ISMD2021
50th International Symposium on Multiparticle Dynamics (ISMD2021)

Measurement of ϕ meson and Ξ^- hyperon production in Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV from STAR experiment

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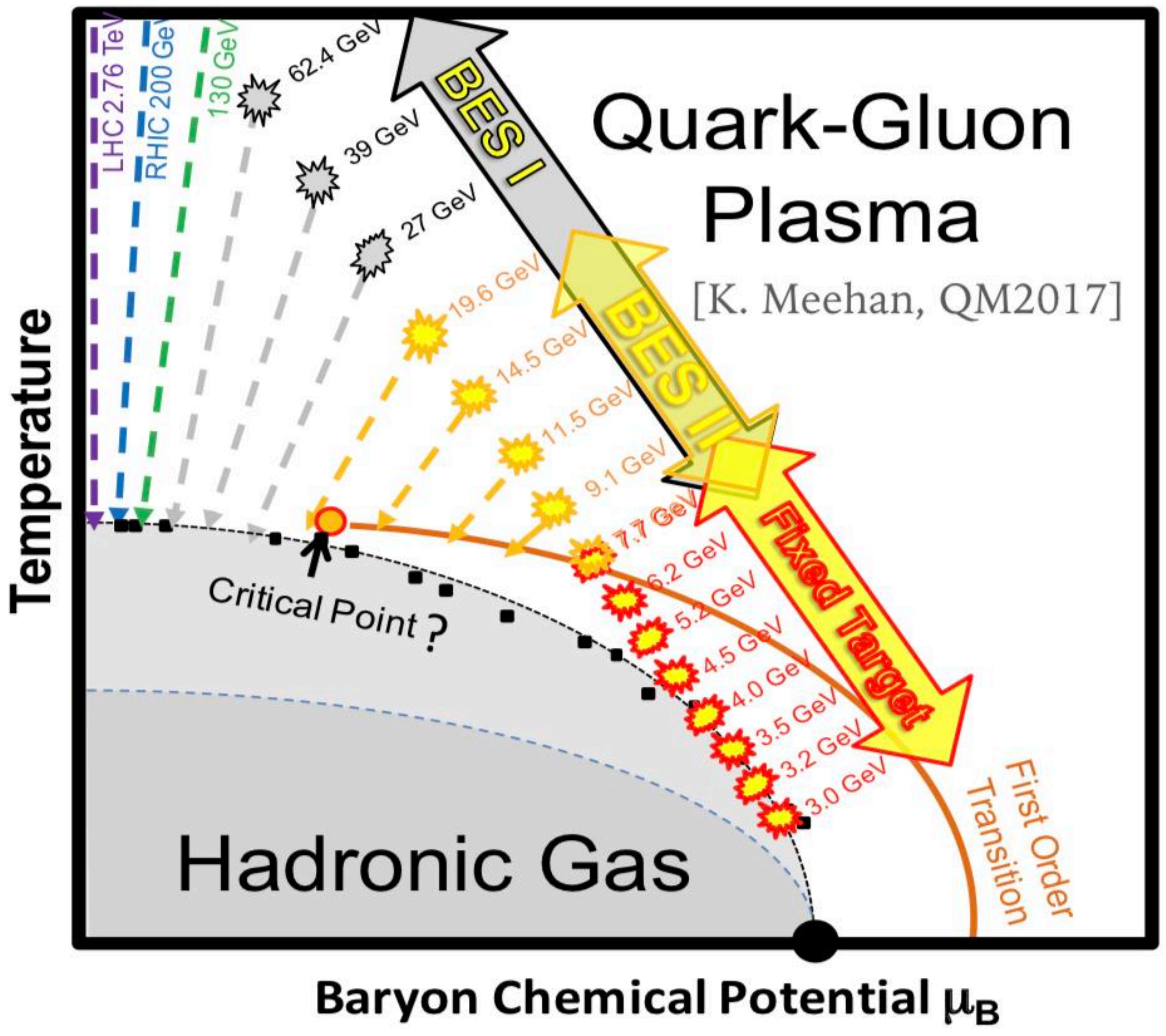
Jul 12, 2021

Supported in part by
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- **Motivation**
- **STAR Fixed Target (FXT) Setup**
- **Results of strange hadron production yields**
  - m_T spectra, rapidity distributions, yield ratios
- **Summary**

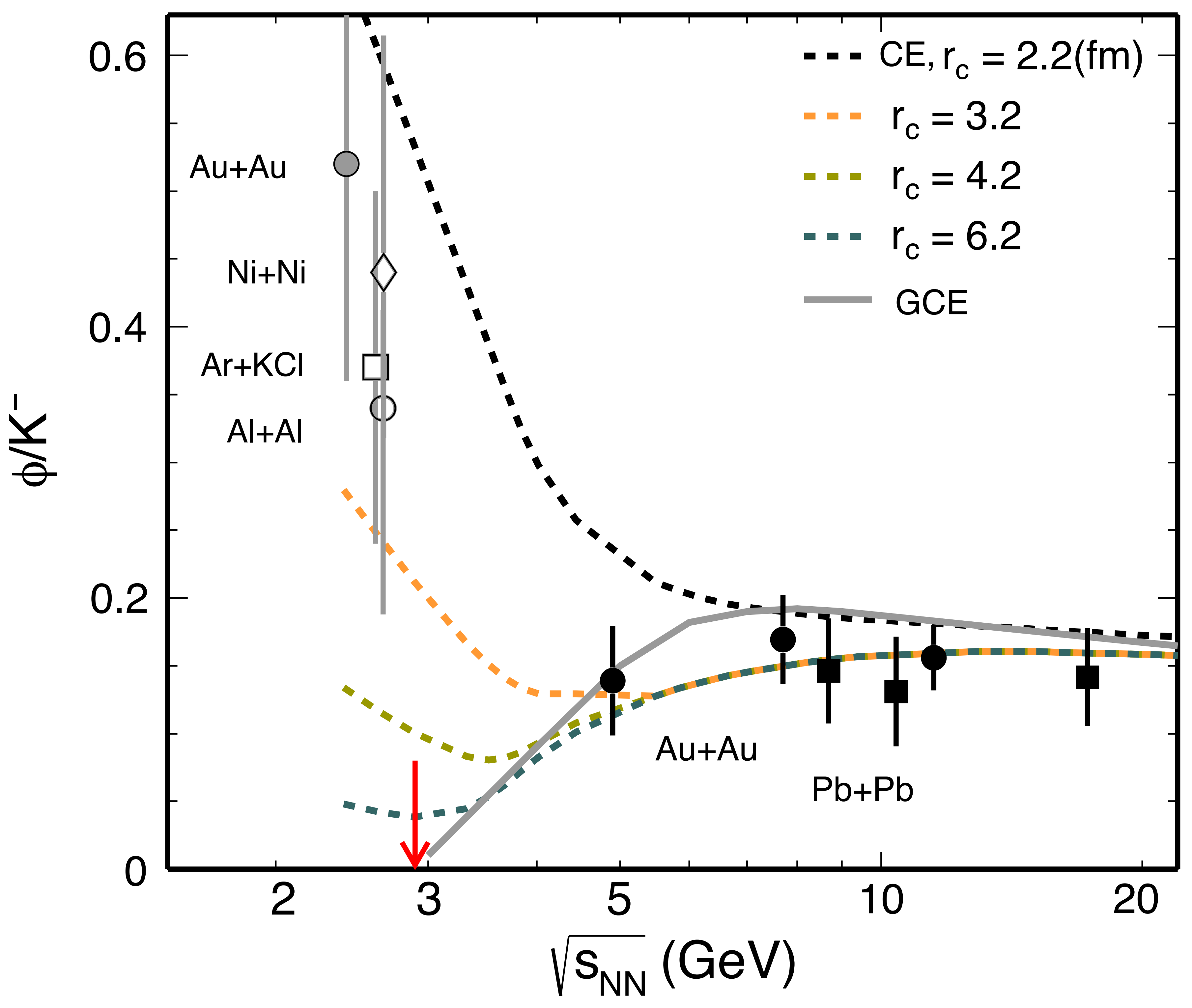
Introduction



- **RHIC BES covers the intermediate baryon density region**
  - **Look for onset of de-confinement, phase boundary and locate critical point**
- **STAR FXT mode $\sqrt{s_{NN}}$ = (3.0 - 13.7) GeV**
  - **High baryon chemical potential μ_B (~276 MeV up to ~ 720 MeV) allows us to study properties of high baryon density matter**
- **We focus on strange particles: kaons, ϕ, Ξ at 3 GeV**
  - **In high baryon region, strangeness is a penetrating probe to understand EOS of the medium**
  - **ϕ ($s\bar{s}$) meson has a small hadronic cross section**
  - **Compare with kaon yield to gain insight on the production mechanism**

A. Shor 1985 Phys. Rev. Lett. 54 1122
μ_B : J. Cleymans et al., PRC73, 034905(2006)

Motivation



HADES: Phys. Lett. B 778, 2018.403-407, Phys. Rev. C. 80.025209. (2009);
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CE,GCE, K. Redlich: Phys. Lett. B 603, 146 (2004); Private Communication;

