Precision Predictions for Polarized Electroweak Bosons

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based on 2102.13583, 2109.14336 and 2204.12394
in collaboration with Mathieu Pellen and Andrei Popescu

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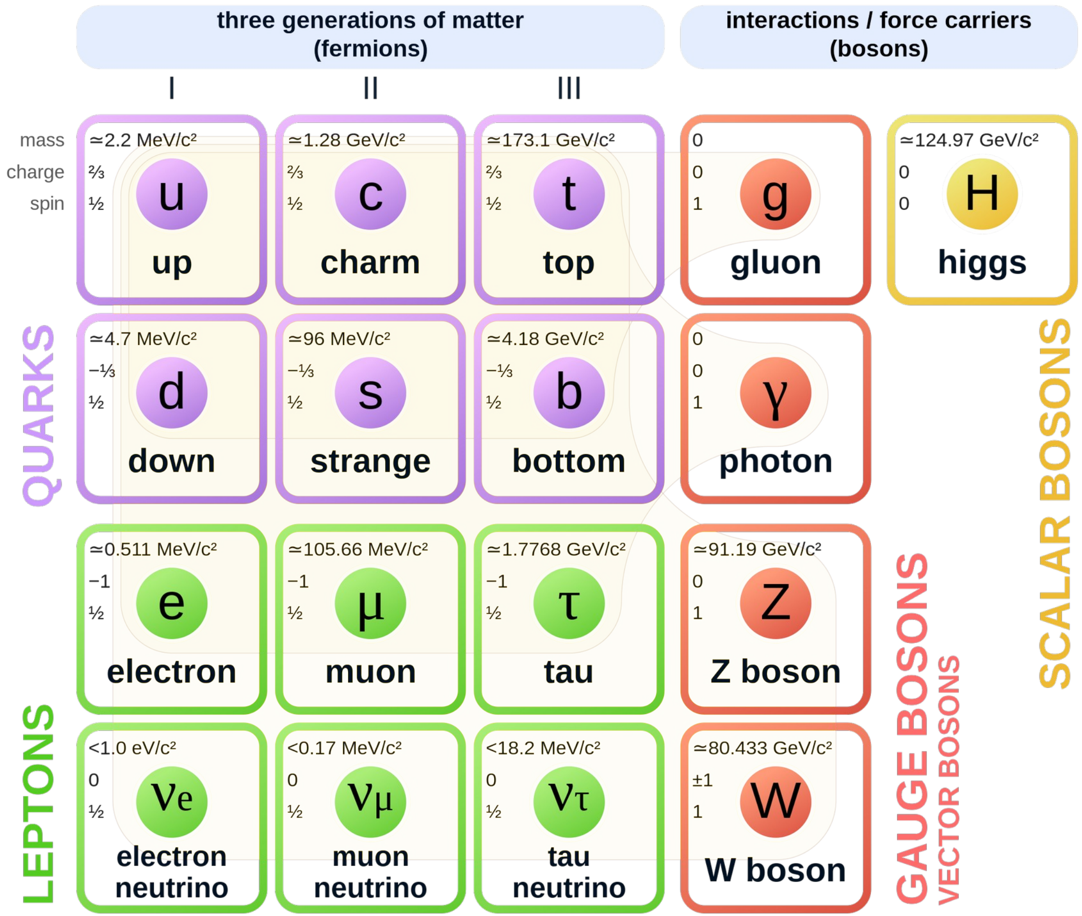
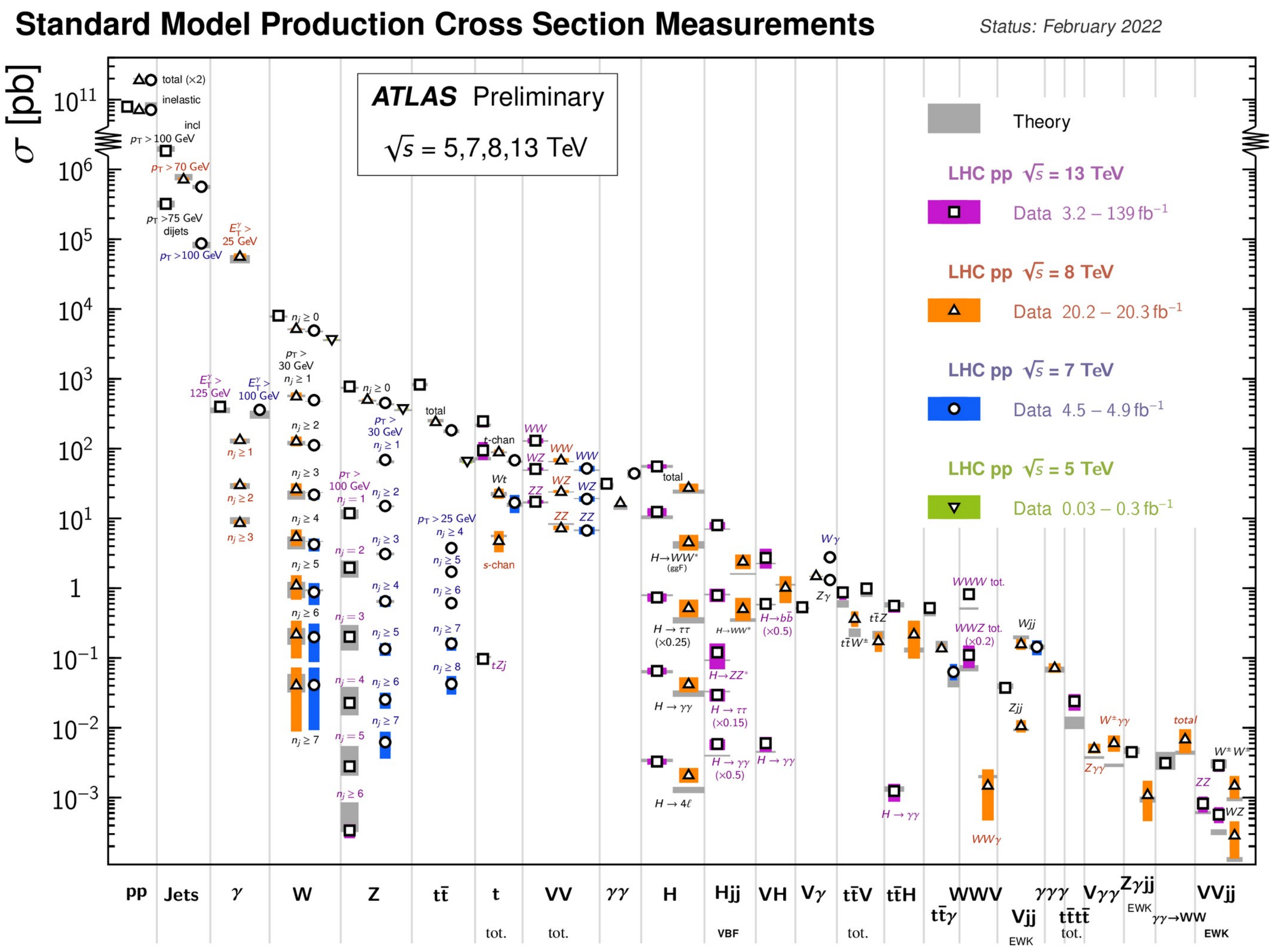
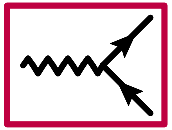
Standard Model of Elementary Particles

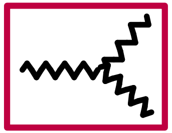



Standard Model Production Cross Section Measurements
Status: February 2022
ATLAS Preliminary
√s = 5,7,8,13 TeV
σ [pb]
Theory
LHC pp √s = 13 TeV
Data 3.2 – 139 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 5 TeV
Data 0.03 – 0.3 fb⁻¹
pp
Jets
γ
W
Z
tt̄
t
tot.
VV
tot.
γγ
H
Hjj
VBF
VH
Vγ
tt̄V
tot.
tt̄H
tt̄γ
WWV
Vjj
EWK
γγγ
tt̄tt̄
tot.
Vγγ
Zγjj
EWK
γγ→WW
VVjj
EWK

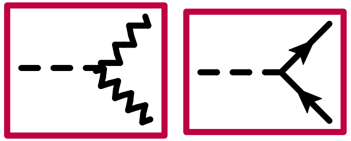
Interactions of the electroweak sector



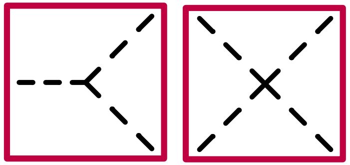
Vff : Drell-Yan processes and decays



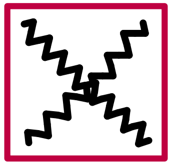
VVV: LEP and VV production at hadron colliders



