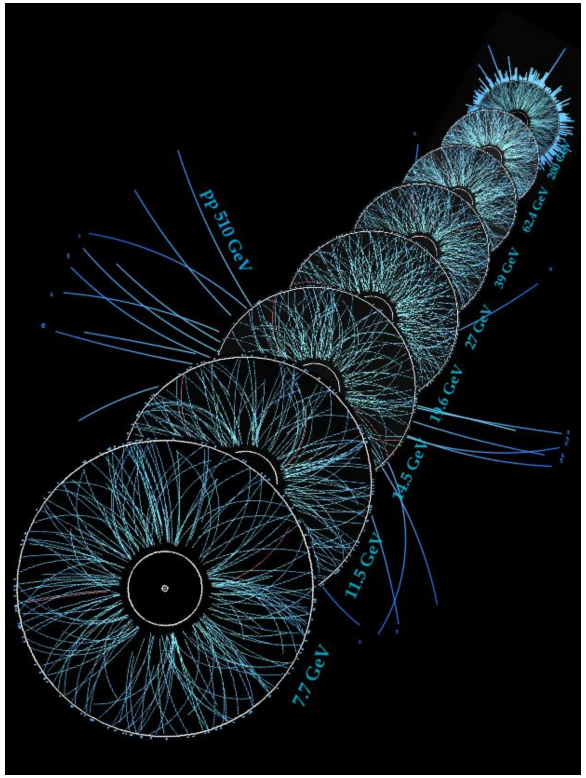
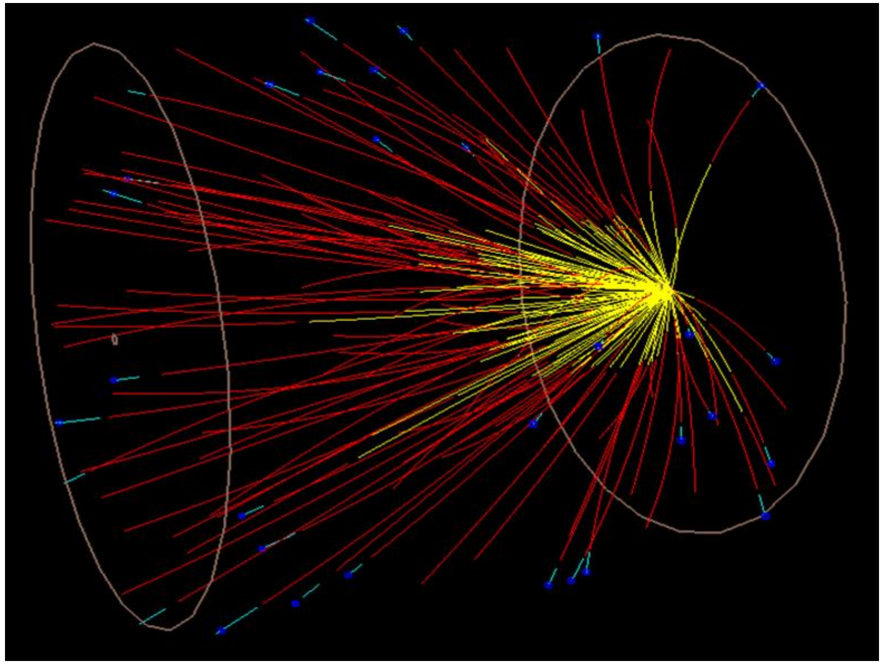
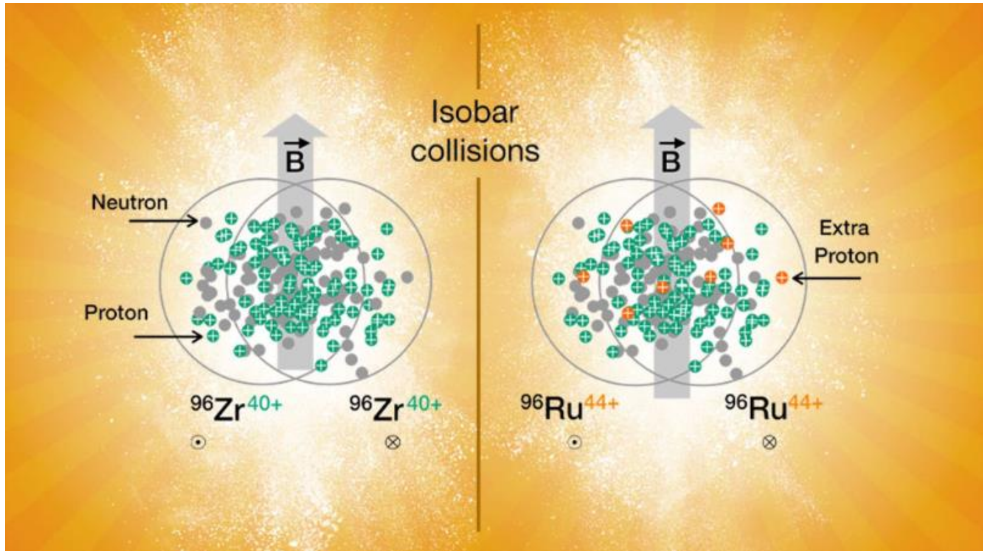
Results from the Beam Energy Scan Program at STAR



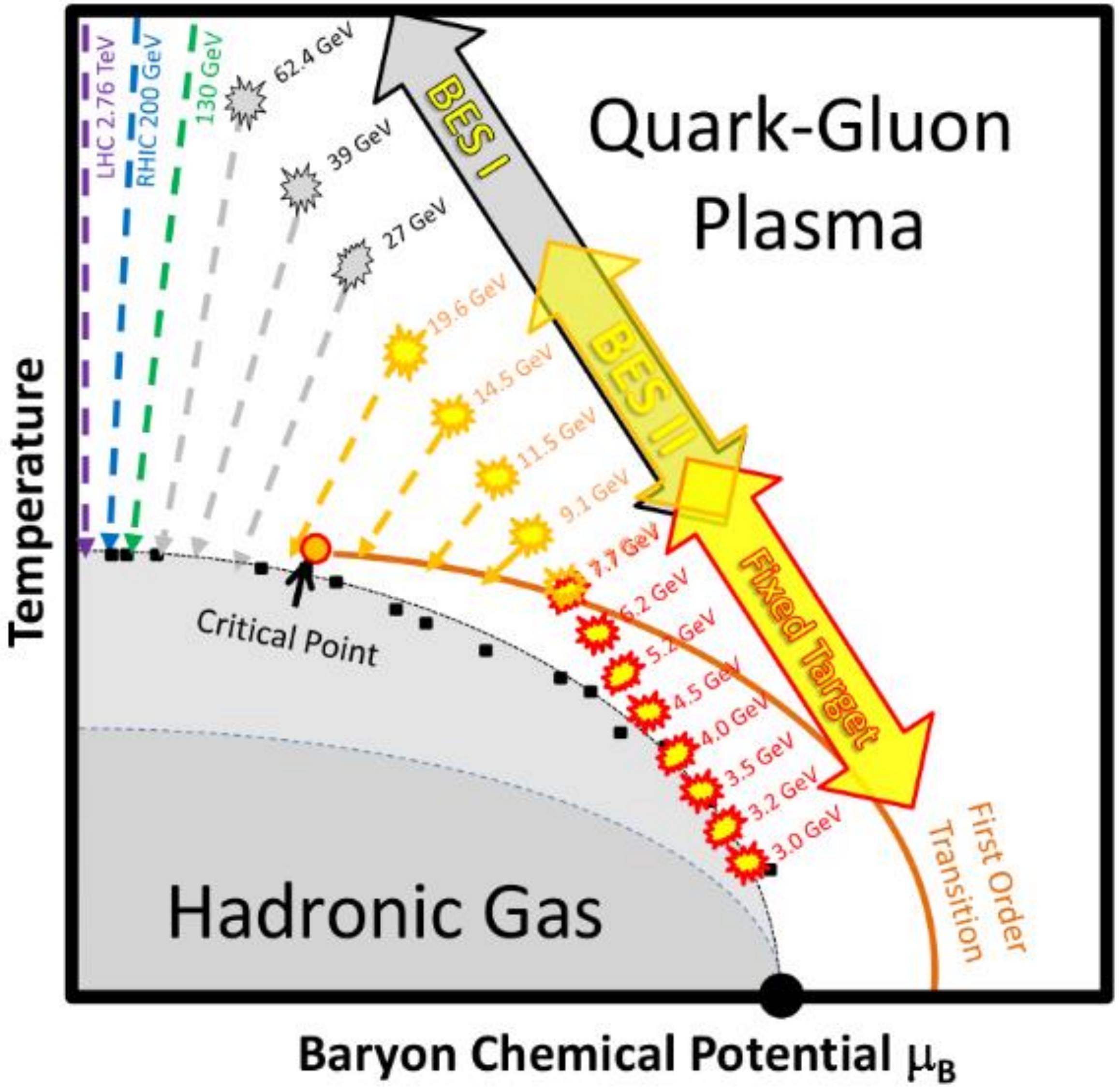


Grigory Nigmatkulov



Infinite and Finite Nuclear Matter. Feb. 27 – Mar. 3, 2023

BES-I -> BES-II and FXT

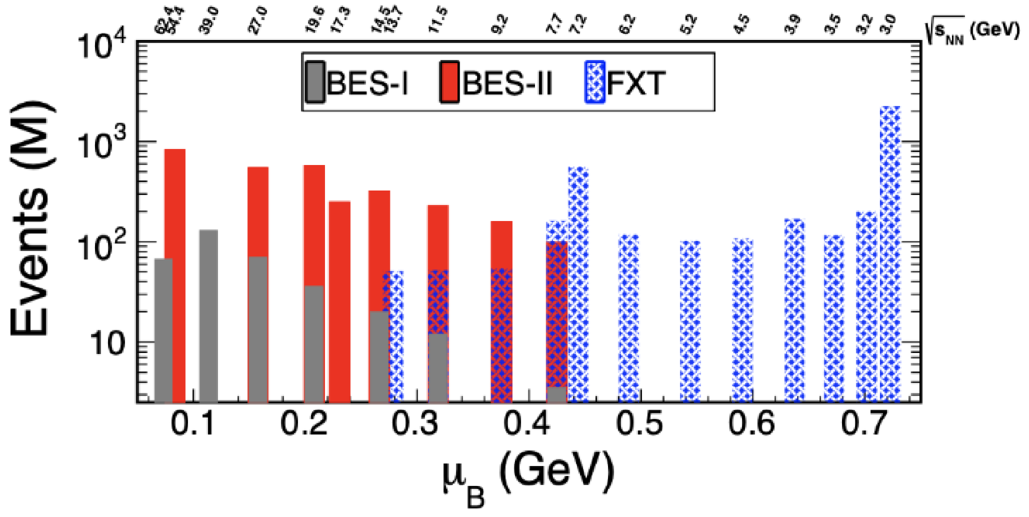


BES-I:

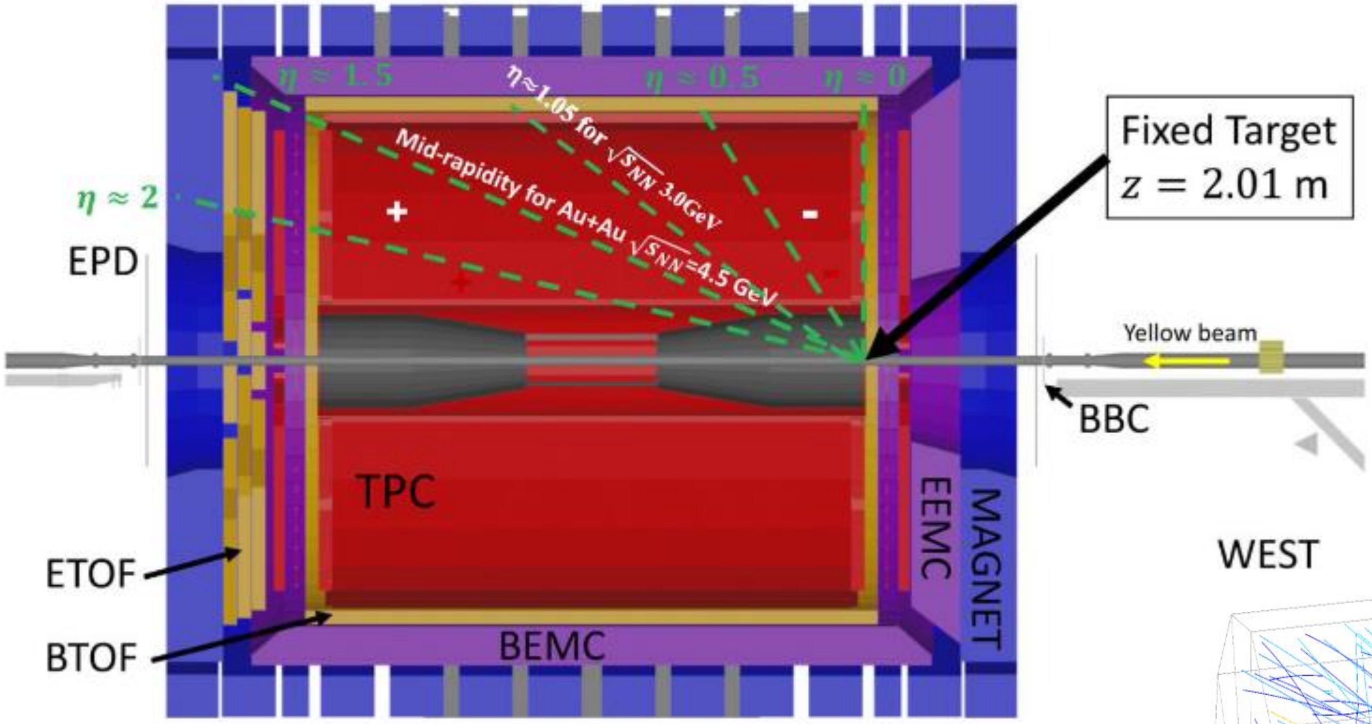
- Search for the QGP turn-off signatures
- Search for the first-order phase transition
- Search for the critical point

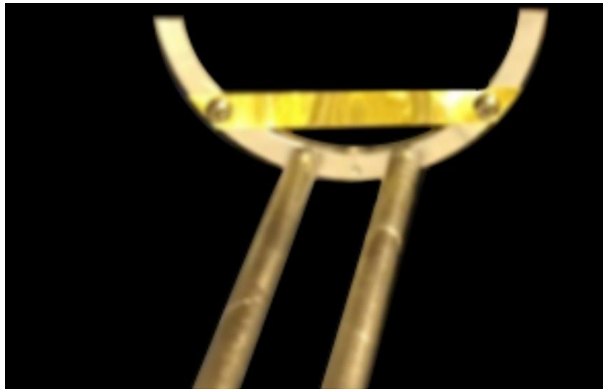
BES-II and fixed-target (FXT) program:

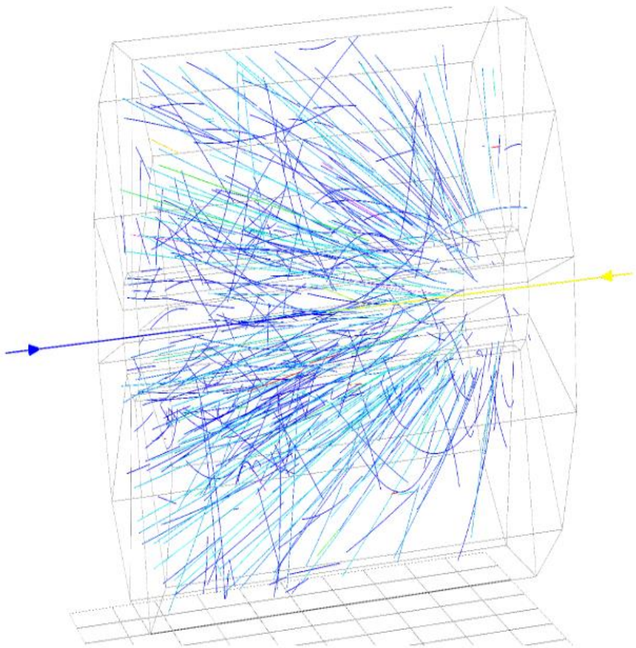
- Need higher statistics (≥10 times than in BES-I) for precise measurements
- Detector upgrades (increased acceptance and PID capabilities)
- Access to energies $\sqrt{s_{NN}}$<7.7 GeV via FXT

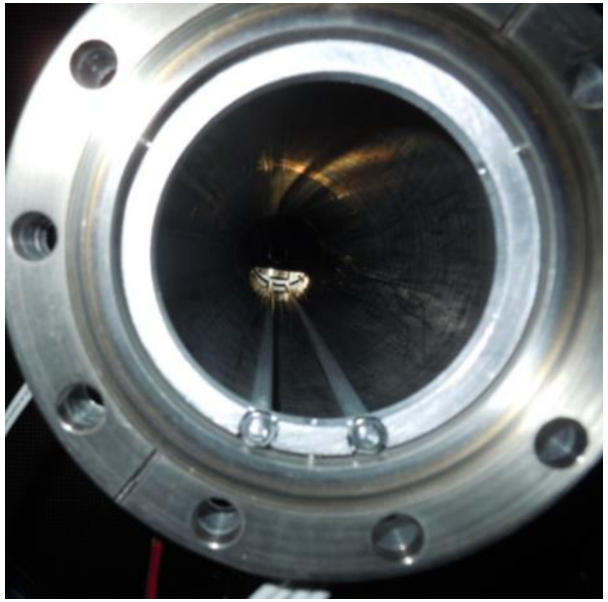


The Fixed-target (FXT) Setup





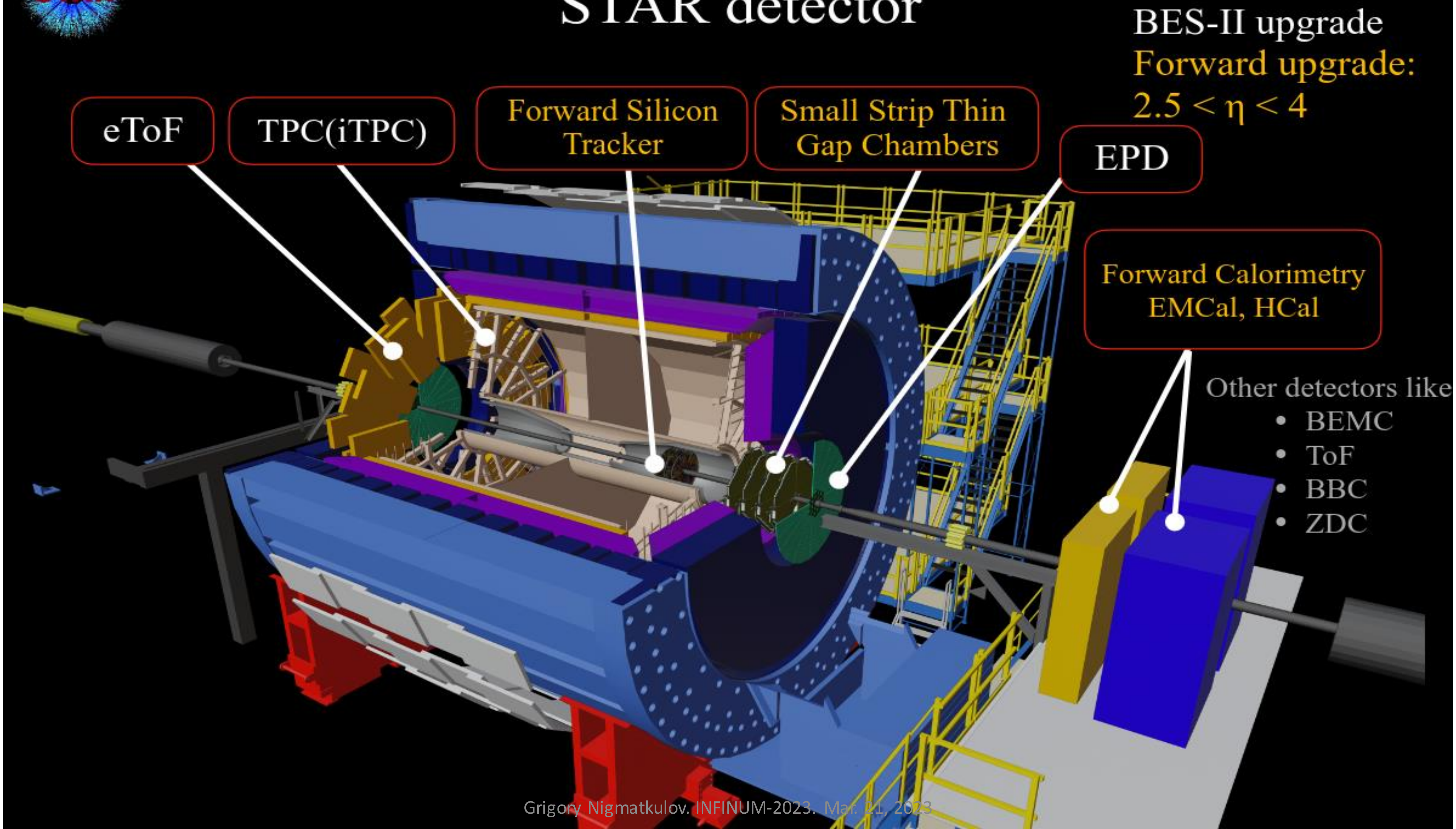




Gold target:

- 2 cm below nominal beam axis
- 2 m from center of STAR
- 250 μm foil

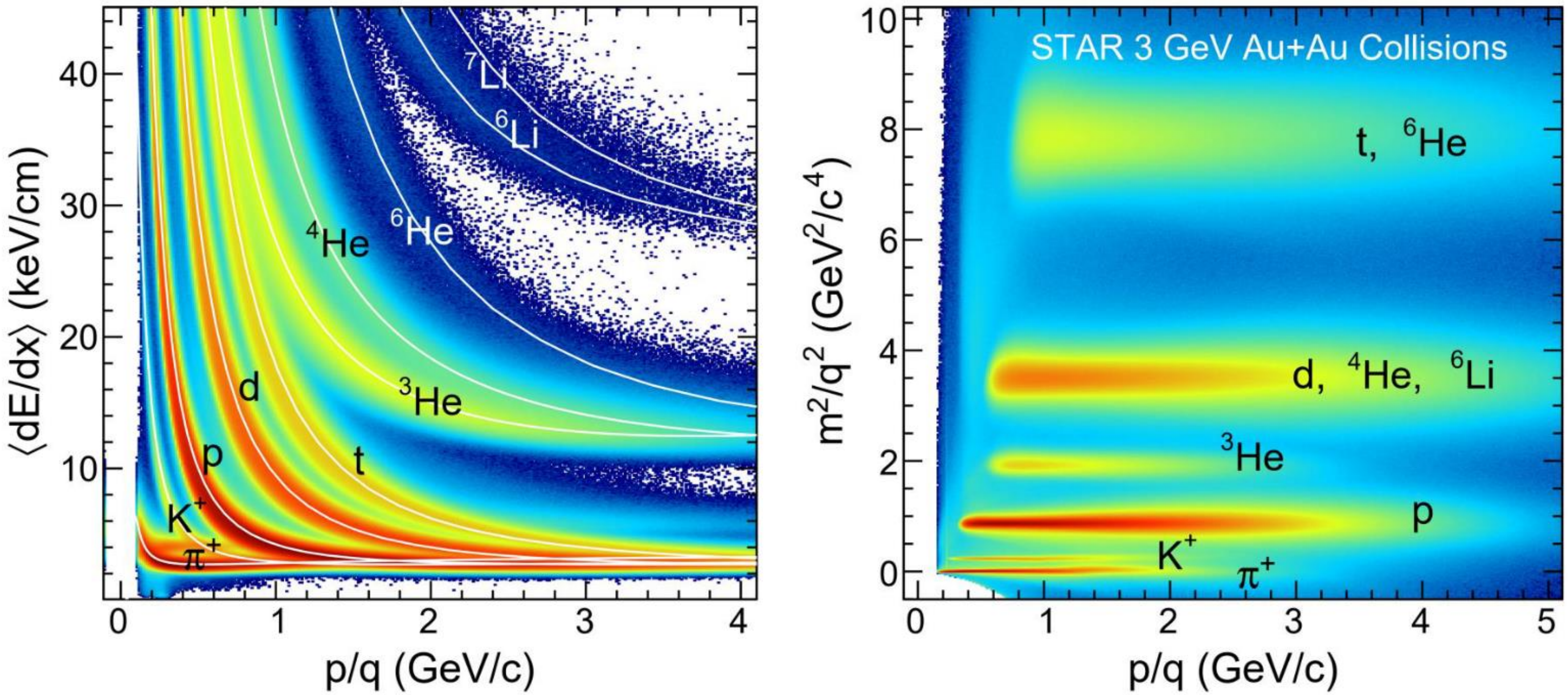
STAR detector



STAR

$\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV/nucleon)	Collider or Fixed Target	$y_{center\ of\ mass}$	μ_B (MeV)	Run Time (days)	No. Events Collected (Request)	Date Collected
200	100	C	0	25	2.0	138 M (140 M)	Run-19
27	13.5	C	0	156	24	555 M (700 M)	Run-18
19.6	9.8	C	0	206	36	582 M (400 M)	Run-19
17.3	8.65	C	0	230	14	256 M (250 M)	Run-21
14.6	7.3	C	0	262	60	324 M (310 M)	Run-19
13.7	100	FXT	2.69	276	0.5	52 M (50 M)	Run-21
11.5	5.75	C	0	316	54	235 M (230 M)	Run-20
11.5	70	FXT	2.51	316	0.5	50 M (50 M)	Run-21
9.2	4.59	C	0	372	102	162 M (160 M)	Run-20+20b
9.2	44.5	FXT	2.28	372	0.5	50 M (50 M)	Run-21
7.7	3.85	C	0	420	90	100 M (100 M)	Run-21
7.7	31.2	FXT	2.10	420	0.5+1.0+ scattered	50 M + 112 M + 100 M (100 M)	Run-19+20+21
7.2	26.5	FXT	2.02	443	2+Parasitic with CEC	155 M + 317 M	Run-18+20
6.2	19.5	FXT	1.87	487	1.4	118 M (100 M)	Run-20
5.2	13.5	FXT	1.68	541	1.0	103 M (100 M)	Run-20
4.5	9.8	FXT	1.52	589	0.9	108 M (100 M)	Run-20
3.9	7.3	FXT	1.37	633	1.1	117 M (100 M)	Run-20
3.5	5.75	FXT	1.25	666	0.9	116 M (100 M)	Run-20
3.2	4.59	FXT	1.13	699	2.0	200 M (200 M)	Run-19
3.0	3.85	FXT	1.05	721	4.6	259 M -> 2B(100 M -> 2B)	Run-18+21

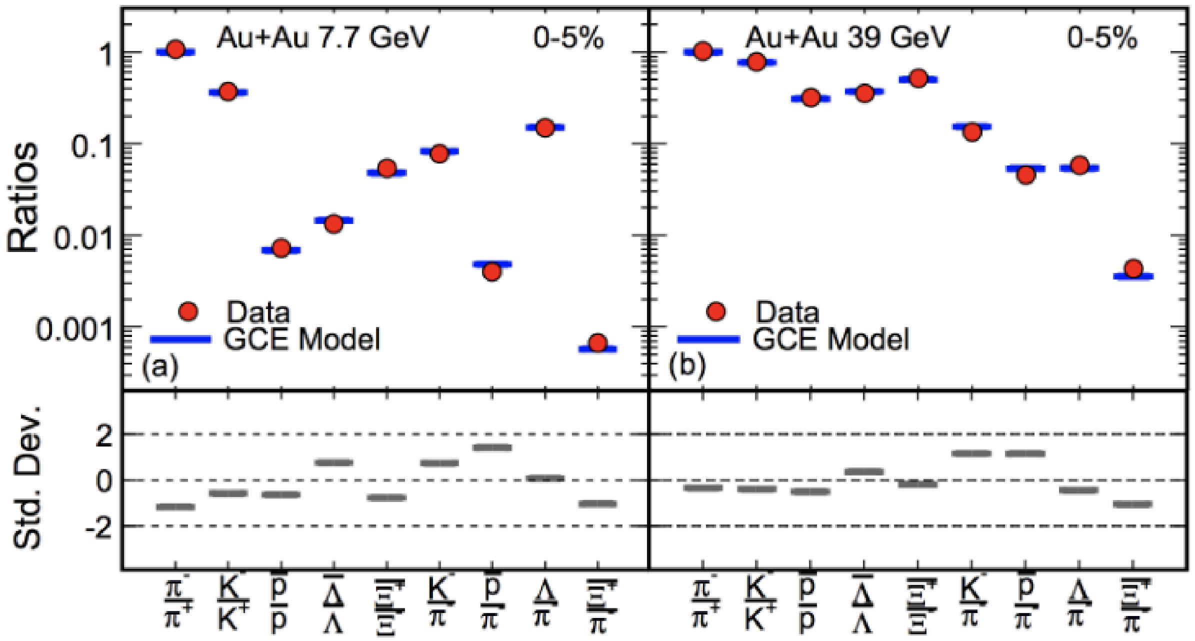
Particle Identification

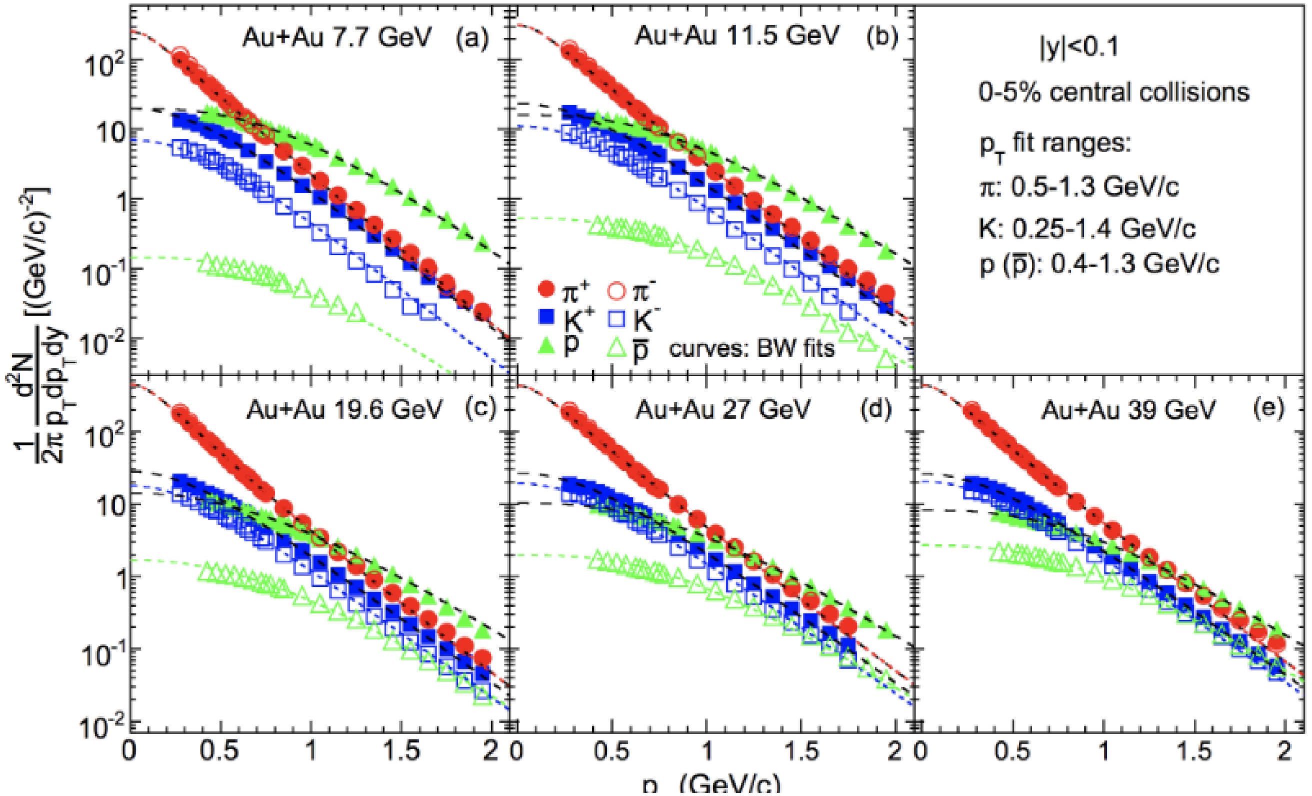


Good particle identification in a broad momentum range using TPC and TOF

Hadron yields/spectra

Phys. Rev. C 96, 44904 (2017)



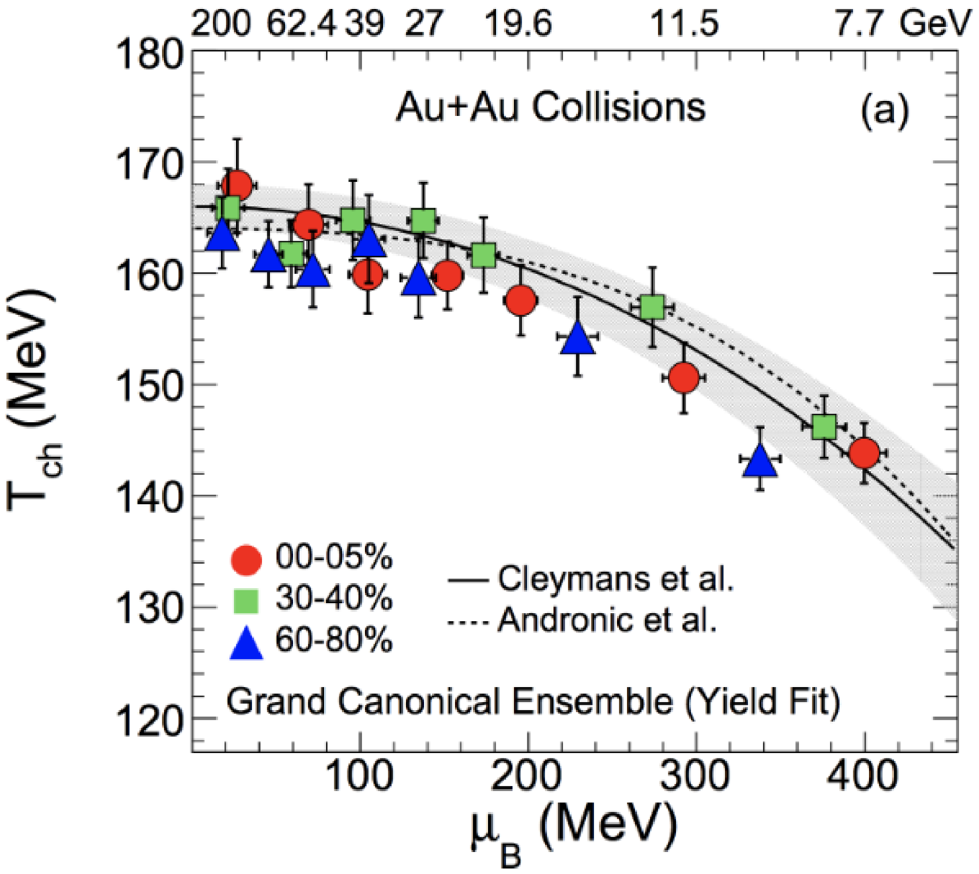


Particle ratios and p_T spectra are measured at BES, from which the freeze-out conditions can be extracted

Freeze-out conditions

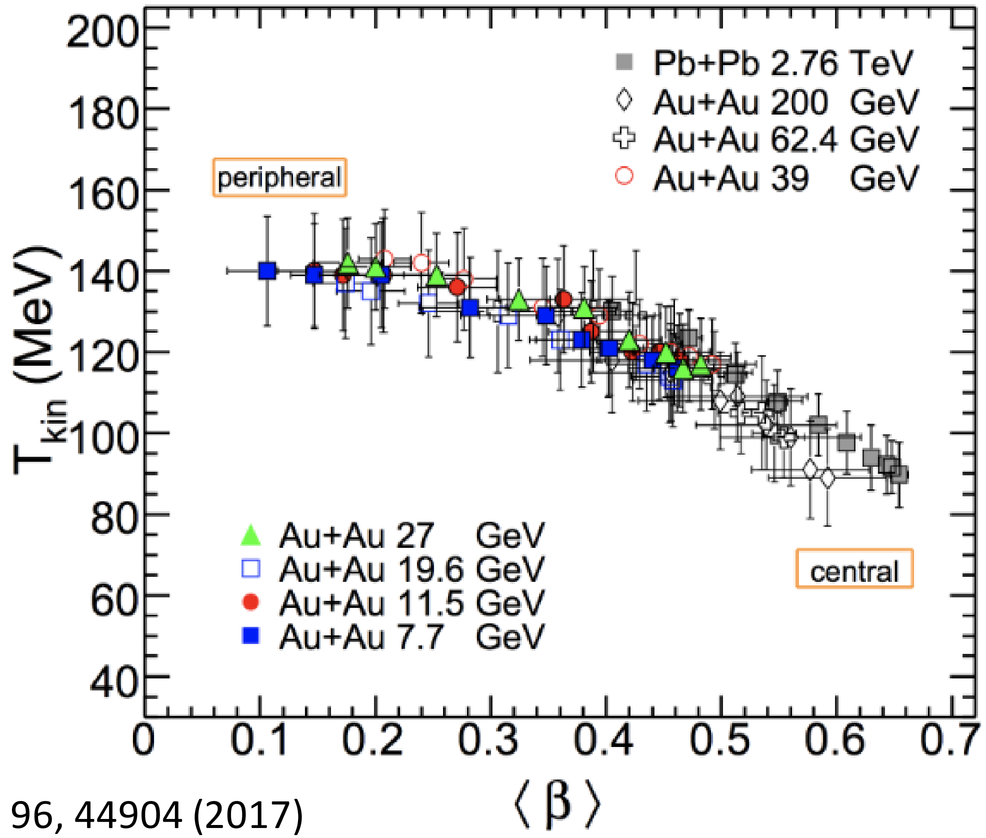
Chemical freeze-out

- Weak temperature dependence
- Centrality dependence of μ_B



Kinetic freeze-out

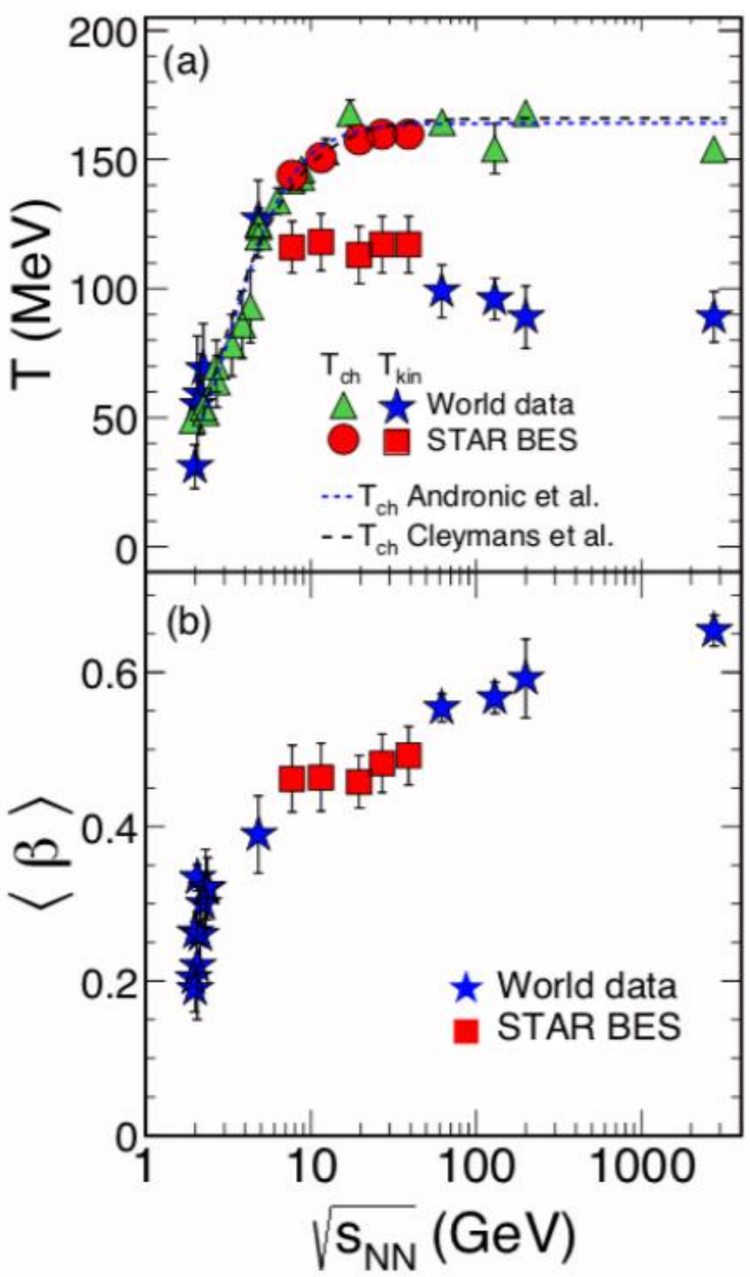
- Central collisions → lower value of T_{kin} and larger collectivity <β>
- Stronger collectivity at higher energy, even for peripheral collisions



Phys. Rev. C 96, 44904 (2017)

Freeze-out conditions

Phys. Rev. C 96, 44904 (2017)

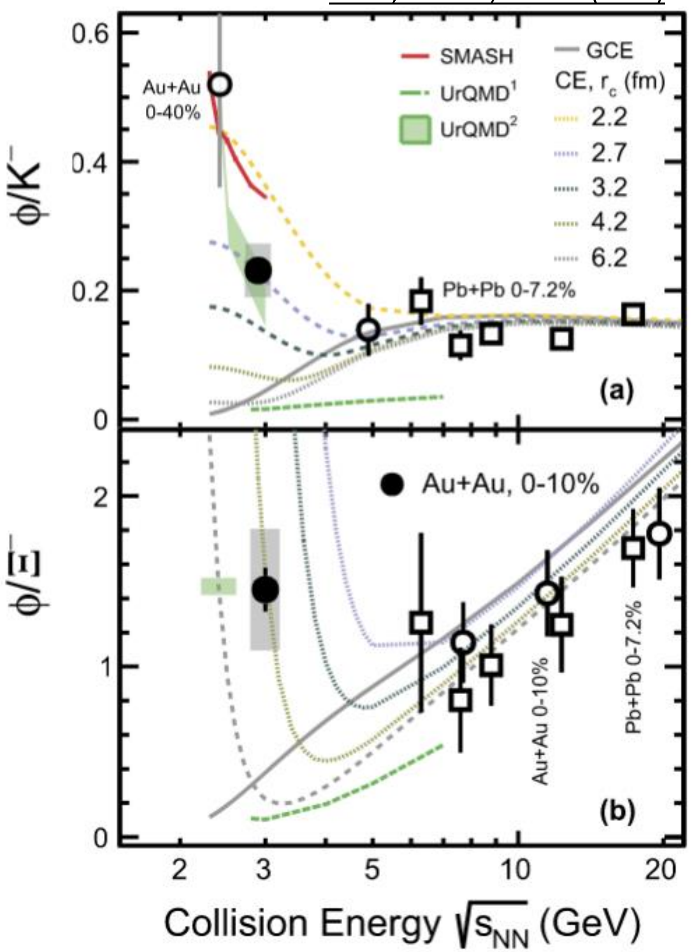


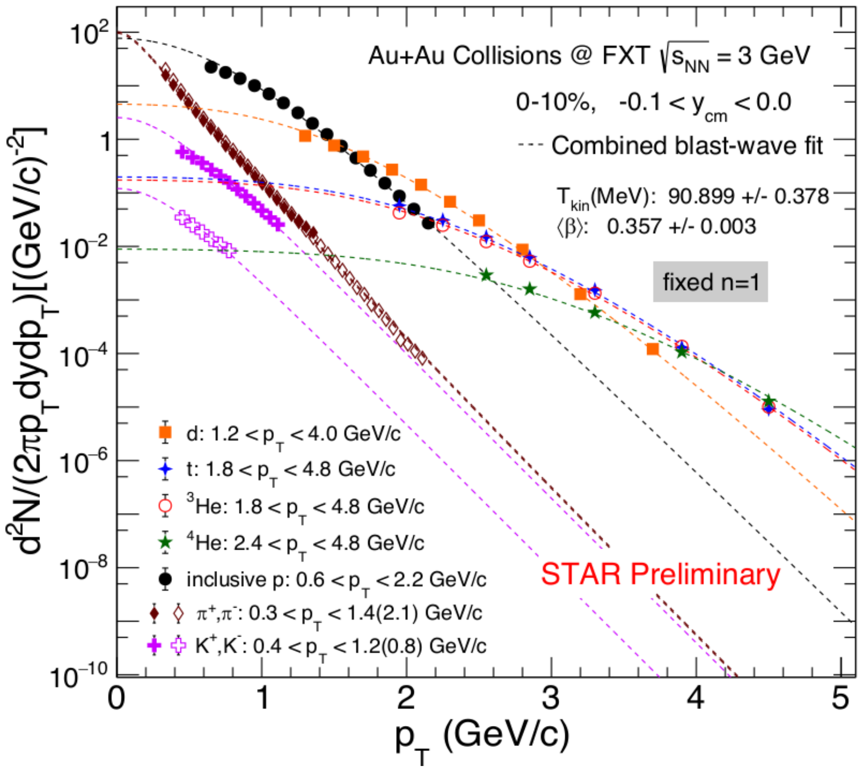
✓ Collectivity increases with beam energy for central collisions

