

ATLAS results on associated top quark production and EFT interpretations

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◆ **The LHC is a top-quark factory** - electroweak couplings of top-quark become directly accessible

- ▶ **Probes of top-quark electroweak interactions** (tZ, tW, ty, tH vertices)
- ▶ **Important backgrounds** to Higgs measurements and BSM searches
- ▶ **Sensitive to Effective Field Theory parameters** and important input for theory

◆ The **full RunII LHC dataset** at 13 TeV with an integrated Lumi of 140/fb allows for exploration of complementary regimes:

- **Rare final states** → first observations & cross section measurements
- **High-energy** phase space where new physics effects grow with energy
- **Differential** and **angular** observables

◆ This talk covers:

[publication link](#)
 $t\bar{t}\gamma\gamma$

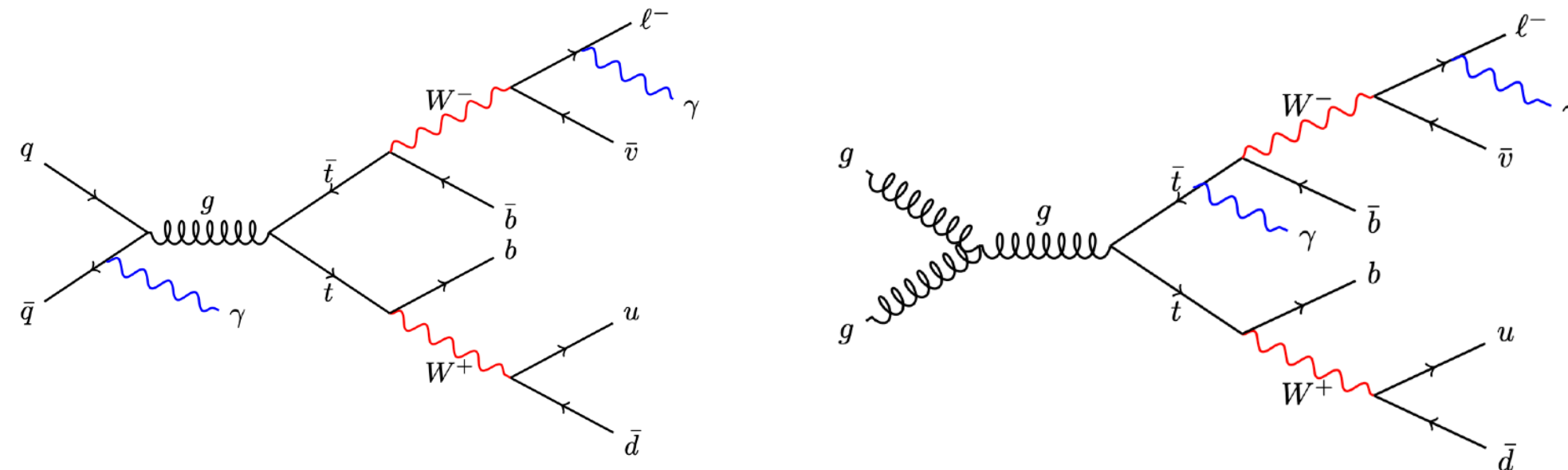
Up-dated
[publication link](#)
 tZq

[publication link](#)
 $t\bar{t}Wj_{EW}$

Brand New!
[publication link](#)
 $cLFV\ e\mu q t$

- ◆ First observation of the $t\bar{t}\gamma\gamma$ with 5.2σ (obs.) / 5.7σ (exp.)

Lepton+jets
channel



- ◆ Challenge: Background reduction & estimation

Mostly fake photon background $\rightarrow$ electrons from $t\bar{t}\gamma$ recon. as photons

Corrected with data-driven rates taken from $t\bar{t}\gamma$ analysis

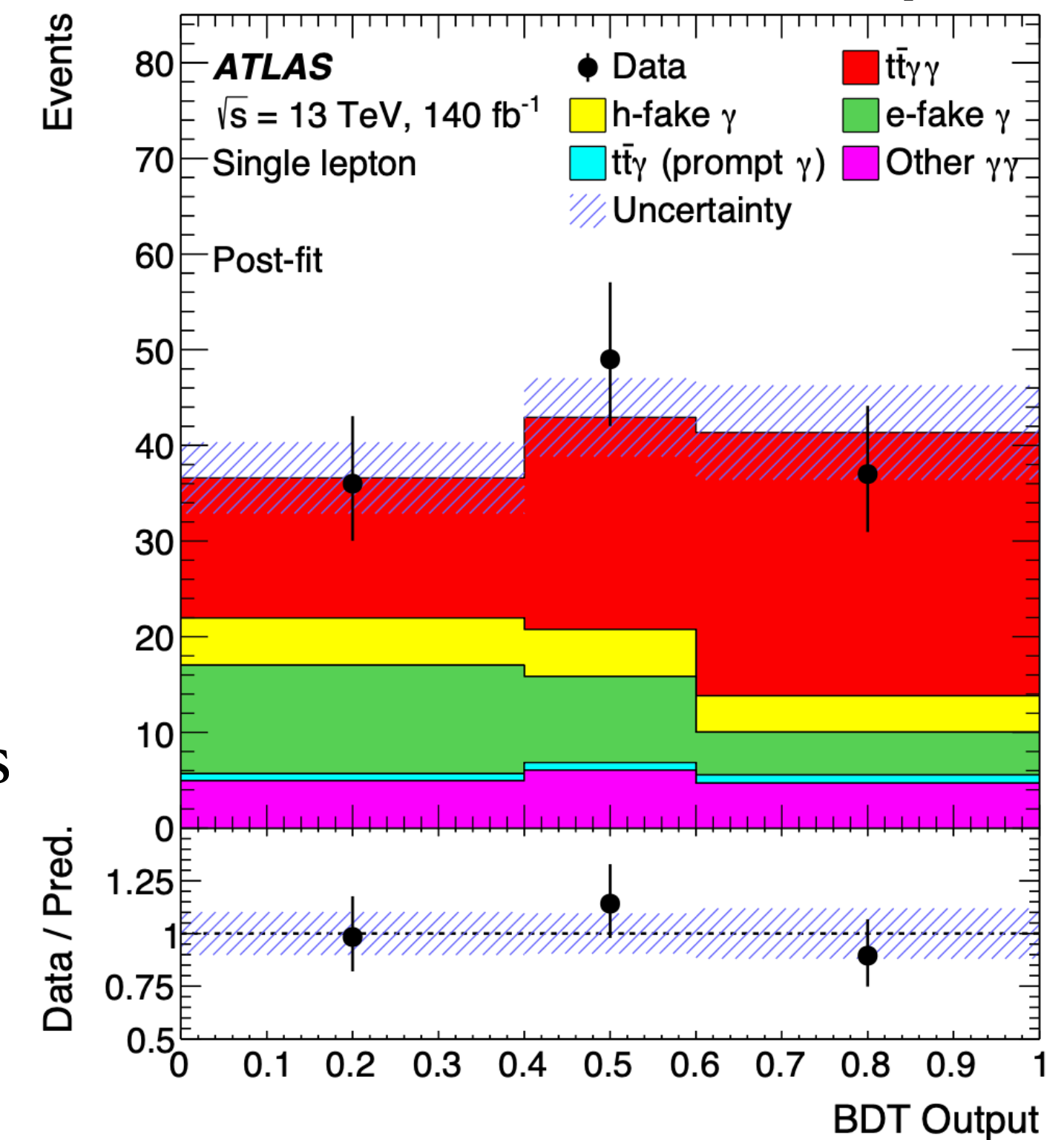
- ◆ Fiducial cross section measured

$$\sigma_{fid}(t\bar{t}\gamma\gamma) = 2.42^{+0.58}_{-0.53} \text{ fb}$$

- ◆ Ratio to $t\bar{t}\gamma$ cross section

$$R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma} = (3.30^{+0.70}_{-0.65}) \times 10^{-3}$$

BDT with 19 inputs



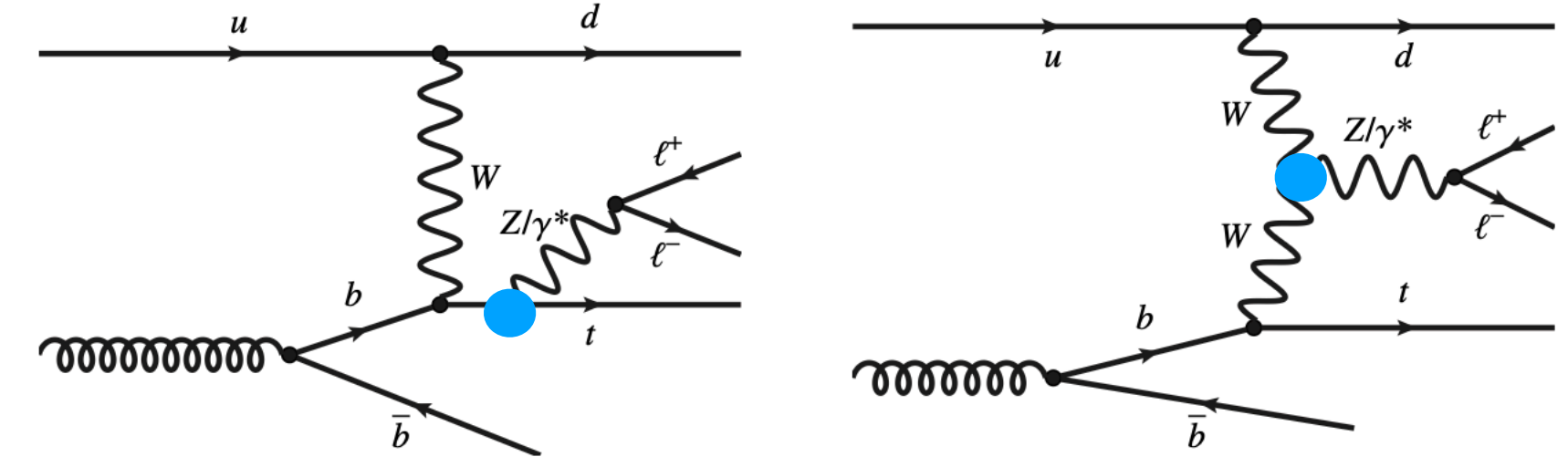
- ▶ Reference measurement for future developments
no generator produces this process at NLO (LO: K-factor: 1.7)
- ▶ Relevant irreducible background to $t\bar{t}H$ ($H \rightarrow \gamma\gamma$) measurement

