Polarized-boson production at the LHC

Current status of theory predictions

Giovanni Pelliccioli

Universität Würzburg, Institut für Theoretische Physik und Astrophysik

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

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

Polarizations of electroweak (EW) bosons

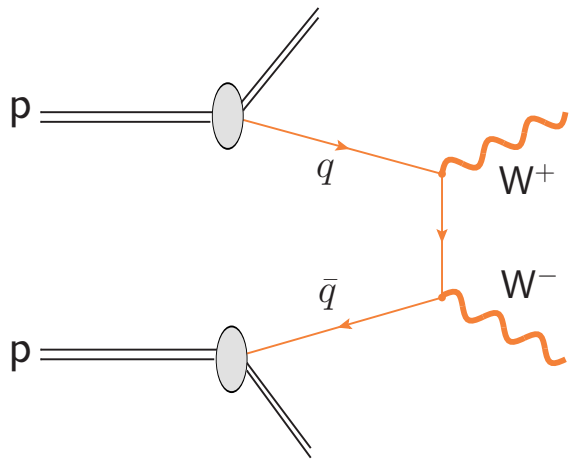
- are non trivial to extract
- are important probes of the Standard Model (SM) gauge and Higgs sectors
- may provide discrimination power between SM and beyond-SM physics

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

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

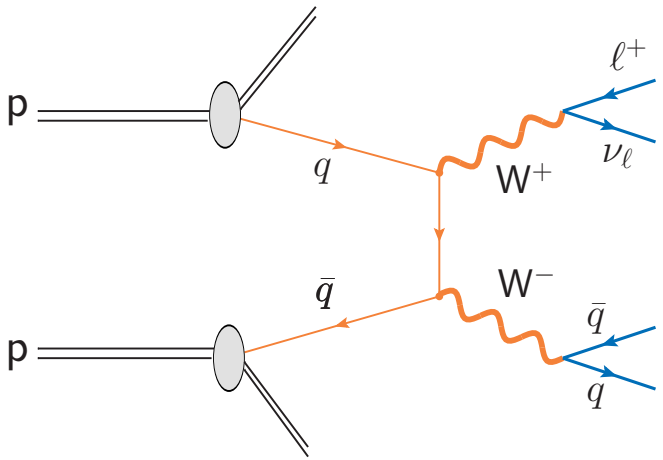
How can we actually access polarizations?

Bottlenecks



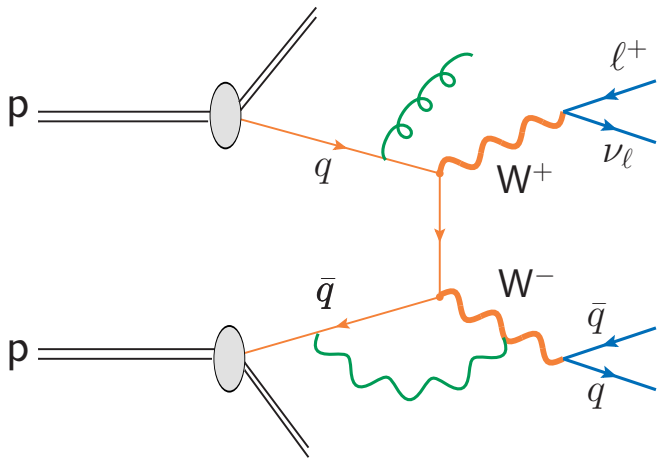
Ideally we would like to measure the polarization of on-shell EW bosons,
but they are unstable.

