Identified Charged Hadron Spectra and Ratios in Au+Au and d+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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NAP Seminar
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Outline

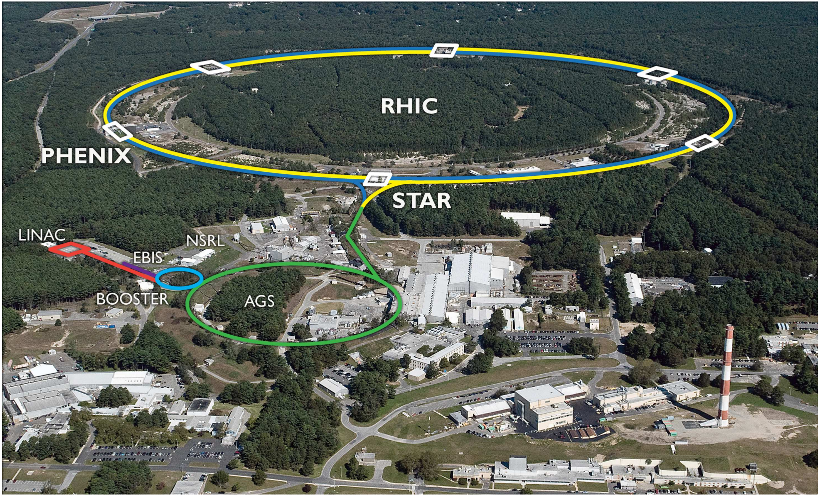
The Relativistic Heavy Ion Collider

- RHIC is the only polarized proton collider in the world
- RHIC is one of two heavy ion colliders, the other being the LHC
- RHIC is a dedicated ion collider and is designed to collide many different species of ions at many different energies

Collision Species	Collision Energies (GeV)
$p\uparrow+p\uparrow$	62.4, 200, 500, 510
d+Au	200
Cu+Cu	22.5, 62.4, 200
Cu+Au	200
Au+Au	5.0, 7.7, 11.5, 19.6, 27.0, 39.0, 56.0, 62.4, 130, 200
U+U	193

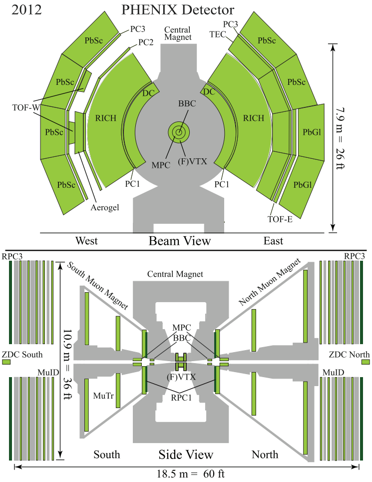
- Two small experiments, PHOBOS and BRAHMS (decommissioned in 2005)
- Two large experiments, PHENIX and STAR (currently active)

RHIC Complex

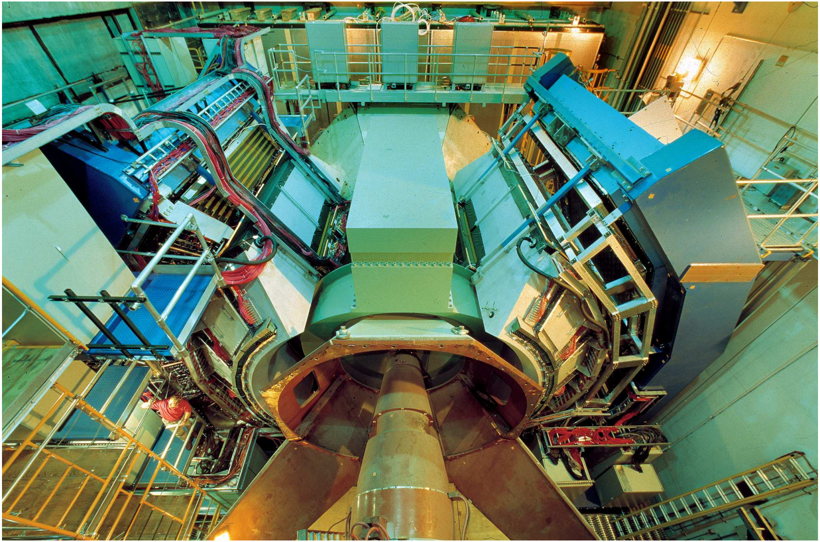


PHENIX

- Weighs approximately 3000 tons
- Three separate magnet systems (Central Arms and Muon North and South) weighing 1700 tons alone
- 16 detector subsystems and 300,000 electronics channels
- 30 feet tall, 40 feet wide, 60 feet long
- Fast DAQ system—up to 10 kHz, 1 GB/s
- Ideally suited for measurements of rare probes, electrons, muons, high p_T photons, etc.



PHENIX

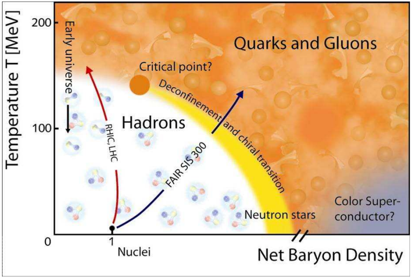


The quark-gluon plasma

At sufficiently high temperature and/or density, the gauge coupling between quarks and gluons becomes sufficiently weak that deconfinement is achieved

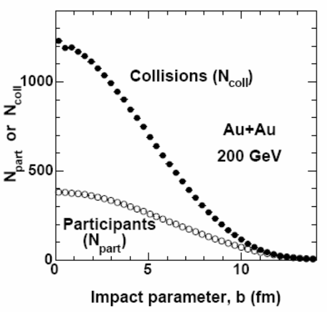
Some basic information about the QGP created at RHIC:

