Search for same-charge top-quark pair production in pp collisions at 13 TeV with the ATLAS detector

17th International Workshop on Top Quark Physics
TOP2024, Saint-Malo, France
26.09.2024

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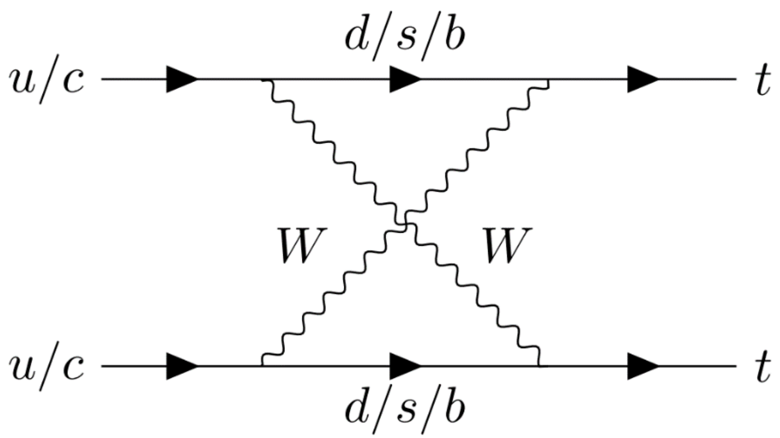
arXiv:2409.14982
TOPQ-2021-14

Motivation

arXiv:2409.14982

- Same-charge (same-sign SS) top-quark pair production is **strongly suppressed** in the Standard Model (SM)
- Very clean signature in the **dileptonic final state**
  - High p_{T} same-charge lepton pair (++ or - -)
  - Two b-jets
  - Missing transverse momentum
- **Observation** would imply the **existence of new underlying physics**
- First ATLAS search for same-sign top-quark pairs using SM Effective Field Theory (SMEFT)



$$\sigma(pp \rightarrow tt)_{SM} \approx 4 \cdot 10^{-15}\ \mathrm{pb}$$

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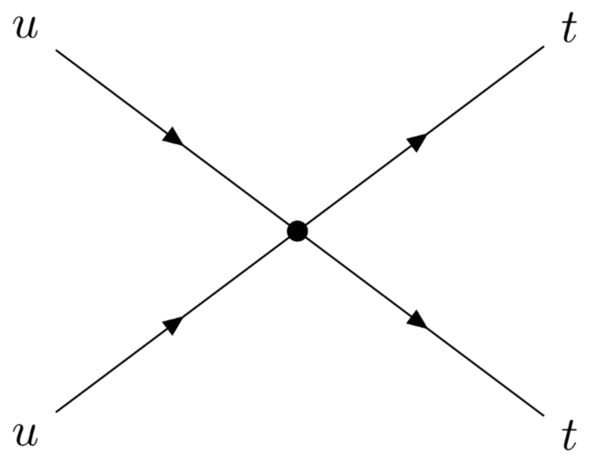
Effective Field Theory

- Three four-fermion operators are considered: $\boldsymbol{O_{tu}^{(1)}}, \boldsymbol{O_{Qu}^{(1)}}, \boldsymbol{O_{Qu}^{(8)}}$ → Different chirality RR / LR
- $\mathcal{L}_{\mathrm{D=6}}^{qq\to tt} = \frac{1}{\Lambda^2}\left(c_{tu}^{(1)}\mathcal{O}_{tu}^{(1)} + c_{Qu}^{(1)}\mathcal{O}_{Qu}^{(1)} + c_{Qu}^{(8)}\mathcal{O}_{Qu}^{(8)}\right) + h.c.$
- Only **quadratic** EFT terms and $\Lambda = 1\ \mathrm{TeV}$
- Default signal sample simulated with following Wilson coefficients (WCs):
  - $\boldsymbol{c_{tu}^{(1)}} = 0.04, \boldsymbol{c_{Qu}^{(1)}} = 0.1, \boldsymbol{c_{Qu}^{(8)}} = 0.2$ → balanced cross-sections
  - $\sigma(pp \to tt) = 97.6$ fb & $\sigma(pp \to \bar{t}\bar{t}) = 2.4$ fb
  - Highly charge-asymmetric
- Different WCs setups created by reweighting



Analysis strategy

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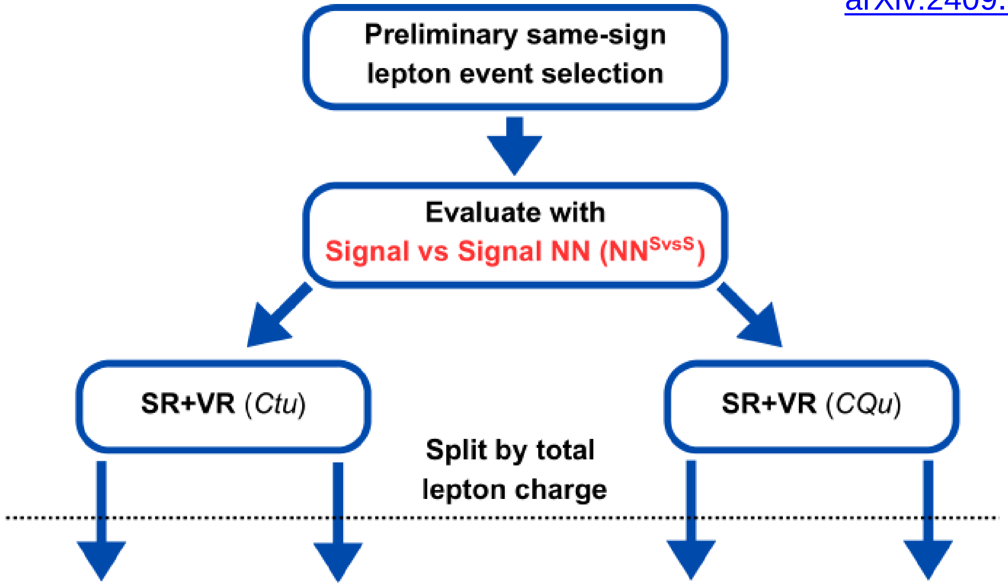
- Full Run 2 pp collision data at $\sqrt{s} = 13$ TeV, 140 fb^{-1}
- Neural networks (NNs) are used to split events in **signal regions (SRs)** and validation regions (VRs)
  - **SRs** are split by **charge** and **EFT operators**
- Control regions (CRs) described on next slides
  - Used to constrain normalisation of the background processes
- Combined **binned profile-likelihood** fit over the **SRs+CRs** simultaneously



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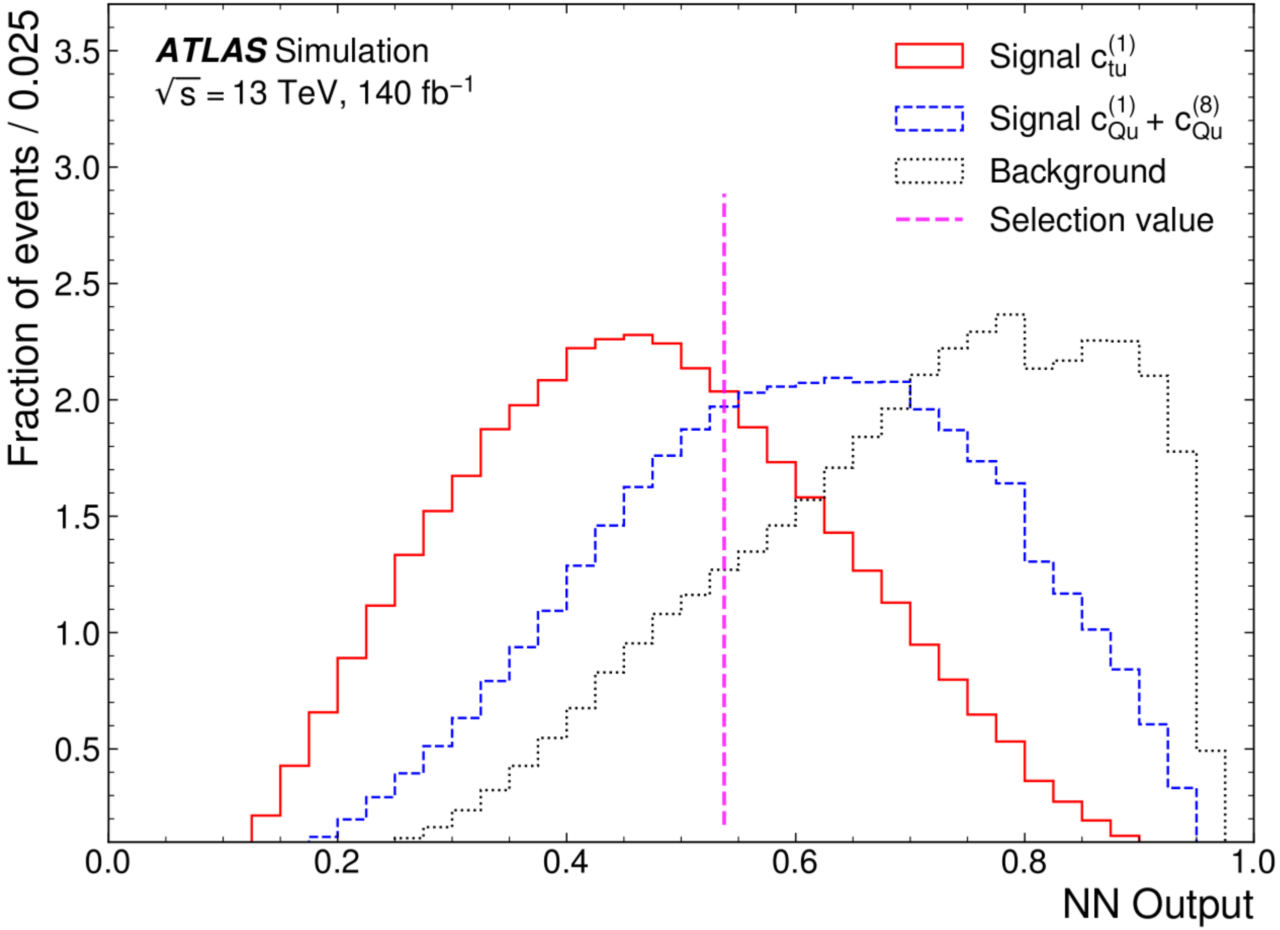
Signal vs Signal NN (NN^{SvsS})

