Polarization Measurement in Same-Charged WW Scattering with the ATLAS Experiment

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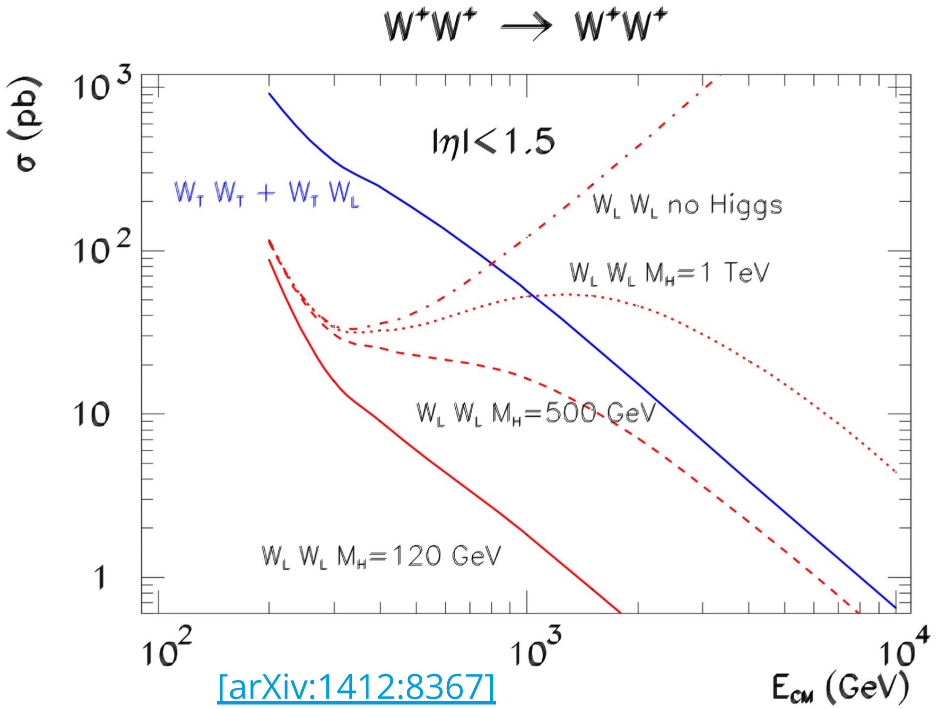
DPG SMuK Göttingen, April 2, 2025

Motivation

- Longitudinal polarization of electroweak gauge bosons is a direct consequence of the EWSB
- **Important test of the Higgs mechanism**
- Particularly interesting: **longitudinal VBS**



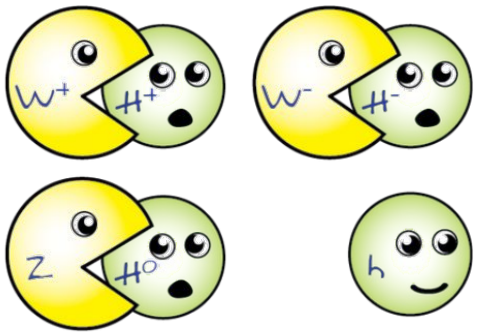
[arXiv:1412:8367]

Higgs mechanism

Massive W and Z bosons

Longitudinal polarization allowed

Goldstone equivalence theorem
"At high energy, longitudinal vector bosons are analogous to goldstone bosons"

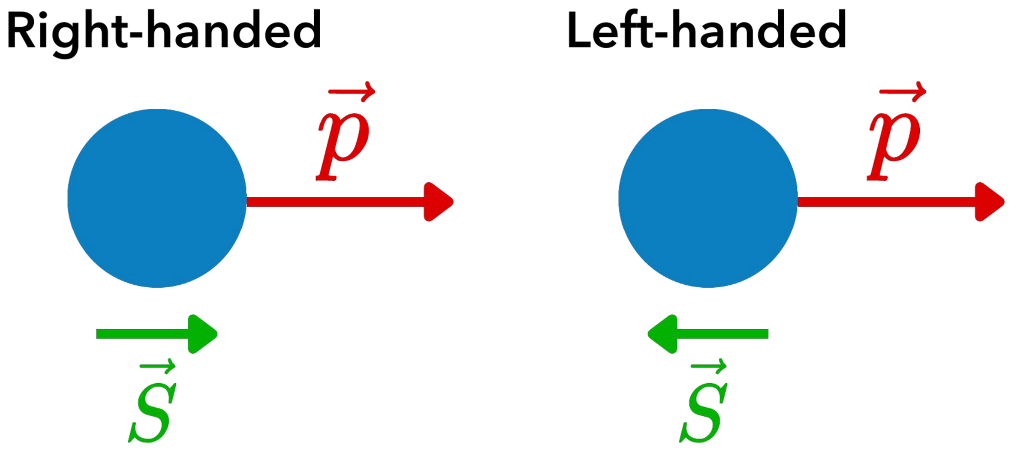


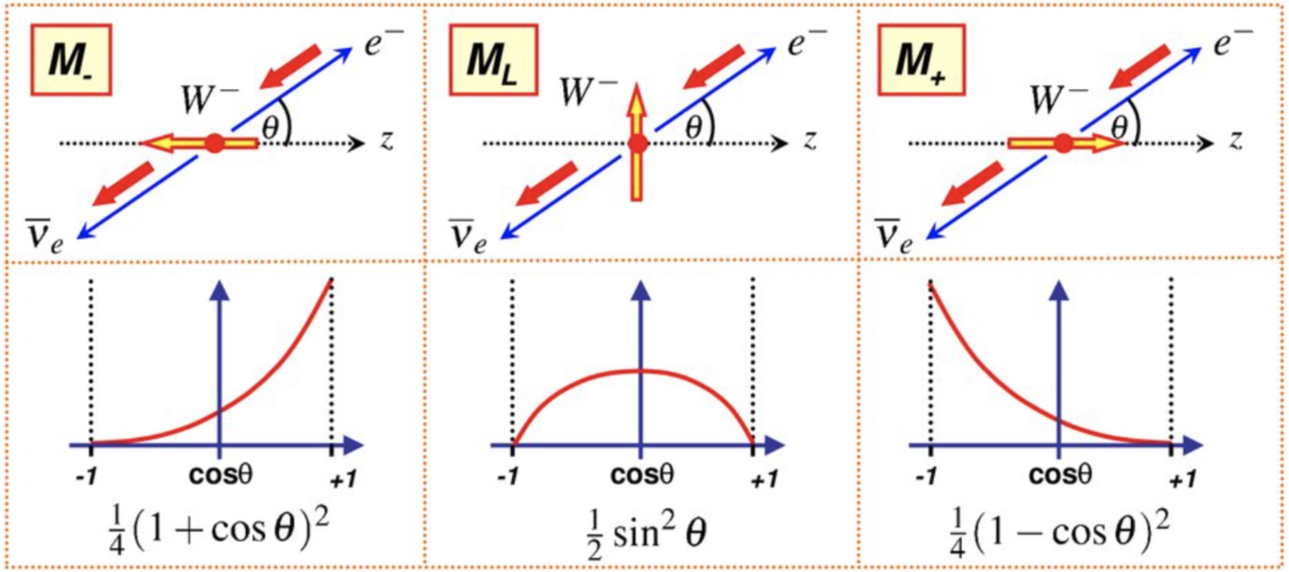
[quantumdiaries.org]

Vector Boson Polarization

- Polarization: **alignment** of a particle's **spin** with its **momentum**
- Helicity: $h = \vec{S} \cdot \frac{\vec{p}}{|\vec{p}|}$
  - **Transverse (T):** $h = \pm 1$
  - **Longitudinal (L):** $h = 0$

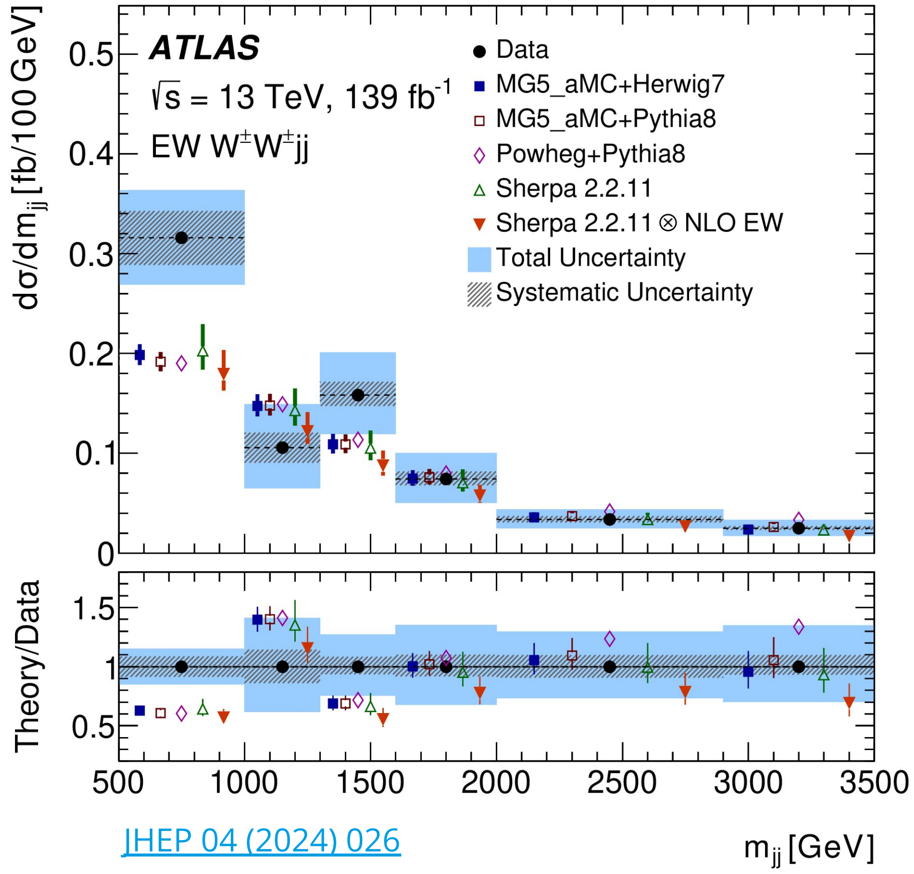
- Parity violation in weak interaction
  $\rightarrow$ **effects on decay products**



