STAR 25 YEARS

IMP

Probing Isospin Violation Under Strong Magnetic Fields via the Production of $K^{*0,\pm}$ Mesons in Heavy-Ion Collisions at RHIC

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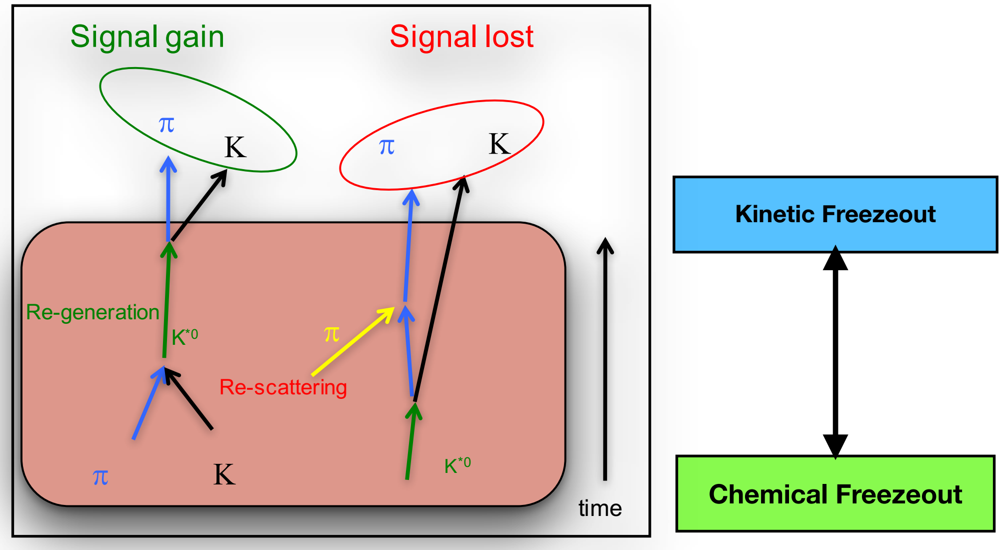
Outline

- Motivation
- STAR Experiment
- Results: Ru+Ru, Zr+Zr and O+O collisions at $\sqrt{s_{NN}} = 200$ GeV
  - K^{*0} and $K^{*\pm}$: spectra, yield (dN/dy) and $\langle p_T \rangle$
  - $K^{*0}/K \rightarrow$ hadronic interaction
  - $K^{*\pm}/K^{*0} \rightarrow$ isospin violation
- Summary and outlook

Particle Species	Mass (GeV/c^2)	Spin	Lifetime (fm/c)	Magnetic moment (μ_N)
$K^{*0}(d\bar{s})$	0.896	1	~ 4	$\mu_d \approx -0.97,\ \mu_{\bar{s}} \approx 0.61\mu_N$
$K^{*+}(u\bar{s})$	0.892	1	~ 4	$\mu_u \approx 1.85,\ \mu_{\bar{s}} \approx 0.61\mu_N$

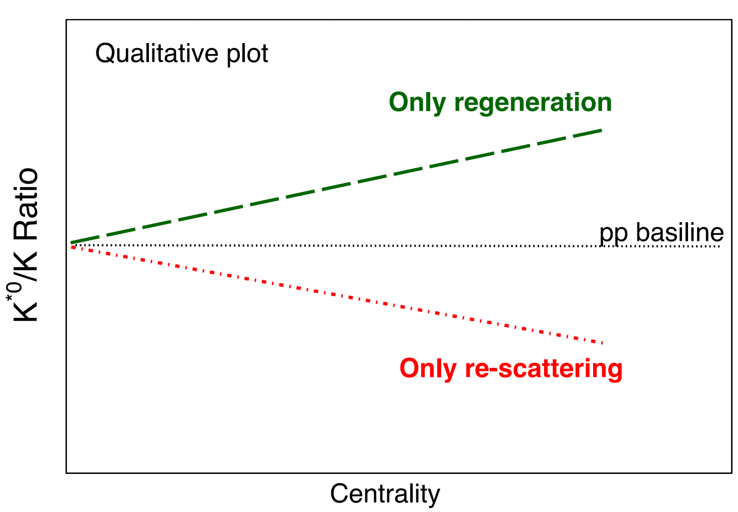
Motivation

Re-scattering and regeneration



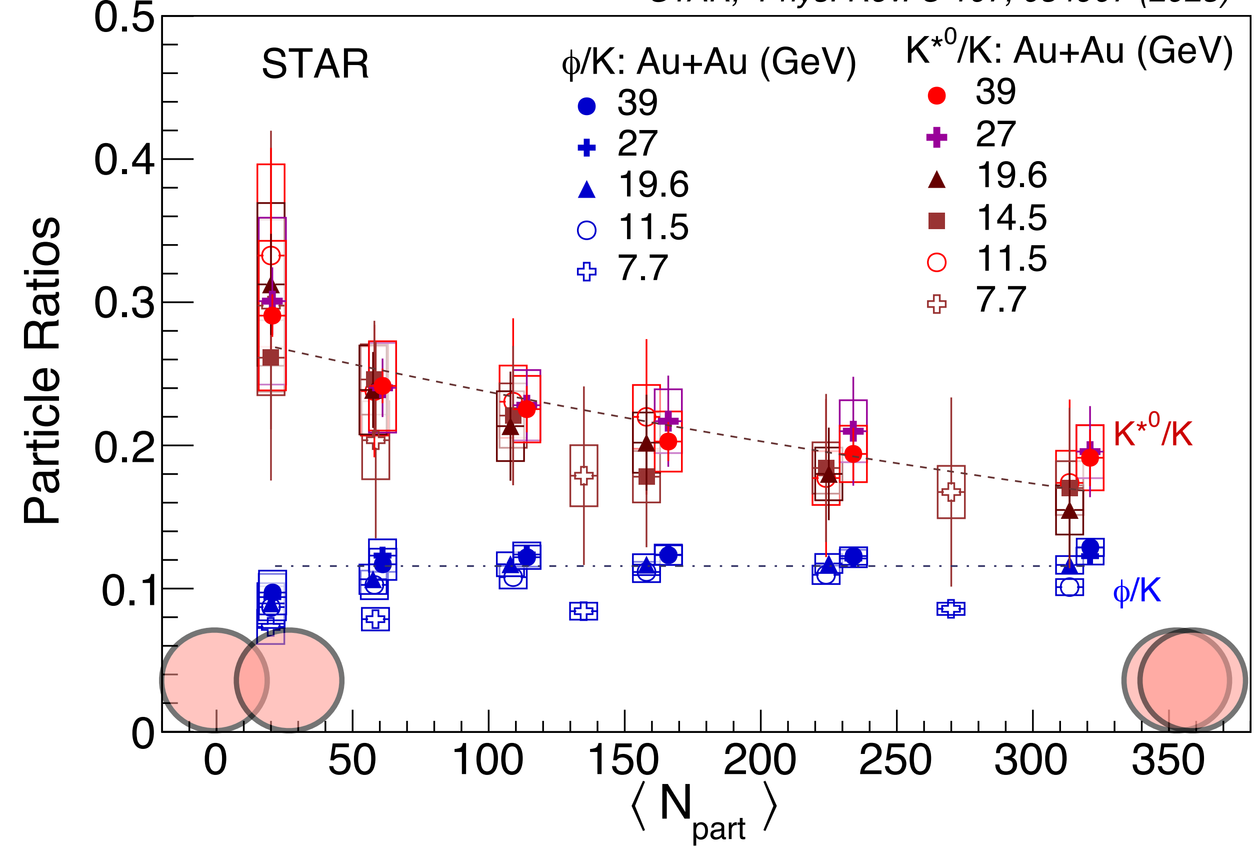
Specie	Decay	Lifetime (fm/c)
K^{*0}	Kπ	4
φ	KK	45

- Re-scattering decreases resonance yields
- Regeneration increases resonance yields
- Final yield decided by the interplay between them



Observation

STAR, Phys. Rev. C 107, 034907 (2023)



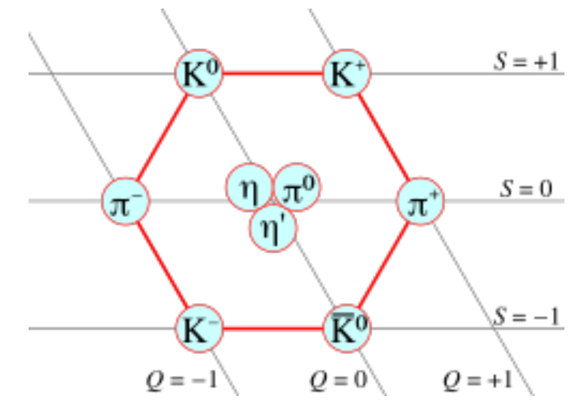
- $(K^{*0}/K)_{\text{central}} < (K^{*0}/K)_{\text{peripheral}}$
- (ϕ/K) ~ centrality independent

Dominance of late stage hadronic interactions

Is there isospin violation in Kaon ratios?

- Isospin → symmetry of strong interaction
- Kaons → isospin doublet $K^{\pm}(u\bar{s})$ and $K^{0}(d\bar{s})$

$$\frac{M_{K^+} - M_{K^0}}{M_{K^+} + M_{K^0}} \sim 0.004$$

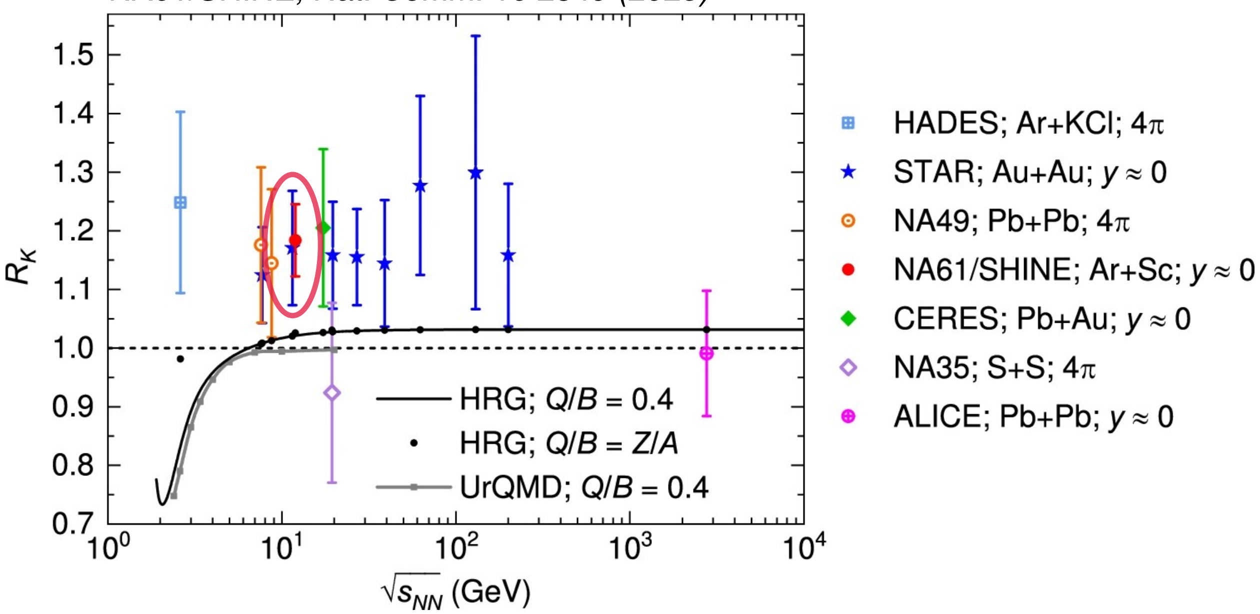


Courtesy: From Wikipedia

A+A collisions:

$$R_K = (K^+ + K^-)/2K^0_S$$

NA61/SHINE, Nat. Comm. 16 2849 (2025)



