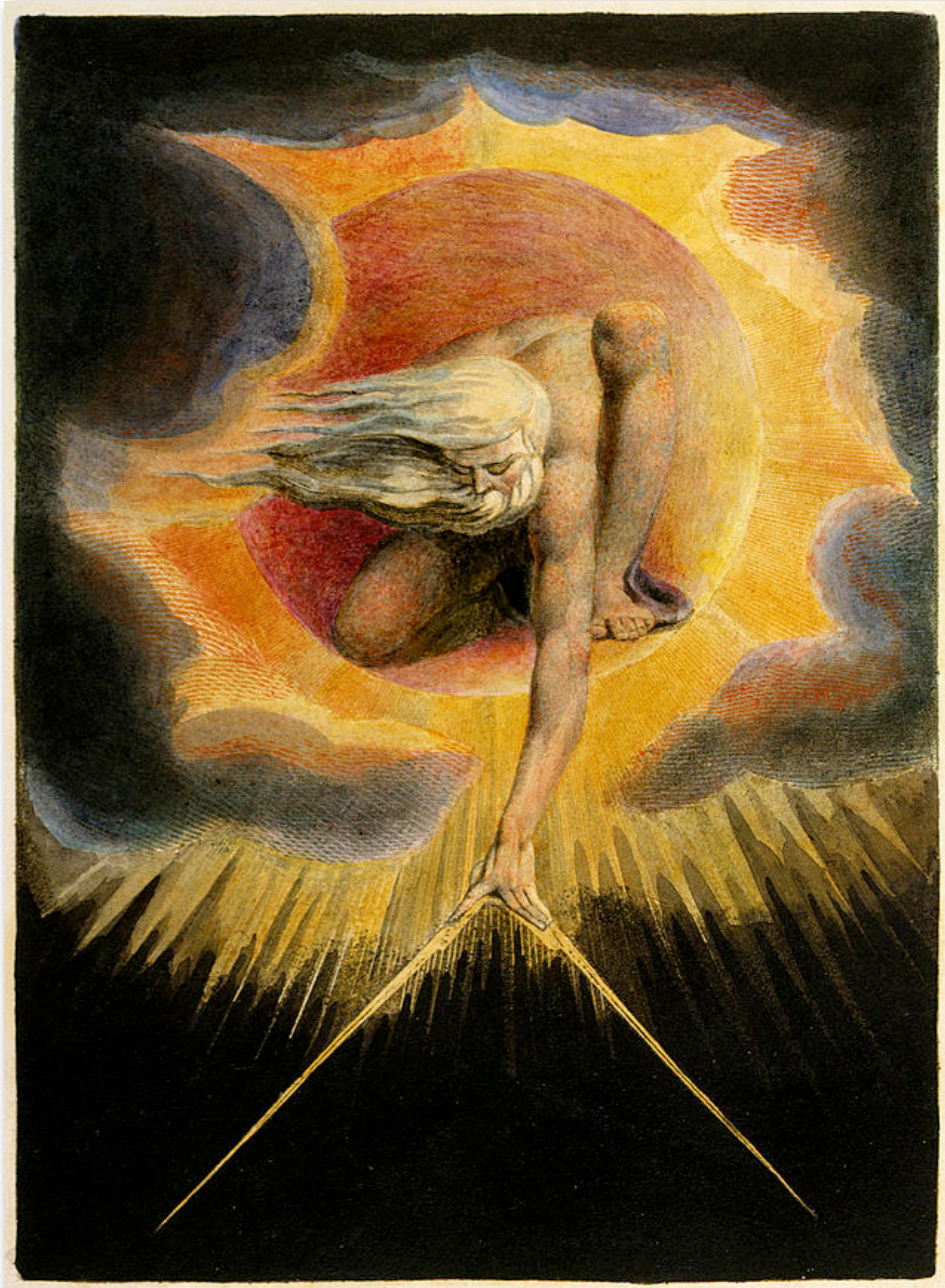
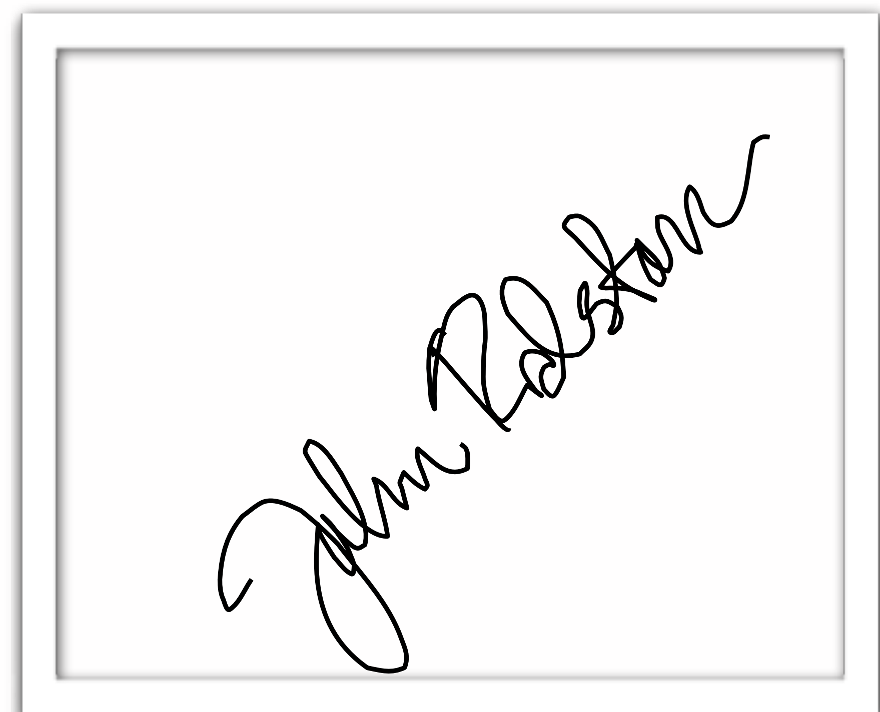


Quantum Tomography at the Collider



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

Eur. Phys. J. C78 2018

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.

The order of presentation is new and also unique by warning about traps to be avoided, while separating topics such as quantum probability to let the Schrodinger equation be appreciated in the simplest way on its own terms. This is also the first book on quantum theory that is not based on arbitrary and confusing axioms or foundation principles. The author is so unprincipled he shows where obsolete principles duplicated basic math facts, became redundant, and sometimes were just pawns in academic turf wars. The book has many original topics not found elsewhere, and completely researched references to original historical sources and anecdotes concerning the unrecognized scientists who actually did discover things, did not all get Nobel Prizes, and yet had interesting productive lives.

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HOW TO UNDERSTAND QUANTUM MECHANICS - JOHN P. RALSTON

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How to Understand Quantum Mechanics

John P. Ralston

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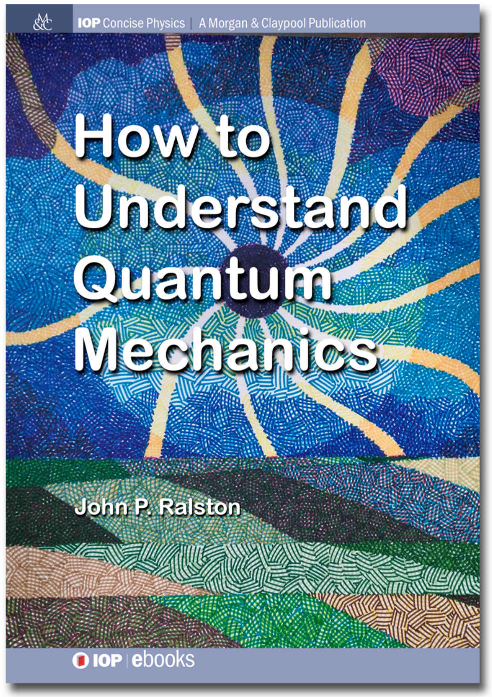
An accessible introduction to understanding quantum mechanics in a natural and intuitive way, which was advocated by Erwin Schroedinger and Albert Einstein



How to Understand Quantum Mechanics

John P. Ralston, *The University of Kansas*

Paperback ISBN: 9781681741628 • eBook ISBN: 9781681742267
May, 2018 • 107 pages
Paperback: $79.95 • eBook: $63.96 • Combo: $99.94

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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

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Made to correct disinformation given to the public

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

Let's Begin with Some Results

"dijets" means
2 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

Actual Real Simulated Data

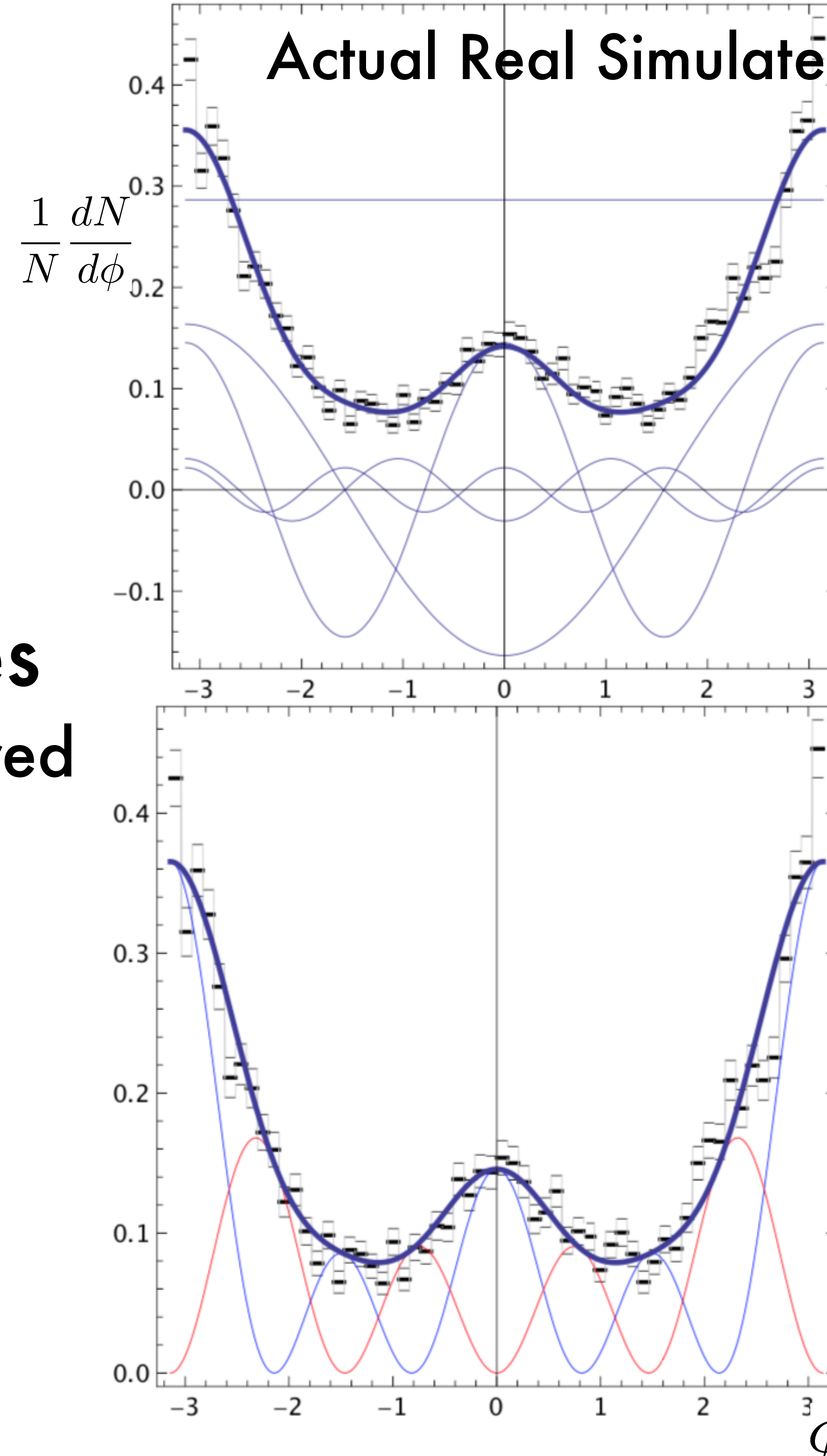


FIG. 4: Top: Maximum likelihood fit, with the contributions of $\cos m\phi$ for $m = 0 - 4$. Bottom: Two weighted distributions defined by $f_+(\phi) = Re(\psi)^2$ (blue) and $f_-(\phi) = Im(\psi)^2$ (red), coming from the eigenstates of the rank two density matrix.

