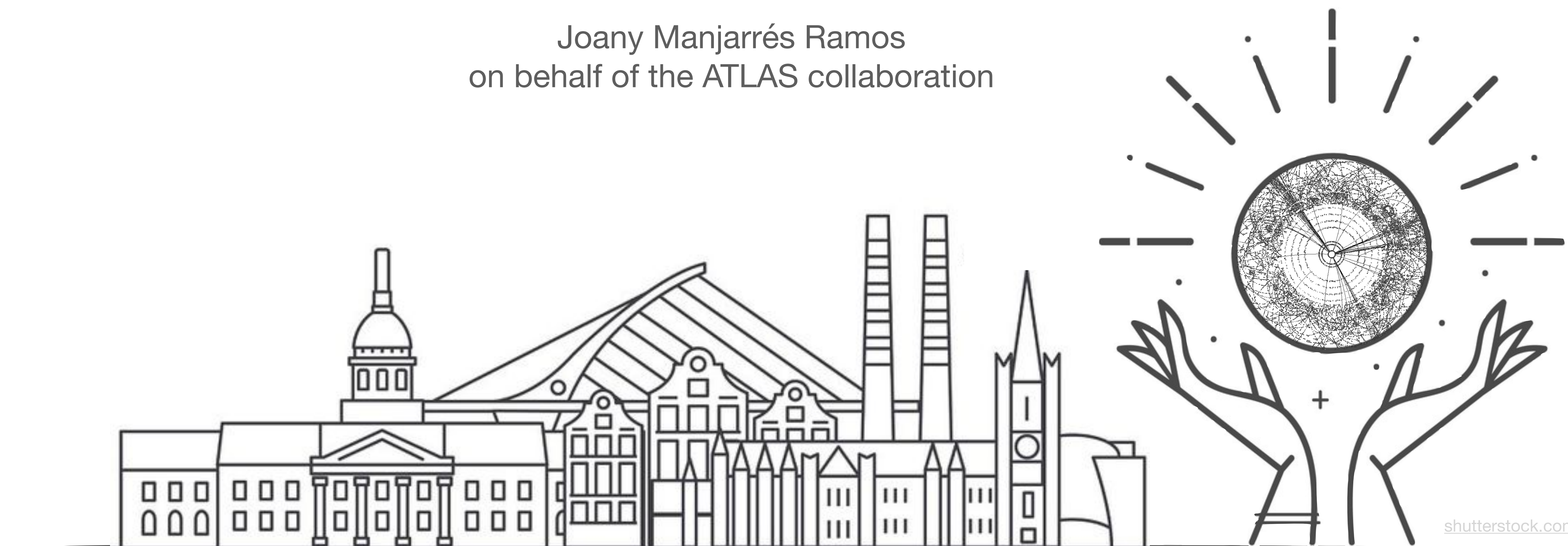
Testing the Electroweak Theory with multi-boson polarization measurements

Latest updates from ATLAS

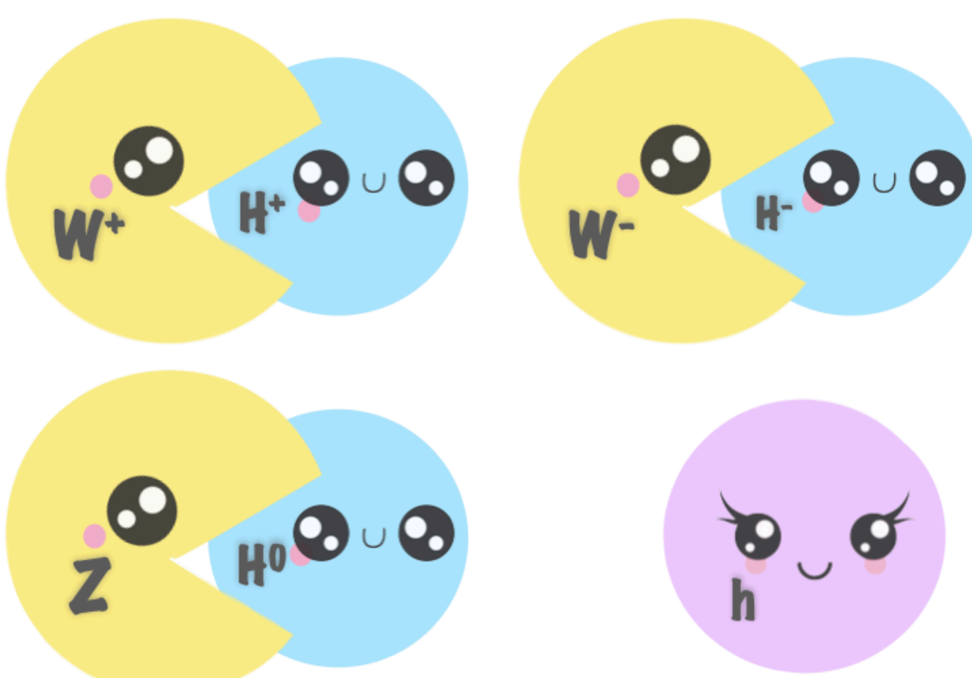
Joany Manjarrés Ramos
on behalf of the ATLAS collaboration



Why weak boson polarization is interesting?

- Gauge boson polarization is strongly related to the structure of the electroweak sector
- The Higgs mechanism predicts the existence of Goldstone bosons, and those are eaten by the W^+, W^-, and Z respectively, providing them with a mass and their longitudinal polarization

Inspired by quantumdiaries.org



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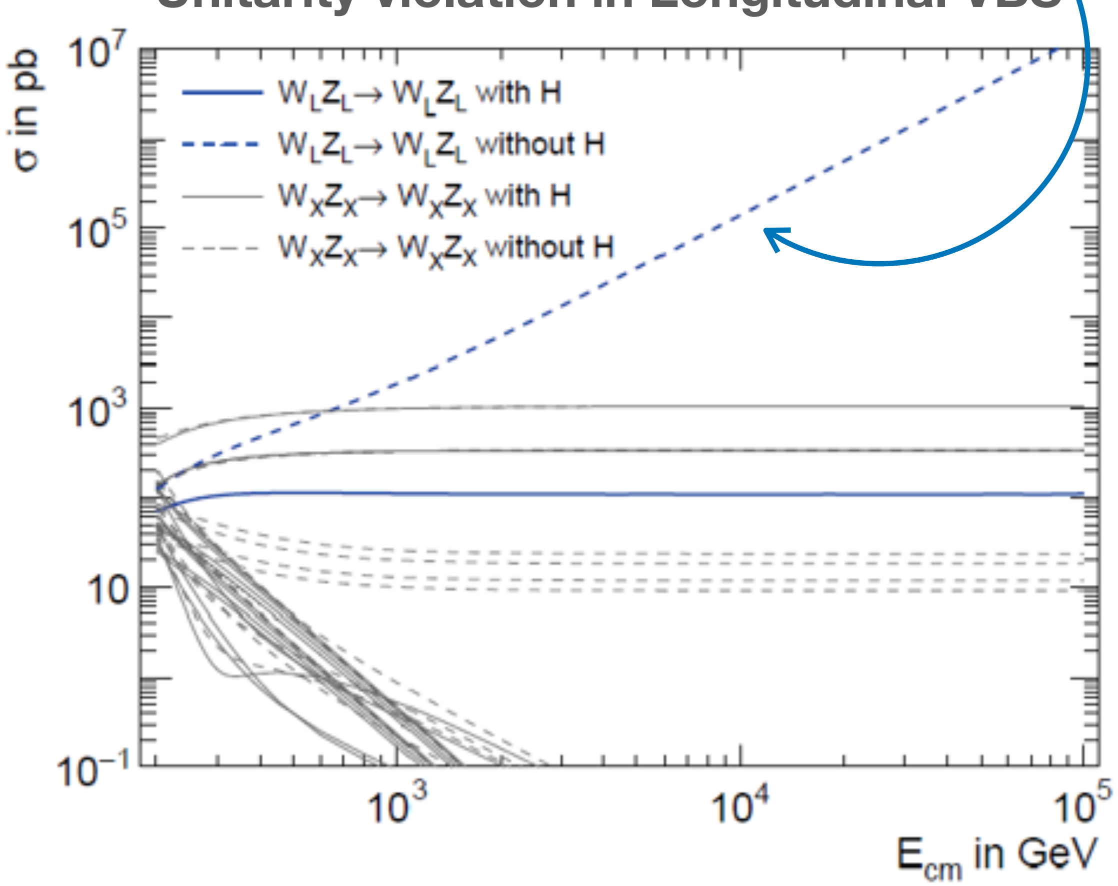
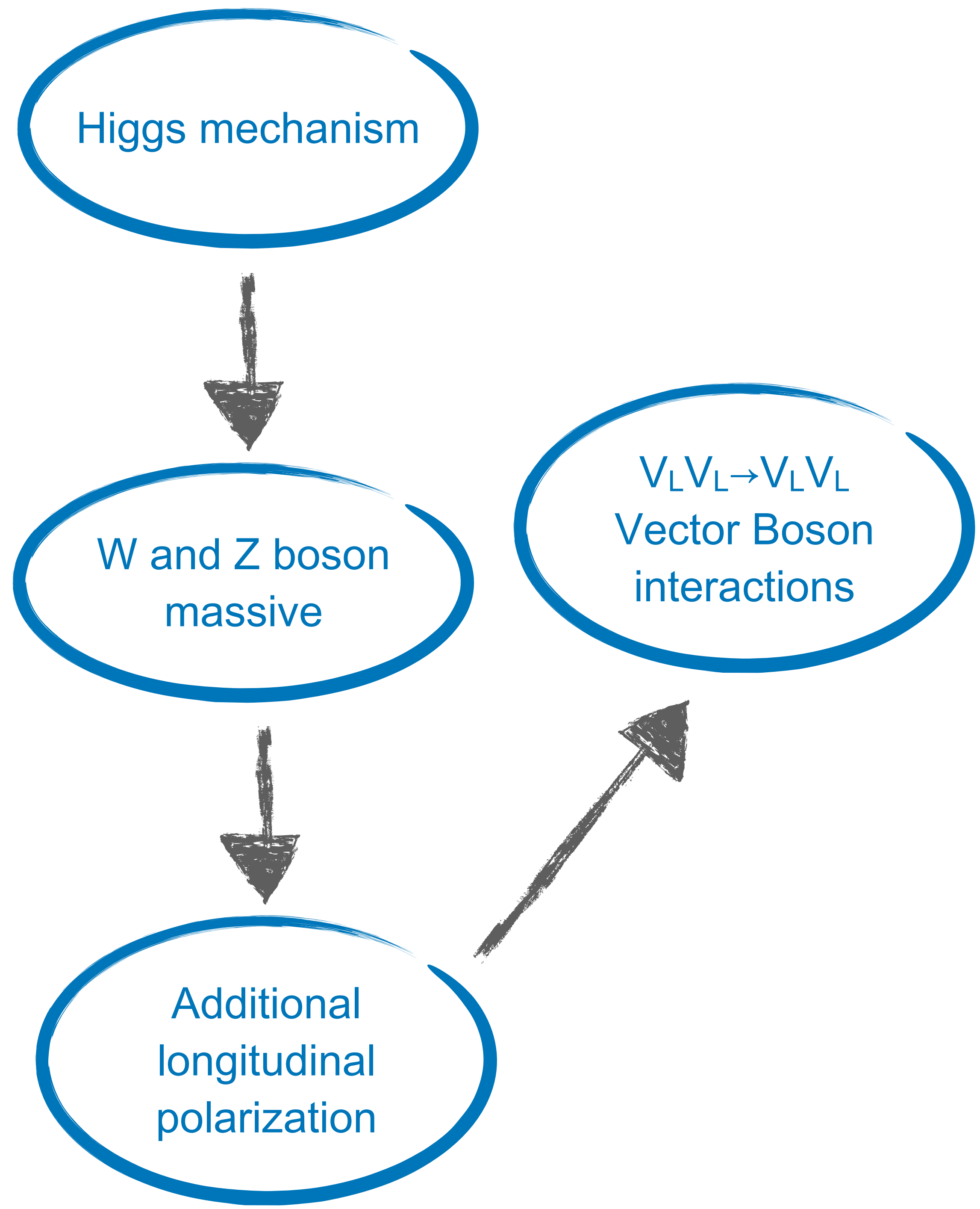
Unitarity violation in Longitudinal VBS





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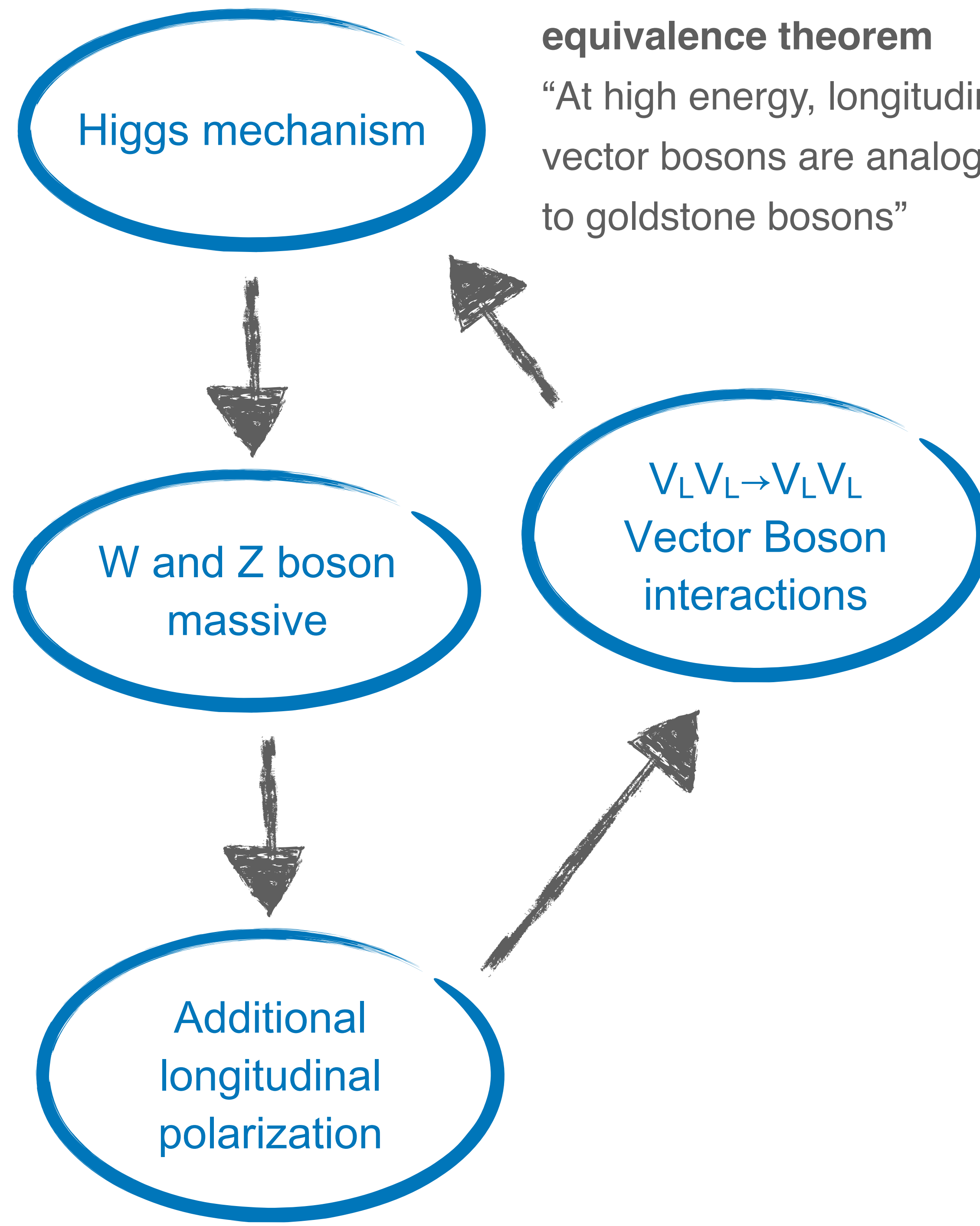
- **Important test of the EWSB**

Goldstone boson equivalence theorem
"At high energy, longitudinal vector bosons are analogous to goldstone bosons"