→ **NA61/SHINE observed isospin violation in HIC**

$$R_K = 1.18 \pm 0.06 \; (\sim \; 3\sigma)$$

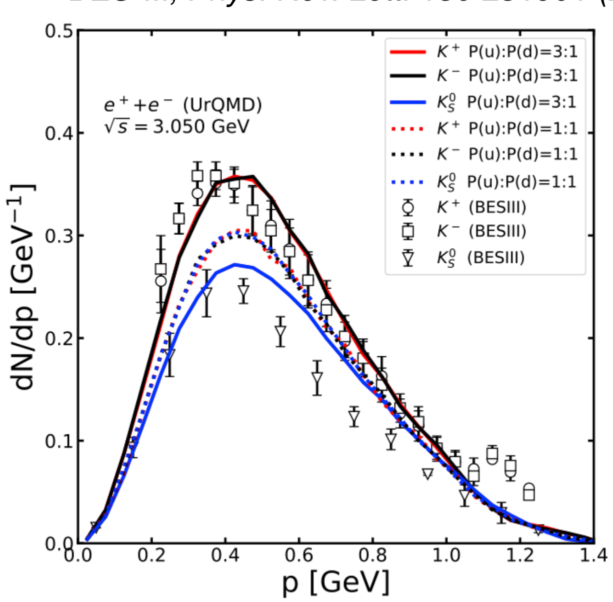
Deviation beyond baseline (e.g. initial isospin asymmetry in colliding nuclei, mass difference of kaons, CP violation in K^0 etc)

Violation also seen in e+e (and p+p) collisions (asymmetry in *u* and *d* quark fragmentation?)

But the reason behind violation is not understood yet!

e+e collisions:

BES-III, Phys. Rev. Lett. 130 231901 (2023); 2502.16084;



T Reichert et al, 2503.10493

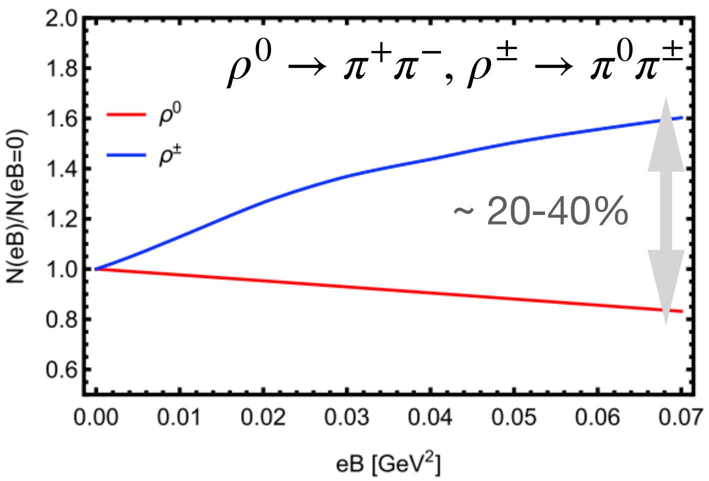
Alternate observable

$R_{K^*} = (K^{*+} + K^{*-})/(K^{*0} + \overline{K^{*0}})$?

[negligible feed-down (mostly primordial)]

Charged and neutral vector mesons under B-field

- Under a strong B-field, one expect $N_{\rho^{\pm}} > N_{\rho^{0}}$ from Landau level splitting (can cause isospin violation)



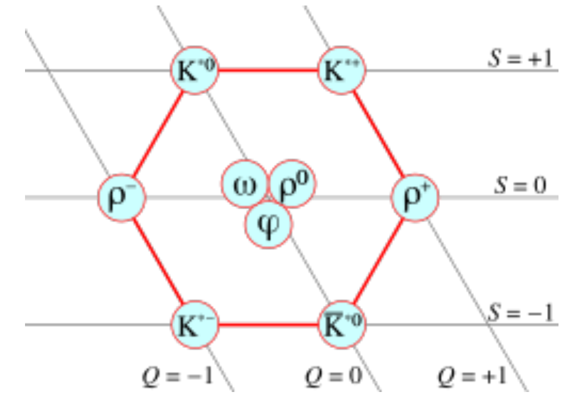
K. Xu et al, Phys. Lett. B 809, 135706 (2020)

M. Chernodub et al, Phys. Rev. D 82, 085011 (2010)

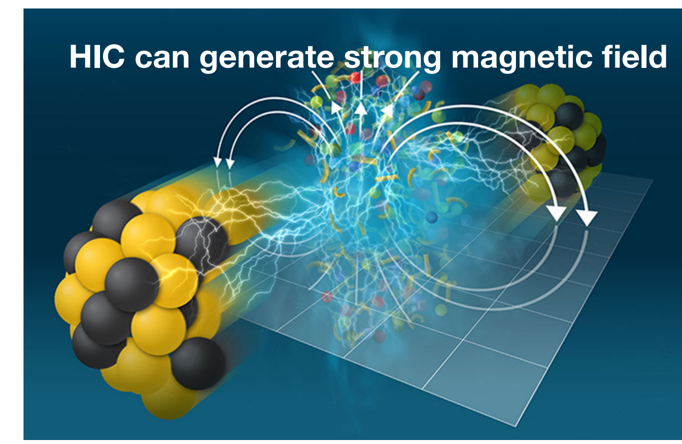
The energy level for a point-like charged particle under static uniform magnetic field B

$$\epsilon^2_{n,s_z}(p_z) = p_z^2 + (2n - 2\ \mathrm{sign}(q)s_z + 1)|qB| + m^2$$

q = electric charge; n = Landau level;
s_z = projection of spin along magnetic field
p_z = momentum along magnetic field



Courtesy: From Wikipedia



$K^{*0} \to K^\pm\pi^\mp,\ K^{*\pm} \to K^0_S\pi^\pm$

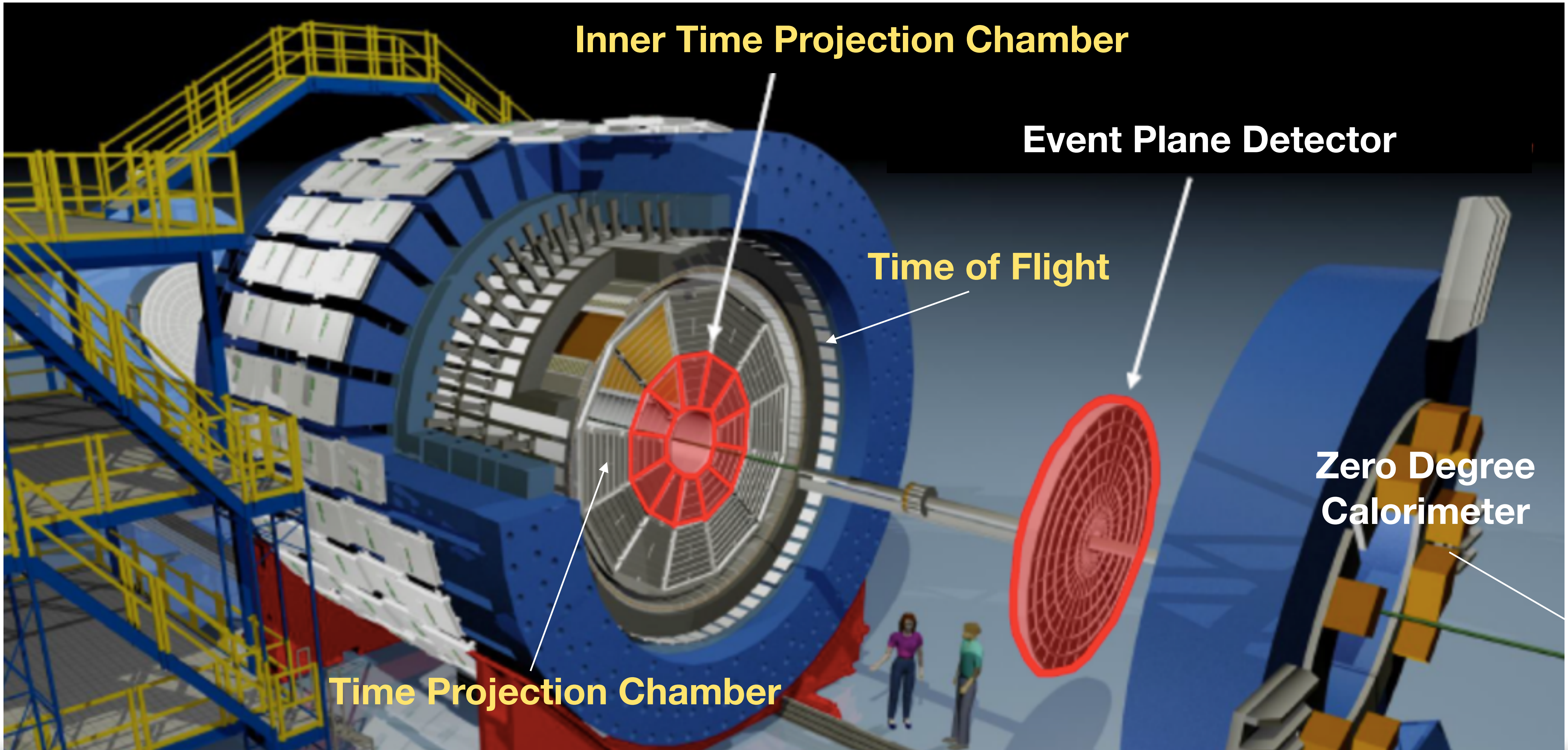
Assumptions:
- Point-like particle
- B-field persists when K^*'s are formed

- Expectation: $K^{*+}(u\bar{s}) > K^{*0}(d\bar{s})$
- The decay daughters of vector mesons ($K^\pm$ and K^0_S) can feed-down to $R_K = (K^+ + K^-)/2K^0_S$

Using vector meson yield ratios $R_{K^*} = (K^{*+} + K^{*-})/(K^{*0} + \overline{K^{*0}})$ one can constrain B-field at freeze-out

Particle Species	Mass (GeV/c²)	Spin	Lifetime (fm/c)	Magnetic moment (μ_N)
$K^{*0}(d\bar{s})$	0.896	1	~ 4	$\mu_d \approx -0.97, \mu_{\bar{s}} \approx 0.61\mu_N$
$K^{*+}(u\bar{s})$	0.892	1	~ 4	$\mu_u \approx 1.85, \mu_{\bar{s}} \approx 0.61\mu_N$

STAR Detector



- Uniform acceptance, full azimuthal coverage, excellent PID capability
- TPC: tracking, centrality and event plane
- TPC+TOF: particle identification

