# The Physics Project and the Phase I & II Trigger activities in ATLAS of the AUTH/HOU group


ARISTOTLE UNIVERSITY OF THESSALONIKI

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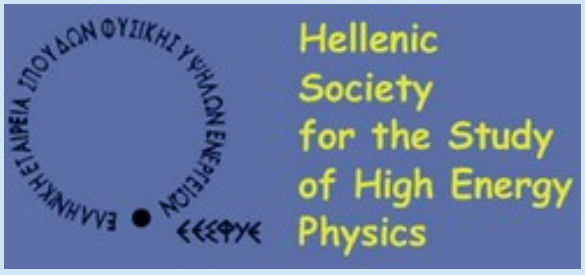
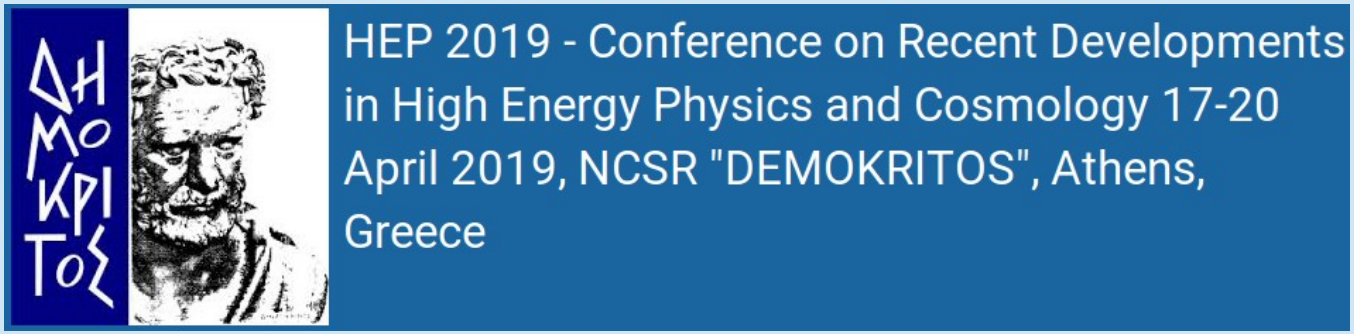


# Outline

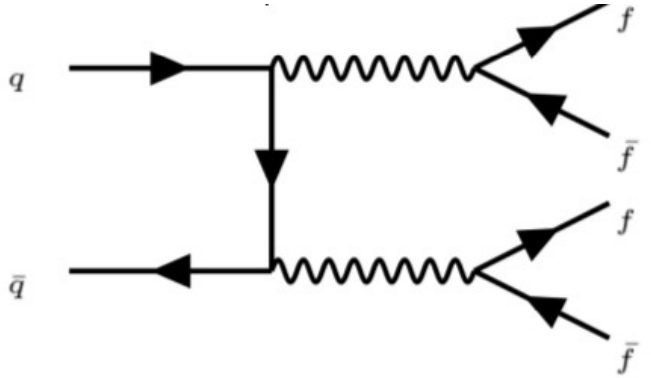
- A) The Physics Project: diboson production
  - Three recent measurements of WZ and ZZ production at 13 TeV
  - Limits on anomalous Triple Gauge Couplings
  - Vector Boson Scattering and probing of Quartic Gauge Couplings.
  - All results available at:
    https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

- B) The Trigger projects: online tracking with hardware
  - The Fast TracKer (FTK) phase I upgrade
  - The Hardware Track Trigger (HTT) phase II upgrade

# A) Diboson production - introduction

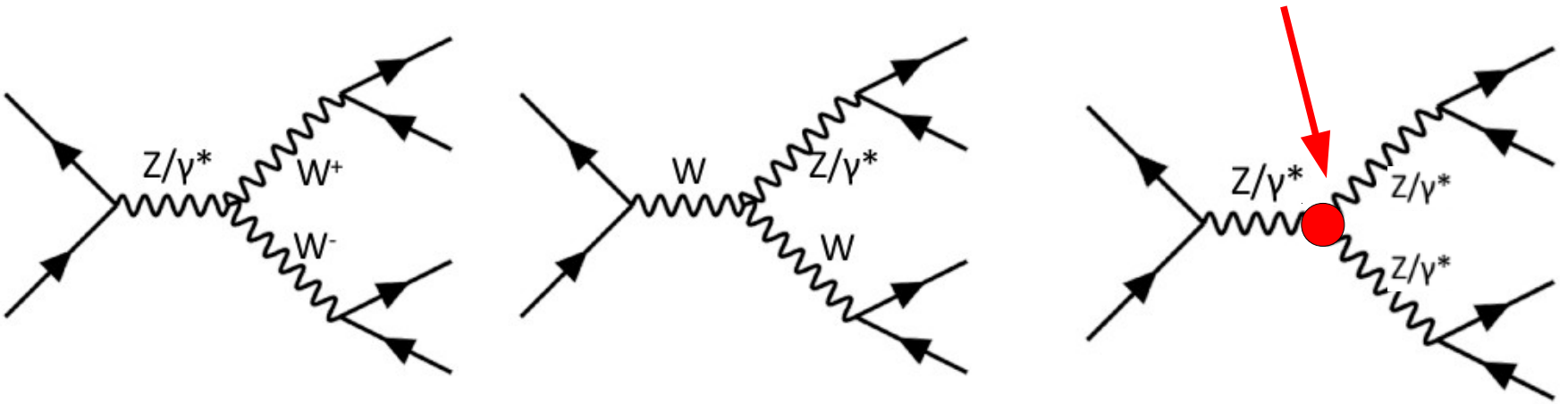
# LO EWK WW/WZ/ZZ production diagrams

- **At Leading Order with all ElectroWeak vertices**:



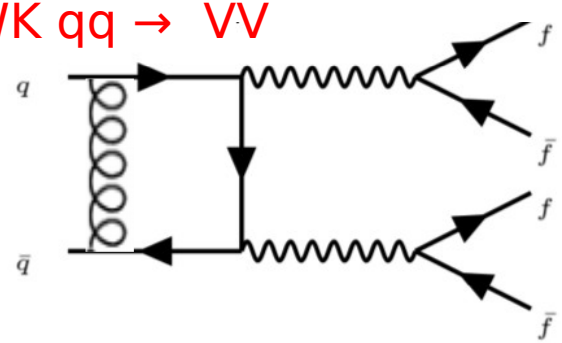

**LO EWK: 4 EWK vertices**

- Also, **Triple Gauge Couplings** (not there in SM when all three neutral):

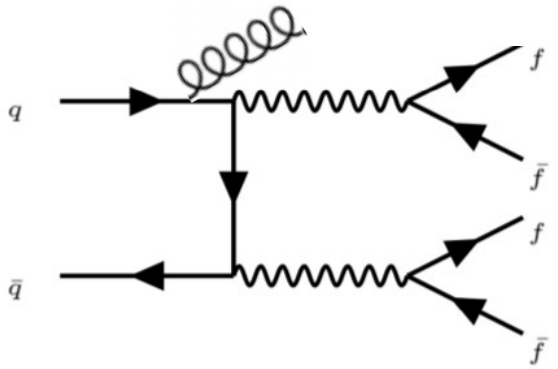


# With extra QCD vertices

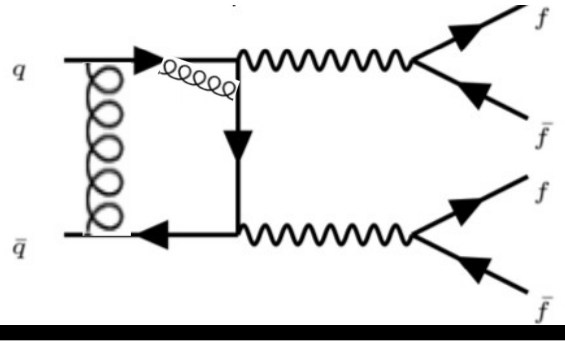
Interference with
LO EWK qq → VV

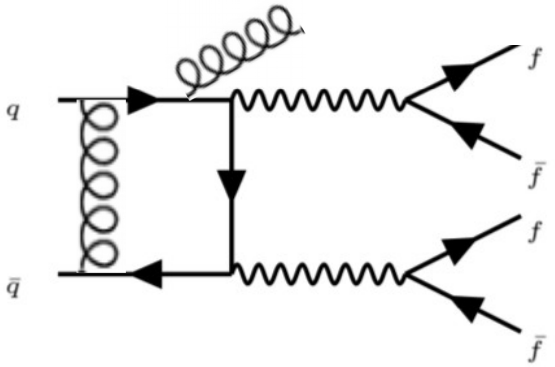



With external gluons:
VV + 1 jet



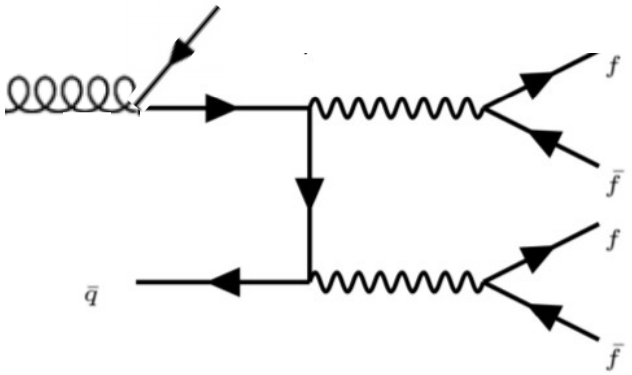

Internal gluons

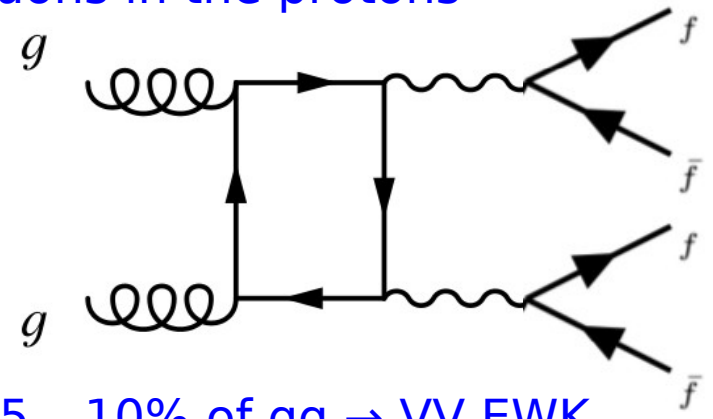



Internal + external
gluons:
VV + 1 jet

Also from gluons in the protons



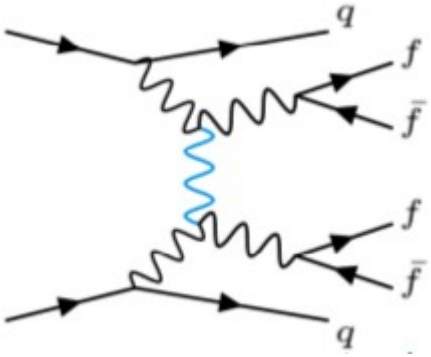




5 – 10% of qq → VV EWK

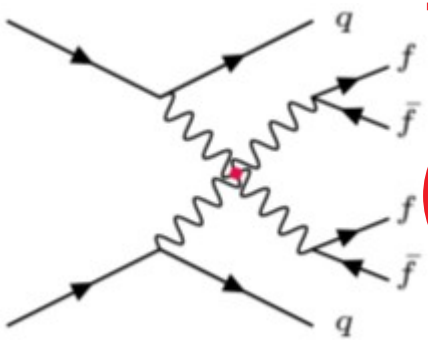
# With >=5 EWK vertices, get VV+2jets: ”Vector Boson Scattering” signature

**Vector Boson Scattering**: incoming quarks act as sources of colliding boson beams

**Signature: VV + 2 forward jets**

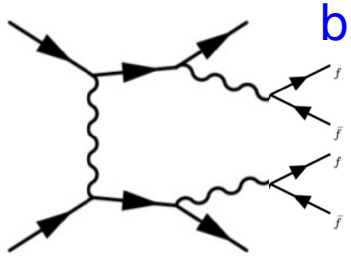



6 EWK vertices: not only vector bosons in the t-channel, but also the Higgs:
important for not letting the cross section explode at high energies (like the ZWW vertex was needed to limit the WW production cross section at e+ e- collisions at LEP)



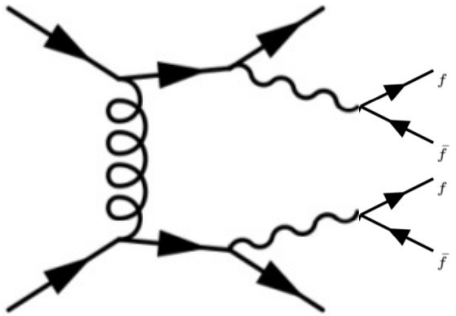

5 EWK vertices
**Quartic Gauge Couplings**:
again, SM does not allow all neutral in the quartic vertex

6 EWK vertices but not VBS...

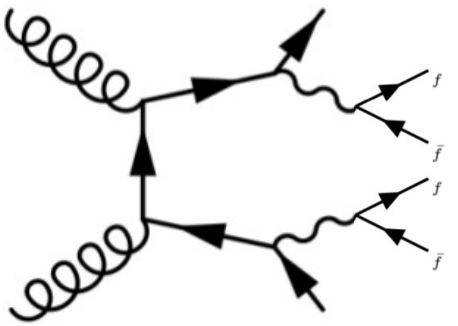



**4 EWK + 2 QCD vertices**:
same final state
→ important background

qq

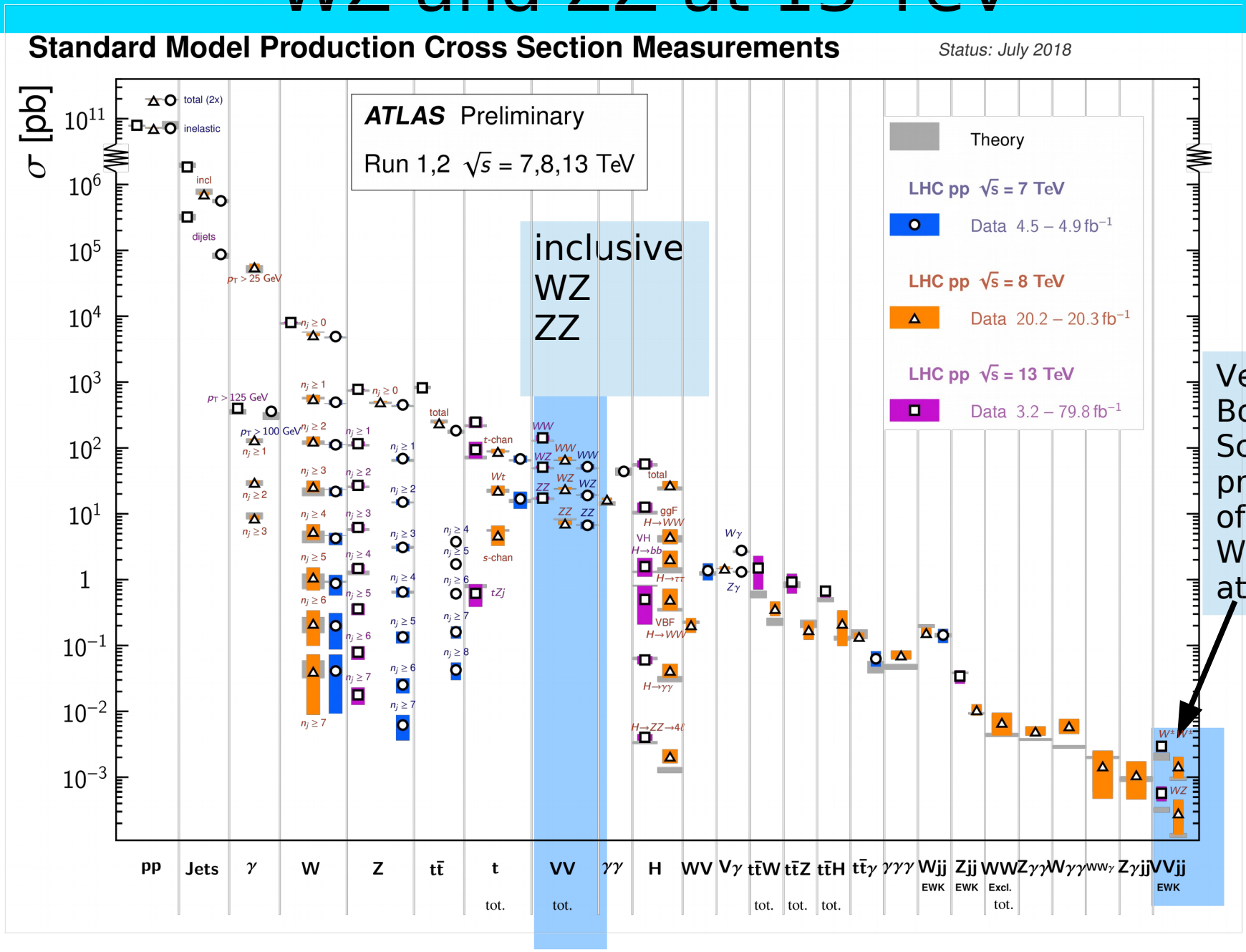



gg




+ ...

