Public page – HEPData

Inclusive and differential $t\bar{t}Z$ cross section measurements at 13 TeV with the ATLAS detector

RAMP Seminar, 28/06/2024

Baptiste Ravina on behalf of the analysis team

ATLAS EXPERIMENT

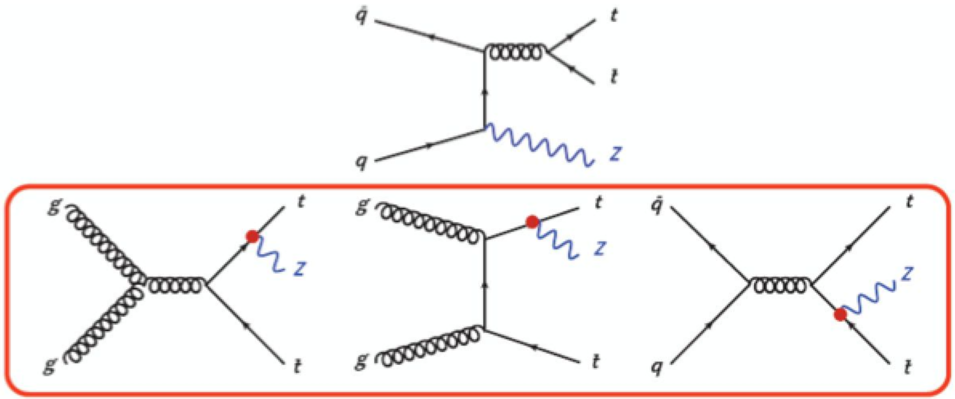
GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN IN PUBLICA COMMODA SEIT 1737

Anatomy of the $t\bar{t}Z$ process

Top pair production in association with a Z boson: rare process! (~800x smaller cross section than $t\bar{t}$)

→ Direct access to the top EW couplings (T_3 and Q)

Key background to many important analyses: $t\bar{t}H$ measurement, $t\bar{t}$+DM searches…



Each decay channel has its own challenges, but **benefit from inclusive approach!**

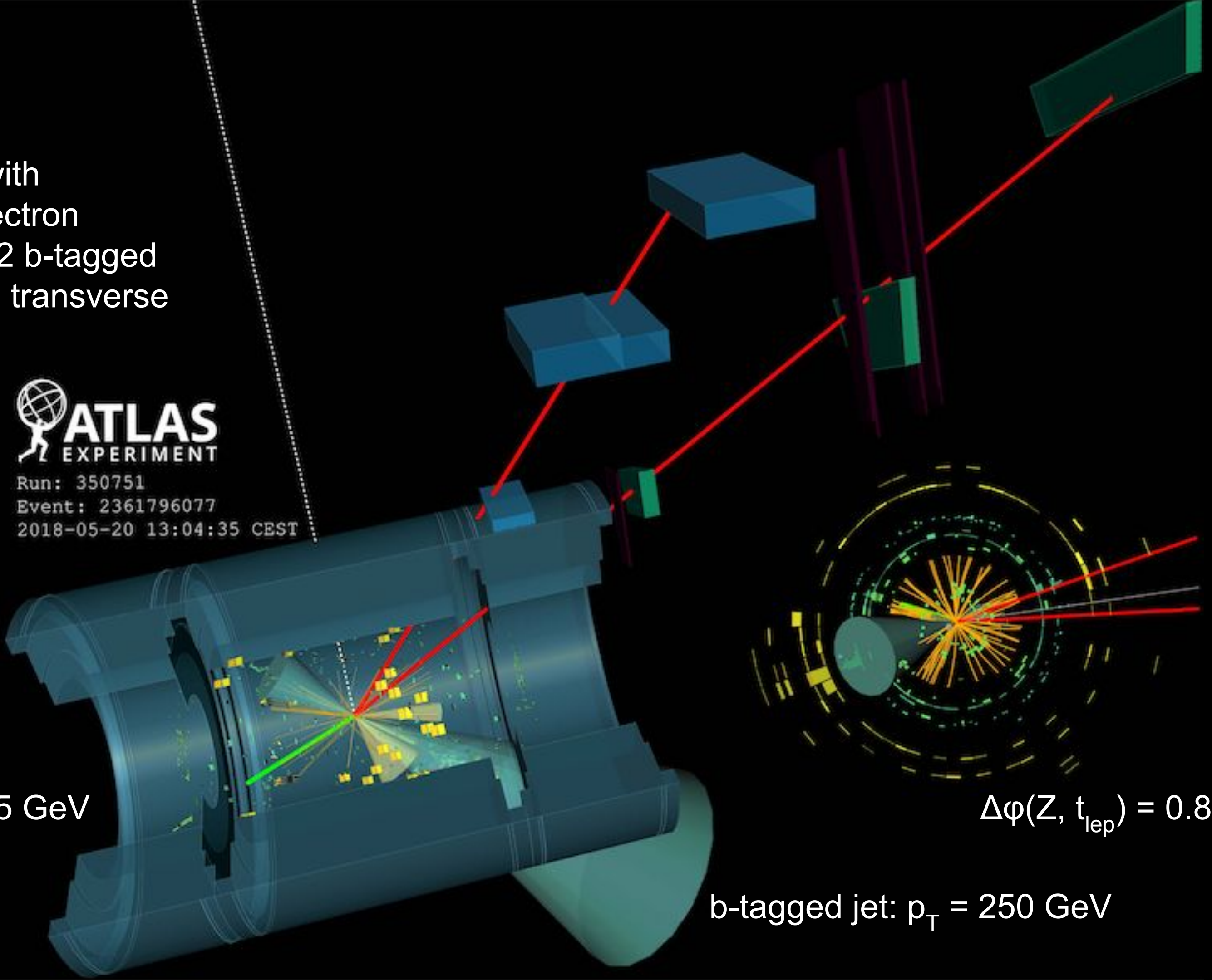
Want to measure the **inclusive production cross section**, but also **differentially** in a number of observables

- test state-of-the-art MC modelling
- recast in terms of BSM exclusions (SMEFT)
- spin correlations

Already measured by ATLAS with the full Run 2 dataset: *Eur. Phys. J. C 81 (2021) 737*

Candidate $t\bar{t}Z$ event with

- 2 muons + 1 electron
- 4 jets, of which 2 b-tagged
- 30 GeV missing transverse energy



$Z \to \mu\mu$
90.6 GeV

electron: p_T = 45 GeV

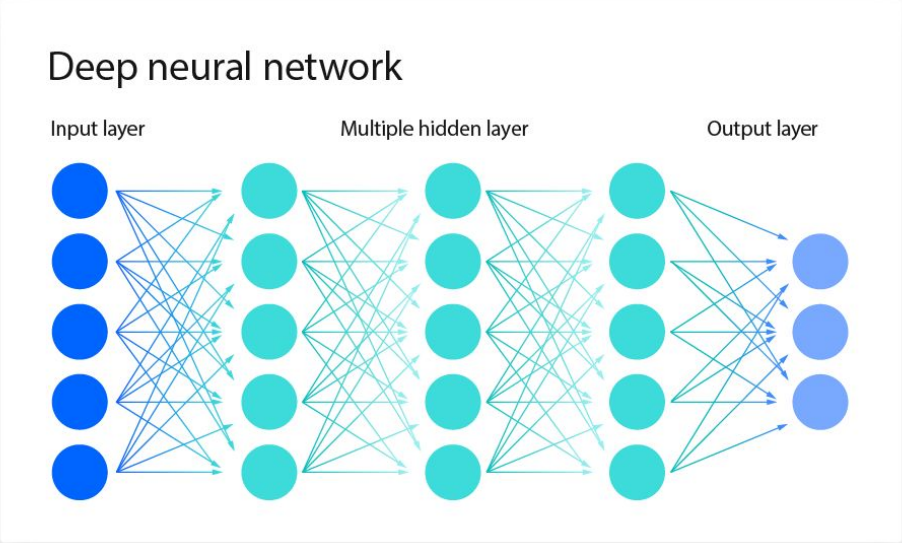
$\Delta\varphi(Z, t_{lep})$ = 0.814 rad/π

b-tagged jet: p_T = 250 GeV

Analysis strategy: 3 channels with DNNs

- Previously had only considered simple topological bins
  - split by number of leptons, number of jets, number of b-jets
  - leads to a partial but **suboptimal** separation of the signal from the backgrounds
- Now rely fully on **Deep Neural Networks** (DNNs)
  - **exploit the full kinematic information of the event**
  - multi-class DNNs: can isolate specific backgrounds to measure in data (**major improvement**)

- Channels based on the decays of the $t\bar{t}$ system
  - all-jets → 2 leptons (2L)
  - lepton+jets → 3 leptons (3L)
  - dilepton → 4 leptons (4L)
  - require at least 1 b-tagged jet
  - try to remain as inclusive as possible → **better MVA perf.**

