Testing the Standard Model with WZ polarization

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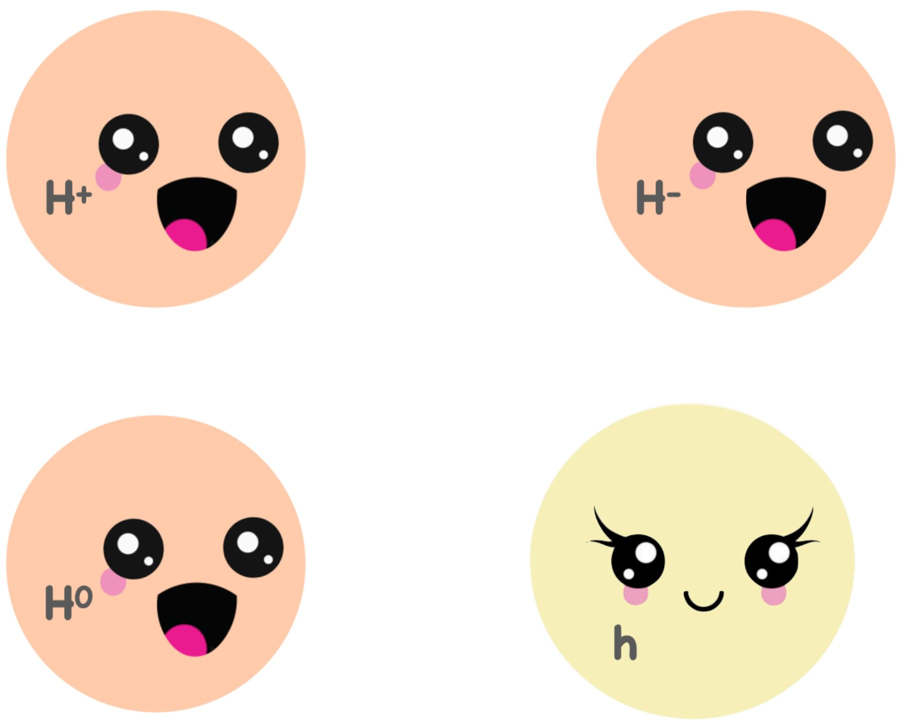
Why Di-Boson Polarizations ?

Higgs mechanism



Why Di-Boson Polarizations ?

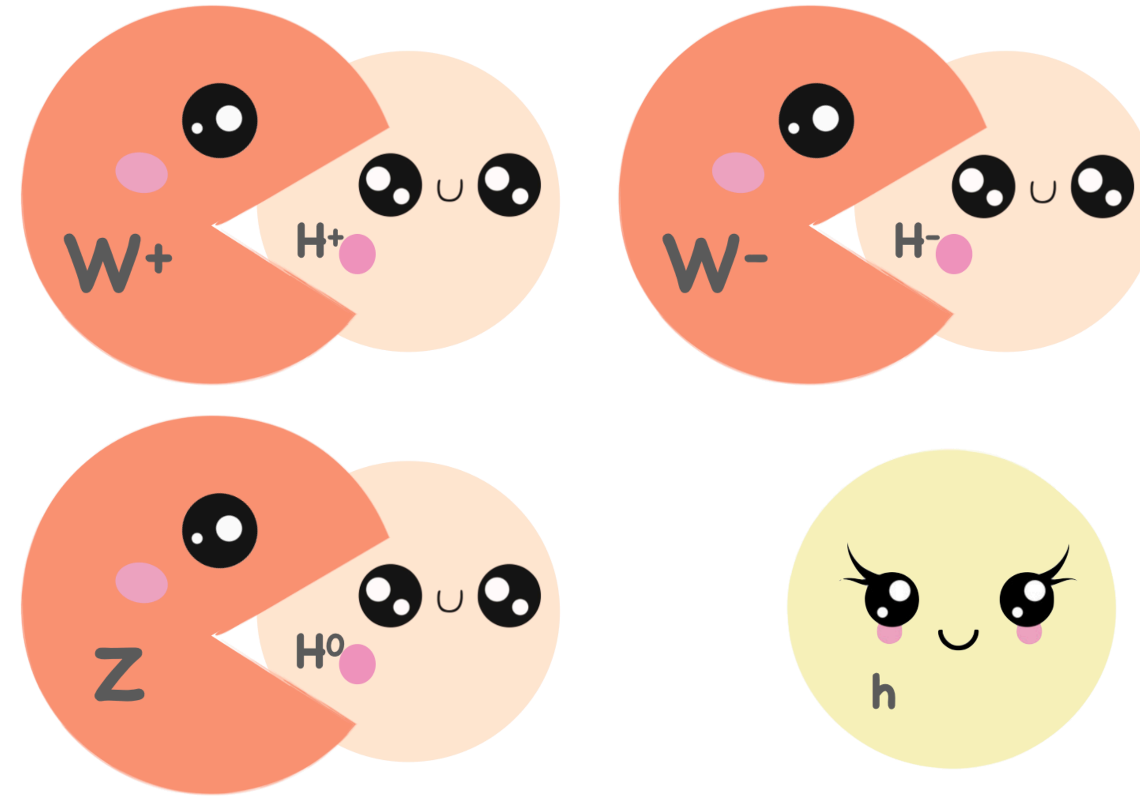
Higgs mechanism

↓

W and Z boson massive

↓

Additional longitudinal polarization



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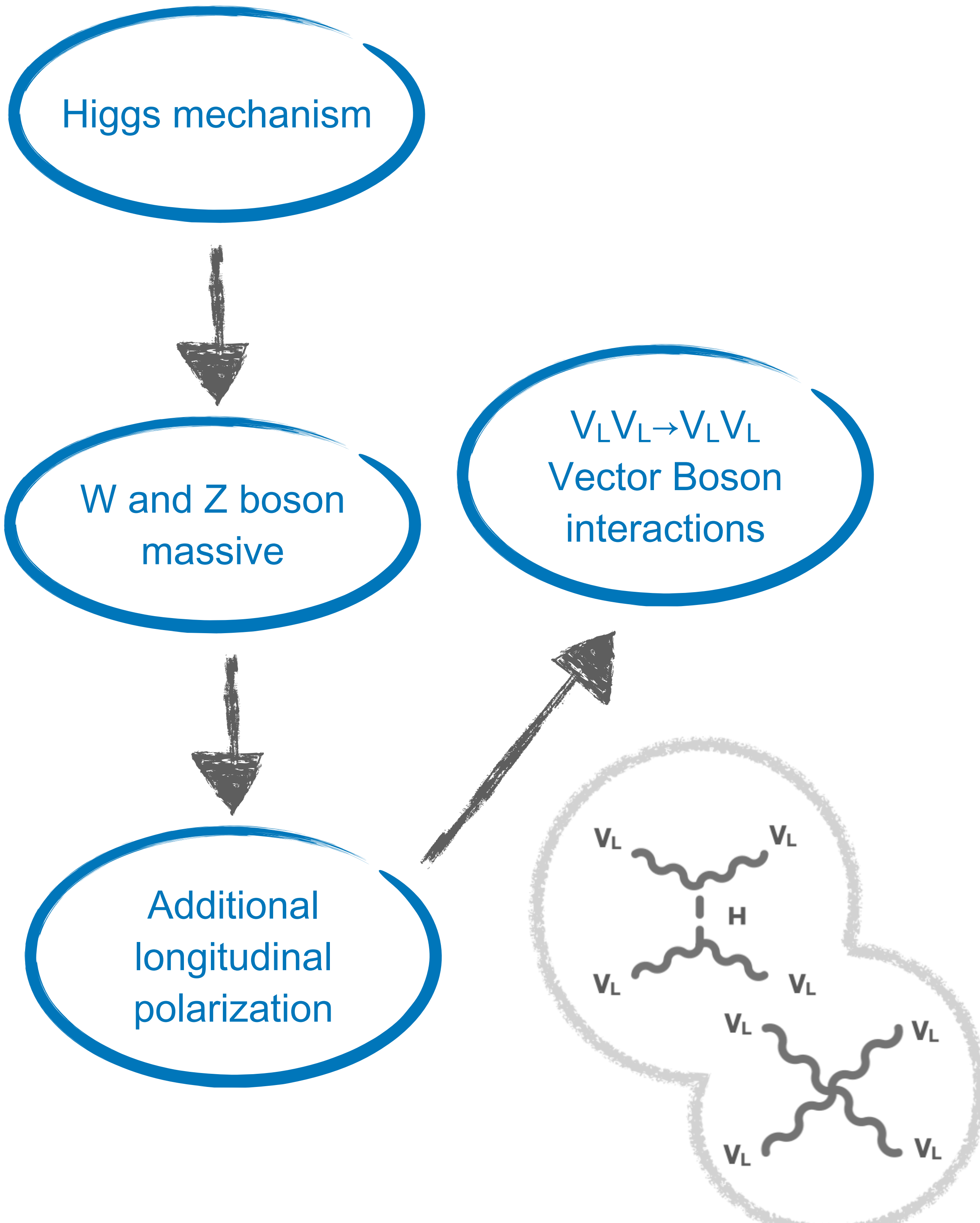
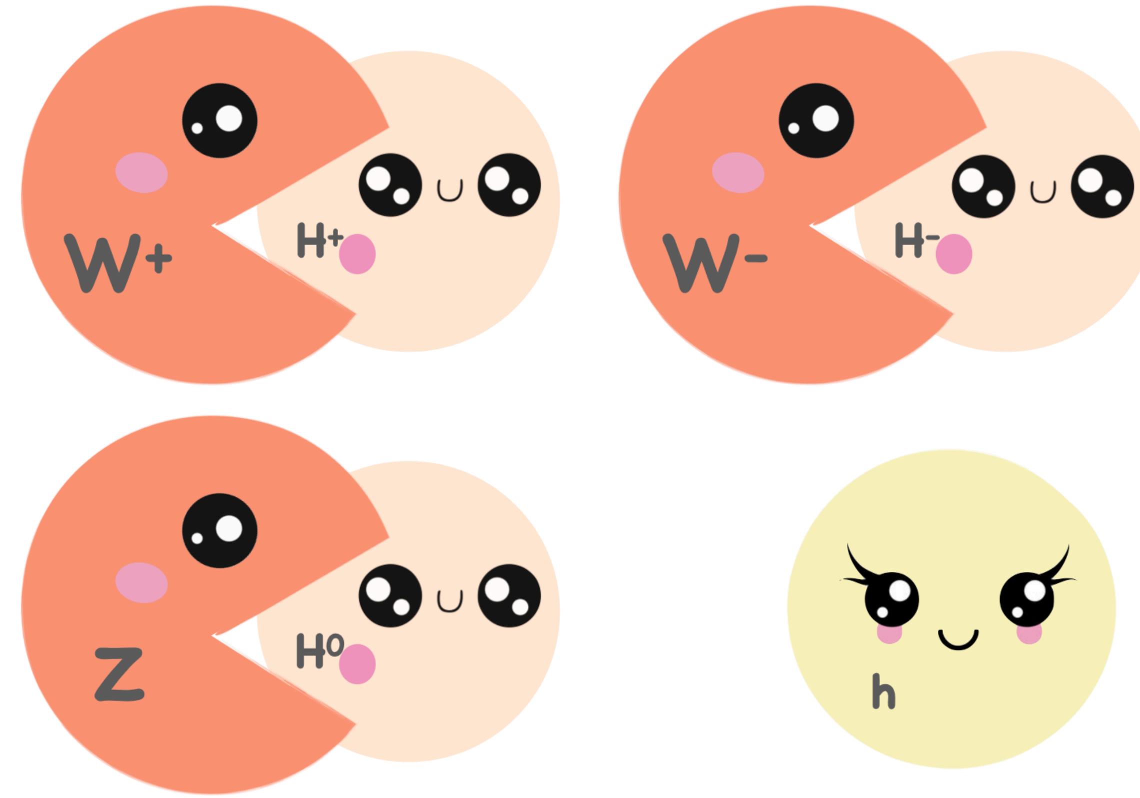
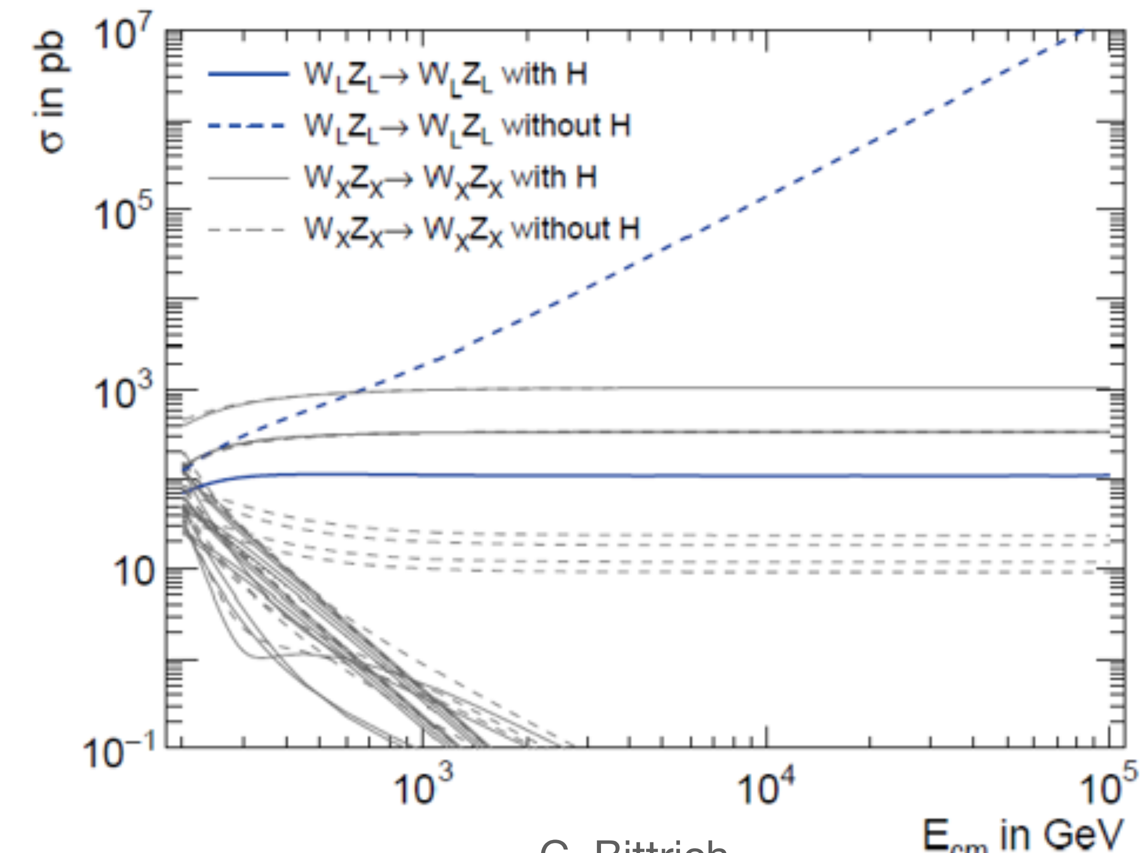


