Polarized $W^{\pm}$ and Z bosons in multi-boson processes at the LHC

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Outline

1. Introduction

Motivations

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

- precise measurements of EW processes,
- in particular of multi-boson production.

Polarization observables for massive vector bosons are

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

Special interest in di-boson production, vector-boson scattering (VBS), Higgs and top-quark decays.

What's needed?

1. precise SM predictions for polarized bosons in relevant LHC processes
2. new ideas to enable the extraction of polarizations from LHC data
3. new-physics studies for polarized bosons

Recent progress: theory and phenomenology (1)

Growing interest from both theoretical and experimental side.

- Seminal works:

V+jets and other multi-boson processes [Bern et al. 1103.5445, Stirling et al. 1204.6427]

Interference and kinematic-selection impact [Stirling et al. 1204.6427, Belyaev et al. 1303.3297]

- SM predictions and automation

Automation of polarized VBS in PHANTOM (at LO) and phenomenology [Ballestrero et al. 1710.09339, 1907.04722, 2007.07133]

Automation at LO of polarized-resonance simulation in MG5 [Buarque-Franzosi et al. 1912.01725]

Polarization-related observables at NLO EW+QCD in $W^{\pm}Z$ production [Baglio et al. 1810.11034, 1910.13746].

NLO QCD [Denner GP 2006.14867, 2010.07149] and NNLO QCD [Poncelet Popescu 2102.13583] SM predictions for polarized di-boson production.

NLO EW + QCD predictions for polarized ZZ production [Denner GP 2107.06579]

Polarized $W^{\pm}$ and Z bosons from Higgs decays in SM [Maina 2007.12080, Maina GP 2105.07972]

Recent progress: theory and phenomenology (2)

- BSM studies in VBS/VBF-Higgs:

Effect of new-physics on polarized VBS [Han et. al 0911.3656, Brass et al. 1807.02512, Ballestrero Maina GP 1907.04722, Buarque-Franzosi et al. 1912.01725].

EFT Higgs coupling to longitudinal and transverse W bosons [Brehmer et al. 1404.5951]

Polarized ZZ to probe the $Zt\bar{t}$ coupling in or beyond SM [Cao et al. 2004.02031]

- New techniques and hadronic decays:

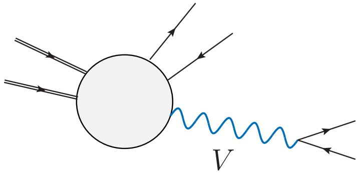
ML techiques to separate polarized contributions to VBS [Searcy et al. 1510.01691, Lee et al. 1812.07591, 1908.05196].

Jet-substructure [De et al. 2008.04318] and DNN [Kim Martin 2102.05124] techniques to disentangle polarizations of boosted, hadronically-decaying W's.

ML techniques to separate polarization in fully-leptonic and semi-leptonic VBS [Grossi et al. 2008.05316]

Separating polarizations (1)

A natural definition for resonant diagrams:



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

At the cross section level,

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

Note that pol. vectors are not Lorentz covariant ($\varepsilon^\mu_\lambda(\Lambda\cdot p) \neq \Lambda^\mu{}_\nu\, \varepsilon^\nu_\lambda(p)$).
Defined in a specific frame: typical choices are the di-boson center-of-mass (CM) or the laboratory frame.

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

Separating polarizations (2)

- At tree-level, for a single resonant boson: the master equation holds (θ^*, ϕ^* are ℓ^+ angles in V rest frame, w.r.t. V direction in the lab) [Bern et al. 1103.5445],

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

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

- If no lepton cuts applied, interferences vanish upon integration over full azimuth ϕ^*:

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

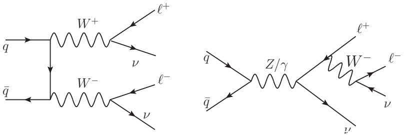
f_L, f_-, f_+ polarization fractions of the decayed V boson ($f_L + f_- + f_+ = 1$).

