



Measurement of $K^{*0,\pm}$ Mesons in Heavy-Ion Collisions at RHIC

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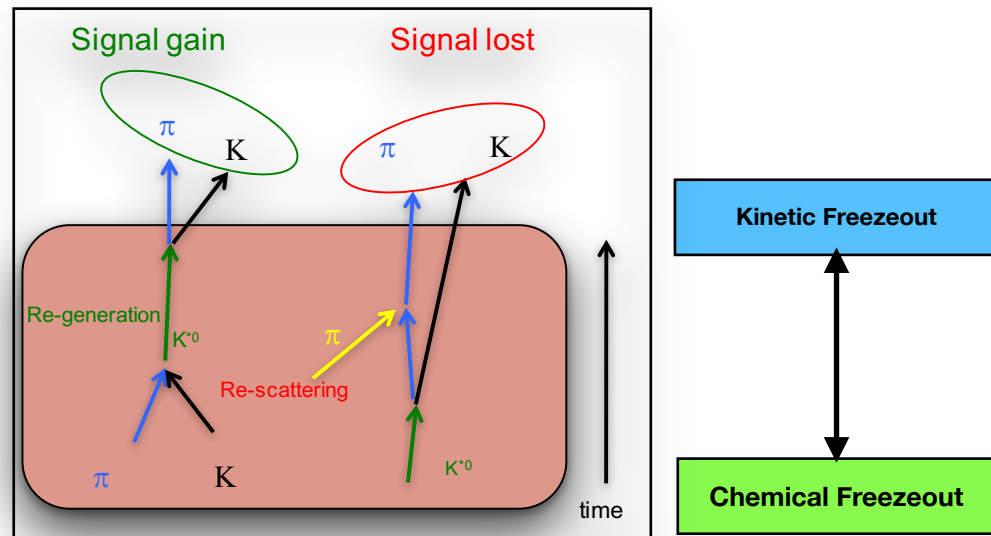


Outline

- 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

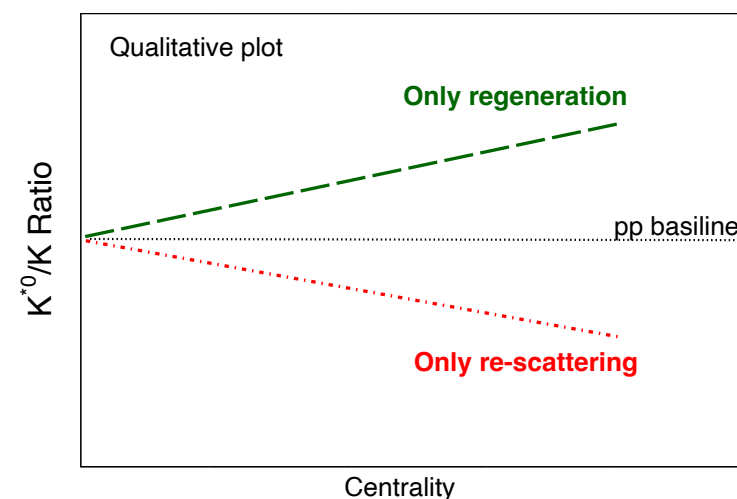
Particle Species	Mass (GeV/c ²)	Spin	Lifetime (fm/c)	Magnetic moment (μ_N)
$K^{*0}(d\bar{s})$	0.896	1	~ 4	$\mu_d \approx -0.97, \mu_{\bar{s}} \approx 0.61\mu_N$
$K^{*+}(u\bar{s})$	0.892	1	~ 4	$\mu_u \approx 1.85, \mu_{\bar{s}} \approx 0.61\mu_N$

Re-scattering and regeneration

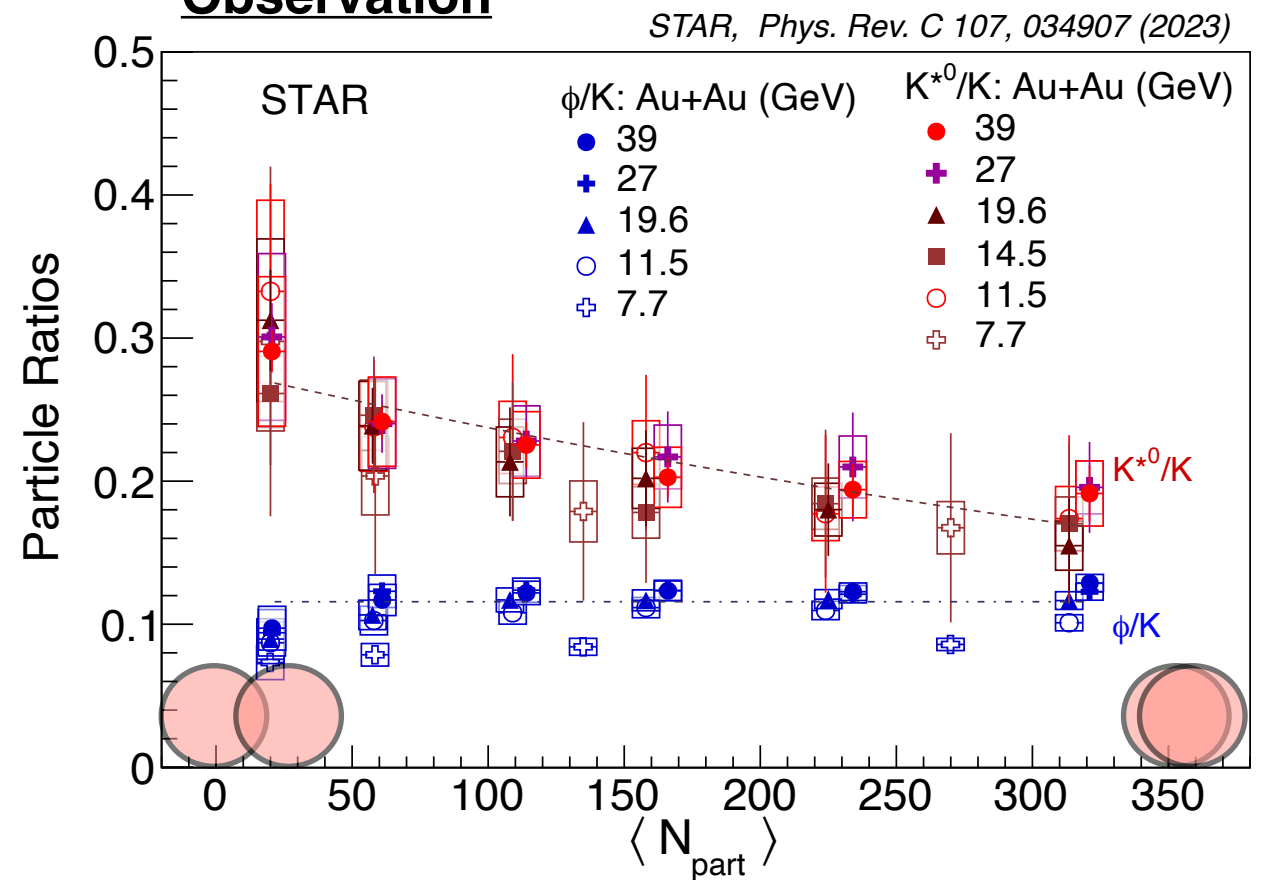


Specie	Decay	Lifetime (fm/c)
K^{*0}	$K\pi$	4
ϕ	KK	45

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



Observation



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

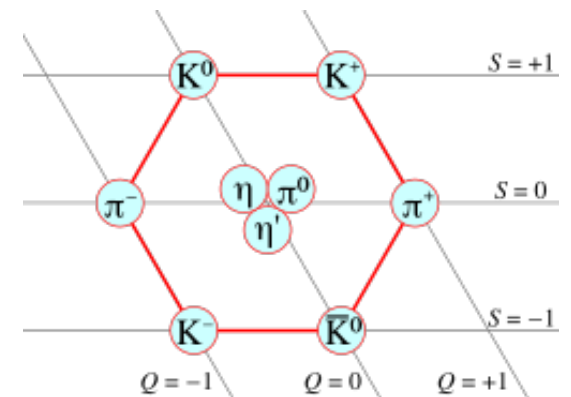
Dominance of late stage hadronic interactions



Is there isospin violation in Kaon ratios?

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

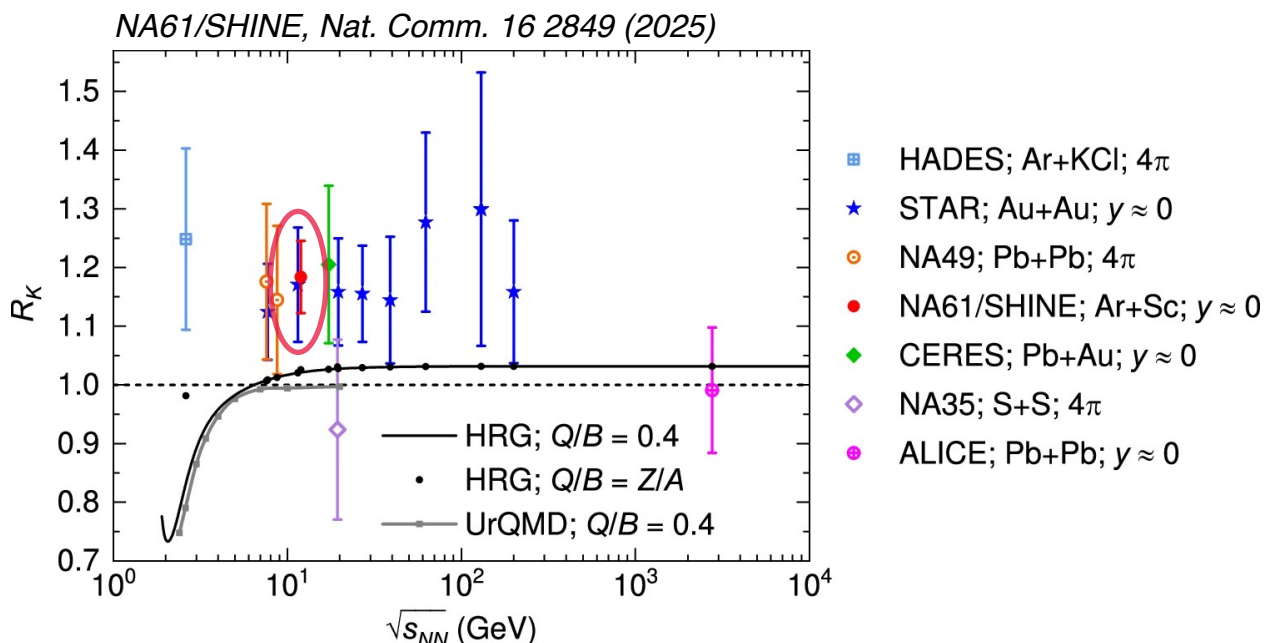
$$\frac{M_{K^+} - M_{K^0}}{M_{K^+} + M_{K^0}} \sim 0.004$$



Courtesy: From Wikipedia

A+A collisions:

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



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

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

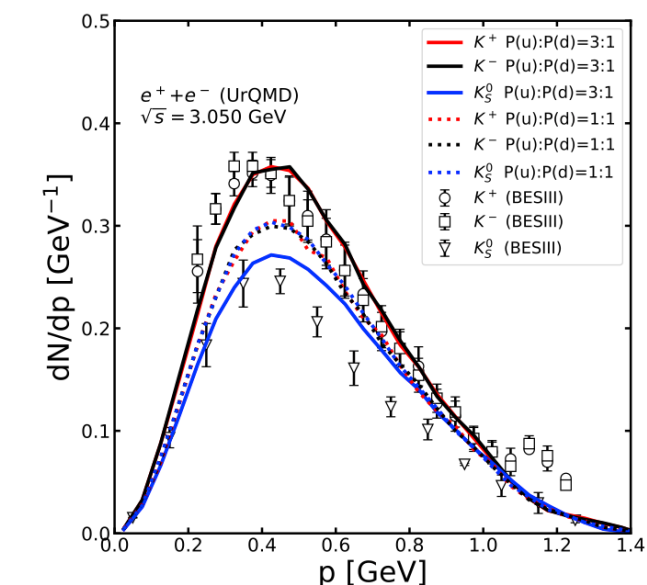
Deviation beyond baseline (e.g. initial isospin asymmetry in colliding nuclei, mass difference of kaons, CP violation in K^0 etc)

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;



Alternate observable

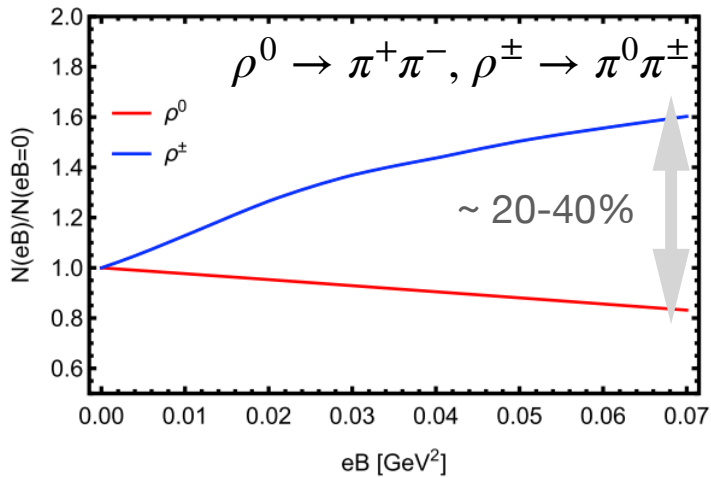
$$R_{K^*} = (K^{*+} + K^{*-})/(K^{*0} + \overline{K}^{*0}) ?$$

[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)

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

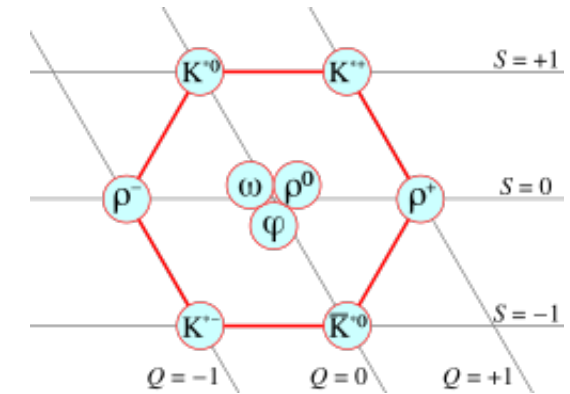
Assumptions:

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

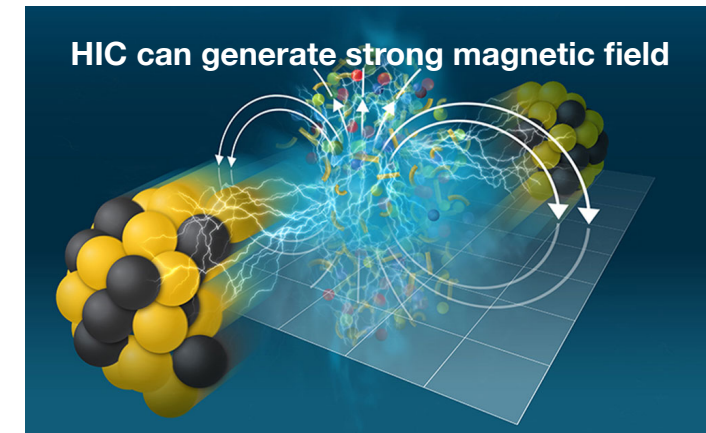
- Expectation: $K^{*+}(u\bar{s}) > K^{*0}(d\bar{s})$
- The decay daughters of vector mesons ($K^\pm$ and K_S^0) can feed-down to $R_K = (K^+ + K^-)/2K_S^0$

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

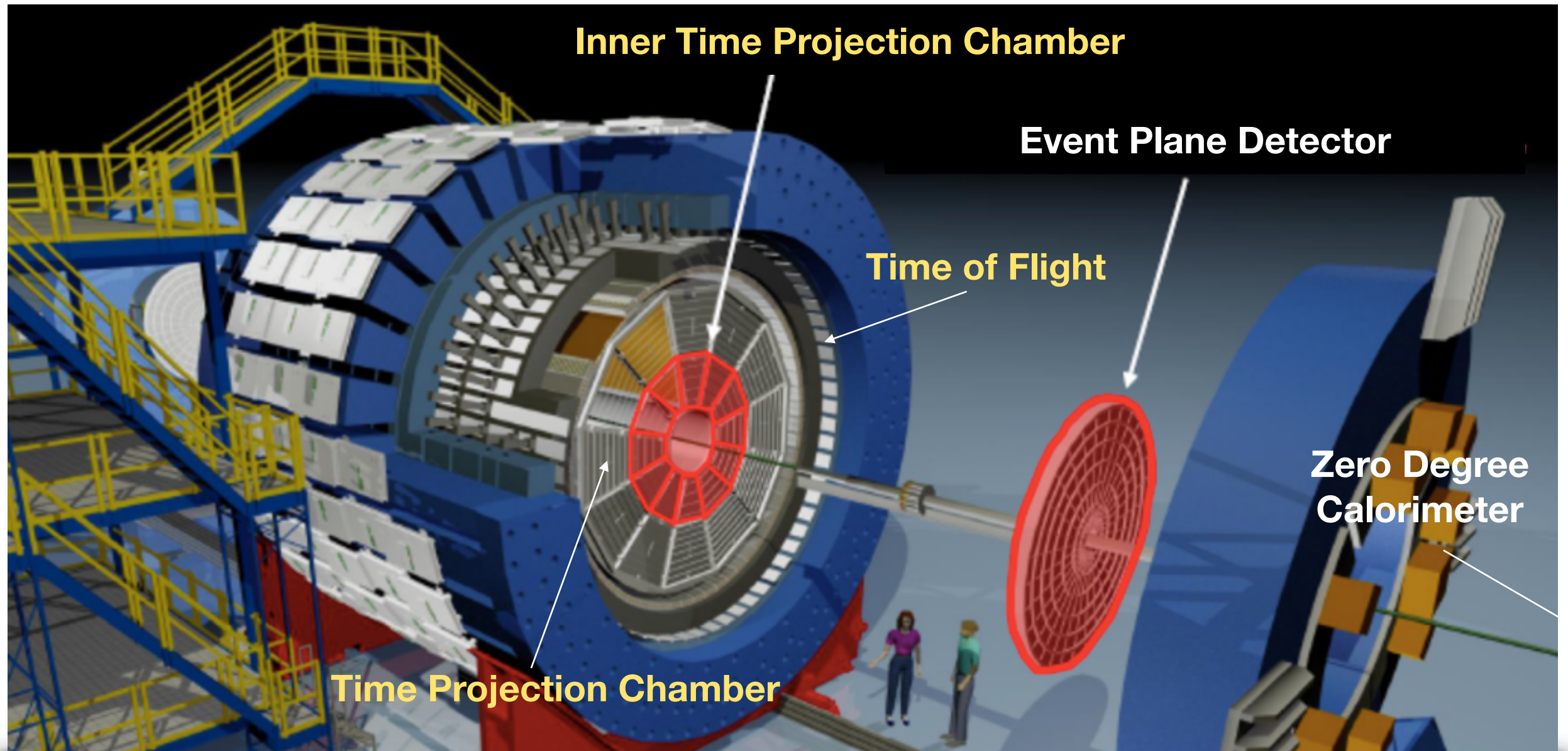
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Courtesy: From Wikipedia



STAR Detector



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



Datasets and analysis details

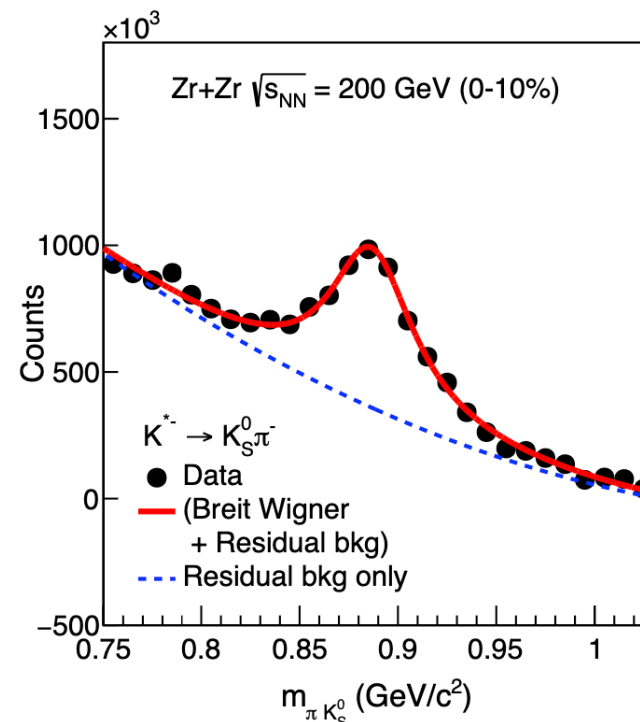
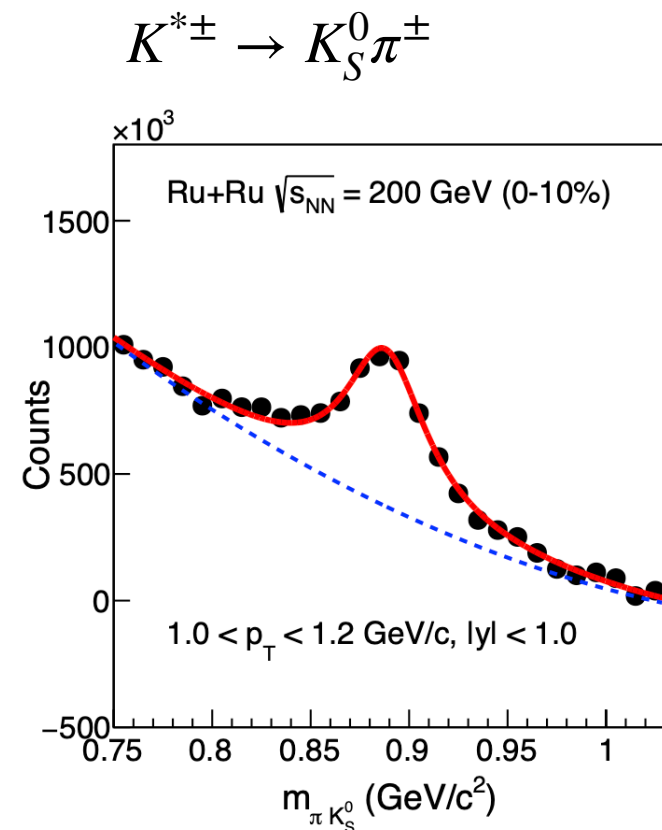
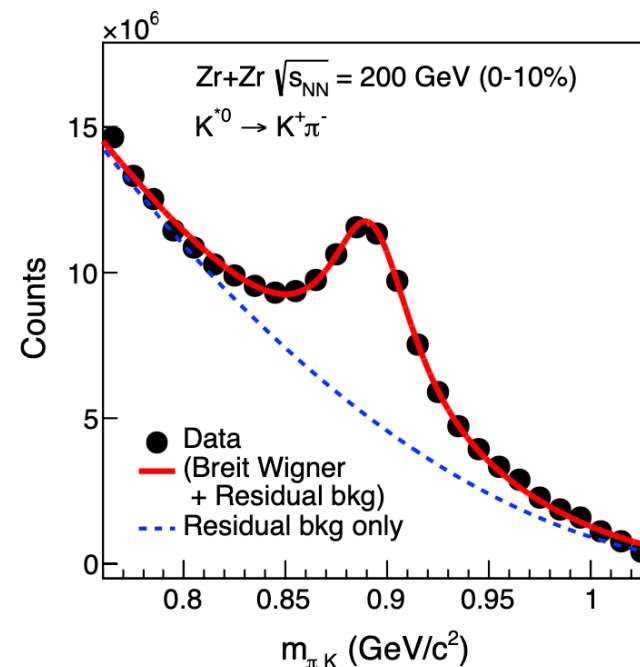
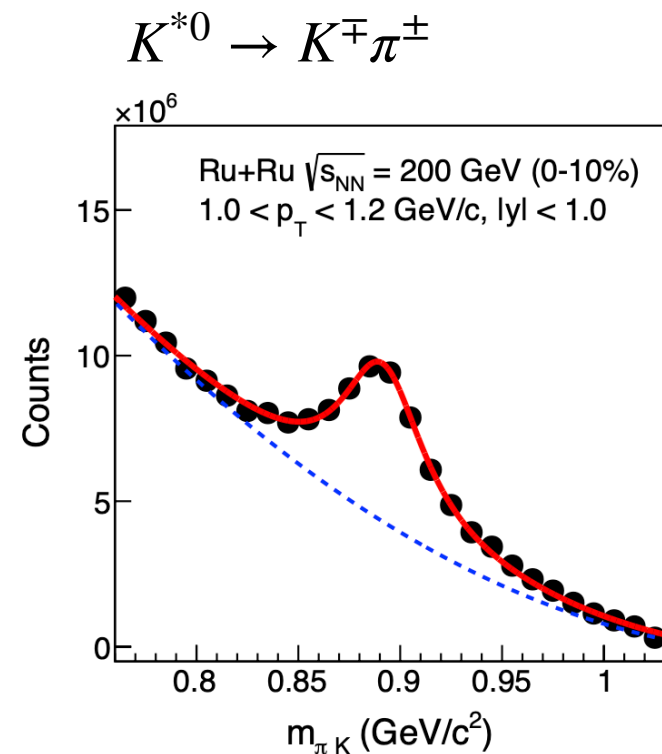
Collision system	Isobar (Ru+Ru and Zr+Zr) and O+O
Beam energy	200 GeV
Trigger	Minimum-bias trigger
K^* reconstruction	$K^{*0} \rightarrow K^{\mp} \pi^{\pm}$ & $K^{*\pm} \rightarrow K_S^0 \pi^{\pm}$
Transverse momentum	$0 < p_T < 10$ & $0 < p_T < 5$ (GeV/c)
Pair-rapidity	$ y _{\text{pair}} < 1.0$
Background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

