Charting the spin structure of WZ events at the LHC in and beyond the Standard Model

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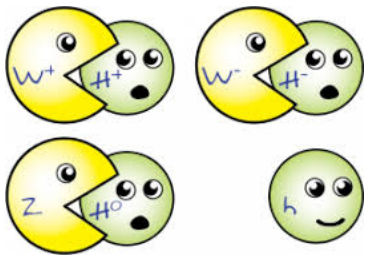
Introduction

Motivations (1)

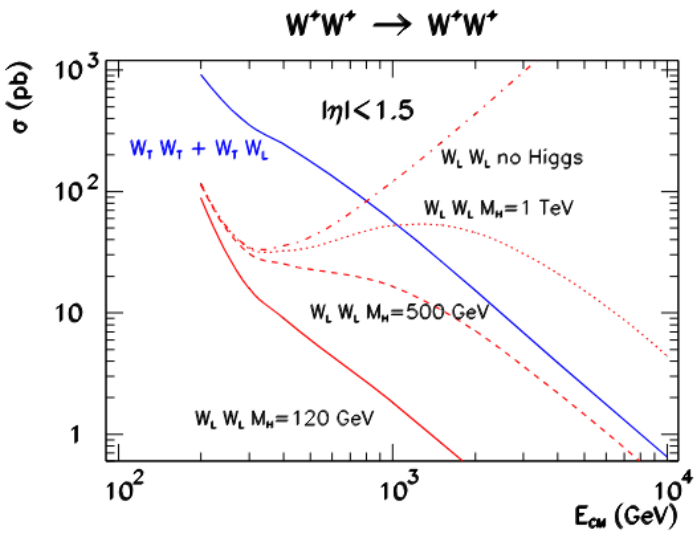
Polarisations of weak bosons at the LHC:

- important probes of SM gauge and scalar sectors



[Quantum Diaries]

- discrimination between BSM and SM



[Szleper 1412.8367]

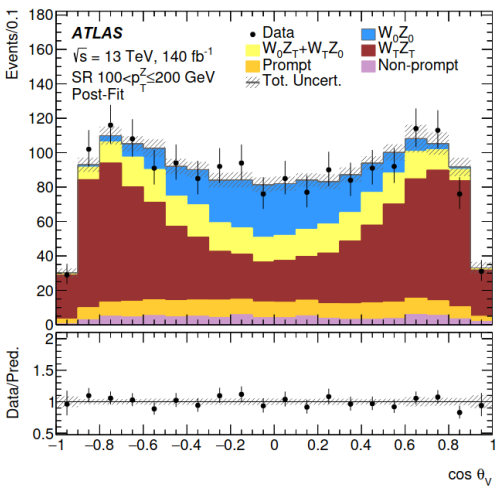
Motivations (2)

Polarisations of weak bosons at the LHC:

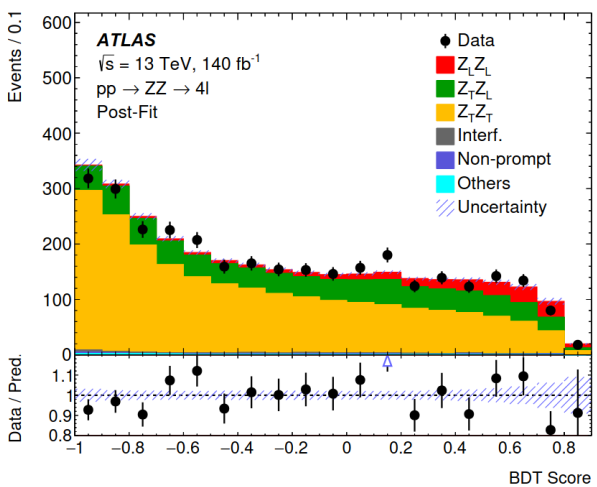
- non trivial to extract from data

Fits of LHC Run-2 data with polarised templates

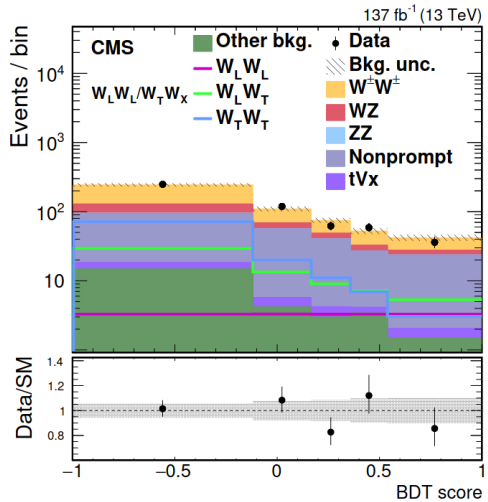
[ATLAS 1902.05759, 2211.09435, 2310.04350, 2402.16365, 2503.11317, CMS 2009.09429, 2110.11231]



WZ [ATLAS 2402.16365]

