STAR experiment “non-spin” highlights

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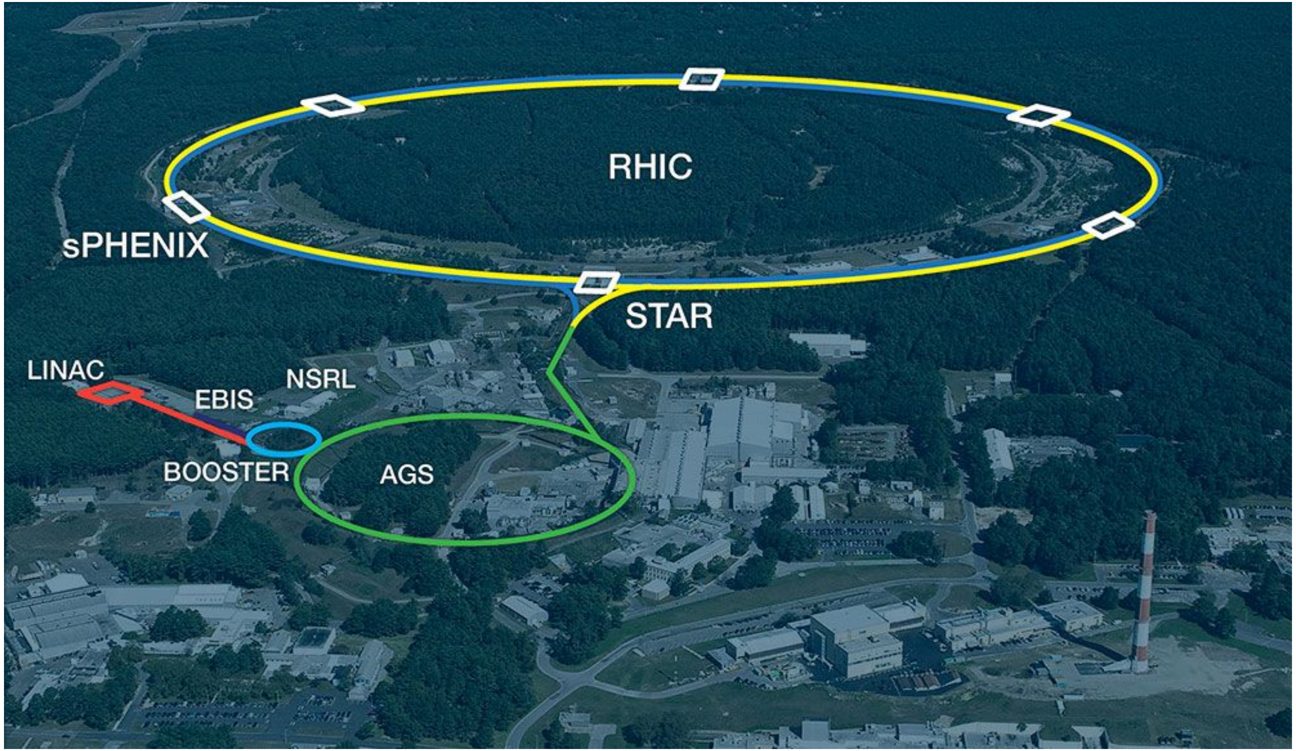
STAR 25 YEARS

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

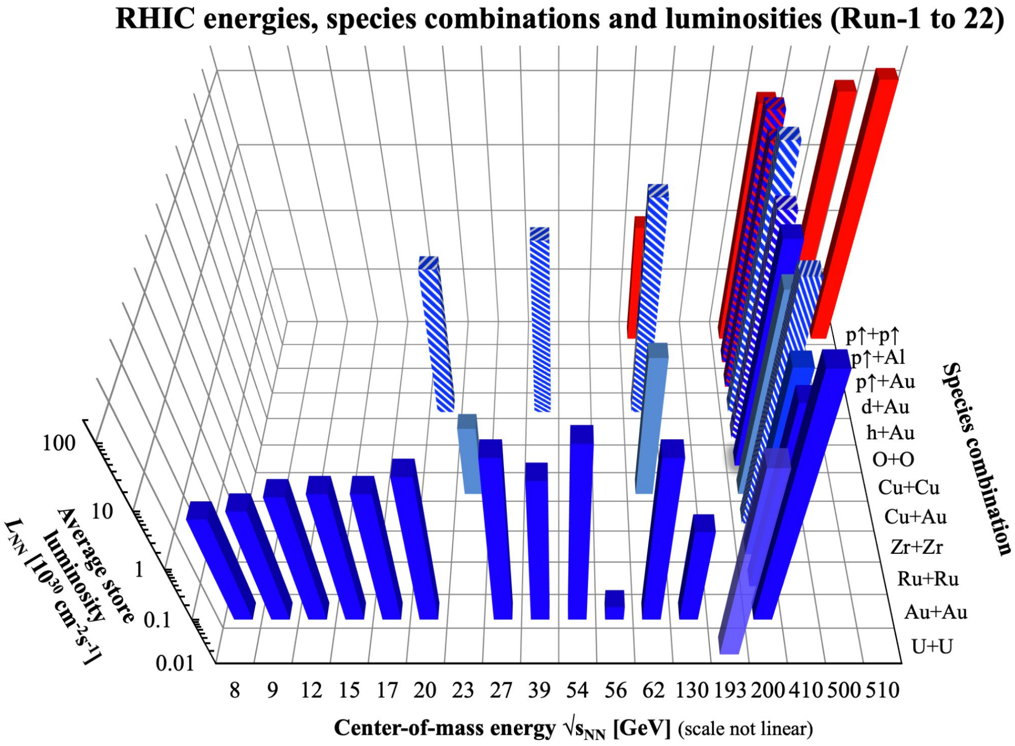
Relativistic Heavy Ion Collider (RHIC)

- Brookhaven National Laboratory (BNL), NY, USA
- Designed for heavy ion collisions, to study QGP and the spin structure of the proton
- World's only polarised proton collider
- Future site of the EIC



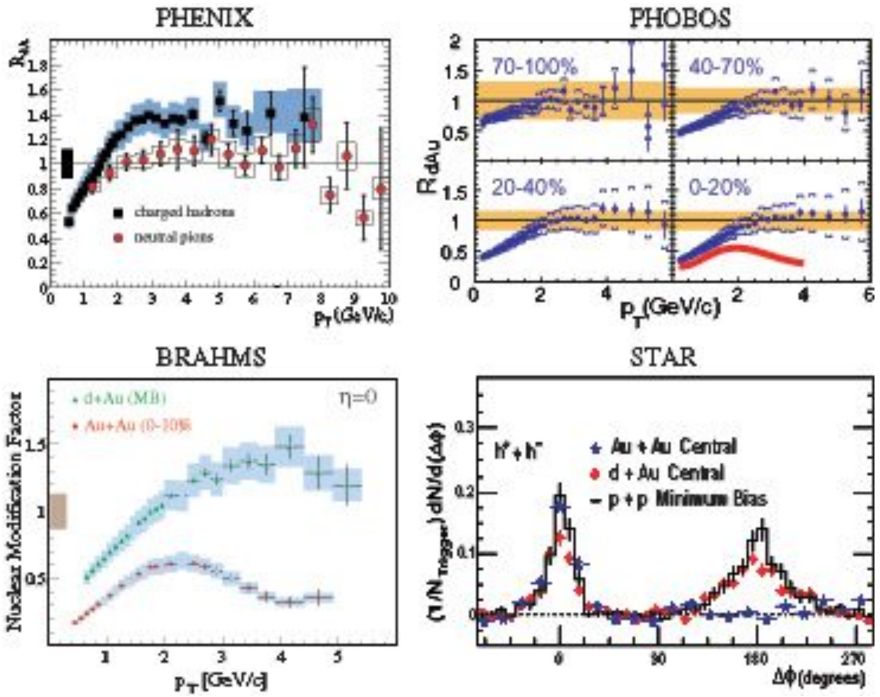
RHIC collider

- Various collision systems and programmes
  - Beam Energy Scan (BES) I and II
  - STAR FiXed Target (FXT) mode
  - Isobar collisions (Zr+Zr, Ru+Ru)
  - O+O collisions
- Top centre-of-mass energy of 510 GeV for p+p, 200 GeV/nucleon for A+A
- 5 major experiments
  - *PHOBOS*
  - *BRAHMS*
  - *PHENIX*
  - **STAR**
  - **sPHENIX**