Bottlenecks



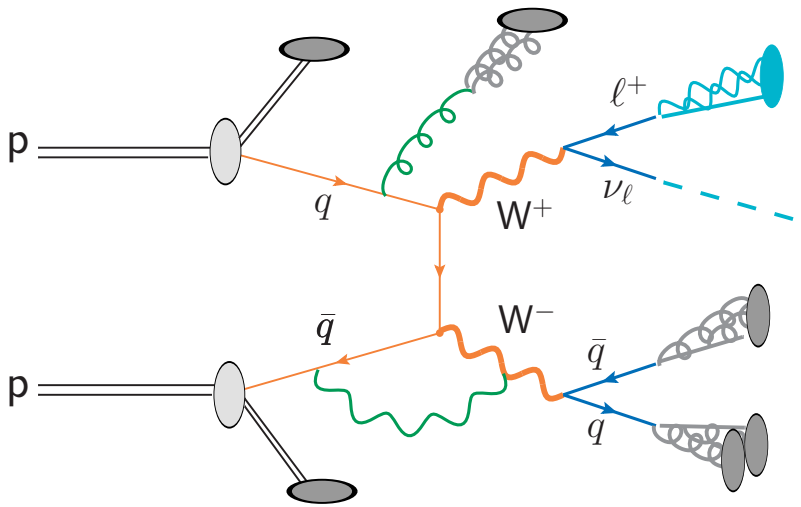
From decay products we can extract polarization information,
but complications both in leptonic (neutrino) and hadronic (jets) decays.

Bottlenecks



Radiative corrections improve description of the hard scattering,
but polarizations well-defined for on-shell bosons, complications in higher-orders.

Bottlenecks



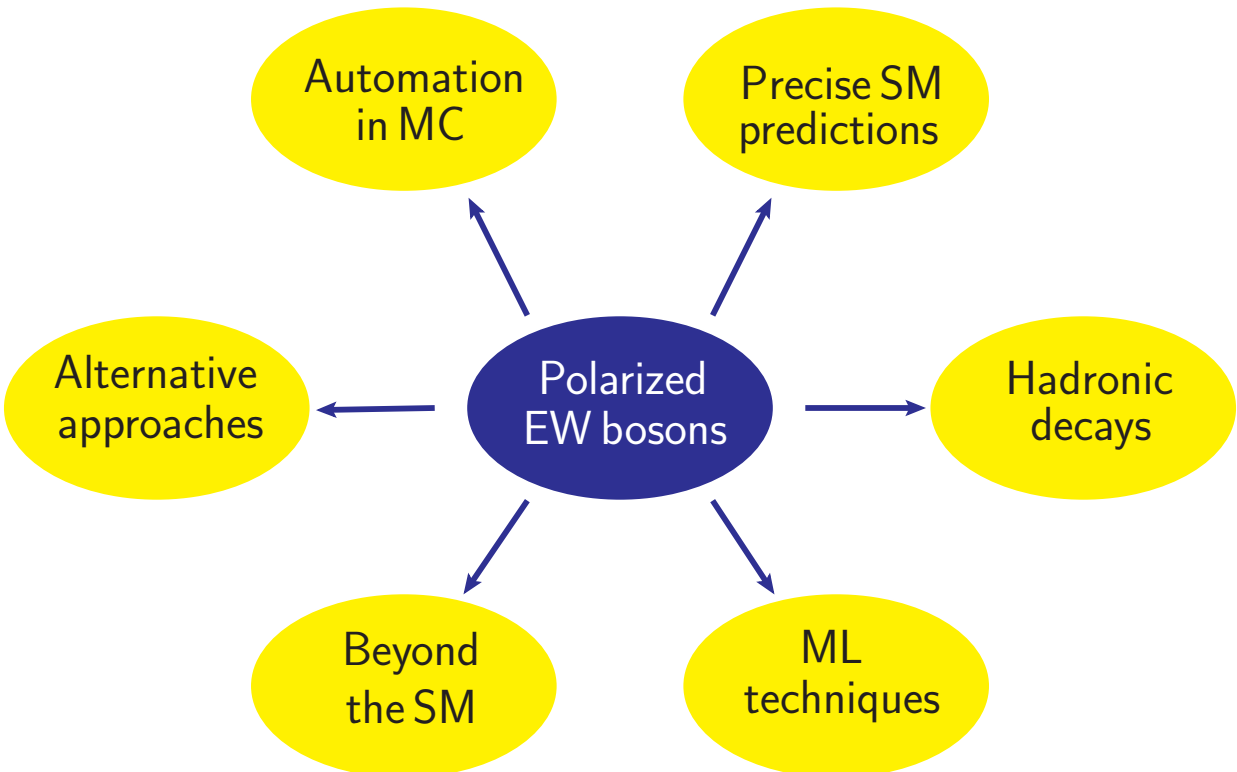
Parton shower and hadronization bring us closer to exp. data,
but deteriorate sensitivity to polarizations.

