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

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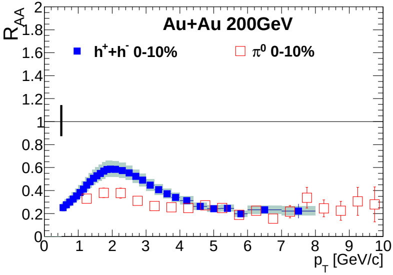
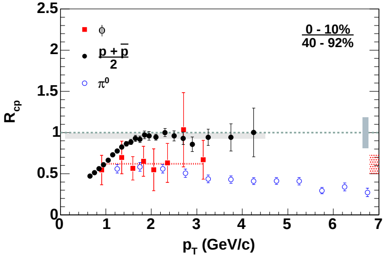
Outline

- Physics Motivation
- PHENIX and the TOFW
- Results
- Conclusion

Physics Motivation: Baryon/Meson Production



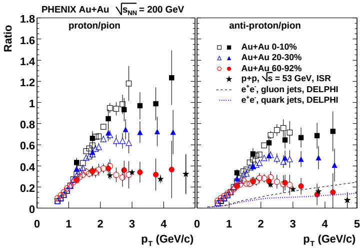
Phys. Rev. C69, 034910 (2004)



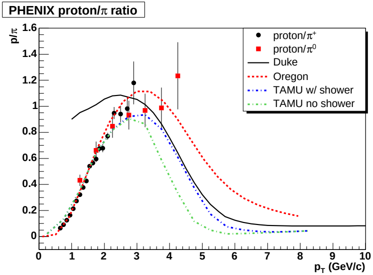
Phys. Rev. C72, 014903 (2005)

- Unidentified hadrons and π^0 are suppressed by a factor of 5(!)
- No suppression of baryons?
- Heavy meson ϕ has similar mass to proton but similar suppression to pion—not a mass effect (e.g. radial flow)

Physics Motivation: Baryon/Meson Production



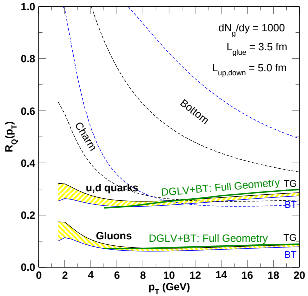
Phys. Rev. Lett., 91, 172301 (2003)



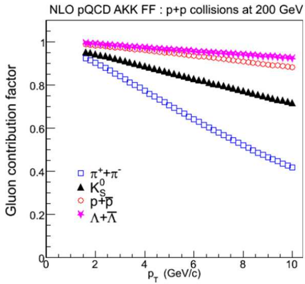
Nucl. Phys. A757, 184-283 (2005)

- 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

Physics Motivation: Color Charge Effects



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

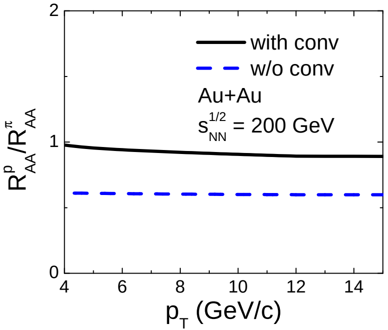


S. Albino et al, Phys. Rev. D75, 184-283 (2007)

- Gluons expected to lose more energy by gluon radiation
  $C_A = 3,\ C_F = 4/3,\ C_A/C_F = 9/4$
- Gluon contribution factor 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: Jet Conversions

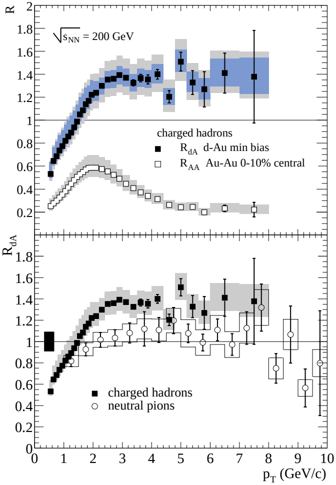
- Elastic scattering in medium change flavor of leading parton of jet
  - Annihilation
    $q + \bar{q} \leftrightarrow g + g$
  - Compton scattering
    $q + g \leftrightarrow g + q$
- Differences between energy loss may be mitigated



