Supported in part by U.S. DEPARTMENT OF ENERGY

Results from the Beam Energy Scan program at STAR

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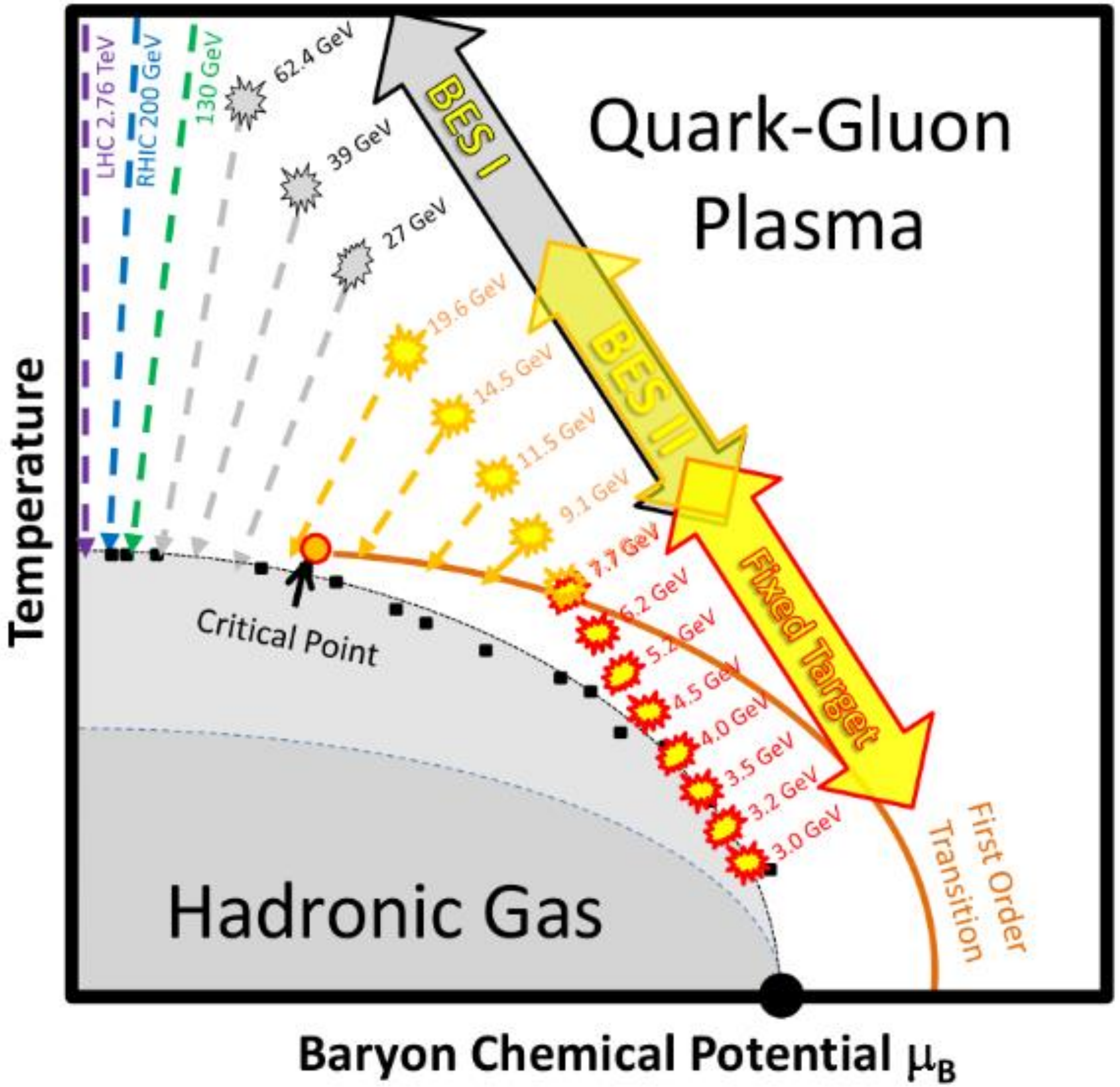
IV International Scientific Forum “Nuclear science and Technologies”
Almaty, Republic of Kazakhstan

Outline

- Introduction
- The STAR experiment
- Searches for the 1st-order phase transition
- Femtoscopic measurements
- Global hyperon polarization
- Particle production at 3 GeV
- Summary

STAR ☆ BES-I -> BES-II and FXT

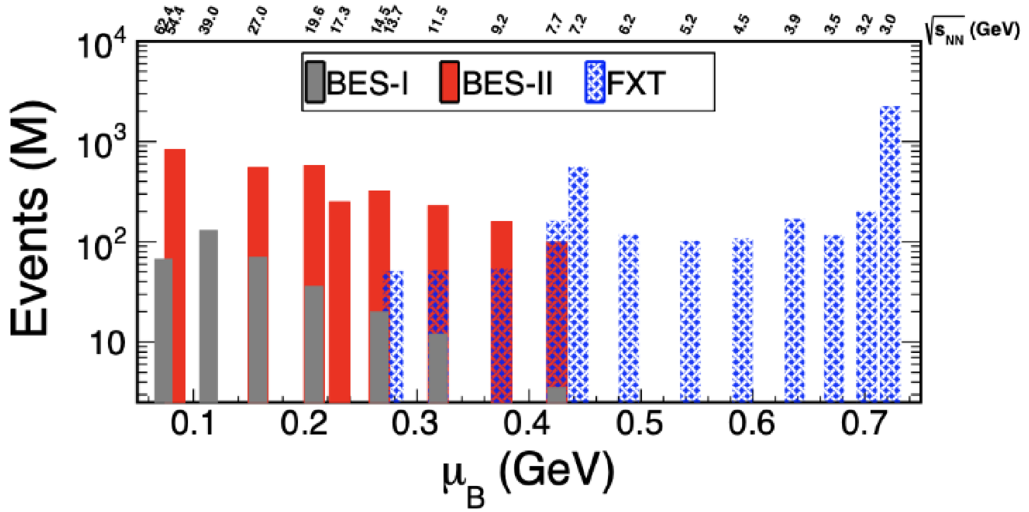


BES-I:

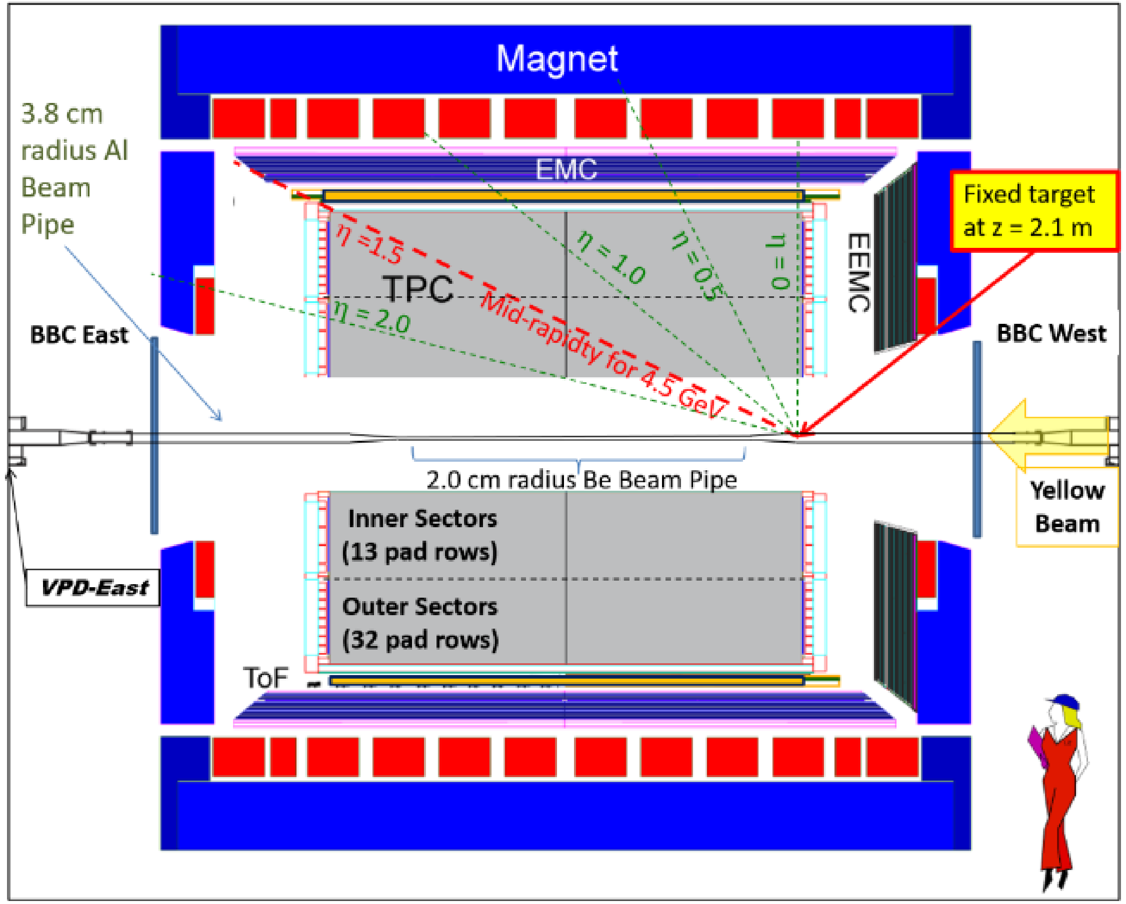
- Search for the QGP turn-off signatures
- Search for the first-order phase transition
- Search for the critical point