RHIC legacy

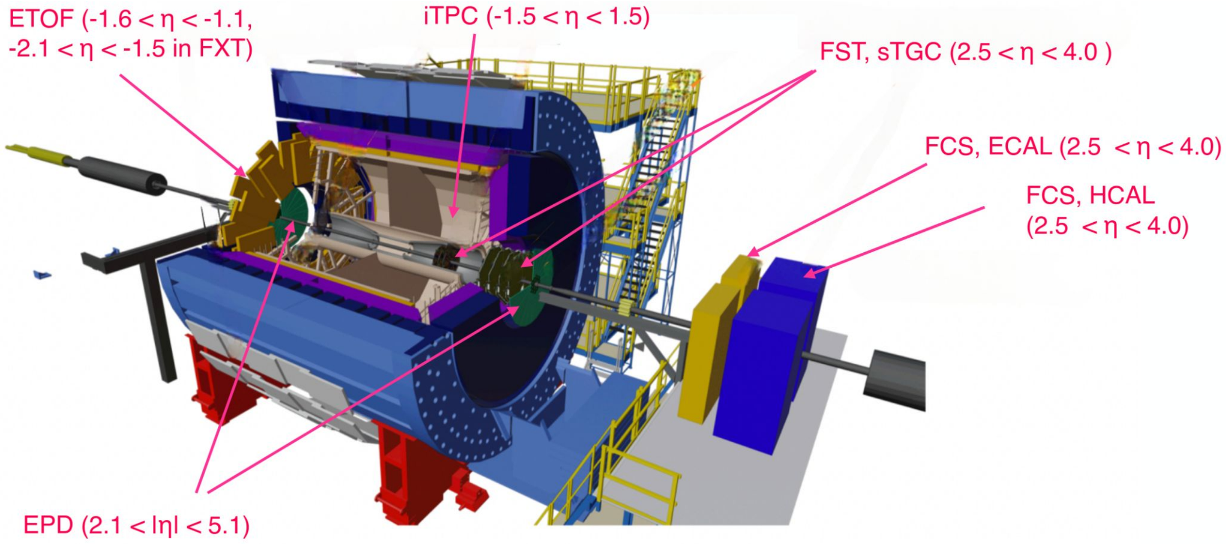
- RHIC and its experiments built with QGP in mind
- QGP observed at RHIC!



[Phys. Rev. Lett. 91]

Solenoidal Tracker at The RHIC (STAR)

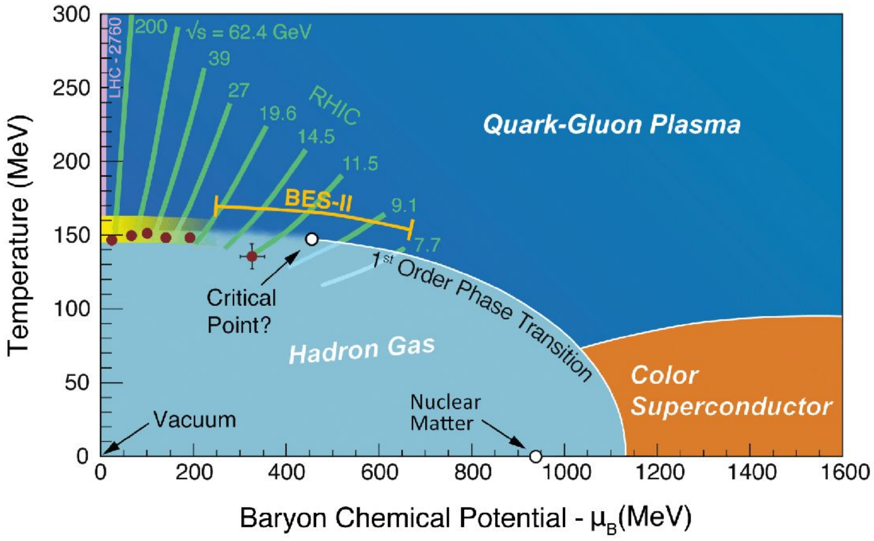
- Commissioned in 2000
- Forward upgrade (commissioned 2022; $2.5 < \eta < 4$)
- Event Plane Detector (EPD)
- Endcap Time of Flight (ETOF)
- Tracking
- Particle IDentification (PID)



QCD diagram studies

QCD phase diagram

- Matter state depends on temperature *T* and net baryon density/baryon chemical potential μ_B
- BES-II dataset covers $100 < \mu_B < 760$ MeV
- **Investigation of phase transition between hadronic matter and QGP**
  - 1st order and cross-over transitions
- **Probing for critical point**



Net-proton cumulants

cumulants

$$C_1 = \langle N \rangle \equiv \mu \text{ [mean]}$$

$$C_2 = \langle (N-\mu)^2 \rangle \equiv \sigma^2 \text{ [variance]}$$

$$C_3 = \langle (N-\mu)^3 \rangle$$

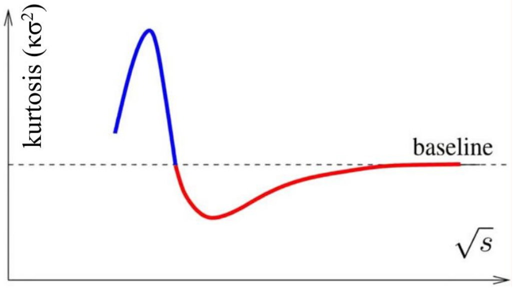
$$C_4 = \langle (N-\mu)^4 \rangle - 3\langle (N-\mu)^2 \rangle^2$$

standardized moments

$$S\sigma = C_3/C_2 \text{ [skewness]}$$

$$\kappa\sigma^2 = C_4/C_2 \text{ [excess kurtosis]}$$

- Net-baryon (N_B - N_{Bbar}) expected to fluctuate near a critical point
- Cumulants of conserved charge distributions related to correlation length in medium
- **Higher order cumulant ratios predicted to be sensitive to the critical point existence**

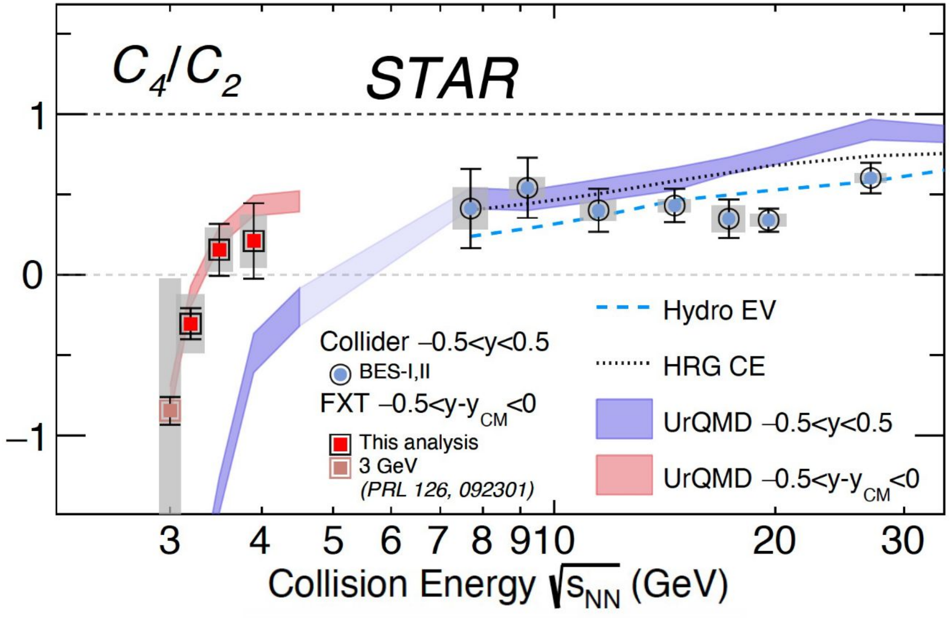


[M. Stephanov. J. Physics G.: Nucl. Part. Phys. 38 (2011) 124147]

