Precise polarisation predictions

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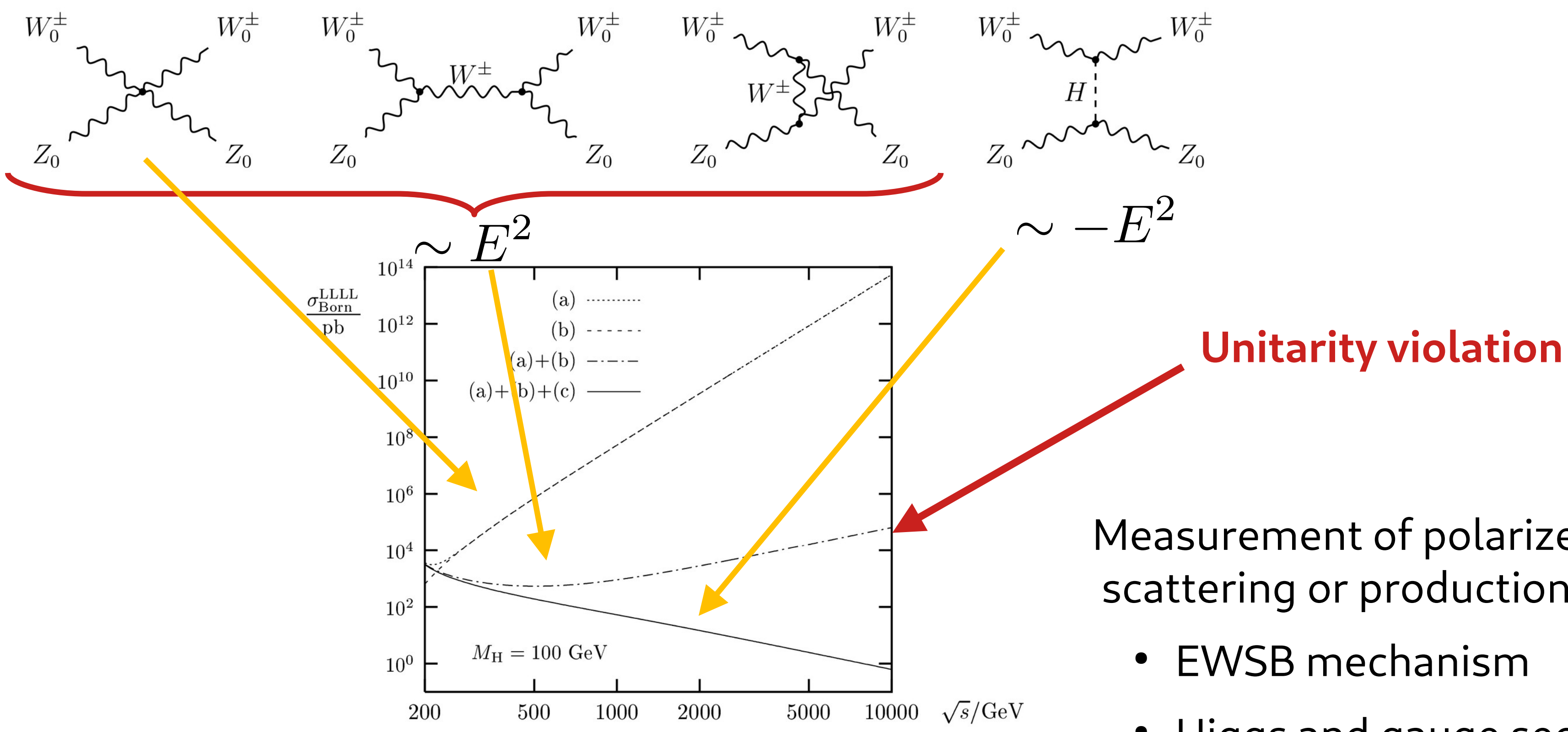
Longitudinal Vector-Boson-Scattering (VBS)



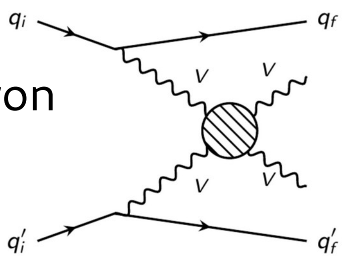
Measurement of polarized boson scattering or production probes:

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

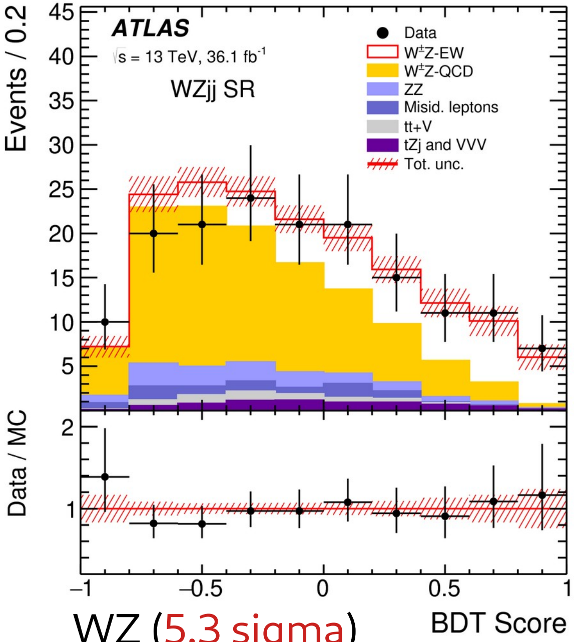
Radiative corrections to W+ W- → W+ W- in the electroweak standard model
A. Denner, T. Hahn hep-ph/9711302

VBS at hadron colliders

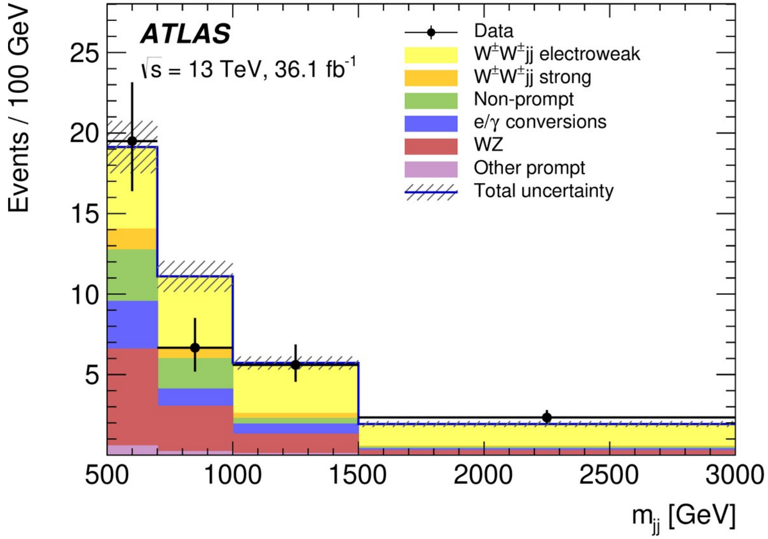
VBS at hadron colliders



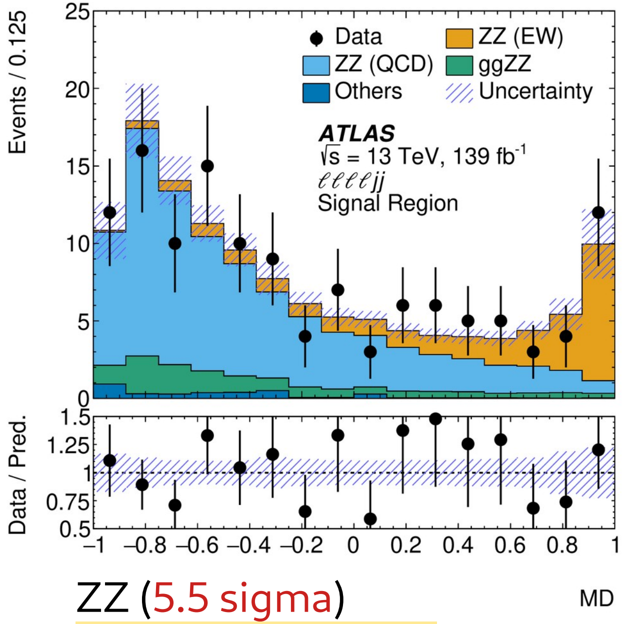
Separate from background processes through VBS topology → a rare process, but observed.



