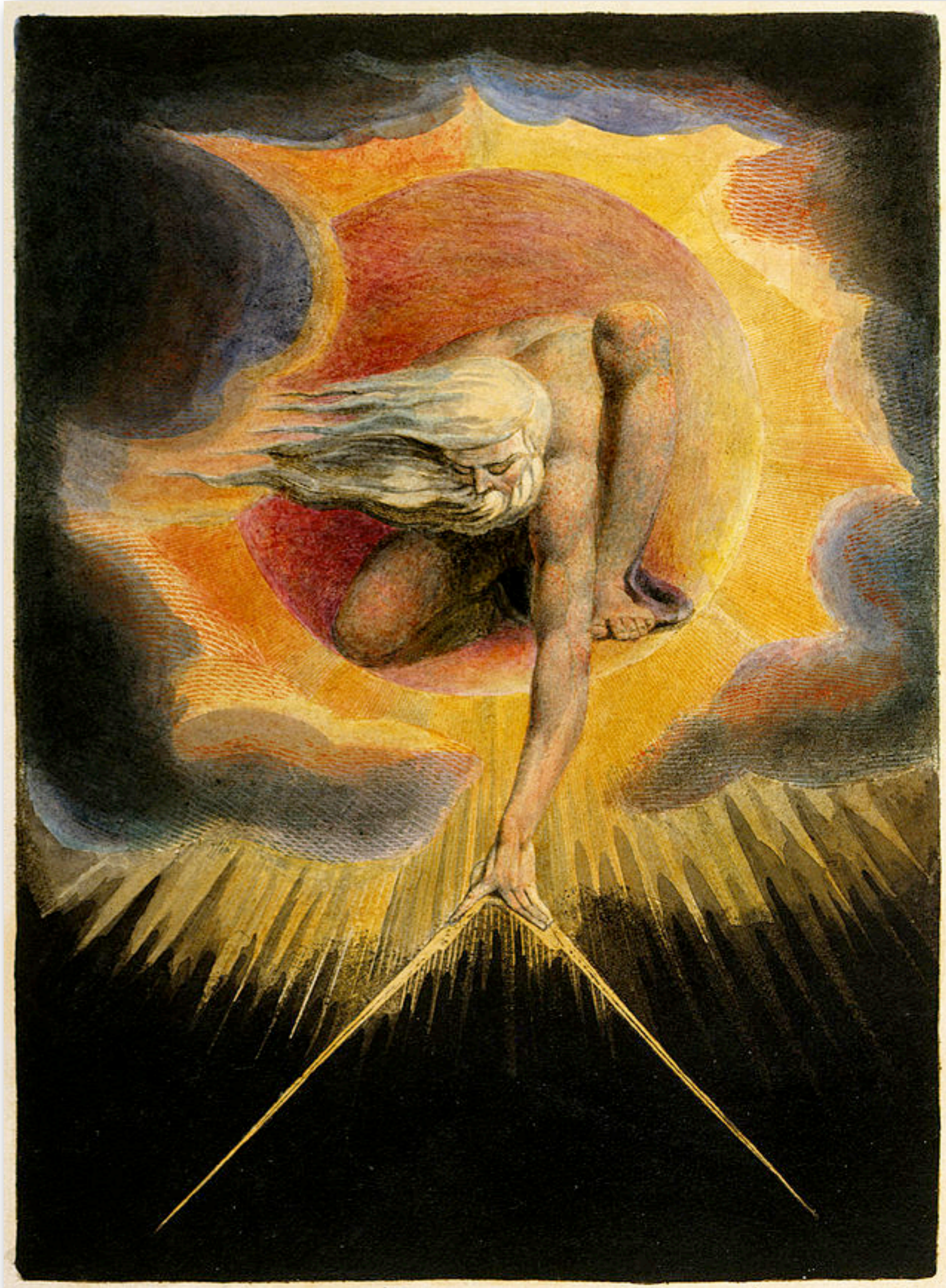
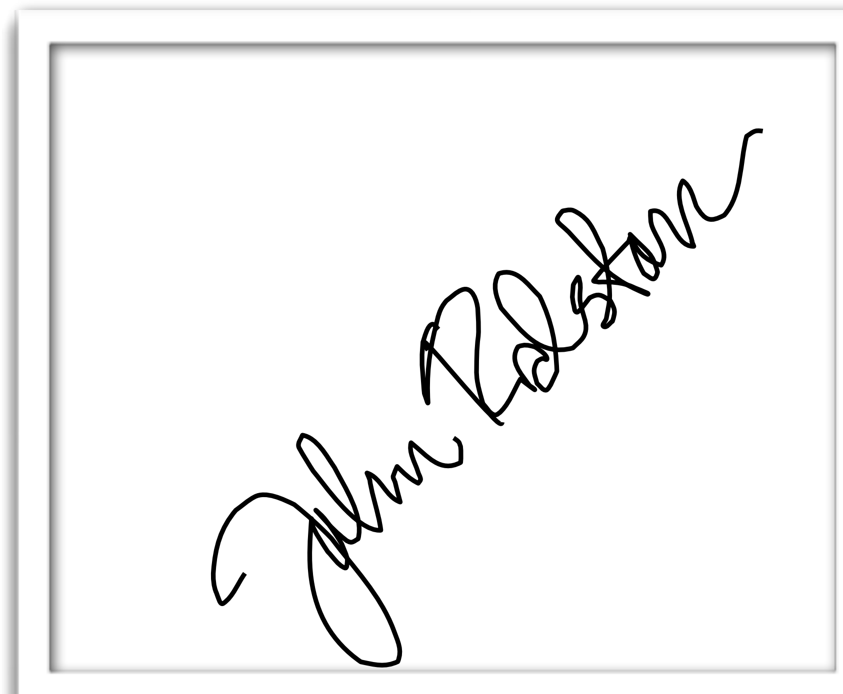


Quantum Tomography Finds Entanglement



with John Martens
and
Daniel Tapia Takaki

Executive Summary

We bypass 75 years of field theoretic formalism and particle physics superstructure to describe systems model-independently in terms of basic quantum mechanics

Schoolbooks talk about wave functions!

Inclusive experiments measure **density matrices** *traced down from larger density matrices*

But first: An advertisement

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How to Understand Quantum Mechanics

John P. Ralston

Cover art by John C. Ralston, the author's son

How to Understand Quantum Mechanics presents an accessible introduction to understanding quantum mechanics in a natural and intuitive way, which was advocated by Erwin Schrodinger and Albert Einstein. A theoretical physicist reveals dozens of easy tricks that avoid long calculations, makes complicated things simple, and bypasses the worthless anguish of famous scientists who died in angst. The author's approach is light-hearted, and the book is written to be read without equations, however all relevant equations still appear with explanations as to what they mean. The book entertainingly rejects quantum disinformation, the MKS unit system (obsolete), pompous non-explanations, pompous people, the hoax of the "uncertainty principle" (it's just a math relation), and the accumulated junk-DNA that got into the quantum operating system by misreporting it.

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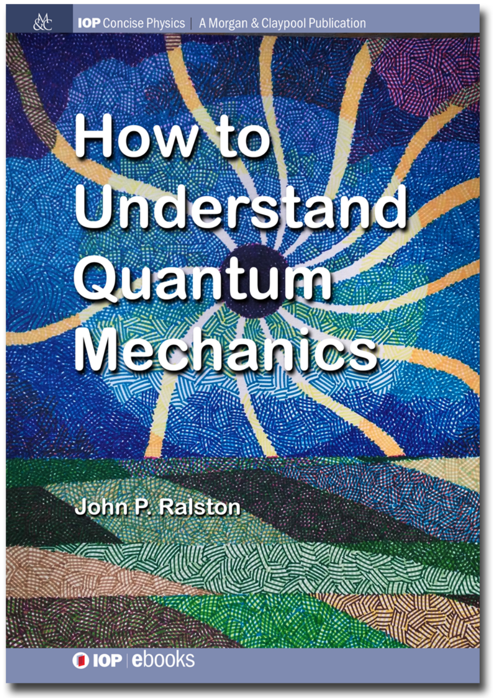
An accessible introduction to understanding quantum mechanics in a natural and intuitive way, which was advocated by Erwin Schroedinger and Albert Einstein



How to Understand Quantum Mechanics

John P. Ralston, *The University of Kansas*

Paperback ISBN: 9781681741628 • eBook ISBN: 9781681742267
May, 2018 • 107 pages
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ABOUT THE AUTHOR

John P Ralston, PhD, is a Professor of Physics and Astronomy at The University of Kansas. He received his PhD in high-energy theory physics from the University of Oregon. His research interests include high energy theory, strong interaction physics, particle astrophysics, cosmology, and practical data analysis.

