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Relativistic Nuclear Physics & Quantum Chromodynamics

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Recent flow and femtoscopy results from STAR

Grigory Nigmatkulov

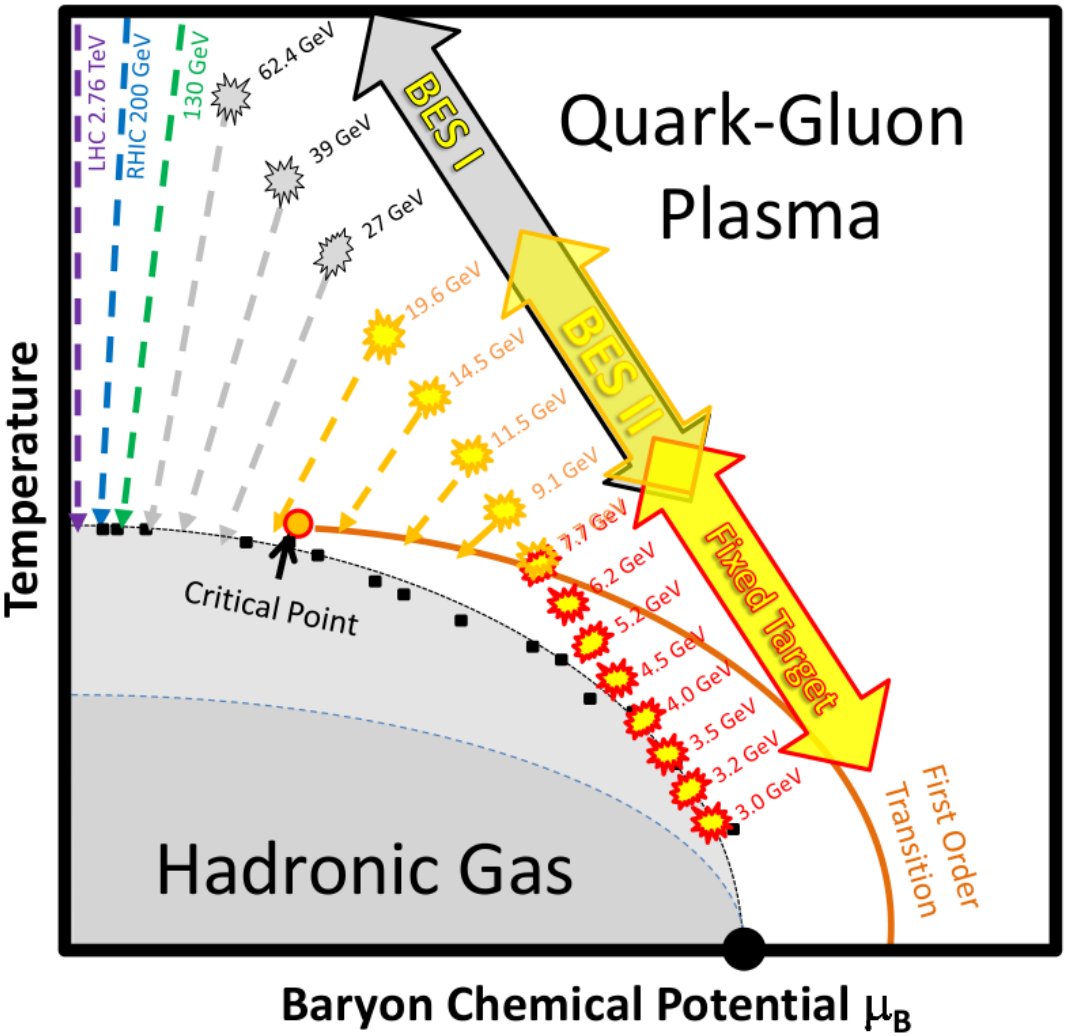
(for the STAR Collaboration)

National Research Nuclear University MEPhI

Outline:

- Introduction
- The STAR experiment
- Directed flow
- Correlation femtoscopy
- Summary

Introduction



Top RHIC energy

p+p, p+Al, p+Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, Ru+Ru, Zr+Zr, Au+Au, U+U

- QCD at high energy density/temperature
- Properties of QGP, Equation of State (EoS)
- Proton spin structure

Beam Energy Scan

Au+Au $\sqrt{s_{NN}}$=7.7-62.4 GeV

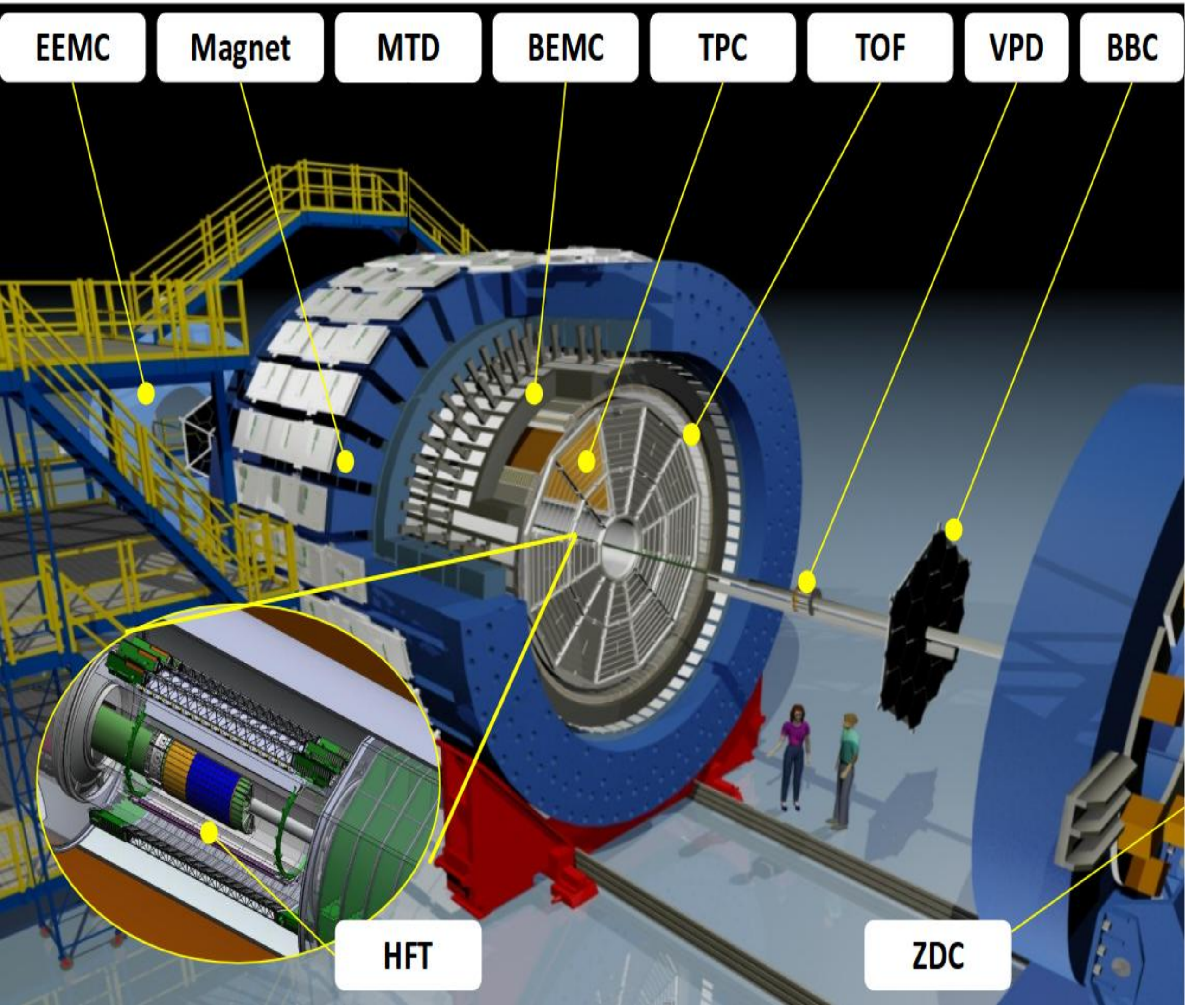
- Search for critical point
- QCD phase transition
- Turn-off of QGP signatures

Fixed-Target Program

Au+Au $\sqrt{s_{NN}}$=3.0-7.7 GeV

- High baryon density (μ_B~420-720 MeV)