- If lepton cuts applied, analytic expression for $d\sigma/d\cos\theta^*$ does not hold anymore: interferences do not vanish (cannot integrate over the full ϕ^* range).

Selecting resonant diagrams

- Remark: not all diagrams that contribute to multi-boson processes are resonant!

To define polarizations, 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.

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

- Consider non-double-resonant diagrams as non-resonant background.

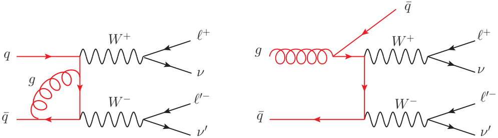
- Treat double-resonant diagrams with double-pole approximation (DPA) [Denner et al. 0006307, Ballestrero et al. 1710.09339, Denner GP 2006.14867] or with a spin-correlated narrow-width approximation (NWA) [Artoisenet et al. 1212.3460, Buarque Franzosi et al. 1912.01725].

- Then separating polarizations is straightforward.

Going beyond leading-order (1)

NLO QCD only affect the initial state in the case of leptonic decays, but

- Born (B), virtuals (V) and reals (R) contribute: $V + R$ is free of IR singularities;



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

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

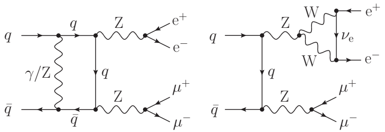
- DPA usually used for LO kinematics (B, V), need for analogous prescription for R and subtraction counterterms (most involved part of the computation), similar considerations hold for NWA;

- separation of polarizations required for all contributions in Eq. 1.

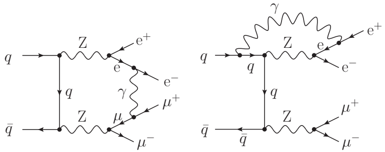
Going beyond leading-order (2)

NLO EW more involved, as production and decay sub-amplitudes are mixed in virtual corrections

Factorizable

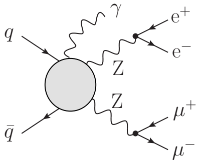


Non-factorizable

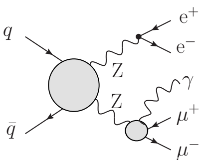


and in real corrections

ISR



FSR

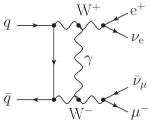


Very recently, a general method has been proposed to separate Z resonant contributions at NLO EW, with leptonic decays [Denner GP 2107.06579].

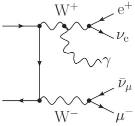
Going beyond leading-order (3)

NLO EW modeling of $W^{\pm}$ bosons is more delicate, as (real and virtual) photons can be radiated off the boson propagator

virtual



real



A tailored treatment, different from the one for Z bosons, is needed for $W^{\pm}$ to ensure the proper subtraction of IR singularities.

2. Di-boson production

W^+W^- and $W^\pm Z$

W^+W^- ($pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$) at NLO QCD + gg-induced [Denner GP 2006.14867]:

- DPA, polarizations defined in the LAB and separated at amplitude level;
- Large K-factor for $W_L^+W_L^-$ ($\approx$ 40%) even with jet veto;
- single-boson polarization fractions roughly conserved from LO to NLO QCD;
- large interferences for some angular distributions.

Extended to NNLO QCD (both with DPA and NWA), no strong modifications of NLO QCD results w.r.t. NLO QCD [Poncelet Popescu 2102.13583].

W^+Z ($pp \to e^+\nu_e\mu^+\mu^-$) at NLO QCD [Denner GP 2010.07149]:

- detailed comparison between LAB and di-boson CM frame definition;
- large K-factors (radiation-zero effect at LO);
- fractions roughly conserved from LO to NLO QCD in the LAB, not in the CM;
- small K-factor for LL in the CM, very large for mixed contributions.

Recently measured by ATLAS (singly-polarized) [ATLAS 1902.05759].

Another approach [Baglio et al. 1810.11034, 1910.13746]: apply master equation to $\cos\theta^*_\ell$ distrib. with lepton cuts $\to$ angular coefficients far from describing polarizations.