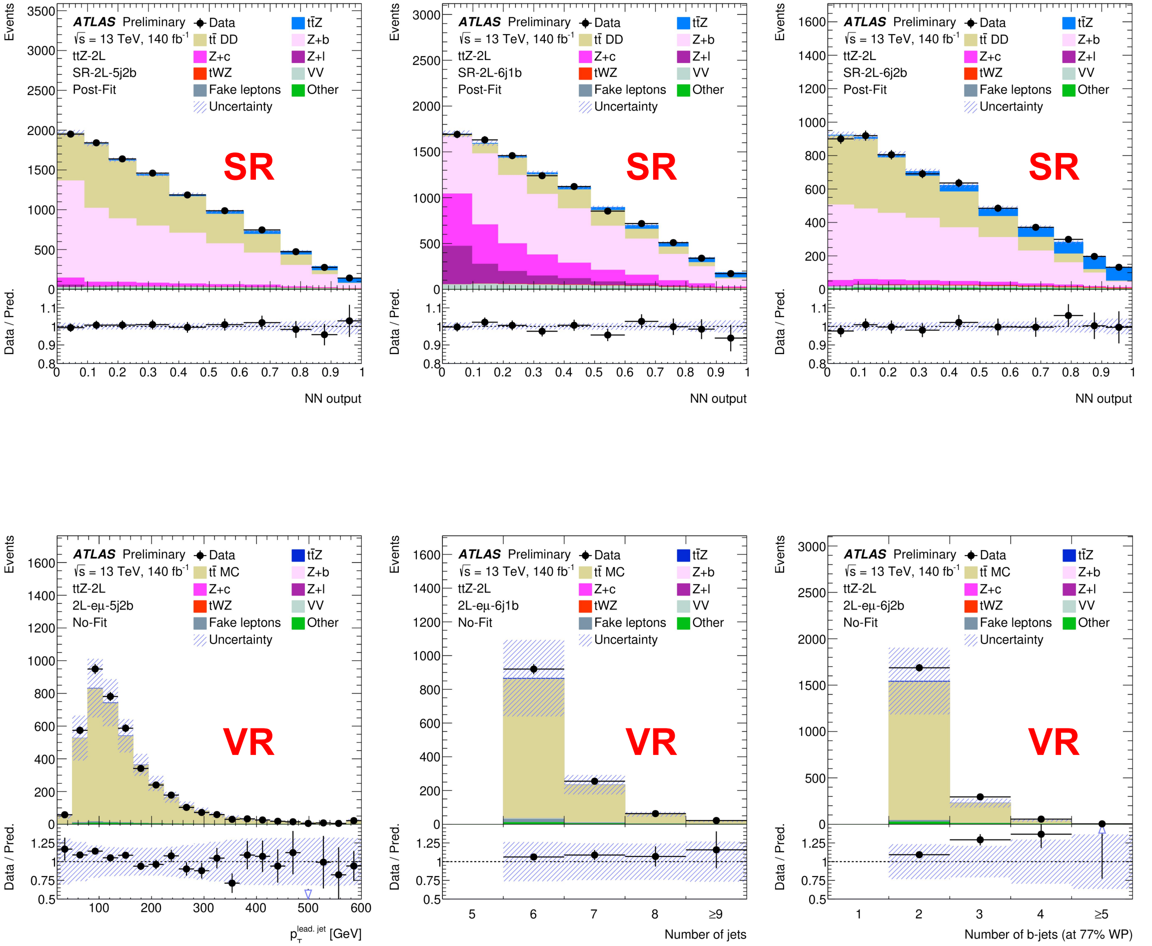


The 2L channel in the detector-level fit

Main **backgrounds** come from **dilepton tt̄ and Z+HF**.

→ we can measure Z+c and Z+b normalisations directly in the fit

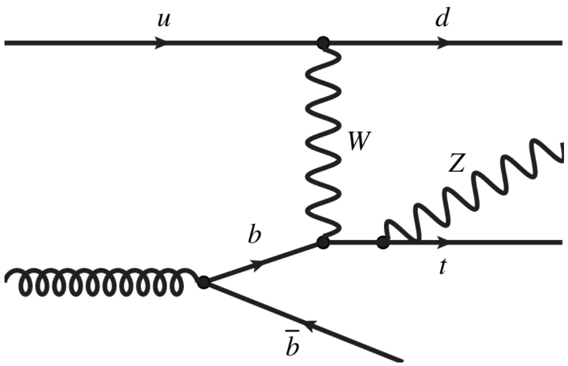
→ tt̄+jets poorly modelled: rely on data-driven approach

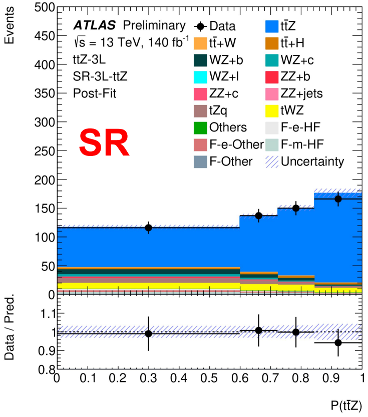


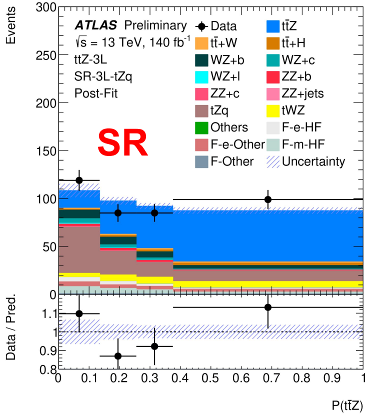
The 3L channel in the detector-level fit

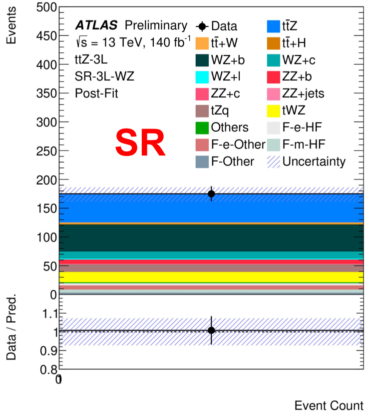
Multi-class DNN allows us to separate the **leading tZq and WZ+HF backgrounds**.

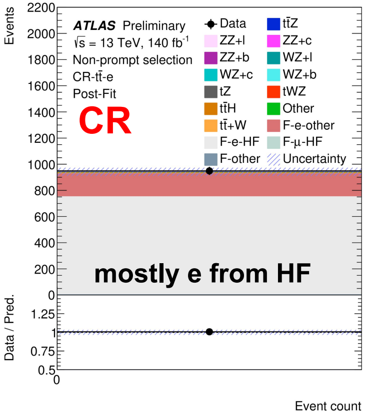
→ not enough stats to measure tZq properly: fixed to SM

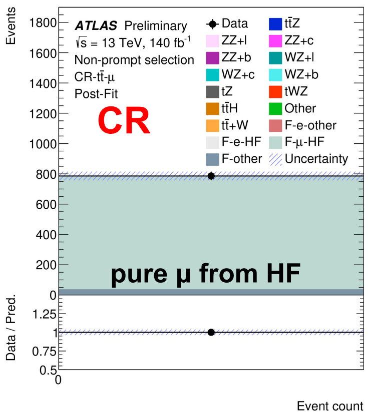


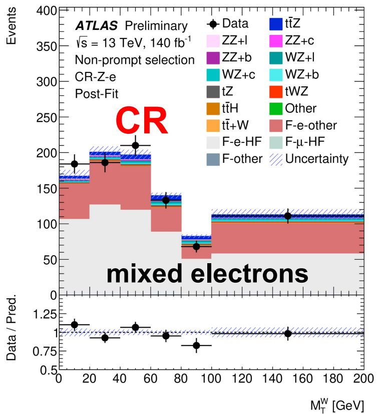










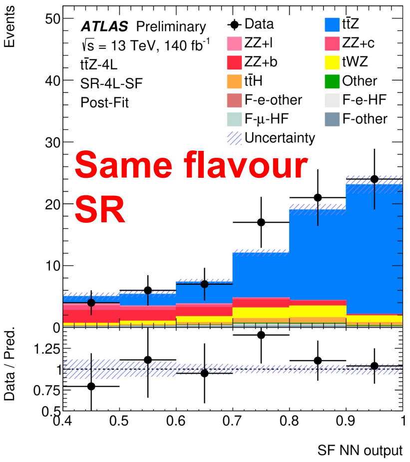


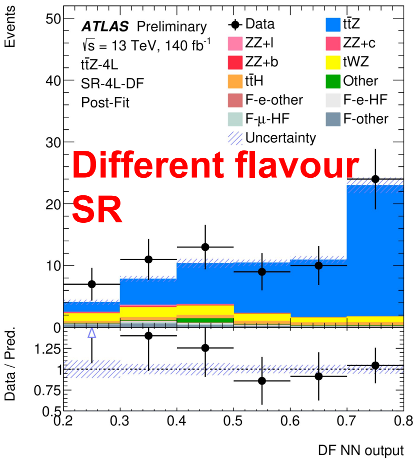
The 4L channel in the detector-level fit

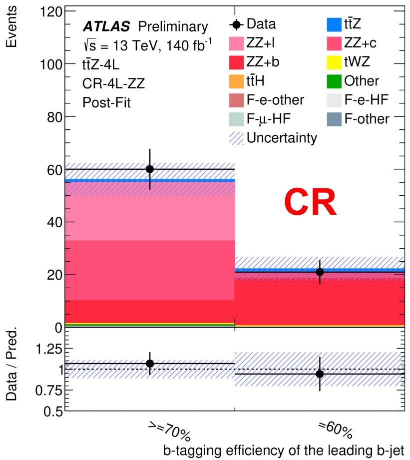
Very pure selection, only two relevant **backgrounds: tWZ and ZZ+HF**.