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- **Important test of the EWSB**
- **Also New physics might couple preferentially to some polarization**

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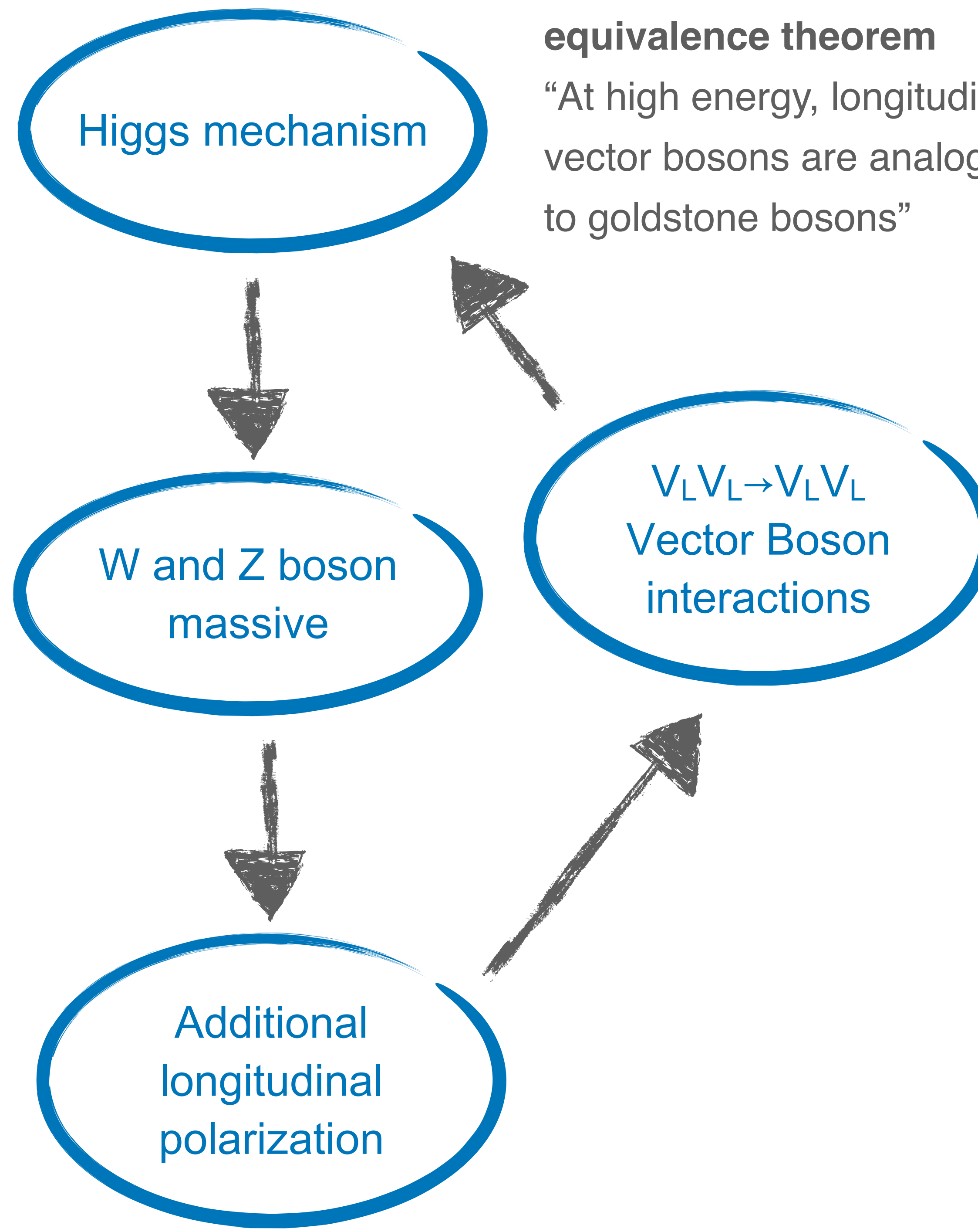


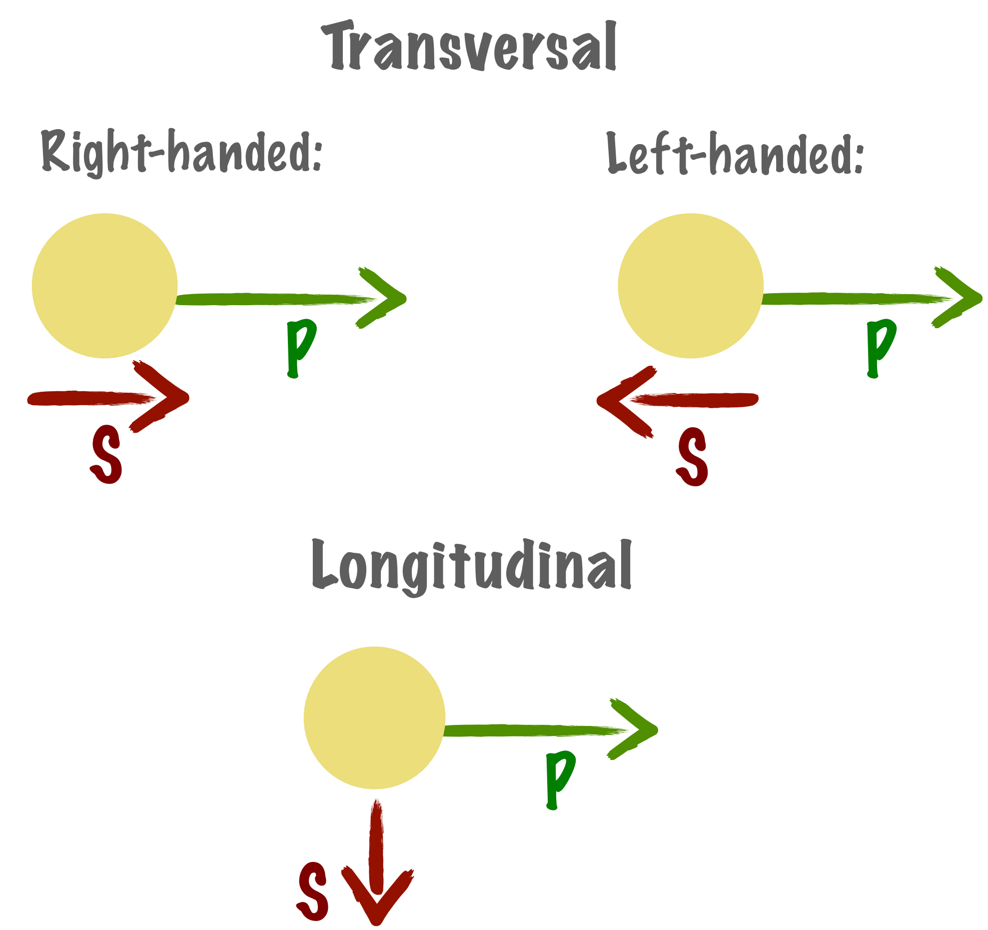
How to measure polarization?

What polarization means?

- Polarization describes the alignment of a particle's spin with its momentum. Quantified using the helicity:

$$h = \vec{S} \cdot \frac{\vec{p}}{|p|}$$

  - Transversal polarization (T): the spin and momenta are (anti)-aligned (h=1, -1)
  - Longitudinal polarization (L or 0): spin orthogonal to the momenta (h=0)



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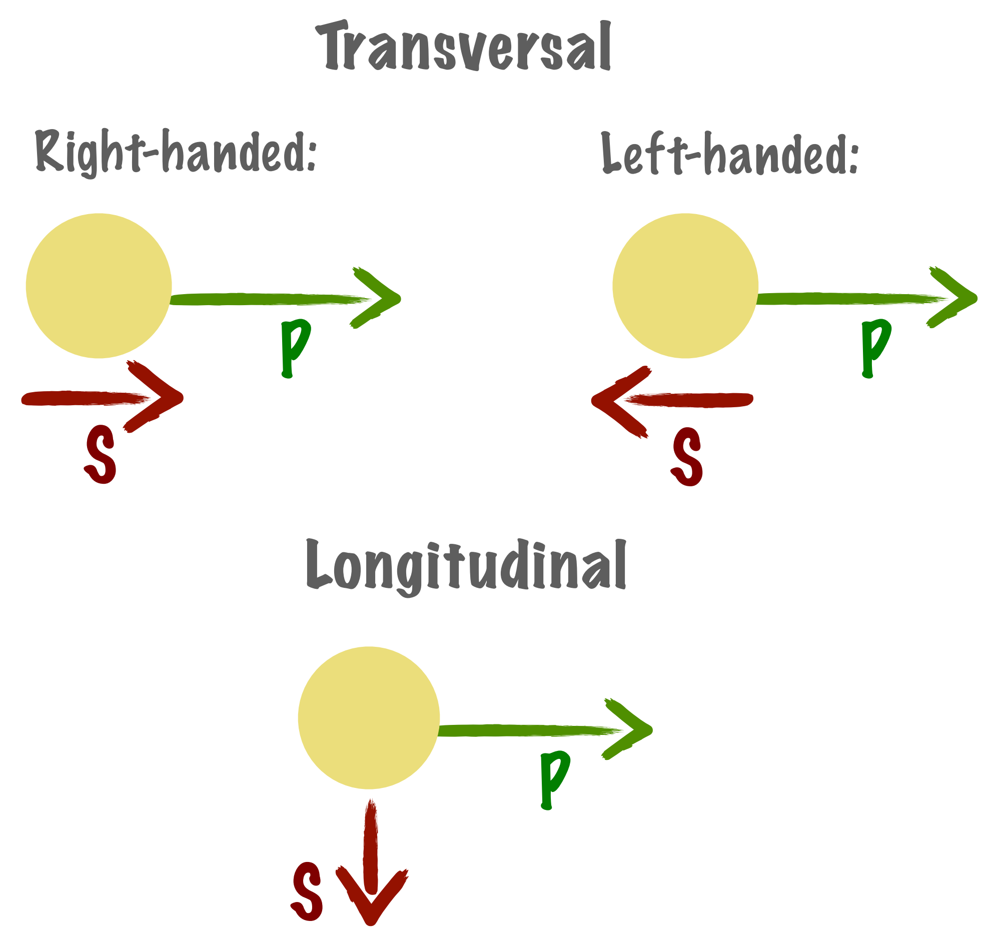

A caveat

- Polarization measurements are frame dependent
- For all measurements you need to define a frame (there is not an universally preferred frame)

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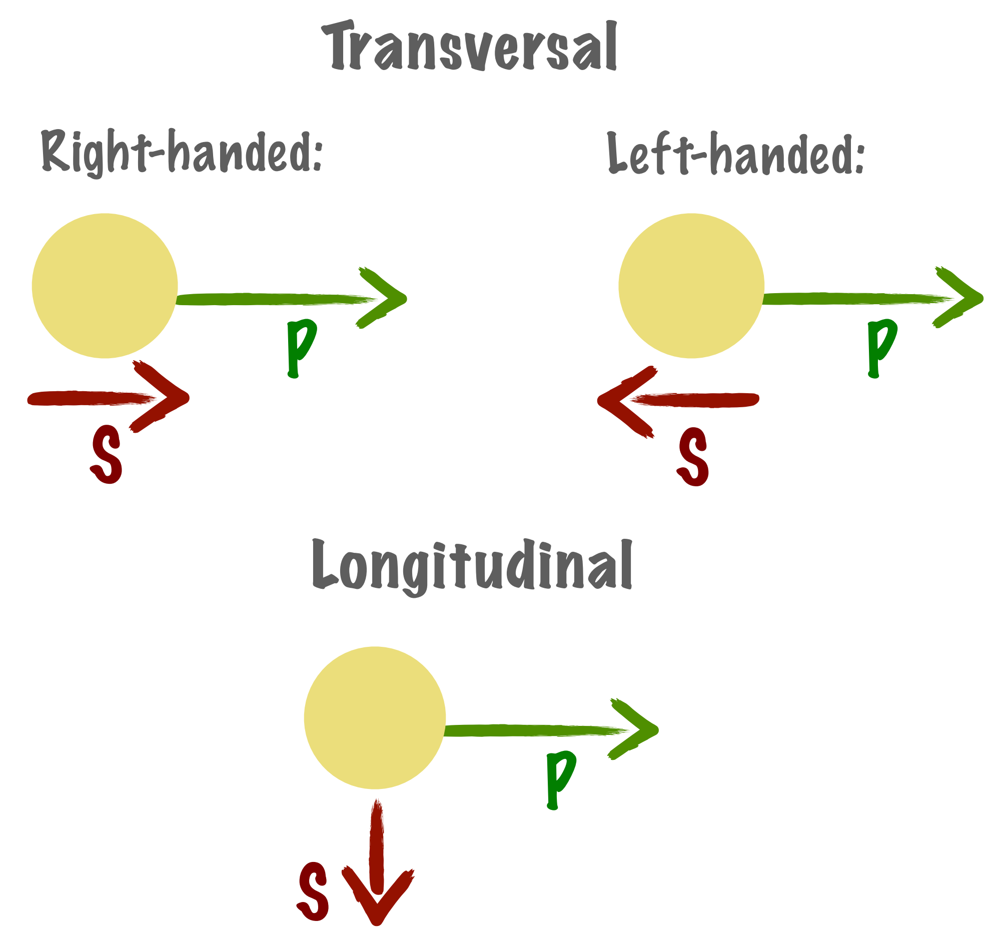

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How to measure polarization?

- Parity violation in weak interactions → polarization has effects on the boson decay products
- Angular variables between the bosons and the decay products are typically used to measure the weak bosons polarizations
- Perform fits to data distributions using ***polarized templates***

Polarized templates how?

