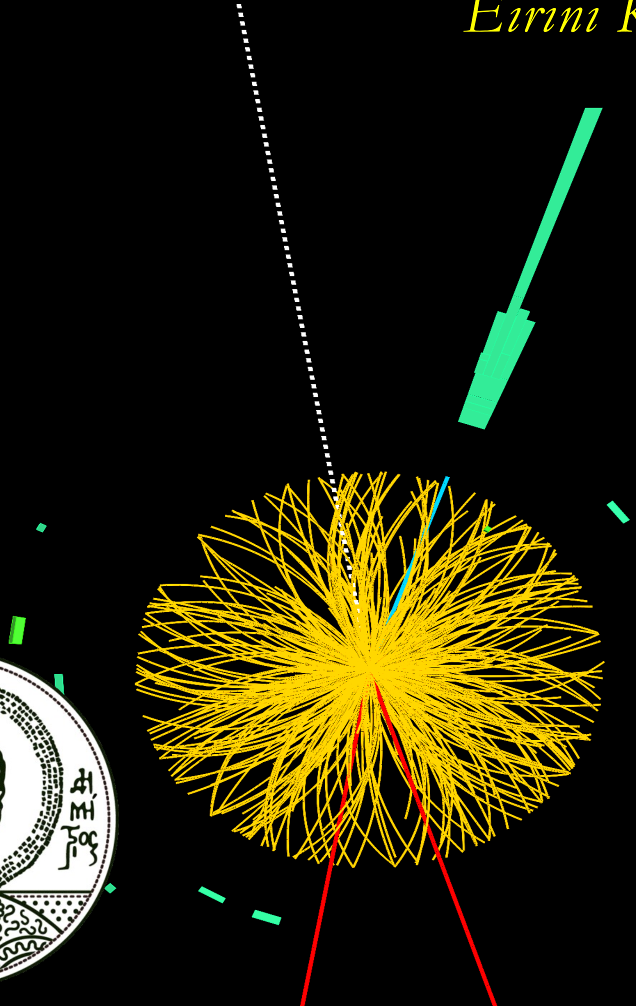
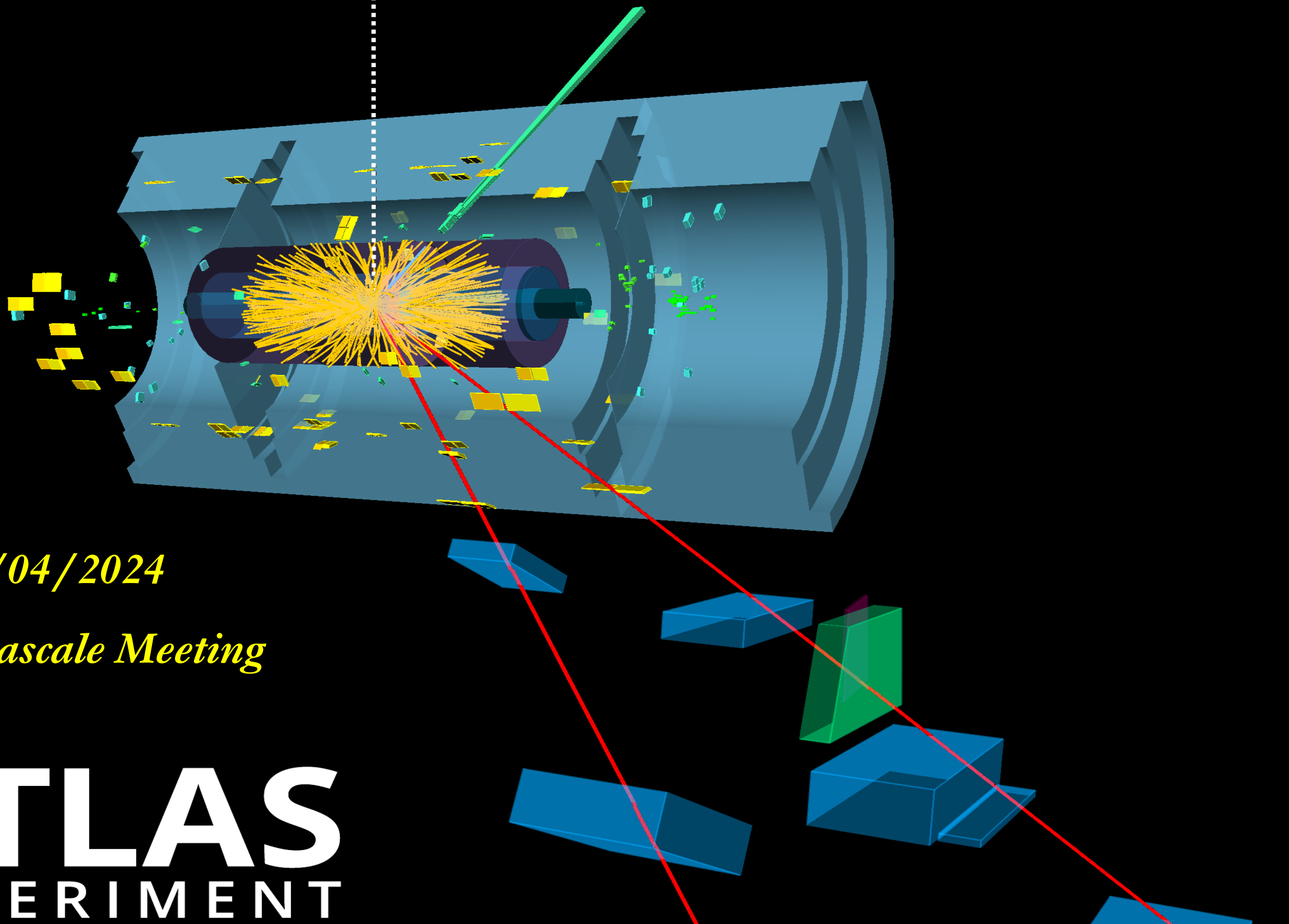
# Electroweak $W^{\pm}Z$ production measurement at $\sqrt{s} = 13$ TeV with the ATLAS detector and an EFT interpretation

*Eirini Kasimi on behalf of the ATLAS collaboration*





***17/04/2024***

***IRN Terascale Meeting***

ATLAS EXPERIMENT

# Overview

- Motivation and theoretical framework
- Analysis overview and cross section measurements
- Effective Field Theory Interpretation results
- Conclusion and prospects

