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Femtoscopic probes in collisions of small and large systems from STAR

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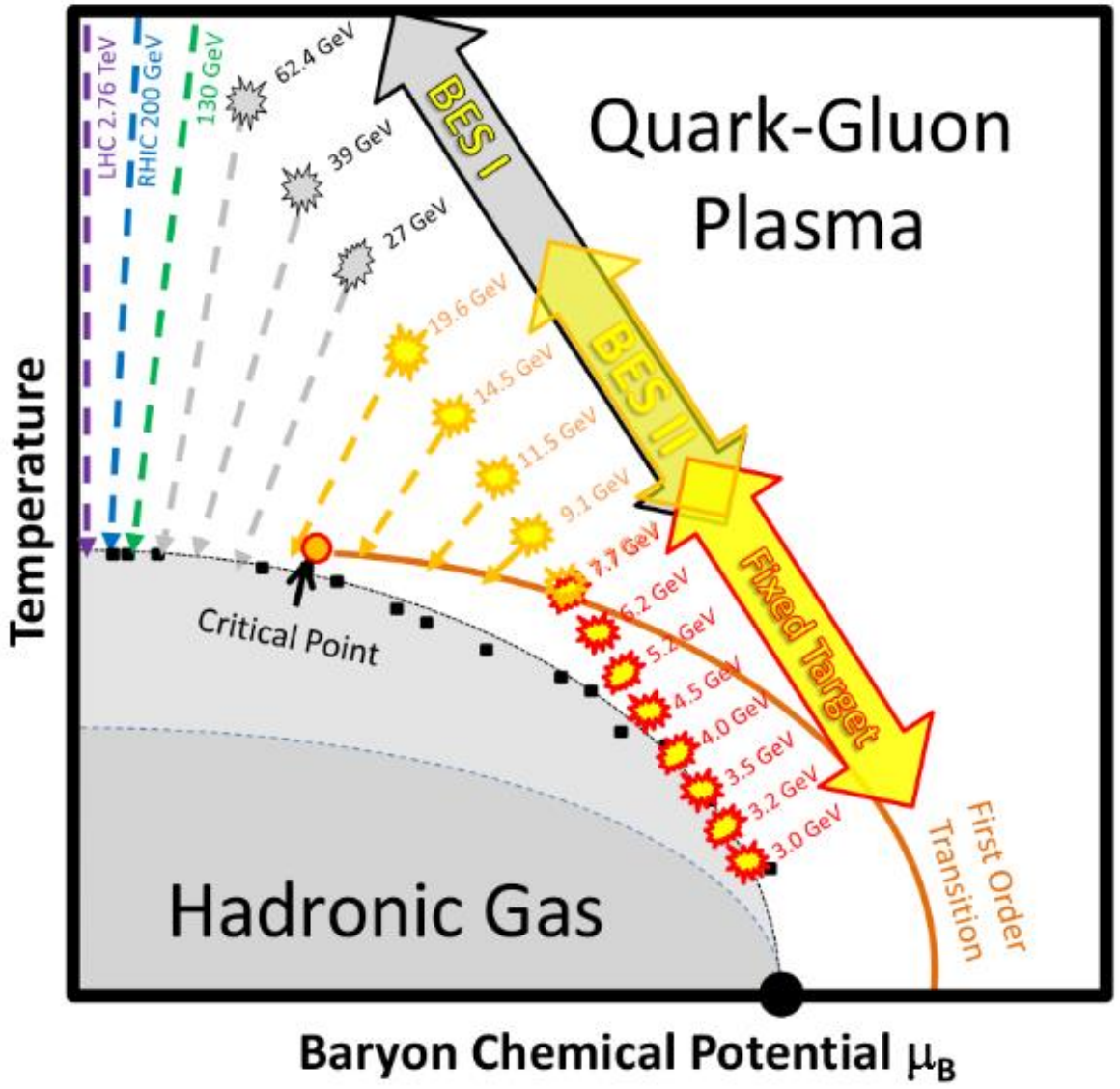
LXXII International Conference "Nucleus-2022: Fundamental problems and applications"

STAR ☆ BES-I -> BES-II and FXT

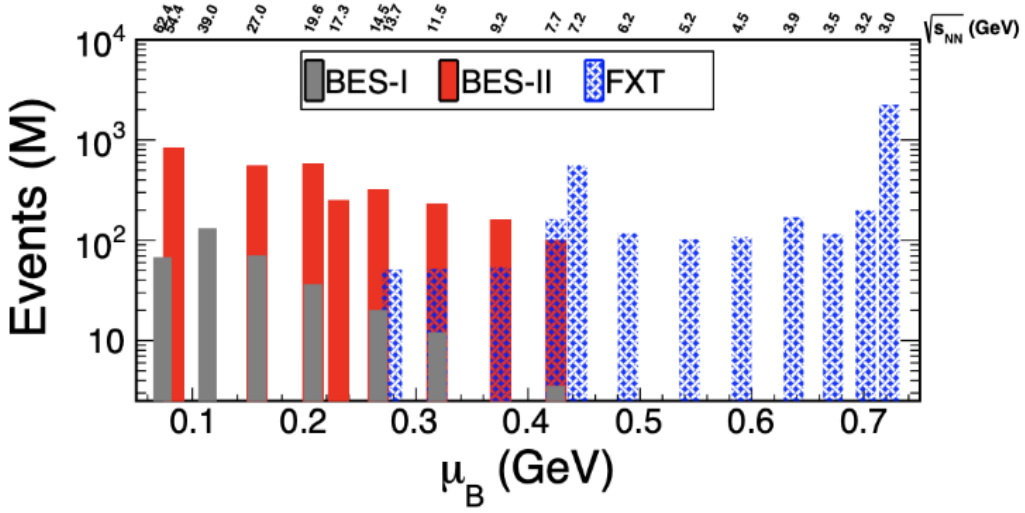


BES-I:

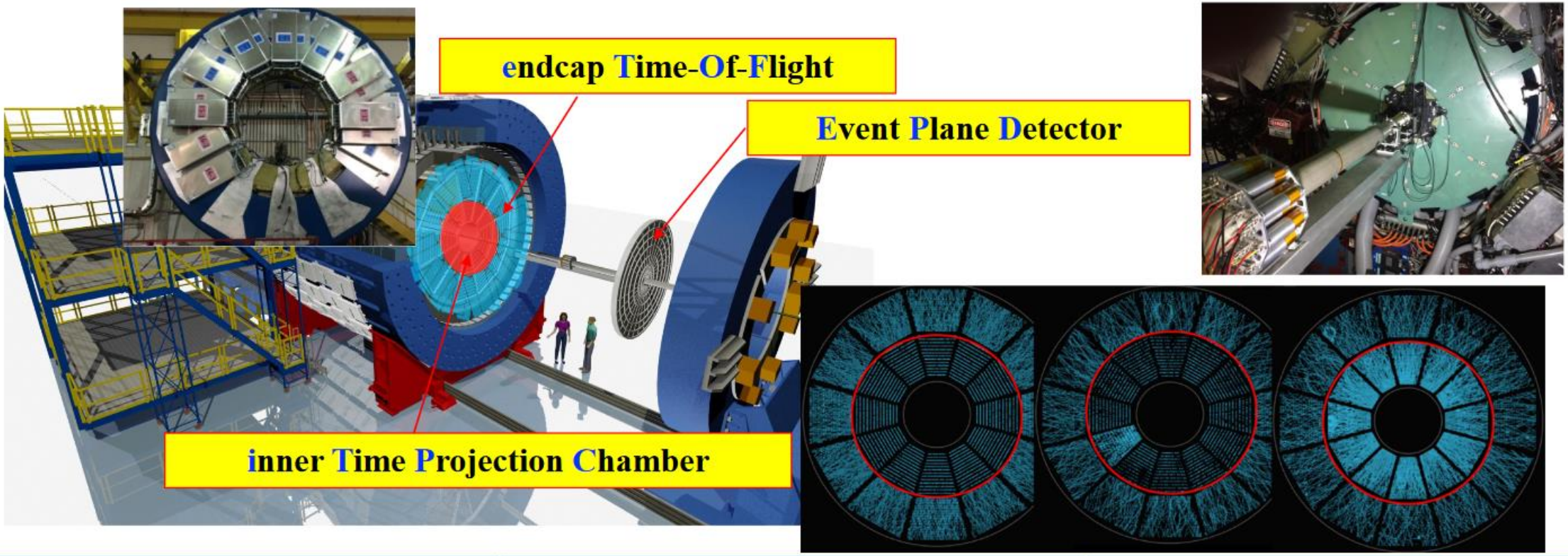
- Search for the QGP turn-off signatures
- Search for the first-order phase transition
- Search for the critical point

