Theory and phenomenology of weak-boson polarisations at the LHC

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Motivations

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

$\longrightarrow$ precise measurements of multi-boson processes.

Polarisations of weak bosons

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

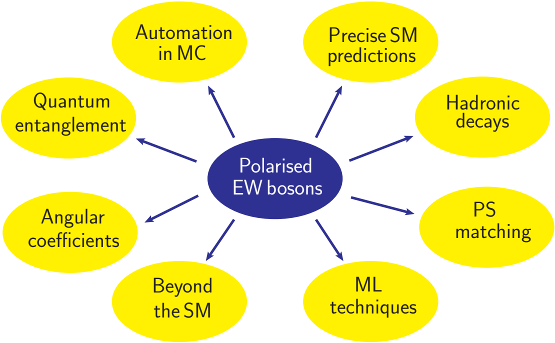
Special interest in di-boson: inclusive production and scattering.

What do we need?

We cannot directly measure polarisations of EW bosons.

We can perform fits of LHC data with polarised templates: inclusive WZ/ZZ [ATLAS 1902.05759, 2211.09435, 2310.04350, 2402.16365, CMS 2110.11231], ss W W scattering [CMS 2009.09429]

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



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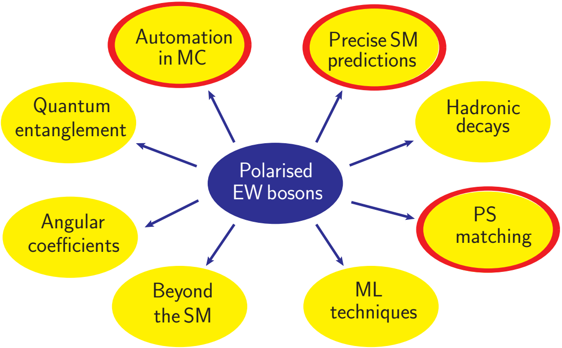
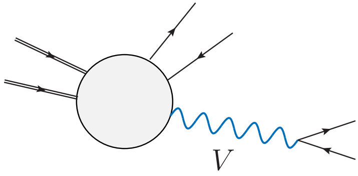


Separating polarisations in amplitudes

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



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

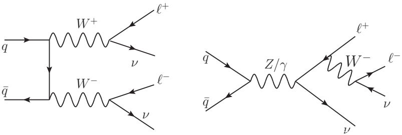
At the cross section level [Ballestrero et al. 1710.09339, Denner GP 2006.14867]:

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

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

Selecting resonant diagrams

To define polarisations, we need a factorised amplitude (production ⊗ propagator ⊗ decay): not possible for all contributions.



Double-resonant and non-double-resonant diagrams at LO: drop the latter, provide a recipe to recover gauge invariance.

Non-resonant diagrams regarded as non-resonant background.

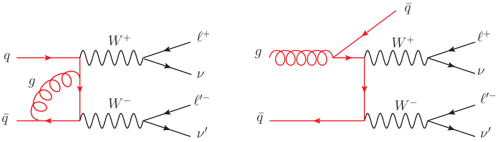
Resonant diagrams treated with

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

→ separating polarisations is then straightforward.

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]:

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

- 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. 1

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

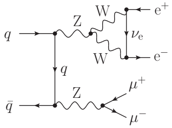
(N)NLO QCD corr. with leptonic decays [Denner GP 2006.14867, Poncelet Popescu 2102.13583].

Going beyond leading-order: NLO corrections to the decays

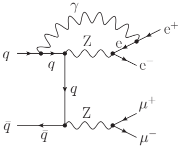
Corrections affect both production and decays of resonance(s).

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

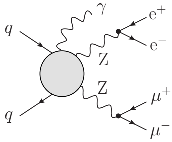
Factorisable



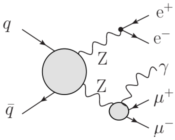
Non-factorisable



ISR



FSR



General method proposed to separate Z resonant contributions at NLO EW (QCD), with leptonic (hadronic) decays [Denner GP 2107.06579, Denner Haitz GP 2211.09040].

Extended to W's [Le Baglio 2203.01470, 2208.09232, Denner Haitz GP 2311.16031, Dao Le 2311.17027, 2409.06396]: photons radiated off the boson propagator at NLO EW.

First calculation of NLO EW+QCD corr. to polarised VBS [Denner Haitz GP 2409.03620].