mandatory diagram for collider theorists

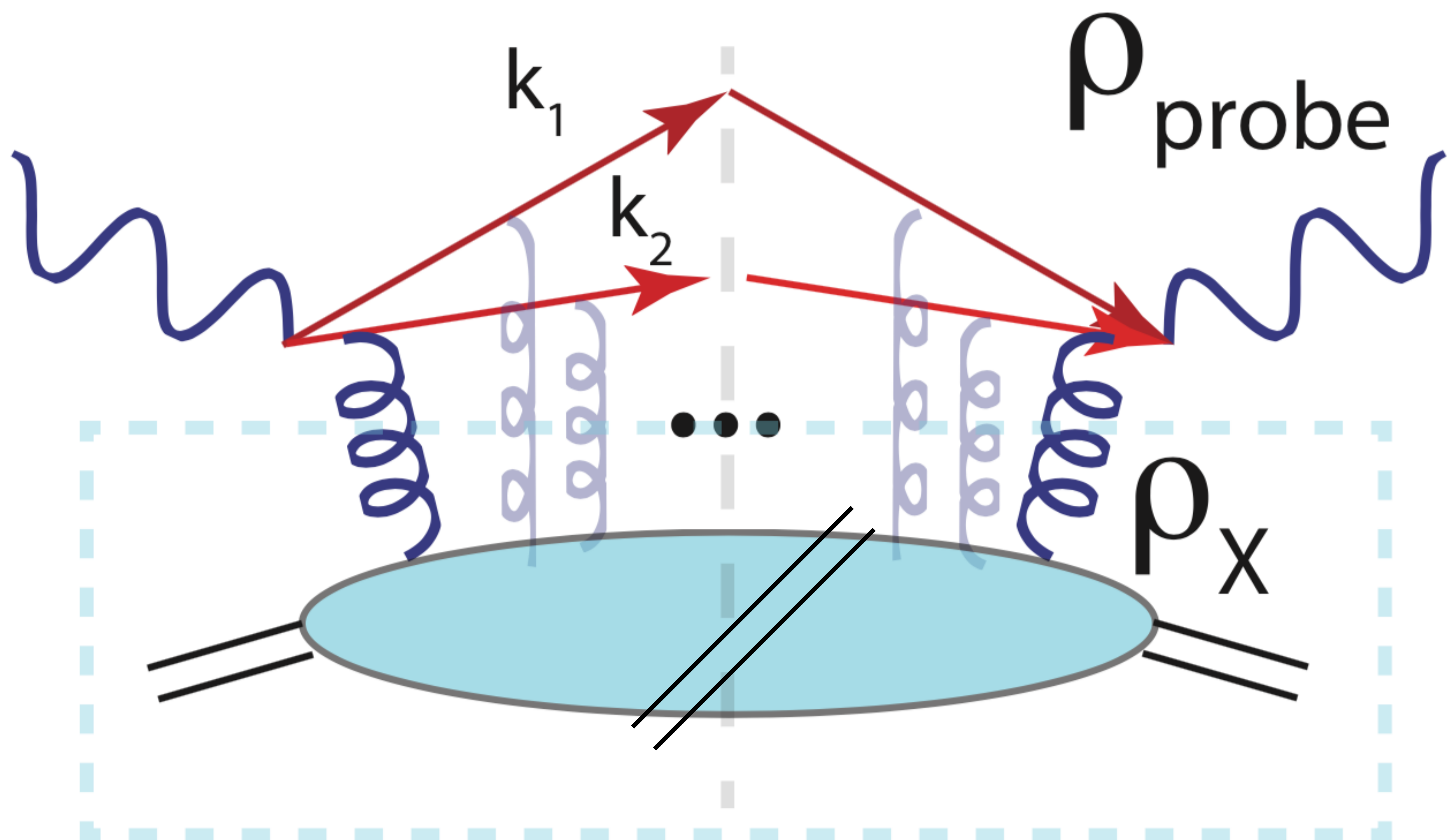


FIG. 1: By analogy with deeply inelastic scattering, a dijet probe replaces the handle of the handbag diagram with a shoulder strap (red) defining new elements of the probe density matrix ρ_{probe}. Each orthogonal element of ρ_{probe} can extract a corresponding projection of the unknown system density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

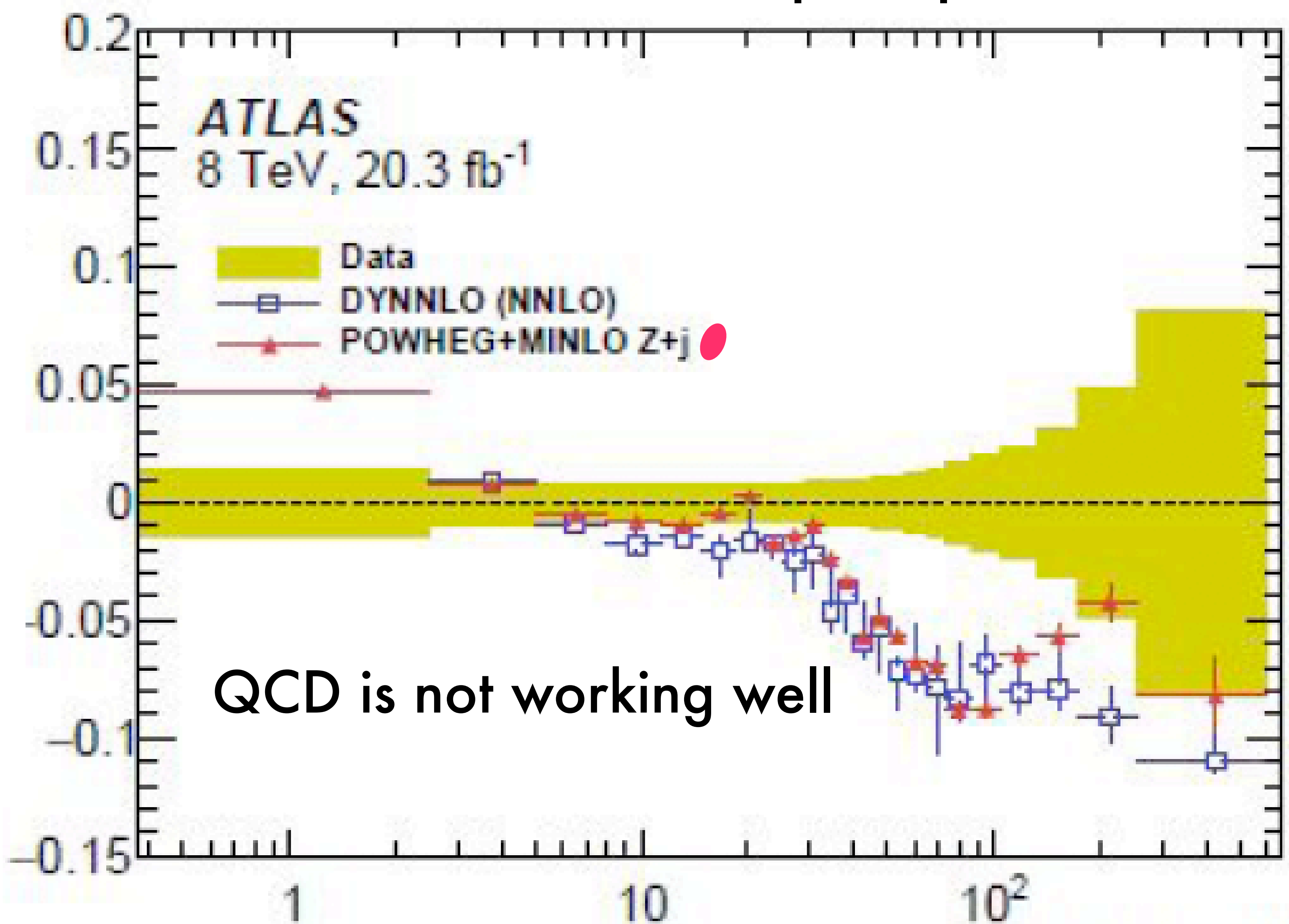
Let's Begin with Some Results

ATLAS data
1606.00689

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

"lepton pairs"

$(A_0 - A_2)$



QCD is not working well

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]

We use the experimental information to measure the polarization density matrix of the Z boson