WZ (5.3 sigma)
ATLAS 1812.09740



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



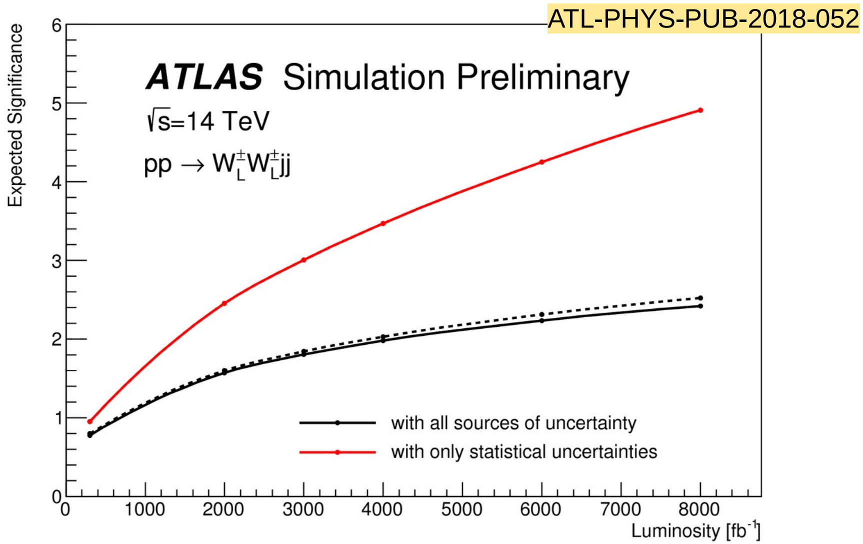
ZZ (5.5 sigma)
ATLAS 2004.10612

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!

ATLAS HL-LHC projection

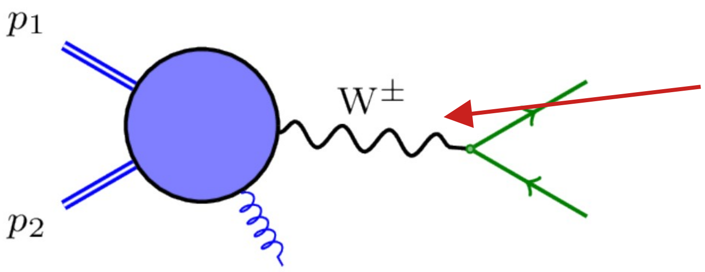


How to improve on the (theory) systematics?

→ Improved signal and background modelling

→ Effective separation of boson polarisations

Polarised boson production



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

λ = +/-/L

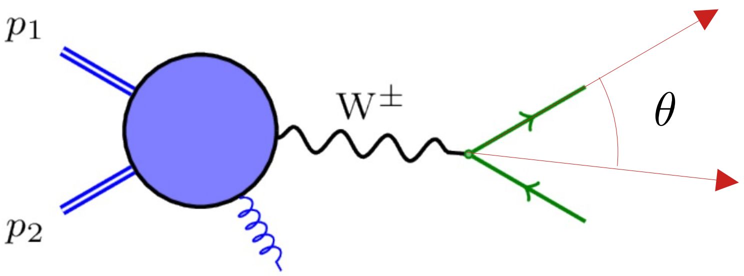
Can we extract the longitudinal component?

Measurements of longitudinal polarisation fractions:

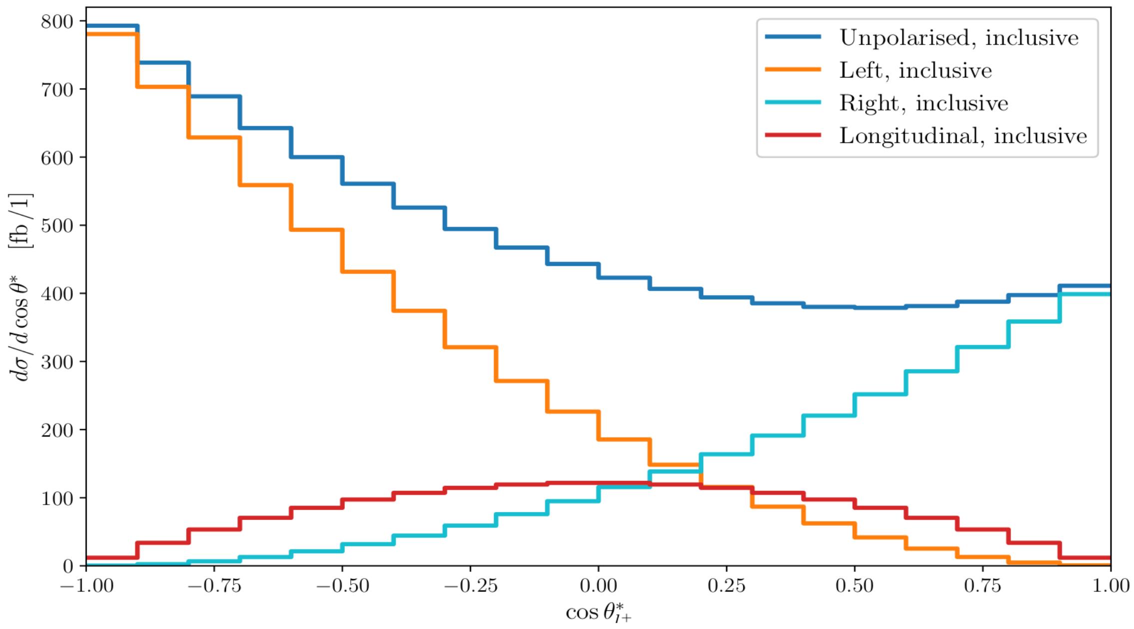
Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC,
CMS 1104.3829
Measurement of the polarisation of W bosons produced with large transverse momentum in pp collisions at \sqrt{s}=7 TeV with the ATLAS experiment,
ATLAS 1203.2165
Measurement of WZ production cross sections and gauge boson polarisation in pp collisions at sqrt(s) = 13 TeV with the ATLAS detector,
ATLAS 1902.05759
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

How to measure polarized bosons?

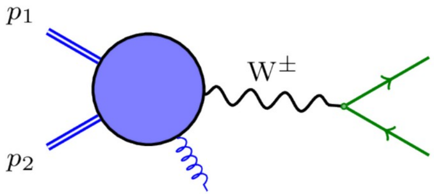
- We can't measure boson polarization directly.
- Luckily decay products can be used as a "polarimeter":



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)

$$|M|^2 = \underbrace{\sum_\lambda |M_\lambda|^2}_{} + \underbrace{\sum_{\lambda \neq \lambda'} M_\lambda^* M_{\lambda'}}_{}$$

→ polarised x-sections Interferences

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

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

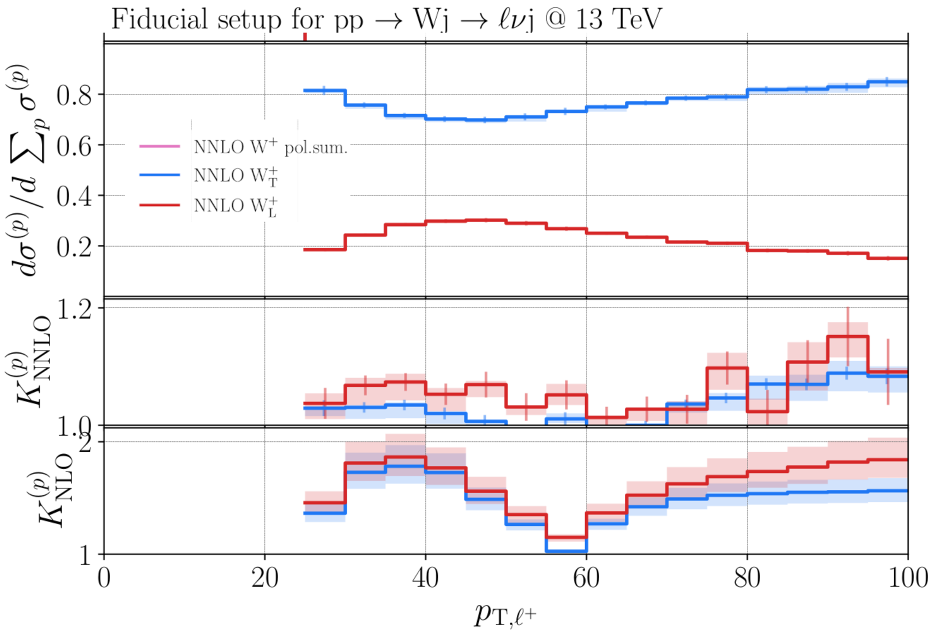
Polarized cross sections

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

- 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

Higher-order QCD/EW corrections + PS
to minimize uncertainties from MHO (scale uncertainties)

Why do we need higher-order corrections?



