U.S. DEPARTMENT of ENERGY

Mirror Quantum Tomography :

For UPC and beyond

Daniel Tapia Takaki

work with John Ralston

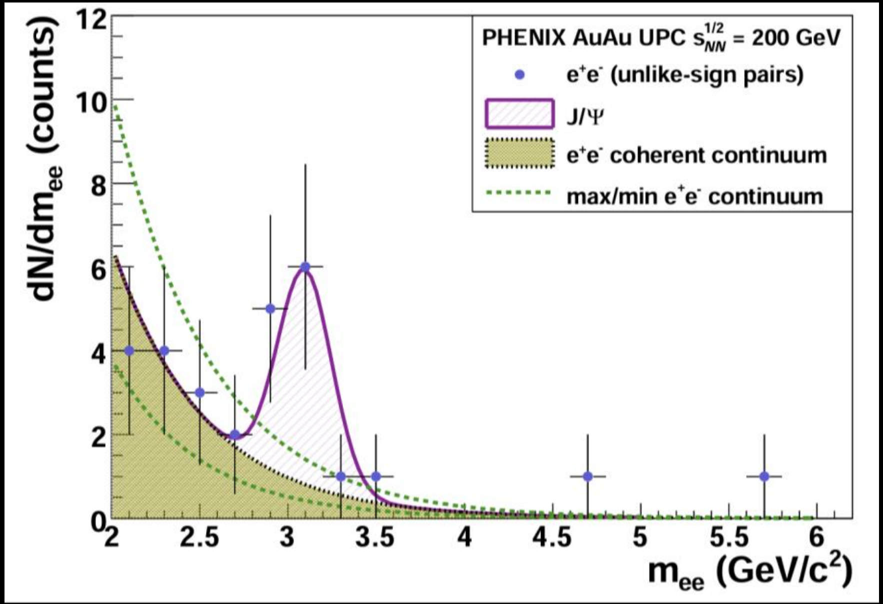
The University of Kansas

AGS&RHIC users meeting

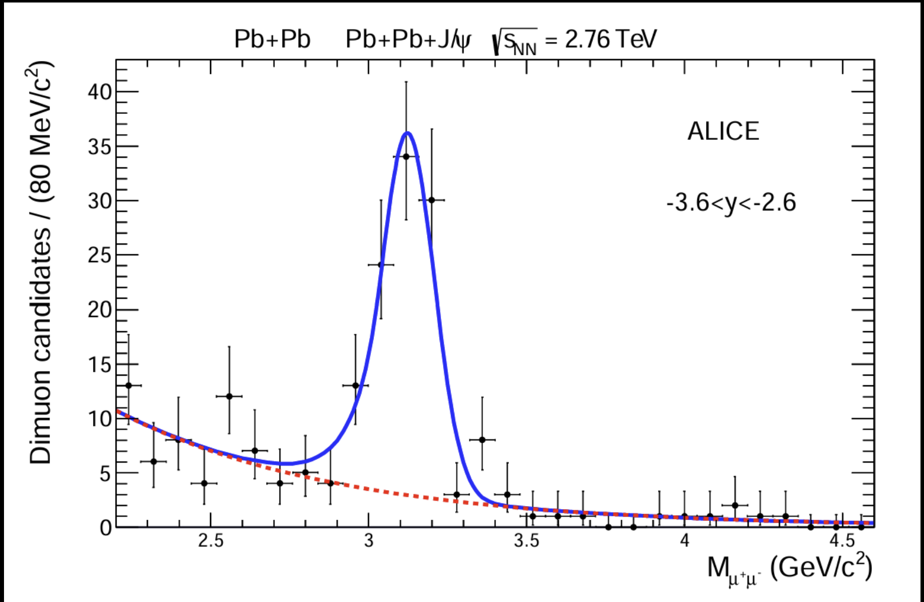
May 12, 2026

Quick recap

Phys. Lett. B 679 (2009) 321-329



Phys. Lett. B 718 (2013) 1273-1283

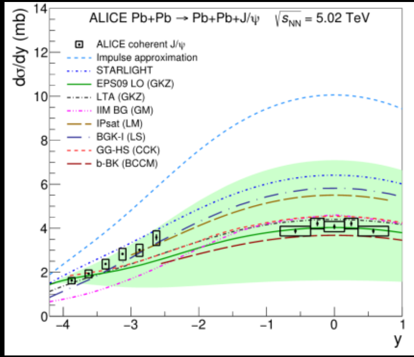


Only a handful of J/ψ candidates from early studies at RHIC and LHC (Run 1)

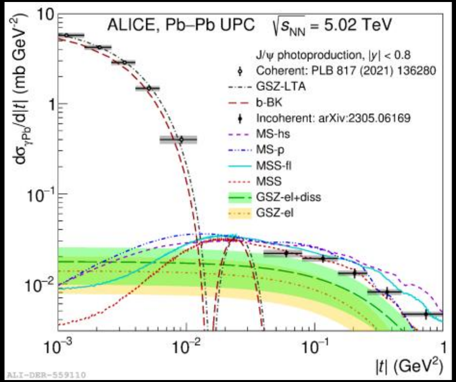
Today, UPC physics is moving to a multi-differential program

