Quantum Tomography of the Z Boson with Monte Carlo Simulations.

Jadihel Antonio Martinez Ramon

FCFM BUAP
Master's degree in applied physics
supervised by
Dr. Alan I. Hernandez Juarez
Dr. Gilberto Tavares Velasco

2026 CFNS Summer School

What is quantum tomography?

Quantum tomography is a method used to experimentally extract all the observable information about a quantum-mechanical system. The method of quantum tomography uses a known "probe" to explore an unknown system.

- J.C. Martens, J.P. Ralston, and J.D. Tapia Takaki, Quantum tomography for collider physics: illustrations with lepton-pair production. Eur. Phys. J. C **78**(1), 5 (2018).
- A. Gautam, J.C. Martens, J.P. Ralston, G. Stejskal, and J.D. Tapia Takaki, Mirror quantum tomography finds unexpected polarization phenomena in Z boson production in pp collisions at the LHC. arXiv:2605.03254 [hep-ph] (2026).

From amplitudes to quantum tomography

Two descriptions of the same observable?

In the conventional approach, the cross section is calculated from scattering amplitudes.

$$d\sigma \sim \sum_{\text{unobserved}} |\mathcal{M}|^2 \, dR. \tag{1}$$

For inclusive lepton-pair production, the resulting bilinear terms can be organized in terms of a probe and a target density matrix,

$$d\sigma \sim \text{Tr}\left[\rho^{\text{probe}}(k,k')\,\rho(X)\right] dR \tag{2}$$

The cross-section obtained from the calculation of amplitudes can be written in terms of density matrices.

What quantum tomography reconstructs

The leptonic decay provides the known probe $\rho^{\text{probe}}(k, k')$. Its angular distribution gives access to the observable components of the unknown polarization density matrix $\rho(X)$.
For $Z/\gamma^* \to \ell^+\ell^-$, these observable components are encoded in the angular coefficients

$$A_0, \dots, A_7.$$

Note that we work directly with the information accessible through the measured leptonic angular distribution

"In any process involving angular distribution, we can reconstruct its density matrix"
J. P. Ralston 05/30/2026

Event generation

Monte Carlo sample

We generated one million events. Although this may appear to be a very large sample, at this first stage we only analyze the LHE event files.
The LHE files contain the parton-level four-momenta required to reconstruct the dilepton system. This allows us to preserve high statistics while avoiding unnecessary computational costs associated with parton showering and detector simulation.

The process

To Study z boson production with madgraph, we chose the process:

$$pp \to Z/\gamma^* \to \ell^+\ell^- + j$$

performed at a center-of-mass energy of $\sqrt{s} = 8$ TeV, using the dilepton invariant-mass window $80 < M_{\ell\ell} < 100$ GeV, this selection reprocue the kinematic regionstudy by atlas and used in quantum tomagraphy

Near the (Z)-boson mass, dilepton production is dominated by $pp \to Z/\gamma^* \to \ell^+\ell^-$. so the final-state leptons provide a direct probe of the polarization of the intermediate vector system. We also required an explicit jet in the final state.

Drell-Yan angular coefficients

Our starting point is the angular distribution of the leptons produced in the Drell-Yan process. In the Collins-Soper frame, it can be written as

$$\frac{dN}{d\Omega} = \frac{3}{16\pi}\Big[(1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) + A_1\sin(2\theta)\cos\phi + \frac{A_2}{2}\sin^2\theta\cos(2\phi) + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin(2\phi) + A_6\sin(2\theta)\sin\phi + A_7\sin\theta\sin\phi\Big] \quad (3)$$

The coefficients $A_0, \ldots, A_7$ encode the polarization and angular structure of the dilepton system.

Reconstruction of the dilepton system

Total dilepton four-momentum

For each event, we reconstruct the total four-momentum of the dilepton system,

$$Q^\mu = p^\mu_{\ell-} + p^\mu_{\ell+}. \tag{4}$$

From Q^μ, we calculate the dilepton invariant mass, transverse momentum, and rapidity,

$$M_{\ell\ell} = \sqrt{Q^\mu Q_\mu}, \qquad Q_T = \sqrt{Q_x^2 + Q_y^2}, \qquad y_{\ell\ell} = \frac{1}{2}\ln\left(\frac{Q^0 + Q^z}{Q^0 - Q^z}\right).$$

Boost to the dilepton rest frame

Velocity of the dilepton system

The angular distribution is defined in the rest frame of the dilepton system. The velocity of this system in the laboratory frame is

$$\vec{\beta}_Q = \frac{\vec{Q}}{Q^0}, \qquad \gamma_Q = \frac{1}{\sqrt{1 - |\vec{\beta}_Q|^2}}. \tag{5}$$

