Max-Planck-Institut
für Physik

Polarized weak bosons at the LHC: automation at NLO QCD+EW accuracy

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Outline

Based on work with A. Ballestrero, E. Maina (Torino), A. Denner, C. Haitz (Würzburg).

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.

Polarizations of EW bosons

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

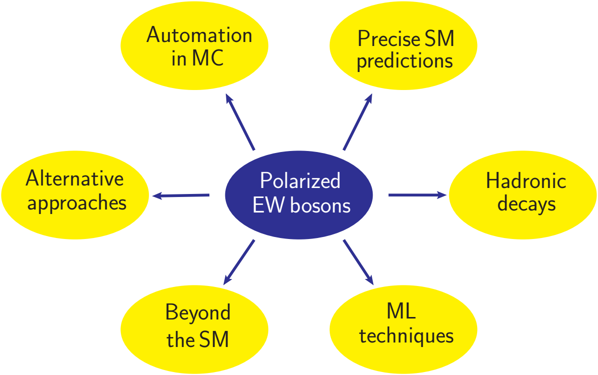
Special interest in di-boson production, vector-boson scattering, Higgs-boson and top-quark decays.

What can we do?

We cannot be directly measure polarizations of EW bosons.

But we can perform fits of LHC data with polarized templates.

Theory input:
proper understanding, precise predictions and new ideas to extract polarizations.



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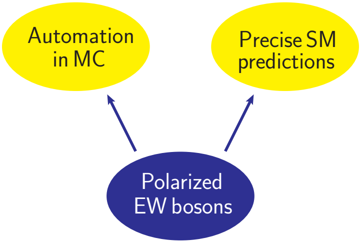
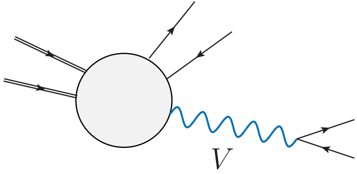


THIS TALK

2. Theory & Monte Carlo

Separating polarizations 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:

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

Note that polarization states are not Lorentz invariant: defined in a specific frame.

Decay-lepton angular distributions reflect polarization state of the decayed V boson [Bern et al. 1103.5445, Stirling et al. 1204.6427, Belyaev et al. 1303.3297].

Angular coefficients: inclusive cuts

• 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]:

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

$X \rightarrow$ independent of decay angles (*e.g.* p_T^V, η_V). $A_i = A_i(X)$.

• No lepton cuts: (i) extract $\{A_i\}$ from unpolarized distrib., via suitable projections.

(ii) interferences vanish upon integration over full azimuth ϕ^*,

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}\mathrm{f}_-\left(1+\cos^2\theta^* - \frac{2(c_L^2-c_R^2)}{(c_L^2+c_R^2)}\cos\theta^*\right) + \frac{3}{8}\mathrm{f}_+\left(1+\cos^2\theta^* + \frac{2(c_L^2-c_R^2)}{(c_L^2-c_R^2)}\cos\theta^*\right) + \frac{3}{4}\mathrm{f}_\mathrm{L}\sin^2\theta^*, \quad (2)$$

$\mathrm{f}_\mathrm{L}, \mathrm{f}_-, \mathrm{f}_+$ polarization fractions of the V boson ($\mathrm{f}_\mathrm{L} + \mathrm{f}_- + \mathrm{f}_+ = 1$).

• If lepton cuts applied, analytic expression for $d\sigma/d\cos\theta^*$ does not hold anymore.

Angular coefficients: realistic effects

• Idea: $\{A_i\}$ extracted from unpol. distrib. with projections [Baglio et al. 1810.11034] or asymmetries [Rahaman Singh 2109.09345] also with lepton cuts and radiative corrections.

Applied to $W^{\pm}Z$ (NLO EW + QCD) [Baglio et al. 1810.11034, 1910.13746], Z+jet (NLO EW) [Frederix Vitos 2007.08867], with EFT effects [Rahaman Singh 1810.11657, 1911.03111, 2109.09345].

