Theory review on polarised bosons

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COMETA workshop on polarization tagging for hadronic boosted bosons
1st & 2nd July 2026





THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES



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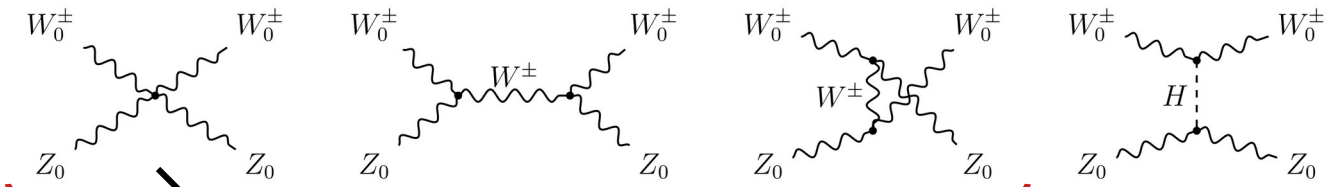
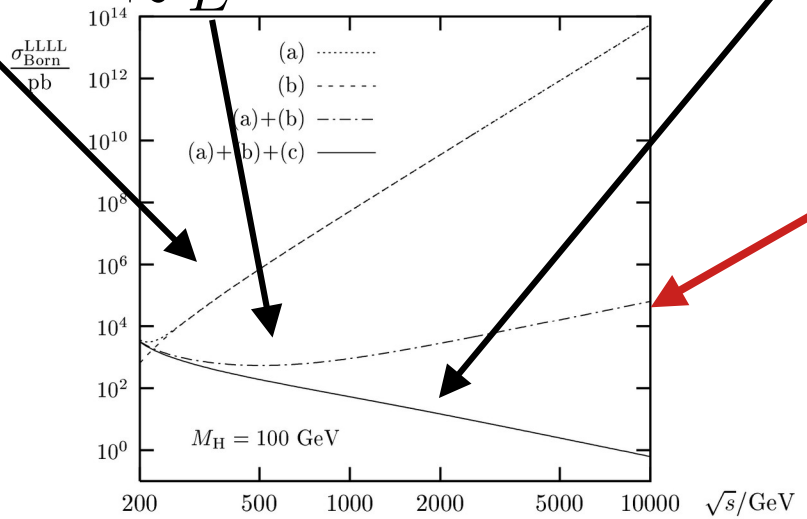
Longitudinal Vector-Boson-Scattering (VBS)



$\sim E^2$

$\sim -E^2$



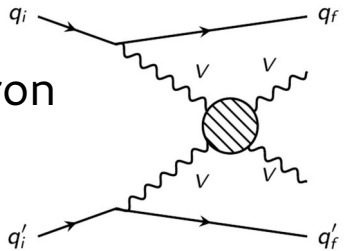
Unitarity violation

Radiative corrections to W+ W- → W+ W- in the electroweak standard model
A. Denner, T. Hahn [hep-ph/9711302]

Measurement of polarized boson scattering or production probes:

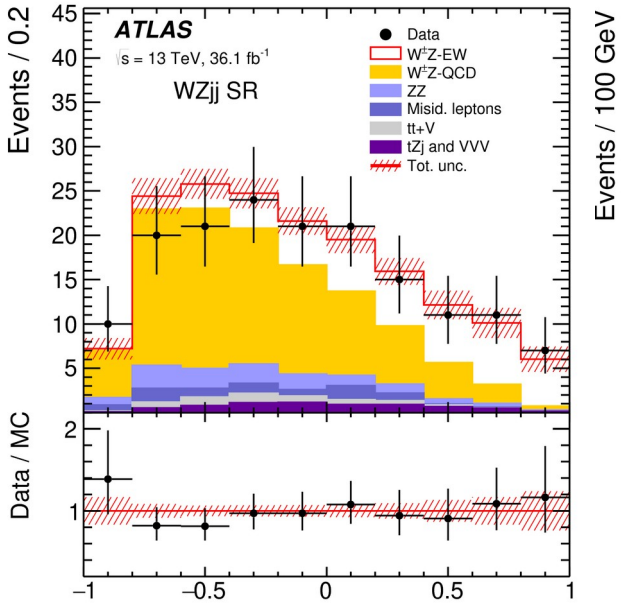
- EWSB mechanism
- Higgs and gauge sector
- New physics models

VBS at hadron colliders

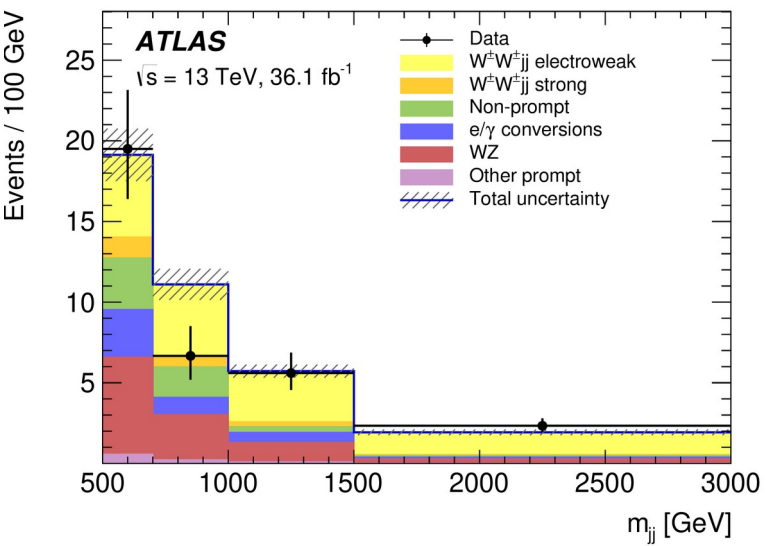


VBS at hadron colliders

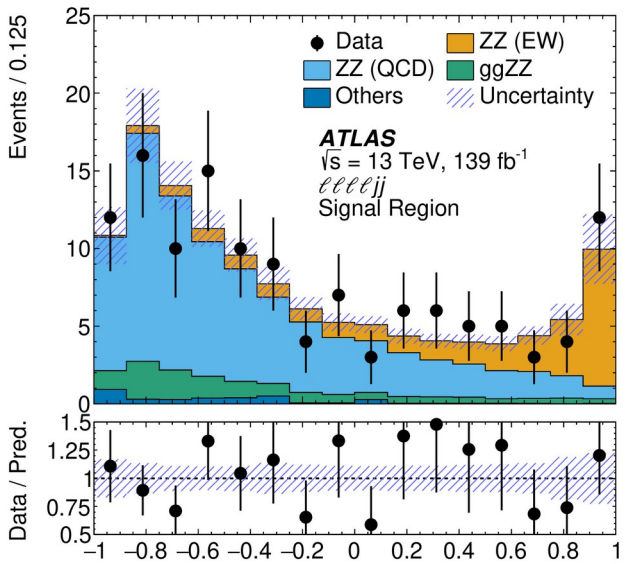
Separate from background processes through VBS topology → a rare process, but observed.



WZ (5.3 sigma)
ATLAS [1812.09740]



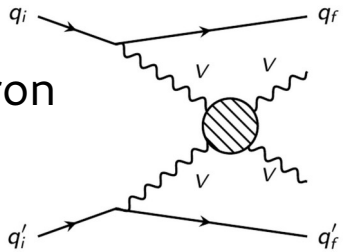
W+W+/W-W- (6.5 sigma)
ATLAS [1906.03203]



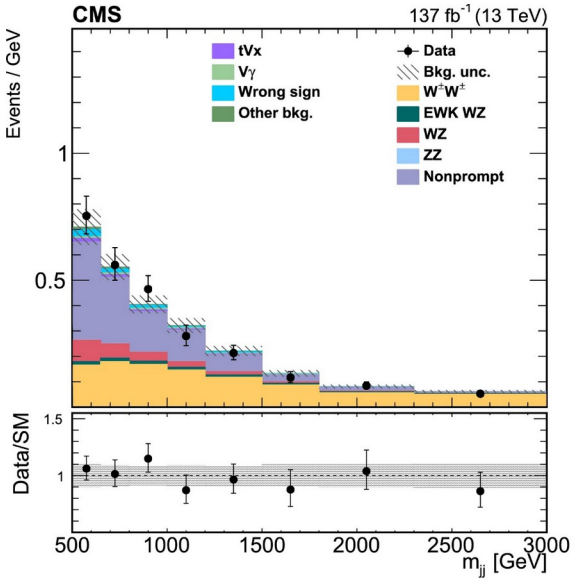
ZZ (5.5 sigma)
ATLAS [2004.10612]

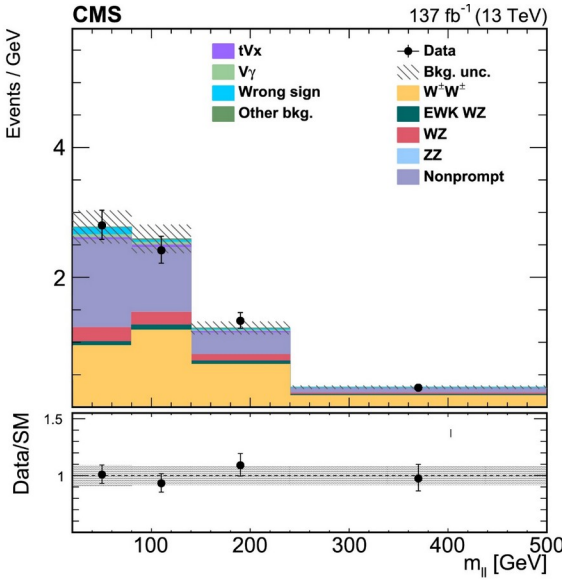
VBS at hadron colliders

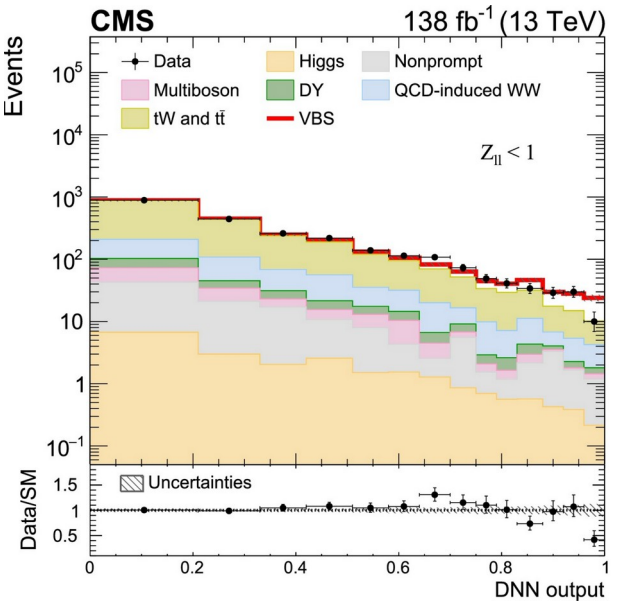
VBS at hadron colliders



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



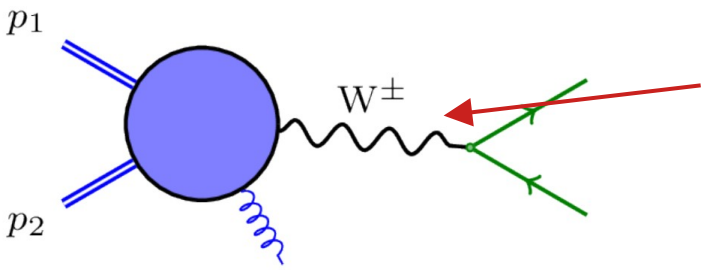




WZ (6.8 sigma) + W+W+/W-W- (diff. xsec)
CMS [2005.01173]

W+W- (5.6 sigma)
CMS [2205.05711]

Polarised boson production



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

λ = +/-/L

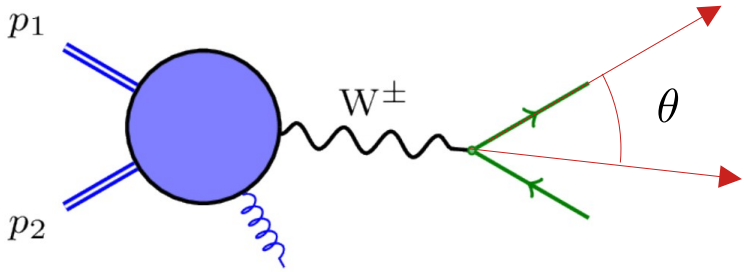
Can we extract the longitudinal component?

Measurements of longitudinal polarisation fractions:

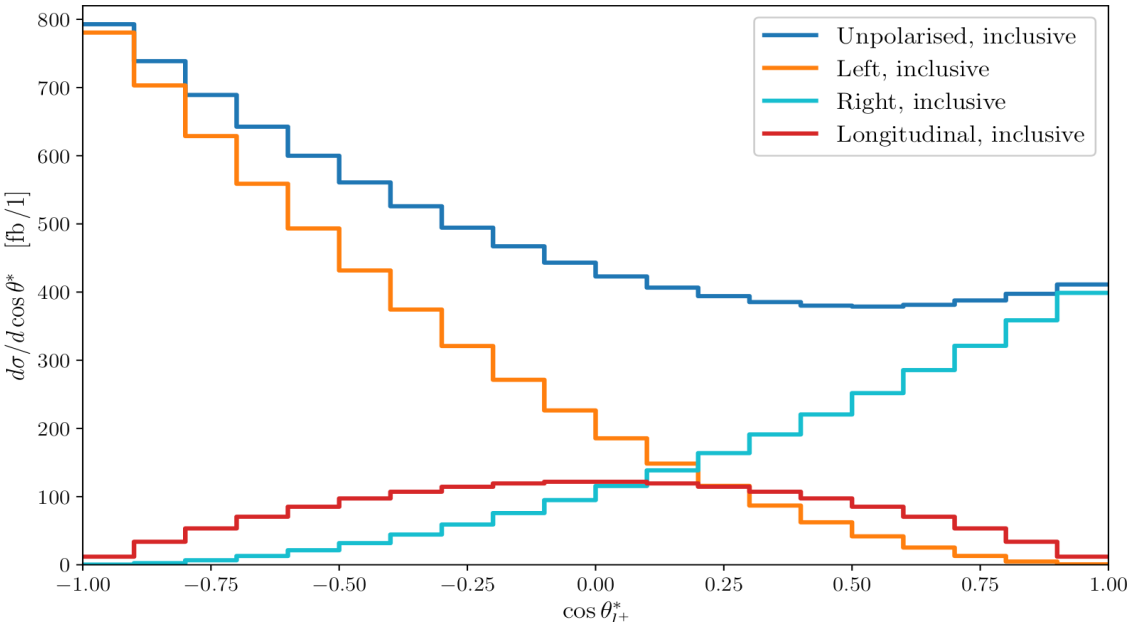
Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC,
CMS [1104.3829]
Measurement of the polarisation of W bosons produced with large transverse momentum in pp collisions at \sqrt{s}=7 TeV with the ATLAS experiment,
ATLAS [1203.2165]
Measurement of WZ production cross sections and gauge boson polarisation in pp collisions at sqrt(s) = 13 TeV with the ATLAS detector,
ATLAS [1902.05759]
Measurements of production cross sections of polarized same-sign W boson pairs in association with two jets in proton-proton collisions at $\sqrt{s} =$ 13 TeV [2009.09429]
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 ZZ → 4ℓ 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]
Evidence for Longitudinally Polarized W Bosons in the Electroweak Production of Same-Sign W Boson Pairs in Association with Two Jets in pp Collisions at s=13 TeV with the ATLAS Detector ATLAS [2503.11317]

How to measure polarized bosons?

