PHENIX: Strangeness production

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Outline

- ❖ Motivation
- ❖ Overview of RHIC and PHENIX detector
- ❖ Strangeness production in p+p, d+Au, Cu+Cu, Au+Au at 200 GeV:
  - ✓ Spectra, nuclear modification factors, particle ratios
  - ✓ Discussion on recombination and radial flow
- ❖ Energy scan, strangeness production at 62.4 GeV
- ❖ Summary

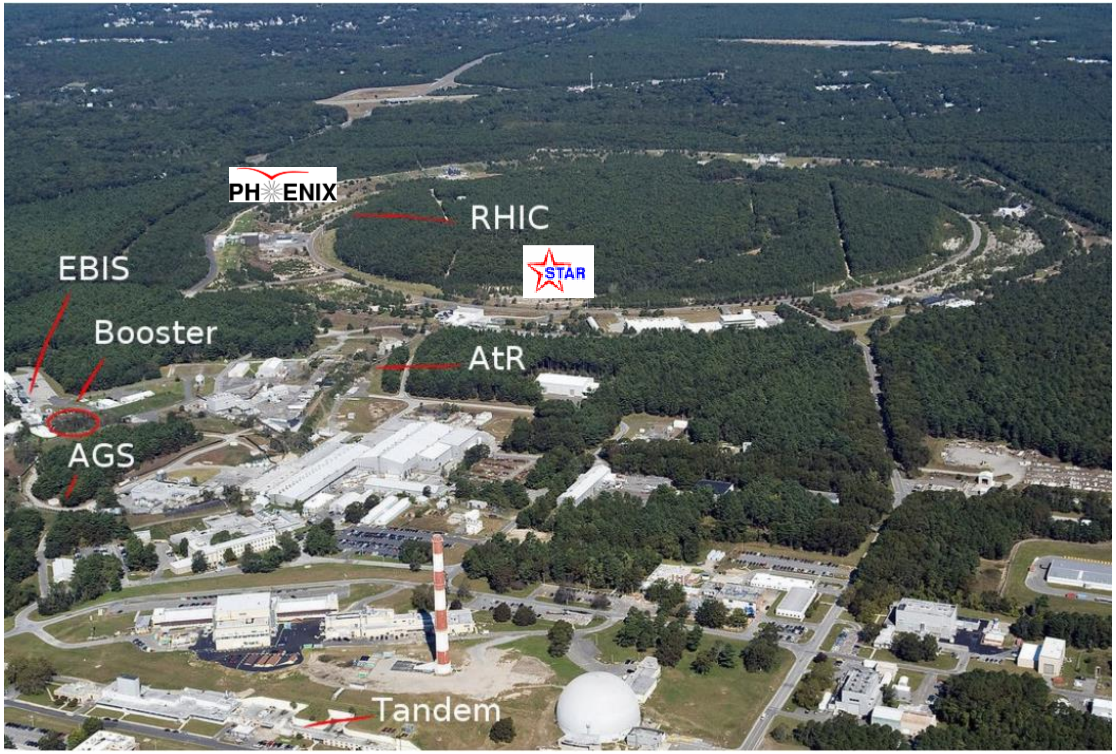
Motivation

- Strongly coupled quark gluon plasma (QGP) was discovered in heavy ion collisions at Relativistic Heavy Ion Collider (RHIC):
  - ✓ Unlike **u** and **d** quarks, strange quarks are not present in colliding nuclei and are formed in collisions between constituents of the QGP.

- Measurements of particles that contain strange quarks is an effective way to compare with hadrons that contain only light quarks:
  - ✓ Study the properties of the hot and dense matter formed in heavy ion collisions.

- Particles with strangeness content cover a wide range of masses and include mesons and baryons:
  - ✓ Perfect tool to study such features of hadron production as recombination and radial flow at intermediate p_T and energy loss flavor dependence at high p_T.

RHIC at Brookhaven National Lab



System	$\sqrt{s_{NN}}$, GeV
p+p	22.4, 62.4, 200, 500, 510
p+Al	200
p+Au	200
d+Au	200
He^3+Au	200
Cu+Cu	22, 62, 200
Cu+Au	200
Au+Au	7, 15, 9, 19, 39, 62, 130, 200
U+U	193

- RHIC is a flexible and reliable accelerator complex with an extensive experimental program;
- A lot of operational time is devoted to beam energy scan and switching between colliding nuclei;
- Beam luminosity is being permanently increased;
- During 15 Runs, RHIC provided 11 energies and 9 combination of nuclei.

PHENIX detector

1. Track reconstruction

Drift Chambers (DC): $\delta p/p = 0.7\% + 1.1\% \cdot p$

Pad Chambers (PC): $\sigma = \pm 1.7$ mm in z direction

2. Energy and coordinates of electrons and γ

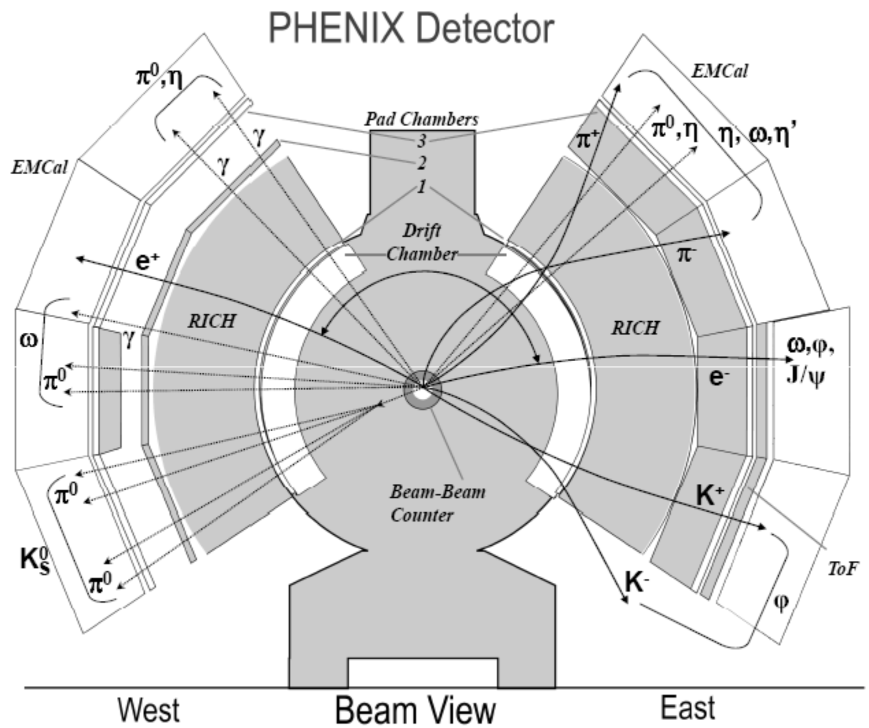
- ✓ EMCal PbSc: $\delta E/E = 2.1\% + 8.1\%/\sqrt{E}$
- ✓ EMCal PbGl: $\delta E/E = 0.8\% + 5.9\%/\sqrt{E}$

3. Particle identification

Time of flight in both arms (TOF.E, TOF.W):

- ✓ $\sigma_\tau \sim 100$ ps;
- ✓ π/K up to 2.5 GeV/c, K/p up to 4.0 GeV/c

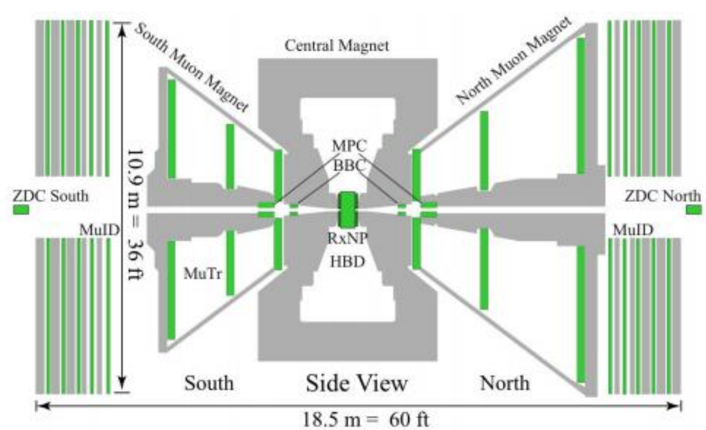
EMCal timing: $\sigma_\tau \sim 300$ ps



Acceptance: $-0.35 < \eta < 0.35$, $\Delta\varphi$ – 2 x 90°

Forward Arms:

- ✓ $1.2 < |\eta| < 2.2$
- ✓ Muon Tracker / Muon ID



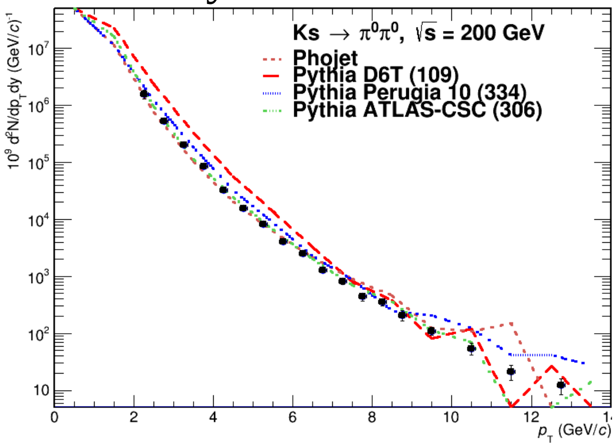
Particles with s-quarks in this talk

Particle	Quark content	System	$\sqrt{s_{NN}}$, GeV	Decay modes	Branching ratio
$K^{\pm}$	$u\bar{s}$	p+p, d+Au, Au+Au	62.4, 200		
K^0_s	$\frac{(d\bar{s} - s\bar{d})}{\sqrt{2}}$	p+p, d+Au, Cu+Cu	200	$\pi^0+\pi^0$	~30%
K*	$d\bar{s}$	p+p, d+Au, Cu+Cu	200	$K^{\pm}+\pi^{\pm}$	~67%
ϕ	$s\bar{s}$	p+p, d+Au, Cu+Cu, Au+Au	62.4, 200	$K^{+}+K^{-}$	~49%
Λ^0	uds	Au+Au	200	$p+\pi^{-}$	~64%

- PHENIX experiment has measured different strange hadrons in p+p, d+Au, Cu+Cu and Au+Au collisions at 62.4 & 200 GeV:
  - ✓ Invariant production spectra in wide p_T ranges using different analyses approaches
  - ✓ Nuclear modification factors for 62.4 and 200 GeV

p+p @ 200 GeV: part 1

PhysRevC.90.054905



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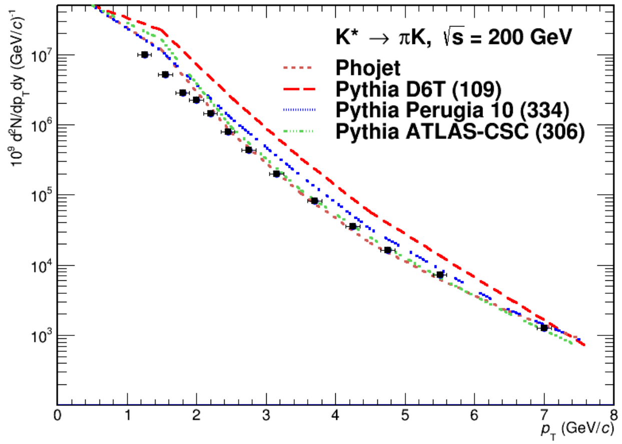
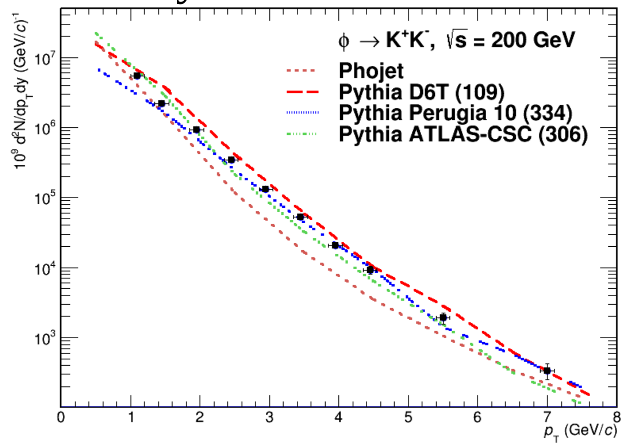


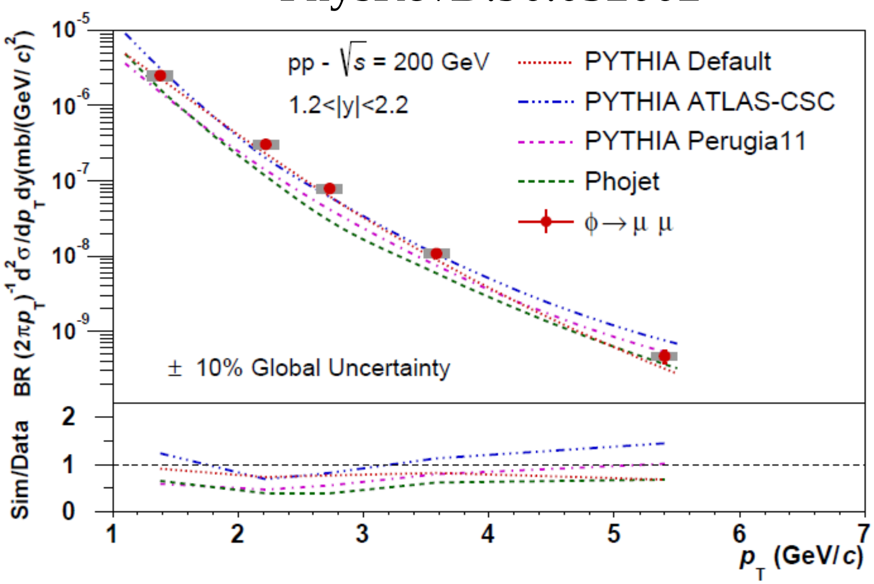
PhysRevD.83.052004



- Invariant spectra of K_s, K* & ϕ mesons are measured in a wide p_T range with hadronic decay modes ($K_s \rightarrow \pi^0\pi^0$, $K^* \rightarrow \pi K$, $\phi \rightarrow K^+K^-$)
- These spectra are used as a baseline to compare with more complex and heavy colliding systems such as d+A and A+A
- Moreover these spectra are needed for event generators tuning, pQCD calculations checks and available parameterizations of fragmentation functions
- Different tunes of Pythia and Phojet are not able to fully describe measured spectra

p+p @ 200 GeV: part 2

PhysRevD.90.052002



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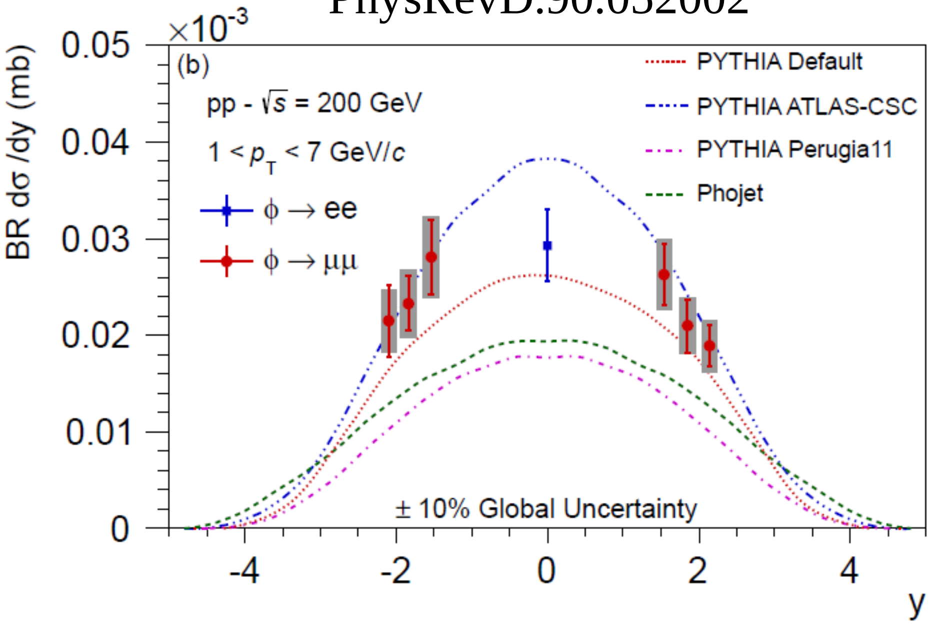