CONTENTS

Made to correct disinformation given to students and all of us

No principles!
No postulates !
Quantum mechanics itself is *descriptive*, not *predictive*

Institute of Physics series will be in your library.

You don't need to buy it

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

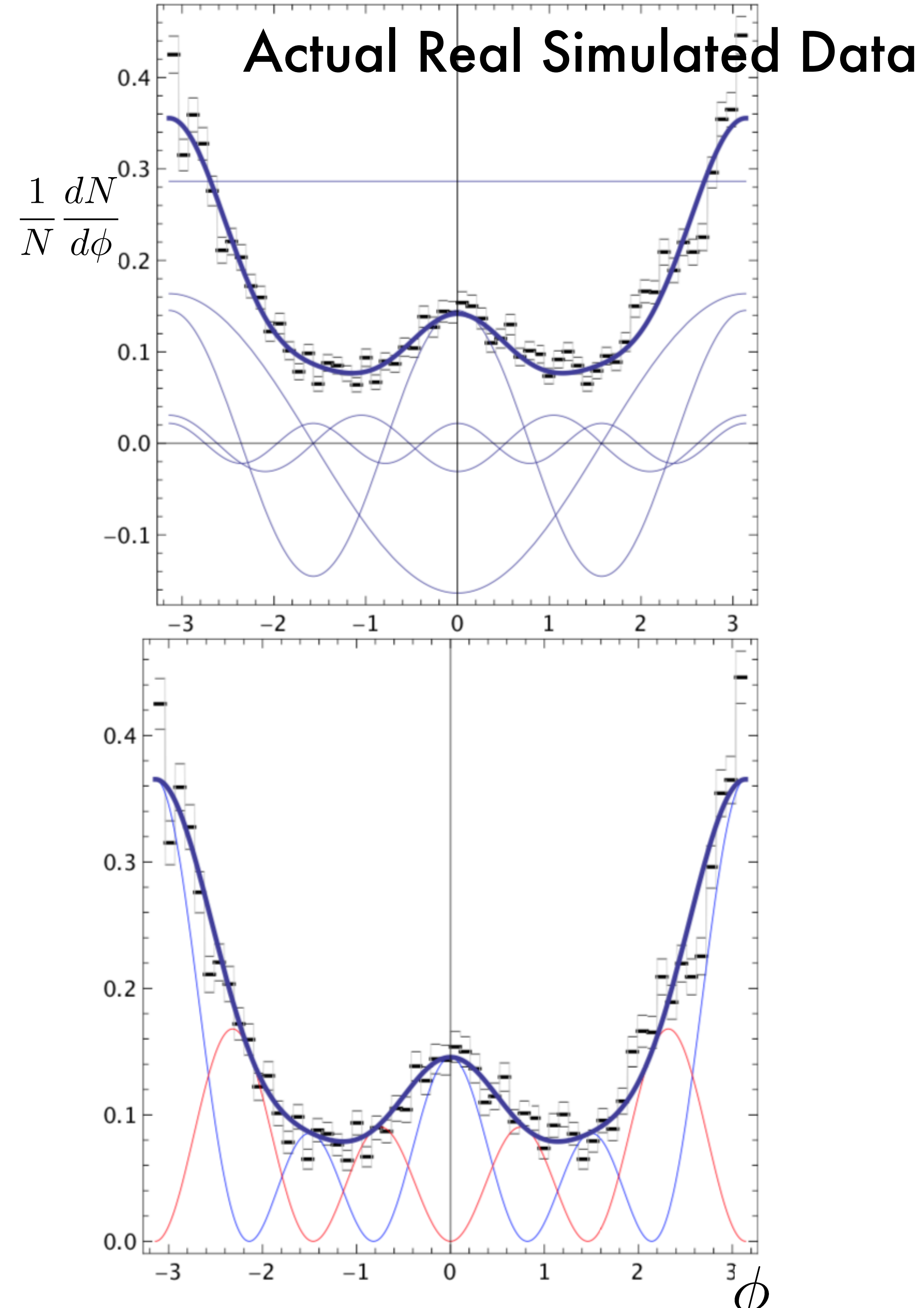


FIG. 4: Top: Maximum likelihood fit, with the contributions of $\cos m\phi$ for $m = 0 - 4$. Bottom: Two weighted distributions defined by $f_+(\phi) = Re(\psi)^2$ (blue) and $f_-(\phi) = Im(\psi)^2$ (red), coming from the eigenstates of the rank two density matrix.

mandatory diagram for collider theorists

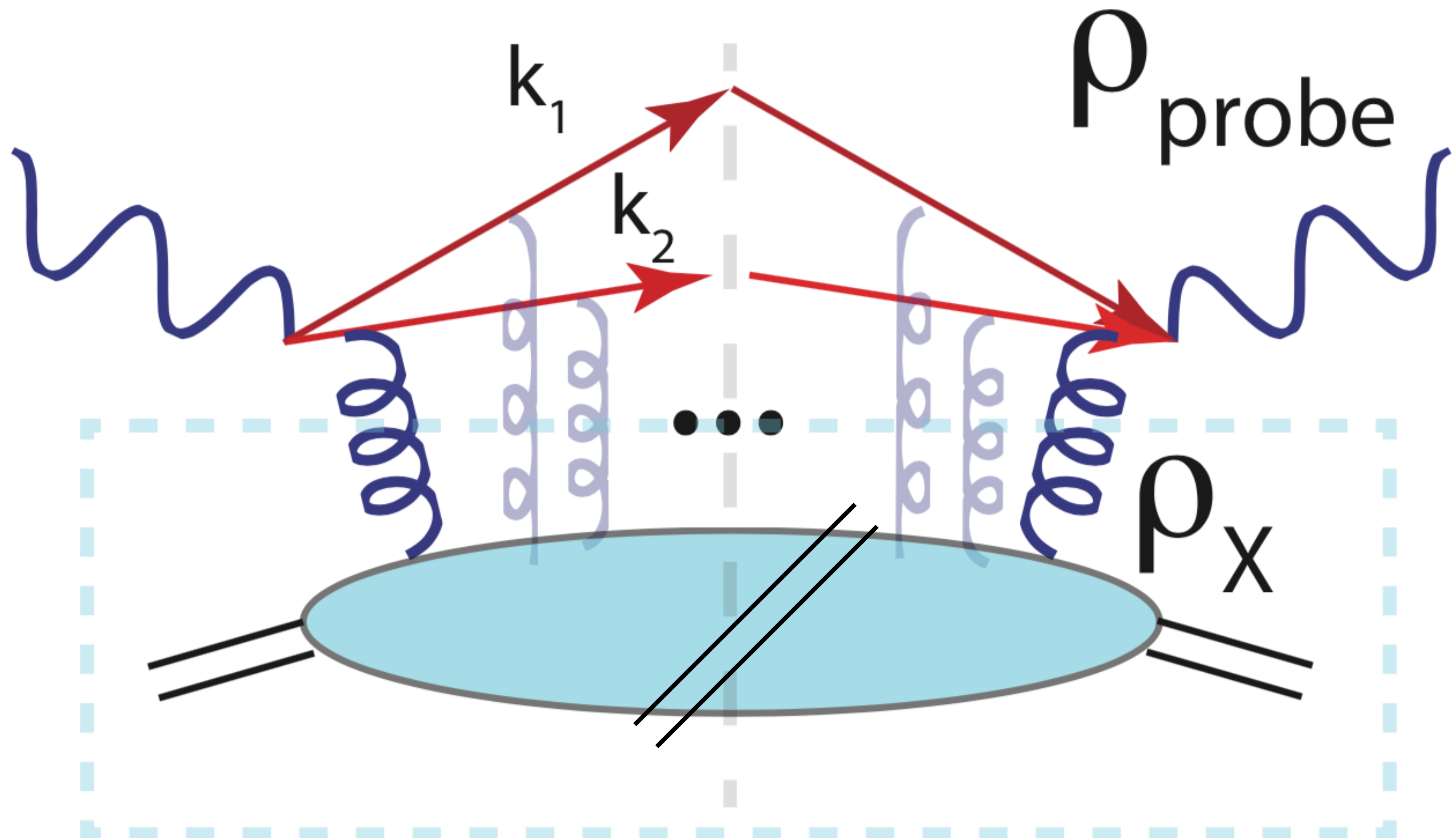


FIG. 1: By analogy with deeply inelastic scattering, a dijet probe replaces the handle of the handbag diagram with a shoulder strap (red) defining new elements of the probe density matrix ρ_{probe}. Each orthogonal element of ρ_{probe} can extract a corresponding projection of the unknown system density 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.