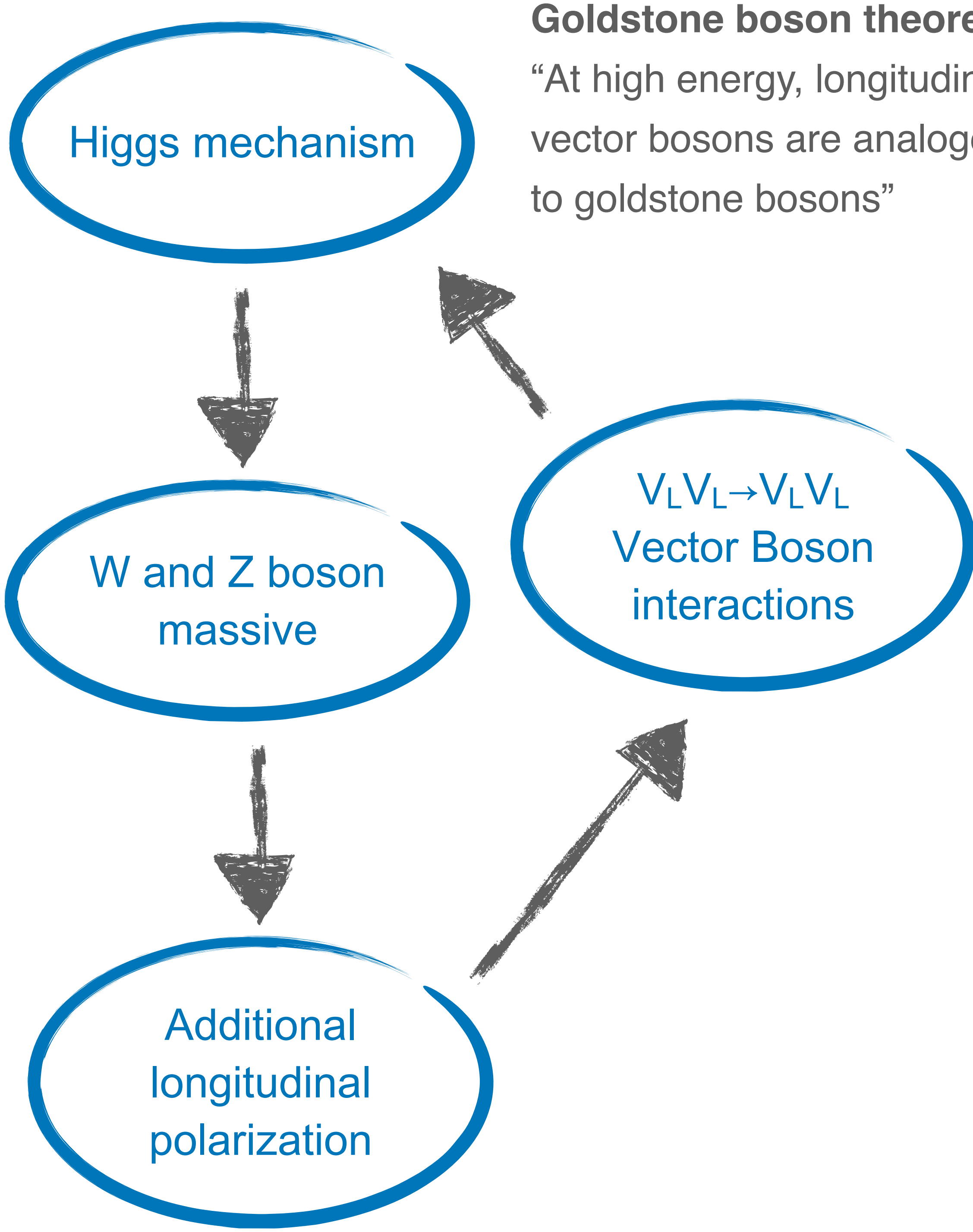


Unitarity violation in Longitudinal VBS

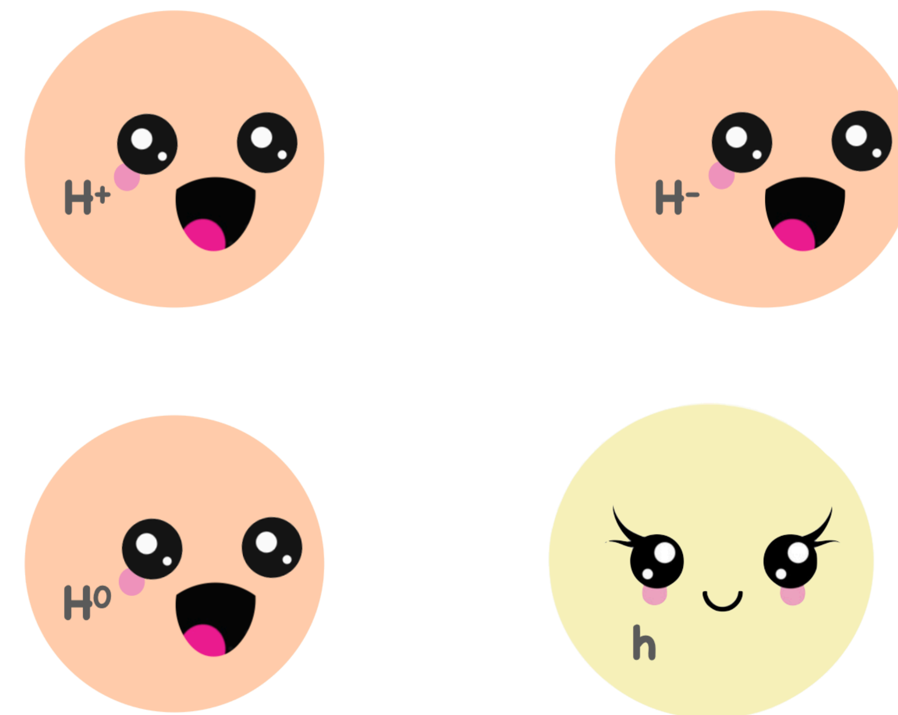


C. Bittrich

Why Di-Boson Polarizations ?



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



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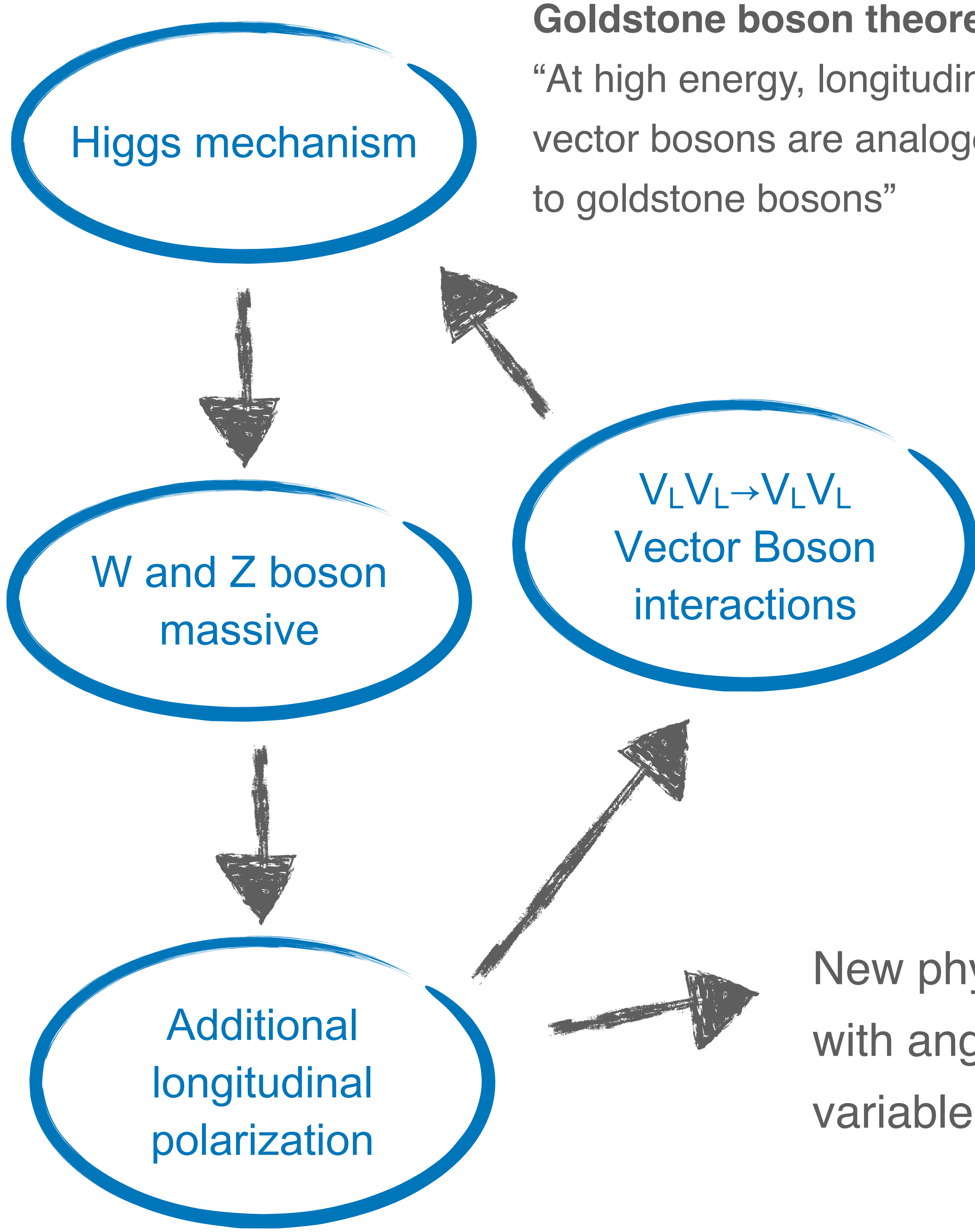