- Particles produced in thermal abundances
- Hydrodynamics models describe the data very well, require fast thermalization at the parton level
- The matter is very hot! Measured by PHENIX to be 300–600 MeV (3–6 $\times 10^{12}$ K), well in excess of $T_c \approx 175$ MeV
- Compare to stellar coronae (10^6 K), core of white dwarf (10^7 K)



Centrality

- Since you can't measure impact parameter, $N_{participants}$, or $N_{collisions}$ find something you can measure
- Event multiplicity, charge sum forward detectors, etc.
- Use geometrical (Glauber model) simulations to determine N_{part} and N_{coll} from detector response



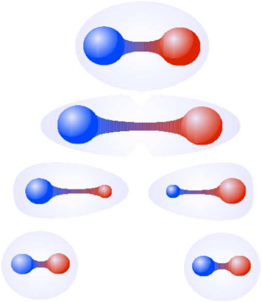
Centrality	$\langle N_{coll} \rangle$	$\langle N_{part} \rangle$
Au+Au		
0-10%	960.2 ± 96.1	325.8 ± 3.8
10-20%	609.5 ± 59.8	236.1 ± 5.5
20-40%	300.8 ± 29.6	141.5 ± 5.8
40-60%	94.2 ± 12.0	61.6 ± 5.1
60-92%	14.8 ± 3.0	14.7 ± 2.9
d+Au		
0-20%	15.1 ± 1.0	15.3 ± 0.8
20-40%	10.2 ± 0.7	11.1 ± 0.6
0-100%	7.6 ± 0.4	8.5 ± 0.4
40-60%	6.6 ± 0.4	7.8 ± 0.4
60-88%	3.1 ± 0.2	4.3 ± 0.2
p+p	≡ 1	≡ 2

Particle production by fragmentation

- Pair creation through stretching and breaking of gluon flux tubes

$$V(r) = -C_F \frac{\alpha_s}{r} + kr$$

- Fragmentation function $D_{c \to h}(z)$—probability that parton c fragments into hadron h with fraction z of the parton momentum

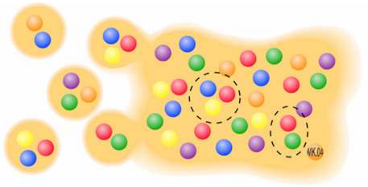


$$E\frac{d^3N_h}{dP^3} = \sum_{abcd} \iiint dz dx_a dx_b f_a(x_a) f_b(x_b) \frac{d\sigma}{d\hat{t}}(ab \to cd) D_{c \to h}(z)/z$$

$$E\frac{d^3N_h}{dP^3} = \int d\Sigma \frac{P \cdot u}{(2\pi)^3} \sum_c \int dz\ z^{-3} w_c(P/z)\ D_{c \to h}(z)$$

Particle production by recombination

- Partons close together in phase space can coalesce into bound states
- Originally introduced to explain particle production in the far forward region in p+p collisions
- The QGP is a system of thermalized partons, so the phase space is large and this is a natural way of thinking about hadronization
- Each parton has a fraction x of the total momentum of the produced hadron



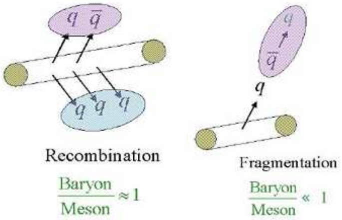
$$E\frac{d^3N^{(Meson)}}{dP^3} = \int d\Sigma \frac{P \cdot u}{(2\pi)^3} \sum_{\alpha\beta} \int dx \; w_\alpha(xP)\bar{w}_\beta((1-x)P) \; |\phi^{(M)}_{\alpha\beta}(x)|^2$$

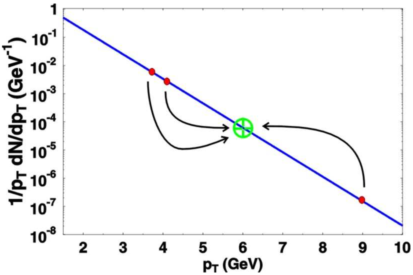
$$E\frac{d^3N^{(Baryon)}}{dP^3} = \int d\Sigma \frac{P \cdot u}{(2\pi)^3} \sum_{\alpha\beta\gamma} \iint dxdx' \; w_\alpha(xP)w_\beta(x'P)w_\gamma((1-x-x')P) \; |\phi^{(B)}_{\alpha\beta\gamma}(x,x')|^2$$

Fragmentation and recombination

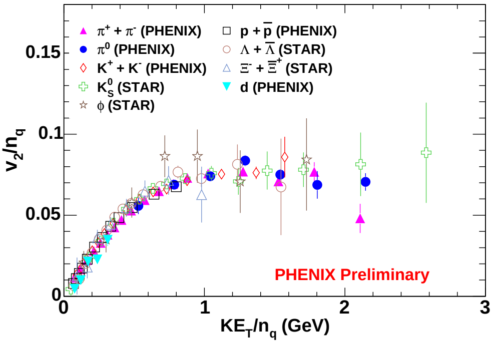
P—hadron momentum
p—parton momentum

- $P < p$ for fragmentation because $P = zp$ and $P > p$ for recombination because $xP = p$
- To make a 6 GeV/c hadron by fragmentation, need one parton with $>$6 GeV/c
- To make a 6 GeV/c meson by recombination, need two partons with $\approx$3 GeV/c
- To make a 6 GeV/c baryon by recombination, need three partons with $\approx$2 GeV/c