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

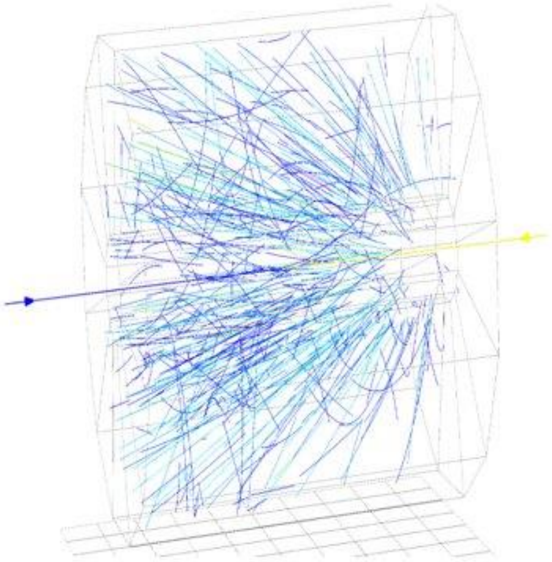
- Need higher statistics (≥10 times than in BES-I) for precise measurements
- Detector upgrades (increased acceptance and PID capabilities)
- Access to energies $\sqrt{s_{NN}}$<7.7 GeV via FXT

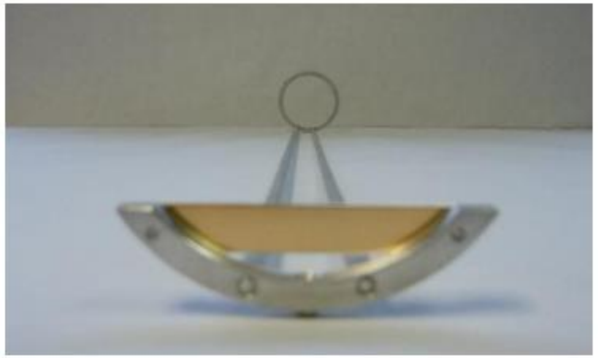


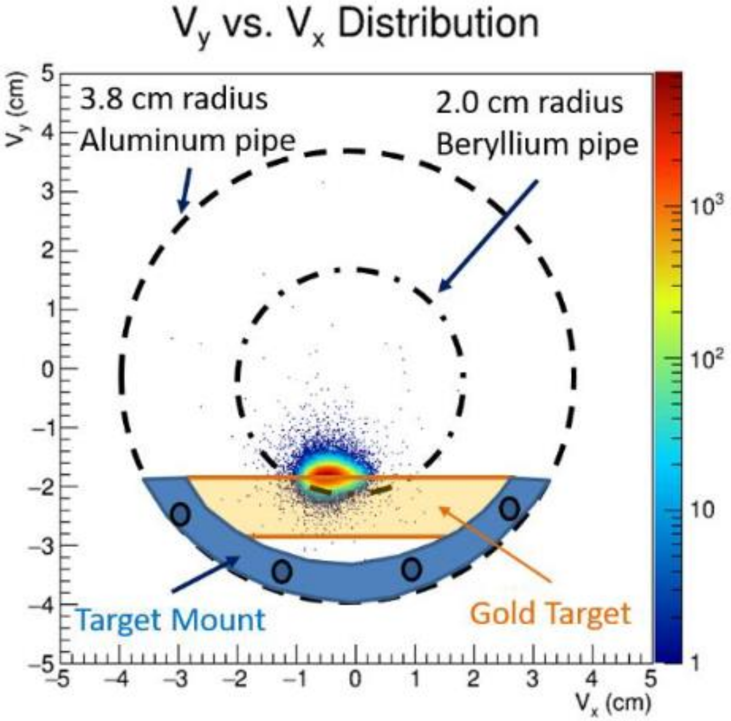
The STAR Experiment at RHIC



$$\eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}| + p_L}{|\mathbf{p}| - p_L}\right)$$