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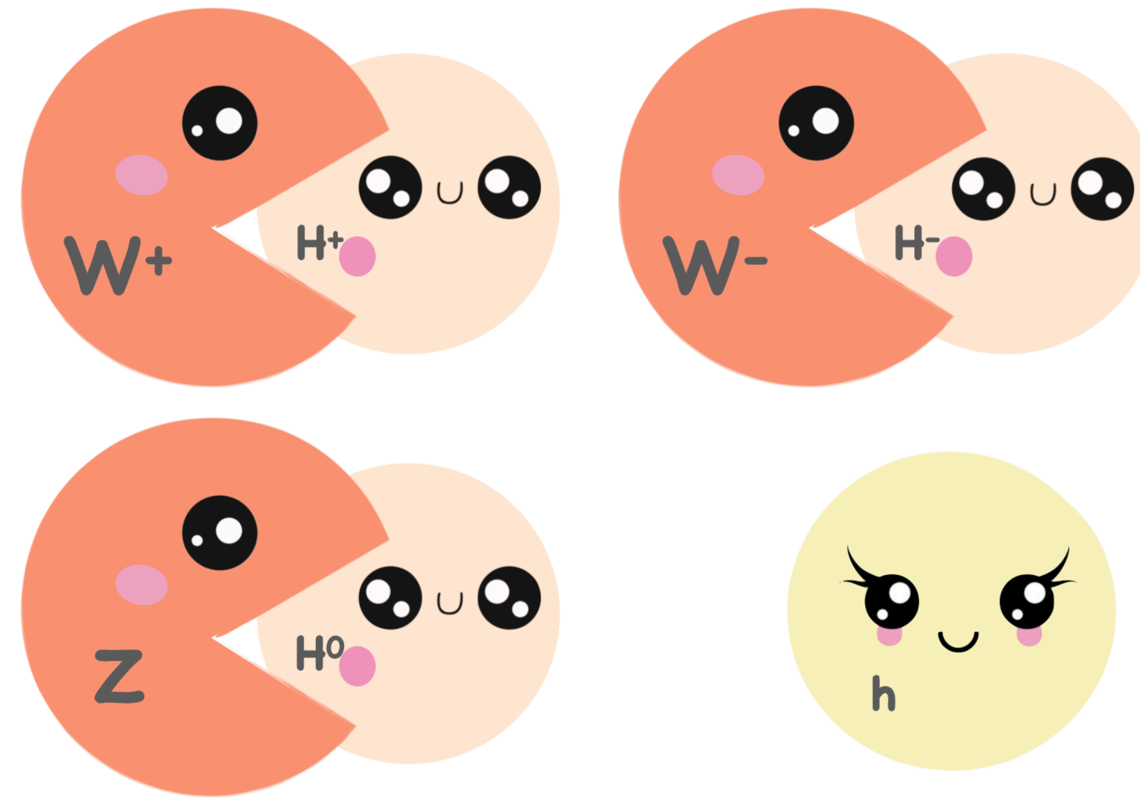
New physics with angular variables?



- They important probes of SM gauge and Higgs sectors
- can provide discrimination power between SM and BSM physics

But….. they are non trivial to extract

The state-of-the-art

Measurements at LEP:

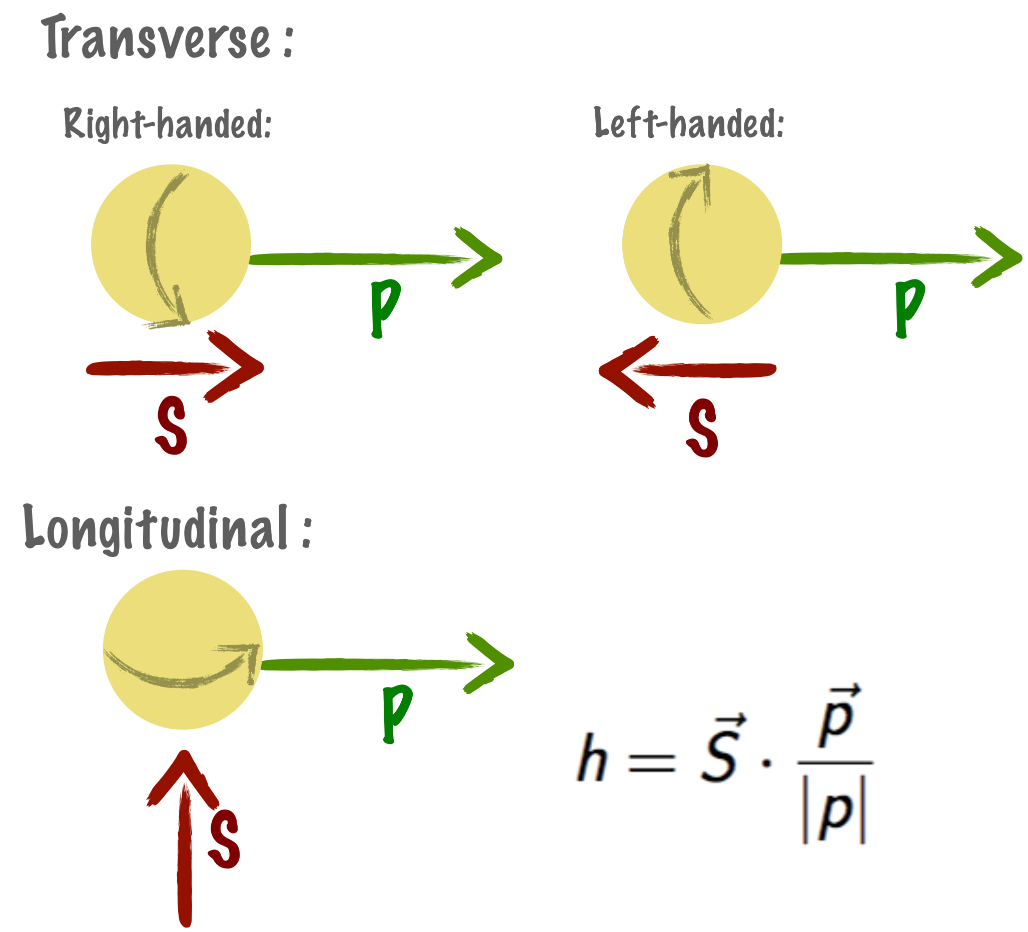
- Only diboson process accessible for such measurements $e^+e^- \to W^+W^-$
  - ***Single boson polarization measurements***: L3 [arXiv:0301027], OPAL [arXiv:0312047], DELPHI [arXiv:0801.1235]
  - ***Joint-polarization measurements***: OPAL [arXiv:0009021], DELPHI [arXiv:0908.1023]
- Never reached observation 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) Phys. Rev. Lett. 133 (2024) 101802 New!
- ***pp → ZZ***
  - ATLAS @13TeV 140 fb-1 (inclusive phase space) JHEP 12 (2023) 107
- ***pp → W±W±jj***
  - CMS @13TeV 137 fb^{-1} (VBS phase space) Phys. Lett. B 812 (2020) 136018

How to measure polarization?

- Polarization can be quantified using the helicity that describes the alignment of a particle's spin with its momentum.
  - Transversal polarization (T): the spin and momenta are (anti)-aligned (h=1, -1)
  - Longitudinal polarization (L or 0): spin perpendicular with the momenta (h=0)



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

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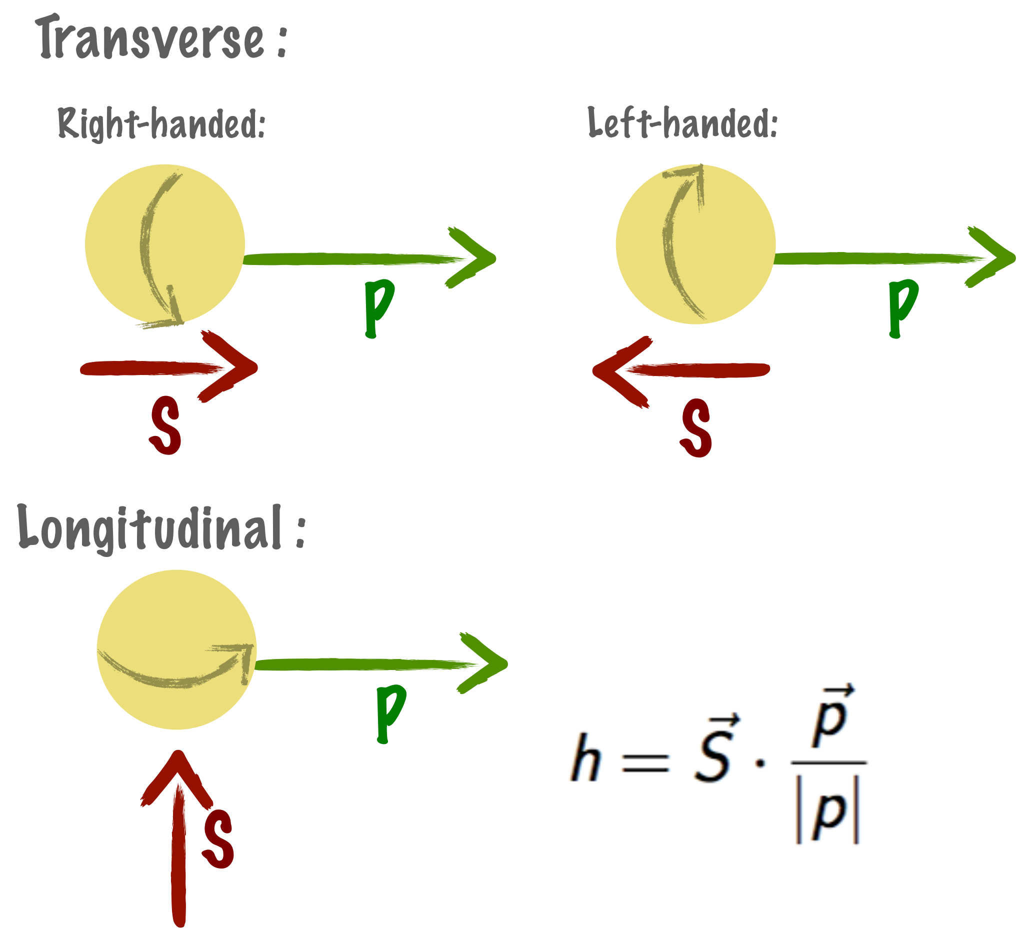