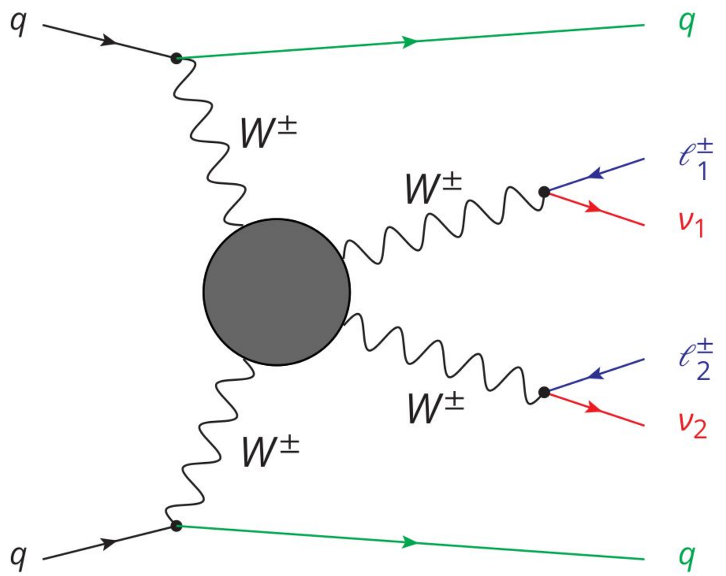


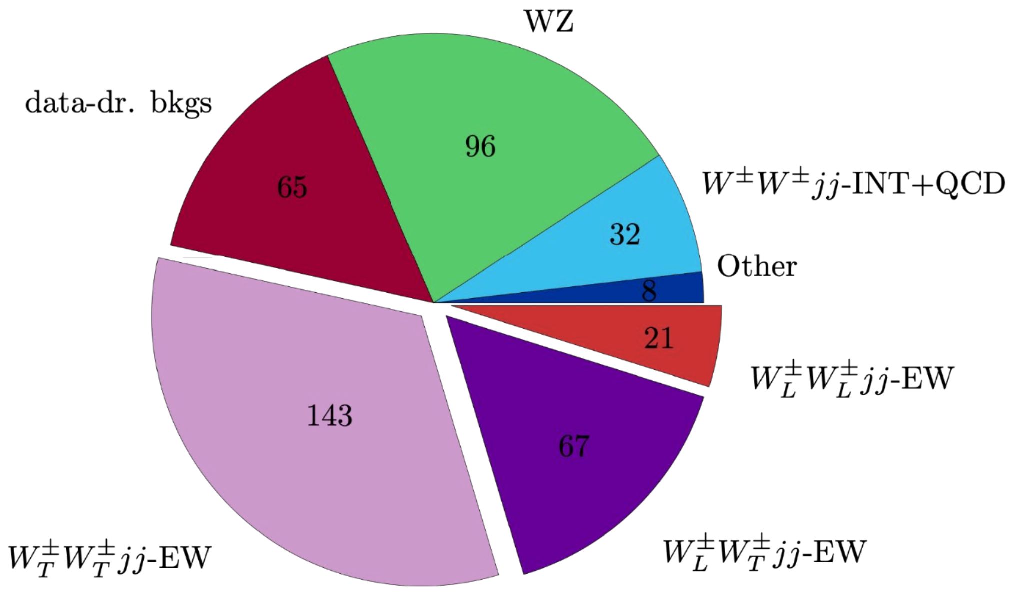
Analysis overview

- <u>Aim</u>: measuring fiducial cross section of $W_L^\pm W_L^\pm$(LL) and $W_L^\pm W^\pm$ (LX)
- Use the full Run 2 data (140 fb^{-1})



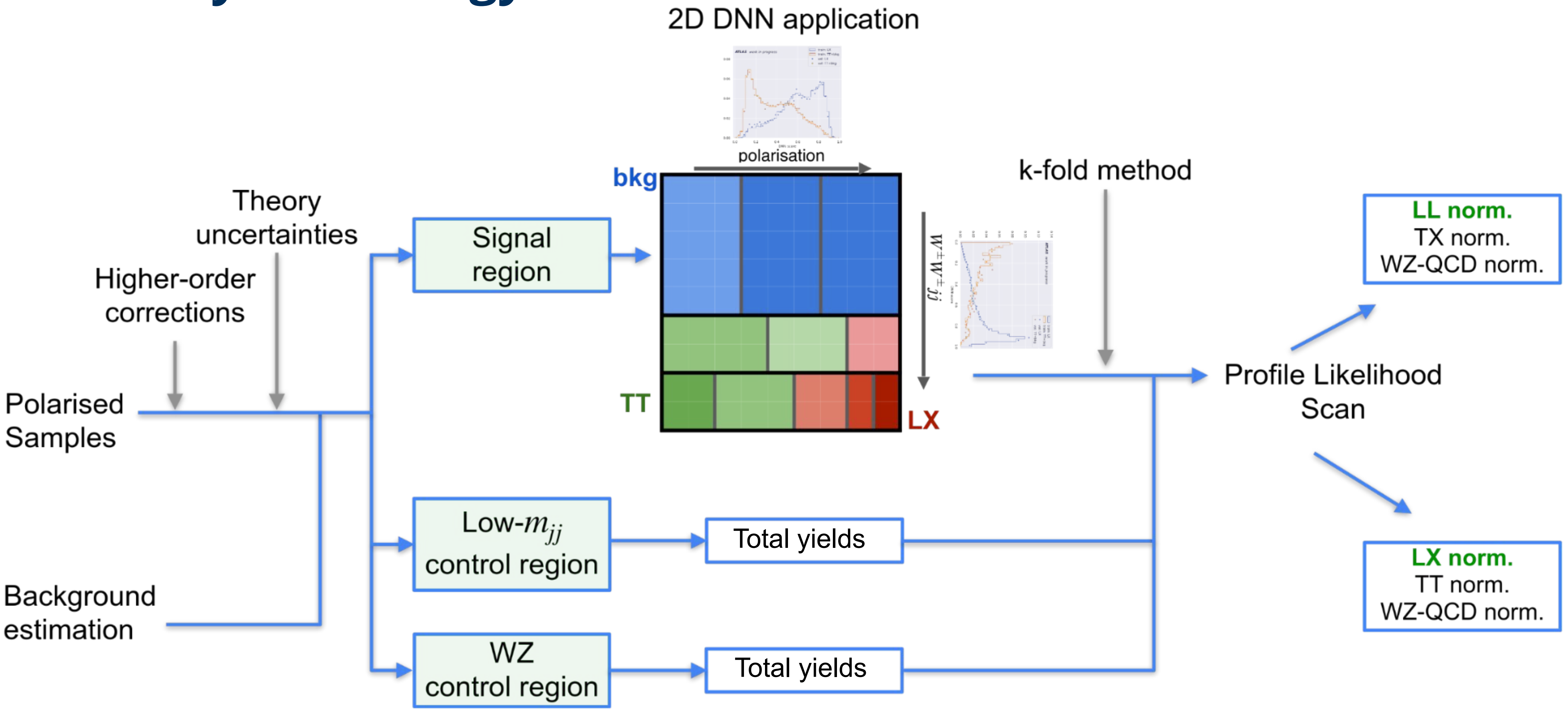
[JHEP 04 (2024) 026](#)





[Stange, M., DPG SMuK 2024]

Analysis strategy



[M. Stange (2024) 'SM approval meeting'. Unpublished.]

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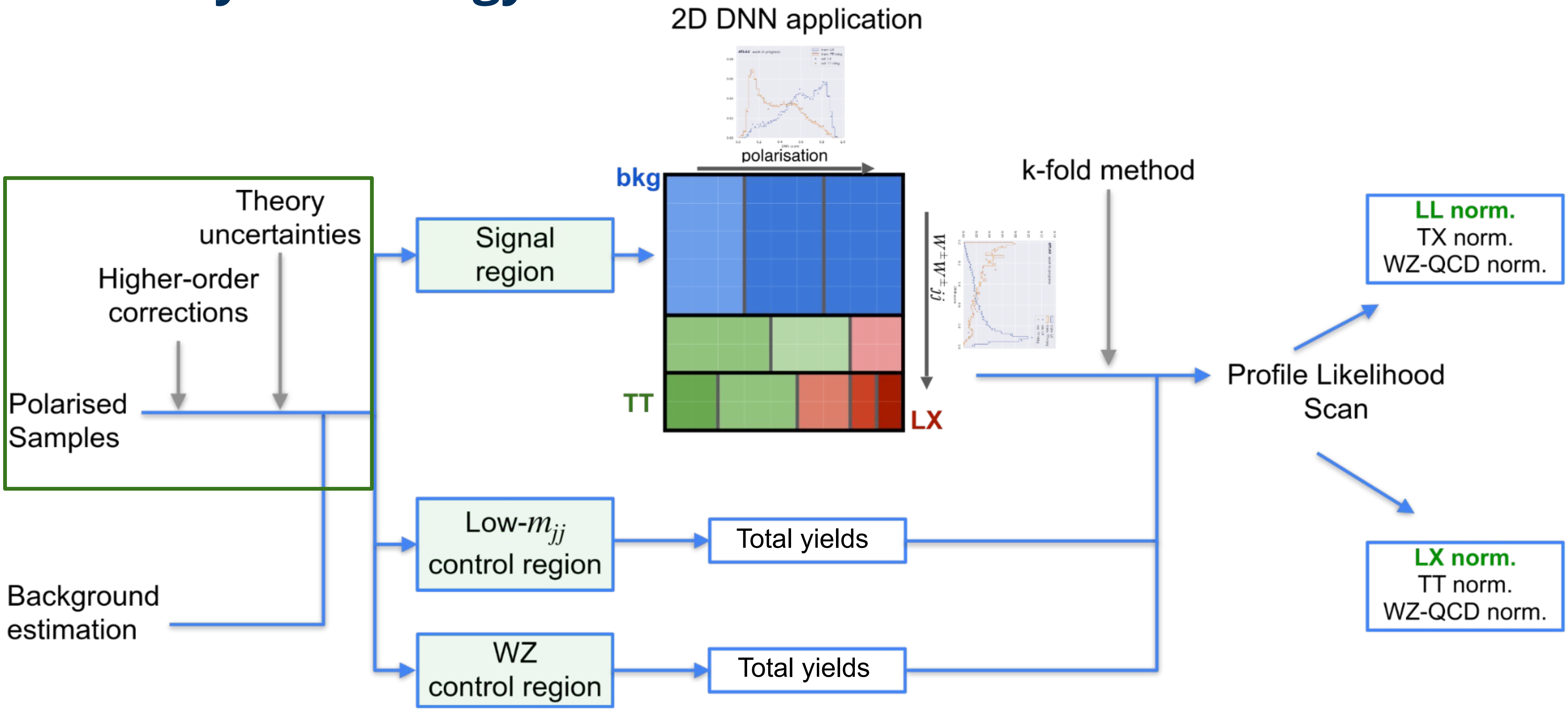