# WZ and ZZ at 13 TeV




https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

# A.2) ZZ and WZ production @ 13 TeV

All 13 TeV measurements so far are with leptonic states:

Increasing cross section

| | ZZ | WZ | WW |
|---|---|---|---|
| Signature: | 4 leptons | 3 leptons + MET(1ν) | 3 leptons + MET(2ν) |
| Backgrounds: | WZ + 1 fake lepton; WW / tt / Drell-Yan + 2 fake leptons | Drell-Yan + 1 fake lepton; ZZ (missing lepton); WW / tt +1 fake lepton | tt ; Drell-Yan |
| Signal purity: | ~98% | ~79% | ~70% |

Increasing purity

Thessaloniki (with Hellenic Open University in ZZ) in all ZZ and WZ analyses

# A.2.1) ZZ production

**"ZZ → 4l cross-section measurements and search for anomalous triple gauge couplings in 13 TeV pp collisions with the ATLAS detector"**

Phys. Rev. D 97 (2018) 032005

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-15/

# ZZ → 4l

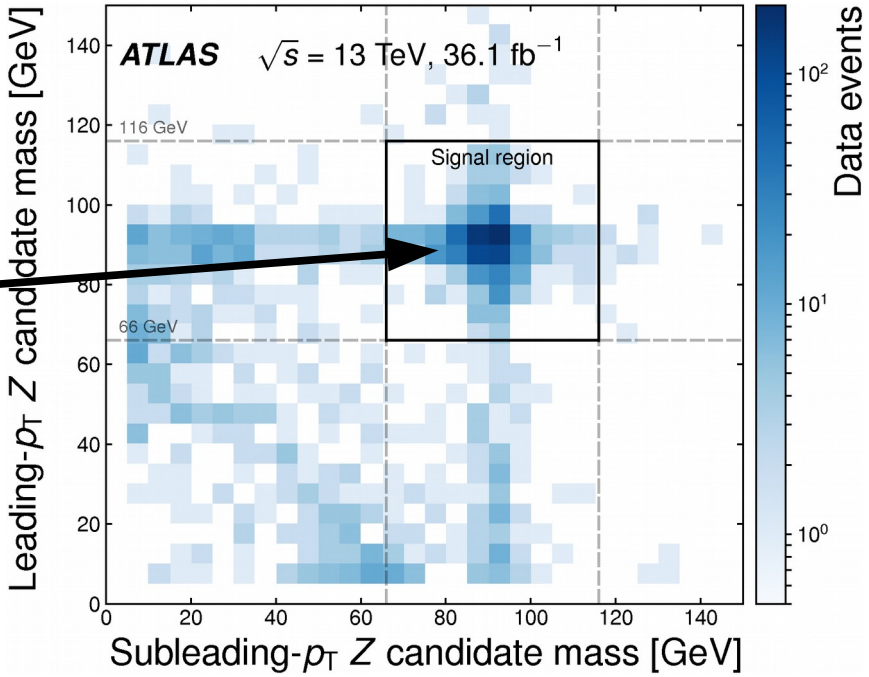
- 36.1 fb$^{-1}$ (2015+2016) √s = 13 TeV data
- Select events with at least 4 leptons with |η|<2.7, pT>20,>15,>10 GeV; the rest >5 GeV
- Only on-shell: 66 < $m_{ll}$ < 116 GeV
- Fully leptonic final state is very clean:

  21.2 bkg events (12.3 from fake leptons) out of 958 total event yield predicted

  – Main background from fake leptons (e.g. in Z + jet events)

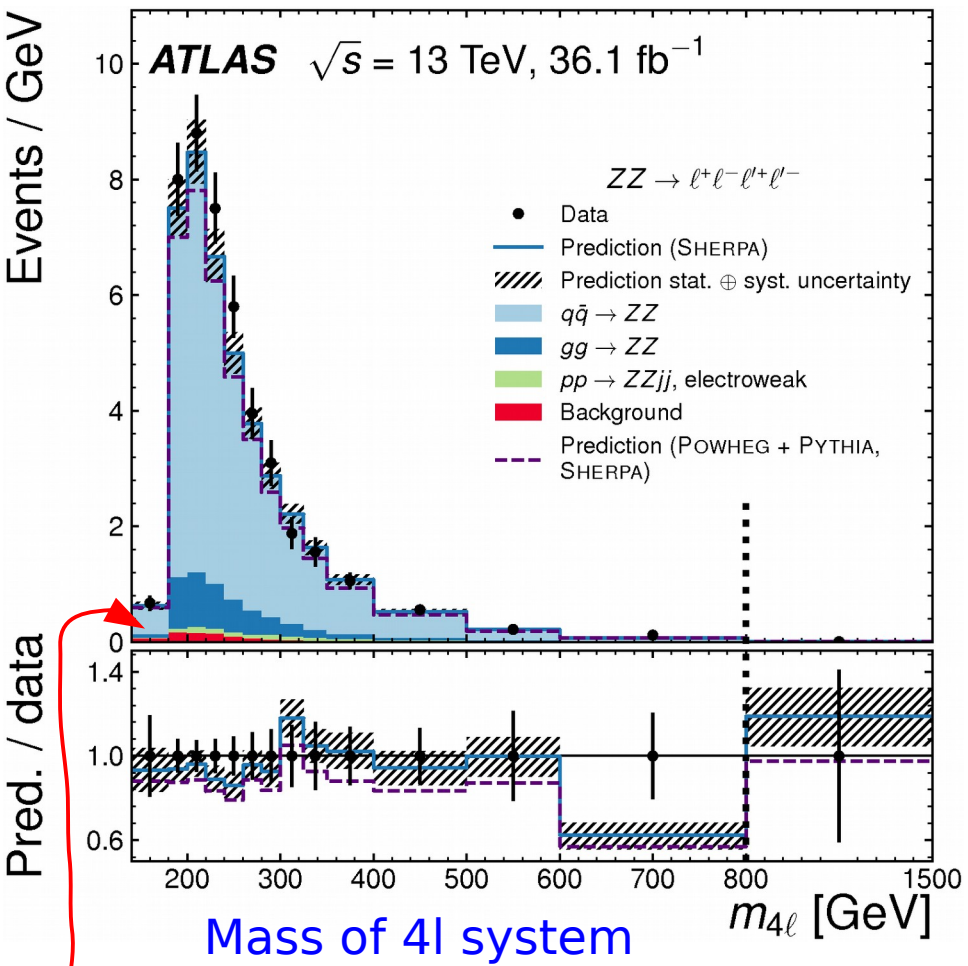
  – SM processes with >4 leptons treated as background (e.g. ZZZ → 6l)

A very pure channel: bkg ~2% of total



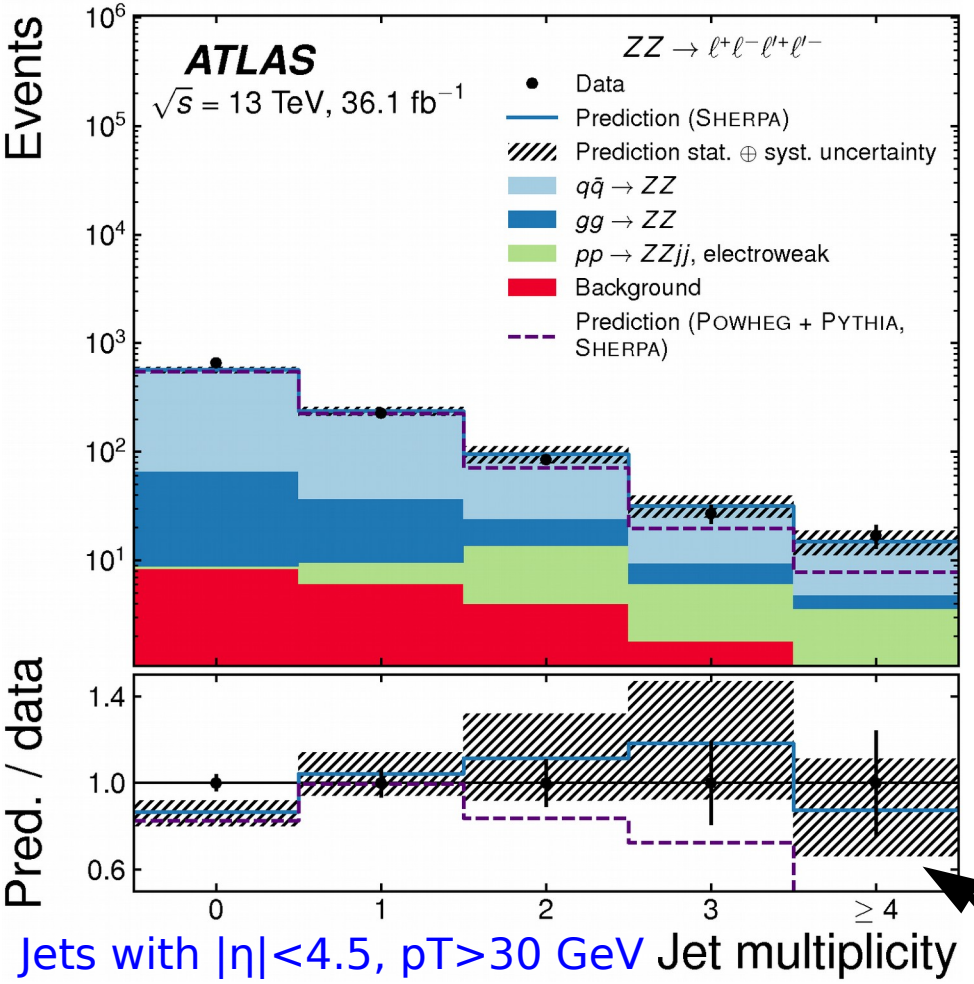

| Contribution | $4e$ | $2e2\mu$ | $4\mu$ | Combined |
|---|---|---|---|---|
| Data | 249 | 465 | 303 | 1017 |
| Total prediction (SHERPA) | $198^{+16}_{-14}$ | $469^{+35}_{-31}$ | $290^{+22}_{-21}$ | $958^{+70}_{-63}$ |
| Signal ($q\bar{q}$-initiated) | $168^{+14}_{-13}$ | $400^{+31}_{-28}$ | $246^{+19}_{-18}$ | $814^{+63}_{-57}$ |
| Signal ($gg$-initiated) | $21.3 \pm 3.5$ | $50.2 \pm 8.2$ | $29.7 \pm 4.9$ | $101 \pm 17$ |
| Signal (EW-$ZZjj$) | $4.36 \pm 0.42$ | $10.23 \pm 0.72$ | $6.43 \pm 0.55$ | $21.0 \pm 1.2$ |
| $ZZ \to \tau^+\tau^-[\ell^+\ell^-,\tau^+\tau^-]$ | $0.59 \pm 0.09$ | $0.55 \pm 0.08$ | $0.55 \pm 0.09$ | $1.69 \pm 0.16$ |
| Triboson | $0.68 \pm 0.21$ | $1.50 \pm 0.46$ | $0.96 \pm 0.30$ | $3.14 \pm 0.30$ |
| $t\bar{t}Z$ | $0.81 \pm 0.25$ | $1.86 \pm 0.56$ | $1.42 \pm 0.43$ | $4.1 \pm 1.2$ |
| Misid. lepton background | $2.1 \pm 2.1$ | $4.9 \pm 3.9$ | $5.3 \pm 5.2$ | $12.3 \pm 8.3$ |
| Total prediction (MATRIX + corrections) | $197^{+15}_{-14}$ | $470^{+34}_{-31}$ | $286^{+22}_{-21}$ | $953^{+69}_{-64}$ |
| Total prediction (POWHEG + PYTHIA with higher-order corrections, SHERPA) | $193 \pm 11$ | $456 \pm 24$ | $286 \pm 17$ | $934 \pm 50$ |

# ZZ → 4l, kinematics etc




Mass of 4l system

Background is small
and located
in low mass & low pT,
like most of the signal




~1000 observed events allow many distributions.
Sherpa prediction is nnNLO (missing e.g. NNLO versions of LO process) ... up to 3 jets in ME (0/1 are NLO, 2/3 are LO)
Powheg+Pythia does not follow at high jet multiplicities, due to lack of jets in ME

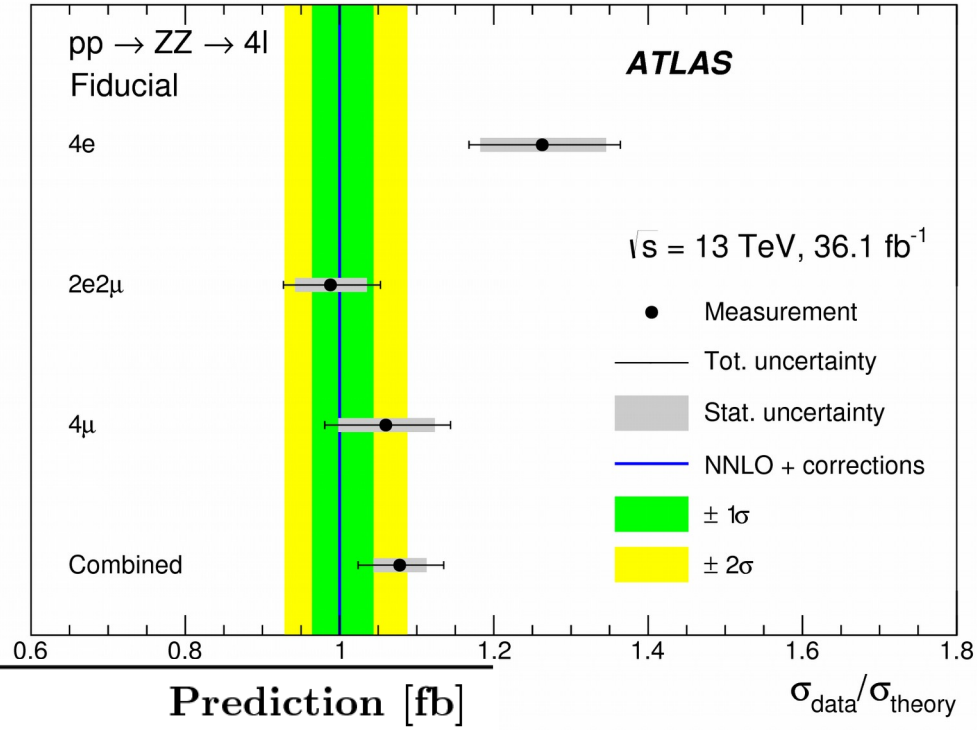
# ZZ fiducial cross section

- "Fiducial cross sections" reported: a fraction A of the total, corresponding to the reduced phase-space and the decay channels of the actual measurements (so it includes the Branching Ratios, BR)

$$\sigma^{fid}(pp \to VV + X, V \to leptons) = \frac{N - B}{L * C}$$

N-B: Observed events – bkg estimate
C: detector efficiency , L: integrated luminosity