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A caveat

- 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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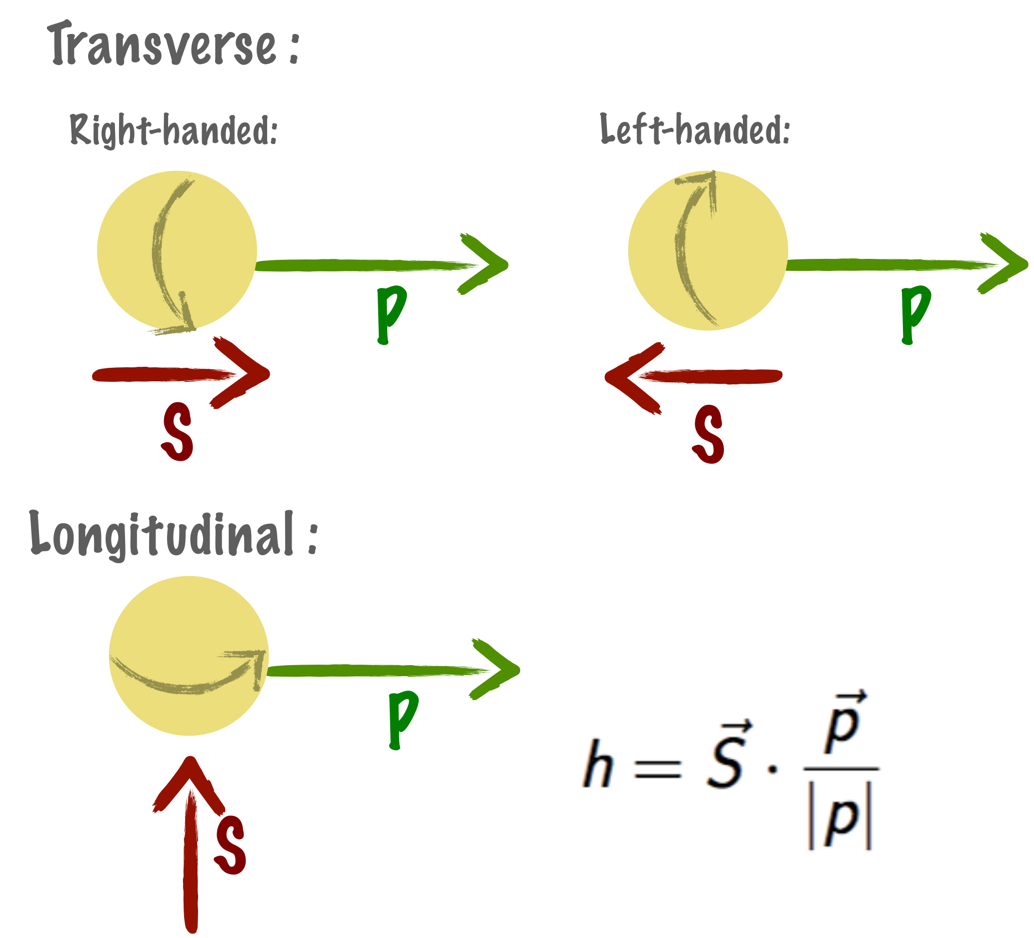

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How to measure polarization?

- Parity violation in weak interactions → polarization has effects on the decay products
- Angular variables between the bosons and the decays 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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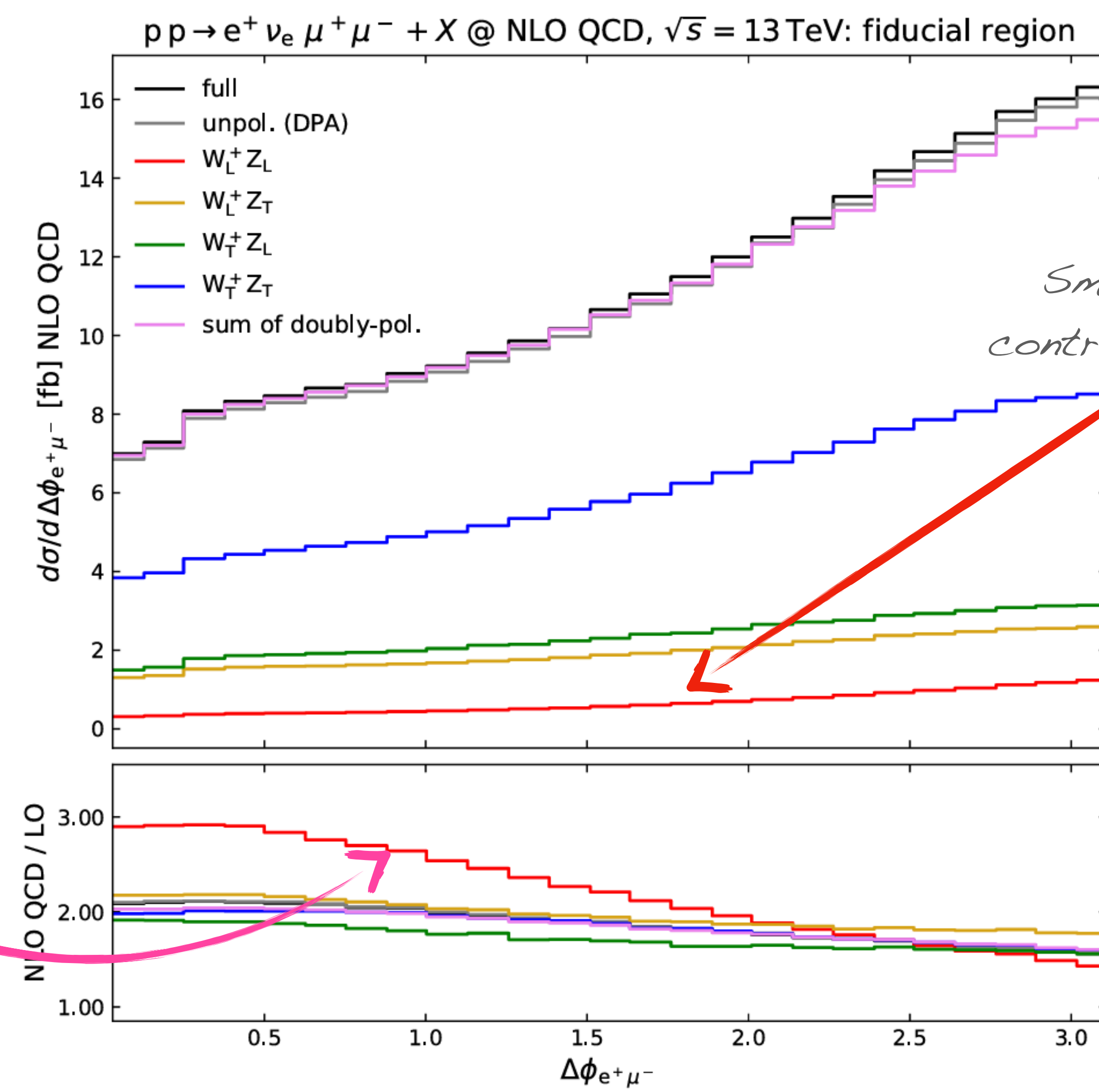
G. Pelliccioli et al

Fix order calculations

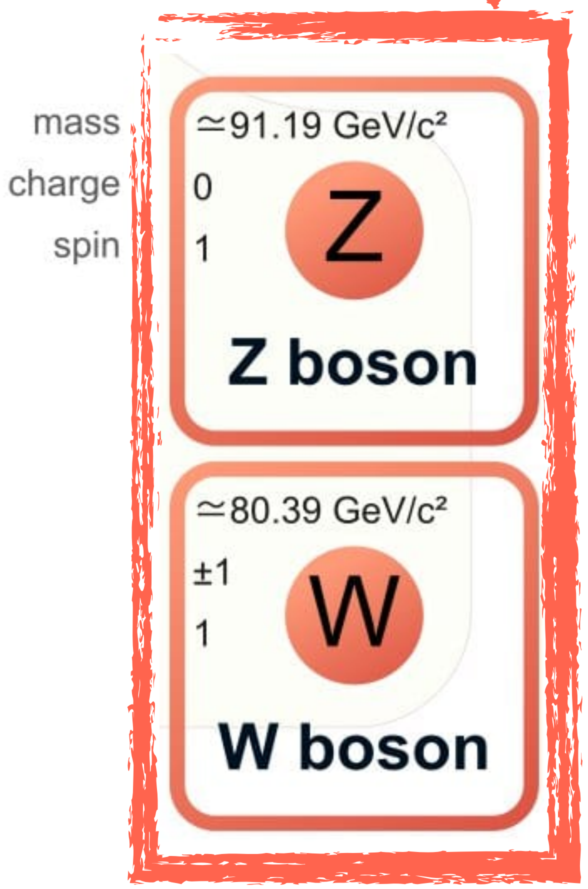
- Fix order calculations available for some processes (NNLO QCD, NLO QCD and EW) show large polarization depended corrections

NLO corrections are polarization aware and have different shape and size

Small LL contribution !



the main actors



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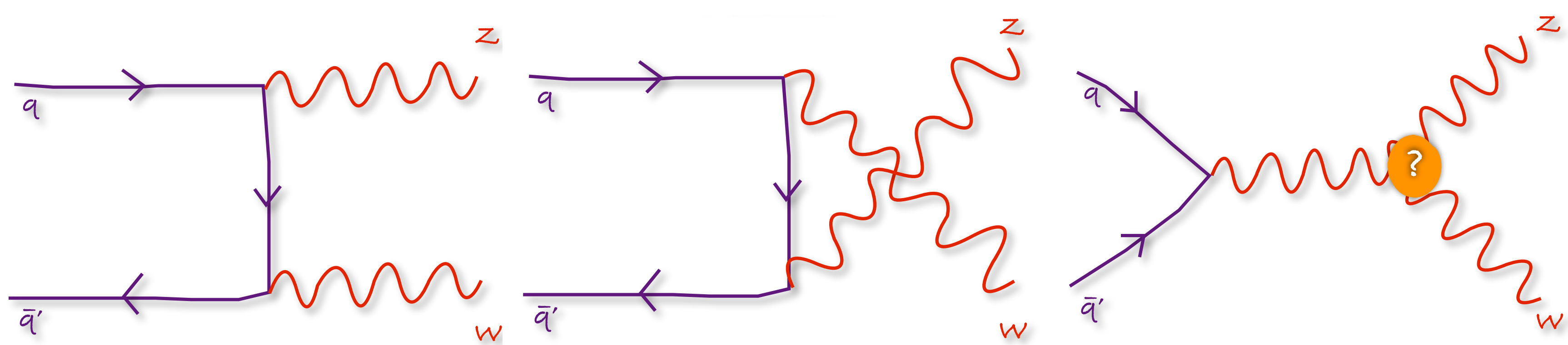
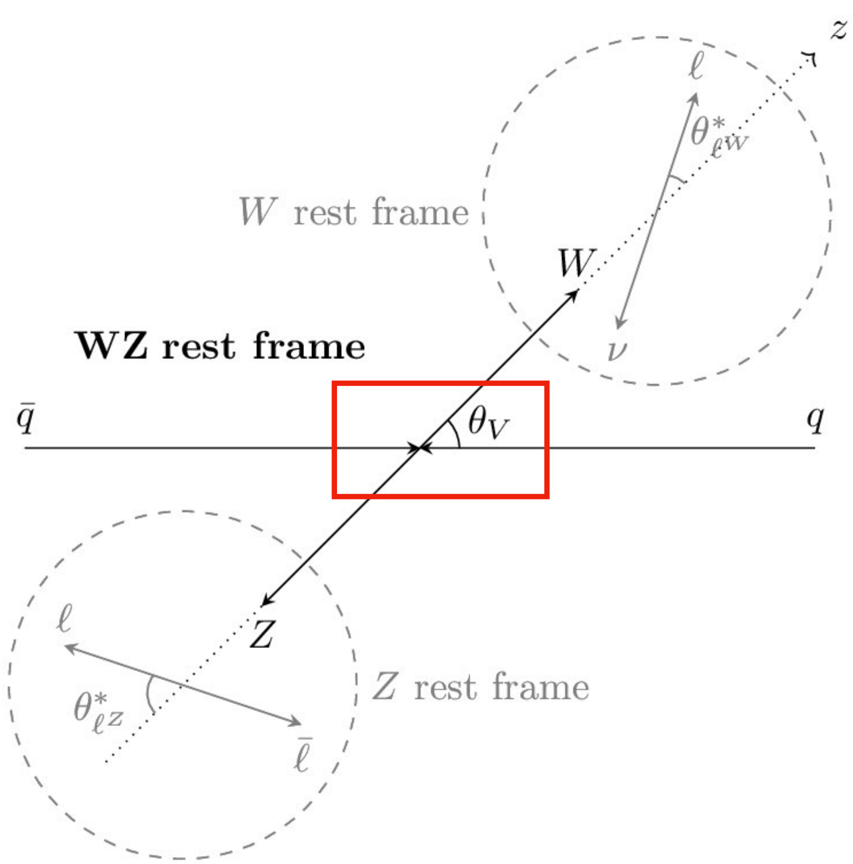
Test two SM predictions

