# Precision Predictions for Polarized Electroweak Bosons

Rene Poncelet
based on 2102.13583 and 2109.14336 in collaboration with Mathieu Pellen and Andrei Popescu

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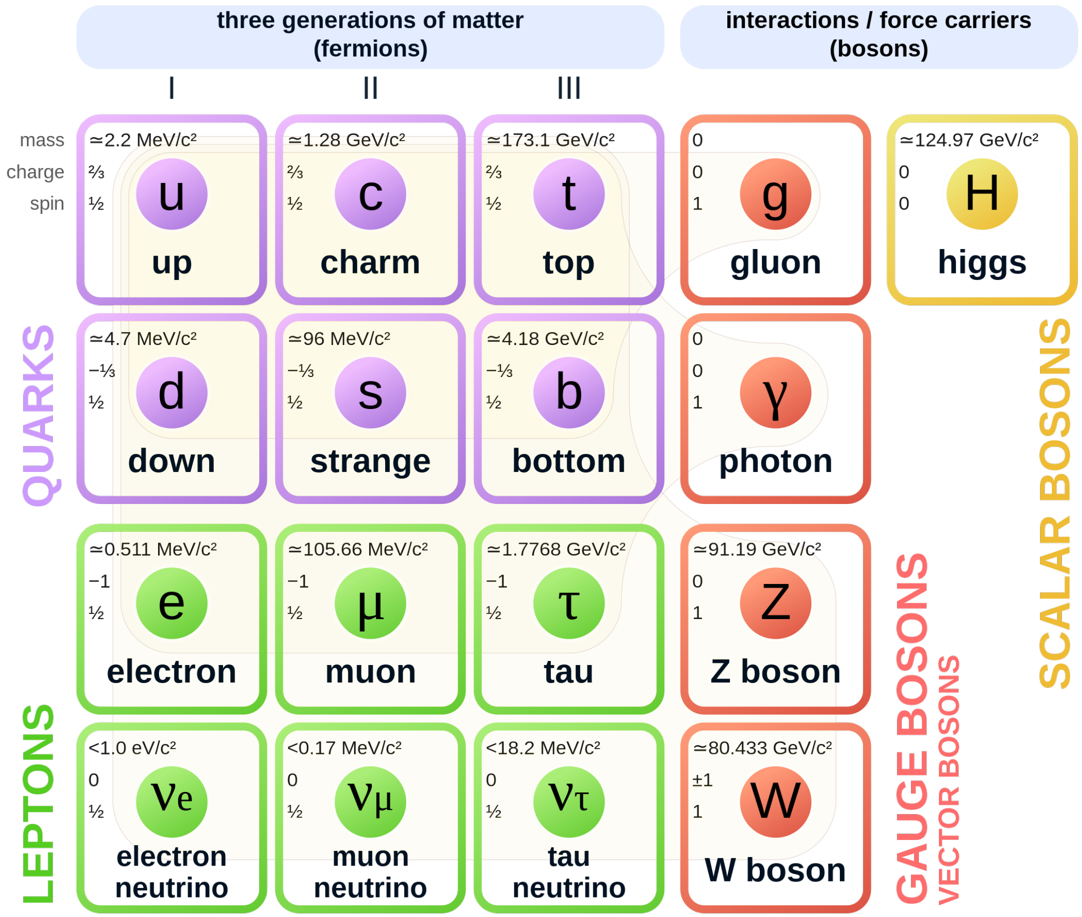
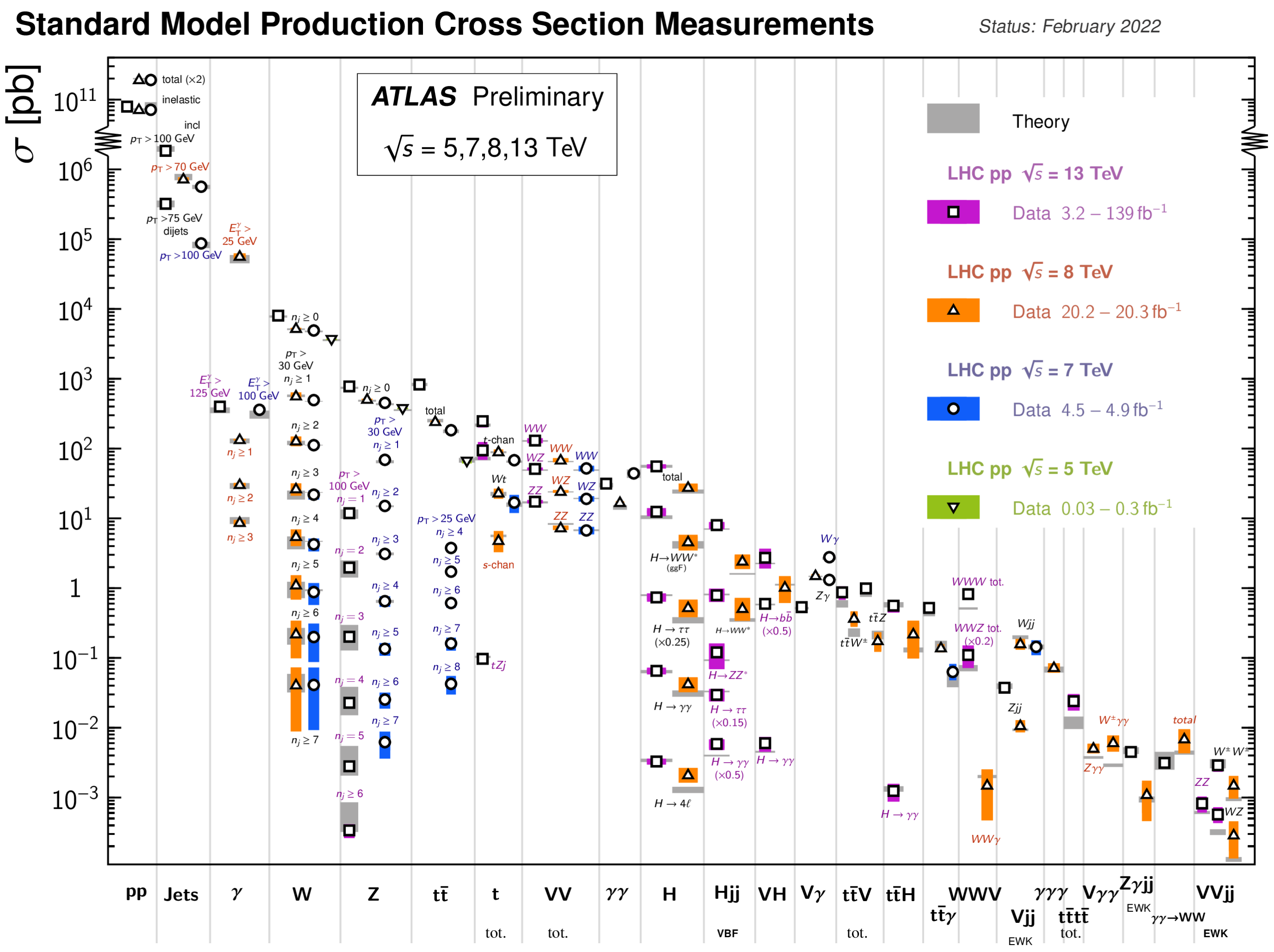
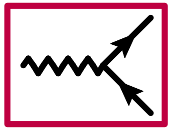
# Standard Model of Elementary Particles

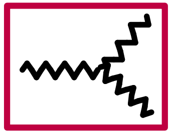



Standard Model Production Cross Section Measurements
Status: February 2022
ATLAS Preliminary
√s = 5,7,8,13 TeV
σ [pb]
Theory
LHC pp √s = 13 TeV
Data 3.2 – 139 fb−1
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb−1
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb−1
LHC pp √s = 5 TeV
Data 0.03 – 0.3 fb−1
total (×2)
inelastic
incl
dijets
total
t-chan
s-chan
Wt
tZj
WW
WZ
ZZ
H→WW*
H → ττ
H → γγ
H → 4ℓ
H→ZZ*
H→bb̄
Wγ
Zγ
tt̄W±
tt̄Z
WWW tot.
WWZ tot.
WWγ
Wjj
Zjj
W±γγ
Zγγ
W±W±
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
Hjj
VH
Vγ
tt̄V
tt̄H
tt̄γ
WWV
Vjj
γγγ
tt̄tt̄
Vγγ
Zγjj
γγ→WW
VVjj
tot.
VBF
EWK

