The study of strange mesons in *p*+*p*, *d*+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV

Priyanka Sett

Senior Research Fellow

Bhabha Atomic Research Center, Mumbai, India

(For PHENIX Collaboration)

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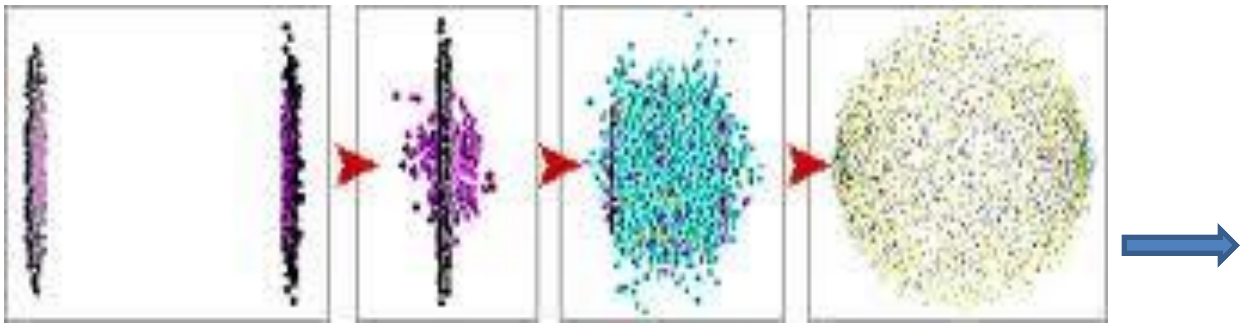
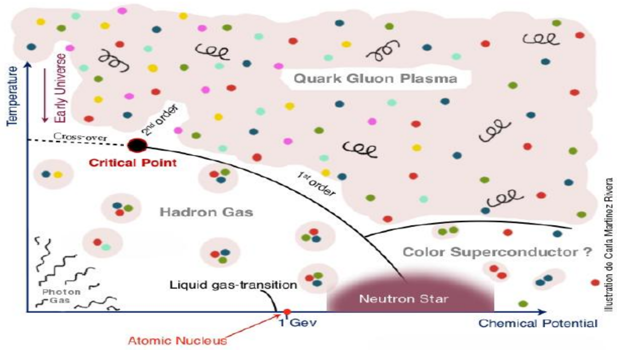
Outline

- ✓ Introduction
- ✓ Earlier measurements on Strange meson
- ✓ Brief overview of PHENIX detector systems
- ✓ Recent Measurements
  - ♦ Analysis
  - ♦ Results
- ✓ Summary and Conclusions

Introduction





G. Martinez arXiv:1304.1452

- High energy heavy ion collisions result in phase transition of hadronic matter to QGP.
- Till date RHIC and LHC are the biggest facilities for the high energy experiments.
- High p_T particle suppression due to energy loss of partons inside the medium, is one of the most important QGP signals.

  (Ref: Phys.Rev. D44 (1991) 2625-2630, Lect.Notes Phys. 785 (2010) 285-339)
- Modification of the spectrum due to energy loss can be quantified by,

$$R_{AB}(p_T) = \frac{d^2N^{AB}/dp_T dy}{(\langle N_{coll}\rangle / d^2N^{pp})/dp_T dy}$$

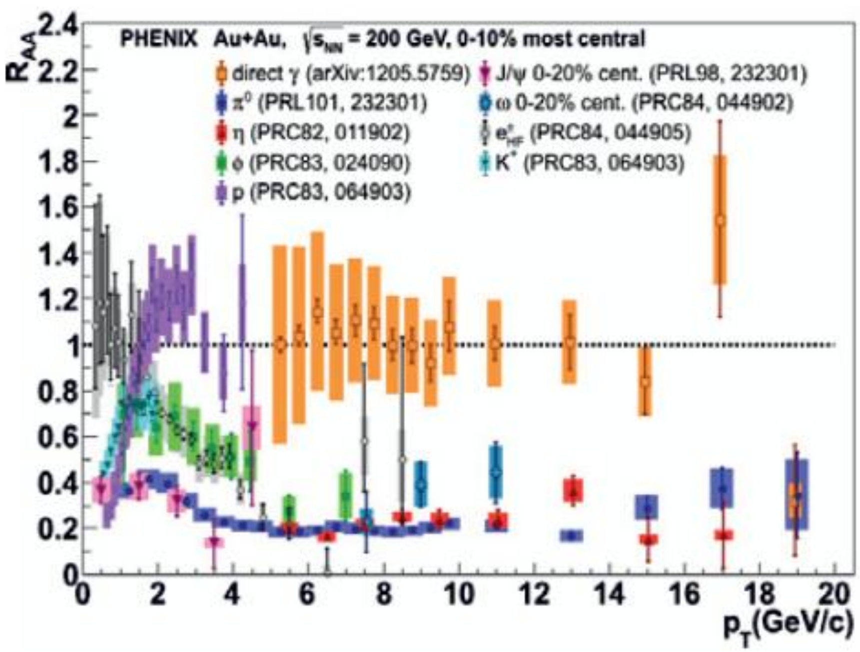
$R_{AB} = 1 \;\rightarrow$ No medium effects present

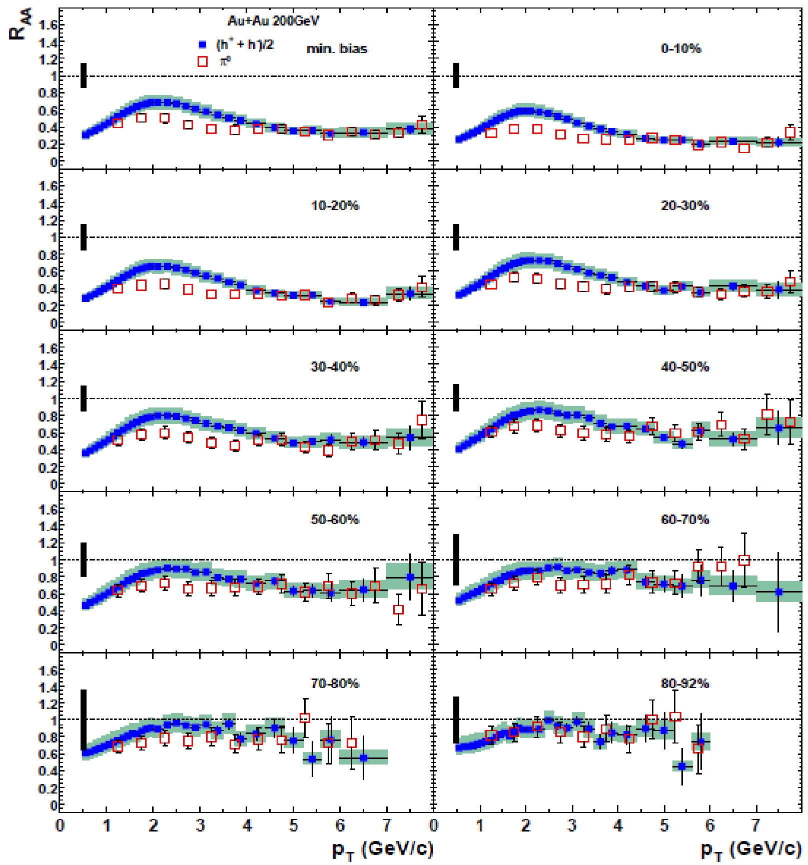
$R_{AB} \neq 1 \;\rightarrow$ Medium effects present

$R_{AB} < 1 \;\rightarrow$ Energy loss occurred due to medium

Introduction

- Experimental evidences of high p_T particle suppression: RHIC





PHENIX Coll. Phys.Rev. C69 (2004) 034910

In RHIC, for central Au+Au collisions, R_{AA} ----

- **decreases from peripheral to central collisions for charged hadrons.**
- **is consistent with unity for photons within uncertainties.**
- **is greater than 1 for protons at intermediate p_T.**
- **is similar for η and π^0 , also ω.**
- **for particles containing strange quarks ($K^{\pm}$, φ) lie in between of other mesons and protons.**

Introduction

- Motivation of strange measurement:
  - Strange particle measurements provide additional constraint on energy-loss model prediction.
  - The effect of flow and recombination on strange hadron production at intermediate p_T is an important study.
  - The behavior of strange hadrons in heavy ion collisions are interesting, as;
    - φ is suppressed as π^0 at high p_T but has a different trend in low and intermediate p_T.
    - η meson is similarly suppressed like π^0 at high p_T.
    - charged kaon suppression in the measured p_T range (< 2 GeV/c) does not show π^0 like behavior.

Measurements of K_S^0 and K^{*0} will provide more systematic in strange hadron study and hence of great importance.

Earlier measurements on strange mesons

PHENIX has already measured different strange mesons in *p*+*p*, *d*+Au, Au+Au, Cu+Cu collisions at different energies.

