The "other" side of RHIC: a little bit about heavy ion physics, with an emphasis on identified hadrons

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Outline

- About RHIC
- Heavy Ion Basics
- Results
- Summary

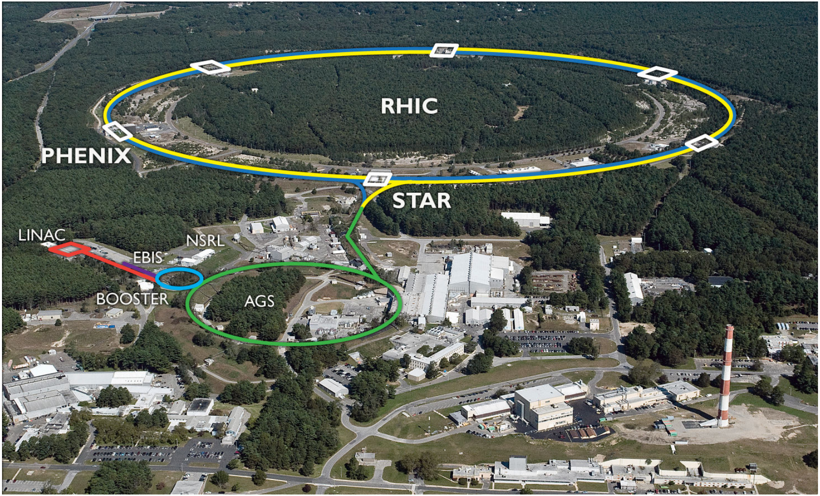
The Relativistic Heavy Ion Collider

- RHIC is the only polarized proton collider in the world (Christine's work)
- RHIC is one of two heavy ion colliders, the other being the LHC (my work)
- 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↑+p↑	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

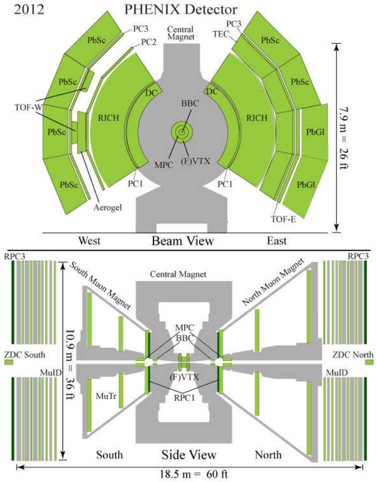
- Two small experiments, PHOBOS and BRAHMS (decommissioned in 2005)
- Two large experiments, PHENIX and STAR (currently active)

RHIC Complex

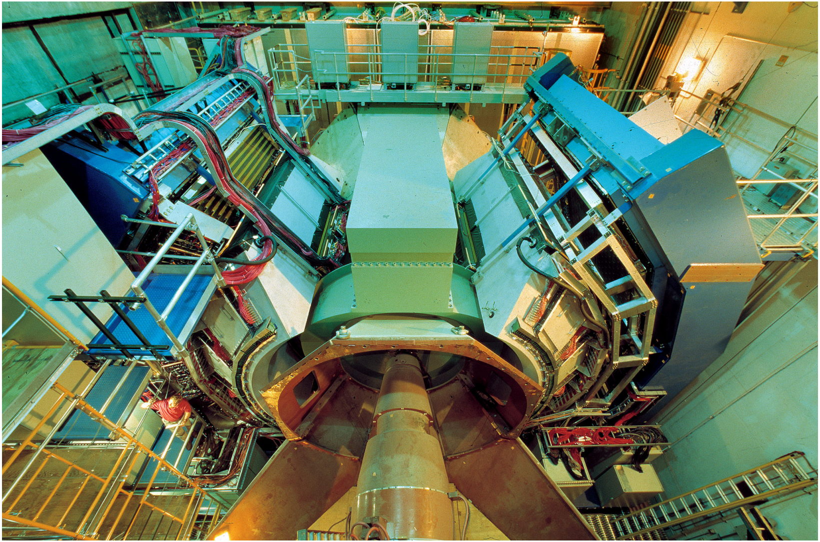


PHENIX

- 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
- Very fast DAQ system—5 kHz, 600 MB/s
- Ideally suited for measurements of rare probes, electrons, muons, high p_T photons, etc.



