

Polarised-boson predictions in multi-boson processes

Rene Poncelet

General LHC EW Meeting 17-19 Nov 2025

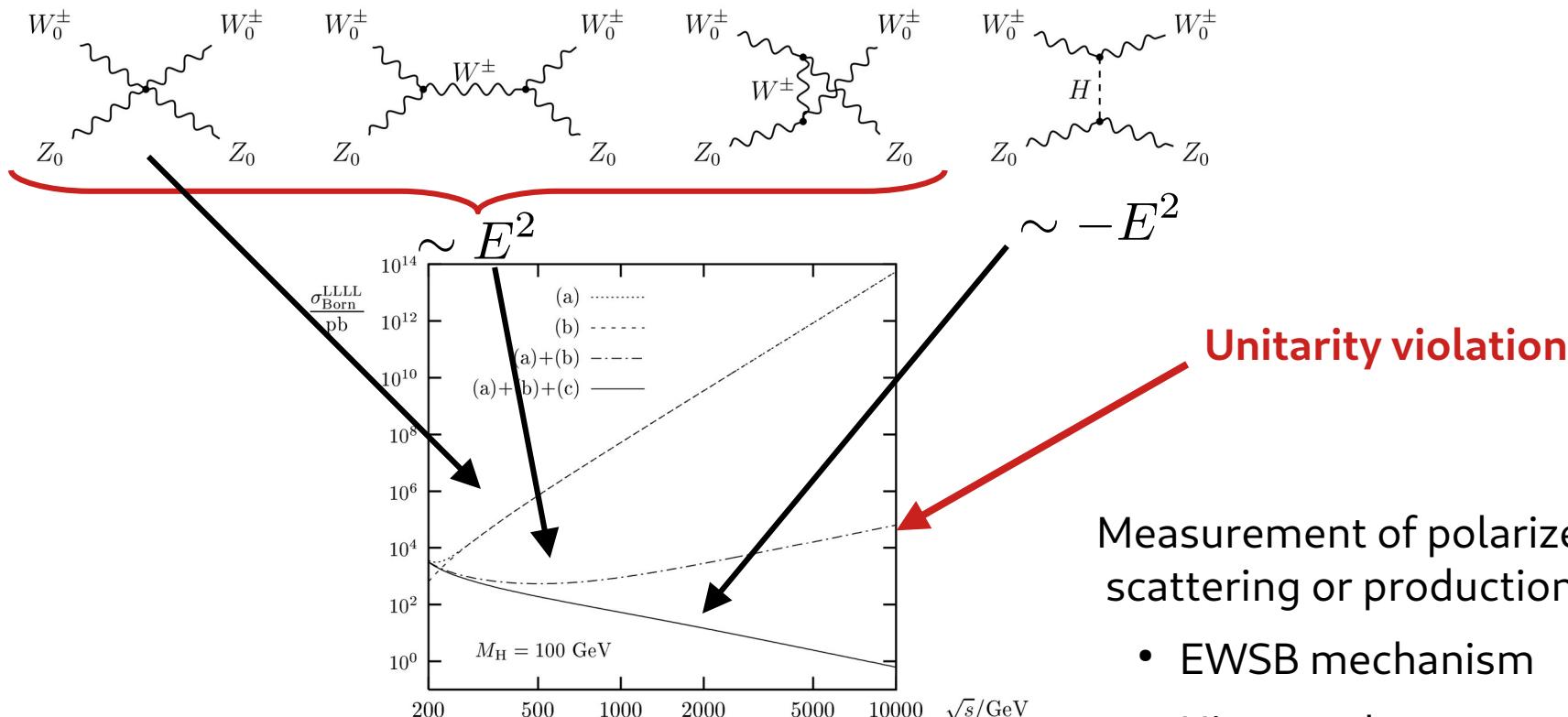


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SONATA 20 UMO-2024/55/D/ST2/00934

Longitudinal Vector-Boson-Scattering (VBS)



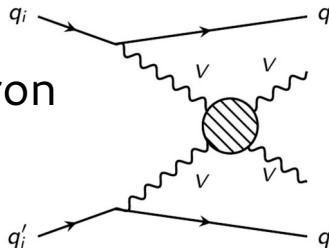
Measurement of polarized boson scattering or production probes:

- EWSB mechanism
- Higgs and gauge sector
- New physics models

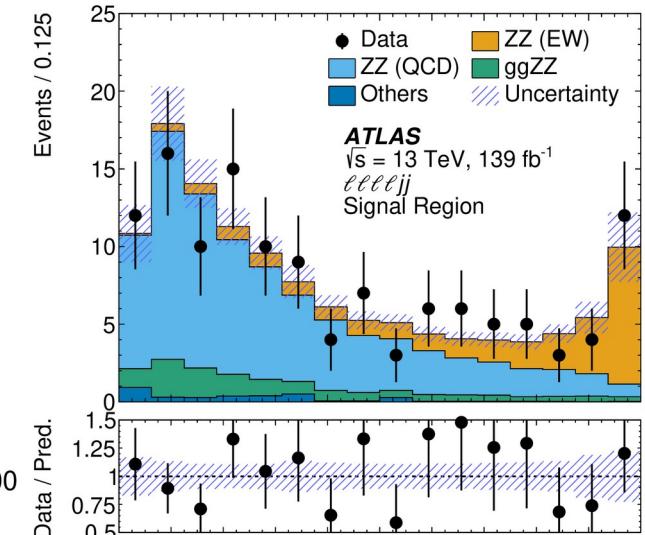
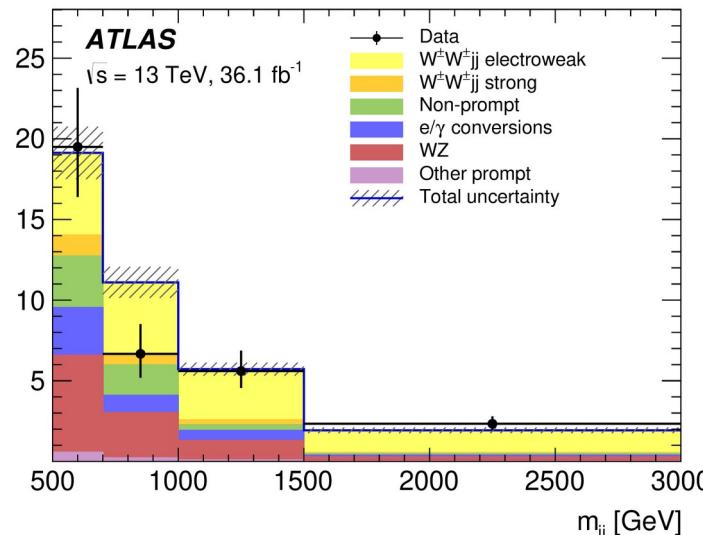
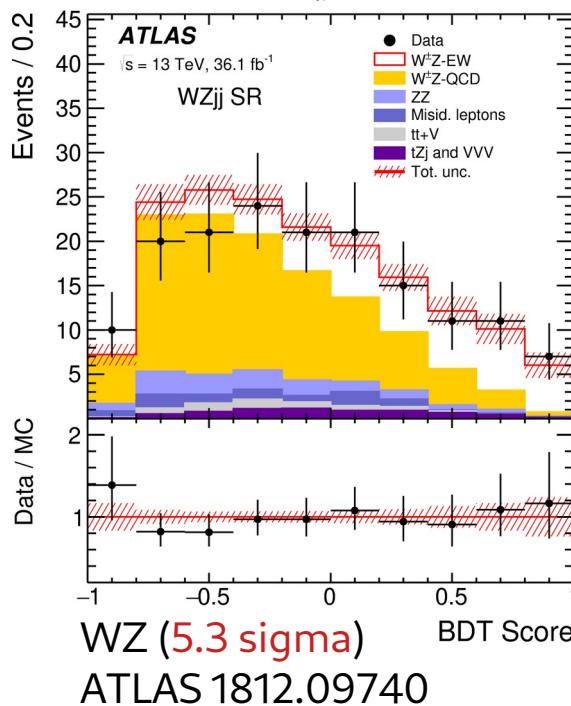
Radiative corrections to $W^+ W^- \rightarrow W^+ W^-$ in the electroweak standard model
A. Denner, T. Hahn [[hep-ph/9711302](#)]

VBS at hadron colliders

VBS at hadron
colliders

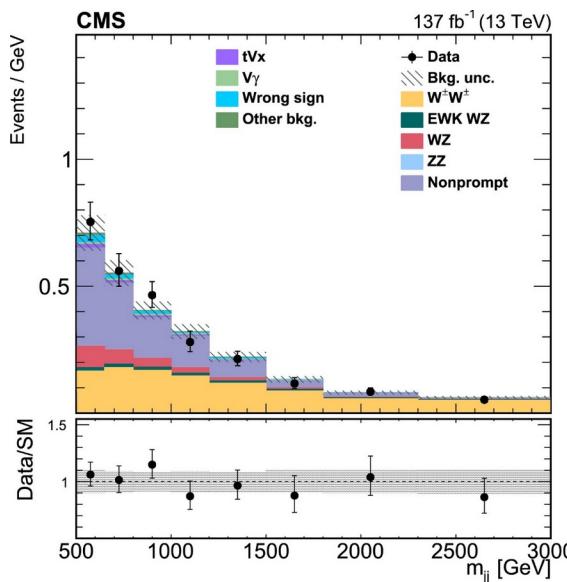
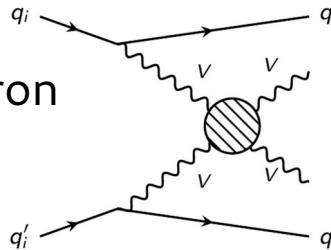


Separate from background processes through VBS topology
→ a rare process, but observed.



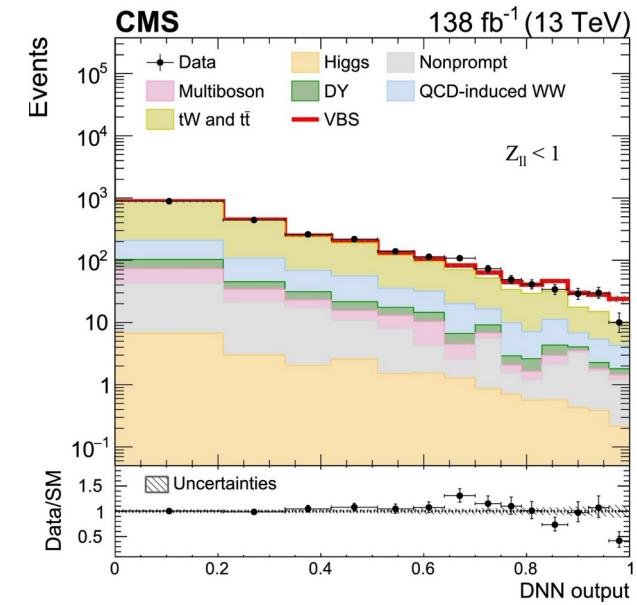
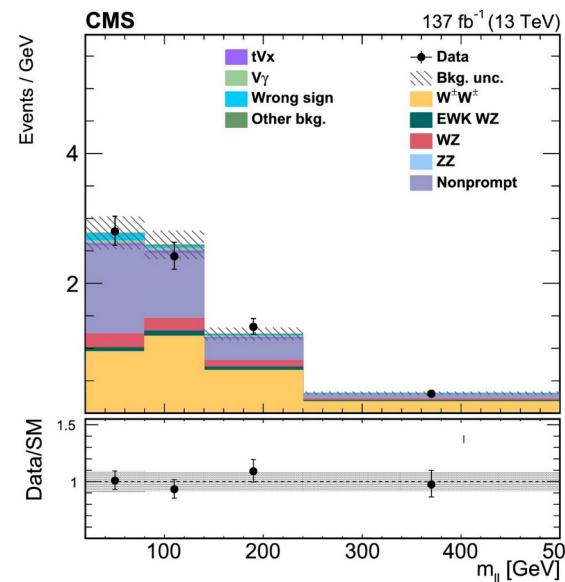
VBS at hadron colliders

VBS at hadron
colliders



WZ (6.8 sigma) + W+W+/W-W- (diff. xsec)
CMS 2005.01173

Separate from background processes through VBS topology
→ a rare process, but observed.



W+W- (5.6 sigma)
CMS 2205.05711

Polarised boson production

$$\left(-g^{\mu\nu} + \frac{k^\mu k^\nu}{k^2} \right) \rightarrow \sum_\lambda \epsilon_\lambda^{*\mu} \epsilon_\lambda^\nu$$
$$\lambda = +/-L$$

Can we extract
the longitudinal
component?

Measurements of longitudinal polarisation fractions:

Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC,

CMS 1104.3829

Measurement of the polarisation of W bosons produced with large transverse momentum in pp collisions at $\sqrt{s}=7$ TeV with the ATLAS experiment,
ATLAS 1203.2165

Measurement of WZ production cross sections and gauge boson polarisation in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector,
ATLAS 1902.05759

Measurement of the inclusive and differential WZ production cross sections, polarization angles, and triple gauge couplings in pp collisions at $\sqrt{s} = 13$ TeV,
CMS 2110.11231

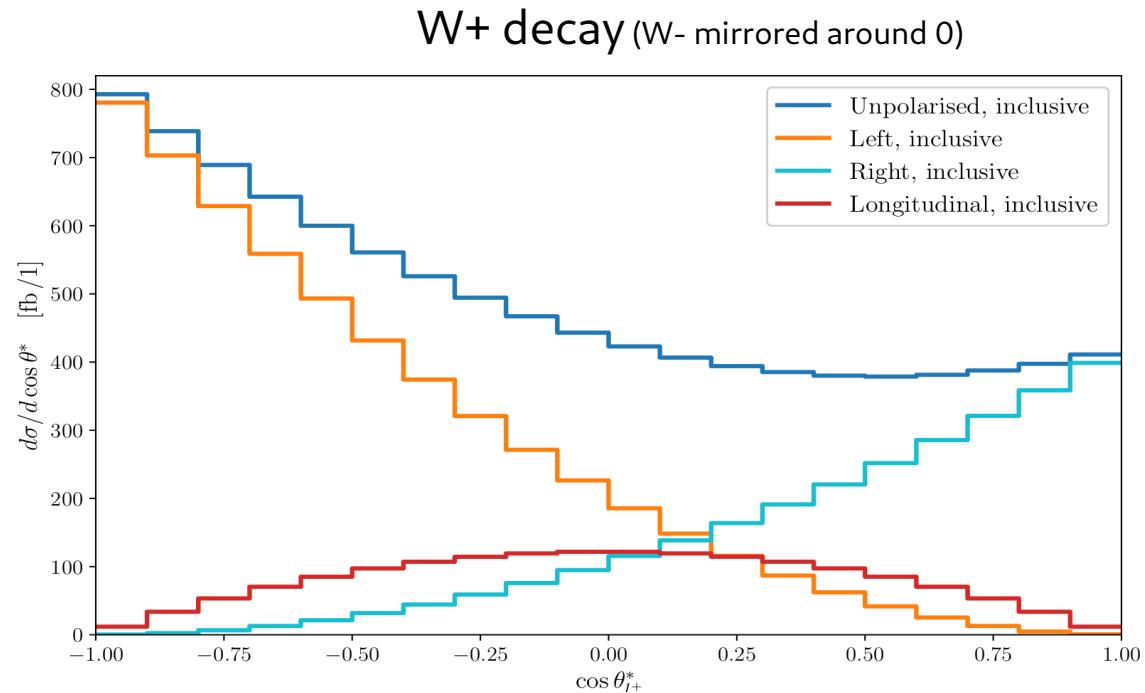
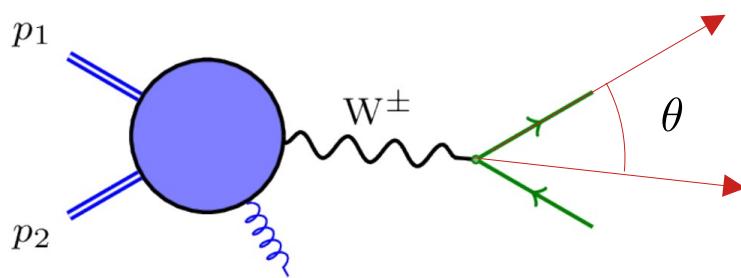
Observation of gauge boson joint-polarisation states in WZ production from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
ATLAS 2211.09435

Evidence of pair production of longitudinally polarised vector bosons and study of CP properties in $Z Z \rightarrow 4\ell$ events with the ATLAS detector at $\sqrt{s} = 13$ TeV
ATLAS 2310.04350

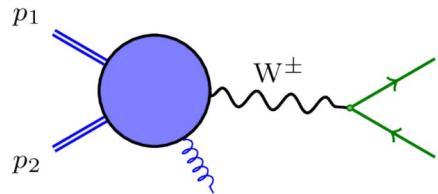
Studies of the Energy Dependence of Diboson Polarization Fractions and the Radiation-Amplitude-Zero Effect in WZ Production with the ATLAS Detector
ATLAS 2402.16365

How to measure polarized bosons?

