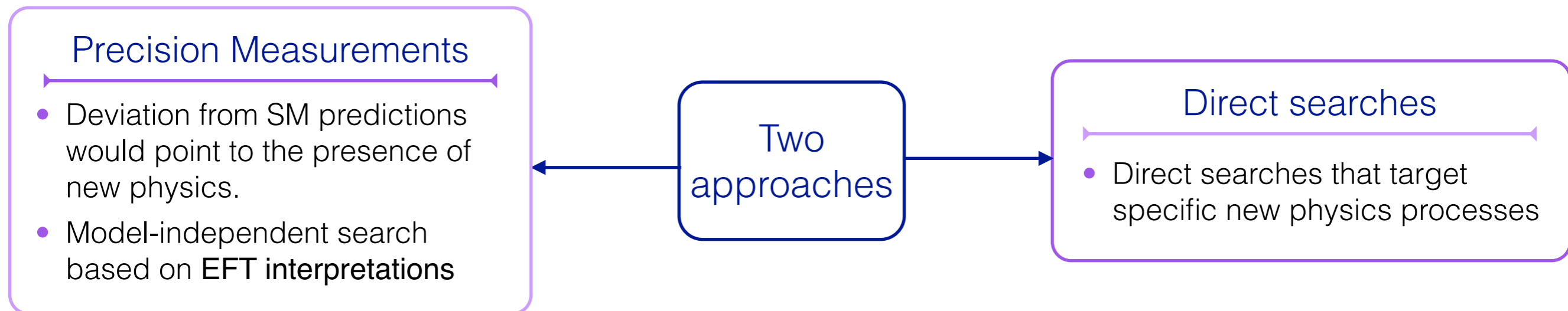
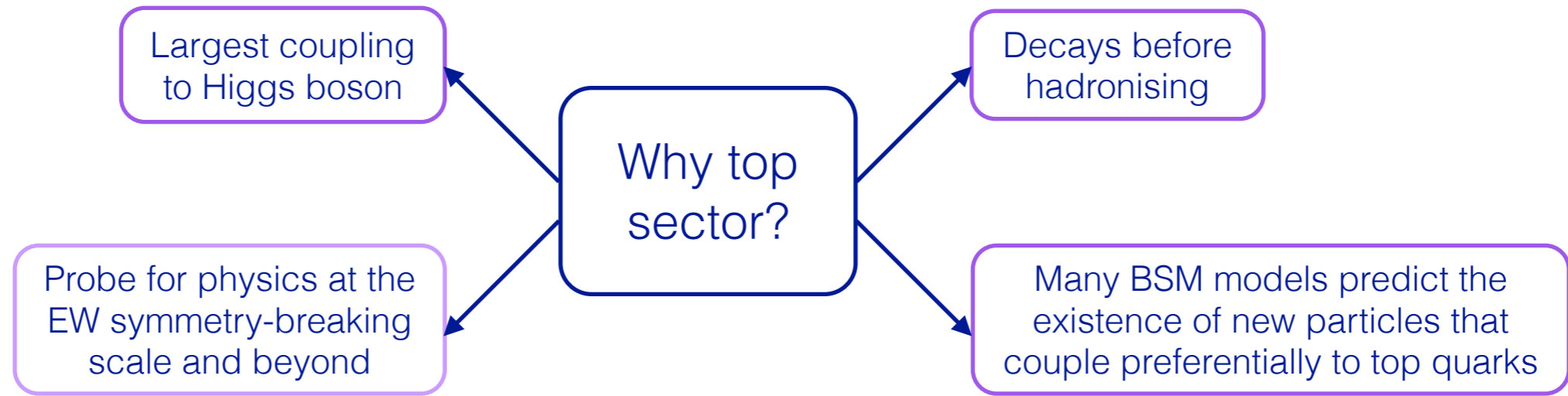




EFT interpretation of measurements in the top quark sector from ATLAS experiment

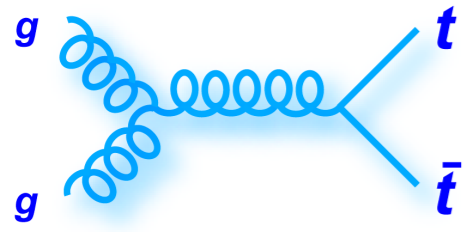
Laura Barranco Navarro
on behalf of the ATLAS Collaboration
16.04.2020
HEFT2020