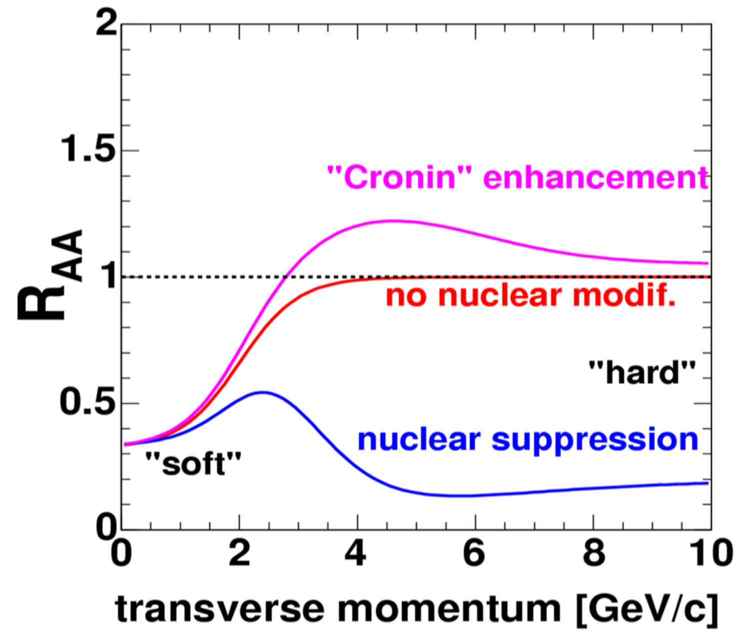
- PHENIX measured $\phi \rightarrow \mu^+\mu^-$ production in p+p @ 200 GeV at forward rapidity
- Event generators, pQCD calculations checks:
  - ✓ Different tunes of Pythia and Phojet are not able to fully describe measured spectra
- Spectra are used to study rapidity dependence of nuclear modification factors

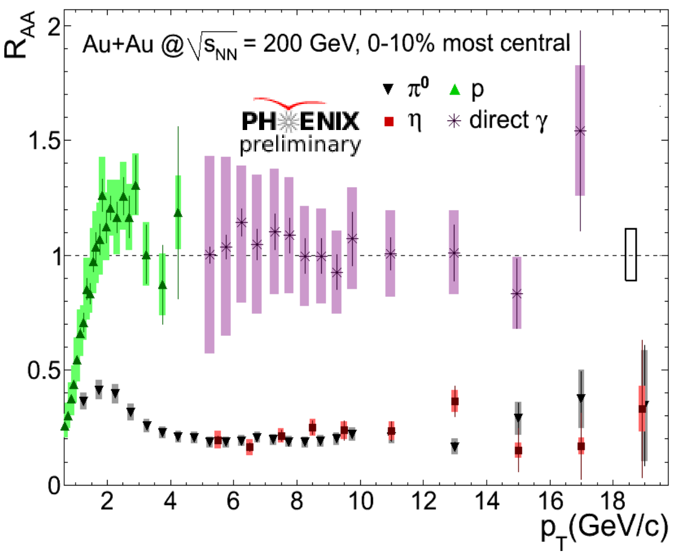
Hard processes, R_{AA}

- ❖ Hard processes scale with N_{coll}
  - ✓ Small cross section
  - ✓ Non-correlated superposition
- ❖ Nuclear modification factors

$$R_{\rm AB}(p_T) = dN_{\rm AB}/(\langle N_{\rm coll}\rangle \times dN_{pp})$$

- ❖ $R_{AB}=1$ – no medium effects
- ❖ $R_{AB}\neq 1$ – collective effects:
  - ✓ $R_{AB}<1$ – suppression
  - ✓ $R_{AB}>1$ – enhancement

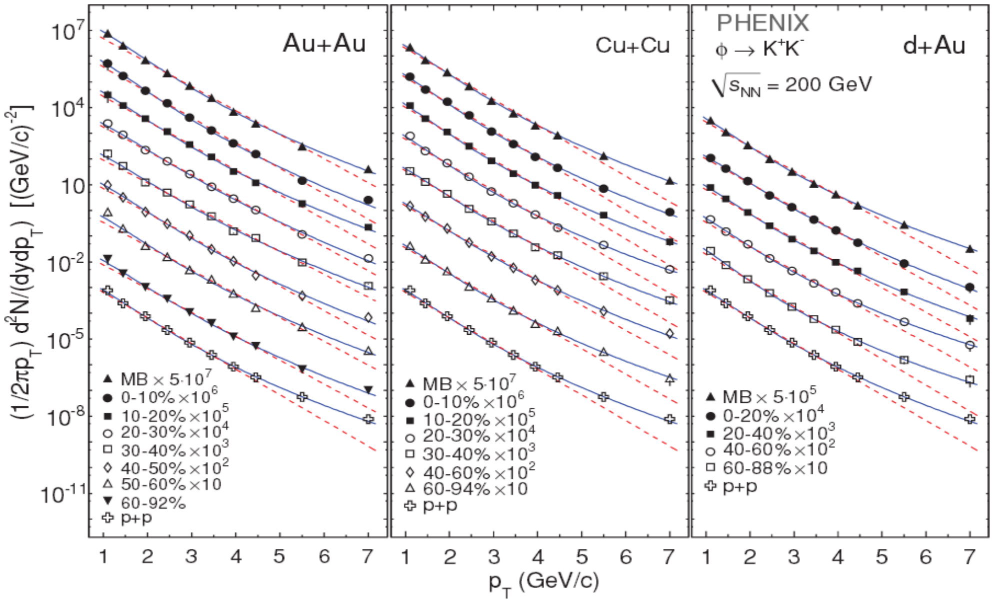


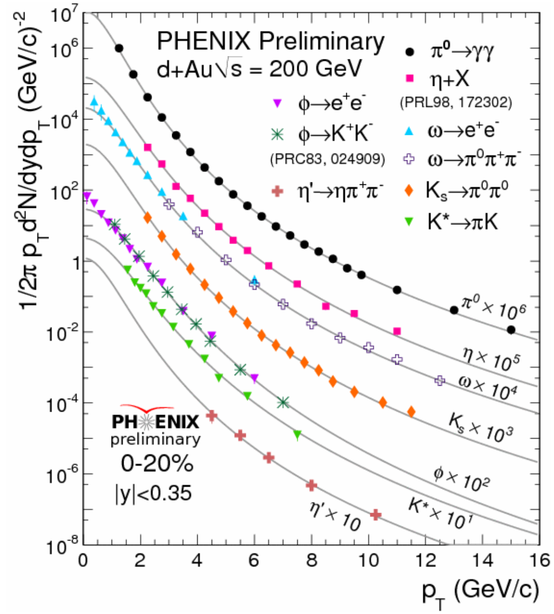


Particle spectra in d+A & A+A @ 200 GeV

Invariant differential production spectra in wide p_T ranges at different centralities using analyses approaches with confident overlap