- We can't measure boson polarization directly.
- Luckily decay products can be used as a "polarimeter":



Polarized cross sections



On-shell bosons:
(DPA or NWA) $\left(-g^{\mu\nu} + \frac{k^\mu k^\nu}{k^2} \right) \rightarrow \sum_\lambda \epsilon_\lambda^{*\mu} \epsilon_\lambda^\nu$

$$M = \mathbf{P}_\mu \cdot \frac{-g_{\mu\nu} + \frac{k^\mu k^\nu}{k^2}}{k^2 - M_V^2 + iM_V\Gamma_V} \cdot \mathbf{D}_\nu$$

$$|M|^2 = \underbrace{\sum_\lambda |M_\lambda|^2}_{\rightarrow \text{polarised x-sections}} + \underbrace{\sum_{\lambda \neq \lambda'} M_\lambda^* M_{\lambda'}}_{\text{Interferences}}$$

\rightarrow polarised x-sections Interferences

Create samples of fixed polarisation:

$$\frac{d\sigma}{dX} = f_L \frac{d\sigma_L}{dX} + f_R \frac{d\sigma_R}{dX} + f_0 \frac{d\sigma_0}{dX} \left(+ f_{int.} \frac{d\sigma_{int.}}{dX} \right)$$

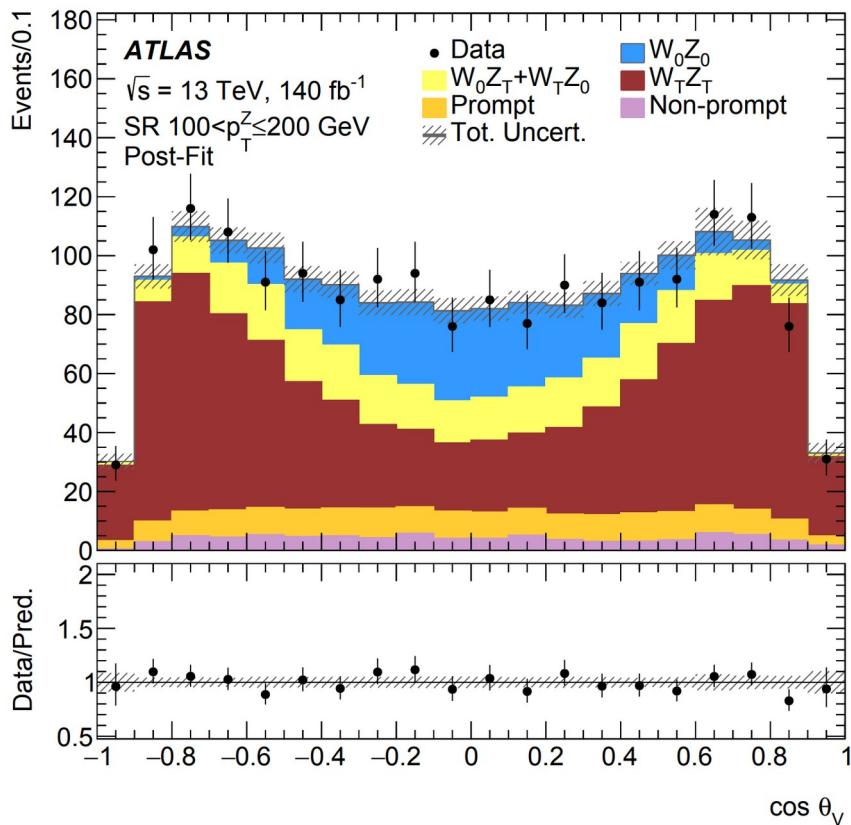
and fit f_L, f_R, f_0 to measured $\frac{d\sigma^{exp.}}{dX}$

Polarized cross sections

$$\frac{d\sigma}{dX} = f_L \frac{d\sigma_L}{dX} + f_R \frac{d\sigma_R}{dX} + f_0 \frac{d\sigma_0}{dX} \left(+ f_{int.} \frac{d\sigma_{int.}}{dX} \right)$$

- Interferences can be handled
- Does not rely on extrapolations to the full phase space
 X can be any observable \rightarrow lab frame observables
- $\frac{d\sigma_i}{dX}$ can be systematically improved

Example polarisation measurement in ATLAS

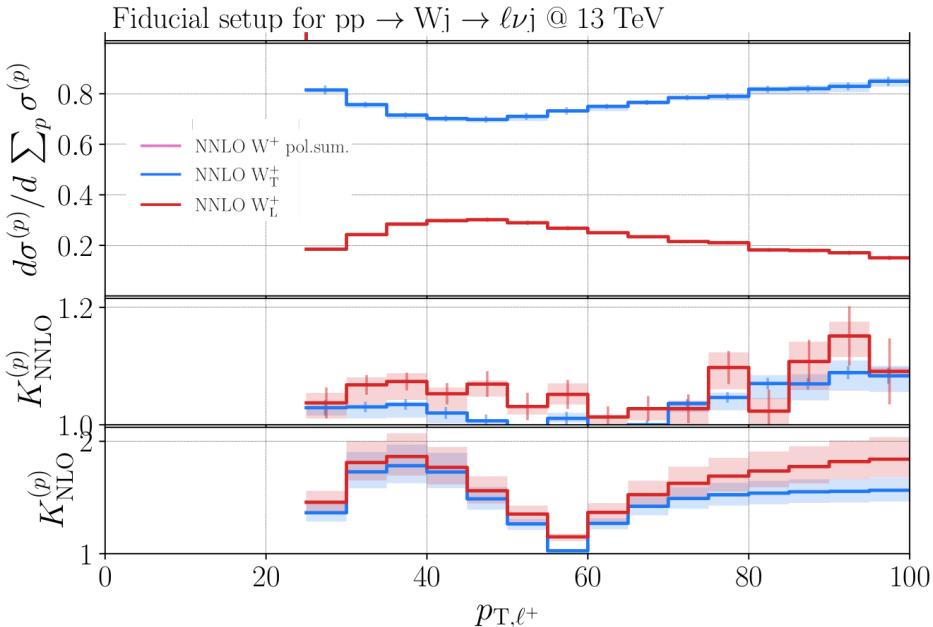


Studies of the Energy Dependence of Diboson Polarization Fractions and the Radiation-Amplitude-Zero Effect in WZ Production with the ATLAS Detector, ATLAS 2402.16365

	Measurement	
	$100 < p_T^Z \leq 200 \text{ GeV}$	$p_T^Z > 200 \text{ GeV}$
f_{00}	$0.19 \pm^{0.03}_{0.03} \text{ (stat)} \pm^{0.02}_{0.02} \text{ (syst)}$	$0.13 \pm^{0.09}_{0.08} \text{ (stat)} \pm^{0.02}_{0.02} \text{ (syst)}$
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08} \text{ (stat)} \pm^{0.05}_{0.06} \text{ (syst)}$	$0.23 \pm^{0.17}_{0.18} \text{ (stat)} \pm^{0.06}_{0.10} \text{ (syst)}$
f_{TT}	$0.63 \pm^{0.05}_{0.05} \text{ (stat)} \pm^{0.04}_{0.04} \text{ (syst)}$	$0.64 \pm^{0.12}_{0.12} \text{ (stat)} \pm^{0.06}_{0.06} \text{ (syst)}$
f_{00} obs (exp) sig.	$5.2 (4.3) \sigma$	$1.6 (2.5) \sigma$

	Prediction	
	$100 < p_T^Z \leq 200 \text{ GeV}$	$p_T^Z > 200 \text{ GeV}$
f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{TT}	0.619 ± 0.007	0.646 ± 0.008

Why do we need higher-order corrections



Inclusive K-factors are not enough

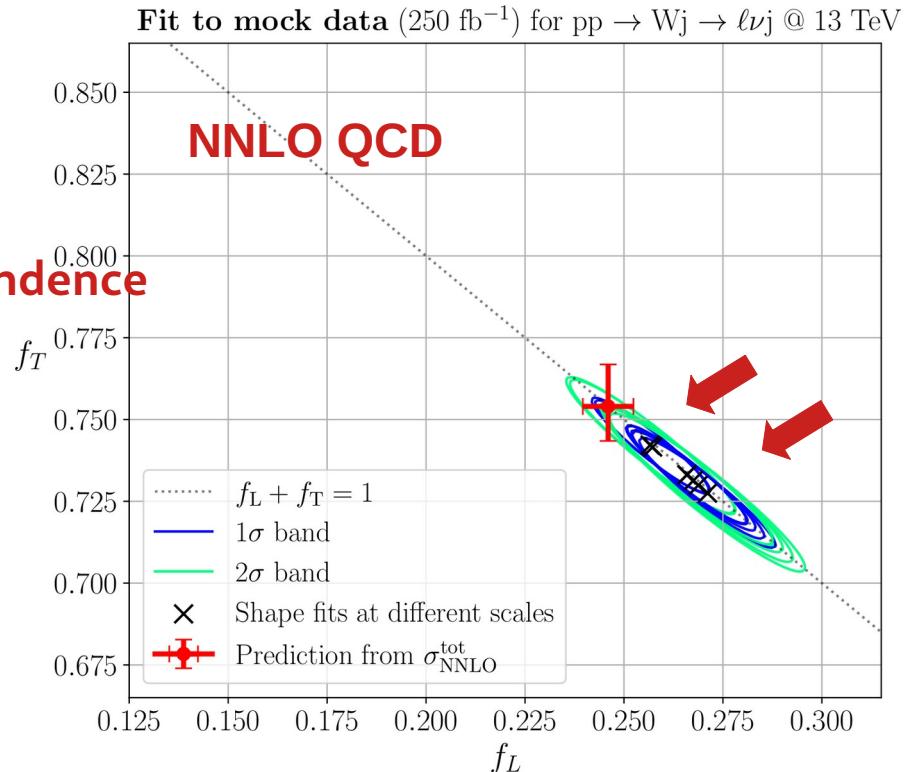
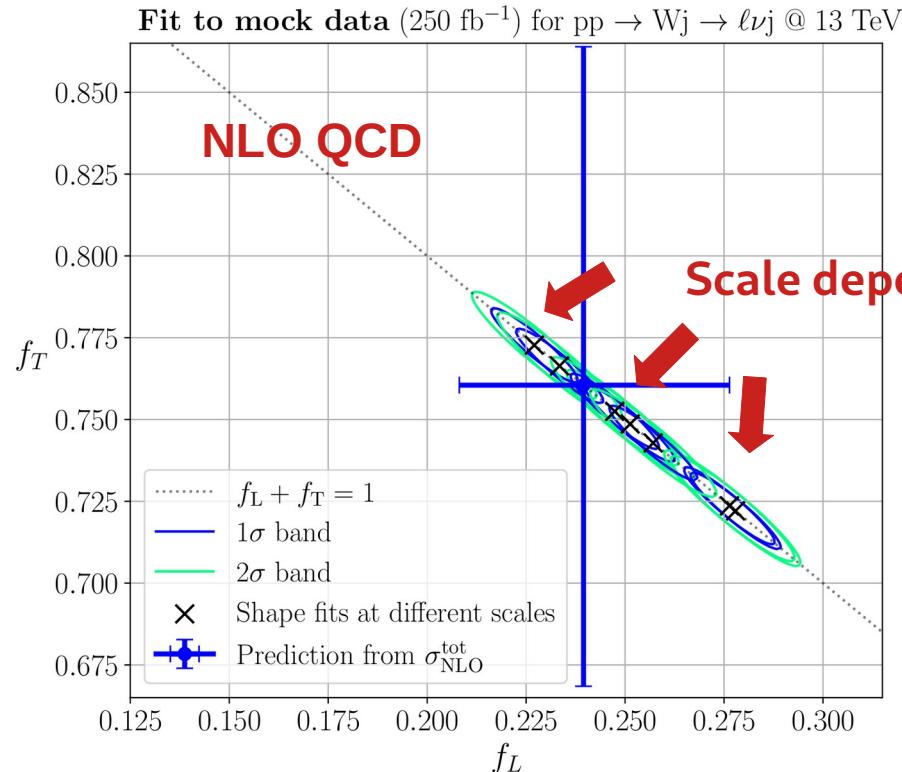
- 1) Differential polarization fraction have shapes
- 2) Higher-order corrections dependent on polarization! Just using unpolarized K-factor would lead to distortion of spectrum.
- 3) NNLO QCD needed to reach percent-level scale-dependence \rightarrow MHOU

Polarised $W+j$ production at the LHC: a study at NNLO QCD accuracy,
Pellen, Poncelet, Popescu 2109.14336

W+jet: mock-data fit

Fit to mock-data (based on NNLO QCD and 250 fb⁻¹ stats):
→ extreme case to see effect of scale dependence reduction

Observable: $\cos(\ell, j_1)$



Theory picture of hadron collision events

Precise theory input needed!

$$Q \gg \Lambda_{\text{QCD}}$$

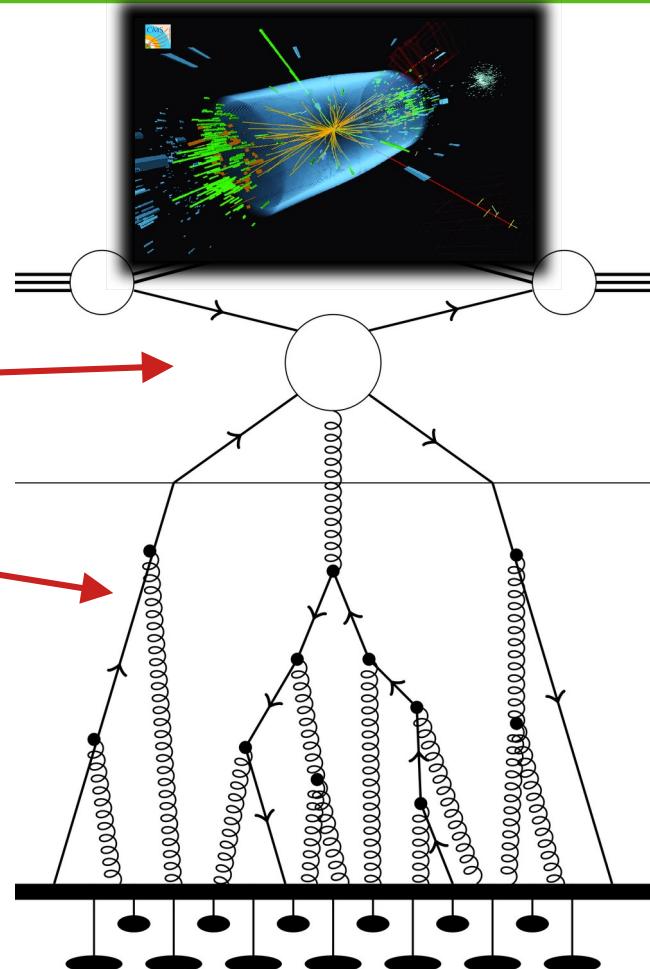
Fixed-order perturbation theory
scattering of individual partons

$$Q \gtrsim \Lambda_{\text{QCD}}$$

Parton-shower/Resummation
all-order bridge between perturbative
and non-perturbative physics

$$Q \sim \Lambda_{\text{QCD}}$$

"Hadronization"/MPI/...
non-perturbative physics



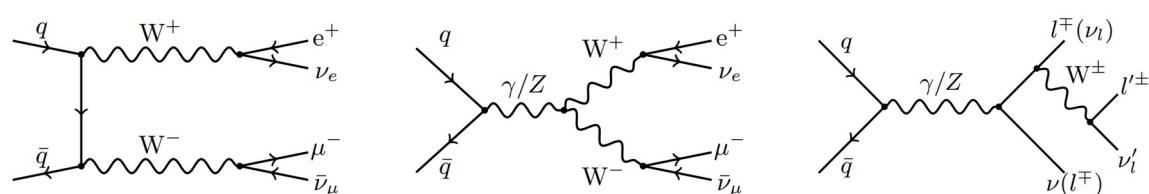
Focus on polarised boson pair production processes

$$pp \rightarrow W^+W^- \rightarrow e^+\mu^-\nu\bar{\nu}$$

NLO QCD: 2006.14867

NLO EW: 2311.16031

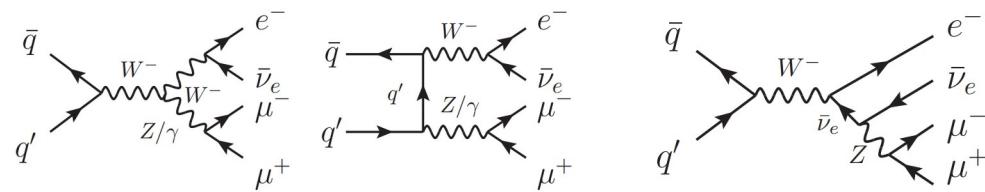
NNLO+LI QCD: 2102.13583



$$pp \rightarrow W^+Z \rightarrow e^+\nu\mu^+\mu^-$$

NLO QCD + EW : 1810.11034

NNLO QCD + NLO EW: 2510.25898

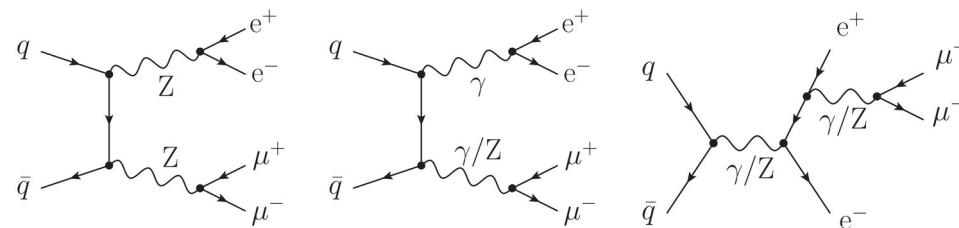


$$pp \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$$

NLO QCD + EW: 2107.06579

NNLO+LI QCD + NLO EW: 2505.09686

LI QCD: 2401.17365



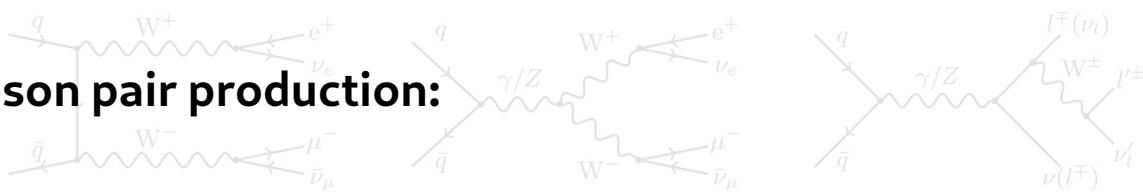
Focus on polarised boson pair production processes

$pp \rightarrow W^+W^- \rightarrow e^+\mu^-\nu\bar{\nu}$

Monte Carlo developments for boson pair production:
NLO QCD: 2006.14867

NLO EW: 2311.16031

NNLO+LI QCD: 2102.13583



- nLO + PS in **SHERPA**
[2310.14803]

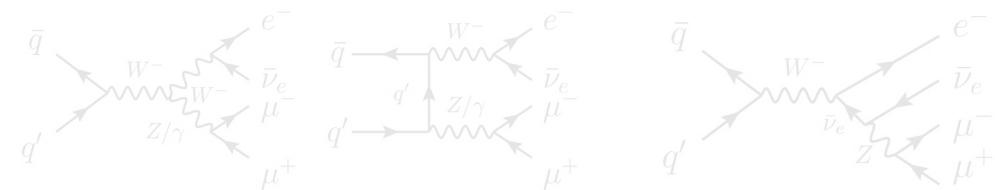
$pp \rightarrow W^+Z \rightarrow e^+\nu\mu^+\mu^-$

- NLO+PS in **Powheg-Box-Res**
[2311.05220]

NLO QCD: 2006.1034

NNLO QCD + NLO EW: 2510.25898

- NLO+PS + SMEFT in **Powheg-Box-Res**
[2507.21768]

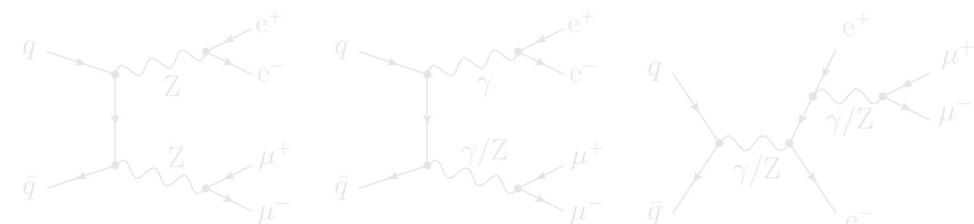


$pp \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$

NLO QCD + EW: 2107.06579

NNLO+LI QCD + NLO EW: 2505.09686

LI QCD: 2401.17365

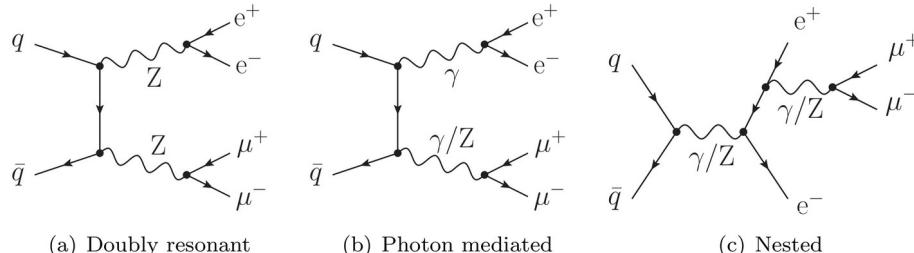


Polarised ZZ: COMETA polarisation study



Precise Standard-Model predictions for polarised
Z-boson pair production and decay at the LHC

