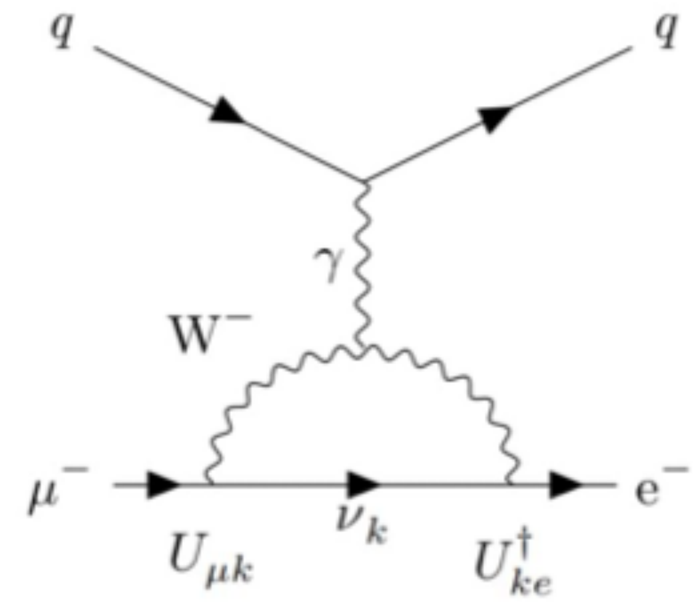
  - observations of slight deviations from comparisons in hadron decays with τ and other leptons, e.g. $R(D)$ and $R(D^*)$

  BaBar[1, 2] | Belle [3, 4, 5, 6] | Belle II [7] | LHCb [8, 9] | HFLAV [10]

  - Neutrino oscillations → LFV in lepton sector, but far beyond any experimental sensitivity

- New Physics → introduce additional terms with lepton fields →LFV (e.g. SUSY, leptoquarks, 2HDMs)





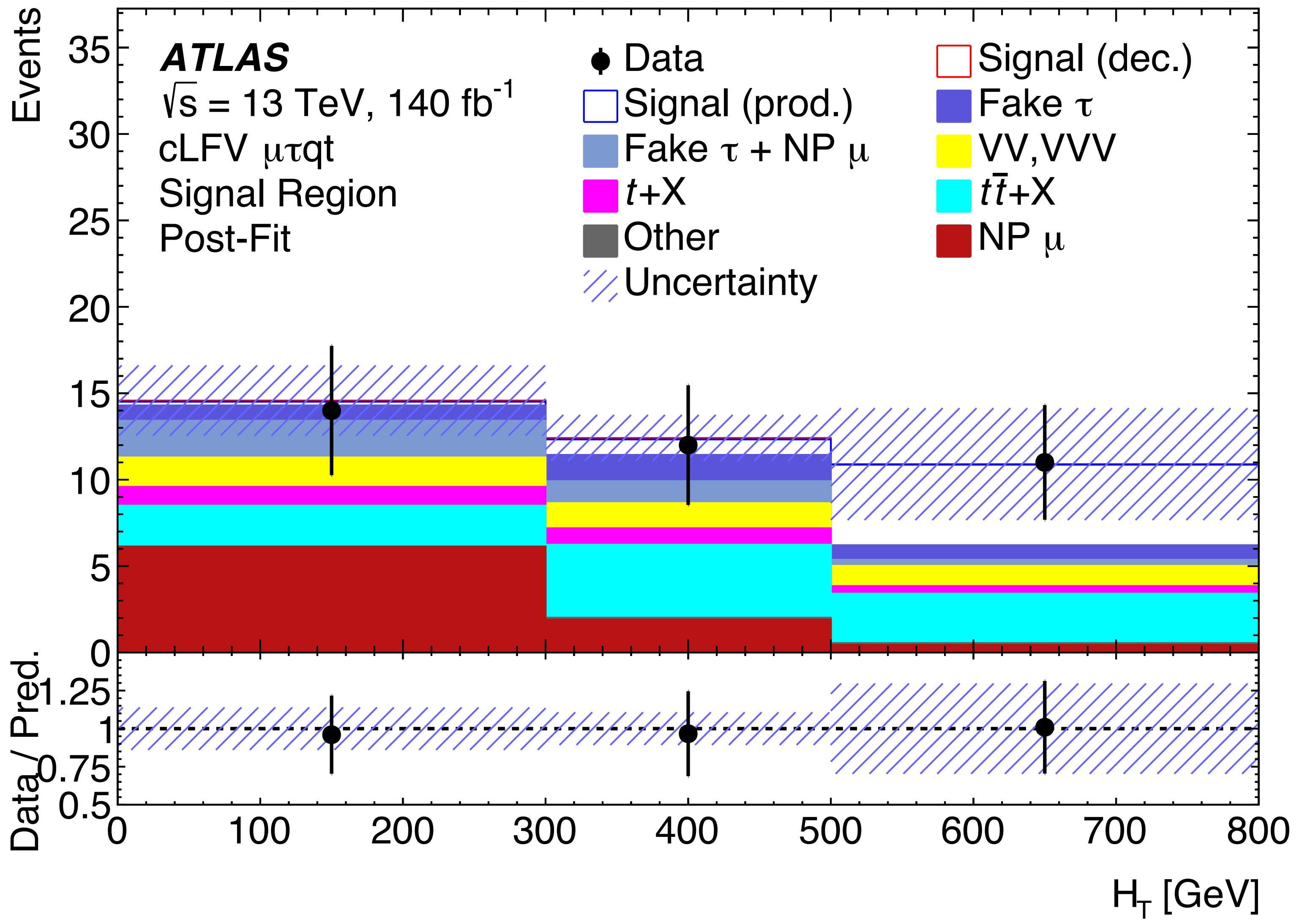
LQ interpretation

- First direct search for cLFV $\mu\tau qt$ coupling!

Source: J. Kempster, CLFV

(3) Charged Lepton Flavour Violation - $\mu\tau q(u,c)t$

- **Event Selection:** same-sign dimuon, one $\tau_{had-vis}$, and at least one jet (one b-tagged jet)



- Norm Factors for EFT signal and NP muon contributions obtained from simultaneous likelihood fit

  - used H_T distribution (separates EFT signal from SM backgrounds - sensitive to high-p_T leptons)

- Small upward fluctuation in data in highest H_T bin

  - but no significant cLFV observed

- **Analysis Strategy**
  - Define analysis regions with CRs for fake backgrounds (selection: $\mu\mu\tau_{had-vis}$ / $e\mu\mu$)
  - Prompt / real backgrounds estimation from MC ($t\bar{t}V, VV, tW$)
  - Data-driven estimation of fake leptons (CRs)

    > Fake $\tau_{had-vis}$ estimation (SF method)

    > Non-prompt (NP) μ (Template fit method)
  - Profile likelihood fit (SRs + NP muon CR)
  - EFT interpretation

(3) EFT Interpretation - cLFV - $\mu\tau q(u,c)t$

- All relevant 2Q2L operators in Warsaw basis
- Non-zero Wilson coefficients

  → larger cross-section (quadratic dependence)
- Top-quark decay width Γ in terms of 6 degrees of freedom:

Operator	Interaction	Lorentz Structure
$O_{\text{lq}}^{1(ijkl)}$	$(\bar{\text{l}}_i\gamma^\mu \text{l}_j)(\bar{\text{q}}_k\gamma_\mu \text{q}_l)$	Vector
$O_{\text{lq}}^{3(ijkl)}$	$(\bar{\text{l}}_i\gamma^\mu\sigma^I \text{l}_j)(\bar{\text{q}}_k\gamma_\mu\sigma_I \text{q}_l)$	Vector
$O_{\text{eq}}^{(ijkl)}$	$(\bar{\text{e}}_i\gamma^\mu \text{e}_j)(\bar{\text{q}}_k\gamma_\mu \text{q}_l)$	Vector
$O_{\text{lu}}^{(ijkl)}$	$(\bar{\text{l}}_i\gamma^\mu \text{l}_j)(\bar{\text{u}}_k\gamma_\mu \text{u}_l)$	Vector
$O_{\text{eu}}^{(ijkl)}$	$(\bar{\text{e}}_i\gamma^\mu \text{e}_j)(\bar{\text{u}}_k\gamma_\mu \text{u}_l)$	Vector
$O_{\text{lequ}}^{1(ijkl)}$	$(\bar{\text{l}}_i \text{e}_j)\varepsilon(\bar{\text{q}}_k \text{u}_l)$	Scalar
$O_{\text{lequ}}^{3(ijkl)}$	$(\bar{\text{l}}_i\sigma^{\mu\nu} \text{e}_j)\varepsilon(\bar{\text{q}}_k\sigma_{\mu\nu} \text{u}_l)$	Tensor

$$\Gamma(t \to \ell_i^+\ell_j^- q_k) = \frac{m_t}{6144\pi^3}\left(\frac{m_t}{\Lambda}\right)^4 \Big\{4|c_{\text{lq}}^{-(ijk3)}|^2 + 4|c_{\text{eq}}^{(ijk3)}|^2 + 4|c_{\text{lu}}^{(ijk3)}|^2 + 4|c_{\text{eu}}^{(ijk3)}|^2 + 2|c_{\text{lequ}}^{1(ijk3)}|^2 + 96|c_{\text{lequ}}^{3(ijk3)}|^2\Big\}$$

- Previous constraints on the Wilson coefficient from re-interpretation of FCNC search in *tZq* channel:
  - $|c_{lequ}^{3(2313)}|/\Lambda^2 < 3.4$ TeV^{-2} for $\mu\tau ut$ with $\mathscr{B}(t \to \mu\tau u) < 3.5 \times 10^{-5}$
  - $|c_{lequ}^{1(2323)}|/\Lambda^2 < 29$ TeV^{-2} for $\mu\tau ct$ with $\mathscr{B}(t \to \mu\tau c) < 3.0 \times 10^{-4}$

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(3) EFT Interpretation - cLFV - $\mu\tau q(u,c)t$

- **Limits on effective coupling strengths**
  - A large improvement from the previous limits (reinterpretation of ATLAS FCNC tZq analysis)
    > from factors of 7.2 for $c_{lequ}^{3(2323)}$ for $\mu\tau ct$ and to 41 for $c_{lequ}^{1(2313)}$ for $\mu\tau ut$!
  - Stronger exclusion limits on $\mu\tau ut$ interactions than $\mu\tau ct$ (signal σ dominated by $gu \to tl^{\pm}l'^{\mp}$)

NOTE: Effective coupling strengths are set individually

	95% CL upper limits on $\lvert c\rvert/\Lambda^2$ [TeV^{-2}]					
	$c_{\text{lq}}^{-(ijk3)}$	$c_{\text{eq}}^{(ijk3)}$	$c_{\text{lu}}^{(ijk3)}$	$c_{\text{eu}}^{(ijk3)}$	$c_{\text{lequ}}^{1(ijk3)}$	$c_{\text{lequ}}^{3(ijk3)}$
Previous (u) [34]	12	12	12	12	18	2.4
Expected (u)	0.33	0.31	0.3	0.32	0.33	0.08
Observed (u)	0.43	0.41	0.4	0.42	0.44	0.10
Previous (c) [34]	14	14	14	14	21	2.6
Expected (c)	1.3	1.2	1.2	1.2	1.4	0.28
Observed (c)	1.6	1.6	1.6	1.6	1.8	0.36

	95% CL upper limits on $\mathcal{B}(t \to \mu\tau q)$ ($\times 10^{-7}$)					
	$c_{\text{lq}}^{-(ijk3)}$	$c_{\text{eq}}^{(ijk3)}$	$c_{\text{lu}}^{(ijk3)}$	$c_{\text{eu}}^{(ijk3)}$	$c_{\text{lequ}}^{1(ijk3)}$	$c_{\text{lequ}}^{3(ijk3)}$
Expected (u)	2.3	2.0	1.9	2.2	1.2	3.0
Observed (u)	4.0	3.6	3.3	3.8	2.0	5.2
Expected (c)	33	32	32	33	20	41
Observed (c)	56	54	53	54	34	67

$$\Gamma(t \to \ell_i^+ \ell_j^- q_k) = \frac{m_t}{6144\pi^3}\left(\frac{m_t}{\Lambda}\right)^4 \Big\{4|c_{\text{lq}}^{-(ijk3)}|^2 + 4|c_{\text{eq}}^{(ijk3)}|^2 + 4|c_{\text{lu}}^{(ijk3)}|^2 + 4|c_{\text{eu}}^{(ijk3)}|^2 + 2|c_{\text{lequ}}^{1(ijk3)}|^2 + 96|c_{\text{lequ}}^{3(ijk3)}|^2\Big\} ,$$

	Cross-section $\sigma^{+\text{scale}}_{-\text{scale}} \pm$ PDF [fb]		
	$c_{\text{vector}}^{(ijk3)}$	$c_{\text{lequ}}^{1(ijk3)}$	$c_{\text{lequ}}^{3(ijk3)}$
Production $\ell\ell' ut$	$118^{+24}_{-19} \pm 1$	$101^{+21}_{-16} \pm 1$	$2150^{+410}_{-320} \pm 20$
Production $\ell\ell' ct$	$7.9^{+1.2}_{-1.0} \pm 1.6$	$6.1^{+1.0}_{-0.8} \pm 1.5$	$153^{+21}_{-18} \pm 29$
Decay $\ell\ell' q_k t$	$6.9^{+1.8}_{-1.3} \pm 0.1$	$3.46^{+0.90}_{-0.66} \pm 0.03$	$166^{+43}_{-32} \pm 2$

