MEASUREMENT OF TT+X INCLUDING 4 TOPS WITH ATLAS

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ON BEHALF OF THE ATLAS COLLABORATION

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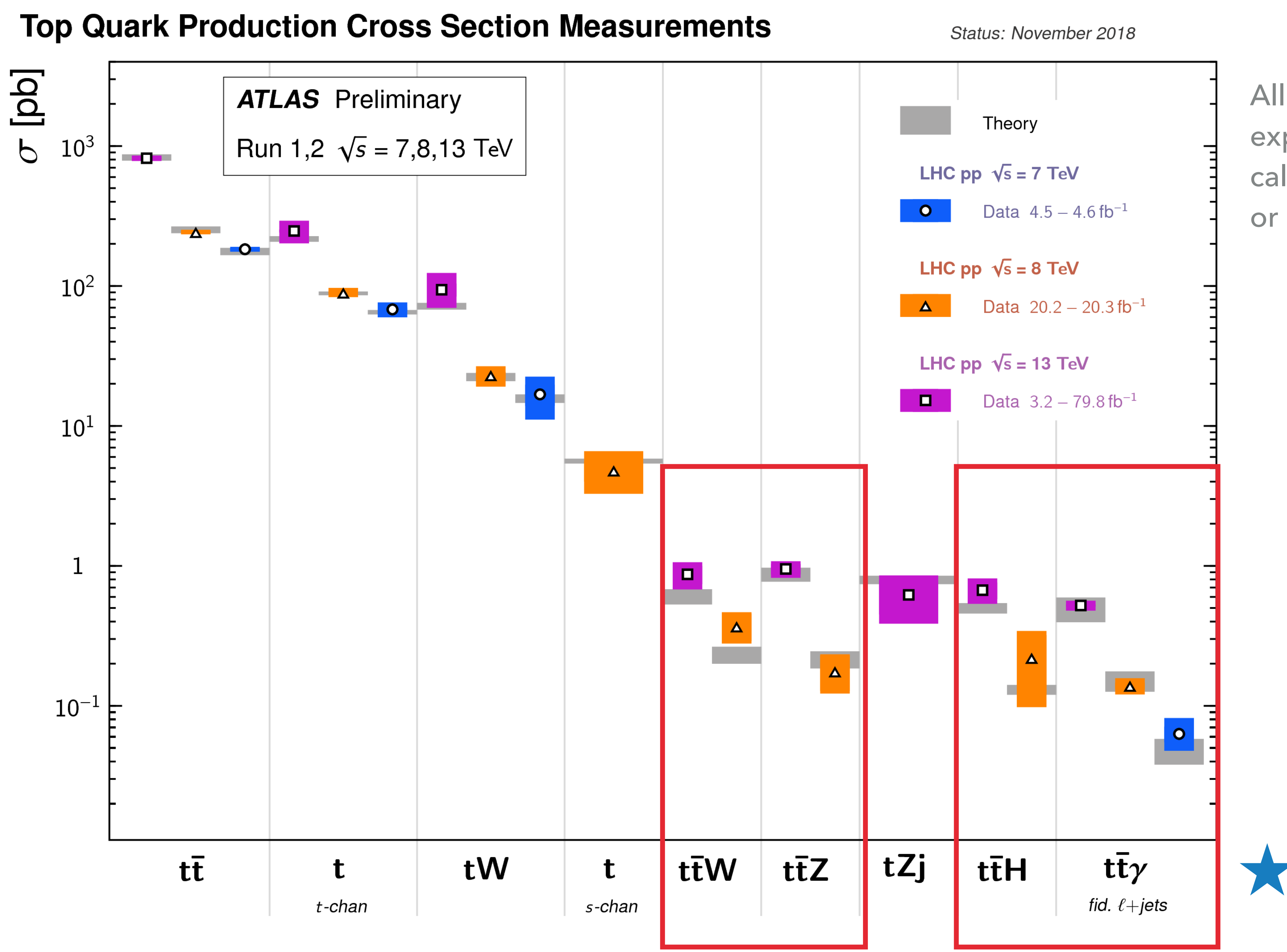
ATLAS EXPERIMENT

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

MEASUREMENT OF TT+X INCLUDING 4TOPS WITH ATLAS

- **Introduction**
- **ttH (briefly)**
  - Associated Production of a Higgs boson and a top quark pair
- **tt+HF**
  - Inclusive and differential fiducial cross-sections of tt production with additional heavy flavour jets
- **ttγ**
  - Production of a top-quark pair in association with a photon
- **ttV**
  - Associated Production of a top quark pair and a vector boson
- **tttt**
  - A search for four-top-quark production
- **Summary and Conclusions**

THE TOP QUARK



All theoretical expectations were calculated at NLO or higher precision.

Theoretical expectation for four tops SM.

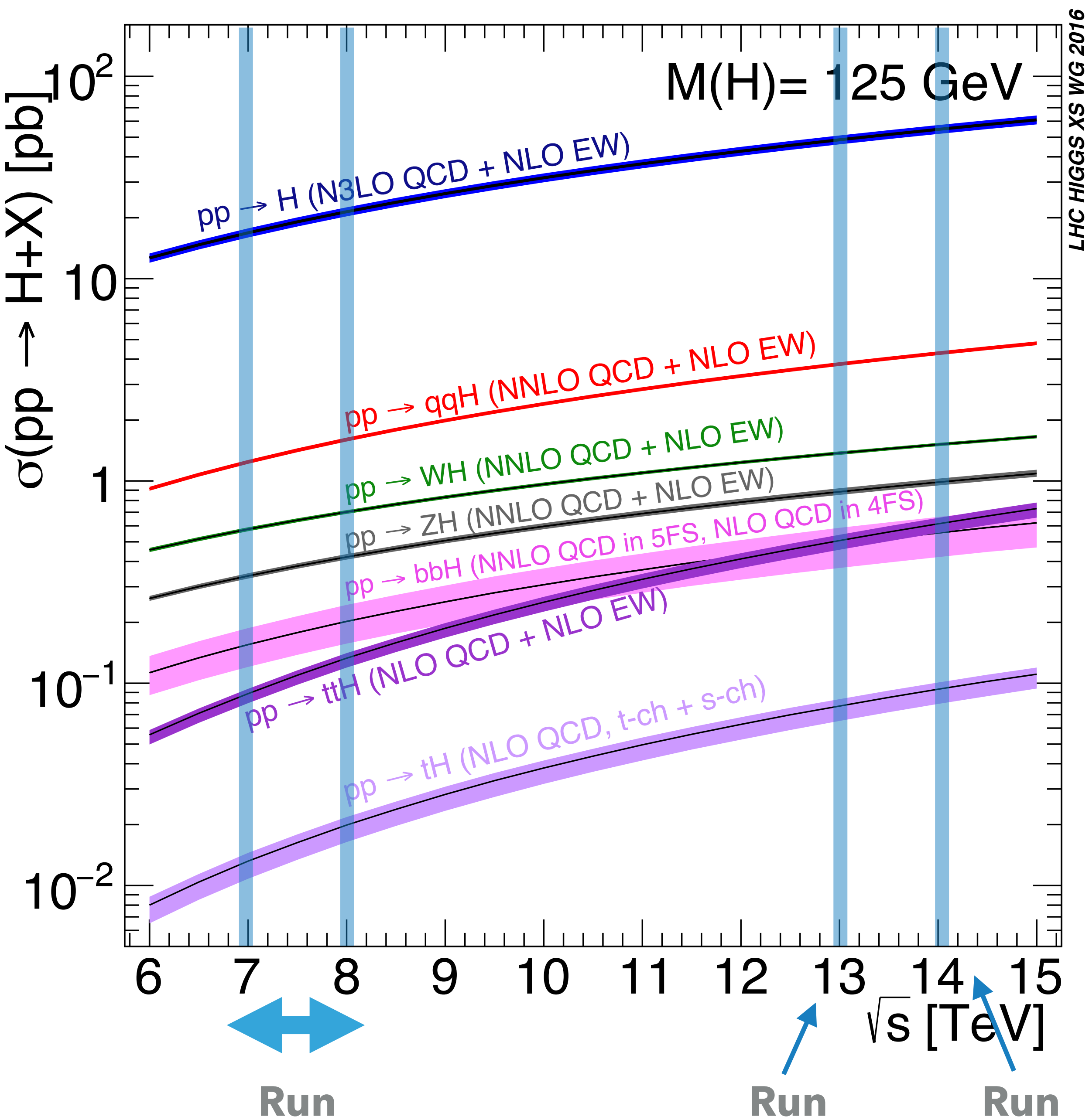
+X

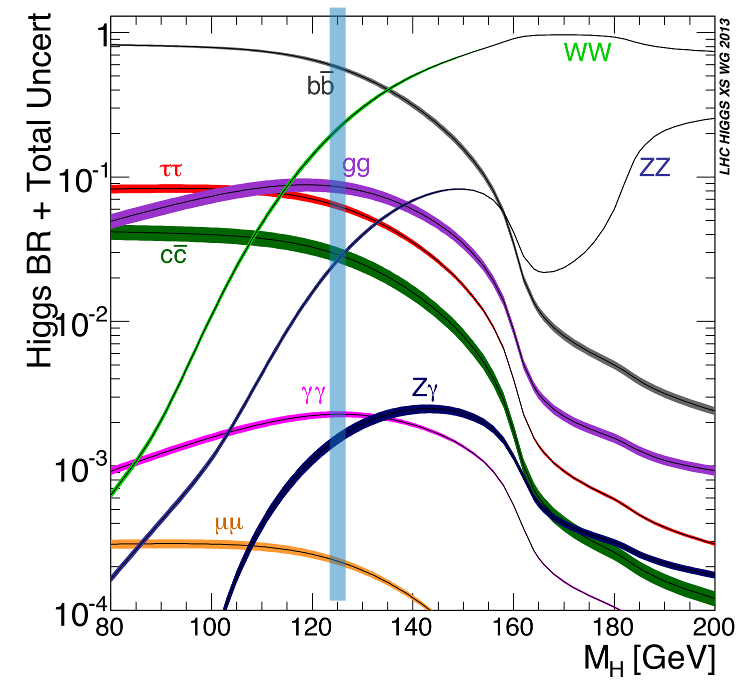
- **Testing the top gauge couplings**
  - To understand the top quark and validate the Standard Model, we need to look at how it interacts with other particles.
    - Higgs Boson - Yukawa coupling (briefly)
    - Heavy Flavour
    - Photons - Determine the charge of the top quark
    - Heavy gauge bosons: Z and W - Direct probe of the weak couplings of the top quark.
    - Four tops - High sensitivity to New Physics.

Photo: Ian Tresman (CC)

ttH

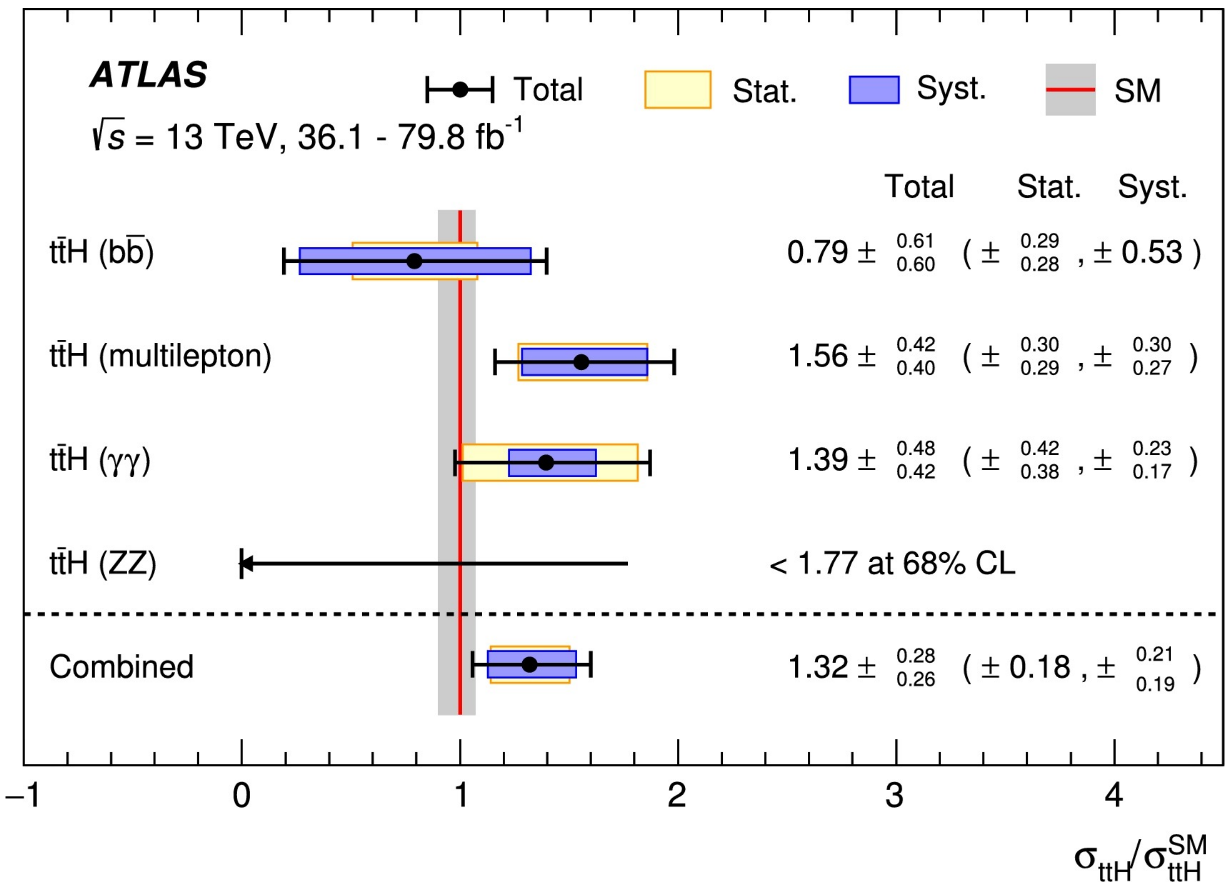
THE DISCOVERY OF THE HIGGS BOSON

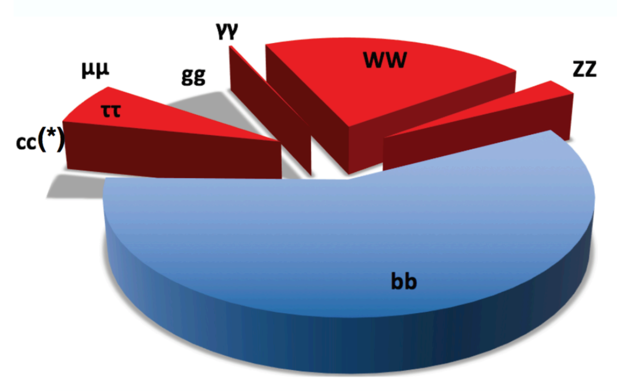


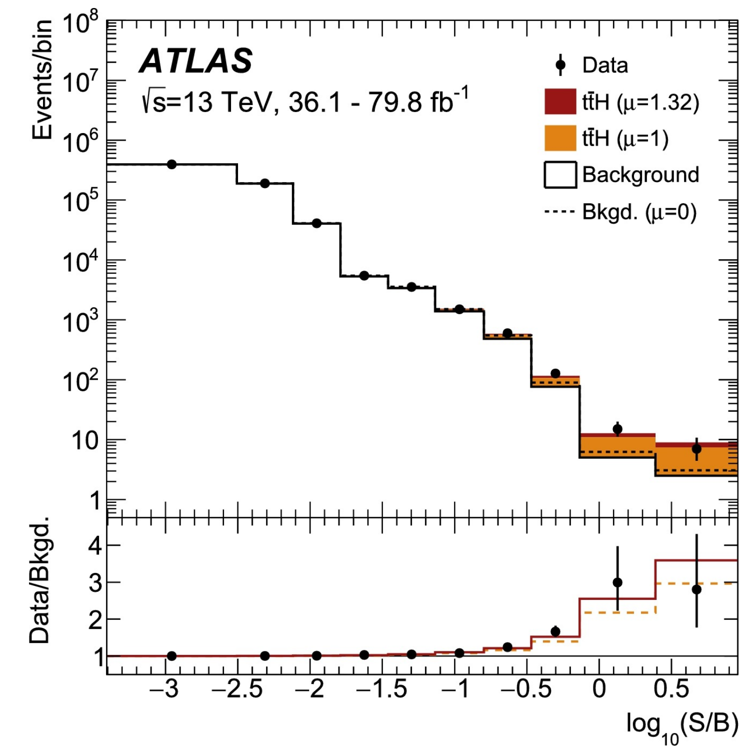


- Indirect constraints on the top Yukawa coupling to the Higgs can be inferred from ggF production, and from H → γγ decays.
  - BUT we also want to measure direct couplings. Therefore need tt̄H.
- tt̄H Channels:
  - $H \rightarrow b\bar{b}$
    - single lepton & opposite-sign dilepton.
  - $H \rightarrow \gamma\gamma$ and $\rightarrow ZZ$
    - Both the hadronic and leptonic tt̄ decay channels.
  - $H \rightarrow (WW^{(*)}, \tau\tau, ZZ^{(*)}) \rightarrow$ leptons
    - two – four final lepton states.

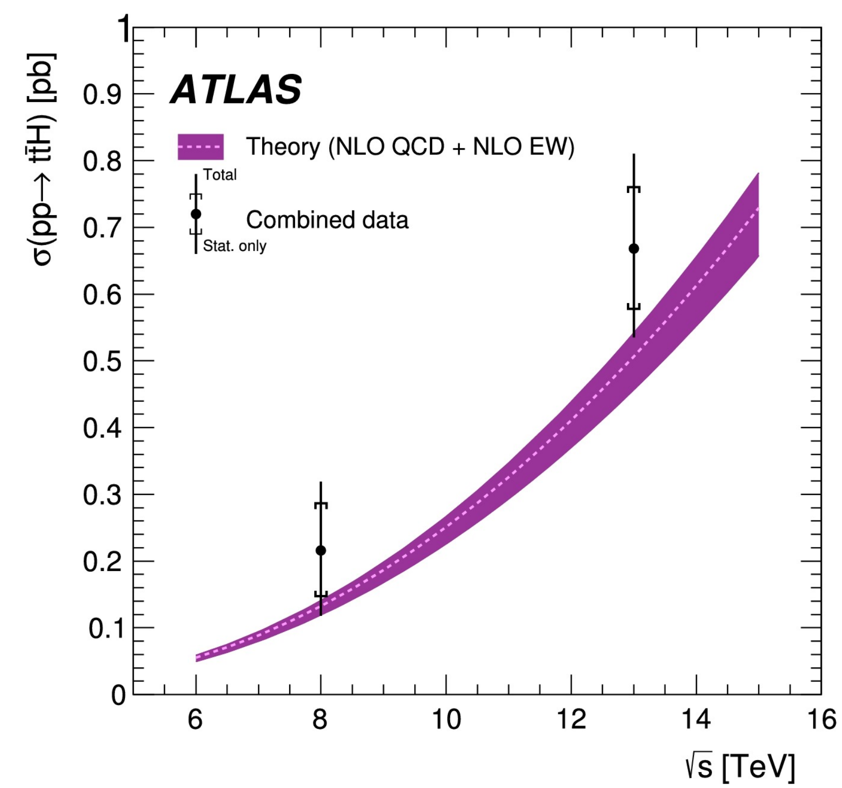
RESULTS







Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H\to\gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1σ	3.7σ
$H\to$ multilepton	36.1	790 ±150 (stat.) $^{+150}_{-140}$ (syst.)	4.1σ	2.8σ
$H\to b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) ± 270 (syst.)	1.4σ	1.6σ
$H\to ZZ^*\to 4\ell$	79.8	<900 (68% CL)	0σ	1.2σ
Combined (13 TeV)	36.1–79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8σ	4.9σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3σ	5.1σ

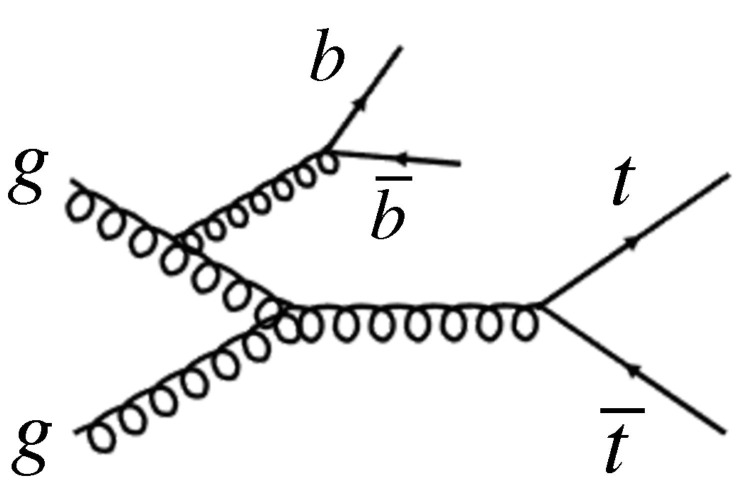


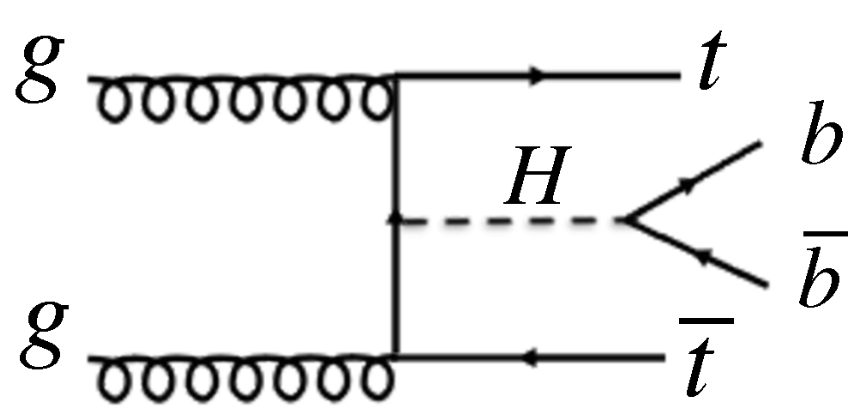
tt+HF

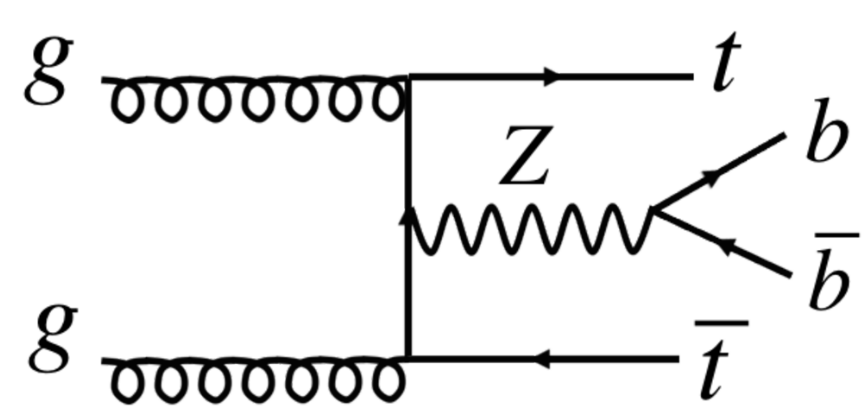
OVERVIEW

- Motivations for tt+HF:
  - Improve understanding of QCD production in heavy quarks.
  - Also a dominant background for various other measurements:
    - ttV, four-tops…

- Measurements of tt̄ production in association with additional b-jets at 13 TeV with 36.1 fb^{-1}.
  - Fiducial cross-sections for dilepton and l+jets.
  - Inclusive cross-sections for 3L and 4L at particle level.
  - Differential cross-sections were measured as a function of global event properties and properties of b-jet pairs.







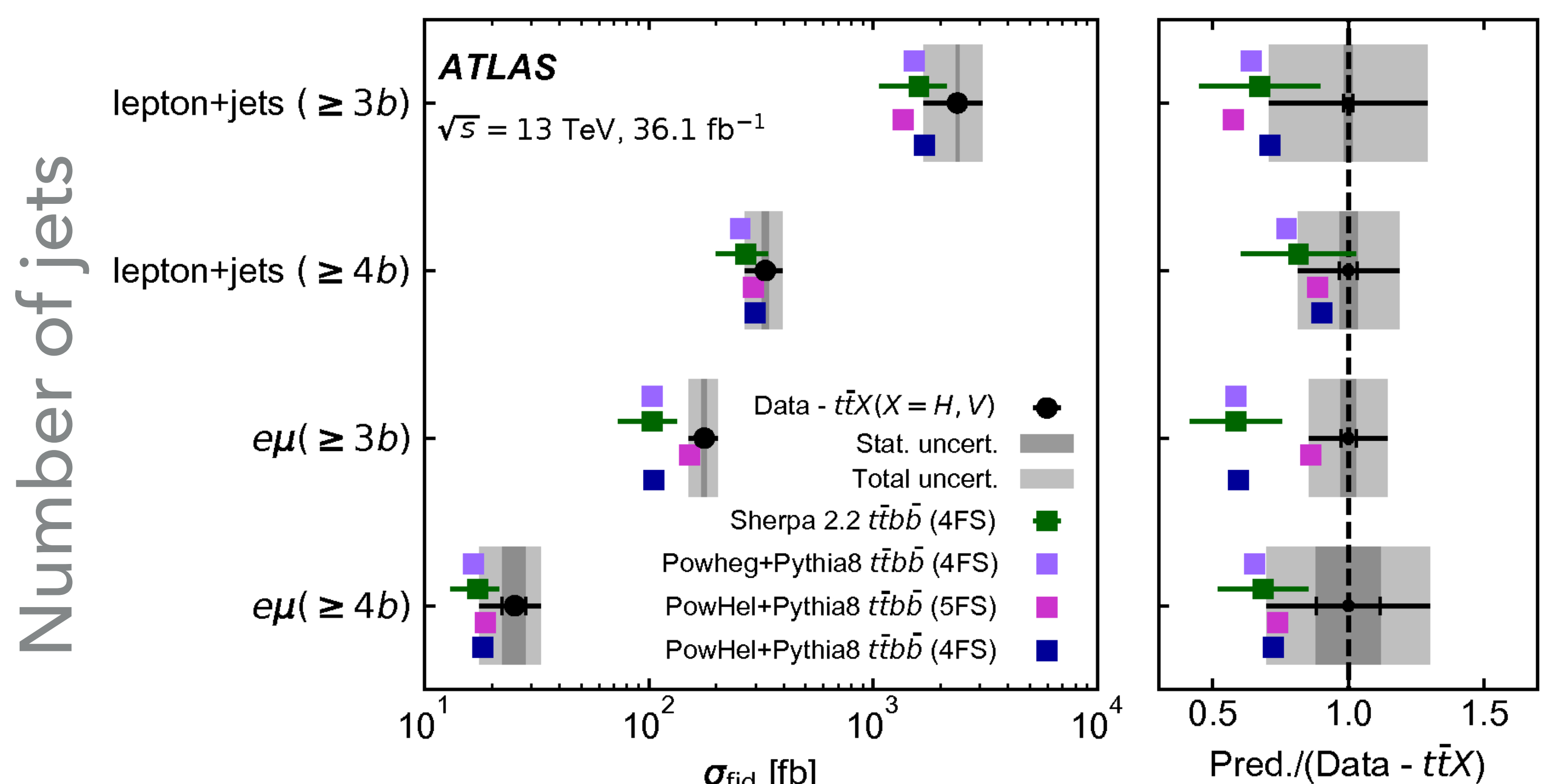
FIDUCIAL CROSS-SECTIONS

- Measured fiducial cross-sections for $t\bar{t}$ production in association with additional at >1 and >2 b-jets.
- Systematic uncertainties dominate:
  - mainly due to $t\bar{t}$ modelling, b-tagging and jet energy scale.
- The measured inclusive fiducial cross-sections **generally exceed the $t\bar{t}b\bar{b}$ predictions** from various NLO matrix element calculations matched to a parton shower.

