Results from the COMETA ZZ polarization study

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COMETA

NARODOWE
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COMETA

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/

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

WG1 leaders

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Ramona Groeber

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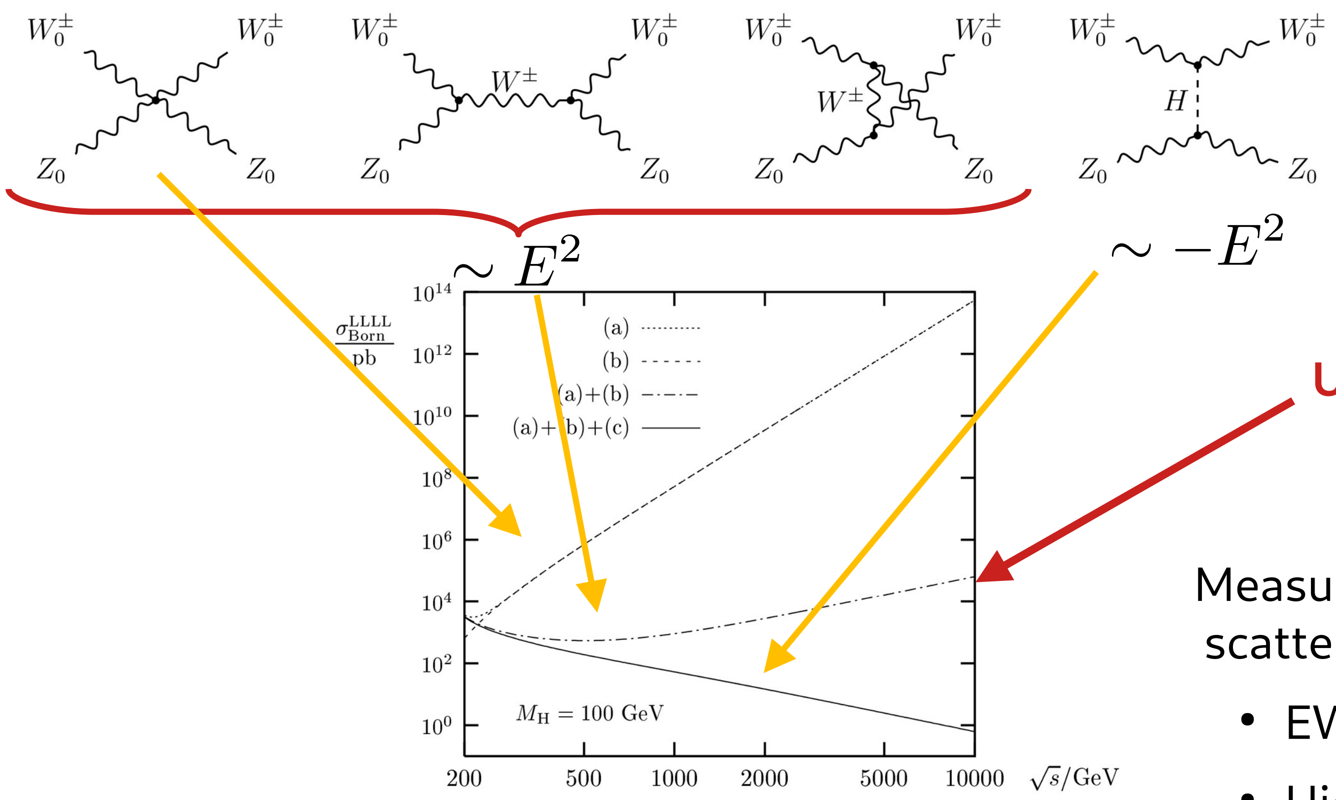
Longitudinal Vector-Boson-Scattering (VBS)



Unitarity violation

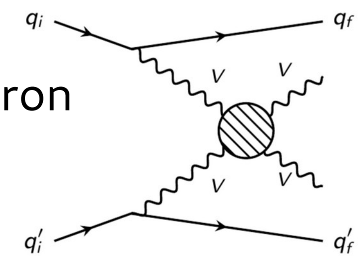
Measurement of polarized boson scattering or production probes:

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

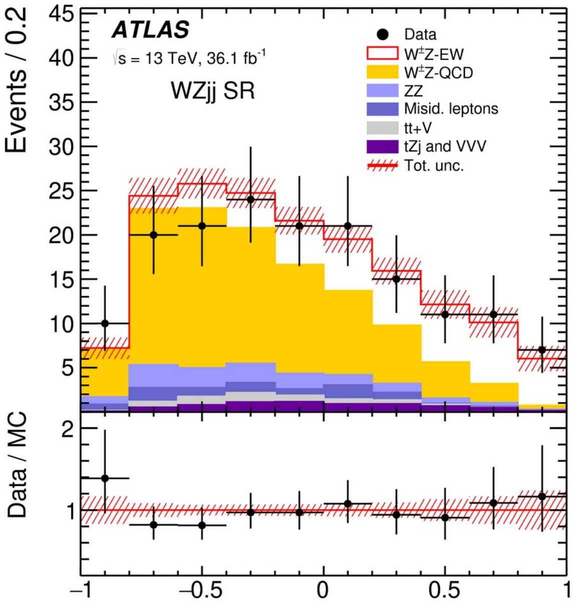
Radiative corrections to W+ W- → W+ W- in the electroweak standard model
A. Denner, T. Hahn hep-ph/9711302

VBS at hadron colliders

VBS at hadron colliders

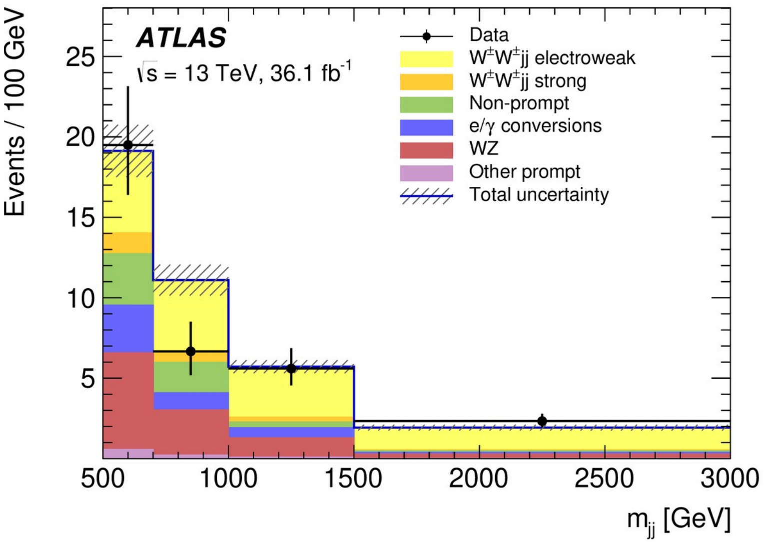


Separate from background processes through VBS topology → a rare process, but observed.



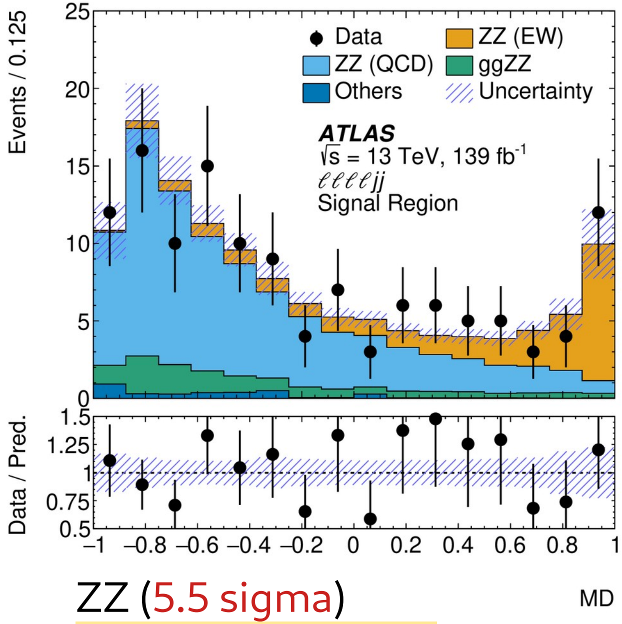
WZ (5.3 sigma)

ATLAS 1812.09740



W+W+/W-W- (6.5 sigma)

ATLAS 1906.03203

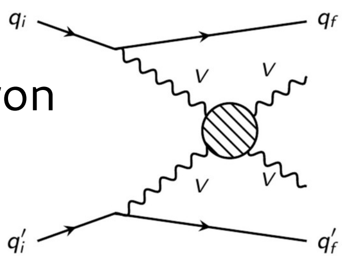


ZZ (5.5 sigma)

ATLAS 2004.10612

VBS at hadron colliders

VBS at hadron colliders



Separate from background processes through VBS topology
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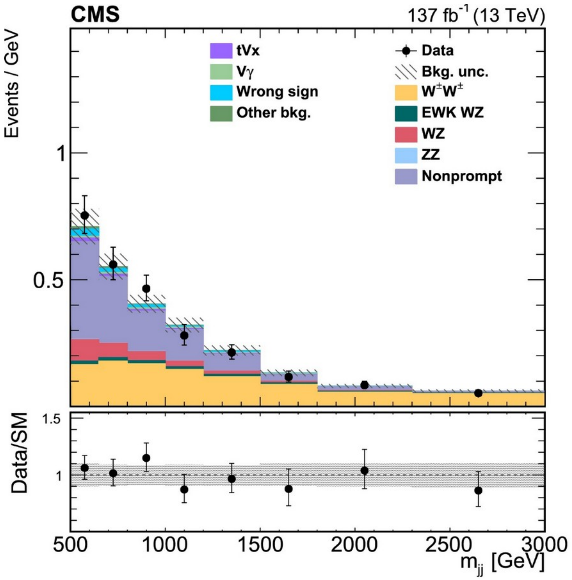
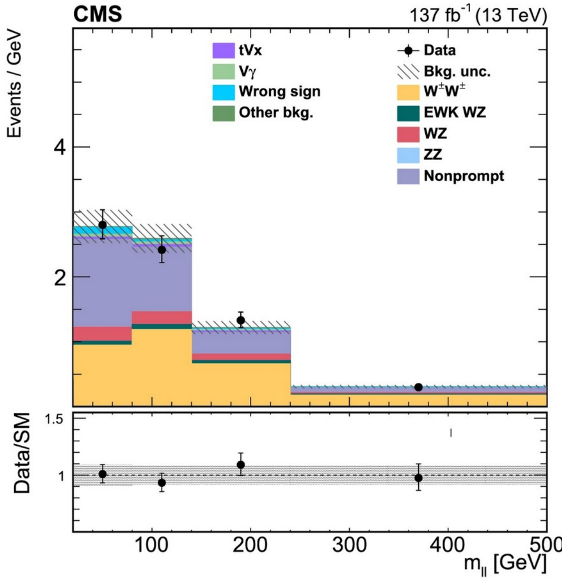
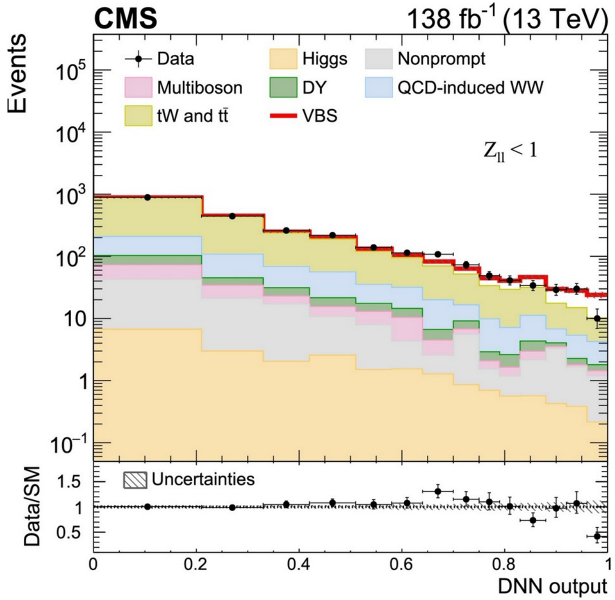