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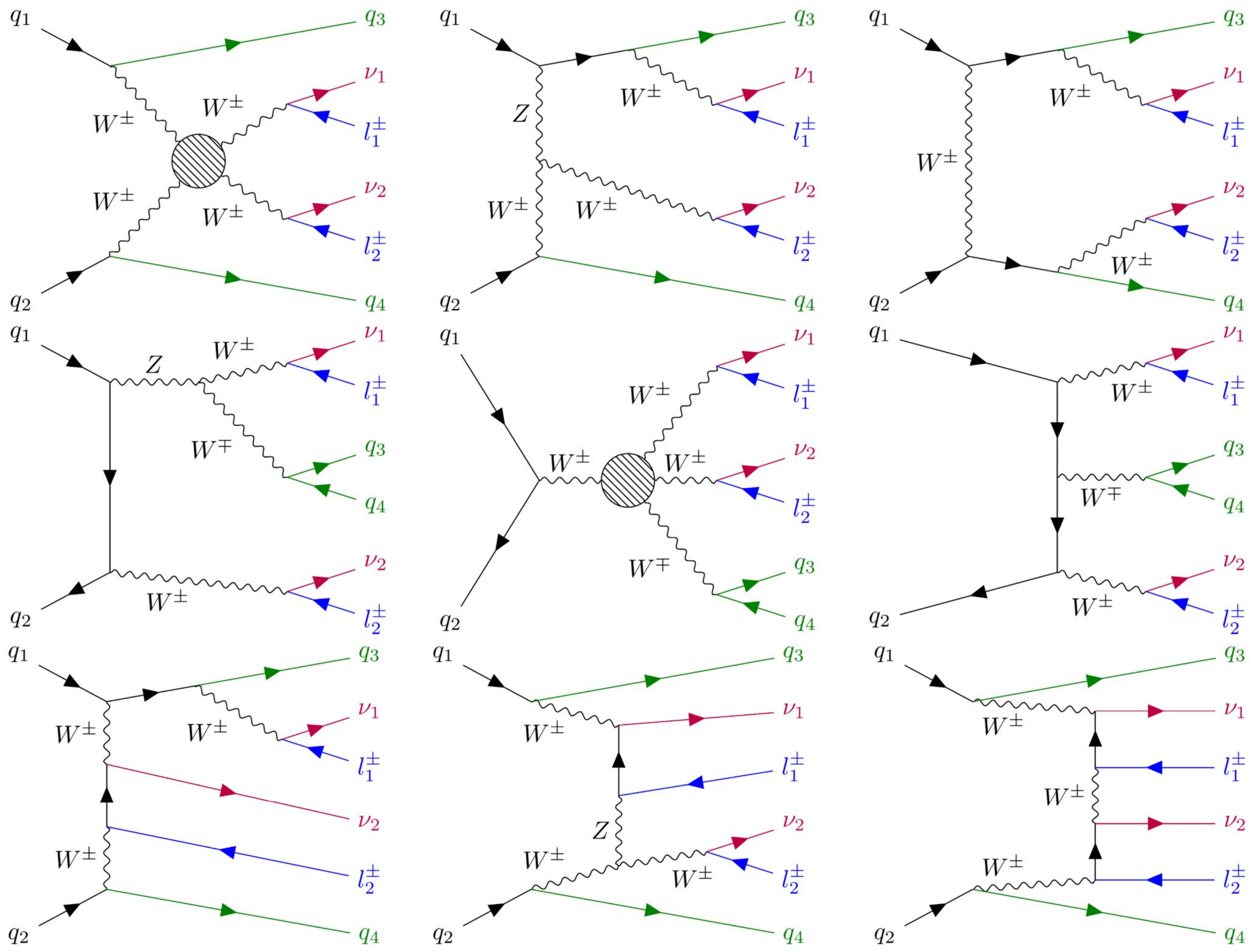
Polarized predictions for $\mathbf{W^{\pm}W^{\pm}jj}$



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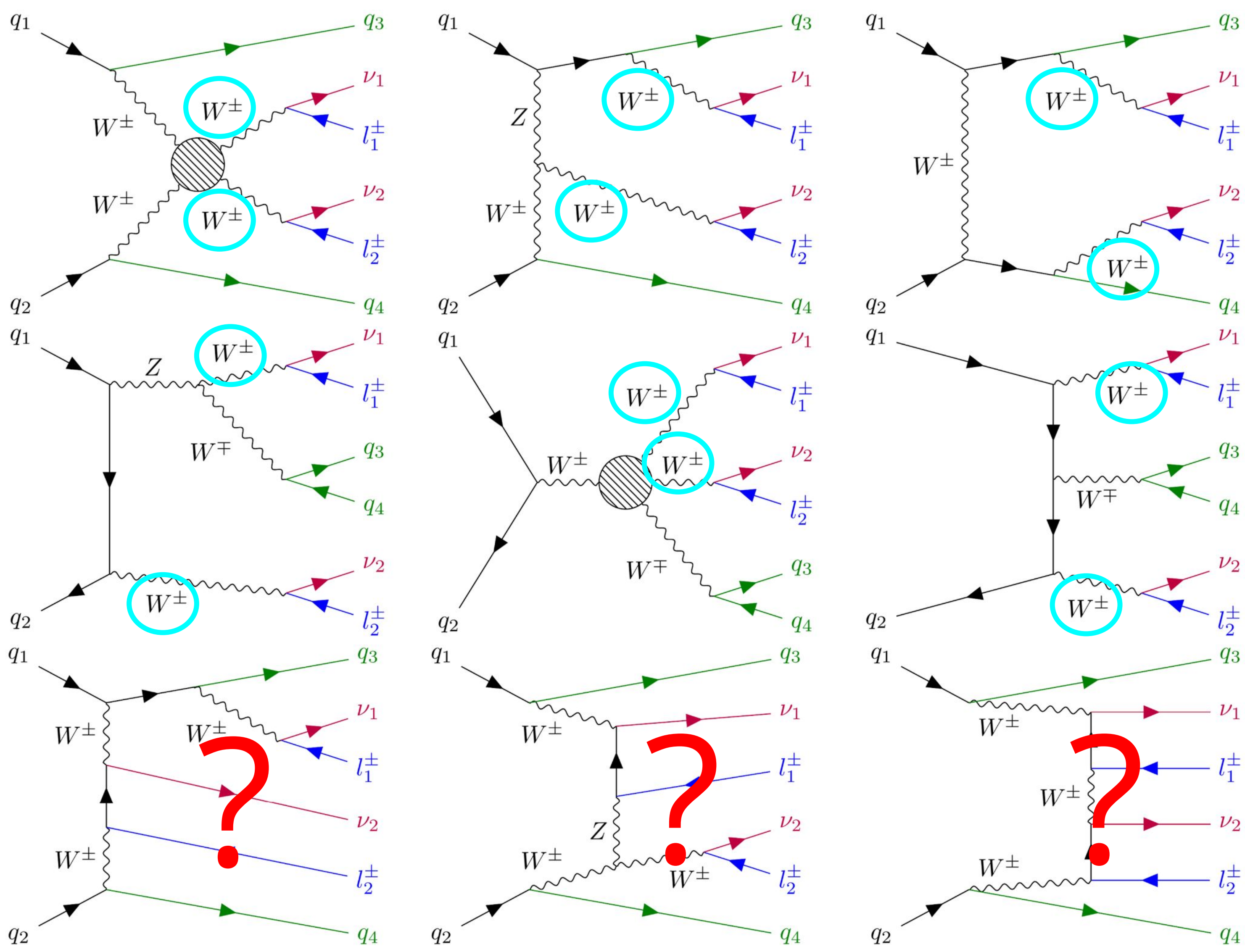
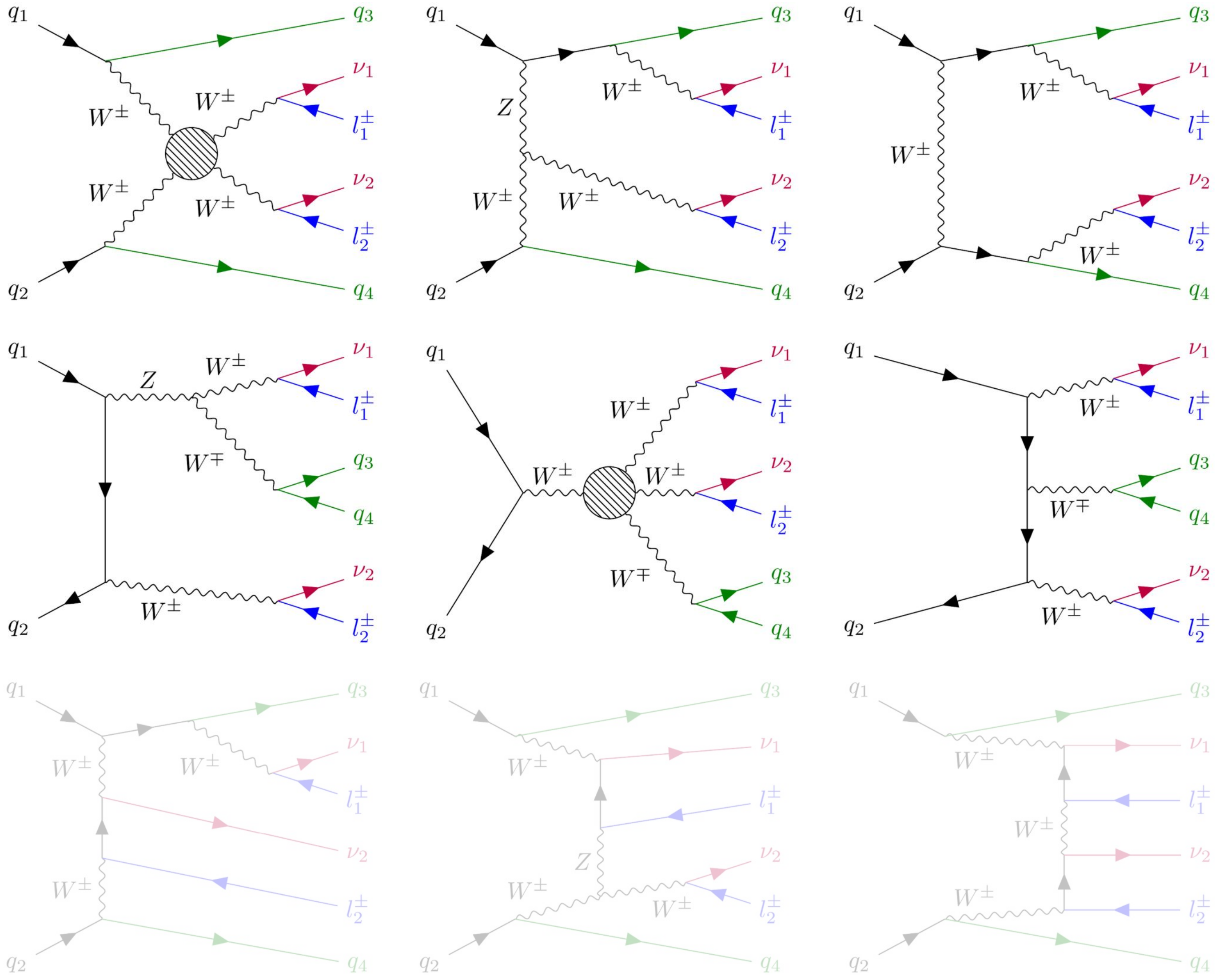


