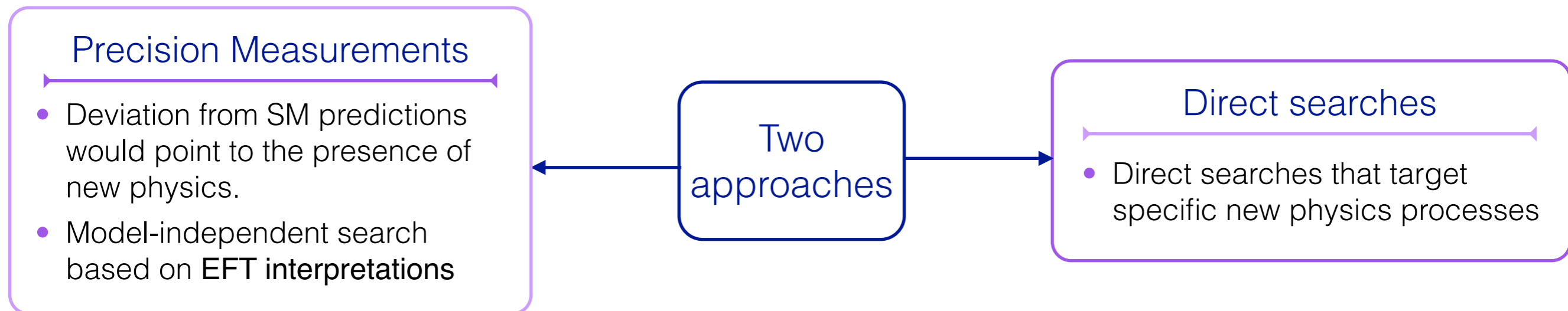
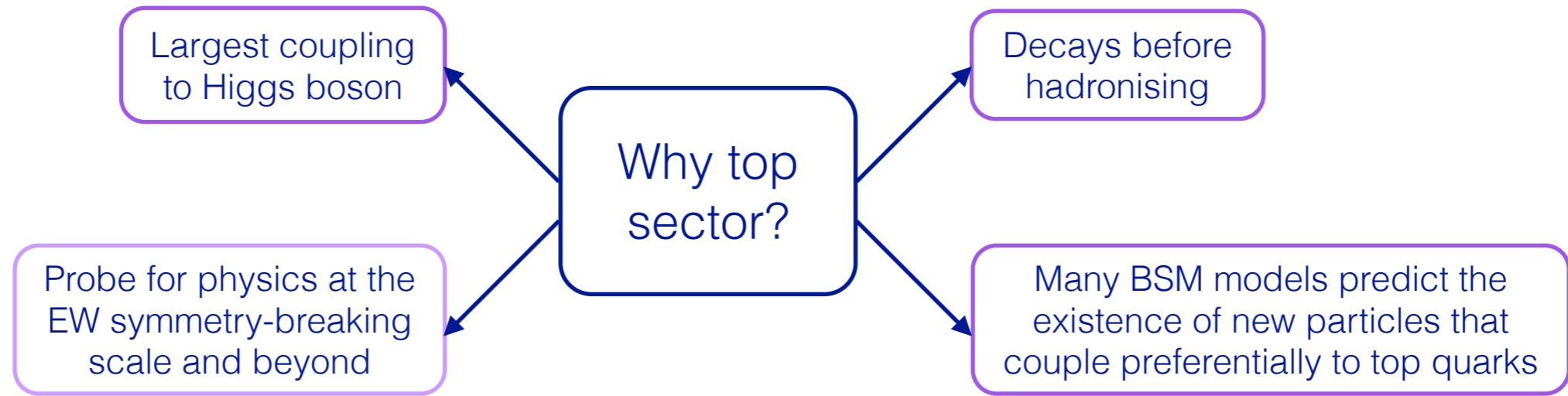




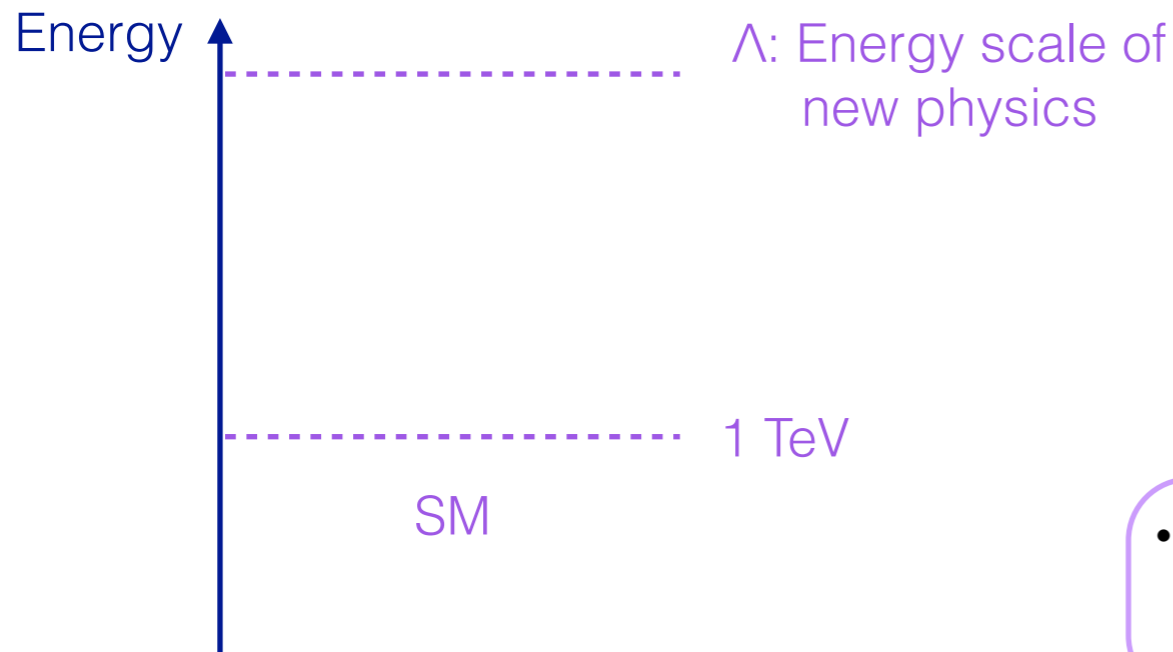
EFT Results from ATLAS

Laura Barranco Navarro
(on behalf of the ATLAS collaboration)
LHCP Conference
7.06.2021

The top quark as a window for new physics



Effective Field Theories (EFT)



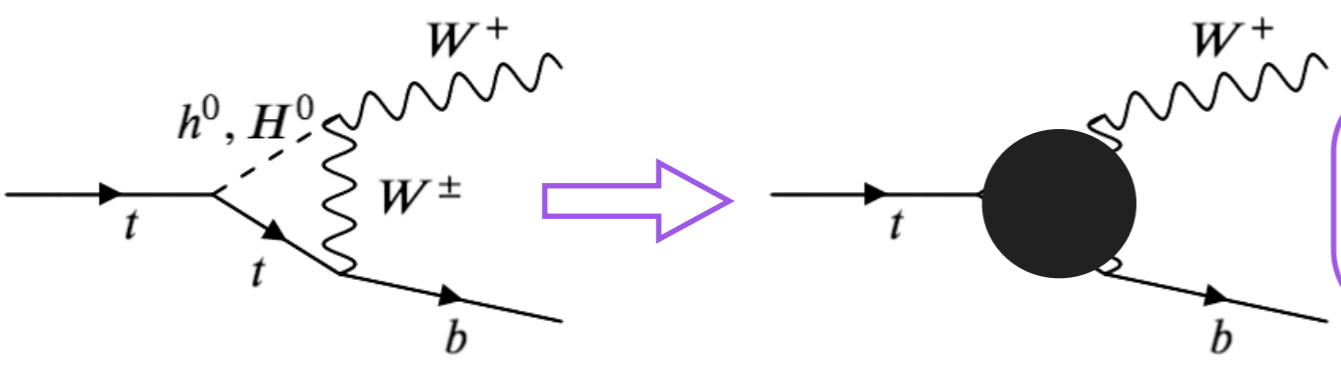
Parameterise the effect of new physics via higher-dimension operators:

$$\mathcal{L}_{eff} = L_0 + \sum \frac{C_x}{\Lambda^2} \mathcal{O}_x$$

- Wilson coefficients: couplings of the SM fields to the new physics

- Dimension-six gauge invariant operators
- Higher terms suppressed by higher powers of Λ

- May induce corrections to the SM couplings.