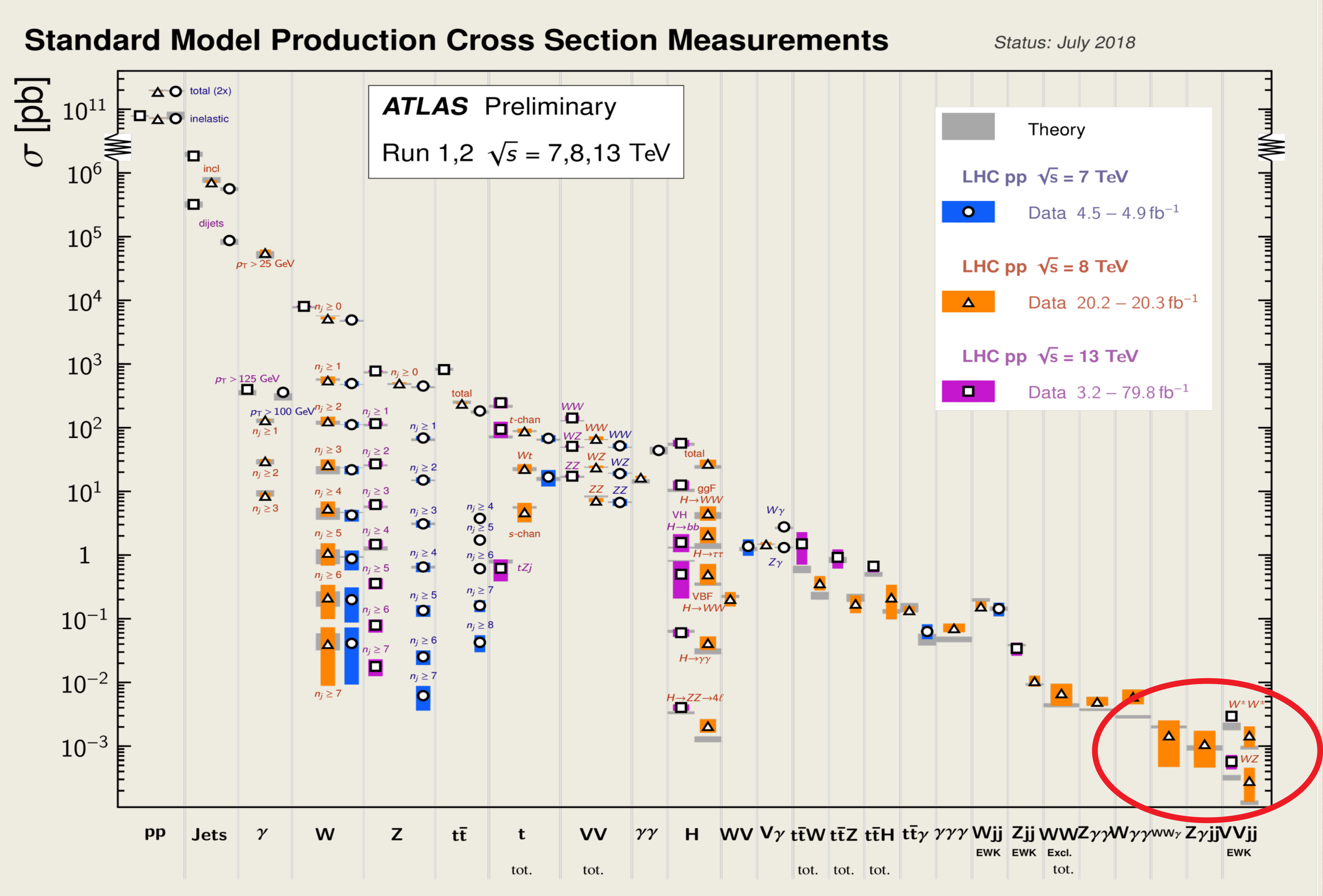
Paper link

# MOTIVATION AND THEORETICAL FRAMEWORK

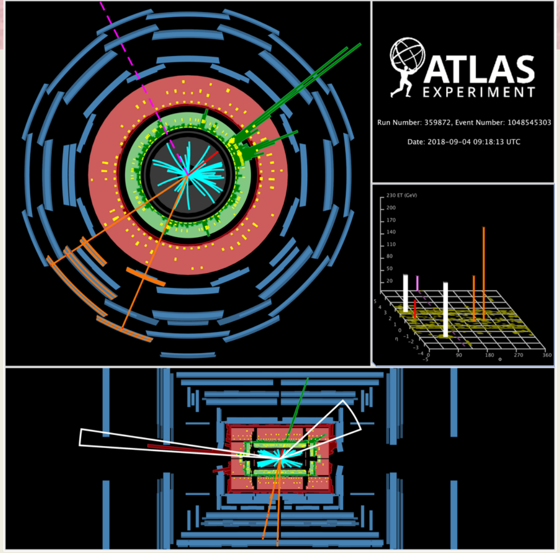
# Vector Boson Scattering(VBS): Motivation

**Previous measurements**
ATLAS
CMS

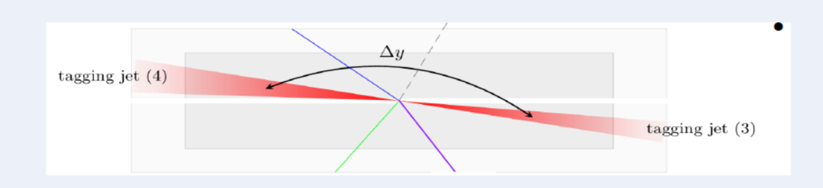
- Vector Boson Scattering (VBS) processes are very rare process ⟶ low cross sections
- VBS provides an alternative way to study the mechanism of electroweak symmetry breaking (EWSB)
- VBS probes information on vector boson self-couplings
  - Explore the existence of New Physics through deviations from SM
- *Importance of WZ VBS process*
  - *Clean signature with only one neutrino*
  - *High cross section w.r.t. the other VBS processes*



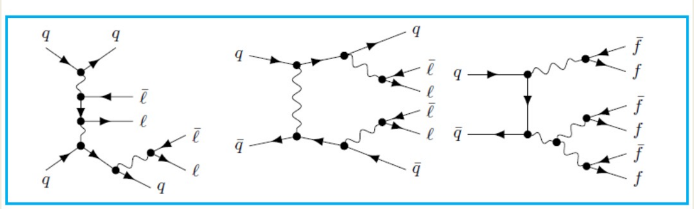
# *Electroweak and QCD WZjj production*

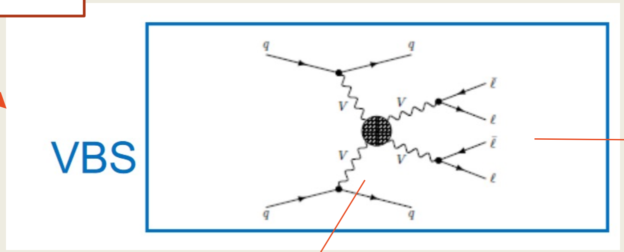



- EWK WZjj production
  - Fully leptonic final state which contains three leptons and two jets
  - Characteristic kinematic signature:
    - the products of two bosons produced centrally and
    - two forward jets with large spatial separation in rapidity and a high invariant mass
  - Challenging separation between the signal and the backgrounds



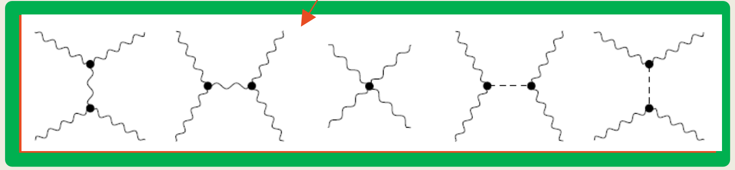

EWK WZjj productions





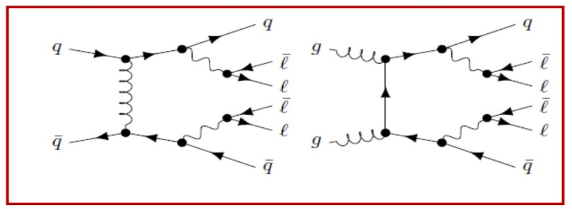

Study of electroweak symmetry breaking through the vector boson self-couplings

Explore the existence of New Physics through deviations from SM

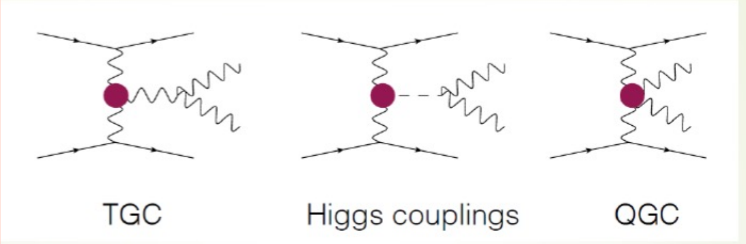


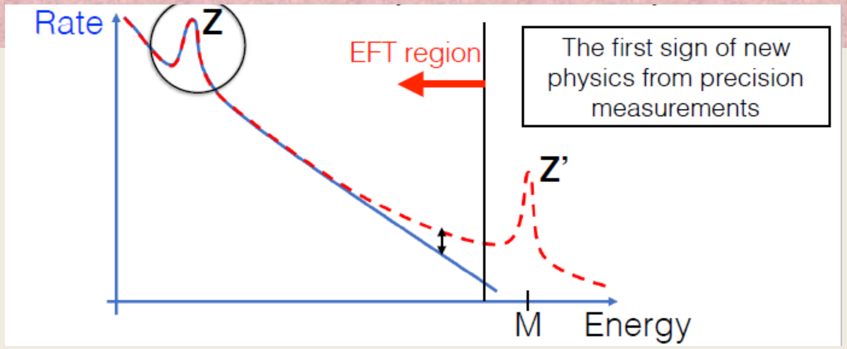
- QCD WZjj production
  - Characteristic kinematic signature
    - Presence of gluons
    - low rapidity separation
    - low invariant mass of the two jets system
  - Fit in SR

