FACULTY OF SCIENCES

DEPARTMENT OF PHYSICS AND ASTRONOMY
RESEARCH GROUP ELEMENTARY PARTICLE PHYSICS AND GRAVITY

Towards quantum state tomography with elementary qutrits

Measuring spin correlations in diboson systems

Gill Jacobs, 30/06/2025

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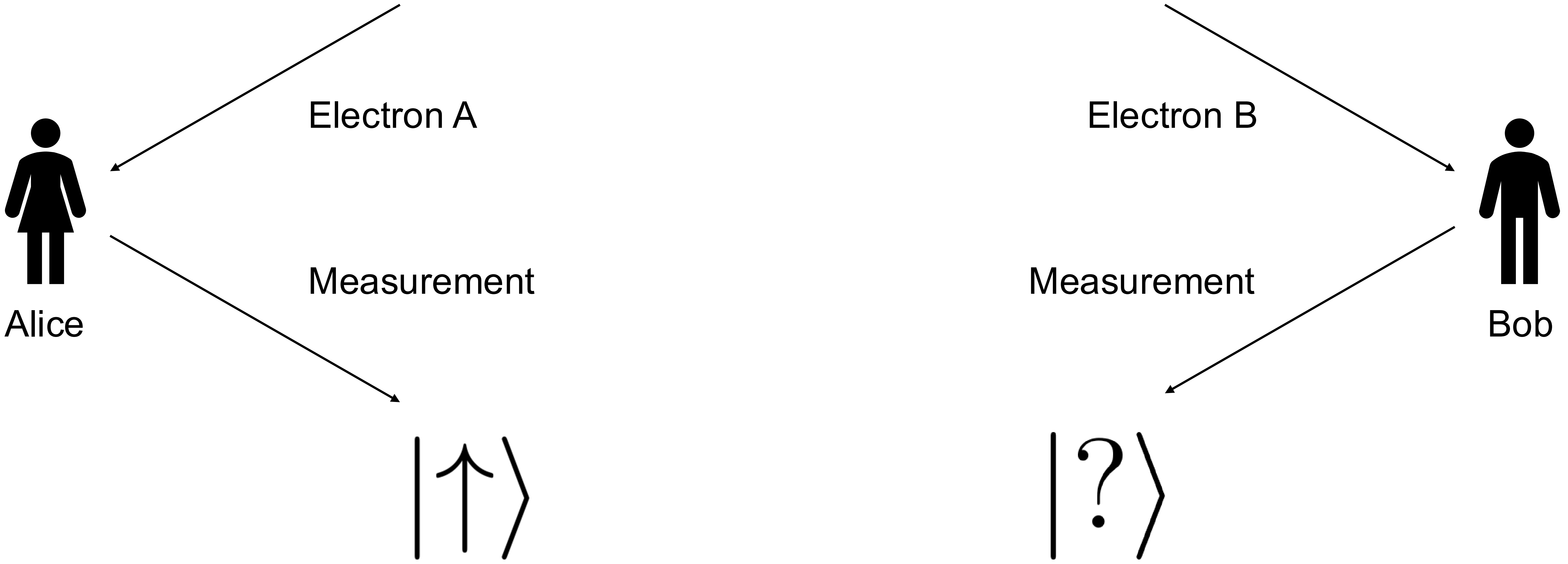
What is entanglement?

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_A \otimes |\downarrow\rangle_B - |\downarrow\rangle_A \otimes |\uparrow\rangle_B\right)$$



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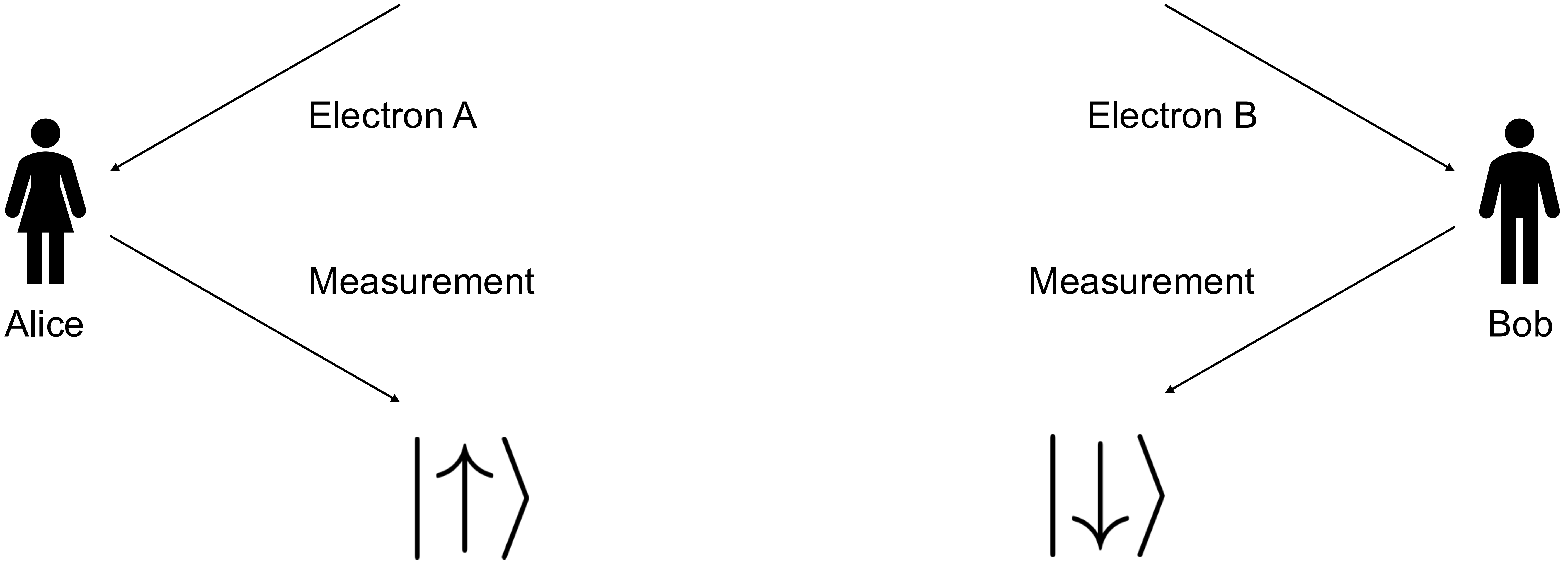
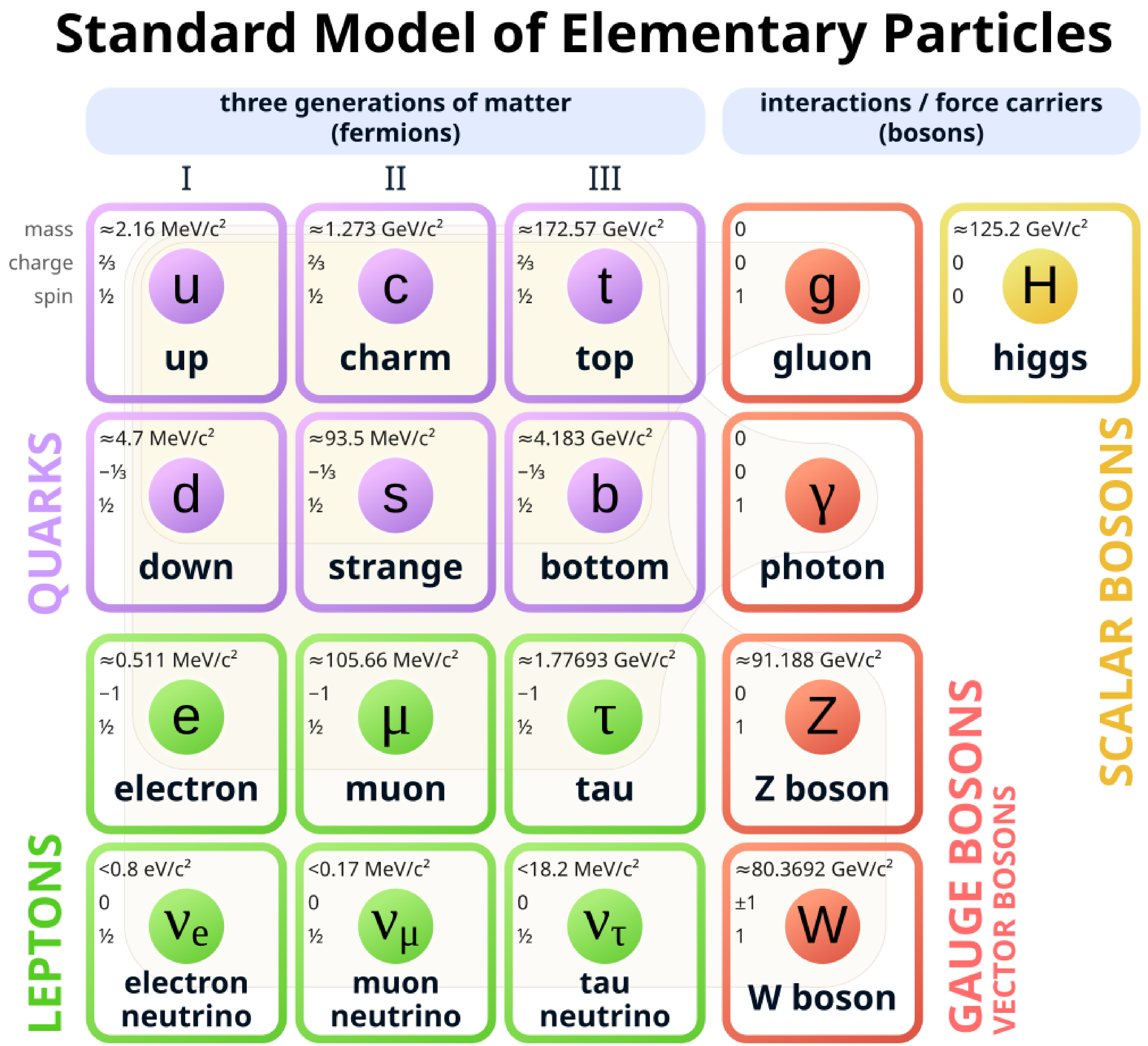


The Standard Model



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https://en.wikipedia.org/wiki/Standard_Model

Probing WZ entanglement

$$pp \to WZ \to \ell_W \, \nu_W + \ell_Z^+ \, \ell_Z^-$$

entangled state e.g.:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\big(|\circlearrowleft, \circlearrowright\rangle - |\circlearrowright, \circlearrowleft\rangle\big)$$

3 states per boson $\Rightarrow$ qutrits

probe **polarization** and **spin correlations** in angular distribution of decay products:

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_+ \mathrm{d}\Omega_-} \sim \left(1 + B^+ \cdot \hat{\ell}^+ + B^- \cdot \hat{\ell}^- - \hat{\ell}^+ \cdot C \cdot \hat{\ell}^-\right)$$

$$|L\rangle = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad |0\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \quad |R\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix},$$