See nice talk by Gian Michele Innocenti for an overview

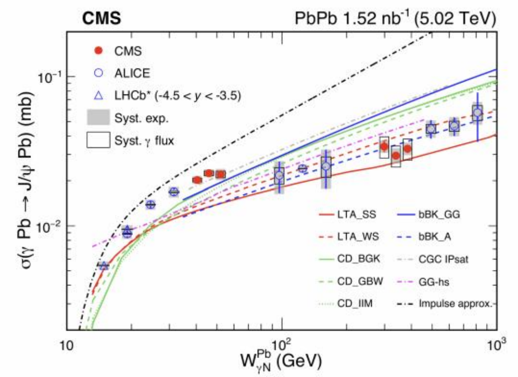
Rapidity dependence



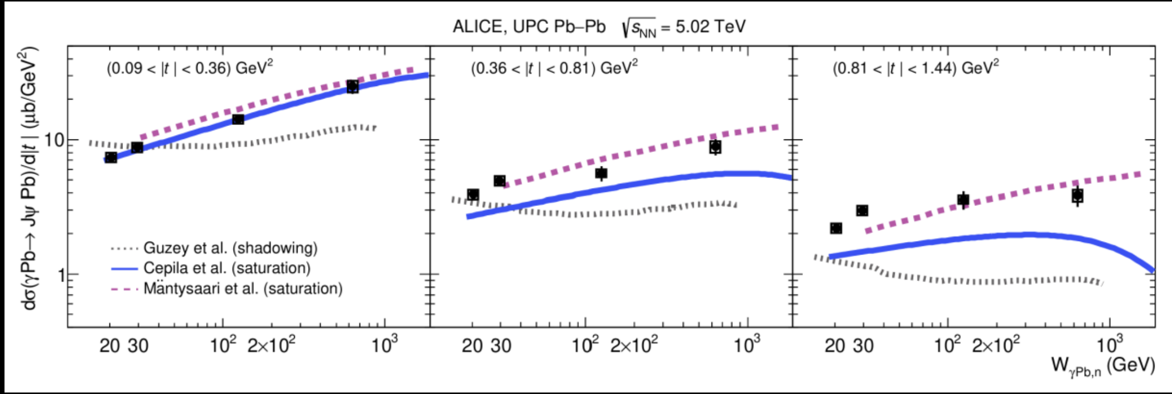
t-dependence



Rapidity + neutrons dependence



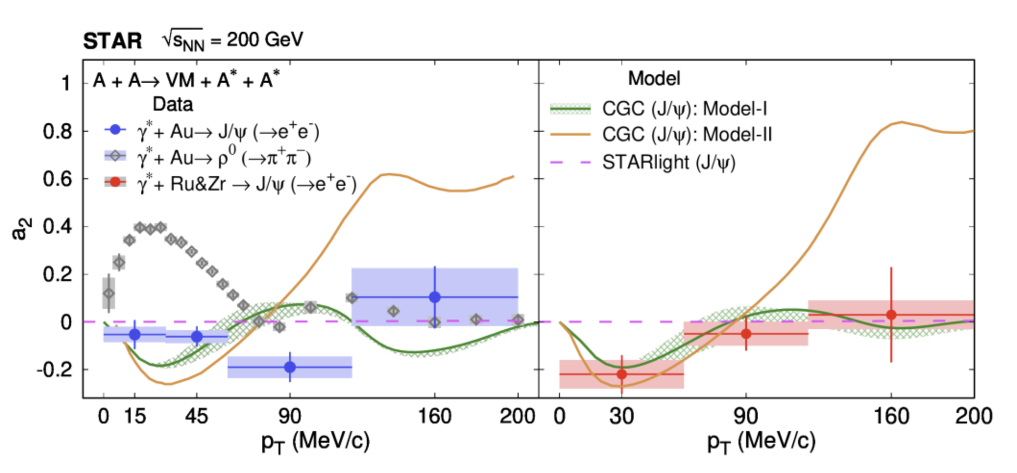
Rapidity, t and neutron dependence!

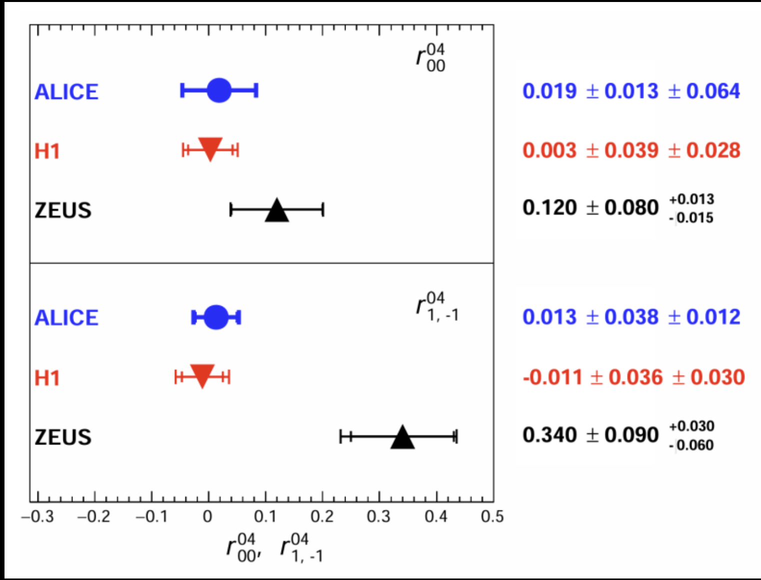


EPJC 81 (2021) 712
PLB 817 (2021) 136280
PRL 132 (2024) 16, 162302
PLB 798 (2019) 134926
EPJC 81 (2021) 712
PRL 131 (2023) 262301
JHEP 10 (2023) 119
JHEP 06 (2023) 146