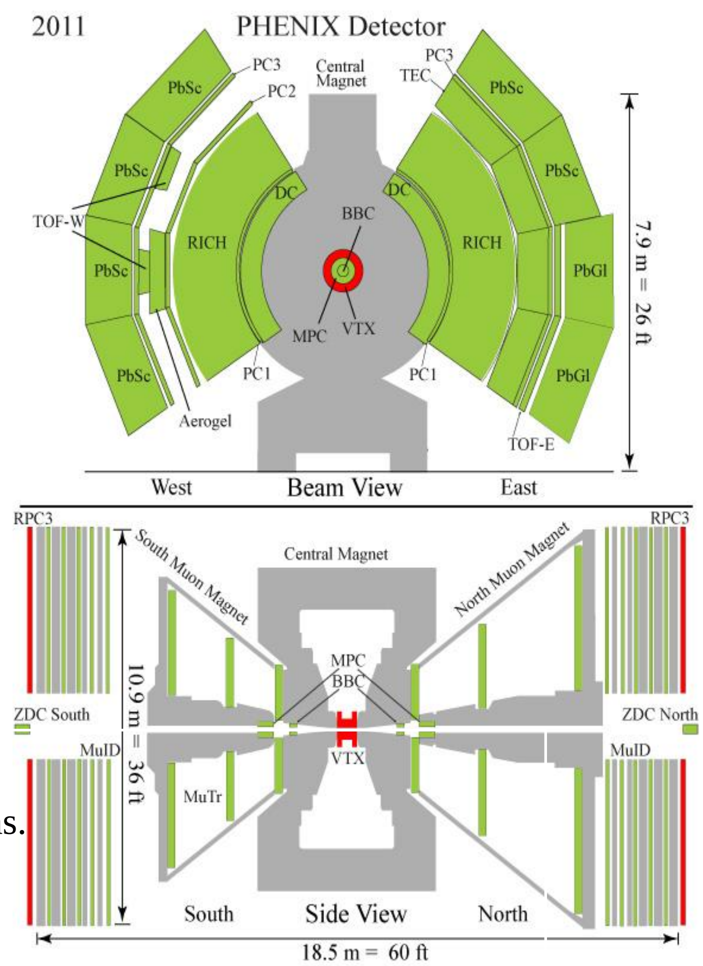
Particles	Systems	$\sqrt{s_{NN}}$ in GeV	Decay Modes
Kaon	*p*+*p*	200, 62.4	
	d+Au and Au+Au	200	
φ	*p*+*p*, *d*+Au, Cu+Cu and Au+Au	200	$K^+ + K^-$ (48.9%)
K_S^0	*p*+*p*, *d*+Au and Cu+Cu	200	$\pi^0 + \pi^0$ (30.69%)
K^{*0}	*p*+*p*, *d*+Au and Cu+Cu	200	$K^{\pm} + \pi^{\pm}$ (~ 67%)

Earlier Measurements

Recent Measurements

Brief overview of PHENIX detector systems

Information used	Detector
i) Event Triggering ii) Collision Time and z_{vertex} & iii) Centrality Determination	Beam-Beam Counter (BBC)
Track reconstruction and momentum determination	Drift Chamber (DC) and 1st Pad Chamber (PC1)
Rejection of secondary tracks	2nd & 3rd Pad Chambers
Charged hadron ID	Time of Flight (ToF)
Photon position and energy measurement	Electro-Magnetic Calorimeter (EMCal)



System Specifications :

- BBC z_{vertex} position resolution: ~ 1.1 cm in $p+p$ to 3 mm in Au+Au collisions.
- Momentum resolution for charged particles with $p_T > 0.2$ GeV/c, $\delta p/p = 0.7 \oplus 1.1\ \%\ p$ (GeV/c).
- ToF timing resolution ~ 130 ps. π/K separation up to $p_T \sim 2.5$ GeV/c and K/p separation up to $p_T \sim 4.5$ GeV/c.
- EMCal energy and spatial resolution for PbSc (PbGl) $\delta E/E = 2.1\ (0.8)\ \% \oplus 8.1\ (5.9)\ \%/\sqrt{E}$ (GeV) % , $\sigma(E) = 1.55\ (0.2) \oplus 5.74\ (8.4)\ \%/\sqrt{E}$ (GeV) mm.

Recent Measurements

arXiv : 1405.3628

Recent measurements consist of :
- Data Analysis.
- Results.

For,
- **K_S^0 meson.**
- **K^{*0} meson.**

Data analysis consist of :
- Meson reconstruction.
- Efficiency Calculation.

Results consist of :
- Invariant yield p_T spectra.
- K_S^0/π^0 ratio.
- Nuclear Modification factor.

	Collision System	Centrality bins (%)	Measured p_T range (GeV/c)
K_S^0	d+Au	0–20, 20–40, 40–60, 60–88	2.0–13.0
	Cu+Cu	0–20, 20–60, 60–94	3.0–12.0
K^{*0}	p+p	————	1.1–8.0
	d+Au	0–20, 20–40, 40–60, 60–88	1.1–8.5
	Cu+Cu	0–20, 20–40, 40–60, 60–94	1.4–8.0

K_S^0 measurement in p+p collisions is studied in Phys. Rev. D83, 052004 (2011).

K_S^0 measurement covers intermediate and high p_T

K^{*0} measurement covers low and intermediate p_T

Data analysis : Meson reconstruction.

K_S^0 meson

$K_S^0 \rightarrow \pi^0(\rightarrow \gamma\gamma)\ \pi^0(\rightarrow \gamma\gamma)$, $c\tau = 2.7$ cm

• π^0 reconstruction from $\gamma\gamma$:

- ➢ $E_\gamma > 0.2$ GeV (d+Au and Cu+Cu peripheral),
  $E_\gamma > 0.4$ (other centrality for Cu+Cu)
- ➢ Both γ forming π^0, are in the same EMCal sector.
- ➢ Asymmetry cut : $|E_1 - E_2|/|E_1 + E_2| < 0.8$

• K_S^0 reconstruction from $\pi^0\ \pi^0$:

- ➢ π^0 $p_T > 1.0$ GeV/c for d+Au,
  > 1.5 GeV/c for Cu+Cu with centrality >20%
  > 2 GeV/c for Cu+Cu centrality < 20%
- ➢ Corrections due to in-flight decay of K_S^0 are included.

K^{*0} meson

$K^{*0} \rightarrow K^+ \pi^-$ or $K^- \pi^+$, $c\tau = 4$ fm

• Track Selection cuts and criteria:

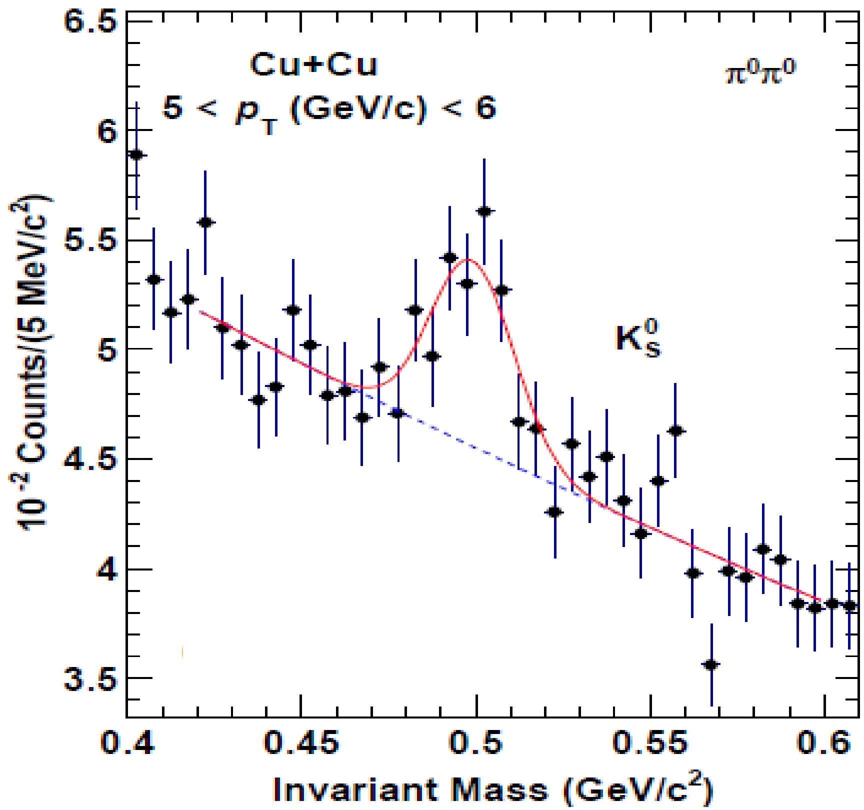
- ➢ $p_T > 0.3$ GeV/c.
- ➢ Two oppositely charged track are selected in an event.
- ➢ Fully identified – Tracks are identified in ToF as kaons and pions .
- ➢ Kaon Identified – Kaons are identified in ToF and the other track is matched in PC3 and given the mass of pion.
- ➢ Unidentified – Both tracks are PC3 matched.