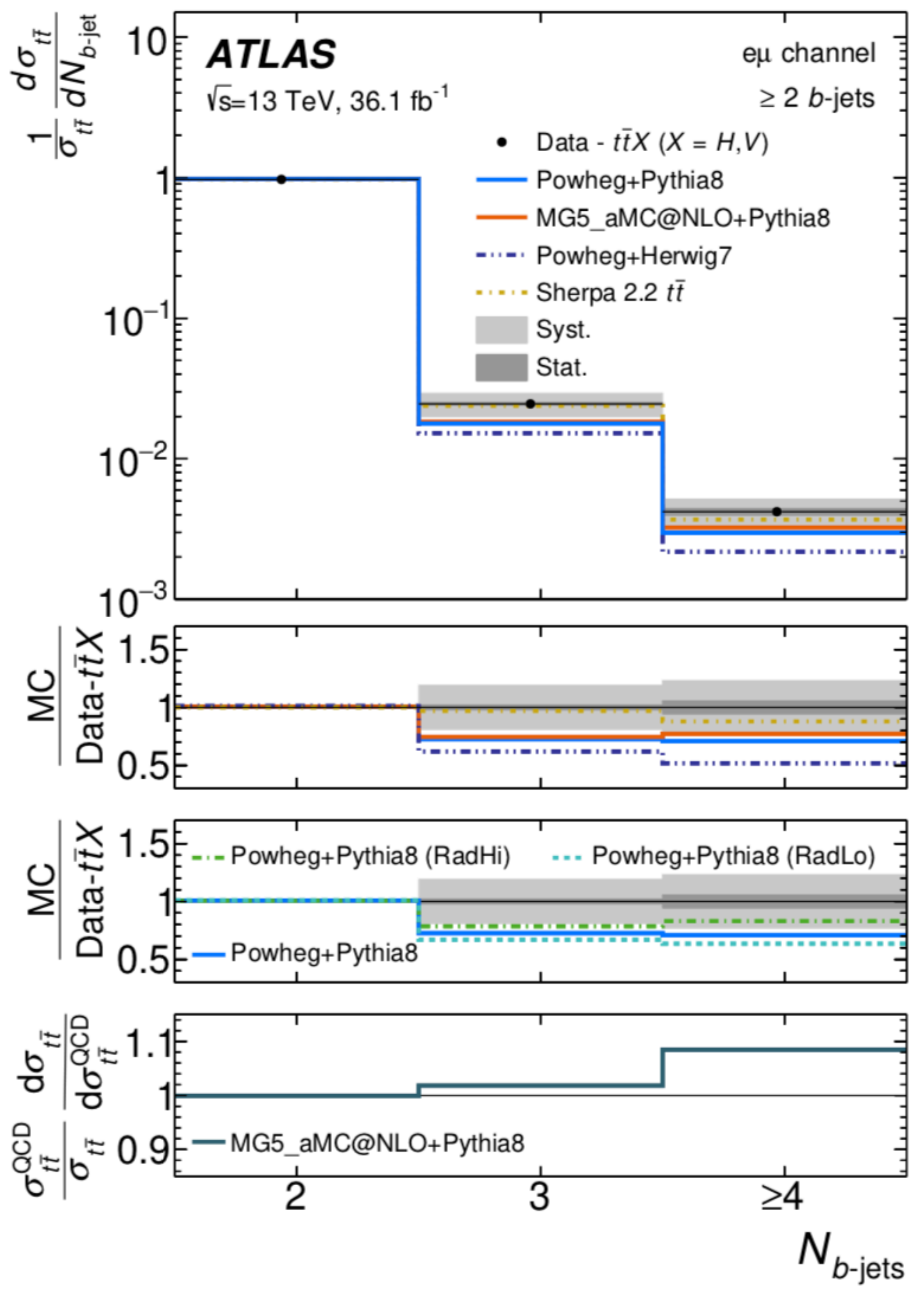
	$e\mu$ [fb]		lepton + jets [fb]	
	$\geq 3b$	$\geq 4b$	$\geq 5j, \geq 3b$	$\geq 6j, \geq 4b$
Measured	181 $\pm$ 5 (stat) $\pm$ 24 (syst)	27 $\pm$ 3 (stat) $\pm$ 7 (syst)	2450 $\pm$ 40 (stat) $\pm$ 690 (syst)	359 $\pm$ 11 (stat) $\pm$ 61 (syst)
$t\bar{t}X (X = H, V)$ MC	4	2	80	28
Measured $-$ $t\bar{t}X$	177	25	2370	331
SHERPA 2.2 $t\bar{t}b\bar{b}$ (4FS)	103 ± 30	17.3 ± 4.2	1600 ± 530	270 ± 70
POWHEG+PYTHIA 8 $t\bar{t}b\bar{b}$ (4FS)	104	16.5	1520	260
POWHEL+PYTHIA 8 $t\bar{t}b\bar{b}$ (5FS)	152	18.7	1360	290
POWHEL+PYTHIA 8 $t\bar{t}b\bar{b}$ (4FS)	105	18.2	1690	300

Uncertainty of 13%

The measured fiducial cross-sections, with $t\bar{t}H$ & $t\bar{t}V$ contributions subtracted from data:



DIFFERENTIAL CROSS-SECTIONS



Relative differential cross-section as a function of the b-jet multiplicity

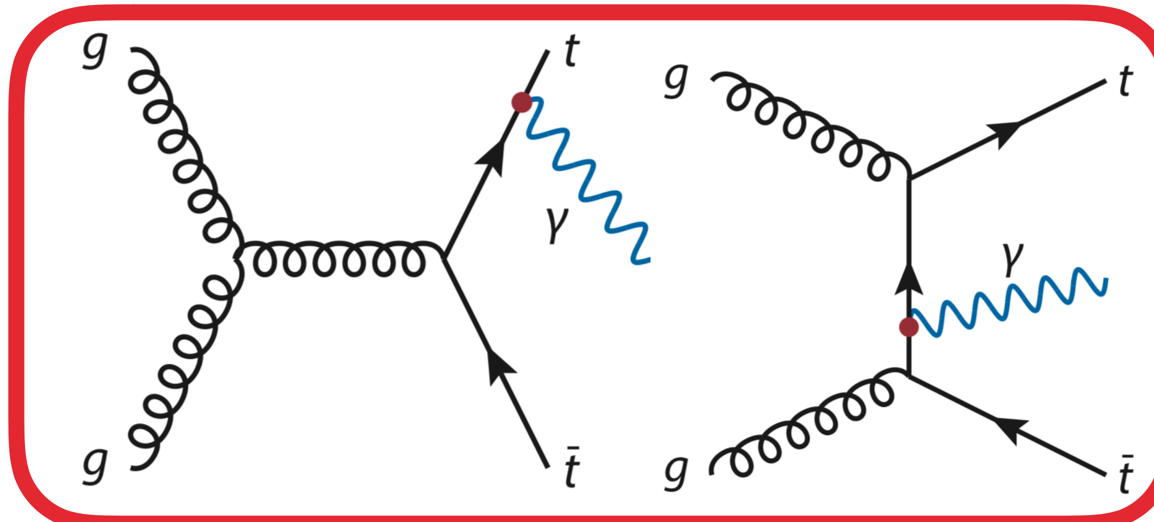
- First two panels show the ratios of various predictions to data
- The third panel shows the ratio of predictions of normalised differential cross-sections from MadGraph5 aMC@NLO+Pythia 8 including (numerator) and not including (denominator) the contributions from $t\bar{t}V$ and $t\bar{t}H$ production.
- Uncertainty bands include stat. & syst. uncertainties.

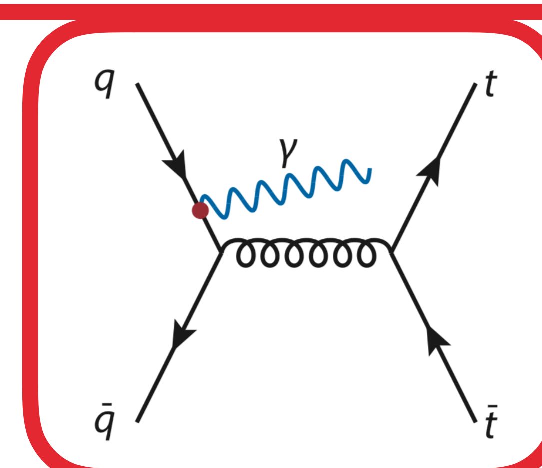
ttγ

OVERVIEW

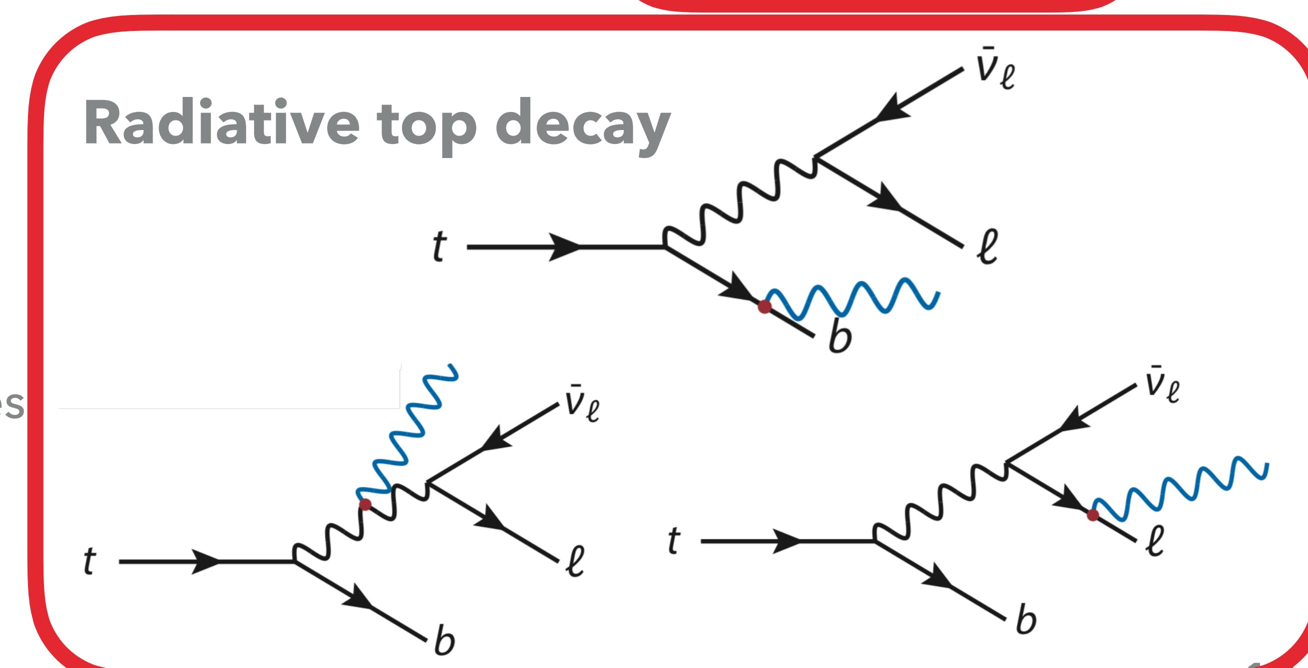
- Motivation:
  - Probe the tγ electroweak coupling (top e-charge)
  - Deviations in photon pT spectrum can hint at New Physics (anomalous dipole moments of the top quark).
  - gg & qq initiated:
    - potential charge asymmetry measurement (would be enhanced compared to $t\bar{t}$)
  - Precision measurements of $t\bar{t}\gamma$ production can constrain some Wilson coefficients of EFT.
  - The main background for ttH(γγ).
- Observation of $t\bar{t}\gamma$ was reported by ATLAS at 7 TeV. **Phys. Rev. D91 (2015) 072007**
- First dilepton $t\bar{t}\gamma$ cross-section measurements.
- Uses the Prompt Photon Tagger (PPT), a Neural Network trained to distinguish prompt photons from hadronic fakes
- This is then used as input to the Event Level Discriminator.

Top radiation



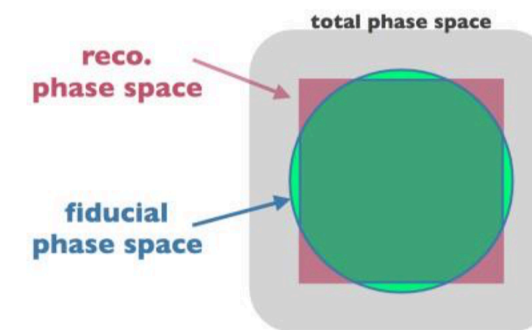


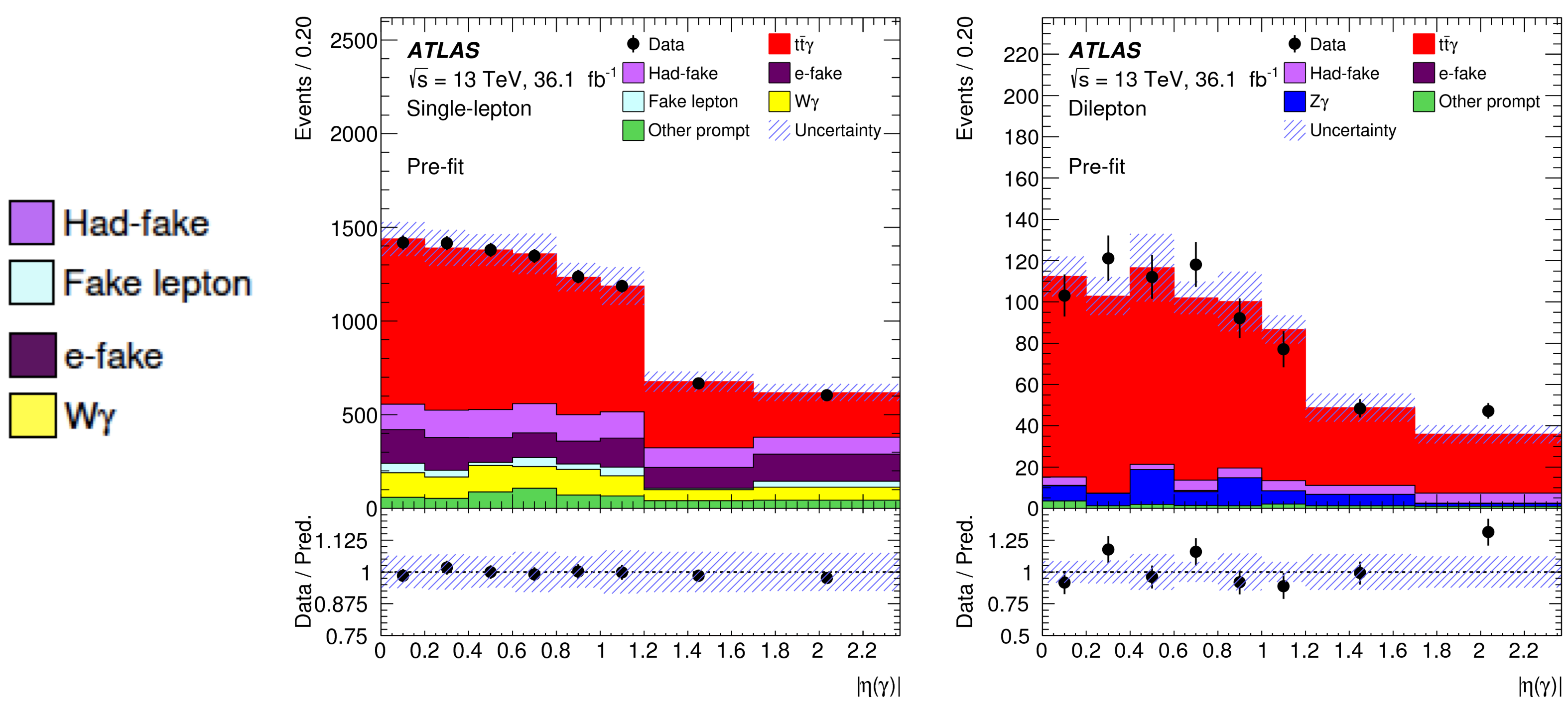
ISR



FIDUCIAL CROSS-SECTION

- Photon can be emitted from the top quark or its charged decay products (FSR). It can also be emitted from an incoming quark (ISR).
- Performed in 1L & 2L channels with 36 fb-1 of data at 13 TeV.
- Selection:
  - 1 or 2 OS leptons (≥ 25 GeV)
  - ≥4 or ≥2 jets, ≥1 b-jet (≥ 25 GeV)
  - =1 photon (≥ 20 GeV)
  - ΔR(l,γ)>1.0

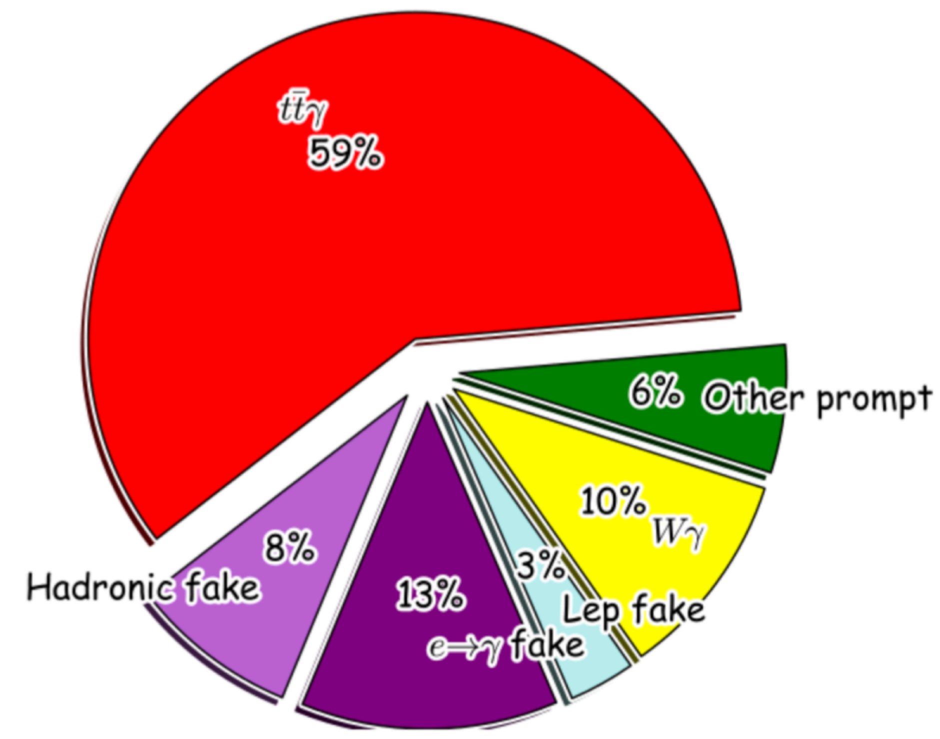




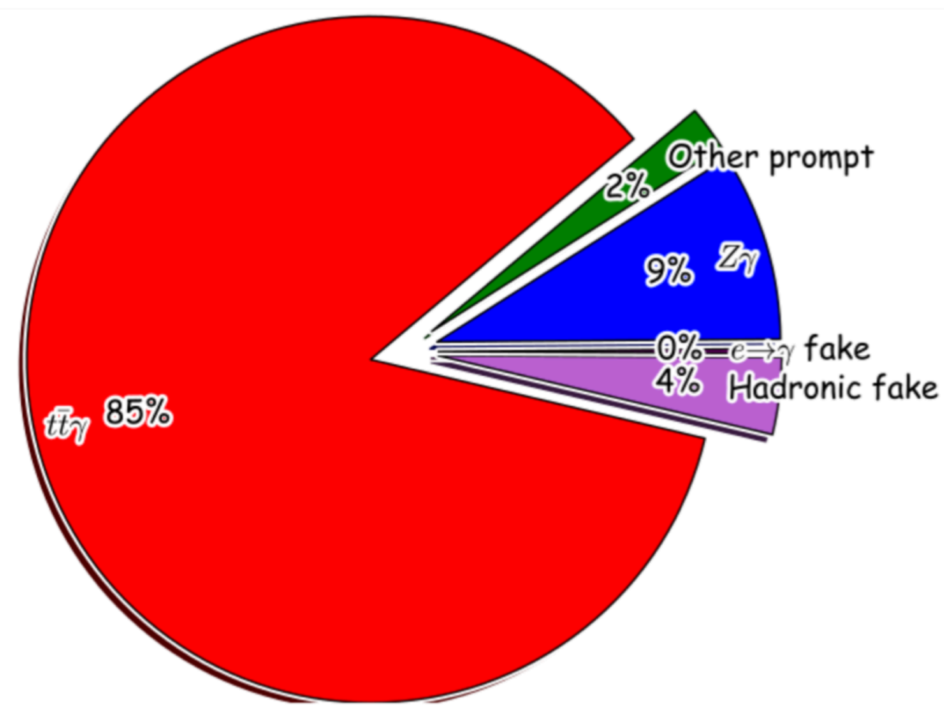
Channel	Single lepton	Dilepton
$t\bar{t}\gamma$	6 490 ± 420	720 ± 34
Hadronic-fake	1 440 ± 290	49 ± 27
Electron-fake	1 650 ± 170	2 ± 1
Fake lepton	360 ± 200	-
$W\gamma$	1 130	
$Z\gamma$		75 ± 52
Other prompt	690 ± 260	18 ± 7
Total	11 750 ± 710	863 ± 78
Data	11 662	902

BACKGROUNDS

- Hadronic fakes:
  - γs from hadrons / jets misidentified as photons
  - Data-driven ABCD method for data/MC SFs
- e→γ fakes:
  - e misidentified as photons
  - Data-driven tag-and-probe method for data/MC scale factors
- Fake leptons & non-prompt
- Prompt photons:
  - Mainly Wγ and Zγ, but also tγ, VVγ
  - Validation regions with Wγ and Zγ



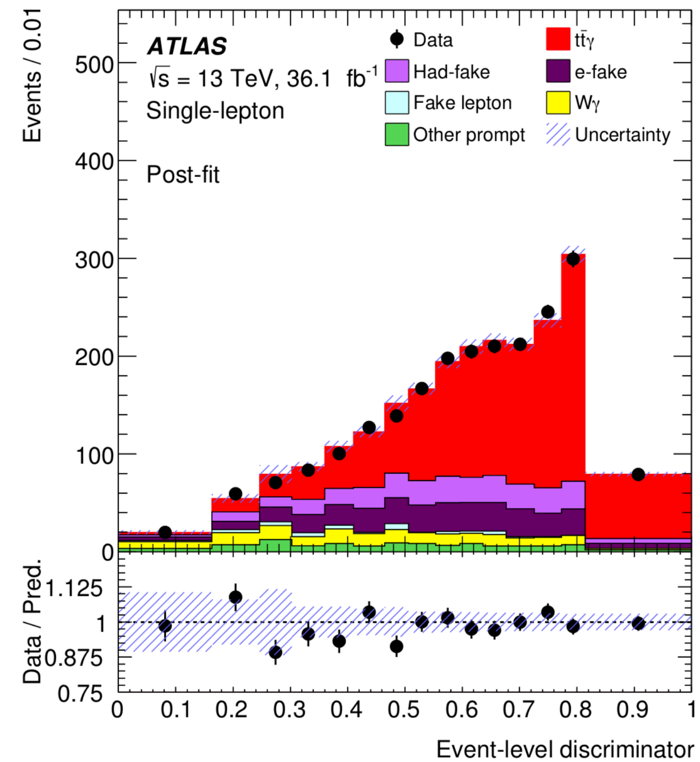
Single-lepton channels

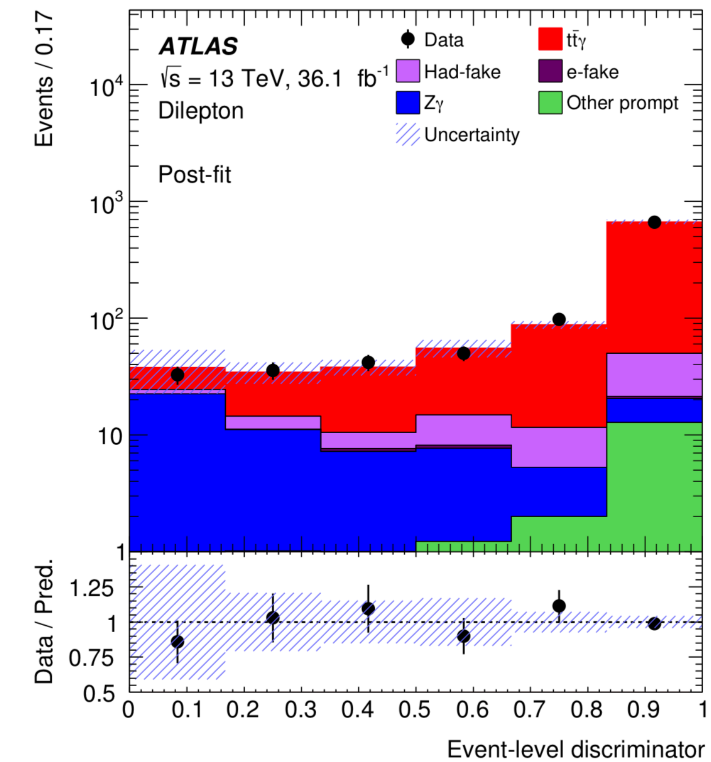


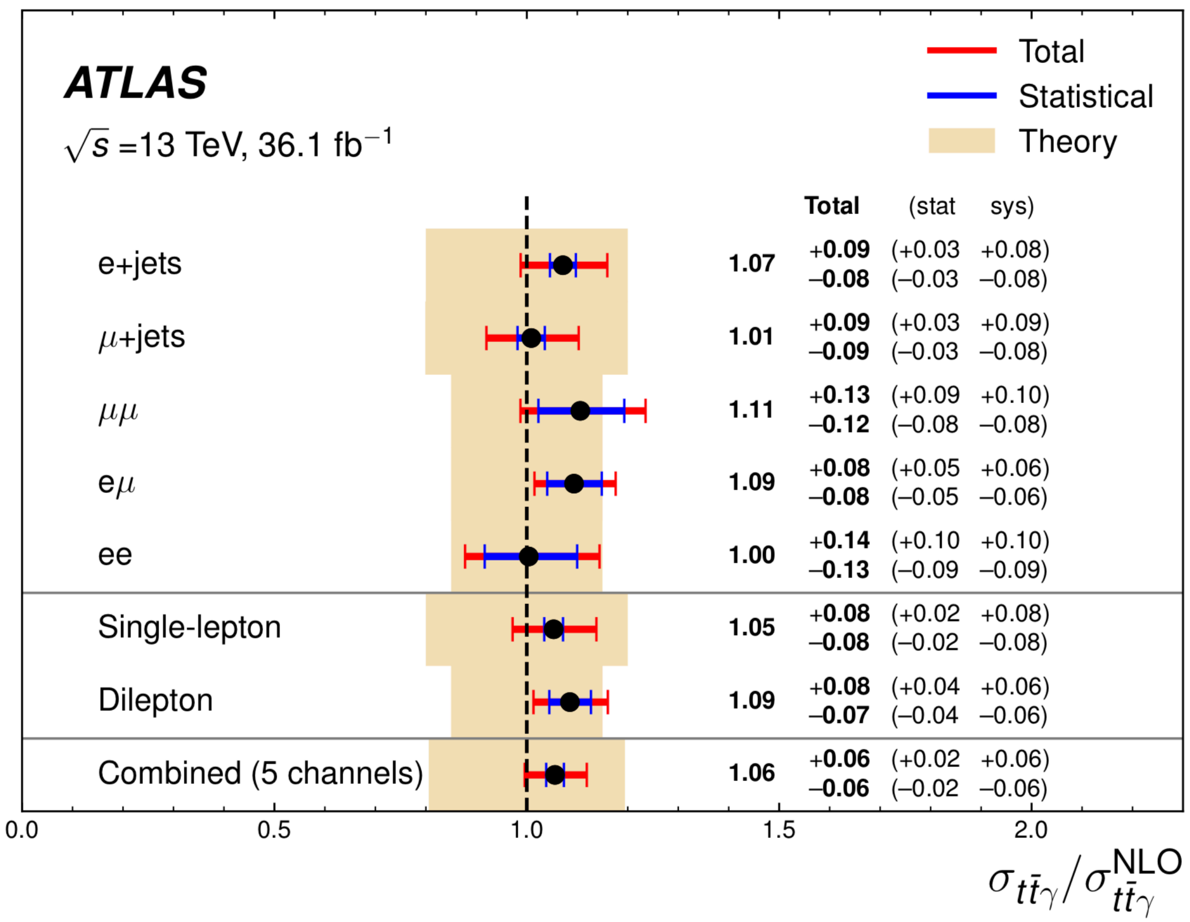
Dilepton channels

FIT

- Fiducial inclusive cross-section: profile likelihood fit to ELD
- Main uncertainties:
  - 1L: jet-related, background modelling and PPT systematics
  - 2L: data statistics, followed by signal and background modelling







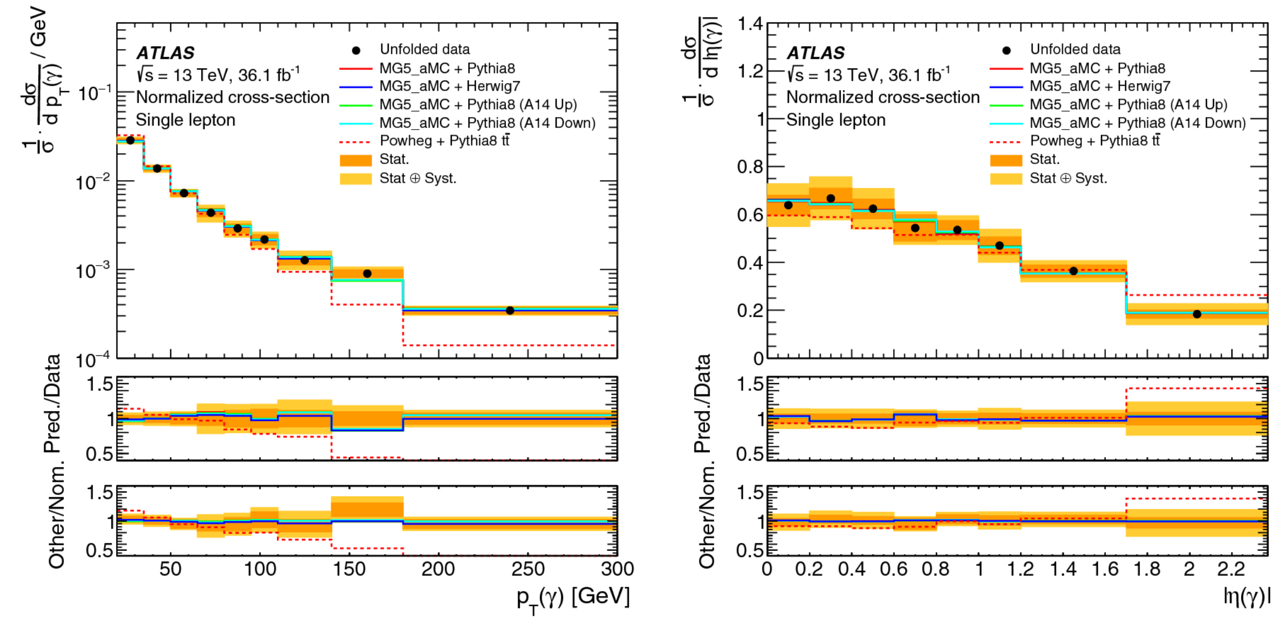
$$\sigma_{\text{fid}}^{\text{SL}} = 521 \pm 9(\text{stat.}) \pm 41(\text{sys.})\ fb \text{ and}$$
$$\sigma_{\text{fid}}^{\text{DL}} = 69 \pm 3(\text{stat.}) \pm 4(\text{sys.})\ fb,$$