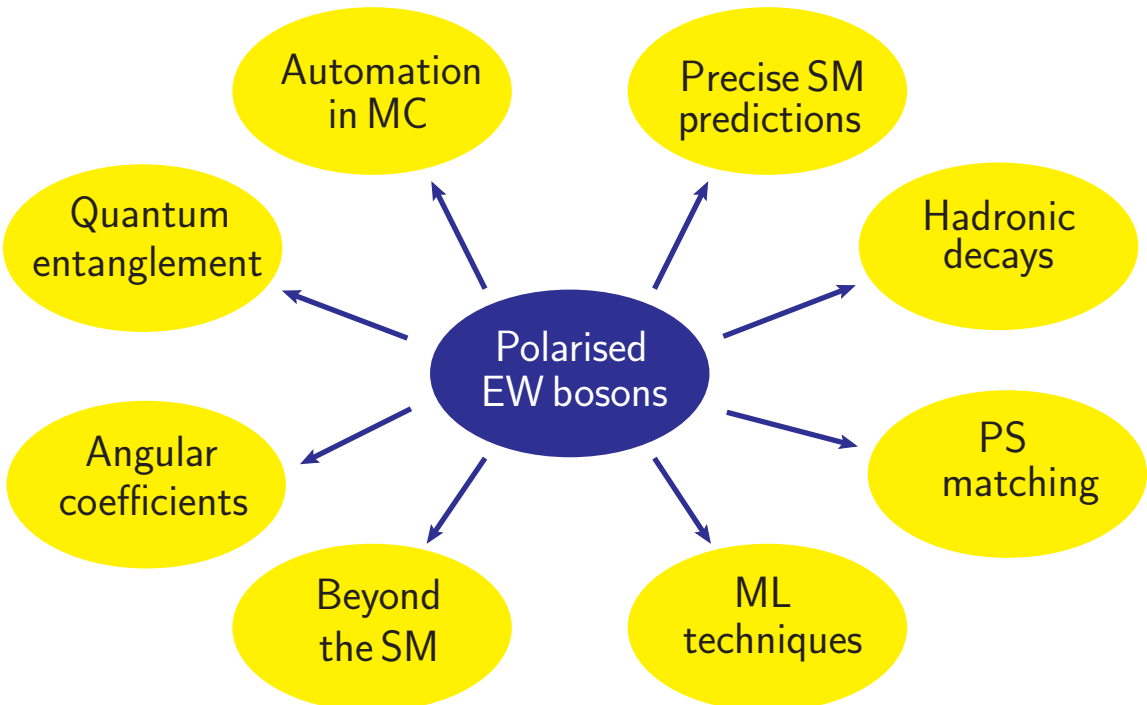


ZZ [ATLAS 2310.04350]

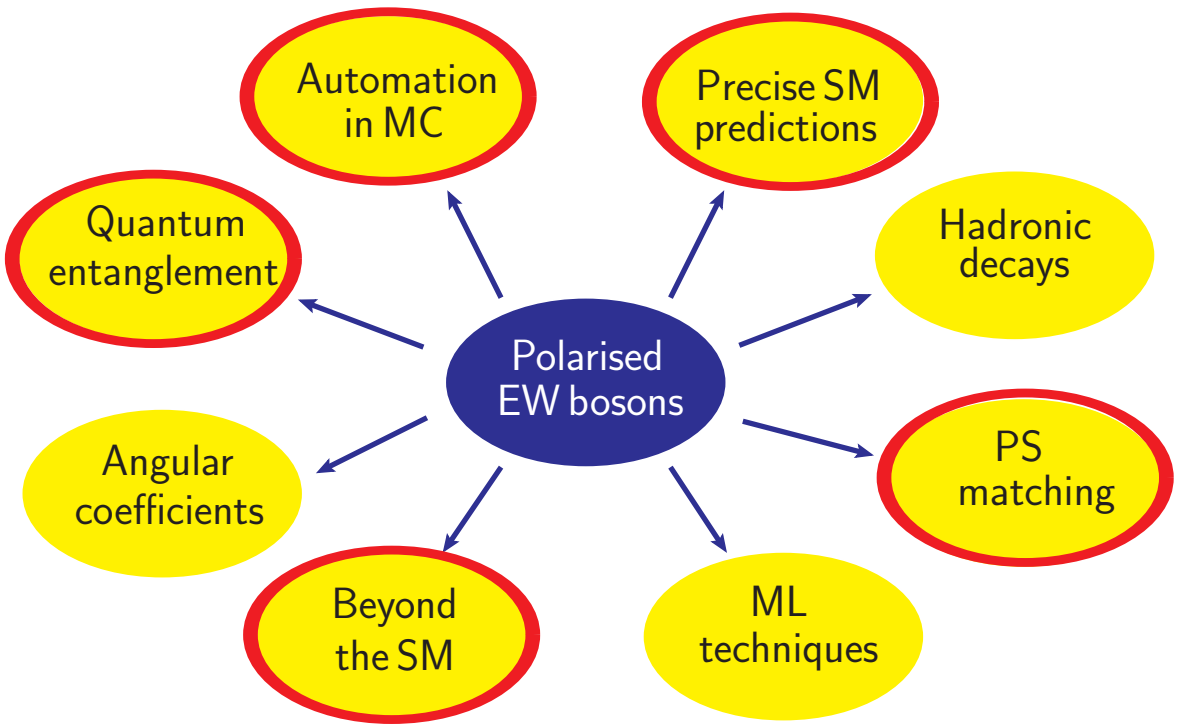


$W^{\pm}W^{\pm}jj$ [CMS 2009.09429]

What do we need (from theory)?