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

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



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



- 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

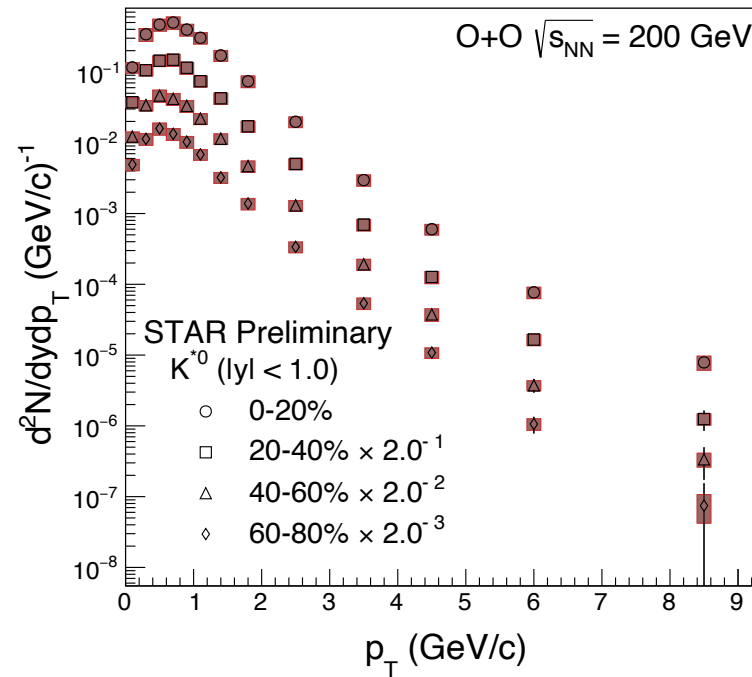
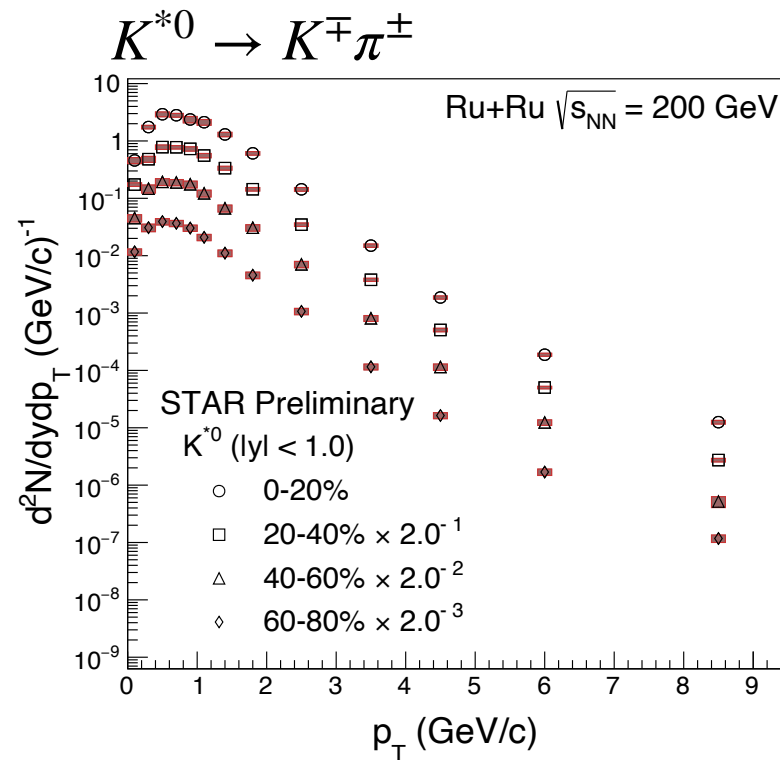
$$\frac{Y}{2\pi} \times \frac{\Gamma_0}{(m - m_0)^2 + (\Gamma_0/2)^2} + AM^2 + BM + C$$

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

*** 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*

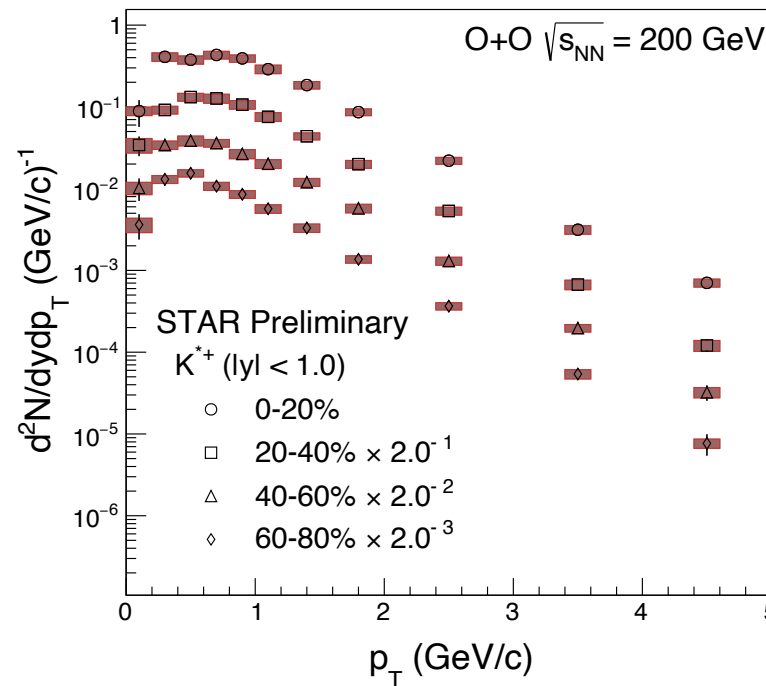
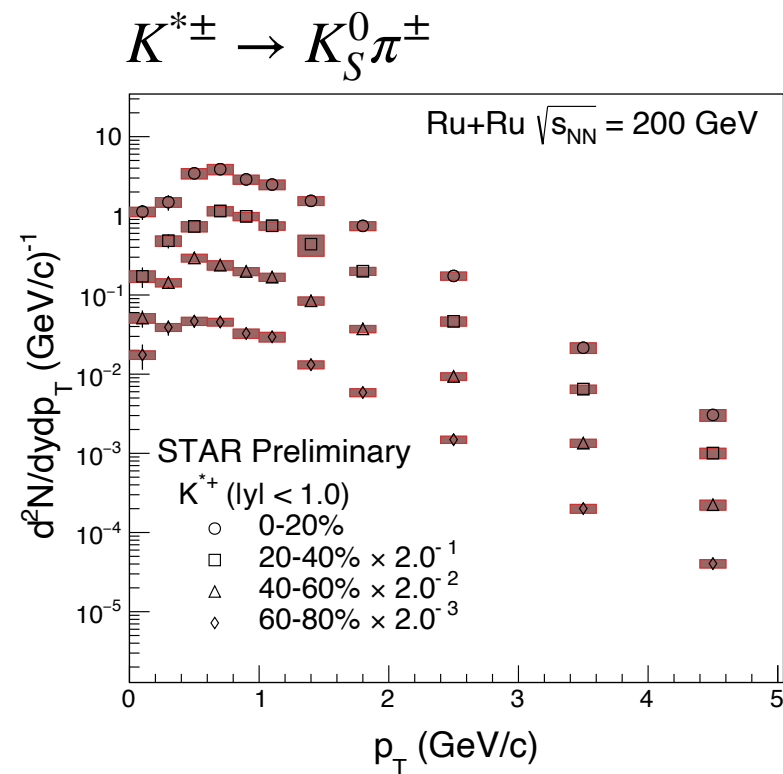


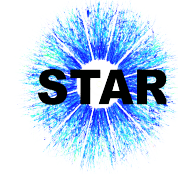
Transverse momentum spectra for K^{*0} and $K^{*\pm}$



