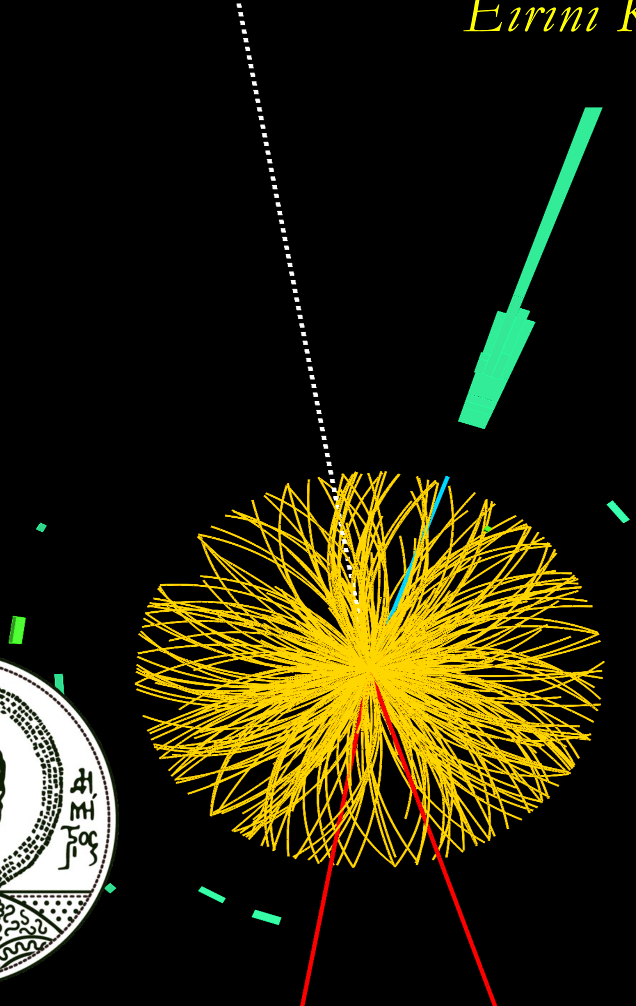
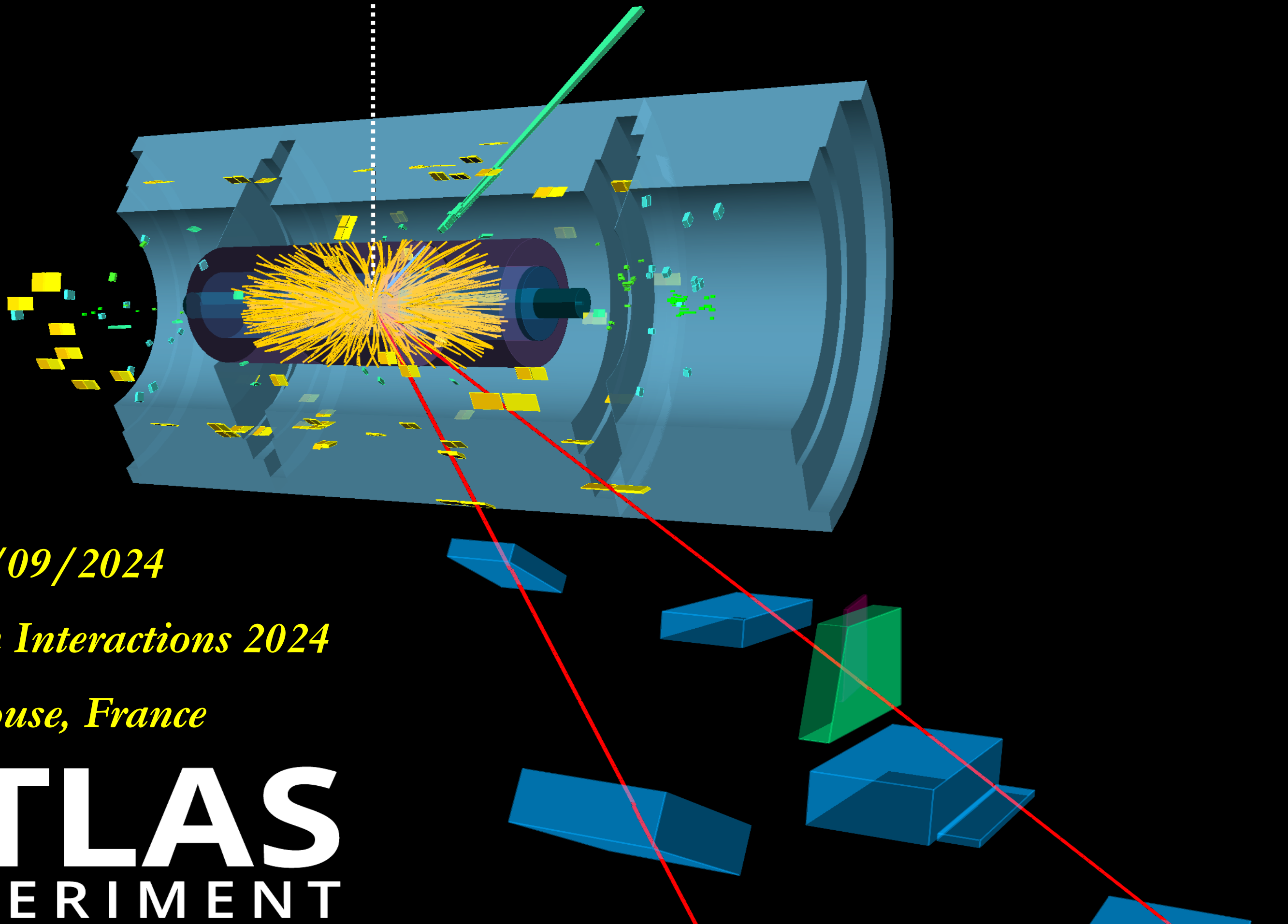
Electroweak $W^{\pm}Z$ production measurement at $\sqrt{s} = 13\ TeV$ with the ATLAS detector and an EFT interpretation