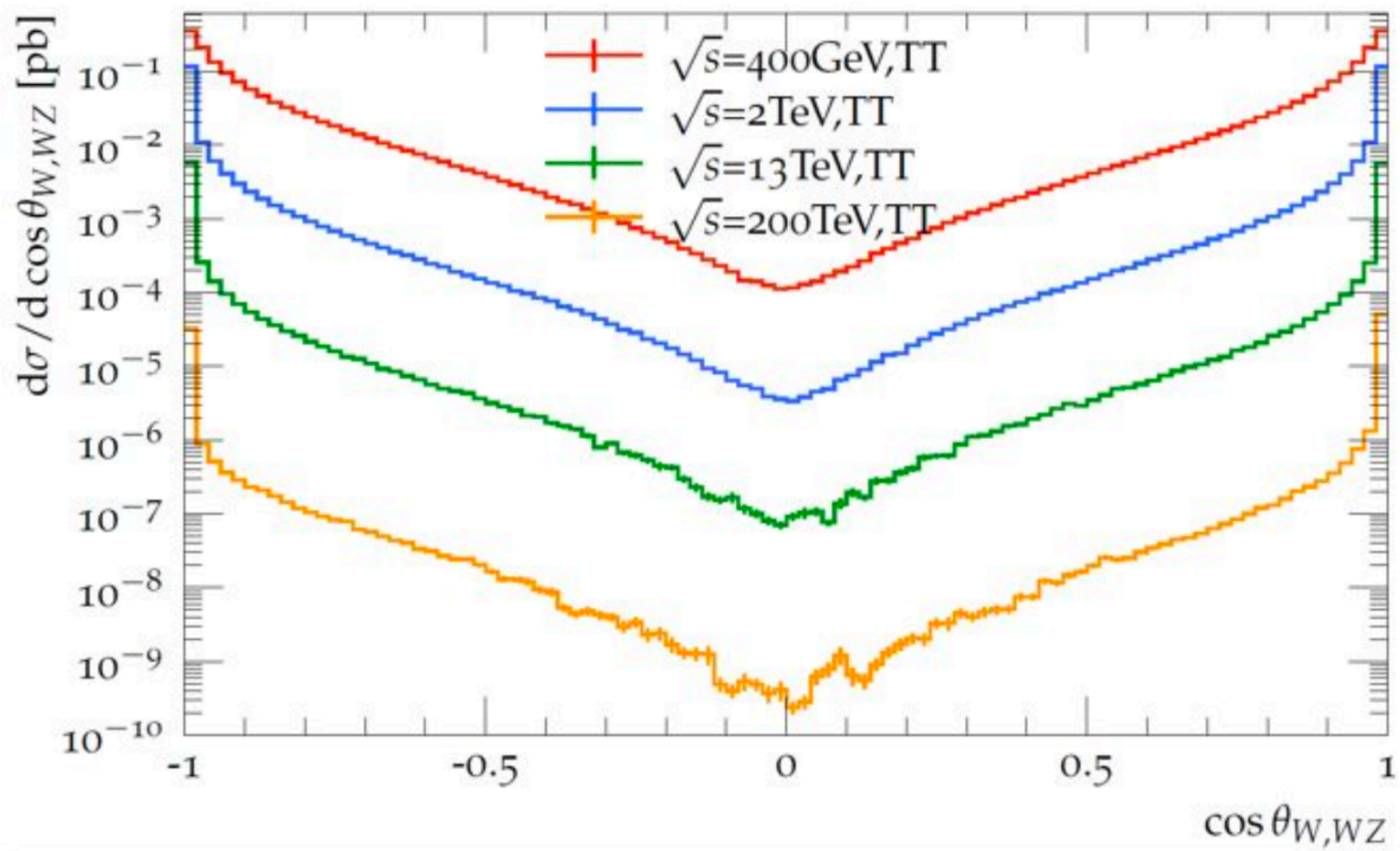
- ☐ Radiation Amplitude Zero Effect
- ☐ Double longitudinal bosons interacting at high p_T



Radiation Amplitude Zero effect

- **At LO strong gauge cancellations** making $\mathcal{M}(\pm,\mp) = 0$ that translates in drop in the TT cross-section (true for WZ and Wγ [D0 result])

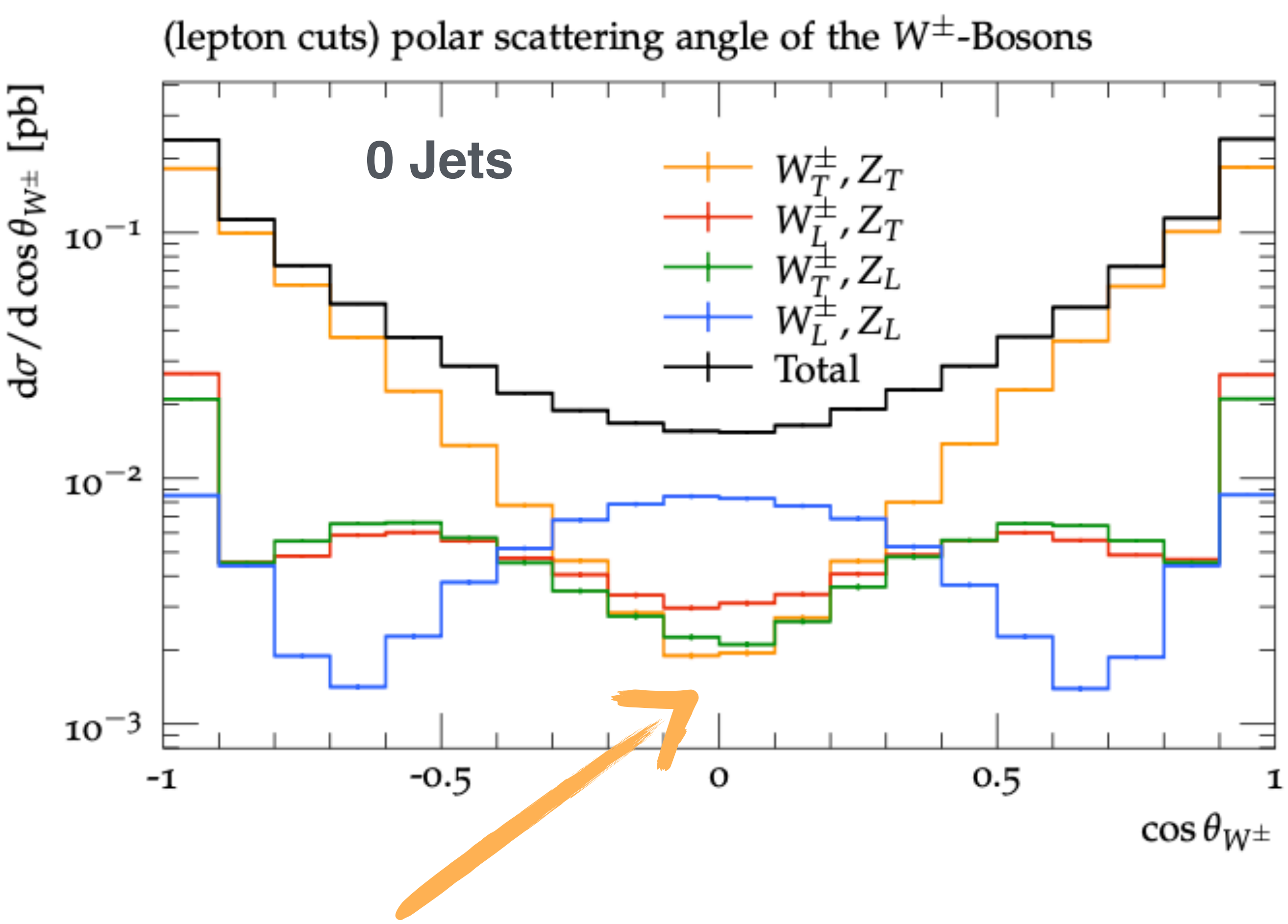


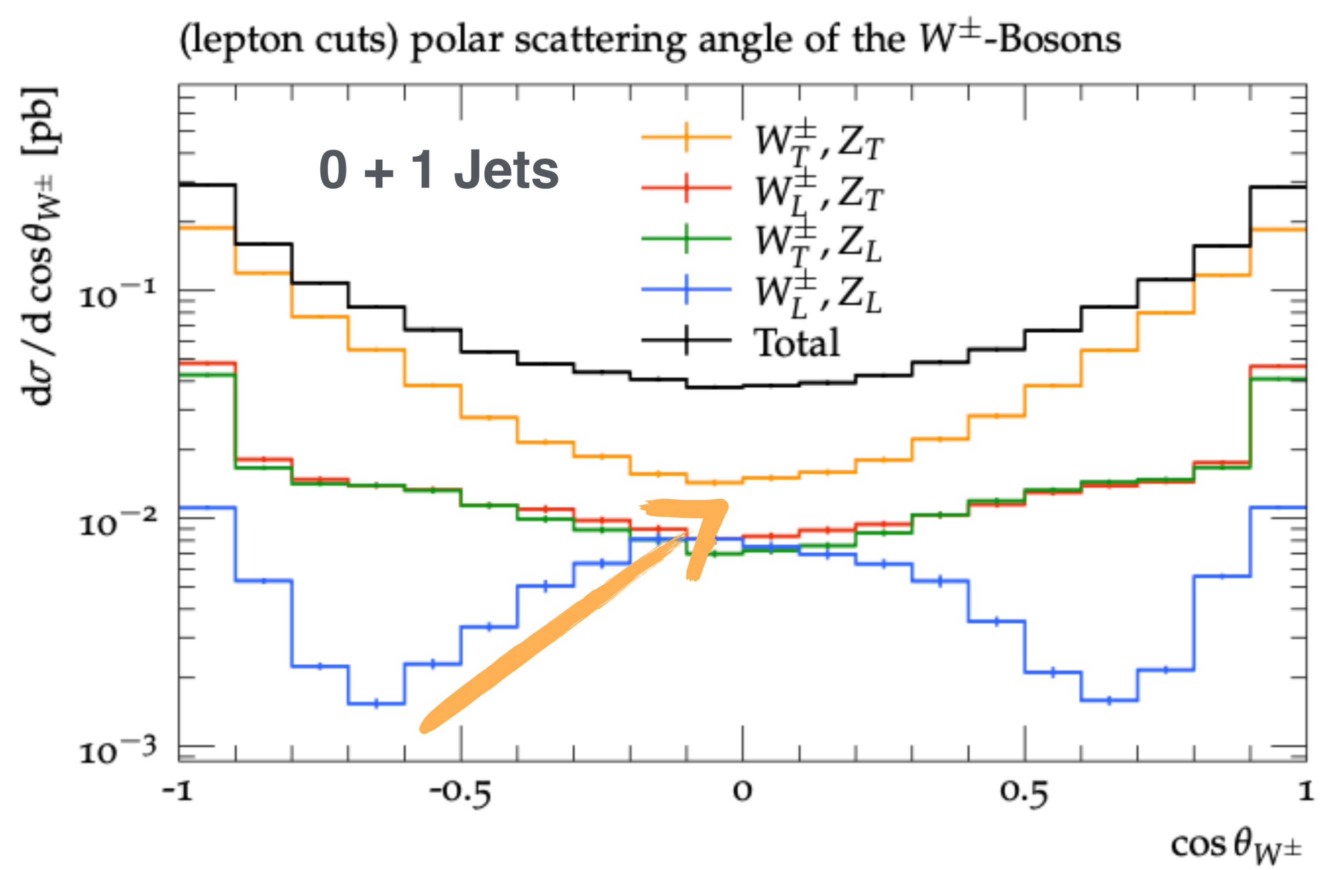


CERN-THESIS-2024-012

Radiation Amplitude Zero effect

- **At LO strong gauge cancellations** making $\mathcal{M}(\pm, \mp) = 0$ that translates in drop in the TT cross-section (true for WZ and Wγ [D0 result])
- At higher orders the dip of the RAZ disappears