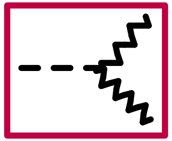
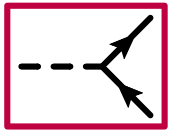
# Interactions of the electroweak sector



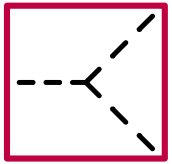
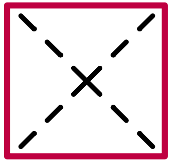
Vff : Drell-Yan processes and decays



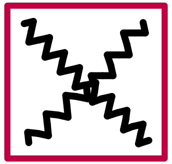
VVV: LEP and VV production at hadron colliders

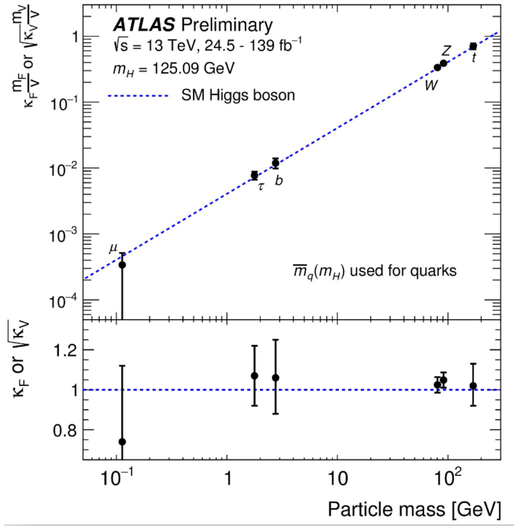
HVV/Hff: Higgs-production and decays

Higgs self-interactions: not yet measured

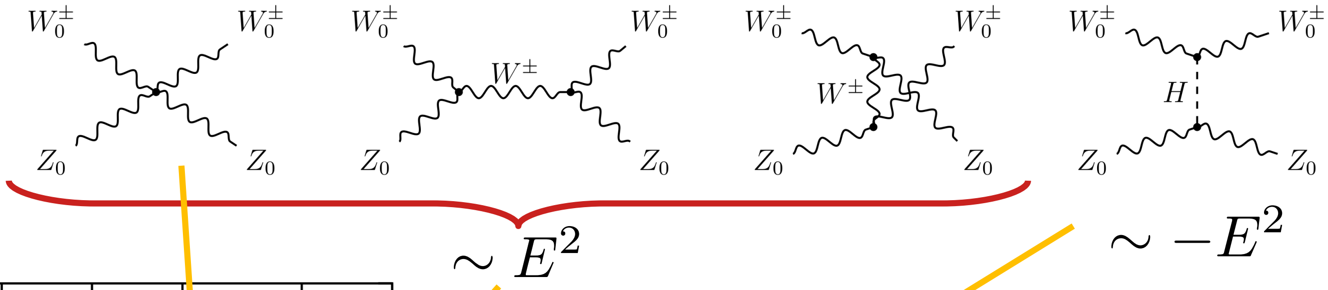


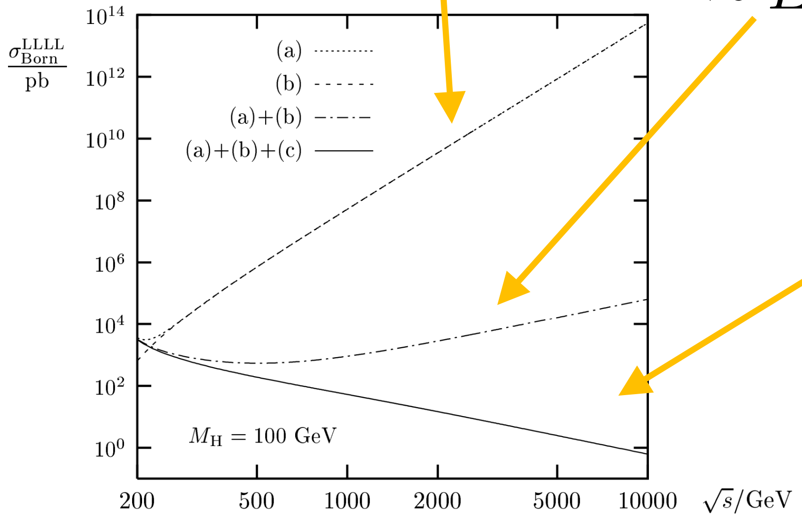
Quartic V-couplings: constraints limited by data




EWSB mechanism?

# Longitudinal Vector-Boson-Scattering (VBS)



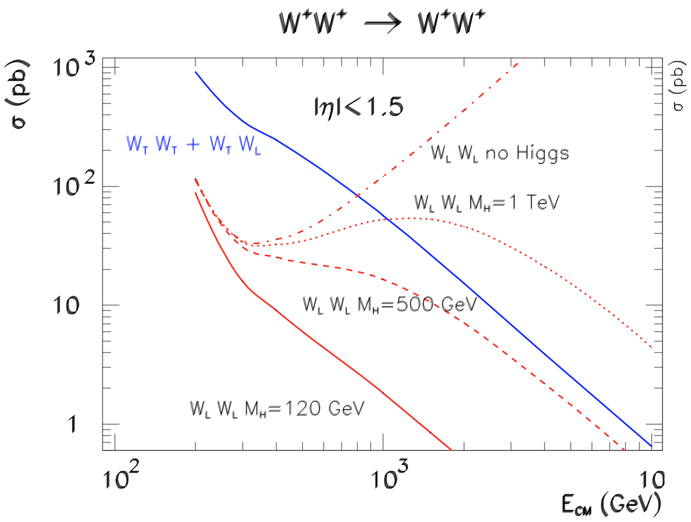

- Measurement of polarized boson scattering or production probes:
  - EWSB mechanism
  - Higgs and gauge sector
  - New physics models

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

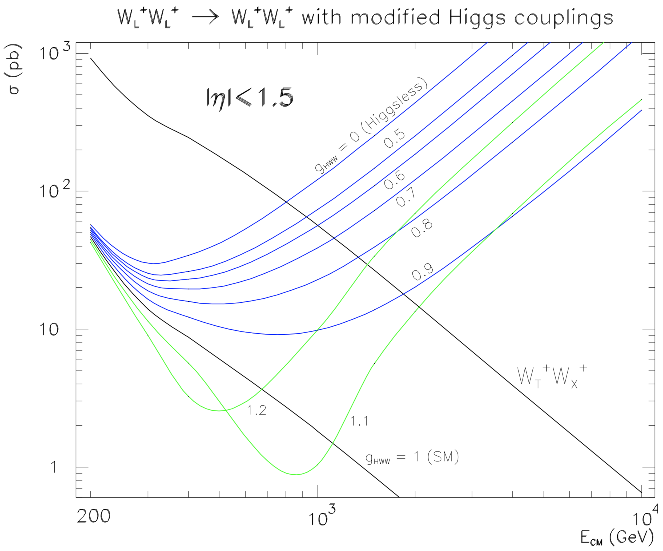
# Longitudinal Vector-Boson-Scattering (VBS)

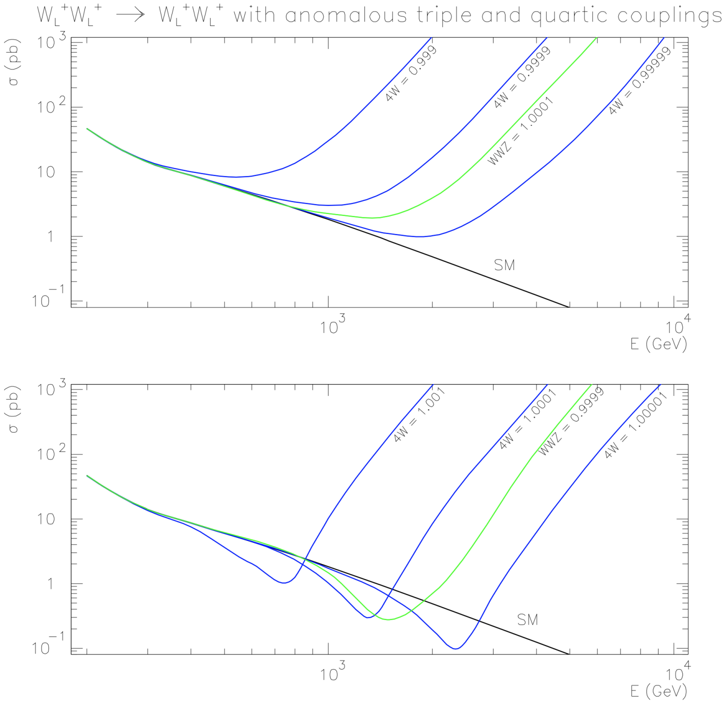
**The Higgs boson and the physics of WW scattering before and after Higgs discovery**
M. Szleper 1412.8367