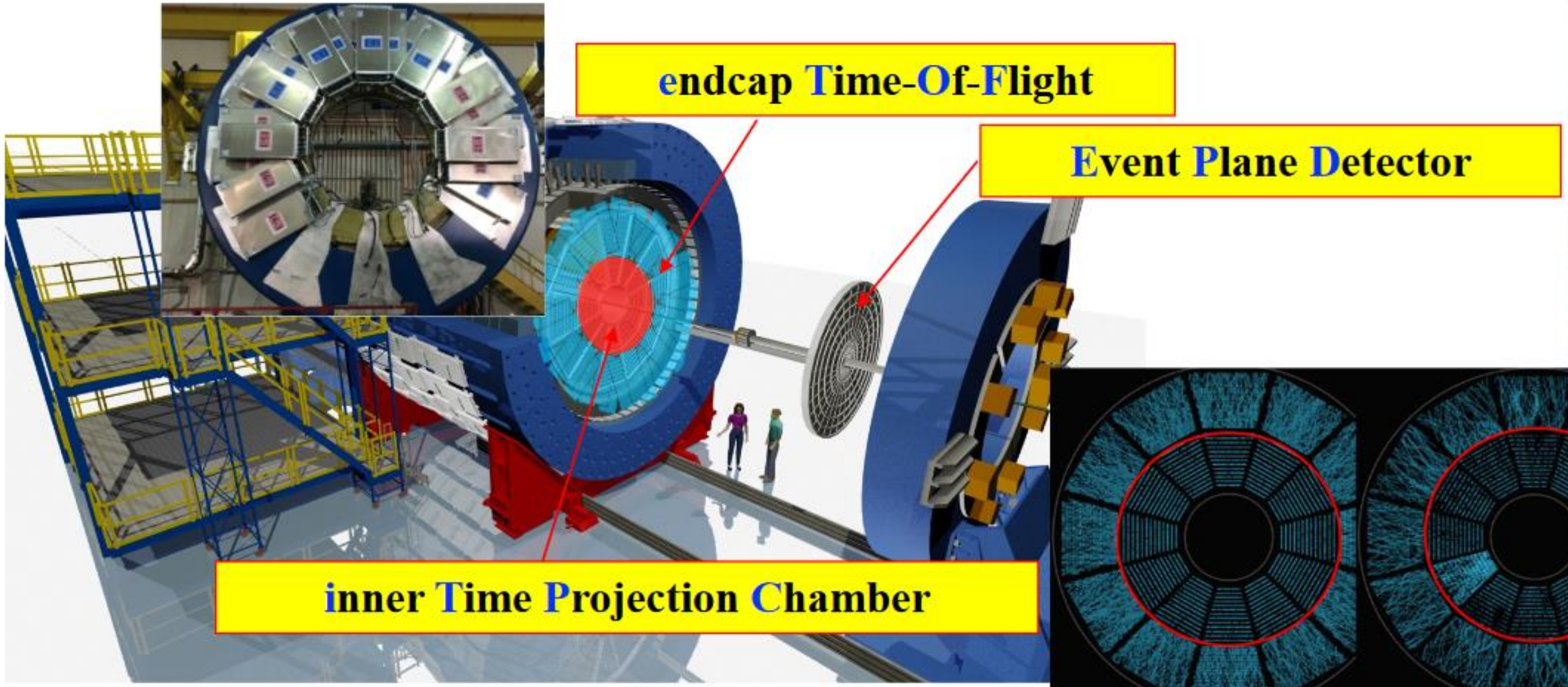


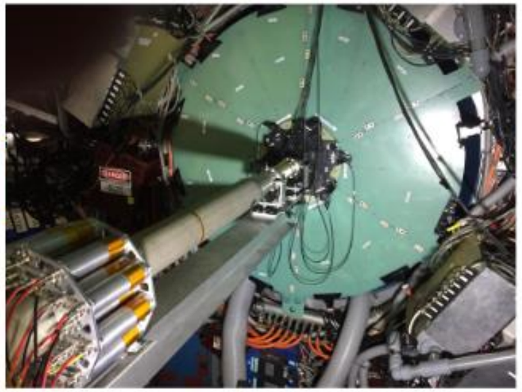


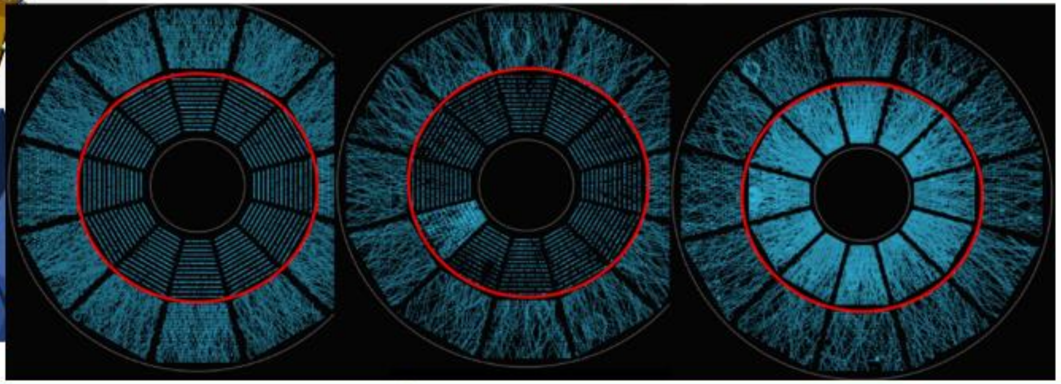
Gold target:

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

STAR ☆ Experimental Setup







iTPC upgrade	EPD upgrade	eTOF upgrade
|η|<1.5	**2.1<|η|<5.1**	**-1.6<η<-1.1**
p_T >60 MeV/c	Better trigger & b/g reduction	Extend forward PID capability
Better dE/dx resolution Better momentum resolution	Greatly improved Event Plane info (esp. 1st-order EP)	Allows higher energy range of Fixed Target program
Fully operational in 2019	**Fully operational in 2018**	**Fully operational in 2019**

STAR ☆

Recent BES-II, FXT and 200 GeV datasets (years 2018-2021)

$\sqrt{s_{NN}}$ (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

BES-I (years 2010, 2011, 2014)

$\sqrt{s_{NN}}$ (GeV)	No. of events (million)
7.7	4
11.5	8
19.6	17.3
27	33
39	111

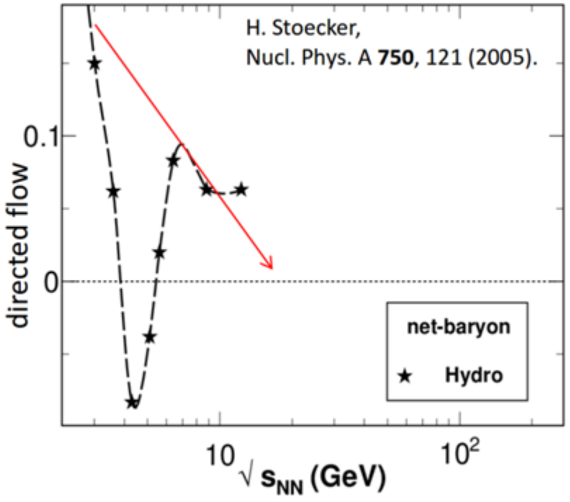
STAR ☆ Searches for the First-order Phase Transition

- Softening of the EoS
  - Could be observed in the dv_1/dy slope
  - Strong softening: consistent with the 1st-order phase transition
  - Weaker softening: likely due to crossover

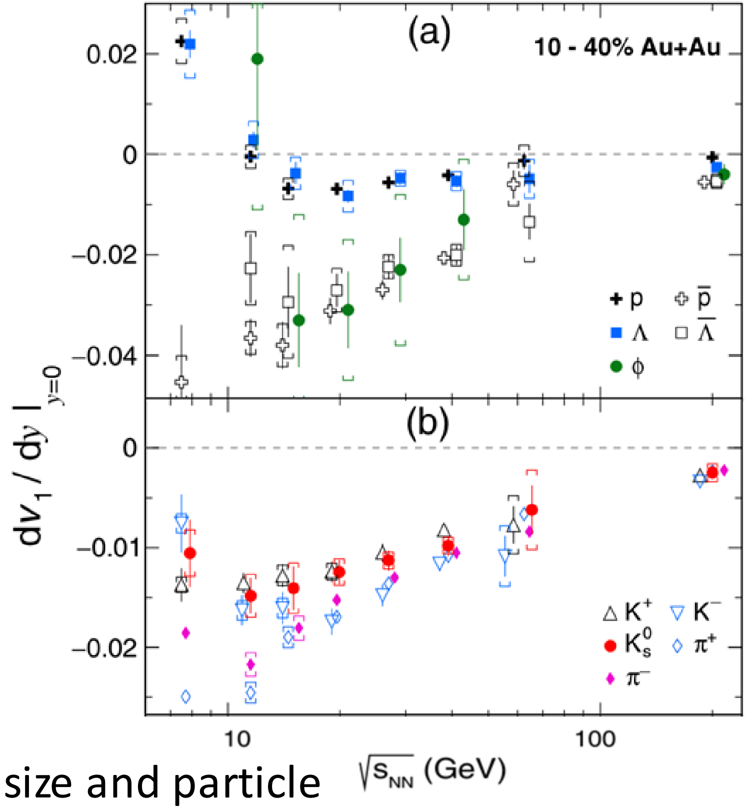
$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\phi-\Psi_r)]\right)$$

$v_1=\langle p_x/p_t\rangle$

ϕ is the azimuthal angle of a produced particle

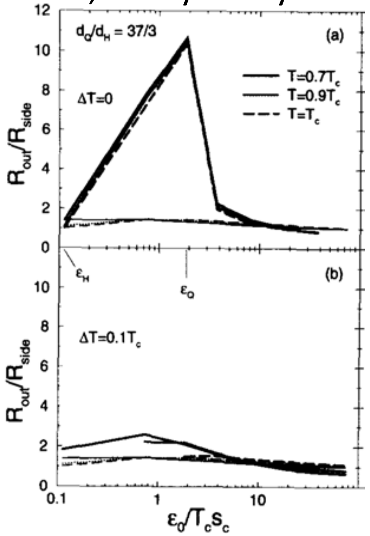


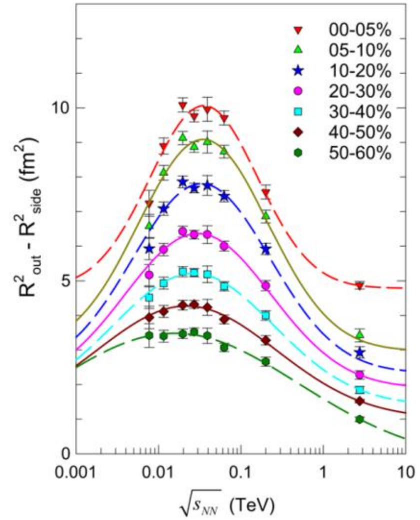
STAR. PRL 120, 062301(2018)