- In agreement with the NLO QCD+LO EW prediction

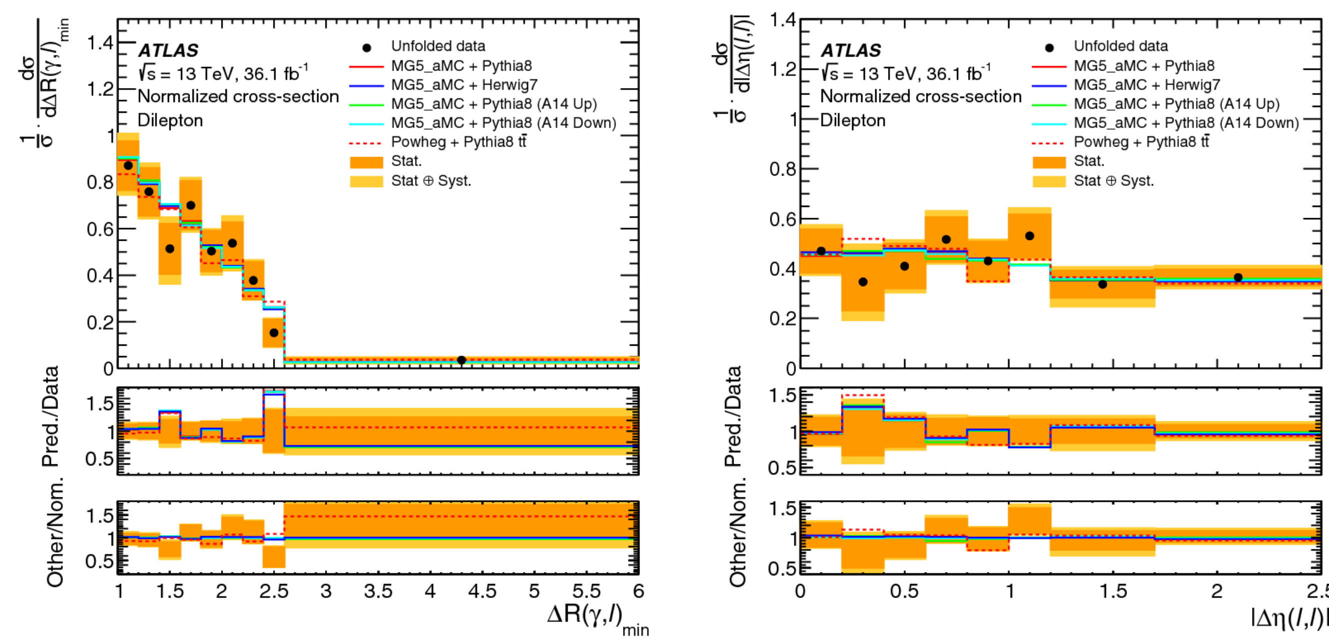
DIFFERENTIAL CROSS-SECTIONS

- Differential cross-sections were measured.
- In both channels as a function of:
  - photon transverse momentum
  - photon absolute pseudorapidity
  - angular distance between the photon and its closest lepton
- In dilepton channel, as a function of:
  - azimuthal opening angle
  - absolute pseudorapidity difference between the two leptons
- **All measurements are in agreement with the theoretical predictions.**

Single lepton:



Dilepton lepton:

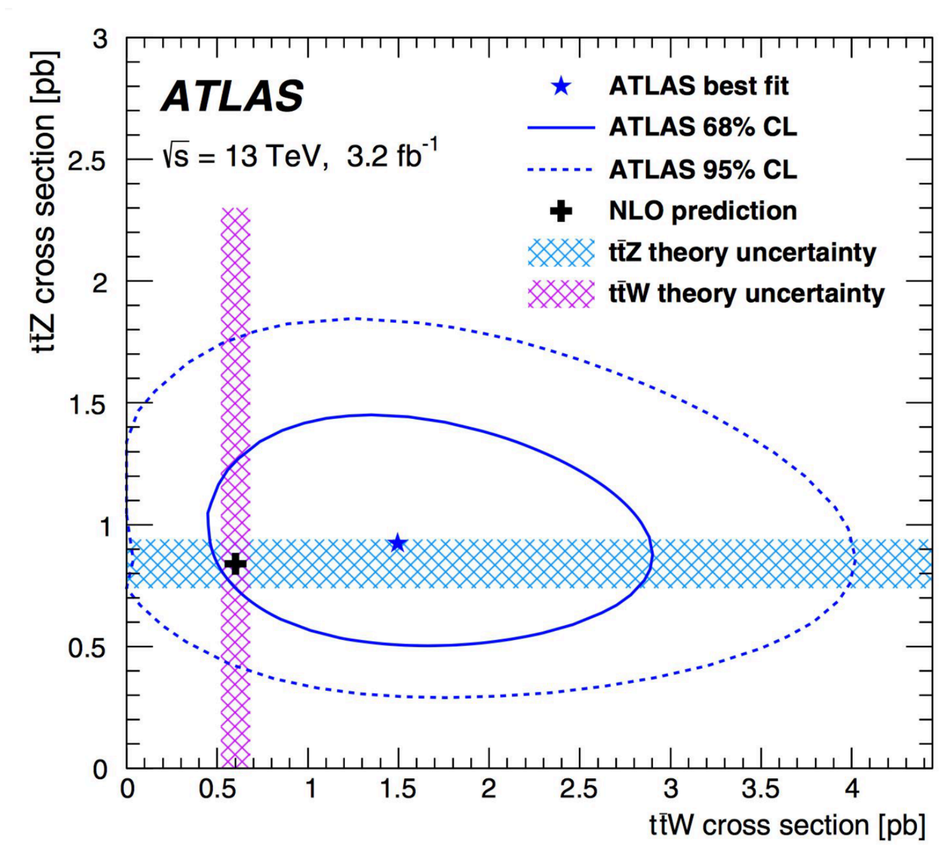


ttV

INTRODUCTION

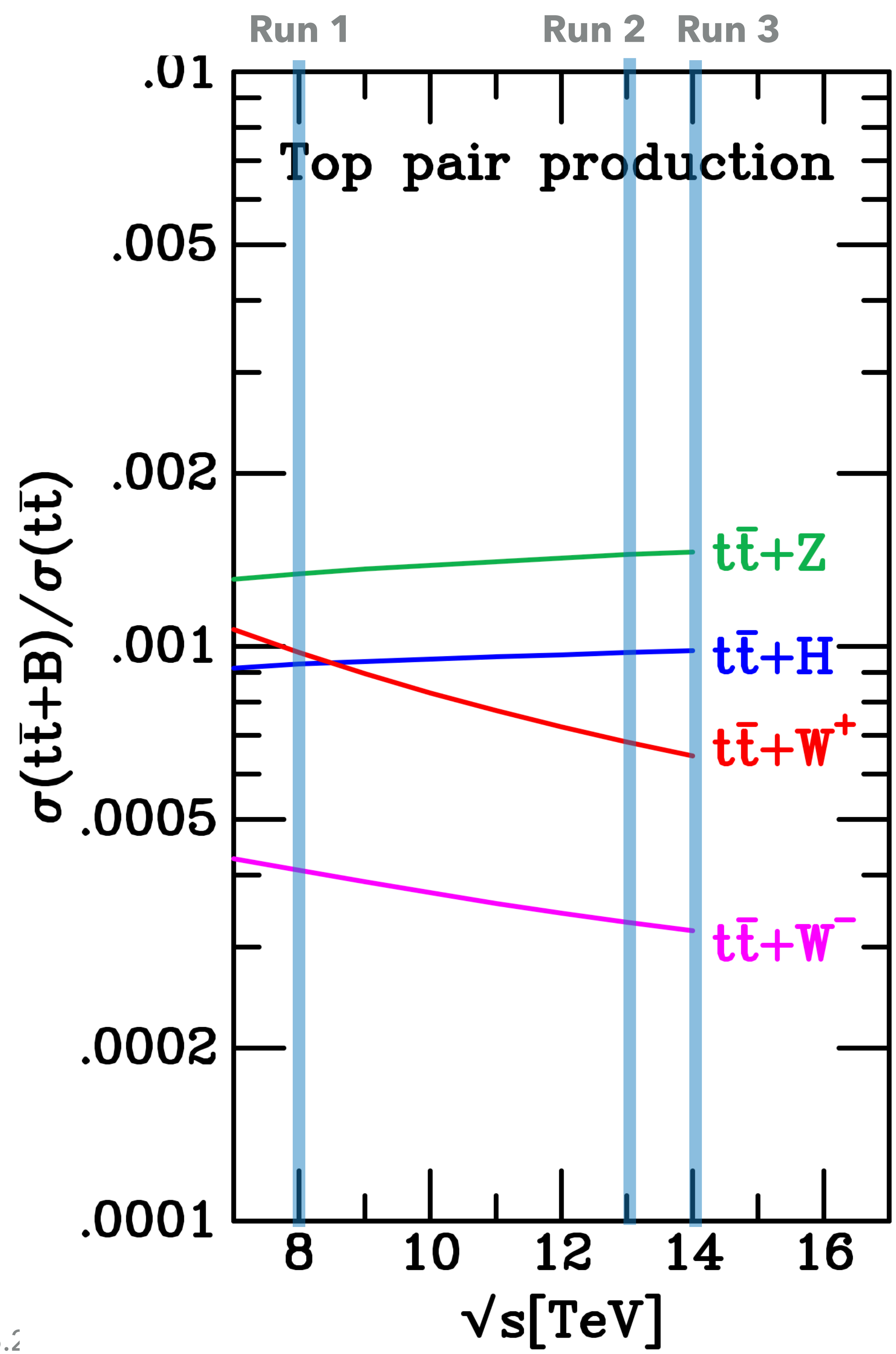
- tt̄V (via tt̄Z) provides a direct probe of the weak couplings of the top quark.
  - NC weak coupling in SM tt̄W only through CC electroweak ISR from quark initiated production.
- It's an important background for Beyond the Standard Model physics searches with various final states.
  - Stop searches and electroweak SUSY productions.
  - Deviations from SM can be probed with Effective Field Theory.
- Also an important background for ttH Multilepton searches and four-top production.

- With the full **8 TeV dataset**
  - significance of 5.0 σ (4.2 σ) over the background-only hypothesis for tt̄W (tt̄Z) production.
- with the 3.2 fb-1 2015 13 TeV dataset Eur. Phys. J. C77 (2017) 40



PREVIOUS MEASUREMENTS

- Limiting factors for 8 TeV measurement:
  - Statistically limited analysis.
  - For tt̄W fit, dominant syst. uncert. was modelling of fake leptons and background processes with misidentified charge.
  - For tt̄Z fit, dominant syst. uncert. source was the modelling of backgrounds from simulation.
- Going from 8 TeV to 13 TeV was **more advantageous for tt̄Z than for tt̄W**, due to rapidly increasing backgrounds for tt̄W.



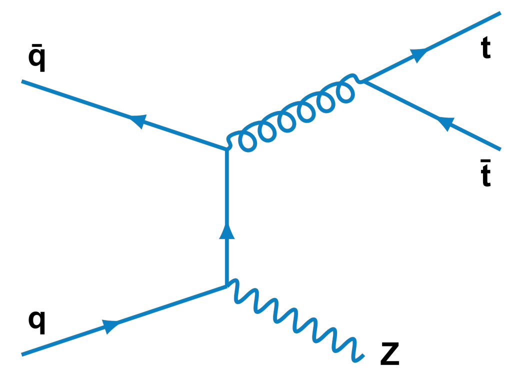
SIGNAL

- A measurement of the $t\bar{t}Z$ and $t\bar{t}W$ production cross sections in final states with 2, 3 or 4 isolated electrons or muons.
- Using 36.1 fb^{-1} from 2015+16 (13 TeV).

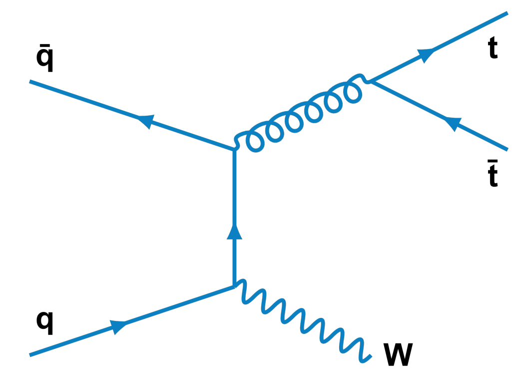
b-tagging WP of 77 %

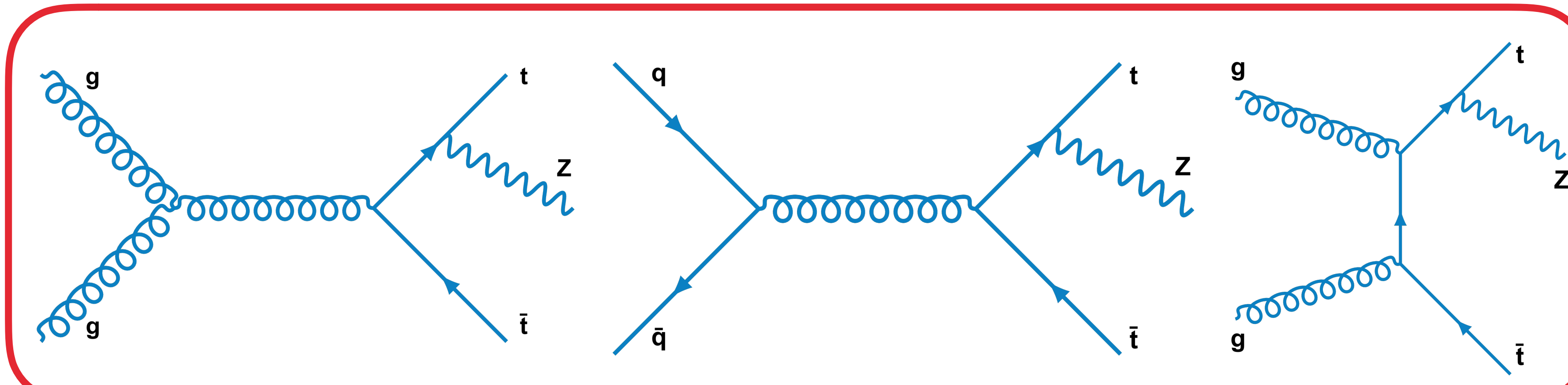
Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{\pm}\nu$	SS dilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	OS dilepton
	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton

$t\bar{t}Z$ (ISR)



$t\bar{t}W$ (ISR)

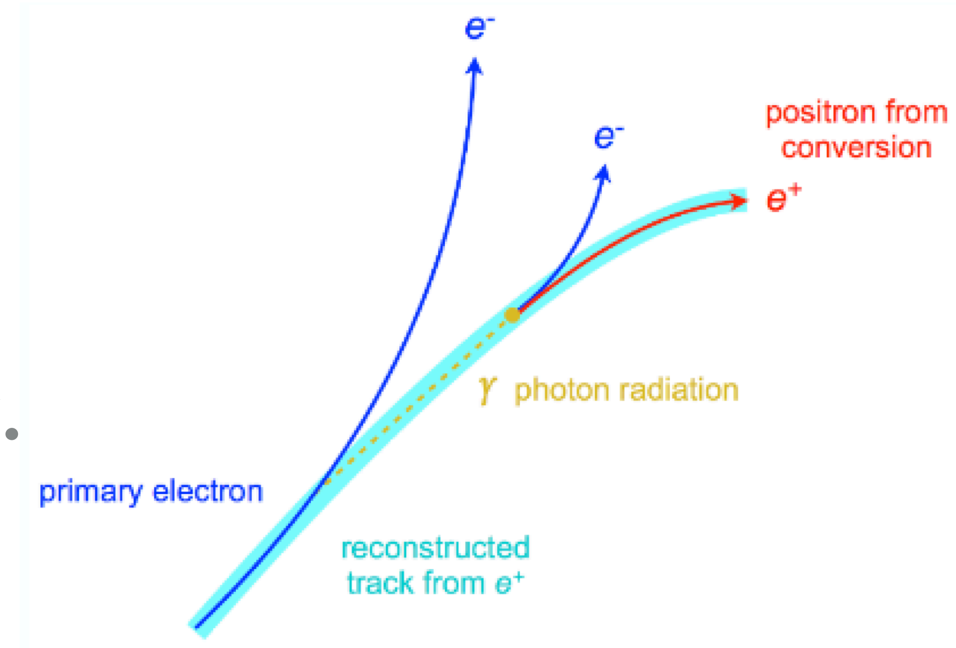




- Each channel is further divided into multiple regions to maximise the sensitivity of the measurement.

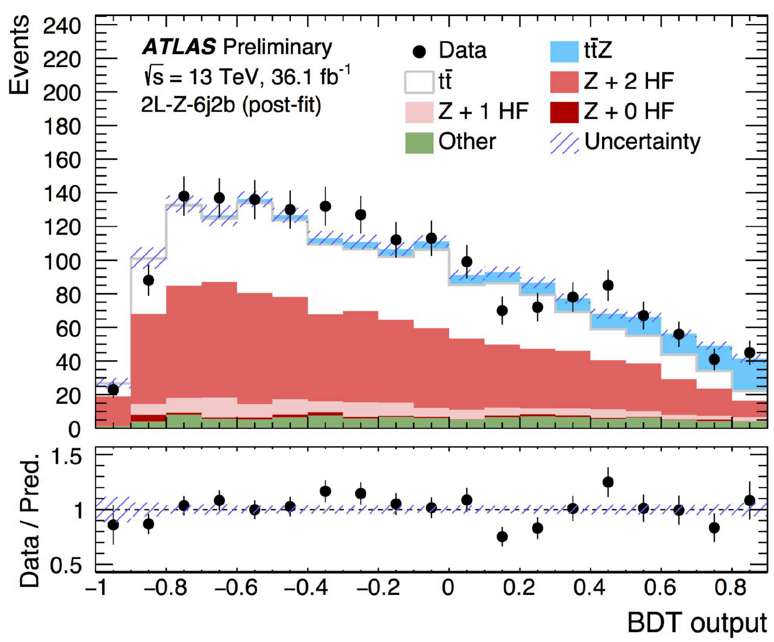
BACKGROUNDS

- Background events **containing prompt leptons determined from MC**.
  - Normalisation corrections obtained from the control regions included in the fit
    - WZ in 3L channel,
    - ZZ in 4L channel,
    - Z+1HF, Z+2HF in 2LOS channel
  - **Data-driven approach for tt background in 2LOS.**
    - VRs: 2l-SF-OS ⟶ 2L-DF-OS
    - Contributions from charge-flip events (significant for 2Lee and 2Leμ) estimated from data.
    - 2Lμμ is negligible - probability of misidentifying the charge of a muon in p_T range is v. small.
  - Backgrounds with ≥ **1 fake leptons modelled using data in dedicated CRs.**



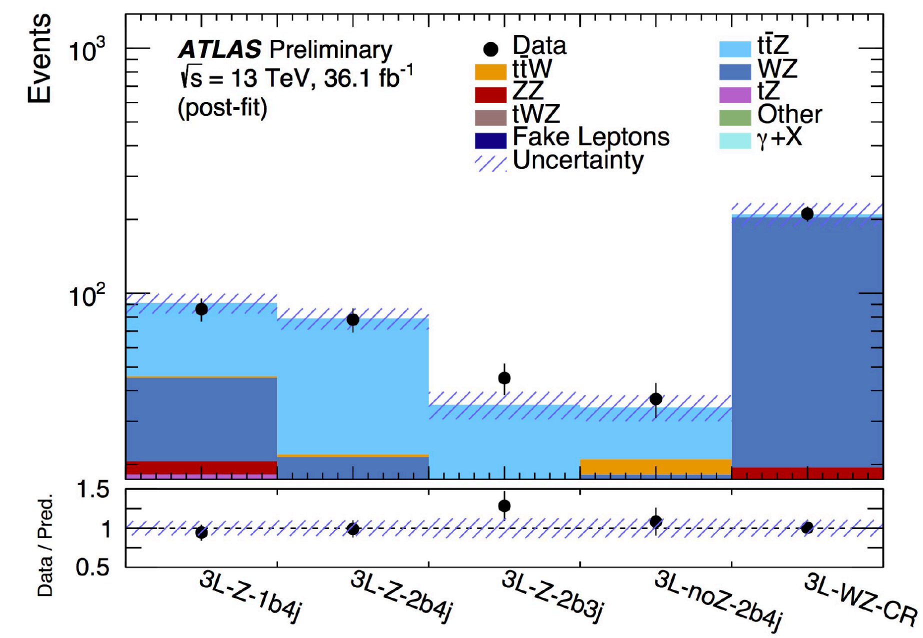
CHANNELS – POST FIT

tt̄Z 2L: OSSF



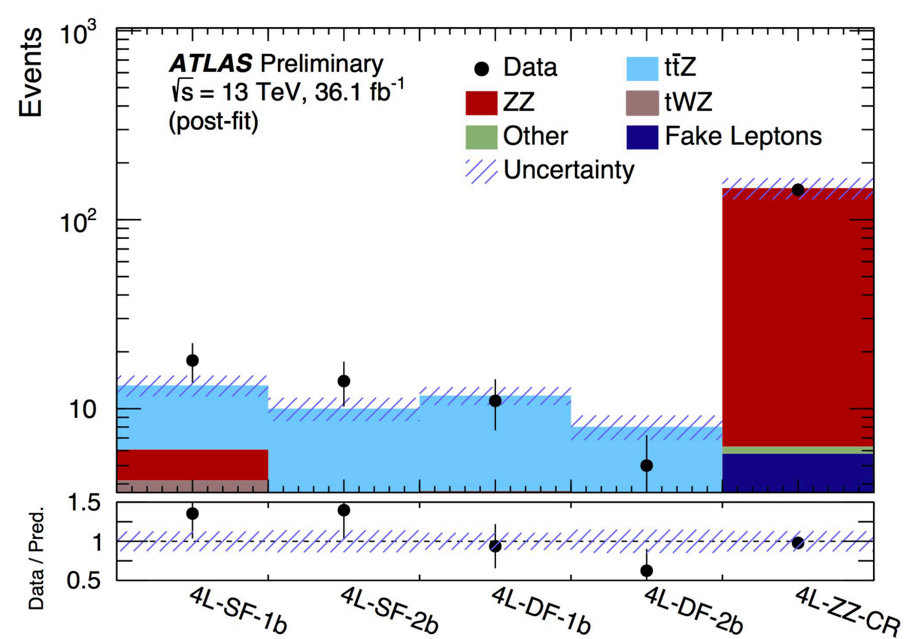
Boosted Decision Trees (BDTs) are used to separate signal from background in each region separately.

tt̄Z 3L



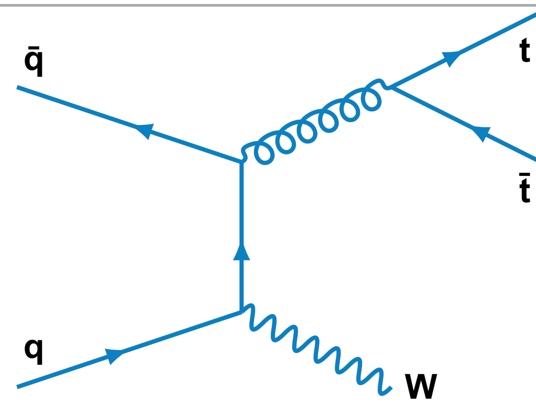
CR used for WZ background, free parameter in the fit.

tt̄Z 4L

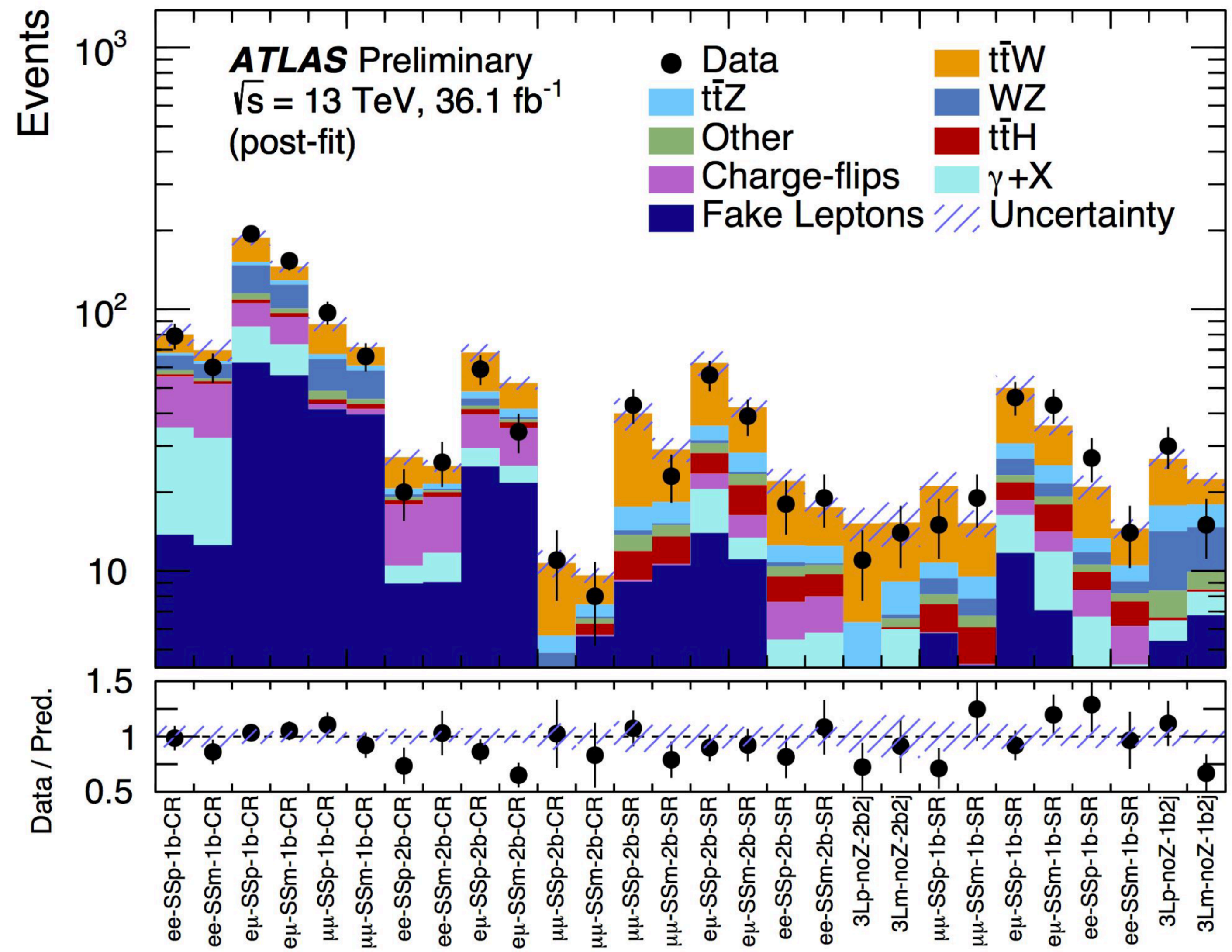


CR used for ZZ background, free parameter in the fit.