• Background removal :

- ➢ Uncorrelated background are removed by event-mixing technique.
- ➢ Contributions from mis-identified tracks are also removed (e.g. $\varphi \rightarrow K^+ K^-$, $K_S^0 \rightarrow \pi^+ \pi^-$).

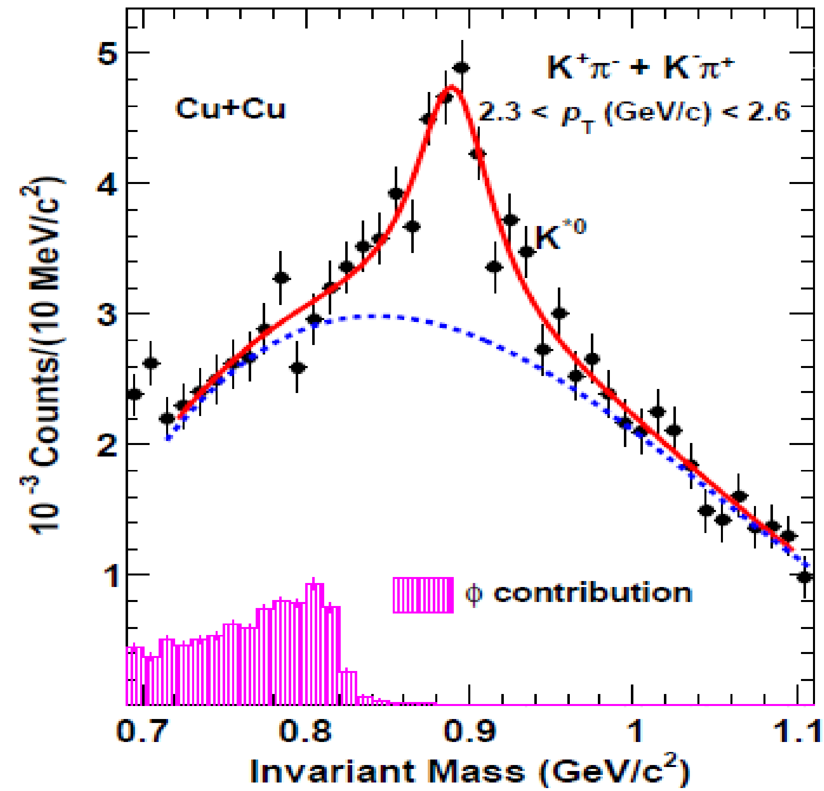
Data analysis : Meson reconstruction.

K_S^0 meson



Red Line – Gaussian+2nd Order Pol
Blue dashed line – background
Black circles – Data

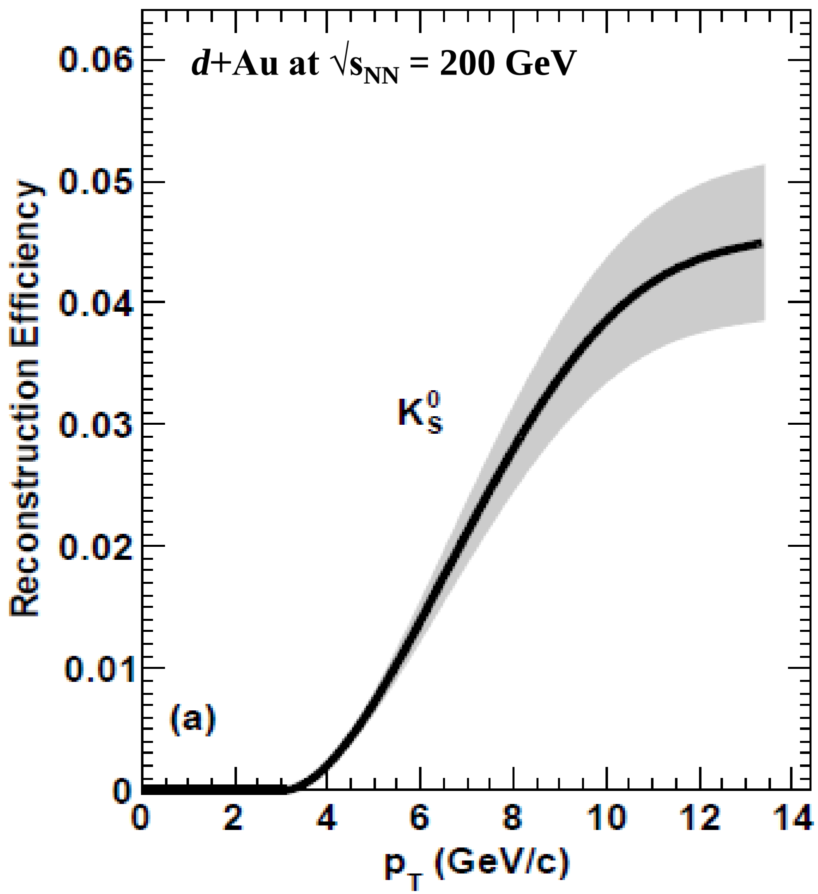
K^{*0} meson



Red Line – Relativistic Breit Wigner + 3rd Order Pol
Blue dashed line – background
Black circles – Data

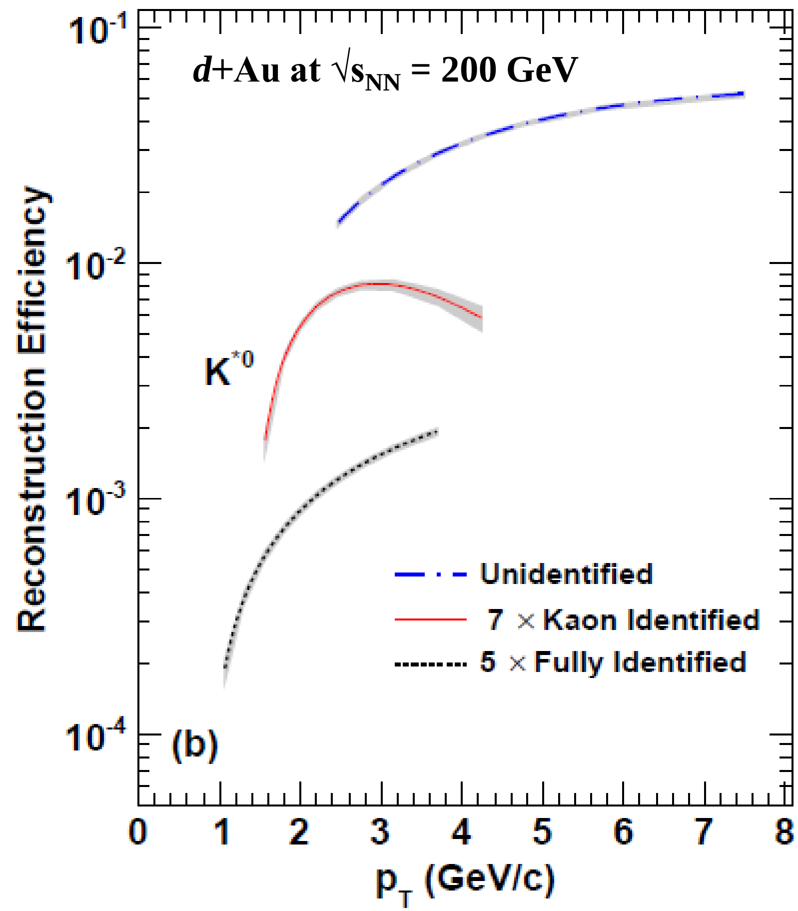
Data analysis : Reconstruction Efficiency (ε)