Eirini Kasimi on behalf of the ATLAS collaboration





25/09/2024

Multi-Boson Interactions 2024

Toulouse, France

Overview

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

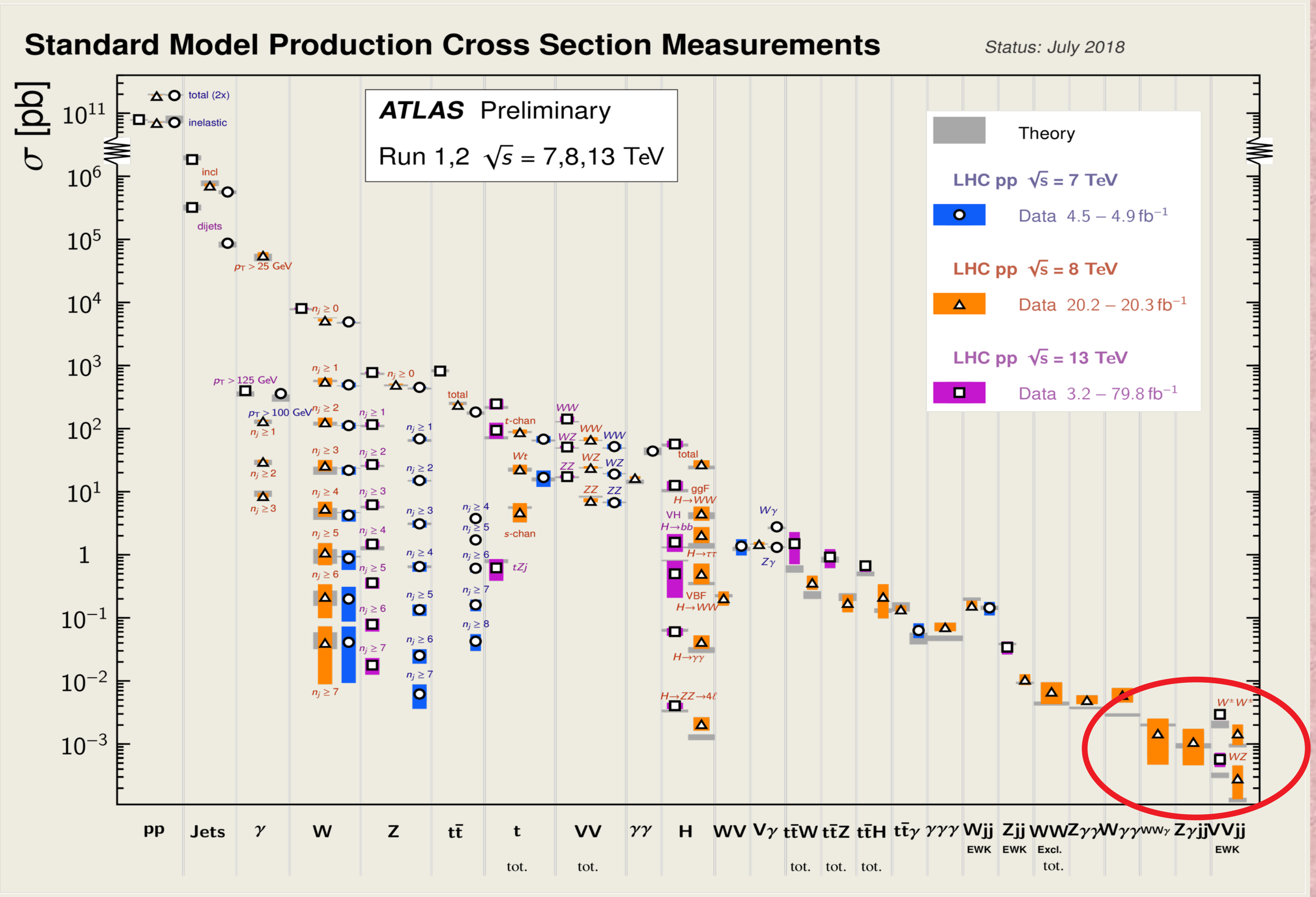
Paper link

MOTIVATION AND THEORETICAL FRAMEWORK

Vector Boson Scattering(VBS): Motivation

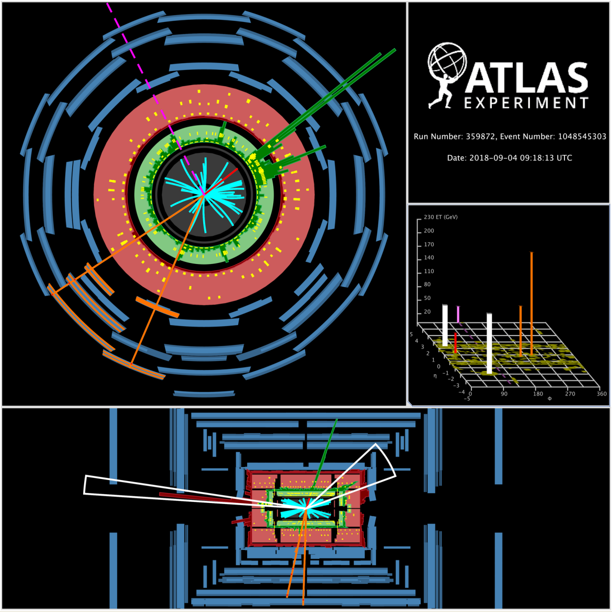
Previous measurements
ATLAS
CMS

- 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*

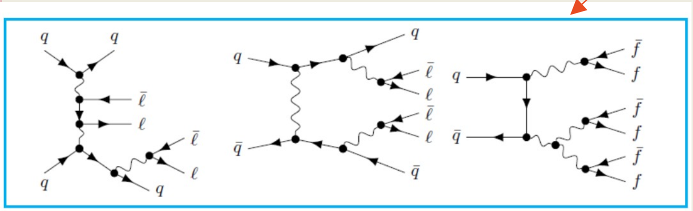


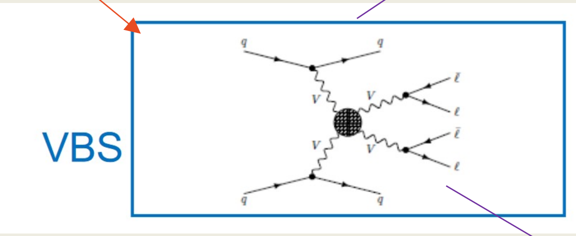
Electroweak and QCD WZjj production

- 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



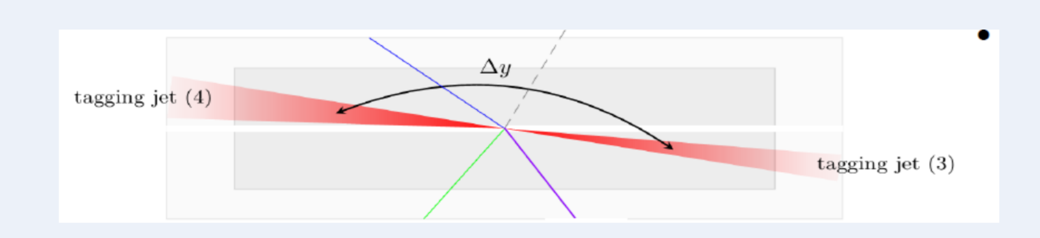
EWK WZjj productions



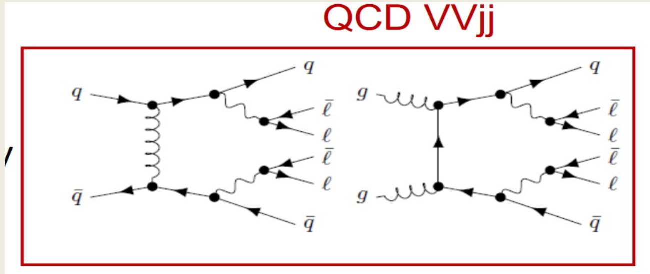


Explore the existence of New Physics through deviations from SM

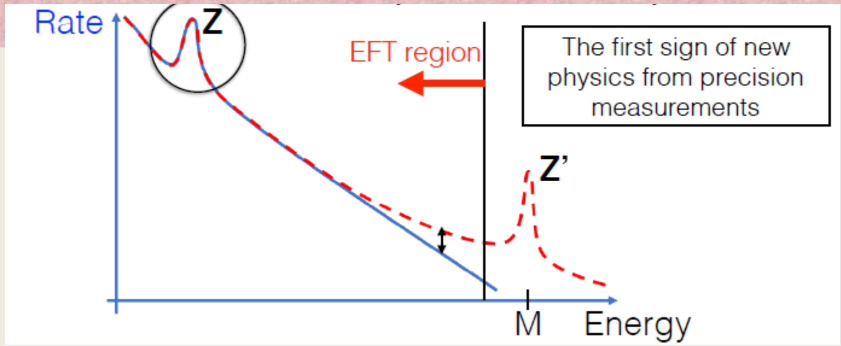
Study of electroweak symmetry breaking through the vector boson self-couplings



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



Effective Field Theory: Overview



The first sign of new physics from precision measurements

- Two methods to look for physics beyond the Standard Model (BSM)
  - Look for new particles
  - 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:

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

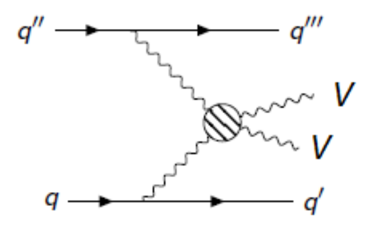
  - Λ is the scale of new physics
  - $O_i^{(6)}$, $O_i^{(8)}$ are the Lorentz and gauge invariant dimension-6 and dimension-8 operators
  - $c_i^{(6)}$, $c_i^{(8)}$ are the dimensionless Wilson coefficients of the dimension-6 and 8 effective operators
- Λ can be assumed as common to all the coefficients,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

