Theoretical predictions for polarized electroweak bosons at the LHC

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Introduction

Motivations

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

$\longrightarrow$ precise measurements of multi-boson processes.

Polarizations of electroweak (EW) bosons

- are non trivial to extract
- are important probes of the Standard Model (SM) gauge and Higgs sectors
- may provide discrimination power between SM and beyond-SM physics

Special interest in vector-boson scattering, due to unitarity cancellations.

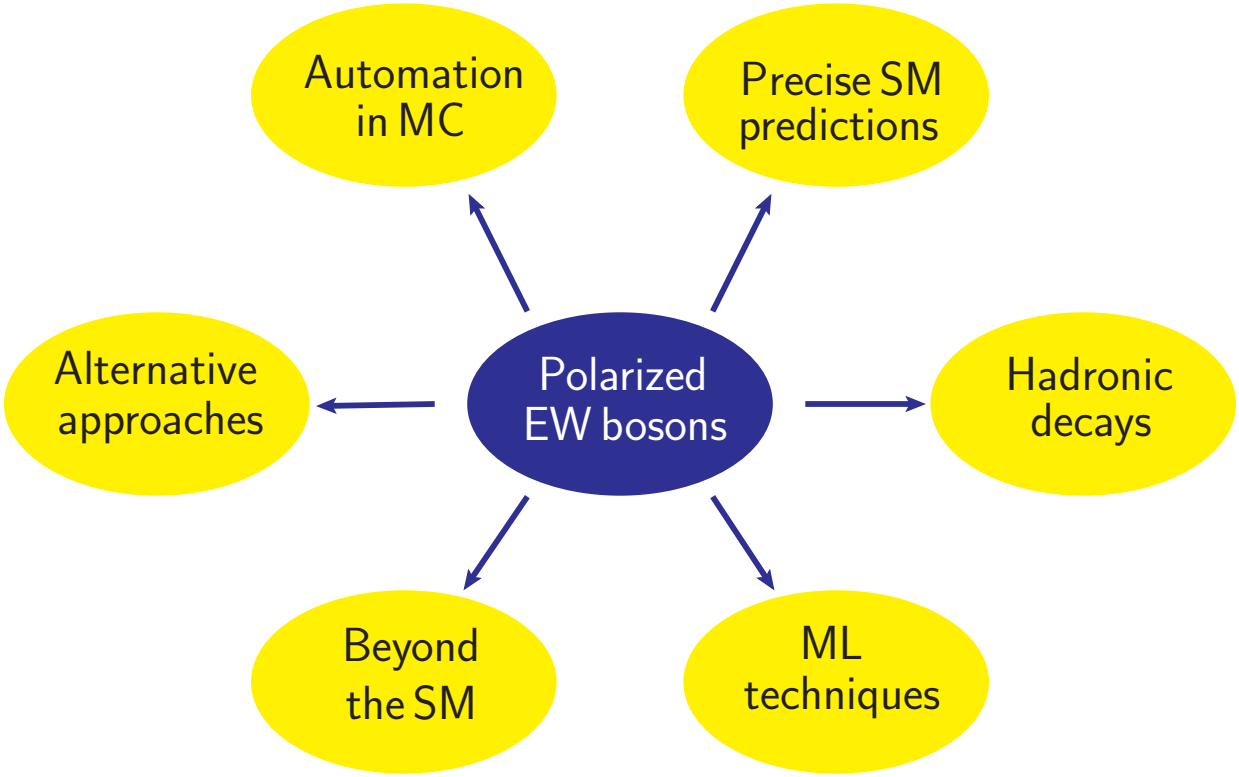
But there is much more: di-boson, top-quark and Higgs decays, V+jet ...

What can we do?

Polarizations of EW bosons cannot be directly measured.

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

What's needed from the theory side?
Precise predictions and new ideas to extract polarizations.



