Polarization modelling in MBI processes/ Precision Predictions for Polarized Electroweak Bosons

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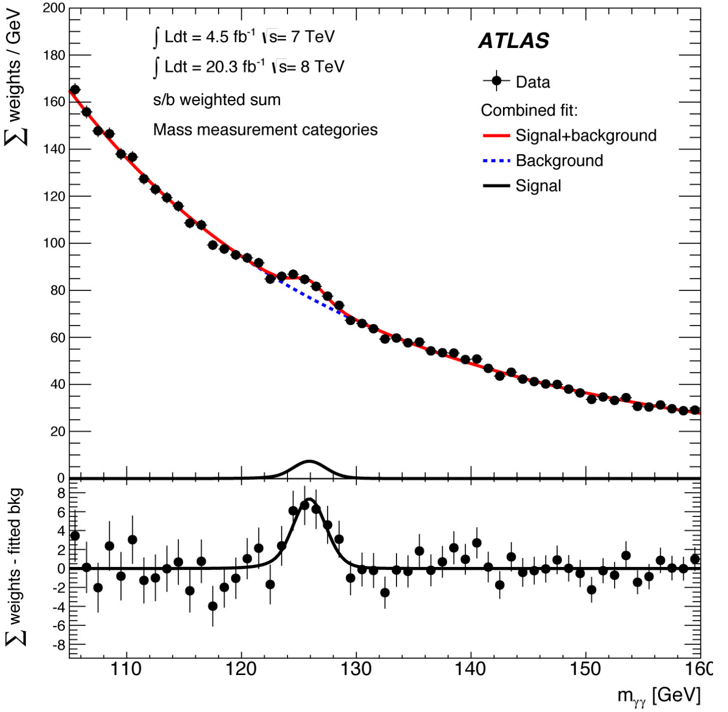
Motivation: Why polarized boson?

- 10 Years Jubilee of the discovery of a “Higgs”-like boson
- New era of precisions measurements of Higgs properties: spin, couplings, self-interactions,…
  To answer fundamental questions like
  - Is the Higgs the Standard Model Higgs?
  - Is it a fundamental scalar?
  - How is the EWSB mechanism realized?
  - …
- Polarized bosons can be a tool to access these questions from a point of view orthogonal to Higgs measurements.



Motivation: Why polarized boson?

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:

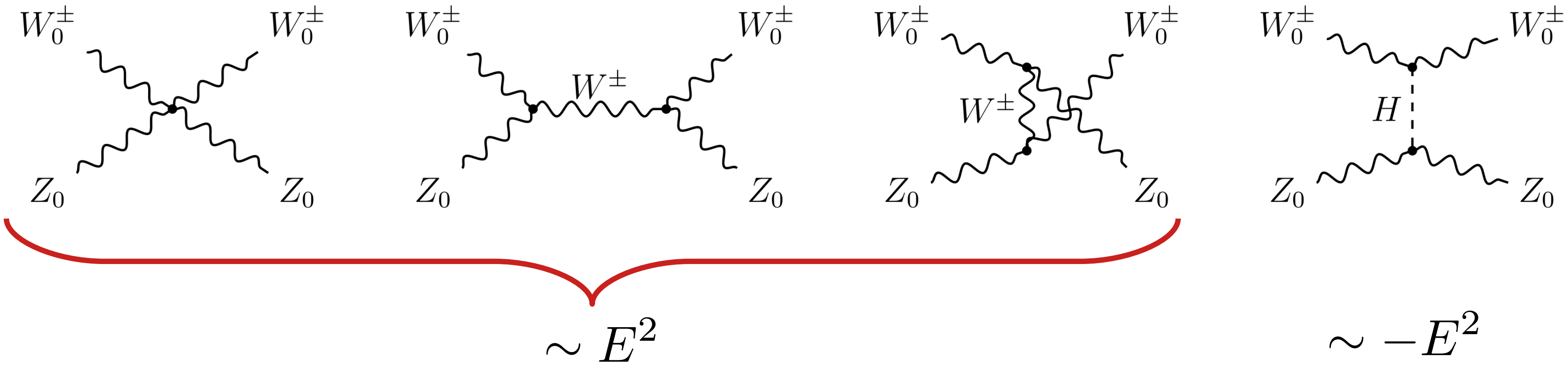
$$\phi = U^{-1}(\pi^i)\phi, \qquad W_\mu = U^{-1}W_\mu U - \frac{i}{g_W}U^{-1}\partial_\mu U$$

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

- Restores renormalizability and unitarity

Motivation: Why polarized boson?

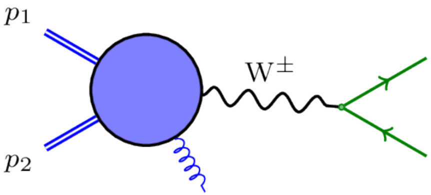
Scattering of longitudinal vector bosons:



- Measurement of polarized boson scattering or production probes:
  - EWSB mechanism
  - Higgs and gauge sector
  - New physics models (for example throw EFTs like SMEFT)

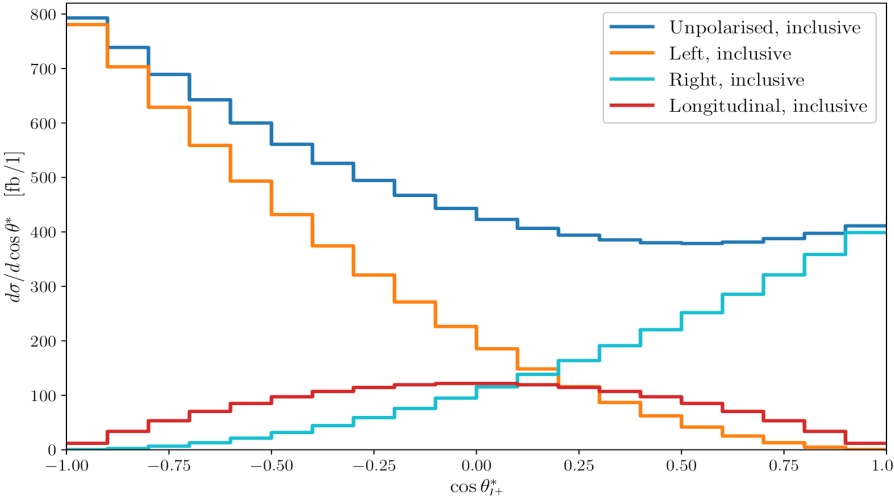
How to measure polarized bosons?