Monte Carlo generators

- Several generators in the market:
  - PHANTOM: 2 → 6 processes @ LO+PS [A. Ballestrero et al. 2008, 2017]
  - Madgraph: arbitrary processes @ LO, PS matching, multi-jet merging [D. Buarque Franzosi et al. 2020]
  - POWHEG-BOX-RES: diboson processes @NLO QCD+PS [G. Pelliccioli, G. Zanderighi 2023]
  - Sherpa: arbitrary processes @nLO QCD, PS matching, multi-jet merging [MH, M. Schönherr, F. Siegert 2023]
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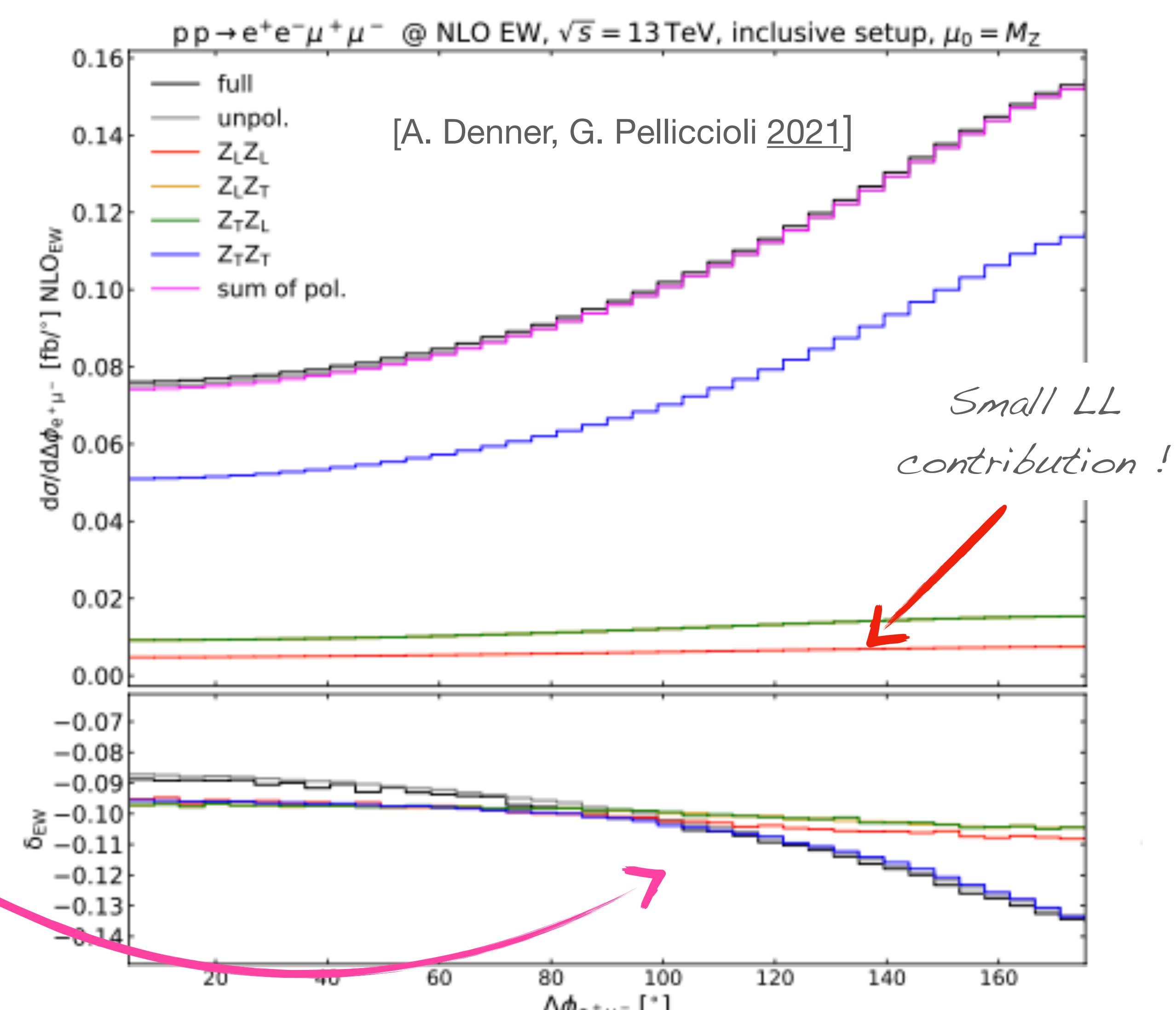
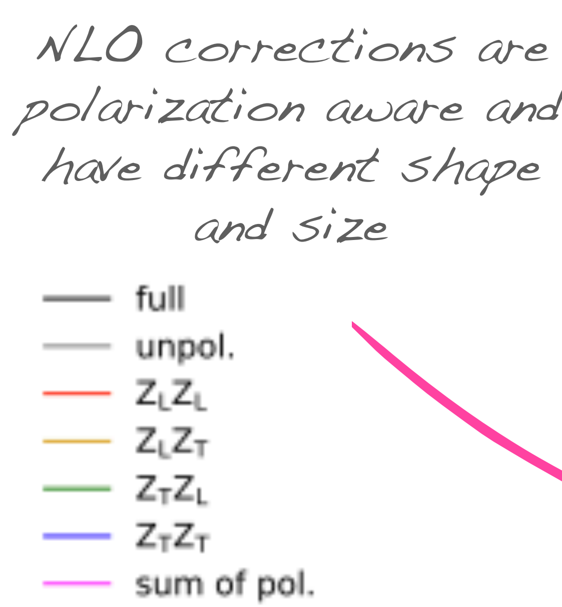
Fix order calculations

- Fix order calculations available show large NLO QCD and EW electroweak polarization depended corrections





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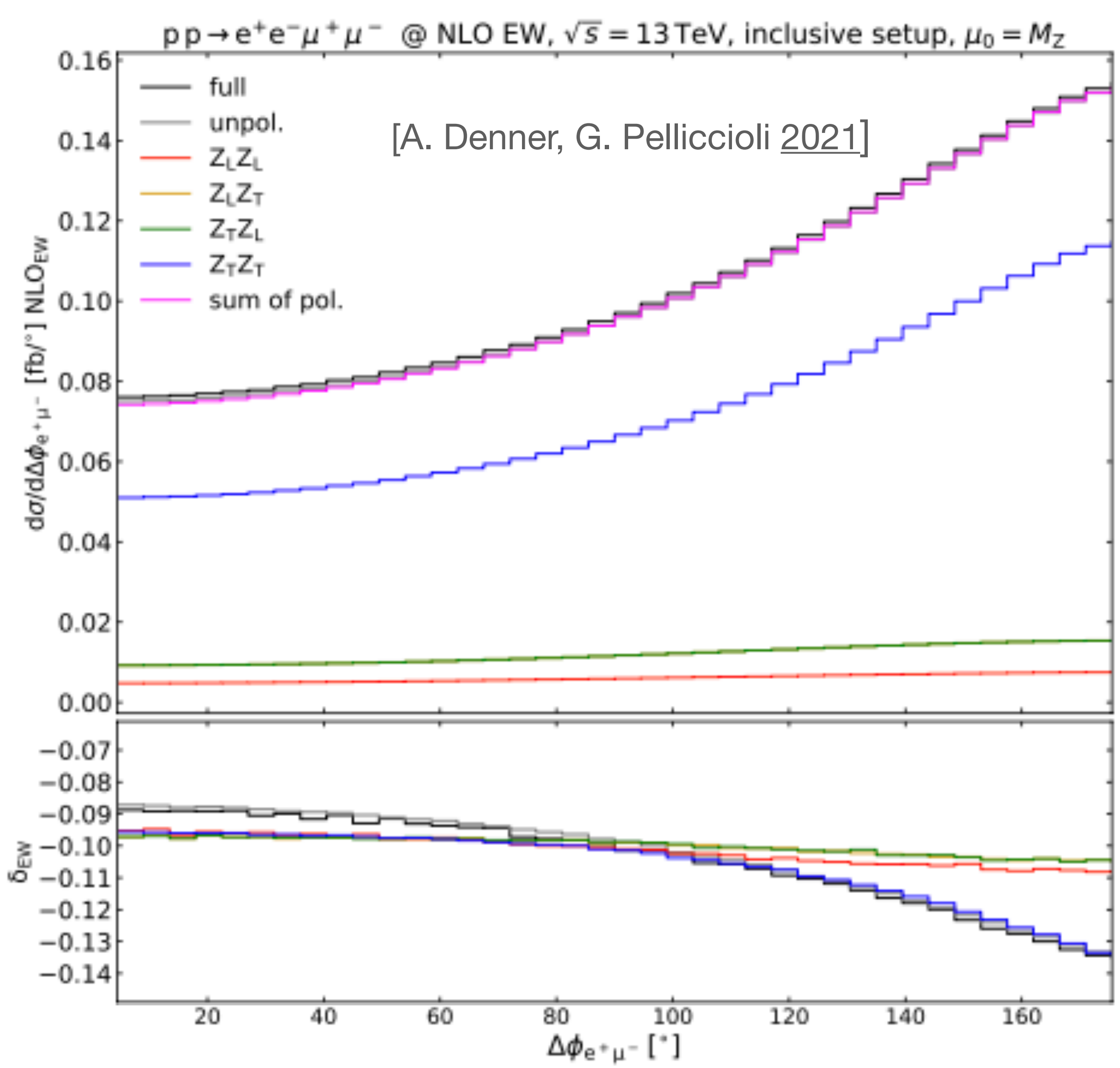

Fix order calculations

- Fix order calculations available show large NLO QCD and EW electroweak polarization depended corrections

Getting polarised templates is a challenge!

MC simulations + multiple reweighing techniques used to include corrections from fix order calculations

The state-of-the-art

Measurements at LEP:

- Only diboson process accessible for such measurements $e^+e^- \rightarrow W^+W^-$
  - ***Single boson polarization measurements***: L3 [arXiv:0301027], OPAL [arXiv:0312047], DELPHI [arXiv:0801.1235]
  - ***Joint-polarization measurements***: OPAL [arXiv:0009021], DELPHI [arXiv:0908.1023]
- Never reached observation level sensitivity for longitudinal-longitudinal joint-polarization

Measurements at the LHC:

- Single and Joint- boson polarization measurements
- ***pp → W±Z***
  - CMS @13TeV 137 fb^{-1} (inclusive phase space) CMS-SMP-20-014
  - ATLAS @13TeV 139 fb^{-1} (inclusive phase space) Phys. Lett. B 843 (2023) 137895
  - ATLAS @13TeV 139 fb^{-1} (high p_T (Z) phase space) Submitted to PRL New!
- ***pp → ZZ***
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- ***pp → W±W±jj***
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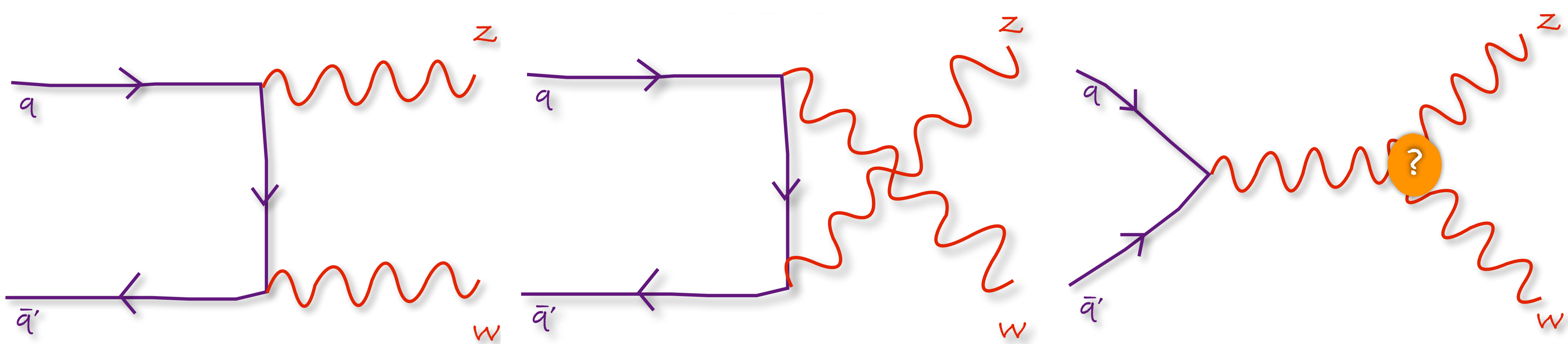
Polarization measurements in WZ



Phys. Lett. B 843 (2023) 137895

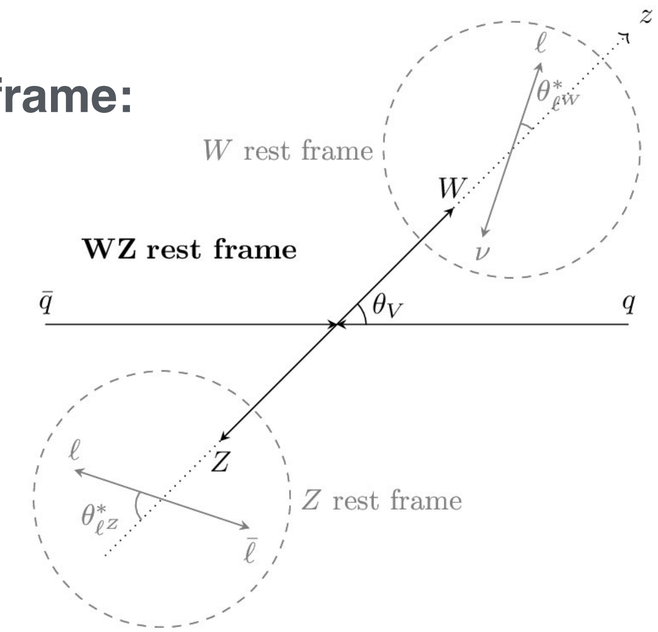
ATLAS Polarization in WZ measurement

- Result with full run-2 **139 fb^{-1}**

The analysis target

- **Singly-polarized final states**
- Joint-polarizations: W_0Z_0, W_TZ_0, W_0Z_T , W_TZ_T

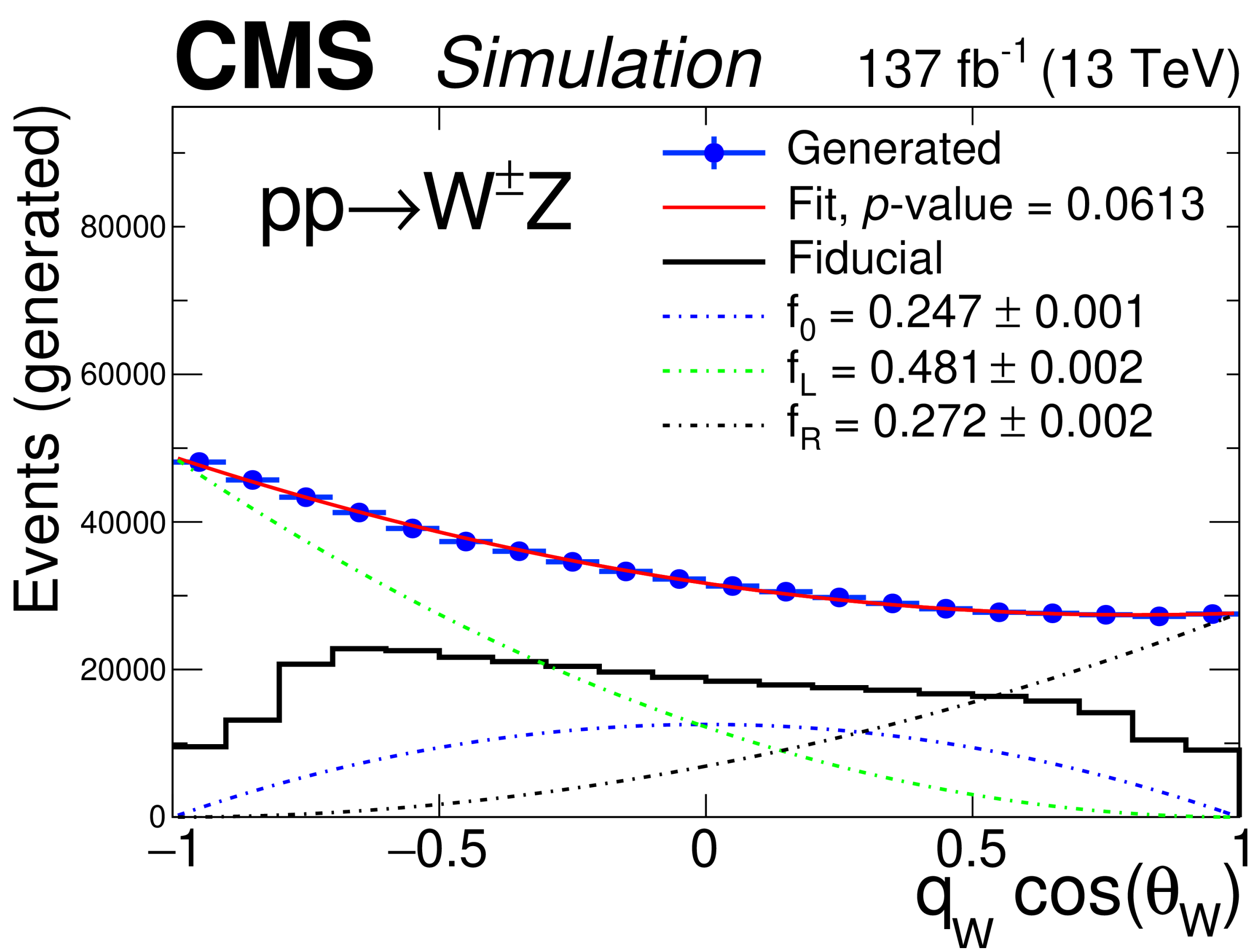
The frame:



How is the analysis performed?