The STAR ☆ Experiment

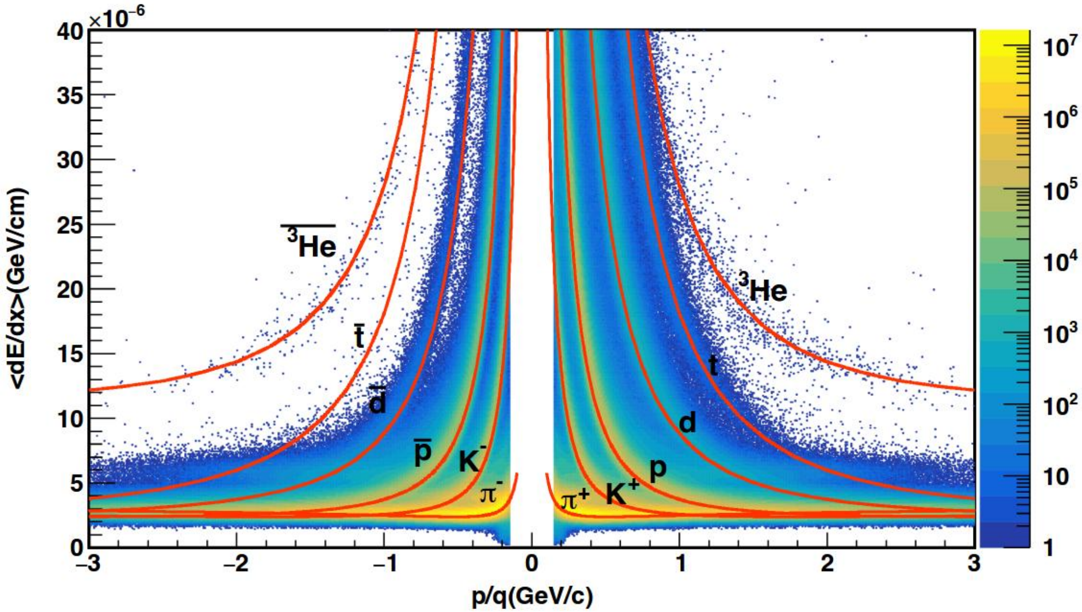


- **Tracking and PID (full 2π)**
  TPC: |η|<1
  TOF: |η|<0.9
  BEMC: |η|<1
  EEMC: 1<|η|<2
  HFT (2014-2016): |η|<1
  MTD (2014+): |η|<0.5

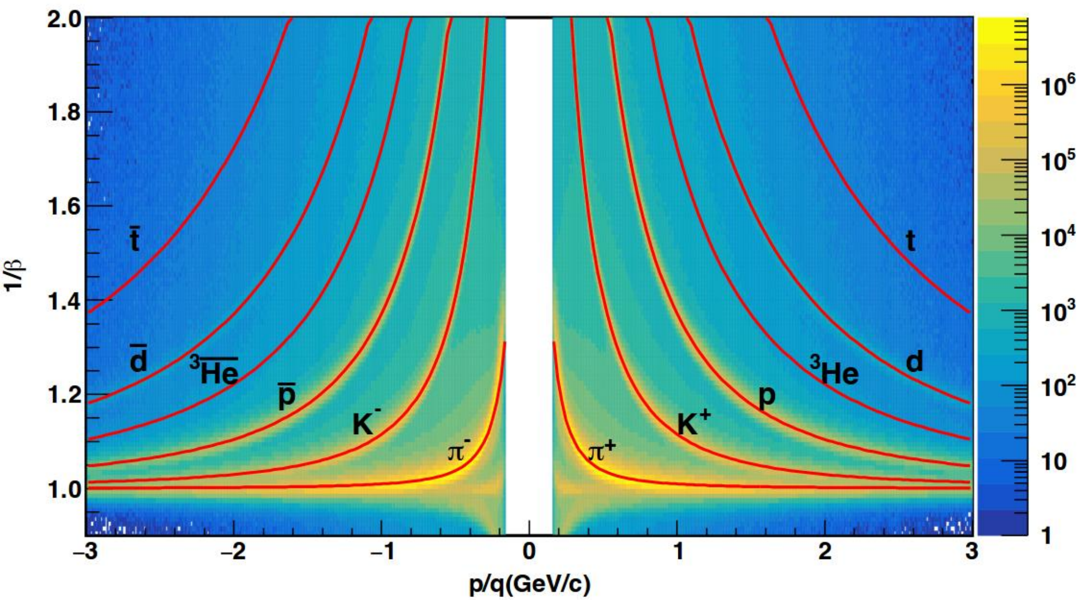
- **MB trigger and event plane reconstruction**
  BBC: 3.3<|η|<5
  EPD (2018+): 3.1<|η|<5.1
  FMS: 2.5<|η|<4
  VPD: 4.2<|η|<5
  ZDC: 6.5<|η|<7.5

- **On-going/future upgrades**
  iTPC (2019+): |η|<1.5
  eTOF (2019+): -1.6<η<-1
  FCS (2021+): 2.5<η<4
  FTS (2021+): 2.5<η<4

Particle Identification with TPC and TOF

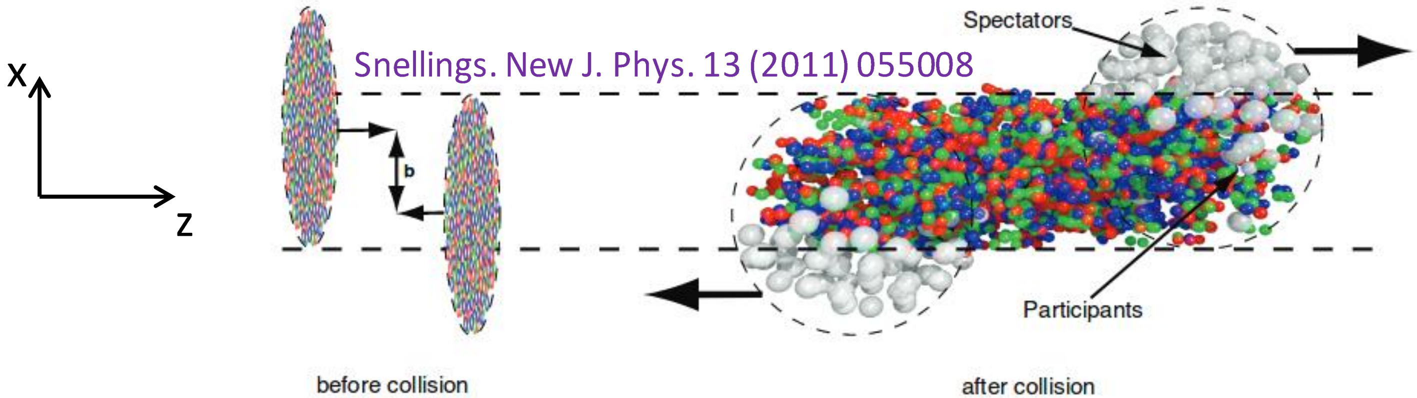


- The <dE/dx> versus rigidity measured by TPC in 2014 Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV



- The 1/β versus rigidity measured by TOF in 2014 Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV

Azimuthal Anisotropy in Heavy-Ion Collisions

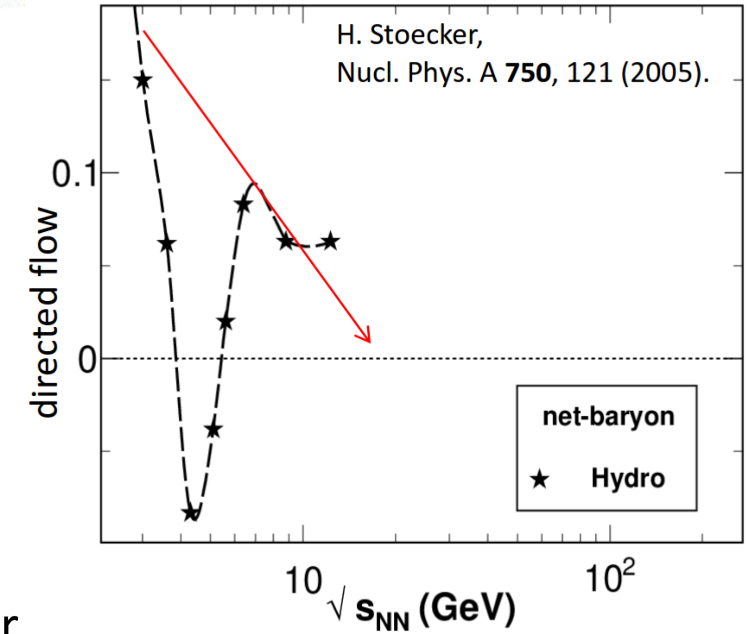


Snellings. New J. Phys. 13 (2011) 055008

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

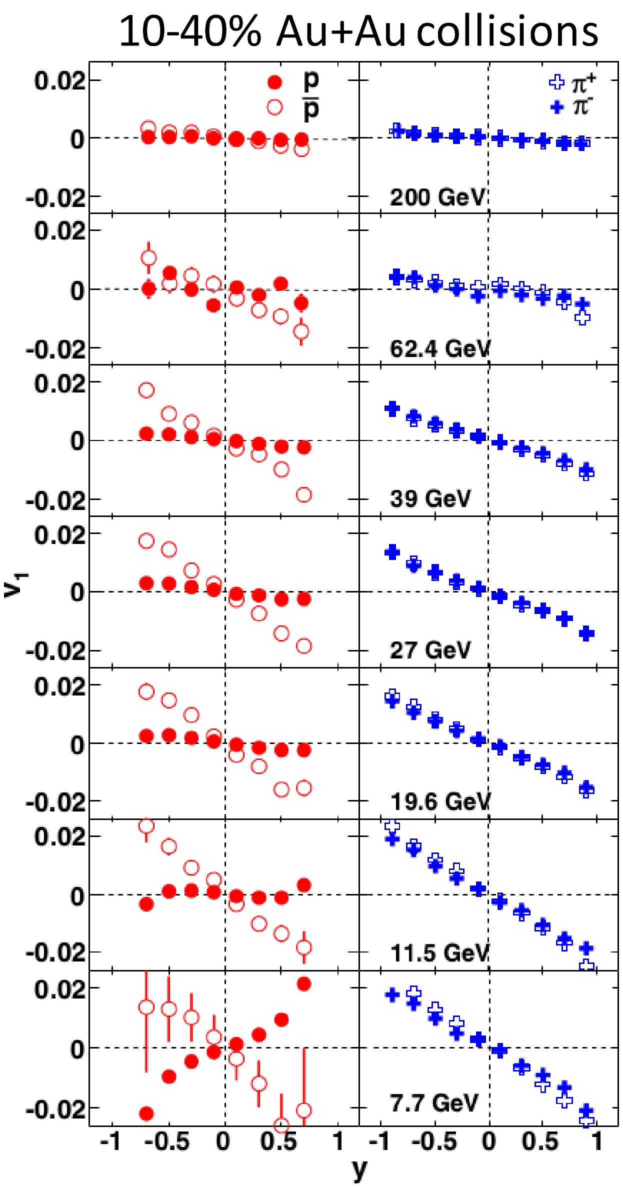
Voloshin , Zhang. Z. Phys. C 70 (1996) 665
Poskanzer, Voloshin. Phys. Rev. C 58 (1998) 1671

