Polarised-boson pairs at the LHC with NLOPS accuracy

Giovanni Pelliccioli

Max-Planck Institute for Physics

(mostly) based on 2311.05220 in collaboration with Giulia Zanderighi

Motivations

LHC luminosities accumulated in Run 2 ($\approx 150\,\text{fb}^{-1}$) and foreseen in next runs ($300\,\text{fb}^{-1}$ in Run 3, and $3000\,\text{fb}^{-1}$ in High-Lumi) at 13/14 TeV CoM energy enable

→ precise measurements of EW processes: multi-boson production.

Polarisations of EW bosons

- are non trivial to disentangle
- are important probes of SM gauge and Higgs sectors,
- provide discrimination power between SM and BSM physics.

Special interest in di-boson (inclusive, VBS, Higgs decays).

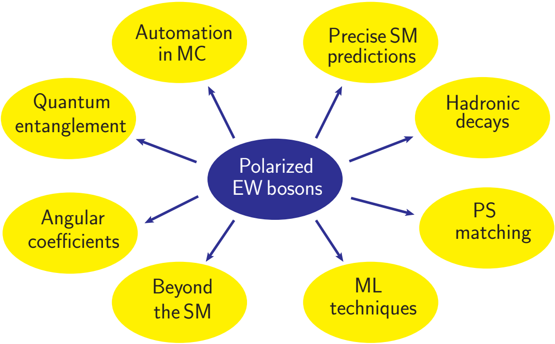
What can we do?

We cannot directly measure polarisations of EW bosons.

But we can perform fits of LHC data with polarised templates.

- inclusive WZ [ATLAS 1902.05759, CMS 2110.11231, ATLAS 2211.09435],
- $W^\pm W^\pm$ scattering [CMS 2009.09429],
- inclusive ZZ [ATLAS 2310.04350].

Theory input: proper understanding, precision and new ideas to extract polarisations.



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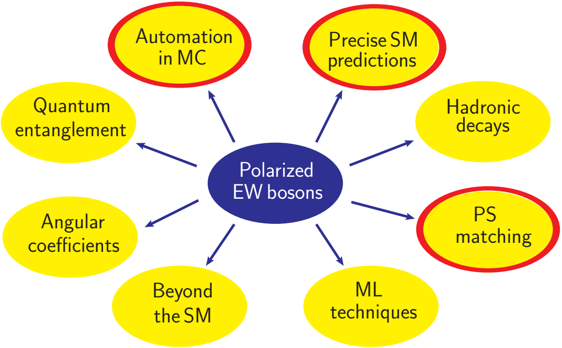
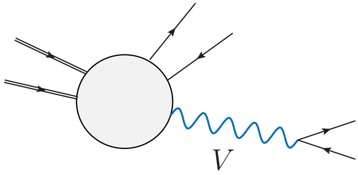


Separating polarisations in amplitudes

A natural definition for resonant diagrams (in pole/narrow-width approximation):



$$\mathcal{A}^{\text{unpol}} = \mathcal{P}_\mu \frac{-g^{\mu\nu}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu$$
$$= \mathcal{P}_\mu \frac{\sum_{\lambda'} \varepsilon^\mu_{\lambda'} \varepsilon^{*\nu}_{\lambda'}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu$$
$$\longrightarrow \mathcal{P}_\mu \frac{\varepsilon^\mu_{\lambda} \varepsilon^{*\nu}_{\lambda}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu = \mathcal{A}_\lambda$$

At the cross section level [Ballestrero et al. 1710.09339, Denner GP 2006.14867]:

$$|\mathcal{A}^{\text{unpol}}|^2 = \underbrace{\sum_\lambda |\mathcal{A}_\lambda|^2}_{\text{incoherent sum}} + \underbrace{\sum_{\lambda\neq\lambda'} \mathcal{A}^*_\lambda \mathcal{A}_{\lambda'}}_{\text{interference terms}} \longrightarrow |\mathcal{A}_\lambda|^2 \propto \text{polarised cross section}$$

Polarisation states are not Lorentz invariant: defined in a specific frame.

Decay-product angular distributions reflect polarisation state of the decayed V boson [Bern et al. 1103.5445, Stirling et al. 1204.6427, Belyaev et al. 1303.3297].

