Precise and accurate predictions for polarised bosons 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.

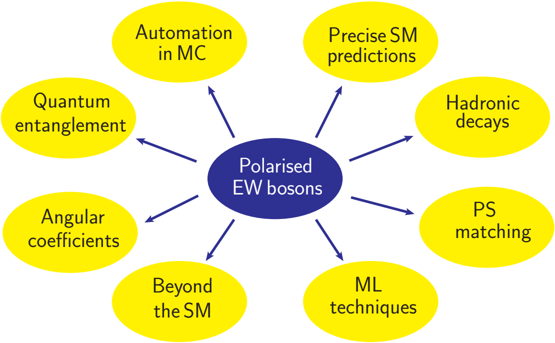
Special interest in di-boson: inclusive production and scattering.

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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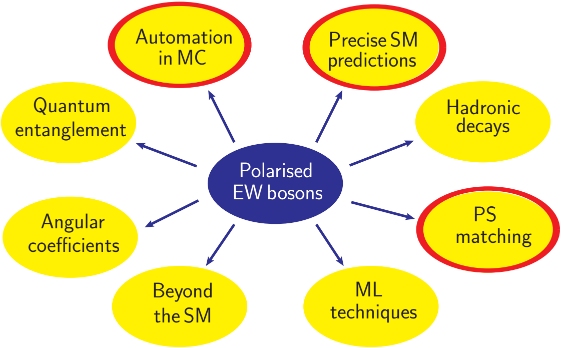
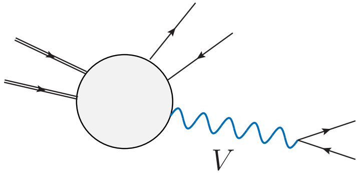


Separating polarisations in amplitudes

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



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

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

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

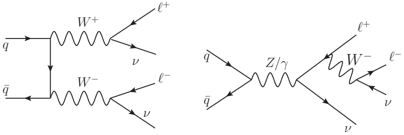
At the cross section level [Ballestrero et al. 1710.09339, Denner GP 2006.14867]:

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

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

Selecting resonant diagrams

To define polarisations, we need a factorised amplitude (production $\otimes$ propagator $\otimes$ 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.

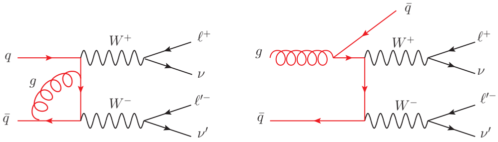
Resonant diagrams treated with

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

$\rightarrow$ 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]:

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

- 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.

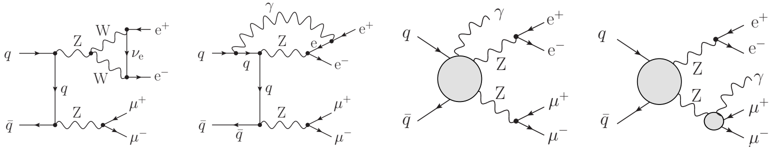
(N)NLO QCD corr. with leptonic decays [Denner GP 2006.14867, Poncelet Popescu 2102.13583].

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].
$\longrightarrow$ talk by Christoph

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, $2 \to 6$ 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.

Selected results #1: W^+W^- at NLO EW

Two independent calculations [Denner Haitz GP 2311.16031, Dao Le 2311.17027].

CMS setup [CMS 2009.00119], Run-3 energy, no jet veto.

state	σ_{LO} [fb]	$\sigma_{\text{NLO EW}}$ [fb]	δ_{EW}[%]	$f_{\text{NLO EW}}$[%]
		$b\bar{b}$, γb, $\gamma\bar{b}$ excluded		
full	254.79(2)	249.88(9)	-1.93	103.5
unp.	245.79(2)	241.48(2)	-1.75	100
LL	18.752(2)	18.510(2)	-1.30	7.7
LT	32.084(3)	32.043(3)	-0.13	13.3
TL	33.244(5)	33.155(5)	-0.27	13.7
TT	182.17(2)	177.83(2)	-2.38	73.6
int.	$-20.46(3)$	$-20.1(1)$	-1.96	-8.3
		$b\bar{b}$ included, γb, $\gamma\bar{b}$ excluded		
full	259.02(2)	253.95(9)	-1.96	103.4
unp.	249.97(2)	245.49(2)	-1.79	100.0
LL	21.007(2)	20.663(2)	-1.64	8.4
LT	33.190(3)	33.115(3)	-0.23	13.5
TL	34.352(5)	34.230(5)	-0.35	13.9
TT	182.56(2)	178.21(3)	-2.38	72.6
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		$b\bar{b}$, γb, $\gamma\bar{b}$ included		
full	259.02(2)	265.59(9)	$+2.54$	-

