Polarised weak-bosons pairs at LHC: a view on the electroweak sector from every angle

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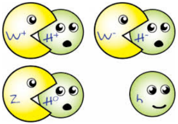
Introduction

Motivations (1)

Polarisations of weak bosons at the LHC:

- important probes of SM gauge and scalar sectors

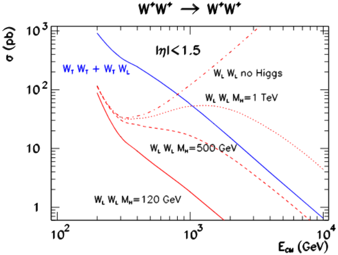


Quantum Diaries

Motivations (2)

Polarisations of weak bosons at the LHC:

- discrimination between BSM and SM



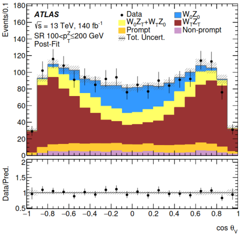
[Szleper 1412.8367]

Polarisations of weak bosons at the **LHC**:

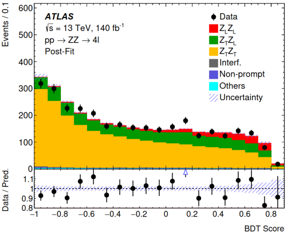
- non trivial to extract from data

Fits of LHC Run-2 data with **polarised templates**

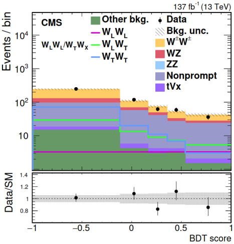
[ATLAS 1902.05759, 2211.09435, 2310.04350, 2402.16365, 2503.11317, CMS 2009.09429, 2110.11231]



WZ [ATLAS 2402.16365]

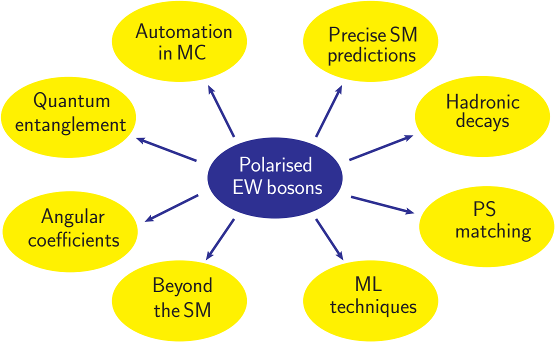


ZZ [ATLAS 2310.04350]

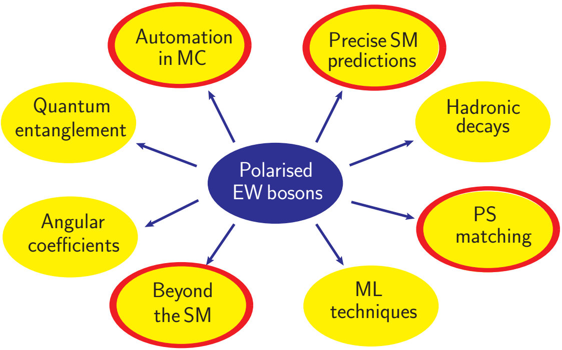


$W^{\pm}W^{\pm}jj$ [CMS 2009.09429]

What do we need (from theory)?



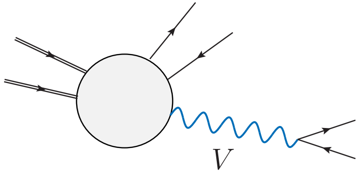
What do we need (from theory)?



Theory aspects: polarised templates

Separating polarisations in amplitudes

Natural definition for resonant diagrams (in PA/NWA) [Denner GP 2006.14867]



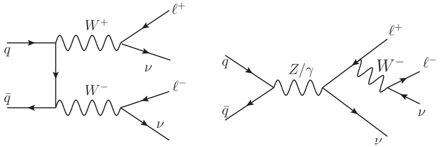
$$
\begin{aligned}
\mathcal{A}^{\text{unpol}} &= \mathcal{P}_\mu \, \frac{-g^{\mu\nu}}{k^2 - M_V^2 + iM_V\Gamma_V} \, \mathcal{D}_\nu \\
&= \mathcal{P}_\mu \, \frac{\sum_{\lambda'} \varepsilon^\mu_{\lambda'} \varepsilon^{*\nu}_{\lambda'}}{k^2 - M_V^2 + iM_V\Gamma_V} \, \mathcal{D}_\nu \\
&\longrightarrow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

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

Polarisation states defined in specific Lorentz frame

Selecting resonant diagrams

Factorised amplitude not possible for all contributions



(1) Non-resonant diagrams regarded as non-resonant background.