ZZ (1)

Very recent calculation of $pp \to e^+e^-\mu^+\mu^- + X$ including NLO QCD+EW corr. and loop-induced contributions [Denner GP 2107.06579]:

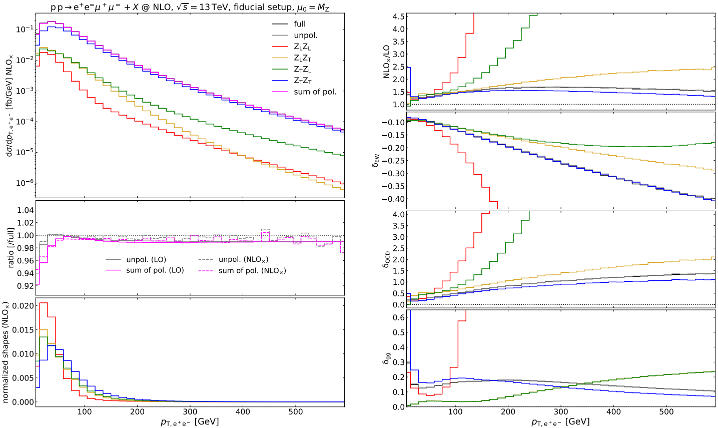
- DPA for both ISR and FSR contributions at NLO EW
- polarizations defined both in LAB and in ZZ-CM at inclusive level, ZZ-CM definition in fiducial setup
- several validation checks in inclusive setup
- fiducial selections mimic those of Ref. [ATLAS 2103.01918]

mode	σ_{LO} [fb]	δ_{QCD}	δ_{EW}	δ_{gg}	σ_{NLO_+} [fb]	$\sigma_{\mathrm{NLO}_\times}$ [fb]
full	$11.1143(5)^{+5.6\%}_{-6.8\%}$	$+34.9\%$	-11.0%	$+15.6\%$	$15.505(6)^{+5.7\%}_{-4.4\%}$	$15.076(5)^{+5.5\%}_{-4.2\%}$
unpol.	$11.0214(5)^{+5.6\%}_{-6.8\%}$	$+35.0\%$	-10.9%	$+15.7\%$	$15.416(5)^{+5.7\%}_{-4.4\%}$	$14.997(4)^{+5.5\%}_{-4.2\%}$
$Z_L Z_L$	$0.64302(5)^{+6.8\%}_{-8.1\%}$	$+35.7\%$	-10.2%	$+14.5\%$	$0.9002(6)^{+5.5\%}_{-4.3\%}$	$0.8769(5)^{+5.4\%}_{-4.1\%}$
$Z_L Z_T$	$1.30468(9)^{+6.5\%}_{-7.7\%}$	$+45.3\%$	-9.9%	$+2.8\%$	$1.8016(9)^{+4.3\%}_{-3.5\%}$	$1.7426(8)^{+4.1\%}_{-3.3\%}$
$Z_T Z_L$	$1.30854(9)^{+6.5\%}_{-7.7\%}$	$+44.3\%$	-9.9%	$+2.8\%$	$1.7933(9)^{+4.3\%}_{-3.4\%}$	$1.7355(8)^{+4.0\%}_{-3.2\%}$
$Z_T Z_T$	$7.6425(3)^{+5.2\%}_{-6.4\%}$	$+31.2\%$	-11.2%	$+20.5\%$	$10.739(4)^{+6.2\%}_{-4.7\%}$	$10.471(3)^{+6.1\%}_{-4.6\%}$

- small non-resonant background (0.5%) and interferences (1.2%)
- multiplicative combination of NLO corr. better motivated (but use with care!)
- fractions conserved from LO to NLO, substantial gg contribution (LL, TT)
- sizeable QCD and EW corrections

ZZ (2)