Using CERN open data is better, but not yet ready to show you

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

ρ_{probe} = known density matrix

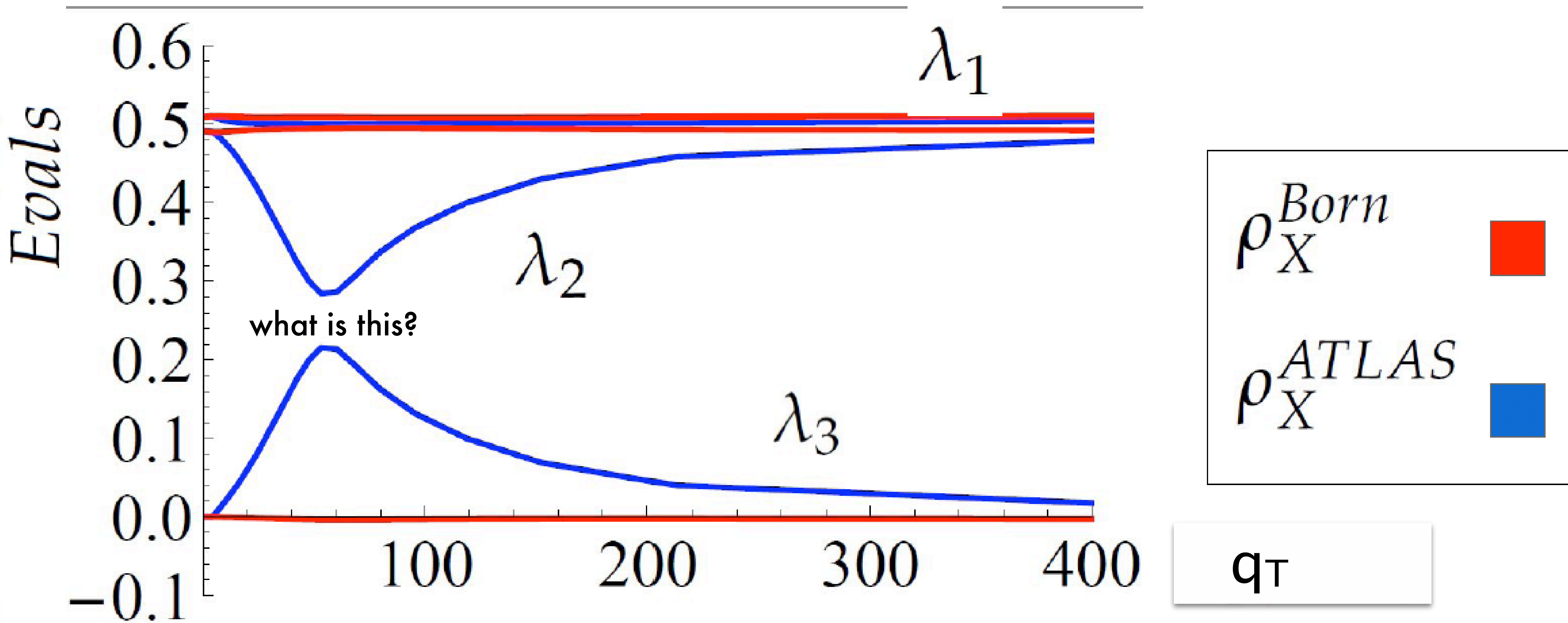
ρ_X = unknown density matrix

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

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

S

this has never been seen before

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:

Fano, 1957

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

Completeness? It's complete for what it spans

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 $Q = k + k'$

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

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

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

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

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

↓

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

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

$\rho(X)$ = unknown density matrix

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

the probe is two "massless" fermions 1/2 x1/2 x 1/2 x 1/2

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

up to spin-2 from symmetry

Standard Model + shelf of books predicts nothing more than two numbers

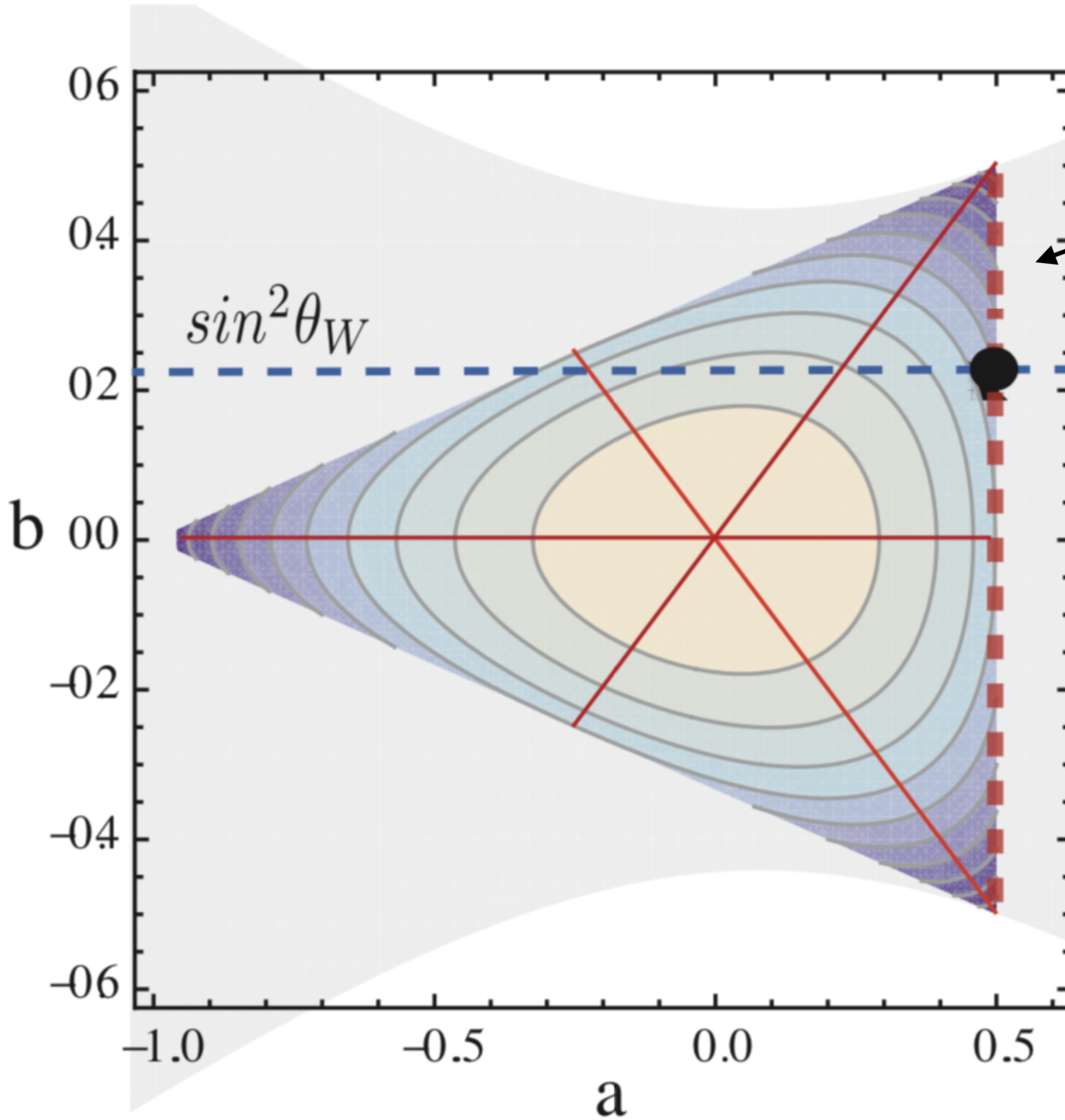
$$a = 1/2; \quad b = \sin^2\theta_W$$

we could get a, b tomographically from another experiment

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

vertical line: on shell helicity conservation

gray: positivity of cross section



color: positivity of eigenvalues

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.

Maintaining positivity when fitting data

$$\rho(X)(m) = M(m) \cdot M^\dagger(m);$$

$$M(m) = \frac{1}{\sqrt{\sum_k m^2(k)}} \begin{pmatrix} m_1 & m_4 + i m_5 & m_6 + i m_7 \\ 0 & m_2 & m_8 + i m_9 \\ 0 & 0 & m_3 \end{pmatrix}$$

Cholesky decomposition

fit the m-parameters

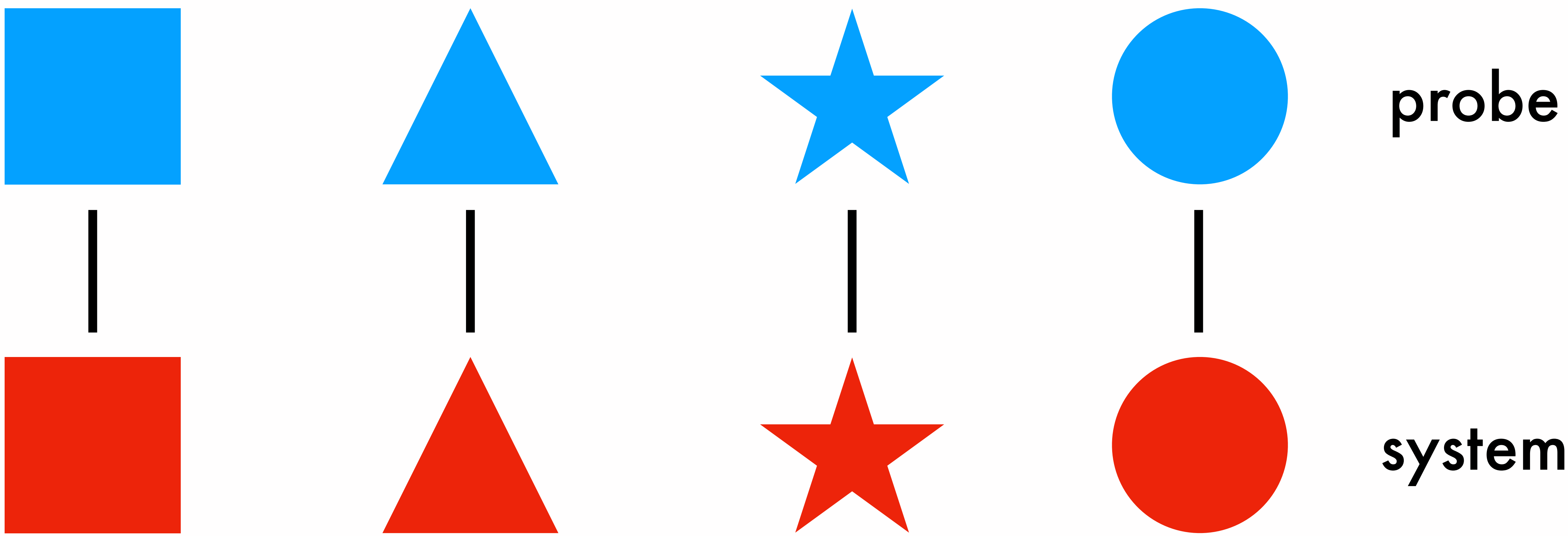
"convex optimization problem"
one and only one minimum of χ^2

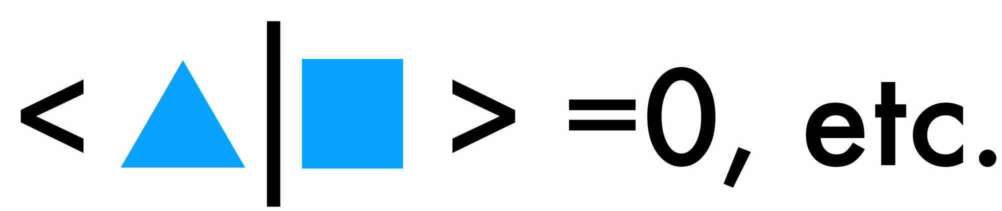
The Mirror Trick

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 $U(X) = U^T(X);$ $tr(U(X)) = 0.$





what is a spin parameter?