K_S^0 meson



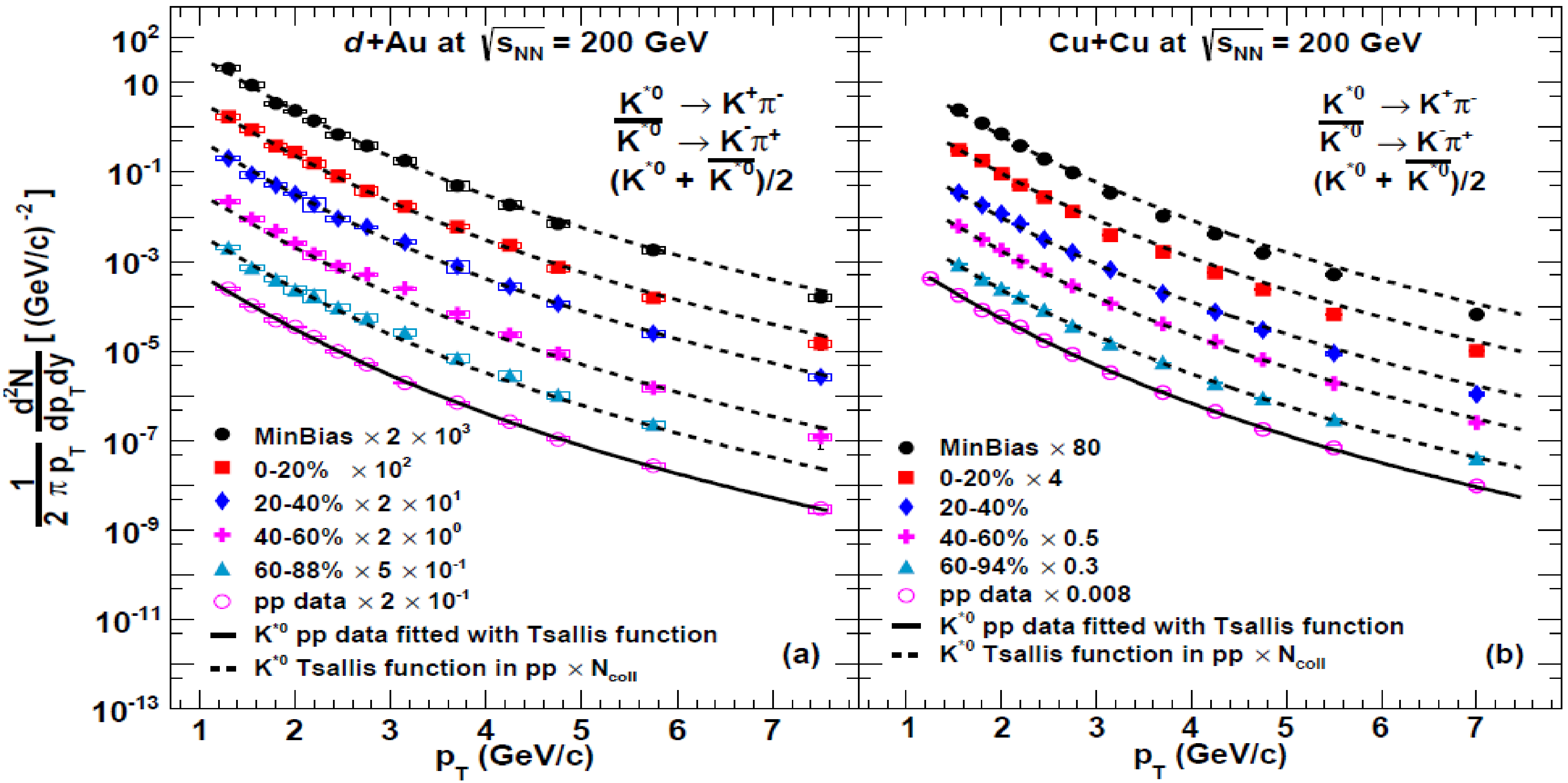
ε increases smoothly with p_T.

K^{*0} meson



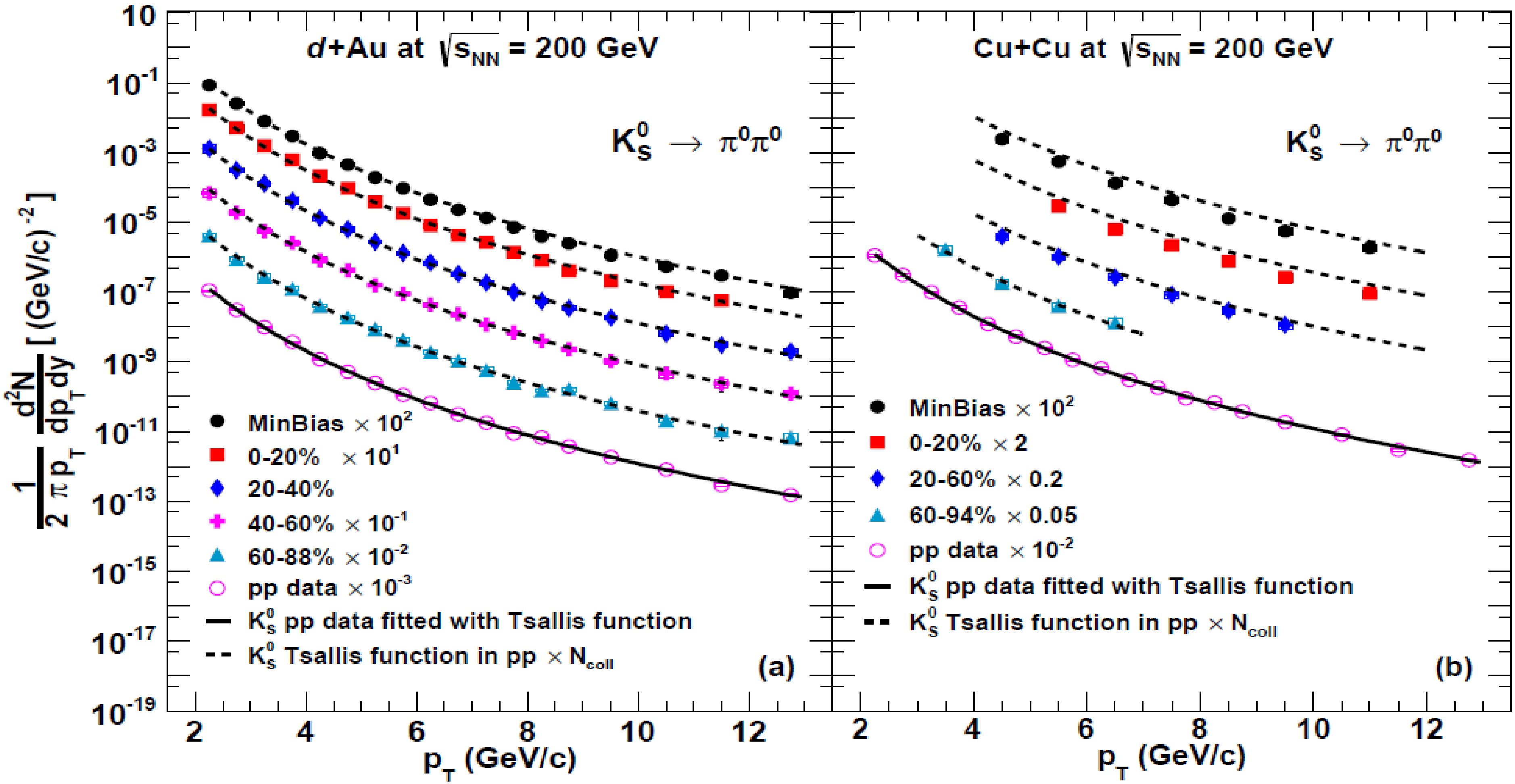
While Unidentified set is the most efficient, the fully identified set has better low p_T reach.

Results : Invariant yield p_T spectra for K^{*0} meson



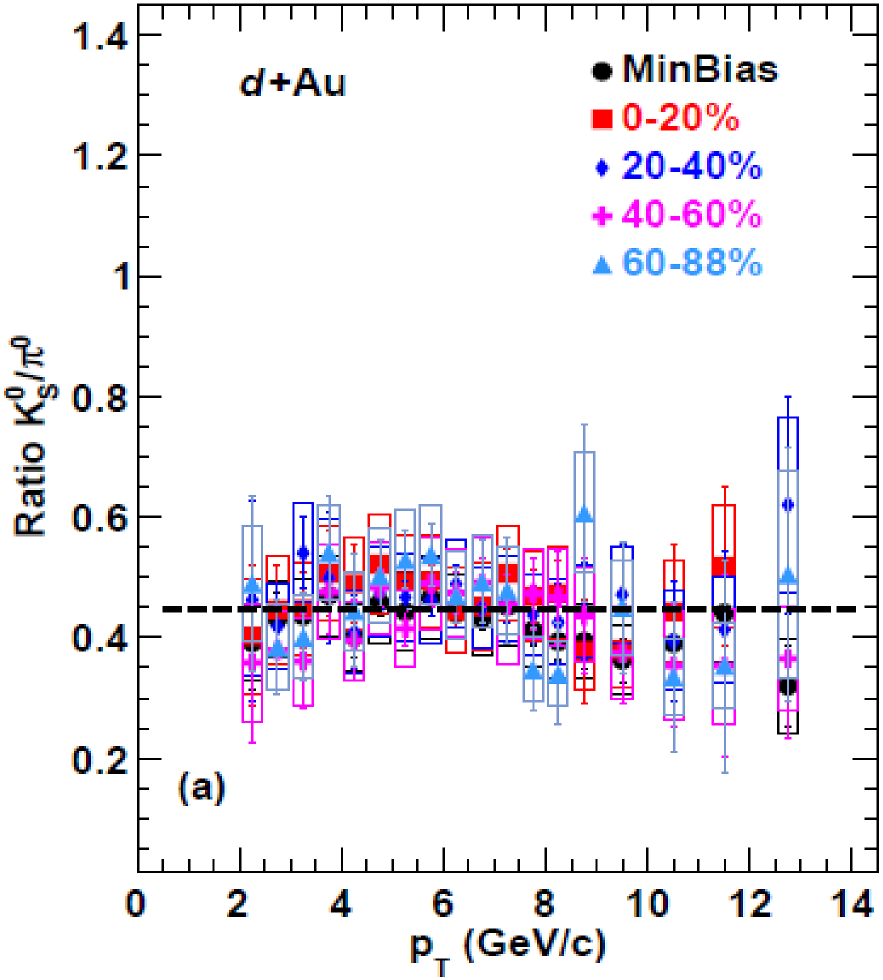
- *d*+Au → binary scaling is followed for all centrality bins.
- Cu+Cu → binary scaling followed only in peripheral bins.
  → Yields in central and semi-central show suppression at high p_T.