Singly-polarized templates challenge:

- Polarization templates obtained by reweighting a POWHEG+Pythia sample based on the generator-level cos(θ_V) distributions
  - Allow us to extract event weights in the inclusive phase space for one polarization at the time



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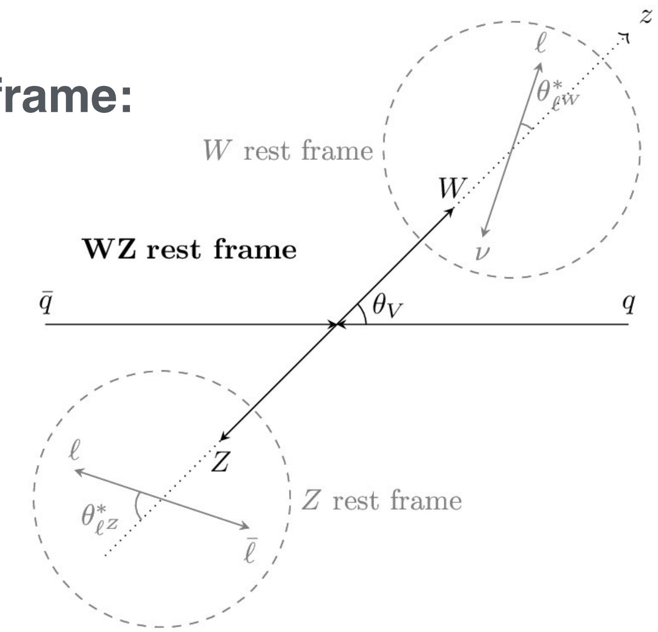

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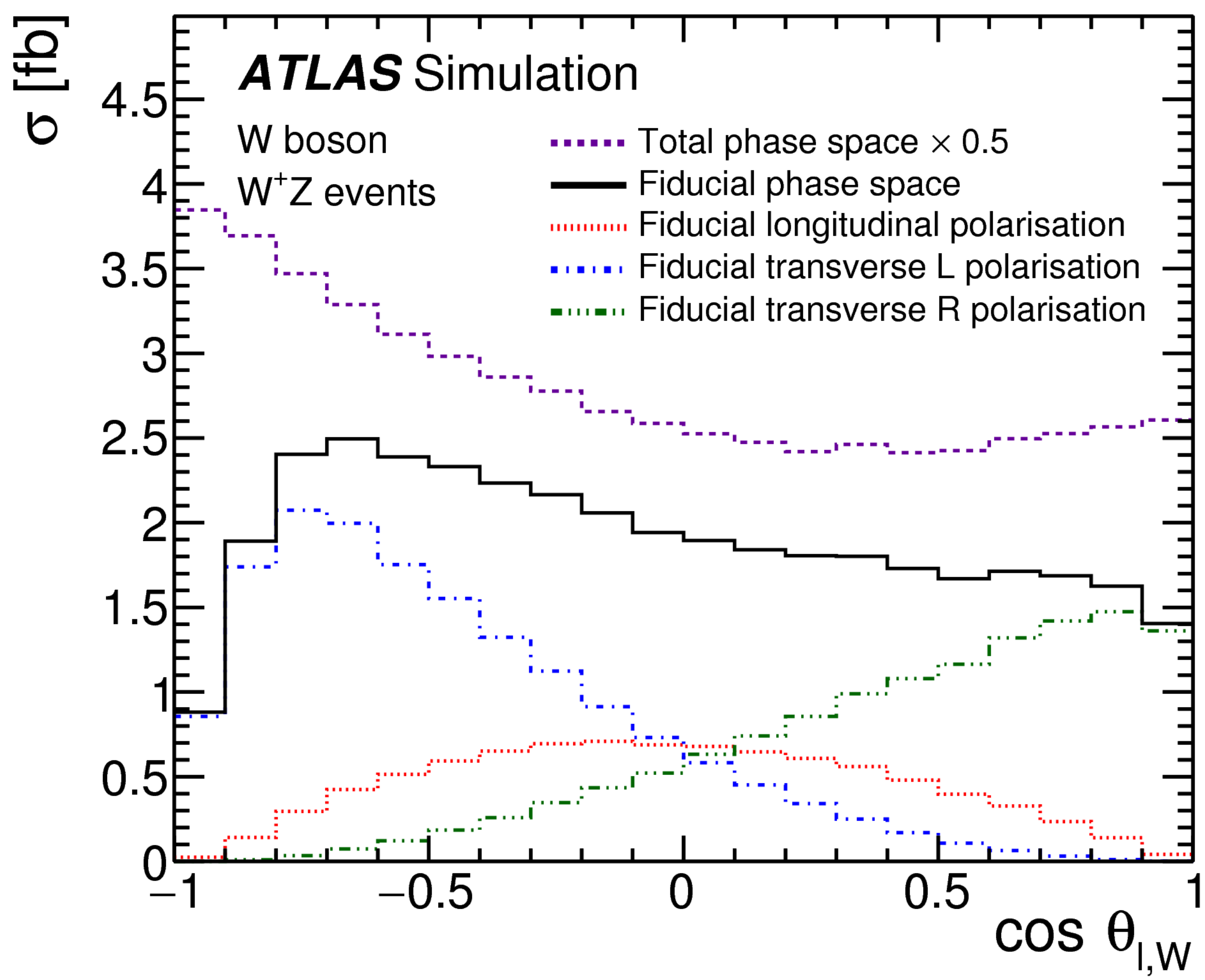
The data analysis

- Signal region, is a cut-based selection :
  - fully leptonic WZ decays: leptons p_T>25 GeV
  - Z mass on-shell (10 GeV window)
  - W reconstructed using pdg mass constrain



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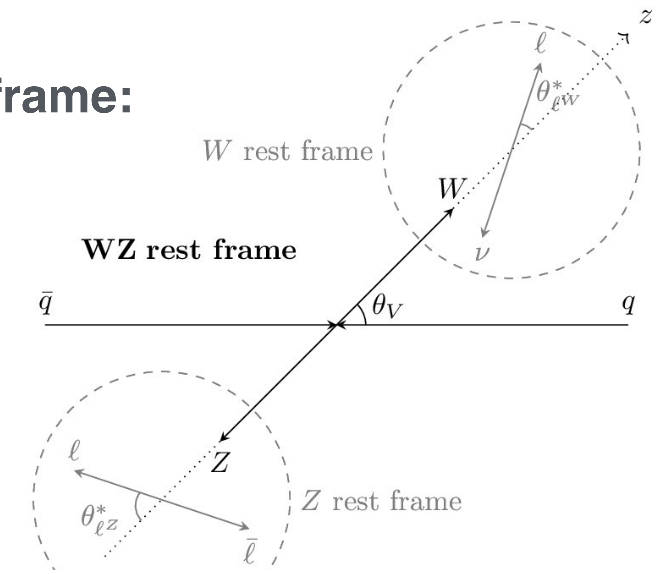

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  - fully leptonic WZ decays: leptons p_T>25 GeV
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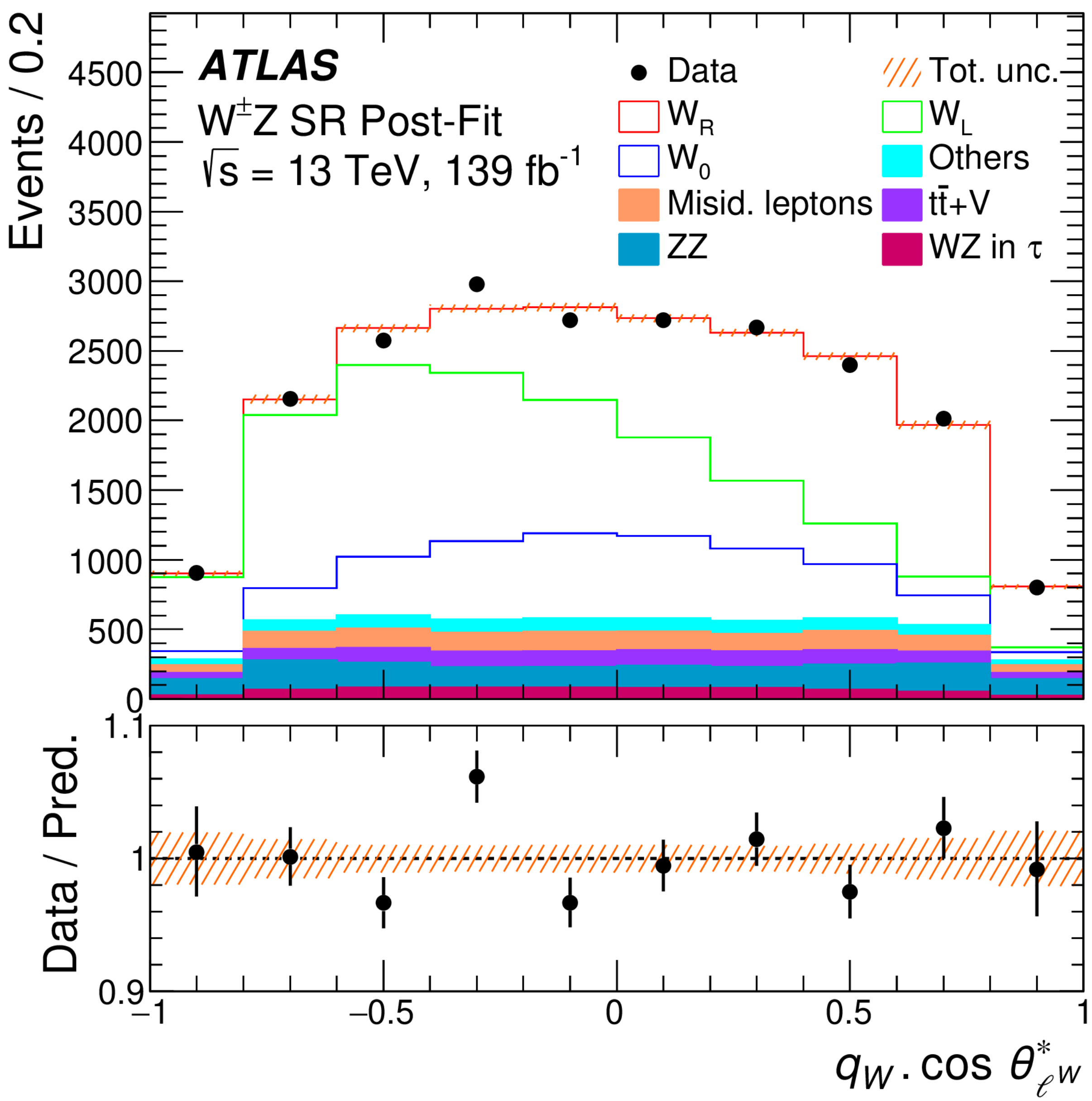
- Fit to the data using the polarised templates
- f_0 measured with 5σ significance even in charge break-down



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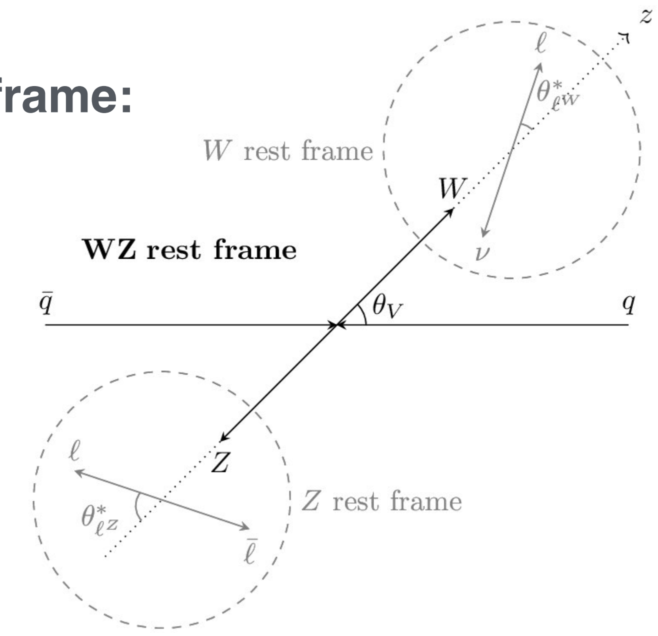


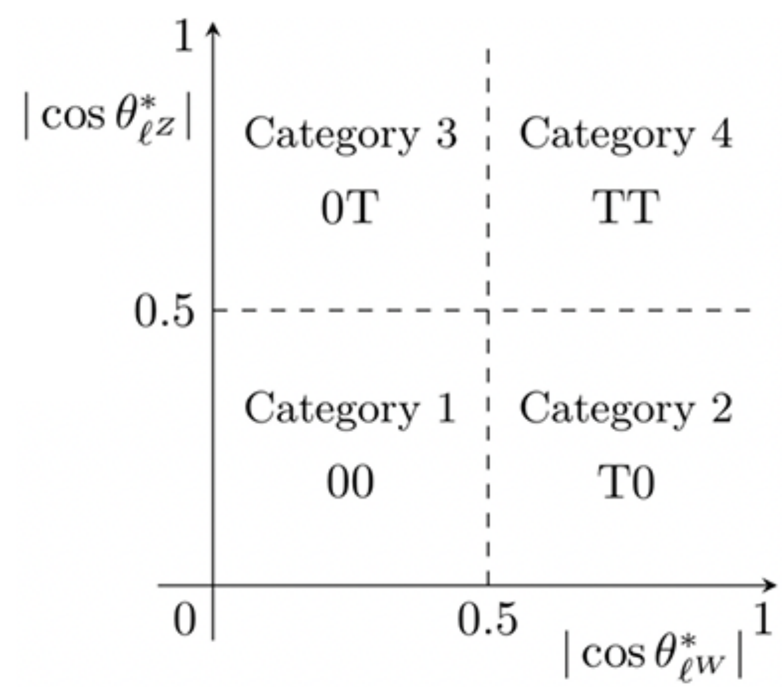
How is the analysis performed?

The joint-polarization templates challenge:

- Polarized templates available with Madgraph 2.7.3 at LO+real corrections → great! but insufficient, bias from 10% to 50% of the fraction values in this phase space
- Joint polarization templates at NLO-QCD obtained using several reweighing techniques
  - NLO-QCD at particle level available (MoCaNLO) [A. Denner and G. Pelliccioli arXiv:2010.07149]
  - Use DNN as a multi-dimensional reweigthing [arXiv:1907.08209]

The joint-polarization extraction challenge:

- Four different polarizations fractions to extract
- DNN classifies each joint polarization state
- Events split in 4 categories based on cosθ* to discriminate mix states (0T, T0)



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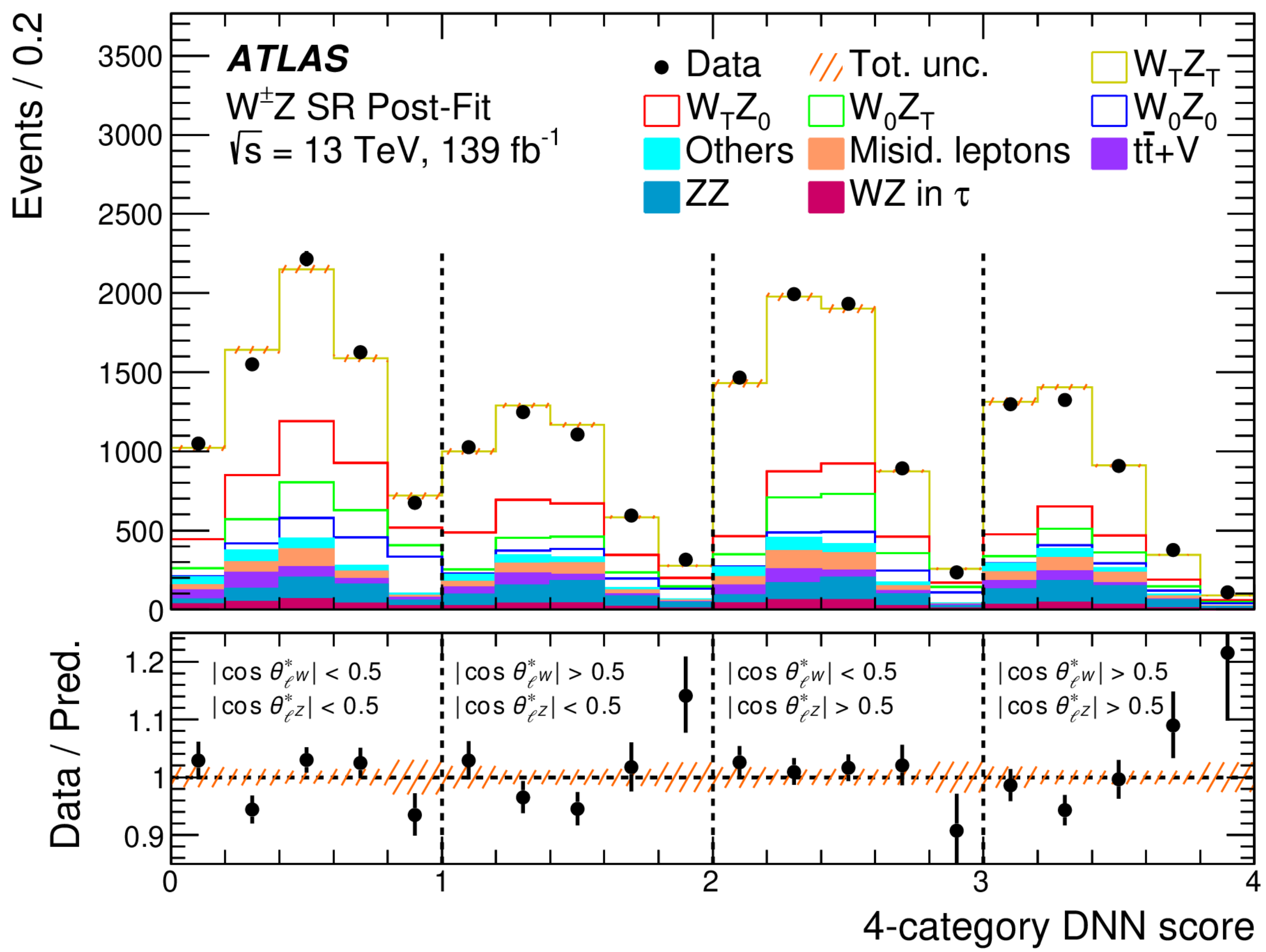
Joint-polarization WZ measurement



