Lecture 1: Quantum Entanglement, Quantum tomography applications in Collider Physics

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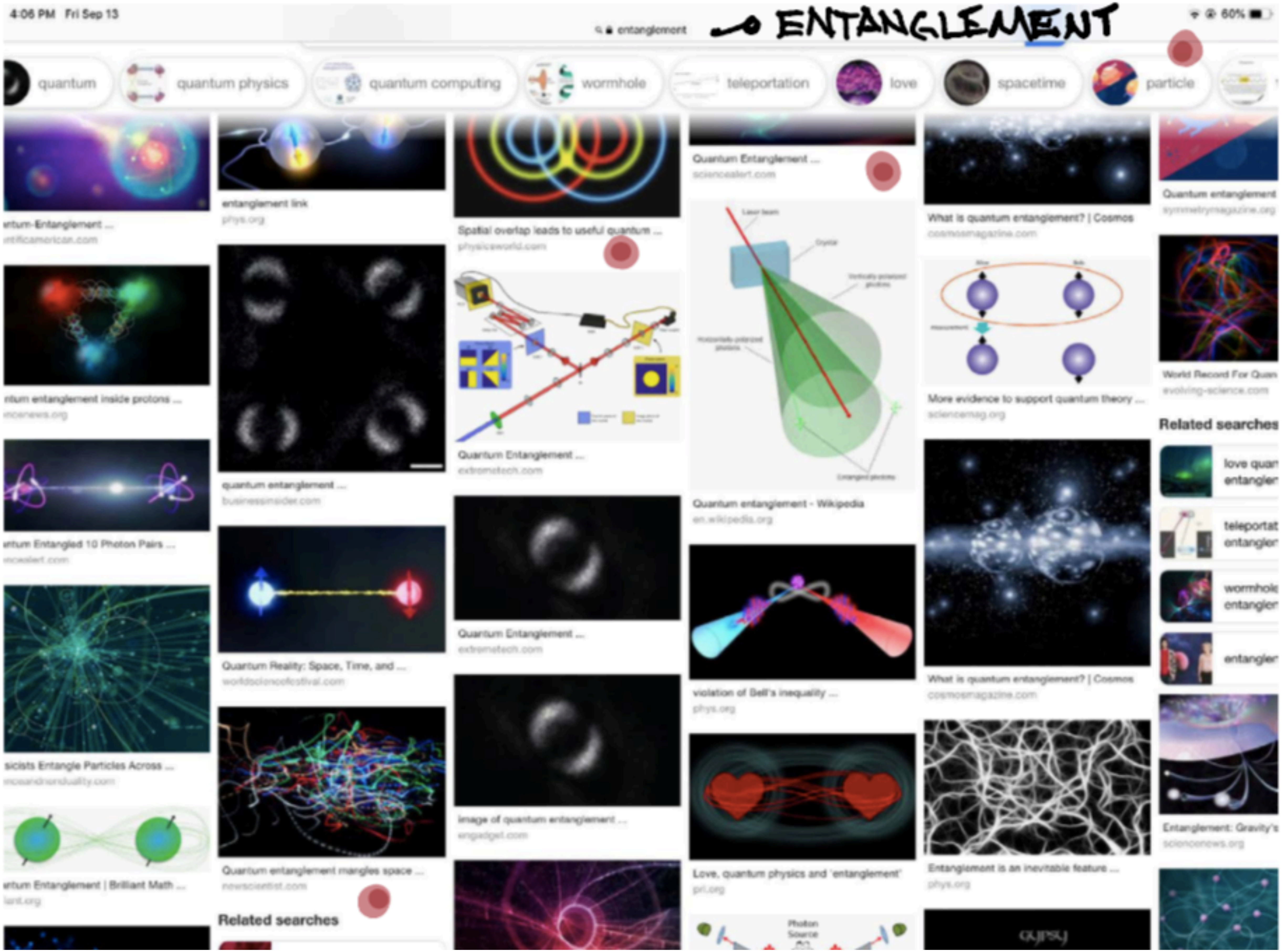
Work with
John Ralston & John Martens

Indian-summer school in Prague
The Emauzy Abbey
Prague, Czech Republic, June 24, 2022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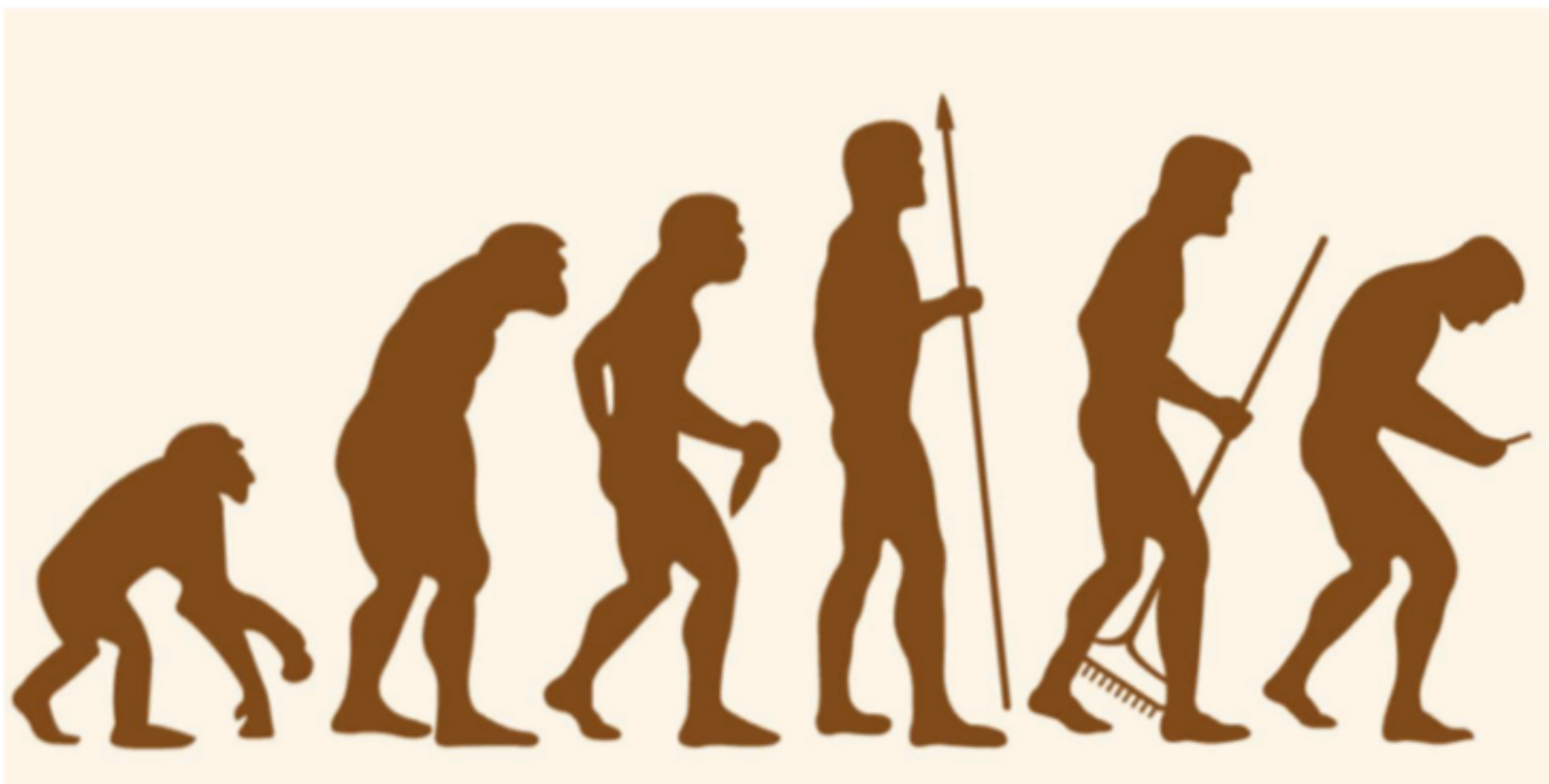
THEORY HAS EVOLVED

COPENHAGEN WENT PAST ITS PULL-DATE

WE NOW HAVE INTERNET COOKIES

INSTALLED IN YOUR BRAIN'S OPERATING SYSTEM



PROBABILITY

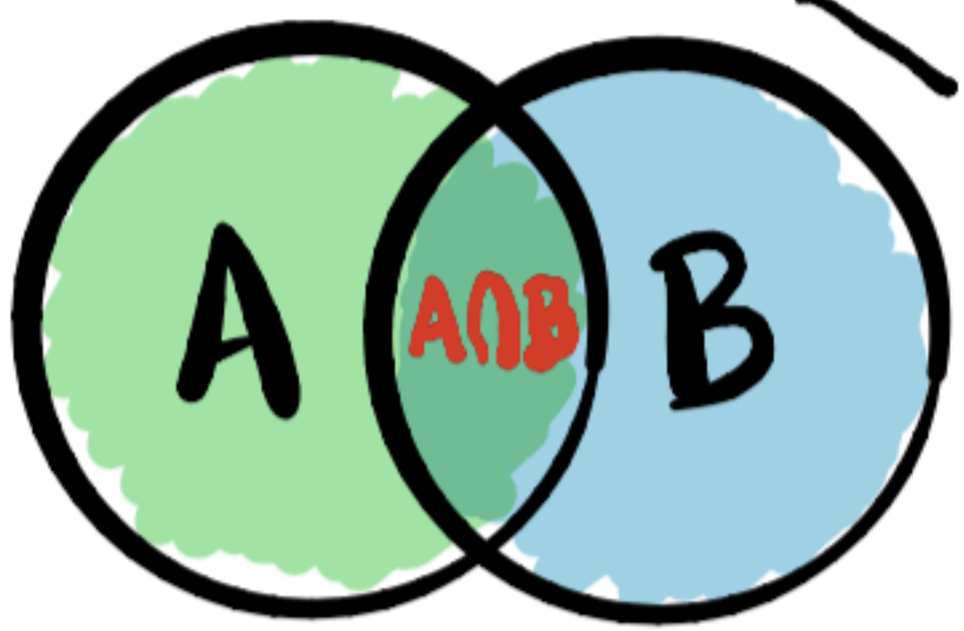
a beautiful subject, try studying it!

Kolmogorov 1930's

- $P > 0$
- something else
- $P(A \cup B) = P(A) + P(B) - P(A \cap B)$

UNION

INTERSECTION



1.2 THE STATISTICAL INTERPRETATION

Griffiths-Intro to QM

But what exactly *is* this "wave function", and what does it do for you once you've *got* it? After all, a particle, by its nature, is localized at a point, whereas the wave function (as its name suggests) is spread out in space (it's a function of x, for any given time t). How can such an object be said to describe the state of a *particle*? The answer is provided by Born's **statistical interpretation** of the wave function, which says that $|\Psi(x,t)|^2$ gives the *probability* of finding the particle at point x, at time t—or, more precisely,[2]

$$|\Psi(x,t)|^2\,dx = \left\{ \begin{array}{l} \text{probability of finding the particle} \\ \text{between } x \text{ and } (x+dx), \text{ at time } t. \end{array} \right\} \qquad [1.3]$$

For the wave function in Figure 1.2, you would be quite likely to find the particle in the vicinity of point A, and relatively unlikely to find it near point B.

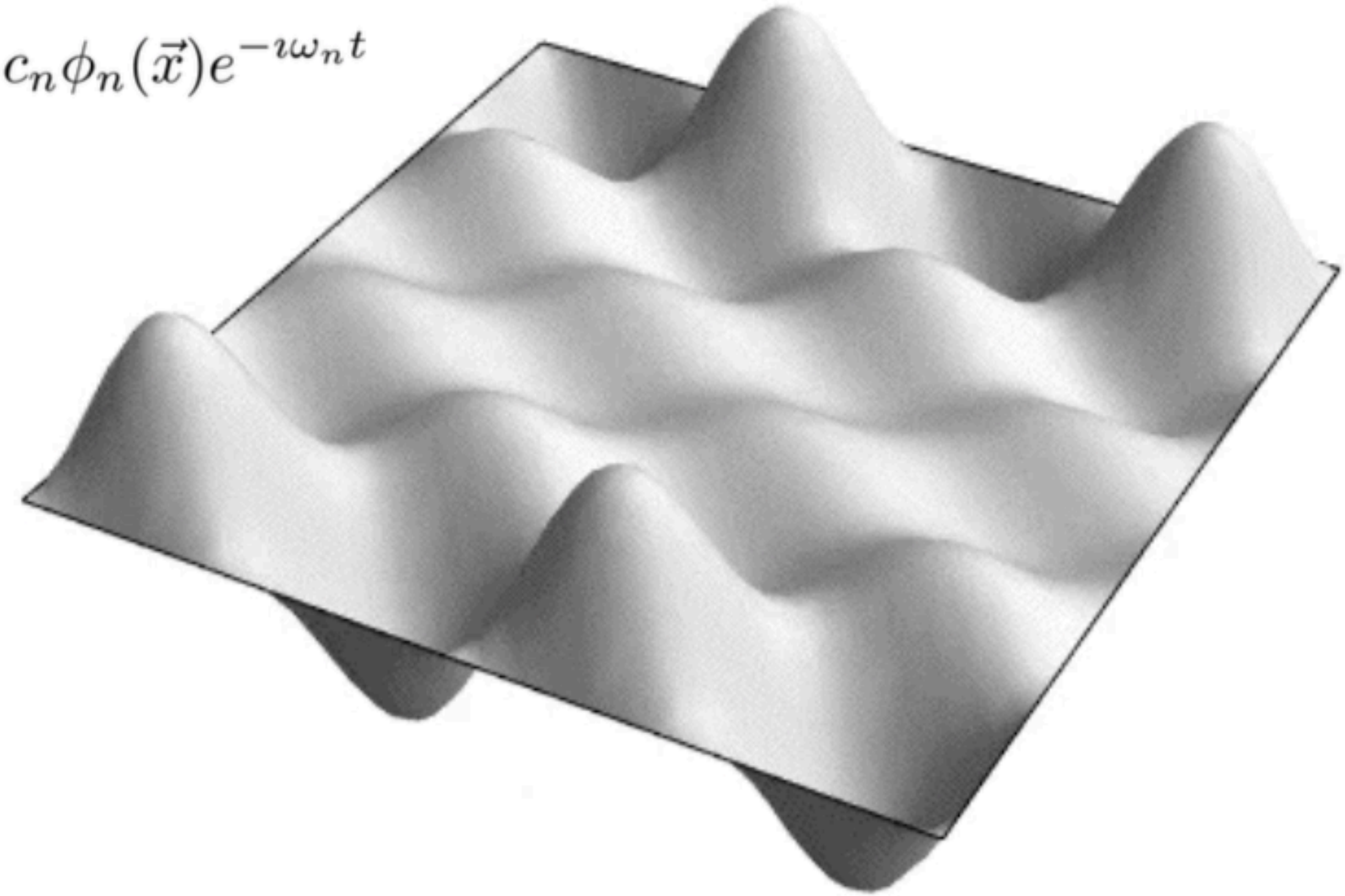
The statistical interpretation introduces a kind of **indeterminacy** into quantum mechanics, for even if you know everything the theory has to tell you about the

[2]The wave function itself is complex, but $|\Psi|^2 = \Psi^*\Psi$ (where Ψ^* is the complex conjugate of Ψ) is real and nonnegative—as a probability, of course, must be.

HEY! wave function -> "Pure State" is actually exceptionally rare

The purpose of the wave function is to calculate frequencies and interactions

$$\psi(\vec{x},\, t) = \sum_n c_n \phi_n(\vec{x}) e^{-\imath \omega_n t}$$



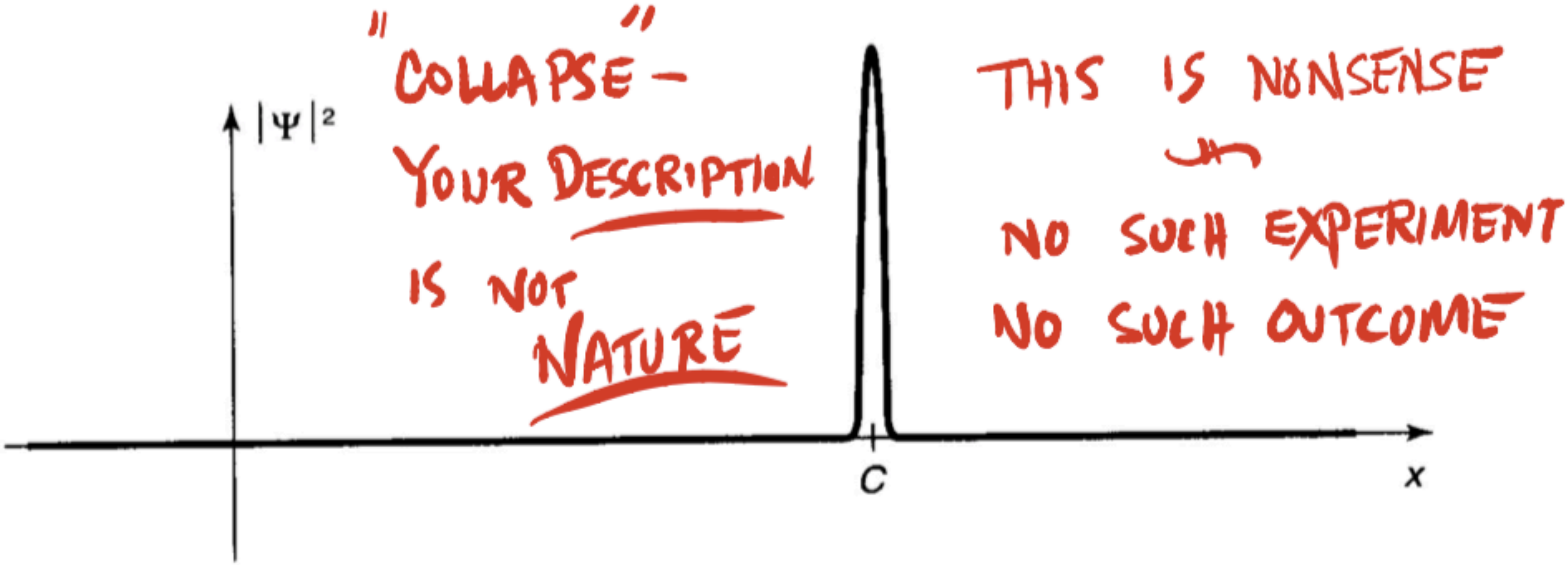


Figure 1.3: Collapse of the wave function: graph of $|\Psi|^2$ immediately after a measurement has found the particle at point C.