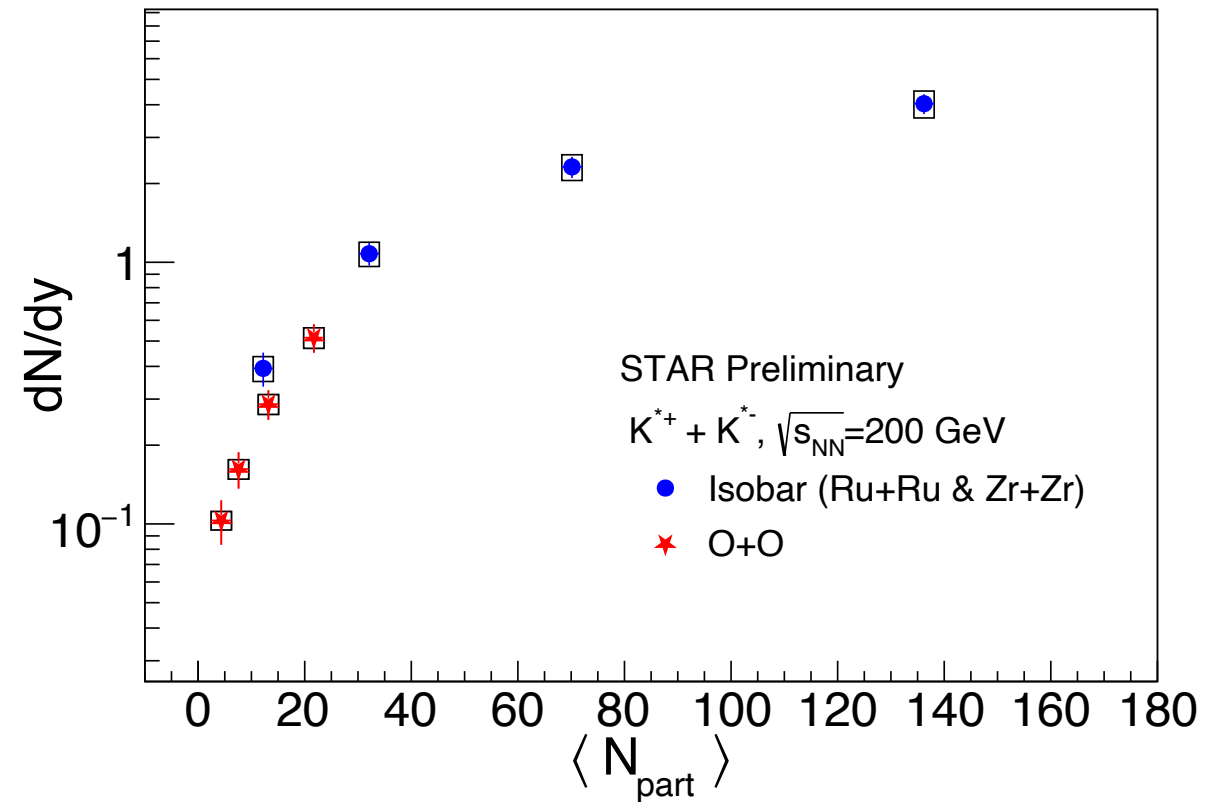
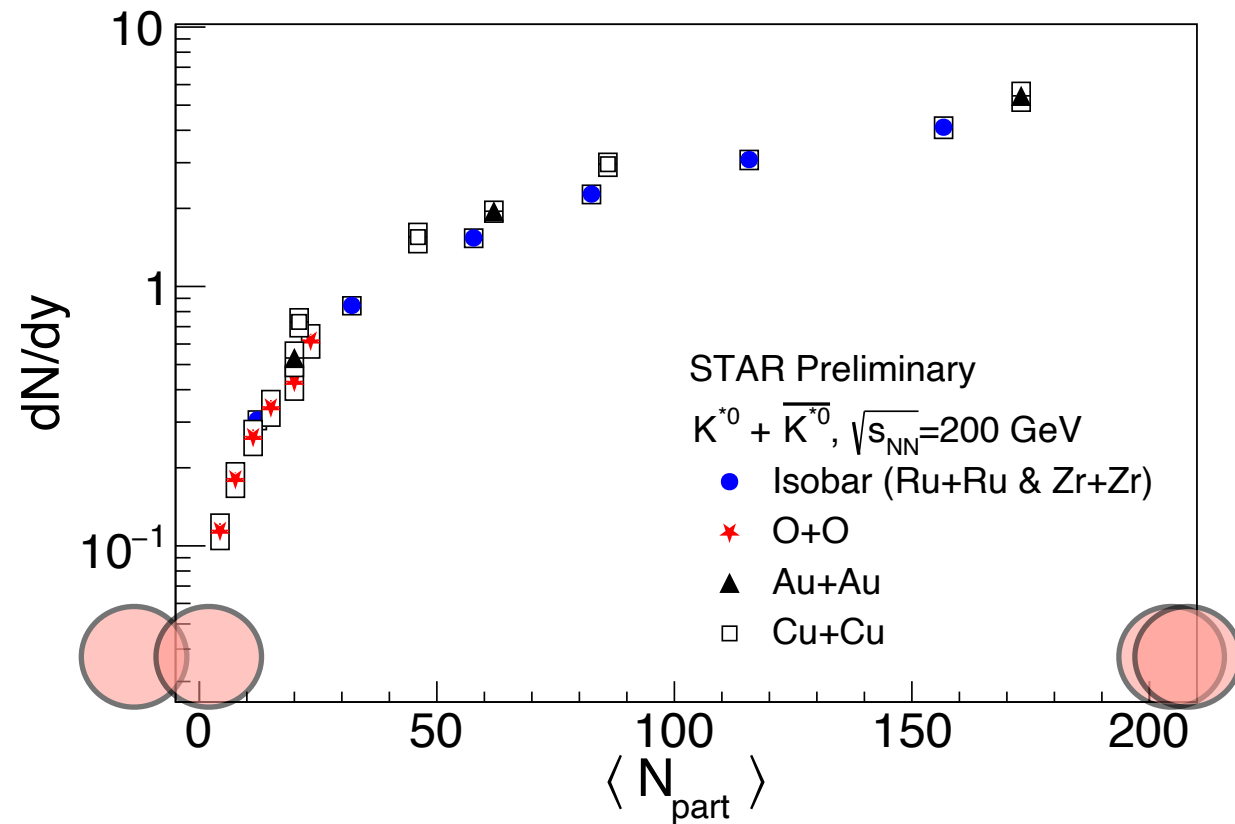
$$\frac{d^2N}{dp_T dy} = \frac{1}{N_{evt}} \times \frac{N^{raw}}{dp_T dy}$$

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



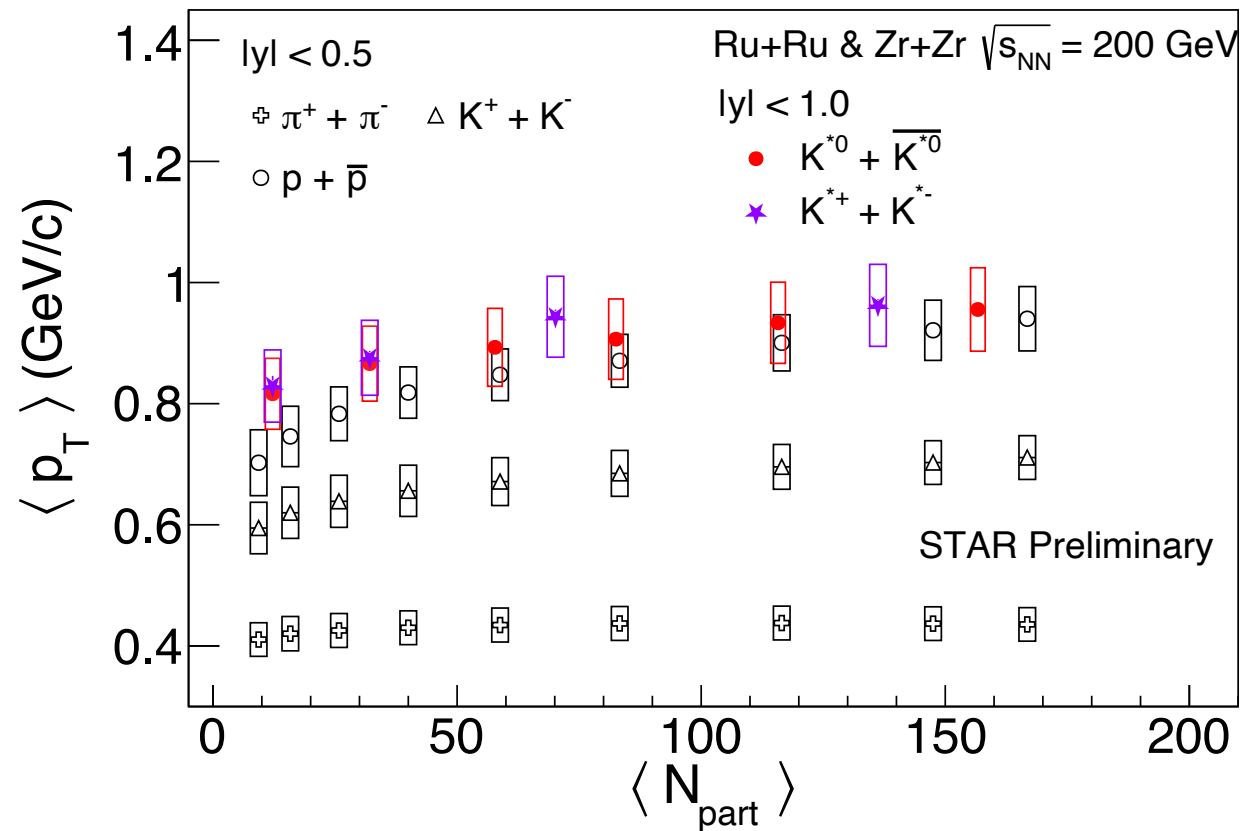


Mid-rapidity yield (dN/dy) of K^{*0} and $K^{*\pm}$

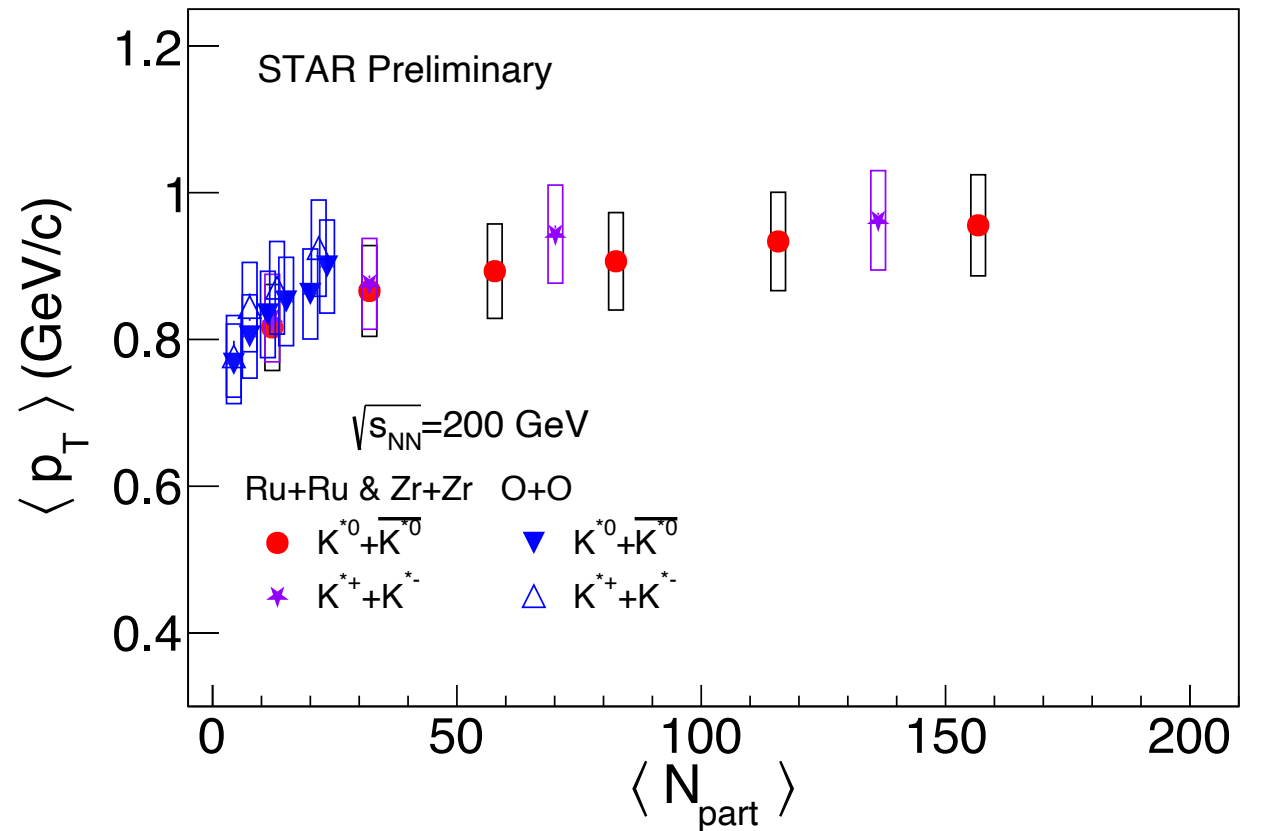


- K^{*0} and $K^{*\pm}$ dN/dy increases with $\langle N_{part} \rangle$
- dN/dy is driven by $\langle N_{part} \rangle$, not by collision species