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.



Interlude: experimental results

With Run-1 data:

$W+$ 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], combined measurements of W-boson polarization in top-quark decay [CMS, ATLAS 2005.03799].

With Run-2 data:

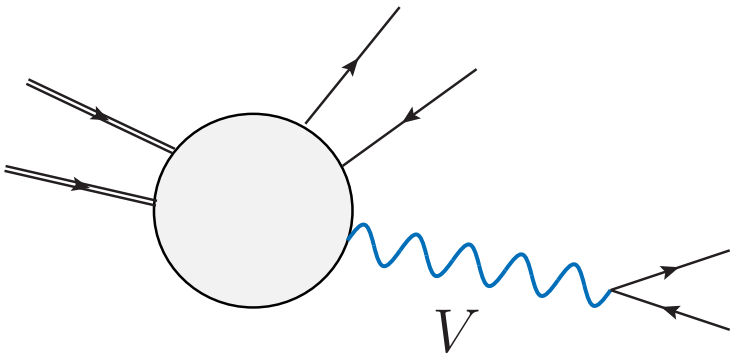
single-boson polarization in inclusive WZ [ATLAS 1902.05759], doubly-polarized signals in $\mathrm{W}^{\pm}\,\mathrm{W}^{\pm}$ scattering [CMS 2009.09429].

More analyses ongoing with Run-2 data.

HL LHC Run will allow for more refined and new measurements [CMS-PAS-FTR-18-014, CERN-LPCC-2018-03, Roloff et al. 2108.00324].

Automation in MC (1)

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 pol. vectors are not Lorentz covariant: 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].

Automation in MC (2)

- 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:

$$\frac{d\sigma}{d\cos\theta^* d\phi^* dX} = g(\theta^*, \phi^*, X) = \sum_{i=1}^{8} A_i(X) P_i(\theta^*, \phi^*)$$

$$\rightarrow \quad A_i(X) = \int_{-1}^{1} d\cos\theta^* \int_0^{2\pi} d\phi^* g(\theta^*, \phi^*, X) P_i(\theta^*, \phi^*)$$

- No lepton cuts: interferences vanish upon integration over full azimuth ϕ^*,

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

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

Automation in MC (3)

• 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:

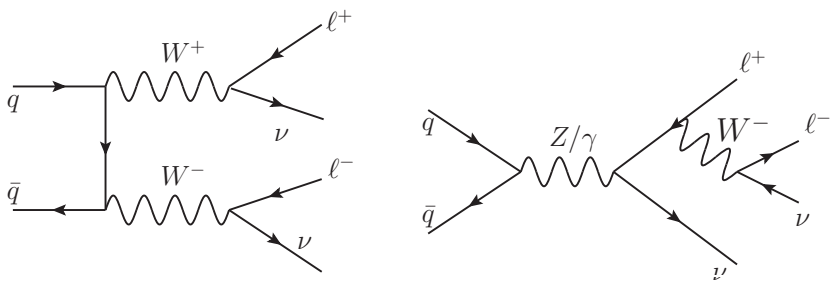
1. radiative corrections modify the LO spin-density matrix (*e.g.* Lam-Tung violation [Gauld et al. 1708.00008]);
2. with cuts on decay products, LO expansion (Eq. 1) does not describe angular distributions $\rightarrow$ coefficients $\{A_i\}$ do not describe properly spin-correlations [Baglio et al. 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!

Automation in MC (4)

- 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.