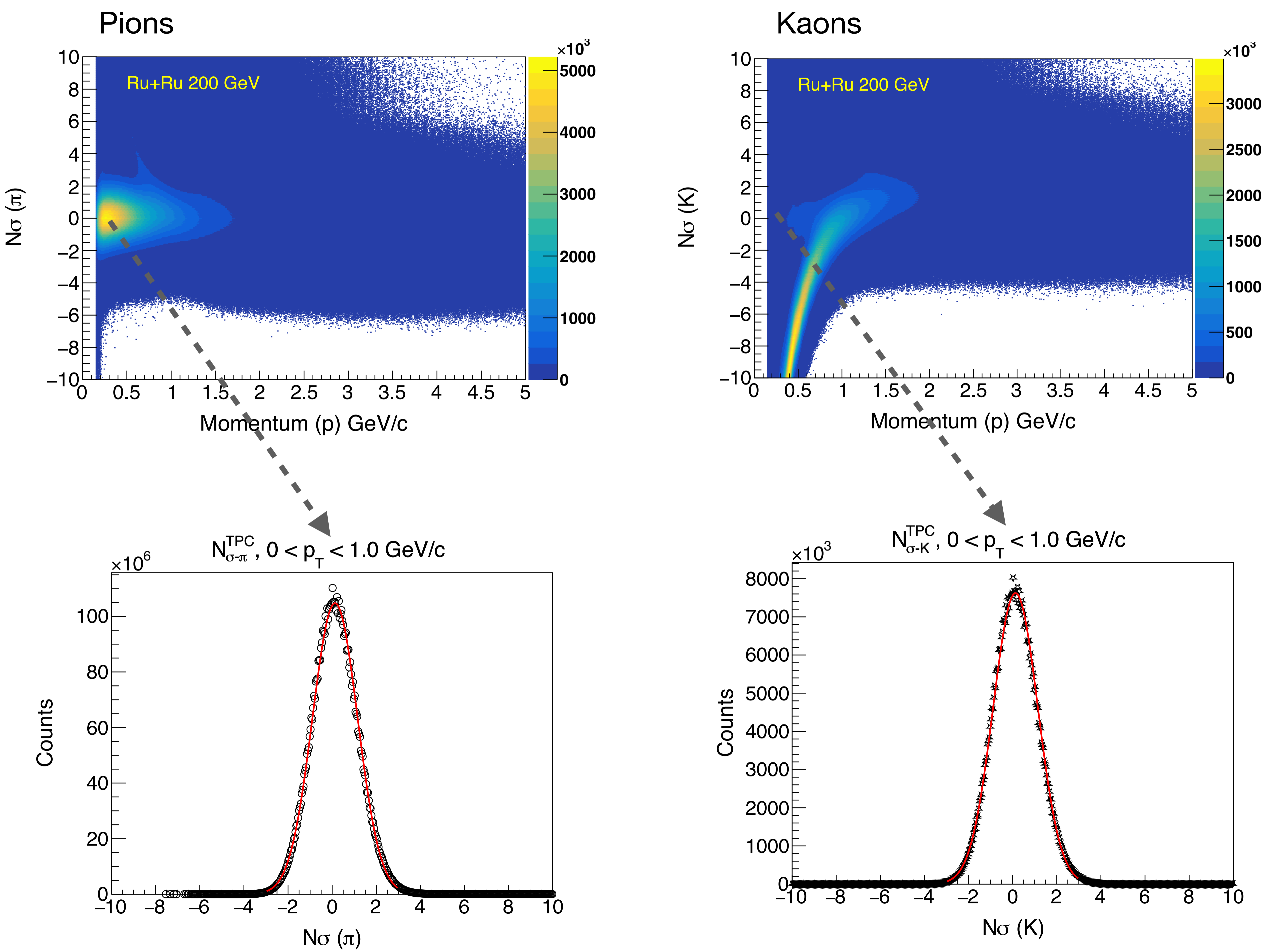
Datasets and analysis details

Collision system	Isobar (Ru+Ru and Zr+Zr) and O+O
Beam energy	200 GeV
Trigger	Minimum-bias trigger
K^* reconstruction	$K^{*0} \rightarrow K^{\mp}\pi^{\pm}$ & $K^{*\pm} \rightarrow K_S^0\pi^{\pm}$
Transverse momentum	$0 < p_T < 10$ & $0 < p_T < 5$ (GeV/c)
Pair-rapidity	$\lvert y \rvert_{\mathrm{pair}} < 1.0$
Background reconstruction	Track rotation technique

Branching ratio:
$K^{*0} \rightarrow$ (2/3) ~ 66%
$K^{*\pm} \rightarrow$ (2/3)*(0.68)*(1/2) ~ 23%

$K_S^0 \rightarrow \pi^+\pi^-$:
reconstructed via topological selection (STAR Helix-method)

Particle Identification



Identification of π and K using energy loss (dE/dx) inside TPC:

$$N\sigma = \frac{\left(\frac{dE}{dx}\right)_{\rm expt} - \left(\frac{dE}{dx}\right)_{\rm theo}}{\sigma_{\rm TPC-PID}}$$

$\left(\frac{dE}{dx}\right)_{\rm expt} \rightarrow$ Measured energy loss

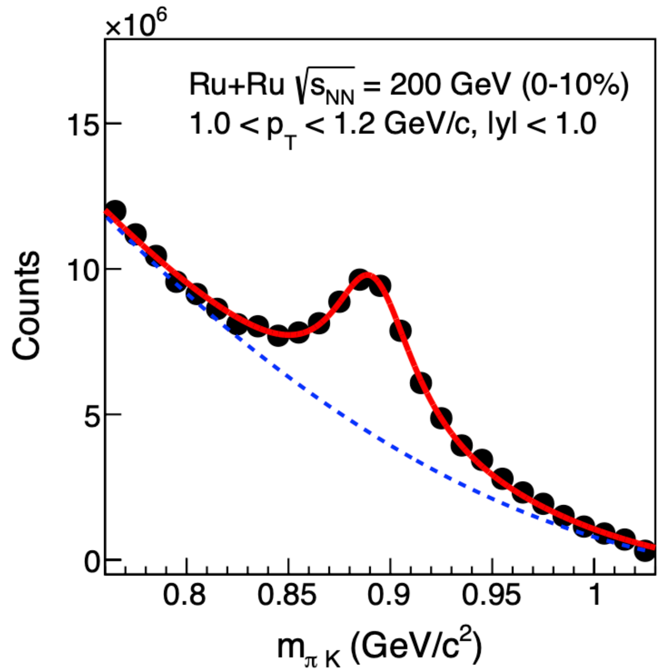
$\left(\frac{dE}{dx}\right)_{\rm theo} \rightarrow$ Bethe-Bloch parameterization

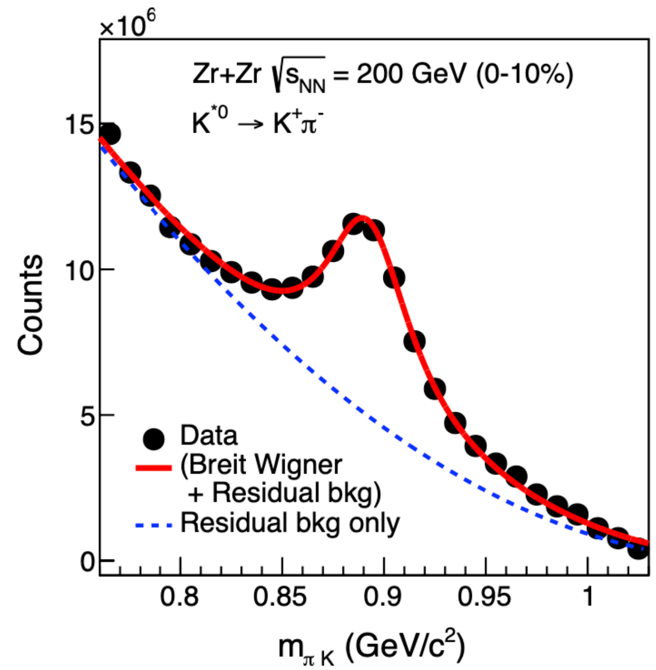
$\sigma_{\rm TPC-PID} \rightarrow \frac{dE}{dx}$ resolution ($\sim 6-8\ \%$)

STAR, Nucl. Instrum. Meth. A 558, 419 (2006)

Invariant mass reconstruction of K^{*0} and $K^{*\pm}$

$K^{*0} \rightarrow K^{\mp}\pi^{\pm}$



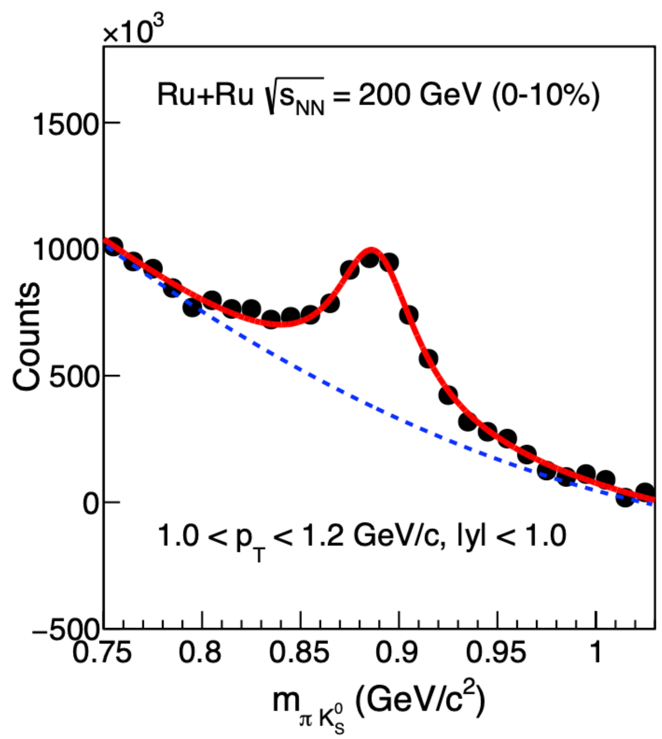


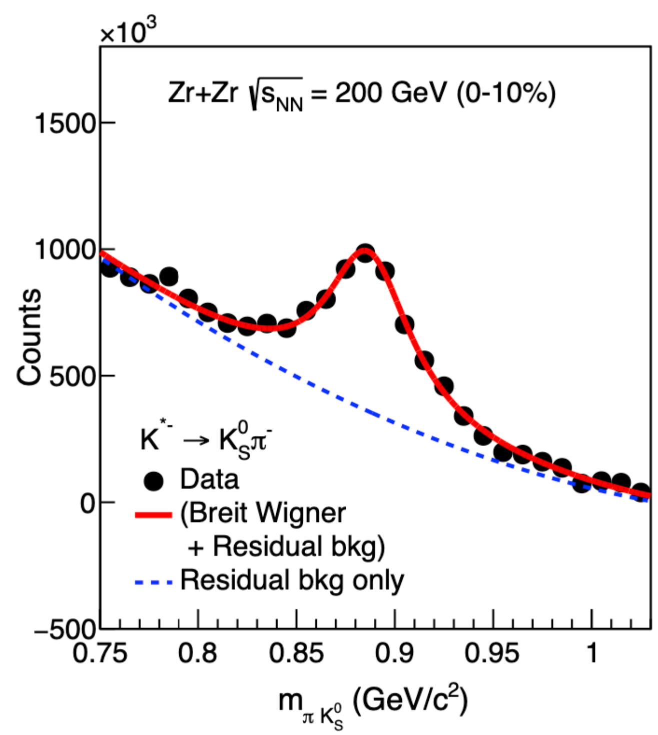
- Combinatorial background is reconstructed by track-rotation
- Signal is fitted with a non-relativistic Breit-Wigner function and a second order polynomial for residual background

$$\frac{Y}{2\pi} \times \frac{\Gamma_0}{(m - m_0)^2 + (\Gamma_0/2)^2} + AM^2 + BM + C$$