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

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

$\vec{S}$ rotation generator

beginning quantum mechanics,
and conventional books, expand in pure states

$$\rho_{pure,\,ij}(\vec{S}) = \frac{1}{2}(\delta_{ij} - \hat{S}_i\hat{S}_j) - \frac{\imath}{2}\epsilon_{ijk}\hat{S}_k.$$

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

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

Everything is Lorentz invariant and easy

improved Collins Soper

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

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

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

To analyze data for each event labeled J:

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

normalized

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

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

use lab momenta to compute invariants

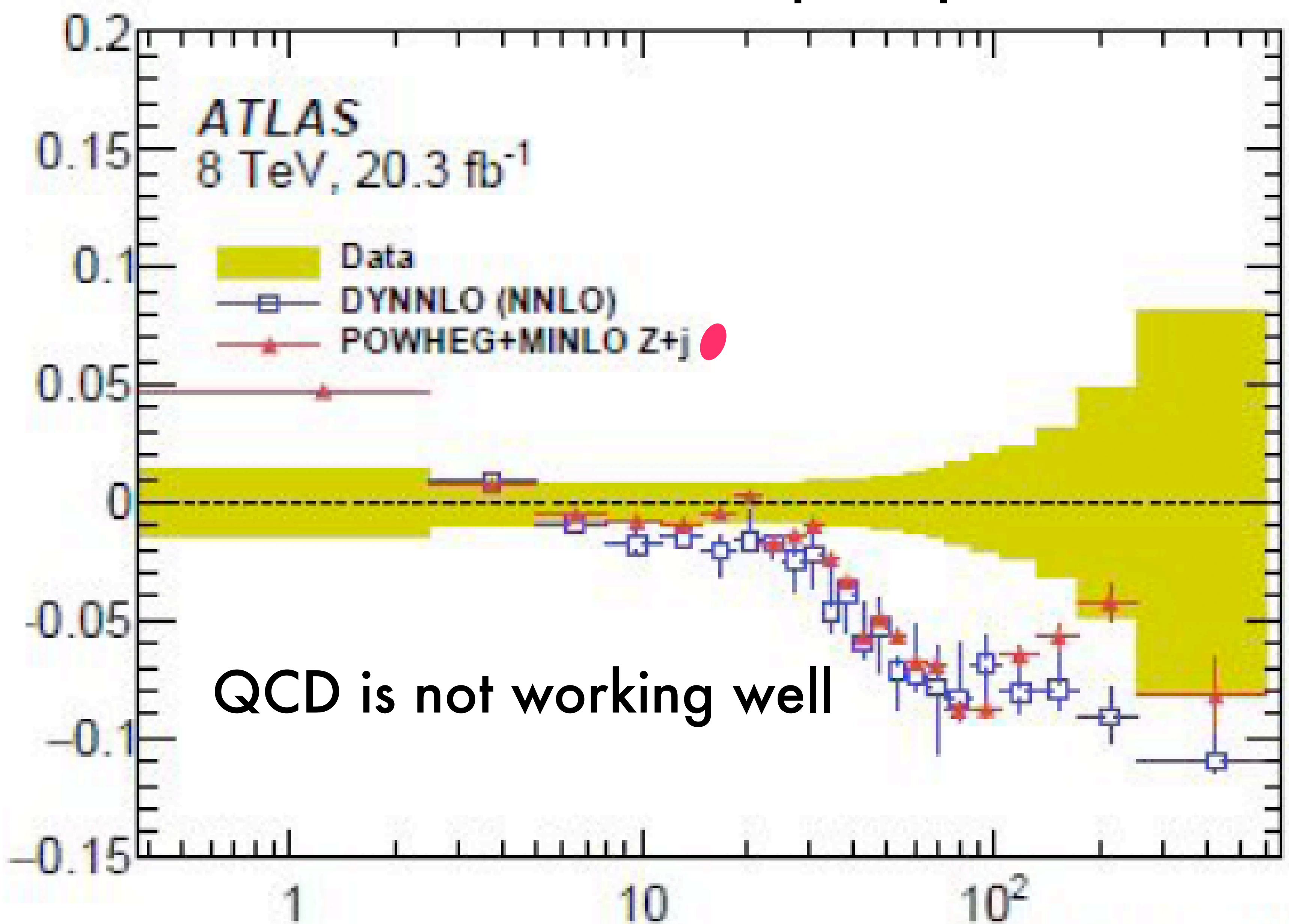
What did we find?

ATLAS data
1606.00689

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

"lepton pairs"

$(A_0 - A_2)$



QCD is not working well

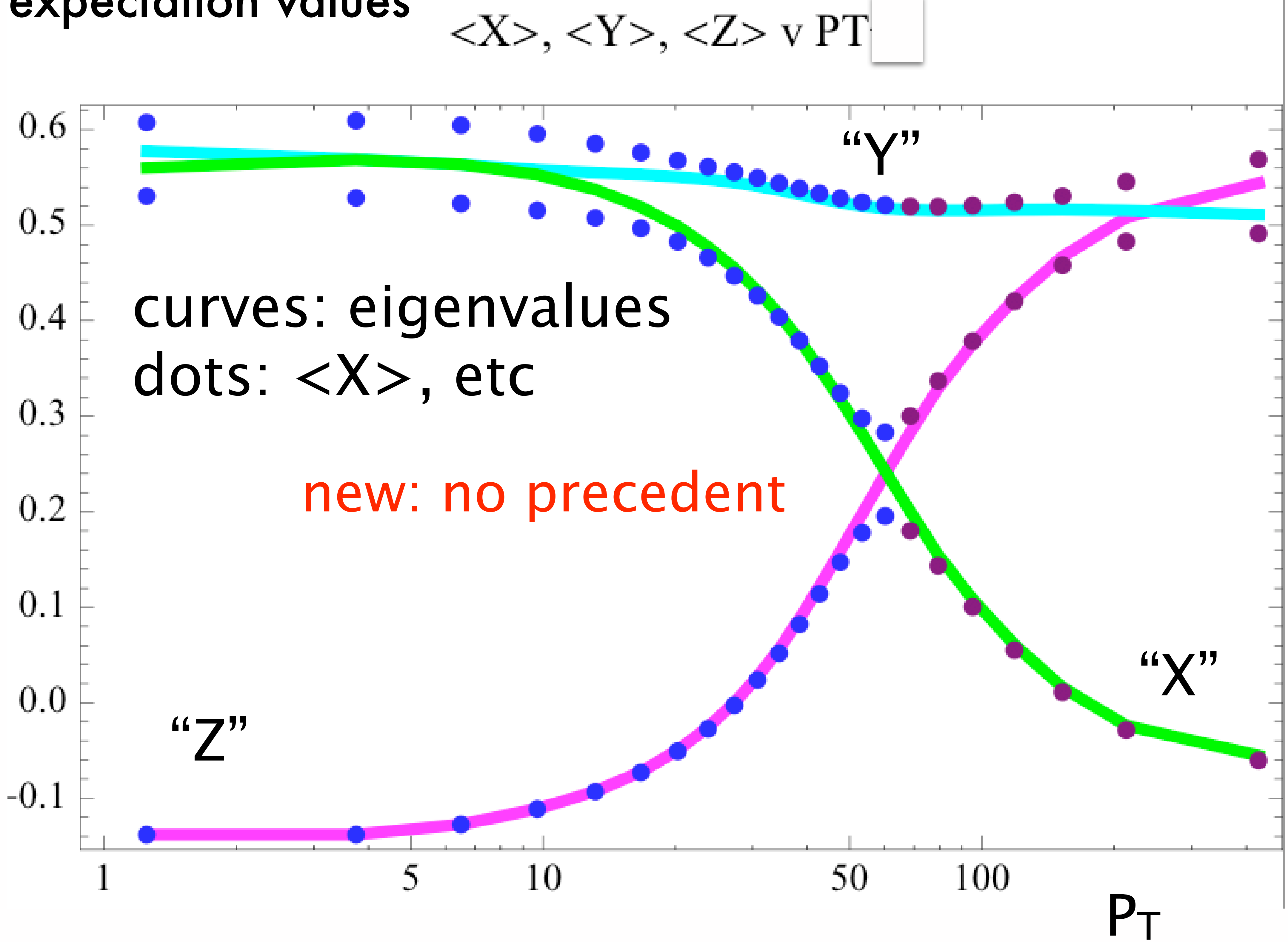
one of many terms in an old traditional expansion of a certain angular distribution

"Lam-Tung fails"

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

Avoided level crossing; eigenvectors swap

quantum expectation values



ATLAS analysis tables lack error bars

P_T of Z = our q_T

the entanglement entropy

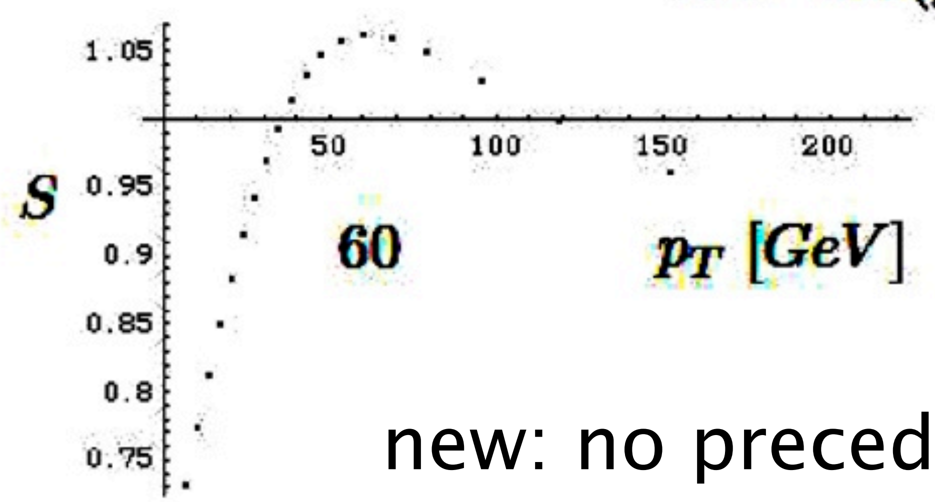
$$\mathcal{S} = -tr(\rho)log(\rho); \qquad 0 < \mathcal{S} < log(N)$$

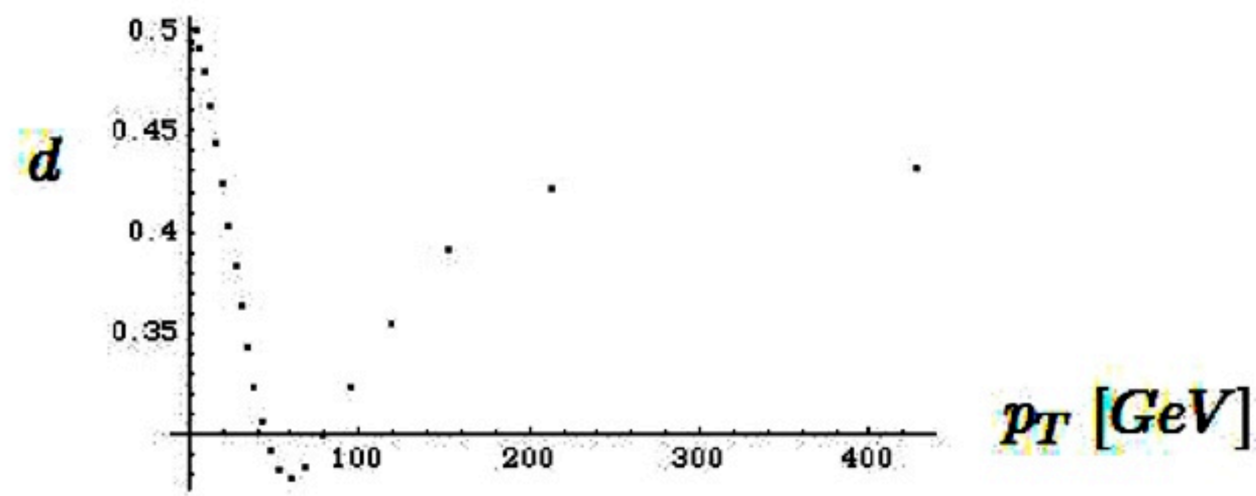
pure — unpolz

What's the bump at pT = 60 GeV about?