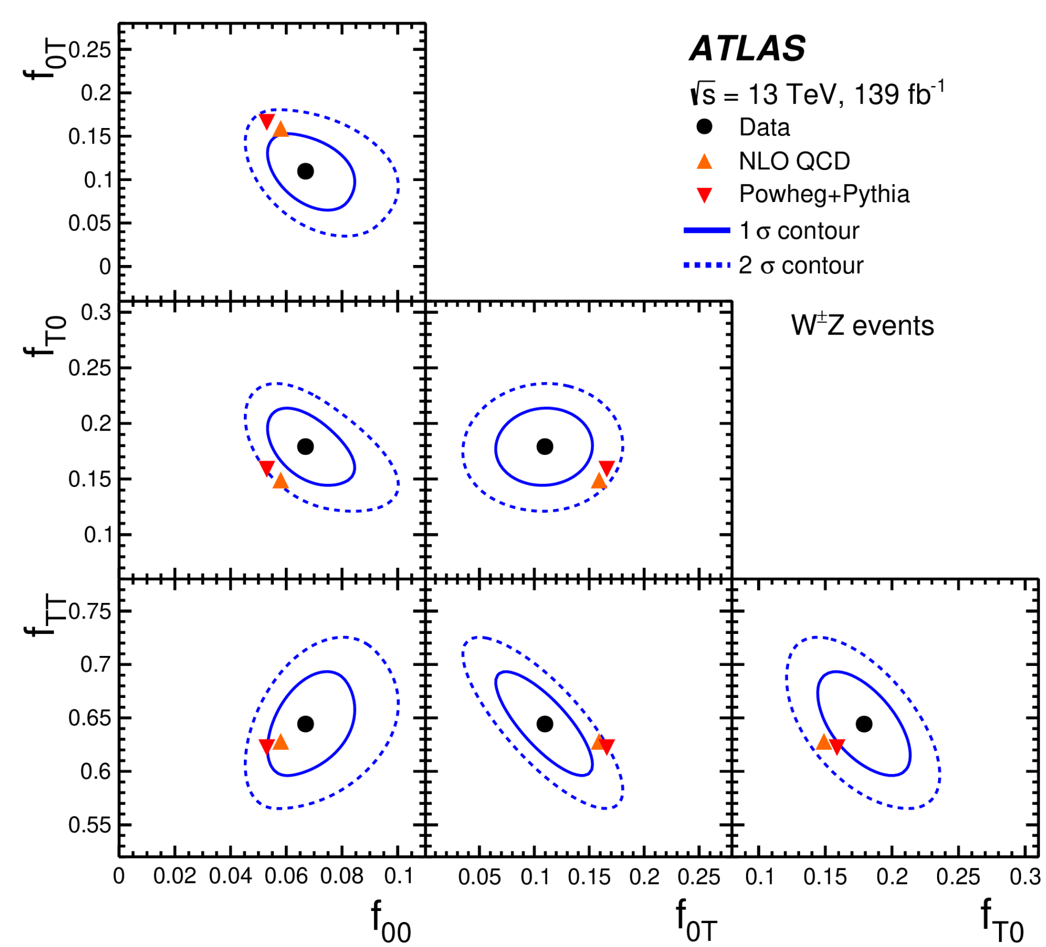
Statistical analysis

- Simultaneous fit of the 4 categories
- Statistical uncertainties at the same level as systematic uncertainties, mainly
  - Template modelling uncertainties **(Higher order QCD shape effects on polarization templates)**
  - QCD scale
  - E_T^{miss}/jets object reconstruction

First observation of joint polarisation states for diboson

- Significance on f_{00} at 7.1σ
- Significance on f_{TT} and f_{T0} >5σ

	Data	Powheg+Pythia	NLO QCD
		$W^{\pm}Z$	
f_{00}	0.067 ± 0.010	0.0590 ± 0.0009	0.058 ± 0.002
f_{0T}	0.110 ± 0.029	0.1515 ± 0.0017	0.159 ± 0.003
f_{T0}	0.179 ± 0.023	0.1465 ± 0.0017	0.149 ± 0.003
f_{TT}	0.644 ± 0.032	0.6431 ± 0.0021	0.628 ± 0.004



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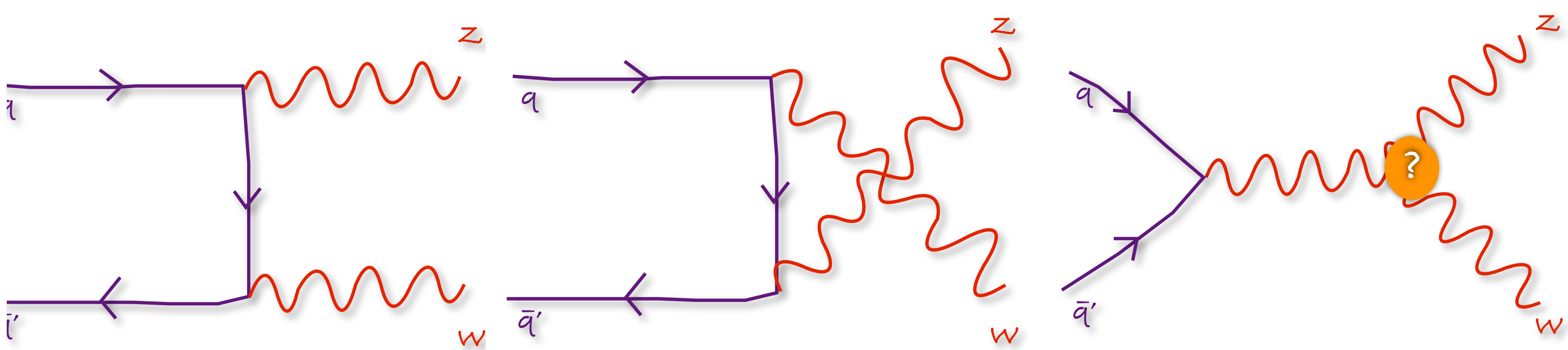
Single boson polarization WZ measurement

Are the polarization correlated?

- The spin correlations using $R_c = \frac{f_{00}}{f_0^W f_0^Z}$
- If uncorrelated $R_c = 1$ while SM (NLO QCD) predicts $R_c = 1.3$
- Measured $R_c = 1.54 \pm 0.35$ (Obs. Significance 1.6σ wrt $R_c = 1$ hypothesis)

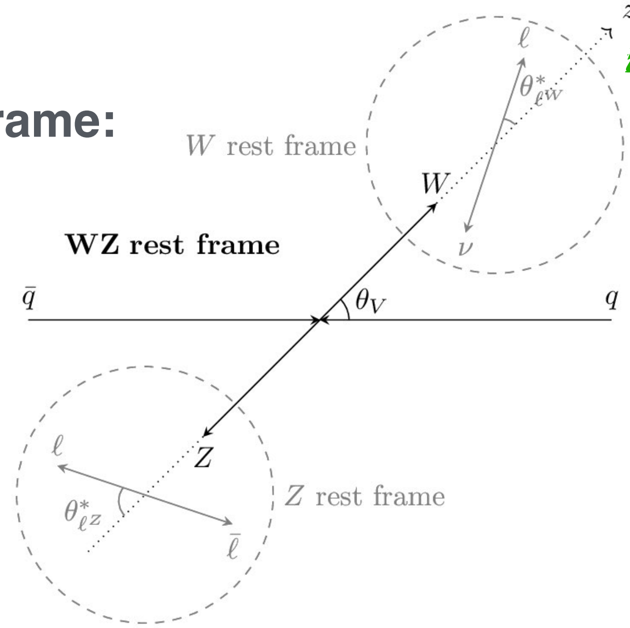


Submitted to PRL (2024)

RAZ effect and energy dependence of WZ polarization fractions

New!

The frame:

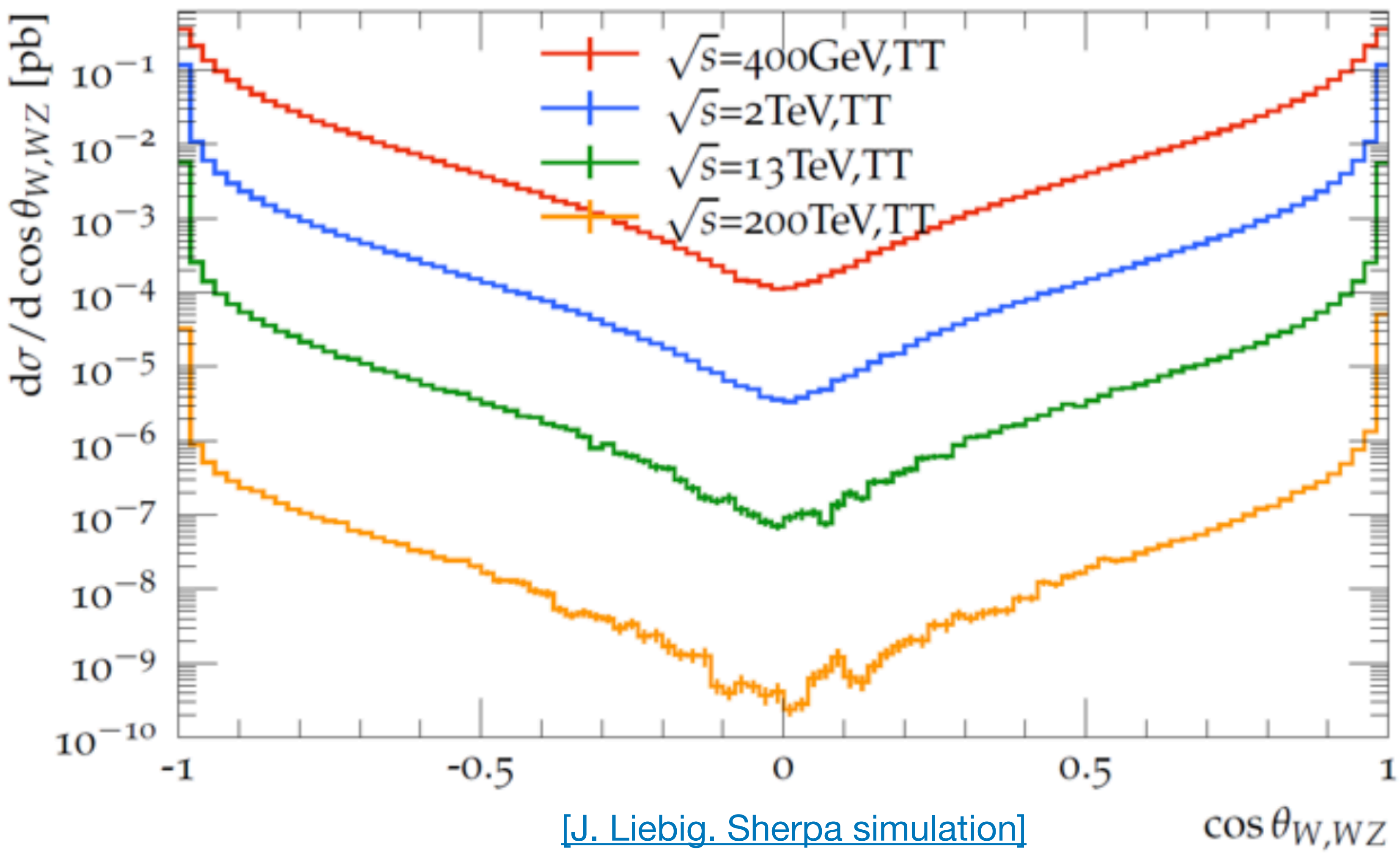


The analysis target

- Radiation Amplitude Zero (RAZ) effect for WZ
- Joint-polarizations at high $p_T(Z)$: W_0Z_0, W_TZ_0, W_0Z_T , W_TZ_T

Radiation Amplitude Zero effect

- At LO strong gauge cancellations making a drop in the TT cross-section (true for WZ and Wγ [D0 result])



[J. Liebig. Sherpa simulation]

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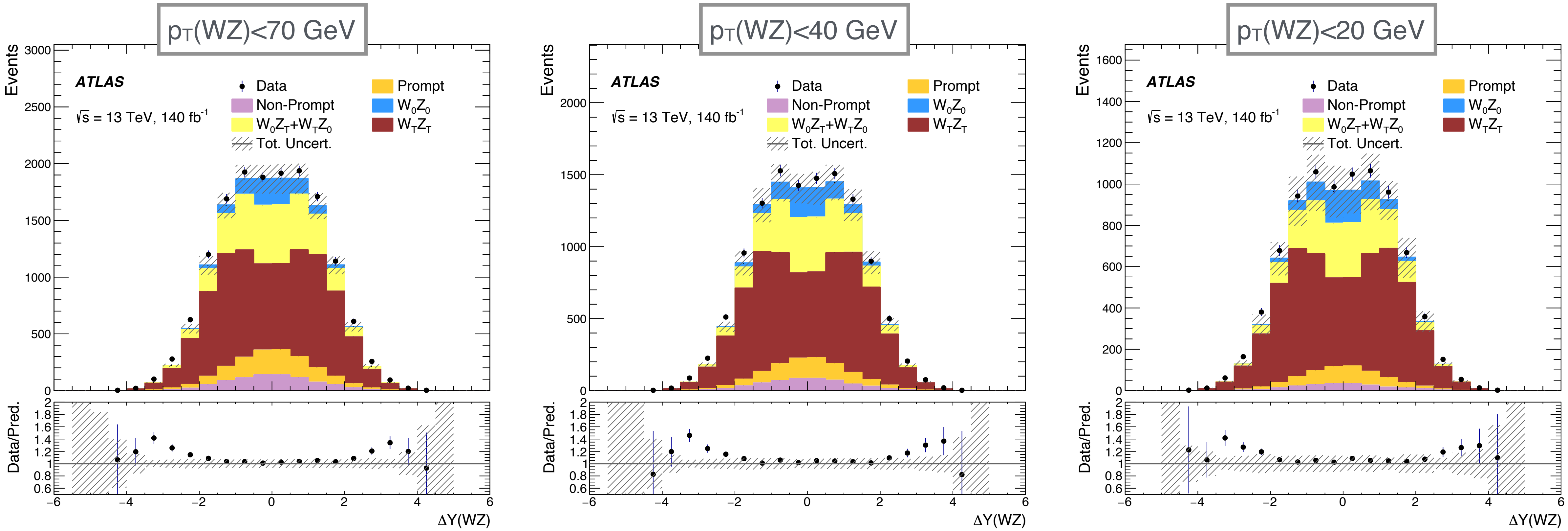
Radiation Amplitude Zero effect

- At LO strong gauge cancellations making a drop in the TT cross-section (true for WZ and Wγ [D0 result])
- Use a $p_T(WZ)$ cut to reduce the jet activity → tighter $p_T(WZ)$ cut → more LO like Phase Space!