- No WW collider… but the LHC produces massive vector bosons abundantly!
- We can’t measure boson polarization directly.
- Luckily decay products can be used as a “polarimeter”:



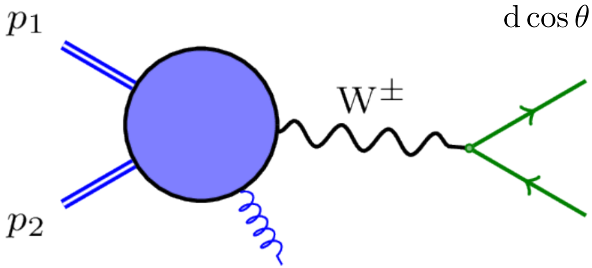
$$M_\lambda = \mathbf{P}_\mu \cdot \frac{-g_{\mu\nu} + \frac{k^\mu k^\nu}{k^2}}{k^2 - M_V^2 + iM_V\Gamma_V} \cdot \mathbf{D}_\nu$$

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



How to measure polarized bosons

Angular decomposition of W decay:



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

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

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

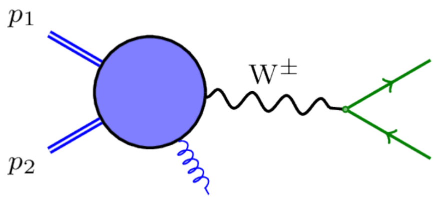
Reality check

This simple idea suffers from:

- Fiducial phase space requirements on the leptons
  - Interferences do not cancel → nice correspondence between fractions (f0,fR,fL) and angular distributions broken.
- Higher order corrections to decay
  - 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



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

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

$$|M|^2 = \underbrace{\sum_\lambda |M_\lambda|^2}_{\to \text{pol. x-section}} + \underbrace{\sum_{\lambda\neq\lambda'} M^*_\lambda M_\lambda}_{\text{Interferences}}$$

Create samples of specified cross section

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

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

Advantages:

- Interferences can be handled
- X can be any observable → lab frame observables
- $\frac{\mathrm{d}\sigma_i}{\mathrm{d}X}$ can be systematically improved

Overview SM results

- Polarised VBS (so far LO):

  W boson polarization in vector boson scattering at the LHC,
  Ballestrero, Maina, Pellicciol 1710.09339
  Polarized vector boson scattering in the fully leptonic WZ and ZZ channels at the LHC,
  Ballestrero, Maina, Pellicciol 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, Pellicciol 2007.07133

- Polarized Diboson NLO QCD / NLO EW : WW / WZ / ZZ

  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, Pellicciol 2006.14867
  NLO EW and QCD corrections to polarized ZZ production in the four-charged-lepton channel at the LHC,
  Denner, Pellicciol 2107.06579
  Breaking down the entire spectrum of spin correlations of a pair of particles involving fermions and gauge bosons,
  Rahama, Singh 2109.09345
  NLO QCD predictions for doubly-polarized WZ production at the LHC,
  Denner, Pellicciol 2010.07149
  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

Overview SM results

- Polarized Diboson NNLO QCD

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

- Single boson production

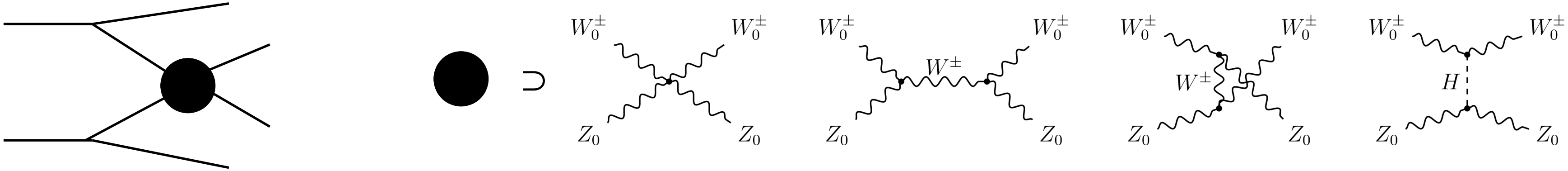
  Left-Handed W Bosons at the LHC,
  Z. Bern et. al. 1103.5445
  Electroweak gauge boson polarisation at the LHC,
  Stirling, Vryonidou 1204.6427
  What Does the CMS Measurement of W-polarization Tell Us about the Underlying Theory of the Coupling of W-Bosons to Matter?,
  Belyaev, Ross 1303.3297
  Polarised W+j production at the LHC: a study at NNLO QCD accuracy,
  Pellen, Poncelet, Popescu 2109.14336

- Experimental works on polarized W production

  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

Polarized VBS

Clear connection to unitarity cancellation:



Extensive studies within the PHANTOM MC and Madgraph at LO:

- Singly and doubly polarized cross sections
- Frame of polarization definition
- Impact of fiducial selection criteria
- Study of off-shell/interference effects