Important

Just using some K-factors is not enough

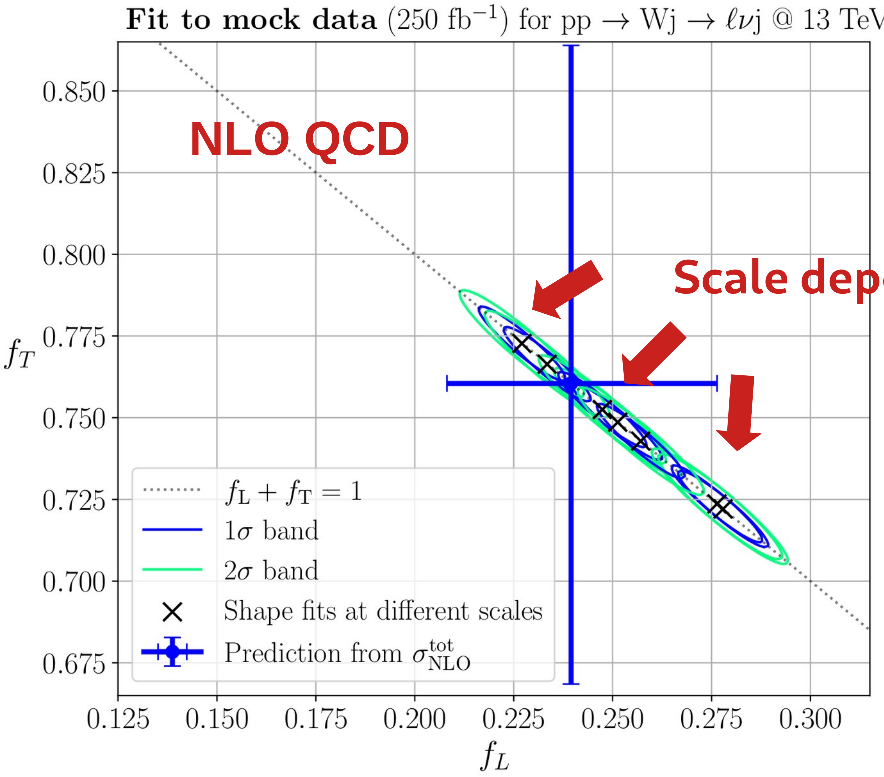
1) Differential polarization fraction have shapes (not just one number!)
2) Higher-order corrections dependent on polarization! Just using polarized K-factor would lead to distortion of spectrum.
3) NNLO QCD needed to reach percent-level scale-dependence → MHO

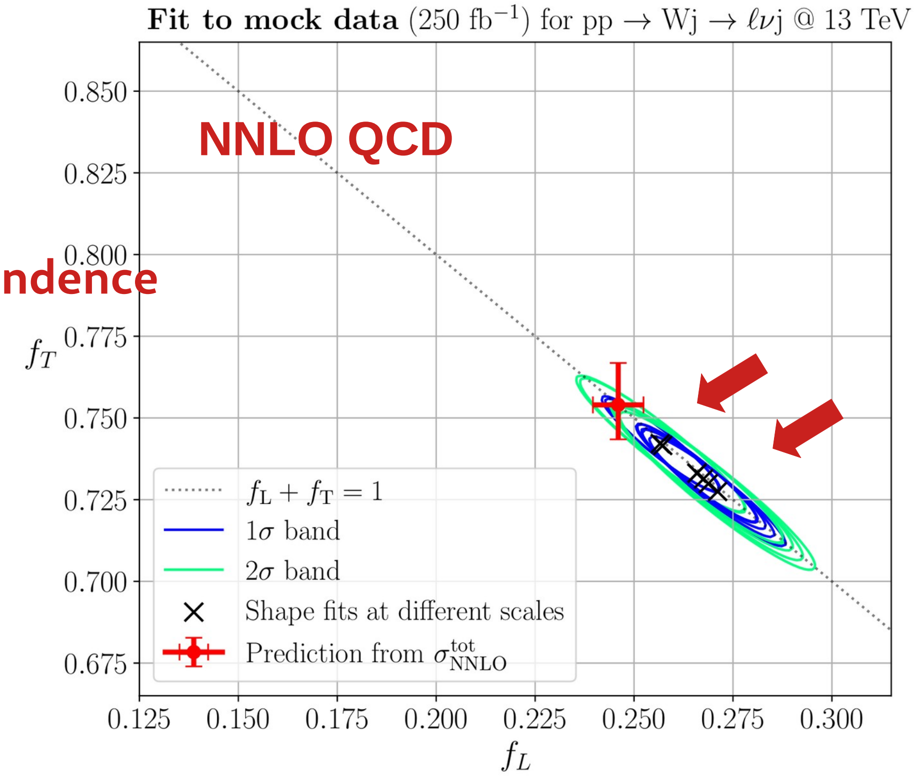
Polarised W+j production at the LHC: a study at NNLO QCD accuracy, Pellen, Poncelet, Popescu 2109.14336

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: $\cos(\ell, j_1)$





Status of polarization precision calculations

(Collection of papers in the backup)

Process	LO	NLO	NLO EW	NNLO	+ PS
pp → WW	X	X	X	X	X
pp → ZZ	X	X	X		X
pp → WZ	X	X	X		X
pp → W/Z	X	X	X	(X)	X
pp → W+j	X	X	(X)	X	
pp → Z+j	X	(X)			
pp → VH	(X)				
pol. VBS	X	X			

Talks by Christopher, Christoph and Mareen on Thursday

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	$\sigma^{\text{nLO+PS}}_{\text{SHERPA}}$ [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)

Polarised NLO+PS: POWHEG

Polarised-boson pairs at the LHC with NLOPS accuracy
Pellicciol, Zanderighi 2311.05220

- NLO QCD + PS in POWHEG-BOX-RES framework
- Study of PS (Pythia8) + hadronisation effects on fractions and differential distributions WW/WZ/ZZ

→ 1-5% effect on distributions, but generally small impact on fractions (~1% effects)

state	σ[fb] LHE	ratio [/unp., %] LHE	σ[fb] PS+hadr	ratio [/unp., %] PS+hadr
Inclusive setup				
full off-shell	$98.36(3)^{+4.8\%}_{-3.9\%}$	101.20	$95.27(3)^{+4.9\%}_{-3.9\%}$	101.28
unpolarised	$97.20(3)^{+4.8\%}_{-3.9\%}$	100	$94.07(3)^{+4.9\%}_{-3.9\%}$	100
LL	$4.499(2)^{+2.8\%}_{-2.3\%}$	$4.63^{+0.13}_{-0.13}$	$4.359(2)^{+2.8\%}_{-2.2\%}$	$4.63^{+0.13}_{-0.13}$
LT	$13.151(4)^{+7.0\%}_{-5.7\%}$	$13.53^{+0.28}_{-0.27}$	$12.730(5)^{+7.0\%}_{-5.7\%}$	$13.53^{+0.28}_{-0.28}$
TL	$12.724(4)^{+7.3\%}_{-5.9\%}$	$13.09^{+0.32}_{-0.31}$	$12.314(5)^{+7.4\%}_{-5.9\%}$	$13.09^{+0.31}_{-0.32}$
TT	$66.88(2)^{+4.0\%}_{-3.3\%}$	$68.81^{+0.47}_{-0.51}$	$64.74(2)^{+4.1\%}_{-3.2\%}$	$68.82^{+0.46}_{-0.51}$
interference	-0.058	-0.06	-0.069	-0.06