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

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

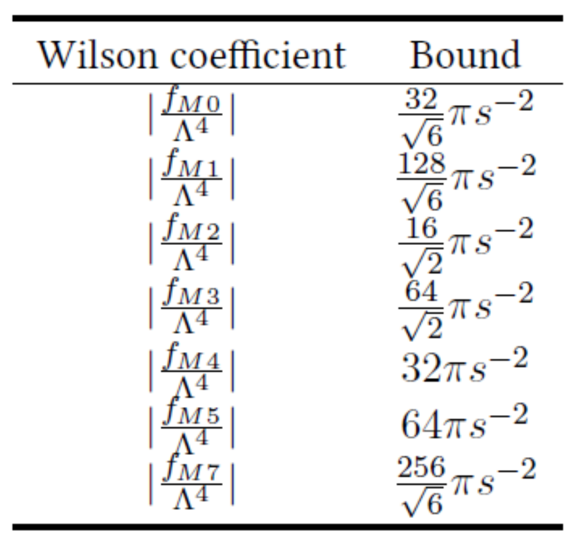
Mixed operators

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

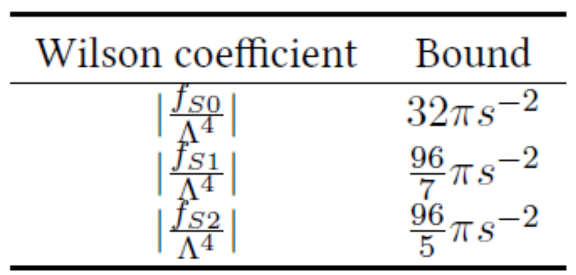
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$,$\mathcal{L}_{M,6}$,$\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$,$\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$,$\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O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

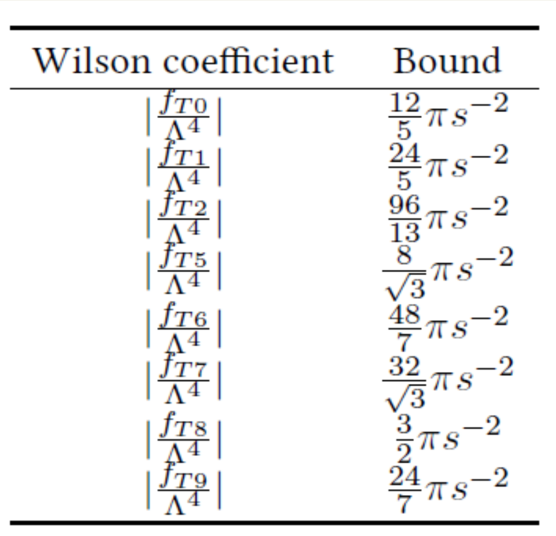
- aQGC terms: disturb the cancellation between different contributions to the scattering amplitude of longitudinally polarized, massive electroweak gauge bosons
- Cross section for the scattering of massive electroweak gauge bosons is rising with increasing centre-of-mass energy but it cannot exceed 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
$\lvert\frac{f_{M0}}{\Lambda^4}\rvert$	$\frac{32}{\sqrt{6}}\pi s^{-2}$
$\lvert\frac{f_{M1}}{\Lambda^4}\rvert$	$\frac{128}{\sqrt{6}}\pi s^{-2}$
$\lvert\frac{f_{M2}}{\Lambda^4}\rvert$	$\frac{16}{\sqrt{2}}\pi s^{-2}$
$\lvert\frac{f_{M3}}{\Lambda^4}\rvert$	$\frac{64}{\sqrt{2}}\pi s^{-2}$
$\lvert\frac{f_{M4}}{\Lambda^4}\rvert$	$32\pi s^{-2}$
$\lvert\frac{f_{M5}}{\Lambda^4}\rvert$	$64\pi s^{-2}$
$\lvert\frac{f_{M7}}{\Lambda^4}\rvert$	$\frac{256}{\sqrt{6}}\pi s^{-2}$



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



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

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

$$
\begin{aligned}
&|\mathcal{A}_{\mathrm{SM}} + \sum_i c_i \mathcal{A}_i|^2 \\
&\quad = \underbrace{|\mathcal{A}_{\mathrm{SM}}|^2}_{\text{SM term}} + \overbrace{\sum_i c_i 2\mathrm{Re}\left(\mathcal{A}^\star_{\mathrm{SM}} \mathcal{A}_i\right)}^{\text{Interference term between SM-EFT (Linear term)}} + \overbrace{\sum_i c_i^2 |\mathcal{A}_i|^2}^{\text{Pure EFT contribution (Quadratic term)}} + \overbrace{\sum_{ij, i \neq j} c_i c_j 2\mathrm{Re}\left(\mathcal{A}^\star_i \mathcal{A}_j\right)}^{\text{Interference term between EFT operators (Cross term)}}
\end{aligned}
$$

ANALYSIS OVERVIEW AND RESULTS

Phase space definition for the cross-section measurements

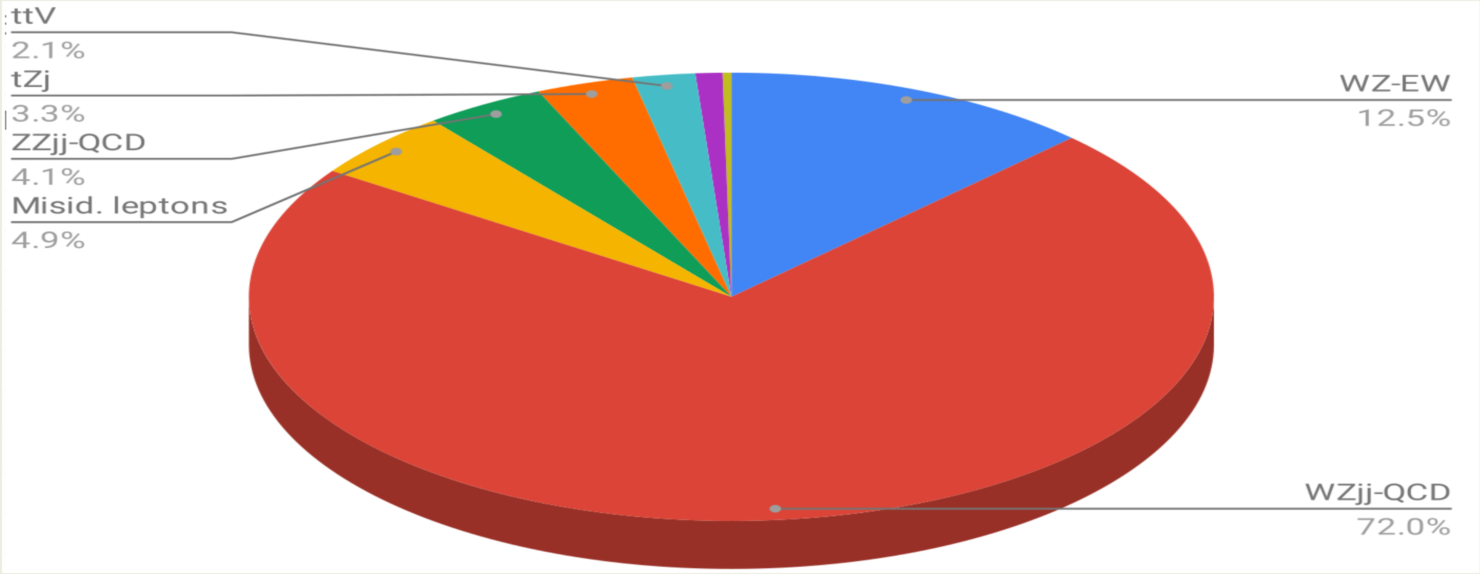
Variable	Fiducial $WZjj$–EW
Lepton $\lvert\eta\rvert$	< 2.5
p_T of ℓ_Z, p_T of ℓ_W [GeV]	> 15, > 20
m_Z range [GeV]	$\lvert m_Z - m_Z^\mathrm{PDG}\rvert < 10$
m_T^W [GeV]	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	> 0.2, > 0.3
p_T two leading jets [GeV]	> 40
$\lvert\eta_j\rvert$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