- Goal: **Discriminate** signal events originating from $c_{tu}^{(1)}$ vs $c_{Qu}^{(1)}$ or $c_{Qu}^{(8)}$
  - No further split between $c_{Qu}^{(1)}$ and $c_{Qu}^{(8)}$ due to being hardly distinguishable
- Only **trained** on **signal events**
- Two different signal samples used for training:
  - $c_{tu}^{(1)} = 0.04$ $\rightarrow c_{Qu}^{(1)} = 0,\ c_{Qu}^{(8)} = 0$
  - $c_{Qu}^{(1)} = 0.1, c_{Qu}^{(8)} = 0.2$ $\rightarrow c_{tu}^{(1)} = 0$
- Simple DNN (5 hidden layers)
- Using odd/even cross-validation
- 9 input variables ($\Delta m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $\Delta R_{\ell\ell}$, …)



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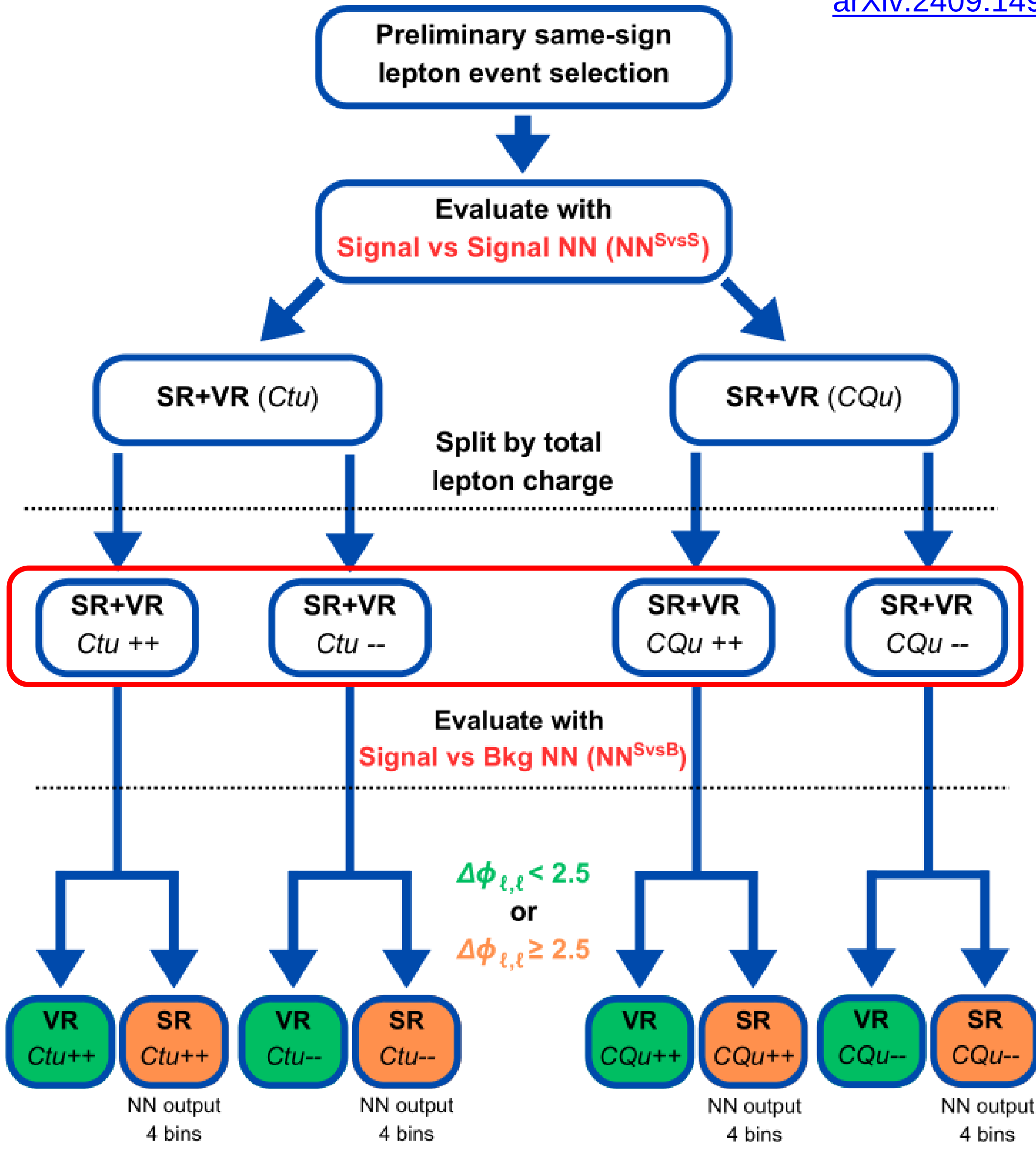
Distinguish background from signal

- Trained $\mathrm{NN}^{\mathrm{SvsB}}$ for each of the four regions
- Same training and architecture as for the $\mathrm{NN}^{\mathrm{SvsS}}$
- Split by charge due to different **kinematics** for tt and $\bar{t}\bar{t}$
  - $\sigma(tt) \geq \sigma(\bar{t}\bar{t}) \rightarrow$ **split** needed to be sensitive to $\bar{t}\bar{t}$
- 6 input variables ($H_{\mathrm{T}}^{\mathrm{lep}}$, $p_{\mathrm{T}}^{\mathrm{jet0}}$, N_{jets}, …)
- $\mathrm{NN}^{\mathrm{SvsB}}$ output distribution used in the profile likelihood fit for the SRs
- Finalize SR definitions by requiring $\Delta\Phi_{\ell,\ell} \geq 2.5$
  - Events with $\Delta\Phi_{\ell,\ell} < 2.5$ used as VRs



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Analysis makes use of **9 CRs**

- **5 dilepton** (2ℓ) **CRs**:
  - All 2ℓ-CRs are enriched in heavy flavor e or μ fakes CRs
  - **Orthogonal** due to $N_{\mathrm{b-tags}}$ and lepton isolation requirements
- **4 three lepton** (3ℓ) **CRs**:
  - $t\bar{t}Z$ CR
  - Diboson CR
  - Material / internal photon conversion CRs
  - **Orthogonal** due to requiring 3 leptons (electrons / muons)
- **Normalization** of **major background processes** constrained in the binned profile likelihood fit with dedicated CRs
- Dominant background: $\boldsymbol{t\bar{t}W}$
  - Normalisation constrained by bins with low NN output score in the SRs

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Systematic Uncertainties

- Apart from statistical uncertainties $t\bar{t}W$ modelling uncertainties have the largest impact on the final results
- Normalizations of major background process constrained via the CRs
  - For all other processes a normalization uncertainty is applied
- For larger backgrounds additional modeling uncertainties are applied by comparing the **nominal** sample with an **alternative sample** → details in paper / backup:
  - Parton shower and hadronization variation ($\boldsymbol{t\bar{t}W, t\bar{t}Z, t\bar{t}H}$)
  - Generator variation ($\boldsymbol{t\bar{t}W, t\bar{t}H}$) → different matrix element generator
  - Scale variations ($\boldsymbol{t\bar{t}W, t\bar{t}Z, t\bar{t}H, VV}$)
- Using the full set of ATLAS **experimental uncertainties**

Statistically dominated analysis !

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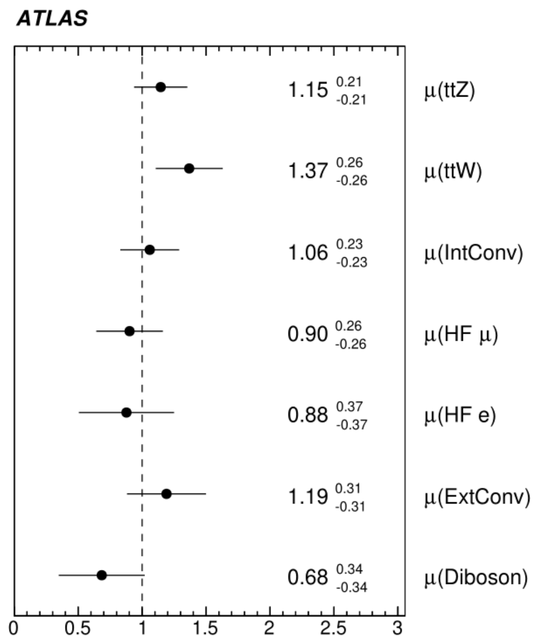
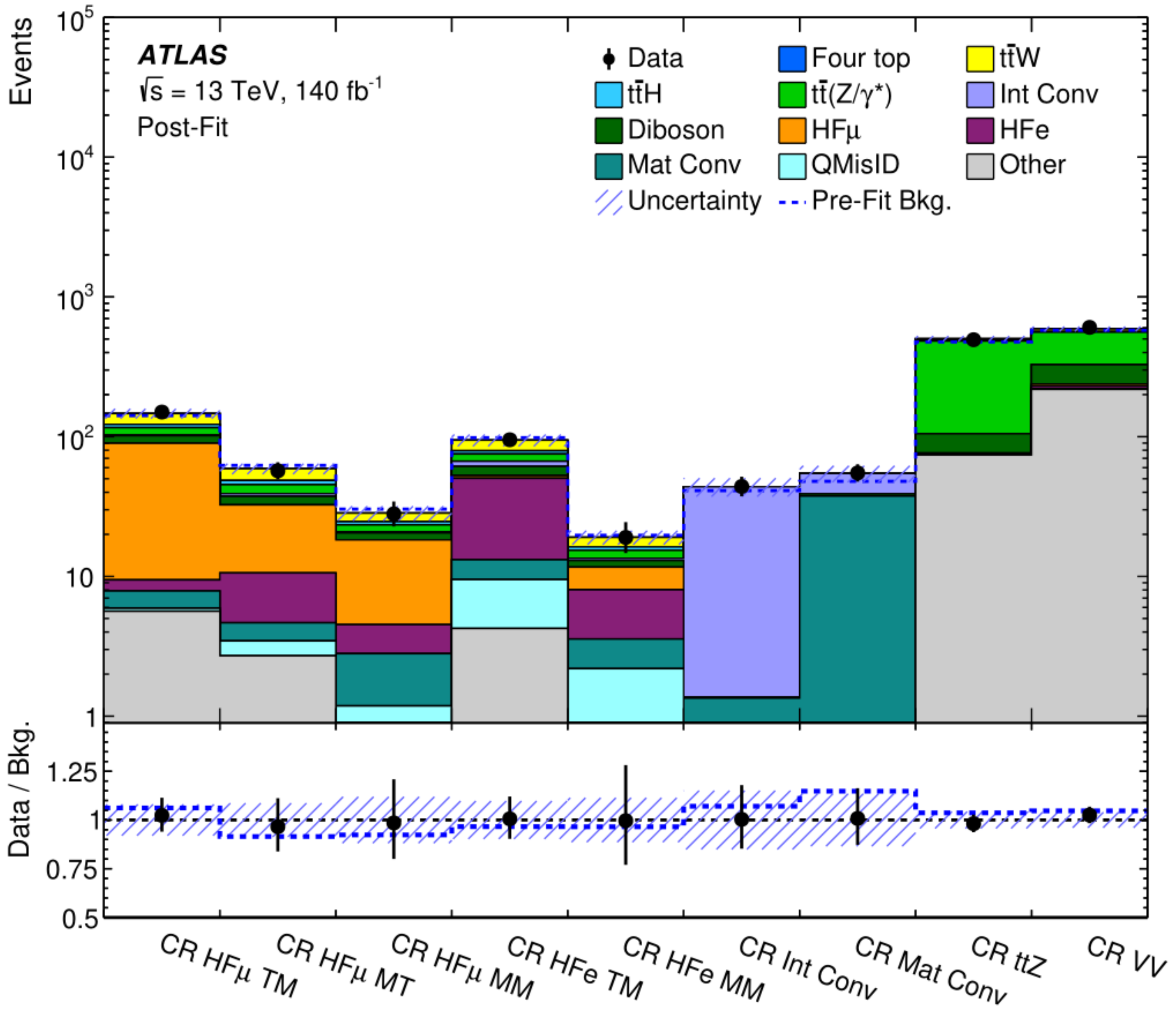
Results – CRs