- "NNLO + corrections":
  - NNLO calculation from Matrix
  - gg-initiated contribution (Sherpa) multiplied by a global NLO correction factor of 1.67.
  - global NLO EW correction factor of 0.95, except to the gg-initiated loop-induced contribution, and the contribution of around 2.5% from EW-ZZjj generated with Sherpa is added.




| Channel | Measurement [fb] | Prediction [fb] |
|---|---|---|
| $4e$ | $13.7^{+1.1}_{-1.0}$ $[\pm 0.9\ (\text{stat.})\ \pm 0.4\ (\text{syst.})\ ^{+0.5}_{-0.4}\ (\text{lumi.})]$ | $10.9^{+0.5}_{-0.4}$ |
| $2e2\mu$ | $20.9^{+1.4}_{-1.3}$ $[\pm 1.0\ (\text{stat.})\ \pm 0.6\ (\text{syst.})\ ^{+0.7}_{-0.6}\ (\text{lumi.})]$ | $21.2^{+0.9}_{-0.8}$ |
| $4\mu$ | $11.5^{+0.9}_{-0.9}$ $[\pm 0.7\ (\text{stat.})\ \pm 0.4\ (\text{syst.})\ \pm 0.4\ (\text{lumi.})]$ | $10.9^{+0.5}_{-0.4}$ |
| Combined | $46.2^{+2.5}_{-2.3}$ $[\pm 1.5\ (\text{stat.})\ ^{+1.2}_{-1.1}(\text{syst.})\ ^{+1.6}_{-1.4}\ (\text{lumi.})]$ | $42.9^{+1.9}_{-1.5}$ |

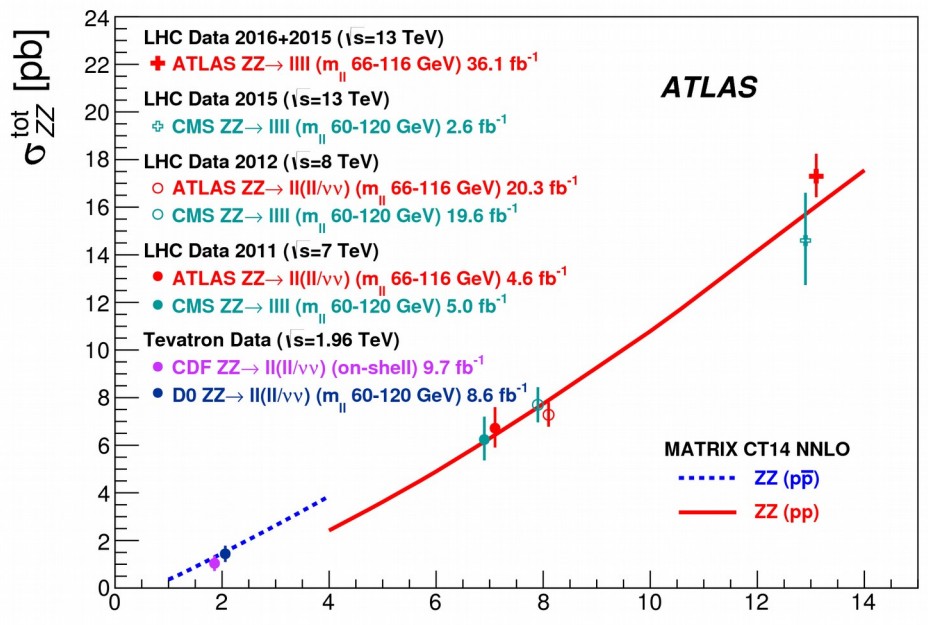
- Statistics limited, dominant systematics lepton identification/reconstruction efficiencies (tension in 4e channel)

# ZZ total cross section & differential fiducial

- Fiducial measurement extrapolated to "total cross sections" by correcting for the BRs and the Acceptance, A.
- Total pp → ZZ production:

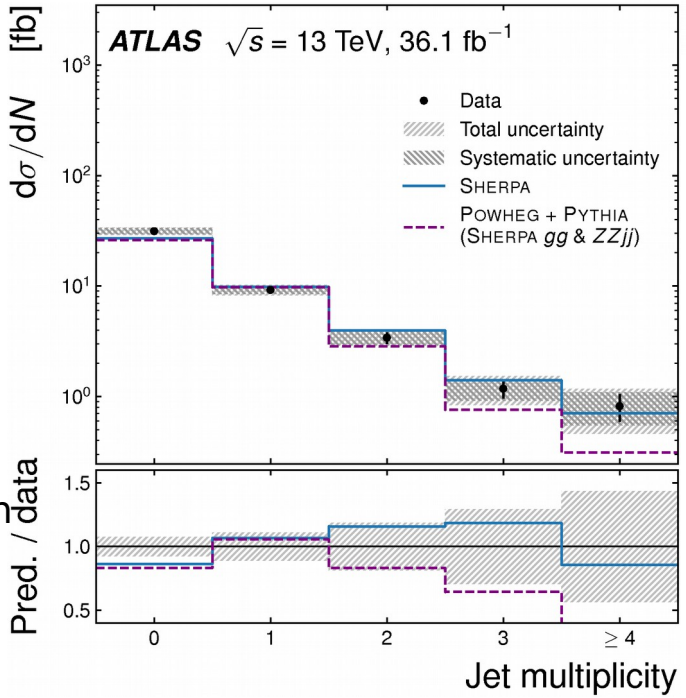
$$17.3 \pm 0.9\ [\pm 0.6\ (\text{stat.}) \pm 0.5\ (\text{syst.}) \pm 0.6\ (\text{lumi.})]\ \text{pb}$$

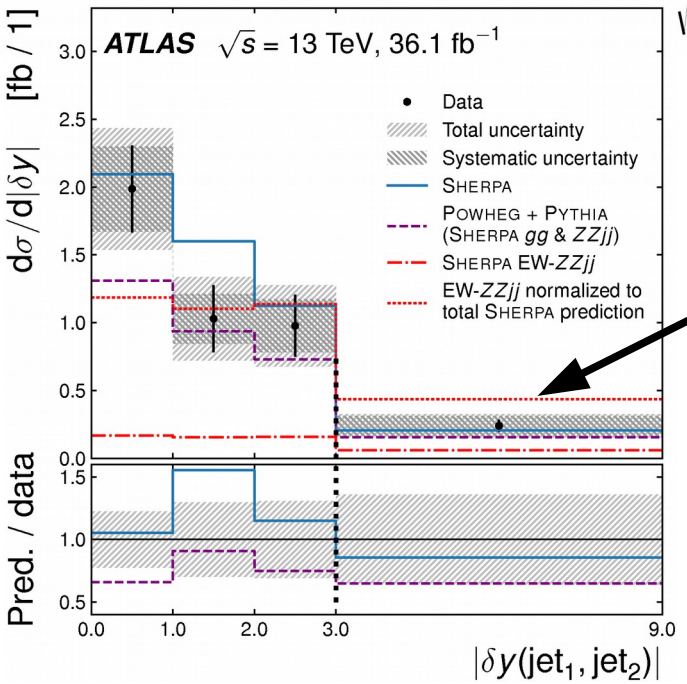
- (Fiducial) differential cross-sections provided in 20 variables, a lot of them for first time:



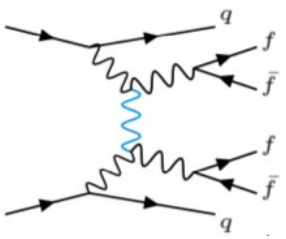

nnNLO Sherpa vs. NLO POWHEG

(Powheg does not follow at high jet muliplicities: parton emission at Matrix-Element level necessary




Large distance in rapidity between jets: important for VBS topology



# A.2.2) Inclusive WZ production

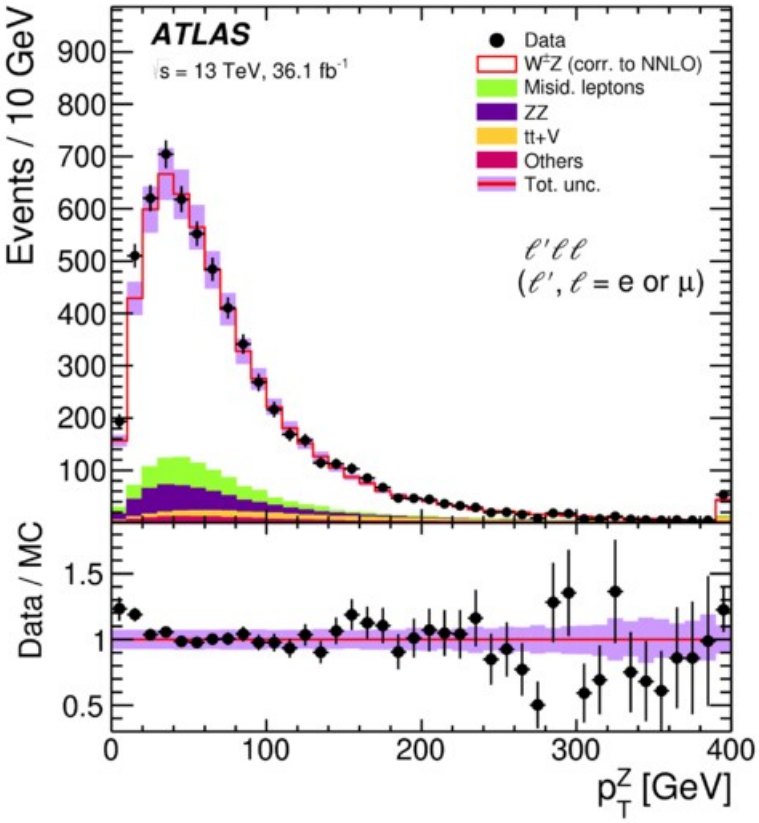
**"Measurement of $W^{\pm}Z$ production cross sections and gauge boson polarisation in pp collisions at $s=\sqrt{13}$ TeV with the ATLAS detector"**

https://arxiv.org/abs/1902.05759 , submitted to EPJC

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2018-03/

# WZ → 3l ν : fiducial cross section

- 36.1 fb$^{-1}$ $\sqrt{s}$ = 13 TeV data
- Includes 3e, 3μ, μ2e, and e2μ final states
- Biggest uncertainty from fake-lepton estimate (3% , from a total of ~7% )




| Channel | *eee* | | *μee* | | *eμμ* | | *μμμ* | | All | |
|---|---|---|---|---|---|---|---|---|---|---|
| Data | 1279 | | 1281 | | 1671 | | 1929 | | 6160 | |
| Total Expected | 1221 | ± 7 | 1281 | ± 6 | 1653 | ± 8 | 1830 | ± 7 | 5986 | ± 14 |
| $WZ$ | 922 | ± 5 | 1077 | ± 6 | 1256 | ± 6 | 1523 | ± 7 | 4778 | ± 12 |
| Misid. leptons | 138 | ± 5 | 34 | ± 2 | 193 | ± 5 | 71 | ± 2 | 436 | ± 8 |
| $ZZ$ | 86 | ± 1 | 89 | ± 1 | 117 | ± 1 | 135 | ± 1 | 426 | ± 3 |
| $t\bar{t}$+V | 50.0 | ± 0.7 | 54.0 | ± 0.7 | 56.1 | ± 0.7 | 63.8 | ± 0.8 | 225 | ± 1 |
| $tZ$ | 23.1 | ± 0.4 | 24.8 | ± 0.4 | 28.8 | ± 0.4 | 33.5 | ± 0.5 | 110 | ± 1 |
| $VVV$ | 2.5 | ± 0.1 | 2.8 | ± 0.1 | 3.2 | ± 0.1 | 3.6 | ± 0.1 | 12.0 | ± 0.1 |

- From event count

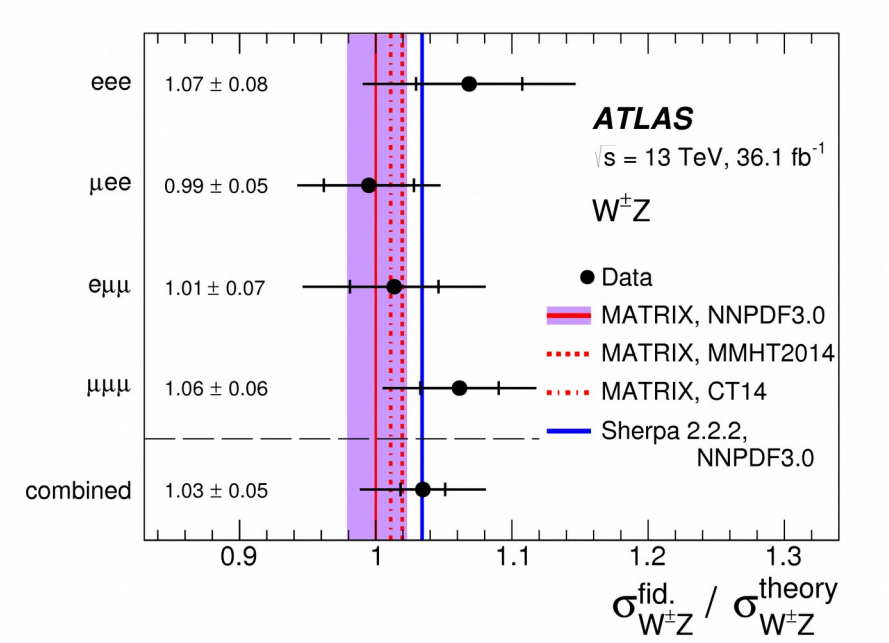
  (Nobs = 6160 , with NexpectedBkg = 1208)