(2) Resonant diagrams treated with

DPA: double-pole approximation [Denner et al. 0006307]

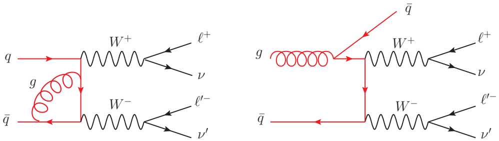
NWA: spin-correlated narrow-width approximation [Artoisenet et al. 1212.3460]

(3) Separate polarisations

Radiative corrections to the production

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

- Virtual (V) and real (R) contributions, $V + R$ free of IR singularities



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

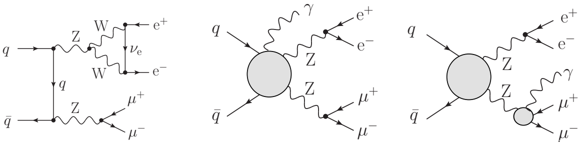
$$d\sigma_{\text{nlo}}/d\xi = \int d\phi_n (B + V + \int d\phi_{\text{rad}}\, D)_{d=4}\, \delta_\xi^{(n)} + \int d\phi_{n+1} (R\, \delta_\xi^{(n+1)} - D\, \delta_\xi^{(n)})_{d=4}$$

- DPA/NWA and separation of polarisations for all contributions

Radiative corrections to the decays

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

Factorisable ISR FSR



Z bosons [Denner GP 2107.06579, Denner Haitz GP 2211.09040]

W bosons [Le Baglio 2203.01470, Denner Haitz GP 2311.16031, 2409.03620, Dao Le 2311.17027]

Fixed-order SM predictions

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

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

→ $\mathrm{Z}(\ell^+\ell^-)\,\mathrm{Z}(\ell'^+\ell'^-)$: NNLO QCD + NLO EW [Denner GP 2107.06579, Carrivale GP et al. 2505.09686]

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

→ $\mathrm{W}^\pm(\mathrm{jj}/\mathrm{J})\,\mathrm{Z}(\ell'^+\ell'^-)$: NLO QCD [Denner Haitz GP 2211.09040]

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

Matching to parton shower

QCD PS does not factorise from spin of the EW system

At least NLO QCD accuracy required

Event generators for intermediate polarised bosons (matched to PS):

1. PHANTOM: LO [Ballestrero Maina GP 1710.09339, 1907.04722, 2007.07133, Maina GP 2105.07972]
2. MG5_AMC: LO [Buarque-Franzosi et al. 1912.01725], loop-ind. [Javurkova et al. 2401.17365] (also MJM)
3. SHERPA: approx. NLO [Hoppe et al. 2310.14803] (also MJM)
4. POWHEG-BOX-RES: NLO [GP Zanderighi 2311.05220, Haisch GP et al. 2507.21768]

Effort needed to incorporate EW effects

What about BSM effects?

Polarised signals with BSM effects:

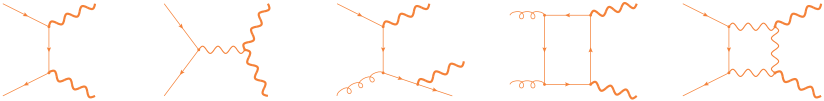
→ VBS: LO in HSESM with PHANTOM [Ballestrero Maina GP 1907.04722], in CH models with MADGRAPH5 [Buarque-Franzosi et al. 1912.01725]

→ inc. *VV*: NLO QCD + PS in SMEFT (dim. 6) with POWHEG-BOX-RES [Haisch GP et al. 2507.21768]