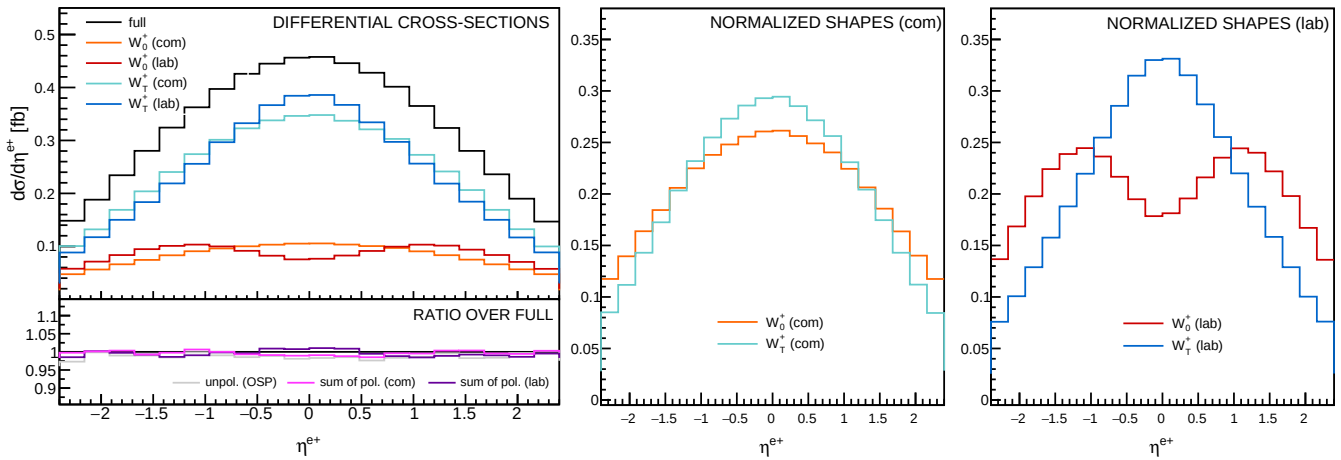
Separating resonant contributions is delicate: the only "truth" is the full computation.

- 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.

Automation in MC (5)

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].

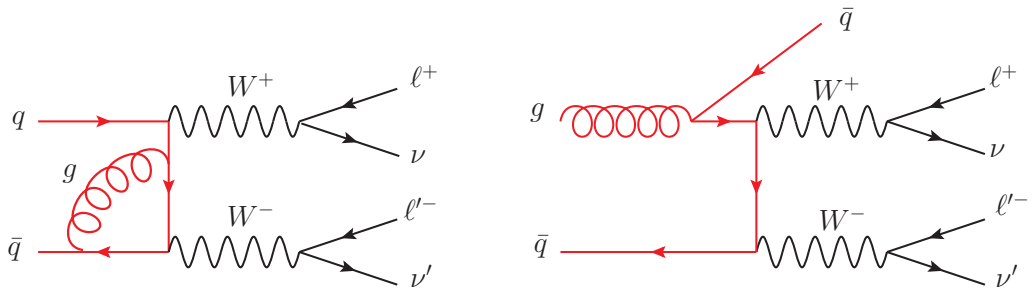
Both MC's are interfaced to parton-shower.

NLO QCD automation planned in MG5_aMC@NLO.

Precise SM predictions (1)

We need to go beyond LO:

- NLO QCD: virtual (V) and real (R) contributions, $V + R$ free of IR singularities;