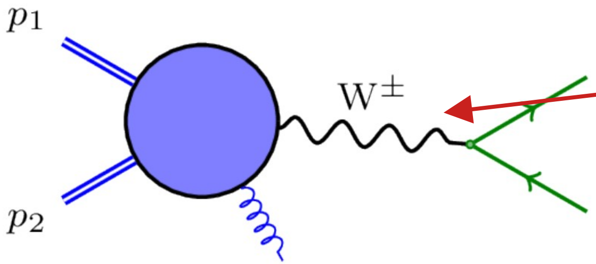




WZ (6.8 sigma) + W+W+/W-W- (diff. xsec)
CMS 2005.01173

W+W- (5.6 sigma)
CMS 2205.05711

Polarised boson production



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

Can we extract the longitudinal component?

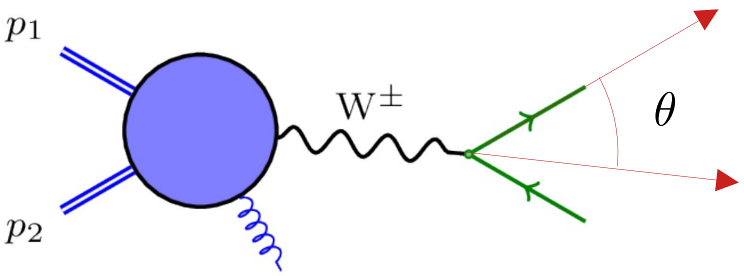
λ = +/-/L

Measurements of longitudinal polarisation fractions:

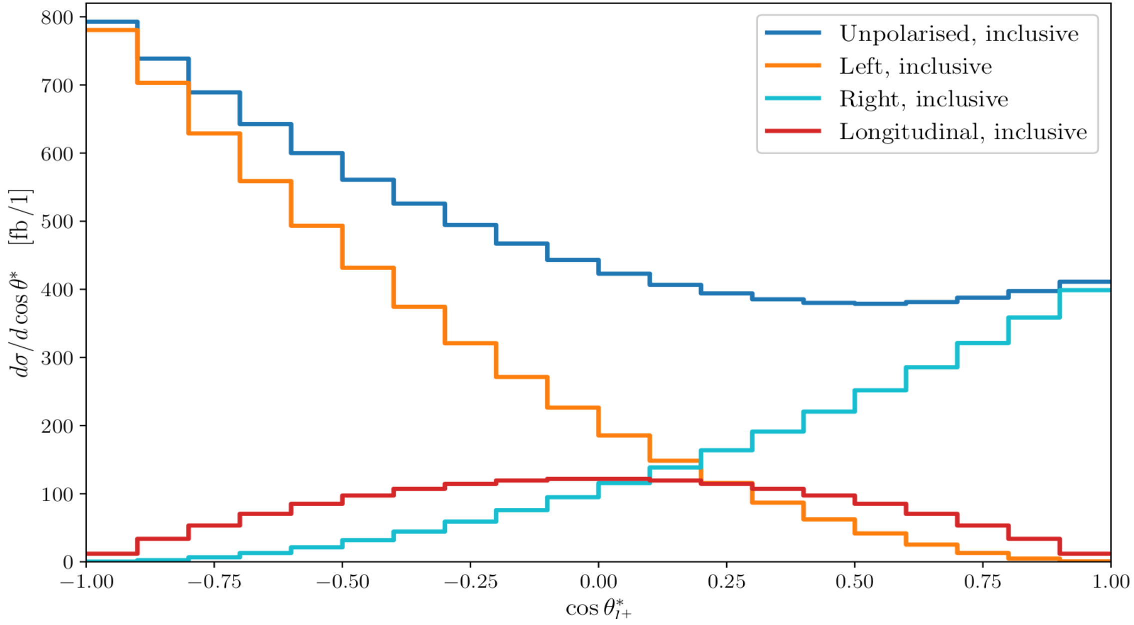
Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC,
CMS 1104.3829
Measurement of the polarisation of W bosons produced with large transverse momentum in pp collisions at \sqrt{s}=7 TeV with the ATLAS experiment,
ATLAS 1203.2165
Measurement of WZ production 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 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

How to measure polarized bosons?

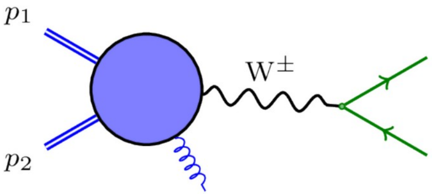
- We can't measure boson polarization directly.
- Luckily decay products can be used as a "polarimeter":



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:
(DPA or NWA)

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

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

Create samples of fixed polarisation:

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

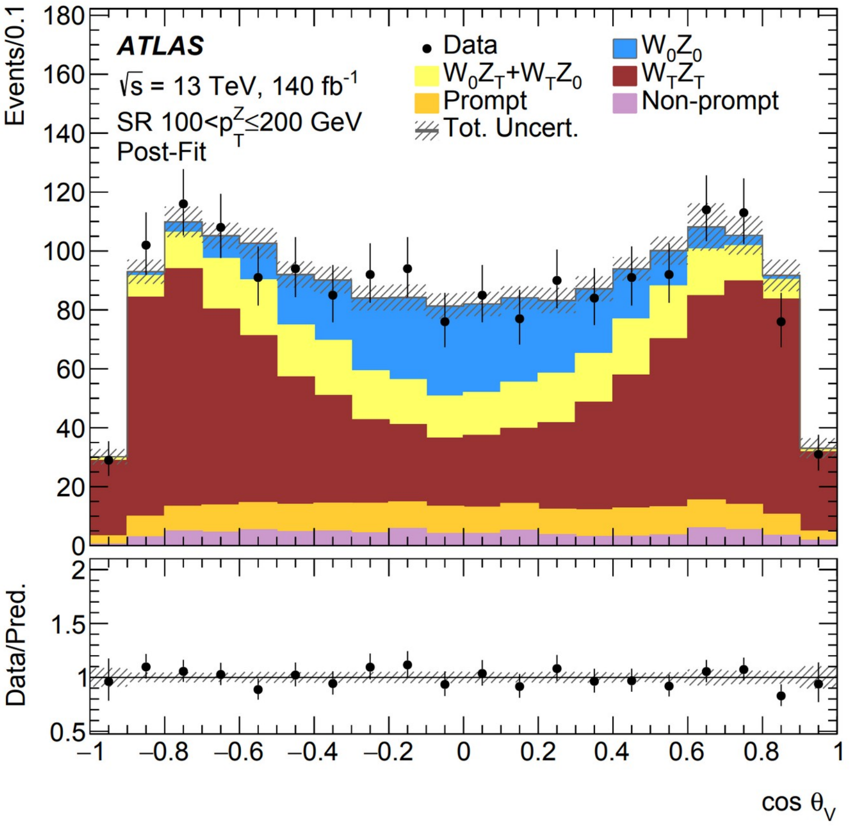
and fit f_L, f_R, f_0 to measured $\frac{\mathrm{d}\sigma^{exp.}}{\mathrm{d}X}$

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

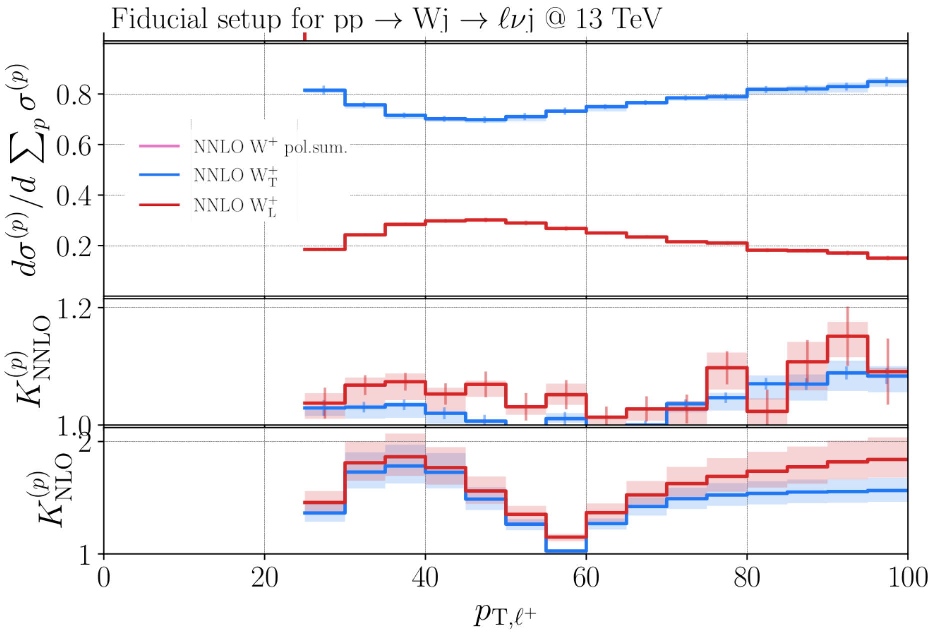


Studies of the Energy Dependence of Diboson Polarization Fractions and the Radiation-Amplitude-Zero Effect in WZ Production with the ATLAS Detector, ATLAS 2402.16365