PHENIX

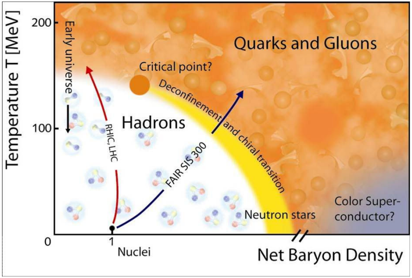


The quark-gluon plasma

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

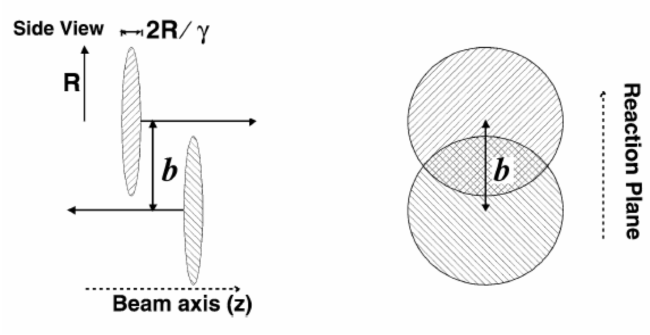
Some basic information about the QGP created at RHIC:

- 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 (3–6×10^{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)



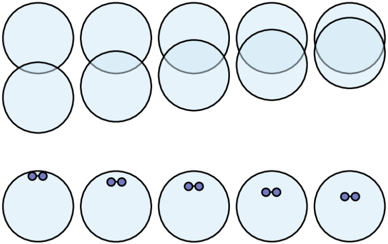
When nuclei collide: centrality

- Need to characterize the overlap of the two nuclei
- The most natural choice is impact parameter
- Other things you might like to know are:
  how many nucleons are there in the overlap region (N_{part}) and
  how many nucleon-nucleon collisions occurred (N_{coll})



When nuclei collide: 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

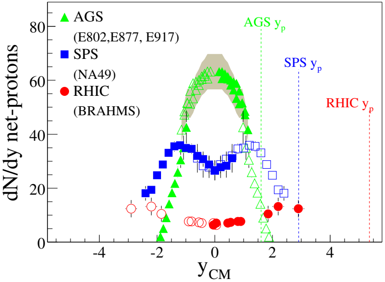
When nuclei collide: Landau vs. Bjorken

Landau

- Nuclei hit each other and stop
- Rapidity distribution dN/dy of net baryons is Gaussian
- L. Landau, Izv. Akad. Nauk SSSR Ser. Fiz. 17, 51 (1953)
- See e.g. P. Carruthers and M. Duong-van, PRD 8, 869 (1973)

Bjorken

- Nuclei pass through each other
- dN/dy of net baryons is flat at mid-rapidity with peaks near the projectile rapidities (forward and back)
- J. Bjorken PRD 27, 140 (1983)

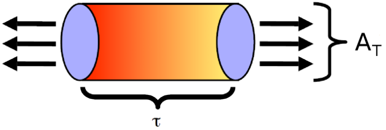


Phys. Rev. Lett. 93, 102301 (2004)

Estimating the energy density

The Bjorken picture of impact is the applicable one at RHIC energies
Use the Bjorken formula to estimate the energy density
The energy density at RHIC is well above the critical energy density for QGP formation

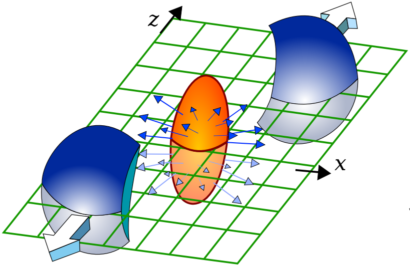
$\varepsilon_{\text{nuclear matter}} \approx 0.15\ \text{GeV/fm}^3$
$\varepsilon_{\text{proton}} \approx 0.5\ \text{GeV/fm}^3$
$\varepsilon_{\text{critical}} \approx 1.0\ \text{GeV/fm}^3$
$\varepsilon_{\text{RHIC}} \approx 5.4\ \text{GeV/fm}^3$

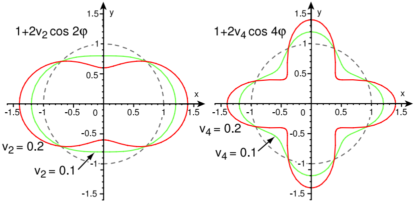


$$\varepsilon = \frac{1}{\tau A_T}\frac{dE_T}{dy}$$

τ := characteristic time (usually thermalization time)
A_T := transverse area of the system
E_T := total transverse energy produced in the collision $(\sum_i \sqrt{p_{T,i}^2 + m_i^2})$