Angular coefficients: realistic effects

• At tree-level, decay of a single resonant boson (θ^*, ϕ^* are ℓ^+ angles in V rest frame, w.r.t. V direction in some Lorentz frame) [Bern et al. 1103.5445], no cuts on decay prod.:

$$\frac{d\sigma}{d\cos\theta^* d\phi^* dX} = \frac{d\sigma}{dX}\frac{3}{16\pi}\Big[(1+\cos^2\theta^*) + (A_0/2)(1-3\cos^2\theta^*) + A_1 \sin 2\theta^* \cos\phi^* + (A_2/2)\sin^2\theta^* \cos 2\phi^* + A_3 \sin\theta^* \cos\phi^* + A_4\cos\theta^* + A_5 \sin^2\theta^* \sin 2\phi^* + A_6 \sin 2\theta^* \sin\phi^* + A_7 \sin\theta^* \sin\phi^*\Big] \quad (1)$$

• Idea: $\{A_i\}$ extracted from unpol. distrib. with projections or asymmetries also with cuts on decay prod. and radiative corrections. [Baglio et al. 1810.11034, Frederix Vitos 2007.08867, Pellen et al. 2204.12394, Rahaman Singh 1810.11657, 1911.03111, 2109.09345].

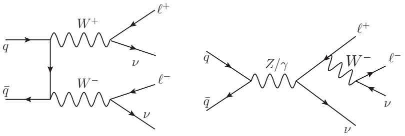
Nice, but:

1. radiative corrections: spin-density matrix modified, possible 3-body decays;
2. cuts on decay products: coefficients $\{A_i\}$ from Eq. 1 do not describe properly polarisation fractions and spin-correlations [Stirling et al.1204.6427, Belyaev et al.1303.3297, Ballestrero et al. 1710.09339, Baglio et al. 1810.11034, Frederix Vitos 2007.08867].

→ we can do better: generate polarised events!

Selecting resonant diagrams

To define polarisations, we need a factorised amplitude (production $\otimes$ propagator $\otimes$ decay): not possible for all contributions. *E.g.* diboson (fully leptonic):



Double-resonant and non-double-resonant diagrams at LO. For the latter polarisations cannot be defined: drop them, providing a recipe to recover gauge invariance.

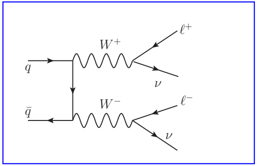
Non-resonant diagrams regarded as non-resonant background.

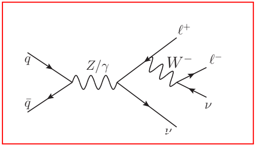
Resonant diagrams treated with

- DPA: double-pole approximation [Denner et al. 0006307]
- NWA: spin-correlated narrow-width approximation [Artoisenet et al. 1212.3460].

$\rightarrow$ separating polarisations is then straightforward.

DPA details





$$\mathcal{A}_{\text{full}}(x_1,x_2;\ k_{1\dots4}) = \mathcal{A}_{\text{res}}(x_1,x_2;\ k_{1\dots4}) + \mathcal{A}_{\text{nonres}}(x_1,x_2;\ k_{1\dots4}) \longrightarrow \mathcal{A}_{\text{res}}(x_1,x_2;\ k_{1\dots4})$$

$$\mathcal{A}_{\text{res}}(x_1,x_2;\ k_{1\dots4}) \quad = \quad \mathcal{P}_{\mu\nu}(x_1,x_2;\ k_{12},k_{34}) = \frac{-\mathrm{i}\,g^{\mu\alpha}}{k_{12}^2 - M_1^2 + \mathrm{i}\Gamma_1 M_1}\,\frac{-\mathrm{i}\,g^{\nu\beta}}{k_{34}^2 - M_2^2 + \mathrm{i}\Gamma_2 M_2}\mathcal{D}_\alpha(k_1,k_2)\,\mathcal{D}_\beta(k_3,k_4)$$

$$\mathcal{A}_{\text{res}}(x_1,x_2;\ k_{1\dots4}) \xrightarrow{\text{DPA}} \mathcal{A}_{\text{res}}(x_1,x_2;\ \tilde{k}_{1\dots4}) = \mathcal{P}_{\mu\nu}(x_1,x_2;\ \tilde{k}_{12},\tilde{k}_{34})$$
$$\times \quad \frac{-\mathrm{i}\,g^{\mu\alpha}}{k_{12}^2 - M_1^2 + \mathrm{i}\Gamma_1 M_1}\,\frac{-\mathrm{i}\,g^{\nu\beta}}{k_{34}^2 - M_2^2 + \mathrm{i}\Gamma_2 M_2}\mathcal{D}_\alpha(\tilde{k}_1,\tilde{k}_2)\,\mathcal{D}_\beta(\tilde{k}_3,\tilde{k}_4)$$