- TT dominates

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- different EW corr. for various pol. states (from −0.1% to −2.4%)

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- large interferences: $p_{\rm T}$ cuts + pure left-handed W coupling

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- small but non negligible off-shell effects

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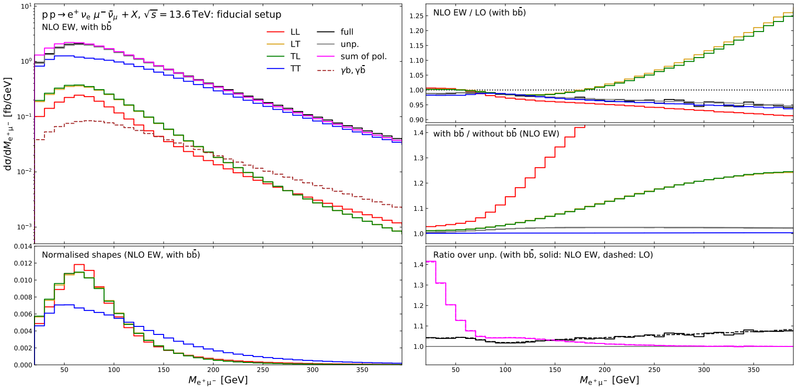
- sizeable change in LL fraction due to $b\bar{b}$

Selected results #1: W^+W^- at NLO EW

Distribution in the invariant mass of the lepton-pair system [Denner Haitz GP 2311.16031]



- EW-log enhancement for LL and TT at large invariant mass, positive EW corrections to mixed (LO suppression)
- TT dominates 2 orders of magnitude larger than LL at 400GeV
- increasing $b\bar{b}$ contribution to LL at large energies
- up to -40% interferences in low-mass region

Recently included NLO EW+QCD for b-induced channels in DPA [Dao Le 2409.06396]

Method to subtract the tW background and constrain the interference with WW.

ATLAS setup [ATLAS 1905.04242], Run-2 energy, no jet veto:

	$\sigma_{\rm NoB}$ [fb]	$\sigma_{\rm NoTW}$ [fb]	$\sigma_{\rm YesTW}$ [fb]	$K^{\rm LO}_{b\bar{b}}$	$K_{\rm NoTW}$	$K_{\rm YesTW}$	$\hat{\delta}_{\rm TW\text{-}int}$ [%]	$f_{\rm NoB}$ [%]	$f_{\rm NoTW}$ [%]	$f_{\rm YesTW}$ [%]
Unpol.	$327.94(4)^{+5.4\%}_{-4.2\%}$	$334.17(4)^{+5.4\%}_{-4.1\%}$	$620.13(4)^{+8.3\%}_{-6.5\%}$	1.01	1.02	1.89	0.62	100	100	100
$W^+_L W^-_L$	$18.68^{+4.1\%}_{-3.3\%}$	$21.04(1)^{+4.0\%}_{-2.9\%}$	$83.66(1)^{+9.9\%}_{-9.5\%}$	1.11	1.13	4.48	1.04	5.7	6.3	13.5
$W^+_L W^-_T$	$43.33^{+6.0\%}_{-4.9\%}$	$44.86(1)^{+6.1\%}_{-4.8\%}$	$110.18(1)^{+9.5\%}_{-8.1\%}$	1.02	1.04	2.54	1.12	13.2	13.4	17.8
$W^+_T W^-_L$	$44.22(1)^{+6.2\%}_{-4.9\%}$	$45.77(1)^{+6.2\%}_{-4.8\%}$	$111.06(1)^{+9.5\%}_{-8.1\%}$	1.02	1.03	2.51	1.12	13.5	13.7	17.9
$W^+_T W^-_T$	$221.43(3)^{+5.3\%}_{-4.1\%}$	$222.80(3)^{+5.3\%}_{-4.1\%}$	$321.82(3)^{+7.2\%}_{-5.6\%}$	1.00	1.01	1.45	0.43	67.5	66.7	51.9
Pol-int	0.28(5)	−0.30(5)	−6.60(5)	−−	−−	−−	−−	0.1	−0.1	−1.1

Selected results #3: WZ at NLOPS

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]