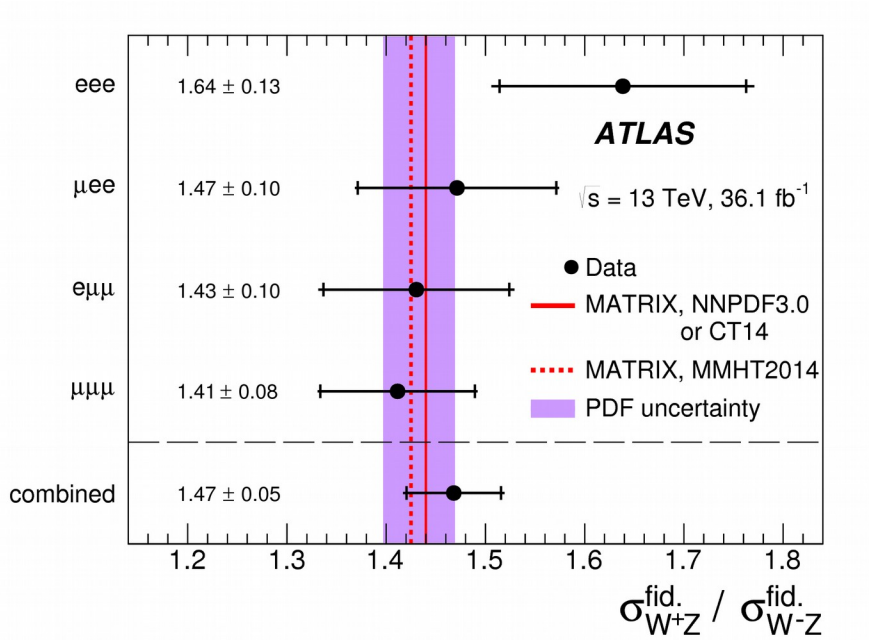
  to fiducial cross section:

$$\sigma^{\text{fid.}}_{W^{\pm}Z\to\ell'\nu\ell\ell} = 63.7 \pm 1.0\,(\text{stat.}) \pm 2.3\,(\text{syst.}) \pm 1.4\,(\text{lumi.})\ \text{fb}$$

# WZ → 3l ν : ratios of W+ Z & W- Z

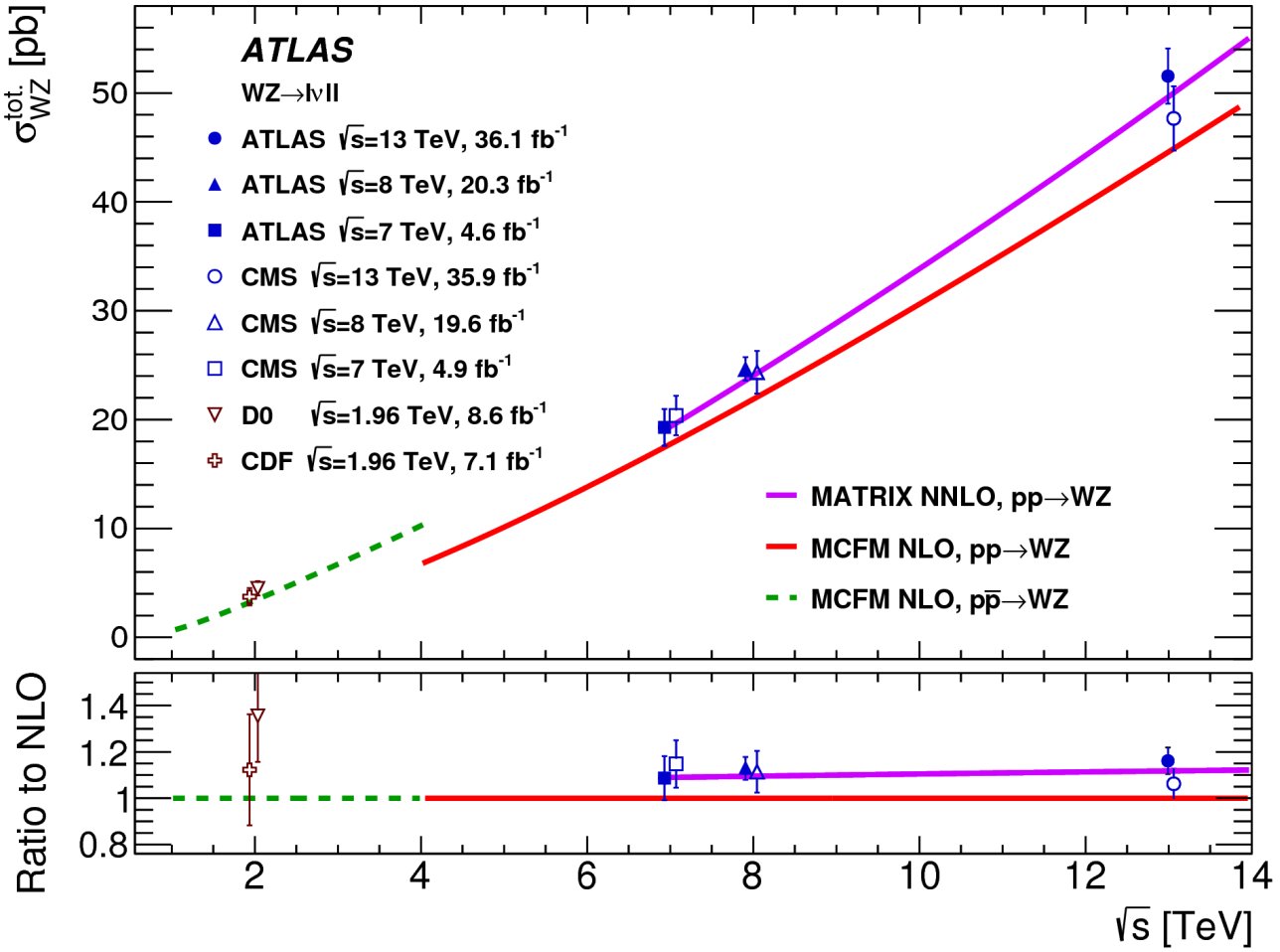
- 36.1 $fb^{-1}$  $\sqrt{s}$ = 13 TeV data
- W+ Z and W- Z  compared to theory and to each other (ratio sensitive to PDFs)
- Theoretical predictions: NNLO QCD from MATRIX & NLO QCD from Sherpa



# WZ → 3l ν : total cross section

- 36.1 fb$^{-1}$ $\sqrt{s}$ = 13 TeV data
- W Z cross section extrapolated to total phase-space and comparison to theory



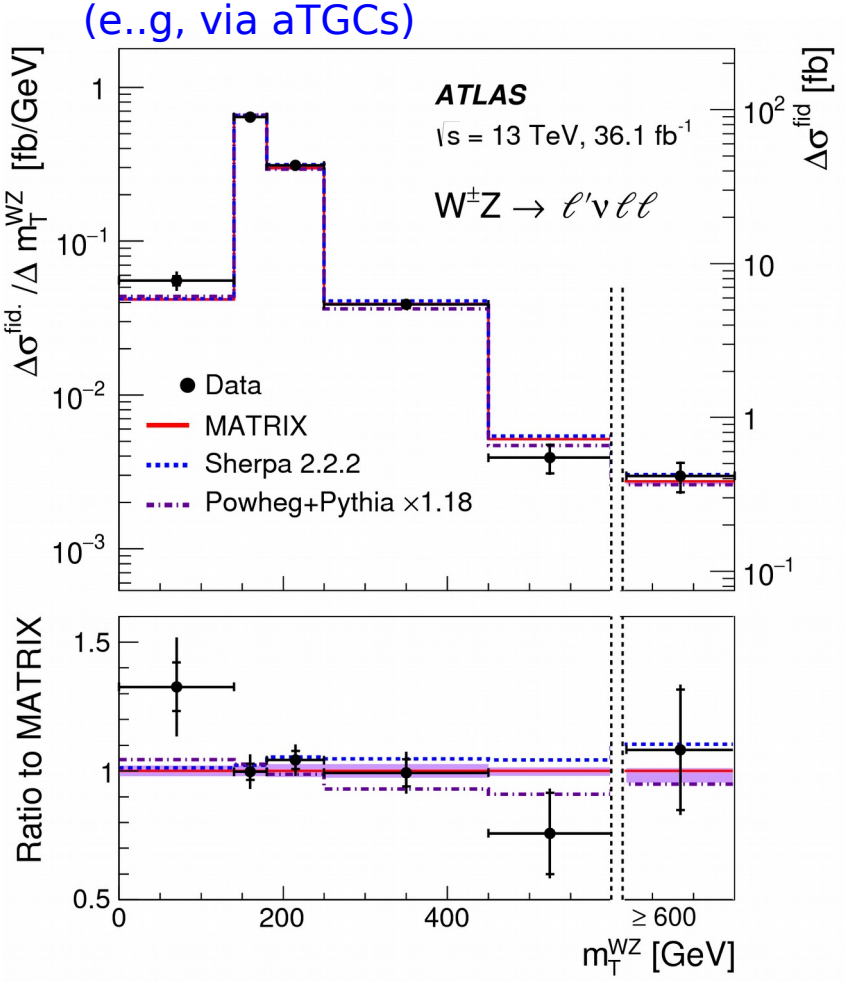

The need for the extra order in QCD calculations is evident.

Measurements are in agreement with these NNLO QCD predictions

# WZ → 3l ν : differential fiducial cross sections

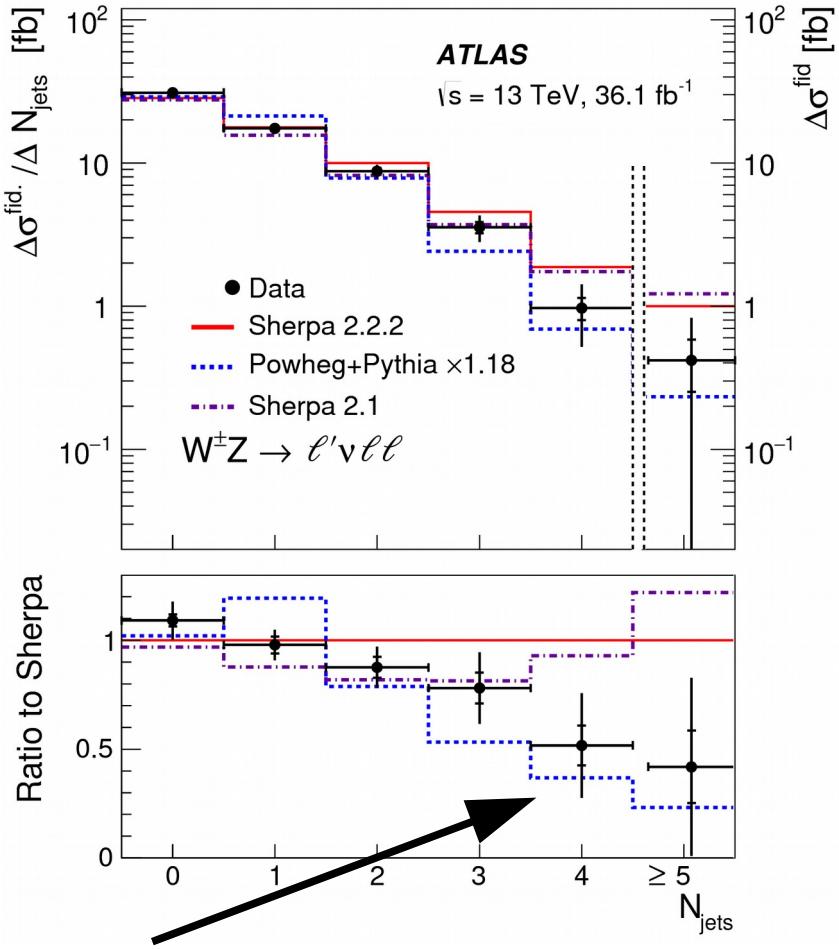
- Differential fiducial cross section measured as well: in $p_T^Z$ , $m_T^{WZ}$ , $N_{jets}$

$m_T$(WZ) sensitive to New Physics (e..g, via aTGCs)




There was need to enhance by 18% the Powheg+Pythia prediction to match the data

Njets sensitive to QCD modelling




Powheg needs extra jets in Matrix Element
(Powheg+Pythia does not follow data,
While Sherpa2.2 does, as we also saw in ZZ)

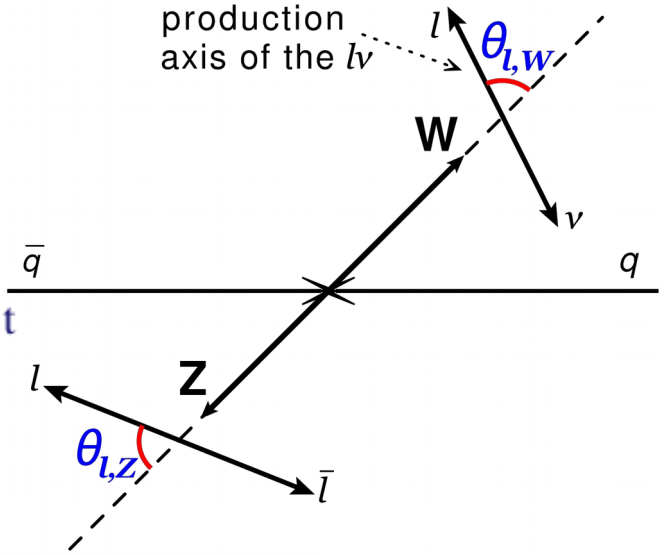
# WZ → 3l ν : boson polarization fractions

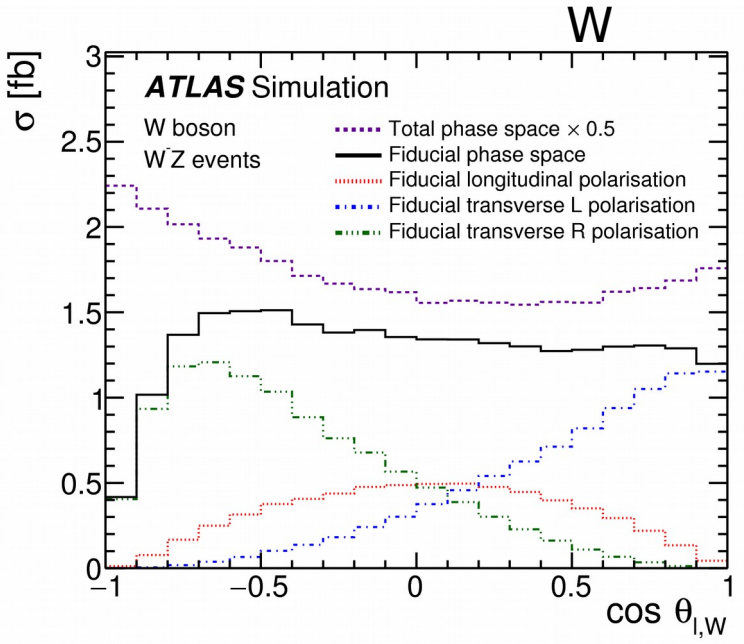
- Gauge-Boson polarization determined from angular distribution of decay leptons
- For the W (and similarly for the Z):