Costanza Carrivale,^a Roberto Covarelli,^b Ansgar Denner,^c Dongshuo Du,^d Christoph Hultz,^c Mareen Hoppe,^e Martina Javurkova,^f Duc Ninh Le,^g Jakob Linder,^h Rafael Coelho Lopes de Sa,^f Olivier Mattelaer,ⁱ Susmita Mondal,^j Giacomo Ortona,^k Giovanni Pelliccioli,^{k,1} Rene Poncelet,^{l,1} Karolos Potamianos,^m Richard Ruiz,^l Marek Schönherr,ⁿ Frank Siegert,^e Lailin Xu,^d Xingyu Wu,^d Giulia Zanderighi^h



Main targets

- validation of MC codes
- comprehensive study of modelling choices: NWA/DPA/offshell, matching+merging
- higher order QCD/EW corrections
- Provide **best predictions** and compare to ATLAS pol. fractions and modelling [ATLAS 2310.04350]

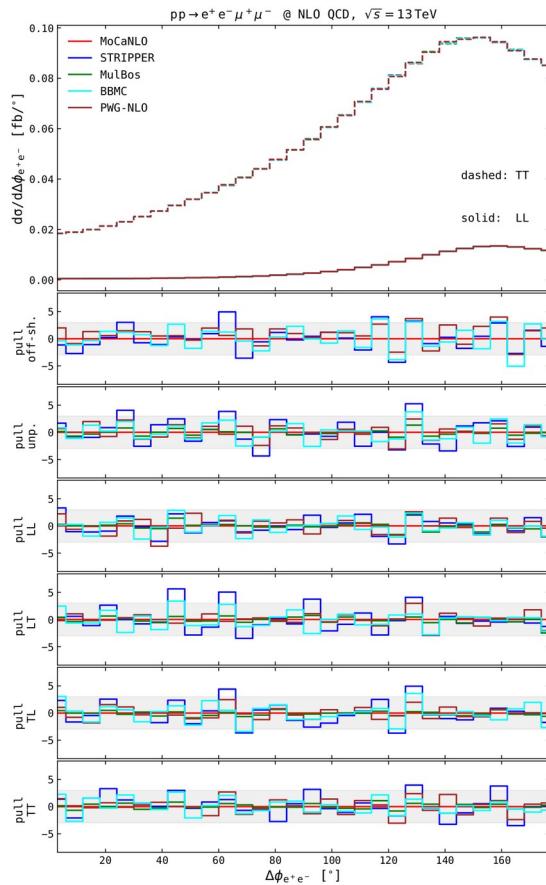
phase space definition

ZZ production in the ee/ $\mu\mu$ channel

MC code	OS approx.	LO tree	LO loop-ind.	NLO QCD	NNLO QCD	NLO EW	LO \times PS	NLO \times PS	MJ merging
MoCANLO	DPA	✓	✓	✓	✗	✓	✗	✗	✗
STRIPPER	DPA	✓	✓	✓	✓	✗	✗	✗	✗
MULBos	DPA	✓	✓	✓	✗	✓	✗	✗	✗
BBMC	DPA	✓	✗	✓	✗	✓	✗	✗	✗
SHERPA	NWA	✓	✗	(✓)	✗	✗	✓	(✓)	✓
MG5_AMC	BW	✓	✓	✗	✗	✗	✓	✗	✓
PowHEG-Box	DPA	✓	✗	✓	✗	✗	✓	✓	✗

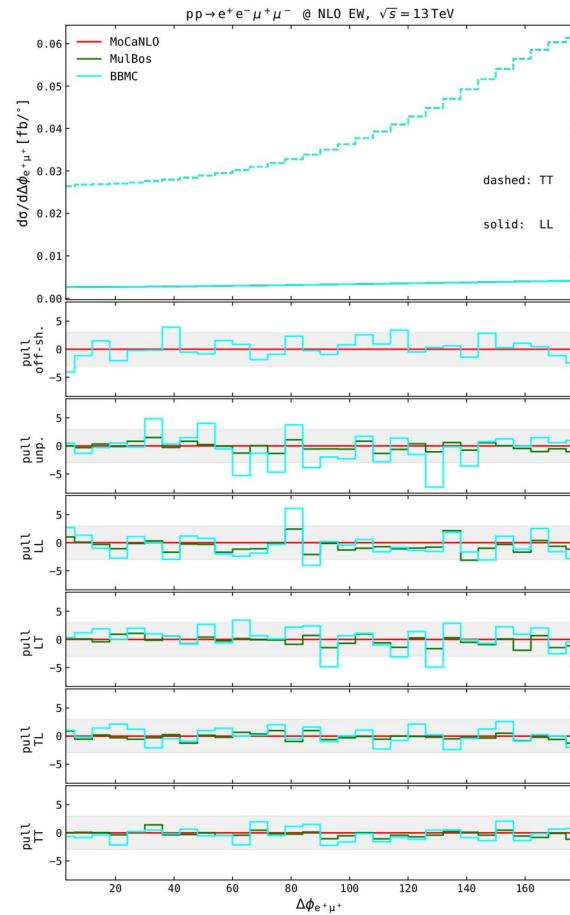
[Many thanks to Giovanni Pelliccioli]

Validation and NLO QCD and NLO EW



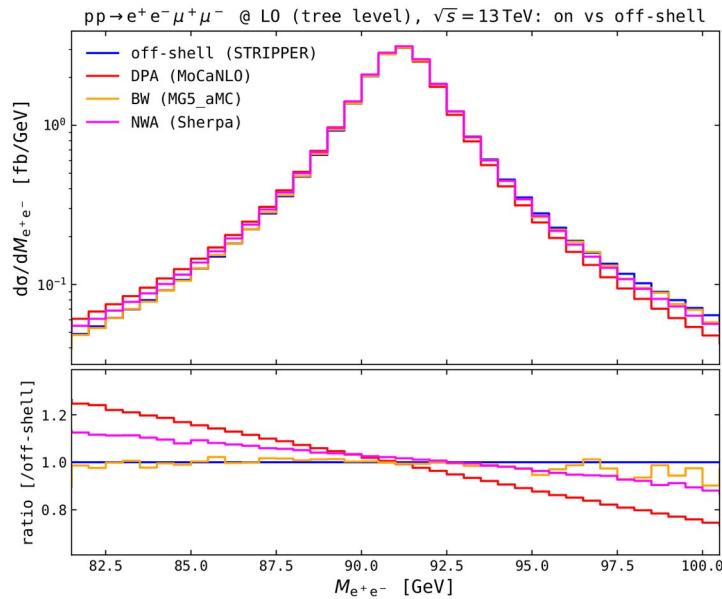
Validation of NLO

QCD ← → EW

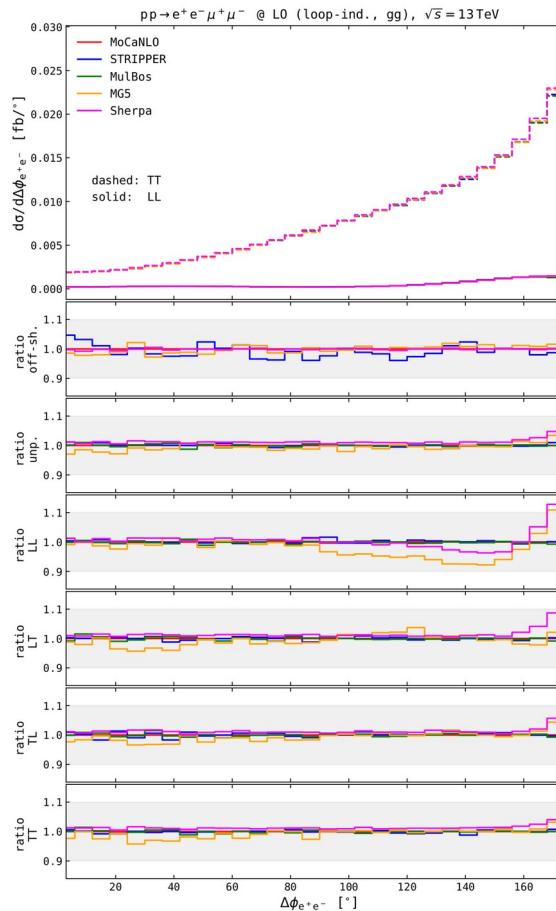


Different resonance treatment

Unpolarised ZZ:



Imprint in various distributions



Offshell

Complete processes

DPA

double-pole approximation

NWA / BW

Narrow width approximation
+ Breit-Wigner smearing

Higher-order predictions

MC code	OS approx.	LO tree	LO loop-ind.	NLO QCD	NNLO QCD	NLO EW	LO × PS	NLO × PS	MJ merging
MoCANLO	DPA	✓	✓	✓	✗	✓	✗	✗	✗
STRIPPER	DPA	✓	✓	✓	✓	✗	✗	✗	✗
MULBos	DPA	✓	✓	✓	✗	✓	✗	✗	✗
BBMC	DPA	✓	✗	✓	✗	✓	✗	✗	✗
SHERPA	NWA	✓	✗	(✓)	✗	✗	✓	(✓)	✓
MG5_AMC	BW	✓	✓	✗	✗	✗	✓	✗	✓
PowHEG-Box	DPA	✓	✗	✓	✗	✗	✓	✓	✗

Best predictions:

$$\text{NNLO}_{\text{QCD},gg}^{\text{EW}} = \sigma_{qq}^{\text{LO}}(1 + \delta_{\text{QCD}}^{\text{NLO}} + \delta_{\text{QCD}}^{\text{NNLO}} + \delta_{\text{EW}}^{\text{NLO}}) + \sigma_{gg}^{\text{LO}}$$

$$\text{NLOPS}_{\text{had.}} = \text{NLO}_{\text{QCD}} \times \text{PS}_{\text{QCD,QED}} + (\text{had.} + \text{MPI.})$$

$$\text{nLO-MJM}_{\text{had}} = (\text{nLO}_{\text{QCD}}^{(0j)} + \text{nLO}_{\text{QCD}}^{(1j)} + \text{LO}_{\text{QCD}}^{(2j)}) + \text{PS}_{\text{QCD,QED}} + (\text{had.} + \text{MPI})$$

Absolute predictions for polarised cross sections

	LL	LT	TL	TT
NLO _{QCD}	0.8899(3) ^{+3.1%} _{-2.5%}	1.9313(5) ^{+3.6%} _{-2.9%}	1.9243(2) ^{+3.6%} _{-2.9%}	10.209(1) ^{+2.8%} _{-2.2%}
NNLO _{QCD}	0.976(1) ^{+2.2%} _{-1.9%}	2.107(2) ^{+2.1%} _{-1.9%}	2.094(2) ^{+2.0%} _{-1.8%}	10.63(1) ^{+1.1%} _{-1.0%}
NNLO ⁽⁺⁾	0.909(1) ^{+2.9%} _{-2.1%}	1.973(2) ^{+2.7%} _{-2.0%}	1.960(2) ^{+2.6%} _{-1.9%}	9.76(1) ^{+1.6%} _{-1.1%}
NNLO ^(×)	0.876(1) ^{+2.1%} _{-1.9%}	1.895(2) ^{+2.0%} _{-1.9%}	1.884(2) ^{+1.9%} _{-1.8%}	9.439(9) ^{+0.9%} _{-1.0%}
NLOPS _{QCD}	0.8918(3) ^{+3.0%} _{-2.5%}	1.9367(6) ^{+3.6%} _{-2.9%}	1.9293(6) ^{+3.5%} _{-2.8%}	10.215(4) ^{+2.7%} _{-2.2%}
nLOPS _{QCD}	0.924(5) ^{+2.7%} _{-2.4%}	2.002(2) ^{+3.2%} _{-2.5%}	1.991(1) ^{+3.1%} _{-2.5%}	10.23(2) ^{+2.8%} _{-2.3%}
NLOPS _{had}	0.8321(3) ^{+3.0%} _{-2.5%}	1.8110(6) ^{+3.6%} _{-2.9%}	1.8036(6) ^{+3.5%} _{-2.8%}	9.576(3) ^{+2.7%} _{-2.2%}
nLOPS _{had}	0.8481(4) ^{+2.6%} _{-2.4%}	1.8429(8) ^{+3.1%} _{-2.5%}	1.8374(6) ^{+3.1%} _{-2.5%}	9.460(9) ^{+2.8%} _{-2.2%}
nLO-MJM _{had}	0.963(1) ^{+14.0%} _{-6.7%}	2.093(2) ^{+15.2%} _{-7.3%}	2.074(2) ^{+13.9%} _{-7.0%}	10.32(1) ^{+13.2%} _{-6.4%}

+ ~10 % NNLO QCD
- ~10% NLO EW

Small differences
in normalisation between
Powheg and Sherpa

MJM close to NNLO QCD
→ higher-order QCD corr.
dominated by hard recoil

ZZ polarization fractions – ATLAS comparison

Polarisation fractions:

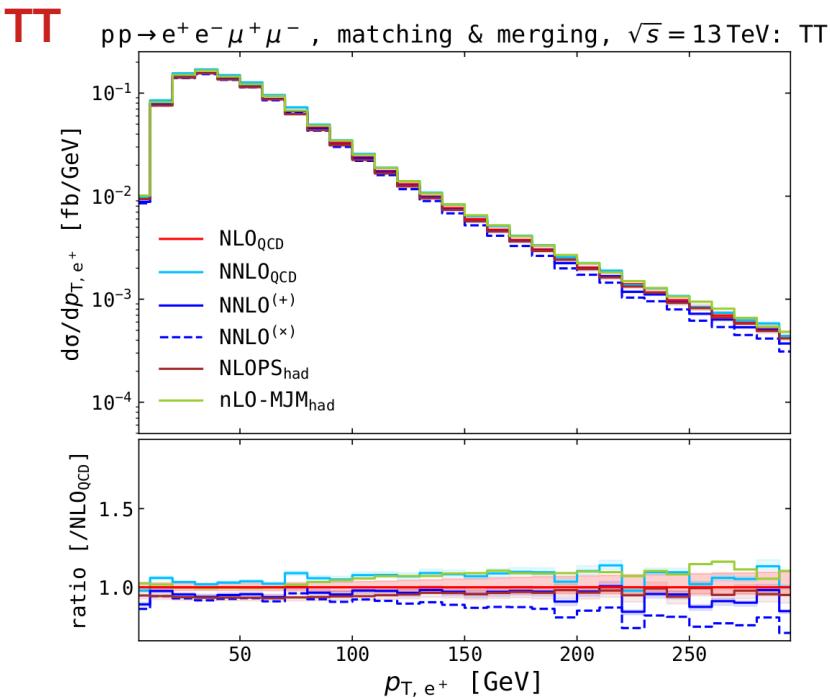
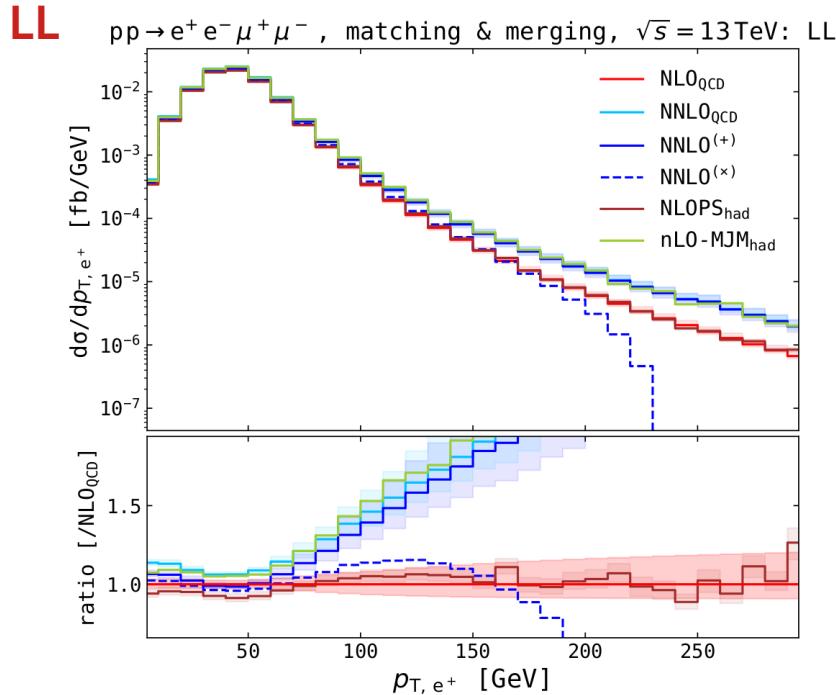
$$f_{\lambda\lambda'} = \frac{\sigma_{\lambda\lambda'}}{\sigma_{\text{unp}}}, \quad \lambda, \lambda' = L, T$$

Theory-experiment in agreement

→ dominated by exp. unc.
(stat. > sys.)