The top quark as a window for new physics

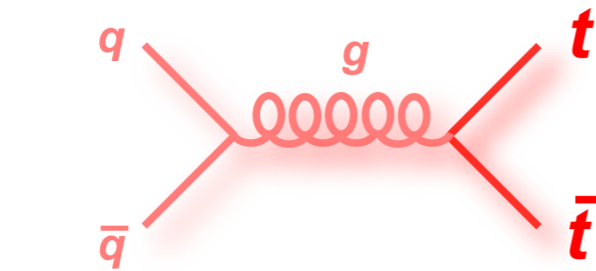


Top quark production at the LHC

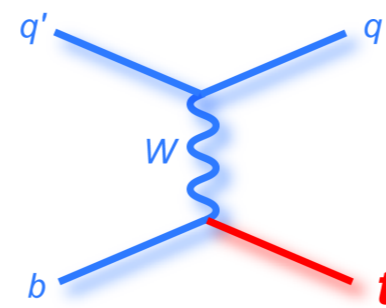
QCD top pair production



gluon-gluon fusion
67%

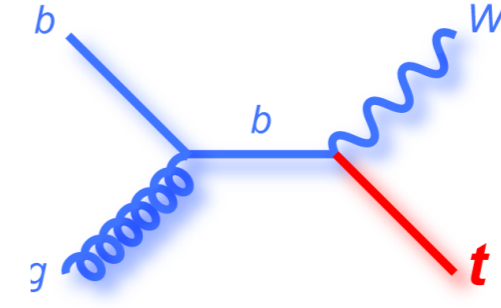


quark-antiquark annihilation
7%

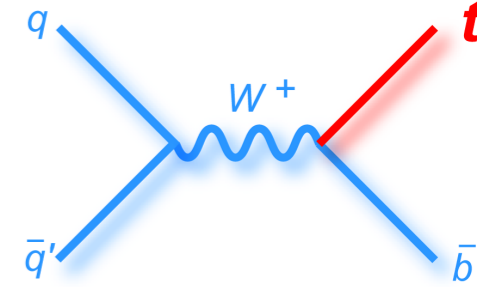


t-channel
19%

EW single top production

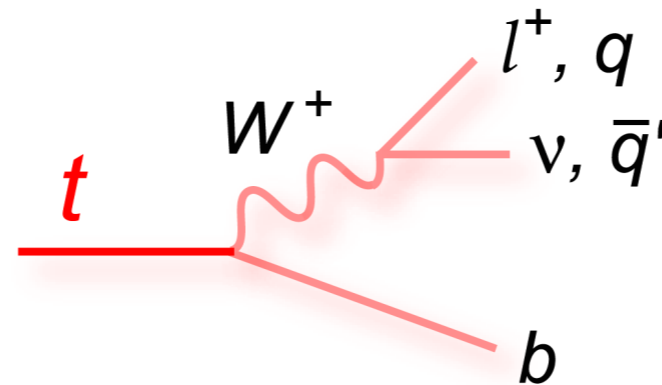


Wt-production
6%

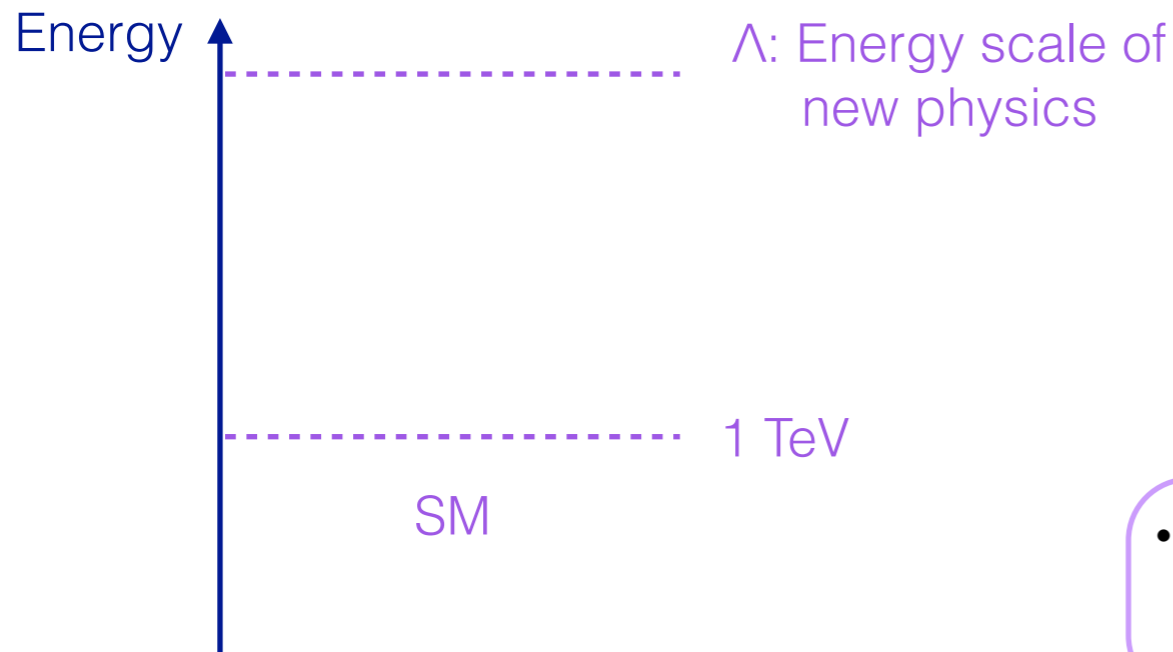


s-channel
1%

- Due to its large mass, the top quark decays before hadronising
- It decays almost exclusively through the Wtb vertex into a real W boson and a b quark
 - Depending on the subsequent W boson decay, there are leptonic and hadronic top quark decay channels



Effective Field Theories (EFT)



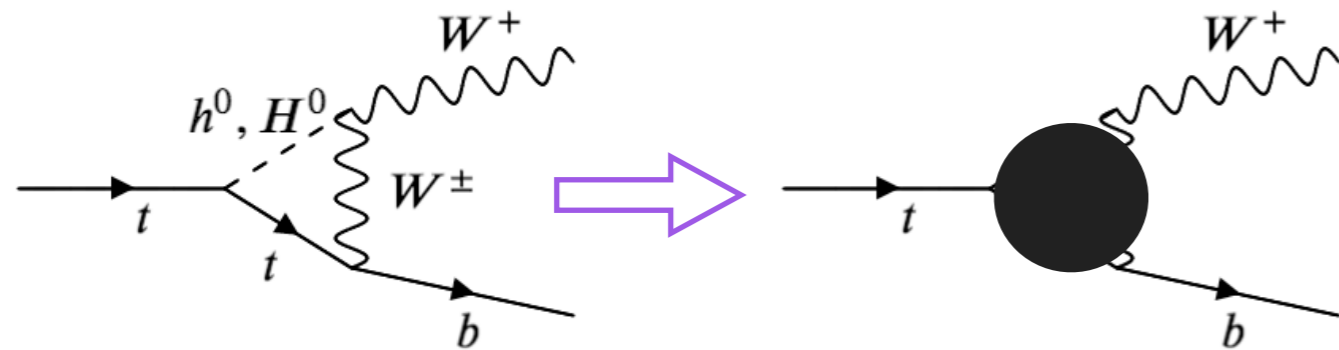
Parameterise the effect of new physics via higher-dimension operators:

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

- 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. For instance, **anomalous couplings of the top quarks to the gauge bosons.**



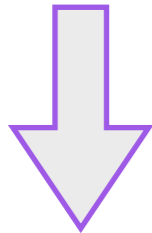
Two approaches for an EFT interpretation

Individual channels

Top-Down

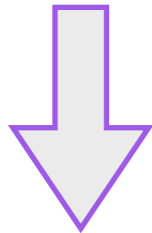
Approach followed in results in next slides

Signal Model



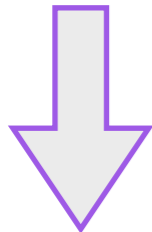
Simulate the signal to predict a reco-level observable

Observable (reco)



Compare to data for an EFT interpretation

Data



EFT interpretation

Combinations

Bottom-Up

EFT interpretation

Signal Model



Compare to particle-level signal model for an EFT interpretation

Observable (truth)



Use data to measure a particle-level observable. Simulation for unfolding detector response

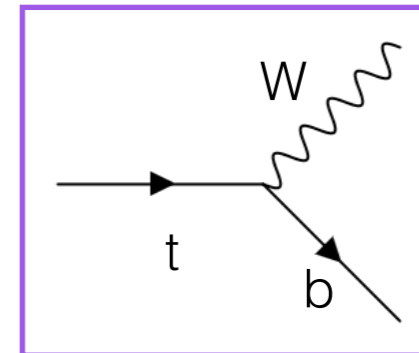
Data



Flavour Changing Neutral Currents

FCNC in the top quark sector

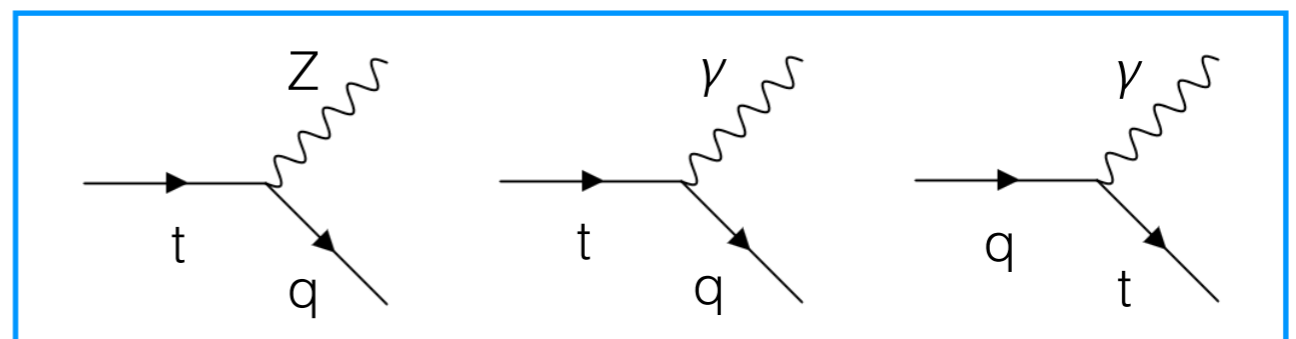
- ◉ Dominant SM top decay: $t \rightarrow Wb$
- ◉ FCNC decays: $t \rightarrow Zq$, $t \rightarrow gq$, $t \rightarrow Hq$, $t \rightarrow \gamma q$
 - **Forbidden** at **tree level** in the **SM**
 - Strongly suppressed at higher orders via the GIM mechanism
 - **Increasing rates** by several orders 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 $t \rightarrow Zq$



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

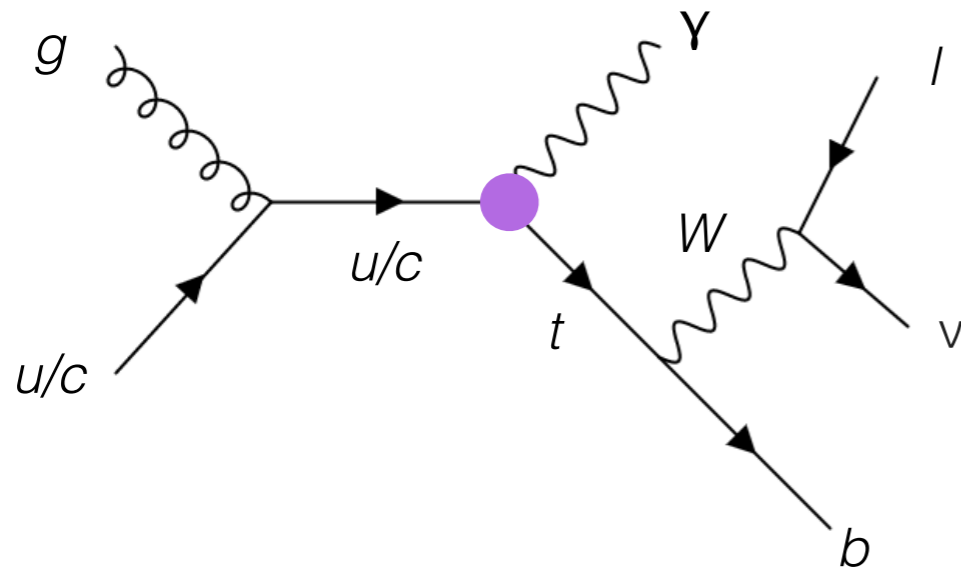
$$\mathcal{O}_{uW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j) \tilde{\phi} W_{\mu\nu}^I$$