Concerning the three leptons

Concerning the two jets

Backgrounds

- **Challenging separation between the signals and the backgrounds**
- Backgrounds:
  - Reducible background: $Z + jets$, $Z\gamma$, $t\bar{t}$ and Wt
  - Irreducible background: $t\bar{t}V$, tZ, VVV, $ZZjj - QCD$ and $ZZjj - EW$

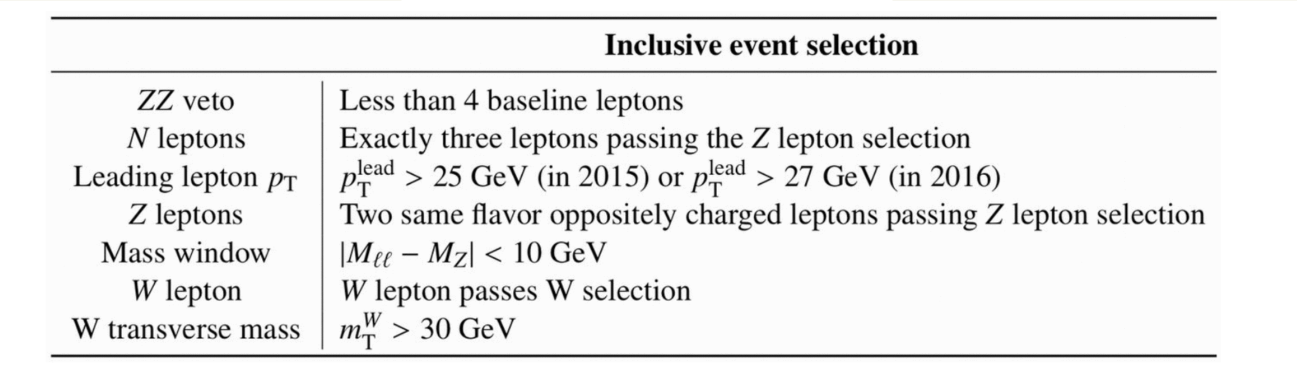


- At least one “fake” lepton
- Matrix method technique

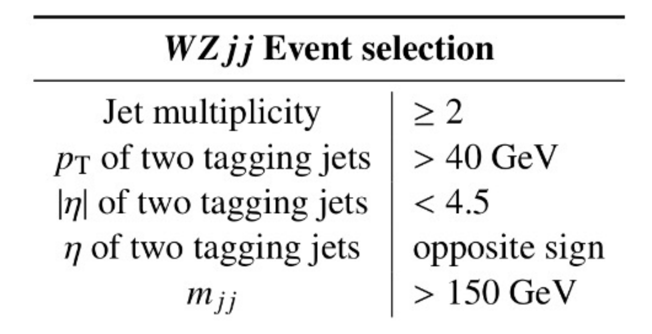
- At least three prompt leptons in the final state
- Simultaneous fit in dedicated CRs

WZjj Event selection and global WZjj strategy

Baseline event selection:

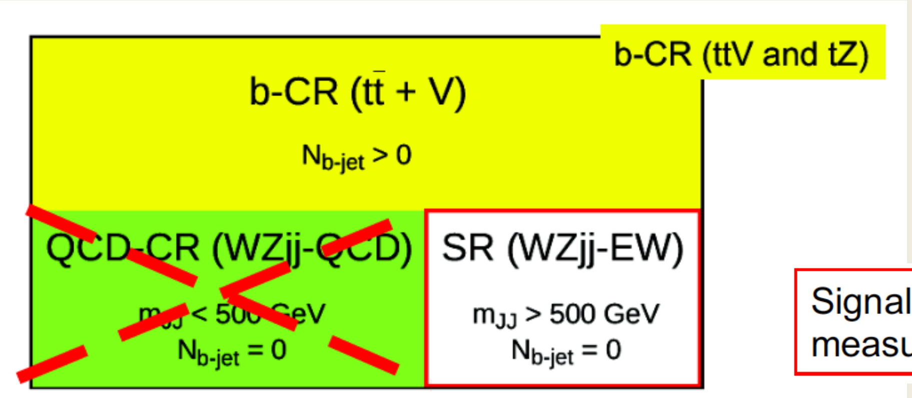


Inclusive event selection	
ZZ veto	Less than 4 baseline leptons
N leptons	Exactly three leptons passing the *Z* lepton selection
Leading lepton p_T	$p_T^{\text{lead}} > 25$ GeV (in 2015) or $p_T^{\text{lead}} > 27$ GeV (in 2016)
Z leptons	Two same flavor oppositely charged leptons passing *Z* lepton 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	≥ 2
p_T of two tagging jets	> 40 GeV
$\lvert\eta\rvert$ of two tagging jets	< 4.5
η of two tagging jets	opposite sign
m_{jj}	> 150 GeV

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



b-CR (ttV and tZ)

b-CR ($t\bar{t}$ + V)

$N_{b\text{-jet}} > 0$

~~QCD-CR (WZjj-QCD)~~

~~$m_{JJ} < 500$ GeV~~

~~$N_{b\text{-jet}} = 0$~~

SR (WZjj-EW)

$m_{JJ} > 500$ GeV

$N_{b\text{-jet}} = 0$

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

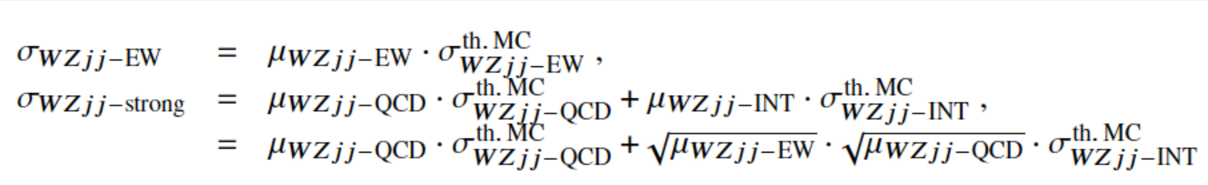
Not used in the cross section measurement or any step of the analysis

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

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

- 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.

