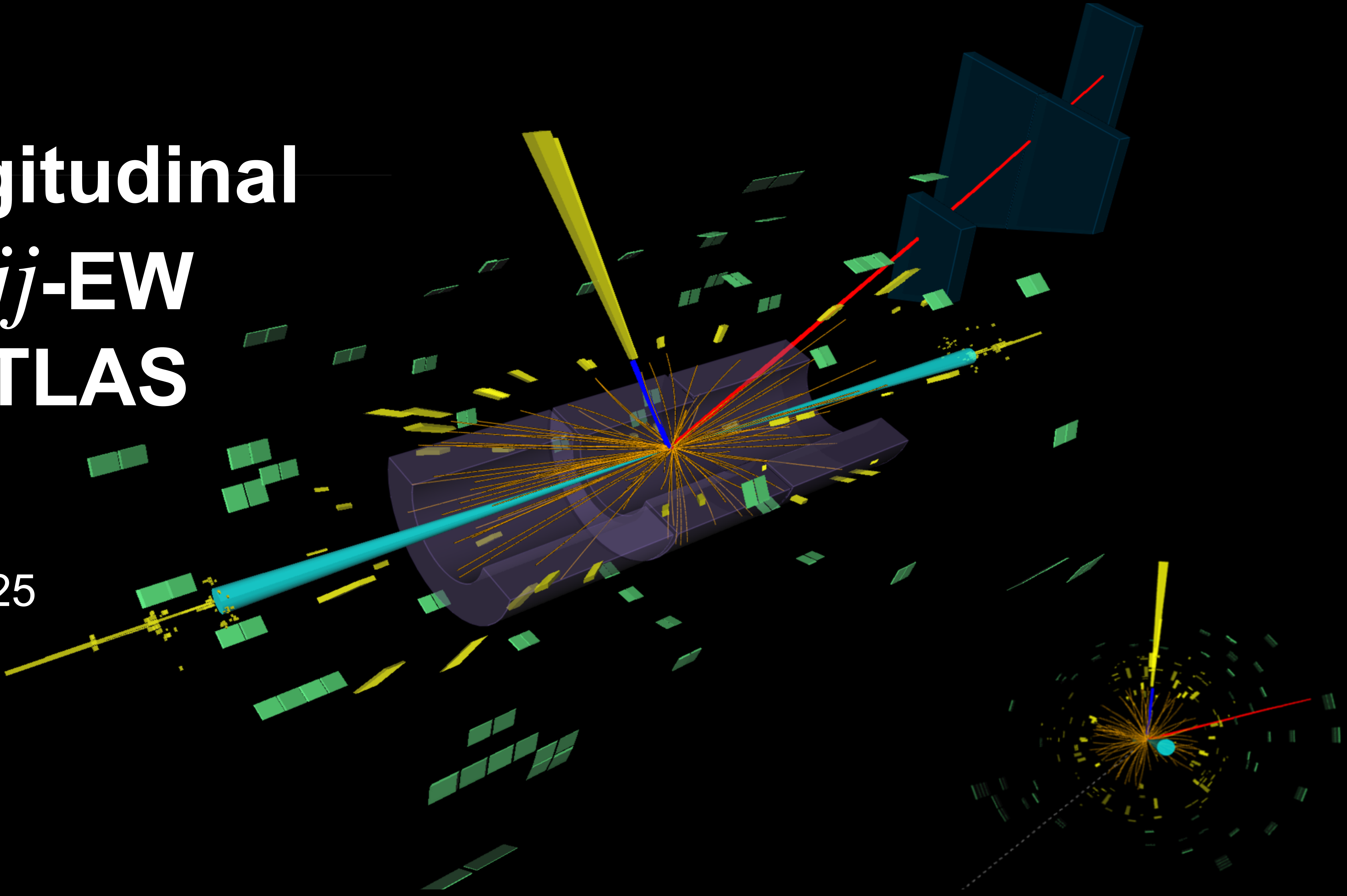
# Evidence for longitudinal polarized $W^{\pm}W^{\pm}jj$-EW scattering with ATLAS

[arXiv:2503.11317]

59th Rencontres de Moriond 2025

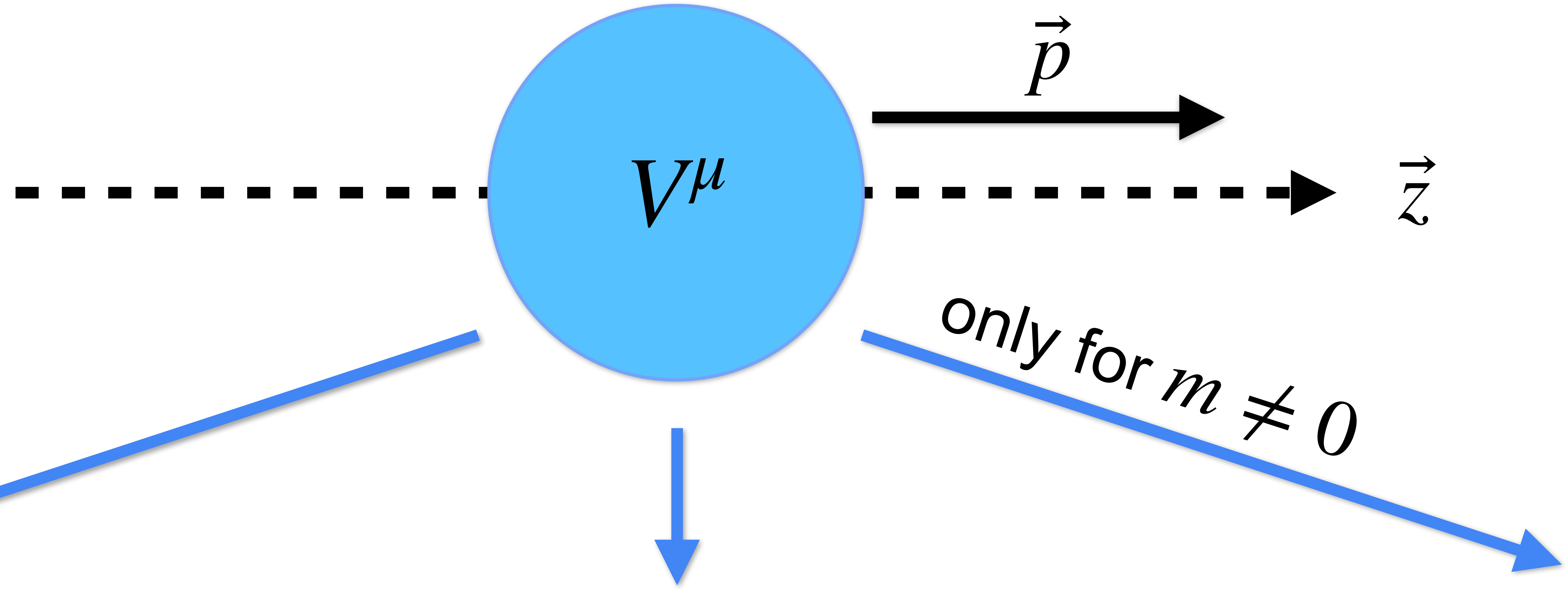

Max Stange on behalf of the ATLAS Collaboration

TECHNISCHE UNIVERSITÄT DRESDEN

[Phys. Rev. Lett. 123 (2019) 161801]

# Polarization States




$\epsilon^\mu_+(\vec{p}) = (0,1,i,0)$

Right-handed

$\epsilon^\mu_-(\vec{p}) = (0,1,-i,0)$

Left-handed

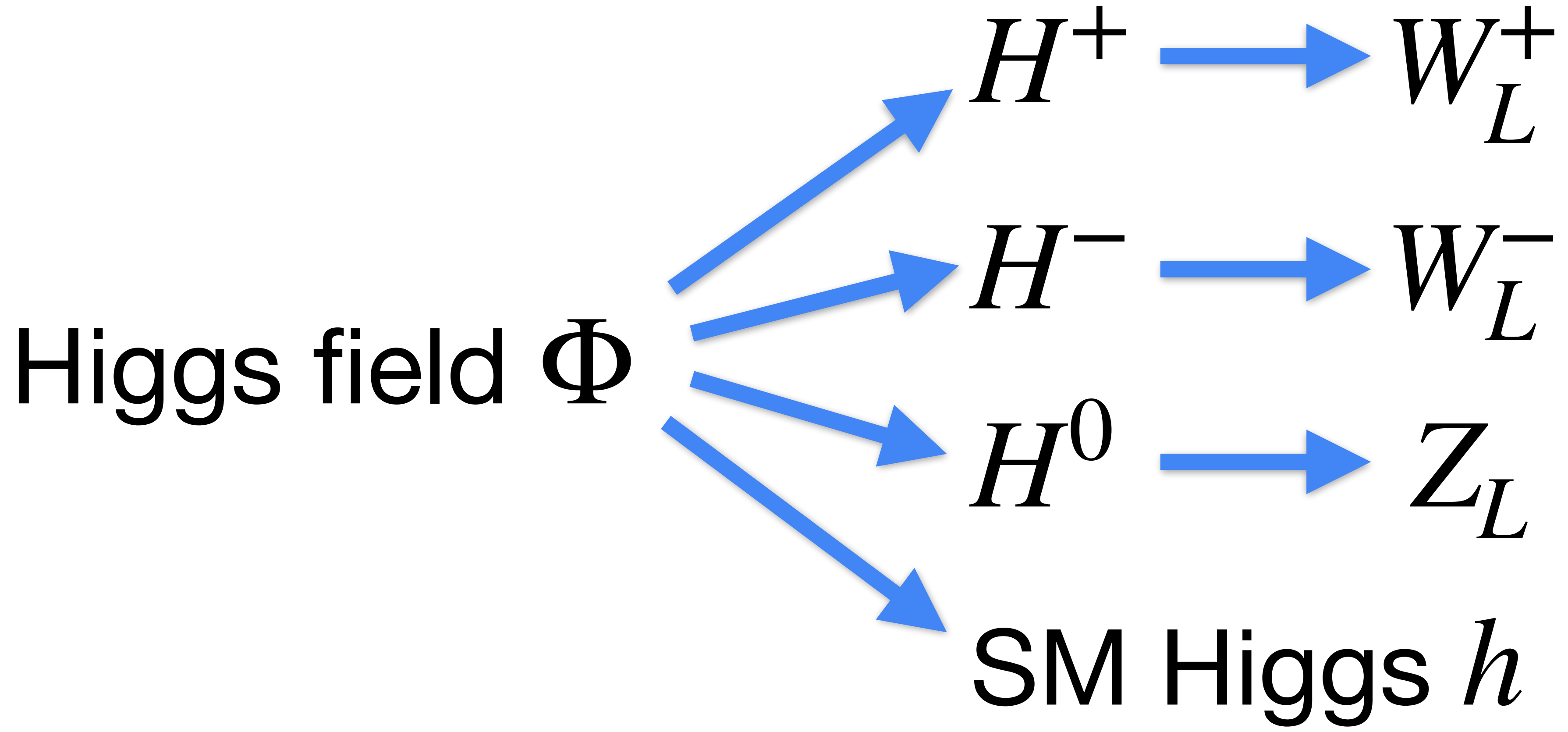
Transverse (T)

$\epsilon^\mu_L(\vec{p}) = \frac{1}{m}(|\vec{p}|,0,0,E)$

Longitudinal (L)

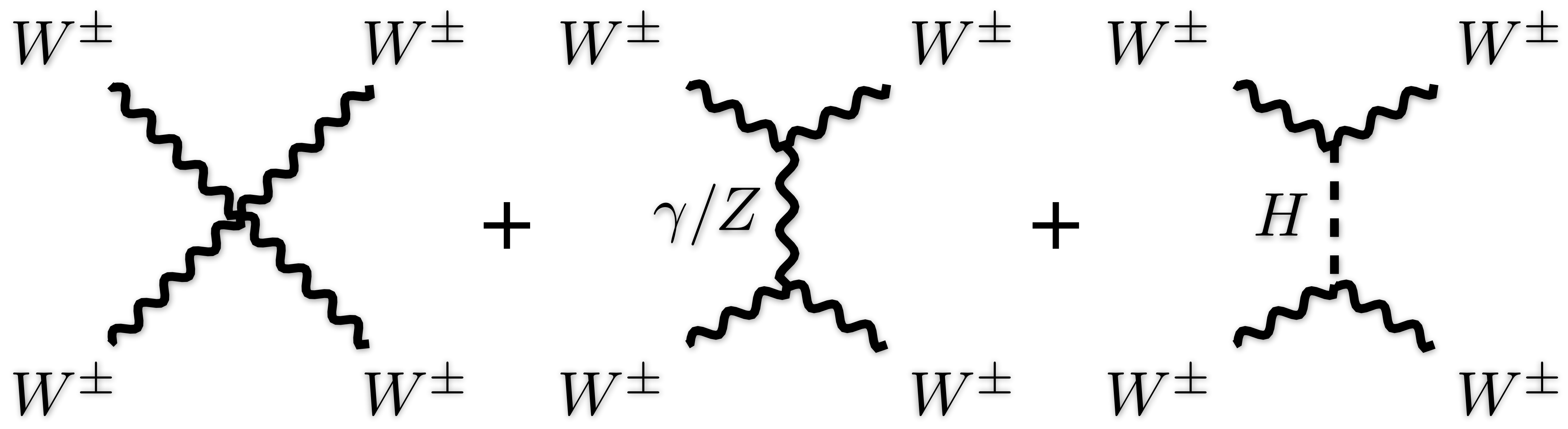
# Importance of $W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm$