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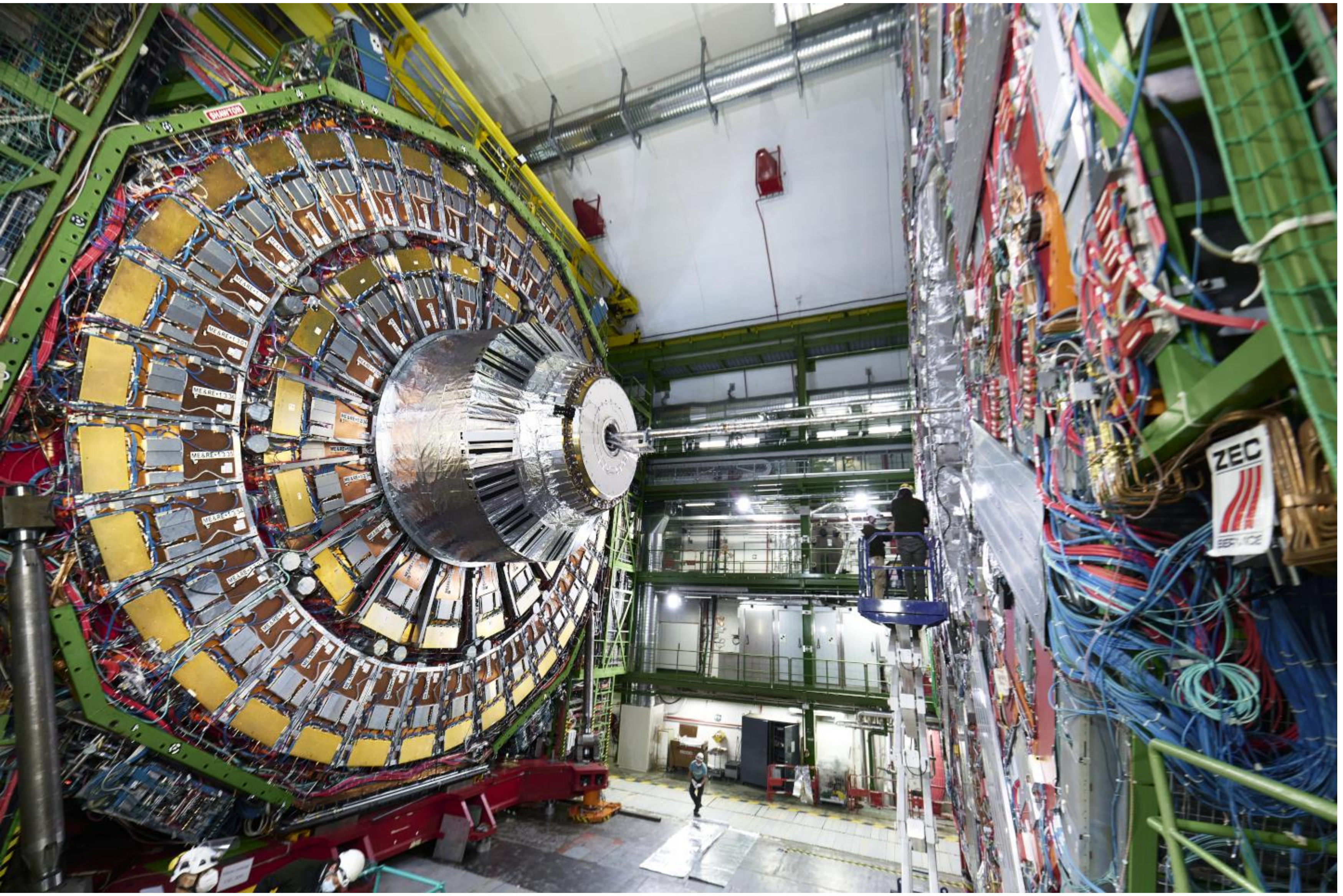
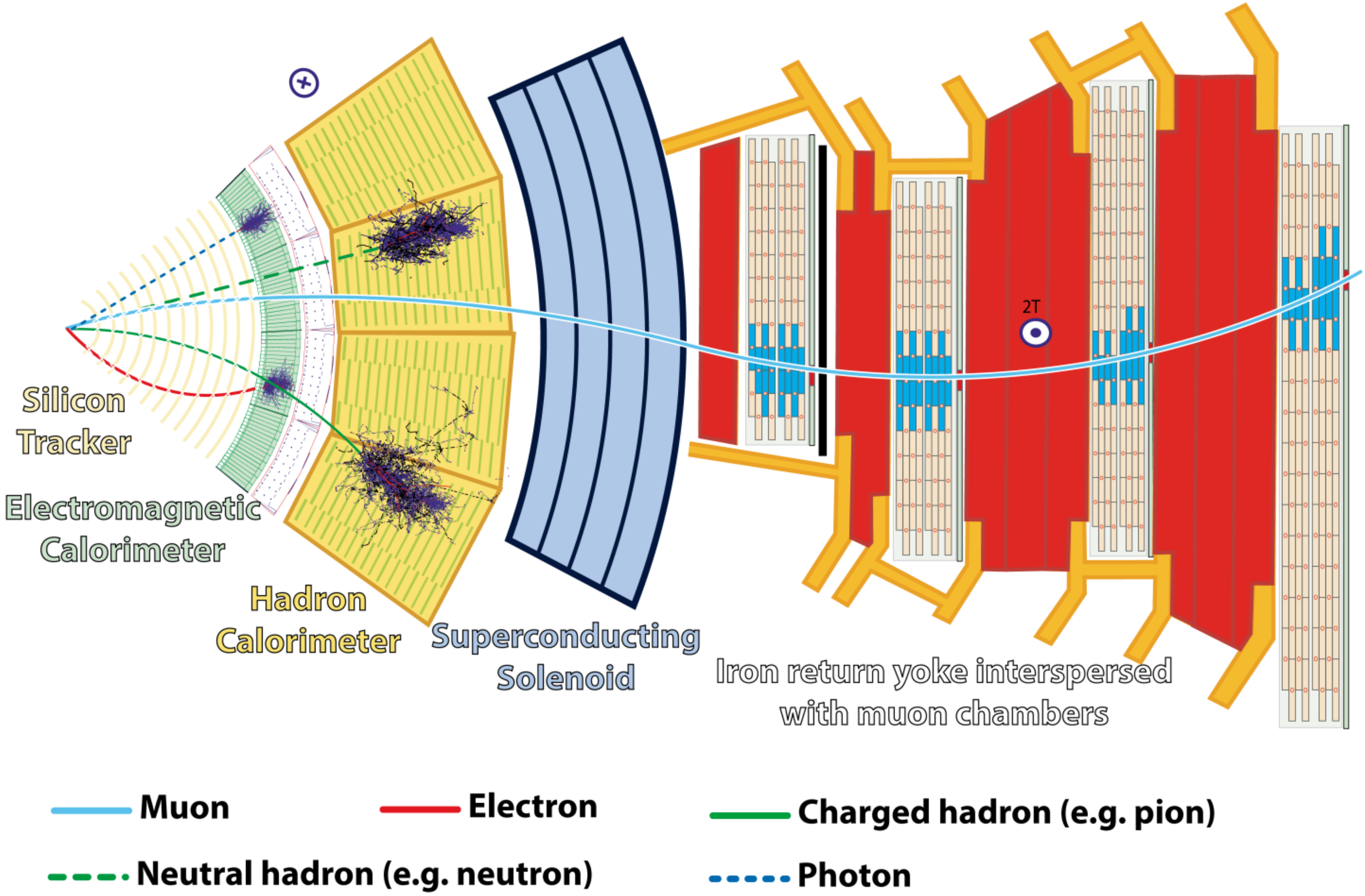
Courtesy of Joscha Knolle