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

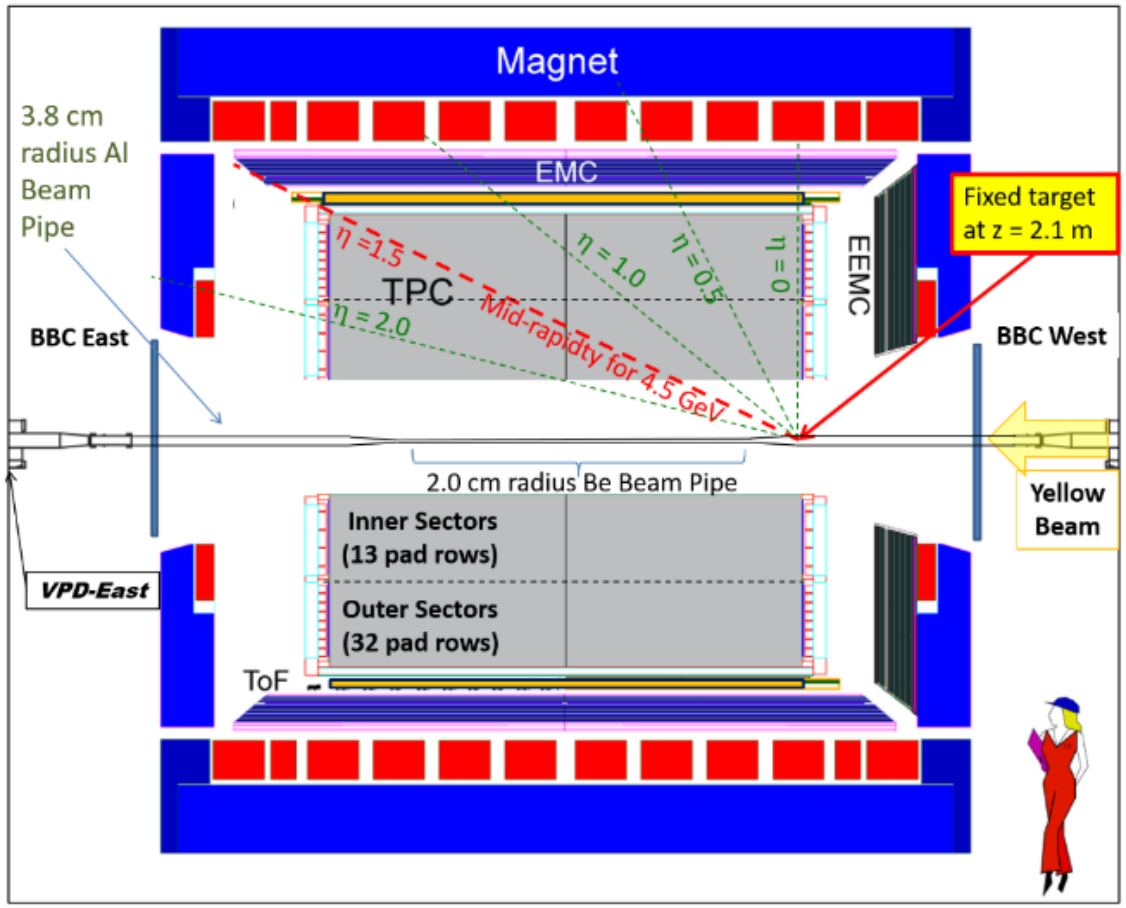


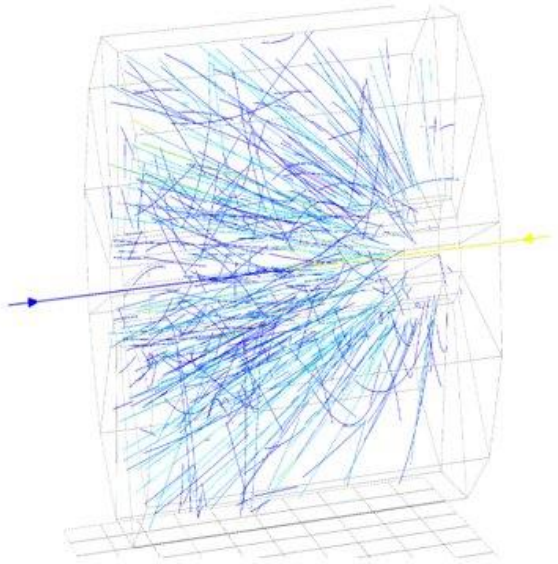
STAR ☆ Experimental Setup

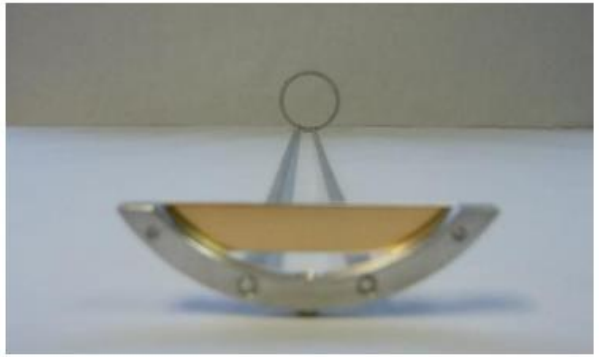


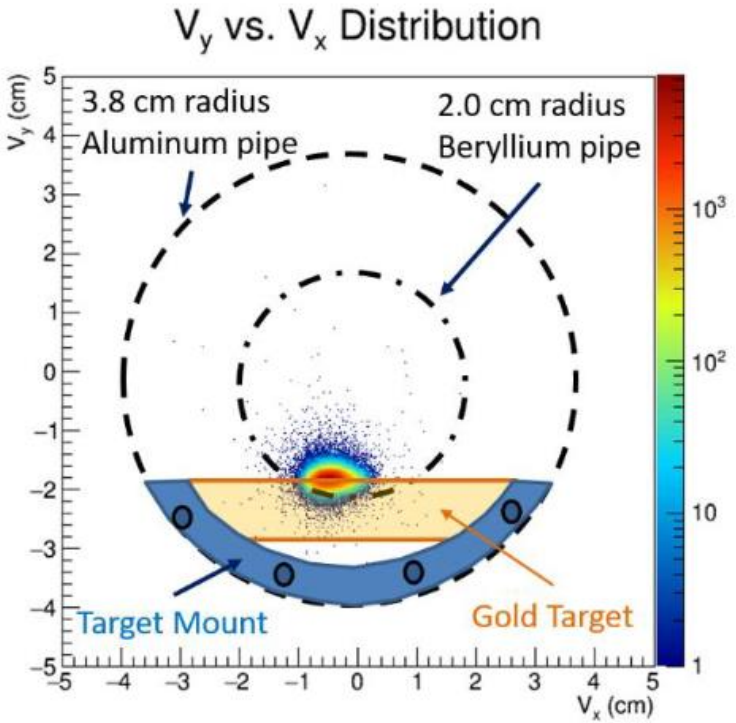
iTPC upgrade	EPD upgrade	eTOF upgrade
$\|\eta\|<1.5$	$2.1<\|\eta\|<5.1$	$-1.6<\eta<-1.1$
p_T >60 MeV/c	Better trigger & b/g reduction	Extend forward PID capability
Better dE/dx resolution Better momentum resolution	Greatly improved Event Plane info (esp. 1st-order EP)	Allows higher energy range of Fixed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