Net-proton cumulants

UrQMD

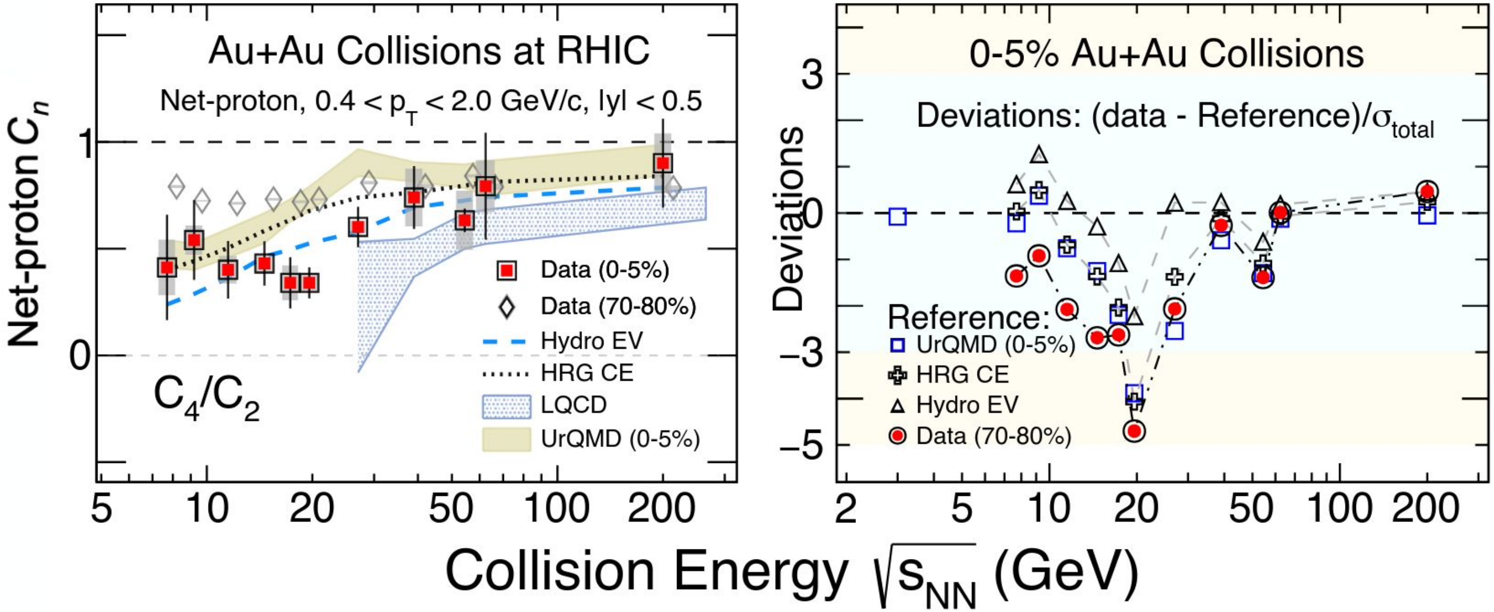
- *Hadron transport model*
- *No phase transition/partonic phase included*



- Precise measurements from BES-II
- Final results for collider energies from 7.7 to 19.6 GeV and FXT energies 3.2, 3.5 and 3.9 GeV in 0-5% central Au+Au collisions
- In FXT energies C_4/C_2 consistent with UrQMD predictions
- **Deviation seen at higher energies**

Net-proton cumulants

- BES-II data - 4.5 times better σ_{stat} and 3-4 times σ_{sys}
- **2-5σ deviation from calculations** without CP, peripheral data

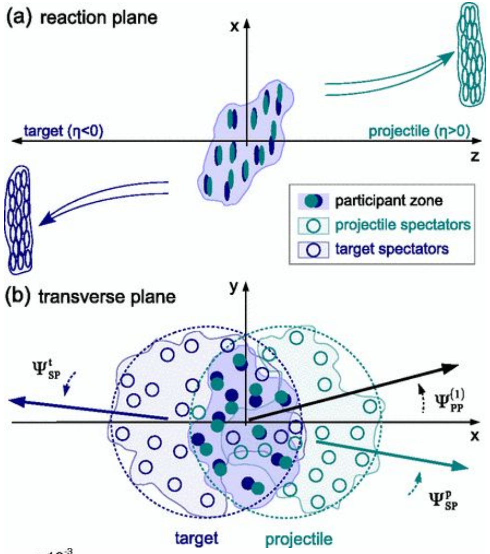


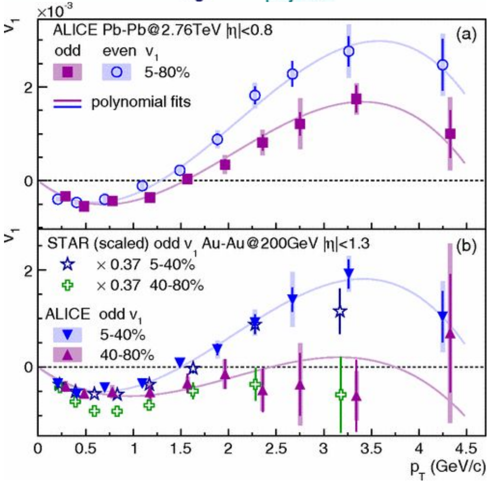
Collectivity and flow

Flow

$$f(\phi; y, p_t) \propto 1 + 2 \sum_{n=1,2} v_n(y, p_t) \cos(n\phi)$$

- **Collective behaviour of particles produced in relativistic collisions**
- Particle azimuthal distribution (w.r.t. collision system planes) can be Fourier decomposed
- Harmonic coefficients v_n called flow coefficients, proportional to eccentricities ε_n
- Directed flow characterised by v_1, elliptic flow by v_2 and triangular flow by v_3