Assumption: LO spin-density matrix, two-body decays, full acceptance in the decay.

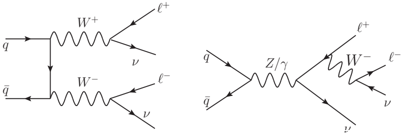
A nice idea, but:

1. radiative corrections modify the LO spin-density matrix;
2. with cuts on decay products, LO expansion (Eq. 1) does not describe angular distributions → coefficients $\{A_i\}$ do not describe properly spin-correlations [Baglio et al. 1810.11034, Frederix Vitos 2007.08867]; interferences do not vanish (cannot integrate over full ϕ^* range) → $\{f_i\}$ extracted from Eq. 2 are not pol. fractions [Stirling et al.1204.6427, Belyaev et al.1303.3297].

→ we can do better: generate polarized events!

Selecting resonant diagrams

To define polarizations, we need a factorized amplitude (production $\otimes$ propagator $\otimes$ 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.

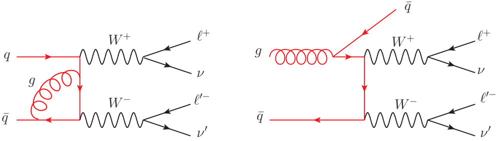
- Non-resonant diagrams regarded as non-resonant background.

- Resonant diagrams treated 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].

$\rightarrow$ separating polarizations 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]:

$$d\sigma_{\text{nlo}}/d\xi = \int d\phi_n \Big(B + V + \int d\phi_{\text{rad}}\, D\Big)_{d=4} \delta_\xi^{(n)} + \int d\phi_{n+1} \Big(R\, \delta_\xi^{(n+1)} - D\, \delta_\xi^{(n)}\Big)_{d=4}\,; \quad (3)$$

- DPA/NWA usually used for LO kinematics (B, V), need analogous prescription for R and subtraction c-terms (most involved part of the computation);

- separation of polarizations required for all contributions in Eq. 3.

Corrections only affect production of resonance(s) $\longrightarrow$ conceptually straightforward.

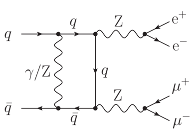
This is the case of N(N)LO QCD corrections in the presence of leptonic decays [Denner GP 2006.14867, Poncelet Popescu 2102.13583].

Going beyond leading-order: NLO corrections to the decays

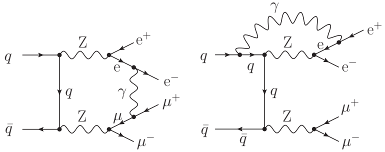
Corrections affect both production and decays of resonance(s) $\longrightarrow$ more involved: production and decay sub-amplitudes are mixed in virtual and real corrections.

This is the case of NLO EW corrections to Z boson(s) with leptonic decays.

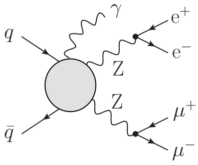
Factorizable



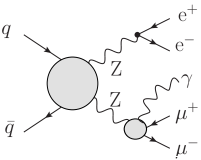
Non-factorizable



ISR



FSR



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: technical details

DPA applied to the subtracted real:

- Only factorizable corrections considered:

$$|\mathcal{A}^{(n+1)}_{\rm ISR}+\mathcal{A}^{(n+1)}_{\rm FSR_1}+\mathcal{A}^{(n+1)}_{\rm FSR_2}|^2 \longrightarrow |\mathcal{A}^{(n+1)}_{\rm ISR}|^2+|\mathcal{A}^{(n+1)}_{\rm FSR_1}|^2+|\mathcal{A}^{(n+1)}_{\rm FSR_2}|^2$$

- ISR treated with DPA for two 2-body decays:

$$|\mathcal{A}^{(n+1)}_{\rm ISR}|^2 \xrightarrow{\rm DPA(2,2)} |\overline{\mathcal{A}}^{(n+1)}_{\rm ISR}|^2$$

- $\rm FSR_{(\mathit{i})}$ treated with DPA for one 2-body and one 3-body decay:

$$|\mathcal{A}^{(n+1)}_{\rm FSR_{(i)}}|^2 \xrightarrow{\rm DPA(3,2)} |\overline{\mathcal{A}}^{(n+1)}_{\rm FSR_{(i)}}|^2$$

- Subtraction dipoles must be treated consistently: first DPA, second Catani-Seymour (CS) mappings (no commutation for FSR).

