U.S. DEPARTMENT of ENERGY

Quantum Tomography for Collider Physics:

From Data-Driven Foundations to AI-Enhanced Methods

Daniel Tapia Takaki

work with John Ralston

The University of Kansas

DIS workshop

Bologna– May 6, 2026

Executive Summary

WE BYPASS 75 YEARS OF FIELD THEORETIC SUPERSTRUCTURE TO DESCRIBE SYSTEMS USING QUANTUM MECHANICS WITHOUT NEEDING MODELS

GIVE US DATA WE'LL FIND A DENSITY MATRIX

ENTANGLEMENT DEFINED

"SEPARABLE"

$$\Psi(A,B) \neq \Psi_a(A)\Psi_b(B)$$

'SEPARABLE'

IN GENERAL: $$\rho(A,B) \neq \sum_\alpha p_\alpha \rho_\alpha(A) \rho_\alpha(B)$$

WERNER 1989

57 YEARS AFTER SCHRÖDINGER 1932

$p_\alpha \geq 0$

CONVEX SUM

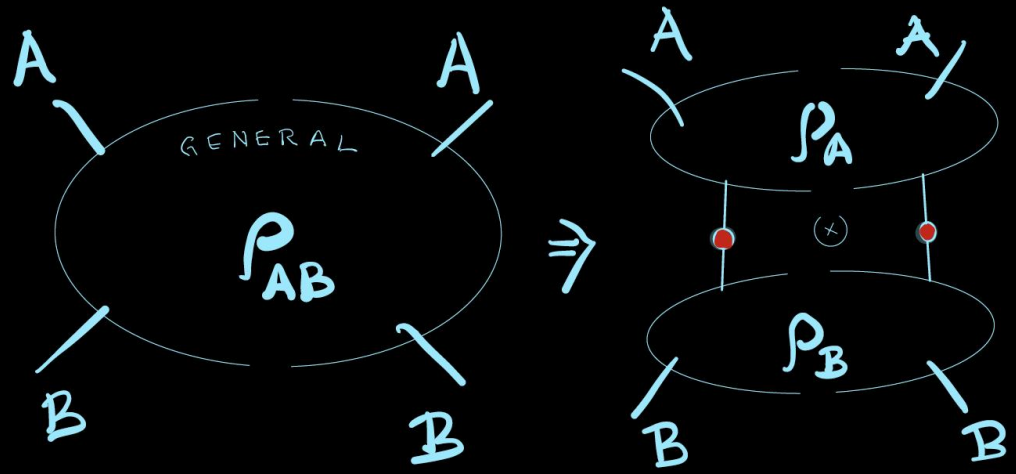
ENTANGLED DOES NOT MEAN "INTERACTING"

NOT ENTANGLED DOES NOT MEAN "NON-INTERACTING"

TO FIND ENTANGLEMENT,
FIRST DEFINE ENTANGLEMENT

$$\rho(A,B) = \sum_{\alpha} \rho_{\alpha}(A) \otimes \rho_{\alpha}(B)$$

SEPARABLE,
NOT ENTANGLED

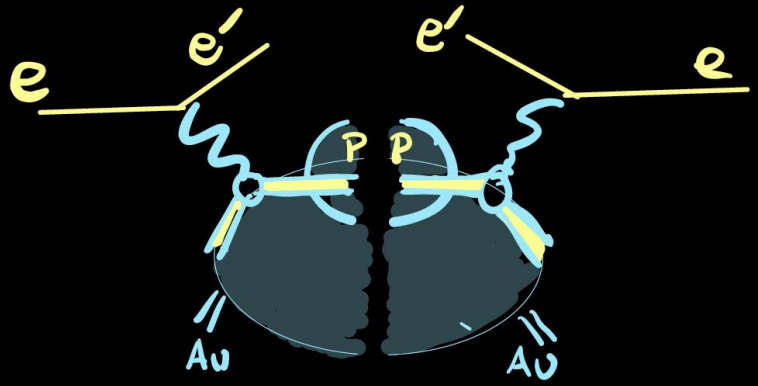


FACTORIZATION

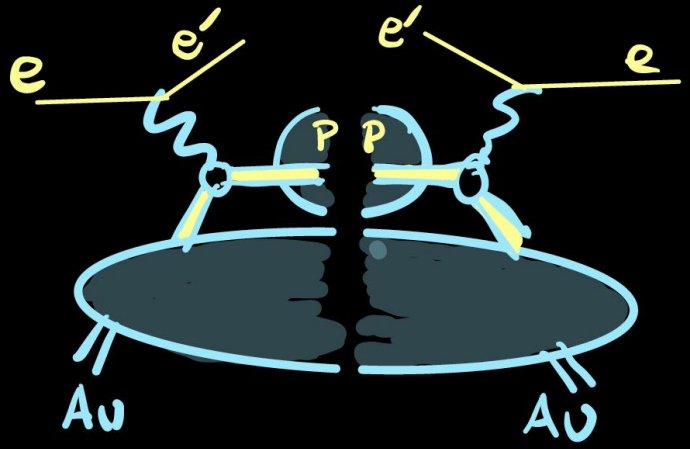
HAS A NON-PERTURATIVE DEFINITION!
THIS IS NEW