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

Physics Motivation: Cold Nuclear Matter Effects

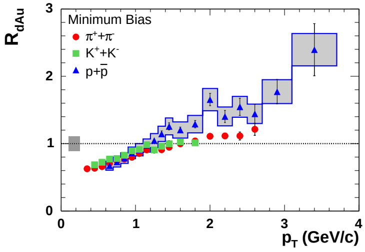
- In addition to effects from the QGP, there are initial state effects caused by the cold nuclear matter
- Some models proposed particle suppression at RHIC could be from initial state effects, but the data show Cronin enhancement
- Cronin enhancement: enhancement of particle yield at intermediate p_T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



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

Physics Motivation: Cold Nuclear Matter Effects

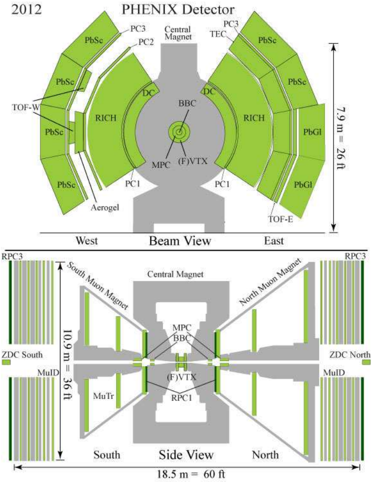
- Strong particle species dependence for Cronin enhancement
- Most models of the Cronin enhancement rely on initial state effects, like multiple parton rescatterings, and have no particle species dependence
- Recombination model applied to d+Au uses final state effect in cold nuclear matter and finds greater Cronin enhancement for baryons than for mesons, discussed in Phys. Rev. Lett. 93, 082302 (2004) by R.C. Hwa and C.B. Yang



Phys. Rev. C91, 024904 (2006)

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
- Very fast DAQ system—5kHz, 600 MB/s
- Ideally suited for measurements of rare probes, electrons, muons, high p_T photons, jets(?)
- This study makes use of DC/PC1 and PC3 for tracking and TOFW for particle ID



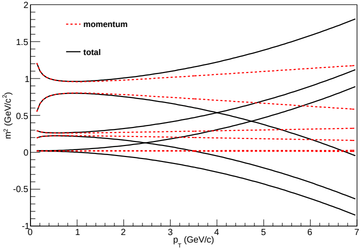
PID by TOFW

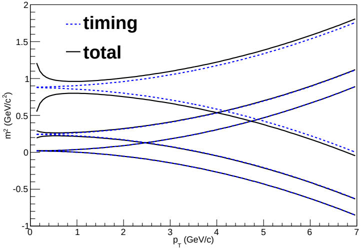
Particles are identified by their mass, and we determine mass from time-of-flight:

$$m^2 = \frac{p^2}{c^2}\left(\frac{t^2c^2}{L^2} - 1\right)$$

Parametrize variance of m^2 distribution:

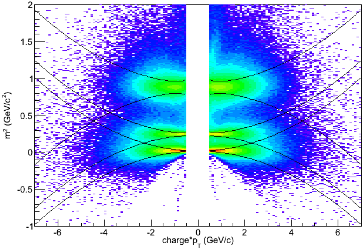
$$\sigma^2_{m^2} = \frac{\sigma^2_\alpha}{K_1^2}\left(4m^4p^2\right) + \frac{\sigma^2_{ms}}{K_1^2}\left(4m^4\left(1+\frac{m^2}{p^2}\right)\right) + \frac{\sigma_t^2c^2}{L^2}\left(4p^2\left(m^2+p^2\right)\right)$$

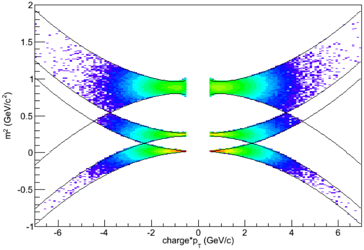




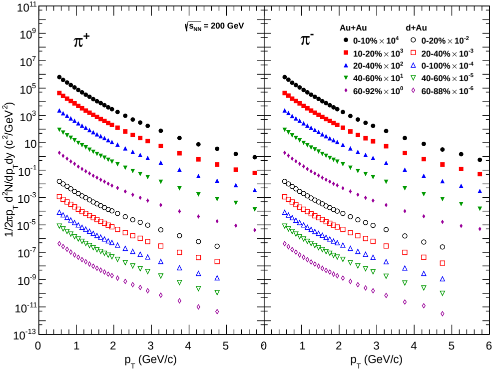
PID by TOFW

To determine which tracks in m^2–p_T space belong to which particle species, we make cuts on two standard deviations of one particle and exclude two standard deviations of the other (2σ window with 2σ veto):