We plot the entropy S and the degree of polarization d

$$S = -tr(\rho_X log \rho_X) \qquad d = \sqrt{(3tr(\rho_X) - 1)/2}$$





new: no precedent

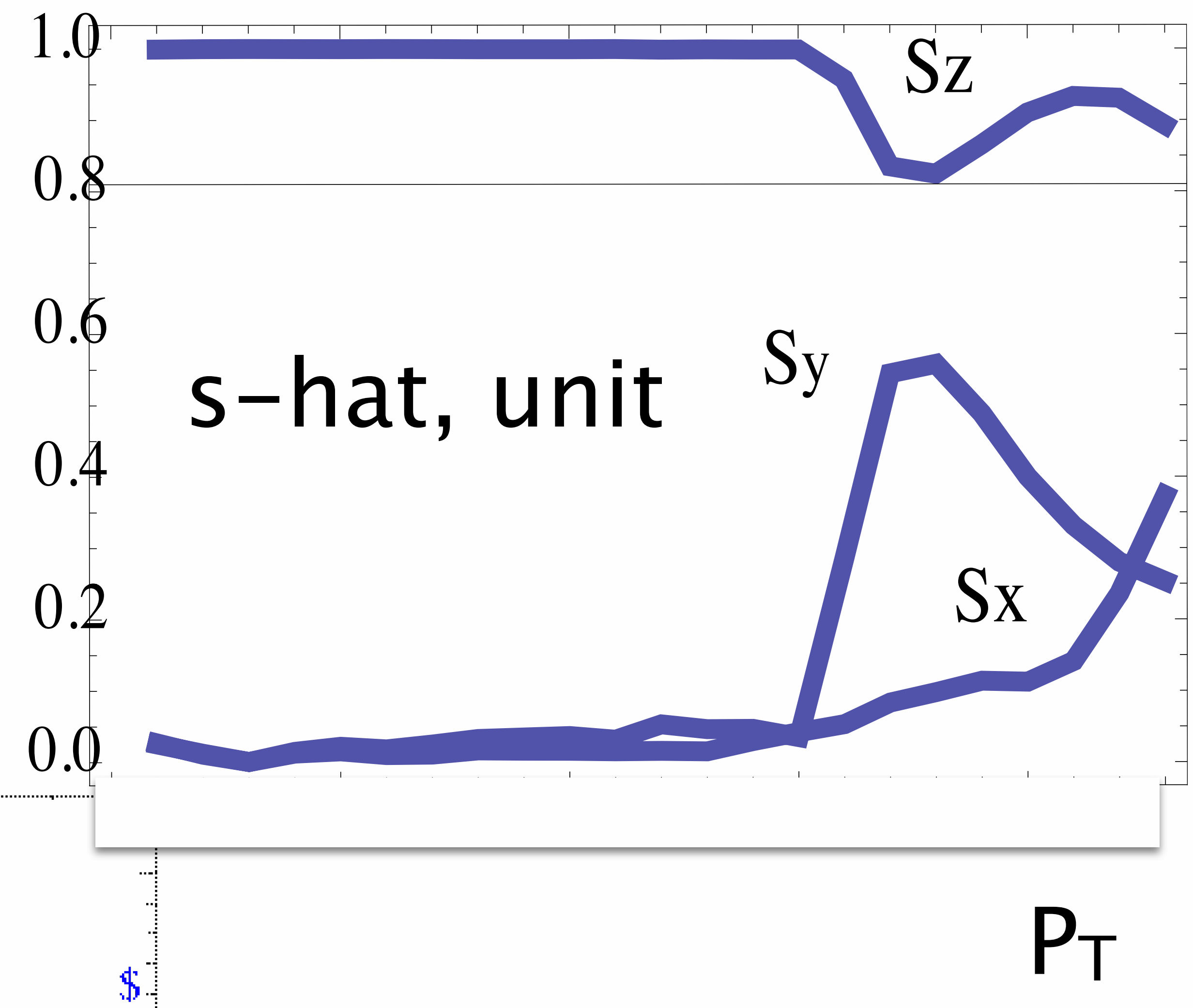
60

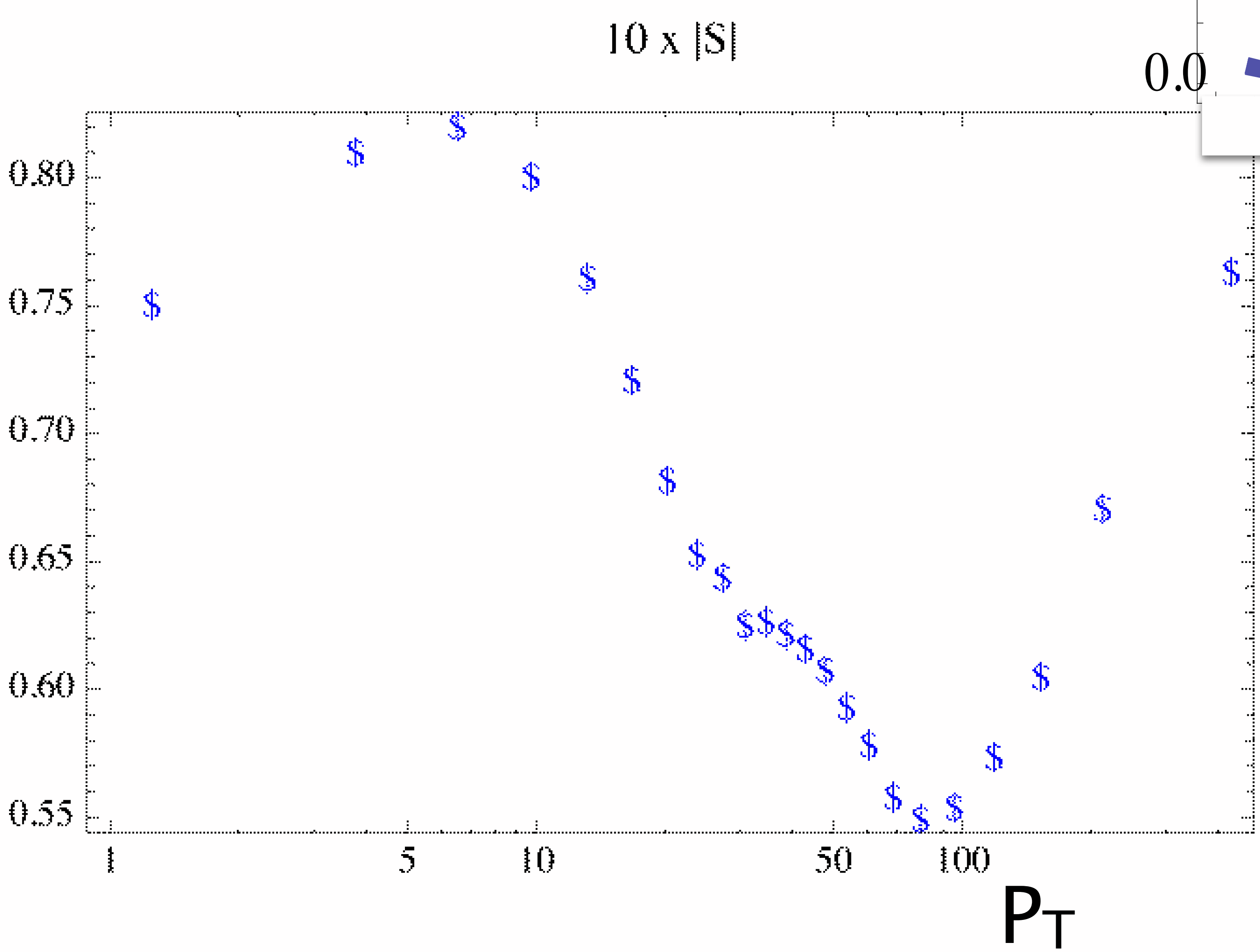
P_T of Z = our q_T

Bump has the accidents if not the substance of a phase transition..