- $v_1 = \langle p_x/p_t \rangle$ – directed flow
- Describes the sideward collective motion of particles within the reaction plane (x-z)
- Probe of the softening of the EoS:
  - Strong softening: consistent with the 1st-order phase transition
  - Weaker softening: more likely due to crossover



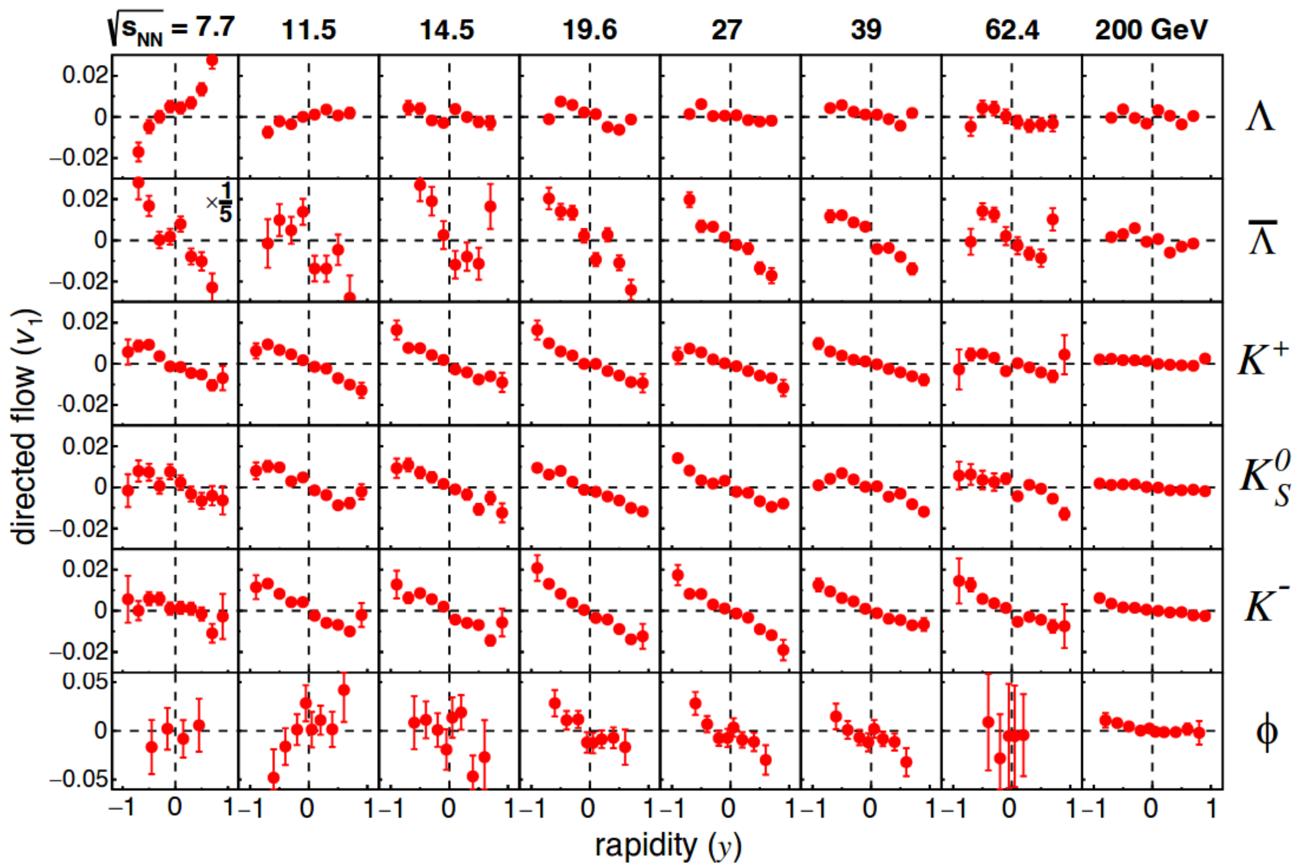
Nara, Niemi, Steinheimer, Stöker. Phys. Lett. B 769 (2017) 543
Ivanov, Soldatov. Phys. Rev. C 91 (2015) 024915

Directed Flow Measurements

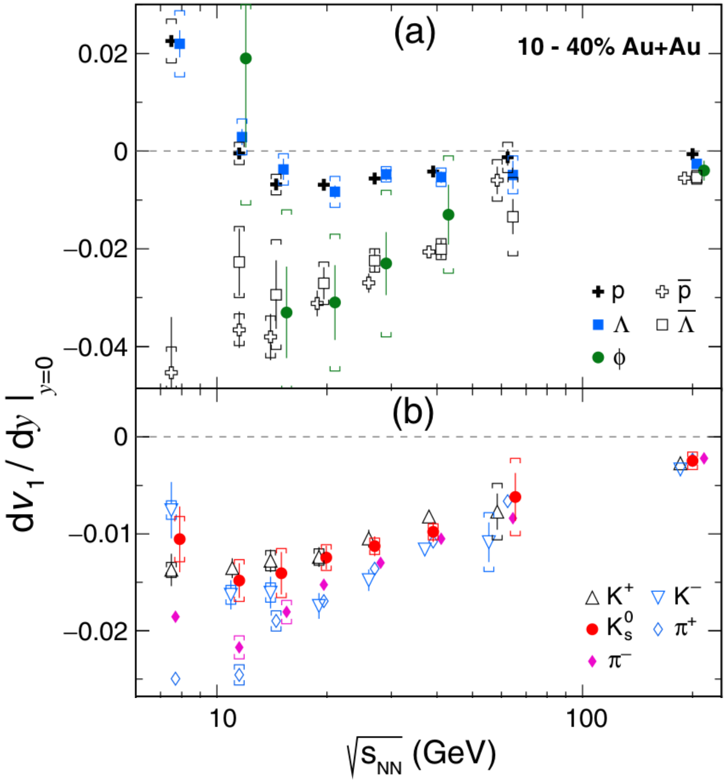


To extract v_1 slope, linear fit was used over $|y|<0.6$ for ϕ meson and over $|y|<0.8$ for all other species

STAR. Phys. Rev. Lett. 112 (2014) 162301
STAR. Phys. Rev. Lett. 120 (2018) 062301

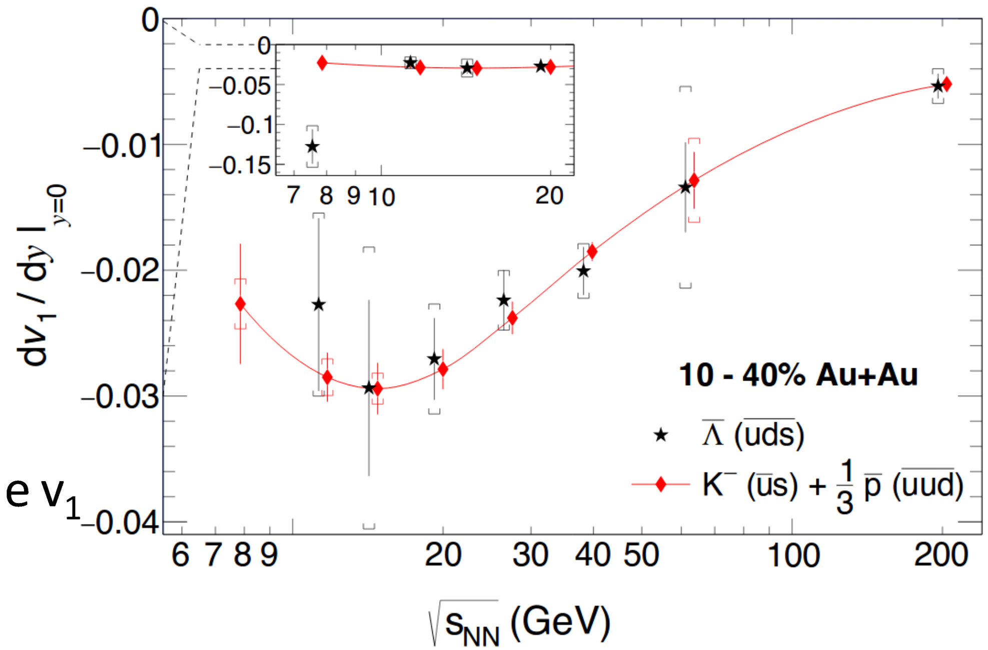


STAR ☆ Beam Energy Dependence of Directed Flow



- 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-p, anti-Λ, and ϕ) with produced quarks show similar behavior for $\sqrt{s_{NN}}$>14.5 GeV
- Mesons show negative dv_1/dy

STAR. Phys. Rev. Lett. 120 (2018) 062301



Assumptions for coalescence sum rule:

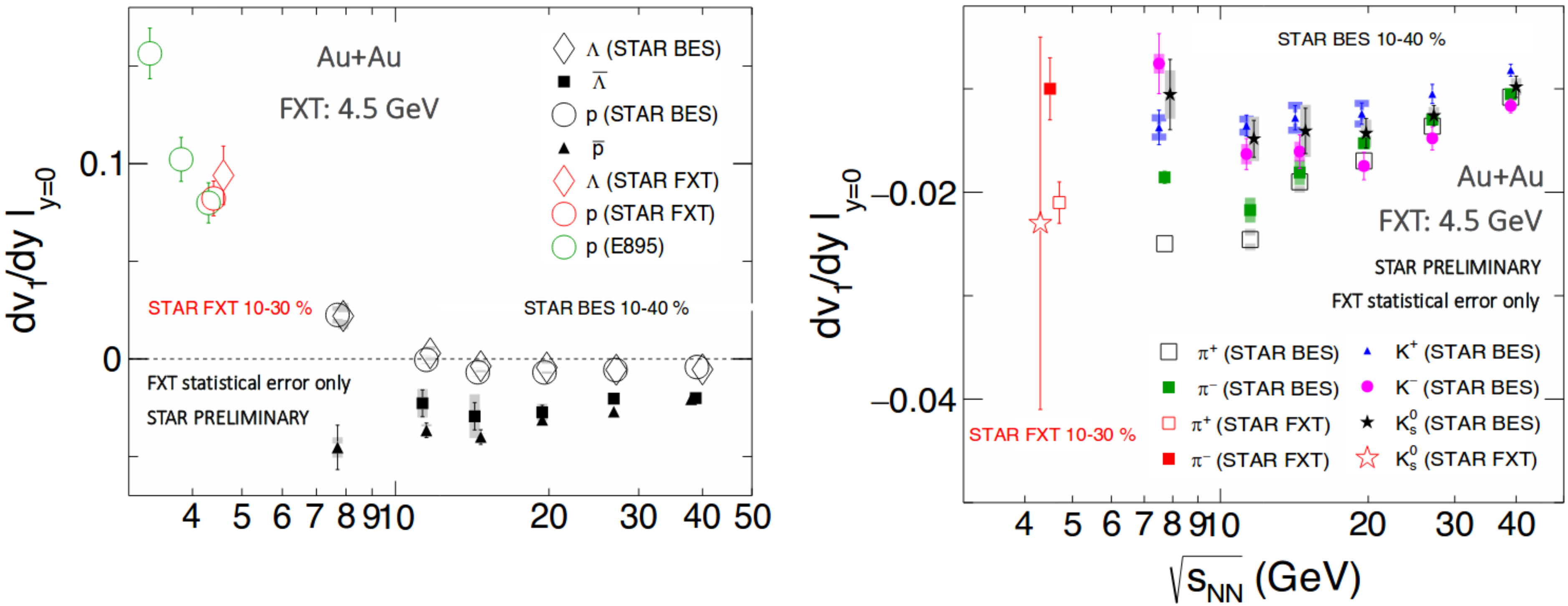
- v_1 is developed at pre-hadronic stage
- Specific types of quarks have the same v_1
- Hadrons are formed via coalescence

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

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

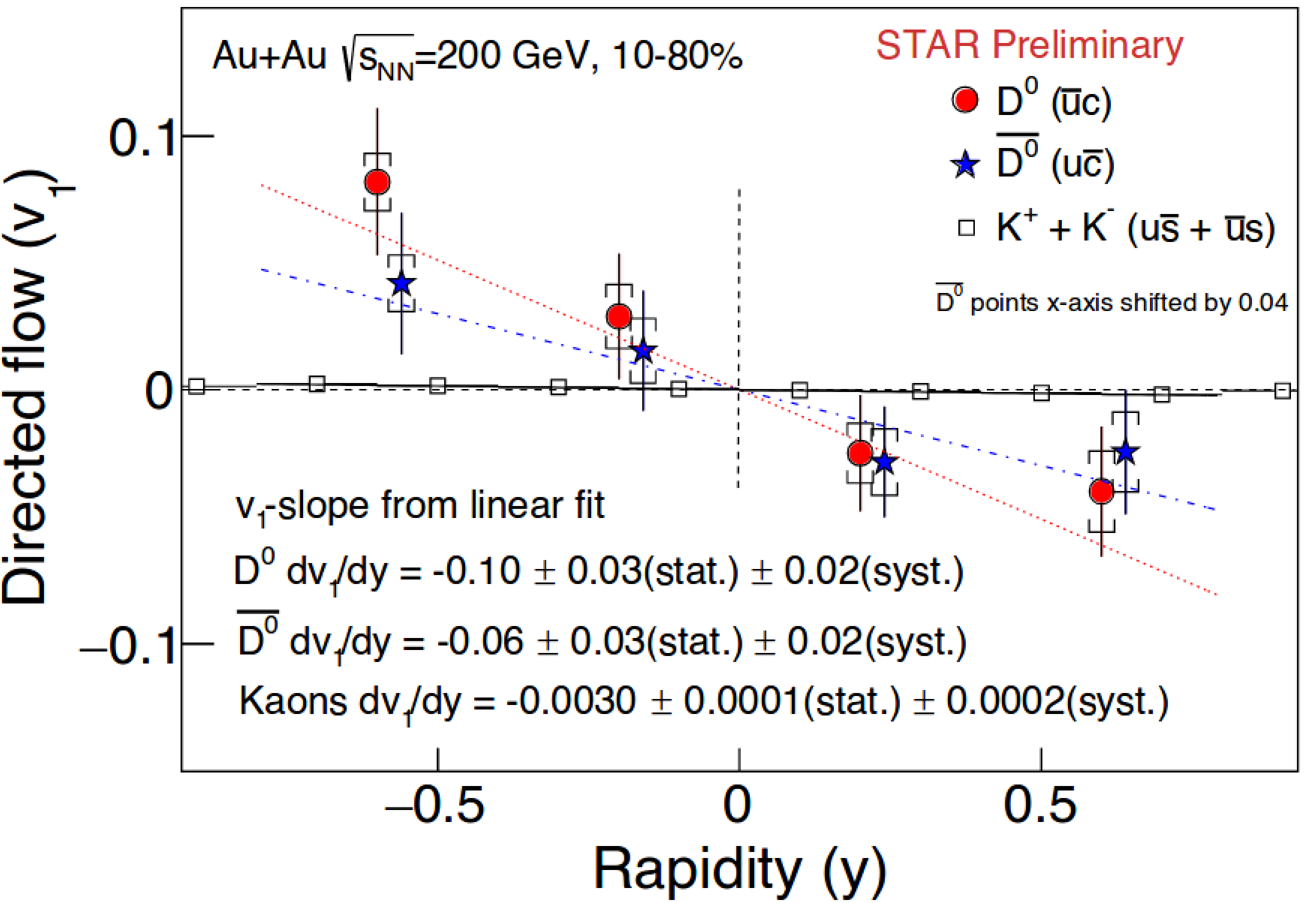
Directed Flow Measurements from FXT

E895. Phys. Rev. Lett. 84 (2000) 005488
STAR . Phys. Rev. Lett. 112 (2014) 162301

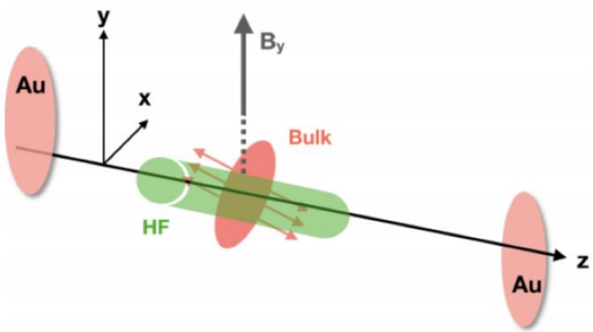


- Proton v_1 is consistent with E895. Λ v_1 is close to that of proton
- First pion v_1 measurements in this energy range
- π^+, π^- ordering supports the idea that transported quarks have bigger effect on π^-

v_1 of D^0 in Au+Au at 200 GeV



Interplay between the drag by the tilted bulk and the EM field



Chatterjee, Bozek. Phys. Rev. Lett. 120 (2018) 192301

First evidence for non-zero D^0 v_1 from 2014+2016 Heavy Flavor Tracker (HFT) data:

$$D^0 + \overline{D^0}\ dv_1/dy = -0.081 \pm 0.021(stat.) \pm 0.017(syst.)$$

Correlation femtoscopy

Allows to extract spatial and temporal information about particle-emitting source

- Two-particle correlation function:

$$CF(p_1, p_2) = \int d^4r\, S(r, k)\, |\Psi_{1,2}(r, k)|^2$$

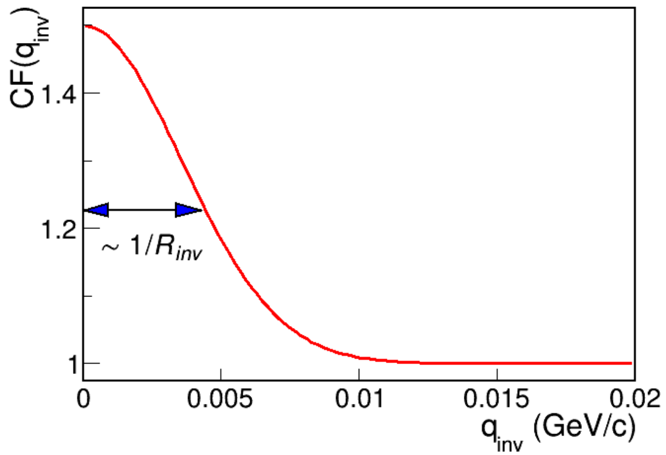
$$r = x_1 - x_2 \text{ and } q \equiv q_{inv} = p_1 - p_2$$