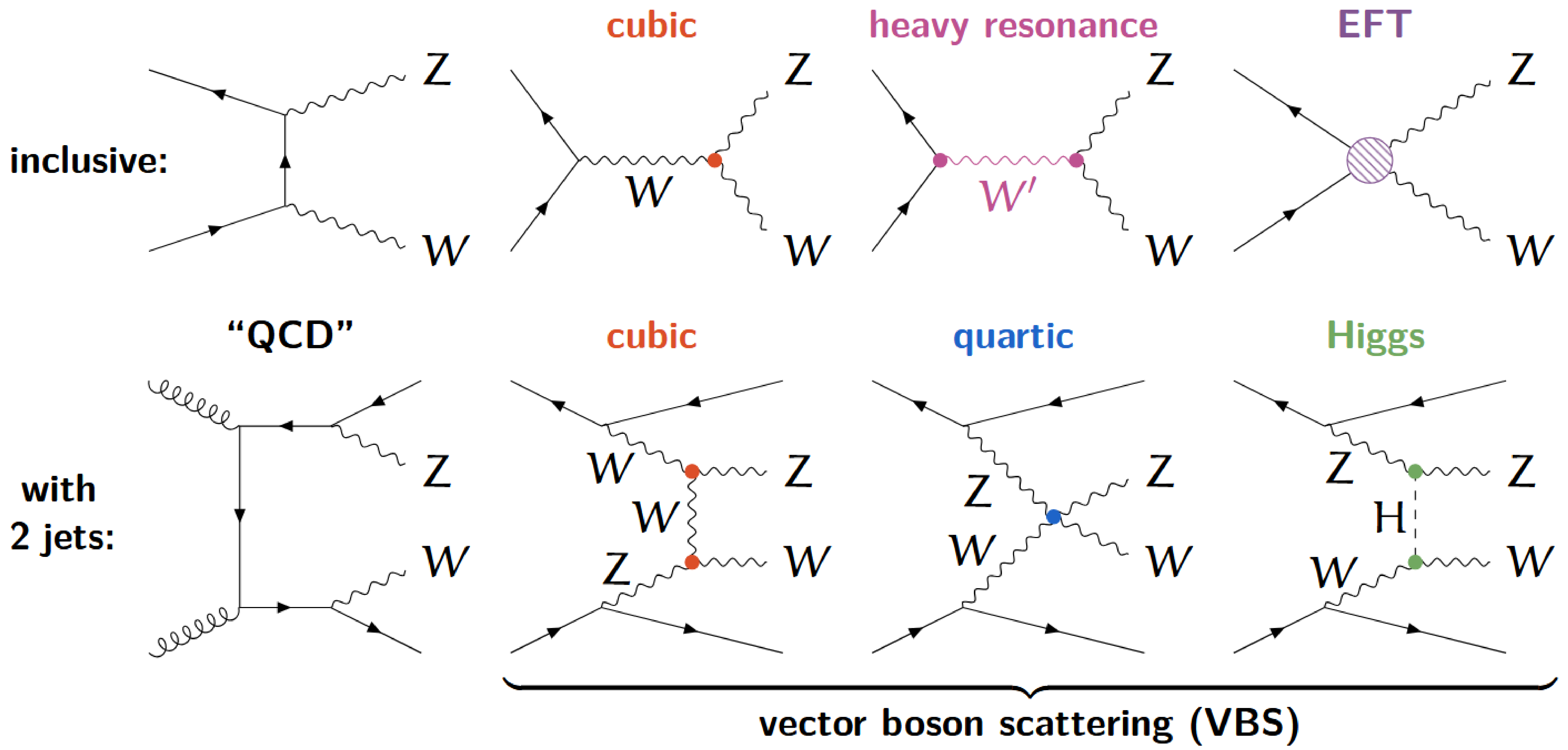
The CMS detector





https://home.cern/science/experiments/cms
https://cds.cern.ch/record/2120661

WZ production

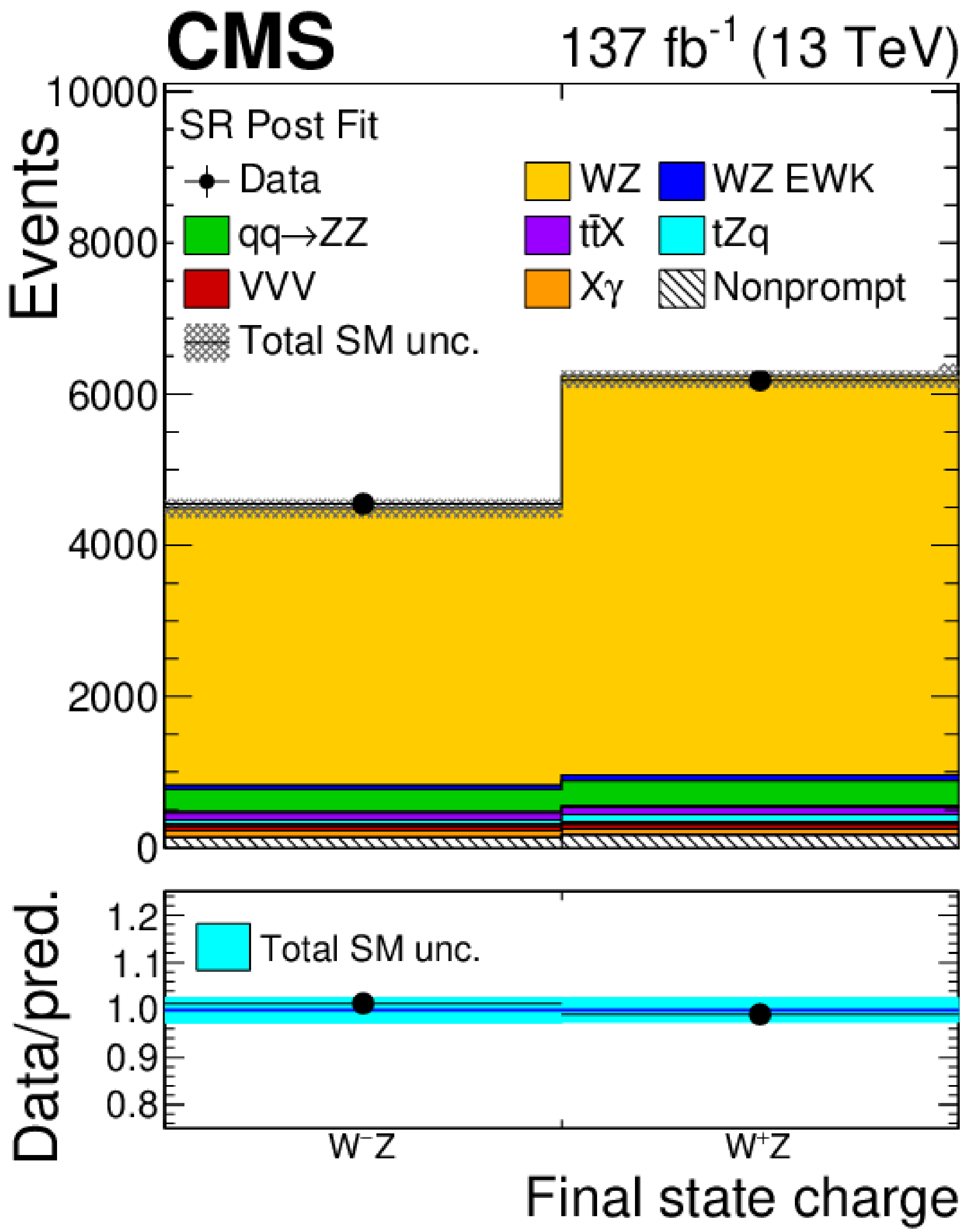


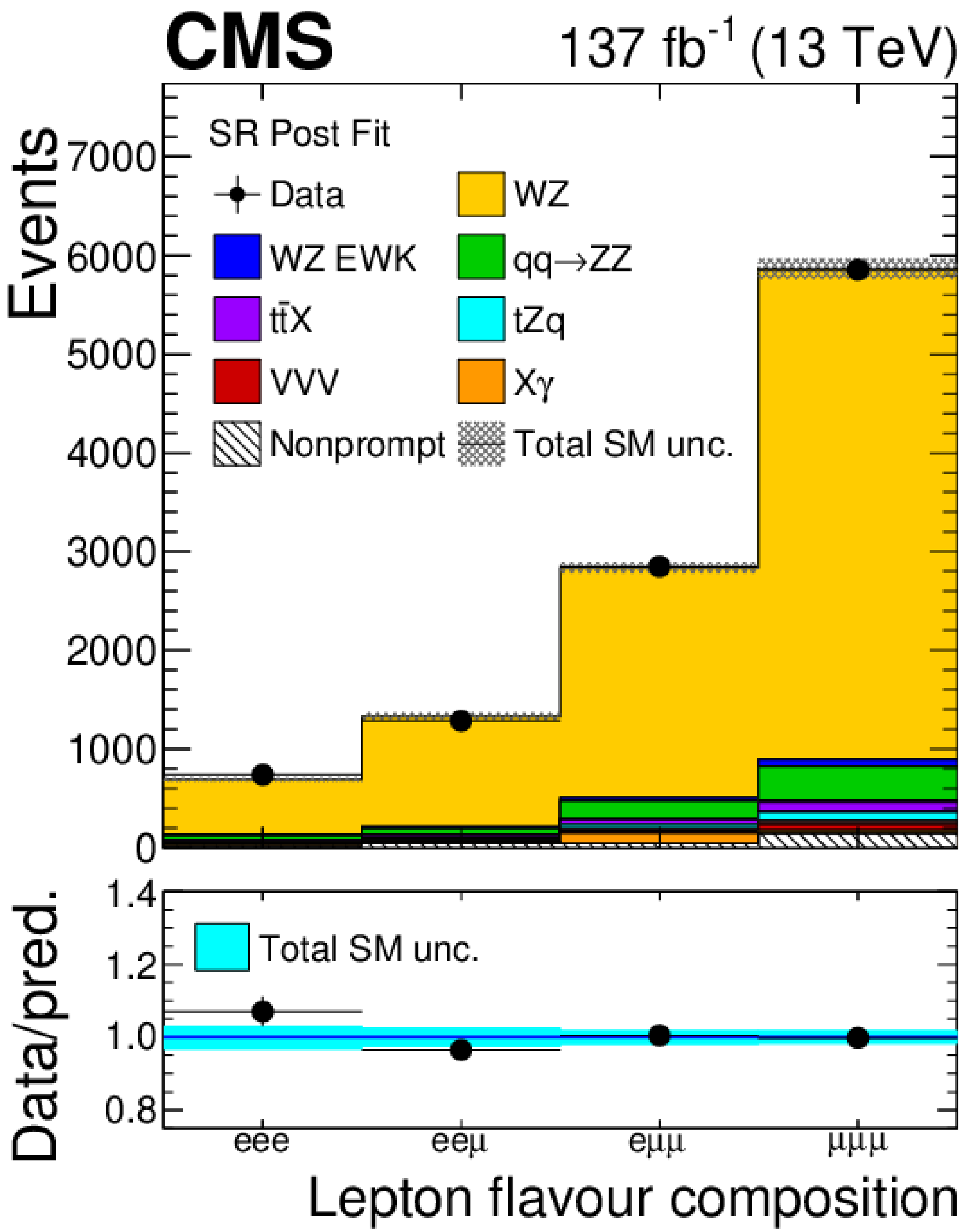
Courtesy of Joscha Knolle

How to measure WZ events

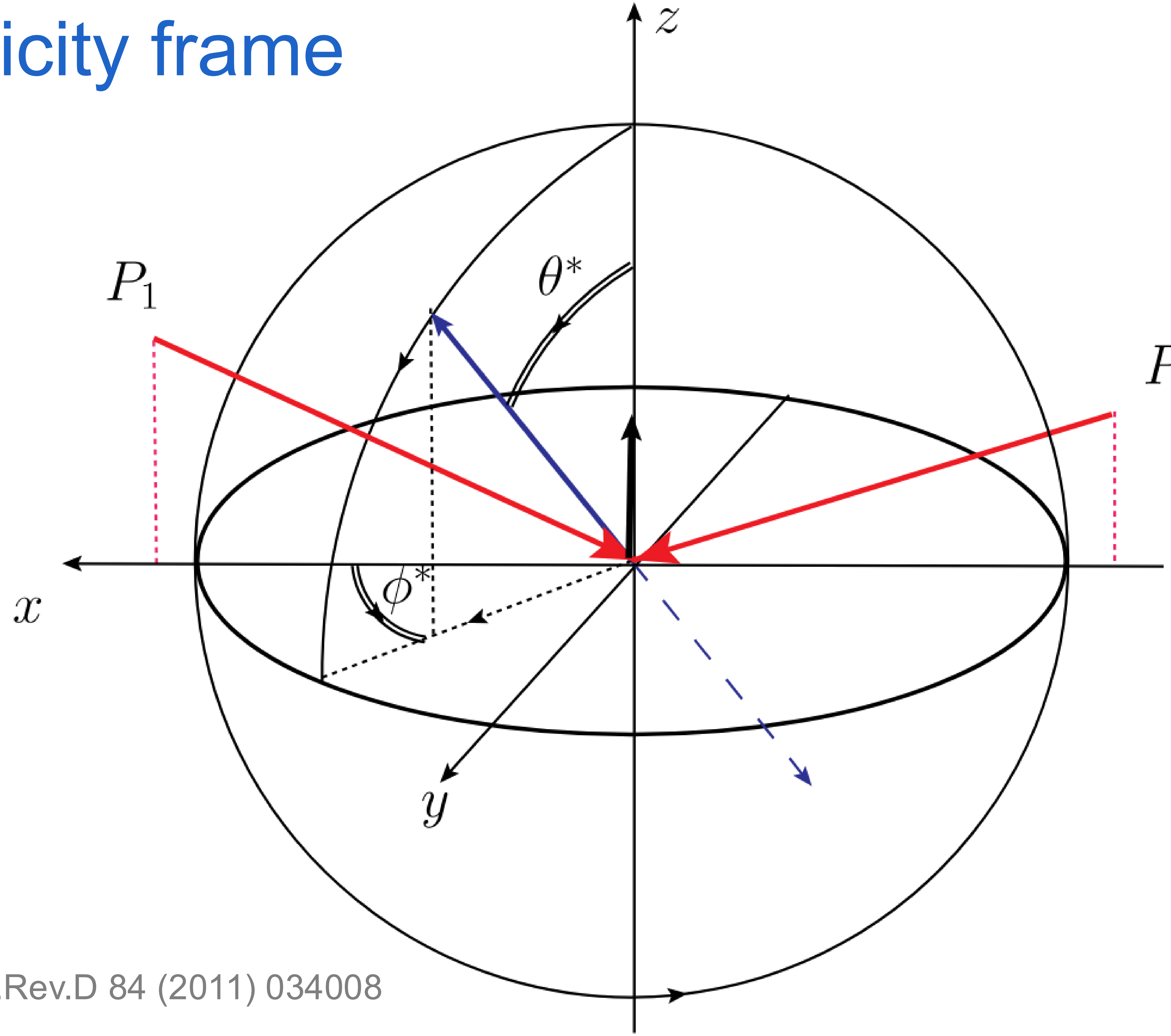
We select the following events:

- Exactly 3 leptons (electrons or muons)
- Exactly 1 OSSF pair of leptons with invariant mass M(ℓℓ) ~ M(Z)
- p_T^{miss} > 30 GeV
- …





The helicity frame



Phys.Rev.D 84 (2011) 034008

Polarization & correlation coefficients

$$A_1 = 4 - 10\,\langle\cos^2(\theta)\rangle, \qquad A_2 = \langle 5\sin(2\theta)\cos(\phi)\rangle, \qquad A_3 = \langle 10\sin^2(\theta)\cos(2\phi)\rangle,$$
$$A_4 = \langle 4\sin(\theta)\cos(\phi)\rangle, \qquad A_5 = \langle 4\cos(\theta)\rangle, \qquad A_6 = \langle 4\sin(\theta)\sin(\phi)\rangle,$$
$$A_7 = \langle 5\sin(2\theta)\sin(\phi)\rangle, \qquad A_8 = \langle 5\sin^2(\theta)\sin(2\phi)\rangle.$$

$$\begin{aligned} C_{ij} &= A_i \times B_j \\ \text{For example: } C_{47} &= A_4 \times B_7 \\ &= \langle 4\sin(\theta_W)\cos(\phi_W)\cdot 5\sin(2\theta_Z)\sin(\phi_Z)\rangle \end{aligned}$$

Phys.Rev.D 84 (2011) 034008

MATRIX and MadGraph

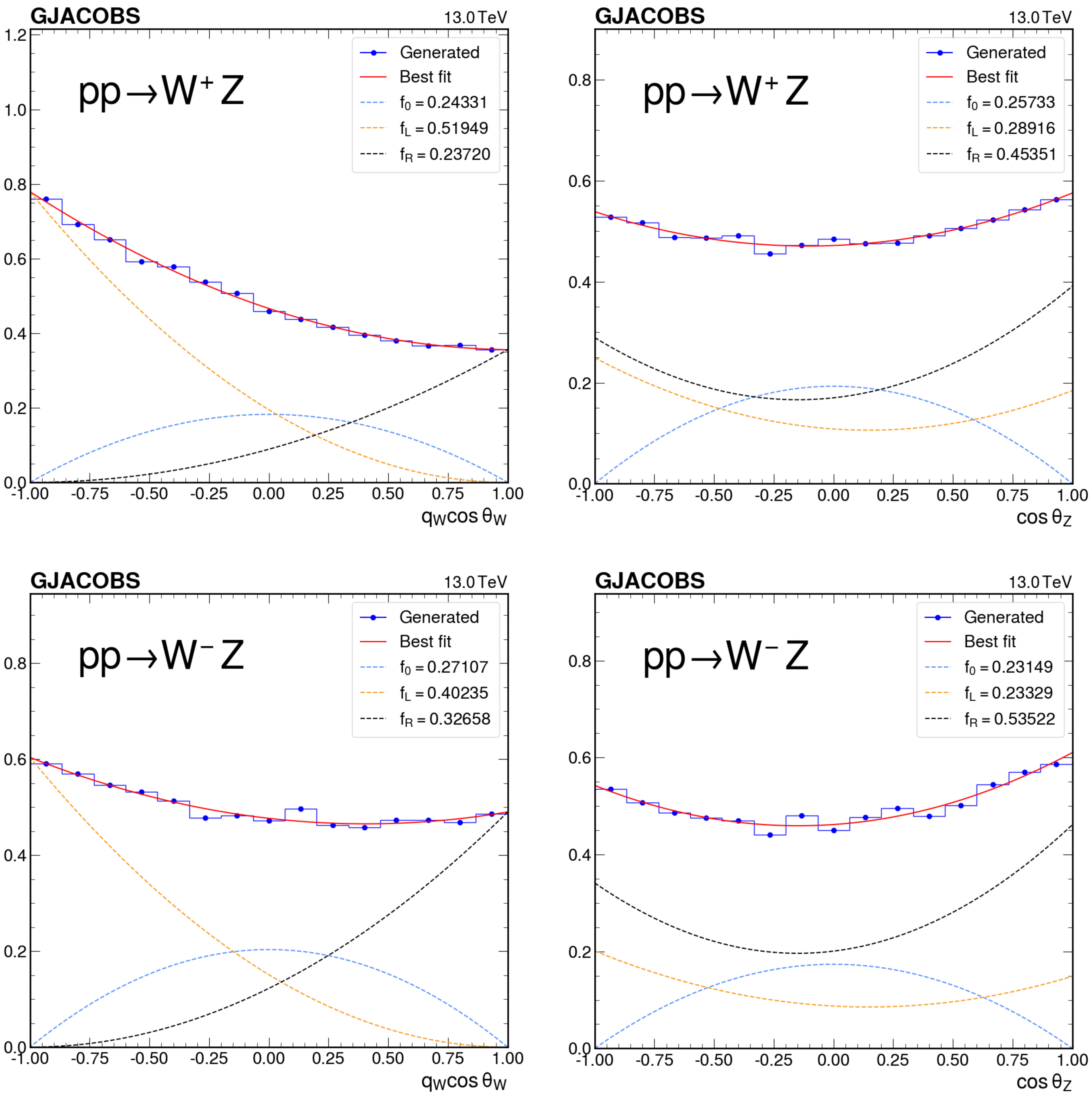
MATRIX

- Calculates differential cross-section directly
- Needs to be specified before running
- Limited number of processes
- Up to NNLO

MadGraph

- Monte Carlo event generator
- For any (B)SM process whose Feynman rules are implemented
- Can be interfaced to simulate parton shower/ detector int.
- Up to NLO

MATRIX
cos(θ)



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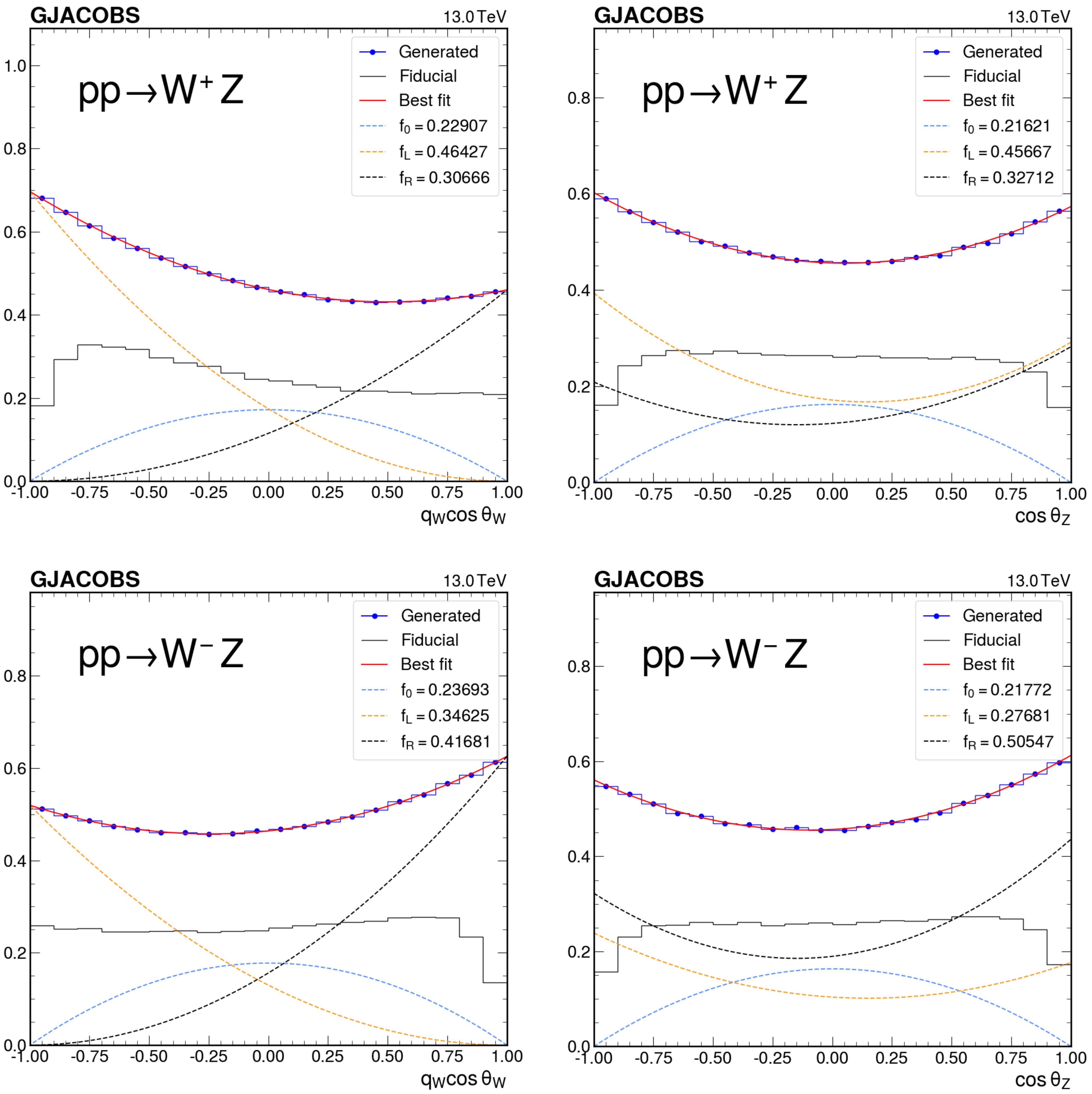
MadGraph cos(θ)