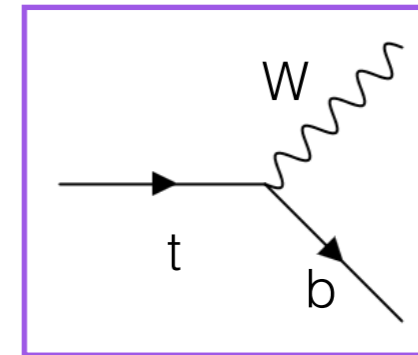
ATLAS Top EFT interpretations in a nutshell

- **SMEFT** framework
- **Warsaw** basis
- $\Lambda = 1$ TeV
- Focus on a **small set of operators** or combination of operators
 - Typically one operator (or combination) at a time
- Interpretation strategy usually tailored for individual analysis
- Two types of measurements:
 - Direct searches at detector level (ex. FCNC)
 - Precision measurements unfolded to parton/particle level (ex. Angular observables)

[JHEP 10 \(2010\) 085](#)
[1802.07237 \[hep-ph\]](#)

FCNC in the top quark sector

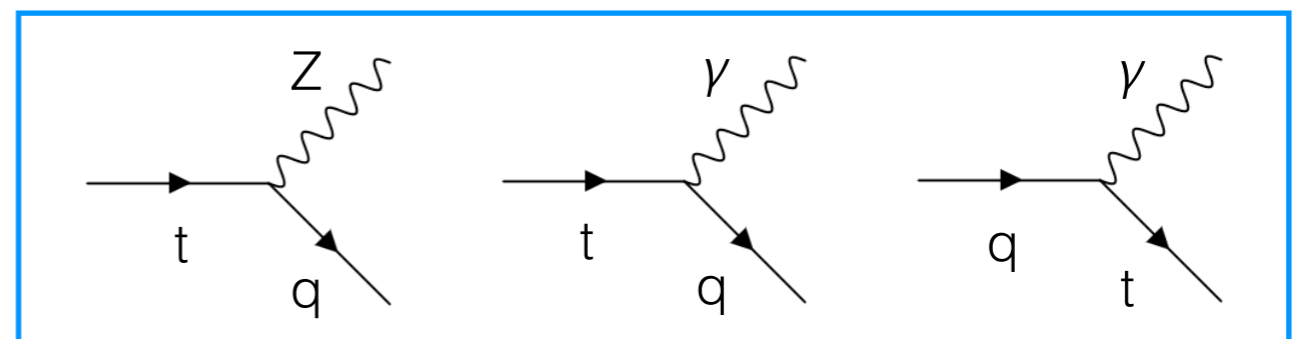
- Dominant SM top decay: $t \rightarrow Wb$
- FCNC decays: $t \rightarrow Zq$, $t \rightarrow gq$, $t \rightarrow Hq$, $t \rightarrow \gamma q$
 - **Forbidden** at **tree level** in the **SM**
 - Strongly suppressed at higher orders via the GIM mechanism
 - **Increasing rates** by several orders in **BSM** models as quark singlets, two Higgs doublets models, supersymmetric extensions of the SM...
- Relevant **effective operators** for FCNC contributions to the production and decay modes* $q \rightarrow t\gamma$, $t \rightarrow \gamma q$ and $t \rightarrow Zq$



$$\mathcal{O}_{uB}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} u_j) \tilde{\phi} B_{\mu\nu}$$

$$\mathcal{O}_{uW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j) \tilde{\phi} W_{\mu\nu}^I$$

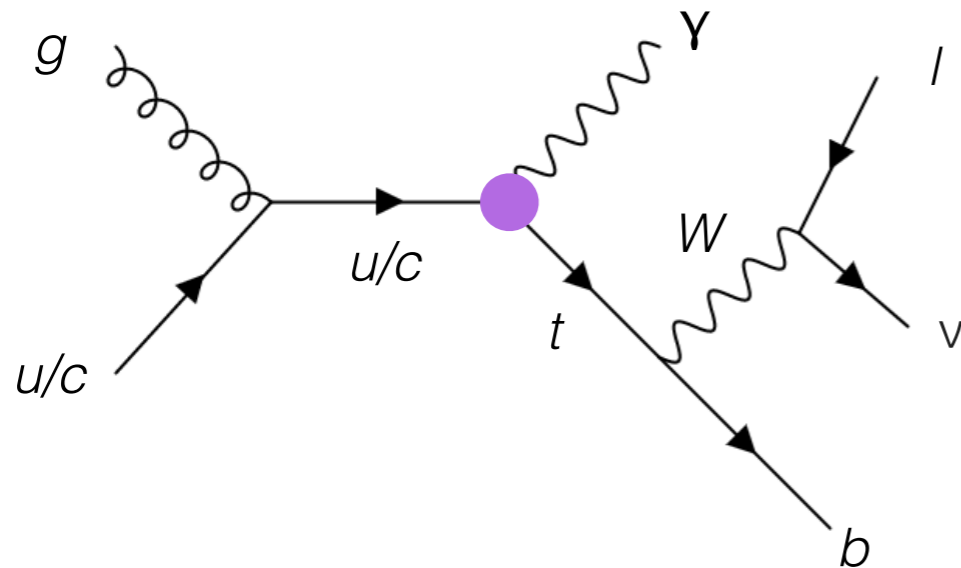
with $i \neq j$ and either $i=3$ or $j=3$



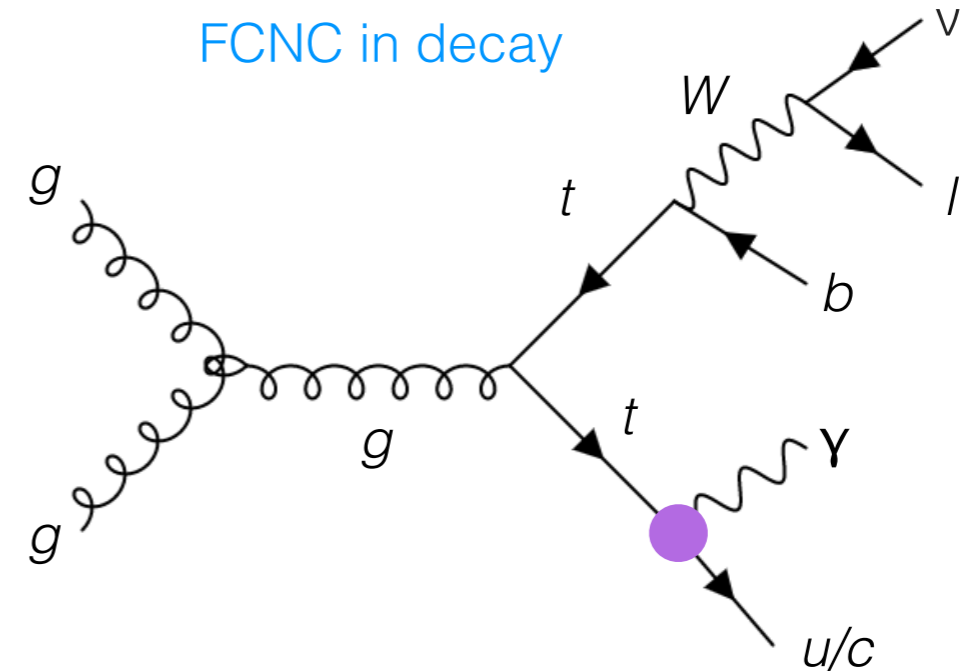
$t \rightarrow q\gamma$ and $q \rightarrow t\gamma$

13 TeV, $L=81\text{fb}^{-1}$
Phys. Lett. B 800 (2019) 135082

FCNC in production



FCNC in decay



Signature

- SR: 1γ , 1 charged lepton (e or μ), 1 b-tagged jet, $E_T^{\text{miss}} > 30$ GeV
- CRs: $W+\gamma+\text{jets}$, $Z+\gamma+\text{jets}$