- Signal fit free parameters

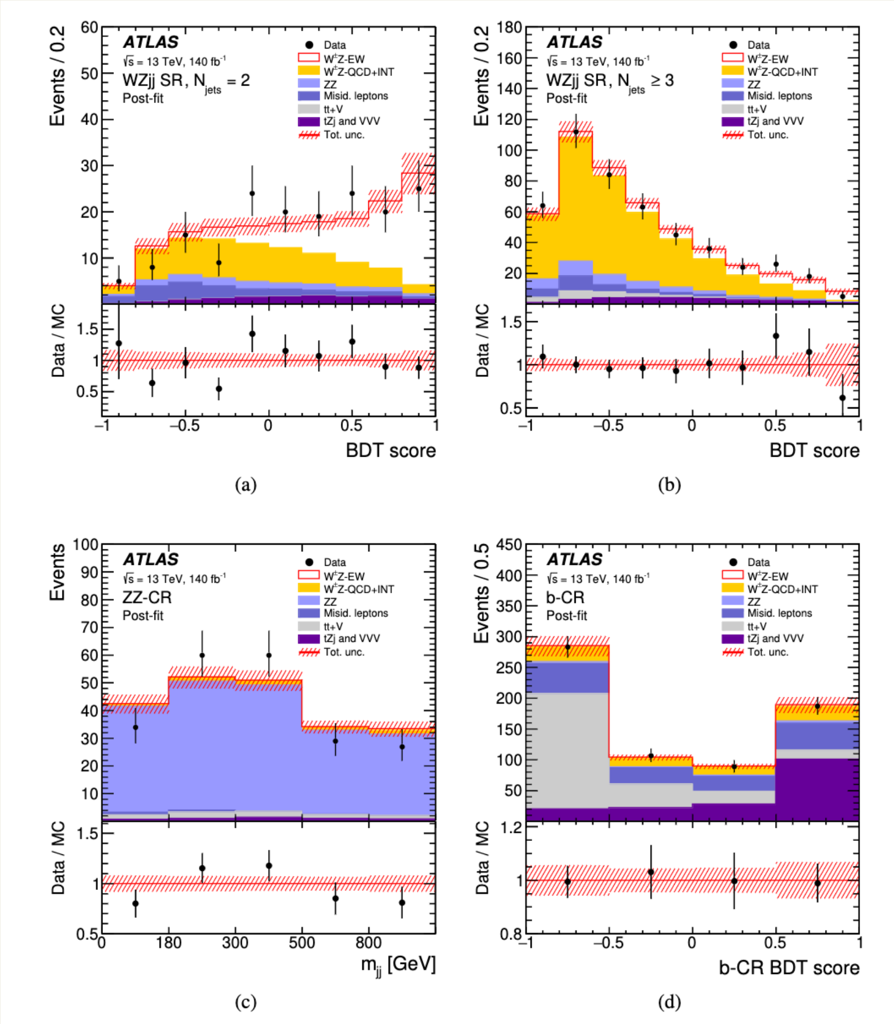


$$
\begin{aligned}
\sigma_{WZjj\text{–EW}} &= \mu_{WZjj\text{–EW}} \cdot \sigma^{\text{th. MC}}_{WZjj\text{–EW}}\,, \\
\sigma_{WZjj\text{–strong}} &= \mu_{WZjj\text{–QCD}} \cdot \sigma^{\text{th. MC}}_{WZjj\text{–QCD}} + \mu_{WZjj\text{–INT}} \cdot \sigma^{\text{th. MC}}_{WZjj\text{–INT}}\,, \\
&= \mu_{WZjj\text{–QCD}}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

- Background normalization parameters
  - μ_{ttV} and μ_{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

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

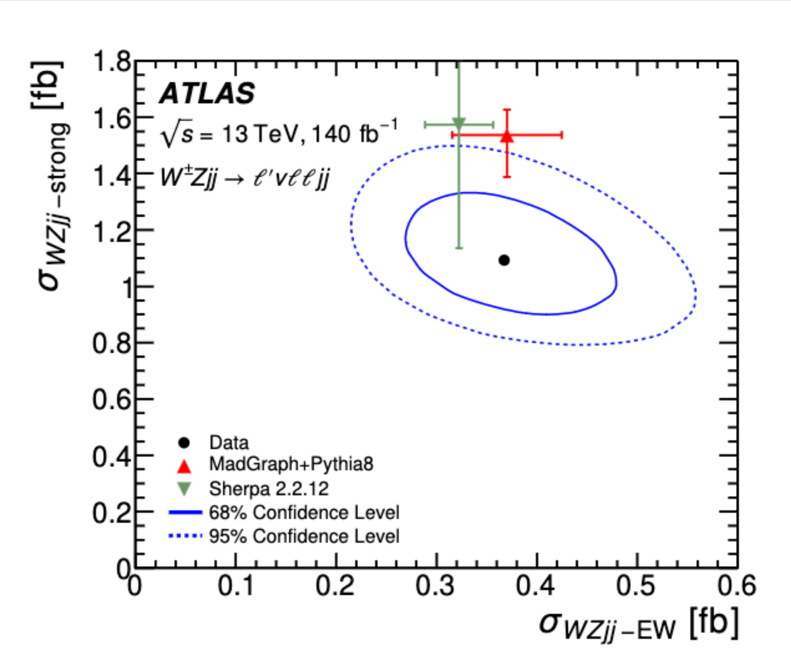


(a)

(b)

(c)

(d)



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

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
  - μ_{ttV} and μ_{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}:

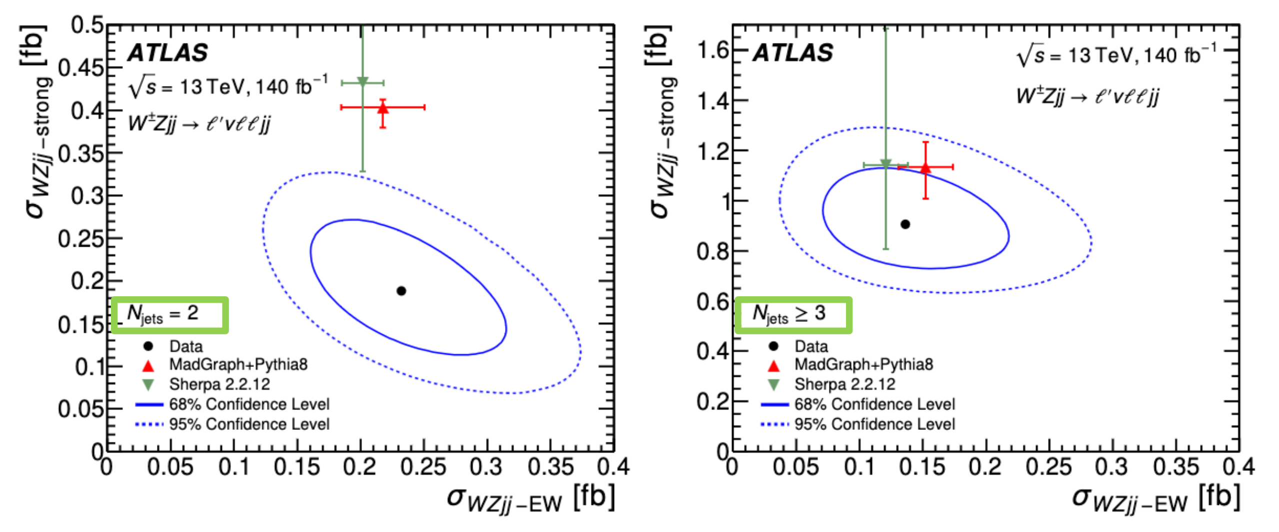
- 500-1300 GeV
- 1300-2000 GeV
- >2000 GeV

Signal sub-regions for N_{jets}:

- Exactly 2 jets
- >2 jets

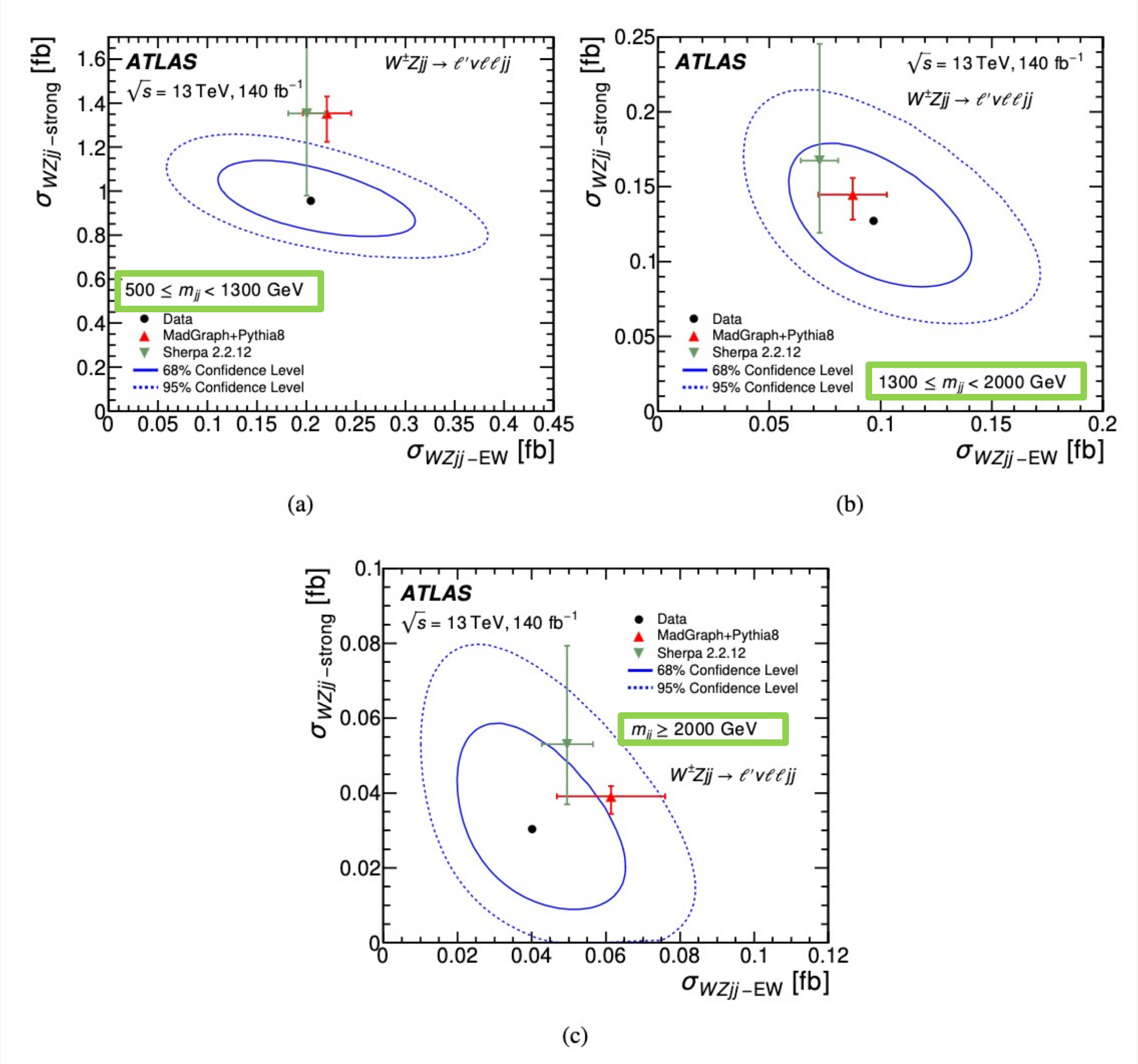
Differential $\sigma_{WZjj\text{-}EW}$ *and* $\sigma_{WZjj\text{-}strong}$ *measurement*