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

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

ρ_{probe} = known density matrix

ρ_X = unknown density matrix

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

Begin with Some Results

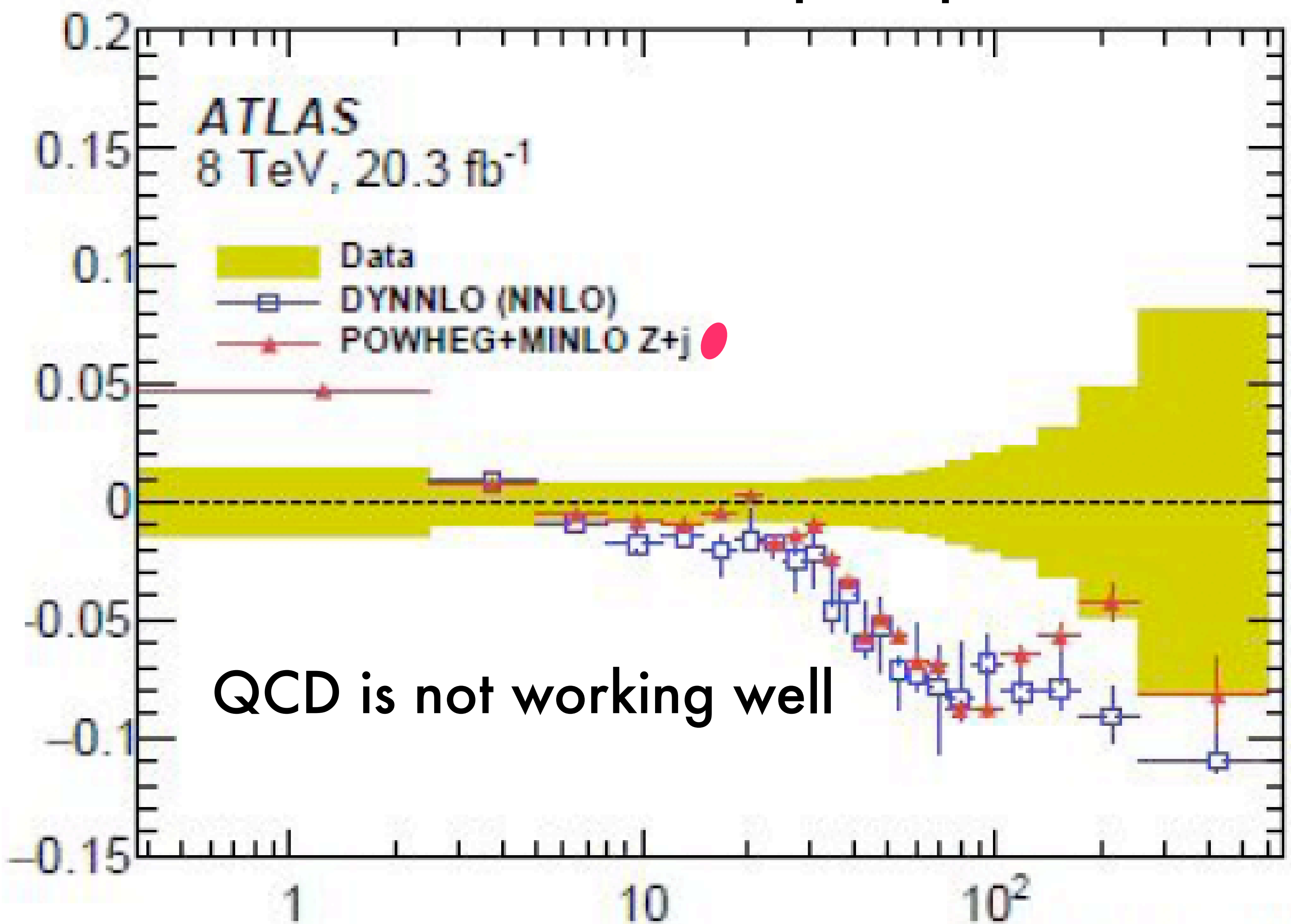
ATLAS data
1606.00689

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

"lepton pairs"

$(A_0 - A_2)$

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



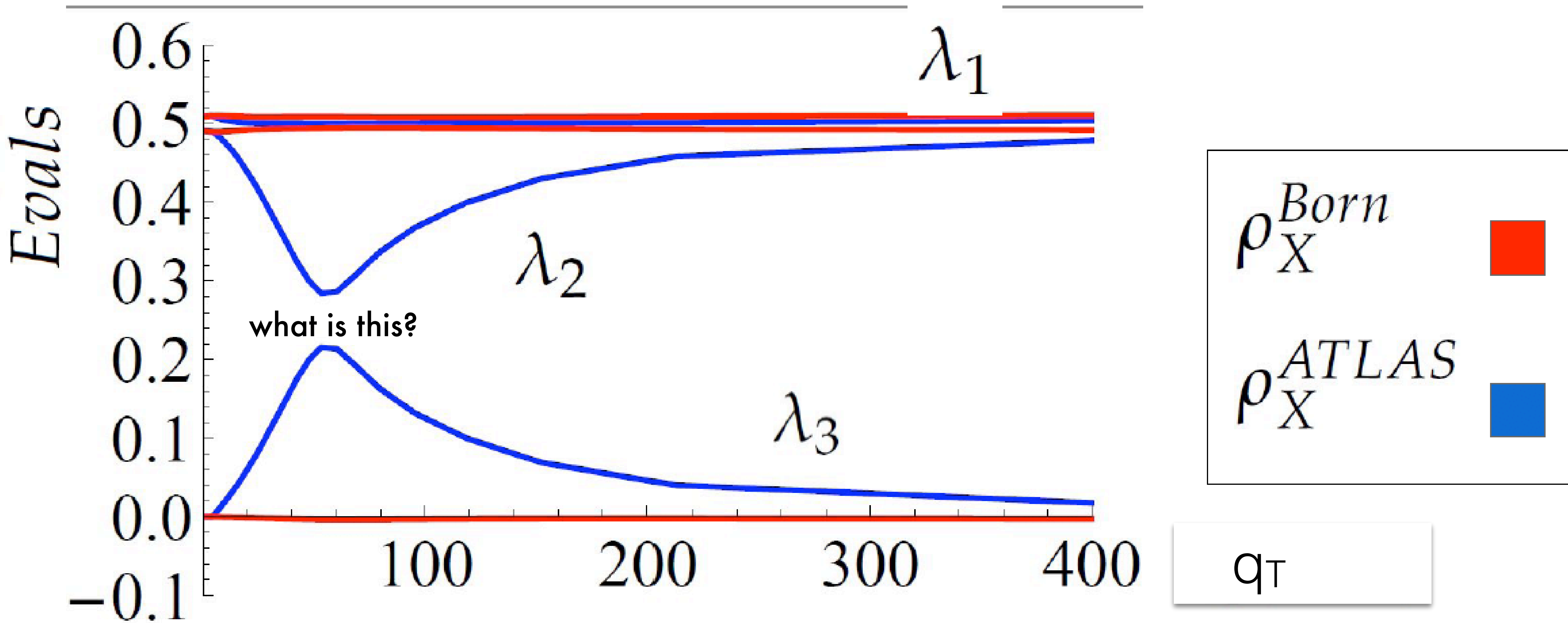
"Lam-Tung fails"

