Heavy ion collisions
and
nuclear structure

**"Celebrating Wanda's birthday:
a career devoted to the richness of nuclear
many-body physics"**

Istituto Galileo Ferraris, Torino

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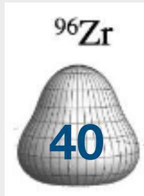
Heavy ion collisions and nuclear structure

Low-energy structure of nuclei affects the outcome of high-energy collisions between nuclei

Numerous evidences for the influence of "intrinsic" nuclear shapes, e.g Ru/Zr ratios



Observations made at colliders impact our knowledge of nuclear structure

The large sensitivity to initial configurations of nucleons allows for a precise determination of deformation parameters, neutron skin, etc

That fine details of nuclear structure survive the complexity of a nucleus-nucleus collision at high energy is amazing…

[For a representative publication with many references see arXiv 2402.05995]

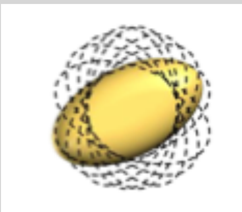
Shape of nuclei matters

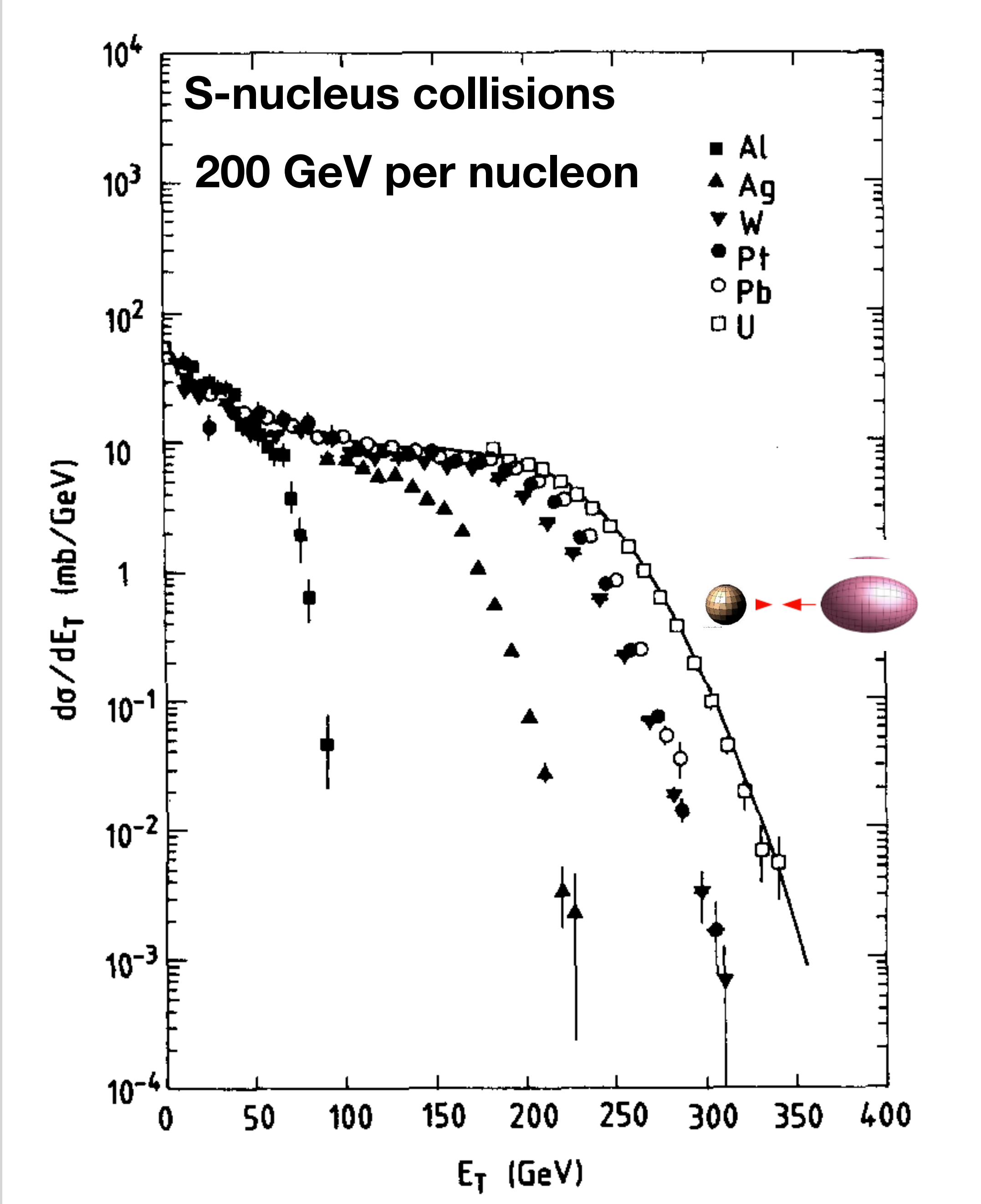
(an old story)

The tail of the transverse energy distribution depends on the orientation of the Uranium nucleus

HELIOS collaboration,
(CERN SPS)
Phys. Lett. B 214 (1988) 295

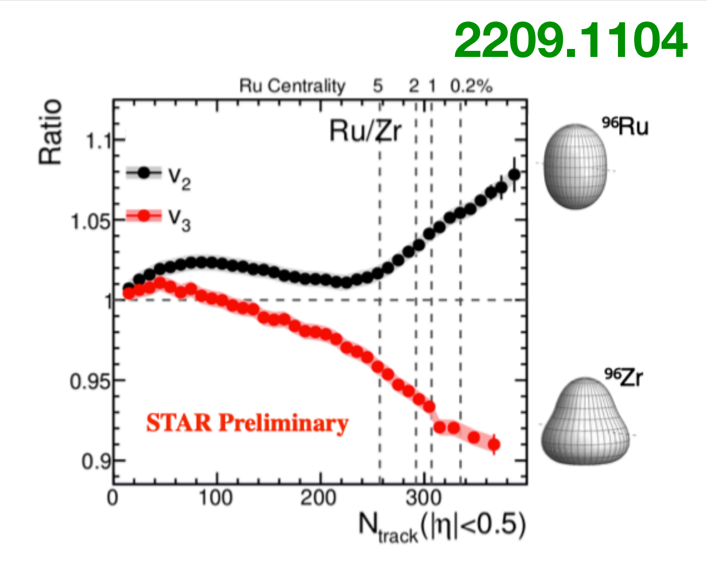
Analogous finding in electron scattering on deformed nuclei [Hofstadter, 1956]