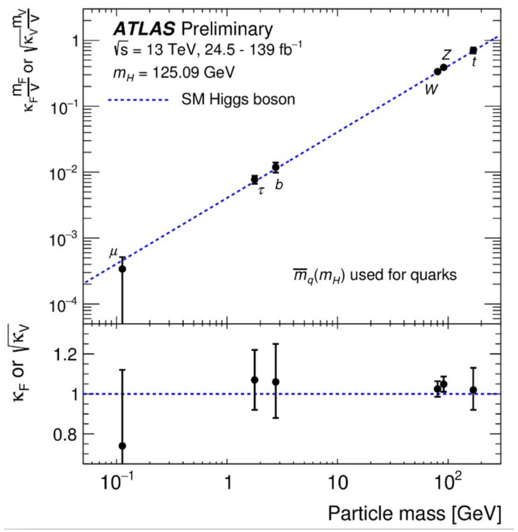
HVV/Hff: Higgs-production and decays



Higgs self-interactions: not yet measured

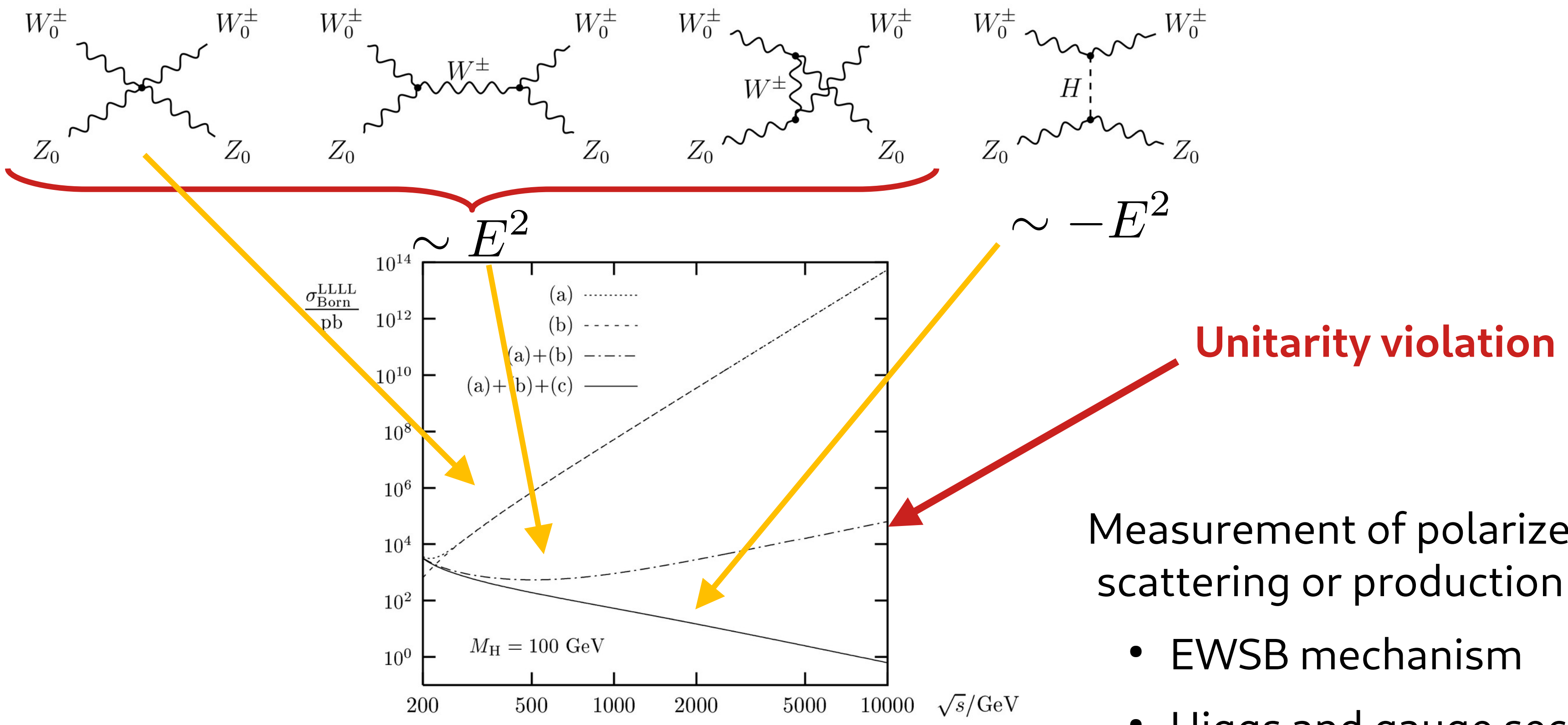


Quartic V-couplings: constraints limited by data



EWSB mechanism?

Longitudinal Vector-Boson-Scattering (VBS)



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

Measurement of polarized boson scattering or production probes:

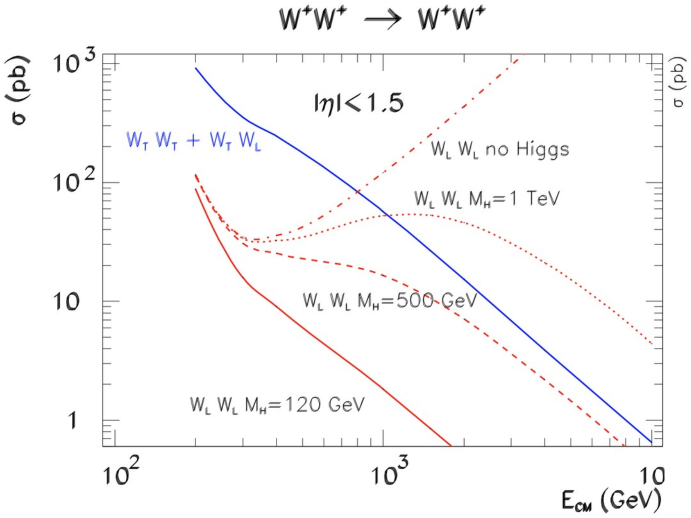
- EWSB mechanism
- Higgs and gauge sector
- New physics models

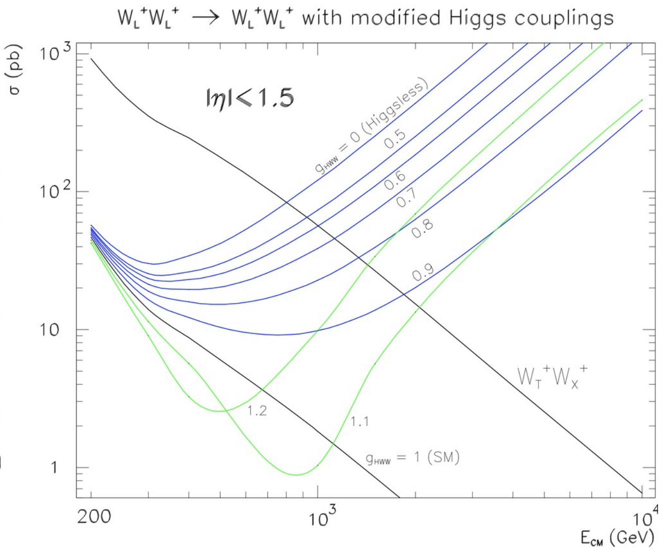
Longitudinal Vector-Boson-Scattering (VBS)

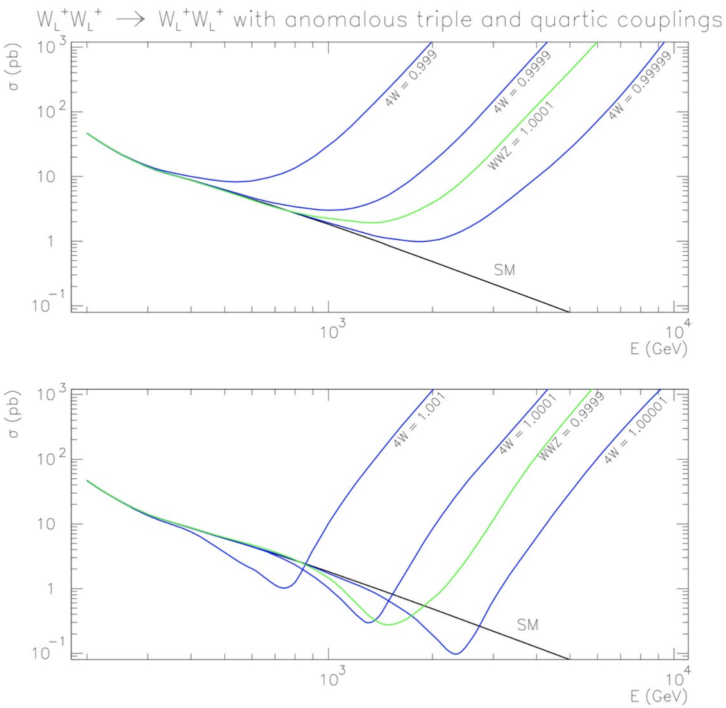
The Higgs boson and the physics of WW scattering before and after Higgs discovery
M. Szleper 1412.8367