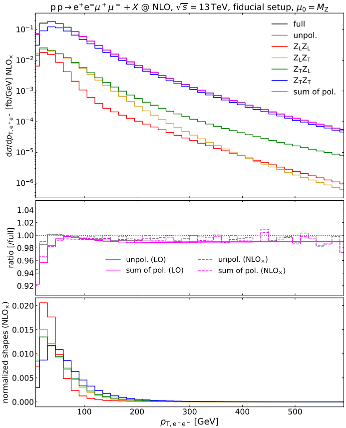
Transverse momentum of the Z boson [$\to e^+e^-(\gamma)$]

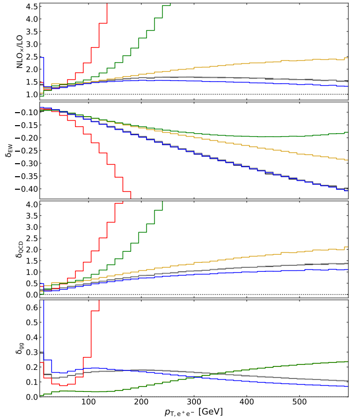


- LL is strongly suppressed at LO (by $1/s^2$ w.r.t. to TT)
- large negative EW (large virtuals) and QCD corrections to LL (huge reals)
- large gluon-induced contributions to LL

ZZ (2)

Transverse momentum of the Z boson [$\rightarrow$ e$^+$e$^-$(γ)]

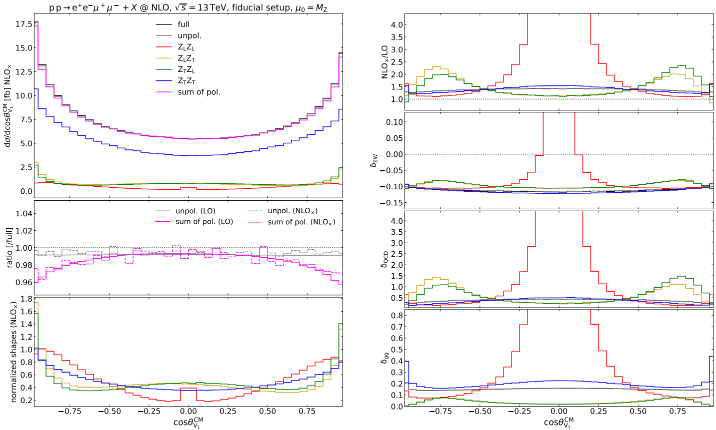




- large QCD corrections to TL (the transverse one decays into $e^+e^-(\gamma)$)
- sizeable interference and non-resonant effects only in soft region
- rather sizeable shape differences among polarized states

ZZ (3)

Scattering angle of Z [$\to e^+e^-(\gamma)$] in the ZZ frame (w.r.t. ZZ-sys. direction in LAB)



- huge radiative corrections to LL around $\theta^{CM}_{V_1} = \pi/2$ (LL vanishes at LO)
- artificial effect for LL due to multiplicative approach, at $\theta^{CM}_{V_1} = \pi/2$
- non-flat K-factors for LT, TL, TT; 3% interferences in (anti)collinear regimes
- marked shape differences among various polarization states

3. Vector-boson scattering

W^+W^-, $W^\pm Z$ and ZZ

Extensive phenomenological studies with PHANTOM Monte Carlo [Ballestrero et al. 0801.3359] at leading order [$\mathcal{O}(\alpha^6)$]:

- double- or single-pole approximation;
- separation of polarizations at amplitude level (SM, SESM, Higgsless);
- possibility to choose between LAB and CM definitions of polarization (v. 1.7);
- first study in W^+W^- [Ballestrero Maina GP 1710.09339] reproduced with MG5 [Buarque-Franzosi et al. 1912.01725];
- realistic study of W^+Z (with neutrino reconstruction) and ZZ, comparison with reweighting method [Ballestrero Maina GP 1907.04722];
- comparison of different polarization definitions in W^+W^+ [Ballestrero Maina GP 2007.07133].

Comparison between SM, Singlet Extension and Higgsless SM [Ballestrero Maina GP 1710.09339, 1907.04722].

Comparison between SM and Composite-Higgs models in the fully-automated (LO) MG5 [Buarque-Franzosi et al. 1912.01725]$\rightarrow$ spin-correlated NWA.