Elliptic flow

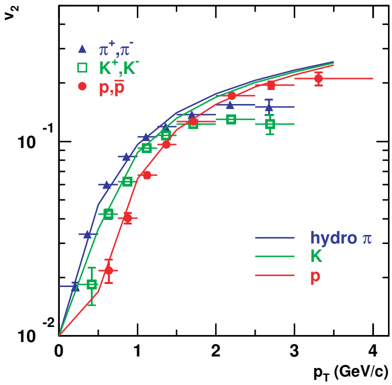


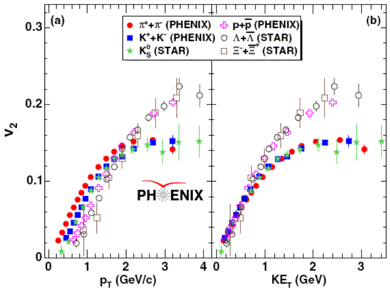


$$\frac{dN}{d\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varphi = \phi - \phi_{RP}$$

- Collisions that are not fully overlapping have almond-shape overlap region
- Initial state spatial anisotropy creates pressure gradients that drive final state momentum anisotropy—the elliptic flow builds up early and self quenches
- Azimuthal distribution of particles can be described as Fourier series with coefficients v_n—dominant term is v_2

Elliptic flow





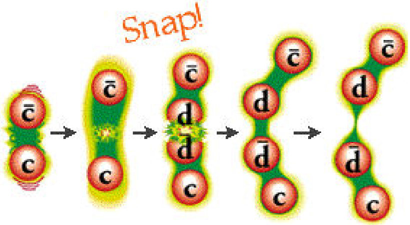
- Hydrodynamics models describe the data well at low transverse momentum p_T
- Mass splitting from common flow velocity, plotting vs transverse kinetic energy $KE_T = \sqrt{p_T^2 + m^2} - m$ makes them line up
- At higher p_T baryons and mesons group together...

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

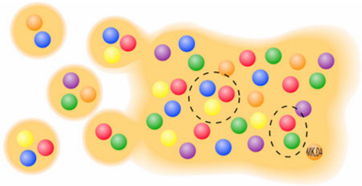


$$E\frac{d^3N_h}{dP^3} = \sum_{abcd} \iiint dz dx_a dx_b f_a(x_a) f_b(x_b) \frac{d\sigma}{d\hat{t}}(ab \to cd) D_{c \to h}(z)/z$$

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

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



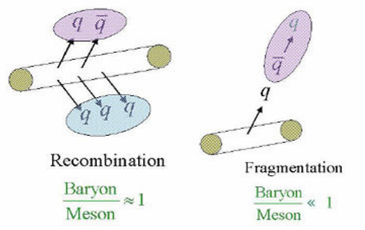
$$E\frac{d^3N^{(Meson)}}{dP^3} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3} \sum_{\alpha\beta} \int dx\ w_\alpha(xP)\bar{w}_\beta((1-x)P)\ |\phi^{(M)}_{\alpha\beta}(x)|^2$$

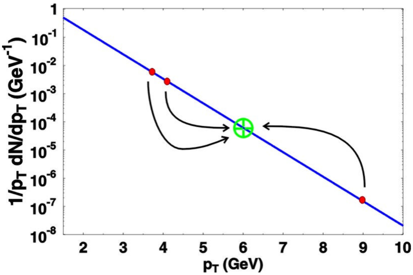
$$E\frac{d^3N^{(Baryon)}}{dP^3} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3} \sum_{\alpha\beta\gamma} \iint dxdx'\ w_\alpha(xP)w_\beta(x'P)w_\gamma((1-x-x')P)\ |\phi^{(B)}_{\alpha\beta\gamma}(x,x')|^2$$