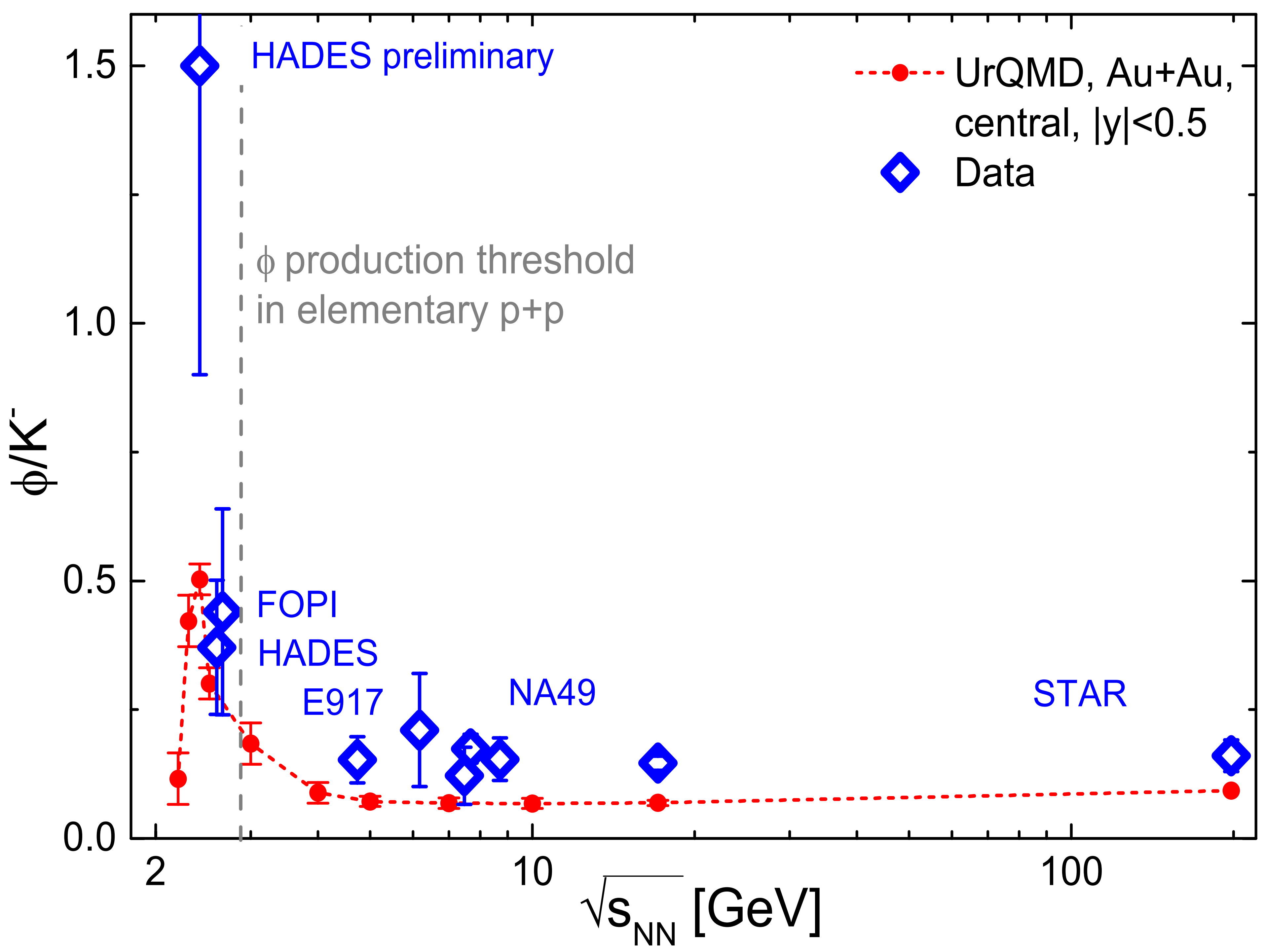
ϕ $(s\bar{s})$
K^- $(s\bar{u})$

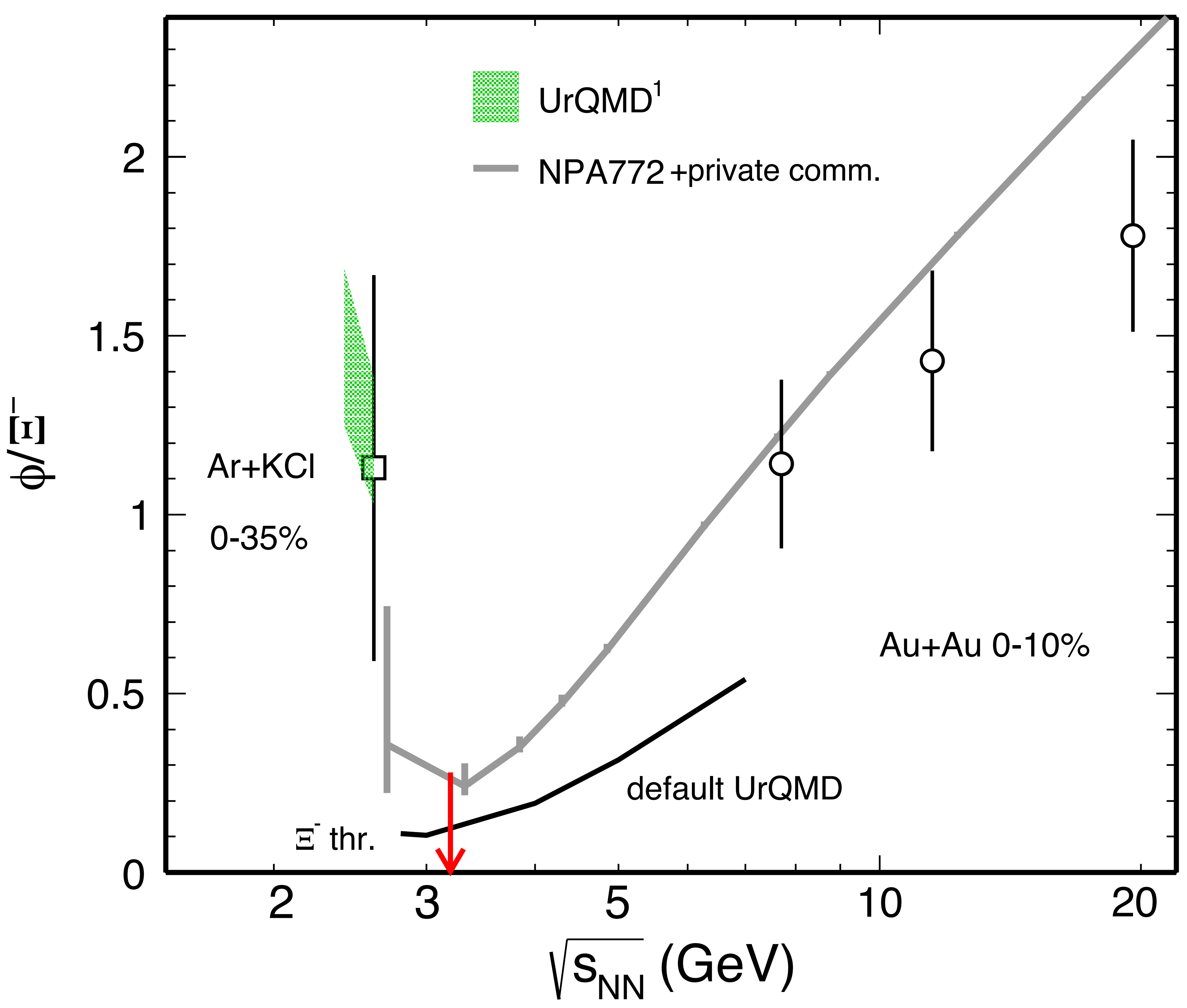
- **Sizeable increase of ϕ/K^- ratio below production threshold**
- **Grand canonical ensemble (GCE) and canonical ensemble (CE) calculations are quite different at low energy**

Motivation

UrQMD: J. Phys. G: Nucl. Part. Phys. 43 (2016) 015104 (14pp)

ϕ $(s\bar{s})$
K^- $(s\bar{u})$
Ξ^- (dss)