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 $|y(j)| < 4.5$

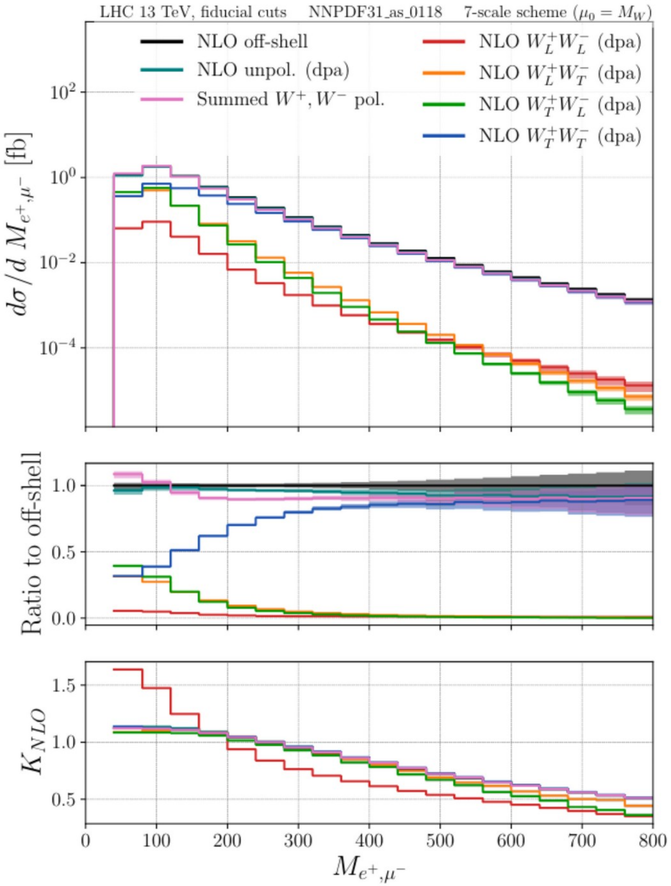
Doubly polarised cross sections

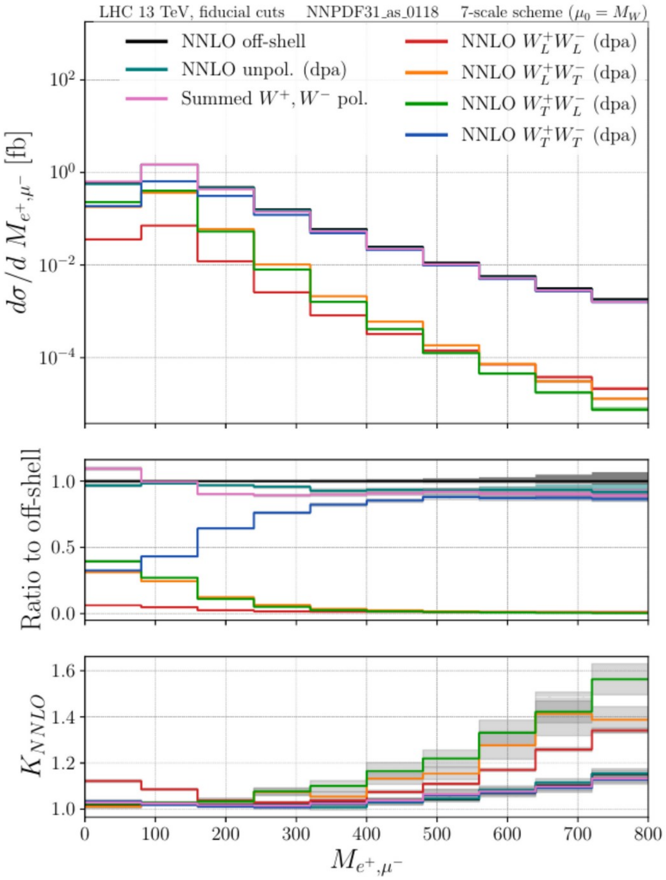
	NLO	NNLO	K_{NNLO}	LI	NNLO+LI
off-shell	$220.06(5)^{+1.8\%}_{-2.3\%}$	$225.4(4)^{+0.6\%}_{-0.6\%}$	1.024	$13.8(2)^{+25.5\%}_{-18.7\%}$	$239.1(4)^{+1.5\%}_{-1.2\%}$
unpol. (nwa)	$221.85(8)^{+1.8\%}_{-2.3\%}$	$227.3(6)^{+0.6\%}_{-0.6\%}$	1.025	$13.68(3)^{+25.5\%}_{-18.7\%}$	$241.0(6)^{+1.5\%}_{-1.1\%}$
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 (→ polarization frame)

Polarised di-boson production

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





Take home messages

- Higher-order corrections are vital to pin down polarization fractions and to minimize theory systematics
- NLO QCD/EW (+PS) are the state-of-the-art for polarized EW boson processes
  → WW is available at NNLO QCD
- Future/mid-term goals:
  - fixed-order: completion of di-boson processes @ NNLO QCD (+ NLO EW)
    → Comparisons between NNLO QCD and NLO+PS calculations
  - event-generators: NNLO QCD/EW-effects, SMEFT

Backup

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, Pellicciolі 2006.14867
NLO QCD predictions for doubly-polarized WZ production at the LHC,
Denner, Pellicciolі 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, Pellicciolі 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, Pellicciolі 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
Pellicciolі, Zanderighi 2311.05220
NLO EW corrections to polarised W+W- production and decay at the LHC
Denner, Haitz, Pellicciolі 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, Pellicciolì 1710.09339
  Polarized vector boson scattering in the fully leptonic WZ and ZZ channels at the LHC,
  Ballestrero, Maina, Pellicciolì 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, Pellicciolì 2007.07133

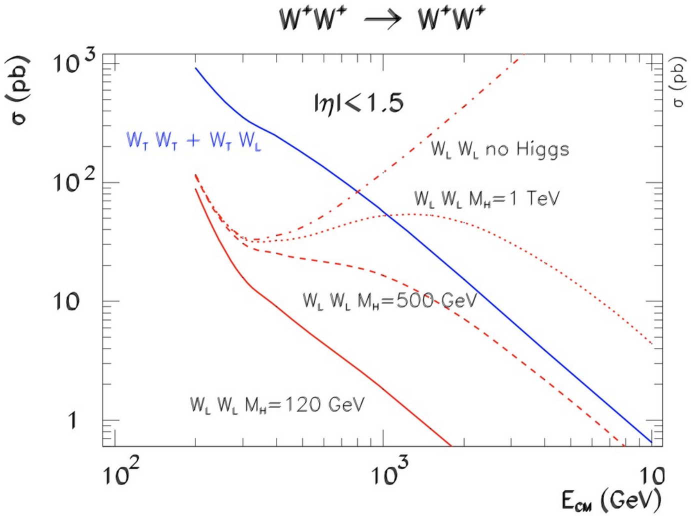
- Single boson production

  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

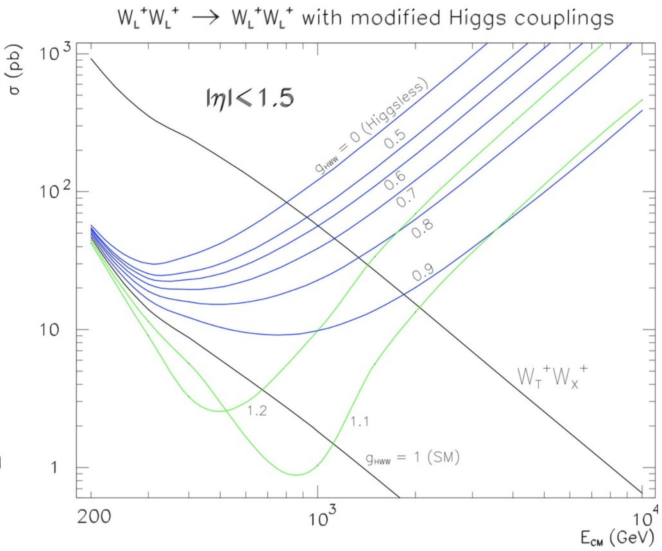
Longitudinal Vector-Boson-Scattering (VBS)

