VLVL: Precision Predictions for Polarized Electroweak Bosons

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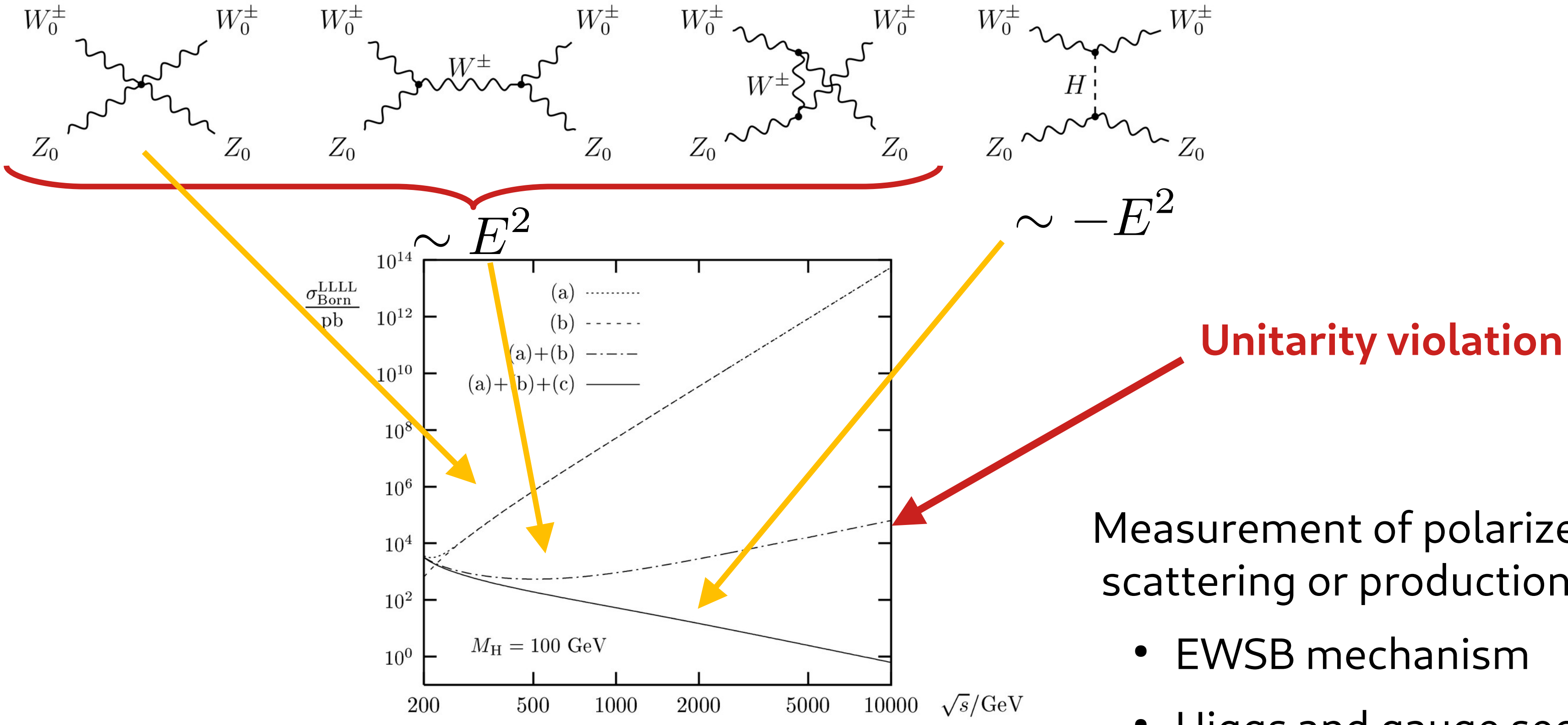
Longitudinal Vector-Boson-Scattering (VBS)



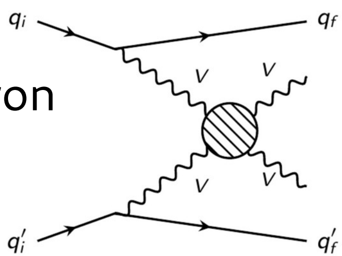
Measurement of polarized boson scattering or production probes:

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

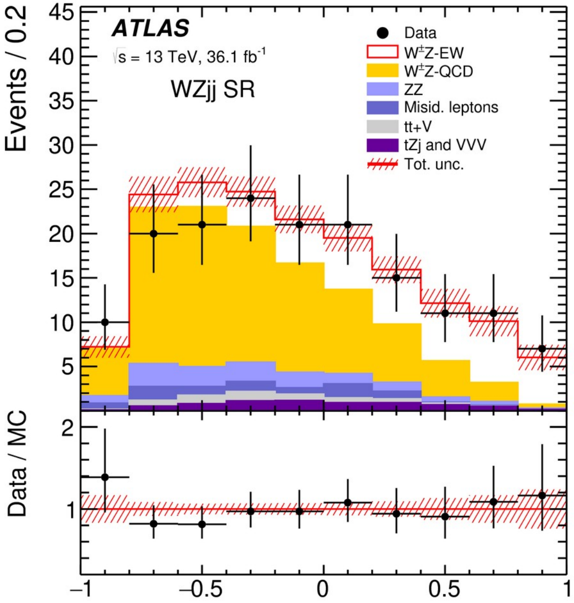
Radiative corrections to W+ W- → W+ W- in the electroweak standard model
A. Denner, T. Hahn hep-ph/9711302

VBS at hadron colliders

VBS at hadron colliders

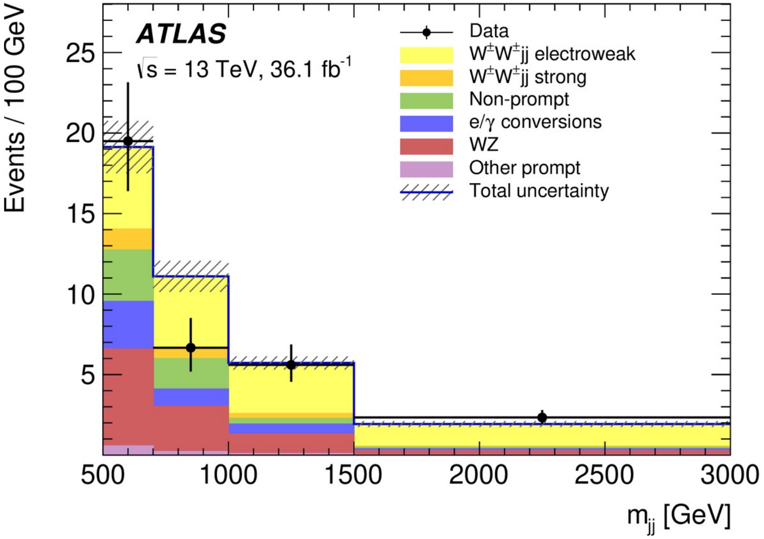


Separate from background processes through VBS topology → a rare process, but observed.