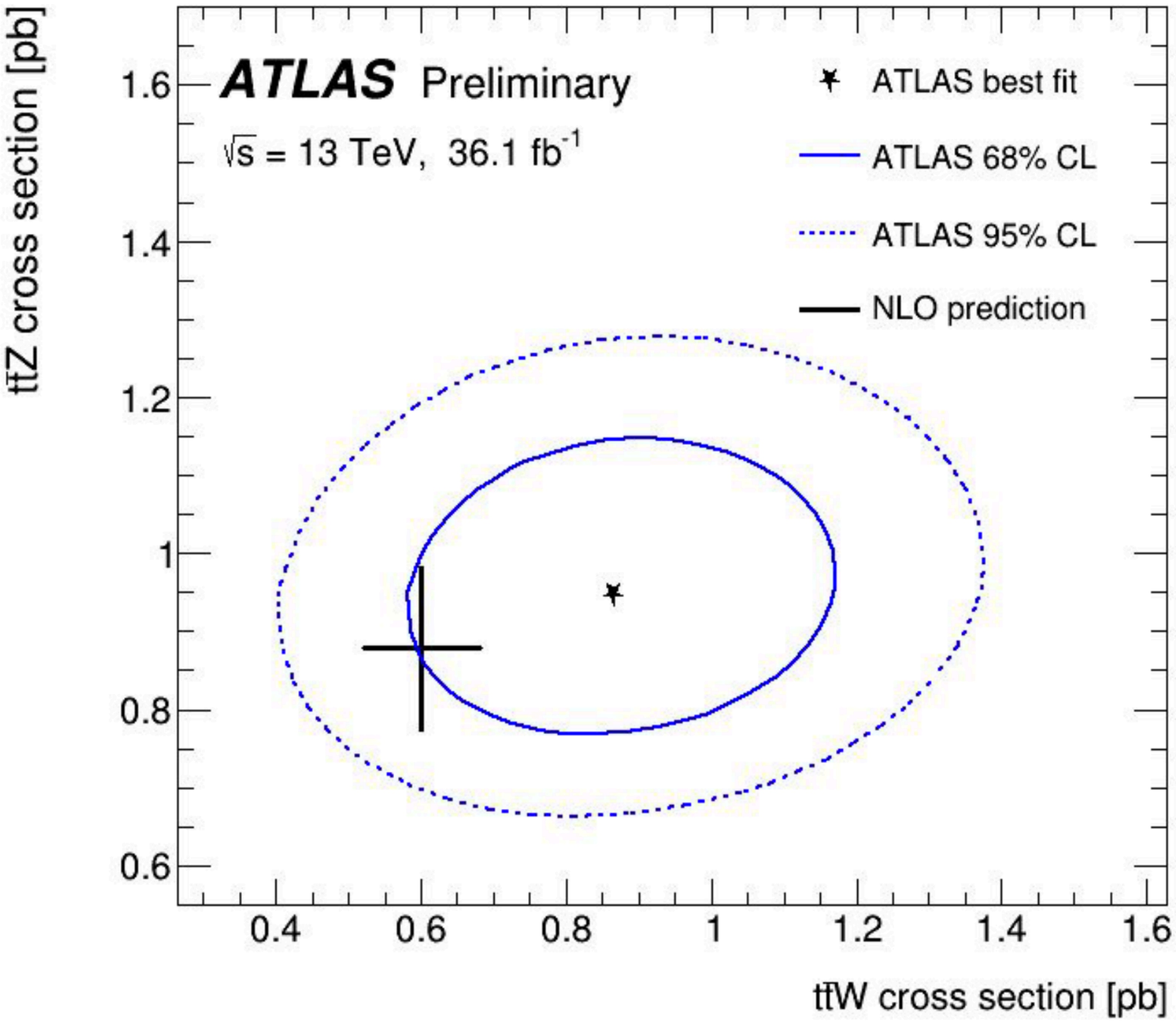
ANALYSIS



- Initial state is qq only.
- A rare source of SS leptons
- 2LSS selection:
  - 12 dilepton same sign regions depending on #b-jets, lepton flavour and charge.
  - |Mll − MZ| > 10 GeV for 2e and 2μ.
  - Major backgrounds:
    - **Fake leptons and charge flips**.
- Non-negligible signal contamination in CRs
  - Used in the fit
  - Signal strength, μ(ttW), and fake lepton background are anti-correlated.
- 3L selection:
  - Four trilepton regions sensitive to tt̄W depending on #b-jets and lepton charge
  - Major backgrounds:
    - **Fake leptons and diboson.**



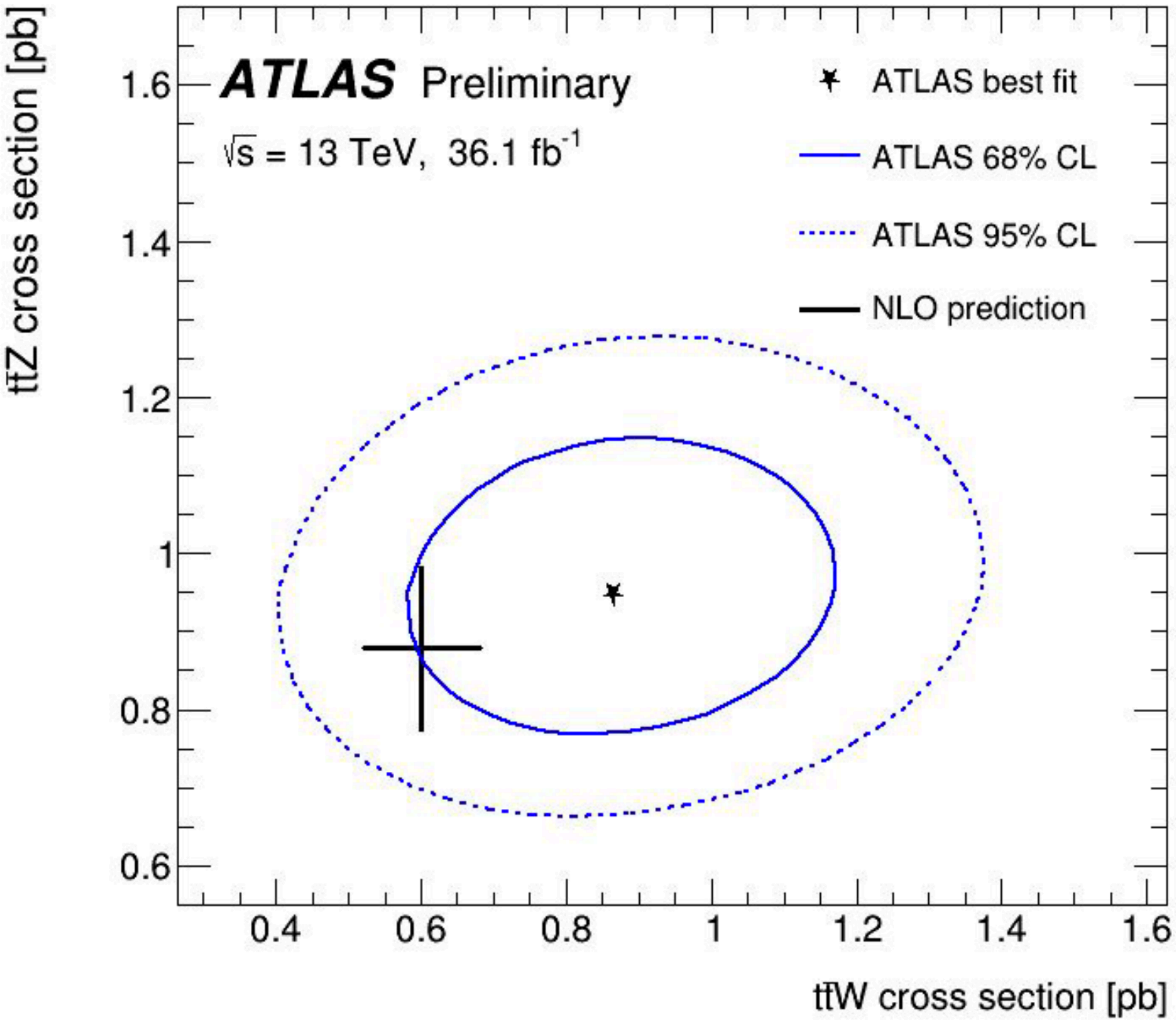
SIMULTANEOUS FIT



Fit configuration	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$
Combined	1.08 ± 0.14	1.44 ± 0.32
2ℓ-OS	0.73 ± 0.28	-
3ℓ $t\bar{t}Z$	1.08 ± 0.18	-
2ℓ-SS and 3ℓ $t\bar{t}W$	-	1.41 ± 0.33
4ℓ	1.21 ± 0.29	-

- Combined fit measured:
  - σ(ttZ) = 0.95 ± 0.13 pb
  - σ(ttW) = 0.87 ± 0.19 pb
- and yields significance of:
  - ttW: 4.3σ (3.4σ) observed (expected)
  - ttZ has a significance > 5σ.

SIMULTANEOUS FIT



Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.9%	4.5%
CR and simulated sample statistics	1.8%	7.6%
JES/JER	1.9%	4.1%
Flavor tagging	4.2%	3.7%
Other object-related	3.7%	2.5%
Data-driven background normalization	2.4%	3.9%
Modeling of backgrounds from simulation	5.3%	2.6%
Background cross sections	2.3%	4.9%
Fake leptons and charge misID	1.8%	5.7%
$t\bar{t}Z$ modeling	4.9%	0.7%
$t\bar{t}W$ modeling	0.3%	8.5%
Total systematic	10.2%	16.0%
Statistical	8.4%	15.2%
Total	13.0%	22.2%

CONSTRAINTS ON BSM

- Interpretations of the inclusive cross-section measurement in terms of Effective Field Theory (EFT).
  - Set constraints on the five operators which modify the ttZ vertex. $O_{\phi Q}^{(3)}, O_{\phi Q}^{(1)}, O_{\phi t}, O_{tW}, O_{tB}$
  - First two enter the $t\bar{t}Z$ vertex as a linear combination:
    - Measurement is sensitive to the difference. $C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)}$
  - Only one operator is considered at a time.

Coefficient	Expected limits at 68% and 95 % CL	Observed limits at 68% and 95 % CL	Previous constraints at 95 % CL JHEP 05 (2016) 052
$(C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)})/\Lambda^2$	[-2.1, 1.9], [-4.6, 3.7]	[-1.0, 2.7], [-3.4, 4.3]	[-3.4, 7.5]
$C_{\phi t}/\Lambda^2$	[-3.8, 2.8], [-23, 5.0]	[-2.0, 3.6], [-27, 5.7]	[-2.0, 5.7]
C_{tB}/Λ^2	[-8.3, 8.6], [-12, 13]	[-11, 10], [-15, 15]	[-16, 43]
C_{tW}/Λ^2	[-2.8, 2.8], [-4.0, 4.1]	[-2.2, 2.5], [-3.6, 3.8]	[-0.15, 1.9]

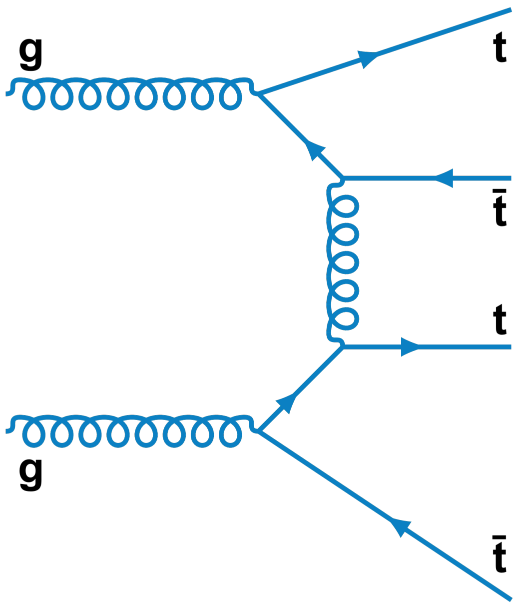
A SEARCH FOR FOUR-TOP-QUARK PRODUCTION

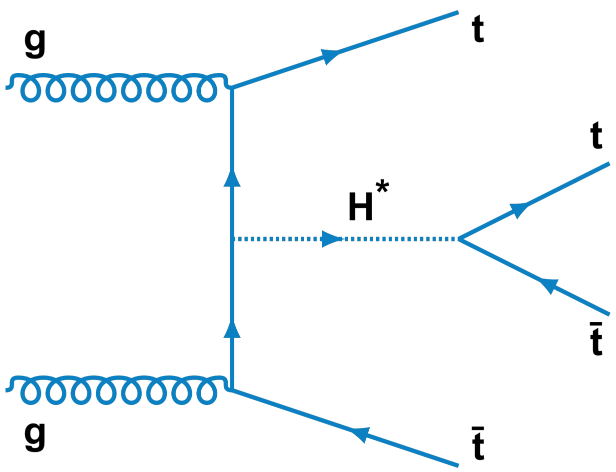
$t\bar{t}t\bar{t}$

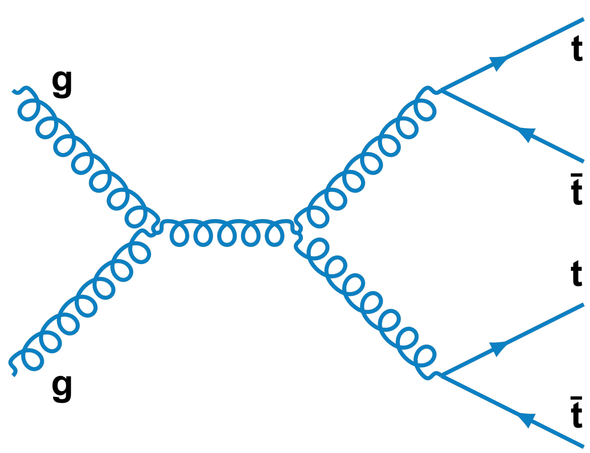
MOTIVATION

- Measurement of SM four-top cross-section becoming possible with current LHC statistics.
- Possible enhancement of SM cross-sections from new physics through the production of heavy objects in association with a top-quark pair.
- Previous measurements:
    - 3.2 fb^{-1} with 13 TeV: ATLAS-CONF-2016-020
        - Observed (expected) upper limit of: *21 (16) x four-top SM σ at 95% CL.*
        - Single lepton channel only.

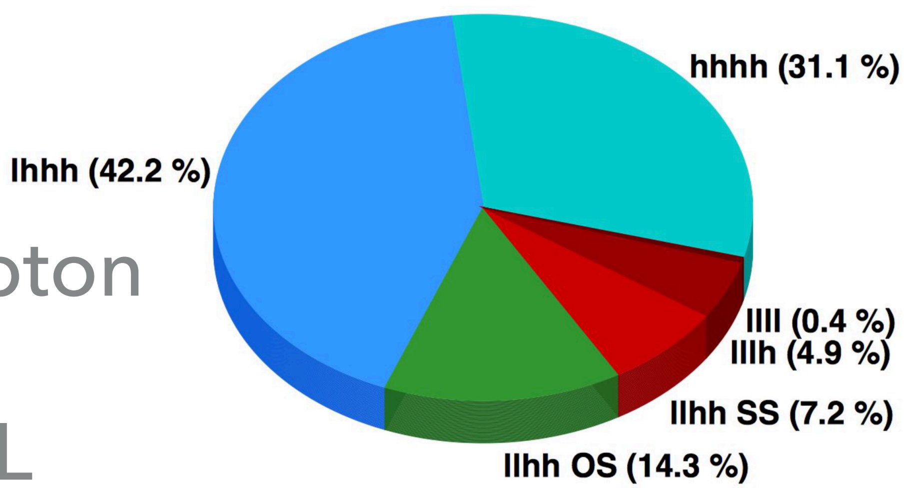
SIGNAL







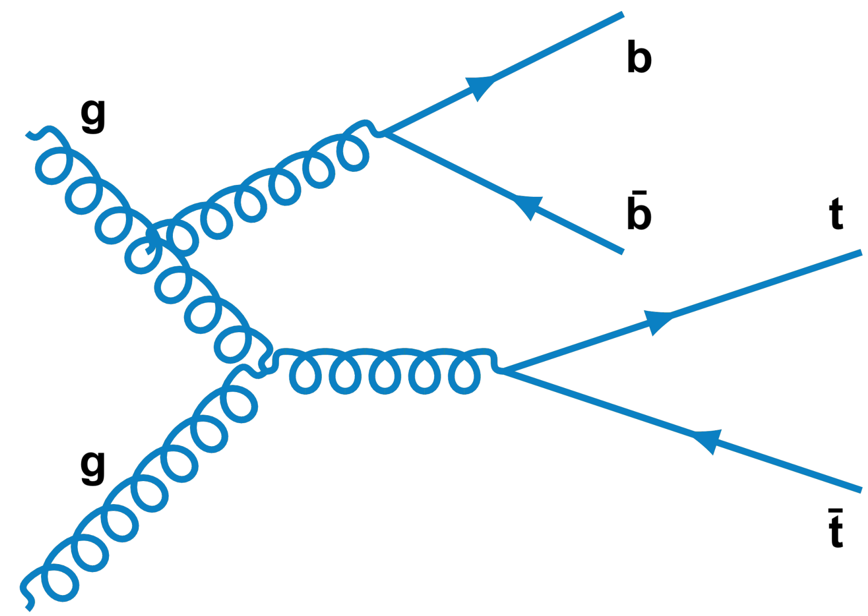
- Very busy signal with no narrow resonance.
  - Many b-jets and jets in the final state.
  - Channels split into:
    - l+jets & OS dilepton
    - SS dilepton & ML

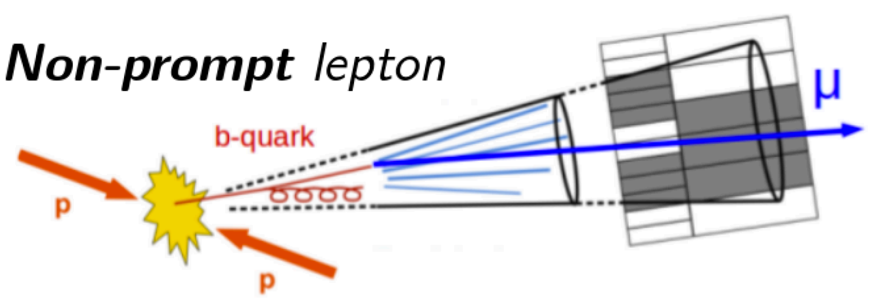


  - Expected total cross-section: 9.2 fb at LO.
    - Only ~100 events per year.

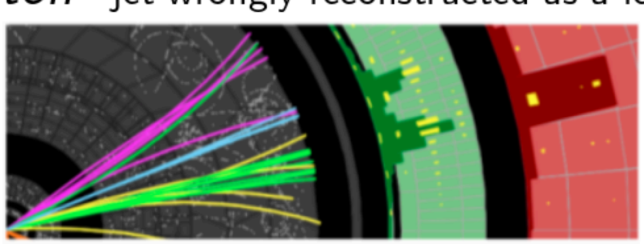
BACKGROUNDS

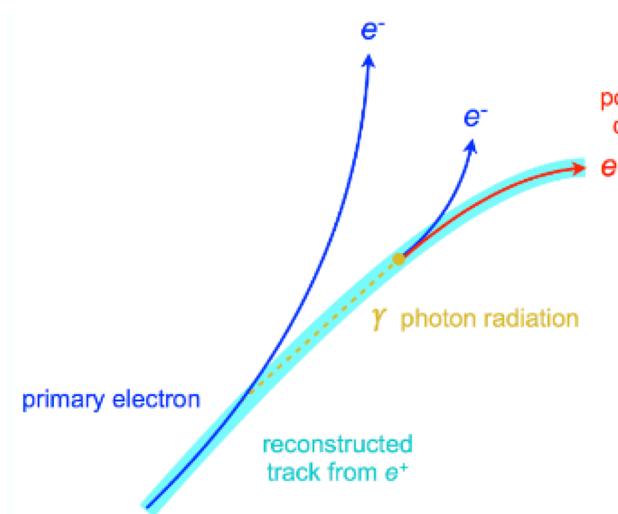
- Generally two types of backgrounds to consider:
  - **Physical processes:**
    - $t\bar{t}$ + jets, $t\bar{t}V$ + jets, diboson
  - **Instrumental backgrounds:**
    - Fake leptons and charge misID



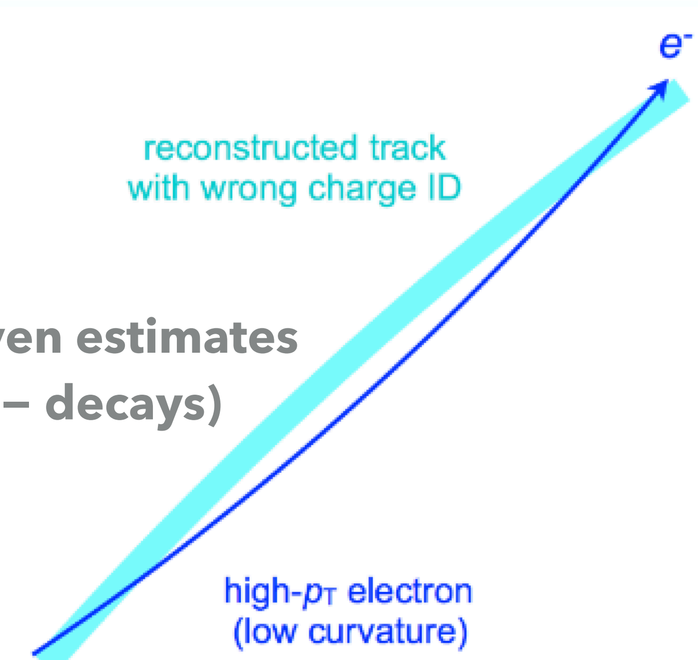


Fake lepton - jet wrongly reconstructed as a lepton



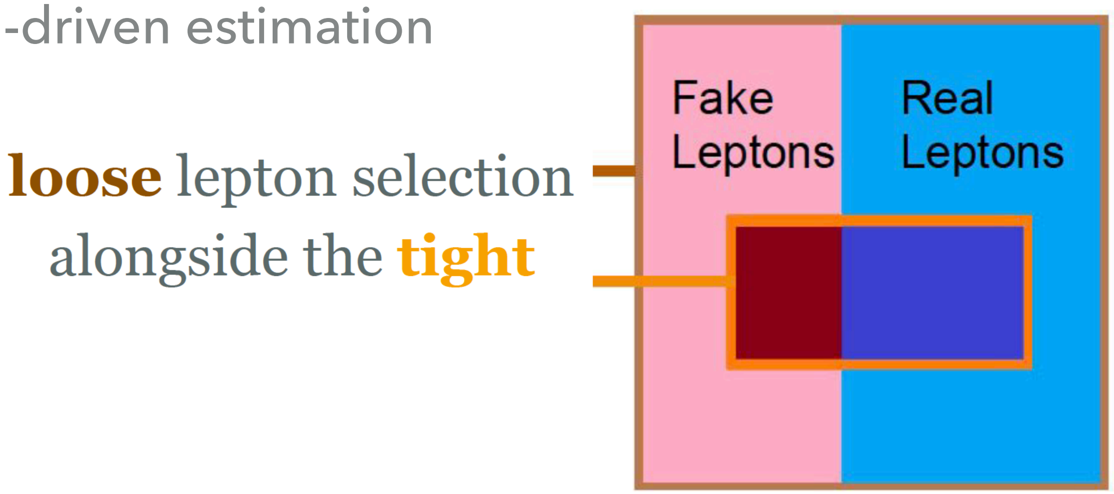


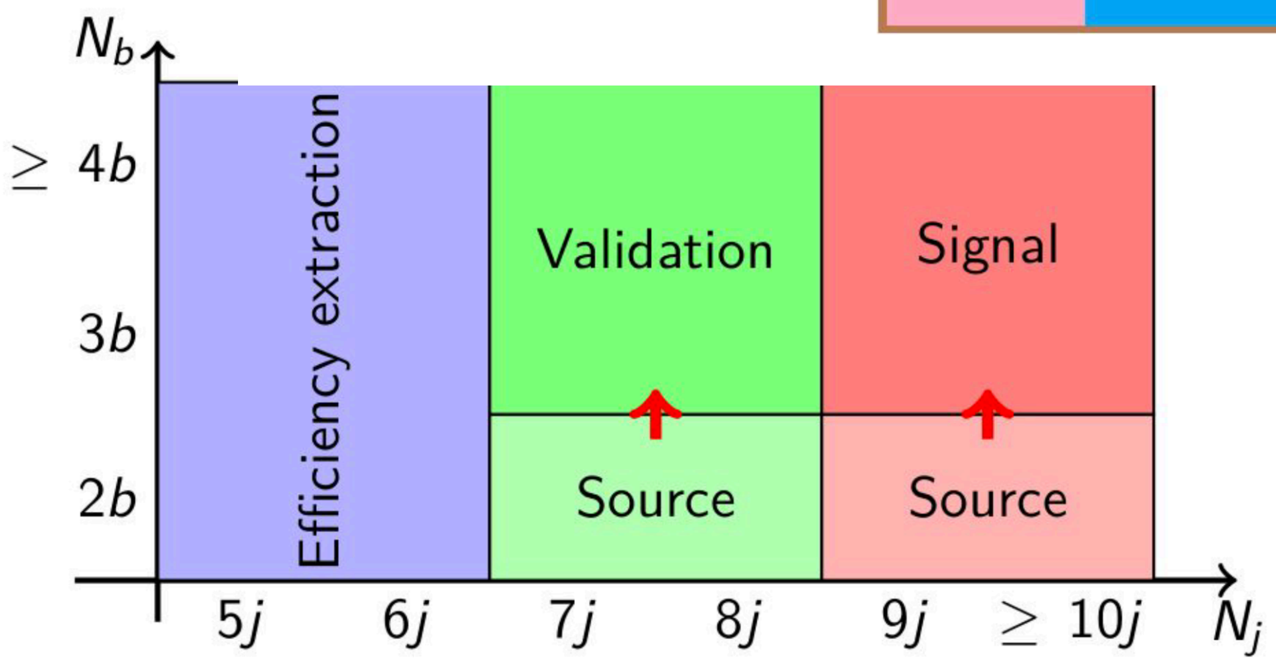
Data driven estimates
(Z → e+e− decays)



1L/2LOS

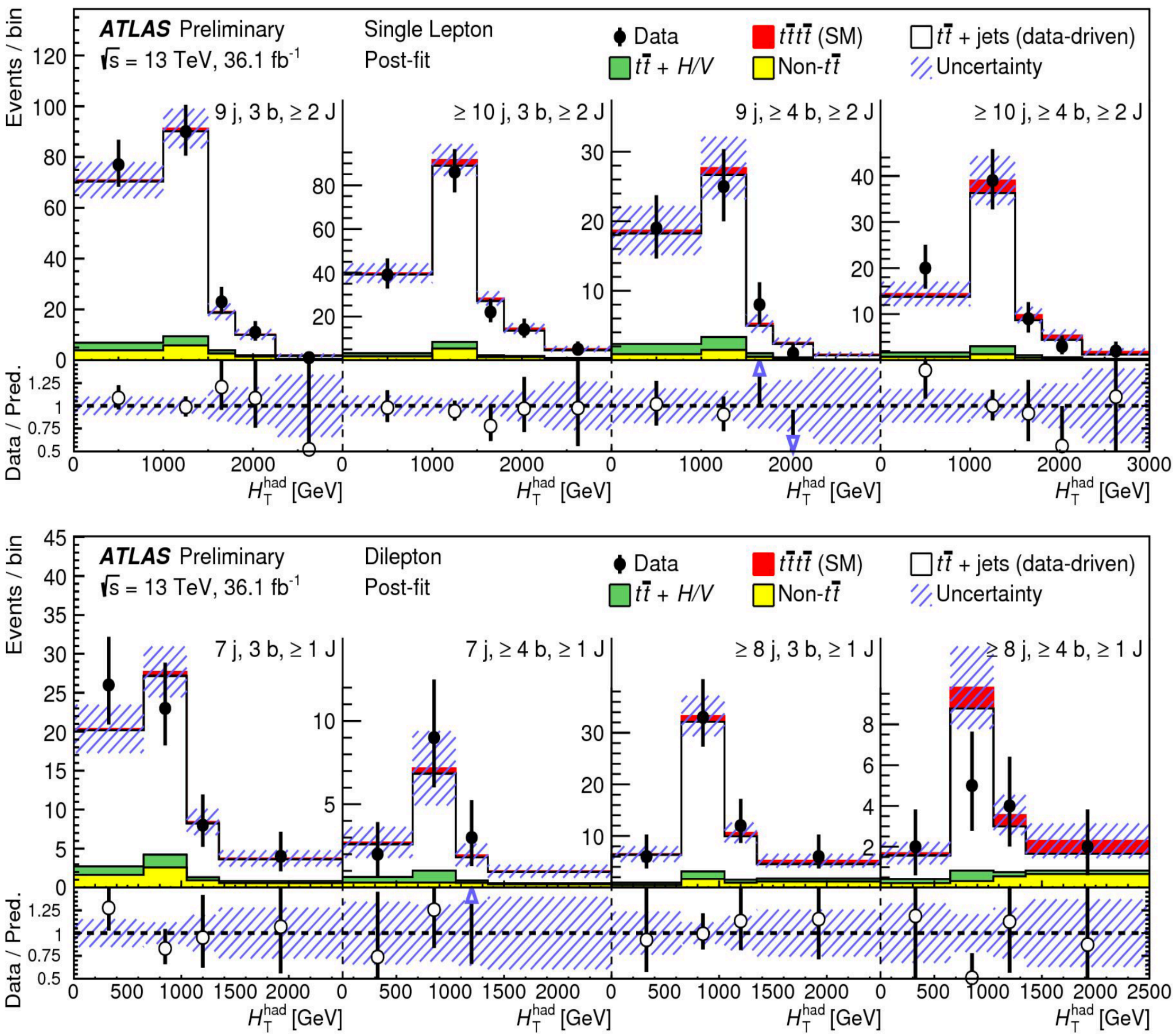
- Events categorised according to **jet, b-tagged jet and mass-tagged reclustered large-R jet multiplicities**.
- **Dominated by $t\bar{t}b\bar{b}$ background**
  - Not expected to be modelled well
  - Data-driven estimation





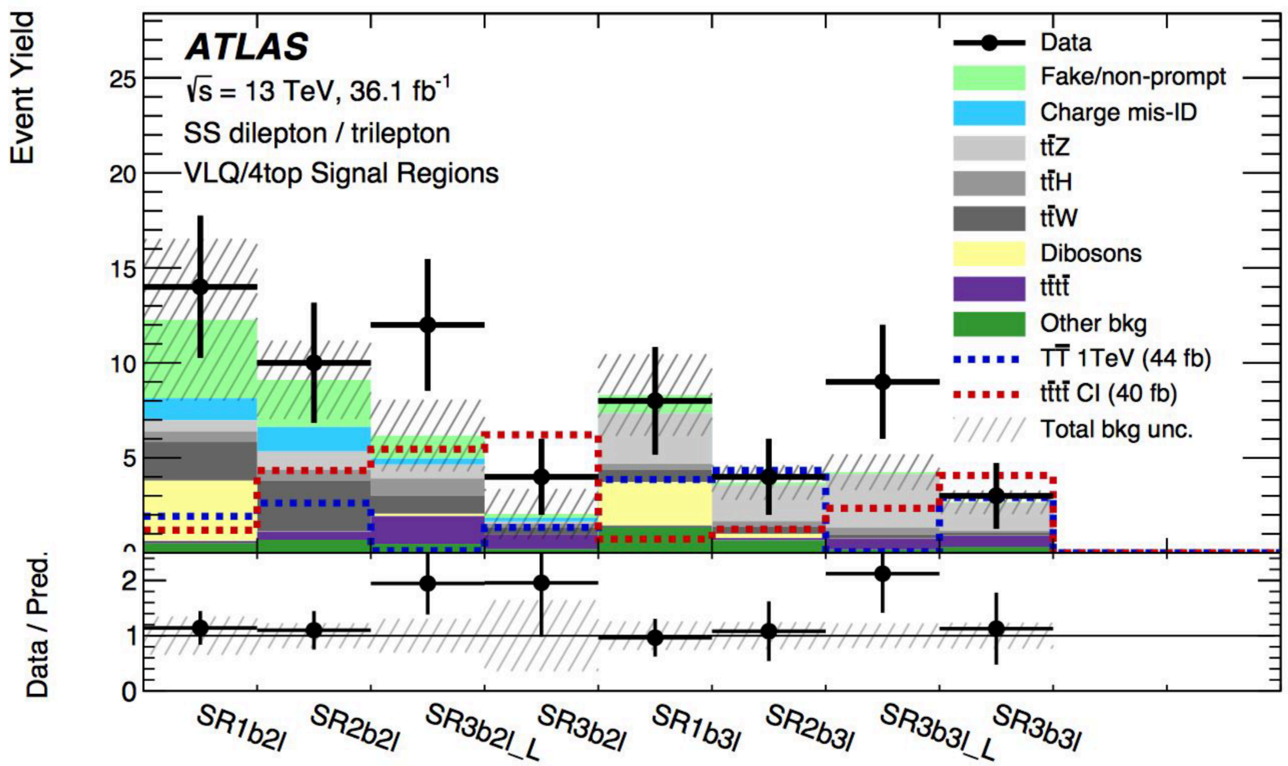
- 1L:
  - Background from events with a fake or non-prompt lepton estimated directly from data using matrix method.
  - **tt Tag Rate Function to estimate $t\bar{t}$ + jets:**
    - ttTRF gives the probability that a jet is b-tagged
    - Three phases: extraction, validation, application.
    - Reweight data in low # b-jet bins with weights from low # jet bins.
    - Implement MC-correction factors to account for extrapolation assumption.
- OS2L:
  - **Background is estimated from MC.**
    - Less than 8% of total background in signal region.