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

The density matrix eigenvalues are strange

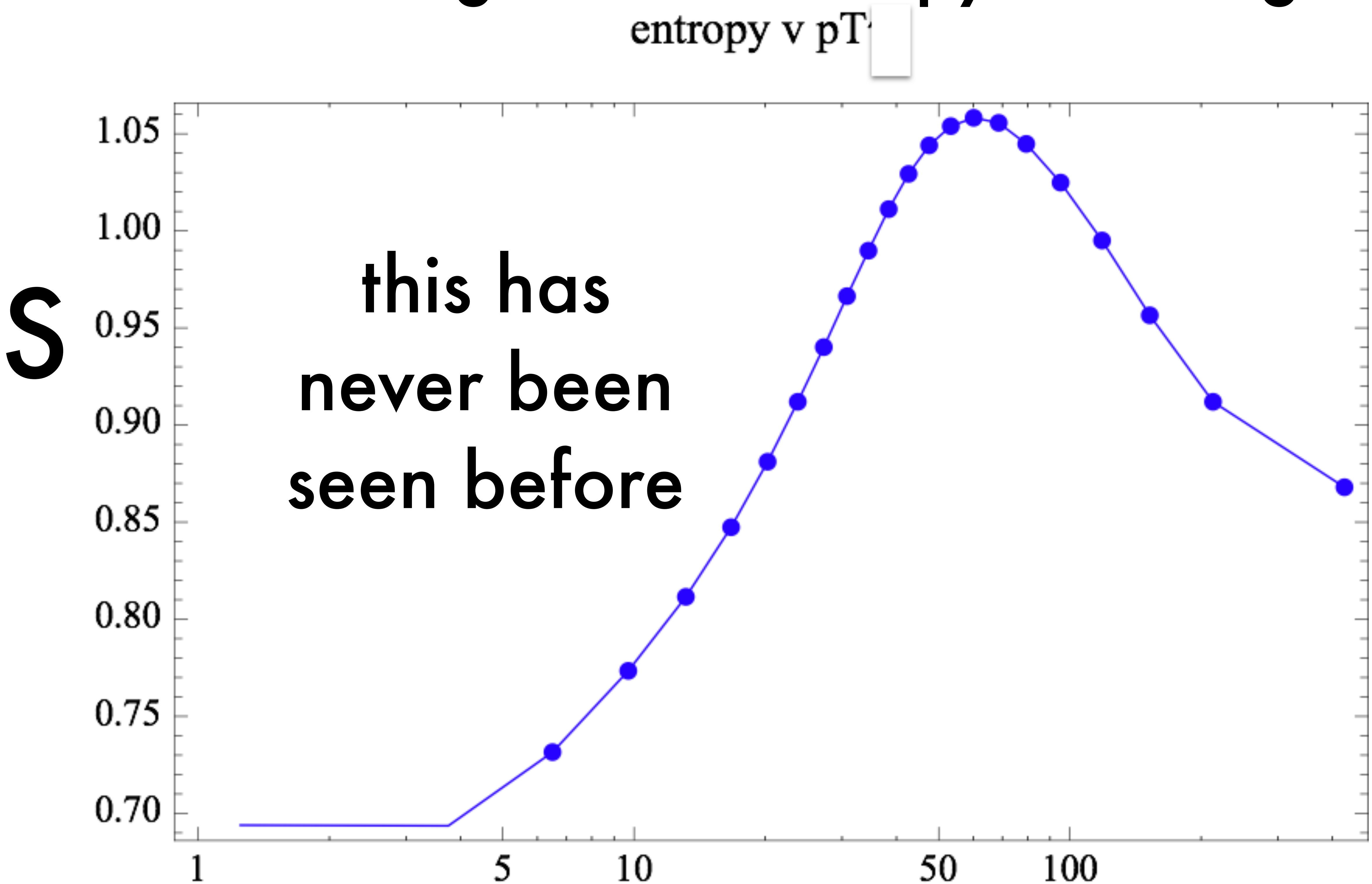
y-integrated data. **arXiv: 1606.00689**

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



p_T (same as q_T) of pair in GeV units

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.

It encodes observable data.

If and when rank=1,

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

defines $|\psi >$

Wave functions are observable, up to the undetermined phase of eigenstates

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

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

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

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

$\rho(X)$ = unknown density matrix

reconstruction:

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

IF probe is two "massless" fermions 1/2 x 1/2 x 1/2 x 1/2

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

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 from another experiment. Indeed we did.

We don't need a theory. Sometimes less theory is better theory.