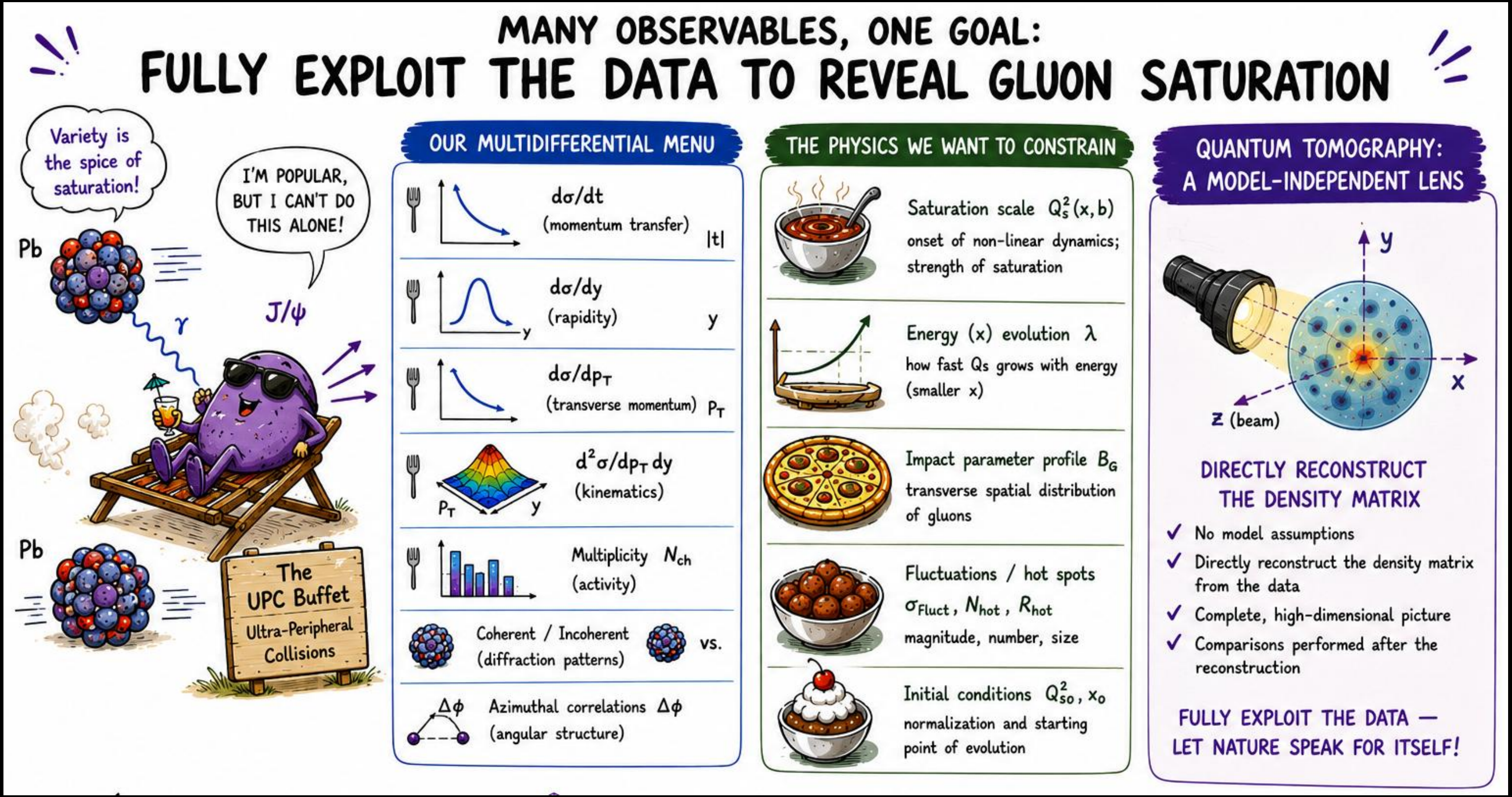
Polarization sensitive measurements

$$\frac{dN}{d\phi} \propto 1 + a_2 \cos(2\phi)$$





Phys. Lett. B 865 (2025) 139466
arXiv:2512.02865 [nucl-ex]


MANY OBSERVABLES, ONE GOAL:
FULLY EXPLOIT THE DATA TO REVEAL GLUON SATURATION
Variety is the spice of saturation!
I'M POPULAR, BUT I CAN'T DO THIS ALONE!
Pb
γ
J/ψ
Pb
The UPC Buffet
Ultra-Peripheral Collisions
OUR MULTIDIFFERENTIAL MENU
dσ/dt
(momentum transfer)
|t|
dσ/dy
(rapidity)
y
dσ/dp$_T$
(transverse momentum)
p$_T$
d^{2}σ/dp$_T$ dy
(kinematics)
P$_T$
y
Multiplicity N$_{ch}$
(activity)
Coherent / Incoherent
(diffraction patterns)
vs.
Δφ
Azimuthal correlations Δφ
(angular structure)
THE PHYSICS WE WANT TO CONSTRAIN
Saturation scale $Q_s^2(x, b)$
onset of non-linear dynamics; strength of saturation
Energy (x) evolution λ
how fast Qs grows with energy (smaller x)
Impact parameter profile B_G
transverse spatial distribution of gluons
Fluctuations / hot spots
σ_{Fluct}, N_{hot}, R_{hot}
magnitude, number, size
Initial conditions Q^2_{s0}, x_0
normalization and starting point of evolution
QUANTUM TOMOGRAPHY: A MODEL-INDEPENDENT LENS
y
x
z (beam)
DIRECTLY RECONSTRUCT THE DENSITY MATRIX
✓ No model assumptions
✓ Directly reconstruct the density matrix from the data
✓ Complete, high-dimensional picture
✓ Comparisons performed after the reconstruction
FULLY EXPLOIT THE DATA — LET NATURE SPEAK FOR ITSELF!

Mirror Quantum Tomography

A genuinely model independent data analysis technique

THE RENAISSANCE OF QUANTUM MECHANICS AND HAND-MADE SLIDES

Entanglement is HOT!

literature | find ti entanglement and d 2025

Literature | Authors | Jobs | Seminars | Conferences | Data BETA

ation Summary

Exclude self-citations

	Citeable	Published
Papers	2,103	1,309
Citations	5,525	4,508

iNSPIRE HEP

literature | FIND TI ENTANGLEMENT AND D 2020

Literature | Authors | Jobs | Seminars | Conferences | More...

Citation Summary

Exclude self-citations

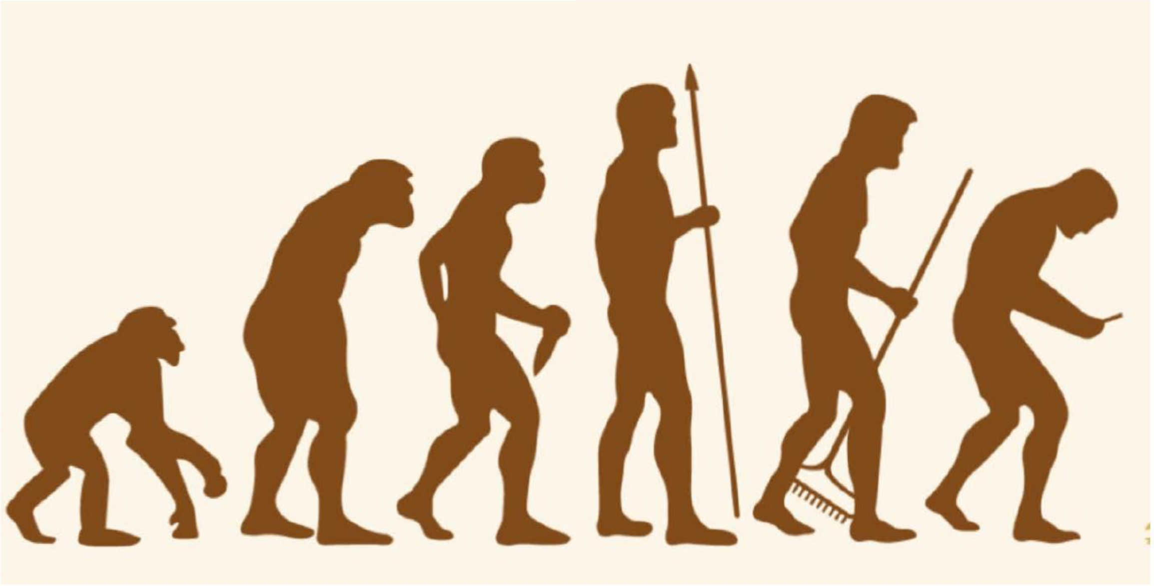
	Citeable	Published
Papers	538	452
Citations	8,157	7,597