- $K^{*0,\pm}$ yield is calculated by histogram integration

$K^{*\pm} \rightarrow K^0_S\pi^{\pm}$

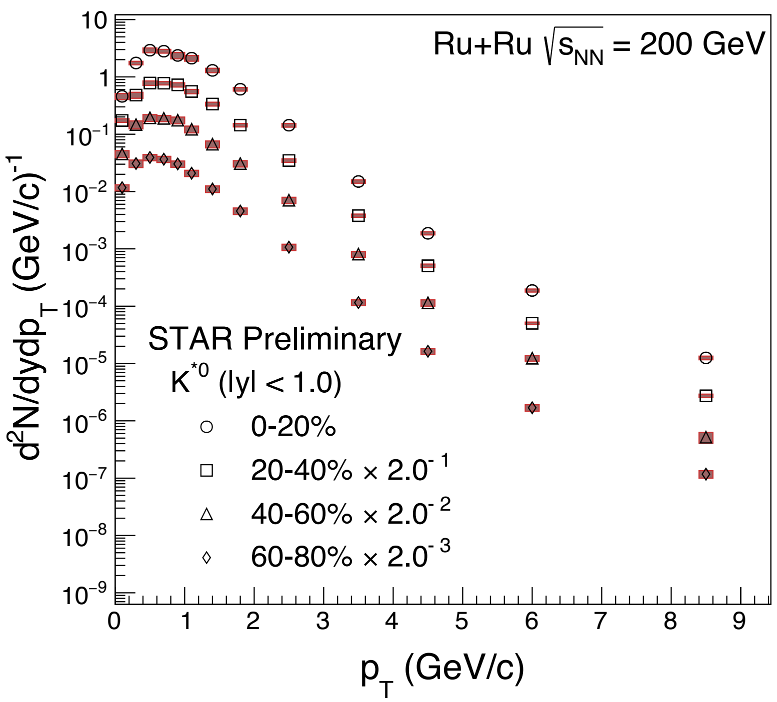


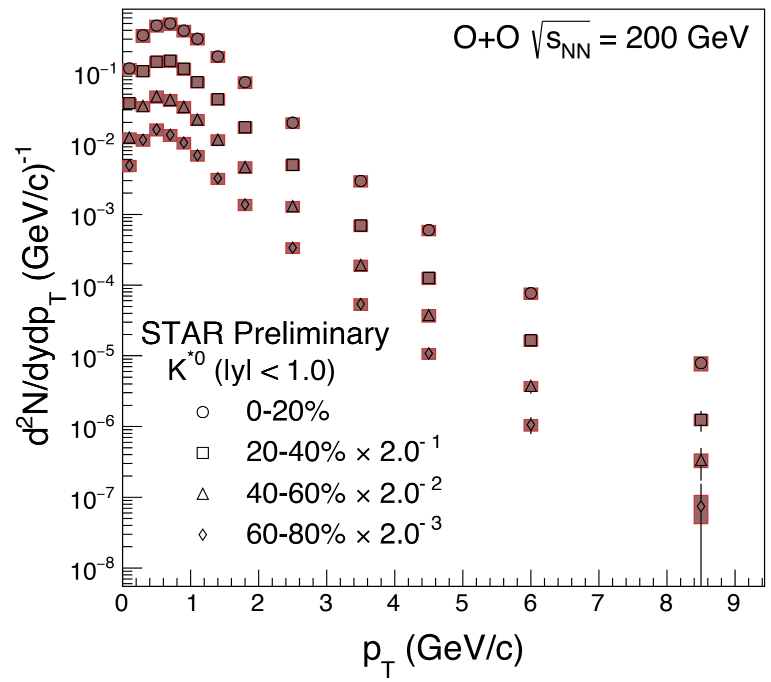


*** Source of systematic uncertainty on yield: Signal extraction (fit range and background variation); Yield calculation (histogram vs function integration); Event, track quality and PID selection variation; tracking uncertainty*

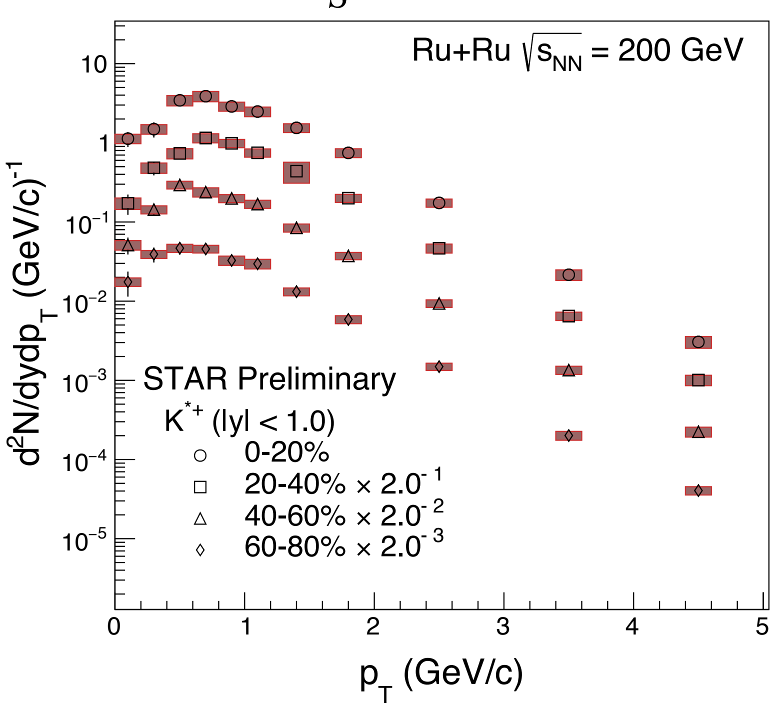
Transverse momentum spectra for K^{*0} and $K^{*\pm}$