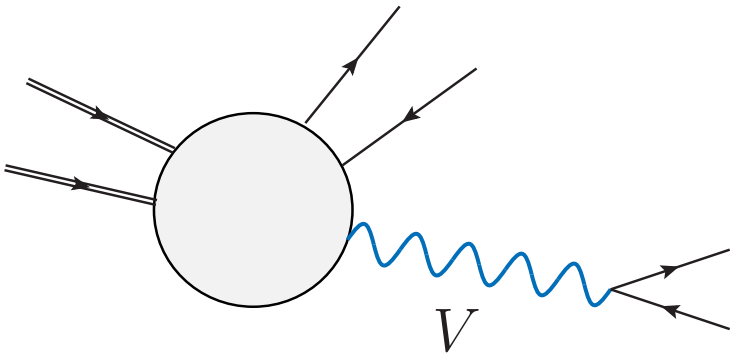
What do we need (from theory)?



Theory aspects: polarised templates

Separating polarisations in amplitudes

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



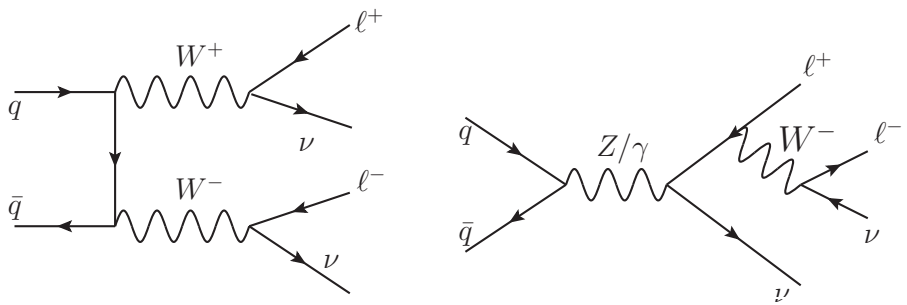
$$\begin{aligned}
\mathcal{A}^{\text{unpol}} &= \mathcal{P}_\mu \frac{-g^{\mu\nu}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu \\
&= \mathcal{P}_\mu \frac{\sum_{\lambda'} \varepsilon^\mu_{\lambda'} \varepsilon^{*\nu}_{\lambda'}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu \\
\longrightarrow \quad &\mathcal{P}_\mu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

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

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

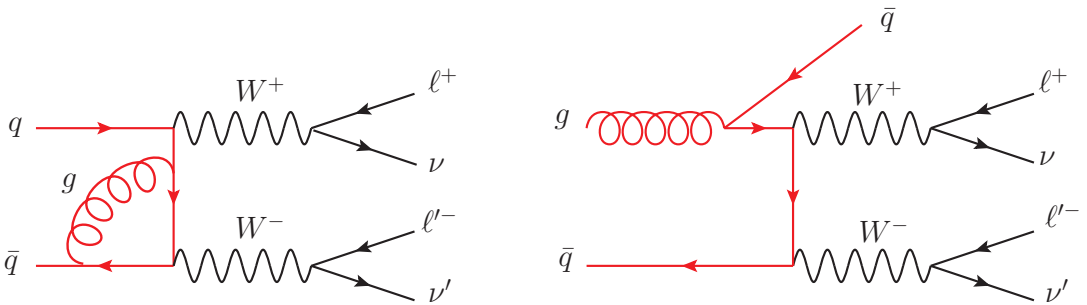
DPA: double-pole approximation [Denner et al. 0006307]