(3) EFT Interpretation - cLFV - $\mu\tau q(u,c)t$

- Inclusive BR limit

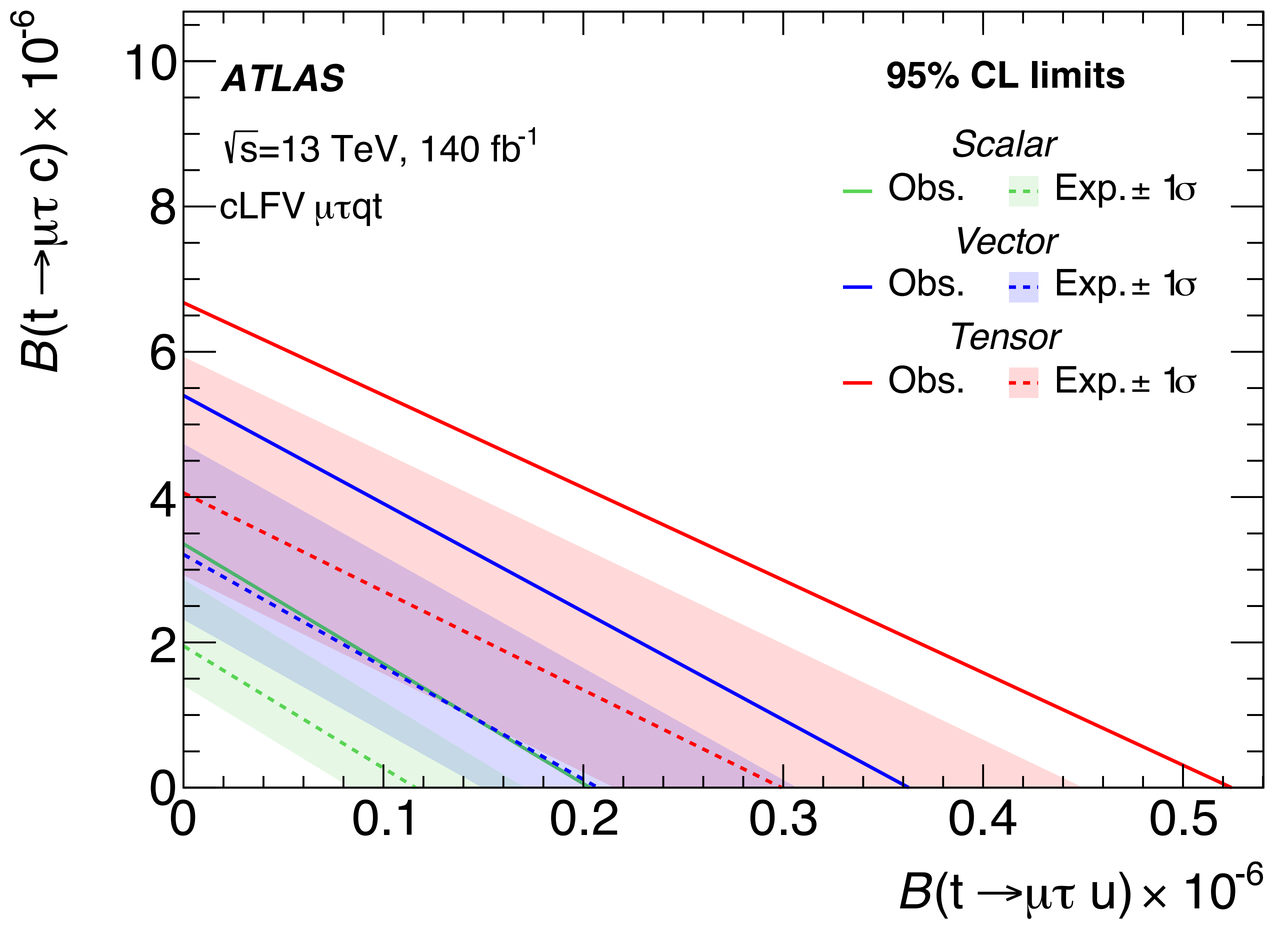
	95% CL upper limits on $\mathcal{B}(t \to \mu\tau q)$	
	Stat. uncertainty	**Stat.+syst. uncertainties**
Expected	4.6×10^{-7}	5.0×10^{-7}
Observed	8.2×10^{-7}	8.7×10^{-7}

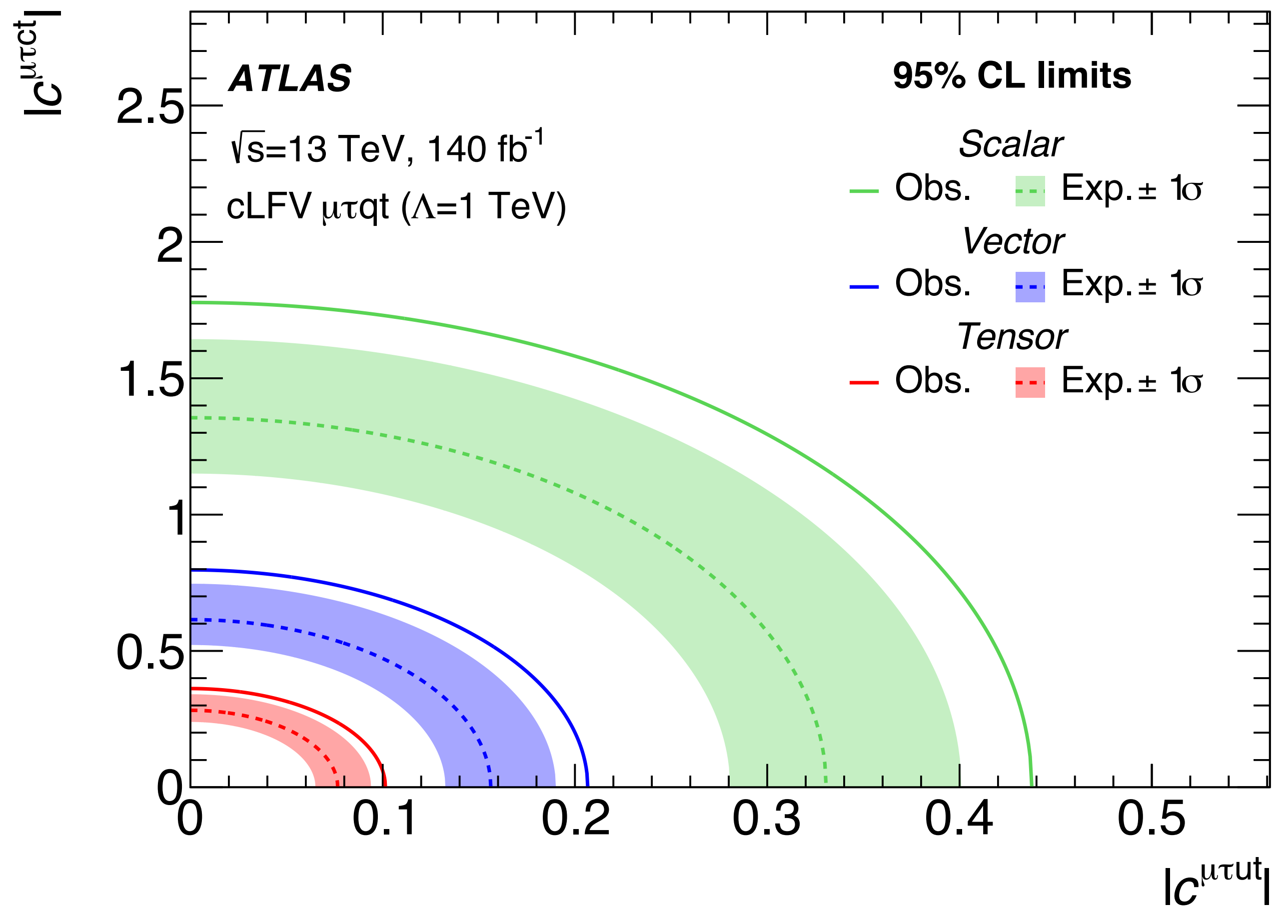
- This search complements searches for cLFV in $e\mu qt$ interactions by CMS **arXiv: 2312.03199 (Submitted to PRD)**

  - $\mathcal{B}(t \to e\mu u) < 0.12 \times 10^{-7}$ (scalar-structure up-quark coupling)

  - $\mathcal{B}(t \to e\mu c) < 4.98 \times 10^{-7}$ (tensor-structure charm-quark coupling)

- Interesting scenario: what if all vector operators contribute simultaneously with same effective coupling strength (assuming NP couples equally to LH and RH fermions)?

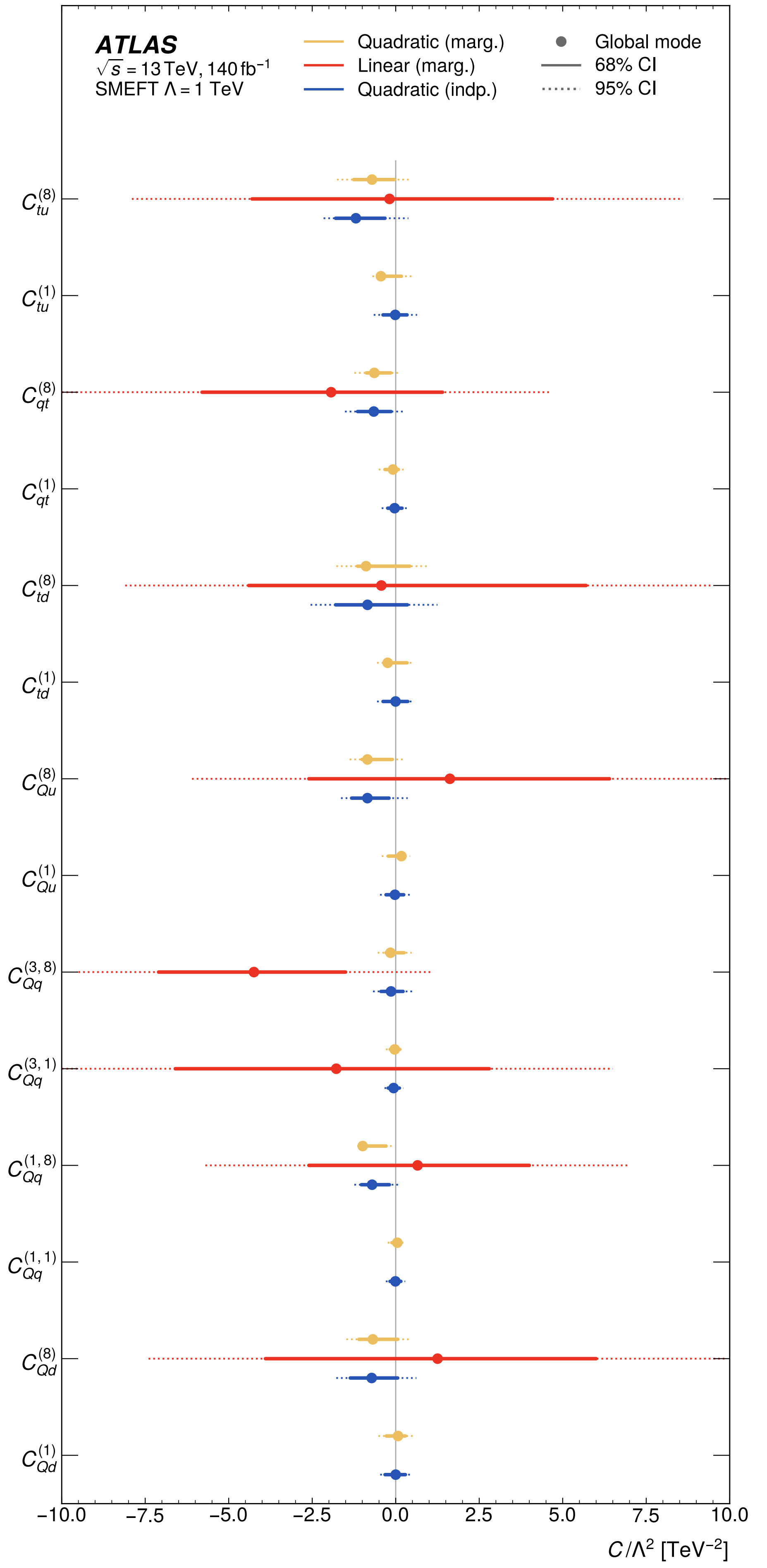




- CLs 95% upper limits on BR($t \to \mu\tau q$) and relevant Wilson coefficient for scalar, vector, tensor couplings -

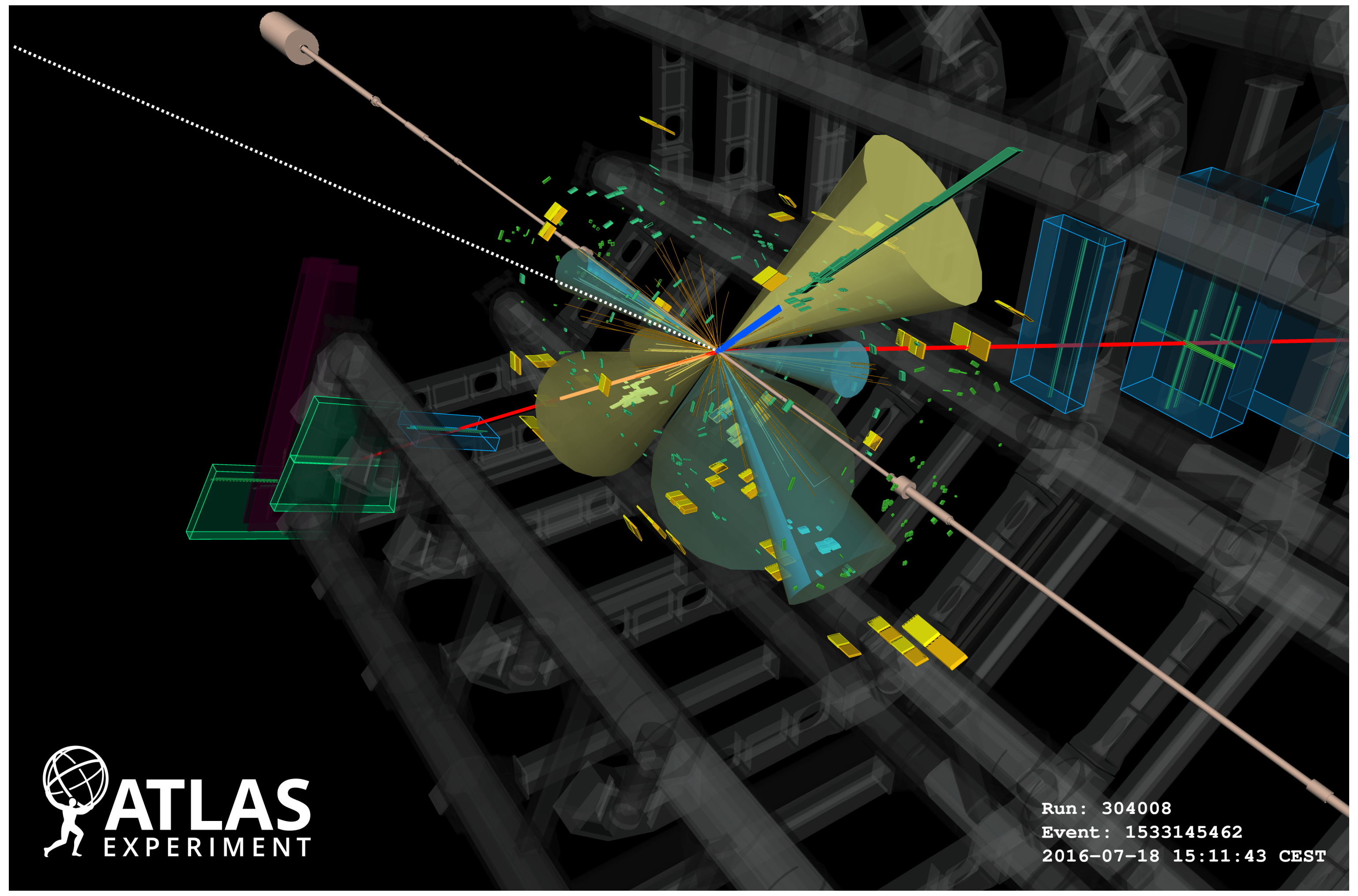
More Analyses with EFT Interpretation..