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

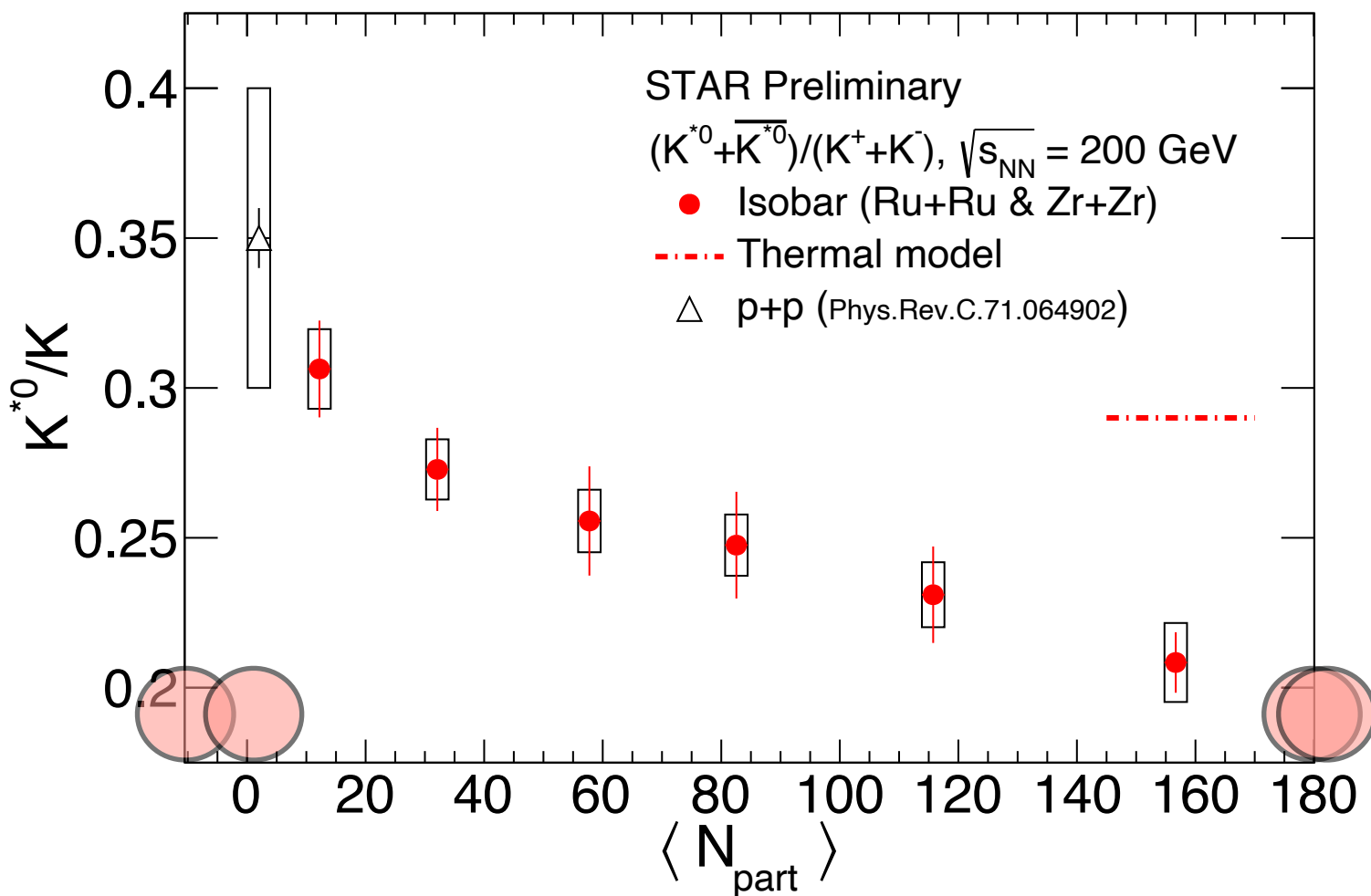


- $\langle p_T \rangle$: $K^{*0} \sim K^{*\pm}$
- $\langle p_T \rangle$ increases with mass
- $K^{*0,\pm} \langle p_T \rangle$ is close to proton
- Consistent with radial flow



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

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



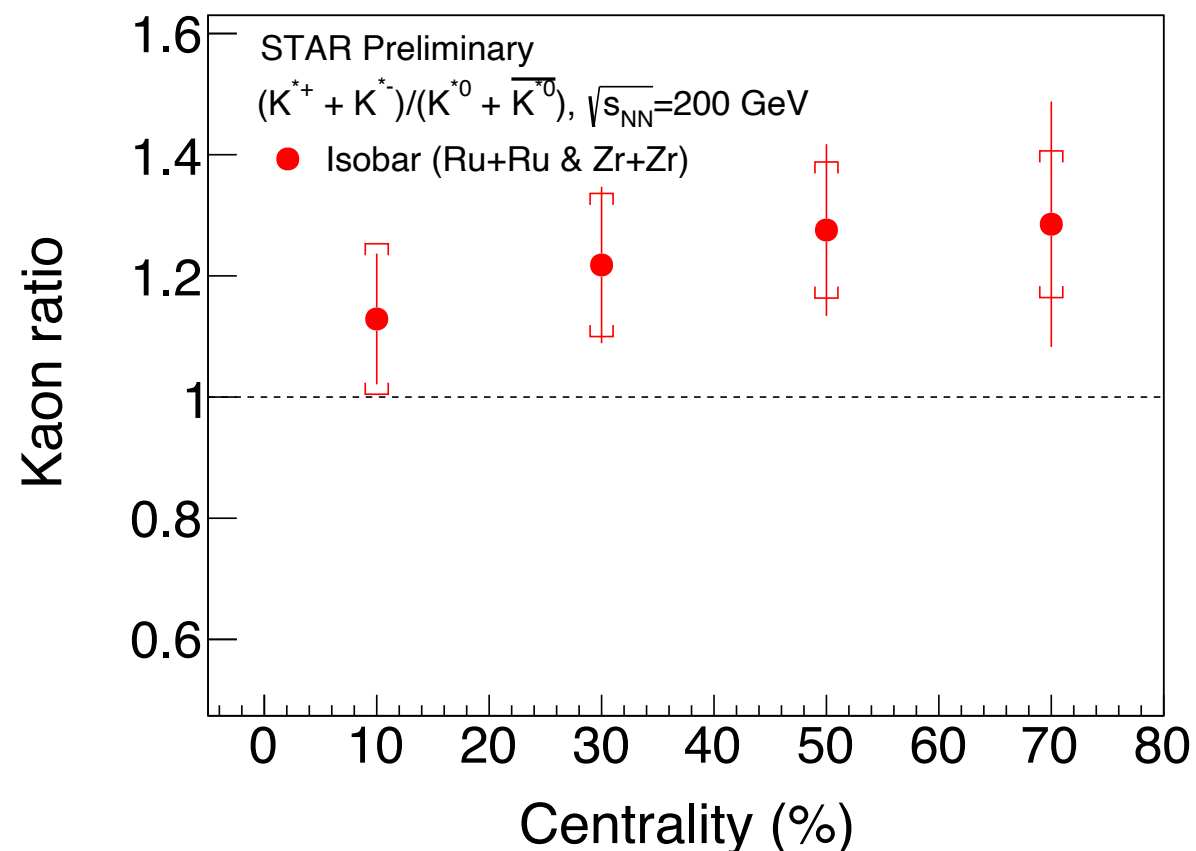
- Clear centrality dependence
- $(K^{*0}/K)_{\text{central}} \ll (K^{*0}/K)_{\text{peripheral}}$
 $(\sim 3.2 \sigma)$
- $(K^{*0}/K)_{\text{central}} \ll (K^{*0}/K)_{\text{Thermal model}}$

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:

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

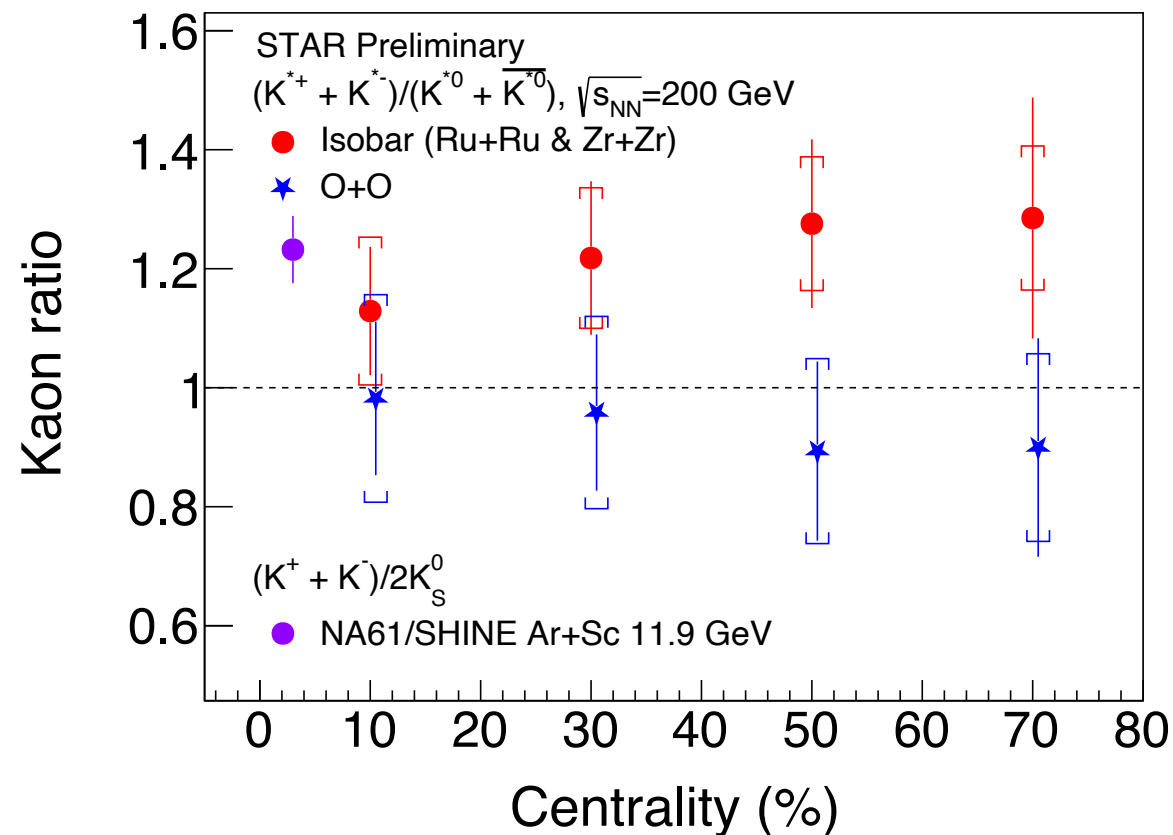
$$\rightarrow K^{*\pm}(d\bar{s}) > K^{*0}(u\bar{s})$$