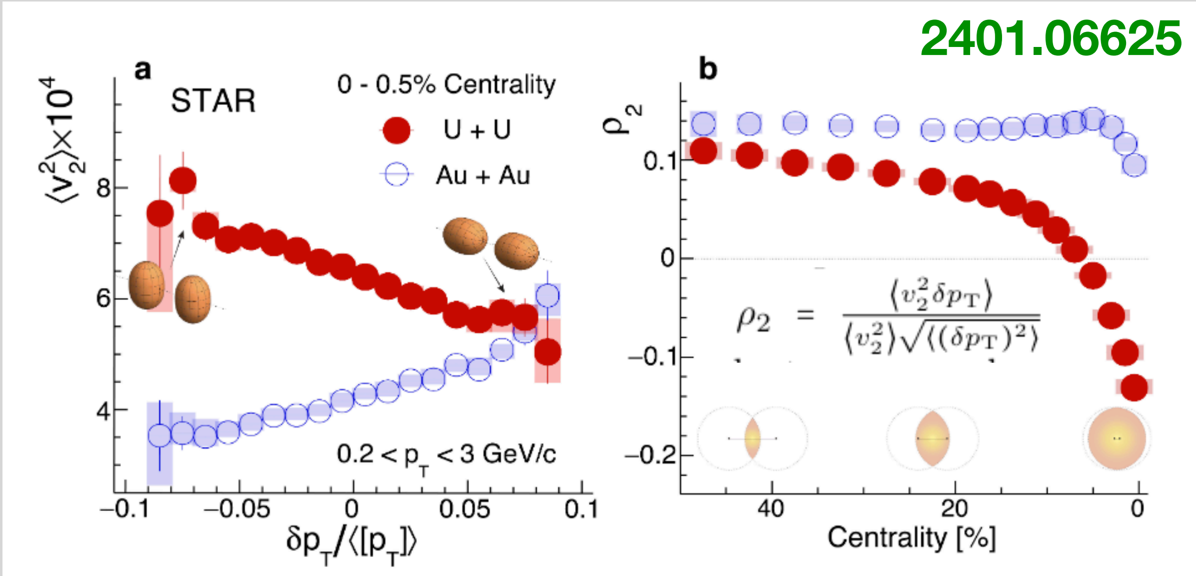




Shape of nuclei matters
(WHAT IS NEW ?)

High statistics, allowing measurements of correlations with high precision





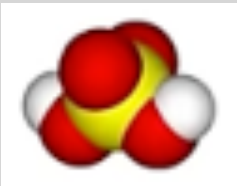
High energy, allowing us to resolve dynamics on very short time scales

The importance of time scales

IMAGING NUCLEI on YOCTOSECOND (*) TIME SCALE

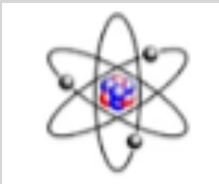
Nobel prize 2023 (P. Agostini, F. Krausz, A l'Huillier)

"for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter."



$$\mathrm{fs} = 10^{-15}\mathrm{s}$$

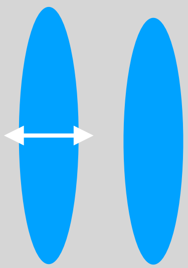
[Molecule internal dynamics]



$$\mathrm{as} = 10^{-18}\mathrm{s}$$

[Electronic motion]

[Heavy Ion collisions at LHC]



$$\mathrm{ys} = 10^{-24}\mathrm{s} \simeq 0.3\mathrm{fm/c}$$

$$\Delta x = (2R)/\gamma \simeq 10^{-2}\mathrm{fm}$$

Very short time scale as compared to the time scale of internal nucleus dynamics

Typical time for a nucleon to cross a nucleus

$$\Delta t \simeq 10\,\mathrm{ys} \quad (v_F/c \approx 0.3)$$

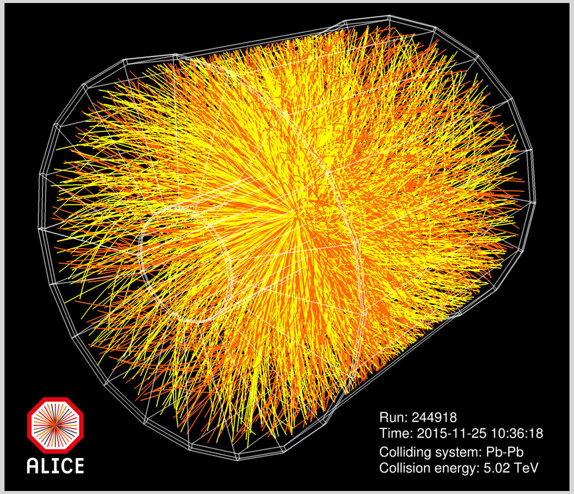
Time scale associated with excitation energy of 1 MeV

$$\Delta t \simeq 200\,\mathrm{fm/c} \approx 650\mathrm{ys}$$

(*)Title inspired by A. Ipp et al. "Yoctosecond pulses from the quark-gluon plasma", PRL 103.152301

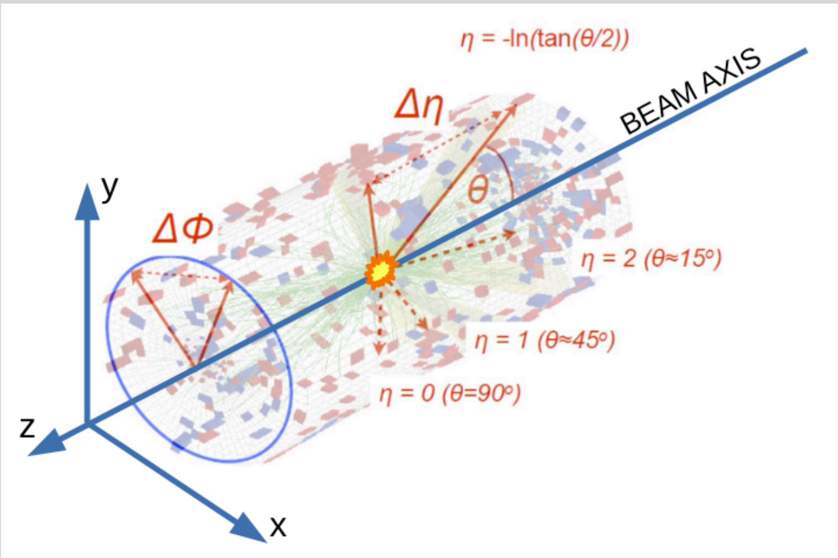
Azimuthal structure of particle production

What do we measure in HI collisions?