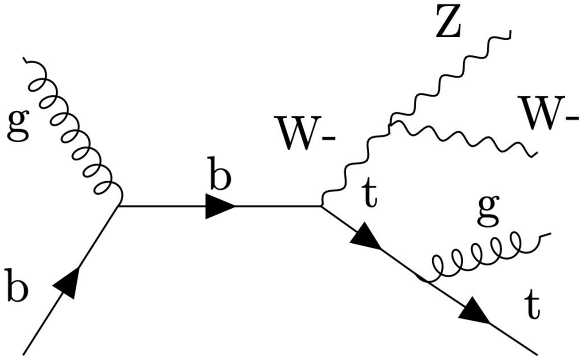
→ we can measure ZZ+b directly in the fit, ZZ+c/light are suppressed

→ not enough statistics to measure tWZ (irreducible, semi-resonant tt̄Z) properly: fixed to SM









Results of the inclusive detector-level fit

Simultaneously fit all regions:

- fit is well behaved and stable
- background normalisations consistent with SM
- 2L and 3L yield almost exactly the SM prediction, 4L has slight excess
- leading systematics related to background normalisation and JES/Flavour tagging

Channel	$\sigma_{t\bar{t}Z}$
Dilepton	$0.84 \pm 0.11\,\text{pb} = 0.84 \pm 0.06\,(\text{stat.}) \pm 0.09\,(\text{syst.})\,\text{pb}$
Trilepton	$0.84 \pm 0.07\,\text{pb} = 0.84 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{syst.})\,\text{pb}$
Tetralepton	$0.97\,^{+0.13}_{-0.12}\,\text{pb} = 0.97 \pm 0.11\,(\text{stat.}) \pm 0.05\,(\text{syst.})\,\text{pb}$
Combination ($2\ell, 3\ell \& 4\ell$)	$0.86 \pm 0.06\,\text{pb} = 0.86 \pm 0.04\,(\text{stat.}) \pm 0.04\,(\text{syst.})\,\text{pb}$

Theory prediction (NLO+NNLL)
Eur. Phys. J. C 79 (2019) 249

$$\sigma_{t\bar{t}Z} = 0.863^{+0.07}_{-0.09}\,(\text{scale}) \pm 0.03\,(\text{PDF} + \alpha_S)\,\text{pb}.$$

Comparison to previous analysis

Uncertainty	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
$t\bar{t}Z$ parton shower	3.1
tWZ modelling	2.9
b-tagging	2.9
WZ/ZZ + jets modelling	2.8
tZq modelling	2.6
Lepton	2.3
Luminosity	2.2
Jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	2.1
Fake leptons	2.1
$t\bar{t}Z$ ISR	1.6
$t\bar{t}Z$ μ_{f} and μ_{r} scales	0.9
Other backgrounds	0.7
Pile-up	0.7
$t\bar{t}Z$ PDF	0.2
Total systematic	8.4
Data statistics	5.2
Total	10

Previous analysis

Eur. Phys. J. C 81 (2021) 737

Uncertainty Category	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
Background normalisations	2.0
Jets and E_T^{miss}	1.9
b-tagging	1.7
$t\bar{t}Z$ μ_F and μ_R scales	1.6
Leptons	1.6
Z +jets modelling	1.5
tWZ modelling	1.1
$t\bar{t}Z$ showering	1.0
$t\bar{t}Z$ A14	1.0
Luminosity	1.0
Diboson modelling	0.8
tZq modelling	0.7
PDF (signal & backgrounds)	0.6
MC statistical	0.5
Other backgrounds	0.5
Fake leptons	0.4
Pile-up	0.3
Data-driven $t\bar{t}$	0.1

This analysis

Cross sections (in pb)

Theory prediction

[~10%] 0.86 ± 0.08 (scale) ± 0.03 (PDF)

Previous measurement

[~10%] 0.99 ± 0.05 (stat) ± 0.08 (syst)

This measurement

[~6.5%] 0.86 ± 0.04 (stat) ± 0.04 (syst)

35% improvement overall, but systematics cut down in half!