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

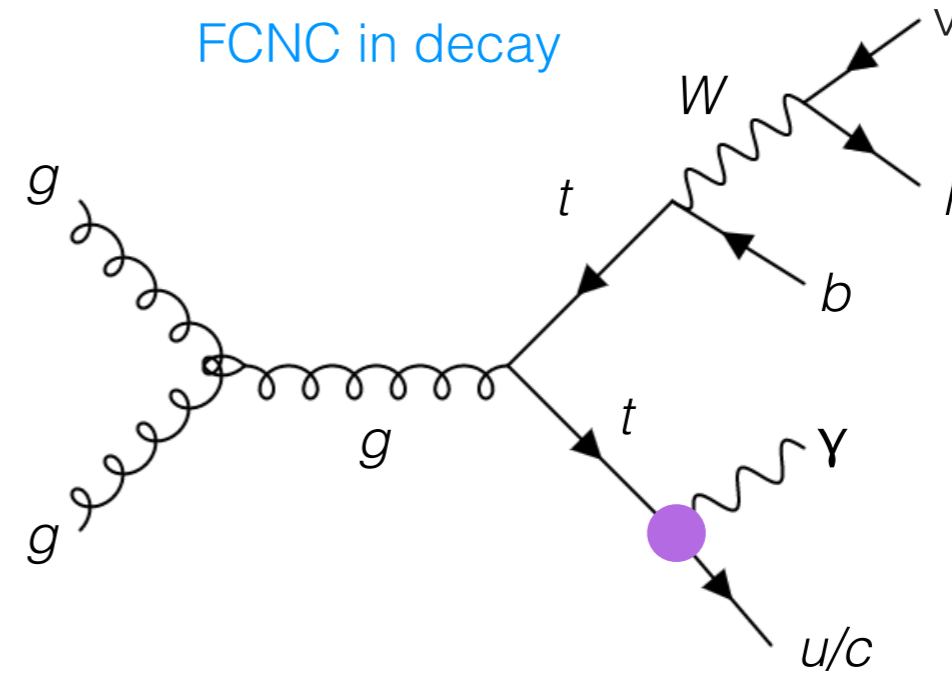


$t \rightarrow q\gamma$ and $q \rightarrow t\gamma$

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: $W+\gamma$ +jets, $Z+\gamma$ +jets

Main backgrounds

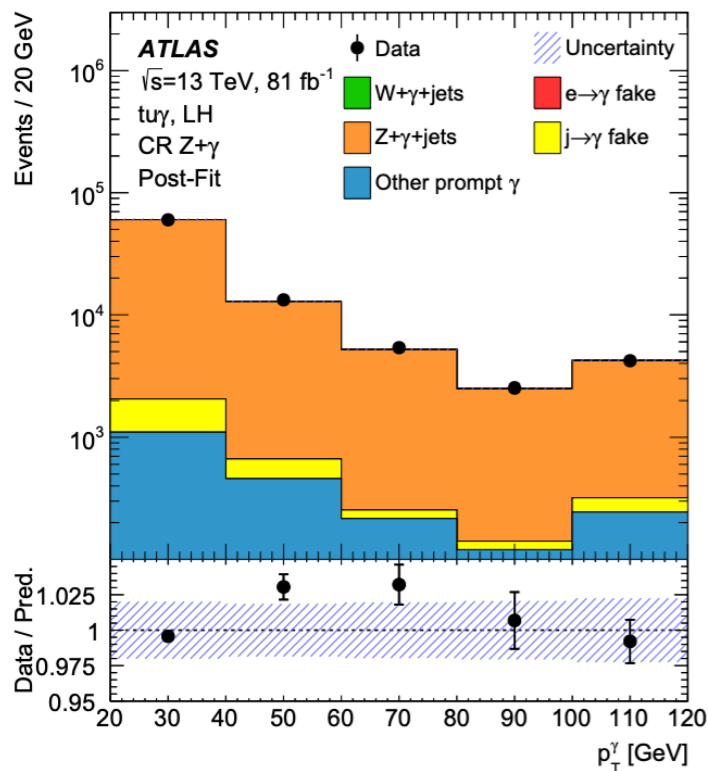
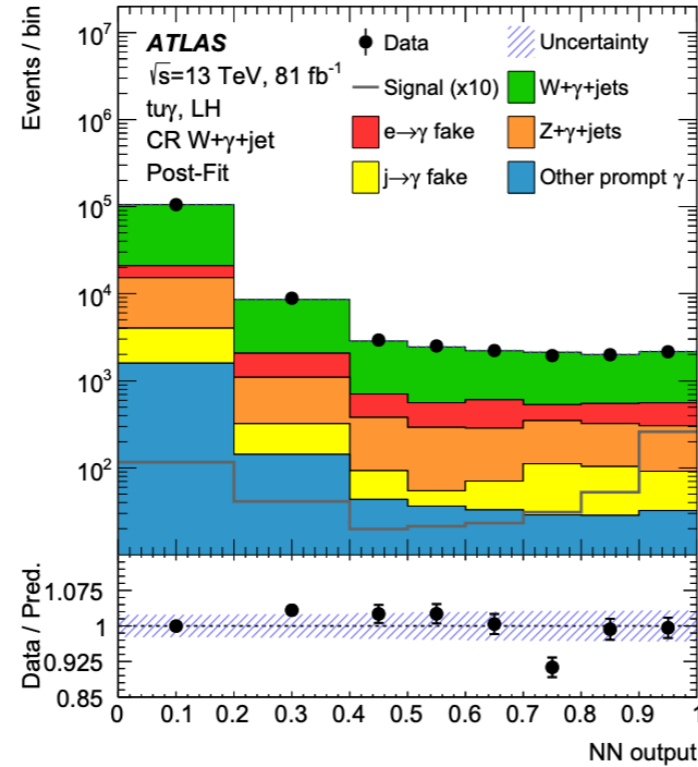
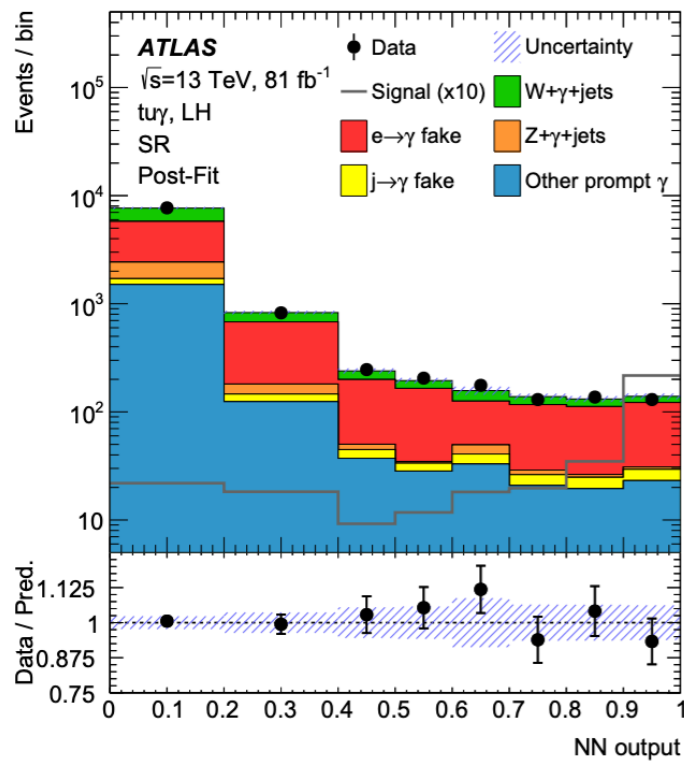
- Electrons misidentified as photons from tt events
- Processes with prompt γ