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,
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Automated predictions from polarized matrix elements
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Different polarization definitions in same-sign WW scattering at the LHC,
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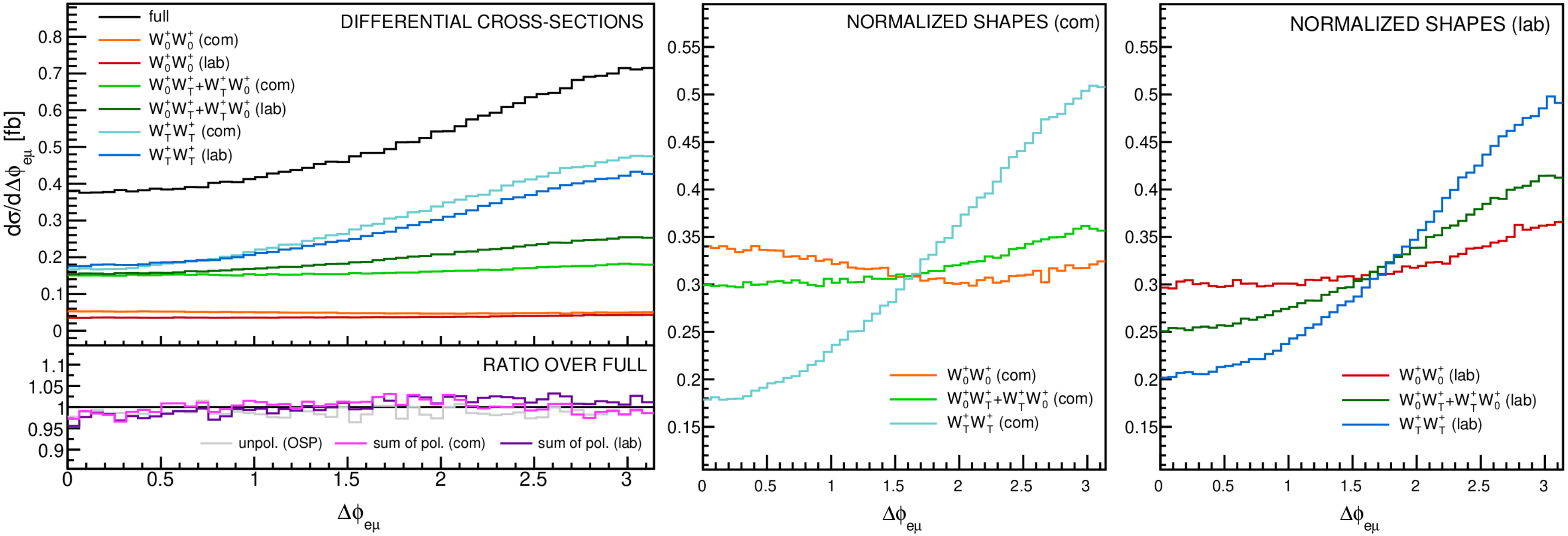
Polarized VBS: same-sign WW

Different polarization definitions in same-sign WW scattering at the LHC,
Ballestrero,Maina, Pelliccioli 2007.07133

- Visibly different shapes for double longitudinal polarized (LL) component
- However small total contribution of LL: ~10% of total cross section.

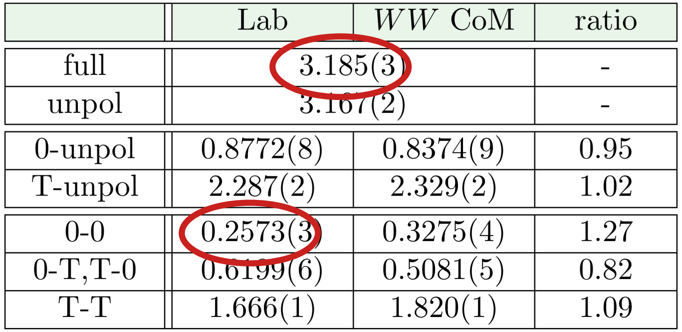


Polarized VBS: same-sign WW

Different polarization definitions in same-sign WW scattering at the LHC,
Ballestrero,Maina, Pellicciolі 2007.07133

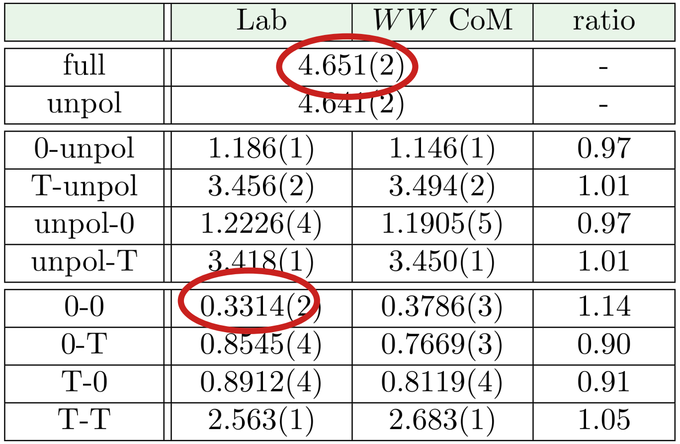
- Visibly different shapes for double longitudinal polarized (LL) component
- However small total contribution of LL: ~10% of total cross section.
  => Similar also for other VBS channels

W+W+



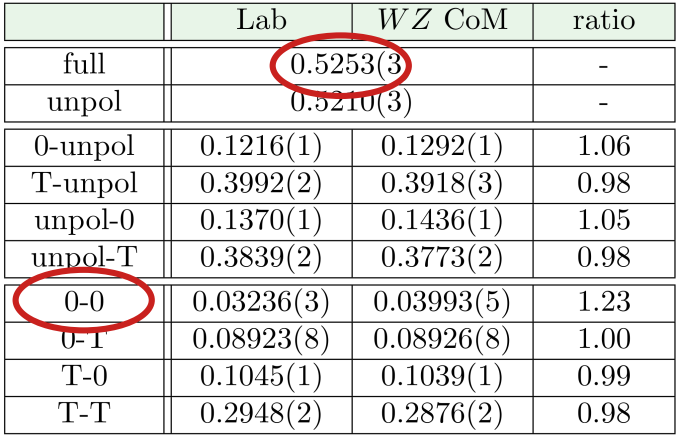
	Lab	*WW* CoM	ratio
full	3.185(3)		-
unpol	3.167(2)		-
0-unpol	0.8772(8)	0.8374(9)	0.95
T-unpol	2.287(2)	2.329(2)	1.02
0-0	0.2573(3)	0.3275(4)	1.27
0-T,T-0	0.6199(6)	0.5081(5)	0.82
T-T	1.666(1)	1.820(1)	1.09

W+W-



	Lab	*WW* CoM	ratio
full	4.651(2)		-
unpol	4.641(2)		-
0-unpol	1.186(1)	1.146(1)	0.97
T-unpol	3.456(2)	3.494(2)	1.01
unpol-0	1.2226(4)	1.1905(5)	0.97
unpol-T	3.418(1)	3.450(1)	1.01
0-0	0.3314(2)	0.3786(3)	1.14
0-T	0.8545(4)	0.7669(3)	0.90
T-0	0.8912(4)	0.8119(4)	0.91
T-T	2.563(1)	2.683(1)	1.05

WZ



	Lab	*WZ* CoM	ratio
full	0.5253(3)		-
unpol	0.5210(3)		-
0-unpol	0.1216(1)	0.1292(1)	1.06
T-unpol	0.3992(2)	0.3918(3)	0.98
unpol-0	0.1370(1)	0.1436(1)	1.05
unpol-T	0.3839(2)	0.3773(2)	0.98
0-0	0.03236(3)	0.03993(5)	1.23
0-T	0.08923(8)	0.08926(8)	1.00
T-0	0.1045(1)	0.1039(1)	0.99
T-T	0.2948(2)	0.2876(2)	0.98