Inclusive/Differential Cross-Section $t\bar{t}Z$ Measurements JHEP 07 (2024) 163



4-top productions in multi-lepton final states EPJC 84 (2024) 156

Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
O^1_{QQ}	[-2.5, 3.2]	[-4.0, 4.5]
O^1_{Qt}	[-2.6, 2.1]	[-3.8, 3.4]
O^1_{tt}	[-1.2, 1.4]	[-1.9, 2.1]
O^8_{Qt}	[-4.3, 5.1]	[-6.9, 7.6]



FCNC couplings between top and Higgs in multi-lepton final states

EPJC 84 (2024) 7, 757

Signal	Observed (expected) 95% CL upper limits $\mathcal{B}(t \to Hq)$	$\lvert C^{qt,tq}_{u\phi} \rvert$
tHu	2.8 (3.0) × 10^{-4}	0.71 (0.73)
tHc	3.3 (3.8) × 10^{-4}	0.76 (0.82)

Poster Session by Shayma

Joker talks?

Credit: ChatGPT

Conclusion

- Effective field theories (EFTs) are highly powerful “UV agnostic” tools for exploring new physics and understanding physics in general
- In the top quark sector, SMEFT continues to evolve, keeping pace with increasing precision of experimental data from the LHC
- EFT interpretations have been applied to recent top analyses:

  arXiv: 2403.09452 (Accepted by JHEP) | **JHEP 05 (2024) 305** | **PRD 110 (2024) 1, 012014** | **JHEP 07 (2024) 163** | **EPJC 84 (2024) 156** **EPJC 84 (2024) 7, 757**

- To optimise EFT analyses, we can

  - Focus on continuing interpretations + excluding EFT parameters.

  - Make use of advanced statistical techniques, high-precision theoretical calculation, and extensive datasets from LHC.

- These analyses show significant progress in EFT interpretation in top quark sector, with further insights expected from the upcoming Run 3 data and advancements in analysis techniques!

Back-up

SMEFT Interpretation

Source: K. Minasu, EFTforTop

- Global likelihood in SMEFT parameter space
- *Individual* + *marginalised* confidence intervals

  - Individual: fix all other parameters to 0 except one → might only be able to detect whether this parameter is non-zero, especially if it is the dominant one.

  - Marginalised: integrate (or marginalise) over other parameters's uncertainties → more realistic confidence interval for the parameter of interest.

- Impact of whether including squared EFT terms or not

$$\sigma = \sigma_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\sigma_i^{(6)} + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4}\sigma_{ij}^{(6)} + \cancel{\sum_i \frac{c_i^{(8)}}{\Lambda^4}}\sigma_i^{(8)} + \cdots$$

  - $(D=6)^2$ ~ same order as $D=8$ interference
  - $D=8$: unknown or not feasible in general.
  - If $(D=6)^2$ is relevant, UV interpretations favour strongly coupled models (large c's)

EFT Parameter Constraints from Experimental Data

- When using binned unfolded data, the likelihood for each bin is given by $\mathscr{L}(N_p \,|\, \mathbf{c}, \theta)$, where N_p, $\mathbf{c}$, and θ represents each measured bin, the vector of EFT parameters, and the vector of nuisance parameters, respectively.
- To combine bins (or measurements), multiply their likelihoods together.
- For extreme SMEFT scenarios, at least 1350 bins with varying EFT parameter dependencies are needed to solve the equations and extract the parameters effectively.
  - More bins improve accuracy.
- In contrast, if we fix all other parameters to 0 except one, we might only be able to detect whether this parameter is non-zero, especially if it is the dominant one. However, understanding its exact value requires knowledge of its relationship with all other parameters. Testing both approaches is valuable.

Experimental Signatures and Observables

- What type of data is required?

  - Search for specific final states and phase-space regions that are sensitive to the parameters, i.e. $\frac{c_i}{\Lambda^2}$, in questions by using MC simulations.

- Measurable physics quantities = differential cross-sections
- Measurements can be performed in either binned or un-binned (event-by-event) formats:

  - Binned: simpler to handle + tailored to experimental conditions, but may not ideal.

  - Un-binned (event-by-event): more complex but can provide results closer to optimal.

Top quark related operators in $\mathscr{L}^{(6)}$

Source: arXiv: 1706.08945

- In the Warsaw basis, there are 28 operators that directly involve the top quark at $\mathscr{L}^{(6)}$ in unitary gauge:

$$\mathcal{Q}_{uH},\ \mathcal{Q}_{Hu},\ \mathcal{Q}_{Hq}^{(1),(3)},\ \mathcal{Q}_{Hud},\ \mathcal{Q}_{uW},\ \mathcal{Q}_{uB},\ \mathcal{Q}_{uG},\ \mathcal{Q}_{dW},$$
$$\mathcal{Q}_{qq}^{(1),(3)},\ \mathcal{Q}_{lq}^{(1),(3)},\ \mathcal{Q}_{uu},\ \mathcal{Q}_{ud}^{(1),(8)},\ \mathcal{Q}_{eu},\ \mathcal{Q}_{lu},\ \mathcal{Q}_{qe},\ \mathcal{Q}_{qu}^{(1),(8)},\ \mathcal{Q}_{qd}^{(1),(8)},$$
$$\mathcal{Q}_{ledq},\ \mathcal{Q}_{quqd}^{(1),(8)},\ \mathcal{Q}_{lequ}^{(1),(3)}.$$

- Other operators relevant for a global analysis of the top sector through an involvement in top couplings from input parameter definitions (left) or modification of other interactions in top production processes (right).

$$\mathcal{Q}_{H\Box},\ \mathcal{Q}_{HD},\ \mathcal{Q}_{HWB},\ \mathcal{Q}_{ll},\ \mathcal{Q}_{Hl}^{(3)}, \qquad \mathcal{Q}_{G},\ \mathcal{Q}_{\tilde{G}},\ \mathcal{Q}_{HG},\ \mathcal{Q}_{H\tilde{G}}.$$

- 1179 independent parameters (622 absolute values + 557 complex phases) in a general flavour scenario
  - With additional symmetry requirements for quarks, the number can be further reduced.
  - e.g. first two generations with $U(2)^3$ symmetry + flavor universality in the lepton sector leads to 85 independent parameters (68 absolute values + 17 phases)

Experimental Data - Detector Effects

- Experimental data are folded with detector effects.
- Two Approaches to solve this issue:

  \- Unfolding:

  > Unfold data to particle-level cross-sections (PLXS) and compare with PL EFT models

  > Preferred option for legacy measurements (free of ill-defined TRUTH objects)

  > This method is “model independent” and works well if resolution is high and background subtraction is accurate. (simplicity in interpretations)

  > Challenges: subtraction of background from data (EFT may impact both S and B).

  \- Folding:

  > Apply folding to the model and compare it with the folded data.

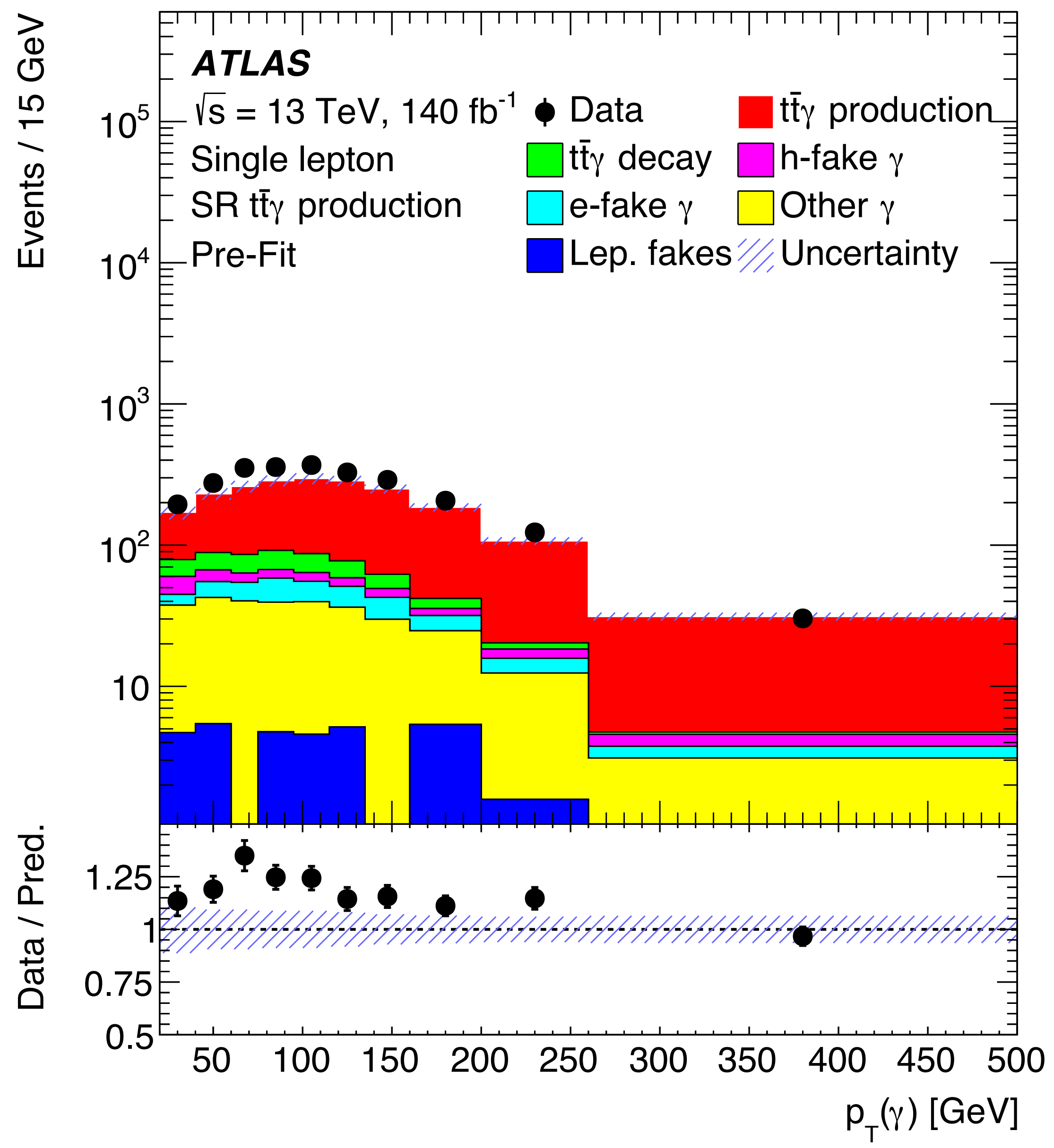
  > Provides the most accurate extraction of model parameters.

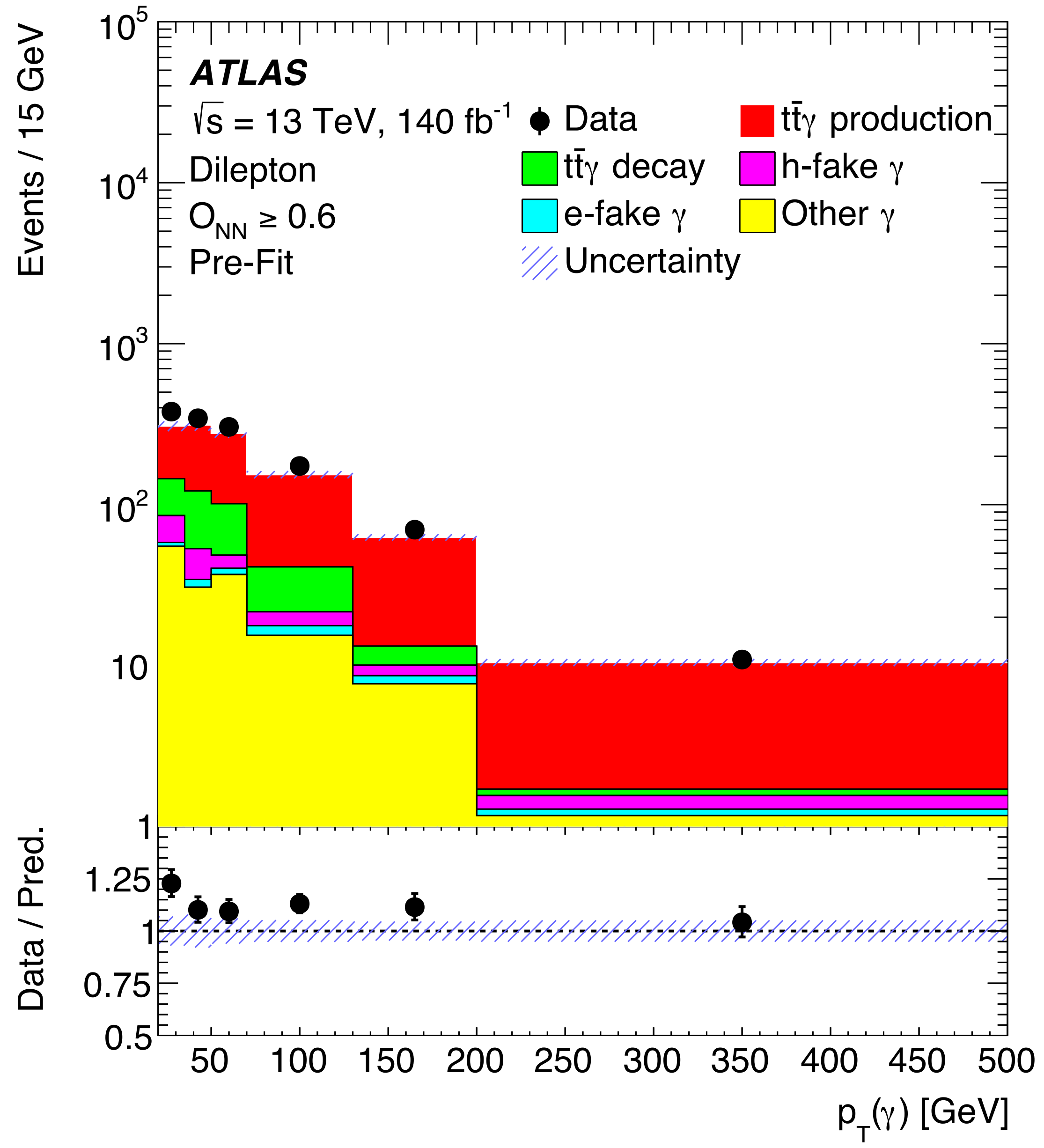
  > Challenges: a need in an accurate folding prescriptions for different models and difficulties in combining with other measurements while managing systematics.