Analysis strategy

- NN to discriminate signal from background
- Profile likelihood fit to the NN output and the p_T^γ distributions in the SR and CRs

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

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



Observable	Vertex	Coupling	Obs.	Exp.
$ C_{uW}^{(13)*} + C_{uB}^{(13)*} $	$t\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$ C_{uW}^{(31)} + C_{uB}^{(31)} $	$t\gamma$	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	$0.59^{+0.12}_{-0.09}$
$\sigma(pp \rightarrow t\gamma)$ [fb]	$t\gamma$	LH	36	52^{+21}_{-14}
$\sigma(pp \rightarrow t\gamma)$ [fb]	$t\gamma$	RH	78	75^{+31}_{-21}
$\sigma(pp \rightarrow t\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
$\sigma(pp \rightarrow t\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}
$\mathcal{B}(t \rightarrow q\gamma)$ [10^{-5}]	$t\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \rightarrow q\gamma)$ [10^{-5}]	$t\gamma$	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}

Leading uncertainties

- 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

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

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

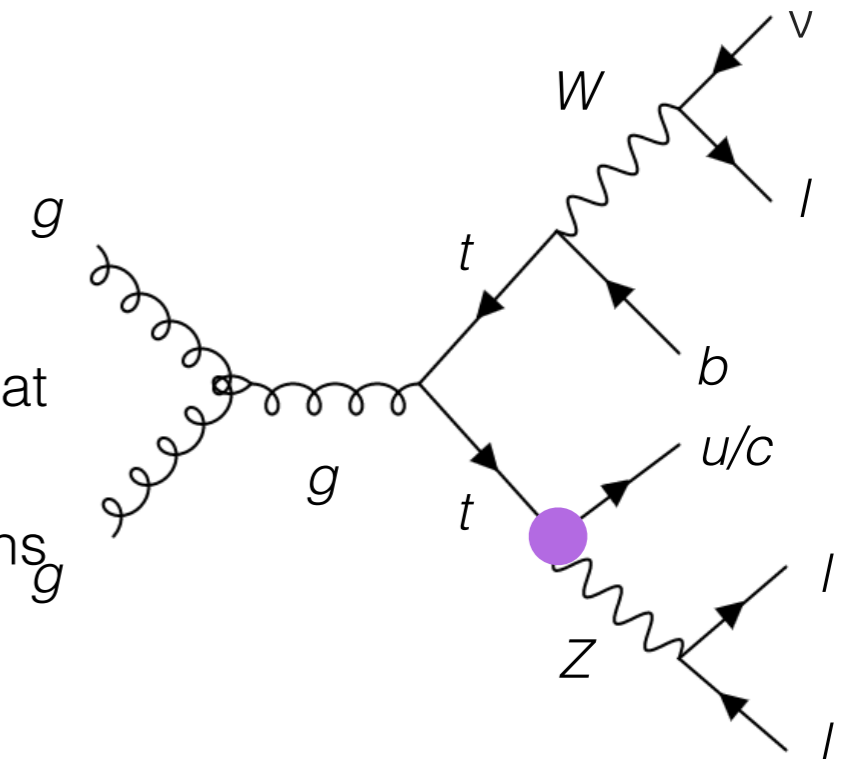
- ttZ, tZ and diboson processes

Analysis strategy

- χ^2 minimisation to reconstruct the events

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

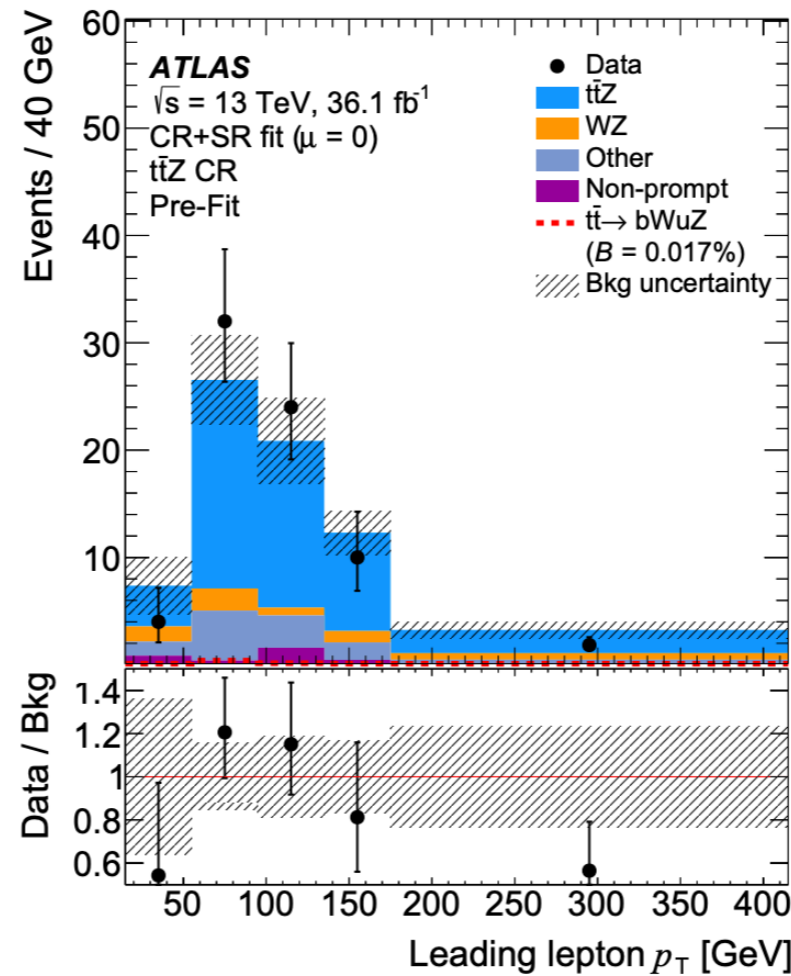
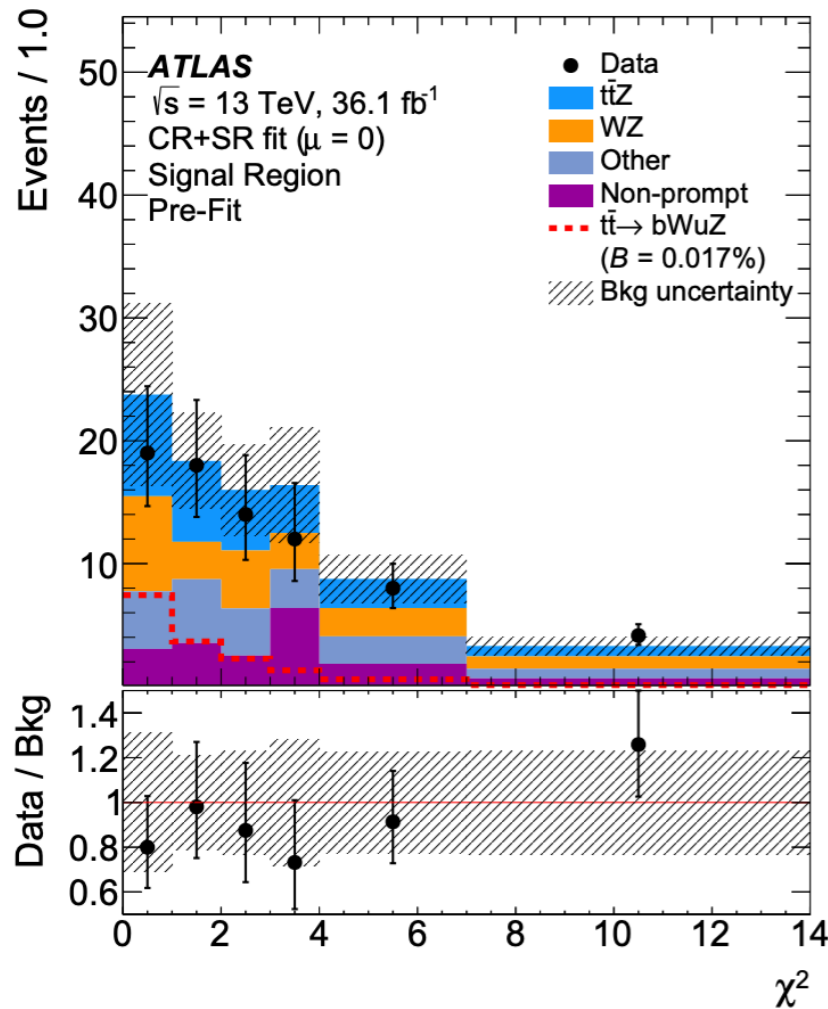
- Profile likelihood fit to the χ^2 distribution in the SR, the leading lepton pT for the non-prompt leptons and ttZ CRs, the transverse mass for the WZ CR and the reconstructed mass of the four leptons for the ZZ CR



