From wounded nucleons to nuclear structure

Physics of Strong Interactions
under Extreme Conditions

Cracow School of Theoretical Physics
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Outline

Wounded nucleons
Nuclear geometry and initial entropy

Collective flows and fluctuations

Connections to nuclear structure
Imaging nuclei at yoctosecond time scale
Conceptual issues

Wounded nucleons

The wounded nucleon model (1)

Inspired by the phenomenology of particle production

- No intra nuclear cascade
- The observed multiplicity is not proportional to the number of binary collisions

$$N_{pA} = \frac{1}{2}\left(\nu_A + 1\right) N_{pp}$$

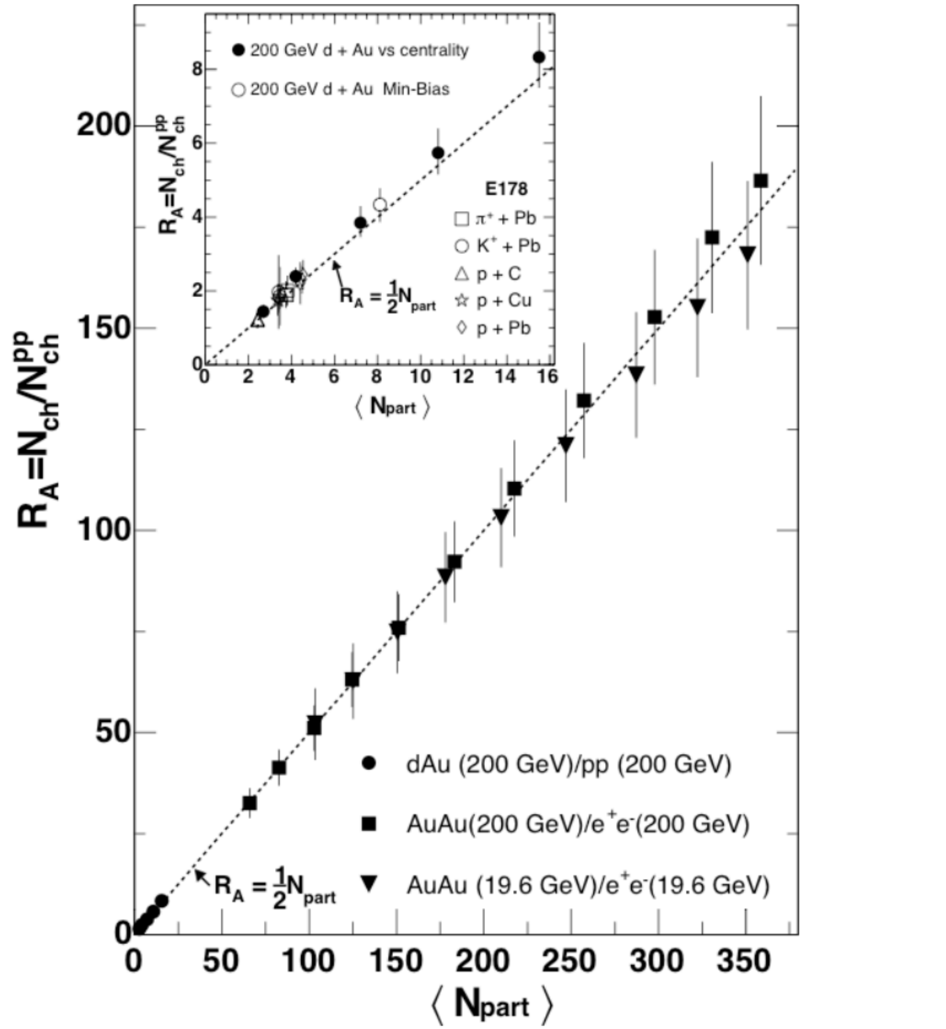
- Particles are not produced instantaneously

- The multiplicity does not depend on how many times a nucleon is hit

→ Wounded nucleons (participants)

[Bialas, Bleszynski, Czyz (1976)]