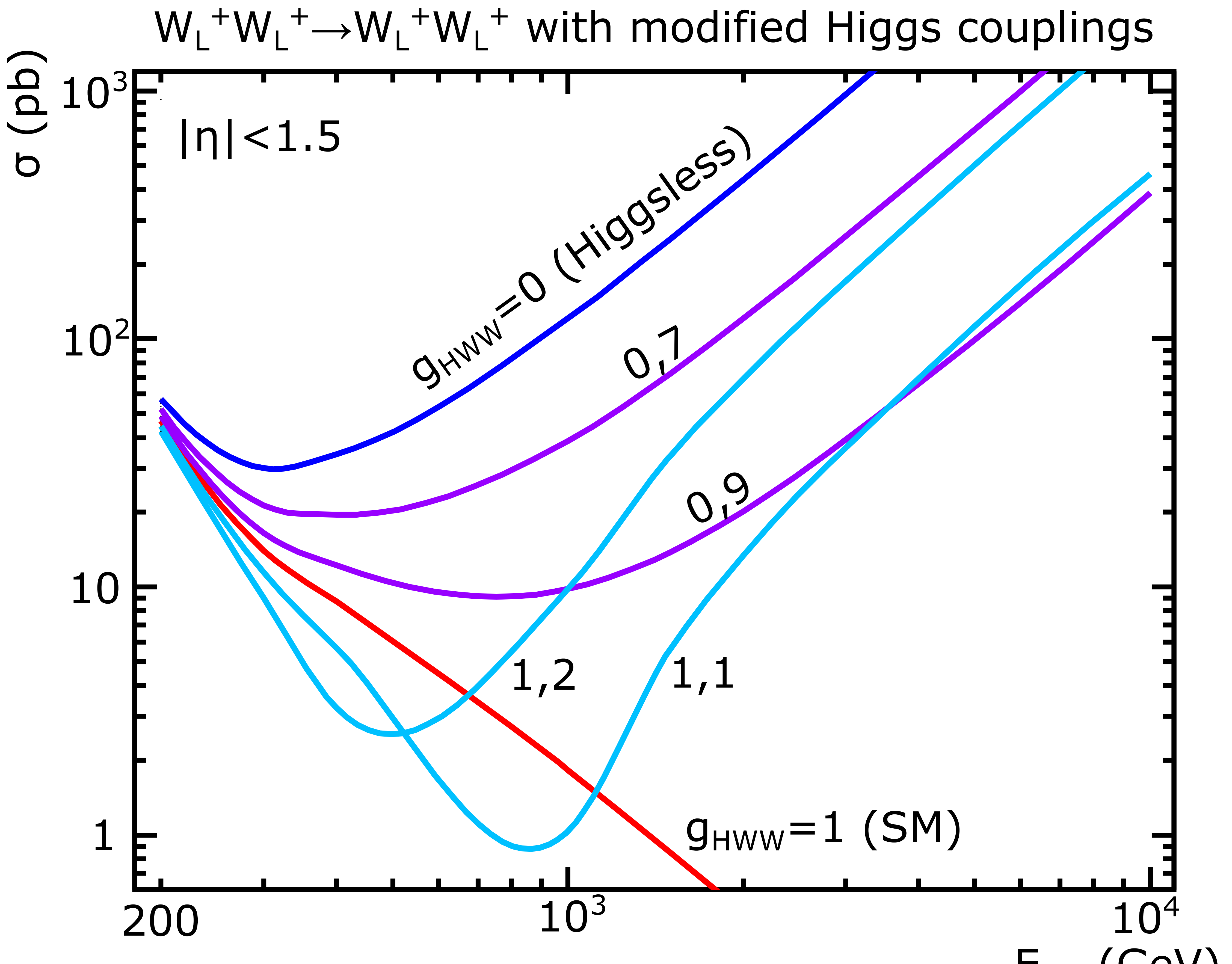
- Higgs Goldstone bosons result in longitudinal polarized vector bosons:




- Longitudinal $W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm$ would **violate unitarity if Higgs coupling deviates from SM prediction**

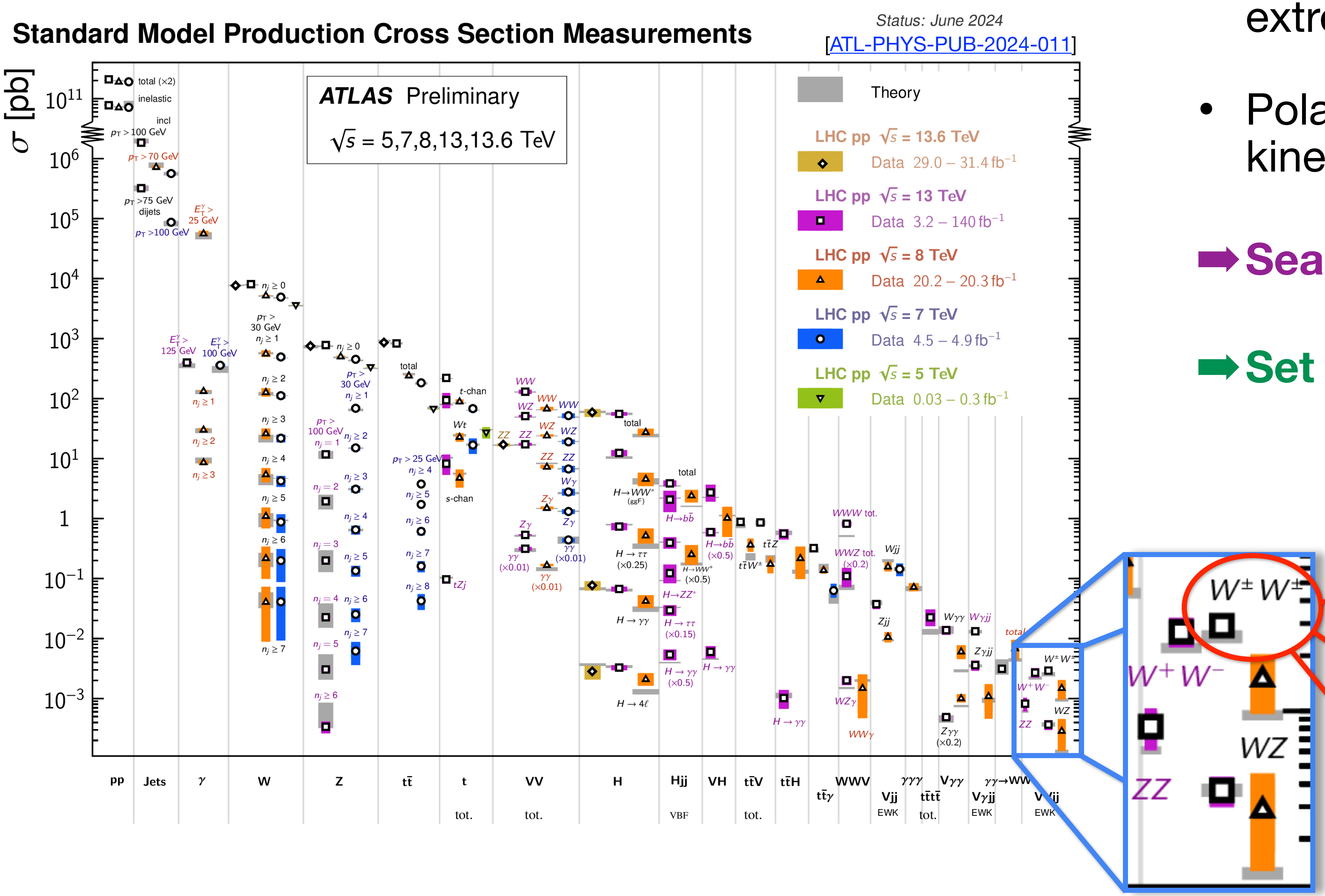
➡ $W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm$ is a **unique opportunity to probe electroweak symmetry-breaking**




[adapted from arXiv:1412.8367]

# Rare, Rarer, $W_L^{\pm}W_L^{\pm}$




- $W^{\pm}W^{\pm} \to W^{\pm}W^{\pm}$ is extremely rare
- Polarization states are kinematically very similar

➡ **Search for $W_L^{\pm}W^{\pm}$**

➡ **Set limits on $W_L^{\pm}W_L^{\pm}$**

Expected fractions:

61% $W_T^{\pm}W_T^{\pm}$

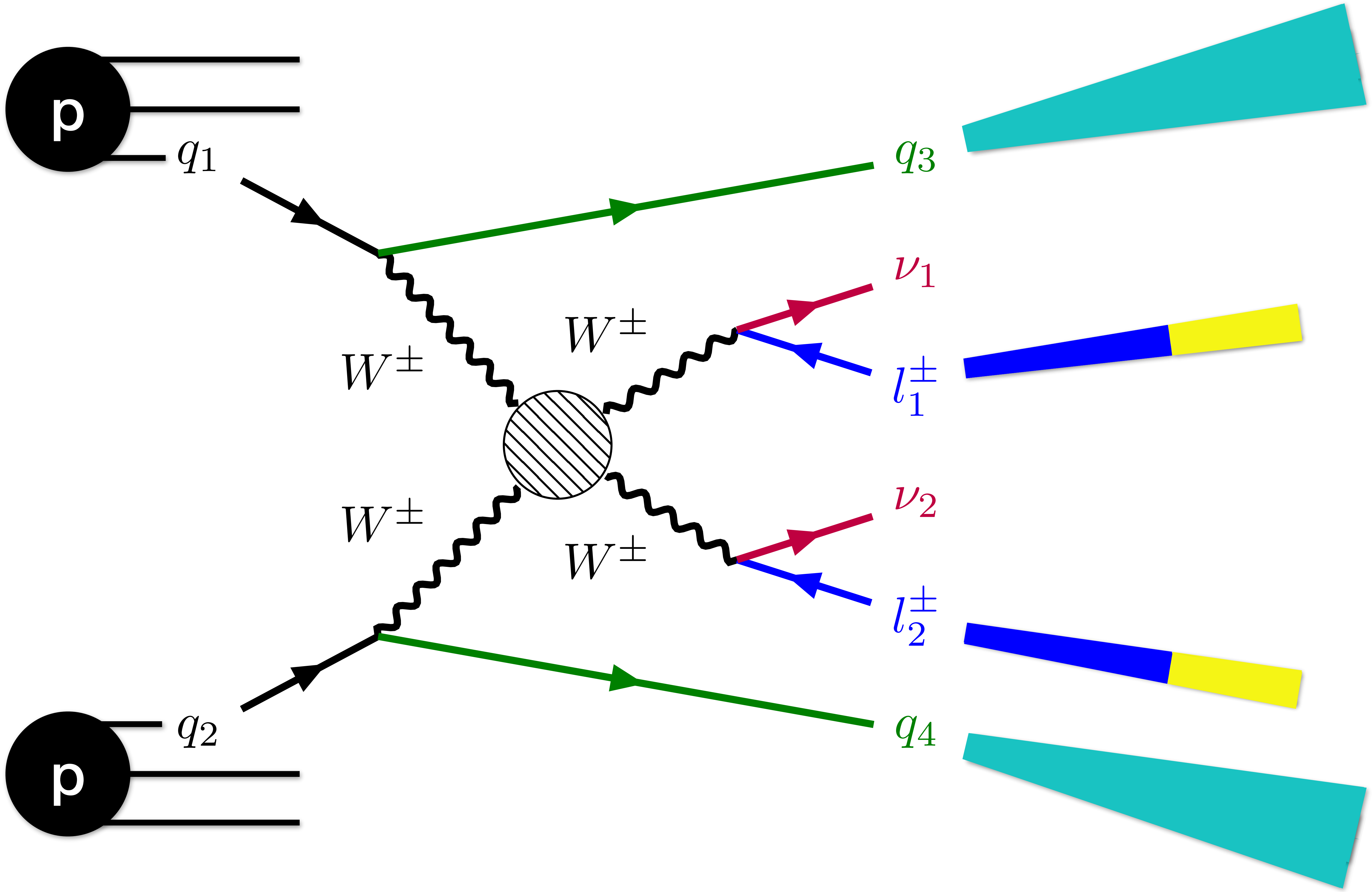
29% $W_T^{\pm}W_L^{\pm}$

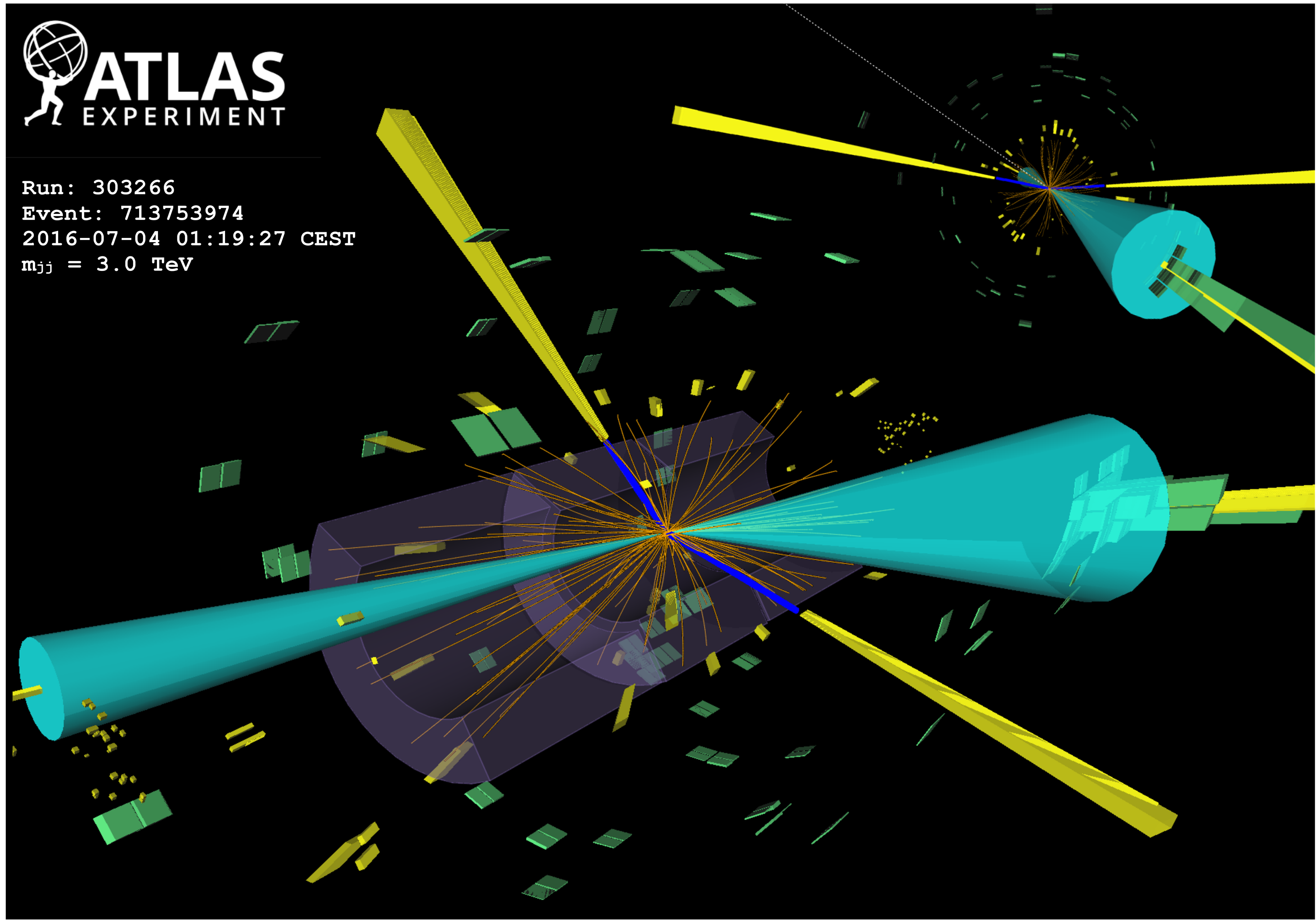
10% $W_L^{\pm}W_L^{\pm}$

39% $W_L^{\pm}W^{\pm}$

# Signature of $W^{\pm}W^{\pm}jj$ EW

[Phys. Rev. Lett. 123 (2019) 161801]