Sensitivity to the Higgs mass

Modified HVV, VVV, VVVV couplings

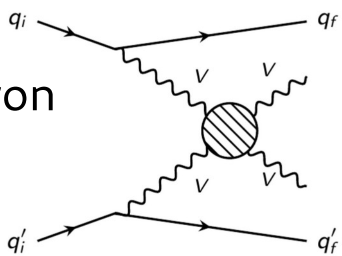




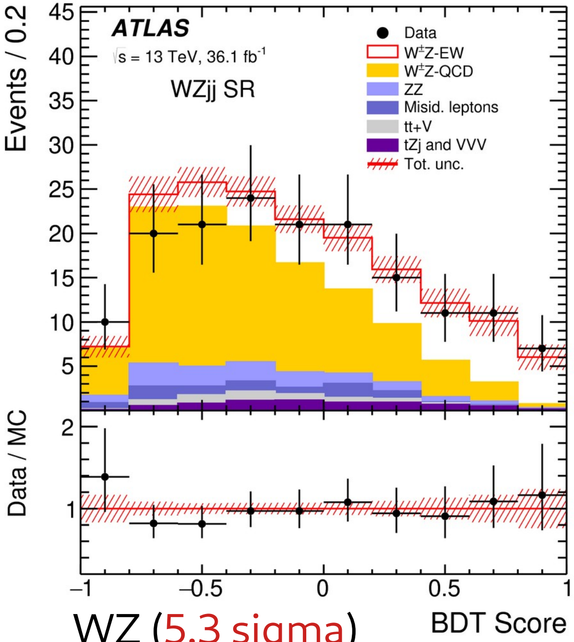


VBS at hadron colliders

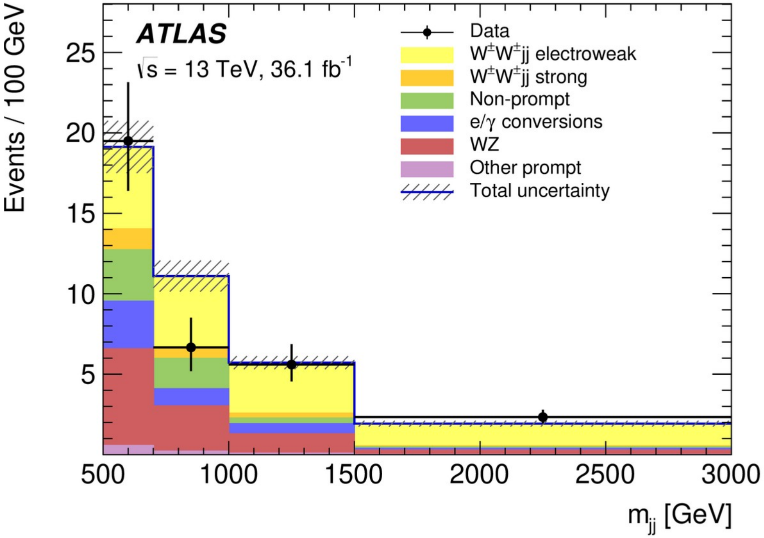
VBS at hadron colliders



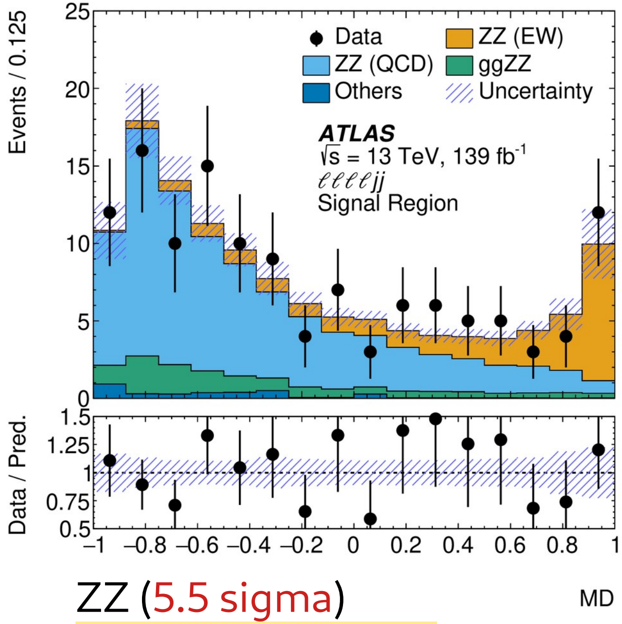
Separate from background processes through VBS topology
→ a rare process, but observed.



WZ (5.3 sigma)
ATLAS 1812.09740



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



ZZ (5.5 sigma)
ATLAS 2004.10612

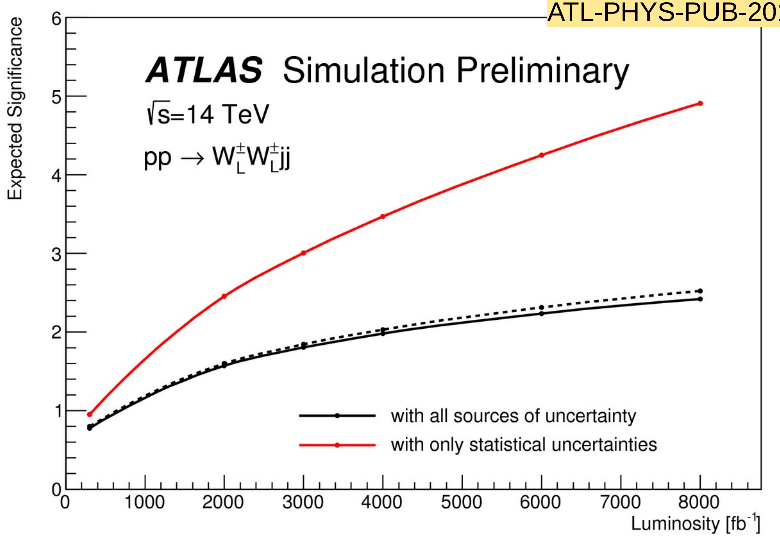
Polarised VBS at HL-LHC

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

ATL-PHYS-PUB-2018-052

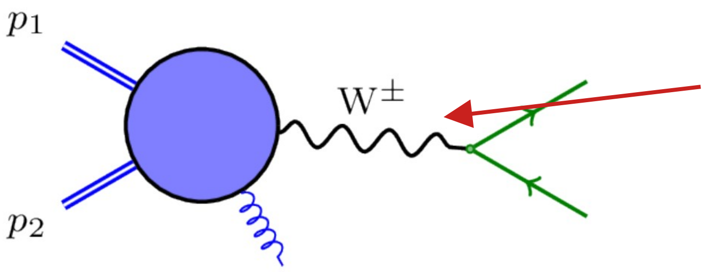


How to improve on the (theory) systematics?

→ Improved signal and background modelling

→ Effective separation of boson polarisations

Polarised boson production



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

λ = +/-/L

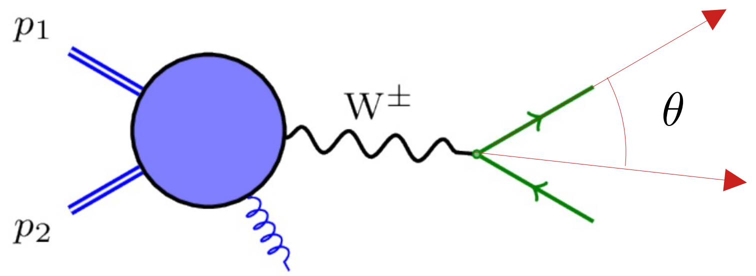
Can we extract the longitudinal component?