Lorentz transformation

For an arbitrary four-vector $p^\mu = (E, \vec{p})$, the boost to the dilepton rest frame is

$$E^* = \gamma_Q \left(E - \vec{\beta}_Q \cdot \vec{p}\right), \qquad \vec{p}^* = \vec{p} + \left[\frac{\gamma_Q - 1}{\beta_Q^2}\left(\vec{\beta}_Q \cdot \vec{p}\right) - \gamma_Q E\right]\vec{\beta}_Q. \quad after \quad Q^{*\mu} = (M_{\ell\ell}, \vec{0}).$$

The Collins-Soper coordinate system

Definition of the basis

The Collins-Soper frame defines three mutually orthogonal axes, X_{CS}, Y_{CS}, and Z_{CS}, using the directions of the two proton beams in the dilepton rest frame.
The unit vector along the selected lepton direction is written as

$$\hat{\ell} = (\sin\theta_{CS}\cos\phi_{CS},\ \sin\theta_{CS}\sin\phi_{CS},\ \cos\theta_{CS})\,. \tag{6}$$

Therefore,

$$\cos\theta_{CS} = \hat{\ell}\cdot\hat{Z}_{CS},$$

while ϕ_{CS} describes the orientation of the lepton around the Collins-Soper Z axis.

PARTÍCULAS ELEMENTALES

Orthogonality conditions

The Collins-Soper basis is described by three spacelike four-vectors, X^μ, Y^μ, and Z^μ, orthogonal to the dilepton four-momentum Q^μ:

$$Q \cdot X = Q \cdot Y = Q \cdot Z = 0,$$
$$X \cdot Y = Y \cdot Z = X \cdot Z = 0.$$

After normalization, the axes satisfy

$$X^2 = Y^2 = Z^2 = -1.$$

Covariant Collins–Soper axes

Covariant construction

We define two lightlike vectors along the proton-beam directions,

$$P_A^\mu = (1, 0, 0, 1), \qquad P_B^\mu = (1, 0, 0, -1). \tag{7}$$

The Collins–Soper axes are then constructed as

$$\begin{aligned} \widetilde{Z}^\mu &= P_A^\mu \left(Q \cdot P_B\right) - P_B^\mu \left(Q \cdot P_A\right), \\ \widetilde{X}^\mu &= Q^\mu - P_A^\mu \frac{Q^2}{2Q \cdot P_A} - P_B^\mu \frac{Q^2}{2Q \cdot P_B}, \\ \widetilde{Y}^\mu &= \epsilon^{\mu\nu\alpha\beta} P_{A\nu} P_{B\alpha} Q_\beta \end{aligned} \tag{8}$$

Definition of the dilepton angles

Projection onto the Collins-Soper basis

The selected lepton momentum and the Collins-Soper axes are boosted to the dilepton rest frame. The normalized lepton direction is then projected onto the Collins-Soper basis:

$$\hat{\ell} = \left(\hat{\ell}\cdot\hat{X}_{CS},\, \hat{\ell}\cdot\hat{Y}_{CS},\, \hat{\ell}\cdot\hat{Z}_{CS}\right) \tag{9}$$

$$= (\sin\theta_{CS}\cos\phi_{CS},\, \sin\theta_{CS}\sin\phi_{CS},\, \cos\theta_{CS})\,. \tag{10}$$

Therefore,

$$\cos\theta_{CS} = \hat{\ell}\cdot\hat{Z}_{CS}, \qquad \phi_{CS} = \mathrm{atan2}\left(\hat{\ell}\cdot\hat{Y}_{CS}, \hat{\ell}\cdot\hat{X}_{CS}\right).$$

PARTÍCULAS ELEMENTALES

Event-by-event analysis

For each LHE event, we reconstruct the dilepton four-momentum Q^μ, calculate Q_T, and determine the Collins–Soper angles θ_{CS} and ϕ_{CS}. Specific angular functions are averaged within each Q_T bin. These averages are then used to extract

$$A_0, \ldots, A_7.$$

The coefficients A_3, A_4, and A_7 are directly related to the components of the spin vector:

$$S_x = \frac{A_3}{4}, \qquad S_y = \frac{A_7}{4}, \qquad S_z = \frac{A_4}{4}.$$

PARTÍCULAS ELEMENTALES

Extraction of the angular coefficients

The angular functions are averaged over all events inside each Q_T bin. The coefficients are then calculated using the method of moments. For example,

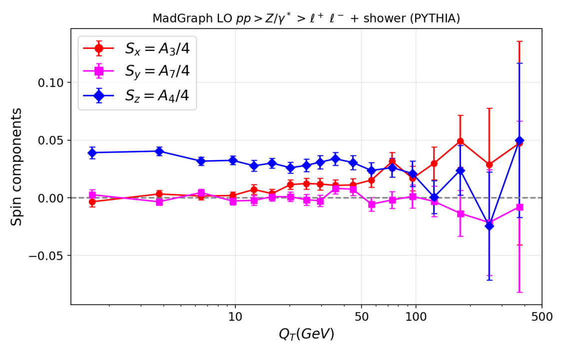
$$A_3 = 4\,\langle \sin\theta \cos\phi \rangle\,,$$
$$A_4 = 4\,\langle \cos\theta \rangle\,,$$
$$A_7 = 4\,\langle \sin\theta \sin\phi \rangle\,.$$