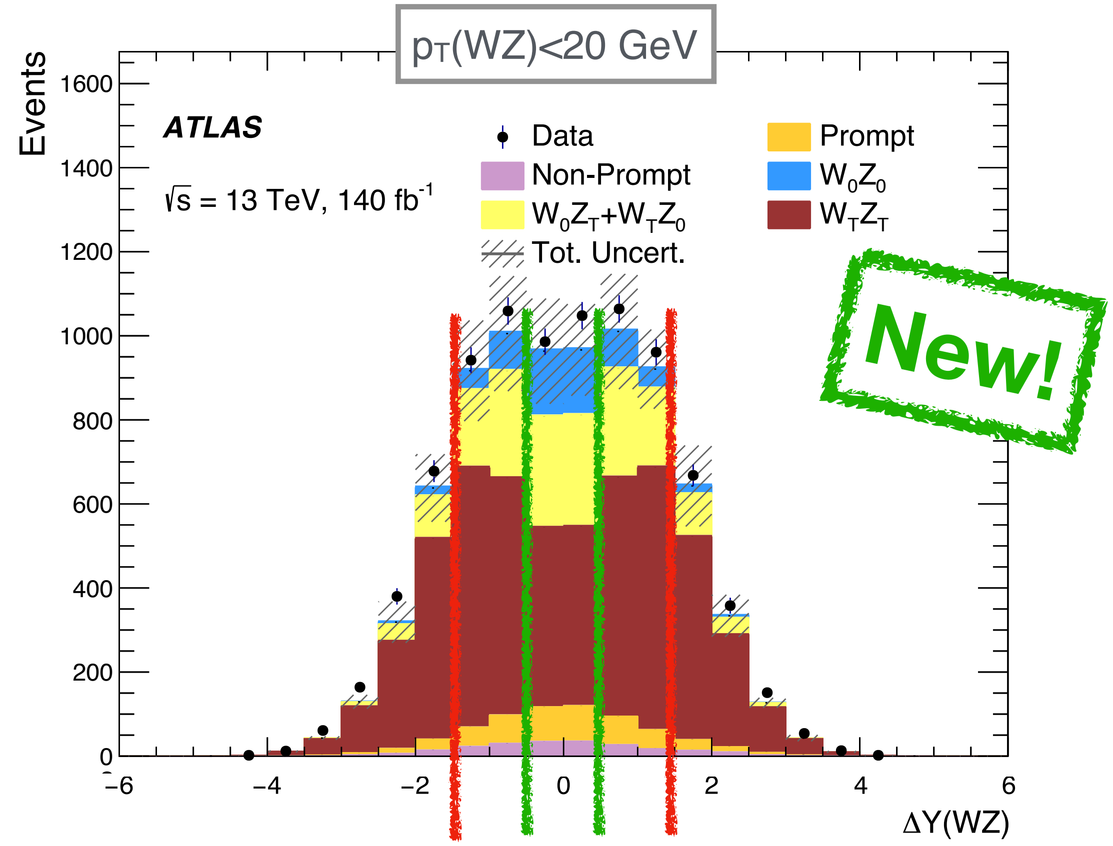
- **Polarization modelling:** Madgraph LO 0+1j merged samples. Uncertainties by reweighing to NLO QCD+EW based on fix order predictions (G. Pelliccioli, Duc Ninh Le)

Radiation Amplitude Zero effect in WZ

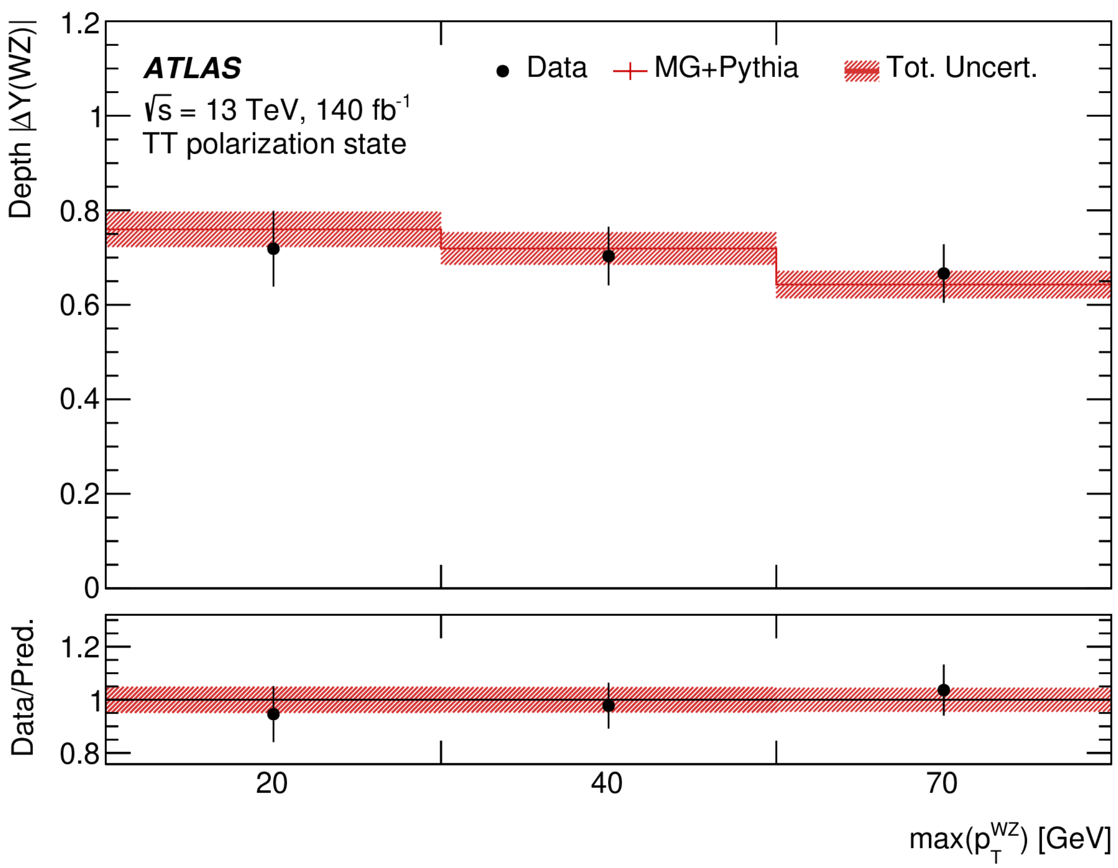
- Define a Depth variable to qualify the TT dip

$$D = 1 - 2 \times \frac{N_{\rm unf}^{\rm central}}{N_{\rm unf}^{\rm sides}}$$

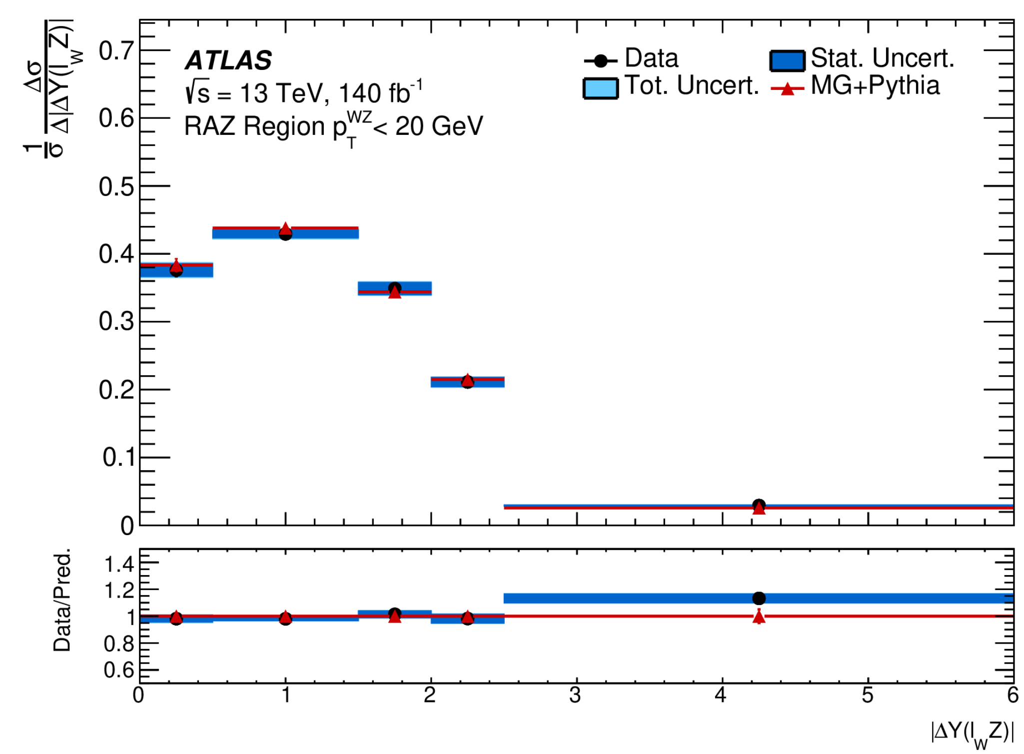
- D = 0 no dip
- D < 0 an excess
- D > 0 means there is a dip



- Calculated the depth using unfolded TT only distributions (00+0T+T0-subtracted) for different p_T(WZ) cuts



- Unfolded angular variables (w.o subtracting any polarization state)

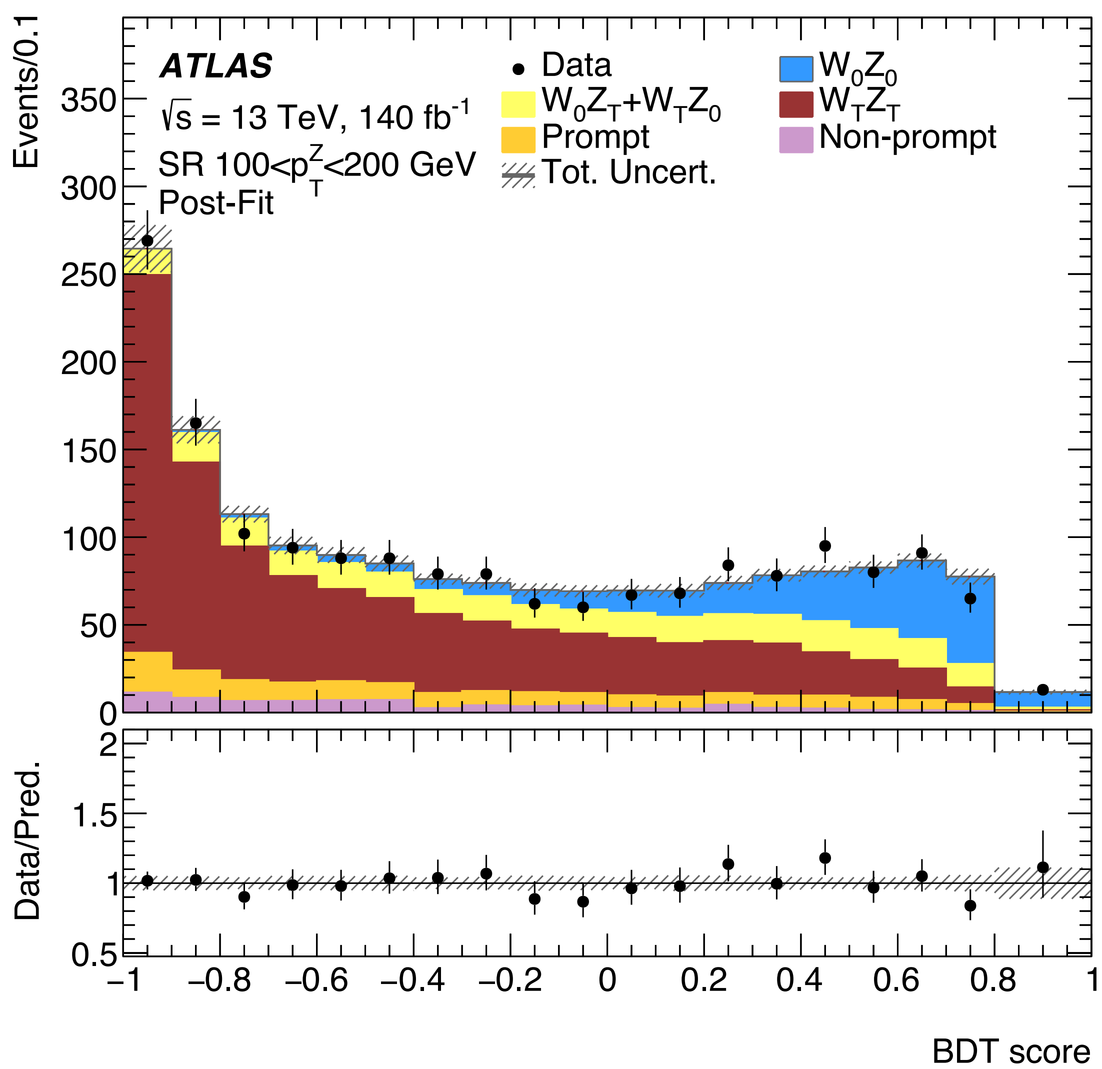


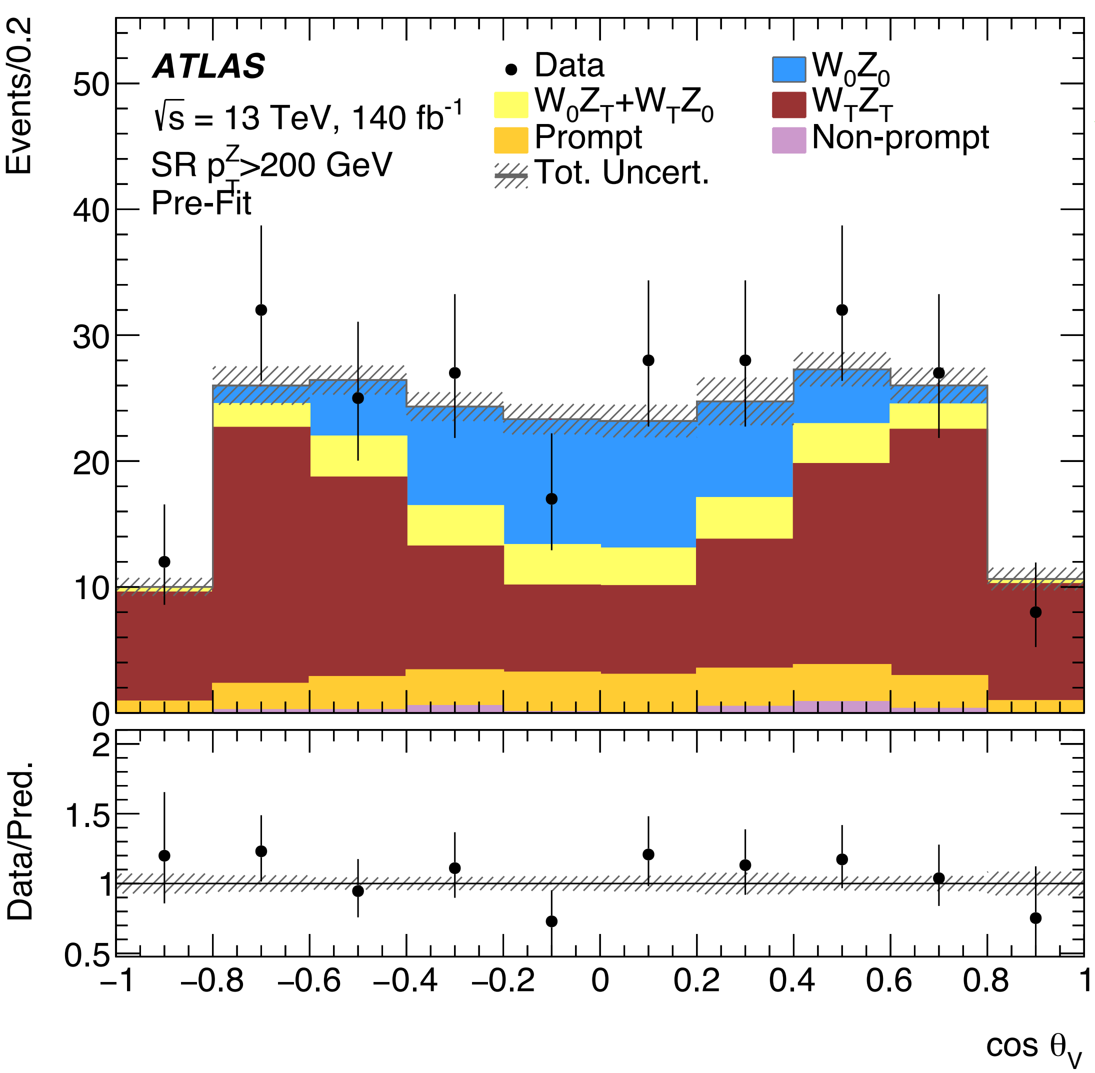
- **Depth variable well above 0 ! We see the RAZ dip !**

WZ join polarization - 00-enhaced region

- To increase the contribution of the longitudinal component we use $p_T(WZ)$<70 GeV and do the measurement in 2 $p_T(Z)$ bins [100,200] and [200, inf] GeV
- Double Longitudinal component increased up to 23%
- Relative s-channel contribution expected to be higher at high $p_T(Z)$
- To separate the polarization components dedicated BDT were trained for each $p_T(Z)$ bin

	Prediction	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{TT}	0.619 ± 0.007	0.646 ± 0.008





New!