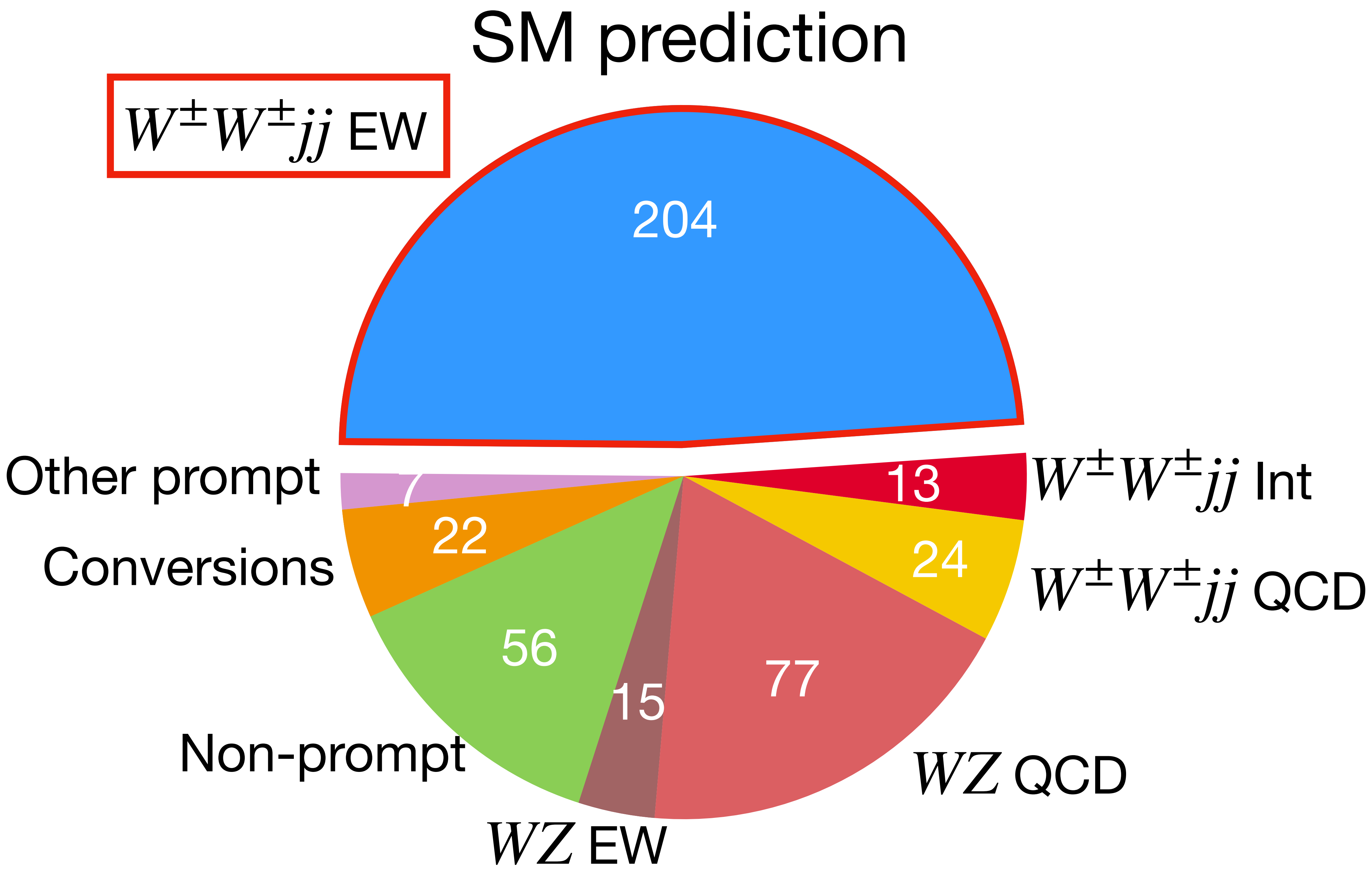

- Exactly **two same-charged leptons**
- At least **two well-separated jets** with $m_{jj} > 500$ GeV
- **Missing transverse momentum** $E_T^{miss} \geq 30$ GeV

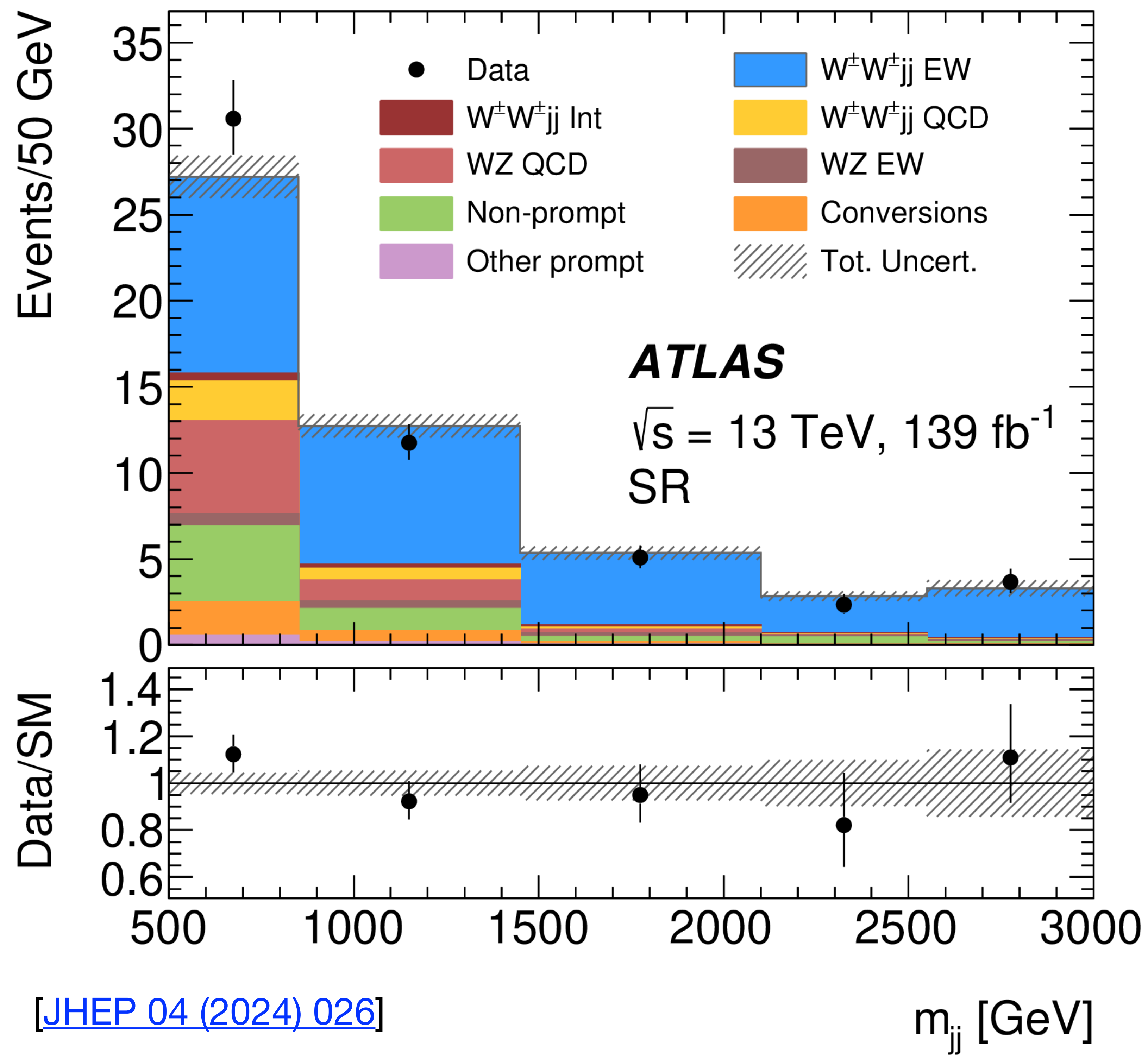
# Analysis Baseline

- **ATLAS Run 2 dataset with 140 fb$^{-1}$ at 13 TeV**
- Chosen signature suppresses $W^{\pm}W^{\pm}jj$ QCD

  ➡Mostly **vector boson scattering**

- 2023: **Differential measurement and interpretation** [JHEP 04 (2024) 026]
  - Cross-section measured with 10% accuracy



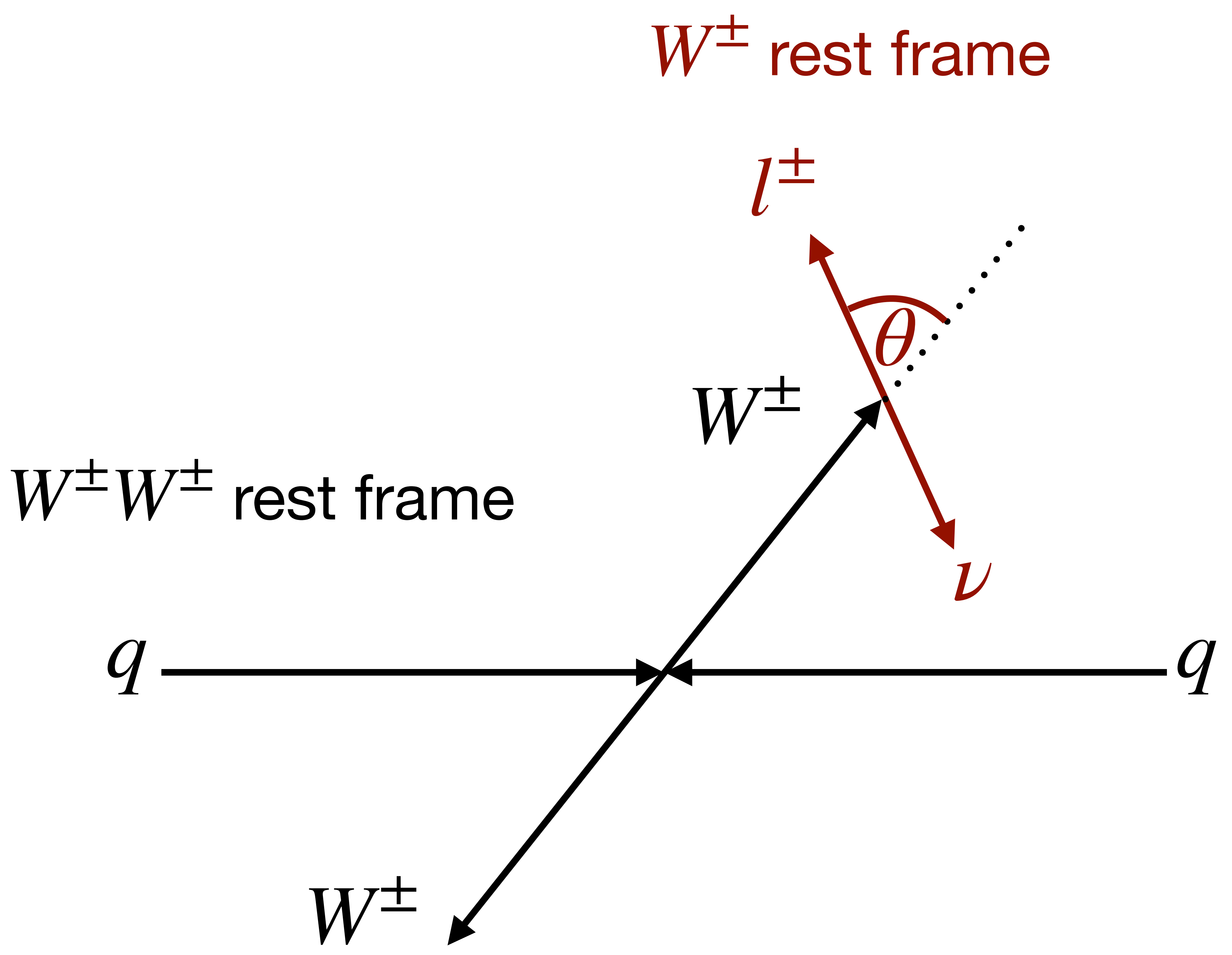

[JHEP 04 (2024) 026]

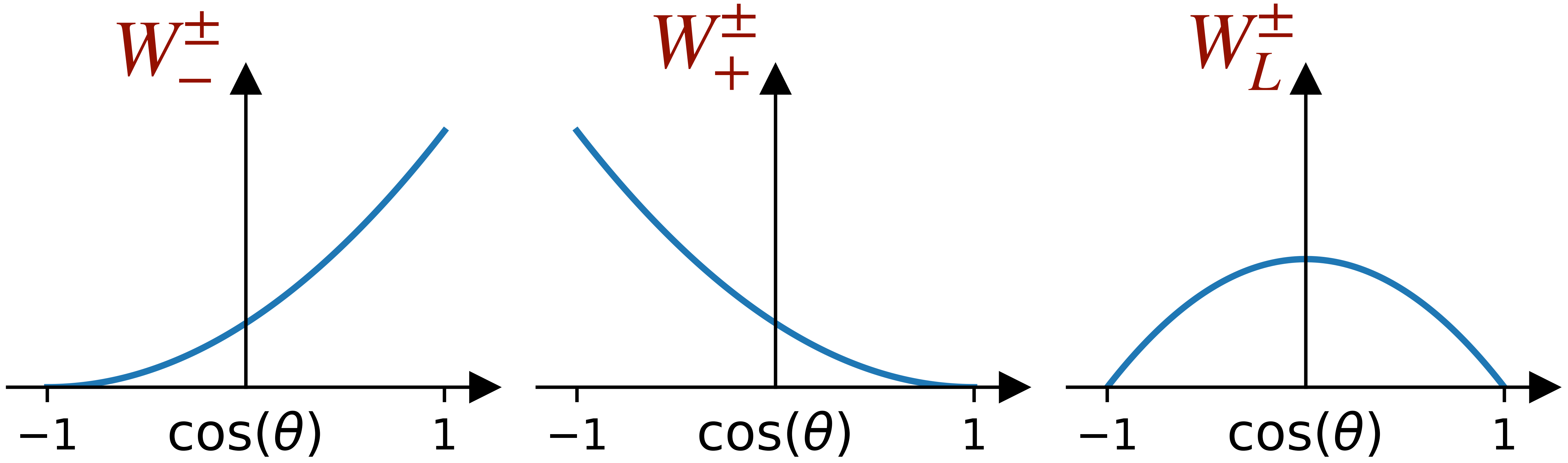
# Access Polarization Information

- $W^{\pm}$ polarization determines decay angle

➡ BUT: Cannot access $W^{\pm}$ rest frame since the **two neutrinos are not reconstructable**