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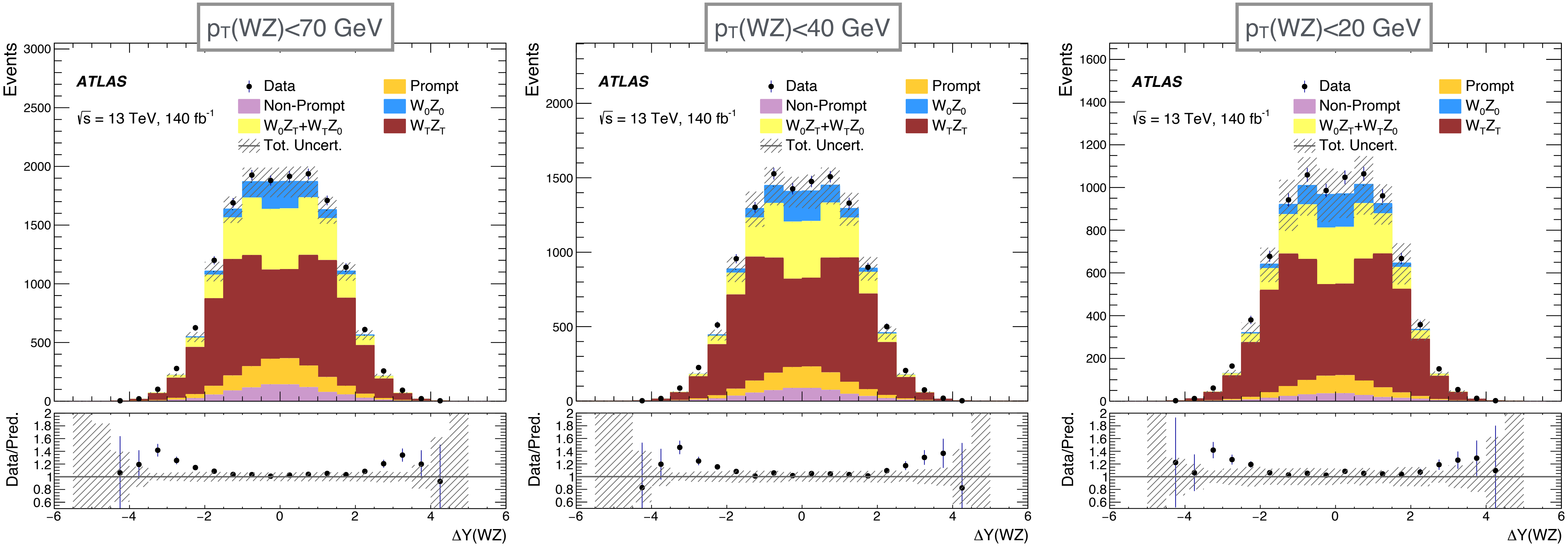
Radiation Amplitude Measurement in WZ

Phys. Rev. Lett. 133 (2024) 101802

- Used 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)

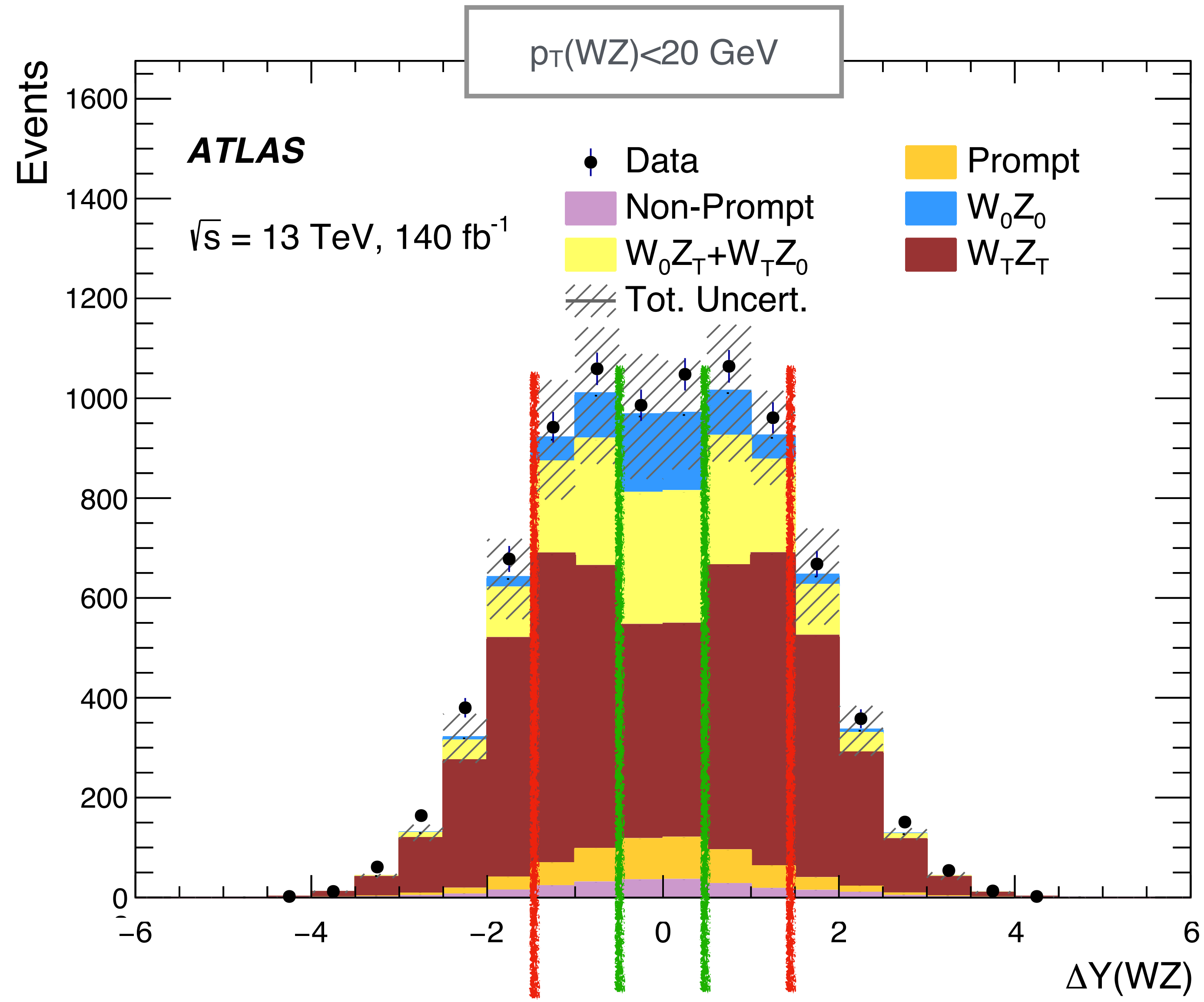
Radiation Amplitude Zero effect in WZ

Phys. Rev. Lett. 133 (2024) 101802

- Define a Depth variable to qualify the deepness TT dip

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

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



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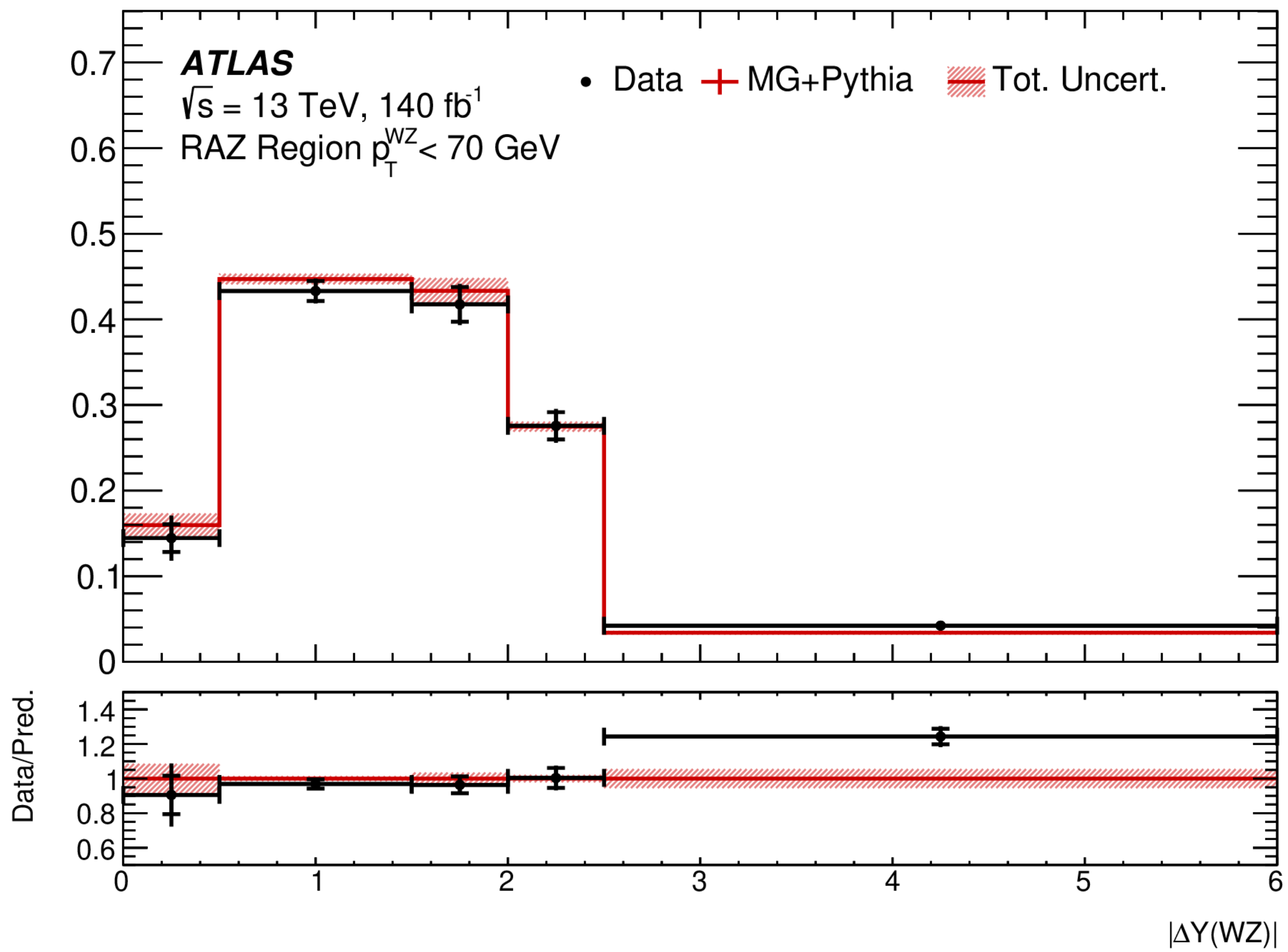
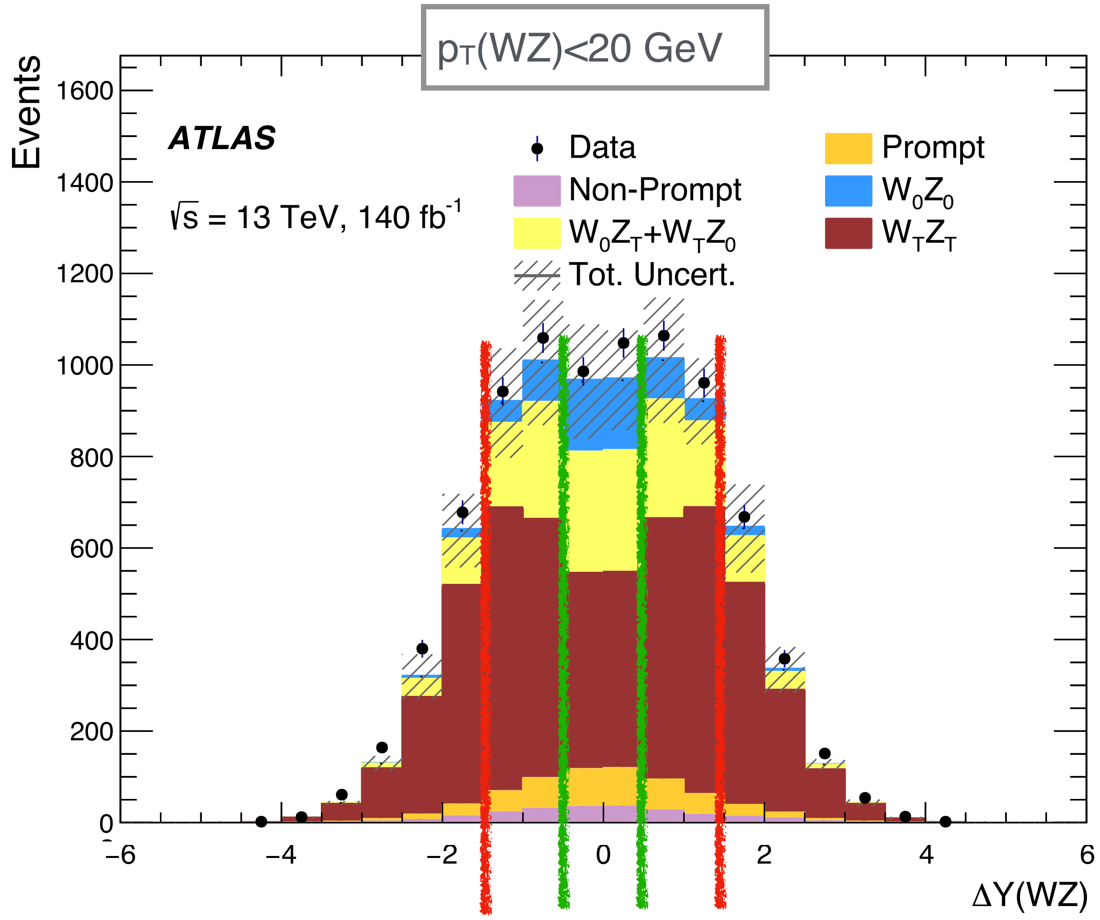
- Calculated the depth using unfolded TT only distributions (00+0T+T0-subtracted) for different $p_T(WZ)$ cuts