One-particle distribution

$$\frac{dN}{p_T\, dp_T\, d\varphi\, d\eta}$$

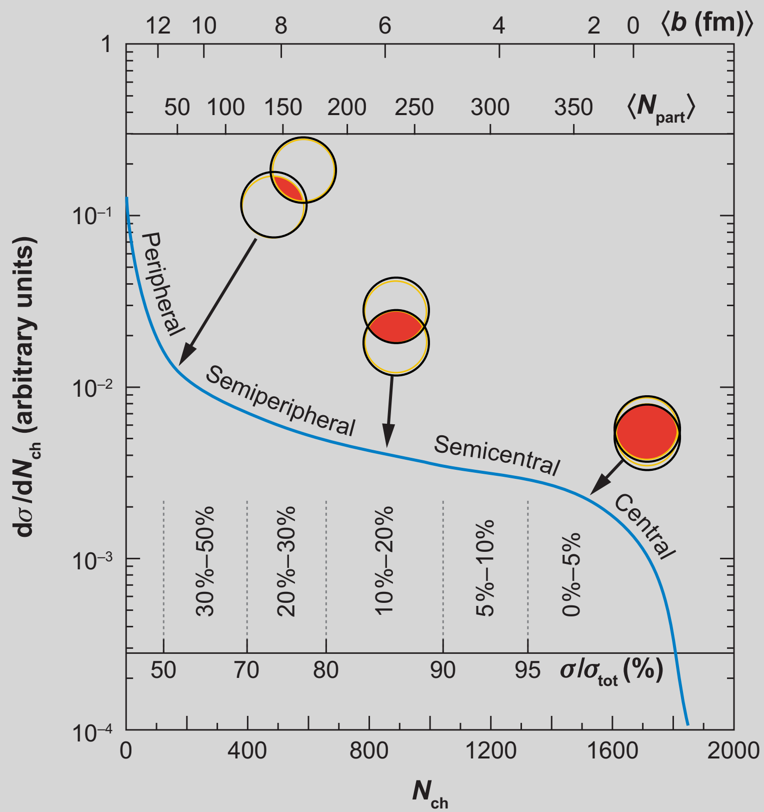


(from G. Giacalone, Talk ESNT, 2022)

Transverse energy distribution

$$\frac{d\sigma}{dN_{ch}} \sim \frac{d\sigma}{dE_T}$$

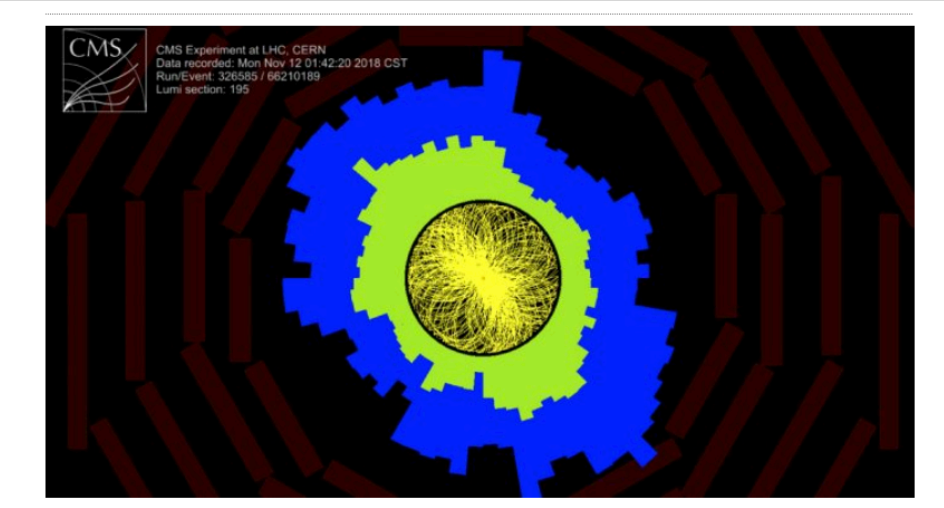
$|\eta| < 1$



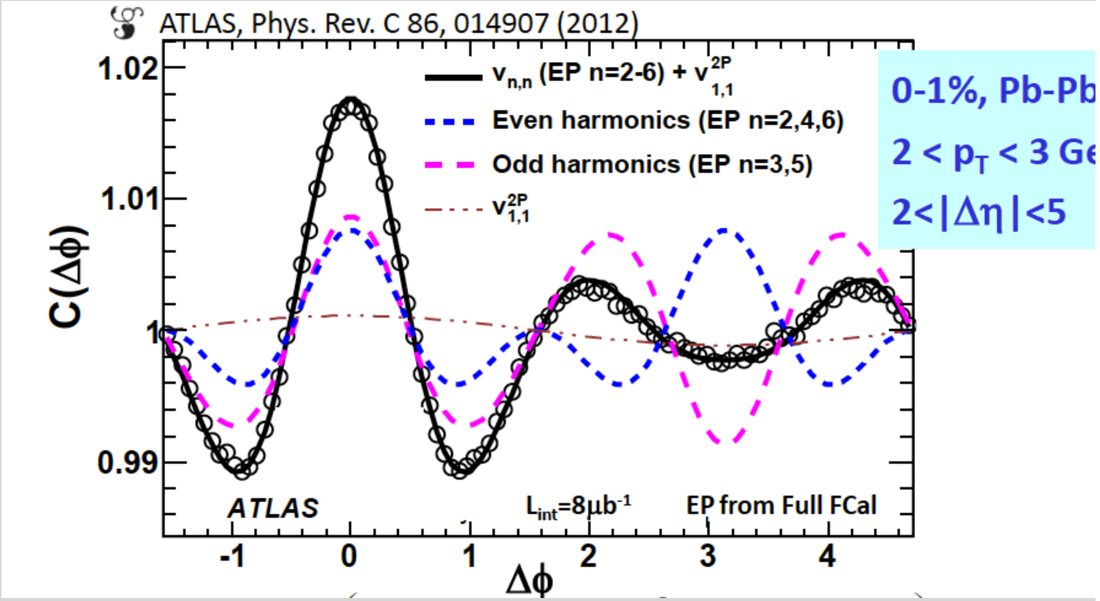
(Miller et al., Annu. Rev. Nucl. Part. Sci. 2007. 57:205–43)