Fixed-order results

Recent precise predictions in the SM:

→ $\mathrm{W}^+(\ell^+\nu_\ell)\,\mathrm{W}^-(\ell'^-\bar{\nu}_{\ell'})$: NLO QCD in DPA [Denner GP 2006.14867], NNLO QCD in DPA and NWA [Poncelet Popescu 2102.13583], NLO EW in DPA [Denner Haitz GP 2311.16031, Dao Le 2311.17027, 2409.06396] ;

→ $\mathrm{W}^\pm(\ell^\pm\nu_\ell)\,\mathrm{Z}(\ell'^+\ell'^-)$: NLO QCD [Denner GP 2010.07149] and NLO EW [Le Baglio 2203.01470, 2208.09232] in DPA;

→ $\mathrm{Z}(\ell^+\ell^-)\,\mathrm{Z}(\ell'^+\ell'^-)$: NLO EW + QCD in DPA [Denner GP 2107.06579];

→ $\mathrm{W}^\pm(\ell^\pm\nu_\ell)+\mathrm{j}$: NNLO QCD in NWA [Pellen et al. 2109.14336];

→ $\mathrm{W}^\pm(\mathrm{jets})\,\mathrm{Z}(\ell'^+\ell'^-)$: NLO QCD in DPA [Denner Haitz GP 2211.09040];

→ $\mathrm{W}^+(\ell^+\nu_\ell)\,\mathrm{W}^+(\ell'^+\nu_{\ell'})+\mathrm{jj}$: NLO EW + QCD in DPA [Denner Haitz GP 2409.03620].

Matching to parton shower

QCD PS effects do not factorise from spin structure of the EW system.

NLO QCD accuracy required.

MC codes simulating intermediate polarised bosons:

1. PHANTOM (v1.7): LO, 2 → 6 in 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 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 NWA, multi-jet merging and PS matching, UFO models for BSM/EFT [Hoppe et al. 2310.14803]
4. POWHEG-BOX-RES: NLO, diboson in DPA, PS matching [GP Zanderighi 2311.05220]
5. MG5_AMC@NLO: now possible to generate "polarised" Feynman rules with tailored UFO model for loop-induced [Javurkova et al. 2401.17365]

Effort needed to incorporate EW effects.

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Effort needed to incorporate EW effects.

Inclusive WZ at NLOPS: integrated results

Diboson implementation with DPA & VV-CM pol. frame [GP Zanderighi 2311.05220] in POWHEG-BOX-RES [Alioli et al. 1002.2581, Jezo Nason 1509.09071, Chiesa et al. 2005.12146]

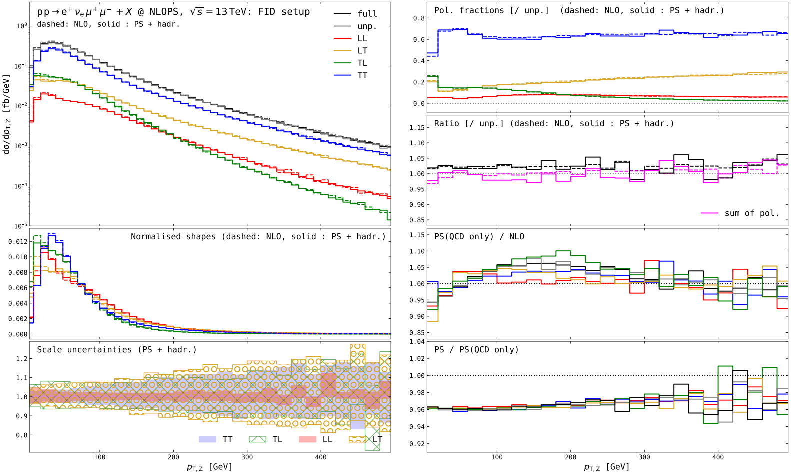
Fiducial setup [ATLAS 2211.09435] vs boosted setup ($p_{T,Z} > 200$GeV, $p_{T,WZ} < 70$GeV).

fiducial	σ[fb] LHE	ratio [/unp., %] LHE	σ[fb] PS+hadr	ratio [/unp., %] PS+hadr
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	σ[fb] LHE	ratio [/unp., %] LHE	σ[fb] PS+hadr	ratio [/unp., %] PS+hadr
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

Inclusive WZ at NLOPS: differential results

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



Inclusive WZ at NLOPS: comparison with ATLAS

Compared our best prediction (NLO QCD matched to PYTHIA8 QCD+QED PS & hadronisation) from POWHEG-BOX-RES [GP Zanderighi 2311.05220] with recent WZ [ATLAS 2211.09435] ATLAS analysis.

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

Remark: reweighting does not account for interference and non-resonant bkg's, and gives mis-modeling of some observables if not fully differential.

Where do we stand?