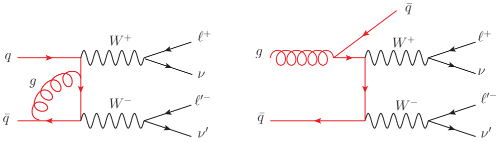
On-shell mapping: $\quad \Phi_4 = \{x_1,x_2;k_{1\dots4}\} \xrightarrow{\text{DPA}} \tilde{\Phi}_4 = \{x_1,x_2;\tilde{k}_{1\dots4}\}$

where $\tilde{k}_{12}^2 = (\tilde{k}_1+\tilde{k}_2)^2 = M_1^2$ and $\tilde{k}_{34}^2 = (\tilde{k}_3+\tilde{k}_4)^2 = M_2^2$ ($M_1,\ M_2 =$ masses of the two gauge bosons), and $(k_1+k_2+k_3+k_4)^2 > (M_1+M_2)^2$.

Polarisation selection: $-g_{\mu\nu} \longrightarrow \varepsilon_\mu^{(\lambda)}(k)\,\varepsilon_\nu^{(\lambda)\,*}(k)\,, \qquad \lambda = \mathrm{L},+,-$

Going beyond leading-order: NLO corrections to the production

- NLO: virtual (V) and real (R) contributions, $V + R$ free of IR singularities;



- subtraction counterterms needed, *e.g.* dipole formalism [Catani, Seymour 9605323]:

$$d\sigma_{\rm nlo}/d\xi = \int d\phi_n \Big(B + V + \int d\phi_{\rm rad}\, D\Big)_{d=4}\, \delta_\xi^{(n)} + \int d\phi_{n+1} \Big(R\, \delta_\xi^{(n+1)} - D\, \delta_\xi^{(n)}\Big)_{d=4}\,; \quad (2)$$

- DPA/NWA usually used for n-body (B, V) $\rightarrow$ also needed for R and D terms;
- separation of polarisations required for all contributions in Eq. 2.

Corrections only affect production of resonance(s) $\longrightarrow$ conceptually straightforward.

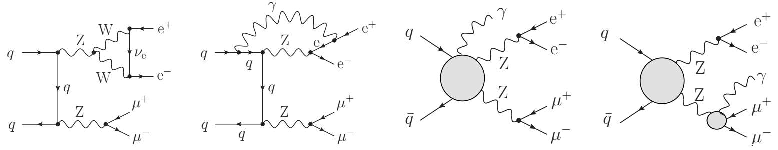
N(N)LO QCD corr. with leptonic decays [Denner GP 2006.14867, Poncelet Popescu 2102.13583].

Going beyond leading-order: NLO corrections to the decays

Corrections affect both production and decays of resonance(s).

NLO EW (QCD) corrections to Z/ W bosons with leptonic (hadronic) decays.

Factorisable | Non-factorisable | ISR | FSR



General method has been proposed to separate Z resonant contributions at NLO EW, with leptonic decays [Denner GP 2107.06579].

Also applied to NLO QCD in semi-leptonic decay channels [Denner Haitz GP 2211.09040].

Extended to W bosons in inclusive WZ [Le Baglio 2203.01470, 2208.09232] and W^+W^- [Denner Haitz GP 2311.16031, Dao Le 2311.17027]: photons radiated off the boson propagator.

Ongoing effort towards NLO corr. to polarised VBS.