strange spin magnitudes and directions

multiplied by 10



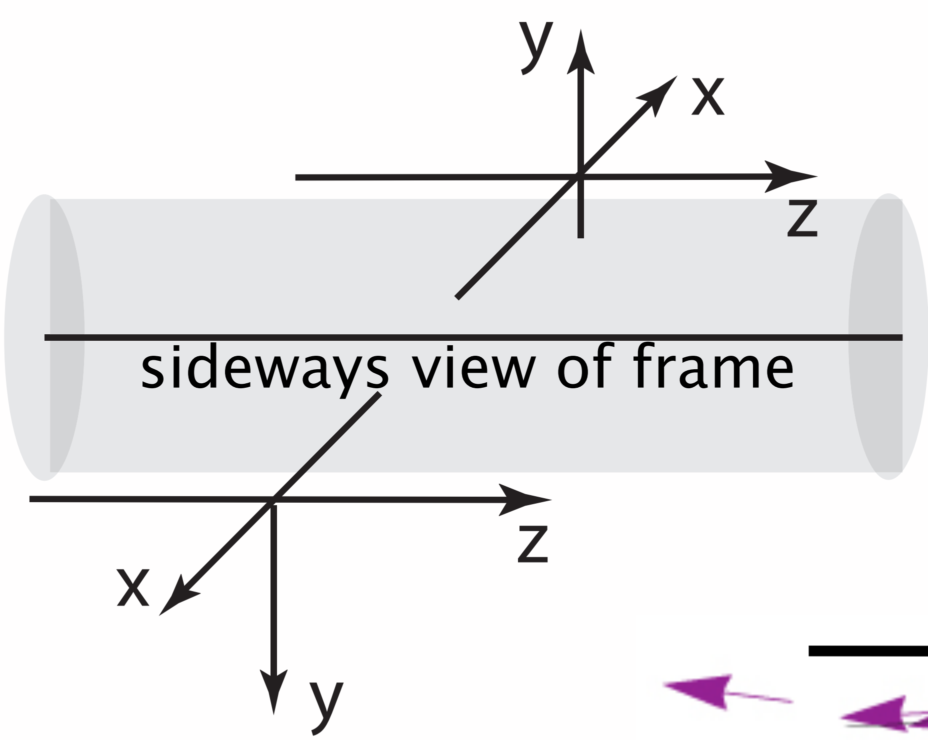


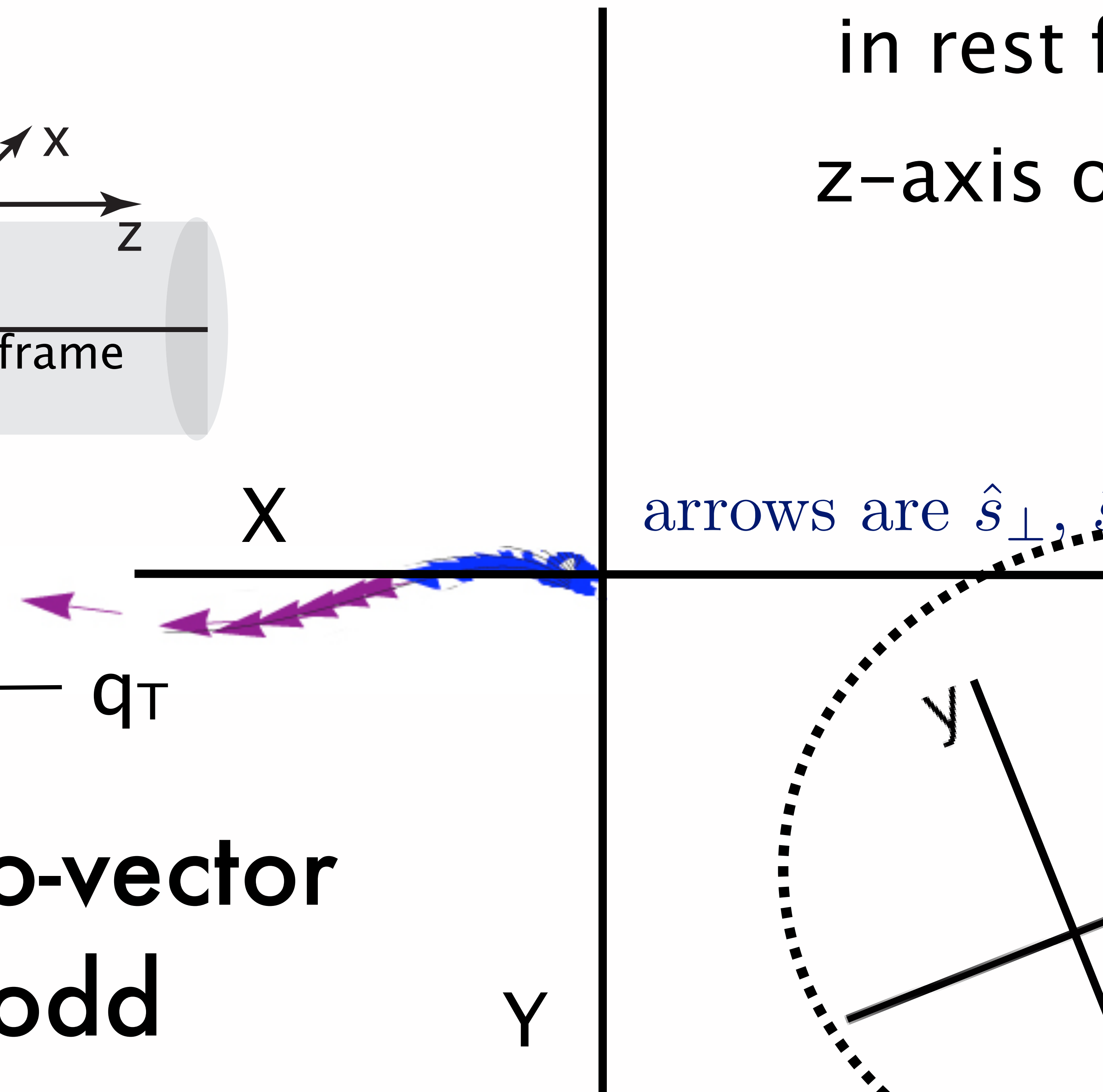
P_T of Z = our q_T

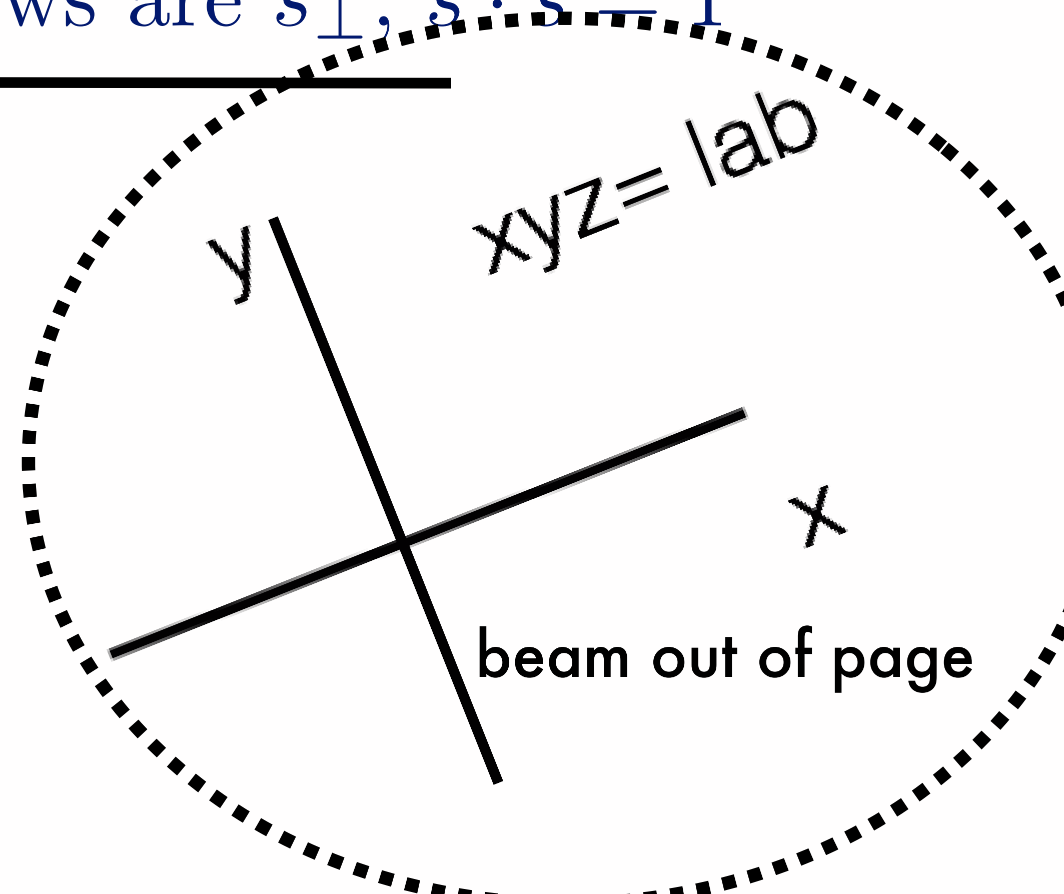
Unexpected discovery in spin parameters of the Z

