Polarized Weak Bosons at the LHC

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Based on works performed in collaboration with A. Ballestrero, E. Maina (INFN, Uni. Torino) and A. Denner (Uni. Würzburg).

1. Motivations

LHC physics and polarizations

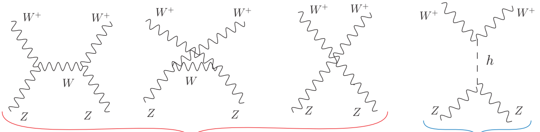
- LHC luminosities accumulated in Run 2 ($\approx 150\,\text{fb}^{-1}$) at 13 TeV CoM energy and foreseen in next runs ($300\,\text{fb}^{-1}$ in Run 3, and $3000\,\text{fb}^{-1}$ in High-Lumi)

$\longrightarrow$ precise measurements of electroweak bosons production processes.

- Polarization observables for W/Z non trivial to disentangle (unstable bosons!), but:
  1. are important probes of Standard Model (SM) gauge and Higgs sectors
  2. and may provide discrimination power between SM and beyond-SM physics.

- ATLAS measured polarizations in $W^{\pm}Z$ production [ATLAS 1902.05759]. More measurements expected in diboson and vector boson scattering (VBS).

- VBS plays a crucial role: unitarity cancellations in on-shell longitudinal scattering



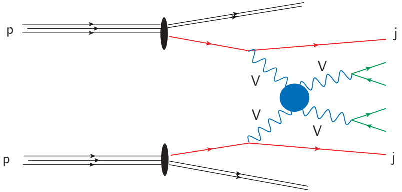
$$-\frac{s}{v^2}(1-\cos\theta) \qquad + \frac{s}{v^2}(1-\cos\theta)$$

Longitudinal vector boson scattering

- Longitudinal cross section depends on the specific realization of ElectroWeak Symmetry Breaking mechanism (EWSB).
- New physics could interfere with the SM: search for beyond-SM effects.

Accurate theory predictions for polarized VBS needed, to be used in LHC experimental analyses.

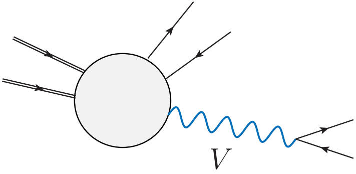
At the LHC: two weak bosons radiated from quark-lines scatter, then decay into stable particles. Quarks b ecome two tagging jets with large invariant mass and large rapidity separation.



2. Theory & Monte Carlo

Separating polarizations

A natural definition for resonant diagrams, in the unitary gauge:



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

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

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

At the cross section level,

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

Note that pol. vectors are not Lorentz invariant $(\varepsilon^\mu_\lambda(\Lambda \cdot p) \neq \Lambda^\mu{}_\nu\, \varepsilon^\nu_\lambda(p))$.

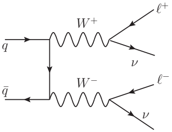
Decay leptons angular distributions reflect polarization state of the decayed V boson.

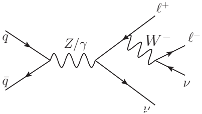
If no lepton cuts, interferences vanish: analytic expression for the decay rate $d\sigma/d\cos\theta^*_\ell$.
If lepton cuts, analytic expression doesn't hold anymore: interferences don't vanish.

- Bottleneck: not all diagrams that contribute to multiboson processes are resonant!

Selecting resonant diagrams

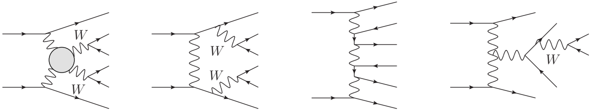
To define polarizations in multiboson, we need a factorized amplitude (production ⊗ propagator ⊗ decay): not possible for all contributions. *E.g.* diboson (fully leptonic):





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

For VBS, many more diagrams (double-res., single-res. and non-res.):



$+ \quad \ldots$

Separating resonant contributions is delicate: the only "truth" is the full computation.

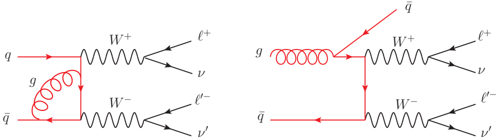
- Our strategy: Double Pole Approximation (DPA) [Denner et al. 0006307]: project weak bosons on-shell, mantaining off-shell kinematics in Breit-Wigner modulation.

- Then separating polarizations is straightforward.

Going beyond leading-order

- The LO implementation available in `PHANTOM` ($2 \to 6$ proc.) and `MOCANLO` (general).

- NLO QCD is in principle easy (no coupling to EW boson leptonic decays), but
  - on top of Born (B), virtuals (V) and reals (R) contribute: no IR singularities;



  - subtraction counterterms needed, *e.g.* dipoles D in Catani-Seymour formalism

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

  - DPA only used for LO kinematics (B,V), need for analogous prescription for R and subtraction counterterms (most involved part of the computation);
  - separation of polarizations required for all contributions in Eq. 1.