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WZ join polarization - 00-enhaced region

Statistical analysis

- Fit performed using 2 configurations (more free parameters less model dependent):
  - 3 parameters: 00, T0+0T and TT
  - 2 parameters: 00 vs T0+0T+TT
- Dominated by statistical uncertainties, but NLO EW and QCD uncertainties have the largest impact!

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New!

3 free parameters

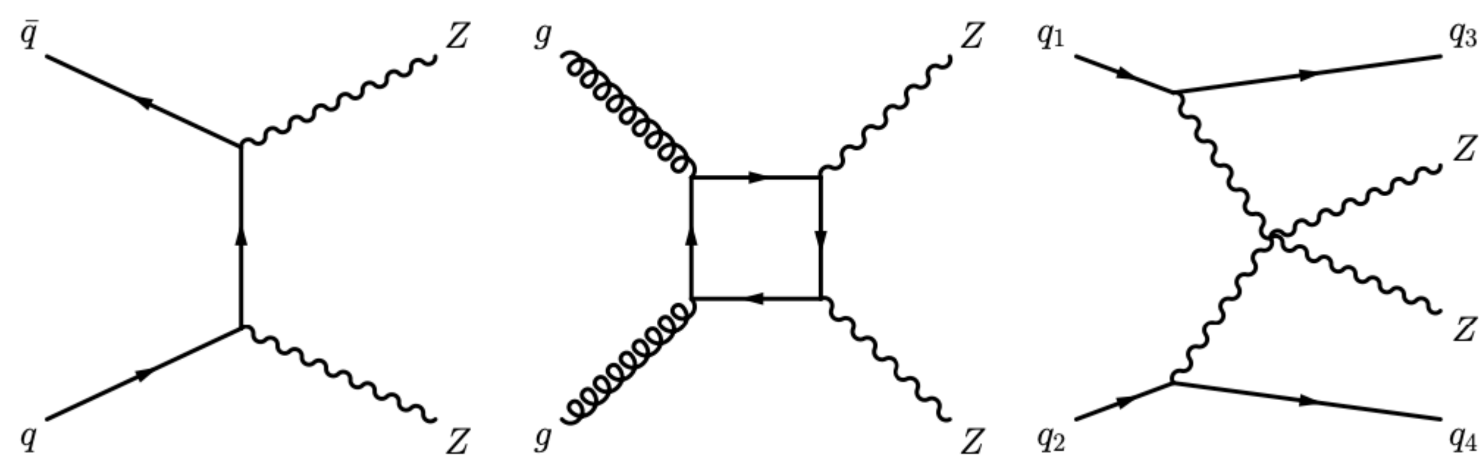
	Measurement	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.19 \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13 \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23 \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (syst)
f_{TT}	$0.63 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.04}_{0.04}$ (syst)	$0.64 \pm^{0.12}_{0.12}$ (stat) $\pm^{0.06}_{0.06}$ (syst)
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ

2 free parameters

	Measurement	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.17 \pm^{0.02}_{0.02}$ (stat) $\pm^{0.01}_{0.02}$ (syst)	$0.16 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.02}_{0.03}$ (syst)
f_{XX}	$0.83 \pm^{0.02}_{0.02}$ (stat) $\pm^{0.02}_{0.01}$ (syst)	$0.84 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.03}_{0.02}$ (syst)
f_{00} obs (exp) sig.	7.7 (6.9) σ	3.2 (4.2) σ

- **We are able to reach observation/ evidence of double longitudinal bosons at high p_T (Z) !!** → approaching the regime where longitudinal bosons already behave as Goldstone bosons

Polarization measurement in ZZ



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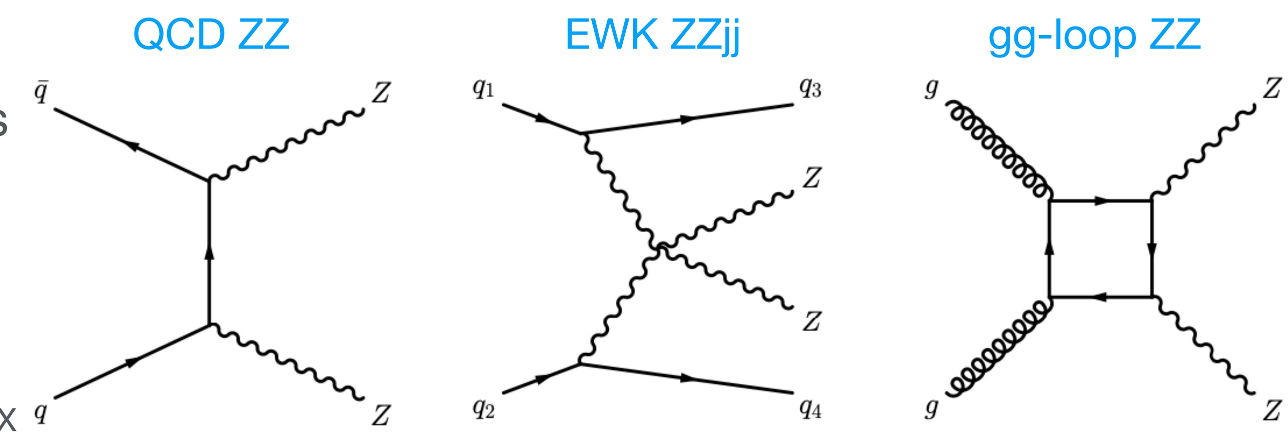
ATLAS ZZ →4ℓ Polarization

The analysis target

- Joint-polarizations: Z_LZ_L and Z_LZ_T+Z_TZ_T
- The frame: The centre-of-mass frame of the two Z bosons



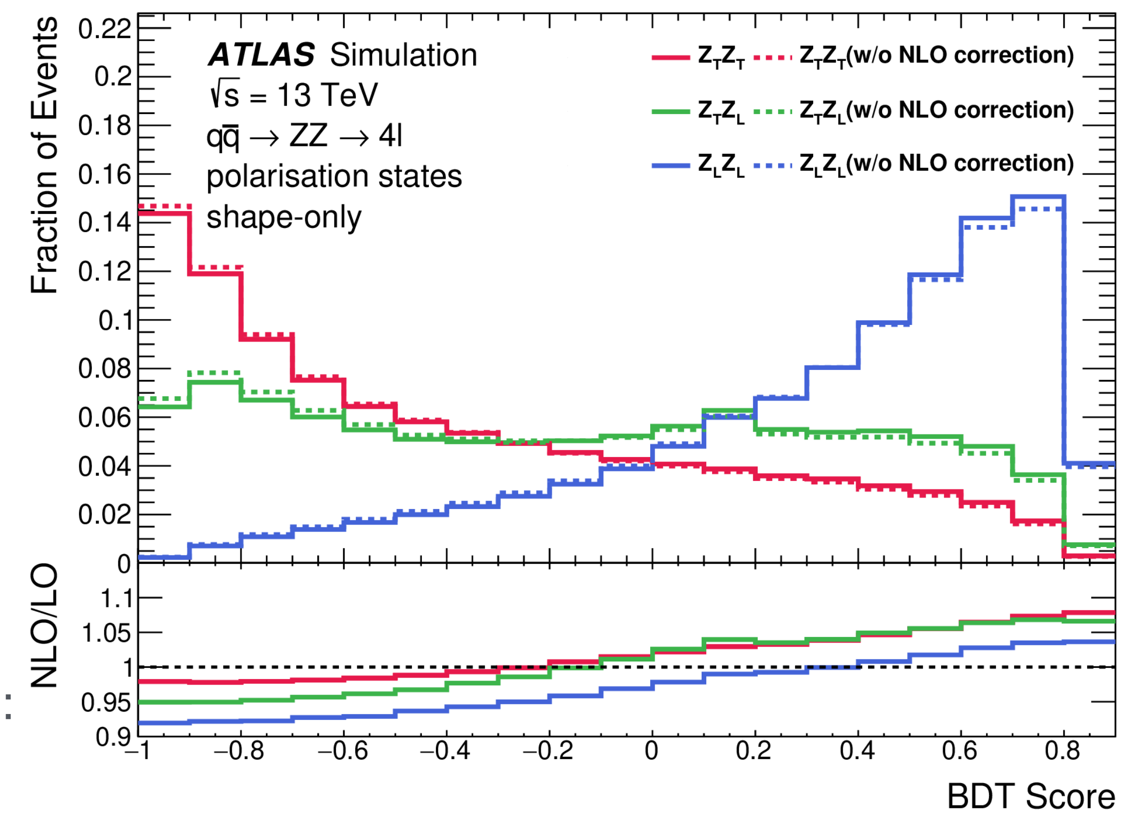
How is the analysis performed?

The joint-polarization extraction challenge:

- Boosted Decision Tree trained to discriminate Z_LZ_L vs Z_TZ_X
- Using the leptons and Z bosons angular variables

The templates challenge:

- Polarized templates available with Madgraph 2.7.3 for
  - QCD and EWK, but…
  - It was not possible back then for the loop-induced gg (actually possible now)
- NLO EW + QCD corrections and the loop-induced gg calculations are available for ZZ at particle level (MoCaNLO) [A. Denner and G. Pelliccioli JHEP10(2021)097]
- A three step reweighing method using 1D and 2D distributions to:
  - Incorporate NLO EW + QCD corrections to the Madgraph 2.7.3 simulation
  - Obtain polarized templates from the unpolarized Sherpa the loop-induced gg MC sample
  - Include interference effects among the polarization templates (non-negligible for some observables)



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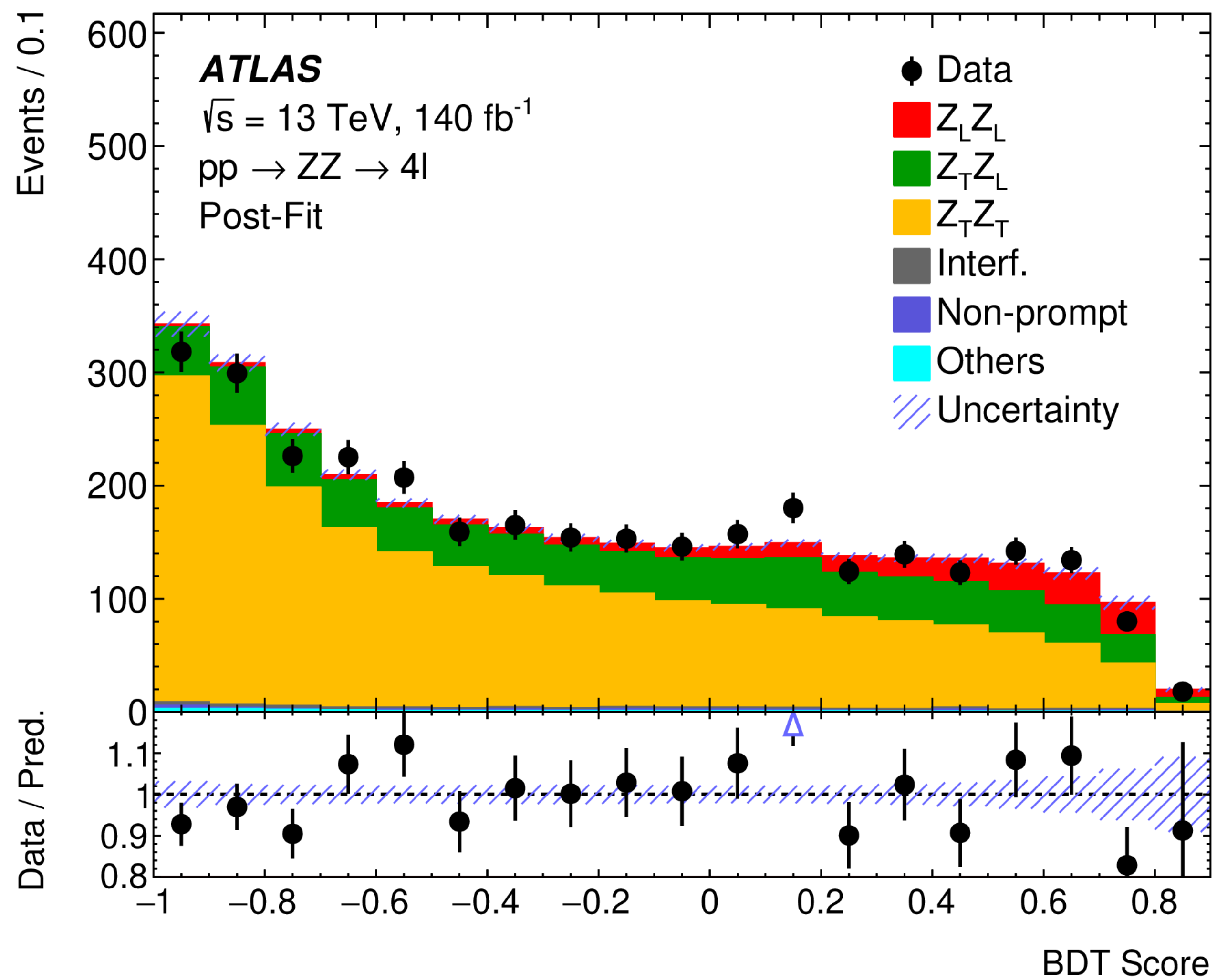
ATLAS ZZ →4ℓ Polarization

Evidence of longitudinally polarized bosons in ZZ!

- Fit using 2 free parameters Z_LZ_L vs Z_TZ_X
- **Evidence for Z_LZ_L with 4.3σ (3.8σ exp.)**
- Measured Z_LZ_L cross section in agreement with predictions $\sigma^{\text{pred.}}_{Z_LZ_L} = 2.10 \pm 0.09$ fb.