QCD VVjj



WZjj probes:






# *Effective Field Theory: Overview*

- Two methods to look for physics beyond the Standard Model (BSM)
  - Look for new particles (model-dependent)
  - Look for new interactions of SM particles (model-independent) → Try to notice deviations in the tails of the distributions of some kinematical variables
- The Effective Field Theory (EFT) is the natural way to expand the SM such that the gauge symmetries are respected
- The EFT provides a way to search for effects of BSM
- Construction of an EFT Lagrangian:
  - SM: general theory of quark and lepton fields and their interactions with vector boson and the Higgs fields
  - Extend the theory: Add operators of higher dimension
- The EFT Lagrangian can be expressed as:

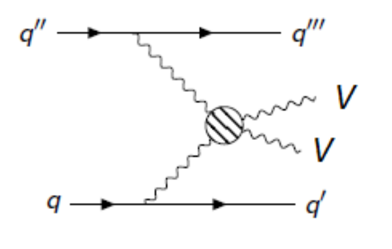
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} O_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda_i^4} O_i^{(8)} + \ldots$$

  - $\Lambda$ is the scale of new physics
  - $O_i^{(6)}$ , $O_i^{(8)}$ are the Lorentz and gauge invariant dimension-6 and dimension-8 operators
  - $c_i^{(6)}$ , $c_i^{(8)}$ are the dimensionless Wilson coefficients of the dimension-6 and 8 effective operators
- $\Lambda$ can be assumed as common to all the coefficients, the Wilson coefficients can be written as:

$$f_i^{(6)} = \frac{c_i^{(6)}}{\Lambda^2}, f_i^{(8)} = \frac{c_i^{(8)}}{\Lambda^4}, \ldots$$

Energy scale of the interaction must be $E < \Lambda$

# Effective Field Theory: dimension-8 operators




- The dimension-8 operators are dominant in aQGCs

They are divided into three categories: Longitudinal ($L_S$), transverse ($L_T$) and mixed ($L_M$)

$$\mathcal{L}_{S,0} = \frac{c_{S,0}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger (D_v\Phi)\right] \times \left[(D^\mu\Phi)^\dagger (D^v\Phi)\right]$$
$$\mathcal{L}_{S,1} = \frac{c_{S,1}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger (D^\mu\Phi)\right] \times \left[(D_v\Phi)^\dagger (D^v\Phi)\right]$$
$$\mathcal{L}_{S,2} = \frac{c_{S,2}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger (D_v\Phi)\right] \times \left[(D^v\Phi)^\dagger (D^\mu\Phi)\right]$$

Scalar operators: Pure Higgs field

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

Tensor operators: field strength tensor

Mixed operators

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

| | WWWW | WWZZ | ZZZZ | WWAZ | WWAA | ZZZA | ZZAA | ZAAA | AAAA |
|---|---|---|---|---|---|---|---|---|---|
| $\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$ | X | X | X | O | O | O | O | O | O |
| $\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$, $\mathcal{L}_{M,6}$, $\mathcal{L}_{M,7}$ | X | X | X | X | X | X | X | O | O |
| $\mathcal{L}_{M,2}$, $\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$, $\mathcal{L}_{M,5}$ | O | X | X | X | X | X | X | O | O |
| $\mathcal{L}_{T,0}$, $\mathcal{L}_{T,1}$, $\mathcal{L}_{T,2}$ | X | X | X | X | X | X | X | X | X |
| $\mathcal{L}_{T,5}$, $\mathcal{L}_{T,6}$, $\mathcal{L}_{T,7}$ | O | X | X | X | X | X | X | X | X |
| $\mathcal{L}_{T,9}$, $\mathcal{L}_{T,9}$ | O | O | X | O | O | X | X | X | X |

# *Effective Field Theory: Unitarity bounds*

- aQGC terms: disturb the cancellation between different contributions to the scattering amplitude of longitudinally polarized, massive electroweak gauge bosons
- Cross section for the scattering of massive electroweak gauge bosons is rising with increasing centre-of-mass energy but it cannot exceed the physical upper bound
- Range of validity of the specific EFT model: $E^2 < \Lambda \leq s^U$ , where $s^U \equiv s^U(f_i)$ is the unitarity bound

| Wilson coefficient | Bound |
|---|---|
| $\left\|\frac{f_{M0}}{\Lambda^4}\right\|$ | $\frac{32}{\sqrt{6}}\pi s^{-2}$ |
| $\left\|\frac{f_{M1}}{\Lambda^4}\right\|$ | $\frac{128}{\sqrt{6}}\pi s^{-2}$ |
| $\left\|\frac{f_{M2}}{\Lambda^4}\right\|$ | $\frac{16}{\sqrt{2}}\pi s^{-2}$ |
| $\left\|\frac{f_{M3}}{\Lambda^4}\right\|$ | $\frac{64}{\sqrt{2}}\pi s^{-2}$ |
| $\left\|\frac{f_{M4}}{\Lambda^4}\right\|$ | $32\pi s^{-2}$ |
| $\left\|\frac{f_{M5}}{\Lambda^4}\right\|$ | $64\pi s^{-2}$ |
| $\left\|\frac{f_{M7}}{\Lambda^4}\right\|$ | $\frac{256}{\sqrt{6}}\pi s^{-2}$ |

| Wilson coefficient | Bound |
|---|---|
| $\left\|\frac{f_{S0}}{\Lambda^4}\right\|$ | $32\pi s^{-2}$ |
| $\left\|\frac{f_{S1}}{\Lambda^4}\right\|$ | $\frac{96}{7}\pi s^{-2}$ |
| $\left\|\frac{f_{S2}}{\Lambda^4}\right\|$ | $\frac{96}{5}\pi s^{-2}$ |

| Wilson coefficient | Bound |
|---|---|
| $\left\|\frac{f_{T0}}{\Lambda^4}\right\|$ | $\frac{12}{5}\pi s^{-2}$ |
| $\left\|\frac{f_{T1}}{\Lambda^4}\right\|$ | $\frac{24}{5}\pi s^{-2}$ |
| $\left\|\frac{f_{T2}}{\Lambda^4}\right\|$ | $\frac{96}{13}\pi s^{-2}$ |
| $\left\|\frac{f_{T5}}{\Lambda^4}\right\|$ | $\frac{8}{\sqrt{3}}\pi s^{-2}$ |
| $\left\|\frac{f_{T6}}{\Lambda^4}\right\|$ | $\frac{48}{7}\pi s^{-2}$ |
| $\left\|\frac{f_{T7}}{\Lambda^4}\right\|$ | $\frac{32}{\sqrt{3}}\pi s^{-2}$ |
| $\left\|\frac{f_{T8}}{\Lambda^4}\right\|$ | $\frac{3}{2}\pi s^{-2}$ |
| $\left\|\frac{f_{T9}}{\Lambda^4}\right\|$ | $\frac{24}{7}\pi s^{-2}$ |