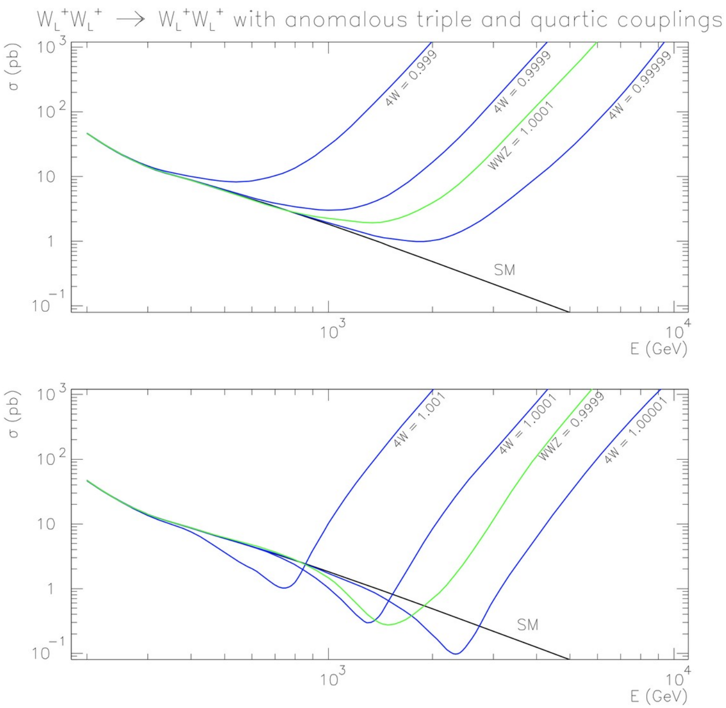
The Higgs boson and the physics of WW scattering before and after Higgs discovery
M. Szleper 1412.8367

Sensitivity to the Higgs mass



Modified HVV, VVV, VVVV couplings





EWSB

The reason is the EWSB in the SM:

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

- 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:

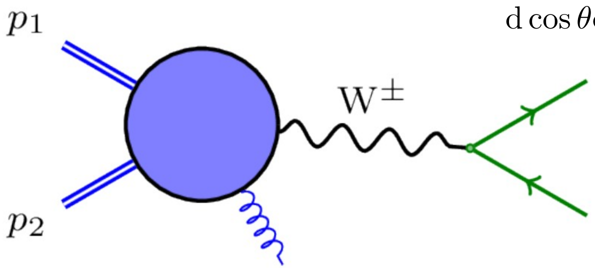
$$\phi = U^{-1}(\pi^i)\phi, \qquad W_\mu = U^{-1}W_\mu U - \frac{i}{g_W}U^{-1}\partial_\mu U$$

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

- Restores renormalizability and unitarity

Angular coefficients

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:

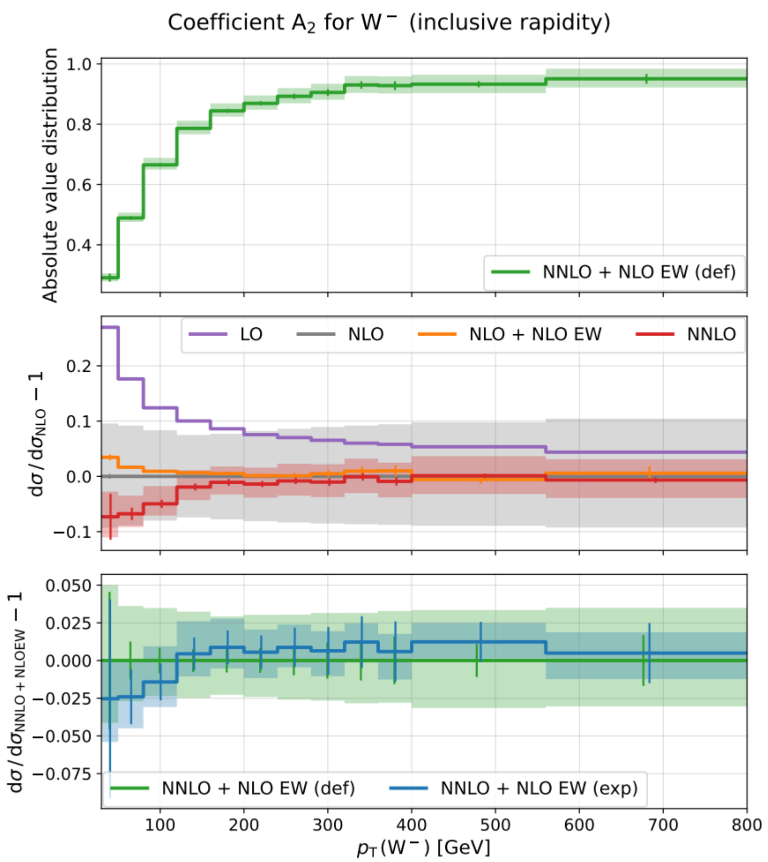
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\cos\theta} = \frac{3}{4}\sin\theta f_0 + \frac{3}{8}(1-\cos\theta)^2 f_L + \frac{3}{8}(1+\cos\theta)^2 f_R$$

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:

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



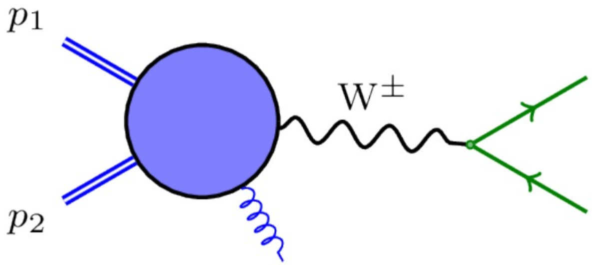
Angular coefficients in W+j production at the LHC with high precision
Pellen, Poncelet, Popescu, Vitos, 2204.12394

Angular coefficients, practical considerations

This simple idea suffers from:

- Fiducial phase space requirements on the leptons:
  → Interferences do not cancel
  → Correspondence between fractions (f_0, f_L, f_R) and angular distributions broken.
- Higher order corrections to decay (QED radiation 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

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 W+jet: LHC @ 13 TeV

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

Inclusive phase space:

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

Fiducial phase space:

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

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

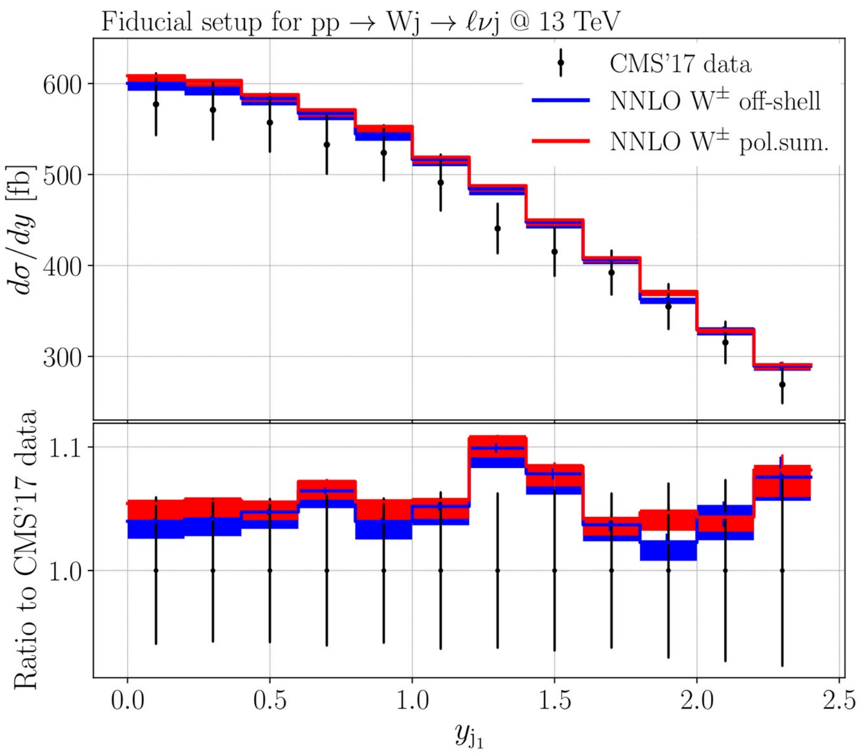
Technical aspects:

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

Extraction of polarisation fractions

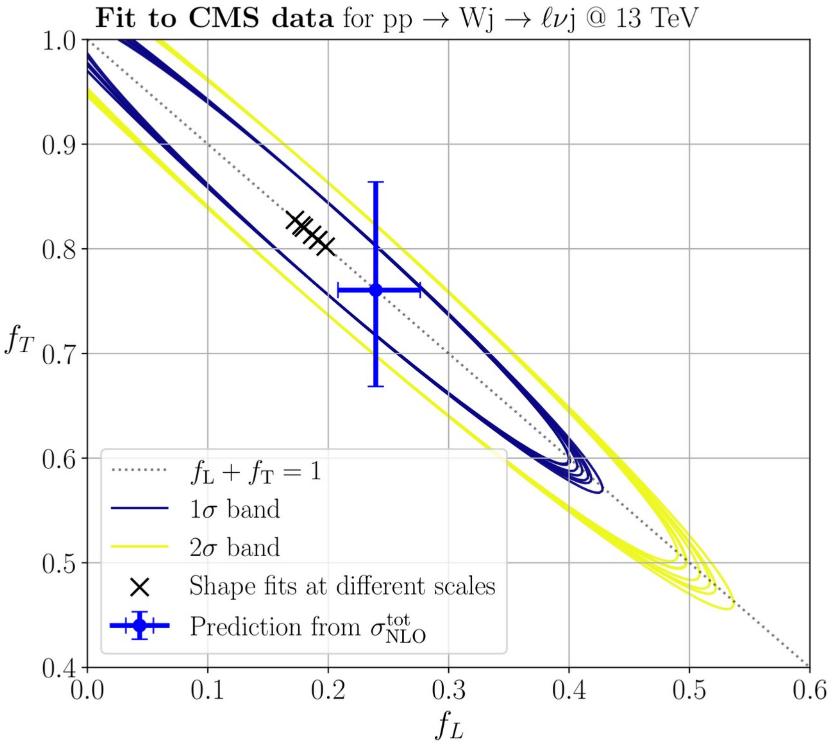
Identified 4 observables (ranges) with
→ Small interference effects (<2%)
→ Small off-shell effects (<2%)
→ Shape differences between L and T

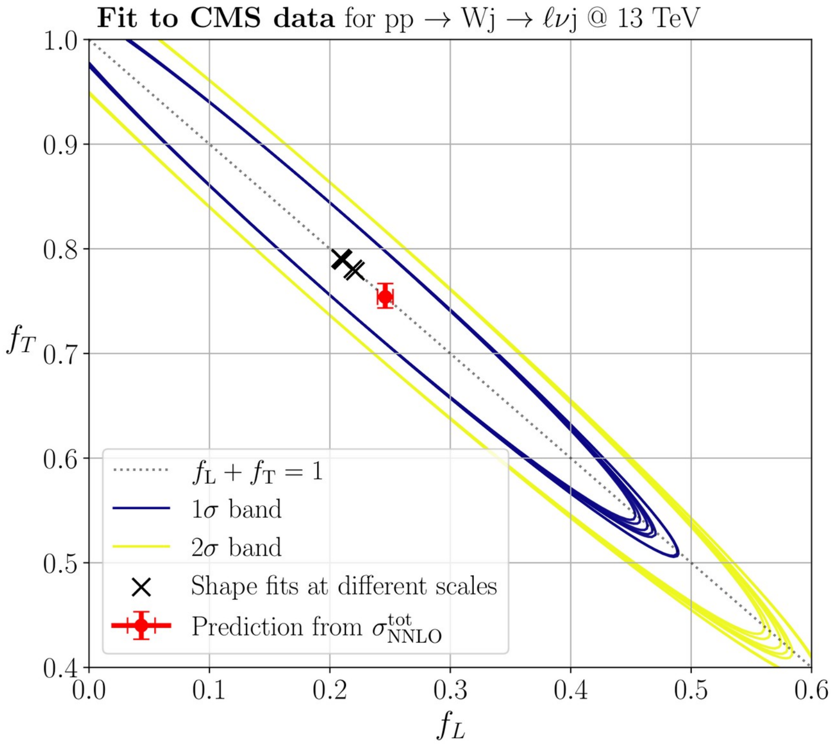
- $\Delta\phi(\ell, j_1) \geq 0.3$
- $25 \text{ GeV} \leq p_T(\ell) < 70 \text{ GeV}$
- $\cos(\theta^*_\ell) \geq -0.75$
- $|y(j_1)| \leq 2$



W+jet : fit to CMS data

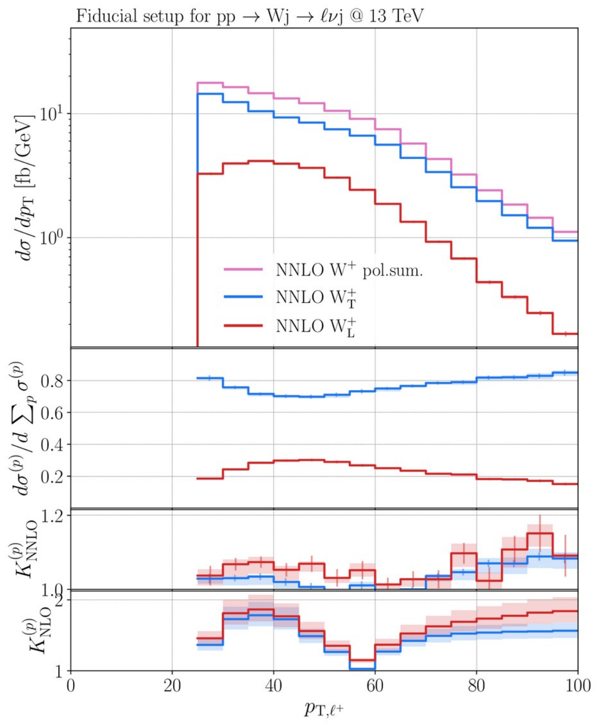
Fit to actual data, here $|y(j_1)|$
→ dominated by experimental uncertainties (no correlations available)