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

- Leading uncertainties
 - Theoretical normalisation
 - Background modelling

	$\mathcal{B}(t \rightarrow uZ)$	$\mathcal{B}(t \rightarrow cZ)$
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}

$t\bar{t}Z$ and $t\bar{t}W$ cross sections

ttV measurements

- ttZ and ttW provide a direct probe of the weak couplings of the top quarks.
- Important background in searches involving final states with multiple leptons and b-quarks as well as associated production of the Higgs boson with top quarks.
- ttZ cross section measurement used to constrain ttZ couplings
- Involved operators

$$\mathcal{O}_{\varphi q}^{1(ij)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{q}_i \gamma^\mu q_j)$$

$$\mathcal{O}_{\varphi q}^{3(ij)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi) (\bar{q}_i \gamma^\mu \tau^I q_j)$$

with $i = j = 3$

$$\mathcal{O}_{\varphi u}^{(ij)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{u}_i \gamma^\mu u_j)$$

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

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

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

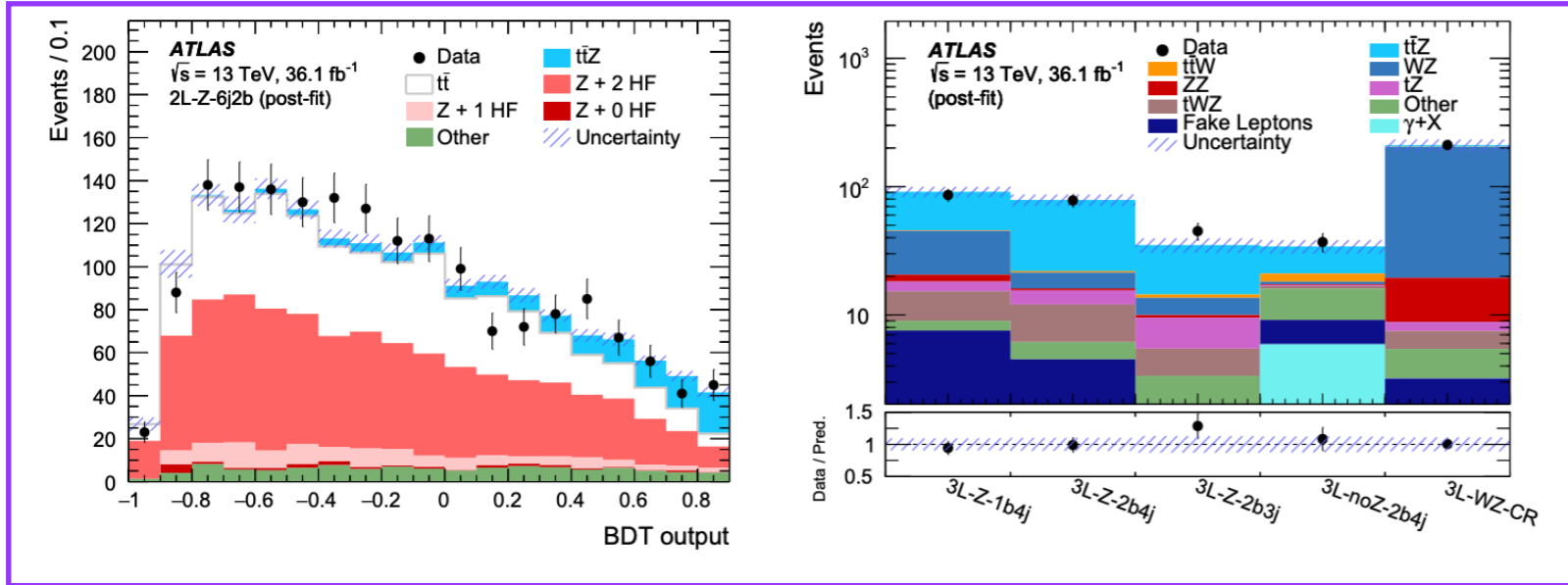
- The signal strength for ttW and ttZ are extracted simultaneously from a binned likelihood fit in the dilepton, trilepton and tetralepton signal and control regions
- ttZ and ttW SRs and CRs are also fitted separately