PhysRevC.83.024909





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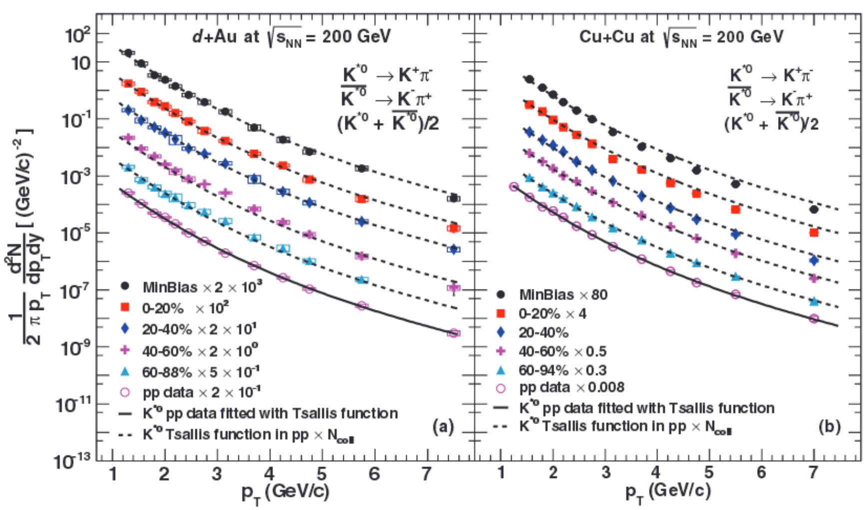
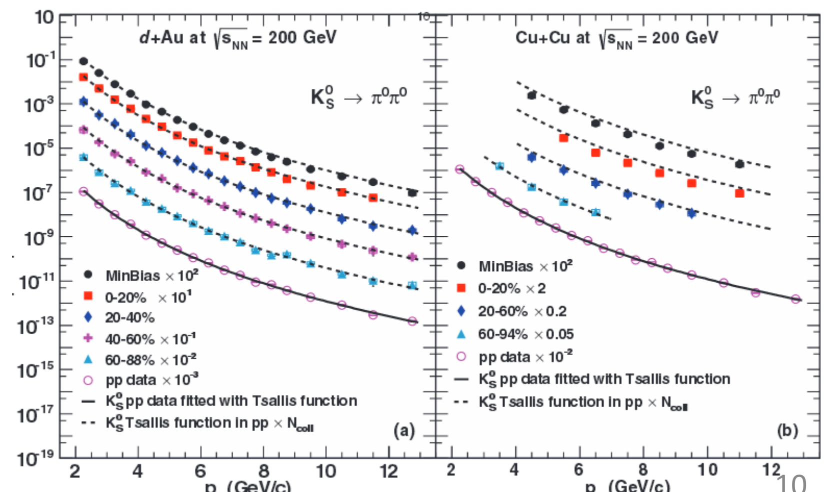
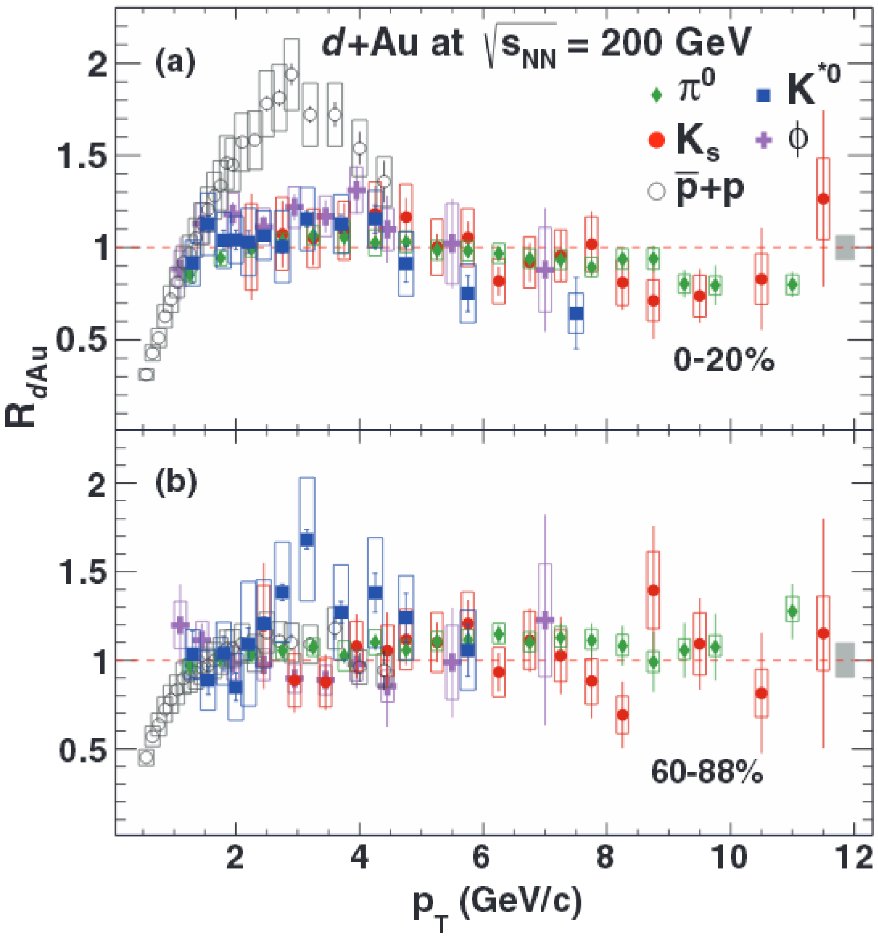




d+Au @ 200 GeV: part 1

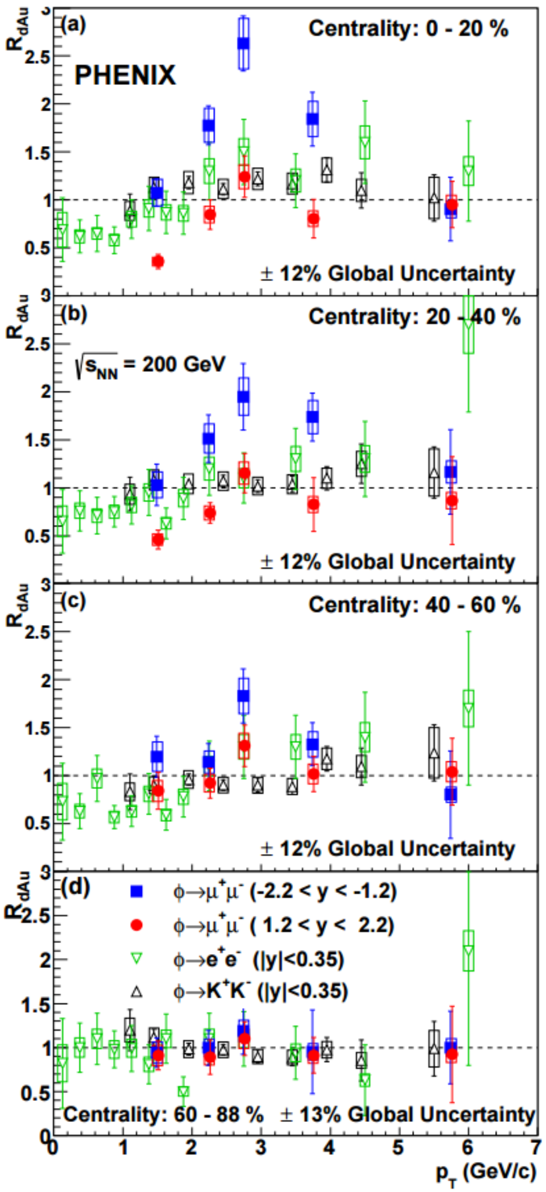
PhysRevC.90.054905



- d+Au collisions are used as a control experiment where QGP is not formed:
  - ✓ Study cold nuclear matter effects
- R_{dAu} ~ 1 in peripheral collisions:
  - ✓ Sequential non correlated nucleon interactions
- $R_{dAu} \neq 1$ in central collisions:
  - ✓ Non-zero enhancement at intermediate p_T ($2 < p_T$ (GeV/c) < 5)
  - ✓ Significant difference in baryon and meson behavior
  - ✓ Hint of hadron suppression at high $p_T > 6 – 8$ GeV/c
- Behavior of strange mesons is the same as for other mesons