➡ **Simulate full event kinematic** of polarization states predicted by SM

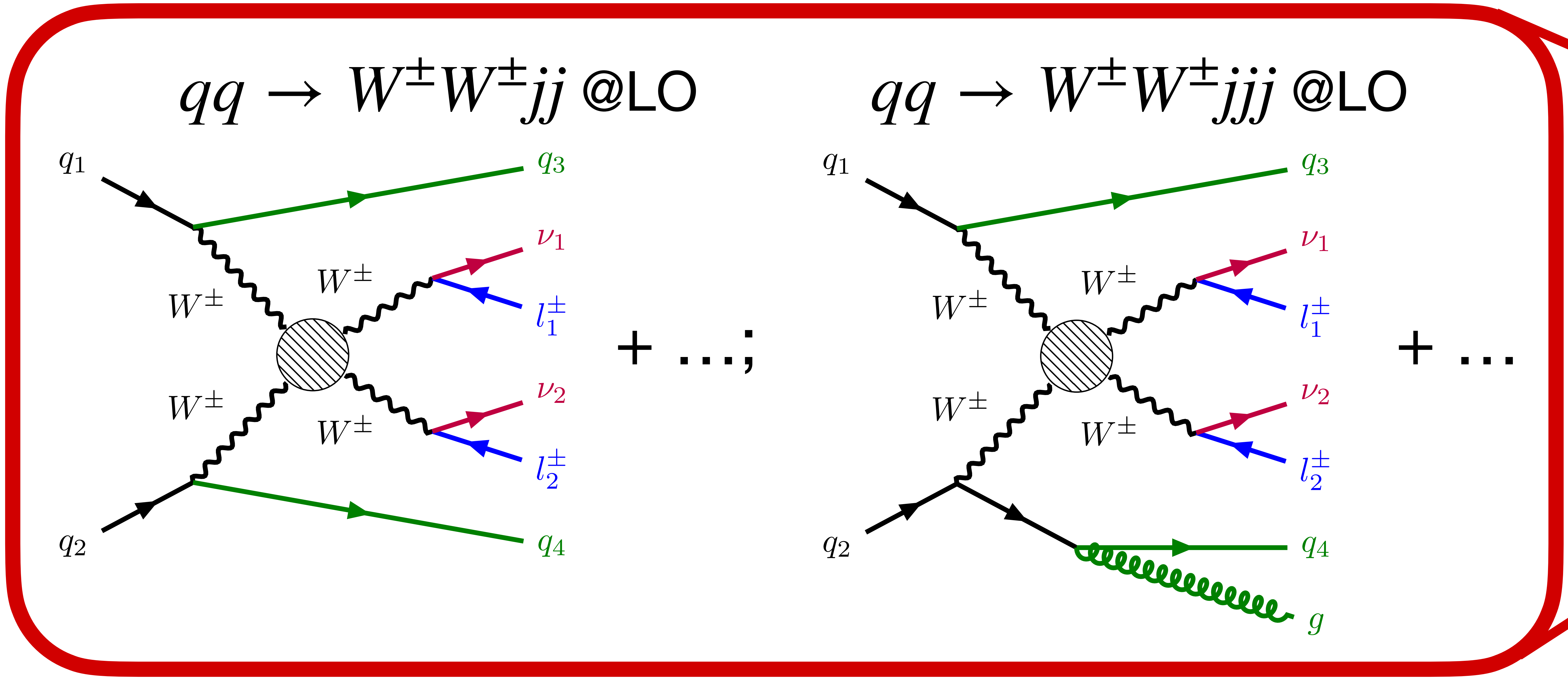


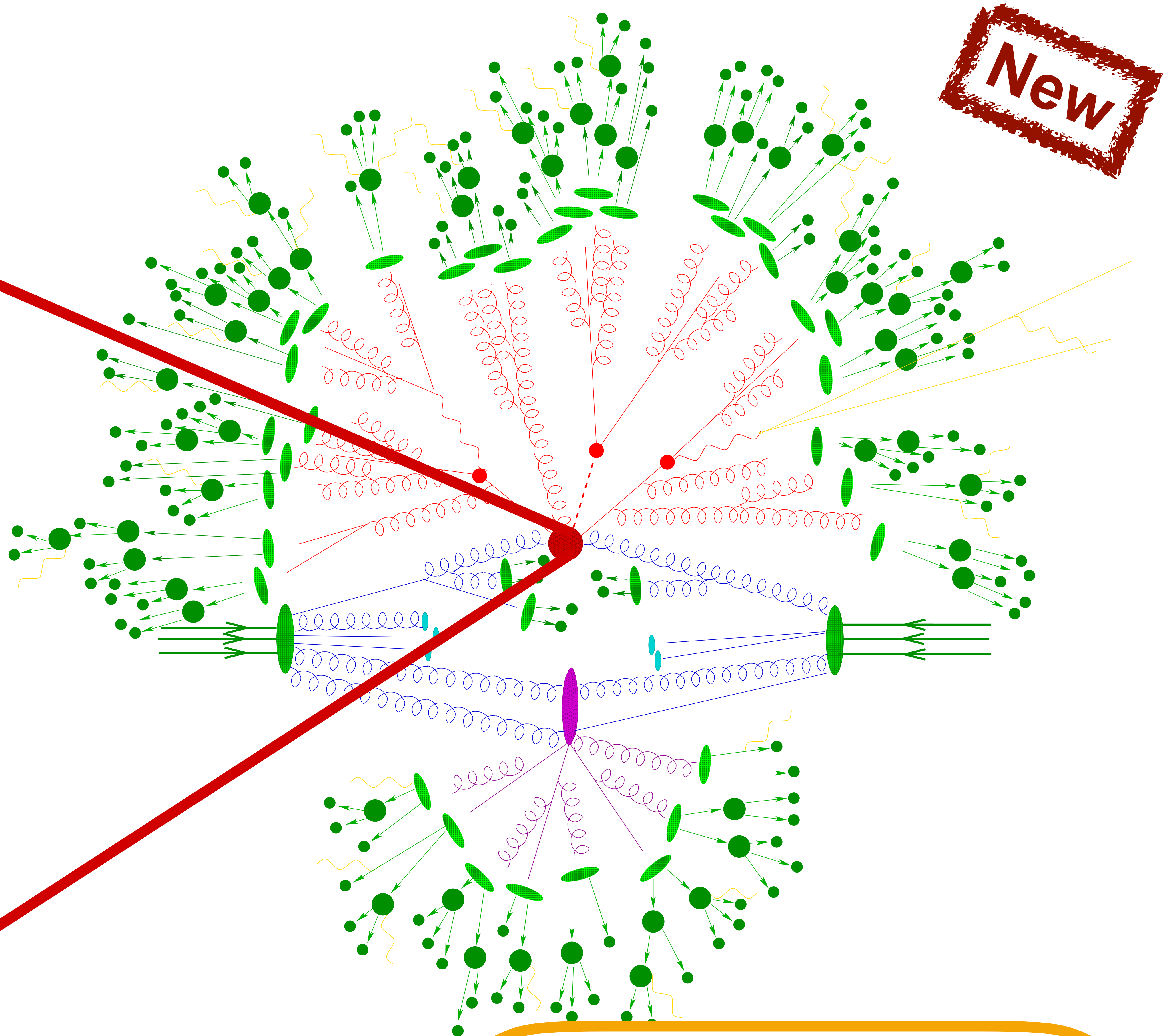



# Simulation of Polarization States

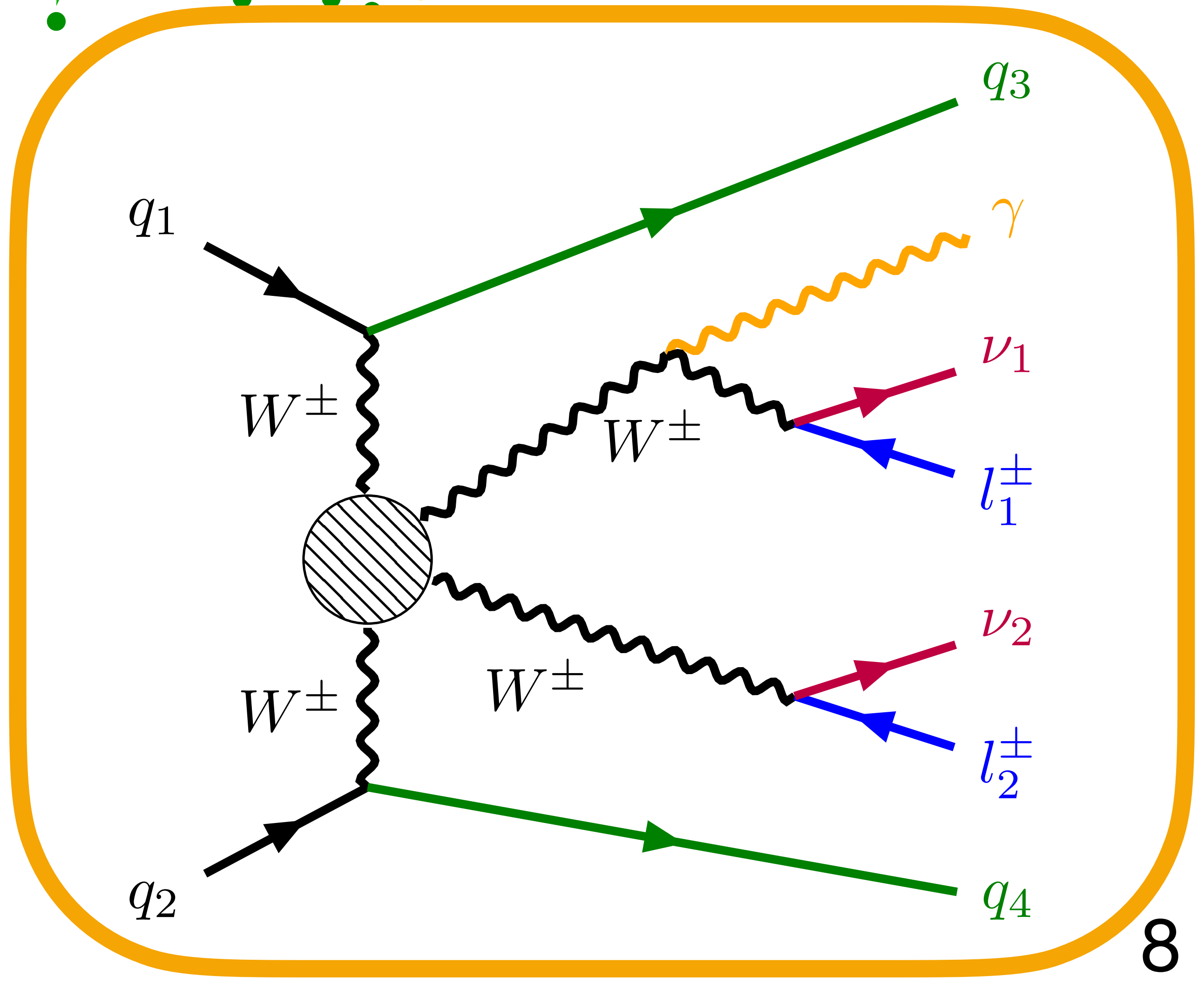
New

Matrix Element calculation



- Leading order calculation **merged with additional real QCD emission** → DNNs used to correct approximations
- Polarization states provided as **event weights:** $s_{LL}$, $s_{TL}$, $s_{TT}$, **and** $s_{Int}$ [JHEP04(2024) 001]
- **NLO EW correction** provided by authors of [JHEP11(2024) 115] →



# How to Distinguish Polarization States?

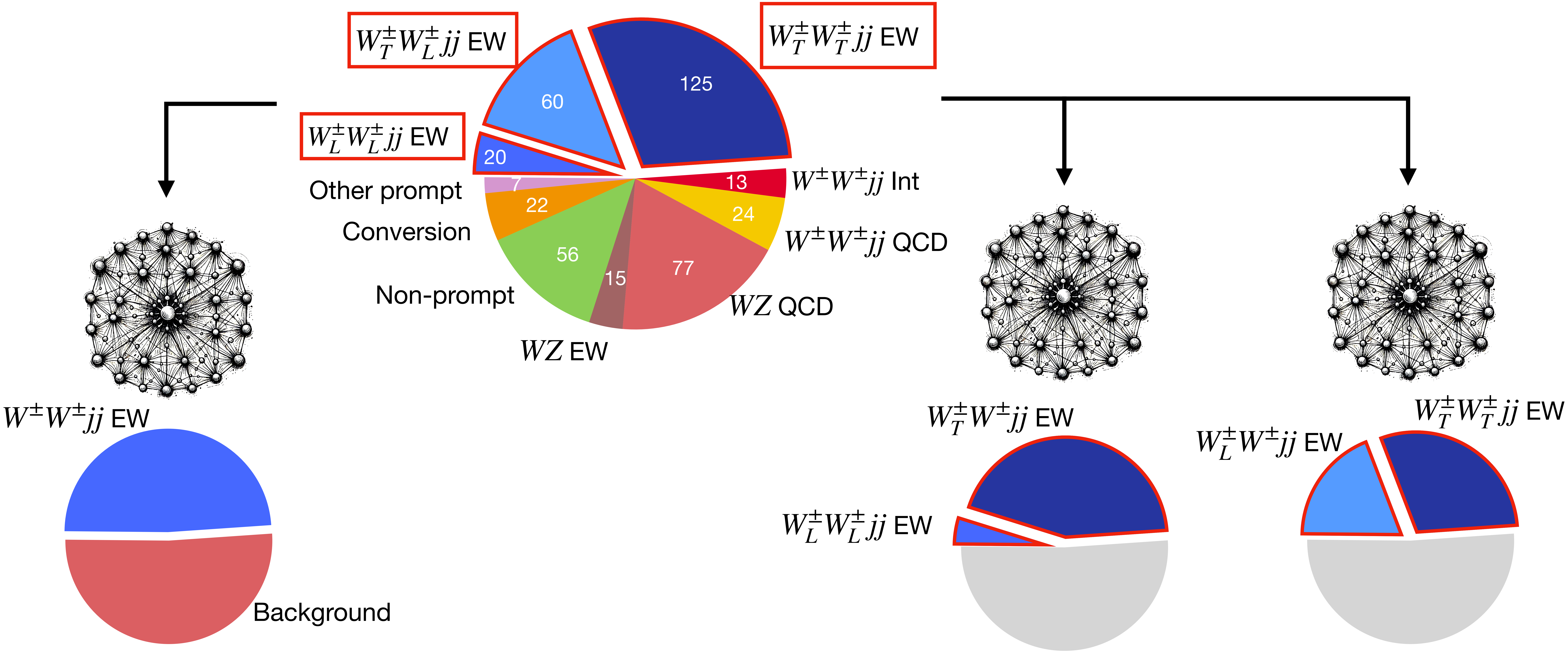
New


Polarization states differ in di-lepton and jet kinematic

**Maximize sensitivity through combination in DNN!**

# Neural Networks Save the Day

New

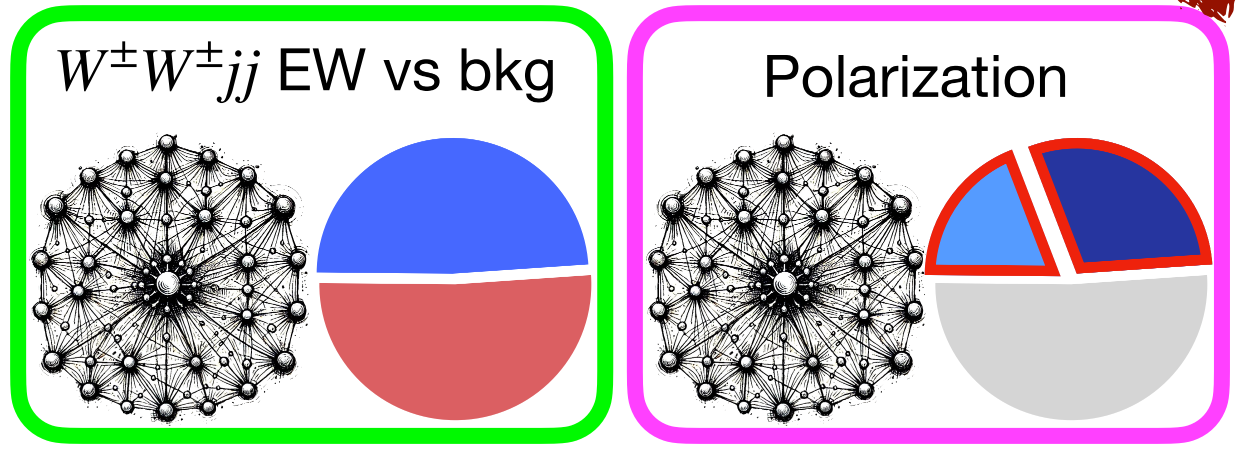



DNN trained to **split signal region in 3 regions** with **increasing $W^\pm W^\pm jj$ EW purity**