our predictions	LL [%]	LT [%]	TL [%]	TT [%]	
LO _{q̄}	5.85 ^{+0.07} -0.08	11.86 ^{+0.09} -0.11	11.89 ^{+0.09} -0.11	69.27 ^{+0.30} -0.26	
LO _{gg}	5.39 ^{+0.02} -0.02	2.12 ^{+0.01} -0.01	2.10 ^{+0.01} -0.01	90.48 ^{+0.03} -0.03	
NLO _{EW}	5.89 ^{+0.06} -0.08	11.97 ^{+0.09} -0.11	12.01 ^{+0.09} -0.11	68.98 ^{+0.29} -0.25	
NLO _{QCD}	5.87 ^{+0.03} -0.05	12.74 ^{+0.07} -0.06	12.69 ^{+0.07} -0.06	67.35 ^{+0.14} -0.16	
NNLO _{QCD}	6.07 ^{+0.05} -0.04	13.11 ^{+0.09} -0.08	13.04 ^{+0.08} -0.07	66.20 ^{+0.19} -0.24	
NNLO _{QCD} ^{EW}	6.12 ^{+0.06} -0.04	13.29 ^{+0.09} -0.08	13.21 ^{+0.08} -0.07	65.75 ^{+0.20} -0.25	
NNLO _{QCD, gg} ^{EW}	6.05 ^{+0.03} -0.03	12.15 ^{+0.10} -0.15	12.07 ^{+0.11} -0.16	68.29 ^{+0.30} -0.21	
NLOPS _{QCD}	5.88 ^{+0.03} -0.04	12.76 ^{+0.08} -0.06	12.71 ^{+0.07} -0.06	67.30 ^{+0.13} -0.15	
nLOPS _{QCD}	6.02 ^{+0.05} -0.08	13.04 ^{+0.04} -0.09	12.97 ^{+0.04} -0.09	66.61 ^{+0.14} -0.47	
NLOPS _{had}	5.86 ^{+0.03} -0.04	12.74 ^{+0.08} -0.06	12.69 ^{+0.07} -0.06	67.38 ^{+0.13} -0.15	
nLOPS _{had}	5.98 ^{+0.03} -0.07	12.99 ^{+0.02} -0.09	12.96 ^{+0.02} -0.09	66.70 ^{+0.22} -0.46	
LO-MJM _{QCD}	5.79 ^{+0.08} -0.09	12.91 ^{+0.06} -0.05	12.84 ^{+0.06} -0.06	66.81 ^{+0.24} -0.22	
LO-MJM _{had}	5.91 ^{+0.01} -0.10	12.84 ^{+0.13} -0.23	12.79 ^{+0.12} -0.23	67.14 ^{+1.08} -0.98	
nLO-MJM _{had}	6.14 ^{+0.12} -0.11	13.35 ^{+0.47} -0.32	13.23 ^{+0.32} -0.28	65.85 ^{+1.11} -0.96	
ATLAS measurement					
pre-fit	6.1 ± 0.4		22.9 ± 0.9		69.9 ± 3.9
post-fit	7.1 ± 1.7		22.8 ± 1.1		69.0 ± 2.7

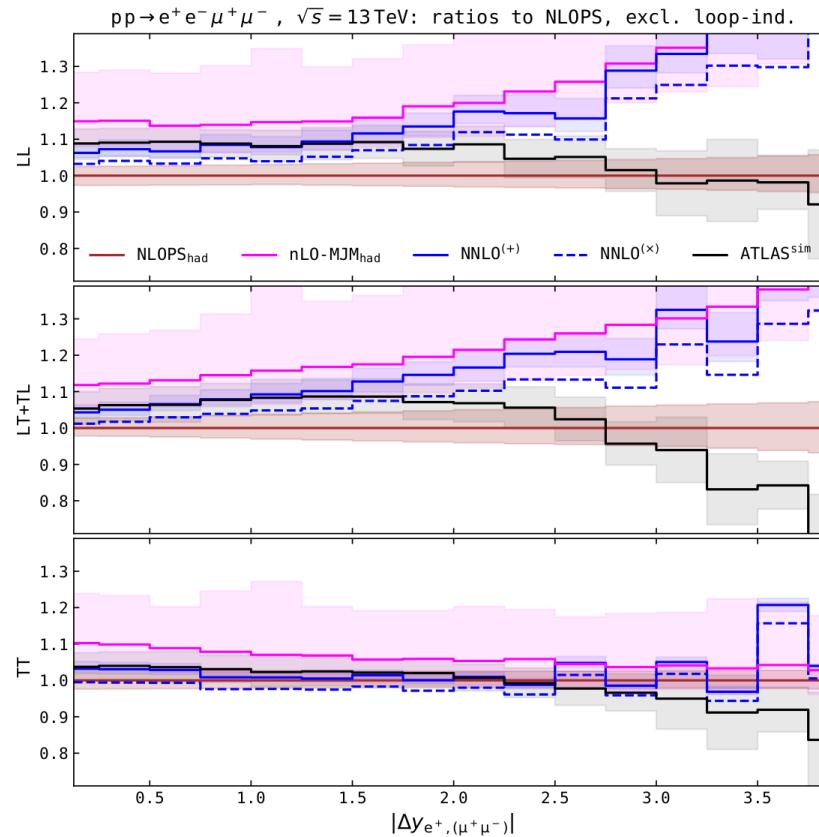
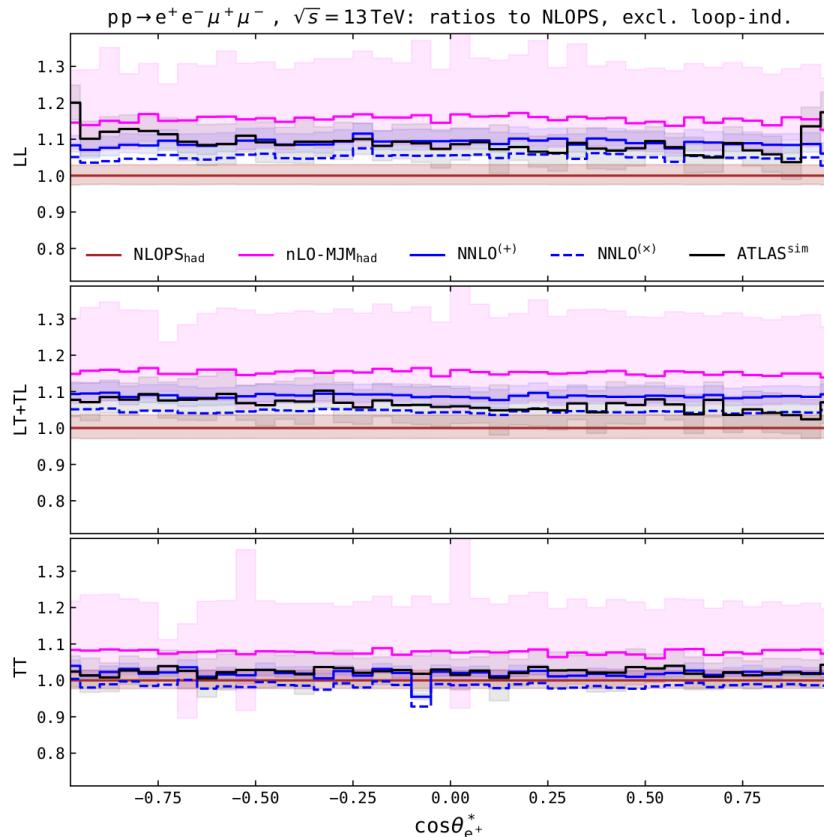
ZZ differential distributions



Large higher-order QCD effects for LL polarization

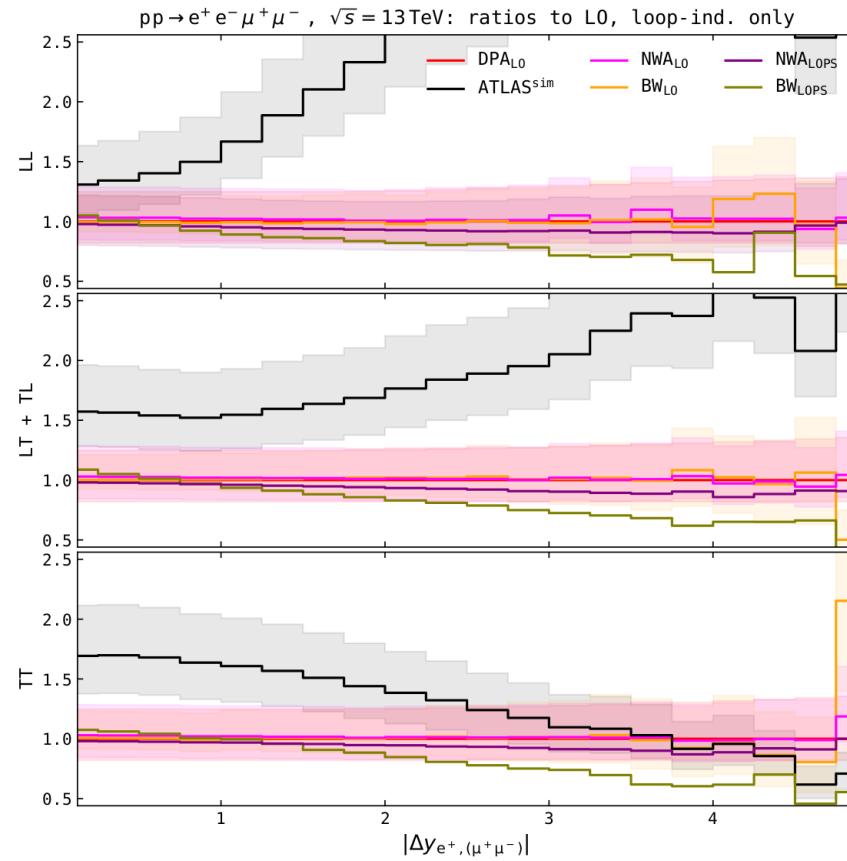
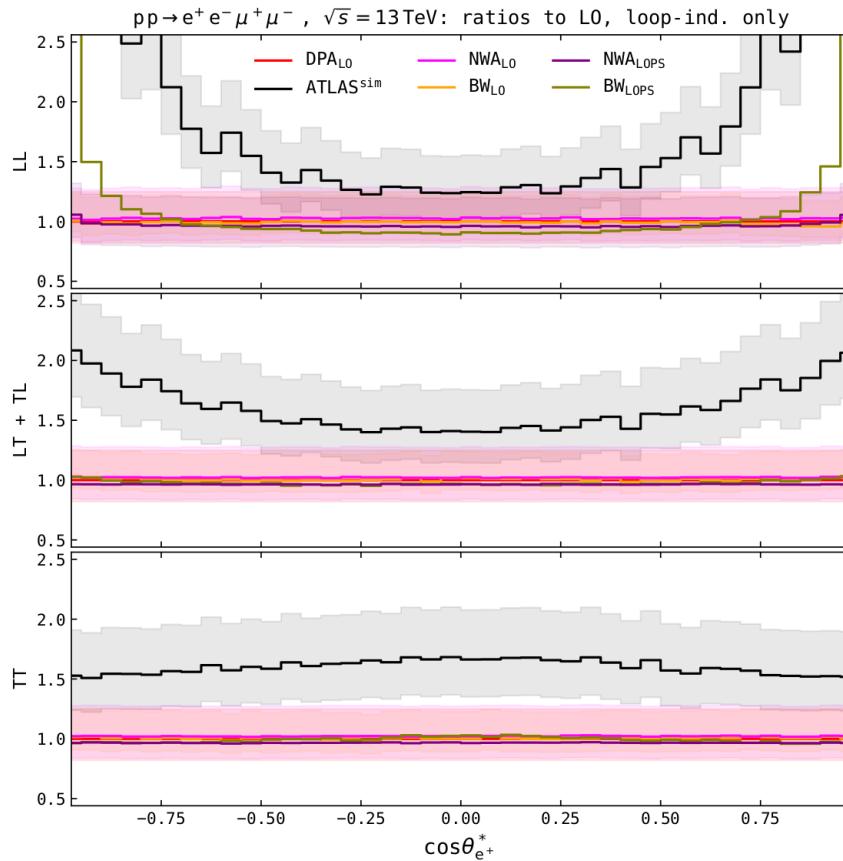
SHERPA nLO-MJM shapes resample NNLO QCD results → impact from hard recoil

Best predictions vs ATLAS modelling: qq-channel



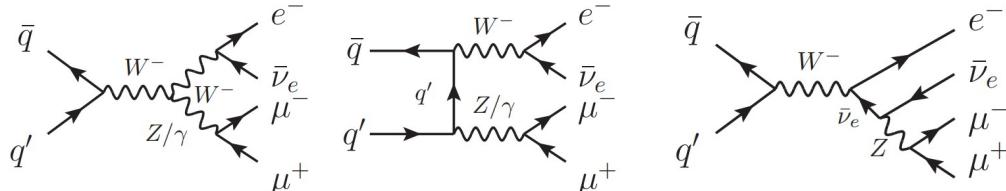
ATLAS modelling from [ATLAS 2310.04350]

Best predictions vs ATLAS modelling: gg-channel



ATLAS modelling from [ATLAS 2310.04350]

Filling the gap: WZ at NNLO QCD + EW



Diagrams from 1810.11034

Precise predictions for joint polarisation fractions in WZ production at the LHC
Pelliccioli, Poncelet [2510.25898]

Combining NNLO QCD and NLO EW corrections:

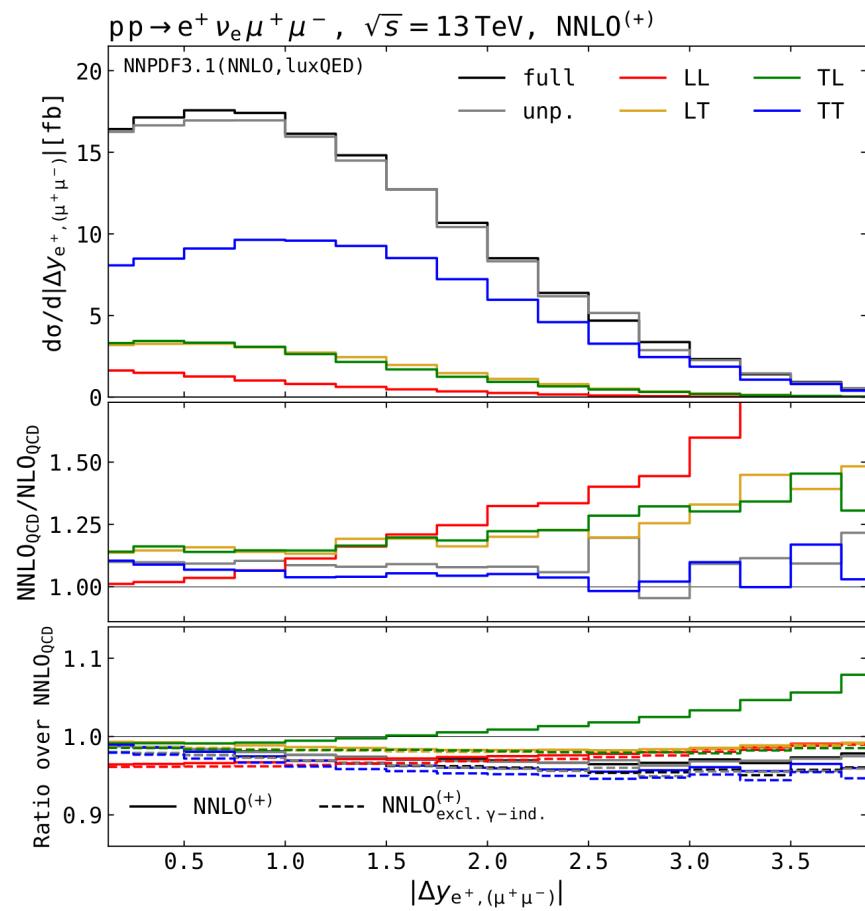
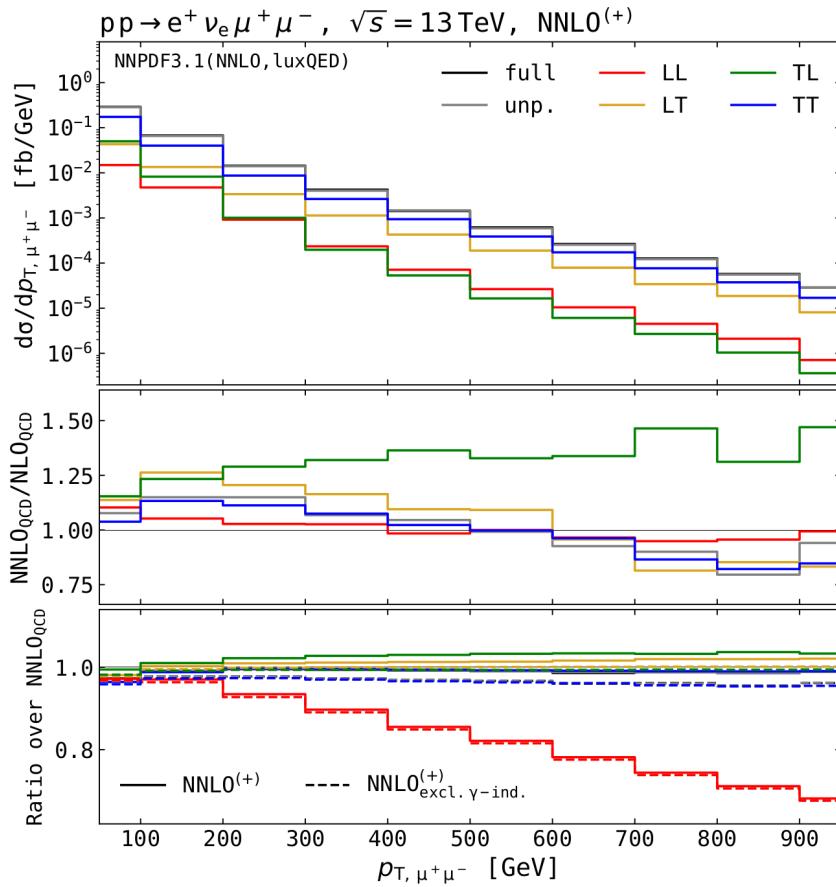
$$d\sigma_{\text{NLO}}^{(+)} = d\sigma_{\text{LO}} \left(1 + \delta_{\text{QCD}, u\bar{d}}^{(1)} + \delta_{\text{EW}, u\bar{d}}^{(1)} \right) + d\sigma_{qg} + d\sigma_{q\gamma},$$

$$d\sigma_{\text{NLO}}^{(\times)} = d\sigma_{\text{LO}} \left(1 + \delta_{\text{QCD}, u\bar{d}}^{(1)} \right) \left(1 + \delta_{\text{EW}, u\bar{d}}^{(1)} \right) + d\sigma_{qg} + d\sigma_{q\gamma},$$

$$d\sigma_{\text{NNLO}}^{(+)} = d\sigma_{\text{LO}} \left(1 + \delta_{\text{QCD}, u\bar{d}}^{(1)} + \delta_{\text{QCD}, u\bar{d}}^{(2)} + \delta_{\text{EW}, u\bar{d}}^{(1)} \right) + d\sigma_{qg} (1 + \delta_{\text{QCD}, qg}^{(1)}) + d\sigma_{qq'} + d\sigma_{gg} + d\sigma_{q\gamma},$$

$$d\sigma_{\text{NNLO}}^{(\times)} = d\sigma_{\text{LO}} \left(1 + \delta_{\text{QCD}, u\bar{d}}^{(1)} + \delta_{\text{QCD}, u\bar{d}}^{(2)} \right) \left(1 + \delta_{\text{EW}, u\bar{d}}^{(1)} \right) + d\sigma_{qg} (1 + \delta_{\text{QCD}, qg}^{(1)}) + d\sigma_{qq'} + d\sigma_{gg} + d\sigma_{q\gamma}$$