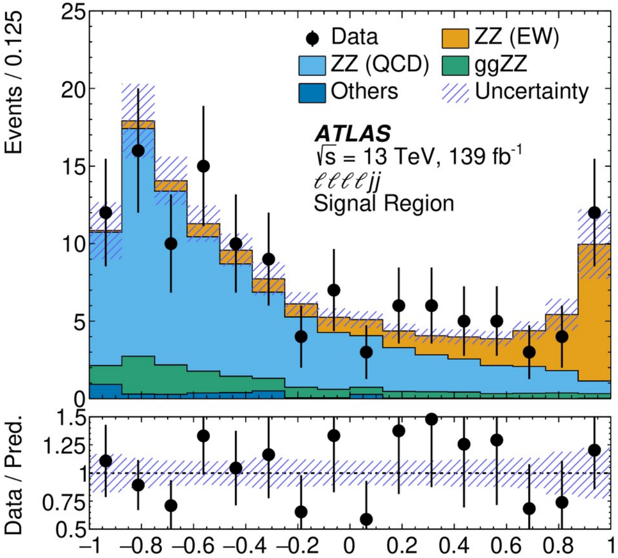
WZ (5.3 sigma)

ATLAS 1812.09740



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

ATLAS 1906.03203



ZZ (5.5 sigma)

ATLAS 2004.10612

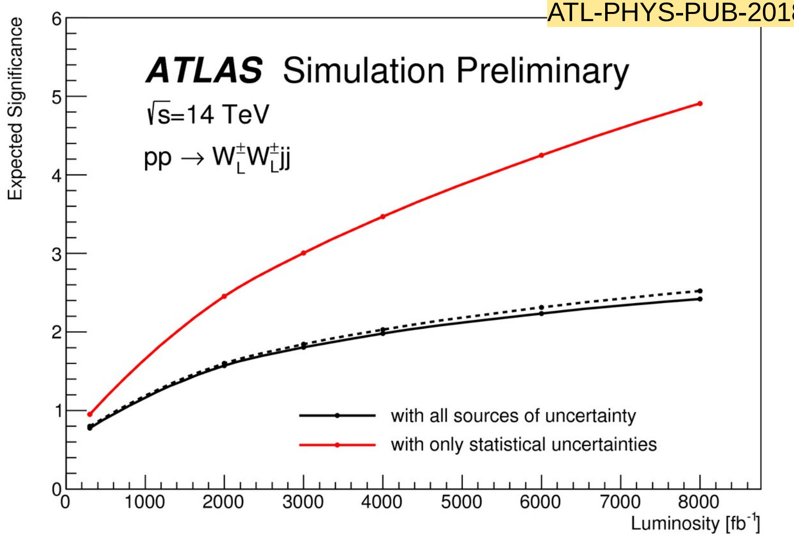
Polarised VBS at HL-LHC

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

ATLAS HL-LHC projection

ATL-PHYS-PUB-2018-052



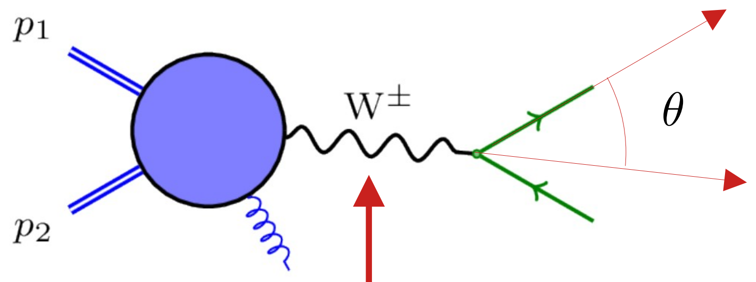
This talk: How to improve on the theory systematics?

→ Improved signal and background modelling

→ Effective separation of boson polarisations

How to measure polarized bosons?

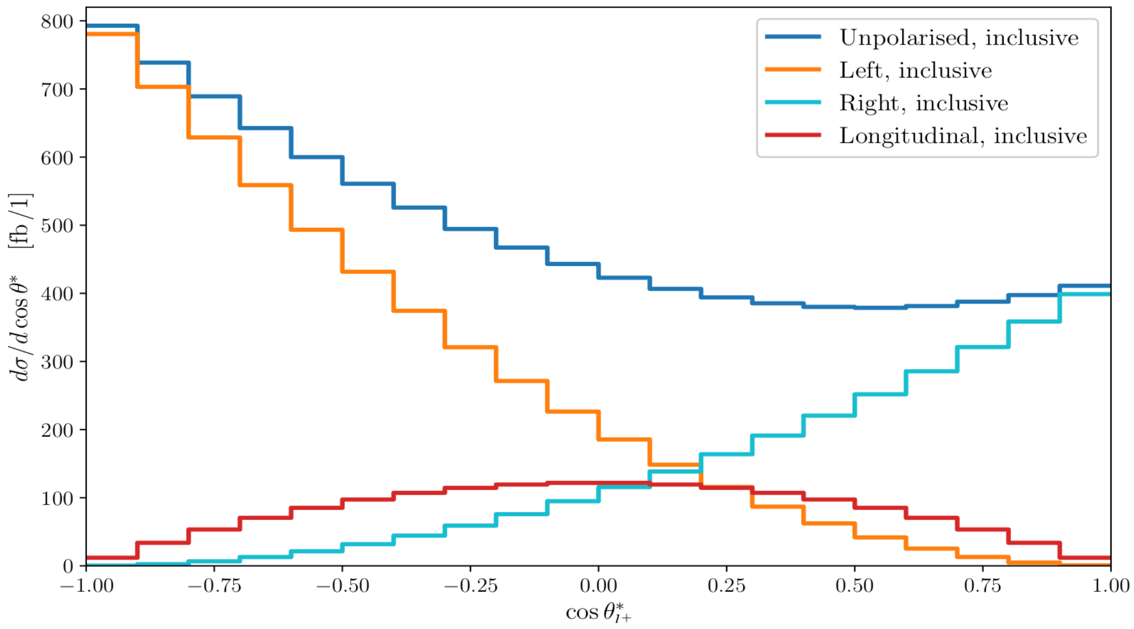
- We can’t measure boson polarization directly.
- Luckily decay products can be used as a “polarimeter”:



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

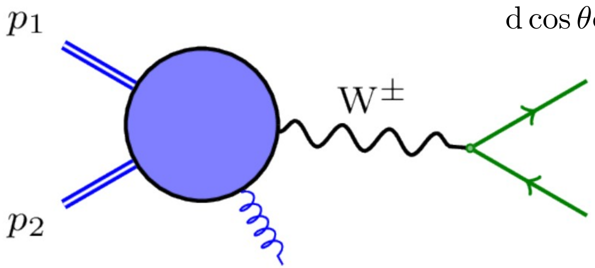
λ = +/-/L

W+ decay (W- mirrored around 0)



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.

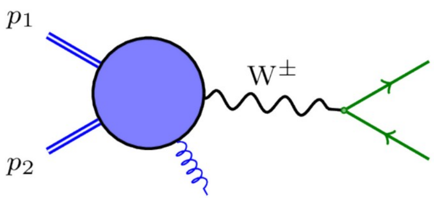
Practical considerations

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

The more general solution is to generate polarized events!

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

(DPA or NWA)

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

→ polarised x-sections Interferences

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

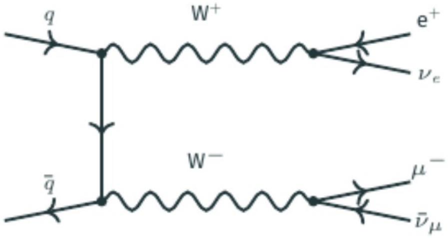
and fit f_L, f_R, f_0 to measured $\frac{\mathrm{d}\sigma^{exp.}}{\mathrm{d}X}$

Polarized cross sections

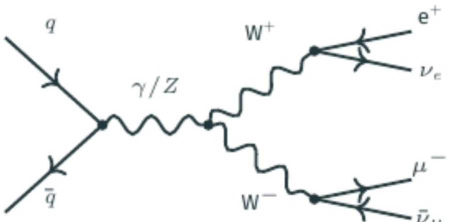
$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = f_L \frac{\mathrm{d}\sigma_L}{\mathrm{d}X} + f_R \frac{\mathrm{d}\sigma_R}{\mathrm{d}X} + f_0 \frac{\mathrm{d}\sigma_0}{\mathrm{d}X} \left(+ f_{int.} \frac{\mathrm{d}\sigma_{int.}}{\mathrm{d}X} \right)$$

- 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 (EW and QCD)

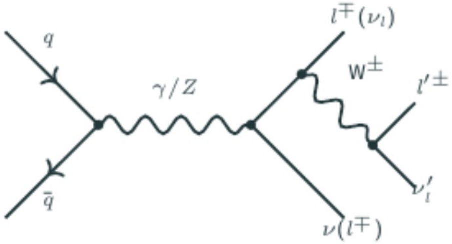
Example: W-boson pair production



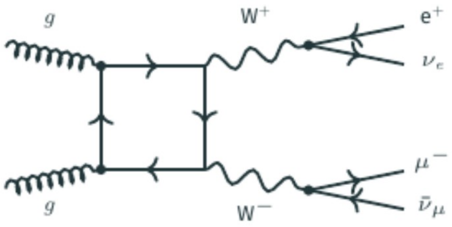
Double resonant (DR)



Double resonant (DR)



Single resonant (SR)

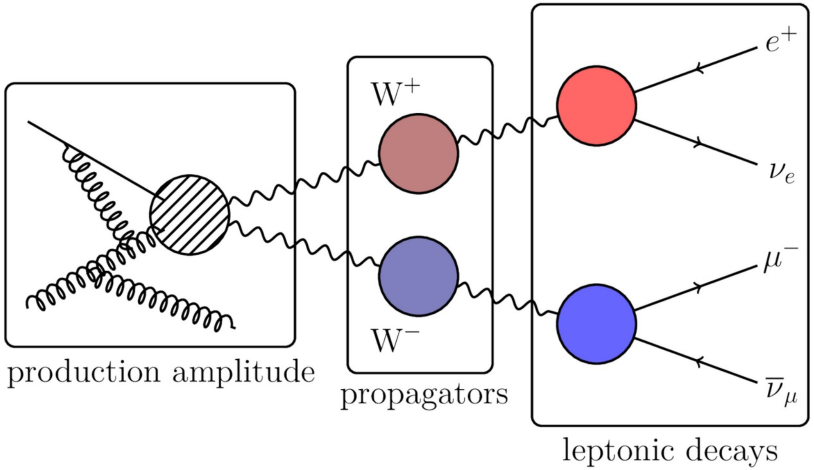


Loop-induced (LI)

Polarization definition + single resonant backgrounds

On-shell projections:

- Double-pole approximation (DPA)
- Narrow-width approximation (NWA)



Polarized VV @ (N)NLO QCD / NLO EW

Selected results

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, ← NNLO QCD
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 ← NLO+PS
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

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
Pellicciolі, 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
- Roughly 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