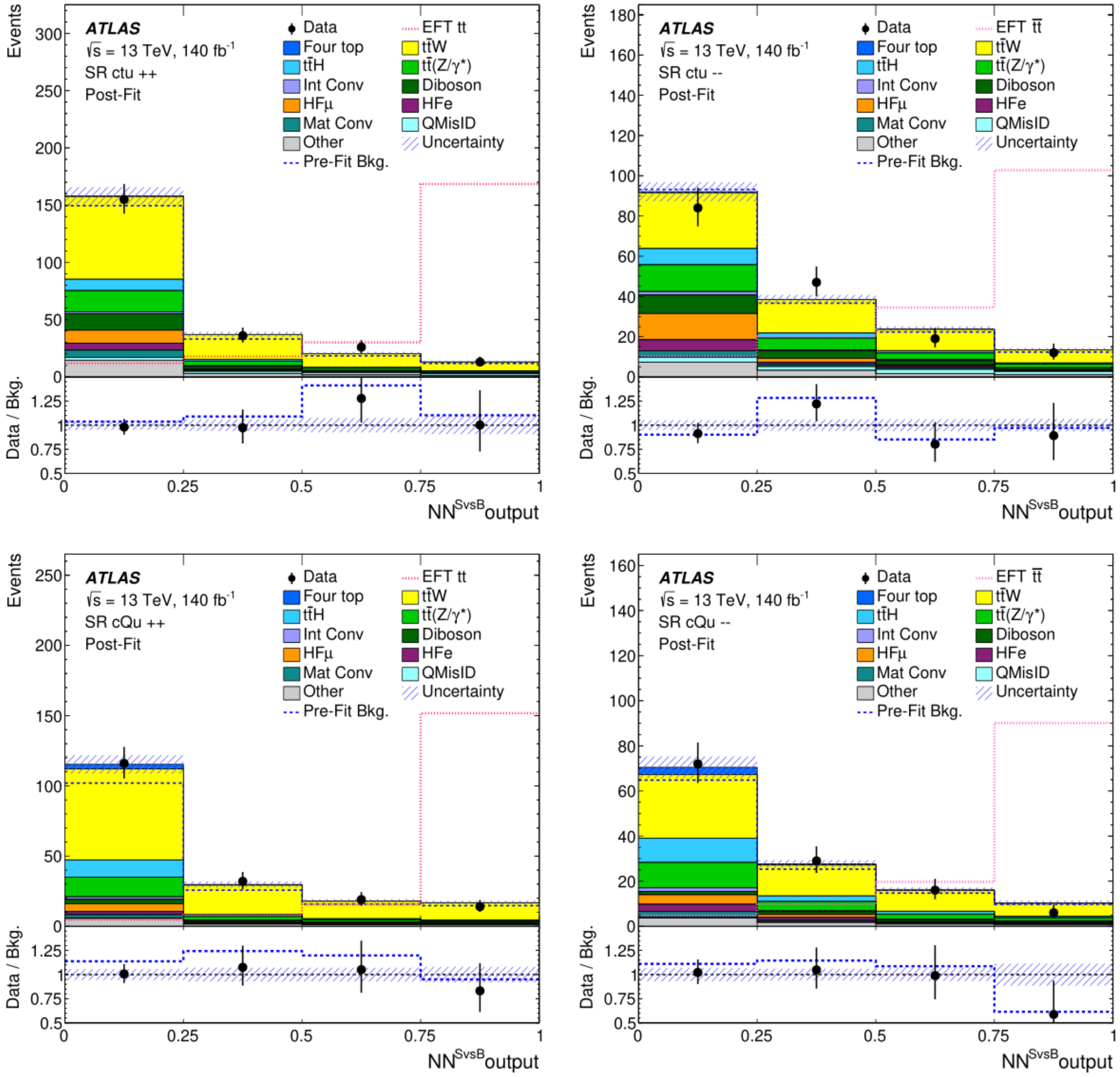
- Very good post-fit agreement in the CRs
- All normalizations are in agreement with the SM, except $t\bar{t}W$
  - Known excess – in agreement with ATLAS $t\bar{t}W$ cross-section measurement





Results – SRs

- Good post-fit agreement in the SRs
- No significant signal contribution observed
  - All three WCs fitted to $< 10^{-6}$
- Negligible signal contribution is not shown in the plots
- Setting 1D-limits on the WCs by scanning the likelihood while varying a single WC at a time



Signal parametrization in the SRs

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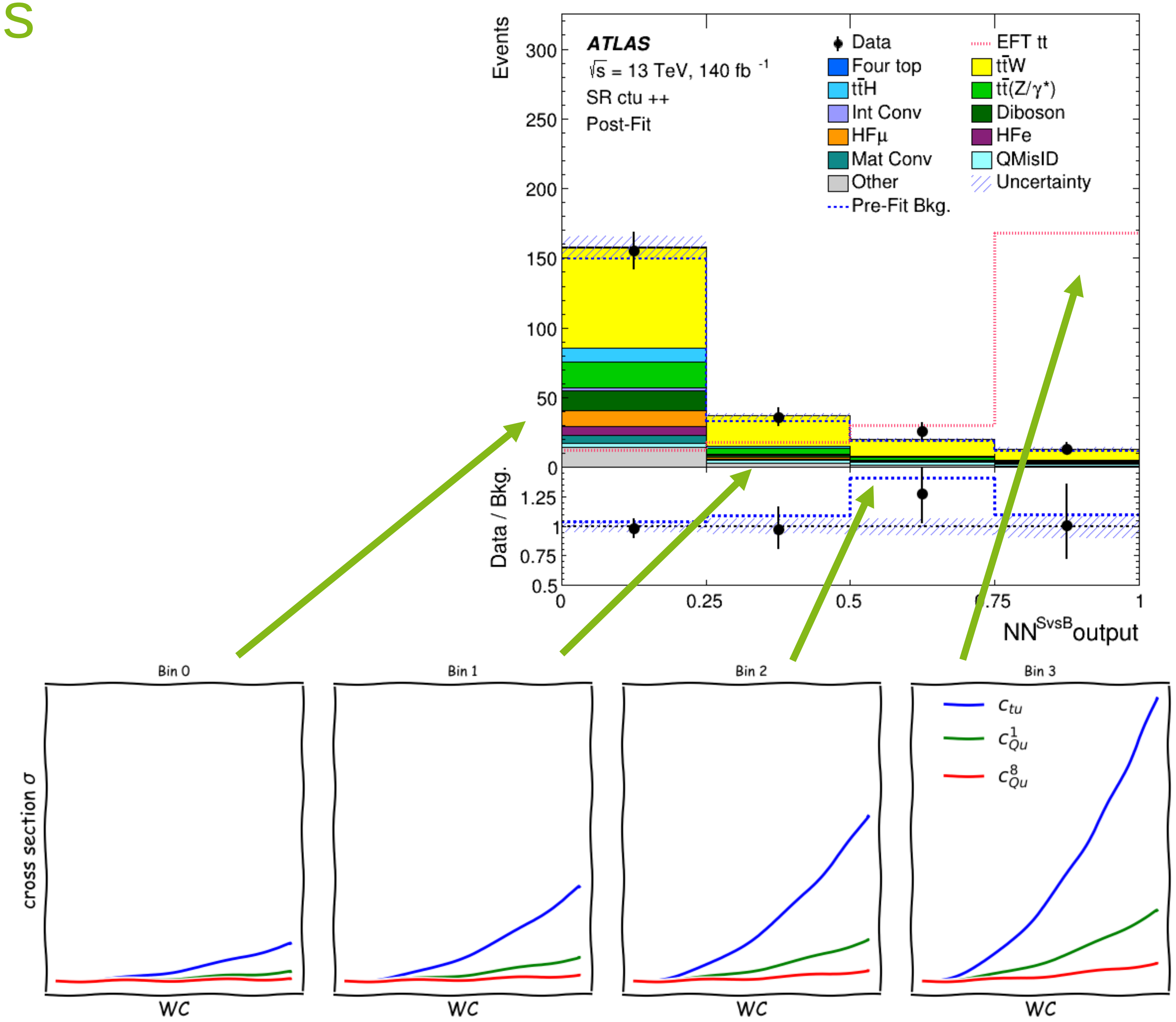
- For each **SR bin** the **EFT parametrization** for the three WCs is fitted
  - Uses all available EFT samples
- Allows to fit **any set of WC values**
- Direct connection between WC values and **cross-section**
- Parameterization is fitted **individually** for each SR
- Used to derive limits by scanning different sets of WC values