N_{jets} categorization



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

M_{jj} categorization

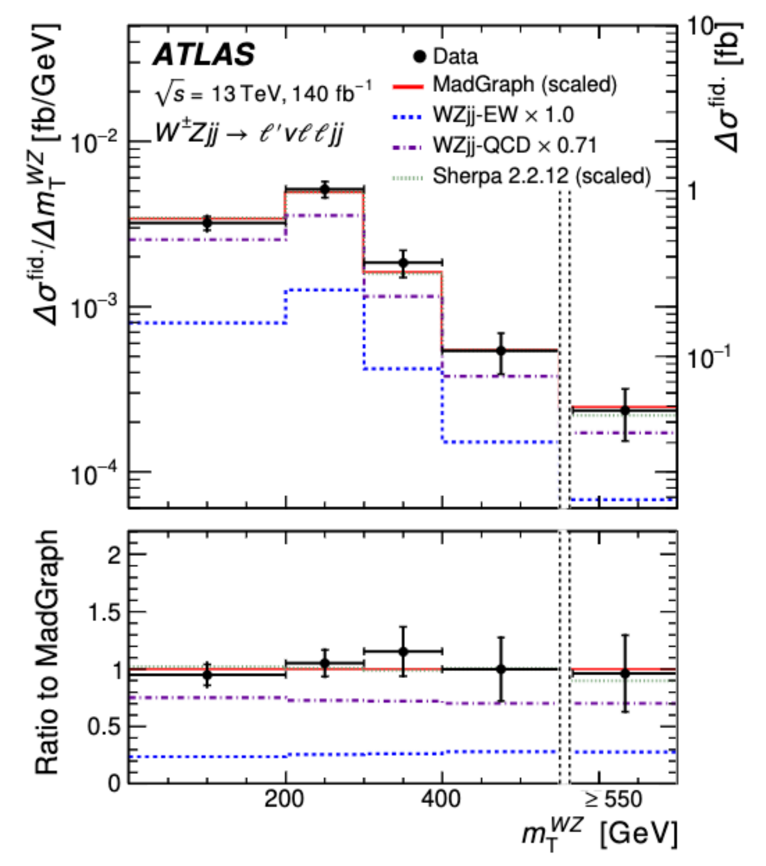


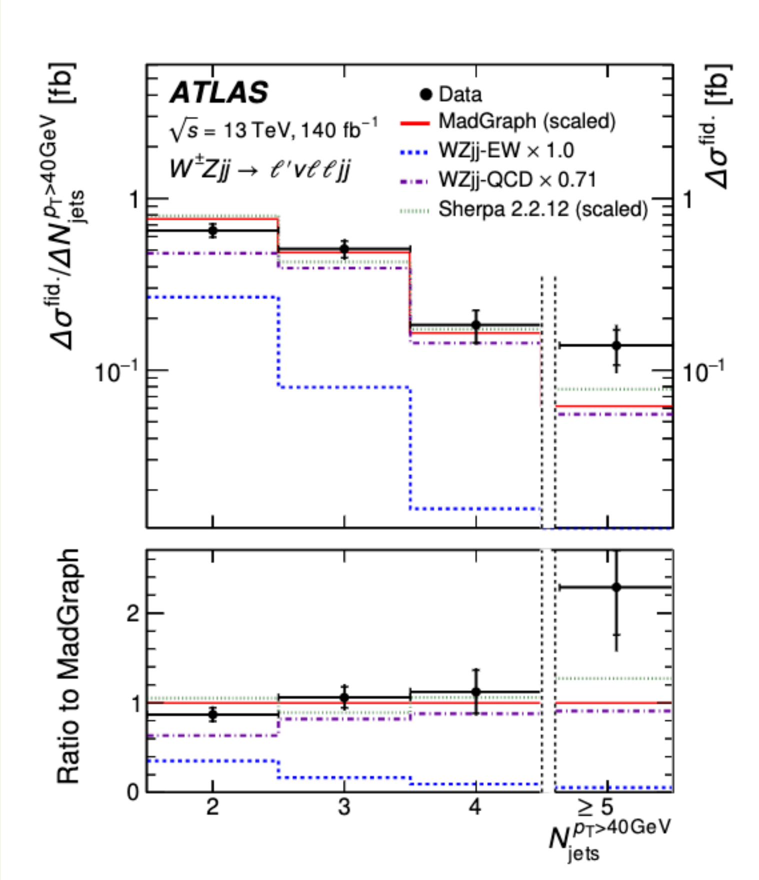
(a) (b)

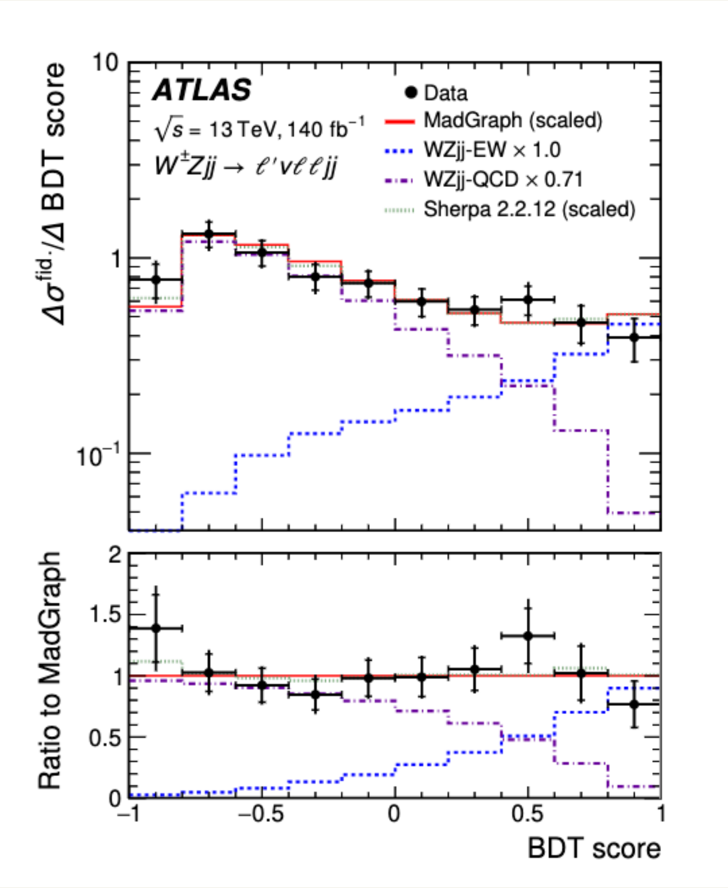
(c)