$$N_{pA} = \frac{1}{2} w_A N_{pp}$$



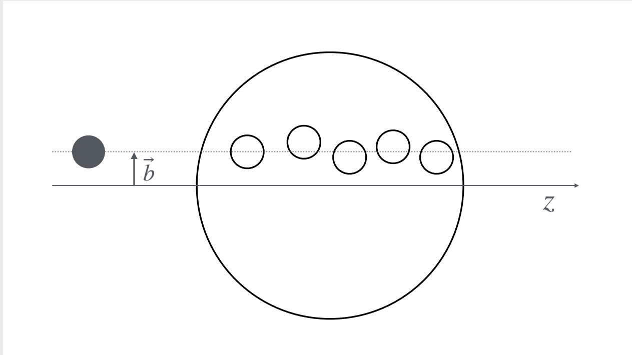
or wounded nucleons*

W. Busza, Acta Phys. Pol. B35 (2004)2873 E178:
W.Busza et al. PRL34 (1975) 836

*A.Biala, M.Bleszczynski, W.Czyz, Nucl.Phys. B111 (1976) 4661

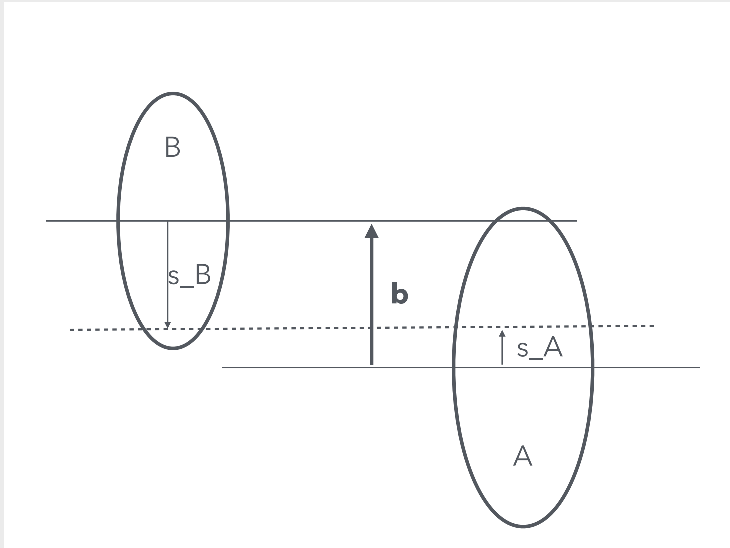
The wounded nucleon model (2)

$$N_{pA} = \frac{1}{2} w_A N_{pp}$$



Extension to AB collisions

$$N_{AB} = \frac{1}{2} w_{AB} N_{pp}$$



Thickness function

$$T_A(\mathbf{s}) = \int_{-\infty}^{\infty} dz\, \rho_A(\mathbf{b}, z)$$

Dependence on impact parameter

$$N_p(\mathbf{b}) = \int d^2\mathbf{s}\; n_p(\mathbf{s}, \mathbf{b})$$

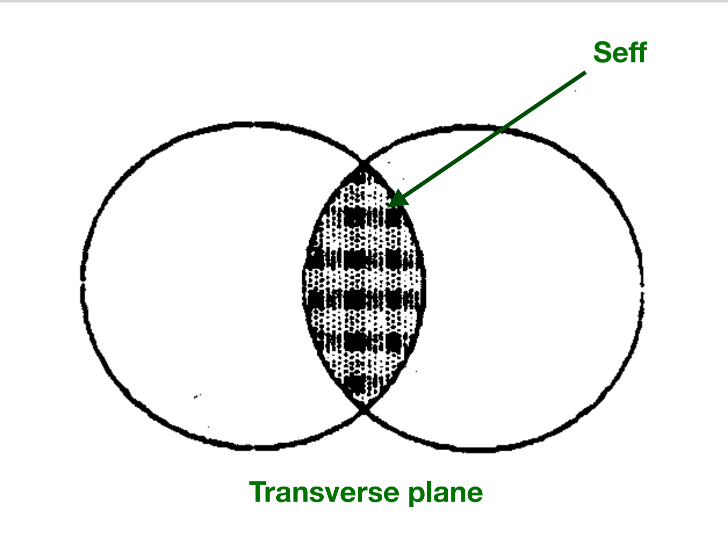
Density of participants

$$n_p(\mathbf{s}, \mathbf{b}) = T_A(\mathbf{s})\left[1 - \exp(-\sigma_N T_B(\mathbf{s} - \mathbf{b}))\right] + T_B(\mathbf{s} - \mathbf{b})\left[1 - \exp(-\sigma_N T_A(\mathbf{s}))\right]$$