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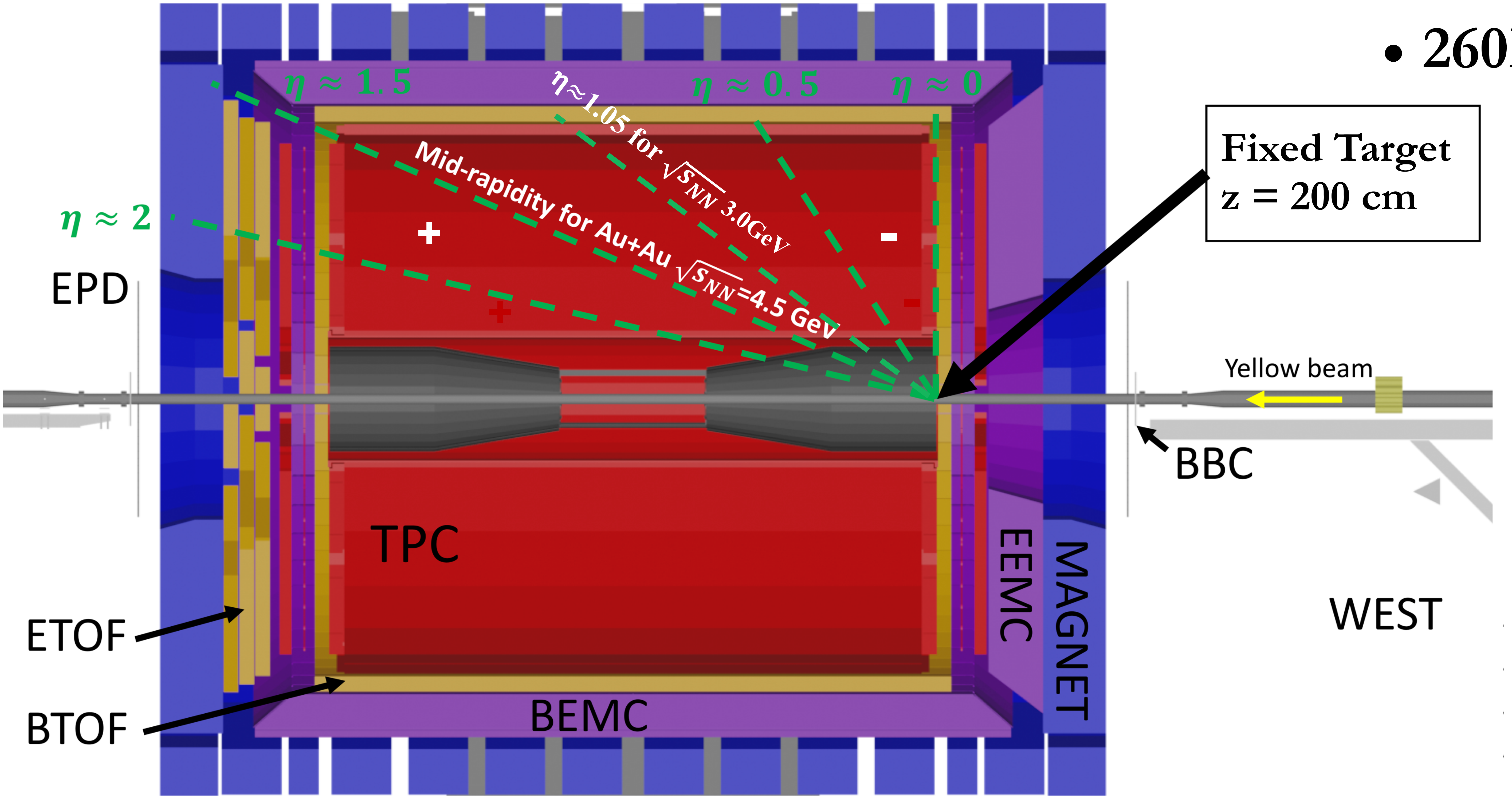
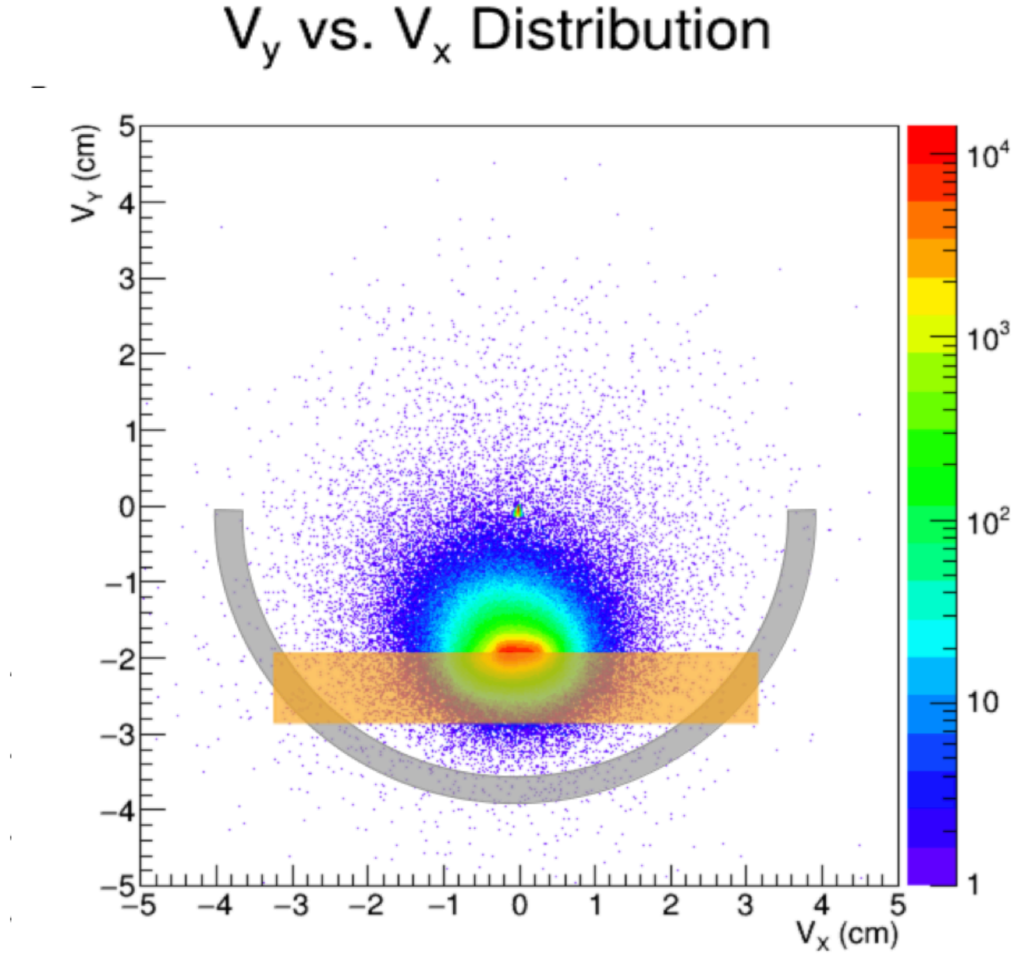
STAR: Phys. Rev. C 102 (2020) 34909
NPA772: A. Andronic et al. Nucl. Phys. A 772, 167 (2006); +private communication
UrQMD[1]: J. Phys. G: Nucl. Part. Phys. 43 (2016) 015104 (14pp);
UrQMD (default version): Prog. Part. Nucl. Phys. 41 (1998) 225-370
NPA772: GCE+ I_0/I_s +V_C = 1500 fm^3

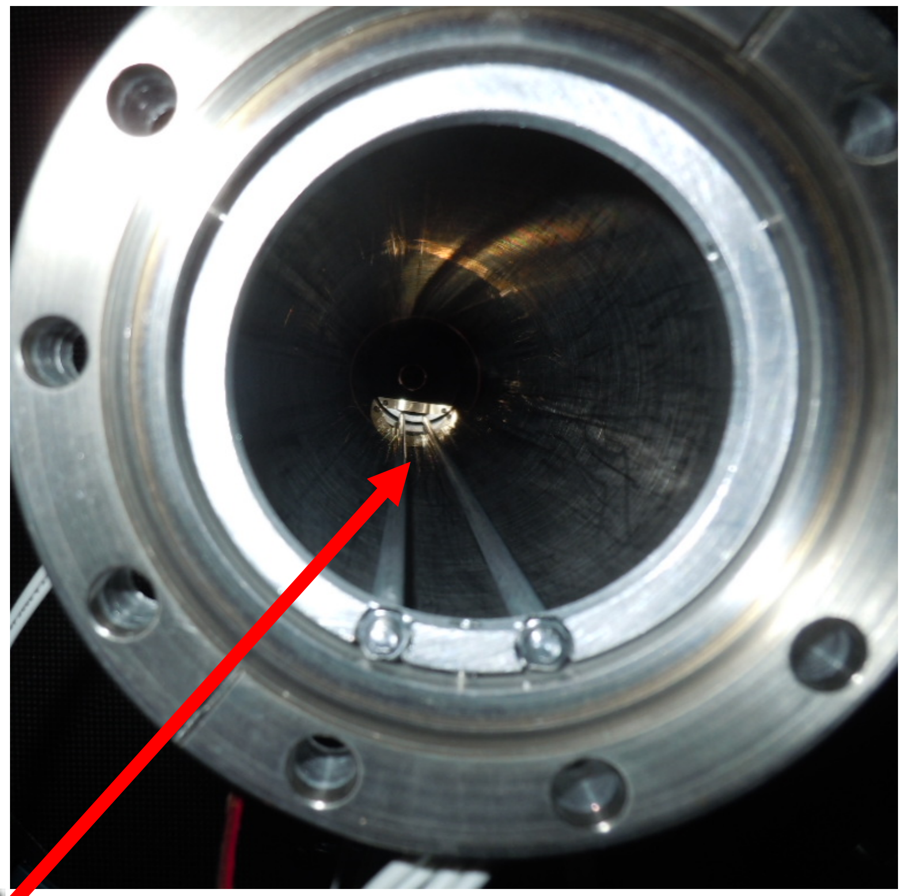
- **Sizeable increase of ϕ/K^- ratio around production threshold**
- **Grand canonical ensemble (GCE) and canonical ensemble (CE) calculations are quite different at low energy**
- **UrQMD suggests that the high baryon resonance decay may be important**
- **Ξ^- has two strange quarks, the canonical suppression should be even larger compared to K^-**
  - **Similar to ϕ/K^- for test of the CE and GCE**