Growing interest in polarised templates for boson-pair processes (TH & EXP):

- fixed-order corrections in the Standard Model ✓ [(N)NLO QCD + NLO EW]
- matching to parton shower and hadronisation ✓ [NLO QCD × PS]
- recommendations for LHC community ✗

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COMETA COST Action

COmprehensive Multiboson Experiment-Theory Action

Info and registration https://www.cost.eu/actions/CA22130/
Official web-page https://cometa.web.cern.ch/
TWiki https://foswiki.web.cern.ch/COMETA/
Mattermost channel https://mattermost.web.cern.ch/cometa/

Polarisation of EW bosons is one main focus.

COMETA project on polarisation

Started in March 2024.

Aims: precise predictions for doubly polarised ZZ at the LHC (leptonic decays, ATLAS fiducial setup [ATLAS 2211.09435]).

Involved all MC tools available on the market and all experts in the field:

R. Covarelli, T.N. Dao, A. Denner, C. Haitz, M. Hoppe, M. Javurkova, D.N. Le, J. Linder, R.C. Lopes de Sa, O. Mattelaer, GP, R. Poncelet, R. Ruiz, M. Schönherr, F. Siegert, G. Zanderighi

MC code	OS approx.	LO tree	LO loop-ind.	NLO QCD	NNLO QCD	NLO EW	LO ×PS	NLO ×PS	multi-jet merging
MoCaNLO	DPA	✓	✓	✓	✗	✓	✗	✗	✗
STRIPPER	DPA	✓	✓	✓	✓	✗	✗	✗	✗
MulBos	DPA	✓	✓	✓	✗	✓	✗	✗	✗
BBMC	DPA	✓	✗	✓	✗	✓	✗	✗	✗
Sherpa	NWA	✓	✗	(✓)	✗	✗	✓	(✓)	✓
MadGraph	NWA	✓	✓	✗	✗	✗	✓	✗	✓
PowHeg-Box	DPA	✓	✗	✓	✗	✗	✓	✓	✗

Work in progress for numerical simulations and interpretation of the results.

Preliminary results: integrated cross sections at LO

Tree-level:

code	OS approx.	full	unpol.	LL	LT	TL	TT
MoCaNLO	DPA	11.336(1)	11.242(1)	0.6574(1)	1.3332(2)	1.3370(2)	7.7874(8)
STRIPPER	DPA	11.3357(4)	11.2451(2)	0.6560(0)	1.3326(0)	1.3365(0)	7.7925(1)
MulBos	DPA	—	11.2393(3)	0.6572(0)	1.3329(1)	1.3366(1)	7.7846(2)
BBMC	DPA	11.3372(4)	11.2424(3)	0.6574(0)	1.3333(1)	1.3372(1)	7.7872(2)
Sherpa	NWA	11.363(6)	11.513(4)	0.6767(4)	1.3538(6)	1.3734(6)	7.952(3)
MadGraph	NWA	11.38(2)	11.29(2)	0.660(1)	1.335(2)	1.338(2)	7.81(1)
PowHeg-Box	DPA	11.335(1)	11.245(1)	0.6575(1)	1.3333(1)	1.3374(1)	7.7885(8)

Loop-induced:

code	OS approx.	full	unpol.	LL	LT	TL	TT
MoCaNLO	DPA	1.6968(6)	1.6978(6)	0.0914(0)	0.0360(0)	0.0356(0)	1.5360(5)
STRIPPER	DPA	1.682(7)	1.700(2)	0.0912(1)	0.0360(0)	0.0357(0)	1.538(2)
MulBos	DPA	—	1.6981(9)	0.0913(1)	0.0360(0)	0.0357(0)	1.5363(8)
MadGraph	NWA	1.699(6)	1.697(6)	0.0902(3)	0.0355(1)	0.0359(1)	1.539(6)

Good agreement at LO . . .

Preliminary results: integrated cross sections at NLO

NLO QCD:

code	OS approx.	full	unpol.	LL	LT	TL	TT
MoCaNLO	DPA	15.282(1)	15.158(2)	0.8899(3)	1.9313(5)	1.9243(2)	10.2095(9)
STRIPPER	DPA	15.284(3)	15.159(1)	0.8899(1)	1.9305(1)	1.9241(1)	10.2098(7)
MulBos	DPA	—	15.1575(9)	0.88997(6)	1.9305(1)	1.9240(1)	10.2106(6)
BBMC	DPA	15.284(1)	15.158(1)	0.8898(1)	1.9306(2)	1.9240(2)	10.2085(7)
PowHeg-Box	DPA	15.280(2)	15.156(2)	0.8909(2)	1.9306(4)	1.9239(5)	10.206(1)
Sherpa	NWA	15.304(4)	15.441(5)	0.9266(5)	2.093(1)	2.041(1)	10.289(4)