Valence quark scaling of elliptic flow



In recombination model, estimate of hadron v_2 is

$$v_2^{(M)}(P) = v_2^q(xP) + v_2^q((1-x)P), \quad v_2^{(B)}(P) = v_2^q(xP) + v_2^q(x'P) + v_2^q((1-x-x')P)$$

Assuming all the hadron momentum is carried by the valence quarks, and that it is equally divided among them ($x = 1/2$ for mesons, $x = 1/3$ for baryons)

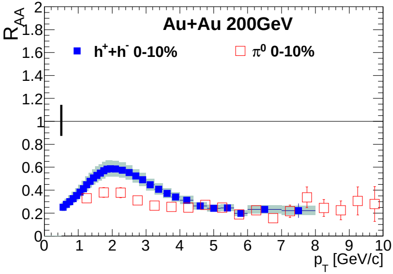
$$v_2^{(M)}(P) = 2v_2^q(P/2), \quad v_2^{(B)}(P) = 3v_2^q(P/3)$$

hence quark number scaling

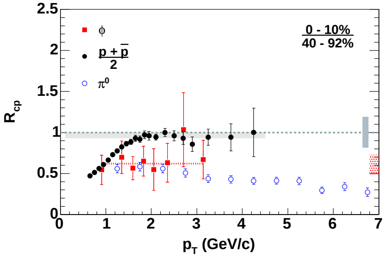
Утро в сосновом лесу

Утро в сосновом лесу

Baryon vs. meson production



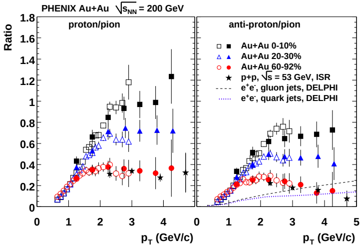
PHENIX, Phys. Rev. C69, 034910 (2004)



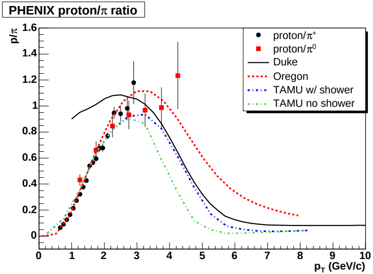
PHENIX, Phys. Rev. C72, 014903 (2005)

- R_{AA} of unidentified hadrons and π^0 shows factor of 5(!) suppression
- R_{CP} shows no suppression of baryons?
- Heavy meson ϕ has similar mass to proton (1.019 GeV/c^2 cf 0.938 GeV/c^2) but similar suppression to pion—not a mass effect

Baryon vs. meson production



PHENIX, Phys. Rev. Lett., 91, 172301 (2003)

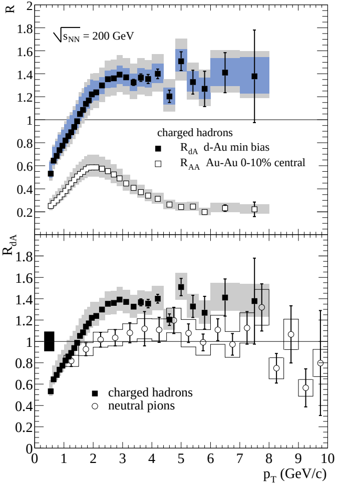


PHENIX, Nucl. Phys. A757, 184-283 (2005)

- Baryon production significantly enhanced relative to meson production
- Hadronization by string fragmentation yields similar baryon/meson ratios in p+p and Au+Au
- Hadronization by parton recombination may explain this enhancement (also explains quark number scaling found in elliptic flow data)

Cold nuclear matter effects

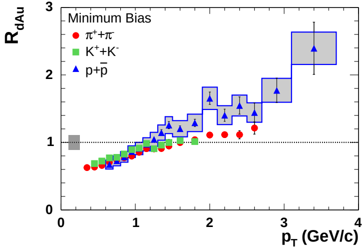
- In addition to effects from the QGP, there are initial state effects caused by the cold nuclear matter
- Some models proposed particle suppression at RHIC could be from initial state effects, but the data show Cronin enhancement
- Cronin enhancement: enhancement of particle yield at intermediate p_T in p+A collisions relative to p+p
- Unidentified hadrons show greater enhancement than neutral pions...



PHENIX, Phys. Rev. Lett. 91, 072303 (2003)

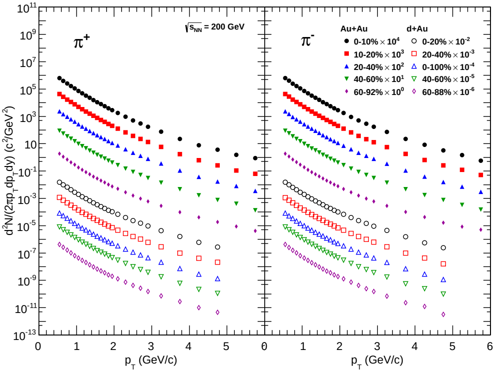
Cold nuclear matter effects

- Strong particle species dependence for Cronin enhancement
- Most models of the Cronin enhancement rely on initial state effects like multiple parton rescatterings—no particle species dependence
- Recombination model applied to d+Au uses final state effect in cold nuclear matter, greater Cronin enhancement for baryons than for mesons—discussed in Phys. Rev. Lett. 93, 082302 (2004) by R.C. Hwa and C.B. Yang
- Soft partons at low x can take place of thermal partons in hot nuclear matter, so recombination may make sense here



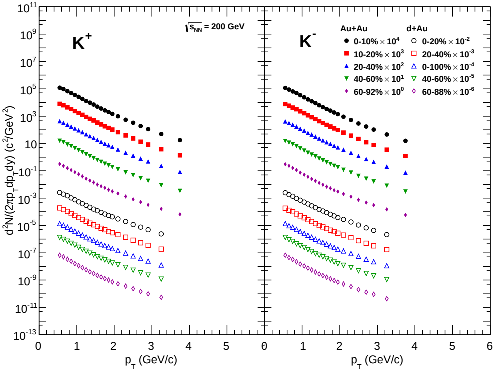
PHENIX, Phys. Rev. C91, 024904 (2006)