AND

PRECLUDES
ENTANGLEMENT

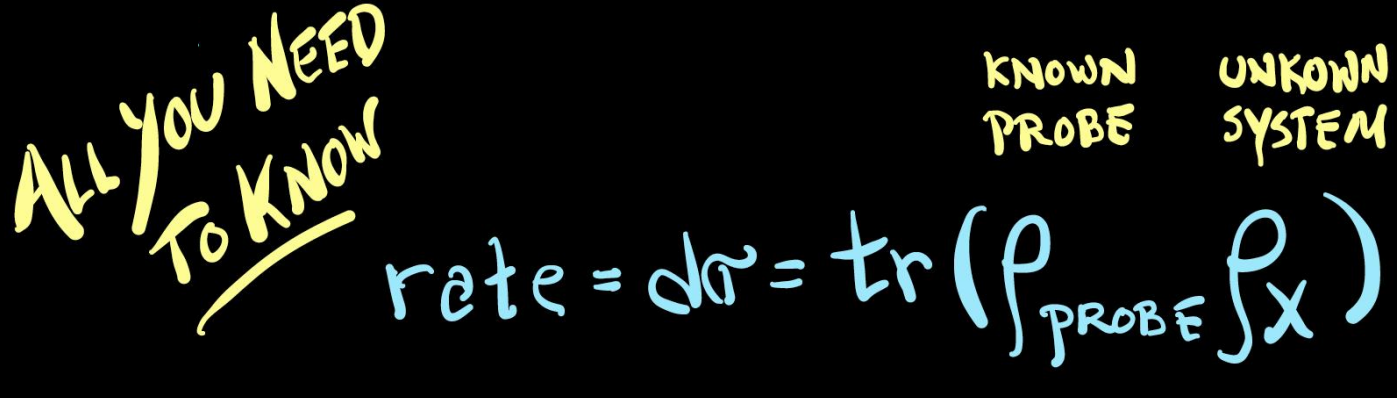


GENERAL



FACTORIZED

MAYBE THAT WAS WRONG


ALL YOU NEED TO KNOW
KNOWN PROBE
UNKOWN SYSTEM
rate = dw = tr(ρ_PROBE ρ_X)

ALL YOU NEED TO KNOW

KNOWN PROBE UNKOWN SYSTEM

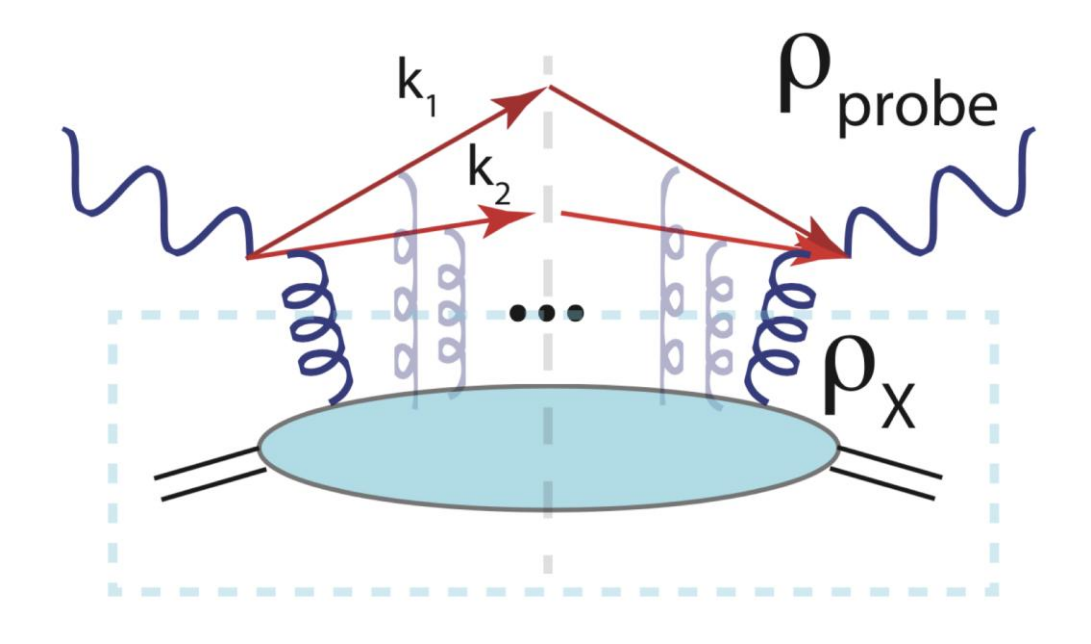
$$\text{rate} = d\sigma = \text{tr}\left(\rho_{\text{PROBE}}\,\rho_X\right)$$

ALSO: THIS IS AN INNER PRODUCT

ALSO: EVERY $\rho_{ij} = (M M^\dagger)_{ij}$

EVERY $d\sigma_{ij} = \sum_X M_{iX} M^*_{jX}$

INCLUSIVE REACTIONS



QUANTUM TOMOGRAPHY IN ONE PAGE

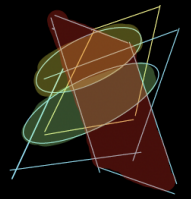
$A = A^\dagger, \rho = \rho^\dagger$

"PROBE-1"

$$\langle A_\ell \rangle = \mathrm{tr}(A_\ell^\dagger \rho) = \langle A_\ell | \rho \rangle$$

"OBSERVABLE"

A PROJECTION, AN INNER PRODUCT OF OPERATORS



$$\mathbb{1} = \sum_\ell |A_\ell\rangle\langle A_\ell|$$

COMPLETENESS; GENERATORS of U(N)

NO MODEL OF THE TARGET

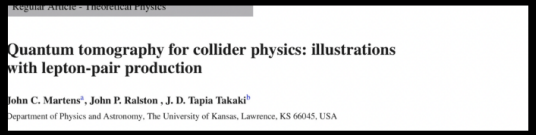
$$\rho = \sum_\ell |A_\ell\rangle\langle A_\ell|\rho\rangle$$