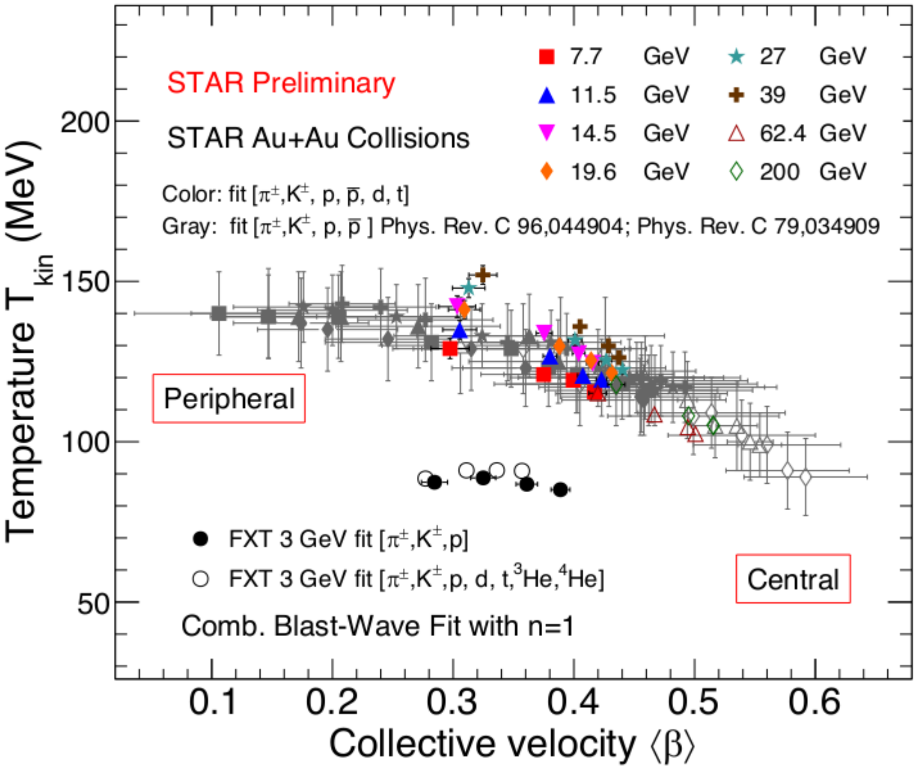
✓ Gap between chemical and kinetic freeze-out temperatures increases with beam energy, which suggests hadronic system interacts for longer duration in high energy collisions.

Particle Production at 3 GeV

STAR, PLB831, 137152(2022)







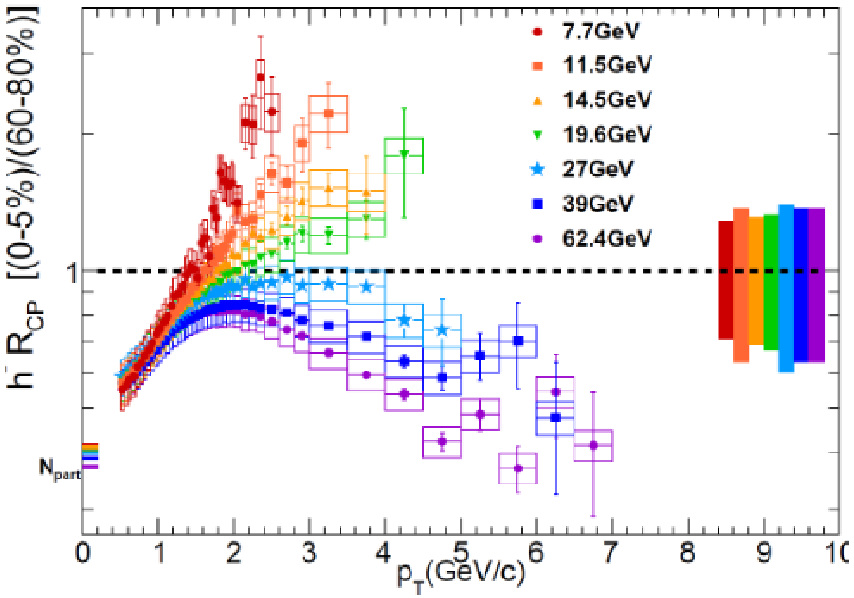
Strange particle ratios indicate the thermal particle phase space at low energies is far from the GCE limit and the local treatment of strangeness conservation is crucial

- Light nuclei p_T and rapidity distributions have been studied
- Midrapidity blast-wave fits:
  - Light nuclei prefer slightly higher T_{kin}, lower β
  - Combined fit to all particles successful

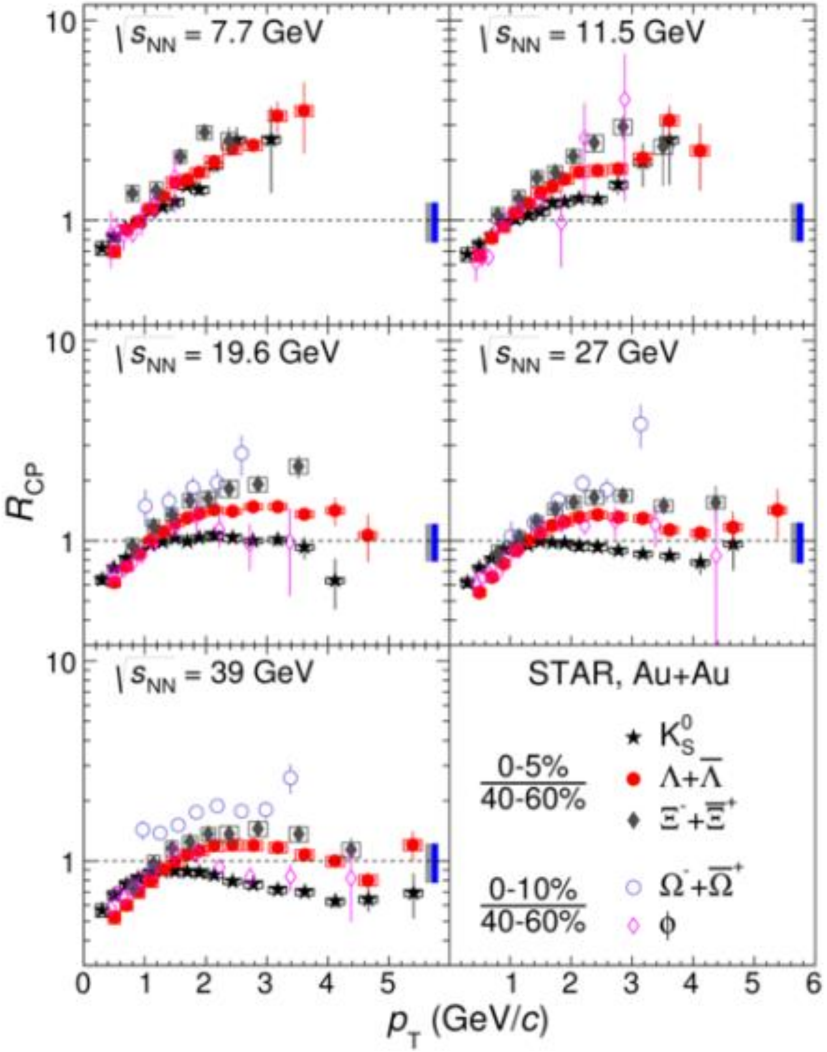
Different trend as compared to higher $\sqrt{s_{NN}}$ - different EOS at 3 GeV?

Nuclear Modification in the Medium

$$R_{cp} = \frac{d^2Ndp_t d\eta / < N_{coll} > (central)}{d^2Ndp_t d\eta / < N_{coll} > (peripheral)}$$



Phys. Rev. C **102** (2020) 34909
Phys. Rev. Lett. **121** (2018) 32301



R_{CP} has two regimes in the behavior depending on the collision energy:

- decrease of particle production with high p_T in central collisions at high energies
- smooth growth of particle production in central collisions at low collision energies.

R_{CP} behavior changes at $\sqrt{s_{NN}}$~30 GeV

High statistics of BES-II will allow to measure R_{CP} in high p_T region at low collision energies

Fluctuations of conserved quantities

PRL 112, 032302 (2014) : STAR Collaboration

✦ Net-baryon, net-charge and net-strangeness

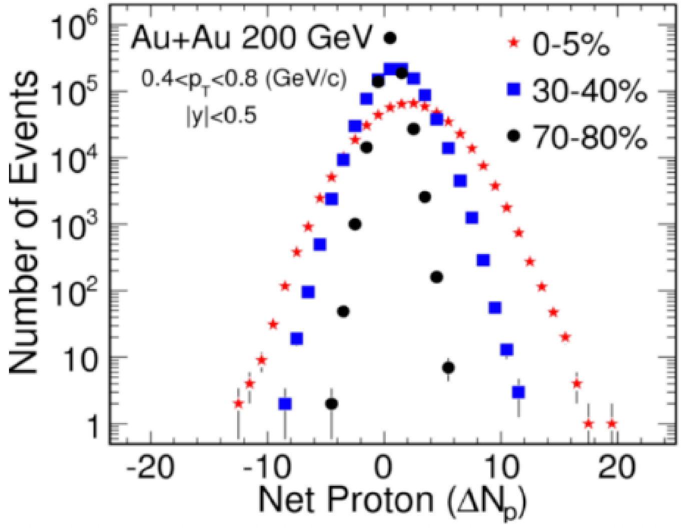
"Net" : positive - negative

$$\Delta N_q = N_q - N_{\bar{q}}, \quad q = B, Q, S$$

No. of positively charged particles in one collision

No. of negatively charged particles in one collision

Fill in histograms over many collisions



→neutrons cannot be measured

(1) Sensitive to correlation length

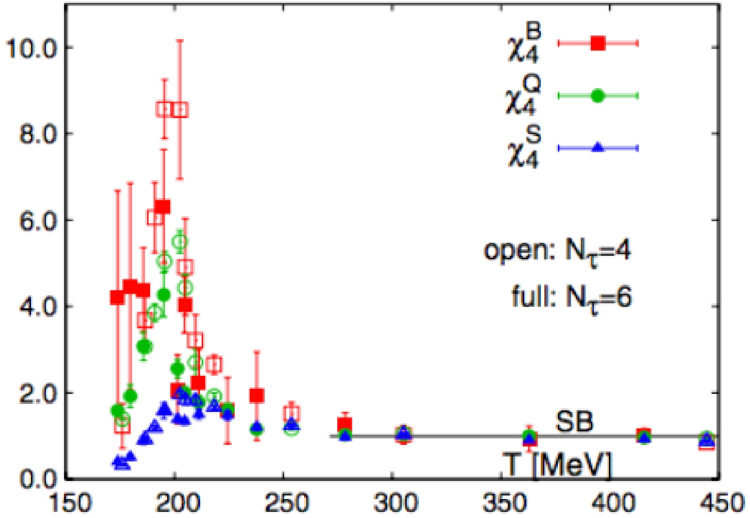
$$C_2 =< (\delta N)^2 >_c \approx \xi^2 \quad C_5 =< (\delta N)^5 >_c \approx \xi^{9.5}$$
$$C_3 =< (\delta N)^3 >_c \approx \xi^{4.5} \quad C_6 =< (\delta N)^6 >_c \approx \xi^{12}$$
$$C_4 =< (\delta N)^4 >_c \approx \xi^7$$

(2) Direct comparison with susceptibilities.

$$S\sigma = \frac{C_3}{C_2} = \frac{\chi_3}{\chi_2} \quad \kappa\sigma^2 = \frac{C_4}{C_2} = \frac{\chi_4}{\chi_2} \quad \frac{C_6}{C_2} = \frac{\chi_6}{\chi_2}$$

$$\chi_n^q = \frac{1}{VT^3} \times C_n^q = \frac{\partial^n p/T^4}{\partial \mu_q^n}, \quad q = B, Q, S$$

Volume **dependence can be canceled by taking the ratio.**



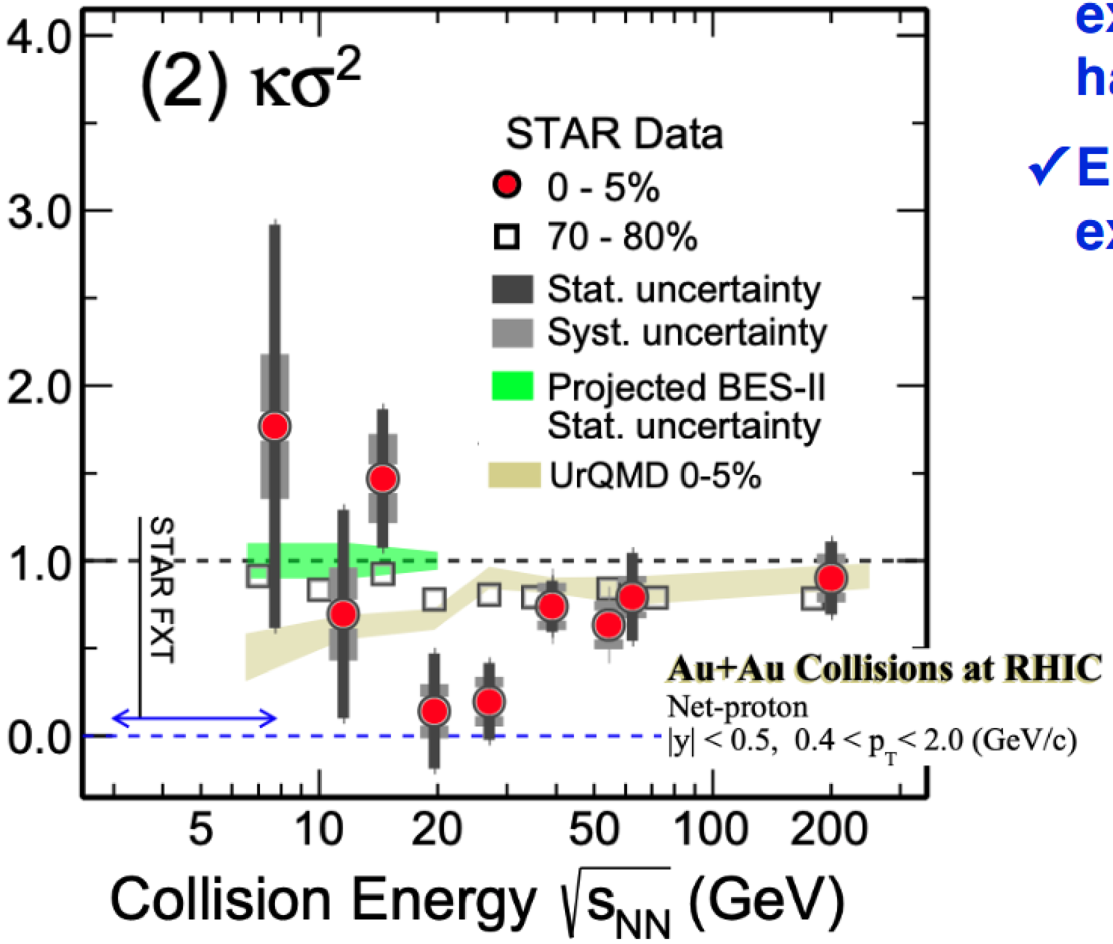
M. Cheng et al, PRD 79, 074505 (2009)

Hints of Critical Fluctuations

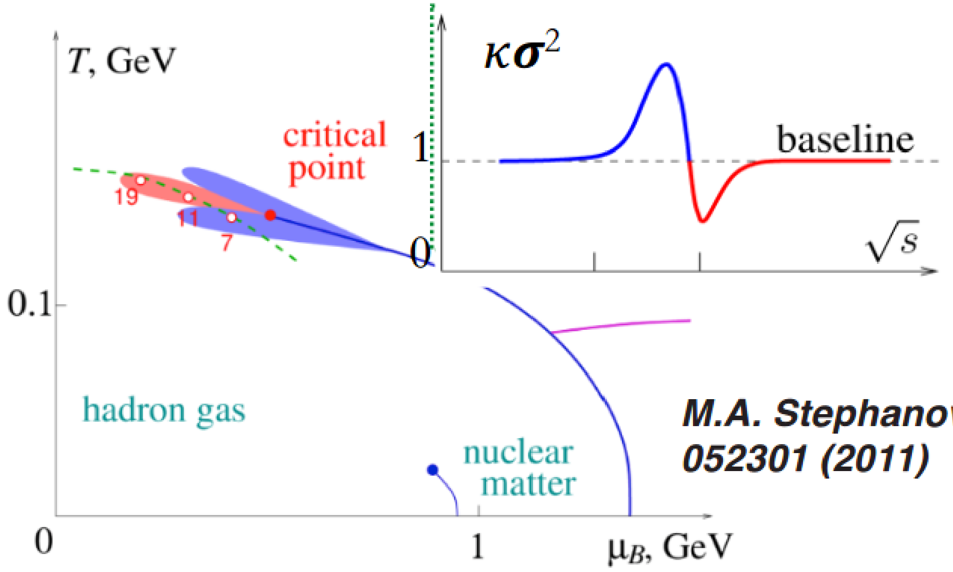
$$< \delta N >= N - < N >$$
$$C_1 = M =< N >$$
$$C_2 = \sigma^2 =< (\delta N)^2 >$$
$$C_3 = S\sigma^3 =< (\delta N)^3 >$$
$$C_4 = \kappa\sigma^4 =< (\delta N)^4 > -3 < (\delta N)^2 >^2$$

PRL **126** (2021) 92301

STAR Collaboration, PRC **104** (2021) 24902



- ✓ **Net-proton $\kappa\sigma^2$ (C_4/C_2) shows a non-monotonic behaviour. The trend is consistent with the expectation from theoretical calculations having a critical point.**
- ✓ **Enhancement at low beam energies cannot be explained by baryon number conservation.**

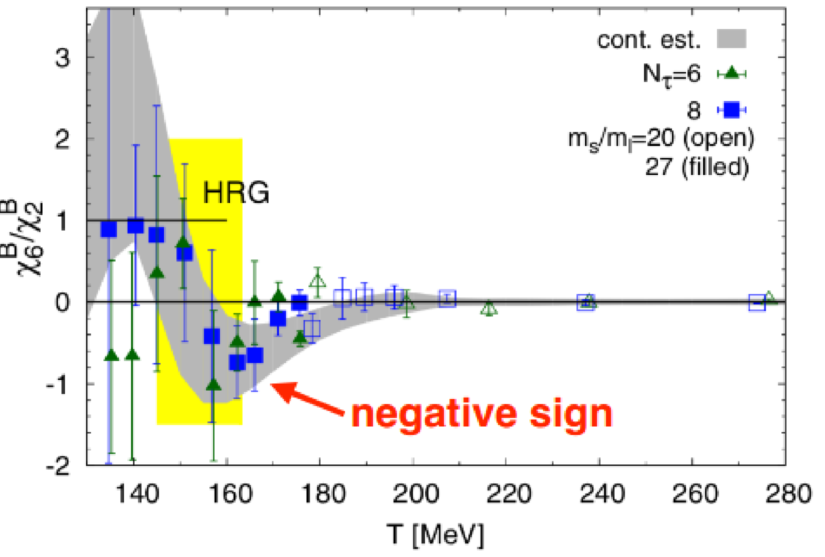


M.A. Stephanov, PRL107, 052301 (2011)

Hints of Critical Fluctuations

- There isn't yet any direct experimental evidence for the smooth cross over at μ_B~0 MeV
- $C_6/C_2 < 0$ is predicted as a signature of cross over transition
- High-statistics data sets at $\sqrt{s_{NN}}$ = 27, 54.4, and 200 GeV are analyzed to look for the experimental signature of cross over transition