Sensitivity to the Higgs mass



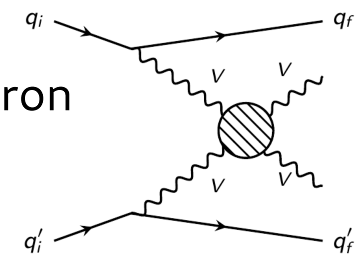

Modified HVV, VVV, VVVV couplings



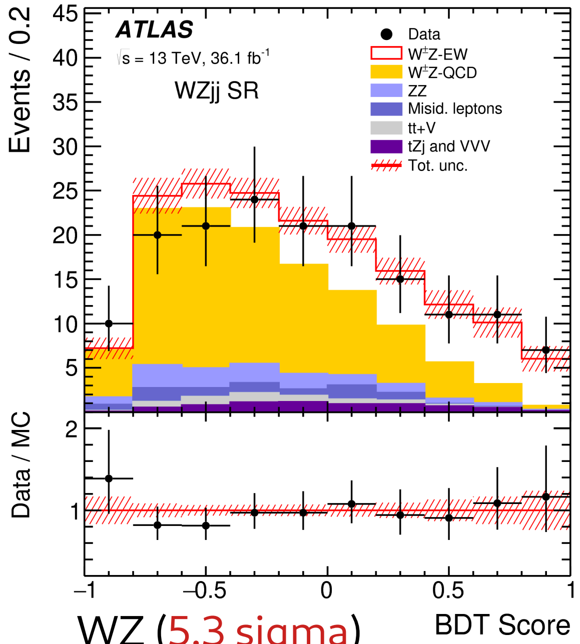



# VBS at hadron colliders

VBS at hadron colliders

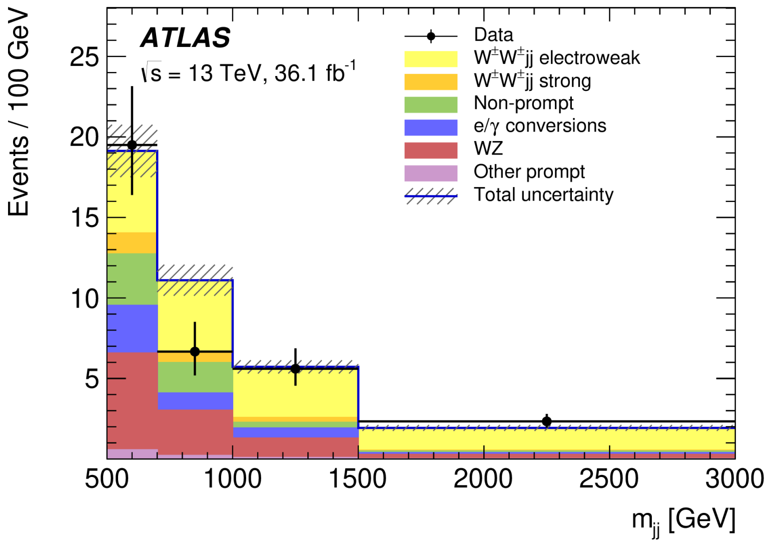



Separate from background processes through VBS topology
→ a rare process, but observed.



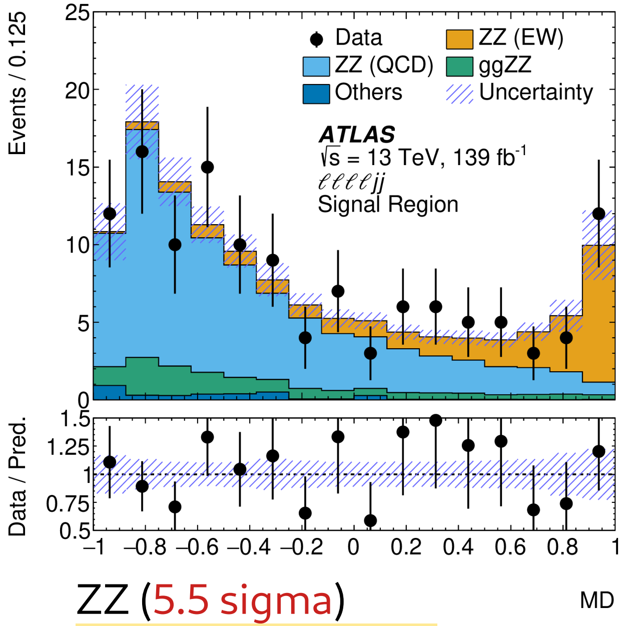

WZ (5.3 sigma)

ATLAS 1812.09740




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

ATLAS 1906.03203




ZZ (5.5 sigma)

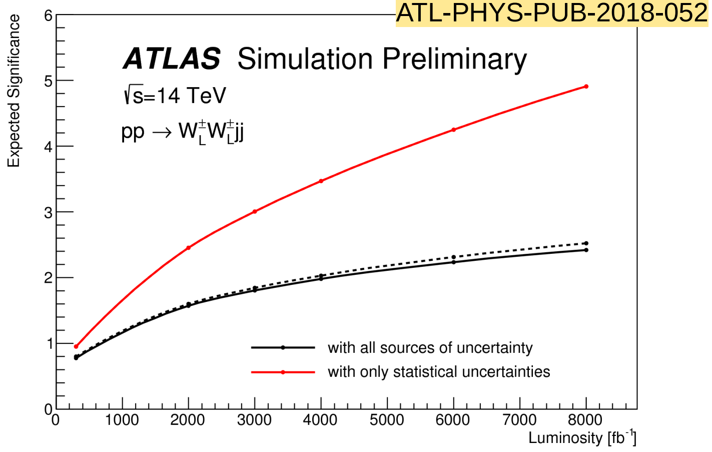
ATLAS 2004.10612

# 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

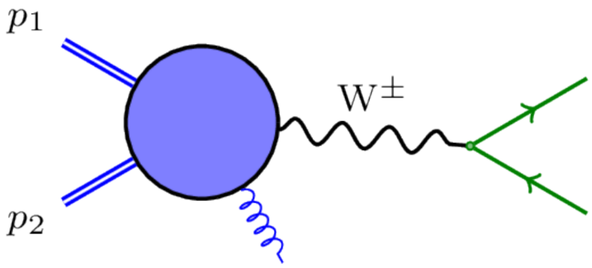



Complementary investigation of polarized bosons in other processes:

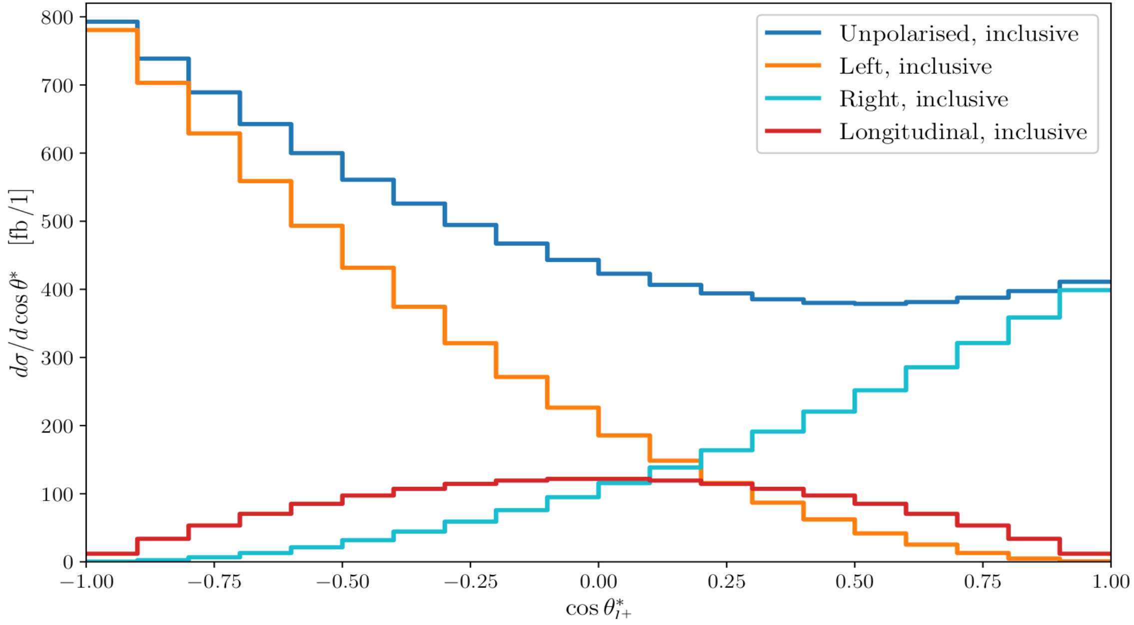
**Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC,**
CMS 1104.3829
**Measurement of the polarisation of W bosons produced with large transverse momentum in pp collisions at \sqrt{s}=7 TeV with the ATLAS experiment,**
ATLAS 1203.2165
**Measurement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

