# Precise predictions for polarised weak bosons at the LHC

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# 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 enable

$\rightarrow$ precise measurements of EW processes: multi-boson production.

Polarisations 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.

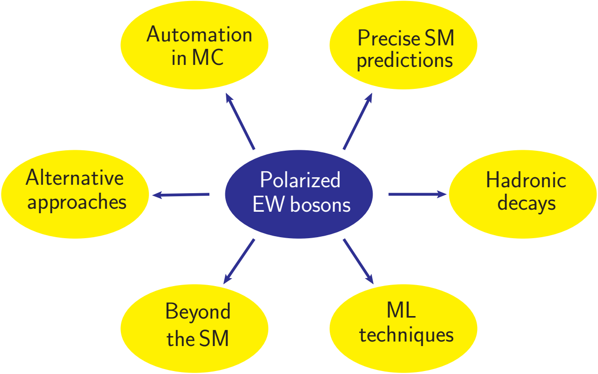
Interest in boson+jet, inclusive di-boson production, Higgs-boson and top-quark decays but the "golden channel" is vector-boson scattering.

# What can we do?

We cannot be directly measure polarisations of EW bosons.

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

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



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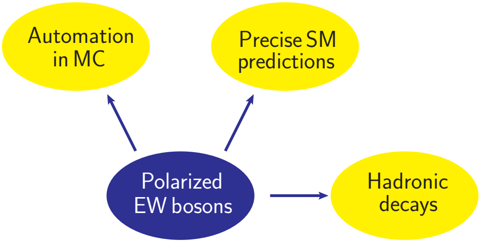



THIS TALK

# Interlude: experimental results

Past analyses relied on angular-coefficient extraction:

- W+jets [ATLAS 1203.2165, CMS 1104.3829, CMS 2008.04174],
- Z+jets [CMS 1504.03512, ATLAS 1606.00689],
- $t\bar{t}$ [CMS 1605.09047, ATLAS 1612.02577, CMS ATLAS 2005.03799].

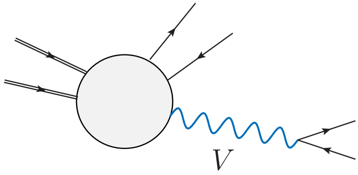
Recent effort in data fits with polarised templates:

- WZ, singly polarised [ATLAS 1902.05759, CMS 2110.11231],
- $W^{\pm}W^{\pm}$ scattering [CMS 2009.09429],
- WZ, doubly polarised [ATLAS 2211.09435].

More ongoing analyses and promising sensitivity studies at High-Lumi [CMS-PAS-FTR-18-014, CERN-LPCC-2018-03, Roloff et al. 2108.00324].

# Separating polarisations 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:

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

Polarisation states are not Lorentz invariant: defined in a specific frame.

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

# Angular coefficients: realistic effects

- At tree-level, decay of a single resonant boson ($\theta^*, \phi^*$ are $\ell^+$ angles in $V$ rest frame, w.r.t. $V$ direction in some Lorentz frame) [Bern et al. 1103.5445], no cuts on decay prod.:

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

- Idea: $\{A_i\}$ extracted from unpol. distrib. with projections or asymmetries also with cuts on decay prod. and radiative corrections. [Baglio et al. 1810.11034, Frederix Vitos 2007.08867, Pellen et al. 2204.12394, Rahaman Singh 1810.11657, 1911.03111, 2109.09345].

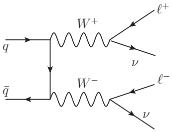
Nice, but:

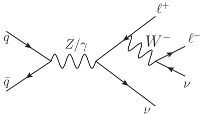
1. radiative corrections: spin-density matrix modified, possible 3-body decays;
2. cuts on decay products: coefficients $\{A_i\}$ from Eq. 1 do not describe properly polarisation fractions and spin-correlations [Stirling et al.1204.6427, Belyaev et al.1303.3297, Baglio et al. 1810.11034, Frederix Vitos 2007.08867].

→ we can do better: generate polarised events!

# Selecting resonant diagrams

To define polarisations, 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 polarisations cannot be defined: drop them, providing a recipe to recover gauge invariance.

Non-resonant diagrams regarded as non-resonant background.