Pion spectra



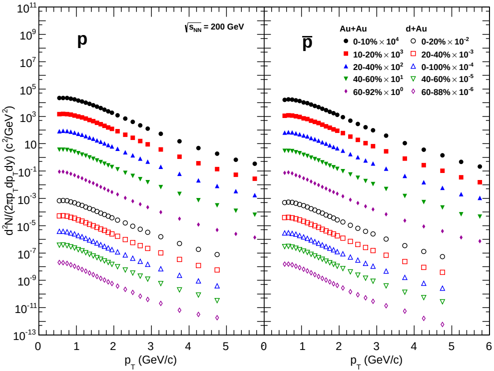
- New PHENIX results, Phys. Rev. C88, 024906 (2013)
- Au+Au up to 6 GeV/c and d+Au up to 5 GeV/c

Kaon spectra



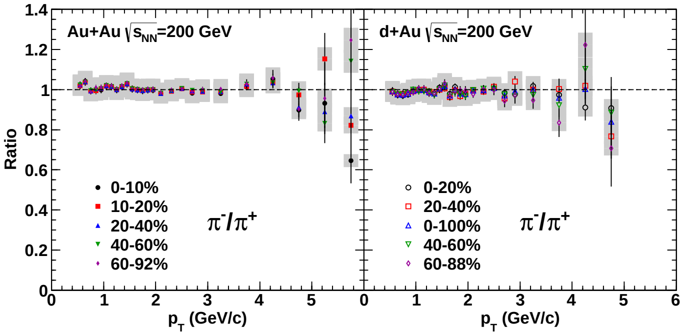
- New PHENIX results, Phys. Rev. C88, 024906 (2013)
- Au+Au up to 4 GeV/c and d+Au up to 3.5 GeV/c

Proton spectra



- New PHENIX results, Phys. Rev. C88, 024906 (2013)
- Au+Au up to 6 GeV/c and d+Au up to 5 GeV/c

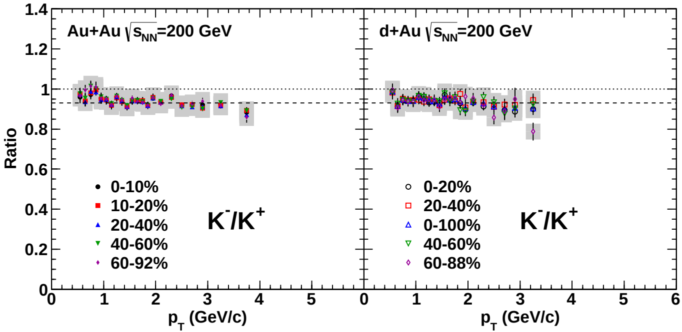
Ratio π^-/π^+



PHENIX, Phys. Rev. C88, 024906 (2013)

- π^-/π^+ ratio is independent of p_T, centrality, and collision system
- Ratio is essentially equal to unity

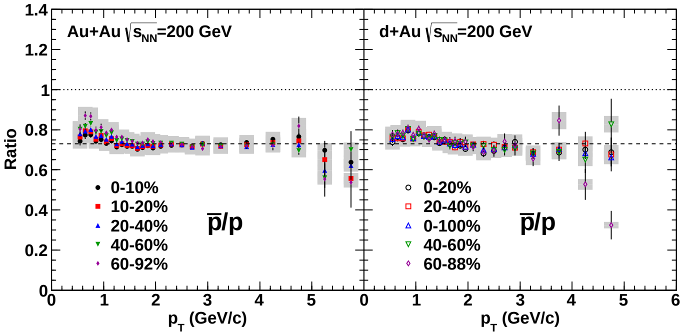
Ratio K^-/K^+



PHENIX, Phys. Rev. C88, 024906 (2013)

- K^-/K^+ ratio is independent of p_T, centrality, and collision system
- Ratio is slightly less than unity (0.93)

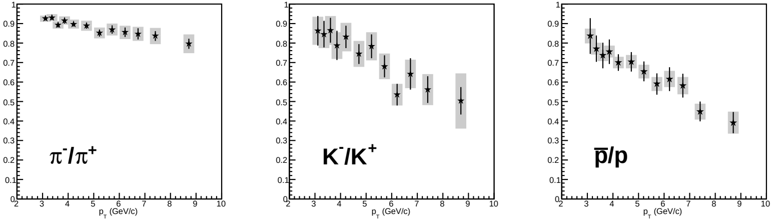
Ratio $\bar{p}/p$



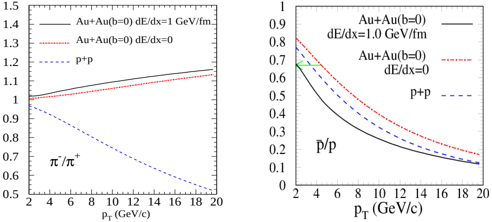
PHENIX, Phys. Rev. C88, 024906 (2013)

- $\bar{p}/p$ ratio is independent of p_T, centrality, and collision system
- Ratio is roughly 0.73

Antiparticle/particle ratios in p+p



STAR, Phys. Rev. Lett. 108, 072302 (2012)

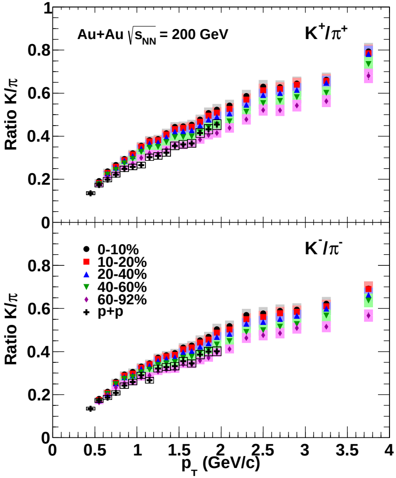


X.-N. Wang, Phys. Rev. C58, 2321 (1998)

What did we learn from antiparticle/particle ratios?