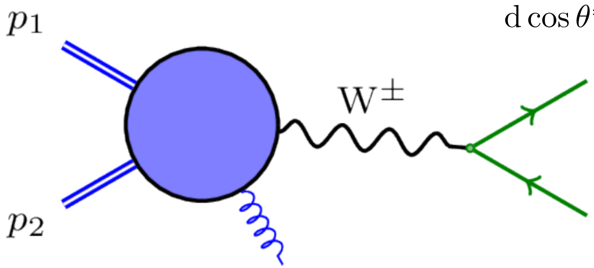



W+ decay (W- mirrored around 0)



# 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.

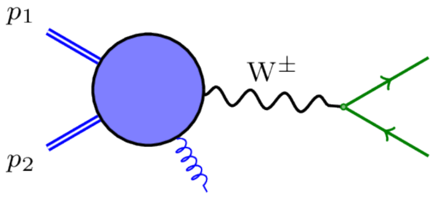
# Practical considerations

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

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

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

# Overview SM results

- Polarised VBS (so far LO):
  **W boson polarization in vector boson scattering at the LHC,**
  Ballestrero, Maina, Pelliccioli 1710.09339
  **Polarized vector boson scattering in the fully leptonic WZ and ZZ channels at the LHC,**
  Ballestrero, Maina, Pelliccioli 1907.04722
  **Automated predictions from polarized matrix elements**
  Buarque Franzosi, Mattelaer, Ruiz, Shil 1912.01725
  **Different polarization definitions in same-sign WW scattering at the LHC**,
  Ballestrero,Maina, 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

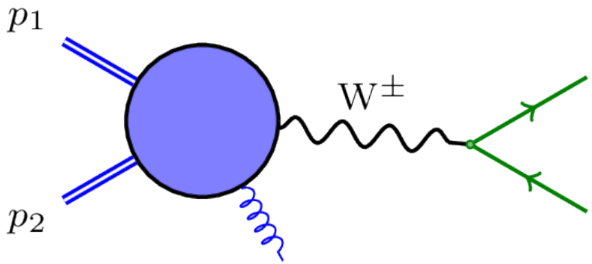
# Overview SM results

## Polarized Diboson (N)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, 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 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 relatively 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

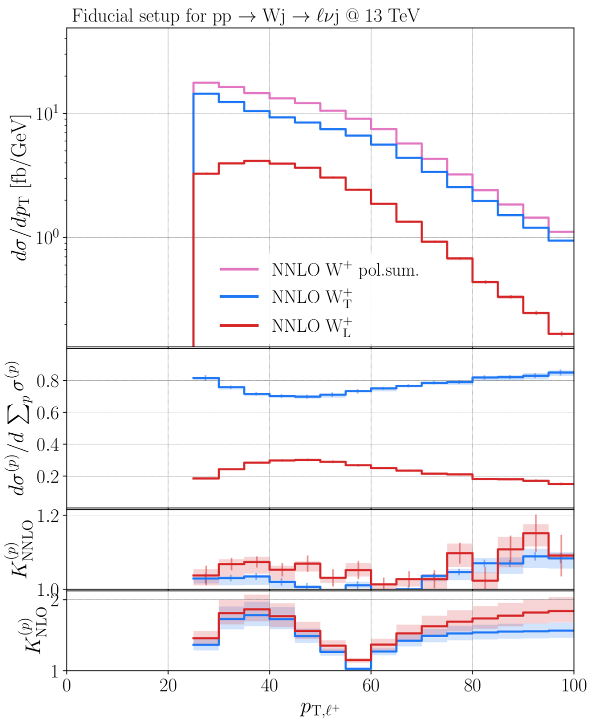
- Lepton cuts: $p_T(\ell) \geq 25$ GeV, $|\eta(\ell)| \leq 2.5$ and $\Delta R(\ell, j) > 0.4$
- Transverse mass of the W: $M_T(W) = \sqrt{m_W^2 + p_T^2(W)} \geq 50$ GeV

Technical aspects:

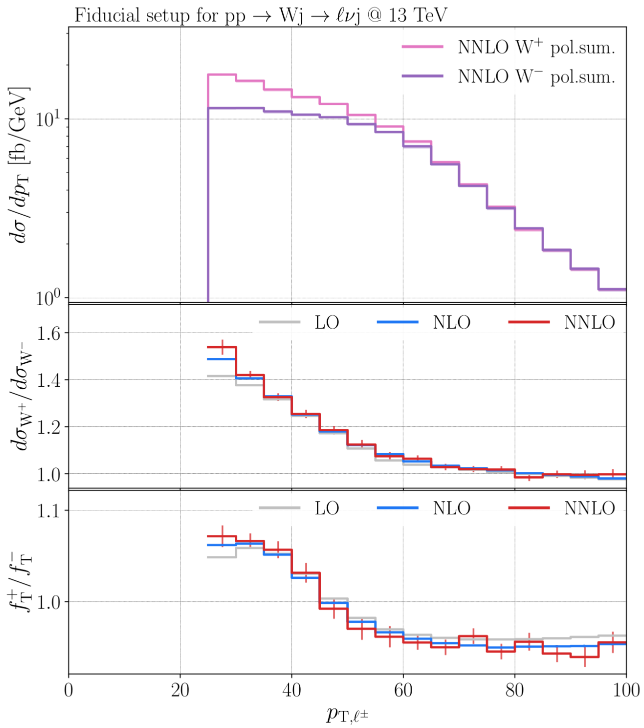
- NNPDF31 and dynamical scale choice: $\mu_R = \mu_F = \frac{1}{2}\left(m_T(W) + \sum p_T(j)\right)$
- Implementation in STRIPPER framework (NNLO QCD subtractions) [1408.2500]
  - Narrow-Width-Approximation and OSP/Pole-Approximation
  - Matrix elements from: AvH[1503.08612], OpenLoops2 [1907.13071](cross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