THEORY HAS EVOLVED

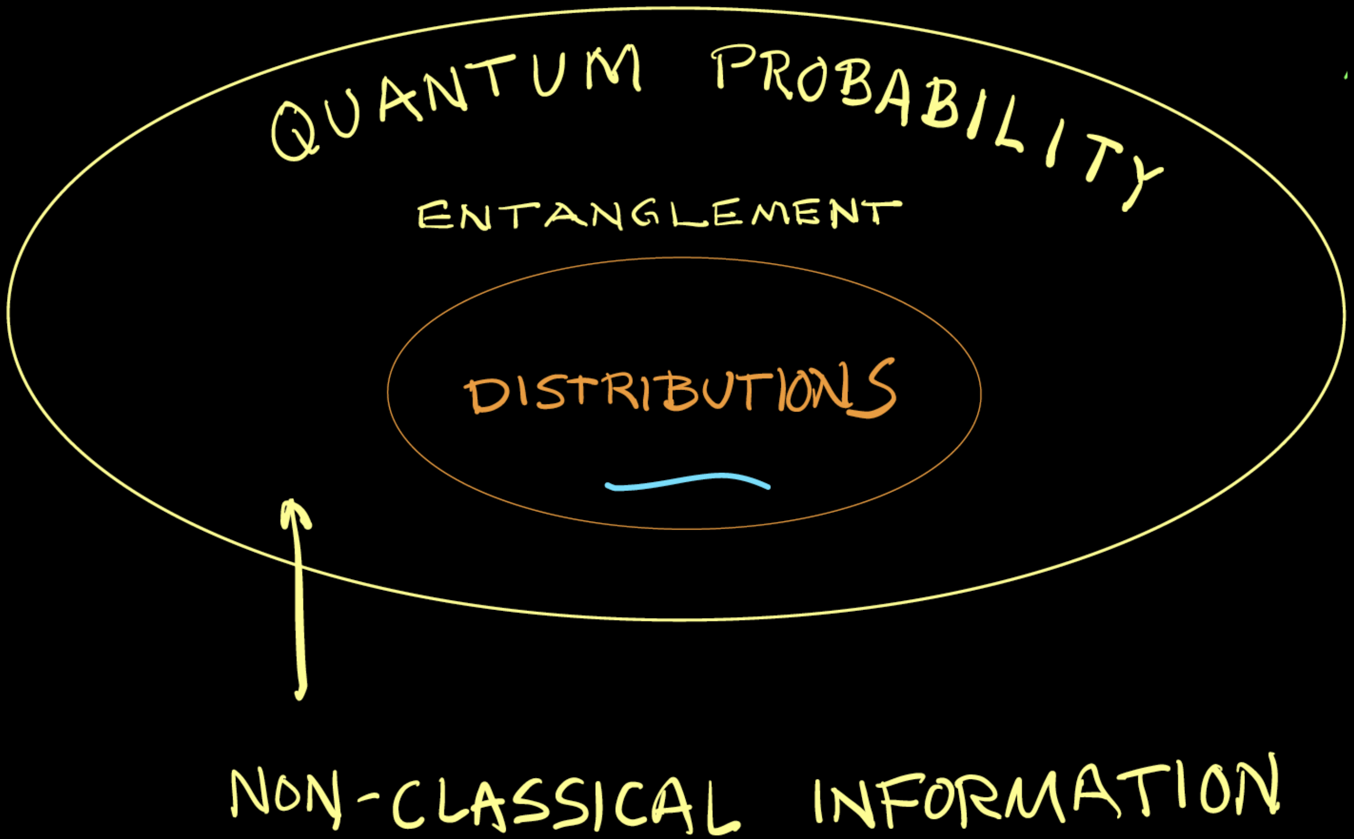
COPENHAGEN WENT PAST ITS PULL-DATE

WE NOW HAVE INTERNET COOKIES

INSTALLED IN YOUR BRAIN'S OPERATING SYSTEM



Quantum Information



ENTANGLEMENT DEFINED

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

Not Entangled Is Exceptional

WHY GET EXCITED?

ENTANGLED DOES NOT MEAN "INTERACTING"

NOT ENTANGLED DOES NOT MEAN "NON-INTERACTING"

ENTANGLEMENT DEFINED

"SEPARABLE"

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

'SEPARABLE'

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

$p_\alpha \geq 0$

CONVEX SUM

WERNER 1989

57 YEARS AFTER SCHRÖDINGER 1932

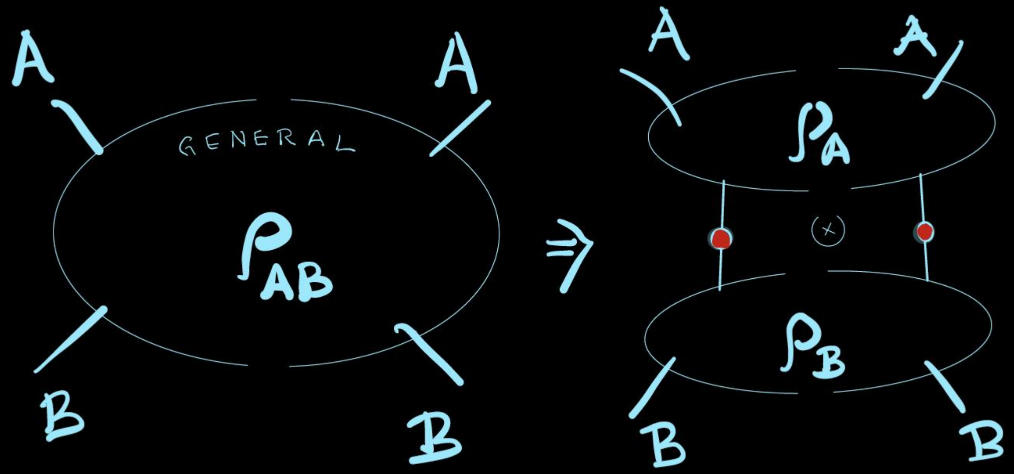
ENTANGLED DOES NOT MEAN "INTERACTING"