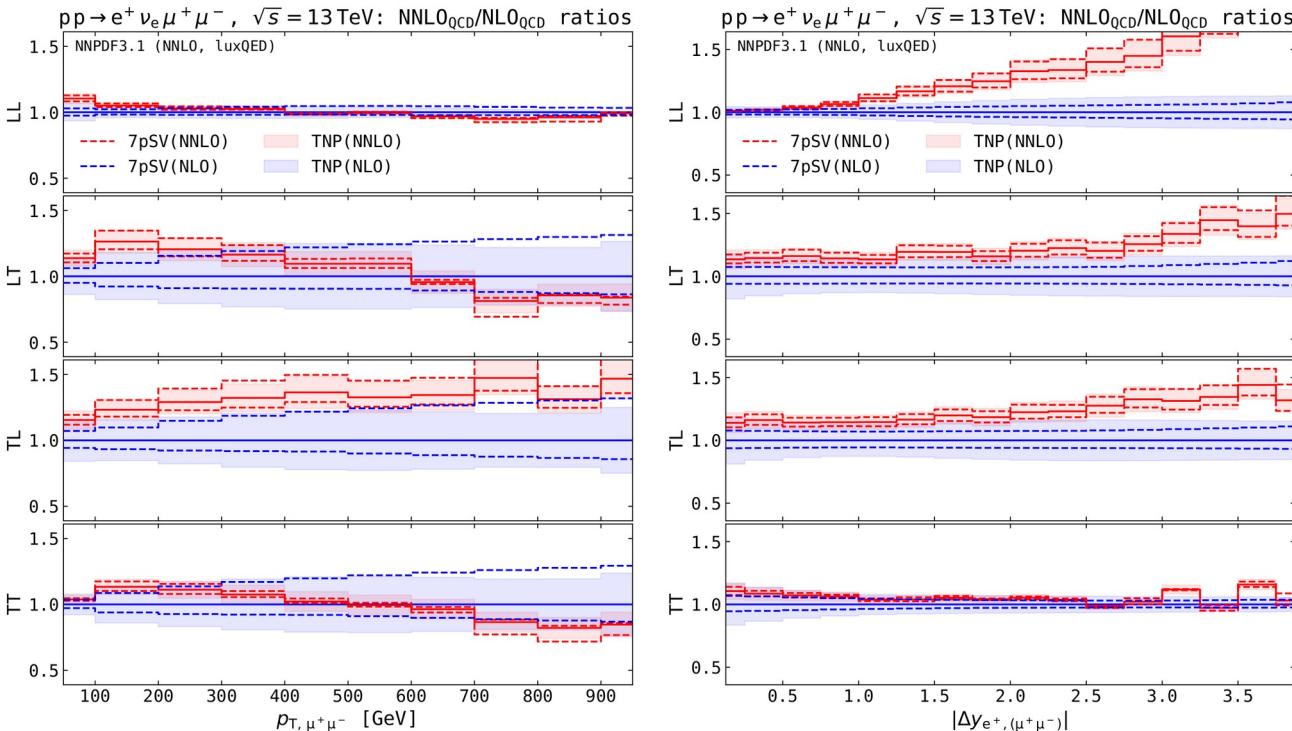
WZ NNLO QCD + NLO EW



Theory uncertainties from Theory-Nuisance-Parameters

TNP [Tackmann'24] Parametrization
based on [Lim, Poncelet'24]:

$$d\sigma = \alpha_s^n N_c^m d\bar{\sigma}^{(0)} \left[1 + \alpha_s N_c \left(\frac{d\bar{\sigma}^{(1)}}{d\bar{\sigma}^{(0)}} \right) + \alpha_s^2 N_c^2 \left(\frac{d\bar{\sigma}^{(2)}}{d\bar{\sigma}^{(0)}} \right) + \dots \right]$$



Approximation for next missing term:

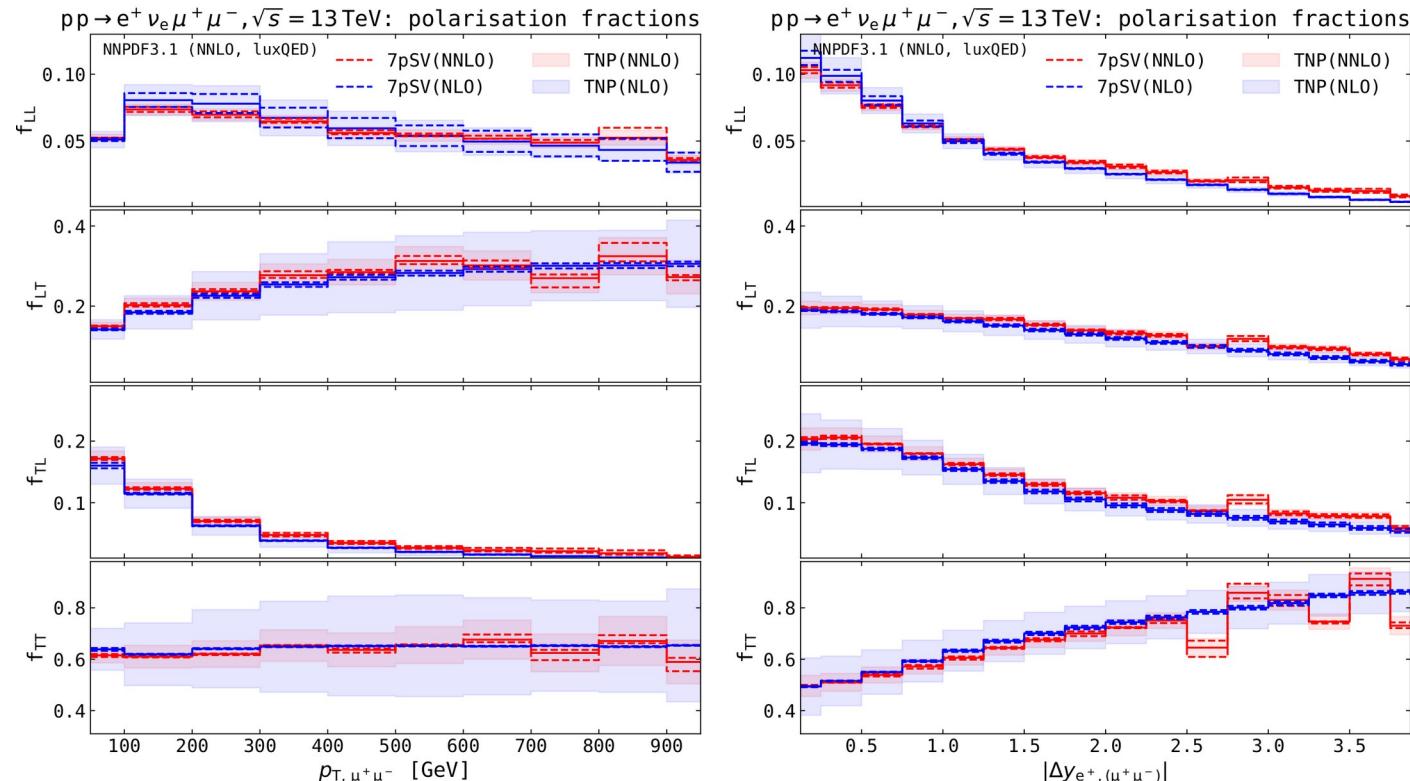
$$\frac{d\bar{\sigma}_{\text{TNP}}^{(N+1)}}{d\bar{\sigma}^{(0)}} = \sum_{j=1}^N f_k^{(j)}(\vec{\theta}, x) \left(\frac{d\bar{\sigma}^{(j)}}{d\bar{\sigma}^{(0)}} \right)$$

Chebychev Polynomials

Differential polarization fractions

Uncorrelated TNP unc.
 → similar to uncorrelated
 scale variation

$$f_{\lambda\lambda'} = \frac{d\sigma_{\lambda\lambda'}}{d\sigma_{\text{unp}}}, \quad \text{and} \quad \Delta f_{\lambda\lambda'}^{\text{TNP}} = \frac{d\sigma_{\lambda\lambda'}}{d\sigma_{\text{unp}}} \sqrt{\left(\frac{d\Delta\sigma_{\lambda\lambda'}^{\text{TNP}}}{d\sigma_{\lambda\lambda'}} \right)^2 + \left(\frac{d\Delta\sigma_{\text{unp}}^{\text{TNP}}}{d\sigma_{\text{unp}}} \right)^2}$$



Polarised bosons in SMEFT at NLO + PS

NLO+PS in Powheg-Box-Res framework

[Haisch,Linder, Pelliccioli, Re, Zanderighi [2507.21768](#)]

Loop matrix elements: Recola2 [[1711.07388](#)]

Operators (dim-6 and dim-8)

$$Q_{HB} = H^\dagger H B_{\mu\nu} B^{\mu\nu}, \quad Q_{H\widetilde{B}} = H^\dagger H B_{\mu\nu} \widetilde{B}^{\mu\nu},$$

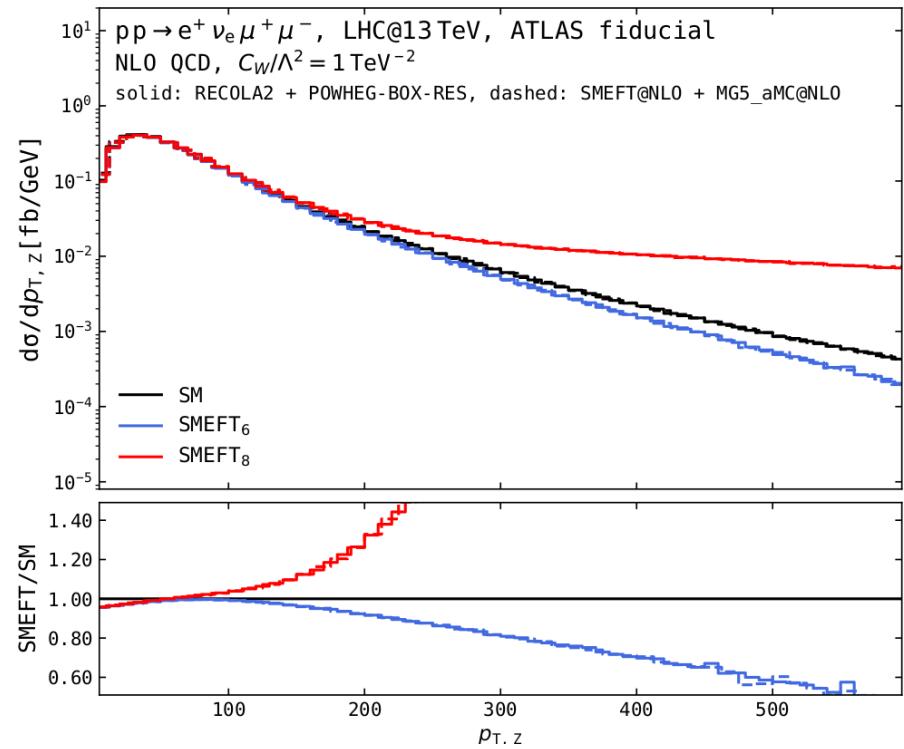
$$Q_{HW} = H^\dagger H W_{\mu\nu}^i W^{i,\mu\nu}, \quad Q_{H\widetilde{W}} = H^\dagger H W_{\mu\nu}^i \widetilde{W}^{i,\mu\nu},$$

$$Q_{HWB} = H^\dagger \sigma^i H W_{\mu\nu}^i B^{\mu\nu}, \quad Q_{H\widetilde{W}B} = H^\dagger \sigma^i H \widetilde{W}_{\mu\nu}^i B^{\mu\nu},$$

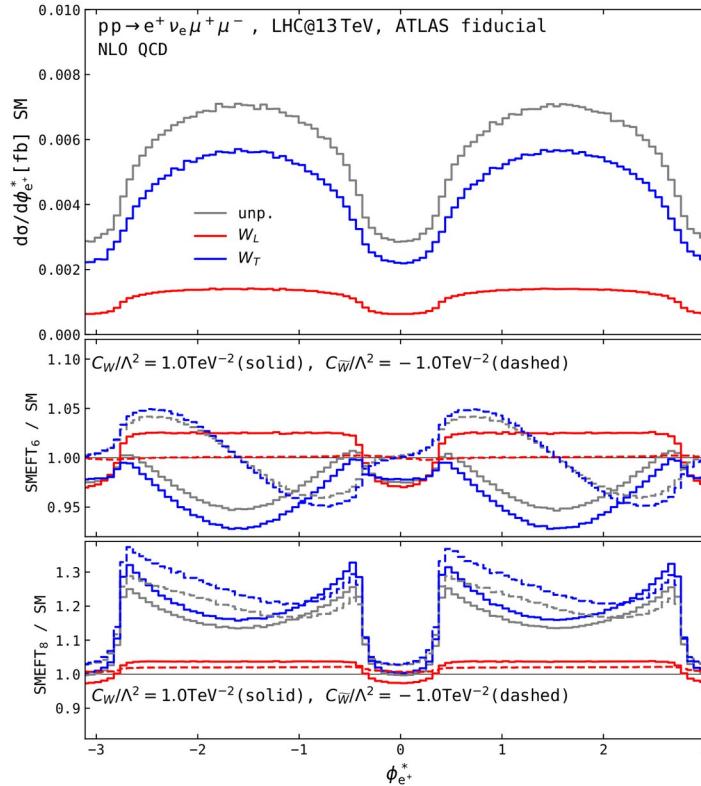
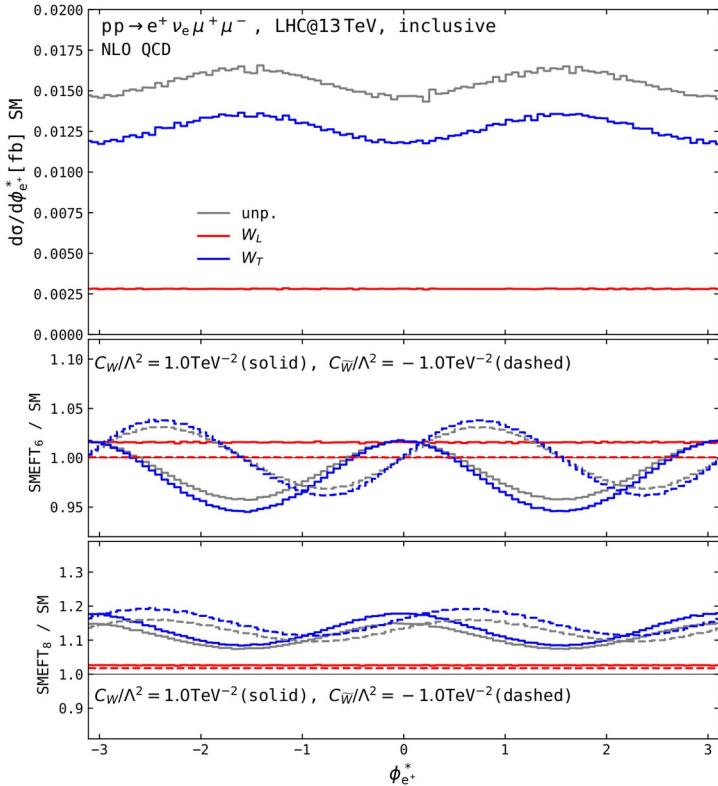
$$Q_W = \epsilon_{ijk} W_\mu^{i,\nu} W_\nu^{j,\lambda} W_\lambda^{k,\mu}, \quad Q_{\widetilde{W}} = \epsilon_{ijk} W_\mu^{i,\nu} W_\nu^{j,\lambda} \widetilde{W}_\lambda^{k,\mu}.$$

CP-even

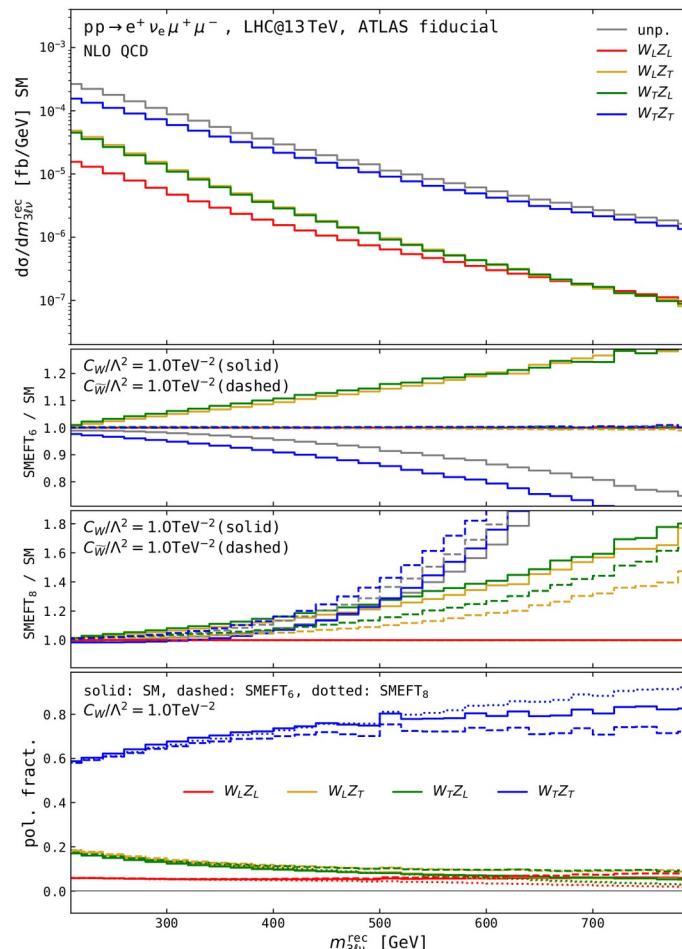
CP-odd



SMEFT imprint in fiducial cross sections



SMEFT effects in polarisation fractions



contribution	σ [fb], ATLAS fiducial, Eq. (44)				
	unpolarized	$W_L Z_L$	$W_L Z_T$	$W_T Z_L$	$W_T Z_T$
SM	34.64(2)	1.968(1)	5.357(2)	5.100(2)	21.99(2)
Q_W (lin.)	-0.975(1)	0	0.1229(3)	0.1435(3)	-1.264(1)
Q_W (quad.)	6.299(2)	0	0.0803(0)	0.1001(0)	6.110(2)
$Q_{\widetilde{W}}$ (lin.)	-0.013(1)	0	-0.0039(1)	0.0056(1)	0.0102(9)
$Q_{\widetilde{W}}$ (quad.)	6.443(2)	0	0.1312(1)	0.1661(1)	6.132(2)

$$Q_W = \epsilon_{ijk} W_\mu^{i,\nu} W_\nu^{j,\lambda} W_\lambda^{k,\mu}, \quad Q_{\widetilde{W}} = \epsilon_{ijk} W_\mu^{i,\nu} W_\nu^{j,\lambda} \widetilde{W}_\lambda^{k,\mu}.$$

CP-odd operators do not interfere
with SM \rightarrow only dim-8 effect

Moderate effect on polarisation fractions

Summary

- Increasing interest in studying polarized bosons
 - triggered by exciting prospects for future precise measurements
 - tests of the SM with links to the EWSB through the longitudinal component
- Higher order corrections are crucial to measure/model polarization fractions accurately.
 - Efforts to provide higher-order predictions at (N)NLO QCD and NLO EW + PS
- ZZ polarization study by COMETA:
 - validation of MC codes
 - comprehensive study of modelling choices: NWA/DPA/offshell, matching+merging
 - higher order QCD/EW corrections have impact on normalisation and shape
 - Comparison to ATLAS models demonstrate improvement potential
- WZ at NNLO QCD + EW
- SMEFT effects on polarisation observables @ NLO+PS reality

Thank you!