- Time delays of the particle emission
  - Could be observed using femtoscopy technique (via R_{out}/R_{side} or R_{out}^2-R_{side}^2)

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



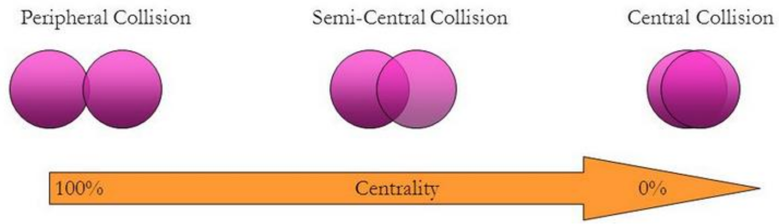


R. Lacey. PRL 114 142301(2015)

R_{side} – geometrical size

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

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



STAR ☆ # Correlation Femtoscopy

$$q_{inv} = \sqrt{(\vec{p_1} - \vec{p_2})^2 - (E_1 - E_2)^2}$$

- Two-particle correlation function (CF):

$$CF(\vec{p}_1, \vec{p}_2) = \int d^3\vec{r}\, S(\vec{r}, \vec{k})\, |\Psi_{1,2}(\vec{r}, \vec{k})|^2$$

$$\vec{r} = \vec{x}_1 - \vec{x}_2 \text{ and } \vec{q} \equiv \vec{p}_1 - \vec{p}_2$$

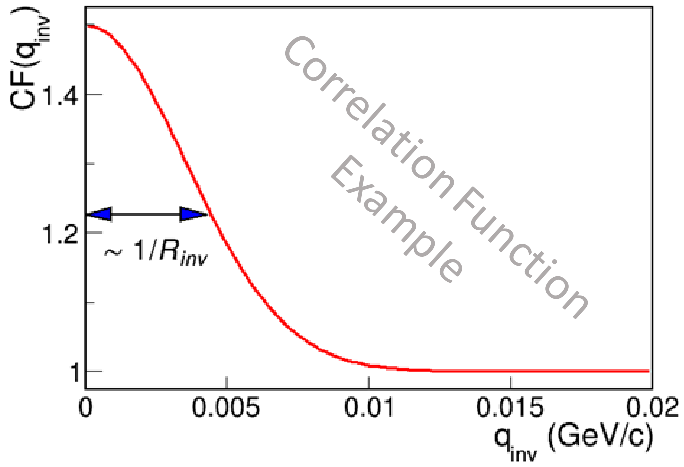
$S(\vec{r}, \vec{k})$ - source function

$\Psi_{1,2}(\vec{r}, \vec{k})$ - wave function of a pair, includes QS and FSI

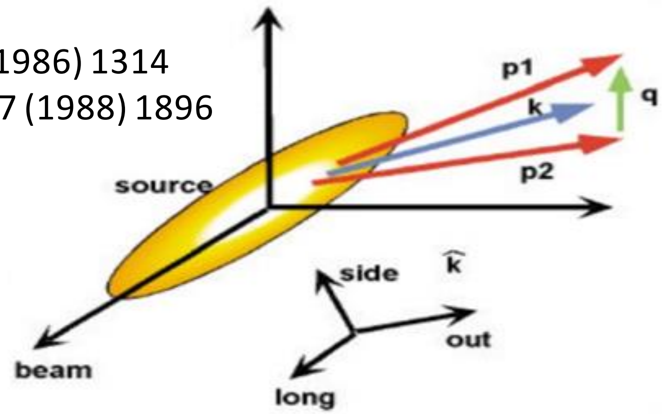
- Experimentally:

$$CF(\vec{q}) = A(\vec{q})/B(\vec{q})$$

  - $A(\vec{q})$ – contain quantum statistical (QS) correlations and final state interactions (FSI)
  - $B(\vec{q})$ – obtained via mixing technique (does not contain QS and FSI)



S. Pratt. PRD 33 (1986) 1314
G. Bertsch. PRC 37 (1988) 1896



The relative pair momentum can be projected onto the Bertsch-Pratt, out-side-long system:

q_{long} – along the beam direction

q_{out} – along the transverse momentum of the pair

q_{side} – perpendicular to longitudinal and outward directions

Correlation functions are constructed in Longitudinally Co-Moving System (LCMS), where $\vec{p}_{1z} + \vec{p}_{2z} = 0$

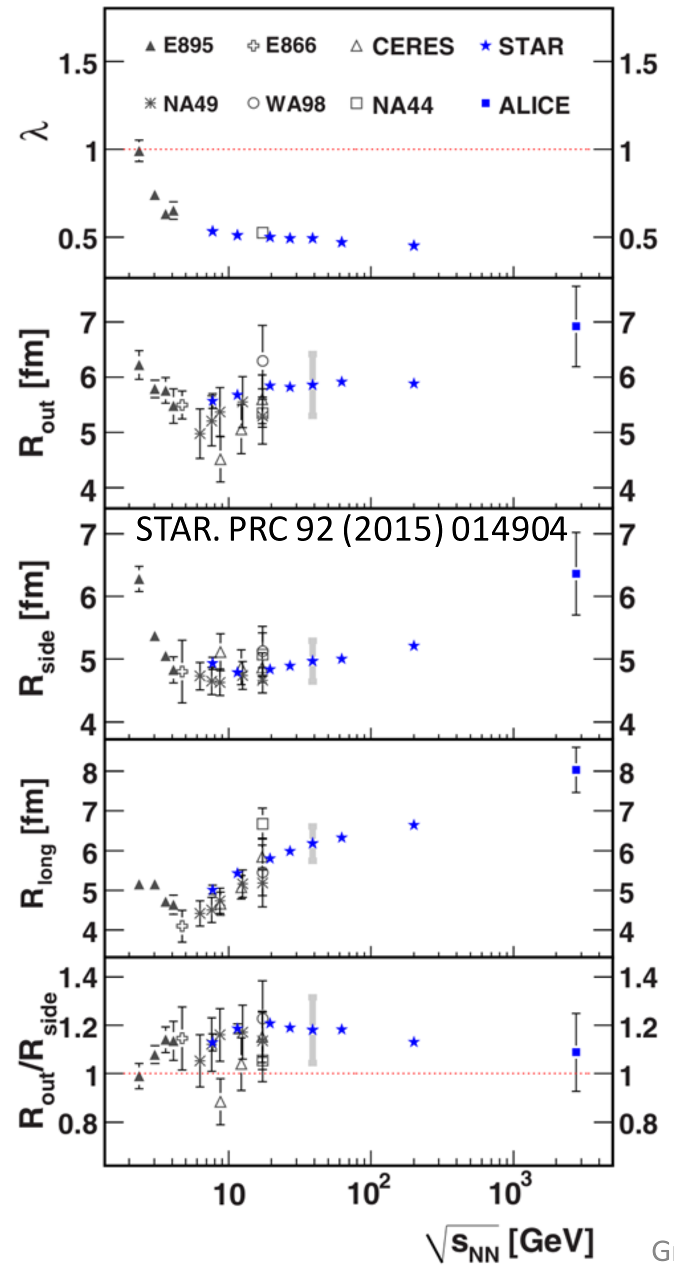
$$C(\mathbf{q}) = N\left[(1-\lambda) + \lambda K(q_{inv})\left(1 + \exp(-R^2_{out}q^2_{out} - R^2_{side}q^2_{side} - R^2_{long}q^2_{long})\right)\right]$$