DNN trained as **discriminant variable to measure $W_L^\pm W_L^\pm jj$ EW / $W_L^\pm W^\pm jj$ EW**

# Single Boson Polarization $W_L^{\pm}W^{\pm}$

New

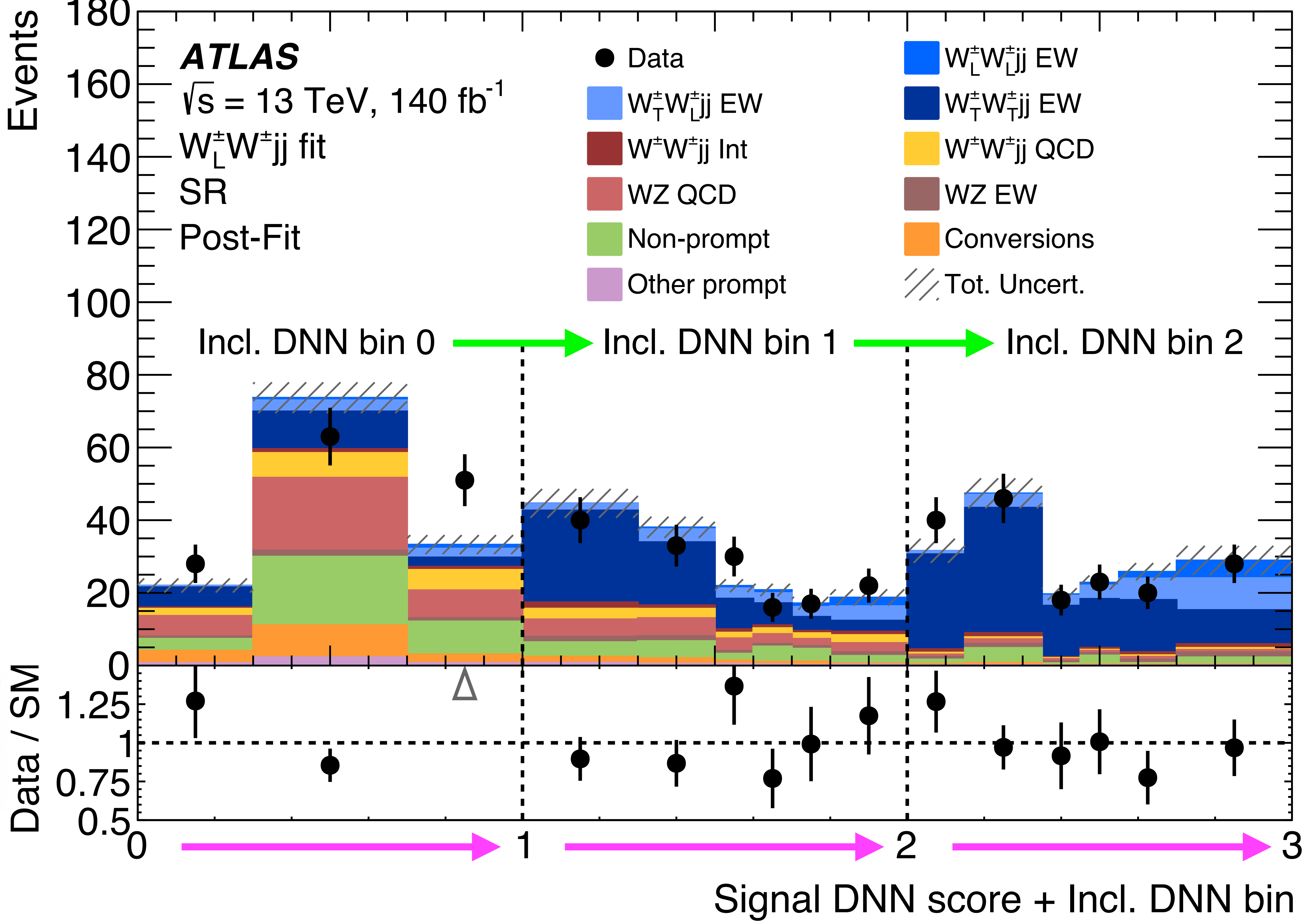



- **Significance of 3.3 $\sigma$** for $W_L^{\pm}W^{\pm}jj$ (expected 4.0 $\sigma$)

➡ **First evidence for longitudinal polarization in vector boson scattering**

- Measured cross-section **in agreement with the Standard Model**

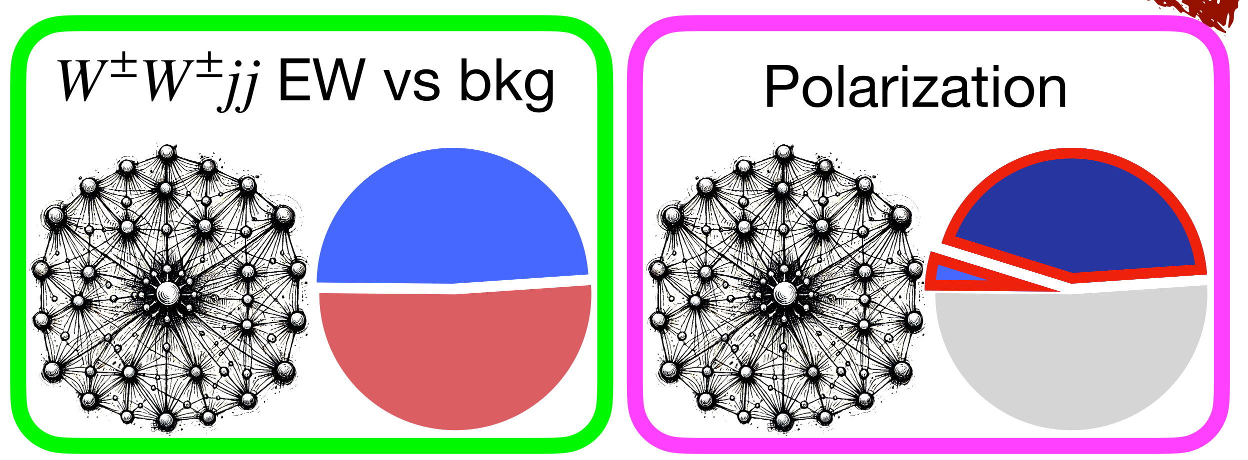
- Dominated by **statistical uncertainty**




| Prediction | Measured $\sigma\mathcal{B}$ (fb) | Uncertainty breakdown (fb) |
|---|---|---|
| 1.18 ± 0.29 | 0.88 ± 0.30 (tot.) | ±0.28 (stat.) ± 0.08 (mod. syst.) ± 0.05 (exp. syst.) |

# Double Boson Polarization $W_L^{\pm}W_L^{\pm}$

New



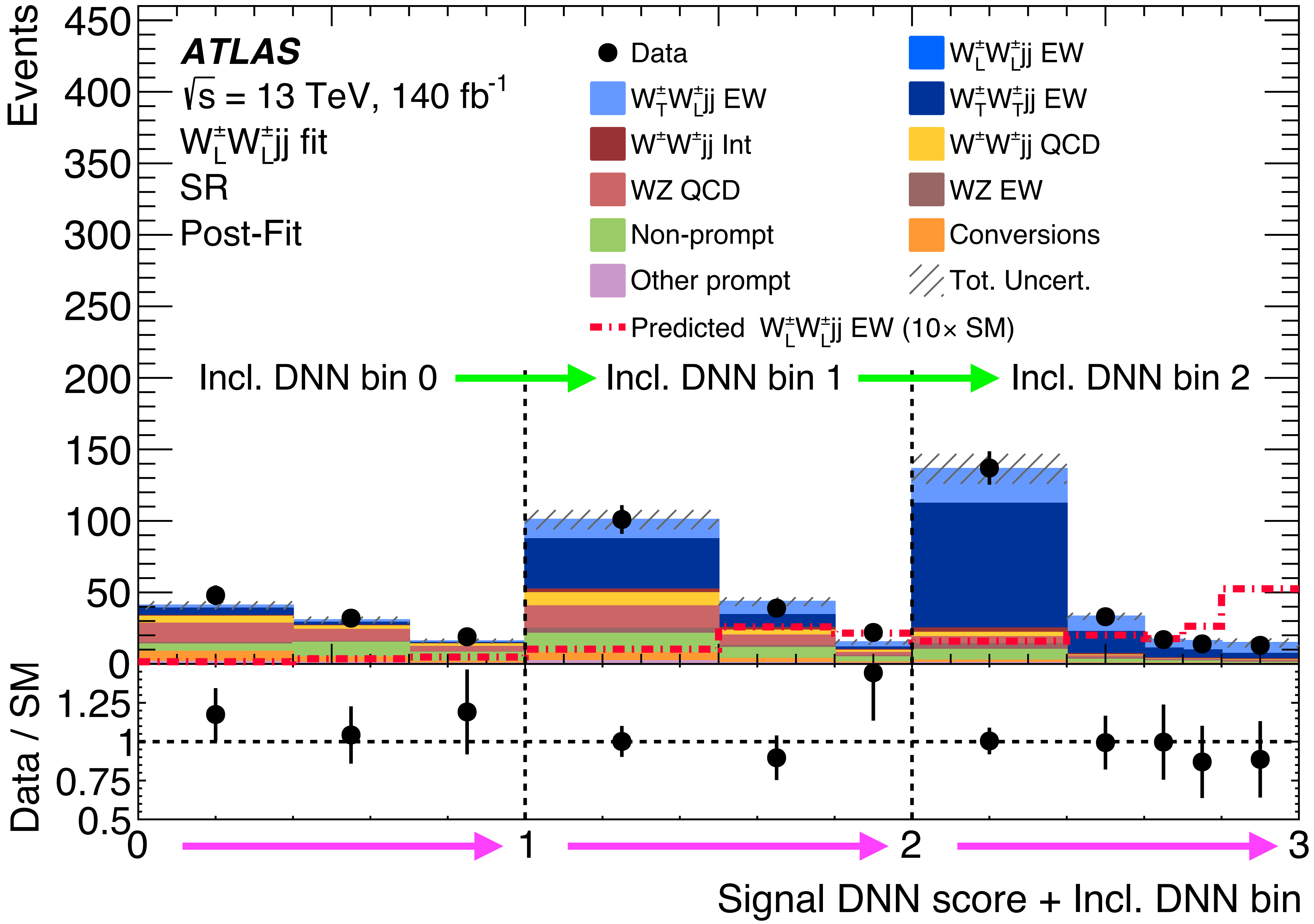

- **95% CL upper limit of 0.45 fb** (expected 0.70 fb)

➡ **Most stringent limit for fully longitudinally polarized $W^{\pm}W^{\pm}jj$ EW**

- Measured cross-section **in agreement with the Standard Model**

- Dominated by **statistical uncertainty**

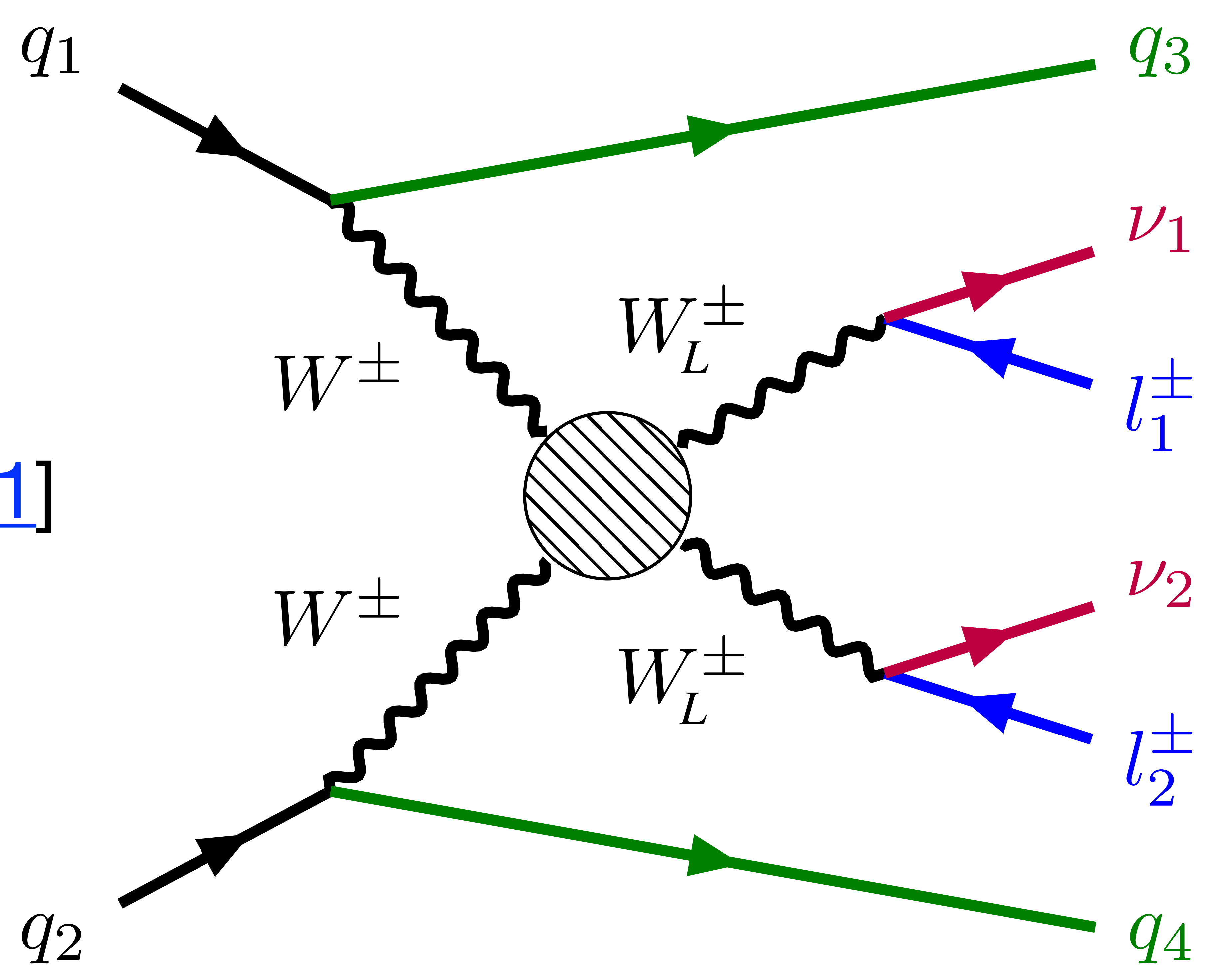
| Prediction | Measured $\sigma\mathcal{B}$ (fb) | Uncertainty breakdown (fb) |
|---|---|---|
| 0.29 ± 0.07 | 0.01 ± 0.21 (tot.) | ±0.20 (stat.) ± 0.05 (mod. syst.) ± 0.02 (exp. syst.) |