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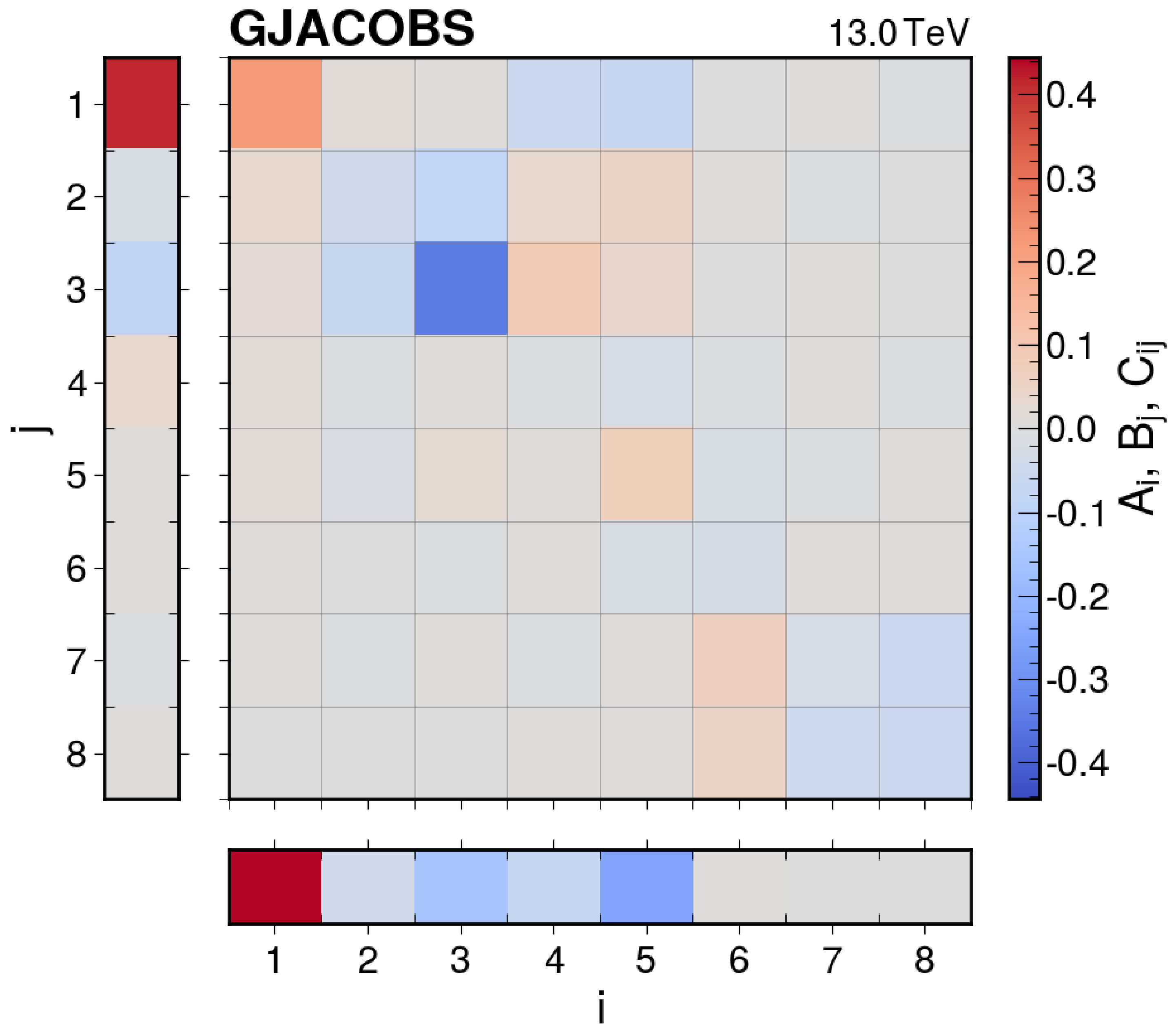
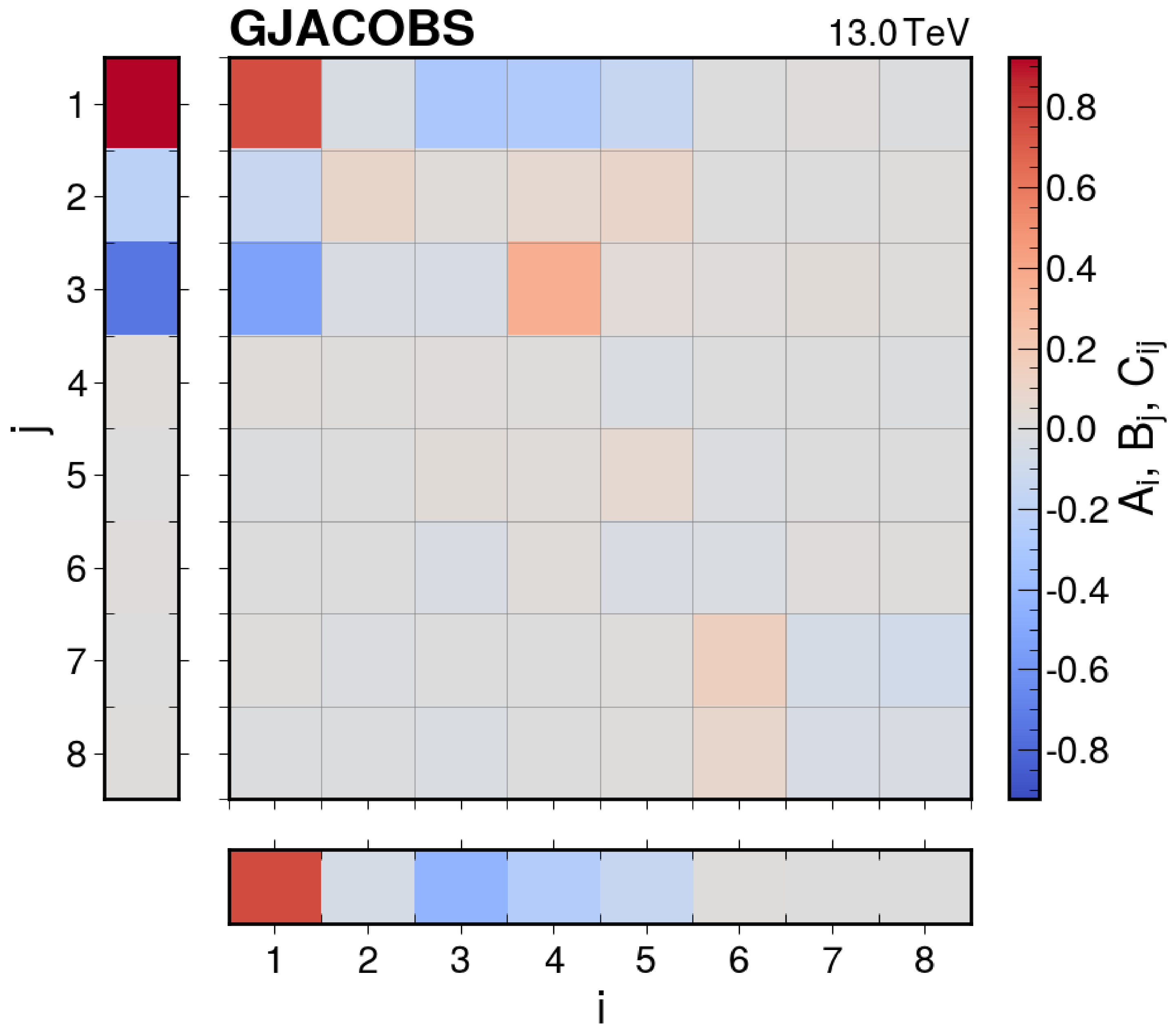
Combined A_i, B_j, C_{ij} (MadGraph)

Full phase space



With fiducial cuts



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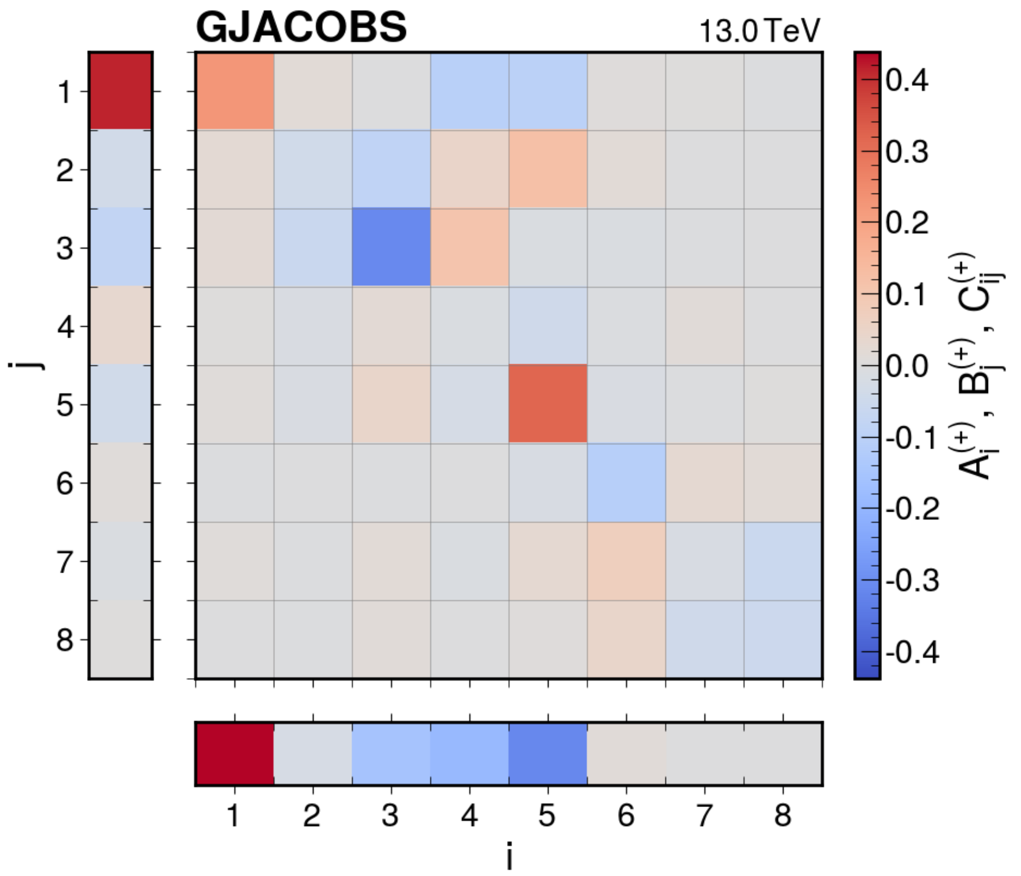
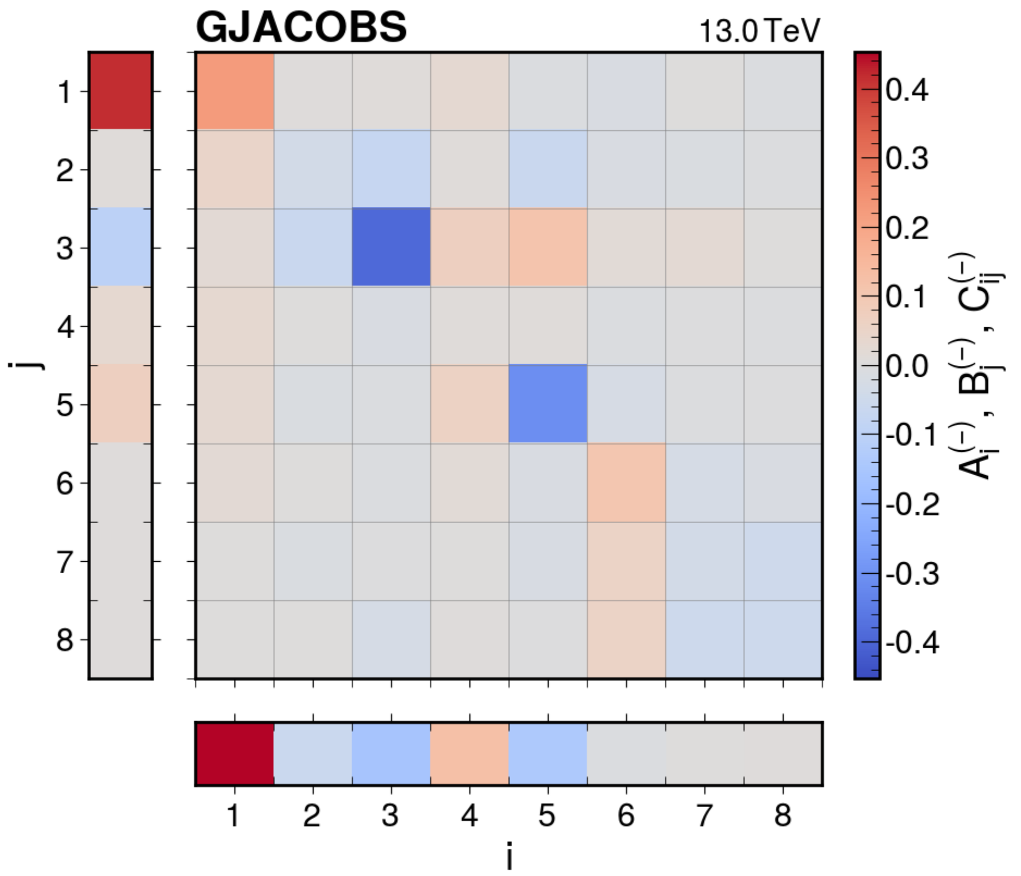
A_i, B_j, C_{ij} separated by charge (MadGraph)