Inclusive di-boson production

[Carrivale GP et al. 2505.09686, Haisch Linder GP Re Zanderighi 2507.21768, GP Poncelet *to appear*]

General features



- Huge QCD corr. from large IR logs [Rubin et al. 1006.2144]
- Sizeable loop EW corr. in the tails from Sudakov logs [Denner Pozzorini 0010201]
- sensitive to anomalous TGC and Vff couplings [Azatov et al. 1707.08060, Baglio et al. 1708.03332, Panico et al. 1708.07823, . . .]
- interplay with top sector in gg $\rightarrow VV$ [Grazzini et al. 1811.09593, Rossia et al. 2306.09963, . . .]

ZZ (1): a community effort

Coordination within COMETA network [Carrivale GP et al. 2505.09686]

pp $\to$ $e^+e^-\mu^+\mu^-$ in ATLAS fiducial setup [ATLAS 2310.04350]

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

MC code	OS approx.	LO tree	LO loop-ind.	NLO QCD	NNLO QCD	NLO EW	LO ×PS	NLO ×PS	MJ merging
MoCaNLO	DPA	✓	✓	✓	✗	✓	✗	✗	✗
STRIPPER	DPA	✓	✓	✓	✓	✗	✗	✗	✗
MulBos	DPA	✓	✓	✓	✗	✓	✗	✗	✗
BBMC	DPA	✓	✗	✓	✗	✓	✗	✗	✗
Sherpa	NWA	✓	✗	(✓)	✗	✗	✓	(✓)	✓
MG5_aMC	BW	✓	✓	✗	✗	✗	✓	✗	✓
PowHeg-Box	DPA	✓	✗	✓	✗	✗	✓	✓	✗

ZZ (2): notation

Our best predictions:

$$\text{NNLO}^{\text{EW}}_{\text{QCD, gg}} \longrightarrow \sigma^{\text{LO}}_{q\bar{q}} \left(1 + \delta^{(\text{NLO})}_{\text{QCD}} + \delta^{(\text{NNLO})}_{\text{QCD}} + \delta^{(\text{NLO})}_{\text{EW}}\right) + \sigma^{\text{LO}}_{\text{gg}}$$

$$\text{NLOPS}_{\text{had}} \longrightarrow \text{NLO}_{\text{QCD}} \times \text{PS}_{\text{QCD,QED}} + (\text{hadr.}+\text{MPI})$$

$$\text{nLO-MJM}_{\text{had}} \longrightarrow (\text{nLO}^{(0\text{j})}_{\text{QCD}} + \text{nLO}^{(1\text{j})}_{\text{QCD}} + \text{LO}^{(2\text{j})}) + \text{PS}_{\text{QCD,QED}} + (\text{hadr.}+\text{MPI})$$

Pol. fraction = cross-sect. ratio, *e.g.* $f_{\text{L L}} = \sigma_{\text{L L}}/\sigma_{\text{unp}}$

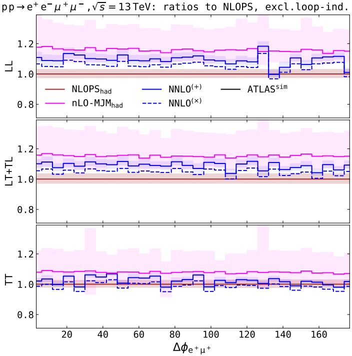
Comparison with pre/post-fit results by ATLAS [ATLAS 2310.04350]

