The Study of Polarised ZZ Vector Boson Scattering

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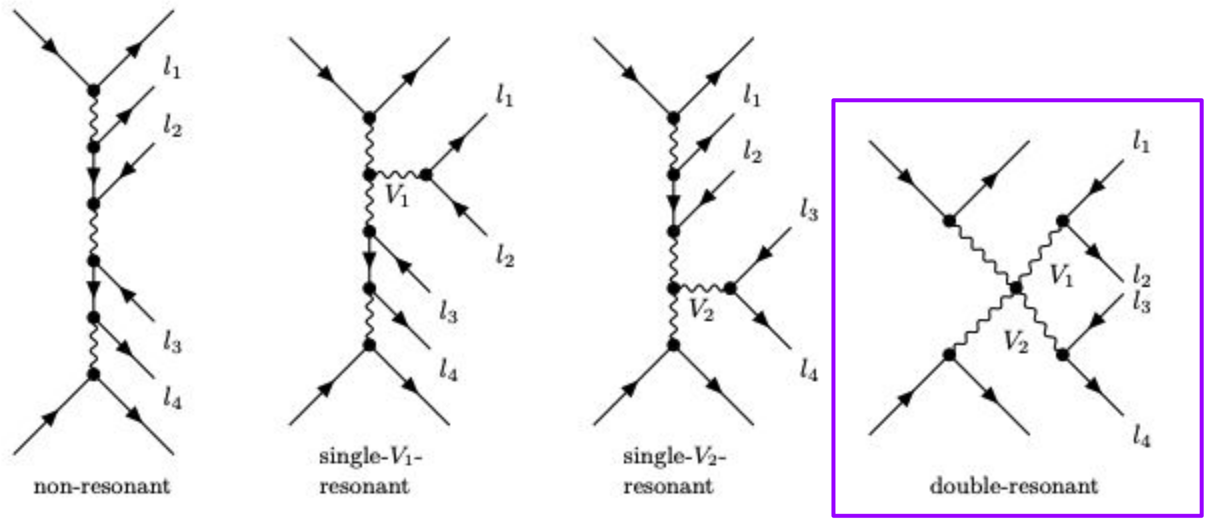
Why study VBS?

- There is particular interest in studying the longitudinal component of VVjj VBS
- Testing the EWSB mechanism
  - The longitudinal components of the vector bosons arise from “eaten” Goldstone bosons
  - Deviations from SM predictions implies alterations to the Higgs mechanism
- Sensitivity to NP BSM
  - Many models (i.e. strongly coupled dynamics, composite Higgs, extra dimensions…) are affected by polarisation-dependent interactions of vector bosons
  - Can probe the anomalous triple and quartic gauge couplings. For example, ZZjj EW process is sensitive to WWZZ and WWZ self-interaction couplings
- Testing unitarity of a theory - cancellation between V_L mediated and Higgs mediated diagrams

EW VVjj VBS



We are only interested in double-resonant diagrams as we want two on-shell intermediate state VBs. Including these extra diagrams would mean we could not separate the VBs polarisations

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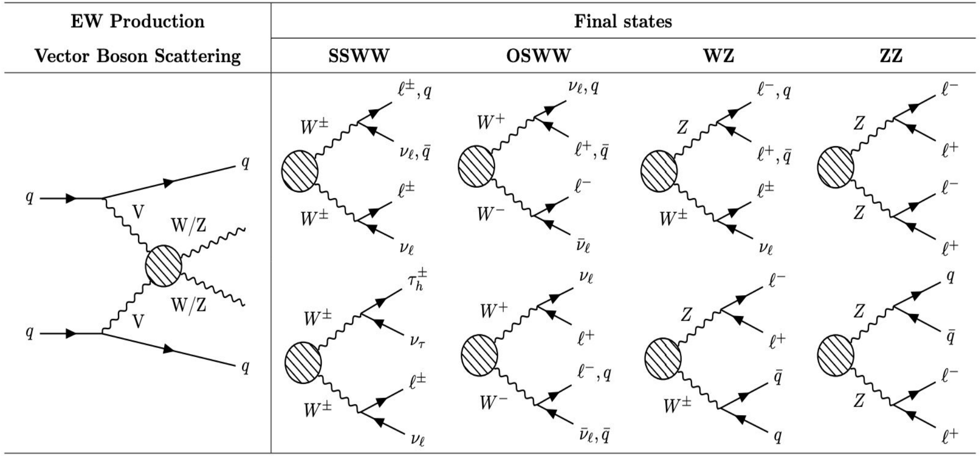
How to perform polarisation measurements