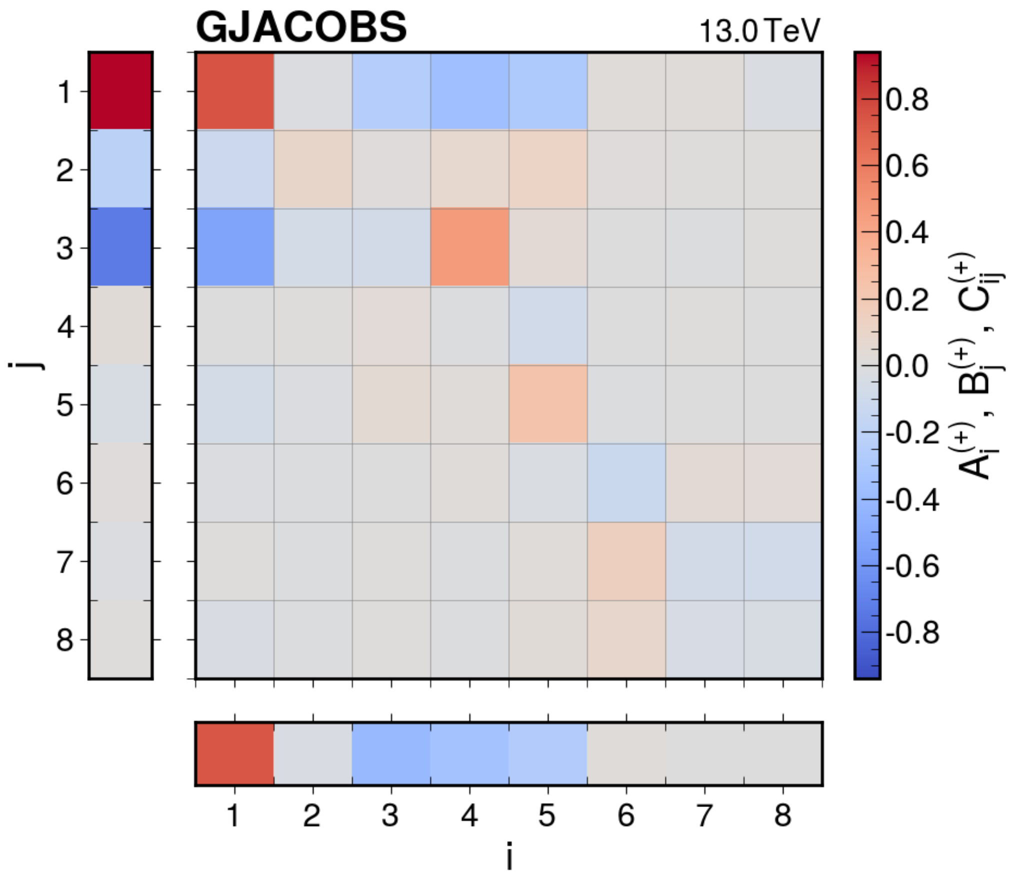
Full (+)



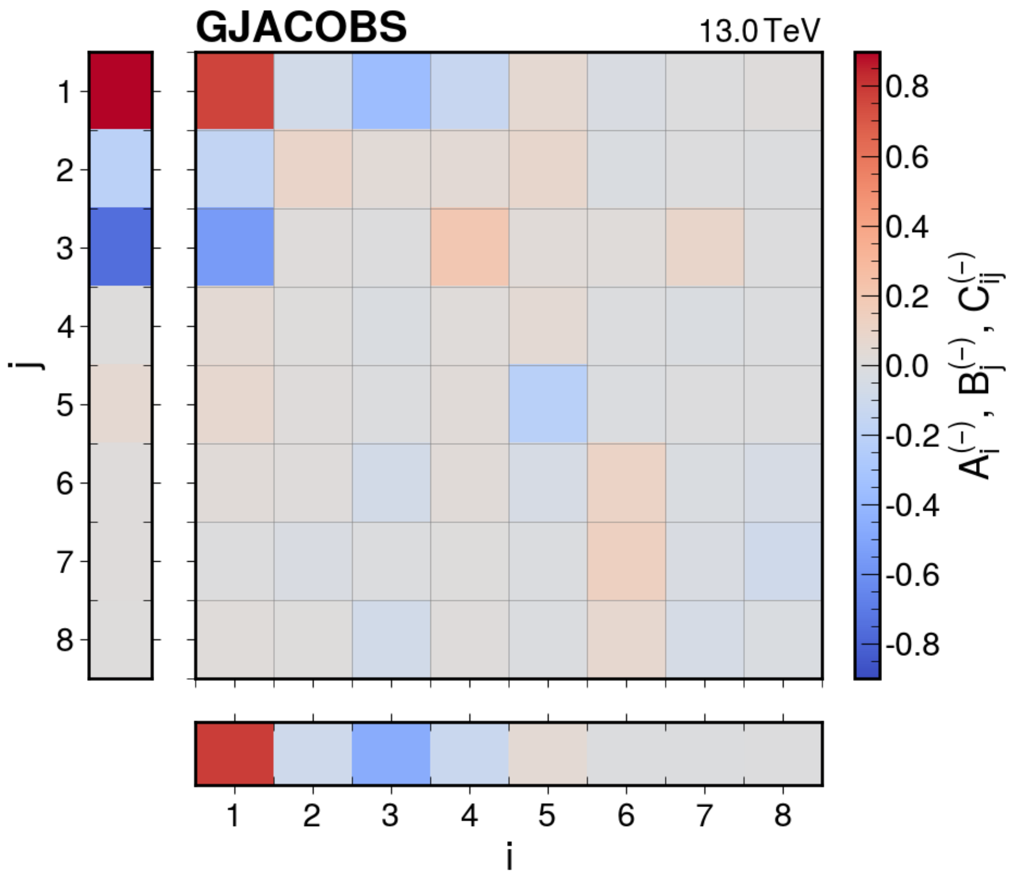
Full (-)



Fid. (+)



Fid. (-)



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Conclusion and future research

Conclusion

- Discrepancy between MadGraph and MATRIX cos(θ)
- Some correlations between W and Z boson were found
- No entanglement in full phase space was found

Future research

- Extend results using the MATRIX framework
- Reconstruction of full phase space from detector data
- Look into specific phase space regions
- Other two-particle systems

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Why the WZ system?

- Great test for electroweak interactions
- Fully leptonic decay channels are clean
- Relatively easy to separate from background
- MATRIX and MadGraph for calculation
- Some research for comparison already exists

Qutrit framework and entanglement

$$\rho = \sum_{i=1}^{m} p_i |\psi_i\rangle\langle\psi_i| \,, \quad \text{with } p_i \geq 0 \text{ and } \sum_{i=1}^{m} p_i = 1.$$

$$\text{Separable if: } \rho = \sum_{i=1}^{m_A} \sum_{j=1}^{m_B} p_{ij} \rho_i^{(A)} \otimes \rho_j^{(B)} \,.$$

$$|L\rangle \equiv \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \qquad |0\rangle \equiv \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \qquad |R\rangle \equiv \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}.$$