- ♦ Electroweak t-channel single top + Z, purely EW at LO, allows direct access to the tZ & WWZ couplings
- **Trilepton channel:** 3L, OSSF pair, 2-4 jets, 1-2 b-tags, forward spectator jet
- **Neural-network discriminant** (19 inputs)
- SR + 6 CRs for ttZ, diboson and non-prompt leptons
- **Looser selection** than the 2020 observation **helps to reduce stat. uncertainty**
- ♦ **Inclusive cross section measured**

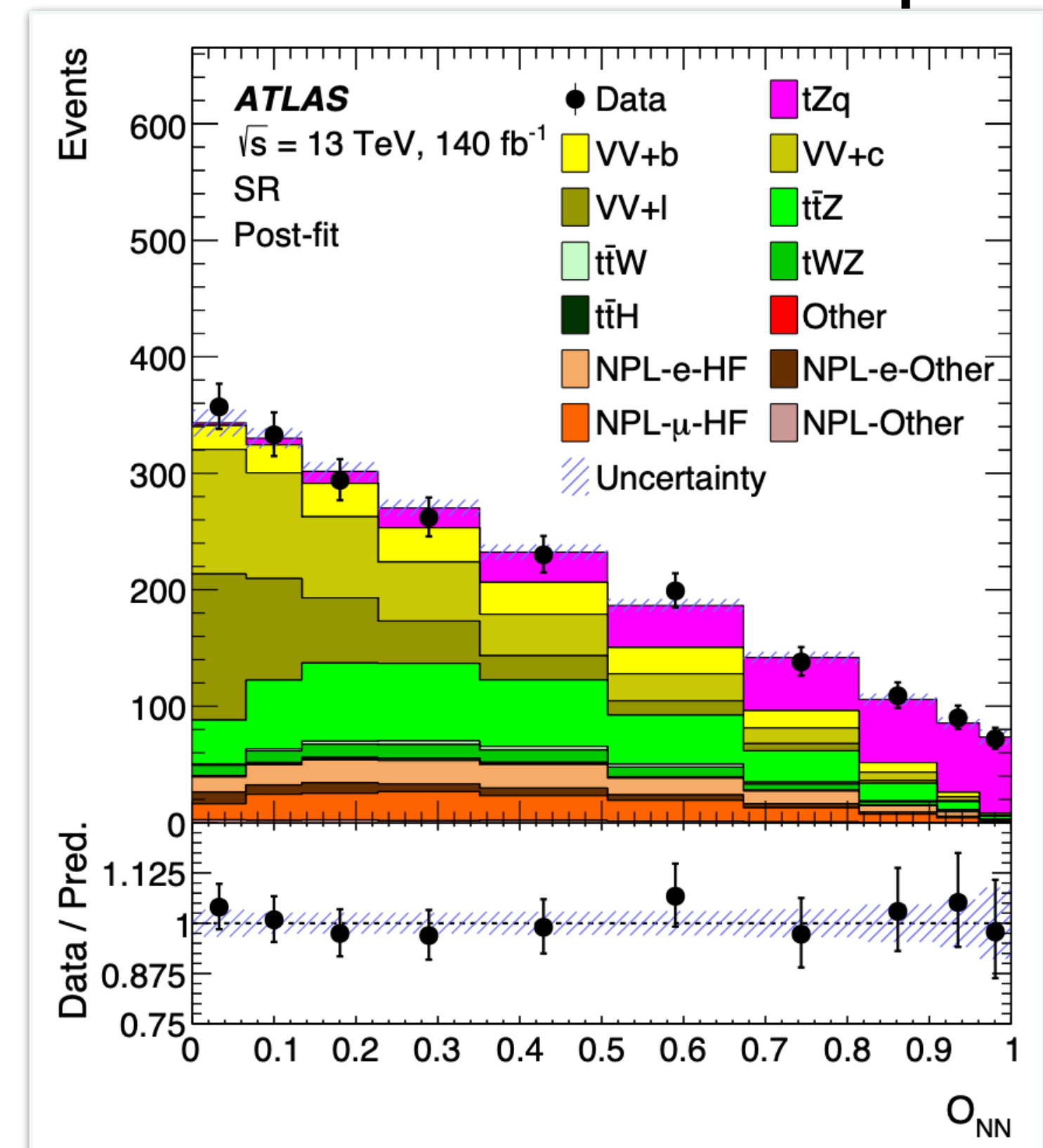
$$\sigma_{incl}(tZq) = 95.2^{+8.5}_{-7.9} \text{ fb}$$

Improvement!
Unc. 14% → 10%

- ▶ Agreement with the 5FS NLO QCD prediction
- ▶ Still statistically limited! Leading syst. uncertainty tZq modelling (4%)
- ▶ **First separate $t/\bar{t}$ measurement** - the ratio is sensitive to proton PDFs
- ▶ tZq is an important background to tHq and a **clean benchmark for the top electroweak sector**

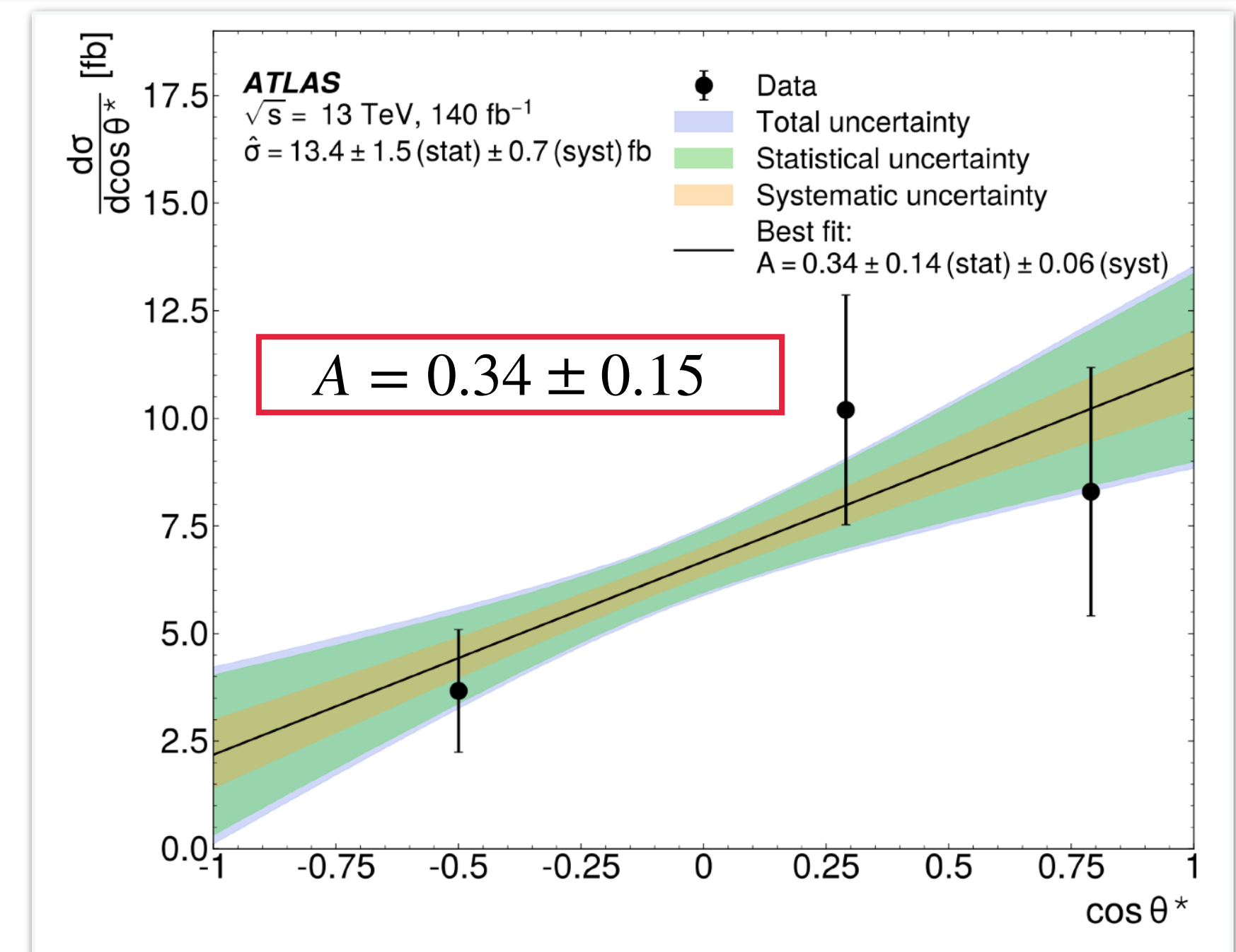
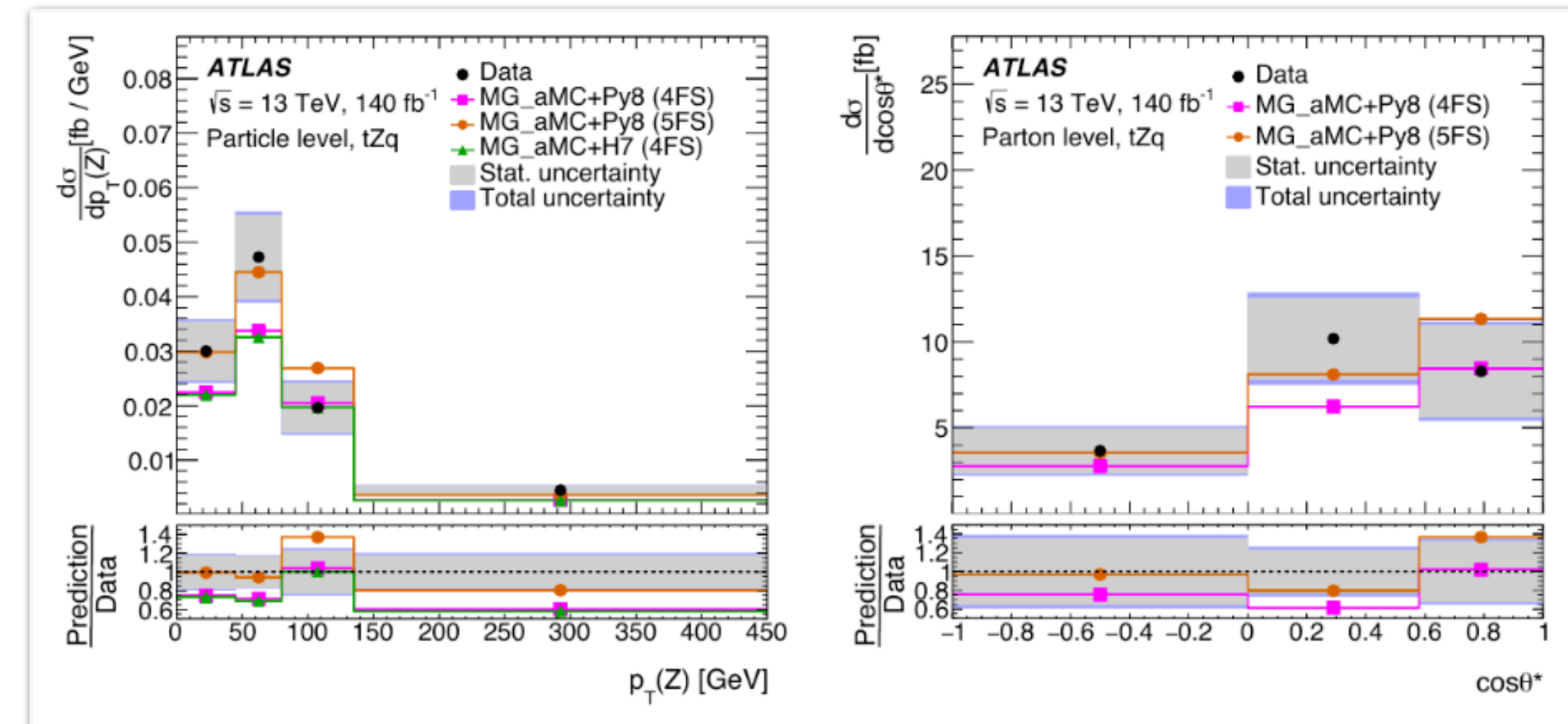