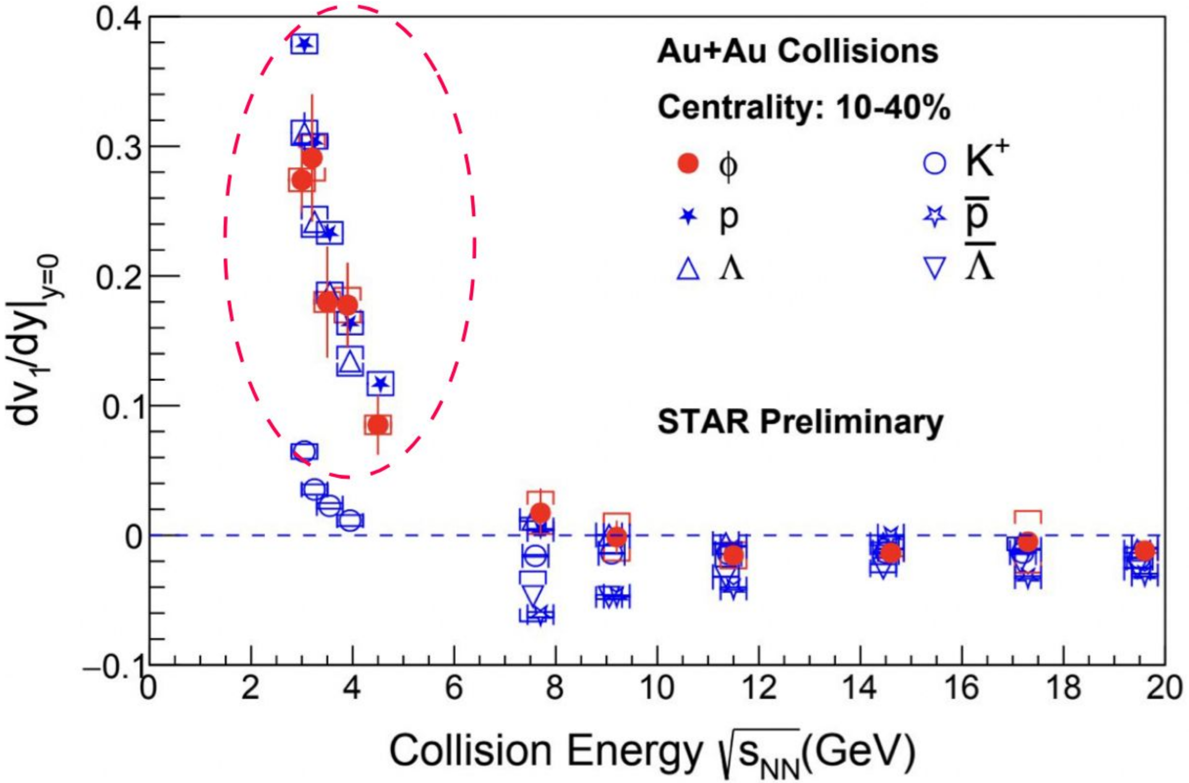




*[Phys. Rev. Lett. **111**, 232302]*

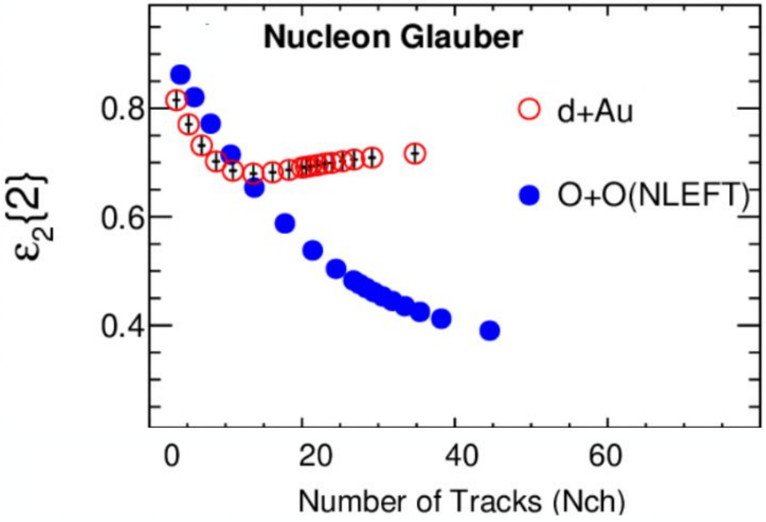
Directed flow

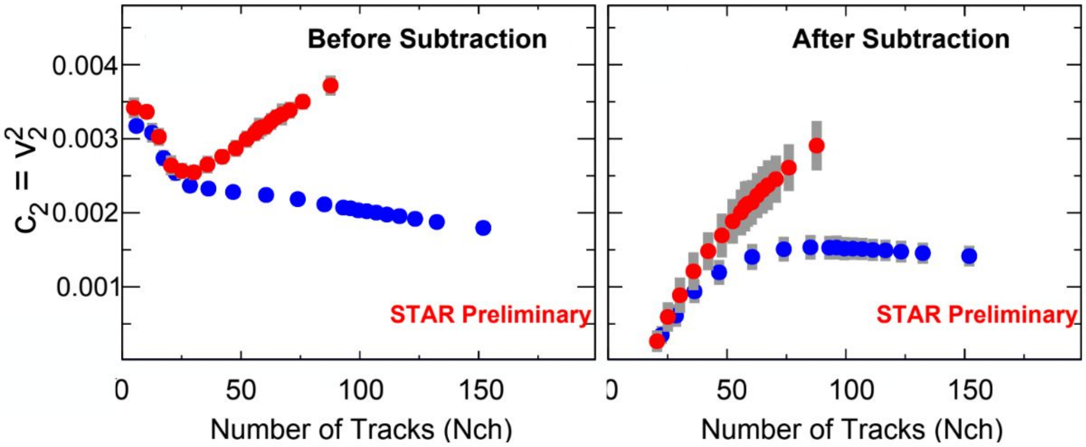
- Sensitive to early time interactions and Equation of State (EoS)
- Kaons show similar sign change as protons, minimum between 4.5 and 7.7 GeV
- **ϕ meson v_1 large in high μ_B region, comparable to proton and Λ**



Collectivity in small systems

- d+Au and O+O similar-sized systems, but large difference in ε_2
- Scaling with geometry
- **Origin of small-system v_2 from geometry response**