Measurements of longitudinal polarisation fractions:

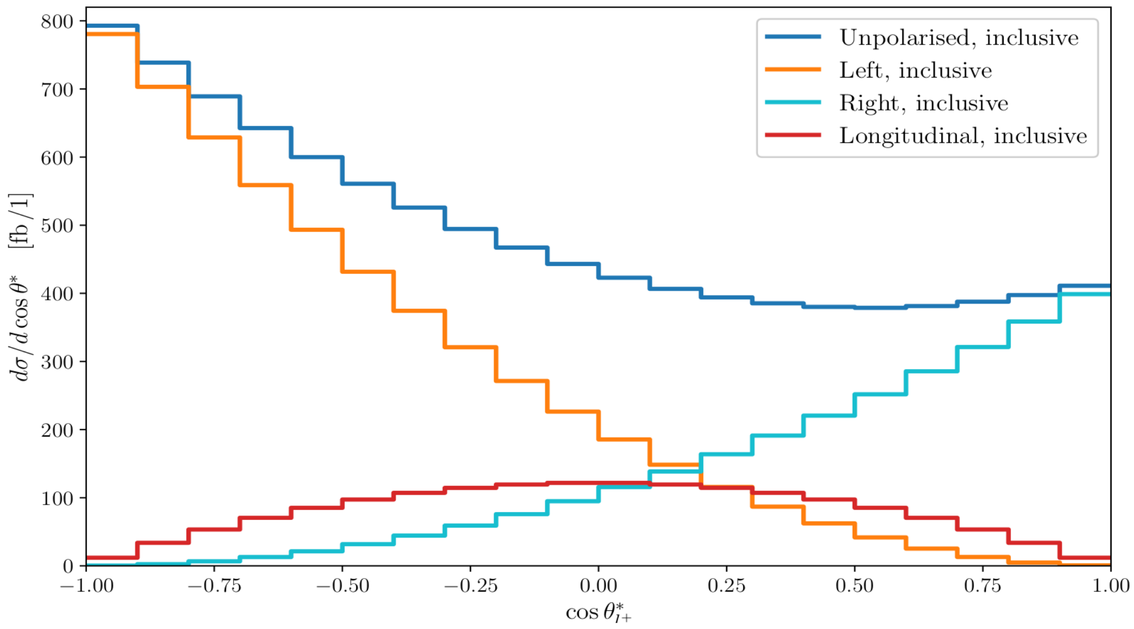
Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC,
CMS 1104.3829
Measurement of the polarisation of W bosons produced with large transverse momentum in pp collisions at \sqrt{s}=7 TeV with the ATLAS experiment,
ATLAS 1203.2165
Measurement of WZ production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

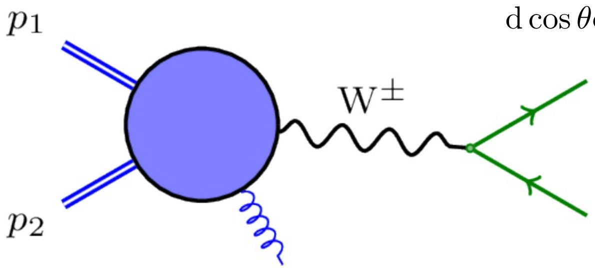


W+ decay (W- mirrored around 0)



How to measure polarized bosons?

Angular decomposition of 2-body W decay:



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

$$+ A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big]$$

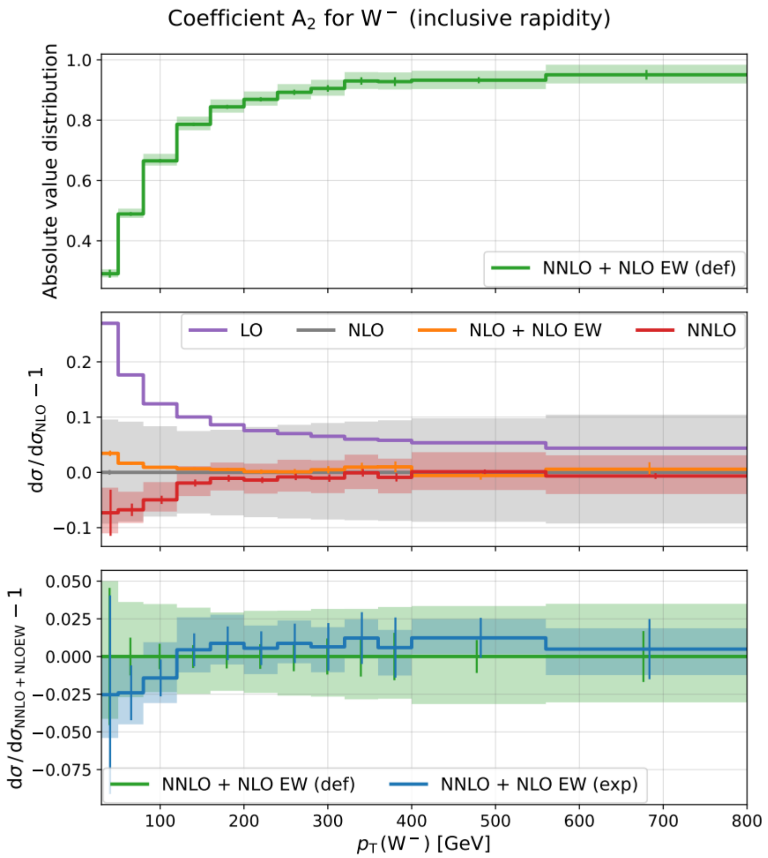
After azimuthal integration:
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\cos\theta} = \frac{3}{4}\sin\theta f_0 + \frac{3}{8}(1-\cos\theta)^2 f_L + \frac{3}{8}(1+\cos\theta)^2 f_R$$

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

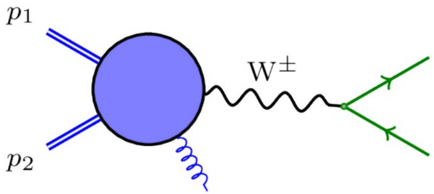
Practical considerations

This simple idea suffers from:

- Fiducial phase space requirements 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)

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

→ 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

Overview SM results

- 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

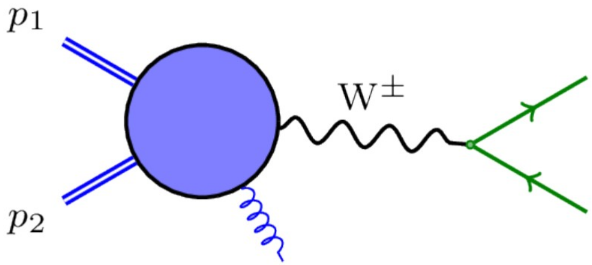
Overview SM results

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, 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 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 $p_T(j) \geq 30$ 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

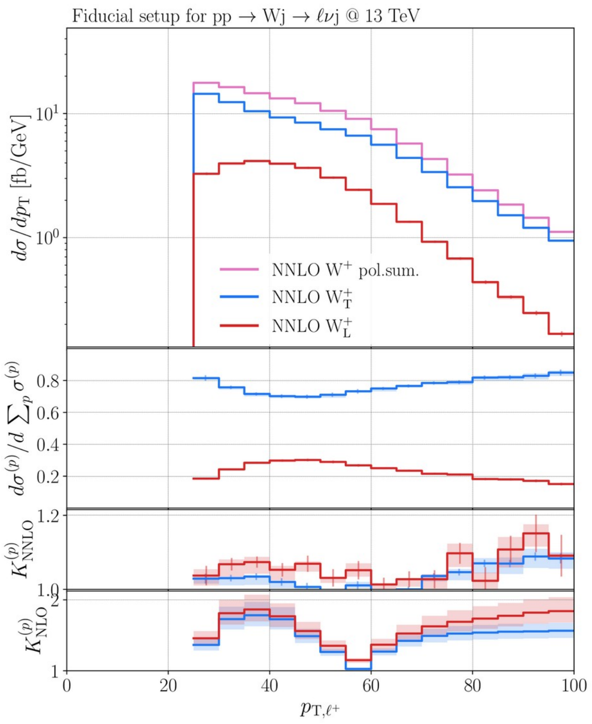
- Lepton cuts: $p_T(\ell) \geq 25$ GeV, $|\eta(\ell)| \leq 2.5$ and $\Delta R(\ell, j) > 0.4$
- Transverse mass of the W: $M_T(W) = \sqrt{m_W^2 + p_T^2(W)} \geq 50$ GeV

Technical aspects:

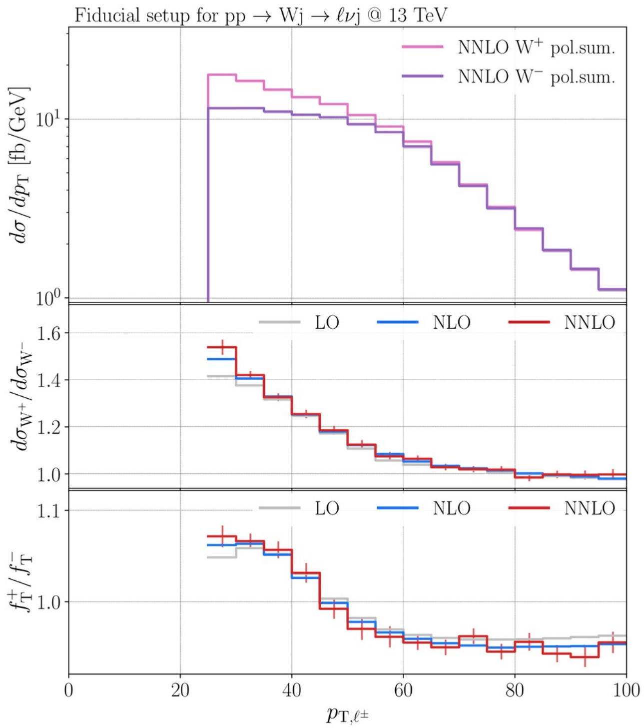
- NNPDF31 and dynamical scale choice: $\mu_R = \mu_F = \frac{1}{2}\left(m_T(W) + \sum p_T(j)\right)$
- Implementation in STRIPPER framework (NNLO QCD subtractions) [1408.2500]
  - Narrow-Width-Approximation and OSP/Pole-Approximation
  - Matrix elements from: AvH[1503.08612], OpenLoops2 [1907.13071](cross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