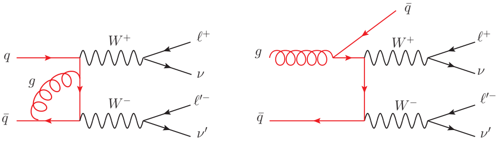
Resonant diagrams treated with

- DPA: double-pole approximation [Denner et al. 0006307]
- NWA: spin-correlated narrow-width approximation [Artoisenet et al. 1212.3460].

→ separating polarisations 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]:

$$d\sigma_{\text{nlo}}/d\xi = \int d\phi_n \Big(B + V + \int d\phi_{\text{rad}}\, D\Big)_{d=4} \delta_\xi^{(n)} + \int d\phi_{n+1} \Big(R\, \delta_\xi^{(n+1)} - D\, \delta_\xi^{(n)}\Big)_{d=4} ; \quad (2)$$

- DPA/NWA usually used for $n$-body $(B, V) \to$ also needed for $R$ and $D$ terms;
- separation of polarisations required for all contributions in Eq. 2.

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

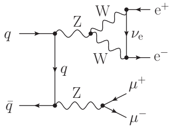
N(N)LO QCD corr. with leptonic decays [Denner GP 2006.14867, Poncelet Popescu 2102.13583].

# Going beyond leading-order: NLO corrections to the decays

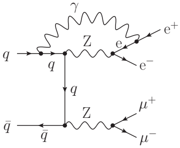
Corrections affect both production and decays of resonance(s).

NLO EW (QCD) corrections to Z/ W bosons with leptonic (hadronic) decays.

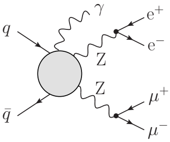
Factorisable



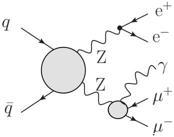

Non-factorisable




ISR




FSR




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

Extended to W bosons [Le Baglio 2203.01470, 2208.09232]: photons can be radiated off the boson propagator.

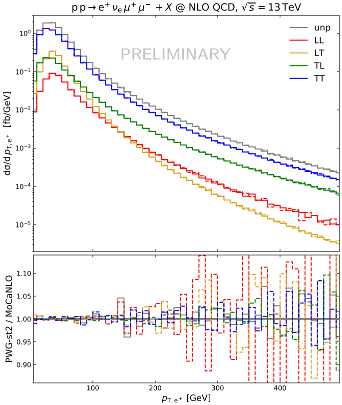
# Matching to parton shower

Predictions matched to parton showers (PS) needed for polarised-signal modeling in realistic LHC setups.

Usual assumption: factorisation of PS effects from spin-structure of the multi-boson system
$\rightarrow$ not true already with one real emission.

Effort needed to provide at least NLOPS predictions in QCD with underlying polarised bosons.

Implementation in POWHEG-BOX-RES [Nason 0409146, Jezo Nason 1509.09071] with DPA approach [GP Zanderighi in preparation]: preliminary results at fixed order (NLO QCD) agree well with MoCaNLO predictions [Denner GP 2010.07149]



# SM results relevant for the LHC

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

1. PHANTOM (v1.7): $2 \to 6$ processes, 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, NWA, interfaced with PS [Buarque-Franzosi et al. 1912.01725] $\to$ ongoing extension to NLOPS (talk by Richard Ruiz).
3. SHERPA: ongoing effort, polarised bosos in the NWA, interfaced with PS [Hoppe Schönherr Siegert presented at DPG Spring Meeting 2023].

Recent precise predictions:

- $\to$ $\mathrm{W}^+(\ell^+\nu_\ell)\,\mathrm{W}^-(\ell'^-\bar{\nu}_{\ell'})$: NLO QCD + loop-ind. in the DPA [Denner GP 2006.14867], NNLO QCD + loop-ind. in the DPA and NWA [Poncelet Popescu 2102.13583];
- $\to$ $\mathrm{W}^\pm(\ell^\pm\nu_\ell)\,\mathrm{Z}(\ell'^+\ell'^-)$: NLO QCD [Denner GP 2010.07149] and NLO QCD+EW [Le Baglio 2203.01470, 2208.09232] in the DPA;
- $\to$ $\mathrm{Z}(\ell^+\ell^-)\,\mathrm{Z}(\ell'^+\ell'^-)$: NLO EW + QCD in the DPA [Denner GP 2107.06579];
- $\to$ $\mathrm{W}^\pm(\ell^\pm\nu_\ell)\,\mathrm{j}$: NNLO QCD in the NWA [Pellen et al. 2109.14336];
- $\to$ $\mathrm{W}^\pm(\mathrm{jets})\,\mathrm{Z}(\ell'^+\ell'^-)$: NLO QCD in the DPA [Denner Haitz GP 2211.09040];
- $\to$ $V_1(\ell\ell/\ell\nu_\ell)\,V_2(\ell'\ell'/\ell'\nu'_\ell)$: NLOPS in the DPA [GP Zanderighi in preparation].