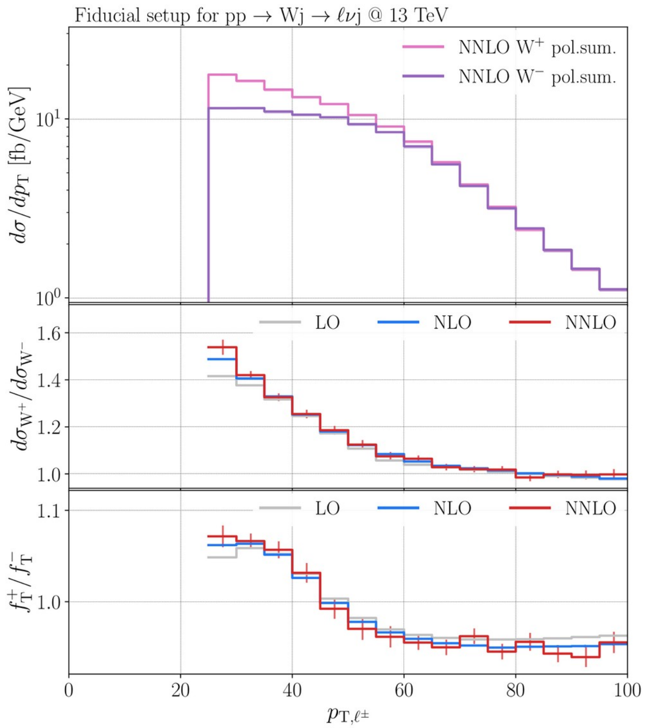


Example: lepton transverse momentum

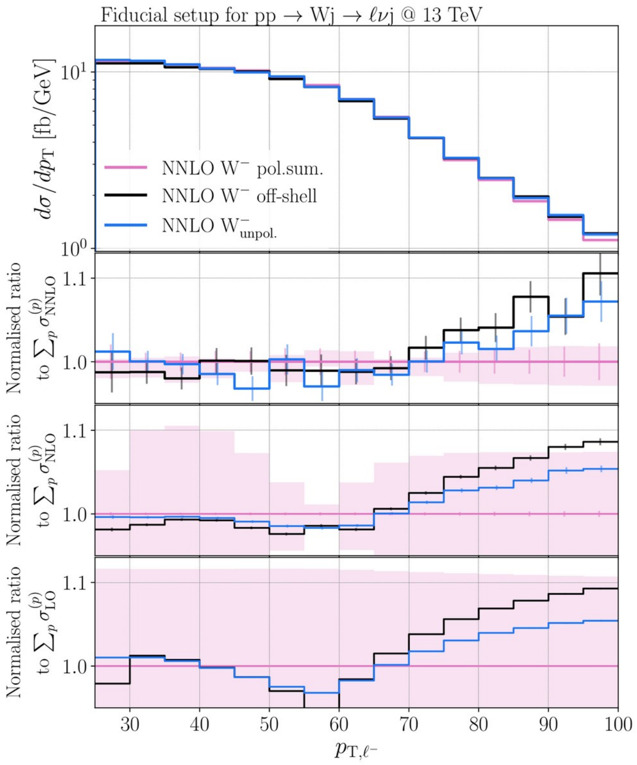
Perturbative corrections



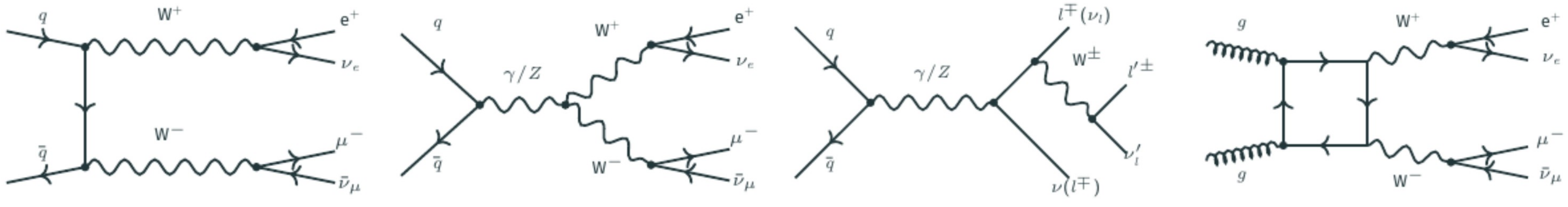
Charge differences



Off-shell/Interference effects

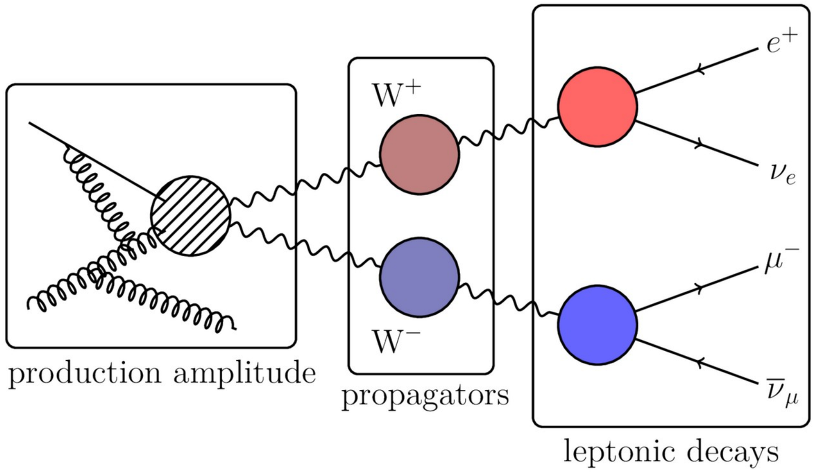


W-boson pair production



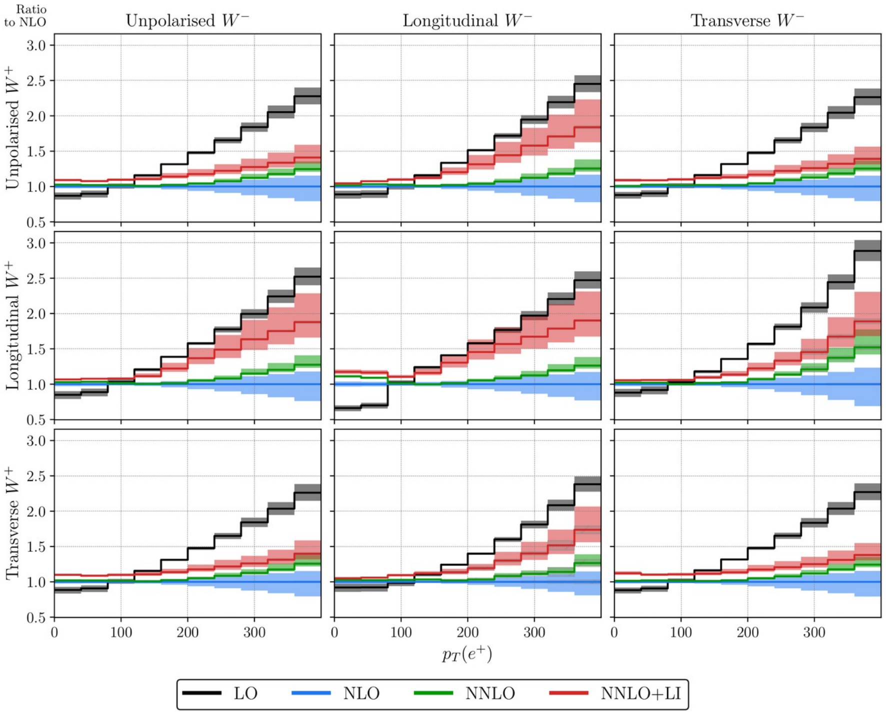
Double resonant (DR) | Double resonant (DR) | Single resonant (SR) | Loop-induced (LI)

- Single resonant backgrounds: Definition of polarizations states in DPA [1710.09339] and NWA
- LI enters at NNLO → large corrections