Example: lepton transverse momentum

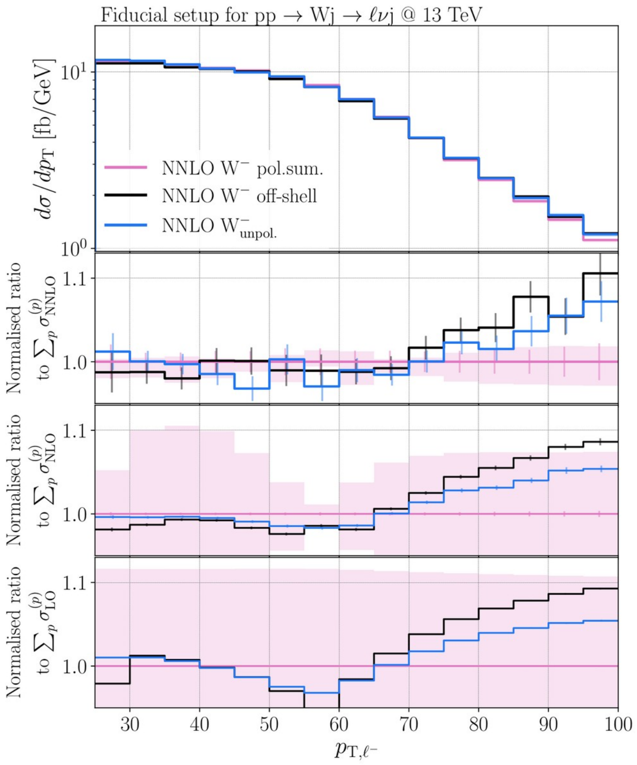
Perturbative corrections



Charge differences



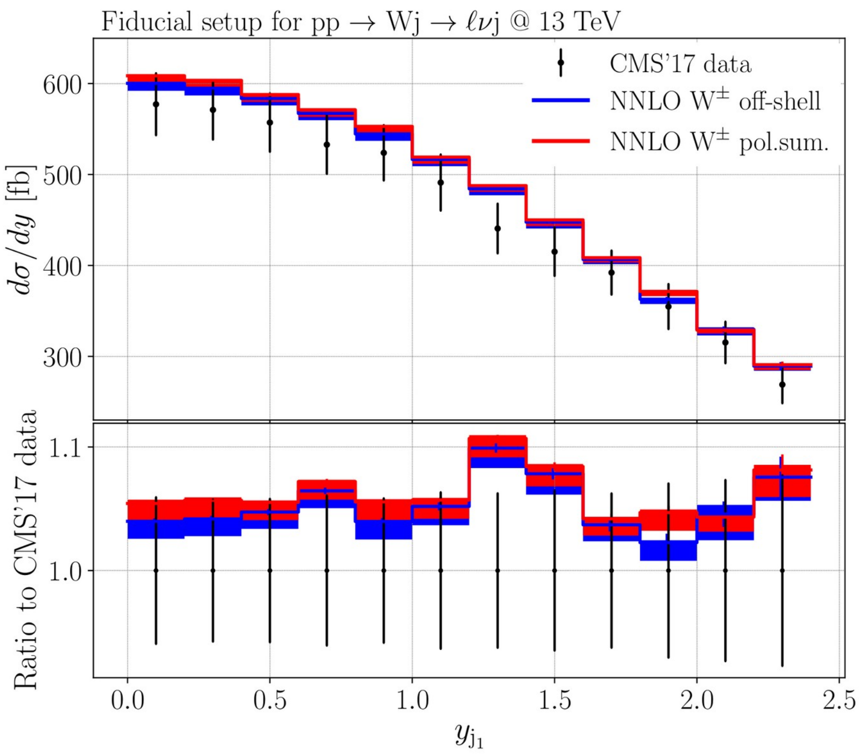
Off-shell/Interference effects



Extraction of polarisation fractions

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

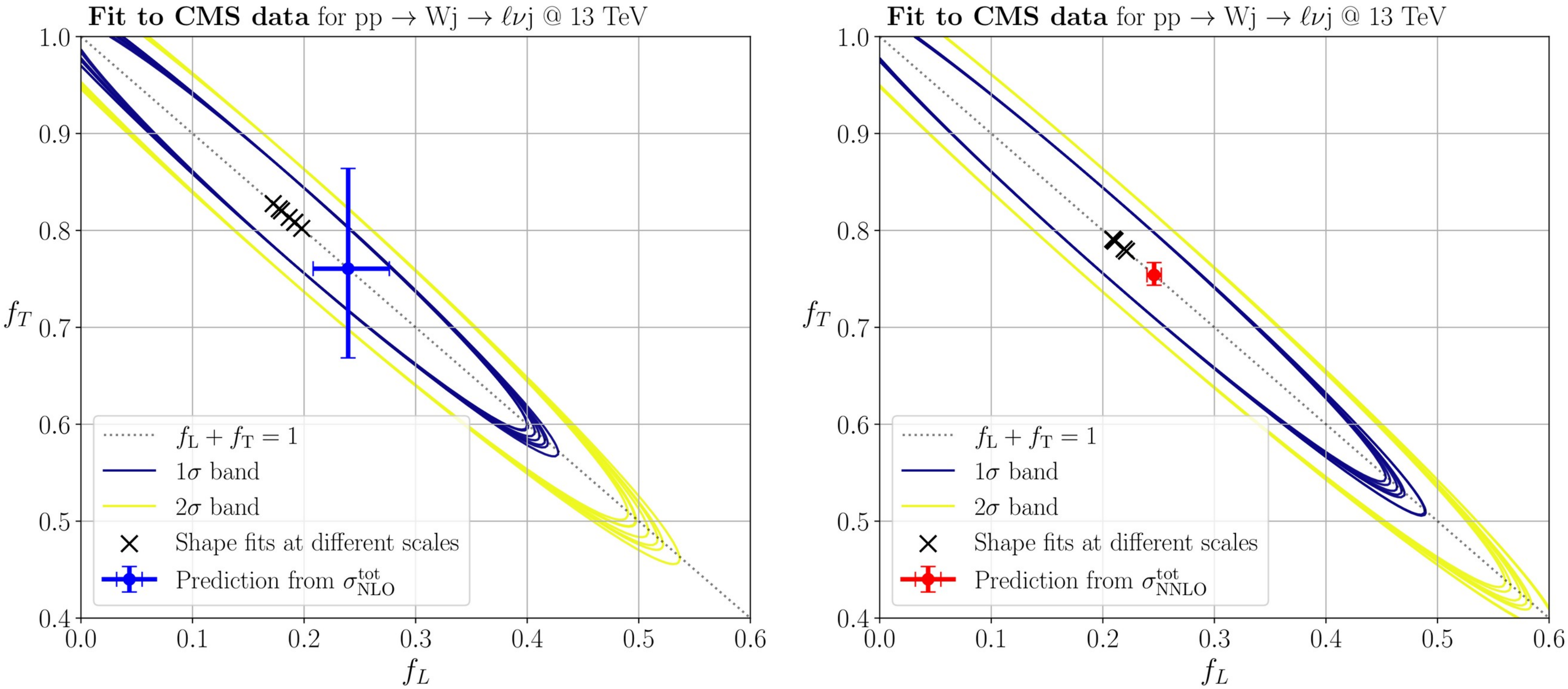
- $\Delta\phi(\ell, j_1) \geq 0.3$
- $25 \text{ GeV} \leq p_T(\ell) < 70 \text{ GeV}$
- $\cos(\theta^*_\ell) \geq -0.75$
- $|y(j_1)| \leq 2$