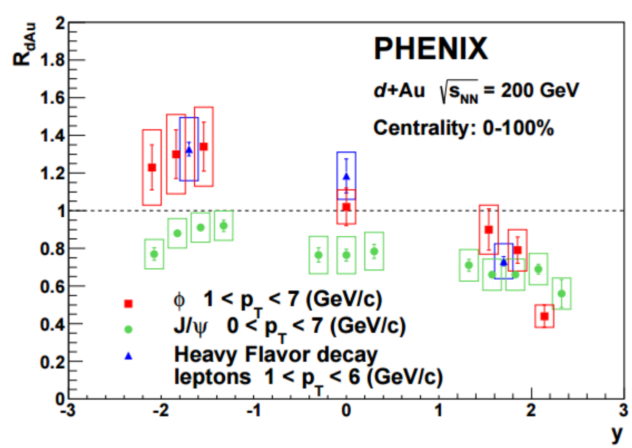
d+Au @ 200 GeV: part 2

arXiv:1506.08181



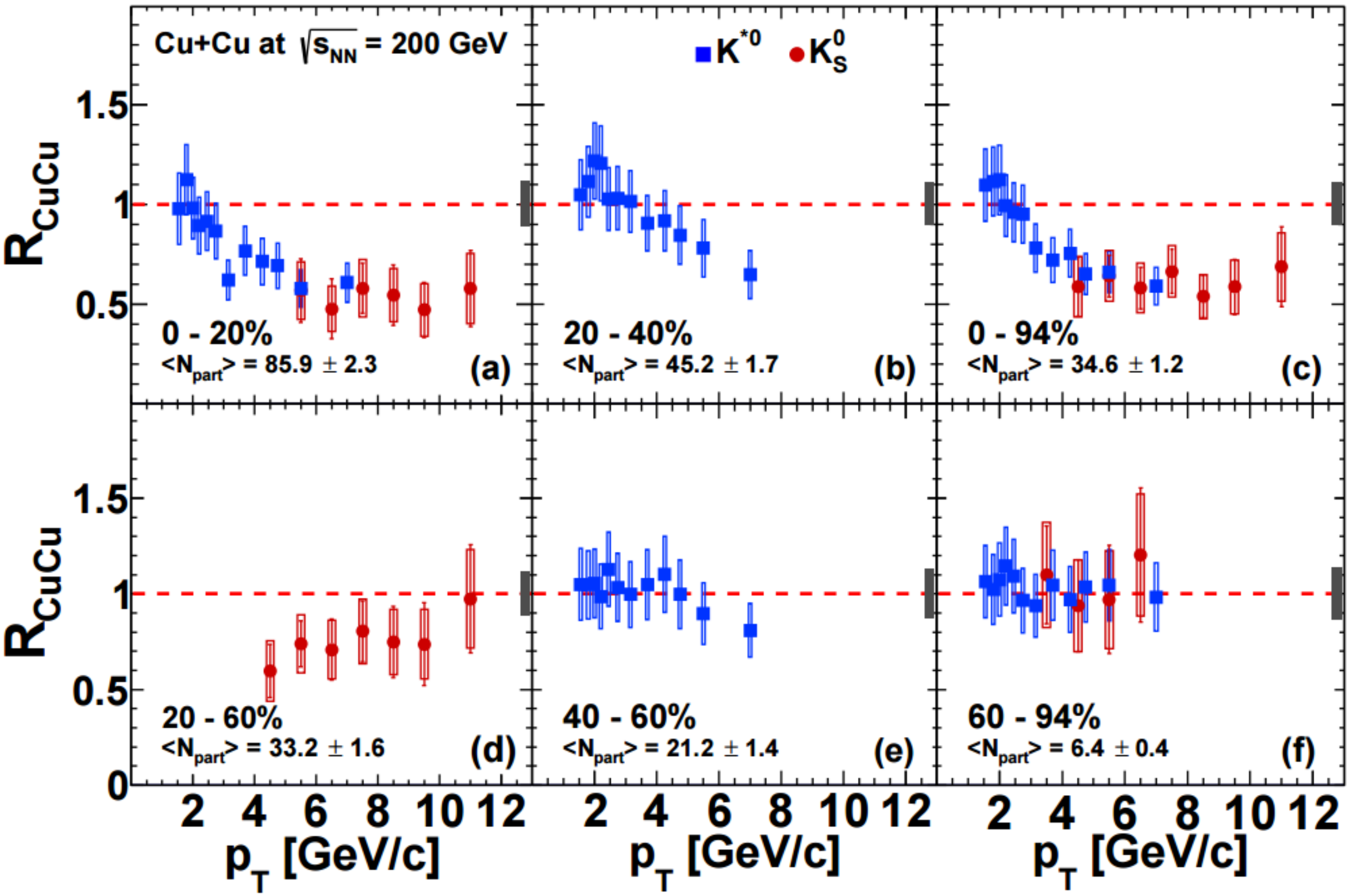
- Au-going direction: -2.2 < |y| < -1.2
  - ✓ Cronin-like enhancement
- d-going direction: 1.2 < |y| < 2.2
  - ✓ Suppression may suggest influence of shadowing
- Effect was also observed by PHOBOS in charged hadron density
- Enhancement (suppression) decreases gradually from central to peripheral collisions

arXiv:1506.08181



- Rapidity dependence for φ and HF is similar:
  - ✓ Similar CNM effects?

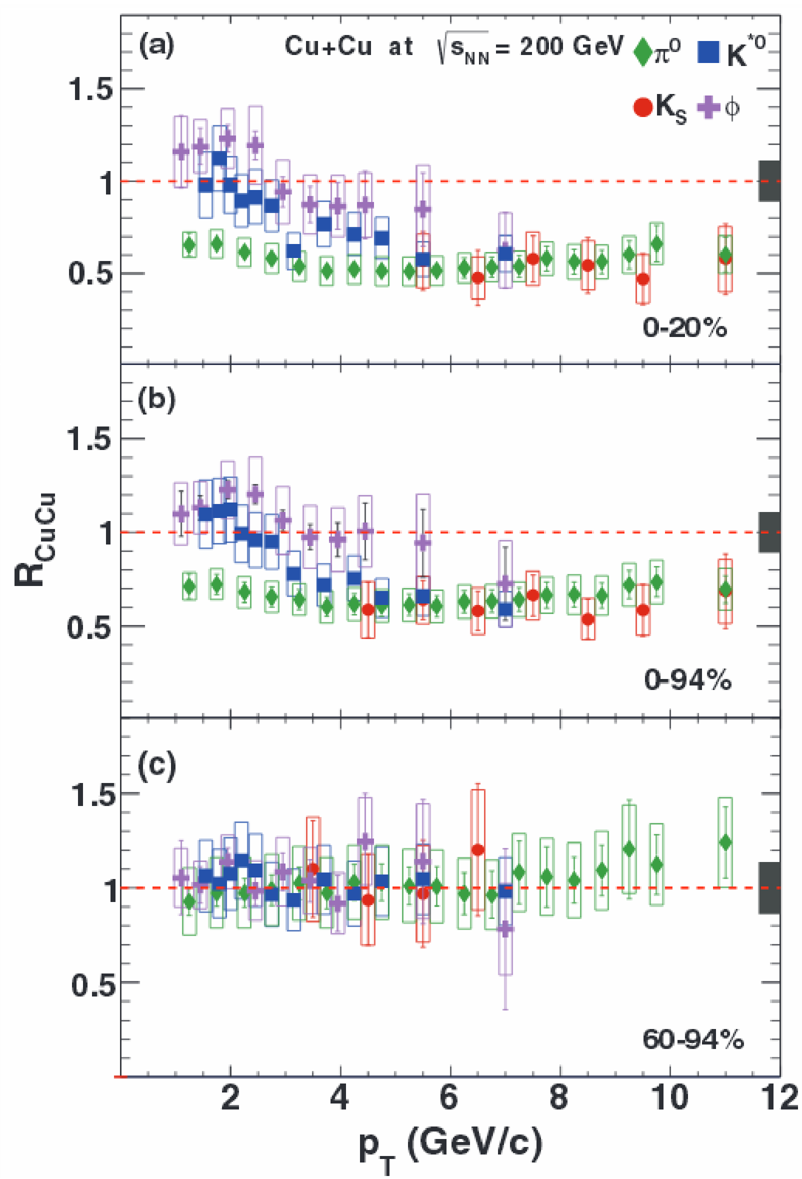
Cu+Cu @ 200 GeV: part 1



PhysRevC.90.054905

- ❖ In peripheral Cu+Cu collisions the production of K_s^0 and K^{*0} mesons follows the binary scaling
- ❖ R_{CuCu} factors become smaller from peripheral to central collisions. For the most central collisions, R_{CuCu} reaches a value of 0.5 at p_T > 5 GeV/c