Differential WZjj measurements

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



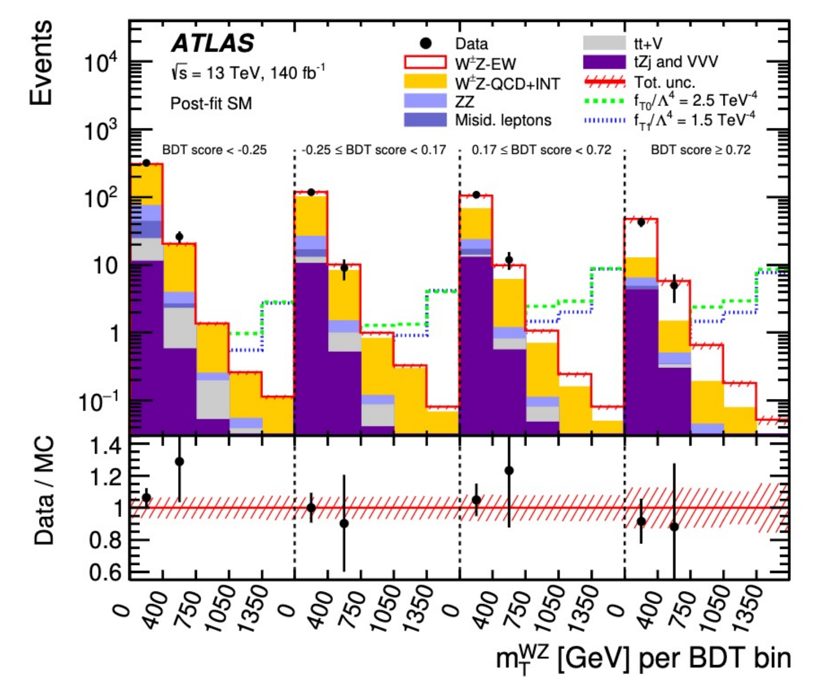




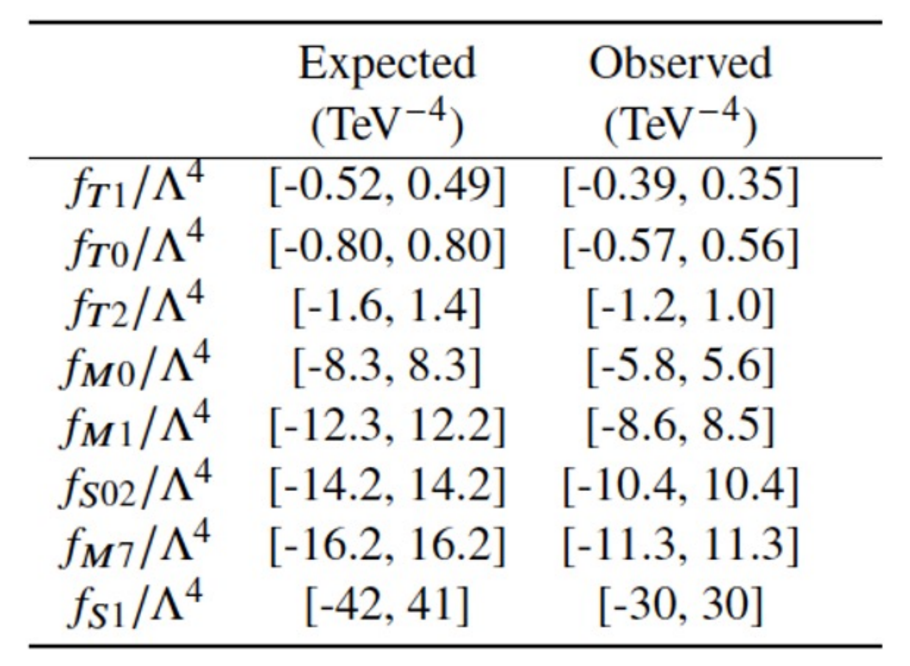
EFT INTERPRETATION RESULTS

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



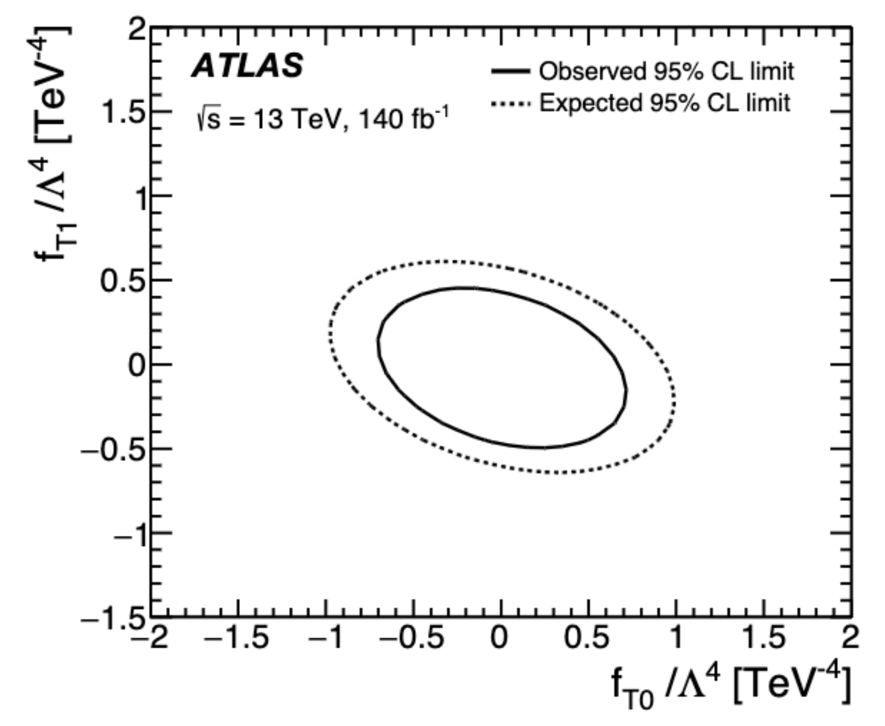
Expected and observed lower and upper 95% CL limits on the Wilson coefficients