Fixed-target (FXT) Setup in STAR









Gold target:

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

STAR ☆

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

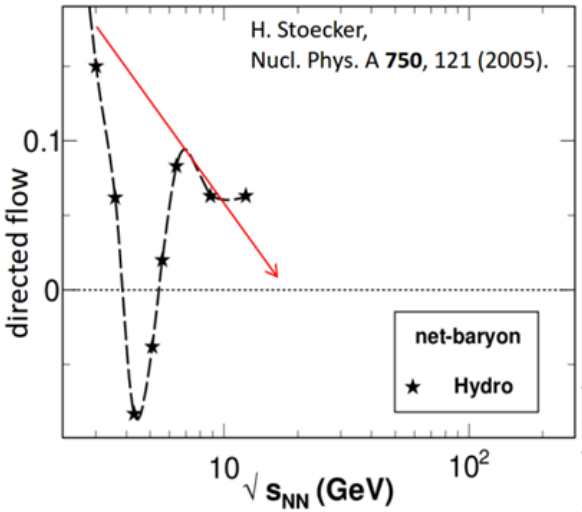
BES-I (years 2010, 2011, 2014)

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

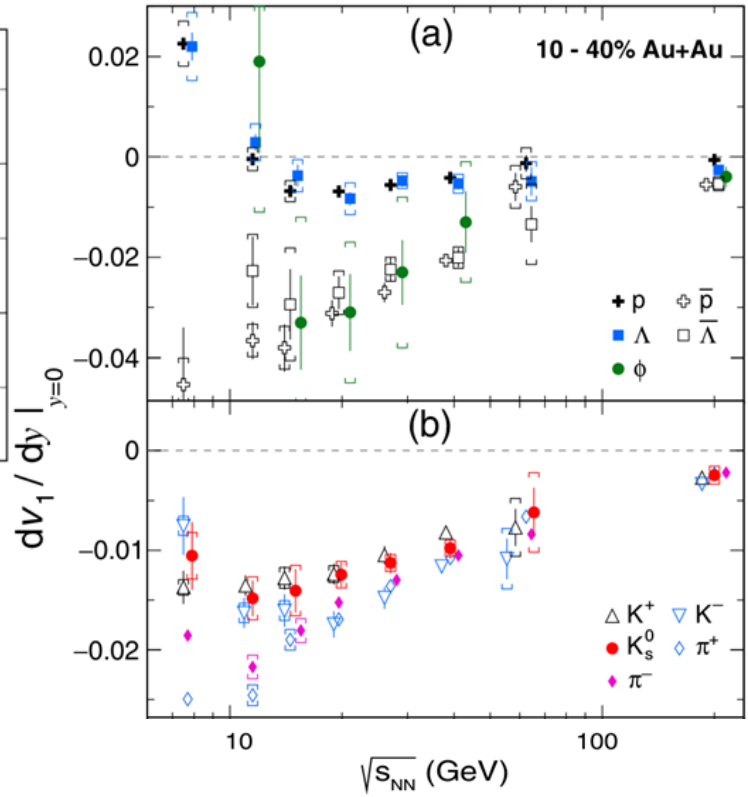
$\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV/nucleon)	Collider or Fixed Target	$y_{center\ of\ mass}$	μ_B (MeV)	Run Time (days)	No. Events Collected (Request)	Date Collected
200	100	C	0	25	2.0	138 M (140 M)	Run-19
27	13.5	C	0	156	24	555 M (700 M)	Run-18
19.6	9.8	C	0	206	36	582 M (400 M)	Run-19
17.3	8.65	C	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

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

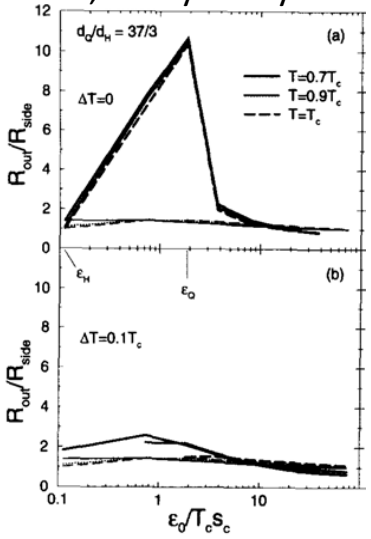


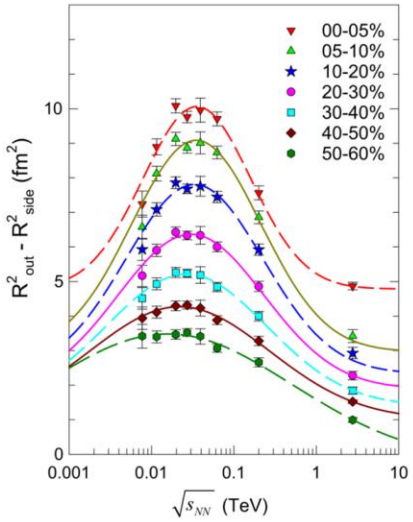
STAR. PRL 120 (2018) 062301



- 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





Lacey. PRL 114 (2015) 142301

STAR ☆ Correlation Femtoscopy

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

- Two-particle correlation function (CF):

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

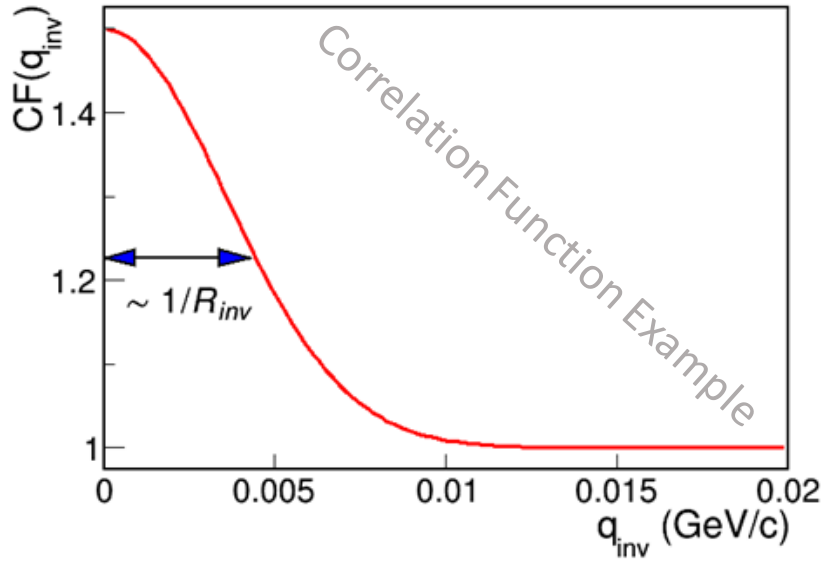
$$\vec{r} = \vec{x}_1 - \vec{x}_2 \text{ and } \vec{q} \equiv \vec{p}_1 - \vec{p}_2$$