NOT ENTANGLED DOES NOT MEAN "NON-INTERACTING"

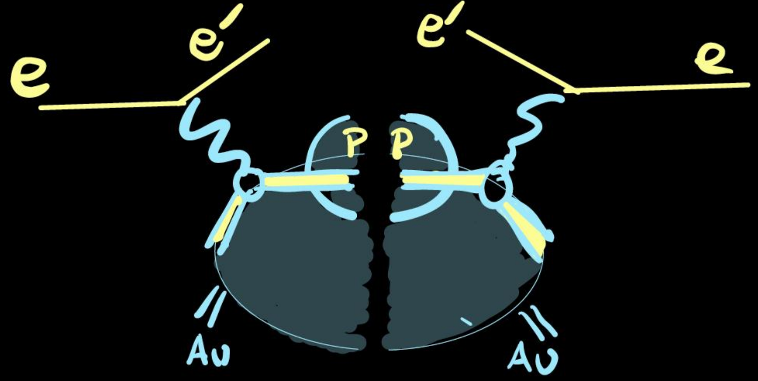
TO FIND ENTANGLEMENT,
FIRST DEFINE ENTANGLEMENT

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

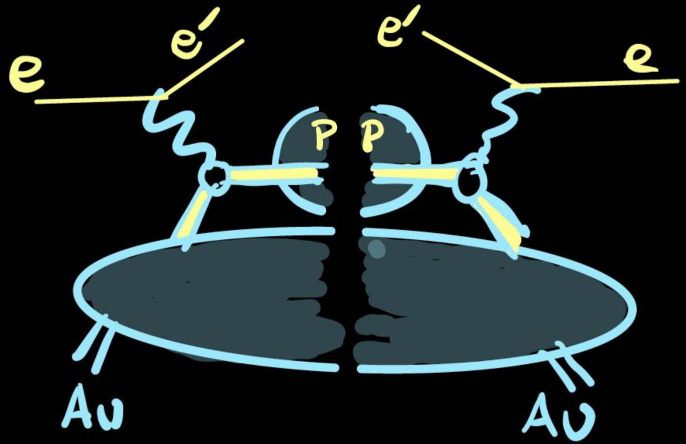
SEPARABLE,
NOT ENTANGLED



FACTORIZATION
HAS A NON-PERTURBATIVE DEFINITION!
THIS IS NEW
AND
PRECLUDES
ENTANGLEMENT



GENERAL



FACTORIZED

MAYBE THAT WAS WRONG

ALL YOU NEED TO KNOW

KNOWN PROBE

UNKOWN SYSTEM

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

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

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

$$= \mathrm{tr}(A\rho); \qquad \rho = \sum_\alpha |\psi_\alpha\rangle p_\alpha \langle\psi_\alpha|$$

THE DENSITY MATRIX

ALL YOU NEED TO KNOW

KNOWN PROBE   UNKOWN SYSTEM

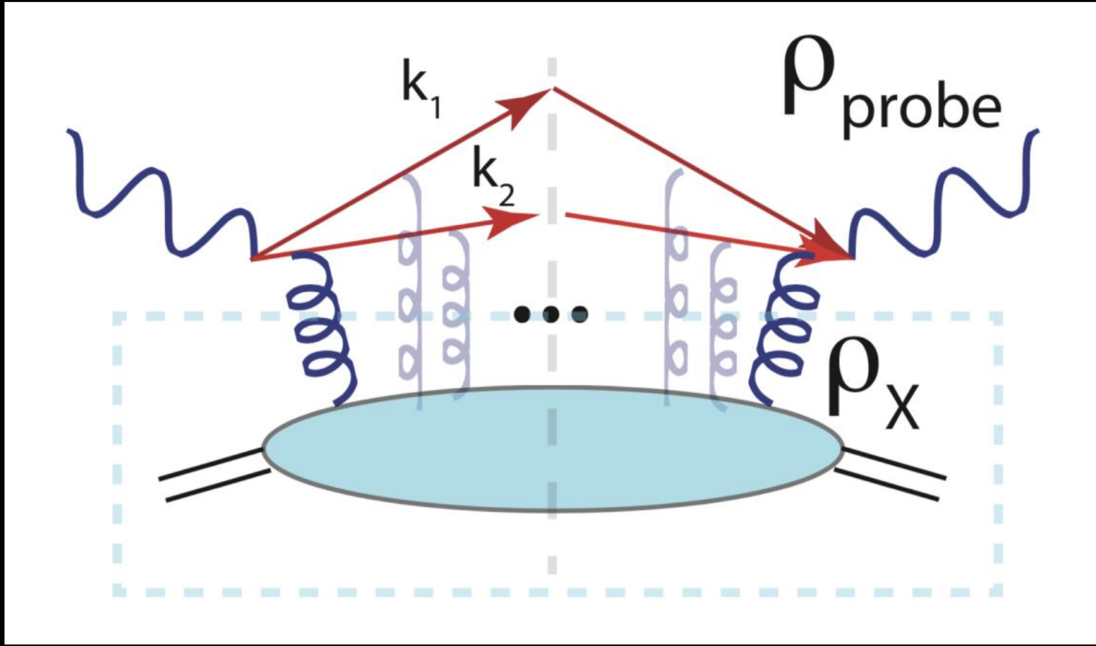
$$\text{rate} = d\sigma = \mathrm{tr}\left(\rho_{PROBE}\,\rho_X\right)$$