# Di-boson production with semi-leptonic decays (1)

Based on recent work with A. Denner and C. Haitz [2211.09040, Phys.Rev.D 107(2023)5,053004].

Calculated with MoCaNLO/BBMC + Recola1 [Actis et al. 1605.01090] + Collier [Denner et al. 1604.06792]. Fiducial selections of CMS analysis [CMS 2111.13669].

$$\mathrm{p\,p} \to \mathrm{Z}(\to \mathrm{e}^+ \mathrm{e}^-)\ \mathrm{W}^+(\to \mathrm{jets}) \quad @\,\text{NLO QCD}, \sqrt{s} = 13.6\text{TeV}$$

Boosted regime ($p_{\mathrm{T},V} > 200$GeV) with two setups:

- resolved: $\geq$2 AK4 jets, jet system = 2 jets with $M_{\mathrm{jj}}$ closest to $M_{\mathrm{W}}$
- unresolved: $\geq$1 AK8 jets, jet system = single jet with the largest $p_{\mathrm{T}}$

Polarisations defined in the center-of-mass frame (CM) of the two bosons.

# Di-boson production with semi-leptonic decays (2)

Integrated cross sections [Denner Haitz GP 2211.09040]:

| state | $\sigma_{LO}$ [fb] | $f_{LO}$[%] | $\sigma_{NLO}$ [fb] | $f_{NLO}$[%] | $K_{NLO}$ | $K_{NLO}^{(no\ g)}$ |
|---|---|---|---|---|---|---|
| resolved, $Z(e^+e^-)W^+(jj)$ | | | | | | |
| unpol. | $1.8567(2)^{+1.2\%}_{-1.4\%}$ | 100 | $3.036(2)^{+6.8\%}_{-5.3\%}$ | 100 | 1.635 | 1.033 |
| $Z_L W^+_L$ | $0.64603(5)^{+0.2\%}_{-0.6\%}$ | 34.8 | $0.6127(4)^{+0.9\%}_{-0.7\%}$ | 20.2 | 0.948 | 1.031 |
| $Z_L W^+_T$ | $0.08687(1)^{+0.2\%}_{-0.6\%}$ | 4.7 | $0.17012(6)^{+8.6\%}_{-6.8\%}$ | 5.6 | 1.958 | 0.967 |
| $Z_T W^+_L$ | $0.08710(1)^{+0.1\%}_{-0.6\%}$ | 4.7 | $0.24307(7)^{+10.2\%}_{-8.2\%}$ | 8.0 | 2.791 | 1.017 |
| $Z_T W^+_T$ | $0.97678(7)^{+2.0\%}_{-2.2\%}$ | 52.6 | $2.0008(7)^{+8.9\%}_{-7.1\%}$ | 65.8 | 2.048 | 1.059 |
| interf. | 0.0595(1) | 3.2 | 0.009(2) | 0.4 | — | — |
| unresolved, $Z(e^+e^-)W^+(J)$ | | | | | | |
| unpol. | $1.6879(2)^{+1.9\%}_{-2.1\%}$ | 100 | $3.112(2)^{+7.6\%}_{-6.1\%}$ | 100 | 1.843 | 1.193 |
| $Z_L W^+_L$ | $0.61653(5)^{+1.0\%}_{-1.3\%}$ | 36.5 | $0.6799(5)^{+0.9\%}_{-0.7\%}$ | 21.9 | 1.103 | 1.170 |
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| $Z_T W^+_L$ | $0.07437(1)^{+0.6\%}_{-0.9\%}$ | 4.4 | $0.24742(8)^{+11.0\%}_{-8.9\%}$ | 8.0 | 3.327 | 1.193 |
| $Z_T W^+_T$ | $0.88233(9)^{+2.9\%}_{-2.9\%}$ | 52.3 | $2.0041(8)^{+9.6\%}_{-7.7\%}$ | 64.3 | 2.271 | 1.227 |
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Large NLO corrections mostly from gluon initiated real emission processes