Folks, this is malpractice…

1.3 PROBABILITY

Because of the statistical interpretation, **probability** plays a central role in quantum mechanics, so I digress now for a brief discussion of the theory of probability. It is mainly a question of introducing some notation and terminology, and I shall do it in the context of a simple example.

Imagine a room containing 14 people, whose ages are as follows:

one person aged 14

one person aged 15

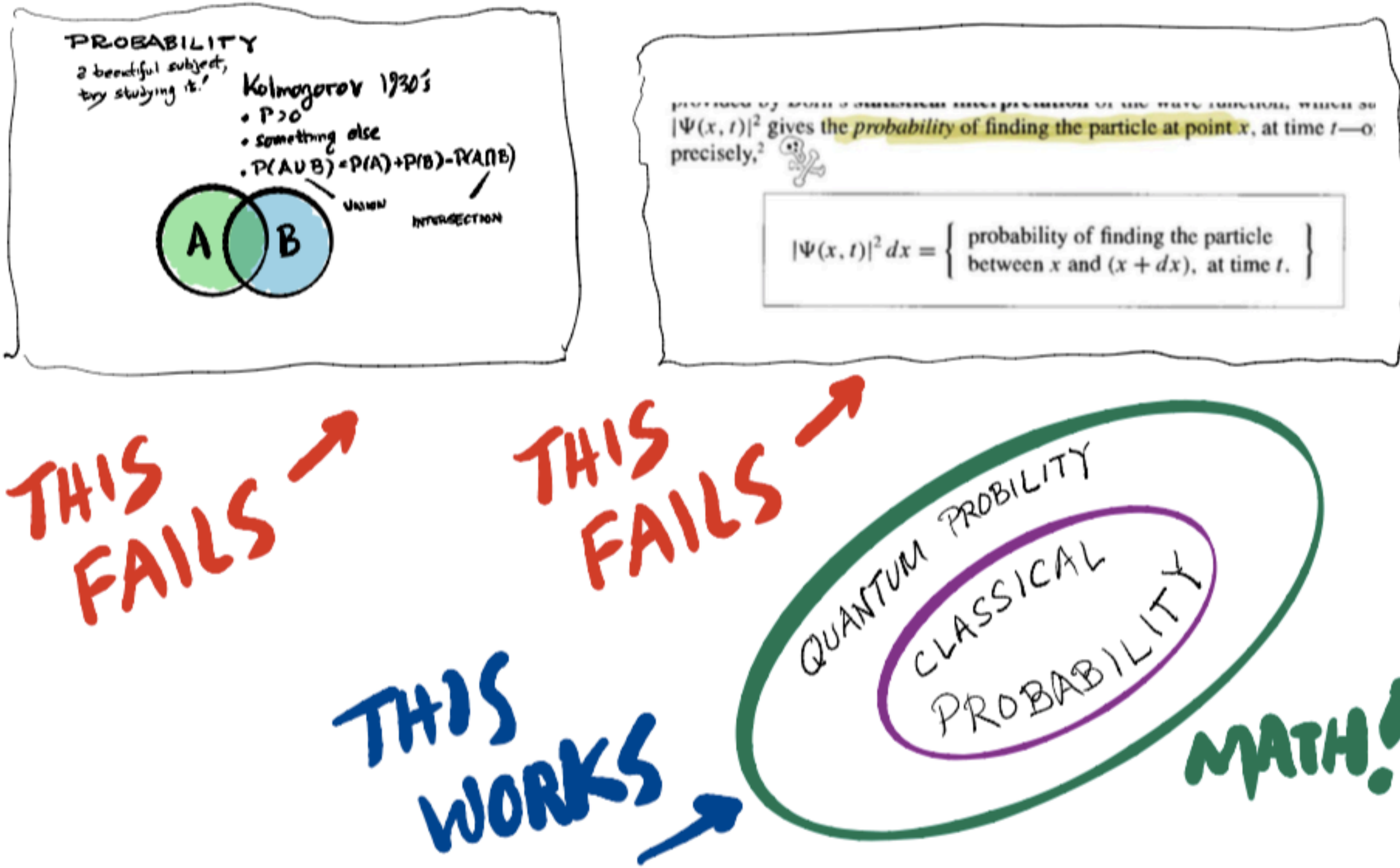
three people aged 16

two people aged 22

two people aged 24

five people aged 25.

If we let $N(j)$ represent the number of people of age j, then


PROBABILITY
a beautiful subject, try studying it.'
Kolmogorov 1930's
• P>0
• something else
• P(A∪B) = P(A)+P(B)-P(A∩B)
UNION
INTERSECTION
A
B
|Ψ(x, t)|² gives the probability of finding the particle at point x, at time t—or more precisely,²
|Ψ(x, t)|² dx = { probability of finding the particle between x and (x + dx), at time t. }
THIS FAILS
THIS FAILS
THIS WORKS
QUANTUM PROBILITY
CLASSICAL PROBABILITY
MATH!

Unlike Newton's mechanics, or Maxwell's electrodynamics, or Einstein's relativity, quantum theory was not created—or even definitively packaged—by one individual, and it retains to this day some of the scars of its exhilirating but traumatic youth. There is no general consensus as to what its fundamental principles are, how it should be taught, or what it really "means." Every competent physicist can "do" quantum mechanics, but the stories we tell ourselves about what we are doing are as various as the tales of Scheherazade, and almost as implausible. Richard Feynman (one of its greatest practitioners) remarked, "I think I can safely say that nobody understands quantum mechanics."

GRIFFITHS

Add, from Griffiths: Niels Bohr said "If you are not confused by quantum mechanics, you have not studied it".

QUANTUM MECHANICS DESCRIBES DATA

WITH NO MUMBO-JUMBO

$\langle\hat{A}\rangle, \langle\hat{B}\rangle, \langle\hat{C}\rangle$ = numbers from experiment

$|\psi\rangle$ = wave function = concise code

AND EXCEPTIONAL CASE OF MORE GENERAL DESCRIPTION

$$\langle\hat{A}\rangle = \langle\psi|\hat{A}|\psi\rangle = \psi_i^* \hat{A}_{ij} \psi_j = \hat{A}_{ij} \psi_j \psi_i^*$$

$$= tr(\hat{A}|\psi\rangle\langle\psi|)$$

tr = TRACE

* TRACE COMPUTES AN INNER PRODUCT

"HOW MUCH DOES PROBE A LOOK LIKE $|\psi\rangle\langle\psi|$"

WAVE FUNCTIONS DESCRIBE SPECIAL CASES

$\langle \hat{A} \rangle = \langle \psi | \hat{A} | \psi \rangle = \psi_i^* \hat{A}_{ij} \psi_j = \hat{A}_{ij} \psi_j \psi_i^*$

$= tr(\hat{A} |\psi\rangle\langle\psi|)$

* TRACE COMPUTES AN INNER PRODUCT

Let $|\psi\rangle\langle\psi| \rightarrow \sum_l |\psi_l\rangle \lambda_l \langle\psi_l|$

A MORE GENERAL KIND OF EXPERIMENTAL AVERAGE

$\uparrow$

ρ, a "density matrix"

THE ONLY GENERAL DESCRIPTION OF A QUANTUM SYSTEM

$\langle \hat{A} \rangle = tr(\hat{A}\rho)$

"HOW MUCH $\hat{A}$ LOOKS LIKE THE SYSTEM ρ"

A theory of CORRELATIONS

AVERAGE OF YOUR DATA

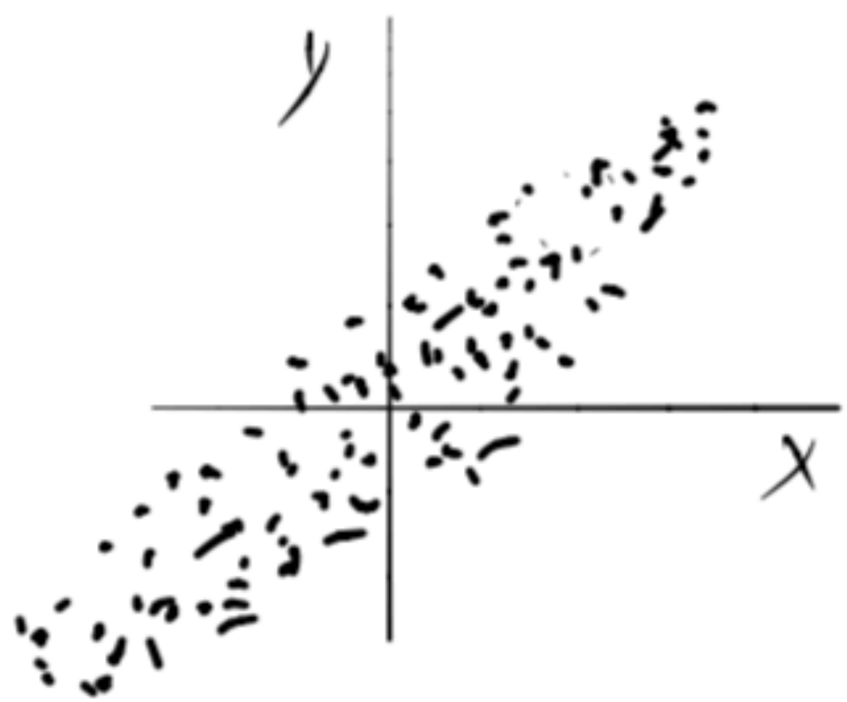
CARTESIAN ELECTRIC FIELD

$$\rho_{ij} = \langle E_i E_j^* \rangle$$

DENSITY MATRIX IN Q.M.

CORRELATION OF POLARIZATIONS i, j

"STOKES MATRIX" 1850's



$\langle x \rangle = 0$

$\langle y \rangle = 0$

$\langle xy \rangle = 0.7$

GENERIC DATA

d_i^K ← EVENT

i ← COMPONENT

QM TEXTBOOK

average over events

$$\rho_{ij} = \sum_K d_i^K d_j^K$$

FACT: $\rho = \rho^\dagger$

USE $\sum_K d_i^{K*} d_j^K$ FOR COMPLEX

$$\rho |e^\alpha\rangle = \lambda_\alpha |e^\alpha\rangle$$

$$\lambda_\alpha > 0$$

EIGENVALUES OF $\rho > 0$

"POSITIVE MATRIX"

EMPIRICAL RULE:

NOBODY COULD POSSIBLY EXPLAIN A POSTULATE

$$\rho = \begin{pmatrix} p_1 & & \\ & p_2 & \\ & & p_3 \end{pmatrix}$$

$p_l > 0 \quad p_1 + p_2 + p_3 = 1$

probability of $|e^\alpha\rangle$:

$$p_\alpha = \langle e^\alpha | \rho | e^\alpha \rangle$$

the BORN RULE of QUANTUM PROBABILITY

(we have a analytic proof, of course)

WHERE IS THE BEGINNER'S BORN RULE?

$$P(|\psi_{ANY}\rangle \,|\, \rho) = \langle \psi_{ANY} | \rho | \psi_{ANY} \rangle$$

pure state !

CONSIDER SPECIAL CASE! ρ HAS ONE EIGENVECTOR

$$\rho |\psi_0\rangle = |\psi_0\rangle; \quad \rho = |\psi_0\rangle\langle\psi_0|$$

THEN $\langle \psi_{ANY} | \rho | \psi_{ANY} \rangle = \langle \psi_{ANY} | \psi_0 \rangle\langle \psi_0 | \psi_{ANY} \rangle$

$$= |\langle \psi_{ANY} | \psi_0 \rangle|^2$$

$$\dot{q}_j = \frac{\partial H}{\partial p_j} \qquad \dot{p}_j = -\frac{\partial H}{\partial q_j}$$

CLASSICAL MECHANICS

$j = 1,..,N,..\infty$

$$\psi_j = (q_j + i p_j)/\sqrt{2} \qquad i = \sqrt{-1}$$

$$i\dot{\psi}_j = \left(i\frac{\partial H}{\partial p_j} + \frac{\partial H}{\partial q_j}\right)/\sqrt{2}$$

ALGEBRA... CHAIN RULE...  ALGEBRA... CHAIN RULE...

$$\rightarrow i\dot{\psi}_j = \hat{H}_{jk}\psi_k$$

WHERE $H(q,p) \rightarrow H(\psi,\psi^*) = \langle\psi|\hat{H}|\psi\rangle$

The Schroedinger Equation IS Hamilton's Equations in Complex NOTATION

$\hbar$ always cancels out... try it!

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Psi - \frac{e^2}{4\pi\varepsilon_0 r}\Psi$$

$$i\cancel{\hbar}\frac{\partial\Psi}{\partial t} = -\frac{\hbar^{\cancel{2}}}{2m}\nabla^2\Psi - \frac{e^2}{4\pi\varepsilon_0\hbar r}\Psi$$

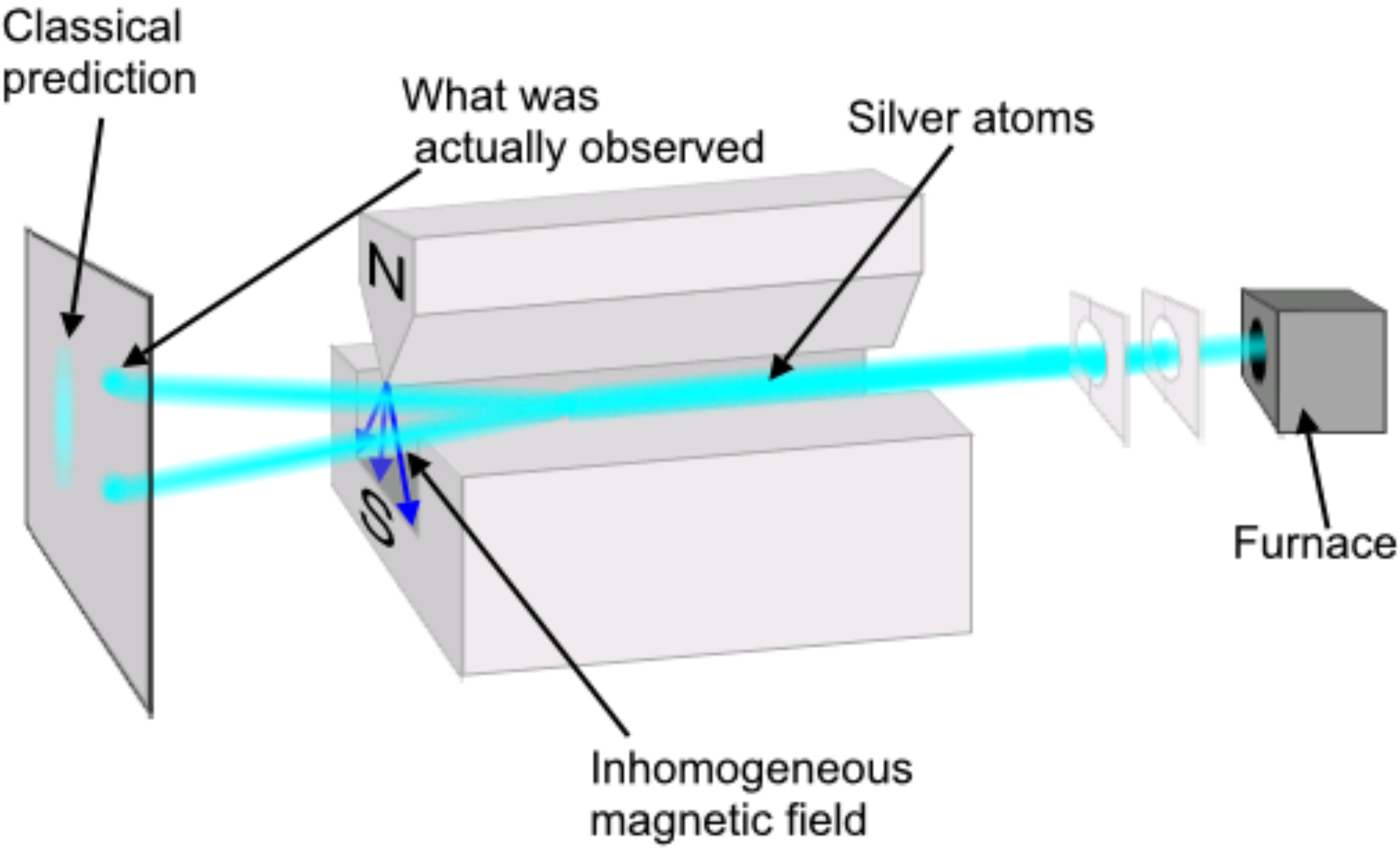
$$i\frac{\partial\Psi}{\partial t} = -\frac{\hbar c^2}{2mc^2}\nabla^2\Psi - \frac{e^2 c}{4\pi\varepsilon_0\hbar c r}\Psi$$

$$i\frac{\partial\Psi}{\partial t} = -c\lambda_c\nabla^2\Psi - \frac{\alpha c}{r}\Psi$$