W^+W^+ (1)

Very recently: first measurement by CMS [CMS 2009.09429].

W^+W^+ scattering ($pp \to e^+\nu_e\mu^+\nu_\mu jj$) at LO [Ballestrero Maina GP 2007.07133] in a realistic setup, comparison between LAB and WW-CM definition of polarizations.

	LAB	WW-CM	ratio
full	1.593(2)		-
unpol	1.572(2)		-
0-unpol	0.4226(4)	0.4036(5)	0.96
T-unpol	1.165(1)	1.182(2)	1.01
0-0	0.1185(1)	0.1552(2)	1.31
0-T,T-0	0.3062(3)	0.2519(3)	0.82
T-T	0.8690(9)	0.9350(9)	1.08

Tab. Total cross-sections (fiducial setup) in fb.

Small non-resonant background (missing off-shell effects): 1.5%.

Small interferences among polarization ($\approx -1\%$).

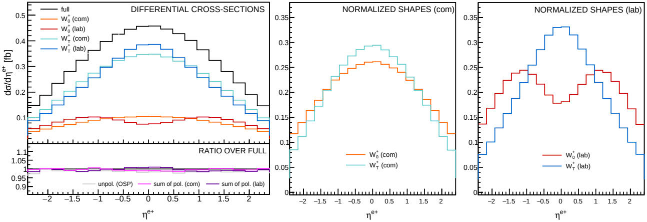
Singly-polarized signals rather insensitive to the polarization definition.

LL and TT signals are enhanced in the WW-CM definition (+31% and +8% respectively). Mixed enhanced in the LAB.

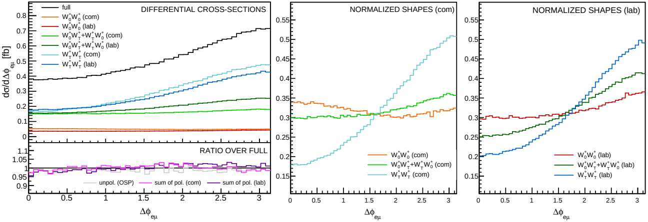
Stronger correlations in the WW-CM (most natural frame in the scattering of bosons).

W^+W^+ (2)

Differential results [Ballestrero Maina GP 2007.07133]:



η_{e^+}: strong shape differences in the transverse mode between two definitions.



$\Delta\phi_{\ell\ell'}$: noticeable shape differences among polarized modes, mostly in the CM.

Results do not favor either of the two definitions, CM better motivated.

4. Higgs-boson decays

Polarized weak bosons from Higgs-boson decays

LO decay amplitude ($\mathrm{H} \rightarrow \mathrm{e}^+\mathrm{e}^-\mu^+\mu^-$): analytic function of decay angles (defined in the Higgs rest frame), $\cos\theta^*_{\mathrm{e}^+}$, $\cos\theta^*_{\mu^+}$ and $\Delta\phi^*_{\mathrm{e}^+\mu^+}$

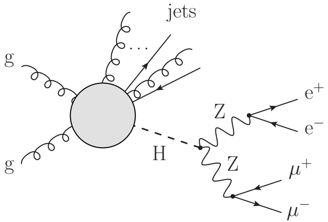
$\rightarrow$ sum of doubly-polarized and interference terms

$$|\mathcal{A}^{\mathrm{SM}}_{\mathrm{H}\rightarrow\mathrm{ZZ}}|^2 = |\mathcal{A}_{\mathrm{L\,L}}|^2 + |\mathcal{A}_{\mathrm{T\,T}}|^2 + 2\,\mathrm{Re}(\mathcal{A}_{\mathrm{L\,L}}{}^*\mathcal{A}_{\mathrm{T\,T}})$$

Polarized events obtained with matrix-element reweighting of unpolarized ones:

$$w_\lambda = \frac{\left|\mathcal{A}_{\lambda\lambda}\right|^2}{\left|\mathcal{A}^{\mathrm{SM}}_{\mathrm{H}\rightarrow\mathrm{ZZ}}\right|^2}\,, \lambda = \mathrm{L},\, \mathrm{T}\,,$$

$\rightarrow$ independently of the production mechanism!