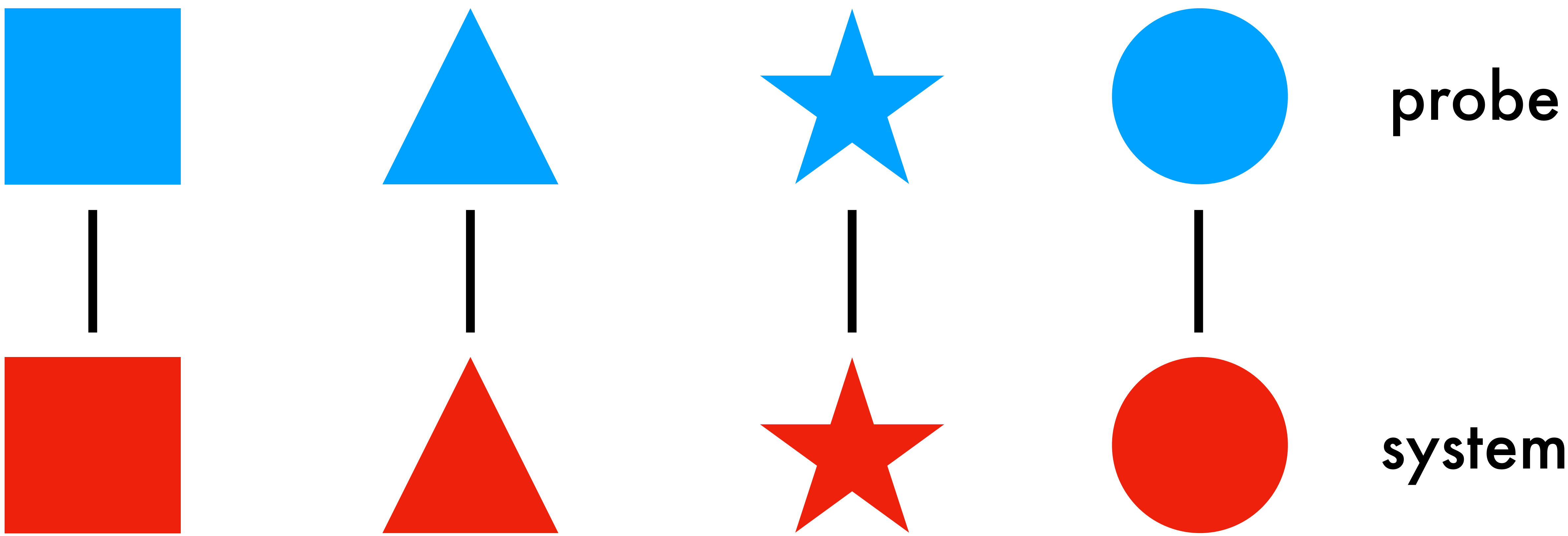
The Mirror Trick

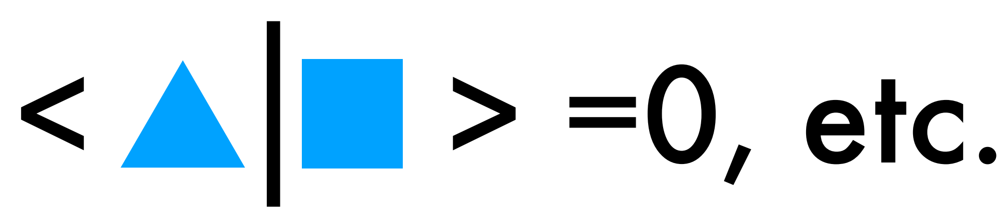
3 spin 1 tensors

5 spin 2 tensors

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

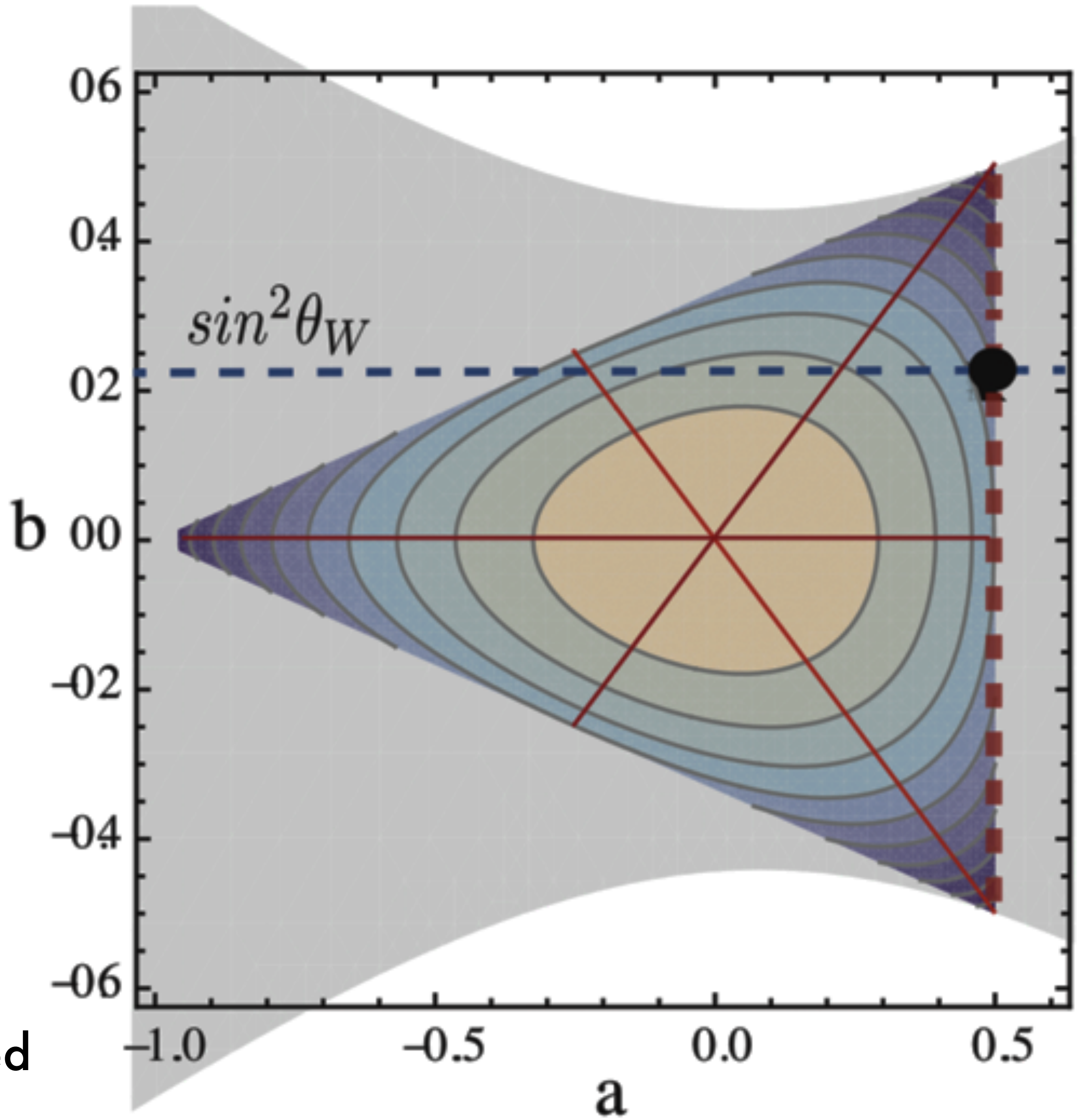
System: $\rho_{ij}(X) = \frac{1}{3}\delta_{ij} + \frac{1}{2}\vec{S}\cdot\vec{J}_{ij} + U_{ij}(X);$ where $U(X) = U^T(X);$ $tr(U(X)) = 0.$





Bonus:

gray:
positivity
of
cross section



color:
positivity
of
eigenvalues

vertical line:on shell
helicity conservation

contours:
constant
entropy

both CMS and ATLAS
have positivity wrong,
when it's even mentioned

FIG. 2: Contours of constant entropy $\mathcal{S}$ of the lepton density matrix $\rho(\ell)$ (Eq. 3) in the plane of parameters (a, b). Contours are separated by 1/10 unit with $\mathcal{S} = 0$ at the central intersection. The horizontal dashed line shows the lowest order Standard Model prediction $b = sin^2\theta_W$. Annihilation with on-shell helicity conservation is indicated by the vertical dashed line $a = 1/2$. The left corner of the triangle is a pure state with longitudinal polarization, while the two right corners are pure states of circular polarization. The interior lines represent matrices with maximal symmetry, where two eigenvalues are equal. They cross at the unpolarized limit. The curved gray region represents the much less restrictive constraints of a positive distribution using Eq. 8 and lepton universality.

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

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

Solve with not quite Collins-Soper:

$$\tilde{Z}^\mu = P_A^\mu Q \cdot P_B - P_B^\mu Q \cdot P_A;$$
$$\tilde{X}^\mu = Q^\mu - P_A^\mu \frac{Q^2}{2Q \cdot P_A} - P_B^\mu \frac{Q^2}{2Q \cdot P_B};$$
$$\tilde{Y}^\mu = \epsilon^{\mu\nu\alpha\beta} P_{A\nu} P_{B\alpha} Q_\beta.$$

Everything is Lorentz invariant and easy

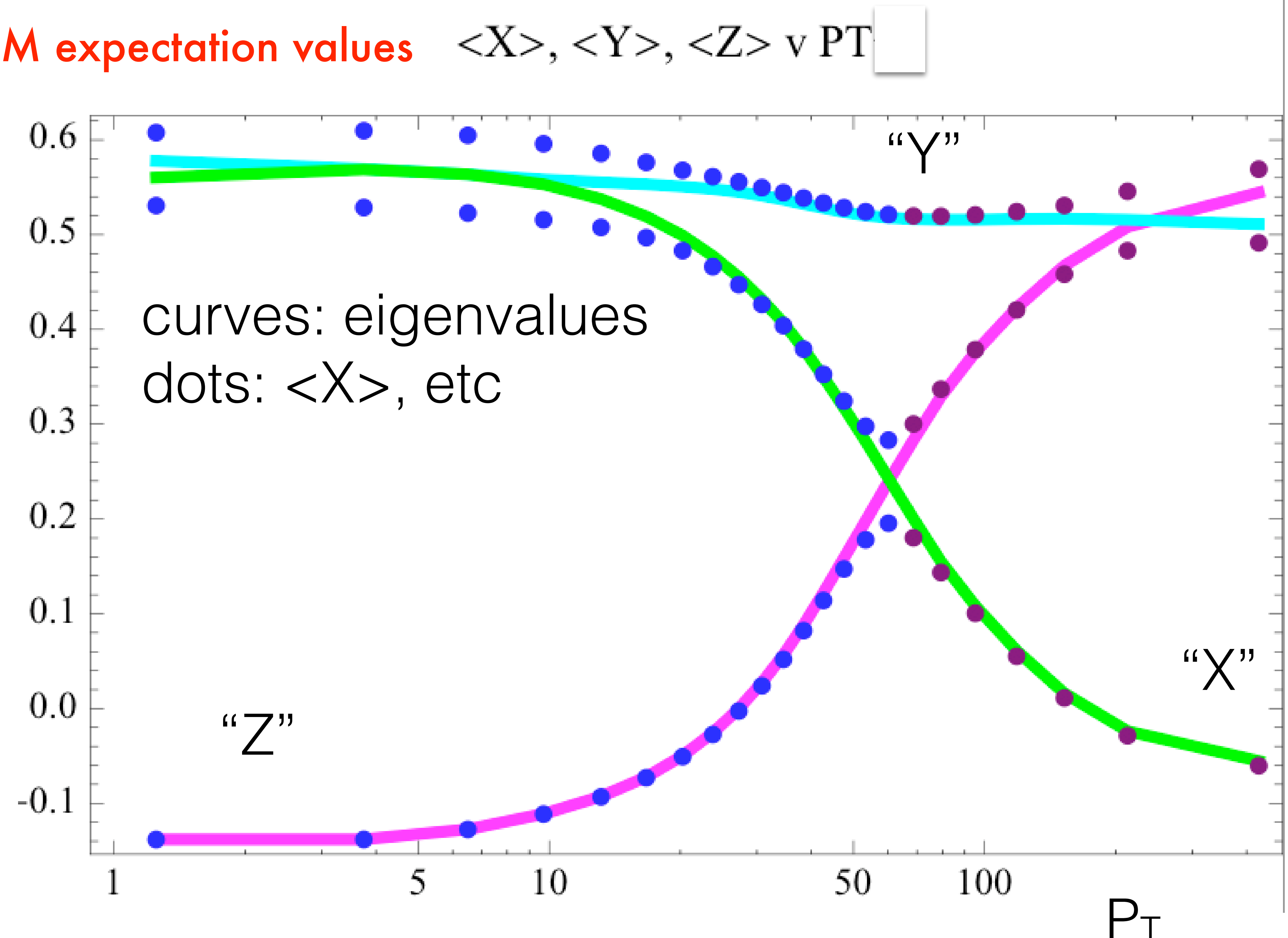
To analyze data for each event labeled J:

$$\text{Compute} \quad Q_{(J)} = k_J + k'_J; \quad \ell_J = k_J - k'_J; \quad (X^\mu_J, Y^\mu_J, Z^\mu_J);$$
$$\vec{\ell}_{XYZ,J} = (X_J \cdot \ell_J, Y_J \cdot \ell_J, Z_J \cdot \ell_J);$$
$$\hat{\ell}_J = \ell_{XYZ,J} / \sqrt{-\ell_{XYZ,J} \cdot \ell_{XYZ,J}}.$$