- The most boring result ever? Minimal dependence on p_T, centrality, and collision species...
- But the result is different in p+p collisions!
- The heuristic argument in p+p is basically isospin conservation—high p_T produced particles should have at least once valence quark from the initial state
- This favors production of $\pi^+(u\bar{d})$, $K^+(u\bar{s})$, and $p(uud)$, so all the ratios decrease with increasing p_T
- The $\pi^-(\bar{u}d)$ also has a valence quark in common with the initial reactants, while $K^-(\bar{u}s)$ and $\bar{p}(\bar{u}\bar{u}\bar{d})$ do not—thus the π^-/π^+ ratio falls off more slowly
- Something similar may happen in d+Au and Au+Au, but if so the p_T regime is higher than in p+p

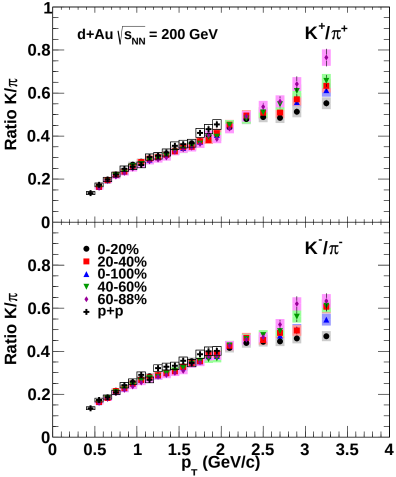
Ratio K/π in Au+Au



PHENIX, Phys. Rev. C88, 024906 (2013)

- No difference between charges (K^-/K^+ and π^-/π^+ are flat)
- Ratios rise steadily over the whole available p_T range, although expected to turn over and decrease at some point
- Overall level rises with centrality—indicative of strangeness enhancement
- Ratios rise more quickly in Au+Au than in p+p up to about 2 GeV/c—may give insight into strangeness production mechanism

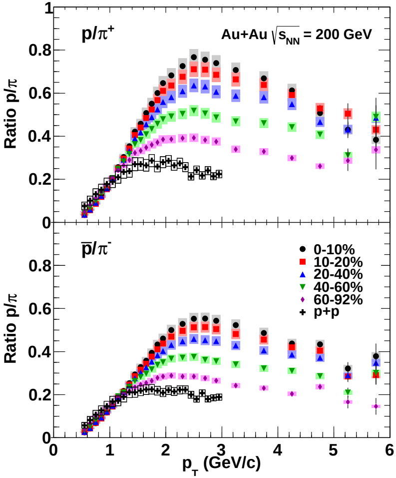
Ratio K/π in d+Au



PHENIX, Phys. Rev. C88, 024906 (2013)

- No difference between charges (K^-/K^+ and π^-/π^+ are flat)
- As with Au+Au, ratios rise steadily over the whole available p_T range
- No centrality dependence and no difference from ratio in p+p
- d+Au seems to be missing the additional strangeness production mechanism present in Au+Au

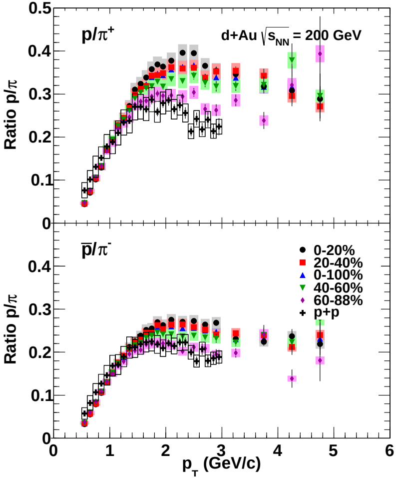
Ratio p/π in Au+Au



PHENIX, Phys. Rev. C88, 024906 (2013)

- Identical centrality dependence and p_T shapes ($\bar{p}/p$ and π^-/π^+ are flat)
- Attempts to explain baryon enhancement as due to strong flow cannot reproduce the strong centrality dependence
- Ratio rises quickly, reaches maximum at about 2.5 GeV/c in the most central collisions, then falls off slowly—the maximum appears to shift to lower p_T as the collisions become more peripheral

Ratio p/π in d+Au



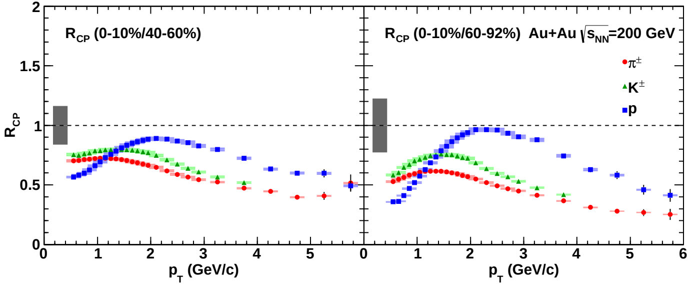
PHENIX, Phys. Rev. C88, 024906 (2013)

- Identical centrality dependence and p_T shapes ($\bar{p}/p$ and π^-/π^+ are flat)
- Ratio rises quickly, reaches maximum at about 2.0 GeV/c, then falls off slowly
- Strong centrality dependence (consider small range of N_{part} and N_{coll} values)—what causes this?