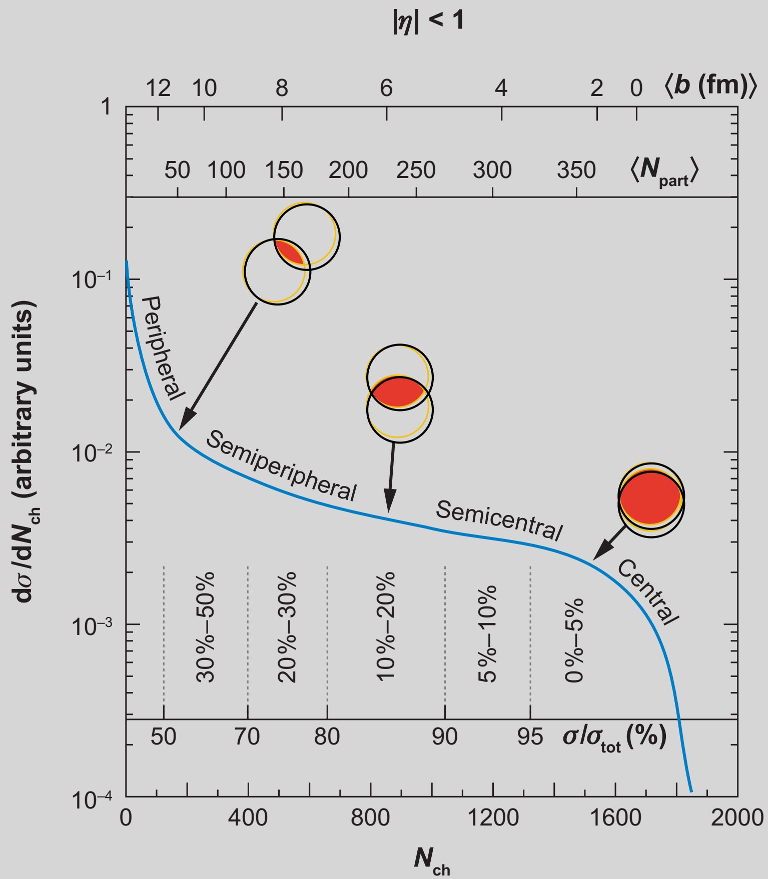
Nuclear geometry

number of nucleons in the overlap region at a given impact parameter

$$\bar{n}(\mathbf{b}) \approx \int_{S_{eff}} d^2\mathbf{s}\left[T_A(\mathbf{s}) + T_B(\mathbf{s}-\mathbf{b})\right]$$



The overlap region depends on Impact parameter



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

$T_A(\mathrm{s})$ depends on the positions of nucleons (projected in the transverse plane) at the "instant" of the collision

The wounded constituent picture suggests that most of the entropy is produced already at the very early stage of the process.
[A Bialas, J. Phys. G 35, 044053]

- **The wounded nucleon model does not resolve the dynamics in the longitudinal direction ("formation time", "formation zone", "soft physics"...)**

- **It suggests that the entropy is deposited locally in the transverse plane, at the location where nucleons are wounded.**

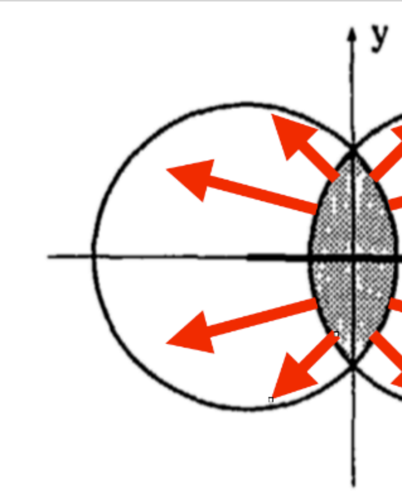
- **Modelling is needed to determine the local entropy $s(r)$, but long range correlations appear to be robust.**

- **It is convenient to view $s(r)$ as a 2D random field, with specific correlations.**

Collective flows and fluctuations

Collective flows

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)

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

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

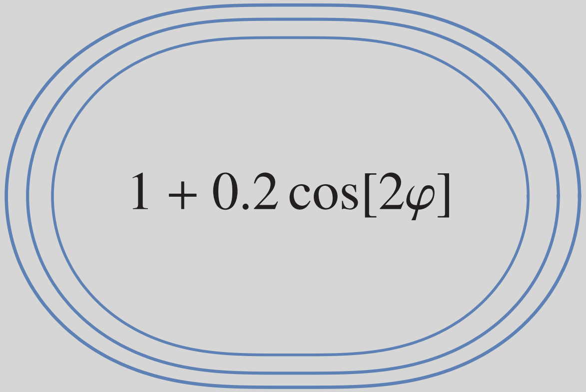
Hence a non vanishing value of the "elliptic flow" v2

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\varphi} = \frac{1}{2\pi}\left[1 + 2v_2\cos[2(\varphi - \Psi_2)]\right]$$