(1) Inclusive/Differential $t\bar{t}\gamma$ Cross Section

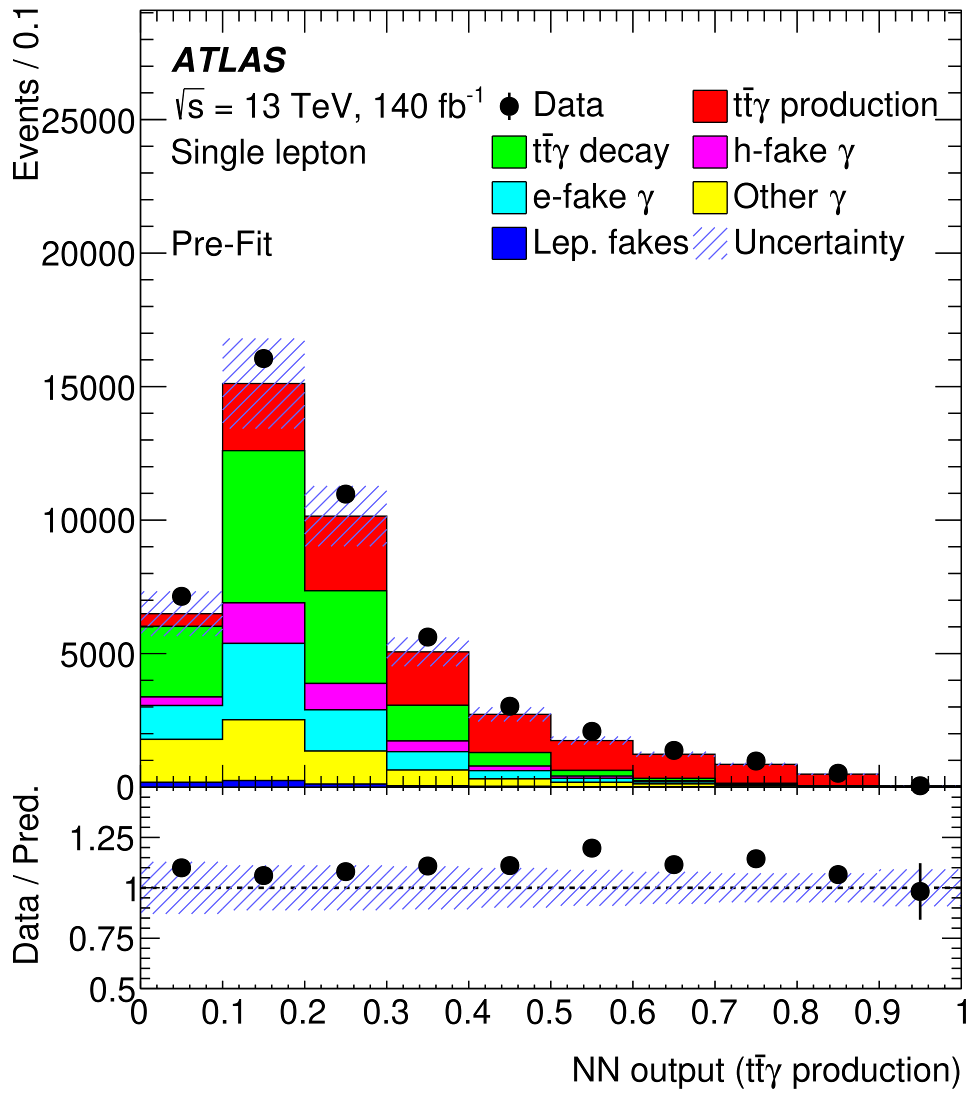
- **Event Selection:** $t\bar{t}$ in single-lepton or di-lepton channel with exactly one photon

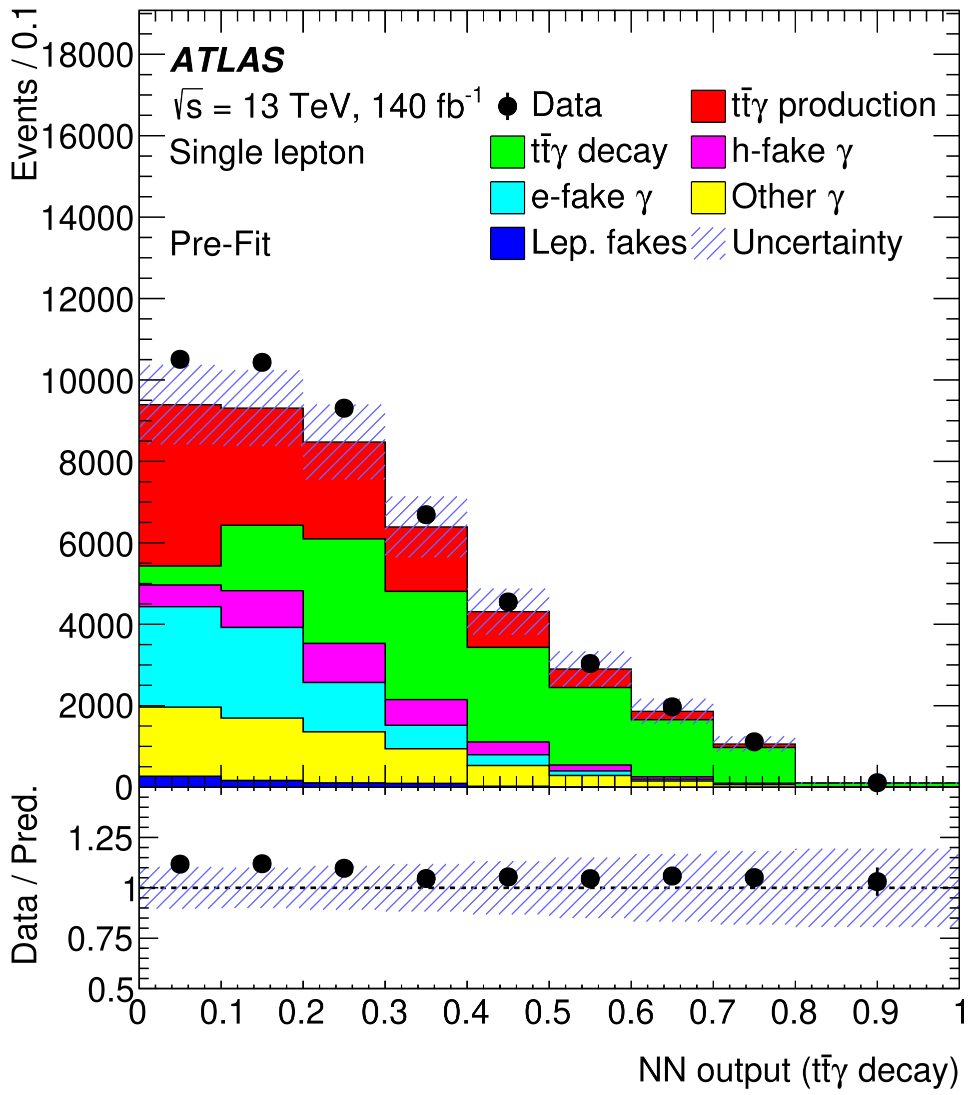
- **Signal:** $t\bar{t}\gamma$ production
- **Background:**
  - $t\bar{t}\gamma$ decay (NLO/LO k-factor applied)
  - Prompt photon background
    (Wγ, Zγ, single-top, diboson, $t\bar{t} + V$ with photon from shower)
  - Fake photon
    > electronic fakes $e \to \gamma$ ($Z \to e\gamma/ee$ CR)
    > hadronic fakes $h \to \gamma$ (ABCD method)
  - Fake leptons (matrix method)

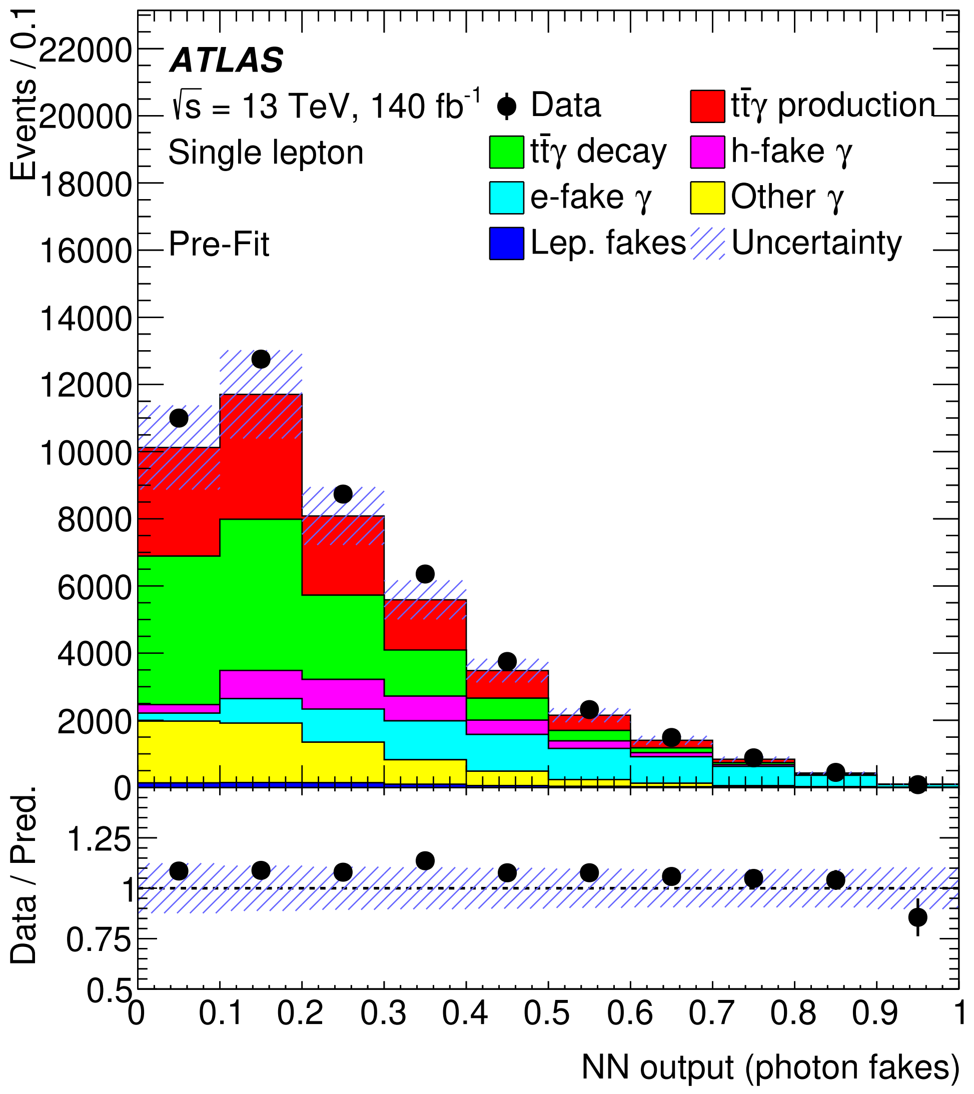


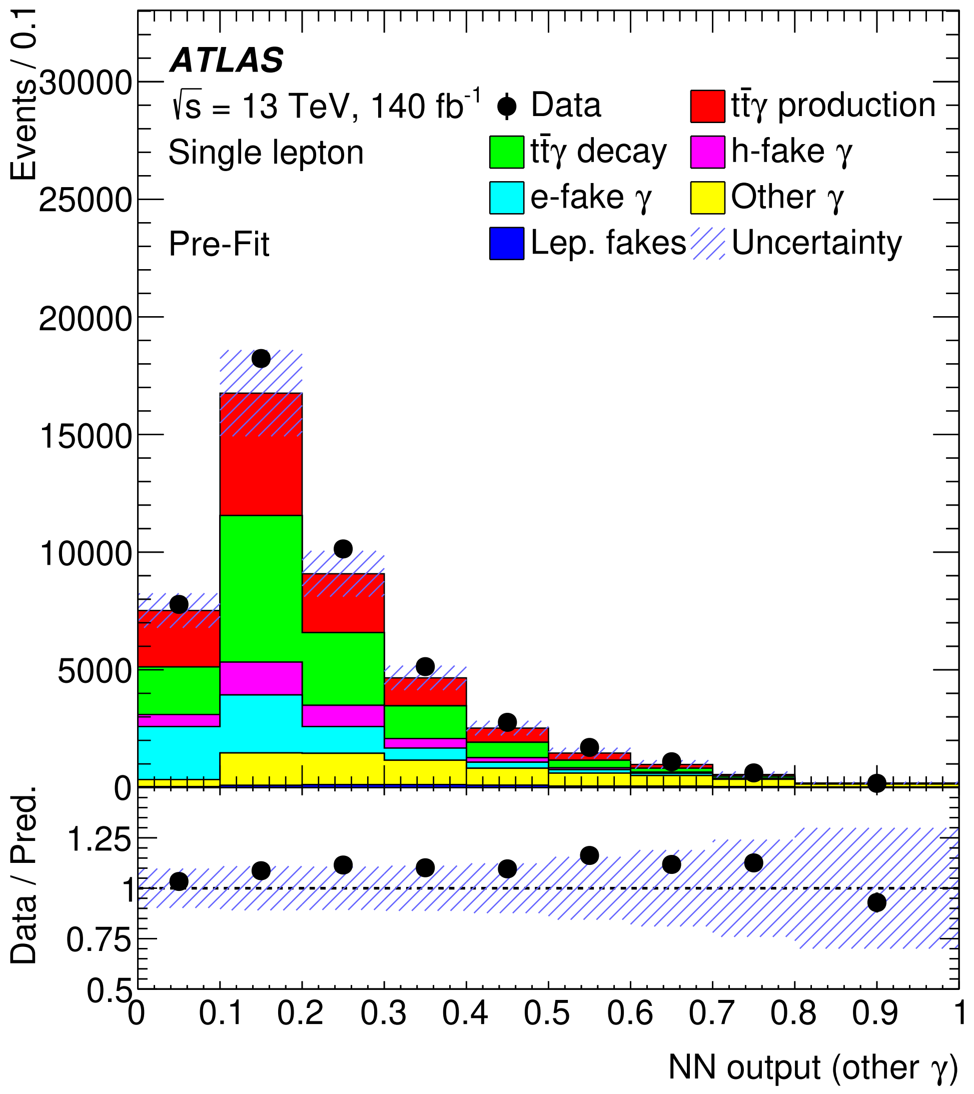


(1) Inclusive/Differential $t\bar{t}\gamma$ Cross Section









(1) Inclusive/Differential $t\bar{t}\gamma$ Cross Section

- **Inclusive cross-section (fiducial)** [fb]