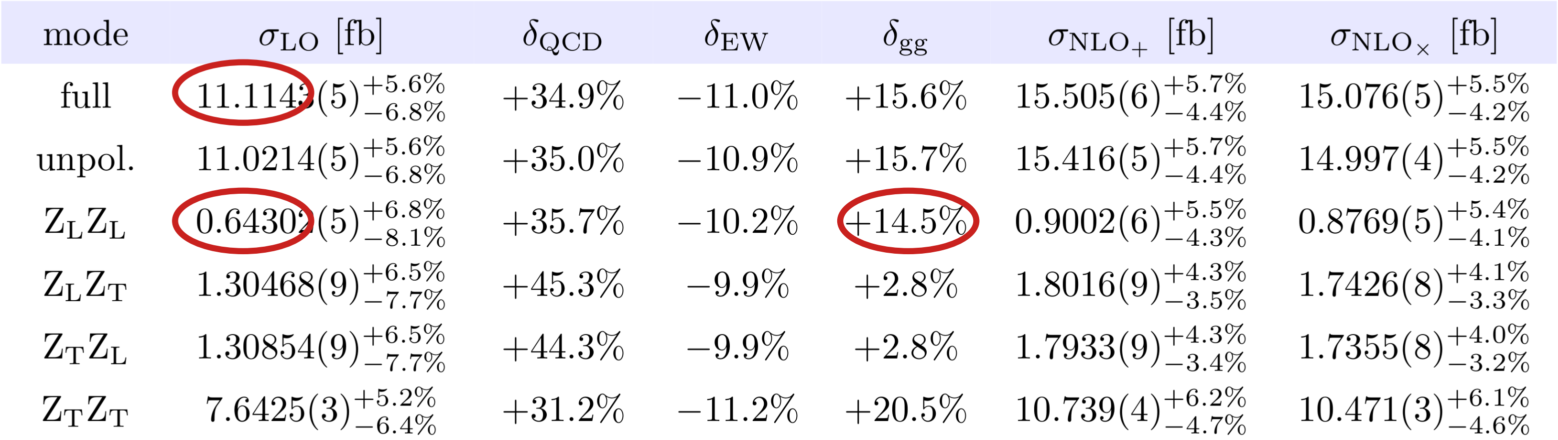
pp → ZZ → 4l NLO EW/QCD

NLO EW and QCD corrections to polarized ZZ production in the four-charged-lepton channel at the LHC, Denner, Pelliccioli 2107.06579

$$pp \to ZZ \to 4l + X$$

Integrated cross sections:

- Small LL contribution
- Sizeable QCD and EW corrections
- Large gg-loop induced contribution
- Fractions preserved from LO to NLO



mode	σ_{LO} [fb]	δ_{QCD}	δ_{EW}	δ_{gg}	σ_{NLO_+} [fb]	$\sigma_{\mathrm{NLO}_\times}$ [fb]
full	$11.1143(5)^{+5.6\%}_{-6.8\%}$	$+34.9\%$	-11.0%	$+15.6\%$	$15.505(6)^{+5.7\%}_{-4.4\%}$	$15.076(5)^{+5.5\%}_{-4.2\%}$
unpol.	$11.0214(5)^{+5.6\%}_{-6.8\%}$	$+35.0\%$	-10.9%	$+15.7\%$	$15.416(5)^{+5.7\%}_{-4.4\%}$	$14.997(4)^{+5.5\%}_{-4.2\%}$
$\mathrm{Z_L Z_L}$	$0.64302(5)^{+6.8\%}_{-8.1\%}$	$+35.7\%$	-10.2%	$+14.5\%$	$0.9002(6)^{+5.5\%}_{-4.3\%}$	$0.8769(5)^{+5.4\%}_{-4.1\%}$
$\mathrm{Z_L Z_T}$	$1.30468(9)^{+6.5\%}_{-7.7\%}$	$+45.3\%$	-9.9%	$+2.8\%$	$1.8016(9)^{+4.3\%}_{-3.5\%}$	$1.7426(8)^{+4.1\%}_{-3.3\%}$
$\mathrm{Z_T Z_L}$	$1.30854(9)^{+6.5\%}_{-7.7\%}$	$+44.3\%$	-9.9%	$+2.8\%$	$1.7933(9)^{+4.3\%}_{-3.4\%}$	$1.7355(8)^{+4.0\%}_{-3.2\%}$
$\mathrm{Z_T Z_T}$	$7.6425(3)^{+5.2\%}_{-6.4\%}$	$+31.2\%$	-11.2%	$+20.5\%$	$10.739(4)^{+6.2\%}_{-4.7\%}$	$10.471(3)^{+6.1\%}_{-4.6\%}$

