European Research Council

IOP Institute of Physics

W-boson and Its Polarisation at NNLO

Andrei Popescu

in collaboration with

Rene Poncelet and Mathieu Pellen

based on 2102.13583, 2109.14336

Tuesday, 5 April 2022

Cavendish Laboratory

UNIVERSITY OF CAMBRIDGE

`popescu@hep.phy.cam.ac.uk`

Motivation

Why study polarised W-boson at NNLO precision?

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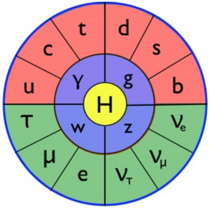

The Standard Model

1. Probe the Electroweak mechanism:
   - → **Longitudinal polarisation** and massiveness of $W^{\pm}, Z$ bosons is the direct consequence of the Electroweak symmetry breaking mechanism.
   - → Processes involving longitudinal boson **constrain** EFT operators.
   - → Any deviation from the Standard Model prediction will hint to **new physics**.

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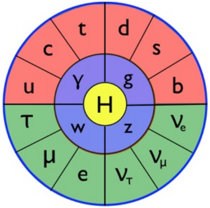

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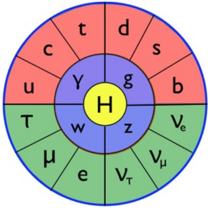

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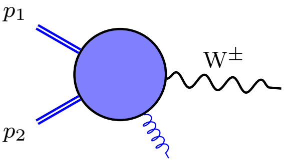
3. Squeeze out all what theory can offer
   - → Higher-order corrections are essential in reducing **theoretical uncertainty**: LO $\sim 12\%$, NLO $\sim 7\%$, NNLO $\sim 2\%$ (process-dependent).

Boson Polarisation

- As a massive spin-1 particle, the on-shell boson has a basis of 3 polarisation vectors ϵ_i^μ:

$$\epsilon_L = \frac{1}{\sqrt{2}}(0,1,-i,0), \quad \epsilon_R = -\frac{1}{\sqrt{2}}(0,1,i,0), \quad \epsilon_0 = \frac{1}{M}(p,0,0,E).$$



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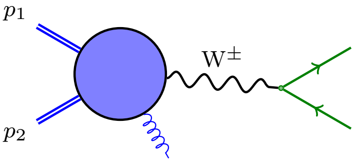

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- Boson is short-lived ($\tau_W \approx 3 \cdot 10^{-25} s$), so we detect its **decay products**, which also prompt interferences between polarised amplitudes A_λ:

$$A_\lambda = \mathbf{P}_\mu \cdot \frac{\epsilon_\lambda^\mu \epsilon_\lambda^{\nu *}}{k^2 - M_V^2 + iM_V\Gamma_V} \cdot \mathbf{D}_\nu \qquad \Longrightarrow \qquad A^2_{\text{unpol.}} = \sum_\lambda \mid A_\lambda \mid^2 + \sum_{\lambda \neq \lambda'} A^*_\lambda \cdot A'_\lambda$$

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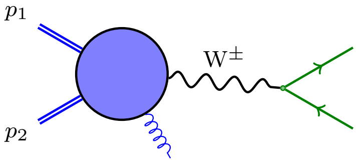

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- For polarisation interpretation one needs **on-shell** W-boson, which can be achieved via:
  - (a) **Narrow-width approximation**: generate on-shell phase space
  - (b) **On-shell projection**: map full phase space to on-shell phase space

These methods introduce *off-shell effects*, which are roughly of order $\Gamma_W / M_W \approx 0.025$.

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- The goal is to break down differential distributions into **polarised** components:

$$\frac{d\sigma}{dX} \longrightarrow \frac{d\sigma_L}{dX} + \frac{d\sigma_R}{dX} + \frac{d\sigma_0}{dX}$$