Non trivial azimutal distribution (1)

Single event is not symmetric



Fourier analysis
"Multiple harmonics"



$$P_{\Psi}(\varphi) = \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} V_n \, e^{-in\varphi}$$

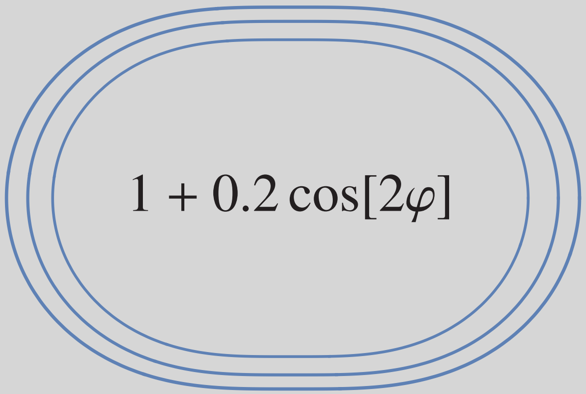
$$V_n = \int_0^{2\pi} d\varphi \, P_{\Psi}(\varphi) \, e^{in\varphi}$$

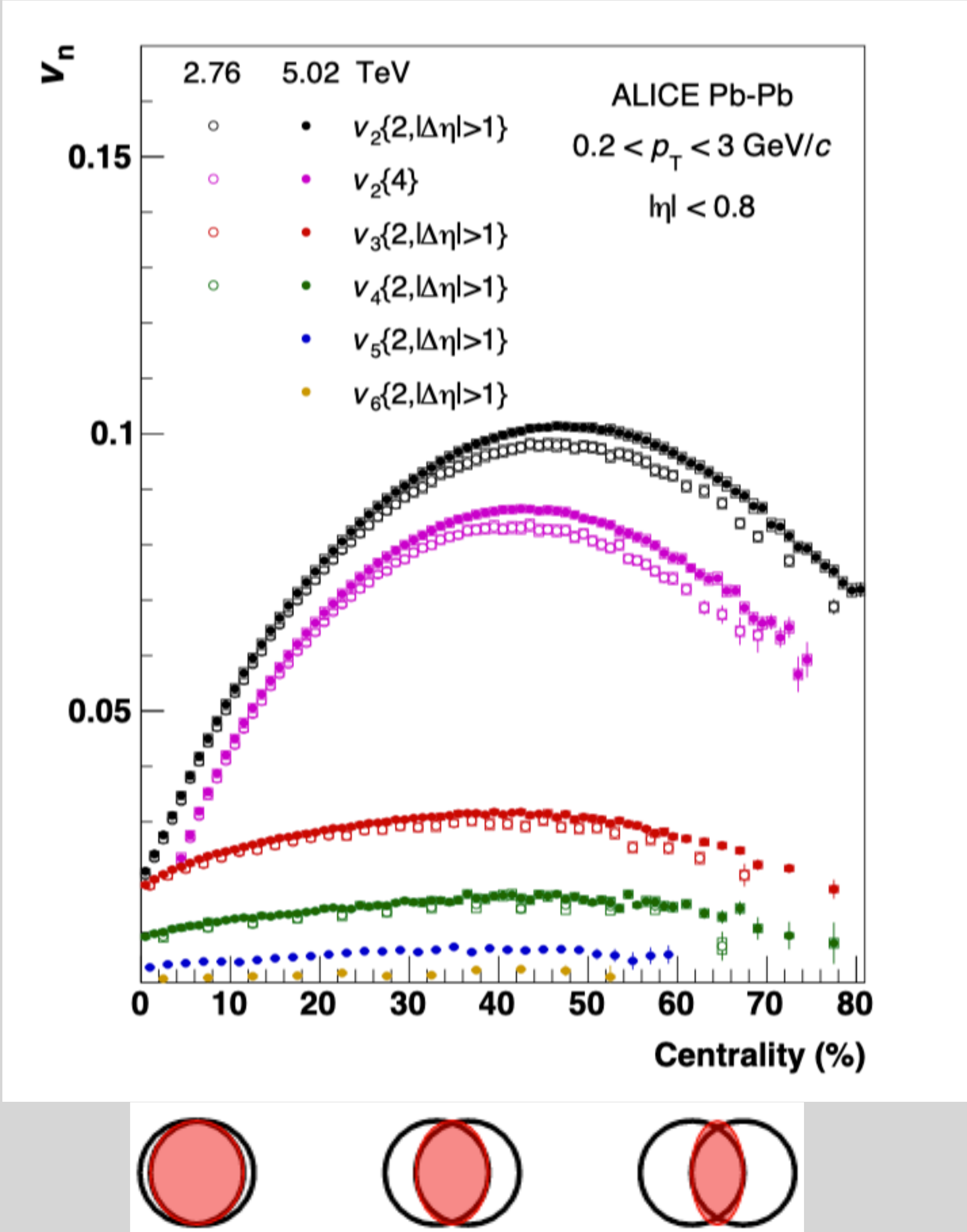
$$V_n = \upsilon_n \, e^{in\Psi_n}$$

$$\frac{1}{N}\frac{dN}{d\varphi} = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} \upsilon_n \cos[n(\varphi - \Psi_n)]\right]$$

Non trivial azimutal distribution (2)

$$\frac{1}{N}\frac{dN}{d\varphi} = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right]$$





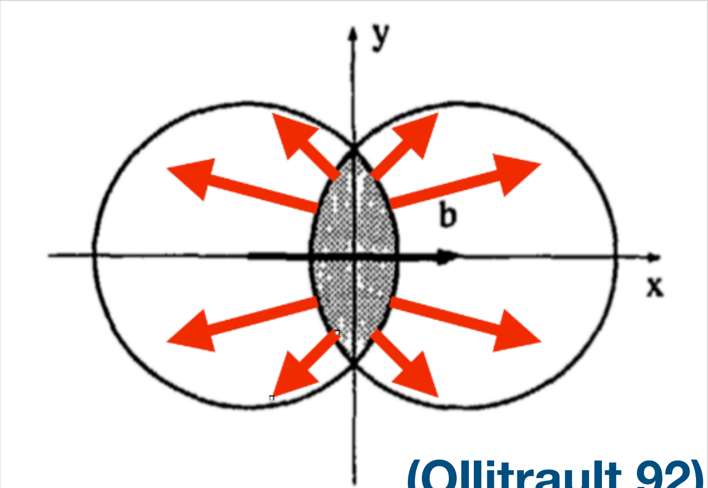
The magnitudes of the coefficients v_n are correlated with the impact parameter of the collision

QUESTIONS

- WHAT IS THE PHYSICAL ORIGIN OF THE EFFET?
- HOW DOES ONE DETERMINE Vn ?