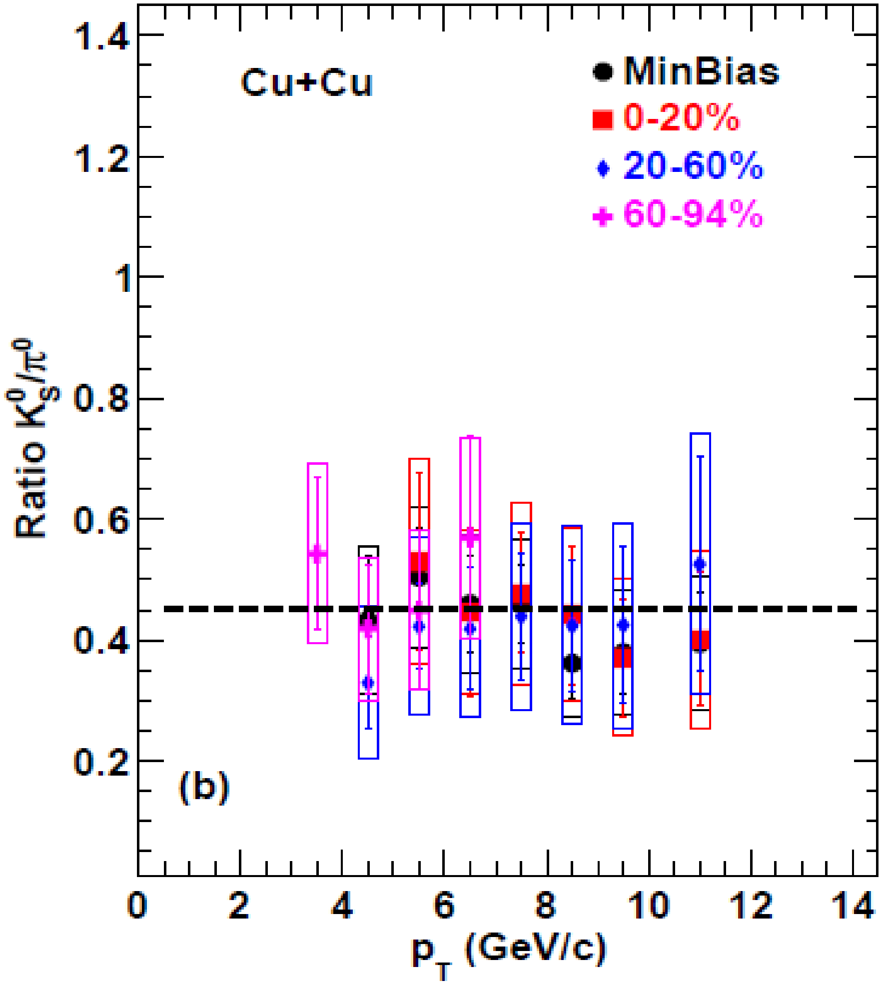
Results : Invariant yield p_T spectra for K_S^0 meson



- *d*+Au → binary scaling is followed for all centrality bins.
- Cu+Cu → binary scaling followed only in peripheral bins.
  → Yields in central and semi-central show suppression at high p_T.

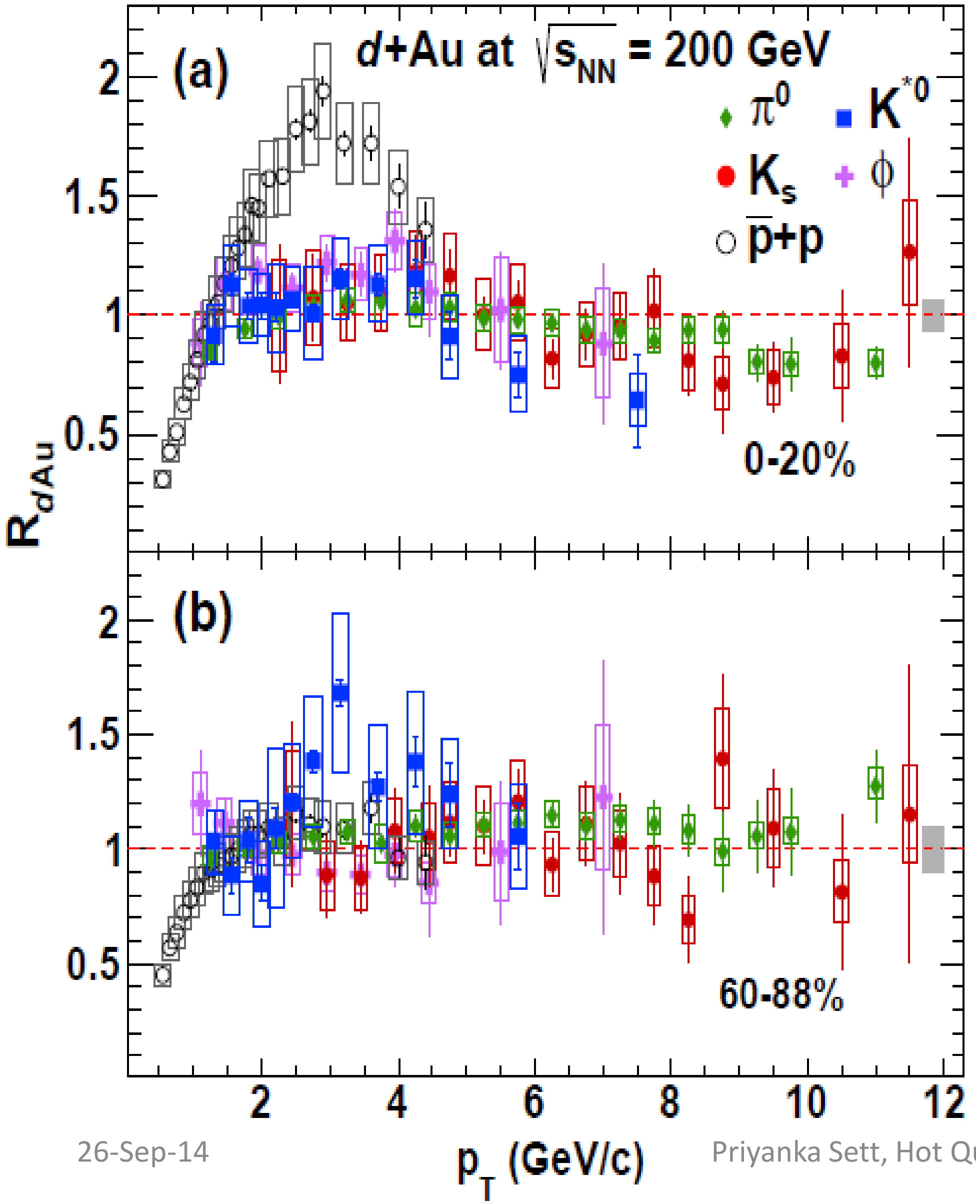
Results : K_S^0/π^0 ratio





The ratio is ~ 0.45 within uncertainties in the measured p_T range.