Polarized predictions for $\mathbf{W^{\pm}W^{\pm}jj}$

- On-shell approximation necessary
  - Sherpa 3: **Narrow-Width Approx.**

$$\boxed{\frac{1}{\left(q^2 - m_V^2\right)^2 + \Gamma_V^2 m_V^2} \to \frac{\pi\delta\left(q^2 - m_V^2\right)}{\Gamma_V m_V}}$$

- Vector boson width set to zero to ensure gauge invariance



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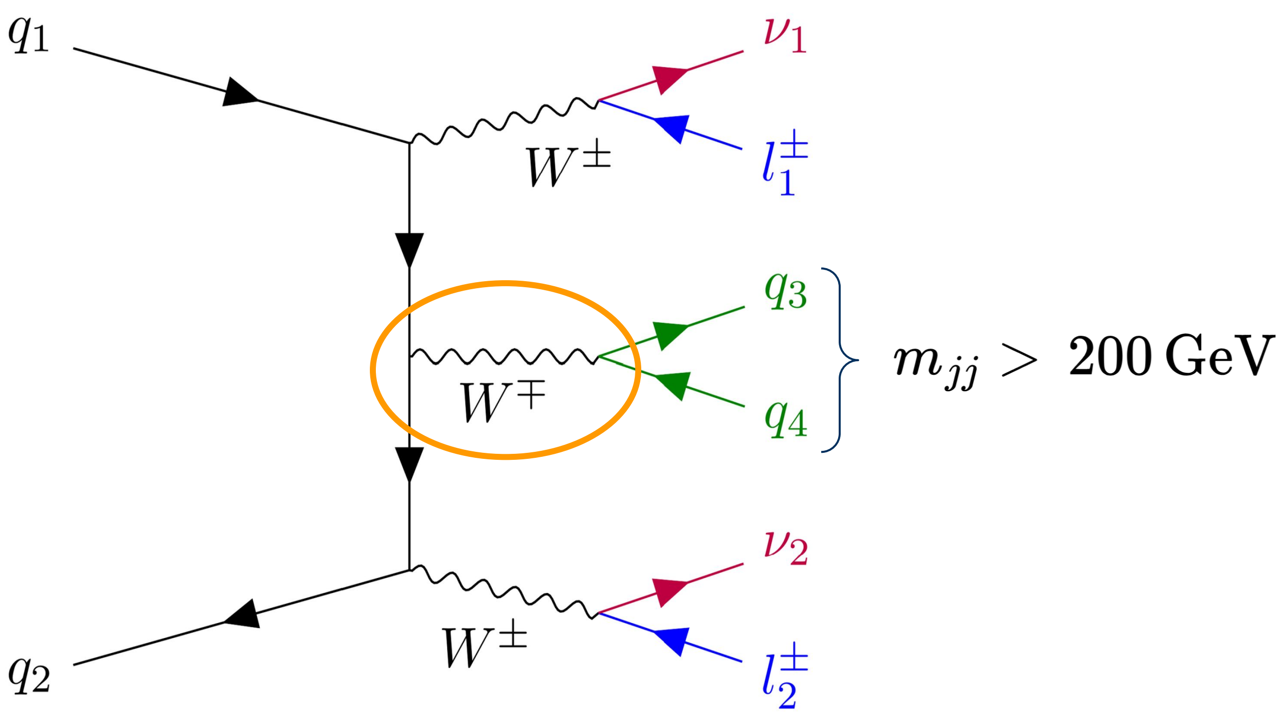
- Vector boson width set to zero to ensure gauge invariance
  $\to$ **divergence at $\mathbf{m_{qq} = m_W}$**



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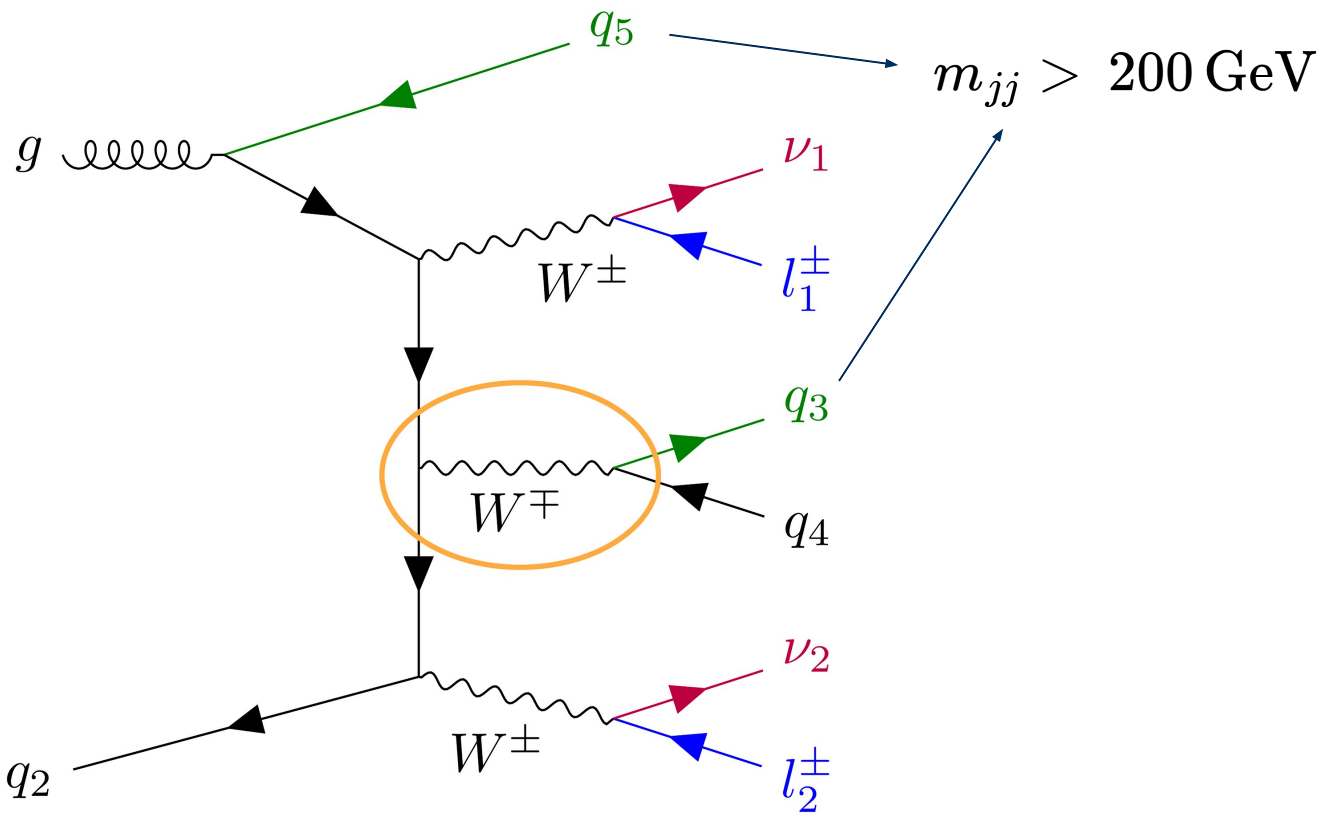
- Vector boson width set to zero to ensure gauge invariance
  $\rightarrow$ **divergence at $\mathbf{m_{qq} = m_W}$**
- **Simulate $\mathbf{W^{\pm}W^{\pm}jj + 0, 1j}$** to include NLO QCD effects
  - need **VBS-approximation** to suppress triboson diagrams