GO TO THE LINK

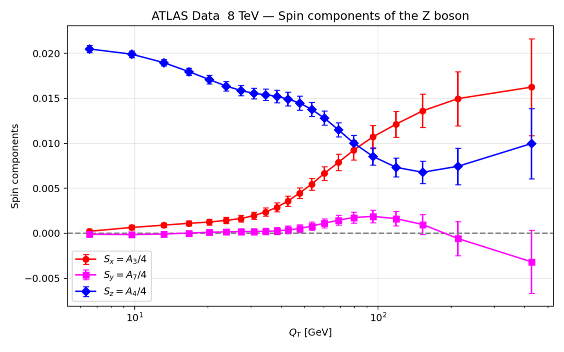
You can see all the code to extract the angular coefficients in https://github.com/jadiarmtz/extract-angular-coeficents-/blob/main/extraercoefCOEFZFOTONMUESIG.py

Results

Simulation

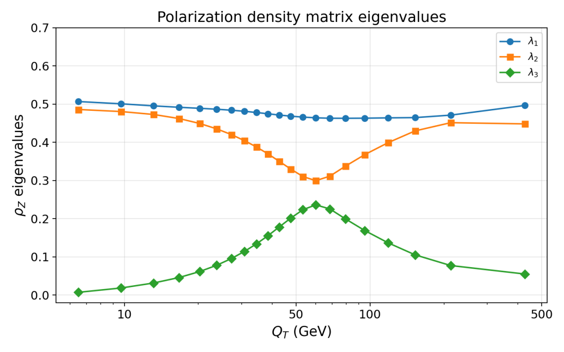


Data from experiment

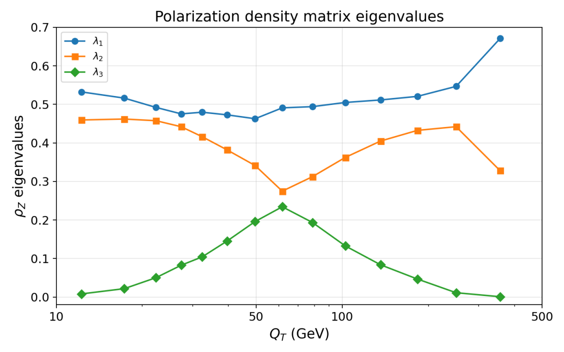


Results

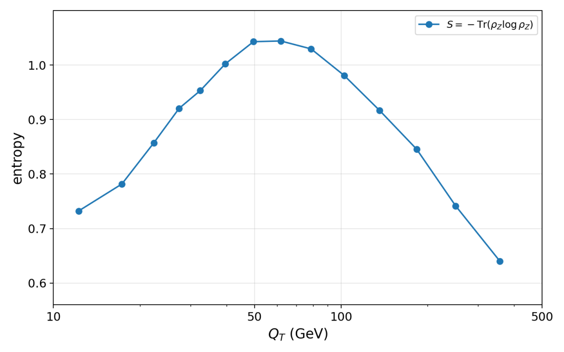
Simulation



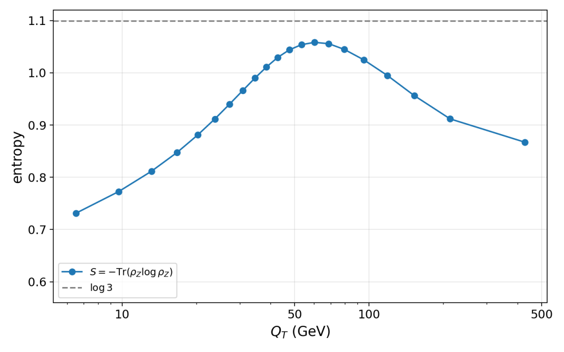
Data from experiment



Simulation



Data from experiment



Conclusions

Main conclusions

- Quantum tomography connects measurable angular distributions with the polarization density matrix.
- The spin components, density-matrix eigenvalues, and von Neumann entropy provide complementary observables for particle-physics studies.
- Monte Carlo simulations can guide the reconstruction of the density matrix before performing a complete detector simulation.

Areas for improvement:

- Include PDF-based quark-direction dilution event by event.
- Extend the analysis to NLO and NLO plus parton-shower predictions.
- Increase the Monte Carlo statistics in the high-Q_T region.

Thank you for your attention!

Questions?

For further questions, please contact my supervisor:

alan.hernandezjua@alumno.buap.mx

Acknowledgments

Special thanks to my advisors, and Dr. Arturo Fernández Téllez, Dr. Daniel Tapia Takaki, for their guidance and support. :)