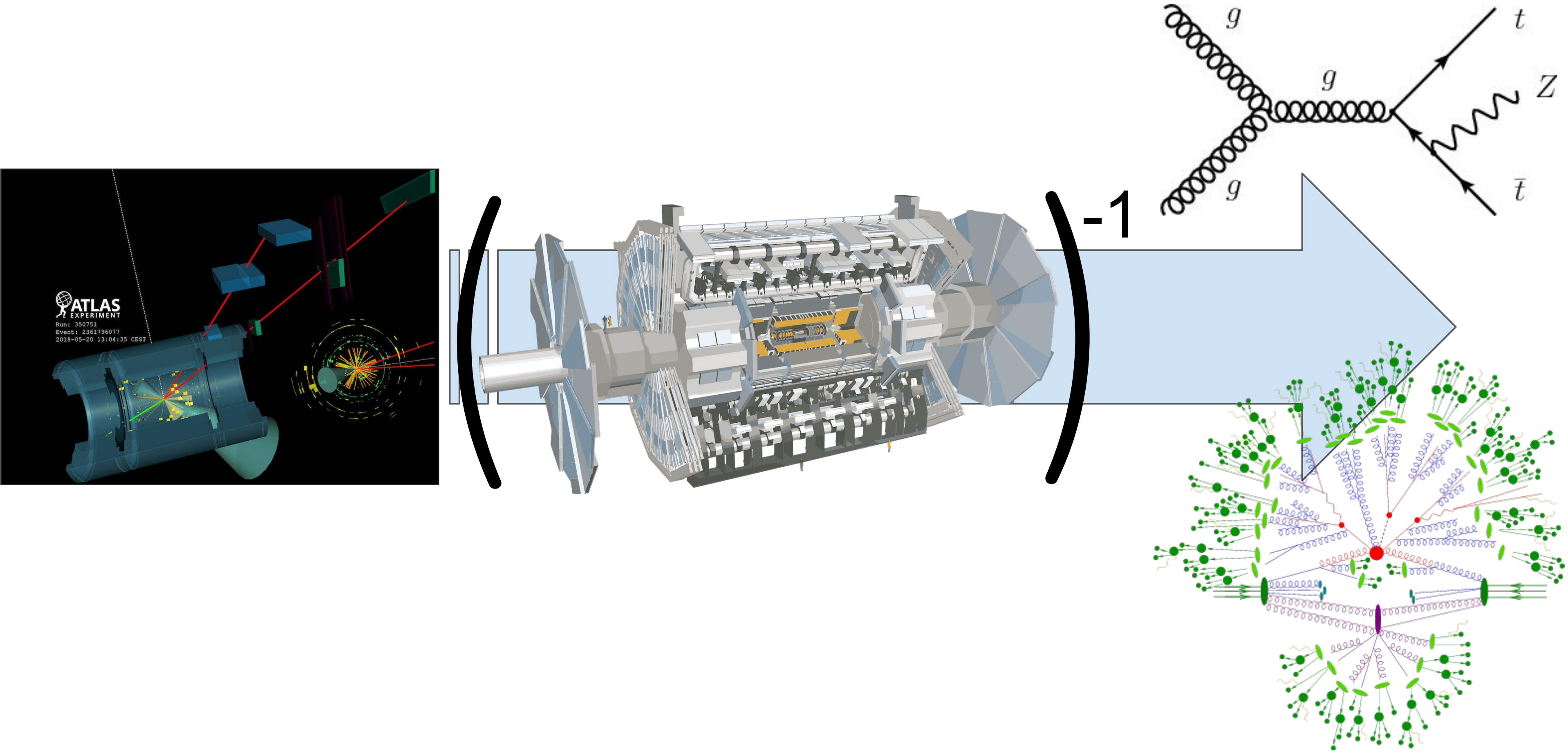
→ better background separation

→ data-driven techniques

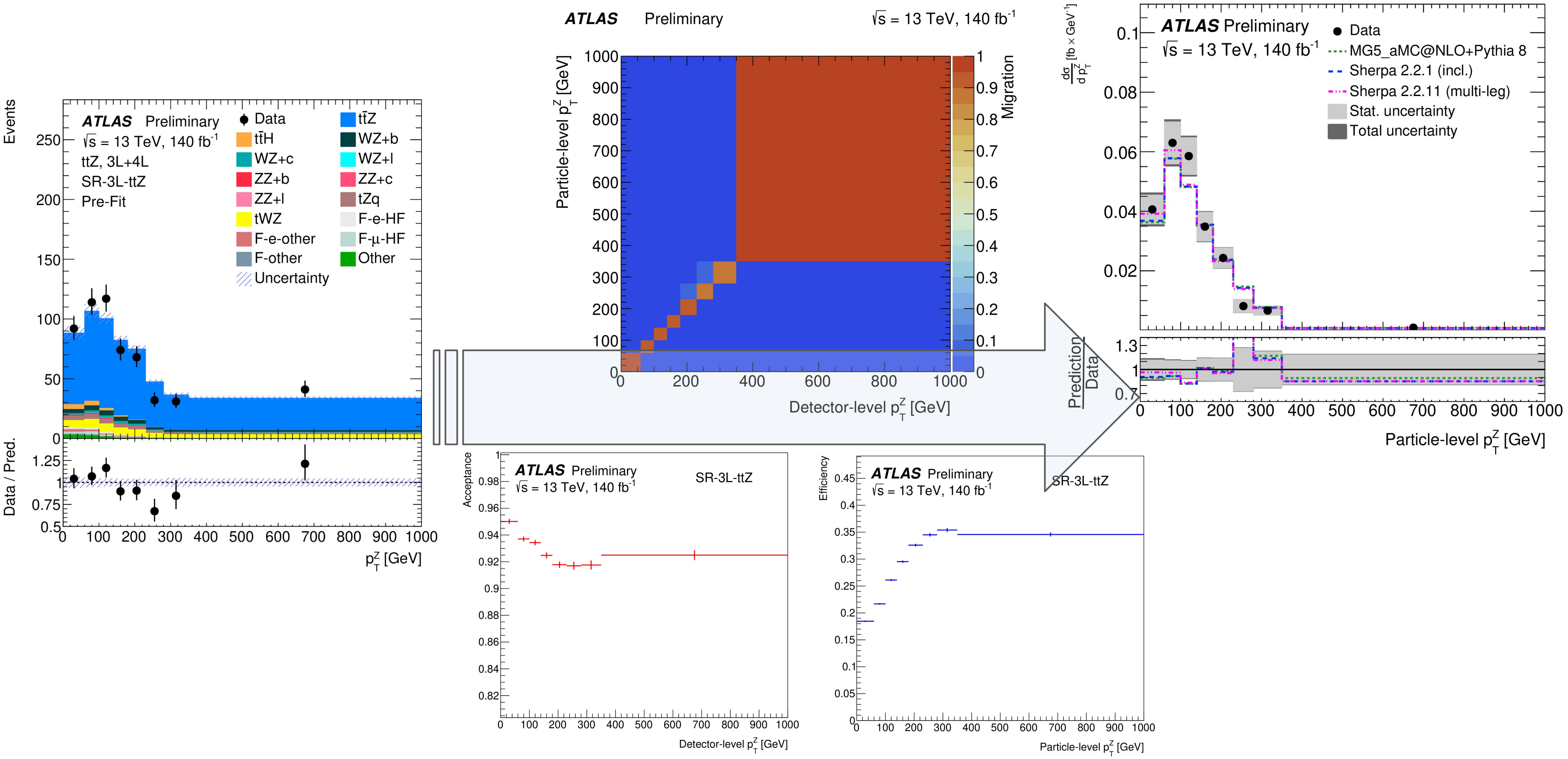
→ improved MC modelling

Re-analysis can be important (e.g. 4tops)

Correcting for detector effects: unfolding



Correcting for detector effects: unfolding



Differential measurements

Recent development in ATLAS: **profile-likelihood unfolding**.

Multiple benefits: pulls and constraints of the uncertainties, normalisation of backgrounds, inclusion of control regions and multiple signal regions, ability to save the full likelihood for HEPdata!

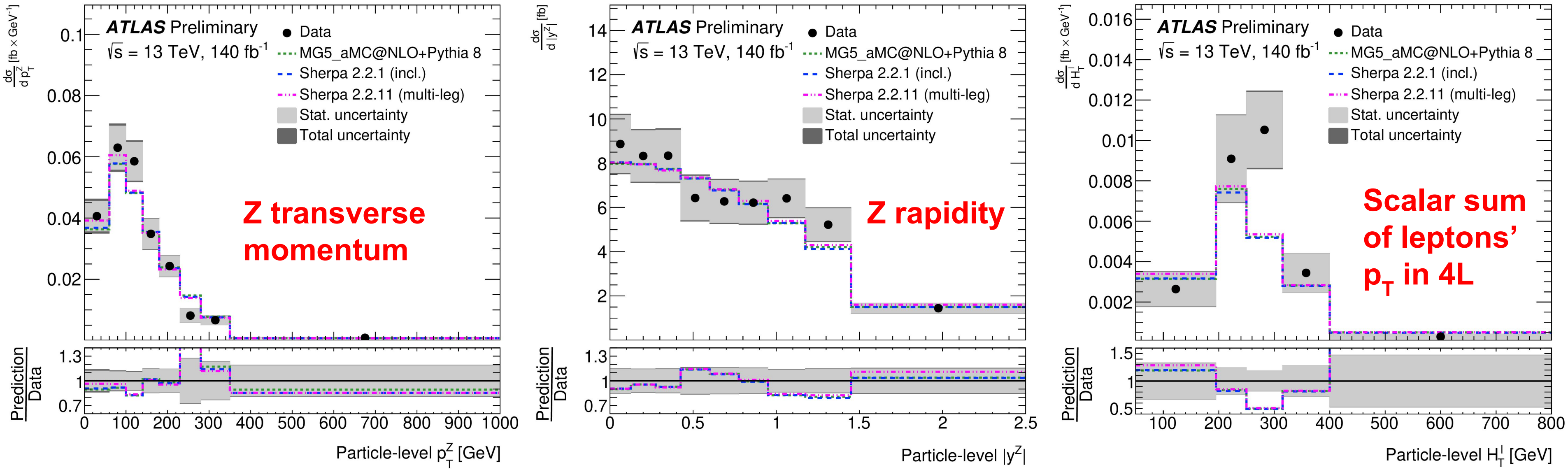
Tikhonov regularisation whenever hadronic top or full $t\bar{t}$ reconstruction is needed.

Observables:

- mainly **kinematics of the Z boson and $t\bar{t}$ system**
- angular distributions, jet multiplicities

	Variable
$3\ell + 4\ell$	p_{T}^{Z}
	$\lvert y^{Z}\rvert$
	$\cos\theta_{Z}^{*}$
	p_{T}^{t}
	$p_{\mathrm{T}}^{t\bar{t}}$
	$\lvert\Delta\phi(t\bar{t}, Z)\rvert$
	$m^{t\bar{t}Z}$
	$m^{t\bar{t}}$
	$\lvert y^{t\bar{t}Z}\rvert$
3ℓ	H_{T}^{ℓ}
	$\lvert\Delta\phi(Z, t_{\mathrm{lep}})\rvert$
	$\lvert\Delta y(Z, t_{\mathrm{lep}})\rvert$
	$p_{\mathrm{T}}^{\ell,\mathrm{non}-Z}$
	N_{jets}
4ℓ	H_{T}^{ℓ}
	$\lvert\Delta\phi(\ell_{t}^{+}, \ell_{\bar{t}}^{-})\rvert$
	N_{jets}

Results of the differential measurements



- 17 observables unfolded to particle- and parton-level, normalised and absolute
- Chosen for relevance to both SM and BSM modelling
- **Still largely stat-dominated** → no single MC generator performs clearly better than the others
- Can be combined using the provided likelihoods and correlations

A legacy measurement of a rare production process

- **Inclusive and differential measurements of the $t\bar{t}Z$ cross section in multi-lepton final states (2L, 3L & 4L) using 140 fb^{-1} of Run 2 data**
  - now also including interpretations (spin correlations & EFT → see backup slides)
- Analysis builds and improves upon the previous one: MC modelling, MVA-based strategy, fake lepton estimation, systematics model.
  - 35% improvement on the inclusive cross section, **50% reduction of systematics**!
- Results are consistent with the SM:
  - cross section is 0.86 ± 0.06 pb → 6.5% uncertainty
  - best theory prediction 0.86 ± 0.09 pb → 10% uncertainty
- Differential measurements are performed for 17 kinematic observables
- First search for $t\bar{t}$ spin correlation effects: still statistically dominated!
- Comprehensive picture of top-EW EFT
- Inclusive & differential likelihoods are available: ready for combinations!

Public page – HEPData

Overview of the available material

We provide:

- **all tables and plots** from the paper, including auxiliary material
  - i.e. also all migration matrices, efficiency and acceptance corrections, and covariance matrices for the differential observables
- **full ranking of uncertainties** for the inclusive cross section combination
- the **likelihood** for the inclusive cross section combination [ATL-PHYS-PUB-2019-029]
- the **likelihood** for each differential distribution
  - particle/parton-level X absolute/normalised
- **1'000 data bootstraps** for the inputs to each differential measurement as well as the inclusive cross section combination [ATL-PHYS-PUB-2021-011]

Upcoming:

- **RIVET routine** to reproduce the $t\bar{t}Z$ fiducial phase-space

Overview of the available material

< Hide Publication Information

Inclusive and differential cross-section measurements of $t\bar{t}Z$ production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, including EFT and spin-correlation interpretations

The ATLAS collaboration

Aad, Georges , Abbott, Braden Keim , Abeling, Kira , Abicht, Nils Julius , Abidi, Haider , Aboulhorma, Asmaa , Abramowicz, Halina , Abreu, Henso , Abulaiti, Yiming , Acharya, Bobby Samir

CERN-EP-2023-252, 2023.

https://doi.org/10.17182/hepdata.146693

INSPIRE | Resources

HistFactory | HistFactory

Abstract (data abstract)
Inclusive and differential cross section measurements of $t\bar{t}Z$ production in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector, including EFT and spin correlations interpretations

The fiducial regions for the dilepton channel are defined as:
- Exactly 2 leptons (e or μ) with transverse momentum greater than 30, 15 GeV for leading and subleading lepton, respectively.
- The sum of the two lepton charges is required to be zero.
- Exactly one opposite-sign-same-flavour (OSSF) lepton pair (considered to be lepton pair from Z boson) with invaraint mass compatible with Z boson ($|m_{\ell\ell}^{Z} - m_Z| < 10$ GeV).