use lab momenta to compute invariants

Avoided level crossing; eigenvectors swap

true QM expectation values

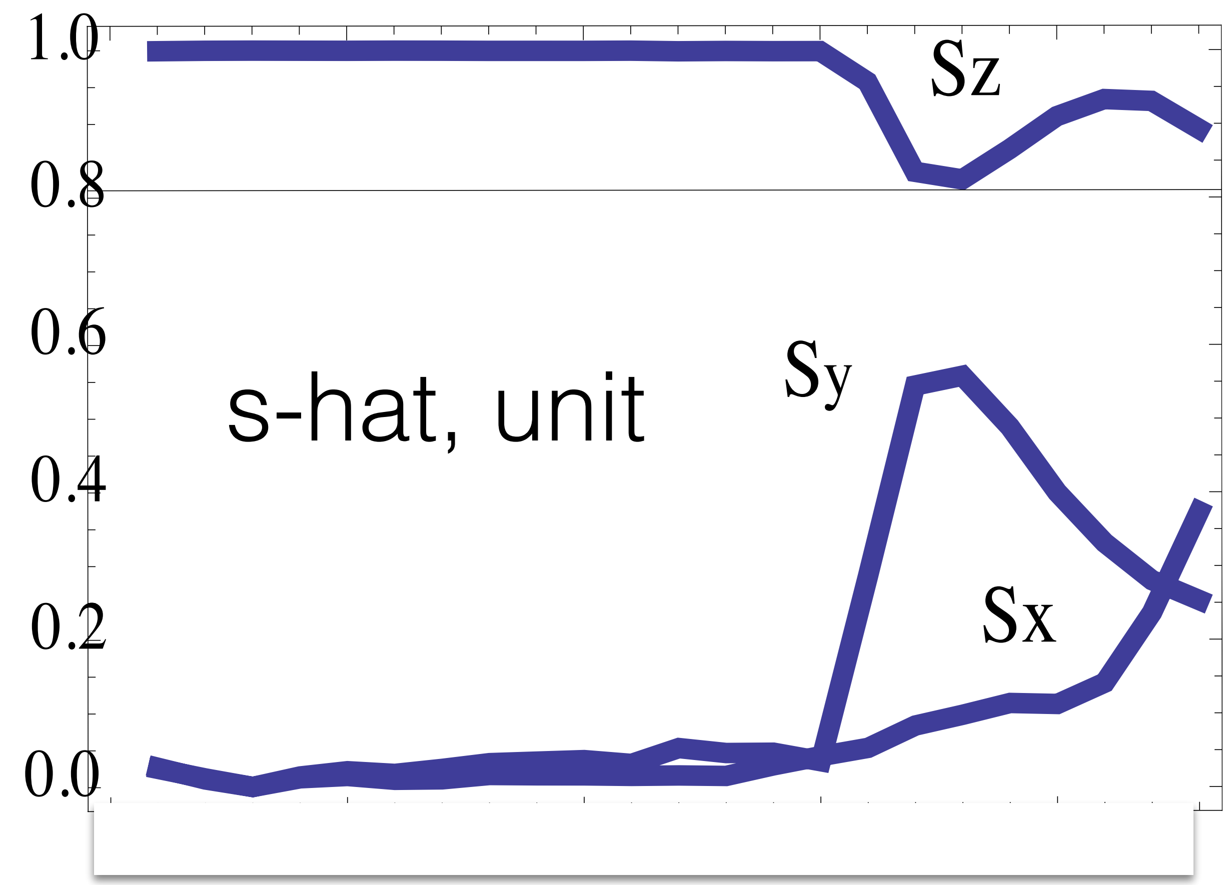


new: no precedent

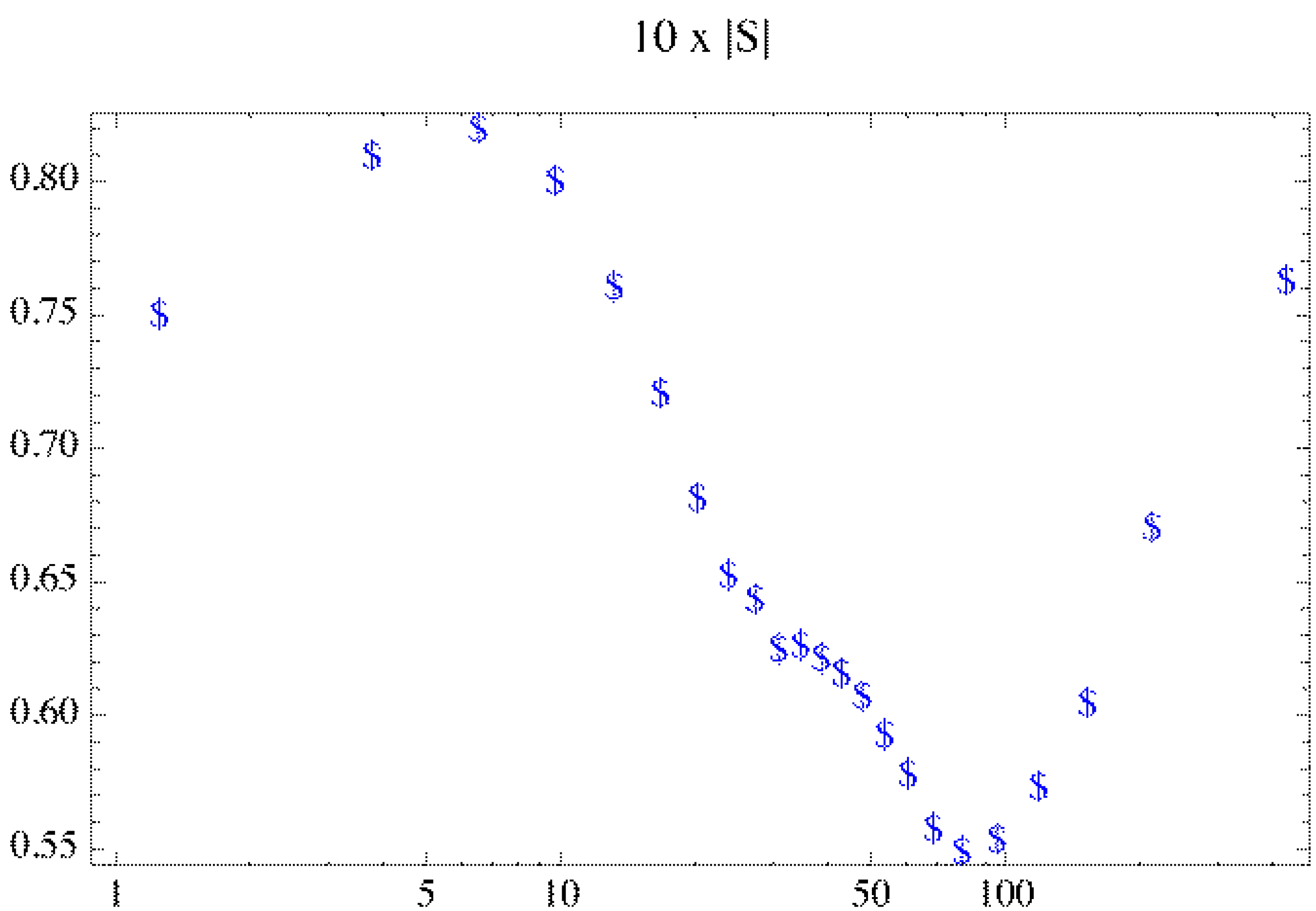
P_T of Z = our q_T

strange spin magnitudes and directions

multiplied by 10



P_T



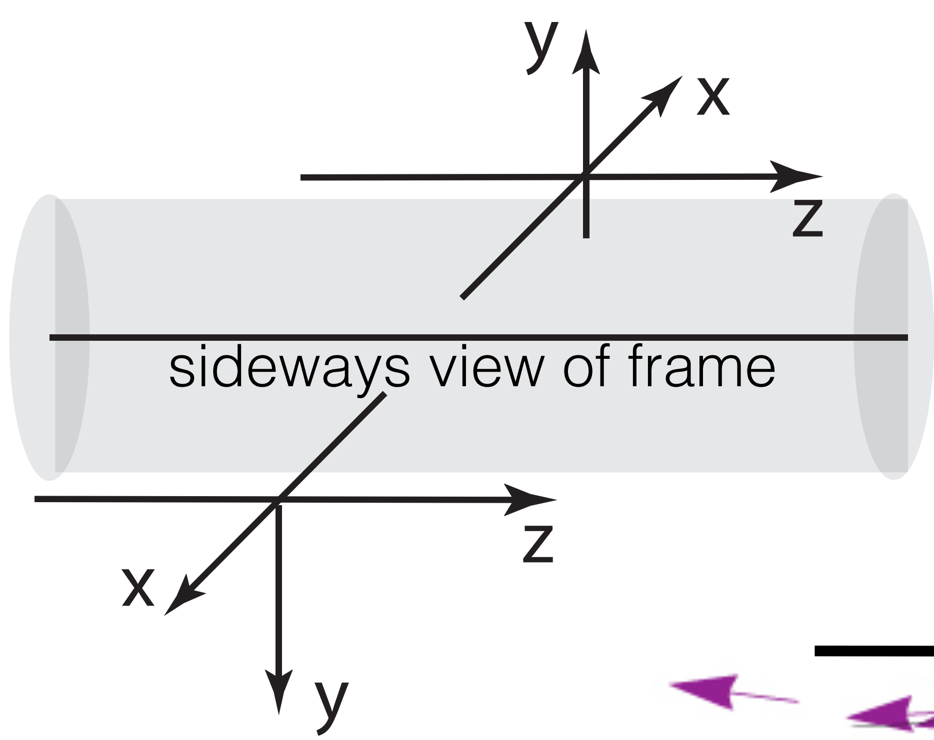
P_T

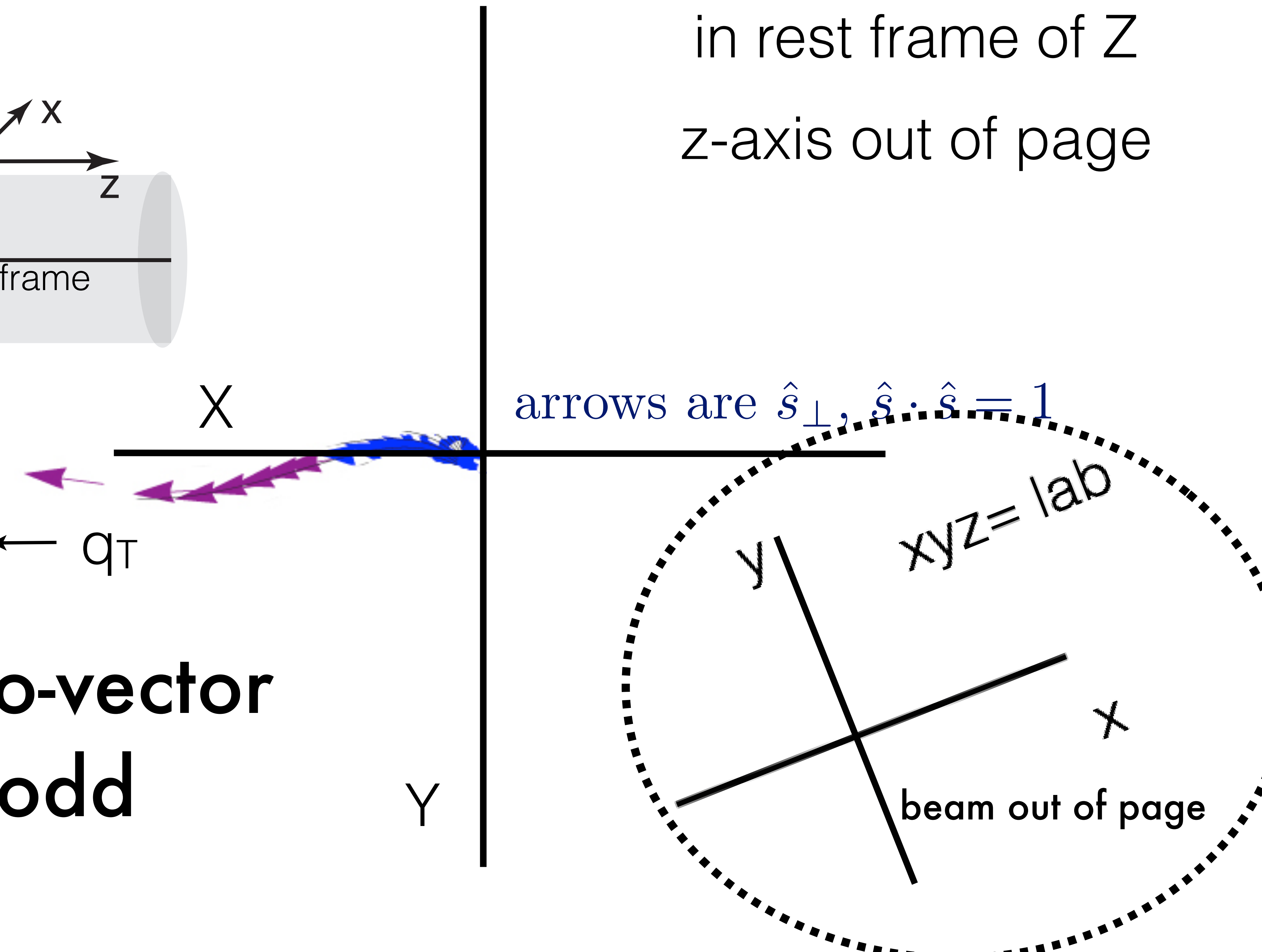