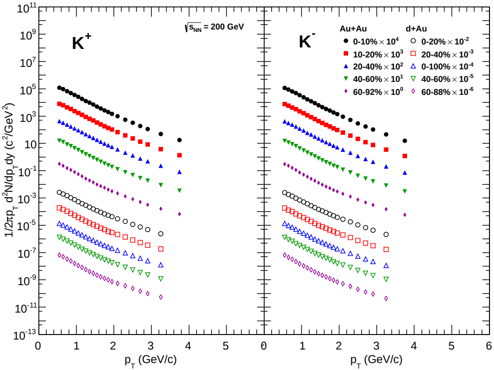


Pion Spectra



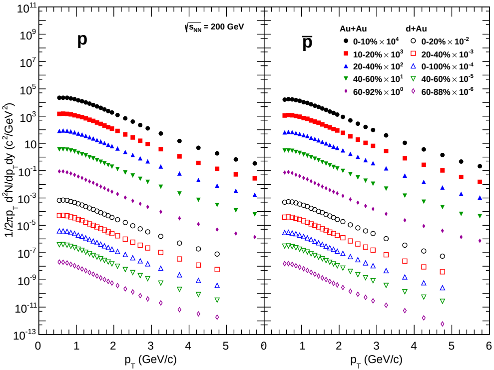
- Au+Au up to 6 GeV/c and d+Au up to 5 GeV/c
- Previous results are up to 3 GeV/c for Au+Au [Phys. Rev. C69, 034909 (2004)] and 2.6 for d+Au [Phys. Rev. C74, 024904 (2006)]

Kaon Spectra



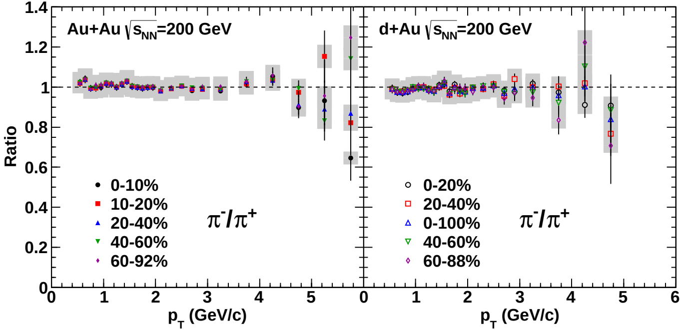
- Au+Au up to 4 GeV/c and d+Au up to 3.5 GeV/c
- Previous results are up to 2 GeV/c for Au+Au [Phys. Rev. C69, 034909 (2004)] and 1.8 for d+Au [Phys. Rev. C74, 024904 (2006)]

Proton Spectra



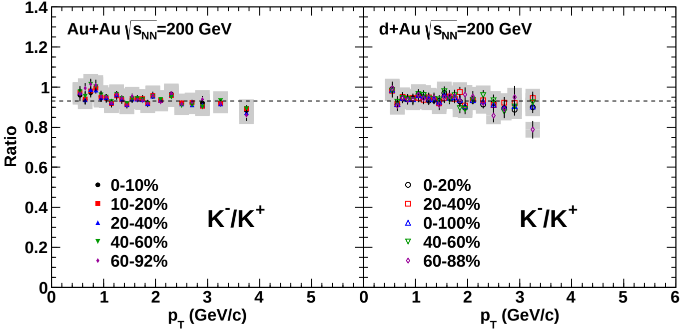
- Au+Au up to 6 GeV/c and d+Au up to 5 GeV/c
- Previous results are up to 4.5 GeV/c for Au+Au [Phys. Rev. C69, 034909 (2004)] and 3.6 for d+Au [Phys. Rev. C74, 024904 (2006)]

Ratio π^-/π^+



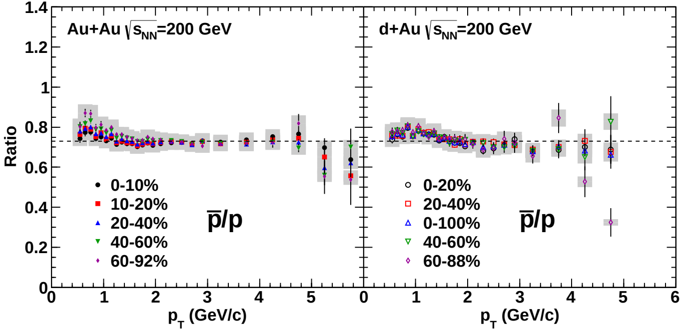
- π^-/π^+ ratio is independent of p_T, centrality, and collision system
- Ratio is essentially equal to unity
- Ratio decreases with increasing p_T in $p+p$