Polarized predictions for $\mathbf{W^\pm W^\pm jj}$

- On-shell approximation necessary
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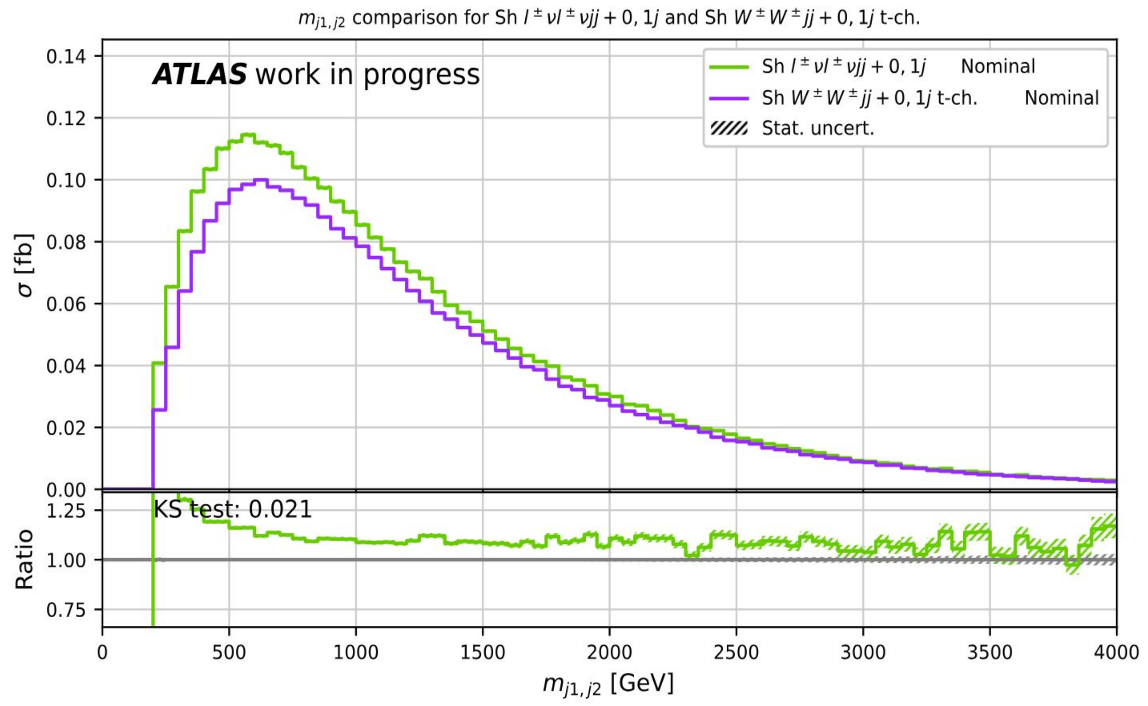
$$\boxed{\frac{1}{\left(q^2-m_V^2\right)^2+\Gamma_V^2 m_V^2} \rightarrow \frac{\pi\delta\left(q^2-m_V^2\right)}{\Gamma_V m_V}}$$

- Vector boson width set to zero to ensure gauge invariance
  $\rightarrow$ **divergence at $\mathbf{m_{qq}=m_W}$**

- **Simulate $\mathbf{W^\pm W^\pm jj+0,1j}$** to include NLO QCD effects
  - need **VBS-approximation** to suppress triboson diagrams

- Full off-shell $\ell^\pm\ell^\pm\nu\nu jj+0,1j$ to **correct missing s-channels and off-shell effects**



Higher-order corrections – NLO QCD

- **Full phase-space reweighting** using DNN
  [A. Andreassen, B. Nachman, arXiv:1907.08209]
  - Likelihood-ratio can be approximated using binary classifier

$$\frac{p_1(x)}{p_2(x)} \approx \frac{\mathrm{DNN}(x)}{1-\mathrm{DNN}(x)}$$

- $\mathrm{DNN}_{\text{s-ch.}}:\ W^{\pm}W^{\pm}jj+0,1j\ (\mathrm{VBSA})$

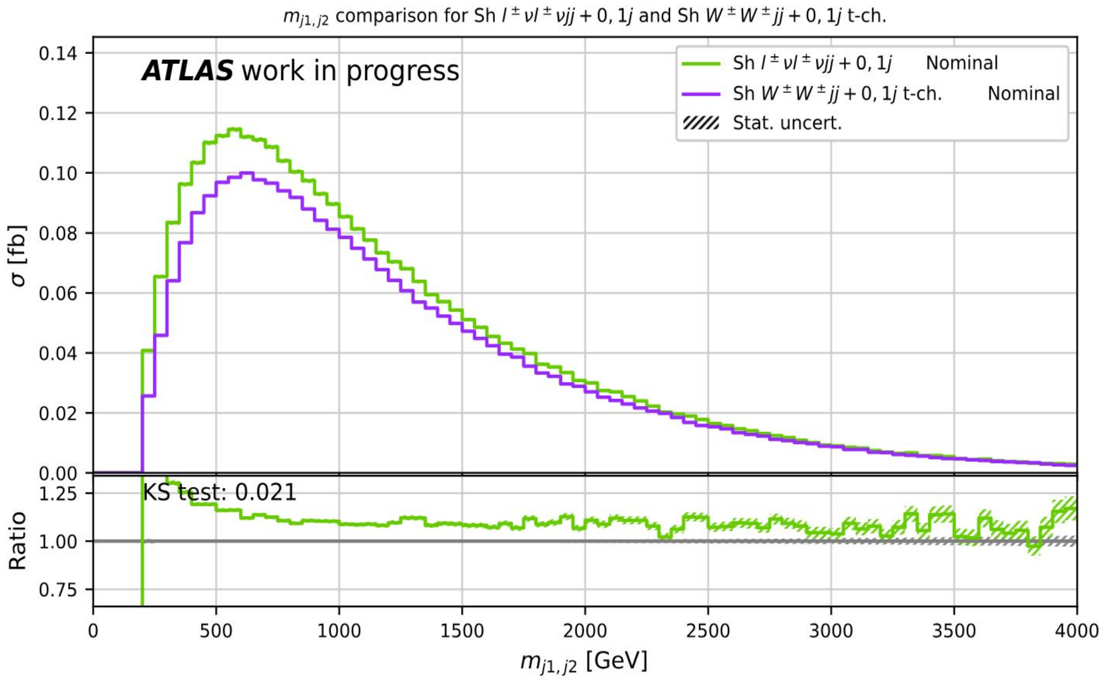
$$\Updownarrow$$

$$\ell^{\pm}\ell^{\pm}\nu\nu jj+0,1j$$

- Per-event correction weight:

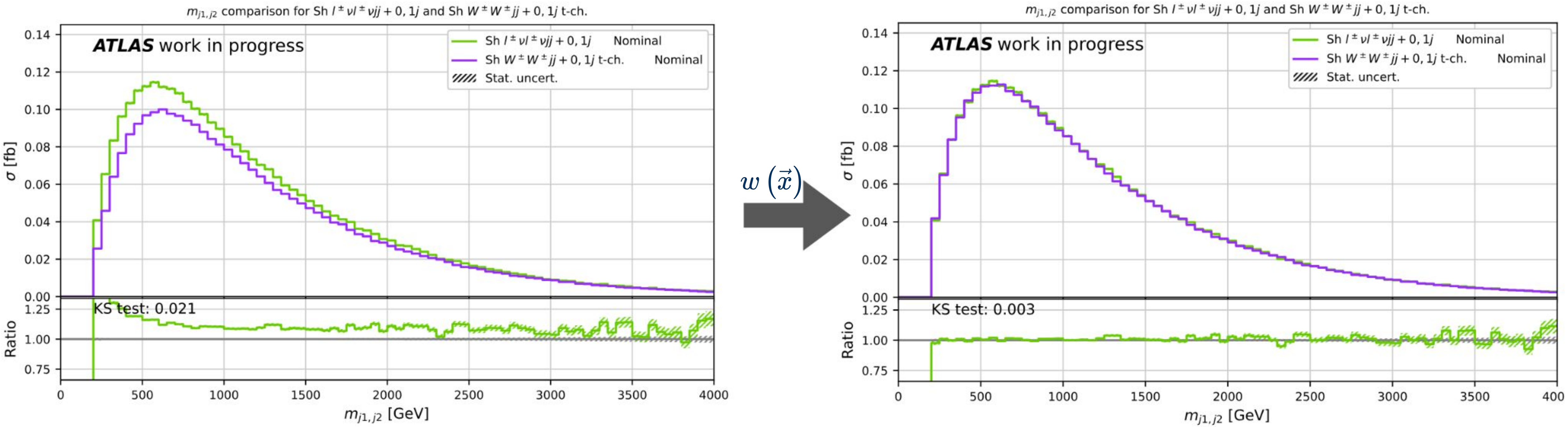
$$\boxed{w\left(\vec{x}\right) = \frac{\mathrm{DNN}_{\text{s-ch.}}\left(\vec{x}\right)}{1-\mathrm{DNN}_{\text{s-ch.}}\left(\vec{x}\right)}}$$