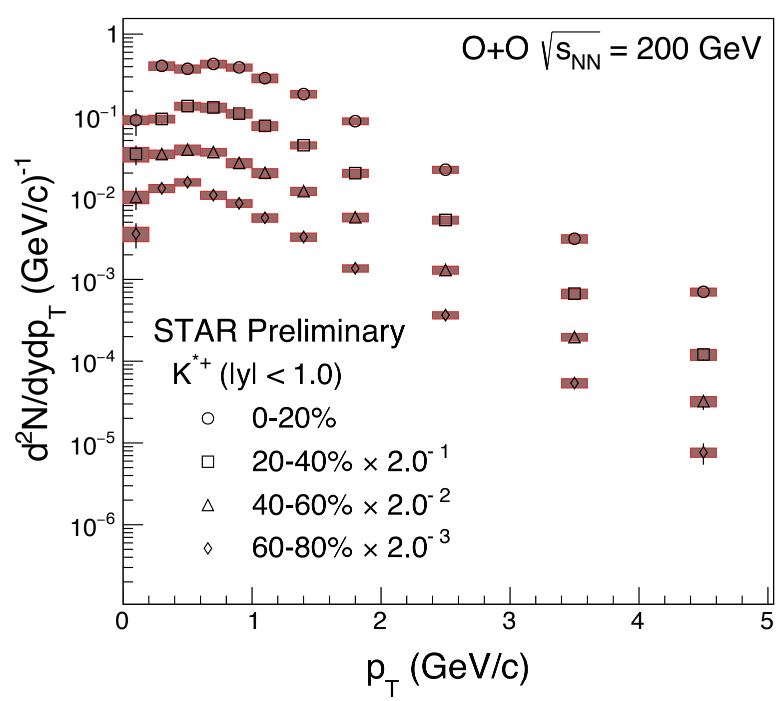
$K^{*0} \rightarrow K^{\mp}\pi^{\pm}$





$K^{*\pm} \rightarrow K^0_S\pi^{\pm}$

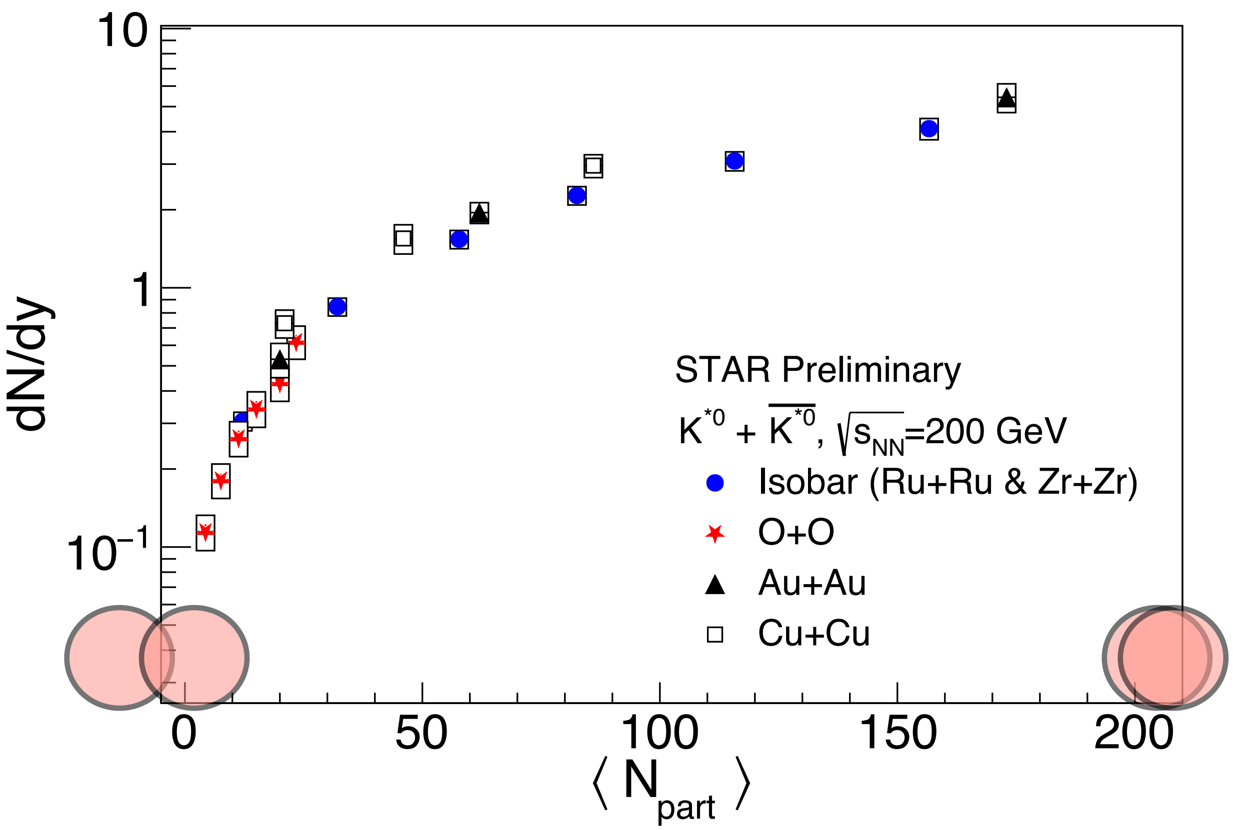


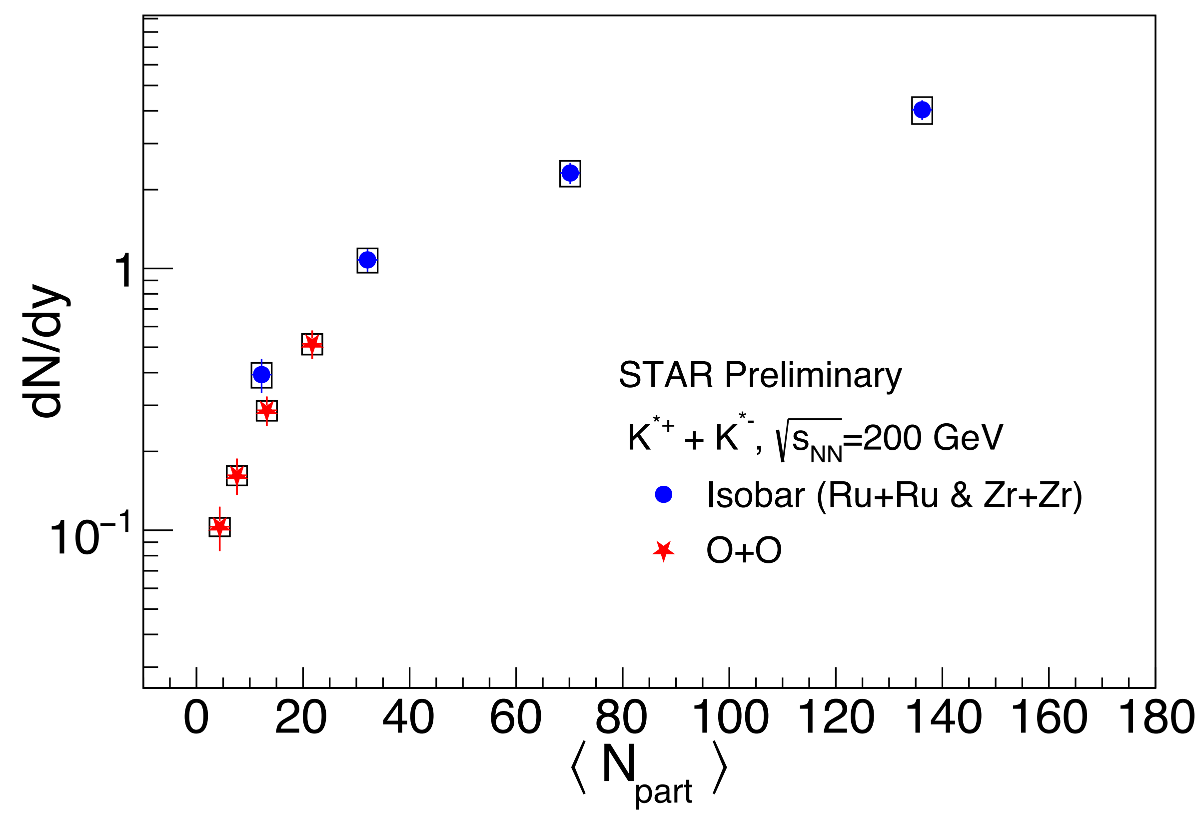


$$\frac{d^2N}{dp_T dy} = \frac{1}{N_{evt}} \times \frac{N^{raw}}{dp_T dy}$$

- Lowest p_T: (0 - 0.2 GeV/c) → no yield extrapolation is needed for dN/dy and $\langle p_T \rangle$

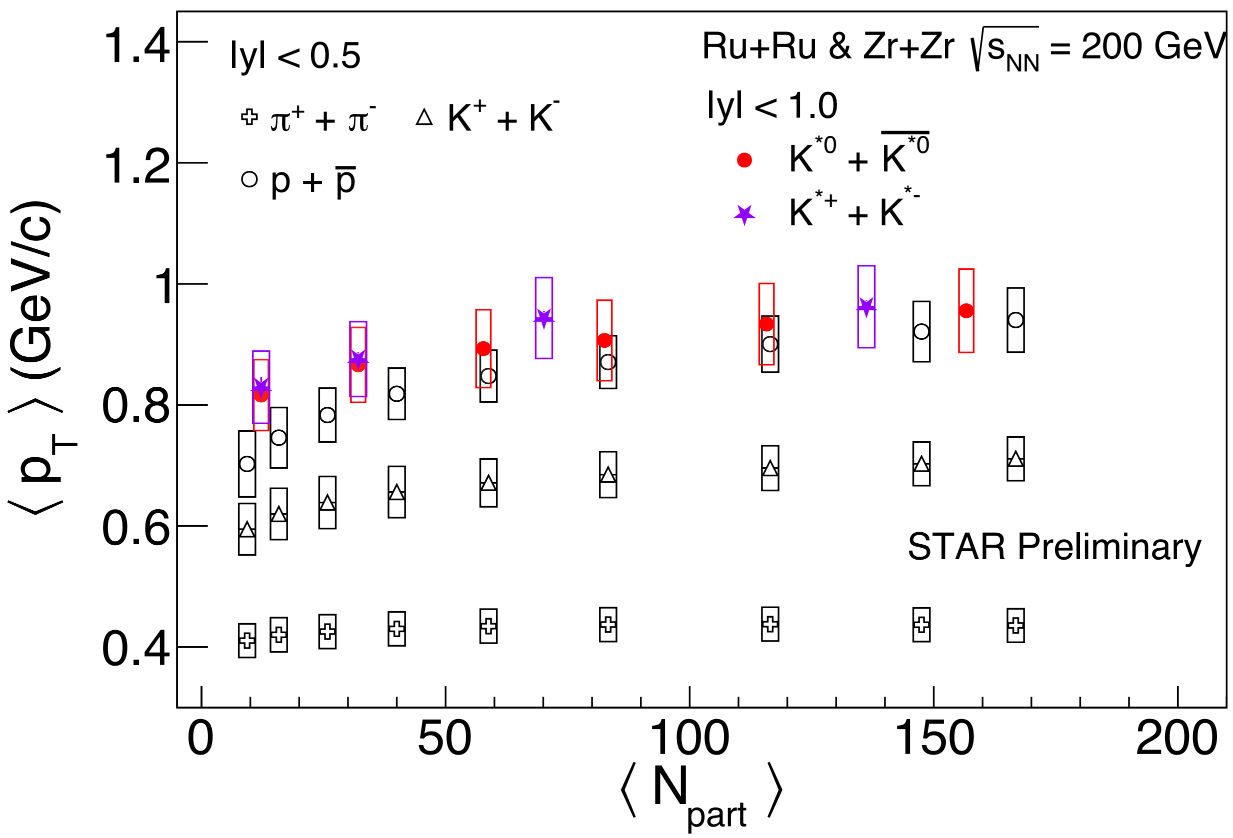
Mid-rapidity yield (dN/dy) of K^{*0} and $K^{*\pm}$



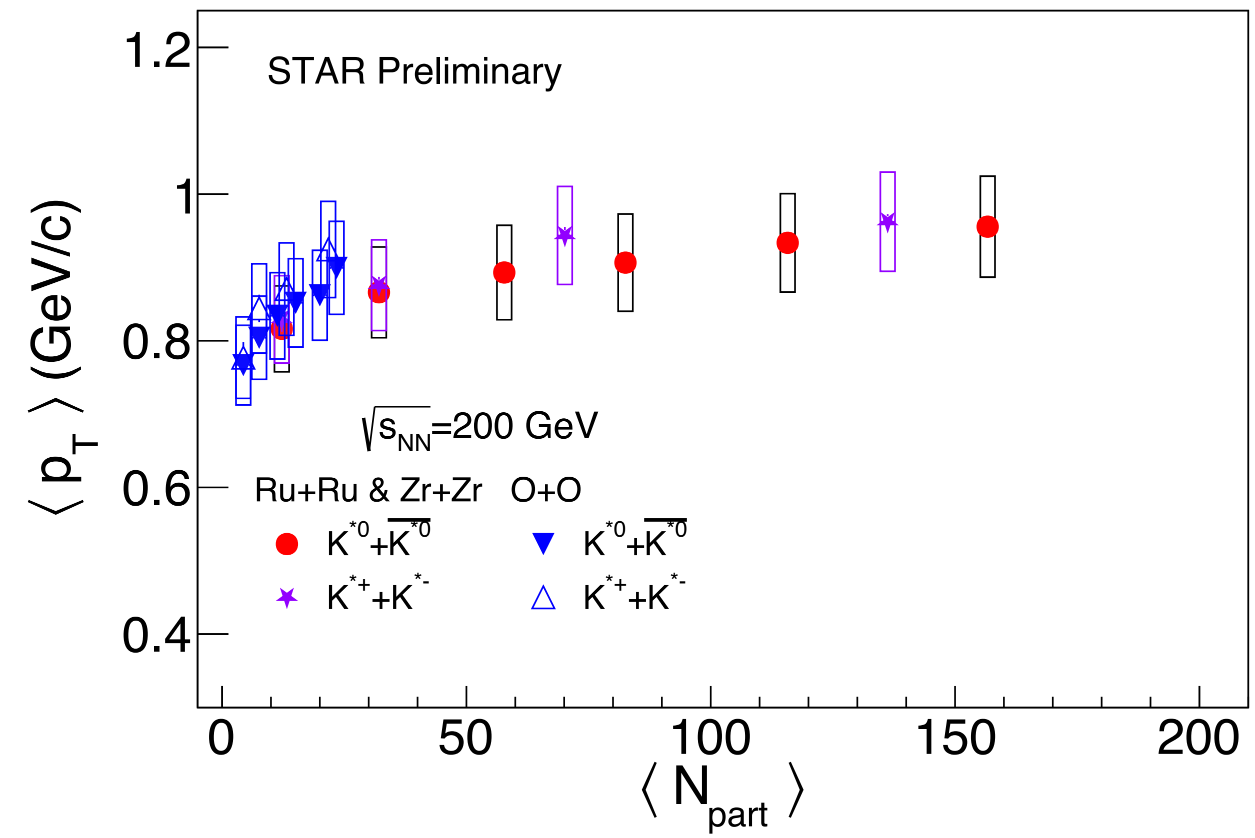


- K^{*0} and $K^{*\pm}$ dN/dy increases with $\langle N_{\text{part}} \rangle$
- dN/dy is driven by $\langle N_{\text{part}} \rangle$, not by collision species