Fixed-order results

Recent precise predictions mostly target inclusive di-boson and V+jet production:

- $\rightarrow$ $\mathrm{W}^+(\ell^+\nu_\ell)\,\mathrm{W}^-(\ell'^-\bar{\nu}_{\ell'})$: NLO QCD in the DPA [Denner GP 2006.14867], NNLO QCD in the DPA and NWA [Poncelet Popescu 2102.13583], NLO EW in the DPA [Denner Haitz GP 2311.16031, Dao Le 2311.17027] ;
- $\rightarrow$ $\mathrm{W}^\pm(\ell^\pm\nu_\ell)\,\mathrm{Z}(\ell'^+\ell'^-)$: NLO QCD [Denner GP 2010.07149] and NLO EW [Le Baglio 2203.01470, 2208.09232] in the DPA, nLO QCD in the NWA [Hoppe et al. 2310.14803];
- $\rightarrow$ $\mathrm{Z}(\ell^+\ell^-)\,\mathrm{Z}(\ell'^+\ell'^-)$: NLO EW + QCD in the DPA [Denner GP 2107.06579];
- $\rightarrow$ $\mathrm{W}^\pm(\ell^\pm\nu_\ell)\,\mathrm{j}$: NNLO QCD in the NWA [Pellen et al. 2109.14336];
- $\rightarrow$ $\mathrm{W}^\pm(\mathrm{jets})\,\mathrm{Z}(\ell'^+\ell'^-)$: NLO QCD in the DPA [Denner Haitz GP 2211.09040].

Matching to parton shower

Usual assumption: factorisation of PS effects from spin-structure of the multi-boson system → not true already with one real emission.

NLO QCD accuracy required.

MC codes simulating intermediate polarised bosons (public or soon-to-be-published):

1. PHANTOM (v1.7): LO, 2 → 6 processes in the DPA, interfaced to PS [Ballestrero Maina GP 1710.09339, 1907.04722, 2007.07133, Maina GP 2105.07972].
2. MG5_aMC@NLO (v2.7): LO, any process in the NWA, multi-jet merging and PS matching, UFO models for BSM/EFT [Buarque-Franzosi et al. 1912.01725].
3. SHERPA: nLO (approx.), any process in the NWA, multi-jet merging and PS matching, UFO models for BSM/EFT [Hoppe et al. 2310.14803]
4. POWHEG-BOX-RES: NLO, diboson processes in the DPA, PS matching [GP Zanderighi 2311.05220].

First efforts towards a public unweighted-event generators capable to treat intermediate polarised bosons beyond LO in SHERPA [Hoppe et al. 2310.14803] and POWHEG-BOX-RES [GP Zanderighi 2311.05220].

Ongoing efforts towards NLO+PS in SHERPA and MG5_aMC@NLO.

Effort needed to incorporate EW effects.

Powheg-Box-Res: technical details

First FKS ($n \to n+1$) mapping, second DPA on-shell mapping:

$$\Phi_{4\ell} = \{x_1, x_2; k_{1\ldots4}\} \quad \xrightarrow{\text{FKS}} \quad (\bar{\Phi}_{4\ell}, \Phi_{\text{rad}}) = \{\bar{x}_1, \bar{x}_2; \bar{k}_{1\ldots4}, k_{\text{rad}}\} \xrightarrow{\text{DPA}}$$
$$\xrightarrow{\text{DPA}} \quad (\tilde{\bar{\Phi}}_{4\ell}, \Phi_{\text{rad}}) = \{\bar{x}_1, \bar{x}_2; \tilde{\bar{k}}_{1\ldots4}, k_{\text{rad}}\}$$

POWHEG master formula (tailored to DPA):

$$\langle \mathcal{O} \rangle = \int \mathrm{d}\Phi_{4\ell}\, \tilde{\mathrm{B}}(\tilde{\Phi}_{4\ell}) \left[\mathcal{O}(\tilde{\Phi}_{4\ell}) \Delta(t_0) + \int_{t>t_0} \mathrm{d}\Phi_{\text{rad}} \mathcal{O}(\tilde{\bar{\Phi}}_{4\ell}, \Phi_{\text{rad}}) \frac{\mathrm{R}(\tilde{\bar{\Phi}}_{4\ell}, \Phi_{\text{rad}})}{\mathrm{B}(\tilde{\Phi}_{4\ell})} \Delta(t) \right]$$

with NLO-accurate $\tilde{B}$ weight,

$$\tilde{\mathrm{B}}(\tilde{\Phi}_{4\ell}) = \mathrm{B}(\tilde{\Phi}_{4\ell}) + \mathrm{V}_{\text{reg}}(\tilde{\Phi}_{4\ell}) + \int \mathrm{d}\Phi_{\text{rad}} \left[\mathrm{R}(\tilde{\bar{\Phi}}_{4\ell}, \Phi_{\text{rad}}) - \mathrm{CT}(\tilde{\bar{\Phi}}_{4\ell}, \Phi_{\text{rad}}) \right]$$