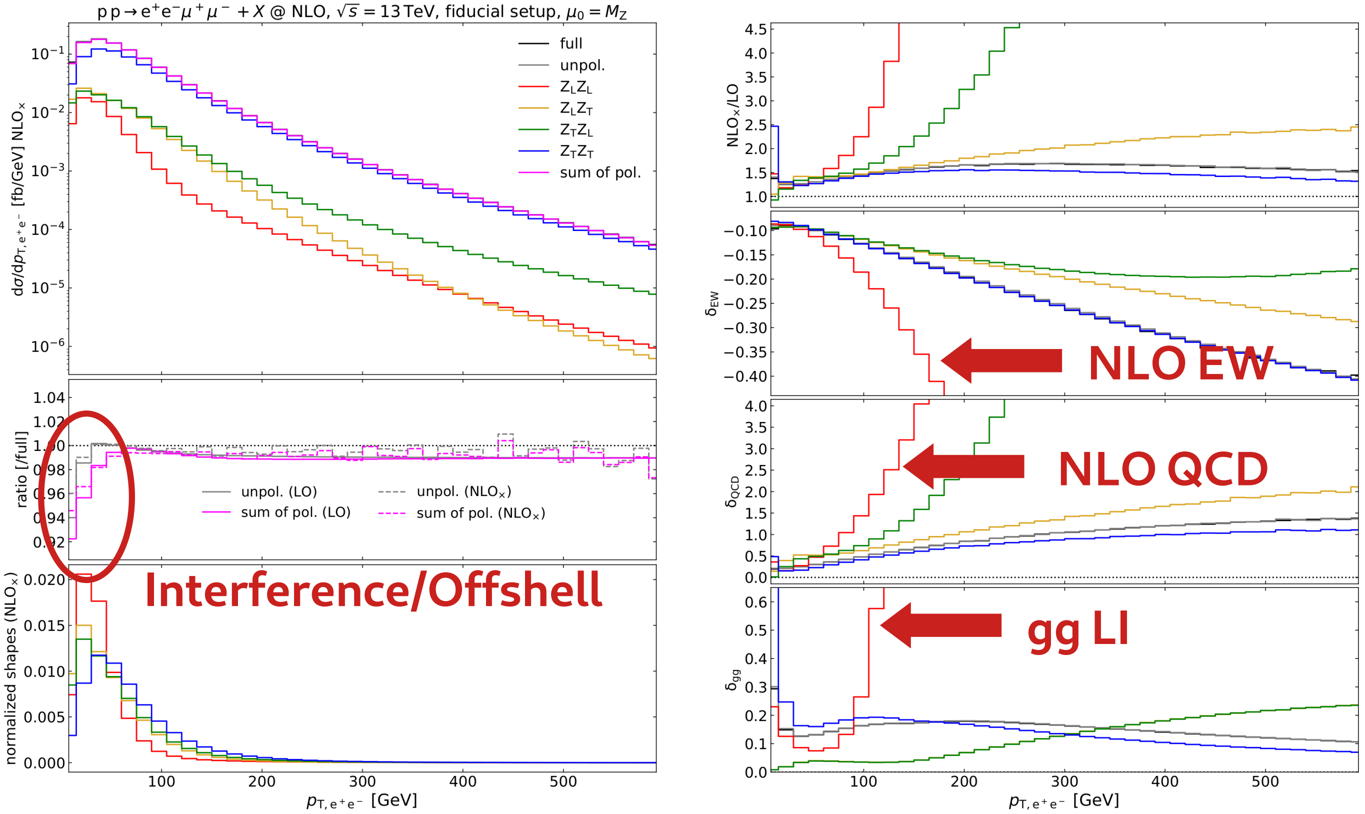
pp → ZZ → 4l NLO EW/QCD

NLO EW and QCD corrections to polarized ZZ production in the four-charged-lepton channel at the LHC,
Denner, Pellicciolì 2107.06579

Differential cross section

- Very large QCD, EW and gg-LI corrections for LL contribution
- Comparison to full predictions reveals interferences and off-shell effects
- Similar findings for WZ and WW final states, for example in:

Doubly-polarized WZ hadronic cross sections at NLO QCD+EW accuracy,
Duc Ninh Le, Baglio 2203.01470