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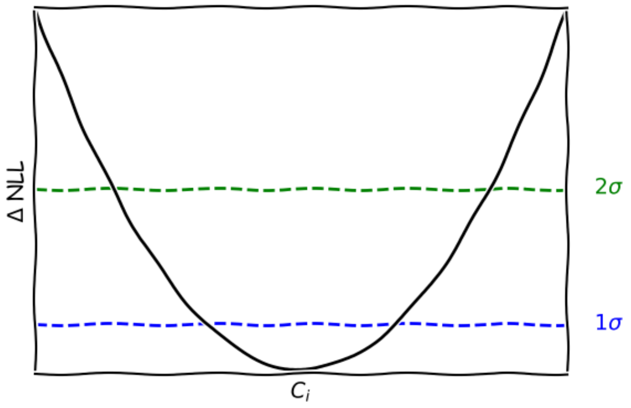
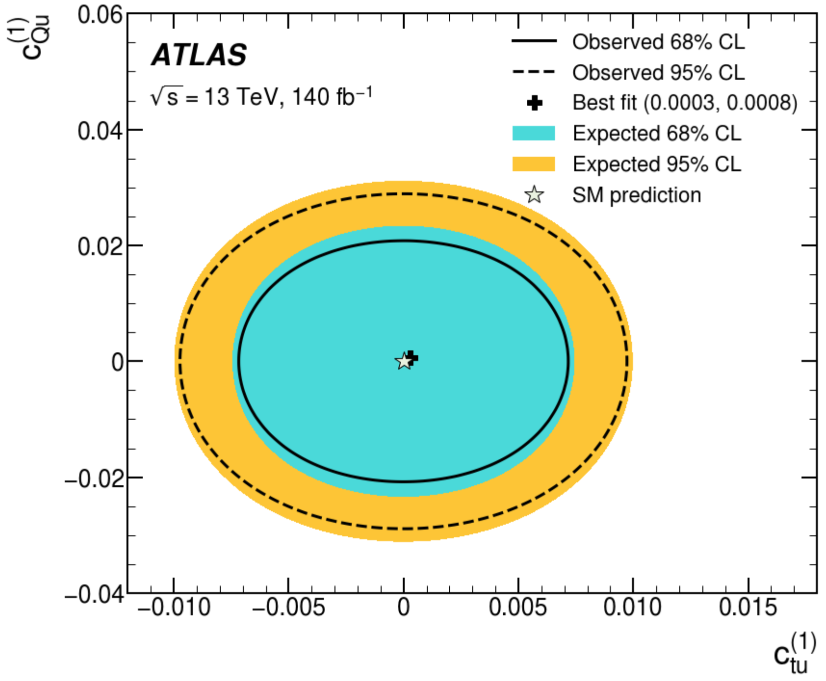
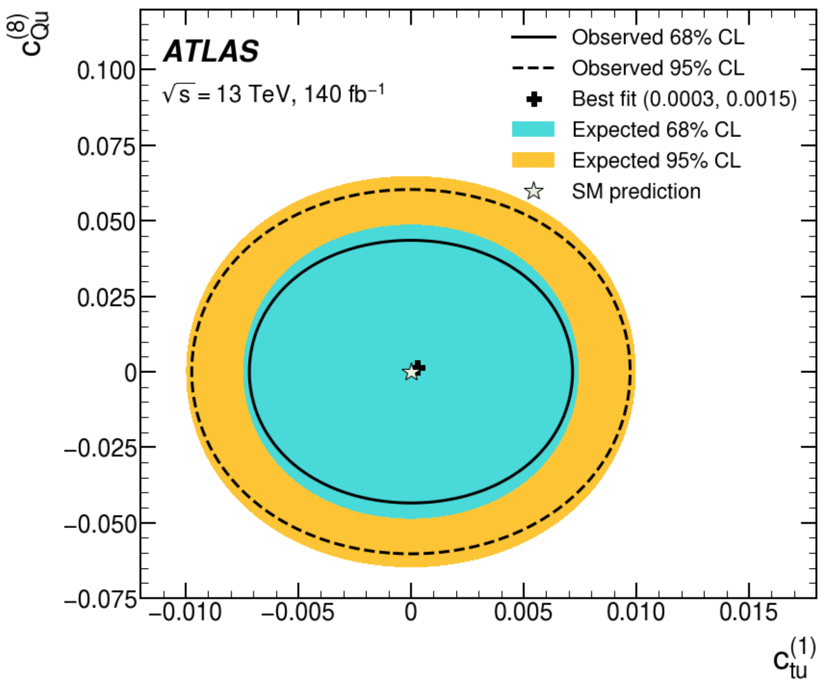
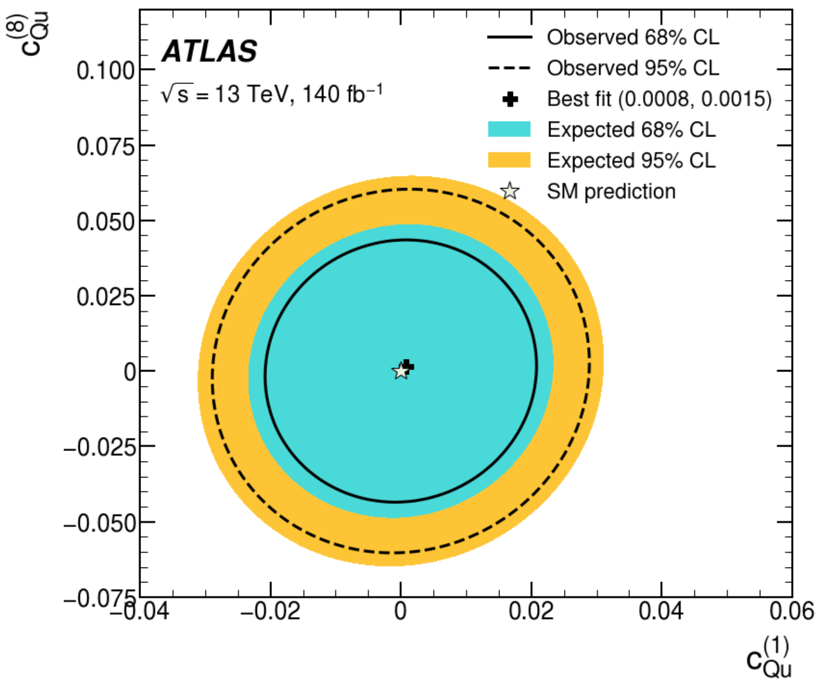
Results – Likelihood scans



- 1D observed (expected) limits at 95% CL:
  - $c_{tu}^{(1)}$ **< 0.0068 (0.0071)** $c_{Qu}^{(1)}$ **< 0.020 (0.022)** $c_{Qu}^{(8)}$ **< 0.041 (0.046)**
- 2D limits for the three sets of WC combinations







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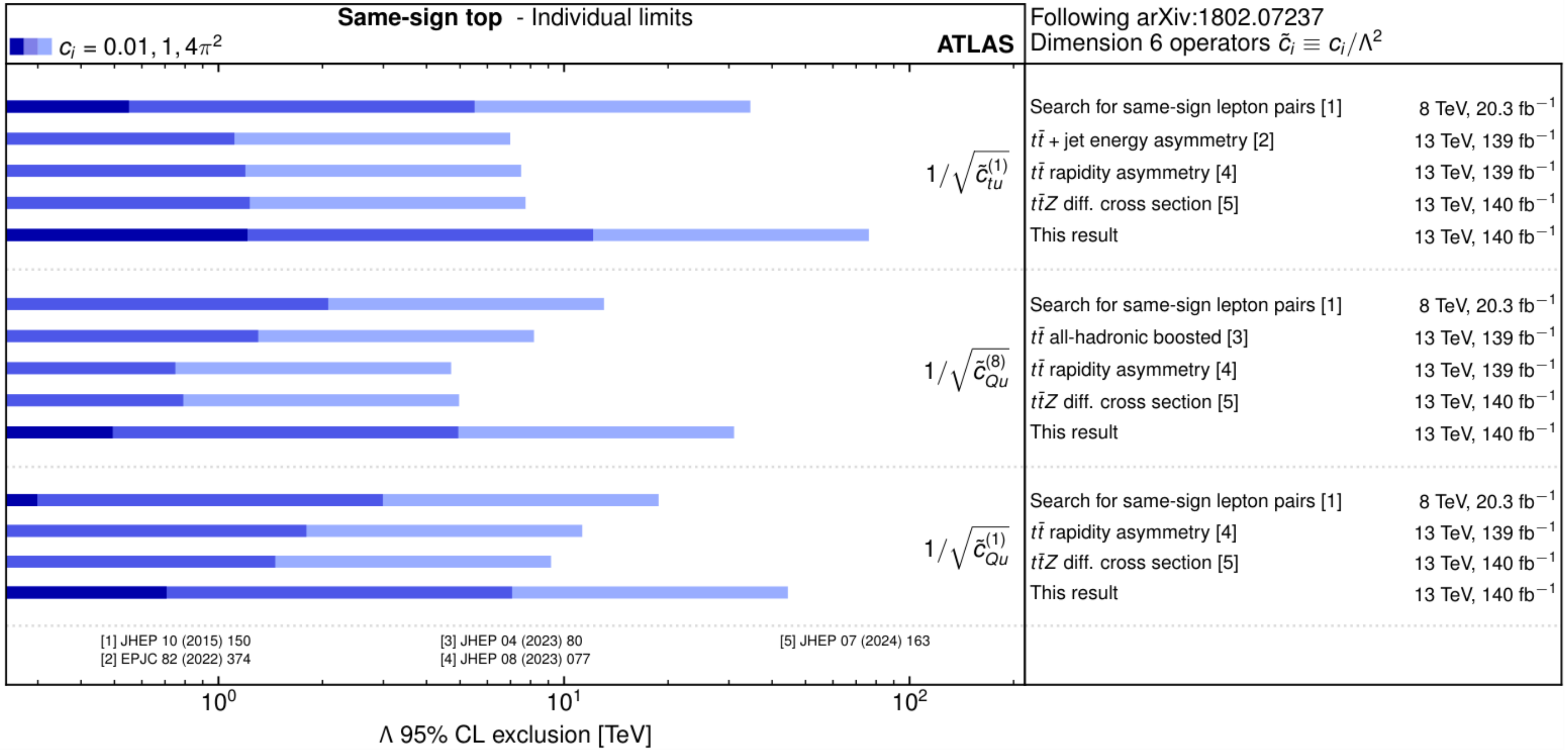
Results – Λ exclusion limits