ZZ (3): joint polarisation fractions

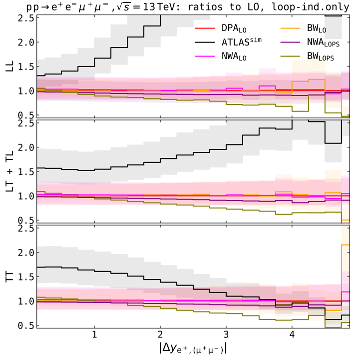
our predictions	LL [%]	LT [%]	TL [%]	TT [%]
$\mathrm{LO}_{q\bar{q}}$	$5.85^{+0.07}_{-0.08}$	$11.86^{+0.09}_{-0.11}$	$11.89^{+0.09}_{-0.11}$	$69.27^{+0.30}_{-0.26}$
$\mathrm{LO}_{\mathrm{gg}}$	$5.39^{+0.02}_{-0.02}$	$2.12^{+0.01}_{-0.01}$	$2.10^{+0.01}_{-0.01}$	$90.48^{+0.03}_{-0.03}$
$\mathrm{NLO}_{\mathrm{EW}}$	$5.89^{+0.06}_{-0.08}$	$11.97^{+0.09}_{-0.11}$	$12.01^{+0.09}_{-0.11}$	$68.98^{+0.29}_{-0.25}$
$\mathrm{NLO}_{\mathrm{QCD}}$	$5.87^{+0.03}_{-0.05}$	$12.74^{+0.07}_{-0.06}$	$12.69^{+0.07}_{-0.06}$	$67.35^{+0.14}_{-0.16}$
$\mathrm{NNLO}_{\mathrm{QCD}}$	$6.07^{+0.05}_{-0.04}$	$13.11^{+0.09}_{-0.08}$	$13.04^{+0.08}_{-0.07}$	$66.20^{+0.19}_{-0.24}$
$\mathrm{NNLO}_{\mathrm{QCD}}^{\mathrm{EW}}$	$6.12^{+0.06}_{-0.04}$	$13.29^{+0.09}_{-0.08}$	$13.21^{+0.08}_{-0.07}$	$65.75^{+0.20}_{-0.25}$
$\mathrm{NNLO}_{\mathrm{QCD,\,gg}}^{\mathrm{EW}}$	$6.05^{+0.03}_{-0.03}$	$12.15^{+0.10}_{-0.15}$	$12.07^{+0.11}_{-0.16}$	$68.29^{+0.30}_{-0.21}$
$\mathrm{NLOPS}_{\mathrm{QCD}}$	$5.88^{+0.03}_{-0.04}$	$12.76^{+0.08}_{-0.06}$	$12.71^{+0.07}_{-0.06}$	$67.30^{+0.13}_{-0.15}$
$\mathrm{nLOPS}_{\mathrm{QCD}}$	$6.02^{+0.05}_{-0.08}$	$13.04^{+0.04}_{-0.09}$	$12.97^{+0.04}_{-0.09}$	$66.61^{+0.14}_{-0.47}$
$\mathrm{NLOPS}_{\mathrm{had}}$	$5.86^{+0.03}_{-0.04}$	$12.74^{+0.08}_{-0.06}$	$12.69^{+0.07}_{-0.06}$	$67.38^{+0.13}_{-0.15}$
$\mathrm{nLOPS}_{\mathrm{had}}$	$5.98^{+0.03}_{-0.07}$	$12.99^{+0.02}_{-0.09}$	$12.96^{+0.02}_{-0.09}$	$66.70^{+0.22}_{-0.46}$
$\mathrm{LO\text{-}MJM}_{\mathrm{QCD}}$	$5.79^{+0.08}_{-0.09}$	$12.91^{+0.06}_{-0.05}$	$12.84^{+0.06}_{-0.06}$	$66.81^{+0.24}_{-0.22}$
$\mathrm{LO\text{-}MJM}_{\mathrm{had}}$	$5.91^{+0.01}_{-0.10}$	$12.84^{+0.13}_{-0.23}$	$12.79^{+0.12}_{-0.23}$	$67.14^{+1.08}_{-0.98}$
$\mathrm{nLO\text{-}MJM}_{\mathrm{had}}$	$6.14^{+0.12}_{-0.11}$	$13.35^{+0.47}_{-0.32}$	$13.23^{+0.32}_{-0.28}$	$65.85^{+1.11}_{-0.96}$
ATLAS measurement				
pre-fit	6.1 ± 0.4	22.9 ± 0.9		69.9 ± 3.9
post-fit	7.1 ± 1.7	22.8 ± 1.1		69.0 ± 2.7

ZZ (4): comparison with ATLAS

Best predictions [Carrivale GP et al. 2505.09686] vs ATLAS modelling [ATLAS 2310.04350]:



(qq) agreement, small QCD unc.