EXPANSION

QUANTUM TOMOGRAPHY →

$$\rho = \sum_\ell |A_\ell\rangle\langle A_\ell|$$

"OBSERVABLE"



Regular Article - Theoretical Physics

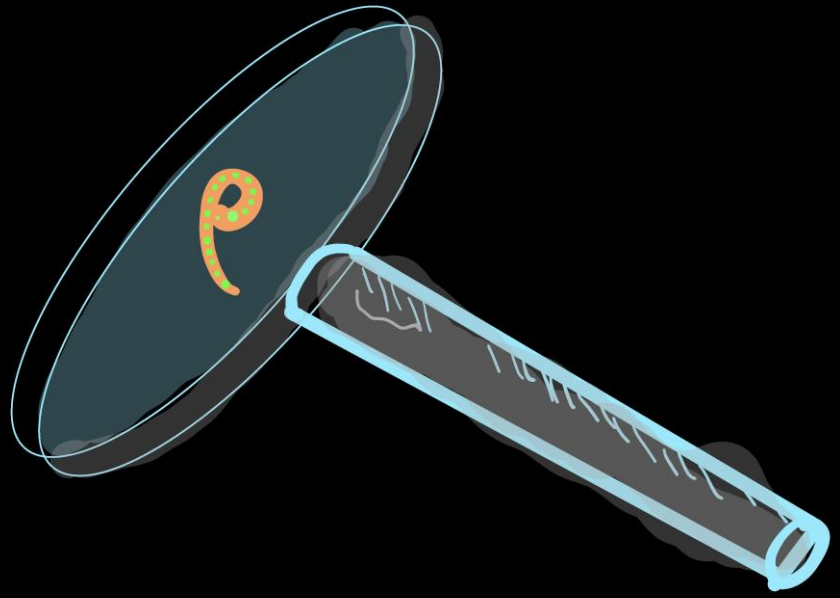
Quantum tomography for collider physics: illustrations with lepton-pair production

John C. Martens[a], John P. Ralston , J. D. Tapia Takaki[b]
Department of Physics and Astronomy, The University of Kansas, Lawrence, KS 66045, USA

Martens, Ralston, Tapia Takaki Eur. Phys. J. C78, 5, 2018

THE DENSITY MATRIX IS OBSERVABLE

IT CLASSIFYS WHAT YOU OBSERVE



THE MIRROR TRICK

YOU DON'T NEED TO MEASURE EVERYTHING

probe $\rho(\ell) = \frac{1}{d}\mathbb{1} + \square + \triangle + \star + \ldots$

system $\rho(X) = \frac{1}{d}\mathbb{1} + \square + \triangle + \star + \ldots$

$\langle \square | \triangle \rangle = 0$ etc

HOW TO EXPLOIT A DENSITY MATRIX

$\neq$ classical entropy $S_{Gibbs} = -\int dx\, f(x) \log f(x)$

INVARIANTS $\rightarrow$ EIGENVALUES λ_k

VON NEUMANN ENTROPY $S = -\mathrm{tr}(\rho \log \rho)$

TRUE QM OBSERVABLES $\langle$ ANYTHING $\rangle$

THE ANGULAR DISTRIBUTION

$$\frac{d\sigma}{d\cos\vartheta\, d\varphi} = \mathrm{tr}\left(\rho_X \rho_L\right)$$

100% LORENTZ INVARIANT

Mirror Quantum Tomography Finds Unexpected Polarization Phenomena in Z Boson Production in pp Collisions at the LHC

A. Gautam (Kansas U.), J.C. Martens (Kansas U.), J.P. Ralston (Kansas U.), G. Stejskal (Kansas U.), J.D. Tapia Takaki (Kansas U.) (May 5, 2026)

e-Print: 2605.03254 [hep-ph]

Begin with Drell-Yan

ATLAS data

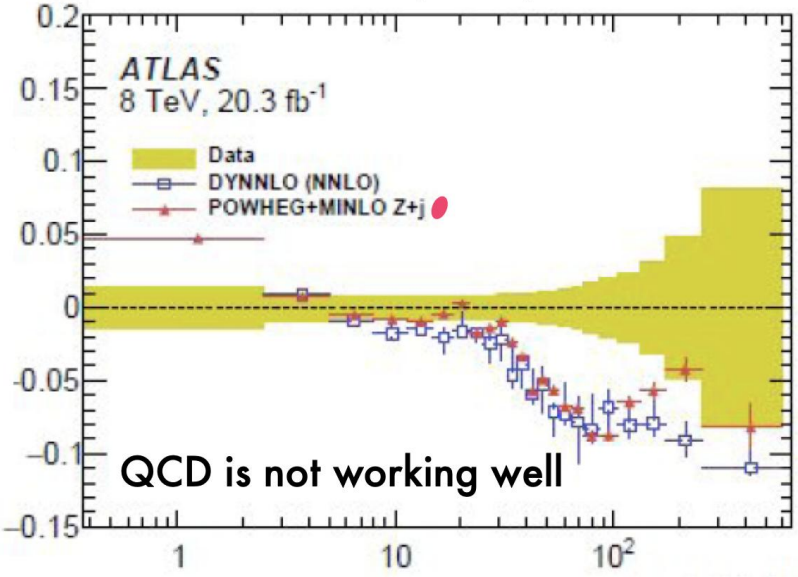
JHEP 08 (2016)159

$$proton + proton \rightarrow Z + anything \rightarrow \mu^+ + \mu^- + anything$$

"lepton pairs"