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Large LL fraction compared to inclusive set-ups (also in fully leptonic [Dao Le 2302.03324])
Goldstone-boson contributions are unsuppressed → triple-gauge-boson vertices

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Sizeable differences between setups at LO (jet recombination), smaller at NLO QCD

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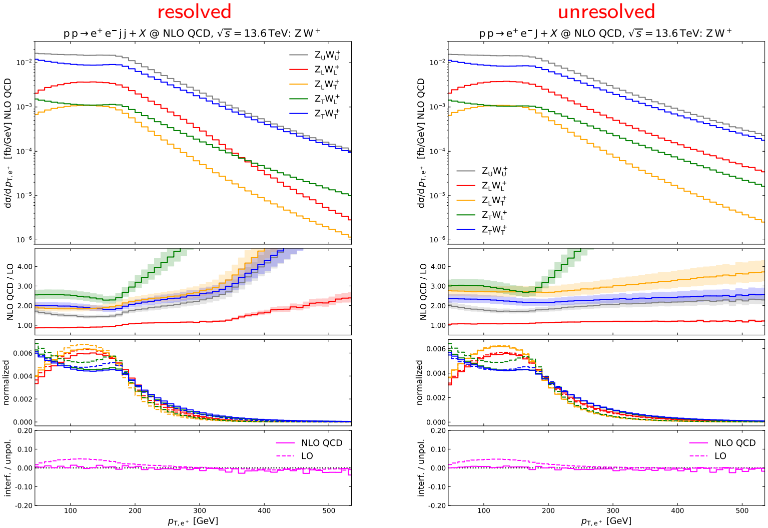
| $Z_L W^+_L$ | $0.64603(5)^{+0.2\%}_{-0.6\%}$ | 34.8 | $0.6127(4)^{+0.9\%}_{-0.7\%}$ | 20.2 | 0.948 | 1.031 |
| $Z_L W^+_T$ | $0.08687(1)^{+0.2\%}_{-0.6\%}$ | 4.7 | $0.17012(6)^{+8.6\%}_{-6.8\%}$ | 5.6 | 1.958 | 0.967 |
| $Z_T W^+_L$ | $0.08710(1)^{+0.1\%}_{-0.6\%}$ | 4.7 | $0.24307(7)^{+10.2\%}_{-8.2\%}$ | 8.0 | 2.791 | 1.017 |
| $Z_T W^+_T$ | $0.97678(7)^{+2.0\%}_{-2.2\%}$ | 52.6 | $2.0008(7)^{+8.9\%}_{-7.1\%}$ | 65.8 | 2.048 | 1.059 |
| interf. | 0.0595(1) | 3.2 | 0.009(2) | 0.4 | — | — |
| unresolved, $Z(e^+e^-)W^+(J)$ | | | | | | |
| unpol. | $1.6879(2)^{+1.9\%}_{-2.1\%}$ | 100 | $3.112(2)^{+7.6\%}_{-6.1\%}$ | 100 | 1.843 | 1.193 |
| $Z_L W^+_L$ | $0.61653(5)^{+1.0\%}_{-1.3\%}$ | 36.5 | $0.6799(5)^{+0.9\%}_{-0.7\%}$ | 21.9 | 1.103 | 1.170 |
| $Z_L W^+_T$ | $0.06444(1)^{+0.7\%}_{-1.0\%}$ | 3.8 | $0.17584(6)^{+10.8\%}_{-8.6\%}$ | 5.7 | 2.729 | 1.158 |
| $Z_T W^+_L$ | $0.07437(1)^{+0.6\%}_{-0.9\%}$ | 4.4 | $0.24742(8)^{+11.0\%}_{-8.9\%}$ | 8.0 | 3.327 | 1.193 |
| $Z_T W^+_T$ | $0.88233(9)^{+2.9\%}_{-2.9\%}$ | 52.3 | $2.0041(8)^{+9.6\%}_{-7.7\%}$ | 64.3 | 2.271 | 1.227 |
| interf. | 0.0503(3) | 3.0 | 0.004(2) | 0.1 | — | — |

Small interferences, especially at NLO

# Di-boson production with semi-leptonic decays (3)




Sensitivity to Z-boson polarisation in low $p_{\mathrm{T},e^+}$ range.
Faster decrease at high $p_{\mathrm{T},e^+}$ at LO in the resolved setup → larger $K$-factors.