Mean-transverse momentum of K^{*0} and $K^{*\pm}$

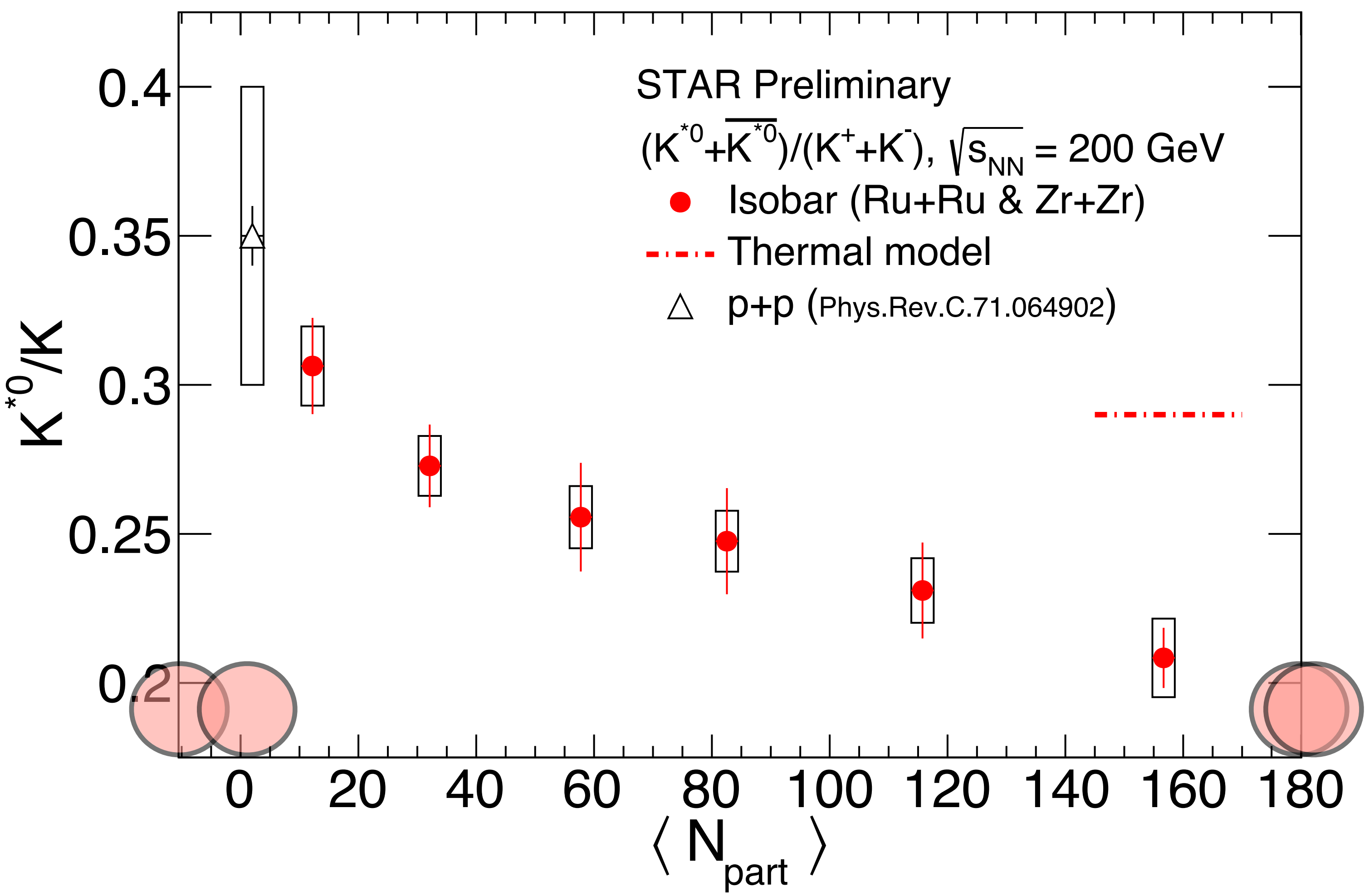


- $\langle p_T \rangle$: $K^{*0} \sim K^{*\pm}$
- $\langle p_T \rangle$ increases with mass
- $K^{*0,\pm}$ $\langle p_T \rangle$ is close to proton
- Consistent with radial flow



- $\langle p_T \rangle$ $K^{*0,\pm}$: Isobar ~ O+O

K^{*0}/K yield ratios in isobar collisions



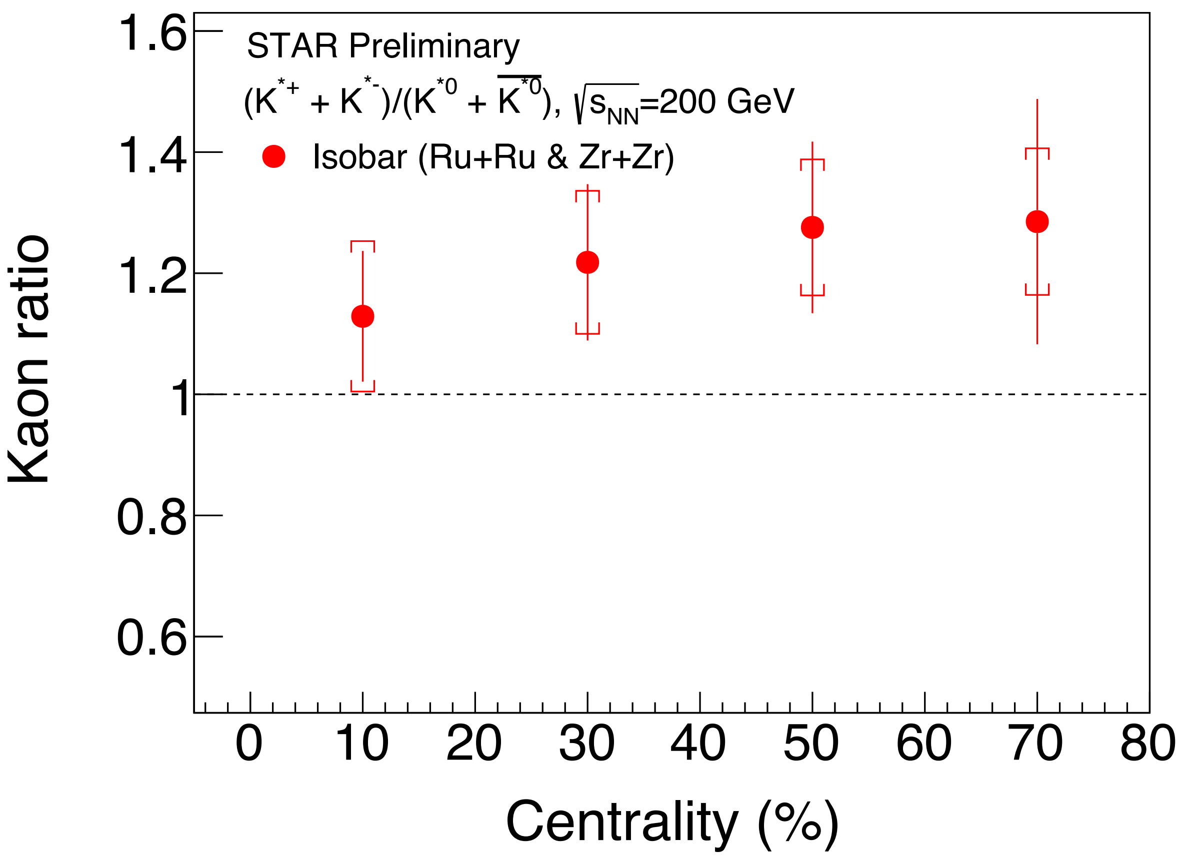
- Clear centrality dependence
- $(K^{*0}/K)_{\text{central}} << (K^{*0}/K)_{\text{peripheral}}$ $(\sim 3.2\ \sigma)$
- $(K^{*0}/K)_{\text{central}} << (K^{*0}/K)_{\text{Thermal model}}$

Data provide precision to establish evidence for dominance of re-scattering at RHIC

System size dependence of $K^{*0,\pm}/K$ ratio ?
Analysis with high statistics Au+Au, O+O and p+p collisions is underway

$K^{*\pm}/K^{*0}$ yield ratios

$R_{K^*} = (K^{*+} + K^{*-})/(K^{*0} + \overline{K^{*0}})$ versus centrality



- Isobar:

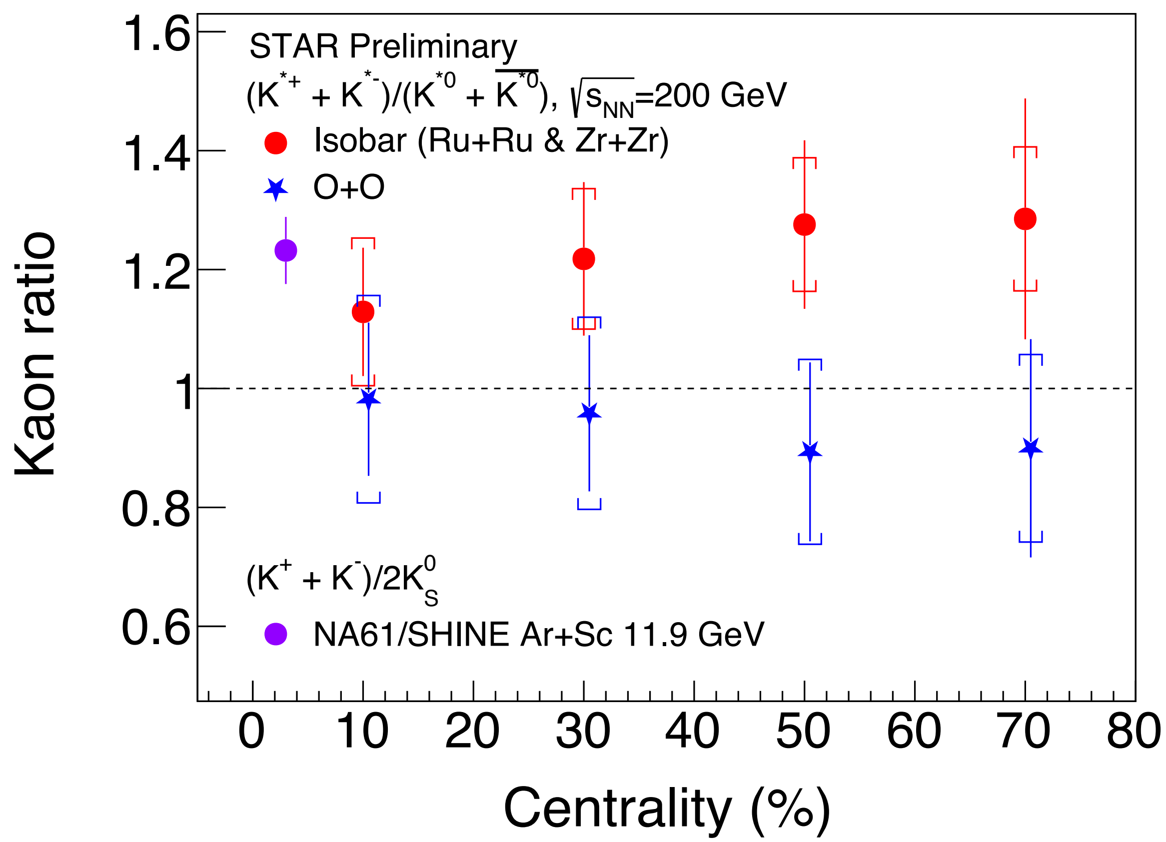
  $R_{K^*} = 1.20 \pm 0.07 \pm 0.12$

  $\rightarrow K^{*\pm}(d\bar{s}) > K^{*0}(u\bar{s})$
- No strong centrality dependence within uncertainties
- Hints of isospin violation?

What happens to ($K^{*+/-}$ and K^{*0}) in O+O collisions, no initial isospin asymmetry unlike Au+Au and isobars (?)