Main backgrounds

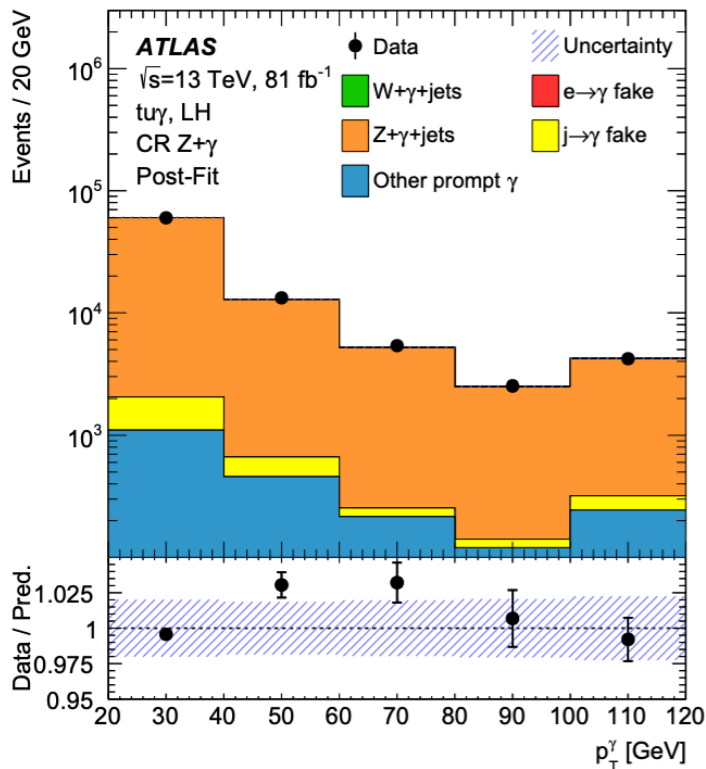
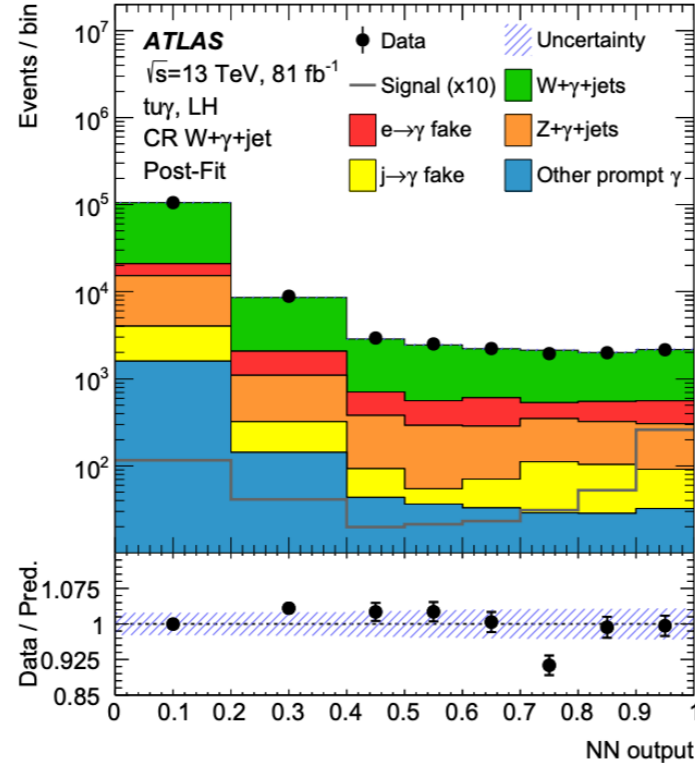
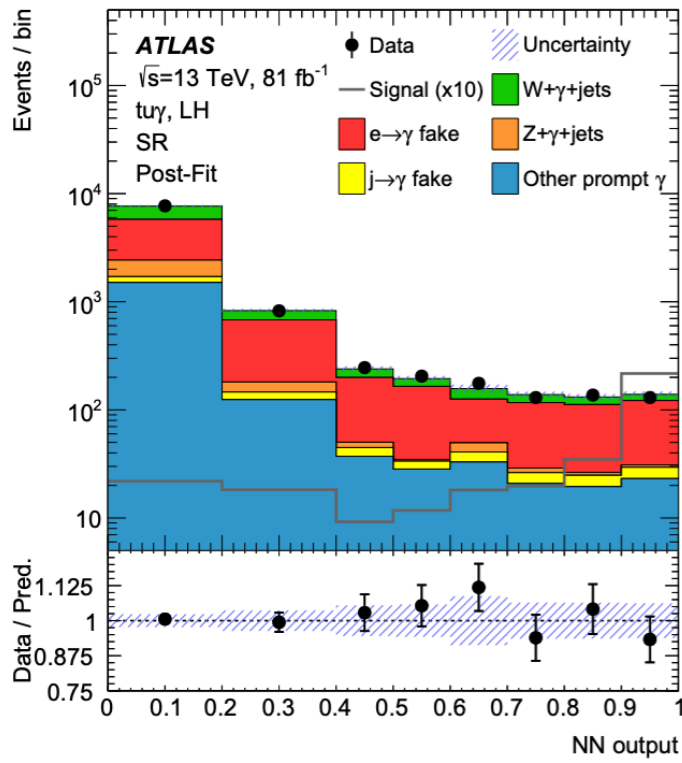
- Electrons misidentified as photons from $t\bar{t}$ events
- Processes with prompt γ

Analysis strategy

- NN to discriminate signal from background
- Profile likelihood fit to the NN output and the $p_{T\gamma}$ distributions in the SR and CRs

$t \rightarrow q\gamma$ and $q \rightarrow t\gamma$

13 TeV, L=81fb⁻¹
 Phys. Lett. B 800 (2019) 135082



Observable	Vertex	Coupling	Obs.	Exp.
$ C_{uW}^{(13)*} + C_{uB}^{(13)*} $	$tq\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$ C_{uW}^{(31)} + C_{uB}^{(31)} $	$tq\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
$ C_{uW}^{(23)*} + C_{uB}^{(23)*} $	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
$ C_{uW}^{(32)} + C_{uB}^{(32)} $	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$
$\sigma(pp \rightarrow tq\gamma)$ [fb]	$tq\gamma$	LH	36	52^{+21}_{-14}
$\sigma(pp \rightarrow tq\gamma)$ [fb]	$tq\gamma$	RH	78	75^{+31}_{-21}
$\sigma(pp \rightarrow tq\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
$\sigma(pp \rightarrow tq\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}
$\mathcal{B}(t \rightarrow q\gamma)$ [10^{-5}]	$tq\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \rightarrow q\gamma)$ [10^{-5}]	$tq\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \rightarrow q\gamma)$ [10^{-5}]	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \rightarrow q\gamma)$ [10^{-5}]	$tc\gamma$	RH	18	28^{+12}_{-8}

95% CL upper limits

Leading uncertainties

- Limited size of data sample
- Jet energy resolution
- Reweighting of the photon p_T
- Factorisation and renormalisation scales
- Choice of generator for the simulation of tt and single top processes
- Limited size of the simulation samples

t → Zq

Signature

- SR: 3 charged leptons (e or μ) with m_{ll} close to the Z mass, at least 2 jets, exactly 1 b-tagged jet, $E_T^{\text{miss}} > 20$ GeV
- CRs: ttZ CR, VZ CR, ZZ CR, 2 regions for non-prompt leptons