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.101.113003

# *Effective Field Theory: Decomposition method*

- MC samples for the effect of higher dimension operators in many values of the coefficients
- In order to avoid the production of large amounts of Monte Carlo samples, we will profit from the decomposition method

$$
\begin{aligned}
&|\mathcal{A}_{\rm SM} + \sum_i c_i \mathcal{A}_i|^2 \\
&= |\mathcal{A}_{\rm SM}|^2 + \sum_i c_i 2\mathrm{Re}\left(\mathcal{A}^\star_{\rm SM}\mathcal{A}_i\right) + \sum_i c_i^2 |\mathcal{A}_i|^2 + \sum_{ij, i\neq j} c_i c_j 2\mathrm{Re}\left(\mathcal{A}^\star_i \mathcal{A}_j\right)
\end{aligned}
$$

SM term

Interference term between SM-EFT (Linear term)

Pure EFT contribution (Quadratic term)

Interference term between EFT operators (Cross term)

# ANALYSIS OVERVIEW AND RESULTS

# *Phase space definition for the cross-section measurements*

| Variable | Fiducial $WZjj$–EW |
|---|---|
| Lepton $\|\eta\|$ | $< 2.5$ |
| $p_T$ of $\ell_Z$, $p_T$ of $\ell_W$ [GeV] | $> 15$, $> 20$ |
| $m_Z$ range [GeV] | $\|m_Z - m_Z^{PDG}\| < 10$ |
| $m_T^W$ [GeV] | $> 30$ |
| $\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$ | $> 0.2$, $> 0.3$ |
| $p_T$ two leading jets [GeV] | $> 40$ |
| $\|\eta_j\|$ two leading jets | $< 4.5$ |
| Jet multiplicity | $\geq 2$ |
| $\eta_{j1} \cdot \eta_{j1}$ | $< 0$ |
| $m_{jj}$ [GeV] | $> 500$ |
| $\Delta R(j, \ell)$ | $> 0.3$ |
| $N_{b-\text{quark}}$ | $= 0$ |

Concerning the three leptons

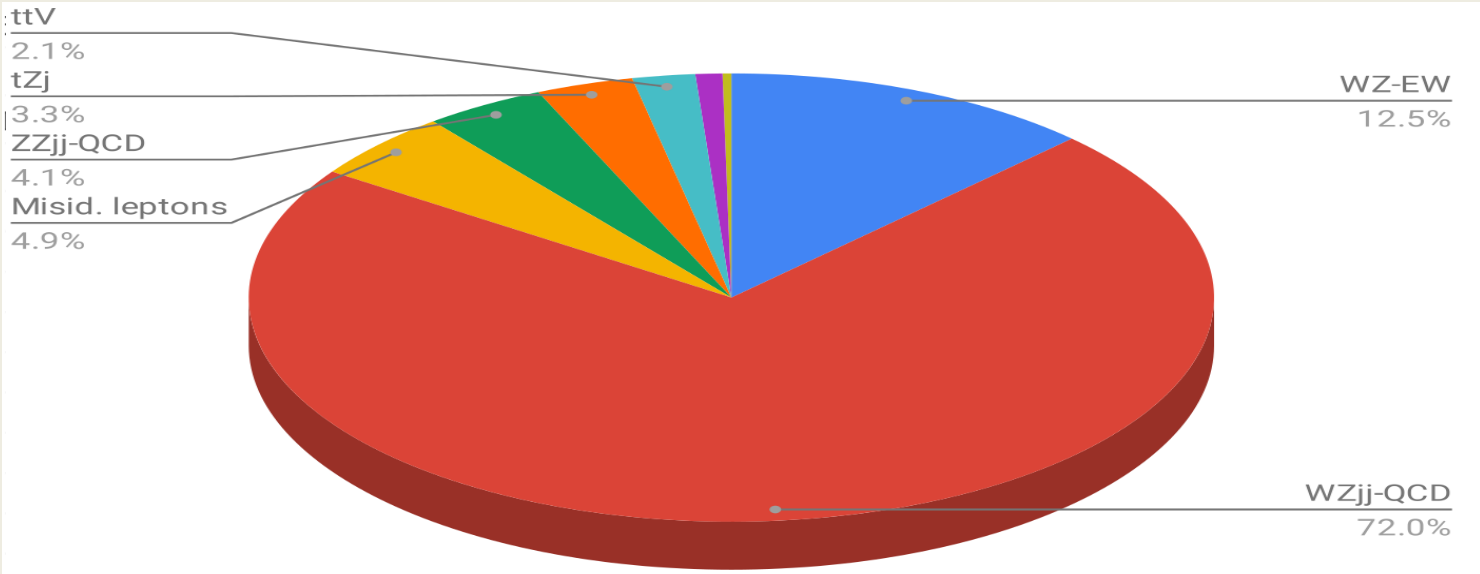
Concerning the two jets

# Backgrounds

- Backgrounds:
  - Reducible background: $Z + jets$, $Z\gamma$, $t\bar{t}$ and $Wt$
  - Irreducible background: $t\bar{t}V$, $tZ$, $VVV$, $ZZjj - QCD$ and $ZZjj - EW$

- At least one "fake" lepton
- Matrix method technique

- At least three prompt leptons in the final state
- Simultaneous fit in dedicated CRs



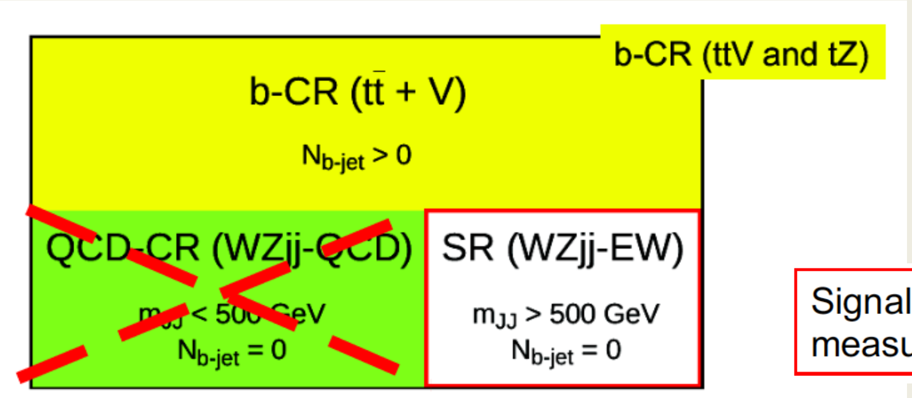
# *WZjj Event selection and global WZjj strategy*

**Baseline event selection:**

| Inclusive event selection | |
|---|---|
| $ZZ$ veto | Less than 4 baseline leptons |
| $N$ leptons | Exactly three leptons passing the $Z$ lepton selection |
| Leading lepton $p_T$ | $p_T^{lead} > 25$ GeV (in 2015) or $p_T^{lead} > 27$ GeV (in 2016) |
| $Z$ leptons | Two same flavor oppositely charged leptons passing $Z$ lepton selection |
| Mass window | $\lvert M_{\ell\ell} - M_Z \rvert < 10$ GeV |
| $W$ lepton | $W$ lepton passes W selection |
| W transverse mass | $m_T^W > 30$ GeV |

| ***WZjj*** **Event selection** | |
|---|---|
| Jet multiplicity | $\geq 2$ |
| $p_T$ of two tagging jets | $> 40$ GeV |
| $\lvert\eta\rvert$ of two tagging jets | $< 4.5$ |
| $\eta$ of two tagging jets | opposite sign |
| $m_{jj}$ | $> 150$ GeV |

**+ one ZZ CR defined by inverting the 4th lepton veto (67,8% expected purity)**




**ttV and tZ**
Using a dedicated BDT to constraint them in this region
(43,8% expected purity on ttV)
(20,3% expected purity on tZ)