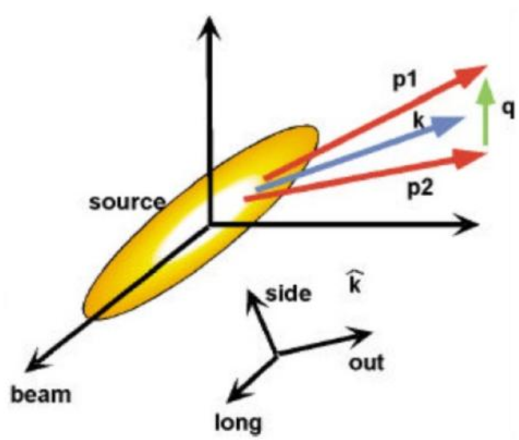
- Experimentally:

$$CF(q) = A(q)/B(q)$$

– A(q) – contain quantum statistical (QS) correlations and final state interactions (FSI)

– B(q) – obtained via mixing technique (does not contain QS and FSI)





S. Pratt. Phys. Rev. D 33 (1986) 1314

G. Bertsch. Phys. Rev. C 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 $p_{1z}+p_{2z}=0$

Fitting procedure

- Femtoscopic radii are extracted by fitting C(**q**) with (Bowler-Sinyukov procedure):

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

M. Bowler. Phys. Lett. B 270 (1991) 69
Yu. Sinyukov et al. Phys. Lett. B 432 (1998) 248

N – normalization factor
λ – correlation strength
K(q_{inv}) – Coulomb correction
R_{side} ~geometrical size of the system
R_{out} ~ geometrical size + particle emission duration
R_{long} ~ medium lifetime

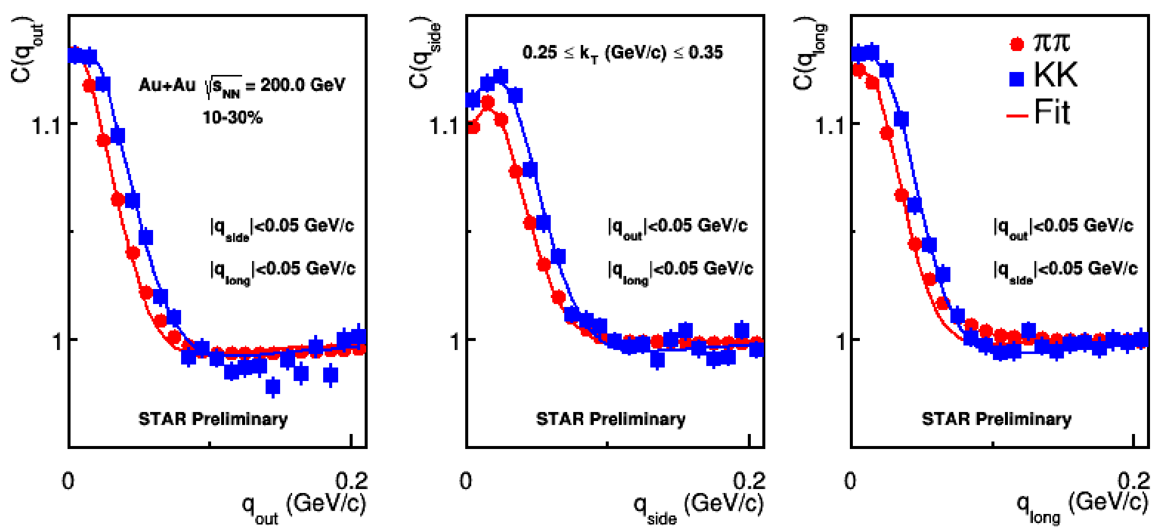
- Fit using Log-likelihood method
  E-802. Phys. Rev. C 66 (2002) 054906

$$\chi^2 = -2\left[A\ln\left(\frac{C(A+B)}{A(C+1)}\right) + B\ln\left(\frac{A+B}{B(C+1)}\right)\right], C = \frac{A}{B}$$

- Fit example

Out, side and long projections of ππ and KK correlation functions

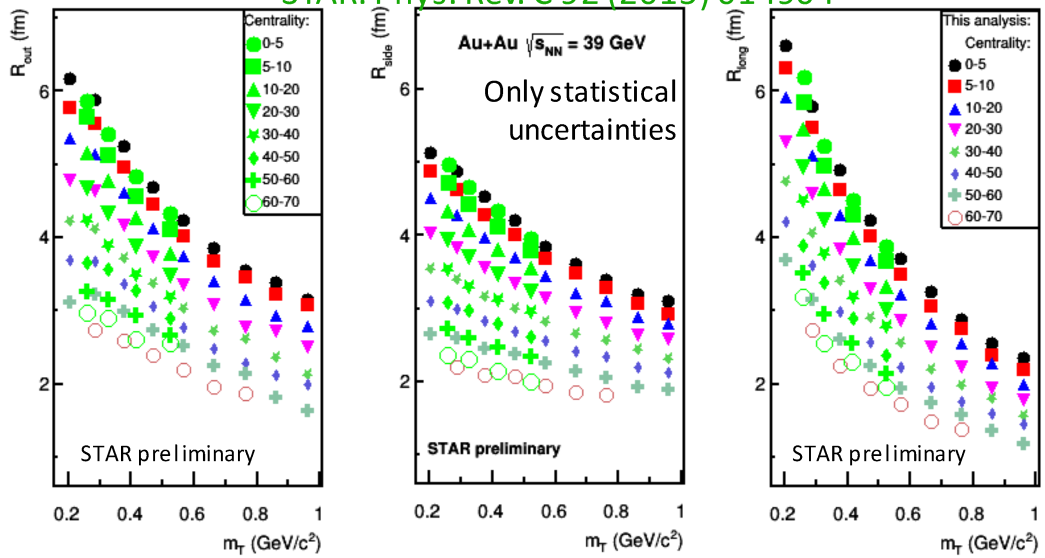
Fits show a good description of the data



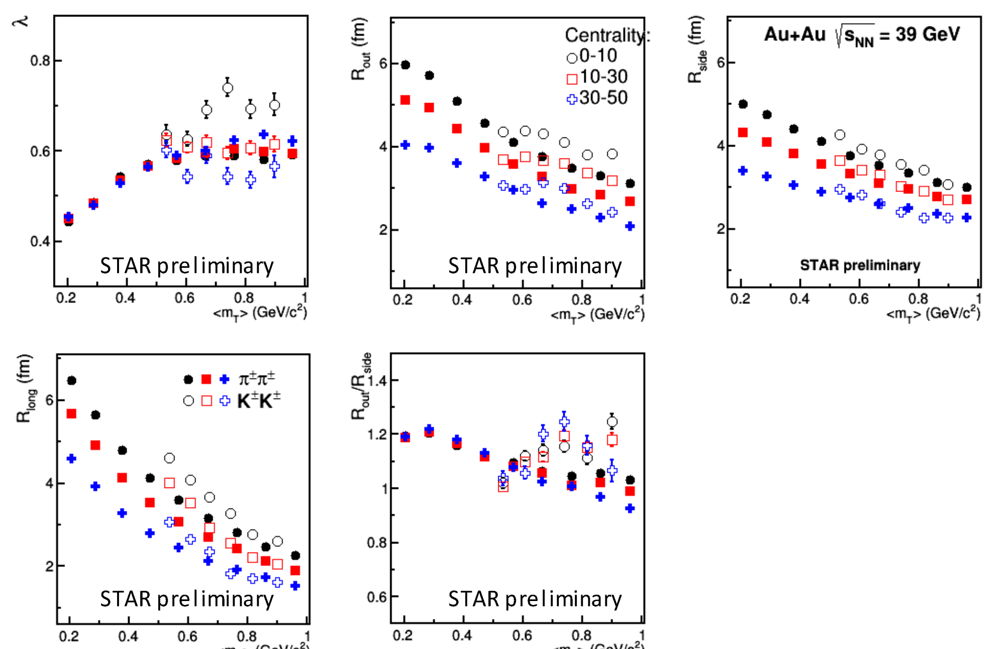
STAR ☆ Femtoscopic Measurements

- Use two-particle momentum correlations to measure spatial and temporal properties of the source at kinetic freeze-out
- Utilizing the information from the TOF detector to extend measurement to higher transverse mass (m_T) region

STAR. Phys. Rev. C 92 (2015) 014904



- Kaon femtoscopic radii in outward and longitudinal directions are generally larger than those for pions at the same m_T → breaking of the m_T-scaling
- In the sideward direction, the pion and kaon radii are similar