Ratio K^-/K^+



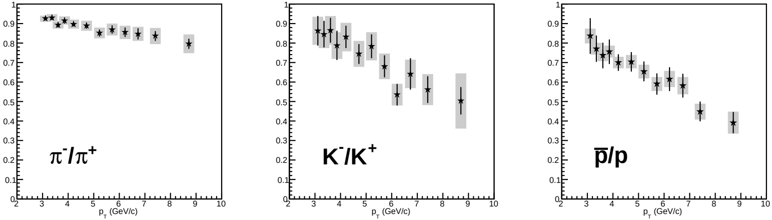
- K^-/K^+ ratio is independent of p_T, centrality, and collision system
- Ratio is slightly less than unity (0.93)
- Ratio decreases with increasing p_T in $p+p$

Ratio $\bar{p}/p$

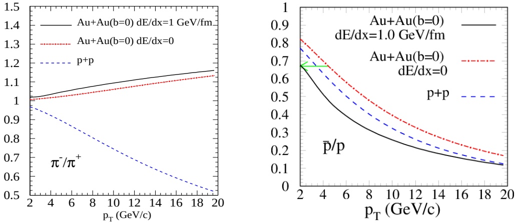


- $\bar{p}/p$ ratio is independent of p_T, centrality, and collision system
- Ratio is roughly 0.73 (consistent with thermal model $\mu_B = 29$ MeV)
- Ratio decreases with increasing p_T in $p+p$

Homogeneous ratios in $p+p$

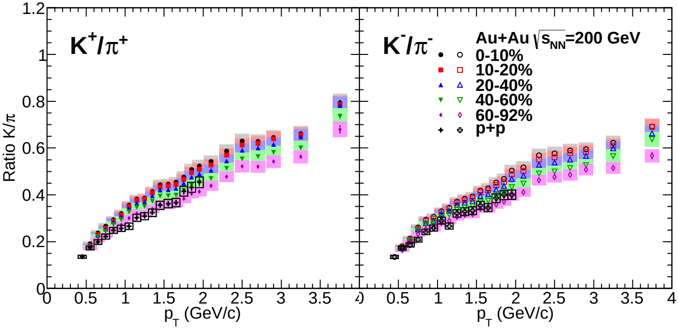


STAR, Phys. Rev. Lett. 108, 072302 (2012)



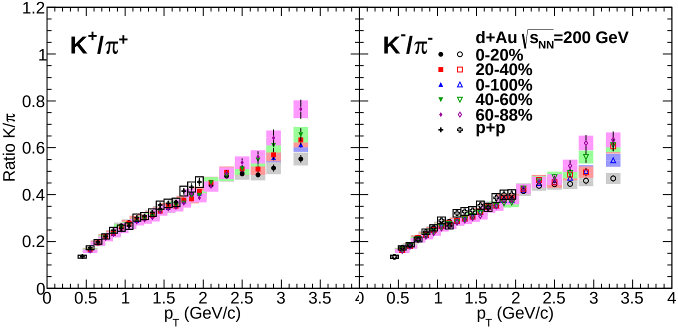
X.-N. Wang, Phys. Rev. C58, 2321 (1998)

Ratio K/π in Au+Au



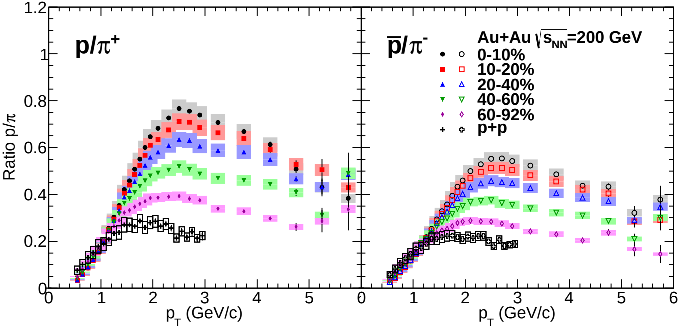
- Identical centrality dependence and p_T shapes (recall K^-/K^+ and π^-/π^+)
- Weak centrality dependence
- Ratio rises steadily over the whole available p_T range