$W^{\pm}W^{\pm}jj+0,1j$ (VBSA)



$\ell^{\pm}\nu\ell^{\pm}\nu jj+0,1j$

Higher-order corrections – NLO QCD

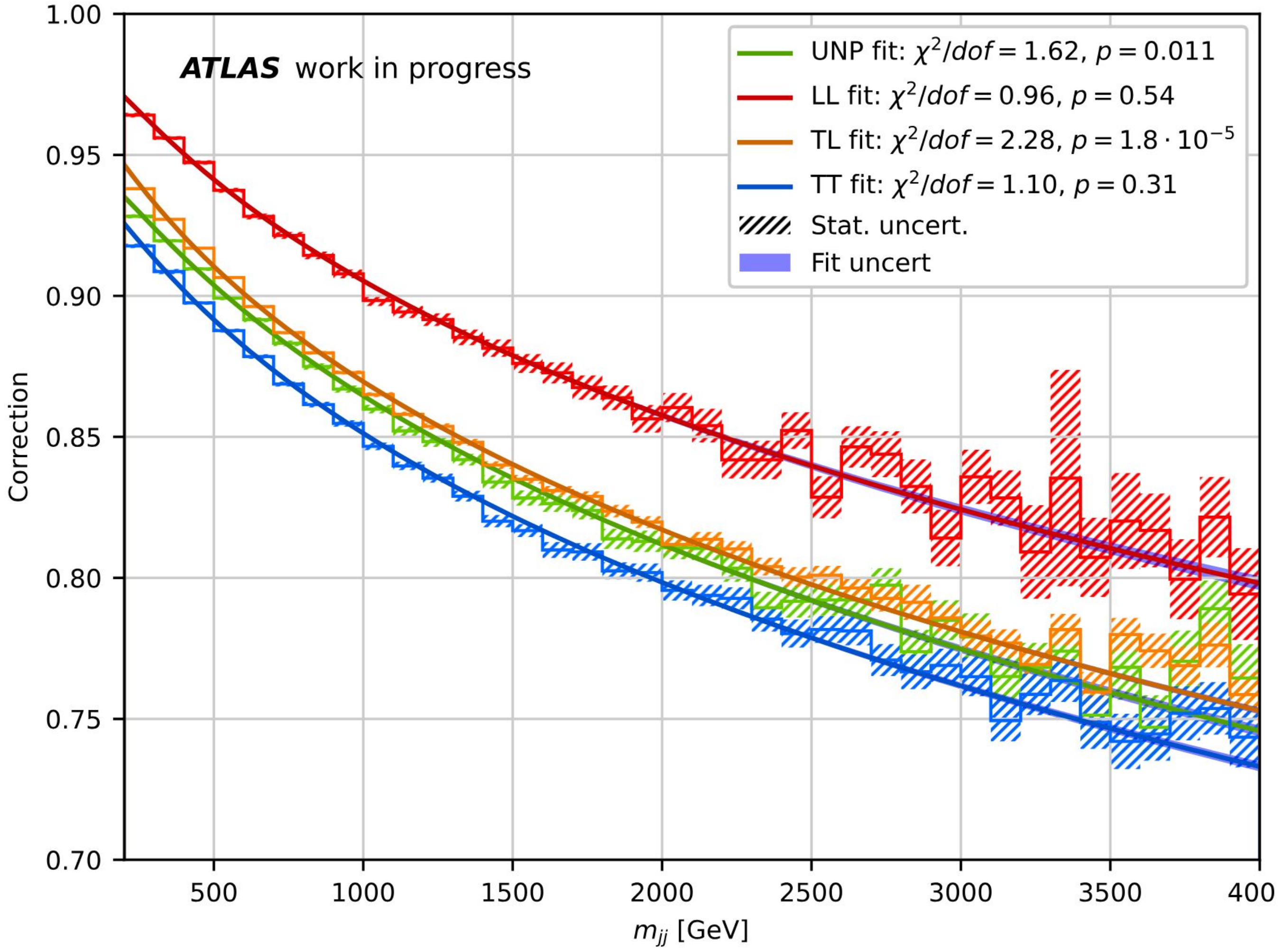


Higher-order corrections – NLO EW

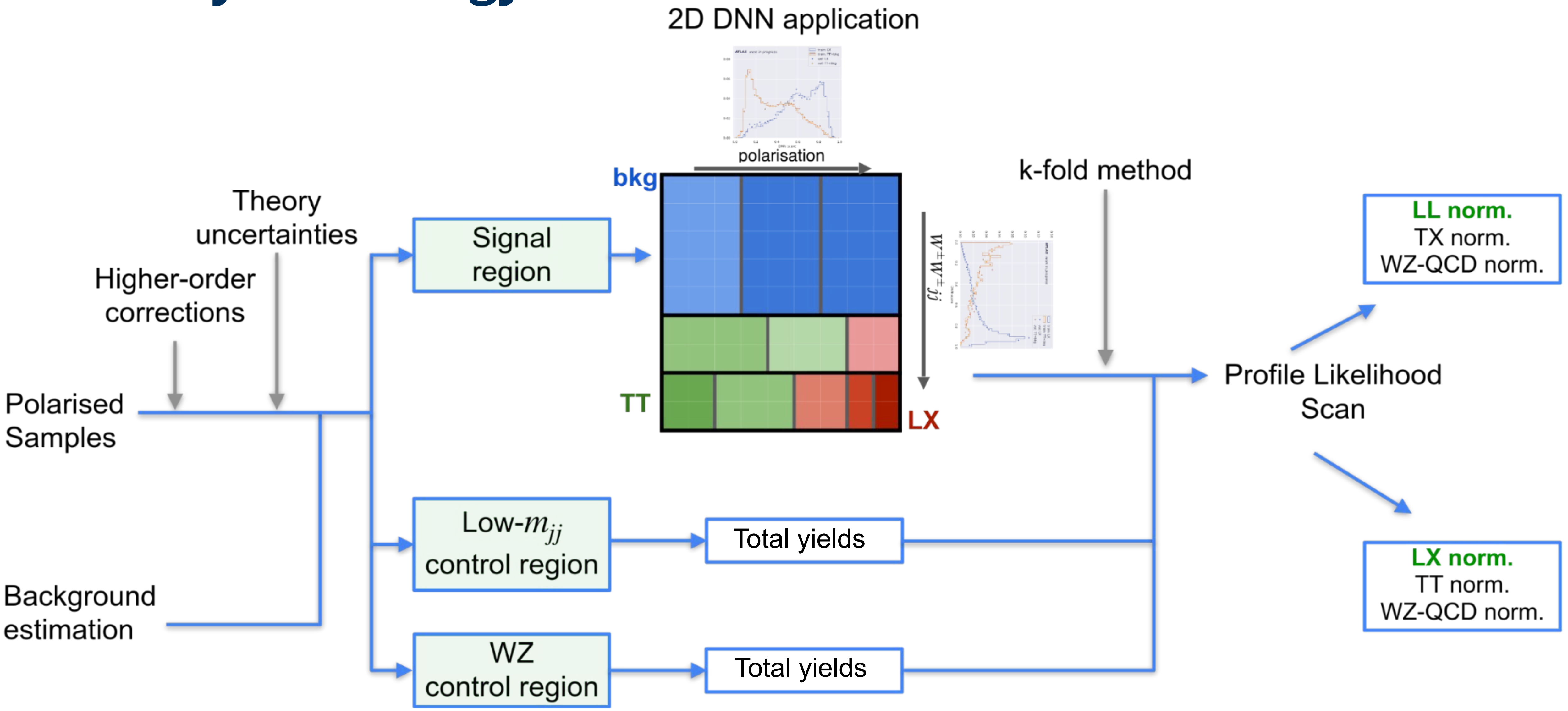
- **Polarized NLO EW corrections** provided by A. Denner et al. [arXiv:2409.03620]

- Perform separate fit for each polarization

$$f(m_{jj}) = p_0 + p_1 \ln \frac{m_{jj}}{\mathrm{GeV}} + p_2 \ln^2 \frac{m_{jj}}{\mathrm{GeV}}$$