Download All ▾

View Analyses ▾

Filter 385 data tables

Table of Contents 10.17182/hepdata.146693.v1/t1

Resources | https://www.hepdata.net/r

Table of Contents

All the entries of this HEP data record are listed. Figure and Table numbers are the same as in the paper.

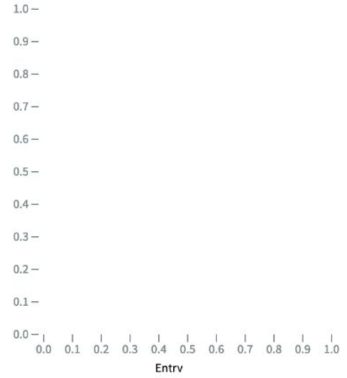
cmenergies: 13000

reactions: P P --> TOP TOPBAR Z

Showing 50 of 384 values — Show All 384 values

Entry	Description
Table 2	Definition of the dilepton signal regions.
Table 3	Definition of the trilepton signal regions.
Table 4	Definition of the tetralepton signal regions.
Table 5	Definition of the fiducial volumes at particle- and parton-level. Leptons refer exclusively to electrons and muons - they are dressed with additional radiation at particle-level, but not at parton-level.
Table 6	Definition of the dilepton $t\bar{t}$ validation regions.
Figure 1a	Pre-fit distribution of the number of b-jets in 2L-$e\mu$-6j2b, this distribution is not used in the fit.
Figure 1b	Pre-fit distribution of the DNN output 2L-$e\mu$-6j1b, this distribution is not used in the fit.

Visualize



Sum errors ☑

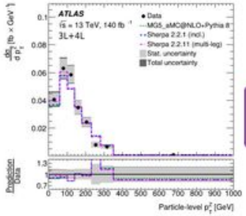
Example: differential distribution

Figure 8a, Unfolded p_T^Z, particle, absolute 10.17182/hepdata.146693.v1/t31 Resources able=Figure%208a%2C%20 JSON

License: CC0

Data from Figure 8a, Unfolded p_T^Z, particle, absolute

Unfolded absolute cross section as a function of p_T^Z in the combination of 3ℓ and 4ℓ channels at particle-level (Figure 8 top-left).



?

cmenergies

13000

observables

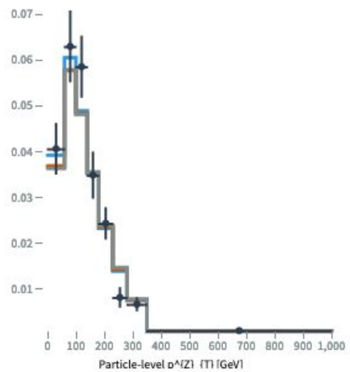
DSIG/DPT_Z

reactions

P P --> TOP TOPBAR Z

$\sqrt{s}$	13000 GeV		
LUMINOSITY	140 fb^{-1}		
Particle-level p_T^Z [GeV]	**Data [fb$\times$GeV^{-1}]**	**MG5_aMC@NLO+Pythia 8 [fb$\times$GeV^{-1}]**	**Sherpa 2.2.1 (incl.) [fl GeV^{-1}]**
30.00 (bin: 0 - 60.00)	0.040608673733725571 ±0.0056460301961192413	0.036321956435238695	0.03682316162497053
80.00 (bin: 60.00 - 100.0)	0.062968294946992492 ±0.0078569109186047963	0.057656937833747653	0.05783501064626973
120.0 (bin: 100.0 - 140.0)	0.058527459078630127 ±0.0067940017417115204	0.04812638479642644	0.04829811076324104

Visualize



Example: acceptance and efficiency corrections

Corrections, p_T^Z, particle 10.17182/hepdata.146693.v1/t155

Resources | ›7BZ%7D_%7BT%7D%24%: | JSON

Differential cross section - input distributions

Particle-level acceptance and selection efficiency histograms for p_T^Z variable.

cmenergies 13000

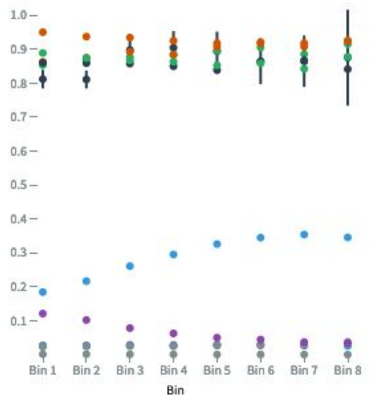
observables PT_Z

reactions P P --> TOP TOPBAR Z

?

$\sqrt{s}$	13000 GeV					
LUMINOSITY	140 fb^{-1}					
Bin	**Acceptance reg_3l_ttZ particle-level**	**Efficiency reg_3l_ttZ particle-level**	**Acceptance reg_3l_tZq particle-level**	**Efficiency reg_3l_tZq particle-level**	**Acceptance reg_3l_WZ particle-level**	**Efficie reg_3l particl level**
Bin 1	0.95011 ±0.00189	0.18453 ±0.00139	0.88883 ±0.00287	0.12127 ±0.00112	0.86033 ±0.00688	0.0233 ±0.0005
Bin 2	0.93704 ±0.00183	0.21679 ±0.00146	0.87364 ±0.00322	0.10216 ±0.00102	0.8588 ±0.00679	0.0246 ±0.0005
Bin 3	0.93431 ±0.00192	0.26111 ±0.00171	0.86729 ±0.00419	0.07843 ±0.00101	0.85752 ±0.00785	0.0252 ±0.0006
Bin 4	0.92477 ±0.00222	0.29532 ±0.0021	0.86292 ±0.00563	0.06282 ±0.00106	0.8497 ±0.00915	0.0253 ±0.0007
Bin 5	0.91783 ±0.00235	0.32596 ±0.00236	0.85251 ±0.00698	0.05036 ±0.00105	0.83827 ±0.00999	0.0268 ±0.0007

Visualize



Sum errors ☑ **Log Scale (Y)** ☐

Deselect variables or hide different error bars by clicking on

Example: migration matrix

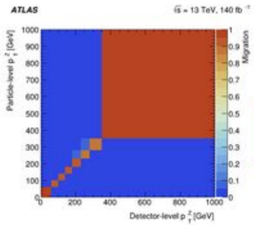
MM, p_T^Z, particle, SR-3L-ttZ 10.17182/hepdata.146693.v1/t247

Resources)_%7BT%7D%24%2C%20p JSON

License: CC0

Differential cross section - input distributions

Migration matrix for p_T^Z variable at particle-level in region SR-3L-ttZ.



cmenergies

13000

observables

PT_Z

reactions

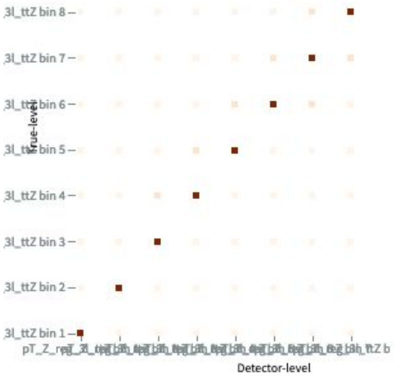
P P --> TOP TOPBAR Z

Showing 50 of 64 values

Show All 64 values

$\sqrt{s}$		13000 GeV
LUMINOSITY		140 fb^{-1}
Detector-level	**True-level**	**migration matrix element**
pT_Z_reg_3l_ttZ bin 1	pT_Z_reg_3l_ttZ bin 1	9.6714e-01
pT_Z_reg_3l_ttZ bin 1	pT_Z_reg_3l_ttZ bin 2	2.3283e-02
pT_Z_reg_3l_ttZ bin 1	pT_Z_reg_3l_ttZ bin 3	5.5323e-03
pT_Z_reg_3l_ttZ bin 1	pT_Z_reg_3l_ttZ bin 4	3.0752e-03
pT_Z_reg_3l_ttZ bin 1	pT_Z_reg_3l_ttZ bin 5	3.0264e-03

Visualize



Example: covariance matrix

Covariance matrix p_T^Z, particle, absolute

10.17182/hepdata.146693.v1/t365

Resources | %5E%7BZ%7D_%7BT%7D% | JSON

Data from Covariance matrix p_T^Z, particle, absolute

Covariance matrix for absolute cross section as a function of p_T^Z at particle-level.

cmenergies: 13000

observables: DSIG/DPT_Z

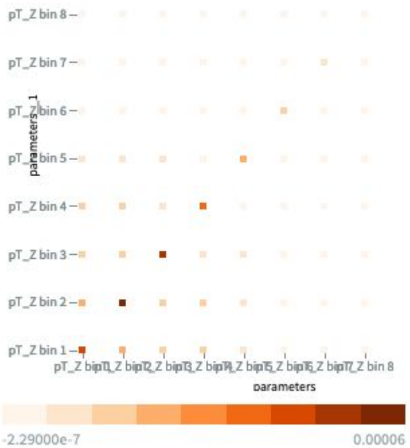
reactions: P P --> TOP TOPBAR Z

?