W+jet : fit to CMS data

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

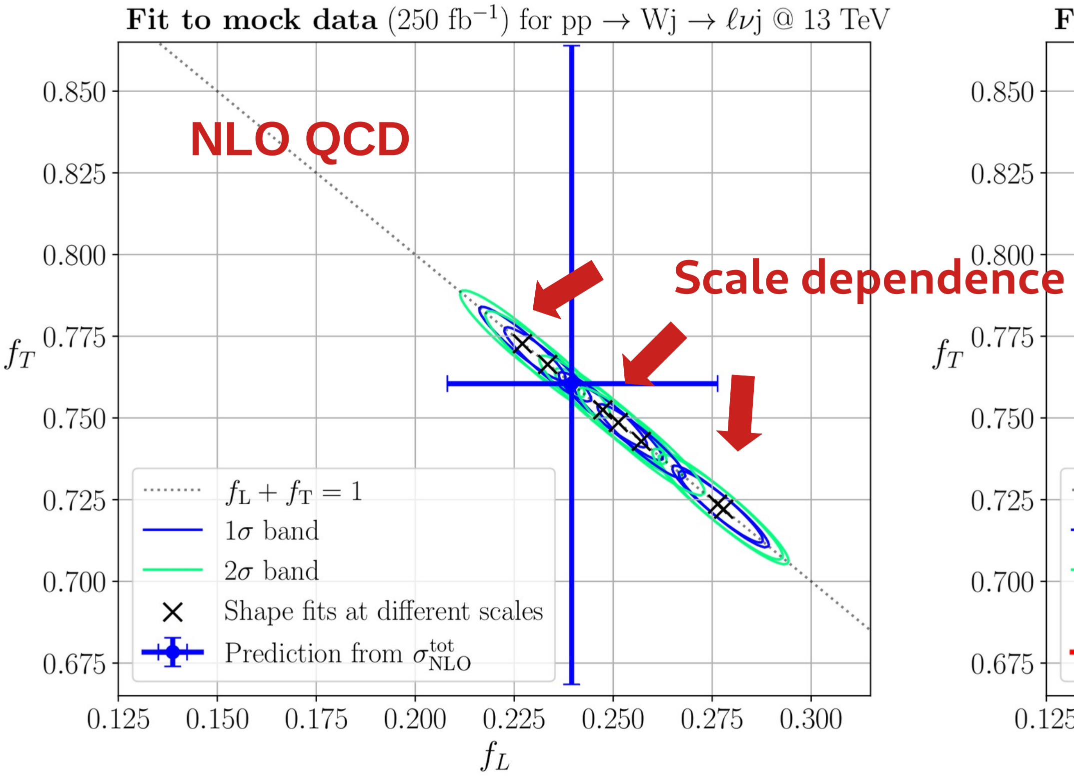
→ dominated by experimental uncertainties (no correlations available)

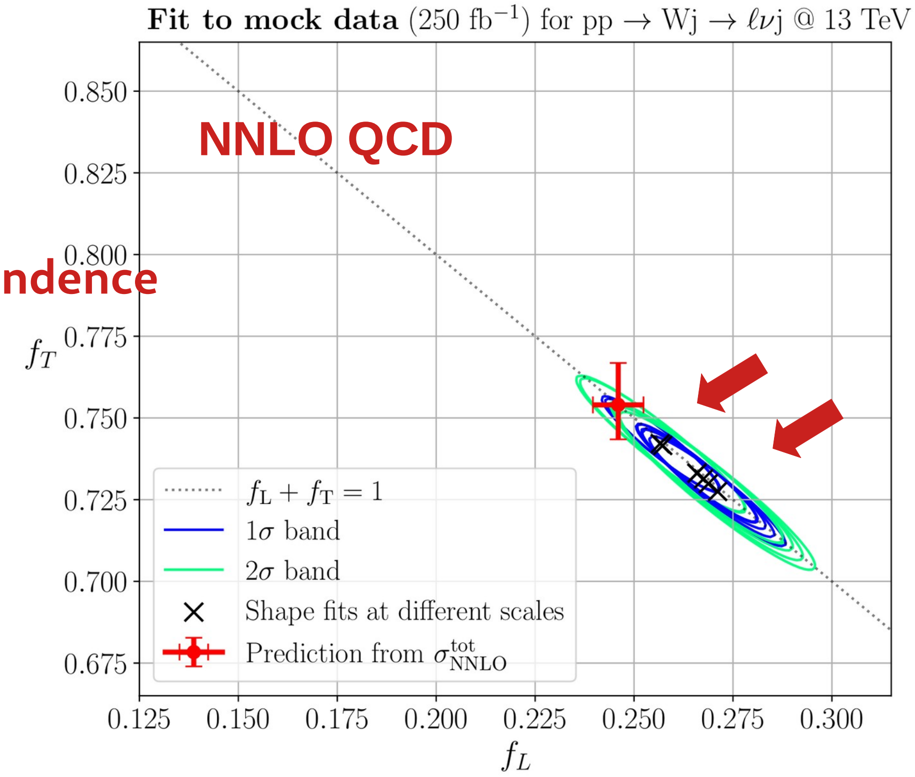


W+jet: mock-data fit

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

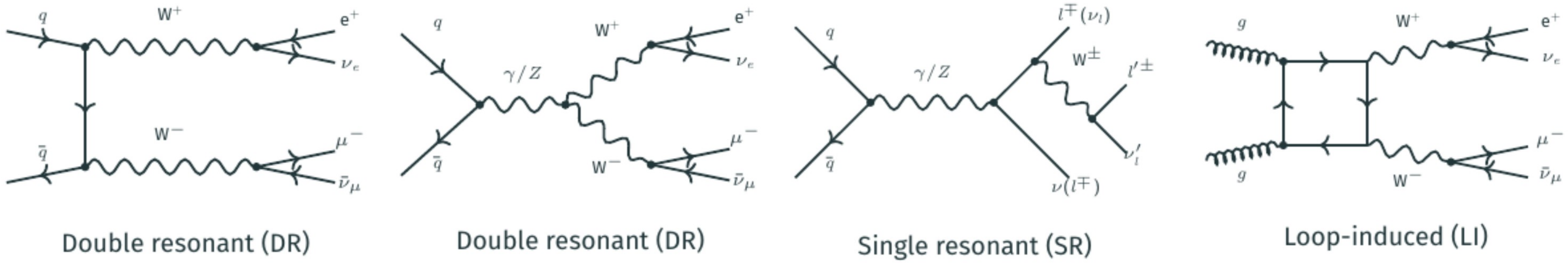
$\cos(\ell, j_1)$



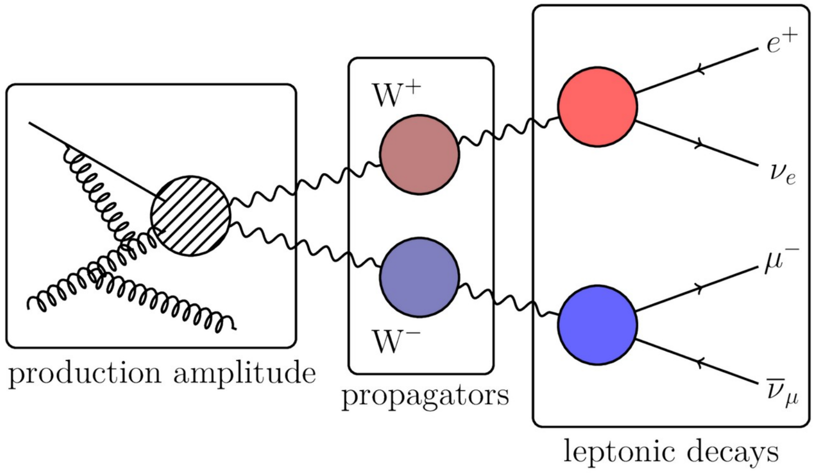


Polarised W+W-

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: $\mu_R = \mu_F = m_W$

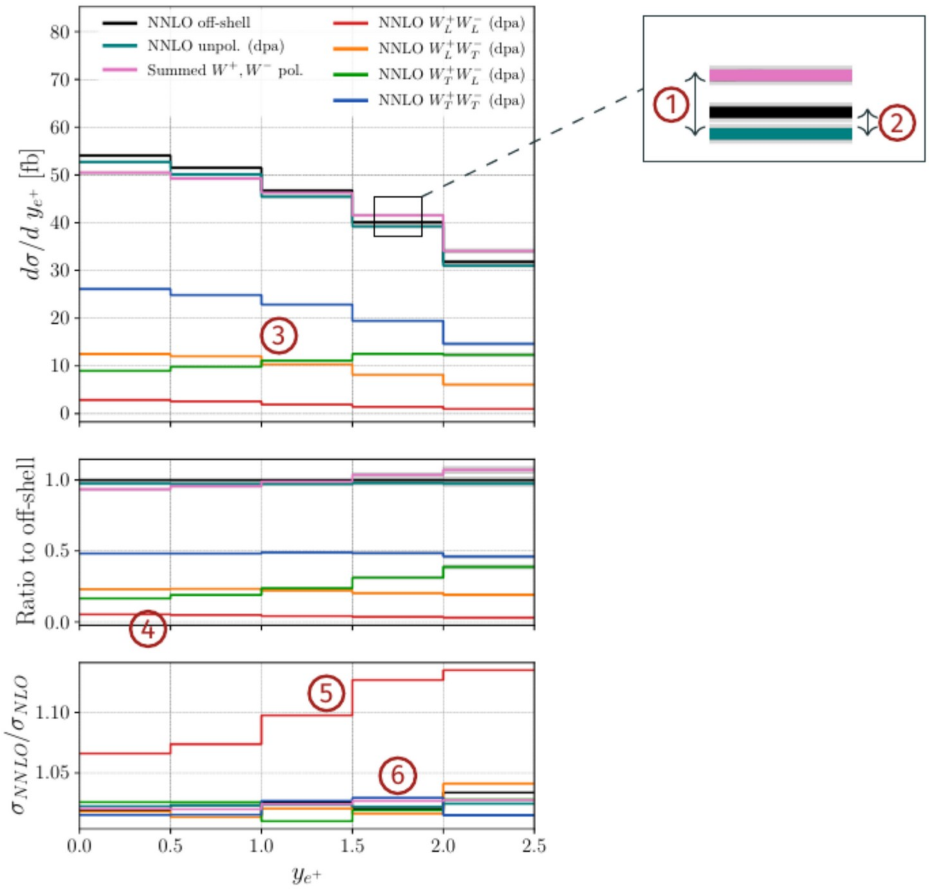
Doubly polarised cross sections

	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:

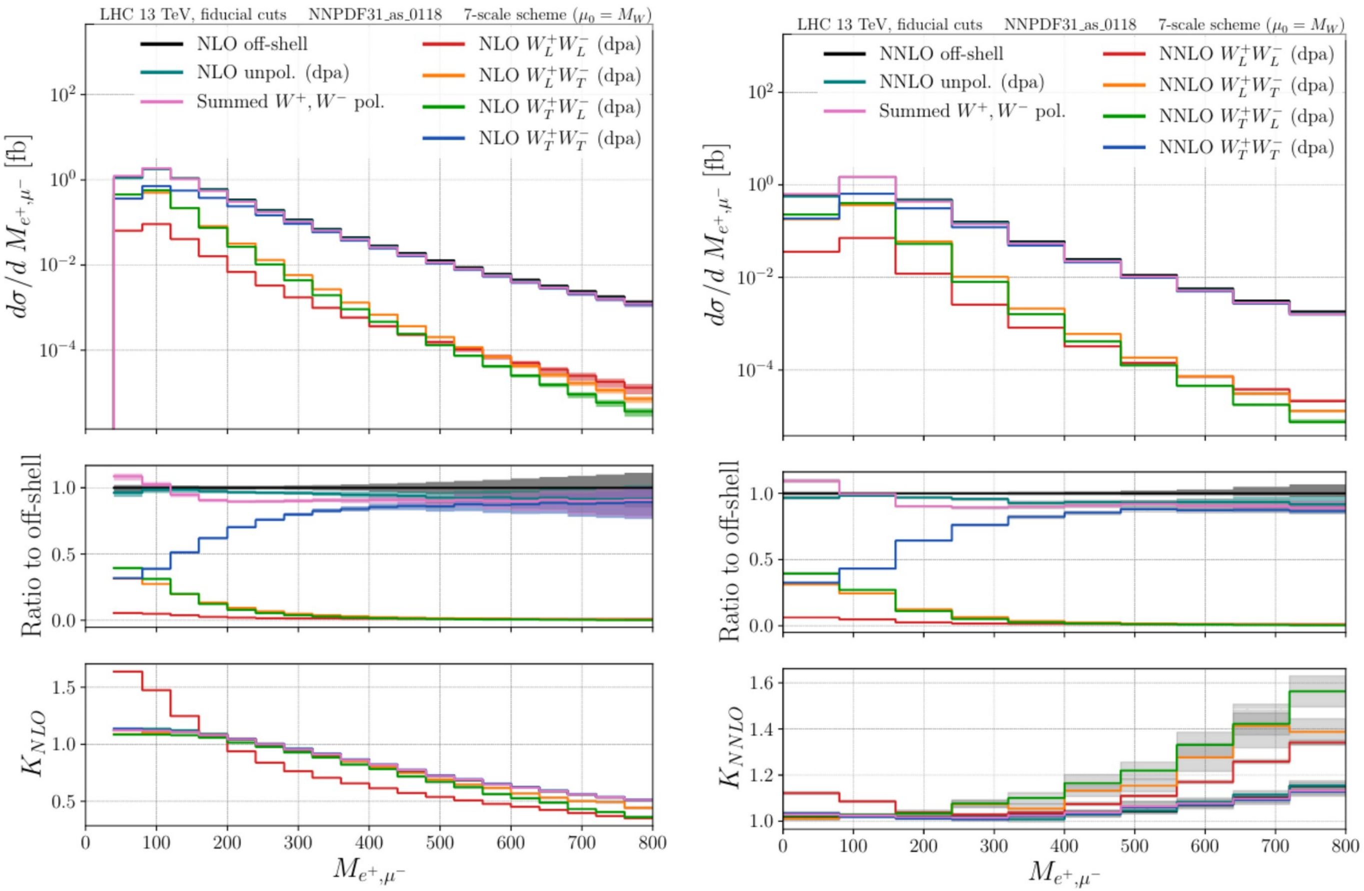
1. Polarisation interference
2. Non-resonant background
3. "Monte-Carlo true" polarisation distributions
4. $W_L^+ W_L^-$ contribution is small, $W_T^+ W_T^-$ dominates
5. Distinct and large K_{NNLO} for $W_L^+ W_L^-$
6. small K-factor for other setups

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.