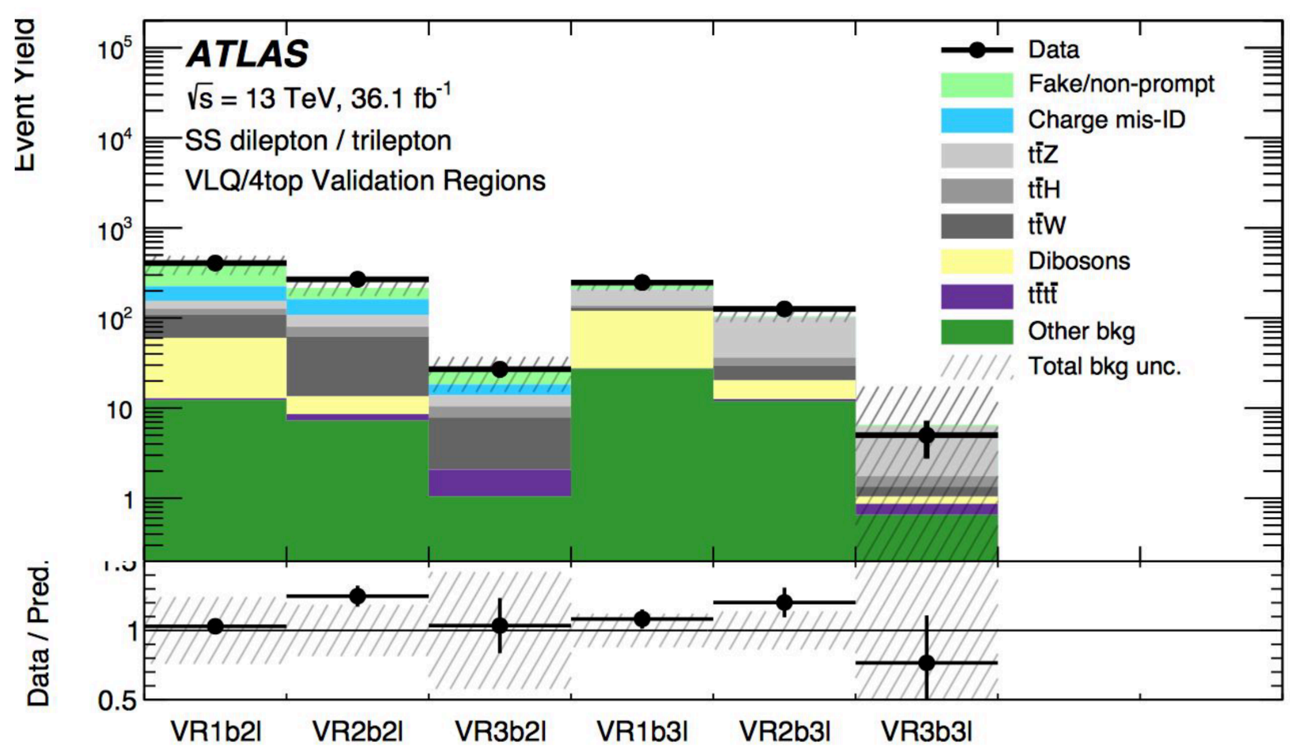
1L/2LOS FIT



- Simultaneous fit in 20 signal regions
  - Non-tt
  - W/Z+jets, single top, diboson productions and multijet backgrounds.
  - Uncertainty stat & syst.
- Observed (expected) 95% CL upper limit on σ(tttt) of 47 fb (33 fb).
  - Upper limit on σ(tttt): 5.1 (3.6) x SM.

SS DILEPTON / MULTILEPTON

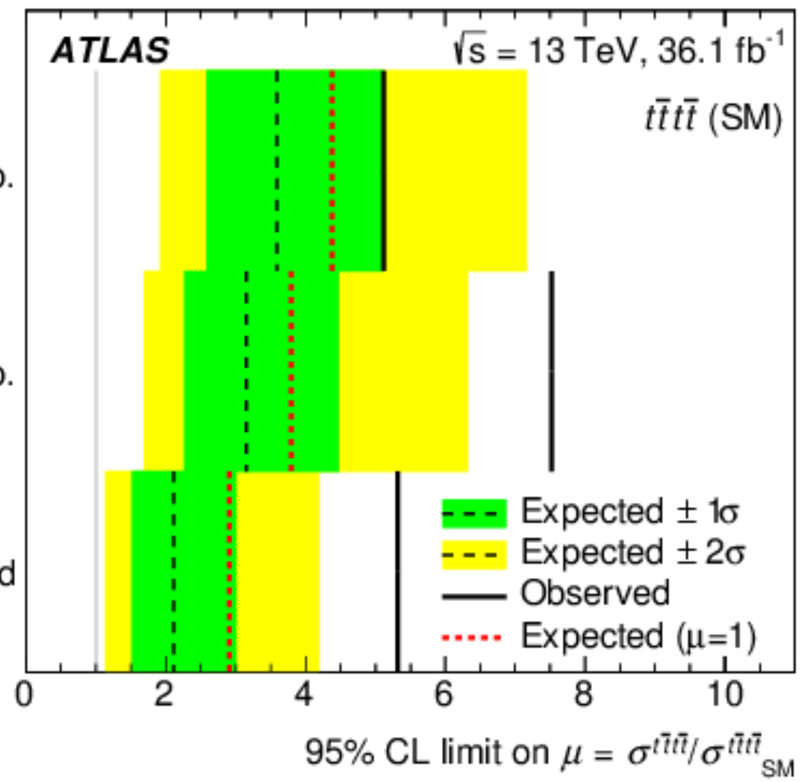




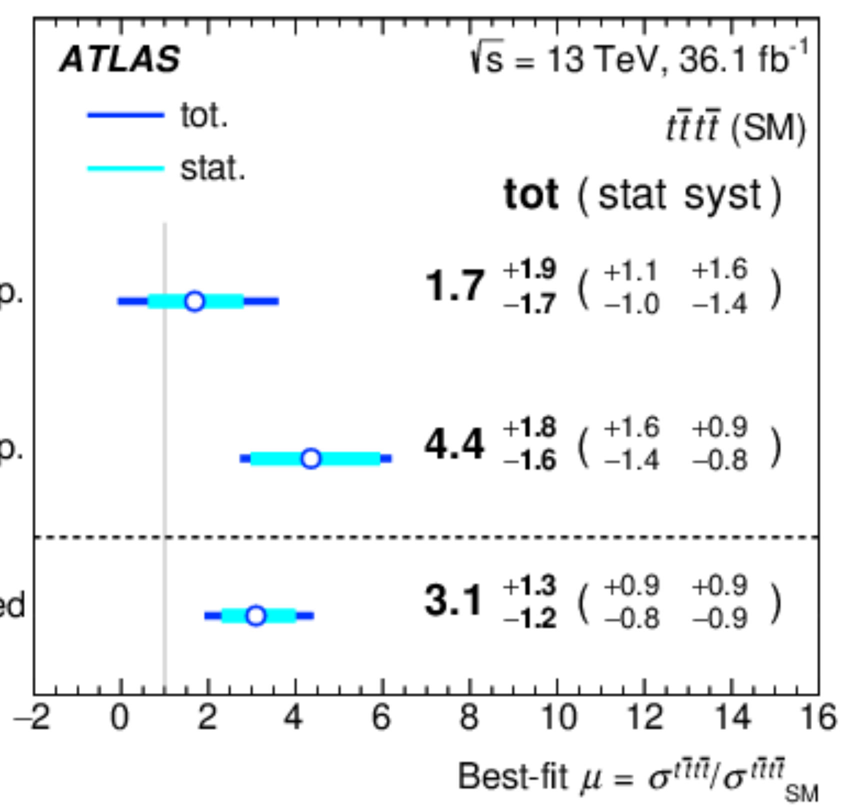
- **Cut and count analysis** in 8 signal regions and 6 validation regions.
  - The SM σ(tttt) upper limit is (expected) 69 (29) fb.
- **Dominated by fakes and ttV background.** Data driven techniques for
  - Fake/non-prompt lepton backgrounds from matrix method
  - 2LSS: charge misidentification
- **Irreducible backgrounds (e.g. ttV) modelled by MC.**

COMBINATION

Upper limit:



Signal Strength:



- Uncertainties treatment:
  - All experimental systematic uncertainties treated as **fully correlated** between channels.
  - Background modelling uncertainties treated as uncorrelated.
- An excess of events over the SM background prediction, excluding the SM tt̄tt̄ production, is observed at 2.8 σ (1.0 σ).
- Observed (expected) 95% CL upper limit on σ(tt̄tt̄) of **49 fb (19 fb)**.
  - Corresponding to an upper limit on σ(tttt), of **5.3 (2.1) x SM**.

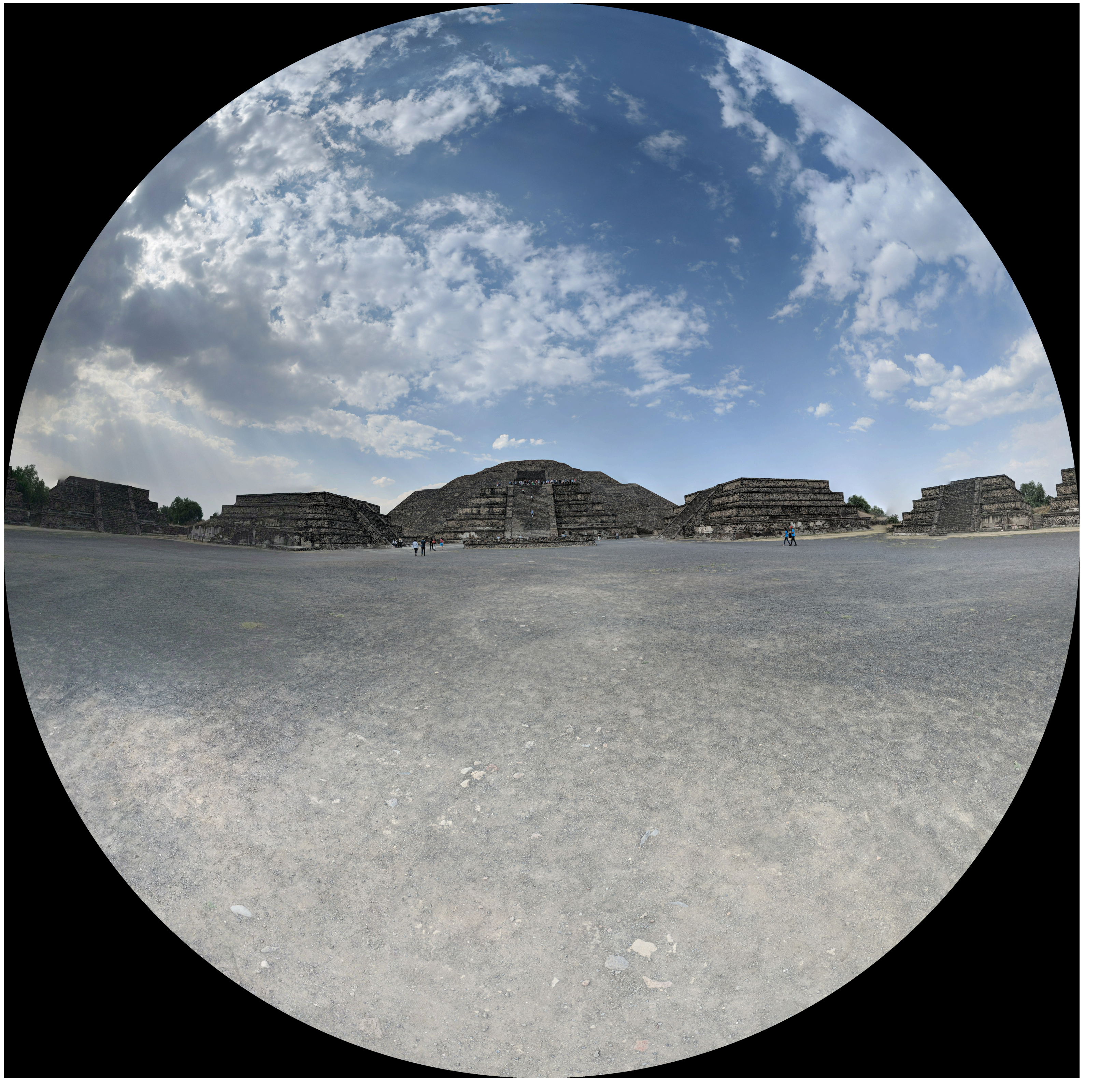
Summary

THE ROAD AHEAD…

- Next steps:
    - More differential and ratio measurements.
    - Major challenges with upgraded LHC: trigger rates and tracking at high pile-up.
- We have collected only a few percent of the anticipated luminosity from the LHC.
- Plenty more to come!

Forest Road in Oregon by Michael Matti

THANK YOU!

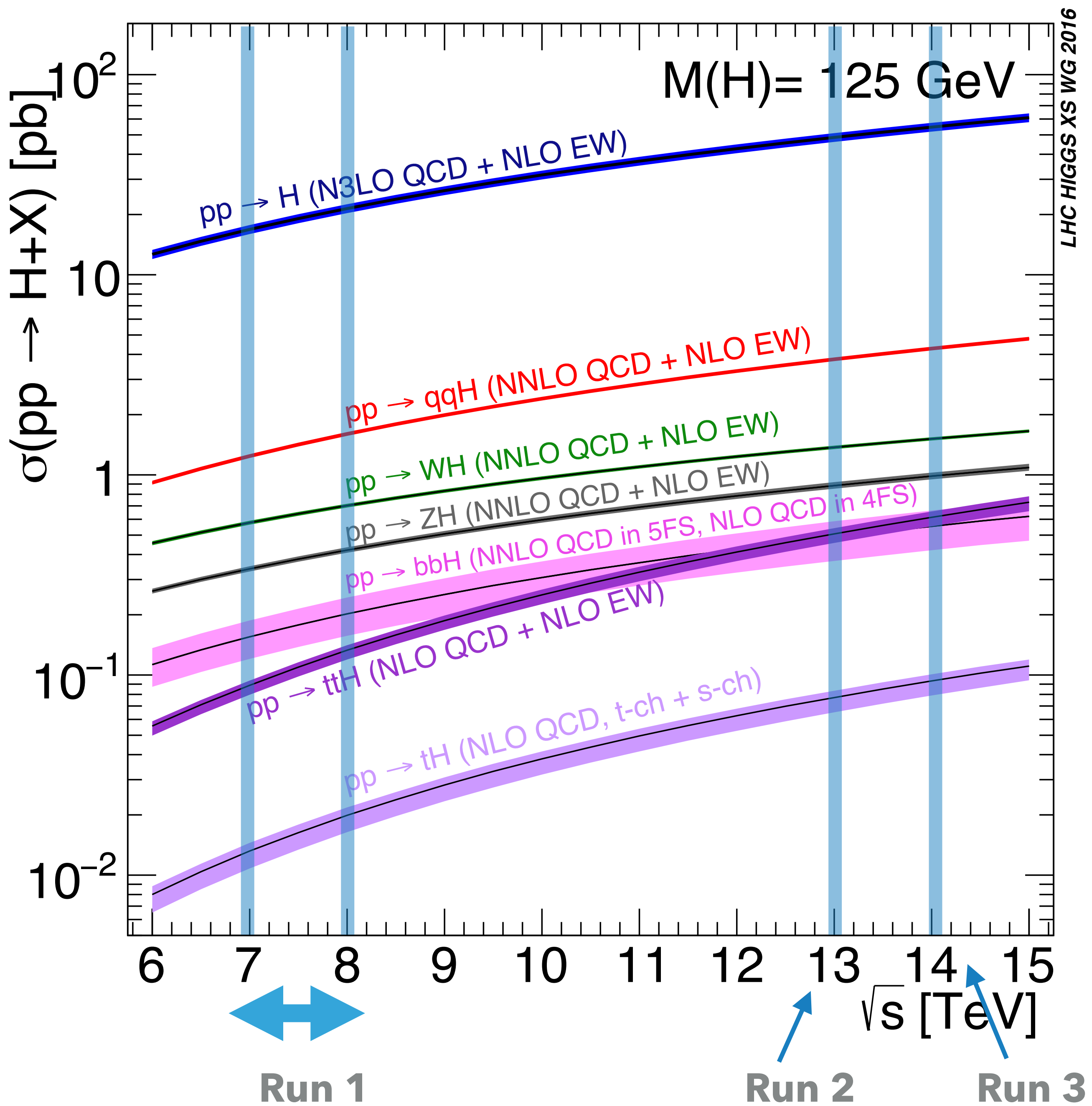


Backup

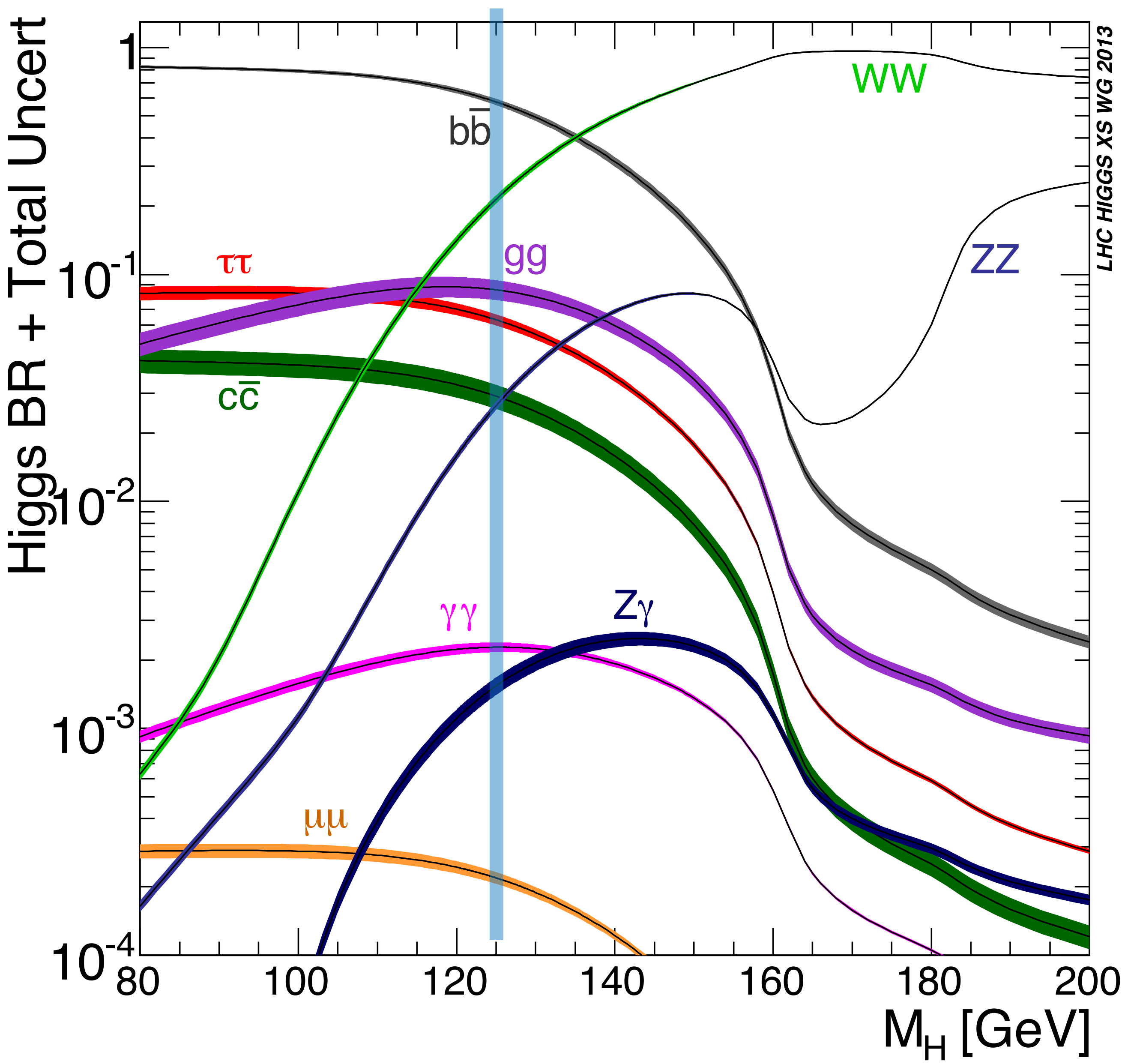
ttH

THE DISCOVERY OF THE HIGGS BOSON

- The Brout-Englert-Higgs (BEH) mechanism extended spontaneous symmetry breaking to gauge fields.
    - The process generates mass for fundamental particles.
- It also predicted a scalar particle, often referred to as the Higgs boson.
    - However, the mass of the Higgs boson is not predicted in the SM.
- In 2012, CERN announced the discovery!
- Once the Higgs mass is measured, the other parameters become fixed and can be measured and compared to SM predictions.



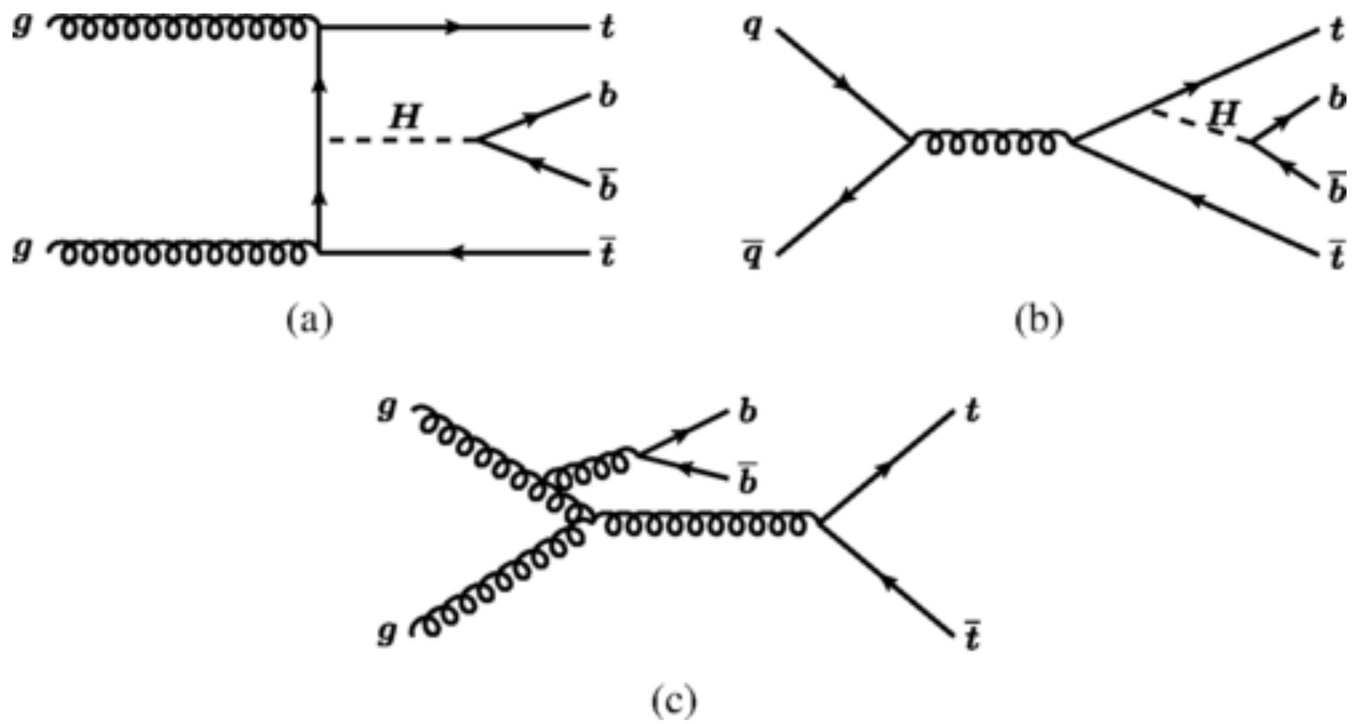
MOTIVATION

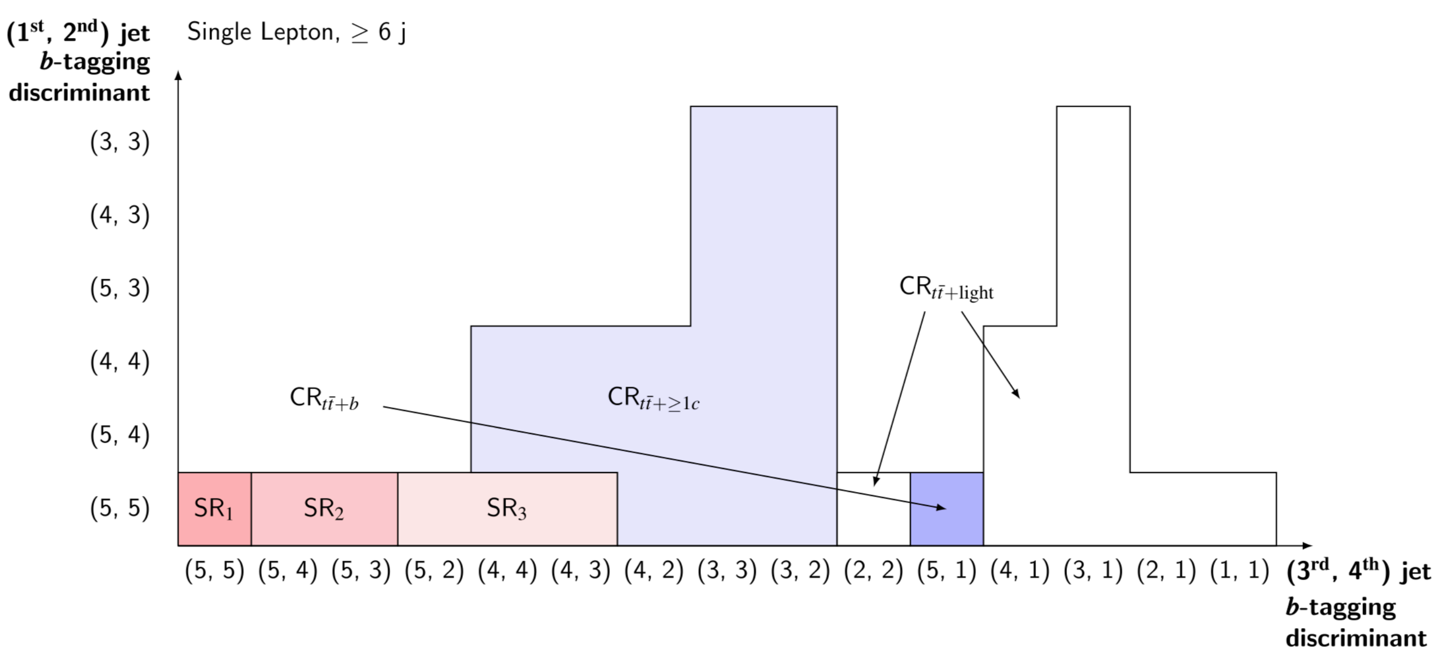


- Indirect constraints on the top Yukawa coupling to the Higgs can be inferred from ggF production, and from H → γγ decays.
  - BUT we also want to measure direct couplings. Therefore need tt̄H.
- tt̄H Channels:
  - H→bb̄
    - single lepton & opposite-sign dilepton.
  - H→γγ and →ZZ
    - Both the hadronic and leptonic tt̄ decay channels.
  - H → (WW(*), ττ, ZZ(*)) → leptons
    - two - four final lepton states.