Fragmentation and recombination

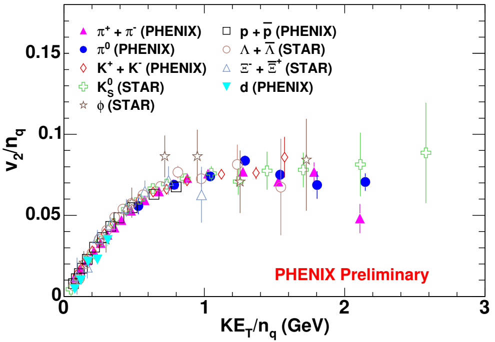
P—hadron momentum
p—parton momentum

- $P < p$ 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 ≈3 GeV/c
- To make a 6 GeV/c baryon by recombination, need three partons with ≈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 valence quark scaling

Nuclear modification factors

- Nuclear modification factors are used to compare particle production in heavy ion collisions to p+p
- We define the nuclear modification for A+B collisions as:

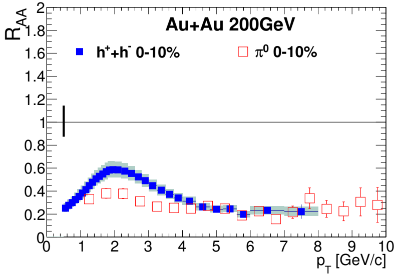
$$R_{AB} = \frac{(dN/dp_T)^{A+B}/N_{coll}^{A+B}}{(dN/dp_T)^{p+p}}$$

- For symmetric collisions, like Au+Au or Pb+Pb, we write R_{AA}
  For asymmetric collisions, like d+Au, we write R_{dA}
- We can define another nuclear modification factor that compares central to peripheral:

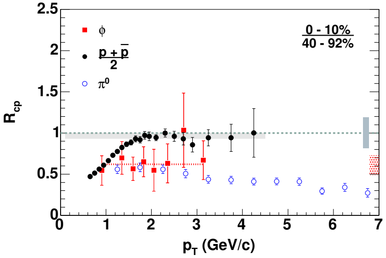
$$R_{CP} = \frac{(dN/dp_T)^{central}/N_{coll}^{central}}{(dN/dp_T)^{peripheral}/N_{coll}^{peripheral}}$$

- Whether peripheral collisions are an acceptable proxy for p+p collisions is debatable (hint: they're not), but sometimes R_{CP} can be useful anyway

Physics motivation: baryon vs. meson production



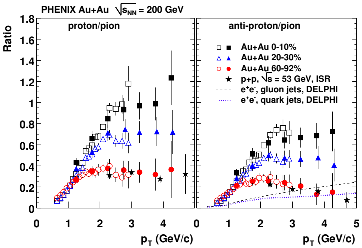
PHENIX, Phys. Rev. C69, 034910 (2004)



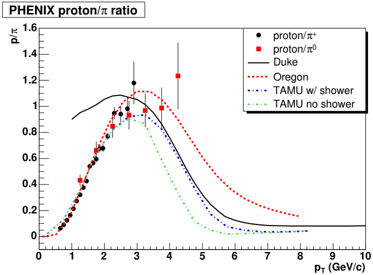
PHENIX, Phys. Rev. C72, 014903 (2005)

- Unidentified hadrons and π^0 are suppressed by a factor of 5(!)
- No suppression of baryons?
- Heavy meson ϕ has similar mass to proton (1.019 GeV/c^2 cf 0.938 GeV/c^2) but similar suppression to pion—not a mass effect

Physics motivation: baryon vs. meson production



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

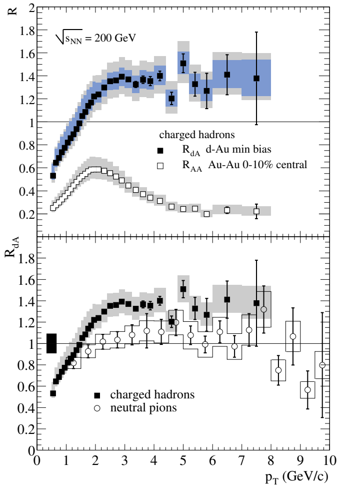


PHENIX, Nucl. Phys. A757, 184-283 (2005)

- 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

Physics motivation: cold nuclear matter effects

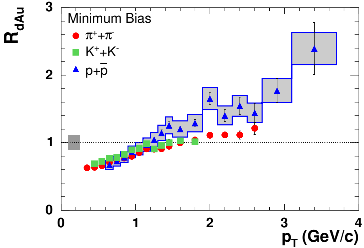
- In addition to effects from the QGP, there are initial state effects caused by the cold nuclear matter
- Some models proposed particle suppression at RHIC could be from initial state effects, but the data show Cronin enhancement
- Cronin enhancement: enhancement of particle yield at intermediate p_T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