BDT with 19 inputs

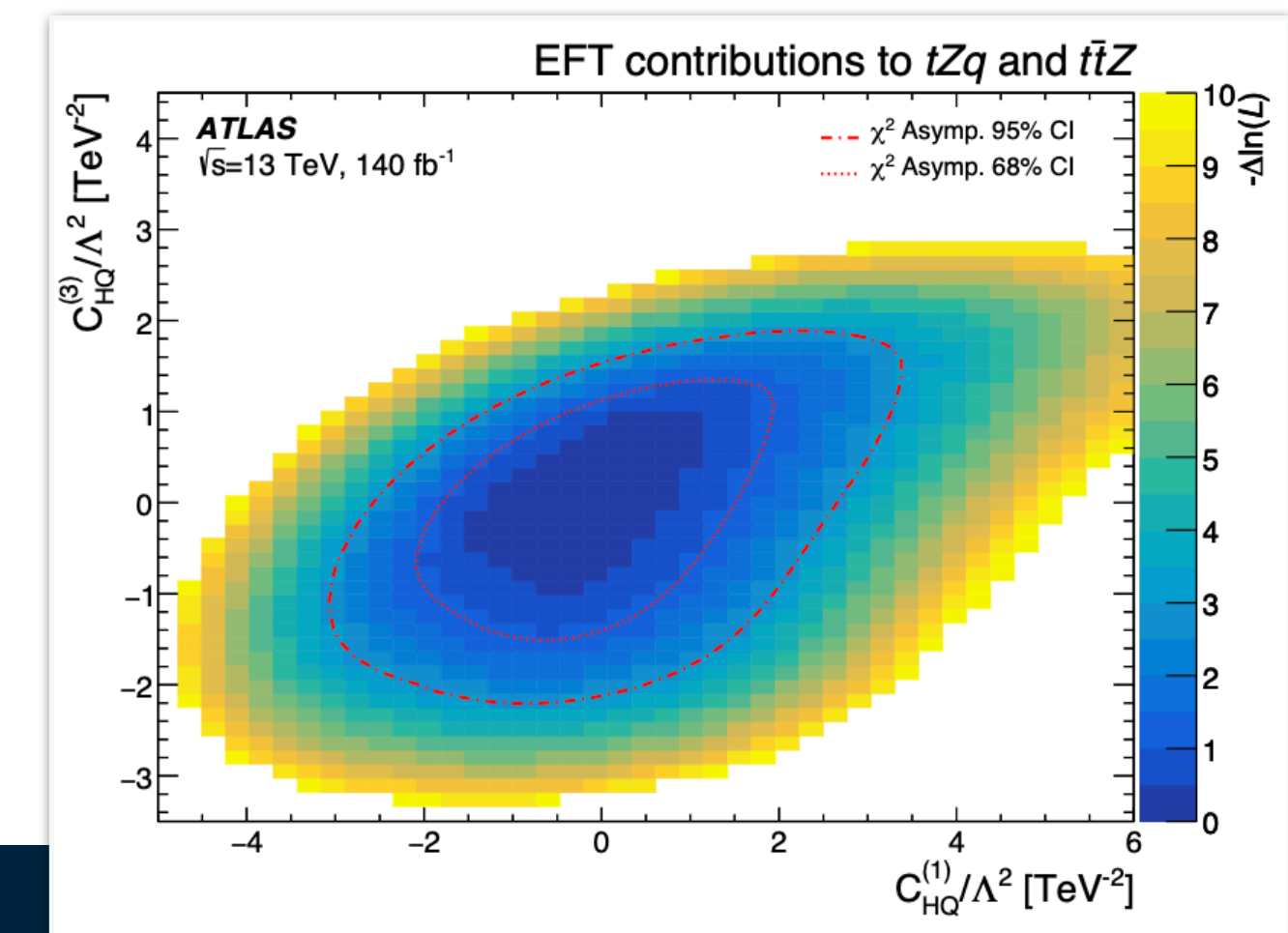
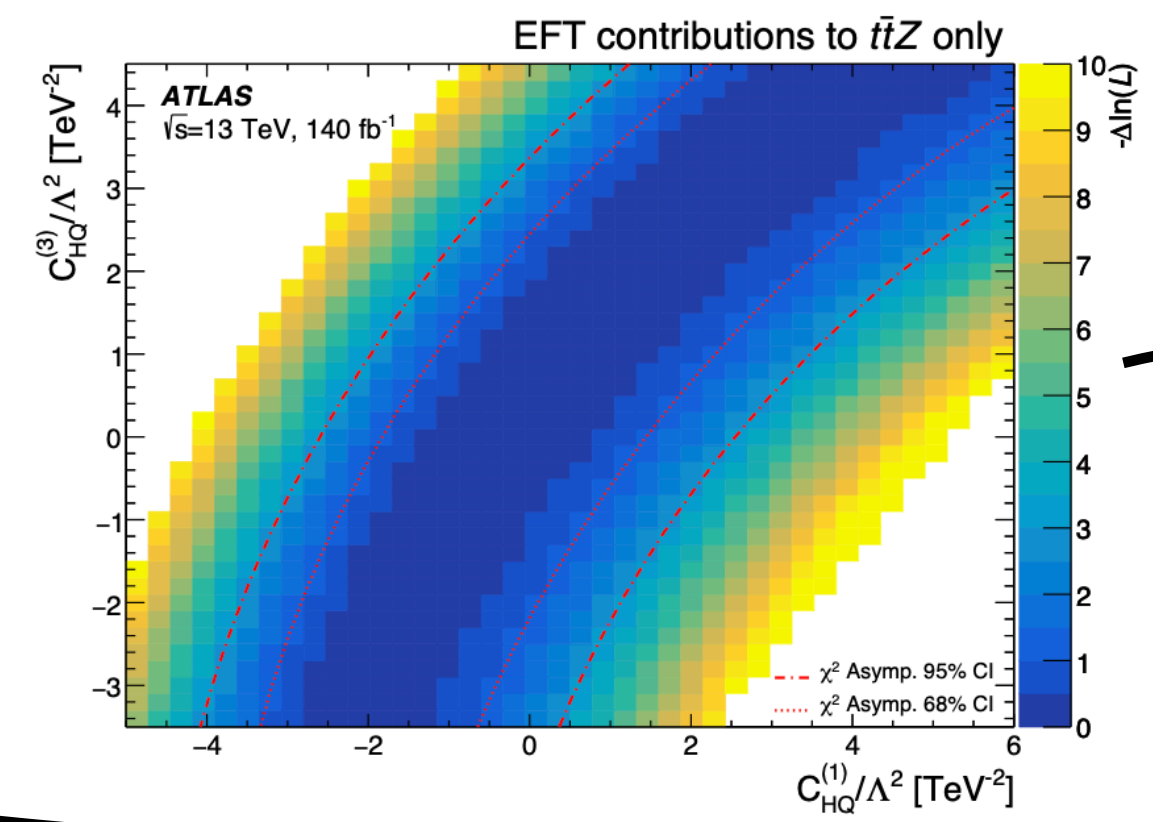
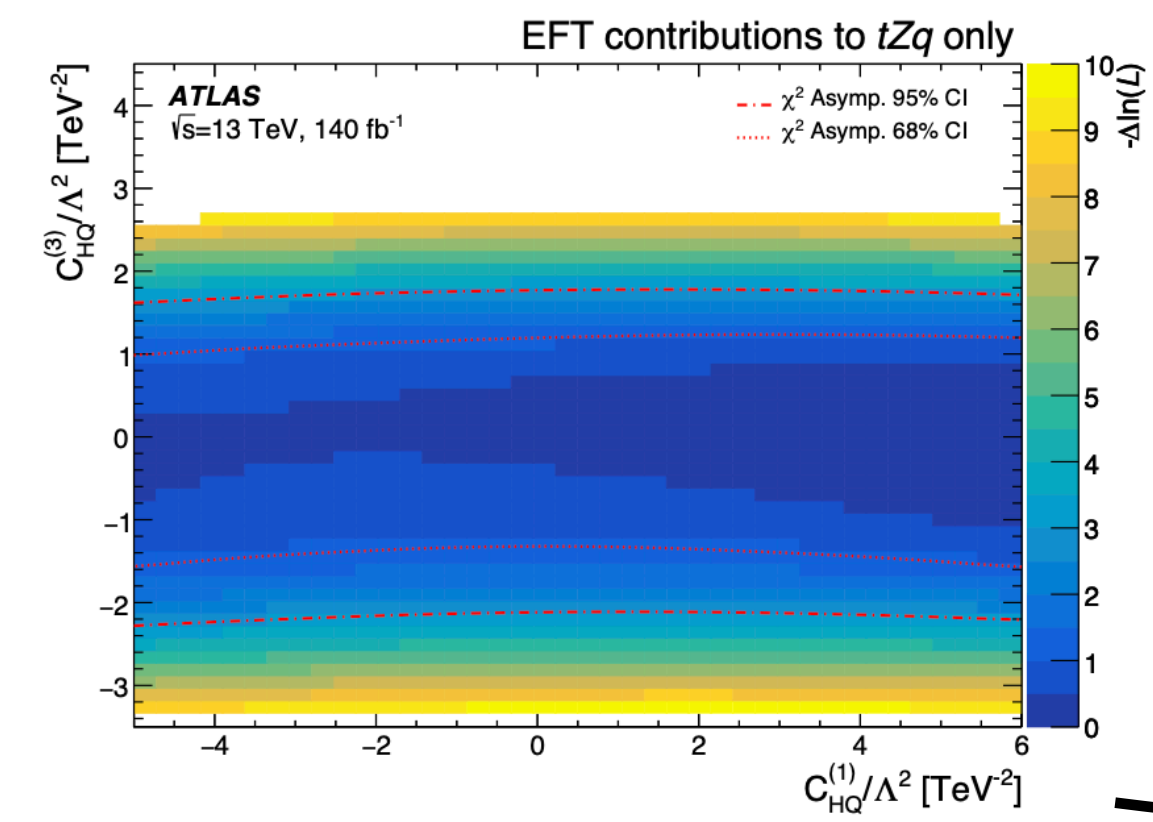
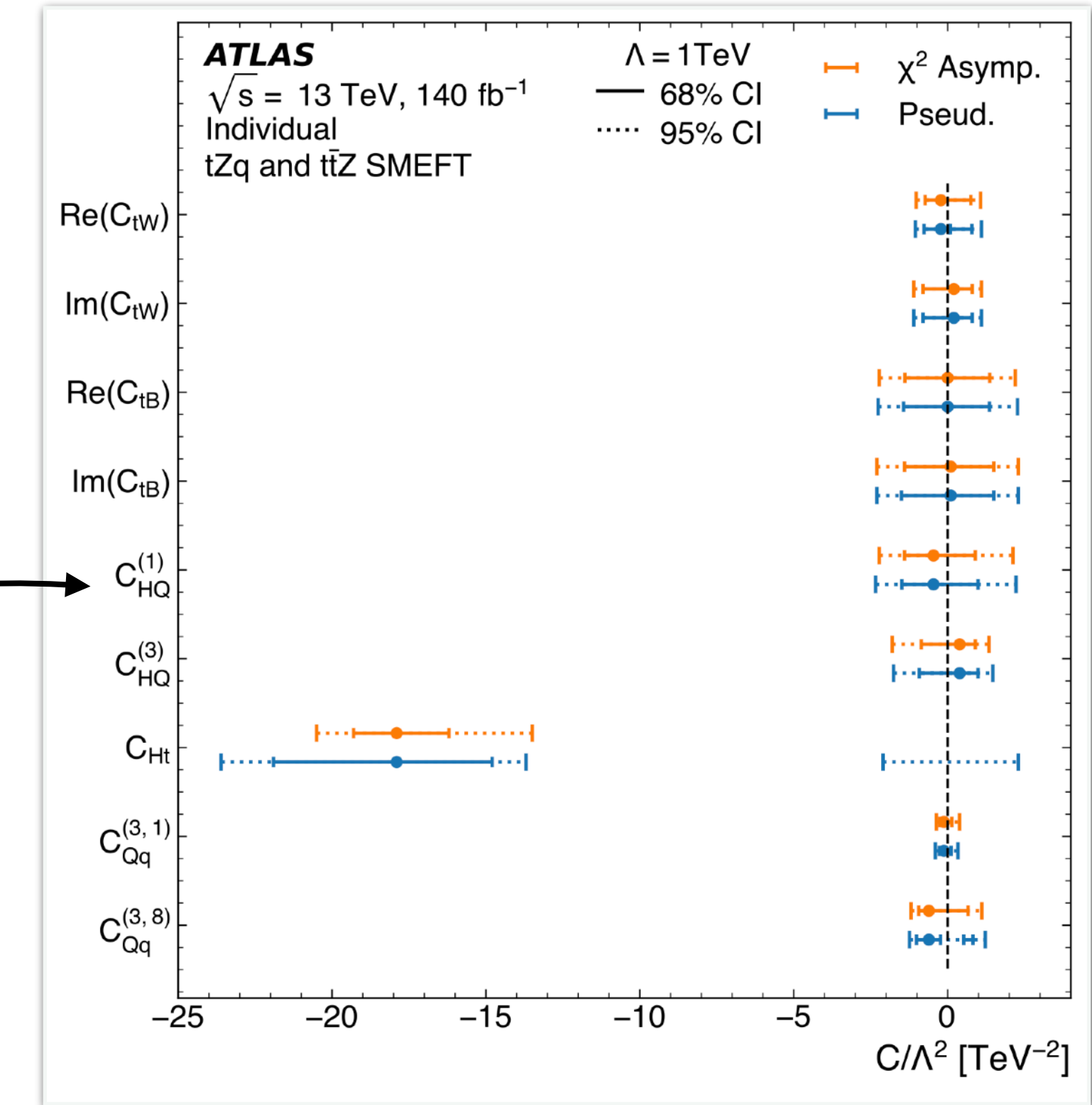


- ◆ First ATLAS differential tZq measurement (at parton and particle level)
- **11 observables unfolded with PLU:**
 - p_T and $|\eta|$ of Z, top & spectator jet
 - the triple-lepton mass, and angular distributions, e.g. $\cos \theta^*$
- **MG5_aMC@NLO + Pythia8**
 - 5FS: Overall good agreement ($p > 0.19$)
 - 4FS: Shape fine, normalisation 30% too low
- ◆ Unfolded $\cos \theta^*$ at parton level $\rightarrow$ top-quark spin asymmetry
 - t-channel produces polarised top quarks (in leading-order $A = 1$)

- ▶ Every bin **stat. limited** $\rightarrow$ can't distinguish PS or PDF variations yet
- ▶ Spectator jets observables probe the QCD radiation modelling of the t-channel topology
- ▶ Parton-level results ready for comparison with future fixed-order (NLO/aNNLO) calculations



- ◆ EFT interpretation at detector-level
→ fit $p_T(Z)$ in 4 bis (SR split by NN score)
- ◆ **Parameterise EFT effects of tZq and ttZ**
 - 9 wilson coefficients (C_{tB} , C_{tW} , $C_{HQ}^{(1)}$, $C_{HQ}^{(3)}$, C_{Ht} , $C_{tq}^{(3,1)}$, $C_{tq}^{(3,8)}$)
 - **Linear + quadratic** terms, LO EFT scaled to NLO SM
 - Quadratic terms can dominate → coverage checked with pseudo data
 - Constraints on $C_{HQ}^{(1)}$, $C_{HQ}^{(3)}$, $C_{tq}^{(3,8)}$ **comparable to the best ATLAS limits**
 - C_{Ht} shows two minima but the SM stays inside 95% CI
- ◆ **No significant deviation from the SM**