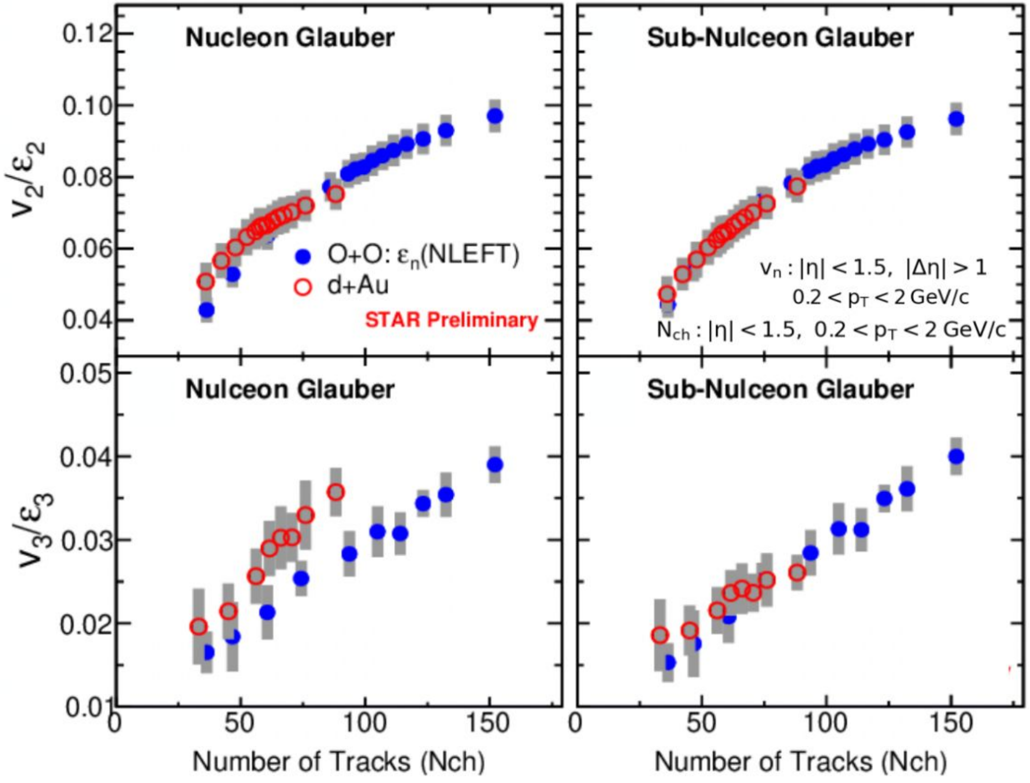




Non-flow subtraction

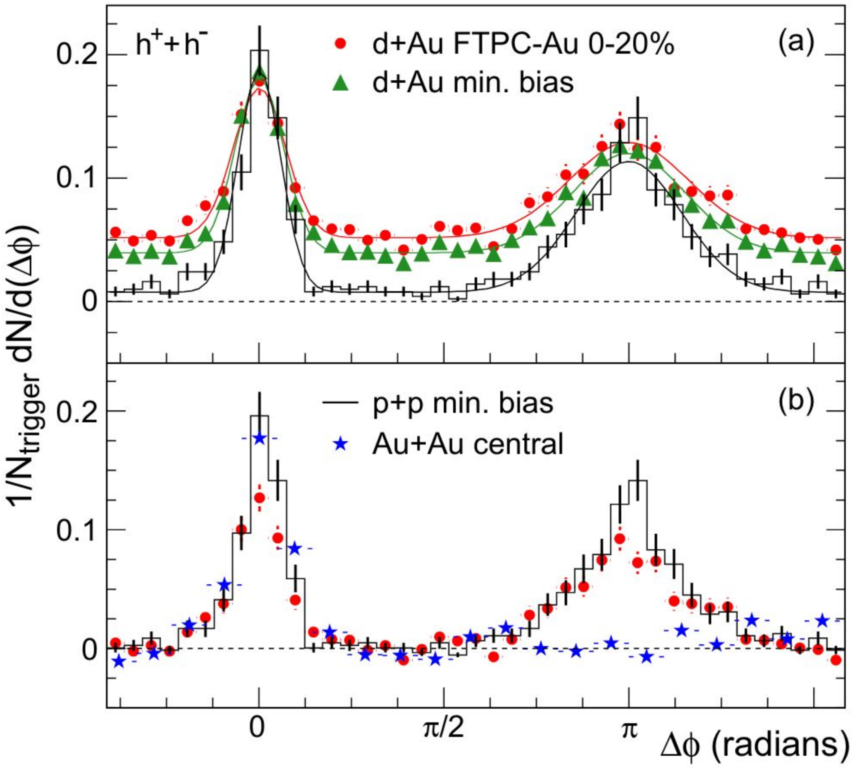
Collectivity in small systems

- Both v_2 and v_3 scale well with eccentricities from sub-nucleon Glauber model



Jet suppression

- Hard scatterings in high-energy particle collisions may produce jets - collimated showers of hadrons
- Jets interact strongly with hot and dense medium (QGP) produced in heavy-ion collisions
- The interaction leads to energy reduction called “jet quenching”
  - suppression of high-p_T particles and back-to-back correlations first observed at the RHIC

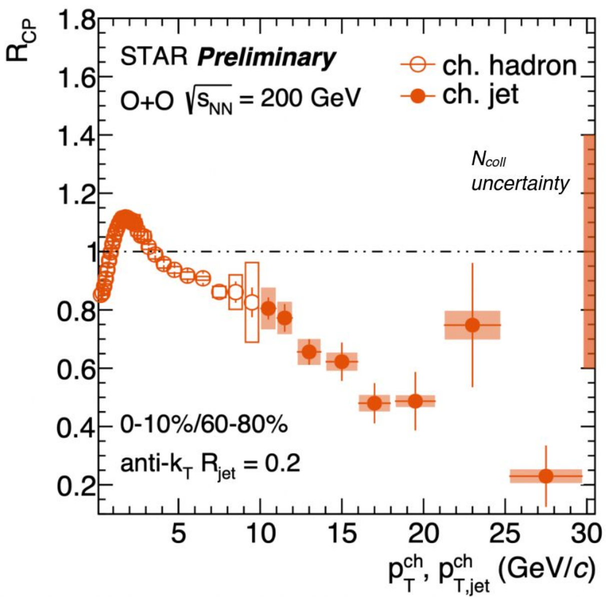


[Rev. Lett. **91**, 072304]

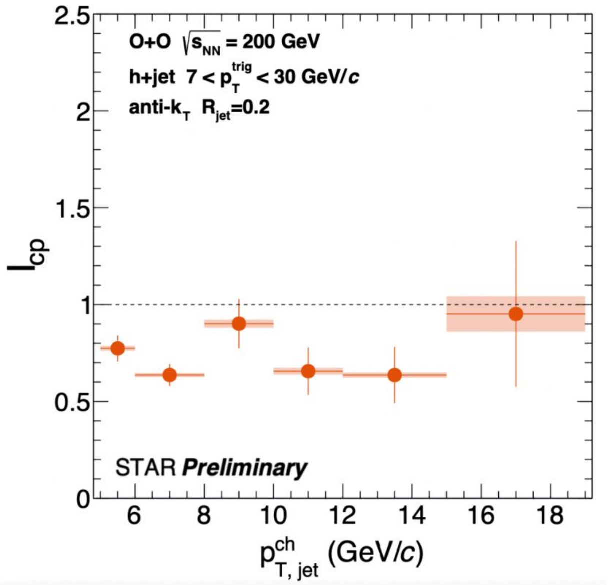
Hadrons and jets in O+O

- Indication of high-p_T jet and hadron suppression in O+O collisions

Inclusive hadrons and jets



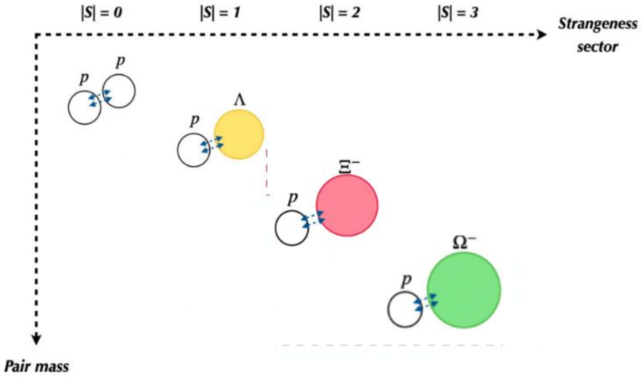
Semi-inclusive h triggered jets



Hyperons

Femtoscopy

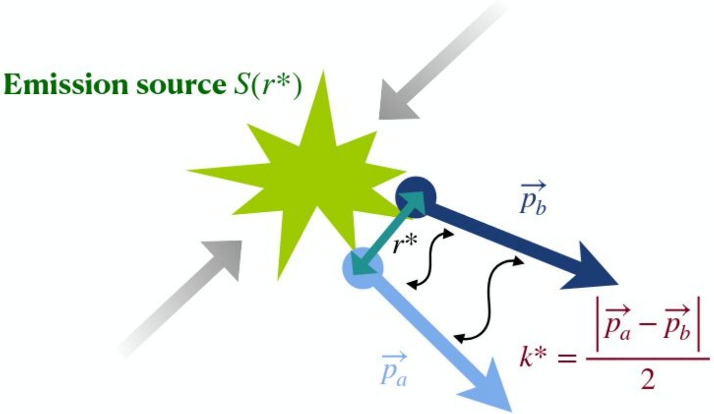
- Correlation femtoscopy - **a study of hyperon-nucleon** (Y-N) **interactions**
- New isobar data available
  - Zr+Zr, Ru+Ru
  - A = 96
- Strange di-baryon bound states?