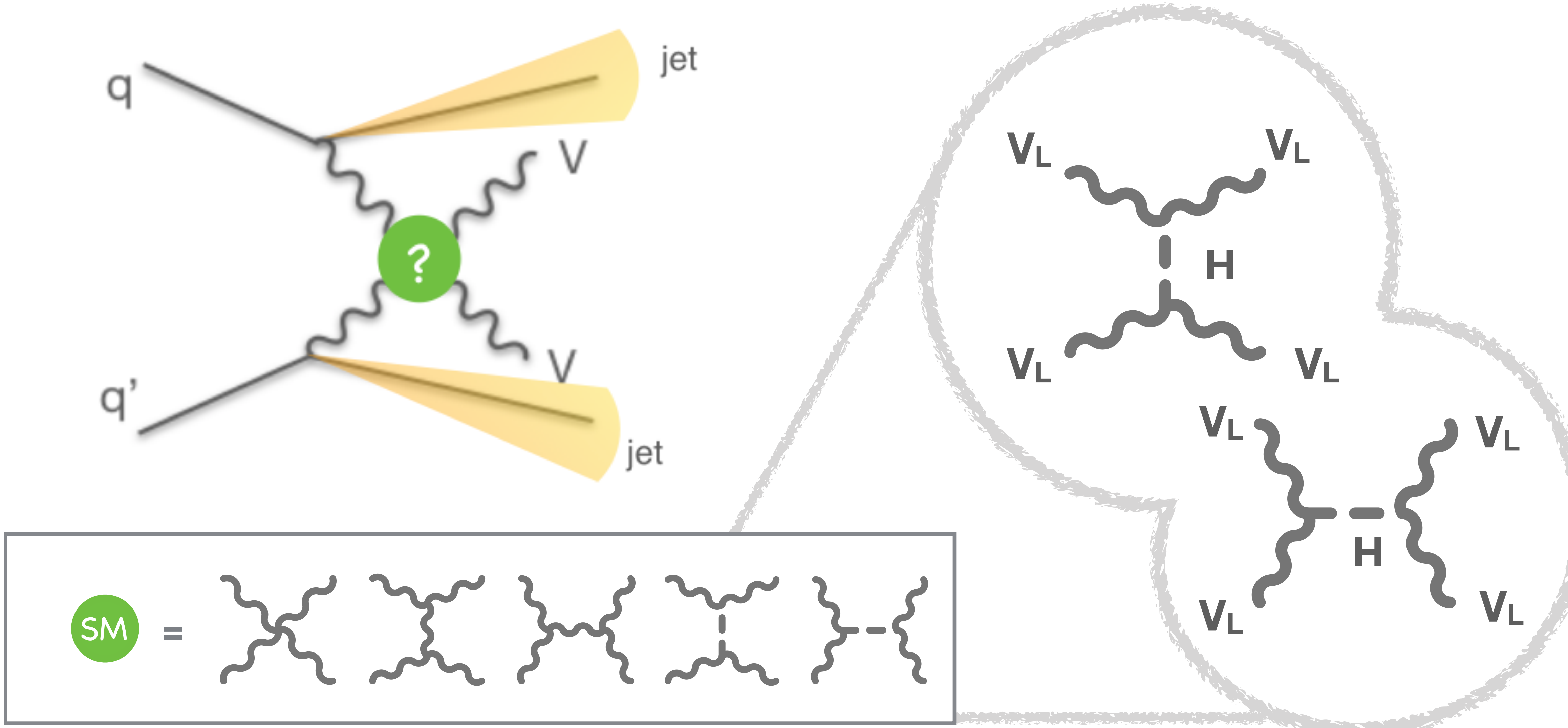
$$\sigma^{\text{obs.}}_{Z_LZ_L} = 2.45 \pm 0.56(\text{stat.}) \pm 0.21(\text{syst.})\ \text{fb}$$

Contribution	Relative uncertainty [%]
Total	24
Data statistical uncertainty	23
Total systematic uncertainty	8.8
MC statistical uncertainty	1.7
Theoretical systematic uncertainties	
$q\bar{q} \to ZZ$ interference modelling	6.9
NLO reweighting observable choice for $q\bar{q} \to ZZ$	3.7
PDF, α_s and parton shower for $q\bar{q} \to ZZ$	2.2
NLO reweighting non-closure	1.0
QCD scale for $q\bar{q} \to ZZ$	0.2
NLO EW corrections for $q\bar{q} \to ZZ$	0.2
$gg \to ZZ$ modelling	1.4
Experimental systematic uncertainties	
Luminosity	0.8
Muons	0.6
Electrons	0.4
Non-prompt background	0.3
Pile-up reweighting	0.3
Triboson and $t\bar{t}Z$ normalisations	0.1



- Modelling uncertainties coming from the reweighing procedure among the most important ones!

Polarization measurements in Vector Boson Scattering



Probably in the future

- Some projection studies for polarization measurements in the HL-LHC can be found in the Yellow Report (using the parton center of mass frame).
- A lot of new results expected as we take more and more data in the future!

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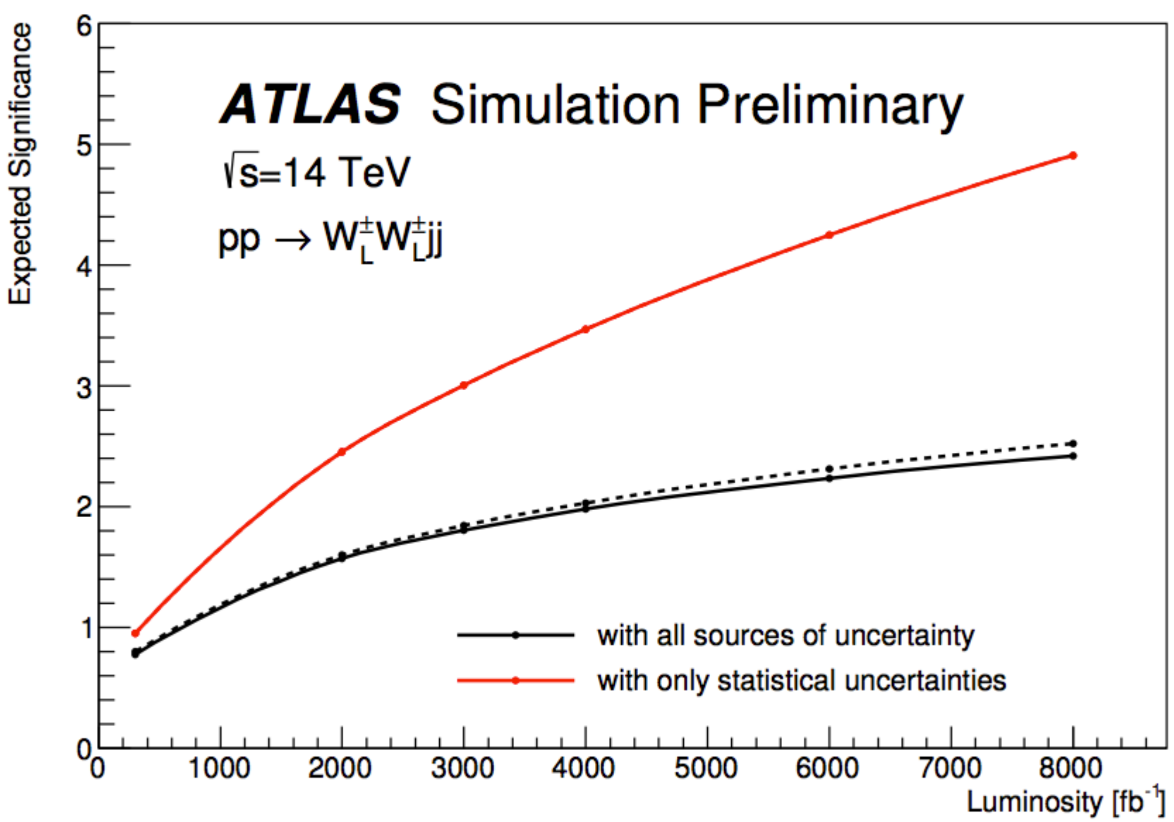
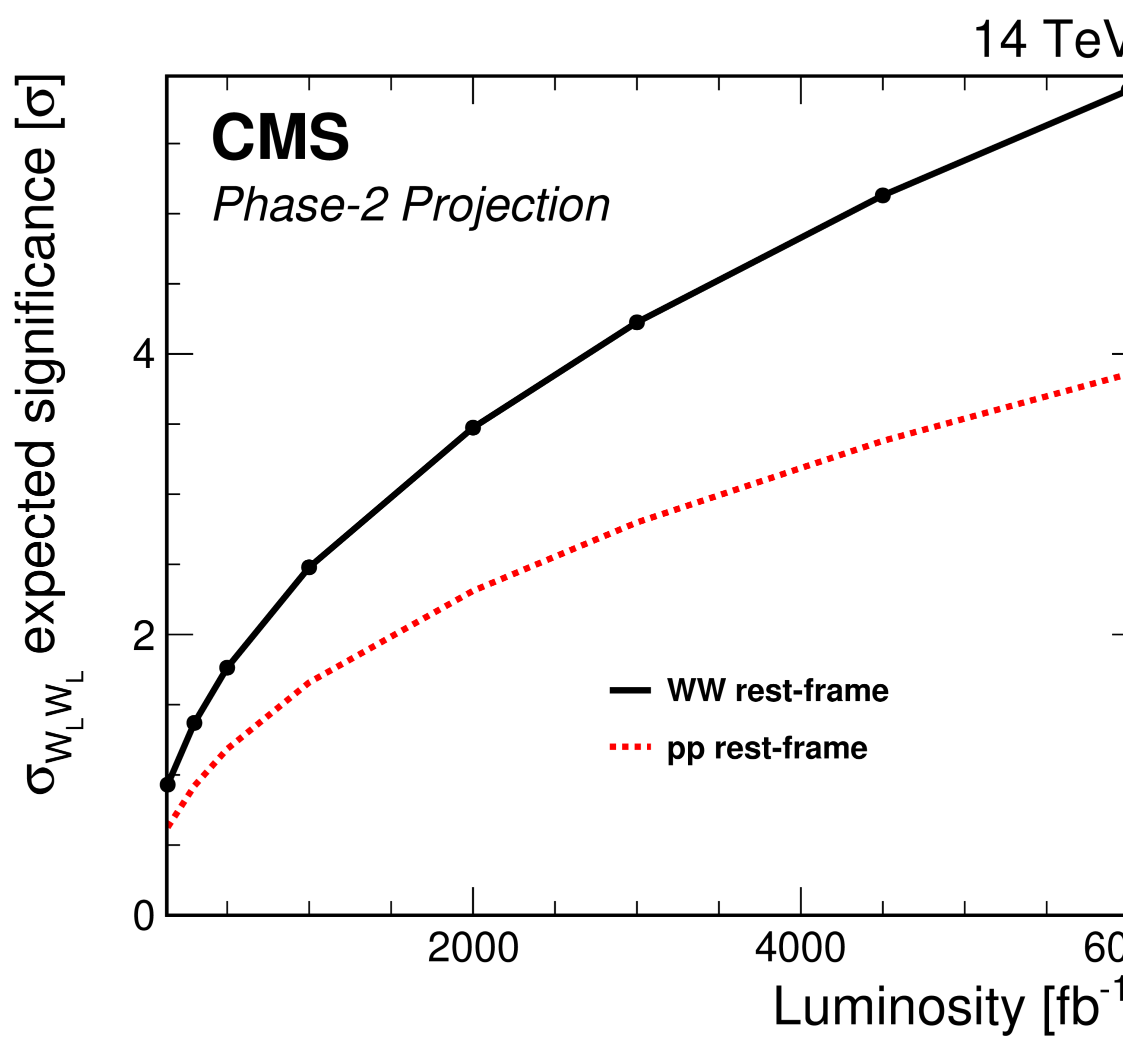


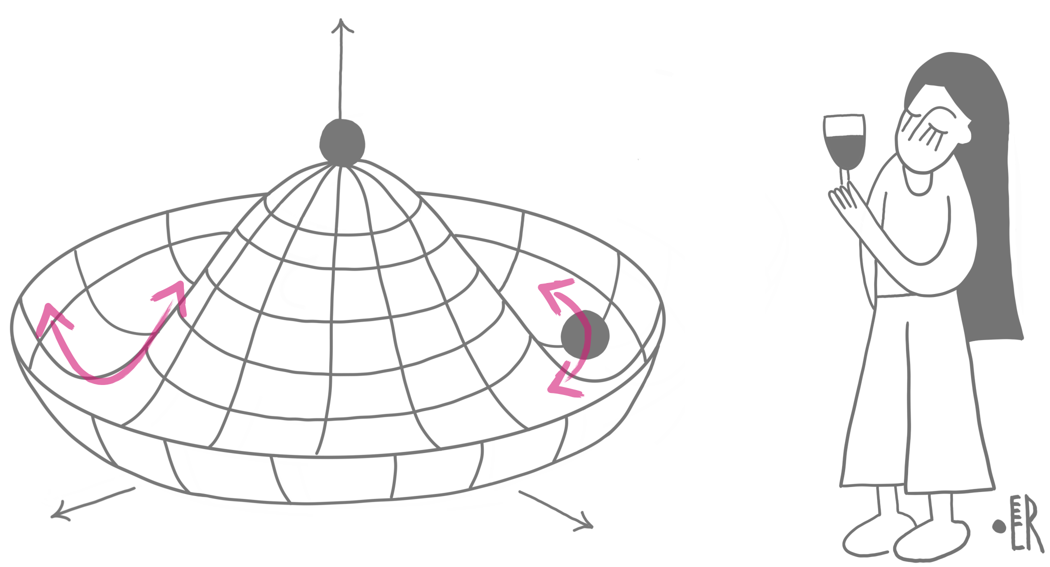


CMS-PAS-FTR-21-001

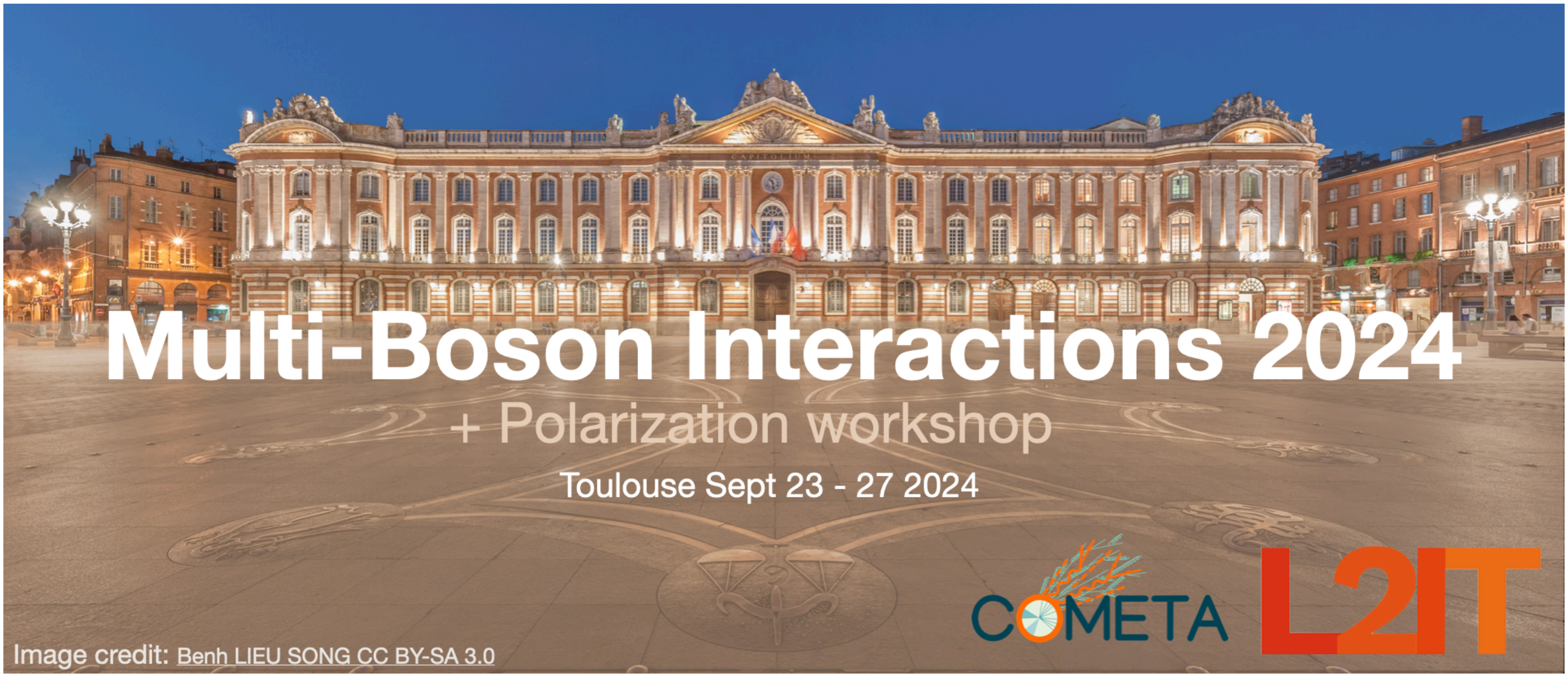
- Simple cut-based analysis

Summary

- The measurements of Weak boson polarization are interesting!
  - they probe the ingredients of the EWSB
  - are an interesting corner to look for new physics
- With our current data we are already able to probe the polarization fractions in VV production.
  - Results include the first evidence or observation of double longitudinally polarized gauge bosons in VV production
  - Big limiting factor for our measurements is the modelling of the polarization templates! → theory community is actively working on the topic!
  - VBS production still severely limited by data statistics, but already showing promise… a lot can be expected as we gather more data!
- While other ATLAS measurements don't provide direct interpretations on the polarization of the gauge bosons, closely related results are often provided. Differential cross section measurements of angular distributions are closely related and can be used for re-interpretations, combinations, etc… we have them for same-sign WWjj, WW and Z VBF



Do you want more on polarization?



Polarization Workshop: https://indico.cern.ch/event/1371888/overview
MBI conference: https://indico.cern.ch/event/1383159/