λ_c: COMPTON WAVELENGTH

α: $\frac{1}{137}$

Stern-Gerlach Experiment with Silver Atoms (1922)



§ 4. *Double Refraction of Light explained by the Wave Theory.*

By means of Iceland spar cut in the proper direction, double refraction is capable of easy illustration. Causing the beam which builds the image of our carbon-points to pass through the spar, the single image is instantly

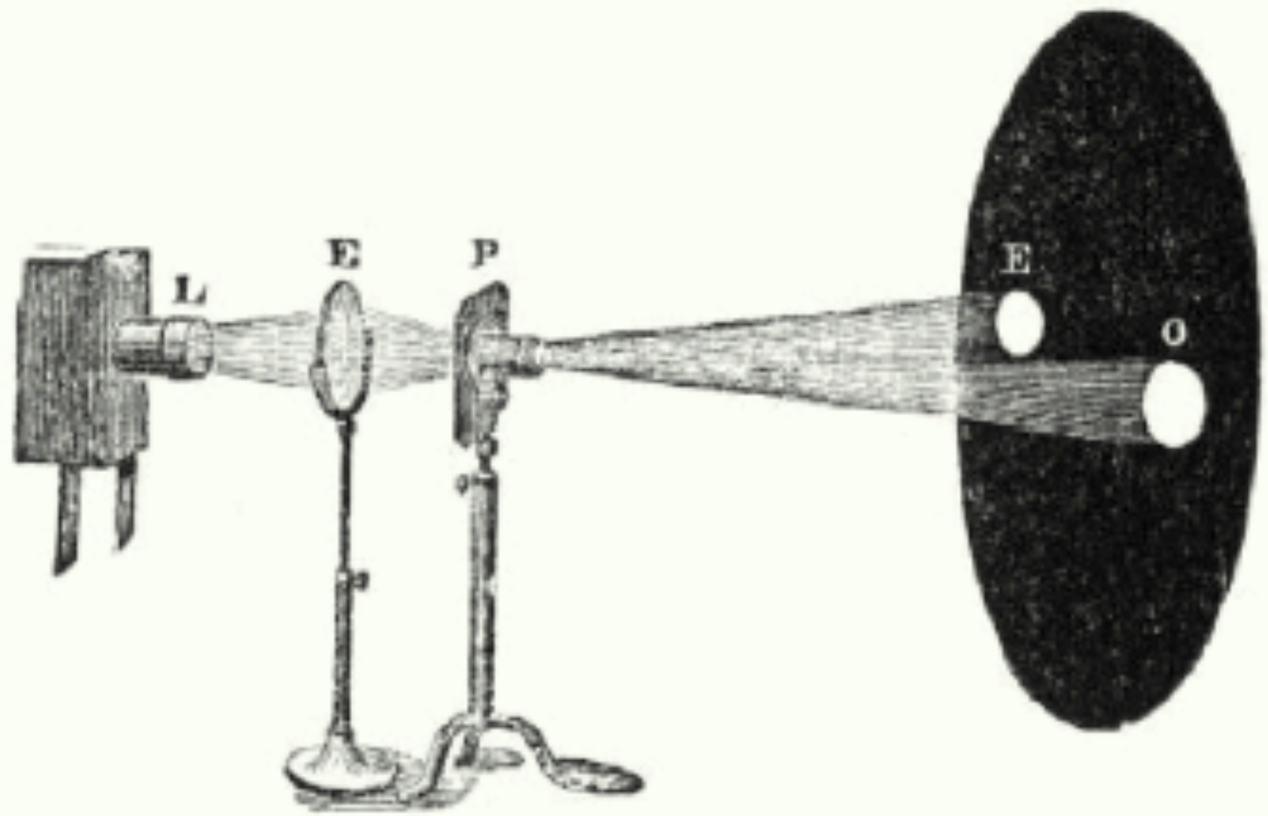


Fig. 26.

divided into two. Projecting (by the lens E, fig. 26) an image of the aperture (L) through which the light issues from the electric lamp, and introducing the spar (P), two luminous disks (E O) appear immediately upon the screen instead of one.

The Stern-Gerlach experiment discovered double refraction of matter waves. It had long been known for light

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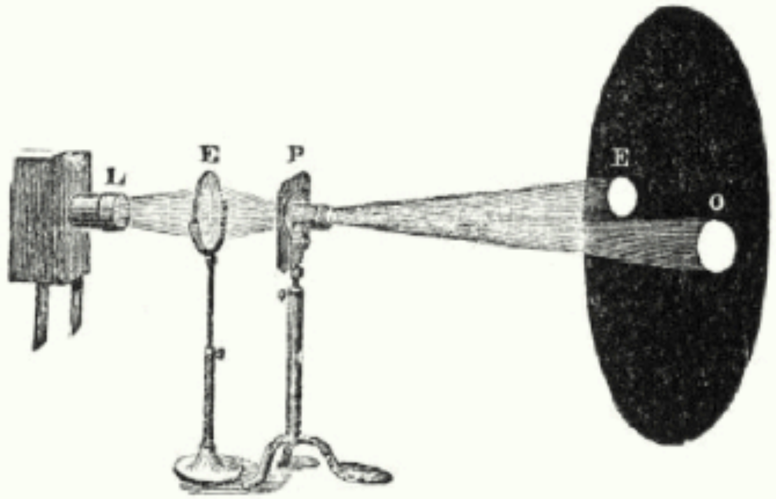

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The figure is from John Tyndall,

Six Lectures on Light
Delivered in the United States in **1872-1873**

Spin was discover by Zeeman
Nature 55, 297, 1897

the thought occurred to me whether the period of the hight edited by a flame might be altered when the flame was acted upon by magnetic force. It has turned out that such an action really occurs. I introduced into an foxy-hydrogen frame placed between the poles of a Ruhmkorff's electromagnet, a filament of asbestos soaked in common salt. The light of the flame was examined with a Rowland's grating. Whenever the circuit was closed both D lines were seen to widen.

- Lorentz predicted that the light from the edges of the widened lines should be circularly polarized …
  - This *electrified* the imagination of the physicists !

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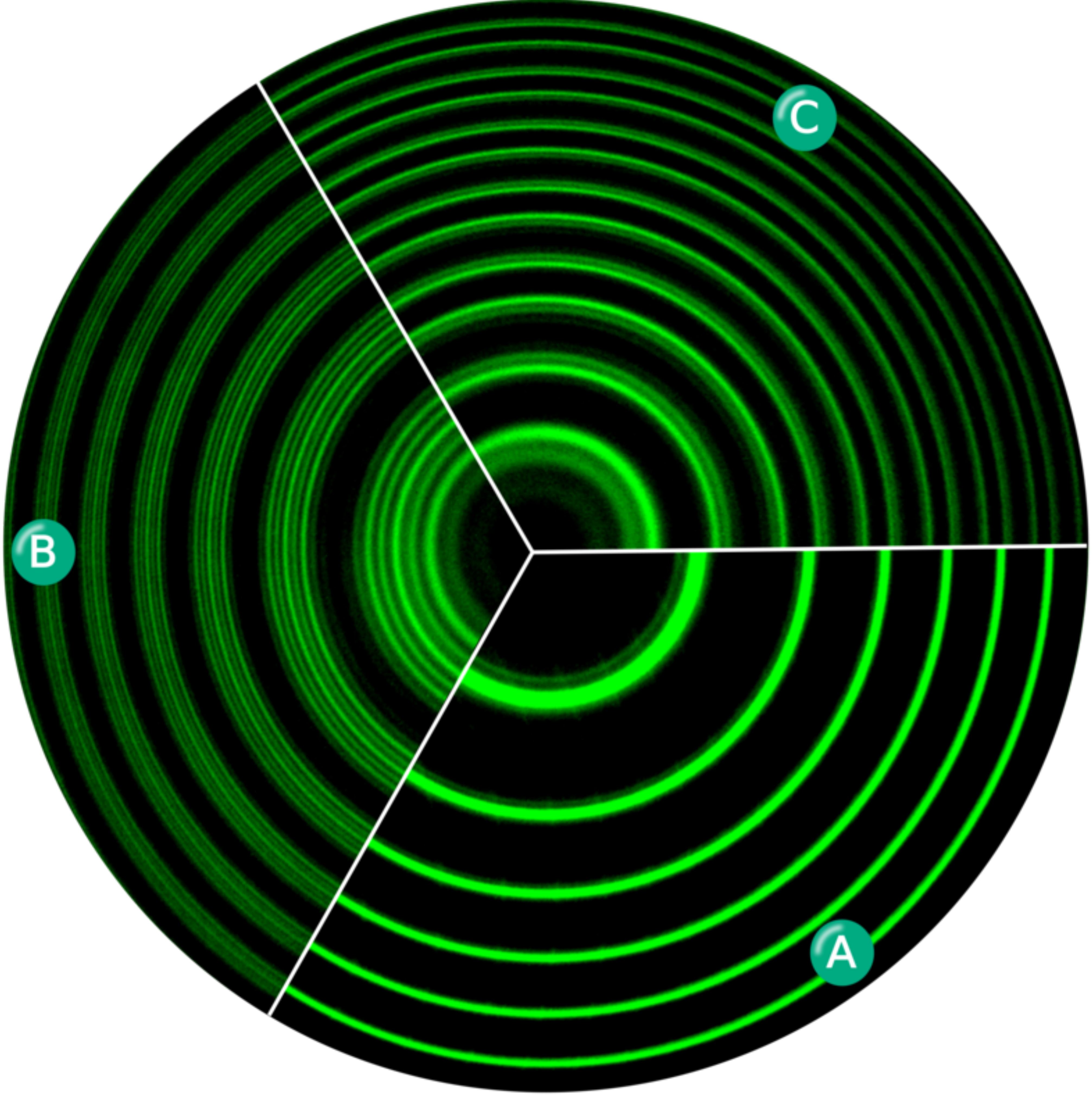
Zeeman effect

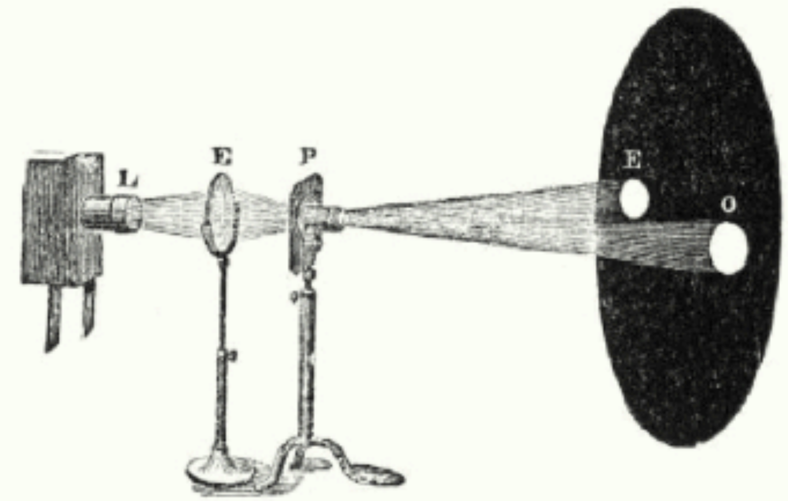
- Zeeman later observed not just widening lines but the multiplication of its numbers


C
B
A

Einstein and Bohr did not pay attention to Double Refraction !

§ 4. Double Refraction of Light explained by the Wave Theory.

By means of Iceland spar cut in the proper direction, double refraction is capable of easy illustration. Causing the beam which builds the image of our carbon-points to pass through the spar, the single image is instantly



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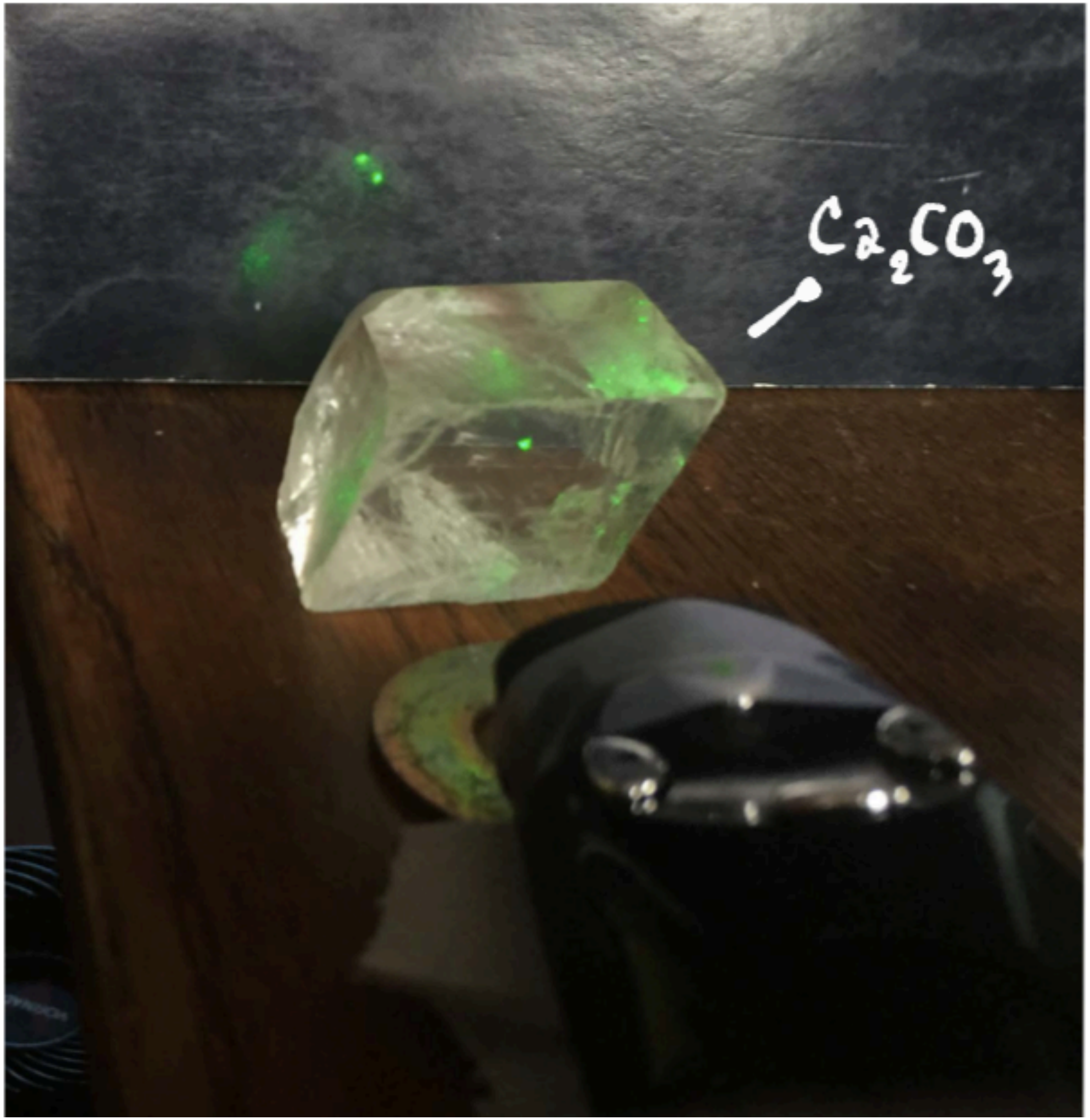
Why there are two spots in the SG experiment?

- Because the matter waves of the atoms of silver have two polarization!

Let's do an experiment!