ANALYSIS STRATEGY

Phys. Rev. D **97**, 072016



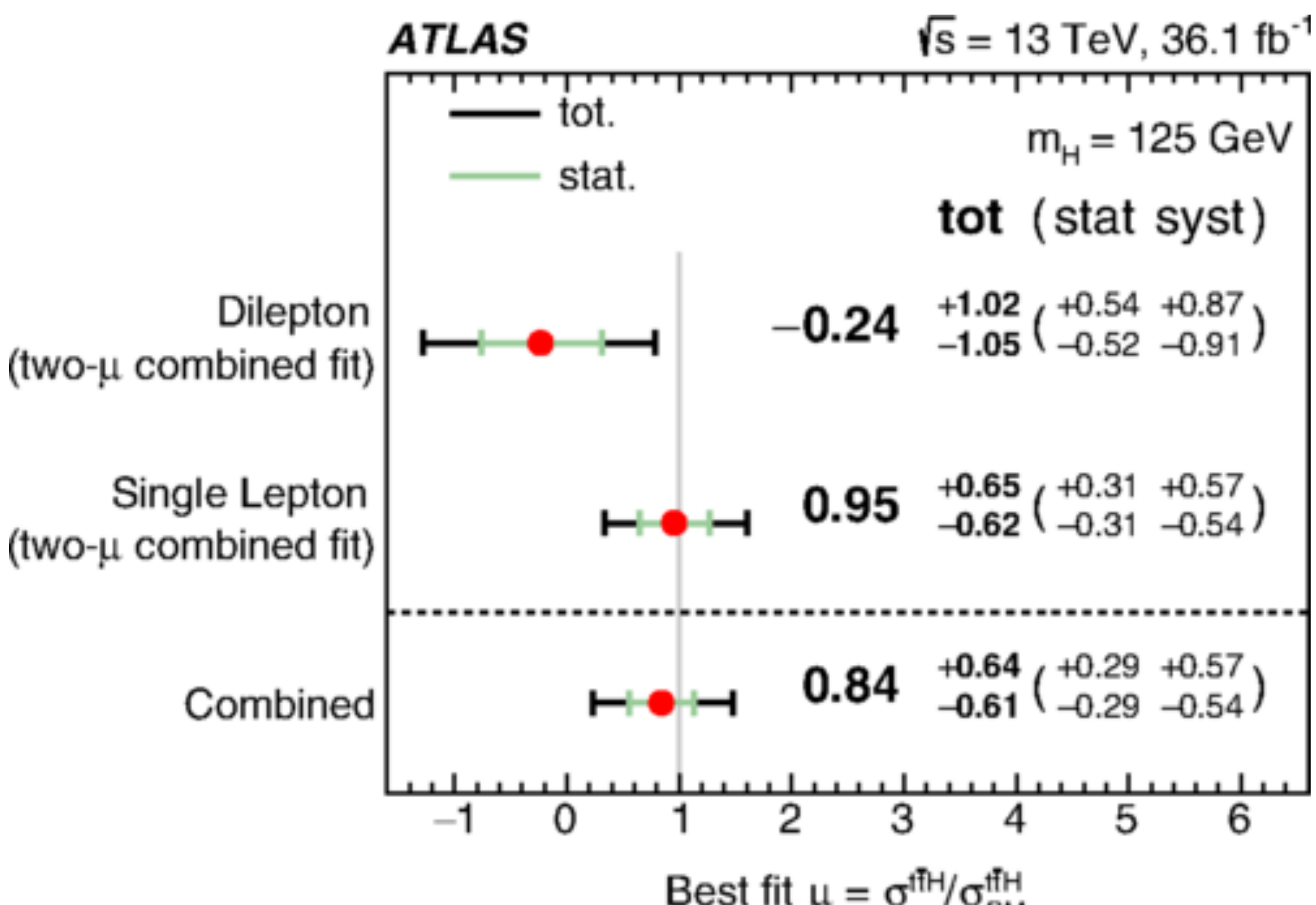


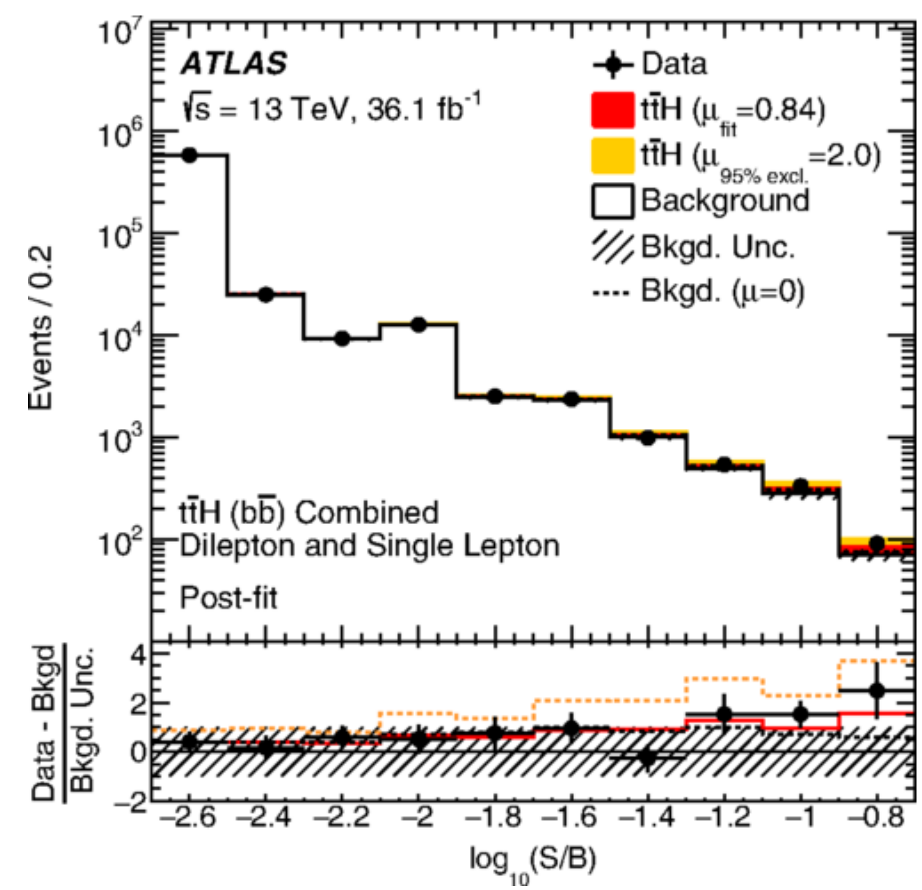
- The most common decay for a SM Higgs is to a pair of b-quarks, at 58%
  - but there are large backgrounds which are difficult to separate from signal
  - Broad mass mass resolution.
- Challenges:
  - Good modelling of the tt̄+HF background
- In each signal region, a classification BDT is used to discriminate between the tt̄H signal and the backgrounds.
  - A reconstruction BDT is used as input.

RESULTS

- A 1.4σ (1.6σ) excess above the expected background is observed (expected.
- Signal strength of 0.84 $^{+0.64}_{-0.61}$
  - Consistent with SM.

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t}+\geq 1c$ modeling	+0.09	−0.11
JVT, pileup modeling	+0.03	−0.05
Other background modeling	+0.08	−0.08
$t\bar{t}$ + light modeling	+0.06	−0.03
Luminosity	+0.03	−0.02
Light lepton (e,μ) id., isolation, trigger	+0.03	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t}+\geq 1b$ normalization	+0.09	−0.10
$t\bar{t}+\geq 1c$ normalization	+0.02	−0.03
Intrinsic statistical uncertainty	+0.21	−0.20
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

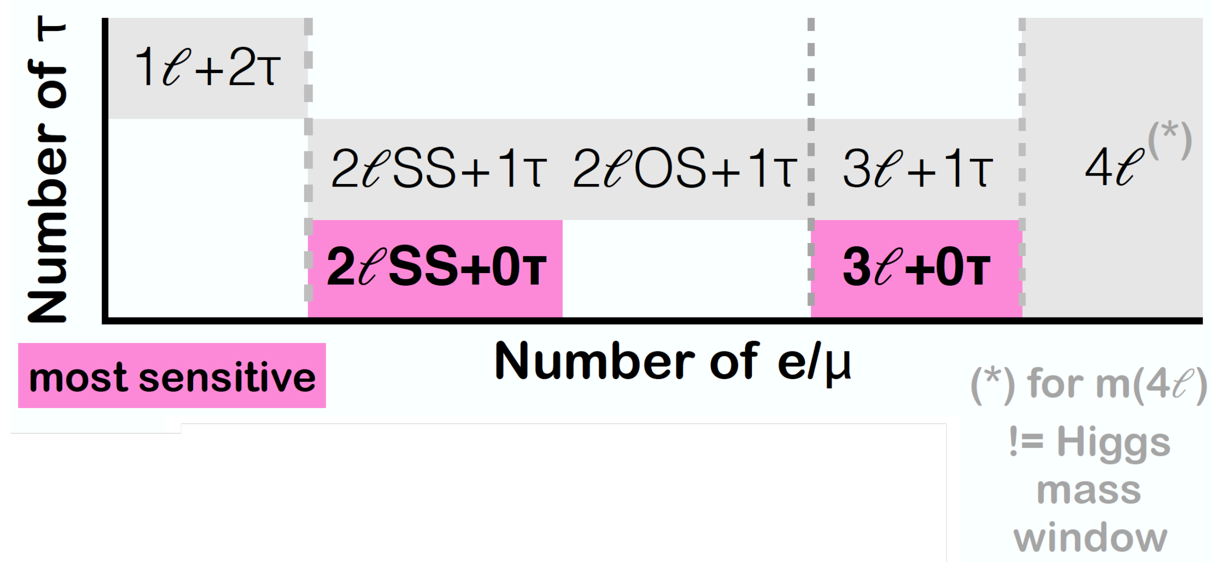


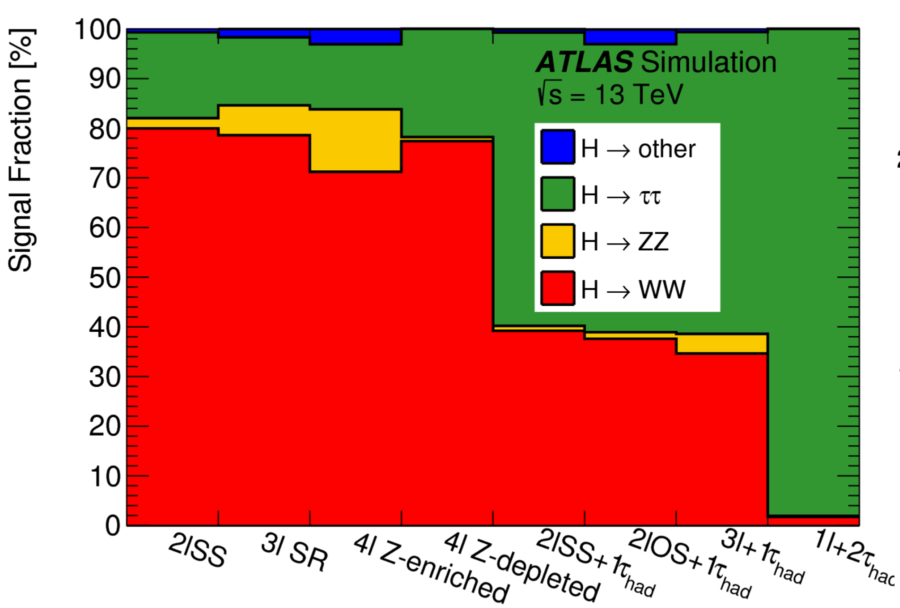


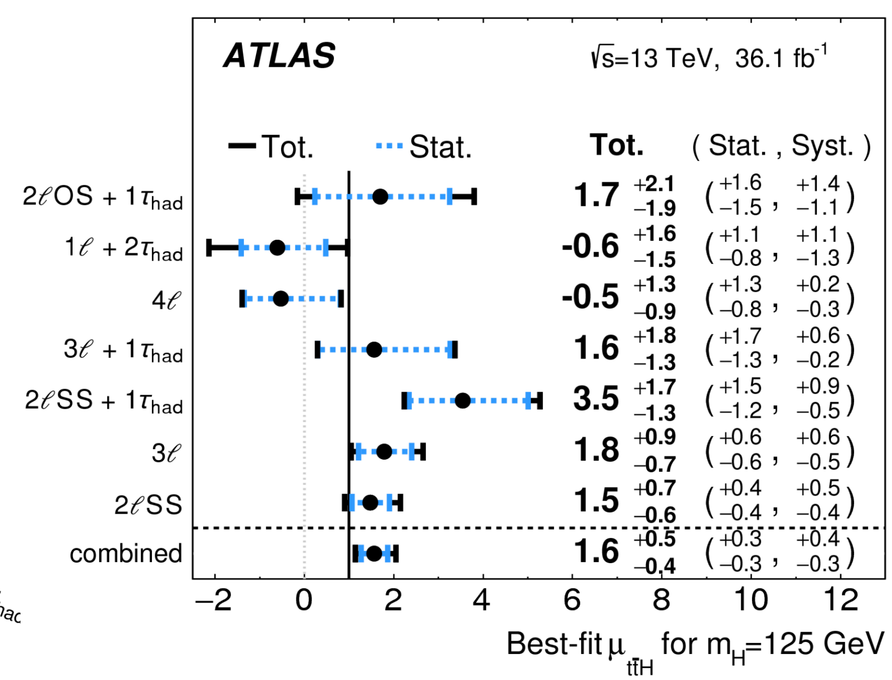
ANALYSIS STRATEGY

- Looking for H→WW/ZZ/ττ with multiple leptons in the final state.

- Signal is extracted by fitting or cutting on BDTs to separate signal from the major backgrounds (except 3ℓ+1τ).





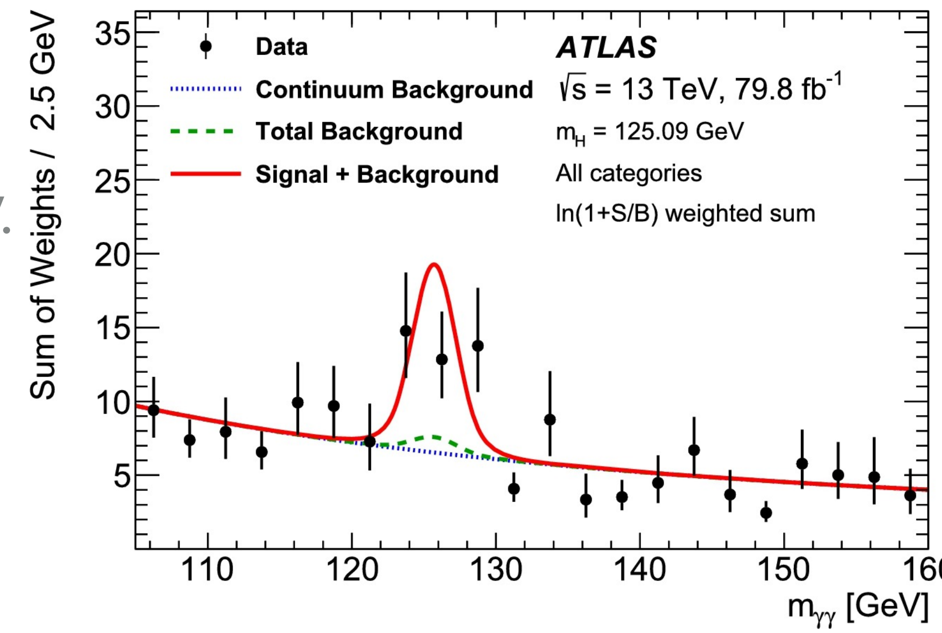


Channel	Significance	
	Observed	Expected
$2\ell OS+1\tau_{had}$	0.9σ	0.5σ
$1\ell+2\tau_{had}$	-	0.6σ
4ℓ (*)	-	0.8σ
$3\ell+1\tau_{had}$	1.3σ	0.9σ
$2\ell SS+1\tau_{had}$	3.4σ	1.1σ
3ℓ	2.4σ	1.5σ
$2\ell SS$	2.7σ	1.9σ
Combined	4.1σ	2.8σ

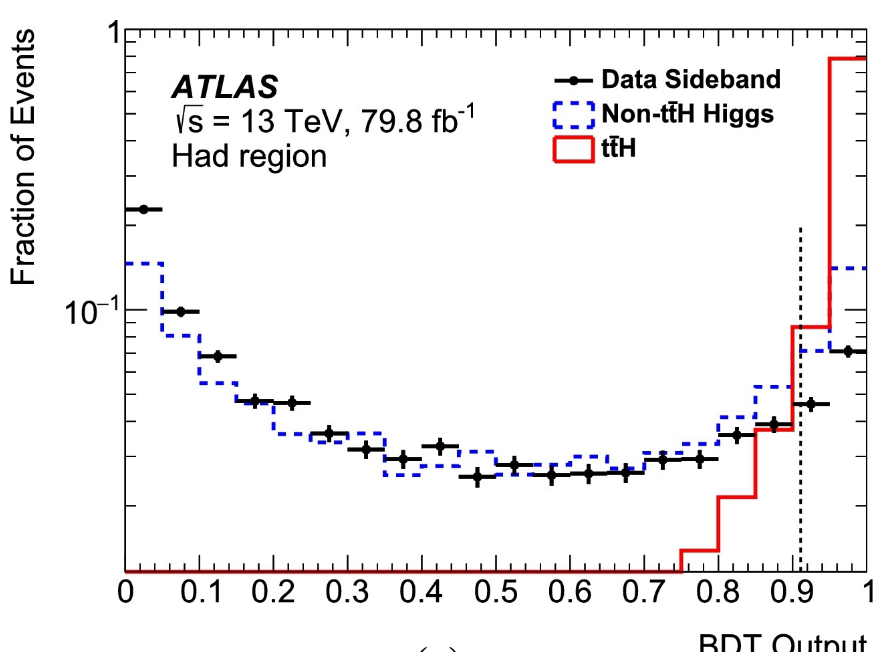
- tt̄Z and tt̄W normalisation free-floating

ANALYSIS STRATEGY

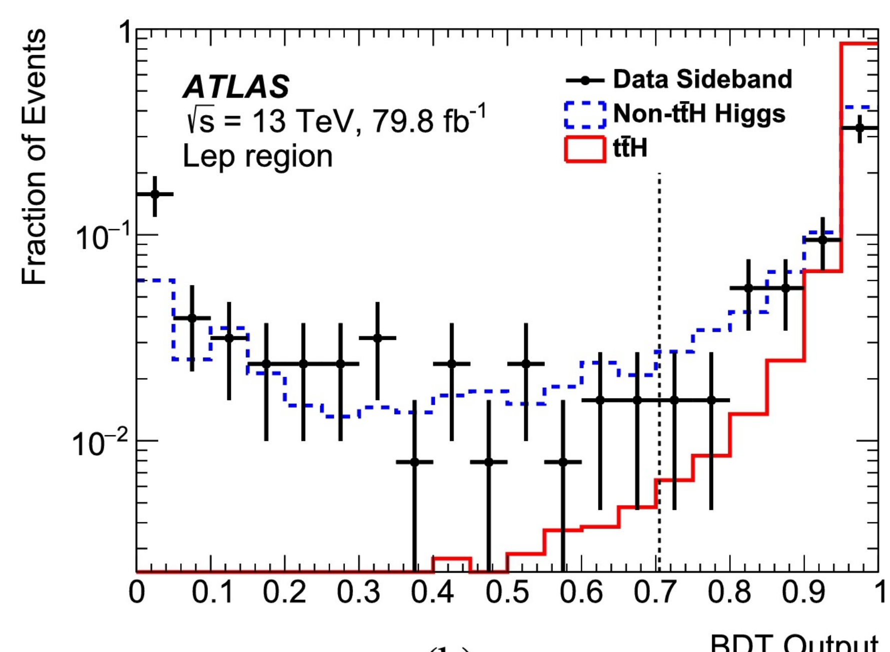
- Using 79.8 ± 1.6 fb^{-1} at 13 TeV.
- Two isolated photon candidates with transverse momenta $p_T > 35$ GeV and 25 GeV are selected and an invariant mass of 105-160 GeV.
- Two dedicated BDTs are trained to discriminate the tt̄H signal from the main background processes:
  - non-resonant diphoton production processes, including tt̄ production together with a photon pair
- Can still benefit from more data with 2018.



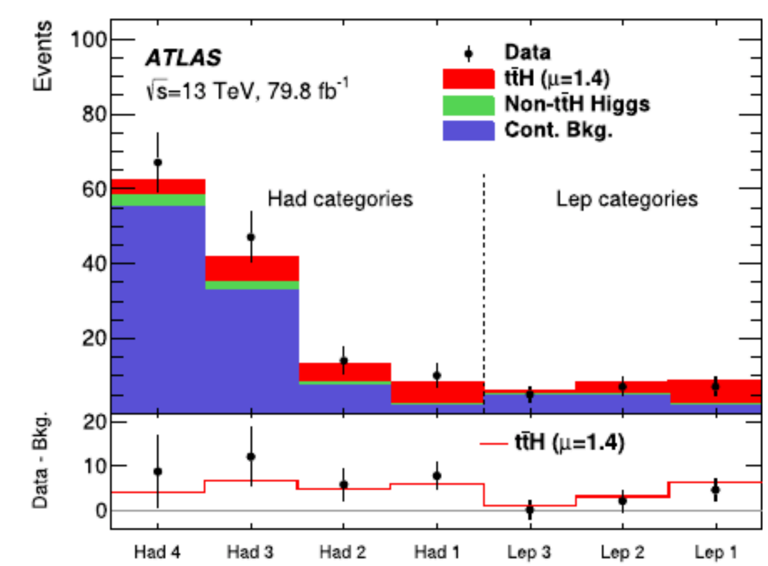
- Fit in the diboson mass



(a)

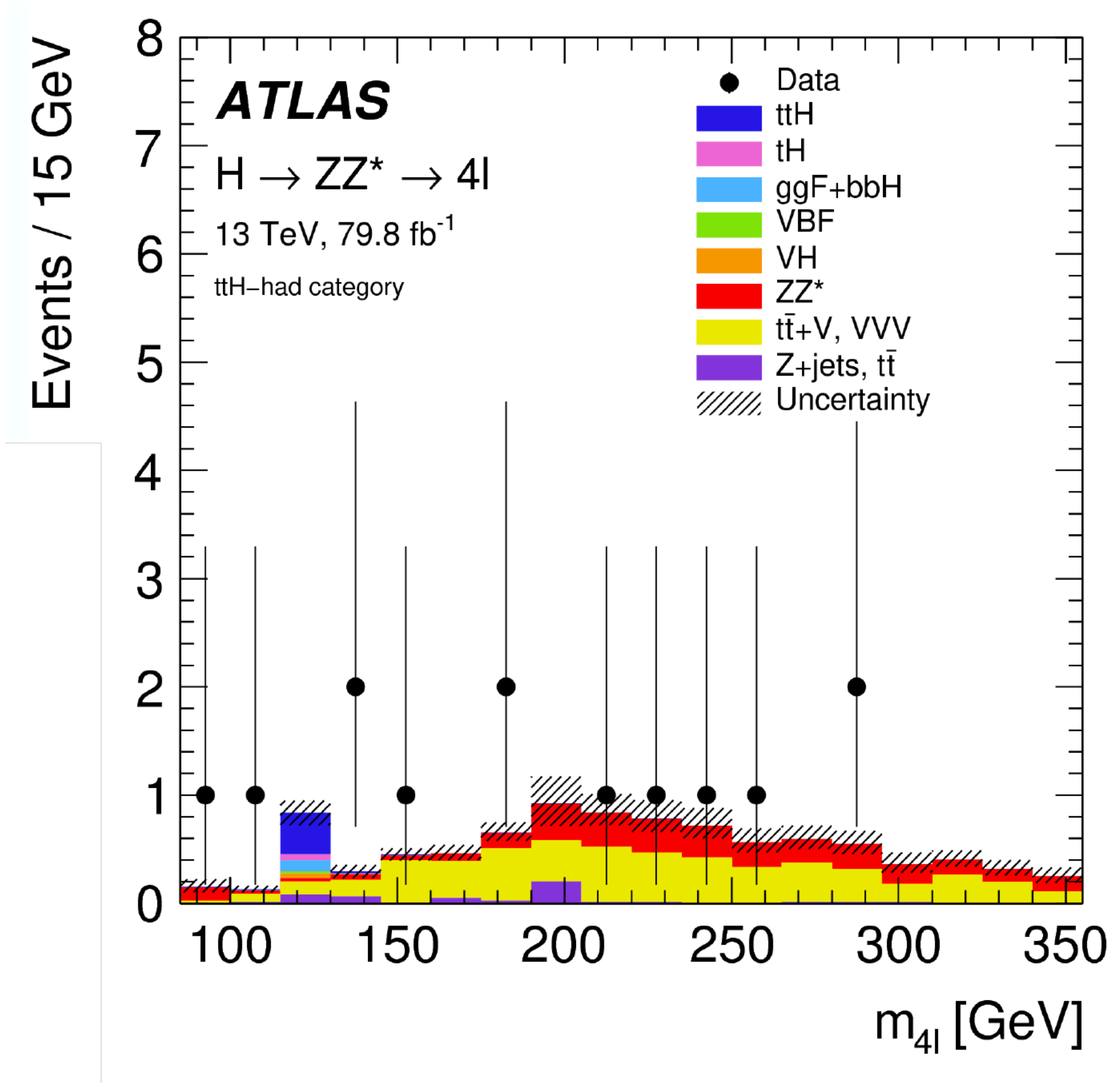


(b)



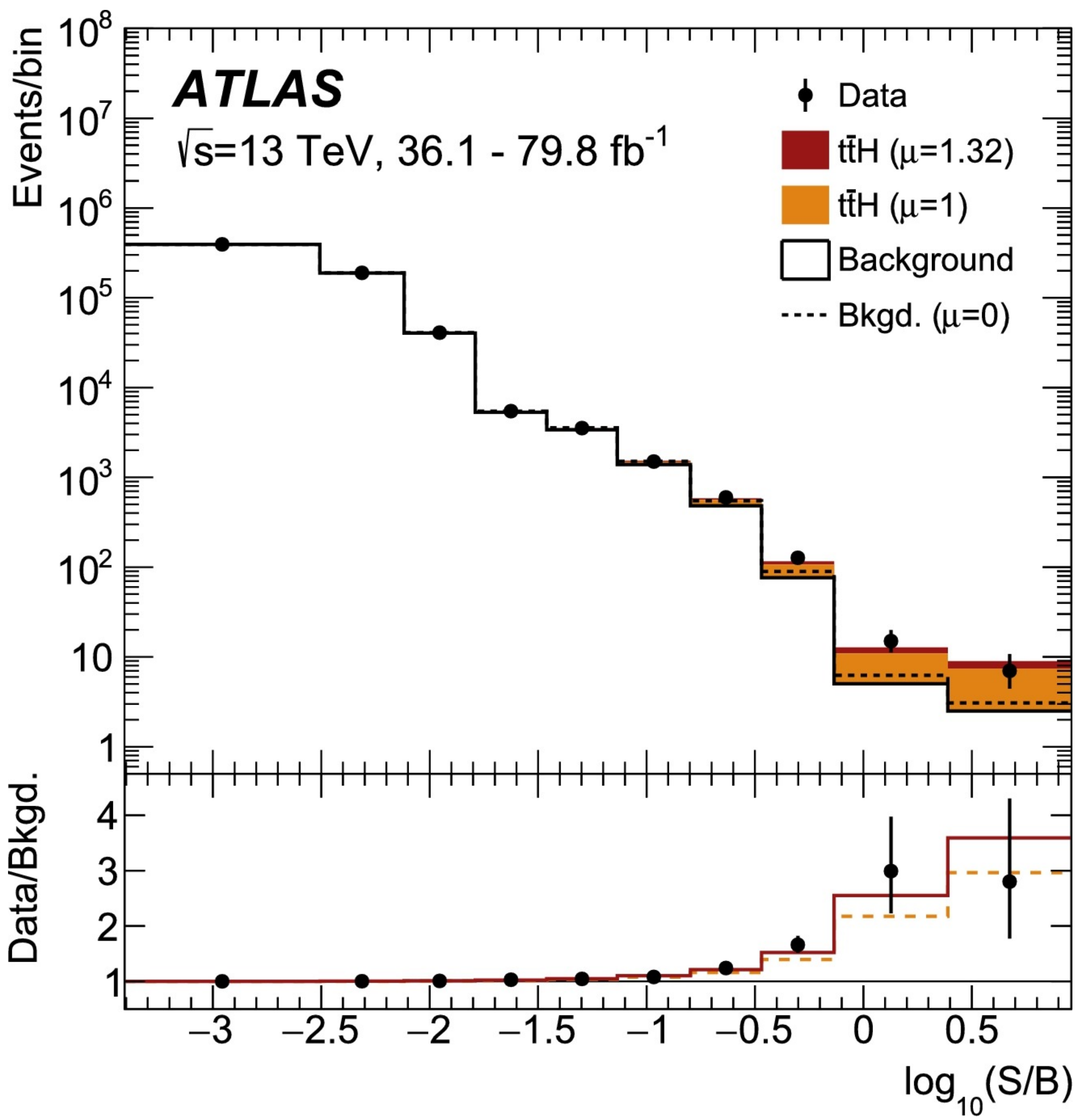
- Gives seven categories

ANALYSIS STRATEGY



- Using the same dataset as in the γγ analysis
- Requires events with at least four isolated leptons
  - (4e, 4μ, or 2e and 2μ) corresponding to two SF-OS pairs.
  - Had: 0 additional ℓ + ≥3 jets
  - Lep: 1 additional ℓ + ≥1 jets
  - ≥1 b-tagged jet
- Higgs boson candidates with $115 < m(4\ell) < 130$ GeV
- **No events observed**
  - Upper limits on $t\bar{t}H$

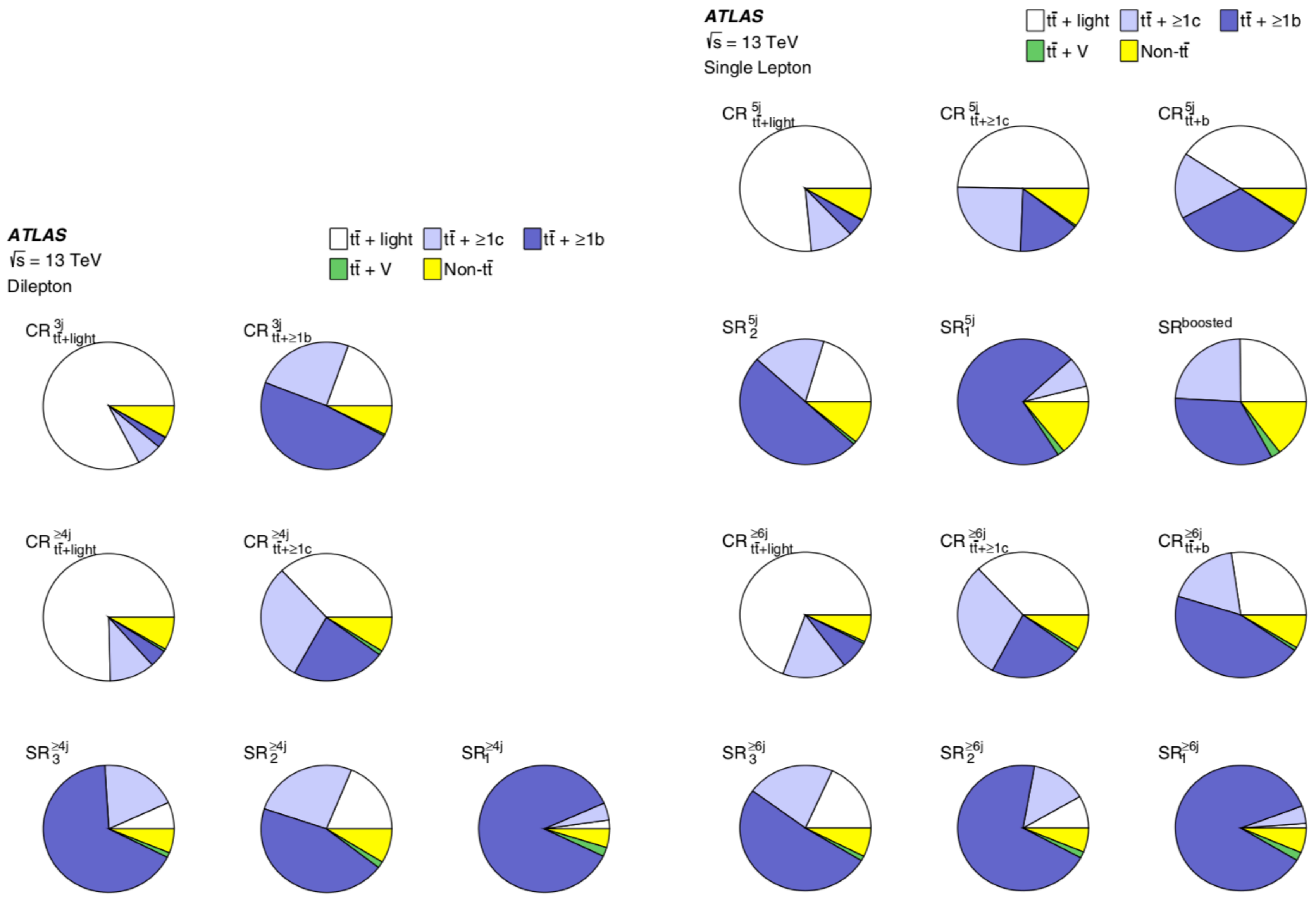
RESULTS



Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-leptons	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4

- All other Higgs boson production processes (including tH), are considered as background.