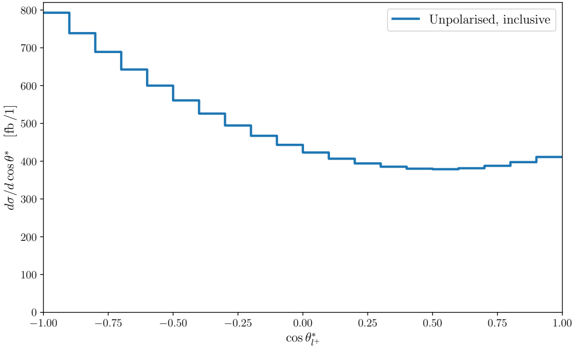

Figure: Angle of lepton emission for W^+ at the LHC

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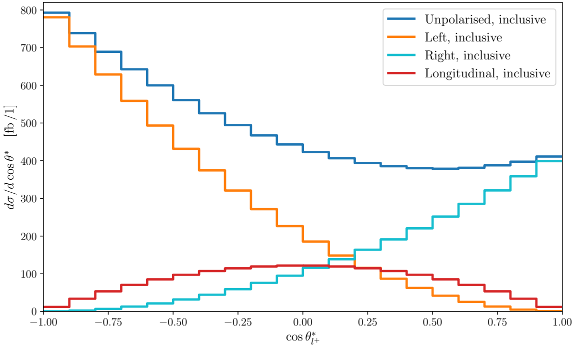

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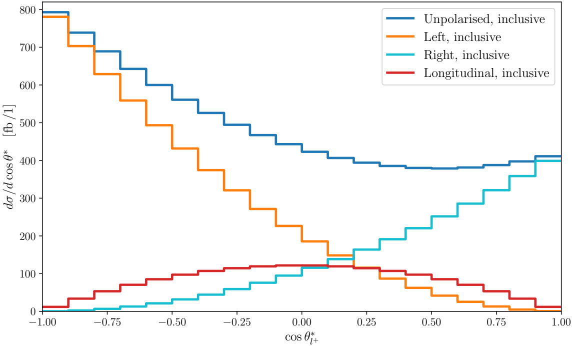
- With **no cuts**, angular emission distribution is described analytically:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{3}{4}\sin^2\theta \cdot f_0 + \frac{3}{8}(1 \mp \cos\theta)^2 \cdot f_L + \frac{3}{8}(1 \pm \cos\theta)^2 \cdot f_R$$

where f_i are coefficients that depend on production part of the process.



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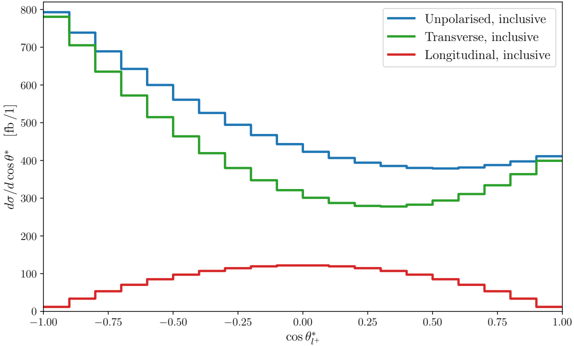

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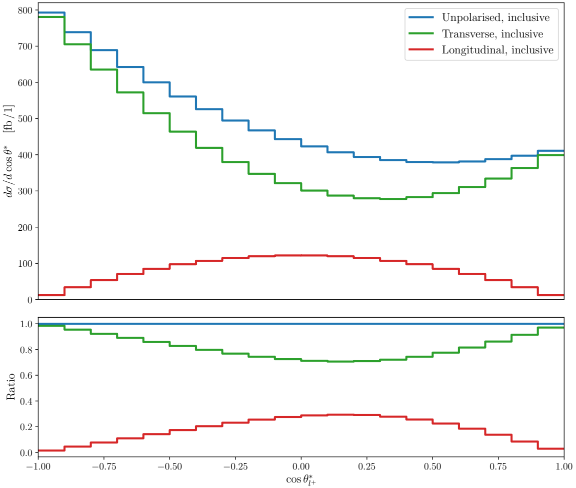

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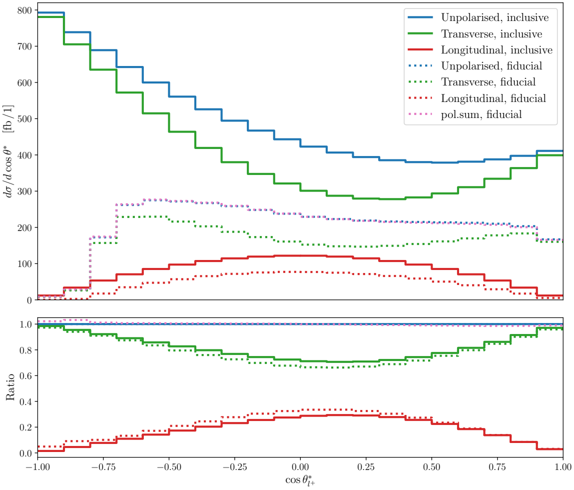
- Experimental cuts modify polarisation shapes and introduce interferences.
  - → We need to pick **phase space regions** where interference and off-shell effects are small.