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



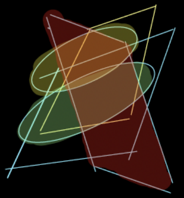
QUANTUM TOMOGRAPHY IN ONE PAGE

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

"PROBE-ℓ"

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

A PROJECTION, AN INNER PRODUCT OF OPERATORS



"OBSERVABLE"

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

COMPLETENESS; GENERATORS of U(N)

NO MODEL OF THE TARGET

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

EXPANSION

QUANTUM TOMOGRAPHY

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

"OBSERVABLE"

Regular Article - Theoretical Physics

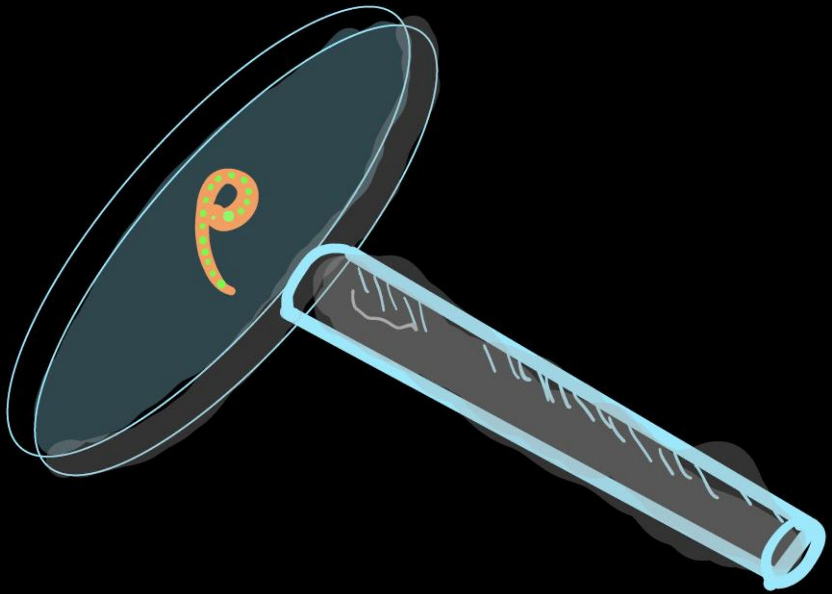
Quantum tomography for collider physics: illustrations with lepton-pair production

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

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

PARAMETERIZING POSITIVITY

REAL NUMBERS

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

POSITIVE EIGENVALUES GUARANTEED

$$d\sigma = \mathrm{tr}(MM^\dagger \hat{A})$$

EXPERIMENTAL PROBE

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

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

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

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

$$+ \ldots$$

... 2 JETS

2 OF ANYTHING ...

FIT m_ℓ WITH LIKELIHOOD

$-1 < m_\ell < 1$

NO LOCAL MAXIMA

CONVEX FUNCTIONS

POSITIVITY is EXACT

THE ANGULAR DISTRIBUTION

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

100% LORENTZ INVARIANT.

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

$$c = 3/(8\sqrt{2}\pi)$$

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 $\rangle$

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

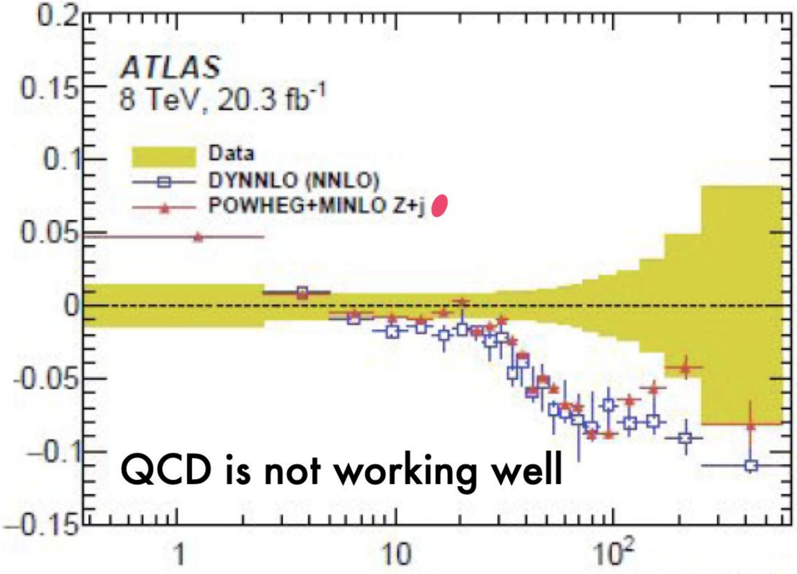
JHEP 08 (2016)159

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

"lepton pairs"