HYDRODYNAMIC FLOW (1)

The shape of the collision zone determines the pressure gradients which accelerate particles



(Ollitrault 92)

$$u_x = u \cos \varphi \qquad u_y = u \sin \varphi$$

(u = flow velocity)

$$\nabla_x P \gg \nabla_y P \longrightarrow |u_x| \gg |u_y|$$

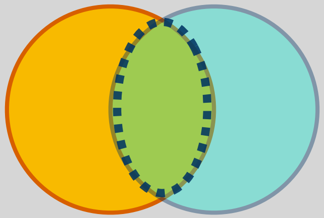
$$\langle \cos 2\varphi \rangle = \langle \cos^2 \varphi - \sin^2 \varphi \rangle > 0$$

Hence a non vanishing value of the "elliptic flow" v2

$$\frac{1}{N}\frac{dN}{d\varphi} = \frac{1}{2\pi}\left[1 + 2v_2 \cos[2(\varphi - \Psi_2)]\right] \qquad v_2 = \langle \cos 2\varphi \rangle = \int \frac{d\varphi}{2\pi}\frac{1}{N}\frac{dN}{d\varphi}\cos(2\varphi)$$

HYDRODYNAMIC FLOW (2)

- The magnitude of v2 is sensitive to the "shape" of the interaction region (in the transverse plane)



$$\varepsilon_2 = \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$$

Average done over the energy density in the transverse plane

- Hydrodynamics response is such that $v_2 \propto \varepsilon_2$

- Hence the dependence of v2 on the impact parameter

- Hydrodynamics then provides a link between the initial distribution of the energy density (its "shape") and the azimuthal structure of the momentum distribution of the observed particles.

HOW DOES ONE DETERMINE Vn ?

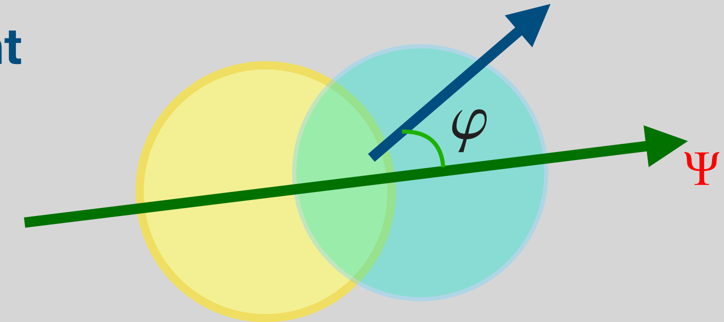
CORRELATIONS

AND

AVERAGE OVER EVENTS

TWO KINDS OF AVERAGE

Distribution of particles produced in a single event



$$P_{\Psi}(\varphi_1, \varphi_2, \cdots, \varphi_N)$$

In a given event emissions of particles are uncorrelated

$$P_{\Psi}(\varphi_1, \varphi_2, \cdots, \varphi_N) = p_{\Psi}(\varphi_1) \cdots p_{\Psi}(\varphi_N)$$

One-point function

$$p^{(1)}_{\Psi}(\varphi) = \int d\varphi_2 \cdots d\varphi_N \, P_{\Psi}(\varphi_1, \varphi_2, \cdots, \varphi_N) = p_{\Psi}(\varphi)$$

For elliptic flow alone

$$p_{\Psi}(\varphi) = \frac{1}{2\pi} \left[1 + 2v_2 \cos 2(\varphi - \Psi)\right]$$

If there were enough particles in the event, one could reconstruct the one-point distribution, that is v2 and Psi.

EMERGENCE OF CORRELATIONS

- **Start from uncorrelated 2-point function**

$$p_{\Psi}^{(2)}(\varphi_1, \varphi_2) = p_{\Psi}^{(1)}(\varphi_1) p_{\Psi}^{(1)}(\varphi_2)$$

- **Integration over Ψ generates correlations**

$$p^{(2)}(\varphi_1, \varphi_2) = \int \mathrm{d}\psi \, p_{\Psi}^{(2)}(\varphi_1, \varphi_2) = 1 + 2v_2^2 \cos 2\Delta\varphi = p^{(2)}(\Delta\varphi)$$

$$\Delta\varphi \equiv \varphi_1 - \varphi_2$$

- **One can determine v2 from a correlation function**

  (count pairs instead of single particles)

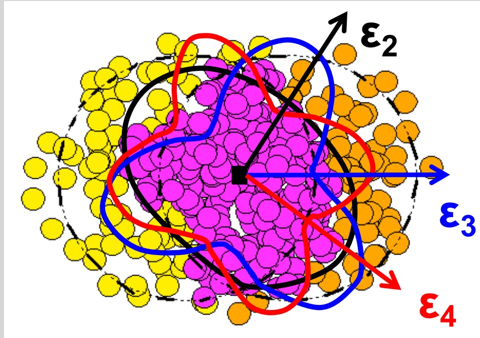
$$\langle \sum_{i \neq j} \cos 2(\Delta\varphi_{ij}) \rangle = N(N-1) \int \frac{\mathrm{d}\Delta\varphi}{2\pi} \, p^{(2)}(\Delta\varphi) \cos(2\Delta\varphi) = N(N-1) v_2^2$$