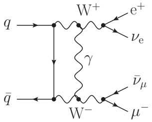
- DPAs preserve angles and energy fractions of decay products in resonance CM frame $\rightarrow$ to avoid mismatch approaching soft and collinear regimes.

- DPA doesn't modify radiation variables: no modification in integrated dipoles.

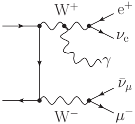
Going beyond leading-order: W bosons

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:

- decay: subtraction dipole for an initial massive particle ($W \to \ell\nu + \gamma$)
- production: subtraction dipoles for final massive particles ($q\bar{q} \to WW$)

Applied very recently for NLO EW corrections to $W^{\pm}Z$ production with leptonic decays [Le Baglio 2203.01470, 2208.09232].

3. Phenomenology

SM results relevant for the LHC

Publicly available MC that simulate (intermediate) polarized bosons are LO accurate:

1. Phantom (v1.7): $2 \to 6$ processes at LO in the DPA, interfaced to PS [Ballestrero Maina GP 1710.09339, 1907.04722, 2007.07133, Maina GP 2105.07972].
2. MG5_aMC@NLO (v2.7): any process at LO in the NWA, interfaced with PS [Buarque-Franzosi et al. 1912.01725]. NLO QCD automation ongoing.

Recent precise predictions mostly target inclusive di-boson and V+jet production:

- $\rightarrow$ $W^+W^-\,(\ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'})$: NLO QCD + loop-ind. in the DPA [Denner GP 2006.14867], NNLO QCD + loop-ind. in the DPA and NWA [Poncelet Popescu 2102.13583];
- $\rightarrow$ $ZZ\,(\ell^+\ell^-\ell'^+\ell'^-)$: NLO EW + QCD in the DPA [Denner GP 2107.06579];
- $\rightarrow$ $W^\pm Z\,(\ell^\pm\nu_\ell\ell'^+\ell'^-)$: NLO QCD [Denner GP 2010.07149] and NLO QCD+EW [Le Baglio 2203.01470, 2208.09232] in the DPA;
- $\rightarrow$ $W^\pm(\ell^\pm\nu_\ell)+j$: NNLO QCD in the NWA [Pellen et al. 2109.14336].

ZZ (4ℓ) production: integrated results

Calculated [Denner GP 2107.06579] with MoCaNLO + Recola1 [Actis et al. 1605.01090] + Collier [Denner et al. 1604.06792]. Fiducial selections of recent ATLAS results [ATLAS 2103.01918].

NLO EW, NLO QCD and loop-induced combined additively and multiplicatively:

$$d\sigma_{\mathrm{NLO}_+} = d\sigma_{\mathrm{LO}}\left(1 + \delta_{\mathrm{QCD}} + \delta_{\mathrm{EW}}\right) + d\sigma_{\mathrm{LO}}\delta_{\mathrm{gg}}$$

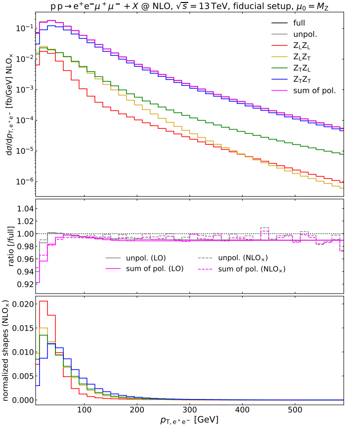
$$d\sigma_{\mathrm{NLO}_\times} = d\sigma_{\mathrm{LO}}\left(1 + \delta_{\mathrm{QCD}}\right)\left(1 + \delta_{\mathrm{EW}}\right) + d\sigma_{\mathrm{LO}}\delta_{\mathrm{gg}}$$