# Summary

[arXiv:2503.11317]

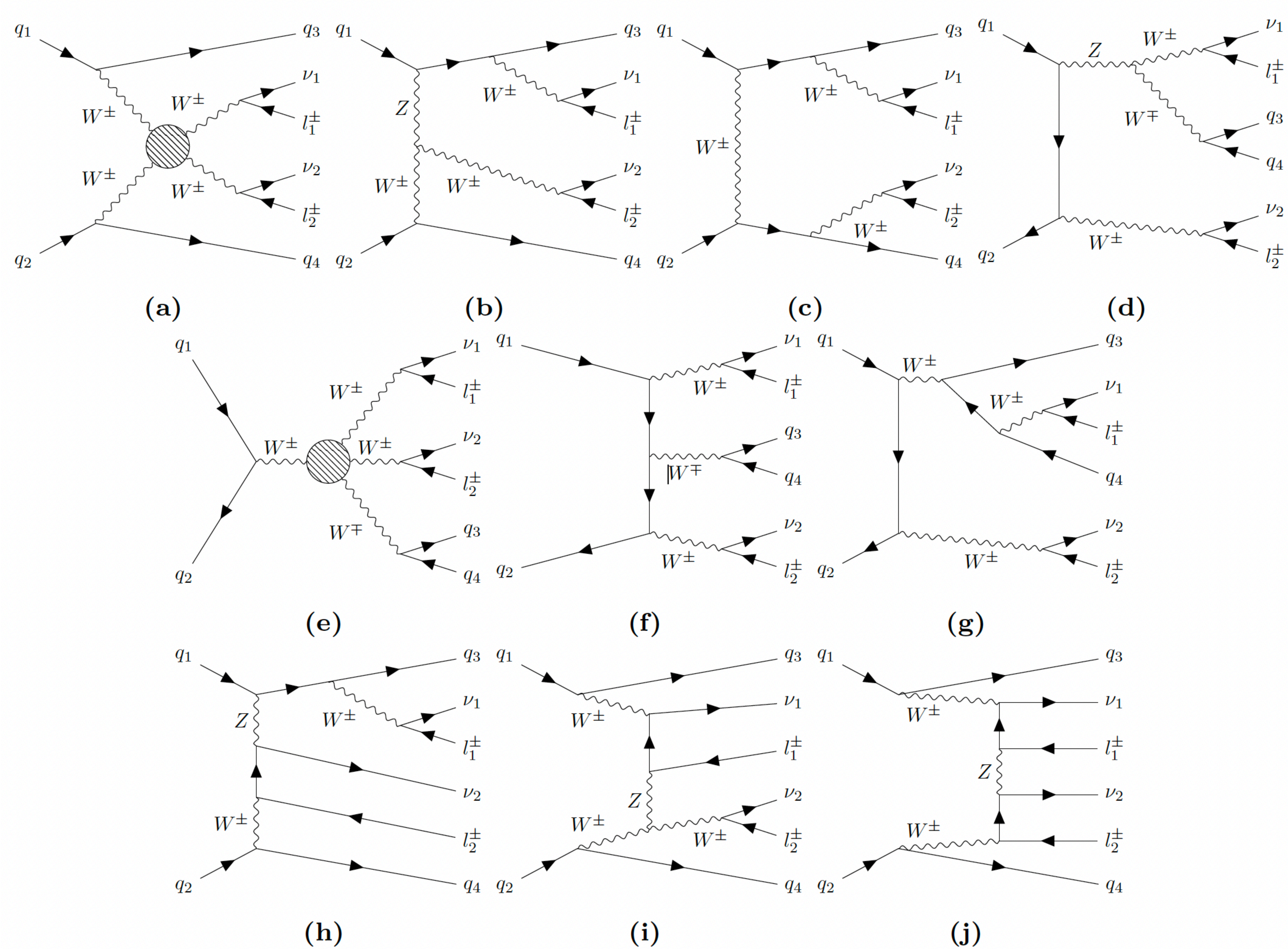
- $W_L^\pm W_L^\pm \rightarrow W_L^\pm W_L^\pm$ is unique opportunity to **probe EWS**
- **State-of-the-art polarization prediction**:
  - Multi-jet merging in matrix element [JHEP04(2024) 001]
  - NLO EW correction [JHEP11(2024) 115]
- **First evidence** for longitudinal polarization in vector boson scattering
- **Most stringent limits** for $W_L^\pm W_L^\pm jj$ EW (1.5 x SM)
- Dominated by **statistical uncertainty**



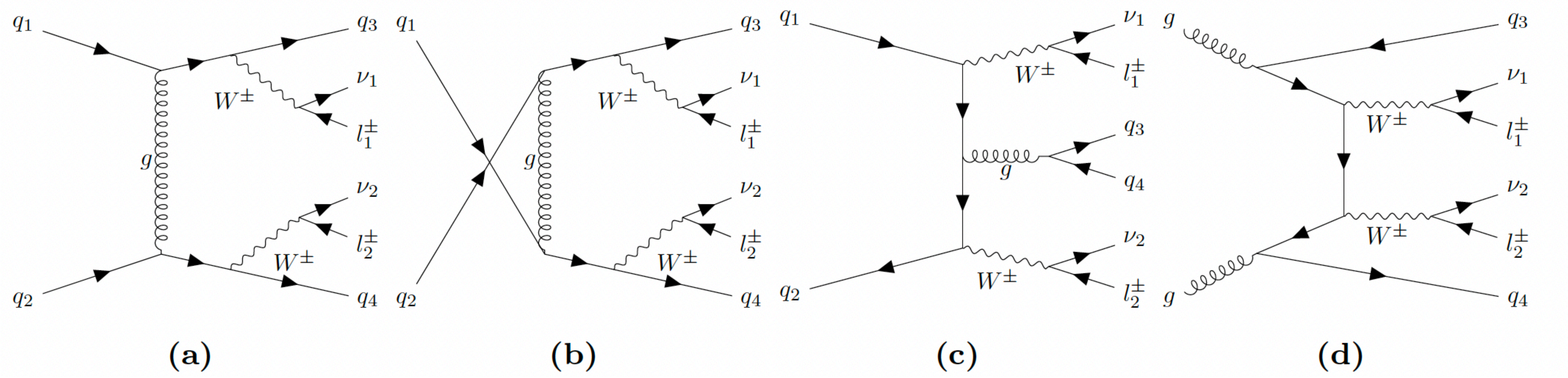

[According to https://hilumilhc.web.cern.ch/content/hl-lhc-project]
HL-LHC
Run 3
Run 2
Run 1
ANA-STDM-2019-29
Integrated Luminosity [fb$^{-1}$]
3000
2500
2000
1500
1000
500
0
2009-
2013
2015-
2018
2022-
2026
starting
2030
Recording Period

# Additional Material

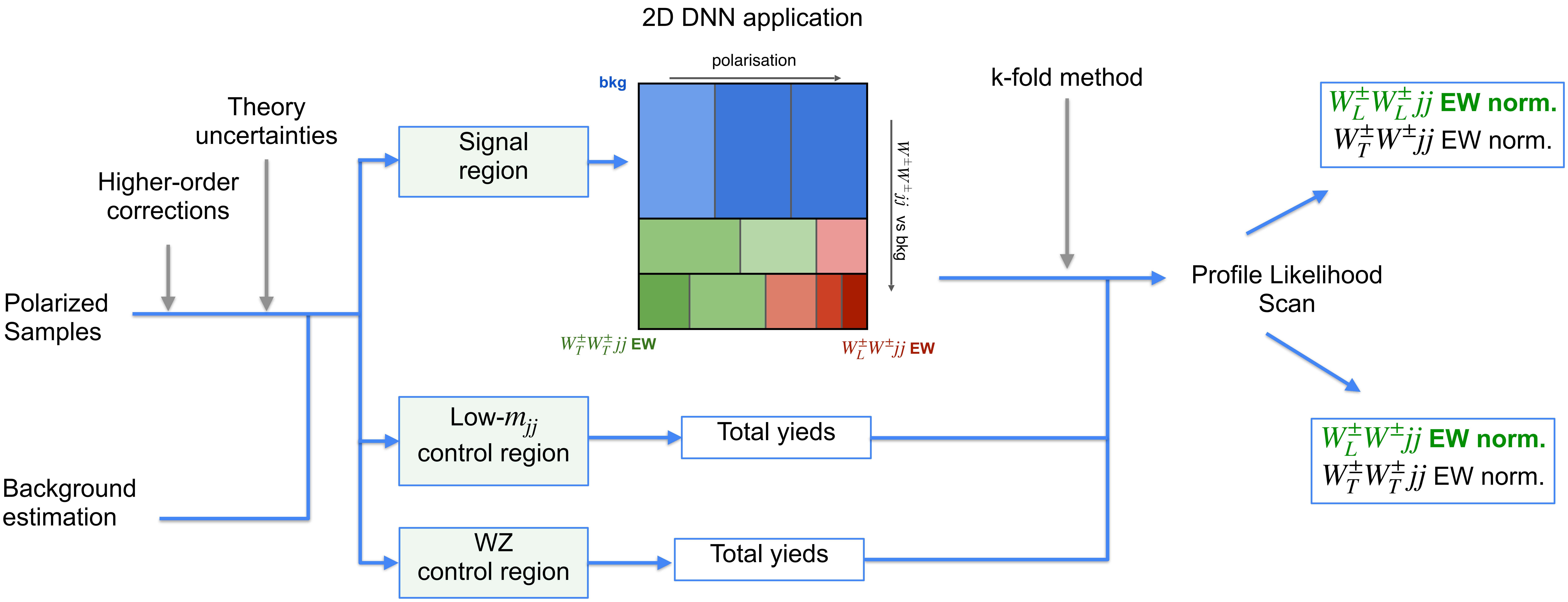
# Feynman Diagrams $W^{\pm}W^{\pm}jj$ EW $\sim \alpha_{EW}^{6}$



# Feynman Diagrams $W^{\pm}W^{\pm}jj$ QCD $\sim \alpha_{EW}^4 \alpha_{QCD}^2$



# Analysis Strategy



# Object Selection

Electrons

| | baseline | signal |
|---|---|---|
| Identification: | `LooseLH` | `TightLH` |
| Kinematic Acceptance: | $p_T > 4.5\,\mathrm{GeV}$ | $p_T > 27\,\mathrm{GeV}$ |
| Geometrical Acceptance: | $\lvert\eta\rvert < 2.47$ | $\lvert\eta\rvert < 2.47$, excluding $1.37 \leq \lvert\eta\rvert \leq 1.52$ |
| Longitudinal Impact parameter: | $\lvert z_0 \times \sin\theta\rvert < 0.5\,\mathrm{mm}$ | $\lvert z_0 \times \sin\theta\rvert < 0.5\,\mathrm{mm}$ |
| Transverse Impact parameter: | $\lvert\frac{d_0}{\sigma_{d_0}}\rvert < 5$ | $\lvert\frac{d_0}{\sigma_{d_0}}\rvert < 5$ |
| Isolation Requirement: | - | `Gradient` |
| `Author` requirement: | - | 1 |
| Charge-flip rejection: | - | `ECIDS` |

Muons

| | baseline | signal |
|---|---|---|
| Identification: | `Loose` | `Medium` |
| Kinematic Acceptance: | $p_T > 3\,\mathrm{GeV}$ | $p_T > 27\,\mathrm{GeV}$ |
| Geometrical Acceptance: | $\lvert\eta\rvert < 2.7$ | $\lvert\eta\rvert < 2.5$ |
| Longitudinal Impact parameter: | $\lvert z_0 \times \sin\theta\rvert < 1.5\,\mathrm{mm}$ | $\lvert z_0 \times \sin\theta\rvert < 0.5\,\mathrm{mm}$ |
| Transverse Impact parameter: | $\lvert\frac{d_0}{\sigma_{d_0}}\rvert < 15$ | $\lvert\frac{d_0}{\sigma_{d_0}}\rvert < 3$ |
| Isolation Requirement: | - | `FixedCutPflowTight` |

Jets

| | baseline | signal |
|---|---|---|
| Clustering: | anti-$k_t$ algorithm with $R = 0.4$ | anti-$k_t$ algorithm with $R = 0.4$ |
| Kinematic Acceptance: | $p_T > 20\,\mathrm{GeV}$ | $p_T > 25\,\mathrm{GeV}$ |
| Geometrical Acceptance: | $\lvert\eta\rvert < 4.5$ | $\lvert\eta\rvert < 4.5$ |
| Vertex Matching: | - | JVT for $p_T < 60\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.4$ |