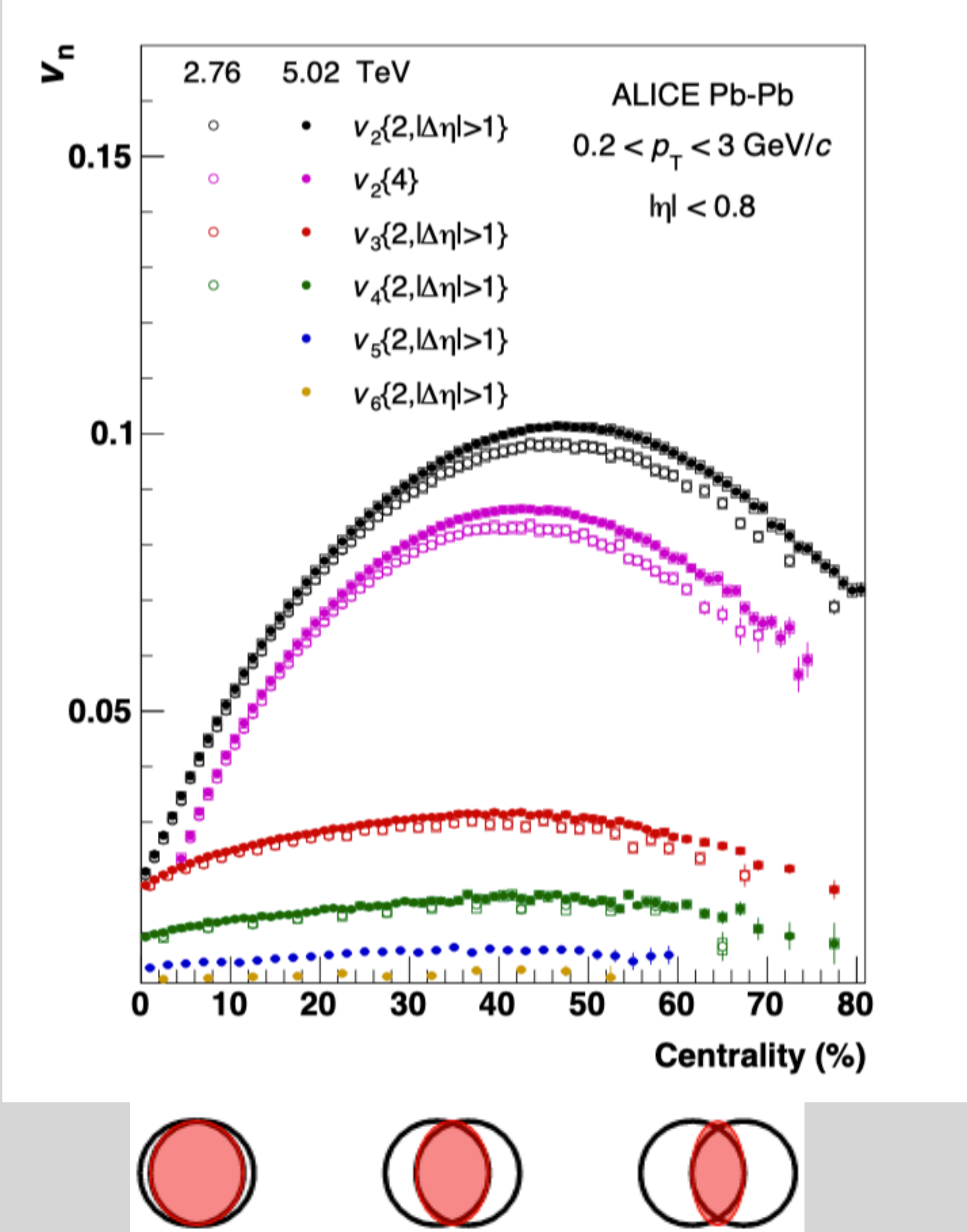
$$v_2 = \langle\cos 2\varphi\rangle = \int\frac{\mathrm{d}\varphi}{2\pi}\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\varphi}\cos(2\varphi)$$

Non trivial azimutal distribution

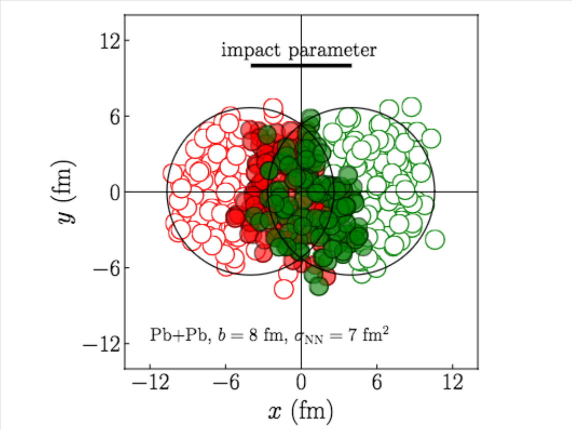
$$\frac{1}{N}\frac{dN}{d\varphi} = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right]$$