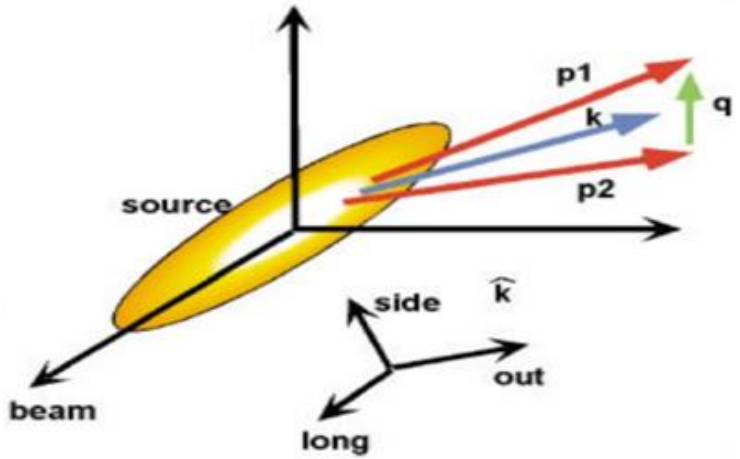
- Experimentally:

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

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

$S(\vec{r}, \vec{k})$ - source function
$\Psi_{1,2}(\vec{r}, \vec{k})$ - wave function of a pair





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

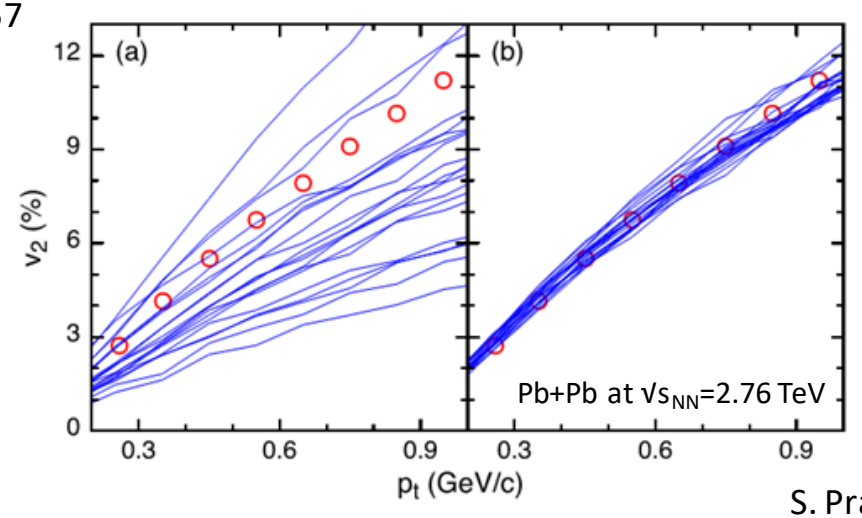
Correlation functions are constructed in Longitudinally Co-Moving System (LCMS), where $\vec{p}_{1z} + \vec{p}_{2z} = 0$

Why Correlation Femtoscopy?

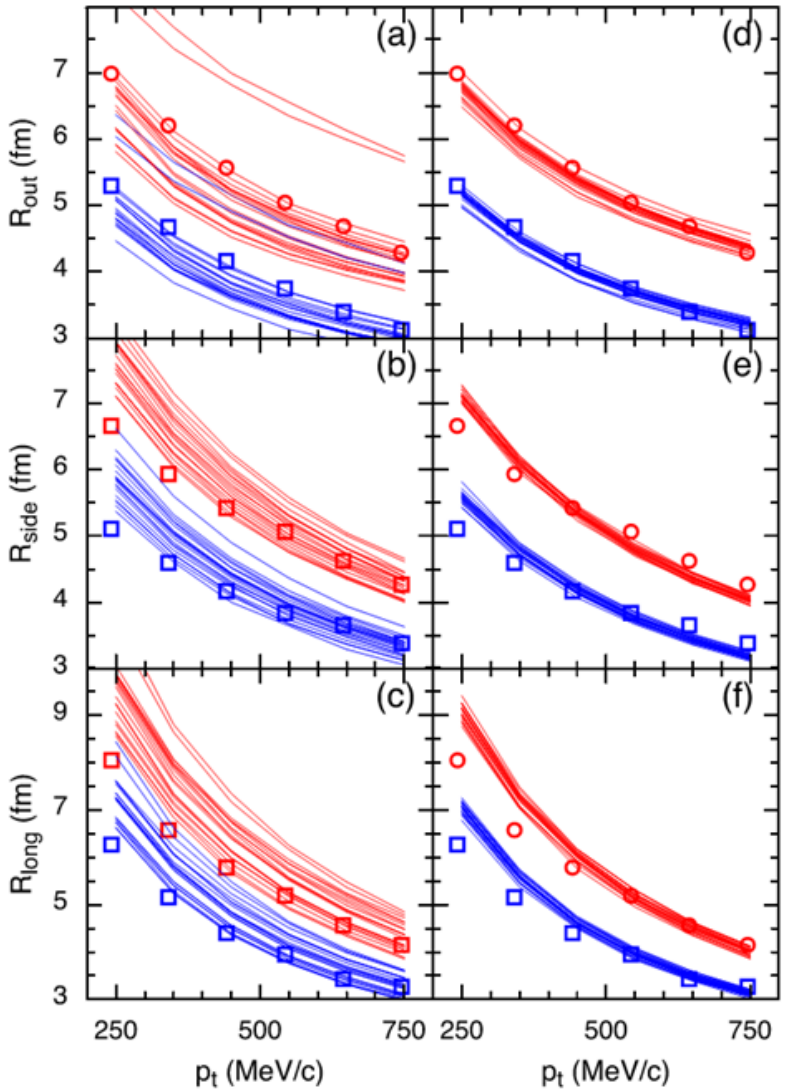
- Access to the spatial and temporal information about a particle-emitting source
- Different particle species are sensitive to various effects (FSI, shear and bulk viscosity, temperature, space and time emission asymmetries, etc...)

V.M. Shapoval et al. NPA 968 (2017) 391
M.A. Lisa et al. Ann. Rev. Nucl. Part. Sci. 55 (2005) 357
D.H. Rischke, M. Gyulassy. NPA 608 (1996) 479
R. Lednicky et al. Phys. Lett. B 373 (1996) 30