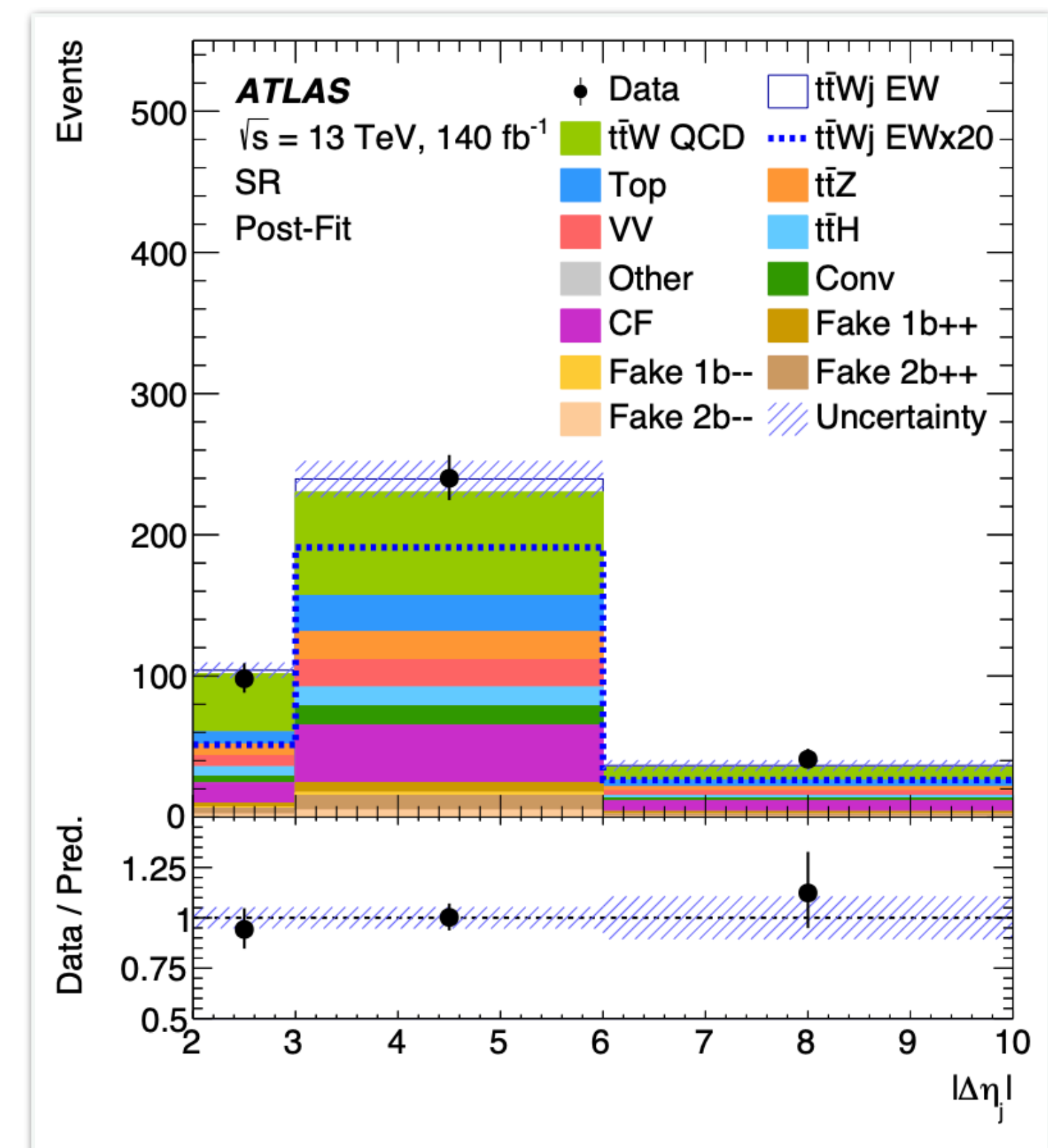
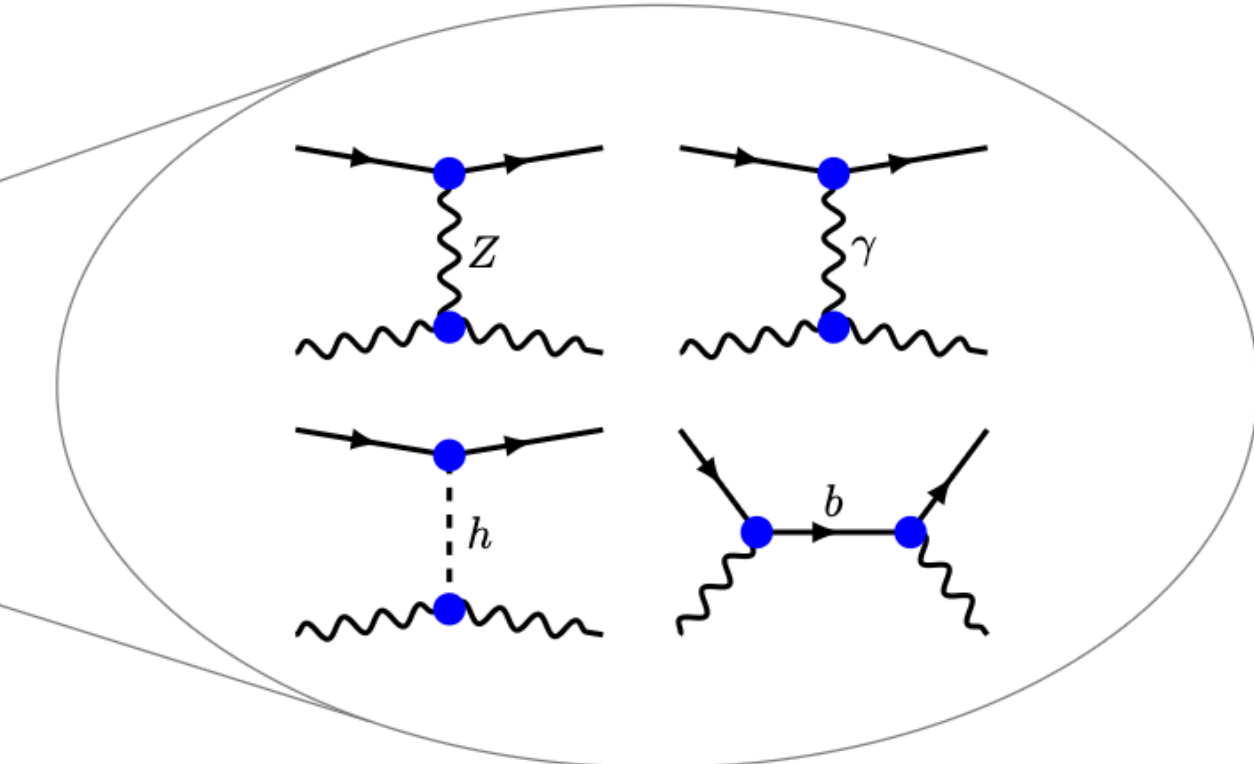
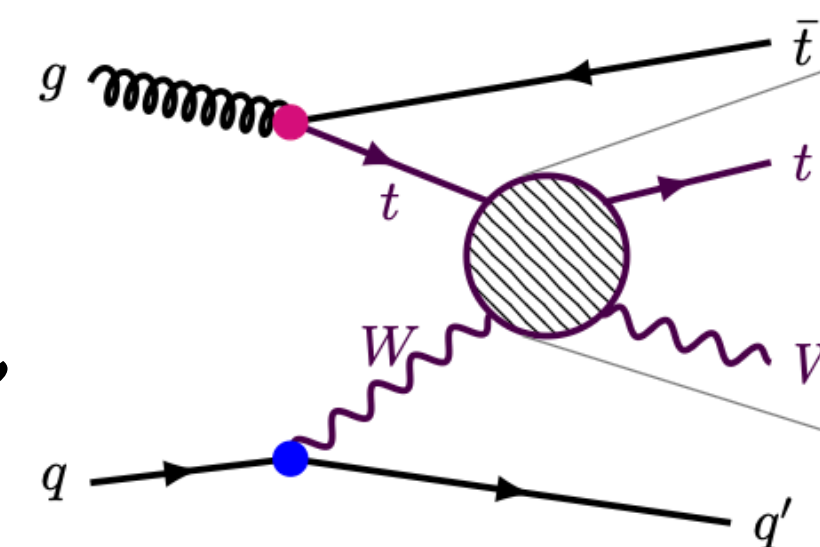


- ◆ First direct probe of the **tW scattering vertex**
- ◆ Sub-leading EW correction to $t\bar{t}W$ has large positive contr.,
- ◆ Contain specific topology $\rightarrow$ tW-scattering vertex
- ◆ **Same-sign dilepton channel**, >4 jets, 1 b-tag, high m_{ll}
- ◆ **Forward-jet** provides handle to separate ttW EW from ttW QCD
- ◆ SR + 7 CR (ttW QCD, ttZ, diboson, conversions/charge flips)
- ◆ **Measured signal strength and cross section:**