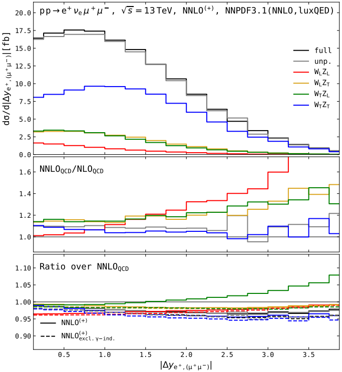
(gg) NLO QCD urgent

WZ (1)

$pp \to e^+\nu_e\mu^+\mu^-$ in ATLAS fiducial setup [2211.09435]

Improved SM pred., NNLO QCD $+/\times$ NLO EW [GP Poncelet to appear], and QCD-scale unc. on joint fractions via TNP approach [Lim Poncelet 2412.14910]

state	$f^{(+)}_{\mathrm{NLO}}$ [%]	$f^{(+)}_{\mathrm{NNLO}}$ [%]
LL	$5.66^{+0.17(+0.34)}_{-0.18(-0.28)}$	$5.63^{+0.04(+0.19)}_{-0.02(-0.16)}$
LT	$15.59^{+0.30(+1.42)}_{-0.29(-1.15)}$	$16.65^{+0.26(+0.81)}_{-0.22(-0.68)}$
TL	$15.01^{+0.28(+1.37)}_{-0.28(-1.10)}$	$16.03^{+0.21(+0.75)}_{-0.19(-0.63)}$
TT	$63.11^{+0.39(+4.48)}_{-0.44(-3.60)}$	$61.07^{+0.45(+1.84)}_{-0.57(-1.64)}$



SMEFT (1)

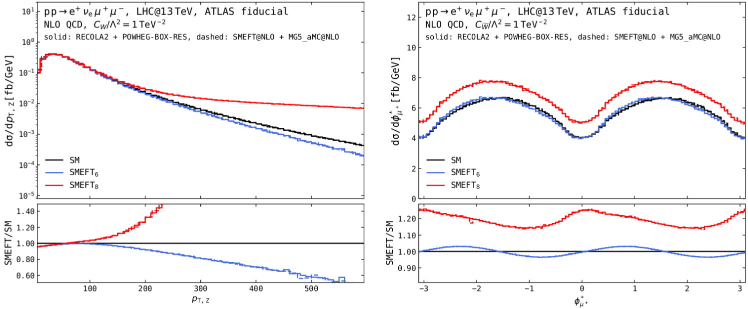
First SMEFT study with polarised-boson signals [Haisch GP et al. 2507.21768].

- automation in DPA based on SM package [GP Zanderighi 2311.05220] in POWHEG-BOX-RES [Alioli et al. 1002.2581, Jezo Nason 1509.09071, Chiesa et al. 2005.12146]
- pol. selection enabled in RECOLA 2 lib. [Denner Lang Uccirati 1711.07388]
- aTGC operators in Warsaw (new UFO) and HISZ basis [Chiesa Denner Lang 1804.01477]

$$
\begin{aligned}
Q_{HB} &= H^\dagger H\, B_{\mu\nu} B^{\mu\nu}\,, & Q_{H\widetilde{B}} &= H^\dagger H\, B_{\mu\nu} \widetilde{B}^{\mu\nu}\,,\\
Q_{HW} &= H^\dagger H\, W^i_{\mu\nu} W^{i,\mu\nu}\,, & Q_{H\widetilde{W}} &= H^\dagger H\, W^i_{\mu\nu} \widetilde{W}^{i,\mu\nu}\,,\\
Q_{HWB} &= H^\dagger \sigma^i H\, W^i_{\mu\nu} B^{\mu\nu}\,, & Q_{H\widetilde{W}B} &= H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B^{\mu\nu}\,,\\
Q_W &= \epsilon_{ijk}\, W^{i,\nu}_{\mu} W^{j,\lambda}_{\nu} W^{k,\mu}_{\lambda}\,, & Q_{\widetilde{W}} &= \epsilon_{ijk}\, W^{i,\nu}_{\mu} W^{j,\lambda}_{\nu} \widetilde{W}^{k,\mu}_{\lambda}\,.
\end{aligned}
$$

SMEFT (2)