$(A_0 - A_2)$

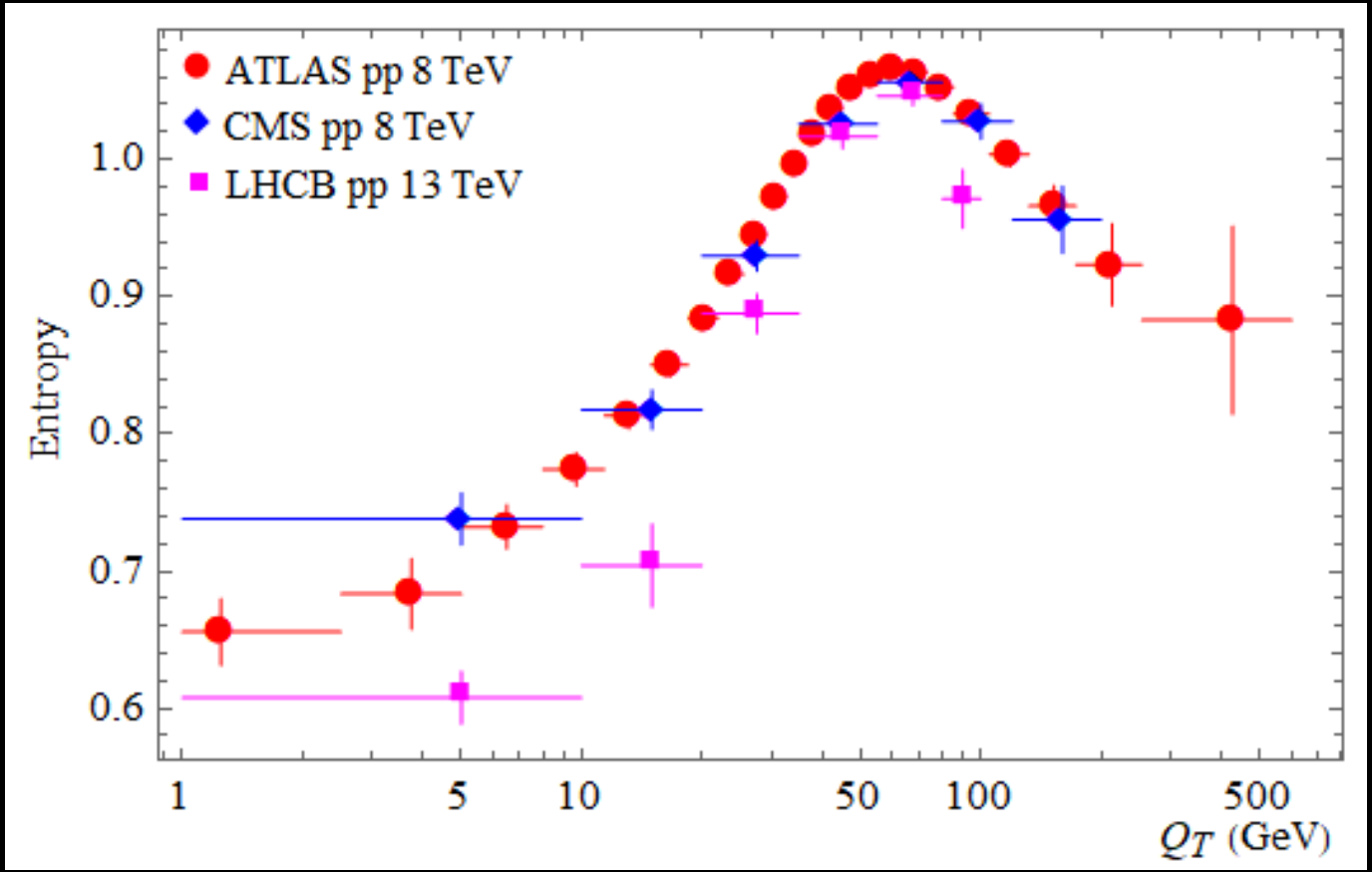
one of many terms in an old traditional expansion of a certain



"Lam-Tung fails"