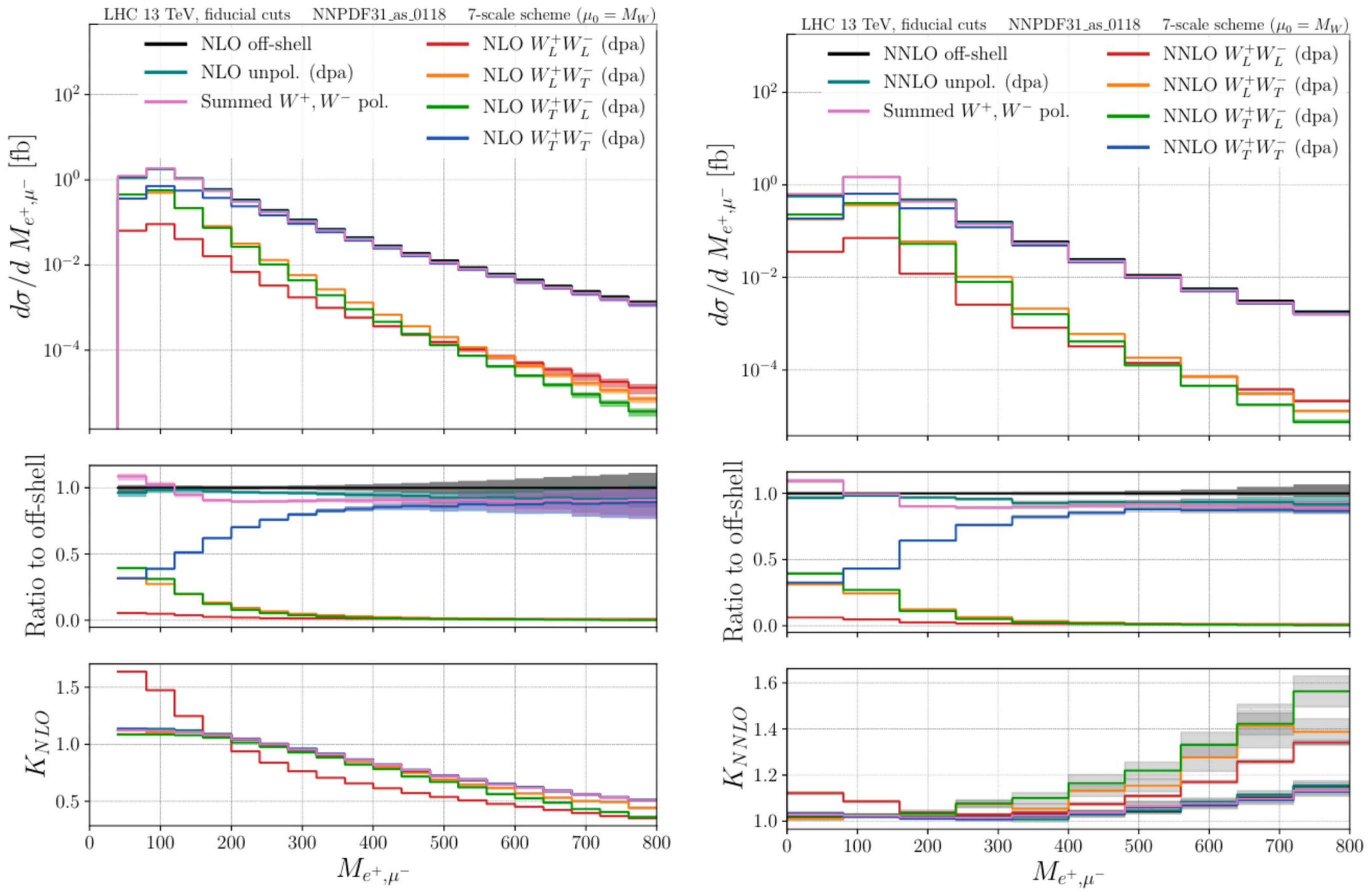
	NLO	NNLO	K_{NNLO}	LI	NNLO+LI
off-shell	$220.06(5)^{+1.8\%}_{-2.3\%}$	$225.4(4)^{+0.6\%}_{-0.6\%}$	1.024	$13.8(2)^{+25.5\%}_{-18.7\%}$	$239.1(4)^{+1.5\%}_{-1.2\%}$
unpol. (nwa)	$221.85(8)^{+1.8\%}_{-2.3\%}$	$227.3(6)^{+0.6\%}_{-0.6\%}$	1.025	$13.68(3)^{+25.5\%}_{-18.7\%}$	$241.0(6)^{+1.5\%}_{-1.1\%}$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



What next?

- Generic frameworks are in place to compute NLO QCD/EW (+PS) and NNLO QCD
- Technically frameworks can handle any combination of V and H
  - WW/ZZ/WZ, WA/ZA, WH/ZH
- Final-states: mostly fully-leptonic, rarer: semi-leptonic, full-hadronic?
- Generation of polarised samples for HighTEA [2304.05993]
  https://www.precision.hep.phy.cam.ac.uk/hightea/
  - Tool far fast+easy differential cross section evaluation at NNLO
  - Flexible observable definitions (→ good to study new ideas)
  - Easy PDF/scale variation
  - Study of correlations/ratios between difference di-boson processes

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 di-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

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:

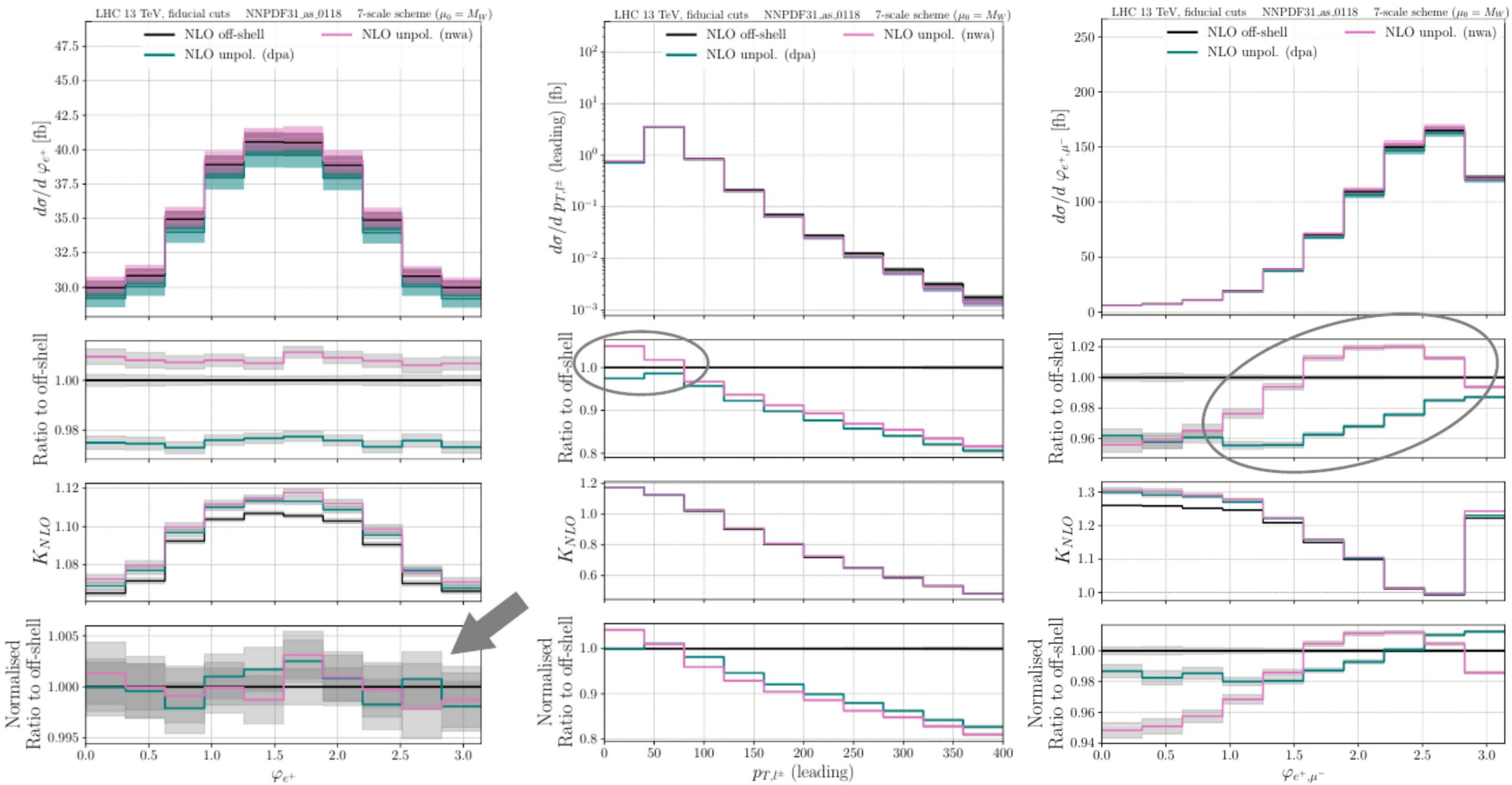
$$\phi = U^{-1}(\pi^i)\phi, \qquad W_\mu = U^{-1}W_\mu U - \frac{i}{g_W}U^{-1}\partial_\mu U$$

$$|D_\mu\phi|^2 \ni \frac{v^2}{8}\left[2g_W^2 W_\mu^+ W^{-\mu} + (g_W W^3_\mu - g'_W B_\mu)^2\right]$$

→ $M_W = \frac{1}{2}vg_W\ , \quad M_Z = \frac{M_W}{\cos\theta_W}$

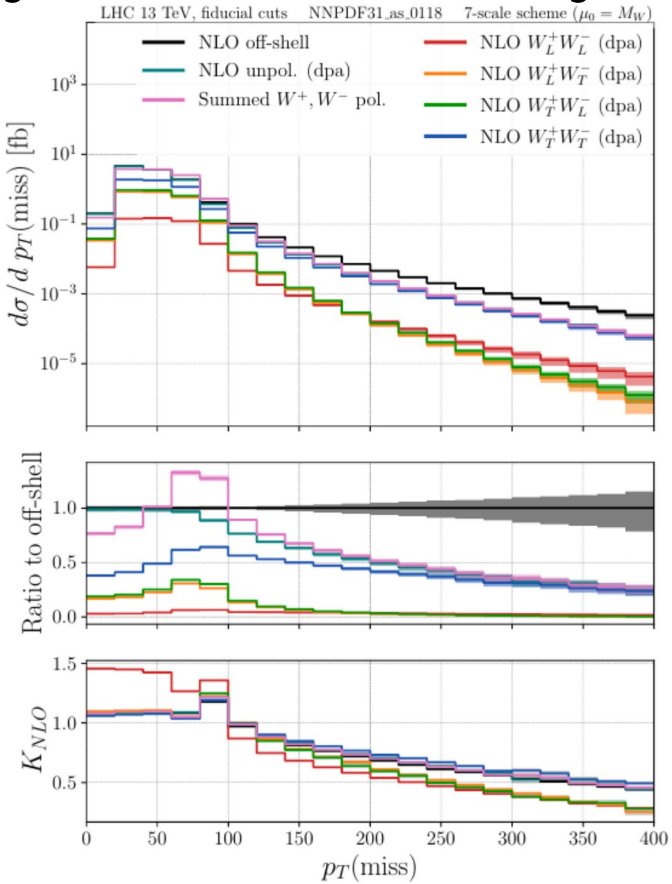
- Restores renormalizability and unitarity