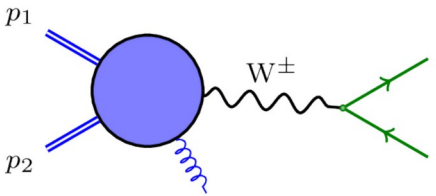
- We can't measure boson polarization directly.
- Luckily decay products can be used as a "polarimeter":



W+ decay (W- mirrored around 0)



Polarized cross sections



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

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

Denner Pelliccioli [2006.14867]

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

Create samples of fixed polarisation: $\frac{\mathrm{d}\sigma}{\mathrm{d}X} = f_L \frac{\mathrm{d}\sigma_L}{\mathrm{d}X} + f_R \frac{\mathrm{d}\sigma_R}{\mathrm{d}X} + f_0 \frac{\mathrm{d}\sigma_0}{\mathrm{d}X} \left(+ f_{int.} \frac{\mathrm{d}\sigma_{int.}}{\mathrm{d}X}\right)$

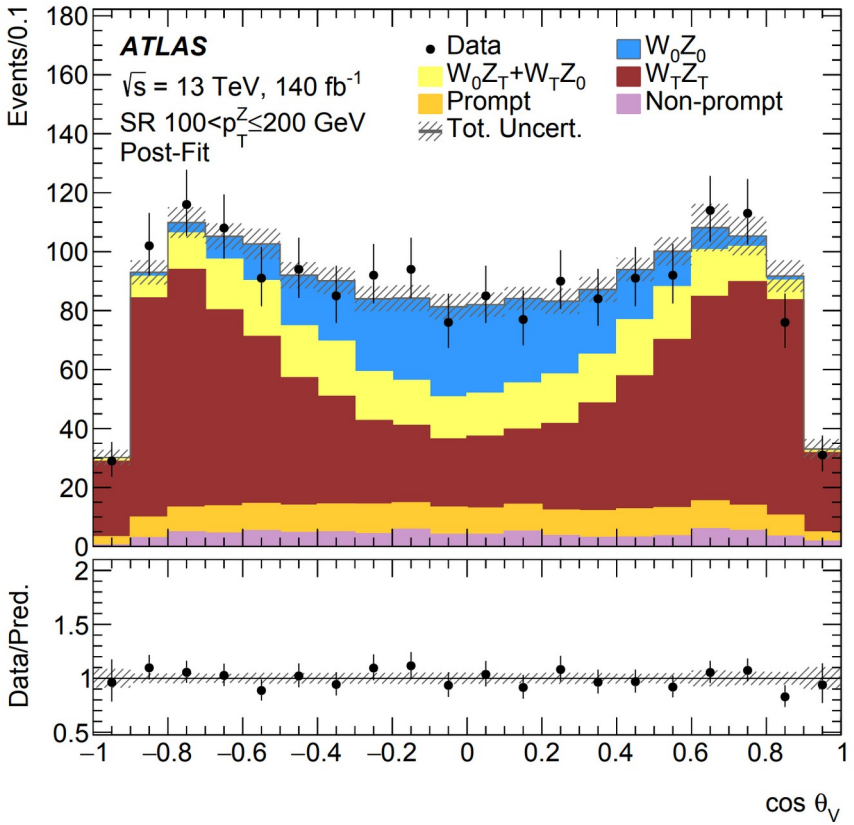
and fit f_L, f_R, f_0 to measured $\frac{\mathrm{d}\sigma^{exp.}}{\mathrm{d}X}$

Polarized cross sections

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

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

Example polarisation measurement in ATLAS

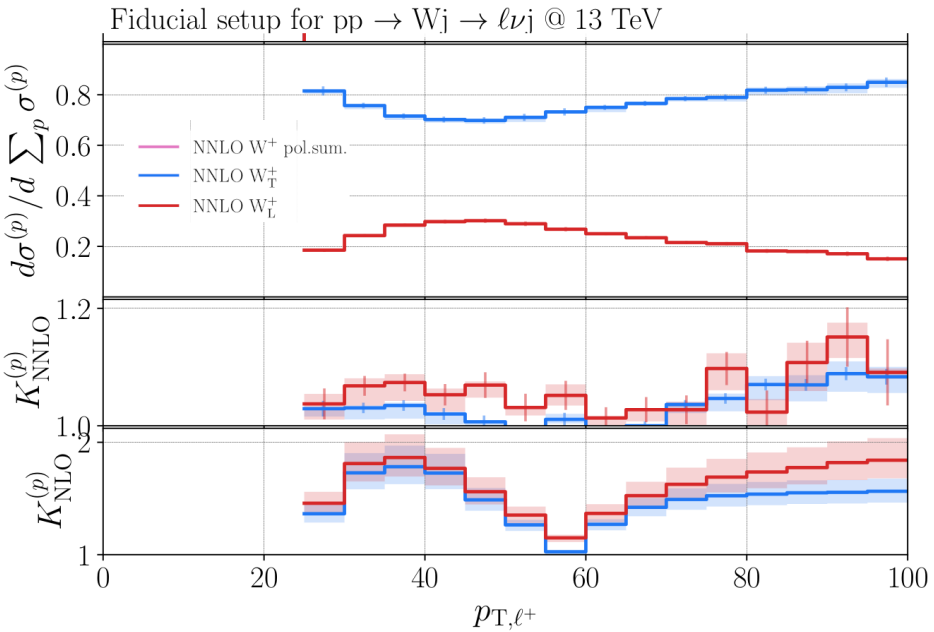


Studies of the Energy Dependence of Diboson Polarization Fractions and the Radiation-Amplitude-Zero Effect in WZ Production with the ATLAS Detector, ATLAS [2402.16365]

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

	Prediction	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ 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

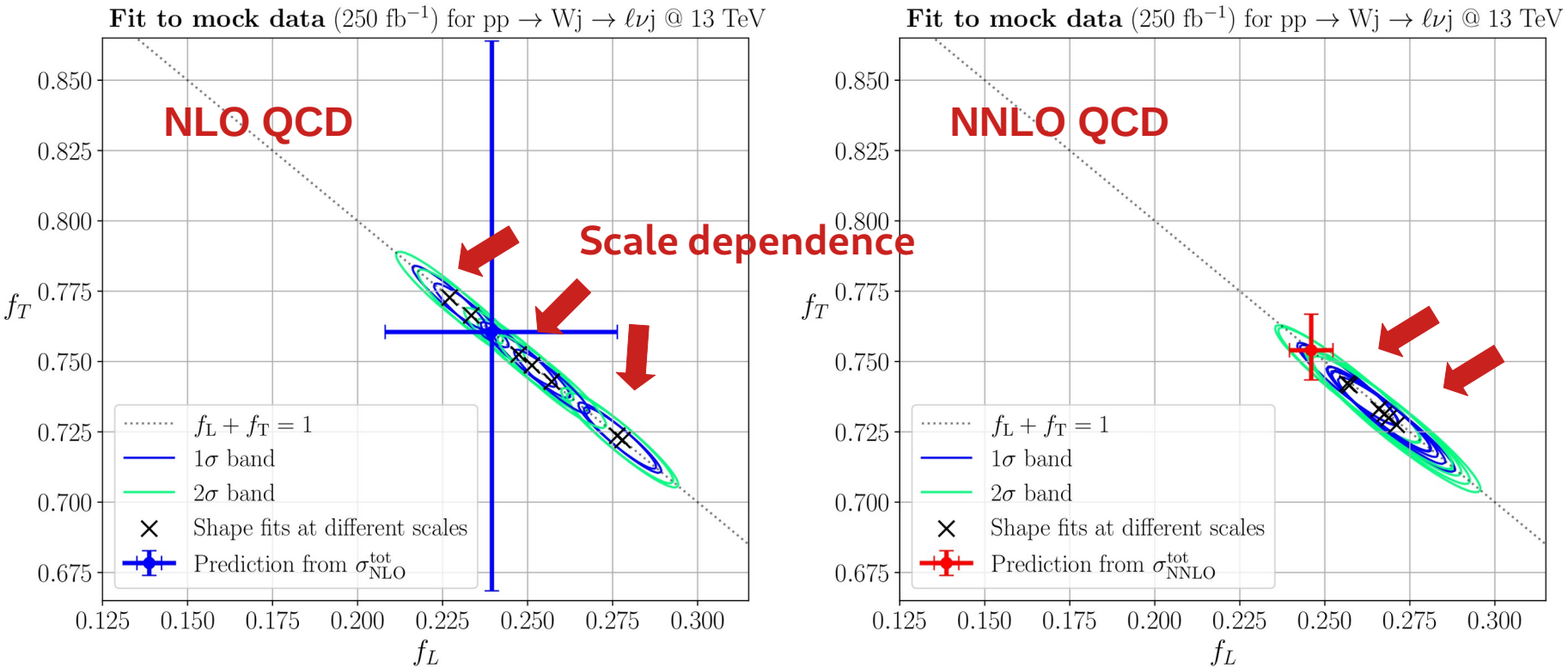
1) Differential polarization fraction have shapes
2) Higher-order corrections dependent on polarization! Just using unpolarized K-factor would lead to distortion of spectrum.
3) NNLO QCD needed to reach percent-level scale-dependence → MHOU

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: $\cos(\ell, j_1)$



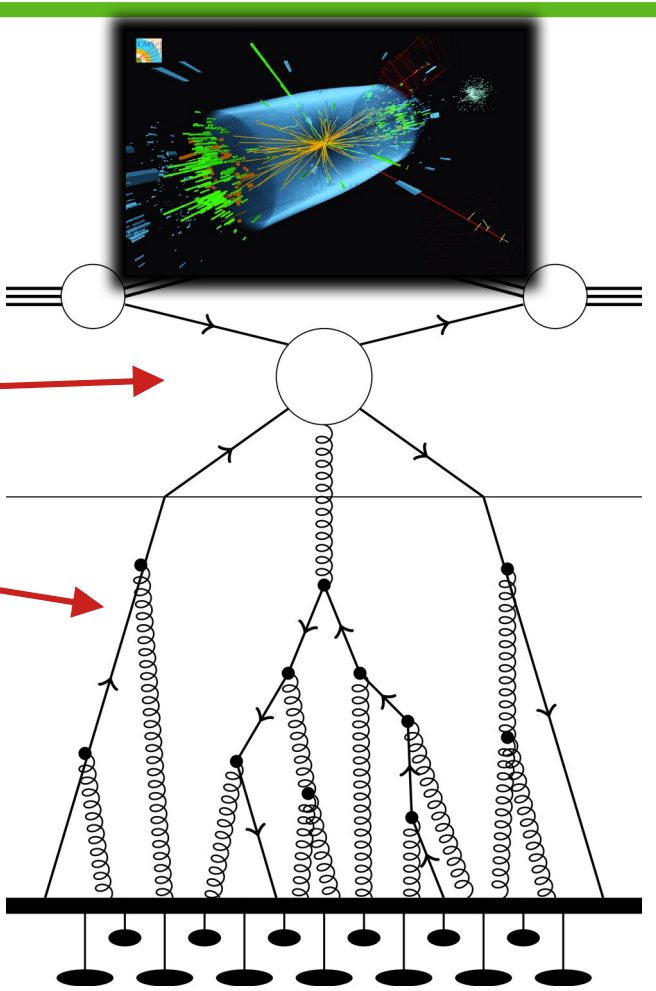
Theory picture of hadron collision events

Precise theory input needed!

$Q \gg \Lambda_{\mathrm{QCD}}$ **Fixed-order perturbation theory**
scattering of individual partons

$Q \gtrsim \Lambda_{\mathrm{QCD}}$ **Parton-shower/Resummation**
all-order bridge between perturbative and non-perturbative physics

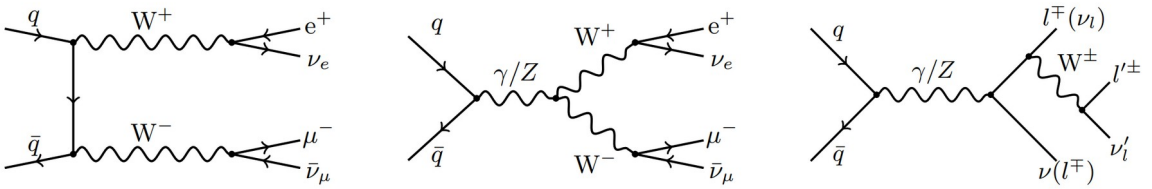
$Q \sim \Lambda_{\mathrm{QCD}}$ **“Hadronization”/MPI/…**
non-perturbative physics



Focus on polarised boson pair production processes

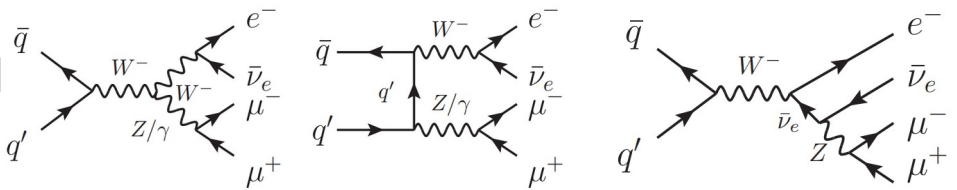
$$pp \to W^+W^- \to e^+\mu^-\nu\bar{\nu}$$

NLO QCD: [2006.14867]
NLO EW: [2311.16031][2311.17027]
NNLO+LI QCD: [2102.13583]



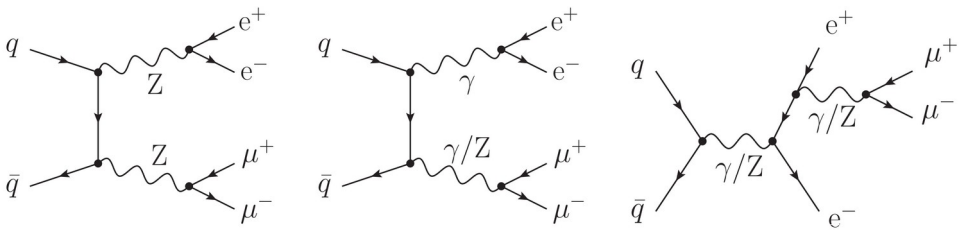
$$pp \to W^+Z \to e^+\nu\mu^+\mu^-$$

NLO QCD + EW : [1810.11034][2010.07149][2203.01470]
NNLO QCD + NLO EW: [2510.25898]
→ Semi-leptonic decays @NLO QCD: [2211.09040]
→ Quantum tomography obs. [2601.09540]



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

NLO QCD + EW: [2107.06579]
NNLO+LI QCD + NLO EW: [2505.09686]
LI QCD: [2401.17365]



Focus on polarised boson pair production processes

Monte Carlo developments for boson pair production:

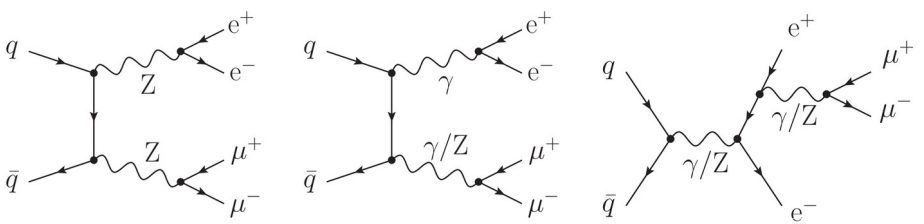
- **LO and MJM in Madgraph**
  [1912.01725]
- **nLO + PS in SHERPA**
  [2310.14803]
- **NLO+PS in Powheg-Box-Res**
  [2311.05220]
- **NLO+PS + SMEFT in Powheg-Box-Res**
  [2507.21768]

Polarised ZZ: COMETA polarisation study

COMETA

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 Haitz,[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]



(a) Doubly resonant (b) Photon mediated (c) Nested

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]

↓

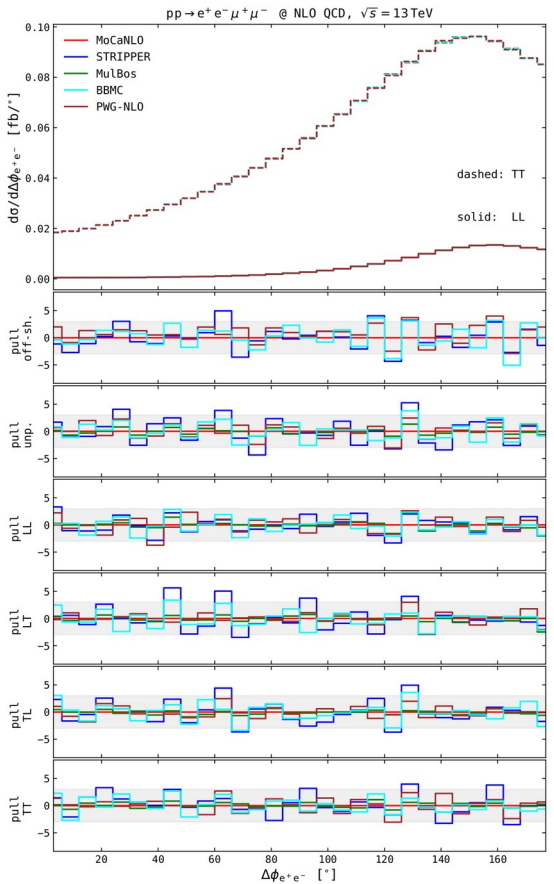
phase space definition

ZZ production in the ee/μμ channel

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	✓	✗	✓	✗	✗	✓	✓	✗

[Many thanks to Giovanni Pelliccioli]