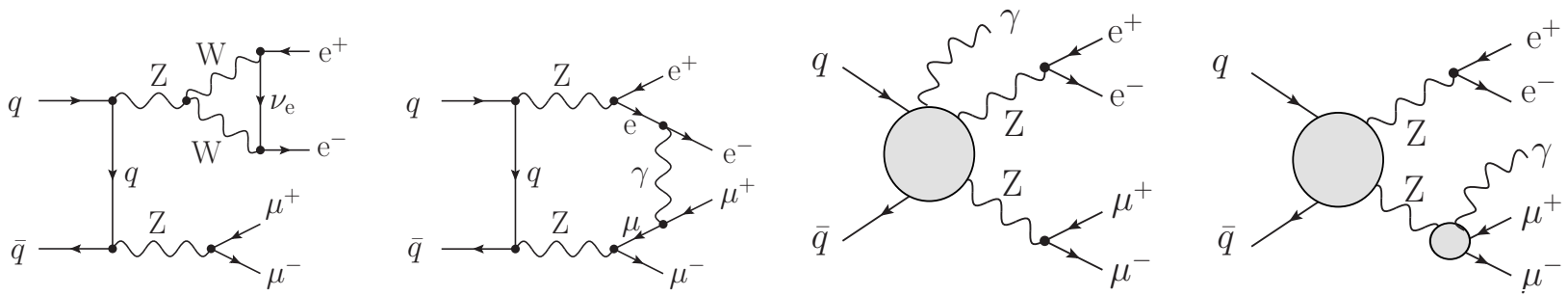
- subtraction counterterms needed, *e.g.* dipole formalism [Catani, Seymour 9605323]:

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

- 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;
- approach applicable to higher QCD orders (considering leptonic decays).

Precise SM predictions (2)

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



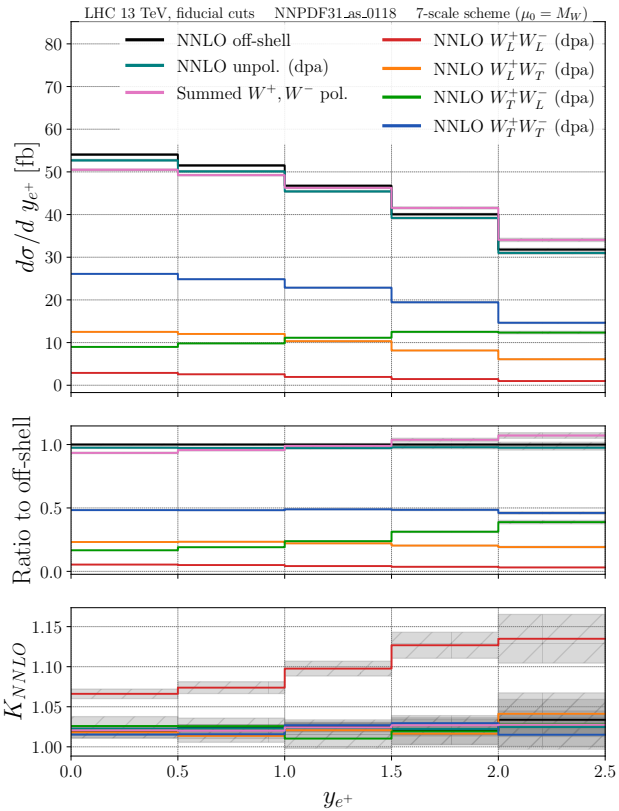
Recently, a general method has been proposed to separate Z resonant contributions at NLO EW, with leptonic decays [Denner GP 2107.06579].

NLO EW modeling of $W^{\pm}$ bosons is more delicate as photons can be radiated off the boson propagator: tailored treatment to ensure proper subtraction of IR singularities.

Precise SM predictions (3)

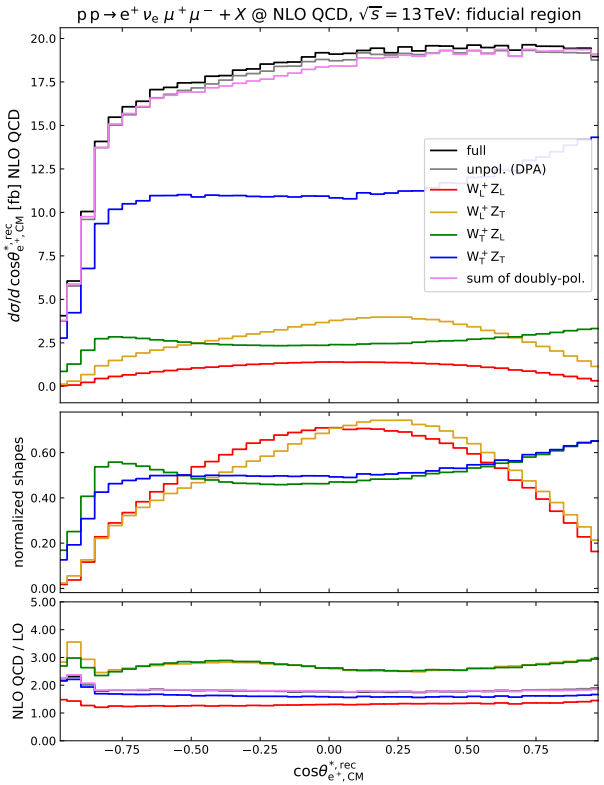
Most of the effort in inclusive di-boson with leptonic decays.