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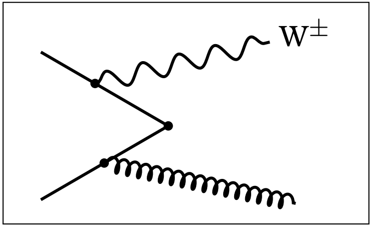
W in Association With One Jet



W in Association With One Jet ::: Literature

Literature

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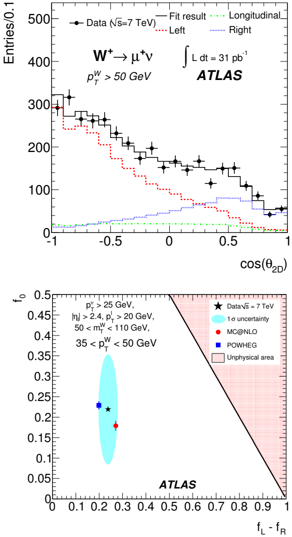

Figure: ATLAS measurements (2012)

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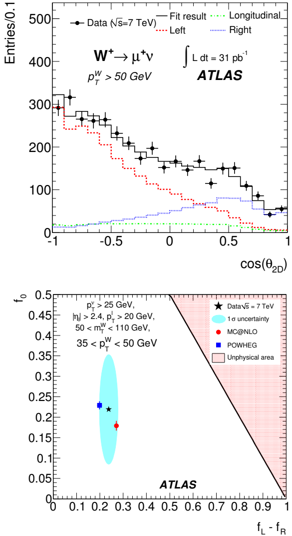

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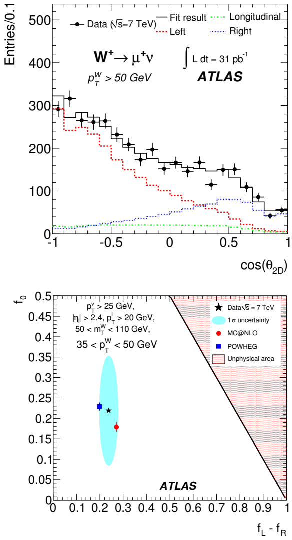

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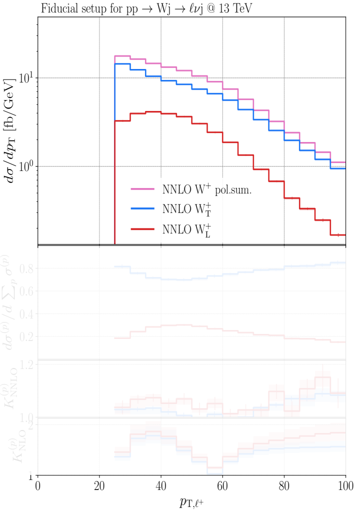

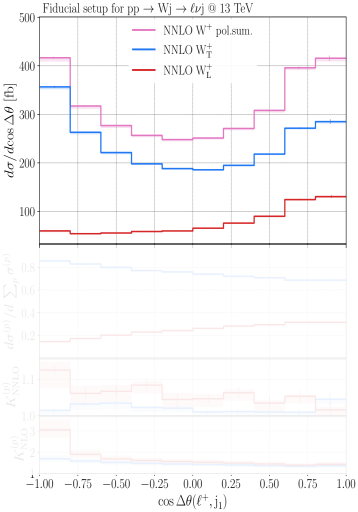

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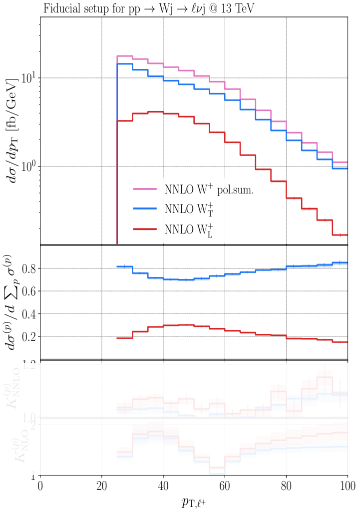