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

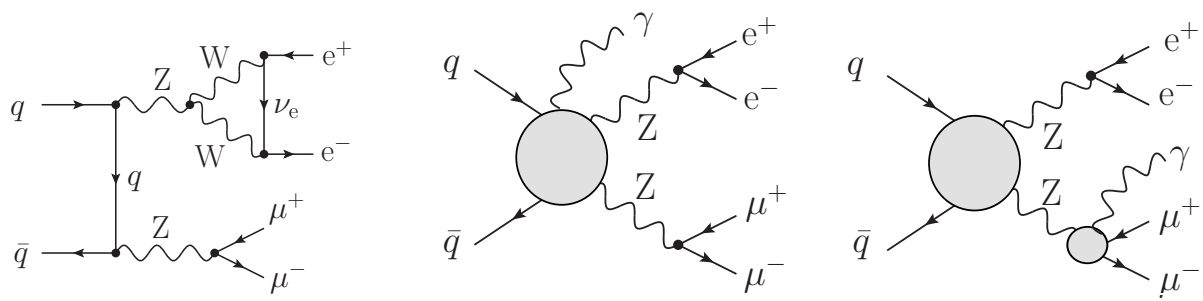
(3) Separate polarisations

Radiative corrections to the production and decay

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

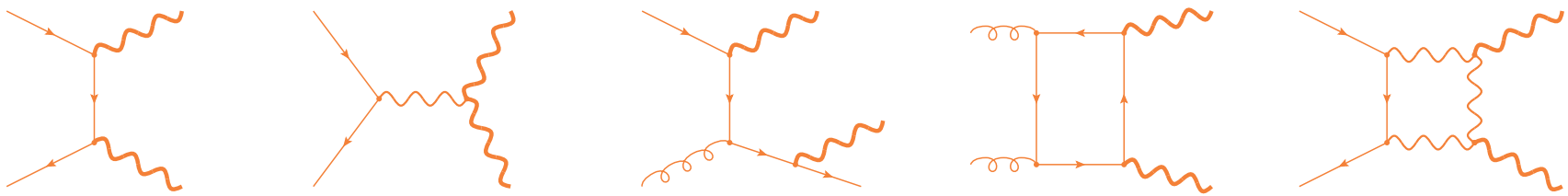


NLO EW (QCD) corr. with leptonic (hadronic) decays [Denner GP 2107.06579, Le Baglio 2203.01470, Denner Haitz GP 2211.09040, Denner Haitz GP 2311.16031, 2409.03620, Dao Le 2311.17027]



Inclusive WZ production

State of the art for polarised predictions



VV-CM natural polarisation frame

→ $W^{\pm}(\ell^{\pm}\nu_{\ell})\,Z(\ell'^{+}\ell'^{-})$: NNLOQCD + NLOEW with MoCaNLO, STRIPPER, MulBos [Denner GP 2010.07149, Le Baglio 2203.01470, 2208.09232, GP Poncelet 2510.25898]

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

→ $W^{+}(\ell^{+}\nu_{\ell})Z(\ell'^{+}\ell'^{-})+jj$ (VBS): NLO EW [Denner GP et al. 2510.26462]

→ MG5_aMC: LO and MJM / [Buarque-Franzosi et al. 1912.01725]

→ Sherpa: approx. NLO QCD and MJM [Hoppe et al. 2310.14803]

→ Powheg-Box-Res: NLO QCD + PS in SM and SMEFT [GP Zanderighi 2311.05220, Haisch GP et al. 2507.21768]

SM (1)

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

Improved SM pred., NNLO QCD (δ_s) +/× NLO EW (δ_{ew}) [GP Poncelet 2510.25898]

$$\begin{aligned} d\sigma^{(+)}_{NNLO} &= d\sigma_{LO}\left(1+\delta^{(1)}_{s,\,u\bar{d}}+\delta^{(1)}_{ew,\,u\bar{d}}+\delta^{(2)}_{s,\,u\bar{d}}\right) \\ &+ d\sigma_{qg}\left(1+\delta^{(1)}_{s,\,qg}\right)+d\sigma_{q\gamma}+d\sigma_{qq'}+d\sigma_{gg} \end{aligned}$$

state	$\delta^{(1)}_{s,u\bar{d}}$	$\frac{d\sigma_{qg}}{d\sigma_{LO}}$	$\delta^{(2)}_{s,u\bar{d}}$	$\frac{d\sigma_{qg}}{d\sigma_{LO}}\delta^{(1)}_{s,\,qg}$	$\frac{d\sigma_{qq'}}{d\sigma_{LO}}$	$\frac{d\sigma_{gg}}{d\sigma_{LO}}$	$\frac{d\sigma_{q\gamma}}{d\sigma_{LO}}$	$\delta^{(1)}_{ew,u\bar{d}}$
LL	31.9%	−2.1%	7.7%	0.2%	2.7%	0.5%	0.6%	−5.1%
LT	50.5%	108.5%	13.3%	19.5%	10.6%	−0.8%	1.4%	−4.9%
TL	50.9%	110.9%	13.7%	20.1%	10.7%	−0.8%	4.1%	−5.0%
TT	29.7%	31.3%	5.7%	−0.8%	3.9%	−0.1%	1.4%	−6.5%

SM (3)

Joint fractions $f_{ij} = \mathrm{d}\sigma_{ij}/\mathrm{d}\sigma_{\mathrm{unp}}$ [GP Poncelet 2510.25898] compared to ATLAS [2211.09435]

QCD-scale unc. on joint fractions: **correlated 7pSV** vs **uncorrelated 7pSV** vs **TNPs**