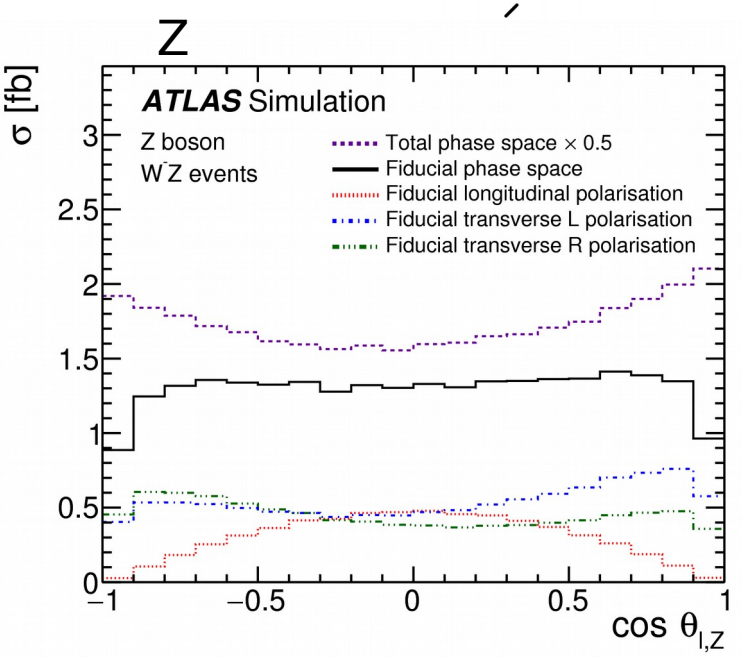
$$\frac{1}{\sigma_{W^{\pm}Z}}\frac{d\sigma_{W^{\pm}Z}}{d\cos\theta_{l,W}} = \frac{3}{8}f_L(1 \mp \cos\theta_{l,W}) + \frac{3}{8}f_R(1 \pm \cos\theta_{l,W}) + \frac{3}{4}f_0\sin^2\theta_{l,W}$$

$\theta_{l,W}$ ⇒ decay angle in the $W^{\pm}$ rest frame of the charged lepton w.r.t the $W^{\pm}$ in the $W^{\pm}Z$ centre-of-mass frame

$f_L, f_R, f_0$ ⇒ helicity fractions



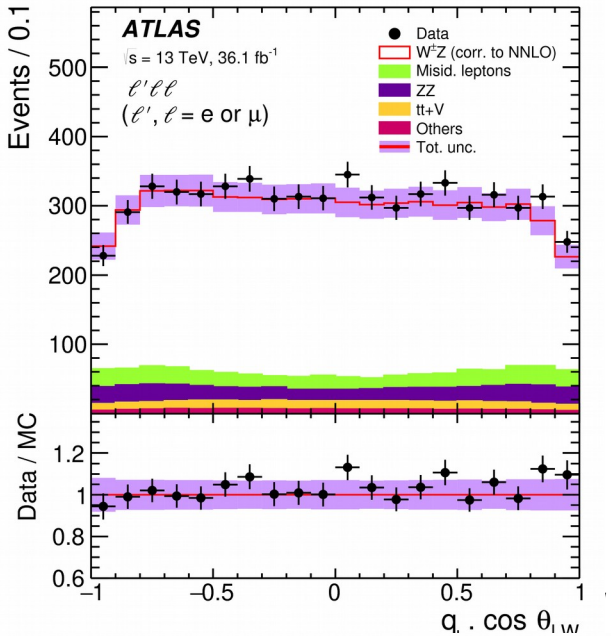



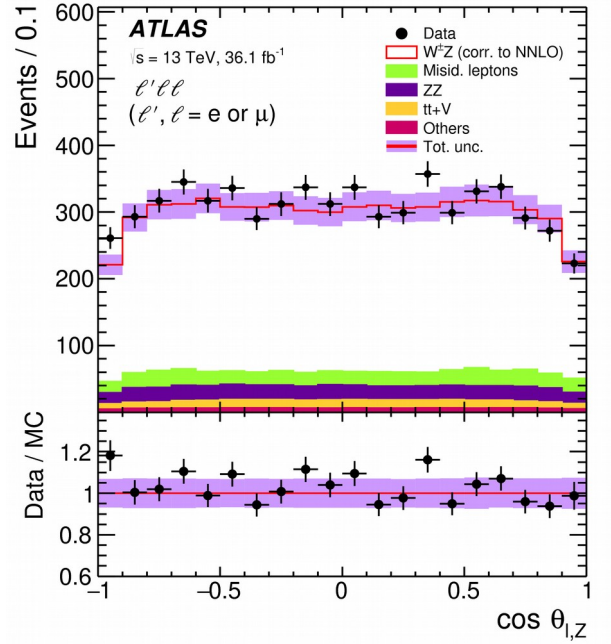

Templates at particle level

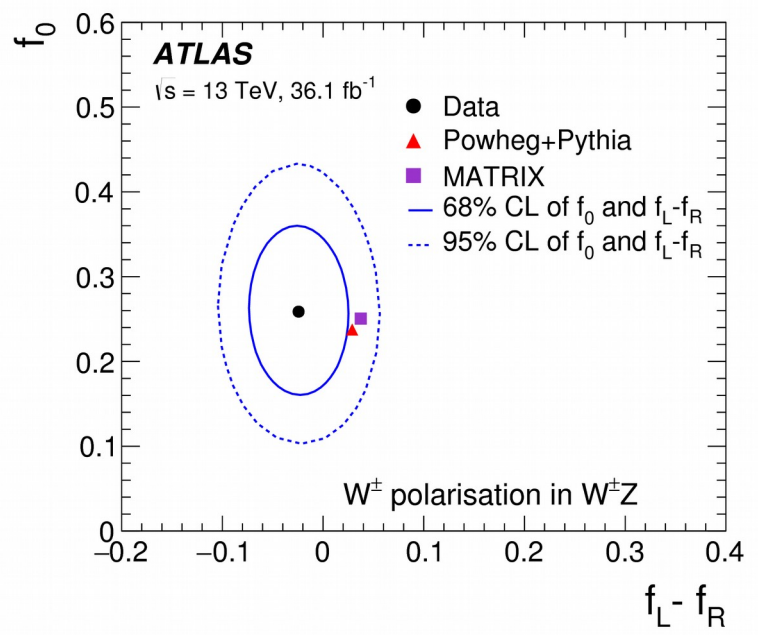
Already sculpted by pT and η fiducial requirements

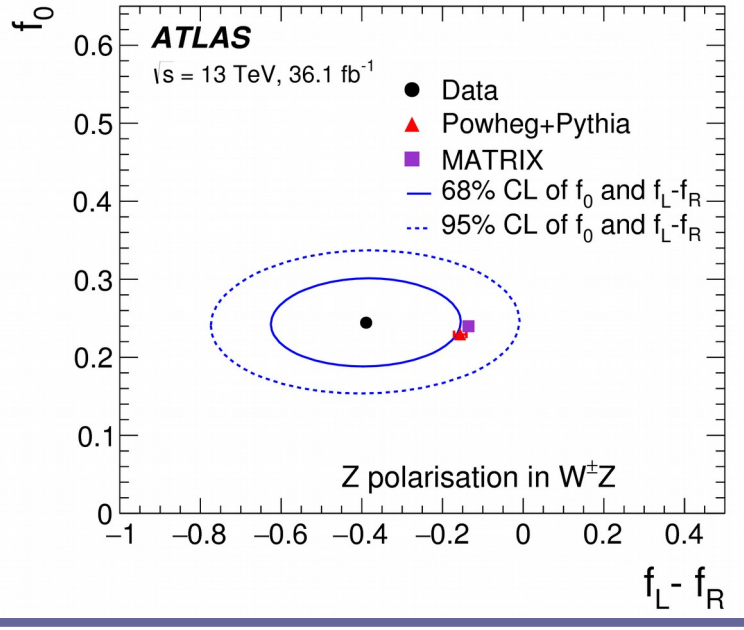
# WZ → 3l ν : boson polarization fractions

Templates at reconstruction level from Powheg + Pythia8 compared to data



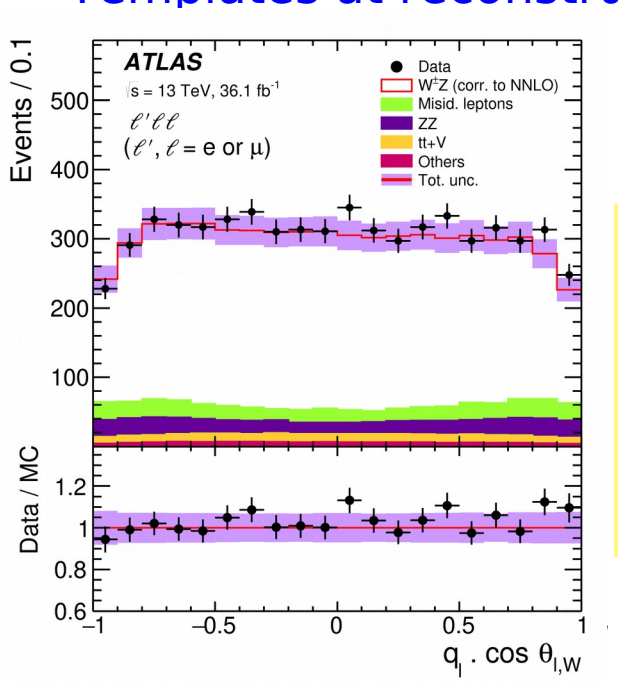



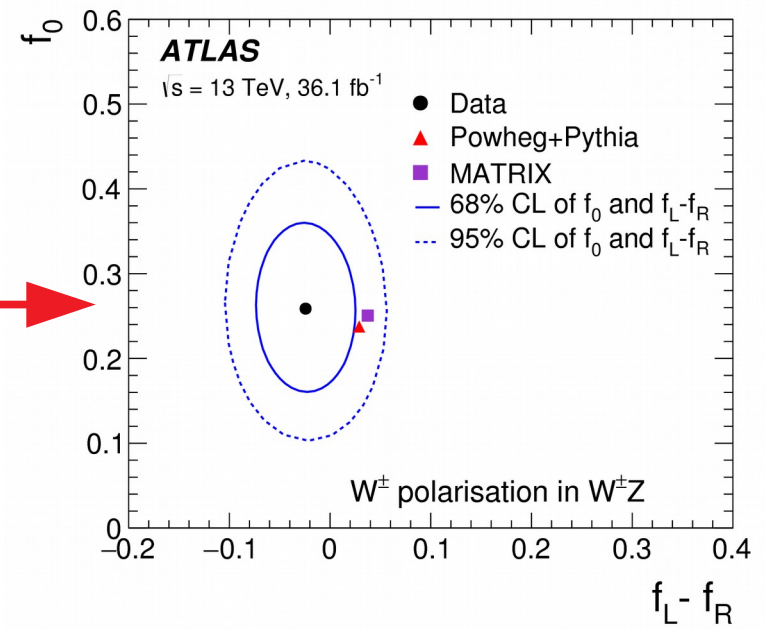



# WZ → 3l ν : boson polarization fractions

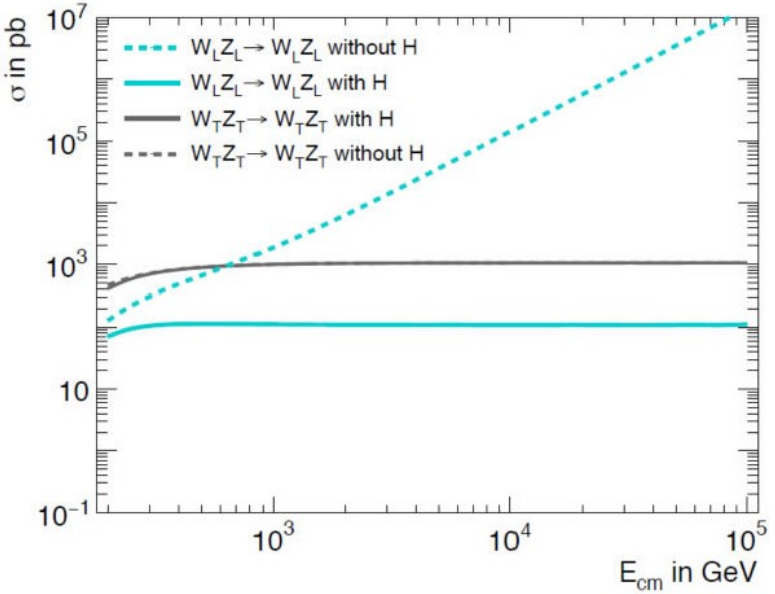
Templates at reconstruction level from Powheg + Pythia8 compared to data




Evidence for Longitudinaly polarized W's
obserced: 4.2σ
(expected: 3.8σ),
statistically limited




Important,
Because we know that without the Higgs the WZ production cross section would explode



# WZ → 3l ν : boson polarization fractions

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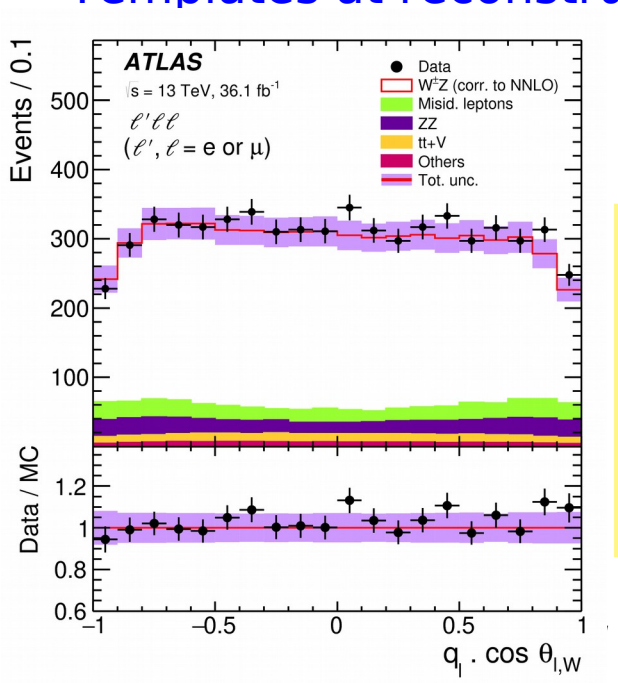


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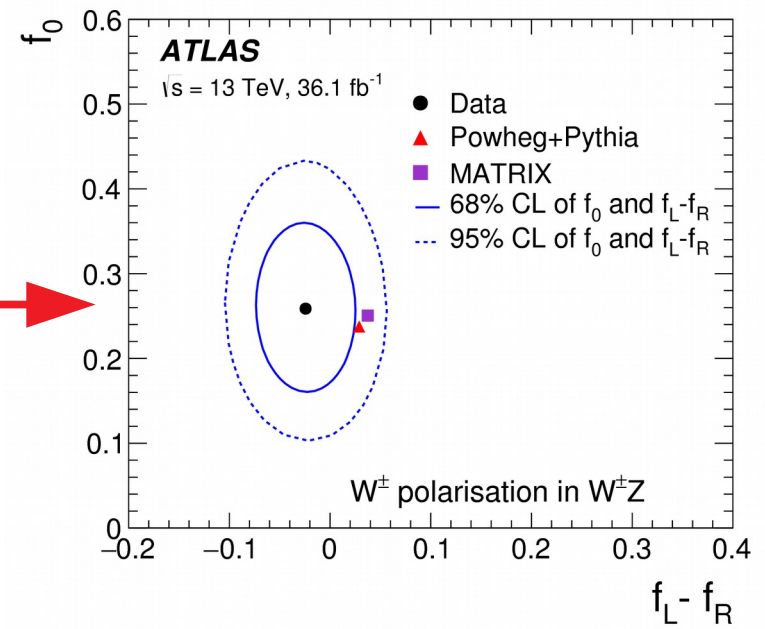