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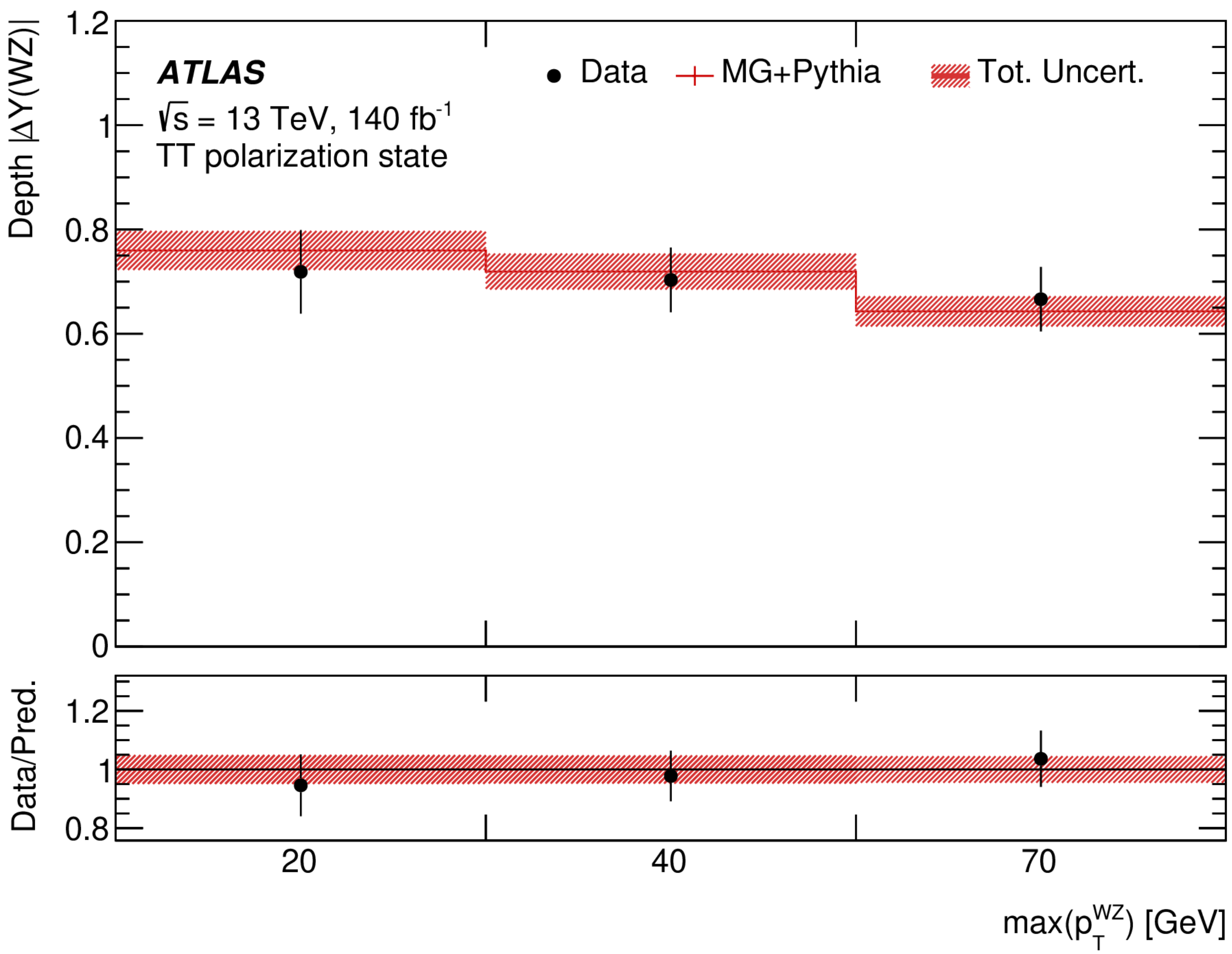
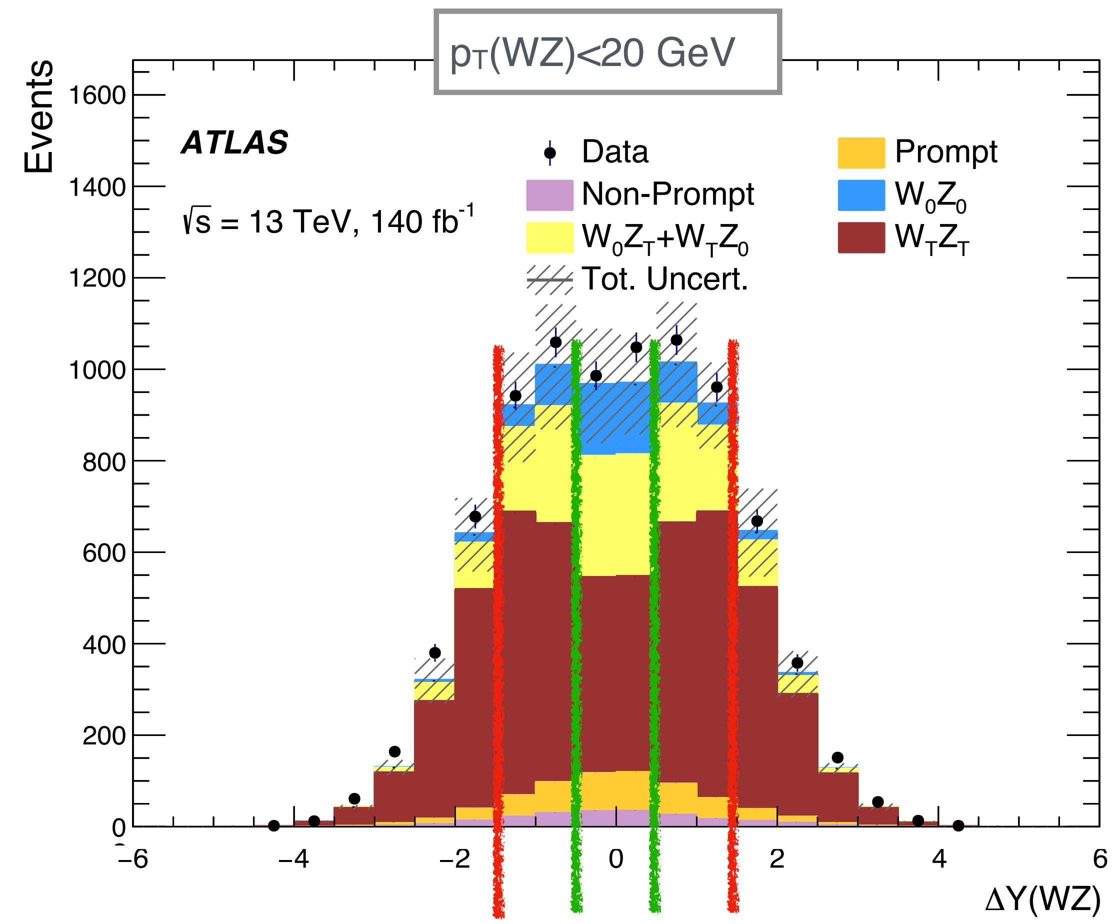
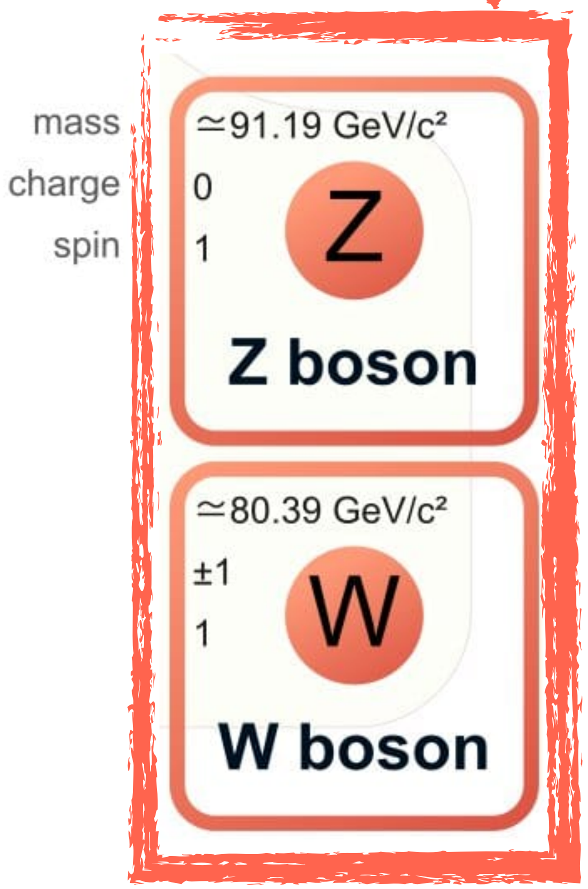




- **Depth variable well above 0 ! We see the RAZ deep !**

the main actors



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Test two SM predictions

- ✔ Radiation Amplitude Zero Effect
- ☐ Double longitudinal bosons interacting at high p_T

supporting actor

Double longitudinal WZ at high p_T

Phys. Rev. Lett. 133 (2024) 101802

	00-enhanced region 1	00-enriched region 2
Pass inclusive WZ event selection	✓	✓
Transverse momentum of the Z boson (p_T^Z)	[100, 200] GeV	> 200 GeV
Transverse momentum of the WZ system (p_T^{WZ})	< 70 GeV	< 70 GeV