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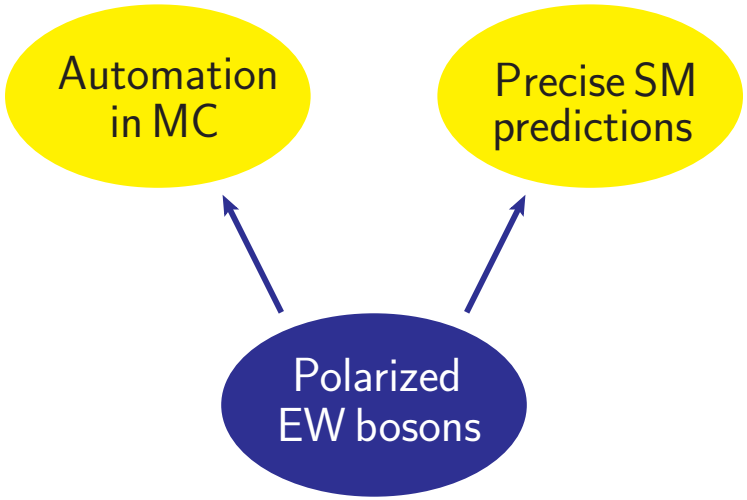
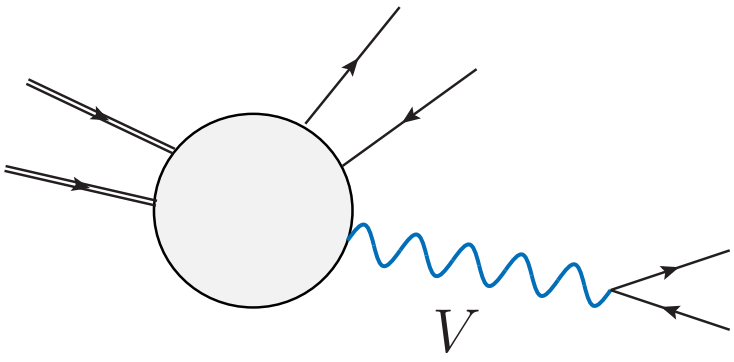


THIS TALK

Theory and Monte Carlo

Separating polarizations in amplitudes

A natural definition for resonant diagrams (in pole/narrow-width approximation):



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

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

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

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

- No lepton cuts: extract $\{A_i\}$ from unpolarized distrib., via suitable projections.
- No lepton cuts: 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 decayed V boson ($\mathrm{f}_\mathrm{L} + \mathrm{f}_- + \mathrm{f}_+ = 1$).

Angular coefficients: realistic effects

• Idea: study unpolarized distributions in terms of $\{A_i\}$ extracted with projections [Baglio et al. 1810.11034] or asymmetries [Rahaman Singh 2109.09345] also in the presence of lepton cuts and radiative corrections.

Applied to inclusive $W^{\pm}Z$ (NLO EW + QCD) [Baglio et al. 1810.11034, 1910.13746], di-boson processes (LO, EFT) [Rahaman Singh 1810.11657, 1911.03111, 2109.09345] and Z+jet (NLO EW) [Frederix Vitos 2007.08867].

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

A nice idea, but:

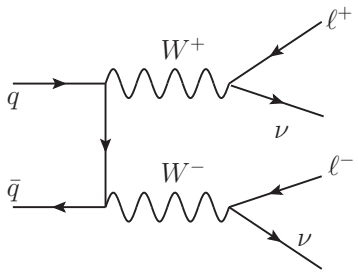
1. radiative corrections modify the LO spin-density matrix;
2. with cuts on decay products, LO expansion (Eq. 1) does not describe angular distributions $\rightarrow$ coefficients $\{A_i\}$ do not describe properly spin-correlations [Baglio et al. 1810.11034, Frederix Vitos 2007.08867]; interferences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

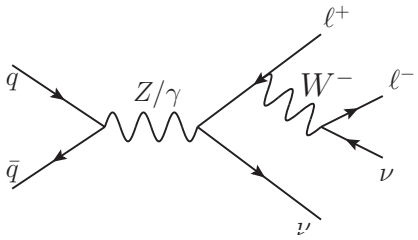
$\rightarrow$ we can do better: generate polarized events!

Separating resonant contributions

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

To define polarizations, we need a factorized amplitude (production $\otimes$ propagator $\otimes$ decay): not possible for all contributions:





For non-resonant ones, polarizations not defined: drop them, providing a recipe to recover gauge invariance.