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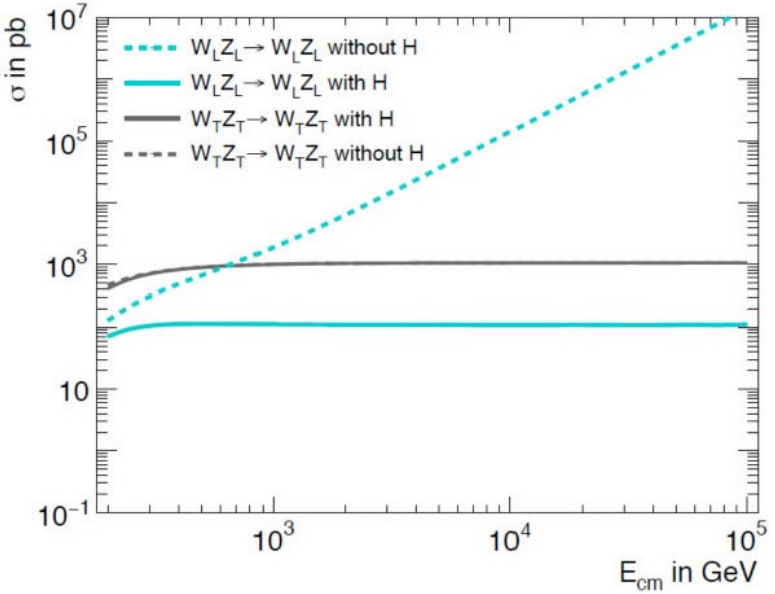


# A.2.3) Electroweak WZ production

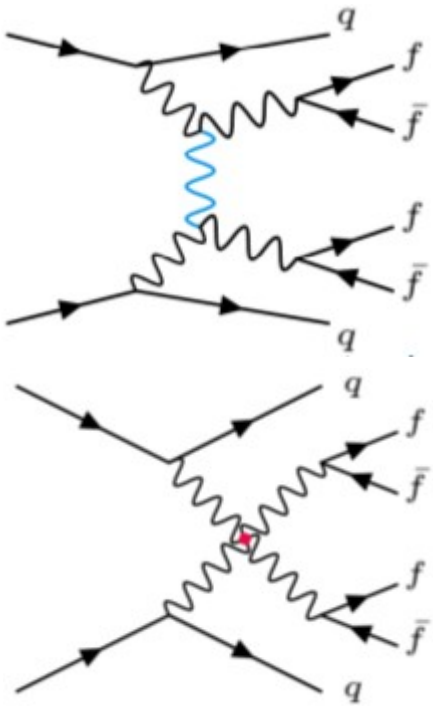
**"Observation of electroweak $W^{\pm}Z$ boson pair production in association with two jets in pp collisions at $\sqrt{s}$ = 13TeV with the ATLAS Detector"**

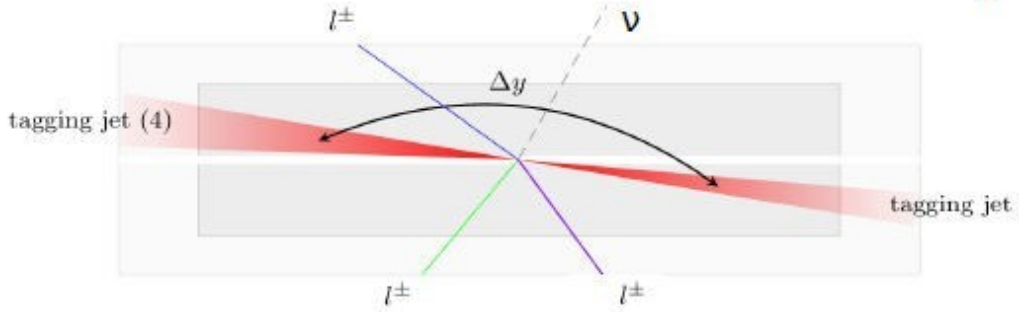
https://arxiv.org/abs/1812.09740 submitted to PLB

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-20/

# WZ → 3l ν : EWK-enhanced production in VBS topology

- 36.1 fb$^{-1}$ $\sqrt{s}$ = 13 TeV data




| | SR |
|---|---|
| Data | 161 |
| Total predicted | 167 ± 11 |
| $WZjj$–EW (signal) | 44 ± 11 |
| $WZjj$–QCD | 91 ± 10 |
| Misid. leptons | 7.8 ± 3.2 |
| $ZZjj$–QCD | 11.1 ± 2.8 |
| $tZj$ | 6.2 ± 1.1 |
| $t\bar{t}+V$ | 4.7 ± 1.0 |
| $ZZjj$–EW | 1.80 ± 0.45 |
| $VVV$ | 0.59 ± 0.15 |

$$\sigma^{\text{fid.}}_{W^{\pm}Zjj} = 68 \pm 0.25 \text{ fb}$$

$$\sigma^{\text{fid.}}_{WZjj-\text{EW}} = 0.57\ ^{+0.14}_{-0.13}\text{(stat.)}\ ^{+0.05}_{-0.04}\text{(exp. syst.)}\ ^{+0.05}_{-0.04}\text{(mod. syst.)}\ ^{+0.01}_{-0.01}\text{(lumi.) fb}$$

A 5.3σ Observation (3.2 expected)

For details , see Iro Koletsou's talk, later today

# A lesson from comparing the measurements to theory perdictions

- Overall good agreement with the Standard Model
  - NNLO QCD improves agreement substantially
  - NNLO reduces uncertainty to 10~20% from NLO at 60% (arXiv: 1604.08576)
- Almost all recent measurements are limited by systematic uncertainties (only ZZ is almost equal to statistics)
- These and many more results in:

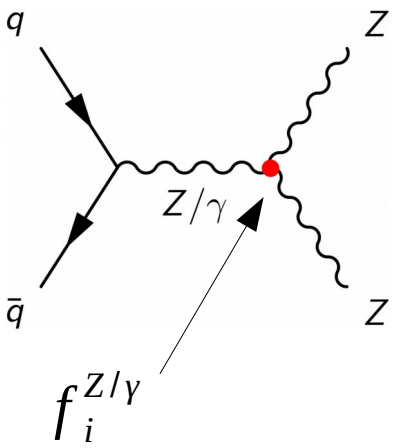
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

# A.3. Anomalous Gauge Couplings (Triple or Quartic : aTGCs or aQGCs)

# anomalous Triple Gauge Couplings (aTGCs), 1

- "Traditional", effective Lagrangian, approach: add terms to the SM Lagrangian to describe the Triple Gauge vertices; the deviation of the triple vector boson couplings from the SM predicted values are introduced as dimensionless anomalous couplings:
  - For the WW+Z/γ vertices, 5 parameters: $\Delta g_1^Z$ , $\Delta\kappa_Z$ , $\lambda_Z$ , $\Delta\kappa_\gamma$ , $\lambda_\gamma$

    * Just 3 in LEP scenario: $\lambda_\gamma = \lambda_Z$, $\Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma$
  - For the ZZ+Z/γ vertices: $f_4^\gamma$, $f_4^Z$, $f_5^\gamma$, $f_5^Z$



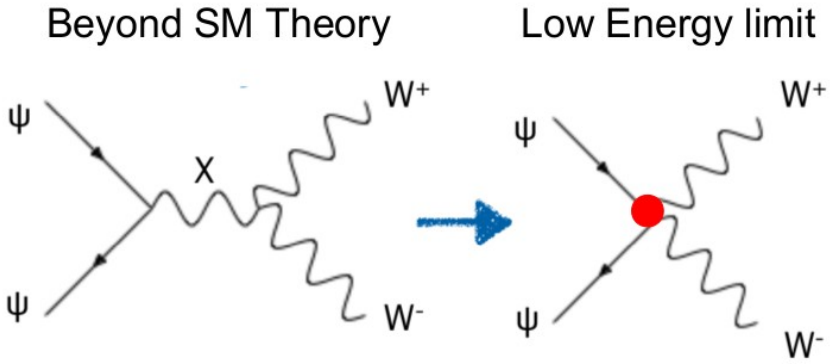

- The contribution of anomalous couplings to the diboson production cross section grows with the partonic centre-of-mass energy s-hat , and quadratically with the TGC value.
- Anomalous TGCs will lead to excesses in high-end tails of sensitive observables, related to the s-hat of the partonic system

With one aTGC active:

$$d\sigma_{SM+TGC} = F_0 + fF_1 + f^2F_2$$

# anomalous Triple Gauge Couplings (aTGCs), 2

- Effective Field Theory (EFT) approach: Standard Model is the low energy limit of a more fundamental theory at scale $\Lambda \gg \sqrt{s}$




At low energies (E << Λ) interactions between SM fields only look like Fermi's contact interaction (which was indeed valid when much below W mass scale)

Add to the SM Lagrangian a linear combination of operators of mass dimension higher than four. Independent operators can lead to anomalous triple vector boson couplings.

$$L_{EFT} = L_{SM} + \sum_{d \geqslant 5} L^d_{EFT} \text{ with } L^d_{EFT} = \sum_i \frac{C^d_i}{\Lambda^{d-4}} O^d_i$$

The dimensionless coefficients $C_i$ represent the strength of the new couplings.

Charged TGC: first contributing operators have dimension 6 ⇒ coupling parameters c/ $\Lambda^2$

Neutral TGC: first contributing operators have dimension 8 ⇒ coupling parameters c/ $\Lambda^4$

There is a one-to-one mapping between EFT coupling parameters and traditional aTGCs

e.g:

Traditional $\Leftrightarrow$ EFT

$$g_1^Z = 1 + c_W \frac{m_Z^2}{2\Lambda^2}$$

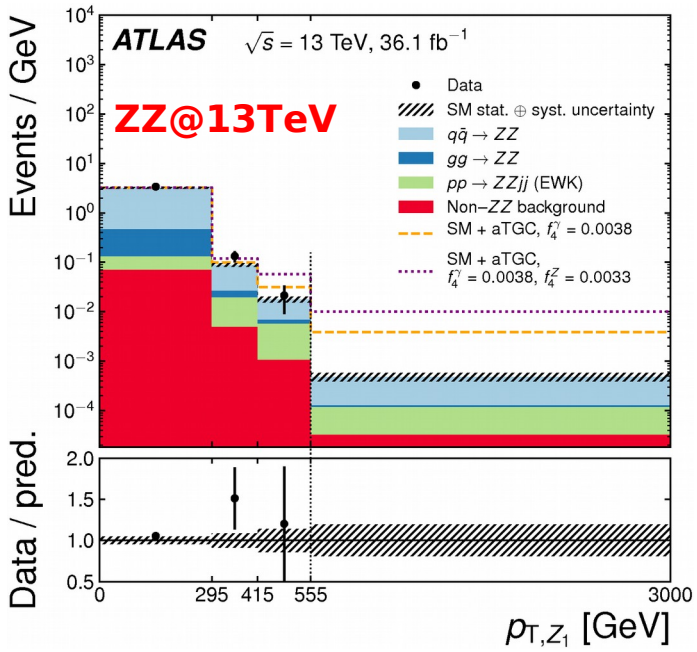
$$\kappa_\gamma = 1 + (c_W + c_B) \frac{m_W^2}{2\Lambda^2}$$

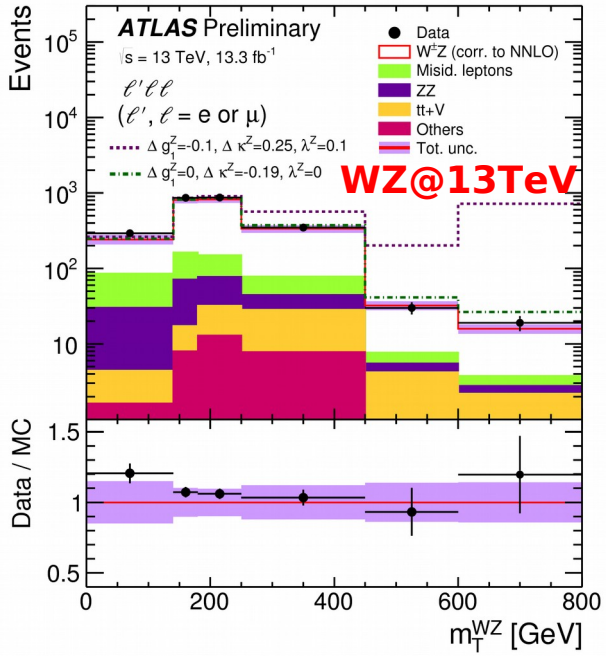
$$\kappa_Z = 1 + (c_W - c_B \tan^2\theta_W) \frac{m_W^2}{2\Lambda^2}$$

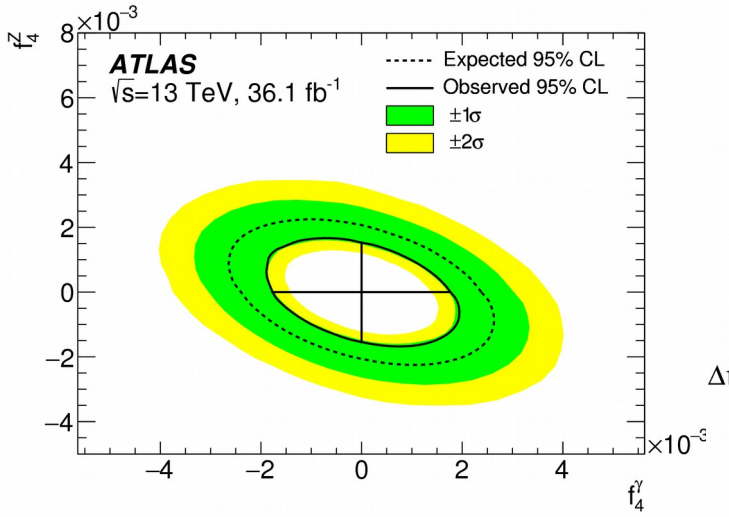
$$\lambda_\gamma = \lambda_Z = c_{WWW} \frac{3g^2 m_W^2}{2\Lambda^2}$$

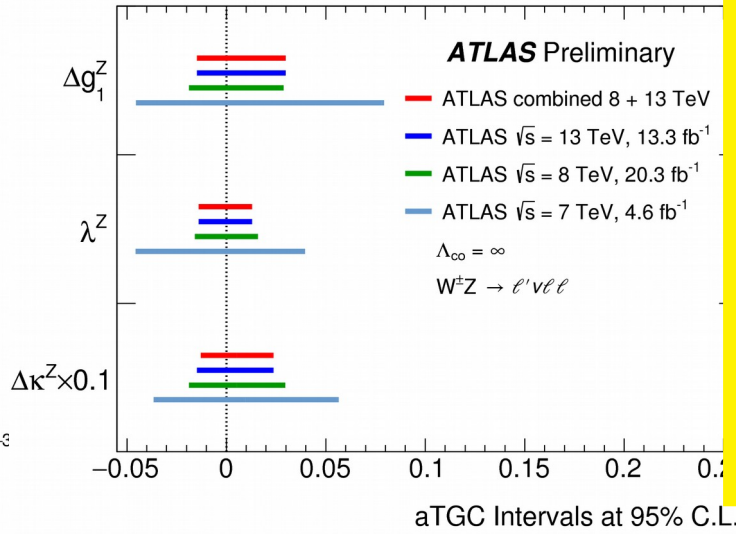
# aTGCs from ZZ, WZ

- Anomalous TGCs will lead to enhanced event yields in high-end tails of sensitive observables, related to the s-hat of the partonic system system.