Ratio K/π in d+Au



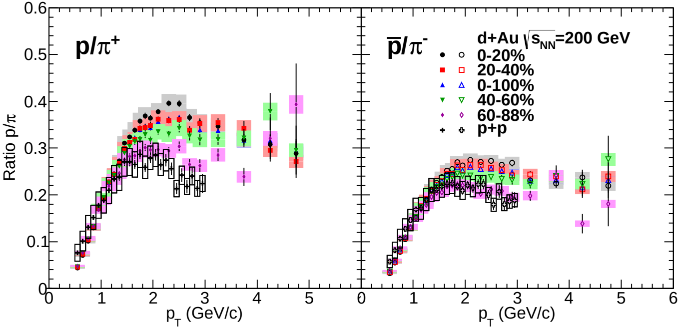
- Identical centrality dependence and p_T shapes (recall K^-/K^+ and π^-/π^+)
- No centrality dependence
- Ratio rises steadily over the whole available p_T range

Ratio p/π in Au+Au



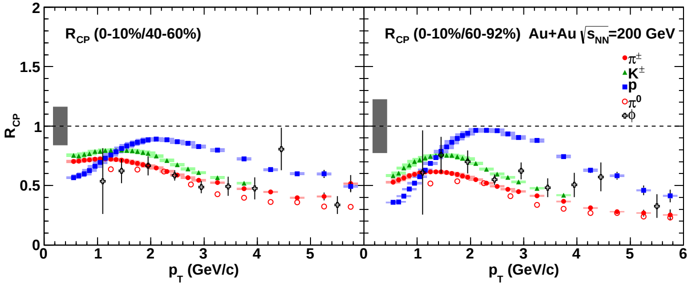
- Identical centrality dependence and p_T shapes (recall $\bar{p}/p$ and π^-/π^+)
- Strong centrality dependence
- Ratio rises quickly, reaches maximum at 2.0–2.5 GeV/c, then falls off slowly

Ratio p/π in d+Au



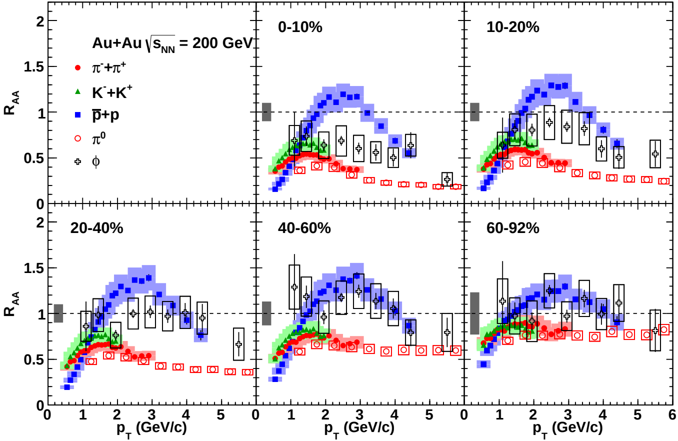
- Identical centrality dependence and p_T shapes (recall $\bar{p}/p$ and π^-/π^+)
- Small but significant centrality dependence
- Ratio rises quickly, reaches maximum at 2.0–2.5 GeV/c, then falls off slowly

Nuclear Modification Factor R_{CP}



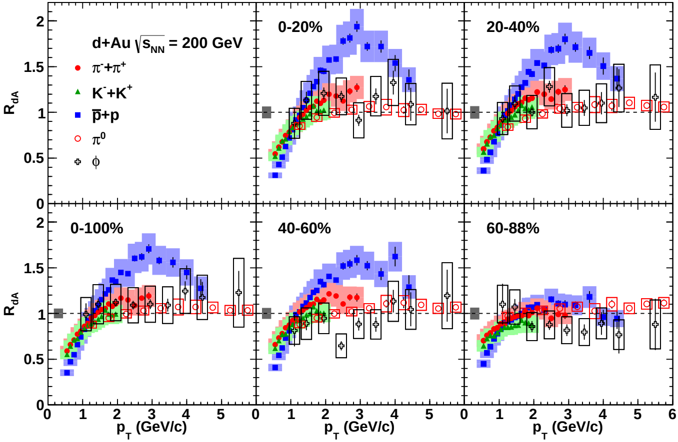
- Protons appear nearly unsuppressed at intermediate p_T, significant suppression of pions
- Kaons show less suppression than pions but more than protons; enhancement relative to pions is decreased for 0–10%/40-60% relative to 0–10%/60–92%