and Sudakov form factor (t = radiation transverse momentum),

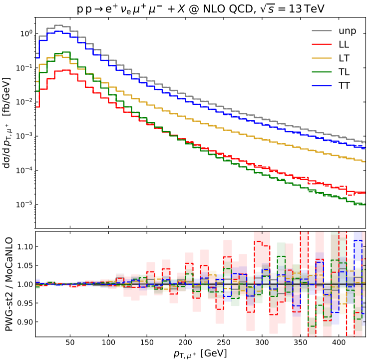
$$\Delta(t) = \exp\left[- \int_{t'>t} \mathrm{d}\Phi'_{\text{rad}} \frac{\mathrm{R}(\tilde{\bar{\Phi}}_{4\ell}, \Phi'_{\text{rad}})}{\mathrm{B}(\tilde{\Phi}_{4\ell})} \right]$$

Powheg-Box-Res: fixed-order validation

Implementation in Powheg-Box-Res code [Nason 0409146, Frixione et al. 0709.2092, Alioli et al. 1002.2581, Jezo Nason 1509.09071, Chiesa et al. 2005.12146] in the DPA [GP Zanderighi 2311.05220]

Results at fixed order (NLO QCD) agree very well with MoCaNLO [Denner GP 2006.14867, 2010.07149, 2107.06579] (table: inclusive cross sections in fb, figure: p_{T,μ^+} distribution in WZ)

	Powheg-Box-Res	MoCaNLO
$\mathrm{W}^+_\mathrm{U}\mathrm{W}^-_\mathrm{U}$	1249.8(9)	1249.2(6)
$\mathrm{W}^+_\mathrm{L}\mathrm{W}^-_\mathrm{L}$	65.92(9)	65.90(8)
$\mathrm{W}^+_\mathrm{L}\mathrm{W}^-_\mathrm{T}$	158.7(1)	158.60(7)
$\mathrm{W}^+_\mathrm{T}\mathrm{W}^-_\mathrm{L}$	162.97(9)	162.91(7)
$\mathrm{W}^+_\mathrm{T}\mathrm{W}^-_\mathrm{T}$	861.6(7)	860.1(5)
$\mathrm{W}^+_\mathrm{U}\ \mathrm{Z}_\mathrm{U}$	97.25(3)	97.19(3)
$\mathrm{W}^+_\mathrm{L}\ \mathrm{Z}_\mathrm{L}$	4.492(1)	4.496(2)
$\mathrm{W}^+_\mathrm{L}\ \mathrm{Z}_\mathrm{T}$	13.146(6)	13.132(4)
$\mathrm{W}^+_\mathrm{T}\ \mathrm{Z}_\mathrm{L}$	12.724(6)	12.716(4)
$\mathrm{W}^+_\mathrm{T}\ \mathrm{Z}_\mathrm{T}$	66.88(3)	66.84(3)
$\mathrm{Z}_\mathrm{U}\ \mathrm{Z}_\mathrm{U}$	28.22(1)	28.21(2)
$\mathrm{Z}_\mathrm{L}\ \mathrm{Z}_\mathrm{L}$	1.665(1)	1.664(2)
$\mathrm{Z}_\mathrm{L}\ \mathrm{Z}_\mathrm{T}$	3.550(3)	3.548(1)
$\mathrm{Z}_\mathrm{T}\ \mathrm{Z}_\mathrm{L}$	3.555(3)	3.548(2)
$\mathrm{Z}_\mathrm{T}\ \mathrm{Z}_\mathrm{T}$	19.44(1)	19.45(1)