GO TO A PARTICLE ACCELLERATOR



RUN 1 2012-2014

OBSERVED 2 SPOTS

"PURELY QUANTUM MECHANICAL EFFECT"

Calcite crystal

Entangled Theory

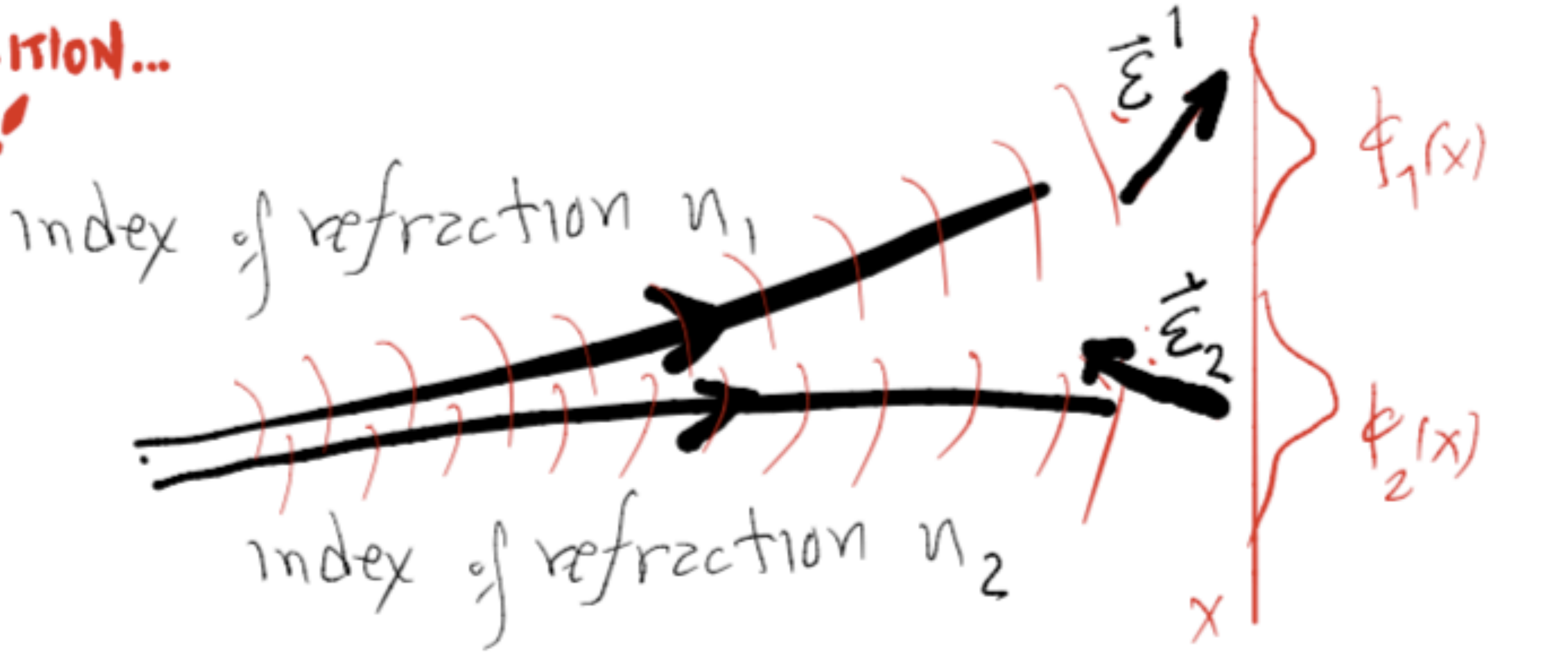
SINGULAR VALUE DECOMPOSITION... MATH!

$$E_a(x) = E_{ax} = \lambda^1 \varepsilon^1_a \phi^1(x) + \lambda^2 \varepsilon^2_a \phi^2(x)$$

$a = 1, 2$

$$\langle \varepsilon^i | \varepsilon^j \rangle = \langle \phi^i | \phi^j \rangle = \delta^{ij}$$

Augustin Fresnel (1788-1827)



STERN-GERLACH IS EXPLAINED

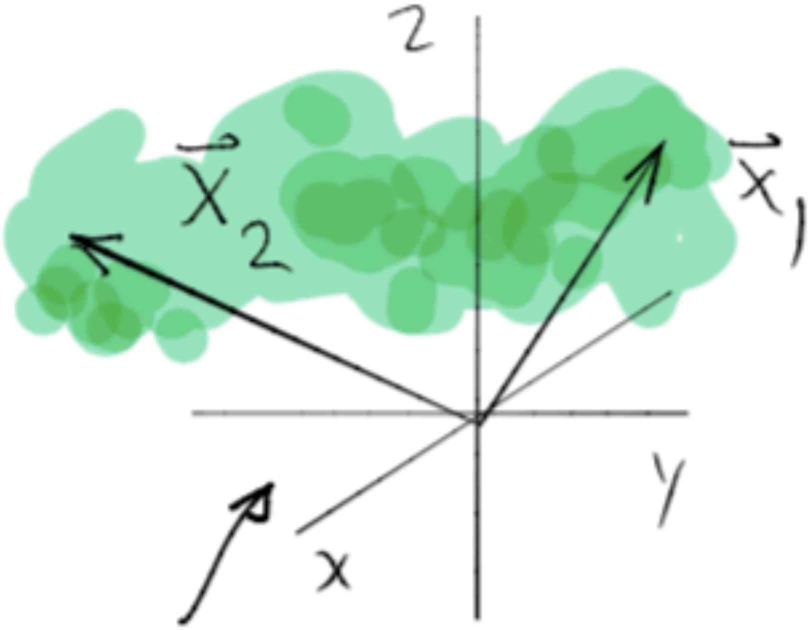
UP TO HERE...

ODINARY CORRELATIONS REPRODUCE QUANTUM MECHANICS

IT AIN'T ALL THAT MYSTERIOUS

SHOW US ENTANGLEMENT!

BABY ENTANGLEMET – WAVE FUNCTIONS



GENERIC GREEN STUFF
NOT A GREEN FUNCTION

generic $f(\vec{x}_1, \vec{x}_2) \neq f_1(\vec{x}_1) f_2(\vec{x}_2)$

$\equiv$

"Entangled"

SCHOOLBOOKS

"Let $\psi(\bar{x}_1, \bar{x}_2) = \psi_1(\bar{x}_1)\psi_2(\bar{x}_2)$

"Not Entangled"

Applications of Quantum Tomography in Collider Physics

ALL YOU NEED TO KNOW

KNOWN PROBE

UNKNOWN SYSTEM

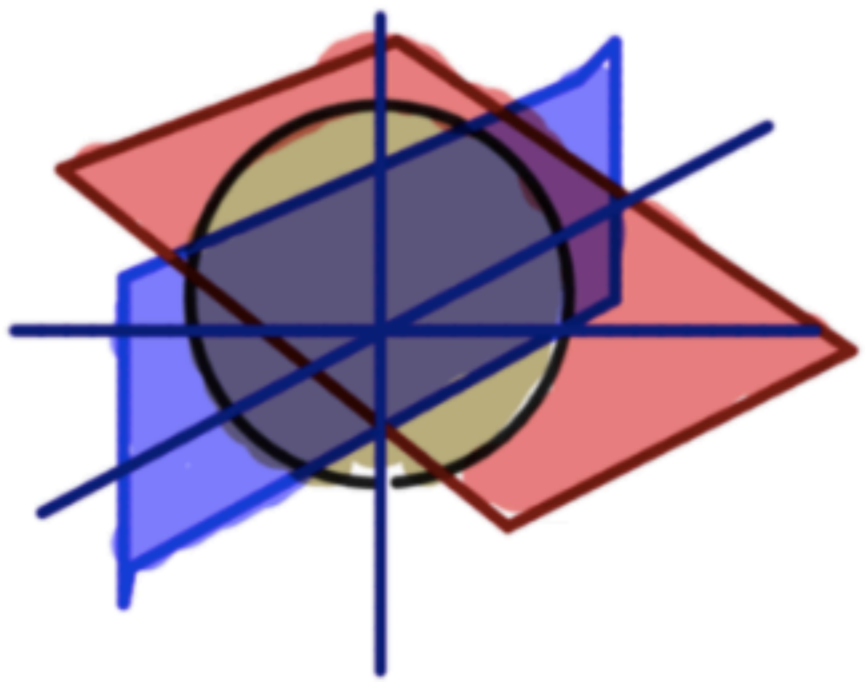
$$\text{rate} = d\sigma = \mathrm{tr}(\rho_{\text{PROBE}}\,\rho_X)$$

ALSO: THIS IS AN INNER PRODUCT

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

TOMOGRAPHY

reconstructs higher dimensional objects from lower dimensional projections



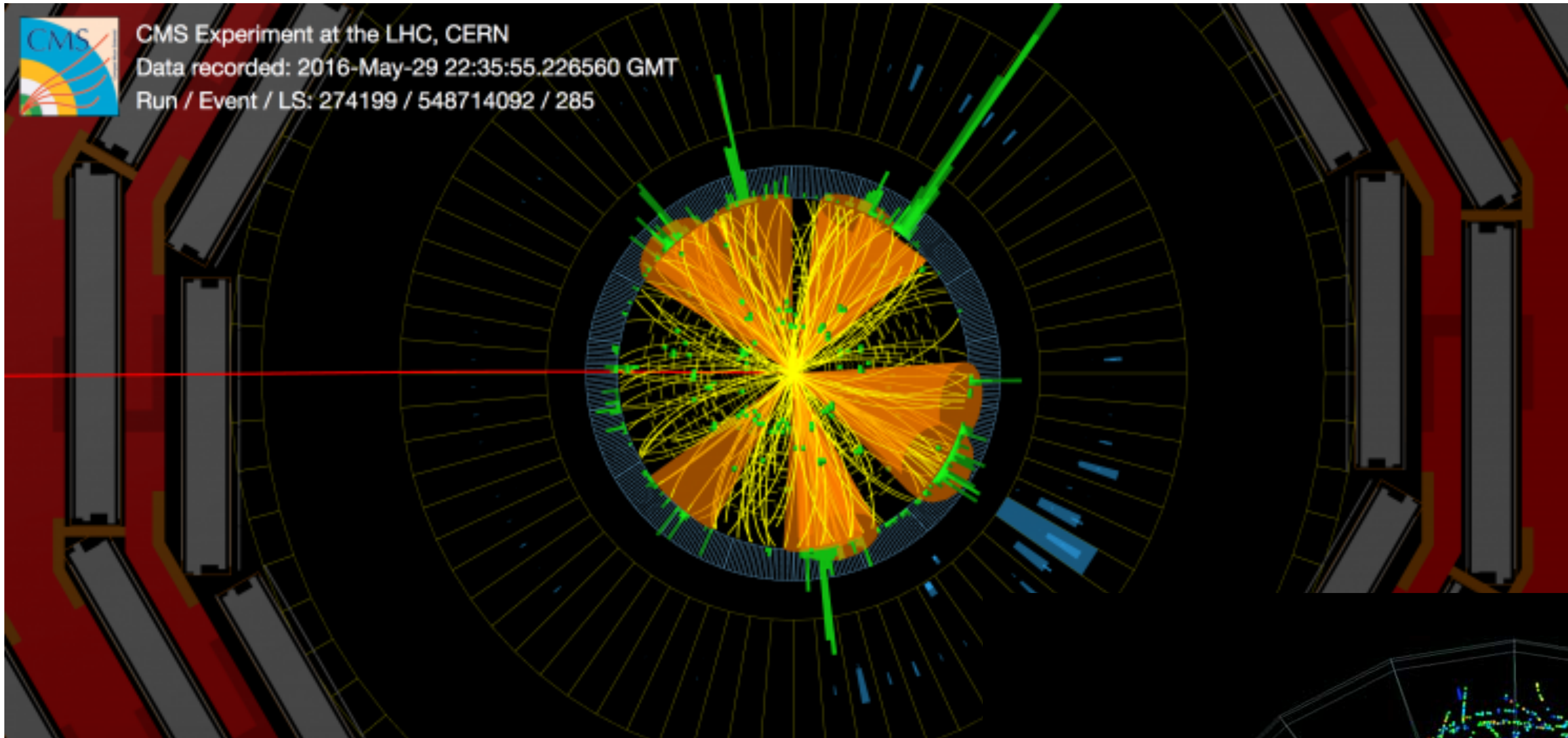
QUANTUM TOMOGRAPHY

reconstructs density matrix or wave function from quantum observables

$$\langle \hat{A} \rangle = \langle \psi | \hat{A} | \psi \rangle \to \mathrm{tr}(\rho \hat{A})$$

$\rho > 0$ positive evals

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


CMS Experiment at the LHC, CERN
Data recorded: 2016-May-29 22:35:55.226560 GMT
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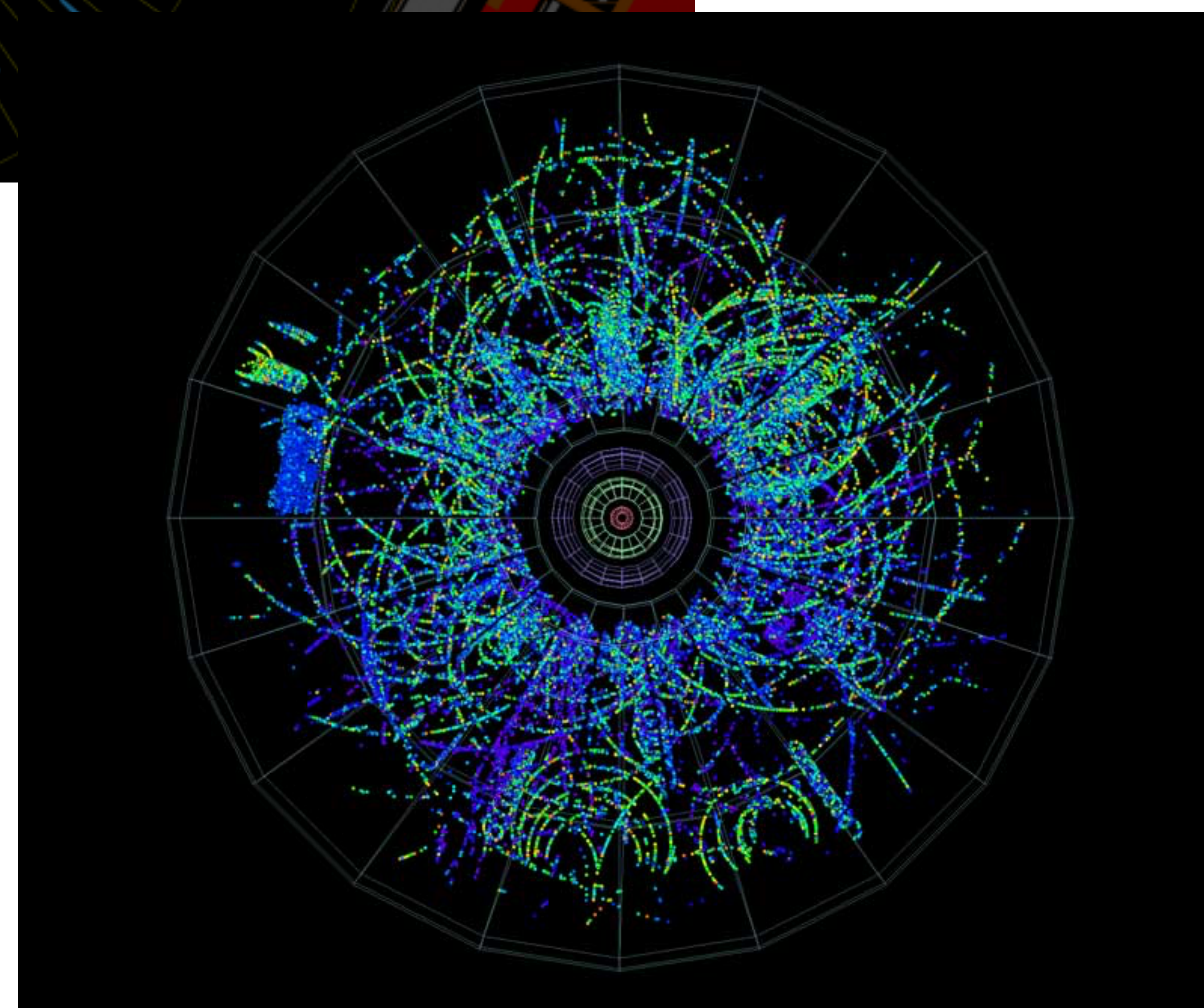
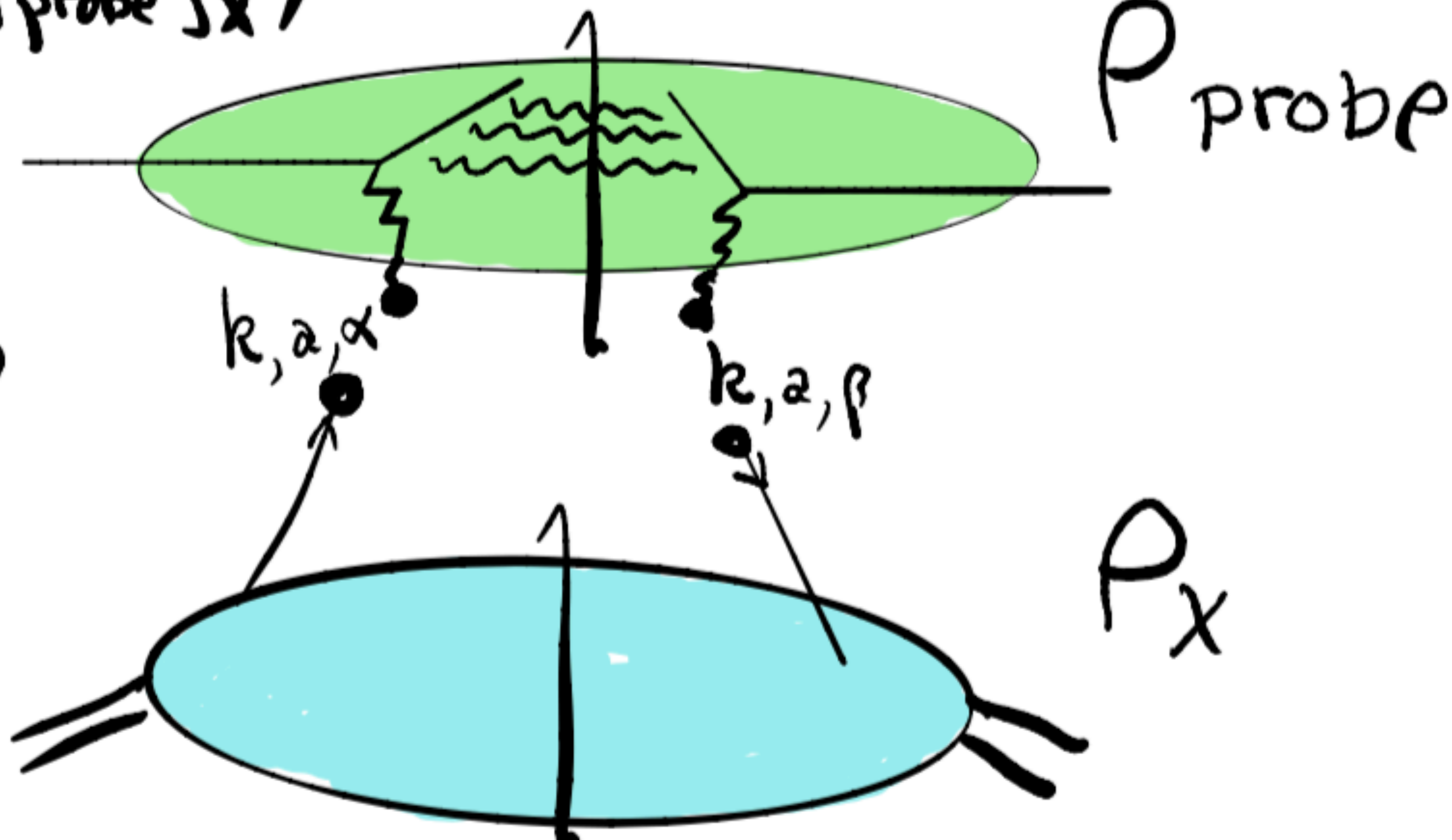