Results : R_{dAu}

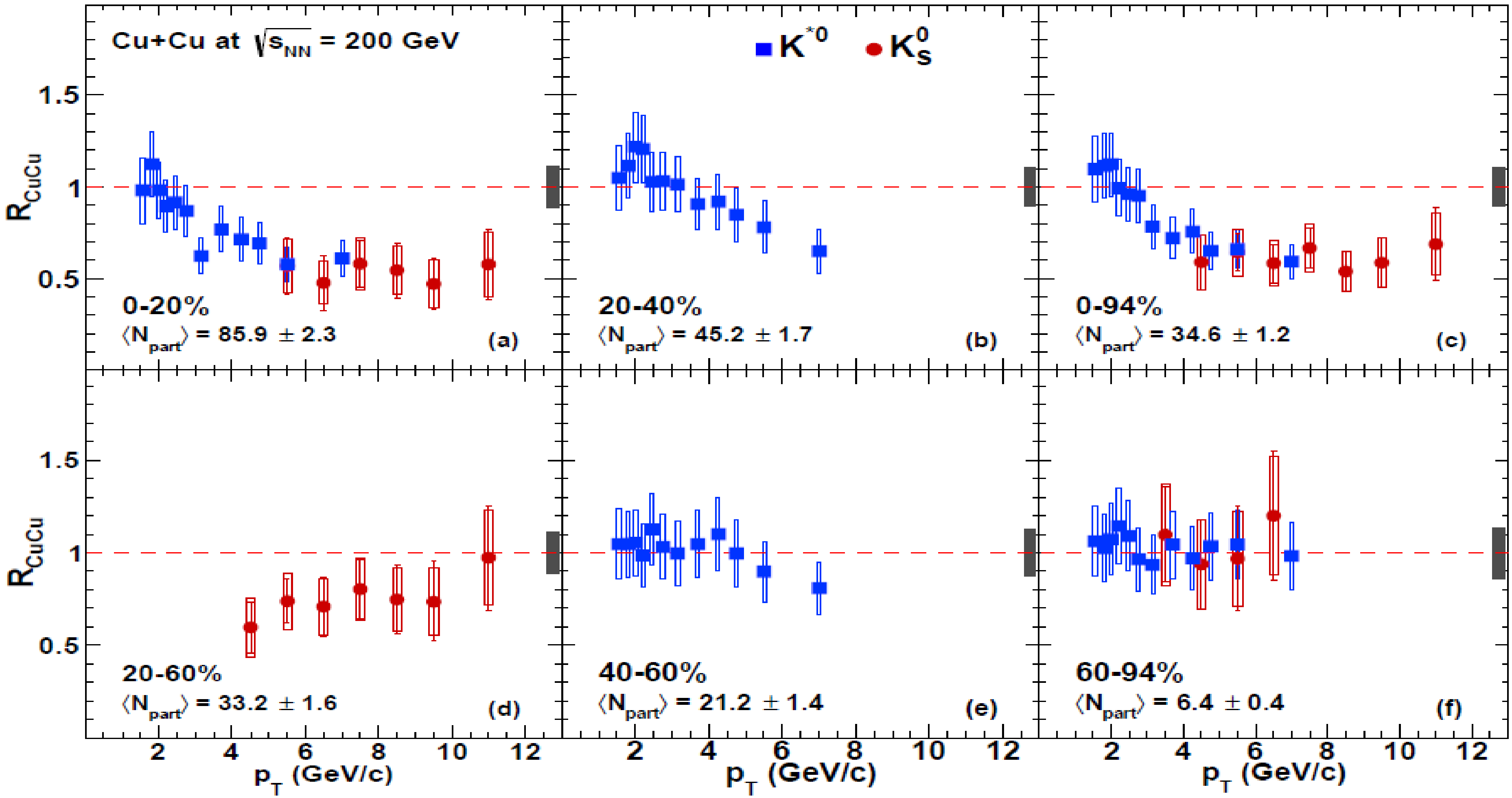


- R_{dAu} for K_S^0 and K^{*0} is -----
  - unity for p_T > 1 GeV/c.
  - similar to the R_{dAu} of φ and π^0 mesons within uncertainties.
- No significant cold nuclear effects observed for mesons.
- Proton shows an enhancement in 0 – 20% centrality.

References :

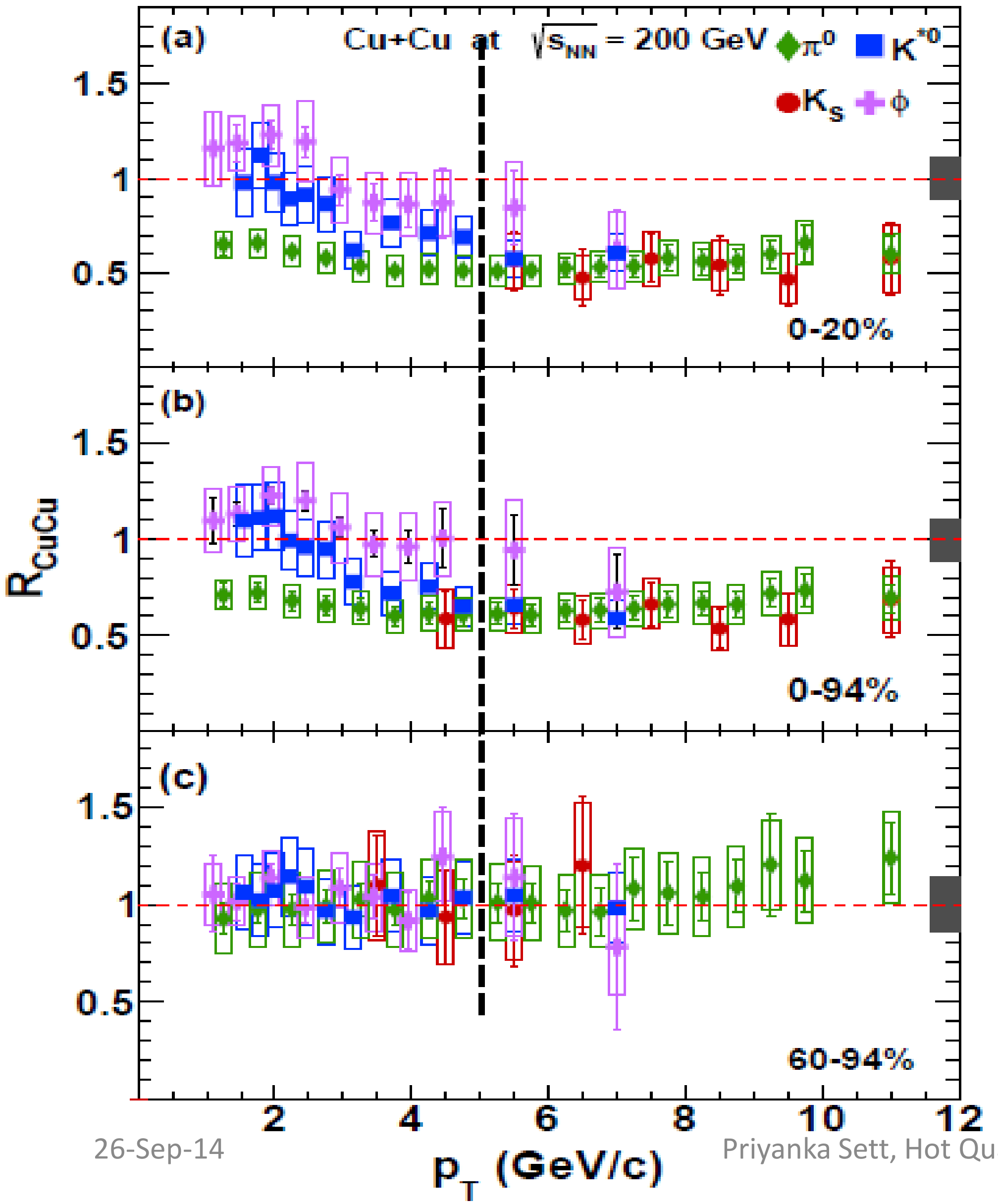
For φ, π^0 and p references please see arXiv: 1405.3628

Results : R_{CuCu} (K_S^0 & K^{*0})



- **Suppression gradually decreases with the decrease of <N_{part}>.**
- **For 0 – 20%, R_{CuCu} ~ 0.5 for both K* and K_S^0 above p_T > 5 GeV/c.**
- **For peripheral collisions, R_{CuCu} is unity within error bars.**