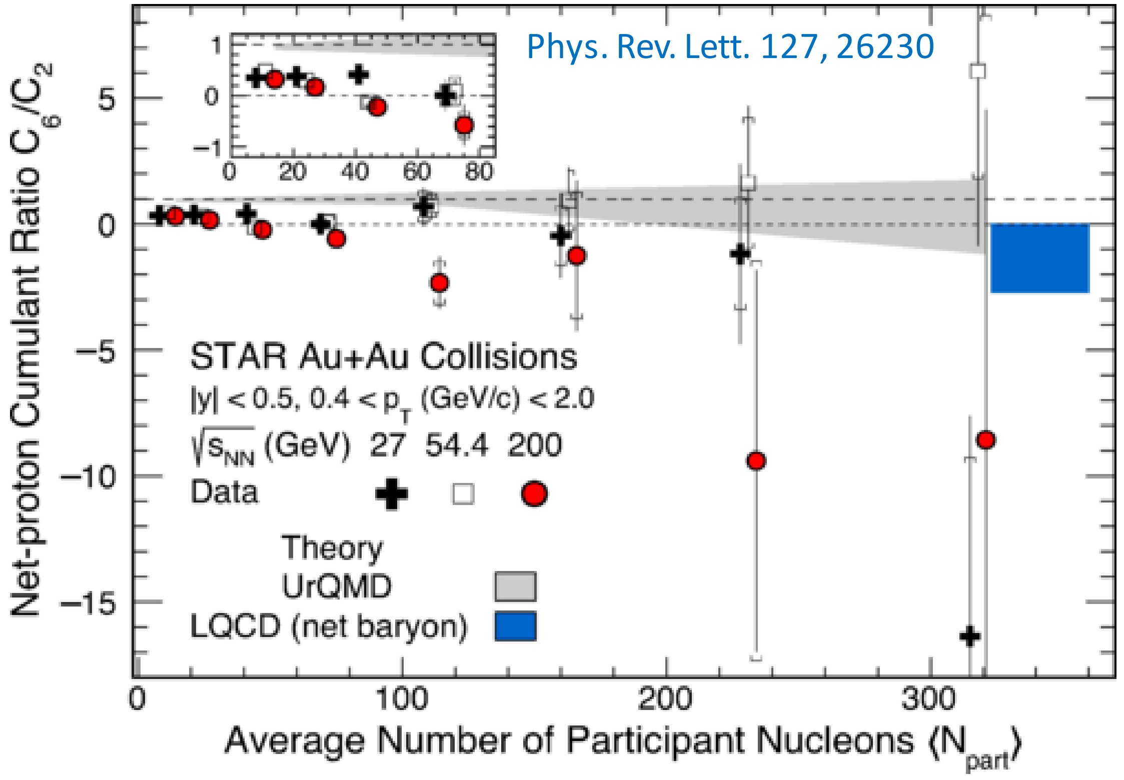
A. Bazavov et al, PhysRevD.95.054504 : LQCD



C.Schmidt,Prog.Theor.Phys.Suppl.186,563–566(2010)
Cheng et al, Phys. Rev. D 79, 074505 (2009)
Friman et al, Eur. Phys. J. C (2011) 71:1694

Freeze-out conditions	χ_4^B/χ_2^B	χ_6^B/χ_2^B	χ_4^Q/χ_2^Q	χ_6^Q/χ_2^Q
HRG	1	1	~2	~10
QCD: $T^{freeze}/T_{pc} \lesssim 0.9$	$\gtrsim 1$	$\gtrsim 1$	~2	~10
QCD: $T^{freeze}/T_{pc} \simeq 1$	~0.5	<0	~1	<0

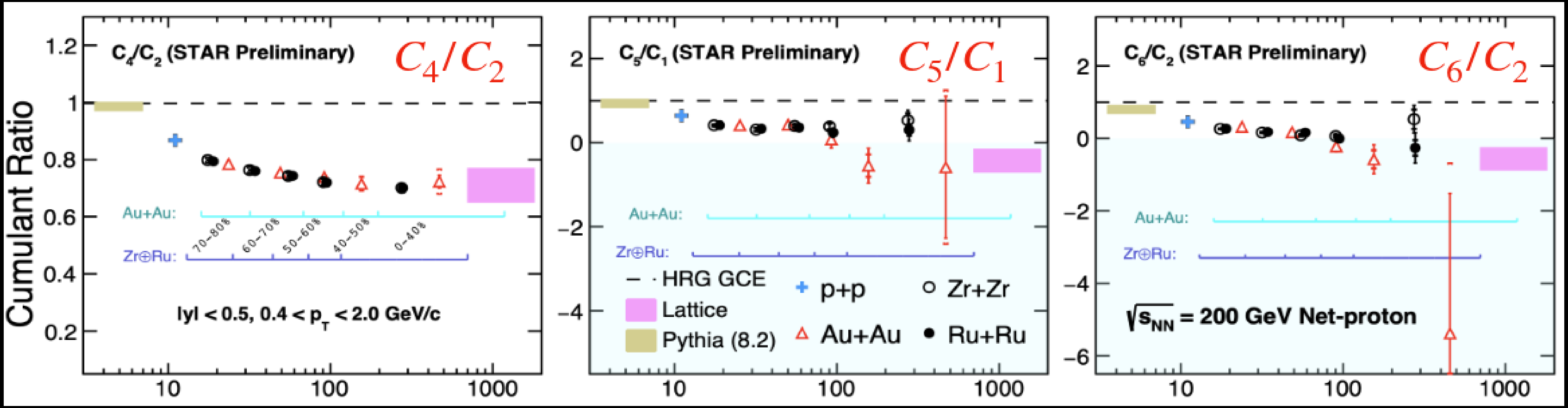
Predicted scenario for this measurement



Suggestive of smooth cross over at top RHIC energies

Mapping QCD phase diagram

Multiplicity dependence of fluctuations



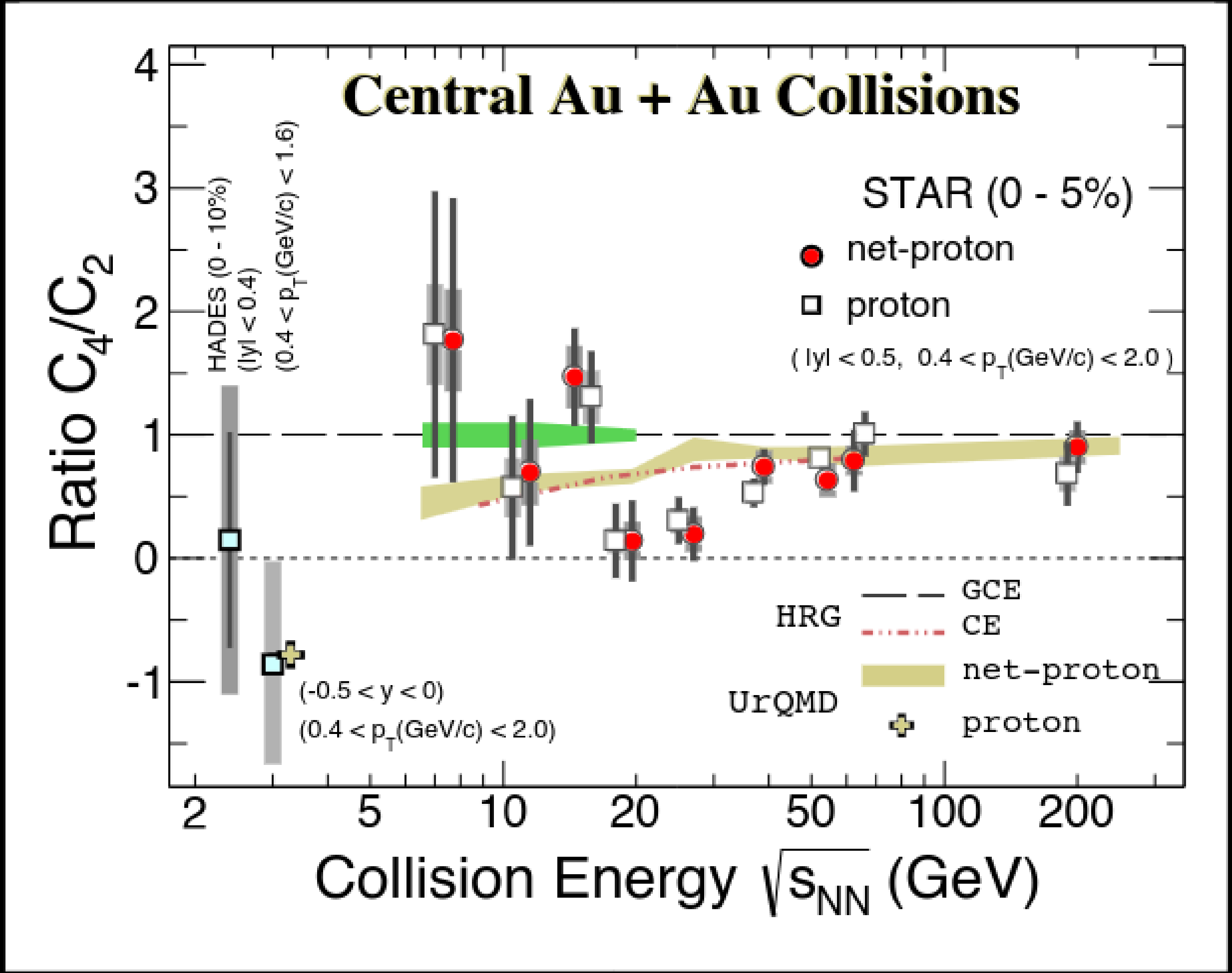
- C_4/C_2, C_5/C_1, and C_6/C_2 decrease with increasing multiplicity
- At high-multiplicity, cumulant ratios approach toward lattice prediction for the thermalized QCD matter and smooth crossover ($\mu_B \sim 0$)

STAR: arXiv: 2207.09837
Lattice: PRD 101 (2020) 7, 074502

Search for QCD critical point

Net-proton fluctuations

STAR: PRL 128, 202303 (2022)



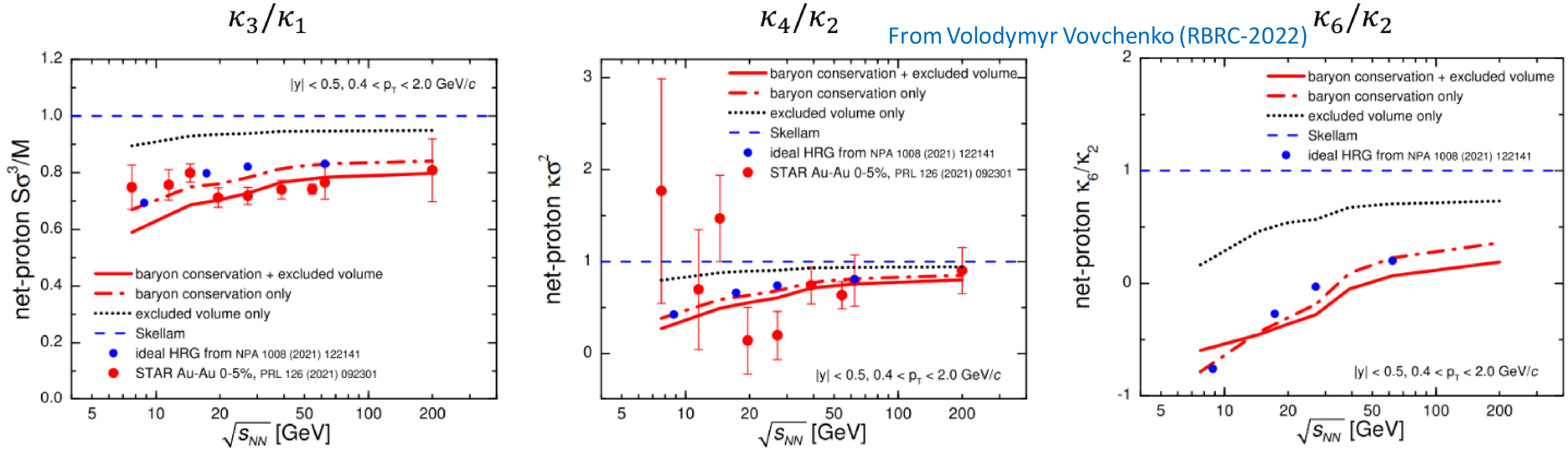
Susceptibility → Cumulants

$$\chi_4/\chi_2 \longrightarrow C_4/C_2$$

- Non-monotonic behavior as a function of $\sqrt{s}_{NN}$
  Significance of 3.1σ relative to Skellam expectation

- At $\sqrt{s}_{NN}$ = 3 GeV, fluctuations driven by baryon number conservation
  Hadronic interaction dominates

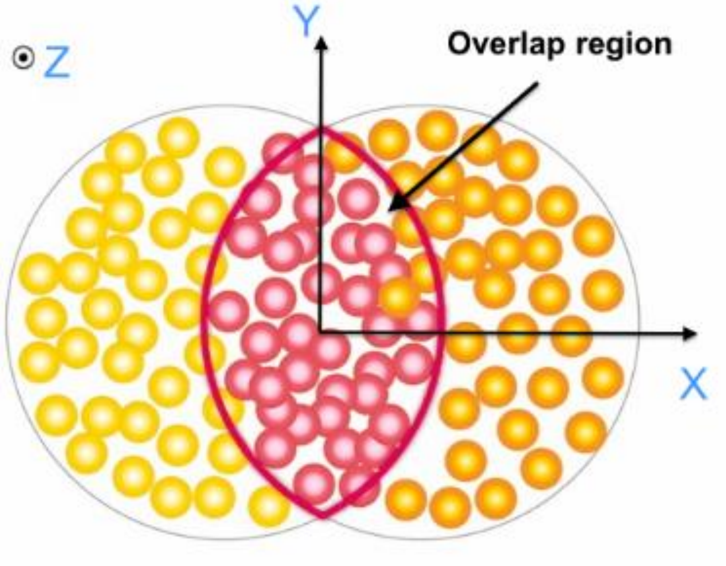
Net-proton Cumulant Ratios (theoretical calculations)



- Both the baryon conservation and repulsion needed to describe data at $\sqrt{s_{NN}} \geq 20$ GeV quantitatively
- Effect from baryon conservation is larger than from repulsion
- Canonical ideal HRG limit is consistent with the data-driven study of [Braun-Munzinger et al., NPA 1008 (2021) 122141]
- κ_6/κ_2 turns negative at $\sqrt{s_{NN}}$~50 GeV

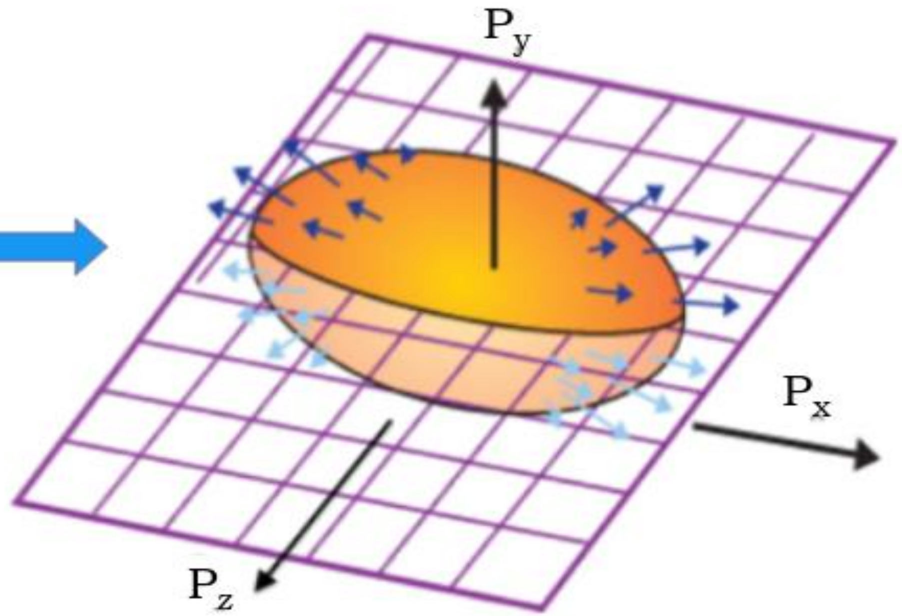
Azimuthal Anisotropy

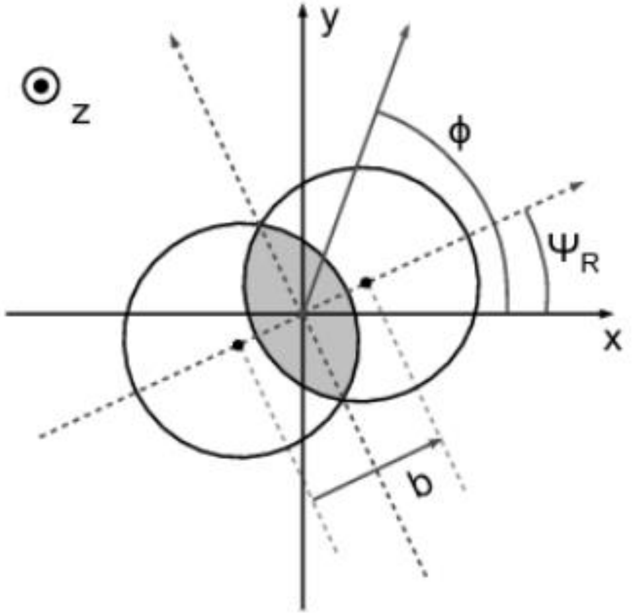
P. Klob, U. W. Heinz, Nucl. Phys. A715, (2003) 653c A
A.M. Poskanzer & S.A. Voloshin, Phys.Rev. C58 (1998)



Interactions
↓
Pressure(P)

$$y > x \rightarrow \frac{\partial P}{\partial x} > \frac{\partial P}{\partial y}$$





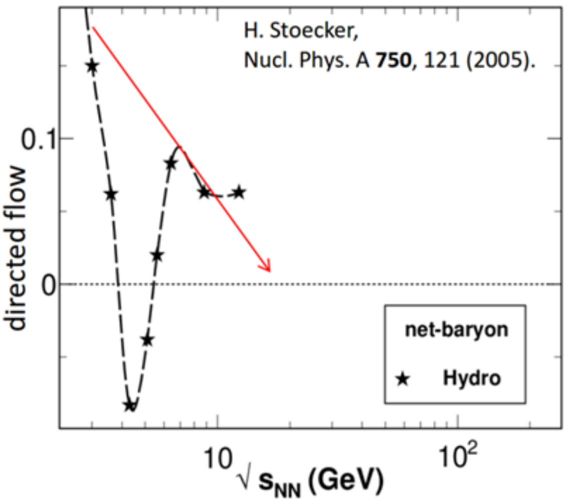
$$\frac{dN}{d\phi} \propto \frac{1}{2\pi}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n(\phi - \psi_{rp})\right)\right]$$

$$v_n = \langle \cos\left(n(\phi - \psi_{rp})\right)\rangle$$

- ✓ Sensitive to early times in the evolution of the system
- ✓ Sensitive to the equation of state

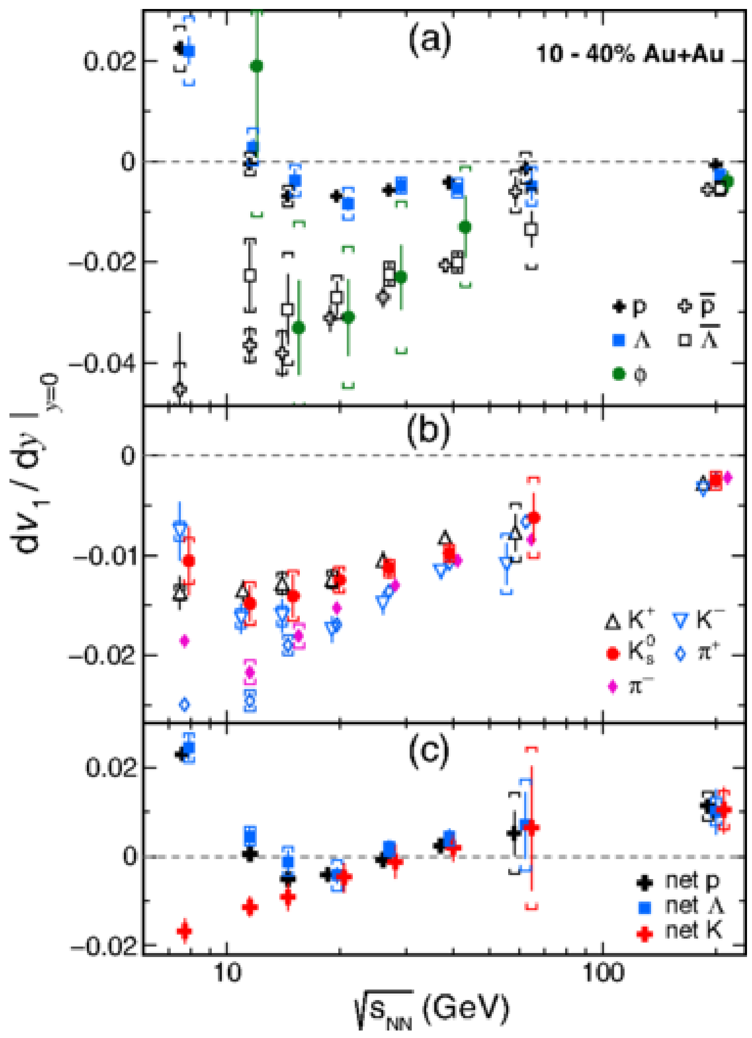
Probe of the early (partonic) stage of the collision