Remark: polarizations defined for off-shell bosons (no DPA possible).

Same treatment as di-boson/VBS only possible for a single boson, via a single-pole approximation, which can be extended to NLO EW.

Polarized W/Z bosons in inclusive gluon-fusion Higgs production [Maina 2007.12080]

Polarized Z bosons: Higgs + 2 jets in gluon-fusion (GGF) and vector-boson fusion (VBF) [Maina GP 2105.07972]

Similar studies were done for anomalous Higgs coupling to longitudinal and transverse boson in WW, within EFT framework [Brehmer et al. 1404.5951]

Higgs + 2 jets in VBF and GGF

Total and differential cross-sections for H+2 jets at the LHC [Maina GP 2105.07972], in the presence of realistic selections.

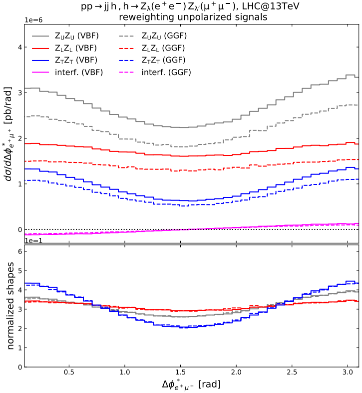
Validation: perfect agreement between reweighted results and Monte-Carlo ones (PHANTOM, MG5).

mode	GGF	VBF
unp.	$6.988(5)\cdot10^{-6}$ pb	$8.566(5)\cdot10^{-6}$ pb
LL	63.60%	64.26%
TT	36.35%	35.67%
interf.	0.05%	0.07%

Polarized signals show the same behaviour in GGF and VBF.

- at the level of polarization fractions
- at the level of polarized-distribution shapes

→ can safely sum over production channels



$\Delta\phi^{*}_{e^+\mu^+}$ (decay angles)

5. Conclusions & outlook

Conclusions & outlook

Very active field, several studies on polarization triggered by recent (and upcoming) experimental measurements.

Much effort is being invested in polarized-boson processes:

- automation of polarized-boson MC simulation (DPA, NWA)
- calculation of higher-order corrections (NLO EW+QCD, NNLO QCD)
- study of polarization-sensitive observables
- techniques for polarization extraction from hadronic decays

with special focus on di-boson production, VBS, Higgs-boson decays.

Wishlist (towards more complete and realistic input for experimental collaborations):

- parton-shower effects in the presence of polarized-bosons
- new-physics effects on polarized-boson production and decay
- more processes and more decay channels

Backup

ZZ production: setup

Process: pp $\rightarrow$ $e^+e^-\mu^+\mu^- + X$.
Accuracy: NLO EW [$\mathcal{O}(\alpha^5)$] + QCD [$\mathcal{O}(\alpha_s\alpha^4)$], gg loop-induced [$\mathcal{O}(\alpha_s^2\alpha^4)$].
Code: in-house Monte Carlo MoCaNLO (makes use of Recola 1 + Collier).
Details: $N_F = 5$, G_μ-scheme for α, Complex-Mass-Scheme for weak bosons.
PDFs.: NNPDF3.1 at NLO with $\alpha_s(M_Z) = 0.118$, LHAPDF interface.
Ren. and fact. scale: $\mu_R = \mu_F = M_Z$.