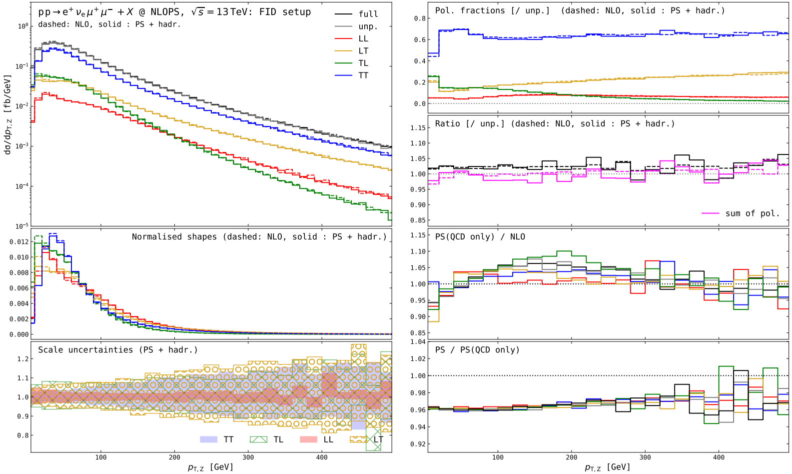
Fiducial setup [ATLAS 2211.09435] vs boosted setup ($p_{T,Z} > 200$GeV, $p_{T,WZ} < 70$GeV).

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

Selected results #3: WZ at NLOPS

Z-boson p_{T}, fiducial setup [ATLAS 2211.09435].



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 at precise predictions for doubly polarised ZZ at the LHC with leptonic decays.

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

code	OS approx.	LO	loop-ind.	NLOQCD	NNLOQCD	NLOEW	LOPS	NLOPS
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: fiducial 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: fiducial 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.

Highlights from the COMETA workshop on vector-boson polarisations

09:00	Welcome & Introduction	Giovanni Pelliccioli et al.	Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	09:00 - 09:20
	Polarisation measurements in ATLAS	Max Vincent Stange	Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	09:20 - 09:55
10:00	Polarisation measurements in CMS	Sergio Blanco Fernandez	Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	09:55 - 10:30
	Coffee break		Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	10:30 - 10:50
11:00	Machine-learning methods for polarisation tagging	Mathieu Pellen	Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	10:50 - 11:25
	Experimental perspectives for polarisation tagging	Antonio Giannini	Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	11:25 - 12:00
12:00	Lunch: Brasserie L'esplanade		Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	12:00 - 14:00
13:00				
14:00	Polarised calculations with MulBos	Duc Ninh Le	Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	14:00 - 14:30
	Polarised calculations with BBMC (and MoCaNLO)	Christoph Haitz	Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	14:30 - 15:00
15:00	Polarised calculations with STRIPPER	Rene Poncelet	Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	15:00 - 15:30
	Coffee break		Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	15:30 - 16:00
16:00	Polarised calculations with SHERPA	Diana Mareen Hoppe	Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	16:00 - 16:30
	Polarised calculations with POWHEG-BOX	Jakob Linder	Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	16:30 - 17:00
17:00	Polarization as a Feynman Rule	Richard Ruiz	Amphi 2, Maison de la Recherche et de la Valorisation, Toulouse (France)	17:00 - 17:30

- 2 days, ∼ 40 people
- talks on ATLAS&CMS results, ML/tagging techniques, MC development
- discussion session on current/future projects in COMETA
- hands-on tutorials of Sherpa, PowHeg-Box, MG5_aMC@NLO
- fruitful discussion, all aspects tackled, new ideas

Stay tuned for Grant-Period-2 activities (starting in mid-October)

Where do we stand?

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

Thank you!

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Thank you!

Backup

Powheg-Box-Res implementation: technical details

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

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

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

PowHeg master formula (tailored to DPA):

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

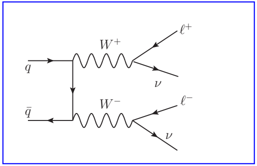
with NLO-accurate $\tilde{B}$ weight,

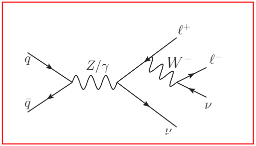
$$\tilde{\mathrm{B}}(\tilde{\Phi}_{4\ell}) = \mathrm{B}(\tilde{\Phi}_{4\ell}) + \mathrm{V}_{\rm reg}(\tilde{\Phi}_{4\ell}) + \int \mathrm{d}\Phi_{\rm rad} \left[\mathrm{R}(\tilde{\bar{\Phi}}_{4\ell}, \Phi_{\rm rad}) - \mathrm{CT}(\tilde{\bar{\Phi}}_{4\ell}, \Phi_{\rm rad}) \right]$$