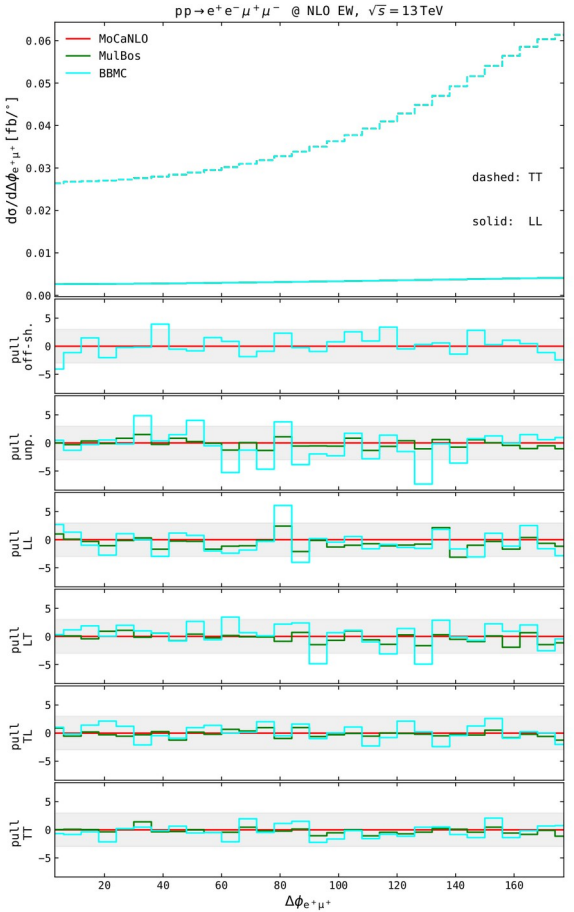
Validation and NLO QCD and NLO EW



Validation of NLO

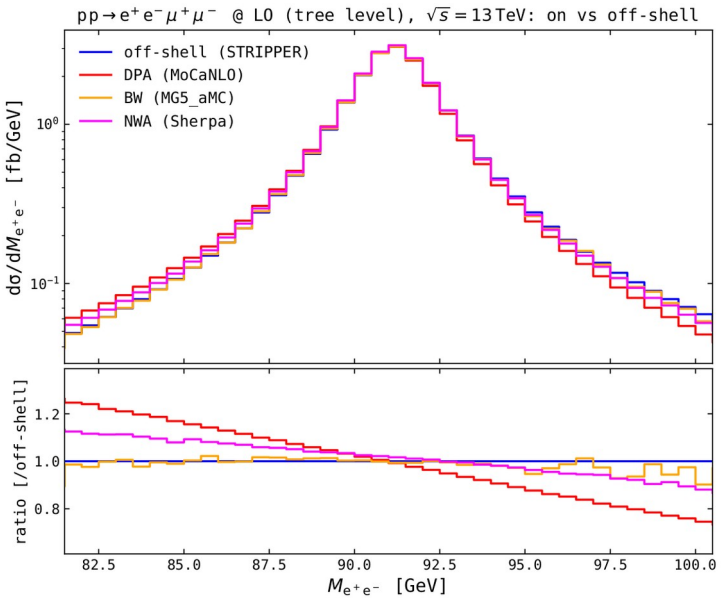
QCD

EW

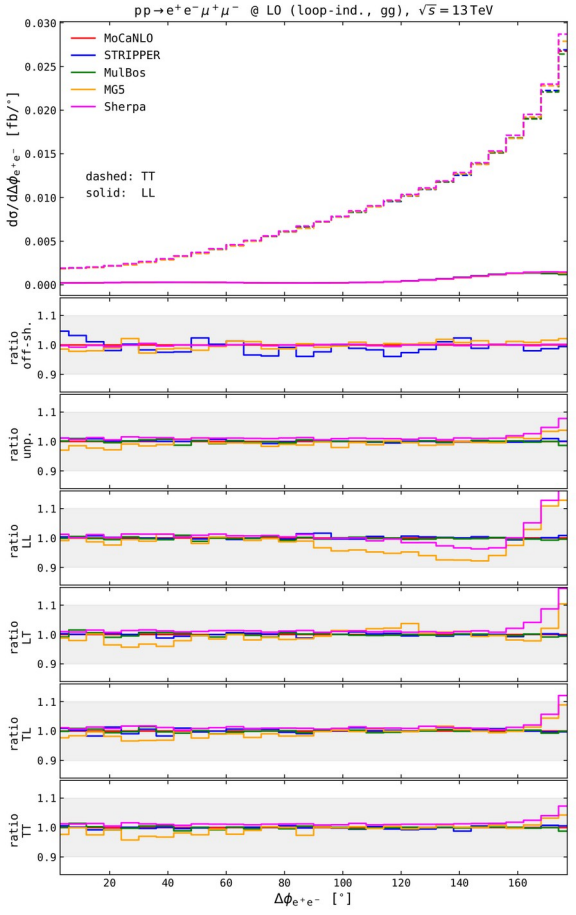


Different resonance treatment

Unpolarised ZZ:



Imprint in various distributions



Offshell

Complete process

DPA

double-pole approximation

NWA

Narrow width approximation
+ Breit-Wigner smearing

BW

Diagram removal
+ phase space constraint

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:

$$\mathrm{NNLO}^{\mathrm{EW}}_{\mathrm{QCD},gg} = \sigma^{\mathrm{LO}}_{qq}(1 + \delta^{\mathrm{NLO}}_{\mathrm{QCD}} + \delta^{\mathrm{NNLO}}_{\mathrm{QCD}} + \delta^{\mathrm{NLO}}_{\mathrm{EW}}) + \sigma^{\mathrm{LO}}_{gg}$$

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

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

Absolute predictions for polarised cross sections

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

+ ~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:

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

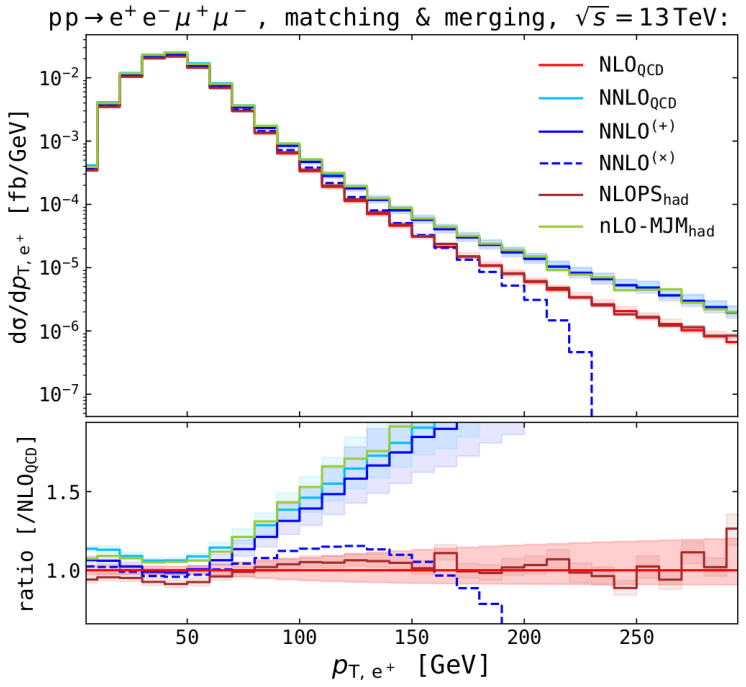
Theory-experiment in agreement

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

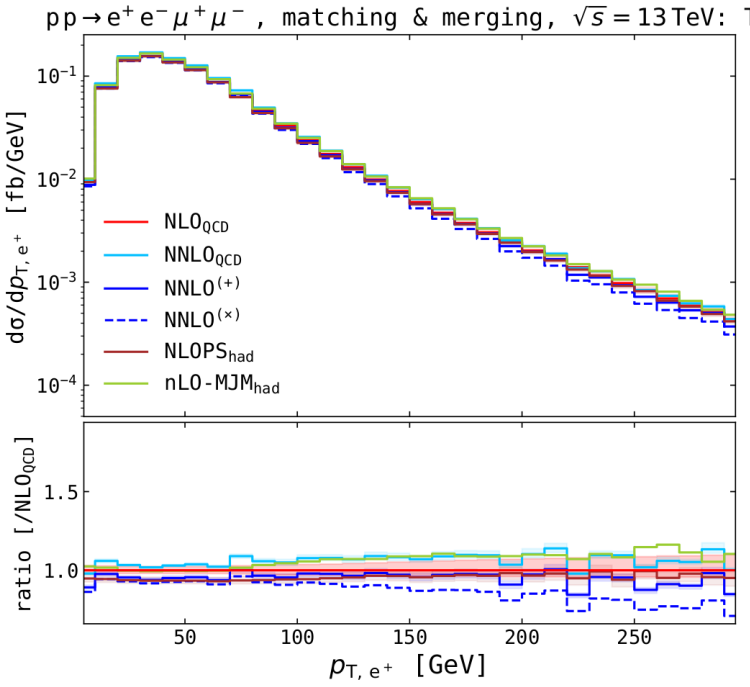
our predictions	LL [%]	LT [%]	TL [%]	TT [%]
$\text{LO}_{q\bar{q}}$	$5.85^{+0.07}_{-0.08}$	$11.86^{+0.09}_{-0.11}$	$11.89^{+0.09}_{-0.11}$	$69.27^{+0.30}_{-0.26}$
LO_{gg}	$5.39^{+0.02}_{-0.02}$	$2.12^{+0.01}_{-0.01}$	$2.10^{+0.01}_{-0.01}$	$90.48^{+0.03}_{-0.03}$
NLO_{EW}	$5.89^{+0.06}_{-0.08}$	$11.97^{+0.09}_{-0.11}$	$12.01^{+0.09}_{-0.11}$	$68.98^{+0.29}_{-0.25}$
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}	$6.07^{+0.05}_{-0.04}$	$13.11^{+0.09}_{-0.08}$	$13.04^{+0.08}_{-0.07}$	$66.20^{+0.19}_{-0.24}$
$\text{NNLO}^{\text{EW}}_{\text{QCD}}$	$6.12^{+0.06}_{-0.04}$	$13.29^{+0.09}_{-0.08}$	$13.21^{+0.08}_{-0.07}$	$65.75^{+0.20}_{-0.25}$
$\text{NNLO}^{\text{EW}}_{\text{QCD, gg}}$	$6.05^{+0.03}_{-0.03}$	$12.15^{+0.10}_{-0.15}$	$12.07^{+0.11}_{-0.16}$	$68.29^{+0.30}_{-0.21}$
$\text{NLOPS}_{\text{QCD}}$	$5.88^{+0.03}_{-0.04}$	$12.76^{+0.08}_{-0.06}$	$12.71^{+0.07}_{-0.06}$	$67.30^{+0.13}_{-0.15}$
$\text{nLOPS}_{\text{QCD}}$	$6.02^{+0.05}_{-0.08}$	$13.04^{+0.04}_{-0.09}$	$12.97^{+0.04}_{-0.09}$	$66.61^{+0.14}_{-0.47}$
$\text{NLOPS}_{\text{had}}$	$5.86^{+0.03}_{-0.04}$	$12.74^{+0.08}_{-0.06}$	$12.69^{+0.07}_{-0.06}$	$67.38^{+0.13}_{-0.15}$
$\text{nLOPS}_{\text{had}}$	$5.98^{+0.03}_{-0.07}$	$12.99^{+0.02}_{-0.09}$	$12.96^{+0.02}_{-0.09}$	$66.70^{+0.22}_{-0.46}$
$\text{LO-MJM}_{\text{QCD}}$	$5.79^{+0.08}_{-0.09}$	$12.91^{+0.06}_{-0.05}$	$12.84^{+0.06}_{-0.06}$	$66.81^{+0.24}_{-0.22}$
$\text{LO-MJM}_{\text{had}}$	$5.91^{+0.01}_{-0.10}$	$12.84^{+0.13}_{-0.23}$	$12.79^{+0.12}_{-0.23}$	$67.14^{+1.08}_{-0.98}$
$\text{nLO-MJM}_{\text{had}}$	$6.14^{+0.12}_{-0.11}$	$13.35^{+0.47}_{-0.32}$	$13.23^{+0.32}_{-0.28}$	$65.85^{+1.11}_{-0.96}$
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

LL

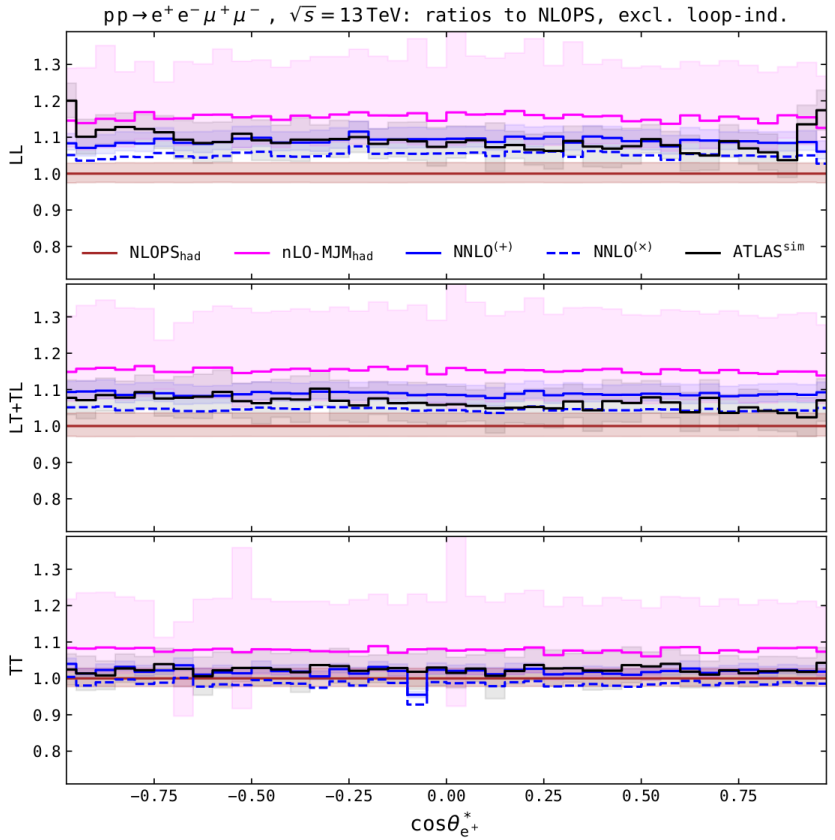


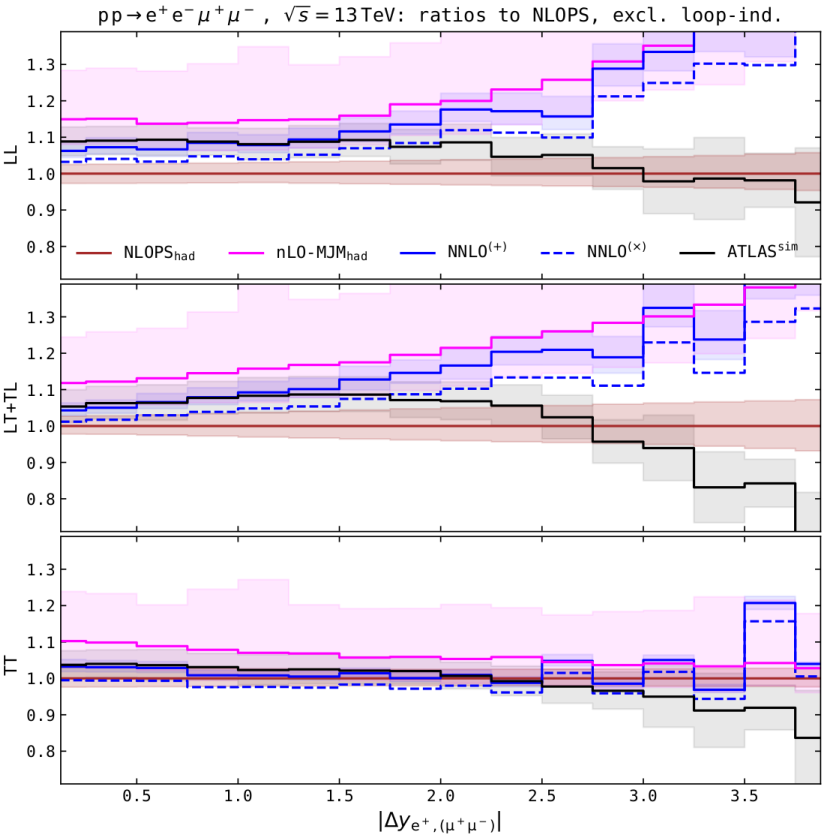
TT



Large higher-order QCD effects for LL polarization
SHERPA nLO-MJM shapes resample NNLO QCD results → impact from hard recoil