# Example: lepton transverse momentum

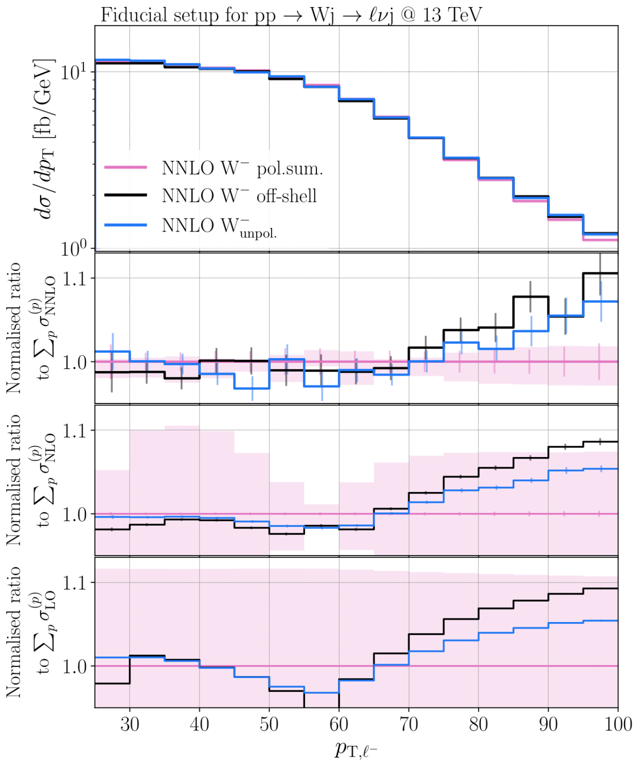
## Perturbative corrections




## Charge differences




## Off-shell/Interference effects



# Extraction of polarisation fractions

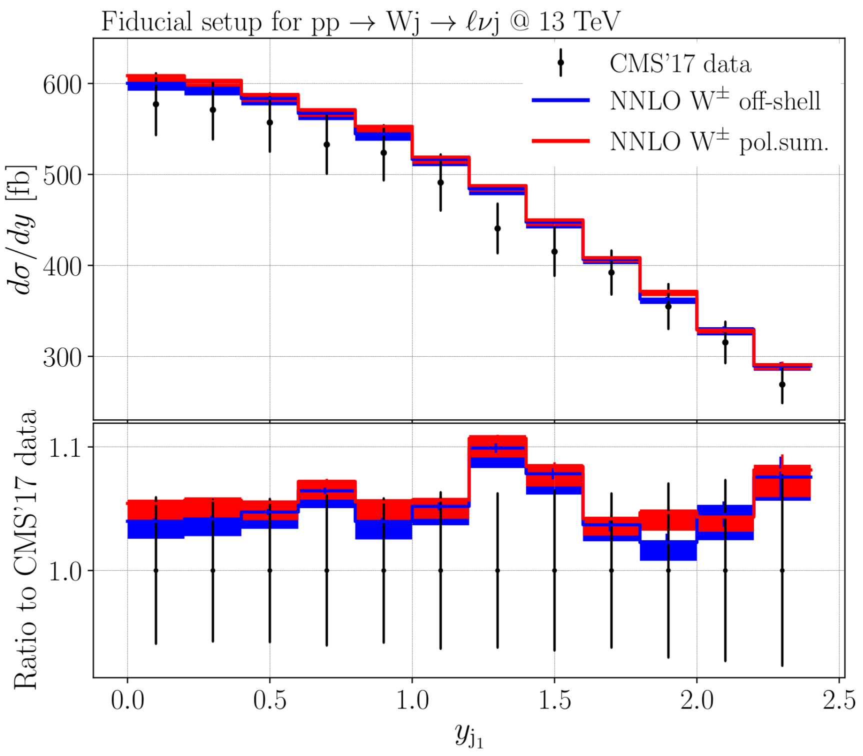
Identified 4 observables (ranges) with

→ Small interference effects (<2%)

→ Small off-shell effects (<2%)

→ Shape differences between L and T

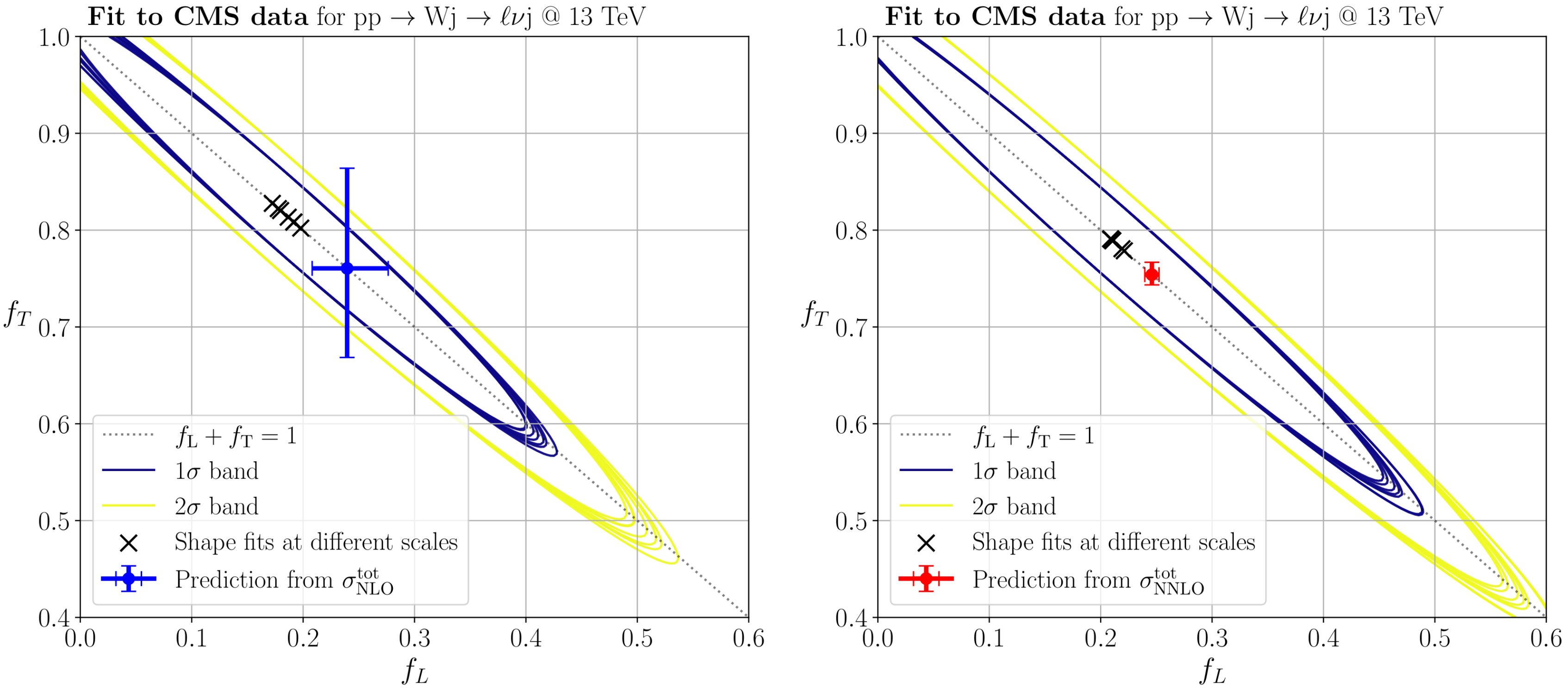
- $\Delta\phi(\ell, j_1) \geq 0.3$
- $25\ \mathrm{GeV} \leq p_T(\ell) < 70\ \mathrm{GeV}$
- $\cos(\theta^*_\ell) \geq -0.75$
- $|y(j_1)| \leq 2$



# W+jet : fit to CMS data

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

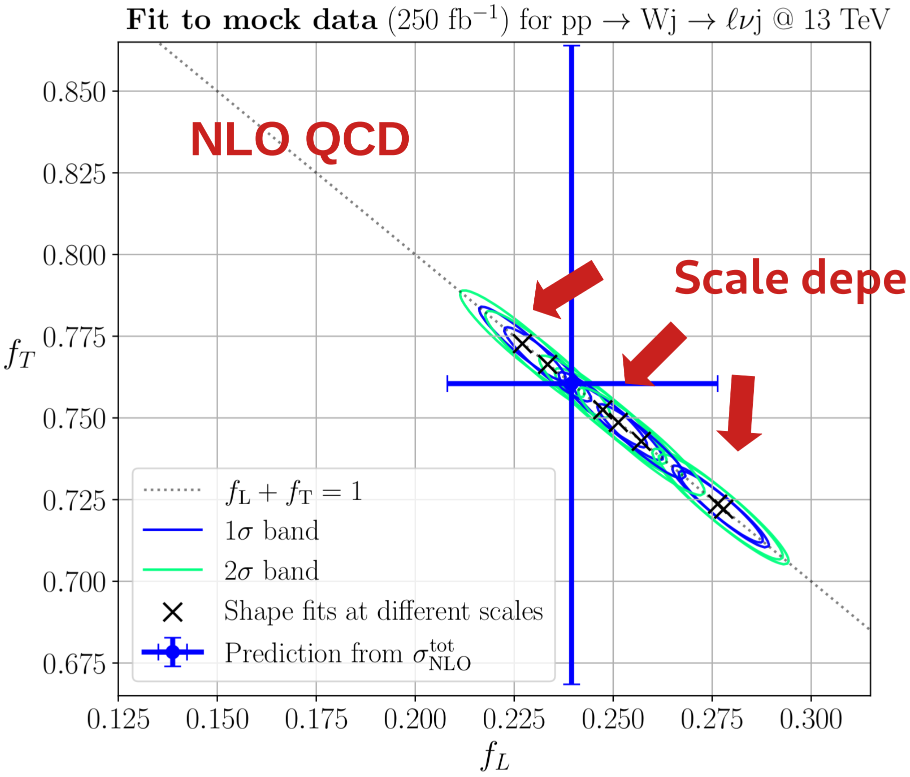
→ dominated by experimental uncertainties (no correlations available)