	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

Motivation for higher-order corrections



Important

Inclusive K-factors are not enough

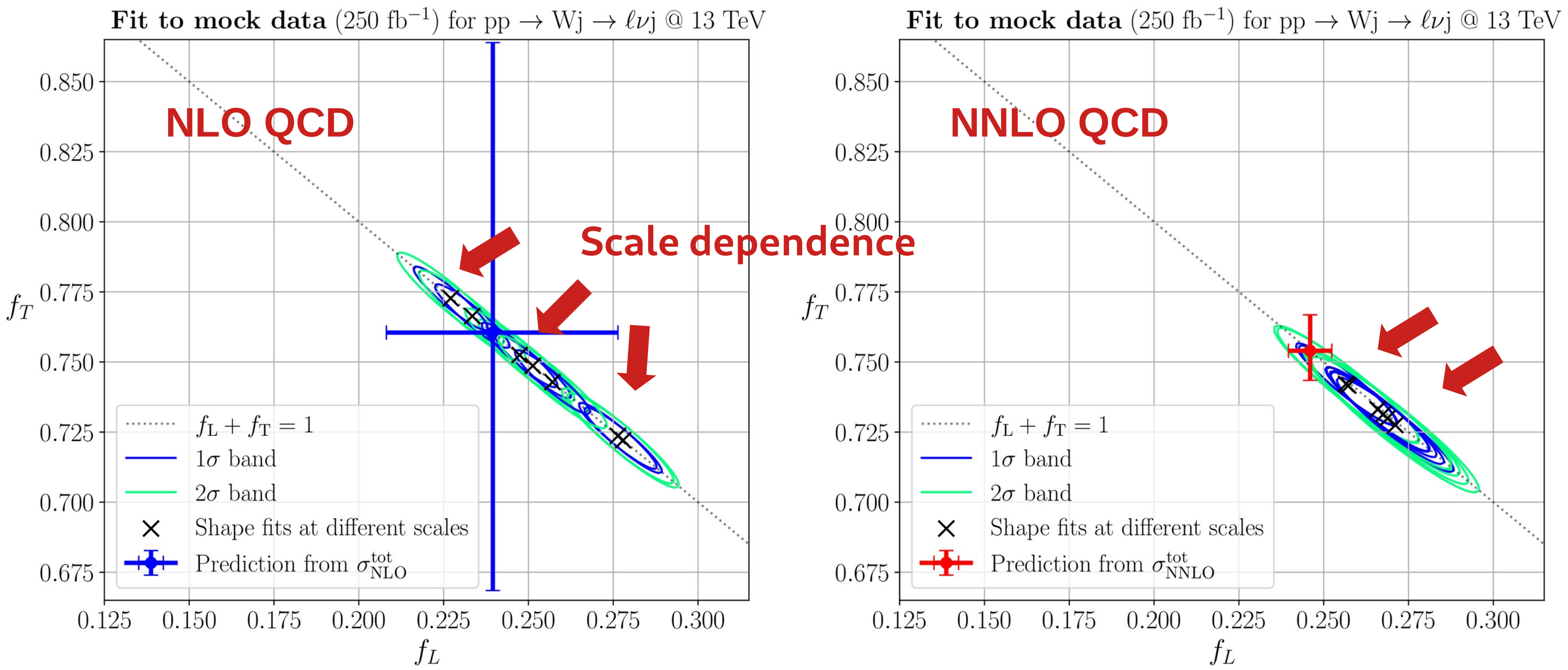
1) Differential polarization fraction have shapes
2) Higher-order corrections dependent on polarization! Just using unpolarized K-factor would lead to distortion of spectrum.
3) NNLO QCD needed to reach percent-level scale-dependence → MHOU

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

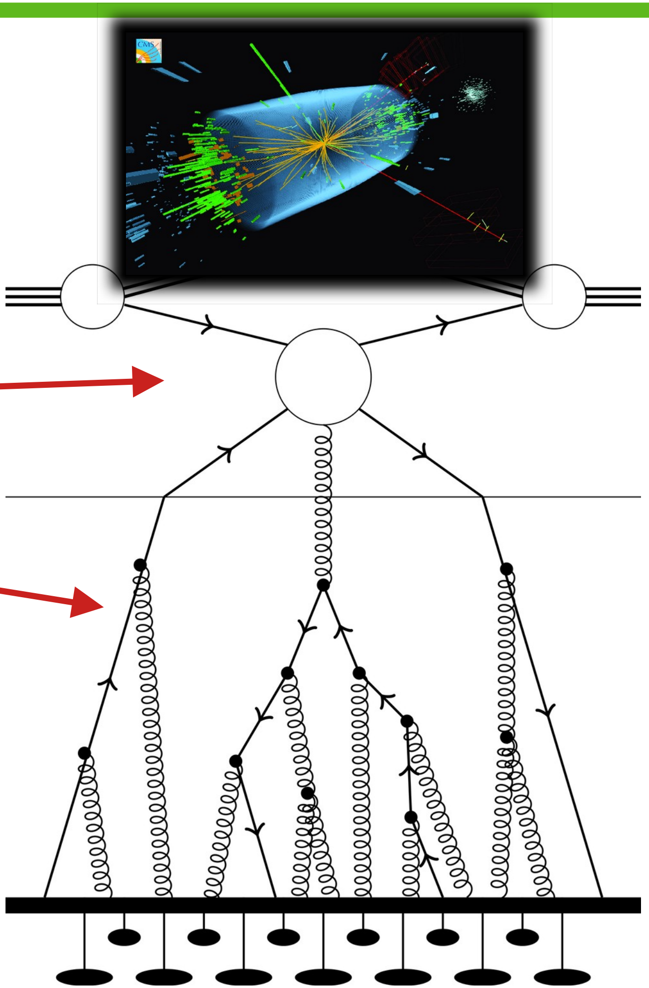
W+jet: mock-data fit

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

COMETA polarisation study

COMETA

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

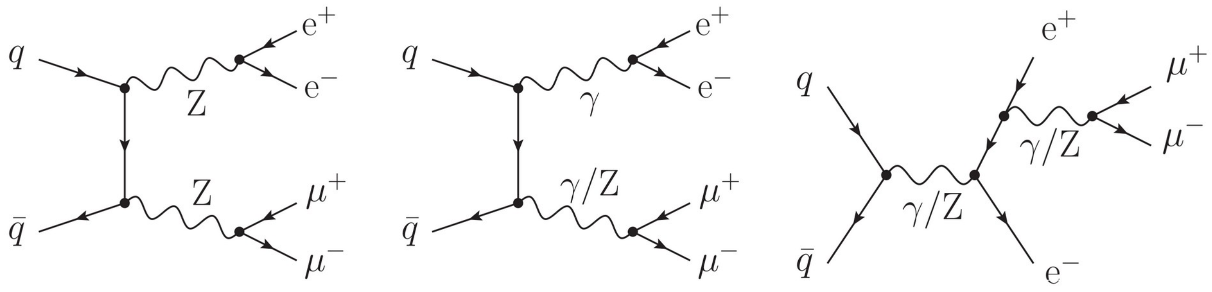
Costanza Carrivale,[a] Roberto Covarelli,[b] Ansgar Denner,[c] Dongshuo Du,[d] Christoph Haitz,[c] Mareen Hoppe,[e] Martina Javurkova,[f] Duc Ninh Le,[g] Jakob Linder,[h] Rafael Coelho Lopes de Sa,[f] Olivier Mattelaer,[i] Susmita Mondal,[j] Giacomo Ortona,[k] Giovanni Pelliccioli,[k,1] Rene Poncelet,[l,1]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

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

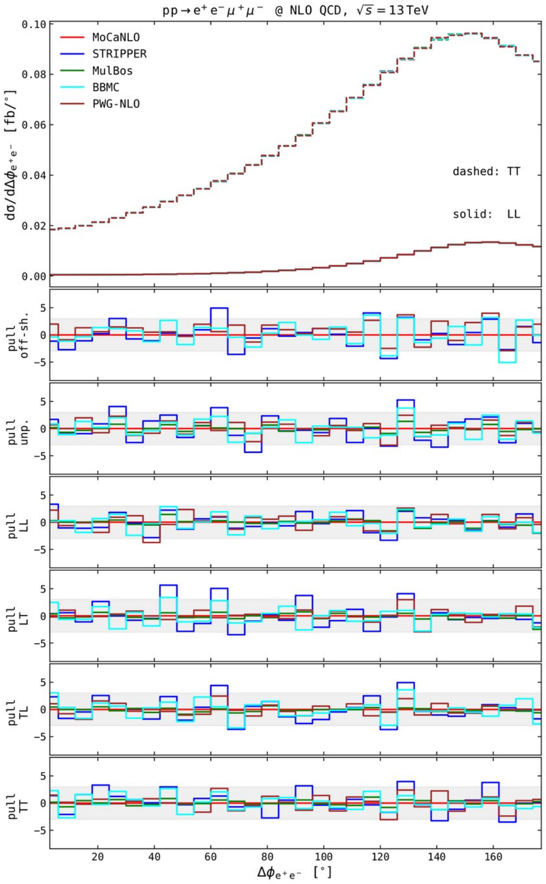


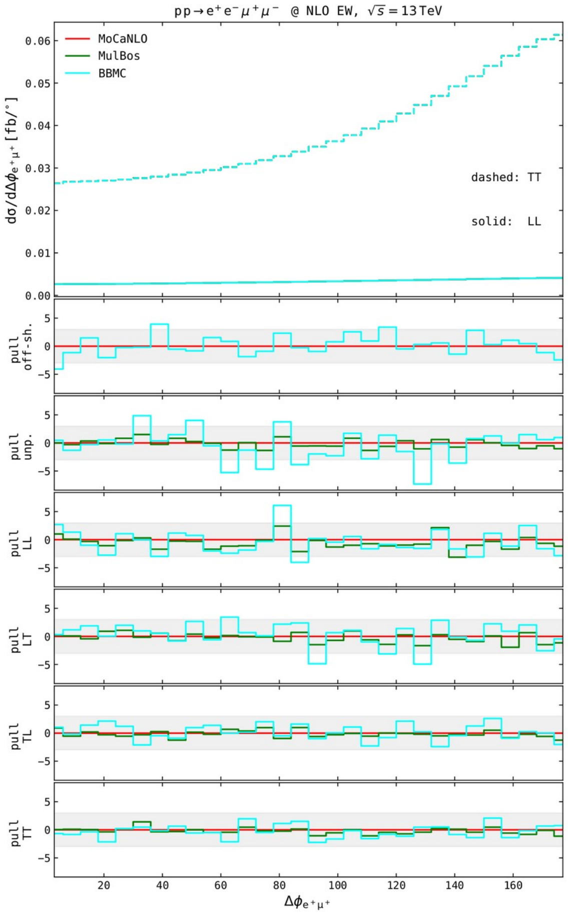
(a) Doubly resonant (b) Photon mediated (c) Nested