# Conclusions

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

Much effort invested in SM predictions for polarised-boson processes:

- automation of polarised-boson MC simulation (DPA, NWA)
- calculation of higher-order corrections (NLO EW+QCD, NNLO QCD)
- study of polarisation-sensitive observables

What's next:

- matching to parton-shower and hadronisation
- higher-order SM predictions for vector-boson scattering ("golden channel")
- BSM/SMEFT effects on production and decay

# Conclusions

We have just won the EU COST grant with a proposal on EWSB and multi-boson:

COMETA, Comprehensive Multiboson Experiment-Theory Action
https://www.cost.eu/uploads/2023/05/oc-2022-1-Approved-Actions-Booklet.pdf (CA22130)

Polarisation is one of the focuses.

Actual start in Fall 2023.

# Backup

# DPA beyond leading-order: technical details

DPA applied to the subtracted real:

- Only factorisable corrections considered:

$$|\mathcal{A}^{(n+1)}_{\mathrm{ISR}} + \mathcal{A}^{(n+1)}_{\mathrm{FSR}_1} + \mathcal{A}^{(n+1)}_{\mathrm{FSR}_2}|^2 \longrightarrow |\mathcal{A}^{(n+1)}_{\mathrm{ISR}}|^2 + |\mathcal{A}^{(n+1)}_{\mathrm{FSR}_1}|^2 + |\mathcal{A}^{(n+1)}_{\mathrm{FSR}_2}|^2$$

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

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

- $\mathrm{FSR}_{(i)}$ treated with DPA for one 2-body and one 3-body decay:

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

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

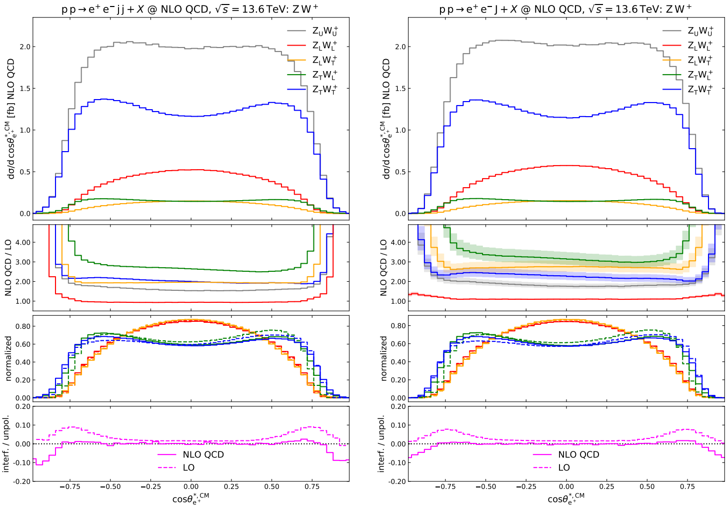
- DPAs preserve angles and energy fractions of decay products in resonance CM frame → to avoid mismatch approaching soft and collinear regimes.