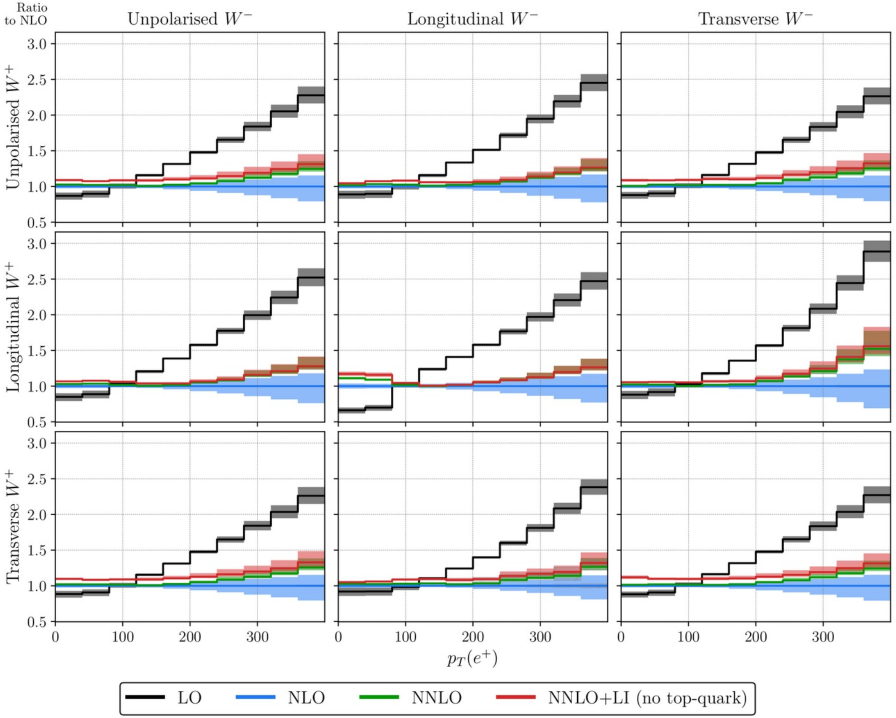


Loop induced gg → WW contributions

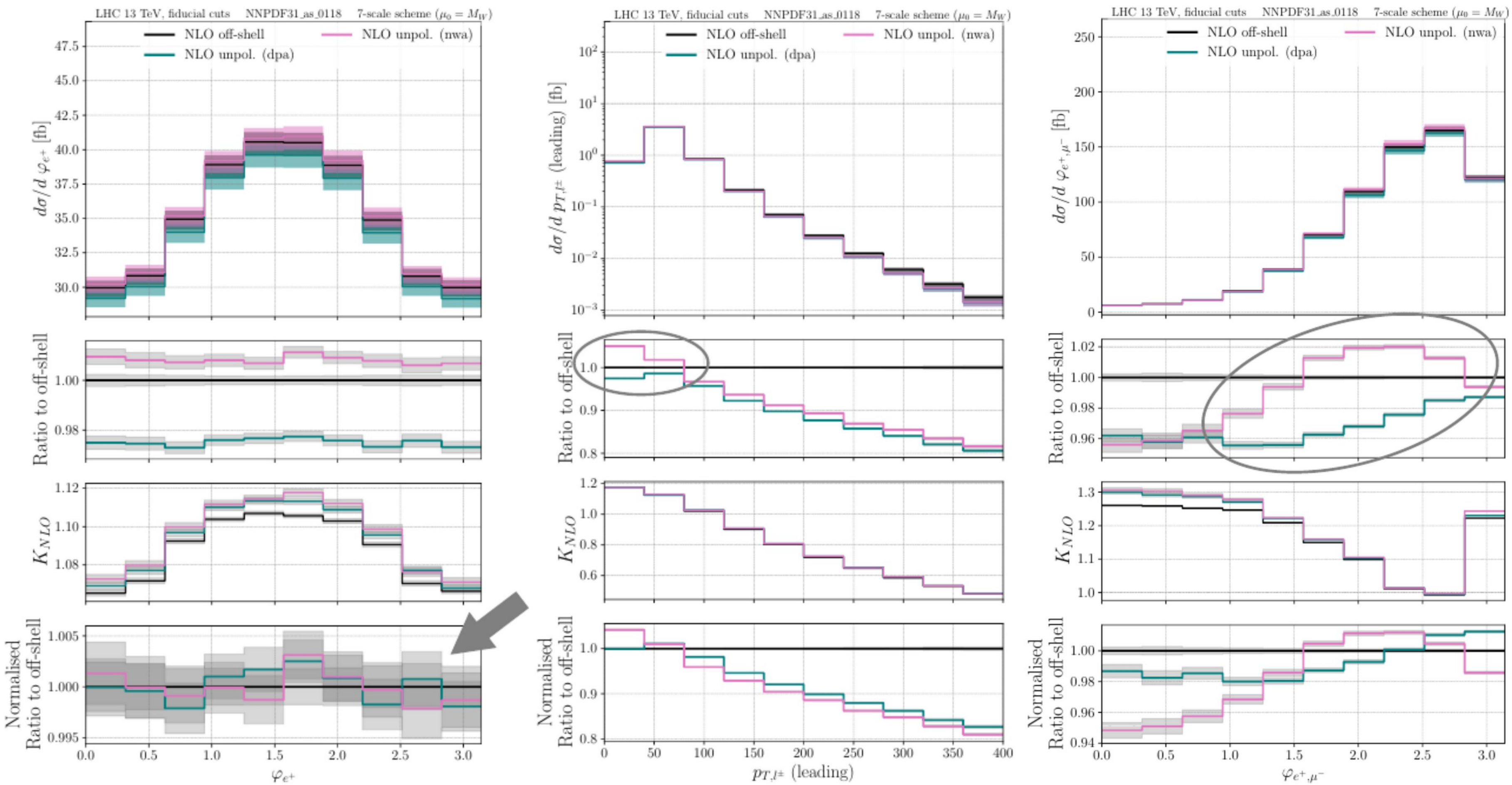
With top-quark loops in gg LI



Without top-quark loops in gg LI

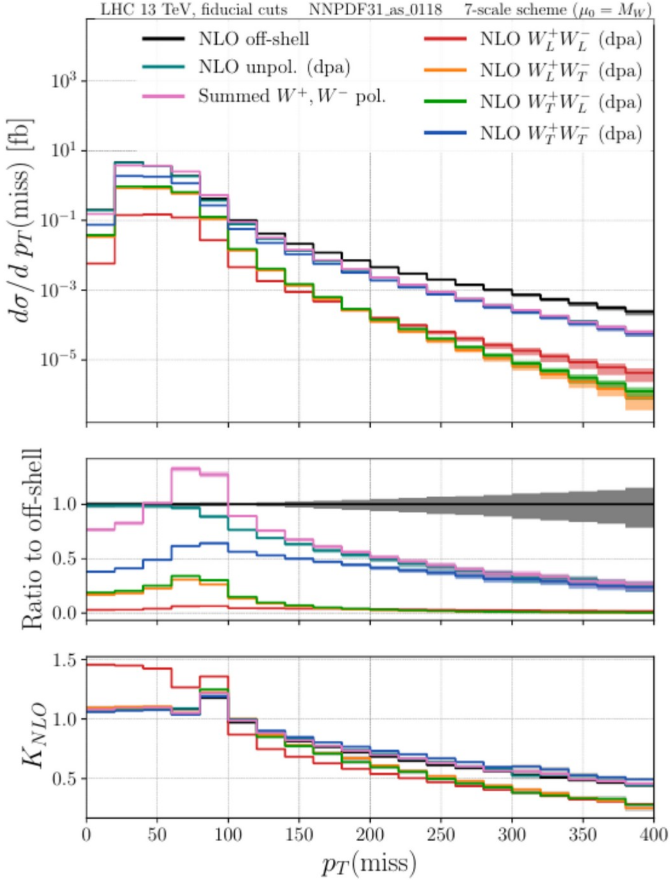


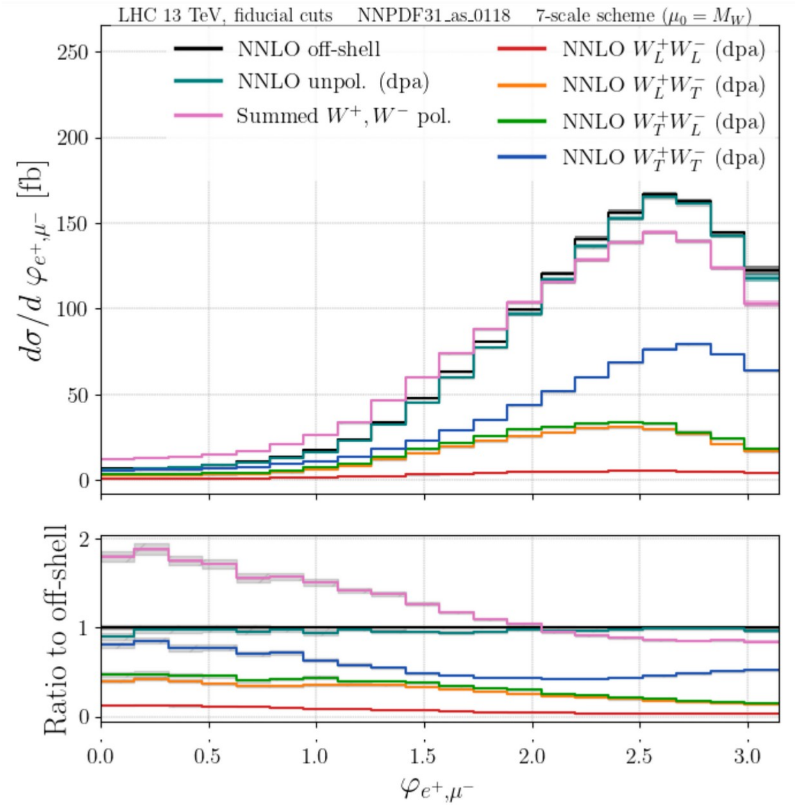
NWA vs. DPA


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