# Event Selection

Measure $W^{\pm}W^{\pm}jj$ EW polarization

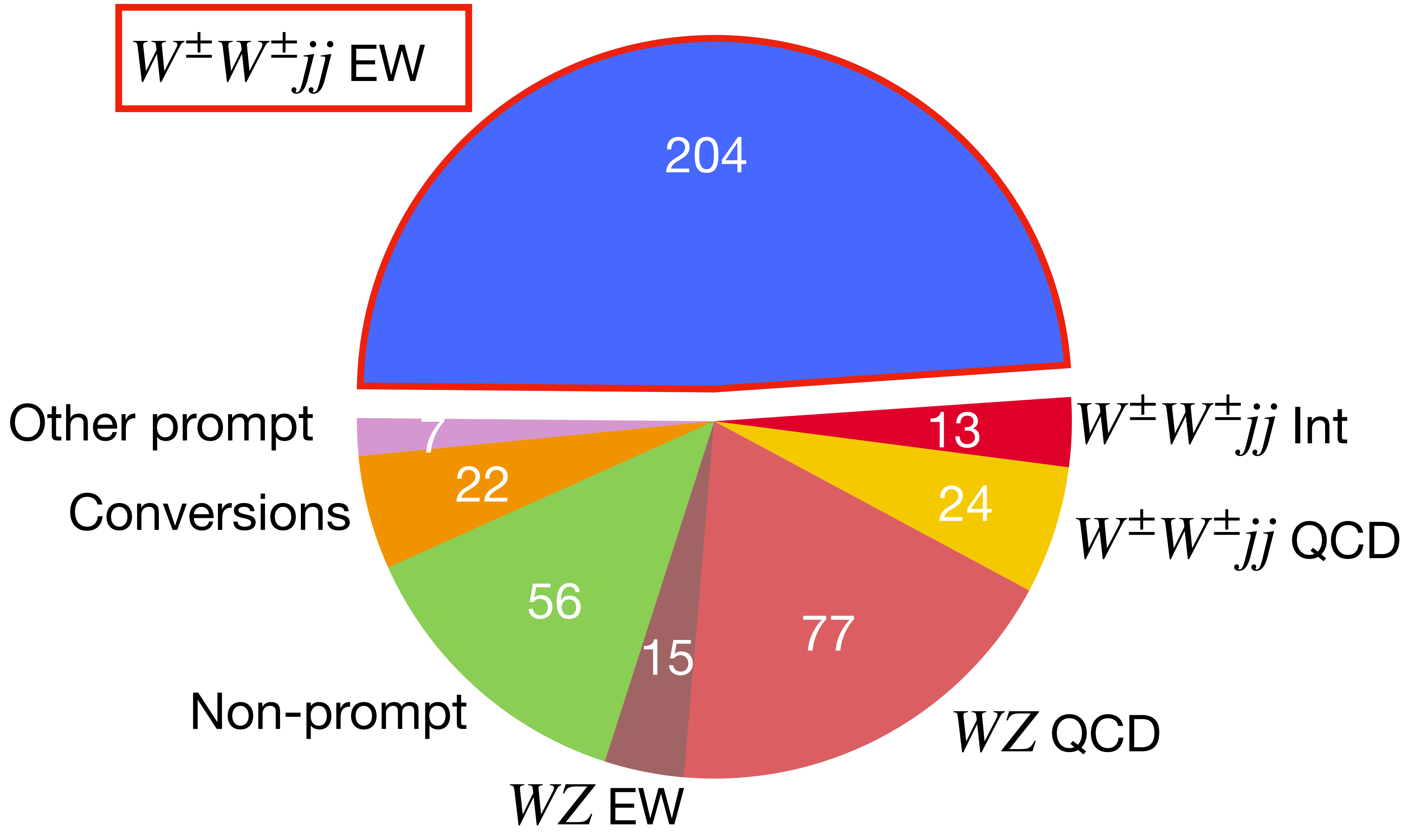
Constrain backgrounds

Constrain and correct $W^{\pm}Z$ background

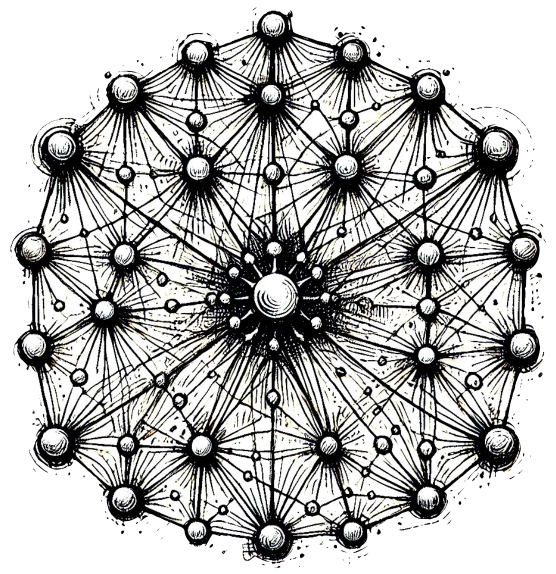
| Requirement | SR | Low-$m_{jj}$ CR | WZ CR |
|---|---|---|---|
| Leading and subleading lepton $p_T$ | $> 27$ GeV | | |
| Electron $\|\eta\|$ | $< 2.47$ (1.37 in $ee$), excluding $1.37 \leq \|\eta\| \leq 1.52$ | | |
| Muon $\|\eta\|$ | $< 2.5$ | | |
| Leading (subleading) jet $p_T$ | $> 65$ (35) GeV | | |
| Additional jet $p_T$ | $> 25$ GeV | | |
| Jet $\|\eta\|$ | $< 4.5$ | | |
| $m_{\ell\ell}$ | $> 20$ GeV | | |
| $E_T^{miss}$ | $> 30$ GeV | | |
| Charge misid. $Z \to ee$ veto | $\|m_{ee} - m_Z\| > 15$ GeV | | – |
| $b$-jet veto | $N_{b\text{-jet}} = 0$, $p_T^{b\text{-jet}} > 20$ GeV, $\|\eta^{b\text{-jet}}\| < 2.5$ | | |
| $N_{\text{veto leptons}}$ | $= 0$ | $= 0$ | $= 1$, $p_T > 15$ GeV |
| $m_{\ell\ell\ell}$ | – | – | $> 106$ GeV |
| $m_{jj}$ | $> 500$ GeV | $200 < m_{jj} < 500$ GeV | $> 200$ GeV |
| $\|\Delta y_{jj}\|$ | $> 2$ | | |

# Analysis Setup

- **ATLAS Run 2 dataset with 140 fb$^{-1}$ at 13 TeV**
- **Monte Carlo simulation**:
  - $W^{\pm}W^{\pm}jj$: EW, Int, and QCD
  - $W^{\pm}Z$: EW and QCD
  - Other minor prompt backgrounds
- **Data-driven estimation**:
  - Conversions: charge-flip of leptons
  - Non-prompt: objects faking leptons

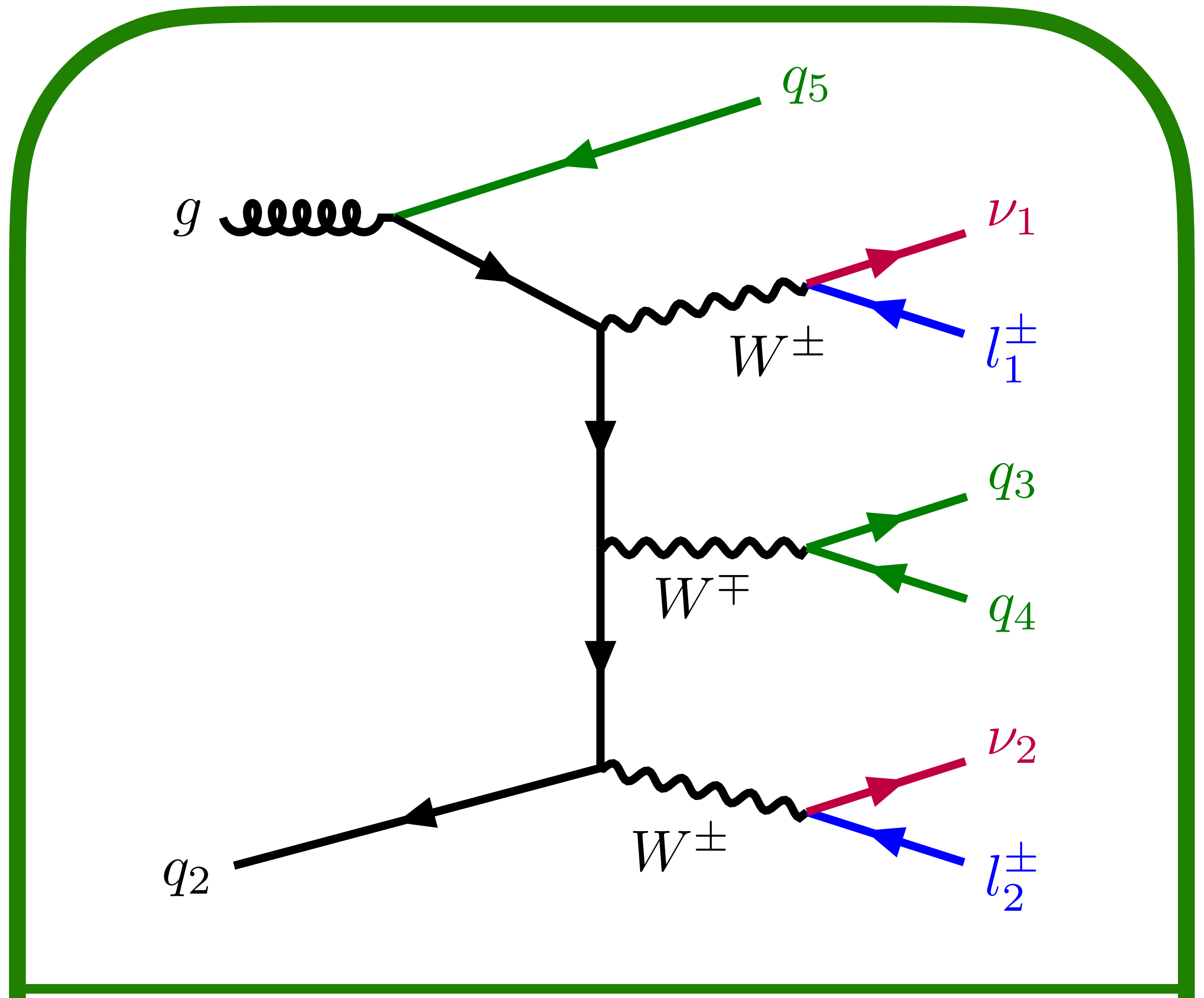


# Every Prediction Can Be Further Improved

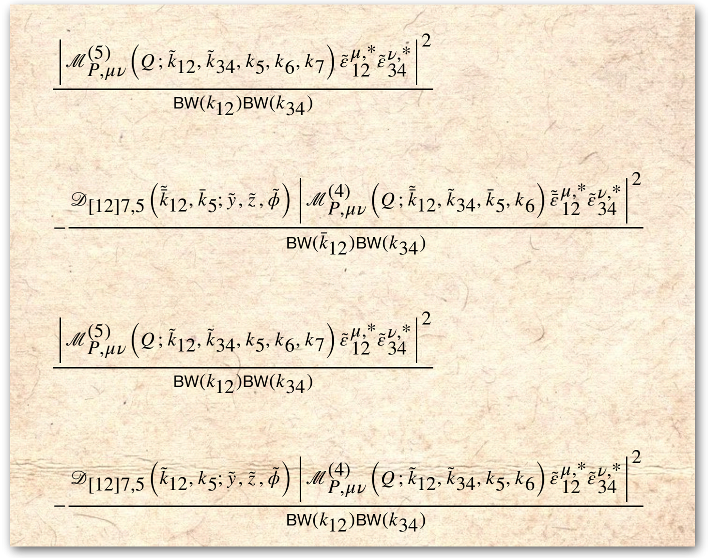


DNN trained to correct

- Missing diagrams with **hadronically decaying** $W^{\pm}$
- Contribution from **off-shell** $W^{\pm}$

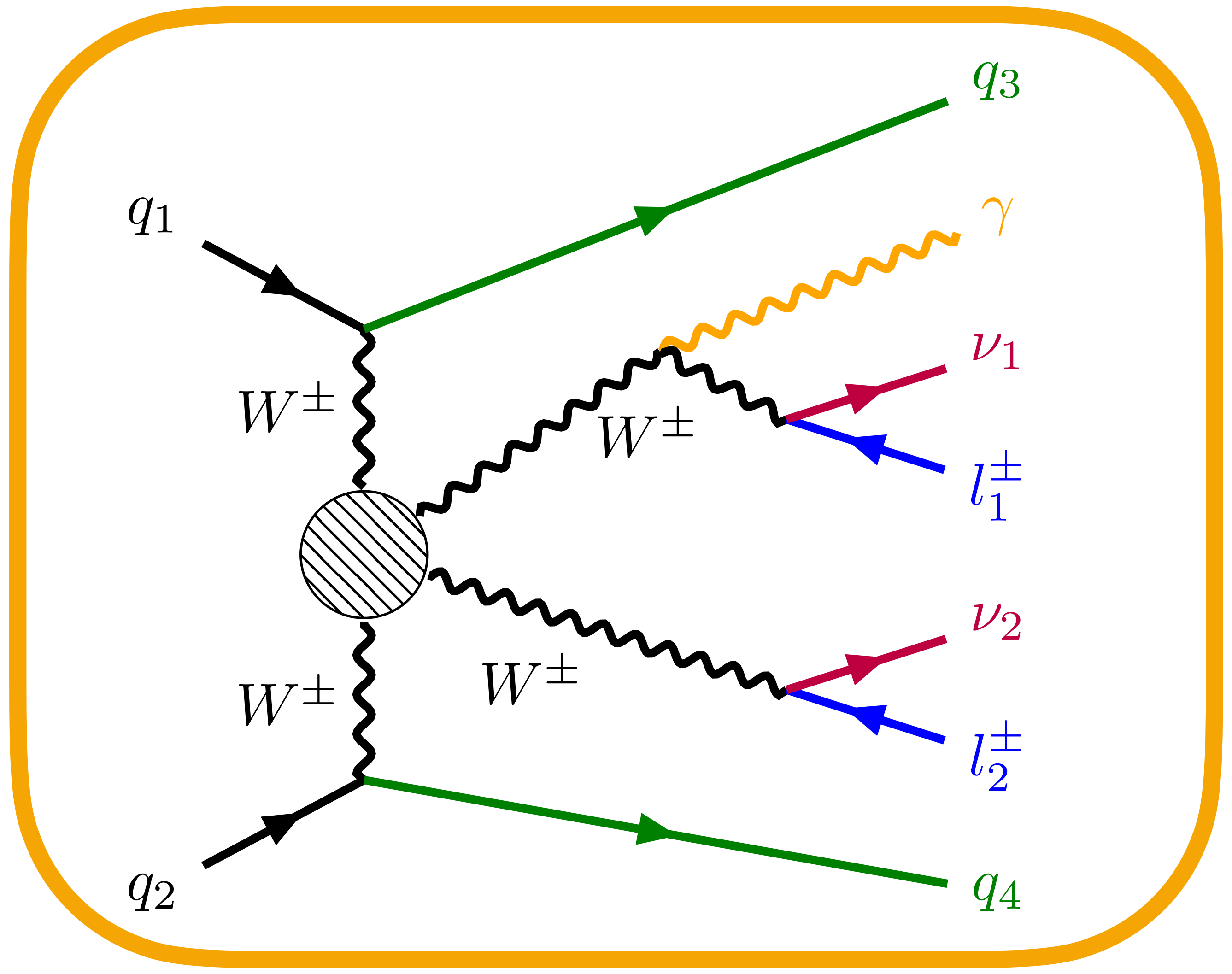



$$\frac{1}{q^2 - m_W^2 + i\Gamma_W m_W}$$



Recent theory calculations [JHEP11(2024) 115]