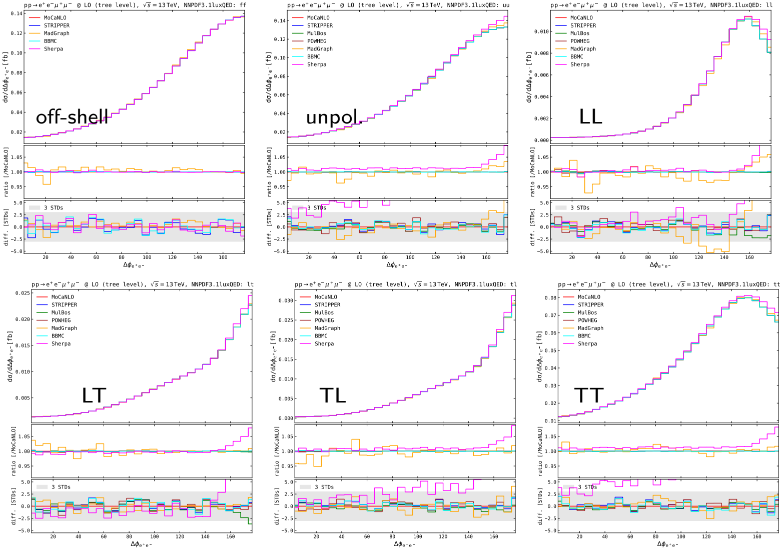
NLO EW:

code	OS approx.	full	unpol.	LL	LT	TL	TT
MoCaNLO	DPA	10.080(2)	10.0213(8)	0.59068(9)	1.1994(1)	1.20293(9)	6.9129(3)
MulBos	DPA	—	10.0203(3)	0.59058(2)	1.19926(4)	1.20294(4)	6.9121(3)
BBMC	DPA	10.082(2)	10.0203(4)	0.59057(4)	1.19949(6)	1.20308(9)	6.9125(3)

. . . and at NLO as well.

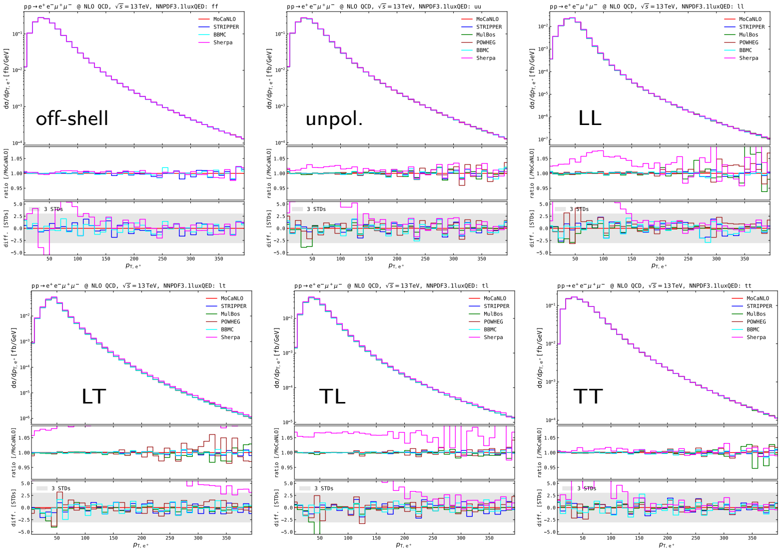
Preliminary results: differential cross sections at LO

Azimuthal separation e^+, e^-. Remark: correlated with $M_{e^+e^-}$ $\rightarrow$ DPA vs NWA.



Preliminary results: differential cross sections at NLO QCD

e^+ transverse momentum. Remark: SHERPA truncated shower after first emission.



Where do we stand?

- fixed-order corrections in the Standard Model ✓ [(N)NLO QCD + NLO EW]
- matching to parton shower and hadronisation ✓ [NLO QCD × PS]
- recommendations for LHC community ✗ → [COMETA work in progress]

Thank you!

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Thank you!

Backup

Selected results #1: W^+W^+ scattering at NLO EW+QCD

Most involved polarised NLO calculation so far [Denner Haitz GP 2409.03620].

$p\,p \to W^+(e^+\nu_e)\,W^+(\mu^+\nu_\mu)\,j\,j$, CMS setup [CMS 2009.09429], Run-3 energy.