- New physics scale Λ exclusion limits for three WCs values: $C_i = 0.01, 1, 4\pi^2$ at 95% CL
- Previously most stringent limits by Run 1 ATLAS search for same-sign lepton pairs



Summary & Conclusion

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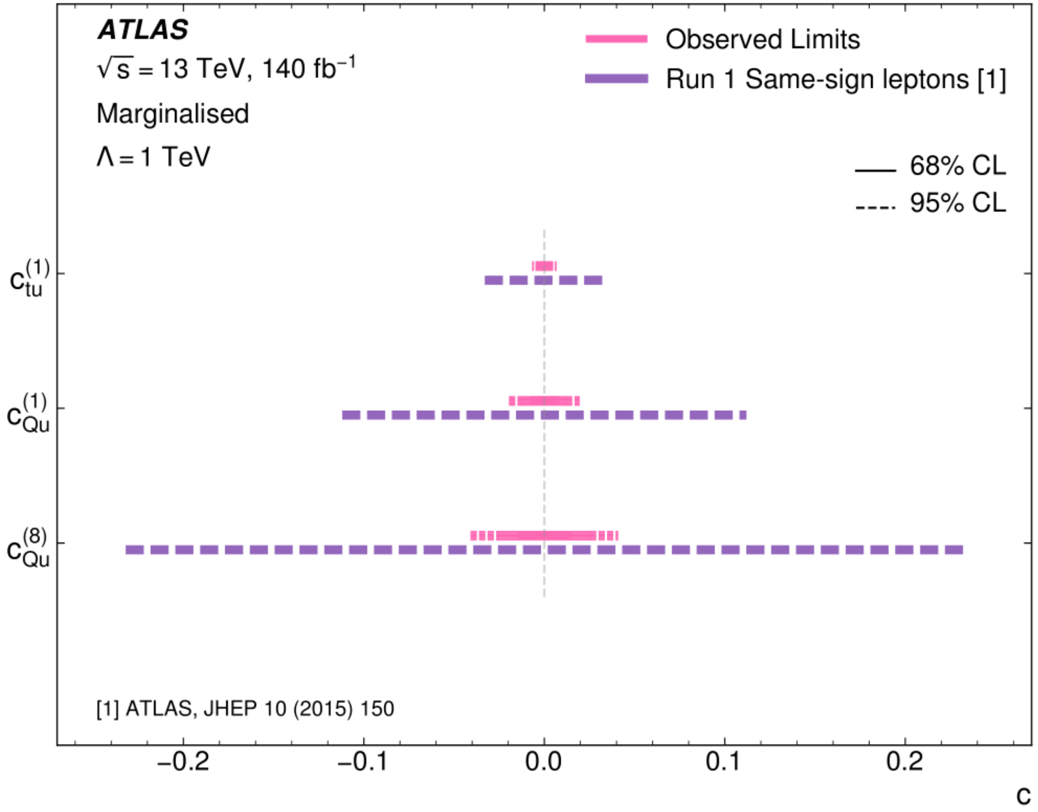
Uncertainties	Wilson Coefficient limits at 95% CL ×100		
	$c_{tu}^{(1)}$	$c_{Qu}^{(1)}$	$c_{Qu}^{(8)}$
Statistical uncertainty only	[-0.65, 0.65]	[-1.9, 1.9]	[-3.9, 3.9]
Statistical + modeling uncertainties	[-0.67, 0.67]	[-1.9, 1.9]	[-4.0, 4.0]
Total uncertainty	[-0.68, 0.68]	[-2.0, 2.0]	[-4.1, 4.1]

- Results are in agreement with SM
- No **significant signal** detected
- Precision **limited by statistical uncertainties**
- Observed upper limit at 95% CL: $\boldsymbol{\sigma(pp \rightarrow tt\,/\,\bar{t}\bar{t})}$ **< 1.6 fb**
- **Most stringent limits on** $\boldsymbol{c_{tu}^{(1)}, c_{Qu}^{(1)}, c_{Qu}^{(8)}}$
  - Improving previous WC limits by a factor of ≈ 10



Backup Slides

Data and MC simulation

- MC samples shown in parentheses are used for the estimation of systematic uncertainties
- Electron charge misidentification background is estimated from data using $Z \to ee$ events

$$O_{tu}^{(1)} = [\bar{t}_R\gamma^\mu u_R][\bar{t}_R\gamma_\mu u_R],$$
$$O_{Qq}^{(1)} = [\overline{Q}_L\gamma^\mu q_L][\overline{Q}_L\gamma_\mu q_L],$$
$$O_{Qq}^{(3)} = [\overline{Q}_L\gamma^\mu\sigma^a q_L][\overline{Q}_L\gamma_\mu\sigma^a q_L],$$
$$O_{Qu}^{(1)} = [\overline{Q}_L\gamma^\mu q_L][\bar{t}_R\gamma_\mu u_R],$$
$$O_{Qu}^{(8)} = [\overline{Q}_L\gamma^\mu T^A q_L][\bar{t}_R\gamma_\mu T^A u_R].$$

Process	Generator	ME order	PS	PDF (ME)	Tune
SS $tt/\bar{t}\bar{t}$ EFT signal	MadGraph5_aMC@NLO	LO	Pythia 8	NNPDF3.0LO	A14
$t\bar{t}W$	Sherpa 2.2.10	NLO	Sherpa	NNPDF3.0NNLO	Sherpa default
	(MadGraph5_aMC@NLO)	(NLO)	(Pythia 8)	(NNPDF3.0NLO)	(A14)
	(Powheg Box)	(NLO)	(Pythia 8)	(NNPDF2.3LO)	(A14)
	(Powheg Box)	(NLO)	(Herwig 7.2)	(NNPDF3.0NLO)	(H7.2-Default)
$t\bar{t}t\bar{t}$	MadGraph5_aMC@NLO	NLO	Pythia 8	NNPDF3.1NLO	A14
$t\bar{t}H$	Powheg Box	NLO	Pythia 8	NNPDF3.0NLO	A14
	(Powheg Box)	(NLO)	(Herwig 7.04)	(NNPDF3.0NLO)	(H7UE-MMHT)
	(MadGraph5_aMC@NLO)	(NLO)	(Pythia 8)	(NNPDF3.0NLO)	(A14)
$t\bar{t}Z/\gamma^*$	MadGraph5_aMC@NLO	NLO	Pythia 8	NNPDF3.0NNLO	A14
	(MadGraph5_aMC@NLO)	(NLO)	(Herwig 7.2)	(NNPDF3.0NLO)	(H7.2-Default)
	(MadGraph5_aMC@NLO)	(NLO)	(Pythia 8)	(NNPDF3.0NLO)	(A14 Var3c)
$t\bar{t}ll$	MadGraph5_aMC@NLO	NLO	Pythia 8	NNPDF3.0NLO	A14
$t\bar{t}$	Powheg Box	NLO	Pythia 8	NNPDF3.0NLO	A14
s-, t-channel, Wt single top	Powheg Box	NLO	Pythia 8	NNPDF3.0NLO	A14
$Z \to l^+l^-$ (matCO)	Powheg Box	NLO	Pythia 8	CT10NLO	AZNLO
$Z \to l^+l^- + (\gamma*)$	Powheg Box	NLO	Pythia 8	CT10NLO	AZNLO
$Z \to l^+l^-$	Sherpa 2.2.1	NLO	Sherpa	NNPDF3.0NNLO	Sherpa default
W+jets	Sherpa 2.2.1	NLO	Sherpa	NNPDF3.0NNLO	Sherpa default
$V\gamma$	Sherpa 2.2.8	NLO	Sherpa	NNPDF3.0NNLO	Sherpa default
VV, $qqVV$, $VV_{lowm_{\ell\ell}}$, VVV	Sherpa 2.2.2	NLO	Sherpa	NNPDF3.0NNLO	Sherpa default
$t(Z/\gamma^*)$, $t\bar{t}t$, $t\bar{t}WH$	MadGraph5_aMC@NLO	LO	Pythia 8	NNPDF2.3LO	A14
$t\bar{t}W^+W^-$, $t\bar{t}ZZ$, $t\bar{t}HH$	MadGraph5_aMC@NLO	LO	Pythia 8	NNPDF2.3LO	A14
$tW(Z/\gamma^*)$, tWH, $tHqb$	MadGraph5_aMC@NLO	NLO	Pythia 8	NNPDF3.0NLO	A14
VH	Powheg Box	NLO	Pythia 8	NNPDF3.0NLO	A14

Event and object reconstruction

Leptons

- Using single- and dilepton-triggers
- $p_{\mathrm{T}} > 10\ \mathrm{GeV}$
- $|\eta_{\mathrm{Cluster}}| < 1.37$ or $1.52 < |\eta_{\mathrm{Cluster}}| < 2.47$ (e) and $|\eta| < 2.5$ (μ)

Jets

- Jets reconstruction via **PFlow**:
  - $\Delta\mathrm{R} = 0.4$ $|\eta| < 2.5$
  - $p_{\mathrm{T}} > 25\ \mathrm{GeV}$ JVT > 0.5 for $p_{\mathrm{T}} < 25\ \mathrm{GeV}$, $|\eta| < 2.4$
- B-tagging of jets via **DL1r:**
  - 60% and 77% WP are used in this analysis