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

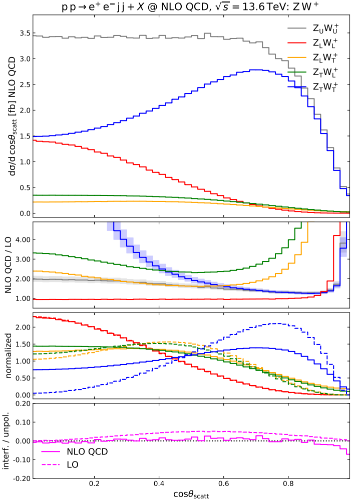
# Semi-leptonic Z $W^+$: detailed setup

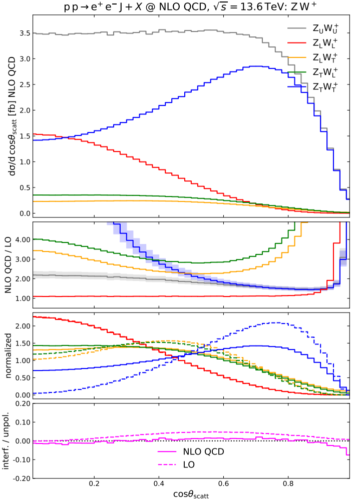
| | | resolved | unresolved |
|---|---|---|---|
| Jet selection | min $p_T$ | 30 GeV | 200 GeV |
| | max $\|y\|$ | 2.4 | 2.4 |
| | min $\Delta R_{Jl^\pm}$ | 0.4 | 0.8 |
| | min $M$ | - | 65 GeV |
| | max $M$ | - | 105 GeV |
| Cuts on the jet system | min $p_T$ | 200 GeV | - |
| | min $M$ | 65 GeV | - |
| | max $M$ | 105 GeV | - |
| Cuts on single leptons | min $p_T$ | 40 GeV | 40 GeV |
| | max $\|y\|$ | 2.4 | 2.4 |
| Cuts on the lepton pair | min $p_T$ | 200 GeV | 200 GeV |
| | min $M$ | 76 GeV | 76 GeV |
| | max $M$ | 106 GeV | 106 GeV |

# Semi-leptonic $Z\,W^+$: positron decay angle

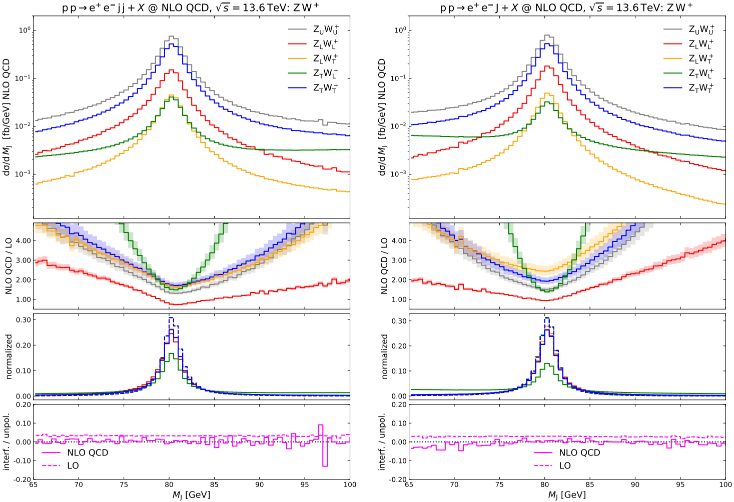


# Semi-leptonic $ZW^+$: scattering angle



# Semi-leptonic $Z\,W^+$: jet-system mass



# ZZ ($4\ell$) 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:

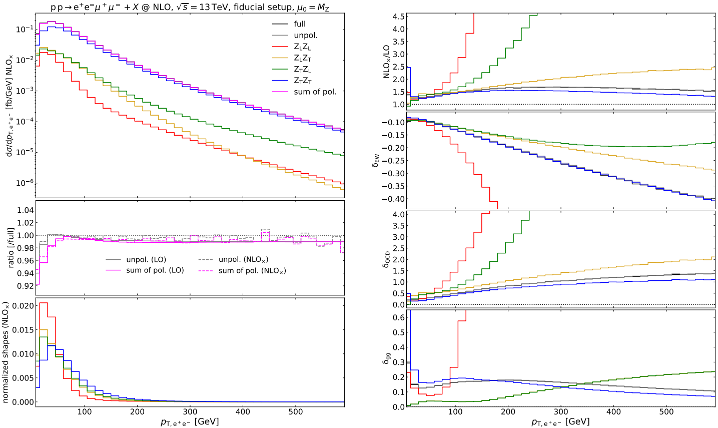
$$\mathrm{d}\sigma_{\mathrm{NLO}_+} = \mathrm{d}\sigma_{\mathrm{LO}}\left(1+\delta_{\mathrm{QCD}}+\delta_{\mathrm{EW}}\right)+\mathrm{d}\sigma_{\mathrm{LO}}\delta_{\mathrm{gg}}$$
$$\mathrm{d}\sigma_{\mathrm{NLO}_\times} = \mathrm{d}\sigma_{\mathrm{LO}}\left(1+\delta_{\mathrm{QCD}}\right)\left(1+\delta_{\mathrm{EW}}\right)+\mathrm{d}\sigma_{\mathrm{LO}}\delta_{\m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