Interference/Offshell

NLO EW

NLO QCD

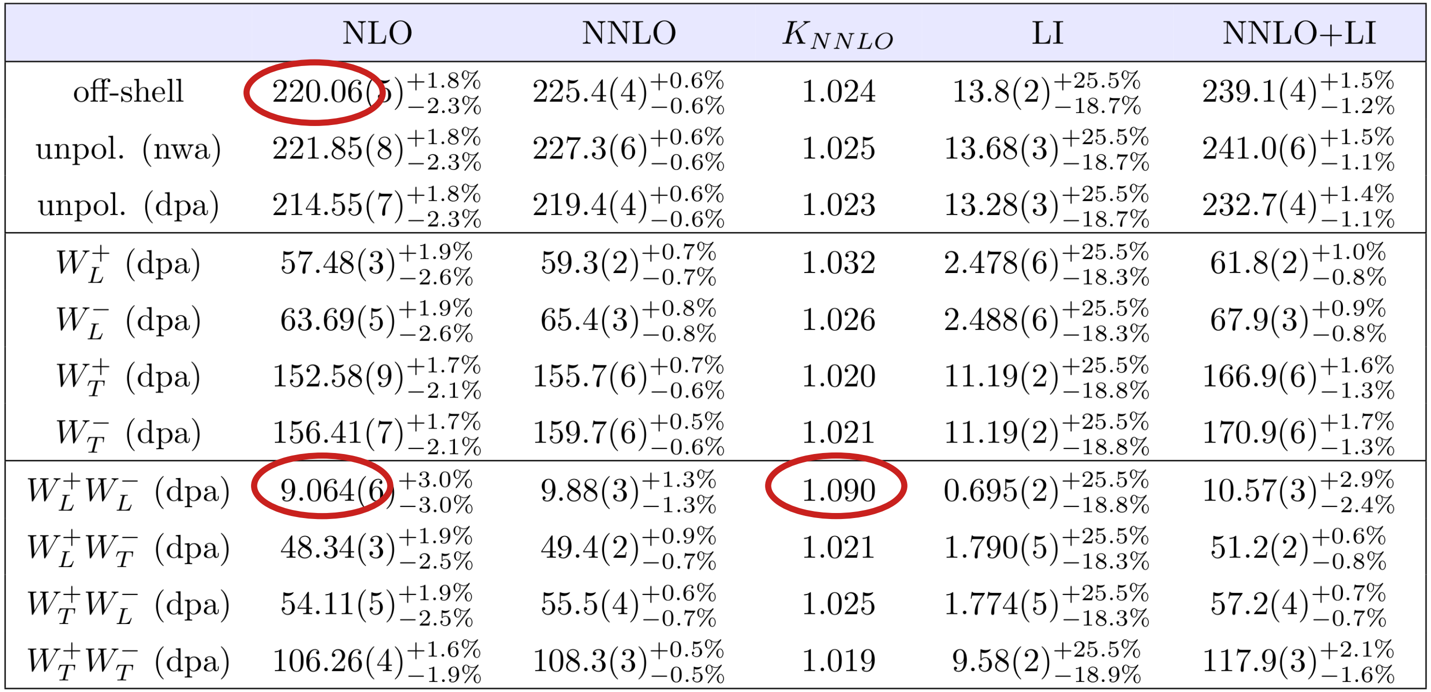
gg LI

pp → W+W- → e+ mu- ve vm NNLO QCD

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

LL gets largest NNLO QCD corrections

LI leads to sizeable corrections and enhanced scale dependence

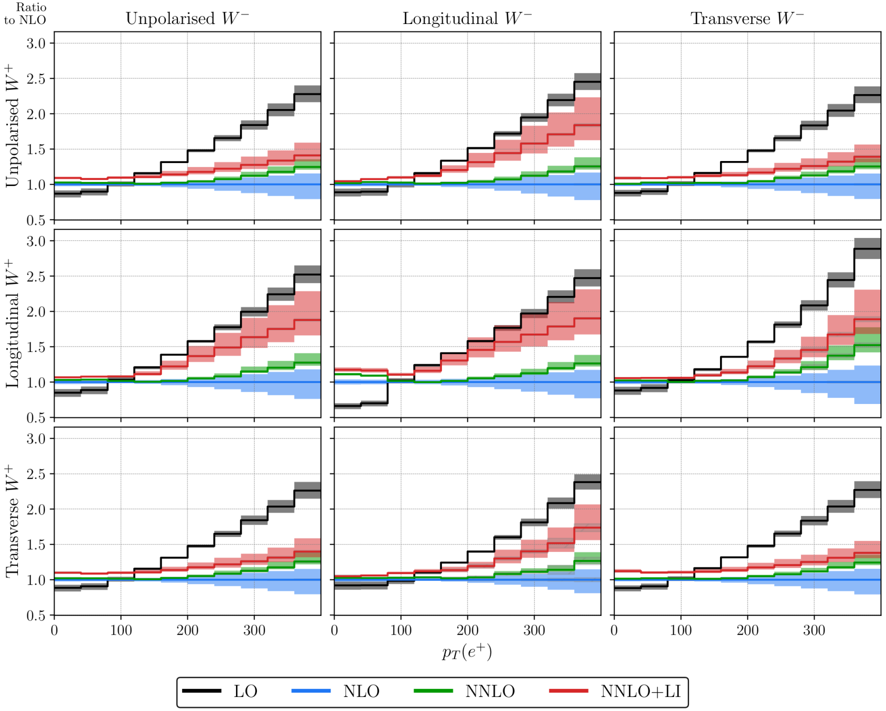


	NLO	NNLO	K_{NNLO}	LI	NNLO+LI
off-shell	$220.06(5)^{+1.8\%}_{-2.3\%}$	$225.4(4)^{+0.6\%}_{-0.6\%}$	1.024	$13.8(2)^{+25.5\%}_{-18.7\%}$	$239.1(4)^{+1.5\%}_{-1.2\%}$
unpol. (nwa)	$221.85(8)^{+1.8\%}_{-2.3\%}$	$227.3(6)^{+0.6\%}_{-0.6\%}$	1.025	$13.68(3)^{+25.5\%}_{-18.7\%}$	$241.0(6)^{+1.5\%}_{-1.1\%}$
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	$9.58(2)^{+25.5\%}_{-18.9\%}$	$117.9(3)^{+2.1\%}_{-1.6\%}$

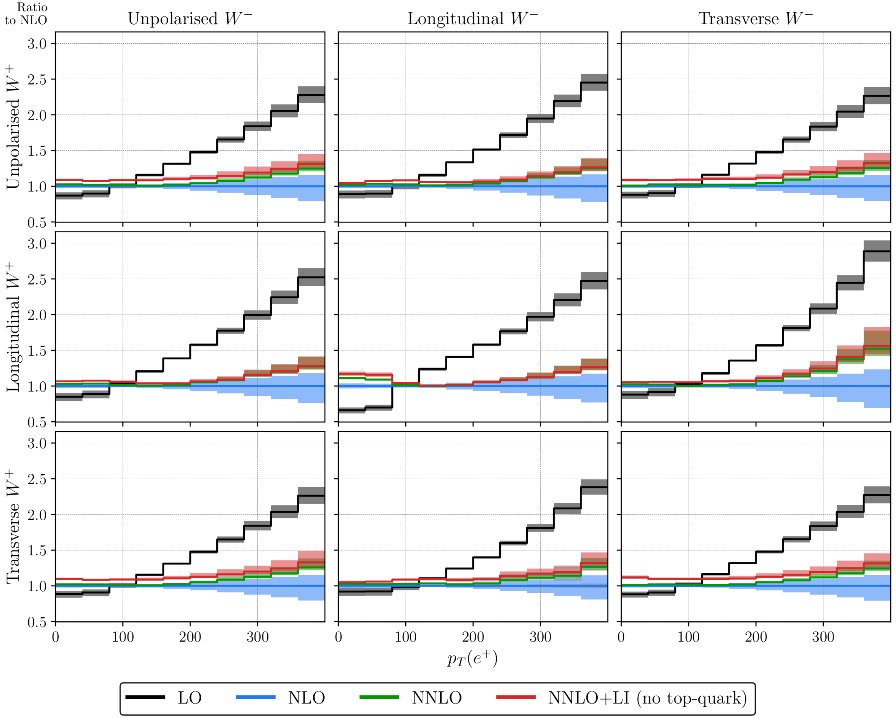
pp → W+W- → e+ mu- ve vm NNLO QCD

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

With top-quark loops in gg LI



Without top-quark loops in gg LI



Polarized W+jet @ NNLO QCD

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

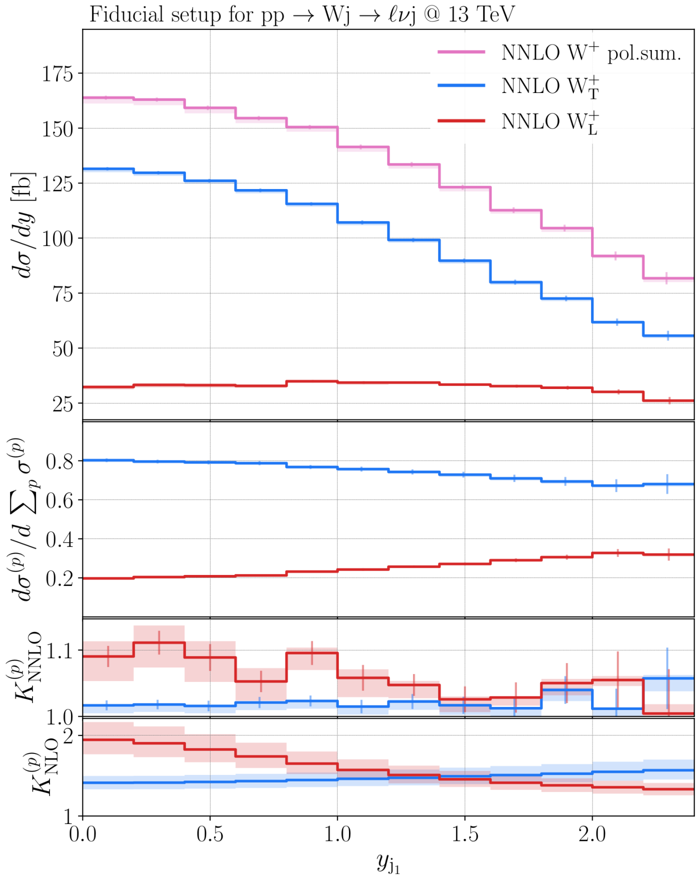
NNLO QCD predictions for polarized W production in fiducial and "inclusive" phase space