STAR Fixed Target (FXT) Setup

- Au-target was installed at the edge of TPC
- Good mid-rapidity coverage
- 260M events for Au+Au FXT at $\sqrt{s_{NN}} = 3$ GeV







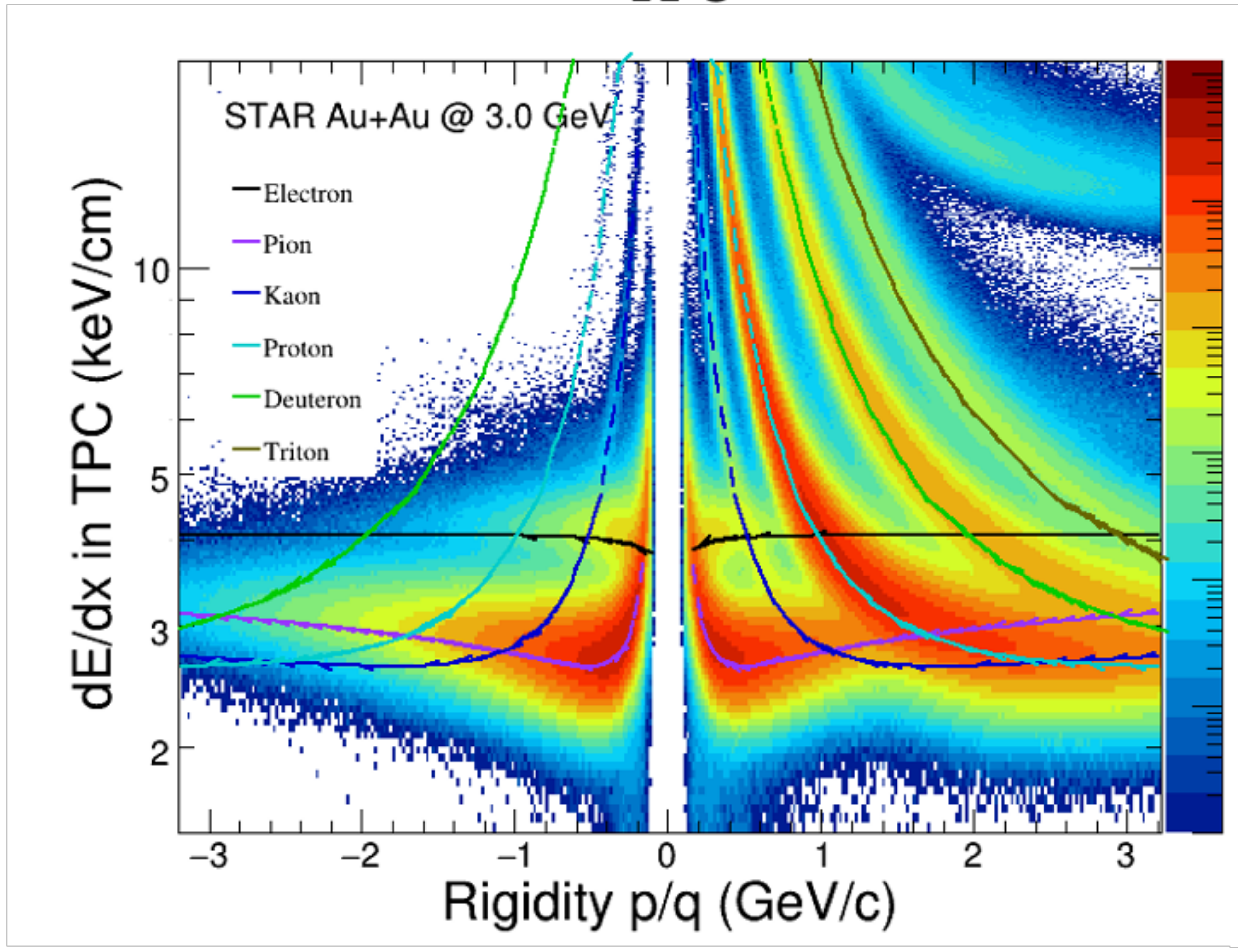
Beam pipe

Au-Target =0.25mm thickness
1% interaction probability

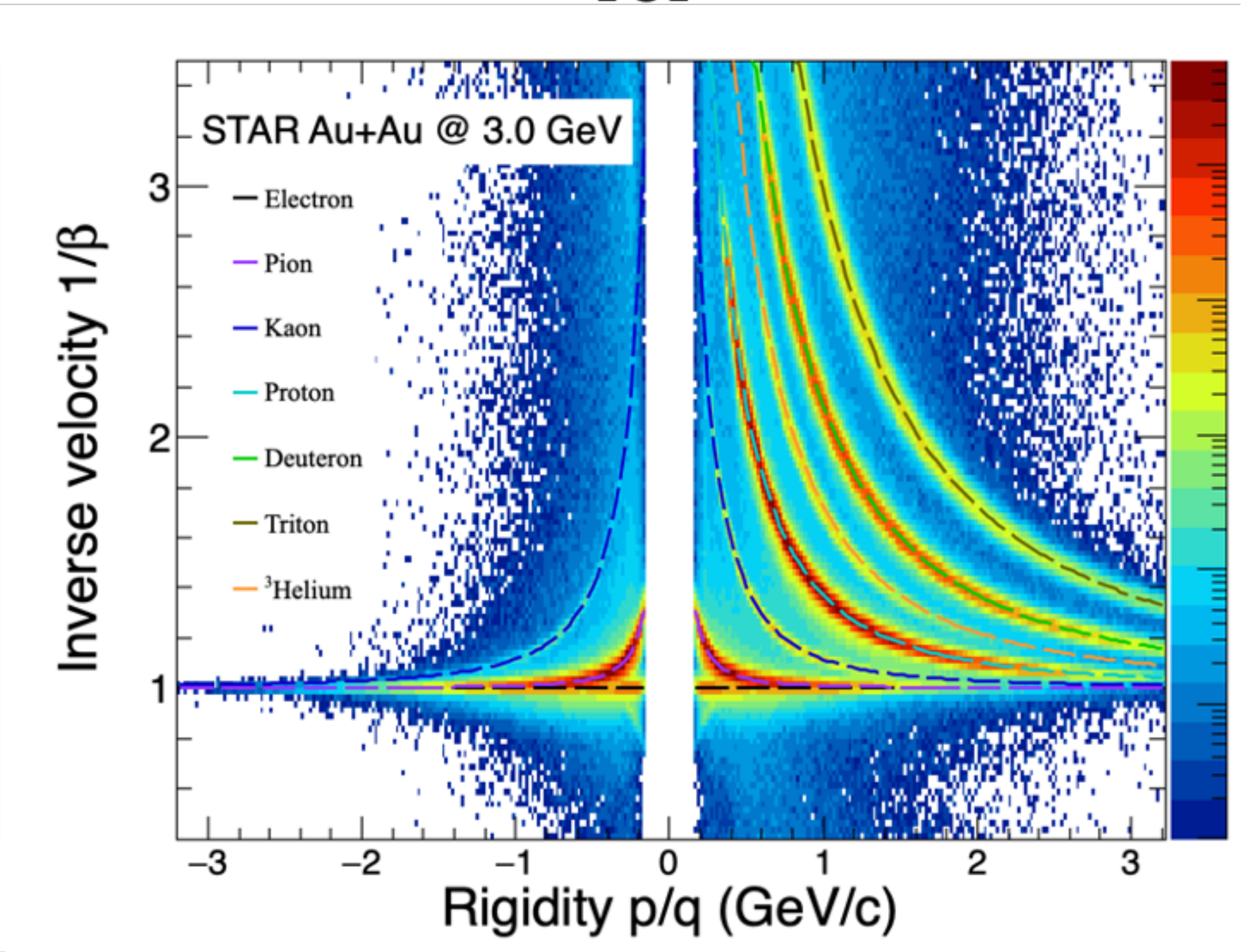
Conventions:
beam-going direction is the positive direction
In C.M. frame, $y_{target} = -1.045$ for the 3GeV collisions