Signal region: where the measurement is done

QCD-VR
Not used in the cross section measurement or any step of the analysis

# *Strategy for inclusive $\sigma_{WZjj\text{-}EW}$ and $\sigma_{WZjj\text{-}strong}$ measurement*

- Goal: simultaneous measurement of the integrated $\sigma_{WZjj-EW}$ and $\sigma_{WZjj-\text{strong}}$ cross sections in the SR
  - separate the signal region into two categories:
    - events with $N_{\text{jets}} = 2$ and $p_t > 25$ GeV
    - events with $N_{\text{jets}} \geq 3$ and $p_t > 25$ GeV
- Signal fit free parameters

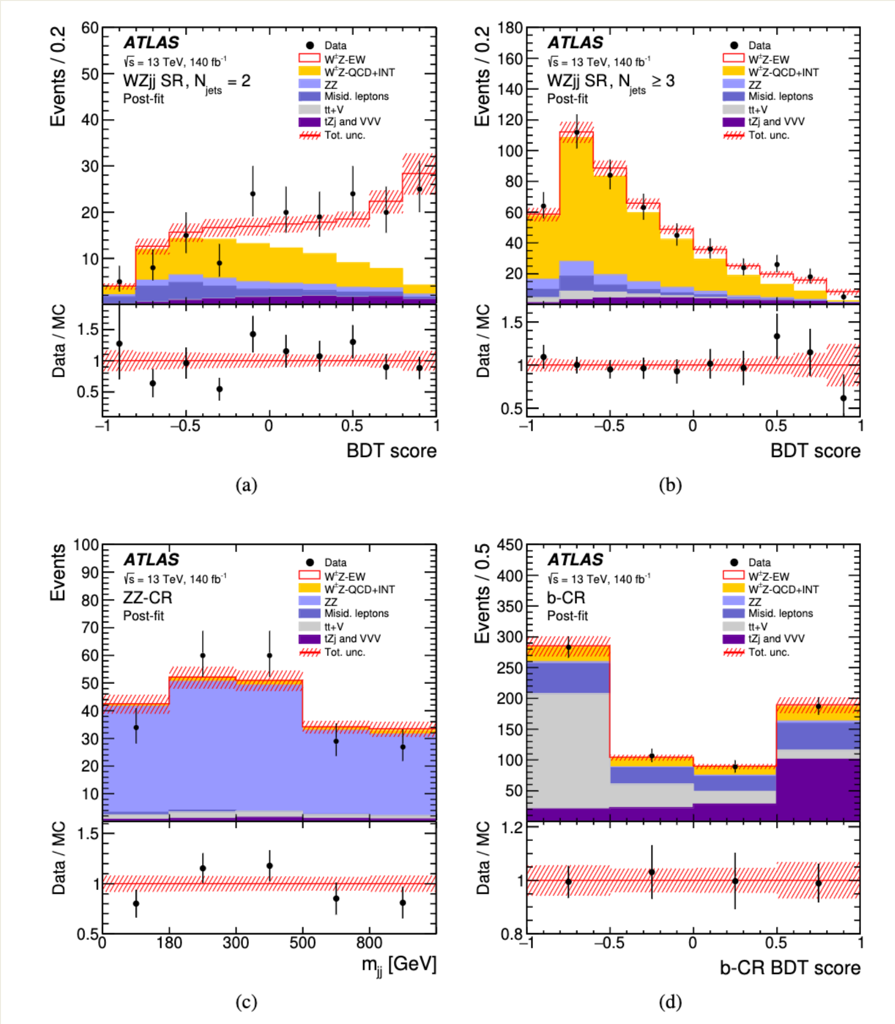
$$
\begin{aligned}
\sigma_{WZjj-\text{EW}} &= \mu_{WZjj-\text{EW}} \cdot \sigma^{\text{th. MC}}_{WZjj-\text{EW}}\,, \\
\sigma_{WZjj-\text{strong}} &= \mu_{WZjj-\text{QCD}} \cdot \sigma^{\text{th. MC}}_{WZjj-\text{QCD}} + \mu_{WZjj-\text{INT}} \cdot \sigma^{\text{th. MC}}_{WZjj-\text{INT}}\,, \\
&= \mu_{WZjj-\text{QCD}} \cdot \sigma^{\text{th. MC}}_{WZjj-\text{QCD}} + \sqrt{\mu_{WZjj-\text{EW}}} \cdot \sqrt{\mu_{WZjj-\text{QCD}}} \cdot \sigma^{\text{th. MC}}_{WZjj-\text{INT}}
\end{aligned}
$$

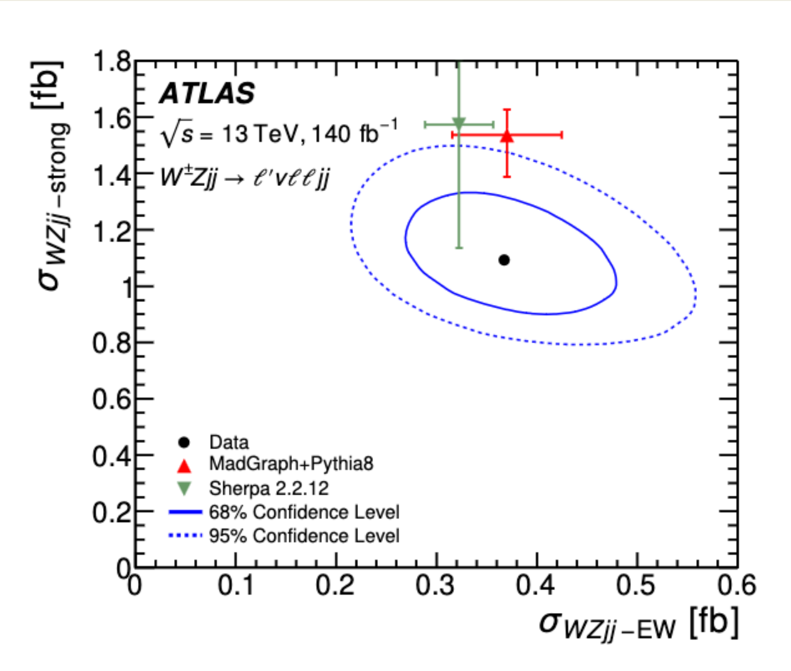
- Background normalization parameters
  - $\mu_{ttV}$ and $\mu_{tZ}$ : normalization parameters, defined in all three regions
  - $\mu_{ZZ\text{-}QCD}$: normalization parameter, defined in the SR and the ZZ-CR
- Uncertainties parametrization
  - Detector related uncertainties: applied in every region in a correlated way
  - Theory uncertainties: parameters of interest → only shape (and migration) effects considered

- Improve the sensitivity and the significance of the $\sigma_{WZjj-EW}$ measurement
- Increase the robustness of the measurement to a mis-modelling of the jet multiplicity for $WZjj$−QCD events.

# Inclusive $\sigma_{WZjj\text{-}EW}$ and $\sigma_{WZjj\text{-}strong}$ measurement: Results

**EWK:** Both generators consistent with data
**Strong:** Both generators more than 2σ above data




$$\sigma_{WZjj-\mathrm{EW}} = 0.368 \pm 0.037\,(\mathrm{stat.}) \pm 0.059\,(\mathrm{syst.}) \pm 0.003\,(\mathrm{lumi.})\ \mathrm{fb}$$
$$= 0.37 \pm 0.07\ \mathrm{fb},$$
$$\sigma_{WZjj-\mathrm{strong}} = 1.093 \pm 0.066\,(\mathrm{stat.}) \pm 0.131\,(\mathrm{syst.}) \pm 0.009\,(\mathrm{lumi.})\ \mathrm{fb}$$
$$= 1.09 \pm 0.14\ \mathrm{fb},$$