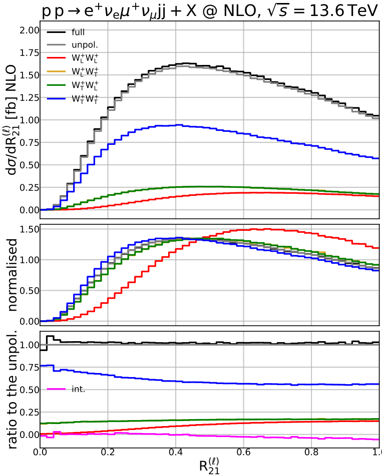
WW-CM definition of polarised states.

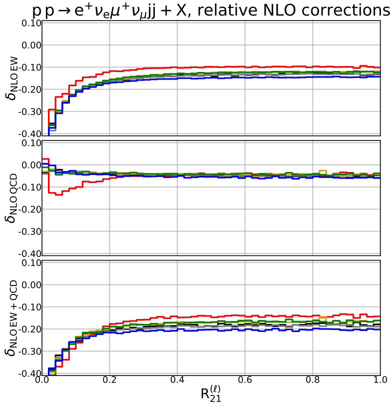
mode	$\sigma_{\rm LO}$ [fb]	$\delta_{\rm EW}$	$\delta_{\rm QCD}$	$\sigma_{\rm NLO\,EW+QCD}$ [fb]
full	$1.4863(1)^{+9.2\%}_{-7.8\%}$	-0.140	-0.047	$1.208(1)^{+1.6\%}_{-3.1\%}$
unp.	$1.46455(9)^{+9.2\%}_{-7.8\%}$	-0.142	-0.050	$1.1836(5)^{+1.7\%}_{-3.3\%}$
LL	$0.14879(1)^{+8.3\%}_{-7.2\%}$	-0.101	-0.044	$0.12715(8)^{+1.0\%}_{-2.1\%}$
LT	$0.23209(2)^{+9.1\%}_{-7.8\%}$	-0.131	-0.042	$0.1919(1)^{+1.4\%}_{-2.8\%}$
TL	$0.23208(2)^{+9.1\%}_{-7.8\%}$	-0.131	-0.042	$0.1918(1)^{+1.4\%}_{-2.8\%}$
TT	$0.87702(7)^{+9.4\%}_{-8.0\%}$	-0.154	-0.054	$0.6944(4)^{+1.9\%}_{-3.7\%}$
int.	$-0.0254(1)^{-8.9\%}_{+10.6\%}$	-0.139	-0.007	$-0.0217(7)^{-1.6\%}_{+0.7\%}$

- TT dominates ($\approx 60\%$), pol. fractions stable against radiative corr.
- large and different EW corr.: Casimirs for EW leading double-logs smaller for L
- small interferences and non-res. bkg (-1.8% and $+2\%$ resp.)
- small (and rather pol. independent) QCD corr.

Selected results #1: $W^+ W^+$ scattering at NLO EW+QCD

Distribution in the ratio between subleading- and leading-lepton p_T's.

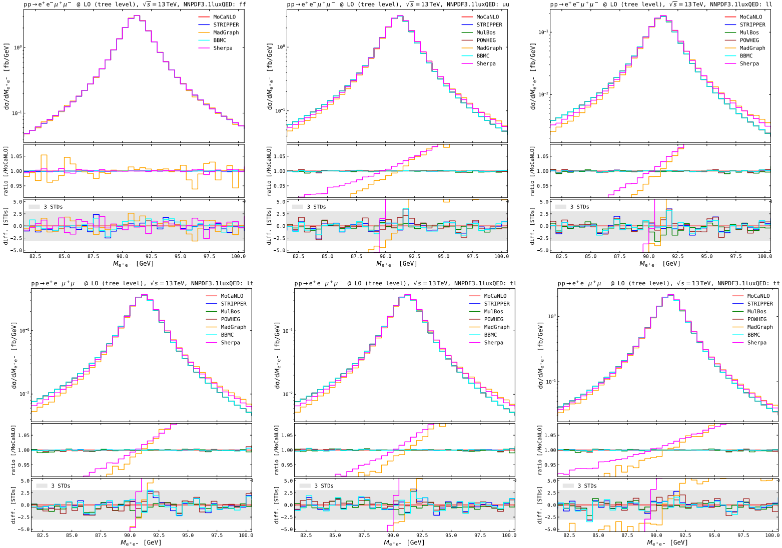




- LL mode favours more similar transverse momenta
- shape difference between LL and other modes: discrimination power
- differential relative NLO corr. driven by EW ones

Preliminary results: differential cross sections at LO

e^+e^- invariant-mass: DPA vs NWA.