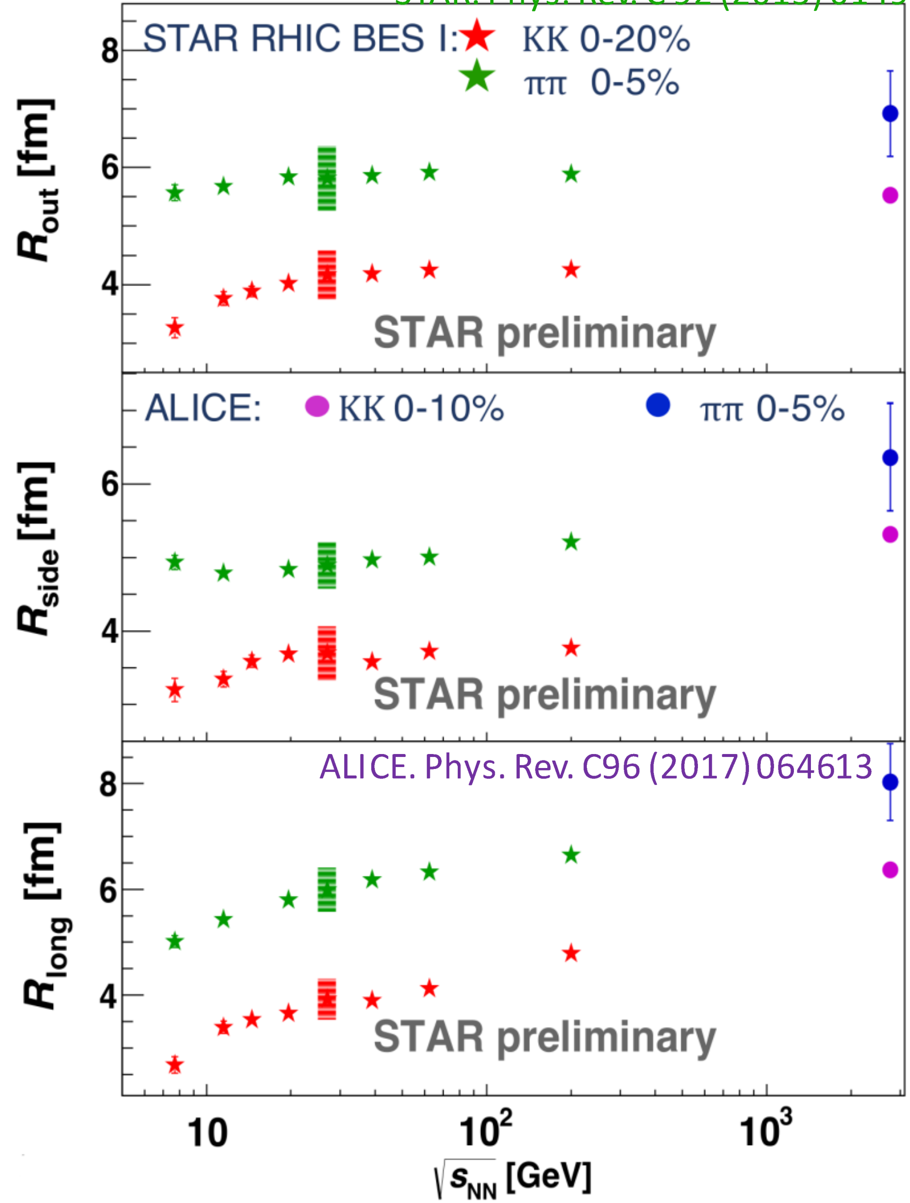
Femtoscopic measurements

The extracted femtoscopic radii smoothly increase with increasing collision energy

The values of R_{out} and R_{side} for both pions and kaons show a very small increase at the RHIC energies and slightly larger at the LHC

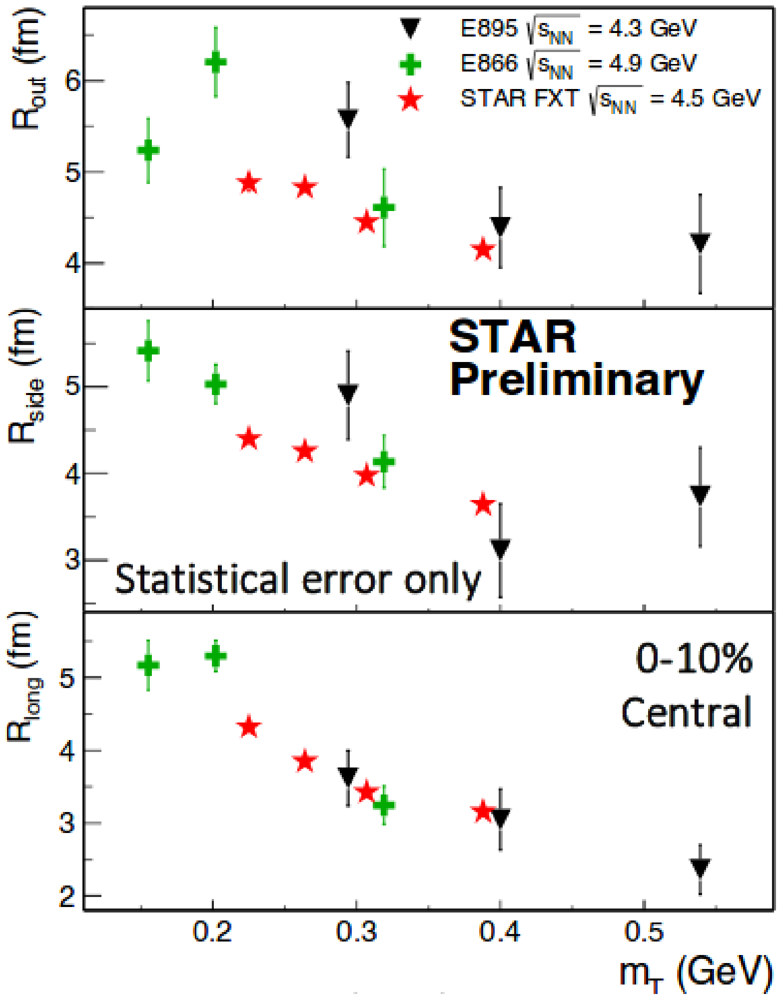
The values of R_{long} suggest that the system lives longer at the LHC energy

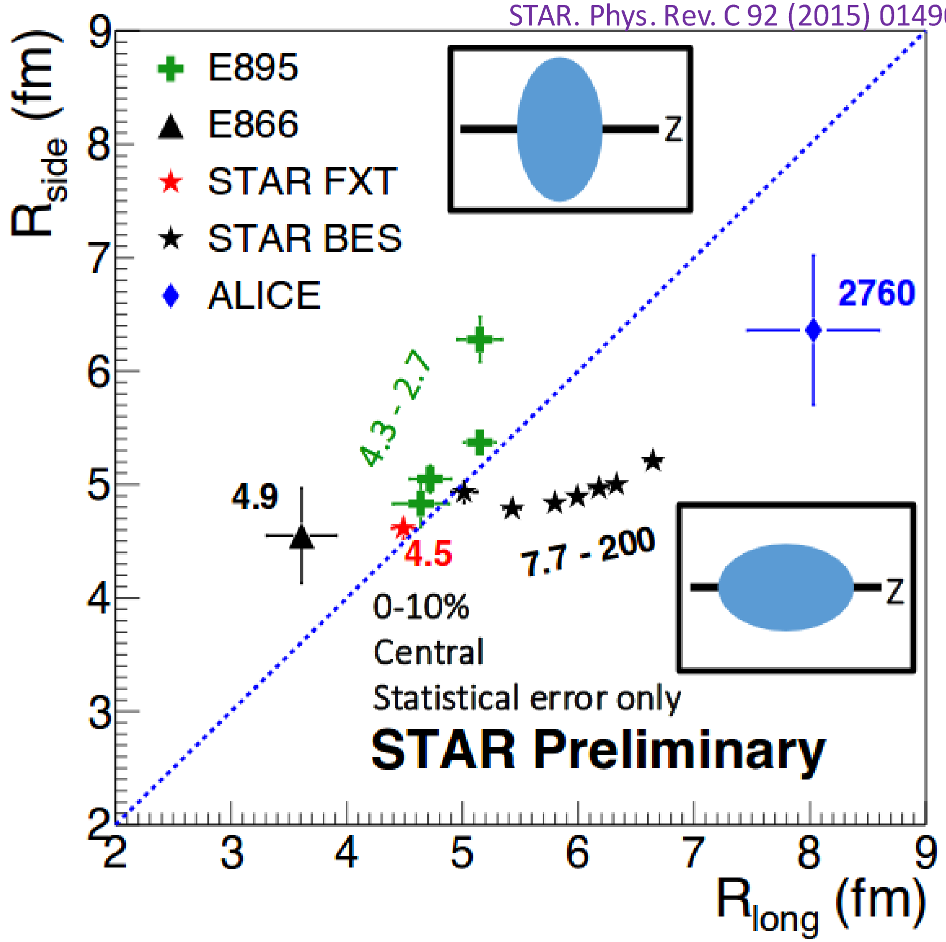
STAR. Phys. Rev. C 92 (2015) 014904



Femtoscopic measurements in FXT

E866. Phys. Rev. C 66 (2002) 054096
E895 .Phys. Rev. Lett. 84 (2000) 2798
ALICE. Phys. Rev. B 696 (2011) 328
STAR. Phys. Rev. C 92 (2015) 014904





- Consistent with results from AGS experiments, with smaller stat. errors
- Apparent source shape evolves from oblate to prolate, as energy increases
- Increased longitudinal expansion above FXT energy