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

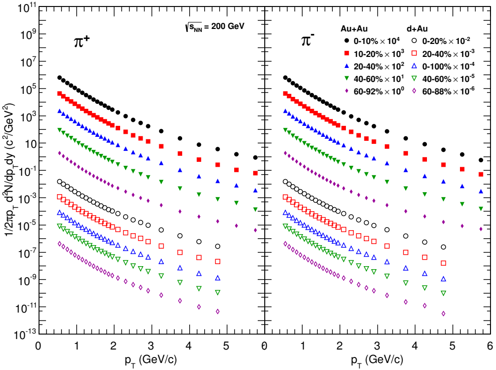
Physics motivation: cold nuclear matter effects

- Strong particle species dependence for Cronin enhancement
- Most models of the Cronin enhancement rely on initial state effects like multiple parton rescatterings—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



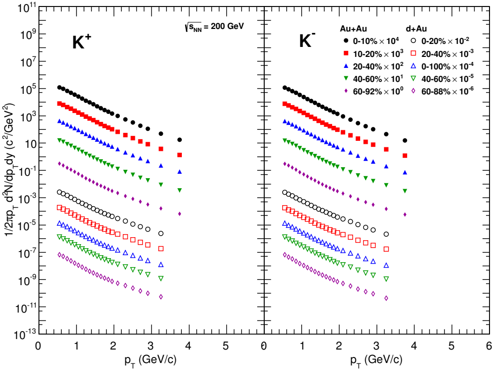
PHENIX, Phys. Rev. C91, 024904 (2006)

New detailed measurements: pion spectra



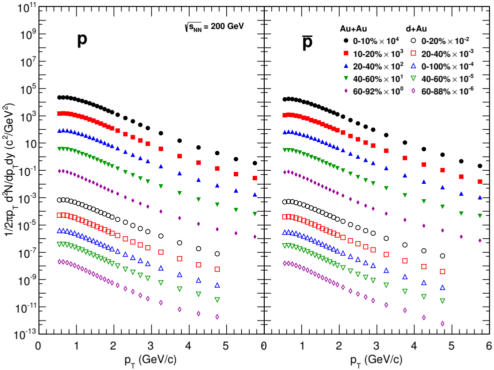
- From R. Belmont Ph.D. thesis
- In preparation with C. Aidala for submission to PRC by PHENIX
- Au+Au up to 6 GeV/c and d+Au up to 5 GeV/c

New detailed measurements: kaon spectra



- From R. Belmont Ph.D. thesis
- In preparation with C. Aidala for submission to PRC by PHENIX
- Au+Au up to 4 GeV/c and d+Au up to 3.5 GeV/c

New detailed measurements: proton spectra

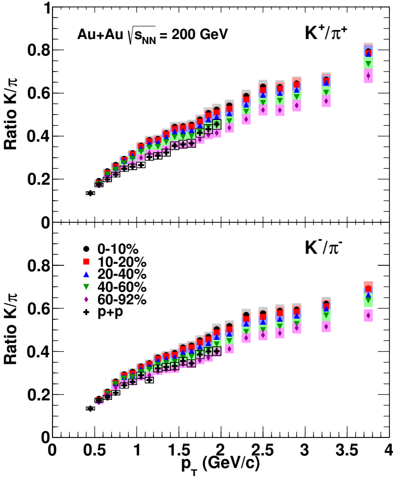


- From R. Belmont Ph.D. thesis
- In preparation with C. Aidala for submission to PRC by PHENIX
- Au+Au up to 6 GeV/c and d+Au up to 5 GeV/c

Particle spectra as building blocks

- Just shown were 1430 data points (740 Au+Au and 690 d+Au)
- All other quantities of interest are derived from these spectra
- We will also employ 152 data points from p+p data published by PHENIX in Phys. Rev. C83, 064903 (2011)