- Polarization-dependent **NLO EW contributions**



# Bin Optimization

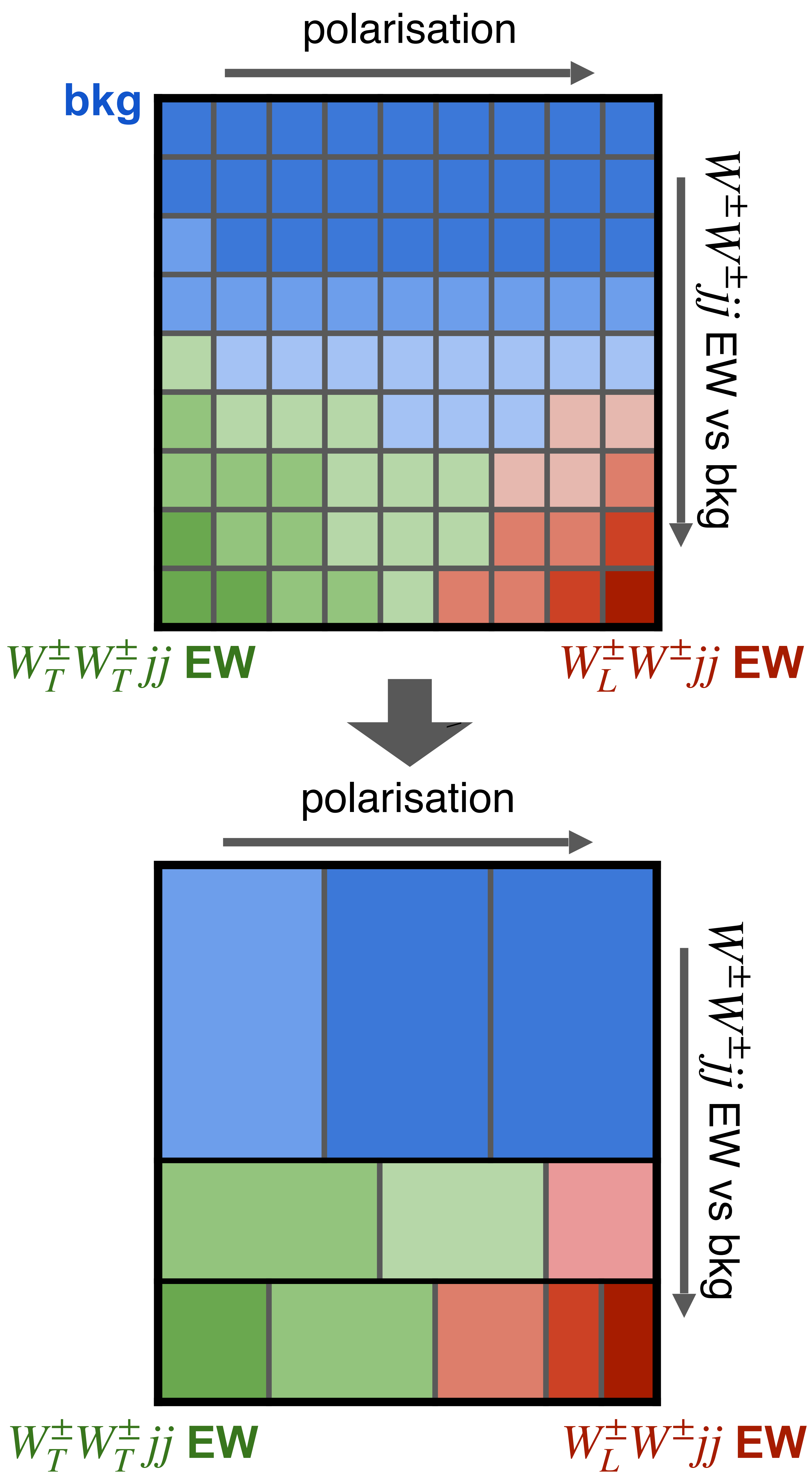
- Likelihood $\mathscr{L}\left(\mu, \mu_T, \vec{a}\right)$ with longitudinal pol. signal strength $\mu$, transversal pol. strength $\mu_T$, and normalization nuisance parameters $\vec{a}$

- **Optimise binning for test statistic**

$$q_{0,A} = -2\ln\left(\mathscr{L}(0,\hat{\hat{\mu}}_T,\hat{\hat{\vec{a}}}) / \mathscr{L}(1,1,\vec{1})\right)$$

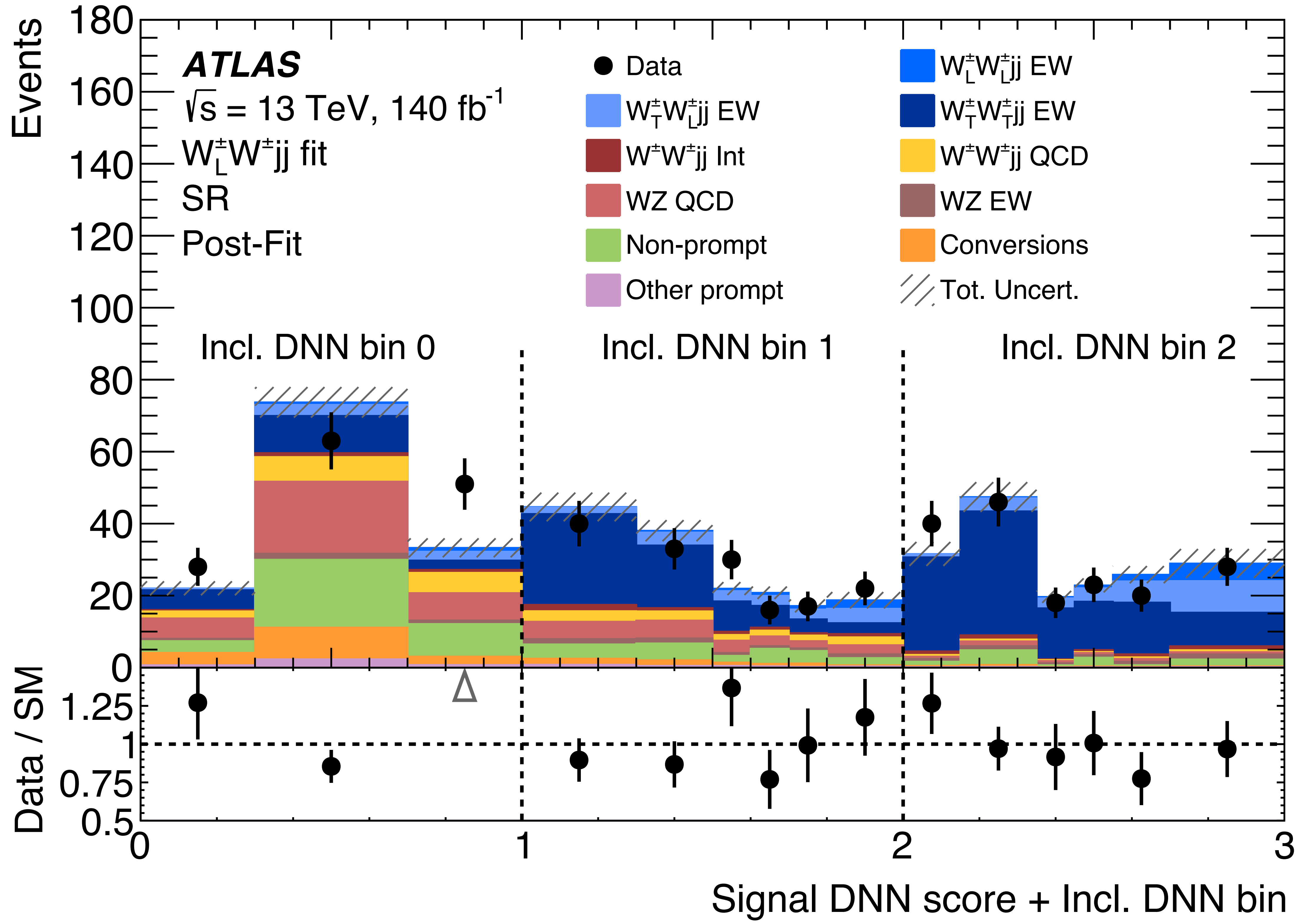
- Start with 2D histogram with 20x20 bins

- Split 2D histogram into **several 1D histograms each with optimized binning**

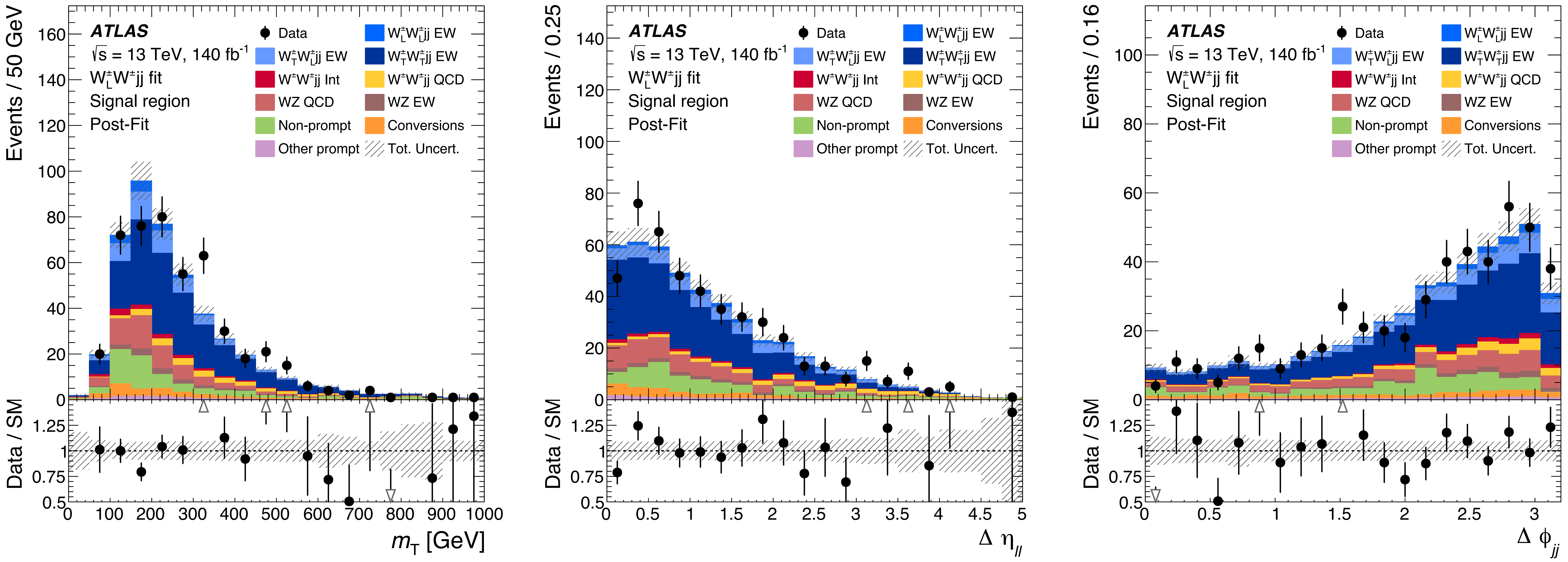


# Postfit Yields for $W_L^{\pm}W^{\pm}jj$ EW Measurement

| Process | Region 0 to 0.3 | Region 0.3 to 0.7 | Region 0.7 to 1 |
|---|---|---|---|
| $W_L^{\pm}W_L^{\pm}jj$ | 1.8 ± 0.7 | 5.6 ± 1.9 | 8.3 ± 2.8 |
| $W_L^{\pm}W_T^{\pm}jj$ | 6.0 ± 2.5 | 17.8 ± 6.2 | 25.7 ± 8.5 |
| $W_T^{\pm}W_T^{\pm}jj$ | 18.4 ± 4.4 | 64.0 ± 10.0 | 111.9 ± 14.7 |
| QCD $W^{\pm}W^{\pm}jj$ | 14.4 ± 4.1 | 12.5 ± 3.5 | 2.6 ± 0.8 |
| Int $W^{\pm}W^{\pm}jj$ | 2.3 ± 0.1 | 6.0 ± 0.2 | 4.8 ± 0.1 |
| QCD $W^{\pm}Zjj$ | 33.3 ± 2.6 | 20.3 ± 1.6 | 4.5 ± 0.4 |
| EW $W^{\pm}Zjj$ | 3.3 ± 0.1 | 6.2 ± 0.2 | 5.5 ± 0.2 |
| Non-prompt | 31.2 ± 4.3 | 20.2 ± 2.9 | 10.4 ± 3.1 |
| Conversions | 14.6 ± 3.7 | 6.2 ± 1.8 | 1.6 ± 0.5 |
| Other prompt | 3.7 ± 0.7 | 2.6 ± 0.6 | 0.8 ± 0.2 |
| Total SM | 129 ± 7 | 161 ± 10 | 176 ± 13 |
| Data | 142 | 158 | 175 |



# Postfit Kinematic Distributions for $W_L^{\pm}W^{\pm}jj$ EW Measurement



# Uncertainties

| Process | Measured $\sigma\mathcal{B}$ (fb) | Uncertainty breakdown (fb) |
|---|---|---|
| $W_L^\pm W_L^\pm jj$ | $0.01 \pm 0.21$ (tot.) | $\pm 0.20$ (stat.) $\pm 0.05$ (mod. syst.) $\pm 0.02$ (exp. syst.) |
| $W_T^\pm W^\pm jj$ | $3.39 \pm 0.35$ (tot.) | $\pm 0.30$ (stat.) $\pm 0.11$ (mod. syst.) $\pm 0.14$ (exp. syst.) |
| $W_L^\pm W^\pm jj$ | $0.88 \pm 0.30$ (tot.) | $\pm 0.28$ (stat.) $\pm 0.08$ (mod. syst.) $\pm 0.05$ (exp. syst.) |
| $W_T^\pm W_T^\pm jj$ | $2.49 \pm 0.32$ (tot.) | $\pm 0.30$ (stat.) $\pm 0.09$ (mod. syst.) $\pm 0.10$ (exp. syst.) |

$W_L^\pm W^\pm jj$ EW measurement

| Source of uncertainty | $\Delta\sigma/\sigma$ [%] |
|---|---|
| Experimental | |
| Lepton calibration | 0.2 |
| Jet energy and $E_T^{miss}$ scale and resolution | 3.9 |
| Pileup modeling | 1.2 |
| Background, misid. leptons | 4.2 |
| Background, charge misrec. | 0.5 |
| Background modeling statistical | 7.2 |
| Luminosity | 1.1 |
| Modeling | |
| $W^\pm W^\pm jj$ EW + QCD uncertainties | 4.7 |
| Background, WZ scale, PDFs & $\alpha_s$ | 0.4 |
| Background, WZ reweighting | 0.3 |
| Small background normalizations | 1.1 |
| Normalization factors | 2.5 |
| Experimental and modeling | 11.1 |
| Data statistical | 32.2 |
| Total | 34.1 |