$K^{*\pm}/K^{*0}$ yield ratios

$R_{K*} = (K^{*+} + K^{*-})/(K^{*0} + \overline{K^{*0}})$ versus centrality



NA61/SHINE, Nat. Comm. 16 2849 (2025)

- Isobar:
  $R_{K*} = 1.20 \pm 0.07 \pm 0.12$
  $\rightarrow K^{*\pm}(u\bar{s}) > K^{*0}(d\bar{s})$
- O+O:
  $R_{K*} = 0.94 \pm 0.07 \pm 0.16$
  $\rightarrow K^{*\pm}(u\bar{s}) \sim K^{*0}(d\bar{s})$

<u>Expectation (without B-field effect)</u>

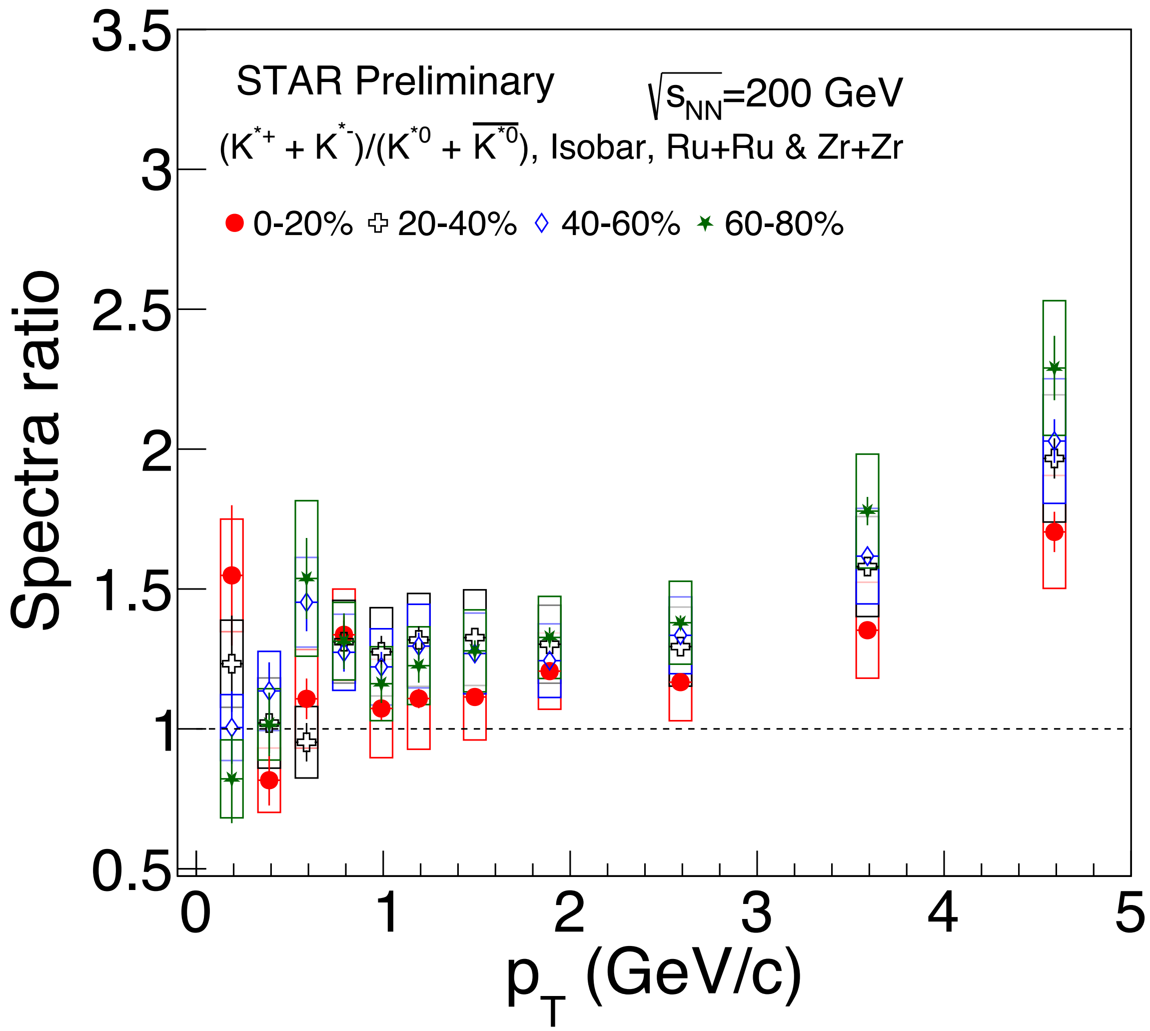
- Isobar (neutron-rich colliding nuclei)
  - $K^{*\pm}(u\bar{s}) < K^{*0}(d\bar{s})$
- O+O (Isospin symmetric colliding nuclei)
  - $K^{*\pm}(u\bar{s}) \sim K^{*0}(d\bar{s})$

What happens if we look at R_{K*} differentially in p_T ?

Charged to neutral K* spectra ratio

$K^{*0}(d\bar{s})$ vs. $K^{*+}(u\bar{s})$

$R_{K*} = (K^{*+} + K^{*-})/(K^{*0} + \overline{K^{*0}})$ versus p_T



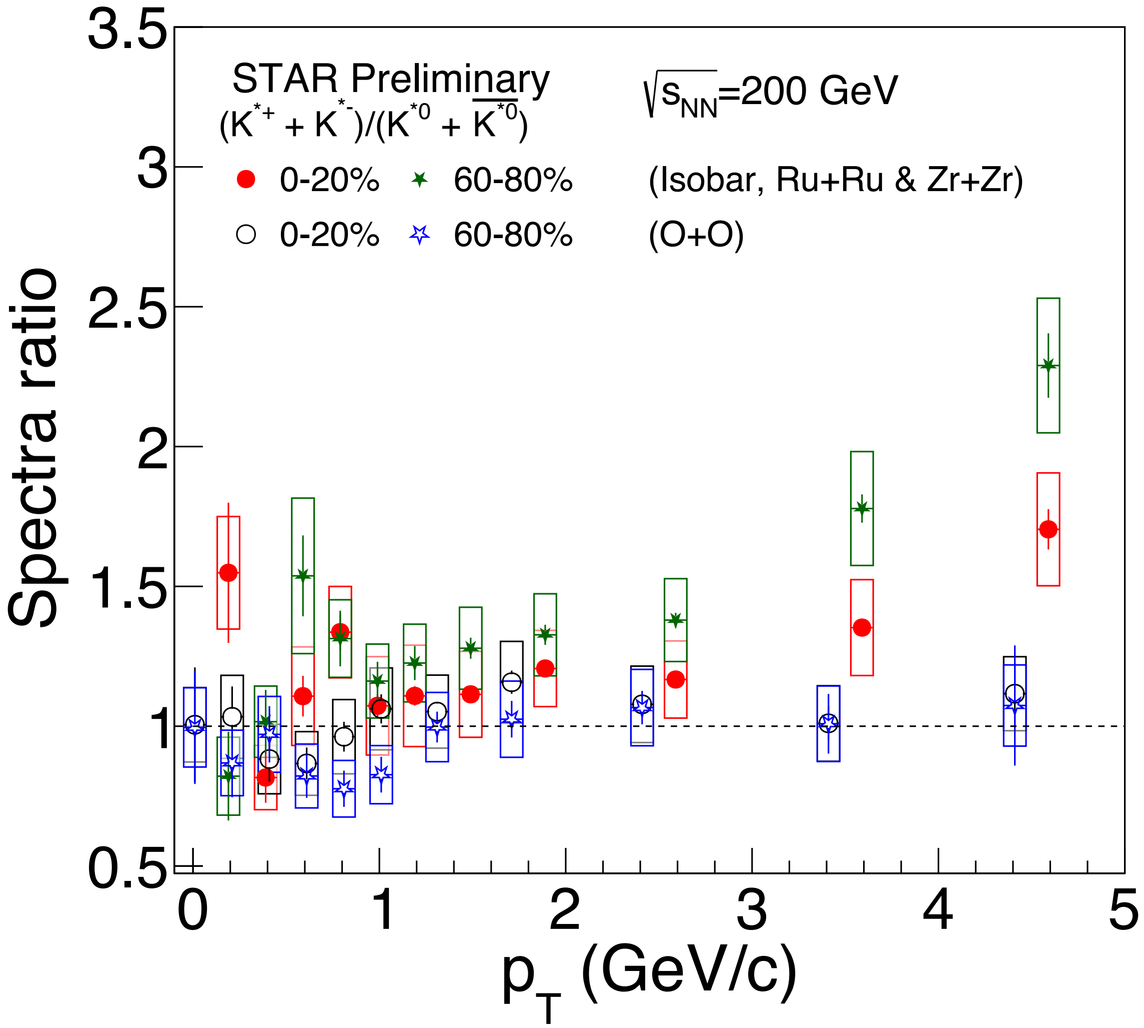
- At high p_T
  - $R_{K*} > 1.0$ in Isobar

- R_{K*}
  - Isobar: observe a centrality dependence 60-80% > 0-20%

Charged to neutral K* spectra ratio

$K^{*0}(d\bar{s})$ vs. $K^{*+}(u\bar{s})$

$R_{K*} = (K^{*+} + K^{*-})/(K^{*0} + \overline{K^{*0}})$ versus p_T



- At high p_T
  - $R_{K*} > 1.0$ in Isobar
  - $R_{K*} \sim 1.0$ in O+O

- R_{K*} for $p_T > 3.0$ GeV/c
- Isobar: centrality dependent
  - (0-20%): $R_{K*} = 1.40 \pm 0.03 \pm 0.19$
  - (60-80%): $R_{K*} = 1.86 \pm 0.05 \pm 0.22$
    ($\sim 3.8\sigma$)

- O+O: centrality independent
  - (0-20%): $R_{K*} = 1.03 \pm 0.05 \pm 0.13$
  - (60-80%): $R_{K*} = 1.02 \pm 0.10 \pm 0.14$

A few possibilities:

- Higher p_T particles escape early & more sensitive to early-time B-field (?)
- Asymmetric production of *u* and *d* quarks in color fragmentation process (*2503.10493*)
- Results are open for interpretation

Summary

- We presented K^{*0} and $K^{*\pm}$ at 200 GeV RHIC Isobar (Ru+Ru and Zr+Zr) and O+O collisions
- $R_{K^*} = (K^{*+} + K^{*-})/(K^{*0} + \overline{K^{*0}})$
- Yield (dN/dy) ratio for 0-80%:
  - $R_{K^*} = 1.20 \pm 0.07 \pm 0.12$ for Isobar
  - $R_{K^*} = 0.94 \pm 0.07 \pm 0.16$ for O+O
- $\langle p_T \rangle$: ($K^{*\pm} \sim K^{*0}$) in Isobar and O+O
- Spectra ratio, at high p_T
  - $R_{K^*} > 1.0$ for Isobar; $R_{K^*} = 1.86 \pm 0.05 \pm 0.22$, $p_T > 3.0$ GeV/c ($> 3\sigma$ for peripheral collisions)
  - $R_{K^*} \sim 1.0$ for O+O