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.

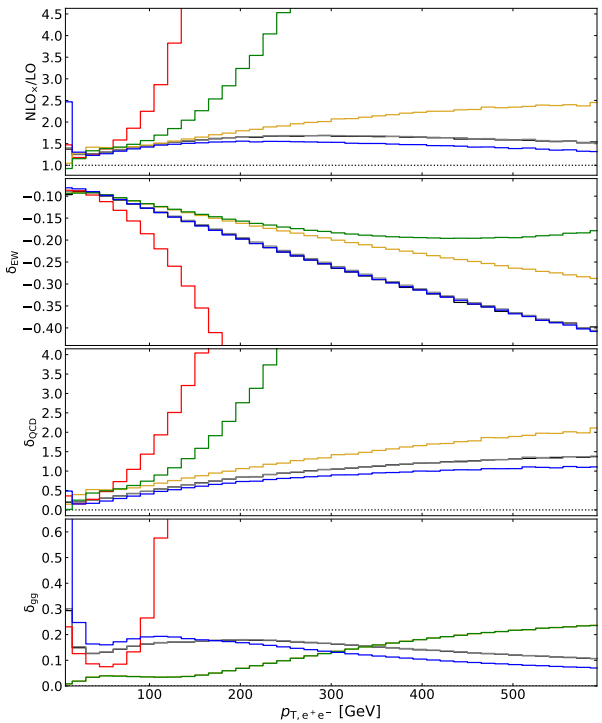
NLO QCD for W^+Z [Denner GP 2010.07149] in the DPA.



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

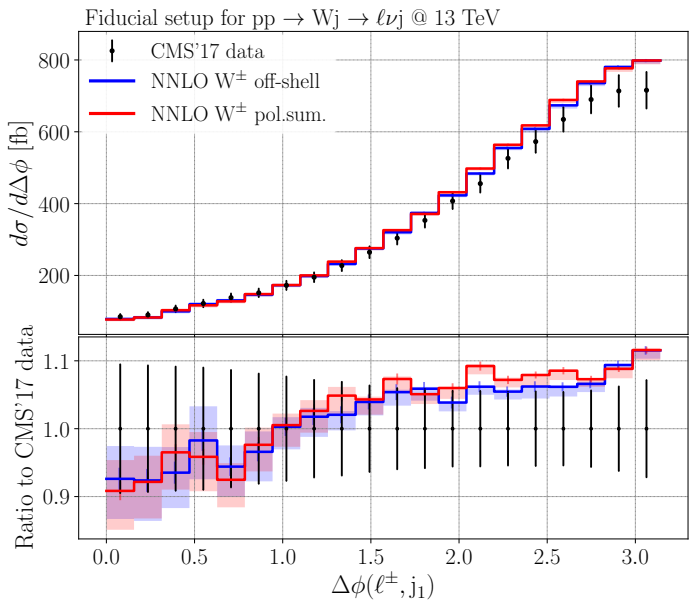
Precise SM predictions (4)

NLO EW + QCD for ZZ [Denner GP 2107.06579] in the DPA (LL is suppressed at LO).



Strong distortions for LL shape (red) due to NLO EW, QCD and loop-induced.

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



Fair comparison against CMS 2017 data.

Also NLO EW+QCD in $W^{\pm}Z$ production [Baglio et al. 1810.11034, 1910.13746] using alternative approach of projections of decay-angle distributions.