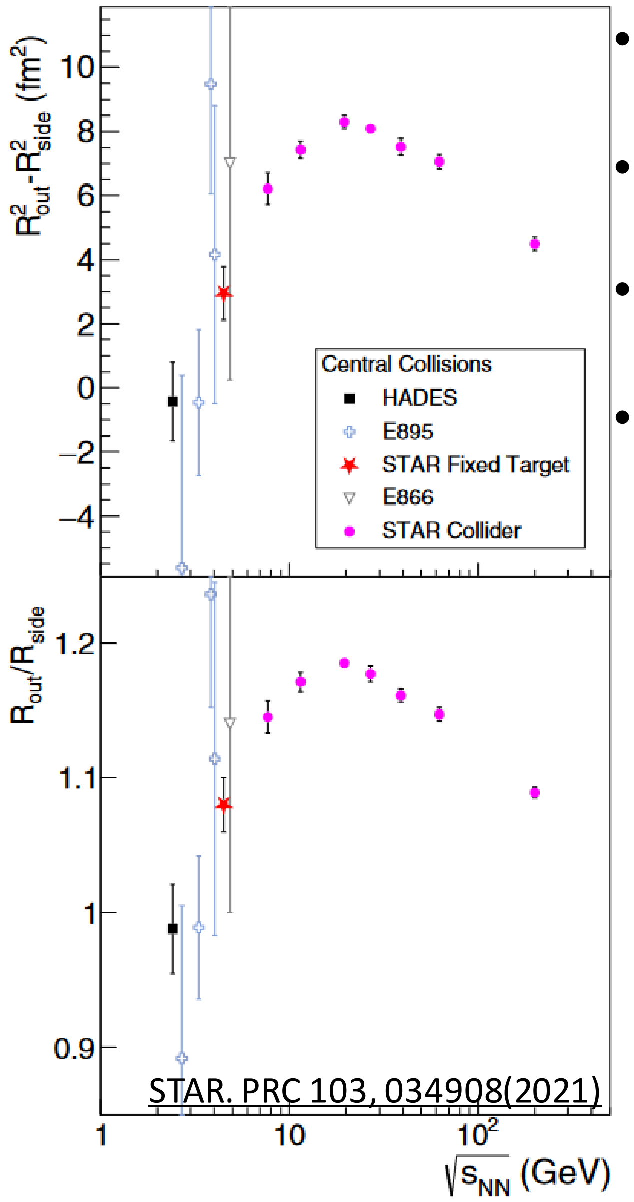
N - normalization factor,

λ - correlation strength,

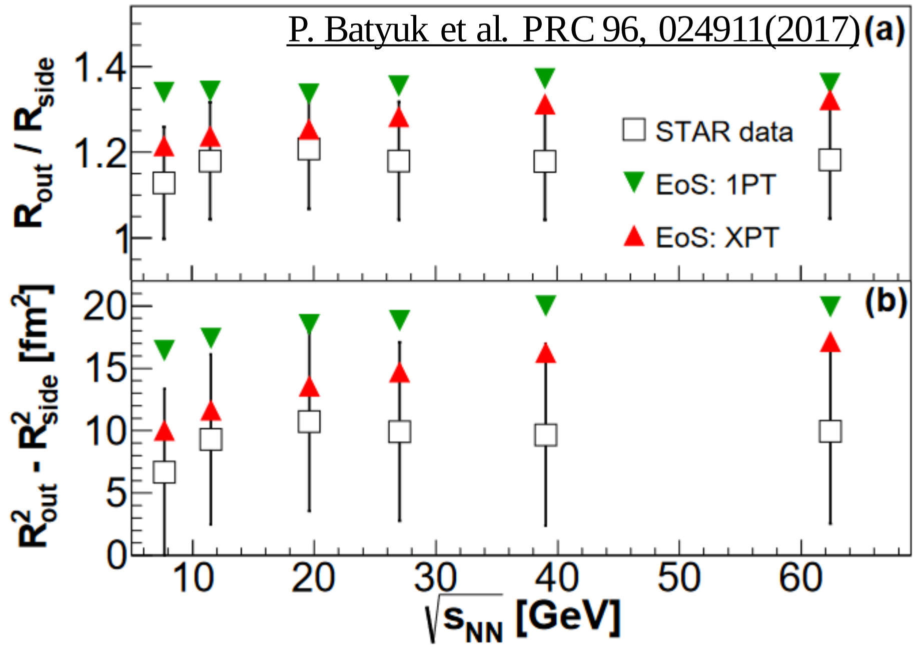
K(q) - Coulomb correction factor

Charged Pion Femtoscopy in Heavy-ion Collisions

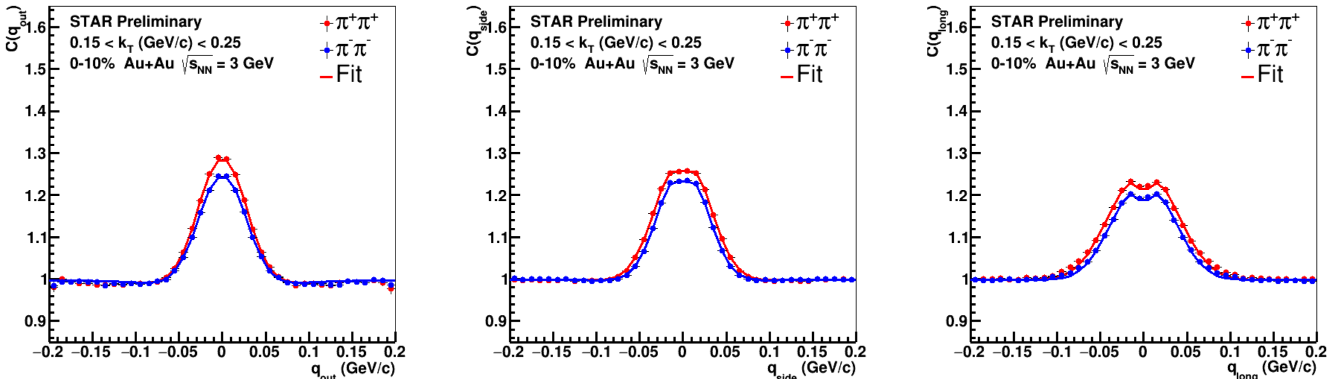


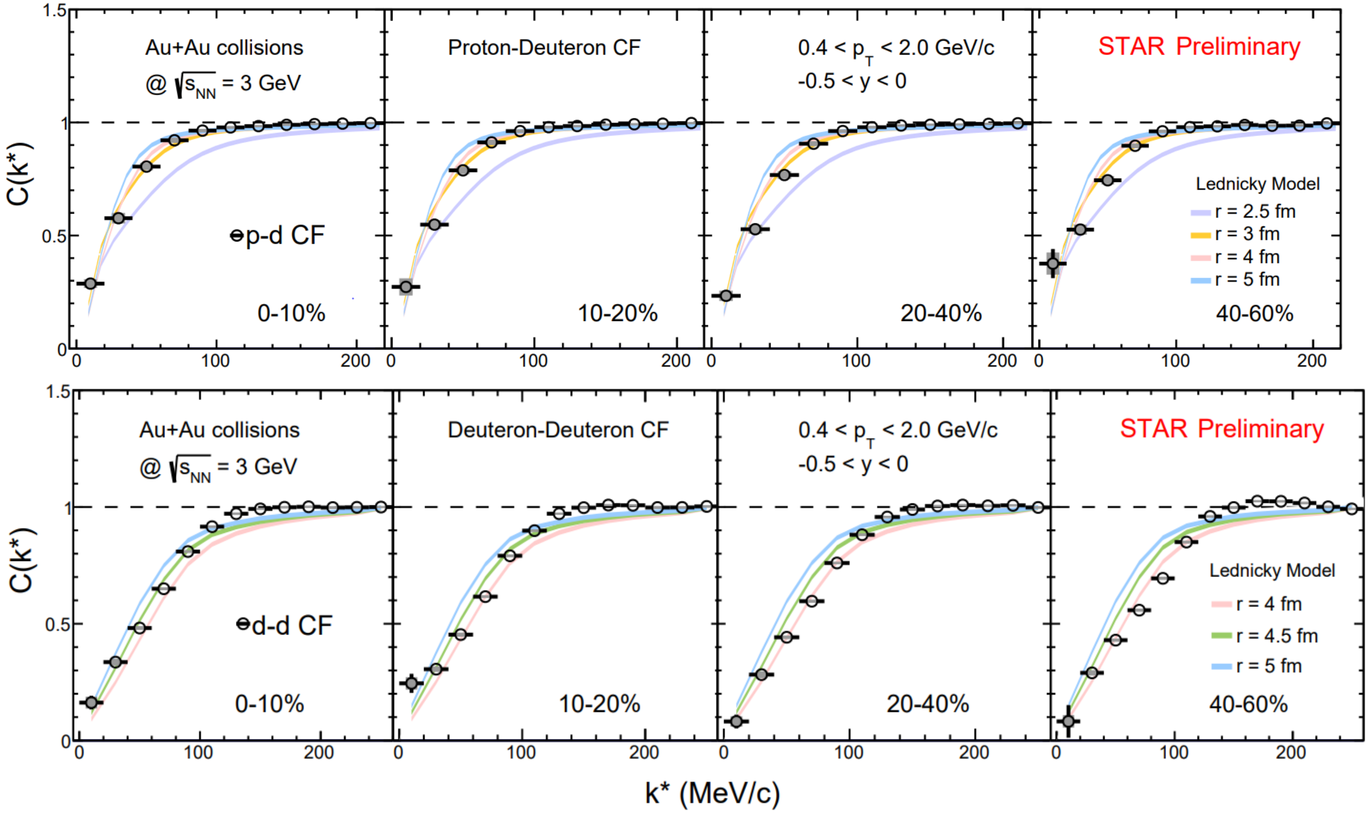


- Precise measurements in a broad energy range (from 2.41 GeV to 2.76 TeV)
- Can be reasonably described with hybrid models (initial conditions + hydrodynamics + hadron cascade)
- Need more high-statistics measurements at low energies