EVERY CROSS SECTION

$$d\sigma = \mathrm{tr}(\rho_{probe}\,\rho_X)$$

DIS



QUANTUM TOMOGRAPHY

$A = A^{\dagger}, \; \rho = \rho^{\dagger}$

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

A PROJECTION, AN INNER PRODUCT OF OPERATORS

"OBSERVABLE"

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

COMPLETENESS; GENERATORS of U(N)

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

EXPANSION

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

QUANTUM TOMOGRAPHY → "OBSERVABLE"

Eur. Phys. J. C (2018) 78:5
https://doi.org/10.1140/epjc/s10052-017-5455-8
THE EUROPEAN PHYSICAL JOURNAL C
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Regular Article - Theoretical Physics

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

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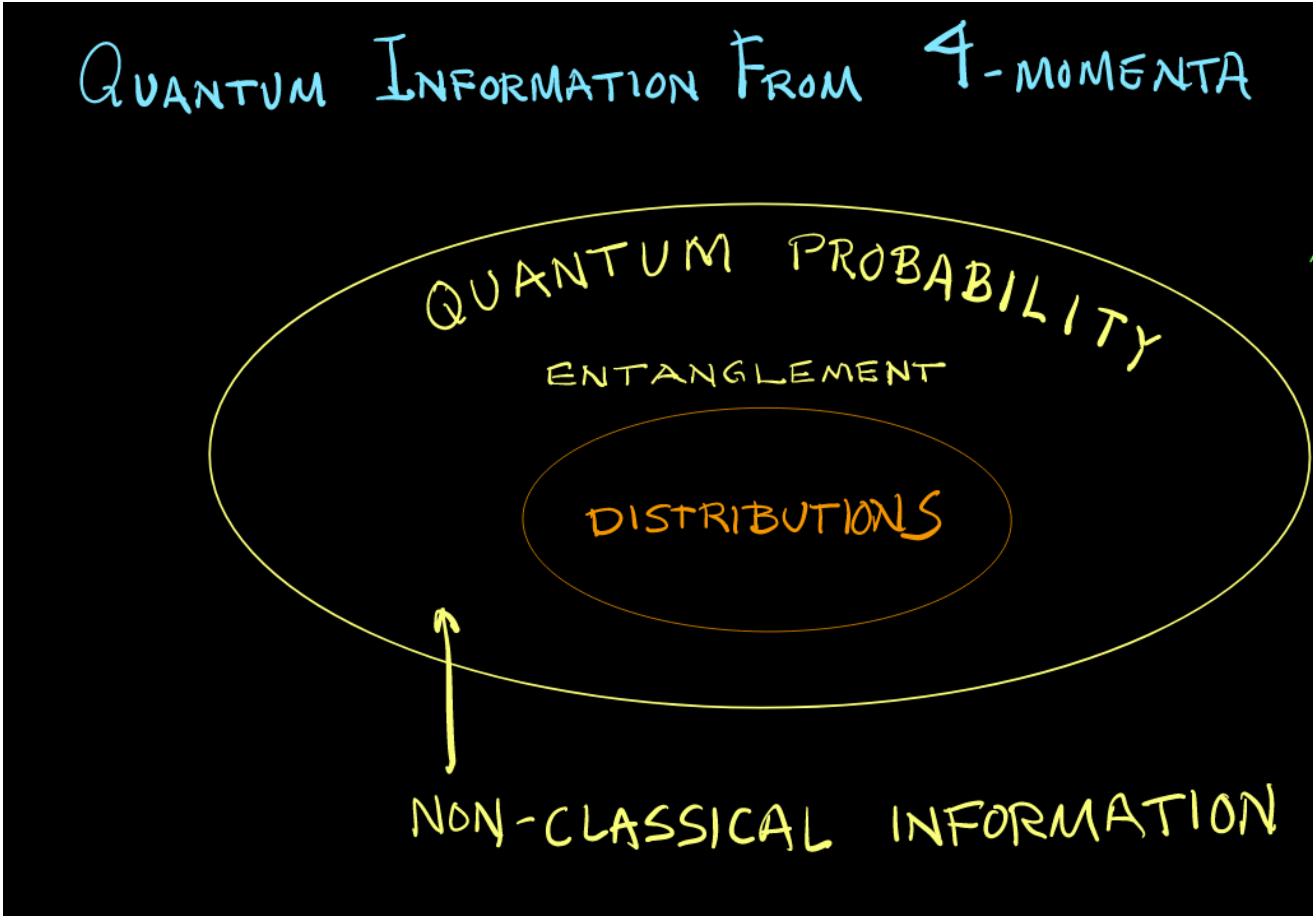
Martens, Ralston, Tapia Takaki Eur. Phys. J. C78, 5, 2018


QUANTUM INFORMATION FROM 4-MOMENTA
QUANTUM PROBABILITY
ENTANGLEMENT
DISTRIBUTIONS
NON-CLASSICAL INFORMATION

THE DENSITY MATRIX

$\rho = \rho^{\dagger} > 0$ POSITIVE EIGENVALUES

$\langle \hat{A} \rangle = \mathrm{tr}(\rho \hat{A})$

PURE STATE IS EXCEPTIONAL

$\rho \to |\psi\rangle\langle\psi|$

$\langle \hat{A} \rangle \Rightarrow \mathrm{tr}(|\psi\rangle\langle\psi|\hat{A}) = \langle\psi|\hat{A}|\psi\rangle$

TEXTBOOKS SHOW THE EXCEPTION

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

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

EXPERIMENTAL PROBE

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi}\left(1 + m_3^2\right) + \frac{1}{4\pi}\left(1 - 3m_3^2 \cos^2\vartheta\right) - \frac{1}{2} m_3 m_6 \sin 2\vartheta \cos\varphi - \frac{1}{2} m_3 m_8 \sin 2\vartheta \sin\varphi + \dots$$

... 2 JETS

2 OF ANYTHING ...

FIT m_ℓ WITH LIKELIHOOD

$-1 < m_\ell < 1$

NO LOCAL MAXIMA

CONVEX FUNCTIONS

POSITIVITY is EXACT

No assumptions on perturbative theory nor one-photon exchange needed

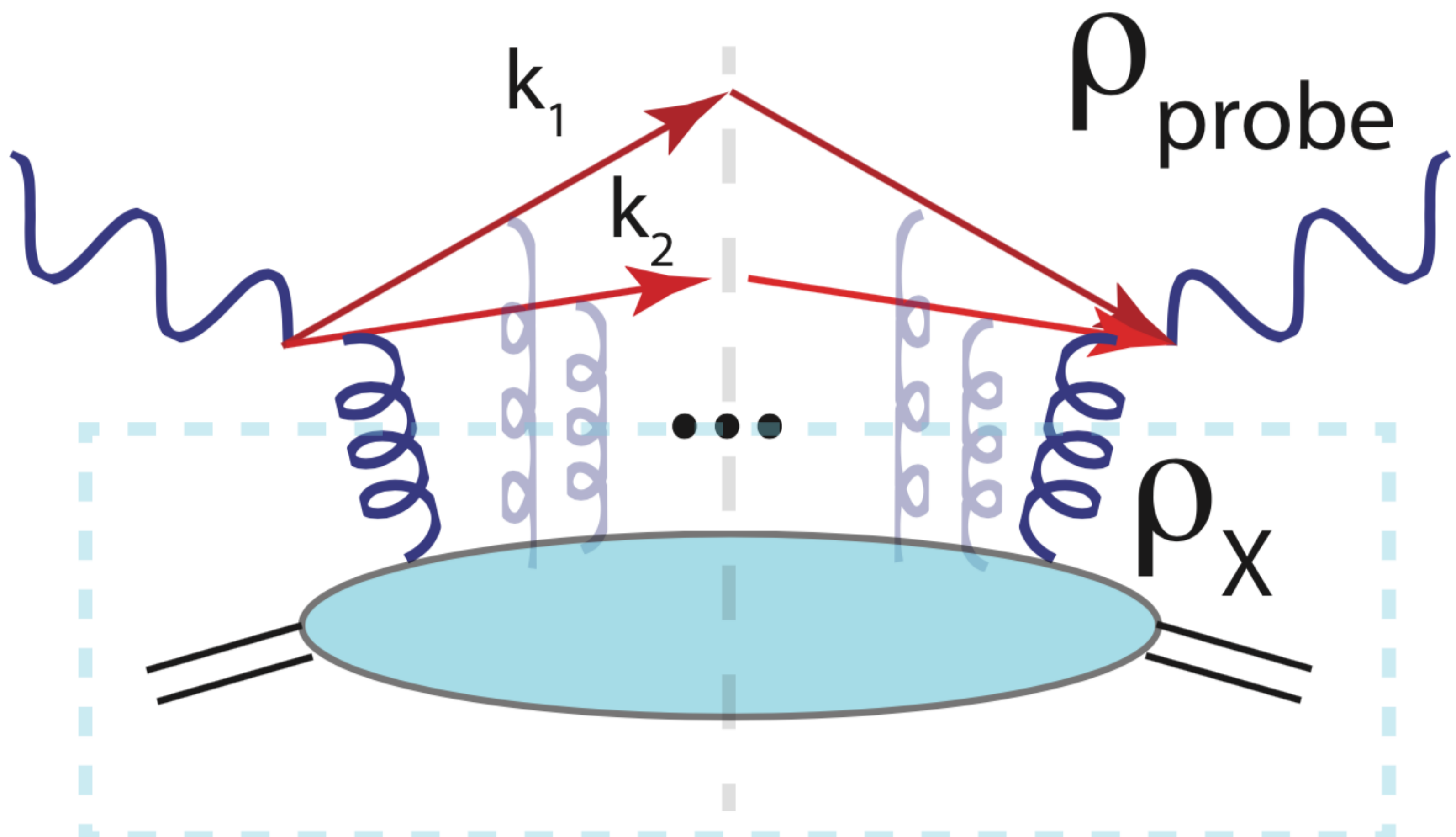


FIG. 1: By analogy with deeply inelastic scattering, a dijet probe replaces the handle of the handbag diagram with a shoulder strap (red) defining new elements of the probe density matrix ρ_{probe}. Each orthogonal element of ρ_{probe} can extract a corresponding projection of the unknown system density matrix ρ_X inside the dashed box. Unlike the deeply inelastic structure functions no assumptions of perturbation theory or one-photon exchange need be made.

Experimentally measure the density matrix

$$\frac{dN}{d\cos\theta d\phi} \sim tr(\rho_{probe}\rho_X)$$

ρ_{probe} = known density matrix

ρ_X = unknown density matrix

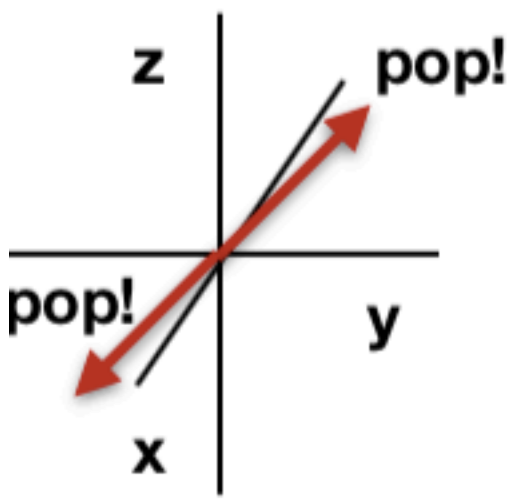
The notation does not look Lorentz invariant,
but the quantities are

Drell-Yan production in pp

EXAMPLE: Experimentally measure the polarization density matrix of a Z boson

Example:

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



$$\frac{dN}{d\cos\theta d\phi} \sim tr(\rho_{probe}\rho_X)$$

ρ_{probe} = known density matrix

ρ_X = unknown density matrix

A weighted sum over expectations makes a density matrix

everything in QM is a density matrix

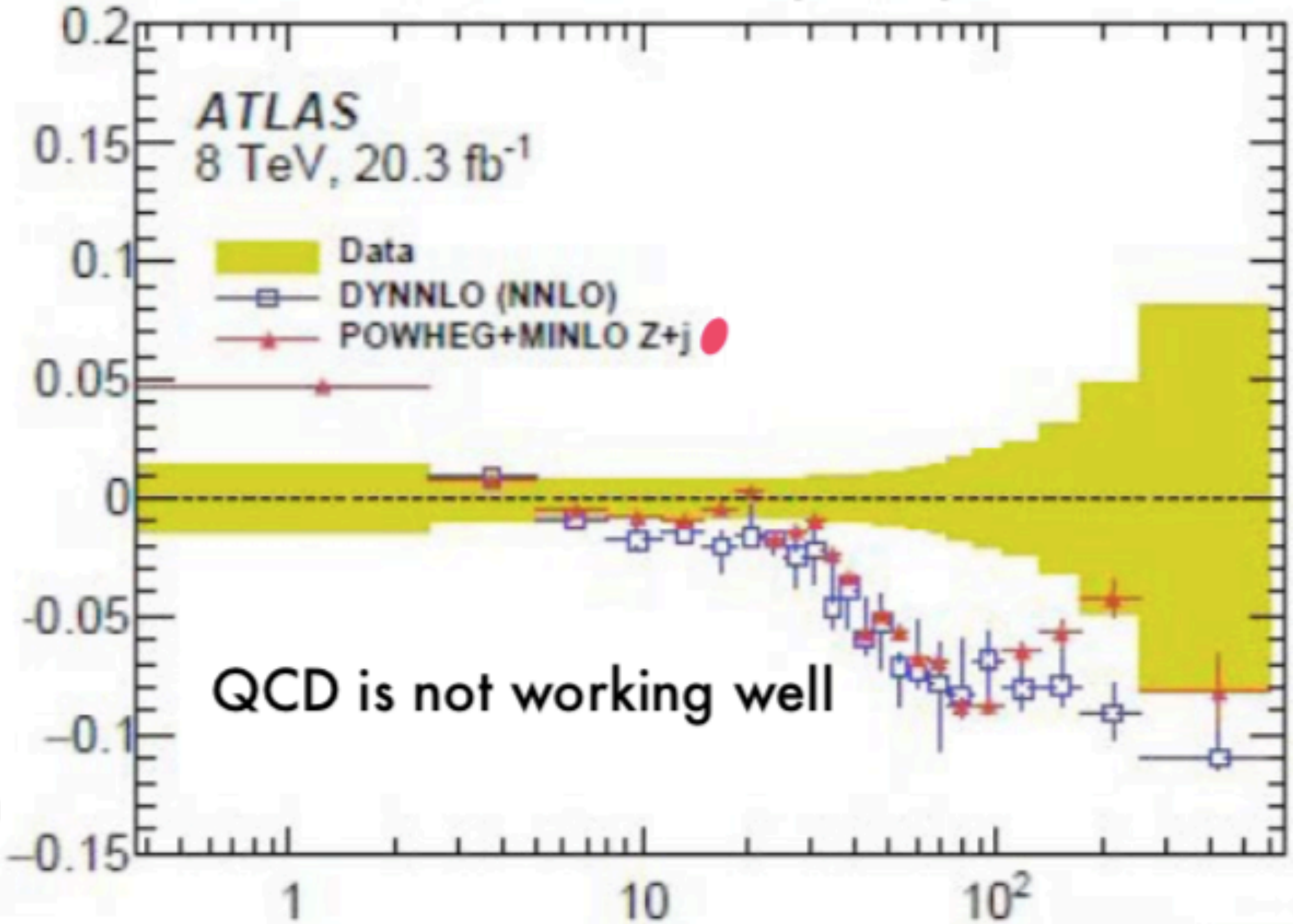
ATLAS data 1606.00689

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

"lepton pairs"

$(A_0 - A_2)$

one of many
terms in an
traditional
expansion
of a certain
angular distribution



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

Bring us data: We'll give you a density matrix

Example : events with 2 particles, or 2 jets plus anything else

4-momenta $k, \, k'$

total pair momentum $Q = k + k'$

$$l^\mu = k^\mu - k^{'\mu} = \sqrt{Q^2}(0, \, \hat{\ell});$$

$$\hat{\ell} = (\sin\theta\cos\phi, \, \sin\theta\sin\phi, \, \cos\theta).$$

pair rest frame $Q^\mu = (\sqrt{Q^2}, \, \vec{0})$

$$P(Q, \, \ell \big| \, init) = P(\ell \big| Q, \, init) P(Q \big| init).$$

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

Everything is Lorentz Invariant and easy !