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	✓	✗	✓	✗	✗	✓	✓	✗

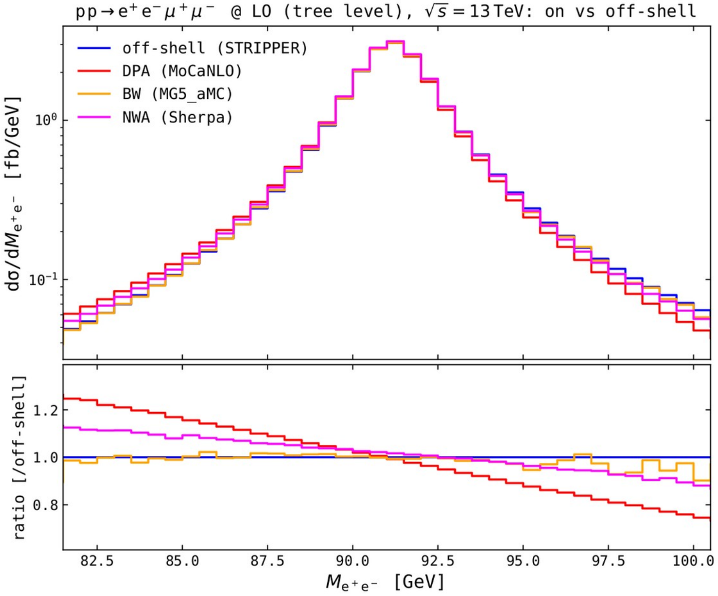
[Many thanks to Giovanni Pellicciolli]

Validation and NLO QCD and NLO EW

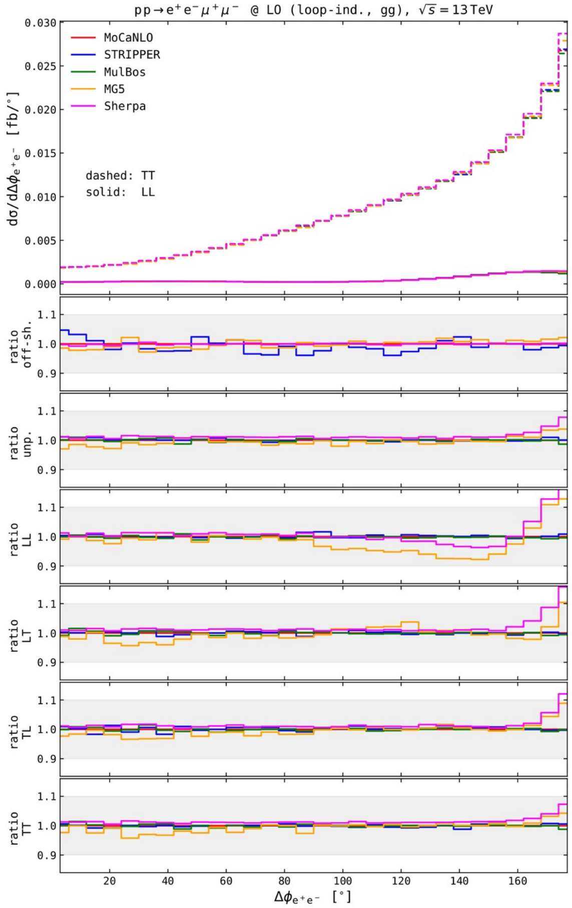




Different resonance treatment



Imprint in various distributions



Offshell

Complete processs

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:

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

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

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

Absolute predictions for polarised cross sections

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

+ ~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:

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

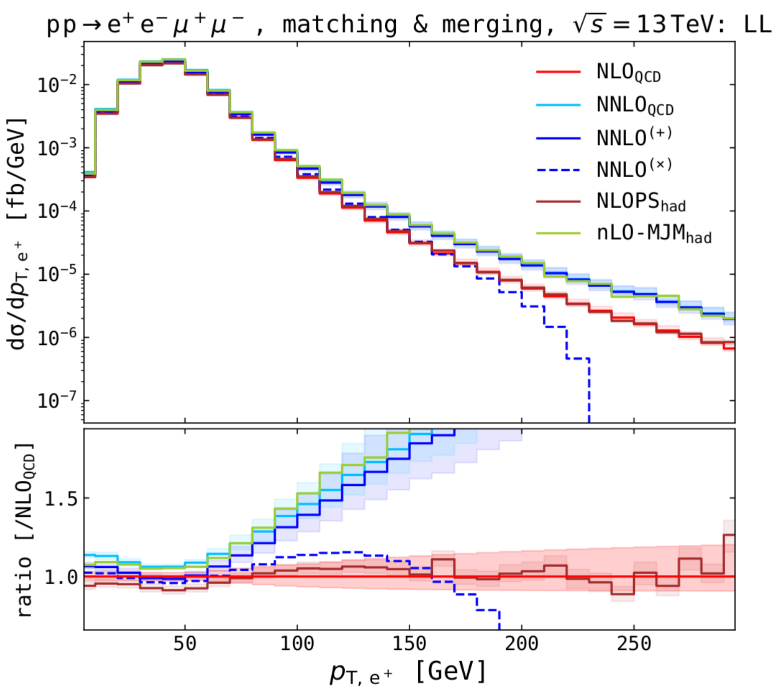
Theory-experiment in agreement

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

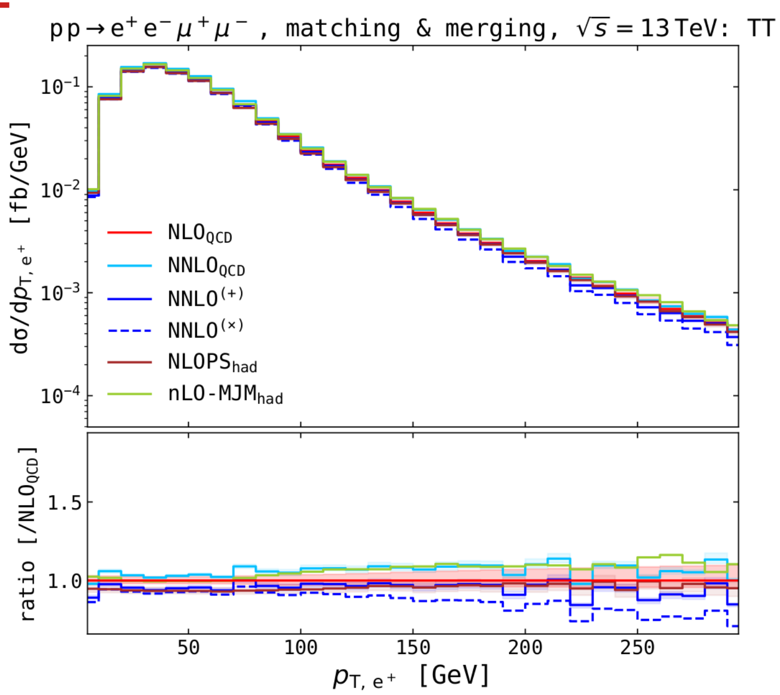
our predictions	LL [%]	LT [%]	TL [%]	TT [%]
$\text{LO}_{q\bar{q}}$	$5.85^{+0.07}_{-0.08}$	$11.86^{+0.09}_{-0.11}$	$11.89^{+0.09}_{-0.11}$	$69.27^{+0.30}_{-0.26}$
LO_{gg}	$5.39^{+0.02}_{-0.02}$	$2.12^{+0.01}_{-0.01}$	$2.10^{+0.01}_{-0.01}$	$90.48^{+0.03}_{-0.03}$
NLO_{EW}	$5.89^{+0.06}_{-0.08}$	$11.97^{+0.09}_{-0.11}$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