PID at STAR FXT

TPC

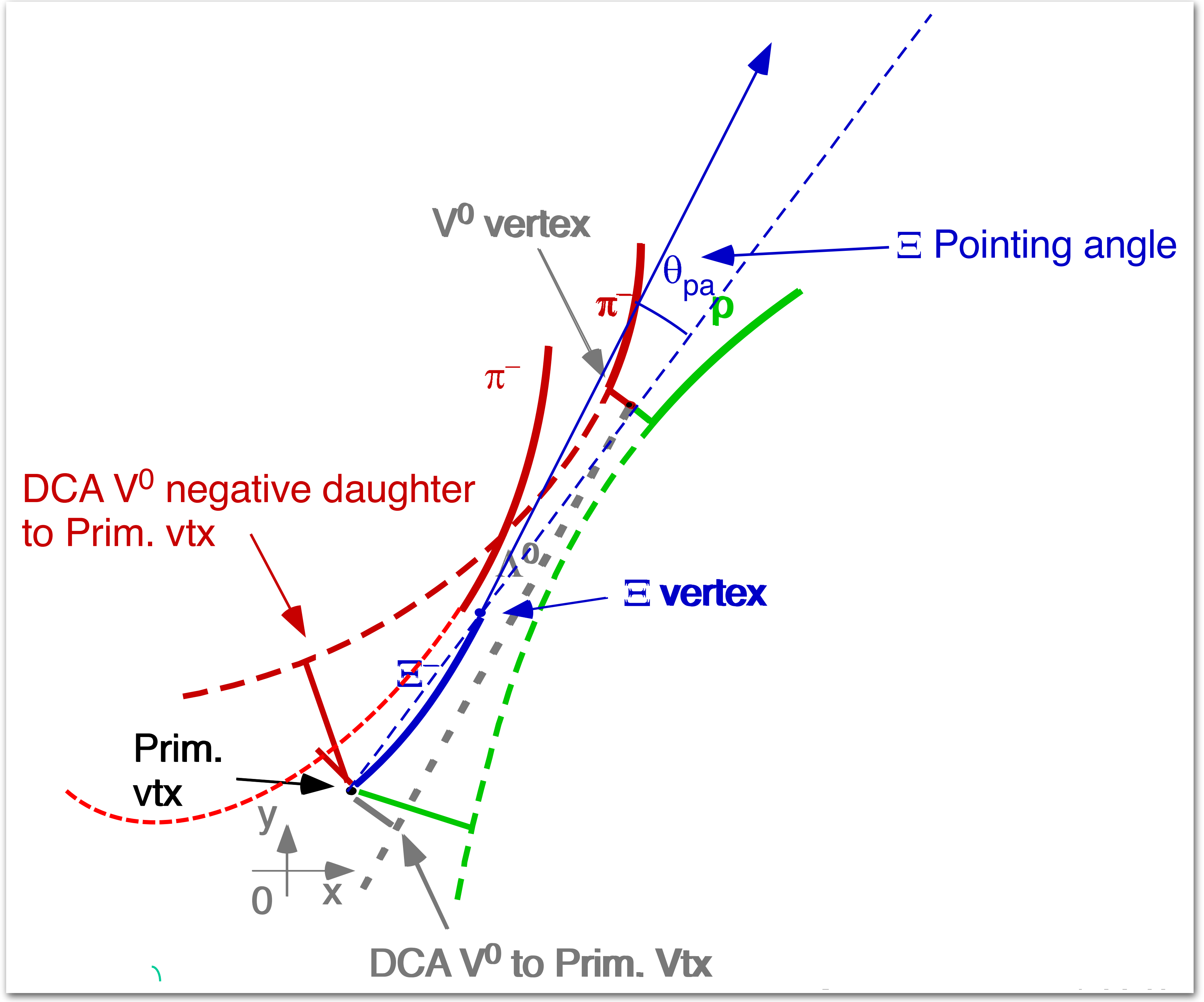


TOF



- **TPC (dE/dx) and TOF (β) for pion, kaon and proton particle identification**
- **Strict K^- PID: TPC+TOF, Hybrid TOF PID(require β cut only if TOF is available) for K^+**
- **Hadronic channel**
  - $\phi \to K^+K^-$
  - $\Xi^- \to \Lambda(p\pi^-) + \pi^-$

Particle reconstruction



KFParticle class describes particles by:

$\mathbf{r} = \{ x, y, z, p_x, p_y, p_z, E \}$

State vector

$$\mathbf{C} = \langle \mathbf{r}\mathbf{r}^T \rangle = \begin{bmatrix} \sigma_x^2 & C_{xy} & C_{xz} & C_{xp_x} & C_{xp_y} & C_{xp_z} & C_{xE} \\ C_{xy} & \sigma_y^2 & C_{yz} & C_{yp_x} & C_{yp_y} & C_{yp_z} & C_{yE} \\ C_{xz} & C_{yz} & \sigma_z^2 & C_{zp_x} & C_{zp_y} & C_{zp_z} & C_{zE} \\ C_{xp_x} & C_{yp_x} & C_{zp_x} & \sigma_{p_x}^2 & C_{p_xp_y} & C_{p_xp_z} & C_{p_xE} \\ C_{xp_y} & C_{yp_y} & C_{zp_y} & C_{p_xp_y} & \sigma_{p_y}^2 & C_{p_yp_z} & C_{p_yE} \\ C_{xp_z} & C_{yp_z} & C_{zp_z} & C_{p_xp_z} & C_{p_yp_z} & \sigma_{p_z}^2 & C_{p_zE} \\ C_{xE} & C_{yE} & C_{zE} & C_{p_xE} & C_{p_yE} & C_{p_zE} & \sigma_E^2 \end{bmatrix}$$

Covariance matrix

Particle	Decay	BR	cτ(cm)
Ξ^-	$\Lambda\pi^-$	99.9%	4.91
Λ	$p\pi^-$	63.9%	7.89

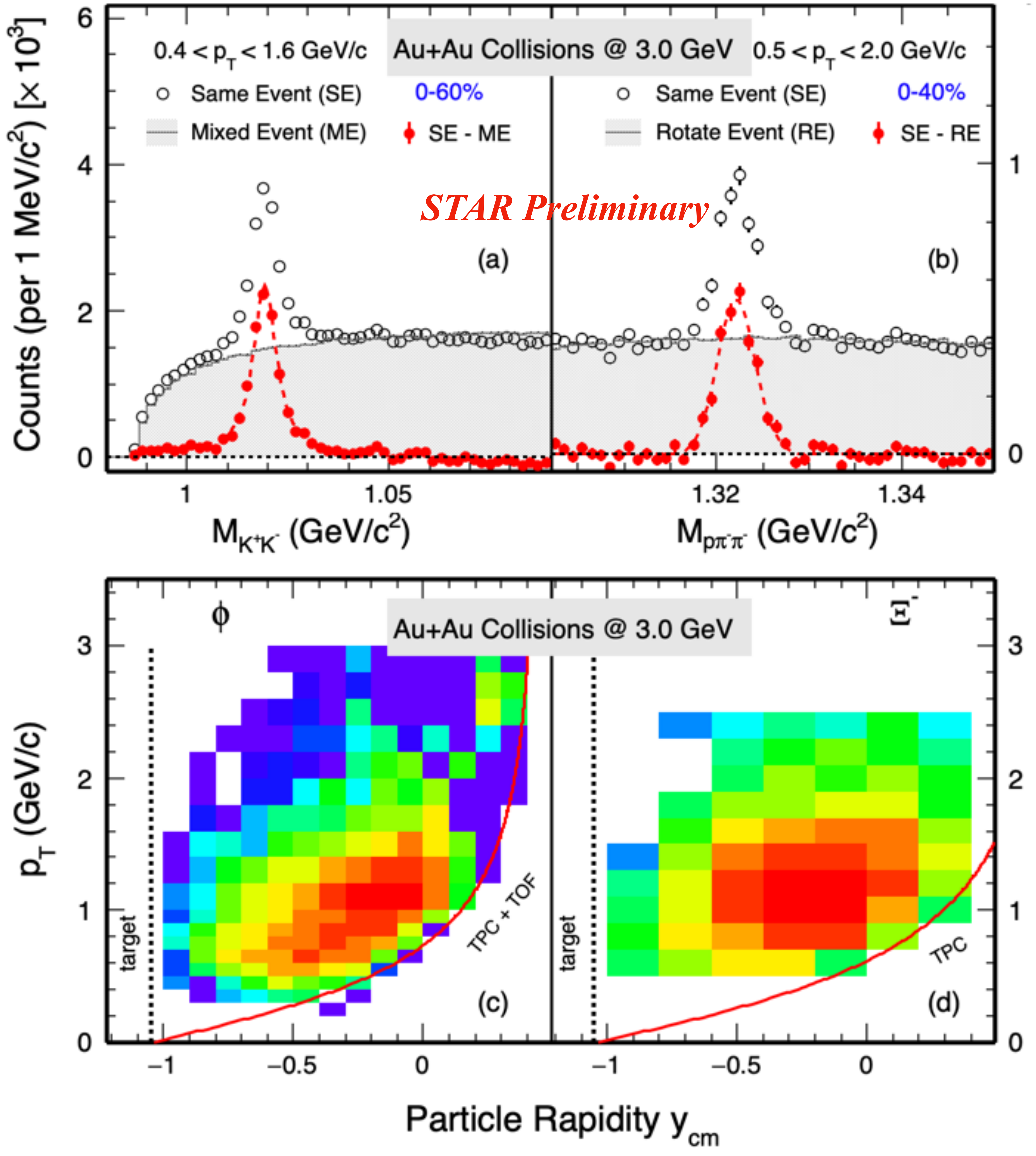
- **Use the KFParticle package for Ξ reconstruction, takes error matrices into account**
  - **Instead of using DCA and point angle θ, KF Particle is using χ^2**