Nuclear Modification Factor R_{AA} for different centralities



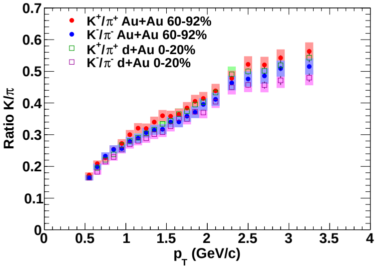
- Pions and kaons have significant and monotonic centrality dependence, separation between them decrease with more peripheral collisions
- Protons have very slight increase with centrality (consistent within uncertainties)

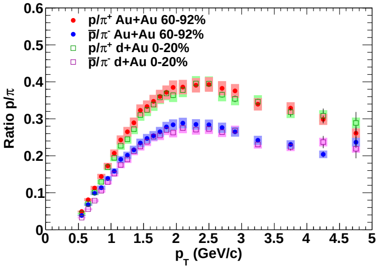
Pion and Proton R_{dA} for different centralities



- The most peripheral data show no modification above 1 GeV/c
- Centralities are consistent for pions and kaons, protons exhibit significant centrality dependence

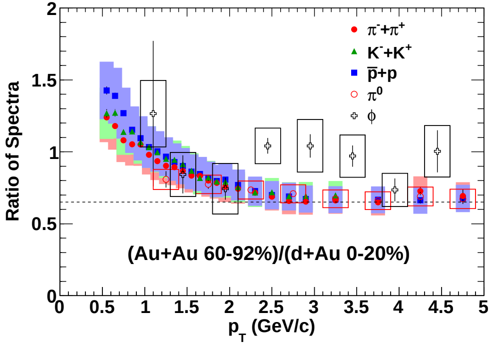
K/π and p/π in peripheral Au+Au and central d+Au





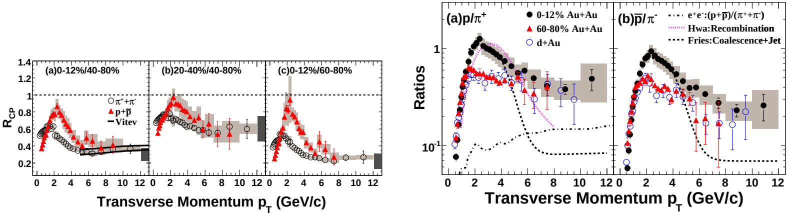
- Remarkable similarity
- Both height and shape are essentially identical for peripheral Au+Au and central d+Au

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



- Scaled by N_{coll}, but 60–92% Au+Au $N_{coll} = 14.8$ 0–20% d+Au $N_{coll} = 15.1$ (2% difference)
- Clear mass dependence at low p_T
- Identical trend above 2.5–3.0 GeV/c

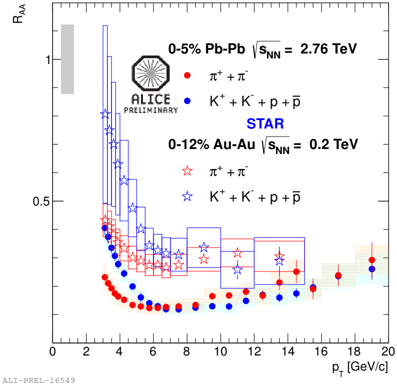
Our good friends in STAR

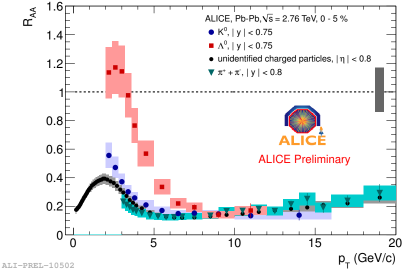


Phys. Rev. Lett. 97, 152301 (2006)