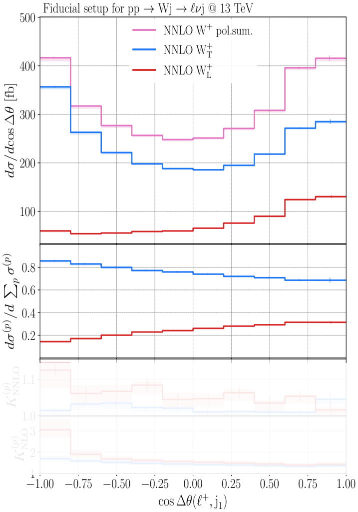

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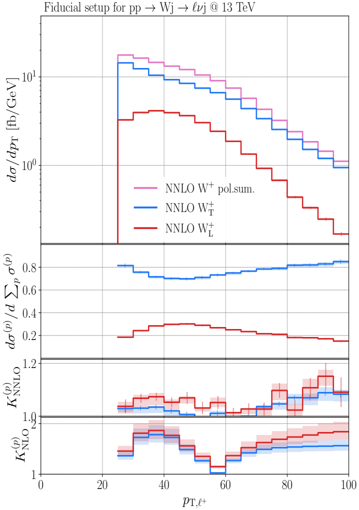
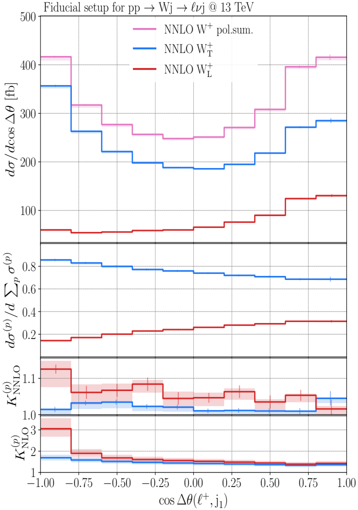
  → NNLO: 5-10%





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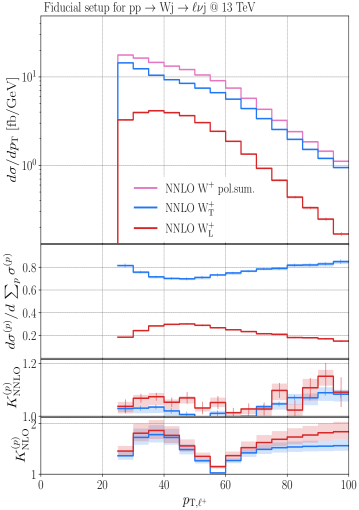

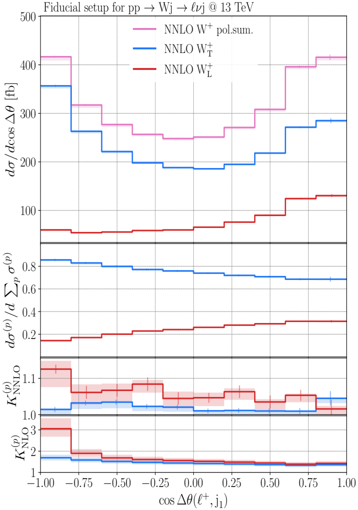

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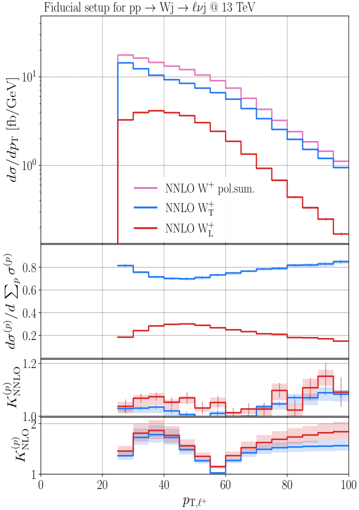
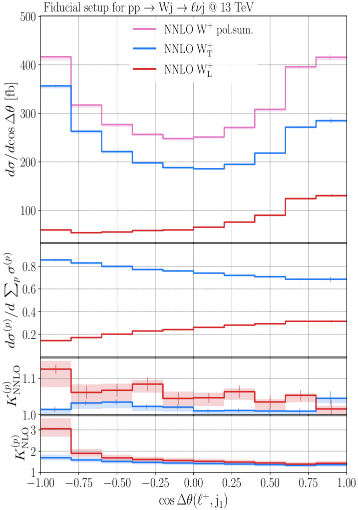
  → Theoretical uncertainty drops from ~7% at NLO to ~2% at NNLO.