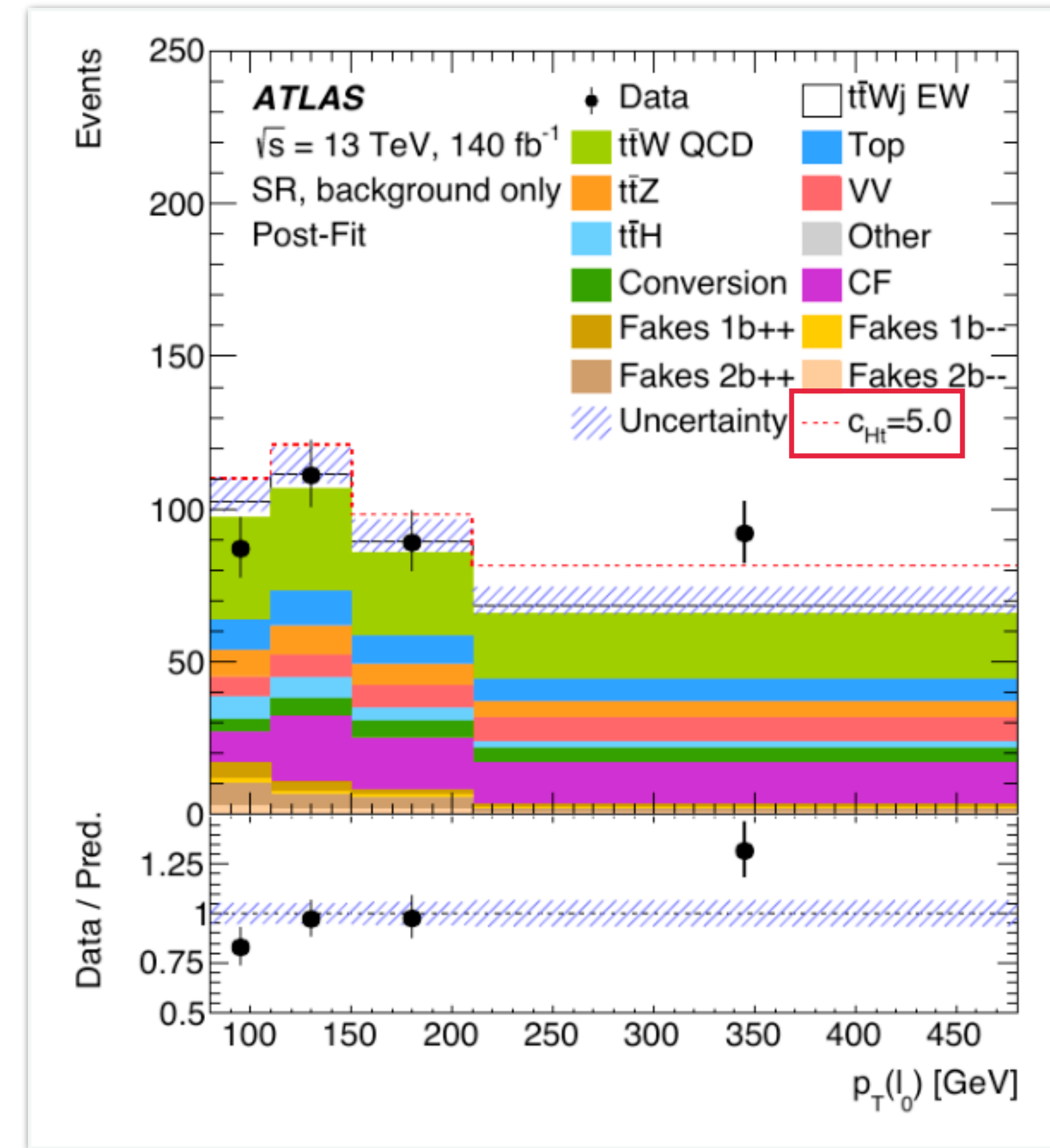
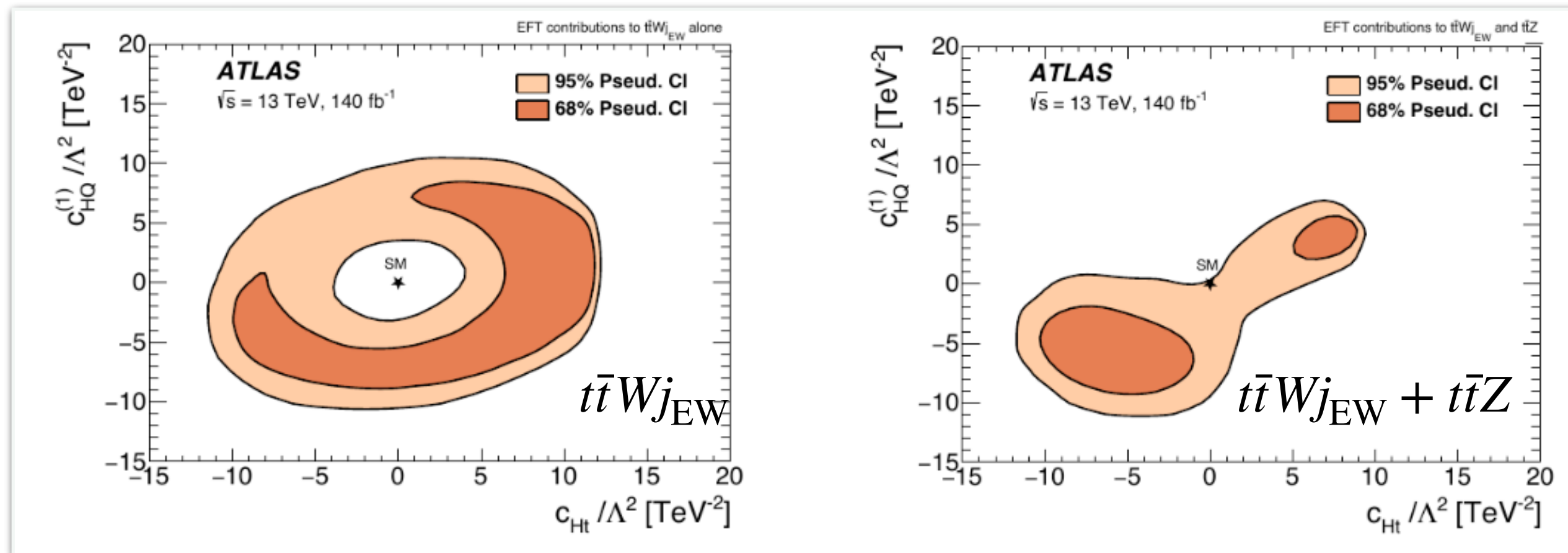
$$\mu(t\bar{t}Wj_{EW}) = 0.9^{+2.4}_{-3.0} = 0.9 \pm 0.9 \text{ (stat.)}^{+2.2}_{-2.8} \text{ (syst.)}$$

$$\sigma(t\bar{t}Wj_{EW}) < 251 \text{ fb at 95 \% CL (expected : 230 fb)}$$

► **Systematics dominated** by ttW QCD normalisation, jets & MET and fake leptons

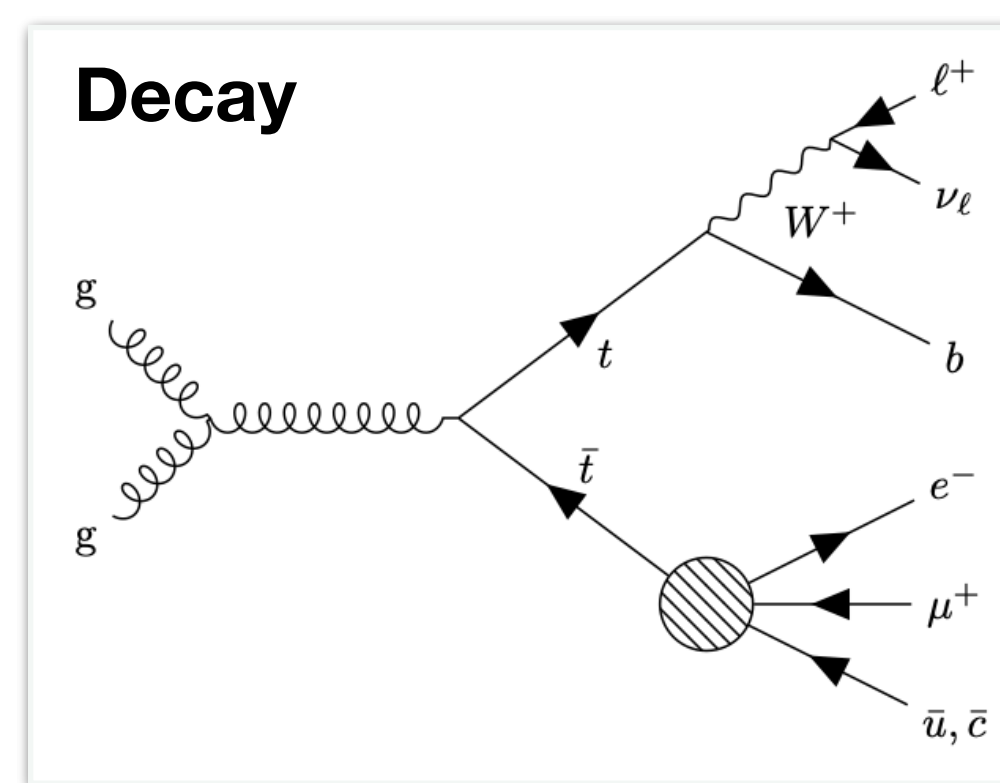
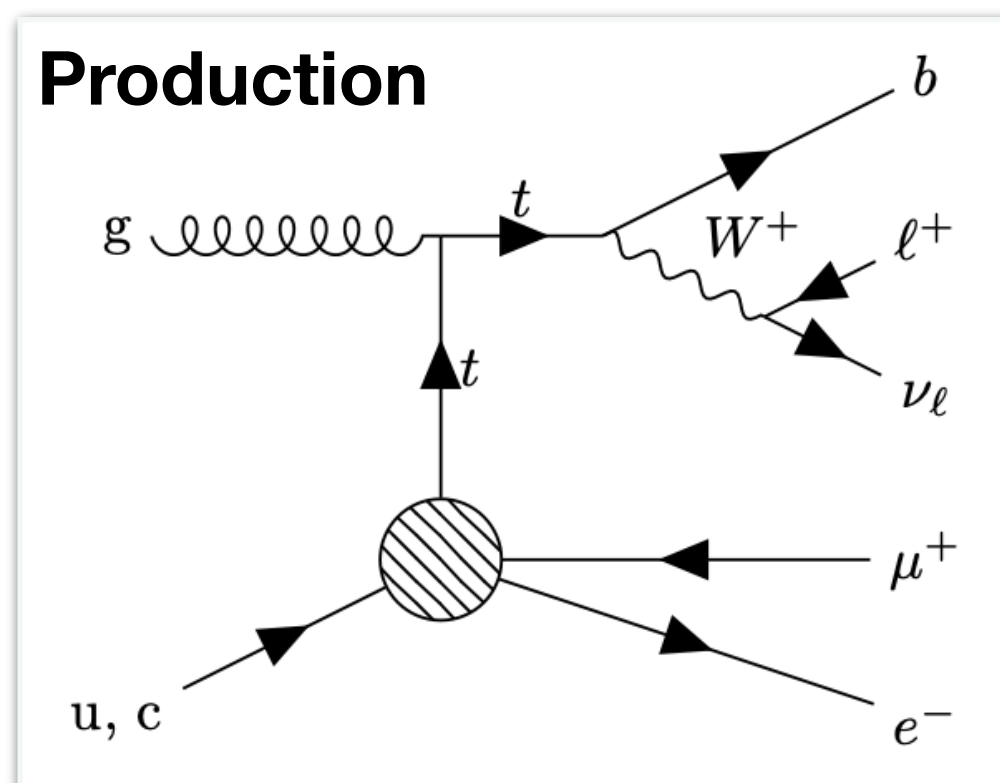