Powheg-Box-Res implementation: technical details

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

$$\Phi_{4\ell} = \{x_1, x_2; k_{1\dots4}\} \quad \xrightarrow{\text{FKS}} \quad (\bar{\Phi}_{4\ell}, \Phi_{\text{rad}}) = \{\bar{x}_1, \bar{x}_2; \bar{k}_{1\dots4}, k_{\text{rad}}\} \xrightarrow{\text{DPA}}$$
$$\xrightarrow{\text{DPA}} \quad (\tilde{\bar{\Phi}}_{4\ell}, \Phi_{\text{rad}}) = \{\bar{x}_1, \bar{x}_2; \tilde{\bar{k}}_{1\dots4}, k_{\text{rad}}\}$$

POWHEG master formula (tailored to DPA):

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

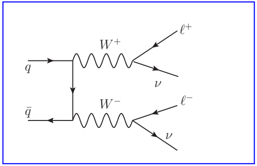
with NLO-accurate $\tilde{B}$ weight,

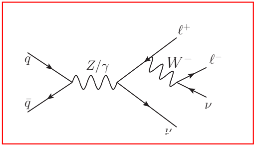
$$\tilde{\mathrm{B}}(\tilde{\Phi}_{4\ell}) = \mathrm{B}(\tilde{\Phi}_{4\ell}) + \mathrm{V}_{\text{reg}}(\tilde{\Phi}_{4\ell}) + \int \mathrm{d}\Phi_{\text{rad}} \left[\mathrm{R}(\tilde{\bar{\Phi}}_{4\ell}, \Phi_{\text{rad}}) - \mathrm{CT}(\tilde{\bar{\Phi}}_{4\ell}, \Phi_{\text{rad}}) \right]$$

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

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

DPA details





$$\mathcal{A}_{\text{full}}(x_1, x_2;\ k_{1\ldots4}) = \mathcal{A}_{\text{res}}(x_1, x_2;\ k_{1\ldots4}) + \mathcal{A}_{\text{nonres}}(x_1, x_2;\ k_{1\ldots4}) \longrightarrow \mathcal{A}_{\text{res}}(x_1, x_2;\ k_{1\ldots4})$$

$$\mathcal{A}_{\text{res}}(x_1, x_2;\ k_{1\ldots4}) \quad = \quad \mathcal{P}_{\mu\nu}(x_1, x_2;\ k_{12}, k_{34}) = \frac{-\mathrm{i}\, g^{\mu\alpha}}{k_{12}^2 - M_1^2 + \mathrm{i}\Gamma_1 M_1} \frac{-\mathrm{i}\, g^{\nu\beta}}{k_{34}^2 - M_2^2 + \mathrm{i}\Gamma_2 M_2} \mathcal{D}_\alpha(k_1, k_2)\, \mathcal{D}_\beta(k_3, k_4)$$

$$\mathcal{A}_{\text{res}}(x_1, x_2;\ k_{1\ldots4}) \quad \xrightarrow{\text{DPA}} \quad \mathcal{A}_{\text{res}}(x_1, x_2;\ \tilde{k}_{1\ldots4}) = \mathcal{P}_{\mu\nu}(x_1, x_2;\ \tilde{k}_{12}, \tilde{k}_{34})$$

$$\times \quad \frac{-\mathrm{i}\, g^{\mu\alpha}}{k_{12}^2 - M_1^2 + \mathrm{i}\Gamma_1 M_1} \frac{-\mathrm{i}\, g^{\nu\beta}}{k_{34}^2 - M_2^2 + \mathrm{i}\Gamma_2 M_2} \mathcal{D}_\alpha(\tilde{k}_1, \tilde{k}_2)\, \mathcal{D}_\beta(\tilde{k}_3, \tilde{k}_4)$$

On-shell mapping: $\Phi_4 = \{x_1, x_2; k_{1\ldots4}\} \xrightarrow{\text{DPA}} \tilde{\Phi}_4 = \{x_1, x_2; \tilde{k}_{1\ldots4}\}$

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 $(k_1 + k_2 + k_3 + k_4)^2 > (M_1 + M_2)^2$.