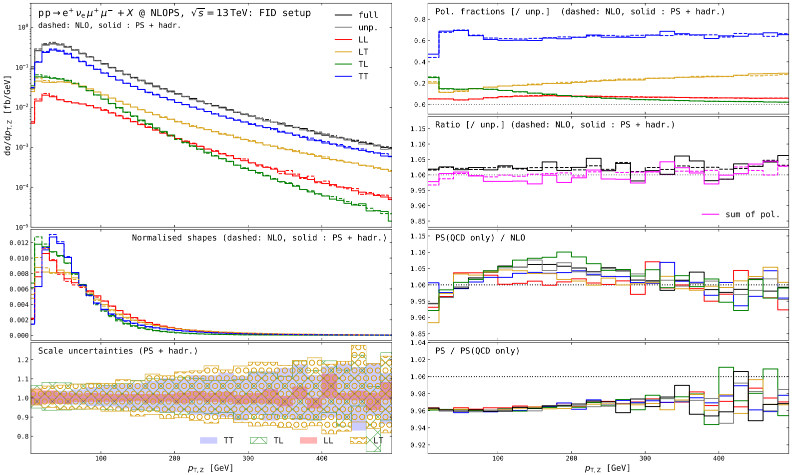
Powheg-Box-Res: integrated results in WZ

Fiducial setup [ATLAS 2211.09435] vs boosted setup ($p_{T,Z} > 200$GeV, $p_{T,WZ} < 70$GeV).

state	σ[fb] LHE	ratio [/unp., %] LHE	σ[fb] PS+hadr	ratio [/unp., %] PS+hadr
		Fiducial setup		
full off-shell	$35.40(5)^{+5.2\%}_{-4.2\%}$	102.15	$34.04(5)^{+5.3\%}_{-4.2\%}$	102.20
unpolarised	$34.65(5)^{+5.2\%}_{-4.2\%}$	100	$33.30(5)^{+5.2\%}_{-4.2\%}$	100
LL	$1.965(3)^{+2.7\%}_{-2.2\%}$	$5.67^{+0.17}_{-0.18}$	$1.892(3)^{+2.7\%}_{-2.2\%}$	$\mathbf{5.68^{+0.18}_{-0.18}}$
LT	$5.344(7)^{+7.3\%}_{-5.9\%}$	$15.42^{+0.31}_{-0.30}$	$5.140(7)^{+7.3\%}_{-5.9\%}$	$15.43^{+0.31}_{-0.30}$
TL	$5.083(7)^{+7.4\%}_{-5.9\%}$	$14.67^{+0.30}_{-0.30}$	$4.888(6)^{+7.4\%}_{-6.0\%}$	$14.68^{+0.30}_{-0.31}$
TT	$22.04(3)^{+4.5\%}_{-3.6\%}$	$63.60^{+0.40}_{-0.45}$	$21.16(3)^{+4.6\%}_{-3.5\%}$	$63.55^{+0.51}_{-0.40}$
interference	0.223	0.64	0.217	0.64
		Boosted setup		
full off-shell	$0.452(5)^{+7.3\%}_{-5.6\%}$	103.56	$0.436(5)^{+7.7\%}_{-5.6\%}$	104.14
unpolarised	$0.437(5)^{+7.2\%}_{-5.5\%}$	100	$0.418(5)^{+7.3\%}_{-4.7\%}$	100
LL	$0.1031(7)^{+2.6\%}_{-1.7\%}$	$23.61^{+0.96}_{-1.02}$	$0.0993(7)^{+2.4\%}_{-1.8\%}$	$\mathbf{23.73^{+0.73}_{-1.08}}$
LT	$0.0223(6)^{+7.4\%}_{-5.7\%}$	$5.11^{+0.03}_{-0.03}$	$0.0214(5)^{+8.3\%}_{-6.0\%}$	$5.12^{+0.10}_{-0.07}$
TL	$0.0207(5)^{+6.7\%}_{-5.1\%}$	$4.75^{+0.02}_{-0.02}$	$0.0200(5)^{+6.3\%}_{-5.5\%}$	$4.77^{+0.11}_{-0.04}$
TT	$0.293(3)^{+8.4\%}_{-6.5\%}$	$66.98^{+0.73}_{-0.69}$	$0.281(3)^{+8.9\%}_{-6.4\%}$	$67.14^{+1.00}_{-1.22}$
interference	−0.002	−0.45	−0.003	−0.45

Powheg-Box-Res: differential results in WZ

Z-boson p_T, fiducial setup [ATLAS 2211.09435].



Powheg-Box-Res: comparison with ATLAS measurements

PS+hadr. results from POWHEG-BOX-RES [GP Zanderighi 2311.05220] compared with recent WZ [ATLAS 2211.09435] and ZZ [ATLAS 2310.04350] ATLAS analyses.