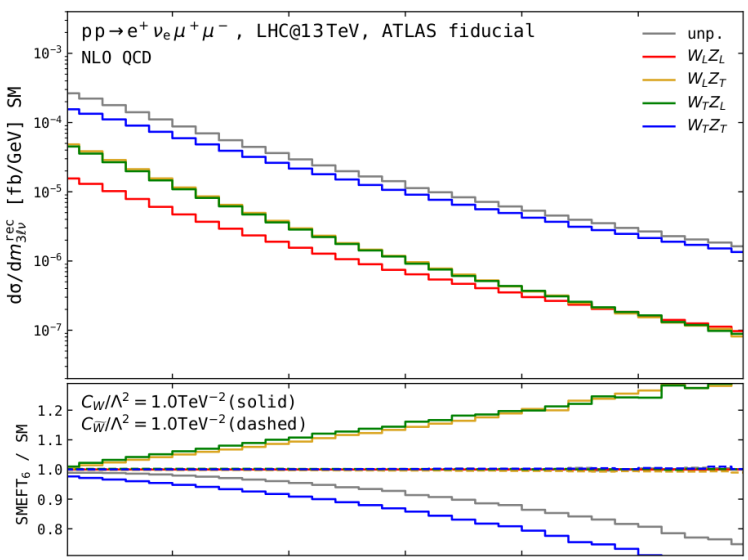
state	$f_{\mathrm{NLO}}^{(\mathrm{QCD})}$ [%]	$f_{\mathrm{NNLO}}^{(\mathrm{QCD})}$ [%]	$f_{\mathrm{NNLO}}^{(+)}$ [%]	f_{meas} [%]
off-sh.	1.88	1.97	1.99	
unpol.	100	100	100	
LL	$5.71^{+0.17(+0.34)}_{-0.18(-0.27)}(\pm 0.56)$	$5.69^{+0.04(+0.18)}_{-0.03(-0.15)}(\pm 0.25)$	$5.63^{+0.04(+0.19)}_{-0.02(-0.16)}$	7.2 ± 1.6
LT	$15.42^{+0.30(+1.38)}_{-0.29(-1.11)}(\pm 2.36)$	$16.46^{+0.27(+0.77)}_{-0.22(-0.65)}(\pm 1.13)$	$16.65^{+0.26(+0.81)}_{-0.22(-0.68)}$	11.9 ± 3.4
TL	$14.68^{+0.29(+1.32)}_{-0.29(-1.06)}(\pm 2.26)$	$15.71^{+0.22(+0.71)}_{-0.20(-0.61)}(\pm 1.08)$	$16.03^{+0.21(+0.75)}_{-0.19(-0.63)}$	15.2 ± 3.3
TT	$63.55^{+0.40(+4.38)}_{-0.45(-3.53)}(\pm 7.24)$	$61.52^{+0.45(+1.72)}_{-0.58(-1.56)}(\pm 3.08)$	$61.07^{+0.45(+1.84)}_{-0.57(-1.64)}$	66.0 ± 4.0
interf.	0.63	0.63	0.62	

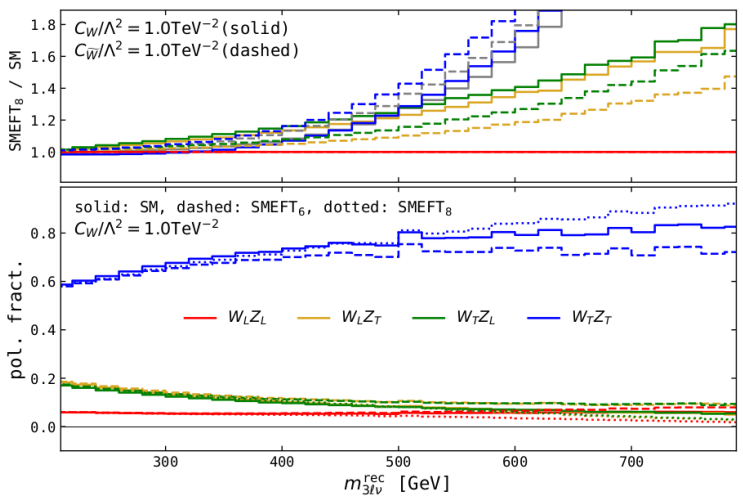
SMEFT (1)

First SMEFT study at NLOPS with polarised signals in DPA [Haisch GP et al. 2507.21768]

- Automation in POWHEG-BOX-RES [Alioli et al. 1002.2581, Jezo Nason 1509.09071, Chiesa et al. 2005.12146, GP Zanderighi 2311.05220] linked to RECOLA 2 [Denner Lang Uccirati 1711.07388]
- aTGC operators in Warsaw (new UFO) and HISZ basis [Chiesa Denner Lang 1804.01477]

$$Q_{HB}\,, \quad Q_{H\widetilde{B}}\,, \quad Q_{HW}\,, \quad Q_{H\widetilde{W}}\,, \quad Q_{HWB}\,, \quad Q_{H\widetilde{W}B}\,, \quad Q_{W}\,, \quad Q_{\widetilde{W}}$$





SMEFT (2)

DPA implementation in POWHEG-BOX-RES [Haisch GP et al. 2507.21768] enables sound QuTom [Del Gratta GP et al. 2509.20456, Grossi GP Vicini 2409.16731]

NLO QCD, Q_W (and $Q_{\tilde{W}}$) dim-6 SMEFT op.: concurrence and purity [GP Re 2601.09540]

$$\rho^{(6)}_{V,ij} = \frac{\sum_x \left[\left(\mathcal{A}^{(4)}_{i,x}\mathcal{A}^{(4)*}_{j,x}\right) + \xi\left(\mathcal{A}^{(4)}_{i,x}\mathcal{A}^{(6)*}_{j,x} + \mathcal{A}^{(6)}_{i,x}\mathcal{A}^{(4)*}_{j,x}\right)\right]}{\sum_x \sum_{a=1}^{3}\left[\left|\mathcal{A}^{(4)}_{a,x}\right|^2 + 2\,\xi\,\mathfrak{Re}\left(\mathcal{A}^{(4)}_{a,x}\mathcal{A}^{(6)*}_{a,x}\right)\right]} \longrightarrow \mathrm{Tr}[{\rho^{(6)}_V}^2] \text{ can be } > 1$$