in rest frame of Z

z-axis out of page







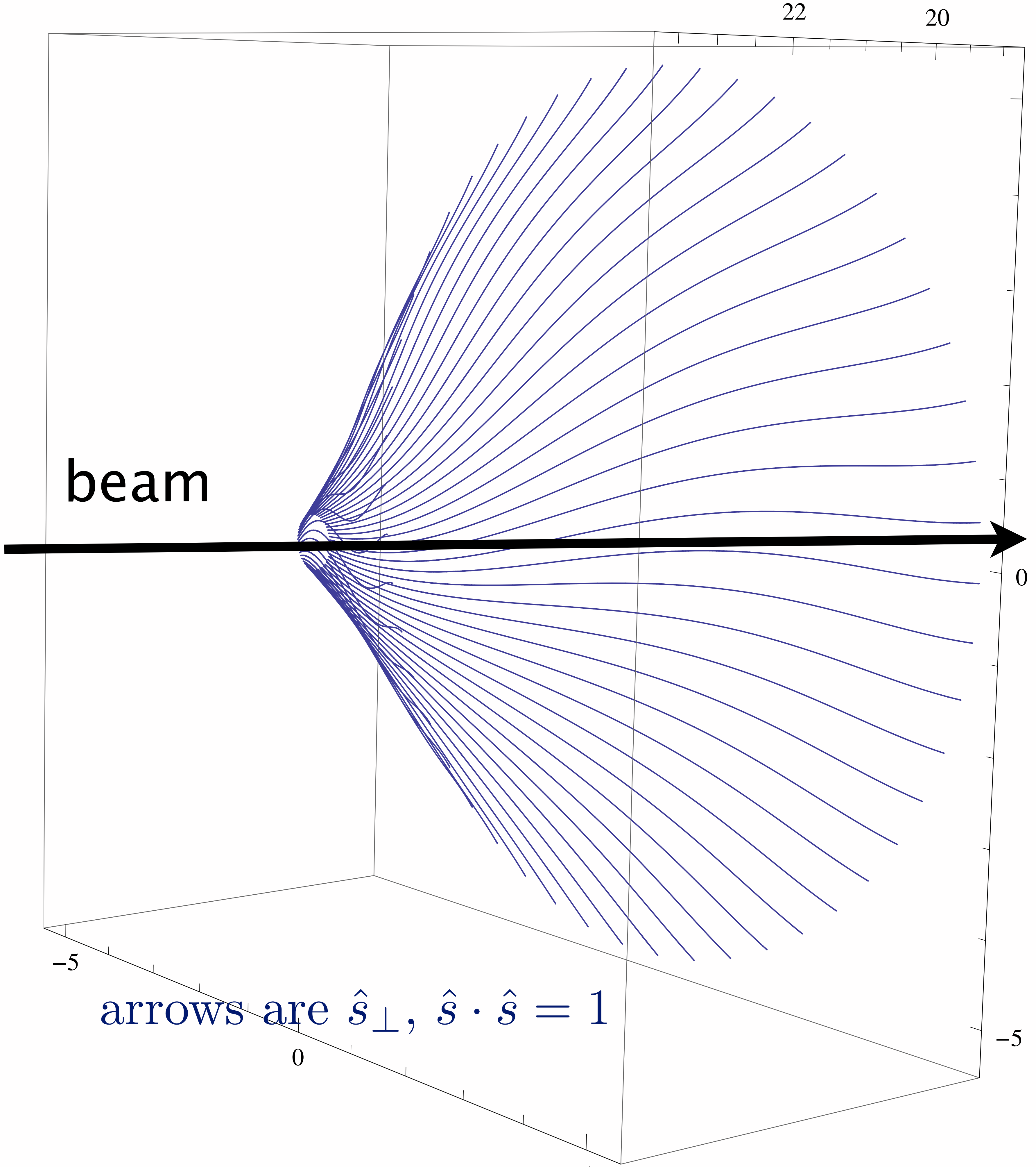
Y is pseudo-vector

S_Y is T-odd

3D holography of the Z spin, lab frame

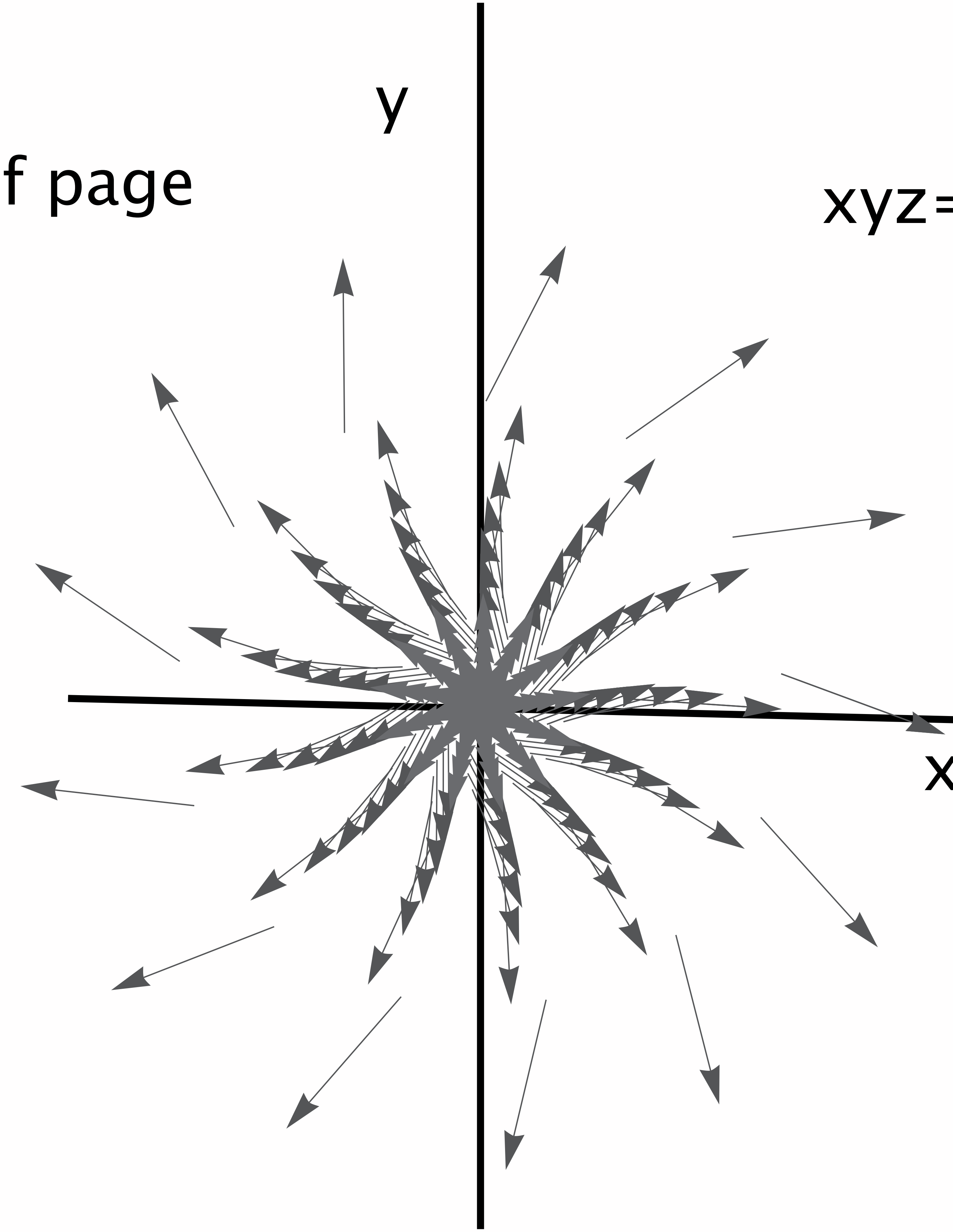
(q_x, q_y, q_z)