P_T of Z = our q_T

Unexpected discovery in spin parameters of the Z

in rest frame of Z

z-axis out of page



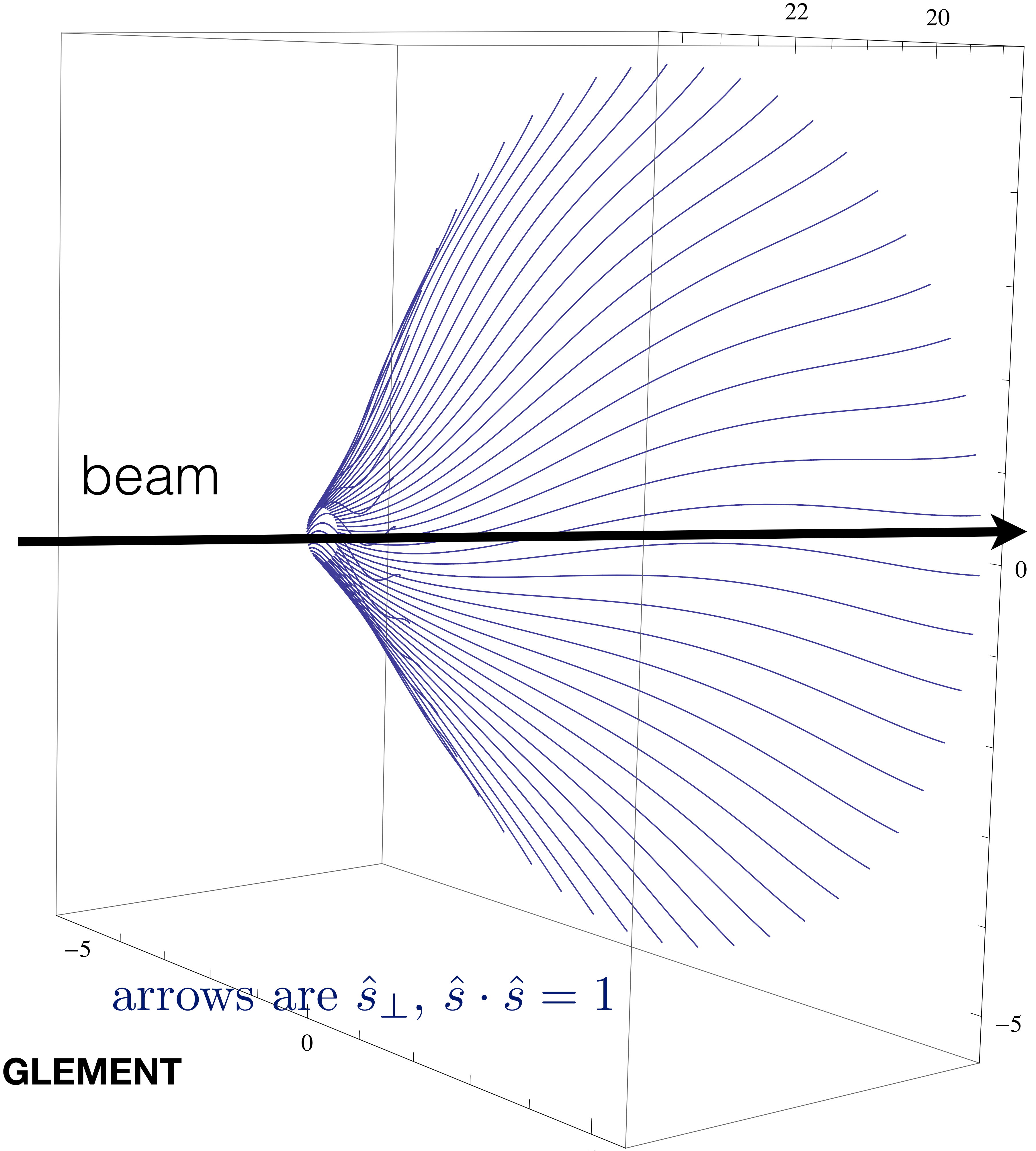


Y is pseudo-vector

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
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pure state
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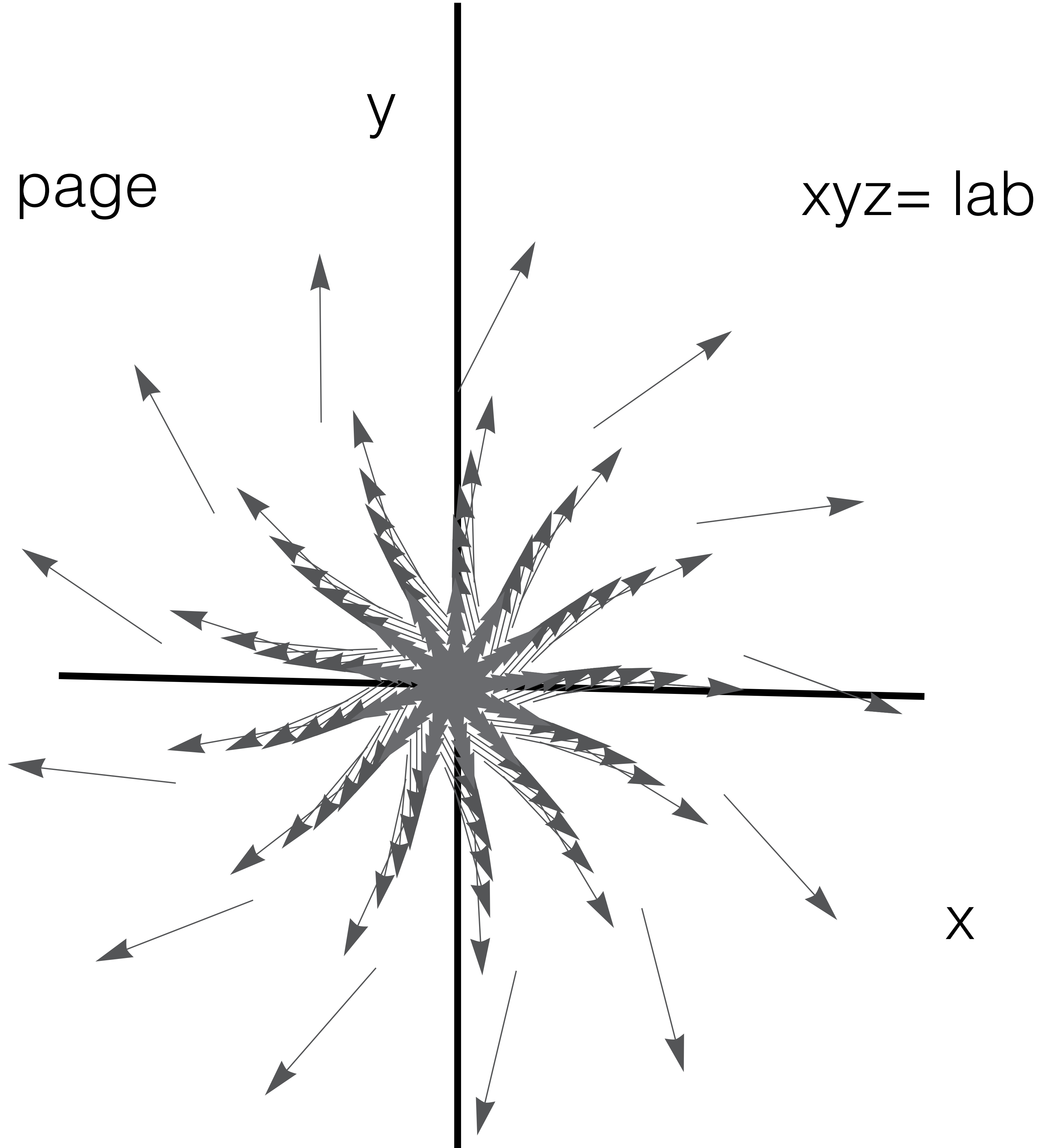