Perform fits to distributions from data using polarisation templates, which are taken from Monte Carlo generators

- Practical
- Accurate in real detector environments
- Can extract polarisation information with minimal assumptions

The polarisation vectors are not Lorentz-covariant, so the choice of frame is very important. In my thesis, everything is defined in the lab frame

The polarised measurements so far

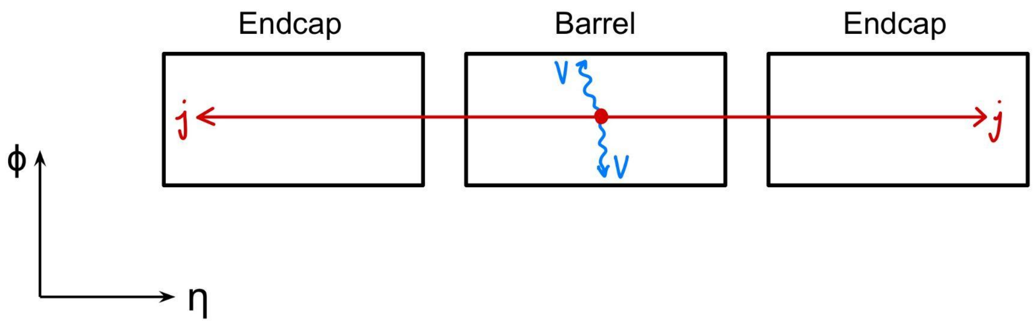


CMS PAS SMP-24-013

Experiment, year	Process	CM energy, L	Observed (expected) significance	What did they measure?
ATLAS 2022	W±Zjj	13TeV, 139fb-1	7.1	Pair production of longitudinally polarised W±Z - joint and individual helicity fractions for both W-Z and W+Z
ATLAS 2025	Same-sign W±W±jj	13TeV, 140fb-1	3.3 (4.0)	At least one of the W bosons is longitudinally polarised

VBS Topology

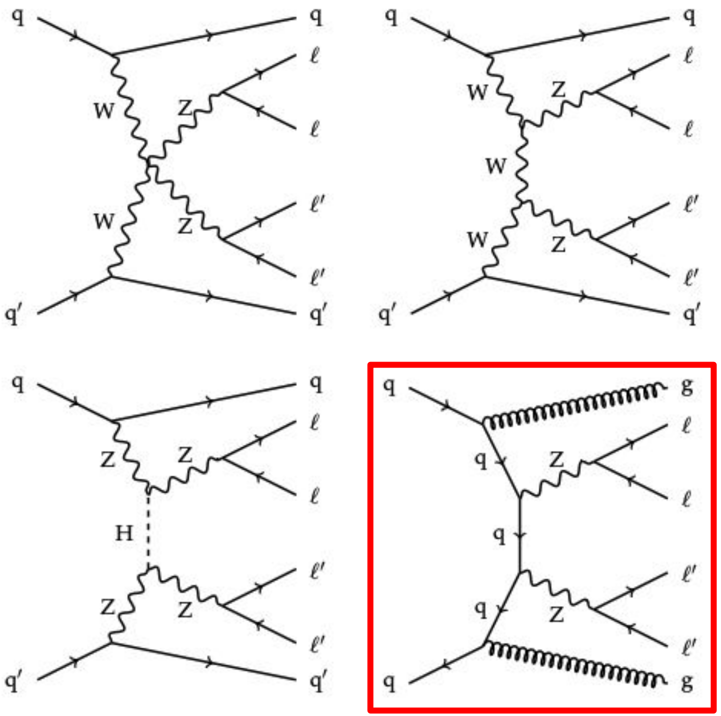
- VBs and their decay products are produced in the central region of the detector
- **High energy tagging jets with large pseudorapidity separation and high dijet invariant mass**
- Central hadronic activity between jets is suppressed due to colour decoherence



Fully Leptonic VBS Process

$$pp \to jjZZ \to jje^+e^-\mu^+\mu^-$$

- Fully reconstructable leptonic final states which have very low backgrounds, excellent momentum resolutions and clean reconstruction of Z boson kinematics
- Limited number of events