- 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



• Isobar:

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

$$\rightarrow K^{*\pm}(u\bar{s}) > K^{*0}(d\bar{s})$$

• O+O:

$$R_{K^*} = 0.94 \pm 0.07 \pm 0.16$$

$$\rightarrow K^{*\pm}(u\bar{s}) \sim K^{*0}(d\bar{s})$$

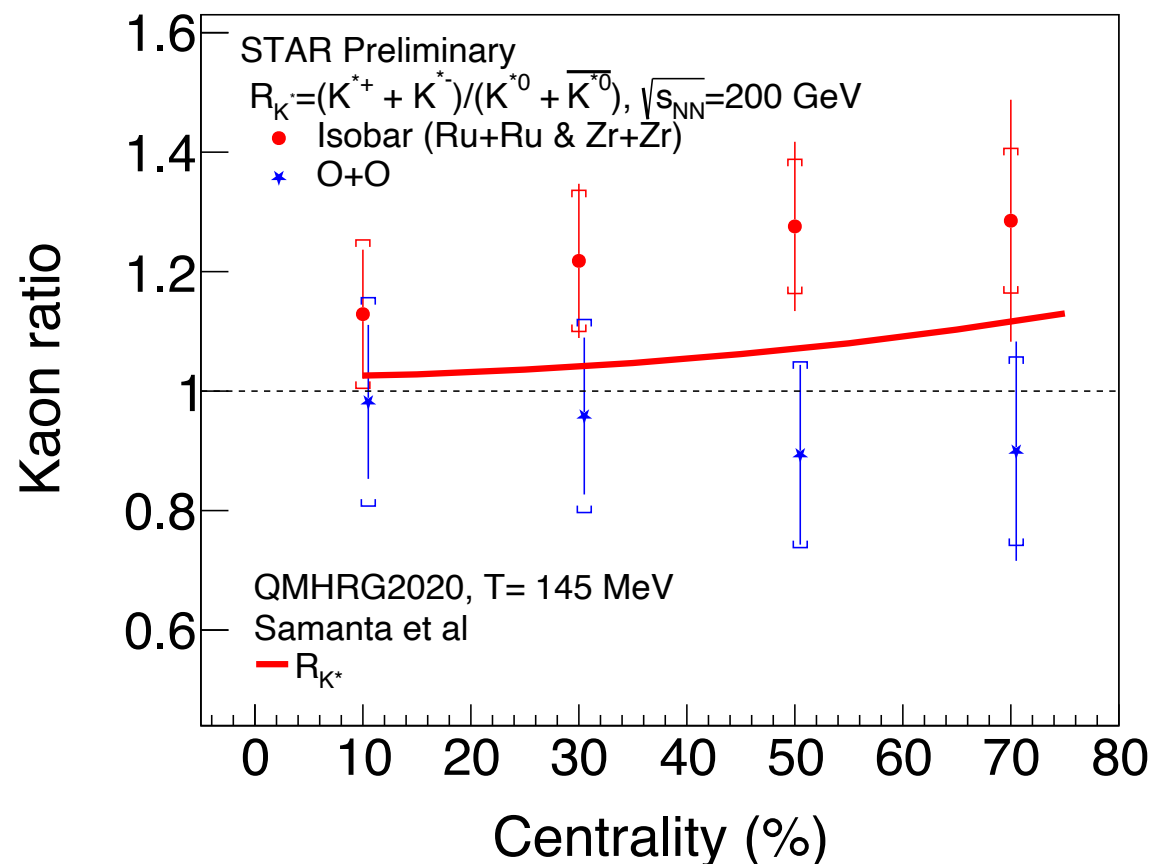
NA61/SHINE, Nat. Comm. 16 2849 (2025)

Expectation (without B-field effect)

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

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

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



• Isobar:

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

$$\rightarrow K^{*\pm}(u\bar{s}) > K^{*0}(d\bar{s})$$

• O+O:

$$R_{K^*} = 0.94 \pm 0.07 \pm 0.16$$

$$\rightarrow K^{*\pm}(u\bar{s}) \sim K^{*0}(d\bar{s})$$

R_{K^*} from isobar collisions is comparable to that from a HRG based model with magnetic field

R. Samanta et al, Phys. Rev. C 112, 045202 (2025)
 (Private communication)

Expectation (without B-field effect)

• Isobar (neutron-rich colliding nuclei)

$$\bullet K^{*\pm}(u\bar{s}) < K^{*0}(d\bar{s})$$

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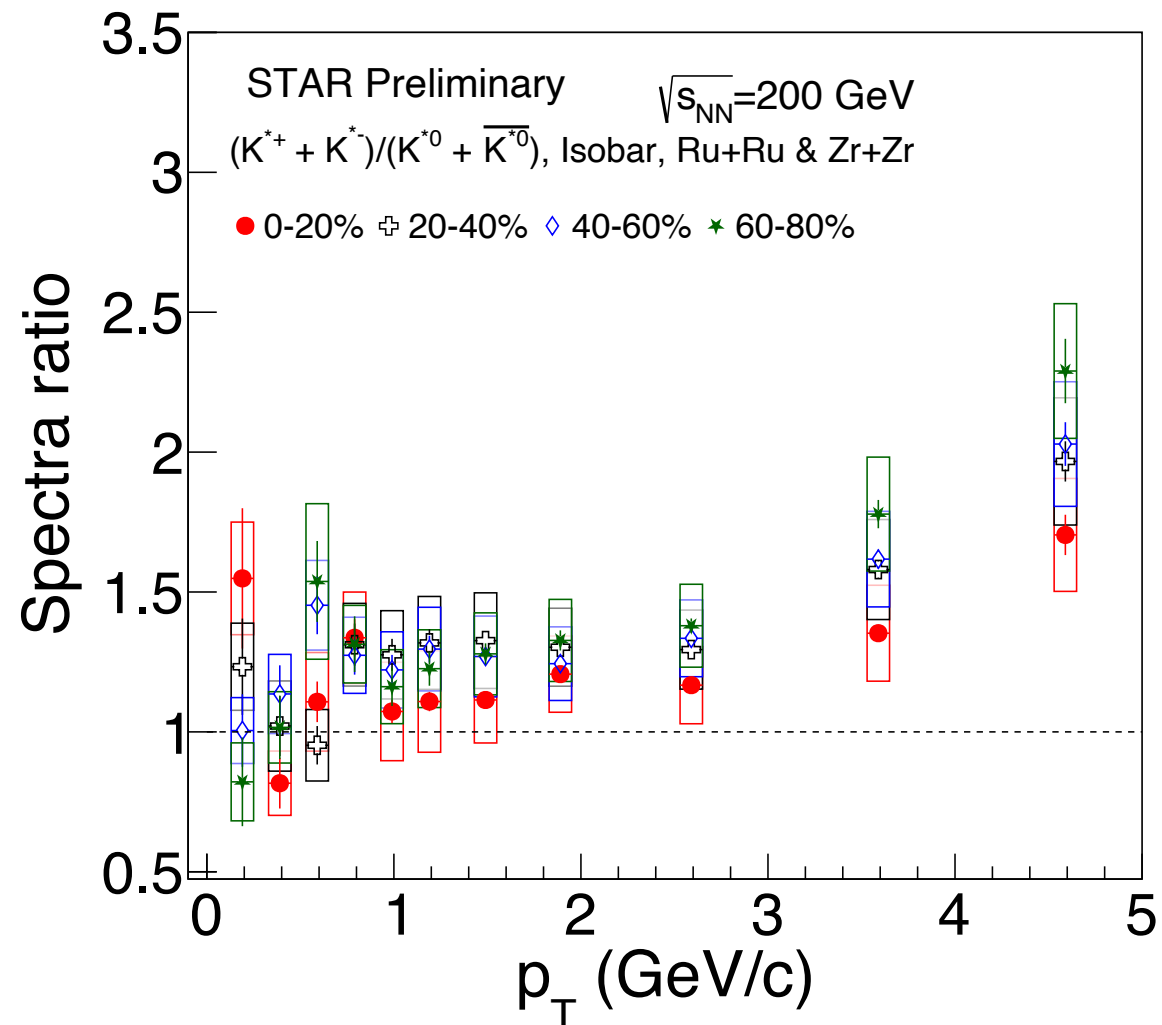
$$\bullet K^{*\pm}(u\bar{s}) \sim K^{*0}(d\bar{s})$$

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

Charged to neutral K^* spectra ratio

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

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

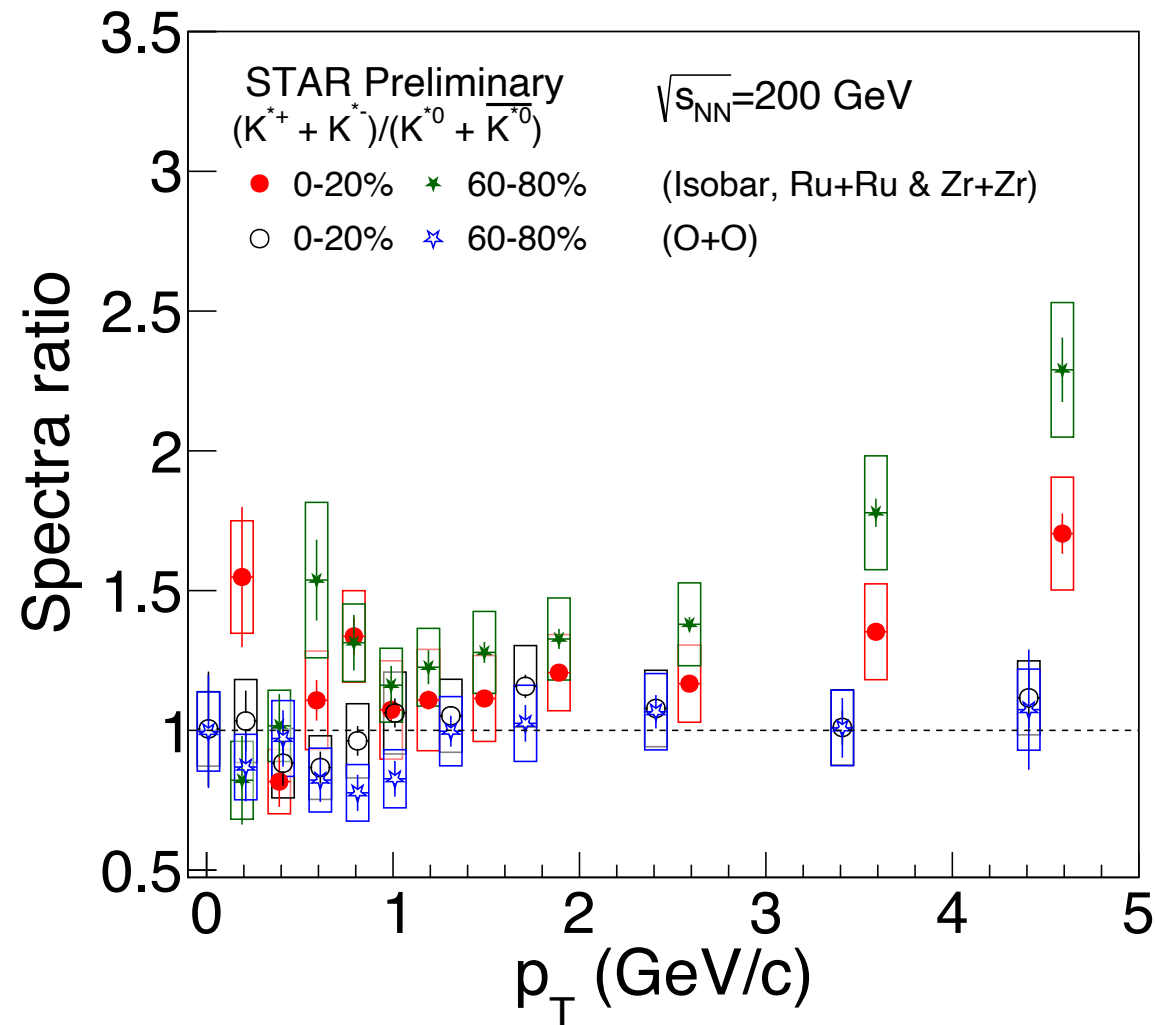


- At high p_T
 - $R_{K^*} > 1.0$ in Isobar
- R_{K^*}
 - Isobar: observe a centrality dependence 60-80% > 0-20%