- Similar findings as in diboson: longitudinal component gets large QCD corrections:
  - up to 100% at NLO and 10 % NNLO
  - significant reduction of scale dependence
- How do higher order corrections impact extractions of polarization fractions?

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = f_T \frac{\mathrm{d}\sigma_T}{\mathrm{d}X} + f_L \frac{\mathrm{d}\sigma_L}{\mathrm{d}X} \left(\cancel{+ f_{int} \frac{\mathrm{d}\sigma_{int.}}{\mathrm{d}X}} \right)$$

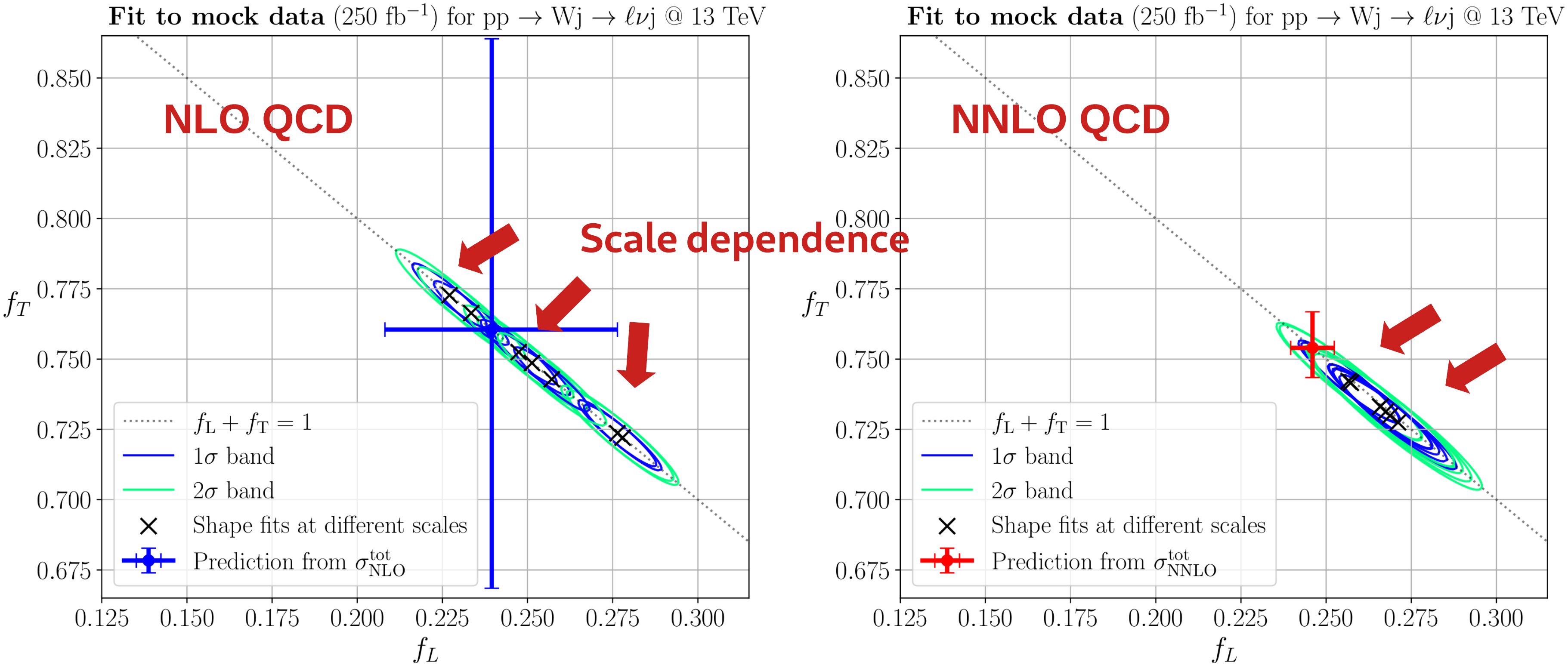
→ 0

(by selecting regions with little interferences)