Showing 50 of 64 values | Show All 64 values

$\sqrt{s}$		13000 GeV
LUMINOSITY		140 fb^{-1}
parameters	**parameters__1**	**parameter covariances**
pT_Z bin 1	pT_Z bin 1	3.19e-05
pT_Z bin 1	pT_Z bin 2	9.36e-06
pT_Z bin 1	pT_Z bin 3	7.93e-06
pT_Z bin 1	pT_Z bin 4	4.48e-06
pT_Z bin 1	pT_Z bin 5	2.38e-06
pT_Z bin 1	pT_Z bin 6	9.86e-07
pT_Z bin 1	pT_Z bin 7	8.11e-07
pT_Z bin 1	pT_Z bin 8	6.24e-08

Visualize



Brushing Enabled? ☐

Example: bootstraps

Bootstraps 1, p_T^Z 10.17182/hepdata.146693.v1/t127

Resources | %5E%7BZ%7D_%7BT%7D%

License: CC0

Differential cross section - input distributions

Bootstrap replicas (0-499) for data, variable p_T^Z. The used bootstrap method is described in ATL-PHYS-PUB-2021-011 (https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-011/).

cmenergies: 13000

observables: PT_Z

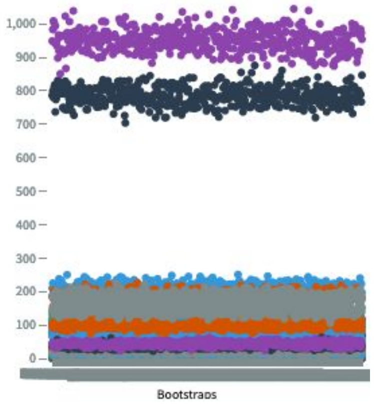
reactions: P P --> TOP TOPBAR Z

Showing 50 of 501 values | Show All 501 values

$\sqrt{s}$	13000 GeV
LUMINOSITY	140 fb^{-1}

Bootstraps	**SR-3L-WZ Bin 1**	**SR-3L-WZ Bin 2**	**SR-3L-WZ Bin 3**	**SR-3L-WZ Bin 4**	**SR-3L-WZ Bin 5**	**SR-3L-WZ Bin 6**	**SR-3L-WZ Bin 7**	**SR-3L-WZ Bin 8**	**SI t… B…**
nominal	43.0	38.0	20.0	26.0	16.0	11.0	8.0	13.0	1
bootstrap_0	48.0	36.0	18.0	29.0	13.0	18.0	7.0	14.0	1
bootstrap_1	37.0	43.0	22.0	19.0	22.0	15.0	8.0	17.0	1
bootstrap_2	34.0	40.0	17.0	30.0	15.0	11.0	6.0	9.0	1
bootstrap_3	40.0	34.0	19.0	26.0	19.0	8.0	3.0	12.0	1
bootstrap_4	31.0	38.0	23.0	25.0	26.0	14.0	9.0	16.0	1

Visualize



Sum errors ☑ **Log Scale (Y)** ☐

Example: likelihood

InclusiveCombination.json   Open with Xcode

{"analyses":[{"domains":["default_domain"],"likelihood":"simPdf_asimovData","name":"simPdf_asimovData","parameters_of_interest":
["mu_XS_ttZ"]},{"domains":["default_domain"],"likelihood":"simPdf_obsData","name":"simPdf_obsData","parameters_of_interest":
["mu_XS_ttZ"]}],"data":[{"axes":[{"max":1.0,"min":0.0,"name":"obs_x_SR3LWZ","nbins":1}],"contents":
[172.05441230810112],"name":"asimovData_SR3LWZ","type":"binned"},{"axes":[{"edges":
[0.0,0.1348,0.255,0.3751,1.0],"name":"obs_x_SR3LtZq"}],"contents":
[102.6008656892159,93.14273479330807,87.59645057872092,82.3753569982013],"name":"asimovData_SR3LtZq","type":"binned"},{"axes":
[{"edges":[0.0,0.5986,0.7229,0.8431,1.0],"name":"obs_x_SR3LttZ"}],"contents":
[113.6536756276964,132.0660765437707,146.4022315595425,172.48838895376846],"name":"asimovData_SR3LttZ","type":"binned"},{"axes":
[{"max":1.0,"min":0.0,"name":"obs_x_r_5j2b","nbins":10}],"contents":
[1888.647054761758,1734.5257525096076,1555.9088287424256,1379.8588872586838,1163.530120444538,939.7925051065836,699.7969503656873,4
75.22070112731285,288.7534740030346,133.63106098655297],"name":"asimovData_r_5j2b","type":"binned"},{"axes":
[{"max":1.0,"min":0.0,"name":"obs_x_r_6j1b","nbins":10}],"contents":
[2056.546186936932,1859.4265147126157,1648.078693457654,1451.160094854776,1237.2509698469687,1019.3995177617593,767.4861725207146,5
61.6245645369833,382.5943960678949,201.69816199719324],"name":"asimovData_r_6j1b","type":"binned"},{"axes":
[{"max":1.0,"min":0.0,"name":"obs_x_r_6j2b","nbins":10}],"contents":
[972.6878927929815,903.6024883580608,822.8462284153659,735.3438891206597,620.9746884034714,499.9116908469307,383.2460546622234,282.
12801700546834,200.99188069721833,136.70361988098685],"name":"asimovData_r_6j2b","type":"binned"},{"axes":
[{"max":0.8,"min":0.2,"name":"obs_x_reg_4l_DF","nbins":6}],"contents":
[3.6980075747072223,7.3397494495541915,9.728425275591952,10.015664199317333,10.45654288106819,21.806657059995747],"name":"asimovDat
a_reg_4l_DF","type":"binned"},{"axes":[{"max":1.0,"min":0.0,"name":"obs_x_reg_4l_FF_CR_e_hf","nbins":1}],"contents":
[997.2706429203533],"name":"asimovData_reg_4l_FF_CR_e_hf","type":"binned"},{"axes":[{"edges":
[0.0,20.0,40.0,60.0,80.0,100.0,200.0],"name":"obs_x_reg_4l_FF_CR_e_other"}],"contents":
[164.71416212469637,200.2691829391784,198.31052298864563,144.20114186477988,85.52922283948861,113.6456150247876],"name":"asimovData
_reg_4l_FF_CR_e_other","type":"binned"},{"axes":[{"max":1.0,"min":0.0,"name":"obs_x_reg_4l_FF_CR_mu_hf","nbins":1}],"contents":
[760.6084269489846],"name":"asimovData_reg_4l_FF_CR_mu_hf","type":"binned"},{"axes":
[{"max":1.0,"min":0.4,"name":"obs_x_reg_4l_SF","nbins":6}],"contents":
[4.629459629437353,5.008161370243511,6.932651958340533,11.40922859261093,17.97216999825754,21.557484137483883],"name":"asimovData_r
eg_4l_SF","type":"binned"},{"axes":[{"max":5.5,"min":3.5,"name":"obs_x_reg_4l_ZZ","nbins":2}],"contents":
[49.611909698037174,19.46782036819036],"name":"asimovData_reg_4l_ZZ","type":"binned"},{"axes":
[{"max":1.0,"min":0.0,"name":"obs_x_SR3LWZ","nbins":1}],"contents":[175],"name":"obsData_SR3LWZ","type":"binned"},{"axes":
[{"edges":[0.0,0.1348,0.255,0.3751,1.0],"name":"obs_x_SR3LtZq"}],"contents":
[119,85,85,99],"name":"obsData_SR3LtZq","type":"binned"},{"axes":[{"edges":
[0.0,0.5986,0.7229,0.8431,1.0],"name":"obs_x_SR3LttZ"}],"contents":[116,137,150,166],"name":"obsData_SR3LttZ","type":"binned"},
{"axes":[{"max":1.0,"min":0.0,"name":"obs_x_r_5j2b","nbins":10}],"contents":
[1950,1841,1639,1460,1186,988,747,473,276,142],"name":"obsData_r_5j2b","type":"binned"},{"axes":
[{"max":1.0,"min":0.0,"name":"obs_x_r_6j1b","nbins":10}],"contents":
[1691,1631,1459,1240,1122,854,718,510,340,172],"name":"obsData_r_6j1b","type":"binned"},{"axes":
[{"max":1.0,"min":0.0,"name":"obs_x_r_6j2b","nbins":10}],"contents":
[900,919,805,691,636,485,371,299,197,132],"name":"obsData_r_6j2b","type":"binned"},{"axes":
[{"max":0.8,"min":0.2,"name":"obs_x_reg_4l_DF","nbins":6}],"contents":
[7,11,13,9,10,24],"name":"obsData_reg_4l_DF","type":"binned"},{"axes":
[{"max":1.0,"min":0.0,"name":"obs_x_reg_4l_FF_CR_e_hf","nbins":1}],"contents":
[949],"name":"obsData_reg_4l_FF_CR_e_hf","type":"binned"},{"axes":[{"edges":
[0.0,20.0,40.0,60.0,80.0,100.0,200.0],"name":"obs_x_reg_4l_FF_CR_e_other"}],"contents":
[184,186,210,133,68,111],"name":"obsData_reg_4l_FF_CR_e_other","type":"binned"},{"axes":
[{"max":1.0,"min":0.0,"name":"obs_x_reg_4l_FF_CR_mu_hf","nbins":1}],"contents":
[786],"name":"obsData_reg_4l_FF_CR_mu_hf","type":"binned"},{"axes":
[{"max":1.0,"min":0.4,"name":"obs_x_reg_4l_SF","nbins":6}],"contents":[4,6,7,17,21,24],"name":"obsData_reg_4l_SF","type":"binned"},
{"axes":[{"max":5.5,"min":3.5,"name":"obs_x_reg_4l_ZZ","nbins":2}],"contents":
[60,21],"name":"obsData_reg_4l_ZZ","type":"binned"}],"distributions":[{"axes":
[{"max":1.0,"min":0.0,"name":"obs_x_SR3LWZ","nbins":1}],"name":"model_SR3LWZ","samples":[{"data":{"contents":
[4.283257298813171],"errors":[0.1222316]},"modifiers":
[{"constraint_name":"lumiConstraint","name":"Lumi","parameter":"Lumi","type":"normfactor"},
{"name":"mu_FakeEl_HF","parameter":"mu_FakeEl_HF","type":"normfactor"},{"constraint":"Gauss","data":
{"hi":0.9748237596442735,"lo":1.0251762403557265},"name":"BTag_B_0","parameter":"alpha_BTag_B_0","type":"normsys"},
{"constraint":"Gauss","data":
{"hi":1.000393813141217,"lo":0.999606186858783},"name":"BTag_B_1","parameter":"alpha_BTag_B_1","type":"normsys"},
{"constraint":"Gauss","data":
{"hi":1.0001821866111853,"lo":0.9998178133888147},"name":"BTag_B_10","parameter":"alpha_BTag_B_10","type":"normsys"},
{"constraint":"Gauss","data":
{"hi":1.0003511486090177,"lo":0.9996488513909824},"name":"BTag_B_12","parameter":"alpha_BTag_B_12","type":"normsys"},
{"constraint":"Gauss","data":
{"hi":0.99912056549439,"lo":1.00087943450561},"name":"BTag_B_13","parameter":"alpha_BTag_B_13","type":"normsys"},
{"constraint":"Gauss","data":
{"hi":0.999889278225808,"lo":1.000110721774192},"name":"BTag_B_14","parameter":"alpha_BTag_B_14","type":"normsys"},
{"constraint":"Gauss","data":
{"hi":1.000371369269481 1,"lo":0.999628630730519},"name":"BTag_B_15","parameter":"alpha_BTag_B_15","type":"normsys"},
{"constraint":"Gauss","data":
{"hi":0.9998693086317013,"lo":1.0001306913682986},"name":"BTag_B_17","parameter":"alpha_BTag_B_17","type":"normsys"},
{"constraint":"Gauss","data":
{"hi":1.0002763952273634,"lo":0.9997236047726366},"name":"BTag_B_18","parameter":"alpha_BTag_B_18","type":"normsys"},
{"constraint":"Gauss","data":