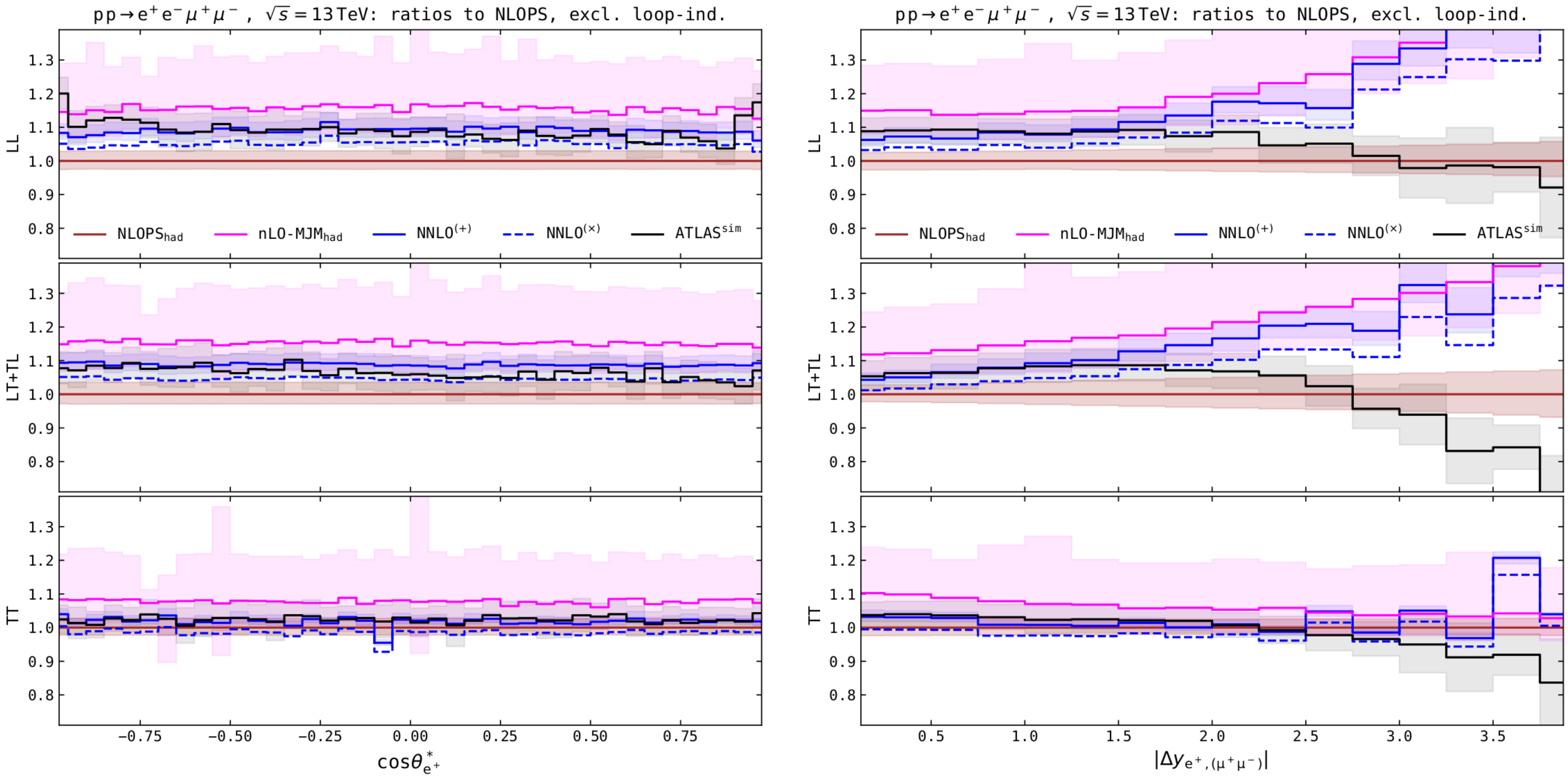
TT



Large higher-order QCD effects for LL polarization

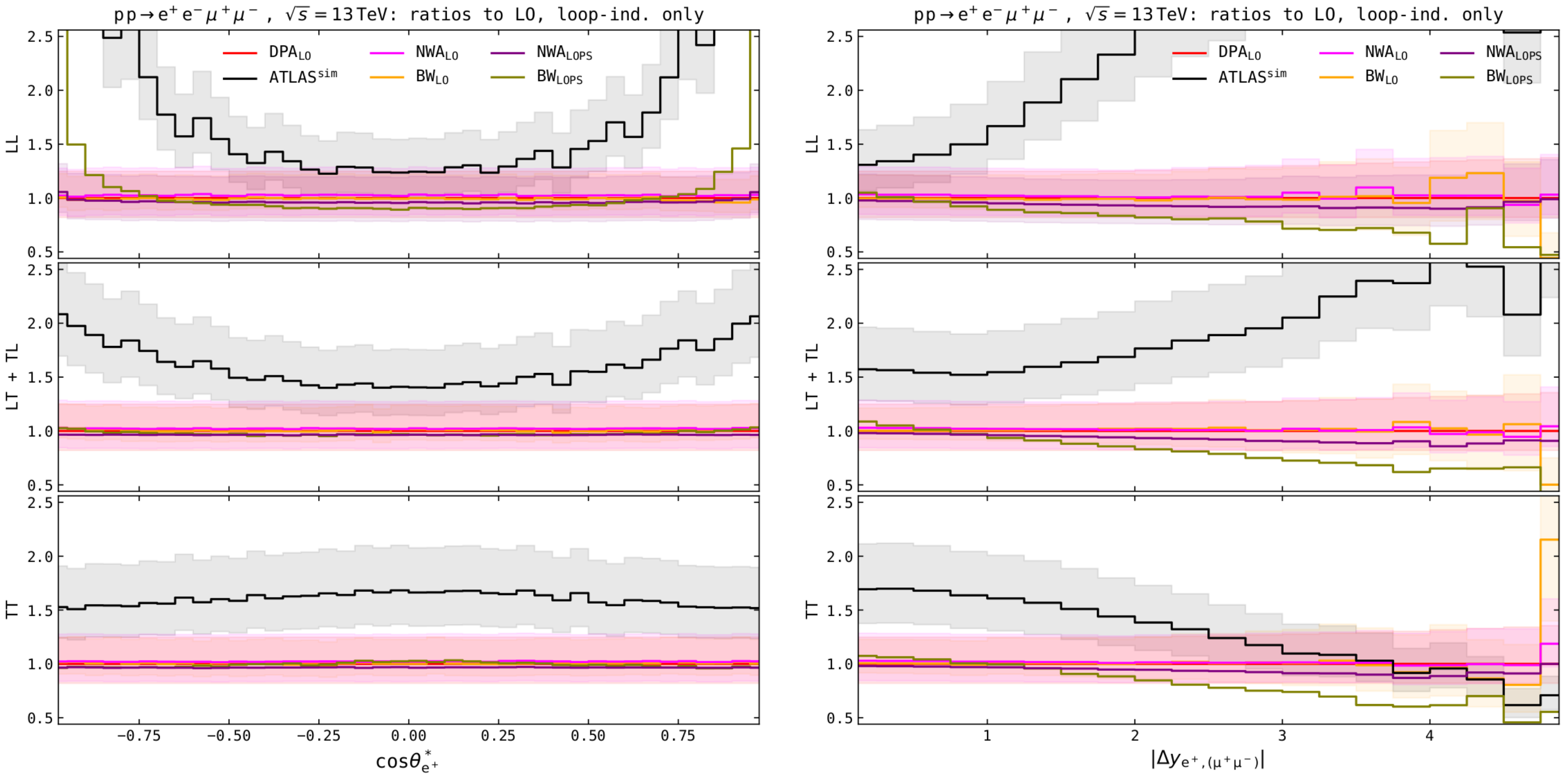
SHERPA nLO-MJM shapes resample NNLO QCD results → impact from hard recoil

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]

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
- COMETA ZZ polarization study:
  - 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

Thank you!

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 $q\bar{q} \to$ 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, Pellicciolі 1710.09339
  Polarized vector boson scattering in the fully leptonic WZ and ZZ channels at the LHC,
  Ballestrero, Maina, Pellicciolі 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, Pellicciolі 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

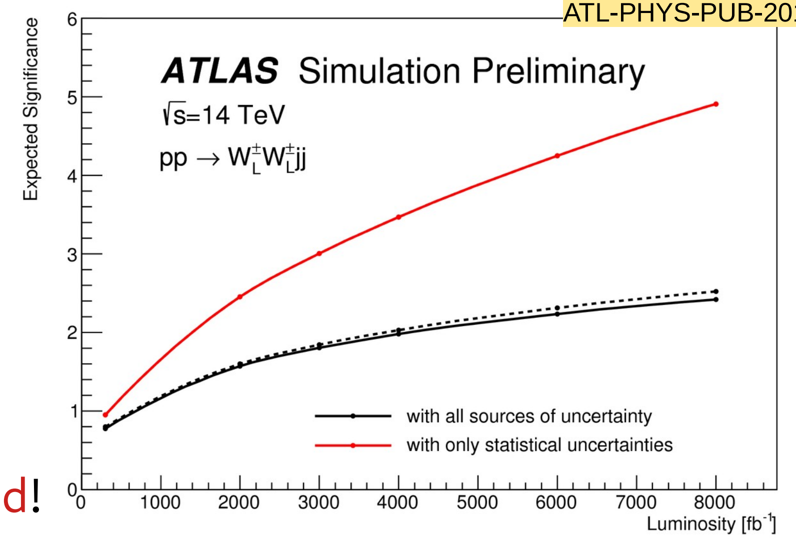
THIS NEEDS AN UPDATE!

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

ATL-PHYS-PUB-2018-052



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

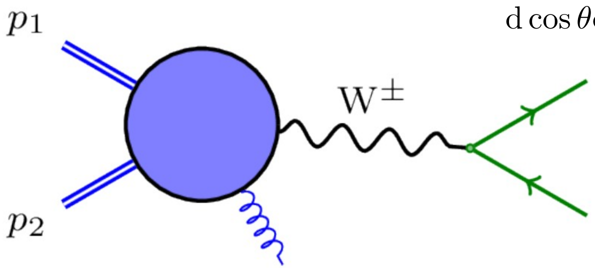
- New bookkeeping of boson polarizations in SHERPA for LO MEs
- Approximate NLO corrections: nLO+PS
  → Reals+matching are treated exact
  → loop matrix elements unpolarised
- Comparison with multi-jet merged calculations

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:



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

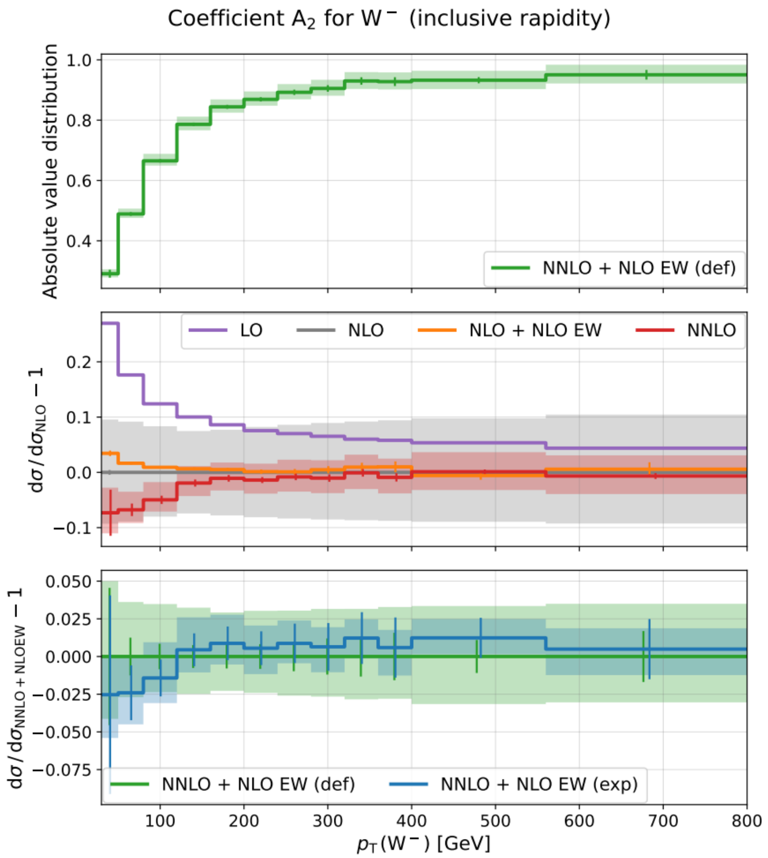
After azimuthal integration: $$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\cos\theta} = \frac{3}{4}\sin\theta f_0 + \frac{3}{8}(1-\cos\theta)^2 f_L + \frac{3}{8}(1+\cos\theta)^2 f_R$$

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:

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

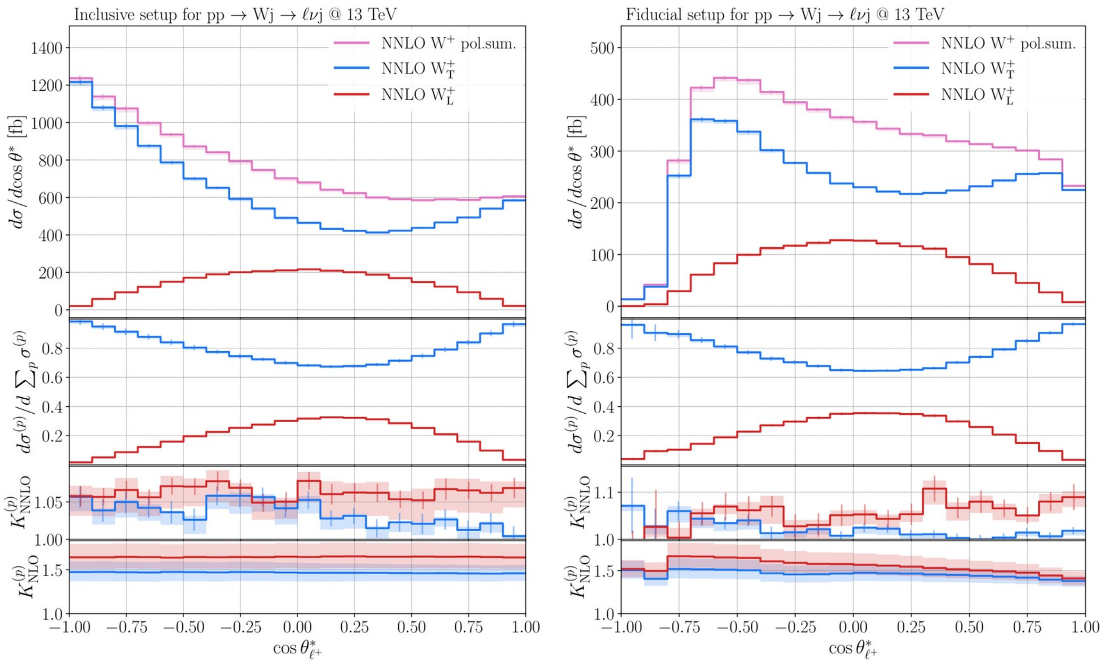


Angular coefficients in W+j production at the LHC with high precision
Pellen, Poncelet, Popescu, Vitos, 2204.12394