Cu+Cu @ 200 GeV: part 2



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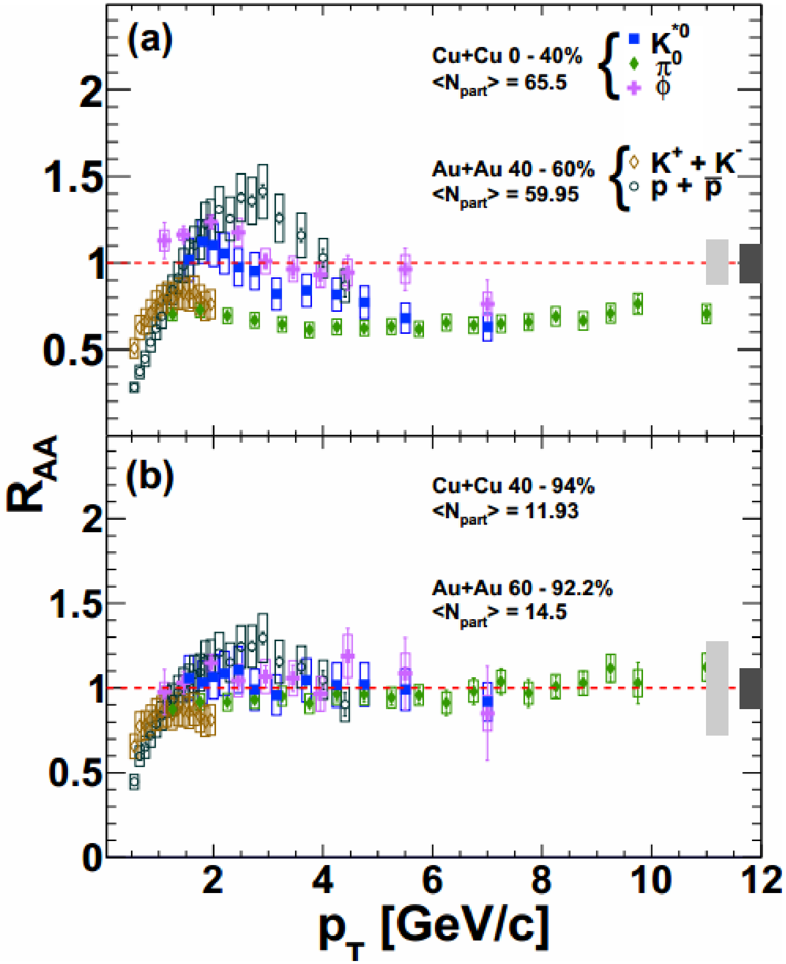
- R_{CuCu} ~ 1 in peripheral collisions:
  - ✓ Sequential non correlated nucleon interactions
- $R_{CuCu} \neq 1$ in central collisions:
  - ✓ All particle yields are suppressed by a factor of 2 at high $p_T > 6$ GeV/c
  - ✓ In the intermediate p_T range suppression of particles containing s-quarks (K_s^0, K^{*0}, ϕ) is significantly smaller than of neutral pions
  - ✓ Despite mass difference all mesons with s-quarks (K_s^0, K^{*0}, ϕ) have the same suppression pattern

Cu+Cu & Au+Au @ 200 GeV

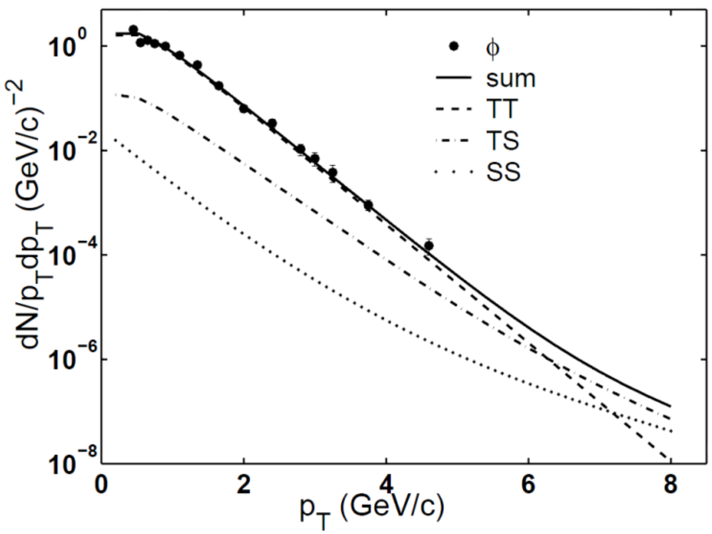
PhysRevC.90.054905



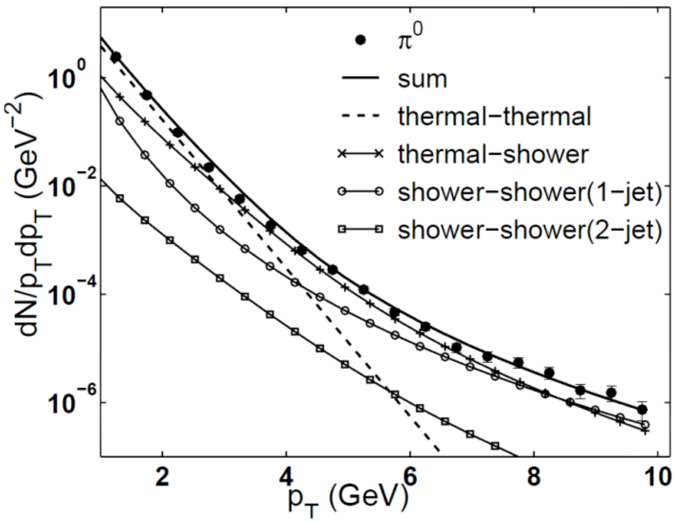
- Cu+Cu & Au+Au results are shown for similar number of participants (nucleons participating in heavy nuclei interaction) N_{part}
- R_{AA} ~ 1 in peripheral collisions:
  - ✓ Non correlated nucleon interactions
  - ✓ Non zero proton enhancement
- In central collisions suppression hierarchy can be easily seen:
  - ✓ $R_{AA}(\pi) < R_{AA}(K_s^0, K^{*0}, \phi) < R_{AA}(p)$

Intermediate p_T: recombination

arXiv:nucl-th/0602024v3



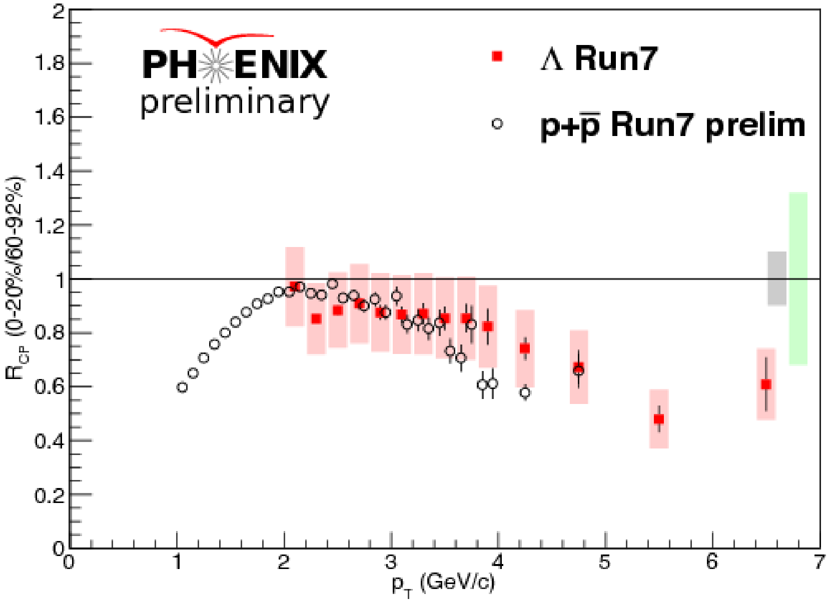
J.Phys. G30 (2004) S1117-1120



- Hadron production is described by recombination: thermal (T) & shower (S) partons
- Difference in $R_{AA}(p_T)$ between ϕ, K^{*0} and π-mesons:
  - ✓ TT recombination for particles with s-quarks dominates over hard processes in a wider p_T range (up to 5-6 GeV/c) than for lighter hadrons (up to 2-3 GeV/c)
- Difference in $R_{AA}(p_T)$ between ϕ, K^{*0} and protons: 2 quarks vs 3 quarks