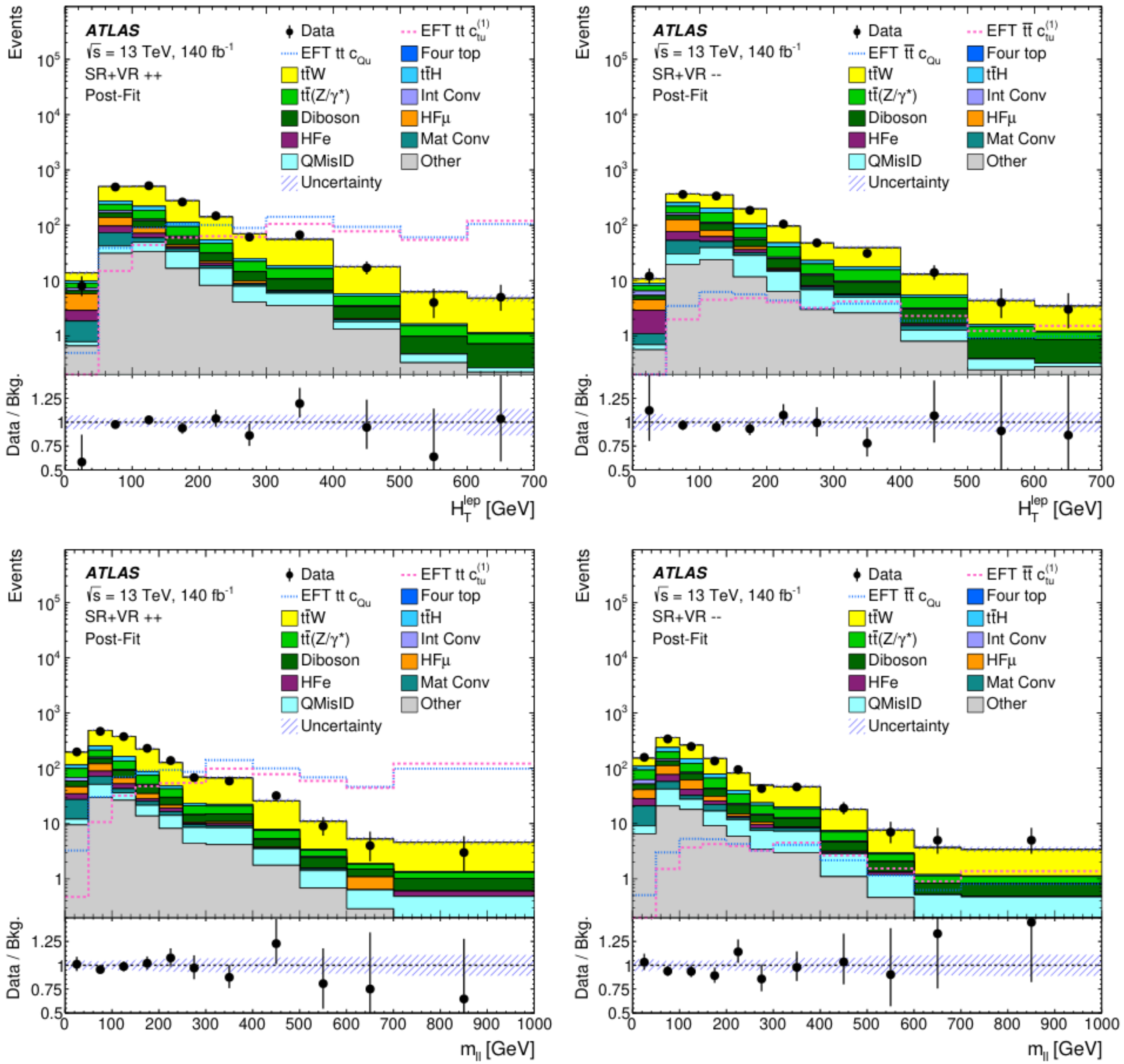
- Use BDT discriminate (**PLIV**) to suppress non-prompt leptons
- Reject background electrons with wrong charge assignment with ECIDS BDT
- Sequential overlap removal

Control region definitions (tables)

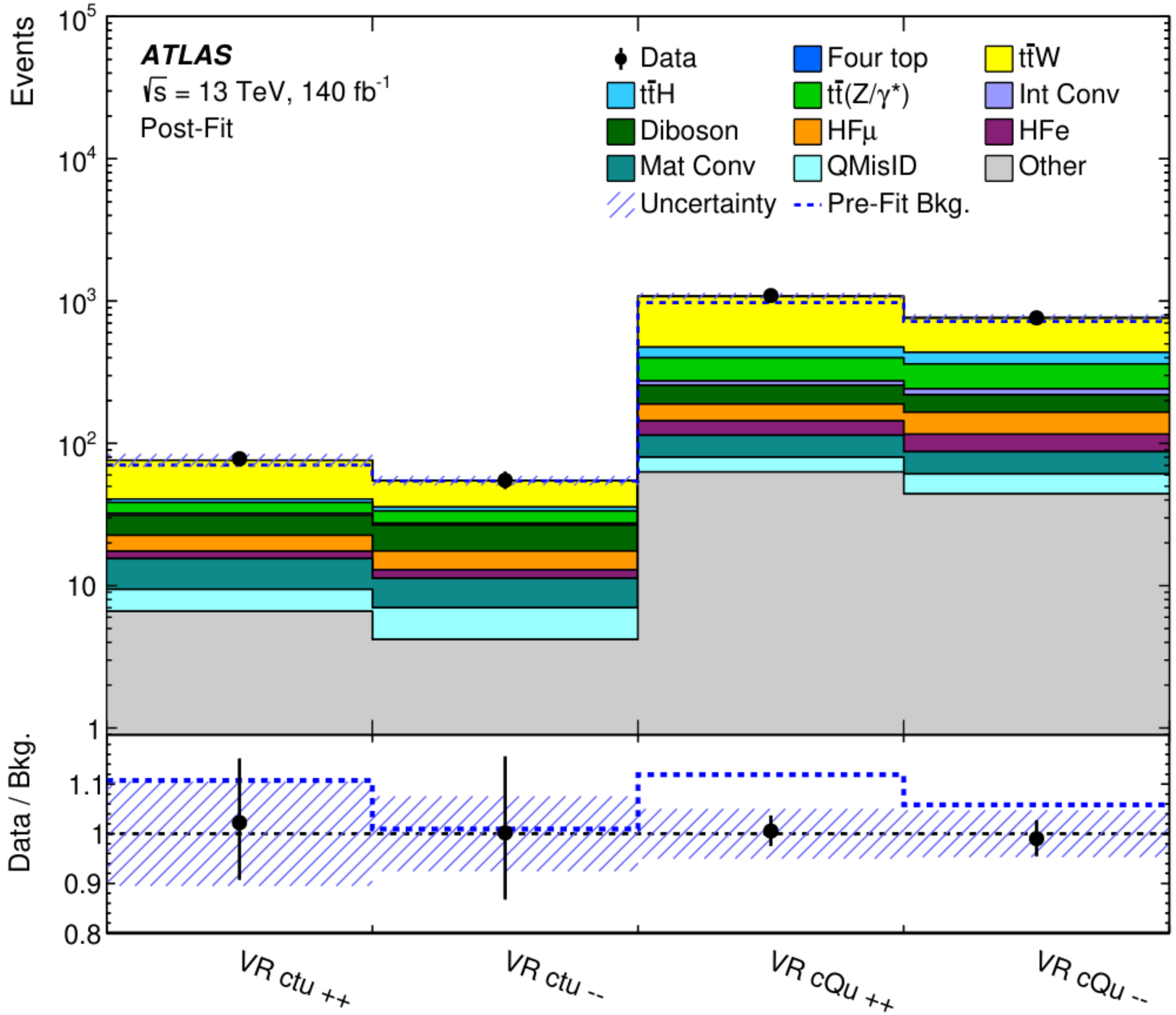
	CR HF TM	CR HF MT	CR HF MM
$p_{\mathrm{T}}^{\mathrm{lep}}$ [GeV]	>20		
BDT WPs (same-sign ℓ pair)	TM	MT	MM
N_{jets}	≥2		
$N_{b-\mathrm{tagged\,jets}}$	1 at 77%		
Total lepton charge	++ or - -		
$m_T(\mathrm{all}\ \ell,\ E_{\mathrm{T}}^{\mathrm{miss}})$	< 250 GeV		-