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

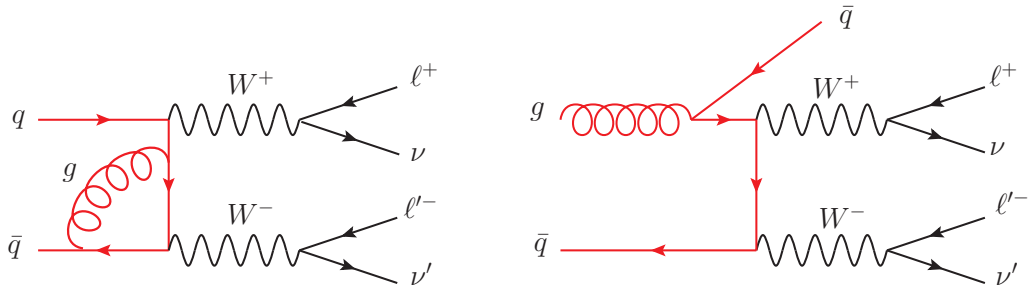
- Treat resonant diagrams with double-pole approximation [Denner et al. 0006307, Ballestrero et al. 1710.09339, Denner GP 2006.14867] or with a spin-correlated narrow-width approximation (NWA) [Artoisenet et al. 1212.3460, Buarque Franzosi et al. 1912.01725].

- Consider non-resonant diagrams and resonant contributions beyond the DPA/NWA as non-resonant background.

- Then separating polarizations is 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]:

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

- 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.

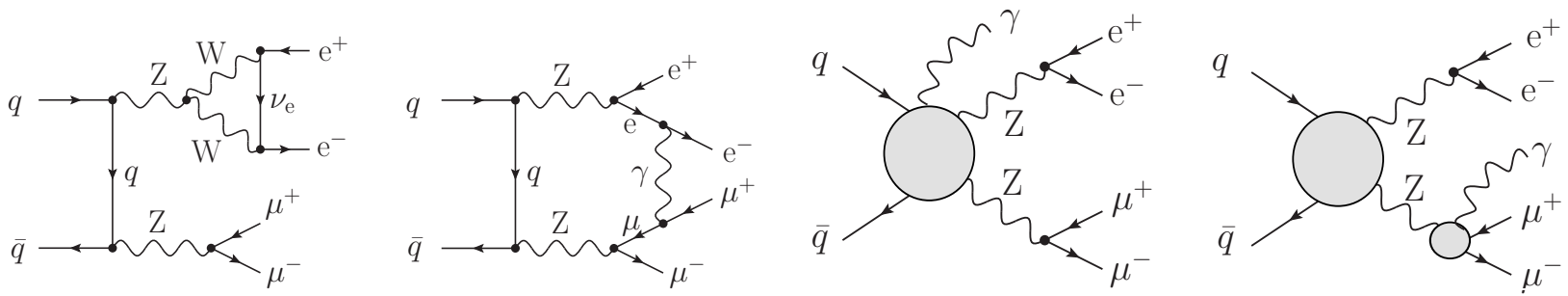
Corrections only affect production of resonance(s) $\longrightarrow$ conceptually straightforward.

This is the case of N(N)LO QCD corrections in the presence of leptonic decays.

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.



A general method has been proposed to separate Z resonant contributions including NLO EW effects in the production and in the decay [Denner GP 2107.06579].

Applicable to NLO QCD corrections in the presence of hadronic decays of W/Z's.

Method extended recently to NLO EW corrections to W boson(s) with leptonic decays: need to account for photon radiation off resonant W bosons [Le Baglio 2203.01470].

Phenomenology

SM results relevant for the LHC

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

1. PHANTOM: $2 \to 6$ processes at LO in the DPA. VBS [Ballestrero et al. 1710.09339, 1907.04722, 2007.07133 and Higgs decays [Maina GP 2105.07972]. Interfaced with PS.
2. MadGraph5_aMC@NLO: any process at LO in the NWA [Buarque-Franzosi et al. 1912.01725]. Interfaced with PS, NLO QCD automation ongoing.