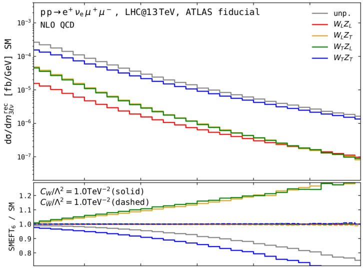
Validation at f.o. (NLO QCD) with updated SMEFT@NLO [El Faham GP Vryonidou 2405.19083] and SM_ATGC [Chiesa Denner Lang 1804.01477] UFOs

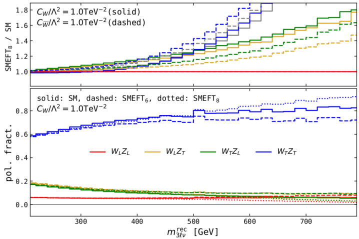


SMEFT (3)

Pheno. for $C_W, C_{\widetilde{W}} = 1\text{TeV}^{-2}$, $C_{H\widetilde{W}B} = 0.01\text{TeV}^{-2}$: large effects on T modes

σ [fb], ATLAS fiducial [2211.09435]					
contribution	unpolarized	$W_L Z_L$	$W_L Z_T$	$W_T Z_L$	$W_T Z_T$
SM	34.64(2)	1.968(1)	5.357(2)	5.100(2)	21.99(2)
Q_W (lin.)	$-0.975(1)$	0	0.1229(3)	0.1435(3)	$-1.264(1)$
Q_W (quad.)	6.299(2)	0	0.0803(0)	0.1001(0)	6.110(2)
$Q_{\widetilde{W}}$ (lin.)	$-0.013(1)$	0	$-0.0039(1)$	0.0056(1)	0.0102(9)
$Q_{\widetilde{W}}$ (quad.)	6.443(2)	0	0.1312(1)	0.1661(1)	6.132(2)

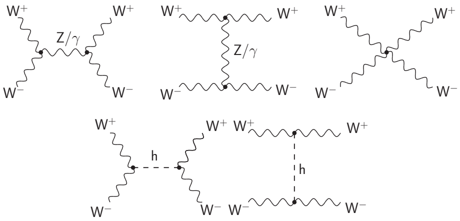




Vector-boson scattering

[Denner Haitz GP 2409.03620, Denner Franken Haitz Lombardi GP *to appear*]

General features



- Sensitive to gauge-Higgs unitarity cancellations
- Large loop EW corr. from EW Sudakov logs [Denner Pozzorini 0010201, Biedermann et al. 1611.02951]
- Sensitive to anomalous TGC, QGC and hVV couplings [Ethier et al. 2101.03180, Bellan et al. 2108.03199, . . .]
- Overlap with Higgs-strahlung and triple-boson [Denner et al. 2406.12301, Denner Haitz GP 2409.03620, . . .]

W^+W^+ (1)

$p\,p \to W^+(e^+\nu_e)\,W^+(\mu^+\nu_\mu)\,j\,j$ [Denner Haitz GP 2409.03620] @ NLO EW + QCD

CMS setup [CMS 2009.09429], Run-3 energy, WW-CM def. of polarised states

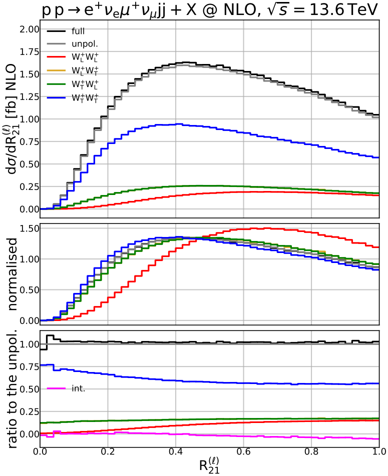
mode	$\sigma_{\rm LO}$ [fb]	$\delta_{\rm EW}$	$\delta_{\rm QCD}$	$\sigma_{\rm NLO\,EW+QCD}$ [fb]
full	$1.4863(1)^{+9.2\%}_{-7.8\%}$	-0.140	-0.047	$1.208(1)^{+1.6\%}_{-3.1\%}$
unp.	$1.46455(9)^{+9.2\%}_{-7.8\%}$	-0.142	-0.050	$1.1836(5)^{+1.7\%}_{-3.3\%}$
LL	$0.14879(1)^{+8.3\%}_{-7.2\%}$	-0.101	-0.044	$0.12715(8)^{+1.0\%}_{-2.1\%}$
LT,TL	$0.23209(2)^{+9.1\%}_{-7.8\%}$	-0.131	-0.042	$0.1919(1)^{+1.4\%}_{-2.8\%}$
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	$-0.0217(7)^{-1.6\%}_{+0.7\%}$