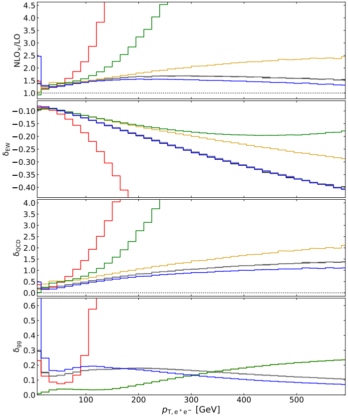
mode	σ_{LO} [fb]	δ_{QCD}	δ_{EW}	δ_{gg}	σ_{NLO_+} [fb]	$\sigma_{\mathrm{NLO}_\times}$ [fb]
full	$11.1143(5)^{+5.6\%}_{-6.8\%}$	$+34.9\%$	-11.0%	$+15.6\%$	$15.505(6)^{+5.7\%}_{-4.4\%}$	$15.076(5)^{+5.5\%}_{-4.2\%}$
unpol.	$11.0214(5)^{+5.6\%}_{-6.8\%}$	$+35.0\%$	-10.9%	$+15.7\%$	$15.416(5)^{+5.7\%}_{-4.4\%}$	$14.997(4)^{+5.5\%}_{-4.2\%}$
$Z_L Z_L$	$0.64302(5)^{+6.8\%}_{-8.1\%}$	$+35.7\%$	-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

Distributions for the Z-boson transverse momentum

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





- 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

Distributions for the Z-boson transverse momentum

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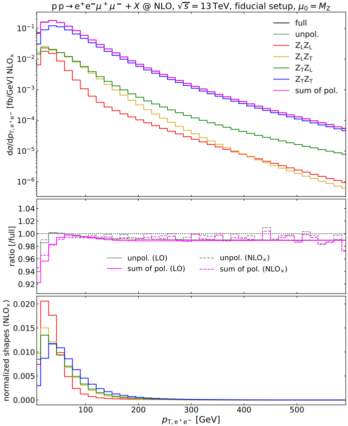
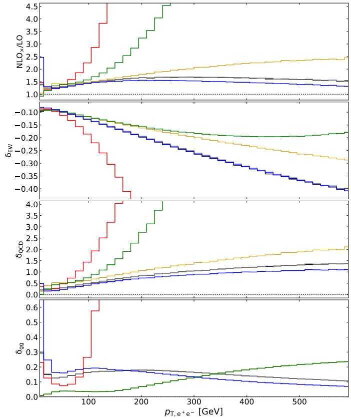
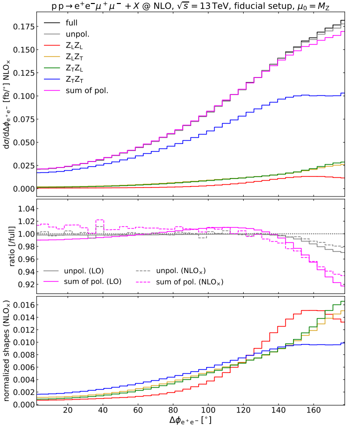


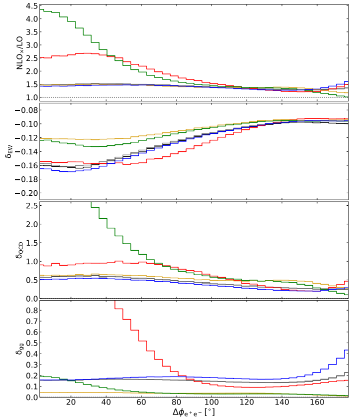


- large QCD corrections to TL (the transverse one decays into $e^+e^-(\gamma)$)
- sizeable interference and non-resonant effects only in soft region
- rather sizeable shape differences among polarized states

Distributions in the azimuthal positron-electron distance

Azimuthal distance between positron and electron.