$(A_0 - A_2)$

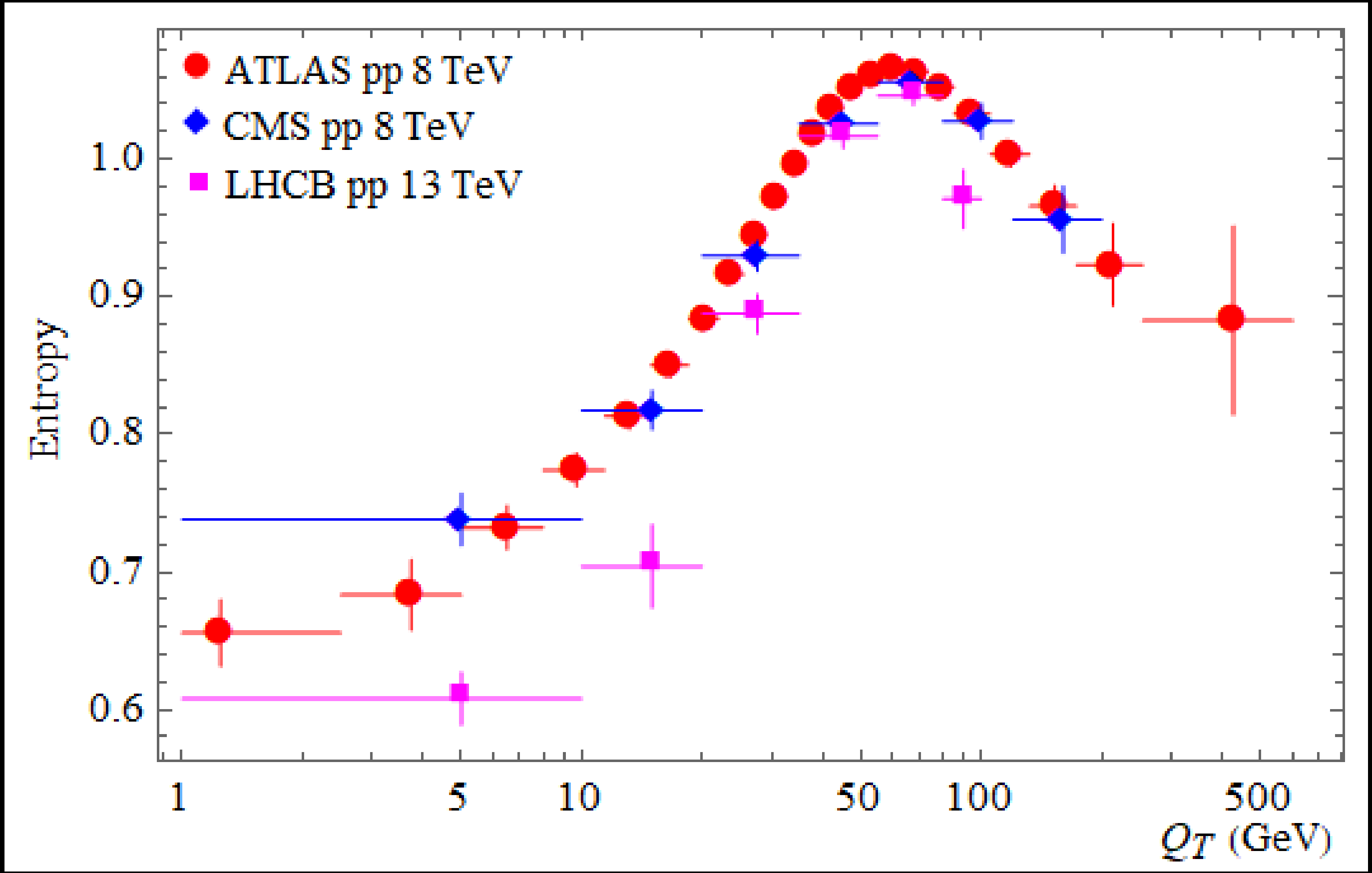
one of many terms in an old traditional expansion of a certain



"Lam-Tung fails"

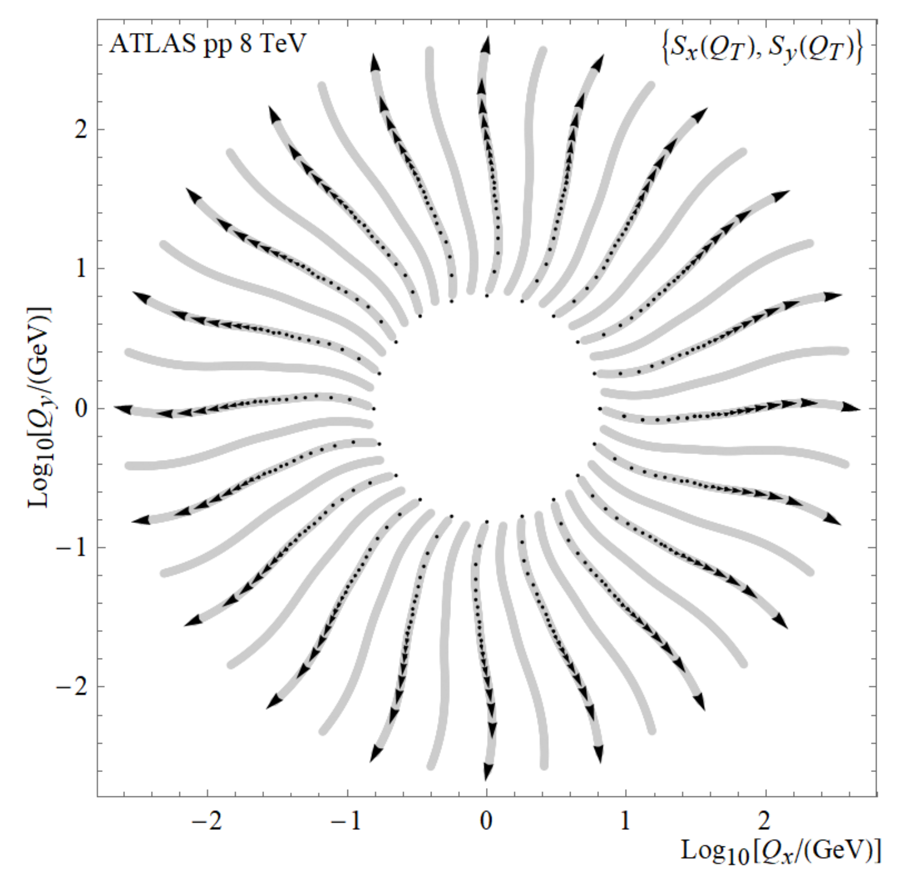
P_T of Z = our q_T p_T [GeV]

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 # = RANK - 1
- QUANTUM ENTROPY