Define spatial axes X^μ, Y^μ, Z^μ satisfying Lorentz invariant

$$Q \cdot X = Q \cdot Y = Q \cdot Z = 0. \tag{1}$$

The frame vectors being orthogonal implies

$$X \cdot Y = Y \cdot Z = X \cdot Z = 0$$

$$\tilde{Z}^\mu = P_A^\mu Q \cdot P_B - P_B^\mu Q \cdot P_A;$$

$$\tilde{X}^\mu = Q^\mu - P_A^\mu \frac{Q^2}{2Q \cdot P_A} - P_B^\mu \frac{Q^2}{2Q \cdot P_B};$$

$$\tilde{Y}^\mu = \epsilon^{\mu\nu\alpha\beta} P_{A\nu} P_{B\alpha} Q_\beta.$$

The first step in our quantum tomographic (QT) analysis expresses everything in a Lorentz-covariant fashion

To analyze data for each event labeled J:

Compute $\quad Q_{(J)} = k_J + k'_J; \quad \ell_J = k_J - k'_J; \quad (X_J^\mu, Y_J^\mu, Z_J^\mu);$

$$\vec{\ell}_{XYZ,J} = (X_J \cdot \ell_J, Y_J \cdot \ell_J, Z_J \cdot \ell_J);$$

$$\hat{\ell}_J = \ell_{XYZ,J} / \sqrt{-\ell_{XYZ,J} \cdot \ell_{XYZ,J}}.$$

use lab momenta to compute invariants

Tomography builds higher dimensional structure from lower dimensional projections

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*

The density matrix is observable

If and when rank=1,

$$\rho|\psi >= |\psi >$$

defines $|\psi >$

<u>Wave functions are observable</u>, up to the undetermined phase of eigenstates

Experimentally measure the density matrix

$$P(Q,\, \ell \big|\, init) = P(\ell \big| Q,\, init) P(Q \big| init).$$

$$\downarrow$$

$$\frac{dN}{d\Omega} = \frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi} tr\left(\rho(\ell)\rho(X)\right),$$

$\rho(\ell)$ = known density matrix $= \sum_\ell c_\ell G_\ell$

$\rho(X)$ = unknown density matrix

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

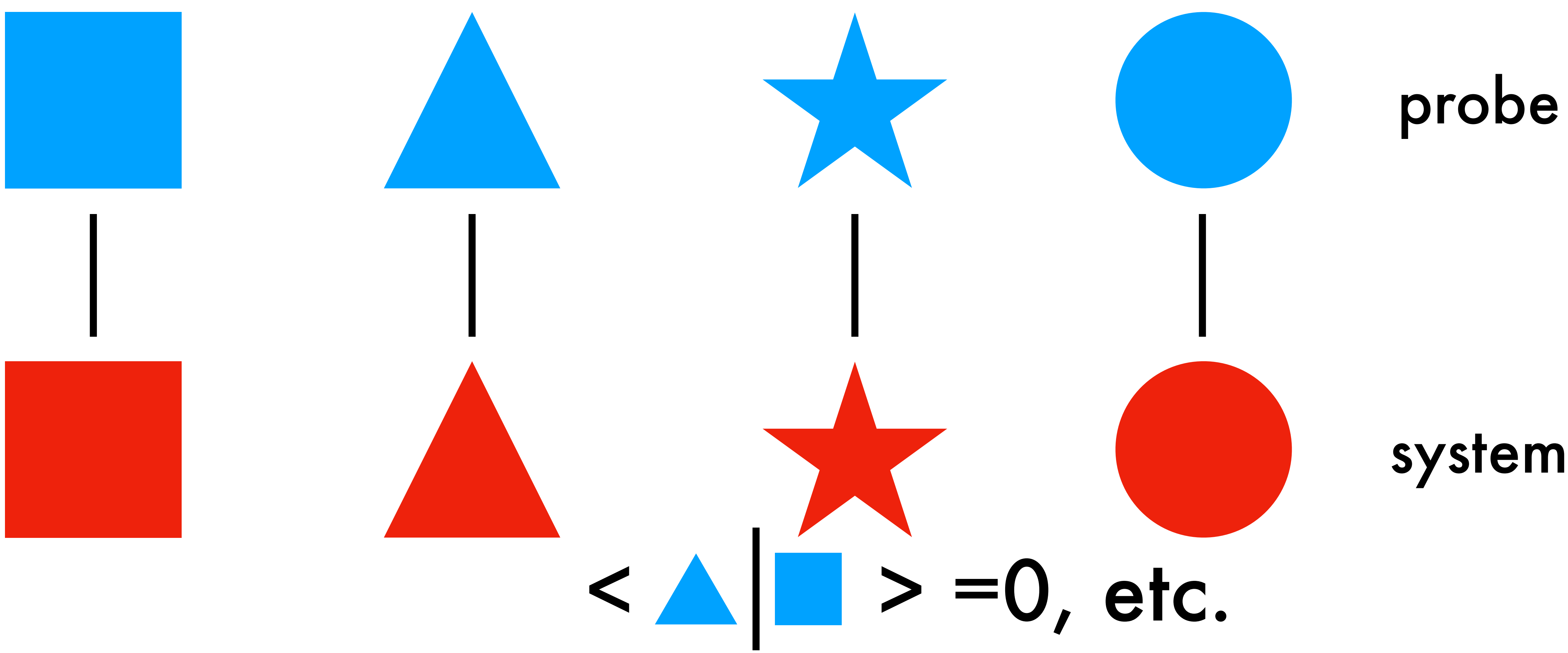
The Mirror trick

3 spin 1 tensors

5 spin 2 tensors

$$\text{Probe:}\quad \rho_{ij}(\ell) = \frac{1}{3}\delta_{ij} + b\hat{\ell}\cdot\vec{J}_{ij} + aU_{ij}(\hat{\ell});\quad \text{where}\quad U_{ij}(\hat{\ell}) = \frac{\delta_{ij}}{3} - \hat{\ell}_i\hat{\ell}_j = U_{ji}(\ell);\ tr(U(\ell)) = 0; \tag{1}$$

$$\text{System:}\quad \rho_{ij}(X) = \frac{1}{3}\delta_{ij} + \frac{1}{2}\vec{S}\cdot\vec{J}_{ij} + U_{ij}(X);\quad \text{where}\quad U(X) = U^T(X);\quad tr(U(X)) = 0.$$



DATA

KNOWN; 8 TERMS

$$\frac{d\sigma}{d\Omega} = \mathrm{tr}(\rho_\ell \, \rho_X)$$

GET 8 TERMS

EIGENVALUES ARE INVARIANTS

$3\times 3 \quad \rho = \rho^\dagger$

$$= \begin{pmatrix} \rho_{11} & \rho_{12} & \rho_{13} \\ \rho_{12}^* & \cdots & \\ & & \end{pmatrix} \rightarrow \begin{pmatrix} \lambda_1 & & 0 \\ & \lambda_2 & \\ 0 & & \lambda_3 \end{pmatrix}$$

READ THE PAPER. MATHEMATICA CODE

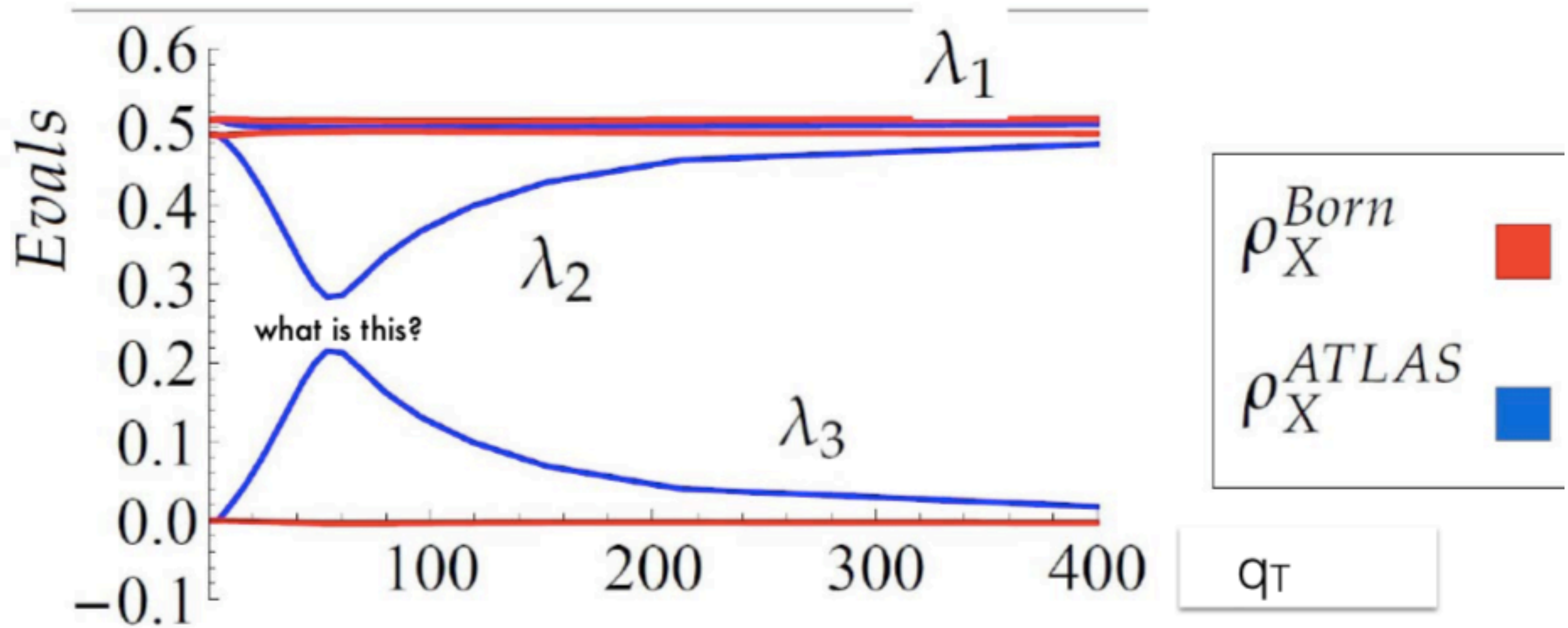
ONLINE PROCESS 10^9 EVENTS = FEW SEC

"CONVEX OPTIMIZATION"

The density matrix eigenvalues are strange

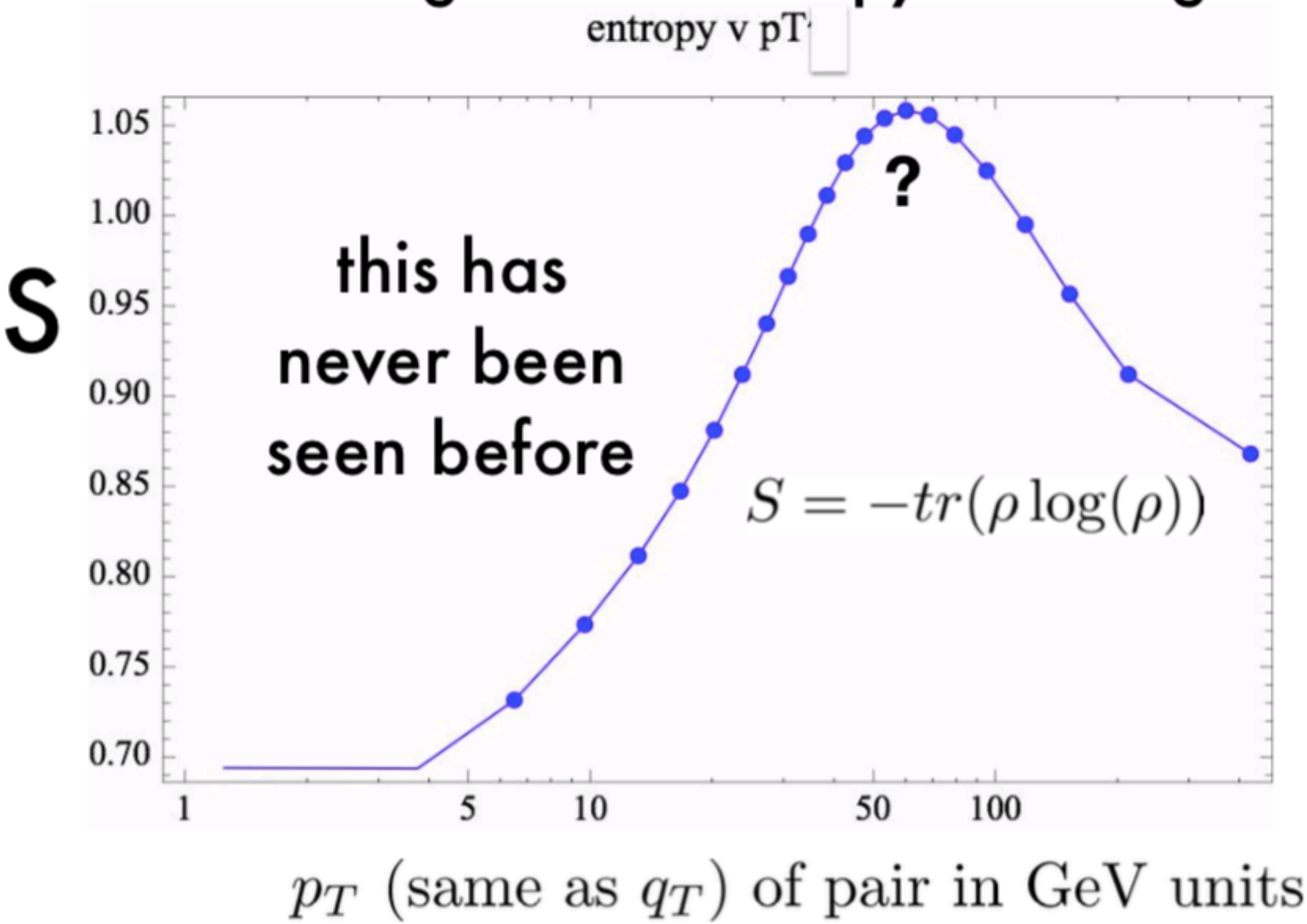
y-integrated data. **arXiv: 1606.00689**