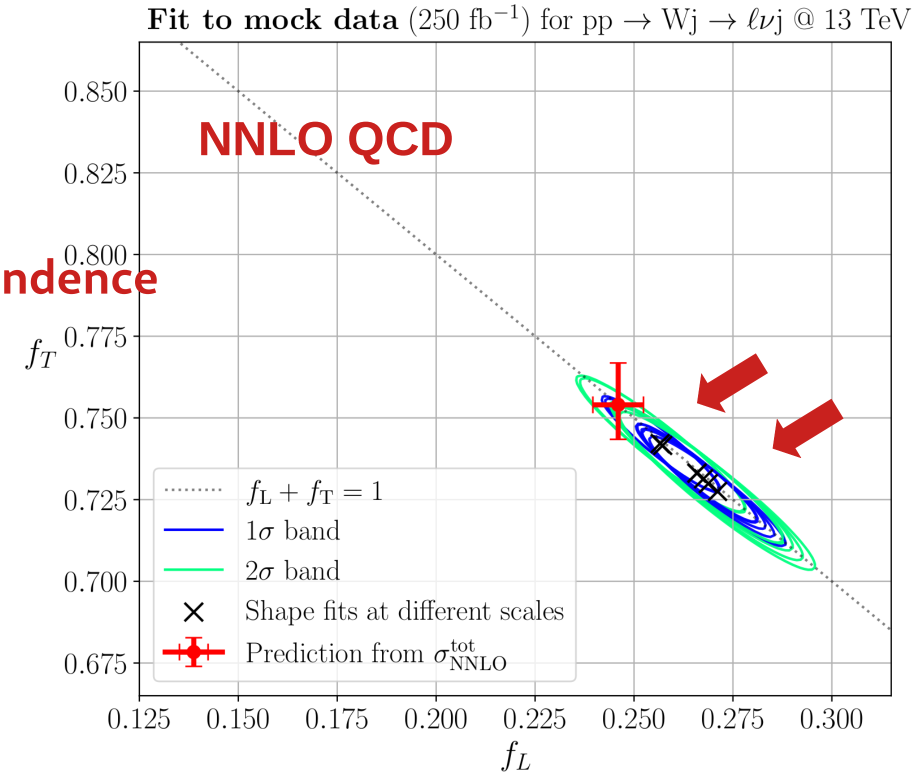


# W+jet: mock-data fit

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

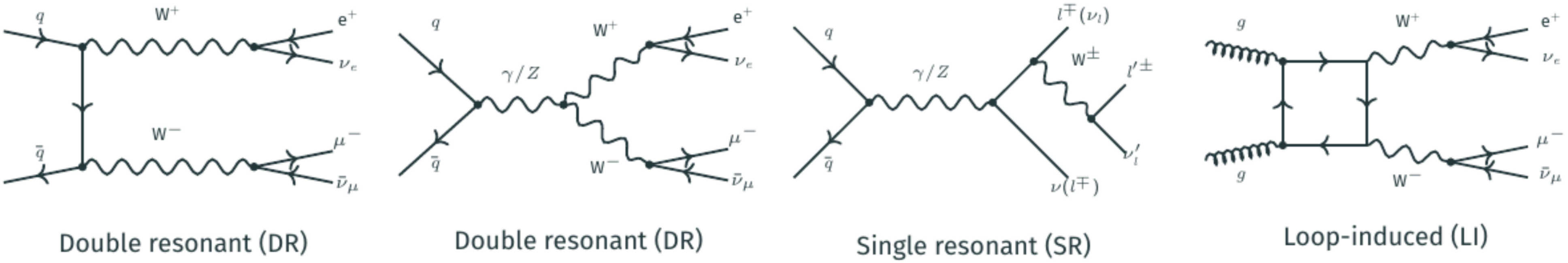
$\cos(\ell, j_1)$



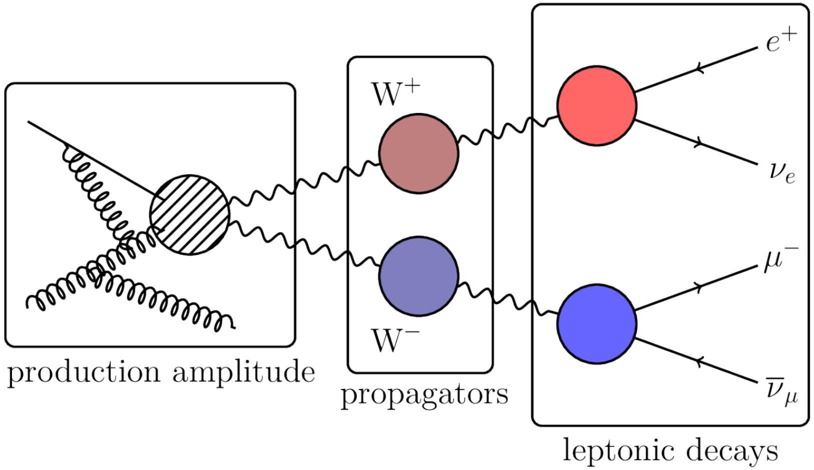



# Polarised W+W-

# W-boson pair production




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



# Setup W-boson pair production

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

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

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

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

Technical aspects:

- Massive b-quarks → get rid of top production ( $pp \to b\bar{b}W^+W^-$ enters at NNLO)
- NNPDF31 and a fixed renormalisation scale: $\mu_R = \mu_F = m_W$
- STRIPPER