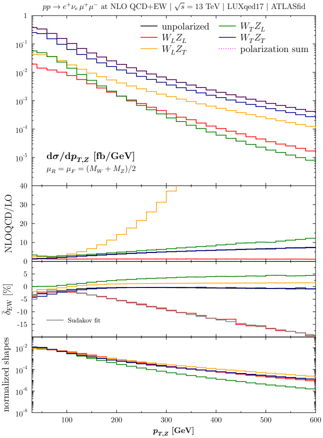




- sizeable non-res. bkg and interferences in most populated region
- huge QCD real corrections (gq) for TL, huge gg-induced contrib. for LL
- marked shape differences for polarized curves: good discrimination power

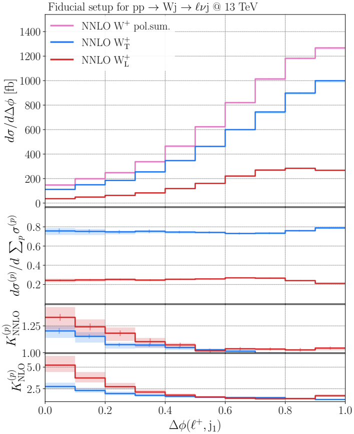
$W^{\pm}Z\,(3\ell)$ and $W^{\pm}$+jet production

NLO QCD+EW [Le Baglio 2203.01470] in the DPA for doubly-polarized $W^{\pm}Z$.



QCD corrections dominate, EW effects relevant for LL in p_T-distribution tails.

NNLO QCD for polarized-W +jet [Pellen et al. 2109.14336] in the NWA.



Higher-order QCD corrections modify differently L and T shapes. Fair comparison against CMS 2017 data.

4. Conclusions

Conclusions

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

Much effort invested in SM predictions for 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.

What's missing (polarized processes):

- matching to parton-shower and hadronization,
- BSM/SMEFT effects on production and decay,
- higher-order SM predictions for VBS
- precise modeling of hadronic decays (boosted topologies)

Backup

A remark for ZZ

Leading-order on-shell ZZ production, polarized partonic cross-sections as functions of s (CoM energy) and θ (scattering angle):

$$\frac{d\sigma_{\mathrm{LL}}}{d\cos\theta} = \frac{\pi\alpha^2(c_{\mathrm{L,q}}^4 + c_{\mathrm{R,q}}^4)}{96\, \mathrm{s_w}^4\, \mathrm{c_w}^4}\, \frac{\mathrm{M_Z}^4\, \cos^2\theta}{s^3 \sin^2\theta} + \mathcal{O}\left(\frac{1}{s^4}\right)$$

$$\frac{d\sigma_{\mathrm{LT}}}{d\cos\theta} = \frac{\pi\alpha^2(c_{\mathrm{L,q}}^4 + c_{\mathrm{R,q}}^4)}{12\, \mathrm{s_w}^4\, \mathrm{c_w}^4}\, \frac{\mathrm{M_Z}^2}{s^2} + \mathcal{O}\left(\frac{1}{s^3}\right)$$

$$\frac{d\sigma_{\mathrm{TT}}}{d\cos\theta} = \frac{\pi\alpha^2(c_{\mathrm{L,q}}^4 + c_{\mathrm{R,q}}^4)}{48\, \mathrm{s_w}^4\, \mathrm{c_w}^4}\, \frac{1+\cos^2\theta}{s\, \sin^2\theta} + \mathcal{O}\left(\frac{1}{s^2}\right)$$

Equivalence theorem: production of $\phi^+\phi^-$ has vanishing cross-section (no triple gauge coupling) $\rightarrow$ LL is much suppressed at high energy.