WZ analysis [ATLAS 2211.09435]

fraction	POWHEG-BOX-RES PS+hadr (our work)	MOCANLO TH1	POWHEG-BOX-V2 TH2 (reweighted)	measured
L L	$5.68^{+0.18}_{-0.18}$	5.7 ± 0.2	5.83 ± 0.12	7.2 ± 1.6
L T	$15.43^{+0.31}_{-0.30}$	15.5 ± 0.3	14.84 ± 0.22	11.9 ± 3.4
T L	$14.68^{+0.30}_{-0.31}$	14.7 ± 0.3	14.61 ± 0.22	15.2 ± 3.3
T T	$63.55^{+0.51}_{-0.40}$	63.5 ± 0.4	64.72 ± 0.26	66.0 ± 4.0

ZZ analysis [ATLAS 2310.04350]

fraction	POWHEG-BOX-RES PS+hadr (our work)	MOCANLO TH (QCD)	MOCANLO TH (QCD+EW+gg)	pre-fit	measured
L L	$5.84^{+0.03}_{-0.05}$	5.9	5.8	6.1 ± 0.4	7.1 ± 1.7
L T + T L	$25.41^{+0.08}_{-0.07}$	25.3	23.2	22.9 ± 0.9	22.8 ± 1.1
T T	$67.52^{+0.09}_{-0.13}$	67.4	69.8	69.9 ± 3.9	69.0 ± 2.7
interference	1.28	1.3	1.2	1.1 ± 0.1	1.1 ± 0.1

Summary (1)

Much effort invested in past few years:

- **automation** of MC simulations within the SM
- calculation of **higher-order** corrections
- study of **polarisation observables**

Started new efforts, recently:

- matching to **parton shower** and hadronisation
- **higher-order** predictions for **complicated processes**
- **public codes** to ease experimental effort
- polarisation observables with **SMEFT** effects
- usage of **ML techniques**
- interplay with **quantum entanglement**

Missing, but crucial:

- **common** recommendations and **Monte Carlo** comparisons
- **workforce** and **coordination** network

Summary (2)

Missing coordination network?

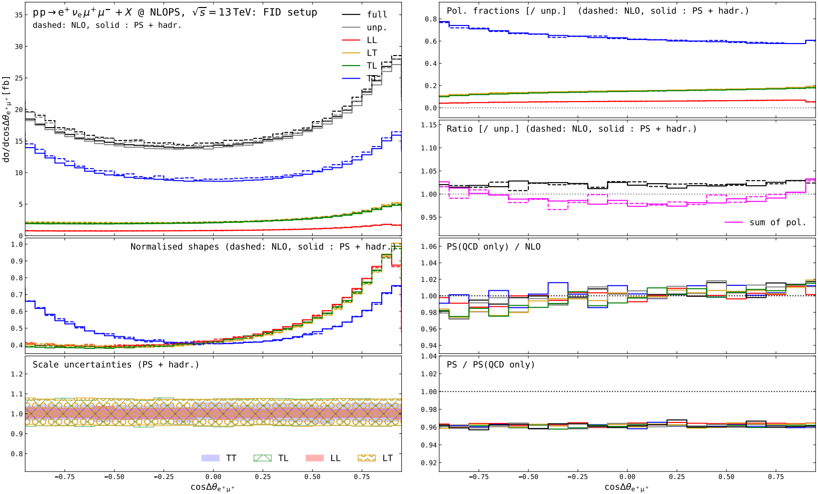
COmprehensive Multiboson Experiment-Theory Action

Info and registration at https://www.cost.eu/actions/CA22130/
TWiki at https://foswiki.web.cern.ch/COMETA/

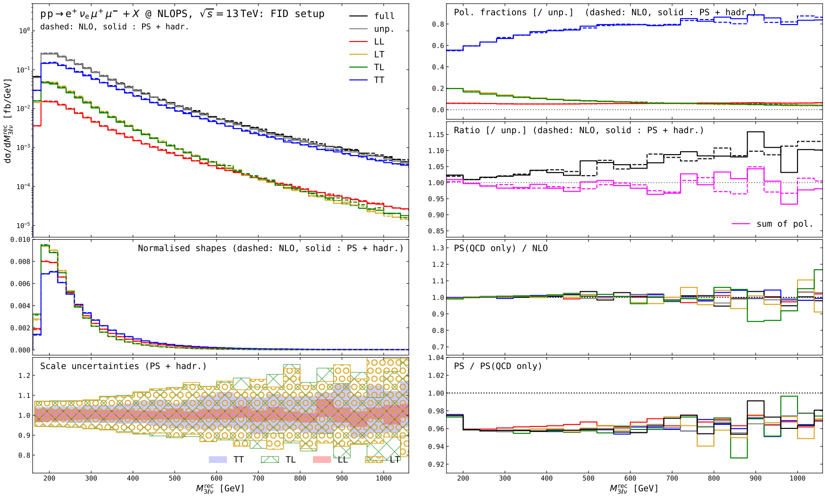
Polarisation of EW bosons is one main focus, activities have just started!