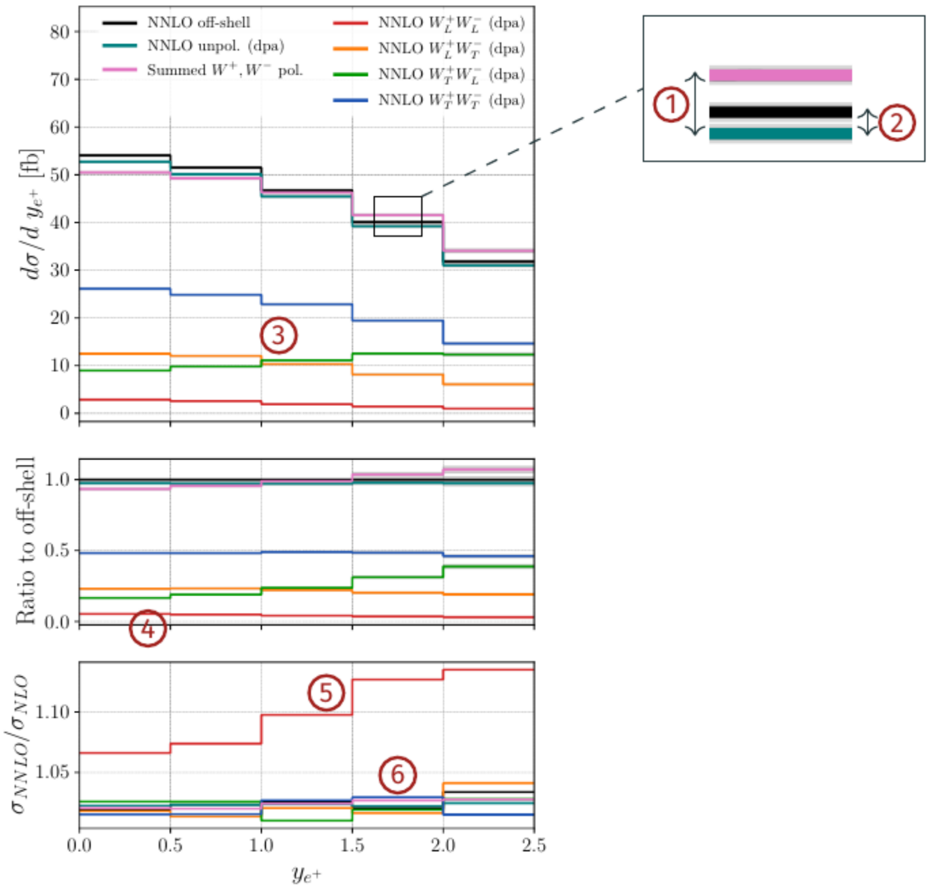
# Doubly polarised cross sections

| | 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

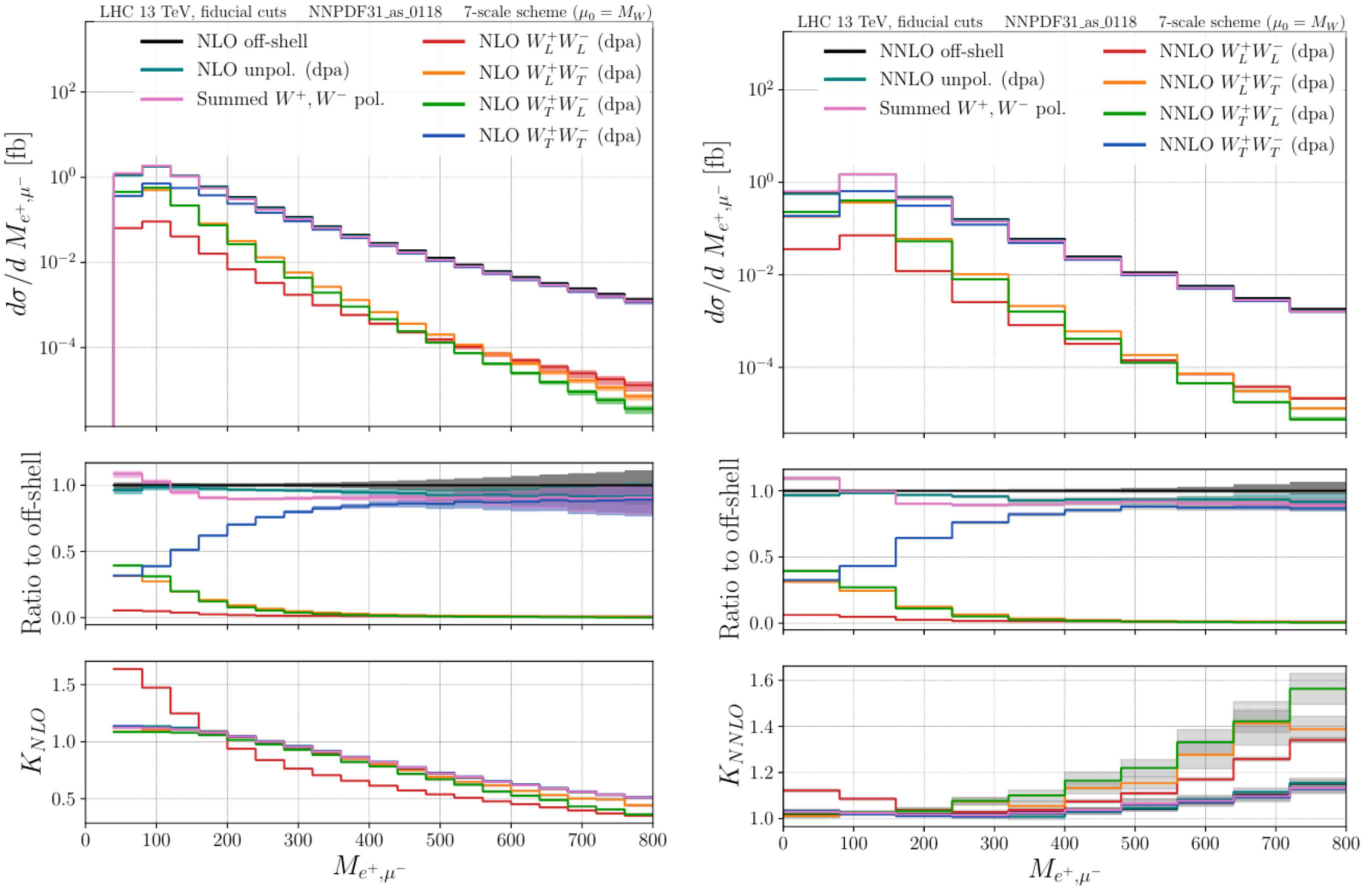
### Summary:

→ NNLO effects are **2-3%** of $\sigma_{tot}$ 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.

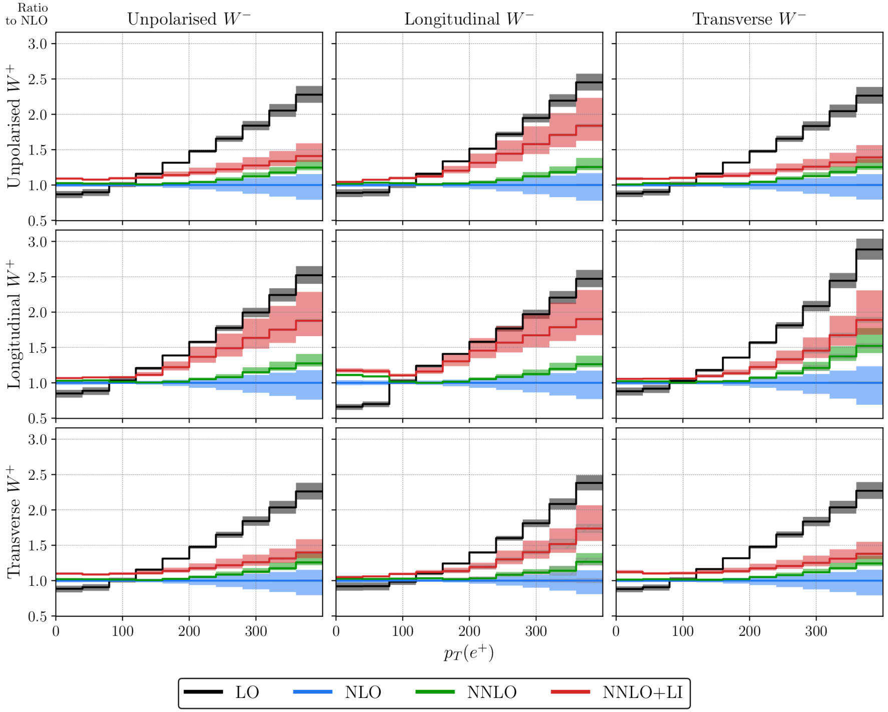
# Polarised di-boson production

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

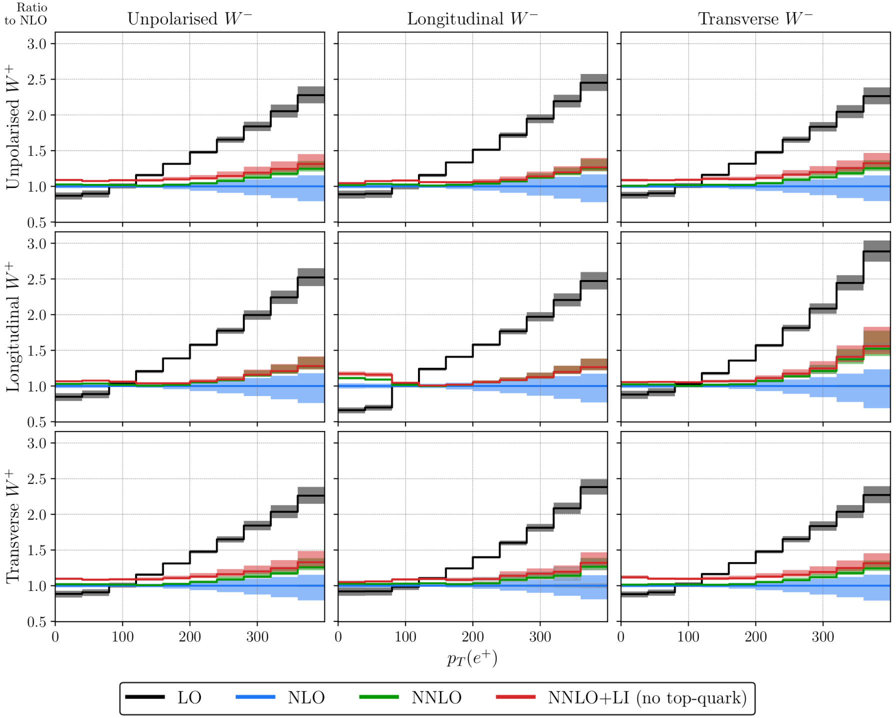


# Loop induced gg → WW contributions

## With top-quark loops in gg LI




## Without top-quark loops in gg LI



# Conclusion & Outlook

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 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 → usable input for experiment
- Higher order corrections for single-boson or boson pairs
  → Corrections to polarized VBS?

Thank you!