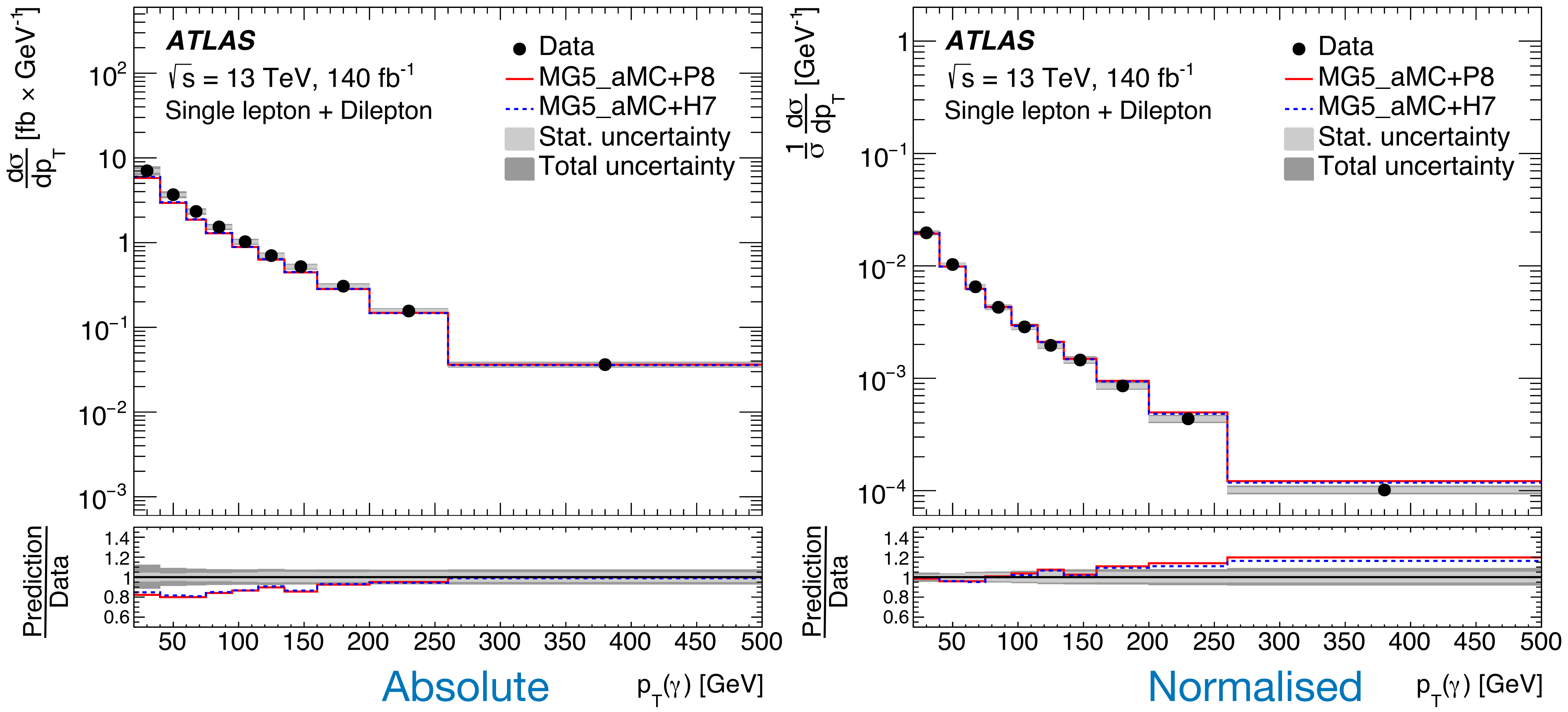
Channel	Production	Production + Decay
Single lepton	$290 \pm 5(\text{stat})^{+20}_{-19}(\text{syst})$	$707 \pm 6\,(\text{stat})\,^{+49}_{-46}\,(\text{syst})$
Dilepton	$46.5^{+1.4}_{-1.3}(\text{stat})^{+3.0}_{-2.8}(\text{syst})$	$117.7 \pm 1.7\,(\text{stat})\,^{+8.1}_{-7.7}\,(\text{syst})$
Combined	$322 \pm 5\,(\text{stat}) \pm 15(\text{syst})$	$793 \pm 5\,(\text{stat})\,^{+38}_{-37}\,(\text{syst})$
NLO MC	$299^{+29}_{-30}(\text{scale})^{+7}_{-4}(\text{PDF})$	-

Source	$\Delta\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}\gamma}$ (%) Single lepton	Dilepton	Combination
Statistical uncertainty	0.8	1.6	0.7
MC statistical uncertainties	1.5	1.5	1.0
Modelling uncertainties			
$t\bar{t}\gamma$ production PS uncertainty	2.3	3.5	0.9
Other $t\bar{t}\gamma$ production modelling	4.9	1.5	2.9
$t\bar{t}\gamma$ decay modelling	0.6	1.3	0.8
$t\bar{t}\gamma$ decay normalisation	4.1	3.7	2.0
Other Background modelling	0.7	0.2	0.5
Prompt background normalisation	1.5	2.1	2.0
Experimental uncertainties			
Jet uncertainties	3.4	2.9	1.7
B-tagging uncertainties	2.6	2.1	1.1
Fake photon background estimate	0.8	1.4	1.6
Fake lepton background estimate	0.4	-	0.1
Photon	0.5	1.6	0.8
Lepton	1.2	1.4	1.2
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.3	0.4	0.4
Pile-up	0.4	0.7	0.5
Luminosity	0.8	1.0	0.8
Total systematic uncertainty	7.5	7.4	5.1
Total uncertainty	7.8	7.7	5.2

MC predictions and measurements well in agreement within total uncertainties!

- **Differential measurements**
  - photon, lepton, jet kinematics, angular separation between those objects
  - Shape generally well described by MC
  - Measured cross section larger than prediction
  - Uncertainties: largely from jets, b-tagging, and stat. uncertainty
    > 8 ~ 10% (absolute), ~ 5% (normalised)

Example: $t\bar{t}\gamma$ production



(1) Inclusive/Differential $t\bar{t}\gamma$ Cross Section

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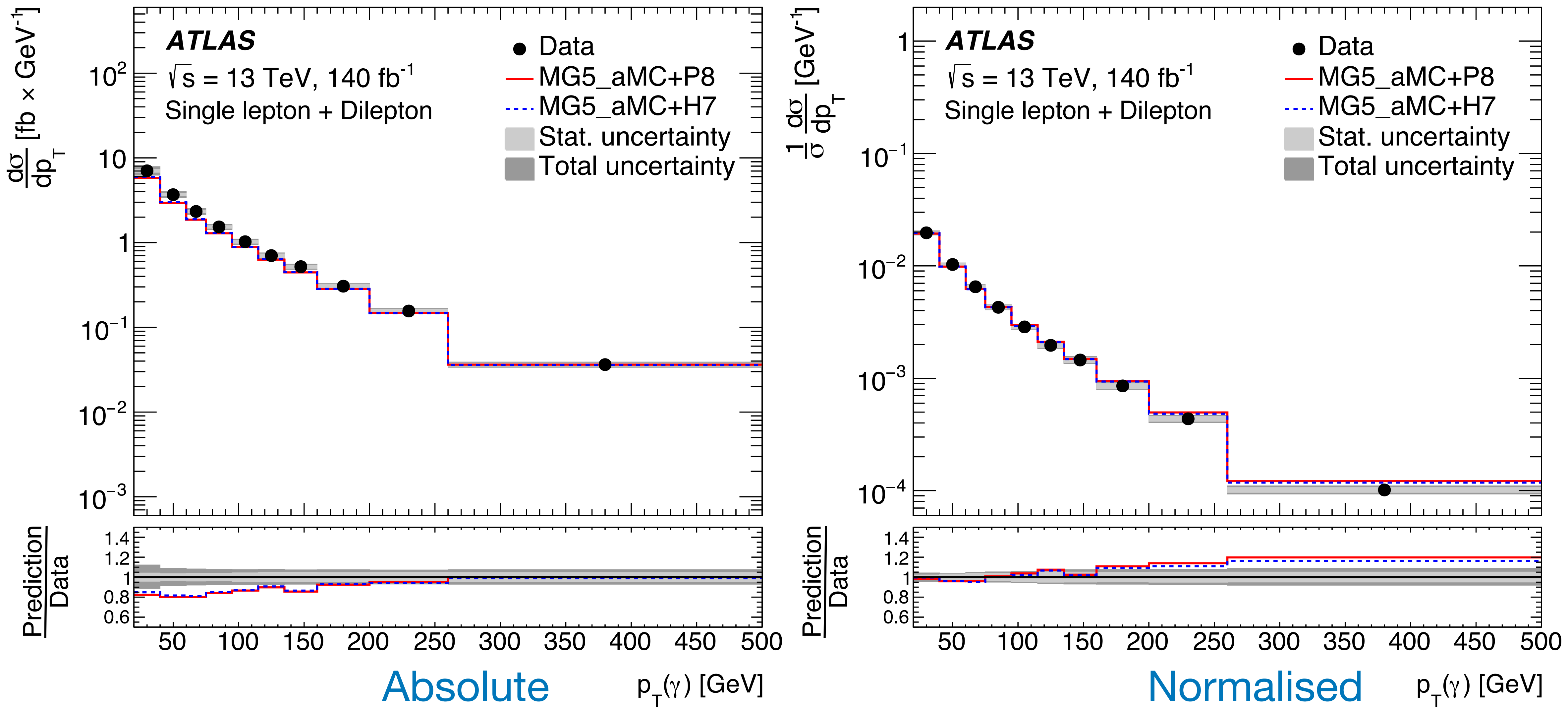
NLO MC	$299^{+29}_{-30}(\text{scale})^{+7}_{-4}(\text{PDF})$	-

- Major uncertainties: $t\bar{t}\gamma$ production modelling, jet, and b-tagging
- Slightly higher cross-section in measurement compared to theoretical calculation
- MC predictions and measurements in good agreement within total uncertainties!

- **Differential measurements**
  - photon, lepton, jet kinematics, angular separation between those objects
  - measured with profile likelihood unfolding
  - Shape generally well described by MC
  - Uncertainties: largely from jets, b-tagging, and stat. uncertainty
    > 8 ~ 10% (absolute), ~ 5% (normalised)