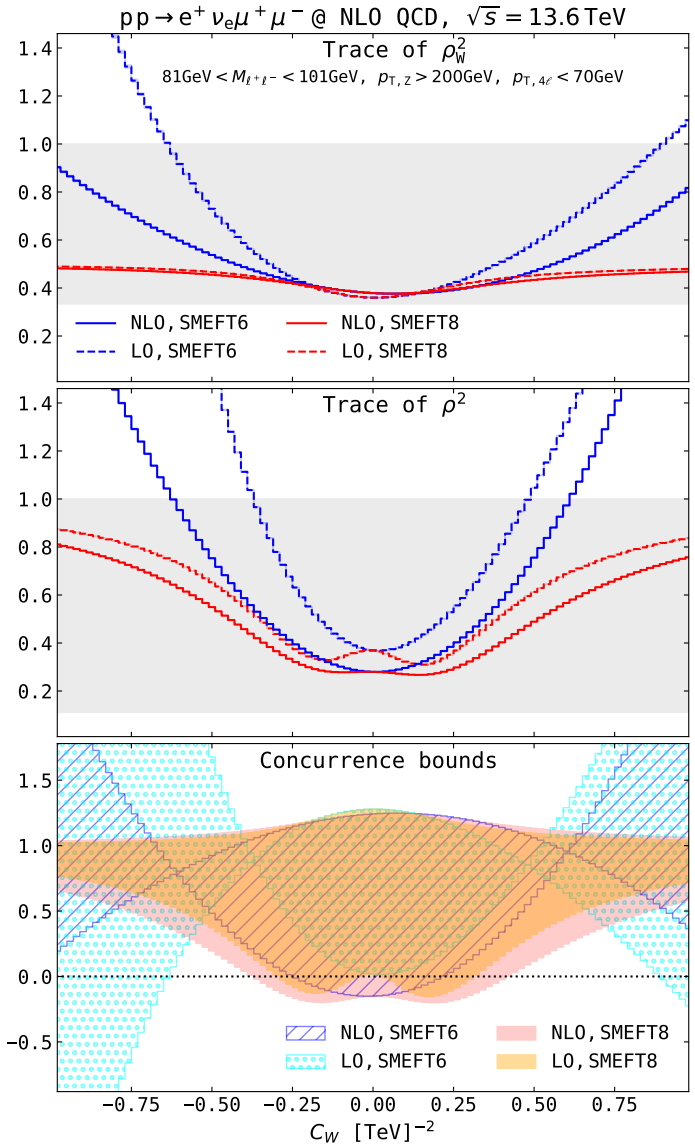
$$\rho^{(8)}_{V,ij} = \frac{\sum_x \left(\mathcal{A}^{(4)}_{i,x} + \xi\mathcal{A}^{(6)}_{i,x}\right)\left(\mathcal{A}^{(4)*}_{j,x} + \xi\mathcal{A}^{(6)*}_{j,x}\right)}{\sum_x \sum_{a=1}^{3}\left|\mathcal{A}^{(4)}_{a,x} + \xi\mathcal{A}^{(6)}_{a,x}\right|^2} \longrightarrow \mathrm{Tr}[{\rho^{(6)}_V}^2] \leq 1$$

Similar conclusions for qubits [Lo Chiatto 2408.04553, Altakach et al. 2601.09558]

SMEFT (3)

Quadratic EFT terms crucial for semi-positive ρ especially in boosted setup ($p_{\mathrm{T,Z}} > 200\,\mathrm{GeV}$, $p_{\mathrm{T,WZ}} < 70\,\mathrm{GeV}$)

Indication of decoherence effects from QCD corrections

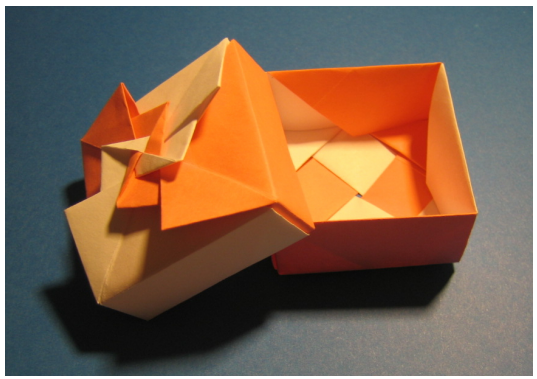


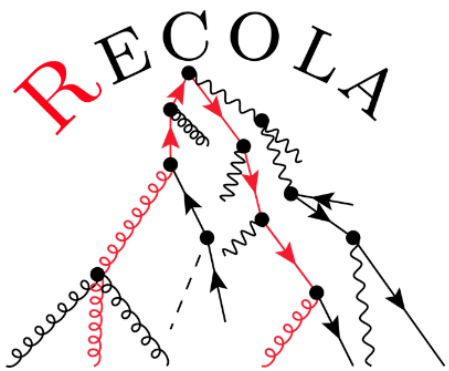
Conclusions & Outlook

Public codes

VV_POL (diboson-specific, NLO QCD, SM & SMEFT) publicly available in POWHEG-BOX-RES git repo and Warsaw-basis aTGC model SM_ATGC_WARSAW now available on public RECOLA 2 webpage