- Strong model constraints

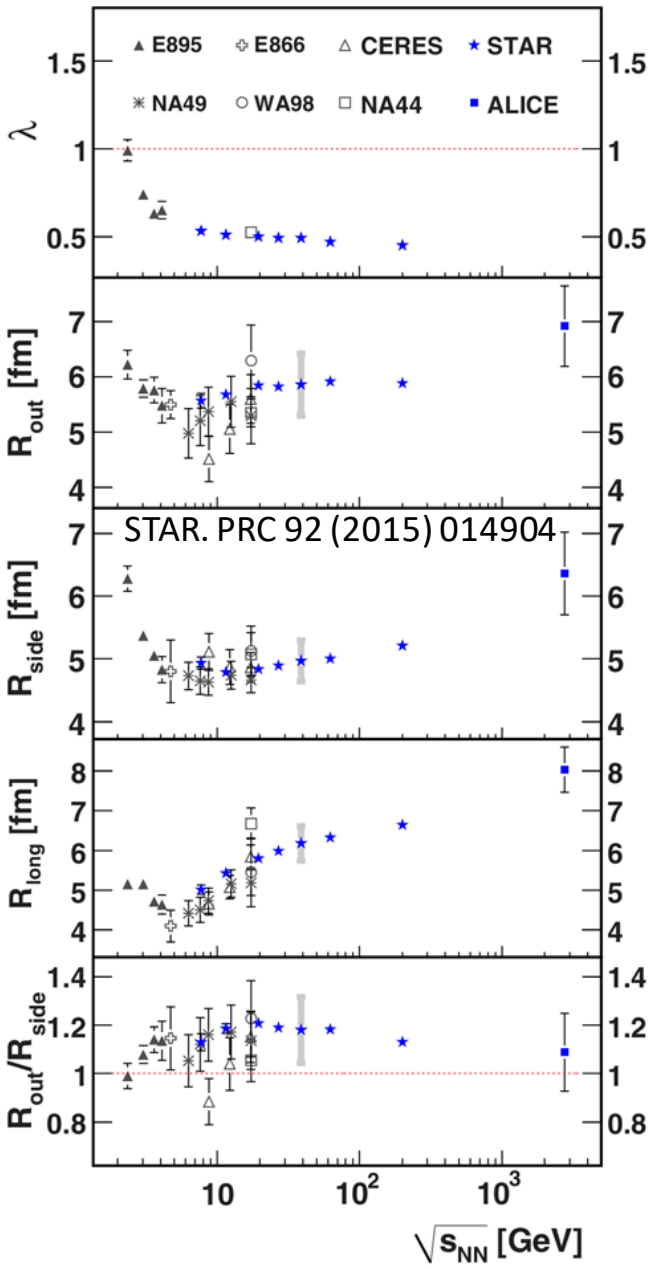


Charged pions in Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

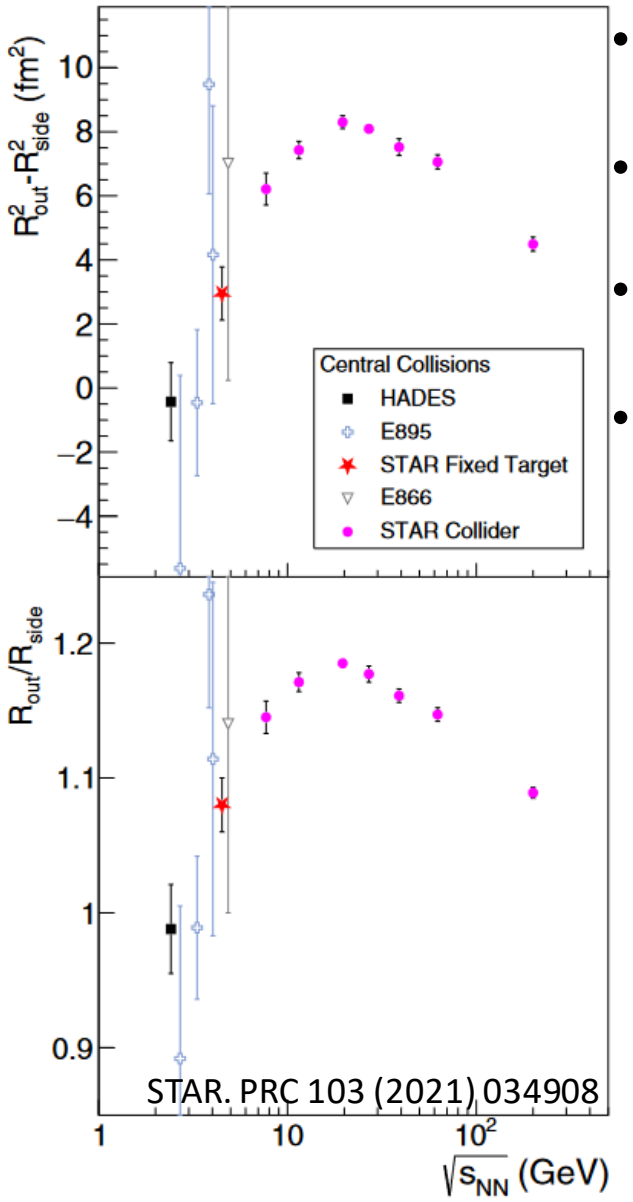


S. Pratt et al. PRL 114 (2015) 202301

Charged Pion Femtoscopy in Heavy-ion Collisions

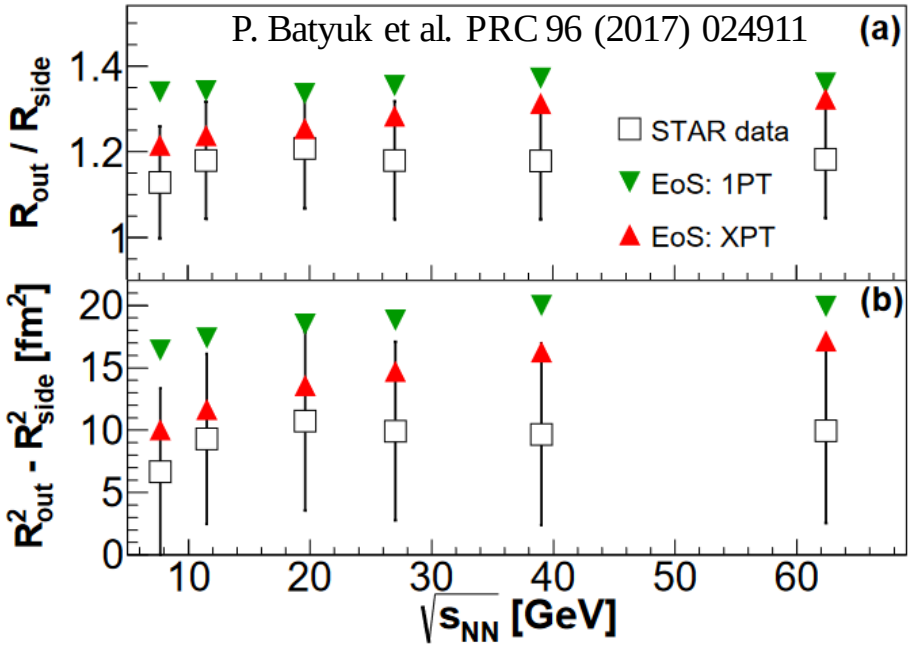


STAR. PRC 92 (2015) 014904



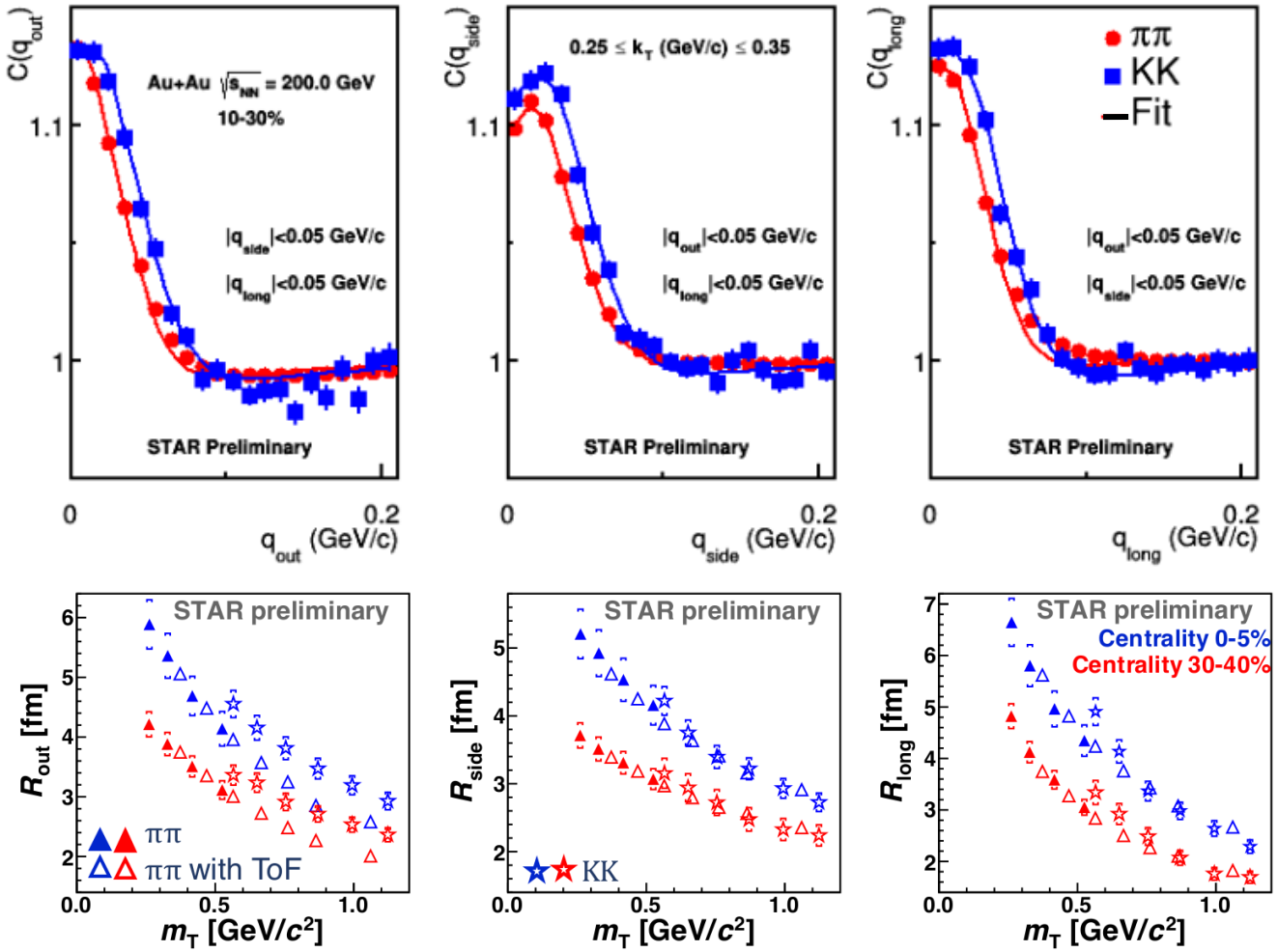
STAR. PRC 103 (2021) 034908

- Precise measurements in a broad energy range (from 7.7 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.)