$t\bar{t}H(bb)$



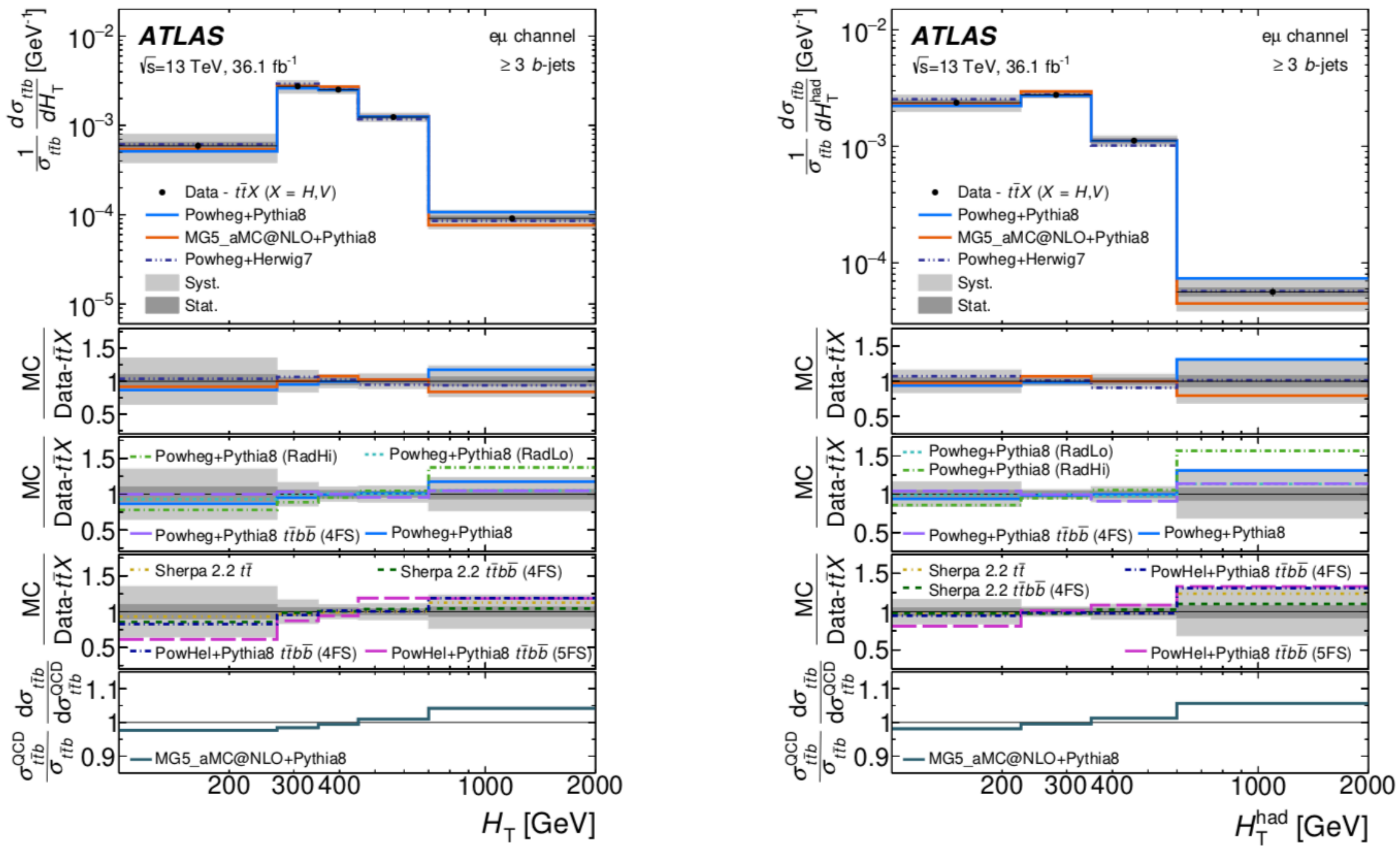
(a) (b)

FIG. 5. Fractional contributions of the various backgrounds to the total background prediction in each analysis category (a) in the dilepton channel and (b) in the single-lepton channel. The predictions for the various background contributions are obtained through the simulation and the data-driven estimates described in Sec. IV. The $t\bar{t}$ background is divided as described in Sec. IV. The predicted event yields in each of the analysis categories, broken down into the different signal and background contributions, are reported in Appendix A.

tt+HF

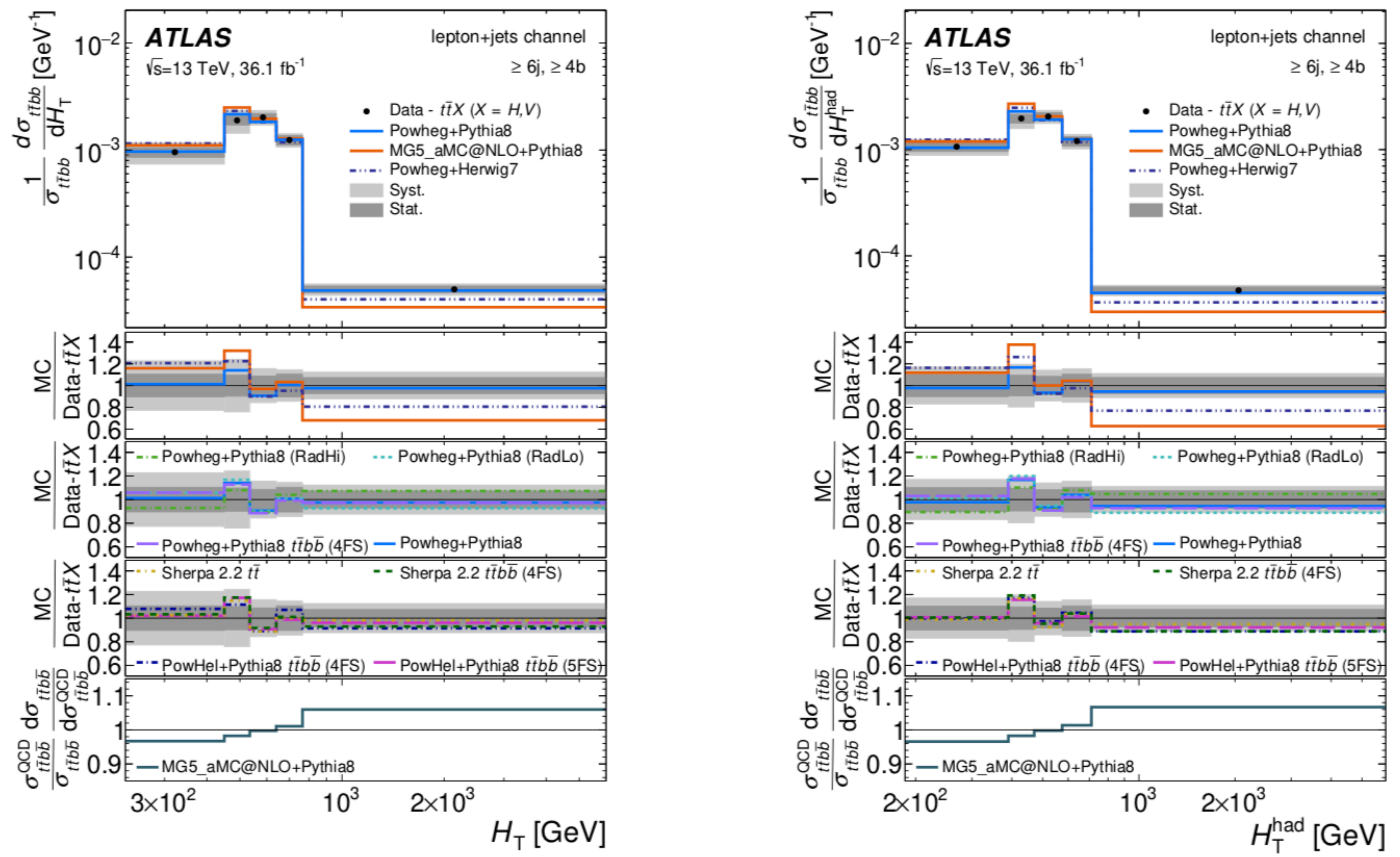
Generator	$m_{bb}^{\Delta\min}$ χ^2 / NDF	p-value	$p_{\mathrm{T},bb}^{\Delta\min}$ χ^2 / NDF	p-value	$\Delta R_{bb}^{\Delta\min}$ χ^2 / NDF	p-value
$e\mu$ channel, ≥ 3 b-jets						
Powheg+Pythia 8	1.37 / 4	0.85	0.42 / 4	0.98	0.78 / 3	0.86
MadGraph5_aMC@NLO+Pythia 8	3.67 / 4	0.45	2.50 / 4	0.65	1.22 / 3	0.75
Sherpa 2.2 $t\bar{t}$	0.17 / 4	1.0	0.06 / 4	1.0	0.99 / 3	0.80
Sherpa 2.2 $t\bar{t}b\bar{b}$ (4FS)	1.36 / 4	0.85	0.52 / 4	0.97	0.21 / 3	0.98
PowHel+Pythia 8 $t\bar{t}b\bar{b}$ (5FS)	0.18 / 4	1.0	12.7 / 4	0.01	27.9 / 3	< 0.01
PowHel+Pythia 8 $t\bar{t}b\bar{b}$ (4FS)	4.29 / 4	0.37	2.36 / 4	0.67	0.81 / 3	0.85
Powheg+Herwig 7	0.87 / 4	0.93	0.06 / 4	1.0	0.95 / 3	0.81
Powheg+Pythia 8 $t\bar{t}b\bar{b}$ (4FS)	1.12 / 4	0.89	1.00 / 4	0.91	0.30 / 3	0.96
Powheg+Pythia 8 (RadHi)	1.94 / 4	0.75	1.31 / 4	0.86	0.51 / 3	0.92
Powheg+Pythia 8 (RadLo)	0.99 / 4	0.91	0.28 / 4	0.99	0.86 / 3	0.84
lepton+jets channel, ≥ 6 jets, ≥ 4 b-jets						
Powheg+Pythia 8	0.86 / 4	0.93	0.99 / 4	0.91	3.22 / 5	0.67
MadGraph5_aMC@NLO+Pythia 8	1.01 / 4	0.91	4.33 / 4	0.36	3.19 / 5	0.67
Sherpa 2.2 $t\bar{t}$	0.66 / 4	0.96	1.21 / 4	0.88	4.98 / 5	0.42
Sherpa 2.2 $t\bar{t}b\bar{b}$ (4FS)	1.44 / 4	0.84	0.89 / 4	0.93	4.07 / 5	0.54
PowHel+Pythia 8 $t\bar{t}b\bar{b}$ (5FS)	1.08 / 4	0.90	1.61 / 4	0.81	3.14 / 5	0.68
PowHel+Pythia 8 $t\bar{t}b\bar{b}$ (4FS)	1.93 / 4	0.75	0.30 / 4	1.0	5.43 / 5	0.37
Powheg+Herwig 7	1.32 / 4	0.86	1.47 / 4	0.83	4.53 / 5	0.48
Powheg+Pythia 8 $t\bar{t}b\bar{b}$ (4FS)	1.05 / 4	0.90	0.82 / 4	0.94	3.87 / 5	0.57
Powheg+Pythia 8 (RadHi)	1.51 / 4	0.83	0.95 / 4	0.92	2.98 / 5	0.70
Powheg+Pythia 8 (RadLo)	0.77 / 4	0.94	1.51 / 4	0.83	3.25 / 5	0.66

Table 11. Values of χ^2 per degree of freedom and p-values between the unfolded normalised cross-sections and the various predictions for the mass, p_{T} and ΔR of the closest two b-jets in the $e\mu$ and lepton + jets channels. The number of degrees of freedom is equal to the number of bins in the measured distribution minus one.



(a) (b)

Figure 9. Relative differential cross-sections as a function of (a) H_{T}, (b) $H_{\mathrm{T}}^{\mathrm{had}}$ in events with at least three b-jets in the $e\mu$ channel compared with various MC generators. The $t\bar{t}H$ and $t\bar{t}V$ contributions are subtracted from data. Four ratio panels are shown, the first three of which show the ratios of various predictions to data. The last panel shows the ratio of predictions of normalised differential cross-sections from MadGraph5_aMC@NLO+Pythia 8 including (numerator) and not including (denominator) the contributions from $t\bar{t}V$ and $t\bar{t}H$ production. Uncertainty bands represent the statistical and total systematic uncertainties as described in section 8. Events with H_{T} ($H_{\mathrm{T}}^{\mathrm{had}}$) values outside the axis range are not included in the plot.



(a) (b)

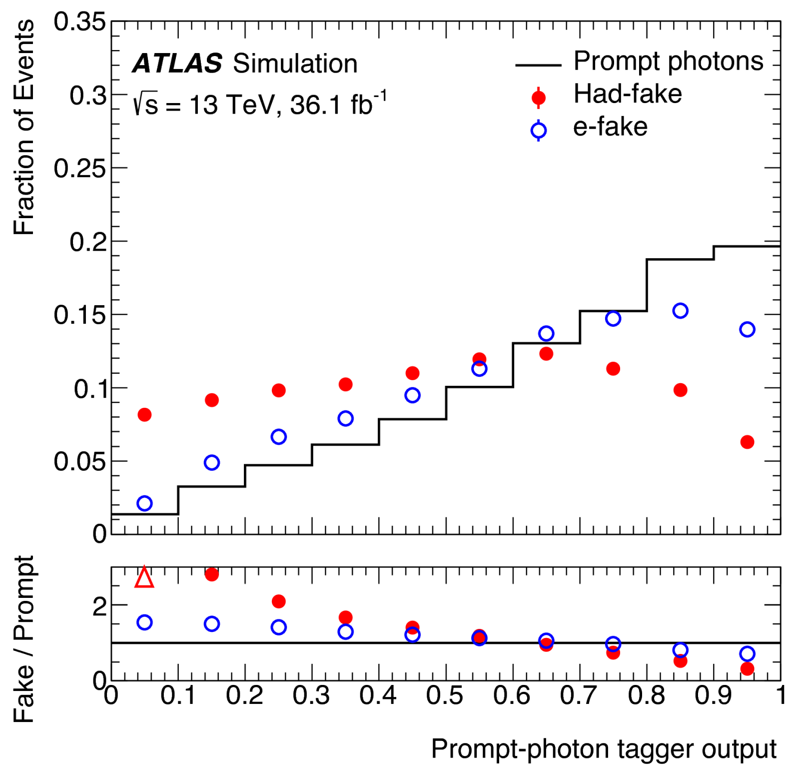
Figure 10. Relative differential cross-sections as a function of (a) H_{T}, (b) $H_{\mathrm{T}}^{\mathrm{had}}$ in events with at least four b-jets in the lepton+jets channel compared with various MC generators. The $t\bar{t}H$ and $t\bar{t}V$ contributions are subtracted from data. Four ratio panels are shown, the first three of which show the ratios of various predictions to data. The last panel shows the ratio of predictions of normalised differential cross-sections from MadGraph5_aMC@NLO+Pythia 8 including (numerator) and not including (denominator) the contributions from $t\bar{t}V$ and $t\bar{t}H$ production. Uncertainty bands represent the statistical and total systematic uncertainties as described in section 8. Events with H_{T} ($H_{\mathrm{T}}^{\mathrm{had}}$) values outside the axis range are not included in the plot.

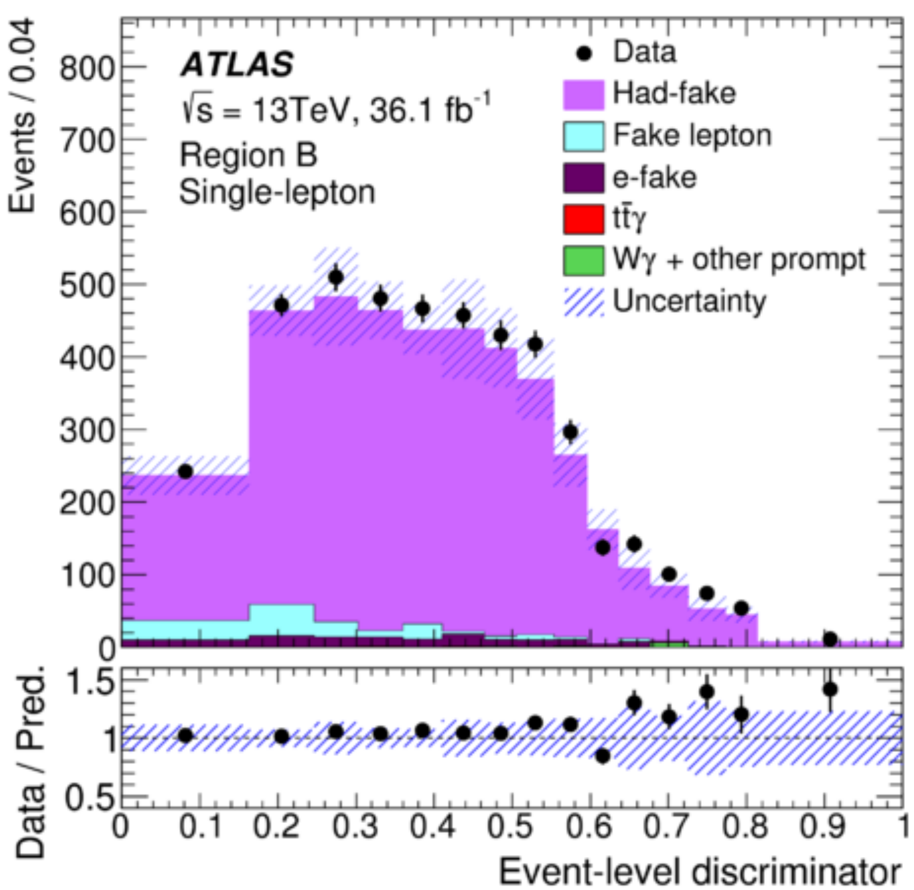
ttγ

EVENT SELECTION

e+jets	μ+jets	ee	$\mu\mu$	$e\mu$
Primary vertex				
1 e	1 μ	2 e, OS	2 μ, OS	1 e + 1 μ, OS
Trigger match				
$\geq$ 4 jets		$\geq$ 2 jets		
$\geq$ 1 b-jet				
1 γ				
$\lvert m(e,\gamma) - m(Z)\rvert > 5$ GeV	-			
-		$m(\ell,\ell) \notin [85,95]$ GeV		-
-		$m(\ell,\ell,\gamma) \notin [85,95]$ GeV		-
-		$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV		-
-		$m(\ell,\ell) > 15$ GeV		
$\Delta R(\gamma,\ell) > 1.0$				

PPT AND ELD





- To discriminate the $t\bar{t}\gamma$ S & B use a neural-network algorithm
  - event-level discriminator (ELD): is trained separately for the 1L & 2L channels
- Given the significant contribution of hadronic-fake photons in 1L use a dedicated NN
  - prompt-photon tagger (PPT), is trained to discriminate between prompt photons and hadronic-fake photons.
  - shower-shape variables as inputs: R_{had}, R_h, R_f, w_2, w_1, f_{side}
  - used as an input to the ELD in the 1L channel.

FIDUCIAL UNCERTAINTIES

Table 5: Summary of the effects of the groups of systematic uncertainties on the fiducial cross-section in the single-lepton and dilepton channels. Due to rounding effects and small correlations between the different sources of uncertainty, the total systematic uncertainty is different from the sum in quadrature of the individual sources.

Source	Single lepton (%)	Dilepton (%)
Signal modelling	± 1.6	± 2.9
Background modelling	± 4.8	± 2.9
Photon	± 1.1	± 1.1
Prompt-photon tagger	± 4.0	-
Leptons	± 0.3	± 1.3
Jets	± 5.4	± 2.0
b-tagging	± 0.9	± 0.4
Pile-up	± 2.0	± 2.3
Luminosity	± 2.3	± 2.3
MC sample size	± 1.9	± 1.7
Total systematic uncertainty	± 7.9	± 5.8
Data sample size	± 1.5	± 3.8
Total uncertainty	± 8.1	± 7.0

ttV

$t\bar{t}V$ - $t\bar{t}Z$ 2L: OSSF

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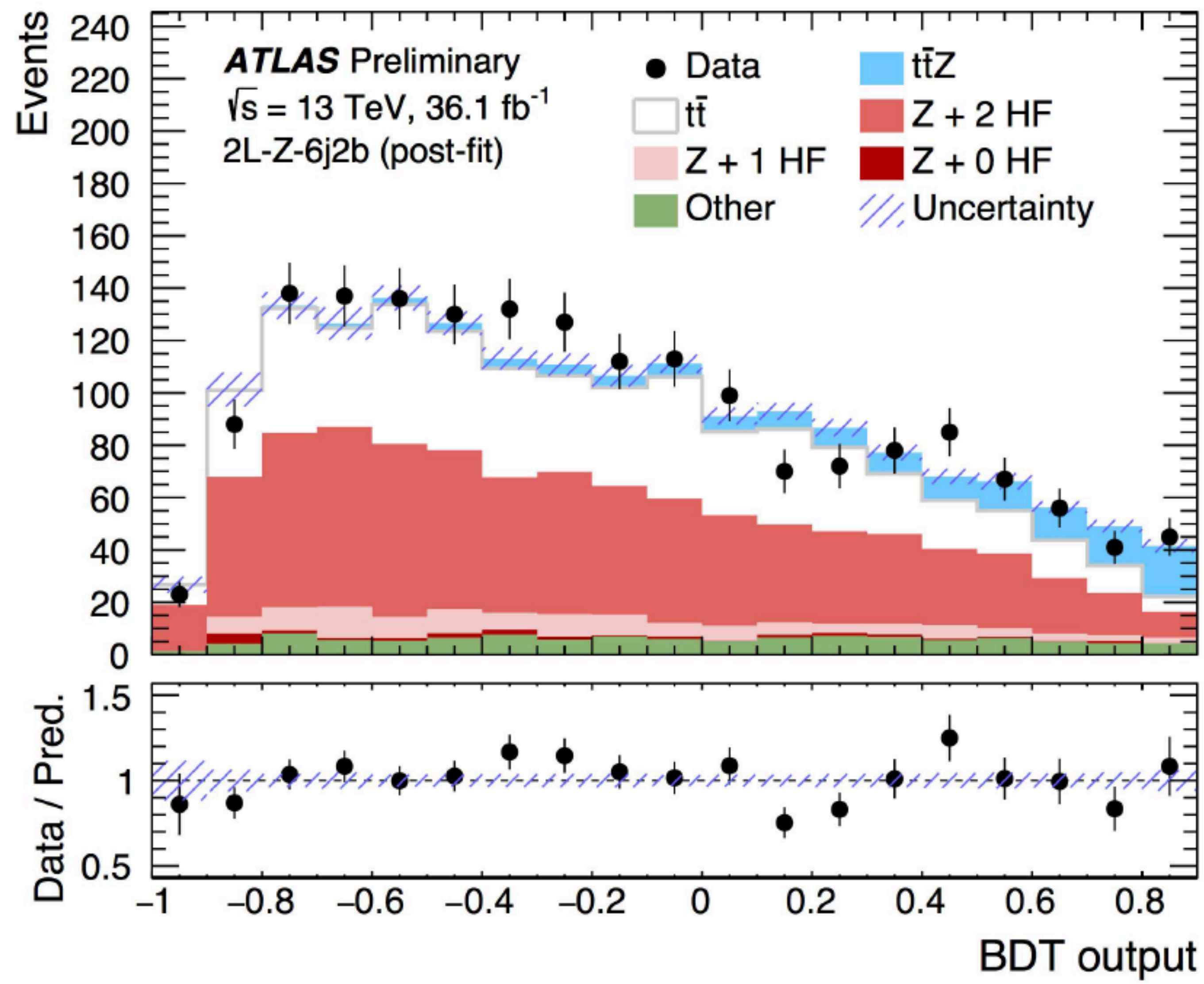
Selection:

- Exactly two leptons with opposite sign and same flavour.
- $|M_{ll} - M_Z| < 10$ GeV
- N_j: ≥6, =5, ≥6
- N_b: =1, ≥2, ≥2 (respectively)

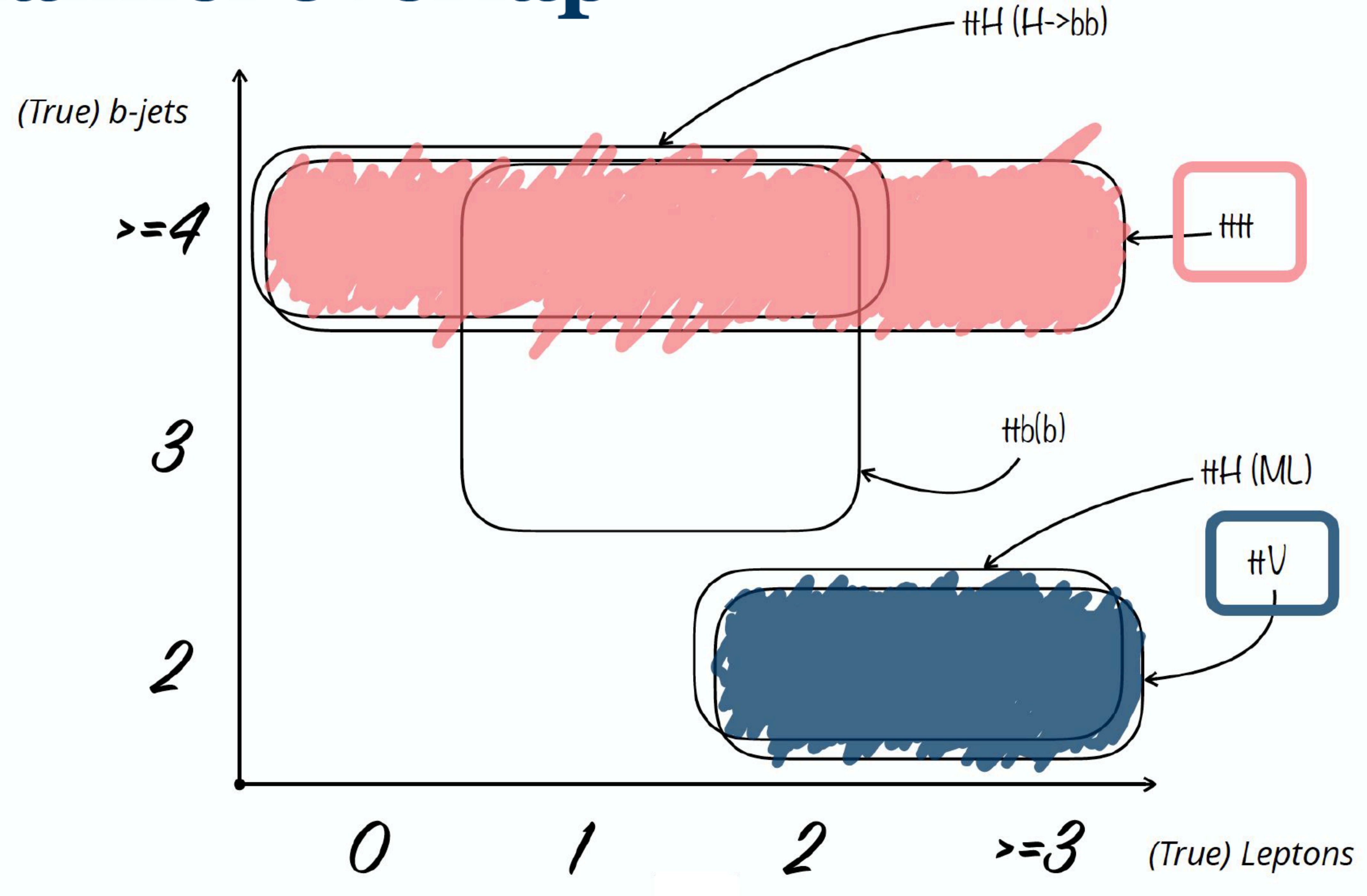
Backgrounds:

- Characterised by large backgrounds from Z+jets and $t\bar{t}$.
- Z+jets is constrained using low BDT score events.
    - Normalisation factors of Z+1HF and Z+2HF are determined in the fit to data.
- Data driven method used for tt background.

Boosted Decision Trees (BDTs) are used to separate signal from background in each region separately.



Channel overlap



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ttV

13 TeV 3.2 fb^{-1} uncertainties:

Table 5 List of dominant and total uncertainties in the measured cross sections of the $t\bar{t}Z$ and $t\bar{t}W$ processes from the fit. All uncertainties are symmetrised

Uncertainty	$\sigma_{t\bar{t}Z}$ (%)	$\sigma_{t\bar{t}W}$ (%)
Luminosity	2.6	3.1
Reconstructed objects	8.3	9.3
Backgrounds from simulation	5.3	3.1
Fake leptons and charge misID	3.0	19
Signal modelling	2.3	4.2
Total systematic	11	22
Statistical	31	48
Total	32	53

$t\bar{t}V$ - $t\bar{t}Z$ 3L

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Four signal regions, with N_j and N_b depending on signal region.