Importantly, theoretical uncertainty on polarised shapes is reduced at NNLO.





W in Association With One Jet ::: Fit to extrapolated data

- Due to **large systematic errors**, currently published data do not allow for precise shape fits.

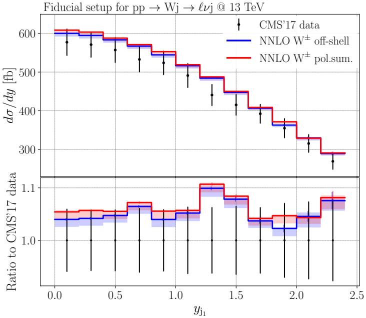


Figure: CMS'17 data shows **6-9% errors** on distribution of rapidity of the hardest jet.

W in Association With One Jet ::: Fit to extrapolated data

- However, we have determined that at **projected luminosity** of 250 fb^{-1} (mid-Run 3), NNLO corrections shrink overlapping fit uncertainty of the fit by a factor of 2 across several observables.

  → distribution of fits (**x**) for each scale is much denser for NNLO shapes.

  → fit uncertainty depends on data errors

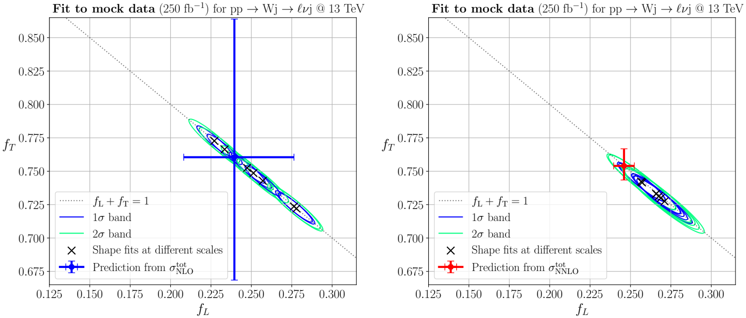
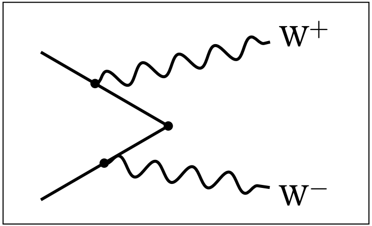


Figure: Fit of polarised shapes at NLO (left) and NNLO (right) to mock data (off-shell distribution) for the distribution of angle between the lepton and the hardest jet.

Diboson production



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Features of W^+W^- (fully-leptonic)

- Largest cross-section among other diboson processes (setup of [1912.00068])

$$\boxed{\sigma_{\mathrm{WW}} \approx 415\,\mathrm{fb}} \qquad \sigma_{\mathrm{ZZ}} \approx 40\,\mathrm{fb} \qquad \sigma_{\mathrm{WZ}} \approx 28\,\mathrm{fb}$$

Diboson Production ::: Overview

Literature

- Theoretical
  - → EFT operators and polarised measurements [Liu, Wang 1804.08688]
  - → Polarised diboson studies at NLO QCD [Denner et al. 2006.14867, 2010.07149]
  - → Double-pole approximation (DPA) [Billoni et al. 1310.1564] [Ballestrero et al. 1710.09339, 1907.04722]
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    First polarised prediction at NNLO!

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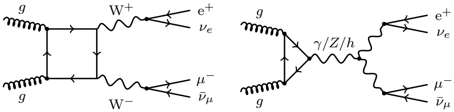
- Polarised W$^+$W$^-$ channels probe EFT operators
- Loop-induced (LI) channel opens up at $\mathcal{O}(\alpha_s^2)$