    Chi2Topo (dca of Ξ to PV in chi2), Chi2ndf (dca of Λ to π in chi2): <10
    Chi2_prim, π ← Λ (DCA of π to PV in chi2): > 10
    Chi2_prim, p ← Λ (DCA of p to PV in chi2): > 10
    Chi2_prim, π ← Ξ (DCA of π to PV in chi2): > 10
    Ξ LdL (normalized decay length): > 6

- **KF Particle package shows a high quality of the reconstructed particles**

KF Particle Finder — M. Zyzak, "Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR," Dissertation thesis, Goethe University of Frankfurt, 2016, http://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/41428z

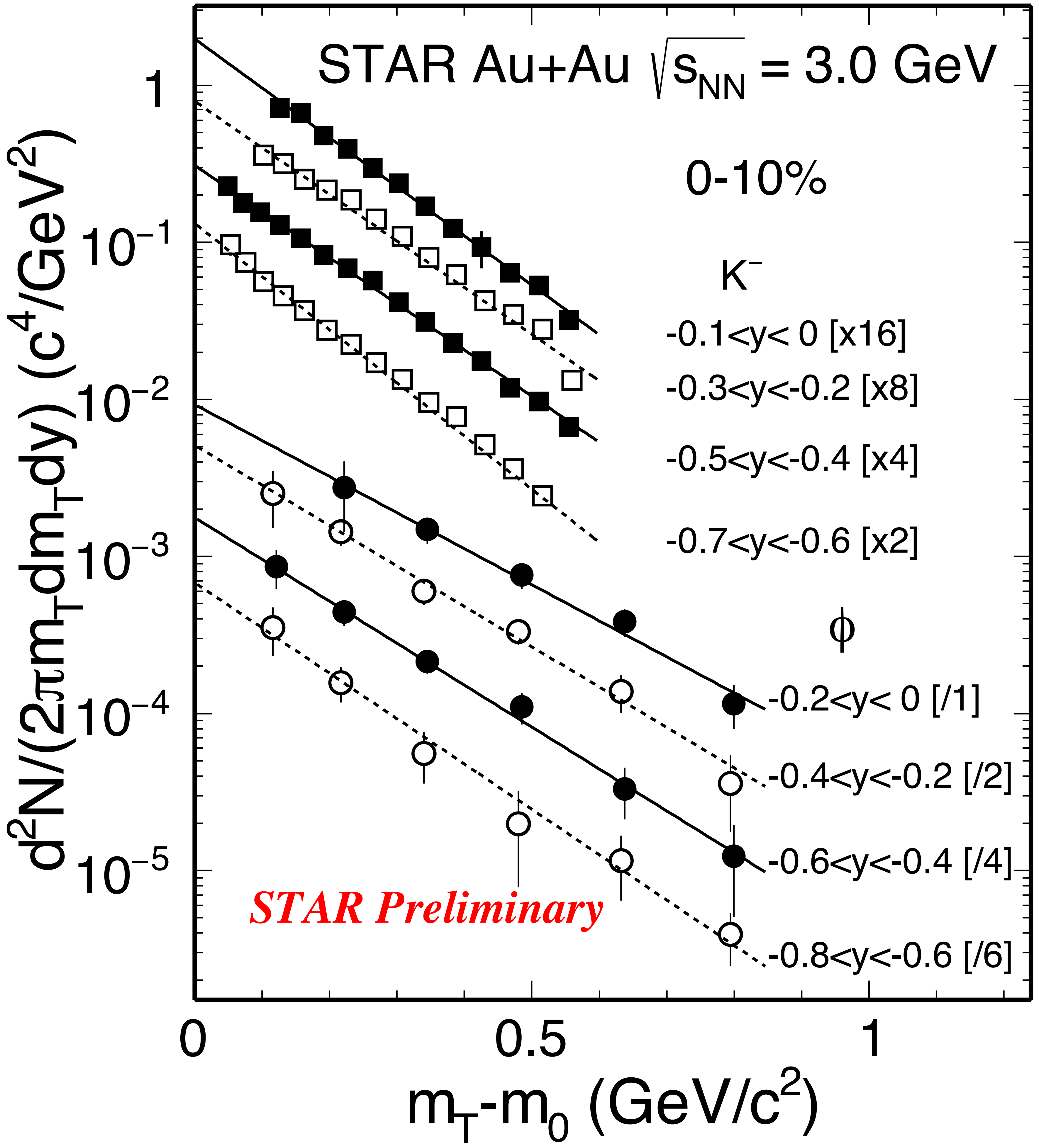
Particle reconstruction



- ϕ meson reconstruction
  - K^+K^- invariant mass
  - Normalized mixed events background
  - Signal: Breit-Wigner function
  - Residual background: Linear function

- Ξ^- reconstruction
  - $\Lambda\pi^-$ invariant mass
  - Normalized rotation background (rotating daughter tracks)
  - Signal: Gaussian function
  - Residual background: Linear function

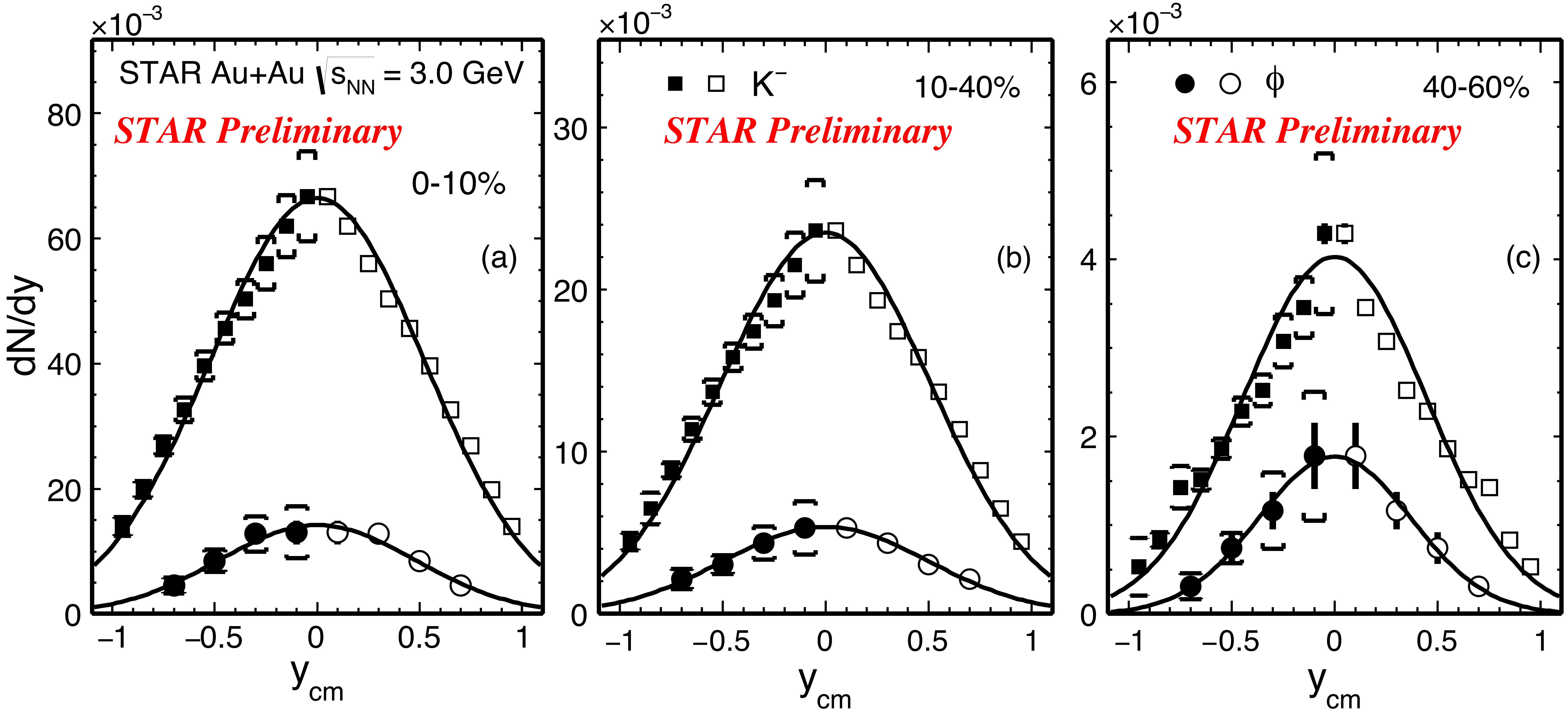
Efficiency corrected m_T spectra



- **Tracking efficiency and acceptance effects are estimated with GEANT simulations embedded into real events**
- **K^- and ϕ-meson invariant yields in 0-10% for various rapidity regions**
- **Low p_T extrapolation: m_T exponential fits**