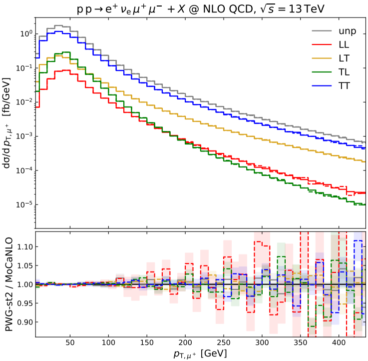
Polarisation selection: $-g_{\mu\nu} \longrightarrow \varepsilon_\mu^{(\lambda)}(k)\, \varepsilon_\nu^{(\lambda)\,*}(k)\,, \qquad \lambda = \mathrm{L}, +, -$

Powheg-Box-Res implementation: fixed-order validation

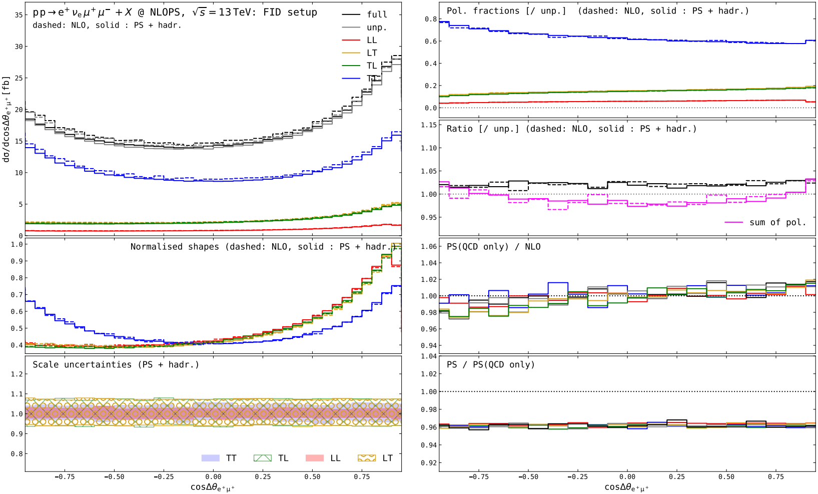
Implementation in POWHEG-BOX-RES code [Nason 0409146, Frixione et al. 0709.2092, Alioli et al. 1002.2581, Jezo Nason 1509.09071, Chiesa et al. 2005.12146] in the DPA [GP Zanderighi 2311.05220]
$\rightarrow$ polarisation defined in the VV-CM frame

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)

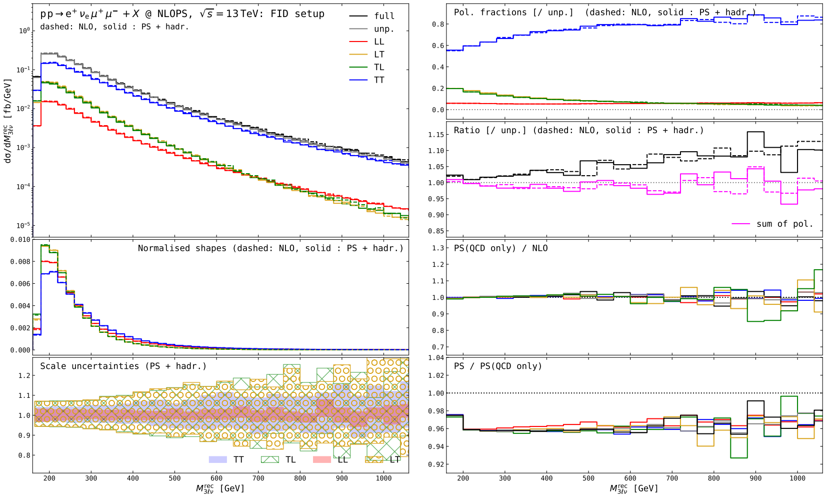
	POWHEG-BOX-RES	MOCANLO
$W^+_U W^-_U$	1249.8(9)	1249.2(6)
$W^+_L W^-_L$	65.92(9)	65.90(8)
$W^+_L W^-_T$	158.7(1)	158.60(7)
$W^+_T W^-_L$	162.97(9)	162.91(7)
$W^+_T W^-_T$	861.6(7)	860.1(5)
$W^+_U Z_U$	97.25(3)	97.19(3)
$W^+_L Z_L$	4.492(1)	4.496(2)
$W^+_L Z_T$	13.146(6)	13.132(4)
$W^+_T Z_L$	12.724(6)	12.716(4)
$W^+_T Z_T$	66.88(3)	66.84(3)
$Z_U Z_U$	28.22(1)	28.21(2)
$Z_L Z_L$	1.665(1)	1.664(2)
$Z_L Z_T$	3.550(3)	3.548(1)
$Z_T Z_L$	3.555(3)	3.548(2)
$Z_T Z_T$	19.44(1)	19.45(1)