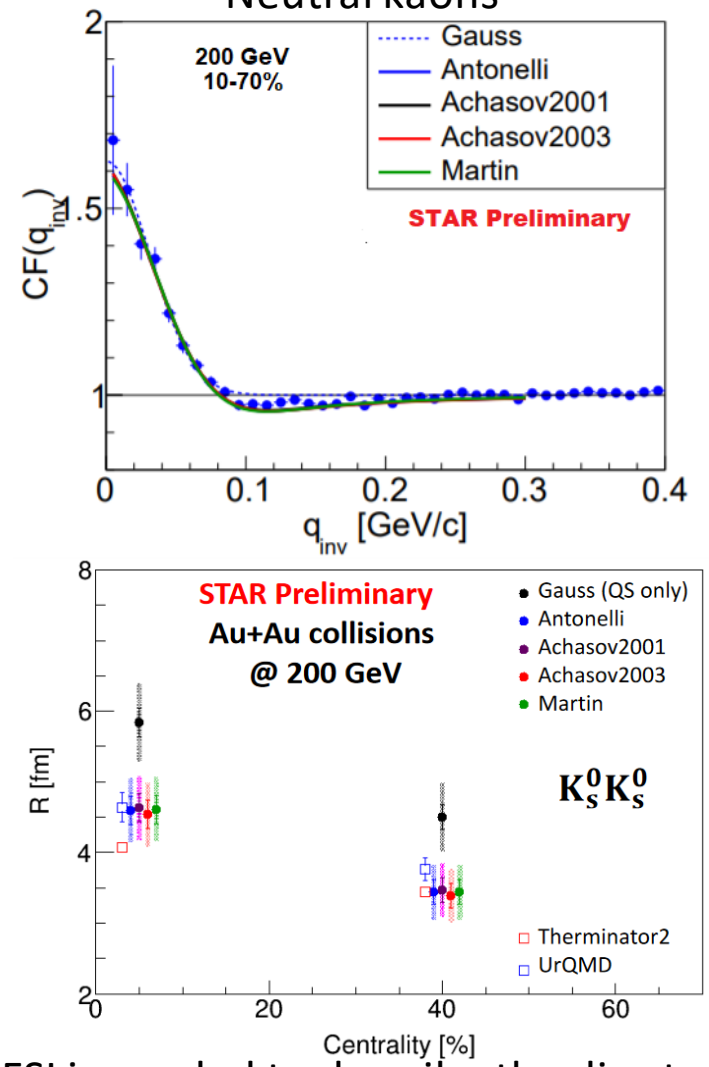
Pion and Kaon Femtoscopy in Au+Au Collisions

Charged kaons



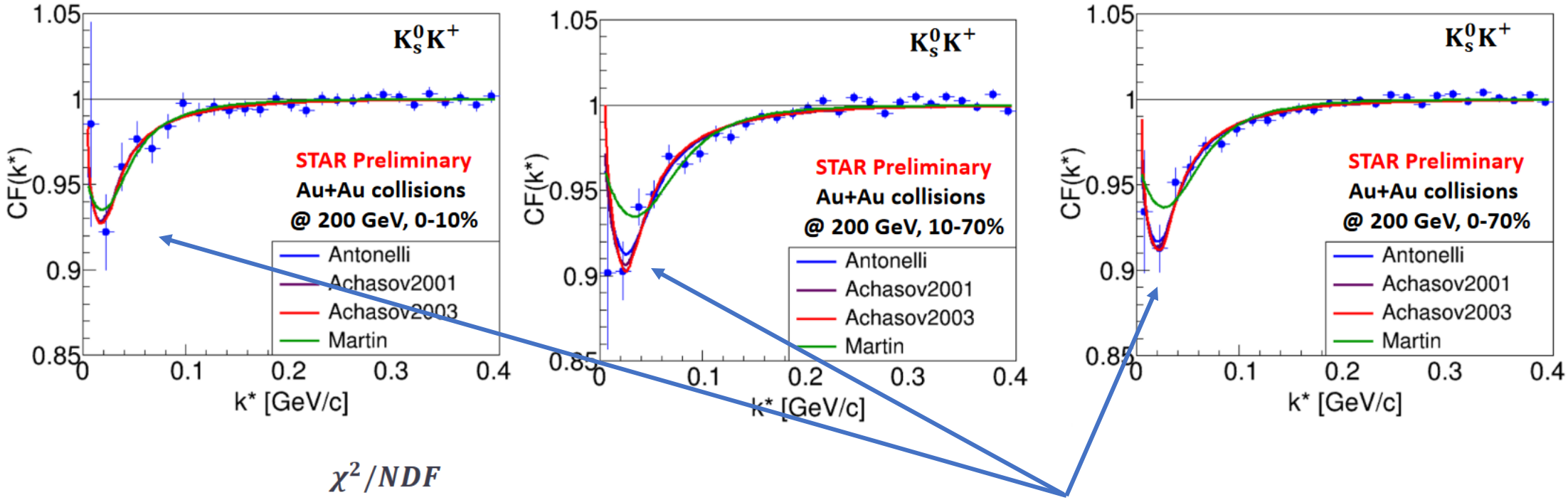
- Adding TOF allows to extend charged pion and kaon PID up p≈1.5 GeV/c
- Kaon femtoscopic radii are slightly larger than those for pions in outward and longitudinal directions

Neutral kaons



- FSI is needed to describe the dip structure of correlation functions
- Neutral kaon femtoscopic radius increases from midcentral to central collisions