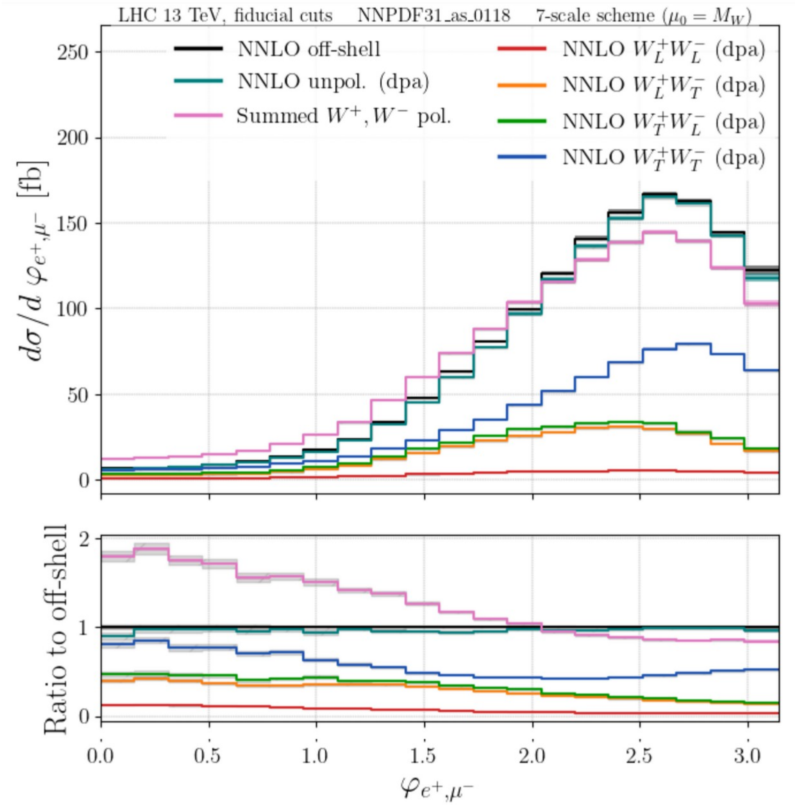
NWA vs. DPA


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

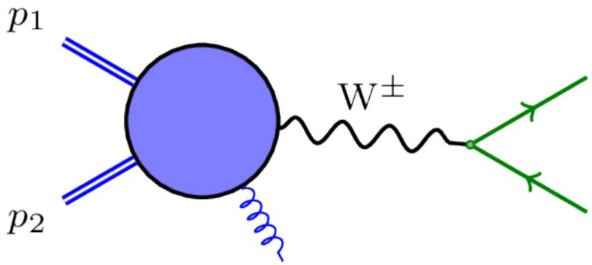
Large off-shell effect from single-resonant contributions





Large interference effects through phase space constraints

Polarised W+jet cross sections



Why looking at polarised W+jet with leptonic decays?

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

Goals:

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

Setup: LHC @ 13 TeV

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

Inclusive phase space:

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

Fiducial phase space:

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

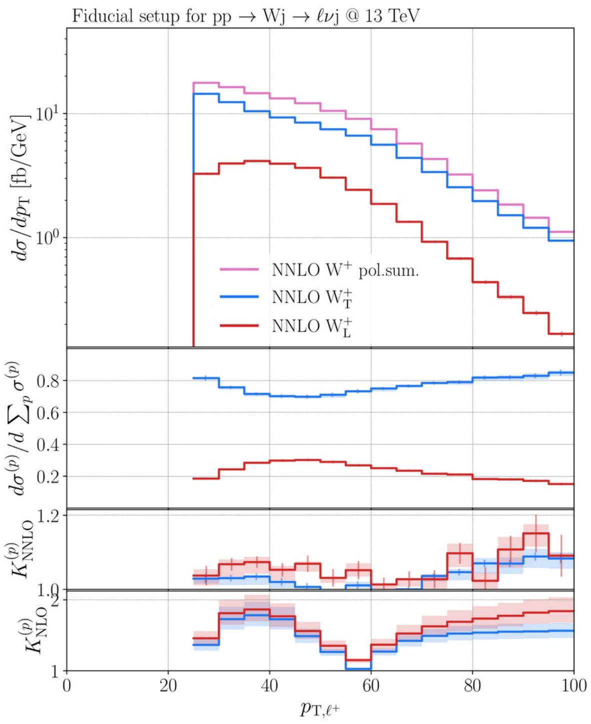
- Lepton cuts: $p_T(\ell) \geq 25$ GeV, $|\eta(\ell)| \leq 2.5$ and $\Delta R(\ell, j) > 0.4$
- Transverse mass of the W: $M_T(W) = \sqrt{m_W^2 + p_T^2(W)} \geq 50$ GeV

Technical aspects:

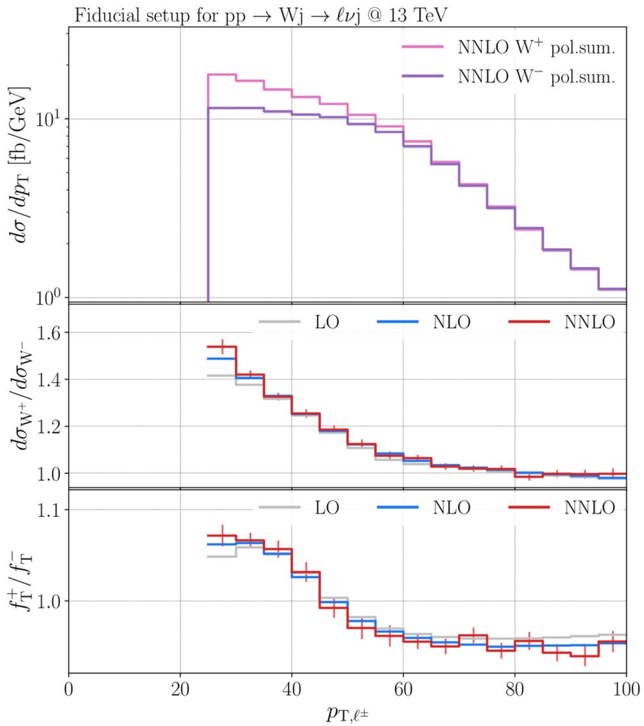
- NNPDF31 and dynamical scale choice: $\mu_R = \mu_F = \frac{1}{2}\left(m_T(W) + \sum p_T(j)\right)$
- Implementation in STRIPPER framework (NNLO QCD subtractions) [1408.2500]
  - Narrow-Width-Approximation and OSP/Pole-Approximation
  - Matrix elements from: AvH[1503.08612], OpenLoops2 [1907.13071](cross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