Directed flow from BES-I



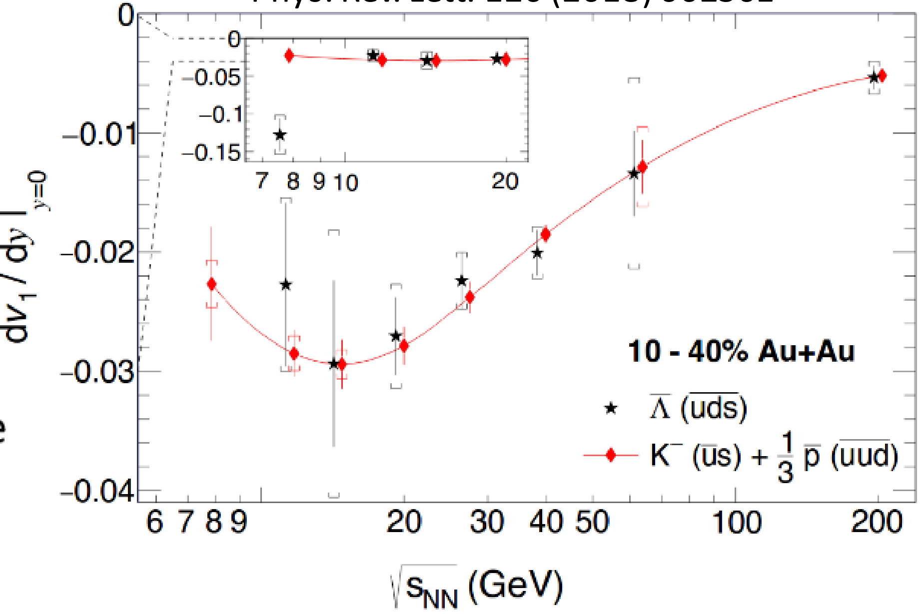
- v_1 proposed as good probe to search for the 1st-order phase transition (strong softening)
- dv_1/dy for Λ and p agree within uncertainties
- dv_1/dy slope for baryons changes sign in the region $\sqrt{s_{NN}}$<14.5 GeV
- Particles (anti-Λ, anti-p, and ϕ) with produced quarks show similar behavior at $\sqrt{s_{NN}}$>14.5 GeV
- Mesons show negative dv_1/dy

Phys. Rev. Lett. 120 (2018) 062301



Minimum in dv_1/dy slope at $\sqrt{s_{NN}}$ ~ 15 GeV

Phys. Rev. Lett. 120 (2018) 062301



Assumption for the coalescence sum rule:

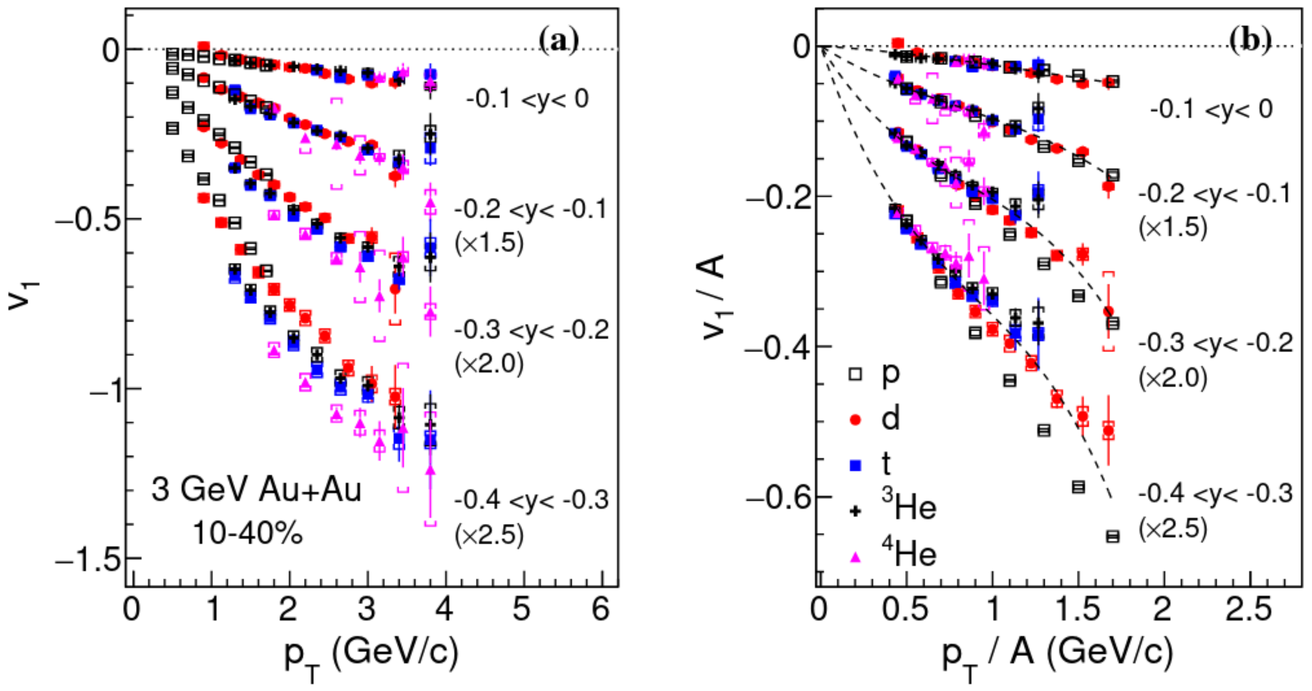
- v_1 is developed at the prehadronic stage
- Specific type of quarks have the same v_1
- Hadrons are formed via coalescence

$$(v_n)_{hadron} = \Sigma(v_n)_{\text{constituent quarks}}$$

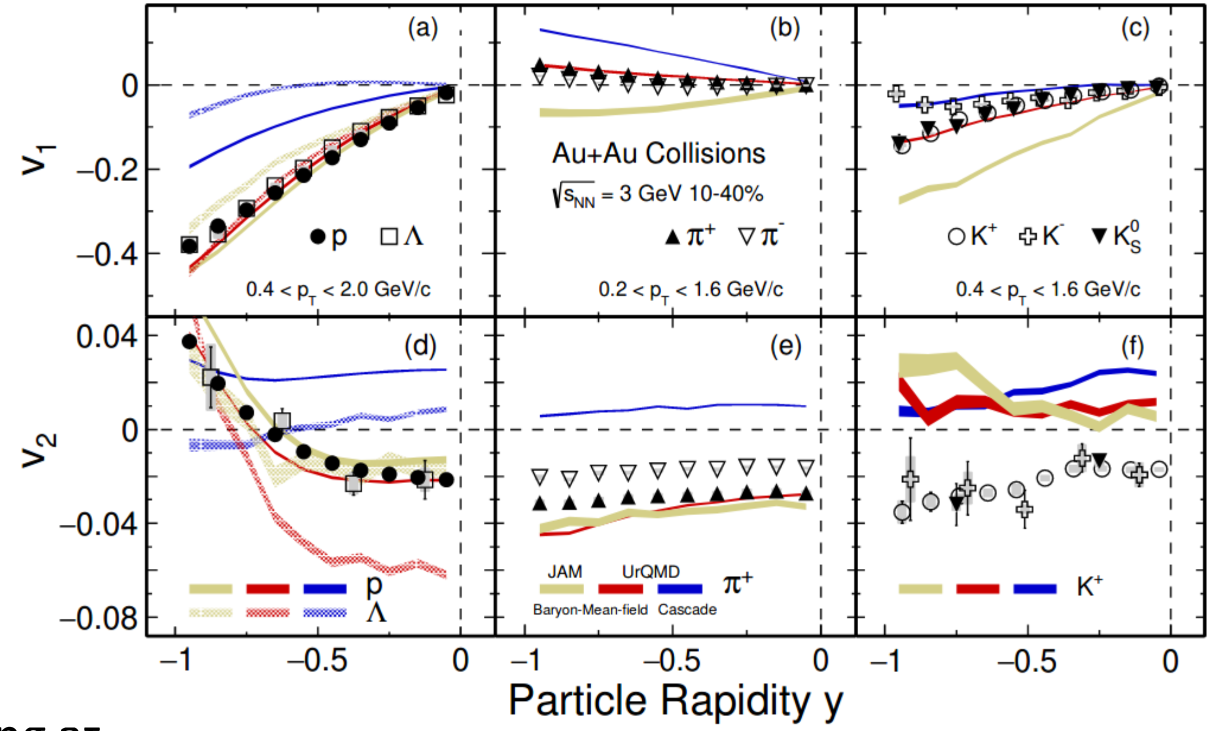
For anti-Lambda, prediction using coalescence sum rule agrees with measured v_1 above $\sqrt{s_{NN}}$=11.5 GeV

Directed and Elliptic Flow

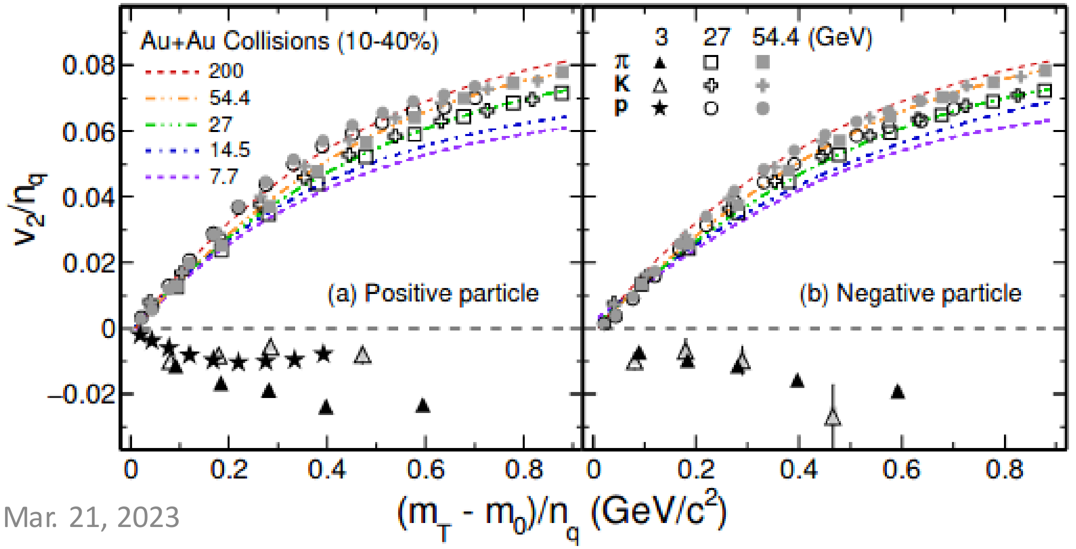
Phys. Lett. B 827 (2022) 136941



Phys. Lett. B 827 (2022) 137003



- Light nucleus $v_1(p_T)$ follows atomic-mass-number (A) scaling at different rapidity bins
- At 3 GeV, the NCQ scaling is absent and the opposite collective behavior is observed: the elliptic flow of all hadrons at midrapidity is negative; the slope of the directed flow of all hadrons, except π^+, at midrapidity is positive.
- Observations imply the vanishing of partonic collectivity and a new EOS, likely dominated by baryonic interactions in the high baryon density region

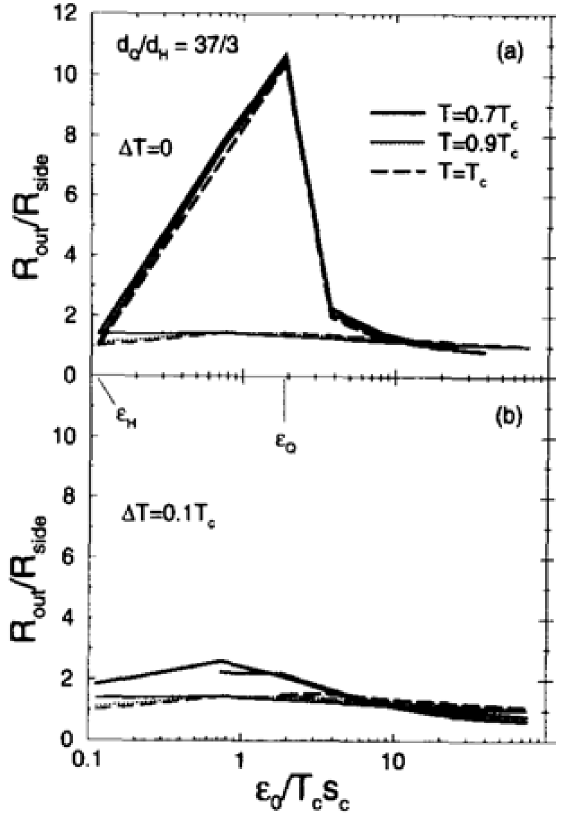


Femtoscopic correlations

- Time delays of the particle emission could be observed using femtoscopy technique (via R_{out}/R_{side} or R_{out}^2-R_{side}^2) and used to search for the 1st-order phase transition

R. Lacey. PRL 114 142301(2015)

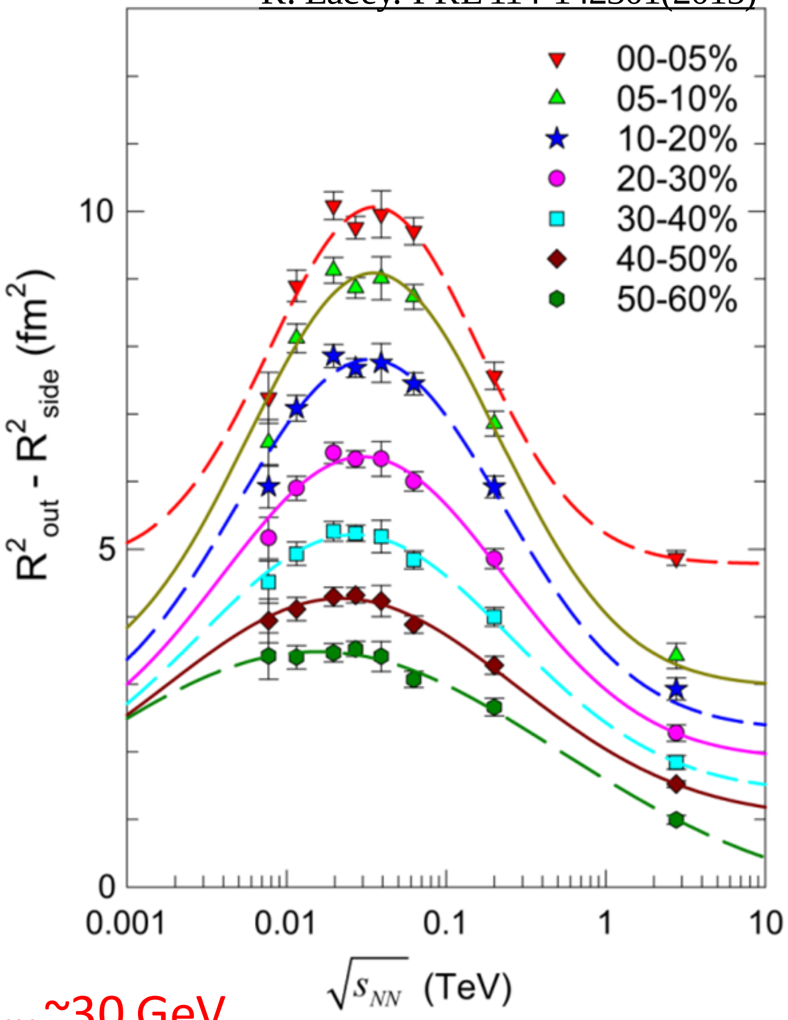
D.H. Rischke, M. Gyulassy. NPA 608 (1996) 479



R_{side} – geometrical size

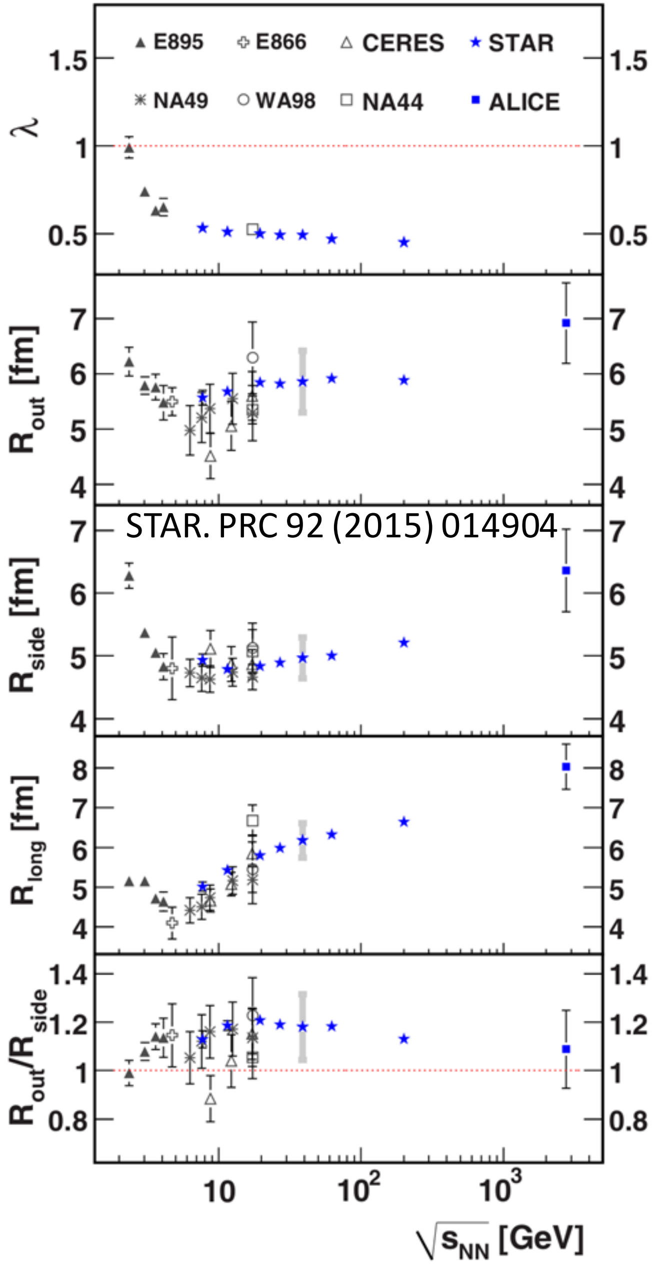
R_{out} – sensitive to geometrical size and particle emission duration

R_{long} – sensitive to the time of maximum emission

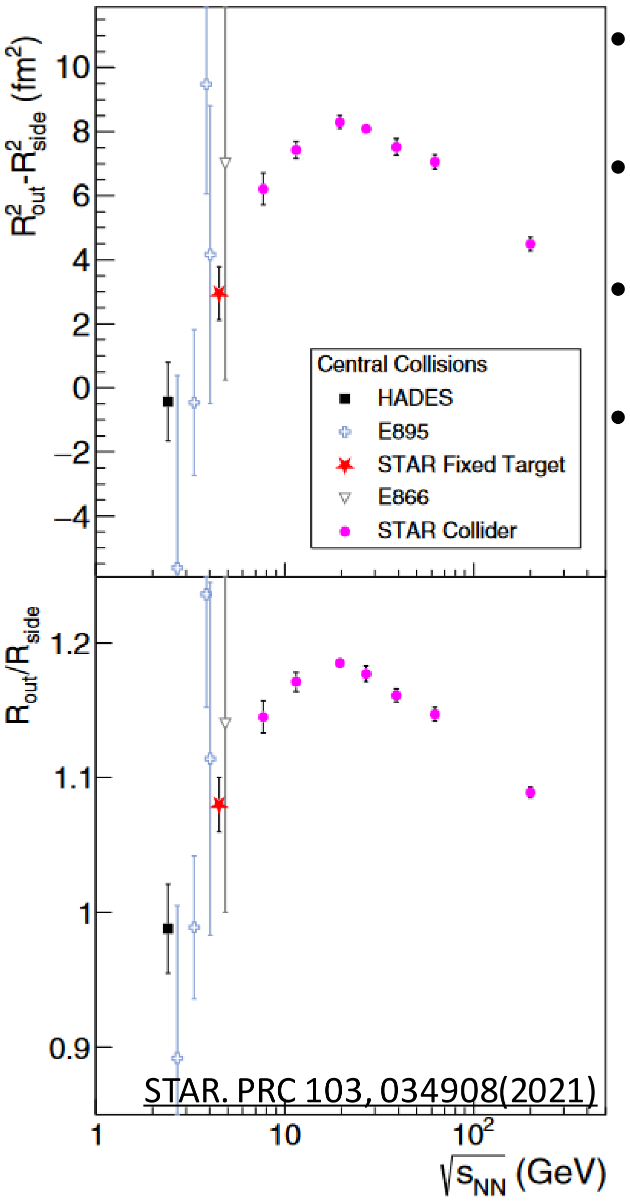


Peak structure with maximum at $\sqrt{s_{NN}}$ ~30 GeV

STAR ☆ Charged Pion Femtoscopy in HIC

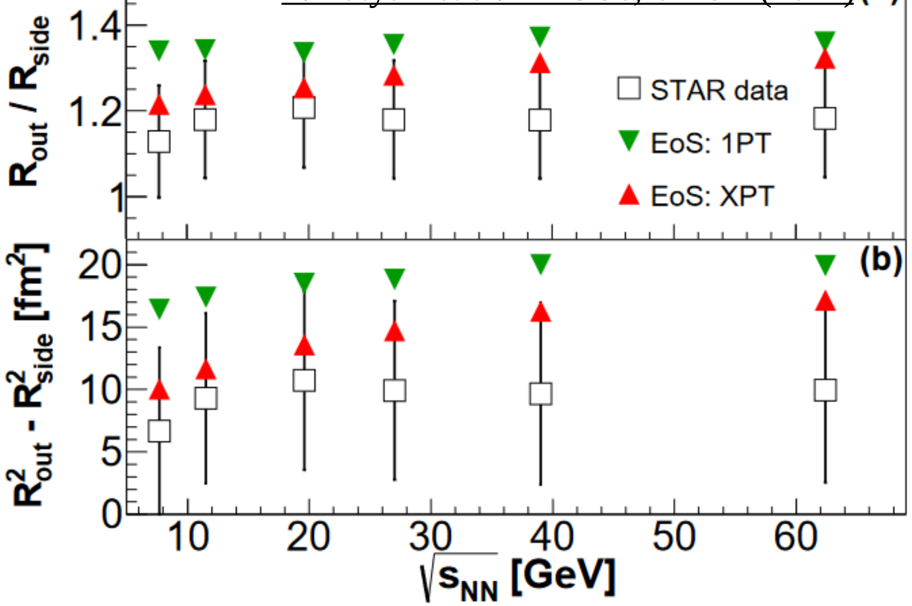


STAR. PRC 92 (2015) 014904



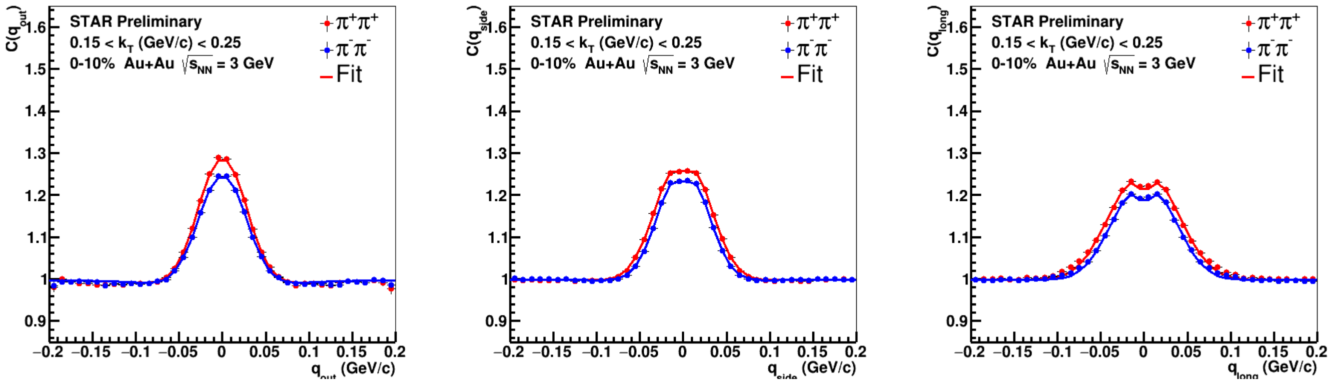
STAR. PRC 103, 034908(2021)