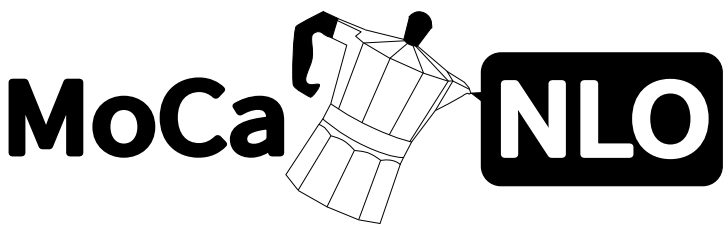
[Haisch Linder GP Re Zanderighi 2507.21768]





MOCANLO (general-purpose, NLO EW + QCD, SM) now public on gitlab

[Denner Lombardi Lopez Pellen GP 2602.19842]



Conclusions

Where do we stand?

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

What is next?

- NNLO+PS automation
- ML polarisation tagging
- Hadronic decays

About hadronic decays

COMETA workshop on hadronic decays of EW bosons and interplay with polarisation

Perugia, 1-2 July 2026 (more info & registration at Indico page)

Backup

Quantum tomography (1)

DPA calculation allows for sound quantum tomography of four-lepton final states [Del Gratta GP et al. 2509.20456, GP Re 2601.09540]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_1\,\mathrm{d}\Omega_2\,\mathrm{d}X}\Big/\frac{\mathrm{d}\sigma}{\mathrm{d}X} = \frac{1}{(4\pi)^2} + \frac{1}{4\pi}\sum_{l=1}^{2}\sum_{m=-l}^{l}\alpha^{(1)}_{lm}(X)\,Y_{lm}(\Omega_1) + \frac{1}{4\pi}\sum_{l'=1}^{2}\sum_{m=-l'}^{l'}\alpha^{(2)}_{l'm'}(X)\,Y_{l'm'}(\Omega_2)$$

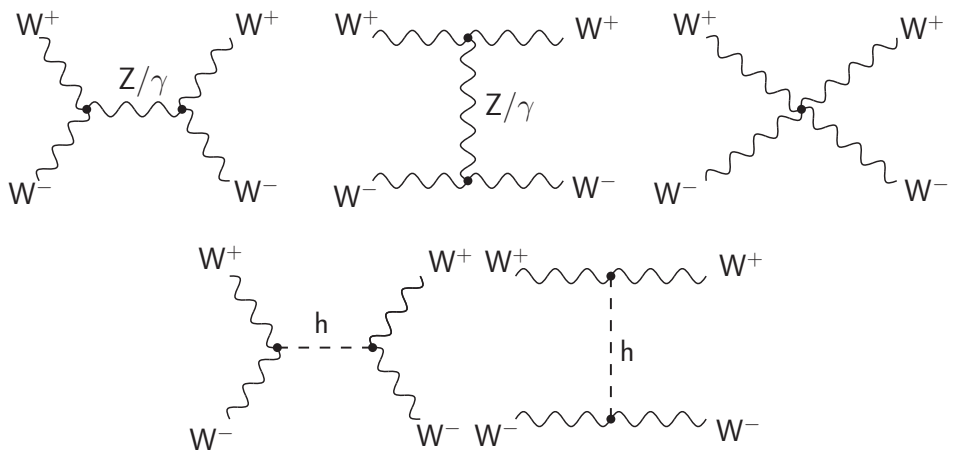
$$+ \sum_{l,l'=1}^{2}\sum_{m=-l}^{l}\sum_{m'=-l'}^{l'}\gamma_{lml'm'}(X)\,Y_{lm}(\Omega_1)\,Y_{l'm'}(\Omega_2)$$

$$= \left(\frac{3}{4\pi}\right)^2\sum_{i,i',j,j'=1}^{3}\rho_{i\,i'\,jj'}(X)\Gamma_{ii'}(\Omega_1)\Gamma_{jj'}(\Omega_2)$$

$\longrightarrow$ $\{\alpha_{lm},\,\gamma_{lml'm'}\}$ to reconstruct spin-density matrix ρ (entanglement, purity ...)

$$9\mathrm{Tr}\left[\rho^2\right] = 1 + \sum_{l=1}^{2}\sum_{m=-l}^{l}\left(\kappa^{(1)}_{l}\alpha^{(1)}_{lm}\right)^2 + \sum_{l'=1}^{2}\sum_{m'=-l'}^{l'}\left(\kappa^{(2)}_{l'}\alpha^{(2)}_{l'm'}\right)^2 + \sum_{l,l'=1}^{2}\sum_{m=-l}^{l}\sum_{m'=-l'}^{l'}\left(\kappa^{(1)}_{l}\kappa^{(2)}_{l'}\gamma_{lml'm'}\right)^2$$

General features of VBS



- 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, . . .]