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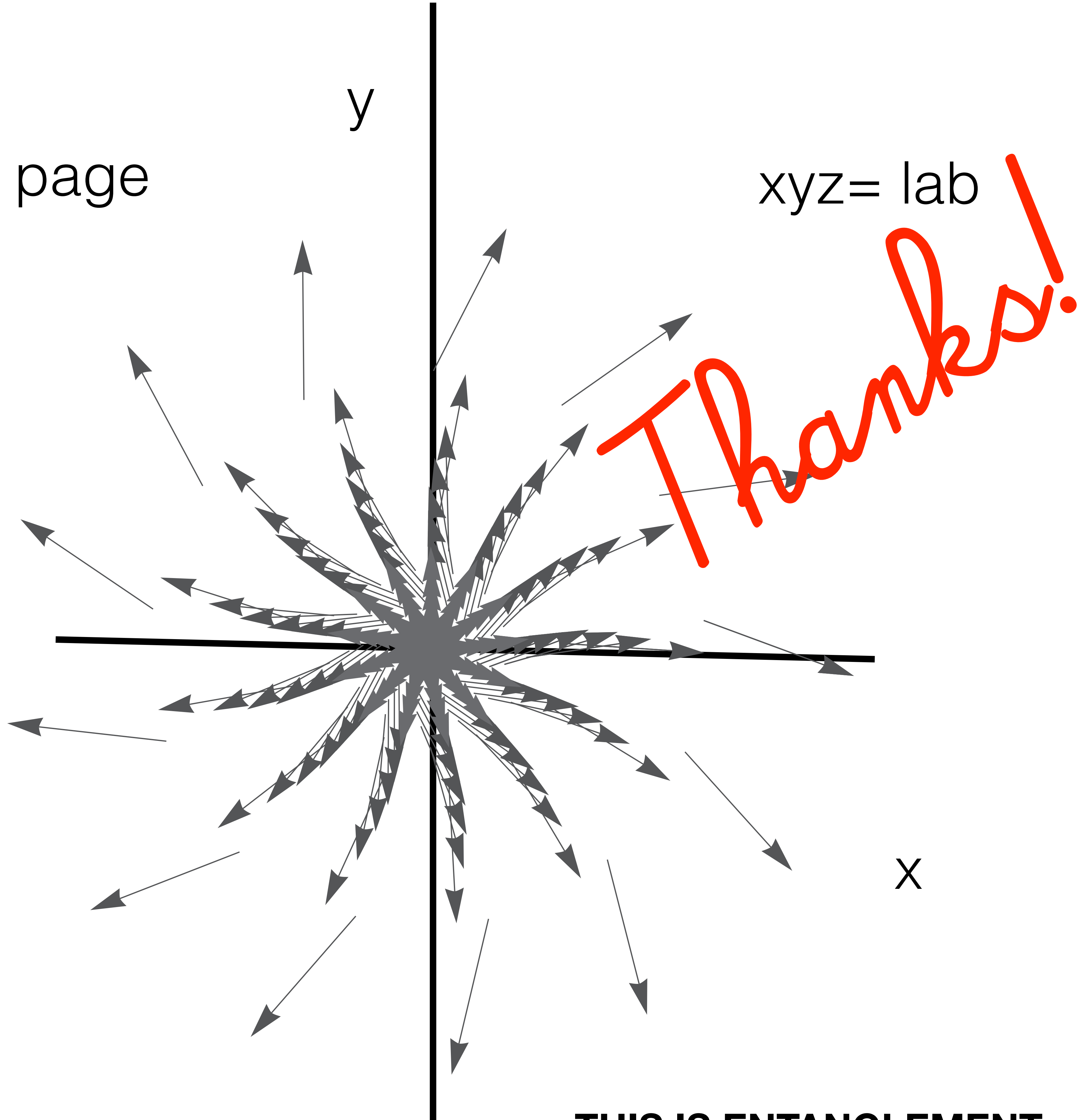
arrows are $\hat{s}_\perp$, $\hat{s} \cdot \hat{s} = 1$

beam-axis out of page



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

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

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