Main backgrounds

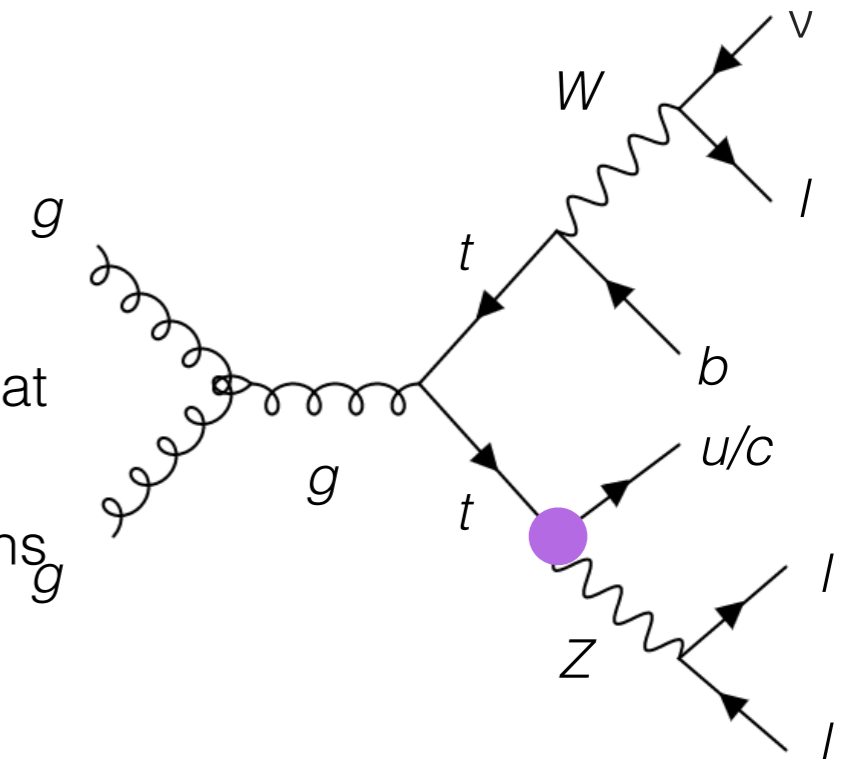
- diboson, ttZ and tZ processes

Analysis strategy

- χ^2 minimisation to reconstruct the events

$$\chi^2 = \frac{\left(m_{j_a l_a l_b}^{\text{reco}} - m_{t_{\text{FCNC}}}\right)^2}{\sigma_{t_{\text{FCNC}}}^2} + \frac{\left(m_{j_b l_c \nu}^{\text{reco}} - m_{t_{\text{SM}}}\right)^2}{\sigma_{t_{\text{SM}}}^2} + \frac{\left(m_{l_c \nu}^{\text{reco}} - m_W\right)^2}{\sigma_W^2}$$

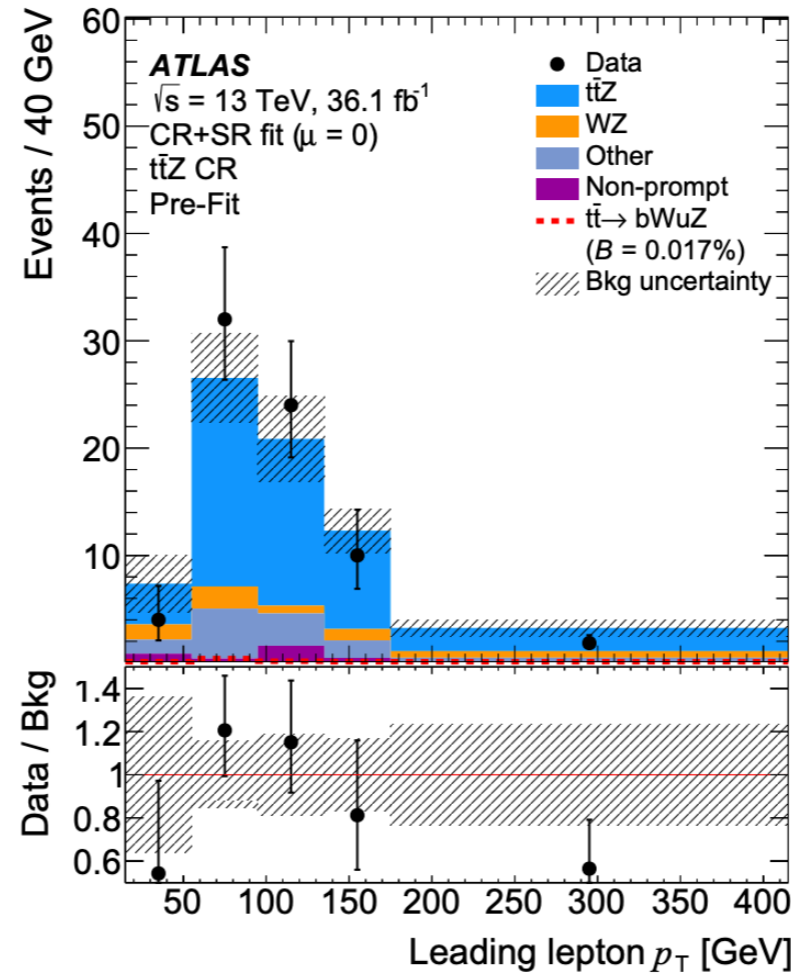
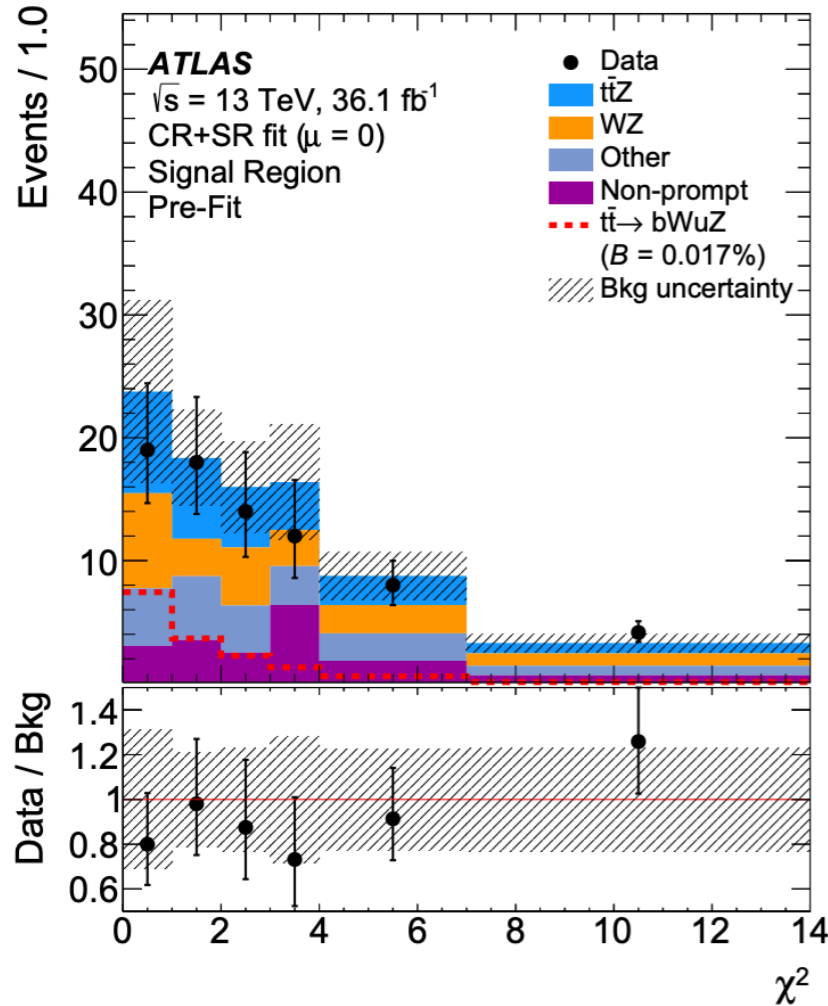
- Profile likelihood fit to the χ^2 distribution in the SR, the leading lepton pT for the non-prompt leptons and ttZ CRs, the W transverse mass for the WZ CR and the reconstructed mass of the four leptons for the ZZ CR



top pair production
13 TeV, L=36.1fb⁻¹
JHEP 07 (2018) 176

$t \rightarrow Zq$

top pair production
 13 TeV, L=36.1 fb⁻¹
 JHEP 07 (2018) 176



Operator	Observed	Expected
$ C_{uB}^{(31)} $	0.25	0.30
$ C_{uW}^{(31)} $	0.25	0.30
$ C_{uB}^{(32)} $	0.30	0.34
$ C_{uW}^{(32)} $	0.30	0.34

95% CL upper limits

- Leading uncertainties
 - Limited size of data sample
 - Theoretical normalisation
 - Background modeling

	$\mathcal{B}(t \rightarrow uZ)$	$\mathcal{B}(t \rightarrow cZ)$
Observed	1.7×10^{-4}	2.4×10^{-4}
Expected -1σ	1.7×10^{-4}	2.2×10^{-4}
Expected	2.4×10^{-4}	3.2×10^{-4}
Expected $+1\sigma$	3.4×10^{-4}	4.6×10^{-4}