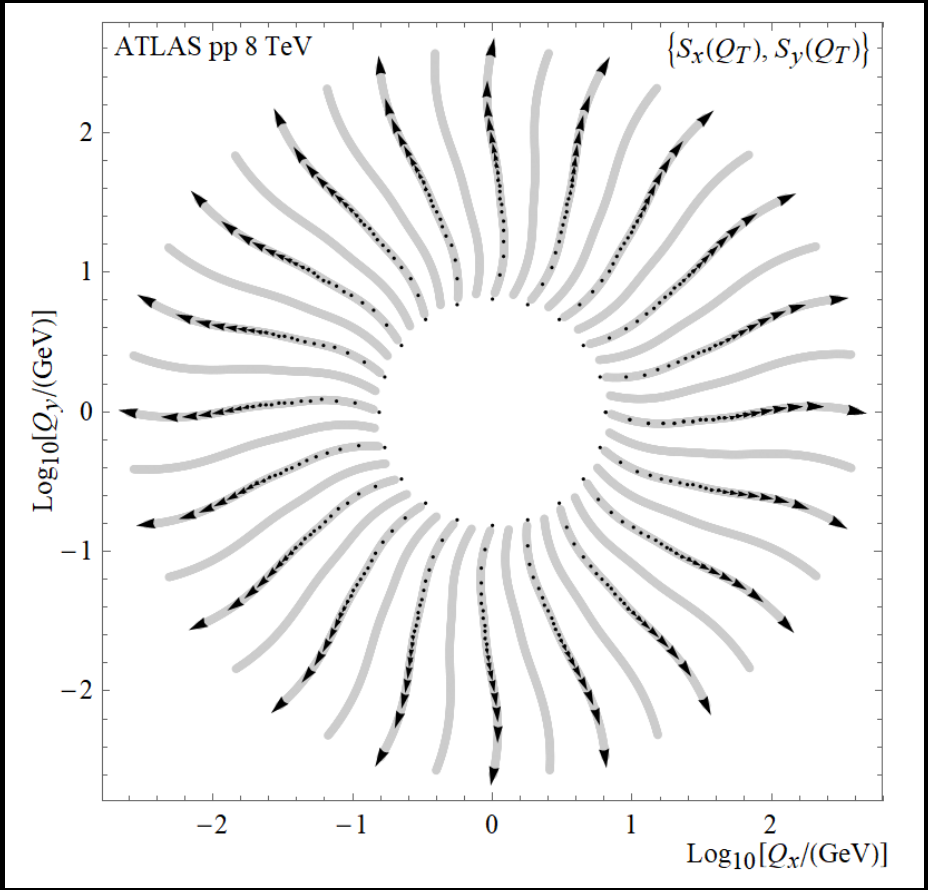
P_T of Z = our q_T $p_T \ [GeV]$

von Neumann Entropy $S = -\mathrm{tr}(\rho \log \rho)$



Beam-axis out of page

xyz = lab



Mirror Quantum Tomography Finds Unexpected Polarization Phenomena in Z Boson Production in pp Collisions at the LHC

arXiv:2605.03254 **[hep-ph]**

WHAT WAS ACCOMPLISHED?

"QUANTUM MECHANICS"
ORGANIZES INFORMATION,
DESCRIPTIVE, NOT PREDICTIVE

- ✓ NO VERTEX
- ✓ NO MODEL
- ✓ NO QFT
- ✓ NO STRUCTURE FUNCTIONS
- ✓ NO PARTONS
- ✓ NO LO, NLO, N^2LO, N^3LO
- ✓ NOTHING BUT OBSERVABLES

CLASSICAL FIT

- ILL CONDITIONED
- MULTIPLE MAXIMA
- ONE DISTRIBUTION

QUANTUM FIT

- ONE MAXIMUM (CONVEX OPTIMIZATION)
- TWO DISTRIBUTIONS (k = RANK - 1)
- QUANTUM ENTROPY

CLASSICAL FIT

- ILL CONDITIONED
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QUANTUM FIT

- ONE MAXIMUM — CONVEX OPTIMIZATION
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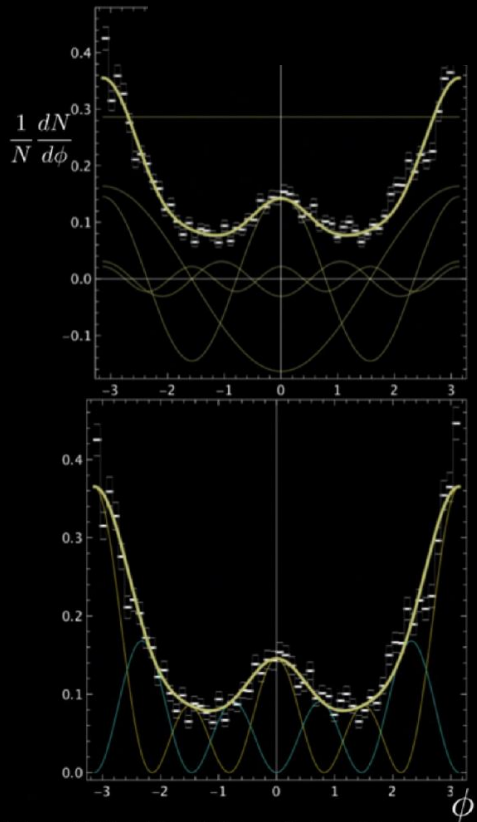
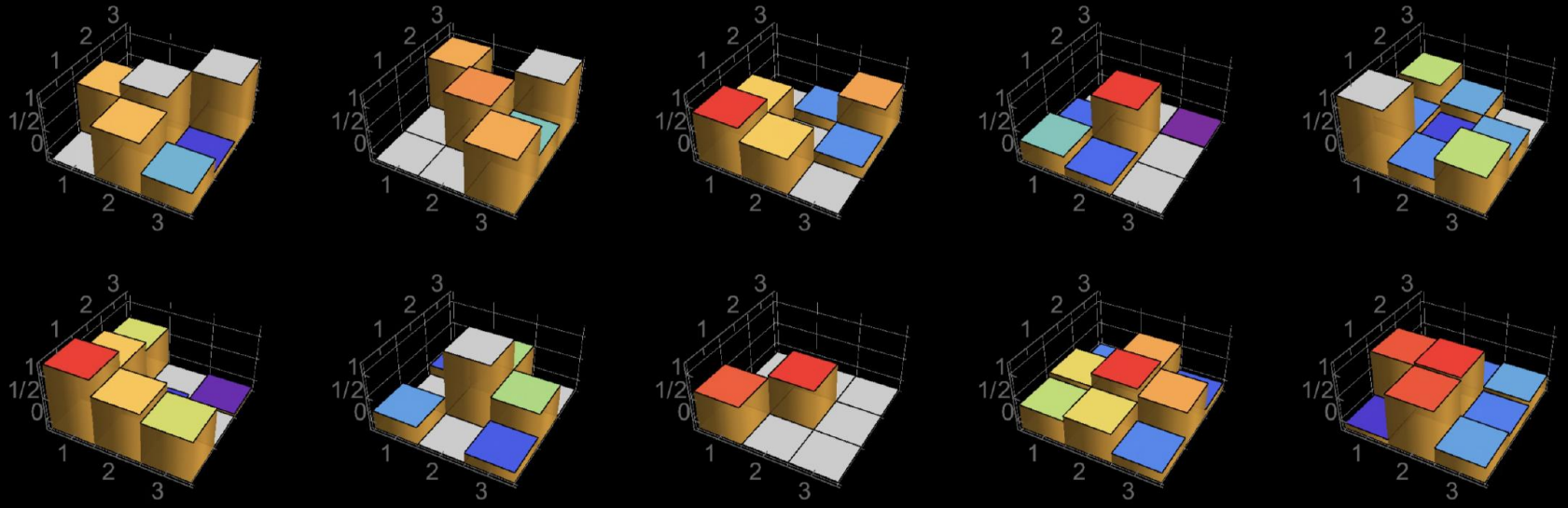