Background

CMS-PAS-FTR-18-014

Monte Carlo Simulations

- LO with MadGraph
  - Showering effects are included using PYTHIA8
- LO with SHERPA for direct comparison with MadGraph
  - Showering effects are included using internal mechanics
- QCD and EW NLO with SHERPA
  - Loop generators OpenLoops, Internal and Recola
  - Born, virtual and real corrections
  - UV divergences: dimensional regularisation, IR divergences: Catani-Seymour dipole subtraction method
- LHE/HepMC3 file is then passed through Delphes to simulate CMS detector effects
- ROOT, Python and C++ are used to analyse the results

Simulation setup

- To minimise $\gamma\gamma$ and γZ contributions: $|M_{l^+l^-} - M_Z| < 15$ GeV
- $p_t^l > 20$ GeV and $|\eta_l| < 2.5$ are applied to define a fiducial region where it is possible to reconstruct the entire final state
- $M_{4l} > 200$ GeV - shields from the Higgs peak and selects large M_{ZZ} most interesting for NP
- $|\Delta\eta_{jj}| > 2.5$
- $M_{jj} > 500$
- $|\eta_j| < 5$
- $p_t^j > 20$ GeV

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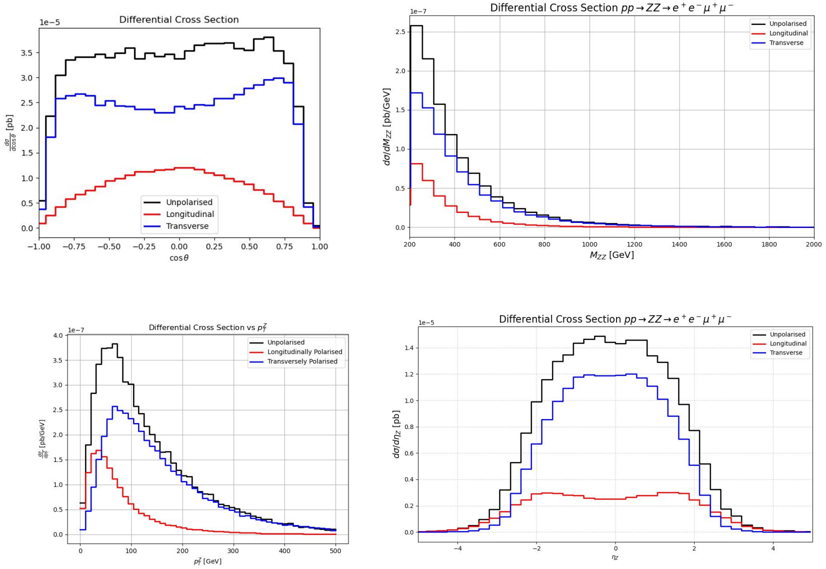
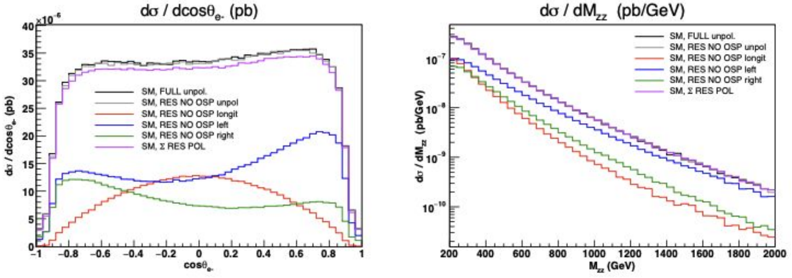
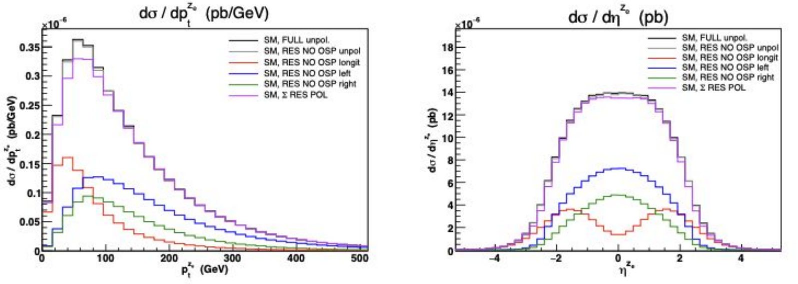
MadGraph Validation

$$pp \rightarrow jjZ^{e}_{pol}Z^{\mu}_{unpol} \rightarrow jje^{+}e^{-}\mu^{+}\mu^{-}$$