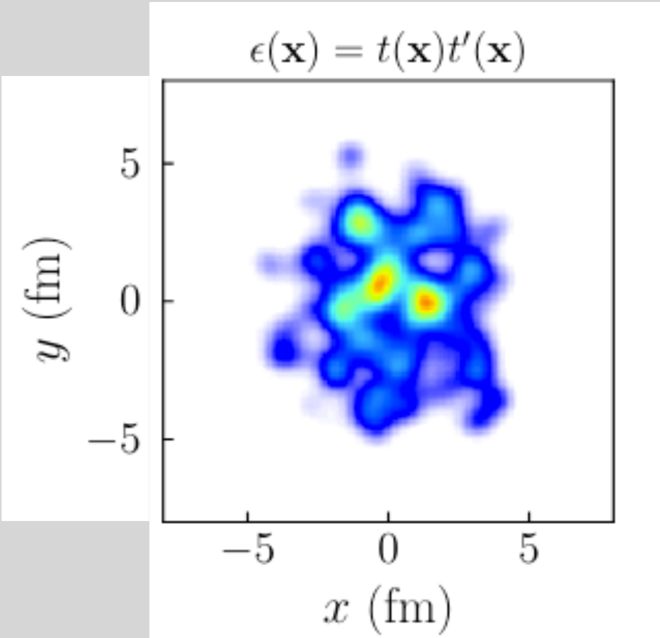
INITIAL FLUCTUATIONS

- RANDOM POSITIONS OF NUCLEONS
- RANDOM ORIENTATION OF NUCLEI
- ZERO POINT COLLECTIVE OSCILLATIONS

GLAUBER INITIAL FLUCTUATIONS

- Energy deposition is a **random process**, with local fluctuations in energy density





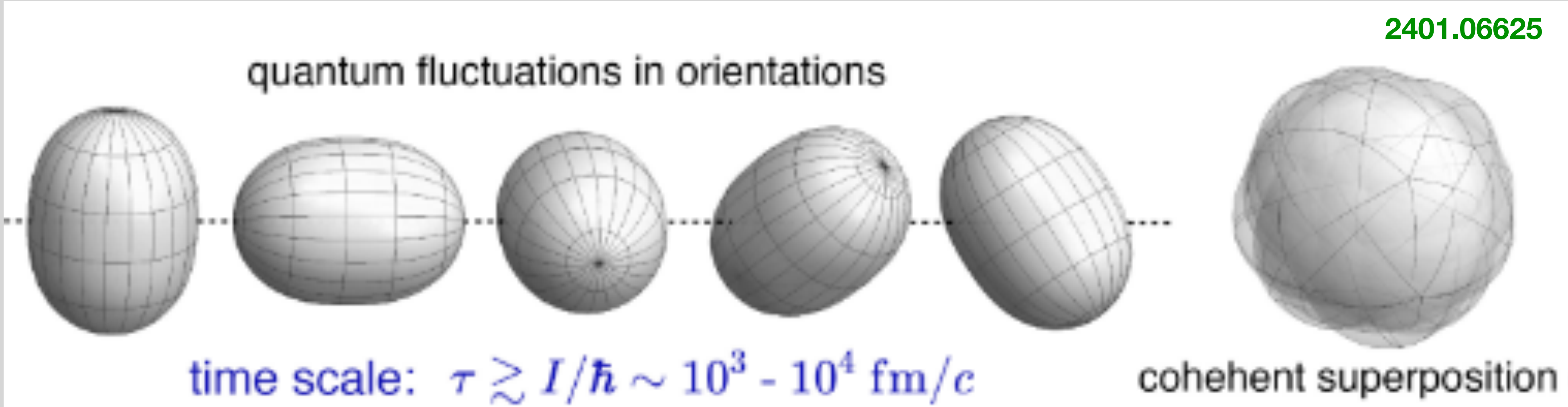
- The **pattern of fluctuations is strongly correlated with that of initial positions**, as given by the Glauber sampling

- As a result of fluctuations, "shapes" emerge, even at **zero impact parameter**, leading to measurable flow effects

- Short wavelength fluctuations average out. What remains, after some transient evolution, are the **long wavelength fluctuations** (low multipoles, "collective variables") that characterize the "shape" of the collision zone.

- The **deformation of nuclei** leads to another source of fluctuations

PROBING THE RANDOM ORIENTATIONS OF DEFORMED NUCLEI



… ASSUMING THE PICTURE OF A WELL DEFORMED INTRINSIC STATE IS VALID

Connection to nuclear structure
deformed nuclei

Why are nuclei "deformed"

- **If nuclei were "liquid drops", their equilibrium shapes would be spherical**
  (the qualification "deformed" refers to deviation from spherical shape)
- **Deformation is intimately connected with single particle motion in a self-consistent mean field**
- **A deformed nucleus is characterised by a non vanishing quadrupole moment of the one-body density** $Q = r^2 P_2(\cos\theta)$

$$\langle Q \rangle = \int \mathrm{d}^3 r \, \rho(\vec{r}) \, Q(\vec{r}) \neq 0 \qquad \rho(\vec{r}) = \int \mathrm{d}^3 r_2 \cdots \mathrm{d}^3 r_N \, |\Phi(\vec{r}, \vec{r}_2, \cdots, \vec{r}_N)|^2$$

where $\Phi(\vec{r}_1, \vec{r}_2, \cdots, \vec{r}_N)$ **is the "deformed" independent particle wave function.**

- **But** Φ **cannot be the ground state of the nuclear Hamiltonian since the ground state carries zero angular momentum**

$$\langle \Psi_{J=0} | Q | \Psi_{J=0} \rangle = 0$$

- **Way out:** Φ **is considered as an "intrinsic" state, function of intrinsic coordinates. The full wave function contains a factor that describe the collective rotation of the system.**

Conceptual issues

- The collective model is physically well motivated, but it remains a model. No unique description. Collective coordinates are (most often) redundant.

- Descriptions based on self-consistent mean fields (or density functional theories) involve spontaneous symmetry breaking.

- Symmetry breaking in finite systems is an approximate concept. Symmetry has to be restored, one way or another (collective model, projection techniques, etc).

- One could even describe nuclear properties without any reference to an intrinsic state. This is the case for instance of shell model wave functions.

  (see e.g. A. Poves et al. "Limits on assigning a shape to a nucleus", arXiv: 1906.07542)

- One touches here a general issue, that of the choice of basis in quantum mechanics. In some basis the "physics" is more "manifest" than in others...