Comprehensive Multiboson Experiment-Theory Action

- brings together theorists, experimentalists and machine learning experts
- COMETA promotes a broad scientific program including:
 - BSM/EFT interpretation of multiboson measurements
 - precise SM predictions and event generation (MC+PS) for multiboson
 - development of theory and tools to measure signals with polarised W and Z bosons
 - development of advanced Machine Learning tools
 - Combined exp. analyses of multiboson processes (H, HH, VV, VVV, VBS...)



Comprehensive Multiboson Experiment-Theory Action

- **WG1 - Theoretical framework, precision calculations and simulation**
- WG2 - Technological innovation in data analysis
- WG3 - Experimental Measurements
- WG4 - Management and Event Organization
- WG5 - Inclusiveness and Outreach

Further information:

<https://www.cost.eu/actions/CA22130/> and <https://cometa.web.cern.ch/>



Comprehensive Multiboson Experiment-Theory Action

- WG1 - Theoretical framework, precision calculations and simulation
- WG2 - Digital innovation in data analysis
- WG3 - Experimental Measurements
- WG4 - Management and Event Organization
- WG5 - Infrastructure and Outreach

WG1 leaders

Giovanni Pelliccioli

Ramona Groeber



Eleni Vryonidou (vryonidou.eleni@ucy.ac.cy)
Rene Poncelet (rene.poncelet@ifj.edu.pl)

Further information:

<https://www.cost.eu/actions/CA22130/> and <https://cometa.web.cern.ch/>

Backup

Uncertainties in ATLAS model (ZZ COMETA study)

- variations of PDF sets and of the strong coupling constant α_s ,
- QCD-scale dependence, evaluated via 7-point scale variations around the central value for the factorisation and renormalisation scales (equal to the Z-boson pole mass),
- inclusion of higher-order QCD corrections via reweighting of the LO-merged MG5_AMC simulations for $q\bar{q} \rightarrow ZZ$, according to polarised MoCANLO K-factors for NLO QCD corrections and to NLO-merged SHERPA unpolarised predictions for PS effects,
- inclusion of NLO EW effects via reweighting LO-merged MG5_AMC predictions with EW corrections obtained with MoCANLO (uncertainty as the difference between multiplicative and additive combination of NLO QCD and EW corrections),
- modelling of interference effects by reweighting unpolarised NLO-merged SHERPA predictions according to the interference-term MoCANLO prediction,
- non-closure of the one-dimensional reweighting due to higher-order corrections,
- inclusion of higher-order QCD effects to $gg \rightarrow ZZ$ through a reweighting of SHERPA unpolarised predictions (LO-merged rescaled with flat NLO QCD corrections) according to LO MoCANLO polarised predictions.

Polarized VV @ (N)NLO QCD / NLO EW

Fiducial polarization observables in hadronic WZ production: A next-to-leading order QCD+EW study,

Baglio, Le Duc 1810.11034

Anomalous triple gauge boson couplings in ZZ production at the LHC and the role of Z boson polarizations,

Rahama, Singh 1810.11657

Polarization observables in WZ production at the 13 TeV LHC: Inclusive case,

Baglio, Le Duc 1910.13746

Unravelling the anomalous gauge boson couplings in ZW+- production at the LHC and the role of spin-1 polarizations,

Rahama, Singh 1911.03111

Polarized electroweak bosons in W+W- production at the LHC including NLO QCD effects,

Denner, Pelliccioli 2006.14867

NLO QCD predictions for doubly-polarized WZ production at the LHC,

Denner, Pelliccioli 2010.07149

NNLO QCD study of polarised W+W- production at the LHC,

Poncelet, Popescu 2102.13583

NLO EW and QCD corrections to polarized ZZ production in the four-charged-lepton channel at the LHC,

Denner, Pelliccioli 2107.06579

Breaking down the entire spectrum of spin correlations of a pair of particles involving fermions and gauge bosons,

Rahama, Singh 2109.09345

Doubly-polarized WZ hadronic cross sections at NLO QCD+EW accuracy,

Duc Ninh Le, Baglio 2203.01470

Doubly-polarized WZ hadronic production at NLO QCD+EW: Calculation method and further results

Duc Ninh Le, Baglio, Dao 2208.09232

NLO QCD corrections to polarised di-boson production in semi-leptonic final states

Denner, Haitz, Pelliccioli 2211.09040

Polarised cross sections for vector boson production with SHERPA

Hoppe, Schönherr, Siegert 2310.14803

Polarised-boson pairs at the LHC with NLOPS accuracy

Pelliccioli, Zanderighi 2311.05220

NLO EW corrections to polarised W+W- production and decay at the LHC

Denner, Haitz, Pelliccioli 2311.16031

NLO electroweak corrections to doubly-polarized W+W- production at the LHC

Thi Nhung Dao, Duc Ninh 2311.17027

Polarized ZZ pairs in gluon fusion and vector boson fusion at the LHC

Javurkova, Ruiz, Coelho, Sandesara 2401.17365

Other polarized cross section calculations

- Polarised VBS (so far LO):

W boson polarization in vector boson scattering at the LHC,

Ballestrero, Maina, Pelliccioli 1710.09339

Polarized vector boson scattering in the fully leptonic WZ and ZZ channels at the LHC,

Ballestrero, Maina, Pelliccioli 1907.04722

Automated predictions from polarized matrix elements

Buarque Franzosi, Mattelaer, Ruiz, Shil 1912.01725

Different polarization definitions in same-sign WW scattering at the LHC,

Ballestrero, Maina, Pelliccioli 2007.07133

- Single boson production

Left-Handed W Bosons at the LHC,

Z. Bern et. al. 1103.5445

Electroweak gauge boson polarisation at the LHC,

Stirling, Vryonidou 1204.6427

What Does the CMS Measurement of W-polarization Tell Us about the Underlying Theory of the Coupling of W-Bosons to Matter?,

Belyaev, Ross 1303.3297

Polarised W+j production at the LHC: a study at NNLO QCD accuracy,

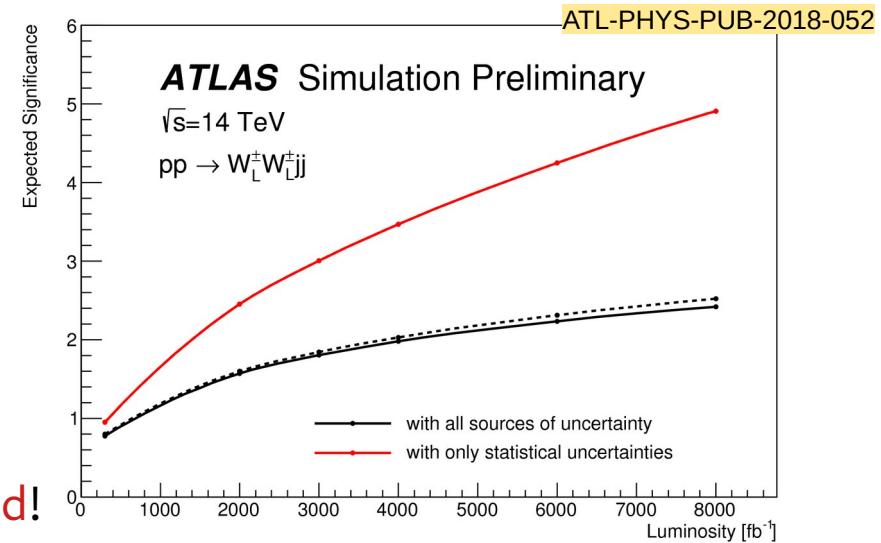
Pellen, Poncelet, Popescu 2109.14336

Polarised VBS at HL-LHC

If we want to study unitarisation/EWSB we need to **extract the longitudinal component**

- only 5-10 % of the total rate
→ **very challenging**
(remember: 130fb^{-1} → $\sim 5\text{-}7$ sigma
→ naive improvement by factor 10 necessary for observation)
- Requires CMS/ATLAS combination
and/or new techniques at HL-LHC
→ **improvement of systematic uncertainties needed!**

ATLAS HL-LHC projection



How to improve on the (theory) systematics?

- Improved signal and background (i.e. transverse part)
- Effective separation of boson polarisation

Polarised nLO+PS: SHERPA

Polarised cross sections for vector boson production with SHERPA
Hoppe, Schönherr, Siegert 2310.14803

- New bookkeeping of boson polarizations in SHERPA for LO MEs
- Approximate NLO corrections: nLO+PS
 - Reals+matching are treated exact
 - loop matrix elements unpolarised
- Comparison with multi-jet merged calculations

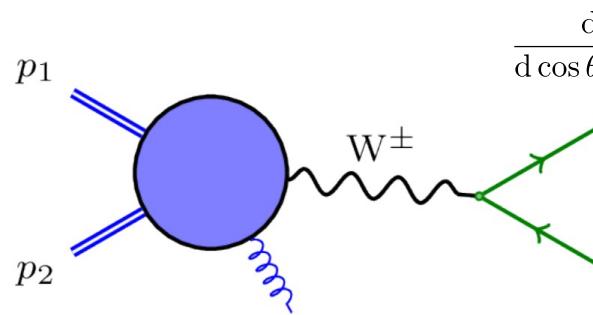
Comparison with literature

- nLO+PS approximation in fair agreement with full NLO
→ good for polarization fractions

W^+Z	σ^{NLO} [fb]	Fraction [%]	K-factor	σ_{SHERPA}^{nLO+PS} [fb]	Fraction [%]	K-factor
full	35.27(1)		1.81	33.80(4)		
unpol	34.63(1)	100	1.81	33.457(26)	100	1.79
Laboratory frame						
L-U	8.160(2)	23.563(9)	1.93	7.962(5)	23.796(25)	1.91
T-U	26.394(9)	76.217(34)	1.78	25.432(21)	76.01(9)	1.75
int	0.066(10) (diff)	0.191(29)	2.00	0.064(7)	0.191(22)	2.40(40)
U-L	9.550(4)	27.577(14)	1.73	9.275(16)	27.72(5)	1.72
U-T	25.052(8)	72.342(31)	1.83	24.156(18)	72.20(8)	1.81
int	0.028(10) (diff)	0.081(29)	-0.49	0.026(7)	0.079(22)	-0.471(34)

How to measure polarized bosons?

Angular decomposition of 2-body W decay:



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

After azimuthal integration:

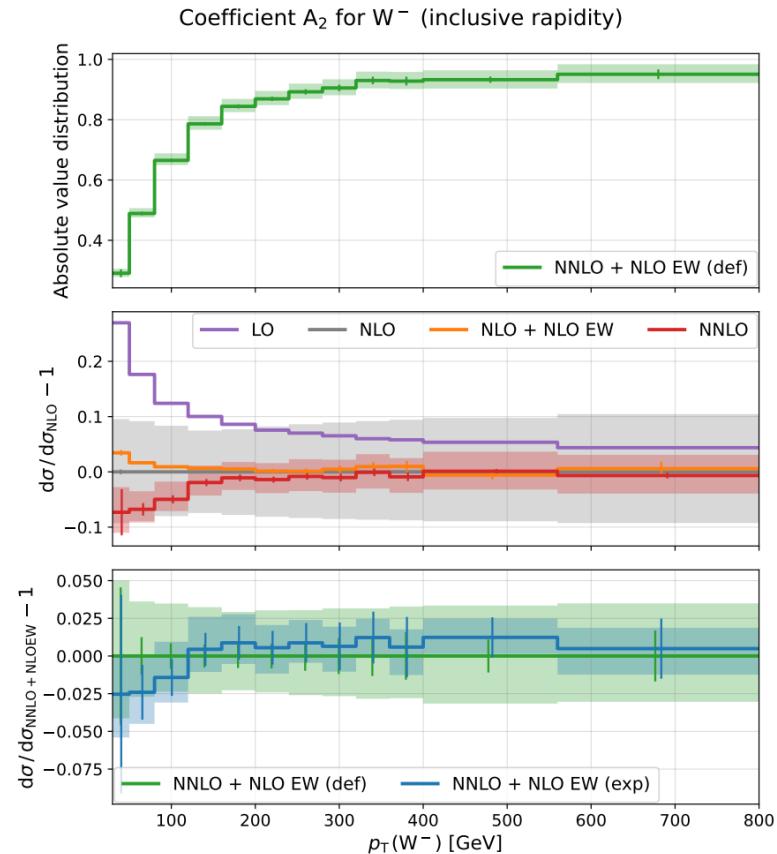
$$\frac{1}{\sigma} \frac{d\sigma}{\cos \theta} = \frac{3}{4} \sin \theta f_0 + \frac{3}{8} (1 - \cos \theta)^2 f_L + \frac{3}{8} (1 + \cos \theta)^2 f_R$$

Idea: Suitable projections (or fits) extract fractions of left, right and longitudinal components.

Angular coefficients as function of V kinematics

Keeping azimuthal dependence & boson kinematics:

$$\frac{d\sigma}{dp_{T,W} dy_W dm_{\ell\nu} d\Omega} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_{T,W} dy_W dm_{\ell\nu}} \left((1 + \cos^2 \theta) + A_0 \frac{1}{2} (1 - 3 \cos^2 \theta) + A_1 \sin 2\theta \cos \phi + A_2 \frac{1}{2} \sin^2 \theta \cos 2\phi + A_3 \sin \theta \cos \phi + A_4 \cos \theta + A_5 \sin^2 \theta \sin 2\phi + A_6 \sin 2\theta \sin \phi + A_7 \sin \theta \sin \phi \right),$$

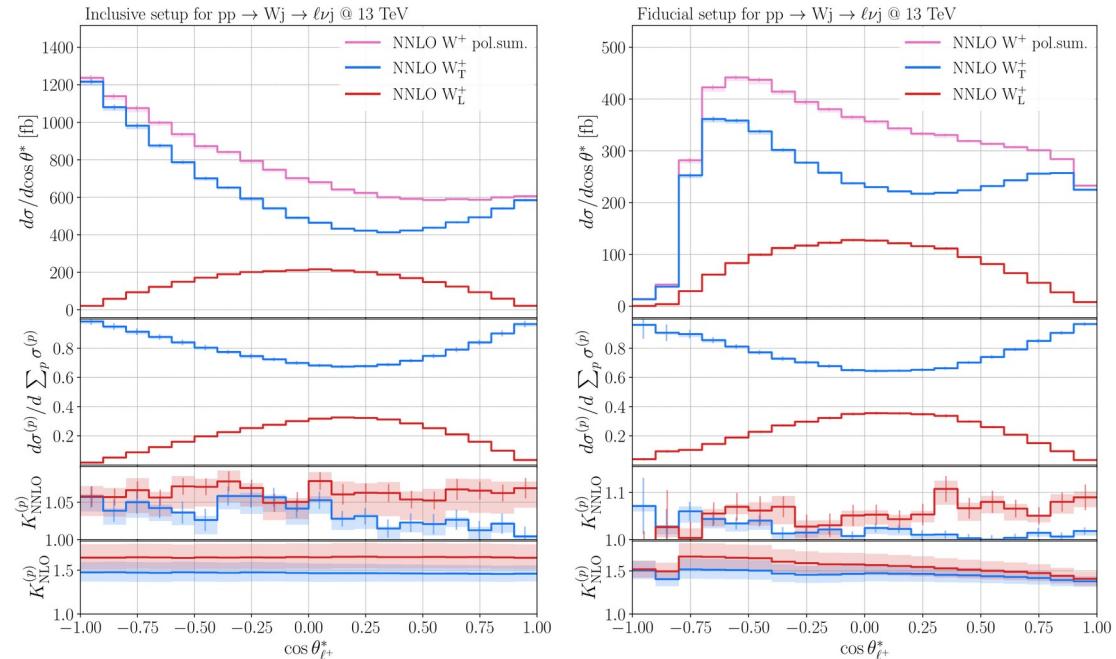


Angular coefficients in $W+j$ production at the LHC with high precision
Pellen, Poncelet, Popescu, Vitos, 2204.12394

Practical considerations

This simple idea suffers from:

- Fiducial phase space requirements
 - Interferences do not cancel
 - Correspondence between fractions (f_0, f_L, f_R) and distributions broken.
- Higher order corrections to decay (QED or QCD in hadronic decays)
 - Decomposition in $\{A_i\}$ does not hold any more
- Angles in boson rest frame
 - Z rest frame accessible, but W more difficult to reconstruct



The more general solution is to generate polarized events!

EWSB

The reason is the EWSB in the SM:

$$\mathcal{L}_{\text{EW}} = -\frac{1}{4}(W_{\mu\nu}^i)^2 - \frac{1}{4}(B_{\mu\nu}^i)^2 + (D_\mu\phi)^2 - V(\phi^\dagger\phi)$$

- Higgs potential and minimum:

$$V(\phi^\dagger\phi) = -\mu^2(\phi^\dagger\phi)^2 + \lambda(\phi^\dagger\phi)^4 \quad \phi = U(\pi^i) \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix} \quad \text{VEV: } \phi^\dagger\phi = \frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2}$$

- Goldstone bosons can be absorbed via gauge transformation (unitary gauge). This gives rise to massive gauge bosons:

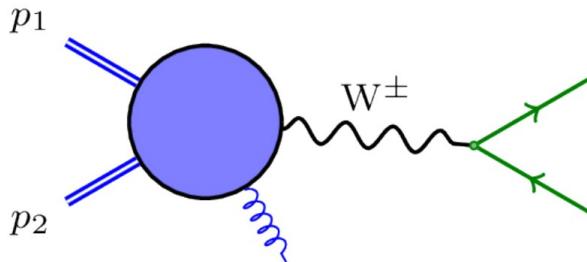
$$\phi = U^{-1}(\pi^i)\phi, \quad W_\mu = U^{-1}W_\mu U - \frac{i}{g_W}U^{-1}\partial_\mu U$$

$$|D_\mu\phi|^2 \ni \frac{v^2}{8} [2g_W^2 W_\mu^+ W^{-\mu} + (g_W W_\mu^3 - g'_W B_\mu)^2] \quad \rightarrow \quad M_W = \frac{1}{2}vg_W, \quad M_Z = \frac{M_W}{\cos\theta_W}$$

- Restores renormalizability and unitarity

Polarised W+j production

Polarised W+jet cross sections



Why looking at polarised W+jet with leptonic decays?