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

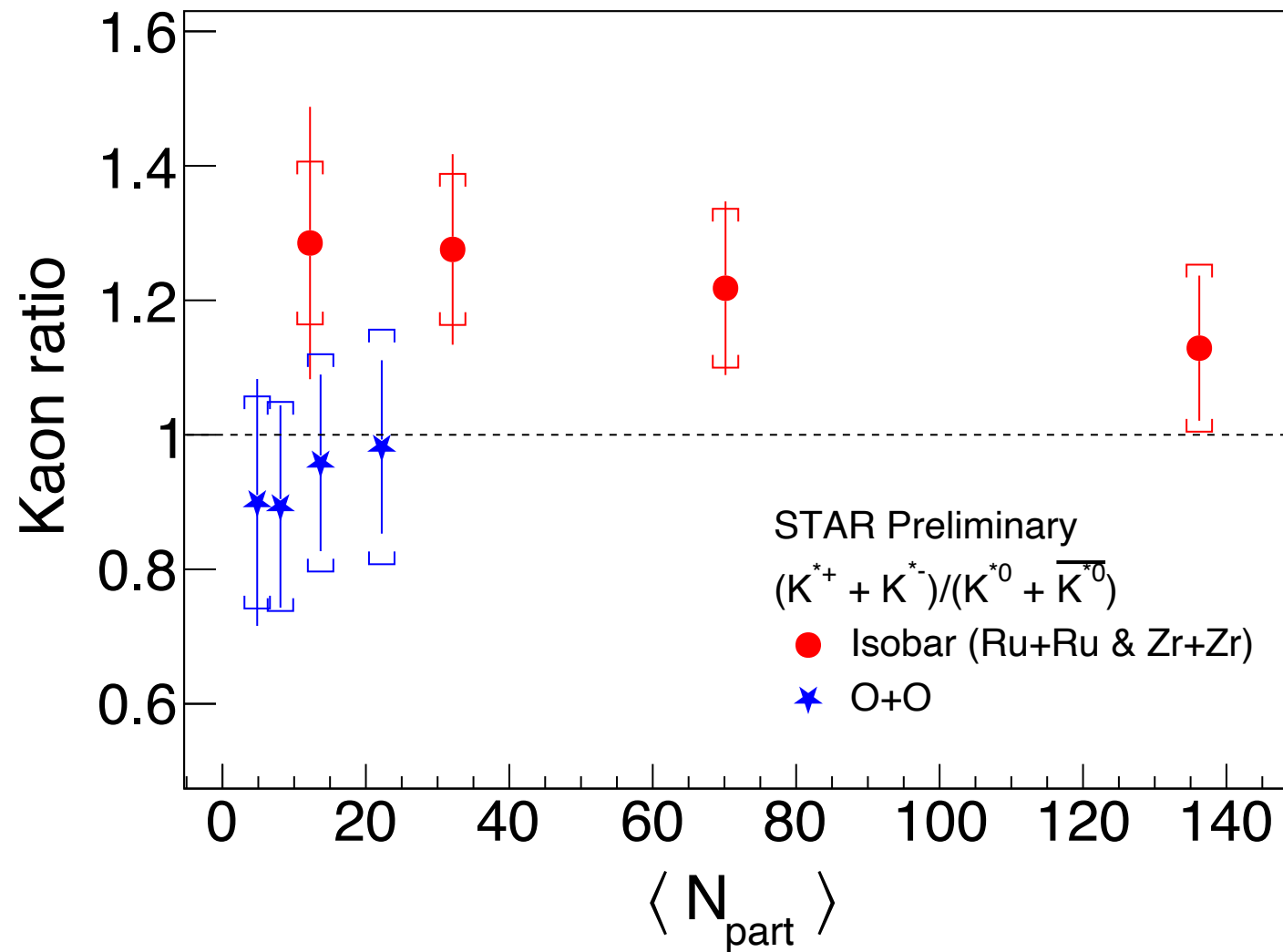
- Combined analysis of K^{*0} , $K^{*\pm}$, K_S^0 and $K^\pm$ species with high statistics p+p and Au+Au (BES-II) collisions is underway

Thank you for your attention!

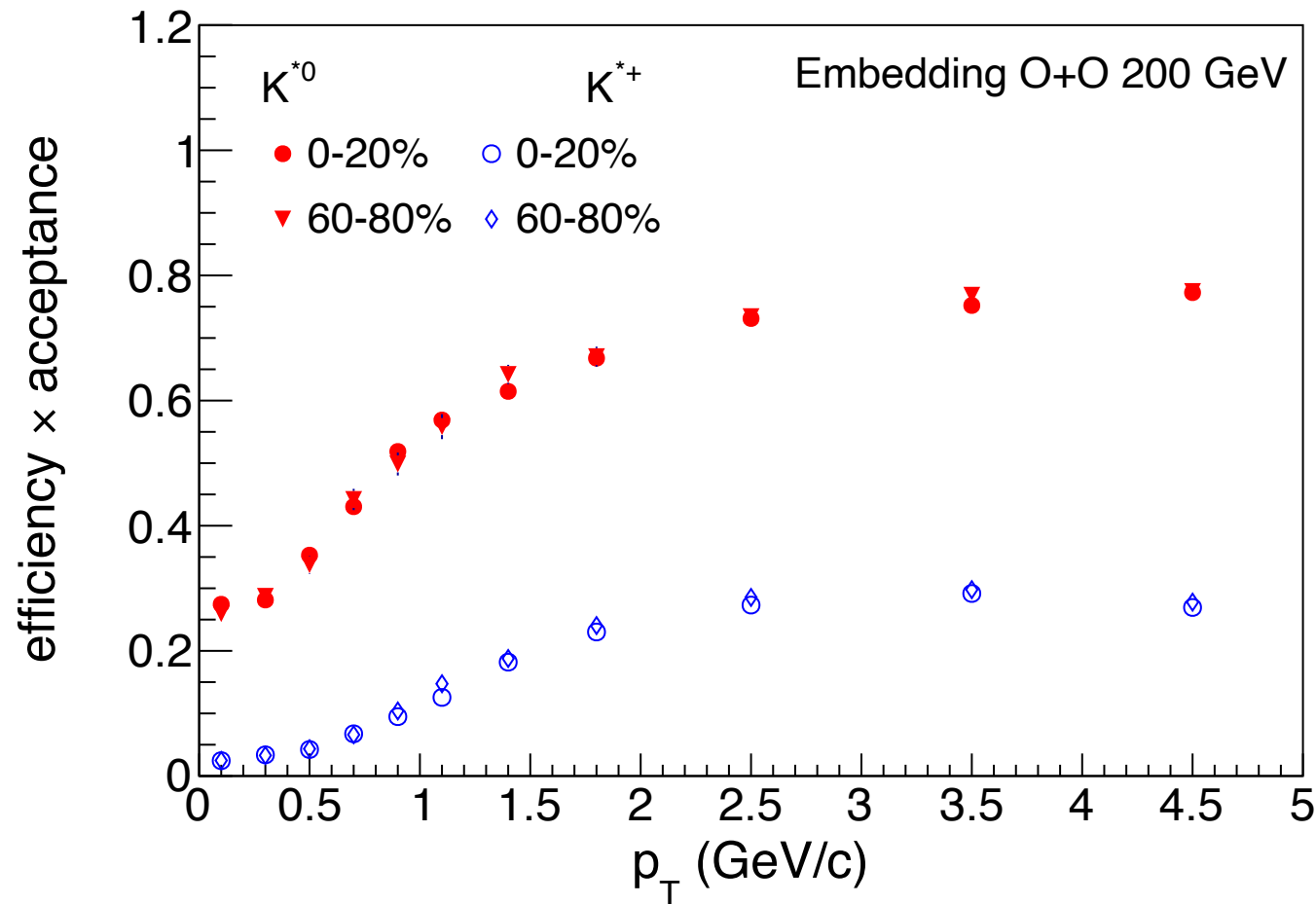


Back up

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



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

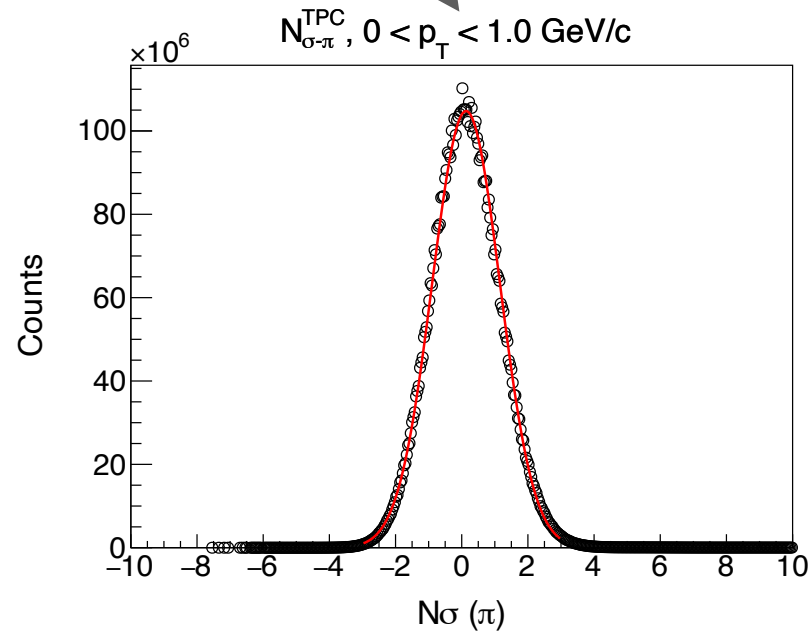
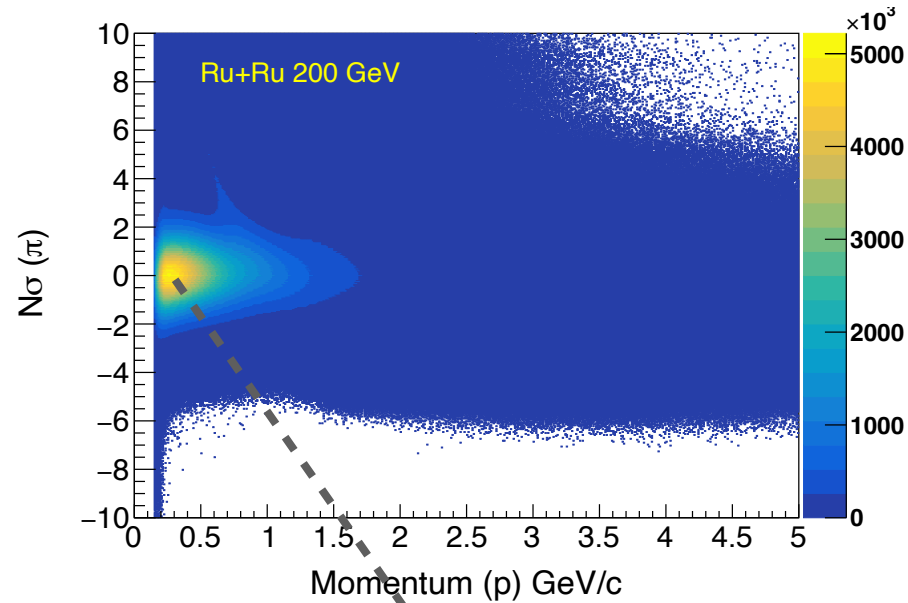