- Deformation can be inferred from invariant moments (Kumar 1972)

$$\langle Q \rangle = 0 \qquad \langle Q^2 \rangle \neq 0 \qquad \qquad \left(\langle Q^4 \rangle - \langle Q^2 \rangle^2 ,\, \langle Q^6 \rangle - \langle Q^3 \rangle^2 \right) \longrightarrow (\Delta\beta, \Delta\gamma)$$

and more broadly by correlation functions

$$\langle Q^2 \rangle = \int_{\boldsymbol{r}_1 \boldsymbol{r}_2} q(\boldsymbol{r}_1) q(\boldsymbol{r}_2)\, S(\boldsymbol{r}_1, \boldsymbol{r}_2) \qquad S(\boldsymbol{r}_1, \boldsymbol{r}_2) = \langle \hat{\rho}(\boldsymbol{r}_1) \hat{\rho}(\boldsymbol{r}_2) \rangle - \langle \hat{\rho}(\boldsymbol{r}_1) \rangle \langle \hat{\rho}(\boldsymbol{r}_2) \rangle$$

From wave functions to correlation functions

Correlation functions

- In the intrinsic state the nucleons are uncorrelated (mean field picture), but the average potential has some "orientation"

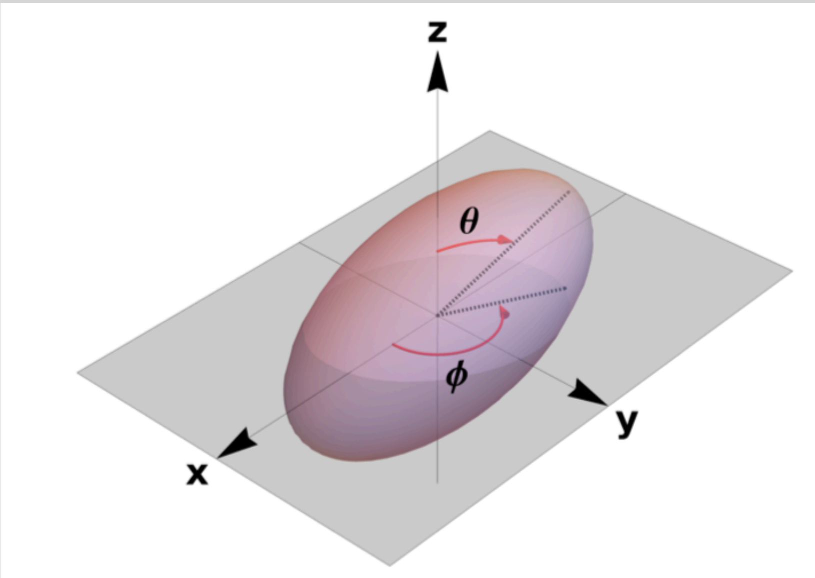
$$P_\Omega(r_1, r_2, \cdots, r_N) = \left|\Phi_\Omega^{\rm int}(r_1, r_2, \cdots, r_N)\right|^2$$

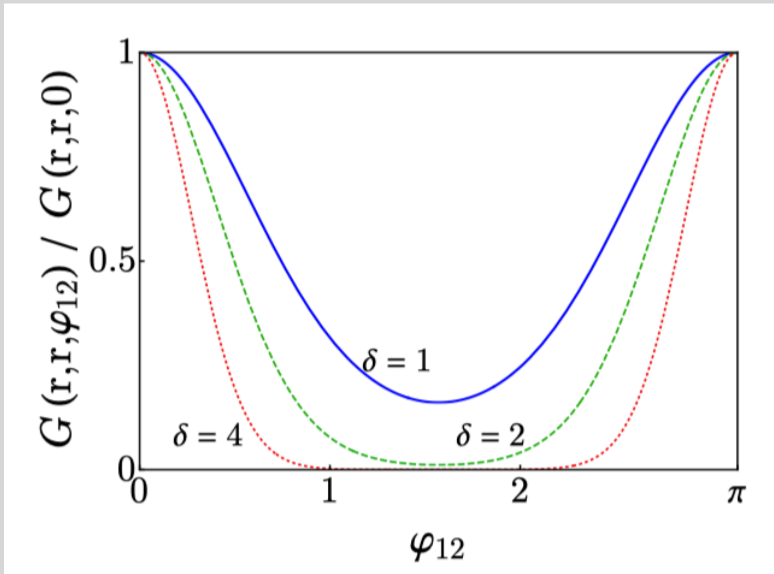
- Averaging over the collective wave function generates correlations (of all orders).

$$P(r_1, r_2, \cdots, r_N) = \int \frac{d\Omega}{4\pi} \left|\Phi_\Omega^{\rm int}(r_1, r_2, \cdots, r_N)\right|^2$$

NB. This average projects onto a spherical state

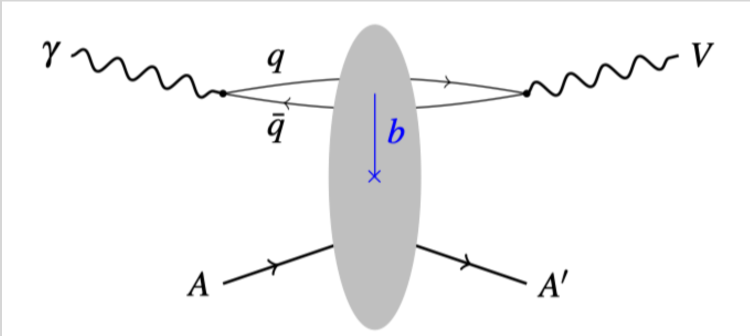
- Calculations based on this (approximate) procedure yield characteristic angular dependence of the density-density correlation function. (JPB, G. Giacalone 2504.15421)





Direct measurement of correlation functions

[Based on old idea by Caldwell and H. Kowalsji, (2010)]
[See also H. Mantysaari, et al. (2023)]



$$T_A(s) = \int \mathrm{d}z\, \rho(s, z)$$

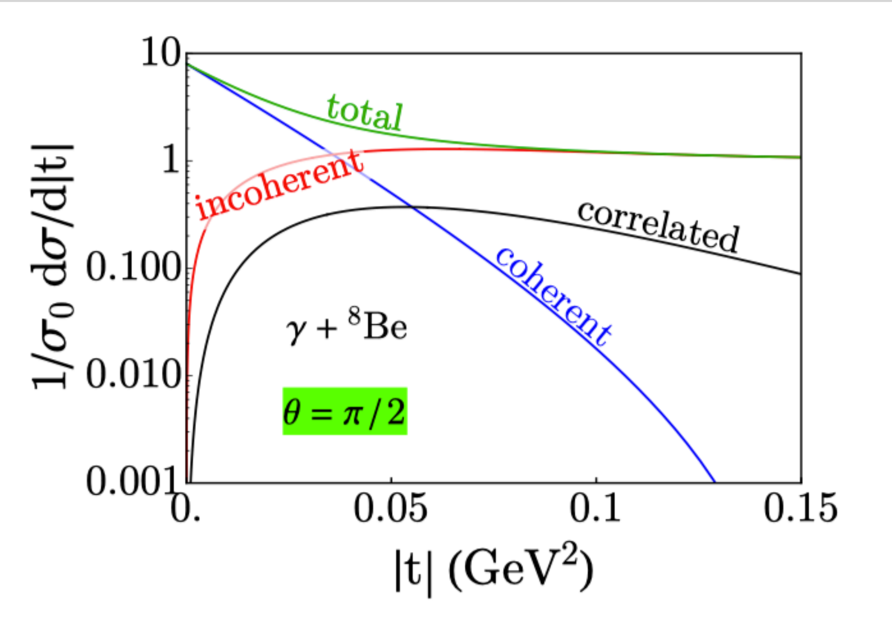
- **The incoherent diffractive production of a vector meson gives access to the density-density correlation function (projected onto transverse plane)**