Source size FSI

$$C(k^*) = \int S(\vec{r})|\Psi(\vec{k}^*,\vec{r})|^2 d^3\vec{r} = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

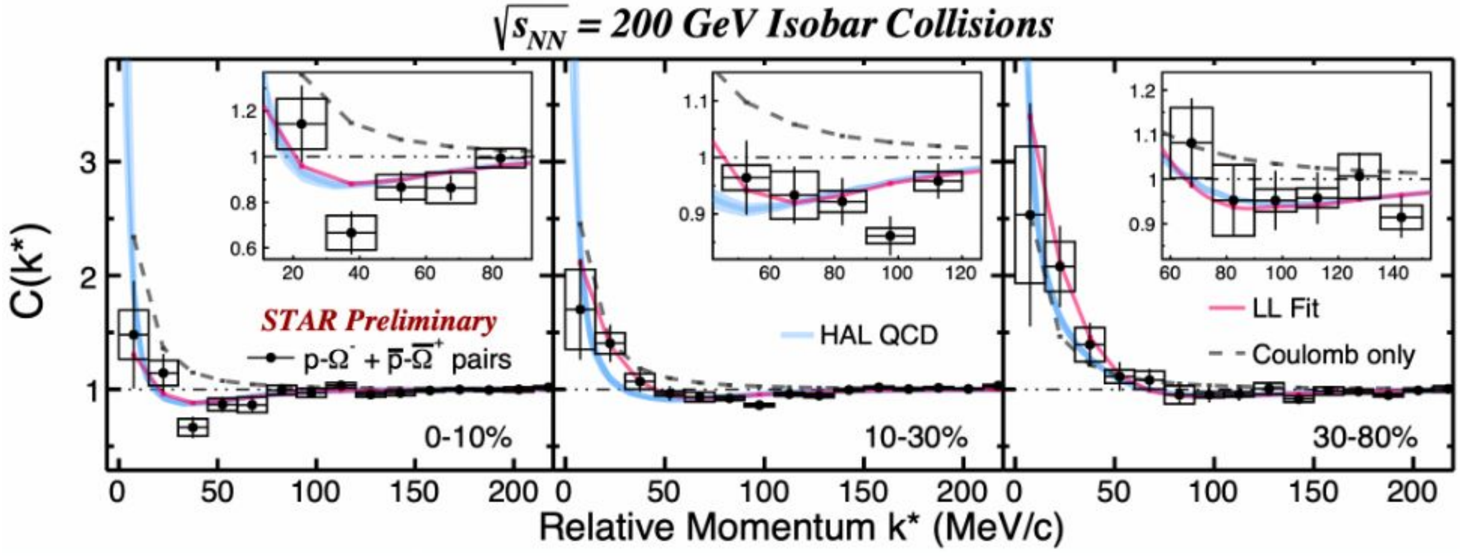
$S(\vec{r})$: Source function
$\Psi(\vec{k}^*,\vec{r})$: Pair wave function
$k^* = \frac{1}{2}|\vec{p}_a - \vec{p}_b|$, relative momentum
$\vec{r}$: relative distance



p-Ω correlations

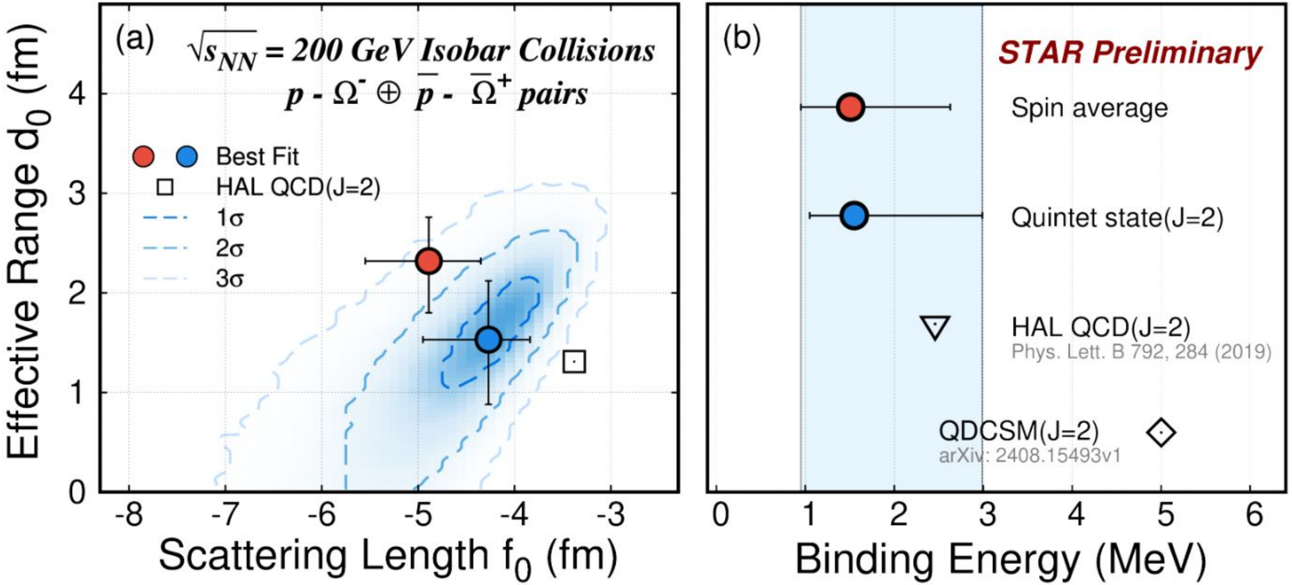
$$BE_{p\Omega} = \frac{1}{2m_{p\Omega}d_0^2}(1 - \sqrt{1 + \frac{2d_0}{f_0}})^2$$

- Depletion in C(k*) at k* ~ 30-100 MeV/c - bound state?
- Lednický-Lyuboshitz fit to extract strong interaction parameters
- Bound states have negative scattering length f_0



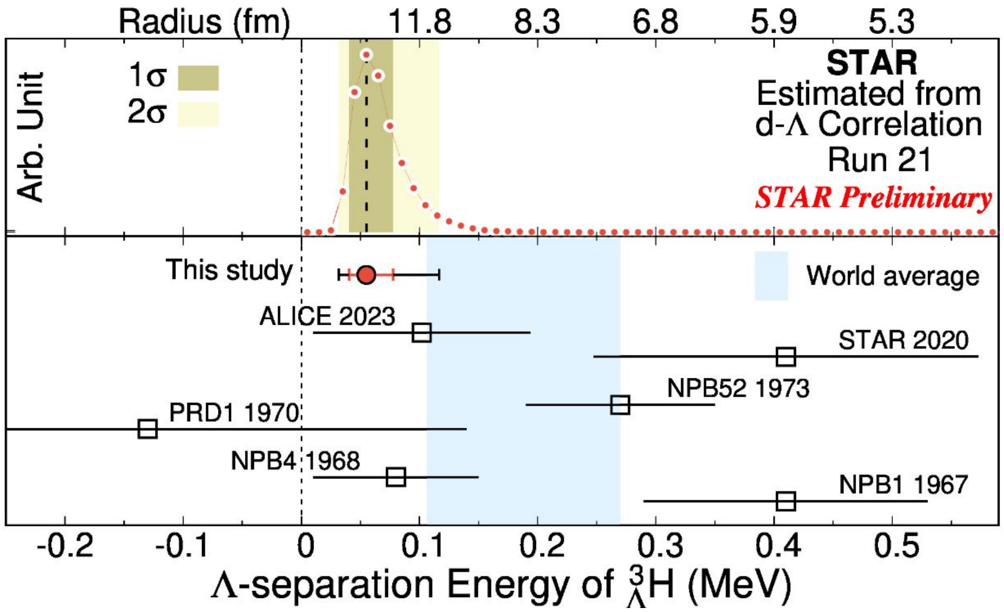
p–Ω correlations

- Negative scattering length f_0 for p-Ω
- **First experimental evidence of strange di-baryon bound state**
- Positive f_0 for p-Ξ and p-Λ