CLASSICAL FIT

- ILL CONDITIONED
- MULTIPLE MAXIMA
- ONE DISTRIBUTION

QUANTUM FIT

- ONE MAXIMUM CONVEX OPTIMIZATION
- TWO DISTRIBUTIONS # = RANK - 1
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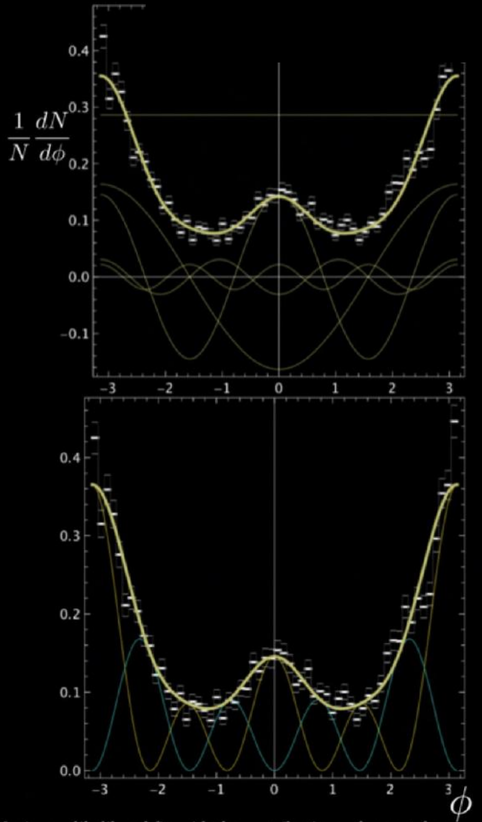
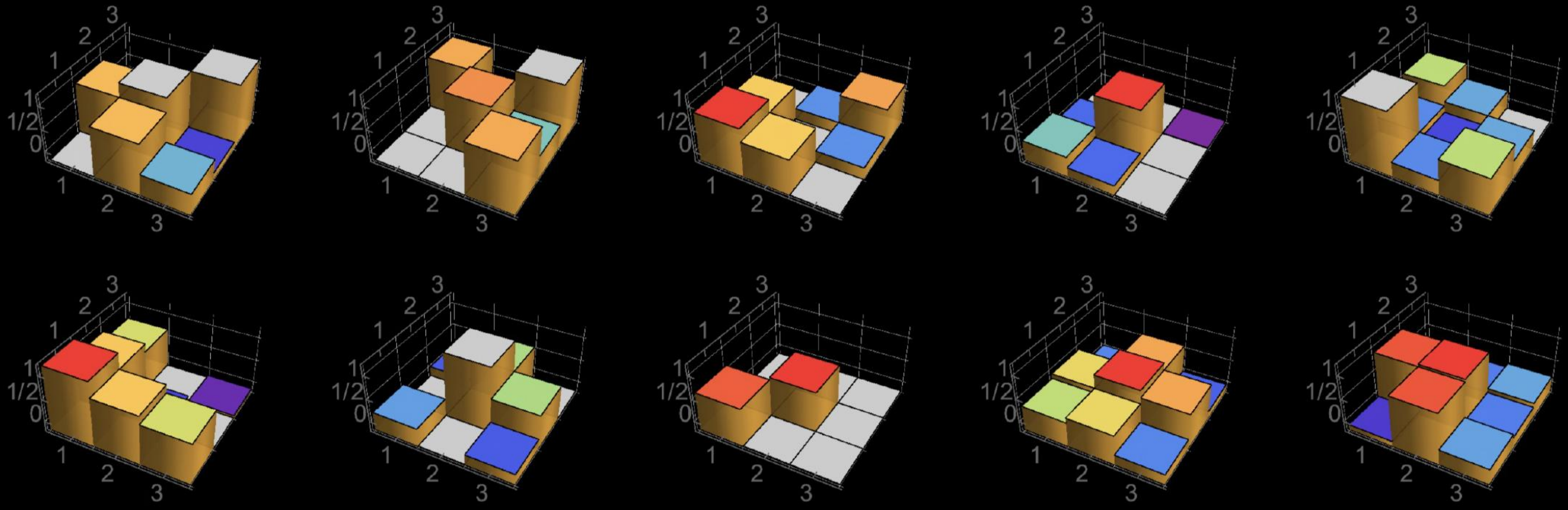


FIG. 4: Top: Maximum likelihood fit, with the contributions of $\cos m\phi$ for $m = 0-4$. Bottom: Two weighted distributions defined by $f_+(\phi) = Re(\psi)^2$ (blue) and $f_-(\phi) = Im(\psi)^2$ (red), coming from the eigenstates of the rank two density matrix.

LHC DIFFRACTIVE DIJETS

10 EVENTS, 10 DENSITY MATRICES



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

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

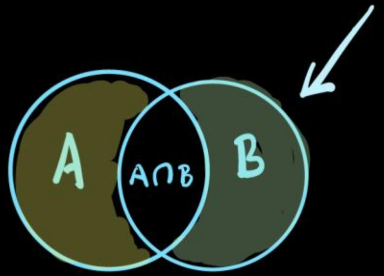
John C. Martens (Kansas U.), John P. Ralston (Kansas U.), J. D. Tapia Takaki (Kansas U.) (Jul 6, 2017)

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

pdf DOI cite claim reference search

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!

HOW TO EXPLOIT A DENSITY MATRIX

YOU SQUEEZE IT LIKE AN ORANGE

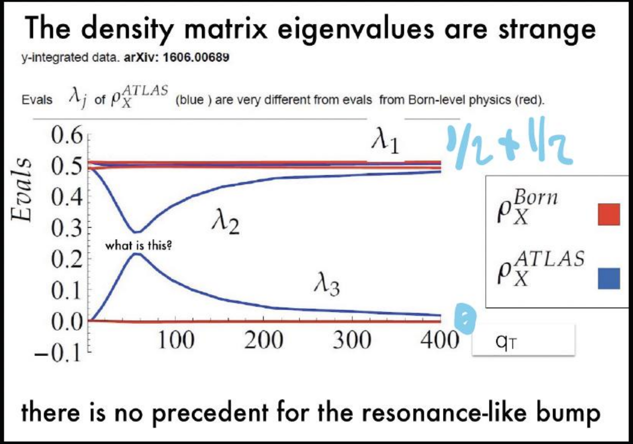
$\neq$ classical entropy $S_{Gibbs} = -\int dx\, f(x) \log f(x)$

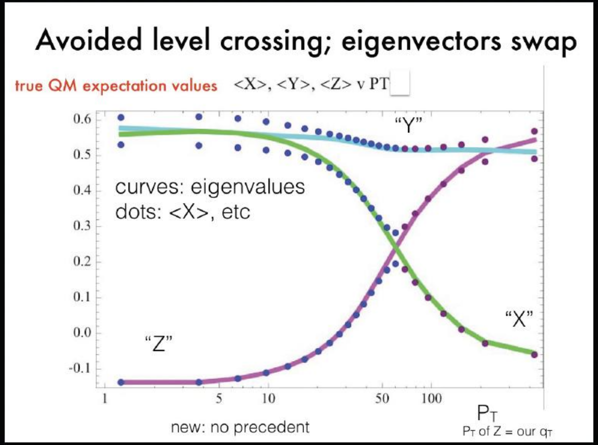
INVARIANTS → EIGENVALUES λ_k

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

$\gamma^* \sim 3 \times 3$

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





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*