Example: lepton transverse momentum

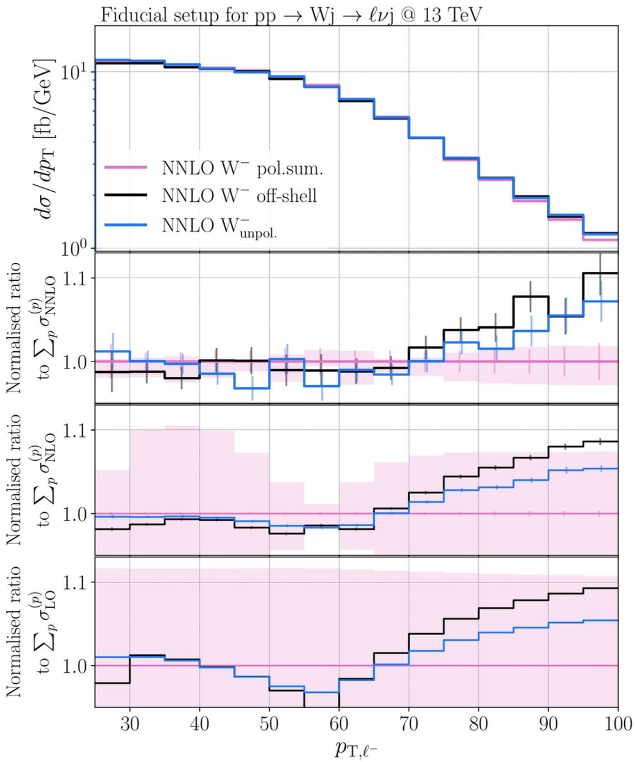
Perturbative corrections



Charge differences



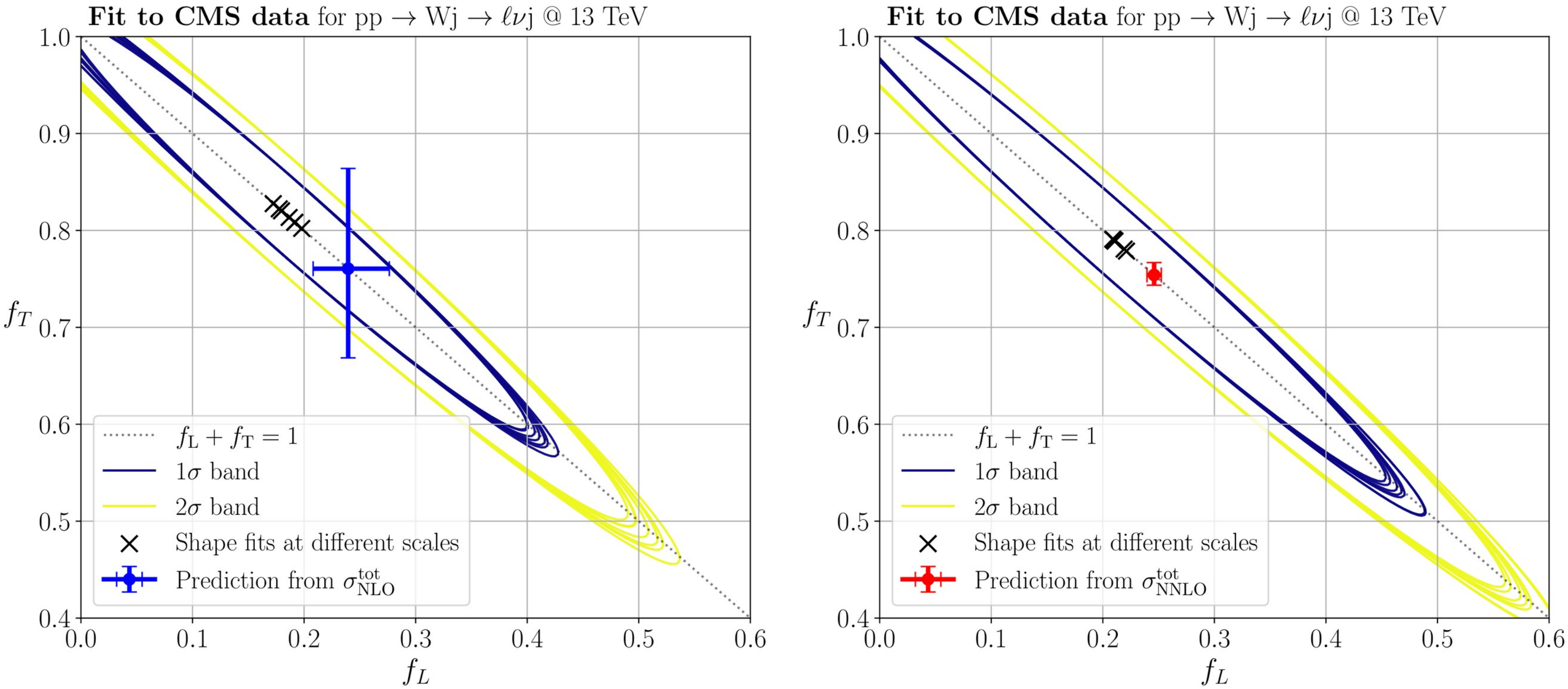
Off-shell/Interference effects



W+jet : fit to CMS data

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

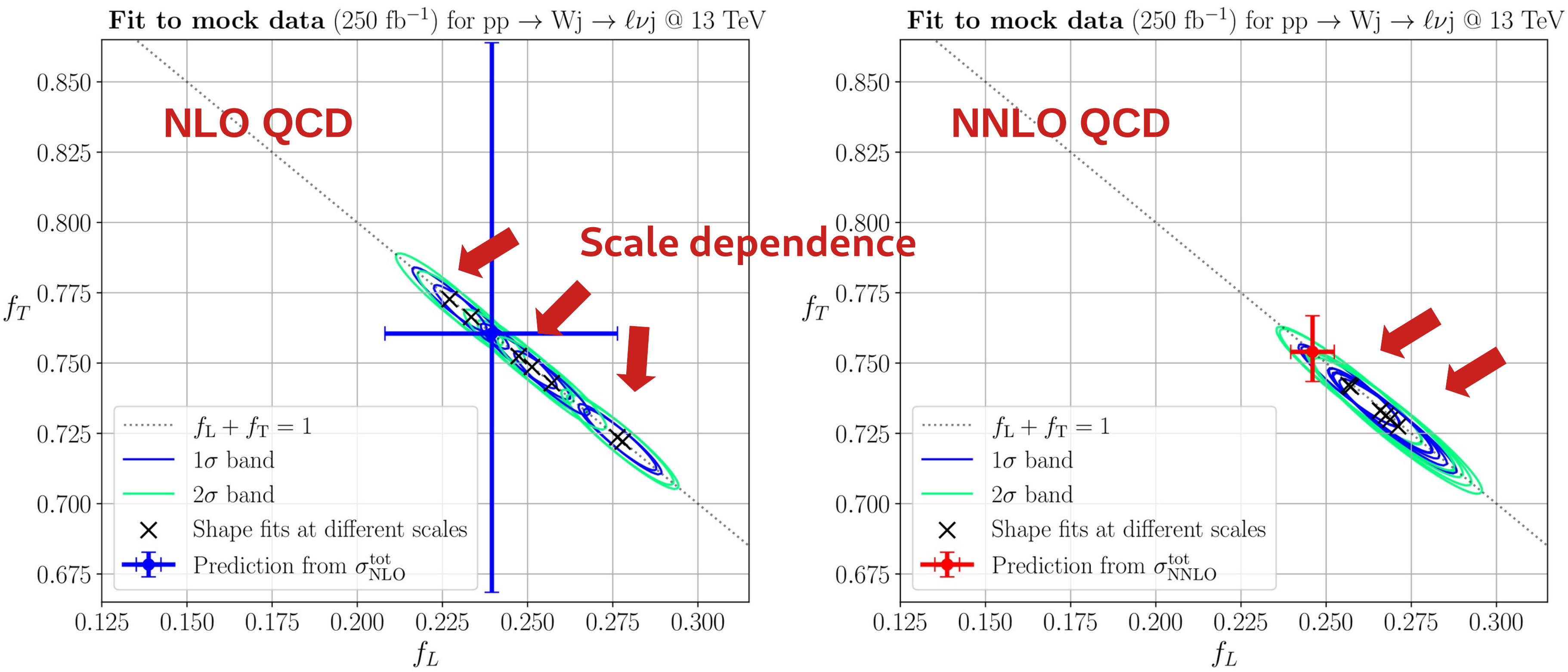
→ dominated by experimental uncertainties (no correlations available)