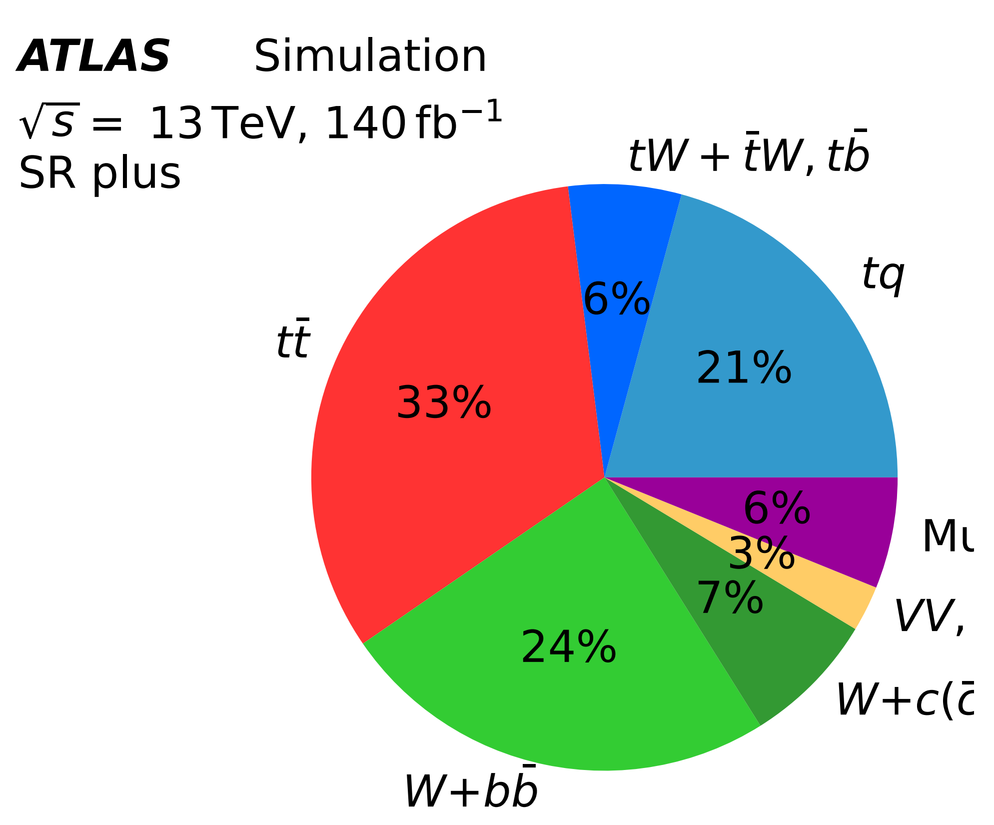
Example: $t\bar{t}\gamma$ production

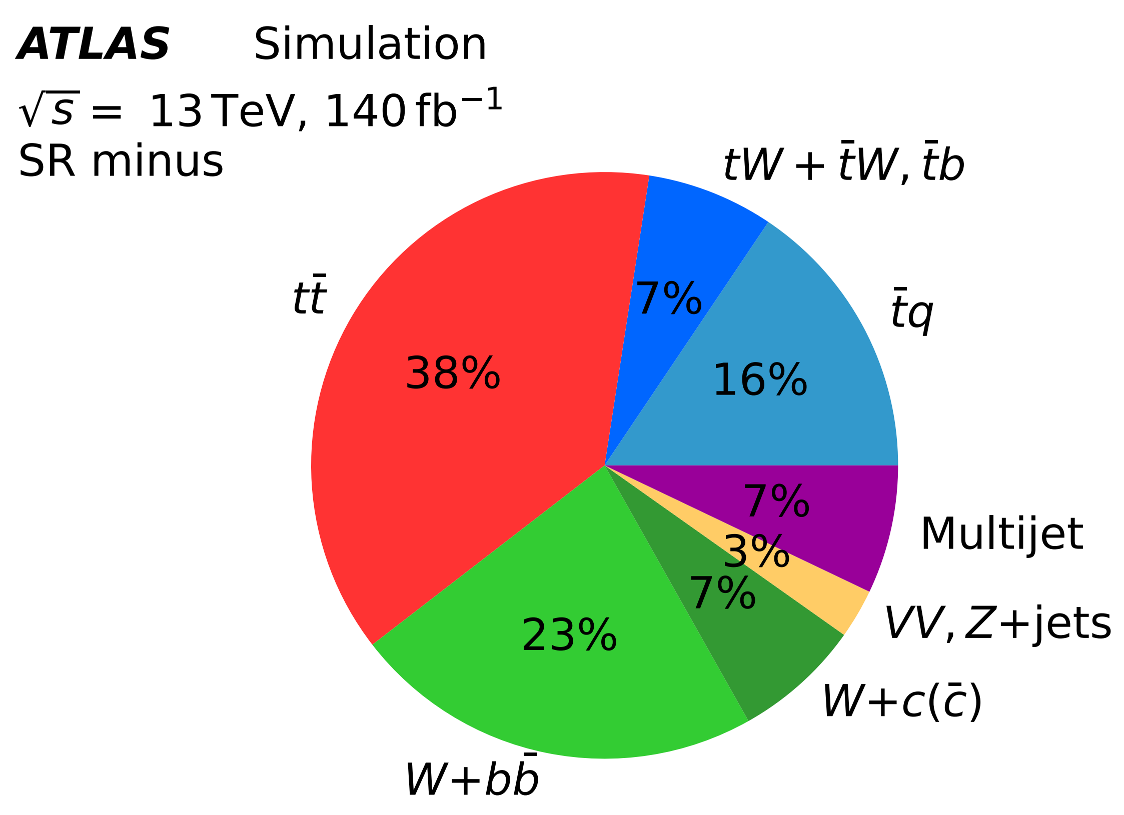


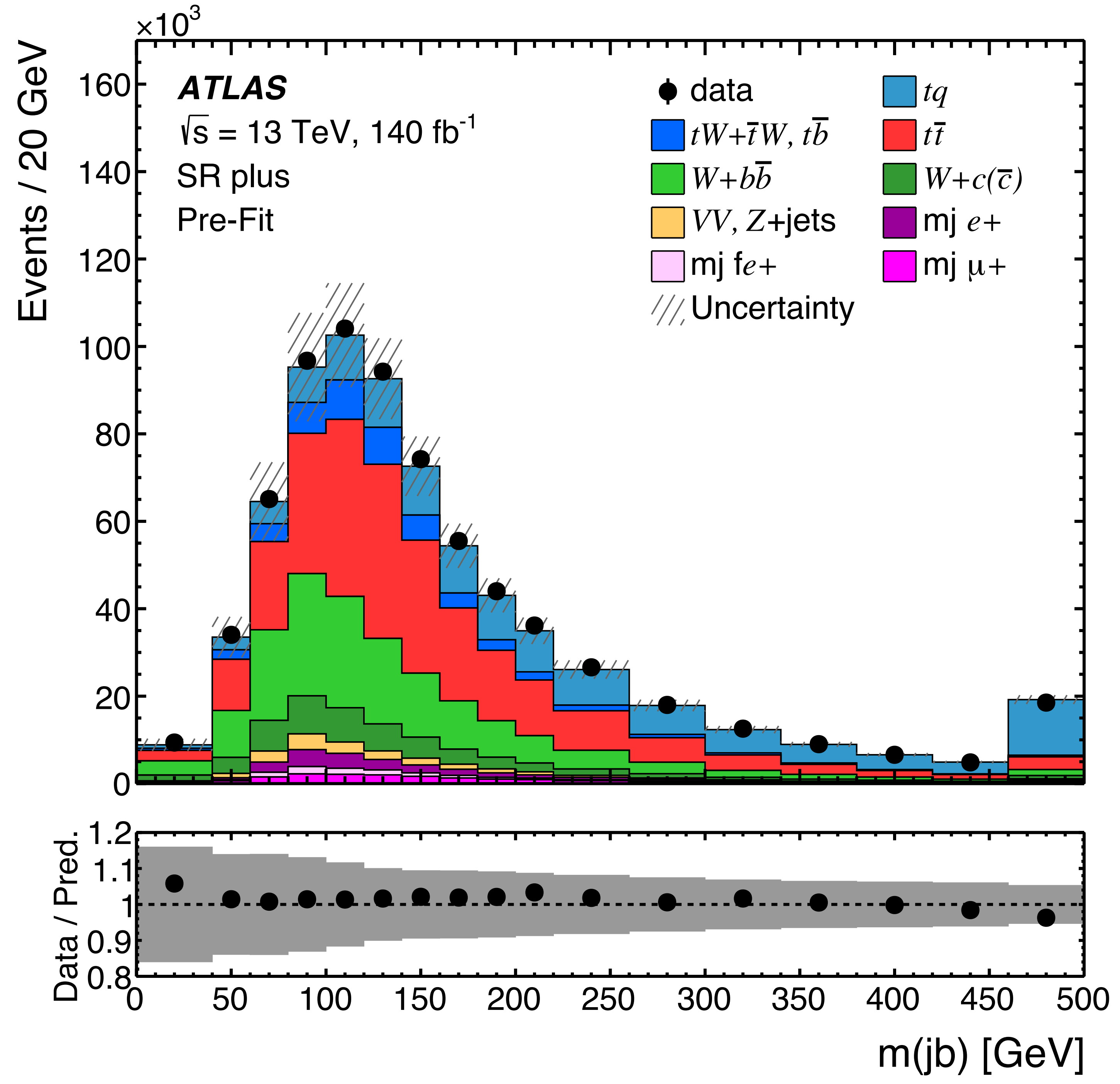
(2) Single top in t-channel

- **Event Selection**: tq, $\bar{t}q$ events + leptonically decaying W bosons

- **Signal**: $t(bW^{+}_{leptonic})\ q$ or $\bar{t}(\bar{b}W^{-}_{leptonic})\ q$
  - 1 e/μ (isolated) + high p_T^{miss}
  - 2 jets (high p_T): 1b-tagged + one forward jet
- **Backgrounds (NNLO in QCD)**
  - $t\bar{t}$
  - $W+b\bar{b}$
  - Single-top process:
    tW, $t\bar{b}/\bar{t}b(W/W^*)$ via s-channel
  - Multijet
  - Diboson, Z+jets







→ Good modelling of NN input (kinematic) variables

(2) Single top in t-channel

- **Analysis Strategy**: multijet (data-driven) + NN to define SRs and background-enriched CR
  - Rate of multijet background from 6 CRs (included in fit)
  - Separation of signal from backgrounds: optimised NN discriminant D_{nn}

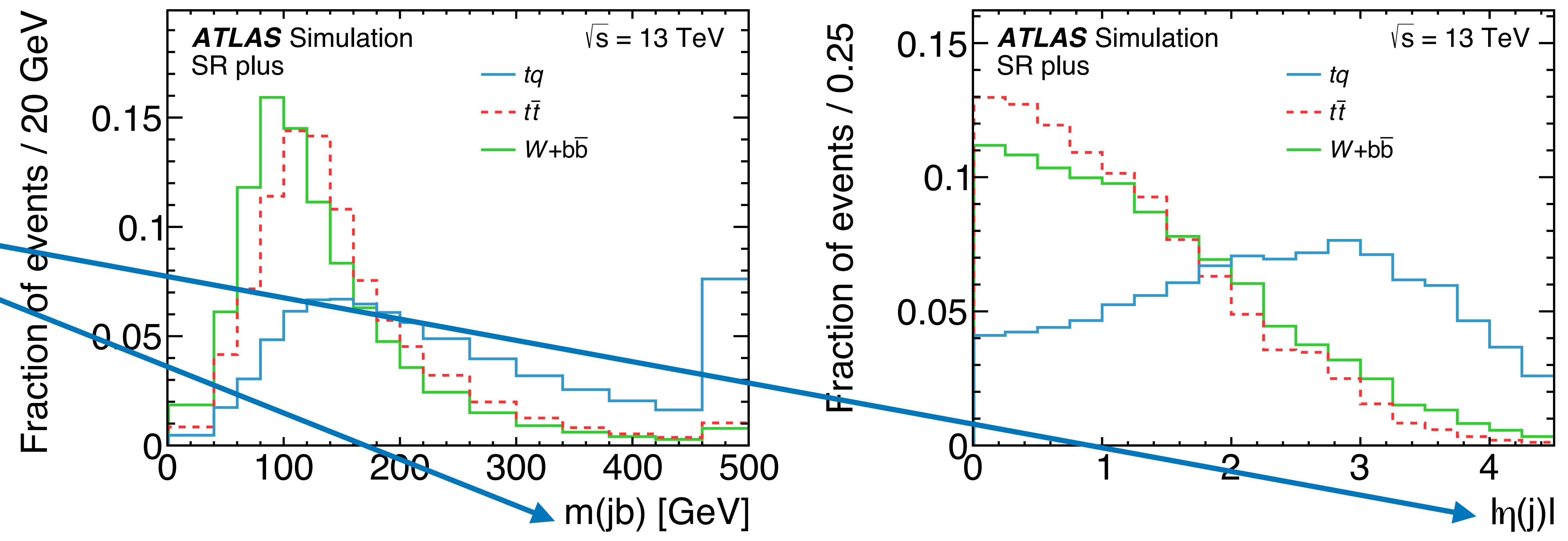
CR name	Requirement
B-e-plus	$q_e/e = +1$, $\lvert\eta(e)\rvert < 1.37$, $E_T^{miss} < 30$ GeV
B-e-minus	$q_e/e = -1$, $\lvert\eta(e)\rvert < 1.37$, $E_T^{miss} < 30$ GeV
EC-e-plus	$q_e/e = +1$, $\lvert\eta(e)\rvert > 1.52$, $E_T^{miss} < 30$ GeV
EC-e-minus	$q_e/e = -1$, $\lvert\eta(e)\rvert > 1.52$, $E_T^{miss} < 30$ GeV
CR μ-plus	$q_\mu/e = +1$, $28\text{ GeV} < p_T(\mu) < 40\text{ GeV} \cdot \frac{\lvert\Delta\phi(j_1,\ell)\rvert}{\pi}$
CR μ-minus	$q_\mu/e = -1$, $28\text{ GeV} < p_T(\mu) < 40\text{ GeV} \cdot \frac{\lvert\Delta\phi(j_1,\ell)\rvert}{\pi}$

Discriminating Variables

No.	Symbol	Description
1.	$m(jb)$	Invariant mass of the untagged jet (j) and the b-tagged jet (b)
2.	$\lvert\eta(j)\rvert$	Absolute value of the pseudorapidity of the untagged jet
3.	$\lvert\Delta p_T(W, jb)\rvert$	Absolute value of the difference in transverse momentum between the reconstructed W boson and the jet pair
4.	$\lvert\Delta\phi(W, jb)\rvert$	Absolute value of the difference in azimuthal angle between the reconstructed W boson and the jet pair
5.	$m(t)$	Invariant mass of the reconstructed top quark
6.	$\lvert\Delta\eta(\ell, j)\rvert$	Absolute value of the difference in pseudorapidity between the charged lepton (ℓ) and the untagged jet
7.	$\Delta R(\ell, j)$	Angular distance of the charged lepton and the untagged jet
8.	$\lvert\Delta\eta(b, \ell)\rvert$	Absolute value of the difference in pseudorapidity between the b-tagged jet and the charged lepton
9.	$m_T(W)$	Transverse mass of the W boson
10.	$m(\ell b)$	Invariant mass of the charged lepton and the b-tagged jet
11.	$H_T(\ell, \text{jets}, E_T^{miss})$	Scalar sum of the transverse momenta of the charged lepton and the jets and E_T^{miss}
12.	$\lvert\Delta\eta(b, j)\rvert$	Absolute value of the difference in the pseudorapidity of the two jets
13.	$\lvert\Delta\phi(j, t)\rvert$	Absolute value of the difference in the azimuthal angle between the untagged jet and the reconstructed top quark
14.	$\cos\theta^*(\ell, j)$	Cosine of the angle θ^* between the charged lepton and the untagged jet in the rest frame of the reconstructed top quark
15.	$\lvert\eta(\ell)\rvert$	Absolute value of the pseudorapidity of the charged lepton
16.	S	Sphericity defined as the sum of the 2nd and 3rd largest eigenvalues of the sphericity tensor multiplied by 3/2
17.	$\lvert\Delta p_T(\ell, j)\rvert$	Absolute value of the difference in transverse momentum of the charged lepton and the untagged jet

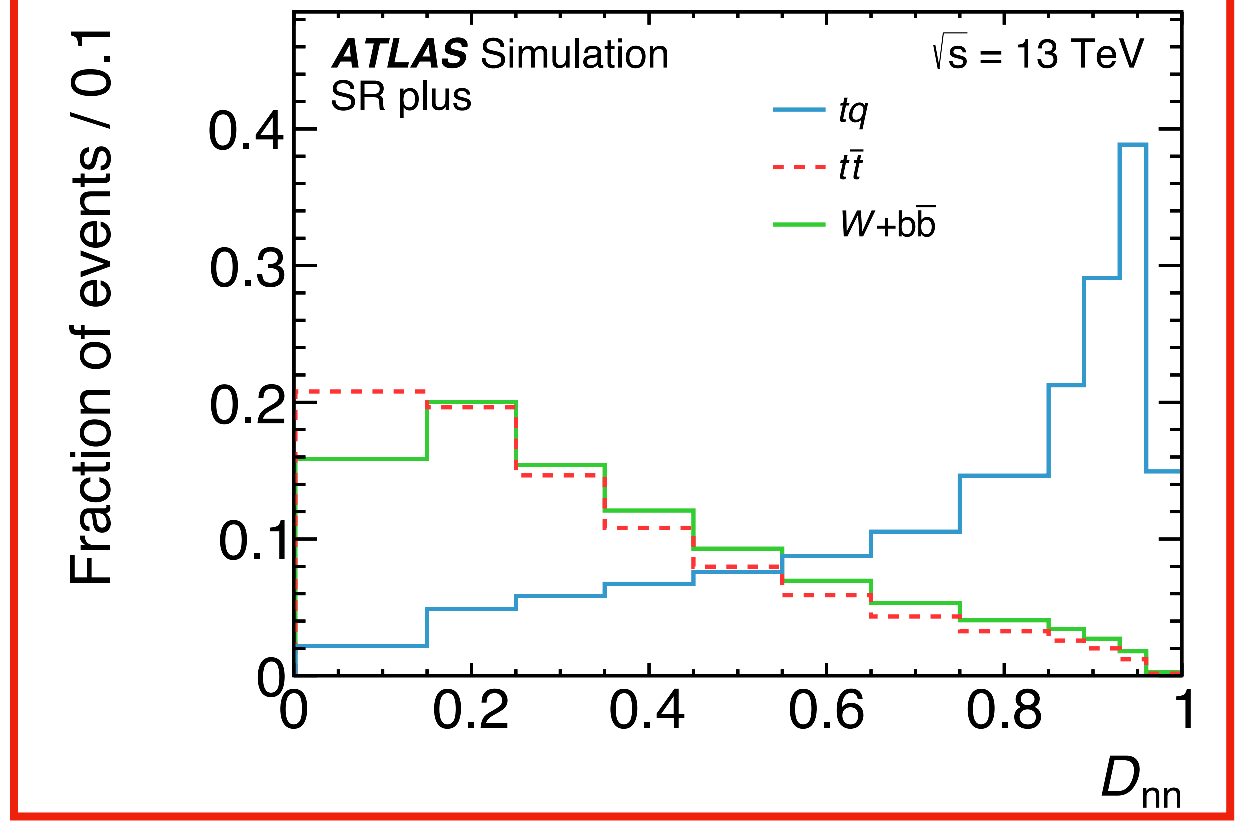
NN Input Variables

Input (Kinematic Variables)



NN Training

NN Score



(2) Single top in t-channel

- **Inclusive cross-section**

$$\sigma(tq) = 137^{+8}_{-8}\,\text{pb} \quad \text{and} \quad \sigma(\bar{t}q) = 84^{+6}_{-5}\,\text{pb}.$$

$$\sigma(tq+\bar{t}q) = 221^{+13}_{-13}\,\text{pb} \quad \text{and} \quad R_t = 1.636^{+0.036}_{-0.034}$$

- Agrees well with NNLO predictions !
- Statistical << systematic (uncertainties)
- Dominant uncertainty: Signal (tq) modelling
- R_t: cancellation of signal modelling