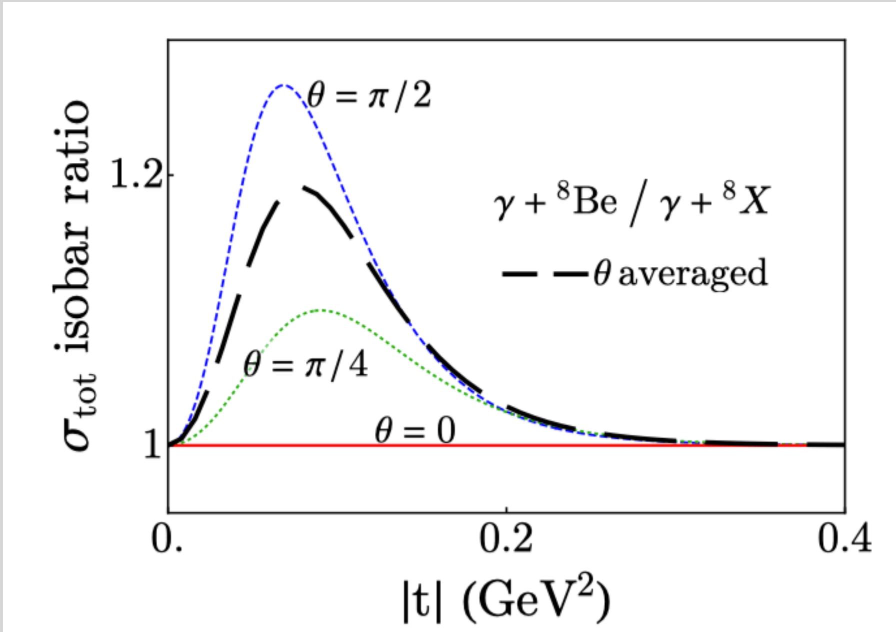
$$\langle T_A(s) T_A(s') \rangle - \langle T_A(s) \rangle \langle T_A(s') \rangle$$

- **If the wave function is approximated by that of a deformed state, an angular average is needed which generates long range correlations (JPB, G. Giacalone 2504.15421)**

$$\int_\Omega \langle T_A(s) T_A(s') \rangle_\Omega - \int_\Omega \langle T_A(s) \rangle_\Omega \int_\Omega \langle T_A(s') \rangle_\Omega$$

A TOY MODEL STUDY
Diffractive production of vector mesons on Berylium





^{8}X **is a fictitious isobar of** ^{8}Be

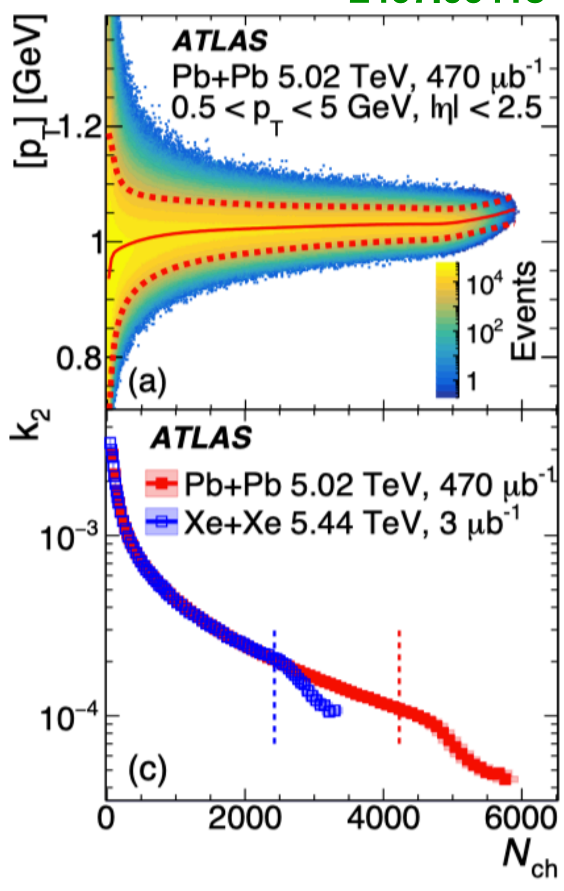
zero point oscillations in nuclear ground states

Ultracentral collisions and vo

Somewhat more speculative… fluctuations of the initial volume

(inspired by 2407.17313, Parida, Samanta, Ollitrault)
(see also B.G. Zakharov (2008.07304)

2407.06413



Volume fluctuations (at zero impact parameters) could be are related to the giant monopole resonance in Pb

They can be estimated accurately (JPB, Phys.Rept. 64 (1980))

$$q \equiv r^2 - \langle r^2 \rangle_0 \qquad \frac{\sqrt{\langle q^2 \rangle}}{\langle r^2 \rangle_0} \simeq 0.03$$

This looks compatible with ATLAS measurements of vo

$$k_2 = \frac{\langle (\delta p_T)^2 \rangle}{\langle [p_T] \rangle^2} = v_0$$

NB. In Oxygen, 0.03 -> 0.1

Conclusions

A FASCINATING DEVELOPMENT

- Heavy ion collisions may offer us the possibility to capture the shapes of deformed nuclei in a more direct way than any other previous experiment.
- Not only does one "see" the deformed shapes, but the values of deformation parameters can be determined with surprisingly high precision.
- One might be able to access/measure magnitude of zero point fluctuations in nuclear ground states
- The information about the (quantum) state of the nuclei is captured on a very short time scale. How can this information survive the complexity of the matter evolution?
- Much remains to be understood/explored….