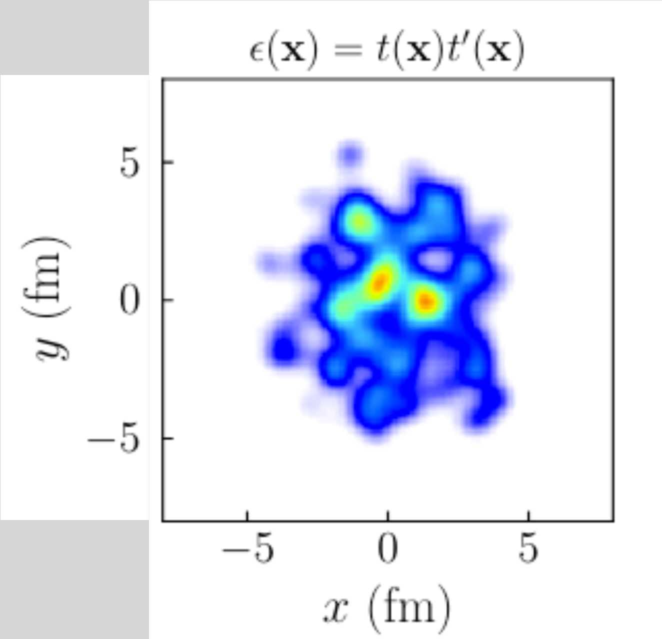
The magnitudes of the coefficients v_n are correlated with the impact parameter of the collision



Fluctuations



- Entropy deposition is a random process, with local fluctuations in entropy density



- Average over events reveal correlations in these fluctuations.

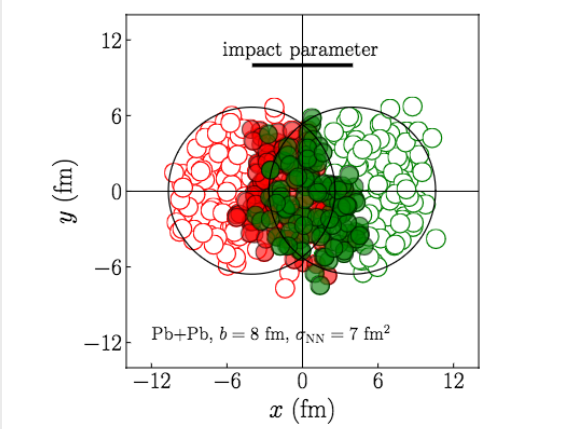
- The pattern of fluctuations is strongly correlated with that of the initial positions of the wounded nucleons

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

- Hydrodynamical evolution preserves that information, which is carried to the momentum distribution (by pressure gradients).

$v_2 \propto \varepsilon_2$ $\qquad$ $v_3 \propto \varepsilon_3$ $\qquad$ (higher multipoles are non linearly coupled)

Monte Carlo sampling



Sensitivity of the flows to the precise location of the nucleons at the instant of the collision

These locations are determined by the many-body wave functions of A and B

$$\left|\Psi_0(\mathbf{s}_1, \cdots, \mathbf{s}_A)\right|^2 = \int dz_1 \cdots dz_A \left|\Psi_0(\mathbf{r}_1, \cdots, \mathbf{r}_A)\right|^2 \qquad \mathbf{r} = (\mathbf{b}, z)$$

Most common approximation

$$\left|\Psi_0(\mathbf{r}_1, \cdots, \mathbf{r}_A)\right|^2 \mapsto \rho(\mathbf{r}_1) \cdots \rho(\mathbf{r}_A)$$