Charge asymmetry in $t\bar{t}$

top pair production
13 TeV, L=139.1fb⁻¹
ATLAS-CONF-2019-026

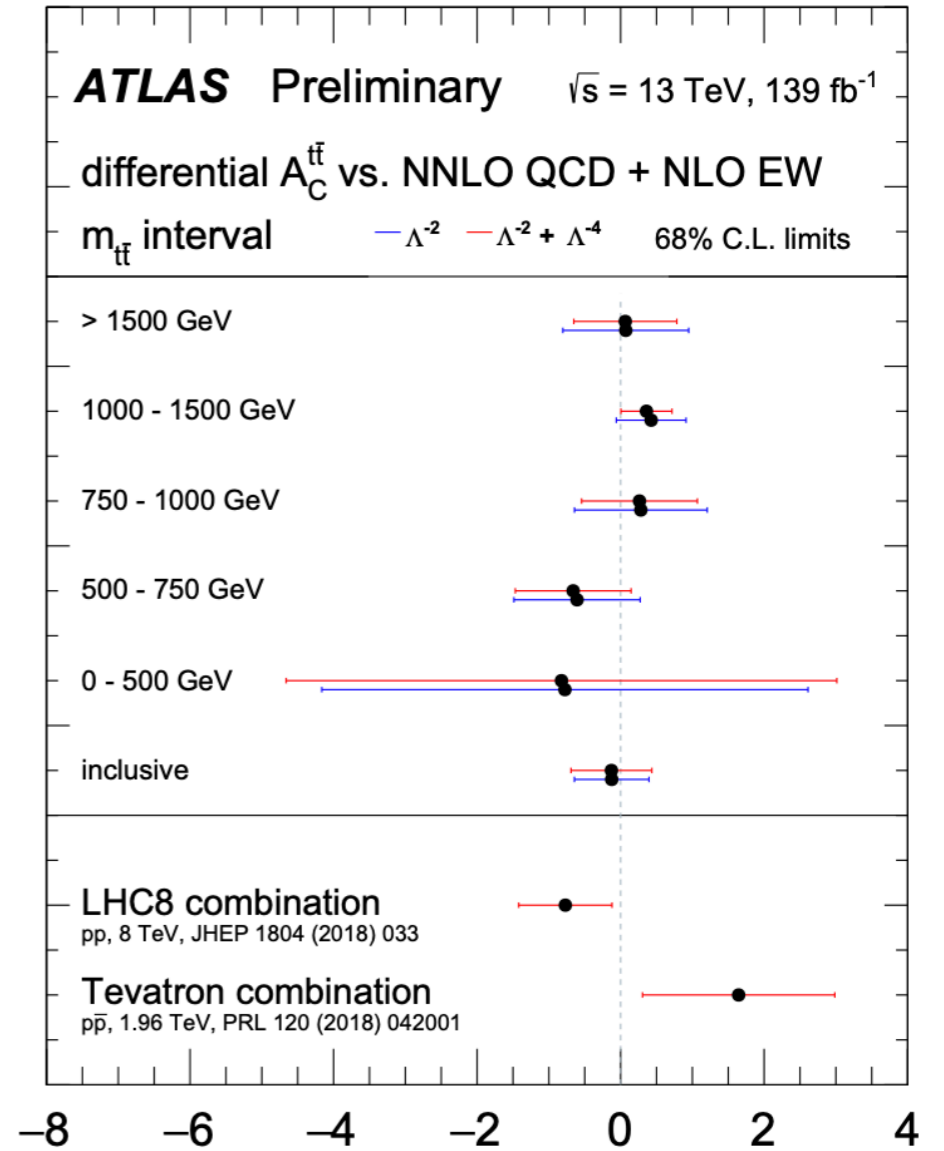
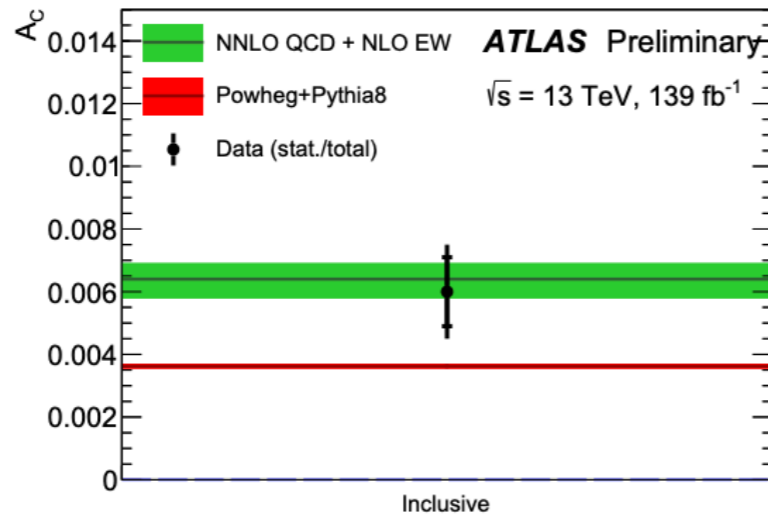
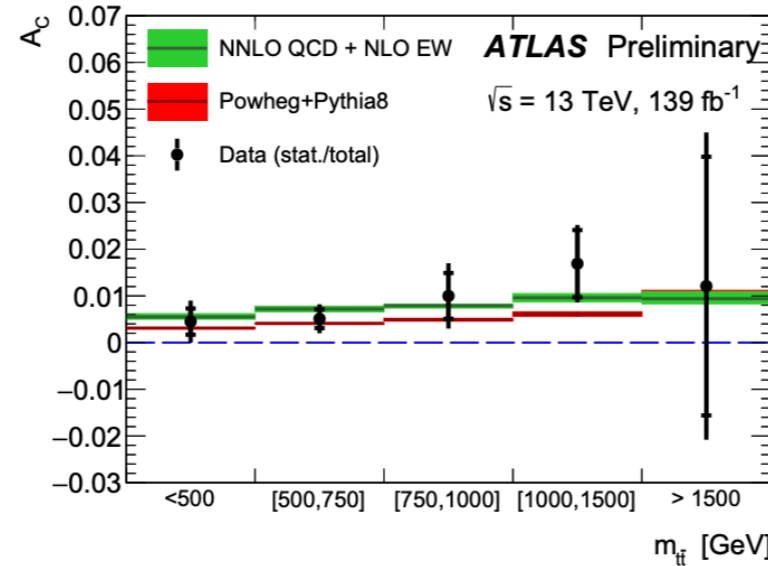
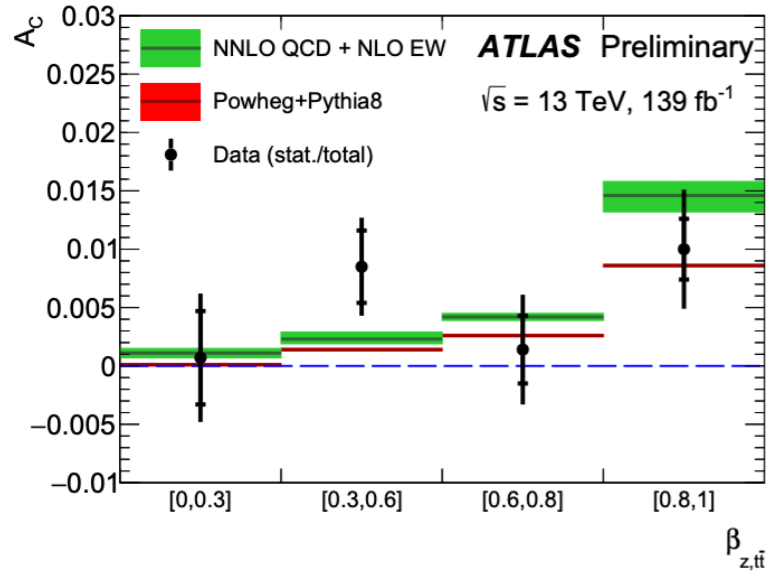
- Asymmetry in t and \bar{t} arise from interference of higher-order amplitudes in the $q\bar{q}$ and qg initial states.
- Due to the difference in the pdf, valence quarks carry larger fraction of proton's momentum than the sea antiquarks
 - More forward top quarks and more central top antiquarks

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

- Signature
 - Lepton + jets in both boosted and resolved topologies
- Main backgrounds
 - W+jets & single top production
- Analysis strategy
 - Combine both topologies and measure A_C inclusively and differentially
 - Acceptance and detector effects corrected with a Bayesian unfolding procedure