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

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

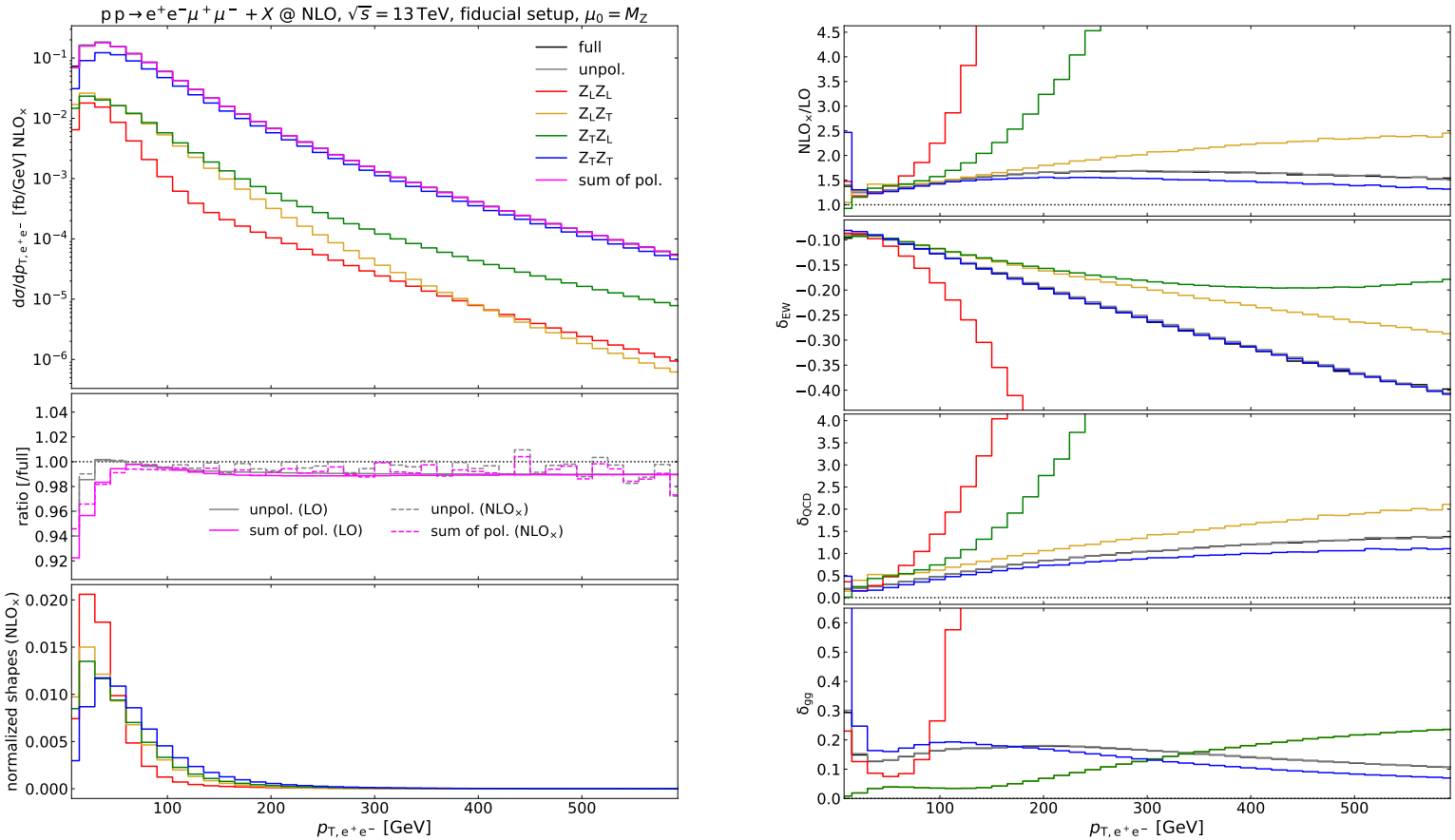
$$d\sigma_{\mathrm{NLO}_+} = d\sigma_{\mathrm{LO}}\,(1+\delta_{\mathrm{QCD}}+\delta_{\mathrm{EW}}) + d\sigma_{\mathrm{LO}}\delta_{\mathrm{gg}}$$
$$d\sigma_{\mathrm{NLO}_\times} = d\sigma_{\mathrm{LO}}\,(1+\delta_{\mathrm{QCD}})\,(1+\delta_{\mathrm{EW}}) + d\sigma_{\mathrm{LO}}\delta_{\mathrm{gg}}$$