| mode | $\sigma_{\mathrm{LO}}$ [fb] | $\delta_{\mathrm{QCD}}$ | $\delta_{\mathrm{EW}}$ | $\delta_{\mathrm{gg}}$ | $\sigma_{\mathrm{NLO}_+}$ [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% | $15.416(5)^{+5.7\%}_{-4.4\%}$ | $14.997(4)^{+5.5\%}_{-4.2\%}$ |
| $Z_LZ_L$ | $0.64302(5)^{+6.8\%}_{-8.1\%}$ | +35.7% | −10.2% | +14.5% | $0.9002(6)^{+5.5\%}_{-4.3\%}$ | $0.8769(5)^{+5.4\%}_{-4.1\%}$ |
| $Z_LZ_T$ | $1.30468(9)^{+6.5\%}_{-7.7\%}$ | +45.3% | −9.9% | +2.8% | $1.8016(9)^{+4.3\%}_{-3.5\%}$ | $1.7426(8)^{+4.1\%}_{-3.3\%}$ |
| $Z_TZ_L$ | $1.30854(9)^{+6.5\%}_{-7.7\%}$ | +44.3% | −9.9% | +2.8% | $1.7933(9)^{+4.3\%}_{-3.4\%}$ | $1.7355(8)^{+4.0\%}_{-3.2\%}$ |
| $Z_TZ_T$ | $7.6425(3)^{+5.2\%}_{-6.4\%}$ | +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

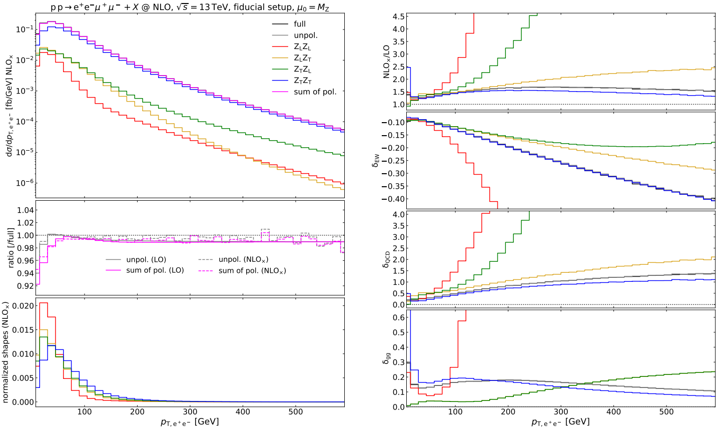
**Transverse momentum** of the Z boson $[\to e^+e^-(\gamma)]$




- 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

# Distributions for the Z-boson transverse momentum

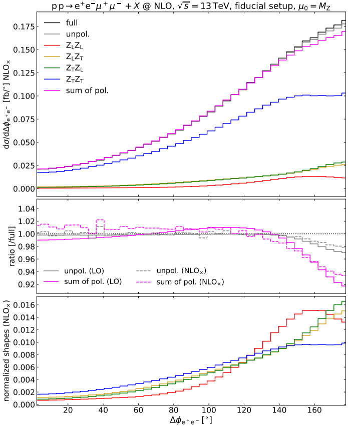
Transverse momentum of the Z boson [$\to e^+e^-(\gamma)$]

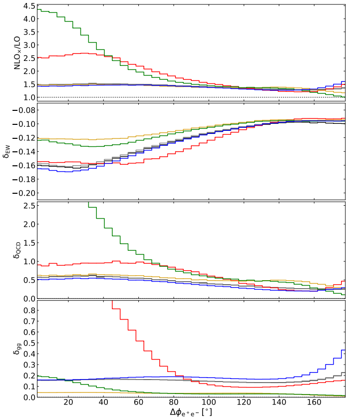



- large QCD corrections to TL (the transverse one decays into $e^+e^-(\gamma)$)
- sizeable interference and non-resonant effects only in soft region
- rather sizeable shape differences among polarised states

# Distributions in the azimuthal positron-electron distance

Azimuthal distance between positron and electron.