Analysis strategy



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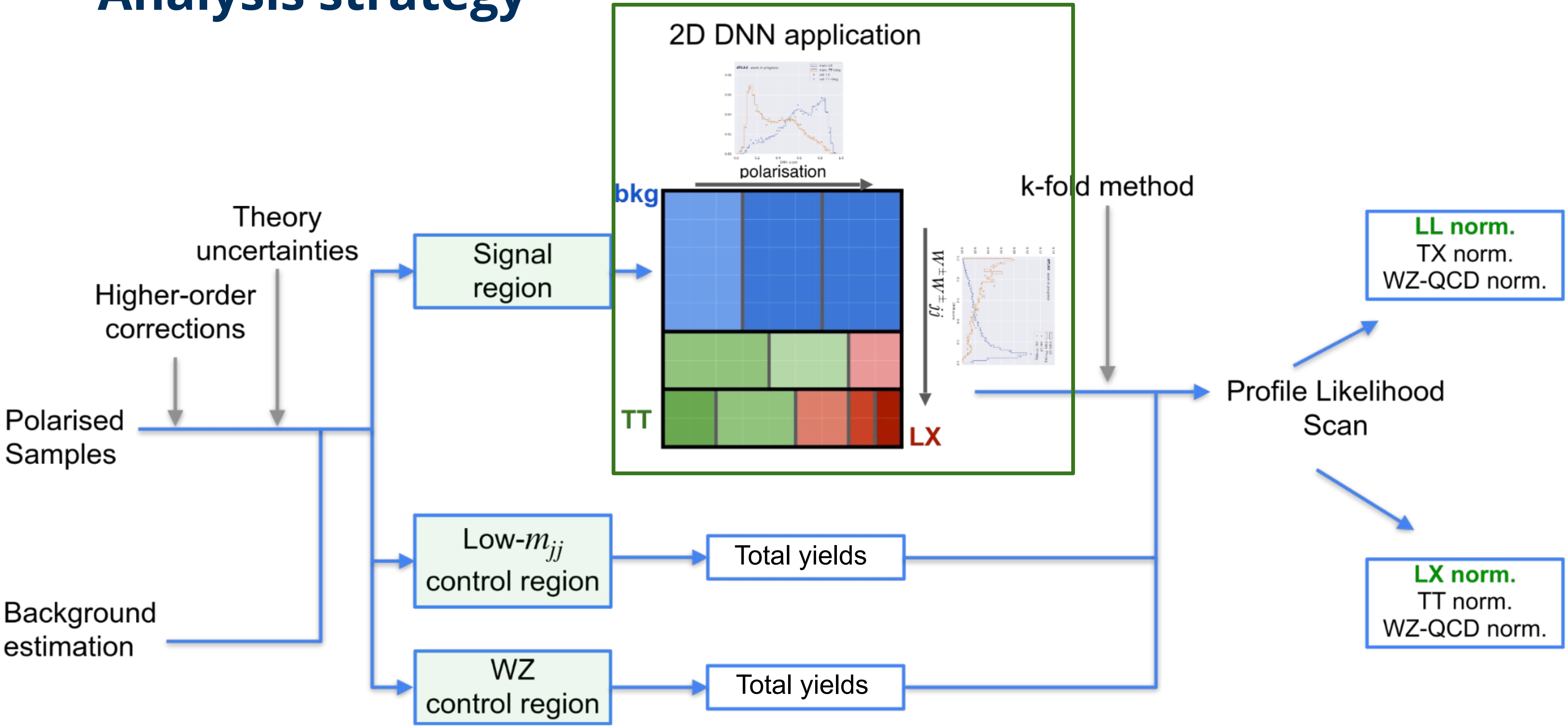

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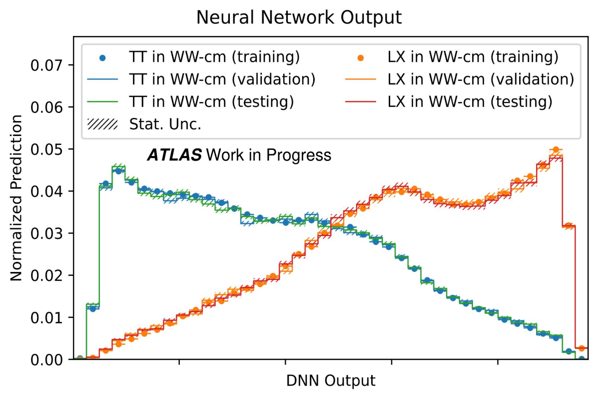
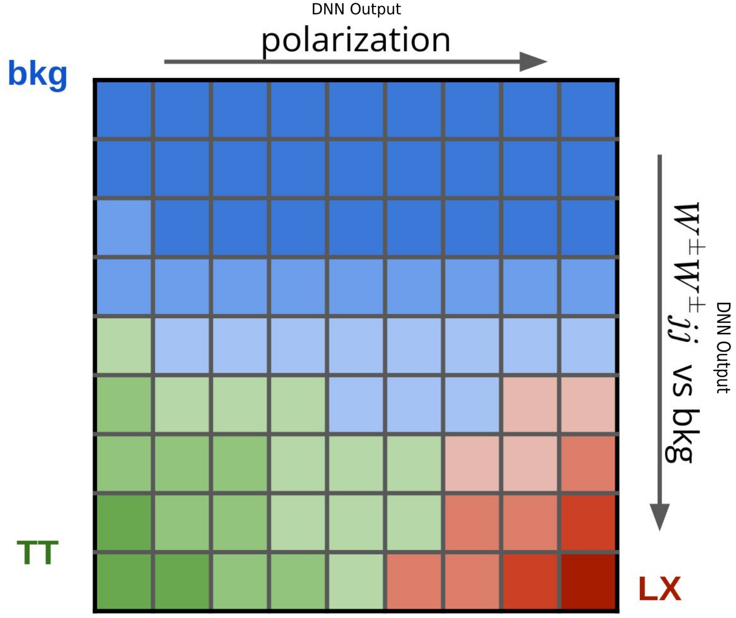
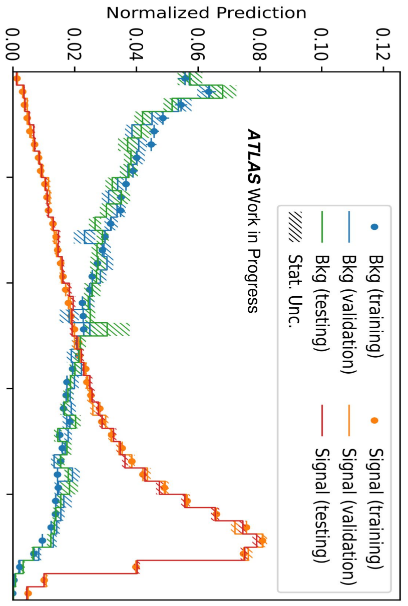
Signal discrimination – Overview

- 2 sets of binary MLP classifiers:
  - $W^{\pm}W^{\pm}jj$-EW vs Bkg.
  - polarization states:
    - LL vs TX
    - LX vs TT
- Build 2D histogram from classifier scores

Simple approach, but well optimized!

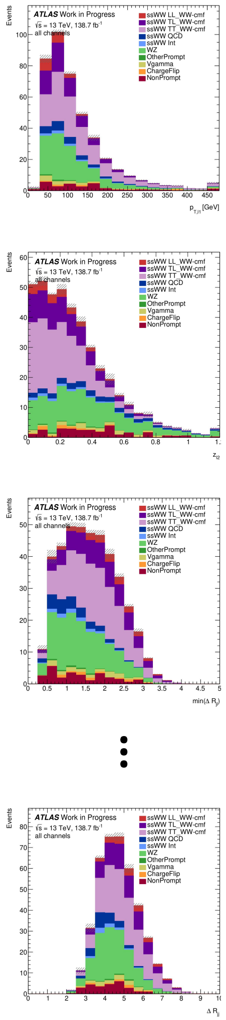






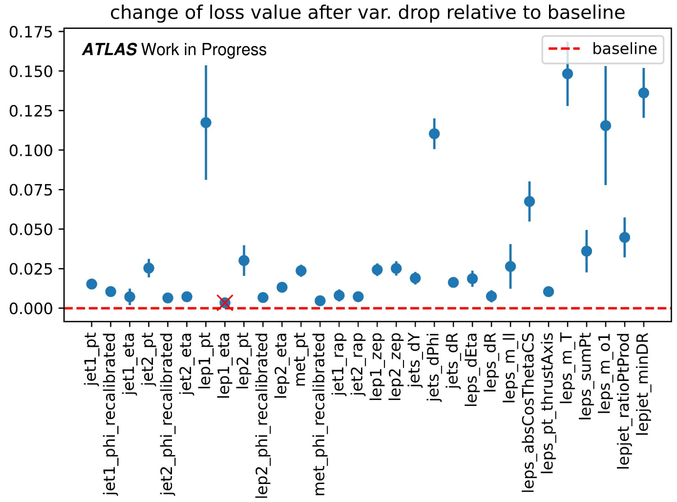
[M. Stange, ATLAS-D, 2023]

Signal discrimination – DNN optimization with `optima-ml`

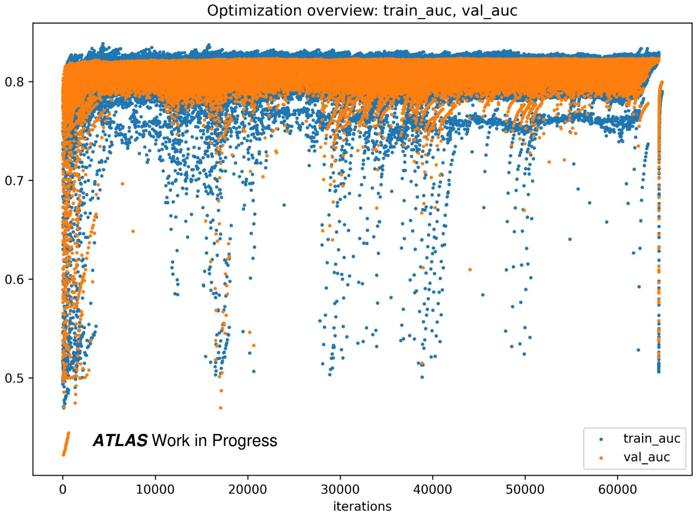


Input Variable Selection → **Hyperparameter optimization (Optuna)** → **Crossvalidation**