Results : R_{CuCu}

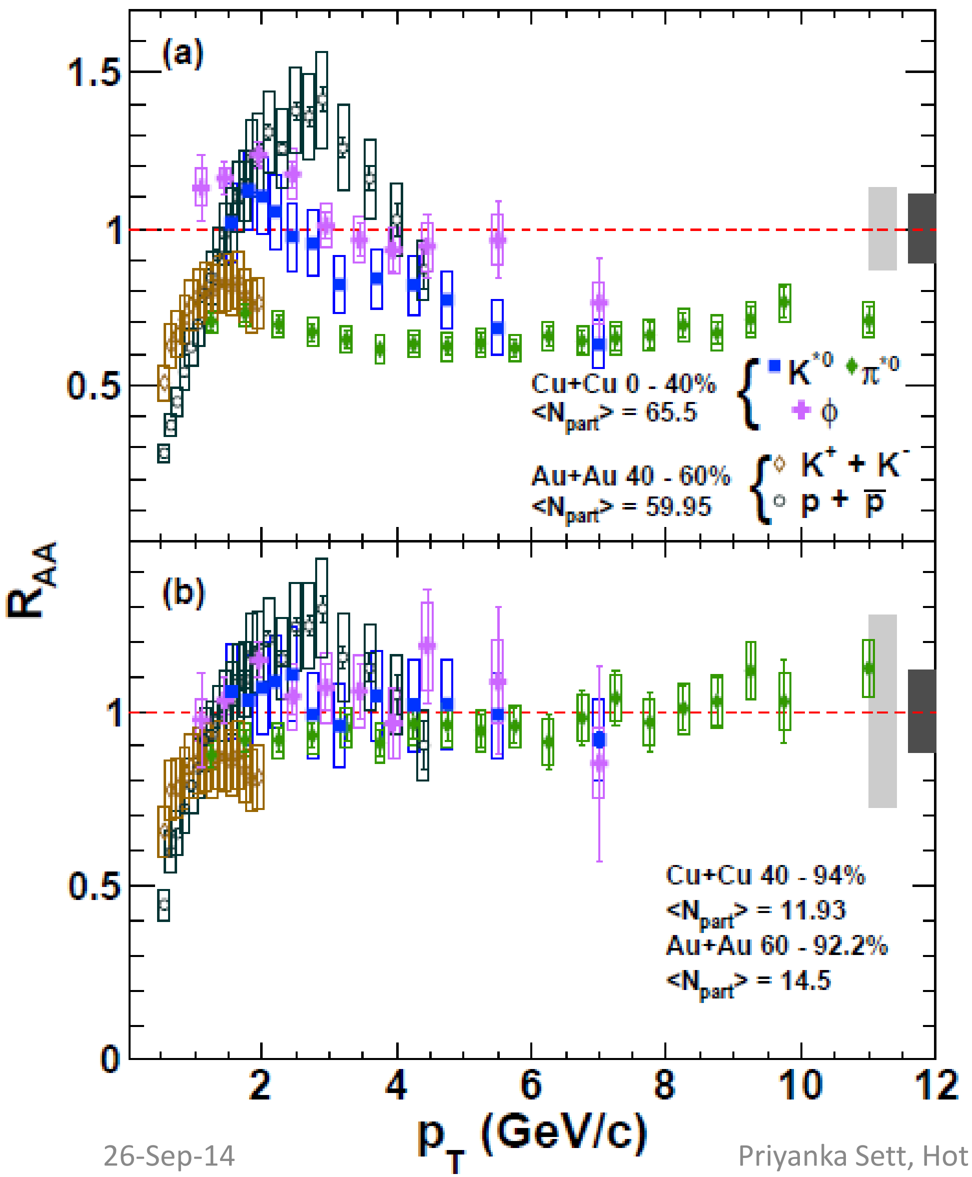


- For $p_T > 5$ GeV/c, $R_{CuCu} < 1$ for all mesons for 0 – 20% and 0 – 94% bins.
- $R_{CuCu} \sim 0.5$ for all mesons for $p_T > 5$ GeV/c for 0 – 20% bin.
- In central and minimum bias collisions, π^0 is most suppressed and is almost flat with p_T.
- For $p_T \sim 1 – 2$ GeV/c, K^{*0} and φ are not suppressed.
- No suppression in peripheral collisions.

References :

For φ, and π^0 references please see arXiv: 1405.3628

Results : R_{AA}



◙ **A comparison is shown among π^0, K^{*0}, φ in Cu+Cu collisions and charged kaons and protons in Au+Au collisions for the similar $\langle N_{part} \rangle$.**

◙ **Central Collisions :**

- **For all p_T π^0 s are the most suppressed.**
- **For 2 < p_T < 5 GeV/c,**
  - **protons are enhanced.**
  - **K^{*0} and φ are less suppressed than π^0 but more suppressed than proton.**
- **At high p_T, suppression is similar for all particles. → energy loss occurs at partonic level.**

◙ **Peripheral Collisions :**

- **R_{AA} is unity for all particles for p_T > 2 GeV/c.**

References :

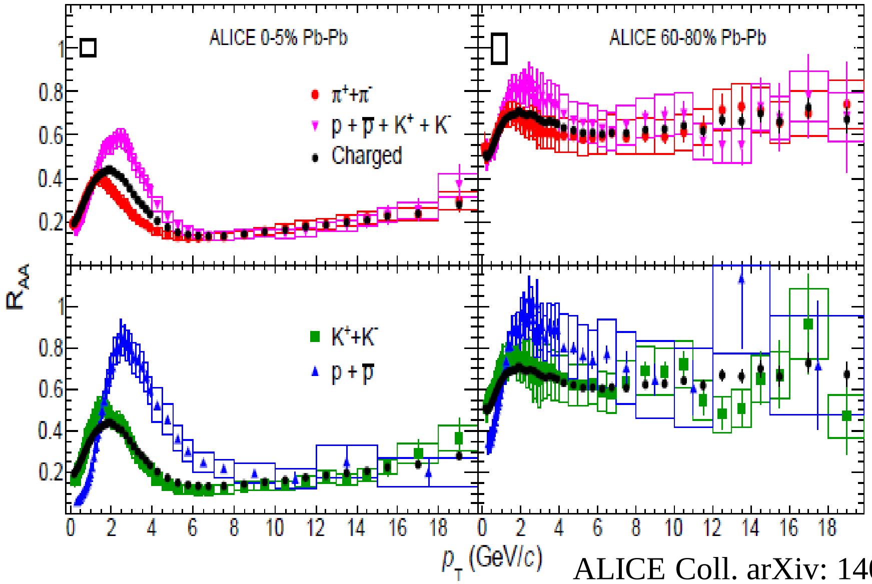
For φ, π^0, p and $K^{\pm}$ references please see arXiv: 1405.3628

Summary & Conclusions :

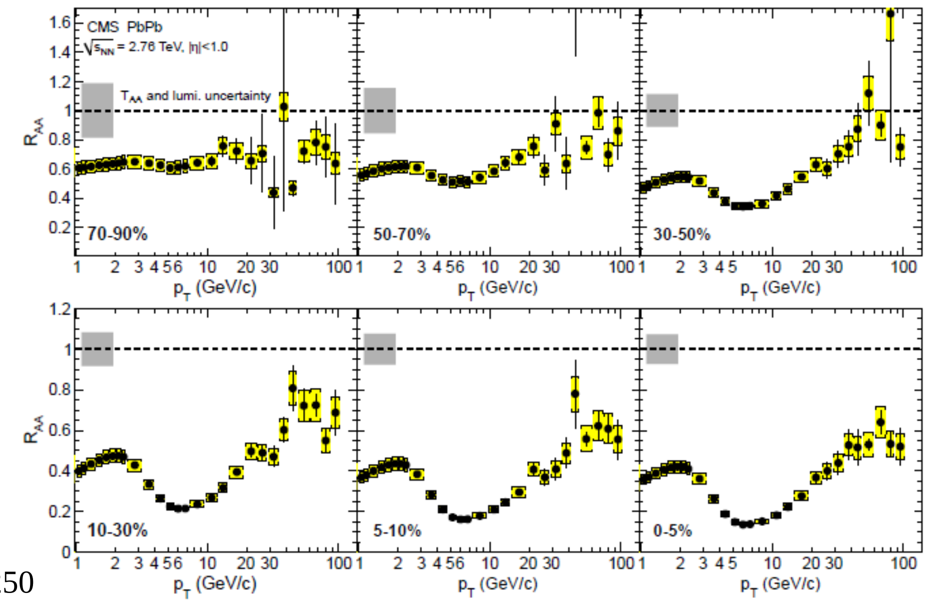
- The p_T distribution and the nuclear modification factors for K_S^0 and K^{*0} meson are presented in *p*+*p*, *d*+Au and Cu+Cu collisions for $\sqrt{s_{NN}}$ = 200 GeV.
- The measurements of K_S^0 and K^{*0} cover p_T = 3-13 GeV/c and 1.1-8.5 GeV/c respectively.
- Similar to other mesons, both of these mesons show no CNM effects in *d*+Au collisions in the measured kinematic range.
- For peripheral Cu+Cu collisions, no nuclear modification is registered for both K_S^0 and K^{*0} meson.
- In central Cu+Cu collision, K_S^0 and K^{*0} suffer suppression. Above $p_T > 5$ GeV/c, all mesons suffer equal energy loss. → energy loss originates at parton level.
- For $2 < p_T$ (GeV/c) < 5, the suppression of strange mesons lie in between of baryons and light quark meson.

Back up – Introduction

- Experimental evidences of high p_T particle suppression: LHC



ALICE Coll. arXiv: 1401.1250



Charge Particle - CMS Coll. Eur.Phys.J. C72 (2012) 1945

In LHC, for central Pb+Pb collisions, R_{AA} for ----

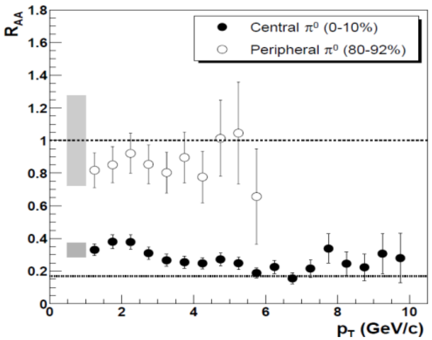
- **charged particles, kaons and pions are similar for p_T > 6 GeV/c.**
- **kaons lie between protons and charge particles in the low and intermediate p_T ~ 0 – 8 GeV/c.**
- **charged particles is ~ 0.14 for p_T = 5 – 10 GeV/c, then increases to 0.5 for p_T > 40 GeV/c.**

Qualitatively, similar behavior is observed in RHIC also : -
Particles show similar suppression for p_T > 5 GeV/c irrespective of flavors with R_{AA} ~ 0.2.
Also, kaon R_{AA} shows an intermediate behavior between protons and light particles.