- PyHF likelihood [ATL-PHYS-PUB-2019-029]
- HS3 JSON format

Contains the full model used in the analysis!

→ reproduce the results

→ re-interpret (replace predictions, uncertainties)

→ **combine** (use bootstraps to evaluate correlations and overlap between ATLAS measurements on the Run 2 dataset)

A tutorial on working with likelihoods!

Exploring Public Likelihoods

> 🚧 May 2024: Under construction

Understanding the ATLAS Statistical Model

ATLAS produces a vast amount of data. Analysing this data requires sophisticated statistical techniques to draw meaningful conclusions about fundamental particles and their interactions. The statistical model, often represented as a likelihood function, is crucial in interpreting experimental results and extracting physical insights.

ANALYSING STATISTICAL WORKSPACES WITH XROOFIT

launch binder

Key Components of the Model

- **Workspace inspection and visualisation**: Before diving into the statistical analysis, it's essential to inspect the workspace content and visualize relevant data to gain insights into the experimental setup.
- **Content extraction**: The extraction process involves isolating specific channels or subsets of data relevant to the analysis, focusing on areas of interest within the experimental data.
- **Reparameterisation**: Reparameterisation techniques are employed to transform the model parameters, simplifying the statistical analysis and improving interpretability.

https://opendata.atlas.cern/docs/tutresearch/public_likelihoods

BACKUP

Systematic uncertainties

- **Detailed description of signal modelling**, based on state-of-the-art MC
  - parton shower and underlying event
  - initial state radiation
  - scale uncertainties as a proxy for unknown NNLO QCD
  - PDF uncertainties (PDF4LHC prescriptions)
  - alternative multi-leg generators used for comparisons
- **Background uncertainties** also revisited
  - measure all dominant backgrounds directly in data
  - only **tZq** can not be constrained precisely enough
    → rely on 14% ATLAS result, motivates future joint measurements?
  - singly-resonant **tWZ**: recent evidence from CMS, but still “unobserved”;
    large theory uncertainty → challenge for modelling!
- **Experimental uncertainties**: 200-300 NPs at the end of Run 2
  - more sophisticated JER, JES, electron and muon efficiencies breakdown
  - as seen in the Top Mass example, this is the way towards **more correct combinations**!

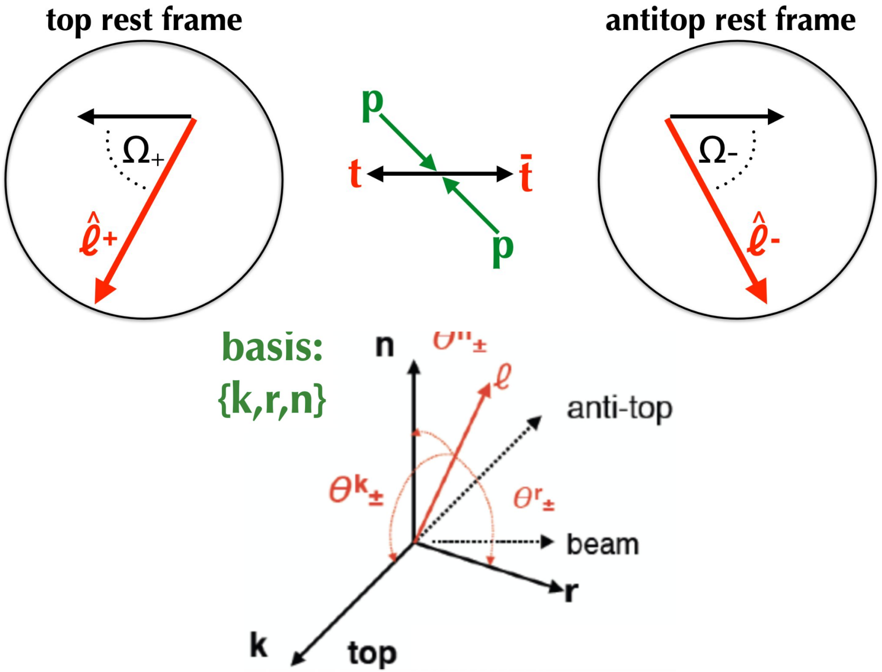
Spin correlations interpretation

Presence of the Z boson modifies the SM expectations for spin correlations between the two tops: attempt to measure this effect **at detector-level**.

Consider 9 angular distributions probing the $t\bar{t}$ spin density matrix, and perform a template fit between SM hypothesis and "spin-off" hypothesis.

For each angular observable, extract f_{SM}, then combine in χ^2 fit (with stat. and syst. correlations)

Null hypothesis disfavoured at 1.8σ level



$$f_{SM}^{obs.} = 1.20 \pm 0.63\ (\text{stat.}) \pm 0.25\ (\text{syst.}) = 1.20 \pm 0.68\ (\text{tot.})$$

Looking forward: additional sensitivity to modification of top-Z coupling.

Differential measurements

Recent development in ATLAS: **profile-likelihood unfolding**.

Multiple benefits: pulls and constraints of the uncertainties, normalisation of backgrounds, inclusion of control regions and multiple signal regions, ability to save the full likelihood for HEPdata!

Tikhonov regularisation whenever hadronic top or full tt̄ reconstruction is needed.

	Variable	Regularisation	τ^{particle}	τ^{parton}	Definition
$3\ell + 4\ell$	p_T^Z	No	-	-	Transverse momentum of the Z boson
	$\lvert y^Z \rvert$	No	-	-	Absolute rapidity of the Z boson
	$\cos\theta_Z^*$	No	-	-	Angle between the direction of the Z boson in the detector reference frame and the direction of the negatively charged lepton in the rest frame of the Z boson
	p_T^t	Yes	1.5	1.4	Transverse momentum of the top quark
	$p_T^{t\bar{t}}$	Yes	1.6	1.5	Transverse momentum of the $t\bar{t}$ system
	$\lvert\Delta\phi(t\bar{t}, Z)\rvert$	Yes	2.4	2.1	Absolute azimuthal separation between the Z boson and the $t\bar{t}$ system
	$m^{t\bar{t}Z}$	Yes	1.5	1.6	Invariant mass of the $t\bar{t}Z$ system
	$m^{t\bar{t}}$	Yes	1.5	1.4	Invariant mass of the $t\bar{t}$ system
	$\lvert y^{t\bar{t}Z}\rvert$	Yes	1.5	1.5	Absolute rapidity of the $t\bar{t}Z$ system
3ℓ	H_T^ℓ	No	-	-	Sum of the transverse momenta of all the signal leptons
	$\lvert\Delta\phi(Z, t_{\text{lep}})\rvert$	No	-	-	Absolute azimuthal separation between the Z boson and the top (anti-top) quark featuring the $W \to \ell\nu$ decay
	$\lvert\Delta y(Z, t_{\text{lep}})\rvert$	No	-	-	Absolute rapidity difference between the Z boson and the top (anti-top) quark featuring the $W \to \ell\nu$ decay
	$p_T^{\ell,\text{non}-Z}$	No	-	-	Transverse momentum of the lepton which is not associated with the Z boson
	N_{jets}	No	-	-	Number of selected jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$
4ℓ	H_T^ℓ	No	-	-	Sum of the transverse momenta of all the signal leptons
	$\lvert\Delta\phi(\ell_t^+, \ell_{\bar{t}}^-)\rvert$	No	-	-	Absolute azimuthal separation between the two leptons from the $t\bar{t}$ system
	N_{jets}	No	-	-	Number of selected jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$

SMEFT interpretation

$t\bar{t}Z$ production is sensitive to **dim-6 EFT operators** both in the top-Z coupling and in the $qq/gg\to t\bar{t}$ vertex.