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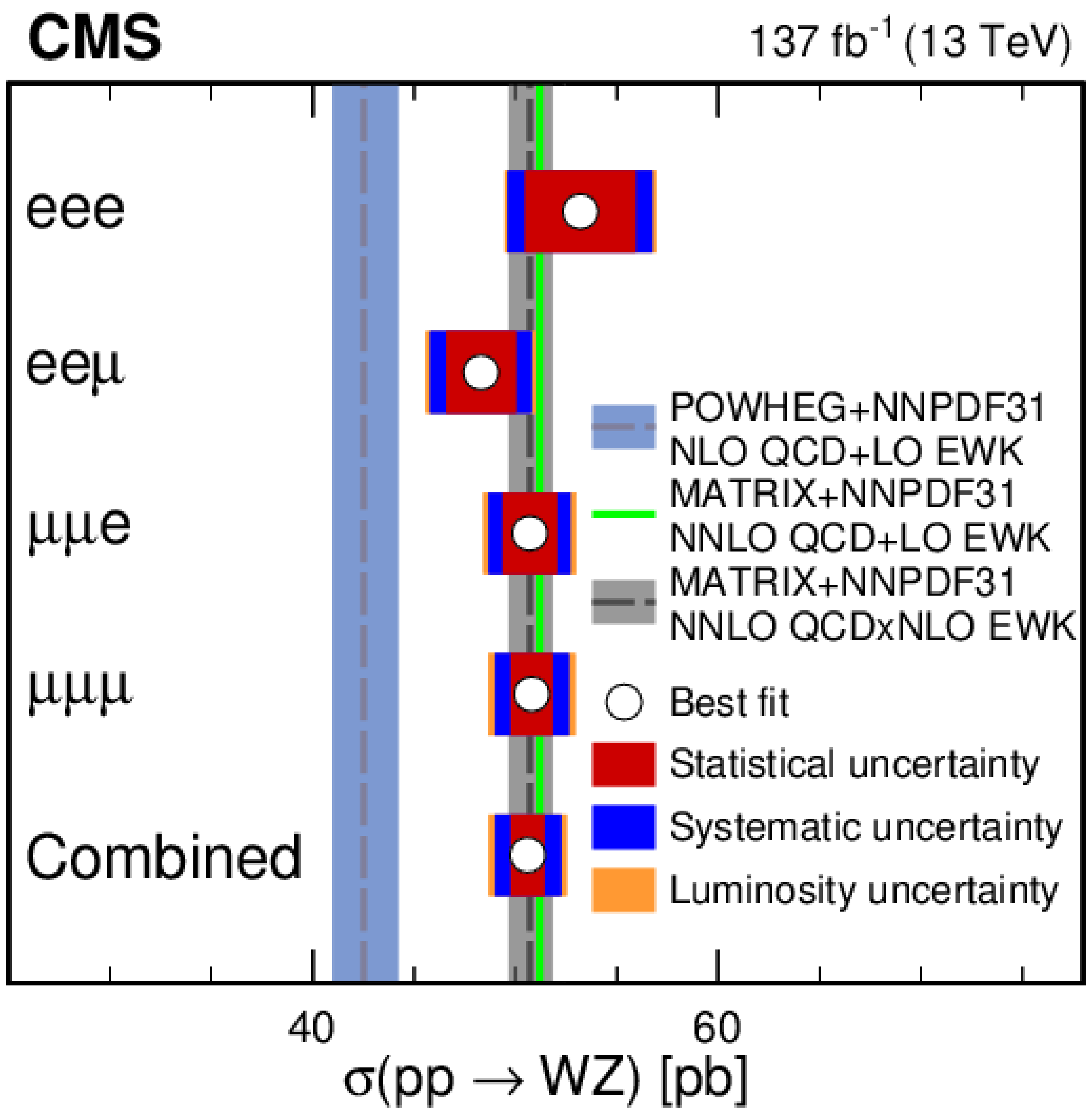
WZ cross-section



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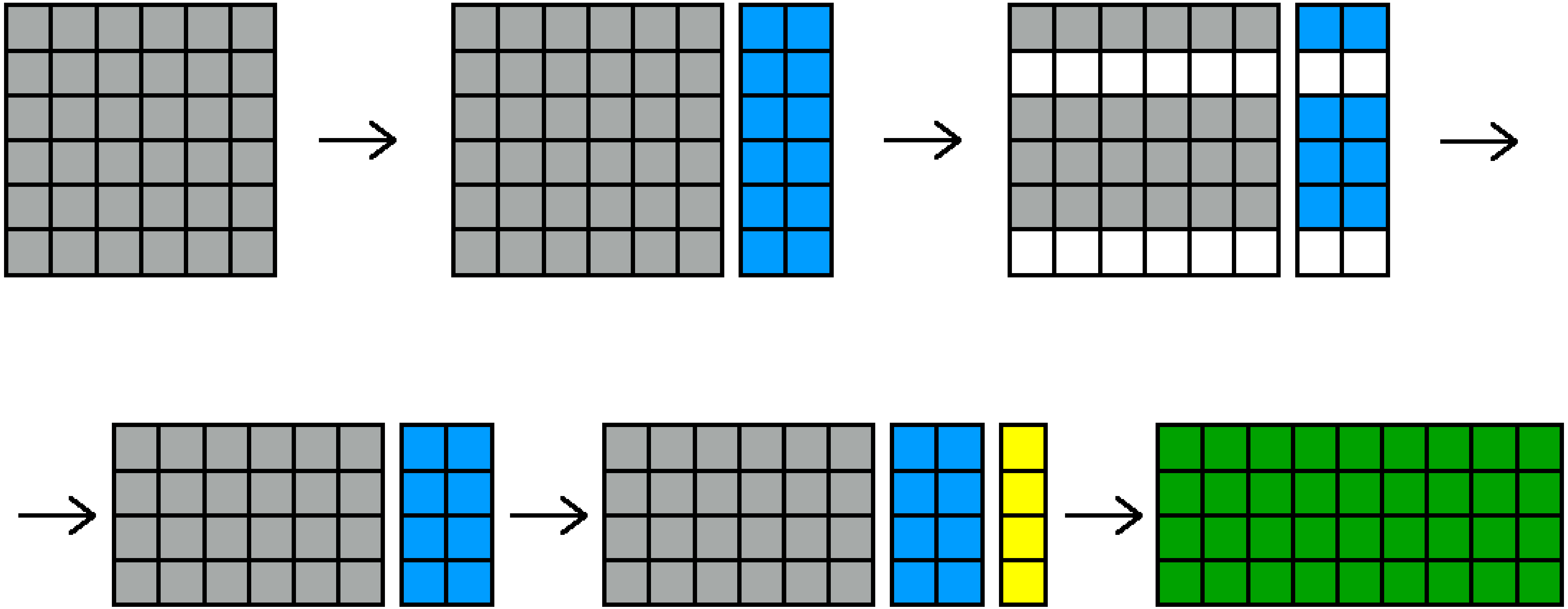
JHEP 07 (2022) 032

Processing MadGraph data with ColumnFlow



cos(θ) formula

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos(\theta_{W^\pm})} = \frac{3}{8}\left[[1 \mp \cos(\theta_{W^\pm})]^2 f_L^W \right. \\ \left. + [1 \pm \cos(\theta_{W^\pm})]^2 f_R^W + 2\sin^2(\theta_{W^\pm}) f_0^W \right]$$

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos(\theta_Z)} = \frac{3}{8}\left[[1 + \cos^2(\theta_Z) - 2c\cos(\theta_Z)] f_L^Z \right. \\ \left. + [1 + \cos^2(\theta_Z) + 2c\cos(\theta_Z)] f_R^Z + 2\sin^2(\theta_Z) f_0^Z \right].$$

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Fiducial cuts

$$|\eta_e| < 2.5, \qquad |\eta_\mu| < 2.4,$$
$$p_{T,e} > 15 \text{ GeV}, \qquad p_{T,\mu} > 20 \text{ GeV},$$
$$\Delta R_{\ell_Z \bar{\ell}_Z} > 0.2, \qquad \Delta R_{\ell_W \ell_Z} > 0.3,$$
$$M_{T,W} > 30 \text{ GeV}.$$

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Previous CMS results: polarization fractions

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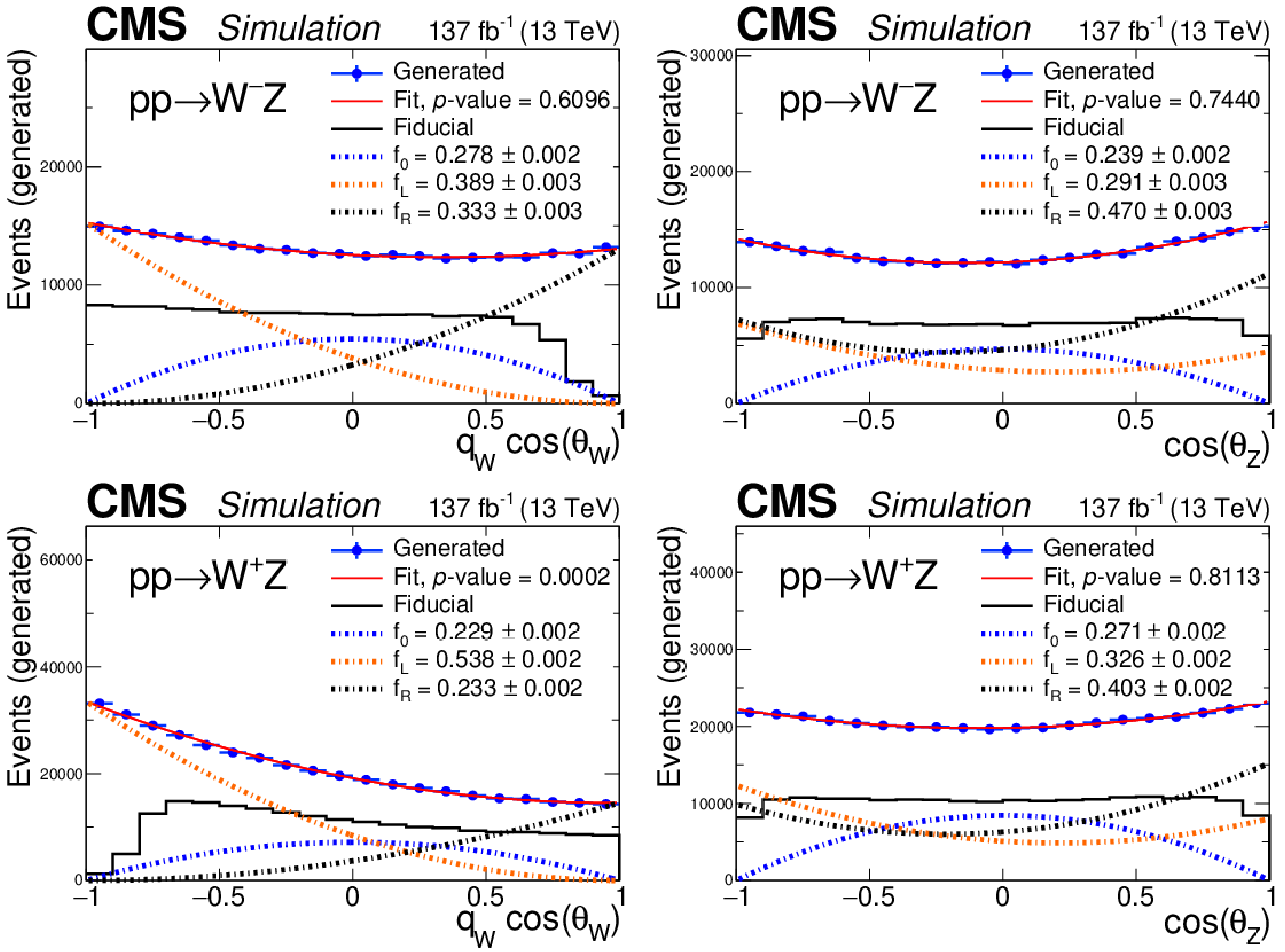