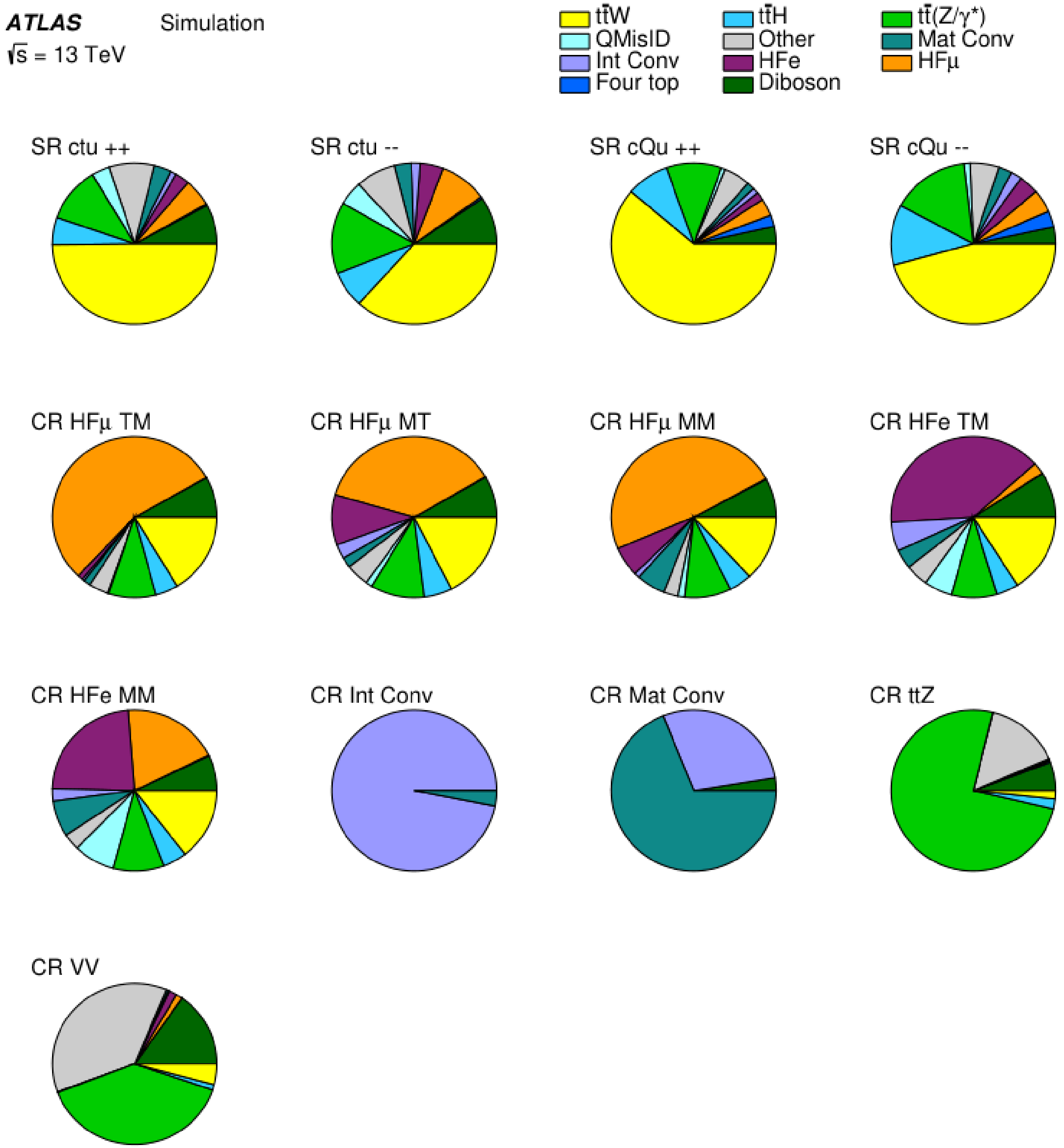
	VV CR	$t\bar{t}Z$ CR	CR Int Conv	CR Mat Conv
$p_{\mathrm{T}}^{\mathrm{lep}}$ [GeV]	> 20 (SS pair), > 10 (OS)			
BDT WPs	$M_{\mathrm{inc}}M_{\mathrm{inc}}$ (SS pair) L_{inc} (OS)			
Total charge	±1			
Electron Conv. candidate	-		Int. Conv.	Mat. Conv.
N_{jets}	2 or 3	≥ 4	≥0	
$N_{b-\mathrm{tagged\,jets}}$	1 b-tagged jet at 60% WP || ≥ 2 b-tagged jets at 77% WP		0 at 77%	
$\lvert m_{SFOS} - m_Z \rvert$	< 10 GeV		> 10 GeV	
$\lvert m(\ell\ell\ell) - m_Z \rvert$	-	-	< 10 GeV	

Merged regions (SR+VR)