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

ZZ (4ℓ) production: differential results

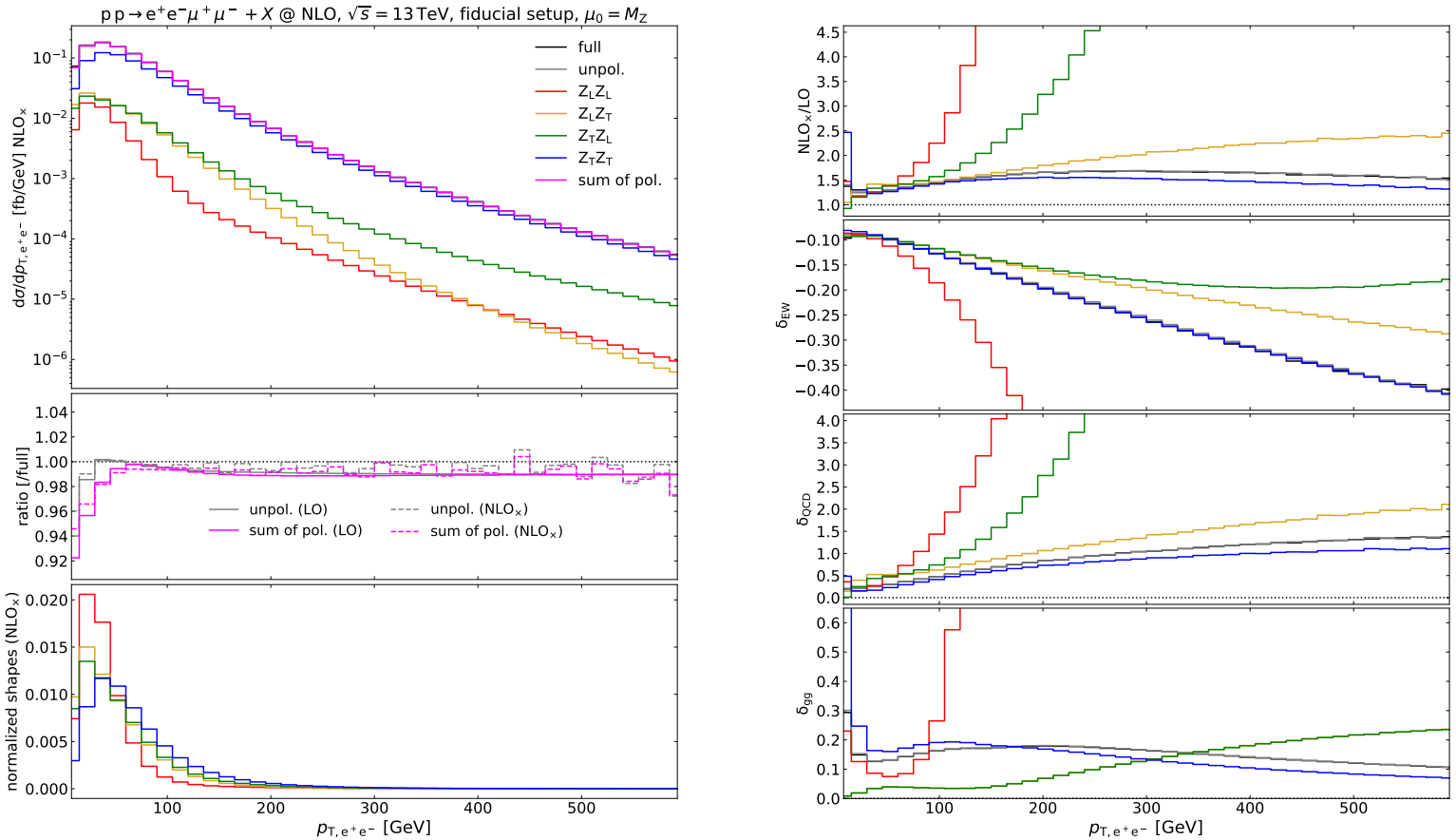
Transverse momentum of the Z boson [$\to e^+e^-(\gamma)$]: an extreme case



- 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 (4ℓ) production: differential results