# *Strategy for differential $\sigma_{WZjj\text{-}EW}$ and $\sigma_{WZjj\text{-}strong}$ measurement*

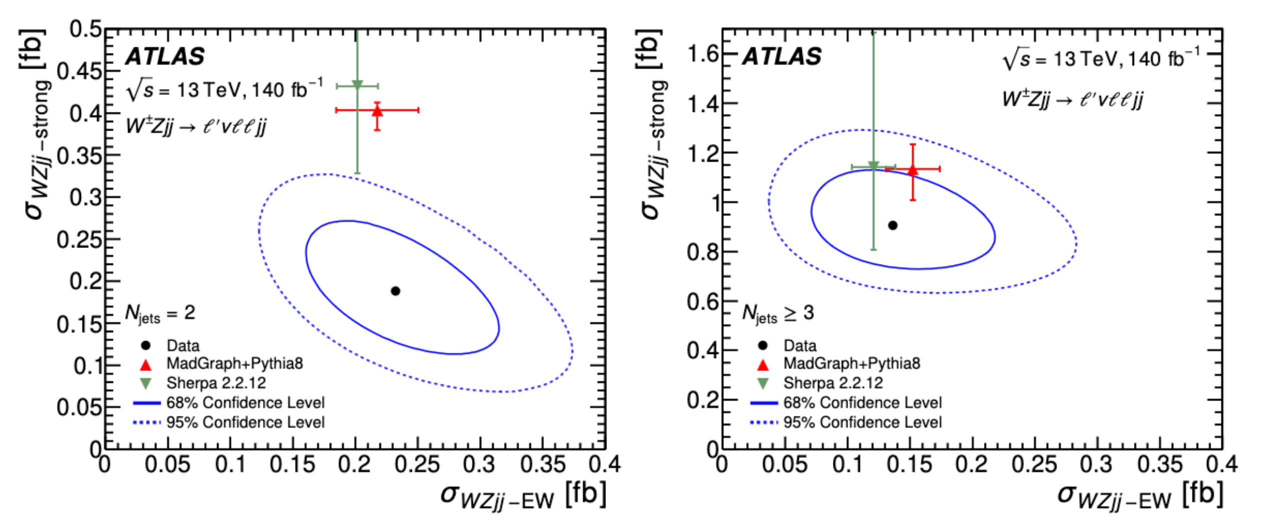
- Goal: simultaneous measurement of $\sigma_{WZjj\text{-}EW}$ and $\sigma_{WZjj\text{-}strong}$ in the corresponding $SR^i$
- Free parameters in the fit
  - $\sigma_{WZjj\text{-}EW}$ and $\sigma_{WZjj\text{-}strong}$: parameters of interest, measured in the $SR^i$
  - $\mu_{ttV}$ and $\mu_{tZ}$ : normalization parameters, defined in all the regions
  - $\mu_{ZZ\text{-}QCD}$: normalization parameter, defined in the SR and the ZZ-CR
  - Theory uncertainties decorrelated between bins (or $SR^i$)

**Signal sub-regions for $M_{jj}$:**
- 500-1300 GeV
- 1300-2000 GeV
- >2000 GeV

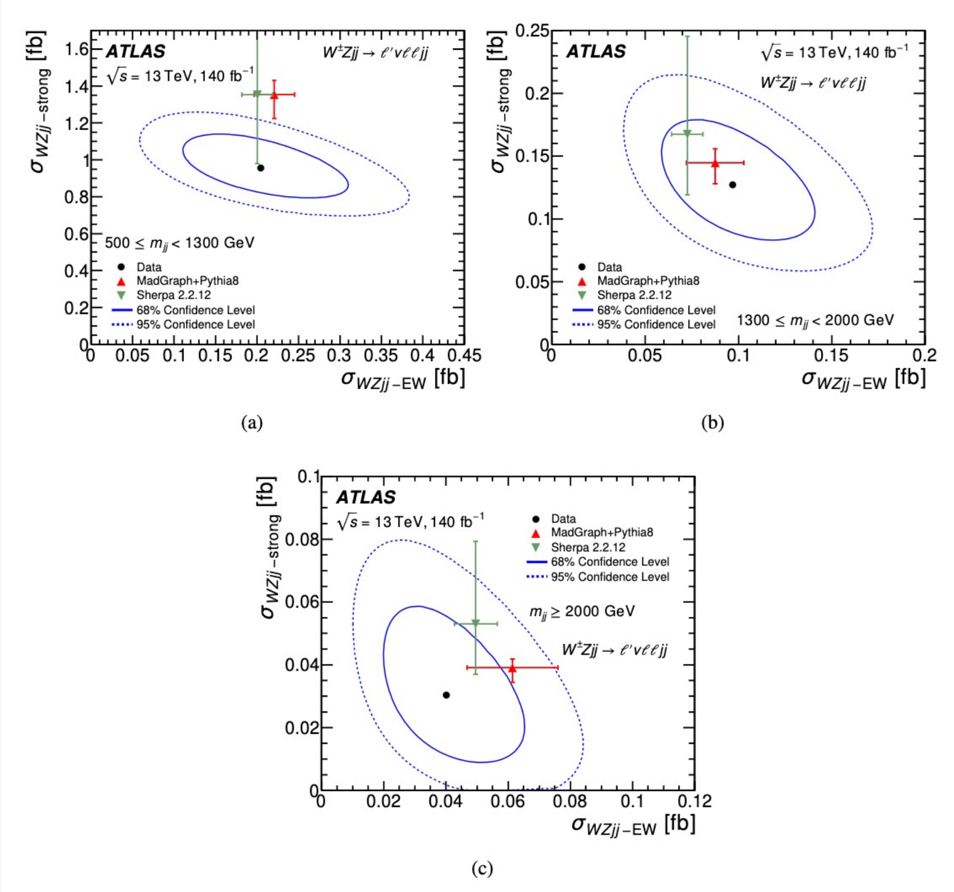
**Signal sub-regions for $N_{jets}$:**
- Exactly 2 jets
- >2 jets