- ◆ Quadratic energy dependance on O_{Ht} and $O_{HQ}^{(1)}$
 tW -scattering involves two longitudinal polarised gauge bosons
 (linear interference suppressed by SM symmetries)
- ◆ Wilk's theorem does not hold → CI derived from pseudo-data
- ◆ Signal region binned in $p_T(l)$
- ◆ Small excess in highest- p_T bin
 → drives a preference for non-zero Wilson coefficients

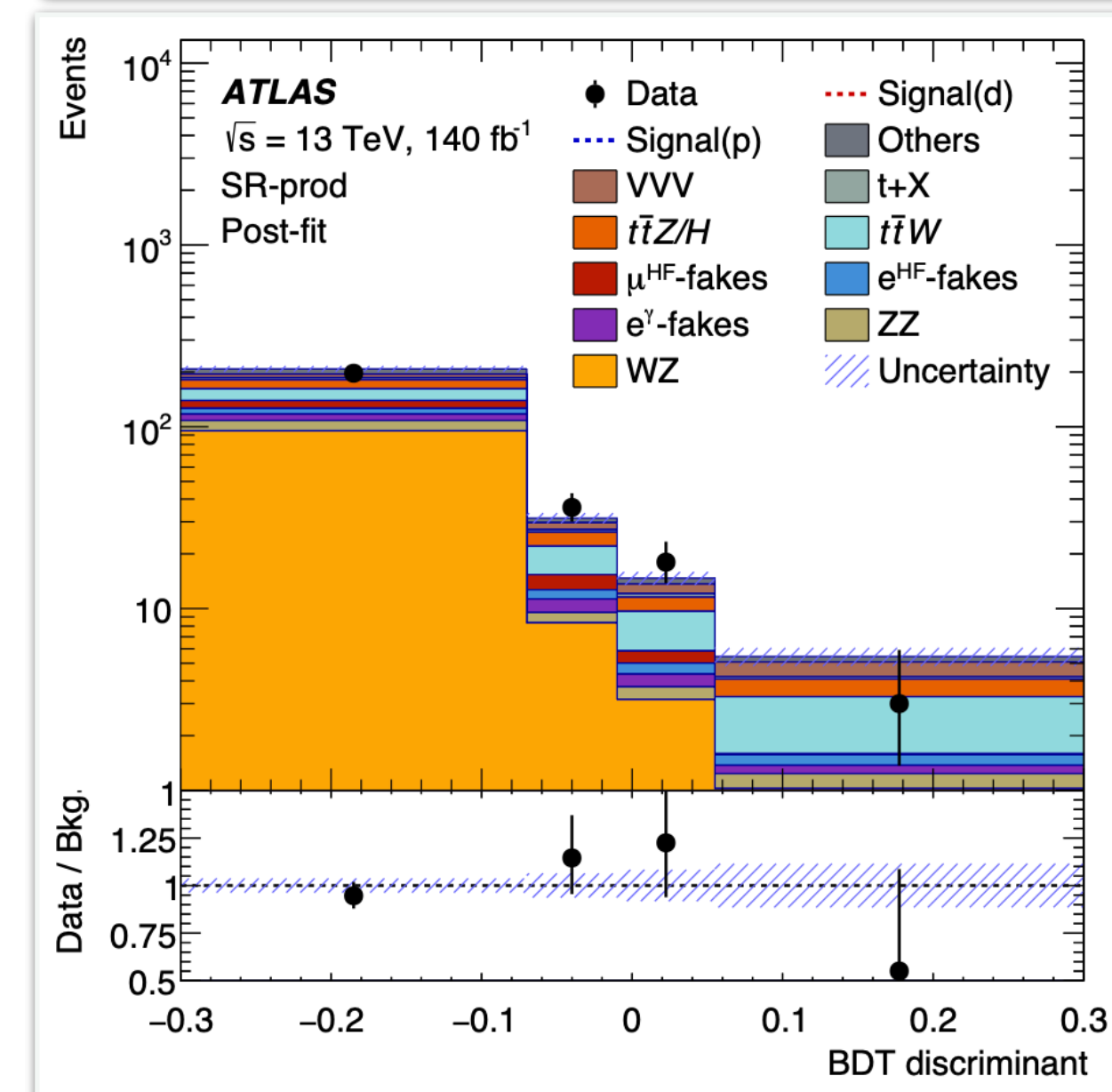
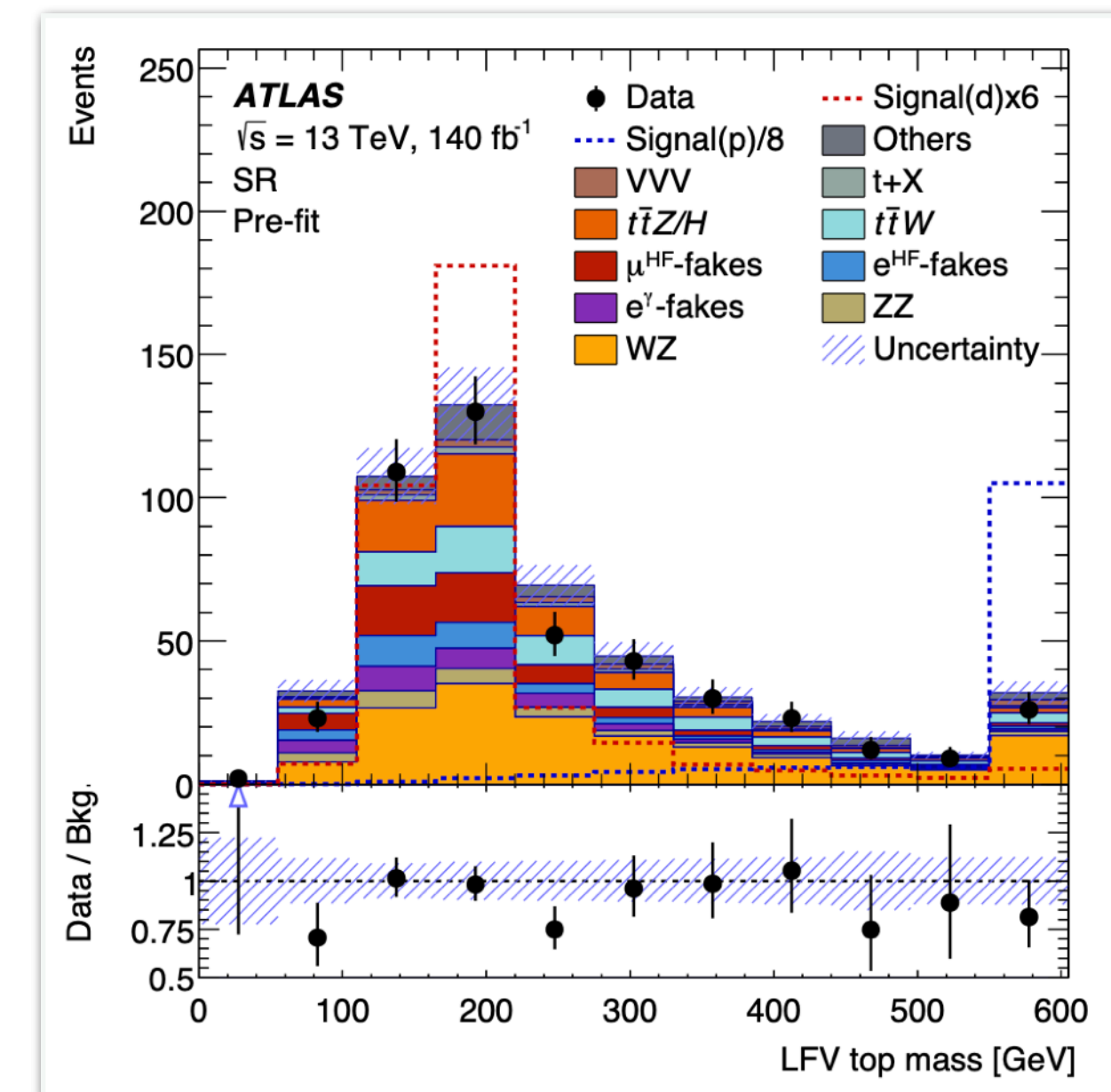


- ▶ Combining $t\bar{t}Wj_{EW}$ with $t\bar{t}Z$ reduces the degeneracy between O_{Ht} and $O_{HQ}^{(1)}$
- ▶ Sensitivity grows with every additional p_T bin → Run3 will help to improve

- ◆ **Charged-lepton-flavour violation** in top production and decay
SM rate $10^{-54} \rightarrow$ any signal is BSM
- ◆ Leptoquark models predict rate within experimental reach
- ◆ **Search for $e\mu qt$ contact interactions (q=up, charm)**



- **Trilepton final state**
kinematic reconstruction of SM top and “LFV top” $\rightarrow e\mu$ pair+jet
- $m(\text{LFVtop}) < 220 \text{ GeV} \rightarrow$ SR-decay
1 jet, $H_T > 400 \text{ GeV} \rightarrow$ SR-prod
- BDT per SR (17 inputs); CRs for WZ and non-prompt e/μ
- ◆ **Six 2Q2L operators:** tensor, vector, scalar structure for up & charm