WZ (1)

$p\,p \to W^+(e^+\nu_e)\,Z(\mu^+\mu^-)\,j\,j$ [Denner Haitz Franken Lombardi GP 2510.26462] @ NLO EW

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

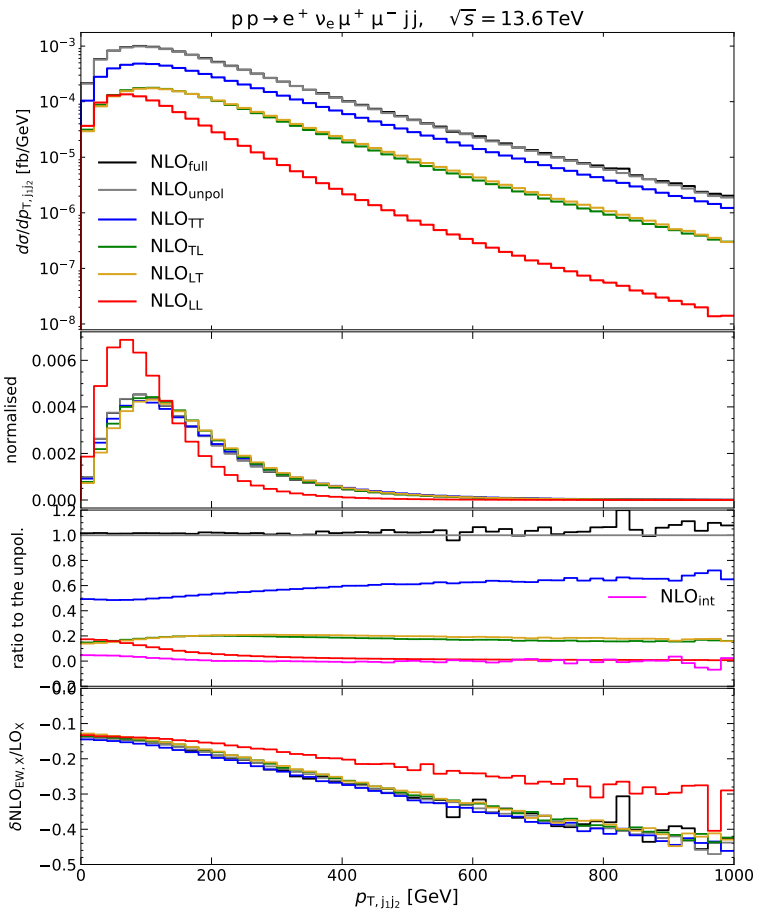
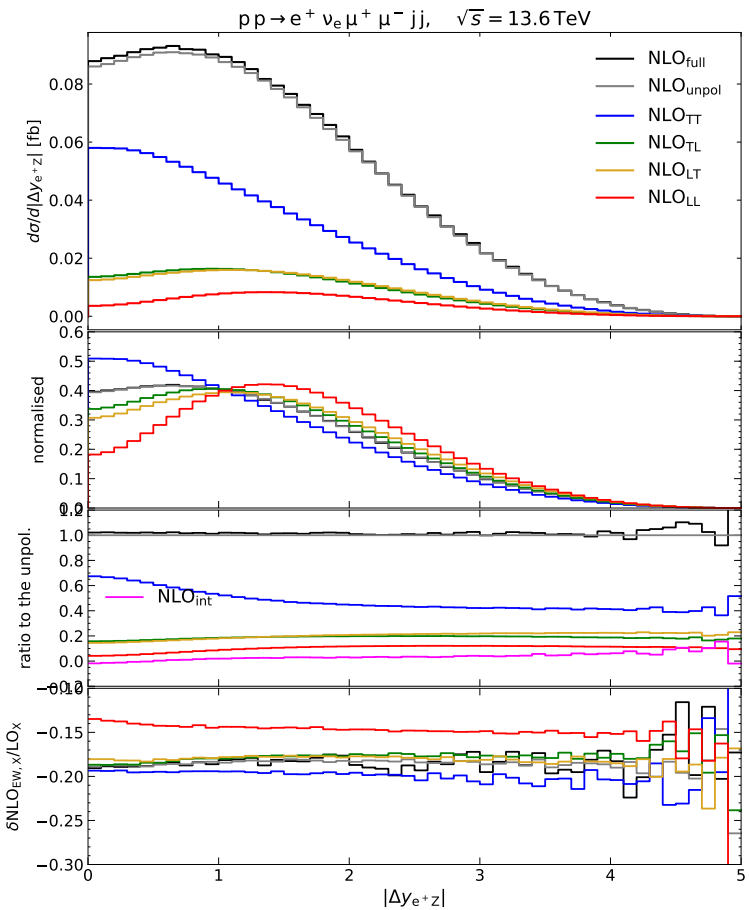
mode	σ_{LO} [fb]	δ_{EW} [%]	σ_{NLOEW} [fb]	f_{LO} [%]	f_{NLOEW} [%]
off-sh.	0.2723(1)	−18.7	0.2215(2)	101.7	101.4
unp.	0.26779(1)	−18.4	0.21838(4)	100.0	100.0
LL	0.023045(2)	−14.4	0.019697(5)	8.6	9.0
LT+TL	0.098391(6)	−17.9	0.08076(2)	36.7	37.0
TT	0.141723(9)	−19.6	0.11394(3)	52.9	52.2
int.	0.00463(2)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

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

New: fudge factors to regulate un-subtractions in WZV topologies.

WZ (2)

p_T of the di-jet system



rapidity sep. between ℓ_W and Z