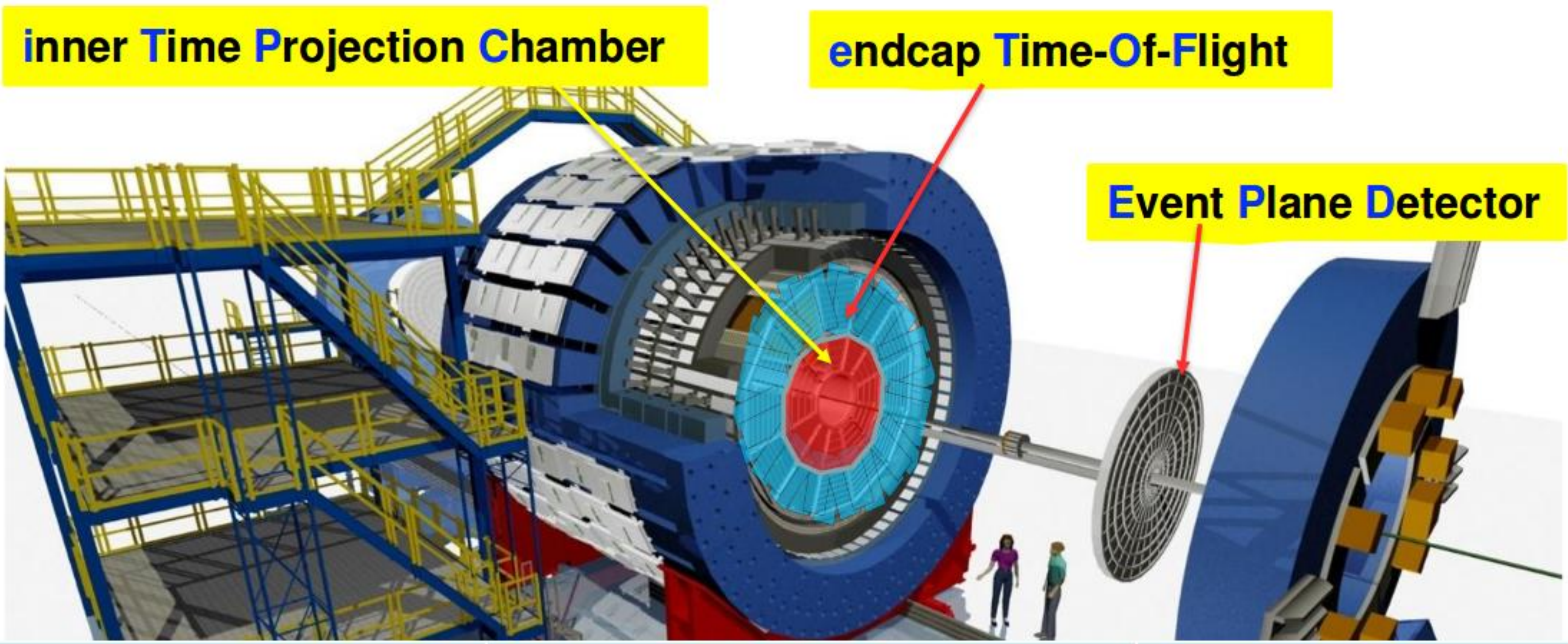
Summary

- Directed flow
  - Extensively measured in Au+Au collisions 4.5, 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 and 200 GeV for particles (π, K, p, Λ) and antiparticles in both collider and fixed-target modes
  - Coalescence sum rule works above $\sqrt{s_{NN}}$=11.5 GeV
  - The first measurement of non-zero D^0 v_1 at Au+Au 200 GeV

- Femtoscopy
  - Centrality dependence of ππ and KK is measured for Au+Au collisions at 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 and 200 GeV
  - Pion and kaon radii seem to follow different m_T trends
  - R_{out}, R_{side} and R_{long} for pions and kaons smoothly increase with increasing collision energy

Backup slides

STAR ☆ Upgrades for BES-II

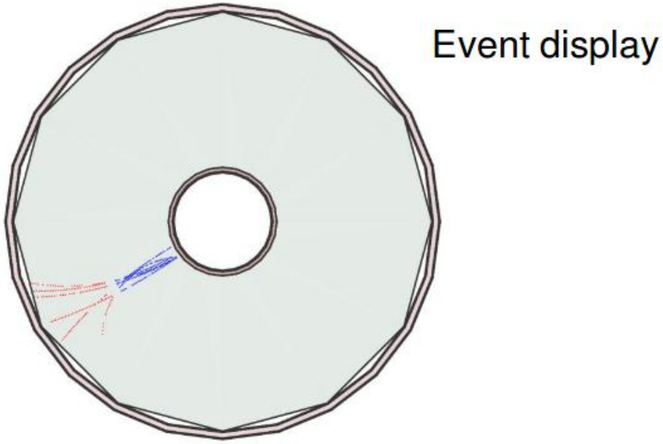


iTPC upgrade	eTOF upgrade	EPD upgrade
Continuous pad rows **Replace all inner TPC sectors**	**Add CBM TOF modules and electronics (FAIR Phase 0)**	**Replace Beam-Beam Counter**
$\|\eta\| < 1.5$	**$-1.6 < \eta < -1.1$**	**$2.1 < \|\eta\| < 5.1$**
$p_T > 60$ MeV/c	Extend forward PID capability	Better trigger & b/g reduction
Better dE/dx resolution Better momentum resolution	Allows higher energy range of Fixed-Target program	Greatly improved Event Plane info (esp. 1st-order EP)

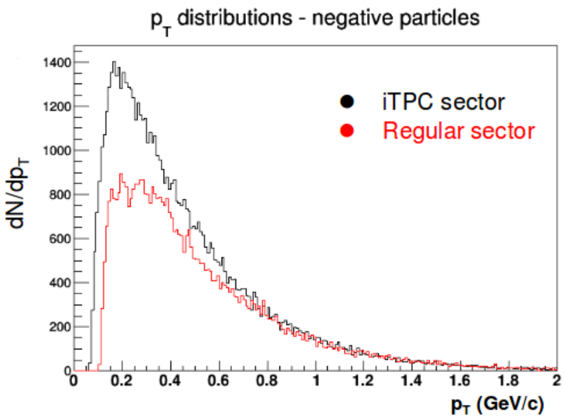
The inner TPC upgrade

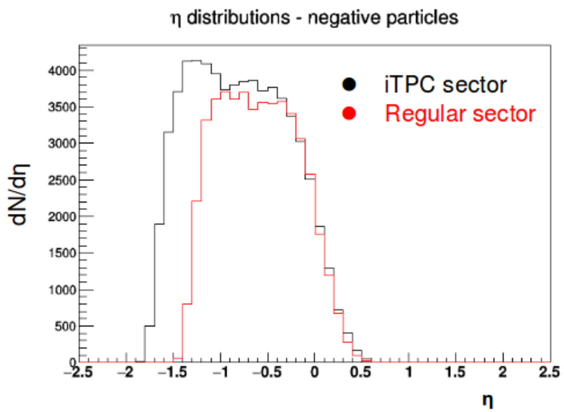
- **Inner Sectors**
  - New designed strongback
  - New wire frames
  - Increase readout pad rows (13 to 40)
- **New electronics for inner sectors**
  - Doubled readout channels. Using ALICE SAMPA chip
- **New designed insertion tooling**
  - Removal and insertion of inner sectors
- **Replace all 24 inner sectors**
  - 2018: One sector has been installed and used in the physics run
  - Full installation in autumn 2018

iTPC (one sector) performance in the current isobar collisions



- Maximum hits per track: 45→72
- Lower transverse momentum threshold of 60 MeV/c
- η coverage extended by 0.4 units

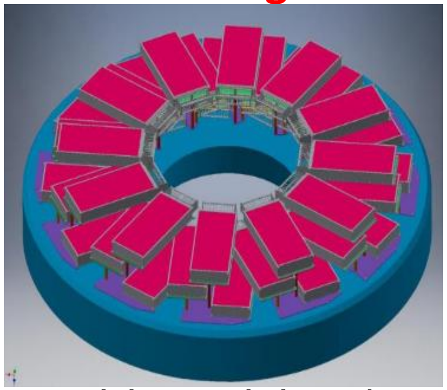




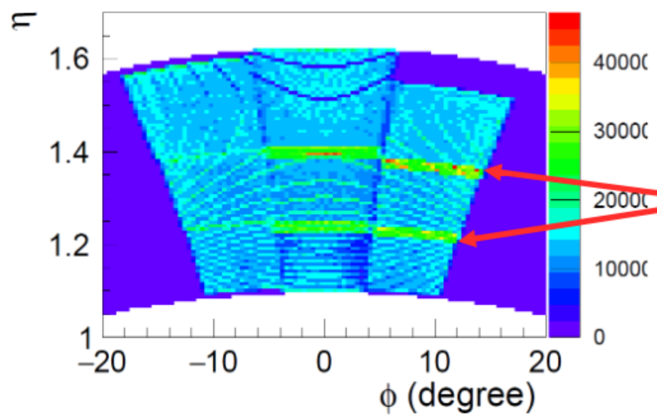
The endcap Time-Of-Flight

- **Install, commission and use 10% of the CBM TOF modules in STAR**
- **Design concept**
  - 3 layers, 12 sectors, 36 modules, 108 MRPCs
- **Provides PID in the forward direction**
  - Extended rapidity and yields
- **One sector with three modules has been installed for runs in 2018**
- **Full installation in autumn 2018**

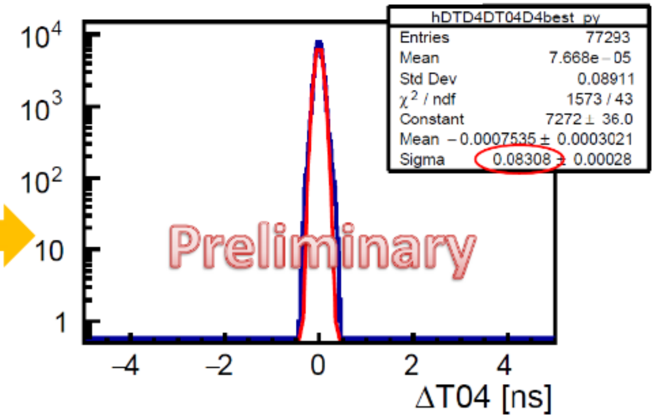
eTOF (three modules) commissioned, integrated and participated in data taking