K^0K^+ Femtoscopy in Au+Au Collisions



χ^2/NDF

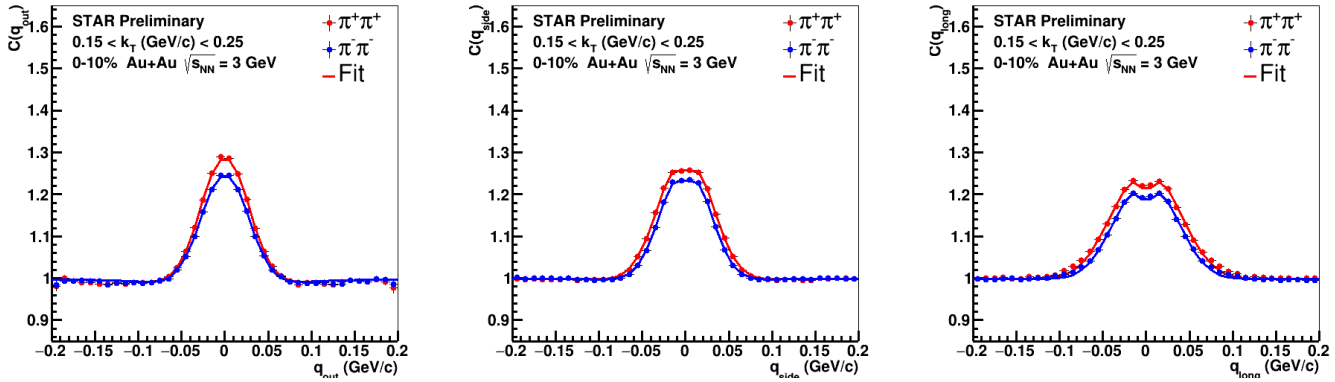
	0-10%	10-70%	0-70%
Antonelli [1]	0.60	1.66	1.04
Achasov2001 [2]	0.59	1.73	1.07
Achasov2003 [3]	0.58	1.85	1.14
Martin [4]	0.65	1.65	1.16

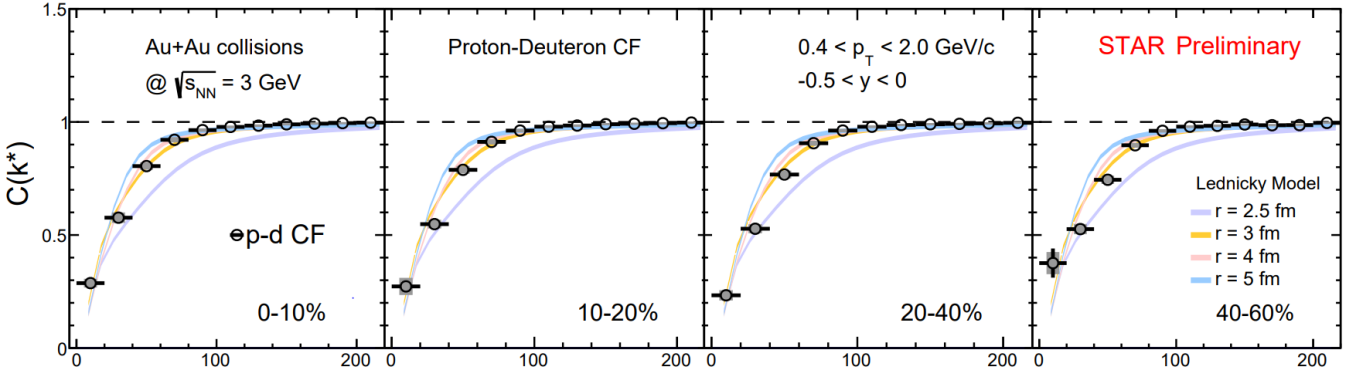
The $a^0(980)$ FSI parametrization gives an excellent representation of the signal region of the data

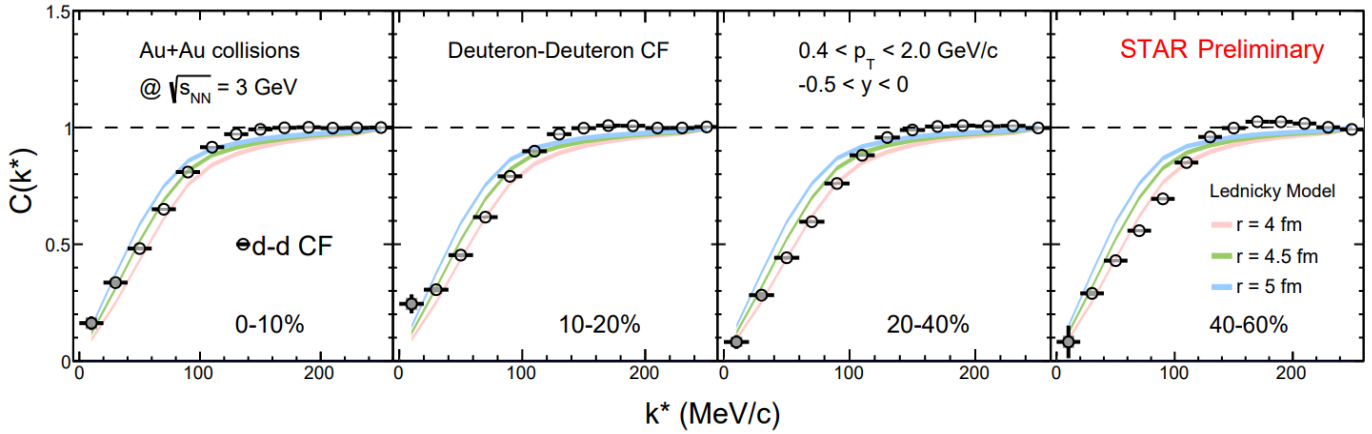
[1] eConf C020620, THAT06 (2002)
[2] Phys. Rev. D 63, 094007 (2001)
[3] Phys. Rev. D 68, 014006 (2003)
[4] Nucl. Phys. B 121, 514–530 (1977)

Femtoscopy Results from the FXT Program

See Anna Kraeva's talk







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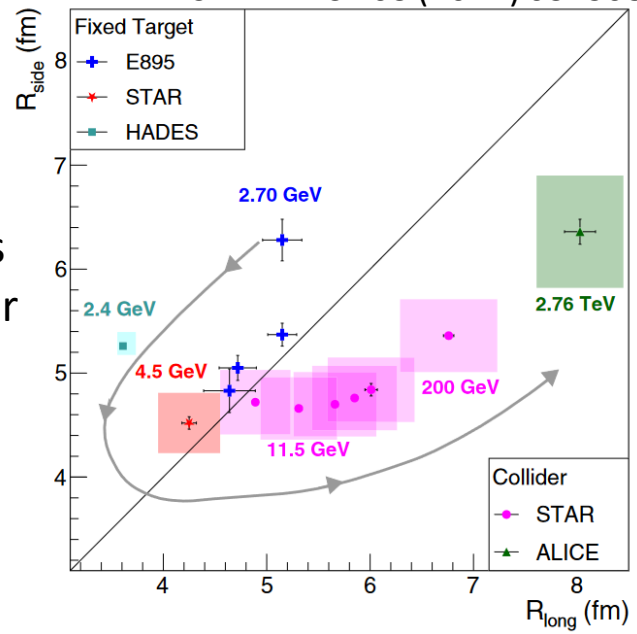
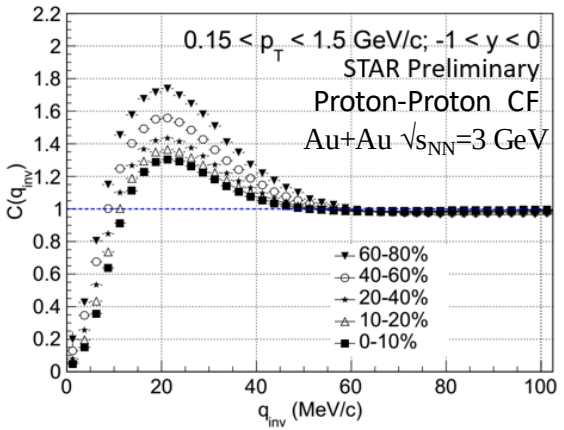
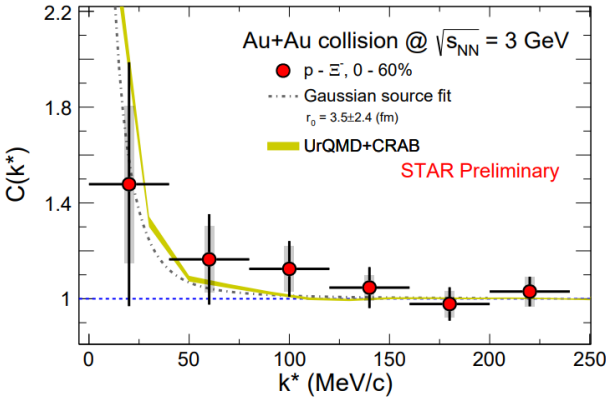