Implemented in `MOCANLO+RECOLA` completely for processes without final state jets, *e.g.* diboson, close to completion for processes with final state jets, *e.g.* VBS.

- NLO EW much more involved: V and R mix production and decay sub-amplitudes.

3. Phenomenology

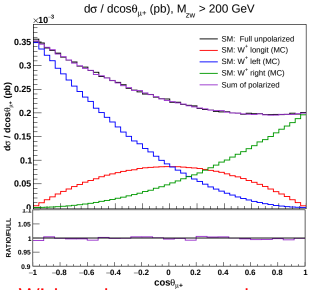
Vector boson scattering at the LHC@13TeV (1)

Extensive study of VBS signal at LO EW ($\alpha_{\rm ew}^6$) with PHANTOM: W^+W^- [1710.09339], W^+W^+ [in preparation], ZZ and W^+Z [1907.04722] (fully leptonic, opposite flavors).

VBS signal: two jets with $M_{jj} > 500 - 600\,\mathrm{GeV}$, $|\Delta\eta_{jj}| > 2.5 - 3.6$.

$W^+Z(\mathrm{pp} \to \mathrm{jj}\mu^+\nu_\mu \mathrm{e}^+\mathrm{e}^-)$: final state known, up to single-ν reco., resonable rate.

- Singly-polarized (no lepton cuts): $\lesssim 1\%$ agreement with analytic results ($\cos\theta^*_\ell$).
- Effect of lepton cuts and ν-reco. on $\cos\theta^*_\ell$: non vanishing interferences, but still discriminating power among polarization modes.



Without lepton cuts and ν reco

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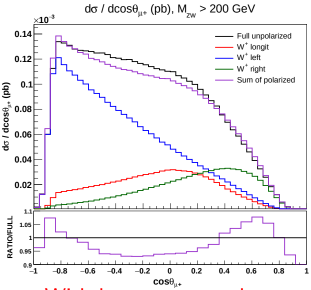


With lepton cuts and ν reco

Vector boson scattering at the LHC@13TeV (2)

• Singly-transverse distributions (both for W^+ and for Z) show (almost) model independence in shape and cross-section (SM, Singlet Ext., Higgsless SM).

• Two different fit techniques using SM distribution templates: few % accurate results.
→ promising results for model indepent extraction of pol. fractions from LHC data.

• Investigated the reweighting method, often used by experimentalists to generate polarized signals, reweighting unpolarized events: proved to be very inaccurate.
Longitudinal cross-section (most interesting!) overestimated by 50% at large M_{WZ}.

Very good description of polarized signals in VBS, with DPA techniques, in all VBS channels, with fully-leptonic (opposite-flavor) decays.

Diboson production at the LHC@13TeV (1)

With MOCANLO+RECOLA at NLO QCD + loop-induced gg: W^+W^- ($\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu$) [in preparation]. Inclusive (no cuts) and ATLAS fiducial region [ATLAS 1905.04242].

- Non-resonant effects small (1.3% inclusive, 2.5% fiducial) at the integrated level.
- Singly-polarized stable against NLO QCD: K-fact. $\approx +10\%$, fractions change by 1%.
- Doubly-longitudinal features +40% NLO QCD corrections, despite jet-veto.
- Fractions very stable against scale-variations.
- gg-channel: largest enhancement to diagonal spin-matrix terms (+9%).

	LO	NLO QCD	K-factor	Δ_{gg}
full	$202.02(3)^{+4.6\%}_{-5.5\%}$	$220.16(8)^{+1.8\%}_{-2.2\%}$	1.09	1.06
unpolarized (DPA)	$195.91(3)^{+4.7\%}_{-5.5\%}$	$214.48(9)^{+1.8\%}_{-2.2\%}$	1.09	1.06
$W^+_0 W^-_{\mathrm{unpol}}$ (DPA)	$50.94(1)^{+5.5\%}_{-6.5\%}$	$57.42(4)^{+1.9\%}_{-2.6\%}$	1.13	1.04
$W^+_T W^-_{\mathrm{unpol}}$ (DPA)	$141.72(2)^{+4.3\%}_{-5.1\%}$	$152.84(9)^{+1.7\%}_{-2.1\%}$	1.08	1.07
$W^+_0 W^-_0$ (DPA)	$6.653(1)^{+4.9\%}_{-5.8\%}$	$9.057(5)^{+2.9\%}_{-3.0\%}$	1.36	1.08
$W^+_0 W^-_T$ (DPA)	$44.08(1)^{+5.6\%}_{-6.5\%}$	$48.24(4)^{+1.9\%}_{-2.5\%}$	1.09	1.04
$W^+_T W^-_0$ (DPA)	$50.19(1)^{+5.5\%}_{-6.4\%}$	$54.02(4)^{+1.9\%}_{-2.5\%}$	1.08	1.03
$W^+_T W^-_T$ (DPA)	$99.61(2)^{+3.7\%}_{-4.6\%}$	$106.20(7)^{+1.6\%}_{-1.9\%}$	1.07	1.09

Tab. Total cross-sections (fiducial setup).