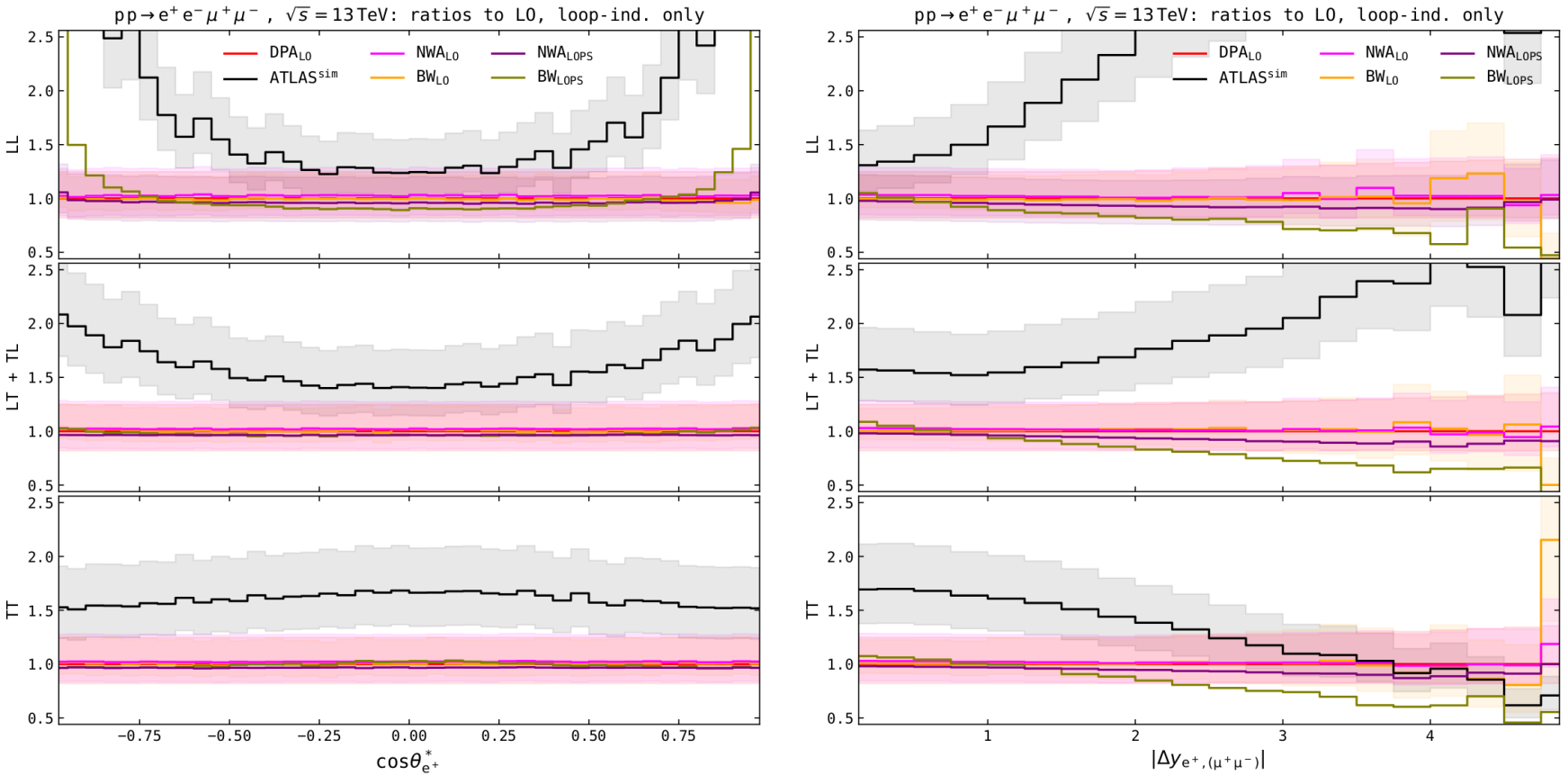
Best predictions vs ATLAS modelling: qq-channel





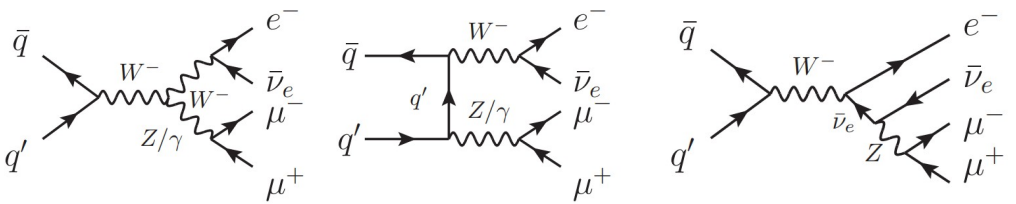
ATLAS modelling from [ATLAS 2310.04350]

Best predictions vs ATLAS modelling: gg-channel



ATLAS modelling from [ATLAS 2310.04350]

Filling the gap: WZ at NNLO QCD + EW



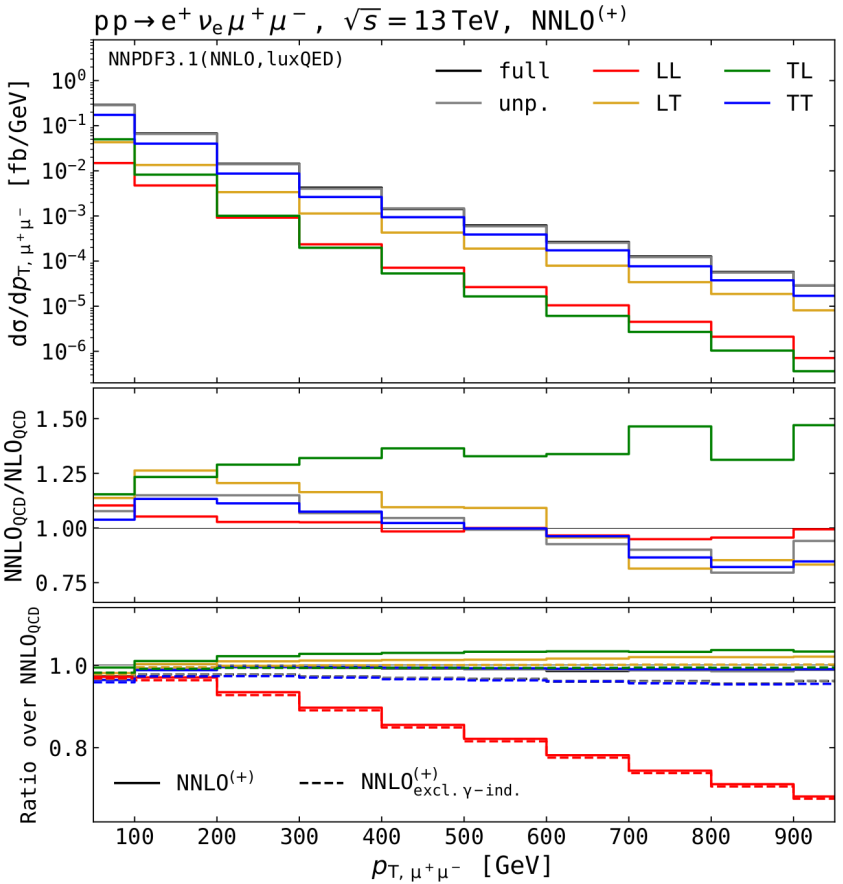
Diagrams from 1810.11034

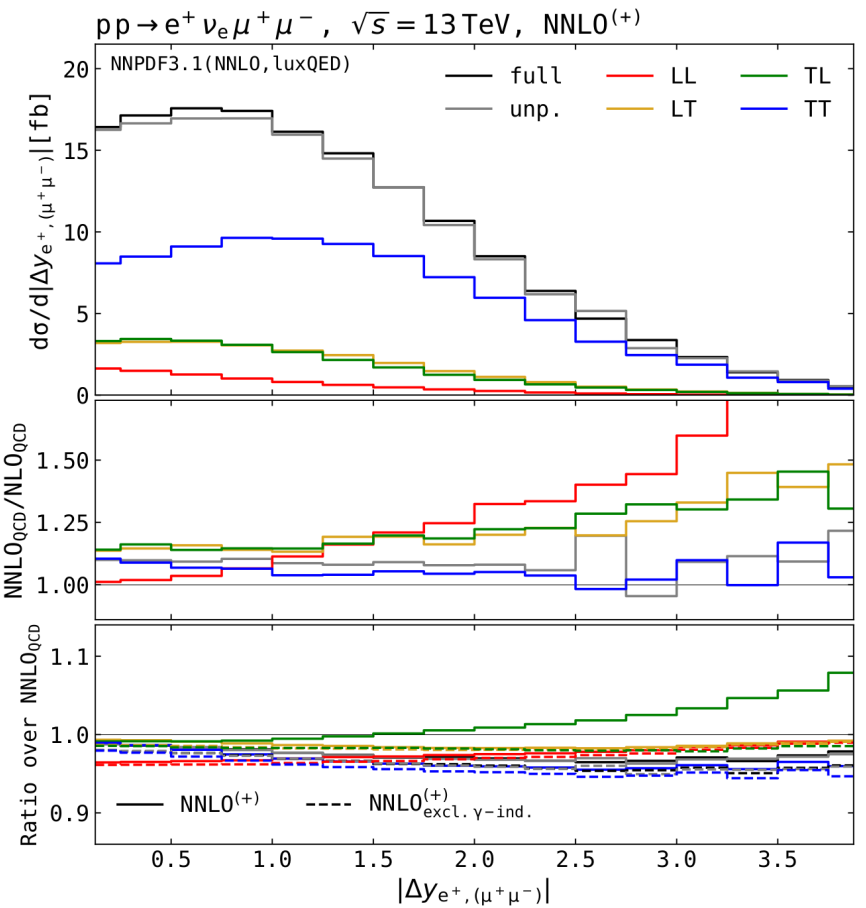
Precise predictions for joint polarisation fractions in WZ production at the LHC
Pelliccioli, Poncelet [2510.25898]

Combining NNLO QCD and NLO EW corrections:

$$
\begin{aligned}
\mathrm{d}\sigma^{(+)}_{\mathrm{NLO}} &= \mathrm{d}\sigma_{\mathrm{LO}} \left(1 + \delta^{(1)}_{\mathrm{QCD},\,\mathrm{u\bar{d}}} + \delta^{(1)}_{\mathrm{EW},\,\mathrm{u\bar{d}}}\right) + \mathrm{d}\sigma_{qg} + \mathrm{d}\sigma_{q\gamma}, \\
\mathrm{d}\sigma^{(\times)}_{\mathrm{NLO}} &= \mathrm{d}\sigma_{\mathrm{LO}} \left(1 + \delta^{(1)}_{\mathrm{QCD},\,\mathrm{u\bar{d}}}\right)\left(1 + \delta^{(1)}_{\mathrm{EW},\,\mathrm{u\bar{d}}}\right) + \mathrm{d}\sigma_{qg} + \mathrm{d}\sigma_{q\gamma}, \\
\mathrm{d}\sigma^{(+)}_{\mathrm{NNLO}} &= \mathrm{d}\sigma_{\mathrm{LO}} \left(1 + \delta^{(1)}_{\mathrm{QCD},\,\mathrm{u\bar{d}}} + \delta^{(2)}_{\mathrm{QCD},\,\mathrm{u\bar{d}}} + \delta^{(1)}_{\mathrm{EW},\,\mathrm{u\bar{d}}}\right) + \mathrm{d}\sigma_{qg}\left(1 + \delta^{(1)}_{\mathrm{QCD},\,qg}\right) + \mathrm{d}\sigma_{qq'} + \mathrm{d}\sigma_{\mathrm{gg}} + \mathrm{d}\sigma_{q\gamma}, \\
\mathrm{d}\sigma^{(\times)}_{\mathrm{NNLO}} &= \mathrm{d}\sigma_{\mathrm{LO}} \left(1 + \delta^{(1)}_{\mathrm{QCD},\,\mathrm{u\bar{d}}} + \delta^{(2)}_{\mathrm{QCD},\,\mathrm{u\bar{d}}}\right)\left(1 + \delta^{(1)}_{\mathrm{EW},\,\mathrm{u\bar{d}}}\right) + \mathrm{d}\sigma_{qg}\left(1 + \delta^{(1)}_{\mathrm{QCD},\,qg}\right) + \mathrm{d}\sigma_{qq'} + \mathrm{d}\sigma_{\mathrm{gg}} + \mathrm{d}\sigma_{q\gamma}
\end{aligned}
$$

WZ NNLO QCD + NLO EW

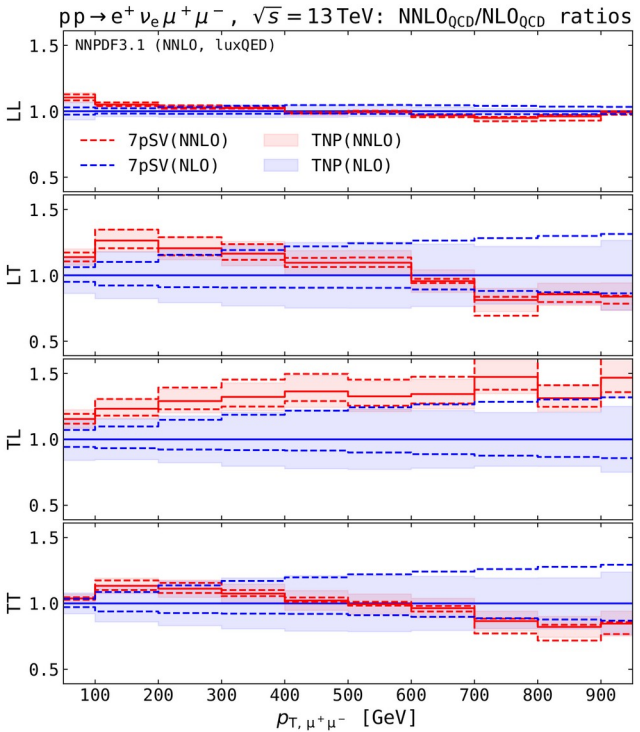


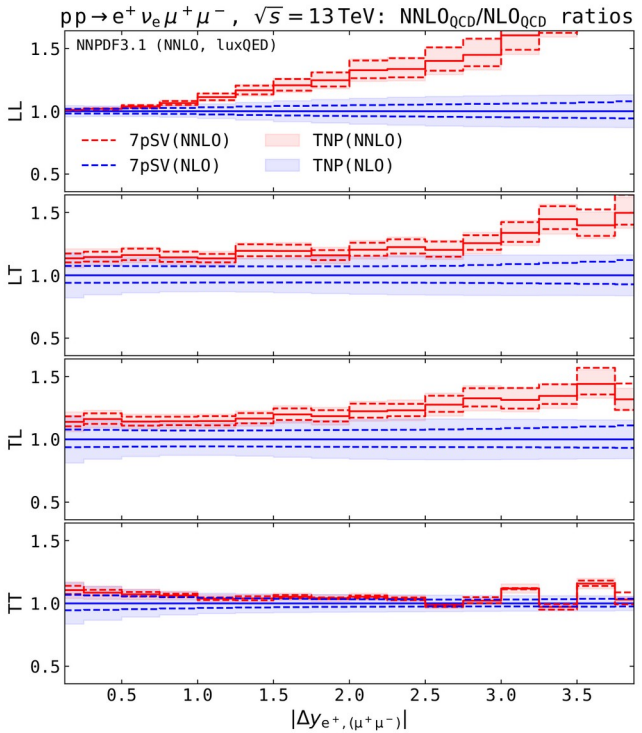


Theory uncertainties from Theory-Nuisance-Parameters

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

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





Approximation for next missing term:

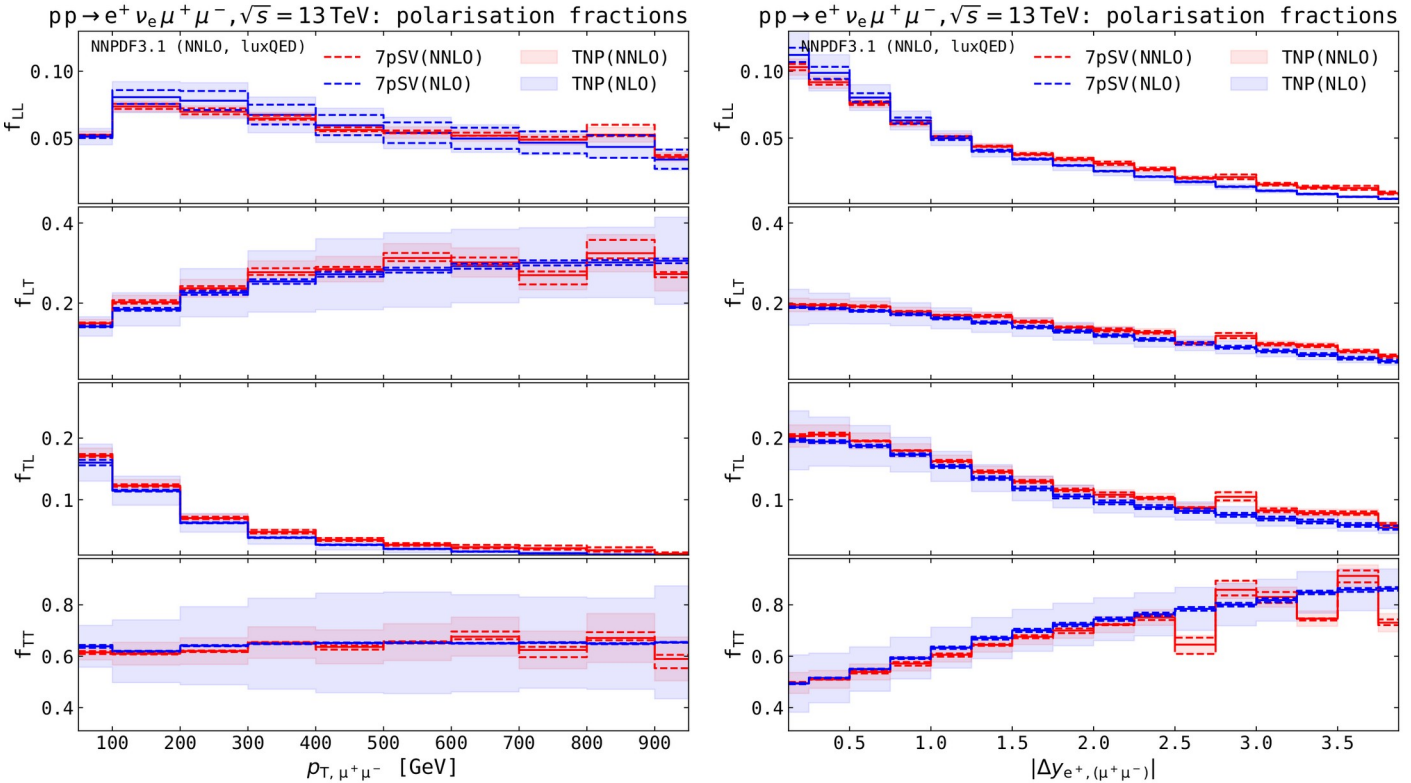
$$\frac{\mathrm{d}\bar{\sigma}_{\mathrm{TNP}}^{(N+1)}}{\mathrm{d}\bar{\sigma}^{(0)}} = \sum_{j=1}^{N} f_k^{(j)}\left(\vec{\theta}, x\right) \left(\frac{\mathrm{d}\bar{\sigma}^{(j)}}{\mathrm{d}\bar{\sigma}^{(0)}} \right)$$

Chebychev Polynomials

Differential polarization fractions

Uncorrelated TNP unc.
→ similar to uncorrelated scale variation

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



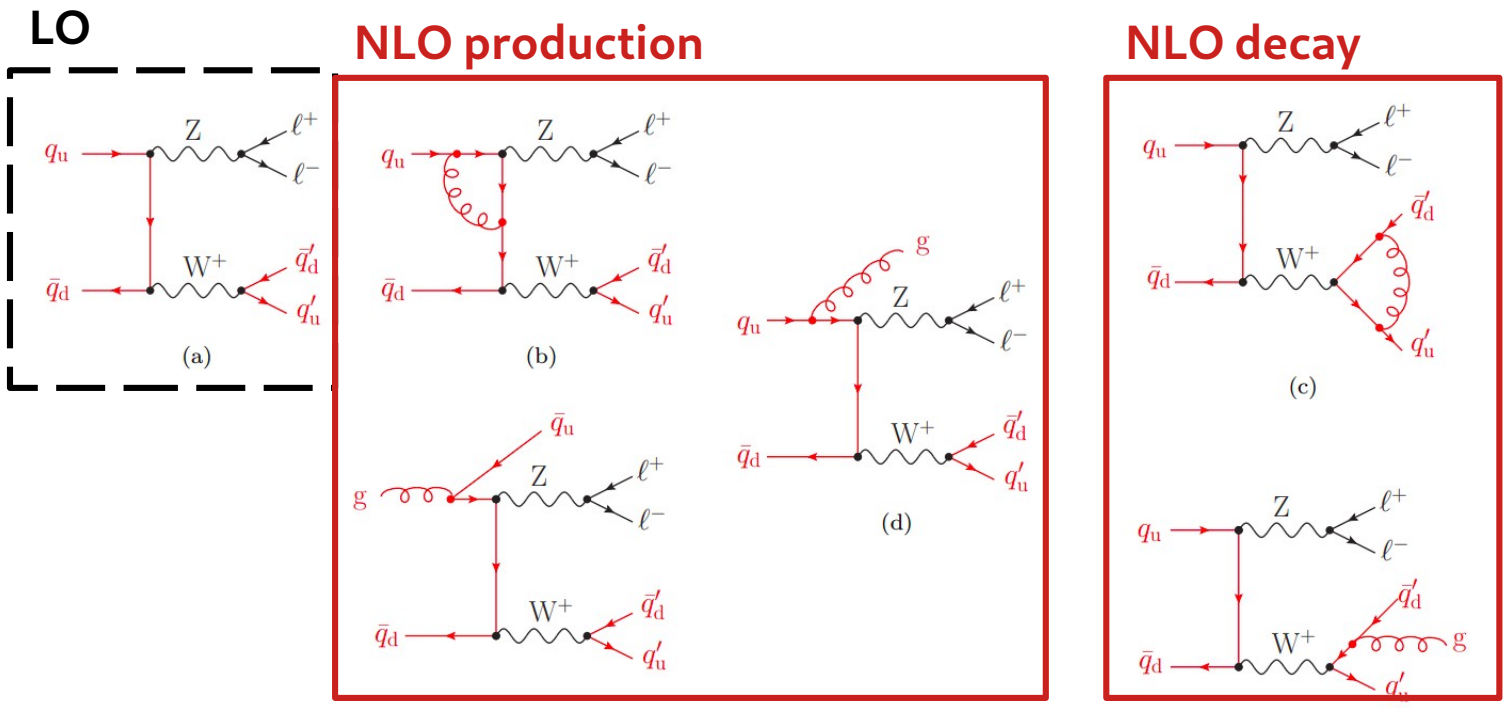
Hadronic final states

Di-boson production with semi-leptonic final states

- Leptonic final states: ‘clean’ signature & accurate reconstruction of observables
- **Main motivation:**
  - larger branching fraction → reduced stats
  - Leptonic W decays
    → missing neutrino momentum leads to ambiguities
    → hadronic decays allow full W momentum reconstruction
- **Main problem is the sensitivity to QCD**
  - V+jj QCD backgrounds → experimentally challenging
  - Radiative corrections in the hadronic decay:
    → pQCD: corrections up to NNLO QCD feasible for resonnant Vs (DPA or NWA)
    → expect sensitivity to parton-shower (matching)

Semi-leptonic decays in polarised WZ

[NLO QCD corrections to polarised di-boson production in semi-leptonic final states – Denner, Haitz, Pelliccioli - ‘23]



→ employing DPA

→ colour structure: non-factorizable contributions vanish

Semi-leptonic decays in polarised WZ

[NLO QCD corrections to polarised di-boson production in semi-leptonic final states – Denner, Haitz, Pelliccioli - '23]

Resolved di-jet: $\mathrm{pp} \to \mathrm{Z}\,(\to \ell^+\ell^-)\,\mathrm{W}^+\,(\to \mathrm{jj}) + X$

- at least two jets (clustered with $R_0 = 0.4$) with $p_{\mathrm{T,j}} > 30\,\mathrm{GeV}$, $|y_{\mathrm{j}}| < 2.4$ and $\Delta R_{\mathrm{j}\ell^\pm} > 0.4$, the two jets with a pair invariant mass closest to M_{W} being selected as *decay jets*,
- the system of the two decay jets with $p_{\mathrm{T,jj}} > 200\,\mathrm{GeV}$ and $65\,\mathrm{GeV} < M_{\mathrm{jj}} < 105\,\mathrm{GeV}$;
- two opposite-sign, same-flavour leptons with $p_{\mathrm{T},\ell^\pm} > 40\,\mathrm{GeV}$, $|y_{\ell^\pm}| < 2.4$, $p_{\mathrm{T},\ell\ell} > 200\,\mathrm{GeV}$ and $76\,\mathrm{GeV} < M_{\ell\ell} < 106\,\mathrm{GeV}$.

Boosted large-R jet: $\mathrm{pp} \to \mathrm{Z}\,(\to \ell^+\ell^-)\,\mathrm{W}^+\,(\to \mathrm{J}) + X$

- at least one jet (clustered with $R_0 = 0.8$) with $|y_{\mathrm{J}}| < 2.4$, $\Delta R_{\mathrm{J}\ell^\pm} > 0.8$, $p_{\mathrm{T,J}} > 200\,\mathrm{GeV}$ and $65\,\mathrm{GeV} < M_{\mathrm{J}} < 105\,\mathrm{GeV}$,
- two opposite-sign, same-flavour leptons with $p_{\mathrm{T},\ell^\pm} > 40\,\mathrm{GeV}$, $|y_{\ell^\pm}| < 2.4$, $p_{\mathrm{T},\ell\ell} > 200\,\mathrm{GeV}$ and $76\,\mathrm{GeV} < M_{\ell\ell} < 106\,\mathrm{GeV}$.

Total cross sections

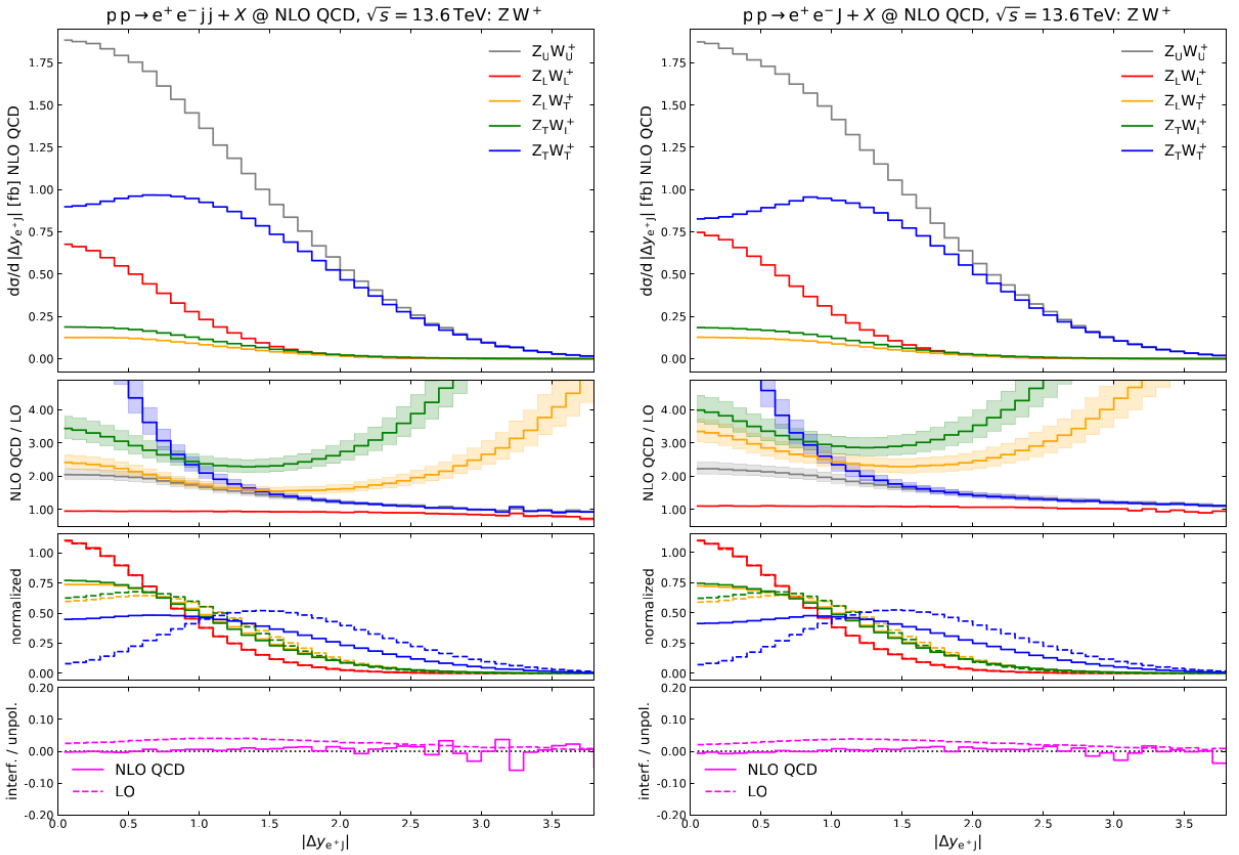
Large corrections from gq channel

state	σ_{LO} [fb]	f_{LO}[%]	σ_{NLO} [fb]	f_{NLO}[%]	K_{NLO}	$K_{\mathrm{NLO}}^{(\mathrm{no\,g})}$
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
$Z_L W_T^+$	$0.06444(1)^{+0.7\%}_{-1.0\%}$	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	–	–

Largest corrections for TT and mixed states
→ LL insensitive to QCD

Resolved vs. Unresolved: overall similar
→ differences in mixed states
→ interplay between cuts and angular dependence for L vs. T W decays

Example differential cross section



(a) Resolved topology

(b) Unresolved topology

Recent works I couldn’t discuss…

- **Vector-boson scattering**
  - NLO EW and QCD corrections to polarised same-sign WW scattering at the LHC [2409.03620]
  - Electroweak corrections to doubly polarised WZ scattering at the LHC [2510.26462]
- **Polarised triple boson**
  - Triply polarized WWW at the LHC: first glimpse at LO [2603.02917]
- **Top-quark effects**
  - Polarized W^+W^- pairs at the LHC: Effects from bottom-quark induced processes at NLO QCD + EW [2409.06396]
- **Polarisation definitions**
  - The Four Polarizations of the W at High Energies [2512.10015]

Take home messages

- 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

- SMEFT effects on polarisation observables @ NLO+PS reality

What's next?

→ **hadronic polarisation taggers**

→ **higher order corrections to decays**

→ **PS matching**

Thank you!