- Precise measurements in a broad energy range (from 2.41 GeV to 2.76 TeV)
- Can be reasonably described with hybrid models (initial conditions + hydrodynamics + hadron cascade)
- Need more high-statistics measurements at low energies
- Results can be described with hybrid models; preference to the cross over phase transition

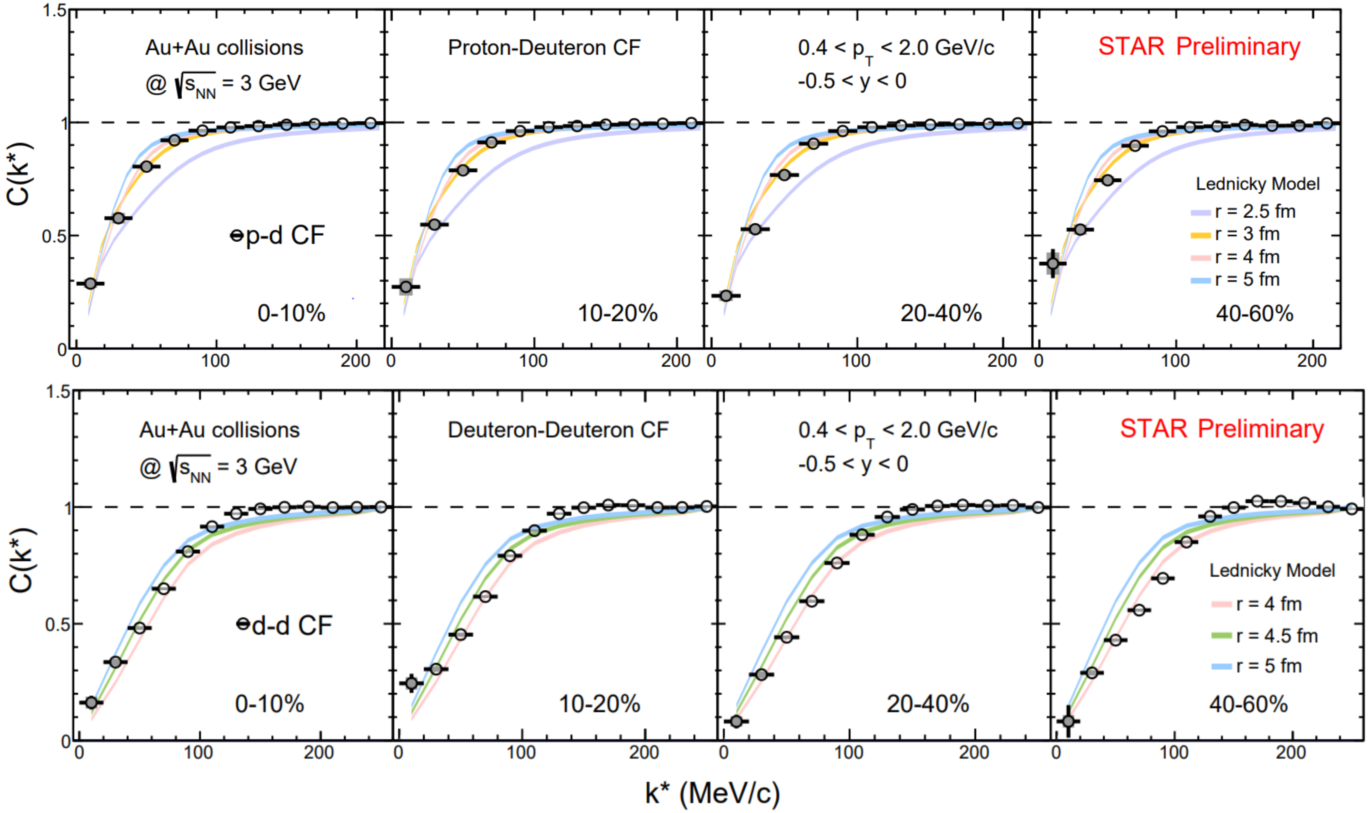


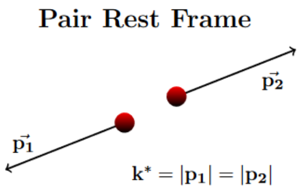
P. Batyuk et al. PRC 96, 024911(2017)

Femtoscopy Results from the FXT Program

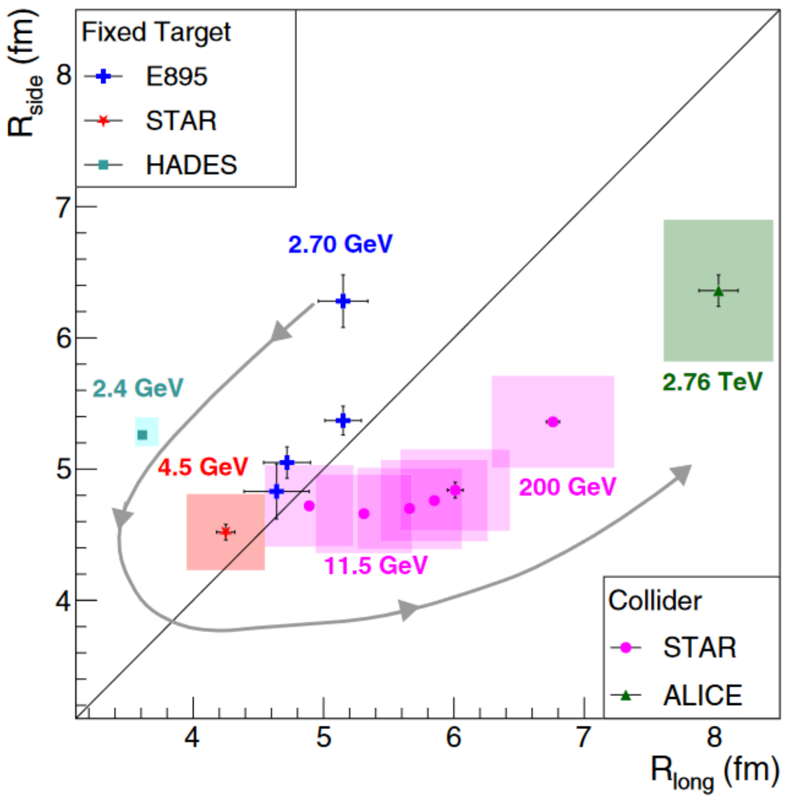


- Many interesting results from low-energy nuclear collisions: ππ, pp, pd, dd, and others
- Provide information about particle interactions
- The source shape evolves from oblate to prolate, as energy increases



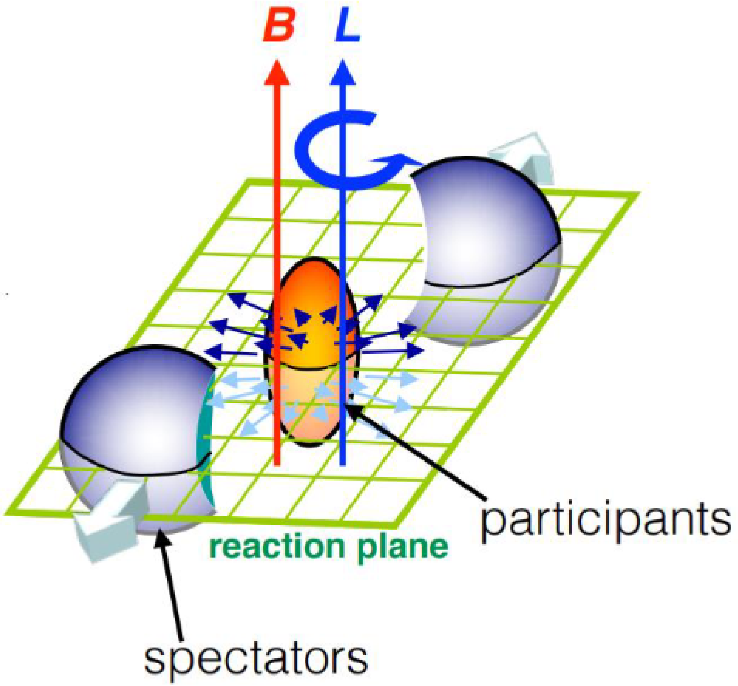


STAR. PRC 103, 034908(2021)



Global hyperon polarization

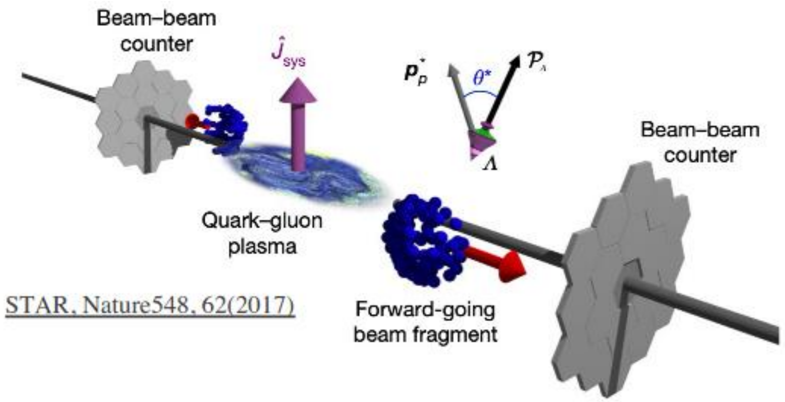
- The Quark-Gluon Plasma (QGP) formed in non-central nucleus-nucleus collisions is associated with large angular momentum, that leads to vorticity in the medium
- Spin-orbit coupling aligns spin directions of produced particles with the direction of vorticity
  - Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)
  - S. A. Voloshin, arXiv:nucl-th/0410089
- Another possible source of particle polarization is magnetic field, created in non-central collisions in the initial stage
  - D. Kharzeev, L. McLerran, and H. Warringa, Nucl.Phys.A803, 227 (2008)
  - McLerran and Skokov, Nucl. Phys. A929, 184 (2014)



Global Polarization in BES and FXT

Phys. Rev. C 104 (2021) 061901

The average vorticity points along the direction of the angular momentum of the $\hat{J}_{sys}$



STAR, Nature548, 62(2017)

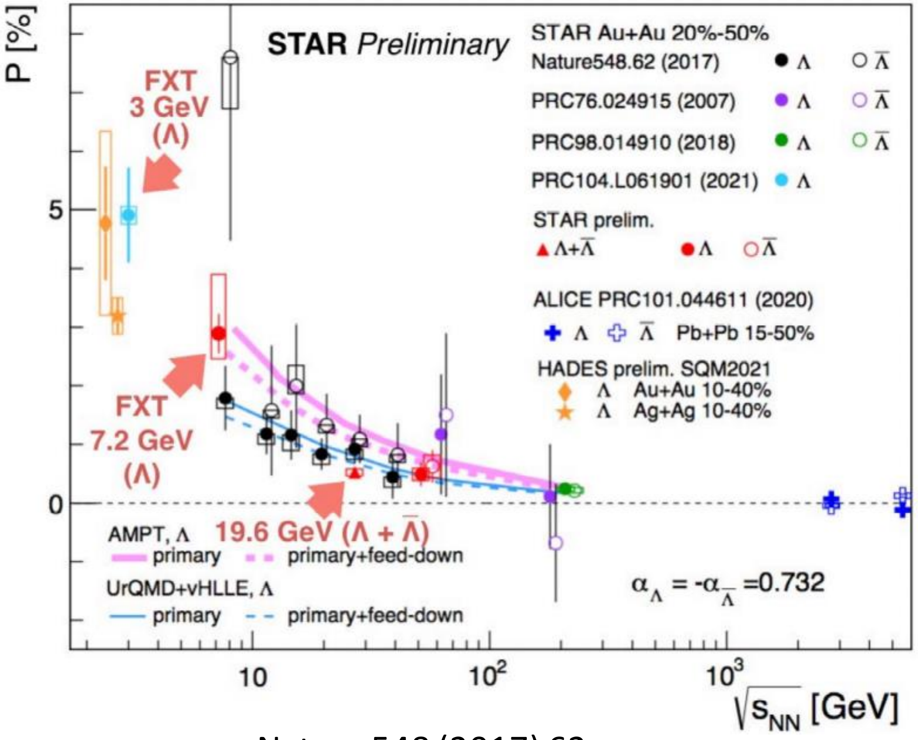
Global polarization is measured from the angular distributions of hyperon decay product:

$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_d^*) \rangle}{\mathrm{Res}(\Psi_1)}$$

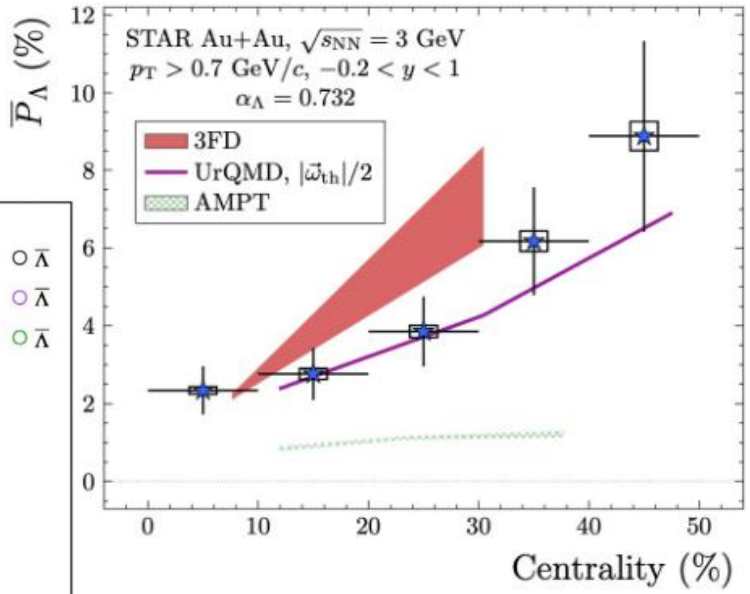
Thermal vorticity:

$$\omega = k_B T (P_\Lambda + P_{\bar{\Lambda}})/\hbar \qquad \omega \sim (9 \pm 1) \times 10^{21} s^{-1}$$

F. Becattini et al., PRC95, 054902(2017)



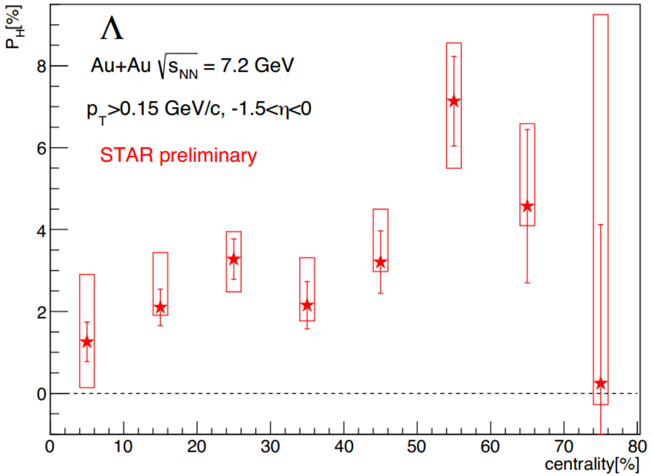
Nature 548 (2017) 62,
PRC 104 (2021) 061901,
arXiv: 2204.02302



Much larger $\bar{P}_\Lambda$ in FXT 3 GeV at 20-50%

4.91 ± 0.81 (stat.) ± 0.15 (syst.)%

Larger hyperon polarization for more peripheral collisions

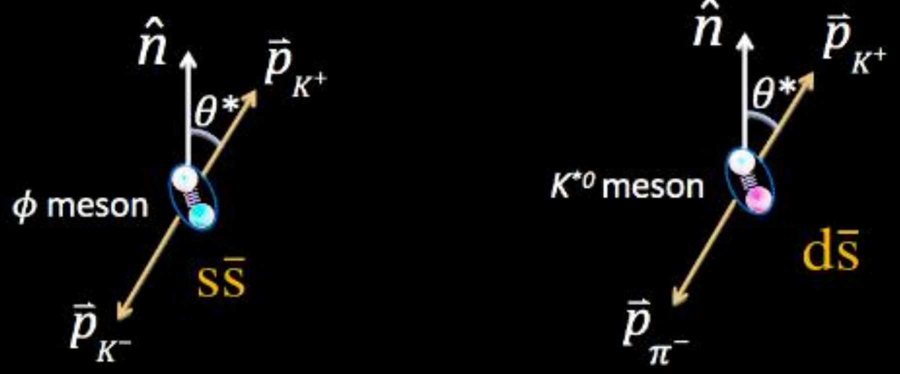


Opens up new directions in the study of the hottest, least viscous and most vortical fluid matter.

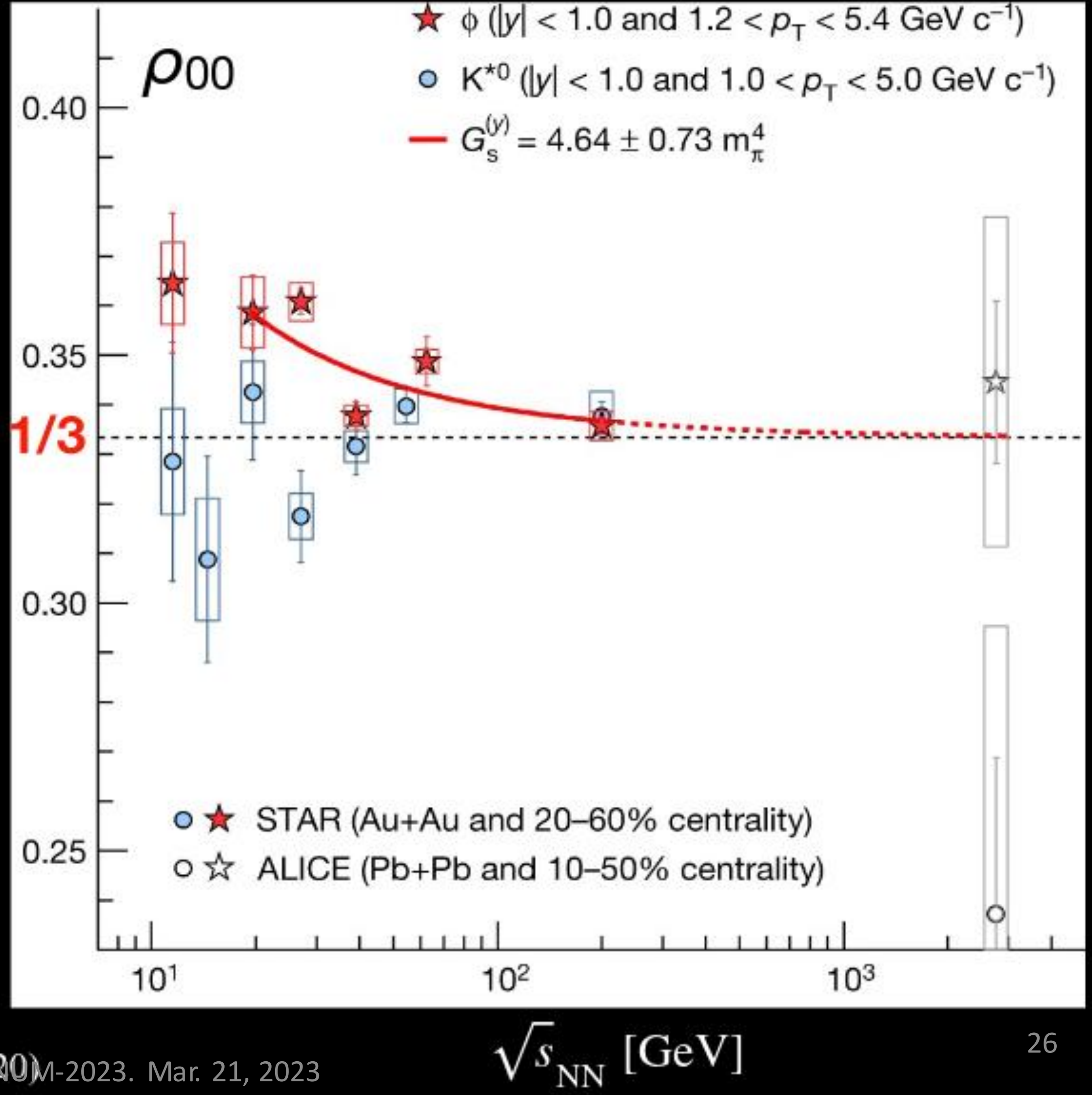
Global spin alignment of vector-mesons in heavy-ion collisions