Use the differential distributions at particle-level as input to the EFT fit (with proper correlations taken into account), relying on LO QCD parameterisation from `SMEFTsim 3.0`.

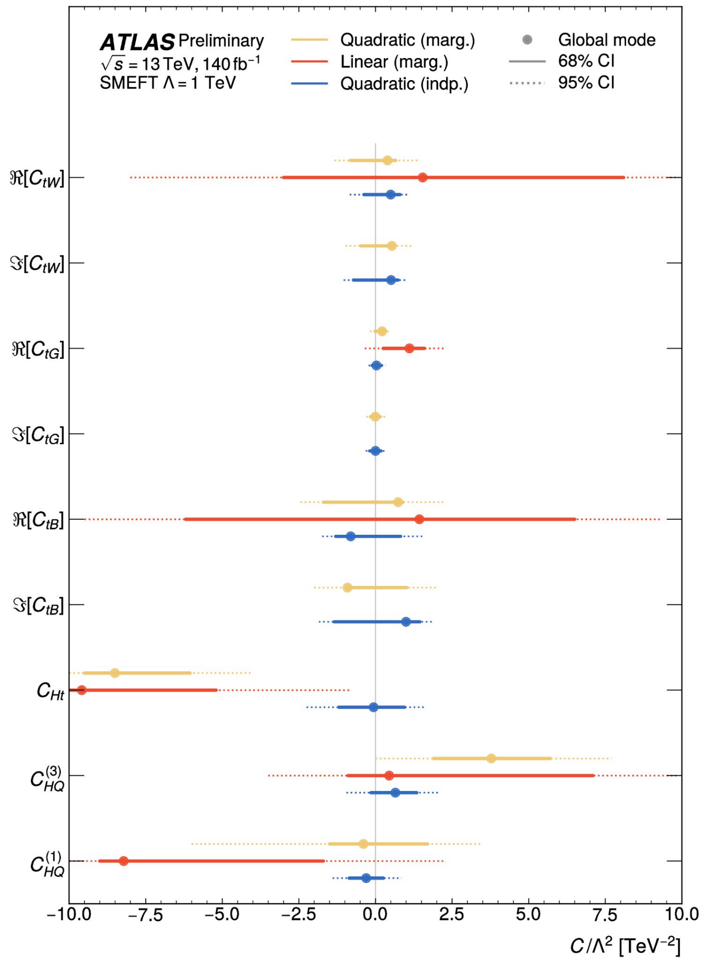
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4} \mathcal{L}^{(d)}, \quad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)}$$

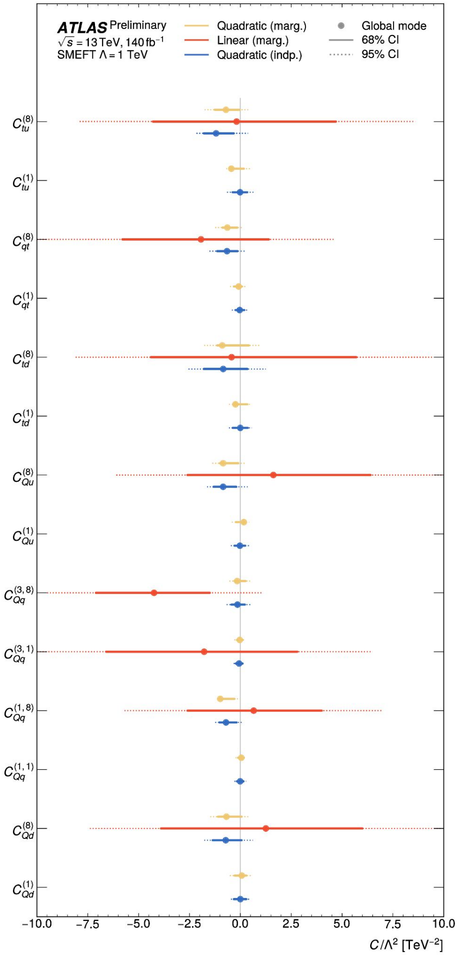
$$\mathcal{O} = \mathcal{O}_{\mathrm{SM}} + \sum_i C_i A_i + \sum_{i,j} C_i C_j B_{ij}.$$

Perform **3 different fits** to assess the relevance of SM/EFT interference and pure EFT terms, and the sensitivity to each operator individually.

Also perform PCA to **identify directions of sensitivity** probed by the measurement.

Results of the SMEFT interpretation



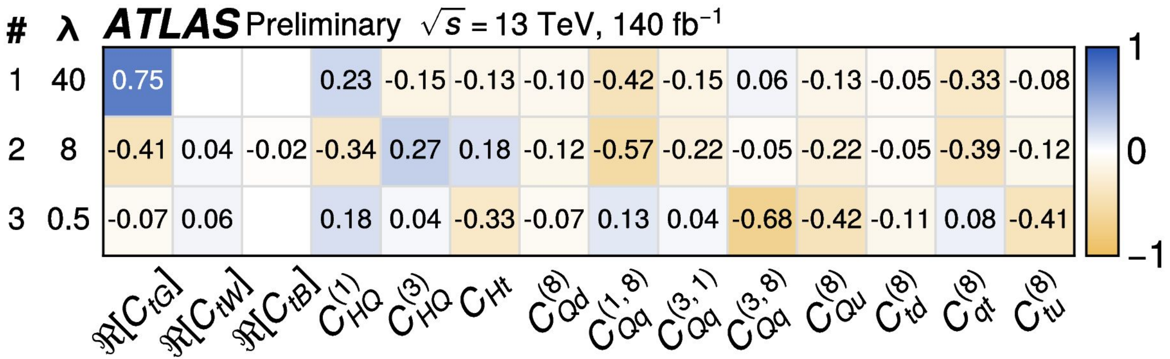


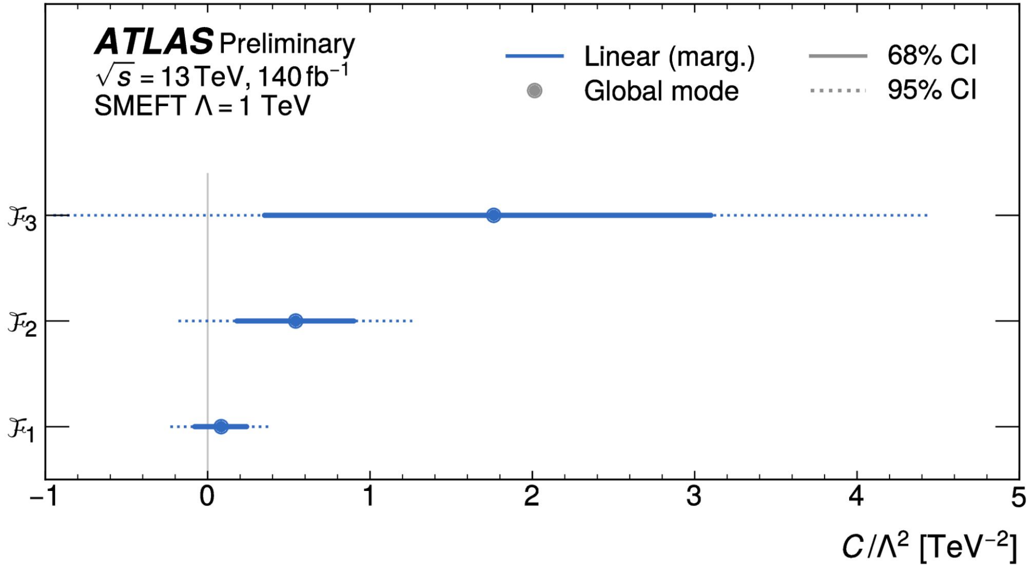
Separate fits to top-boson and four-quark operators in the Warsaw basis: no significant deviation from the SM, but patterns indicating the need to take into account linear combinations → **PCA / Fisher information matrix**

Top-boson operators: affect the strength of the V-A coupling of the Z boson to the top, allow new Lorentz structure (dipole), CP-violation (imaginary parts).

Four-quark operators: only relevant for the subdominant qq→tt̄ channel, but different sensitivity than simple tt̄ due to possible ISR Z.
Particularly important to take into account EFT-EFT interference!

SMEFT interpretation in the rotated basis





Since we are very close to the SM, use a **linear EFT approximation** and **rotate** the Warsaw basis into 3 new directions of sensitivity:

- **ctG dominates** because of large impact on gg→tt̄, but four-quark operators still important;
- **top-boson operators** more discrete, but recover some of the expected linear combinations;
- pattern of positive central values accommodates the slight excess in 4L, but still consistent with SM.