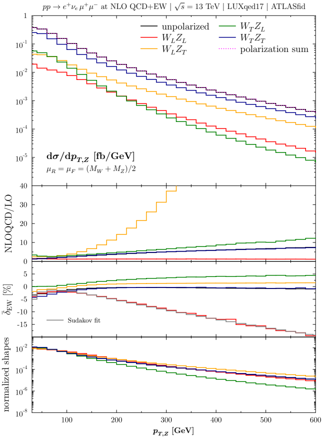



- sizeable non-res. bkg and interferences in most populated region
- huge QCD real corrections (gq) for TL, huge gg-induced contrib. for LL
- marked shape differences for polarised curves: good discrimination power

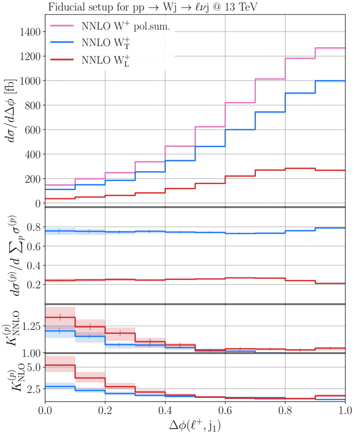
# $W^{\pm}Z\,(3\ell)$ and $W^{\pm}$+jet production

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




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

NNLO QCD for polarised-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.

# A remark for ZZ

Leading-order on-shell ZZ production, polarised partonic cross-sections as functions of $s$ (CoM energy) and $\theta$ (scattering angle):

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

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

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

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: $\mathrm{pp} \to \mathrm{e}^+\mathrm{e}^-\mu^+\mu^- + \mathrm{X}$.

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: $N_F = 5$, $G_\mu$-scheme for $\alpha$, 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:

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

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

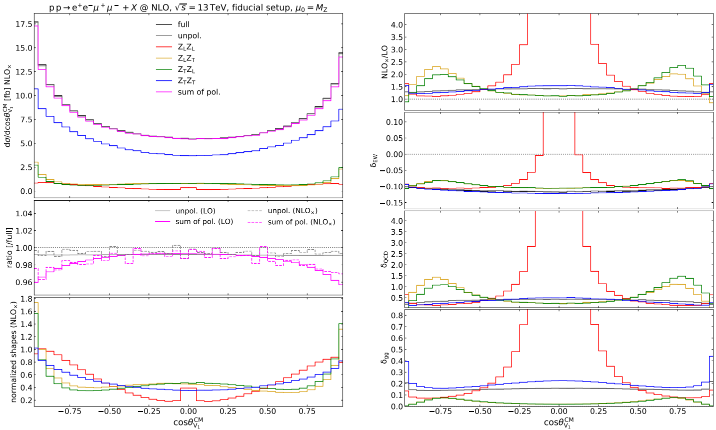
- $p_{\mathrm{T,e}^\pm} > 7\,\mathrm{GeV}$, $p_{\mu^\pm} > 5\,\mathrm{GeV}$, $p_{\ell_1} > 20\,\mathrm{GeV}$, $p_{\ell_2} > 10\,\mathrm{GeV}$
- $\Delta R_{\ell\ell'} > 0.05$, $|\eta_{\mathrm{e}^\pm}| < 2.47$, $|\eta_{\mu^\pm}| < 2.7$
- $M_{4\ell} > 180\,\mathrm{GeV}$, $|M_{\ell^+\ell^-} - M_Z| < 10\,\mathrm{GeV}$

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

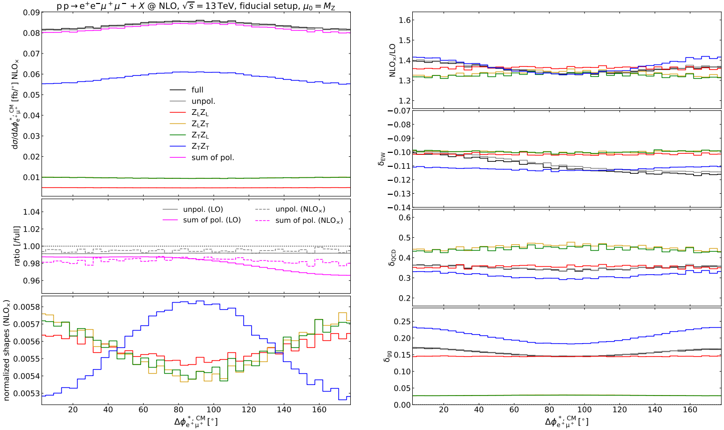
Scattering angle of Z [$\to e^+e^-(\gamma)$] in the ZZ frame (w.r.t. ZZ-sys. direction in LAB)




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

# Distributions for the azimuthal-decay-angle difference

Difference of azimuthal decay angles of $e^+$ and $\mu^+$ 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 polarised distributions