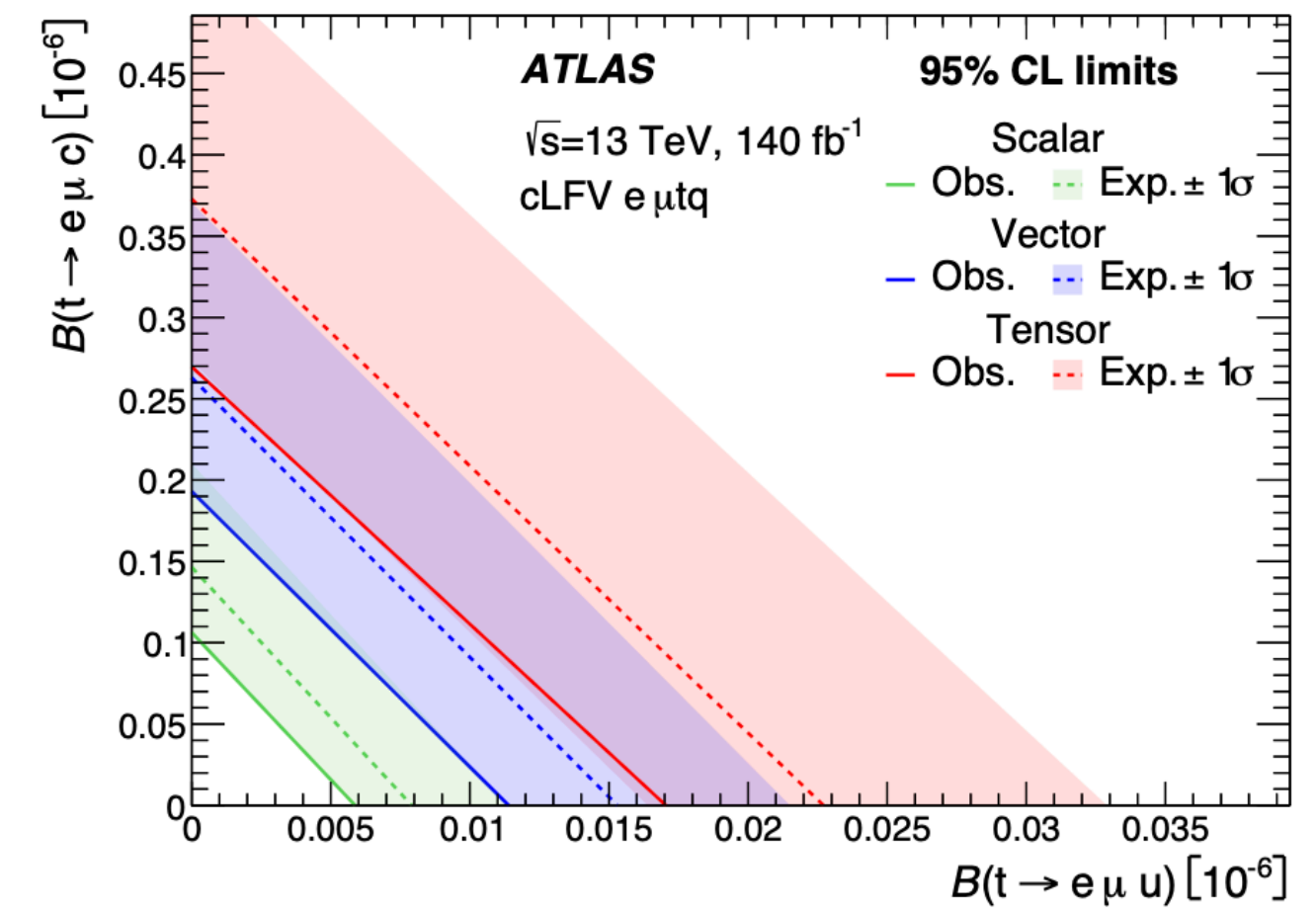
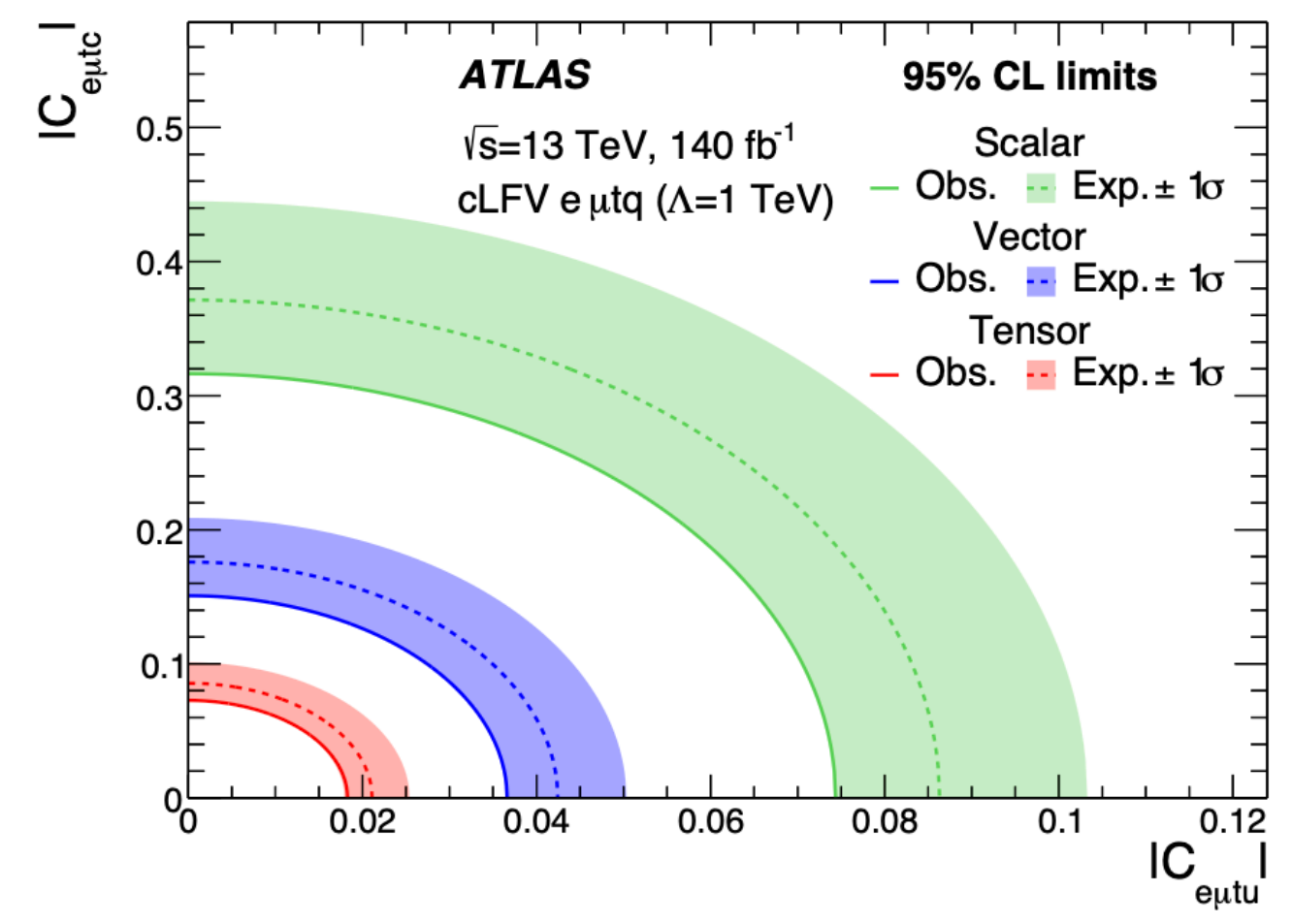
- ◆ No excess seen → background-only p-value is 0.92
- ◆ Limits on Wilson coefficients and branching ratios:

Weaker limits
due to smaller
charm PDF

cLFV coupling	Lorentz Structure	Wilson coefficient	Expected 95% CL limits ($\pm 1\sigma$ range)	Observed 95% CL limits
$e\mu tu$	Tensor	$ C_{e\mu tu}^{\text{tensor}} $	0.021 (0.018 – 0.025)	0.018
	Vector	$ C_{e\mu tu}^{\text{vector}} $	0.042 (0.036 – 0.050)	0.037
	Scalar	$ C_{e\mu tu}^{\text{scalar}} $	0.086 (0.074 – 0.103)	0.074
$e\mu tc$	Tensor	$ C_{e\mu tc}^{\text{tensor}} $	0.086 (0.073 – 0.101)	0.073
	Vector	$ C_{e\mu tc}^{\text{vector}} $	0.18 (0.15 – 0.21)	0.15
	Scalar	$ C_{e\mu tc}^{\text{scalar}} $	0.37 (0.32 – 0.43)	0.32

- ◆ Results can be translated into limits on branching ratio & interpolated between up and charm coupling

$$\Gamma(t \rightarrow \ell_i^+ \ell_j^- q_k) = \frac{m_t}{6144\pi^3} \left(\frac{m_t}{\Lambda}\right)^4 \left\{ 16|C_{ijk3}^{\text{vector}}|^2 + 2|C_{ijk3}^{\text{scalar}}|^2 + 96|C_{ijk3}^{\text{tensor}}|^2 \right\}$$



- ▶ **Statistically limited:** systematics impact is 2% (leading are top+X modelling)
- ▶ Observed limits are about 1σ better than expected because of a downward fluctuation in the most sensitive bin
- ▶ Expected sensitivity matches the CMS $e\mu$ trilepton analysis - **most stringent observed limits** on $e\mu qt$ interaction to date

Recent ATLAS results on Top+X processes with the full Run 2 dataset:

- ▶ Observation of $t\bar{t}\gamma\gamma$
 - *Per-mille process observed at 5σ*
- ▶ Updated results on tZq
 - *10 % precision achieved, first differential analysis of tZq in ATLAS*
- ▶ First probe of tW scattering
 - *Additional data from RunIII will help to improve sensitivity further*
- ▶ Important constraints on the top-quark electroweak sector and on flavour-violating top couplings
 - *EFT sensitivity driven by the high energy observables, complementarity between processes closes flat directions -*
- ▶ Good agreement with the SM in all measurements

Remarkable success of the SM continues (unfortunately) . . .