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:

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

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:

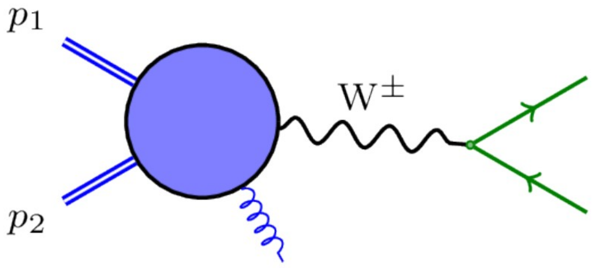
$$\phi = U^{-1}(\pi^i)\phi, \qquad W_\mu = U^{-1}W_\mu U - \frac{i}{g_W}U^{-1}\partial_\mu U$$

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

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

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

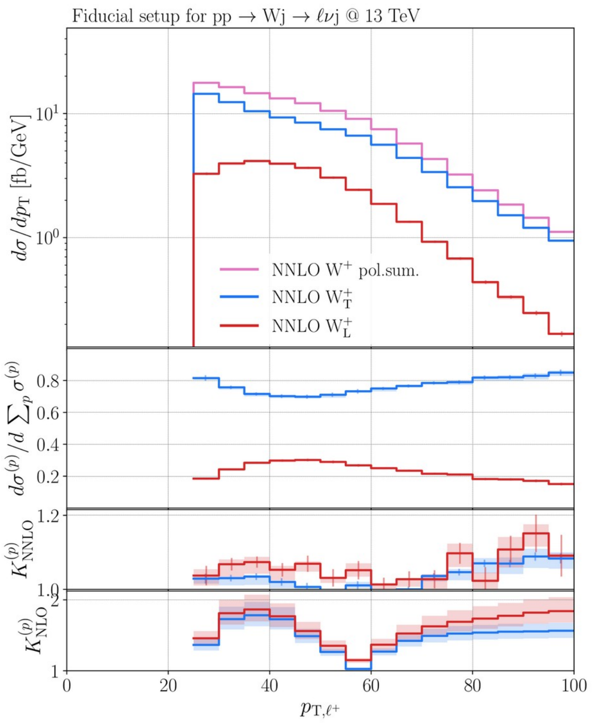
- Lepton cuts: $p_T(\ell) \geq 25\ \mathrm{GeV}$, $|\eta(\ell)| \leq 2.5$ and $\Delta R(\ell, j) > 0.4$
- Transverse mass of the W: $M_T(W) = \sqrt{m_W^2 + p_T^2(W)} \geq 50\ \mathrm{GeV}$

Technical aspects:

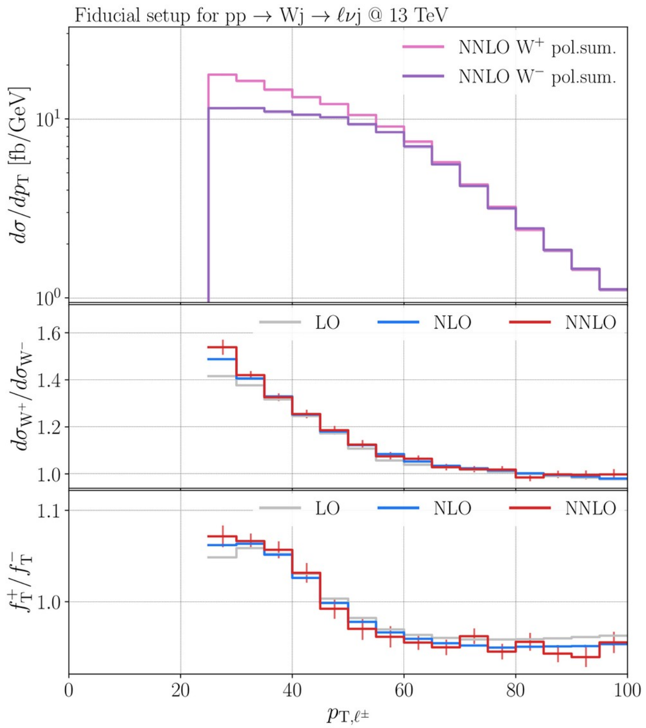
- NNPDF31 and dynamical scale choice: $\mu_R = \mu_F = \frac{1}{2}\left(m_T(W) + \sum p_T(j)\right)$
- Implementation in STRIPPER framework (NNLO QCD subtractions) [1408.2500]
  - Narrow-Width-Approximation and OSP/Pole-Approximation
  - Matrix elements from: AvH[1503.08612], OpenLoops2 [1907.13071](cross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

Example: lepton transverse momentum

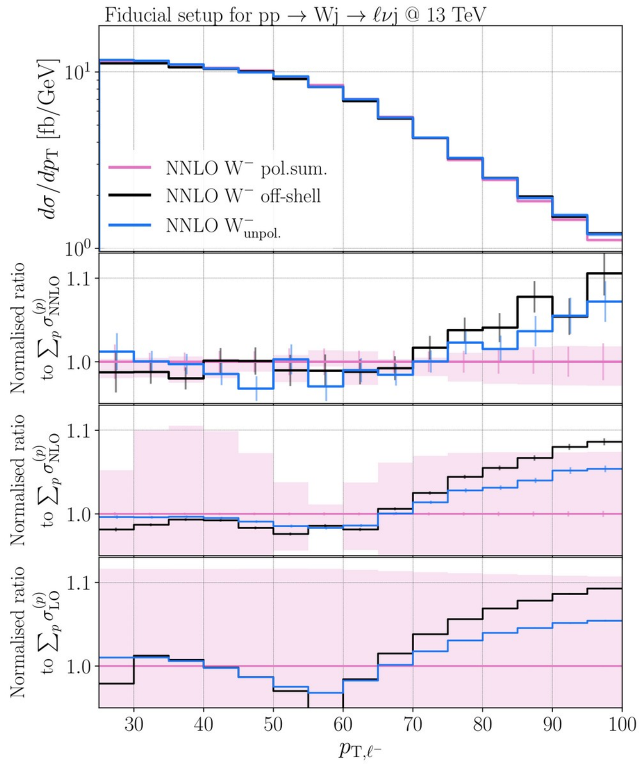
Perturbative corrections



Charge differences



Off-shell/Interference effects



Extraction of polarisation fractions

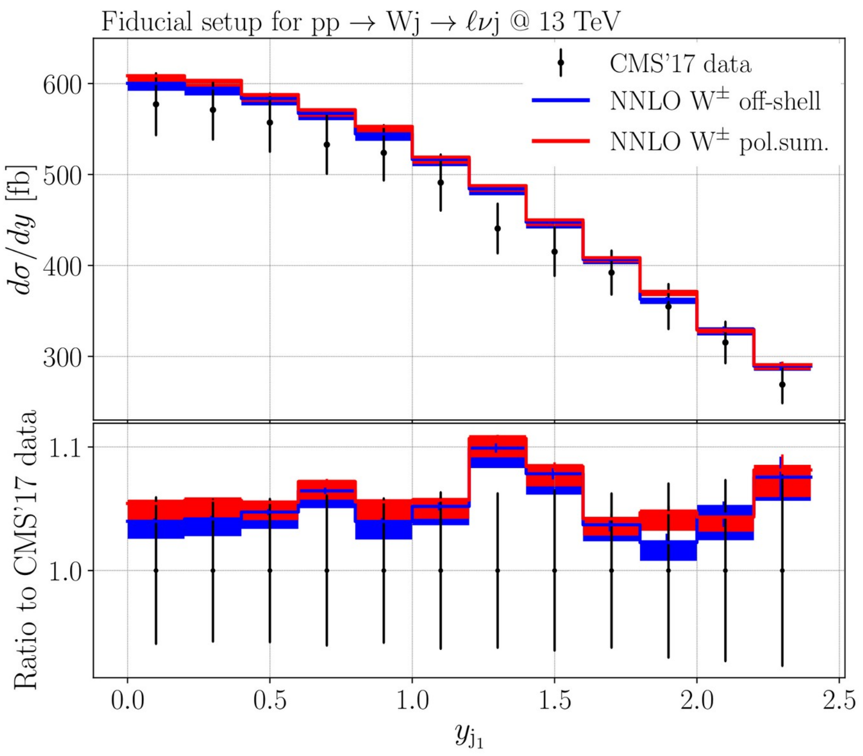
Identified 4 observables (ranges) with

→ Small interference effects (<2%)

→ Small off-shell effects (<2%)