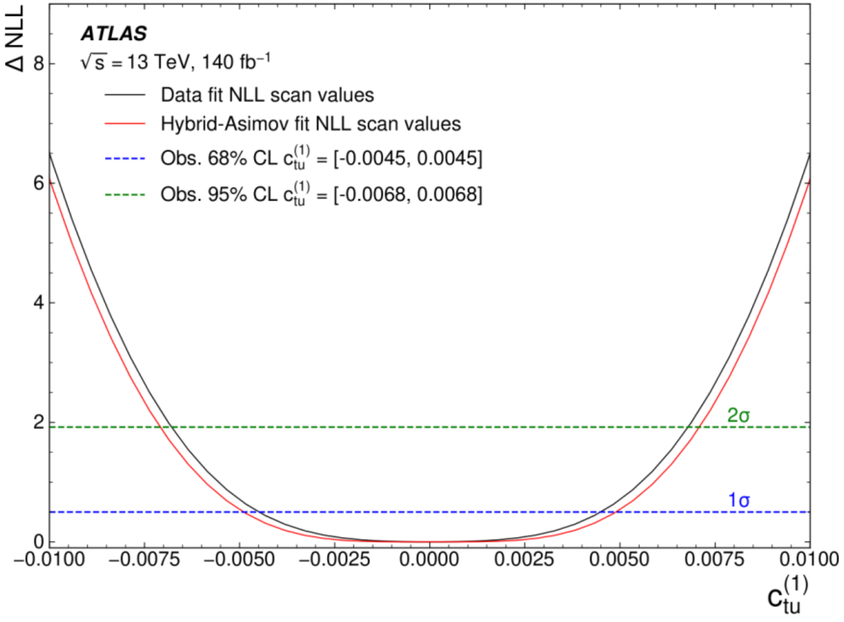


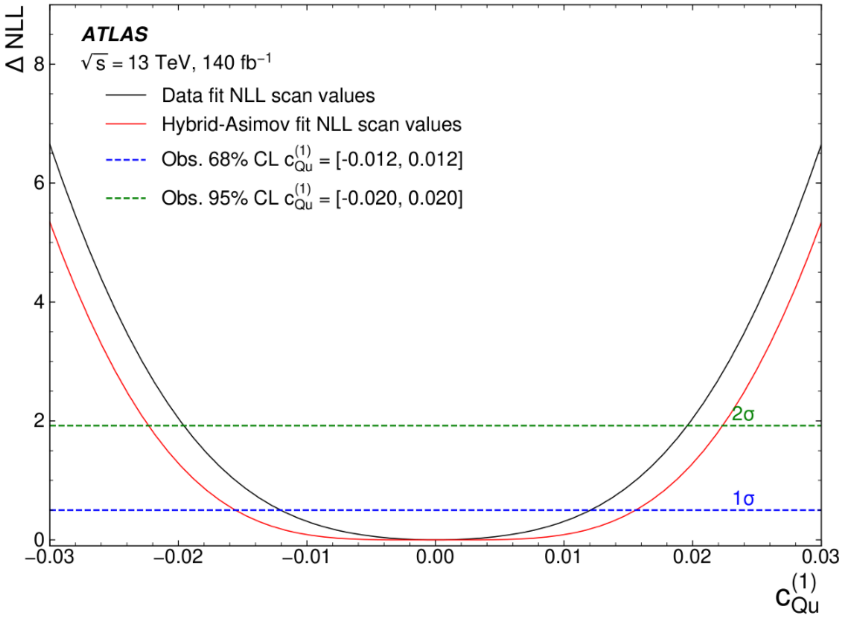
Results – VRs & Pie chart

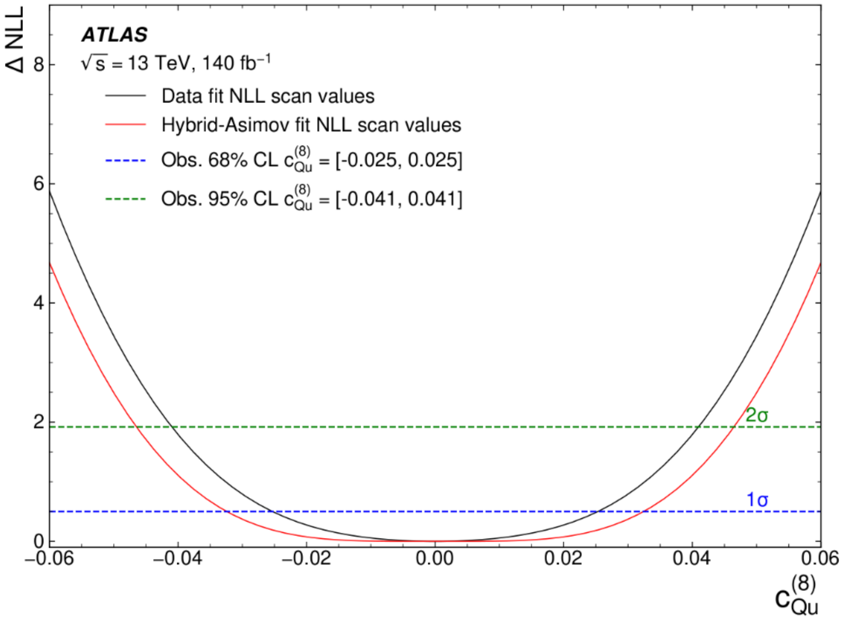




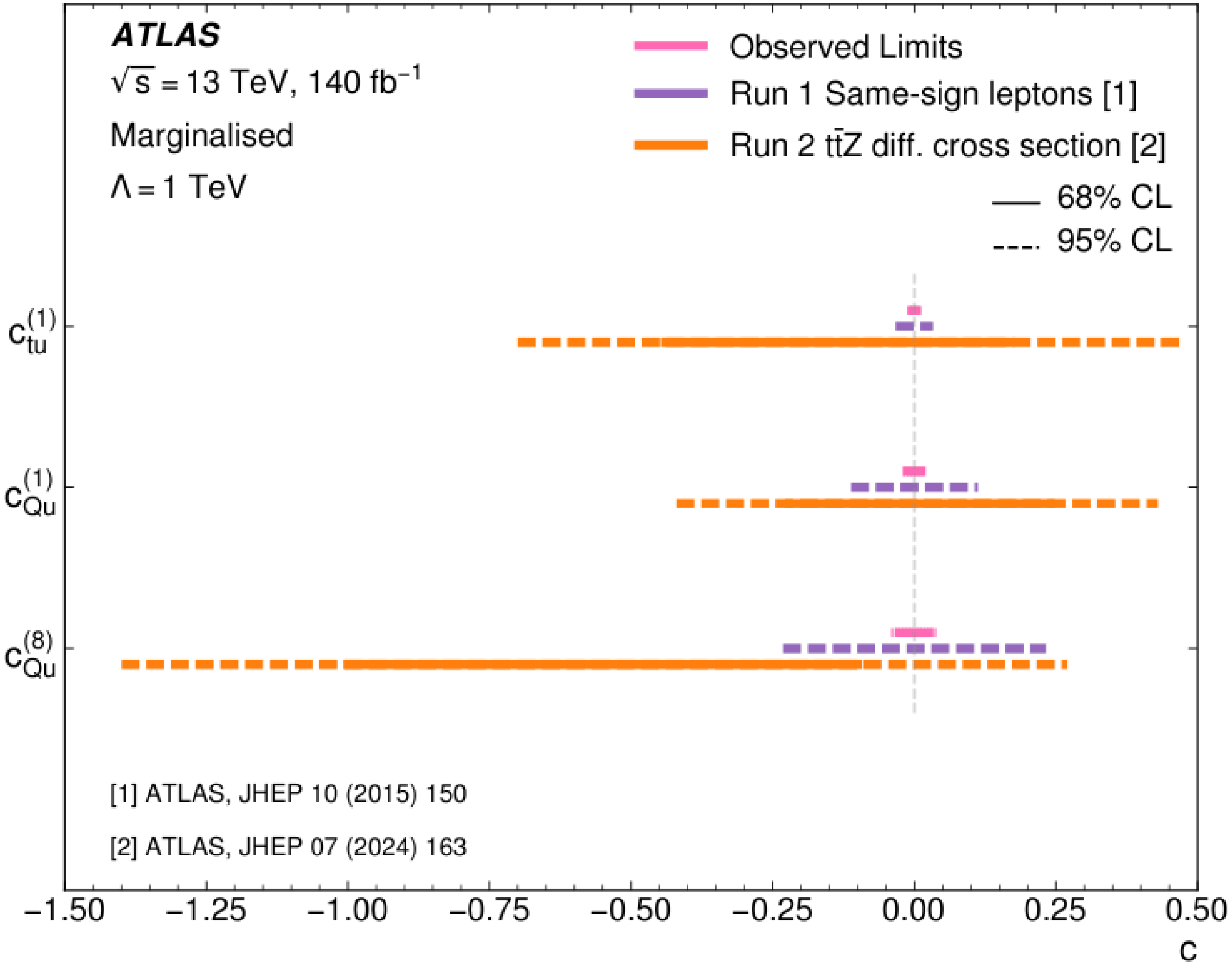
Results – 1D likelihood scans







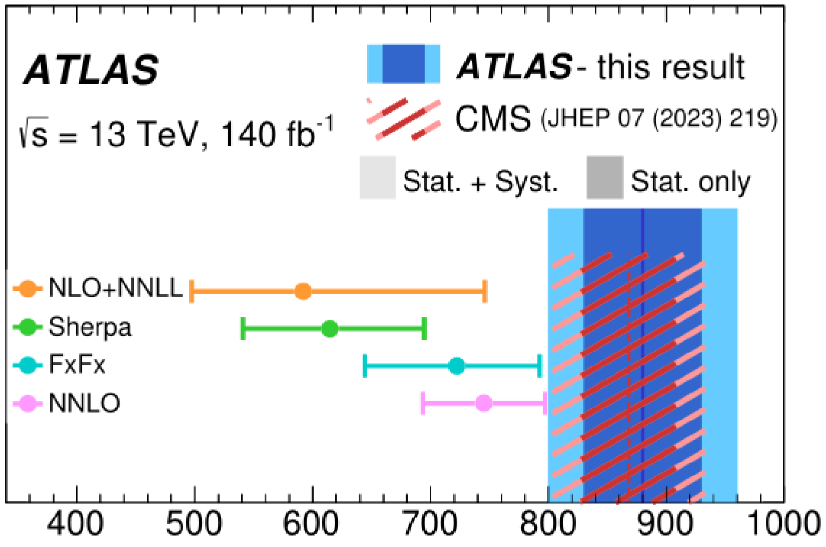
Results – alternative limits comparison



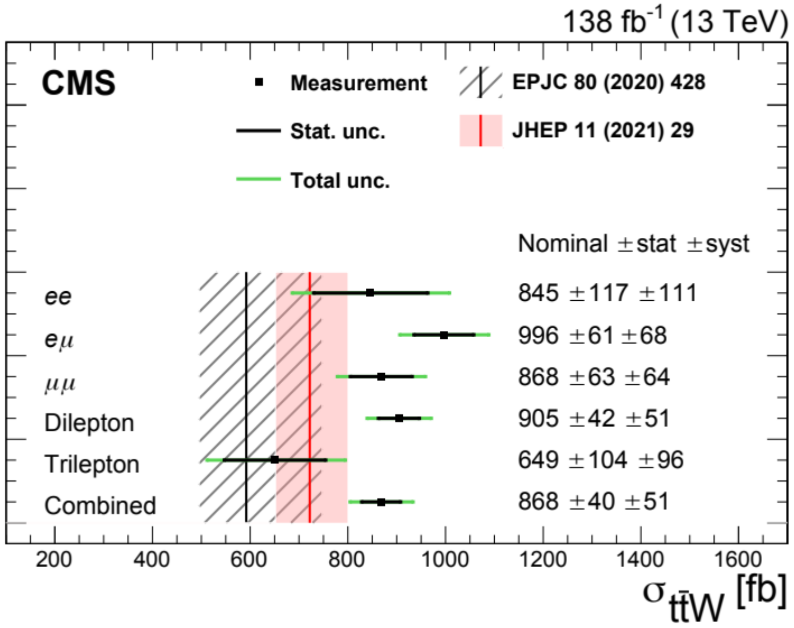
$t\bar{t}W$ measured cross-section

- Previous analysis within ATLAS and CMS saw tension in the measured $t\bar{t}W$ cross-section and the SM
- In this analysis $t\bar{t}W$ is normalized to:
    - QCD: 674.7 fb
    - EW: 47.7 fb
- The normalisation factor for $t\bar{t}W$ QCD is fitted to 1.37
- Post-fit $t\bar{t}W$ cross-section:
    - $\sigma(t\bar{t}W) = 674.7 \text{ fb } \cdot 1.37 + 47.7 \text{ fb} = 972.0 \text{ fb}$

arxiv:2401.05299



arxiv:2208.06485



Yield Tables SRs

Process	SR_{ctu++}	SR_{ctu--}	SR_{cQu++}	SR_{cQu--}
$t\bar{t}W$	114 ± 15	62 ± 10	110 ± 15	56.9 ± 9.0
$t\bar{t}(Z/\gamma*)$	25.5 ± 2.4	24.1 ± 2.6	19.5 ± 1.8	19.1 ± 1.8
$t\bar{t}H$	12.4 ± 7.5	12.3 ± 7.1	15.1 ± 9.6	15.1 ± 9.2
Four top	0.72 ± 0.15	0.69 ± 0.14	4.16 ± 0.83	4.07 ± 0.82
Diboson	18.1 ± 9.3	15.9 ± 8.1	6.3 ± 3.2	4.2 ± 2.1
HFe	6.5 ± 2.9	7.6 ± 3.0	3.0 ± 1.1	4.9 ± 2.5
HFμ	12.6 ± 2.7	15.7 ± 3.2	6.3 ± 1.8	5.7 ± 1.7
Mat Conv	7.6 ± 2.5	5.5 ± 1.6	2.73 ± 0.83	3.3 ± 1.2
Int Conv	2.7 ± 1.6	3.0 ± 1.7	2.1 ± 1.2	2.7 ± 1.6
QMisID	8.1 ± 2.2	8.1 ± 2.2	1.48 ± 0.39	1.48 ± 0.39
Other	20.3 ± 5.4	13.3 ± 3.9	9.3 ± 2.7	7.0 ± 2.6
Total Bkg.	228 ± 11	167.7 ± 7.9	180 ± 10	124.5 ± 6.3
Data	230	162	181	123

Yield Tables 2ℓ CRs

Process	CR HFμ TM	CR HFμ MT	CR HFμ MM	CR HFe TM	CR HFe MM
$t\bar{t}W$	24.0 ± 4.9	10.3 ± 2.0	3.73 ± 0.87	15.1 ± 2.9	2.76 ± 0.59
$t\bar{t}(Z/\gamma*)$	13.6 ± 2.1	6.20 ± 0.97	2.59 ± 0.47	8.4 ± 1.7	1.90 ± 0.32
$t\bar{t}H$	6.6 ± 4.0	3.2 ± 1.9	1.28 ± 0.79	4.1 ± 2.4	0.90 ± 0.58
Four top	0.113 ± 0.028	0.071 ± 0.017	0.046 ± 0.012	0.069 ± 0.019	0.036 ± 0.010
Diboson	11.9 ± 6.1	4.9 ± 2.5	2.2 ± 1.1	8.6 ± 4.4	1.35 ± 0.72
HFe	1.6 ± 1.1	5.9 ± 2.9	1.71 ± 0.97	37 ±12	4.5 ± 1.6
HFμ	80 ± 14	21.9 ± 5.6	13.8 ± 3.2	2.20 ± 0.66	3.62 ± 0.99
Mat Conv	2.0 ± 7.1	1.20 ± 0.56	1.62 ± 0.51	3.7 ± 2.1	1.38 ± 0.43
Int Conv	0.68 ± 0.41	1.7 ± 1.0	0.30 ± 0.18	5.5 ± 3.2	0.48 ± 0.30
QMisID	0.28 ± 0.13	0.75 ± 0.54	0.38 ± 0.26	5.2 ± 2.9	1.6 ± 1.0
Other	5.6 ± 1.5	2.71 ± 0.66	0.81 ± 0.21	4.2 ± 1.0	0.63 ± 0.16
Total Bkg.	147 ± 12	59.0 ± 5.1	28.4 ± 3.4	94.4 ± 9.2	19.1 ± 2.2
Data	150	57	28	95	19

Yield Tables 3ℓ CRs

Process	CR Int Conv	CR Mat Conv	CR ttZ	CR VV
$t\bar{t}W$	–	–	8.4 ± 1.8	24.5 ± 4.7
$t\bar{t}(Z/\gamma*)$	–	–	378 ± 32	230 ± 27
$t\bar{t}H$	–	–	10.0 ± 6.3	6.3 ± 4.0
Four top	–	–	1.61 ± 0.32	0.092 ± 0.020
Diboson	0.025 ± 0.019	1.34 ± 0.72	29 ± 15	90 ± 45
HFe	–	–	0.47 ± 0.35	9.2 ± 6.8
HFμ	–	–	1.04 ± 0.35	7.5 ± 1.8
Mat Conv	1.3 ± 1.1	37.6 ± 8.6	0.59 ± 0.40	2.19 ± 0.77
Int Conv	42.5 ± 6.8	15.6 ± 4.3	0.14 ± 0.15	1.66 ± 0.96
QMisID	–	–	0.22 ± 0.17	0.83 ± 0.41
Other	–	–	74 ± 23	218 ± 40
Total Bkg.	43.9 ± 6.6	54.6 ± 7.3	503 ± 22	590 ± 23
Data	44	55	494	605