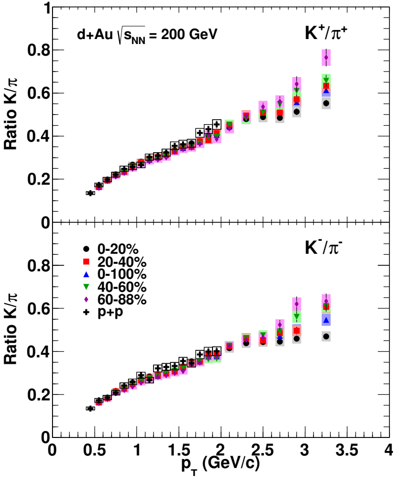
Ratio K/π in Au+Au



PHENIX, in preparation (R. Belmont and C. Aidala)

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

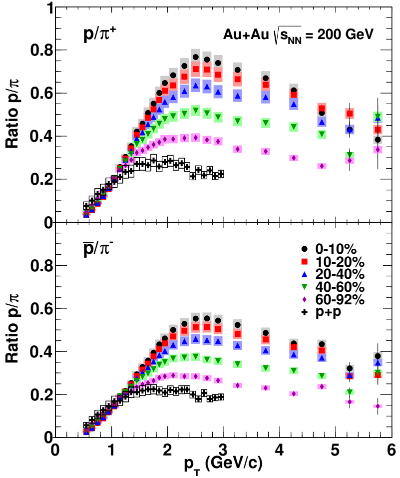
Ratio K/π in d+Au



PHENIX, in preparation (R. Belmont and C. Aidala)

- No difference between charges (K^-/K^+ and π^-/π^+ are flat)
- No centrality dependence and no difference from ratio in p+p—not surprising since we don't expect QGP formation in d+Au...
- As with Au+Au, ratios rise steadily over the whole available p_T range

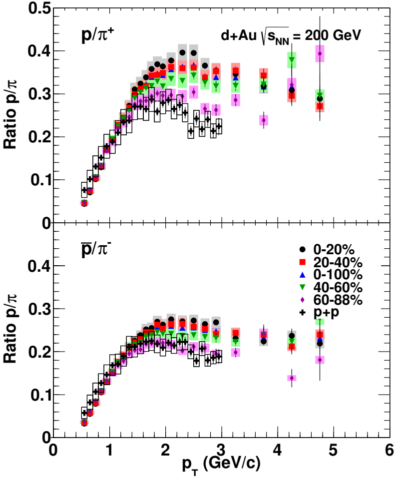
Ratio p/π in Au+Au



PHENIX, in preparation (R. Belmont and C. Aidala)

- Identical centrality dependence and p_T shapes ($\bar{p}/p$ and π^-/π^+ are flat)
- Ratio rises quickly, reaches maximum at about 2.5 GeV/c, then falls off slowly
- Strong centrality dependence—more central collisions create a larger volume, bigger phase space for partons to recombine
- Attempts to explain baryon enhancement as due to strong flow cannot reproduce the centrality dependence

Ratio p/π in d+Au



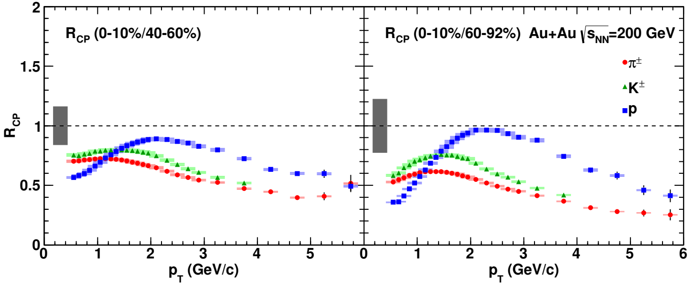
PHENIX, in preparation (R. Belmont and C. Aidala)

- Identical centrality dependence and p_T shapes ($\bar{p}/p$ and π^-/π^+ are flat)
- Ratio rises quickly, reaches maximum at about 2.5 GeV/c, then falls off slowly
- Strong centrality dependence (consider small range of $N_{participants}$ and $N_{collisions}$ values)
- No expectations of thermalization or flow in d+Au

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

- Centrality dependence of K/π in Au+Au is consistent with strangeness enhancement, a signature of the quark-gluon plasma
- 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
- 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
- The centrality dependence of p/π in Au+Au is straightforward to understand based on the system size, but what about d+Au?
- Further theoretical investigation is warranted, but heuristically one could argue that the interaction volume is larger in central d+Au compared to peripheral, so more soft partons at low x can play a role