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

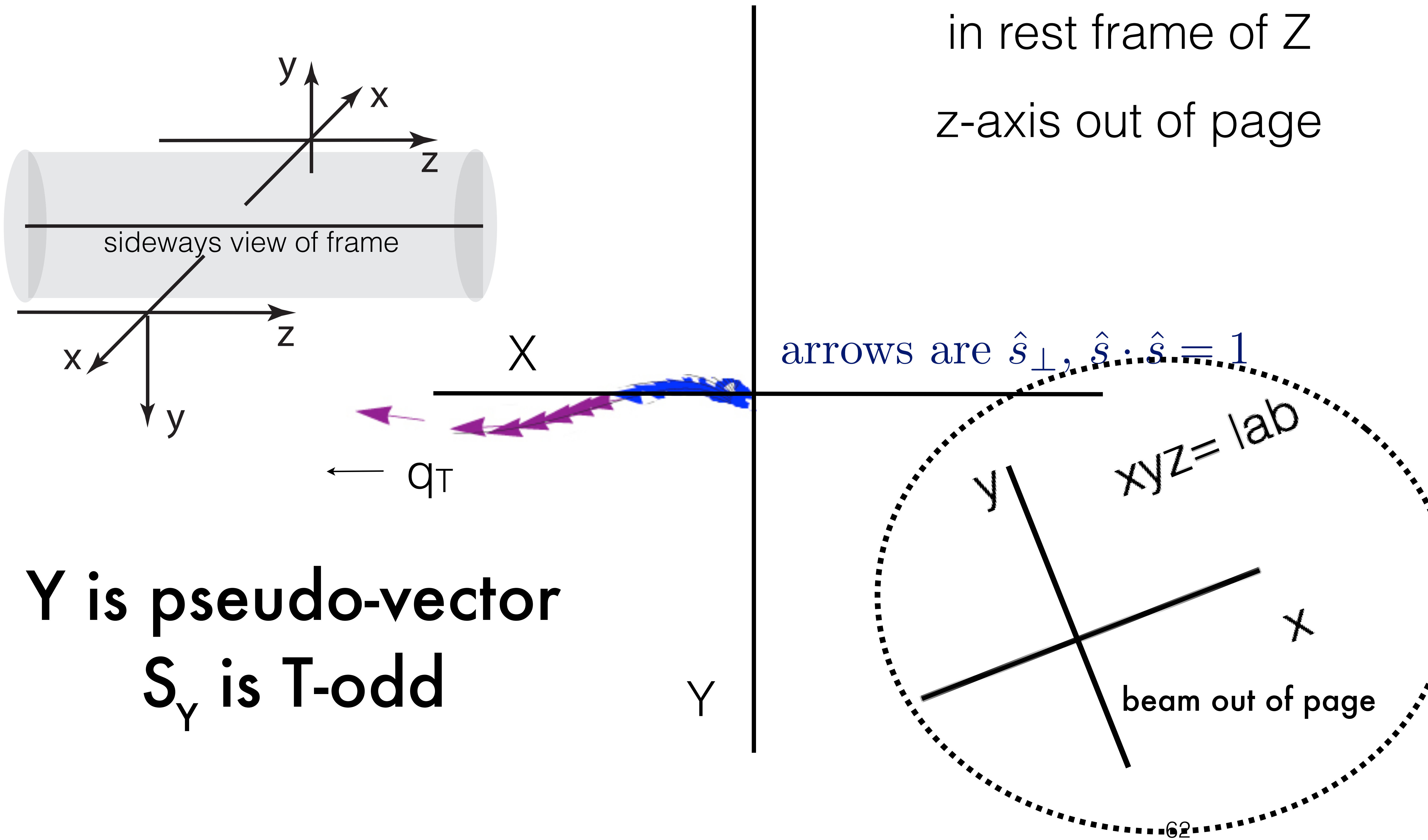


there is no precedent for the resonance-like bump

The entanglement entropy is strange



Unexpected discovery in spin parameters of the Z

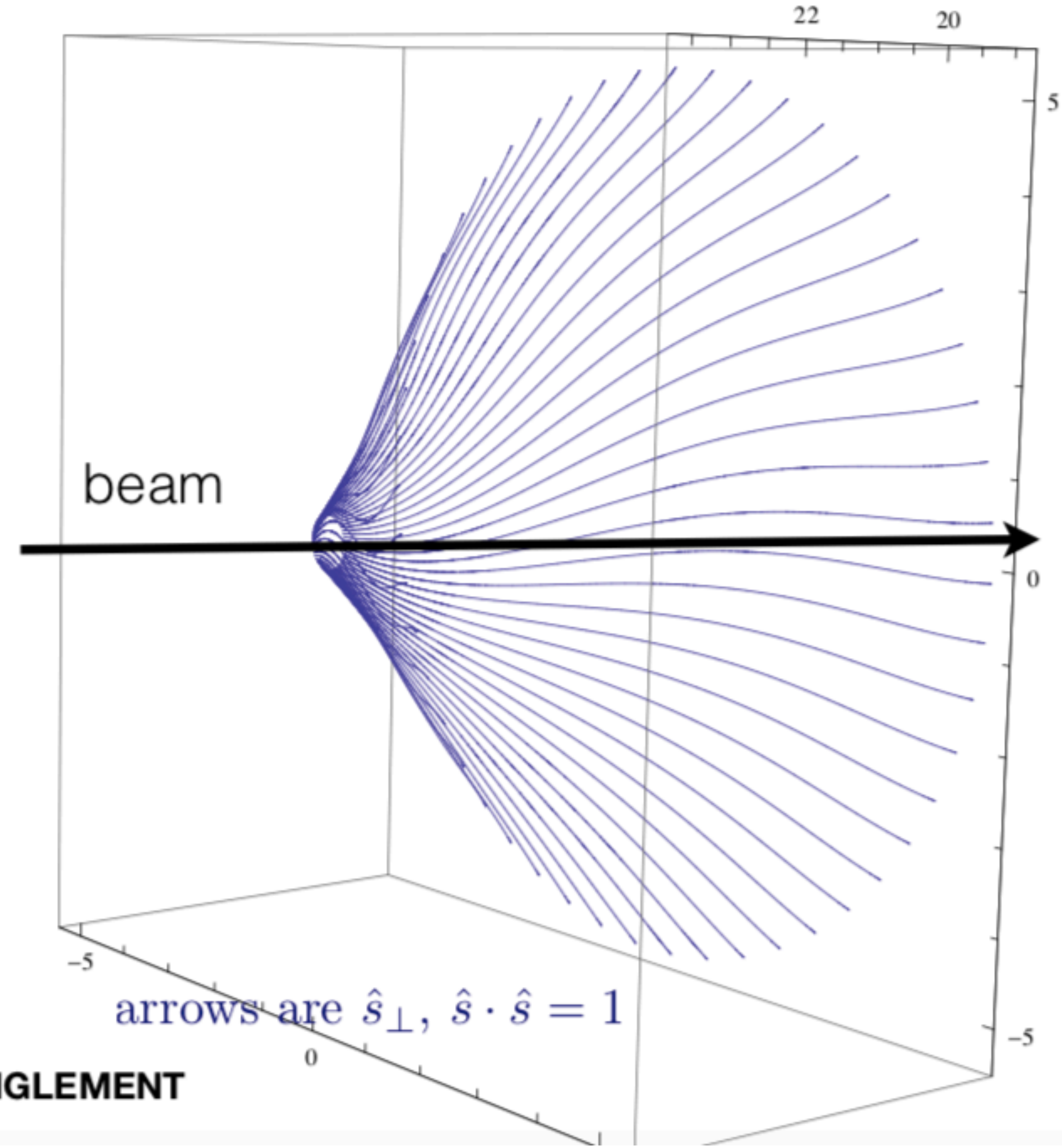


Y is pseudo-vector

S_Y is T-odd

3D holography of the Z spin, lab frame

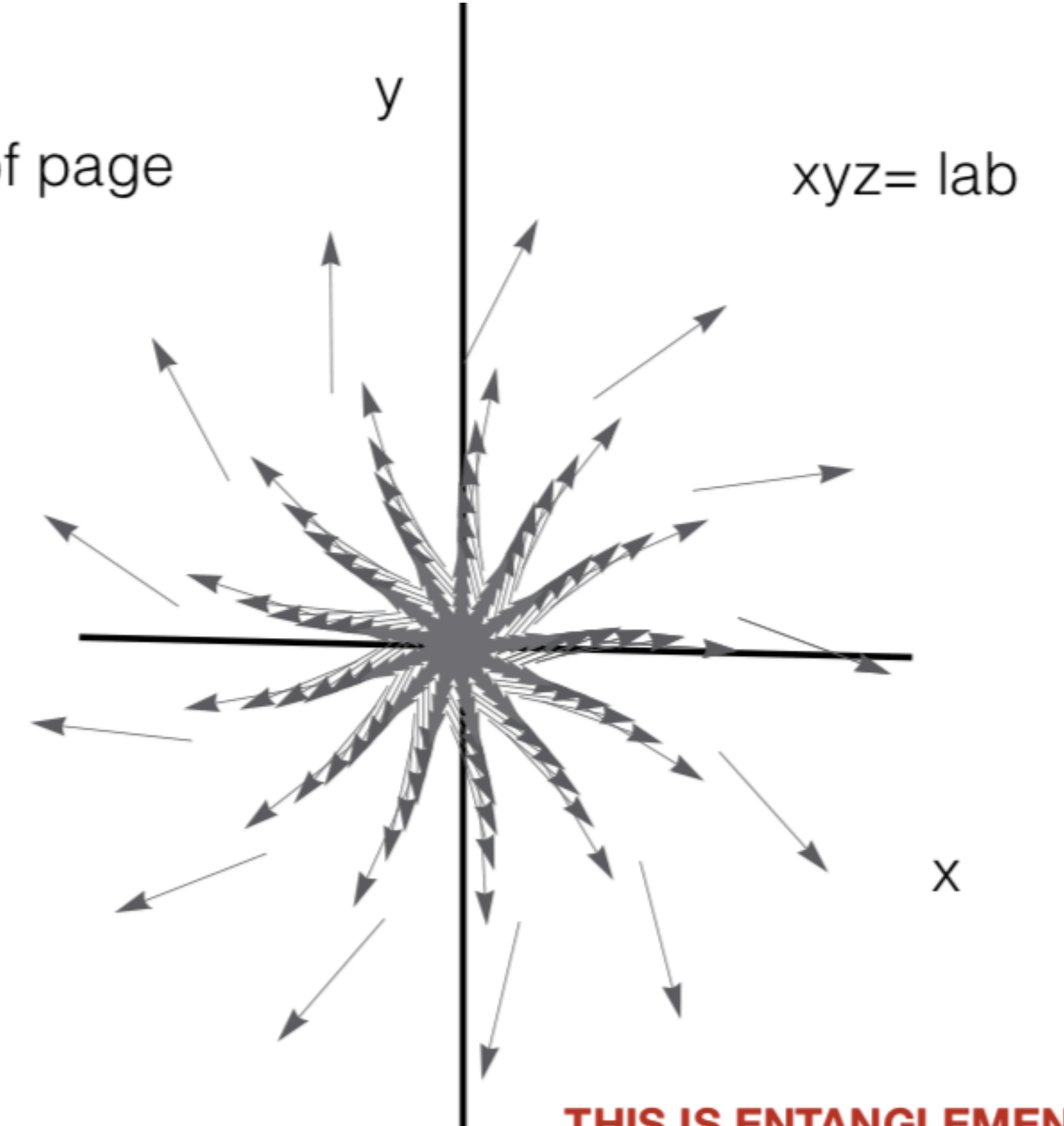
(q_x, q_y, q_z)



2% of Z's are polarized pure state spinning as shown

THIS IS ENTANGLEMENT

beam-axis out of page



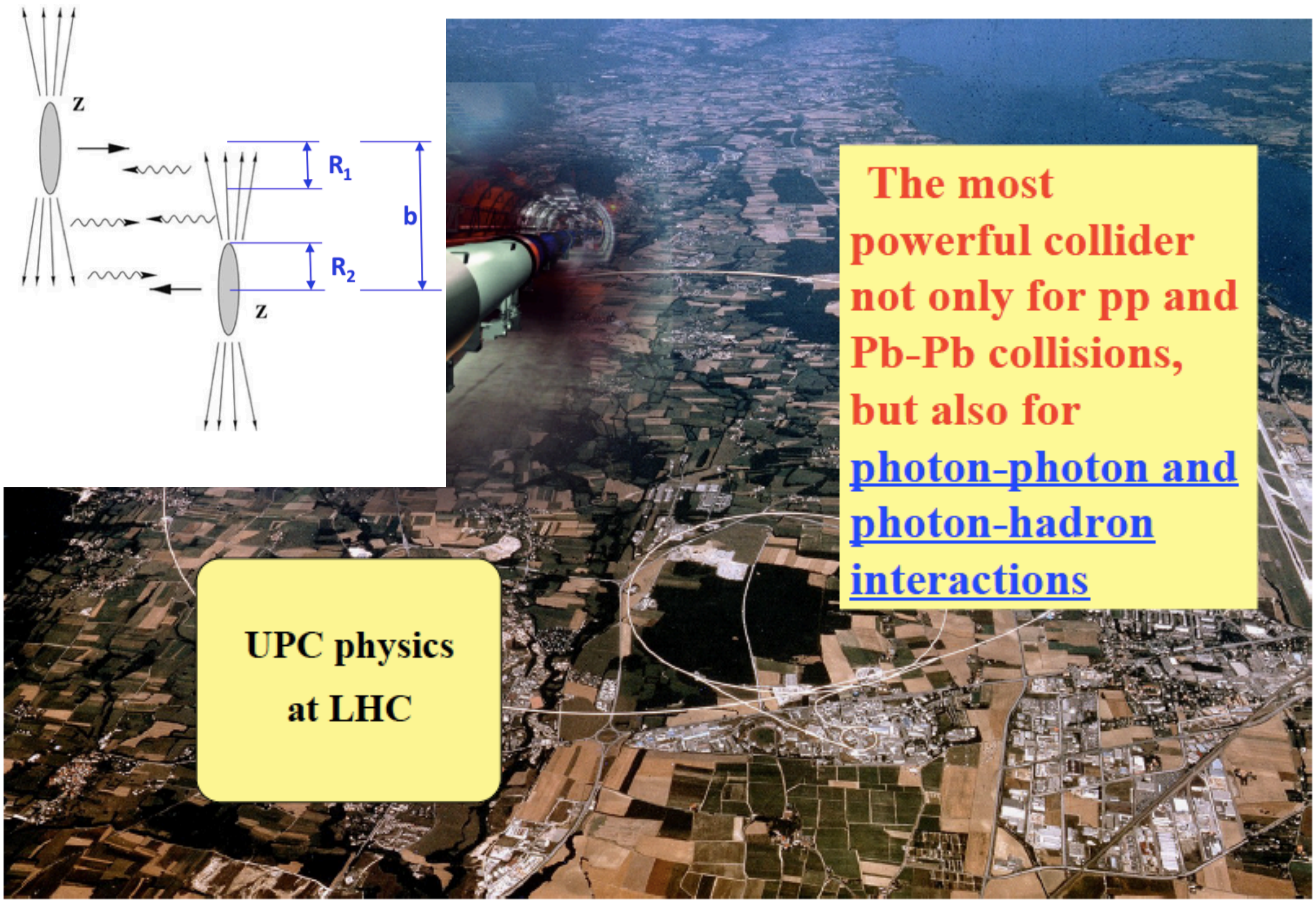
2% of Z's
are
polarized
pure state
spinning
as shown

THIS IS ENTANGLEMENT

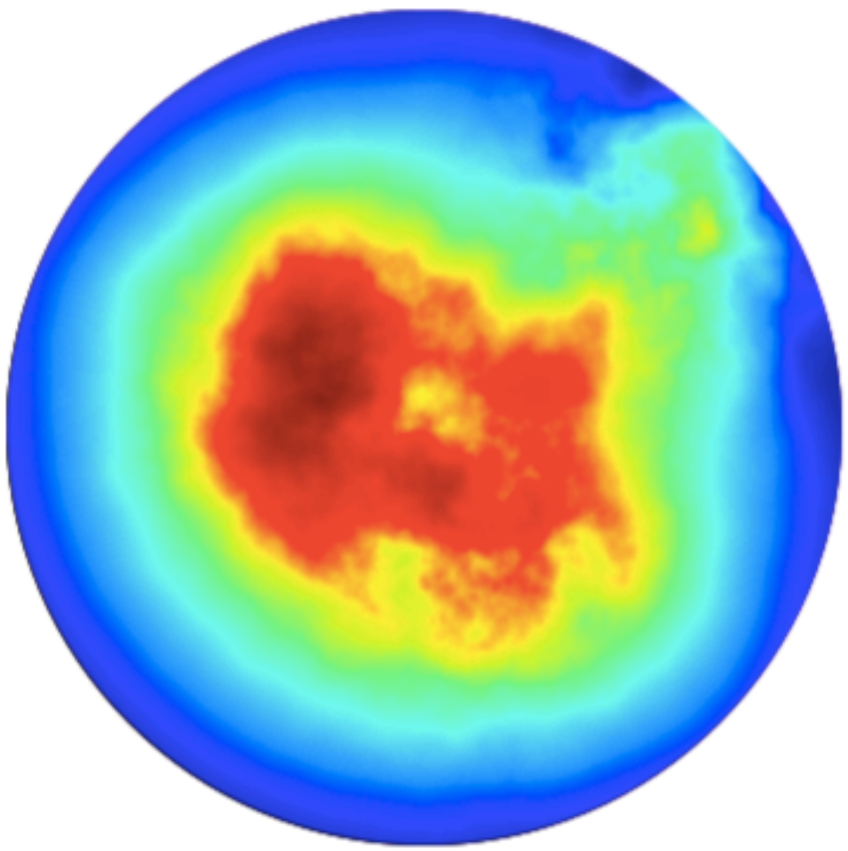
arrows are $\hat{s}_\perp$, $\hat{s} \cdot \hat{s} = 1$