- 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



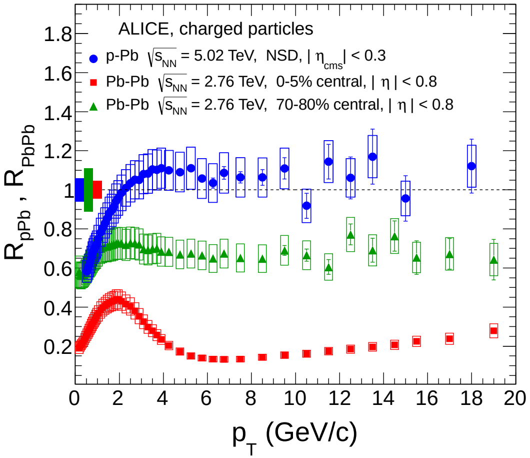


arXiv:1208.5368

- 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 even at 2.76 TeV, though appreciably smaller than at 200 GeV



arXiv:1210.4520

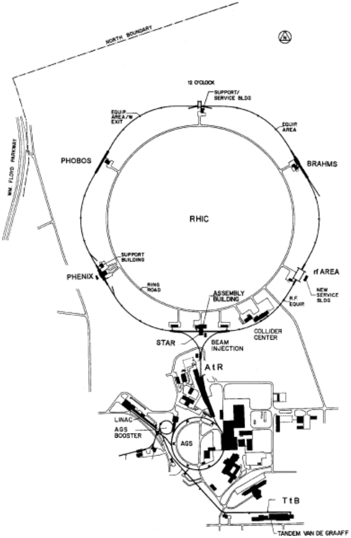
Summary

- Flavor dynamics could be a very interesting probe of the medium
- Jet flavor conversions via elastic 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
- In addition to the theoretical challenges, there are experimental ones as well, but the ALICE results look very promising
- 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 described in a single theoretical framework, at least qualitatively
- I look forward to theoretical investigations of the present work, and more experimental measurements with identified particles at the LHC

Backups

RHIC

- 3833.845 m circumference
- 1740 total magnets, 1600 miles of Nb-Ti wire cooled with liquid helium at 4.6 K, 396 dipole magnets - 3.458 T, 5.093 kA
- Intersecting Storage Ring Collider
  - 120 bunches/ring
  - 10^9 ions/bunch
  - 106 ns crossing time
- Beam Energy
  - 250 GeV for protons
  - 125 AGeV for light nuclei
  - 100 AGeV for heavy nuclei
- Beam Luminosity
  - Au+Au: 10^{26} cm^{-2} s^{-1}
  - p+p: 10^{31} cm^{-2} s^{-1}



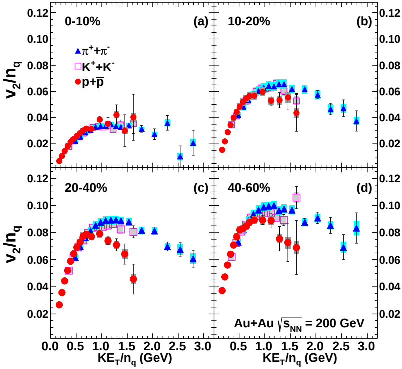
Centrality

Centrality classes and centrality dependent corrections

- High multiplicity in Au+Au collisions means detector occupancy effect—loss of efficiency
- Low multiplicity in d+Au collisions—trigger and centrality bin bias effects

Centrality	$\langle N_{coll} \rangle$	$\langle N_{part} \rangle$	Correction
Au+Au			occupancy efficiency
0-10%	960.2 ± 96.1	325.8 ± 3.8	0.542
10-20%	609.5 ± 59.8	236.1 ± 5.5	0.653
20-40%	300.8 ± 29.6	141.5 ± 5.8	0.783
40-60%	94.2 ± 12.0	61.6 ± 5.1	0.904
60-92%	14.8 ± 3.0	14.7 ± 2.9	0.964
d+Au			bin shift correction
0-20%	15.1 ± 1.0	15.3 ± 0.8	0.94
20-40%	10.2 ± 0.7	11.1 ± 0.6	1.00
0-100%	7.6 ± 0.4	8.5 ± 0.4	0.89
40-60%	6.6 ± 0.4	7.8 ± 0.4	1.03
60-88%	3.1 ± 0.2	4.3 ± 0.2	1.03

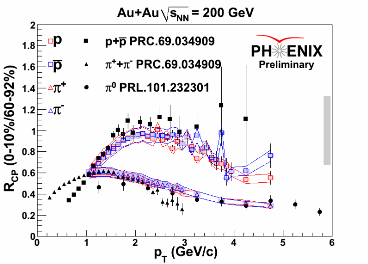
Breaking of NCQ scaling

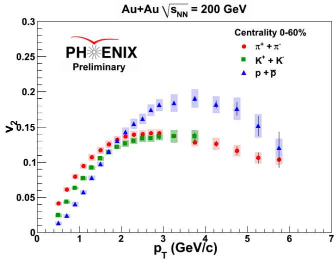


Phys. Rev. C85, 064914 (2012)