- Precise measurements exist only with pions
  - Need heavier particles (kaons, protons, etc.)

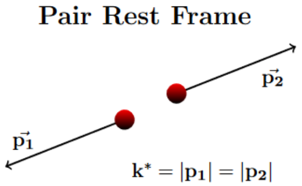


Femtoscopy Results from the FXT Program

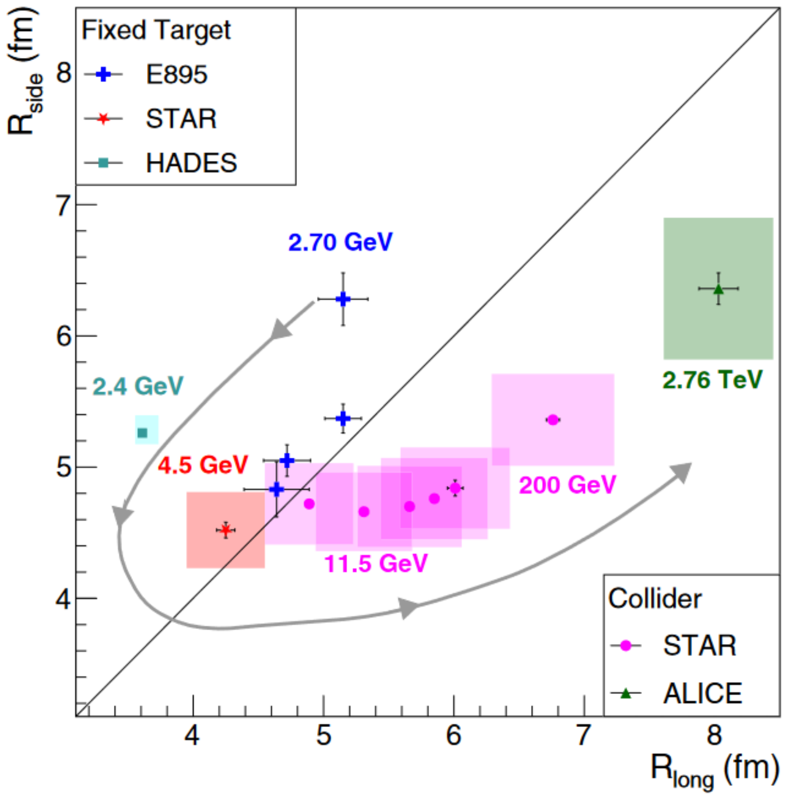




- Many interesting results from low-energy nuclear collisions: ππ, pp, pd, dd, and others
- Provide information about particle interactions
- The source shape evolves from oblate to prolate, as energy increases



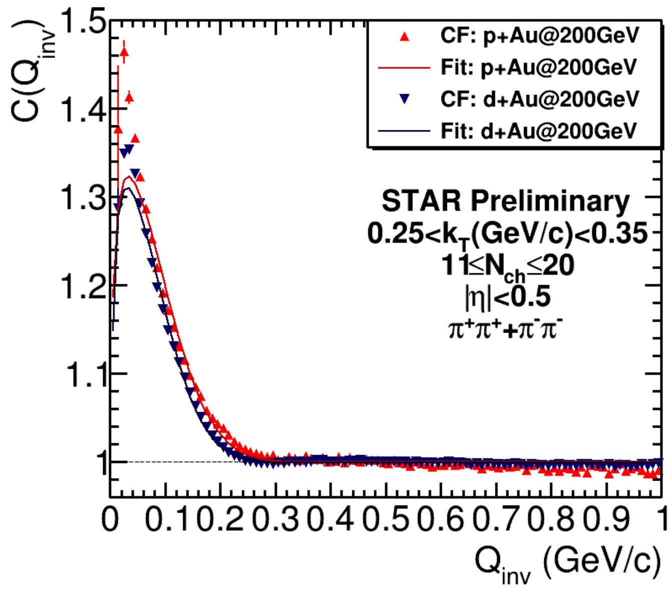
STAR. PRC 103, 034908(2021)