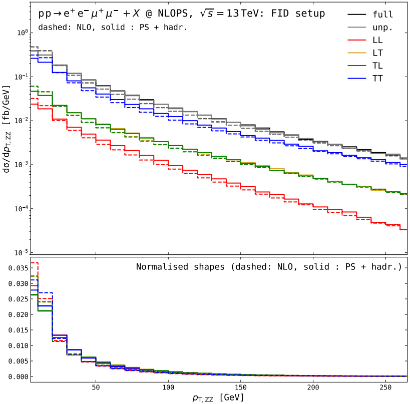
Differential results for WZ (1)

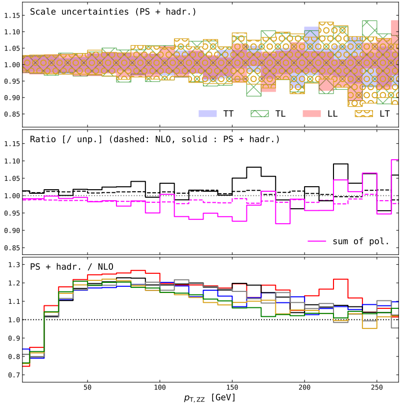


Differential results for WZ (2)

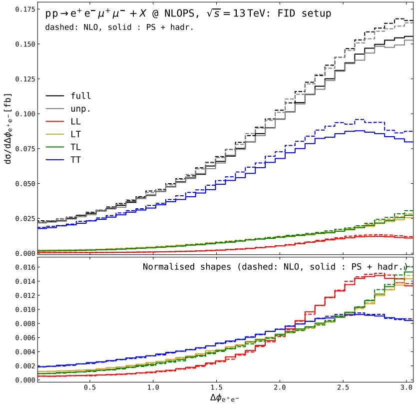


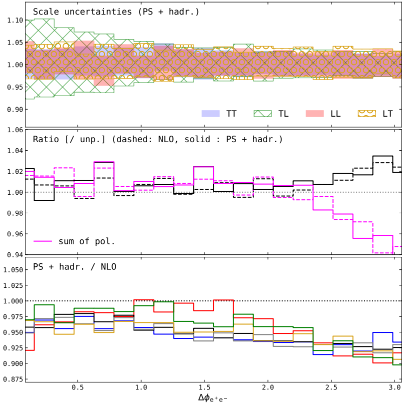
Differential results for ZZ (1)



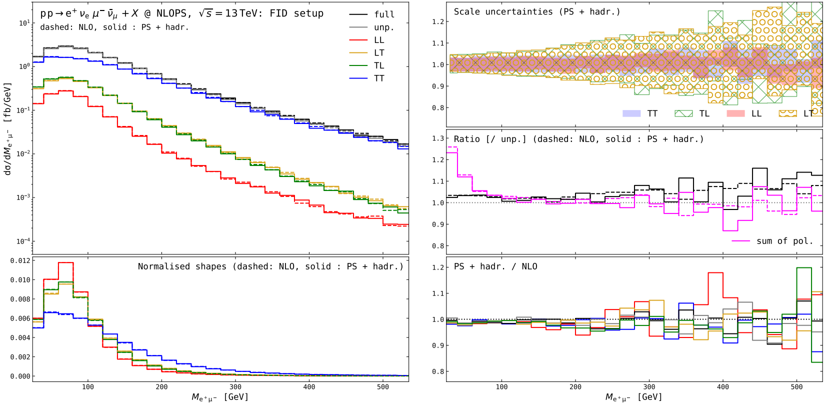


Differential results for ZZ (2)

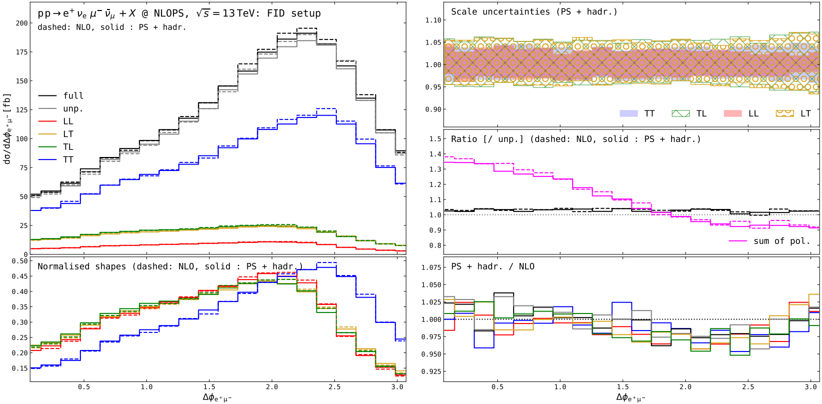




Differential results for WW (1)



Differential results for WW (2)



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.:

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

- 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. 2 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!