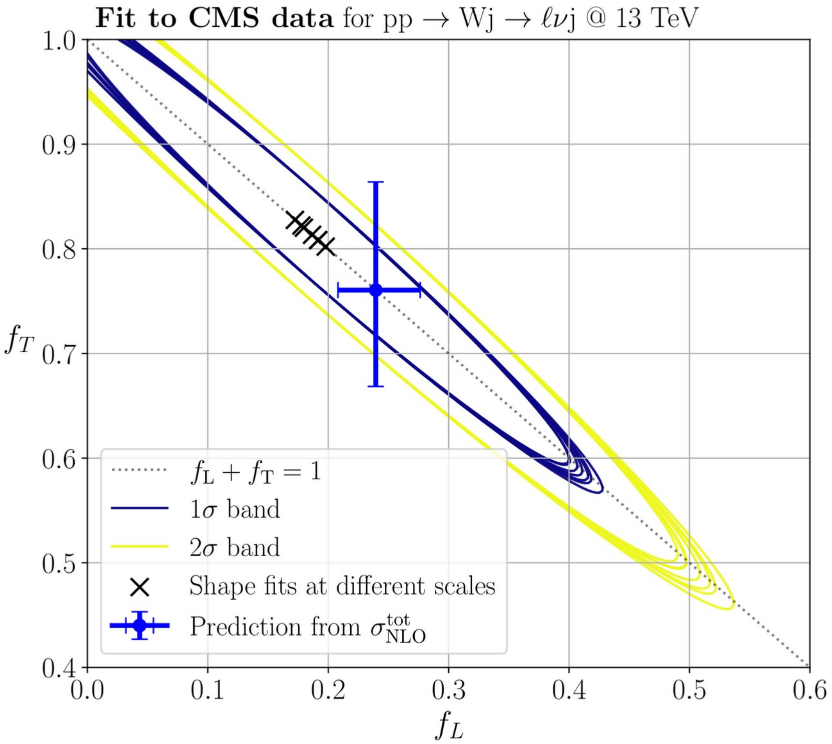
→ Shape differences between L and T

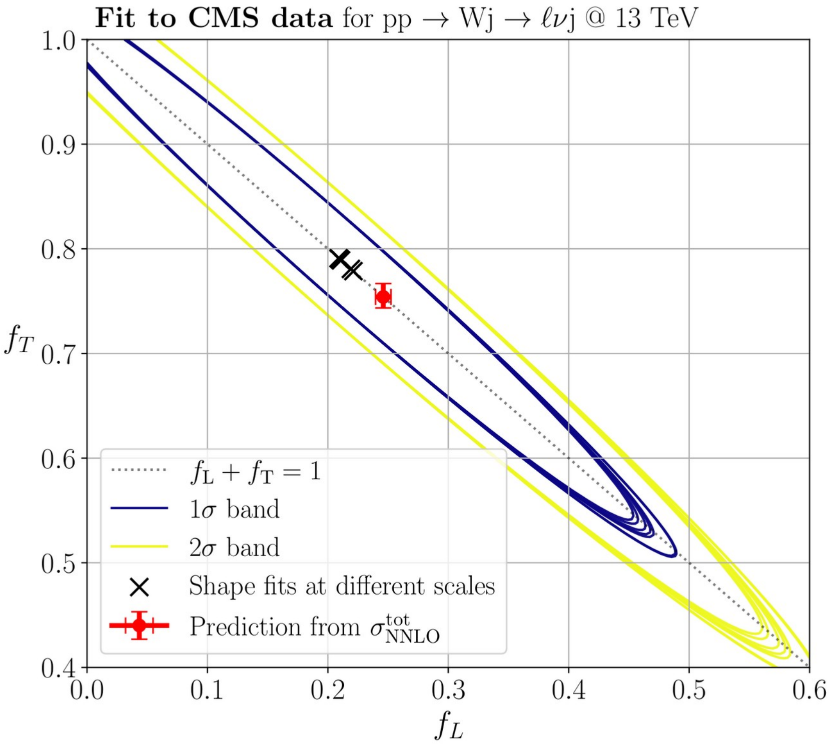
- $\Delta\phi(\ell, j_1) \geq 0.3$
- $25 \text{ GeV} \leq p_T(\ell) < 70 \text{ GeV}$
- $\cos(\theta^*_\ell) \geq -0.75$
- $|y(j_1)| \leq 2$



W+jet : fit to CMS data

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

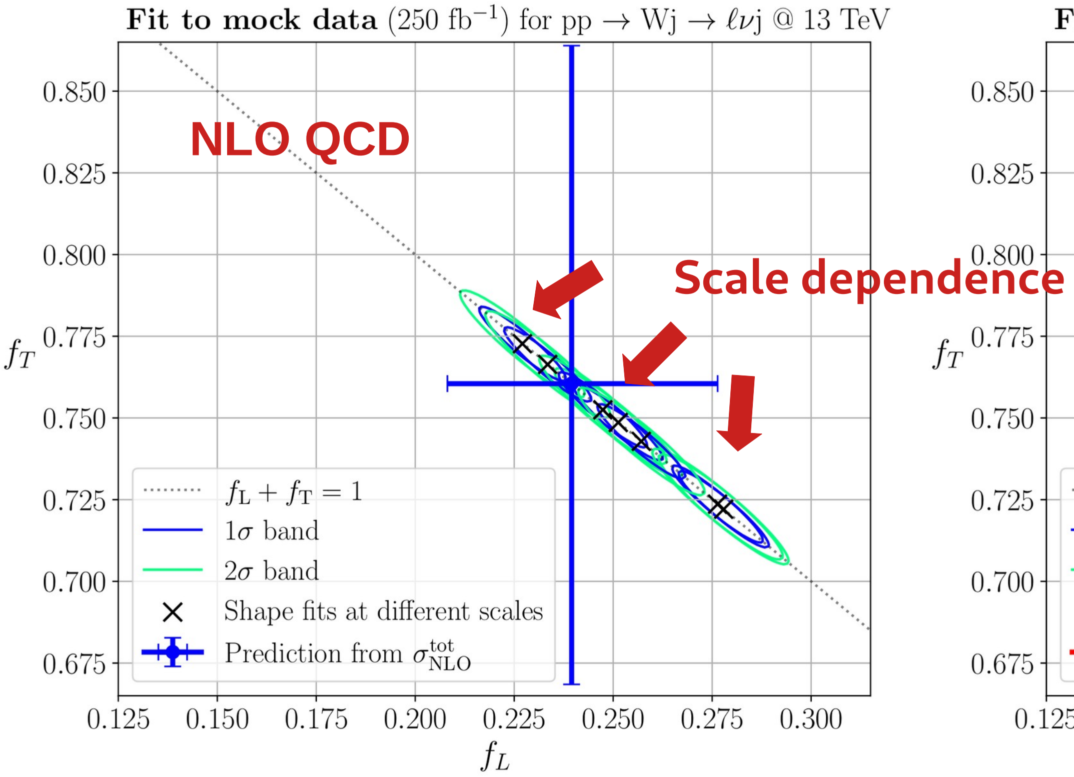


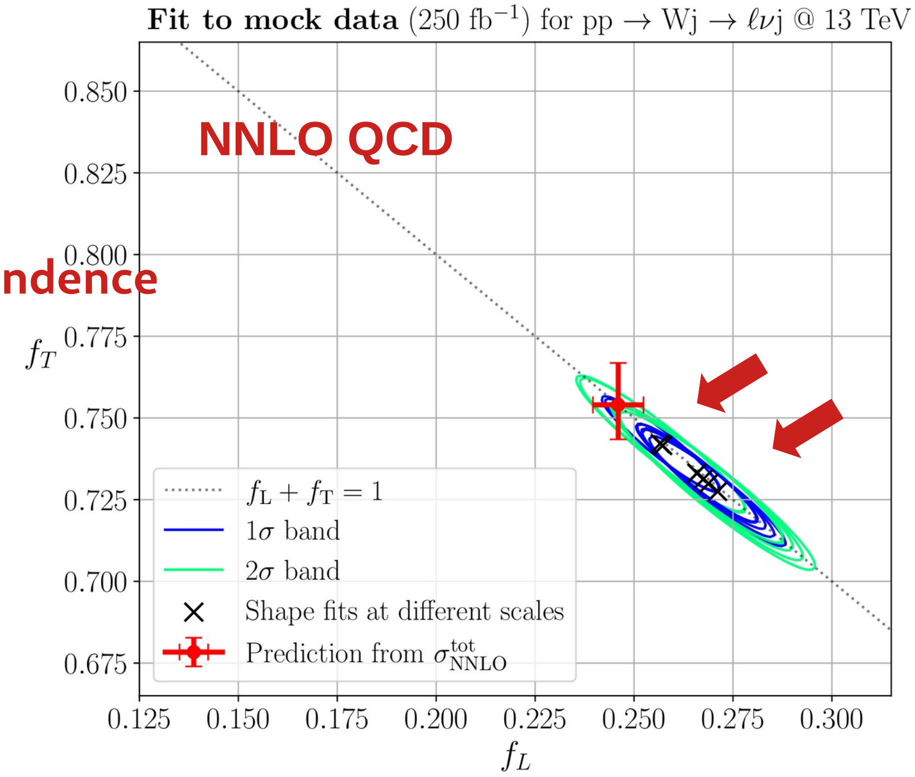


W+jet: mock-data fit

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: $p_T(\ell) \geq 27$ 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 $|y(j)| < 4.5$