- NCQ scaling holds at all p_T in most central, shows breaking in other centralities
- Scaling seems to break at the same point in all centralities, $KE_T/n_q \geq 1$ GeV
- Scaling breaking seems to get stronger with decreasing centrality
- Thermal recombination is not dominant production mechanism for $p_T > 4$ GeV/c, but recombination can transition from TT to TS and from TTT to TTS and TSS
- Scaling breaking as a result of T+S recombination discussed in Phys. Rev. C78, 044903 (2008) by C.B. Chiu, R.C. Hwa, and C.B Yang

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
- No obvious or consistent energy loss effects

Factorization and Fragmentation

Factorization in QCD: express the hadron production cross section in hadron+hadron collisions as

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

Where f are PDFs, $d\sigma/d\hat{t}$ is the hard scattering cross section, and D is the FF; the hard scale Q^2 and factorization scale μ are suppressed, and effects related to parton transverse momentum k_T are ignored

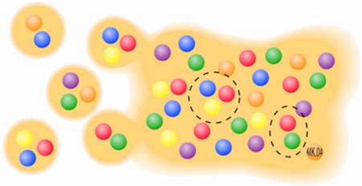
We can think of the QGP as a large collection of partons ab initio, so we can rewrite the hadron production cross section as

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

where Σ is the freeze-out hypersurface, P is the hadron momentum, u is the radial flow velocity, D is the same fragmentation function, and w is the Wigner function, which is a phase-space distribution function for the partons

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 hadron momentum



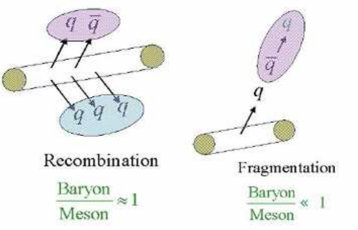
$$E\frac{d^3N^{(M)}}{dP^3} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3} \sum_{\alpha\beta} \int dx\ w_\alpha(xP)\bar{w}_\beta((1-x)P)\ |\phi^{(M)}_{\alpha\beta}(x)|^2$$

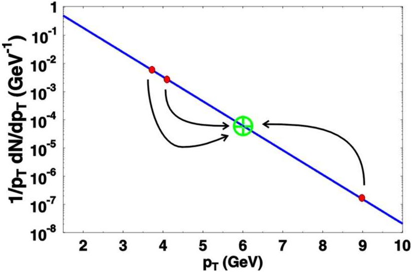
$$E\frac{d^3N^{(B)}}{dP^3} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3} \sum_{\alpha\beta\gamma} \iint dxdx'\ w_\alpha(xP)w_\beta(x'P)w_\gamma((1-x-x')P)\ |\phi^{(B)}_{\alpha\beta\gamma}(x,x')|^2$$

Fragmentation and Recombination

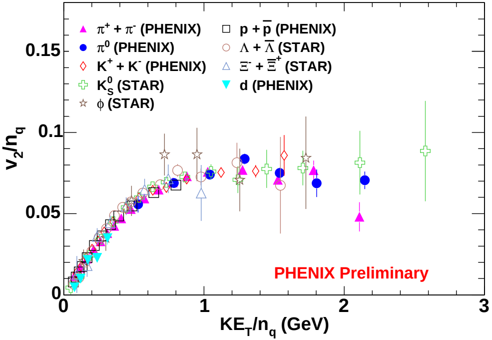
Fragmentation	Recombination
Inclusive	Exclusive
Slower fall-off	Faster fall-off
$P < p$	$P > p$
$N_B \ll N_M$	$N_B \approx N_M$

- $P < p$ for fragmentation because $P = zp$ and $P > p$ for recombination because $xP = p$
- $N_B \ll N_M$ for fragmentation because baryon production requires production of $qq\bar{q}\bar{q}$ instead of just $q\bar{q}$, while $N_B \approx N_M$ for recombination because it's roughly as likely for have qqq or $\bar{q}\bar{q}\bar{q}$ overlap as $q\bar{q}$





NCQ scaling



In recombination model, rough 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 NCQ scaling