What did we learn from K/π and p/π ratios?

- Centrality dependence of K/π in Au+Au is consistent with strangeness enhancement
    - The detailed p_T dependence may shed light on the strangeness production mechanism
    - The K/π ratio in d+Au is centrality independent and consistent with the ratio in p+p, in contrast to Au+Au
- The p/π ratio exhibits strong centrality dependence in both Au+Au and d+Au
    - The enhancement of p/π in Au+Au and d+Au relative to p+p cannot be attributed to flow alone
    - The centrality dependence of p/π in Au+Au is straightforward to understand based on the system size, what about d+Au?

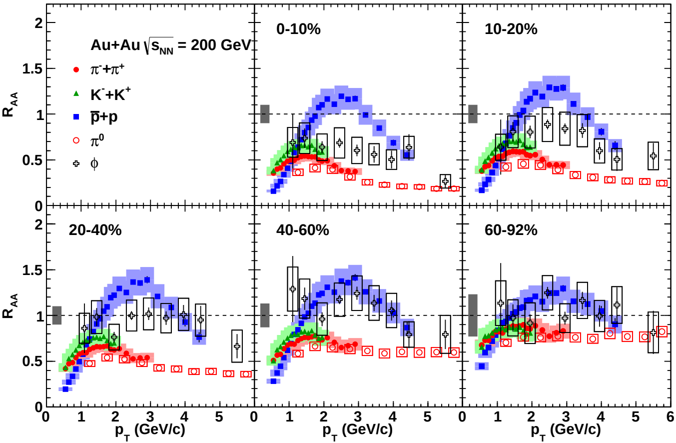
Nuclear modification factor R_{CP} in Au+Au



PHENIX, Phys. Rev. C88, 024906 (2013)

- All particles show a "bump", a rise then a fall—the proton bump is larger and at a higher p_T than that of the mesons
- The kaon bump is higher than the pion but in the same place; the enhancement relative to the pion is decreased for 0–10%/40-60% relative to 0–10%/60–92%

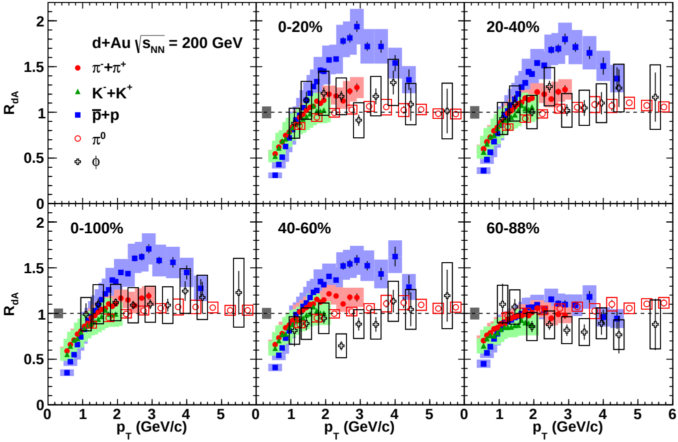
Nuclear modification factor R_{AA} for different centralities



PHENIX, Phys. Rev. C88, 024906 (2013)

- The kaon and pion are most separated in the most central
- The ϕ seems to stay in between the kaon and the proton
- The proton shows little or no centrality dependence

Nuclear modification factor R_{dA} for different centralities



PHENIX, Phys. Rev. C88, 024906 (2013)

- The charged pions and kaons are consistent with each other
- The ϕ meson exhibits minimal modification to higher p_T like the π^0
- All four mesons consistent while protons strikingly different with strong centrality dependence

What did we learn from the nuclear modification factors?

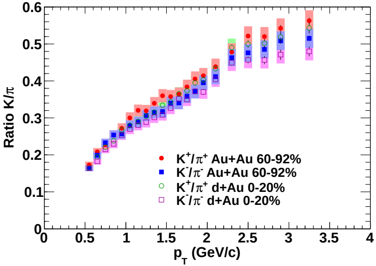
- Two main things to consider—strangeness and baryon production
- The additional strangeness production mechanism present in Au+Au is absent in d+Au
  - Kaon R_{AA} is above pion R_{AA} and the difference varies with centrality, and the ϕ R_{AA} is in between kaons and protons
  - The R_{dA} of pions, kaons, and ϕ are all consistent with each other
  - The K/π ratios tell a similar story
- Both Au+Au and d+Au have significant baryon enhancement
  - The enhancement in d+Au has no dependence on mass or strangeness, but strong dependence on type (baryon vs meson)
  - The enhancement in both systems is strongly centrality dependent, as seen in the p/π ratios as well as the R_{dA}

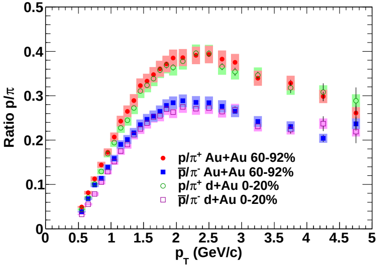
Peripheral Au+Au and central d+Au

Centrality	$\langle N_{coll} \rangle$	$\langle N_{part} \rangle$
Au+Au 60-92%	**14.8 ± 3.0**	**14.7 ± 2.9**
d+Au 0-20%	**15.1 ± 1.0**	**15.3 ± 0.8**

- Peripheral Au+Au and central d+Au have the same N_{coll}
- Peripheral Au+Au and central d+Au have the same N_{part}
- The N_{coll} ratio is 1.02 ± 0.22, the N_{part} ratio is 1.04 ± 0.21
- As an added bonus, all 4 of these numbers are consistent within uncertainties