STAR: Nature
https://www.nature.com/articles/s41586-022-05557-5

Vector meson



$$\frac{dN}{d(\cos\theta^*)} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$



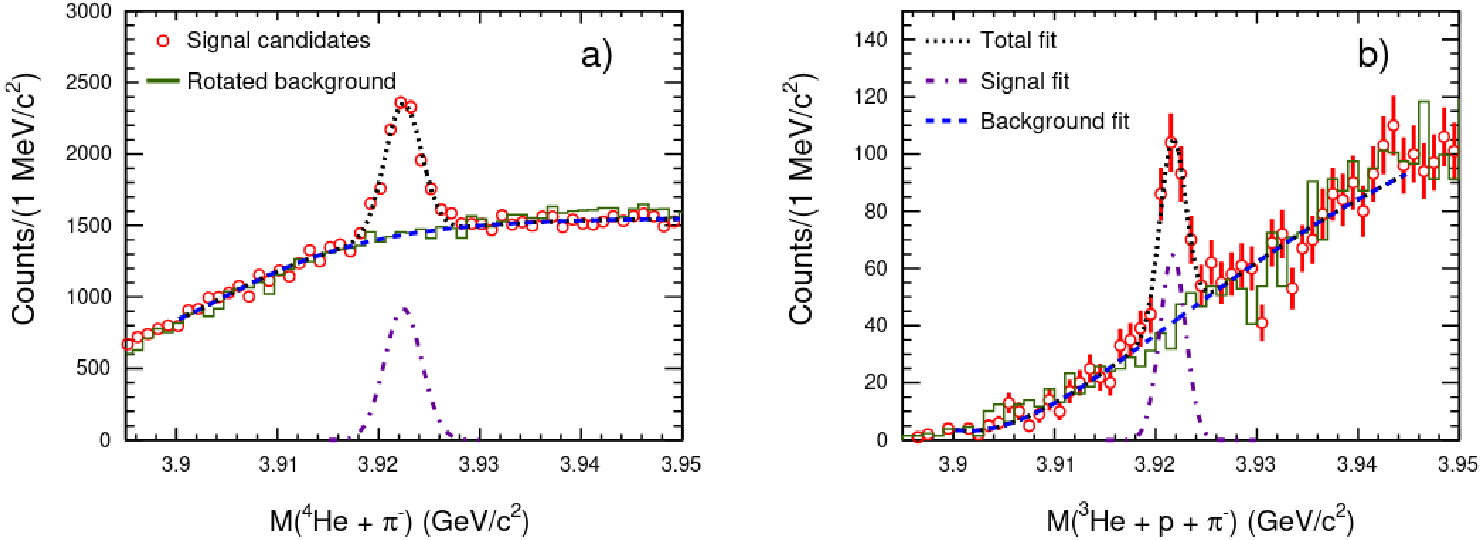
Possible explanation of this deviation for φ-spin alignment from 1/3 → vector meson field

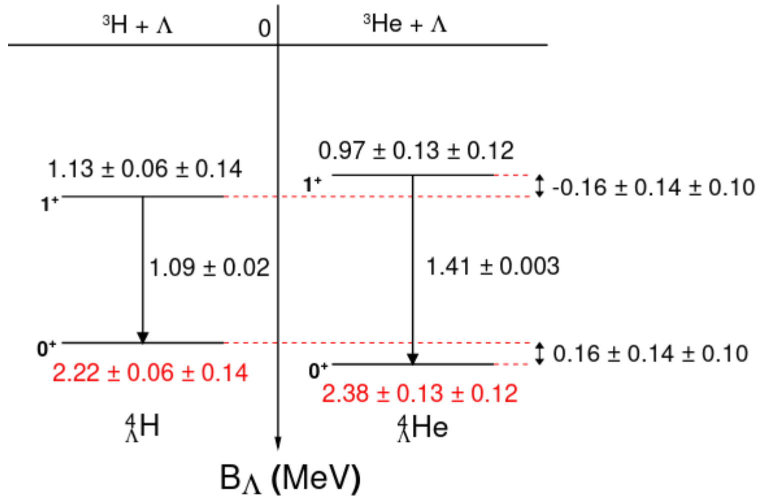
Phys. Rev. D 101 096005 (2020); Phys. Rev. D 102, 056013 (2020)

${}^4_\Lambda$H and ${}^4_\Lambda$He binding energy in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV

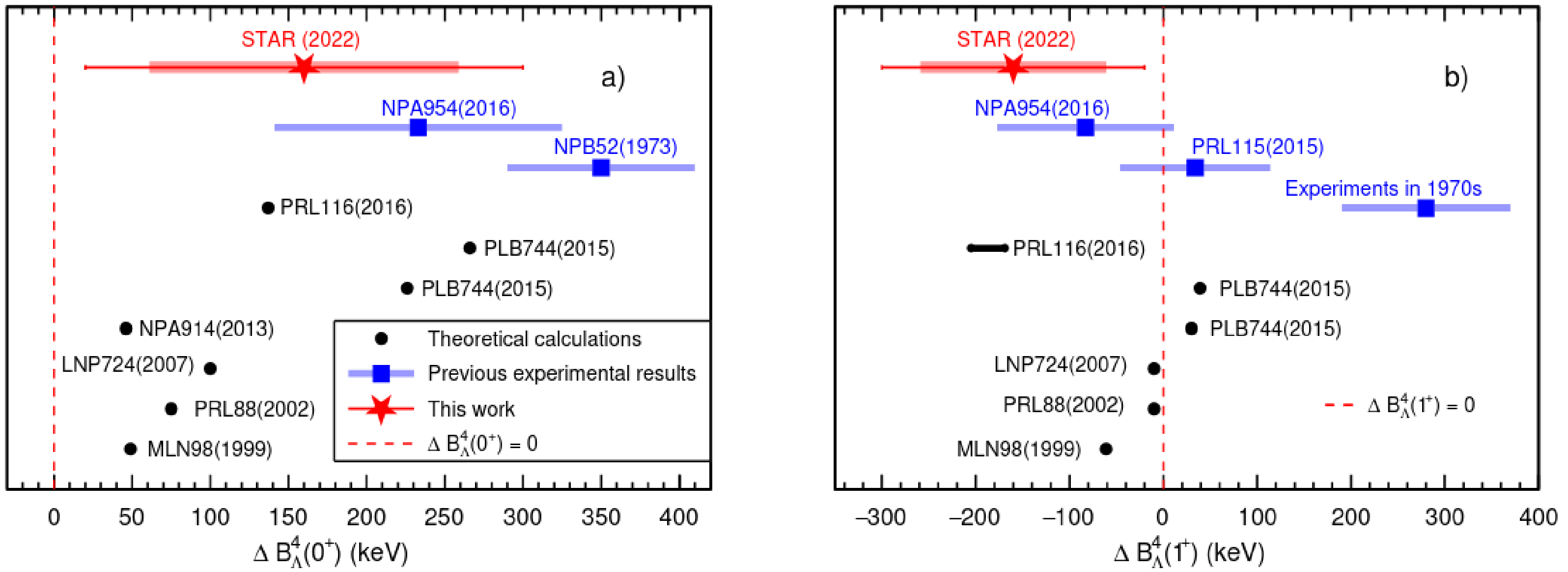
$$B_\Lambda = (M_\Lambda + M_{\mathrm{core}} - M_{\mathrm{hypernucleus}})c^2$$

Phys. Lett. B 834 (2022) 137449





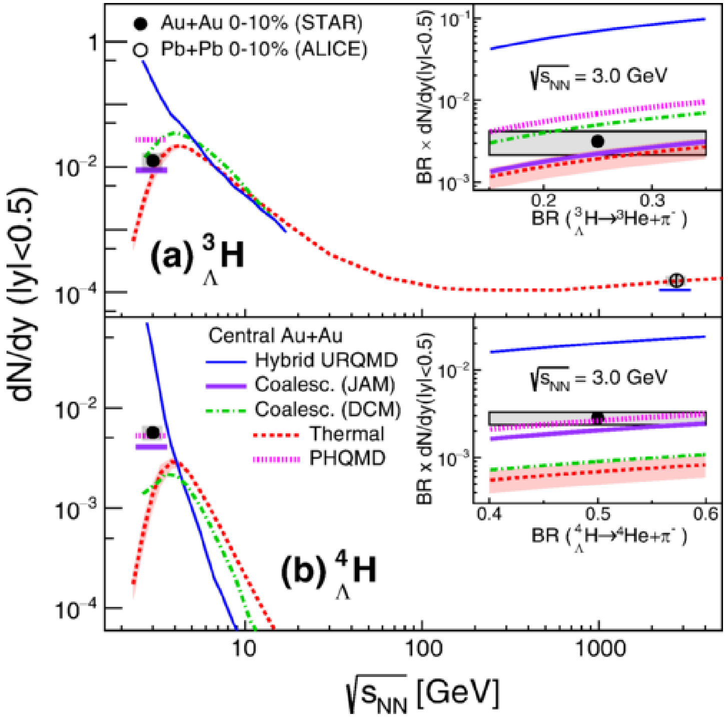
Phys. Lett. B 834 (2022) 137449



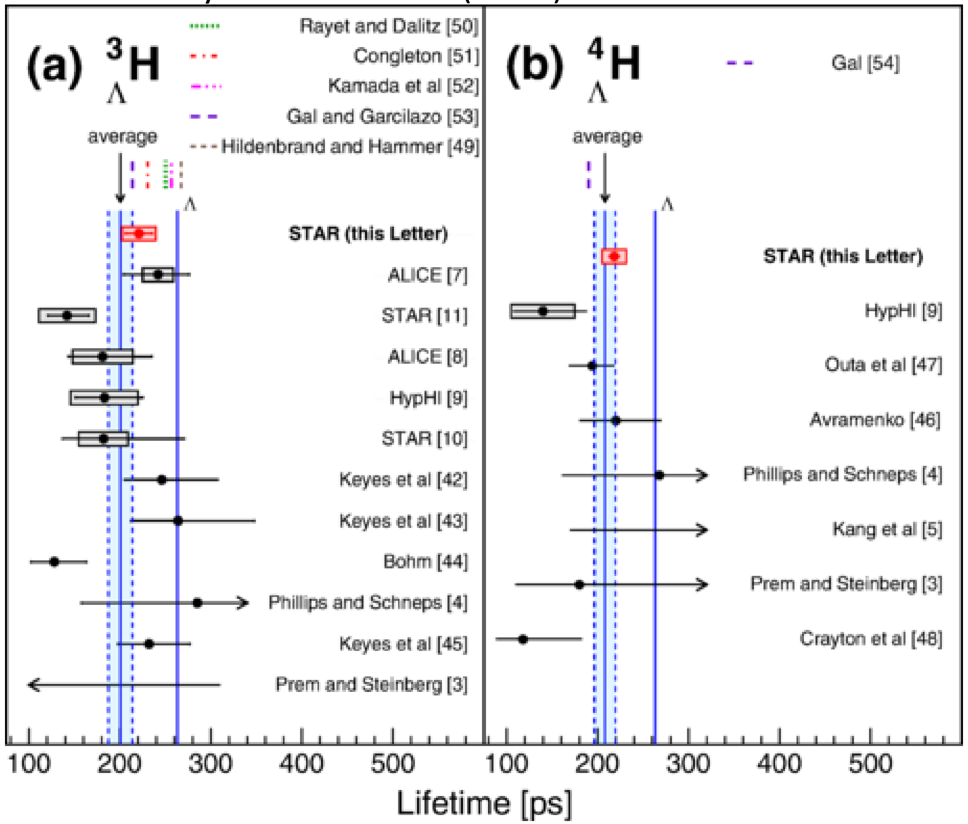
- Masses and the Λ binding energies of the mirror hypernuclei, ${}^4_\Lambda$H and ${}^4_\Lambda$He, are measured in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV.
- By using the γ-ray transition energies of the excited states from previous measurements

STAR ☆ $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ lifetimes and yields in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV

- $\tau(^{3}_{\Lambda}H)$ = 221 ± 15(stat.) ± 19(syst.) ps
  $\tau(^{4}_{\Lambda}H)$ = 218 ± 6(stat.) ± 13(syst.) ps
- Calculations from the thermal model, which adopts the canonical ensemble for strangeness that is mandatory at low beam energies are compared to data
- Thermal model predictions are consistent with the $^{3}_{\Lambda}H$ yield, but underestimates the $^{4}_{\Lambda}H$ yield
- Hadronic transport models JAM and PHQMD calculations reproduce the measured midrapidity reasonably well

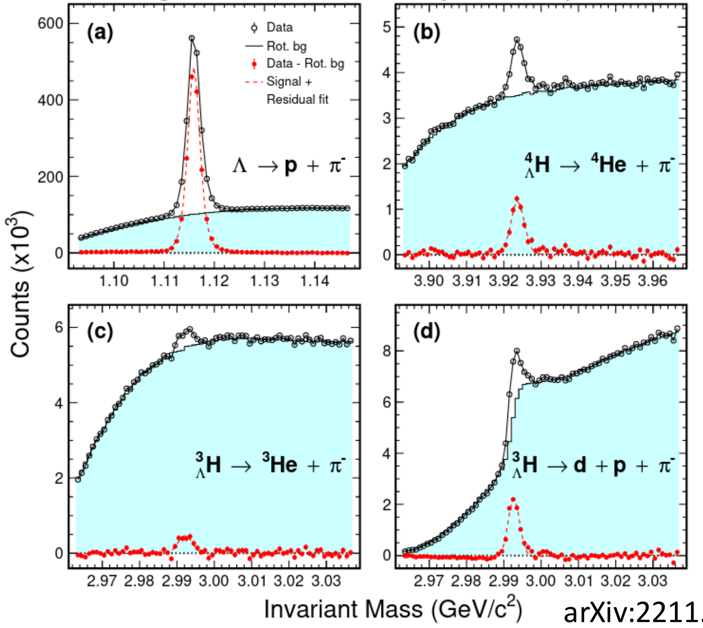


Phys. Rev. Lett. 128 (2022) 202301

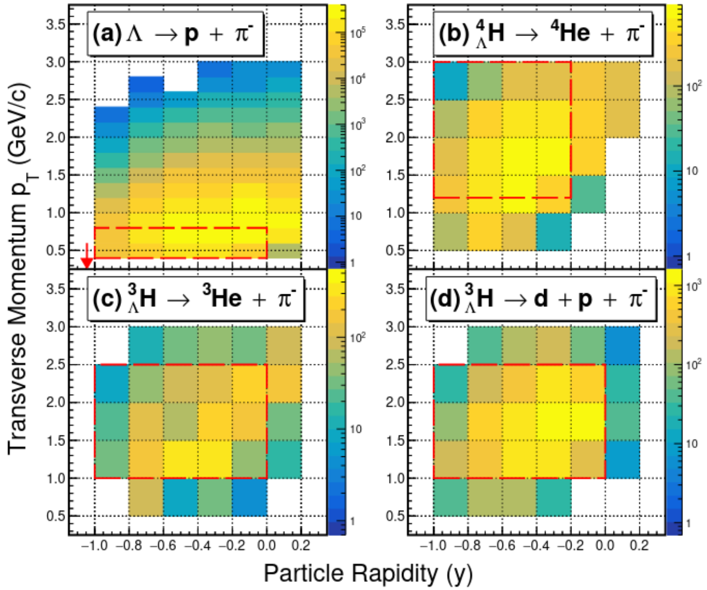


STAR ☆ Hypernuclei flow

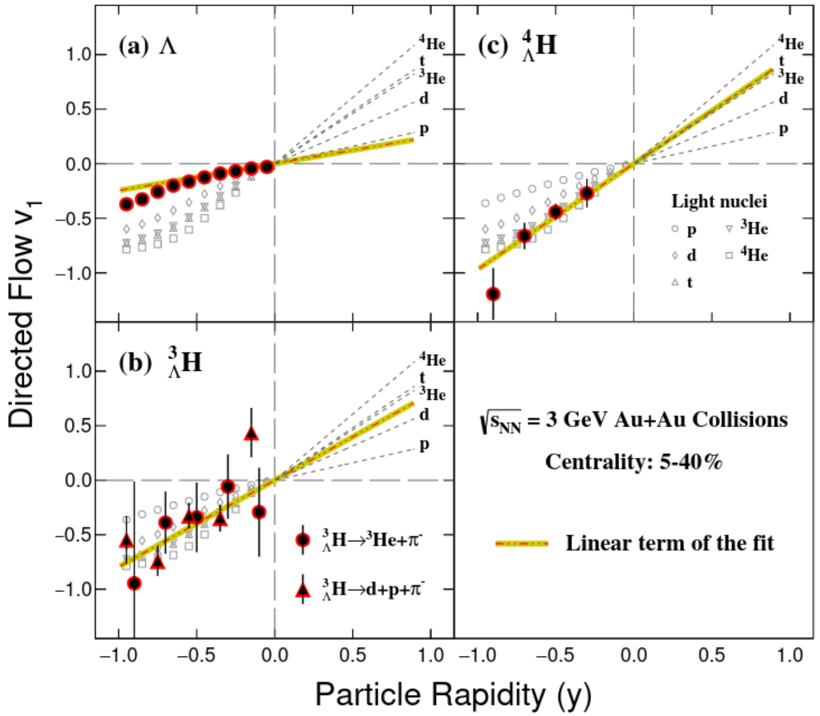
Utilizing 2- and 3-body decay channels



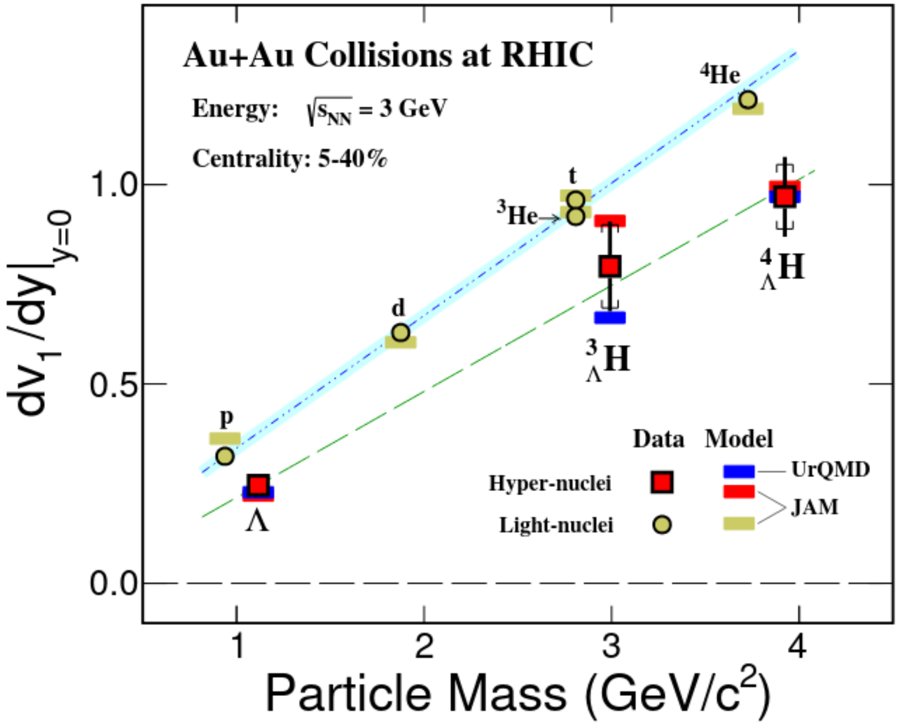
arXiv:2211.16981



arXiv:2211.16981



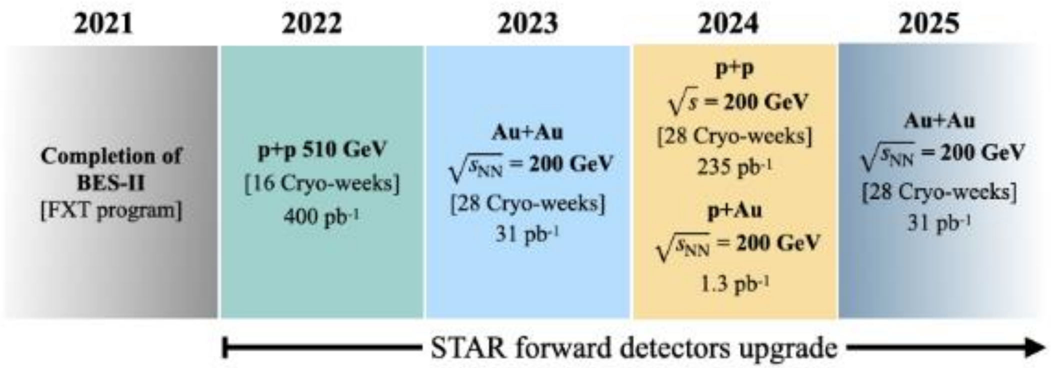
arXiv:2211.16981



- About 280M events were analyzed. Almost 1.7B events will be produced soon.
- JAM and UrQMD plus coalescence afterburner calculations for hypernuclei are in agreement with data within uncertainties
- Data suggest that coalescence of nucleons and hyperon Λ could be the dominant mechanism for the hypernuclei $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H production in such collisions

STAR 2023-2025 Run Plan and Physics Program

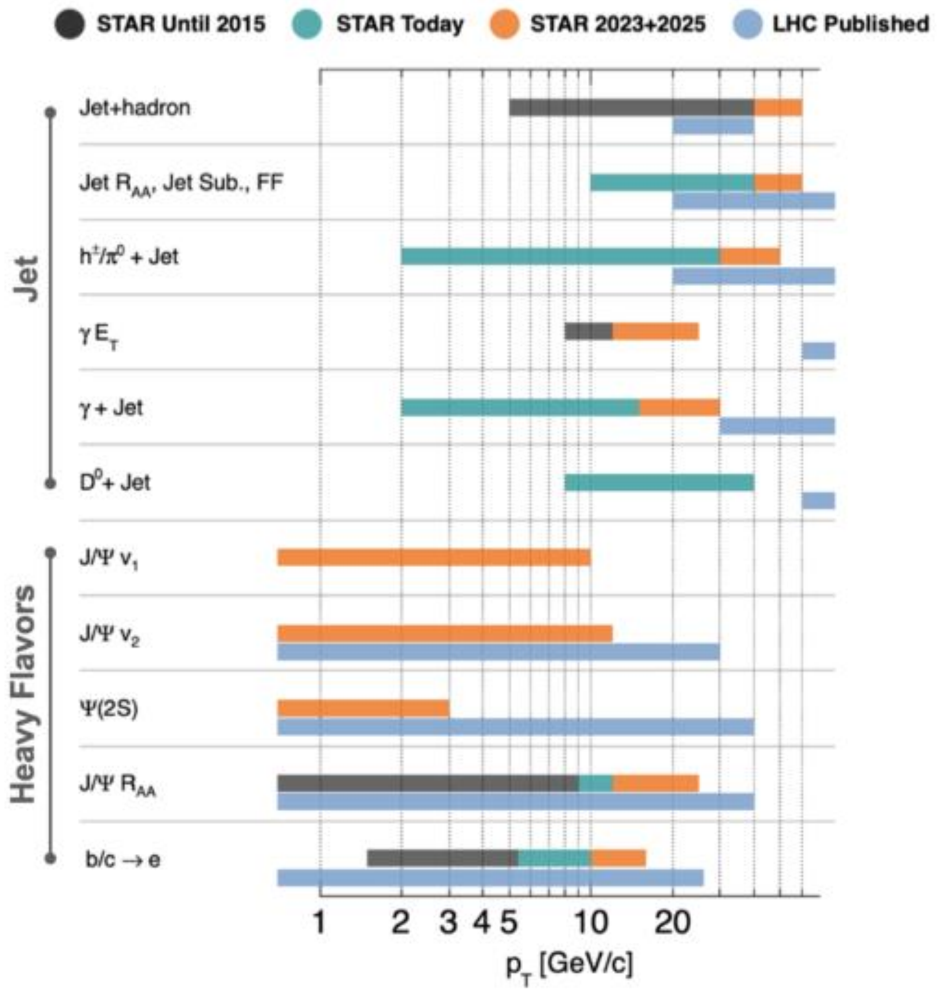
Run plan



It includes Hot-QCD and Cold-QCD STAR programs.