Diboson production at the LHC@13TeV (2)

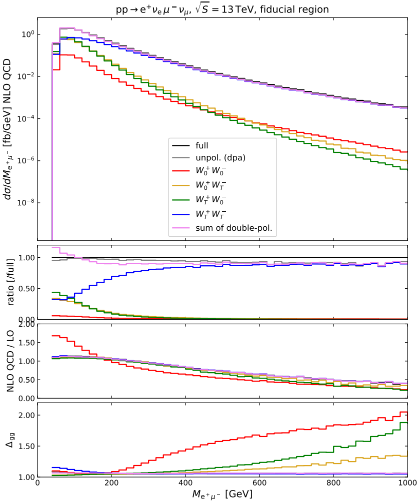


Fig. Differential cross-sections in $e^+\mu^-$ invariant mass.

- Some observables not suitable for polarizations: limited DPA goodness (p_T^{miss}), large interferences ($\Delta\phi_{e^+\mu^-}$).
- Some angular ($\cos\theta_{e^+\mu^-}$), mass ($M_{e^+\mu^-}$), transverse momentum (p_{T,e^+}), rapidity (η_{e^+}) observables very well modeled.
- *gg*-channel more symmetric (PDFs, angular momentum): not negligible.
- *gg* Higgs contribution negligible ($< 0.5\%$).

Good description of polarized signals, first DPA-based calculation at NLO QCD with polarization separation at amplitude level in all parts of the calculation.

4. Conclusions

Conclusions

Study of electroweak bosons polarization is gaining interest in the experimental and theoretical communities: mainly diboson and VBS.

A theory view point.

1. Defining polarized signals is delicate, several strategies (all approximations!).
2. Interferences and non-resonant effects usually small but definitely needed!
3. NLO corr. needed to enable precise analyses: QCD feasible, EW more difficult.
4. Polarized signals at the amplitude level more physically motivated and better behaved than other approaches.

A phenomenology wishlist.

1. Model (in)dependence of polarizations: BSM dynamics (EFT, UV-finite models).
2. Beyond fully-leptonic, opposite-flavor decays: same-flavor and semi-leptonic.
3. More processes: single top, $t\bar{t}$, QCD backgrounds, ...

Backup

Theory studies

Polarized W and Z bosons at the LHC in V+jets [Bern et al. 1103.5445, Stirling et al. 1204.6427], diboson, single-t, $t\bar{t}$, VH [Stirling et al. 1204.6427].

Interference, lepton cuts effects [Stirling et al. 1204.6427, Belyaev et al. 1303.3297].

Recent studies on polarization observables, mainly for diboson [Aguilar-S. et al. 1508.04592, Baglio et al. 1810.11034, 1910.13746].

Automation of polarized particles simulation at the LHC [Buarque-Franzosi et al. 1912.01725]

Vector Boson Scattering (fully leptonic):

Polarized signals, lepton cuts effects with SM dynamics [Doroba et al. 1201.2768, Stirling et al. 1204.6427, Ballestrero et al. 1710.09339, 1907.04722, Buarque-Franzosi et al. 1912.01725]

Polarized bosons with BSM dynamics [Han et. al 0911.3656, Brass et al. 1807.02512, Ballestrero et al. 1710.09339, 1907.04722, Buarque-Franzosi et al. 1912.01725].

Determining pol. fractions with machine learning [Searcy et al. 1510.01691, Lee et al. 1812.07591, 1908.05196].

Experimental results

Polarization measurements with LHC@8TeV data in $W+$ jets [ATLAS 1203.2165, CMS 1104.3829], $Z+$ jets [CMS 1504.03512, ATLAS 1606.00689] and $t\bar{t}$ [CMS 1605.09047, ATLAS 1612.02577].

Measured boson polarizations in WZ [ATLAS 1902.05759] with LHC@13TeV data.

Vector Boson Scattering:

Although measured (unpolarized) by CMS and ATLAS in fully- and semi- leptonic channels, no polarization measurements in VBS yet.

High-Luminosity LHC Run (starting in 2027) will allow for polarization measurements in VBS [CMS-PAS-FTR-18-014, CERN-LPCC-2018-03].

V decay rate: analytic expression

Master eq. (θ, ϕ are ℓ^+ angles in W^+/Z rest frame, w.r.t. boson direction in the lab):

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

where X are kin. variable independent of lepton angles (*e.g.* p_T^V, η_V). $A_i = A_i(X)$.