# Backup

# 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: $\phi^\dagger\phi = \frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2}$

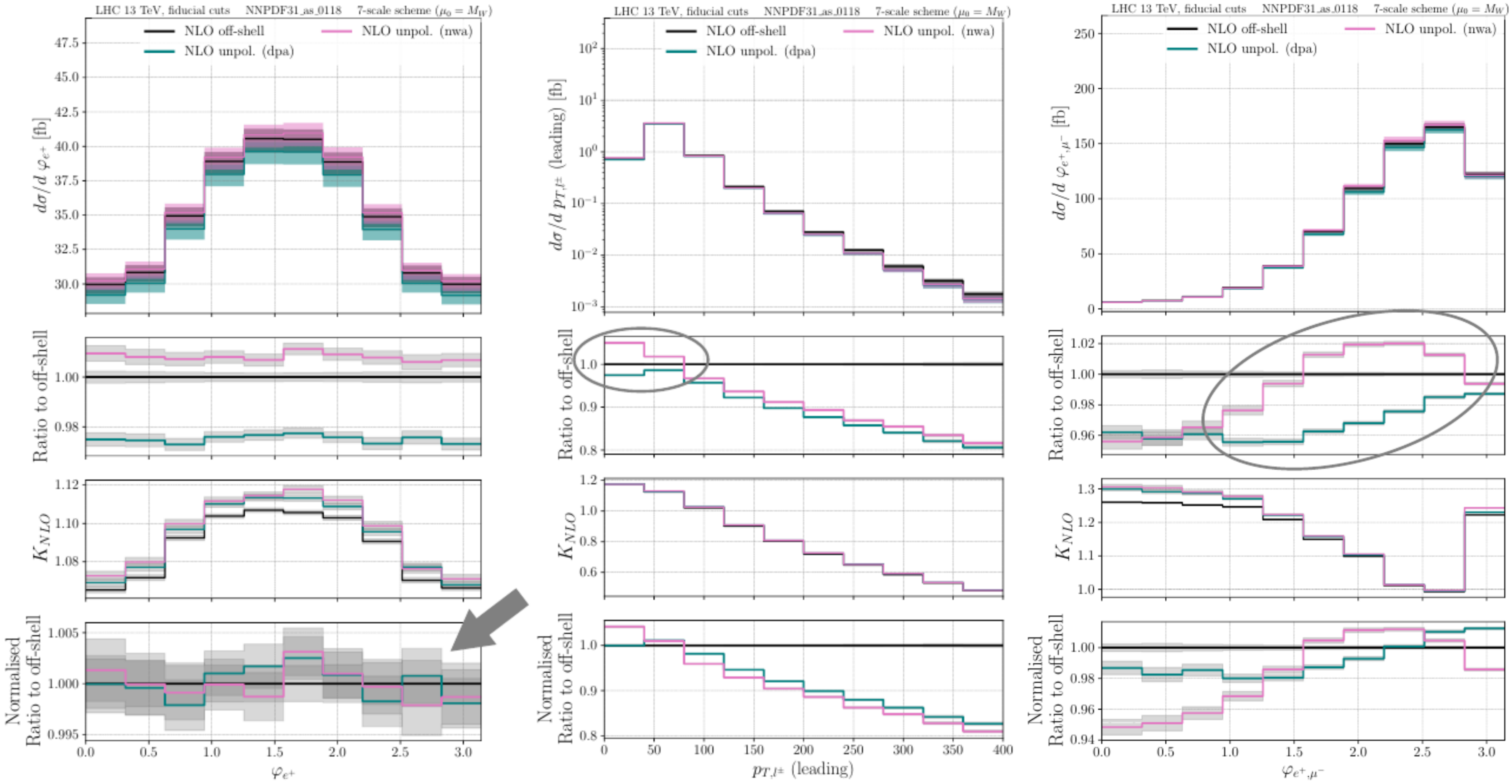
- Goldstone bosons can be absorbed via gauge transformation (unitary gauge).
  This gives rise to massive gauge bosons:

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

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

- Restores renormalizability and unitarity

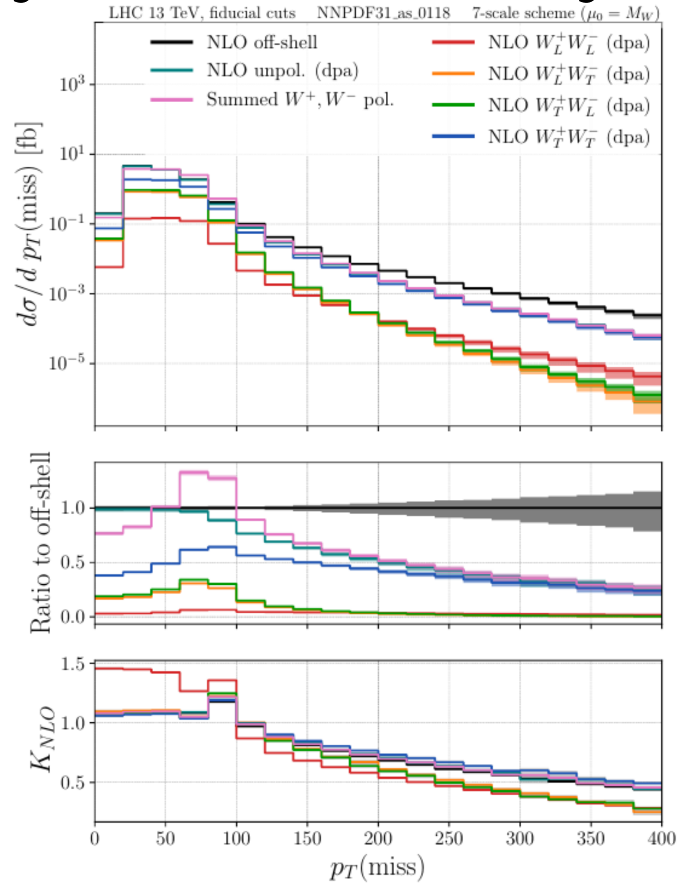
# NWA vs. DPA

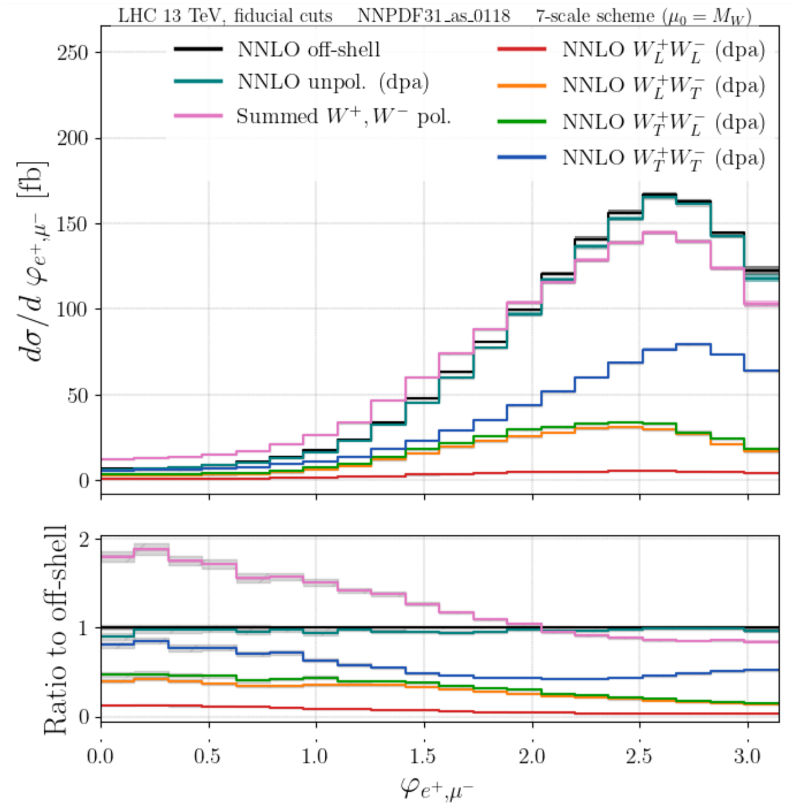


LHC 13 TeV, fiducial cuts NNPDF31_as_0118 7-scale scheme ($\mu_0 = M_W$)
NLO off-shell
NLO unpol. (nwa)
NLO unpol. (dpa)
$d\sigma/d\,\varphi_{e^+}$ [fb]
Ratio to off-shell
$K_{NLO}$
Normalised Ratio to off-shell
$\varphi_{e^+}$
$d\sigma/d\,p_{T,l^\pm}$ (leading) [fb]
$p_{T,l^\pm}$ (leading)
$d\sigma/d\,\varphi_{e^+,\mu^-}$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

# Interference and off-shell effects

Large off-shell effect from single-resonant contributions




Large interference effects through phase space constraints