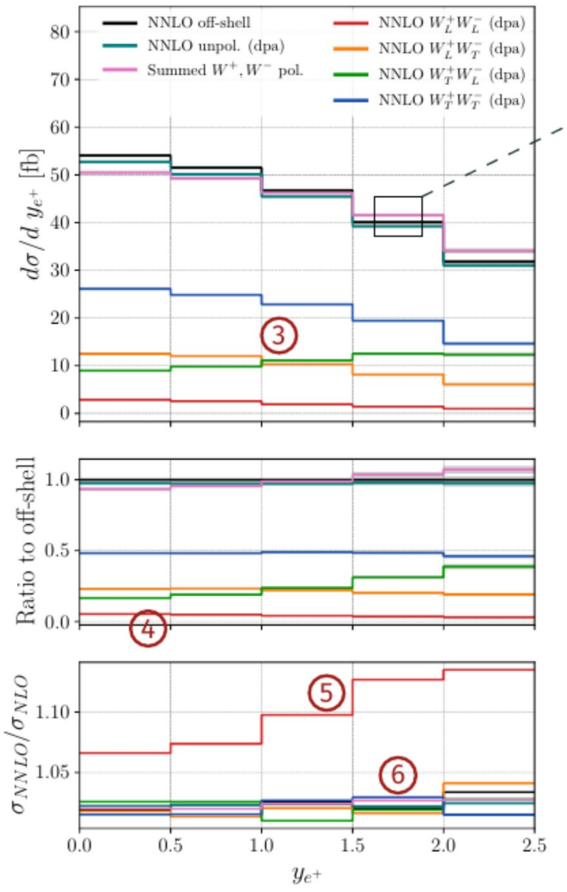
Doubly polarised cross sections

	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

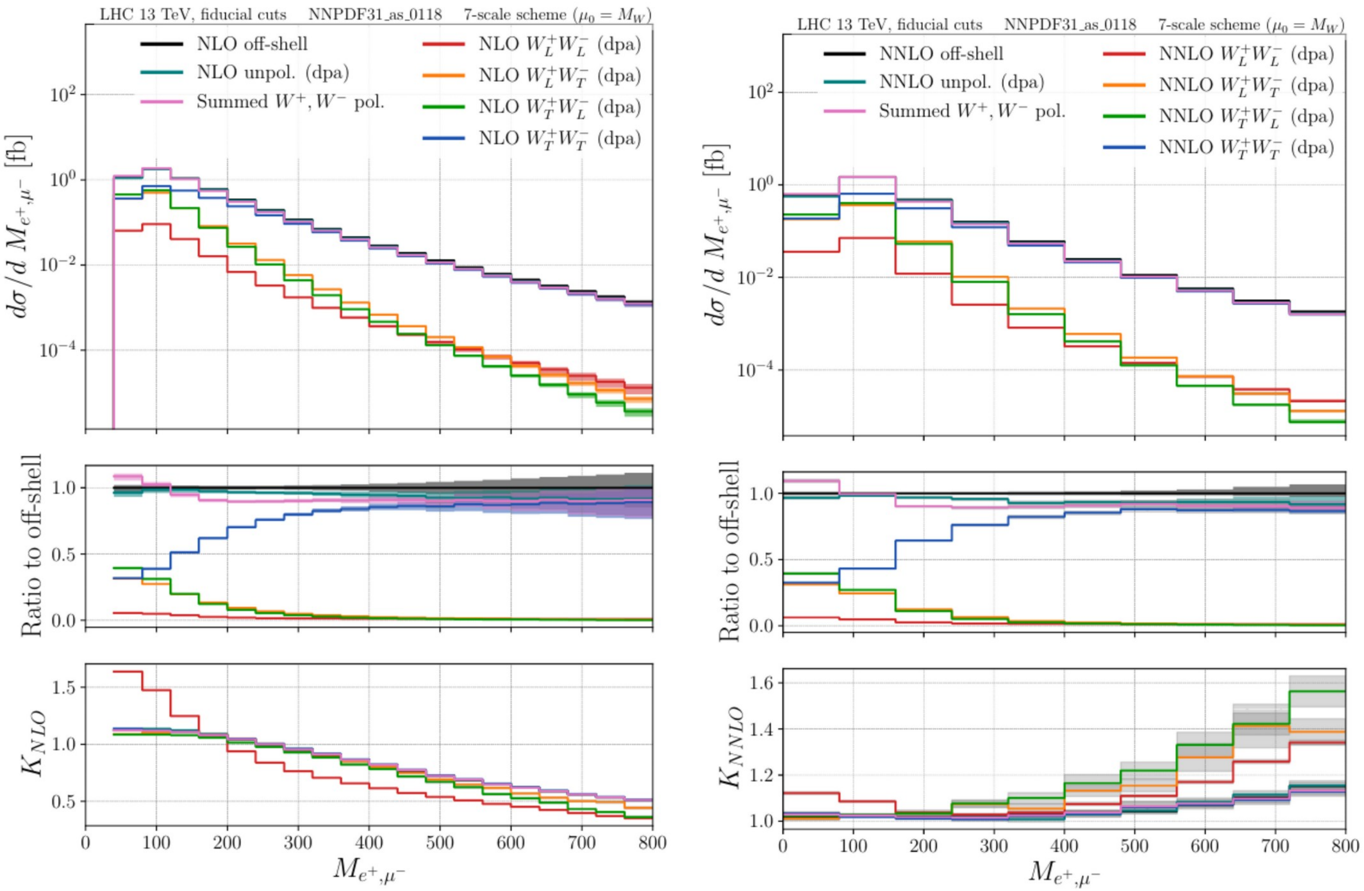
Summary:

→ NNLO effects are **2-3%** of σ_{tot} for all setups except $W_L^+ W_L^-$ where it is **9%**.

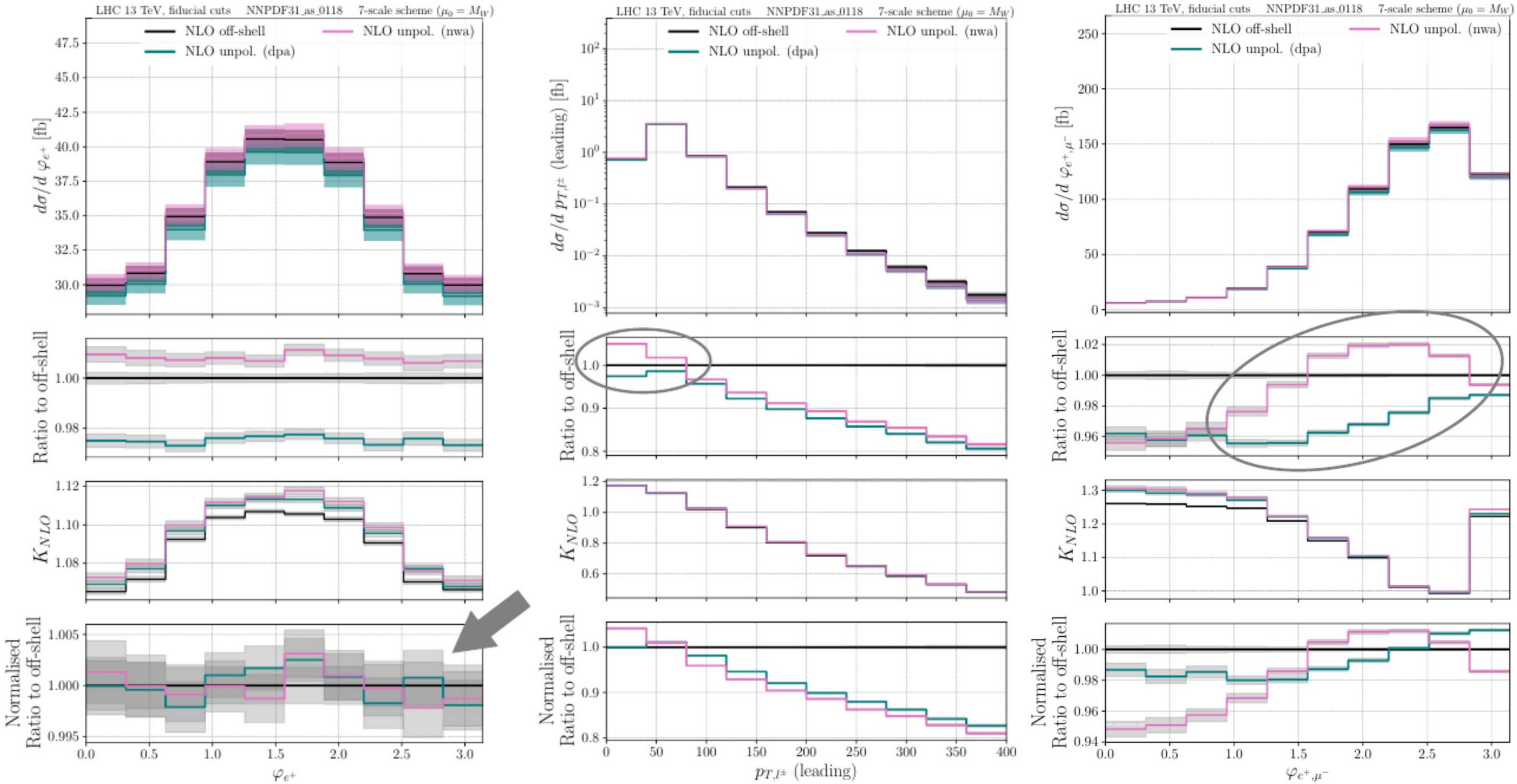
→ Scale uncertainty is reduced by a **factor of 3** w.r.t NLO.

Polarised di-boson production

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



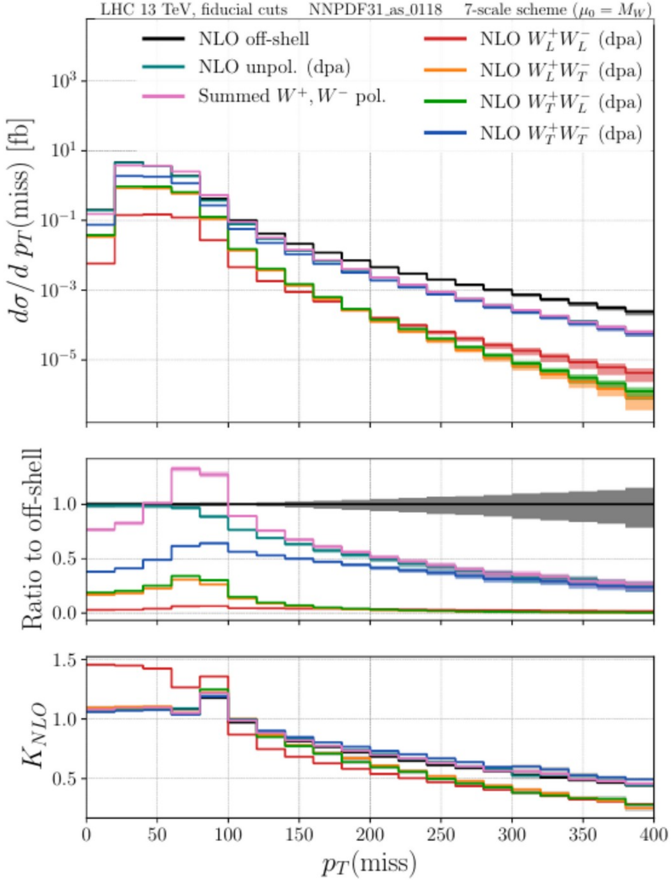
NWA vs. DPA

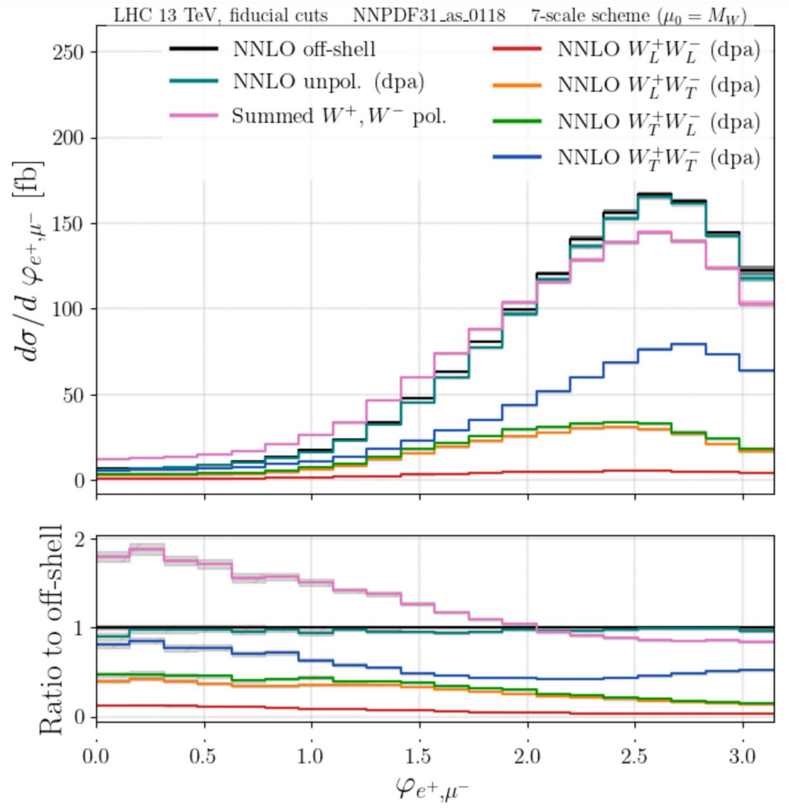


LHC 13 TeV, fiducial cuts
NNPDF31_as_0118
7-scale scheme ($\mu_0 = M_W$)
NLO off-shell
NLO unpol. (nwa)
NLO unpol. (dpa)
$d\sigma/d\,\varphi_{e^+}$ [fb]
$d\sigma/d\,p_{T,l^\pm}$ (leading) [fb]
$d\sigma/d\,\varphi_{e^+,\mu^-}$ [fb]
Ratio to off-shell
K_{NLO}
Normalised Ratio to off-shell
φ_{e^+}
$p_{T,l^\pm}$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

Interference and off-shell effects

Large off-shell effect from single-resonant contributions





Large interference effects through phase space constraints

P3EWSB

[High **P**recision **P**redictions to **P**robe the **E**lectro**W**eak-**S**ymmetry **B**reaking]

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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

[2304.05993]

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