Charge asymmetry in $t\bar{t}$

top pair production
13 TeV, L=139.1fb⁻¹
ATLAS-CONF-2019-026



$$C_u^1 = C_{qq}^{(8,1)} + C_{qq}^{(8,3)} + C_{ut}^{(8)}$$

$$C_u^2 = C_{qu}^{(1)} + C_{qt}^{(1)}$$

$$C_d^1 = C_{qq}^{(8,1)} - C_{qq}^{(8,3)} + C_{dt}^{(8)}$$

$$C_d^2 = C_{qd}^{(1)} + C_{qt}^{(1)}$$



$$C_u^1 = C_d^1 = C^1$$

$$C_u^2 = C_d^2 = C^2$$



$$C^+ = C^1 + C^2$$

$$C^- = C^1 - C^2$$

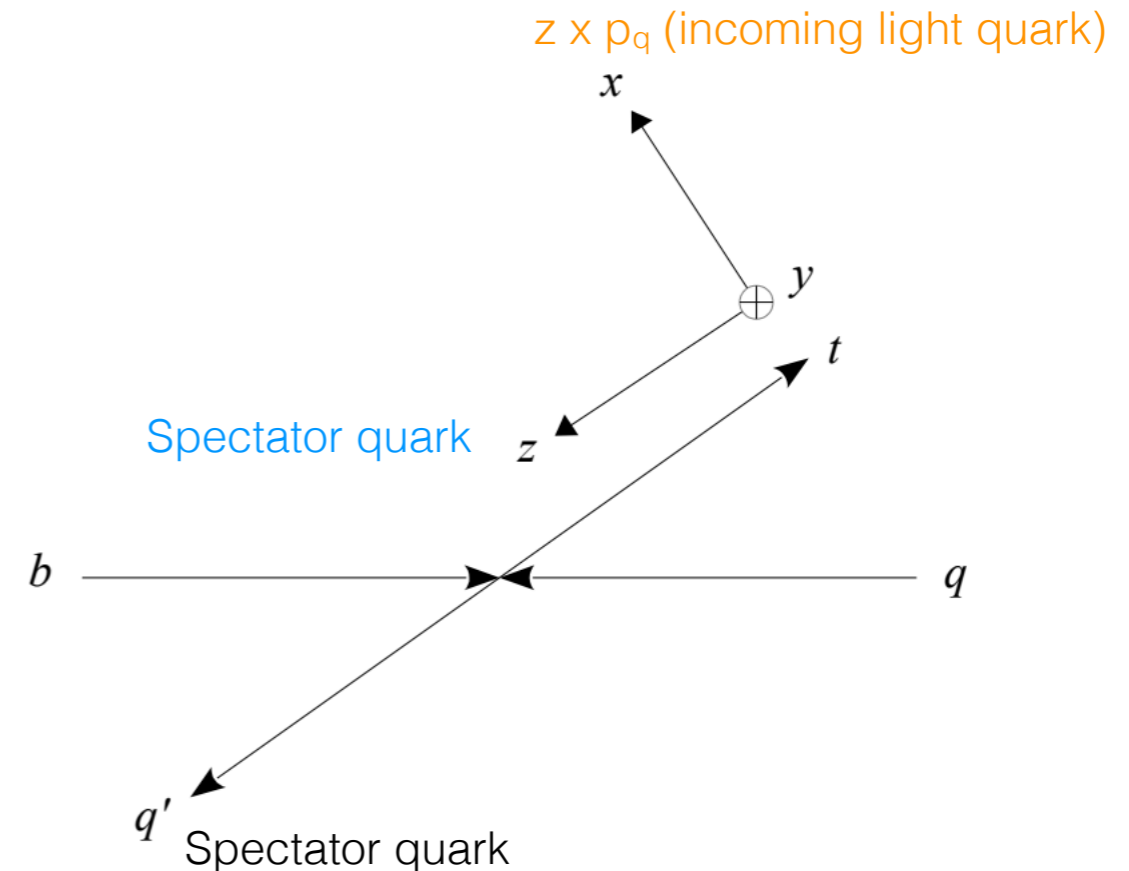
- Leading uncertainties
 - Limited size of data sample
 - Modelling of background and signal

Top quark polarisation

ATLAS-CONF-2021-027 (to appear)

New!

- In the t-channel at LO, single top quarks are produced with their spin completely aligned along the direction of the spectator quark.
- Spin information transmitted to decay products
- Measure $P = (\vec{P}_x, P_y, P_z)$



○ Signature

- t-channel single top production: 1 charged lepton, significant E_T^{miss} & 2 jets

○ Main backgrounds

- Top pair production & W +jets

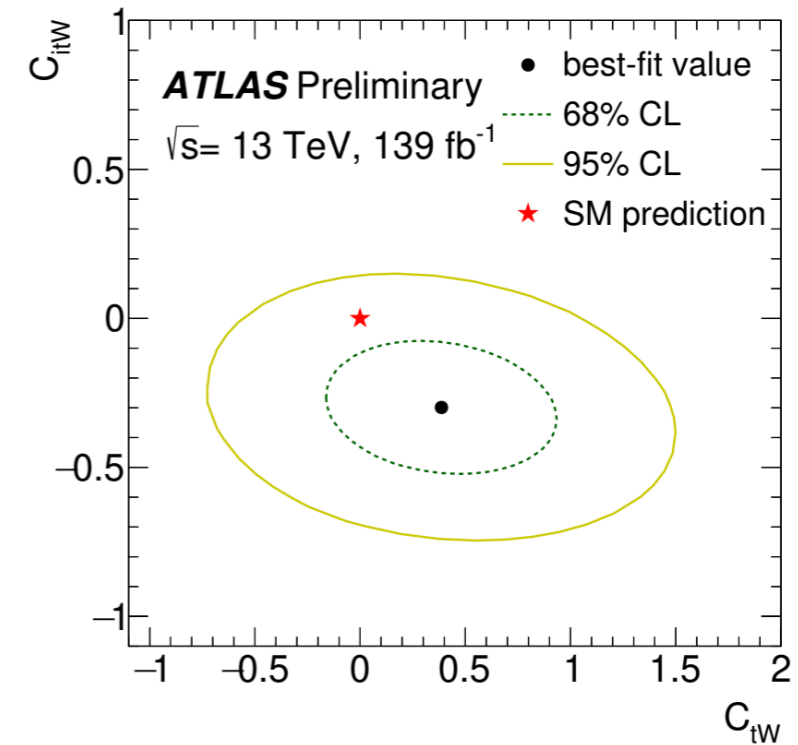
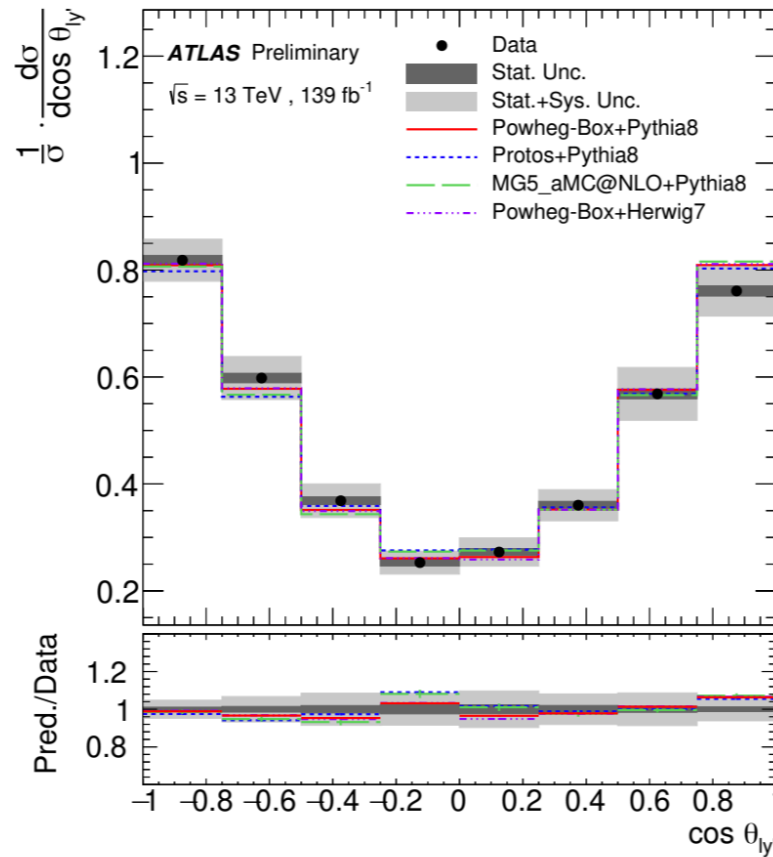
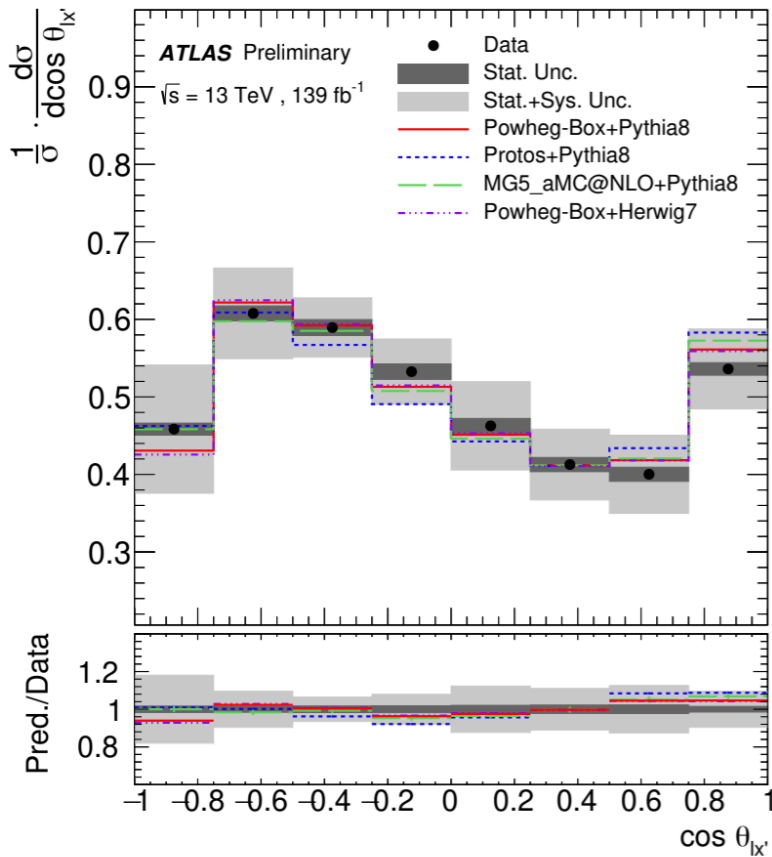
○ Analysis strategy