Backup

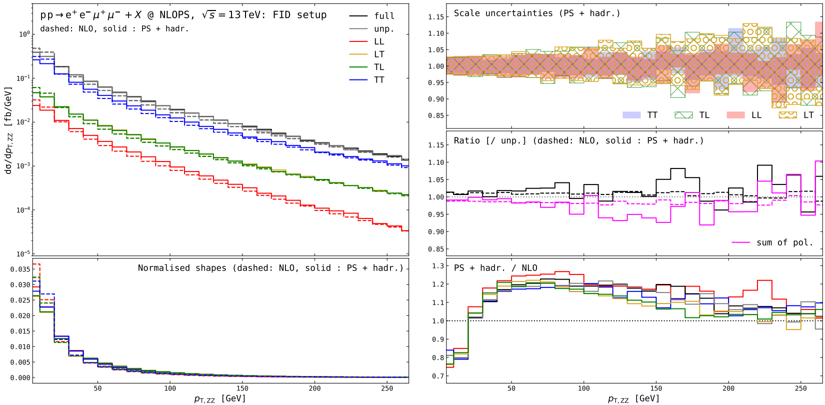
Differential results for WZ (1)



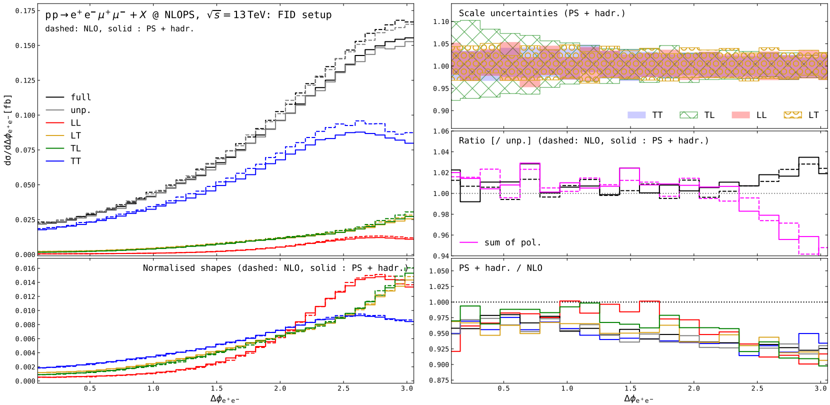
Differential results for WZ (2)



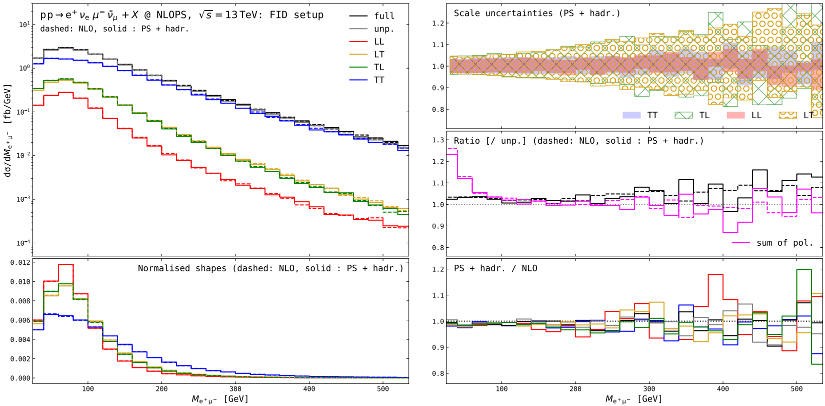
Differential results for ZZ (1)



Differential results for ZZ (2)



Differential results for WW (1)



Differential results for WW (2)