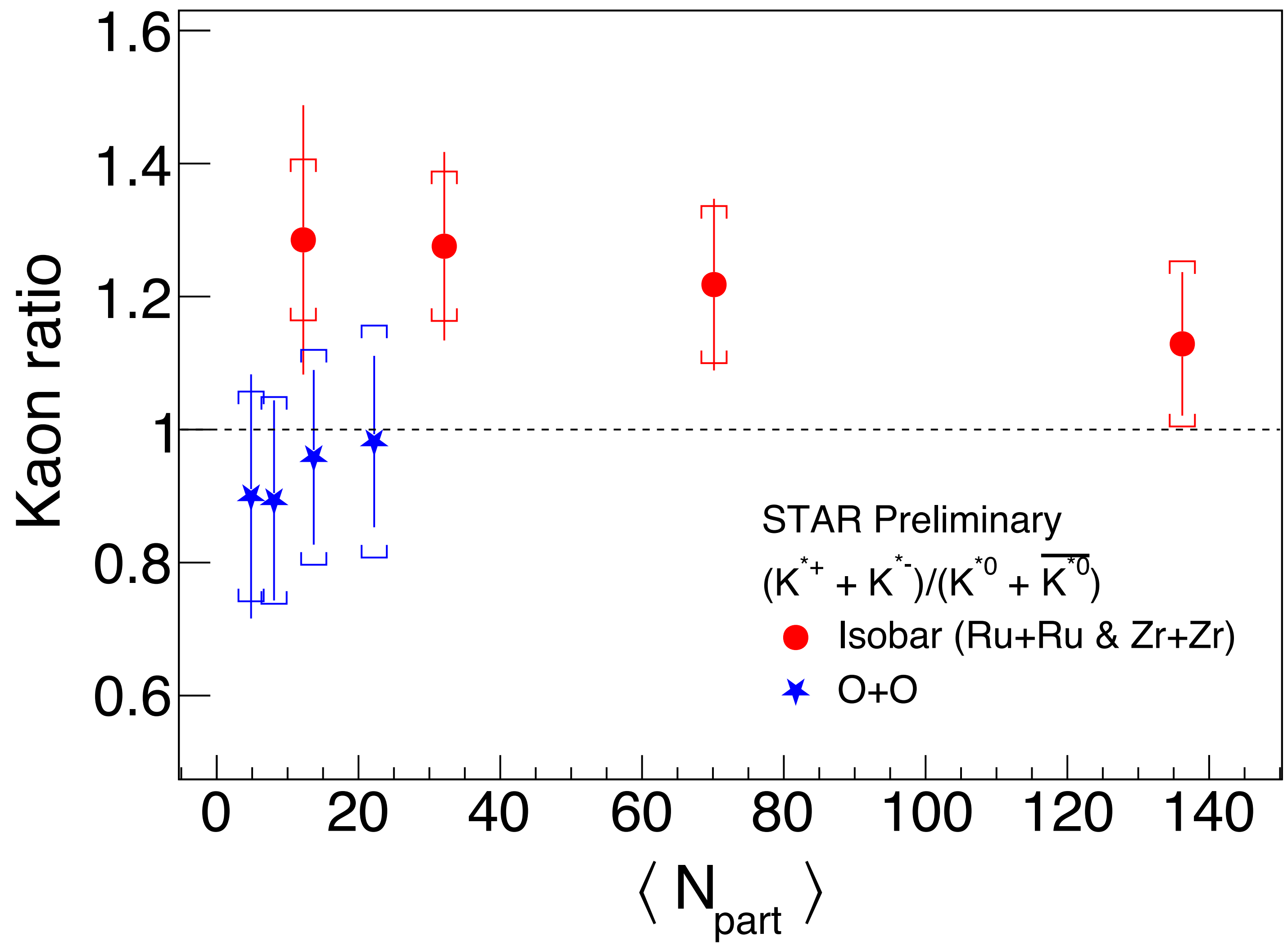
Outlook

- Combined analysis of K^{*0}, $K^{*\pm}$, K_S^0 and $K^{\pm}$ species with high statistics p+p and Au+Au (BES-II) collisions is underway

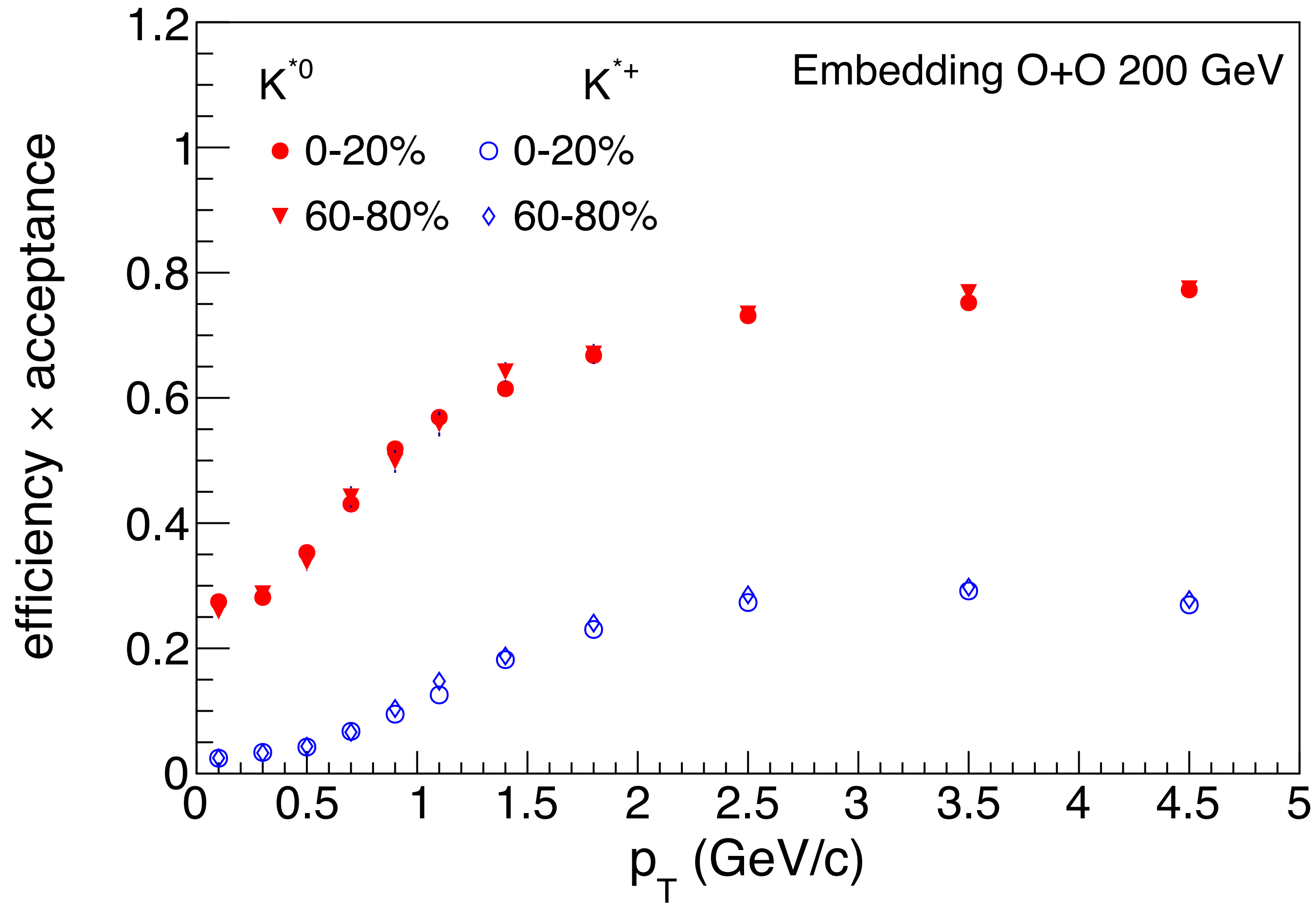
Thank you for your attention!

Back up

$K^{*\pm}/K^{*0}$ yield ratios versus $\langle N_{part} \rangle$



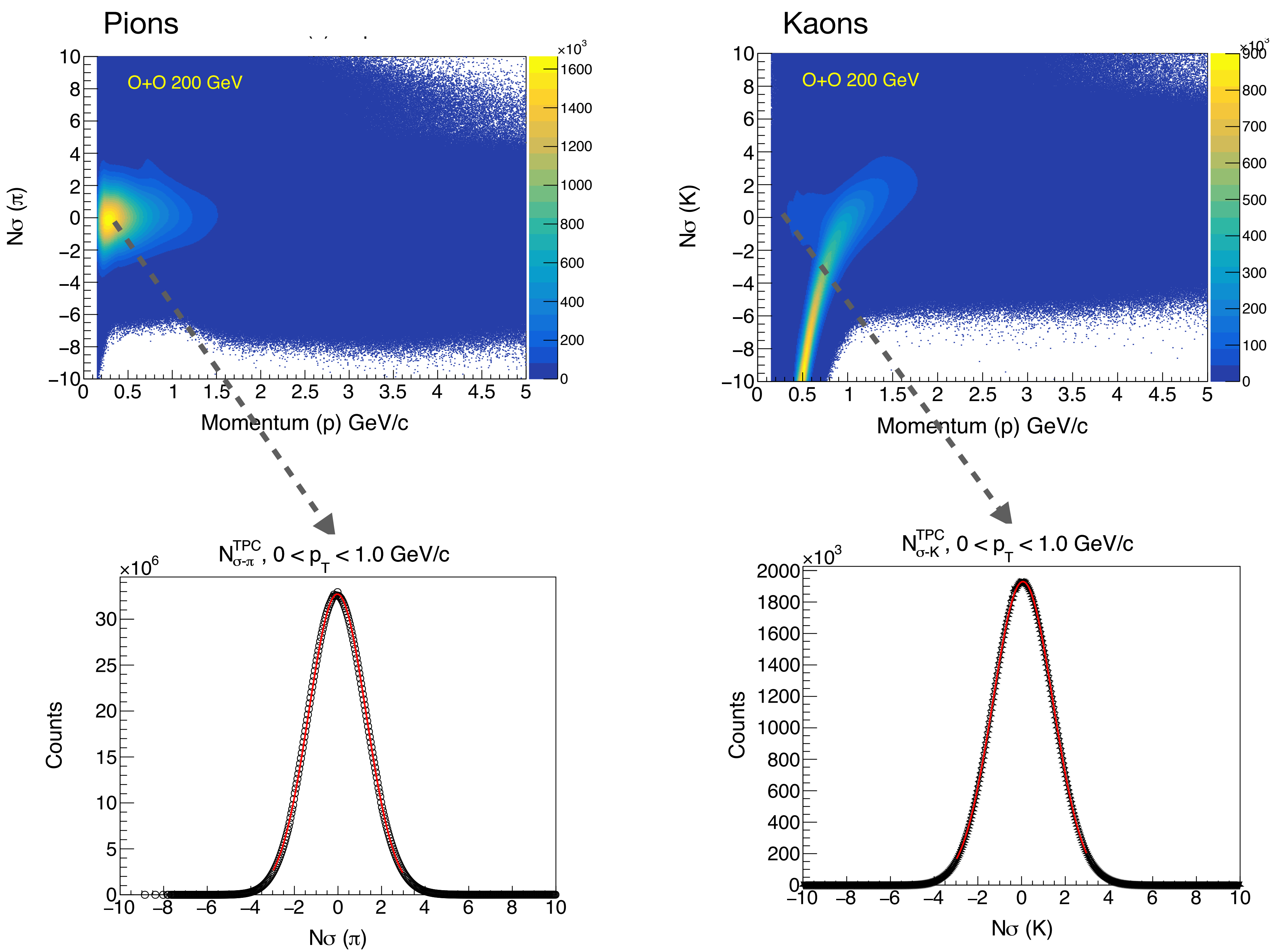
Acceptance × efficiency for $K^{*0,\pm}$



- Acceptance x efficiency obtained from STAR embedding simulations

$$\epsilon_{\rm rec-acc} = \frac{N_{\rm RC-event/track\ selections}}{N_{\rm MC-input}}$$

Particle Identification



Identification of π and K using energy loss (dE/dx) inside TPC:

$$N\sigma = \frac{\left(\frac{dE}{dx}\right)_{\rm expt} - \left(\frac{dE}{dx}\right)_{\rm theo}}{\sigma_{\rm TPC-PID}}$$

$\left(\frac{dE}{dx}\right)_{\rm expt} \rightarrow$ Measured energy loss

$\left(\frac{dE}{dx}\right)_{\rm theo} \rightarrow$ Bethe-Bloch parameterization

$\sigma_{\rm TPC-PID} \rightarrow$ PID resolution