- The EW part is simple:
 - no non-resonant backgrounds
 - neutrino momentum approx. accessible (missing ET)
- Large cross section → precise measurements

Goals:

- Use W+j data to **extract the longitudinal polarisation fraction** (done before by exp.)
→ understand impact of NNLO QCD corrections (reduced scale dependence)
- Study **inclusive** (in terms of W decay products) and **fiducial** phase spaces
→ How does the sensitivity to longitudinal Ws depend on this?
Which observables have **small interference/off-shell** effects?
- Are there any differences between W+ and W-?
From PDFs and the fact that we cut on the charged lepton?

Setup: LHC @ 13 TeV

Polarised W+j production at the LHC: a study at NNLO QCD accuracy,
Pellen, Poncelet, Popescu 2109.14336

Inclusive phase space:

- At least one jet with $|y(j)| \leq 2.4$ and $p_T(j) \geq 30$ GeV

Fiducial phase space:

Measurement of the differential cross sections for the associated production of
a W boson and jets in proton-proton collisions at $\sqrt{s}=13$ TeV, CMS 1707.05979

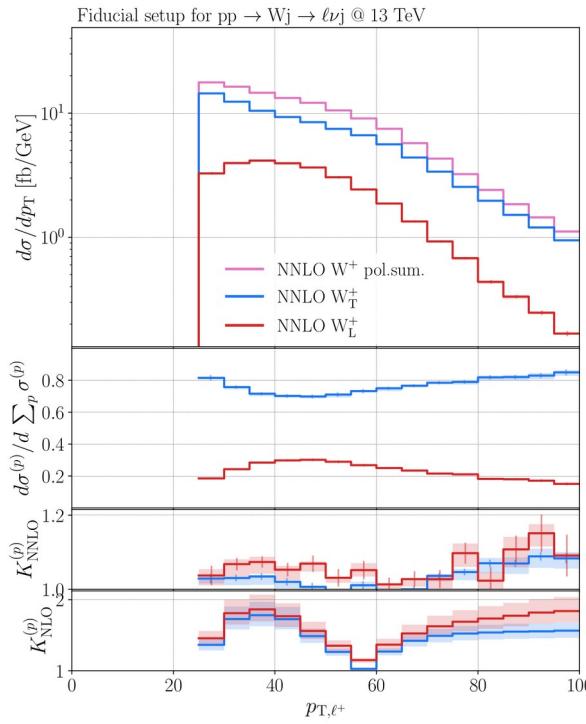
- Lepton cuts: $p_T(\ell) \geq 25$ GeV, $|\eta(\ell)| \leq 2.5$ and $\Delta R(\ell, j) > 0.4$
- Transverse mass of the W: $M_T(W) = \sqrt{m_W^2 + p_T^2(W)} \geq 50$ GeV

Technical aspects:

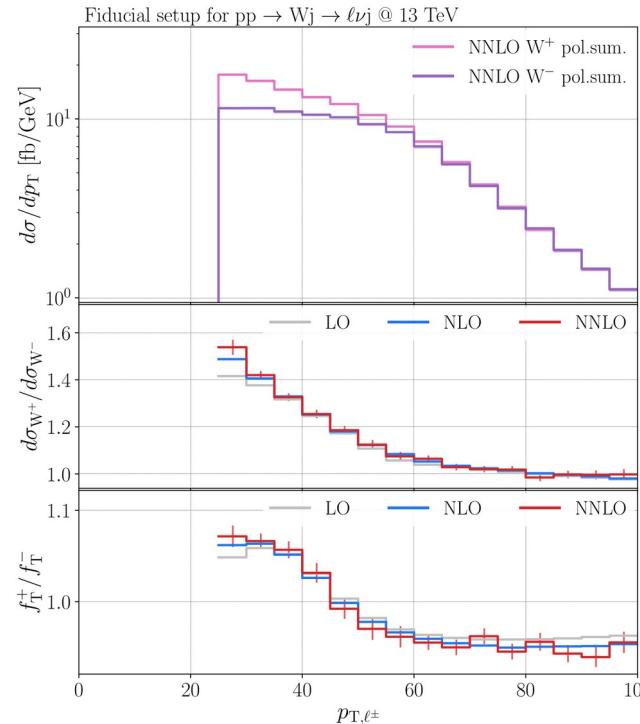
- NNPDF31 and dynamical scale choice: $\mu_R = \mu_F = \frac{1}{2} \left(m_T(W) + \sum p_T(j) \right)$
- Implementation in STRIPPER framework (NNLO QCD subtractions) [1408.2500]
 - Narrow-Width-Approximation and OSP/Pole-Approximation
 - Matrix elements from: AvH [1503.08612], OpenLoops2 [1907.13071] (cross checks with Recola [1605.01090]) and VVamp [1503.04812]

Example: lepton transverse momentum

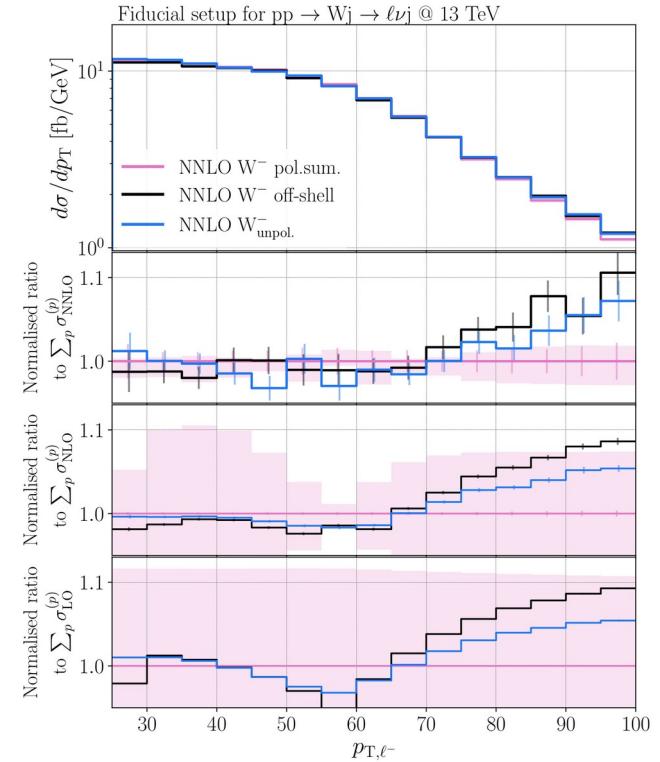
Perturbative corrections



Charge differences



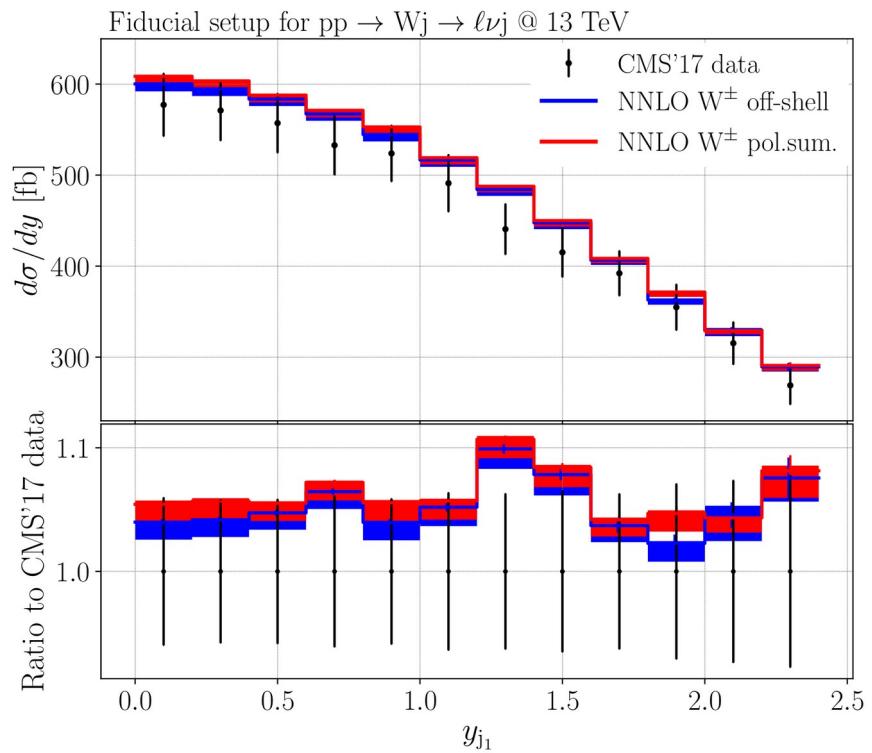
Off-shell/Interference effects



Extraction of polarisation fractions

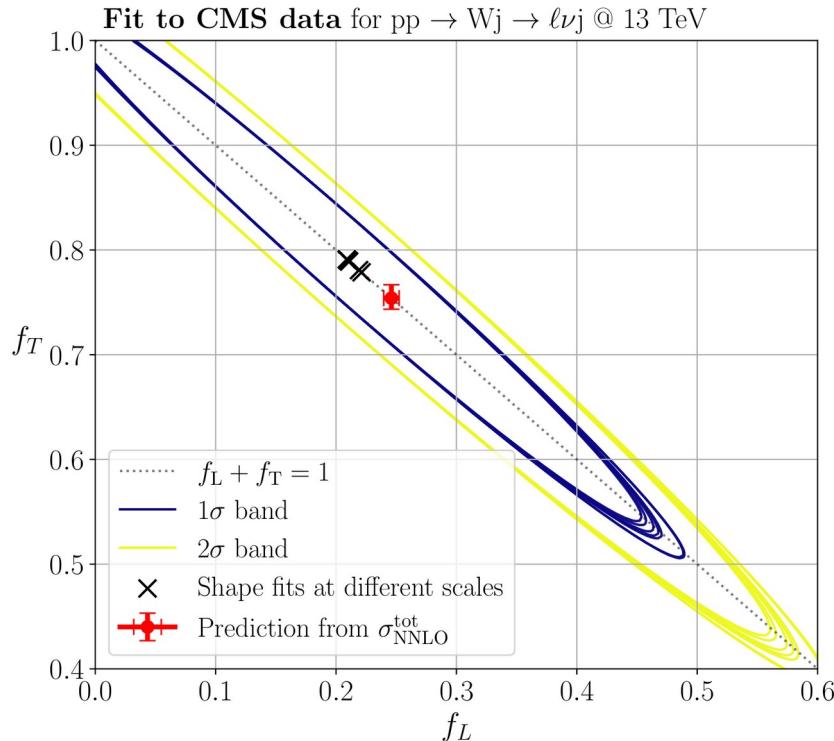
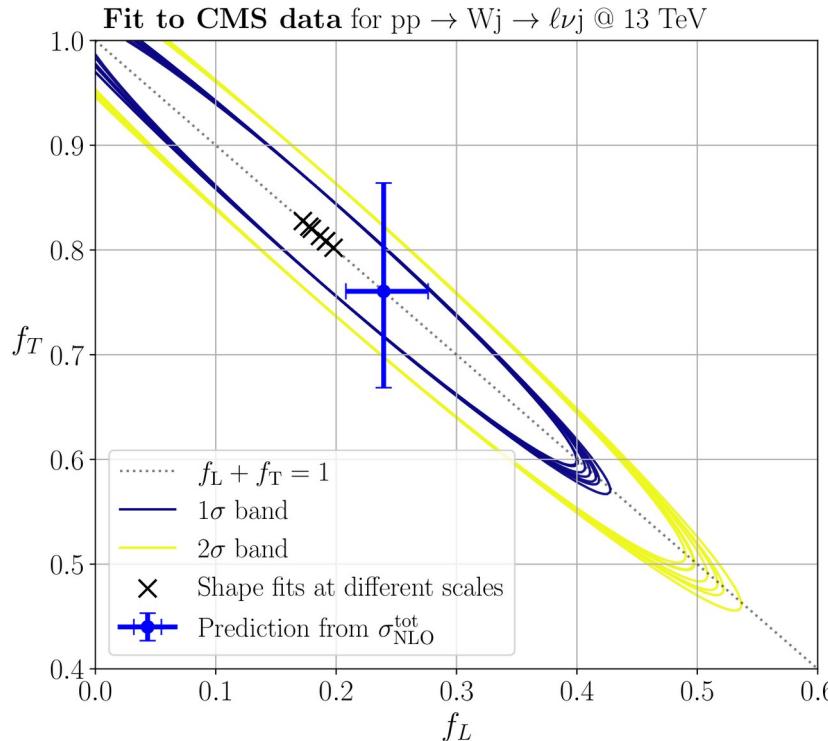
Identified 4 observables (ranges) with
→ Small interference effects (<2%)
→ Small off-shell effects (<2%)
→ Shape differences between L and T

- $\Delta\phi(\ell, j_1) \geq 0.3$
- $25 \text{ GeV} \leq p_T(\ell) < 70 \text{ GeV}$
- $\cos(\theta_\ell^*) \geq -0.75$
- $|y(j_1)| \leq 2$



W+jet : fit to CMS data

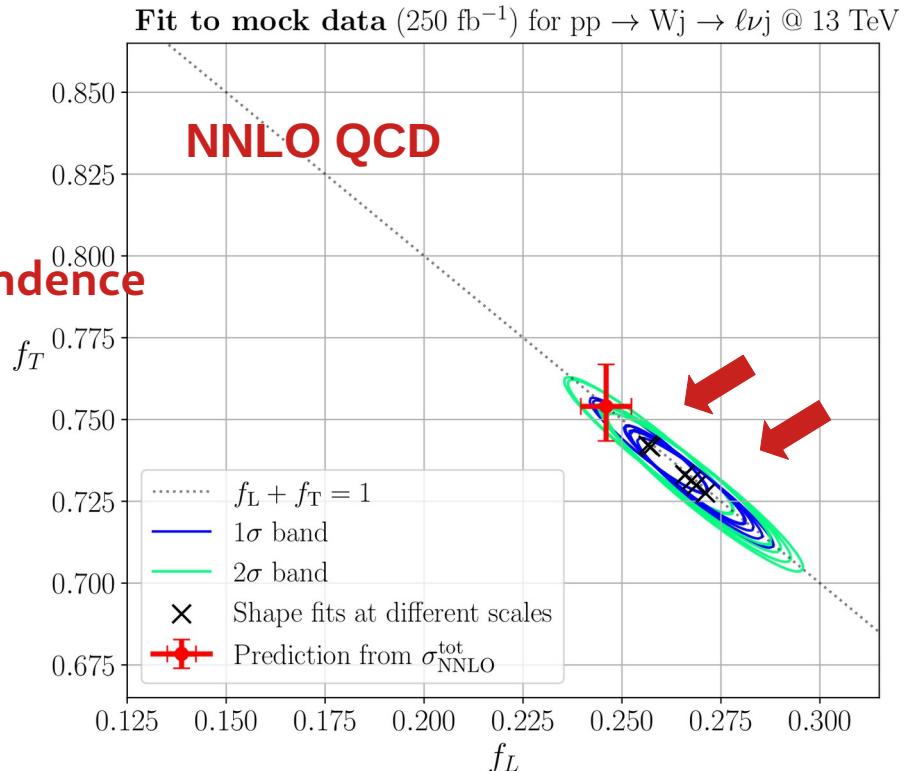
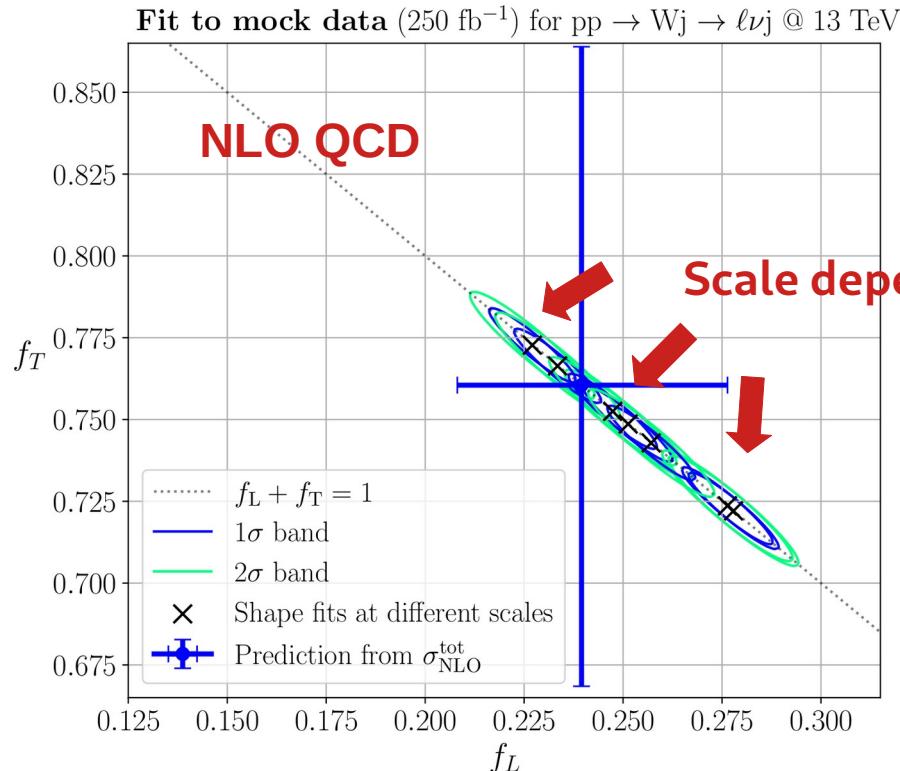
Fit to actual data, here $|y(j_1)|$
→ dominated by experimental uncertainties (no correlations available)



W+jet: mock-data fit

Fit to mock-data (based on NNLO QCD and 250 fb⁻¹ stats):
→ extreme case to see effect of scale dependence reduction

$$\cos(\ell, j_1)$$



Polarised W+W-

NNLO QCD polarized WW production

NNLO QCD study of polarised W+W- production at the LHC,
Poncelet, Popescu 2102.13583

Technical aspects:

- Implementation of NNLO QCD in c++ sector-improved residue subtraction framework [1408.2500,1907.12911]
- Massive b-quarks → get rid of top production ($pp \rightarrow b\bar{b}W^+W^-$ enters at NNLO)
- NNPDF31 and a fixed renormalisation scale: $\mu_R = \mu_F = m_W$

Fiducial phase space

Measurement of fiducial and differential W+W- production cross-sections at $\sqrt{s} = 13$ TeV with the ATLAS detector
ATLAS 1905.04242

- Leptons: $p_T(\ell) \geq 27$ GeV $|y(\ell)| < 2.5$ $m(\ell\bar{\ell}) > 55$ GeV
- Missing transverse momentum: $p_{T,\text{miss}} = p_T(\nu_e + \bar{\nu}_\mu) \geq 20$ GeV
- Jet-veto: $p_T(j) > 35$ GeV $|y(j)| < 4.5$