Backup



Comprehensive **M**ultiboson **E**xperiment-**T**heory **A**ction

- 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 **M**ultiboson **E**xperiment-**T**heory **A**ction

- **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/

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Comprehensive **M**ultiboson **E**xperiment-**T**heory **A**ction

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

WG1 leaders

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/

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 $q\bar{q} \to ZZ$, 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 $gg \to ZZ$ 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

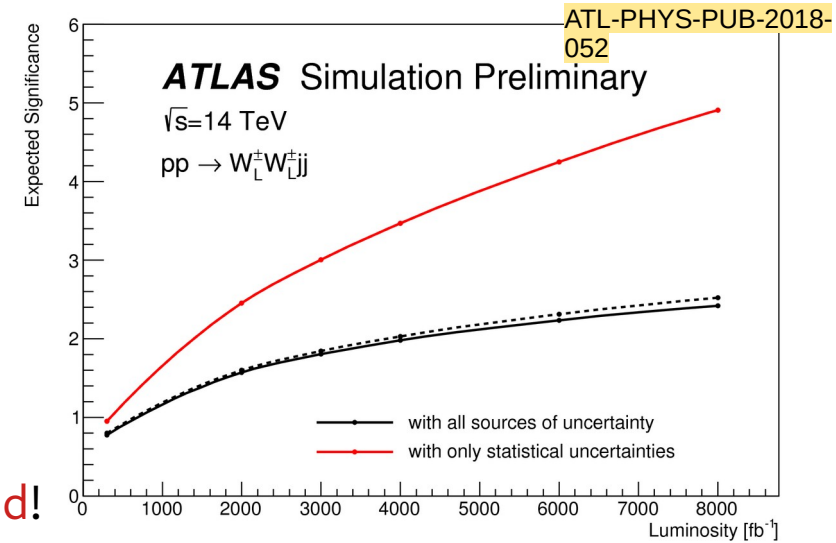
- Single boson production
  Left-Handed W Bosons at the LHC,
  Z. Bern et. al. 1103.5445
  Electroweak gauge boson polarisation at the LHC,
  Stirling, Vryonidou 1204.6427
  What Does the CMS Measurement of W-polarization Tell Us about the Underlying Theory of the Coupling of W-Bosons to Matter?,
  Belyaev, 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} → ~5-7 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

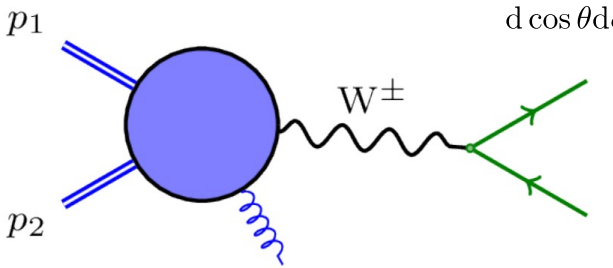
- New bookkeeping of boson polarizations in SHERPA for LO MEs
- Approximate NLO corrections: nLO+PS
  → Reals+matching are treated exact
  → loop matrix elements unpolarised
- Comparison with multi-jet merged calculations

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

W^+Z	σ^{NLO} [fb]	Fraction [%]	K-factor	$\sigma^{\mathrm{nLO+PS}}_{\mathrm{SHERPA}}$ [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:

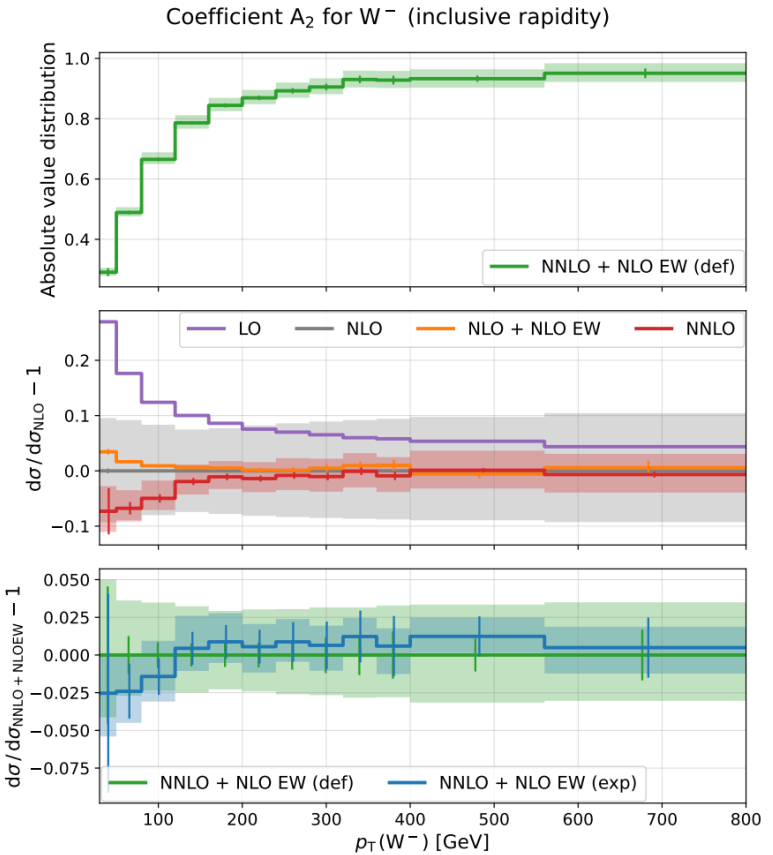
$$\frac{1}{\sigma}\frac{d\sigma}{\cos\theta} = \frac{3}{4}\sin\theta f_0 + \frac{3}{8}(1-\cos\theta)^2 f_L + \frac{3}{8}(1+\cos\theta)^2 f_R$$

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:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T,W}}\,\mathrm{d}y_{\mathrm{W}}\,\mathrm{d}m_{\ell\nu}\,\mathrm{d}\Omega} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma^{U+L}}{\mathrm{d}p_{\mathrm{T,W}}\,\mathrm{d}y_{\mathrm{W}}\,\mathrm{d}m_{\ell\nu}}\Big((1+\cos^2\theta) + \mathrm{A}_0\frac{1}{2}(1-3\cos^2\theta) + \mathrm{A}_1\sin 2\theta\cos\phi + \mathrm{A}_2\frac{1}{2}\sin^2\theta\cos 2\phi + \mathrm{A}_3\sin\theta\cos\phi + \mathrm{A}_4\cos\theta + \mathrm{A}_5\sin^2\theta\sin 2\phi + \mathrm{A}_6\sin 2\theta\sin\phi + \mathrm{A}_7\sin\theta\sin\phi\Big),$$

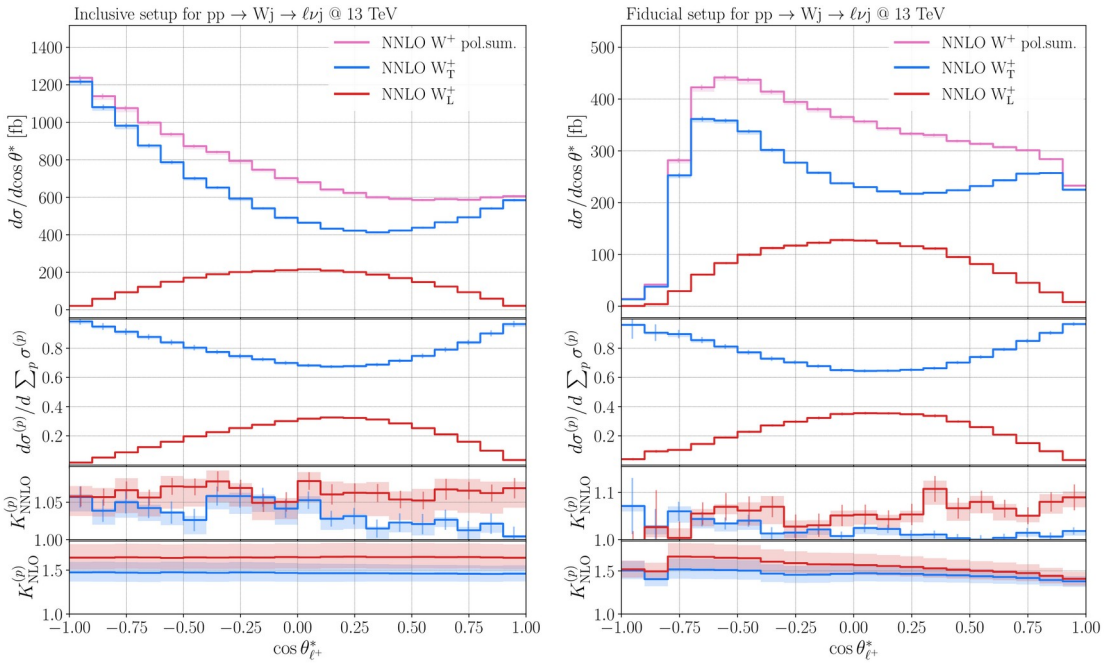


Angular coefficients in W+j production at the LHC with high precision
Pellen, Poncelet, Popescu, Vitos, 2204.12394

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:

$$\mathcal{L}_{\rm EW} = -\frac{1}{4}(W^i_{\mu\nu})^2 - \frac{1}{4}(B^i_{\mu\nu})^2 + (D_\mu\phi)^2 - V(\phi^\dagger\phi)$$

- Higgs potential and minimum:

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

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

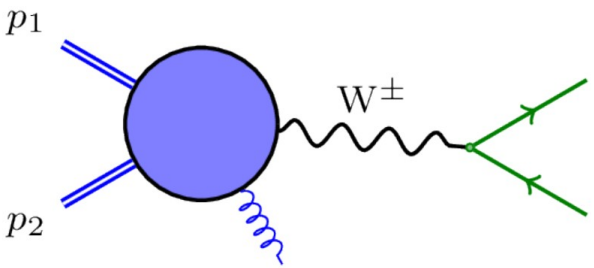
$$\phi = U^{-1}(\pi^i)\phi, \qquad W_\mu = U^{-1}W_\mu U - \frac{i}{g_W}U^{-1}\partial_\mu U$$

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

- 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 $p_T(j) \geq 30\ \mathrm{GeV}$

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

Fiducial phase space:

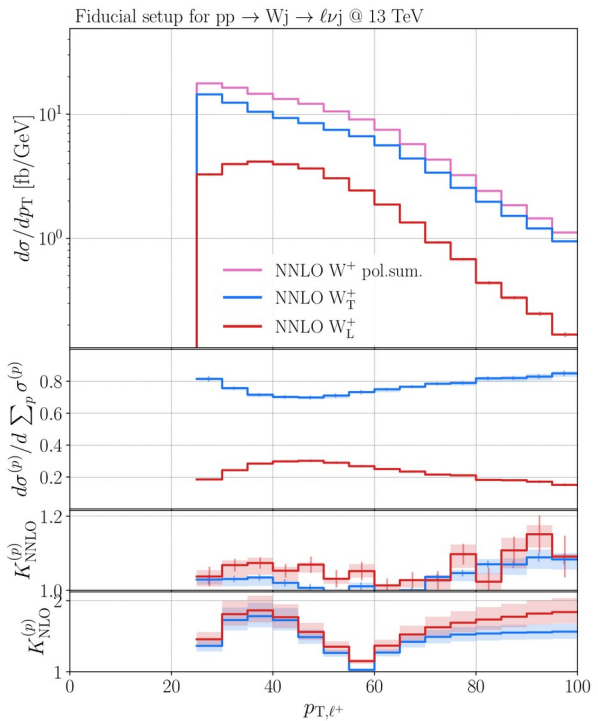
- Lepton cuts: $p_T(\ell) \geq 25\ \mathrm{GeV}$, $|\eta(\ell)| \leq 2.5$ and $\Delta R(\ell, j) > 0.4$
- Transverse mass of the W: $M_T(W) = \sqrt{m_W^2 + p_T^2(W)} \geq 50\ \mathrm{GeV}$

Technical aspects:

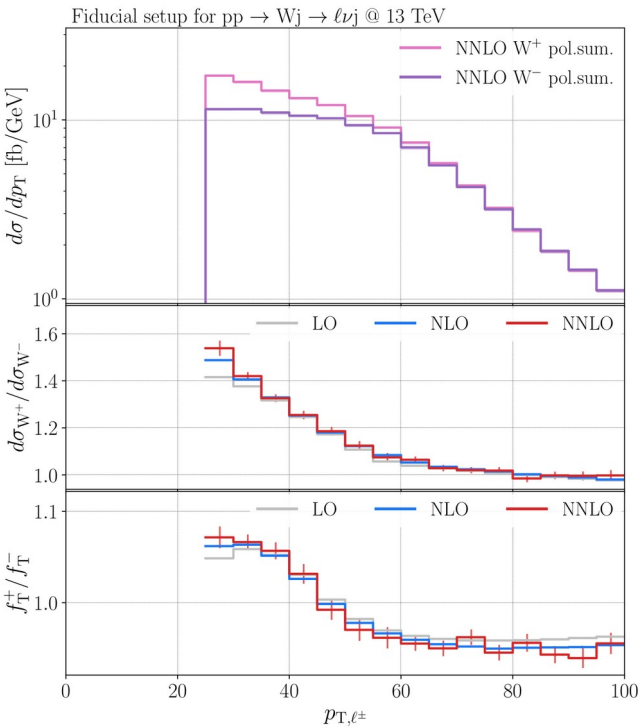
- NNPDF31 and dynamical scale choice: $\mu_R = \mu_F = \frac{1}{2}\left(m_T(W) + \sum p_T(j)\right)$
- Implementation in STRIPPER framework (NNLO QCD subtractions) [1408.2500]
  - Narrow-Width-Approximation and OSP/Pole-Approximation
  - Matrix elements from: AvH[1503.08612], OpenLoops2 [1907.13071](cross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

Example: lepton transverse momentum

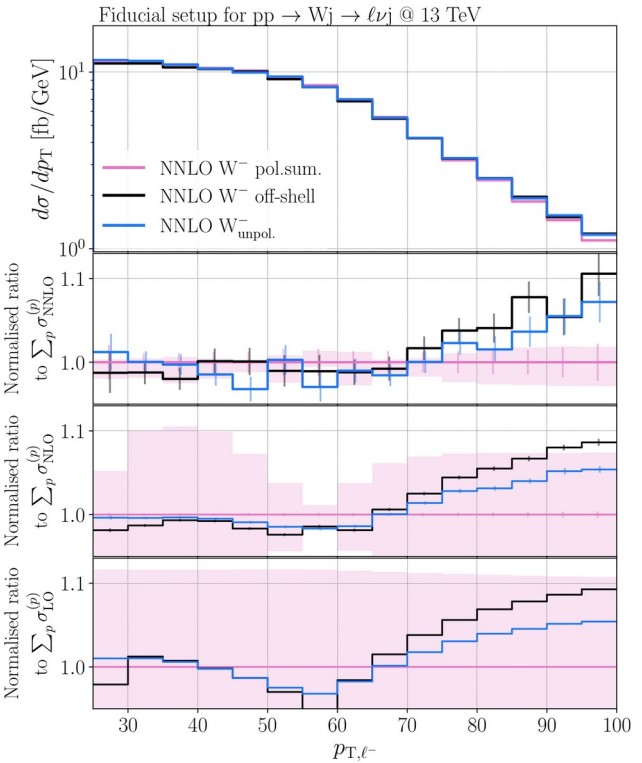
Perturbative corrections



Charge differences



Off-shell/Interference effects



Extraction of polarisation fractions

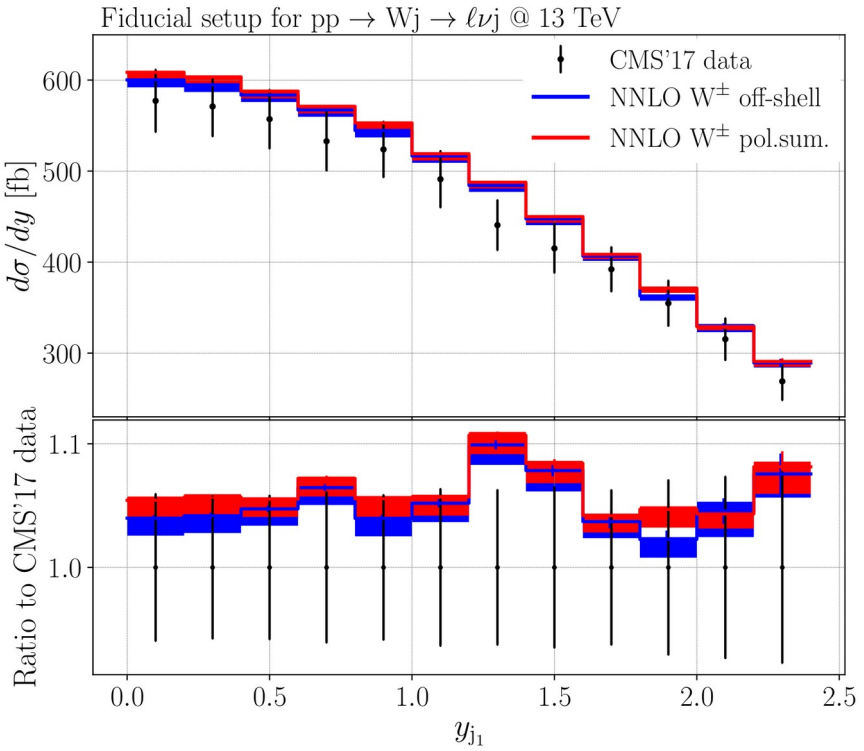
Identified 4 observables (ranges) with

→ Small interference effects (<2%)

→ Small off-shell effects (<2%)