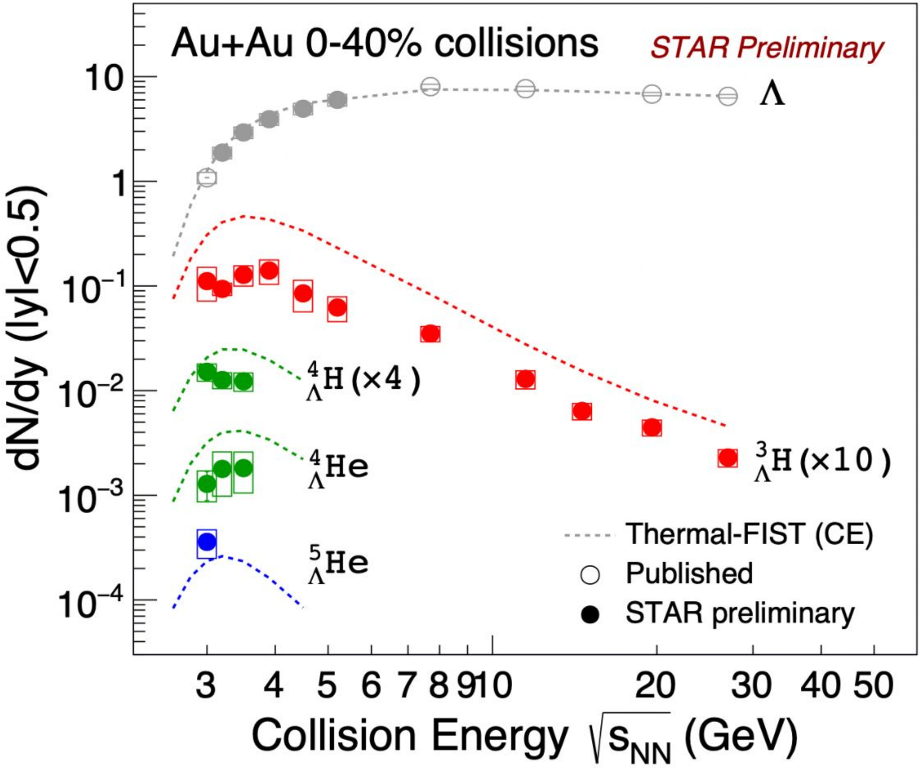
Light nuclei spectroscopy

- Y-N interactions important for neutron star equation of state and hypernuclei structure
- **Most accurate extraction of hypertriton binding energy**
- Measurements also for t-Λ and ^{3}He-Λ correlations



Hypernuclei measurements

- Hypernuclei important for Y-N interaction understanding
- **First measurement of A=5 hypernuclei**
- Thermal model describes Λ, overestimates yields for $_{\Lambda}^{3}H$, $_{\Lambda}^{4}H$, $_{\Lambda}^{4}He$ and slightly underestimates $_{\Lambda}^{5}He$ in high μ_B region
  - feed-down corrections not included for $_{\Lambda}^{5}He$



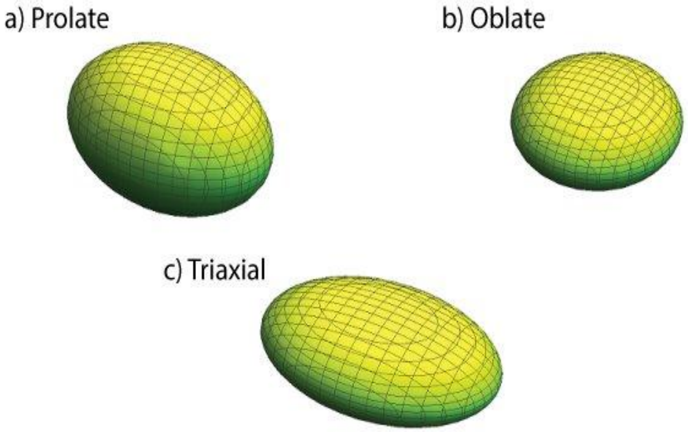
Nuclear shape imaging

Nuclear imaging in HIC

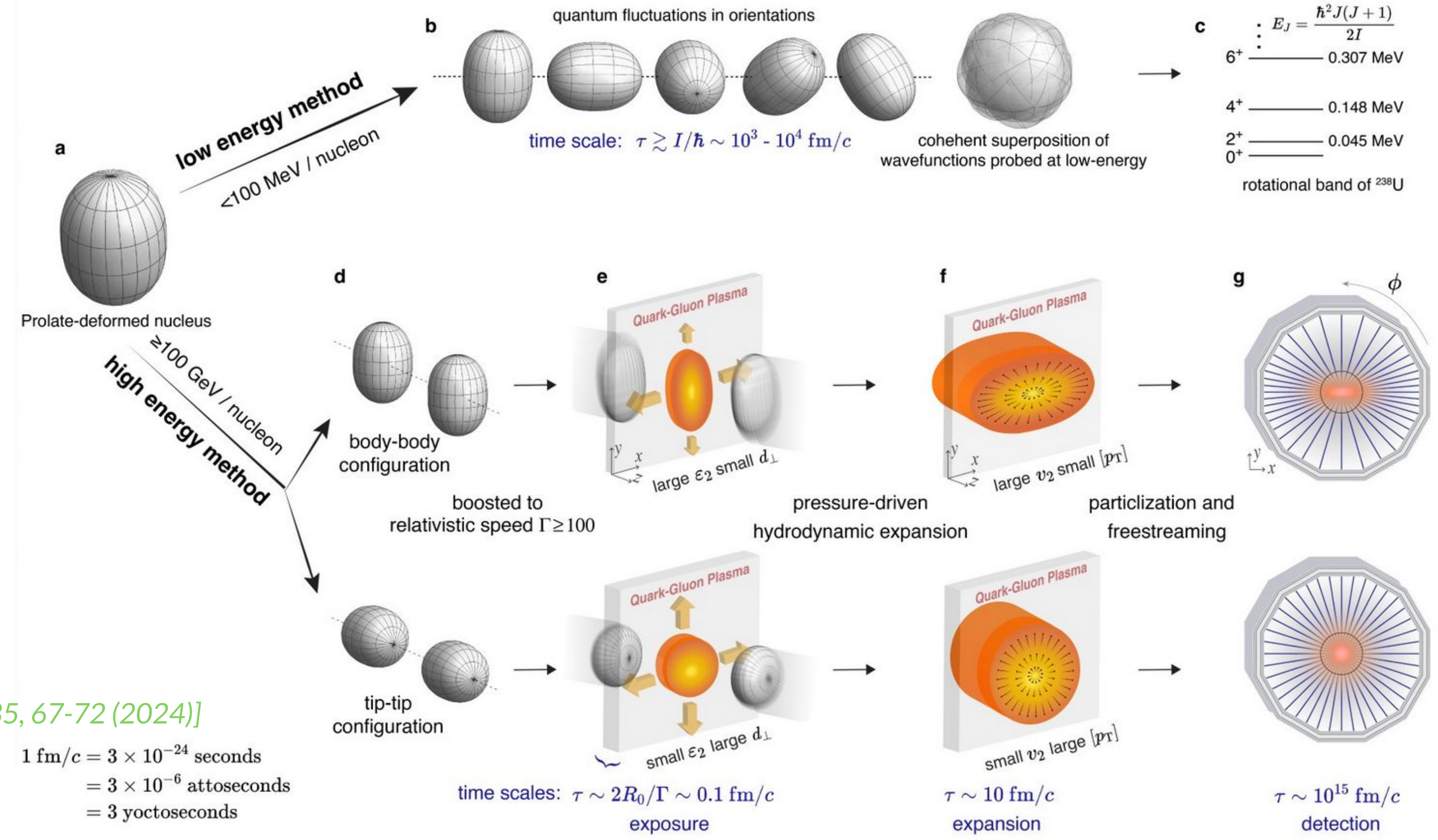
- Traditionally nuclear shapes examined in low-energy spectroscopic experiments
- In high-energy collisions eccentricity ε_2 and inverse area of nuclear overlap $d_\perp$ proportional to experimental observables v_2 and δp_T
- Ratios between well known systems (Au+Au) and unknown systems (U+U) minimises hydrodynamic evolution influence, focusing on nuclear geometry