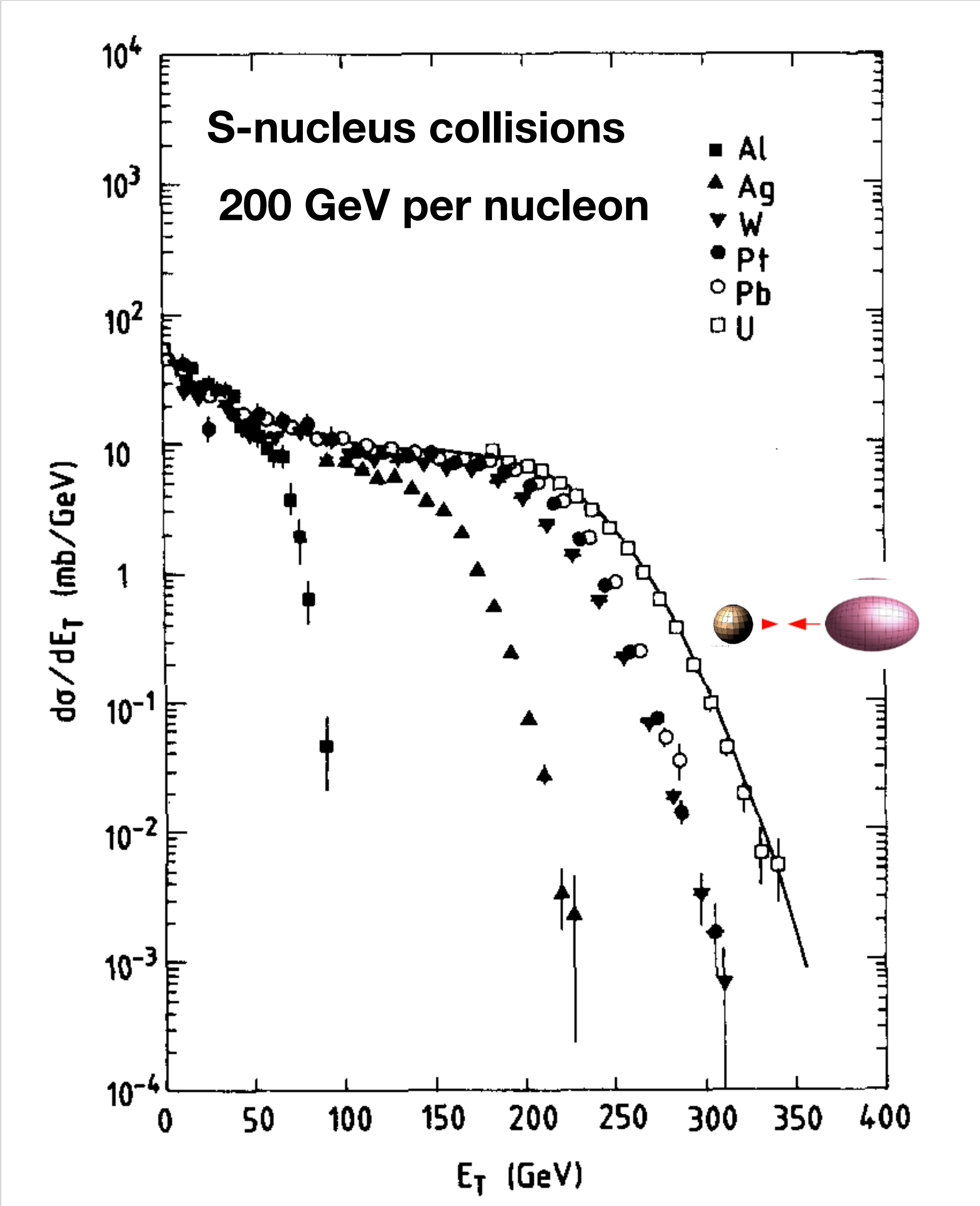
Includes fluctuations of nucleon positions, but ignores all correlations. Still, it works amazingly well….

But one can do better, and learn about specific correlations.

Connection to nuclear structure

Shape matters

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

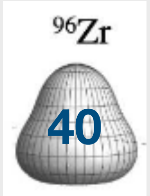


HELIOS collaboration,
(CERN SPS)
Phys. Lett. B 214 (1988) 295

Heavy ion collisions and nuclear structure

Low-energy structure of nuclei affects 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

Precise determination of e.g.

- **deformation parameters :** $^{129}Xe,\ \beta = 0.2, \gamma = 0.27^o$ **[2108.09578]**
- **neutron skin,** $\Delta r_{np} = 0.217 \pm 0.058$ **fm [2305.00015]**

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

Imaging nuclei at the yoctosecond time scale

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

Why are nuclei "deformed"