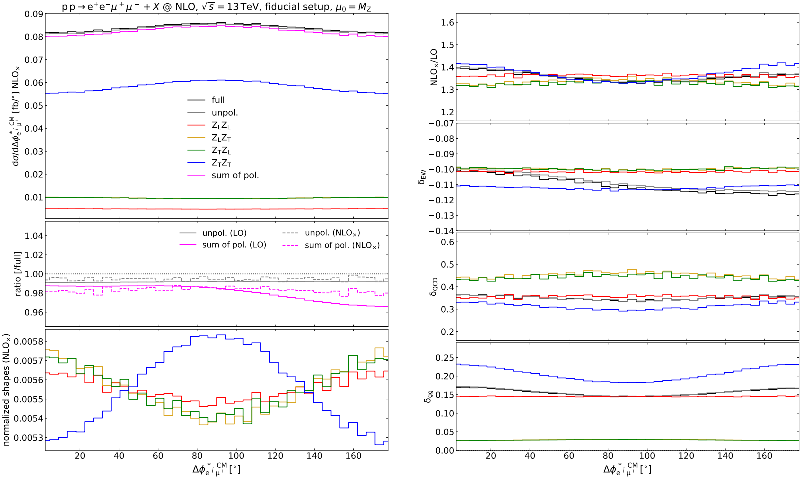
Fiducial selections:

- $p_{T,e^\pm} > 7\,\text{GeV}$, $p_{\mu^\pm} > 5\,\text{GeV}$, $p_{\ell_1} > 20\,\text{GeV}$, $p_{\ell_2} > 10\,\text{GeV}$
- $\Delta R_{\ell\ell'} > 0.05$, $|\eta_{e^\pm}| < 2.47$, $|\eta_{\mu^\pm}| < 2.7$
- $M_{4\ell} > 180\,\text{GeV}$, $|M_{\ell^+\ell^-} - M_Z| < 10\,\text{GeV}$
- no distance cut on QCD-jet kinematics, photon recombination with leptons if $\Delta R_{\ell\gamma} < 0.1$

ZZ production: azimuthal decay angles

Results in the fiducial setup.

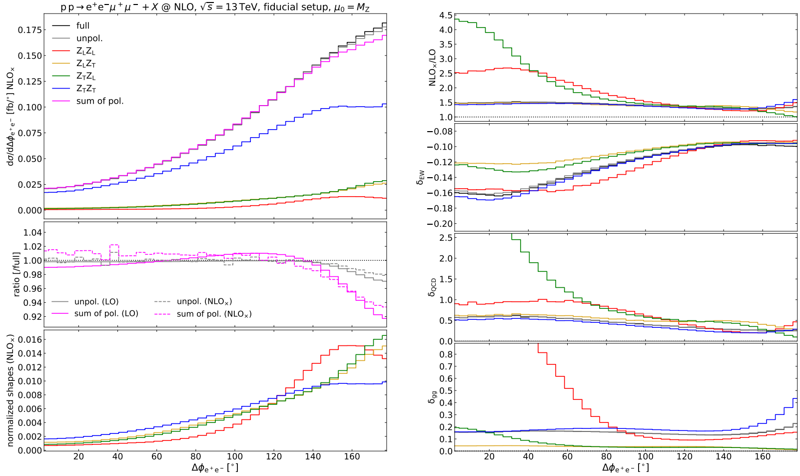
Difference between azimuthal angles of e^+ and μ^+ in the corresponding Z rest frames.



ZZ production: azimuthal positron-electron distance

Results in the fiducial setup.

Azimuthal distance between positron and electron.



W^+W^+ scattering: setup

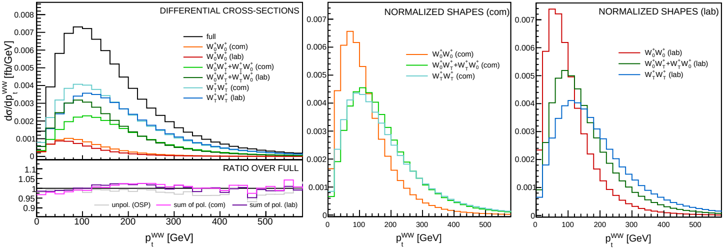
Process: $pp \to e^+\nu_e\mu^+\nu_\mu jj$.
Accuracy: LO EW, $\mathcal{O}(\alpha^6)$.
Code: PHANTOM Monte Carlo.
Details: $N_F = 5$, G_μ-scheme for α, Complex-Mass-Scheme for weak bosons.
PDFs.: NNPDF3.0 at LO with $\alpha_s(M_Z) = 0.118$, LHAPDF interface.
Ren. and fact. scale: $\mu_R = \mu_F = \sqrt{p_{\mathrm{T,j_1}}\, p_{\mathrm{T,j_2}}}$.