$$\frac{d^2N}{2\pi p_T dp_T dy} \propto e^{-\frac{m_T}{T}}$$

Rapidity density distributions

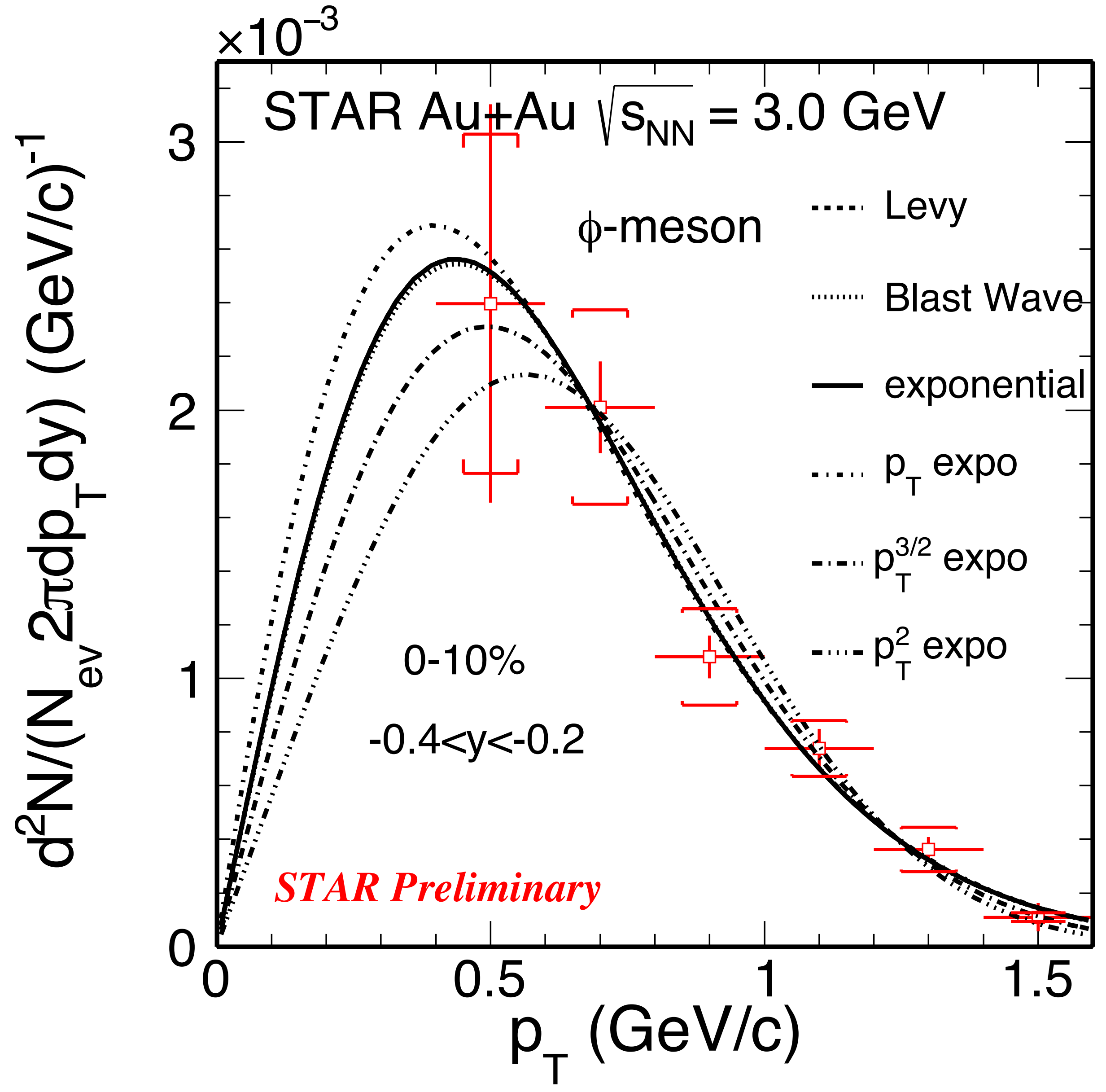


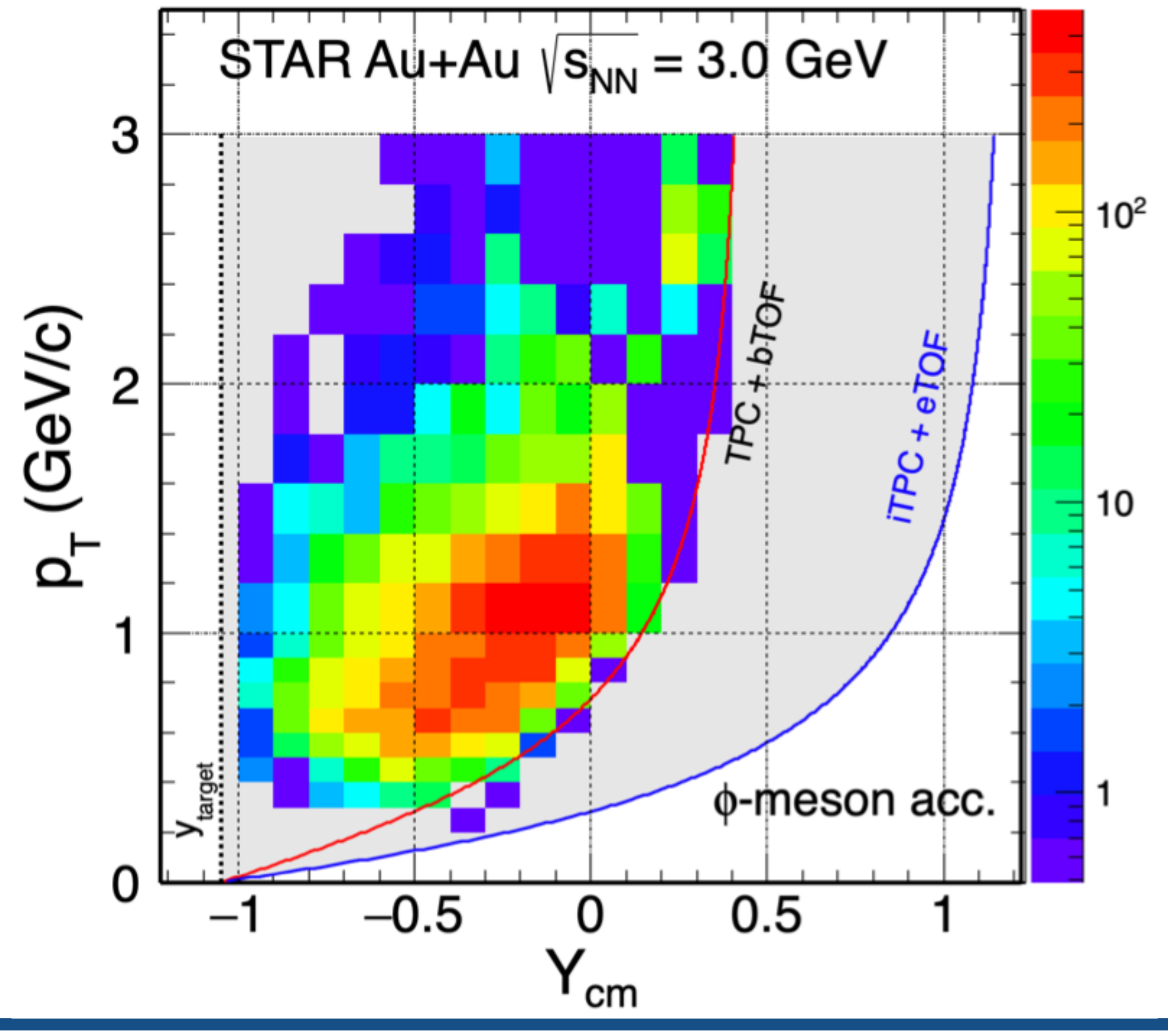
- Rapidity distributions of K^- and ϕ meson for various centrality regions, solid symbols are measured data, open ones are reflection
- Yields obtained from integrating fits of spectra and are then fit with a Gaussian

Systematic uncertainty

- Sources of systematic uncertainties:
  - low p_T extrapolation
  - Single track efficiency
  - PID
  - Topological cuts

- The dominant source is low p_T extrapolation
  - Extrapolation with different functions to estimate yield in the unmeasured p_T range
  - The low p_T range can be extended with iTPC (installed in 2019) + endcap TOF detector (installed in 2019)