- Acceptance $\times$ efficiency obtained from STAR embedding simulations

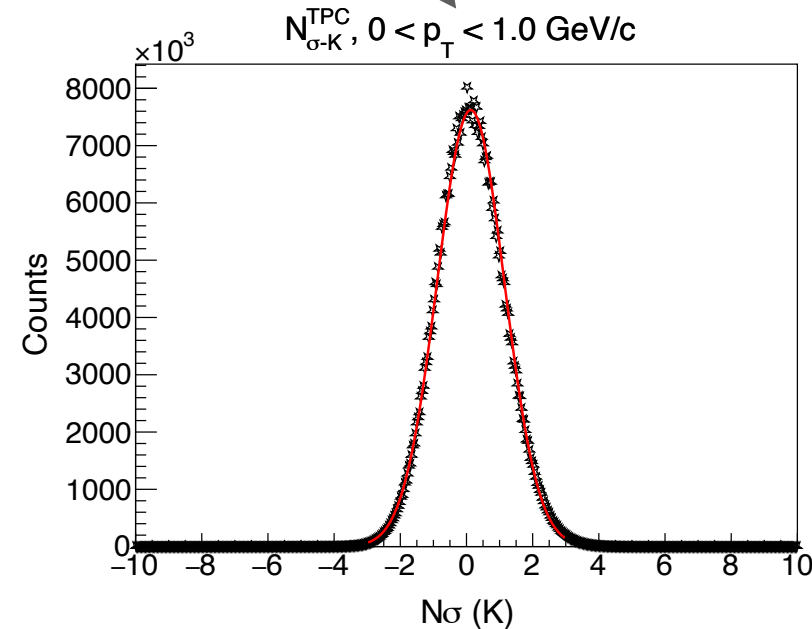
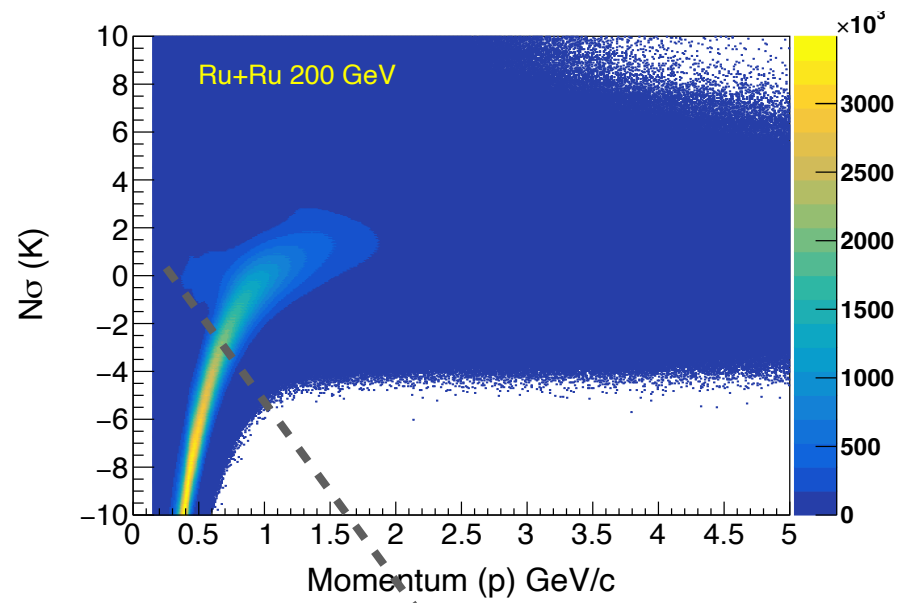
$$\epsilon_{\text{rec-acc}} = \frac{N_{\text{RC-event/track selections}}}{N_{\text{MC-input}}}$$

Particle Identification

Pions



Kaons



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

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

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

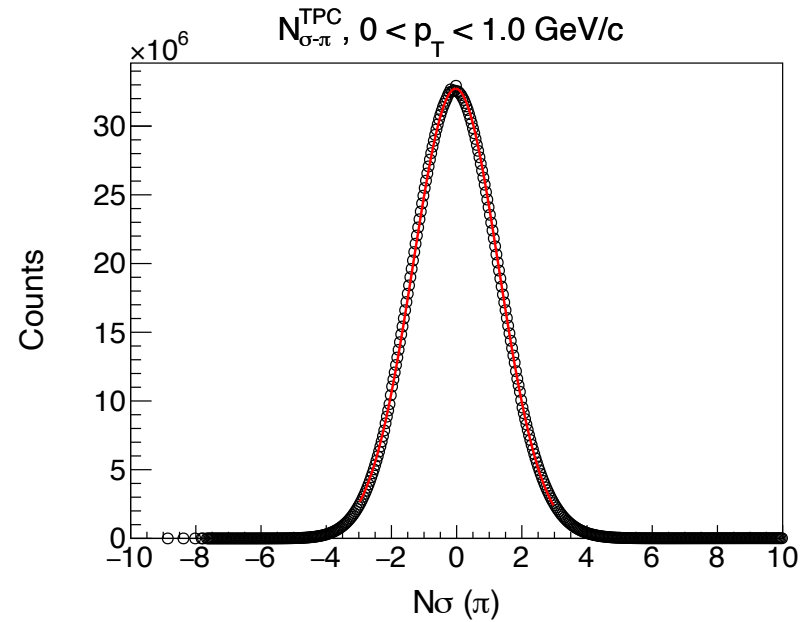
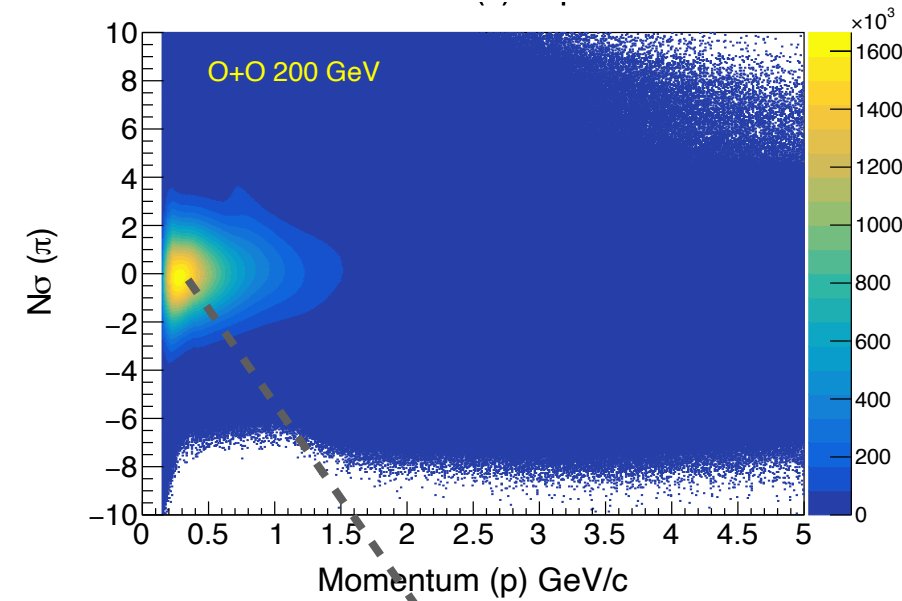
$\left(\frac{dE}{dx}\right)_{\text{theo}} \rightarrow$ Bethe-Bloch parameterization

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

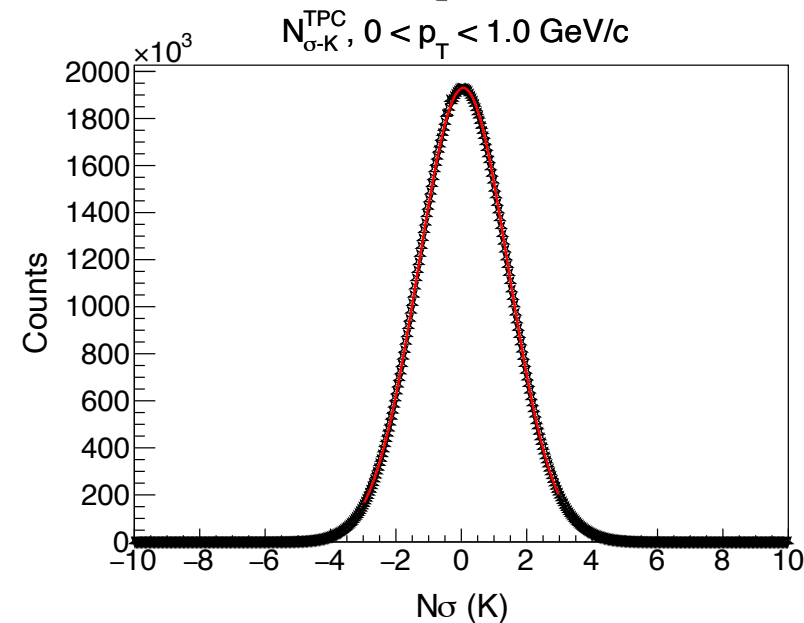
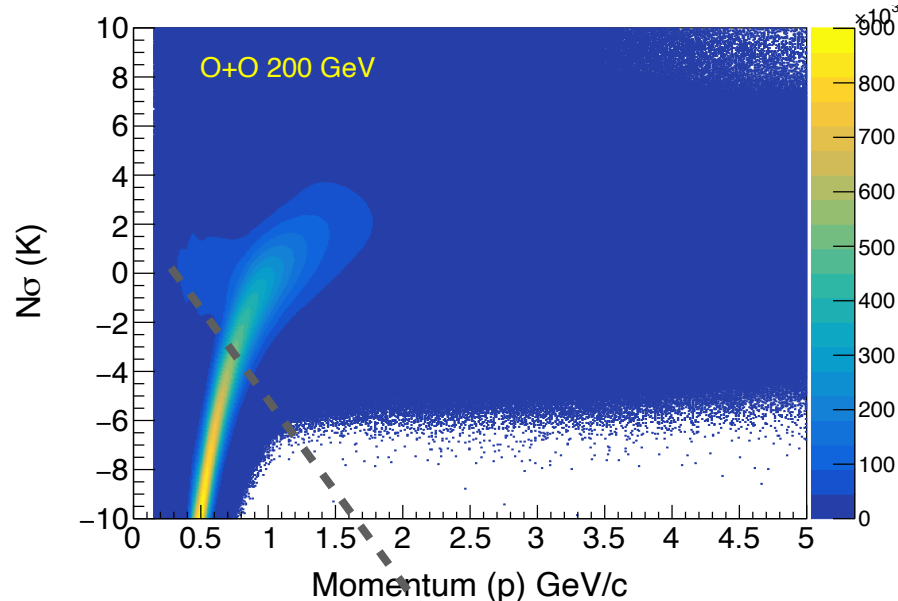
STAR, Nucl. Instrum. Meth. A 558, 419 (2006)

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

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

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