# Differential $\sigma_{WZjj\text{-}EW}$ and $\sigma_{WZjj\text{-}strong}$ measurement

**$N_{jets}$ categorization**



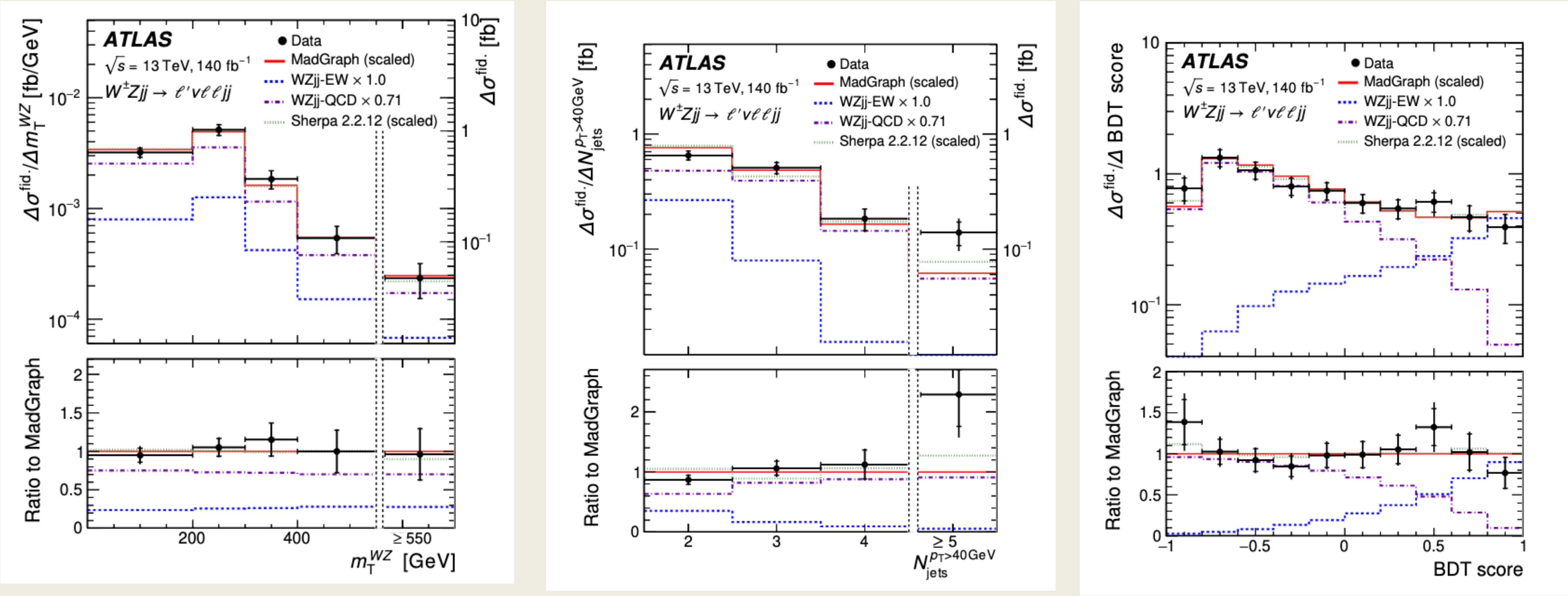

**$M_{jj}$ categorization**




**EWK:** Both generators consistent with data
**Strong:** Both generators more than 2σ above data

# *Differential WZjj measurements*

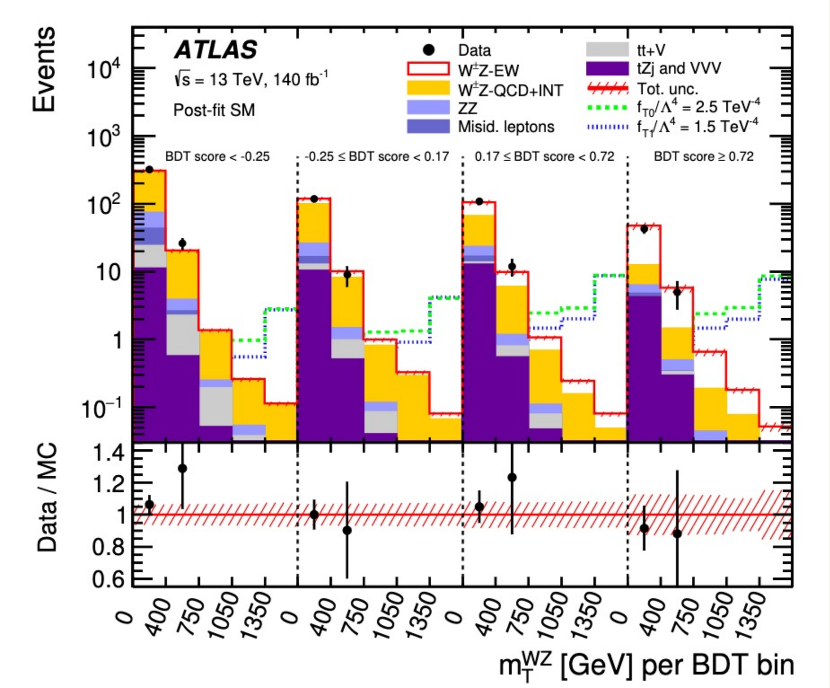
- Kinematical variables:
  - WZ: $M_T^{WZ}$, $\Delta\Phi(W,Z)$
  - Jets: $N_{jets}$, $m_{jj}$, $\Delta y_{jj}$, $\Delta\varphi_{jj}$, $N_{jets}(gap)$, $Z_{j3}$
  - BDT score



# EFT INTERPRETATION RESULTS

# *Extraction of reconstructed level limits*

- Extraction of the limits using
  - two-dimensional distribution $M_T^{WZ}$ - BDT score in the fit
    - Create two-dimensional templates by binning two kinematic variables simultaneously
    - Create one dimension by 'unrolling' the bin contents

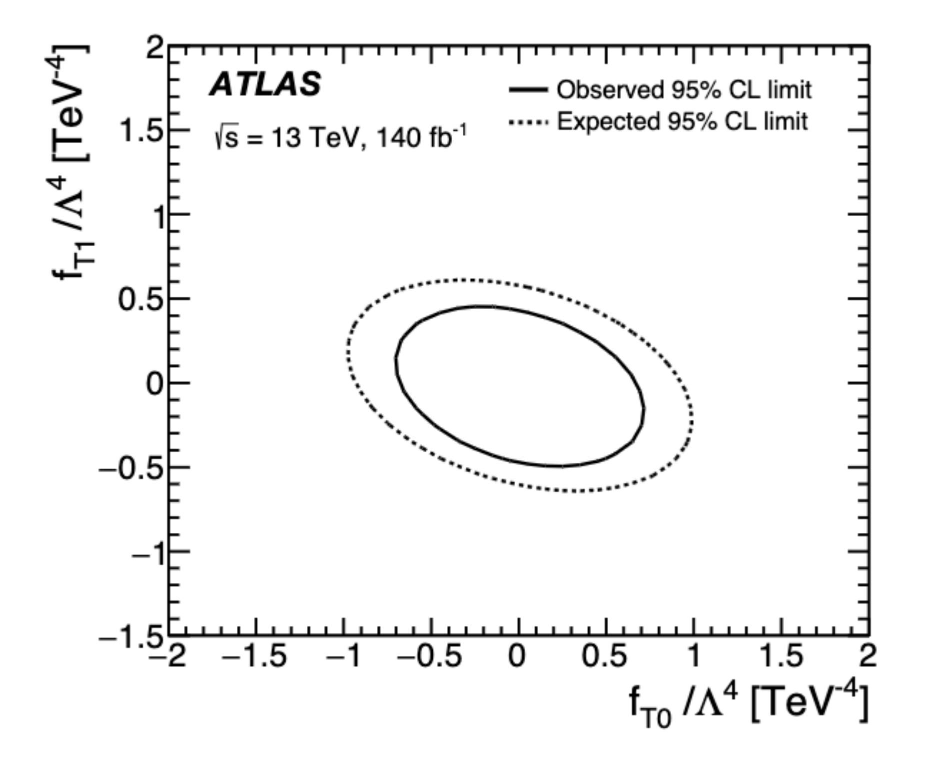



Expected and observed lower and upper 95% CL limits on the Wilson coefficients

| | Expected (TeV$^{-4}$) | Observed (TeV$^{-4}$) |
|---|---|---|
| $f_{T1}/\Lambda^4$ | [-0.52, 0.49] | [-0.39, 0.35] |
| $f_{T0}/\Lambda^4$ | [-0.80, 0.80] | [-0.57, 0.56] |
| $f_{T2}/\Lambda^4$ | [-1.6, 1.4] | [-1.2, 1.0] |
| $f_{M0}/\Lambda^4$ | [-8.3, 8.3] | [-5.8, 5.6] |
| $f_{M1}/\Lambda^4$ | [-12.3, 12.2] | [-8.6, 8.5] |
| $f_{S02}/\Lambda^4$ | [-14.2, 14.2] | [-10.4, 10.4] |
| $f_{M7}/\Lambda^4$ | [-16.2, 16.2] | [-11.3, 11.3] |
| $f_{S1}/\Lambda^4$ | [-42, 41] | [-30, 30] |

# *2-D reconstructed level limits*

- Limits on aQGC Wilson coefficients are also derived fitting two Wilson coefficients simultaneously