→ Shape differences between L and T

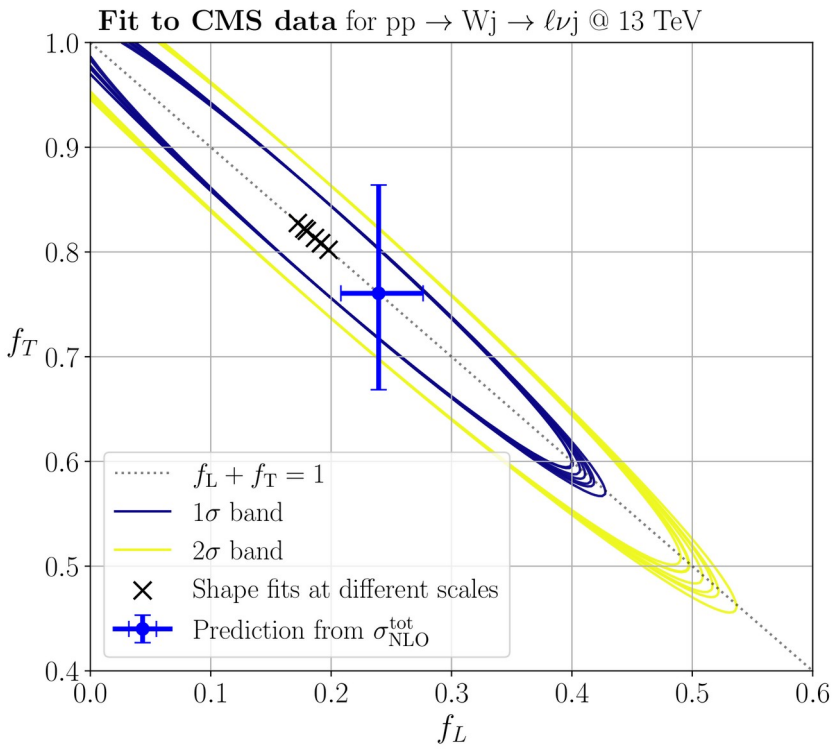
- $\Delta\phi(\ell, j_1) \geq 0.3$
- $25\ \text{GeV} \leq p_T(\ell) < 70\ \text{GeV}$
- $\cos(\theta^*_\ell) \geq -0.75$
- $|y(j_1)| \leq 2$

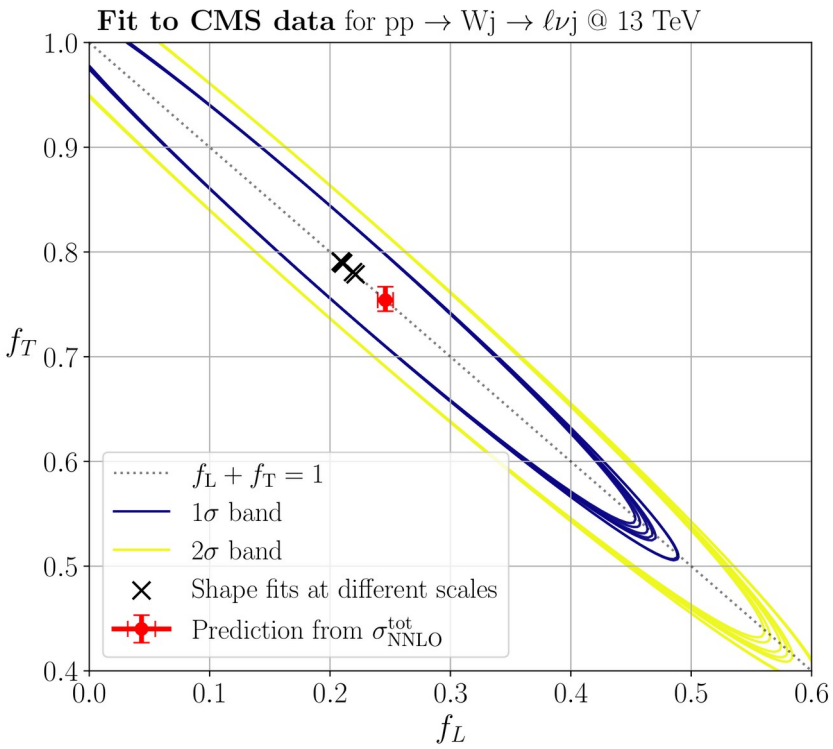


W+jet : fit to CMS data

Fit to actual data, here $|y(j_1)|$

→ dominated by experimental uncertainties (no correlations available)

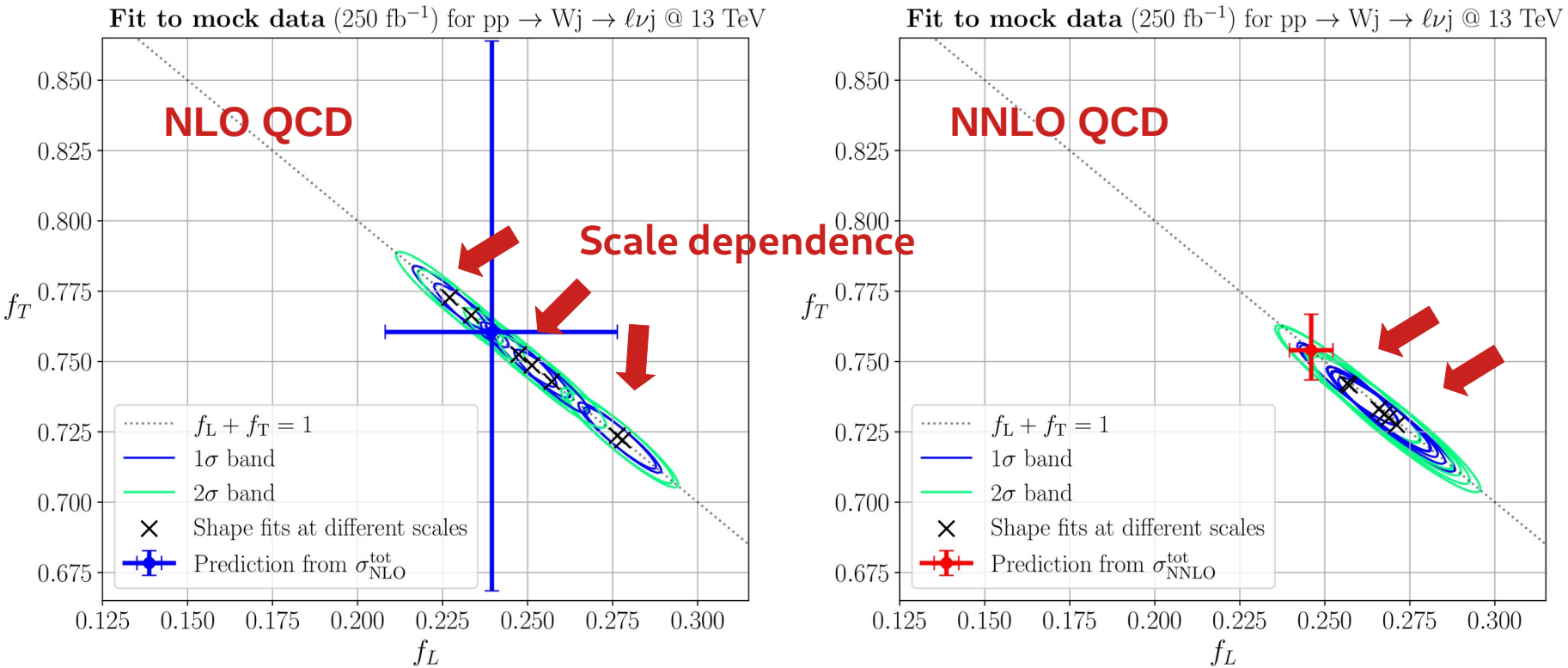




W+jet: mock-data fit

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 ($pp \to b\bar{b}W^+W^-$ enters at NNLO)
- NNPDF31 and a fixed renormalisation scale: $\mu_R = \mu_F = m_W$

Measurement of fiducial and differential W+W- production cross-sections at sqrt(s) = 13 TeV with the ATLAS detector
ATLAS 1905.04242

Fiducial phase space

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

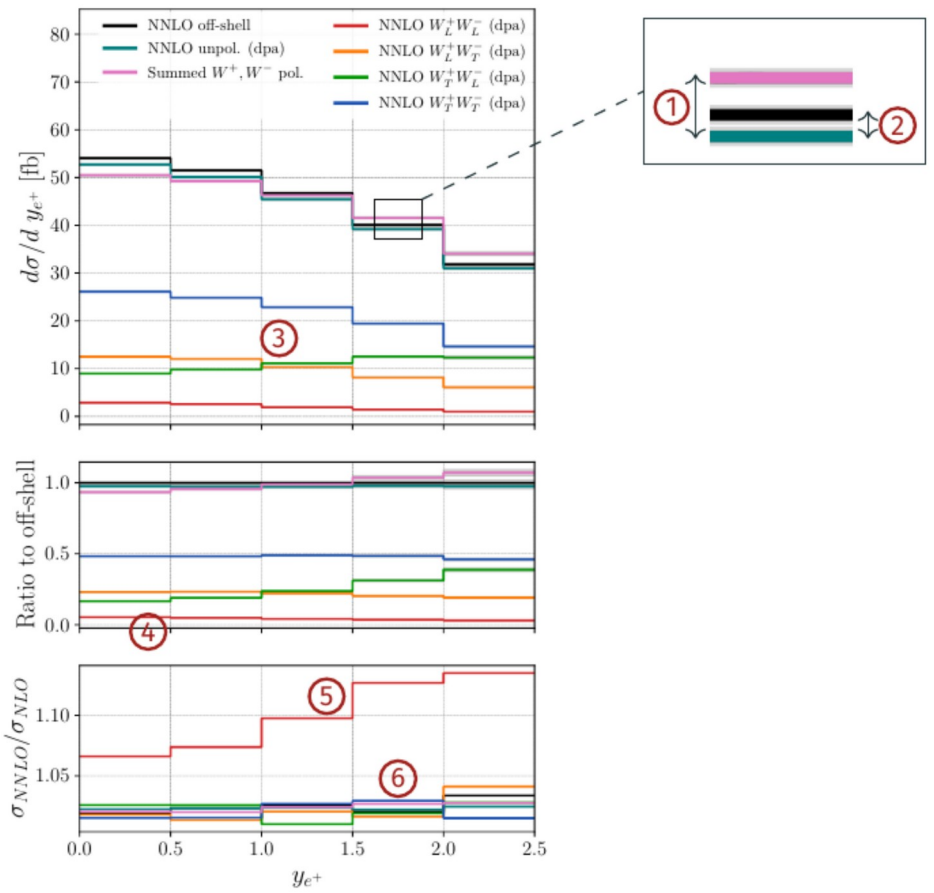
Doubly polarised cross sections

	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:

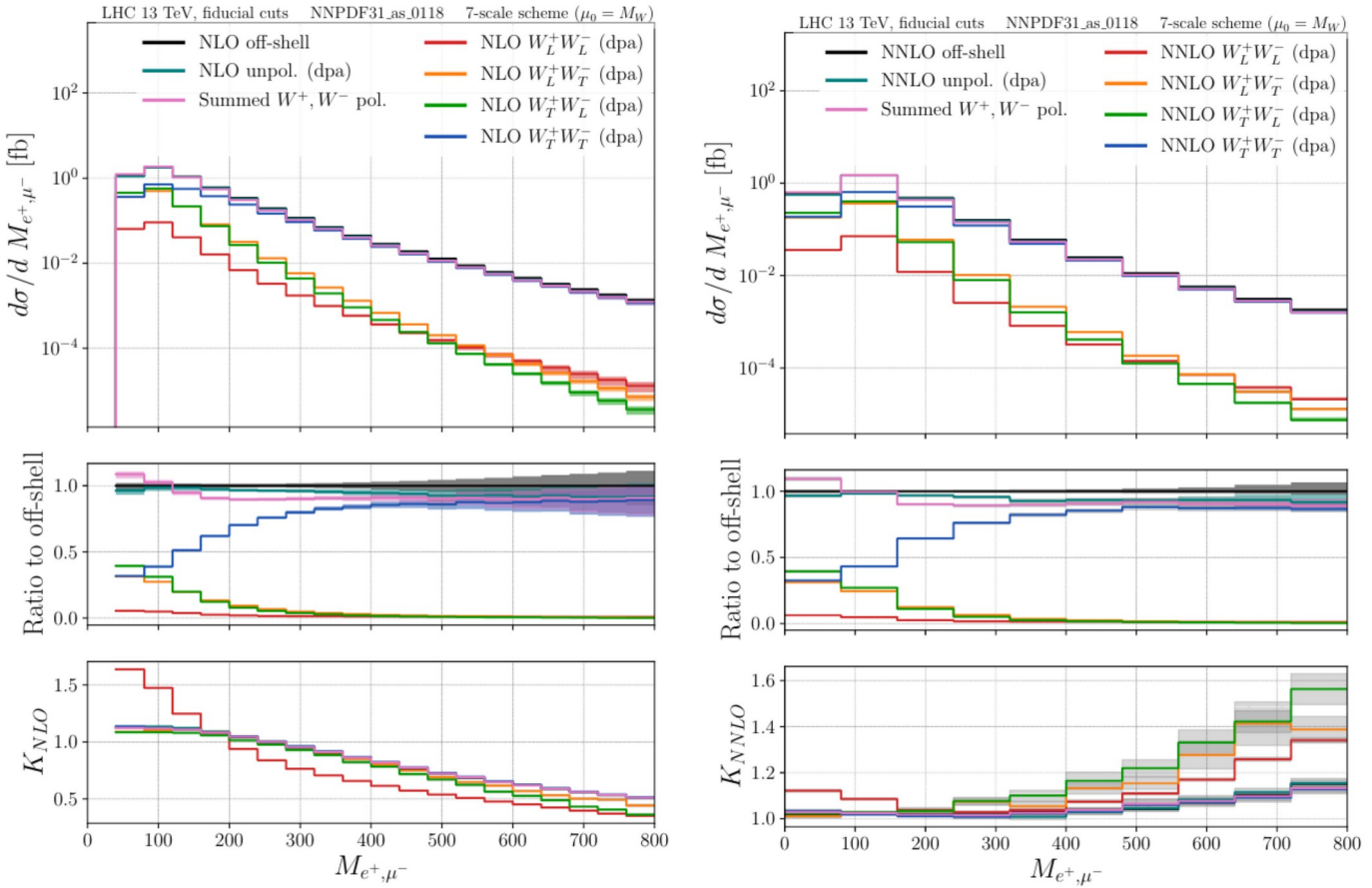
1. Polarisation interference
2. Non-resonant background
3. "Monte-Carlo true" polarisation distributions
4. $W_L^+ W_L^-$ contribution is small, $W_T^+ W_T^-$ dominates
5. Distinct and large K_{NNLO} for $W_L^+ W_L^-$
6. small K-factor for other setups

Summary:

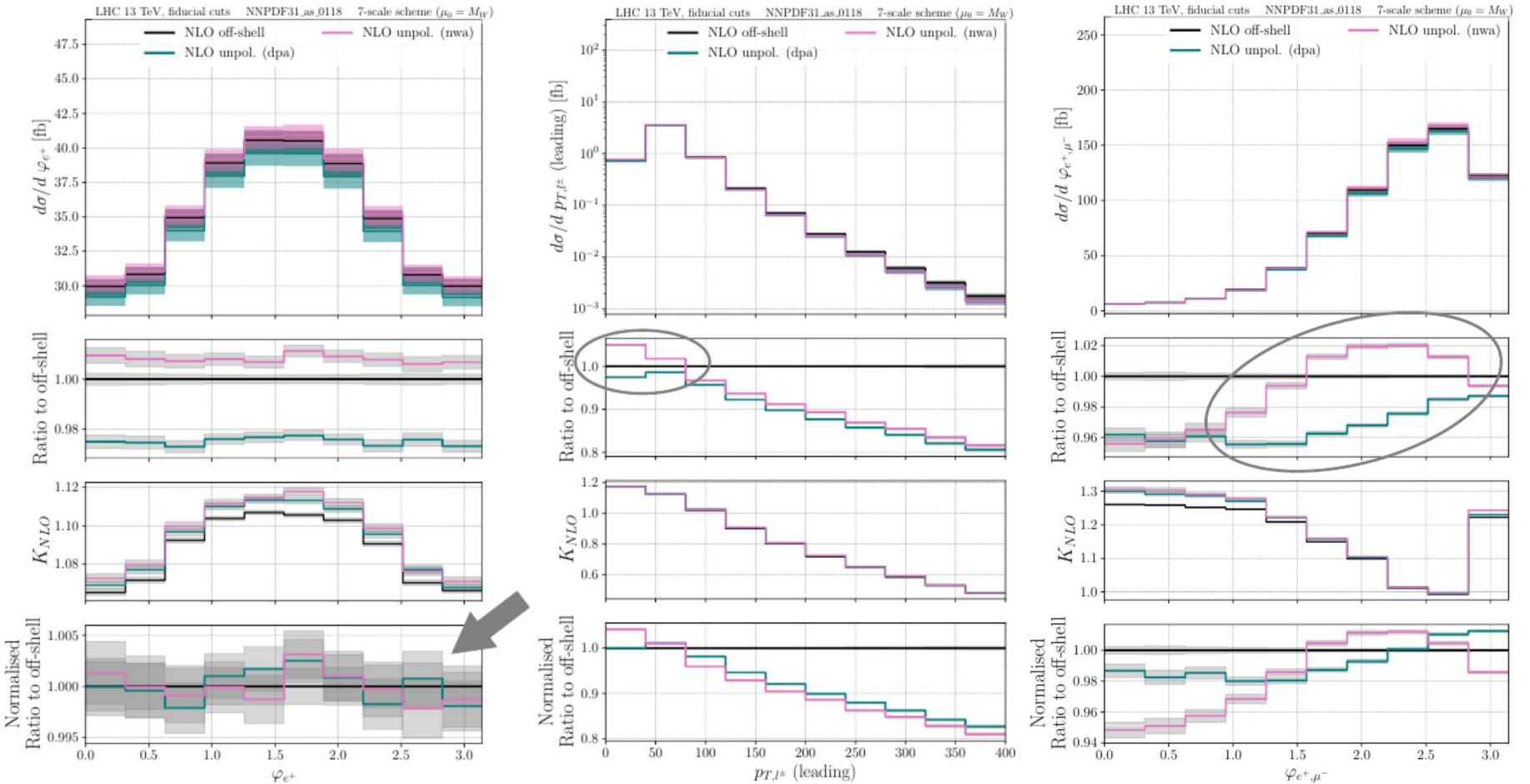
- NNLO effects are **2-3%** of σ_{tot} for all setups except $W_L^+ W_L^-$ where it is **9%**.
- Scale uncertainty is reduced by a **factor of 3** w.r.t NLO.