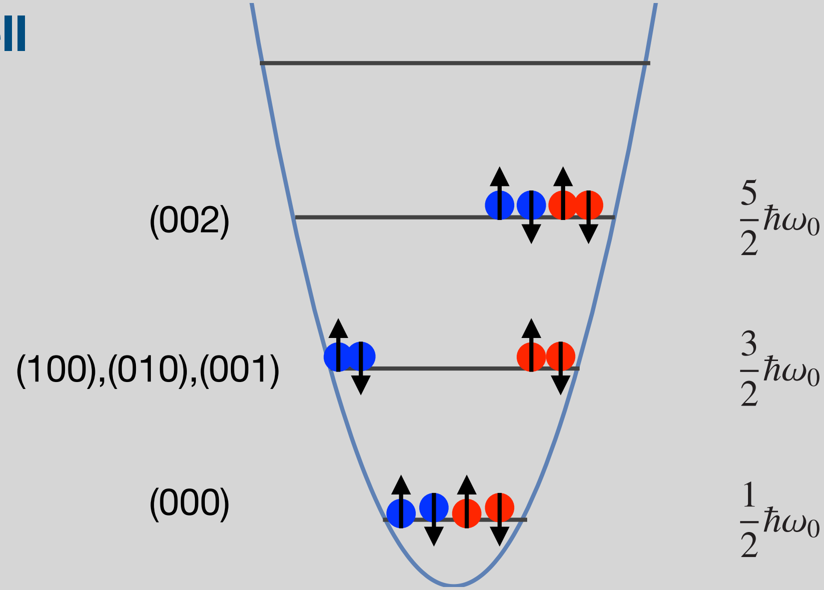
- **If nuclei were "liquid drops", their equilibrium shapes would be spherical**
  (the qualification "deformed" refers to deviation from spherical shape)

- **Deformation is intimately connected with single particle motion in a self-consistent mean field**

- **Independent nucleons in a harmonic potential well**

$$H_0 = \frac{p^2}{2m} + \frac{1}{2}\left(\omega_x x^2 + \omega_y y^2 + \omega_z z^2\right)$$

$$\varepsilon_{n_x n_y n_z} = (n_x + 1/2)\hbar\omega_x + (n_y + 1/2)\hbar\omega_y + (n_z + 1/2)\hbar\omega_z$$



- **The frequencies of the oscillator adjust so as to make the velocity distribution isotropic**

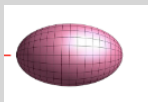
- **Isotropic filling yields a spherical potential**

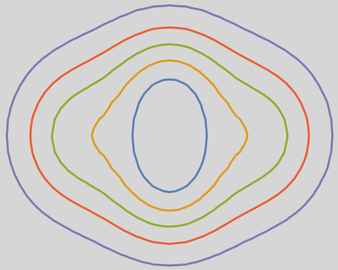
$$^{16}\mathrm{O} \; : \quad \omega_x = \omega_y = \omega_z = \omega_0$$

The deformed shape is energetically favoured

- **Anisotropic filling yields a deformed potential**

$$^{20}\mathrm{Ne} \; : \quad \omega_x = \omega_y, \; \omega_z = \frac{7}{11}\omega_x$$



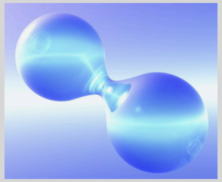


Akin to spontaneous symmetry breaking

Is deformation directly observable ?

- The mean field wave function $\Phi_\Omega(q_1, \cdots, q_A)$ carries the deformation
- It is NOT the ground state of the nuclear Hamiltonian since the ground state carries zero angular momentum. The ground state is of the form

$$\Psi_{J=0} \propto \int \frac{d\Omega}{4\pi} \, \Phi_\Omega(q)$$



[Note analogy with a diatomic molecule]

- One could describe nuclear properties without any reference to an intrinsic state (e.g. shell model wave functions).

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

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

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

… or more generally from correlation functions

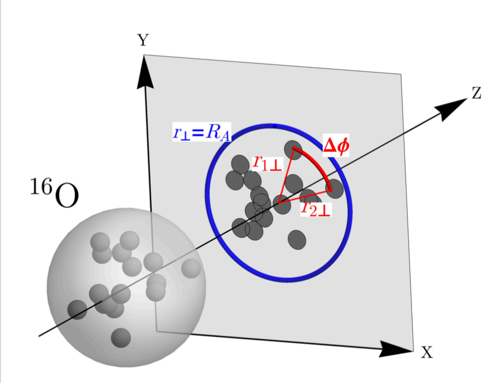
Angular correlations

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

$$P_\Omega(s_1, s_2, \cdots, s_A) = \left|\Phi_\Omega^{\text{int}}(s_1, s_2, \cdots, s_A)\right|^2 \approx \rho_\Omega(s_1)\cdots\rho_\Omega(s_A)$$