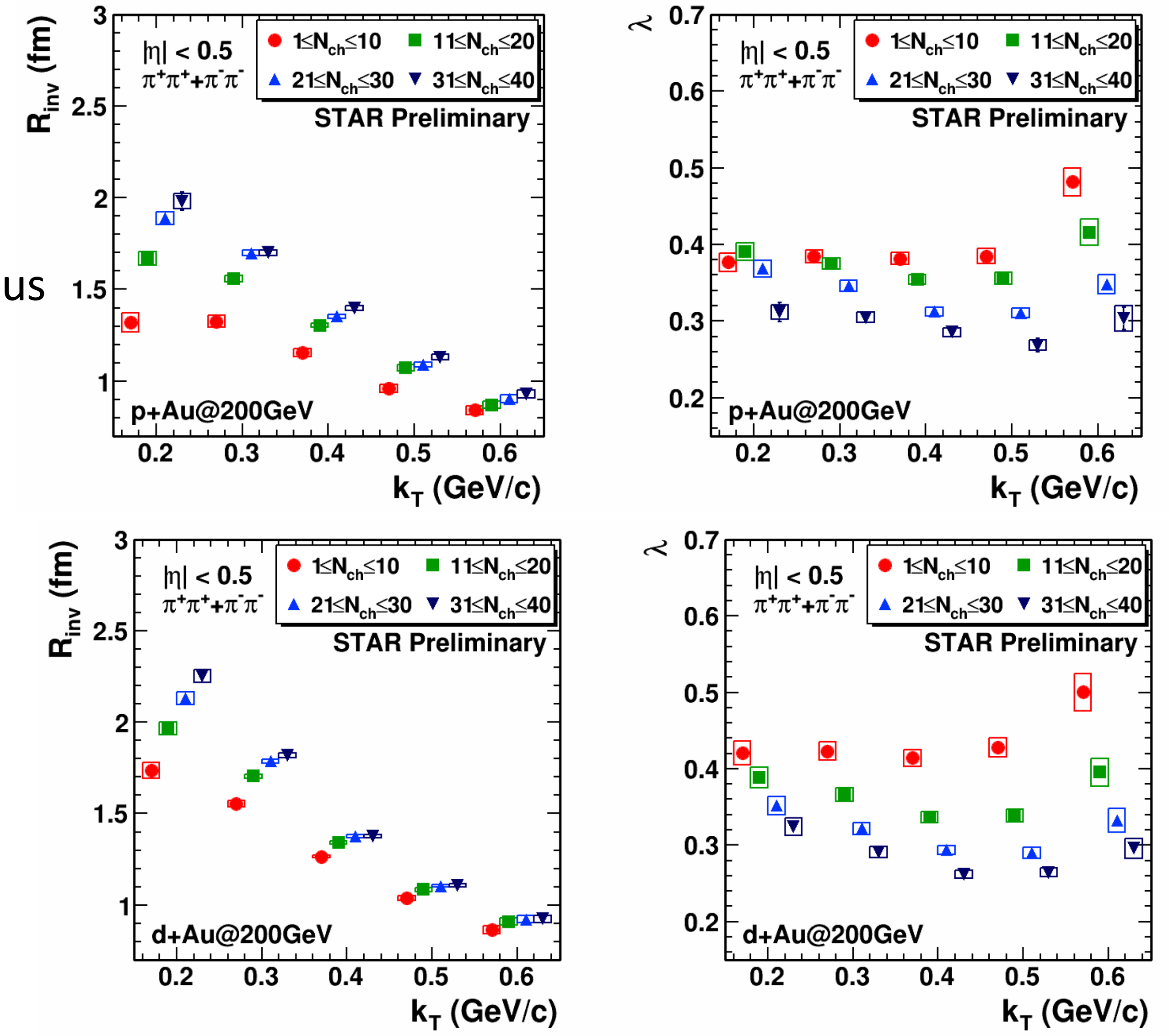


Femtoscopy in Small Collision Systems

$$k_T = |\vec{p}_{1T} + \vec{p}_{2T}|/2$$

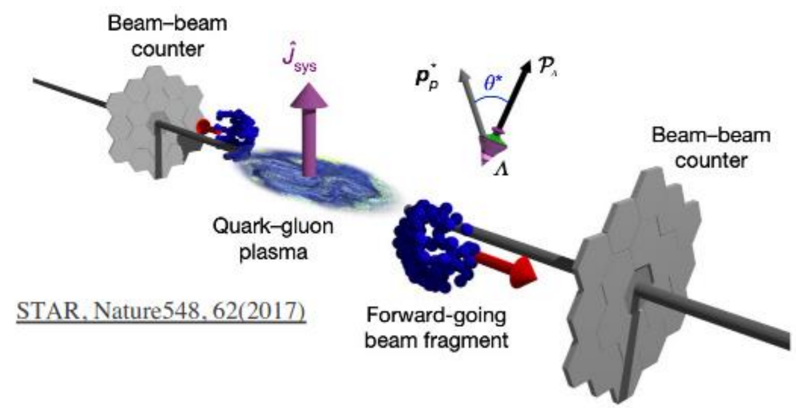
- RHIC provides opportunity to study various colliding species, including p+p, p+Al, p+Au, d+Au, ^{3}He+Au
- Unique opportunity to study collective behavior of particles produced in small collision systems via measurements of k_T dependence of femtoscopic radius
- Similar to heavy ion collisions, femtoscopic radii measured in small systems decrease with increasing pair transverse momentum (k_T)





STAR ☆ Global Polarization in BES and FXT

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:

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

Thermal vorticity:

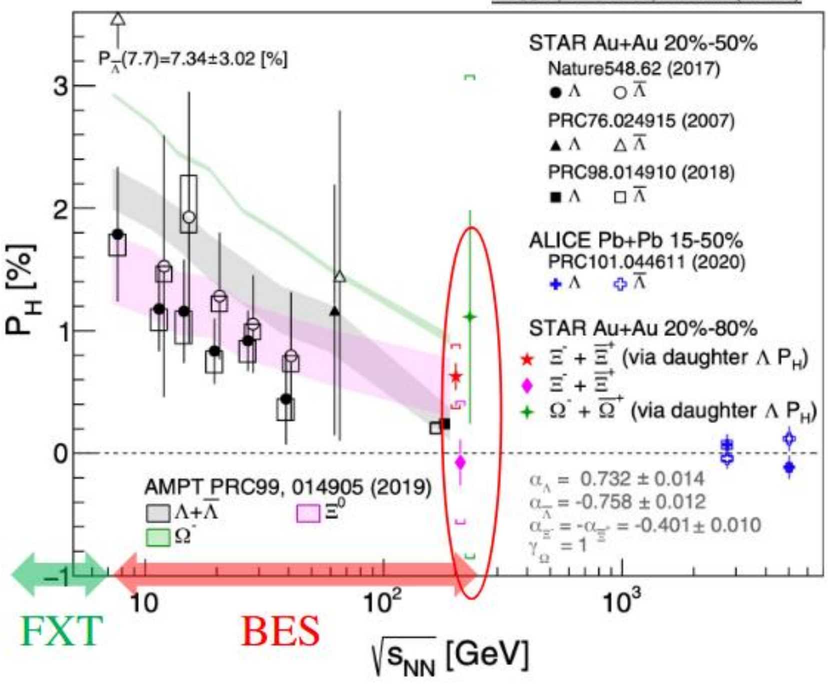
$$\omega = k_B T (P_\Lambda + P_{\bar{\Lambda}})/\hbar \qquad \omega \sim (9 \pm 1) \times 10^{21} s^{-1}$$

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

ϕ^*_d - azimuthal angle of daughter particle in the parent frame

α_H - hyperon decay parameter

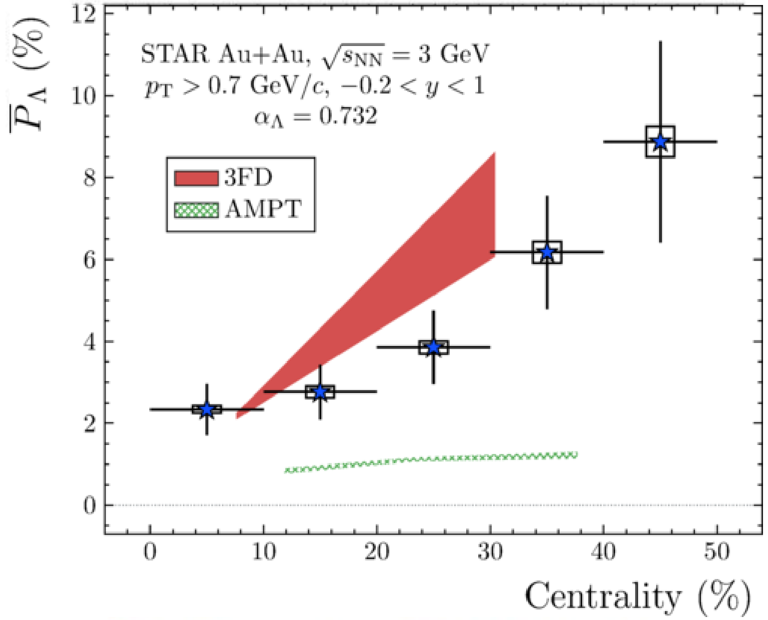
STAR, PRL126, 162301(2021)



Large angular momentum transferred by the two colliding nuclei

Stronger polarization at lower collision energies.