→ expect a large $\mathcal{O}(\alpha_s^2)$ contribution

Diboson Production ::: Polarised distributions

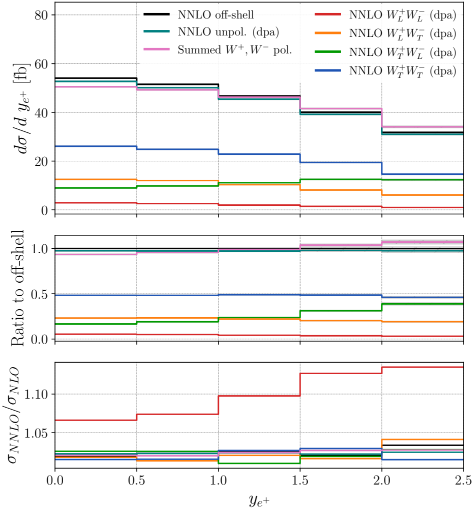


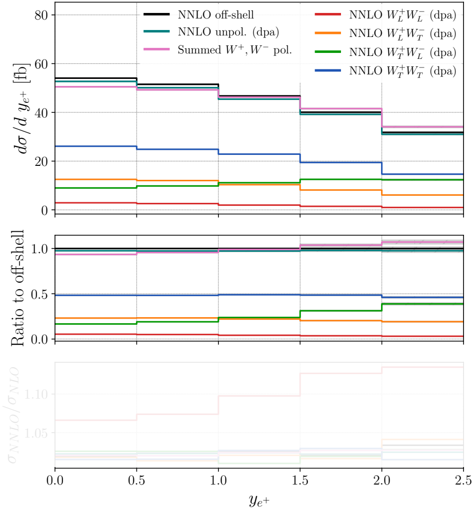
Figure: Positive lepton rapidity at NNLO

Diboson Production ::: Polarised distributions

- Polarisation fractions

TT	**TL**	**LT**	**LL**
48.5%	24.9%	22.1%	4.4%

→ Production is dominated by $\mathrm{W}_\mathrm{T}^+\mathrm{W}_\mathrm{T}^-$, especially at high energies



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- QCD corrections

order	**TT**	**TL**	**LT**	**LL**
NLO	7%	8%	9%	**36%**
NNLO	2%	2%	2%	**9%**

→ small except for LL

→ distinct corrections profile for LL

→ theoretical uncertainty <u>reduced</u> by 3

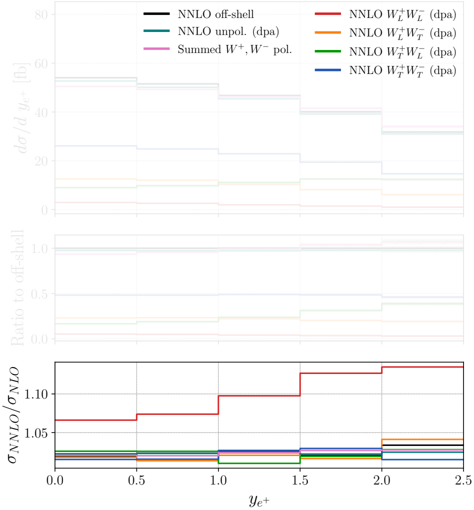

Figure: Positive lepton rapidity at NNLO

Diboson Production ::: Polarised distributions (2)

- QCD corrections

order	TT	TL	LT	LL
NNLO	2%	2%	2%	9%
LI	9%	3%	4%	8%

→ distinct corrections profile for LL

→ theoretical uncertainty increased by 2

⟹ this calls for $\mathcal{O}(\alpha_s^3)$ corrections.

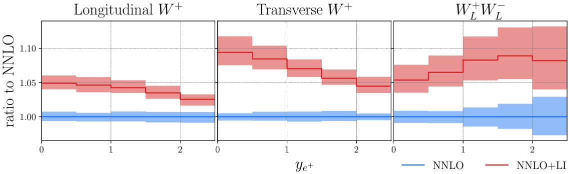

Figure: Loop-induced channel corrections in lepton rapidity.

Summary

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- Polarised bosons are a focused test of the Standard Model

- We provided the first two NNLO-precise studies of polarised W production

- Higher order QCD corrections are:
  - → stable
  - → particularly strong for the longitudinal mode
  - → crucial for precision studies

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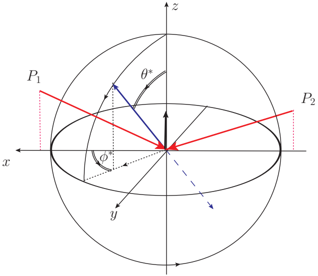
Thank you for your attention!

Appendix

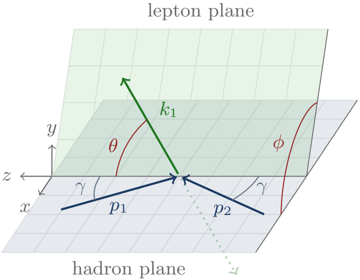
Reference frames

- *Helicity frame* is a rest frame of the W-boson, where z-axis is directed along the boson momentum in lab frame, and x-axis belongs to the plane containing boosted parton momenta $\vec{p}\,'_1, \vec{p}\,'_2$.