In the EFT approach,
There are many operators
Potentially contributing
To the Beyond the SM
Part of the Lagrangian:

Check which Operators
Can single-handendly
Produce an observable
Enhancement

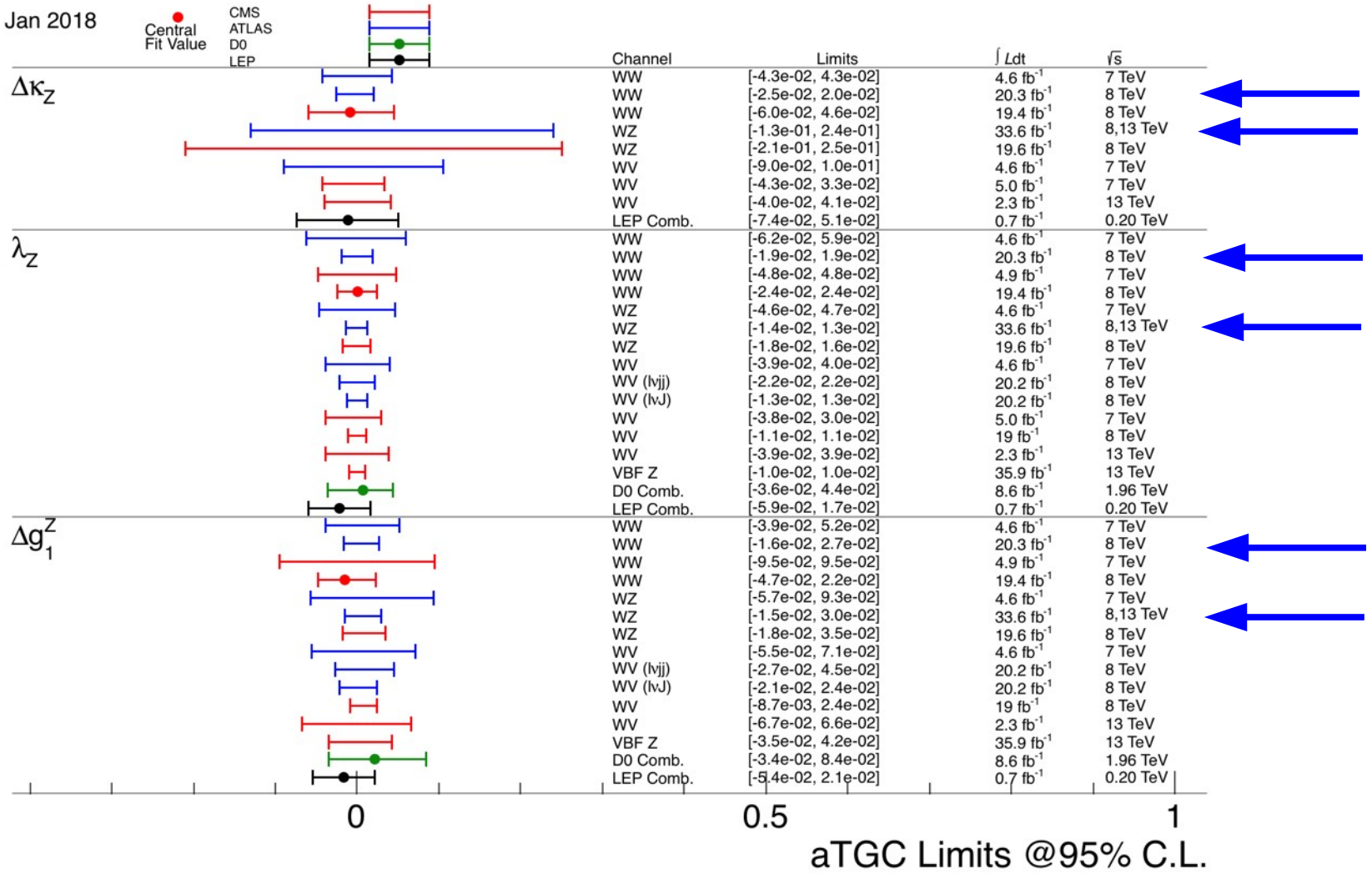
Absence of such an
Enhancement set
Limits
On their contribution

See
Despina Sampsonidou
and
Eirini Kasimi's
talks yesterday

# Charged aTGCs status

Limits comparable between ATLAS and CMS, for similar datasets

- These aTGC limits are better than LEP results by now



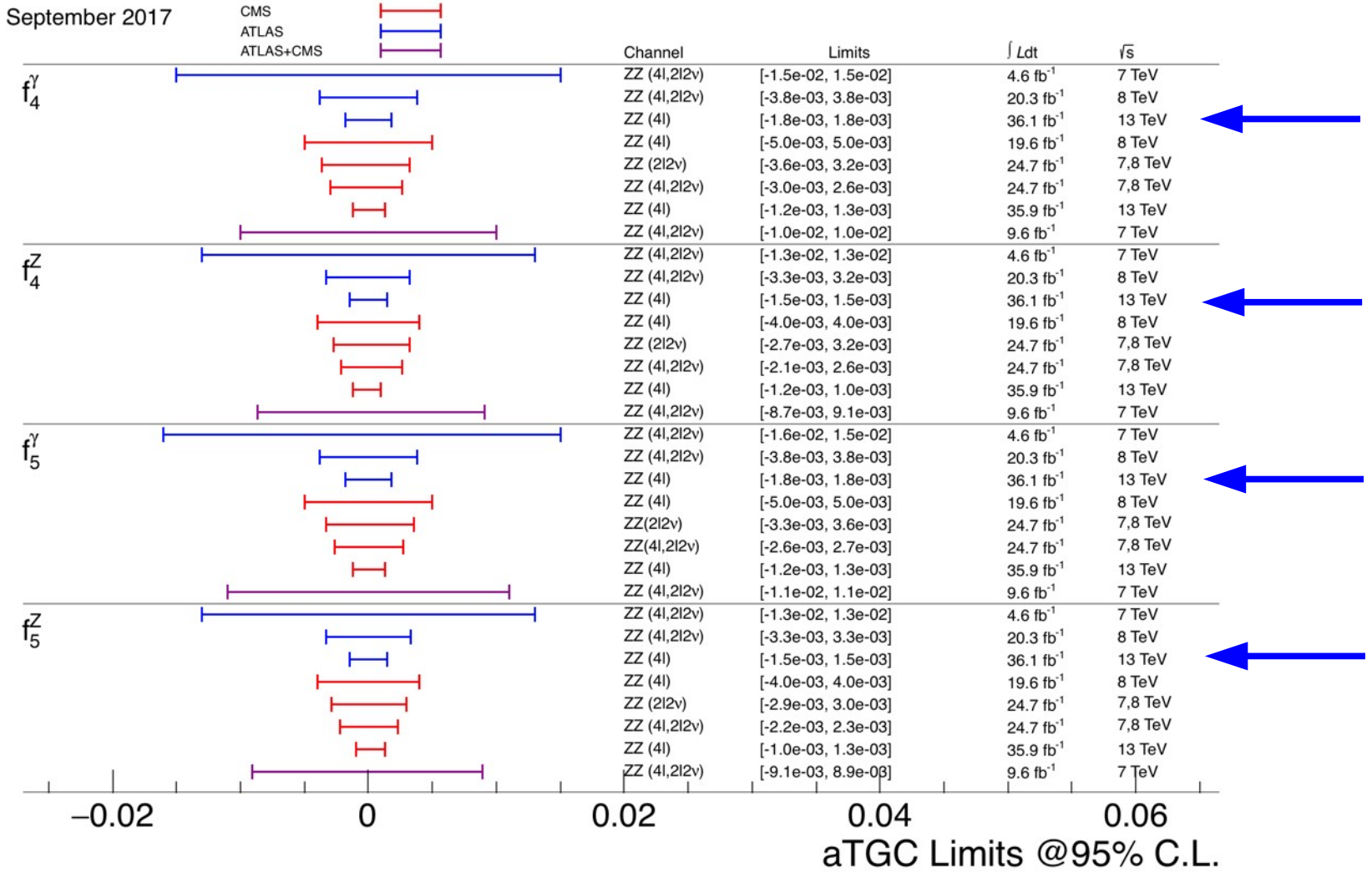

Compilation of ATLAS and CMS results on Triple and Quartic Gauge Couplings at:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

# Neutral aTGCs status

Limits comparable between ATLAS and CMS, for similar datasets

- These aTGC limits constrain a variety of BSM models at higher energies

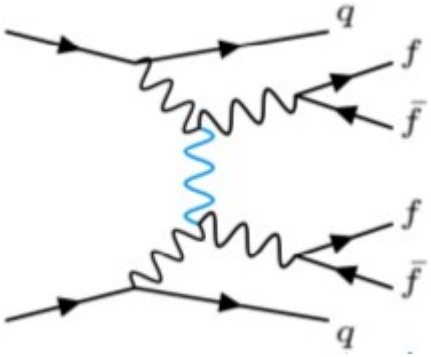



Compilation of ATLAS and CMS results on Triple and Quartic Gauge Couplings at:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

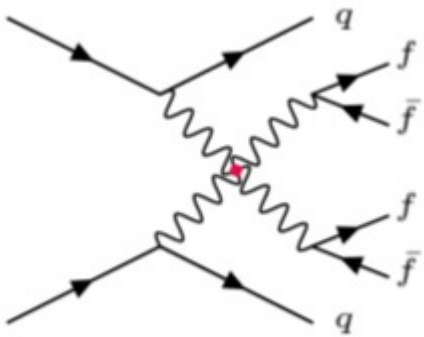
# VBS and anomalous Quartic Couplings

**Vector Boson Scattering**: incoming quarks act as sources of colliding boson beams

**Signature: VV + 2 forward jets**

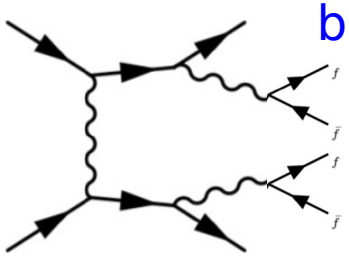



6 EWK vertices: not only vector bosons in the t-channel, but also the Higgs:
important for not letting the cross section explode at high energies (like the ZWW vertex was needed to limit the WW production cross section at e+ e- collisions at LEP)

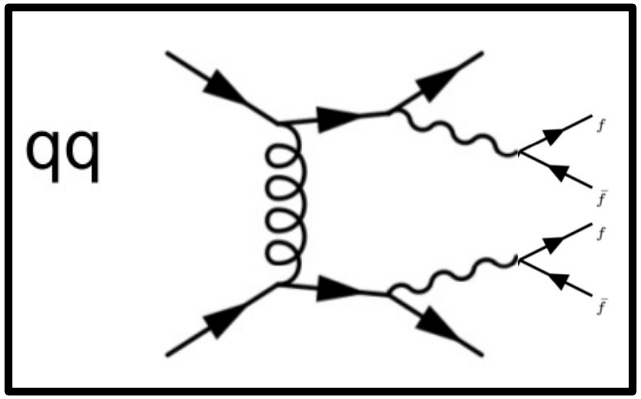


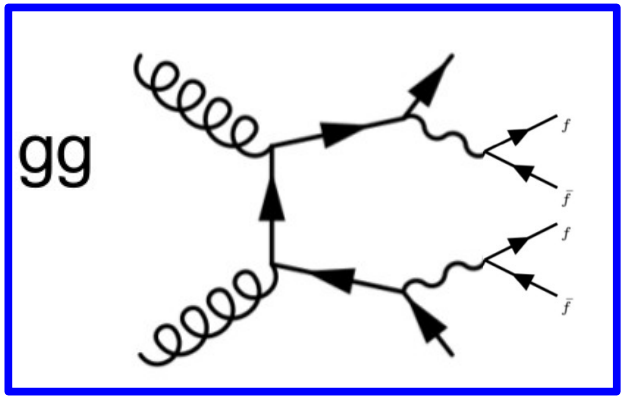

5 EWK vertices
**Quartic Gauge Couplings**:
again, SM does not allow all neutral in the quartic vertex

6 EWK vertices but not VBS...



**4 EWK + 2 QCD vertices**:
same final state
→ important background




+ ...

# VBS and anomalous Quartic Couplings

- Searches of anomalous QGC always assume aTGC=0
- The first operators leading to aQGC but no aTGC have dimension 8

⇒ coupling parameters $c/\Lambda^4$

No time here to show results;
You'll see dedicated discussion on VBS physics by Iro Koletsou

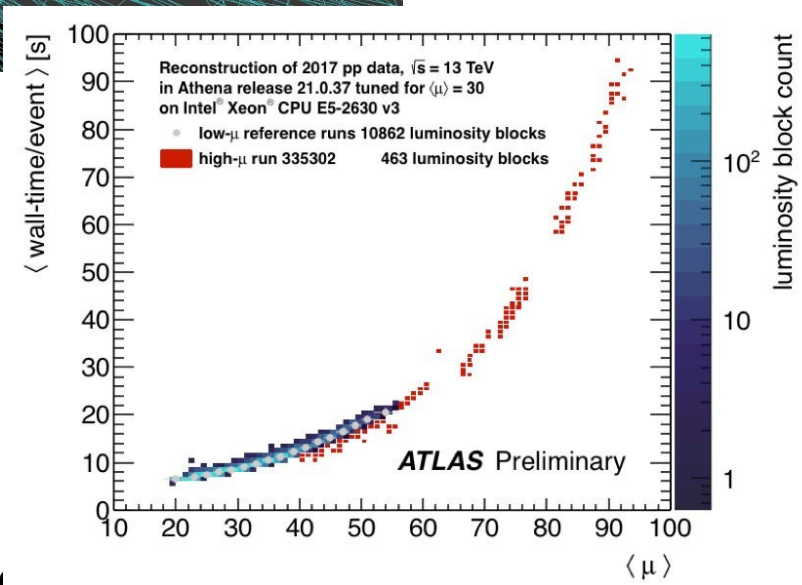
<u>On ZZ EWK production, wihich is not yet observed firmely:</u>

* CMS has ~seen signs of EWK production of ZZ → 4l (~2.7σ, expected 1.6σ) and set limits on aQGC parameters with 36/fb of data

* In ATLAS, we are working with HOU on ZZ with full data set ~165 /fb to establish firmely the EWK production of ZZ , and set limits on aQGCs.