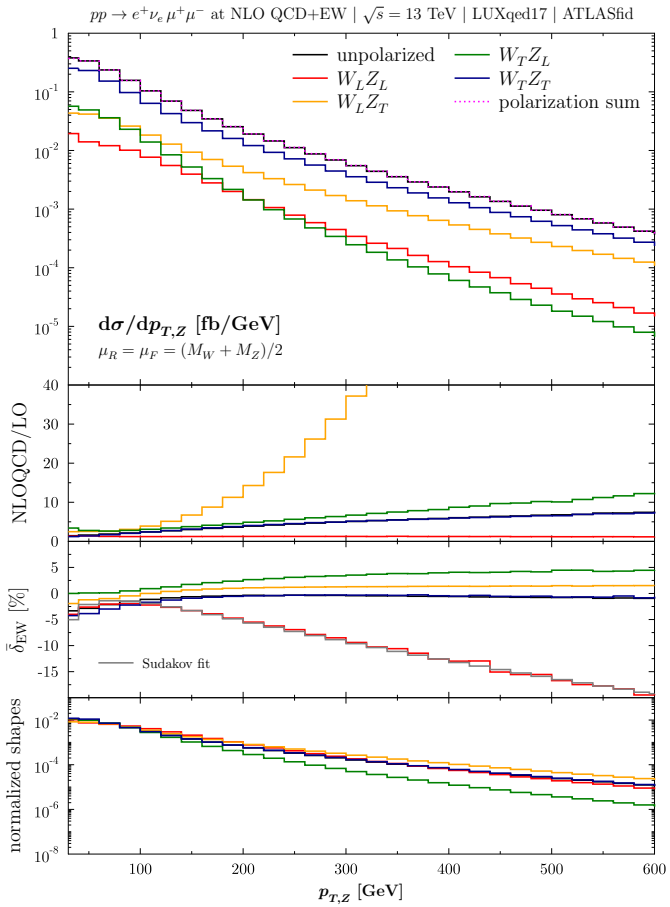
Transverse momentum of the Z boson [$\to e^+e^-(\gamma)$]: an extreme case



- 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

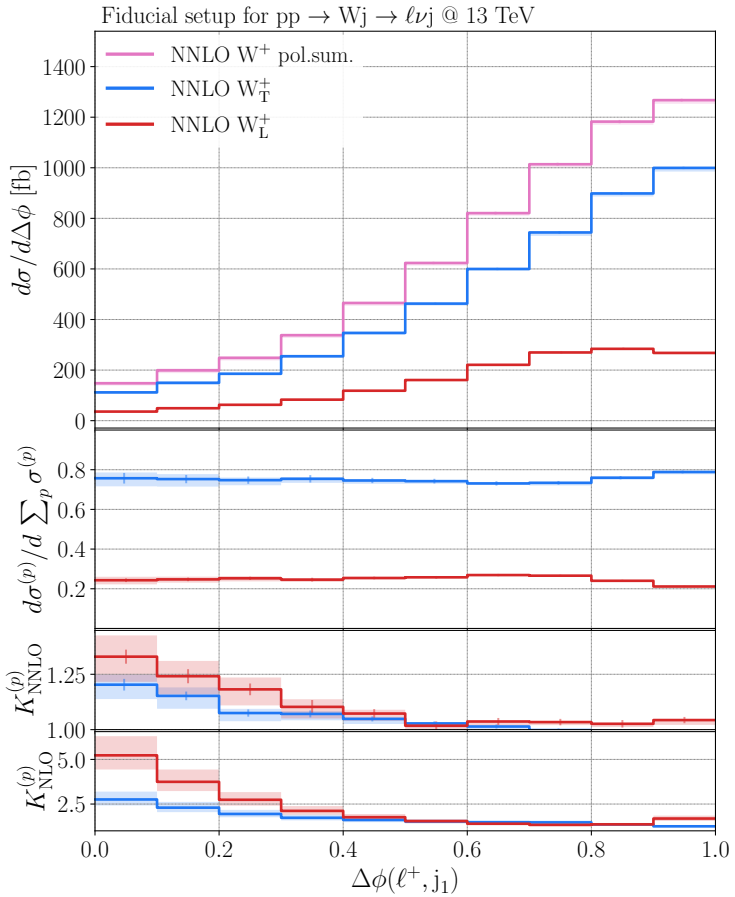
$W^{\pm}Z\,(3\ell)$ and $W^{\pm}$+jet production

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.

Conclusions

Conclusions and outlook

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

Much effort is being 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.