K/π and p/π in peripheral Au+Au and central d+Au

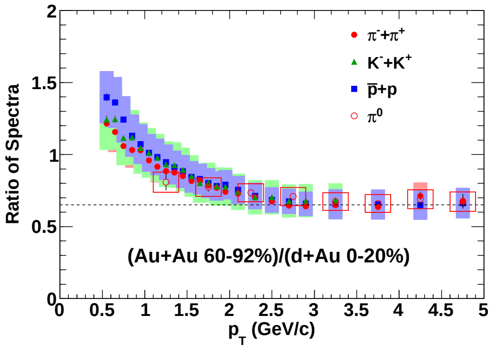




PHENIX, Phys. Rev. C88, 024906 (2013)

- Both height and shape are identical for peripheral Au+Au and central d+Au

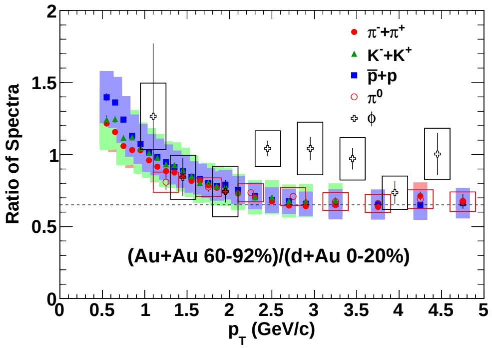
Ratio of yields in peripheral Au+Au to central d+Au



PHENIX, Phys. Rev. C88, 024906 (2013)

- No scaling applied, N_{coll} and N_{part} have very similar values
- Flat in p_T above 2.5–3.0 GeV/c with no species dependence
- Upward trend at low p_T with possible mass ordering
- Which physics effects cancel out and which ones are at play? Rapidity shift? Cronin? Flow? Baryon enhancement? nPDFs?

Ratio of yields in peripheral Au+Au to central d+Au



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What did we learn from this comparison?

- Identical K/π and p/π ratios suggest common mechanisms for strangeness and baryon production in the two systems
- Direct ratio of spectra is flat and independent of species above 2.5 GeV/c
  - Baryon enhancement is quantitatively the same—this is further evidence that the mechanism is the same in both systems
  - Ratio is significantly less than unity—suggests energy loss for all species in peripheral Au+Au
  - The ϕ data don't have enough precision for this measurement, but the kaons seem to suggest that any possible strangeness effects also cancel
- Remarkable similarities between peripheral Au+Au and central d+Au suggest other asymmetric collision species could reveal some very interesting physics
  - Should see rapidity shift
  - nPDFs will be different
  - Strangeness effects may come into play
  - Cu+Au in Run12! ^{3}He+Au planned for Run15! How about Si+Au?

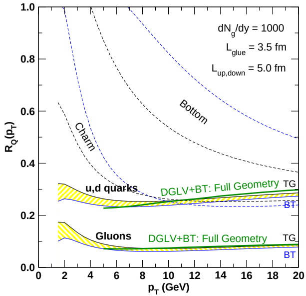
Summary of Results

- Strangeness enhancement in Au+Au but not in d+Au
  - R_{AA} of phi is above kaon, which is above pion
  - K/π ratio in Au+Au show centrality dependent enhancement
  - R_{dA} of strange and non-strange mesons consistent with each other
  - K/π ratio in d+Au has no centrality dependence and is consistent with p+p
- Baryon enhancement in both Au+Au and d+Au
  - p/π ratios have strong centrality dependence in both systems
  - R_{dA} of protons has strong centrality dependence
- Striking similarities between peripheral Au+Au and central d+Au
  - Identical K/π and p/π ratios
  - Direct ratio of spectra is independent of particle species
- Further theoretical investigation and comparison to these precision data is warranted! Viscous hydro, recombination, baryon junctions, color field effects, etc...

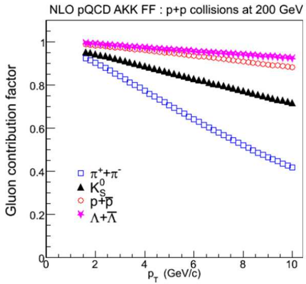
A brief look elsewhere

Let's have a brief look elsewhere...

Physics motivation: color charge effects



S. Wicks et al, Nucl. Phys. A784, 426-442 (2007)

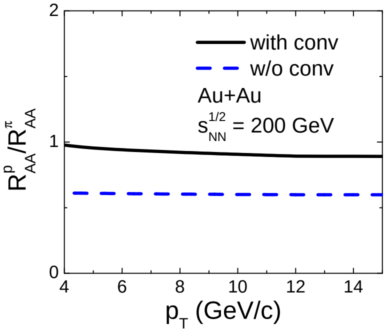


S. Albino et al, Phys. Rev. D75, 184-283 (2007)

- Gluons expected to lose more energy in the quark-gluon plasma by gluon radiation: $C_A = 3,\ C_F = 4/3,\ C_A/C_F = 9/4$
- Gluon contribution factor to fragmentation is larger for protons than for pions
- Measurements of pion and proton nuclear modification factors may help us study flavor dependence of energy loss

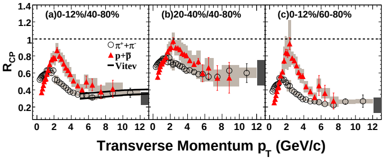
Physics motivation: flavor conversions

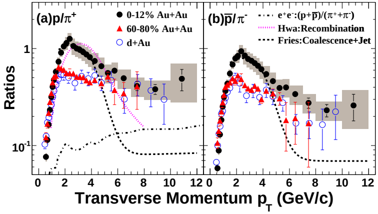
- Scattering in the QGP can change the flavor of a fast parton
  - Annihilation
    $q + \bar{q} \leftrightarrow g + g$
  - Compton scattering
    $q + g \leftrightarrow g + q$
- Differences between energy loss may be mitigated