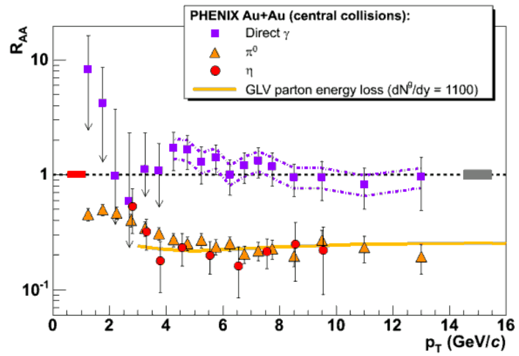
- **protons is less than unity but is higher than kaons and pions.** → **Protons are suppressed more at LHC, though the particle hierarchy remains same as in RHIC.**

Back up – Introduction

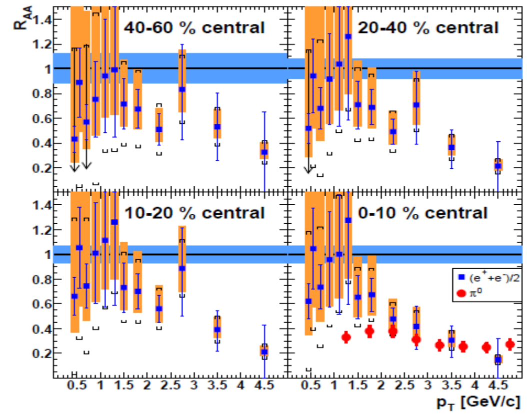
- Some experimental evidences of high p_T particle suppression:



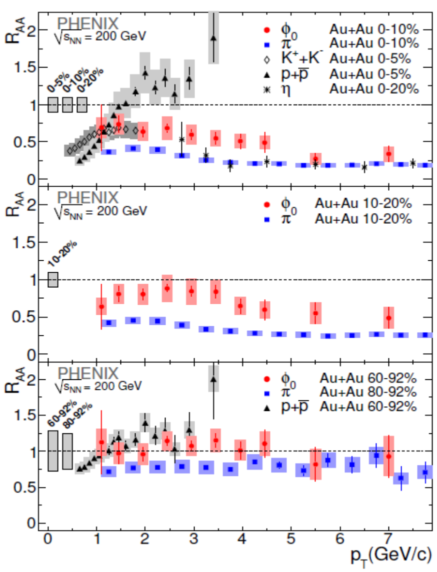
PHENIX Coll. Phys.Rev.Lett. **91** (2003), 072301



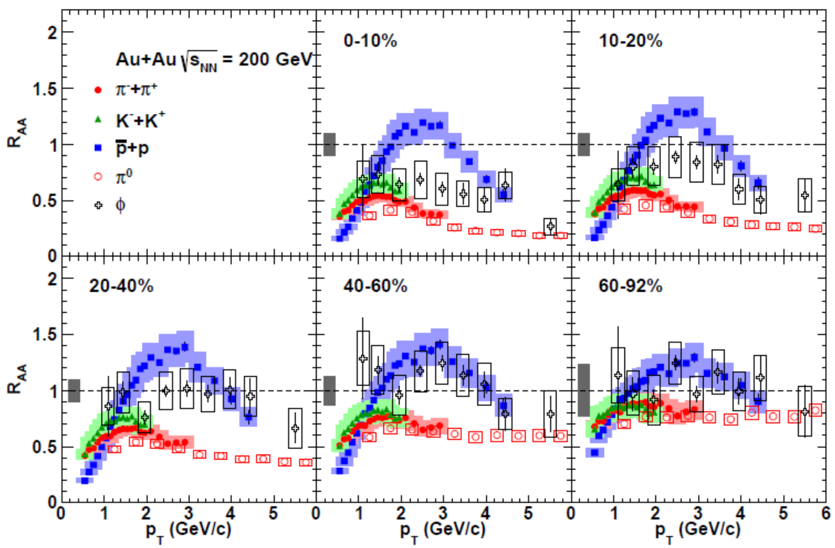
PHENIX Coll. Phys.Rev.Lett. **96** (2006) 202301



PHENIX Coll. Phys.Rev.Lett. **96** (2006) 032301



PHENIX Coll. Phys.Rev. C**83** (2011) 024909



PHENIX Coll. Phys.Rev. C**88** (2013), 2, 024906

Back up – PHENIX Subsystems

SubSystem	$\Delta\eta$	$\Delta\phi$	Special Features
Central (CM)	$\pm$ 0.35	2π	Upto 1.15 Tm
Muon Magnet South	-1.1 - -2.2	2π	0.72 Tm for $\eta = 2$
Muon Magnet South	1.1 - 2.4	2π	0.72 Tm for $\eta = 2$
Beam Beam Counters (BBC)	$\pm$ 3.1 - 3.9	2π	Start timing for TOF collision vertex, Minimum Bias Trigger and Centrality
Zero Degree Calorimeter (ZDC)	3 mrad	2π	Minimum Bias Trigger and Centrality
Drift Chambers (DC)	$\pm$ 0.35	$2\times\pi/2$	Good Momentum and mass resolution Δm = 1% at m = 1 GeV
Pad Chambers (PC)	$\pm$ 0.35	$2\times\pi/2$	Pattern recognization of tracks and tracking for non-bend non-bend direction
Ring Imaging Čerenkov (RICH)	$\pm$ 0.35	$2\times\pi/2$	Identifies electron
Time of Flight (ToF)	$\pm$ 0.35	$2\times\pi/2$	Identifies charged hadrons, resolution<100 ps
Electromagnetic Calorimeter (EMCal)			
EMCal (PbSc)	$\pm$ 0.35	$\pi/2 + \pi/4$	Identifies electron and photon
EMCal (PbGl)	$\pm$ 0.35	$\pi/4$	Identifies electron and photon Good $e^{\pm}/\pi^{\pm}$ separation at $p_T > 1$ GeV/c by EM shower and $p < 0.35$ GeV/c

Back up – Data Analysis

K_S^0 meson

$K_S^0 \rightarrow \pi^0(\rightarrow \gamma\gamma)\ \pi^0(\rightarrow \gamma\gamma)$, $c\tau = 2.7$ cm

- **π^0 reconstruction from $\gamma\gamma$:**

➢ $E_\gamma > 0.2$ GeV (d+Au and Cu+Cu peripheral),
$E_\gamma > 0.4$ (other centrality for Cu+Cu)

➢ Both γ forming π^0, are in the same EMCal sector.

➢ Asymmetry cut $|E_1 - E_2|/|E_1 + E_2| < 0.8$

- **K_S^0 reconstruction from $\pi^0\ \pi^0$:** $p_T > 1.0$ GeV/c for d+Au,
  > 1.5 GeV/c for Cu+Cu with centrality > 20%
  > 2 GeV/c for Cu+Cu centrality < 20%

Correction due to Ks in flight decay

➢ Correction made for the π^0 s coming from K_S^0 decay by, $|M_{\gamma\gamma} - M_{\pi^0} * R_M| < 2\ \sigma_{\pi^0} * R_\sigma$ for a particular p_T, where, $M_{\gamma\gamma}$ = reconstructed invariant mass of γ pair, M_{π^0} and σ_{π^0} parameterizations of the mass and 1-σ width of π^0 peak of inclusive π^0 mesons. R_M and R_σ are the correction factors which accounts the difference between inclusive π^0 and π^0 s from K_S^0 decays.

Back up – Nuclear Modification plots

Detailed ref for R_{dAu} plots :

References :

φ A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. C **83**, 024909 (2011).
π^0 S. S. Adler *et al*. (PHENIX Collaboration), Phys. Rev. Lett **98**, 17302 (2007).
p A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. C **88**, 024906 (2013).

Detailed ref for R_{CuCu} plots :

References :

φ A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. C **83**, 024909 (2011).
π^0 A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. Lett **101**, 162301 (2008).

Detailed ref for R_{AuAu} plots :

References :

φ A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. C **83**, 024909 (2011).
π^0 A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. Lett **101**, 162301 (2008).
p A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. C **88**, 024906 (2013).
$K^{\pm}$ A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. C **88**, 024906 (2013).

Back up – Mathematical forms

$$RBW = \frac{1}{2\pi}\frac{M_{K\pi}M_{K^{*0}}\Gamma}{(M^2_{K\pi} - M^2_{K^{*0}})^2 + M^2_{K^{*0}}\Gamma^2}$$

Tsallis function

$$\frac{1}{2\pi}\frac{d^2\sigma}{dydp_T} = \frac{1}{2\pi}\frac{d\sigma}{dy}\frac{(n-1)(n-2)}{(nT+m(n-1))(nT+m)} \times \left(\frac{nT+m_T}{nT+m}\right)^{-n}$$