Polarised di-boson production

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

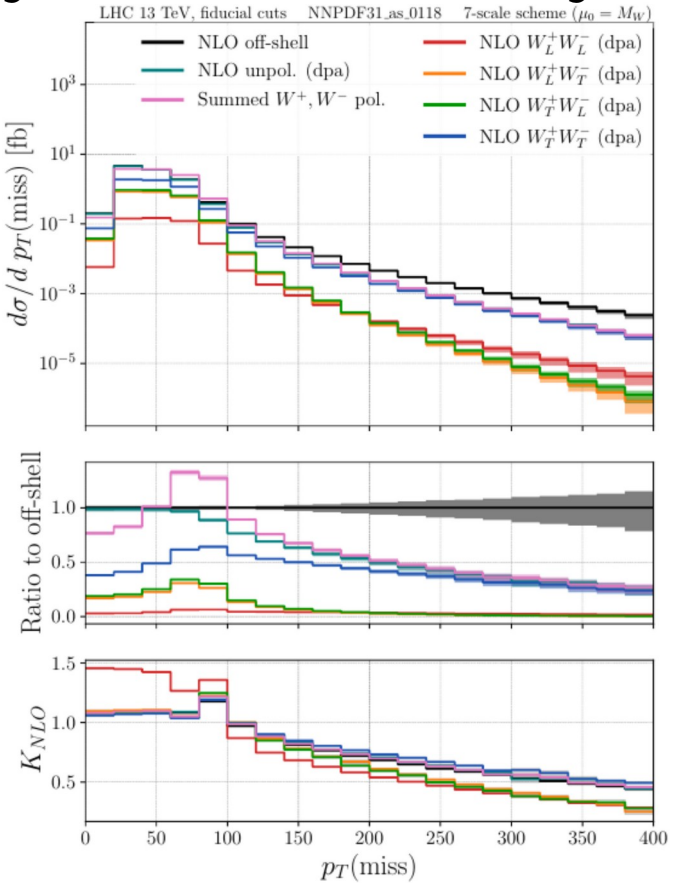


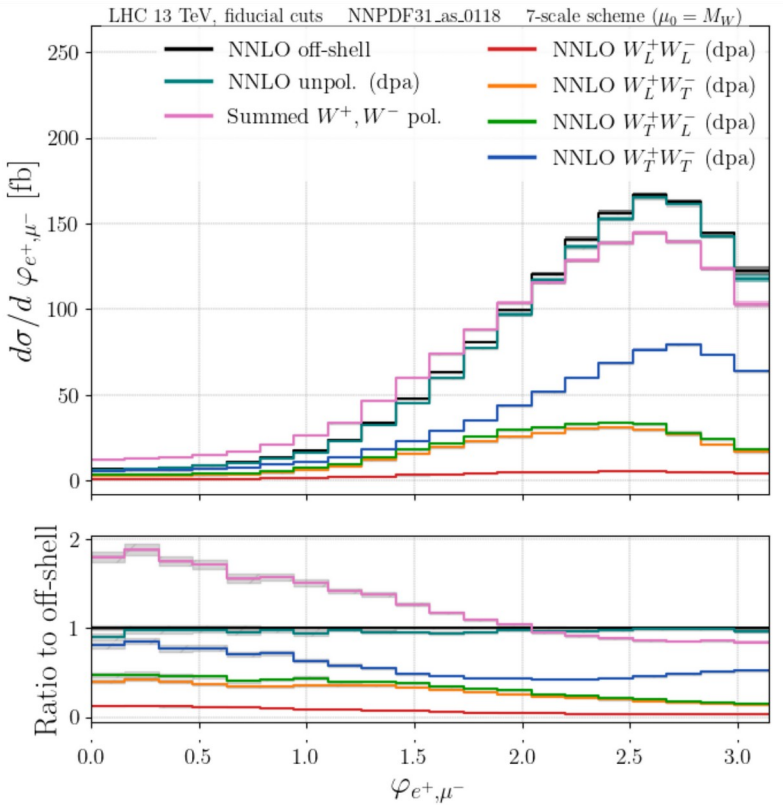
NWA vs. DPA


LHC 13 TeV, fiducial cuts NNPDF31_as_0118 7-scale scheme ($\mu_0 = M_W$)
NLO off-shell
NLO unpol. (nwa)
NLO unpol. (dpa)
$d\sigma/d\,\varphi_{e^+}$ [fb]
Ratio to off-shell
K_{NLO}
Normalised Ratio to off-shell
φ_{e^+}
$d\sigma/d\,p_{T,l^\pm}$ (leading) [fb]
$p_{T,l^\pm}$ (leading)
$d\sigma/d\,\varphi_{e^+,\mu^-}$ [fb]
φ_{e^+,μ^-}

Interference and off-shell effects

Large off-shell effect from single-resonant contributions





Large interference effects through phase space constraints

Polarised bosons in SMEFT at NLO + PS

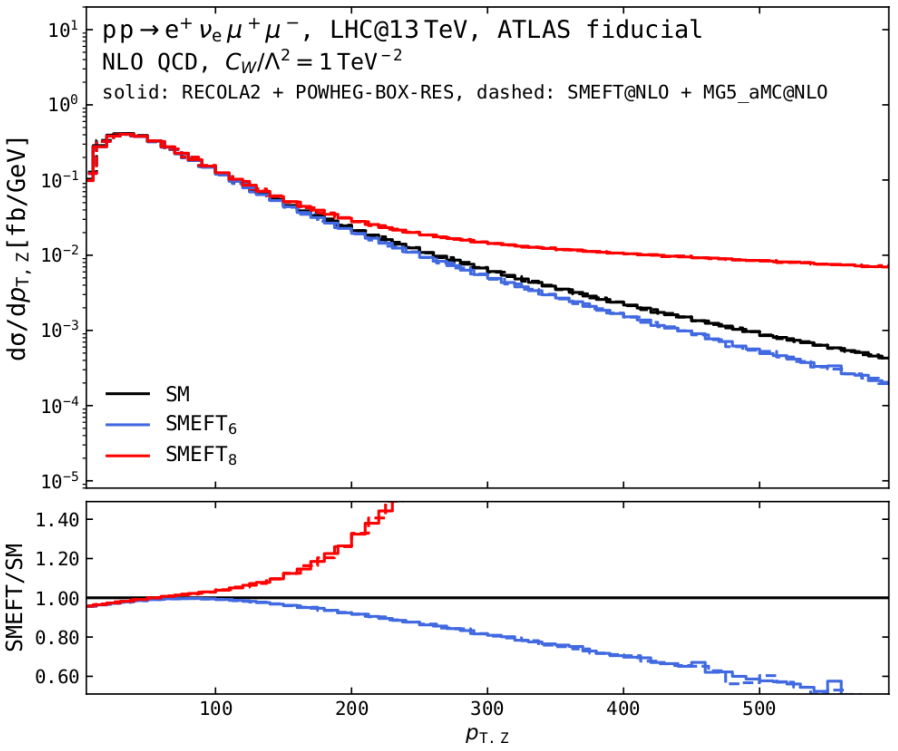
NLO+PS in Powheg-Box-Res framework
[Haisch,Linder, Pelliccioli, Re, Zanderighi 2507.21768]
Loop matrix elements: Recola2 [1711.07388]

$$\mathcal{L}_{\text{SMEFT}} = \sum_i \frac{C_i(\mu)}{\Lambda^2} Q_i$$

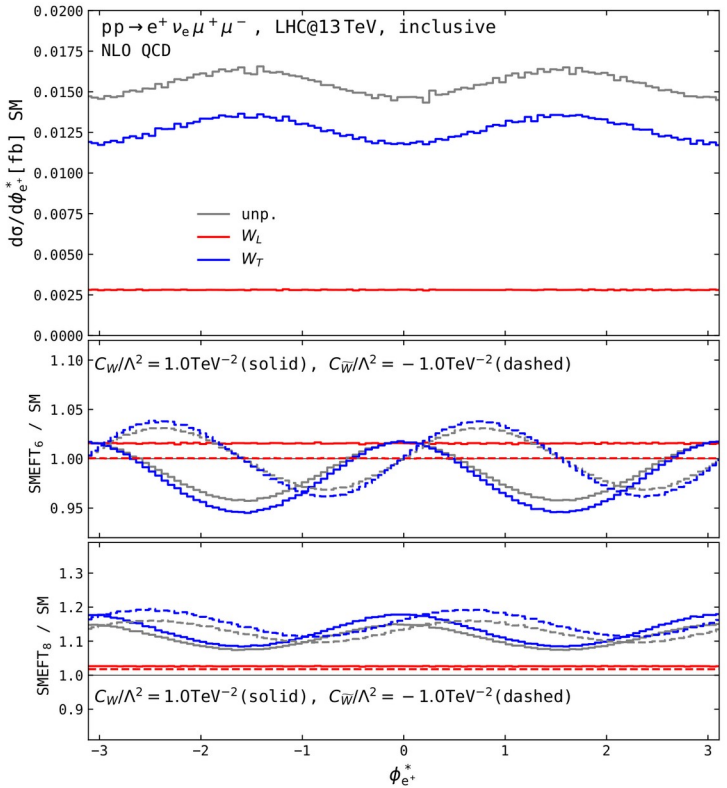
Operators (dim-6 and dim-8)

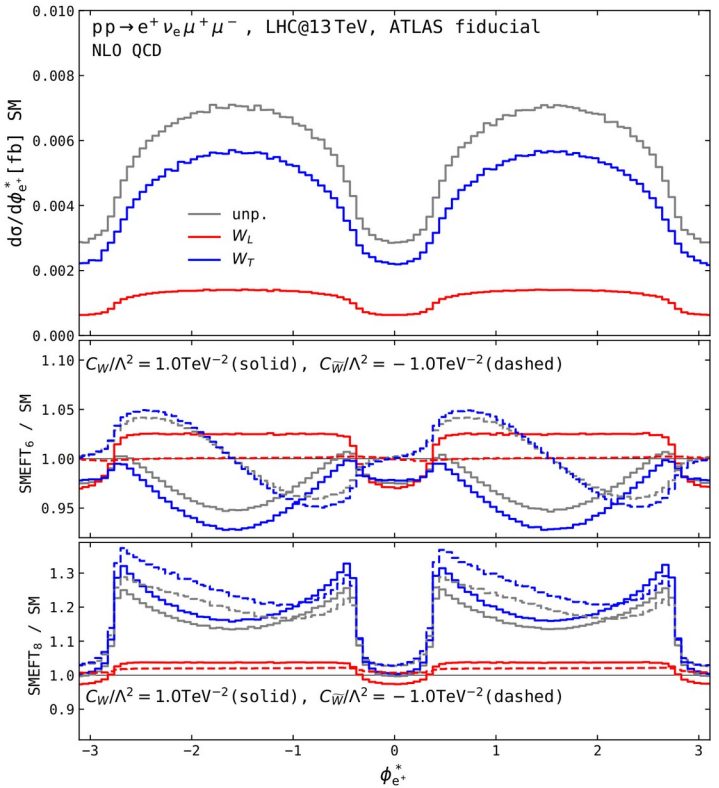
$$Q_{HB} = H^\dagger H B_{\mu\nu} B^{\mu\nu}\,, \qquad Q_{H\widetilde{B}} = H^\dagger H B_{\mu\nu} \widetilde{B}^{\mu\nu}\,,$$
$$Q_{HW} = H^\dagger H W^i_{\mu\nu} W^{i,\mu\nu}\,, \qquad Q_{H\widetilde{W}} = H^\dagger H W^i_{\mu\nu} \widetilde{W}^{i,\mu\nu}\,,$$
$$Q_{HWB} = H^\dagger \sigma^i H W^i_{\mu\nu} B^{\mu\nu}\,, \qquad Q_{H\widetilde{W}B} = H^\dagger \sigma^i H \widetilde{W}^i_{\mu\nu} B^{\mu\nu}\,,$$
$$Q_W = \epsilon_{ijk} W^{i,\nu}_\mu W^{j,\lambda}_\nu W^{k,\mu}_\lambda\,, \qquad Q_{\widetilde{W}} = \epsilon_{ijk} W^{i,\nu}_\mu W^{j,\lambda}_\nu \widetilde{W}^{k,\mu}_\lambda\,.$$

CP-even CP-odd

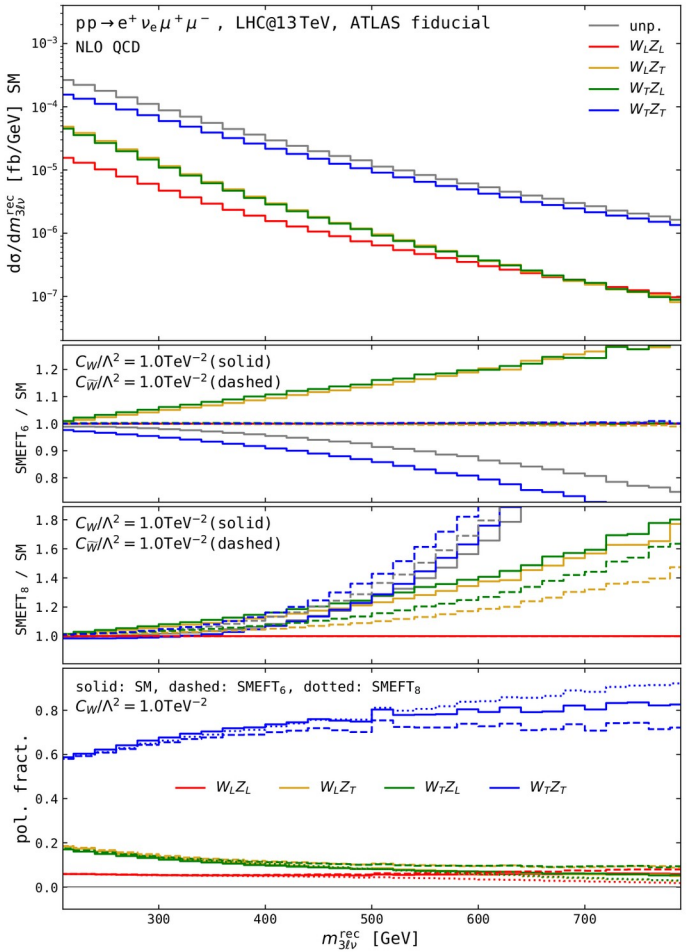


SMEFT imprint in fiducial cross sections





SMEFT effects in polarisation fractions



σ [fb], ATLAS fiducial, Eq. (44)					
contribution	unpolarized	W_LZ_L	W_LZ_T	W_TZ_L	W_TZ_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)

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

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

Moderate effect on polarisation fractions

SMEFT effects for quantum tomography

- DPA enables sound quantum tomographyof leptonic final states Del Gratta GP et al. [2509.20456] Grossi GP Vicini [2409.16731] and quantum-information-inspired observables
- Detailed study for QW at NLO QCD of concurrence and purity Pelliccioli Re [2601.09540]
- Quadratic EFT terms crucial for semi-positive ρ especially in boosted setup (pT,Z > 200 GeV, pT,WZ < 70 GeV)
- Indication of decoherence effects from QCD corrections

[direct copy of slide from Giovanni's talk at Moriond last week]