(a) $\cos\theta_{e^-}$ (b) M_{ZZ}



(c) $p_t^{Z_e}$ (d) η_{Z_e}

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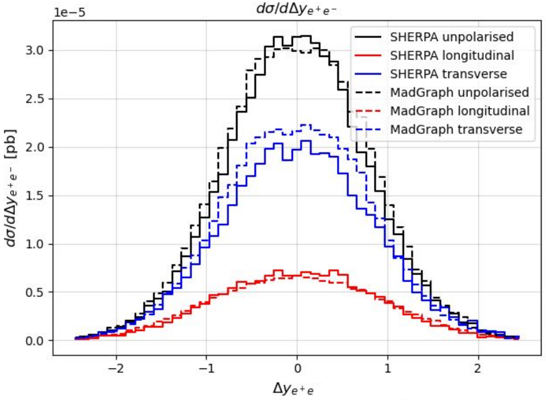
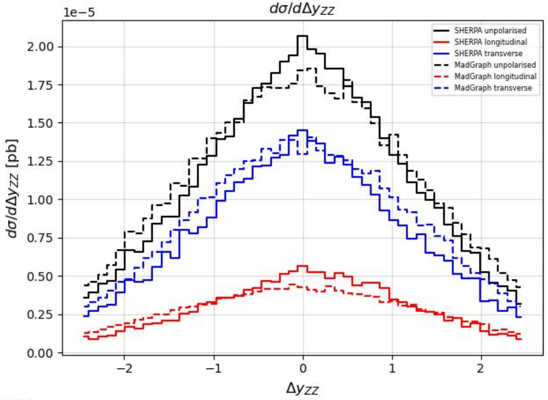
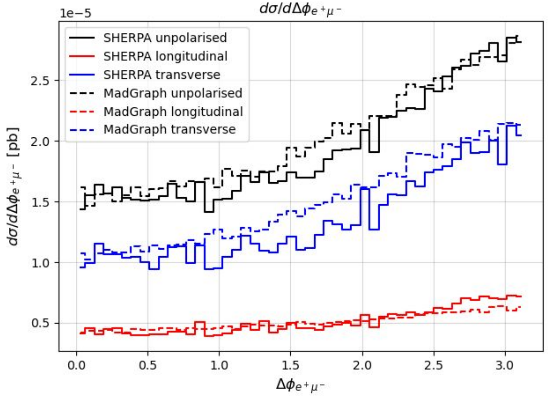
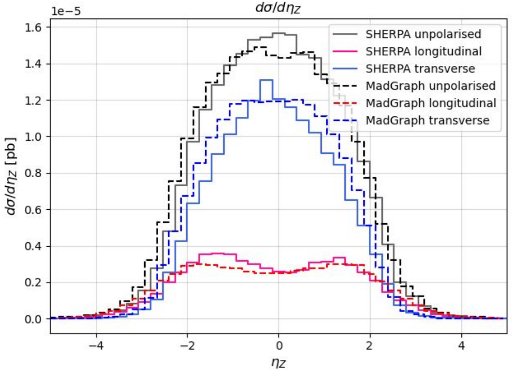
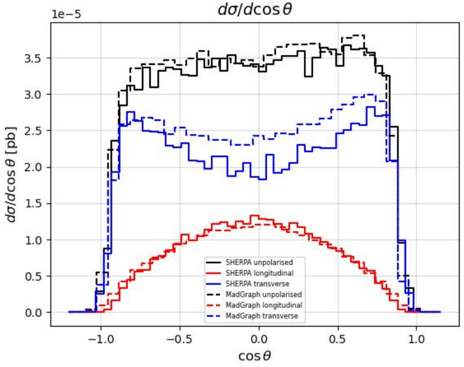
LO SHERPA v MadGraph5