- Reasonable η-ϕ hit distribution
  - eTOF works properly
- Time resolution 59 ps



Overlap range of two MRPCs



✓ System time resolution: 83 ps
✓ Counter time resolution: 59 ps

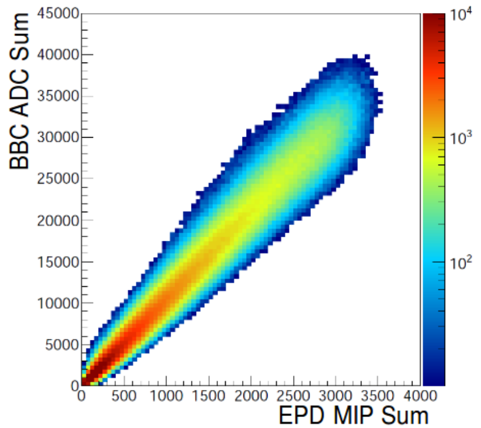
The Event Plane Detector

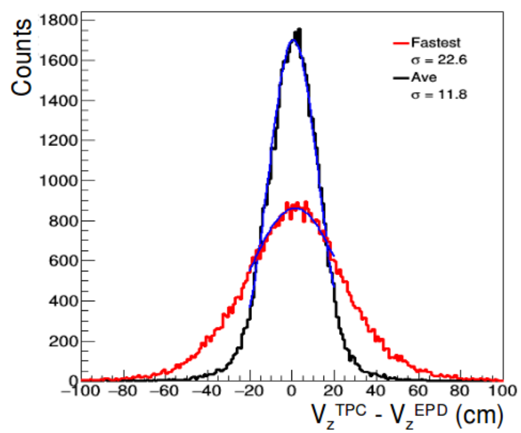
Event Plane Detector

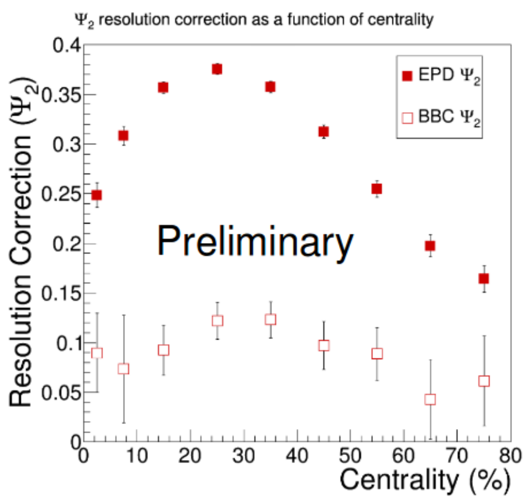
- **2 wheels**
  - East and West EPD (2.1<|η|<5.1)
- **12 super sectors**
  - Scintillator wedges, milled to form 31 tiles
  - Optically separated by epoxy
- **Fiber optics**
  - Wavelength-shifting fibers
  - Grouped in 3D-printed connectors
- **Sensors**
  - Silicon Photon Multipliers (SiPM)

EPD is fully installed and took part in data taking in 2018

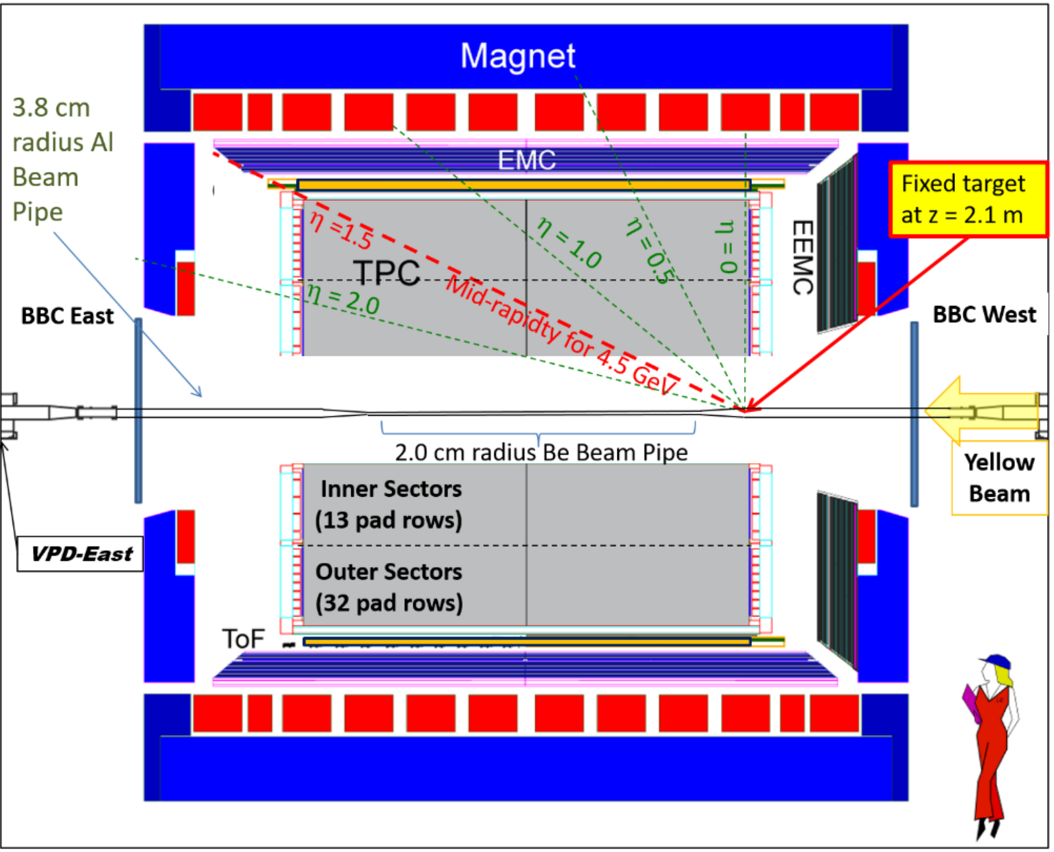
- All 744 tiles are good
- Good correlation between BBC and EPD
  - Correct timing
- Timing resolution is about 0.75 ns with fastest TAC method
  - 0.35 ns with average TAC method, raw slewing correction
- The 2nd-order event plane resolution is 0.37 in 20-30% central events at top energy isobar collisions



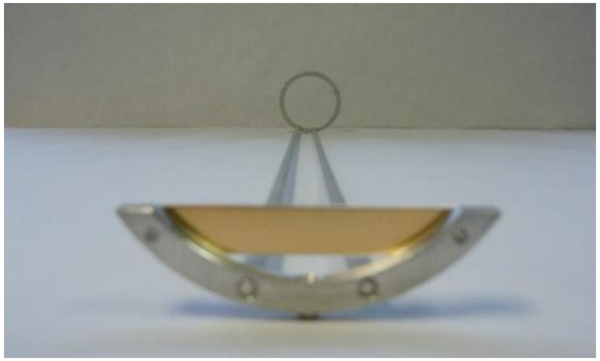


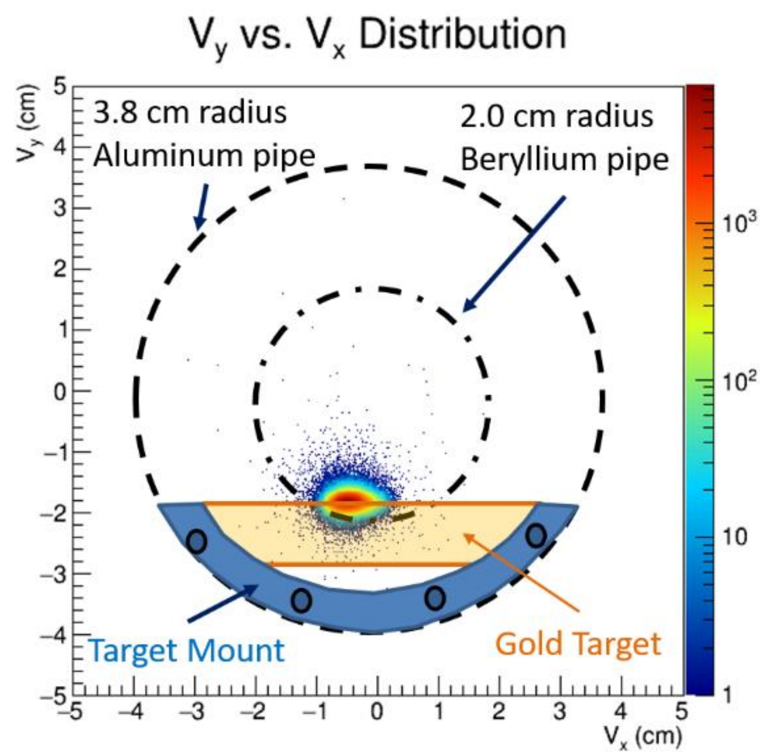


STAR Fixed-Target Program



A 1 mm thick (4% inter. prob.) gold target





1.3M events from half hour test run, top 30% central trigger, Au+Au $\sqrt{s_{NN}}$=4.5 GeV

3.4M events from two hour test run, top 30% central trigger, Al+Au $\sqrt{s_{NN}}$= 4.9 GeV