FIG. 4: Top: Maximum likelihood fit, with the contributions of $\cos m\phi$ for $m = 0 - 4$. Bottom: Two weighted distributions defined by $f_+(\phi) = Re(\psi)^2$ (blue) and $f_-(\phi) = Im(\psi)^2$ (red), coming from the eigenstates of the rank two density matrix.

LHC DIFFRACTIVE DIJETS

Event-by-event Quantum tomography

10 EVENTS, 10 DENSITY MATRICES



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WE BYPASS 75 YEARS OF
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TO DESCRIBE SYSTEMS
USING QUANTUM MECHANICS
WITHOUT NEEDING MODELS

GIVE US DATA WE'LL FIND A DENSITY MATRIX

Part 1:

Mirror Quantum Tomography for Collider Physics

Part 2:

AI-enabled Quantum Tomography for Collider Physics

Due to lack of time here, see talk next week:
2026 RHIC/AGS Annual Users' Meeting & RHIC Science Symposium (11-May 15, 2026): Overview · Indico

THANKS!

Mirror Quantum Tomography Finds Unexpected Polarization Phenomena in Z Boson Production in pp Collisions at the LHC

A. Gautam (Kansas U.), J.C. Martens (Kansas U.), J.P. Ralston (Kansas U.), G. Stejskal (Kansas U.), J.D. Tapia Takaki (Kansas U.) (May 5, 2026)

e-Print: 2605.03254 [hep-ph]

What Can We Learn from Entanglement and Quantum Tomography?

John P. Ralston (Nov 12, 2022)

Published in: *MDPI Physics* 4 (2022) 4, 1371-1383

pdf DOI cite claim reference search

Applying Quantum Tomography to Hadronic Interactions

J.C. Martens (Kansas U.), John Ralston (Kansas U.), Daniel Tapia Takaki (Kansas U.) (Jul 14, 2022)

Published in: *SciPost Phys.Proc.* 8 (2022) 154 • Contribution to: DIS2021, 154

pdf DOI cite claim reference search

Quantum Tomography Measures Entanglement in Collider Reactions

John C. Martens (Kansas U.), John P. Ralston (Kansas U.), Daniel Tapia Takaki (Kansas U.) (Oct 14, 2019)

Contribution to: DPF2019 • e-Print: 1910.06311 [hep-ph]

pdf cite claim reference search

Quantum tomography for collider physics: Illustrations with lepton pair productio

John C. Martens (Kansas U.), John P. Ralston (Kansas U.), J. D. Tapia Takaki (Kansas U.) (Jul 6, 2017)

Published in: *Eur.Phys.J.C* 78 (2018) 1, 5 • e-Print: 1707.01638 [hep-ph]

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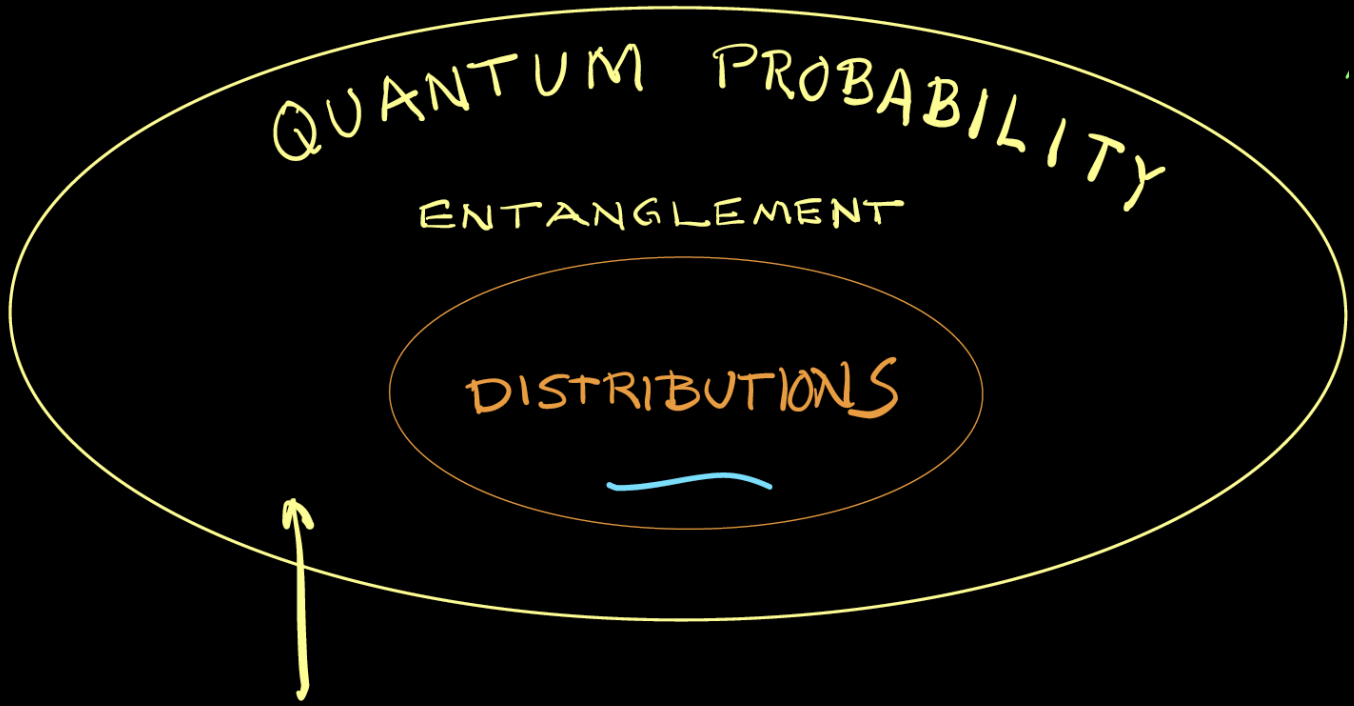
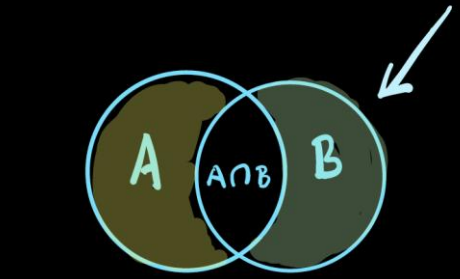
Quantum Information