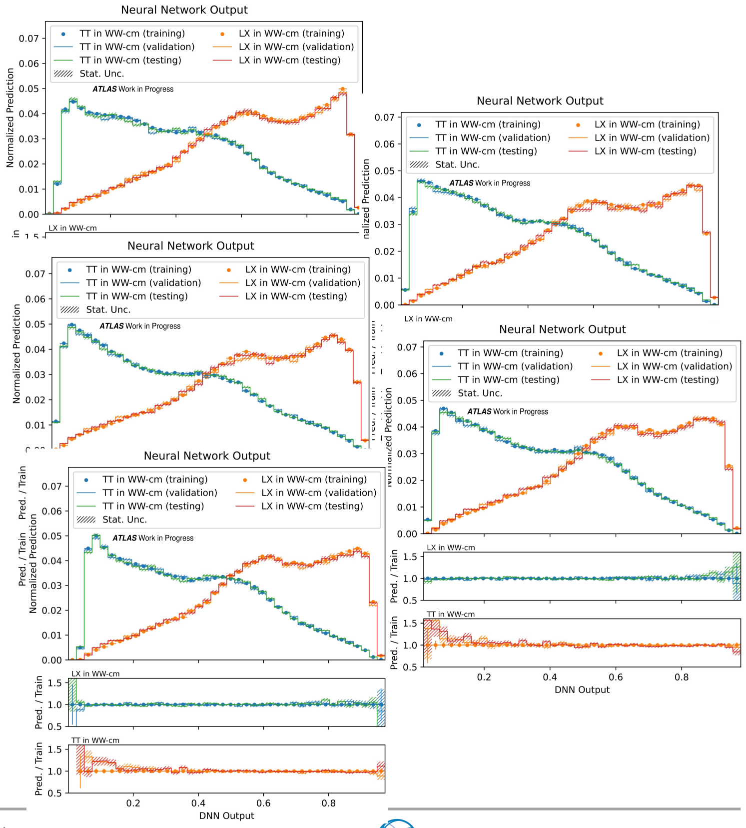
Input Variable Selection
- hyperparameter optimization with all input variables (Optuna)
- optimize input variables with fixed hyperparameters using backwards elimination



Hyperparameter optimization (Optuna)
- find best hyperparameters with optimized input variables



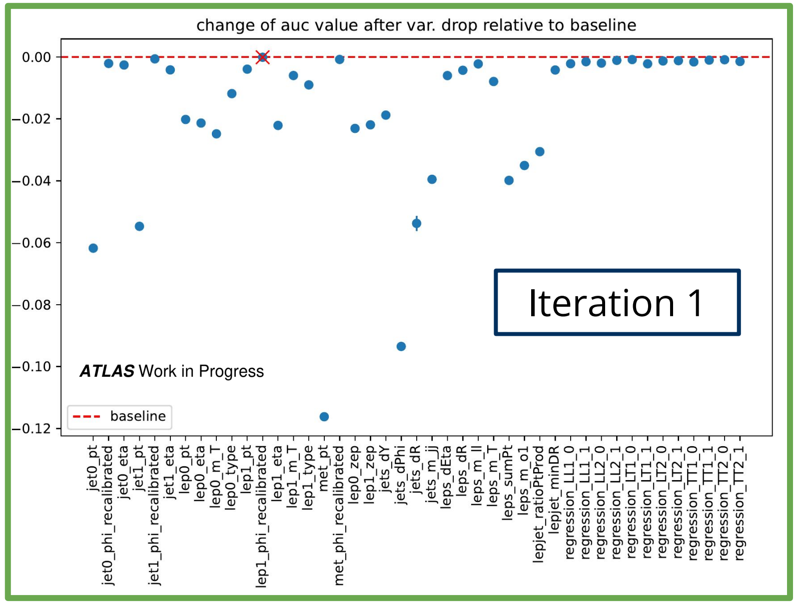
Crossvalidation
- perform 5-fold cross-validation

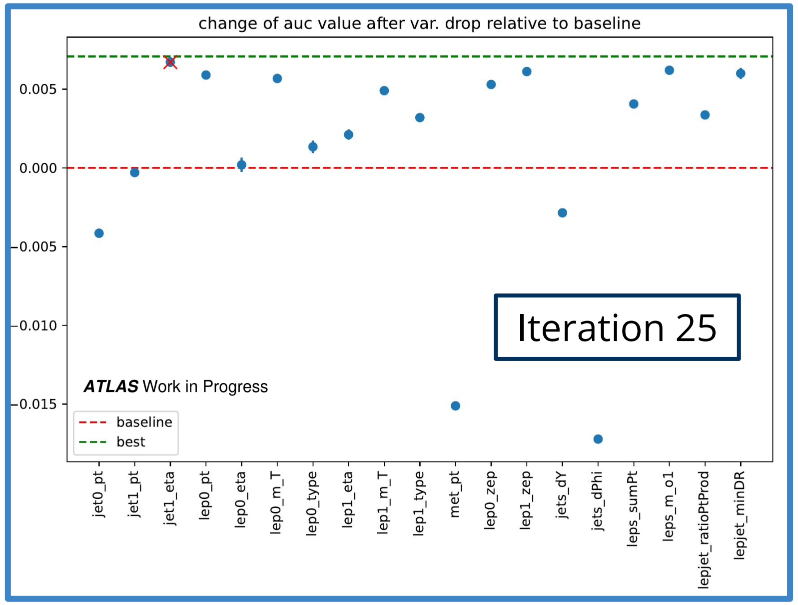


Signal discrimination – DNN input variable selection

Backwards Elimination

- Baseline ANN with all input variables
- Iteratively remove unimportant/redundant input variables
- Evaluate the importance of an input variable based on change of AUC value:
  - random shuffling between events
    → *fast, but no correlations*
  - remove from training set and retrain
    → *computationally expensive, but can identify redundant variables*
- Retrain the models at the end of each iteration





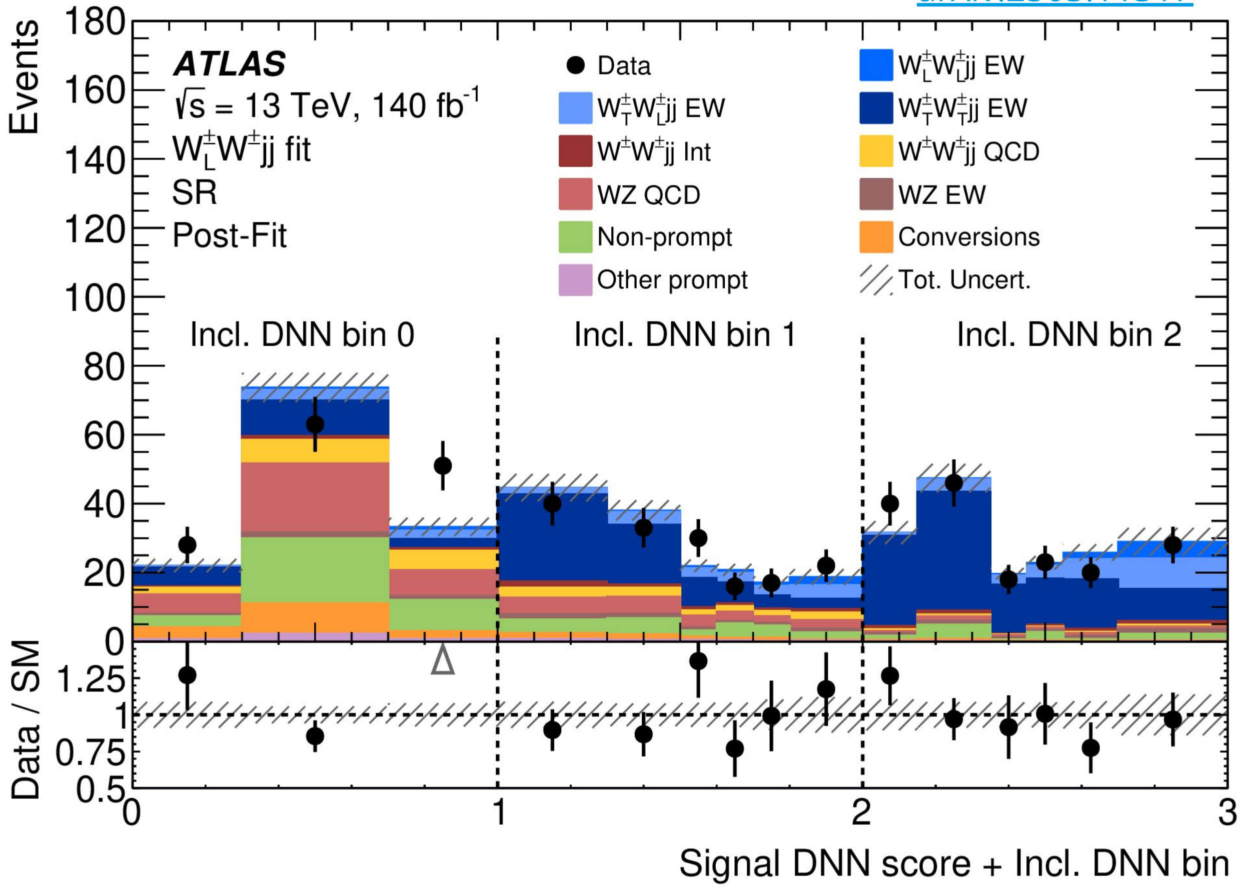
Conclusion

- State of the art higher-order corrections
- Sophisticated neural network optimization techniques → published on PyPI

- **First evidence for longitudinal polarization in vector boson scattering: 3.3 (4.0) σ**

- **Most stringent upper limit on $\mathbf{W^\pm_L W^\pm_L jj}$ production cross section: 0.45 (0.43) fb**

arXiv:2503.11317



How to try OPTIMA?

- Published on PyPI:
  - pip install optima-ml[keras]
  - pip install optima-ml[lightning]
- Source code and detailed usage instructions available on CERN gitlab: gitlab.cern.ch/atlas-germany-dresden-vbs-group/optima
- API documentation at optima-docs.docs.cern.ch
- Roadmap:
  - Support for Keras 3 → Cross-framework support
  - Support for HTCondor

Any feedback is welcome! Send me a mail at erik.bachmann@tu-dresden.de

atlas-germany-dres... / OPTIMA

OPTIMA: an Optimization Platform for Tuning Input Variables and Model Parameters

OPTIMA is a framework to perform highly parallelized hyperparameter optimization and input variable selection of arbitrary Keras or Lightning neural networks for supervised learning tasks.

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