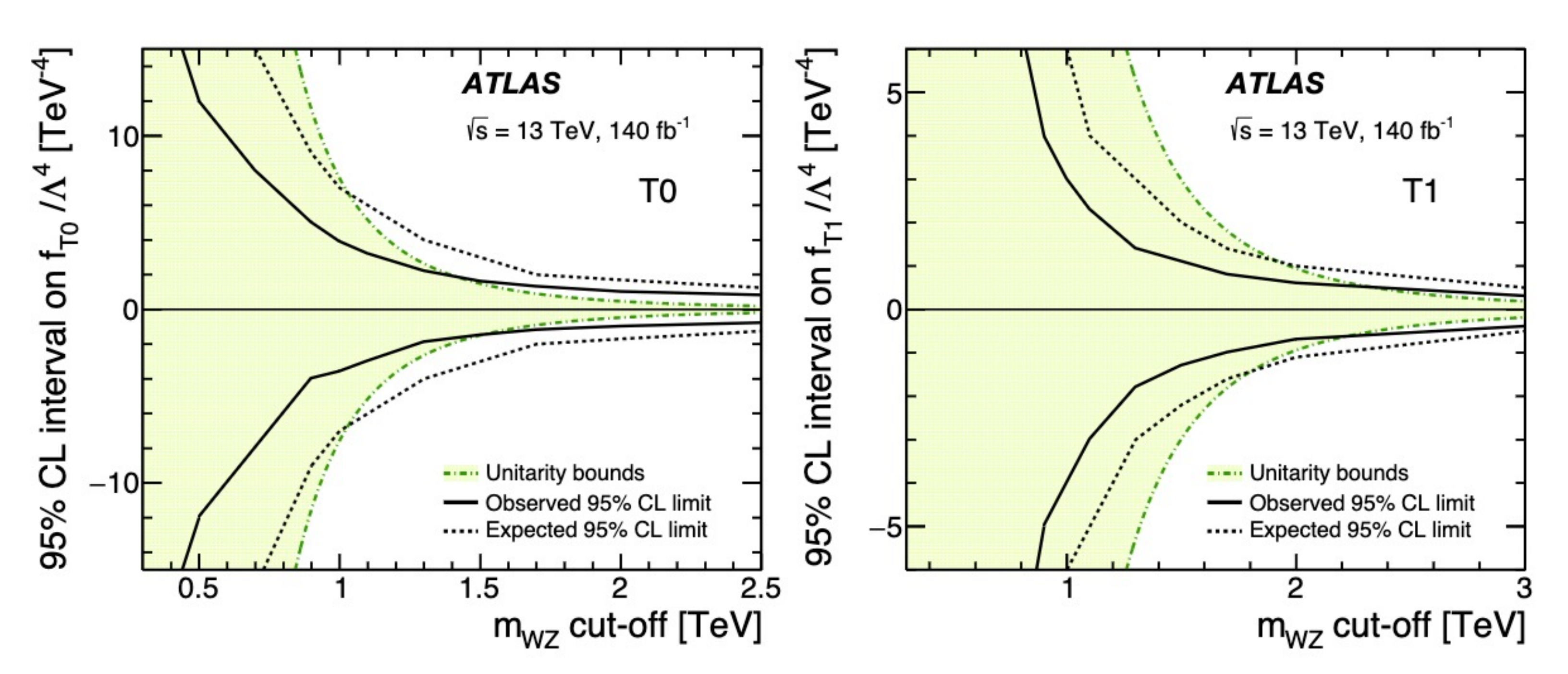


# *Unitarity limits*

- Introduction of EFT operators can violate unitarity
  - for each operator there is an energy scale above which unitarity maybe violated
  - its absolute value is a function of the (arbitrary) cut-off scale

| | Expected $[\mathrm{TeV}^{-4}]$ | Observed $[\mathrm{TeV}^{-4}]$ |
|---|---|---|
| $f_{T0}/\Lambda^4$ | [-7.0, 7.0] | [-1.5, 1.6] |
| $f_{T1}/\Lambda^4$ | [-1.1, 1.0] | [-0.7, 0.6] |
| $f_{T2}/\Lambda^4$ | [-12, 6] | [-2.4, 1.8] |
| $f_{M0}/\Lambda^4$ | [-60, 60] | [-12, 12] |
| $f_{M1}/\Lambda^4$ | [-32, 32] | [-15, 15] |
| $f_{M7}/\Lambda^4$ | [-30, 30] | [-15, 15] |
| $f_{S02}/\Lambda^4$ | [-41, 41] | [-18, 18] |
| $f_{S1}/\Lambda^4$ | — | — |

Evolution of the individual 95%C.L. expected limits of the dimension-8 operators as a function of the cut-off scale



# CONCLUSION AND PROSPECTS

# Conclusion and Prospects

- Run2 WZ VBS analysis
  - Combination of aQGC EFT results combination among many VBS analyses (ssWWjj, ZZjj, Zγjj etc)
- Run3 WZ VBS measurements and combination with Run2
  - SM measurements:
    - Improve QCD modeling
    - Introduce EWK NLO corrections
    - Polarization measurements with one gauge boson (W or Z) longitudinally polarized
  - EFT interpretation:
    - perform a simultaneous study of both dimension-6 and dimension-8 operators
    - Study of effect of dim-6 operators in EWK and QCD production and how to incorporate it in the EFT interpretation
    - machine learning approach to the EFT re-interpretation of the WZ VBS production → results appear very promising from preliminary studies at generator level
- HL-LHC (luminosity 3000 $fb^{-1}$)
  - WZ VBS polarization analysis:
    - First observation of $V_L V_L$ polarized state

# BACKUP SLIDES

# Experimental and theoretical uncertainties

## Experimental uncertainties

- **Dominant experimental uncertainty sources**:
  - reconstruction uncertainties related to
    - jet reconstruction
    - electrons reconstruction
    - muons reconstruction
    - $E_t^{miss}$ reconstruction
  - Luminosity uncertainty
  - uncertainties on the pile-up reweighting procedure
- **Systematic uncertainties on background contributions**
  - Uncertainties on the amount of reducible background events arising from mis-identified leptons and determined using the data-driven matrix method → order of 20 to 25%
  - Irreducible backgrounds: propagate PDF and scale uncertainties in their generated cross sections
    - VVV: 20%
    - ZZ-EW: 25%

## Theoretical uncertainties

- **PDF and $\alpha S$ uncertainties:** 100 NNPDF3.0 MC replicas and alternatives as variations (PDF4LHC recommendations)
- **QCD-scale uncertainties:**
  - Vary the renormalization and factorization scales separately by a factor x=1/2 or x=2 from the nominal
  - For WZjj-EW process
    - alternative definitions for the renormalization and factorizations scales

available at reco level:

$$\mu_0 = \sum_{i=1}^{N} \sqrt{m_i^2 + p_{\mathrm{T},i}^2} = HT$$

$$\mu_0 = HT/2$$

available at truth level:

$$\mu_0 = \sqrt{p_{\mathrm{T}}^{j_1}\, p_{\mathrm{T}}^{j_2}}$$

- **Parton shower uncertainties on the WZjj-EW process :** Estimated using Herwig as an alternative parton shower generator
- **Model uncertainties for the WZjj-QCD process :** Evaluated comparing Madgraph and Sherpa 2.2.12 predictions.

# *Impact of systematic uncertainties*

| Source | $\frac{\Delta\sigma_{WZjj\text{-EW}}}{\sigma_{WZjj\text{-EW}}}$ [%] | $\frac{\Delta\sigma_{WZjj\text{-strong}}}{\sigma_{WZjj\text{-strong}}}$ [%] |
|---|---|---|
| $WZjj$–EW theory modelling | 7 | 1.8 |
| $WZjj$–QCD theory modelling | 2.8 | 8 |
| $WZjj$–EW and $WZjj$–QCD interference | 0.35 | 0.6 |
| PDFs | 1.0 | 0.06 |
| Jets | 2.3 | 5 |
| Pile-up | 1.1 | 0.6 |
| Electrons | 0.8 | 0.8 |
| Muons | 0.9 | 0.9 |
| $b$-tagging | 0.10 | 0.11 |
| MC statistics | 1.9 | 1.2 |
| Misid. lepton background | 2.3 | 2.3 |
| Other backgrounds | 0.9 | 0.23 |
| Luminosity | 0.7 | 0.9 |
| All systematics | 16 | 12 |
| Statistics | 10 | 6 |
| Total | 19 | 13 |