Towards realistic input for experimental collaborations:

- parton-shower effects in the presence of polarized-bosons,
- more processes and decay channels: hadronic decays.

Backup

NLO EW modeling for Z bosons: technical details

DPA applied to the subtracted real:

- Only factorizable corrections considered:

$$|\mathcal{A}_{\rm ISR}^{(n+1)} + \mathcal{A}_{\rm FSR1}^{(n+1)} + \mathcal{A}_{\rm FSR2}^{(n+1)}|^2 \longrightarrow |\mathcal{A}_{\rm ISR}^{(n+1)}|^2 + |\mathcal{A}_{\rm FSR1}^{(n+1)}|^2 + |\mathcal{A}_{\rm FSR2}^{(n+1)}|^2$$

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

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

- FSRi treated with DPA for one 2-body and one 3-body decay:

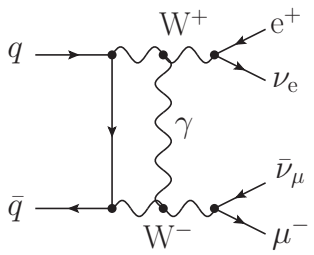
$$|\mathcal{A}_{\rm FSRi}^{(n+1)}|^2 \xrightarrow{\rm DPA(3,2)} |\overline{\mathcal{A}}_{\rm FSRi}^{(n+1)}|^2$$

- 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.

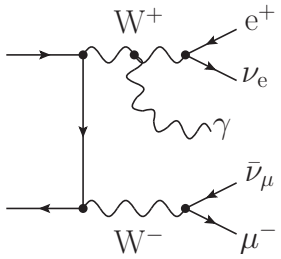
NLO EW modeling for W bosons

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

virtual



real



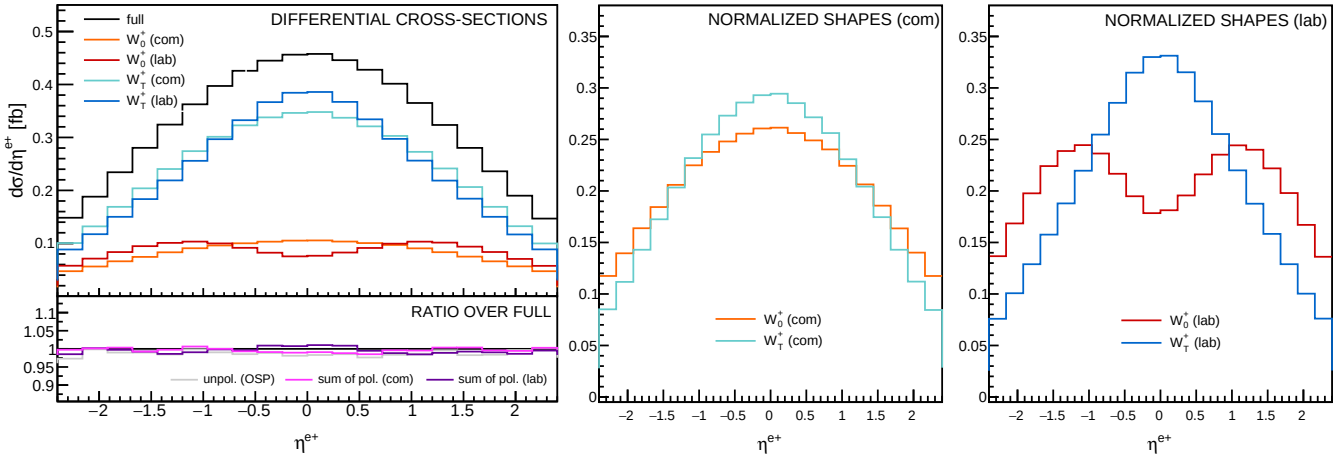
A tailored treatment, different from the one for Z bosons, is needed for $W^{\pm}$ to ensure the proper subtraction of IR singularities:

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

Automation in public MCs

Automation of polarized VBS in PHANTOM (v1.7) at LO EW [Ballestrero et al. 1710.09339, 1907.04722, 2007.07133, Maina GP 2105.07972] using DPA, in SM, SESM and Higgsless SM.