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



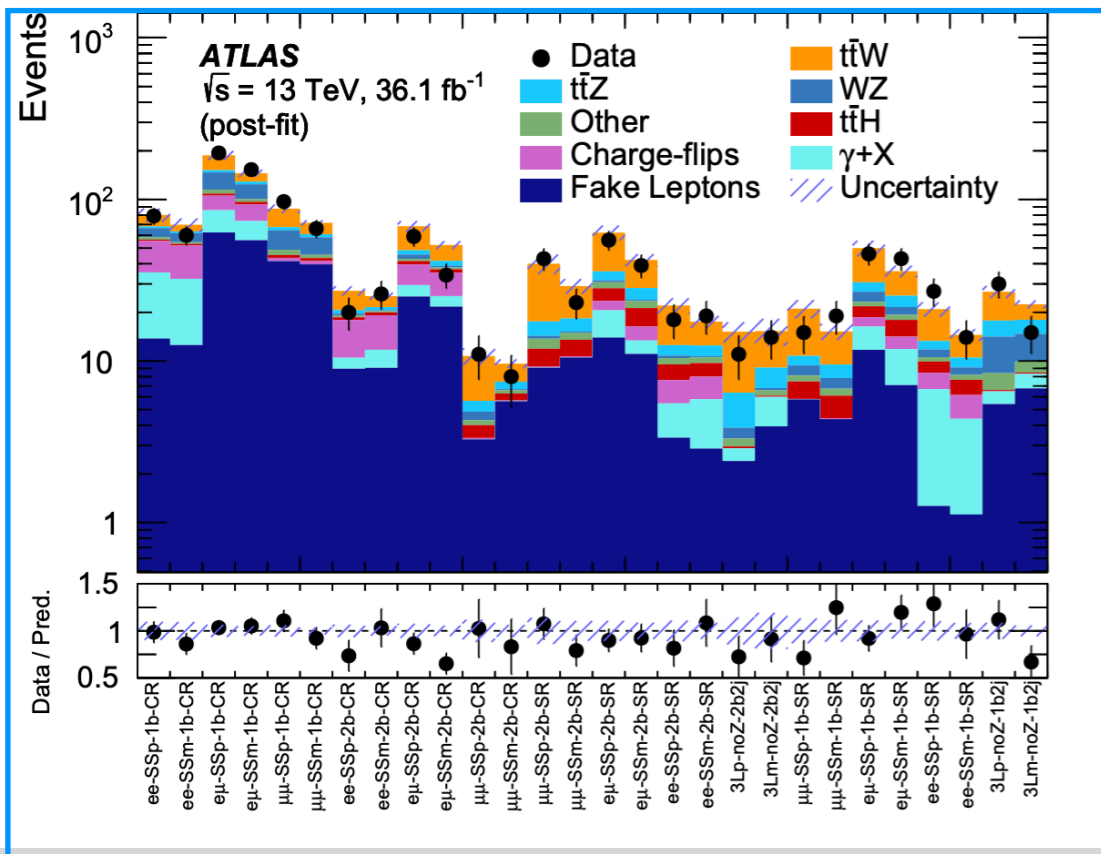
Leading uncertainties

- 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	Observed	Expected
$c_{\varphi q}^{3(33)}/\Lambda^2 (c_{\varphi q}^{1(33)} = 0.0)$	[-3.3,4.2]	[-4.5,3.6]
$c_{\varphi u}^{(33)}/\Lambda^2$	[-25,5.5]	[-23,4.9]
$c_{uB}^{(33)}/\Lambda^2$	[-5.0,5.0]	[-4.2,4.3]
$\text{Re}\{c_{uB}^{(33)}\}/\Lambda^2$	[-2.9,2.9]	[-2.6,2.6]

ttV measurements

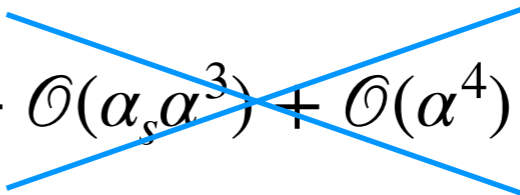
- ttZ couplings constrained from ttZ measurement
- Both ttW and ttZ expected signals simulated at NLO in QCD plus EW corrections

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

$$\sigma_{QCD+EW}^{NLO} = \sigma_{QCD}^{NLO} + \delta\sigma_{EW}$$

$$\sigma_{QCD}^{NLO} = \mathcal{O}(\alpha_s^2\alpha) + \mathcal{O}(\alpha_s^3\alpha)$$

$$\delta\sigma_{EW} = \mathcal{O}(\alpha^3) + \mathcal{O}(\alpha_s\alpha^2) + \mathcal{O}(\alpha_s^2\alpha^2) + \mathcal{O}(\alpha_s\alpha^3) + \mathcal{O}(\alpha^4)$$

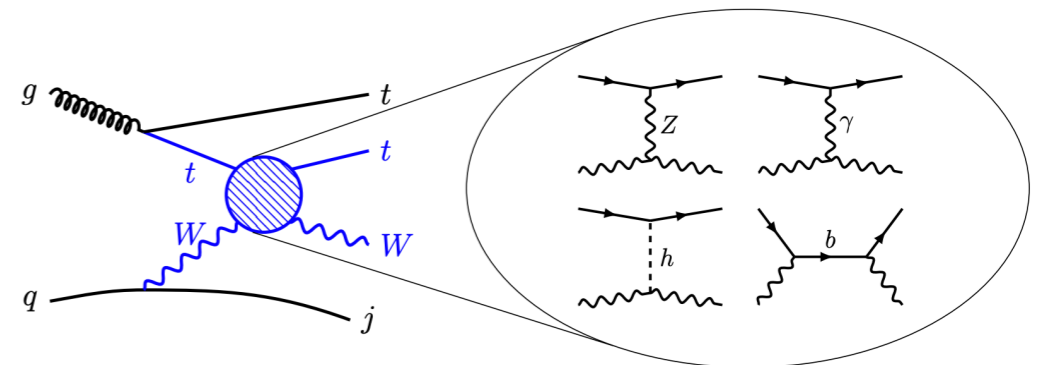


Not included since they are expected to be strongly suppressed

Dror, Farina, Salvioni, Serra
JHEP 1601 (2016) 071

Alternative to constrain ttZ couplings

- Measure the $\mathcal{O}(\alpha_s\alpha^3)$ contribution from tW scattering
- strong dependence in cross section in the presence of EFT couplings
- ttWj signature at the LHC



Summary

- Standard Model of particle physics is widely believed to require extensions
- Top quark as unique opportunity to search for new physics
- Indirect searches as a complementary path to direct BSM searches
 - EFT interpretations more frequent
- Selection of results in this talk
 - Limits derived independently for each analysis
 - Still room for improved results using the whole Run-2 dataset. Stay tuned.