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

$\cos(\ell, j_1)$



Extraction of polarisation fractions

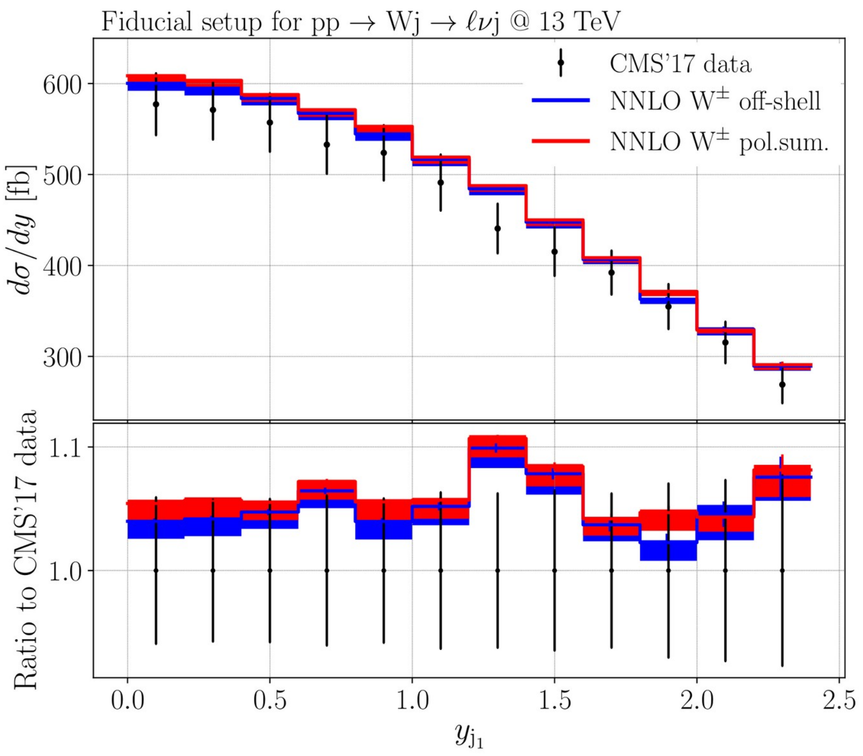
Identified 4 observables (ranges) with

→ Small interference effects (<2%)

→ Small off-shell effects (<2%)

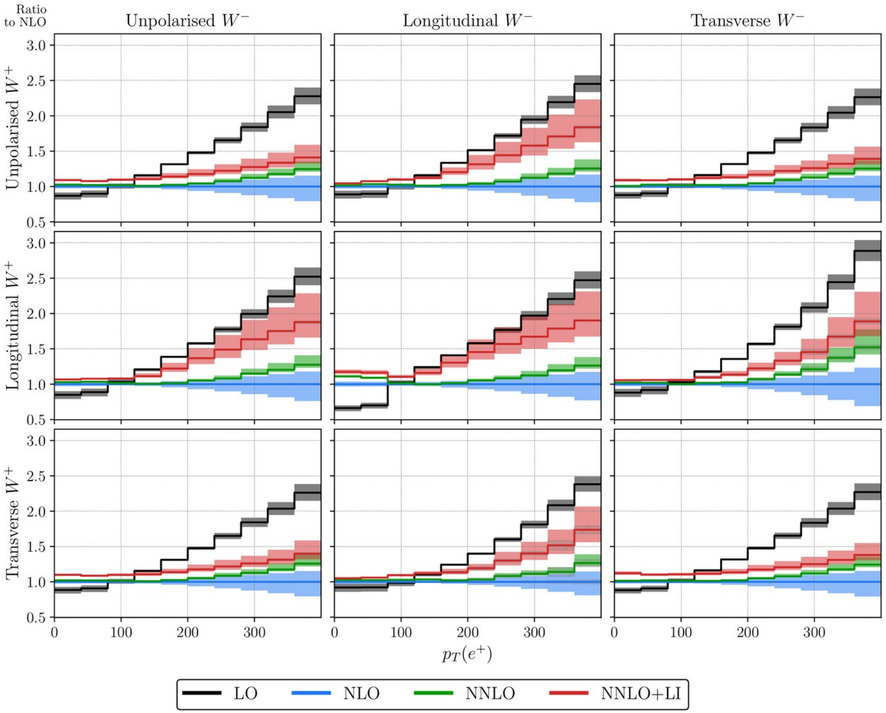
→ Shape differences between L and T

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



Loop induced gg → WW contributions

With top-quark loops in gg LI



Without top-quark loops in gg LI