Systematic uncertainty	$\Delta\sigma(tq)/\sigma(tq)$	$\Delta\sigma(\bar{t}q)/\sigma(\bar{t}q)$	$\Delta\sigma(tq+\bar{t}q)/\sigma(tq+\bar{t}q)$
tq matching scale definition, rate	+3.1 / −2.9	+2.8 / −2.6	+2.9 / −2.8
tq parton shower, rate	+2.6 / −2.5	+3.3 / −3.2	+2.9 / −2.8
tq final-state radiation	+2.1 / −2.0	+2.2 / −2.1	+2.1 / −2.0
tq matching scale definition, shape	+1.6 / −1.5	+1.2 / −1.2	+1.5 / −1.4
JES η intercalibration modelling	+1.2 / −1.2	+1.6 / −1.5	+1.4 / −1.3
b-tagging NP B1	+1.0 / −0.9	+1.0 / −1.0	+1.0 / −0.9
b-tagging NP B0	+1.0 / −0.9	+1.0 / −1.0	+1.0 / −0.9
Luminosity	+0.9 / −0.8	+0.9 / −0.9	+0.9 / −0.8

Systematic uncertainty	$\Delta R_t/R_t$
$W^- + c(\bar{c})$ cross-section	+0.8 / −0.8
tq parton shower, rate	+0.7 / −0.7
$W^+ + c(\bar{c})$ cross-section	+0.5 / −0.5
PDF eigenvector 09	+0.5 / −0.5
MC statistical uncertainty in D_{nn} bin 10 of SR minus	+0.4 / −0.4
JES η intercalibration modelling	+0.4 / −0.4
tq matching scale definition, shape	+0.4 / −0.4
PDF eigenvector 05	+0.4 / −0.4

Uncertainty group	$\Delta\sigma(tq)/\sigma(tq)$	$\Delta\sigma(\bar{t}q)/\sigma(\bar{t}q)$	$\Delta\sigma(tq+\bar{t}q)/\sigma(tq+\bar{t}q)$	$\Delta R_t/R_t$
Data statistics	+0.4 / −0.4	+0.5 / −0.5	+0.3 / −0.3	+0.6 / −0.6
Signal modelling	+4.9 / −4.5	+5.2 / −4.8	+5.0 / −4.6	+0.9 / −0.9
Background modelling	+1.8 / −1.6	+2.1 / −1.9	+1.8 / −1.6	+1.5 / −1.4
MC statistics	+1.0 / −1.0	+1.4 / −1.3	+1.1 / −1.0	+0.8 / −0.8
PDFs	+0.4 / −0.4	+1.2 / −1.0	+0.6 / −0.6	+0.9 / −0.8
Jets	+2.2 / −2.0	+3.0 / −2.7	+2.5 / −2.2	+1.0 / −0.9
b-tagging	+1.6 / −1.5	+1.7 / −1.5	+1.6 / −1.5	+0.2 / −0.1
Leptons	+1.1 / −1.0	+1.1 / −1.0	+1.1 / −1.0	+0.1 / −0.1
Luminosity	+0.9 / −0.8	+0.9 / −0.9	+0.9 / −0.8	< 0.1
Total	+5.9 / −5.5	+6.6 / −6.2	+6.1 / −5.7	+2.2 / −2.1

- **Dependence on m_t**
  - Reference: m_t = 172.5 GeV (central value)
  - Variations: m_t = 171 or 174 GeV

$$\sigma(m_t) = \sigma(172.5\,\text{GeV}) + a \cdot \Delta m_t\,[\text{GeV}]$$

$$a = (-1.50 \pm 0.26)\,\text{pb}\,\text{GeV}^{-1} \text{ for } \sigma(tq)$$
$$a = (-0.85 \pm 0.31)\,\text{pb}\,\text{GeV}^{-1} \text{ for } \sigma(\bar{t}q)$$
$$a = (-2.35 \pm 0.69)\,\text{pb}\,\text{GeV}^{-1} \text{ for } \sigma(tq+\bar{t}q)$$

  - negligible effect for R_t

(2) SM Interpretation - Single top in t-channel

- **Sensitivity of R_t to PDF sets**

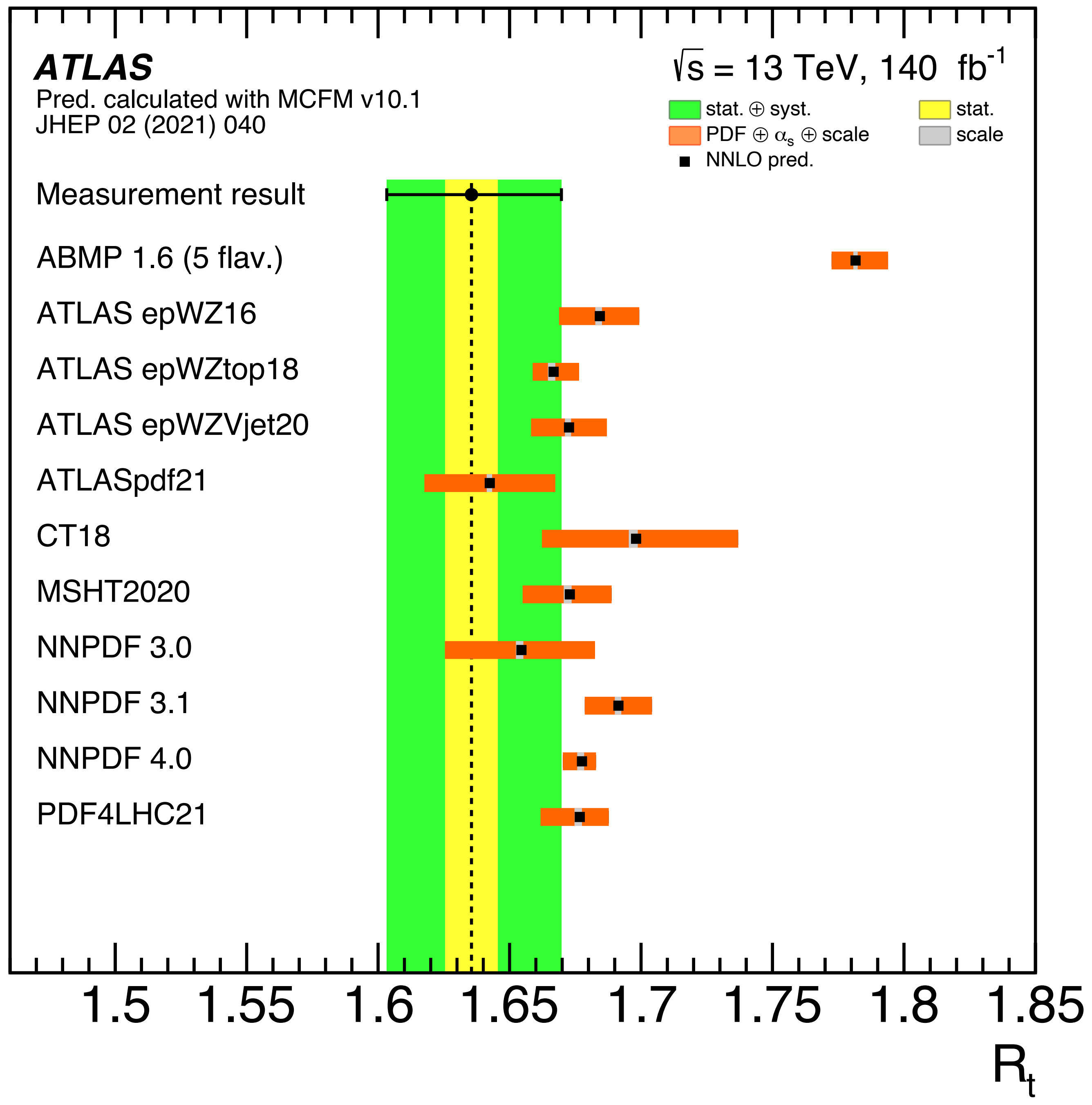
  - PDFs by different groups differ in

    (1) data used

    (2) value of α_s

    (3) values of quark masses used

    (4) treatment of heavy quarks



R_t values from NNLO predictions (MCFM) on different PDF sets

- **Determination of $|V_{tb}|$**

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

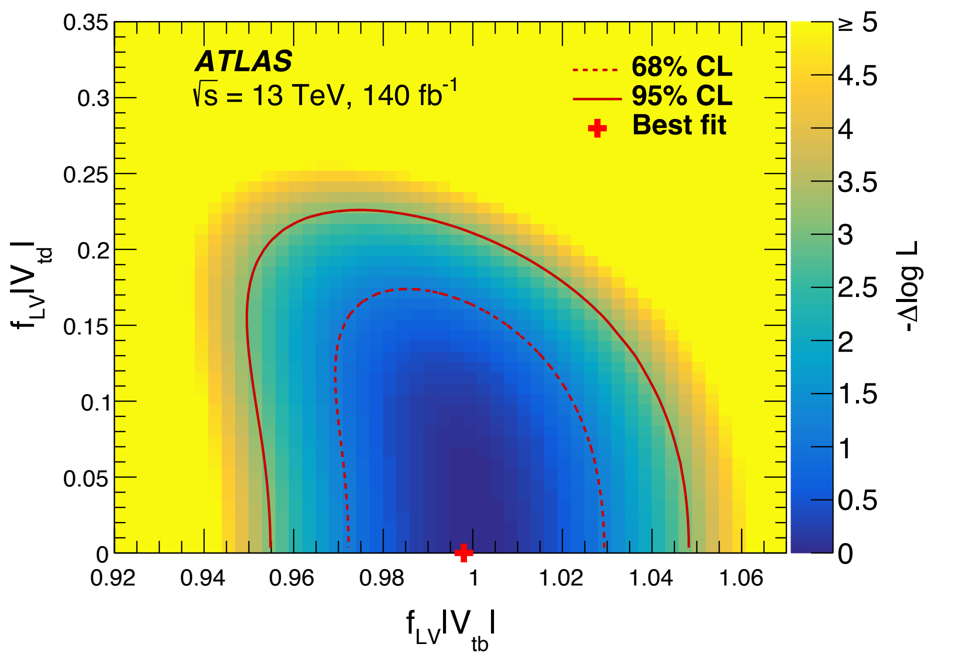
  - **Assumption**: $|V_{td}|, |V_{ts}| \ll |V_{tb}|$

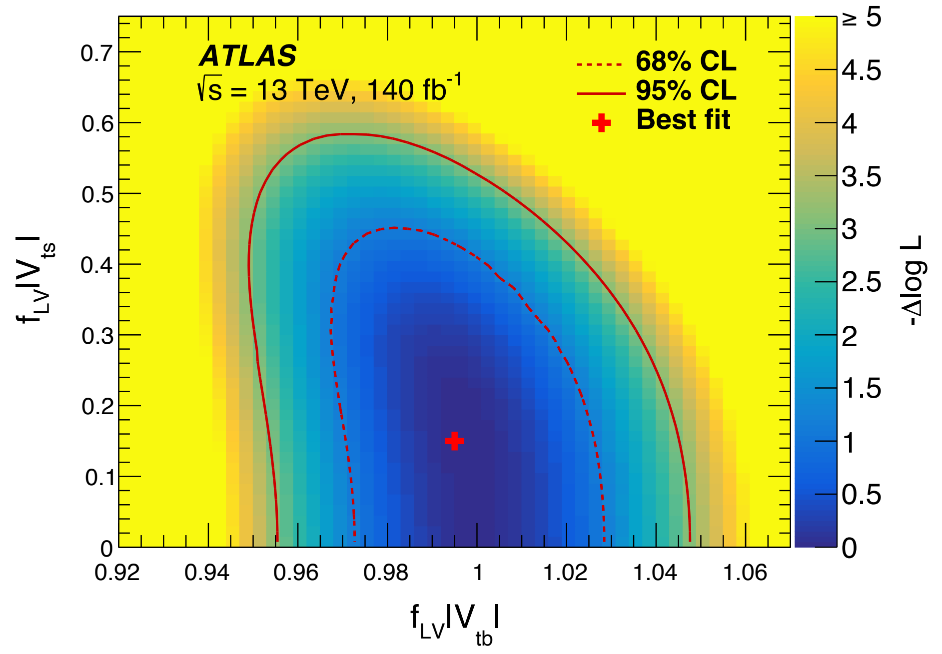
    Wtb interaction (LH weak coupling)

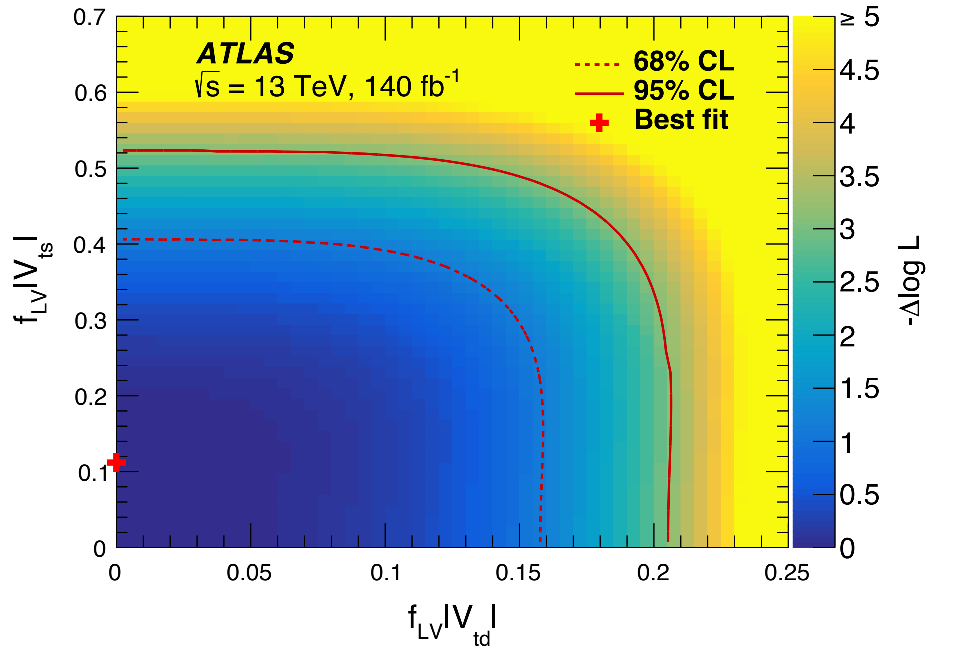
  - Extracted from $\sigma(tq + \bar{t}q)_{meas} / \sigma(tq + \bar{t}q)_{SM}$