If no lepton cuts applied, interferences vanish (integration over full azimuth ϕ):

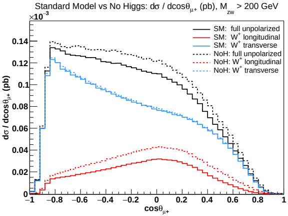
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{3}{8} f_L \left(1+\cos^2\theta - \frac{2(c_L^2 - c_R^2)}{(c_L^2 + c_R^2)}\cos\theta\right) + \frac{3}{8} f_R \left(1+\cos^2\theta + \frac{2(c_L^2 - c_R^2)}{(c_L^2 - c_R^2)}\cos\theta\right) + \frac{3}{4} f_0 \sin^2\theta,$$

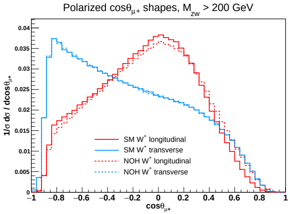
Polarization fractions f_0, f_L, f_R sum to 1, they can be extracted with projections onto first three powers of $\cos\theta$ (or equivalently onto first three Legendre polynomials).

If lepton cuts applied, analytic expression for $d\sigma/d\cos\theta$ doesn't hold anymore: interferences don't vanish (cannot integrate over the full ϕ range).

Polarized VBS with PHANTOM: model-independence

1) Even with lepton cuts (and ν-reco.), the normalized shape of polarized $\cos\theta_\ell$ distrib. shows mild dependence on underlying dynamics (SM, no Higgs-SM, Singlet).





2) Transverse component is (almost) model-independent also in the total cross-section.

$\longrightarrow$ promising ingredients for a model-independent extraction of pol. fractions.

Tried a fit and a direct subtraction (of the transverse): satisfactory results, despite very basic techniques.

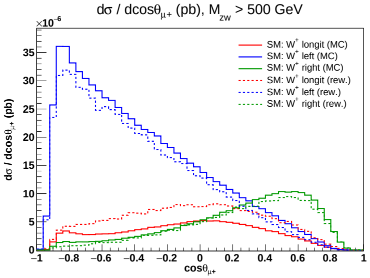
	Cross sections [ab] for a polarized W^+ in WZ scatt.					
	Longitudinal			Transverse		
kinematic region	MC	Fit	Subtr.	MC	Fit	Subtr.
$M_{WZ} > 200$ GeV	46.90	44.93	48.37	133.10	135.16	131.73
$M_{WZ} > 1000$ GeV	4.71	5.20	4.73	5.50	4.79	5.47
$M_{WZ} > 200$ GeV, $p_t^W > 400$ GeV	4.81	4.79	4.84	9.12	9.26	9.03
$M_{WZ} > 200$ GeV, $\lvert\eta_W\rvert > 3$	1.74	1.70	1.73	0.83	0.83	0.82

Polarized VBS with PHANTOM: MC vs reweighting

Experimental analyses have used (so far) reweighting procedure to simulate polarized events (and distributions).

Consider the W^+ boson polarization in W^+Z ($W^+ \to \mu^+\nu_\mu$).

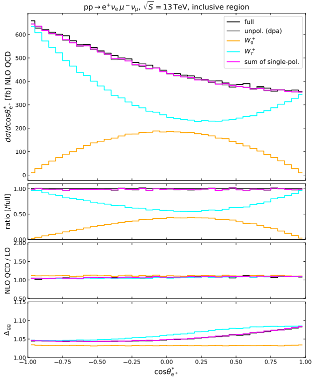
Reweighting: from full unpol. events (no lepton cuts), compute pol. fractions in W $\{p_t, \eta\}$ regions. Assign probability for the W of being longit., left or right, depending on $\cos\theta_\mu$ analytic shape (and pol. fractions), to obtain 3 separated *polarized* samples.



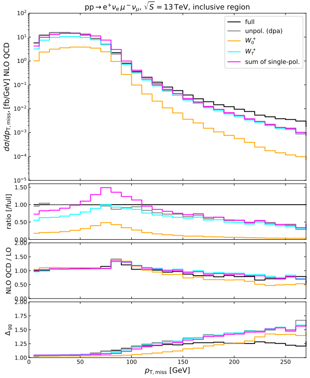
- ▷ Large statistics required (unpol. generation).
- ▷ Compared to polarized amplitudes, reweighting is very inaccurate in reproducing pol. cross sections: up to 70% discrep. for longit., for $M_{WZ} > 500$ GeV.
- ▷ Interferences completely neglected.
- ▷ Dependence of pol. signals on other kinematic variables (other than $\cos\theta_{\mu^+}$) washed out.

More results for diboson at NLO QCD

Inclusive setup (singly-polarized results):



Angular distribution in $\cos\theta^*_{e^+}$



Missing transverse momentum