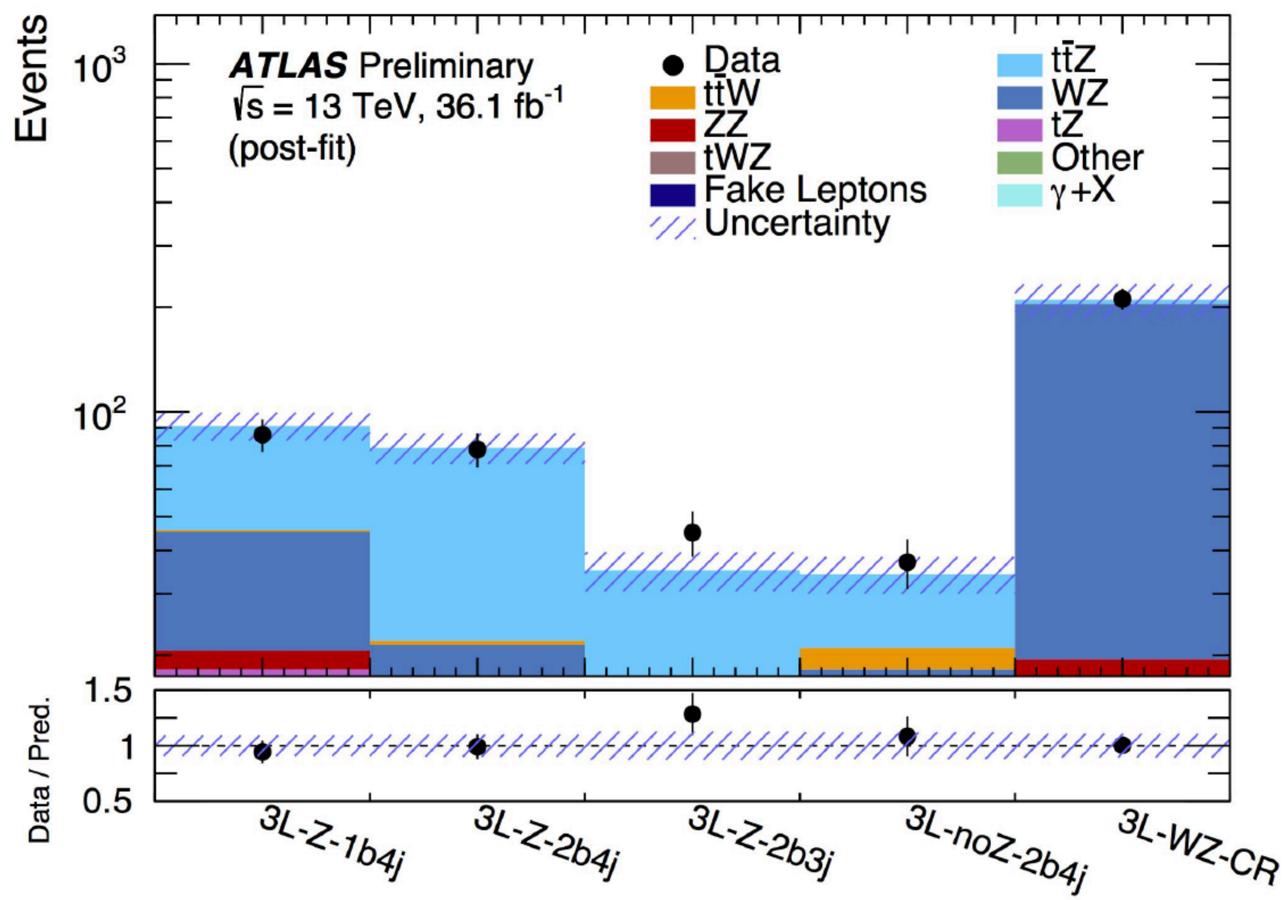
- 3L-noZ-2b4j: targets $t\bar{t}Z$ with an offshell Z* or γ* and is orthogonal to the three leptons regions used for the $t\bar{t}W$ analysis.

Selection: 3 leptons with sum of charges ± 1

- N_j: ≥4, 3, ≥4, ≥4
  N_b: 1, ≥2, ≥2, ≥2 (respectively)
- $|M_{ll} - M_Z| < 10$ GeV, except noZ

Dominant backgrounds:

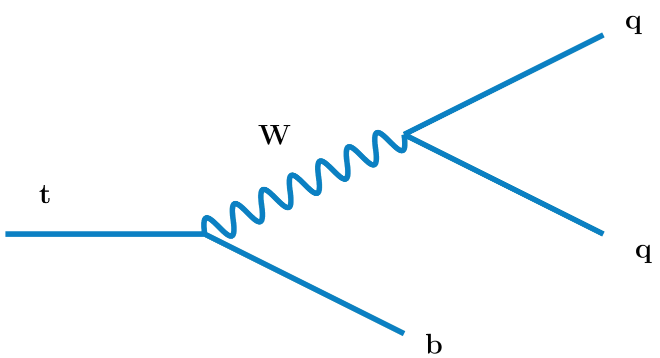
- diboson production, tZ and tWZ, and Z+jets production with fake lepton.

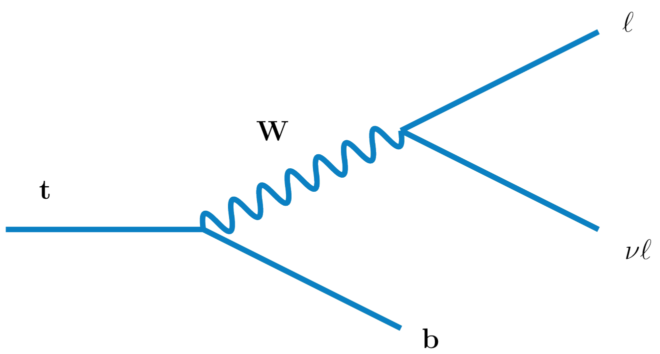


Good pre-fit agreement between observed values and expected

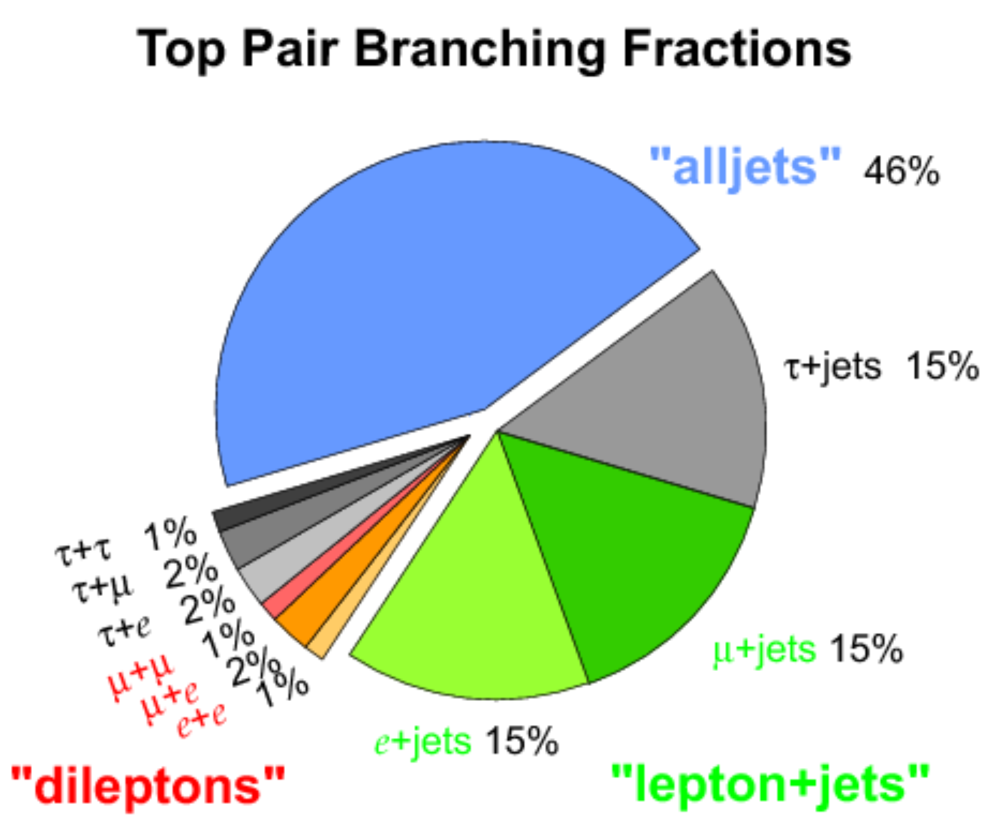
CR used for WZ background, free parameter in the fit.

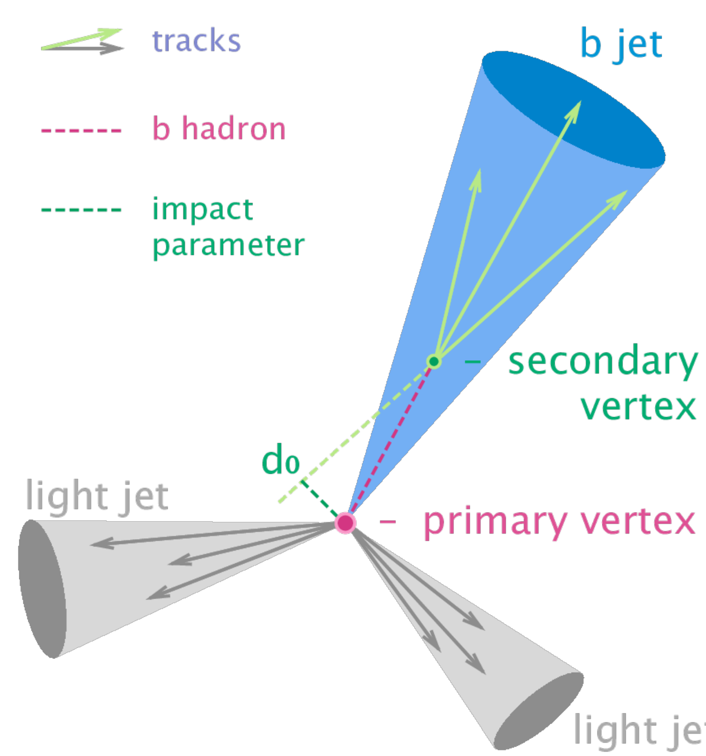
THE TOP QUARK FEATURES



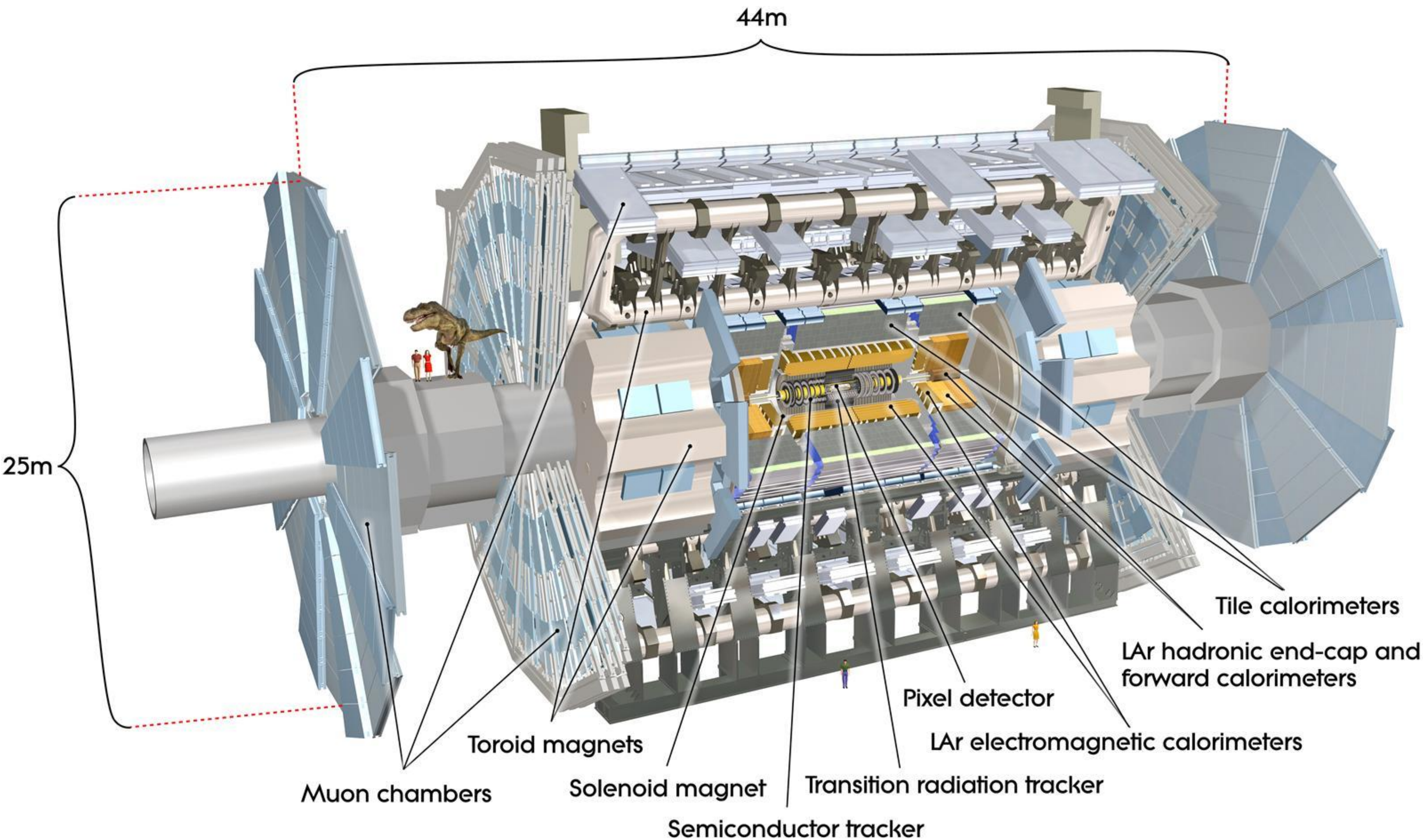


- Decays to a W-boson and a b-quark ~100% of the time.
- Channels defined by the decay products of the W-boson: leptonically or hadronically.
  - The long lifetime of the b-quark means b-tagging can be used for identification.



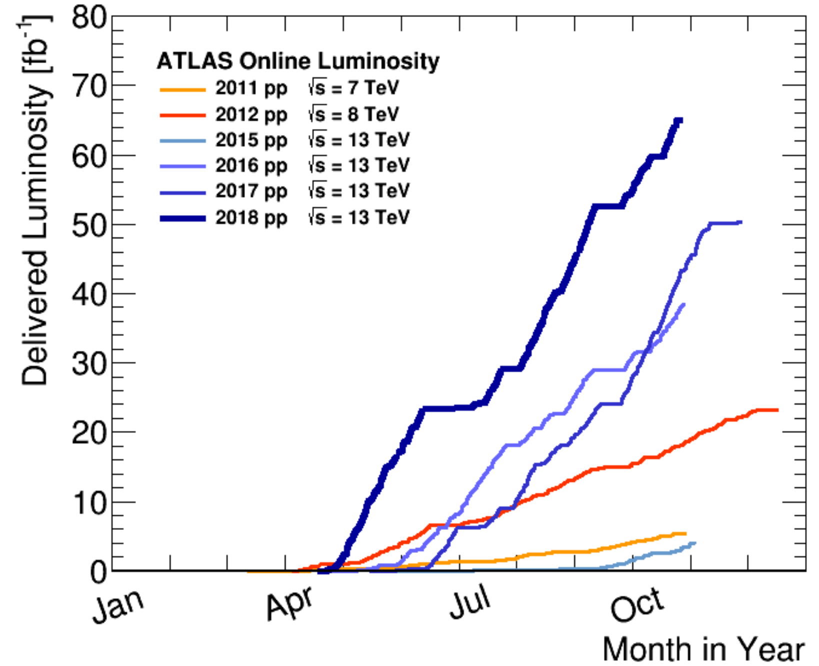


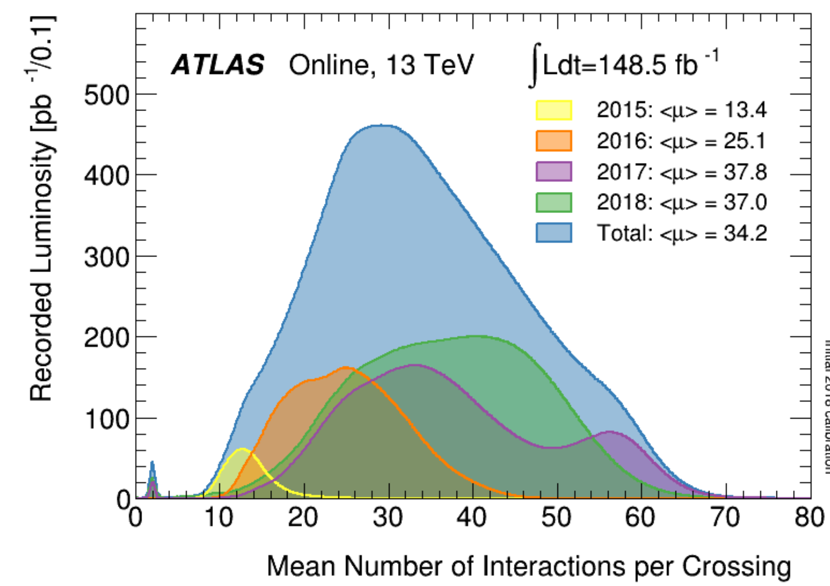
THE ATLAS DETECTOR

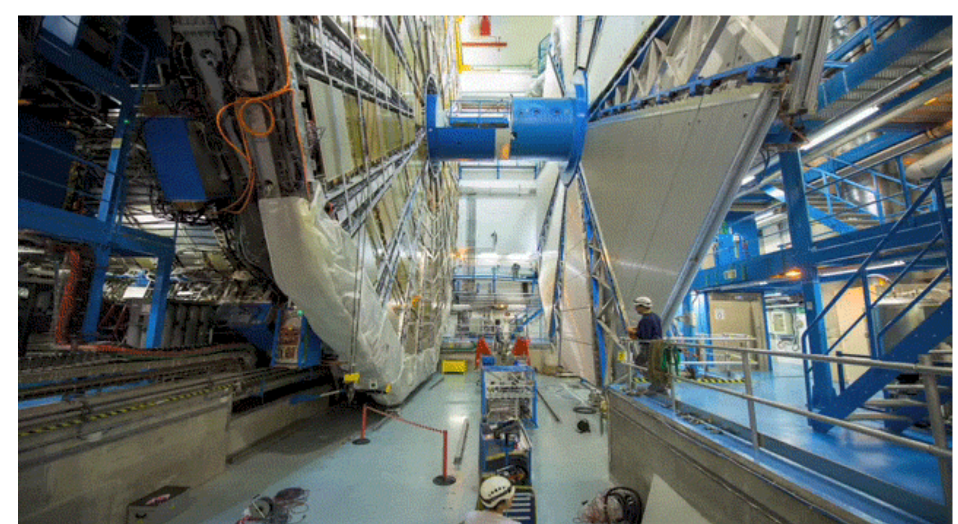


CURRENT STATUS

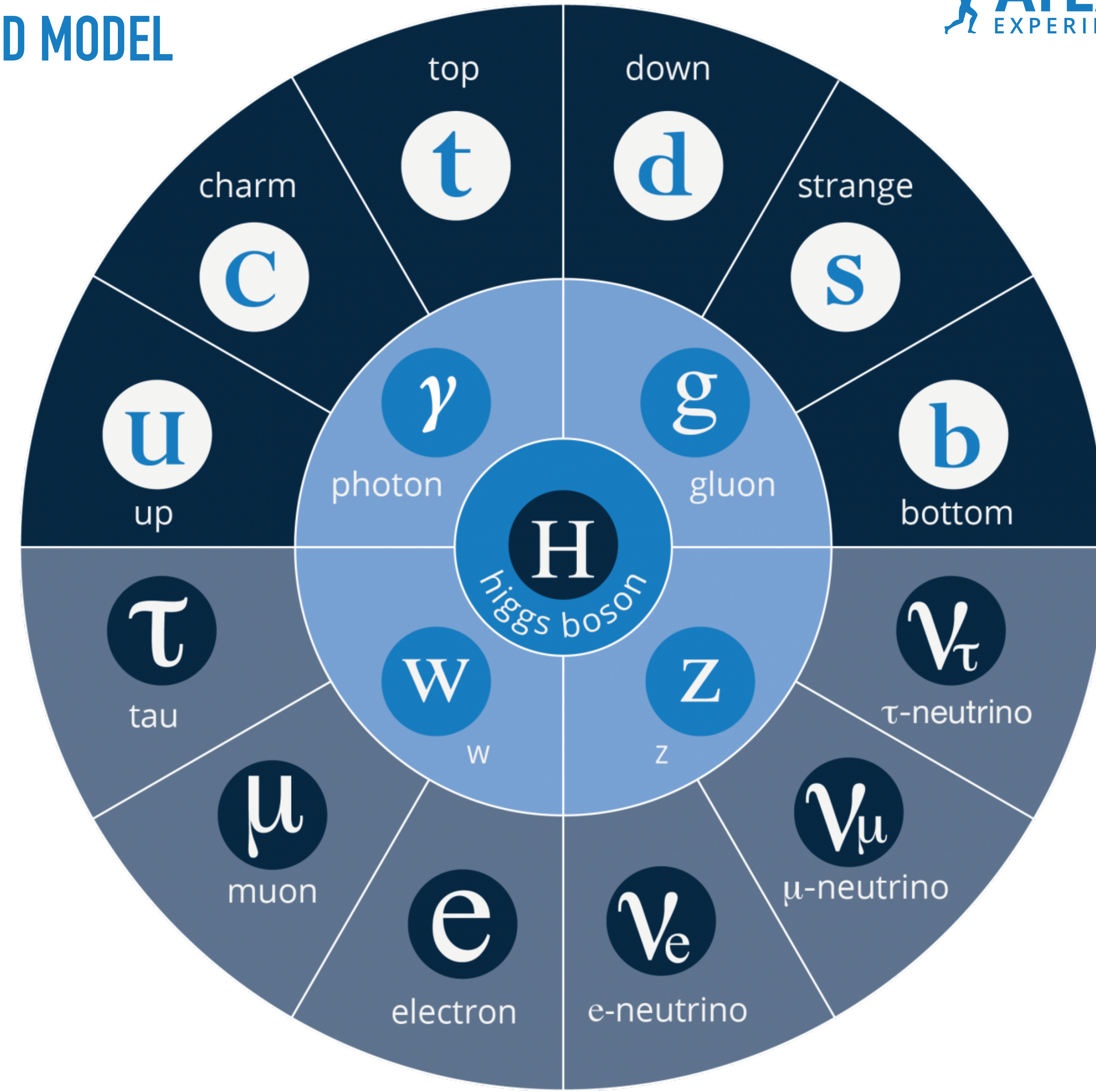
- The LHC Run 2 has *just* finished!
- For proton-proton collisions, we have ~140 fb^{-1} of data at 13 TeV to analyse.
  - Excellent data quality with ~90% efficiency.
- Now the shutdown period has begun and we will begin repairs and a series of upgrades.
- Work is also taking place to prepare the upgrade of the inner tracker, ITk, that will be installed in the next long shutdown ~2024.







THE STANDARD MODEL



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Constraints on BSM

- Interpretations of the inclusive cross-section measurement in terms of Effective Field Theory (EFT).
  - Set constraints on the five operators which modify the $t\bar{t}Z$ vertex: $O_{\phi Q}^{(3)}, O_{\phi Q}^{(1)}, O_{\phi t}, O_{tW}, O_{tB}$
  - First two enter the $t\bar{t}Z$ vertex as a linear combination
    - measurement is sensitive to the difference: $C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)}$
  - Only one operator is considered at a time.

Coefficient	Expected limits at 68% and 95 % CL	Observed limits at 68% and 95 % CL	Previous constraints at 95 % CL JHEP **05** (2016) 052
$(C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)})/\Lambda^2$	[-2.1, 1.9], [-4.6, 3.7]	[-1.0, 2.7], [-3.4, 4.3]	[-3.4, 7.5]
$C_{\phi t}/\Lambda^2$	[-3.8, 2.8], [-23, 5.0]	[-2.0, 3.6], [-27, 5.7]	[-2.0, 5.7]
C_{tB}/Λ^2	[-8.3, 8.6], [-12, 13]	[-11, 10], [-15, 15]	[-16, 43]
C_{tW}/Λ^2	[-2.8, 2.8], [-4.0, 4.1]	[-2.2, 2.5], [-3.6, 3.8]	[-0.15, 1.9]

$t\bar{t}V$ - $t\bar{t}Z$ 4L

More from Sebastian in the YSF!

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Signature:

- Defined according to the relative flavour of the two leptons of *Z*2:
  - different (DF) or same flavour (SF)
  - # of *b*-tagged jets: one or, at least two (1*b*, 2*b*).
- Four signal regions: 4l-DF-1b, 4l-DF-2b, 4l-SF-1b & 4l-SF-2b.

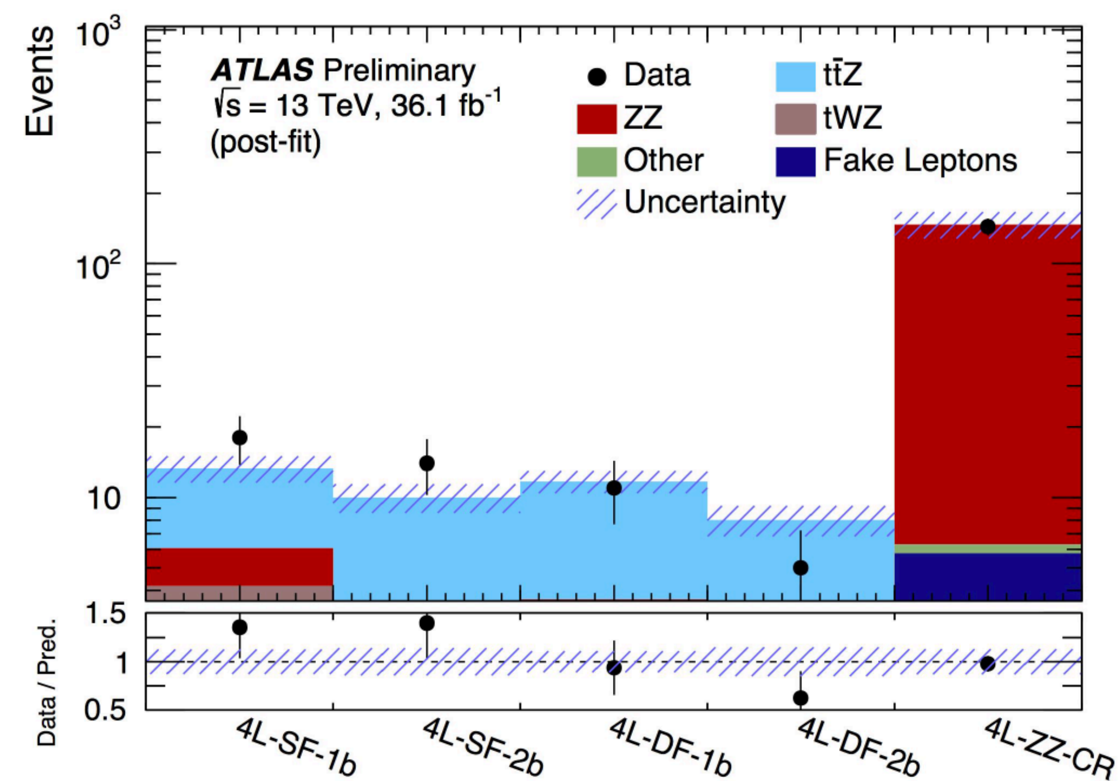
In SF regions:

E_T^{miss} requirements suppress ZZ background.

In 1-b-tag regions:

Requirements on p_{T34}, suppress fake leptons.

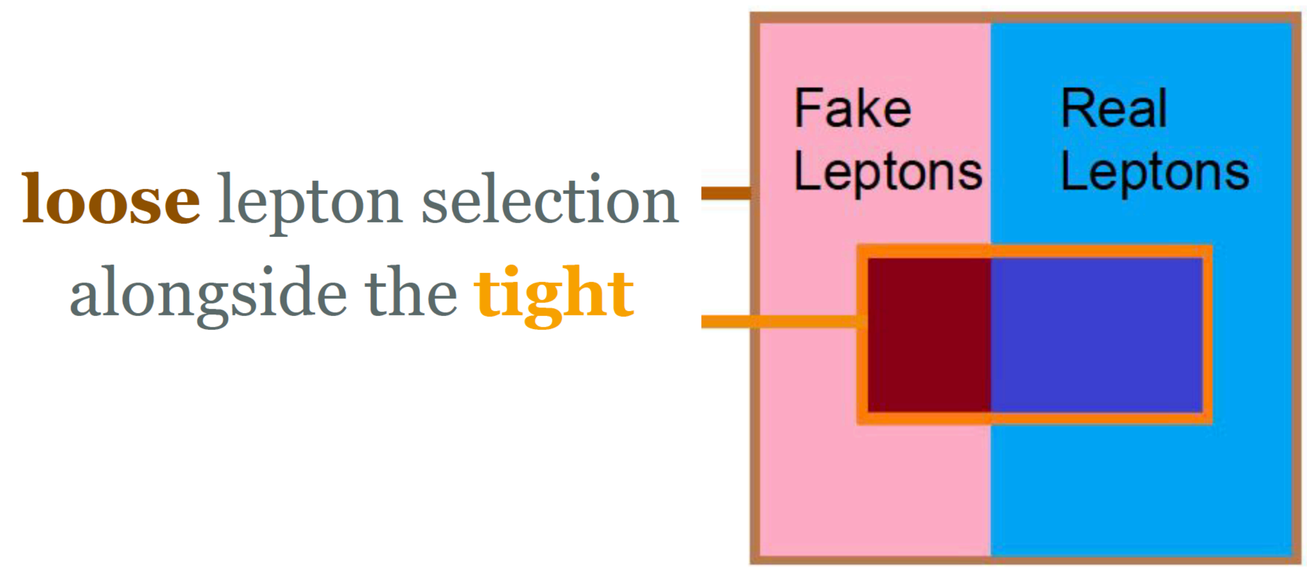
CR used to determine ZZ normalisation, free parameter in the fit.



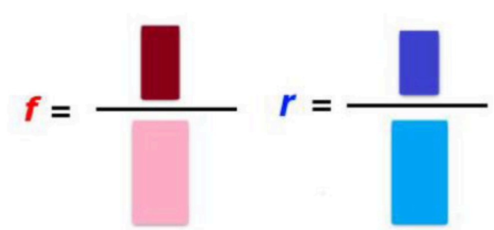
Good pre-fit agreement between observed values and expected

FAKE LEPTON BACKGROUNDS

- In the $t\bar{t}W$ analysis and the 3L $t\bar{t}Z$ channel, the fake lepton background is estimated by using the matrix method.
  - For the 4L region, the semi data-driven fake factor method is used:
    - Correction factors describing the potential data/MC discrepancy are extracted in a dedicated CR enriched with processes that contain >1 fake electron or muon.



Define **fake** and **real** efficiency as



$$N^{\text{loose}} = N^{\text{loose}}_{\text{real}} + N^{\text{loose}}_{\text{fake}}$$
$$N^{\text{tight}} = r \cdot N^{\text{loose}}_{\text{real}} + f \cdot N^{\text{loose}}_{\text{fake}}$$