  - 30% improvement from Run 1 ATLAS + CMS Combination JHEP05(2019)088

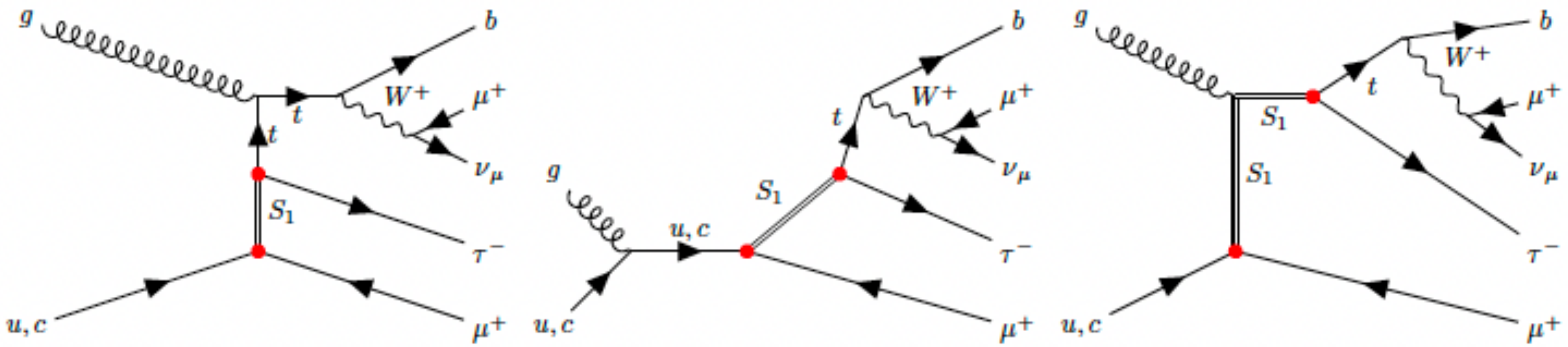
- **Determination of $|V_{tb}|, |V_{td}|, |V_{ts}|$**





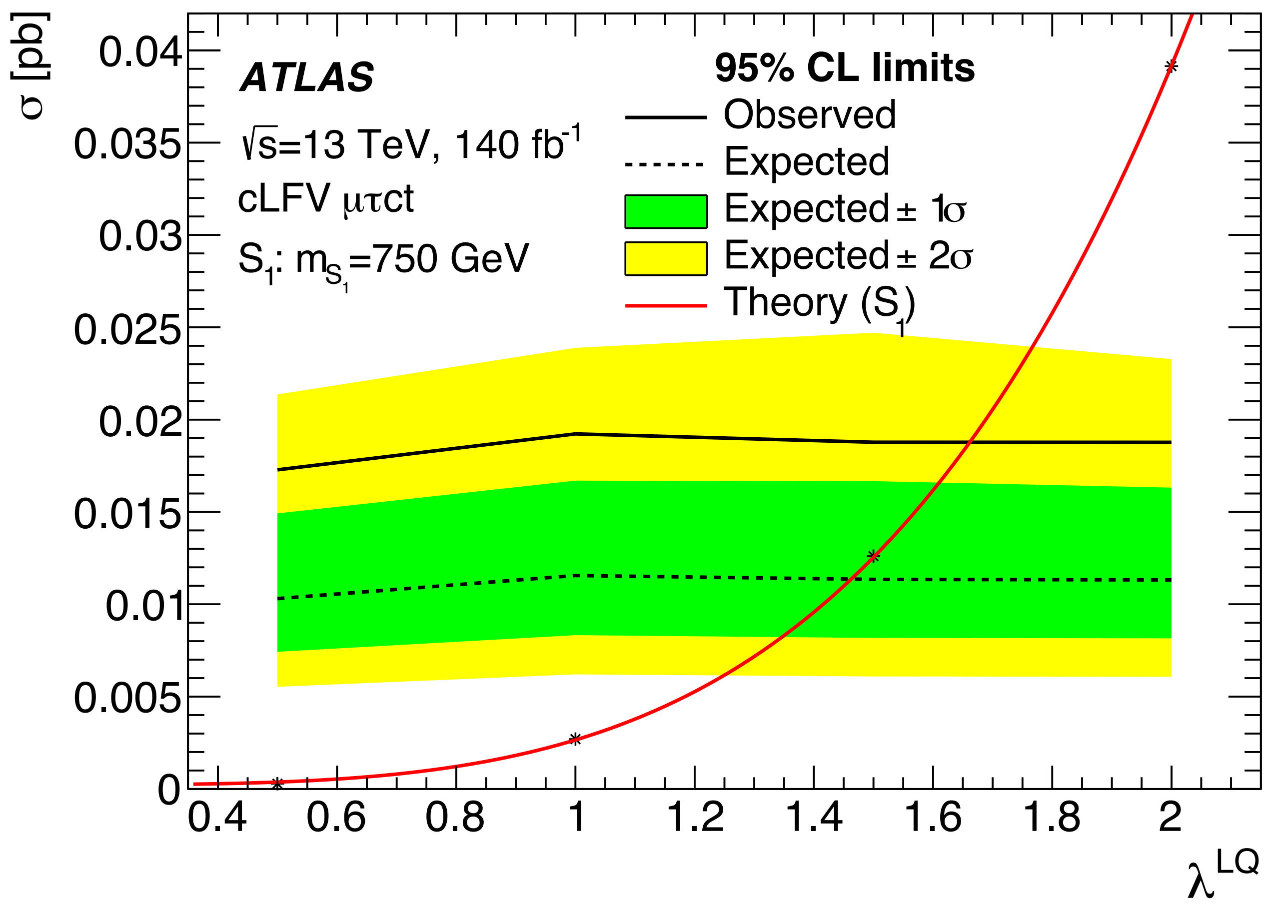


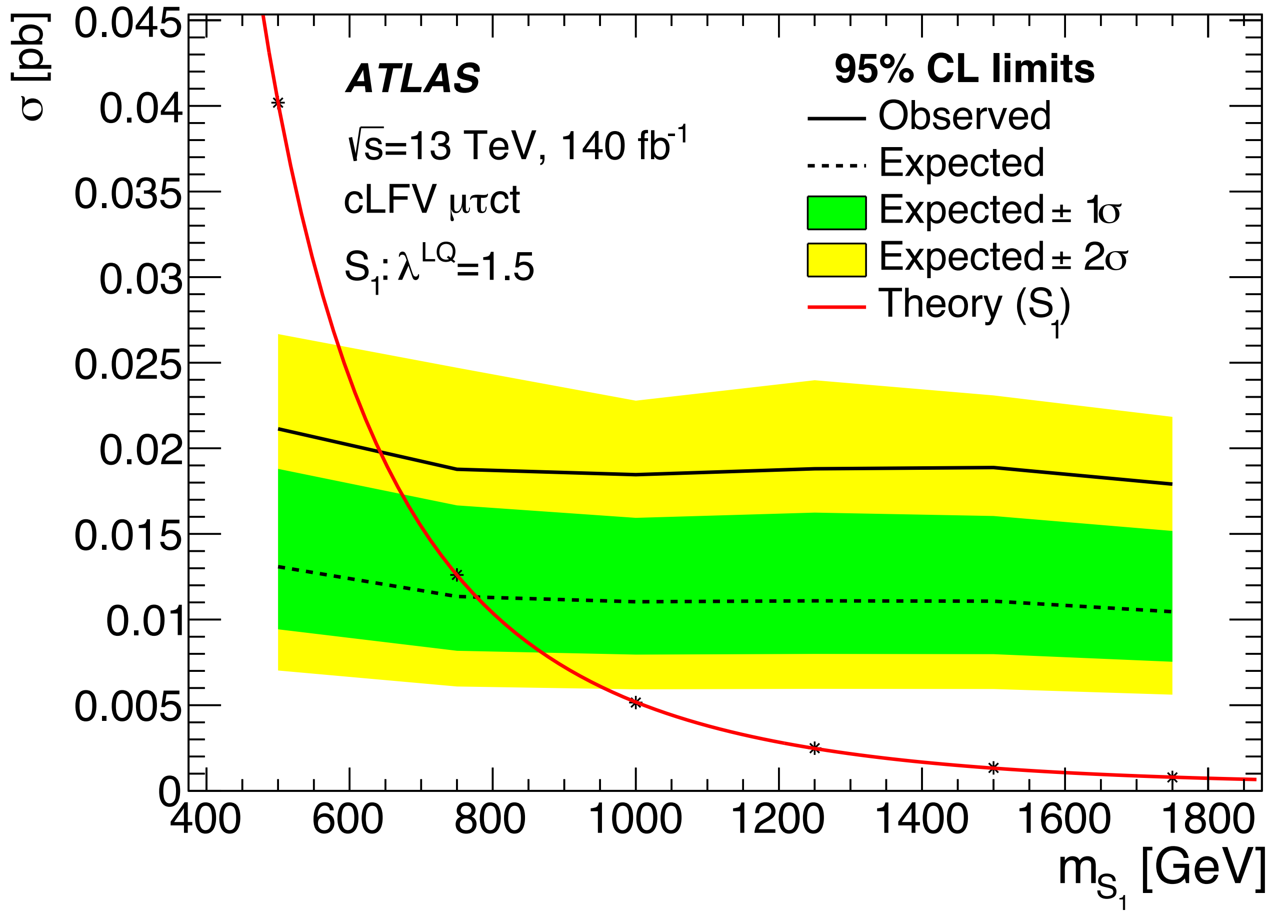
(3) LQ Interpretation - CLFV - $\mu\tau q(u,c)t$

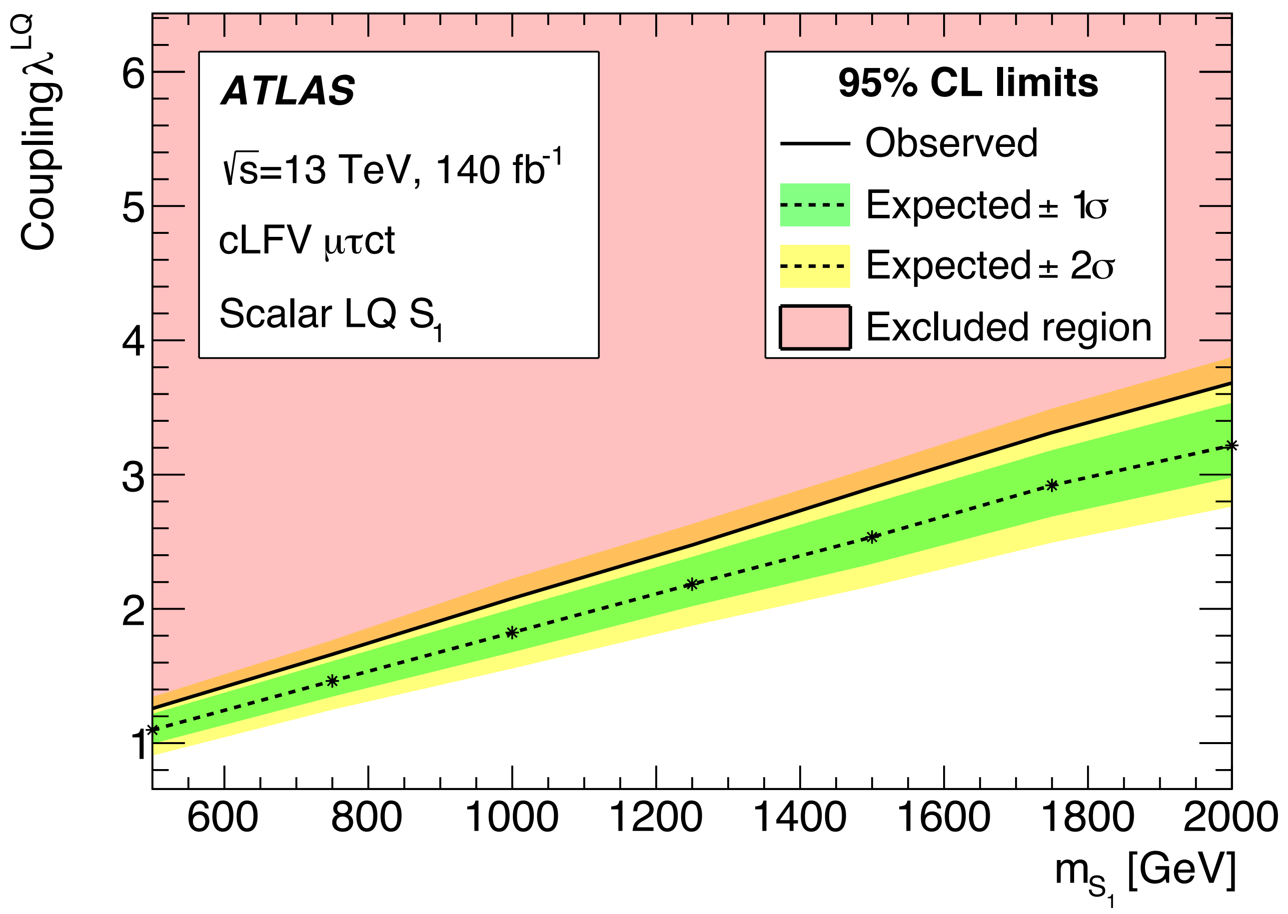


$$\lambda_{ki} \in \begin{pmatrix} \lambda_{t\tau} & \lambda_{c\tau} & \lambda_{u\tau} \\ \lambda_{t\mu} & \lambda_{c\mu} & \lambda_{u\mu} \\ \lambda_{te} & \lambda_{ce} & \lambda_{ue} \end{pmatrix} \equiv \lambda^{\mathrm{LQ}} \begin{pmatrix} 10 & 1 & 0.1 \\ 1 & 0.1 & 0.01 \\ 0.1 & 0.01 & 0.001 \end{pmatrix}$$

- Scalar leptoquark (S_1) model: couplings between all up-type quarks and all charged leptons with production processes shown above: Q=-1/3, S=1, L=1, B=1/3
  - non-resonant, resonant, resonant (off-shell)
- Focus on single leptoquark production coupling to a single lepton with single quark generation only







Outlook on Precision EFT Analysis in Top Quark Sector

With an increase in precision in top quark related measurements, several key aspects need greater attention, which may have been overlooked or considered sub-dominant:

- **Comprehensive grasp of all relevant EFT parameters' impact on top-quark related observables** (e.g. cross-sections, angular distributions, and spin correlations)
- **QCD NLO in general and EWK NLO in distributions**
  - higher order corrections needed, esp. for distributions sensitive to EFT contributions
- **Impact of EFT on key elements**:
  - Top quark propagators and decay widths
  - Backgrounds from $t\bar{t}$, single top, and associated production processes
  - Signal efficiencies in measurements like $t\bar{t}$, tW, and $tZ/t\gamma$ with d=8 operators for future analyses.
- **Parameter management in high-dimensional fits**
  - Balancing a growing number of EFT parameters in likelihood fits, while consistently incorporating systematics.

Then, how do we make the most optimal EFT analysis in top quark sector with the tools we have now?

- So far, EFT analyses have mostly focused on interpretation rather than optimising the exclusion of EFT parameters
- The most efficient way to analyse EFT parameters is to leverage advanced statistical techniques, high-precision theoretical calculations, and extensive datasets from the LHC.