W+jet: mock-data fit

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

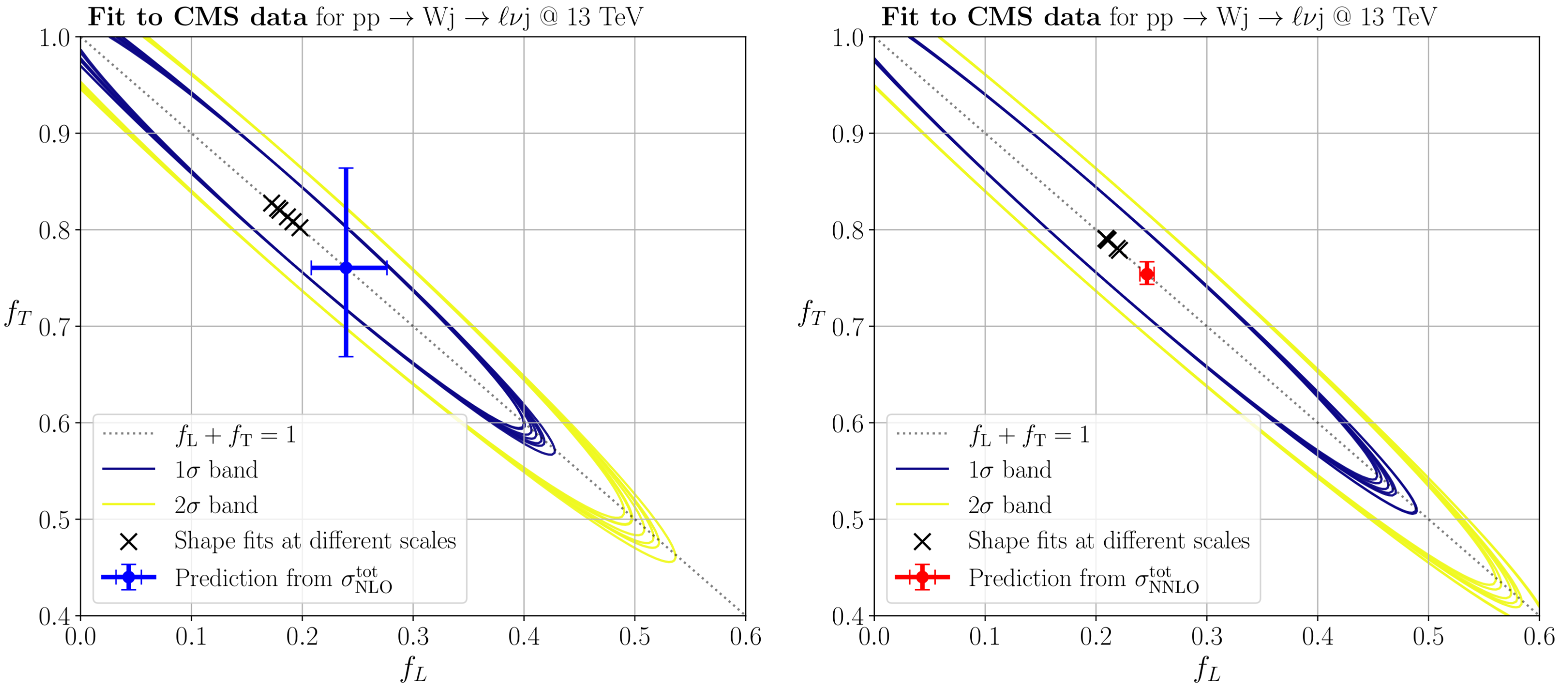


W+jet : fit to CMS data

Second: Fit to actual data

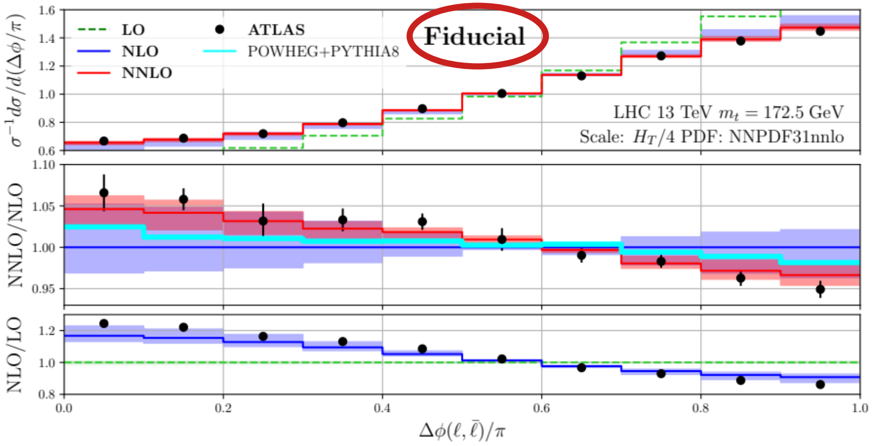
Measurement of the differential cross sections for the associated production of a W boson and jets in proton-proton collisions at \sqrt{s}=13 TeV, CMS 1707.05979

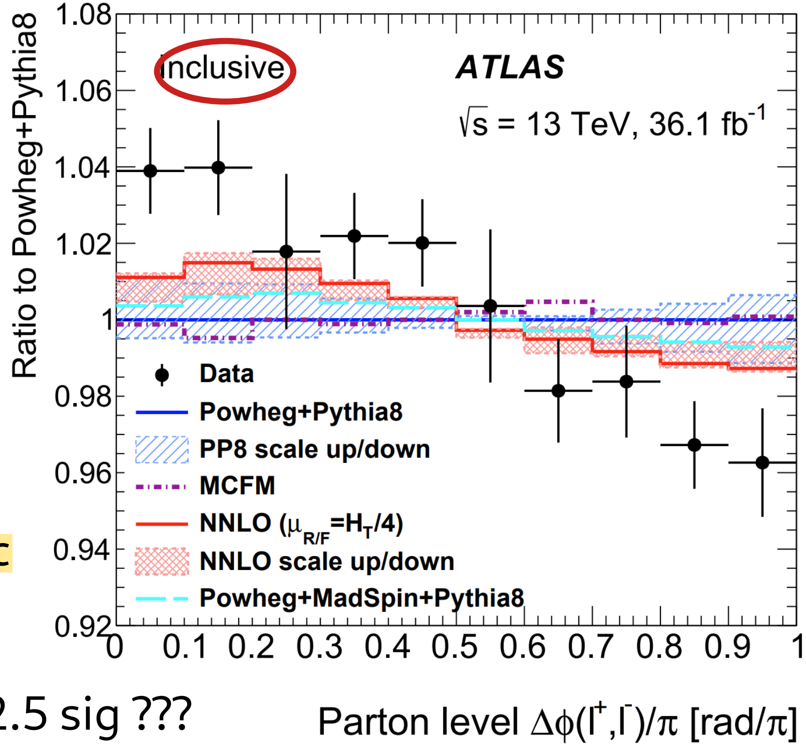
→ so far dominated by experimental uncertainties:



Remark: Lessons from ttbar

Measurements of top-quark pair spin correlations in the e mu channel at \sqrt{s} = 13 TeV using pp collisions in the ATLAS detector, ATLAS 1903.07570





Higher order corrections to spin correlations in top quark pair production at the LHC
Behring, Czakon, Mitov, Papanastasiou, Poncelet 1901.05407

Extrapolation with
Powheg+Pythia (NLO+PS) → ~2.5 sig ???
Higher order corrections?!

Conclusion & outlook

Summary:

- Increasing interest in studying polarized bosons
  → triggered by exciting prospects for future precise measurements
- Higher order corrections are crucial to measure polarization fractions accurately.
  → Efforts to provide fixed order predictions at (N)NLO QCD and NLO EW
  Diboson and single boson final states: WW, WZ, ZZ, W+jet

Outlook:

- More realistic simulations require parton shower effects.
- Higher order corrections for single-boson or boson pairs
  → Corrections to polarized VBS?

Thank you!