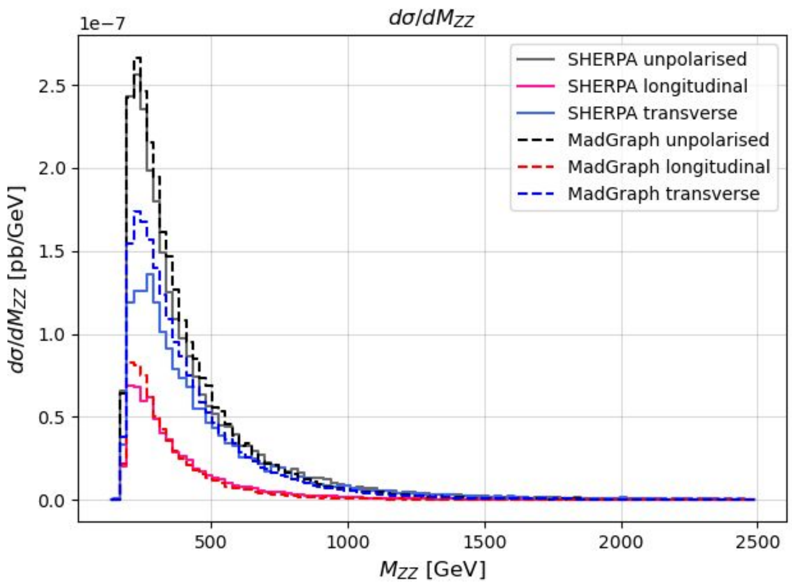


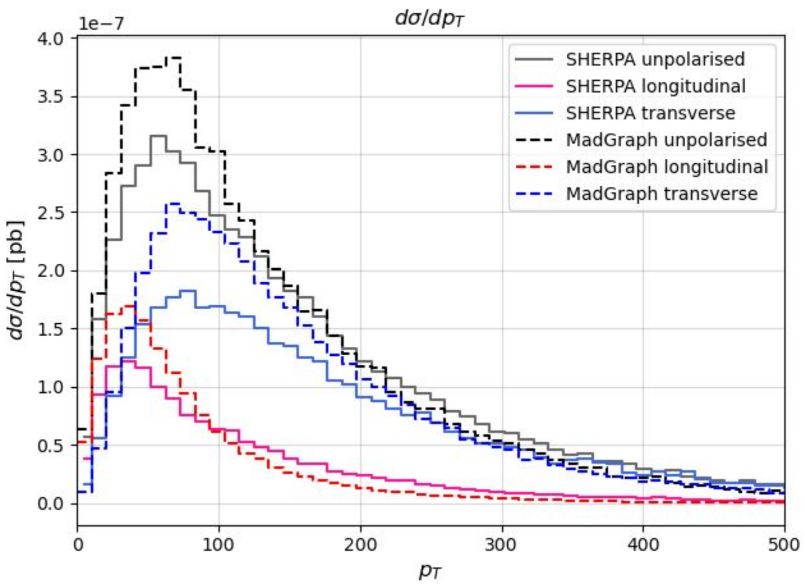






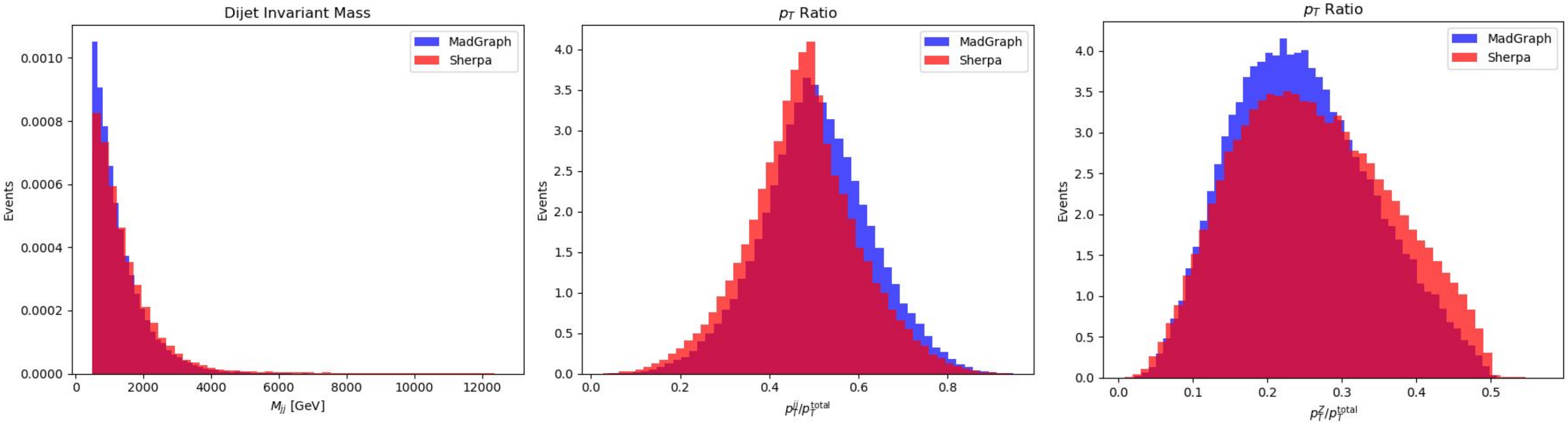
LO SHERPA v MadGraph5





Sherpa gives a significantly harder pT spectrum

The pT Dilemma



- M_jj is a main discriminating variable between VBS and QCD induced processes
- pT ratio is independent to how jj is defined in MadGraph and SHERPA
- Jet multiplicity is the same for both MC generators
- **The problem is believed to originate from the phase space mappings in SHERPA and needs correcting**