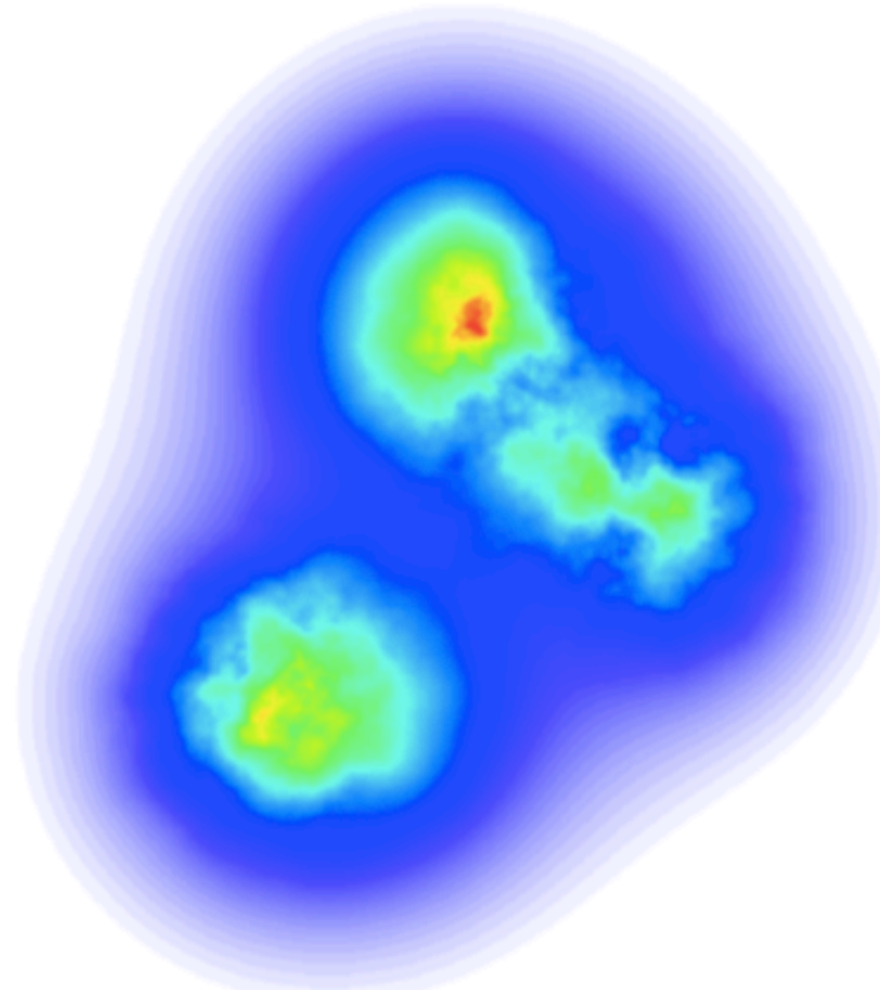
Another example

Photon-photon, photon-p, photon-A collider

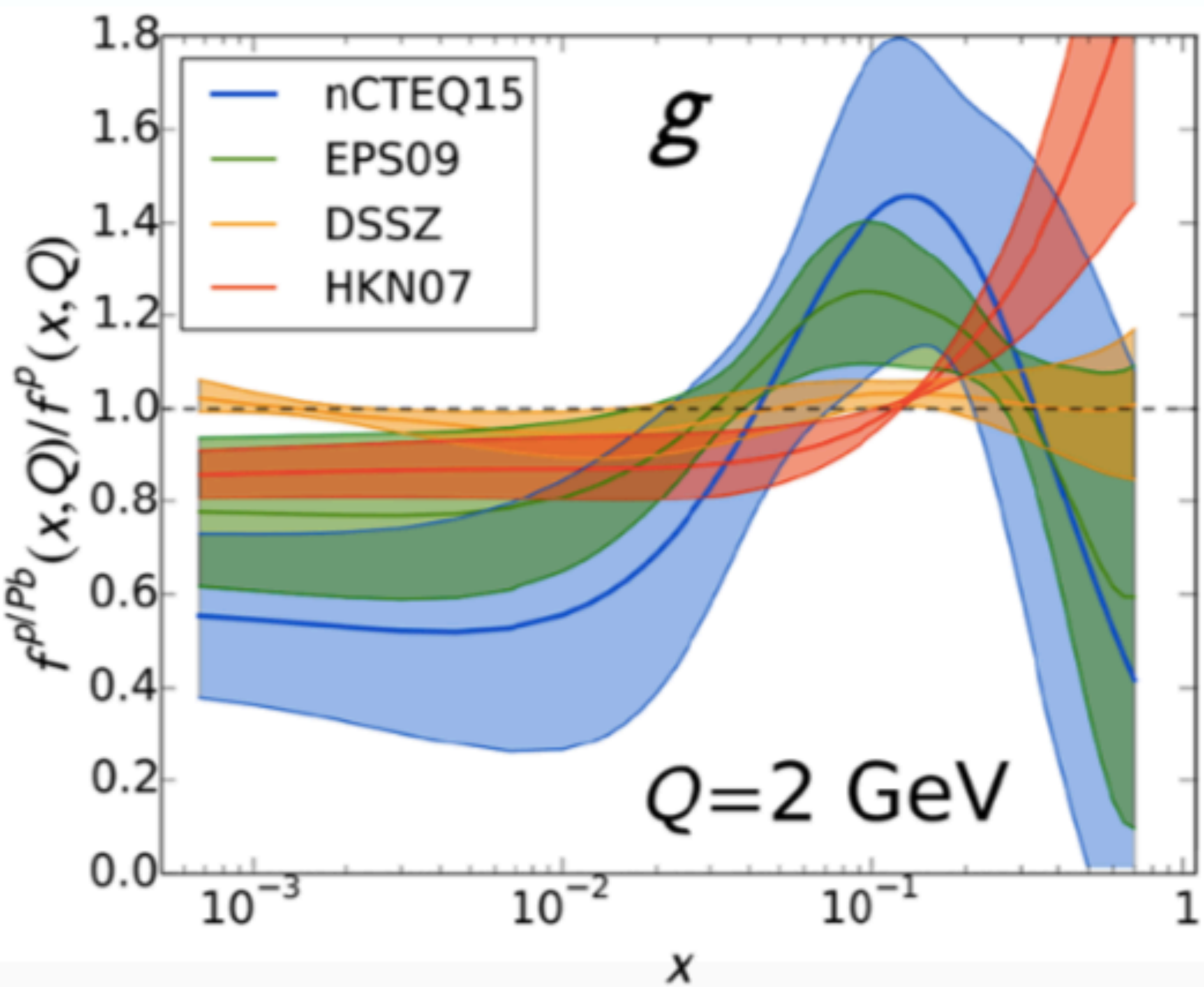


What does the proton look like?





Nuclear gluon density

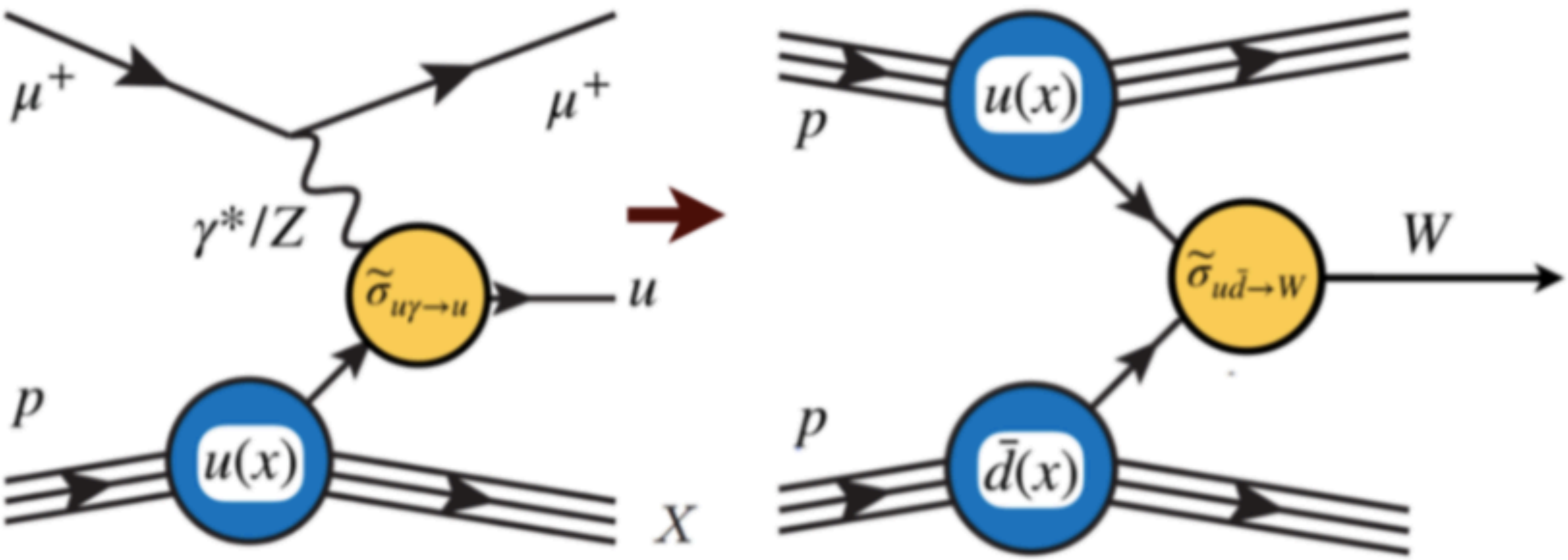


UPC studies provide the best information the community will get for the next 10 years before, the EIC turns on

The Global QCD analysis paradigm

QCD factorisation theorems**: PDF universality**

$$\sigma_{lp\to\mu X} = \widetilde{\sigma}_{u\gamma\to u} \otimes u(x) \quad \rightarrow \quad \sigma_{pp\to W} = \widetilde{\sigma}_{u\bar{d}\to W} \otimes u(x) \otimes \bar{d}(x)$$



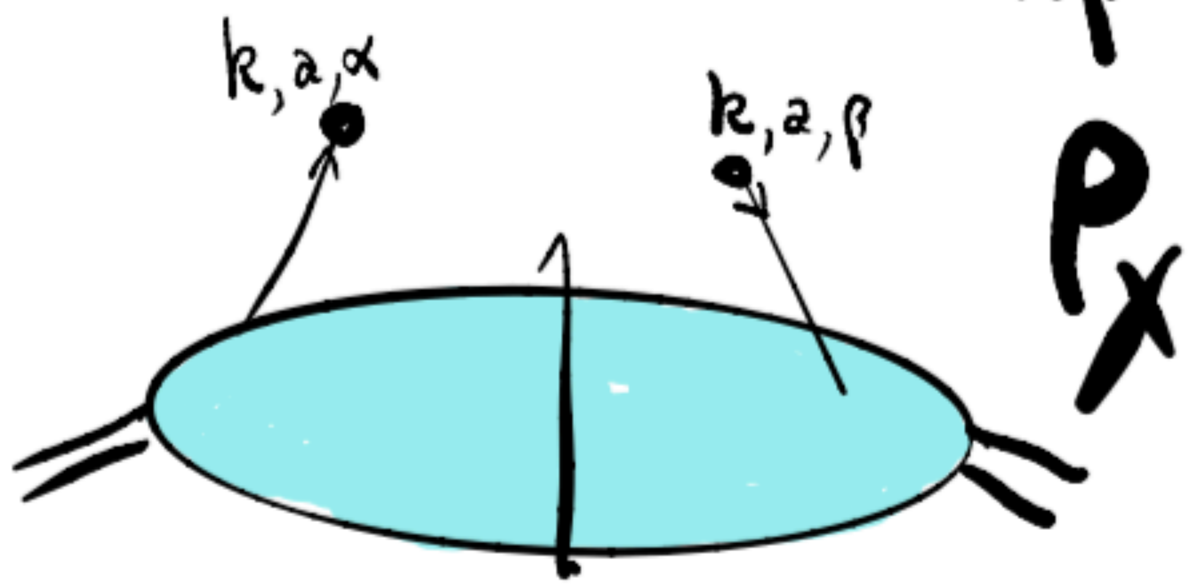
*Determine PDFs from **deep-inelastic scattering**…*

*… and use them to compute predictions for **proton-proton collisions***

From J. Rojo. DIS 2019

PARTON DISTRIBUTIONS AIN'T DISTRIBUTIONS

$$\rho^{\vec{x},\vec{x}'}_{\alpha\beta} \to \rho_{\alpha\beta}(\bar{k})\,\delta(\bar{k}-\bar{k}')$$



PARTON "DISTRIBUTIONS" ARE DENSITY MATRICES

DIAGONAL IN MOMENTUM, NOT POLARIZATION

Begin with Some Results

"dijets" means
2 LHC jets, each
made of many particles
plus everything else not measured

histograms show a
Lorentz-invariant angular
distribution of jet1 v jet 2

measuring a density matrix

raw data processed, bypassing 600 pages of theory papers

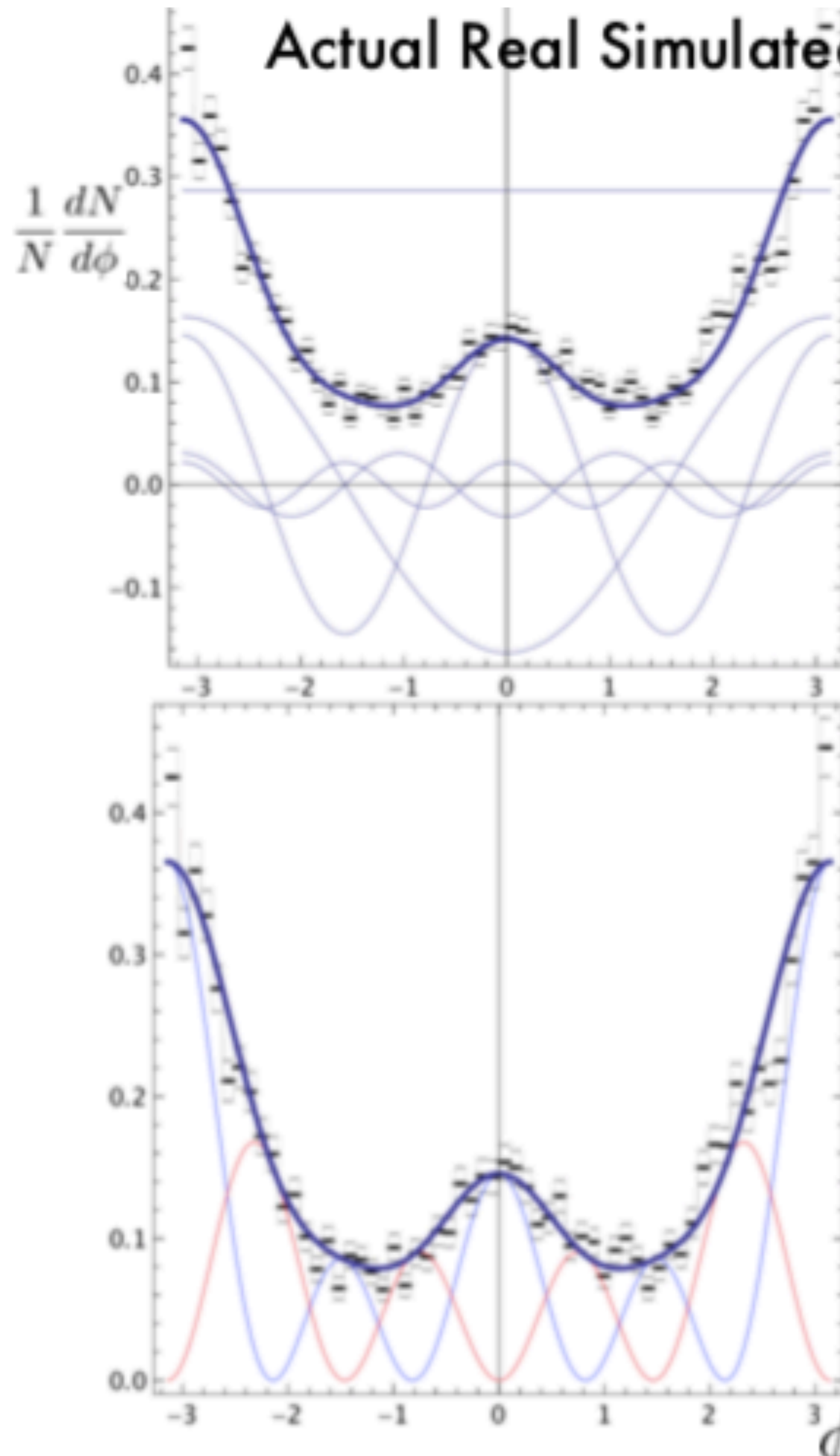


FIG. 4: Top: Maximum likelihood fit, with the contributions of $\cos m\phi$ for $m = 0 - 4$. Bottom: weighted distributions defined by $f_+(\phi) = Re(\psi)^2$ (blue) and $f_-(\phi) = Im(\psi)^2$ (red), coming f the eigenstates of the rank two density matrix.

It’s time to wind this up…

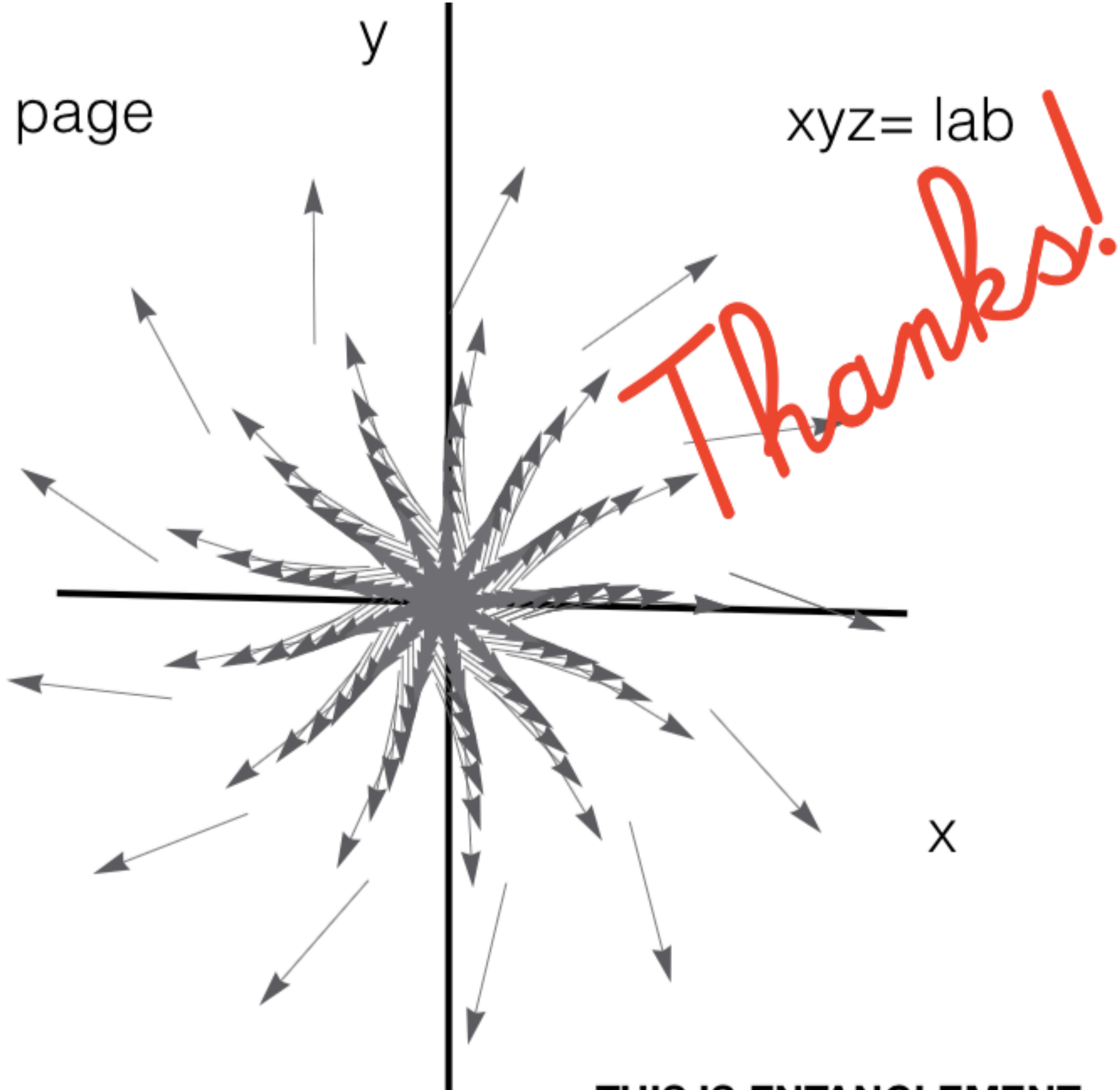
KIDS LEARN WHAT YOU TEACH THEM

20 YEARS of NONSENSE NEVER CORRECTED


Don't Do This!

beam-axis out of page

2% of Z's
are
polarized
pure state
spinning
as shown



THIS IS ENTANGLEMENT

arrows are $\hat{s}_{\perp}$, $\hat{s} \cdot \hat{s} = 1$