Hadronic decays

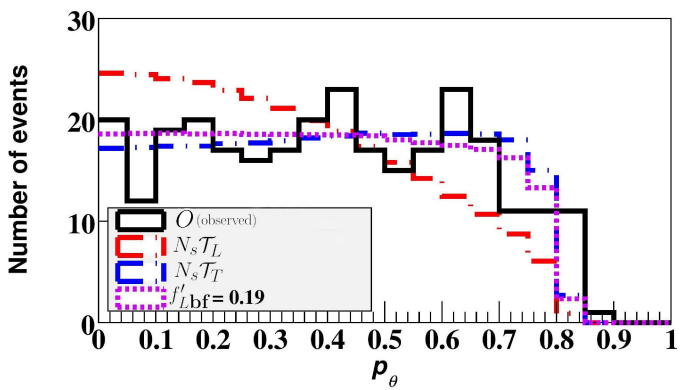
More statistics, no neutrinos, but jet-reconstruction needed.

Decay products are two jets that can be highly collimated (single fat jet) in boosted regimes (*i.e.* $p_{\mathrm{T,V}} \gtrsim 200$ GeV) $\rightarrow$ no access to $\cos\theta^*_q$.
Proxies available [De et al. 2008.04318]:

$$p_\theta = \frac{|E^{\mathrm{reco}}_{\mathrm{subj1}} - E^{\mathrm{reco}}_{\mathrm{subj2}}|}{p^{\mathrm{reco}}_V},$$

which can be reconstructed with N-subjettiness [De et al. 2008.04318, Dey Samui 2110.02773] or with convolutional NN [Kim Martin 2102.05124].

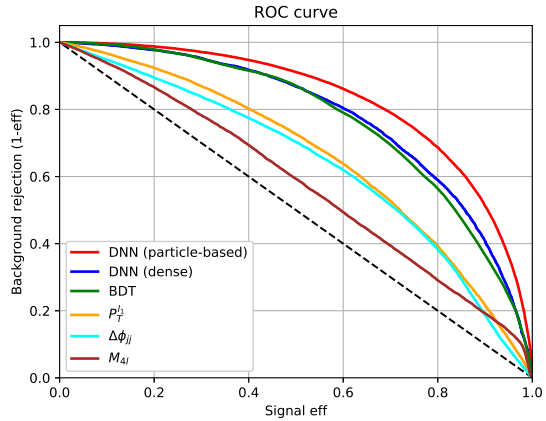
Promising sensitivity studies (with PS, hadronization, MPI included) in VBS [De et al. 2008.04318] and inclusive WZ [Kim Martin 2102.05124] in the semi-leptonic decay channel $\rightarrow$ classify and separate L from T. Figure from [De et al. 2008.04318].



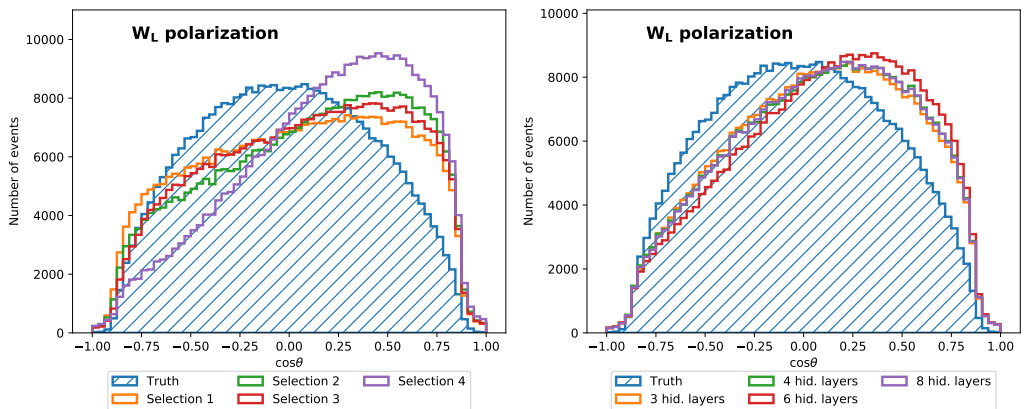
Larger backgrounds: discrimination between V-associated fat jets and QCD jets, discrimination between W and Z.