Recombination models assume that QGP is the source of thermal partons

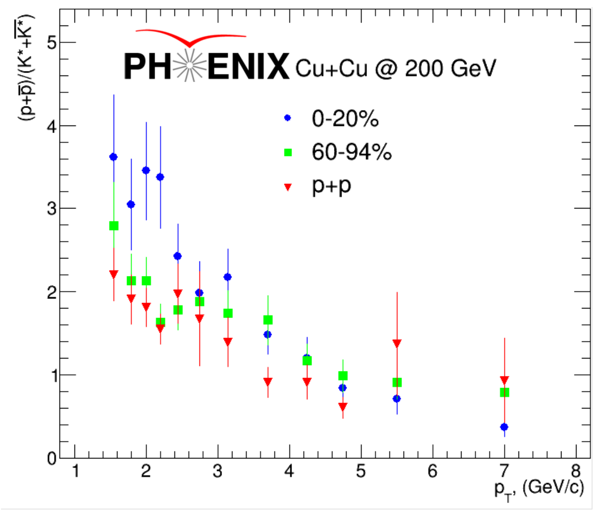
Λ baryon in Au+Au @ 200 GeV



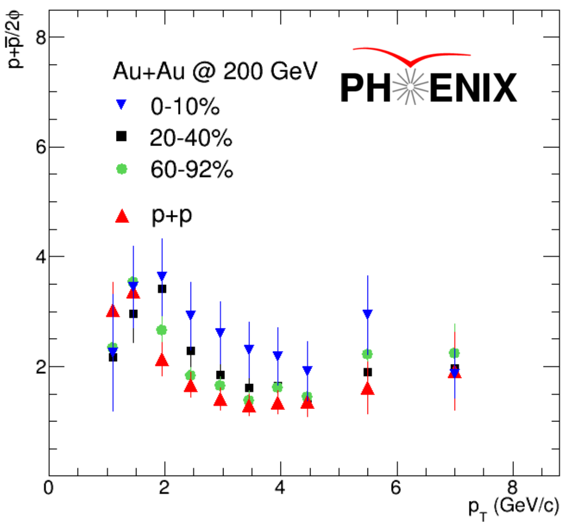
- Λ production for p_T range: 2-6.5 GeV/c
  - ✓ Confident overlap in p_T with protons
- Λ $R_{CP} \approx$ proton R_{CP}:
  - ✓ Enhancement at intermediate p_T looks consistent with quark content (2 vs 3)

Intermediate p_T: radial flow

- High multiplicity of particles produced in central A+A collisions leads to intense interactions between hadrons. Evolution of A+A collision suggests a phase of fast expansion of the strongly interacting system
  - ✓ Each hadron gets increase in velocity equal to velocity of the wave front → radial flow
- The heavier the particle, the more momentum it gets with the same velocity increase
  - ✓ R_{AA} difference between (u, d) mesons and baryons at intermediate p_T (M(p)>>M(π))
- p/K* and p/ϕ ratios show a hint of flattening up to p_T ~2.5 GeV/c
  - ✓ Spectral shapes are determined by mass of the particle in this p_T region



PhysRevC.90.054905
J.Phys.G:Nucl.Part.Phys.34S975



PhysRevC.83.064903
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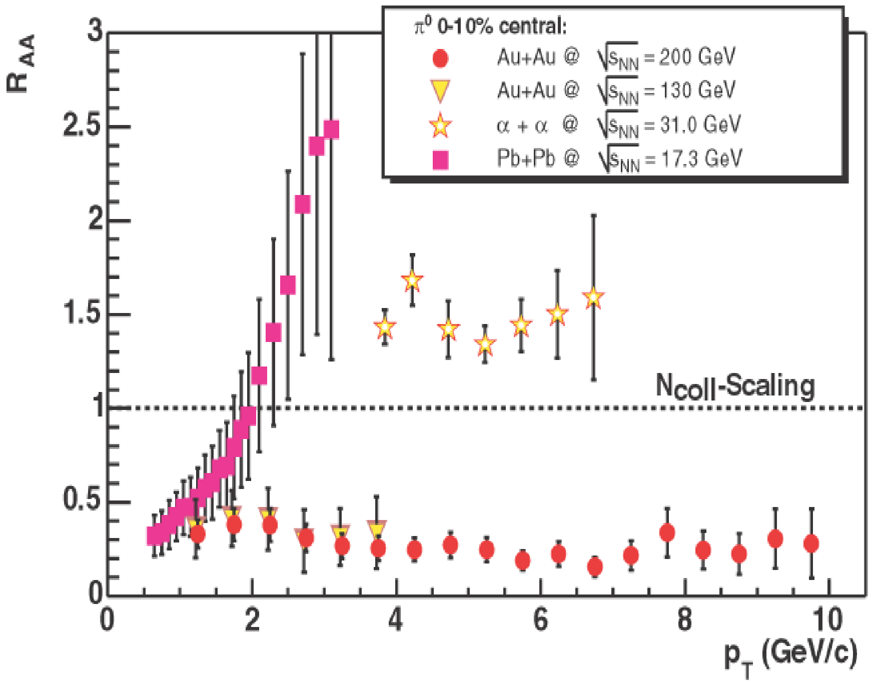
Energy scan: 62.4 GeV

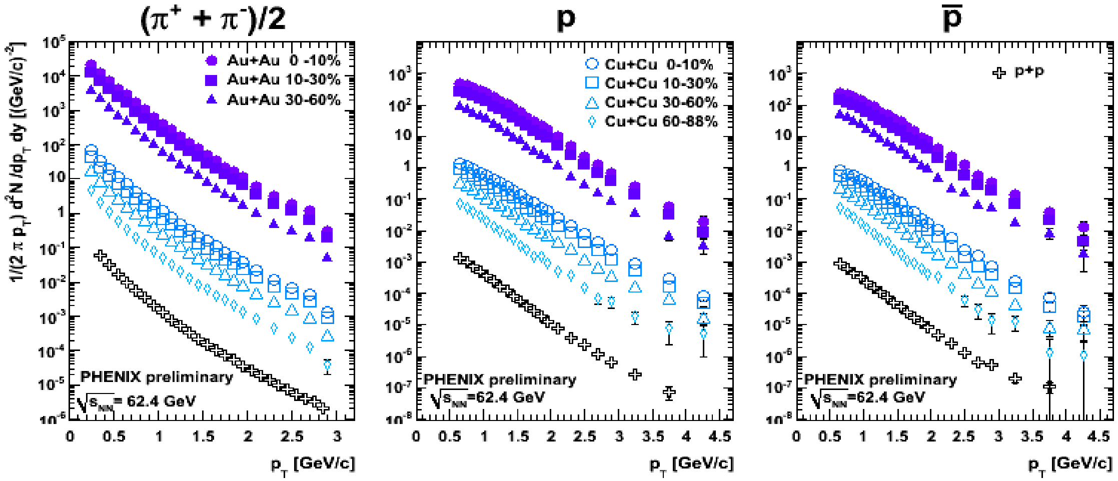


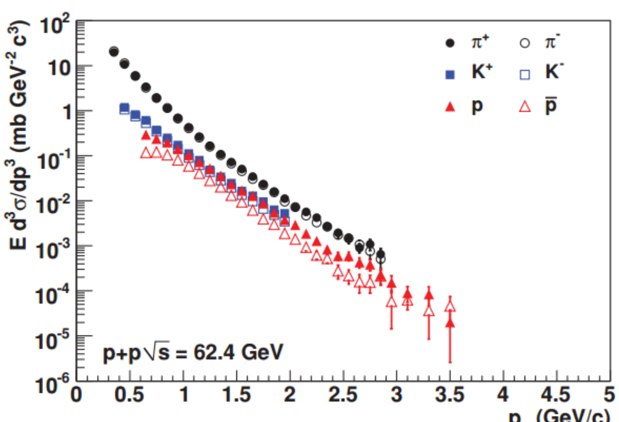
arXiv:nucl-ex/0411049

- ❖ Hadron suppression at 130 and 200 GeV
- ❖ No suppression at 17 GeV
- ❖ Parton energy loss depend on:
  - ✓ system size
  - ✓ gluon density
- ❖ Changing √s:
  - ✓ Different gluon density
  - ✓ Different energy loss
  - ✓ Particle production: fragmentation, recombination