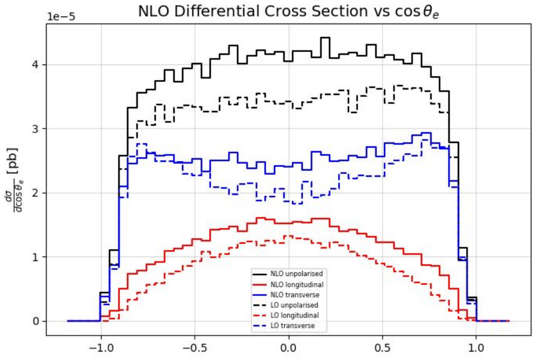
NLO Corrections with SHERPA

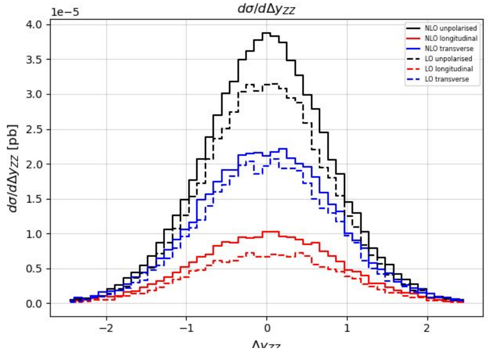
There is a strong relationship between NLO QCD corrections and polarisation effects - LO templates are insufficient!

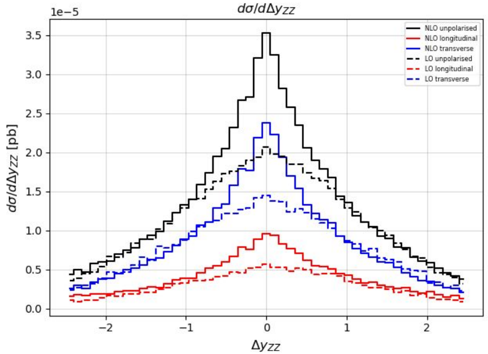
- QCD NLO: cross section is approximately +34% larger than LO

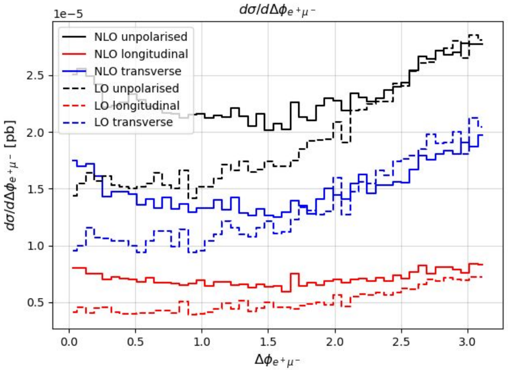
	LO cross section [pb]	QCD NLO cross section [pb]
Unpolarised	6.1789e-05 ± 2.7248e-07	7.2917e-05 ± 2.5824e-07
Longitudinal	1.6038e-05 ± 1.2343e-07	2.2267e-05 ± 1.3474e-07
Transverse	4.2288e-05 ± 2.8496e-07	4.7181e-05 ± 2.6258e-07

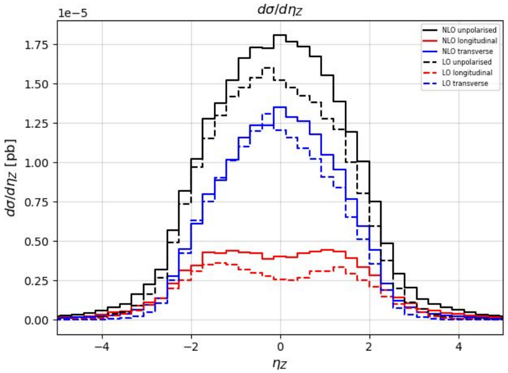
LO vs QCD NLO with SHERPA











Next steps

- EW NLO corrections with Sherpa
- Training a boosted decision tree with these polarisation templates

Thank you