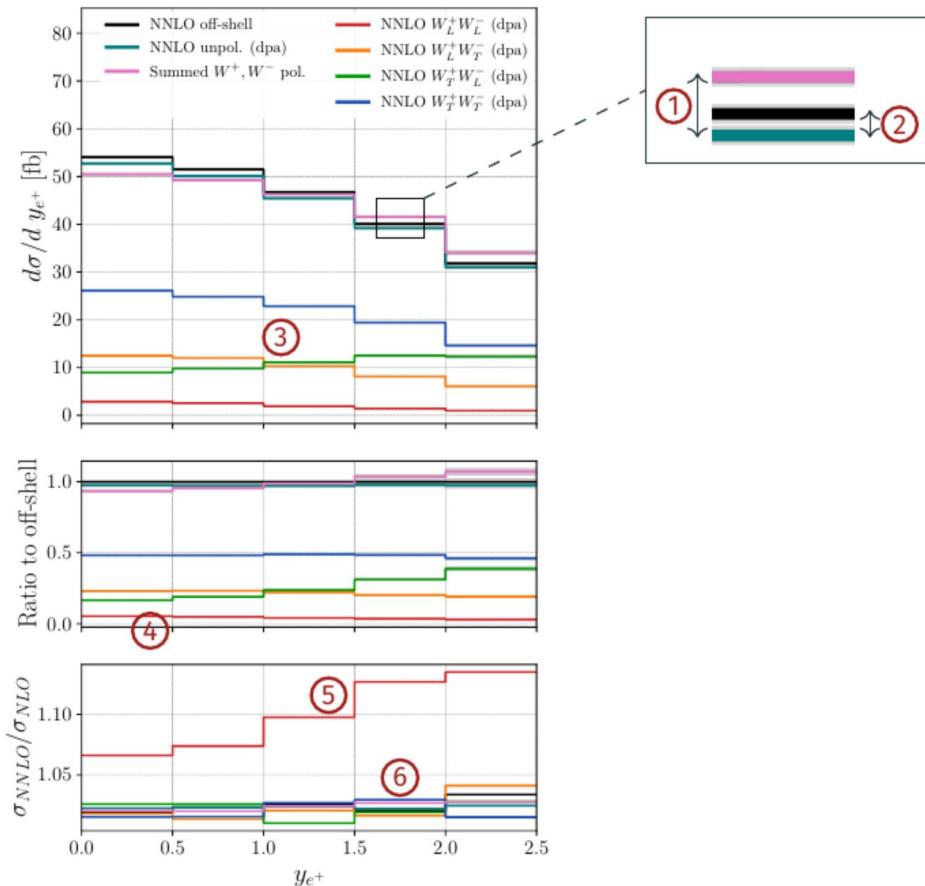
Doubly polarised cross sections

	NLO	NNLO	K_{NNLO}	LI	NNLO+LI
off-shell	$220.06(5)^{+1.8\%}_{-2.3\%}$	$225.4(4)^{+0.6\%}_{-0.6\%}$	1.024	$13.8(2)^{+25.5\%}_{-18.7\%}$	$239.1(4)^{+1.5\%}_{-1.2\%}$
unpol. (nwa)	$221.85(8)^{+1.8\%}_{-2.3\%}$	$227.3(6)^{+0.6\%}_{-0.6\%}$	1.025	$13.68(3)^{+25.5\%}_{-18.7\%}$	$241.0(6)^{+1.5\%}_{-1.1\%}$
unpol. (dpa)	$214.55(7)^{+1.8\%}_{-2.3\%}$	$219.4(4)^{+0.6\%}_{-0.6\%}$	1.023	$13.28(3)^{+25.5\%}_{-18.7\%}$	$232.7(4)^{+1.4\%}_{-1.1\%}$
W_L^+ (dpa)	$57.48(3)^{+1.9\%}_{-2.6\%}$	$59.3(2)^{+0.7\%}_{-0.7\%}$	1.032	$2.478(6)^{+25.5\%}_{-18.3\%}$	$61.8(2)^{+1.0\%}_{-0.8\%}$
W_L^- (dpa)	$63.69(5)^{+1.9\%}_{-2.6\%}$	$65.4(3)^{+0.8\%}_{-0.8\%}$	1.026	$2.488(6)^{+25.5\%}_{-18.3\%}$	$67.9(3)^{+0.9\%}_{-0.8\%}$
W_T^+ (dpa)	$152.58(9)^{+1.7\%}_{-2.1\%}$	$155.7(6)^{+0.7\%}_{-0.6\%}$	1.020	$11.19(2)^{+25.5\%}_{-18.8\%}$	$166.9(6)^{+1.6\%}_{-1.3\%}$
W_T^- (dpa)	$156.41(7)^{+1.7\%}_{-2.1\%}$	$159.7(6)^{+0.5\%}_{-0.6\%}$	1.021	$11.19(2)^{+25.5\%}_{-18.8\%}$	$170.9(6)^{+1.7\%}_{-1.3\%}$
$W_L^+ W_L^-$ (dpa)	$9.064(6)^{+3.0\%}_{-3.0\%}$	$9.88(3)^{+1.3\%}_{-1.3\%}$	1.090	$0.695(2)^{+25.5\%}_{-18.8\%}$	$10.57(3)^{+2.9\%}_{-2.4\%}$
$W_L^+ W_T^-$ (dpa)	$48.34(3)^{+1.9\%}_{-2.5\%}$	$49.4(2)^{+0.9\%}_{-0.7\%}$	1.021	$1.790(5)^{+25.5\%}_{-18.3\%}$	$51.2(2)^{+0.6\%}_{-0.8\%}$
$W_T^+ W_L^-$ (dpa)	$54.11(5)^{+1.9\%}_{-2.5\%}$	$55.5(4)^{+0.6\%}_{-0.7\%}$	1.025	$1.774(5)^{+25.5\%}_{-18.3\%}$	$57.2(4)^{+0.7\%}_{-0.7\%}$
$W_T^+ W_T^-$ (dpa)	$106.26(4)^{+1.6\%}_{-1.9\%}$	$108.3(3)^{+0.5\%}_{-0.5\%}$	1.019	$9.58(2)^{+25.5\%}_{-18.9\%}$	$117.9(3)^{+2.1\%}_{-1.6\%}$

Small LL contribution, with large corrections

Polarised di-boson production

Credit: Andrei Popescu



Features:

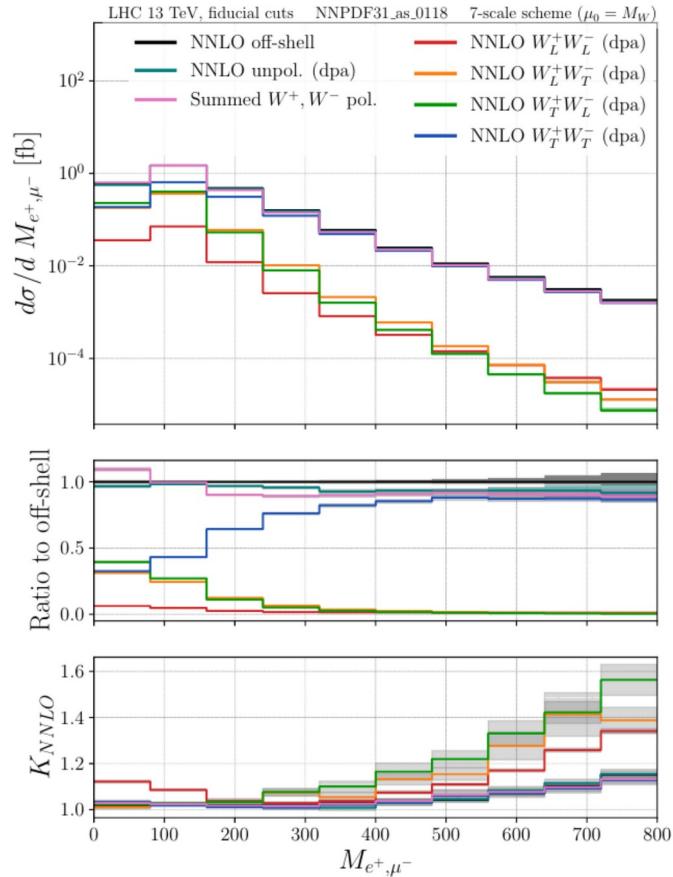
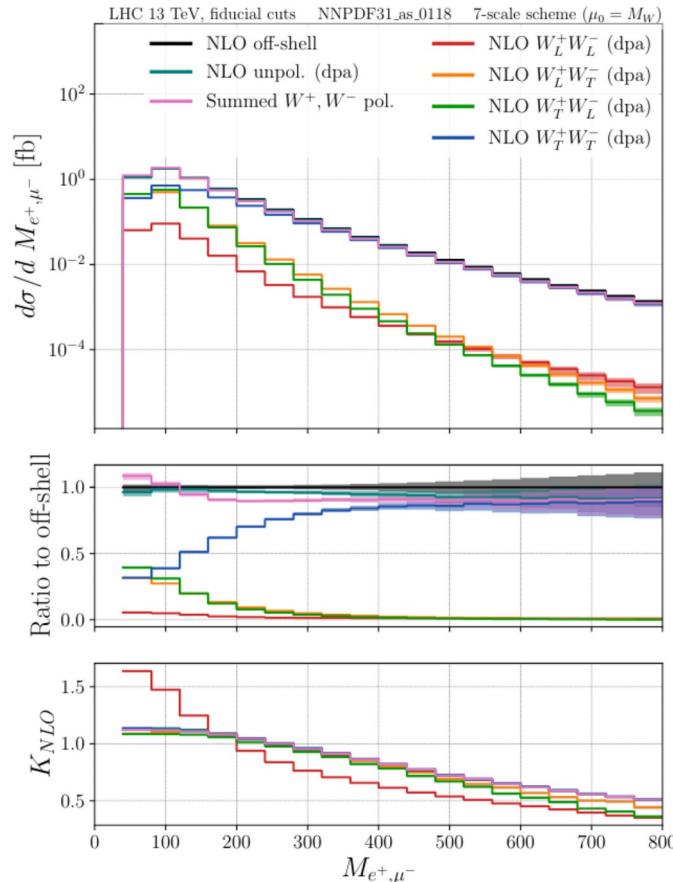
- ① Polarisation interference
- ② Non-resonant background
- ③ "Monte-Carlo true" polarisation distributions
- ④ $W_L^+ W_L^-$ contribution is small,
 $W_T^+ W_T^-$ dominates
- ⑤ Distinct and large K_{NNLO} for $W_L^+ W_L^-$
- ⑥ small K-factor for other setups

Summary:

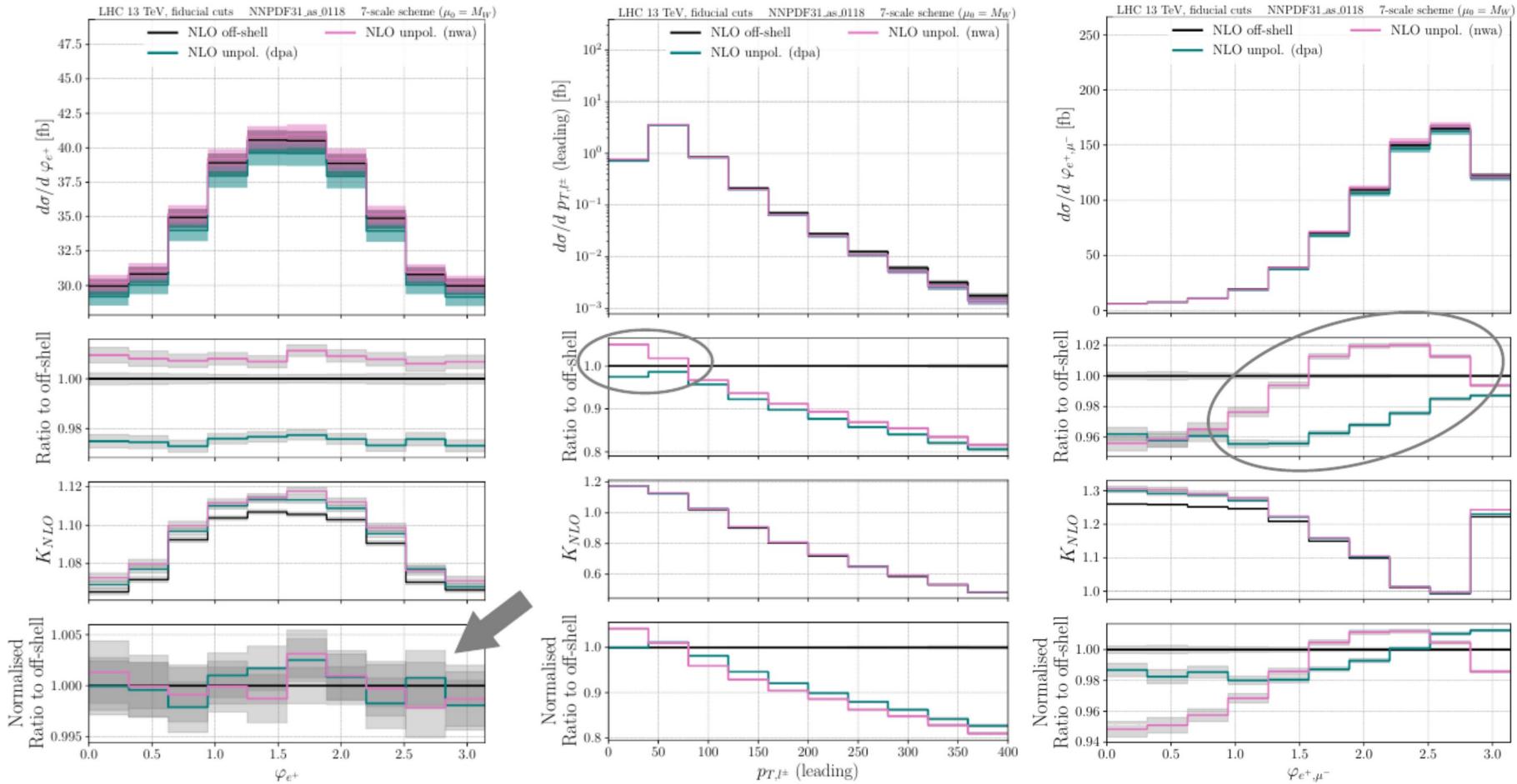
- NNLO effects are 2-3% of σ_{tot} for all setups except $W_L^+ W_L^-$ where it is 9%.
- Scale uncertainty is reduced by a **factor of 3** w.r.t NLO.

Polarised di-boson production

- Longitudinal contribution largest around production threshold.
- At high energy W effectively massless
→ transverse polarised

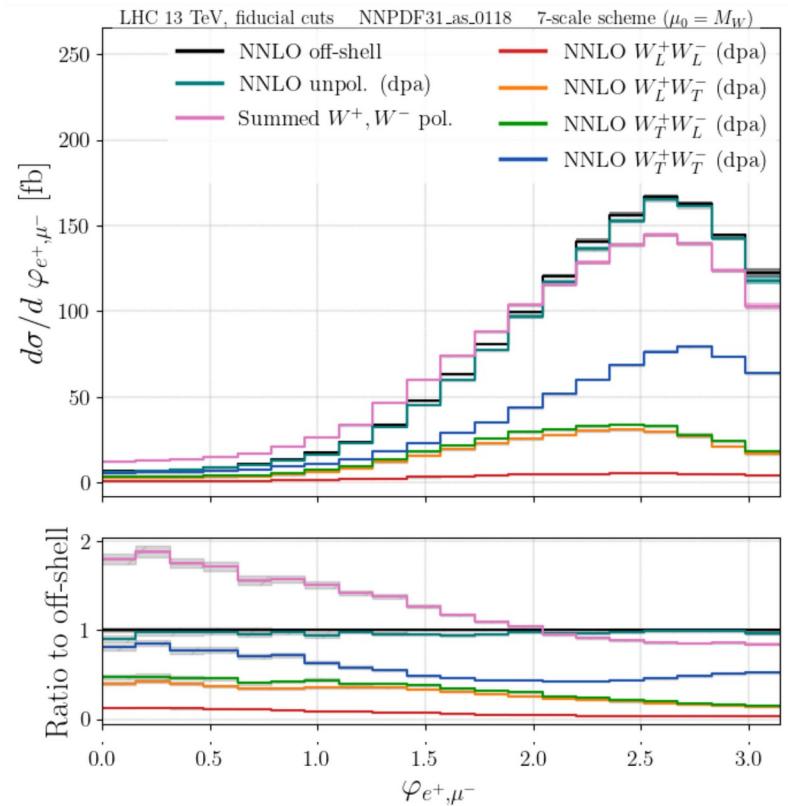
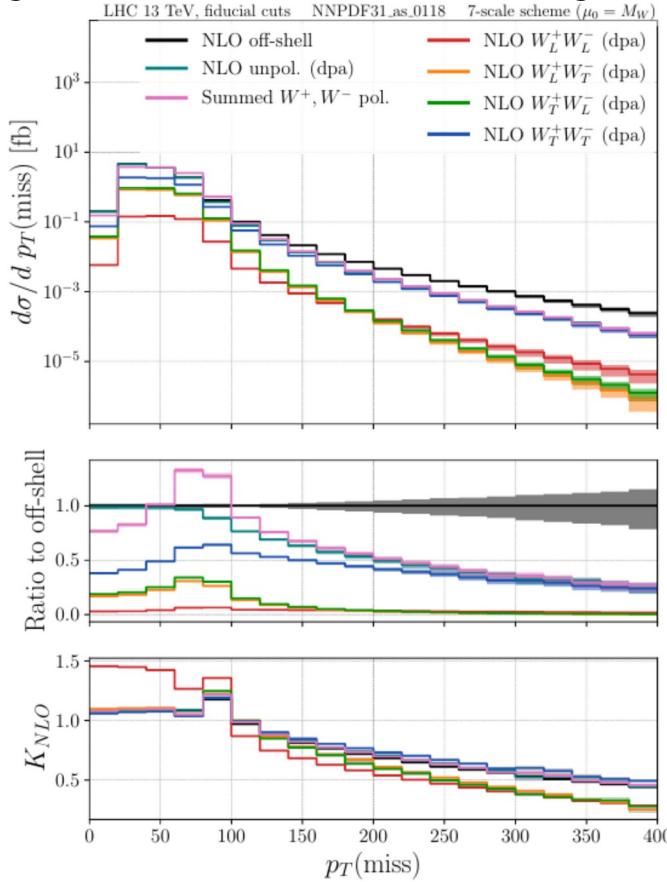


NWA vs. DPA



Interference and off-shell effects

Large off-shell effect from single-resonant contributions



Large interference effects through phase space constraints
Rene Poncelet – IFJ PAN

[High Precision Predictions to Probe the ElectroWeak-Symmetry Breaking]

Funded under SONATA 20 UMO-2024/55/D/ST2/00934



More holistic analysis of NNLO QCD corrections to spin-observables

→ more **polarised LHC processes**: top-quark production, Higgs-strahlung, ...

→ impact on **quantum information observables**

which are typically based of angular correlations

→ implementation in **HighTEA** for easy access



<https://www.precision.hep.phy.cam.ac.uk/hightea>