$$R(\theta,\varphi) = R_0\left(1 + \beta_2\left[\cos\gamma\, Y_{2,0} + \sin\gamma\, Y_{2,2}\right]\right)$$

$$\varepsilon_2 = \frac{\langle x^2\rangle - \langle y^2\rangle}{\langle y^2\rangle + \langle x^2\rangle} \qquad d_\perp \propto 1/\sqrt{\langle x^2\rangle\langle y^2\rangle}$$



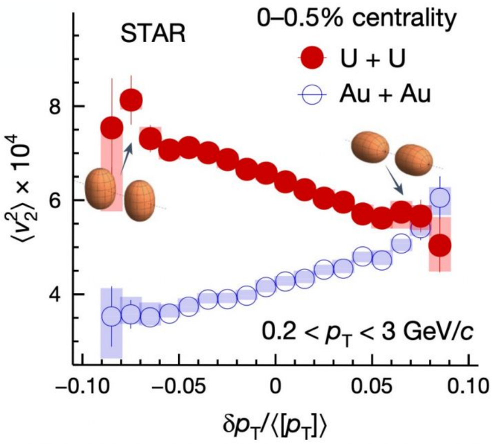
Nuclear imaging in HIC

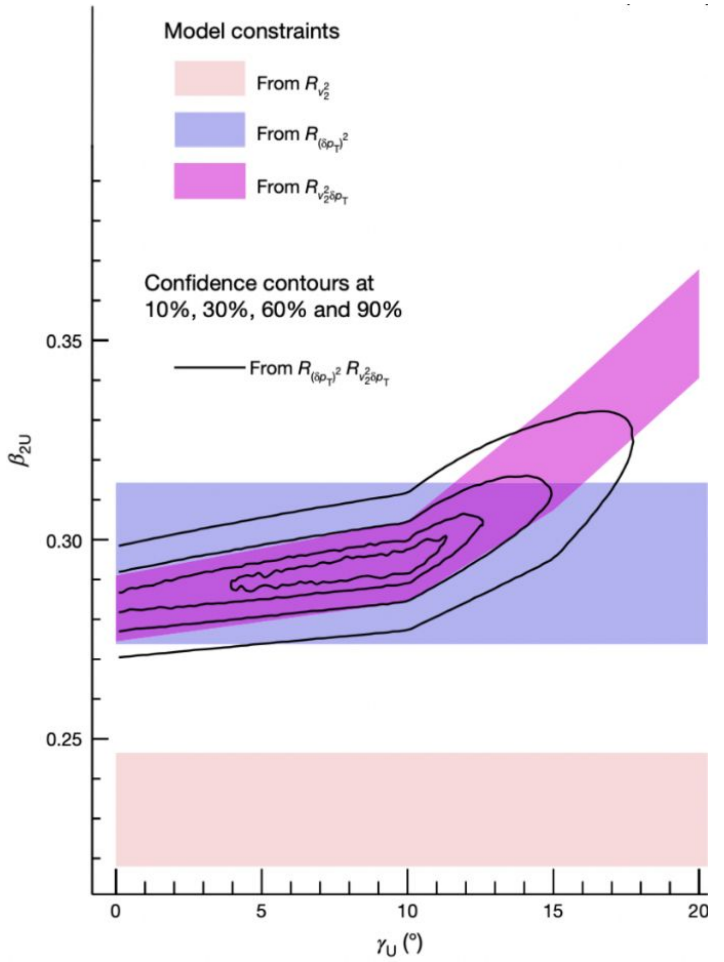


[Nature 635, 67-72 (2024)]

Nuclear imaging in HIC

- Nuclear structure propagates into v_n and δp_T
- **Extracted β_{2U} = 0.297 ± 0.015 and γ_U = 8.5° ± 4.8° - consistent with low energy conventional measurements**
- Large quadrupole deformation, small triaxiality in ground state





[Nature 635, 67-72 (2024)]

STAR: 25 years and beyond!

- BES-II:
  - EoS in different regions
  - critical point and phase boundary search
  - Y-N and N-N interactions
- Run 23 - 25:
  - STAR forward upgrade
  - 5k DAQ rate
  - high statistics Au+Au and p+p
- Run 22 - 25:
  - improved kinematic reach for hard probes
  - overlap with LHC
  - forward physics, connection with EIC

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	8B+**5B** / 1.2 nb^{-1}+**20.8** $\mathbf{nb^{-1}}$	2023+2024+**2025 (20 cryo-weeks)**
200	Au+Au	8B+**9B** / 1.2 nb^{-1}+**28.6** $\mathbf{nb^{-1}}$	2023+2024+**2025 (28 cryo-weeks)**

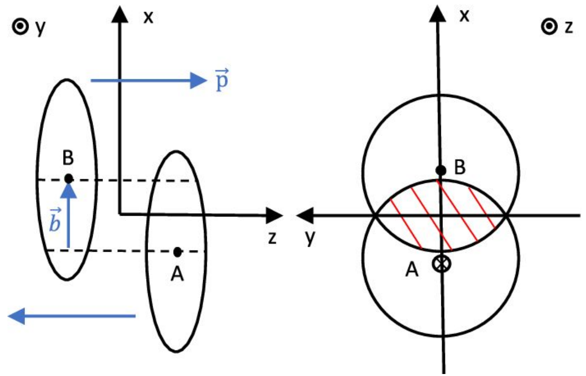
[STAR BUR Runs 24-25]

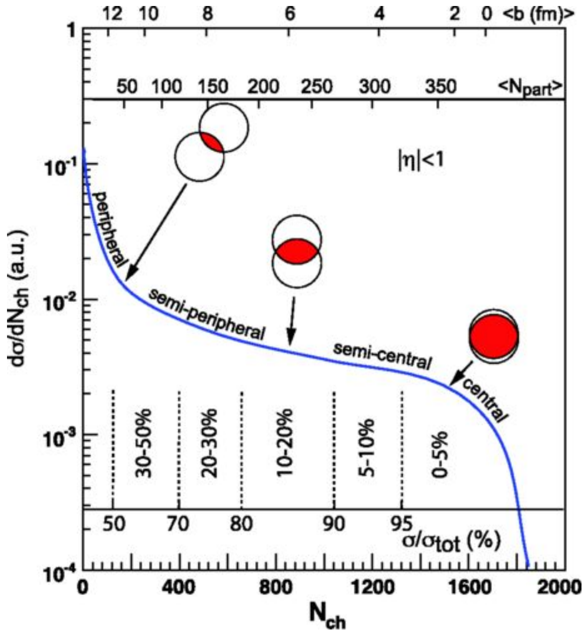
Thank you very much!

Backup

Centrality

- Impact parameter *b* important for classification of nuclear collisions
  - distance between the center of the two nuclei
- Not possible to measure directly
- **Glauber model used to connect impact parameter and experimentally accessible observables**





Rapidity scan of cumulants

- Wider y, p_T windows of measurement enhance potential critical contribution
- **Deviation from UrQMD increases with y acceptance and near 20 GeV**