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

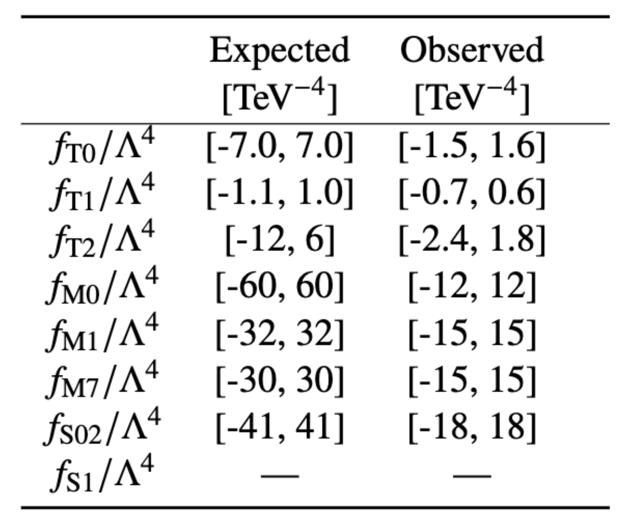
2-D reconstructed level limits

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



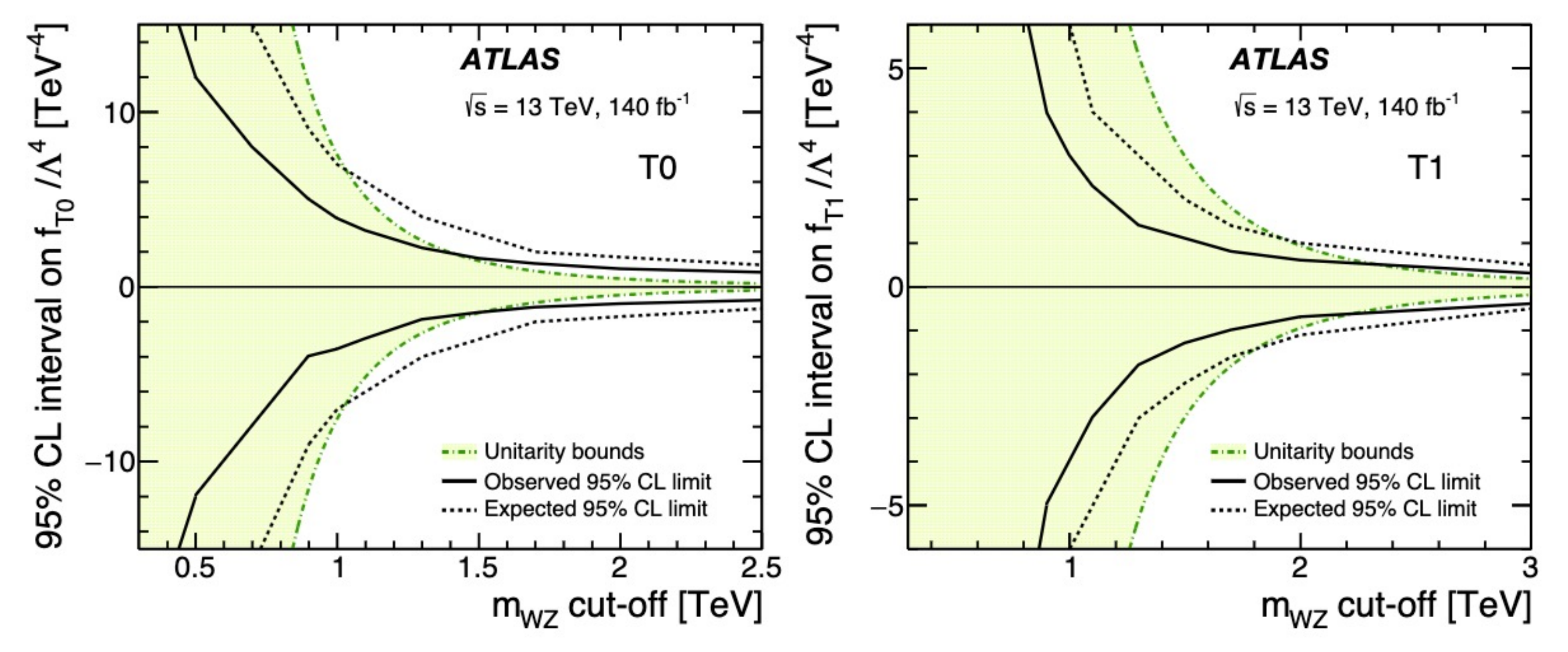
Unitarity limits

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

- Ongoing combination of aQGC Run2 EFT results among many VBS analyses (WZjj, ssWWjj, ZZjj, Zγjj etc)
- Possible improvements on Run 2 measurement:
  - 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 dimension-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})
  - Possible first observation of $W_L Z_L$ polarized state

BACKUP SLIDES

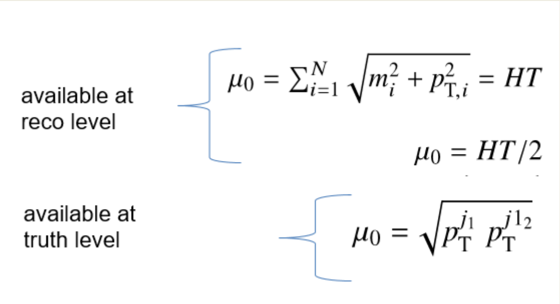
Experimental and theoretical uncertainties

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 αS 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

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

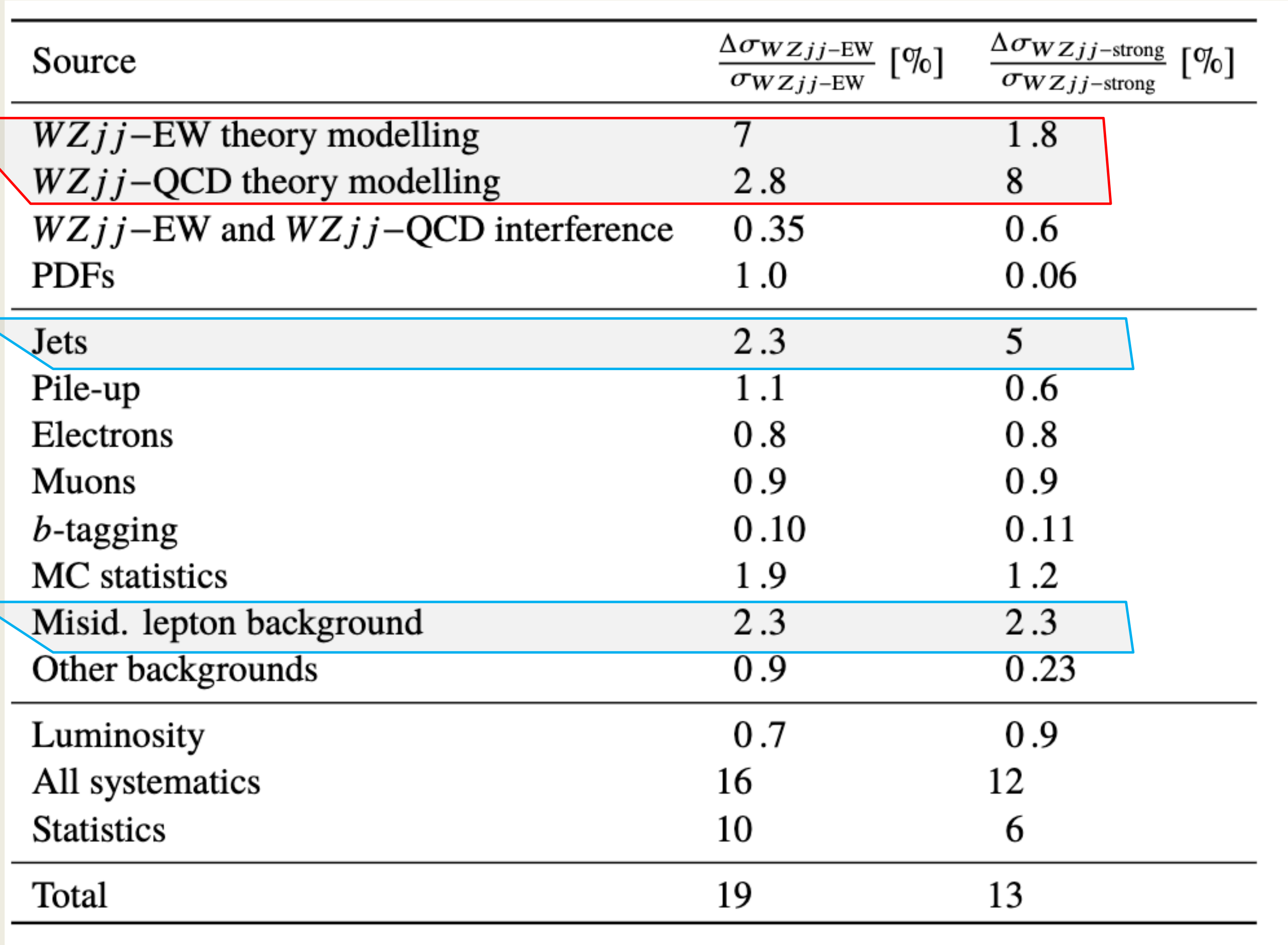
$$\mu_0 = HT/2$$

available at truth level

$$\mu_0 = \sqrt{p_{\mathrm{T}}^{j_1}\ p_{\mathrm{T}}^{j1_2}}$$

- **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