- Hot-QCD program: Study the microstructure of the QGP
  Precision jet and heavy-flavor measurements

Kinematic coverage



Summary

- BES-II upgrades performing at or above expectation
- Excellent performance from RHIC and STAR
- All requested BES-II data collected, providing 17 unique energies from 3-200 GeV with some overlapping collider and FXT energies
- Precision analyses are ongoing with very well understood detector
- Most exciting features:
  - Rcp: change of the behavior at $\sqrt{s_{NN}}$~30 GeV
  - Net-proton fluctuations: hints for criticality at $\sqrt{s_{NN}}$~17 GeV
  - Correlation femtoscopy: peak structure at √sNN~30 GeV
  - Hypernuclei: many new measurements
  - Voritcity: from discovery to the precise measurements
- Many results exist and a lot more will come soon

From Sergei A. Voloshin

PAY ATTENTION TO DETALS: references, definitions and terminology, clearly define physical goals and corresponding measurements/observables

Backup

STAR ☆ Search for the Chiral Magnetic Effect (CME)

- The chiral magnetic effect (CME) is predicted to occur as a consequence of a local violation of P and CP symmetries of the strong interaction amidst a strong electro-magnetic field generated in relativistic heavy-ion collisions.

- Experimental manifestation of the CME involves a separation of positively and negatively charged hadrons along the direction of the magnetic field.

- Previous measurements of the CME-sensitive charge-separation observables remain inconclusive because of large background contributions.

- In order to better control the influence of signal and backgrounds, the STAR Collaboration performed a blind analysis of a large data sample of approximately 3.8 billion isobar collisions of ^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr at $\sqrt{s_{NN}}$= 200 GeV.

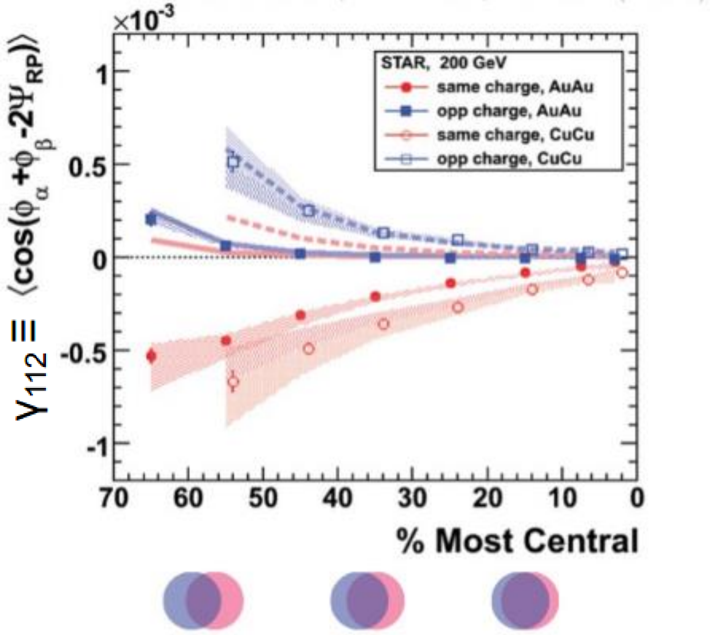
arXiv:2109.00131

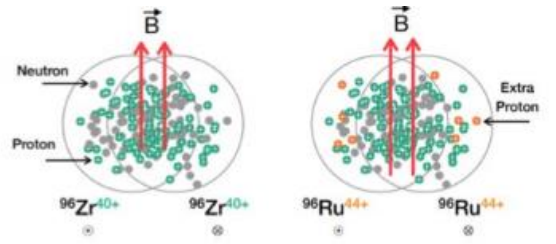
STAR ☆ Search for the CME (History)

First measurements

$\Delta\gamma_{112} = \gamma_{112}^{\text{Opposite Charge}} - \gamma_{112}^{\text{Same Charge}}$

STAR collaboration, PRL 103, 251601 (2009)





$$\Delta\gamma^{Ru+Ru} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

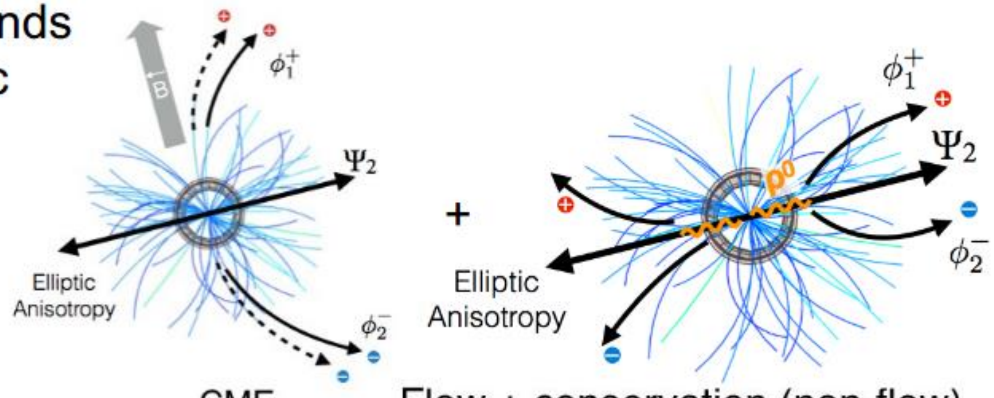
? ≠ ≈ =

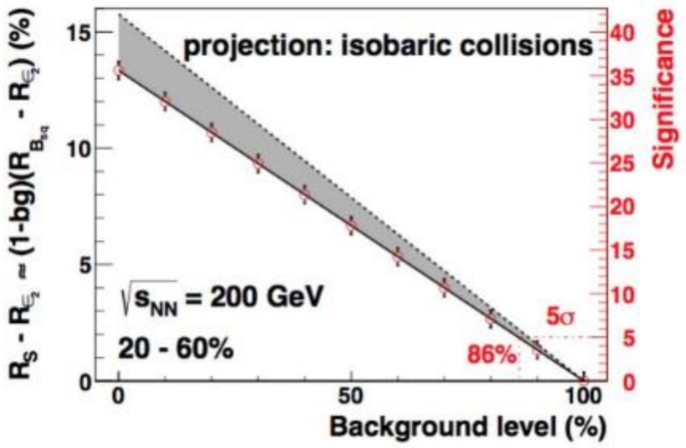
$$\Delta\gamma^{Zr+Zr} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

From B-field
10-18% different

Isobar idea:
Change signal while keeping background fixed

Backgrounds can mimic signal





2018 Beam Use Request: Would see signal if background contributed up to ~80-85% to measure

Previous measurements of the CME-sensitive charge-separation observables remain inconclusive because of large background contributions.

Search for the CME (Precision)

Large data set needed to hit small statistical uncertainty target

Systematic uncertainties between species need to be controlled below that level

Special RHIC conditions See G. Marr et al., in 10th International Particle Accelerator Conference (2019) pp. 28–32

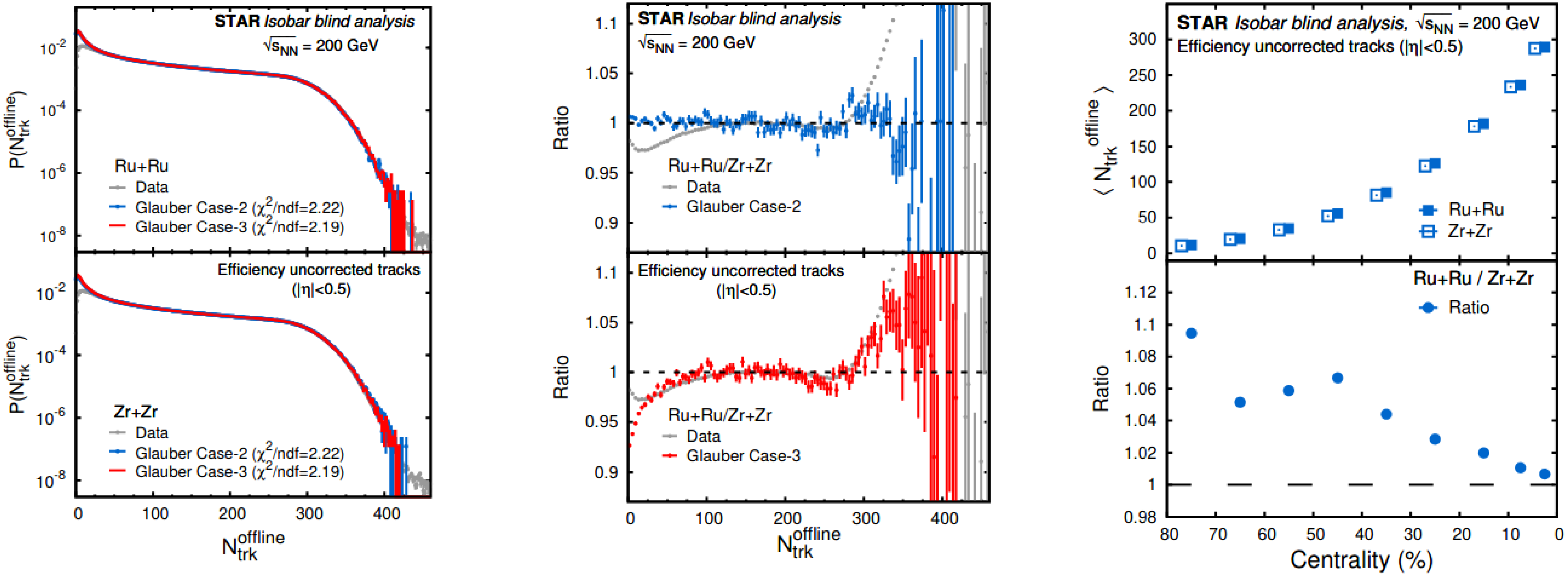
1. Alternate the isobar species between each store of beam in RHIC
2. Keep long stores with constant beam luminosity
3. Match luminosities between the species
4. Adjust the luminosity in such a way that the hadronic interaction rate at STAR is close to 10 kHz.

Precision target achieved:

A precision down to 0.4% is achieved, as anticipated, in the relative magnitudes of the pertinent observables between the two isobar systems

Search for the CME (Centrality)

arXiv:2109.00131



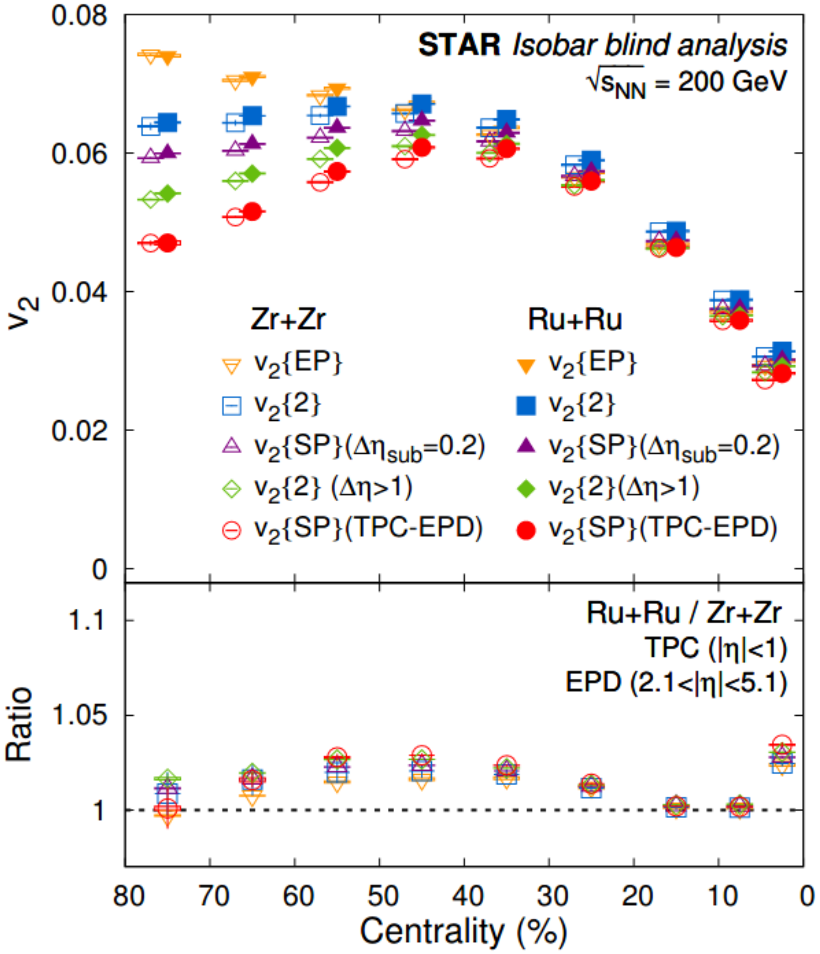
- The 3 sets of Woods-Saxon parameters from the literature have been studied
  - Fit to the multiplicity distributions using the two-component nucleon-based Monte Carlo Glauber
  - Best fit from Case-3: different neutron skin without quadrupole moments

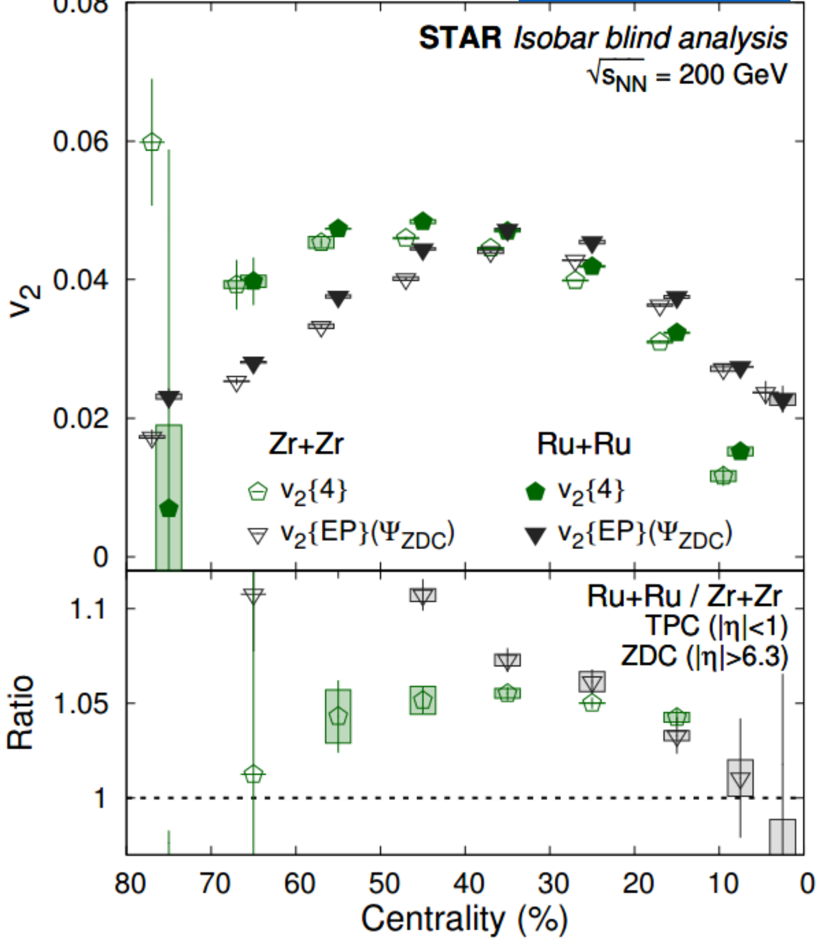
	Case-1 [83]			Case-2 [83]			Case-3 [113]		
Nucleus	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158	5.085	0.46	0.053	5.067	0.500	0
$^{96}_{40}$Zr	5.02	0.46	0.08	5.02	0.46	0.217	4.965	0.556	0

- Result: difference in multiplicity at matching centrality

Search for the CME (Crosschecks)

arXiv:2109.00131

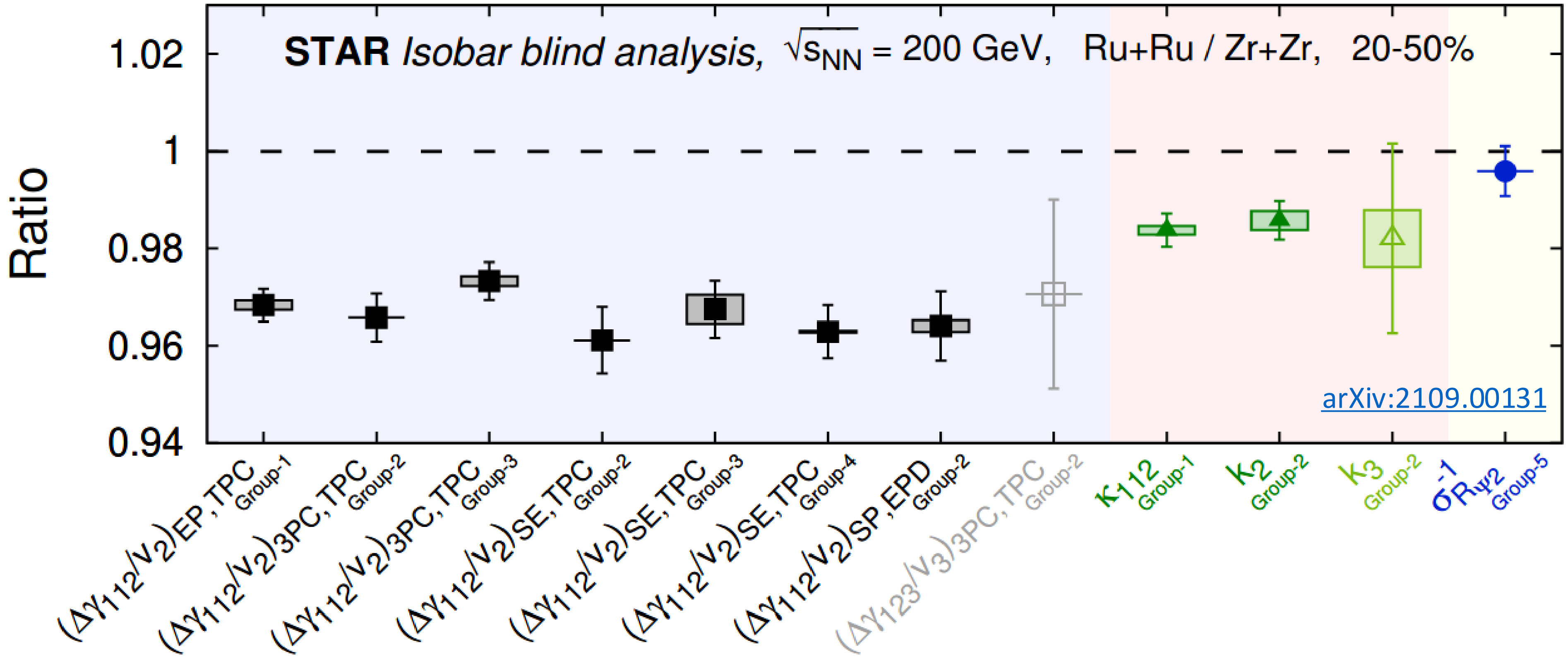




Observed differences in the multiplicity and flow harmonics at the matching centrality suggest that the magnitude of the CME background is different between the two species

Search for the CME (Results)

Predefined CME signatures: ratios involving Ψ_2 > those involving Ψ_3 , and > 1



Not Seen

No CME signature that satisfies the predefined criteria observed

Note: other measurements in paper that I don't have time to show in this talk (spectator-participant analysis for CME signal fraction, Δη dependence of correlations, …): All come to this conclusion