NON-CLASSICAL INFORMATION

POLARIZATION, AND OTHER PROJECTIVE OBSERVABLES, VIOLATE KOLMOGOROV'S AXIOMATIC OPINIONS

$$P(A \cup B) = P(A) + P(B) - P(A \cap B)$$



DON'T DEFINE "PROBABILITY" BY COUNTING FREQUENCIES!

SCHOOLBOOKS SAY

$$\langle A \rangle = \langle \psi | A | \psi \rangle$$

"PURE STATE"

EXCEPTIONAL

NOT TRUE IN GENERAL

von Neumann

$$= \mathrm{tr}\left(A |\psi\rangle\langle\psi| \right)$$

BETTER BOOKS SAY

$$\langle A \rangle_{\text{GENERAL}} = \sum_\alpha p_\alpha \, \mathrm{tr}\left(A |\psi_\alpha\rangle\langle\psi_\alpha|\right) \qquad p_\alpha \geq 0$$

$$= \mathrm{tr}(A\rho);$$

$$\rho = \sum_\alpha |\psi_\alpha\rangle p_\alpha \langle\psi_\alpha|$$

THE DENSITY MATRIX

PARAMETERIZING POSITIVITY

$$\rho = MM^{\dagger}$$

POSITIVE EIGENVALUES GUARANTEED

$$M = \begin{pmatrix} m_1 & m_4 + i m_5 & m_6 + i m_7 \\ 0 & m_2 & m_8 + i m_9 \\ 0 & 0 & m_3 \end{pmatrix}$$

REAL NUMBERS

$$d\omega = \mathrm{tr}\left(MM^{\dagger}\hat{A}\right)$$

EXPERIMENTAL PROBE

$$\rho_{ij}(\ell) = \frac{1+a}{3}\delta_{ij} - a\hat{\ell}_i\hat{\ell}_j - \imath b\epsilon_{ijk}\hat{\ell}_k$$

from symmetry

Standard Model + shelf of books

predicts nothing more than two numbers

$$a = 1/2; \quad b = \sin^2\theta_W$$

One could get a, b tomographically

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi}(1+m_3^2)$$

$$+ \frac{1}{4\pi}(1-3m_3^2\cos^2\vartheta)$$

$$- \frac{1}{2} m_3 m_6 \sin 2\vartheta \cos\varphi$$

$$- \frac{1}{2} m_3 m_8 \sin 2\vartheta \sin\varphi$$

$$+ \ldots \quad \ldots$$

2 JETS
2 OF ANYTHING ...

FIT m_ℓ WITH LIKELIHOOD
$-1 < m_\ell < 1$

NO LOCAL MAXIMA

CONVEX FUNCTIONS

POSITIVITY IS EXACT

HOW TO EXPLOIT A DENSITY MATRIX

YOU SQUEEZE IT LIKE AN ORANGE

INVARIANTS → EIGENVALUES (λ_k)

≠ classical entropy $S_{Gibbs} = -\int dx\, f(x) \log f(x)$

VON NEUMANN ENTROPY $S = -tr(\rho \log \rho)$

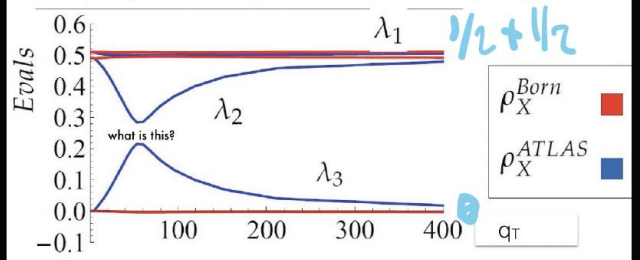
TRUE QM OBSERVABLES ⟨ANYTHING⟩

$\gamma^* \simeq 3 \times 3$

The density matrix eigenvalues are strange

y-integrated data. arXiv: 1606.00689

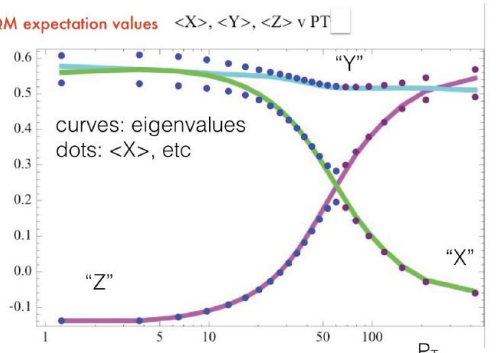
Evals λ_j of ρ_X^{ATLAS} (blue) are very different from evals from Born-level physics (red).