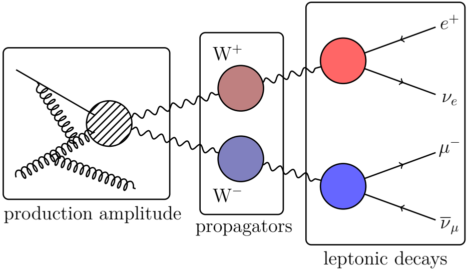
Helicity frame [1103.5445]

- *Collins-Soper (CS) frame* is a rest frame of the W-boson in which the z-axis is taken to bisect the opening angle between incoming proton momenta $\vec{p}_1, \vec{p}_2$, and the y-axis is along the direction of $\vec{p}_1 \times \vec{p}_2$. The azimuthal angle is measured from the x-axis which lies in the scattering plane [hep-ph/0604208] .



Collins-Soper frame [1708.00008]

Method: Double-pole approximation



Full amplitude is approximated by **on-shell sub-amplitudes** and the **off-shell propagators**:

$$A \approx \sum_{\alpha,\beta} A^{pp\to W^+W^-}_{\alpha\beta,\mu\nu} \frac{A^\mu_\alpha(W^+ \to l^+\nu) \cdot A^\nu_\beta(W^- \to l^-\overline{\nu})}{(p_+^2 - M^2)\cdot(p_-^2 - M^2)},$$

boson polarisations

- A selected **on-shell projection** defined on-shell sub-amplitudes *(we choose to preserve leptonic angles in the decay frames, and boson angles in the diboson frame).*
- Cross-term amplitude contributions coming from $A_\alpha A_{\tilde{\alpha}}$ terms create **interferences** for cross sections.

W in Association With One Jet: Off-shell and interference effects

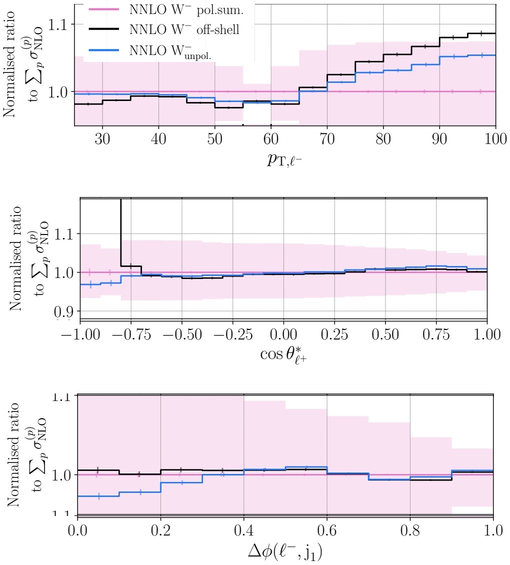
- Off-shell effects mean that on-shell approximation/projection does not agree with off-shell calculation:

$$\frac{d\sigma_{\text{off-shell}}}{dX} \neq \frac{d\sigma_{\text{unpol}}}{dX}$$

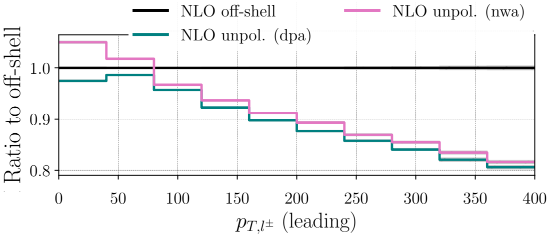
- Interference effects cause polarised sum to break down:

$$\frac{d\sigma_{\text{unpol}}}{dX} \neq \frac{d\sigma_0}{dX} + \frac{d\sigma_T}{dX} \equiv \frac{d\sigma_{\text{pol.sum}}}{dX}$$

- Regions suitable for polarisation fits:
  - → $\Delta\phi(\ell, j_1) > 0.3$
  - → $25 < p_{\mathrm{T},\ell} < 70\,\mathrm{GeV}$
  - → $\cos\theta^*_\ell > -0.75$
  - → $|\, y_j \,| < 2\,\mathrm{GeV}$



Diboson Production: Approximations



Unpolarised narrow-width (NWA), double-pole (DPA) approximations, and off-shell.