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

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

DPA details





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

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

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

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

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

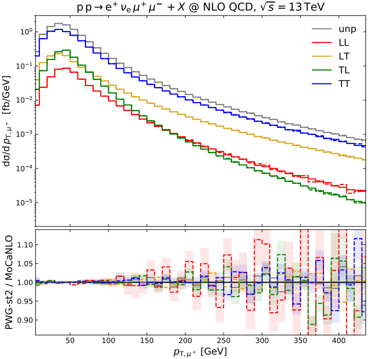
Polarisation selection: $-g_{\mu\nu} \longrightarrow \varepsilon_\mu^{(\lambda)}(k)\, \varepsilon_\nu^{(\lambda)\,*}(k)\,, \qquad \lambda = \mathrm{L}, +, -$

Powheg-Box-Res implementation: fixed-order validation

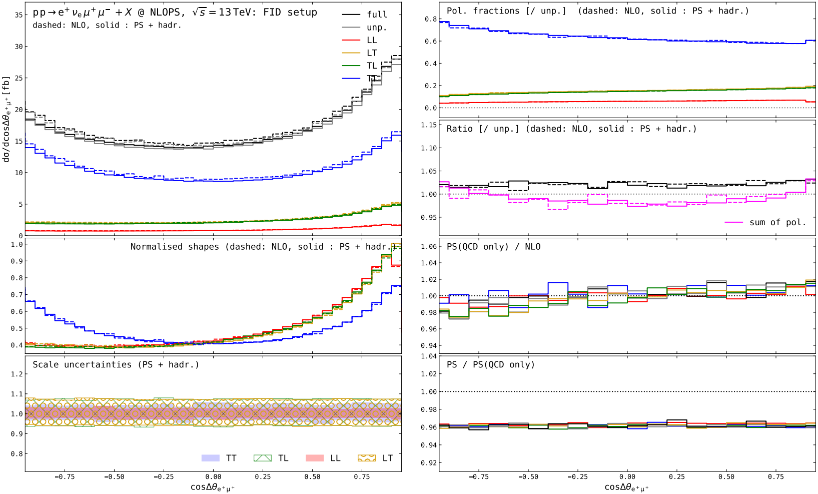
Implementation in Powheg-Box-Res code [Nason 0409146, Frixione et al. 0709.2092, Alioli et al. 1002.2581, Jezo Nason 1509.09071, Chiesa et al. 2005.12146] in the DPA [GP Zanderighi 2311.05220]
→ polarisation defined in the VV-CM frame

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)

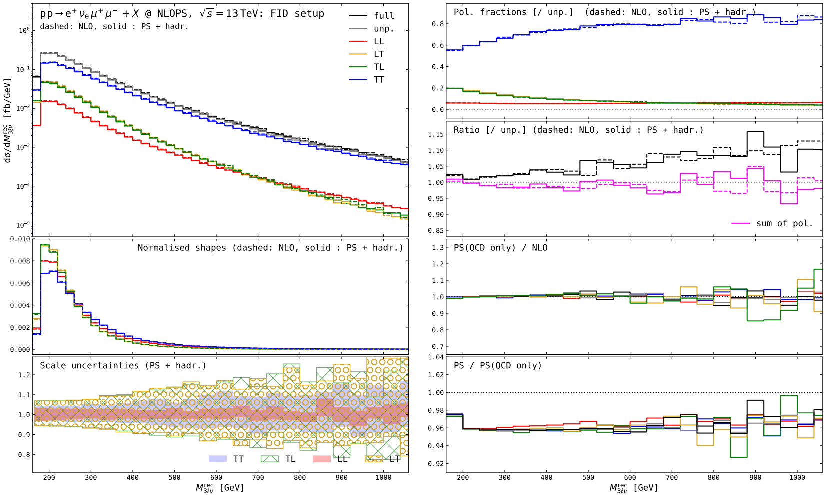
	Powheg-Box-Res	MoCaNLO
$\mathrm{W}^+_{\mathrm{U}}\mathrm{W}^-_{\mathrm{U}}$	1249.8(9)	1249.2(6)
$\mathrm{W}^+_{\mathrm{L}}\mathrm{W}^-_{\mathrm{L}}$	65.92(9)	65.90(8)
$\mathrm{W}^+_{\mathrm{L}}\mathrm{W}^-_{\mathrm{T}}$	158.7(1)	158.60(7)
$\mathrm{W}^+_{\mathrm{T}}\mathrm{W}^-_{\mathrm{L}}$	162.97(9)	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)