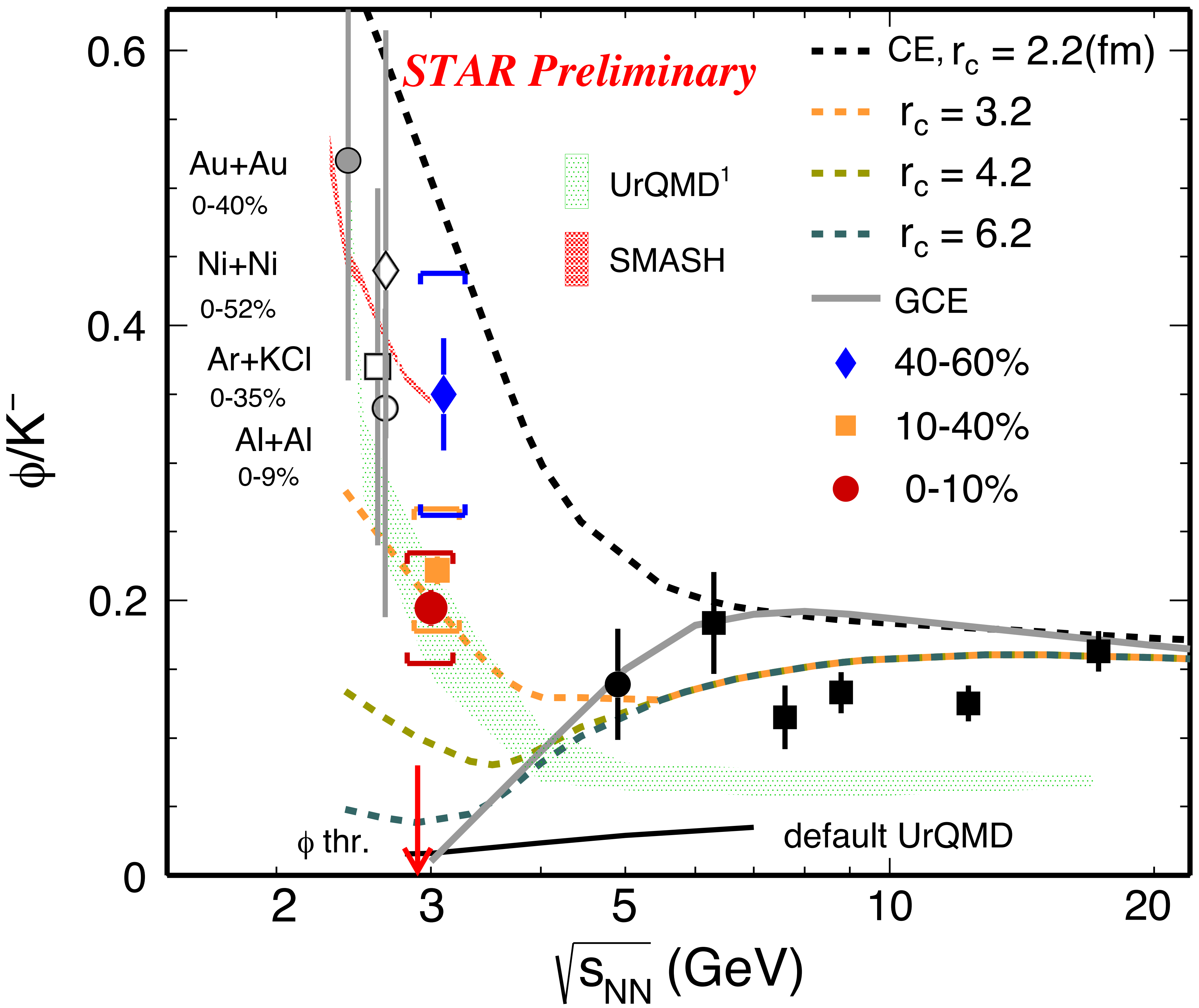




ϕ/K^{-} ratio

Beam energy dependence of strangeness production

$\phi(s\bar{s})$, K^{-} $(s\bar{u})$



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SMASH : Phys. Rev, C 99, 064908 (2019)

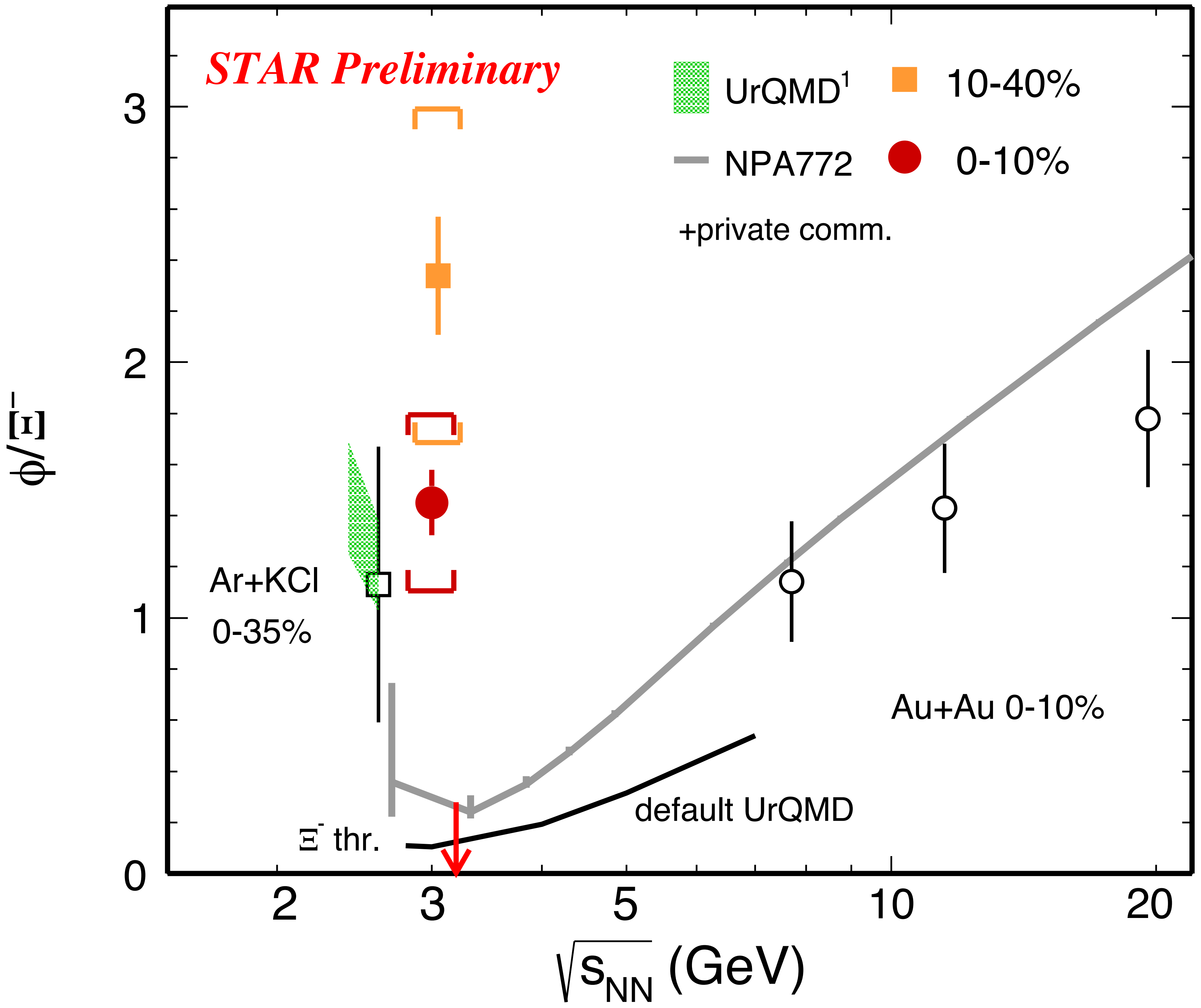
r_c : correlation length, radius of the volume inside which the production of particles with open strangeness is canonically conserved

- **Low energies, strangeness production is rare, local strangeness conservation is required**
- **~5σ deviation from zero (GCE) for 0-10% central collisions. Data favors the CE with r_c~ 3.2 fm**
- **Transport models with high mass resonance can reasonably describe data at low energies**

ϕ/Ξ^- ratio

Beam energy dependence of strangeness production

$\phi(s\bar{s})$, Ξ^- (dss)



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NPA772: GCE+ I_0/I_S +V_C = 1500 fm³

- **NPA772: GCE + I_0/I_S +V_C = 1500 fm³ describes data well at > 5 GeV, but underestimate our measurement at 3 GeV**
- **Canonical suppression is important at low energies**
- **Transport models with high mass resonance decay to ϕ and Ξ^- can reasonably describe previous measurement from SIS energies**

Summary

- Presented measurements on strangeness production in Au+Au 3 GeV collisions
  - Precise measurements of ϕ/K^- and ϕ/Ξ^- show strong effect of canonical suppression
  - Indicating a change of EoS, particle production mechanism may differ from that at high energy

Outlook

- Future precise measurements of ϕ/K^- and ϕ/Ξ^- on the centrality dependence from the STAR BES-II, to constrain the model calculations
  - iTPC+eTOF extend the low p_T reach to reduce systematic uncertainties
  - 2B Au+Au events at $\sqrt{s_{NN}} = 3$ GeV collected in 2021
  - Expected to reduce statistical uncertainty in ϕ/K^- ratio in 40-60% centrality to <5%