Two sets of selection cuts:

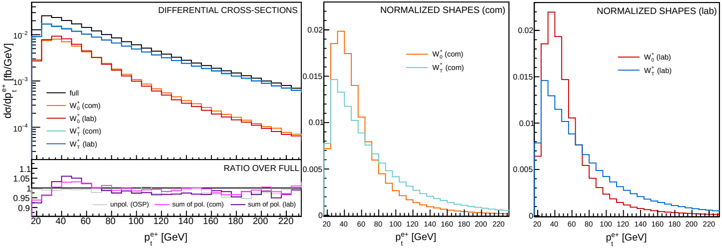
- inclusive: $M_{jj} > 500\,\mathrm{GeV}$, $|\Delta\eta_{jj}| > 2.5$, $|\eta_j| < 5$, $p_{\mathrm{T,j}} > 20\,\mathrm{GeV}$.
- fiducial: $M_{jj} > 500\,\mathrm{GeV}$, $|\Delta\eta_{jj}| > 2.5$, $|\eta_j| < 5$, $p_{\mathrm{T,j}} > 20\,\mathrm{GeV}$, $p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}$, $|y_\ell| < 2.5$, $p_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}$.

W^+W^+ scattering: distributions (fiducial setup)

Transverse momentum of the WW system



Transverse momentum of the positron



$\mathrm{H}+2\mathrm{j}$: setup

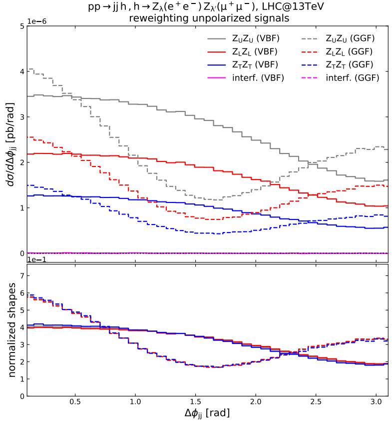
Process: $\mathrm{pp} \to \mathrm{H}(\mathrm{e}^+\mathrm{e}^-\mu^+\mu^-)\,\mathrm{jj}$.
Accuracy: LO EW for VBF, $\mathcal{O}(\alpha^6)$, LO HEFT for GGF, $\mathcal{O}(\alpha_{\mathrm{s}}^2\alpha_{\mathrm{ggH}}\alpha^3)$.
Code: PHANTOM and MADGRAPH 5.
Details: $N_F = 5$, G_μ-scheme for α, Complex-Mass-Scheme for weak bosons.
PDFs.: NNPDF3.0 at LO with $\alpha_{\mathrm{s}}(M_Z) = 0.118$, LHAPDF interface.
Ren. and fact. scale: $\mu_R = \mu_F = \sqrt{p_{\mathrm{T,j_1}}\,p_{\mathrm{T,j_2}}}$.

Fiducial selections:

- $M_{\mathrm{jj}} > 300\,\mathrm{GeV}$, $|\Delta\eta_{\mathrm{jj}}| > 2.5$, $\eta_{\mathrm{j},1}\cdot\eta_{\mathrm{j},2} < 0$, $|\eta_{\mathrm{j}}| < 4.5$, $p_{\mathrm{T,j}} > 25\,\mathrm{GeV}$
- $M_{\mathrm{e}^+\mathrm{e}^-}, M_{\mu^+\mu^-} > 10\,\mathrm{GeV}$, $|\eta_\ell| < 2.5$, $p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}$ ($\ell = \mathrm{e},\mu$)
- $120\,\mathrm{GeV} < M_{4\ell} < 130\,\mathrm{GeV}$

H + 2j: distributions (fiducial setup)

Azimuthal separation between tagging jets



Invariant mass of the $e^+\mu^+$ system