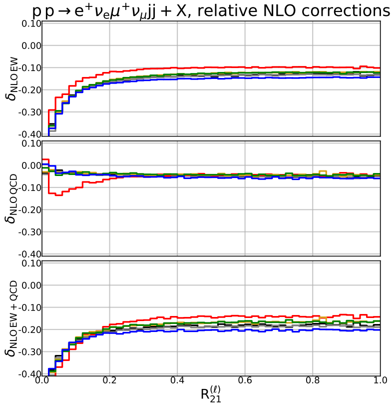
NLO pol. fractions similar to LO

LL: 11%, LT+TL: 32%, TT: 59%, int: −2%, non-res: 2%

$W^+ W^+$ (2)

Ratio between subleading- and leading-lepton p_T's.





WZ (1)

$\mathrm{p\,p} \to \mathrm{W}^+(\mathrm{e}^+\nu_\mathrm{e})\,\mathrm{Z}(\mu^+\mu^-)\,\mathrm{j\,j}$ [Denner Haitz Franken Lombardi GP to appear] @ NLO EW

ATLAS fid. setup [ATLAS 2403.15296], Run-3 energy, WZ-CM pol. def.

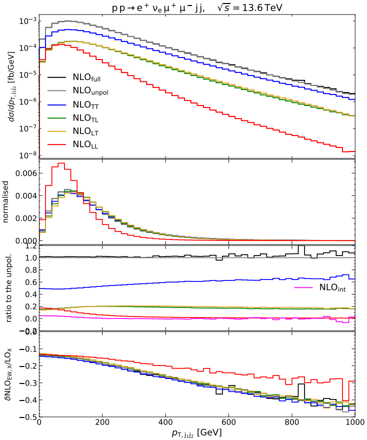
mode	σ_{LO} [fb]	δ_{EW} [%]	σ_{NLOEW} [fb]	f_{LO} [%]	f_{NLOEW} [%]
off-sh.	0.2723(1)	−18.7	0.2215(2)	101.7	101.4
unp.	0.26779(1)	−18.4	0.21838(4)	100.0	100.0
LL	0.023045(2)	−14.4	0.019697(5)	8.6	9.0
LT+TL	0.098391(6)	−17.9	0.08076(2)	36.7	37.0
TT	0.141723(9)	−19.6	0.11394(3)	52.9	52.2
int.	0.00463(2)	−13.9	0.00398(4)	1.7	1.7

Even larger EW corr. (−20% for TT) than in $\mathrm{W}^\pm\,\mathrm{W}^\pm$.

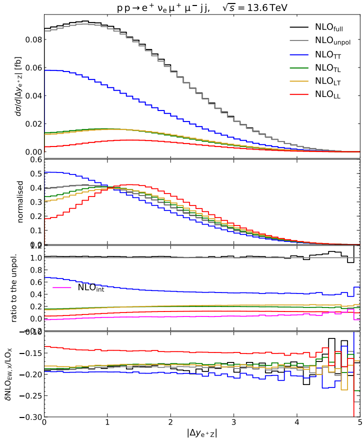
New: fudge factors to regulate un-subtractions in $\mathrm{WZ}V$ topologies.

WZ (2)

p_{T} of the di-jet system



rapidity sep. between ℓ_{W} and Z



Conclusions

Conclusions

Where do we stand?

- fixed-order in the SM ✓ [(N)NLO QCD + NLO EW]
- MC-tool comparison & LHC recommendations ✓ [ZZ]
- matching to PS / merging ✓ [NLO QCD × PS & MJM]
- SMEFT studies ✓ [NLO QCD × PS]

What is next?

- N(N)LOPS automation
- beyond SM with UV matching
- ML / polarisation tagging