W. Liu and R. Fries, Phys. Rev. C77, 054902 (2008)

Our good friends in STAR

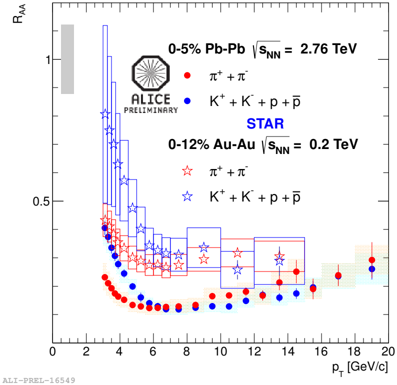


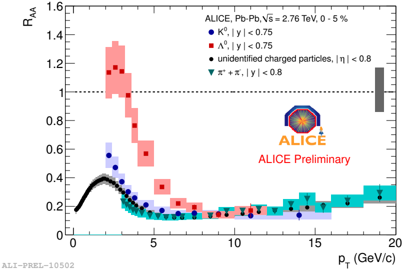


STAR, Phys. Rev. Lett. 97, 152301 (2006)

- STAR sees R_{CP} and p/π with very similar trends as we do
- R_{CP} of proton comes down and gets very close to pion, consistent within (large) uncertainties at highest p_T
- p/π rises quickly, falls off much more slowly than model predictions

A new era at the LHC



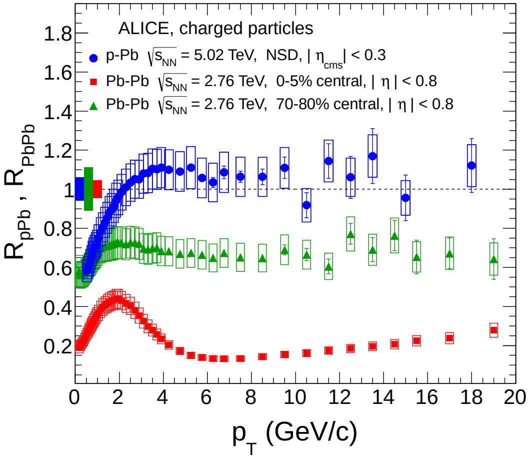


ALICE, arXiv:1208.5368

- ALICE shows very similar suppression for π and $(K + p)$ like STAR
- ALICE shows very similar suppression for Λ and K_S^0

A new era at the LHC

Cronin enhancement at 2.76 TeV?



ALICE, arXiv:1210.4520

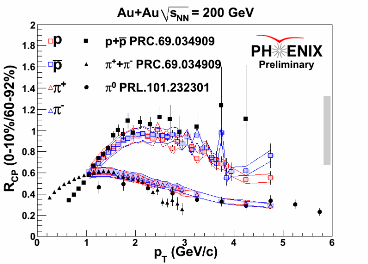
Summary

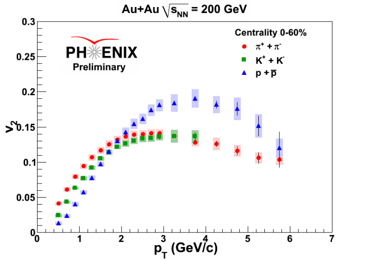
- Flavor dynamics could be a very interesting probe of the medium
- Flavor conversions via 2↔2 scattering are an important ingredient in understanding these dynamics, so are the fragmentation functions
- Recombination effects are clearly important to much higher p_T than what is sometimes considered, so where "high p_T" really begins is a serious question
- There are theoretical and experimental challenges, but the ALICE results look promising, and our theory friends are always improving their techniques
- The remarkable similarities between central d+Au and peripheral Au+Au suggest a common particle production mechanism
- This is bolstered by the evidence that the observed baryon enhancement in Au+Au and d+Au appear to be driven by the same mechanism
- Further theoretical investigation is warranted!
- Asymmetric collisions are very interesting! There are proposals for a p+X(Au,Cu,Si,C) run, how about an X+Au run?

Extra Material

Extra Material

R_{CP} and v_2





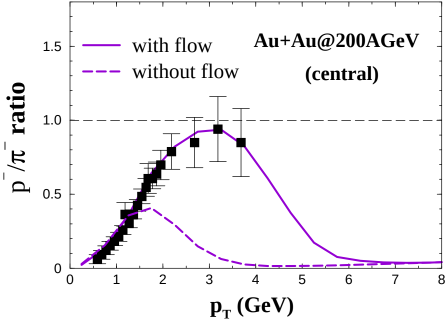
R. Belmont, Nucl. Phys. A830, 697c-700c (2009)

Relative change for protons to pions

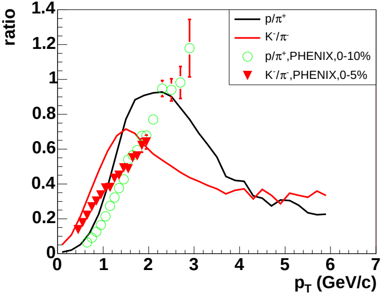
	R_{CP}	v_2
reco	↑	↑
eloss	↓	↑

- Recombination dominates for p_T up to ≈ 4 GeV/c
- Fragmentation or something like it takes over at higher p_T
- At high p_T, proton R_{CP} and v_2 approach pion
- Need PID R_{AA} (or R_{CP}) and v_2 to higher p_T

Radial flow is important



Greco et al., Phys. Rev. C68, 034904 (2003)



Hirano and Nara, Phys. Rev. C69, 034908 (2004)

- Radial flow is important
- Hadron spectra and ratios reflect the interplay of many important and disparate phenomena