ML techniques

DNNs improve substantially the discrimination power between L and T modes in VBS [Searcy et al. 1510.01691, Lee et al. 1812.07591, 1908.05196]: serveral DNN structures investigated, most of them rely on public tools, *e.g.* Keras, TensorFlow. Figure from [Lee et al. 1908.05196]: ZZ scattering (fully-leptonic)



DNNs used for kinematic reconstruction and extract polarizations in semi- and fully-leptonic VBS [Grossi et al. 2008.05316]: binary classifier and regression technique for $\cos\theta_\ell^*$ distributions.
Figure: semi-leptonic VBS.



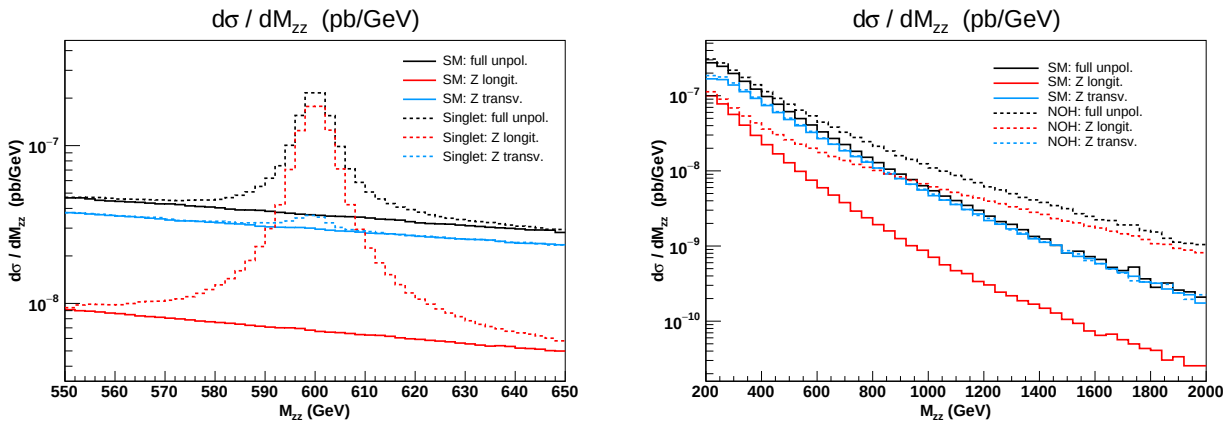
Transformer network (used for anomaly detection [Li et al. 2010.13281]) combined with GANs [Goodfellow et al. 1406.2661] to regress $\cos\theta_\ell^*$ enable to measure polarizations in an (almost) model-independent way: used for fully-leptonic VBS [Li et al. 2109.09924].

NN used for polarization discrimination in hadronic decays [Kim Martin 2102.05124].

Beyond the SM

Effect of new-physics on polarized VBS (LO studies):

- comparison between SM, SILH/Composite-Higgs models [Han et. al 0911.3656, Buarque-Franzosi et al. 1912.01725];
- EFT transverse operators, without EW-boson decays [Brass et al. 1807.02512];
- comparison between SM, Singlet Ext. and Higgsless SM [Ballestrero et al. 1710.09339, 1907.04722]. Figures from [Ballestrero et al. 1907.04722]: ZZ scattering (4ℓ).



EFT effects studied in Higgs decays to W bosons [Brehmer et al. 1404.5951] and inclusive ZZ (to probe $Zt\bar{t}$ coupling) [Cao et al. 2004.02031].

Inclusive polarized-boson-pair production (NLO QCD) with SMEFT effects, without decays [Baglio et al. 1708.03332, 1909.11576].

Decay angles in di-boson enhance to SM/BSM interference [Panico et al. 1708.07823].

Conclusions and outlook

Very active field, several studies 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,
- traditional and ML techniques for polarization extraction, in particular for hadronic decays,

with special focus on di-boson production and VBS.

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 decay channels.