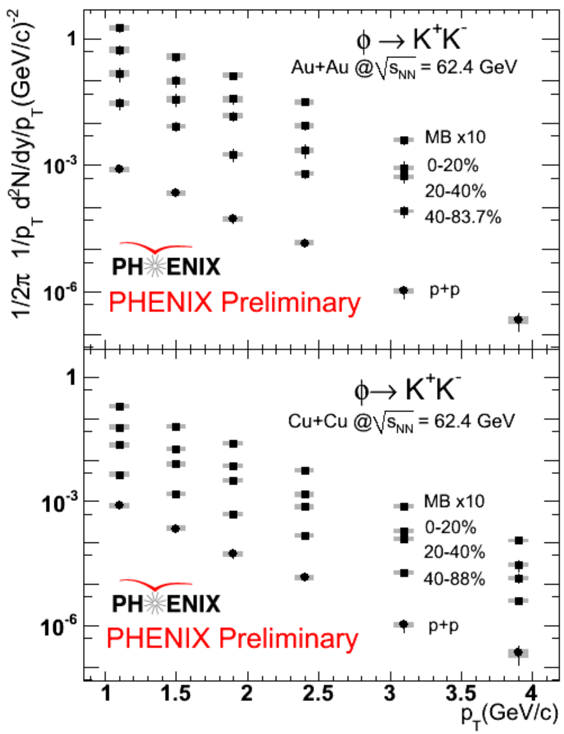
p+p, Cu+Cu, Au+Au @ 62.4 GeV: part 1

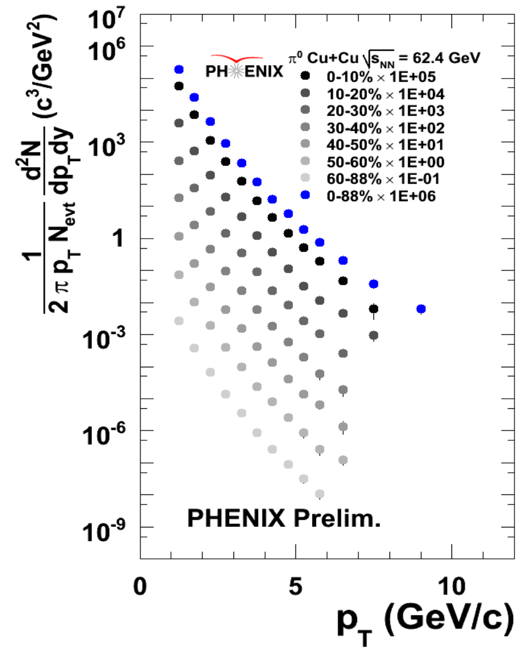
- ❖ A lot of 62.4 GeV results:
- ✓ π^0 up to 7 GeV/c
- ✓ Other hadrons up to 4 GeV/c
- ✓ ϕ-mesons measured both in Cu+Cu and Au+Au in 3 centrality bins → R_{AA} comparison with baryons (protons) is possible!



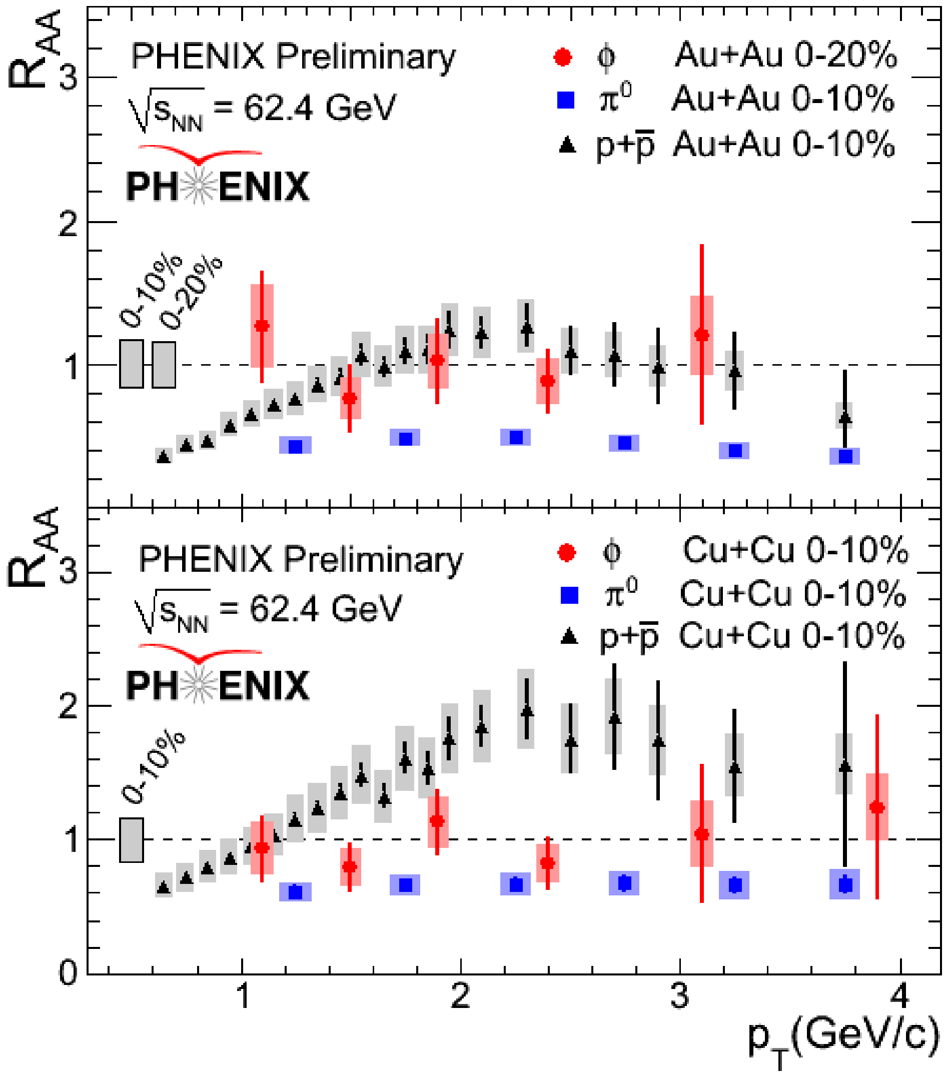


Phys. Rev. C **83**, 064903





p+p, Cu+Cu, Au+Au @ 62.4 GeV: part 2



❖ Hadron yields at 62.4 GeV are less suppressed than at 130 and 200 GeV

❖ Suppression pattern is similar to the one observed at 200 GeV:

- ✓ $R_{AA}(\pi^0) < R_{AA}(\phi) < R_{AA}(p)$

❖ Recombination models can be used to describe hadron production at 62.4 GeV:

- ✓ Source of thermal partons → QGP

Conclusions

- Particles with strangeness content are a perfect tool to study hadron production mechanisms and properties of dense and hot matter formed in central heavy ion collisions

- Strangeness production @ 200 GeV:
  - ✓ in peripheral d+Au and Cu+Cu collisions follows the binary scaling
  - ✓ in central d+Au collisions non-zero CNM effects can be seen:
    - non-zero Cronin effect at intermediate p_T (2-5 GeV/c)
    - hint of hadron suppression at high $p_T > 6$ GeV/c
    - rapidity dependence of nuclear modification factors
  - ✓ in central heavy ion collisions significant collective effects can be seen:
    - at high p_T all mesons are equally suppressed
    - at intermediate p_T suppression of strange mesons lie between baryons and light quark mesons

- Strangeness production @ 62.4 GeV:
  - ✓ Similar hadron suppression pattern to the one observed at 200 GeV

- Recombination and radial flow are 2 alternative explanations of experimental results