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



beam–axis out of page

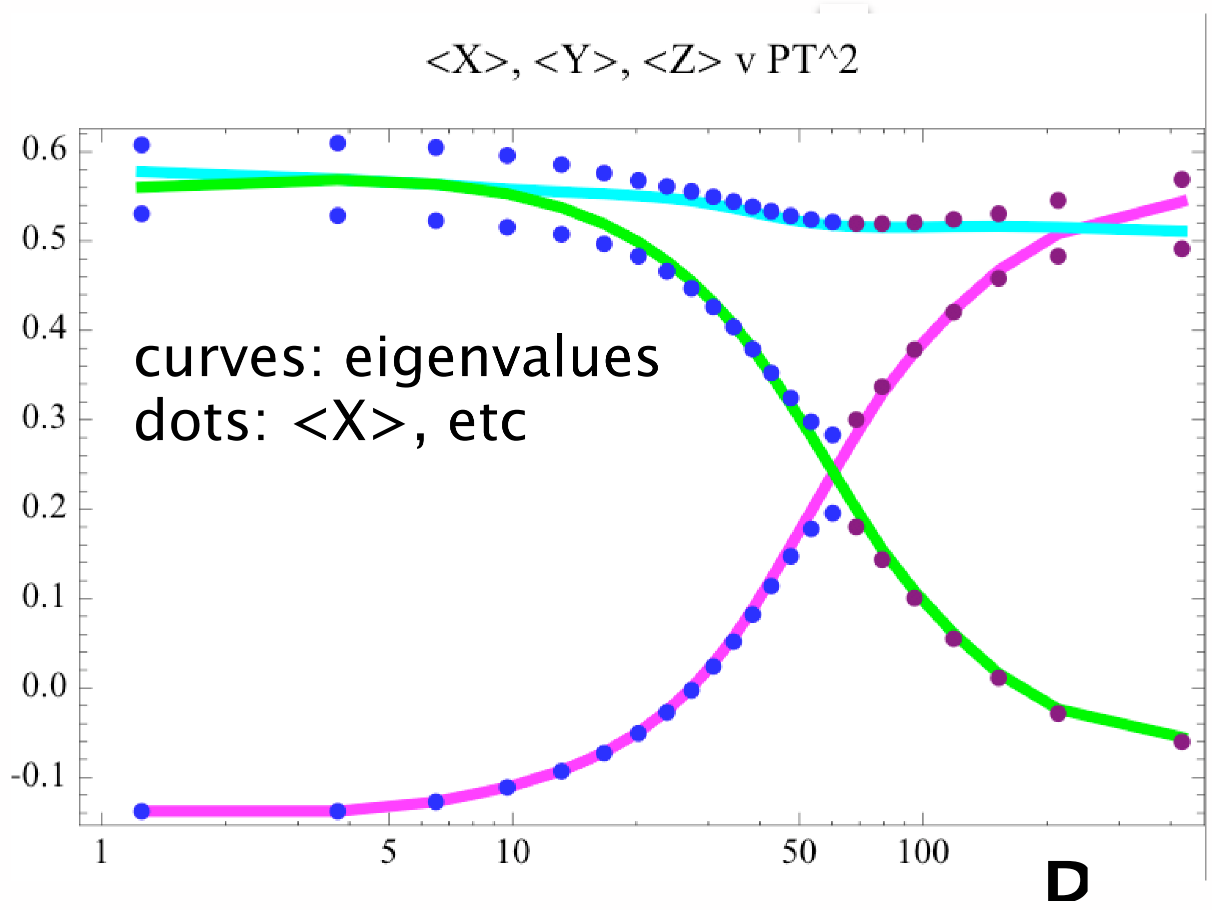
xyz= lab

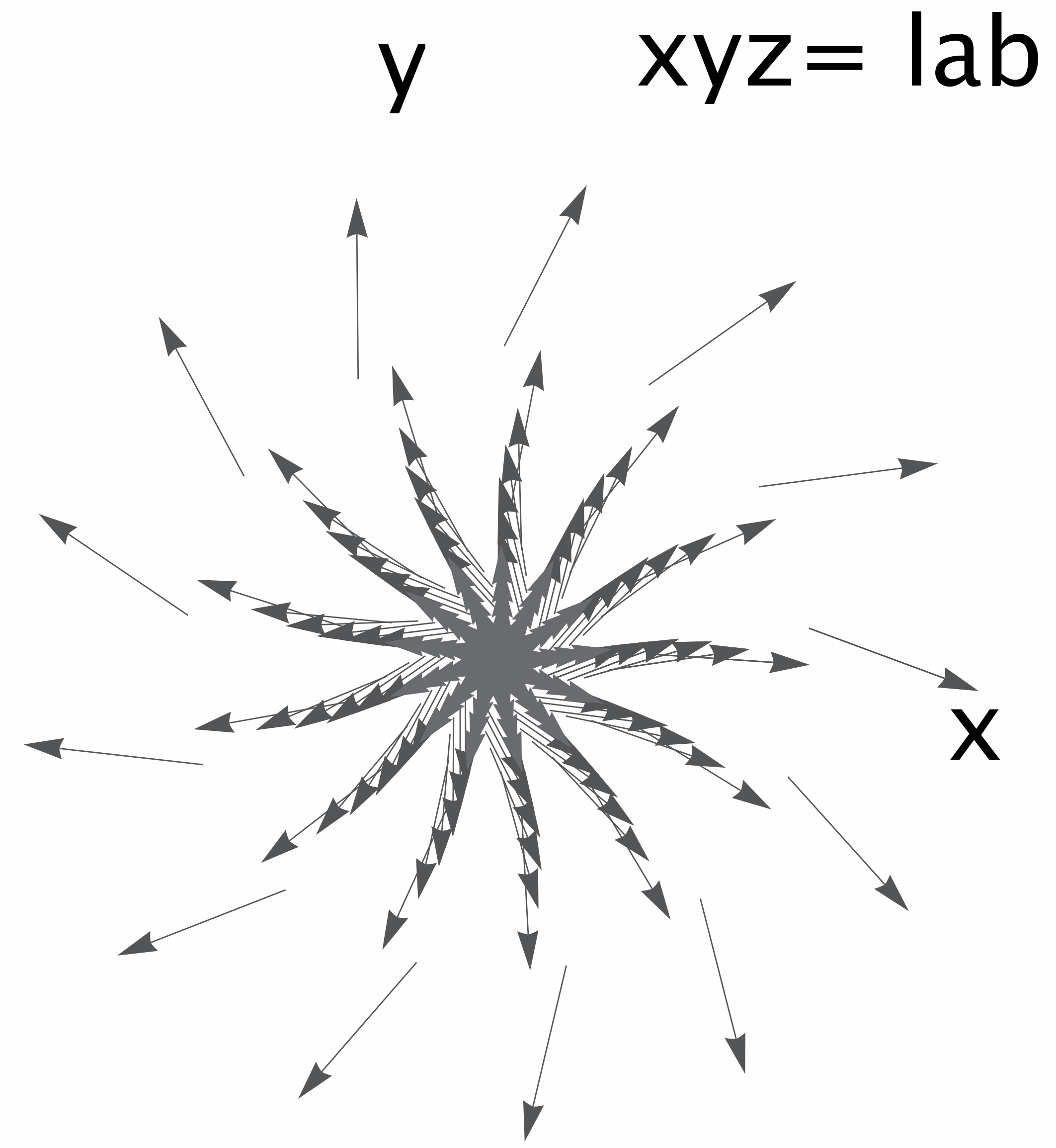


2% of Z's are polarized pure state, spin–correlated with P_T

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

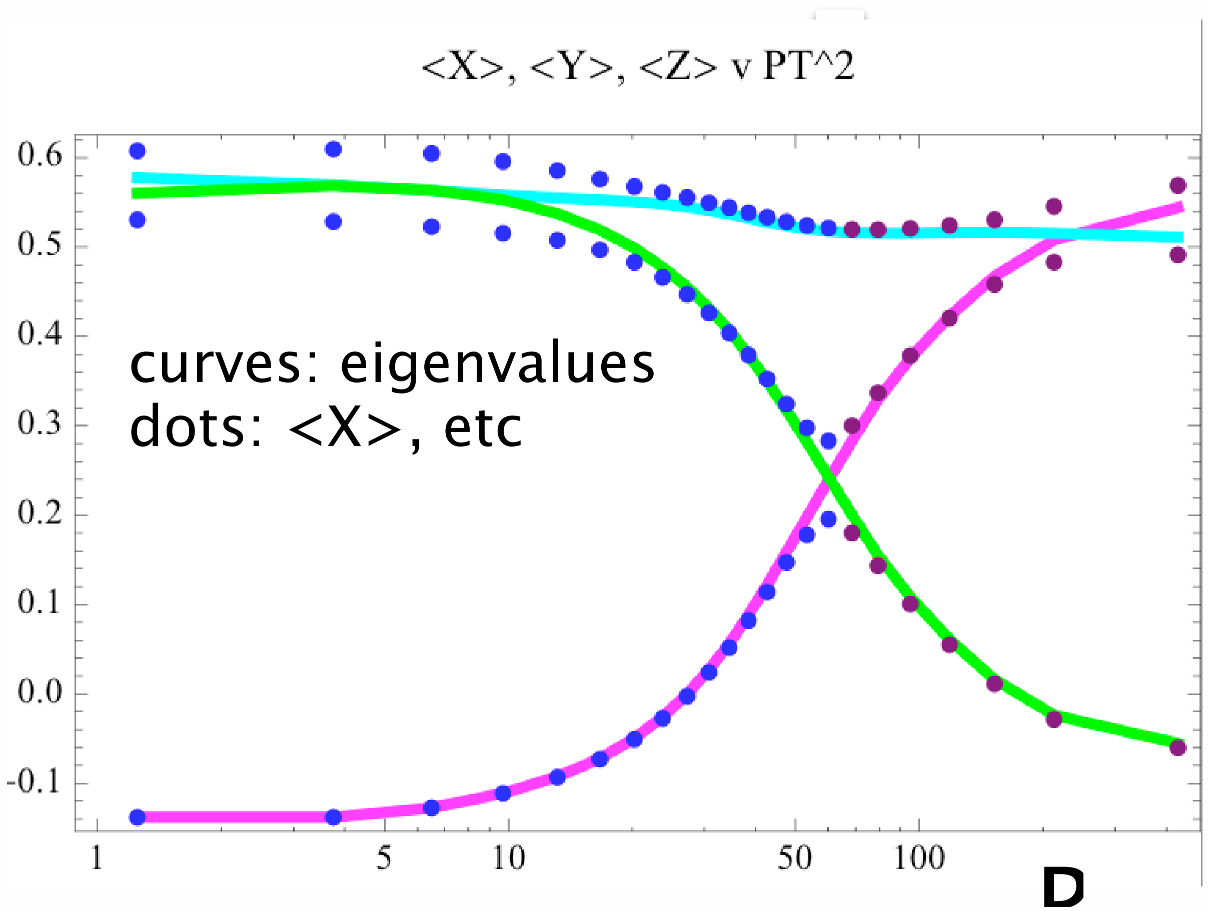
What Does It Mean?

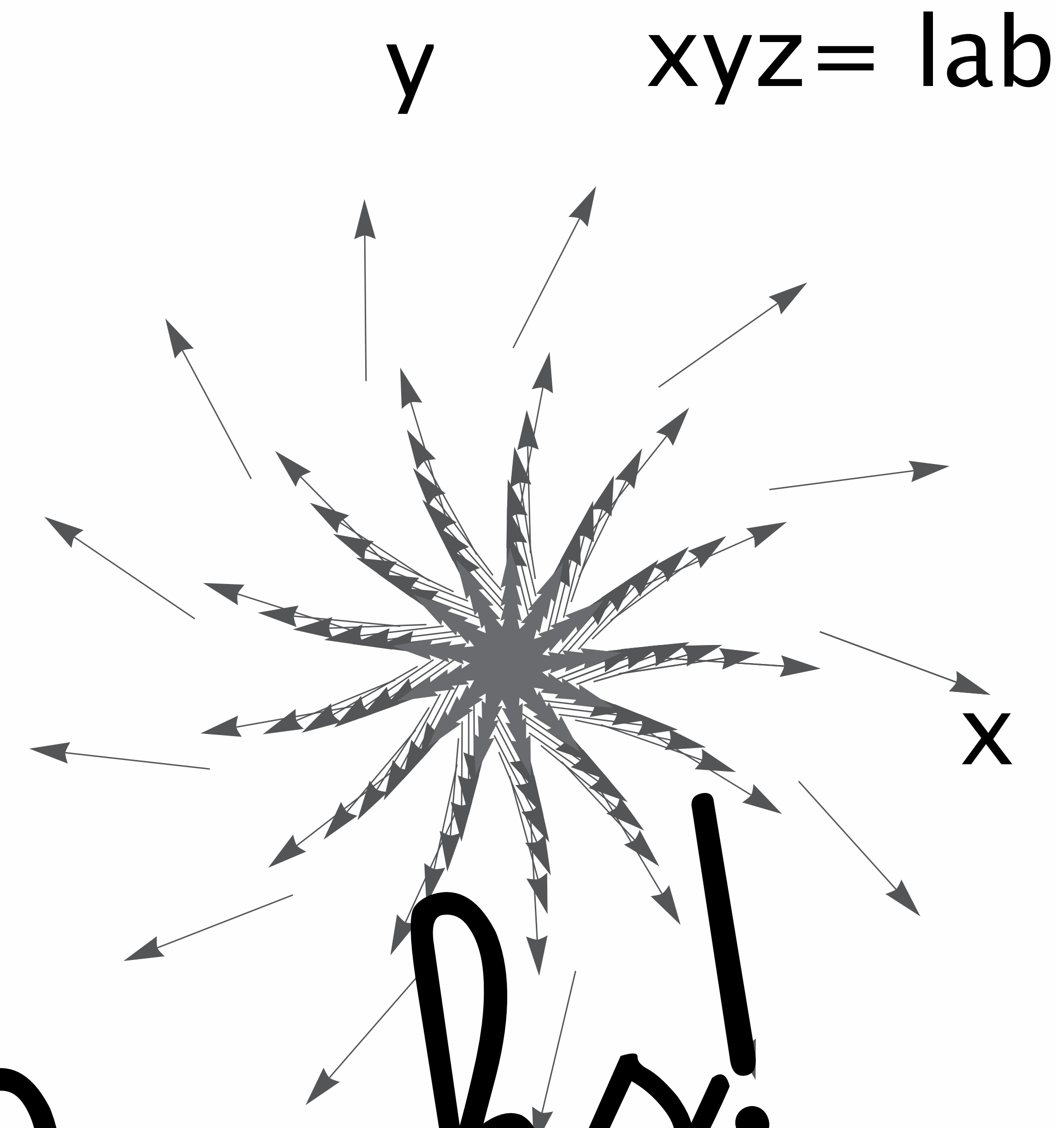




We Don't Know!

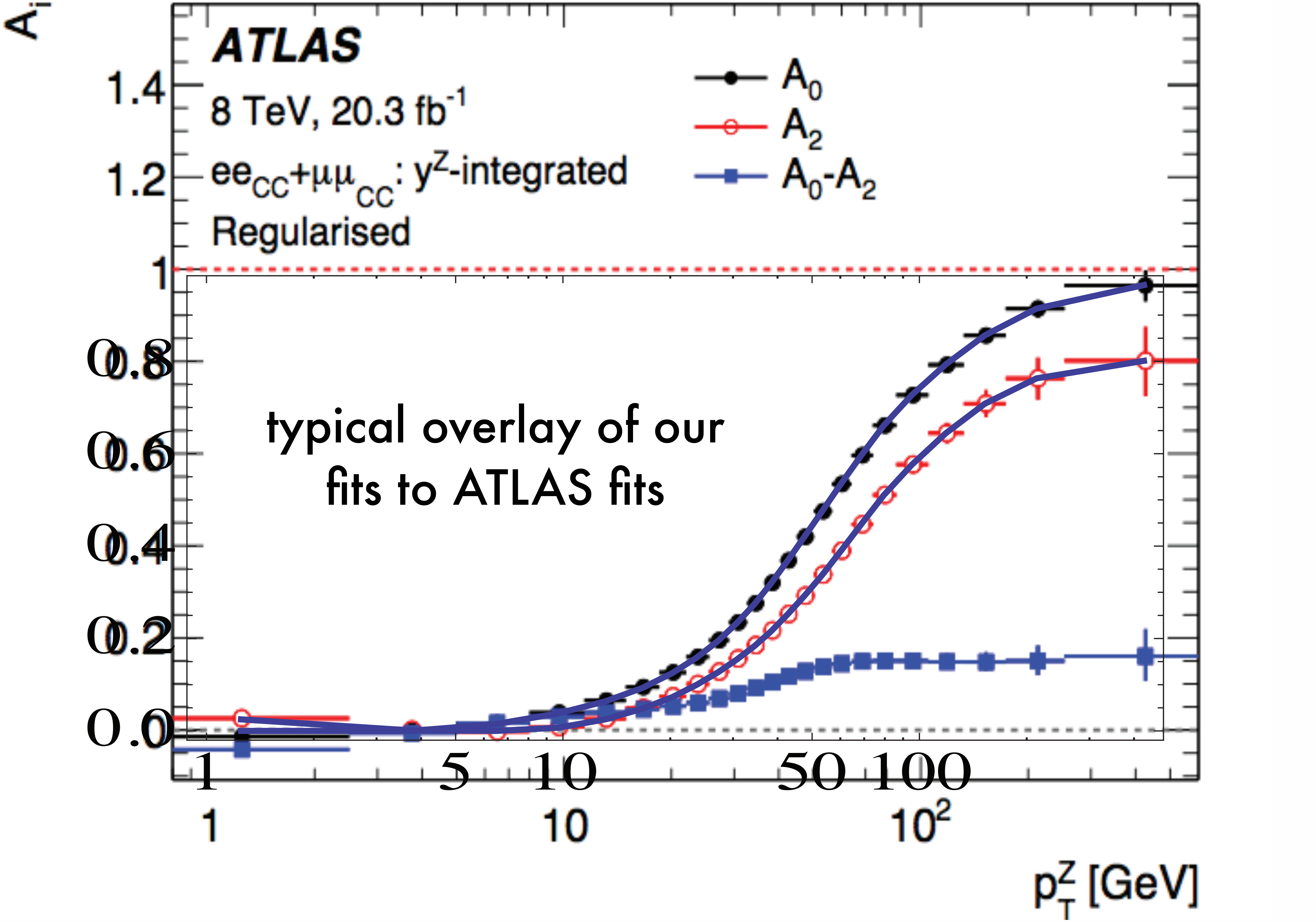
What Does It Mean?





We Don't Know!

Thanks!


ATLAS
8 TeV, 20.3 fb-1
ee_CC+μμ_CC: y^Z-integrated
Regularised
A_0
A_2
A_0-A_2
A_i
1.4
1.2
1
0.8
0.6
0.4
0.2
0.0
1
5
10
50
100
10^2
p_T^Z [GeV]
typical overlay of our fits to ATLAS fits

P_T of Z = our q_T