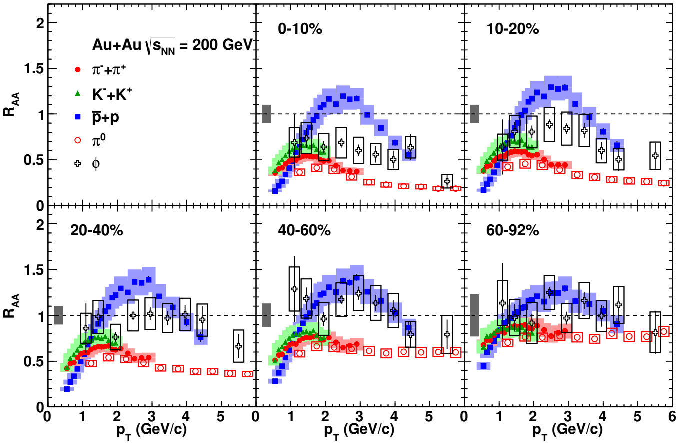
Nuclear modification factor R_{CP} in Au+Au



PHENIX, in preparation (R. Belmont and C. Aidala)

- Protons become nearly unmodified 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%

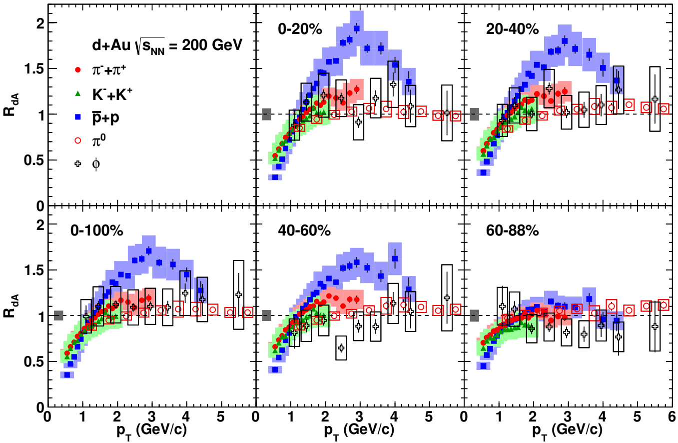
Nuclear modification factor R_{AA} for different centralities



PHENIX, in preparation (R. Belmont and C. Aidala)

- Pions and kaons have clear and monotonic centrality dependence
- Protons show little or no centrality dependence
- Even peripheral R_{AA} shows appreciable modification

Nuclear modification factor R_{dA} for different centralities



PHENIX, in preparation (R. Belmont and C. Aidala)

- The most peripheral data show no modification above 1 GeV/c
- Other centralities are consistent for pions and kaons
- Protons show strong centrality dependence

What did we learn from the nuclear modification factors?

- The two different centrality selections of R_{CP} in Au+Au show different levels of kaon enhancement over pions, indicating centrality dependent strangeness enhancement like what is seen in K/π ratios
- The magnitude of pion suppression in Au+Au seen in R_{AA} decreases monotonically as the collisions become more peripheral—smaller medium induces less partonic energy loss
- The pion enhancement in d+Au seen in R_{dA} is small and appears to be centrality independent, except for the most peripheral bin which shows no enhancement
- On the other hand, the protons tell quite a different story, with R_{AA} being roughly independent of centrality and R_{dA} being strongly centrality dependent
- For proton R_{AA}, parton suppression in conjunction with enhancement driven by recombination could conspire together to produce a roughly constant ratio
- For proton R_{dA}, if the enhancement is driven by recombination, it makes sense that the enhancement is larger when the number of participants is larger

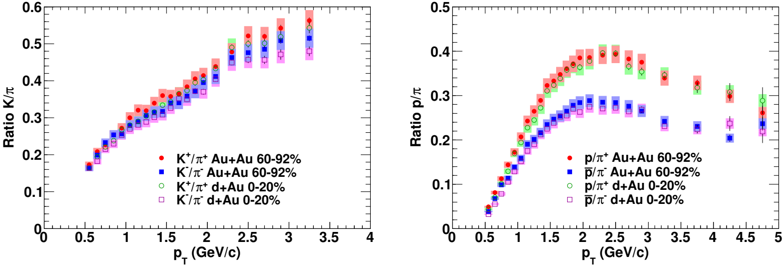
Peripheral Au+Au and central d+Au

Recall the centrality table from the beginning of the talk...