- Polarisation vector for top and anti-top quarks fitted from angular distributions
- Measurement unfolded to particle level

Top quark polarisation

New!

ATLAS-CONF-2021-027 (to appear)



- Leading uncertainties
 - Jet energy scale and resolution
 - Modelling of the signal

	C_{tW}		C_{itW}	
	68% CL	95% CL	68% CL	95% CL
All terms	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^4$	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^2$	[-0.2, 1.0]	[-0.7, 1.7]	[-0.5, -0.1]	[-0.8, 0.2]

- P_x and P_y are affected, respectively, by the real and imaginary parts of the O_{tW} effective operator

Summary

- Standard Model of particle physics is widely believed to require extensions
- Top quark provides a unique opportunity to search for new physics
- EFT interpretations are becoming more popular
- So far, strategies have been tailored for individual analysis
 - Building up on acquired expertise to move forward to a more comprehensive and future-proof approach
 - Considering combinations
 - Exciting results to come

Backup Slides



$t \rightarrow q\gamma$ and $q \rightarrow t\gamma$

- Analysis strategy tailored for Production mode (but decay also included)
- $O_{uB}^{(ij)}$ & $O_{uW}^{(ij)}$ with $i \neq j$ and either $i=3$ or $j=3$
- Analysis strategy:
 - Signal region by loose requirements of kinematic properties of final state objects
 - NN input variables: photon p_T , lepton p_T , jet p_T , lepton charge, E_T^{miss} , lepton-photon invariant mass, lepton-jet invariant mass, $\Delta R(\text{lepton, photon})$, $\Delta R(\text{lepton, jet})$, $\Delta R(\text{jet, photon})$
 - Control regions:
 - $W+\gamma+\text{jets}$
 - $Z+\gamma+\text{jets}$ (γ p_T distribution)

$t \rightarrow q\gamma$ and $q \rightarrow t\gamma$ - Couplings

- Higher efficiency for couplings involving a c -quark due to differences in u - and c -quark PDFs
- Higher efficiency for LH couplings due to differences in the kinematic distributions of the W boson decay products
- $t\gamma$ coupling: production mode is the dominant signal process
- $t\gamma$ coupling: decay also plays an important role since production is suppressed by the c -quark PDF

$t \rightarrow Zq$

top pair production
13 TeV, L=36.1fb⁻¹
JHEP 07 (2018) 176

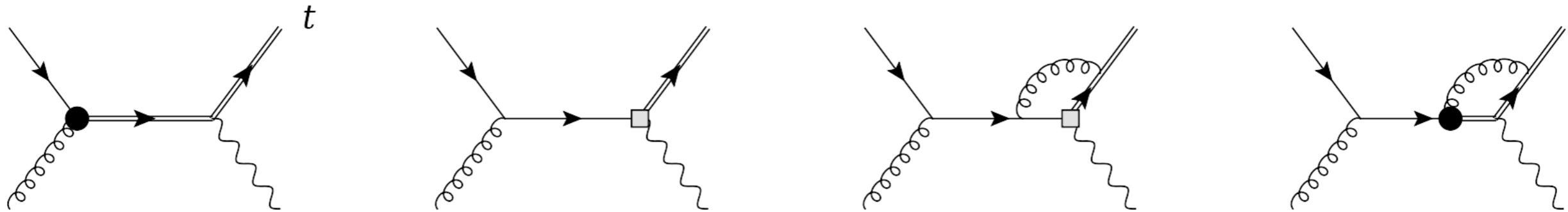
Analysis strategy

- χ^2 minimisation to reconstruct the events

$$\chi^2 = \frac{\left(m_{j_a l_a l_b}^{\text{reco}} - m_{t_{\text{FCNC}}}\right)^2}{\sigma_{t_{\text{FCNC}}}^2} + \frac{\left(m_{j_b l_c \nu}^{\text{reco}} - m_{t_{\text{SM}}}\right)^2}{\sigma_{t_{\text{SM}}}^2} + \frac{\left(m_{l_c \nu}^{\text{reco}} - m_W\right)^2}{\sigma_W^2}$$

- Minimisation gives the most probable value for longitudinal component of the neutrino momentum.
- Combination with minimum χ^2 chosen and SR further defined by:
 - $|m_{j_a l_a l_b}^{\text{reco}} - 172.5 \text{ GeV}| < 40 \text{ GeV}$
 - $|m_{j_b l_c \nu}^{\text{reco}} - 172.5 \text{ GeV}| < 40 \text{ GeV}$
 - $|m_{l_c \nu}^{\text{reco}} - 80.4 \text{ GeV}| < 30 \text{ GeV}$
- Profile likelihood fit to the χ^2 distribution in the SR, the leading lepton pT for the non-prompt leptons and ttZ CRs, the transverse mass for the WZ CR and the reconstructed mass of the four leptons for the ZZ CR

Colour-dipole operator



- $ug \rightarrow tZ$: O_{uG} operator can lead to same tZ/γ final state
- Strong bounds in O_{uG} from previous ATLAS results [Eur. Phys. J. C76 \(2016\) 55](#)

$$|C_{uG}^{(a3)}| \text{ or } |C_{uG}^{(3a)}| \begin{array}{|l} \color{red}{0.041} \\ \color{blue}{0.093} \\ 0 \end{array}$$

[Durieux, Maltoni, Zhang, arXiv: 1412.7166v2](#)

Charge asymmetry in $t\bar{t}$

top pair production
13 TeV, $L=139.1\text{fb}^{-1}$
ATLAS-CONF-2019-026

- Resolved topology
 - 4 small-R jets.
 - BDT to reconstruct $t\bar{t}$ system (correctly assign individual selected jets to the corresponding partons from the decaying top quark)
 - Variables: reconstructed mass of hadronically-decaying top, semileptonically-decaying top and W ; logarithm of likelihood from the KLFilter; b-tagging information; light jet from W ; $\Delta R(\text{b-jet}(\text{semi-leptonic}), \text{lepton})$; $\Delta R(W \text{ light jets})$, $\Delta R(\text{b-jets})$; lepton and b-jet p_T ; $N(\text{jets})$, $\eta(\text{hadronically decaying } t)$.
 - Remove events that fulfill boosted selection
- Boosted topology
 - 1 large-R top-tagged jet $p_T > 350 \text{ GeV}$ (hadronically-decaying top quark)
 - 1 small-R jet close to the selected lepton
 - $m_{t\bar{t}} > 500 \text{ GeV}$
 - Remove events that fulfill boosted selection