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

- In particular density-density correlation functions



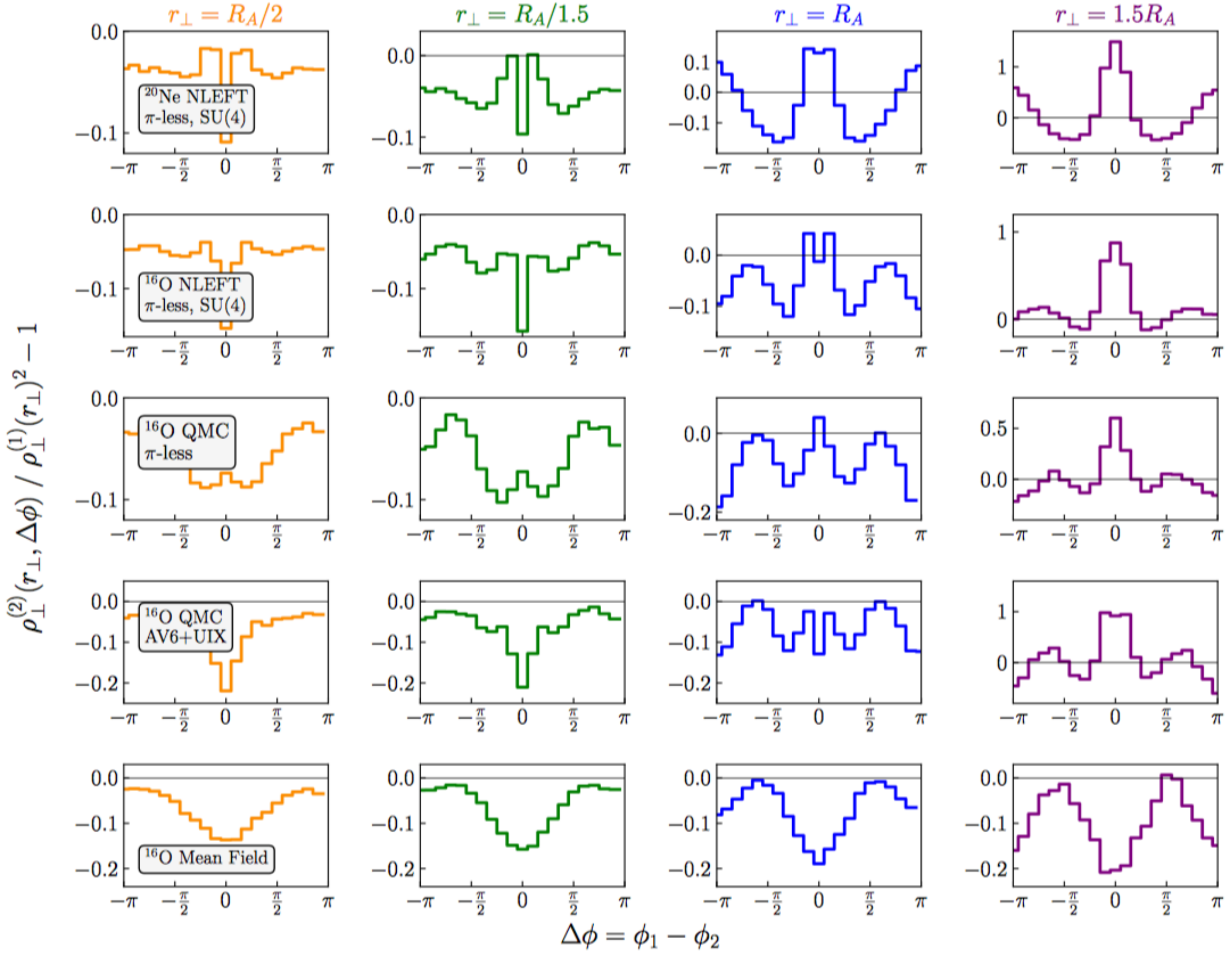
$$\rho(r) = \frac{\rho_0}{1 + e^{(r - R(\theta))/a}} \qquad R(\theta) = R_0(1 + \beta_2 Y_{20}(\theta))$$

$$\rho^{(1)}(r) = \int \frac{d\Omega}{4\pi} \rho_\Omega(r) \qquad \rho^{(2)}(r_1, r_2) = \int \frac{d\Omega}{4\pi} \rho_\Omega^{(1)}(r_1)\rho_\Omega^{(1)}(r_2)$$

$$\rho^{(2)}(r_1, r_2) - \rho^{(1)}(r_1)\rho^{(1)}(r_2) \propto \delta^2\, r_1^2 r_2^2 \cos(2(\varphi_1 - \varphi_2))$$

JPB and G.Giacalone, 2504.15521

Note the analogy with the determination of V2



JPB, G.Giacalone, A Lovato, 2512.18926

Conclusions

- The wounded nucleon model suggests that entropy production occurs locally in the transverse plane at very early time.
- Heavy ion collisions offer the possibility to capture the shapes of deformed nuclei in a direct way. Not only does one "see" the shapes, but the values of deformation parameters can be determined with surprisingly high precision.
- More information on nuclear structure (neutron skin, zero point fluctuations of sizes, etc) can be obtained.
- It is remarkable that the long range correlations present in the initial states survive the complexity of the matter evolution…