Double longitudinal WZ at high p_T

Phys. Rev. Lett. 133 (2024) 101802

<table>
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The signal region yields :

Process	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
W_0Z_0	222 ± 5	47.6 ± 1.5
$W_0Z_T + W_TZ_0$	323 ± 12	23.7 ± 0.8
W_TZ_T	856 ± 31	124 ± 4
Prompt background	169 ± 18	24.1 ± 2.7
Non-prompt background	68 ± 29	2.8 ± 1.1
Total Expected	1640 ± 60	222 ± 8
Data	1740	236

Double longitudinal WZ at high p_T

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The signal region expected fractions :

	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

Polarization WZ at high p_T

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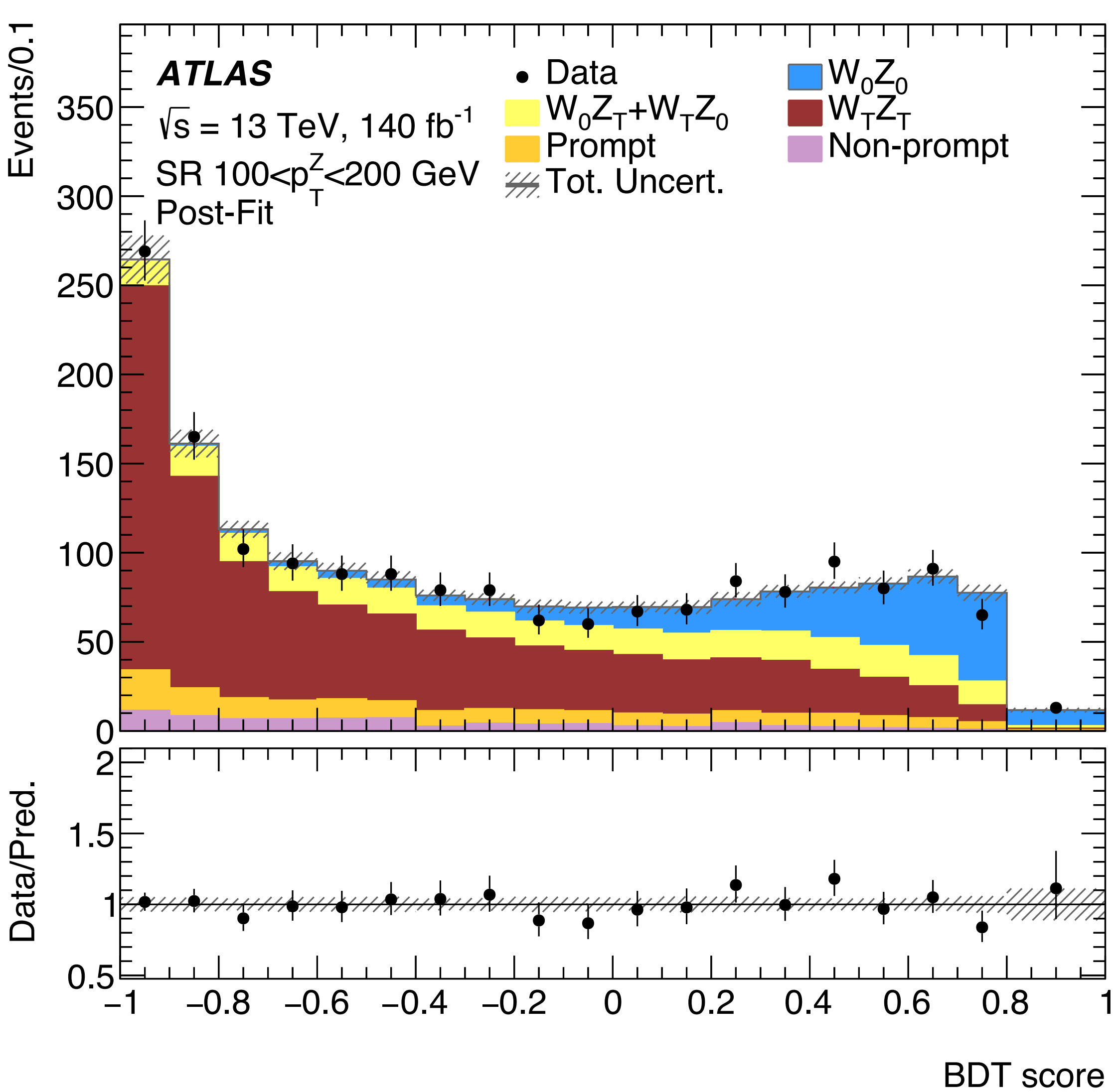
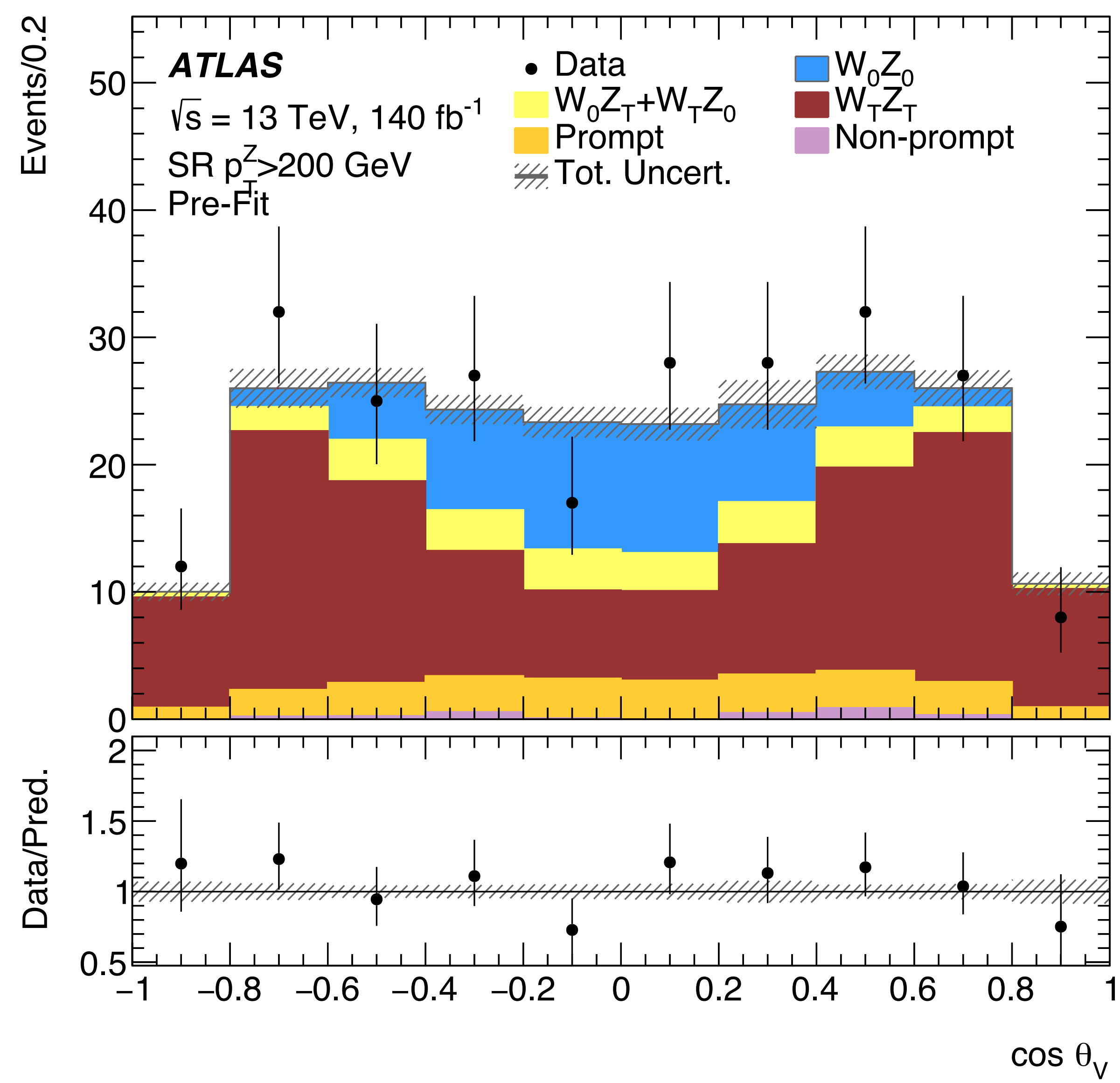
- Double Longitudinal component increased up to 23%
- Relative s-channel contribution expected to be higher at high $p_T(Z)$
- To separate the polarization components dedicated BDT were trained for each $p_T(Z)$ bin





WZ join polarization - 00-enhaced region

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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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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

Uncertainties

ATLAS EXPERIMENT

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Source	Impact on f_{00} [%]	
Experimental	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
Luminosity	0.1	0.2
Electron calibration	1.0	0.9
Muon calibration	1.1	1.3
Jet energy scale and resolution	5.9	9.0
E_T^{miss} scale and resolution	1.0	0.6
Flavor-tagging inefficiency	0.1	0.2
Pileup modelling	1.6	1.1
Non-prompt background estimation	5.8	0.8
Modelling		
Background, other	1.4	1.6
Model statistical	2.5	5.6
NLO QCD effects	6.8	8.2
NLO EW effects	1.1	3.3
Effect of additive vs multiplicative QCD+EW combination	1.3	3.8
Interference impact	1.4	0.7
PDF, Scales, and shower settings	3.5	9.2
Experimental and modelling	12.1	17.7
Data statistical	18.0	64.5
Total	21.7	66.9

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Summary

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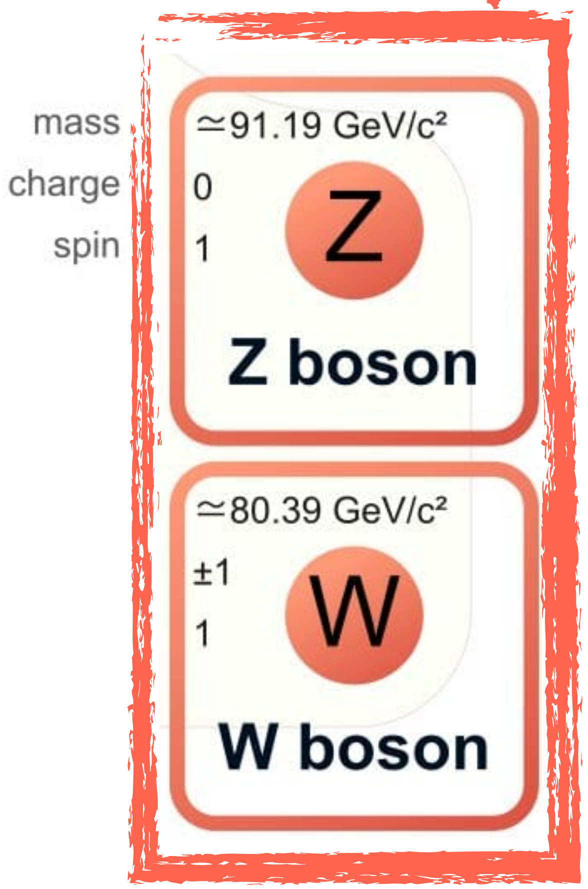

$$
\begin{aligned}
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& + \psi_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

Test two SM predictions

- ✔ Radiation Amplitude Zero Effect
- ✔ Double longitudinal bosons interacting at high p_T

supporting actor

Summary

- Polarization measurements are a new open door to probe the ingredients of the EWSB
- With Run-2 data we are already able to probe the polarization fractions in VV production
  - Results include the evidence or observation of double longitudinally polarized gauge bosons in WZ production at high p_T
  - 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 in same-sign WW production. A lot can be expected as we gather more data!
- An active theory and experimental community exist, first Polarization Workshop was hosted in Toulouse, next one will be announced soon :)