Many interesting results from low-energy nuclear collisions:

- ππ
- pp
- pd
- dd
- pΞ
- and others

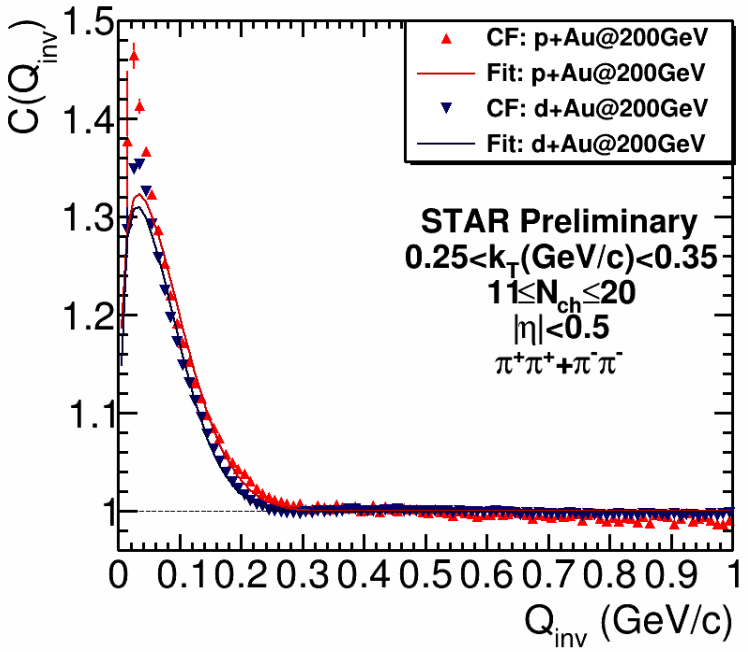


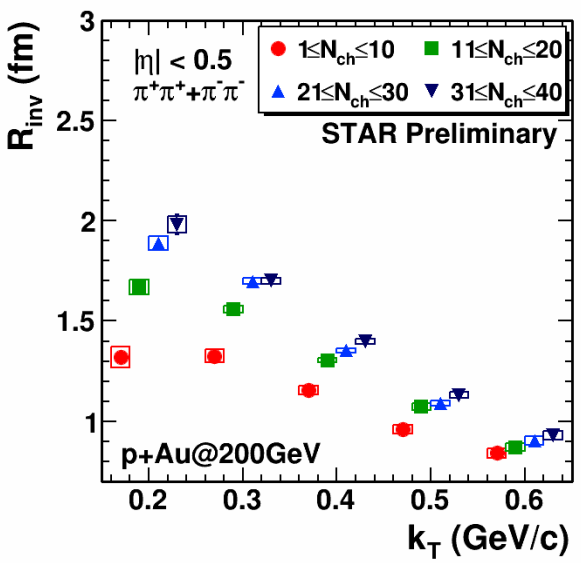


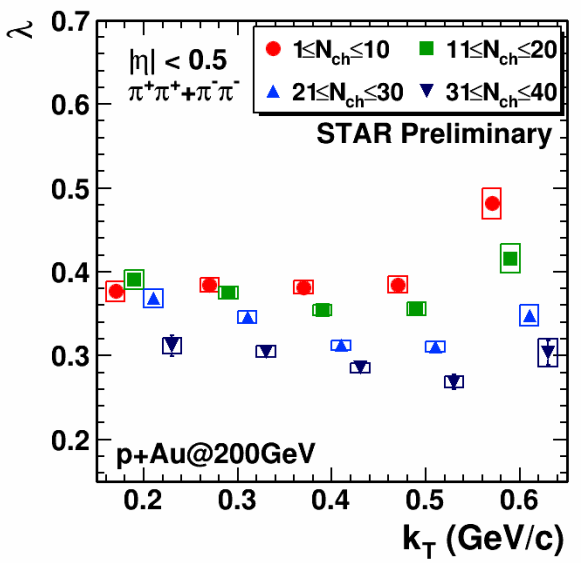
Femtoscopy in Small Collision Systems

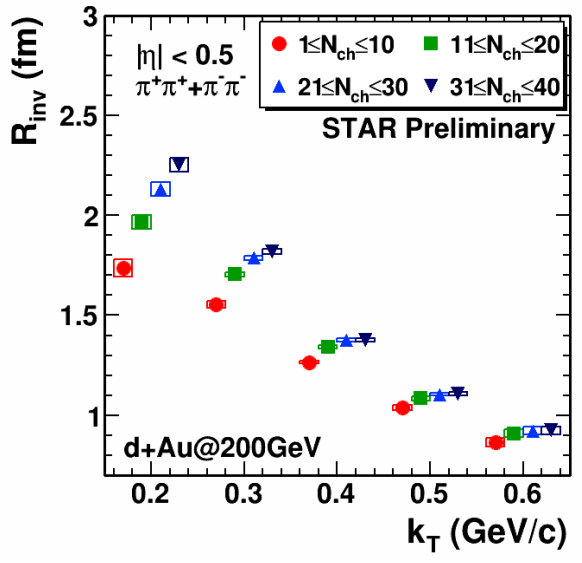
RHIC provides opportunity to study various colliding species, including p+p, p+Al, p+Au, d+Au, ^{3}He+Au

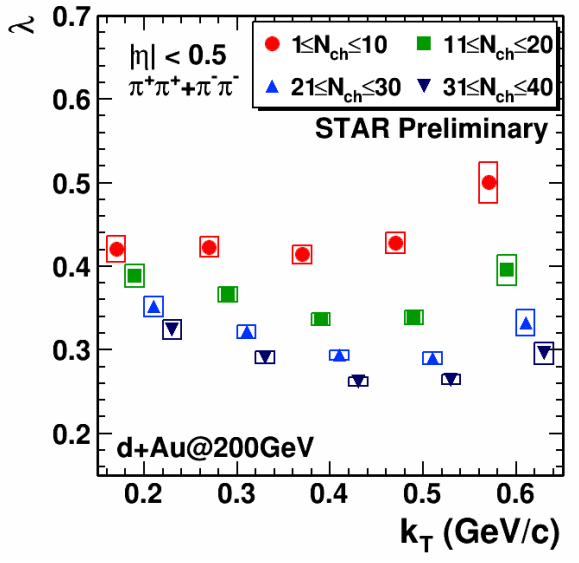
Unique opportunity to study collective behavior of particles produced in small collision systems via measurements of k_T dependence of femtoscopic radius











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