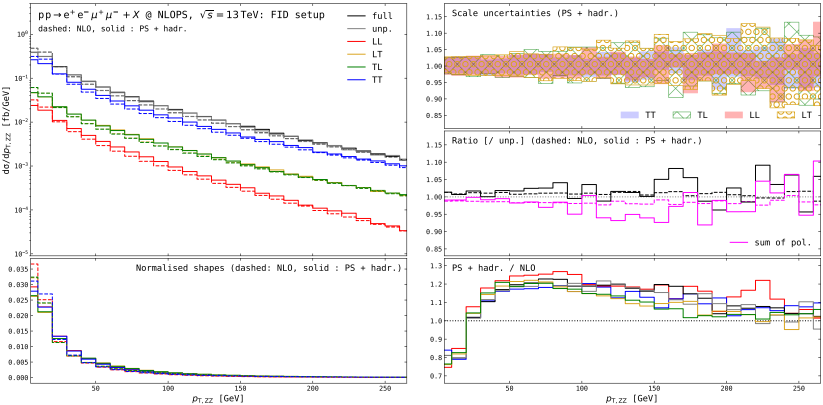
Differential results for WZ (1)



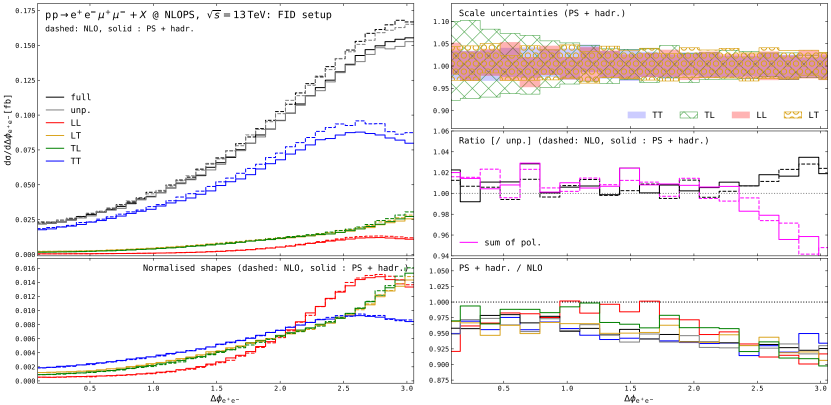
Differential results for WZ (2)



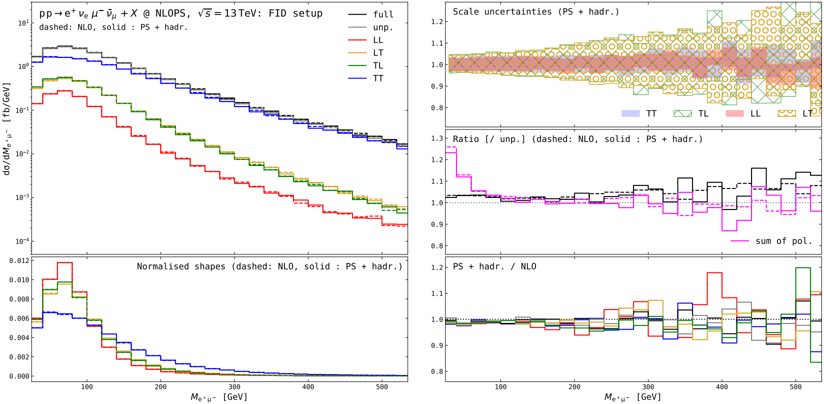
Differential results for ZZ (1)



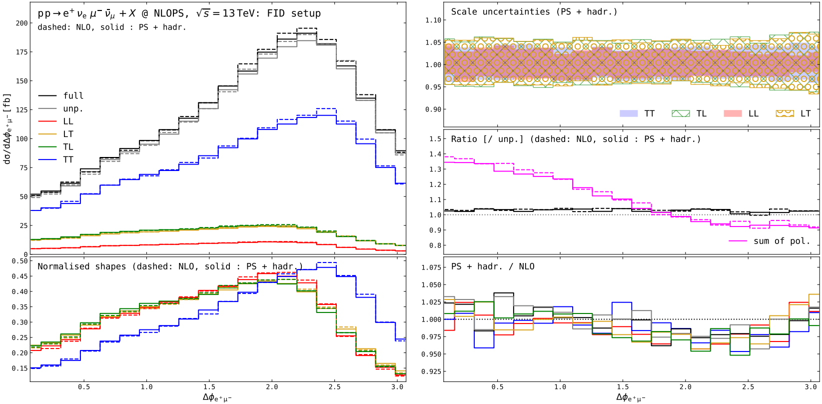
Differential results for ZZ (2)



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!