Fiducial results in W^+W^+ scattering [Ballestrero Maina GP 2007.07133], positron rapidity:



Automation at LO of polarized-resonance simulation in MG5_aMC@NLO (v2.7) [Buarque-Franzosi et al. 1912.01725] using NWA, in SM and BSM models.

- Validation: first study with PHANTOM in W^+W^- scattering [Ballestrero Maina GP 1710.09339] reproduced with MG5 [Buarque-Franzosi et al. 1912.01725].

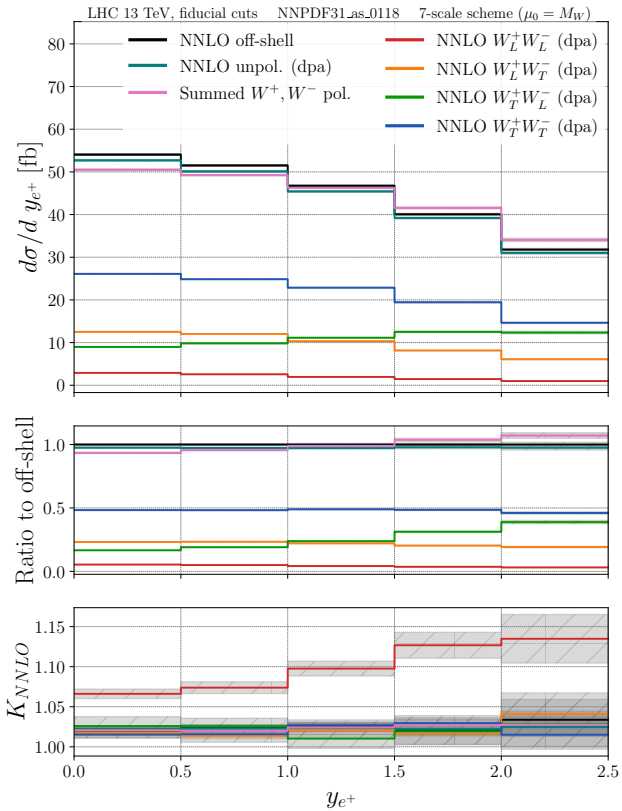
Both MC's are interfaced to parton-shower.

NLO QCD automation planned in MG5_aMC@NLO.

Precise predictions: more results

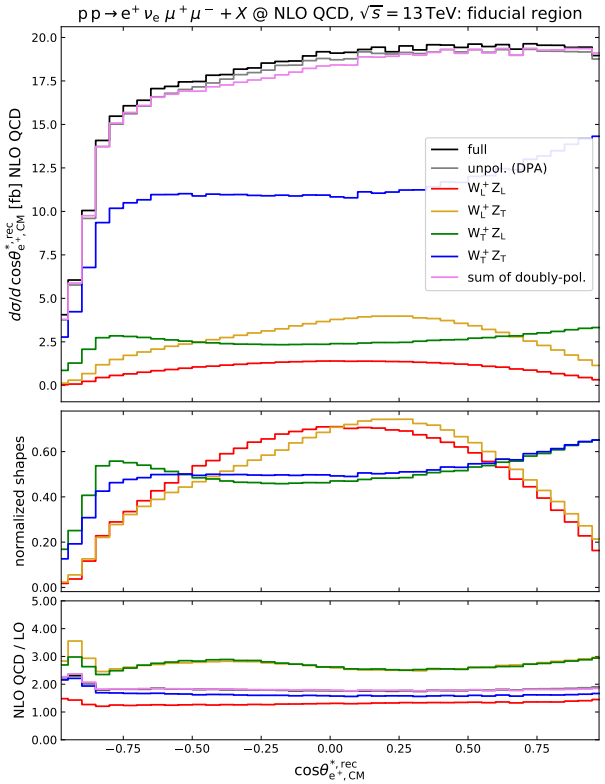
Most of the effort in inclusive di-boson with leptonic decays.

NLO [Denner GP 2006.14867] and NNLO QCD [Poncelet Popescu 2102.13583] for W^+W^- in the DPA and NWA.



QCD corrections distort shapes, milder effect on pol. fractions. Loop-induced gg relevant.

NLO QCD for W^+Z [Denner GP 2010.07149] in the DPA.



Differences between pol. definitions, strong neutrino-reco. effects.