# B) Trigger activities in Phases I and II

# Motivation for helping the online tracking


CPU time to reconstruct all tracks in an event
→ explodes for high pile-up

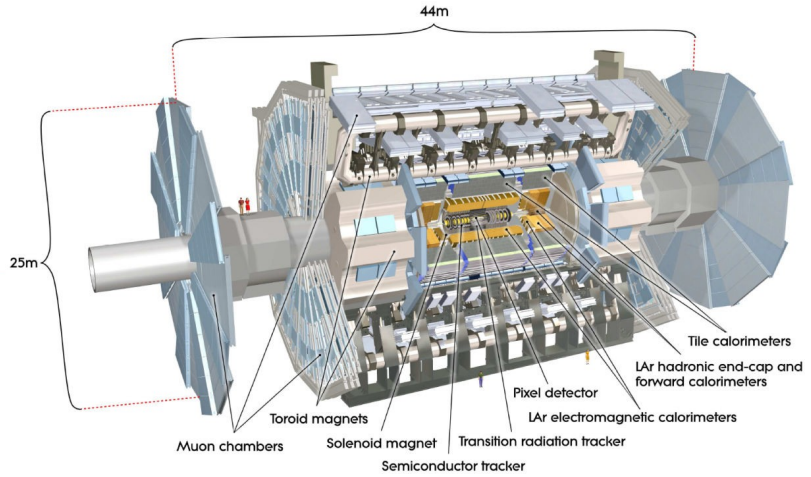
Trigger events in 2 steps: Level 1 (L1: hardware)
and then a High Level Trigger (HLT)

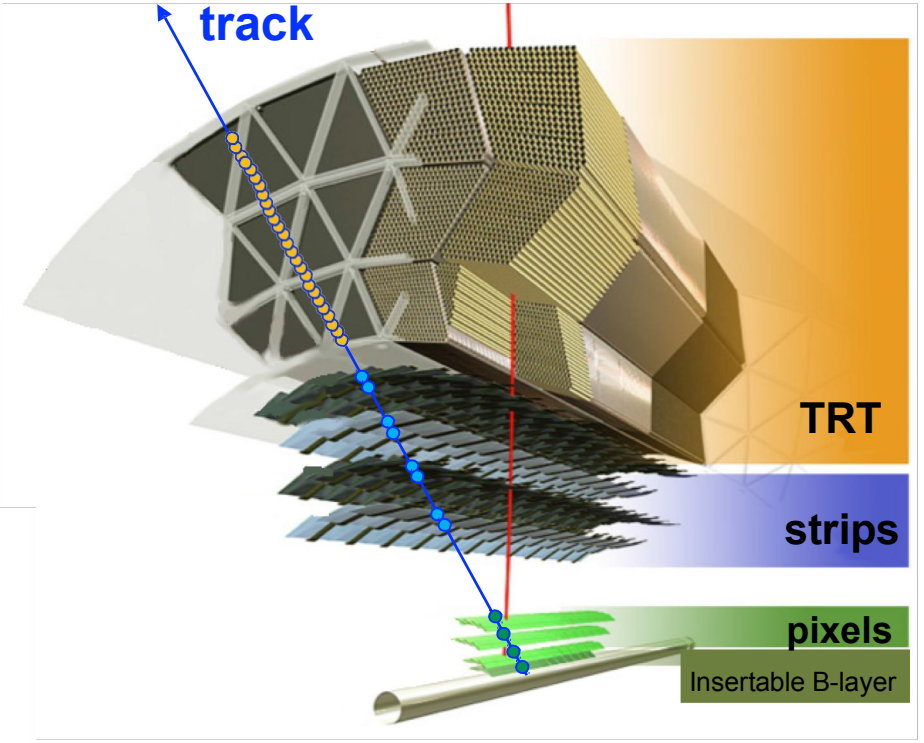
Help the farm with Hardware-based tracking

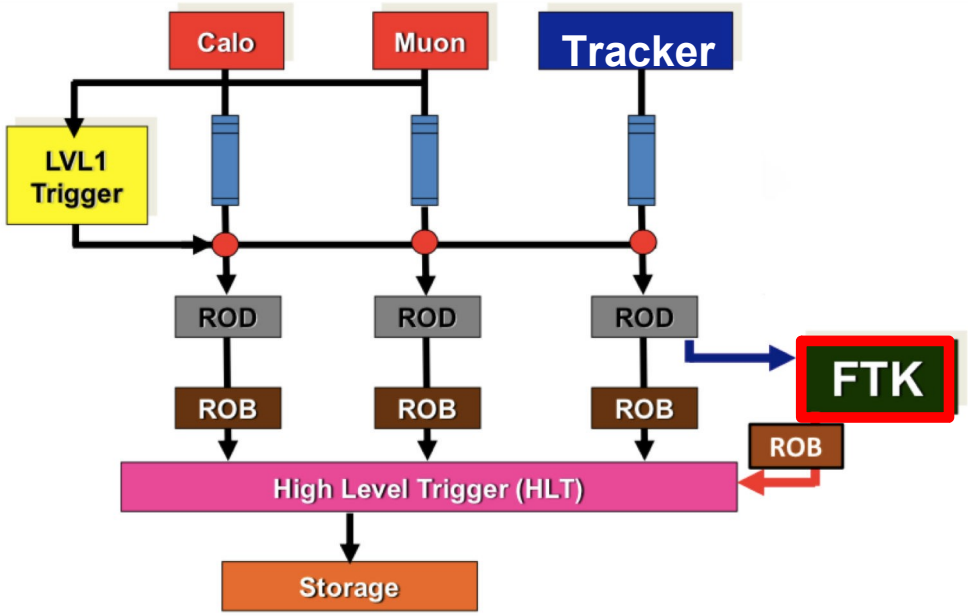
L1 rate : 100 kHz accepts → the HLT has to cope with these.
Help with the Fast TracKer (FTK): do **full-tracking** in **all L1 accepted events (*all, can be tuned with L1 trigger-type)**

In phase-II , L1 accepts: >=1 MHz
Hardware Track Trigger (HTT): do full-event or regional tracking **on-demand**
Option to do regional at Level1

# FTK




- FTK uses ASICS (AM chips) and FPGAs to reconstruct tracks with **$p_T$ > 1 GeV** over **full detector**

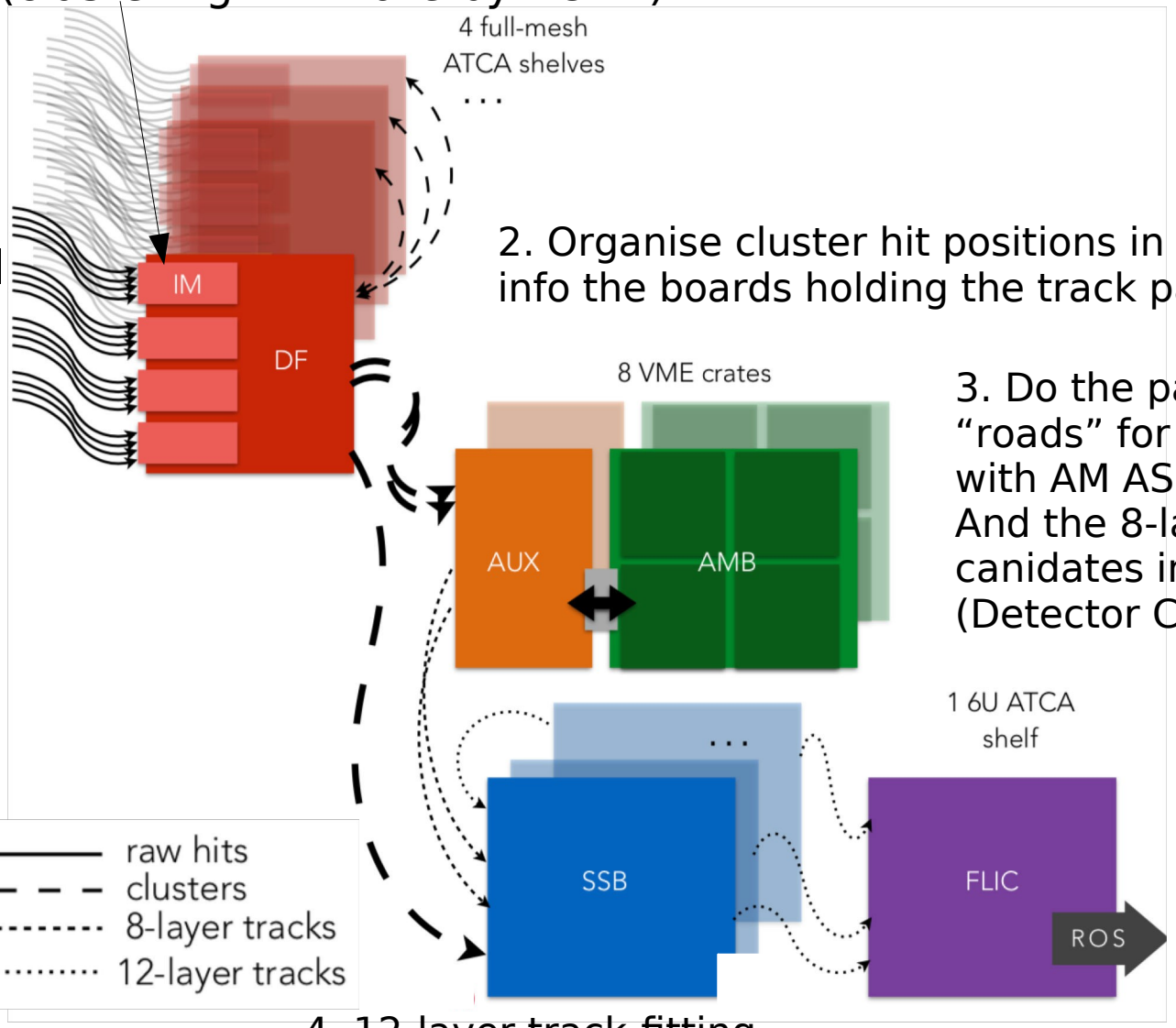
Tracking is performed in **two stages:**

- **1st stage** considers 8 tracker *layers*
- **2nd stage** extends 8-layer tracks to all 12 *layers*

# FTK Hardware

1. Cluster pixels togrther to estimate points particles cross each detector layer (clustering firmware by AUTH)

**strip** and **pixel** data




2. Organise cluster hit positions in coarse bins and forward info the boards holding the track patterns each detector region

3. Do the pattern matching to define "roads" for candidate tracks:
with AM ASICs
And the 8-layer track-fitting of all canidates in each road
(Detector Control by AUTH)

4. 12-layer track-fitting
(firmware contribution by AUTH)

5. All tracks and associated Hits send to buffers,
Waiting to be asked by the HLT
(High-level Online Monitoring by HOU)

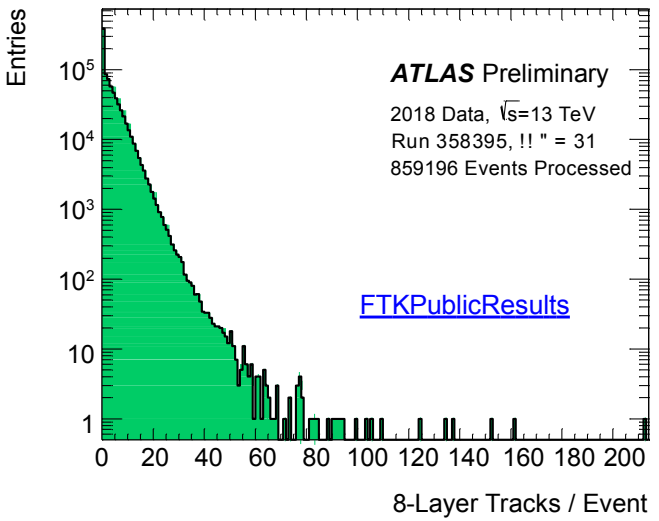
# Status of project

- System hardware is complete for input and output borads
- Enough processing boards for pattern matching and track fitting to full barrel of ATLAS. Boards for end-caps coming along.

- System in commissioning now:
  - Special high pile-up μ = 82 commissioning run collected October 2018

- One of the 64 geometrical towers equiped and ran stably for ~2 hours and outputted tracks to ATLAS special data stream for trigger development and rate predictions

- **Collected ~0.5M FTK tracks**


- 1st tracking stage is outputting tracks
- Validation of AUX firmware

# Summary & Conclusions

- Full programme of ZZ and WZ measurements by AUTH/HOU
  - SM diboson production is often a background to BSM physics searches
- Shown here: electroweak diboson production (WZ,ZZ)
  - Fully-leptonic final states are the first measurements we do of these processes
- These measurements have challenged theorists to compute predictions to NNLO and beyond
  - So far, theorists (and the Standard Model) have risen to that challenge
- No evidence yet of enhancement of these processes from BSM physics
  - Targeting high s-hat regions we have continued to set limits on anomalous Triple Gauge boson Coupling and Quartic Gauge-boson Couplings, in the EFT framework now.
- Trigger: tracking with hardware

# Summary & Conclusions

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# Thank you

# ZZ production cross section

$$N_{sigal}(pp \to ZZ \to 4l) = L \cdot \sigma^{tot}(pp \to ZZ) \cdot BR(ZZ \to 4l) \cdot A \cdot C$$

Measured in a reduced phase-space (geometrical & kinematic requirements on the decay products)
4l = {4e or 4μ or 2e2μ}

Total cross section for ZZ production

$$A = \frac{Fiducial\ events}{Total\ events}$$

Acceptance correction for the geometrical & kinematic criteria

$$C = \frac{Reconstructed\ events}{Generated\ fiducial\ events}$$

Efficiency correction for detector ability to reconstruct these objects

1. We measure a "fiducial cross section", which corresponds to the reduced phase-space of the actual measurement,
* This is a fraction of the total:

$$\sigma^{fiducial}(pp \to ZZ \to 4l) = \frac{N_{obs} - N_{bkg}}{L \cdot C}$$

$$\sigma^{fiducial}(pp \to ZZ \to 4l) = \sigma^{tot}(pp \to ZZ) \cdot BR(ZZ \to 4l) \cdot A$$

2. We then extrapolate to the "total cross section" for ZZ production by extrapolating the leptons to the full phase-space,
and correcting for the BR(ZZ → 4l) ~ 4 * (3.4% * 3.4%) for 4e, 4μ and 2e2μ together

$$\sigma^{tot}(pp \to ZZ \to 4l) = \frac{N_{obs} - N_{bkg}}{L \cdot BR(ZZ \to 4l) \cdot A \cdot C}$$

# Contribution of neutral aTGCs to the cross section

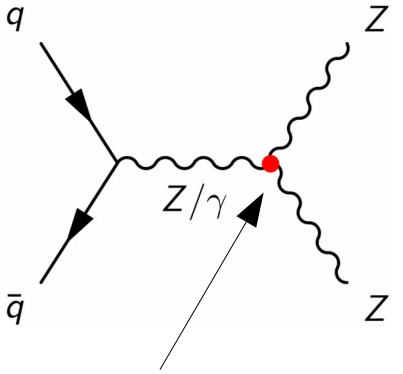
- Traditionally, effective Lagrangian used to include effect of aTGCs: e.g., G.L.Gounaris et al: PRD61 073013; Bauer, Reiwater: PRD 62, 113011

Effective Lagrangian

$$L = \frac{e}{m_Z^2}\left[ f_4^V \left(\partial_\mu V^{\mu\beta}\right) Z_\alpha \left(\partial^\alpha Z_\beta\right) + f_5^V \left(\partial^\sigma V_{\sigma\mu} \tilde{Z}^{\mu\beta} Z_\beta\right) \right], V = Z, \gamma$$

SM values:

$f_4^\gamma = f_4^Z = f_5^\gamma = f_5^Z = 0$




- ZZ cross section enhanced by aTGCs with ~quadratic dependence on them

With one aTGC active:

$$d\sigma_{SM+TGC} = F_0 + fF_1 + f^2 F_2$$

$$d\sigma_{SM+TGC} = \overbrace{F_{00}}^{\text{SM contribution}} + f_4^\gamma F_{01} + f_4^Z F_{02} + f_5^\gamma F_{03} + f_5^Z F_{04}$$
$$+ \left(f_4^\gamma\right)^2 F_{11} + f_4^\gamma f_4^Z F_{12} + f_4^\gamma f_5^\gamma F_{13} + f_4^\gamma f_5^Z F_{14}$$
$$+ \left(f_4^Z\right)^2 F_{22} + f_4^Z f_5^\gamma F_{23} + f_4^Z f_5^Z F_{24}$$
$$+ \left(f_5^\gamma\right)^2 F_{33} + f_5^\gamma f_5^Z F_{34}$$
$$+ \left(f_5^Z\right)^2 F_{44}$$