Charge asymmetry in $t\bar{t}$

top pair production
13 TeV, $L=139.1\text{fb}^{-1}$
ATLAS-CONF-2019-026

- Unfolding of $\Delta|y|$ (after final state radiation but before decay)
- Full Bayesian Unfolding. Systematic uncertainties included as nuisance parameters
- Include uncertainties on the response matrix due to limited MC statistics as well as unfolding bias.

ttV measurements

ttZ & ttW production
 13 TeV, L=36.1fb⁻¹
 Phys. Rev. D 99 (2019) 072009

Signature

- SR: different signal regions according to the number and sign of leptons. Further split in (b-)jets multiplicity and/or lepton flavors

Main backgrounds

- Depending on the channel, VV, Z+jets, ttH and fake leptons

Analysis strategy

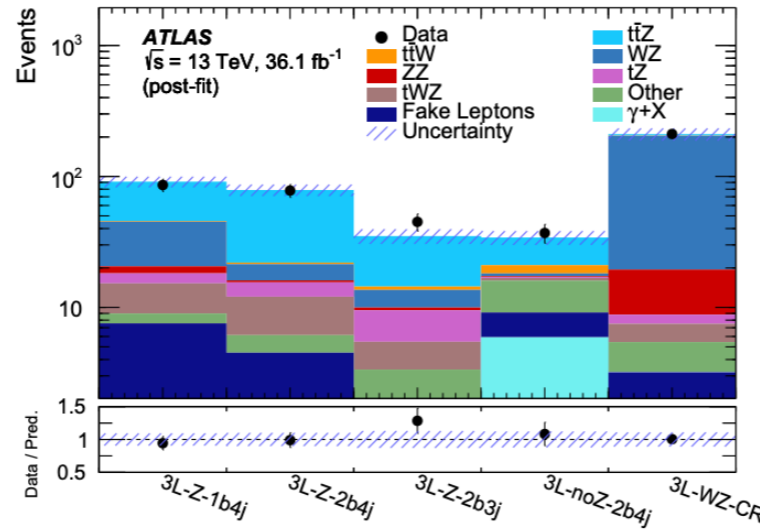
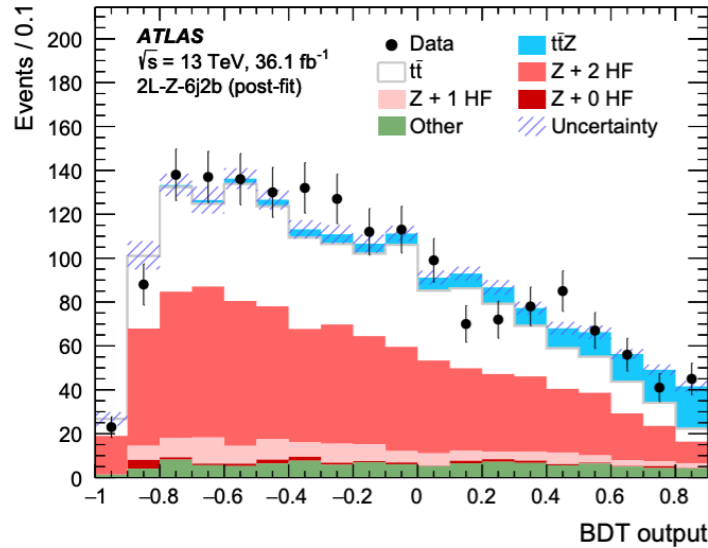
- The signal strength for ttW and ttZ are extracted simultaneously from a binned likelihood fit in the dilepton, trilepton and tetralepton signal and control regions
- ttZ and ttW SRs and CRs are also fitted separately
- EFT limits derived from fit to ttZ regions only

Process	tt decay	V decay	Channel
ttW	$(\ell^\pm \nu b)(qqb)$	$\ell^\pm \nu$	SS dilepton
	$(\ell^\pm \nu b)(\ell^\pm \nu b)$	$\ell^\pm \nu$	Trilepton
ttZ	$(qqb)(qqb)$	$\ell^+ \ell^-$	OS dilepton
	$(\ell^\pm \nu b)(qqb)$	$\ell^+ \ell^-$	Trilepton
	$(\ell^\pm \nu b)(\ell^\pm \nu b)$	$\ell^+ \ell^-$	Tetralepton

ttV measurements

ttZ & ttW production
 13 TeV, L=36.1 fb⁻¹
 Phys. Rev. D 99 (2019) 072009

Regions targeting ttZ production



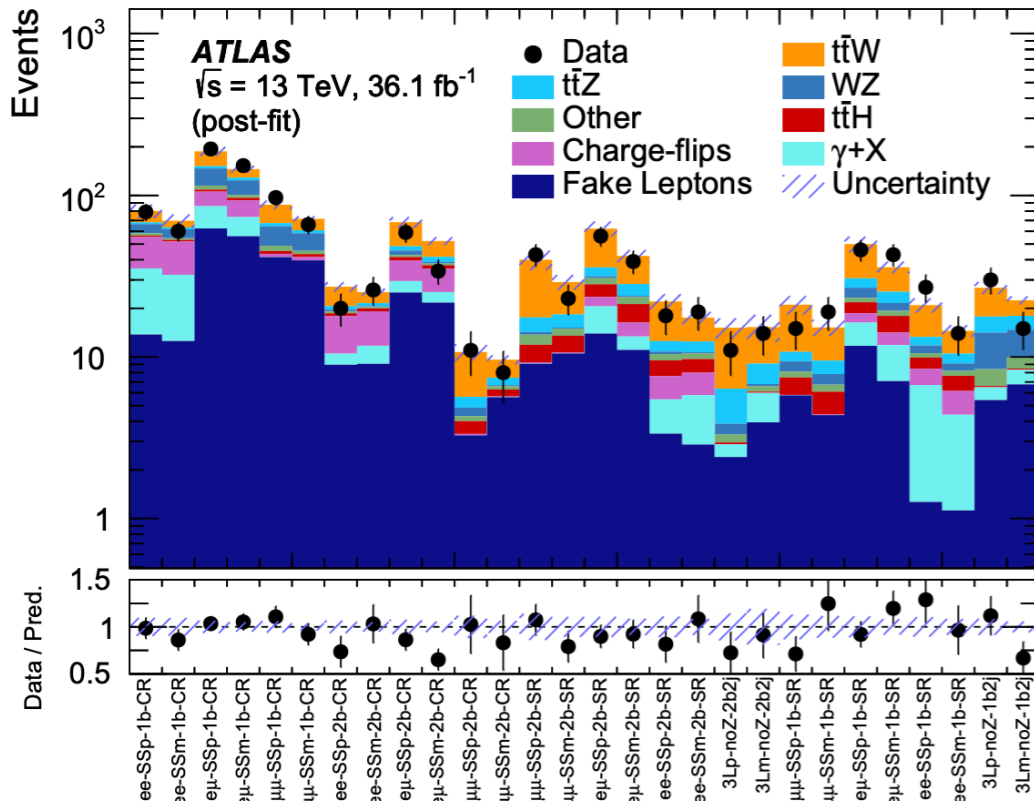
Leading uncertainties

- Modelling of background and signal (ttZ)
- Modelling of signal and limited amount of data (ttW)

$$\sigma_{t\bar{t}Z} = 0.95 \pm 0.08_{\text{stat.}} \pm 0.10_{\text{syst.}}$$

$$\sigma_{t\bar{t}W} = 0.87 \pm 0.13_{\text{stat.}} \pm 0.14_{\text{syst.}}$$

Regions targeting ttW production



Coefficients

Coefficients	$C_{\phi Q}^{(3)}/\Lambda^2$	$C_{\phi t}/\Lambda^2$	C_{tB}/Λ^2	C_{tW}/Λ^2
Expected limit at 68% CL	[-2.1, 1.9]	[-3.8, 2.7]	[-2.9, 3.0]	[-1.8, 1.9]
Expected limit at 95% CL	[-4.5, 3.6]	[-23, 4.9]	[-4.2, 4.3]	[-2.6, 2.6]
Observed limit at 68% CL	[-1.0, 2.7]	[-2.0, 3.5]	[-3.7, 3.5]	[-2.2, 2.1]
Observed limit at 95% CL	[-3.3, 4.2]	[-25, 5.5]	[-5.0, 5.0]	[-2.9, 2.9]

New result:

$$\sigma_{t\bar{t}Z} = 0.99 \pm 0.05_{\text{stat.}} \pm 0.08_{\text{syst.}}$$

13 TeV, L=189 fb⁻¹
 arXiv:2103.12603 (submitted to EPJC)