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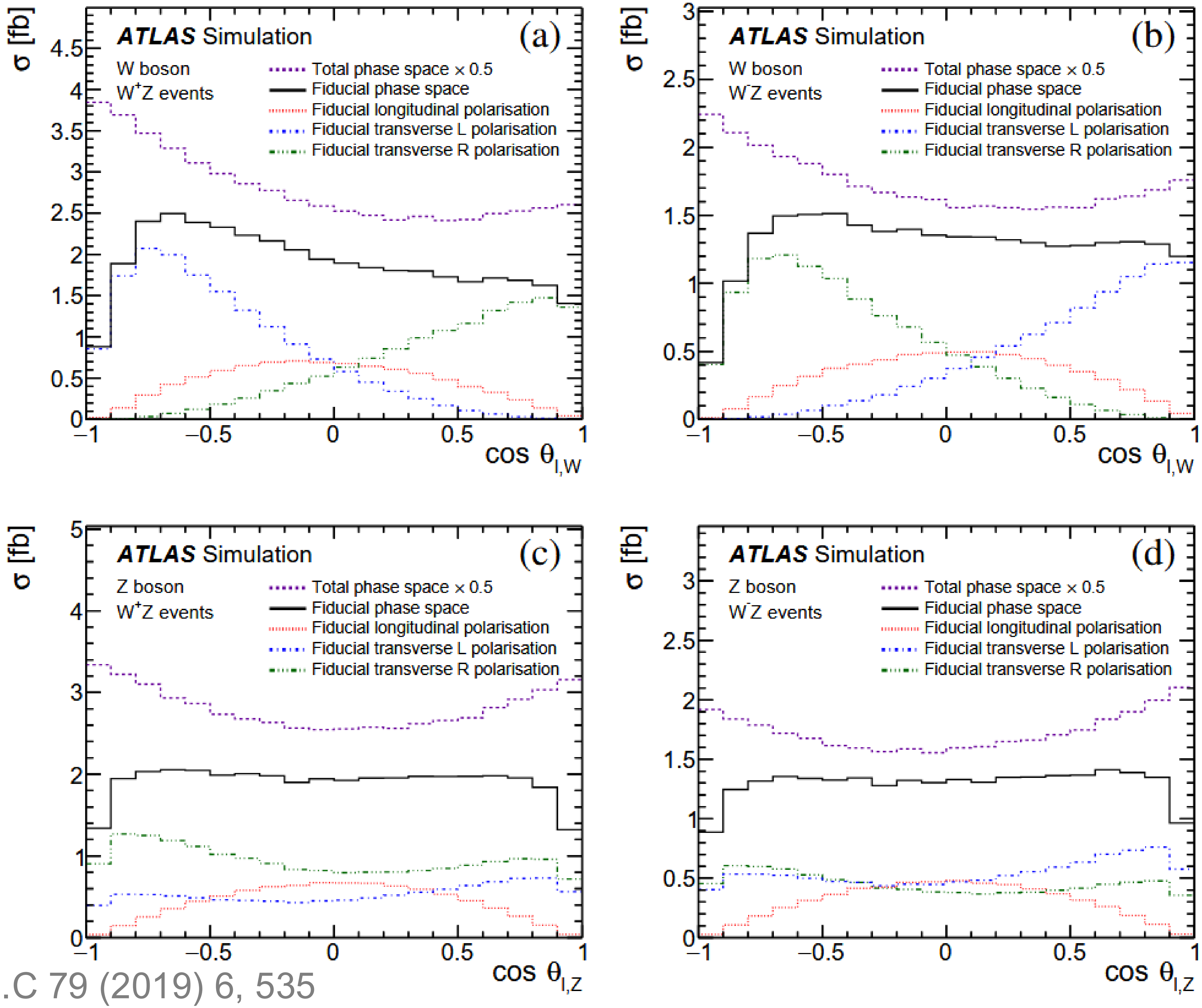
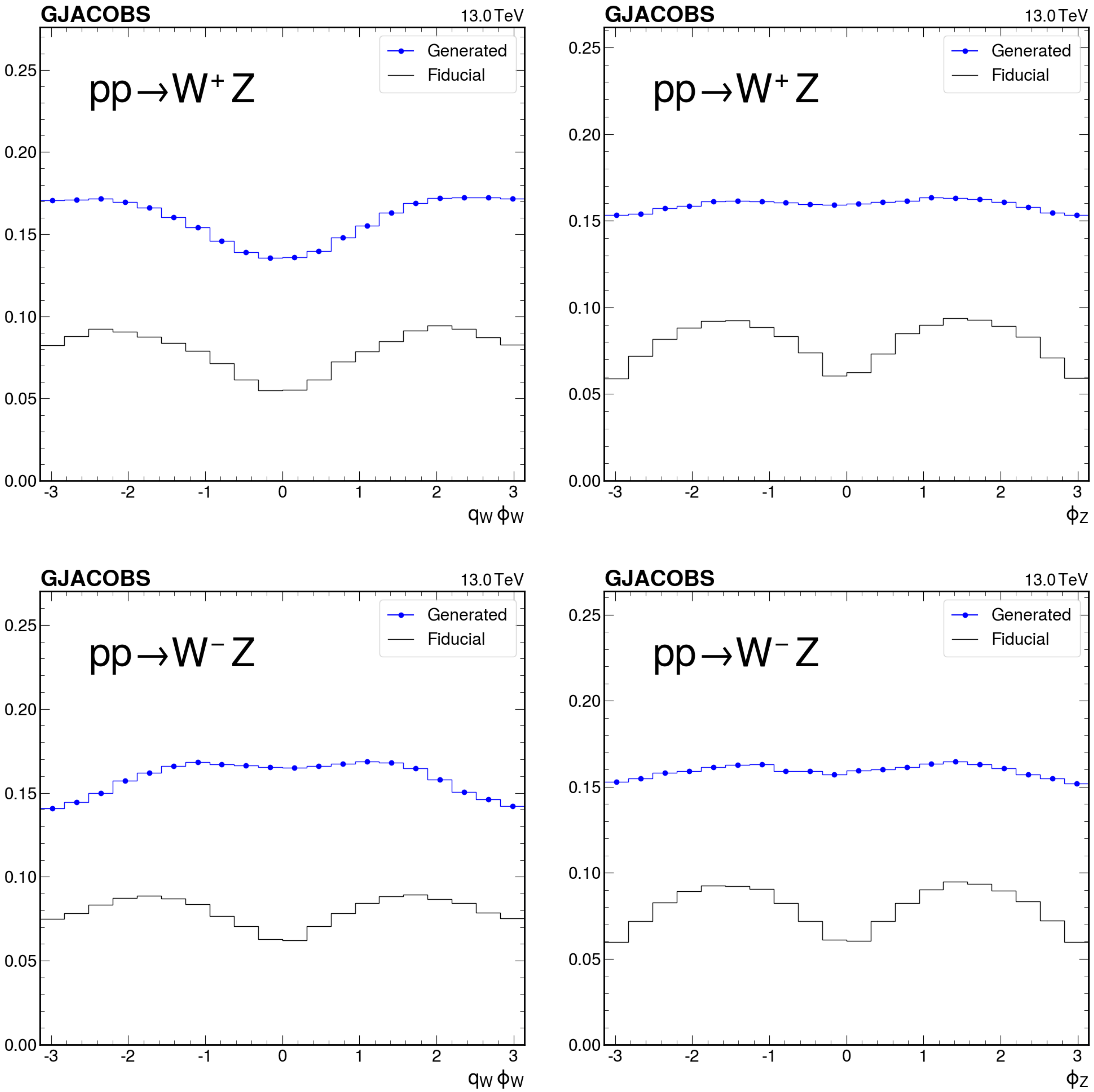
Previous ATLAS results: polarization fractions



Eur.Phys.J.C 79 (2019) 6, 535

MadGraph φ



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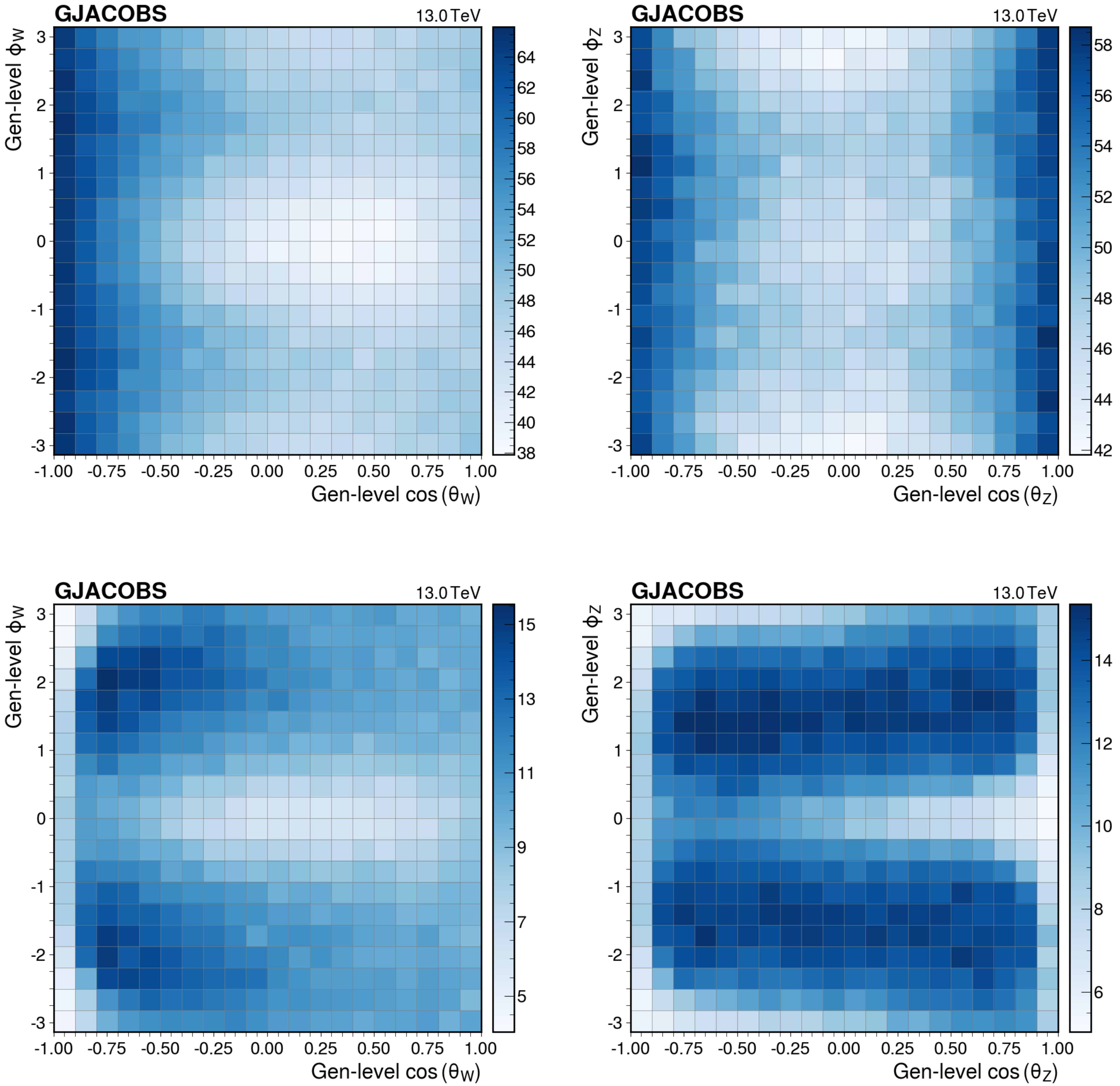
cos(θ) x φ



GJACOBS
13.0 TeV
Gen-level ϕ_W
Gen-level cos (θ_W)
Gen-level ϕ_Z
Gen-level cos (θ_Z)