there is no precedent for the resonance-like bump

Avoided level crossing; eigenvectors swap

true QM expectation values <X>, <Y>, <Z> v PT



new: no precedent

P_T of Z = our q_T

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$$\Psi(A,B) \neq \Psi_a(A)\Psi_b(B)$$ "SEPARABLE"

Not Entangled Is Exceptional

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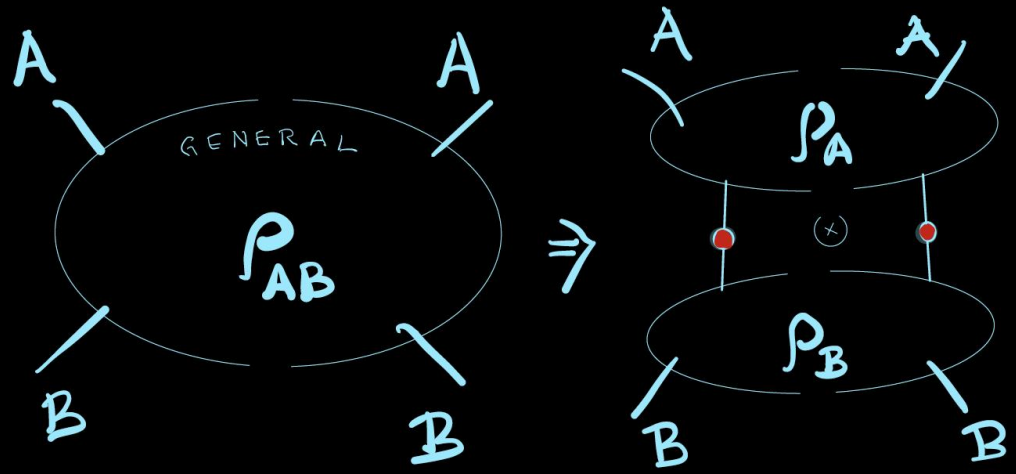

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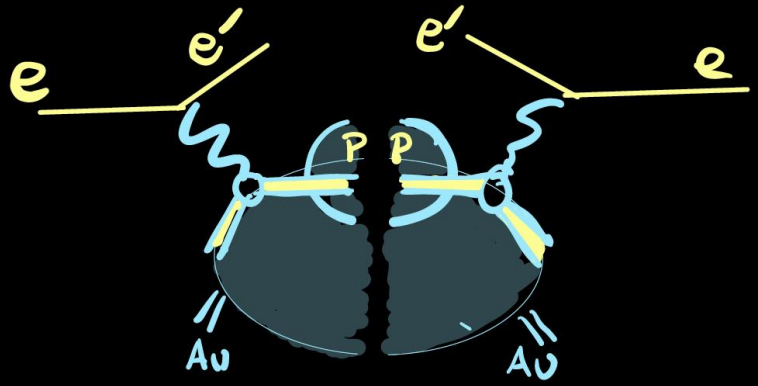
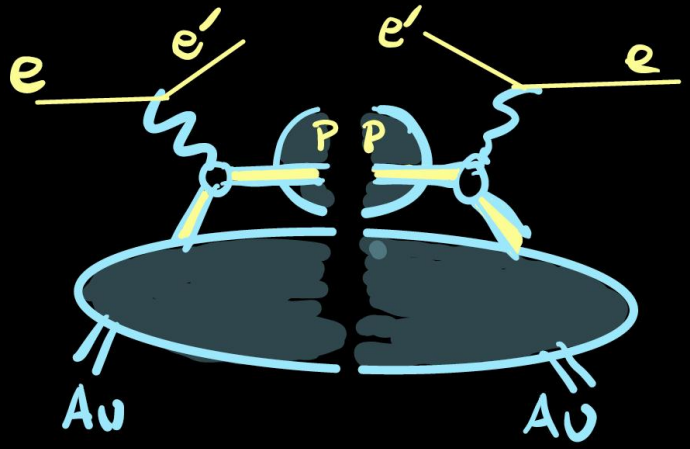


GENERAL



FACTORIZED

MAYBE THAT WAS WRONG

probe operators G_ℓ

$$tr(G_\ell G_k) = \delta_{\ell k} \quad \text{orthonormal matrices}$$

observable:

$$< G_\ell >= tr(G_\ell \rho_X)$$

$$\rho_X = \text{unknown system}$$

reconstruction:

$$\rho_X = \sum_\ell < G_\ell > G_\ell$$

Completeness? *It's complete for what it spans*

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega} = \frac{1}{4\pi} + \frac{3}{4\pi} S_x \sin\theta\cos\phi \qquad c = 3/(8\sqrt{2}\pi)$$
$$+ \frac{3}{4\pi} S_y \sin\theta\sin\phi + \frac{3}{4\pi} S_z \cos\theta$$
$$+ c\rho_0 \left(\frac{1}{\sqrt{3}} - \sqrt{3}\cos^2\theta \right) - c\rho_1 \sin(2\theta)\cos\phi$$
$$+ c\rho_2 \sin^2\theta \cos(2\phi)$$
$$+ c\rho_3 \sin^2\theta \sin(2\phi) - c\rho_4 \sin(2\theta)\sin\phi.$$