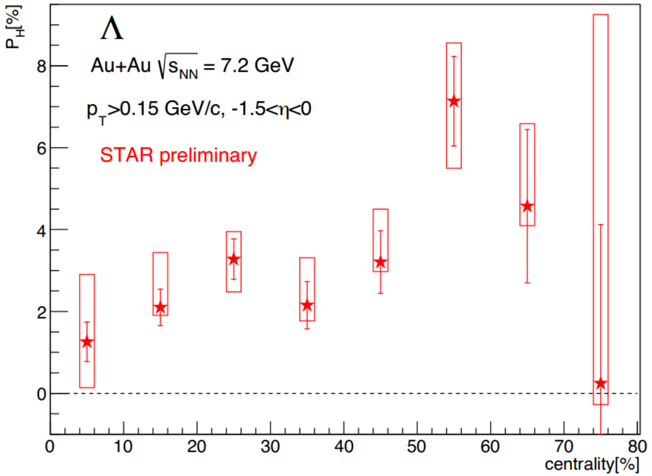
STAR, PRC104, L061901(2021)



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

4.91 ± 0.81 (stat.) ± 0.15 (syst.)%

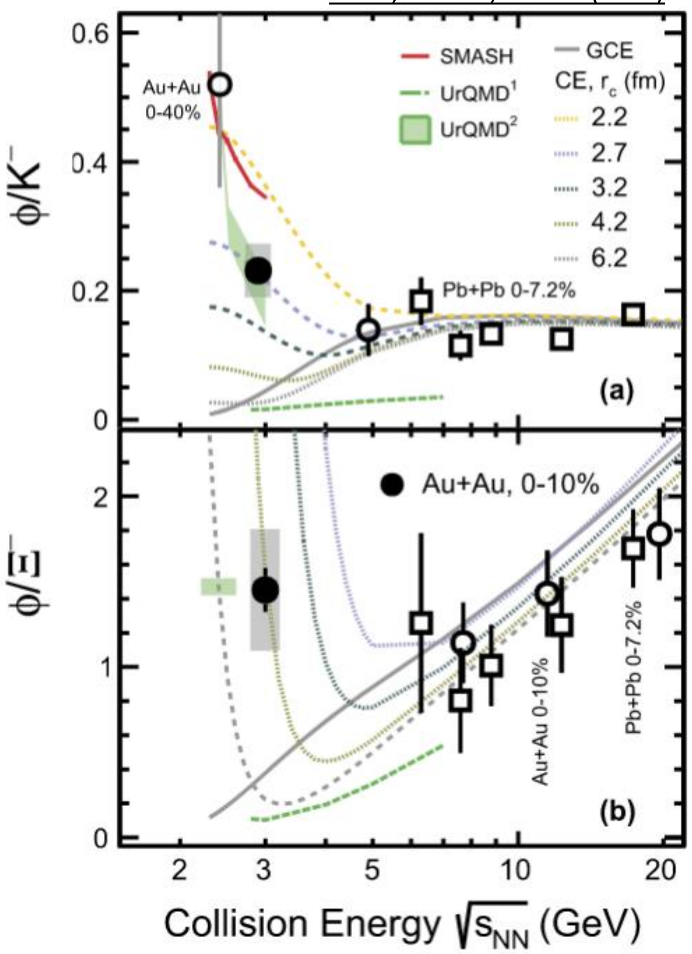
Larger hyperon polarization for more peripheral collisions



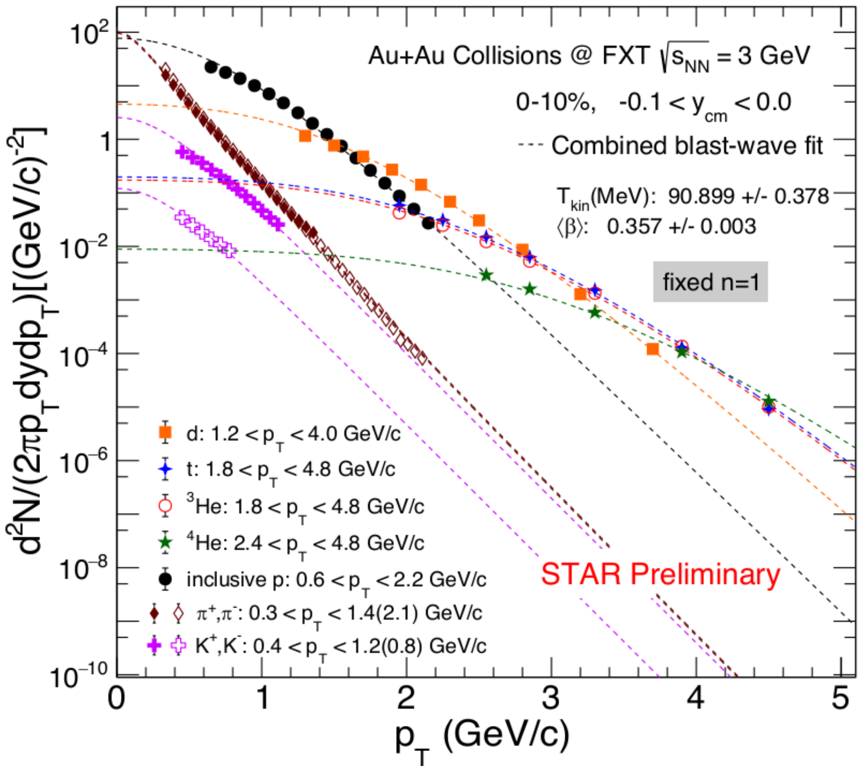
Opens up new directions in the study of the hottest, least viscous and most vortical fluid matter.

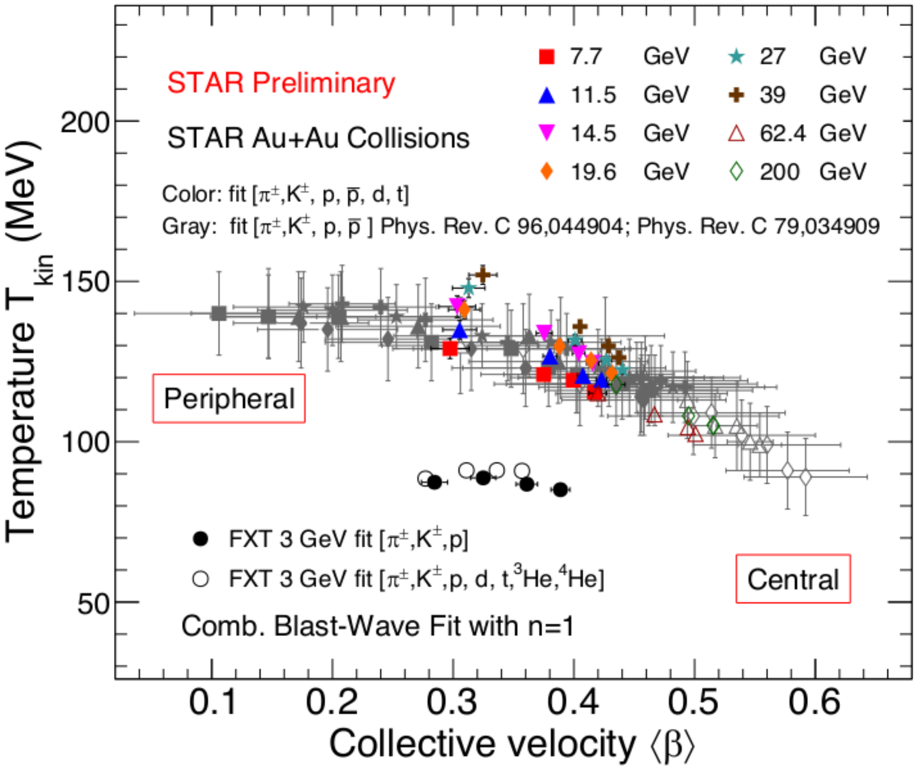
STAR ☆ Particle Production at 3 GeV

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?

Summary

- BES-II detector upgrades performing at or above expectation
- All requested 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
- Exciting correlation femtoscopy program
  - Measurement of the spatial and temporal properties of particle emission process as a function of collision energy
  - Search for the first-order phase transition (identical pions, kaons and (anti)protons)
  - Measurement of the final state interaction between particles (kaons, protons, light ions and others)
  - Collectivity in small collision systems