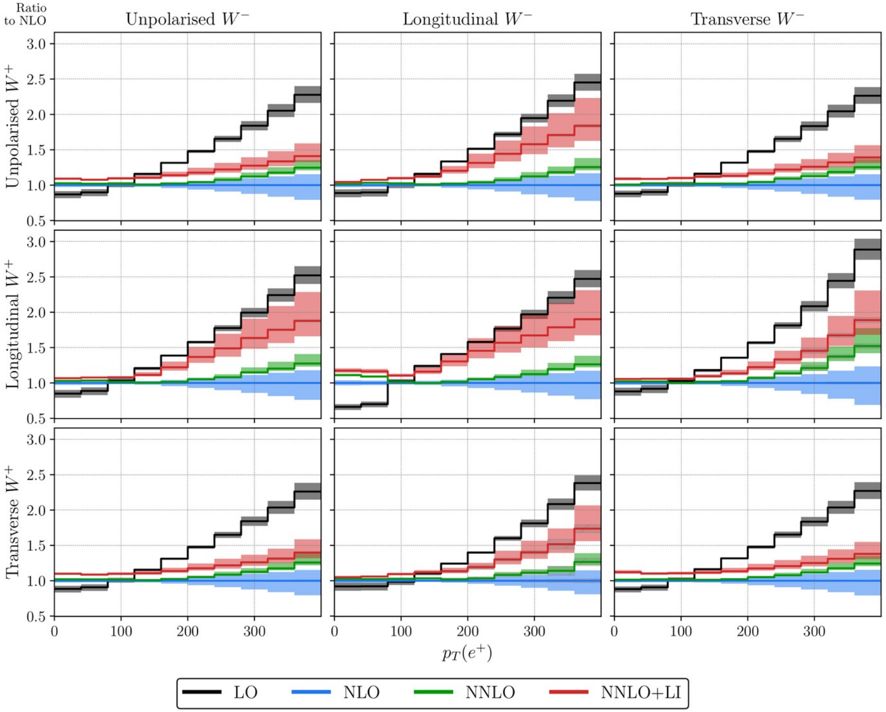
Polarised di-boson production

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

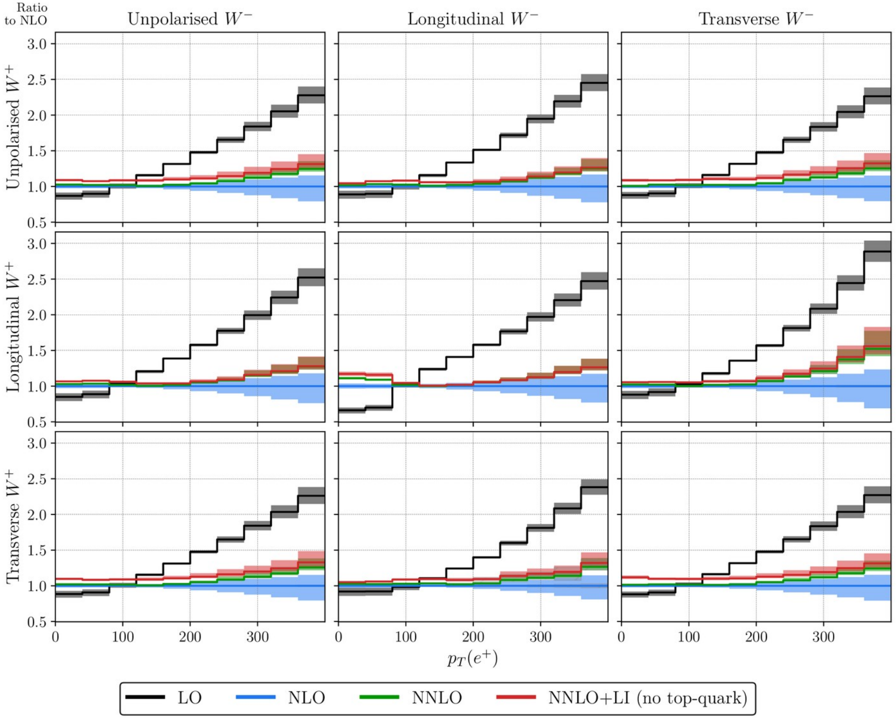


Loop induced gg → WW contributions

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

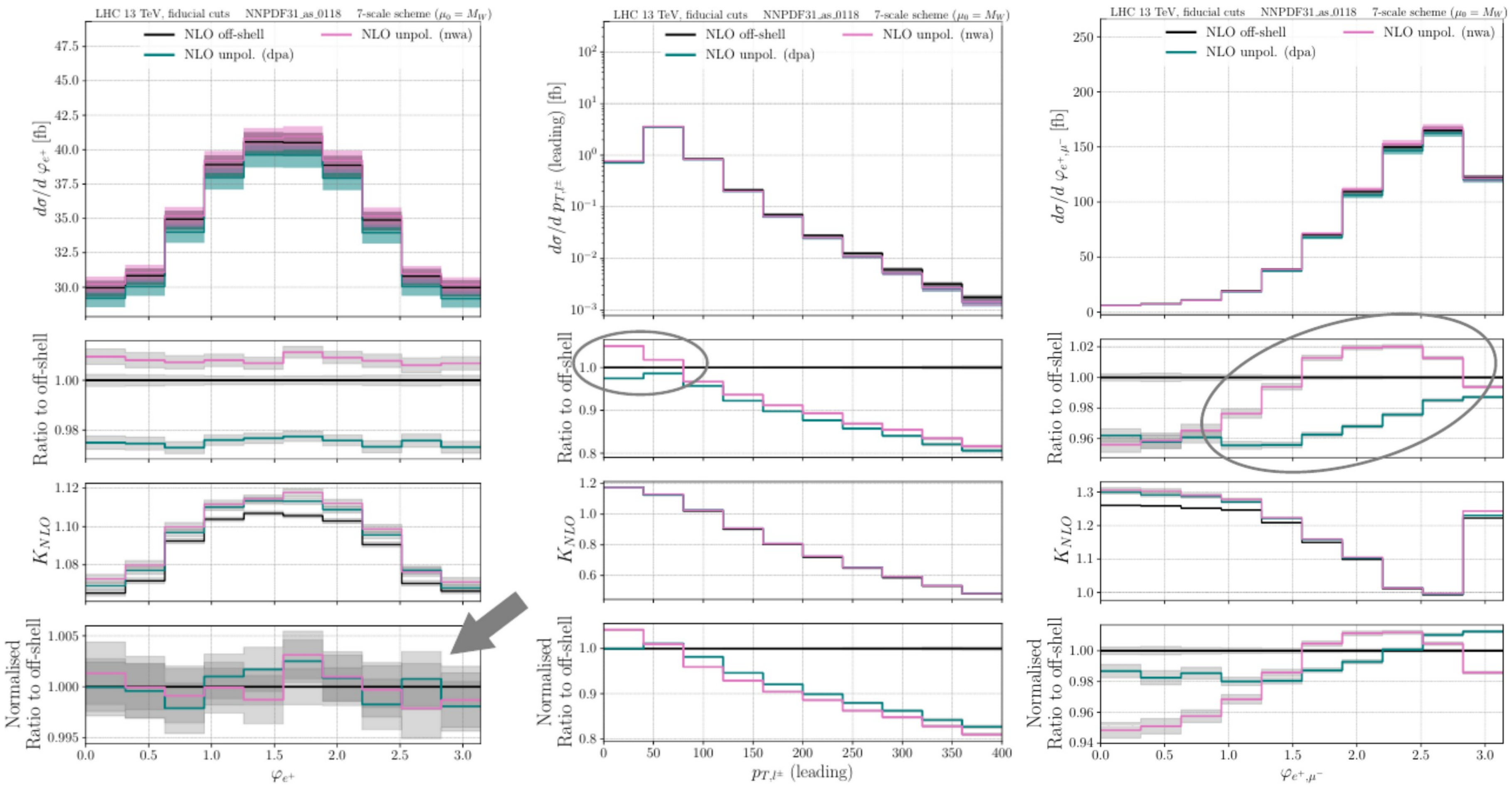
- Goldstone bosons can be absorbed via gauge transformation (unitary gauge). This gives rise to massive gauge bosons:

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

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

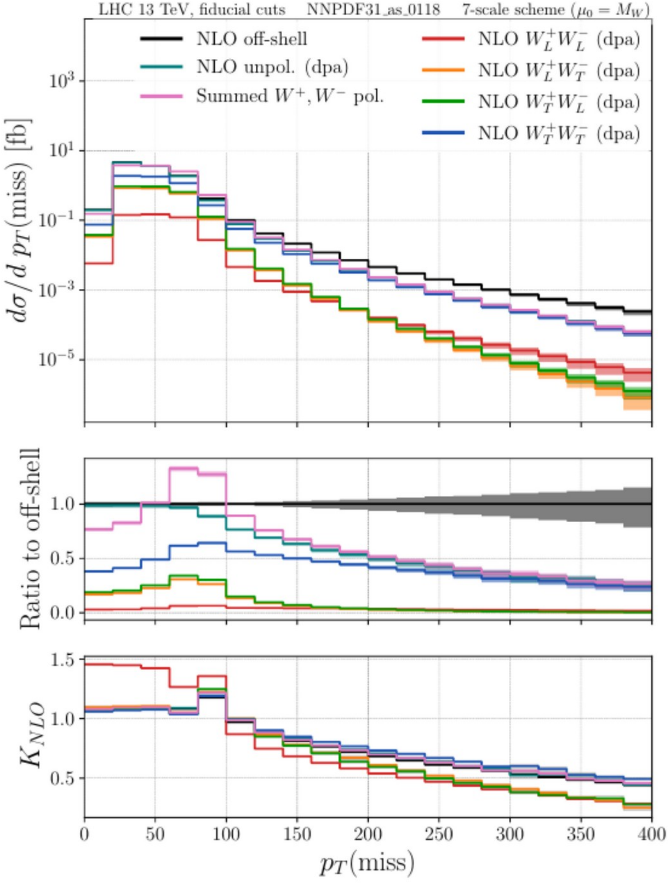
- Restores renormalizability and unitarity

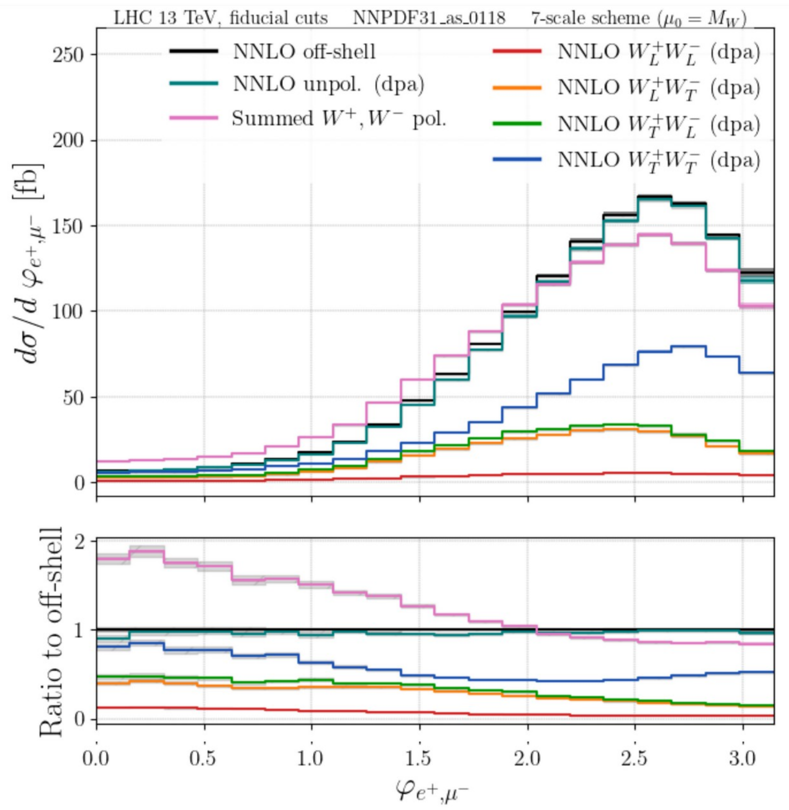
NWA vs. DPA


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