LL also vanishes at $\theta = \pi/2$.

Setup(s)

Process: $pp \to e^+e^-\mu^+\mu^- + X$.

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: $\mu_R = \mu_F = M_Z$.

Inclusive selections:

- $p_\ell > 0.001\,\text{GeV}$, $|M_{\ell^+\ell^-} - M_Z| < 10\,\text{GeV}$

Fiducial selections mimic those of a recent ATLAS measurement [ATLAS 2103.01918]:

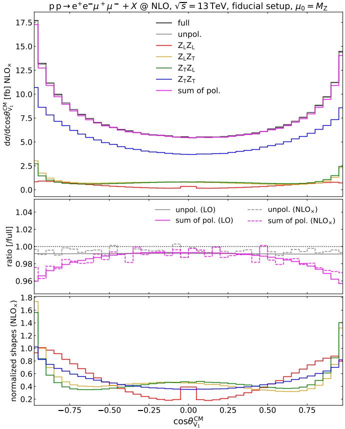
- $p_{T,e^\pm} > 7\,\text{GeV}$, $p_{\mu^\pm} > 5\,\text{GeV}$, $p_{\ell_1} > 20\,\text{GeV}$, $p_{\ell_2} > 10\,\text{GeV}$
- $\Delta R_{\ell\ell'} > 0.05$, $|\eta_{e^\pm}| < 2.47$, $|\eta_{\mu^\pm}| < 2.7$
- $M_{4\ell} > 180\,\text{GeV}$, $|M_{\ell^+\ell^-} - M_Z| < 10\,\text{GeV}$

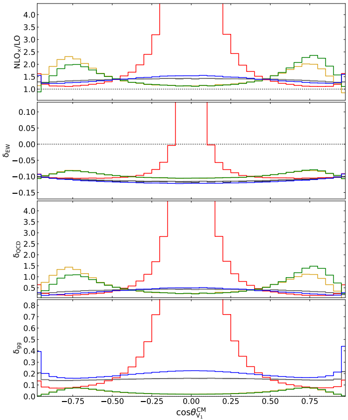
No distance cut on QCD jets, photon recombination with leptons if $\Delta R_{\ell\gamma} < 0.1$.

More details in Ref. [Denner GP 2107.06579].

Distributions for the scattering angle

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

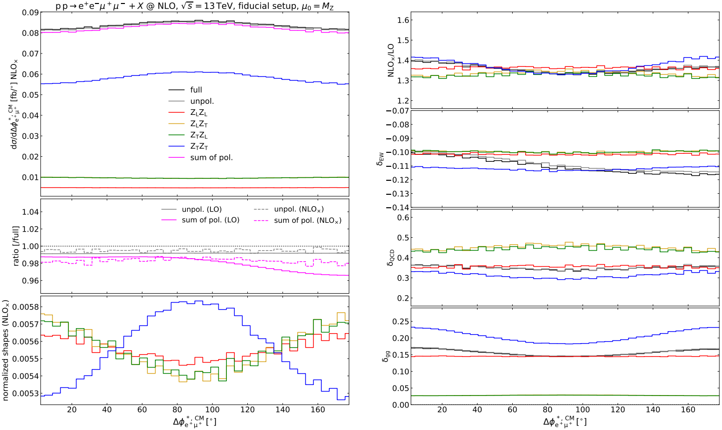




- huge radiative corrections to LL around $\theta_{V_1}^{\mathrm{CM}} = \pi/2$ (LL vanishes at LO)
- artificial effect for LL due to multiplicative approach, at $\theta_{V_1}^{\mathrm{CM}} = \pi/2$
- non-flat K-factors for LT, TL, TT; 3% interferences in (anti)collinear regimes
- marked shape differences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

Distributions for the azimuthal-decay-angle difference

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



- interference pattern at LO, flatter and small for combined NLO
- marked difference in TT shape, compared to LL and mixed ones
- Rather flat K-factors for polarized distributions