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**

- I'd like you to note the following:
- Peripheral Au+Au and central d+Au have the same $N_{collisions}$
- Peripheral Au+Au and central d+Au have the same $N_{participants}$
- As an added bonus, all 4 of these numbers are consistent within uncertainties

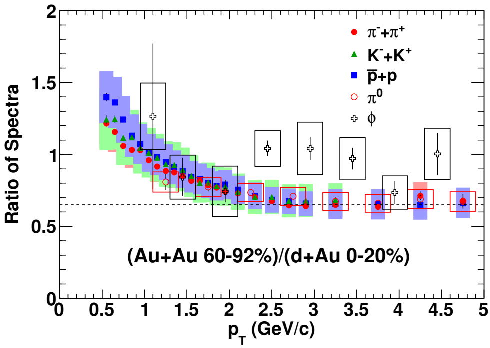
K/π and p/π in peripheral Au+Au and central d+Au



PHENIX, in preparation (R. Belmont and C. Aidala)

- 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, in preparation (R. Belmont and C. Aidala)

- Direct ratio with no scaling
- No obvious mass or type dependence at low p_T
- Identical and flat ratio above 2.5 GeV/c

What did we learn from this comparison?

- K/π and p/π ratios are identical, which is suggestive of common particle production mechanism
- The direct ratio is universal and flat at intermediate and high p_T, which is strongly suggestive of a common particle production mechanisms
- $N_{participants}$ and $N_{collisions}$ are the same for these two systems, so a lot of physical effects cancel out in the ratio, including most (probably not all) cold nuclear matter effects
- That the baryons and mesons lie on the same curve indicates that the mechanism driving the baryon enhancement is the same in both systems
- There are other issues to consider, like the rapidity shift in d+Au, nuclear PDF effects...
- Asymmetric collisions species are extremely important! Should look at existing Cu+Au data, and how about others?

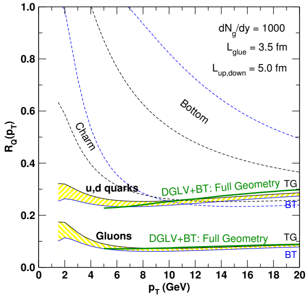
Brief summary of results

- All three antiparticle/particle ratios (π^-/π^+, K^-/K^+, $\bar{p}/p$) are completely independent of p_T, centrality, and even collisions species {more information in backup slides}
- K/π ratio has no centrality dependence in d+Au; centrality dependence in Au+Au consistent with thermal strangeness enhancement, as is enhancement of kaon R_{CP} and R_{AA} relative to the pion
- Strong baryon enhancement in Au+Au, seen in p/π, R_{CP}, and R_{AA} is indicative of hadronization by parton recombination
- Cronin enhancement in d+Au stronger for baryons than mesons, which is also consistent with the recombination picture and not with traditional explanations
- There are remarkable similarities between peripheral Au+Au and central d+Au, indicating a common particle production mechanism as well as a common baryon enhancement mechanism
- Furthermore, I think these measurements suggest it is extremely important to study asymmetric collisions species

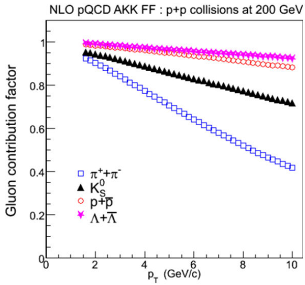
A brief look elsewhere

Let's have a brief look elsewhere...

Physics motivation: color charge effects



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

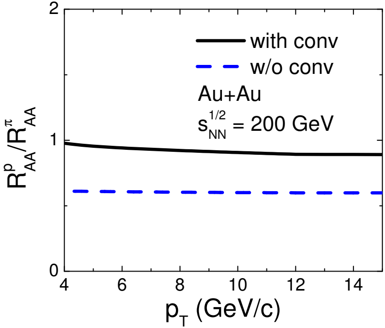


S. Albino et al, Phys. Rev. D75, 184-283 (2007)

- 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

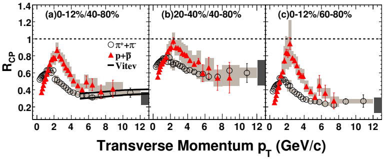
Physics motivation: flavor conversions

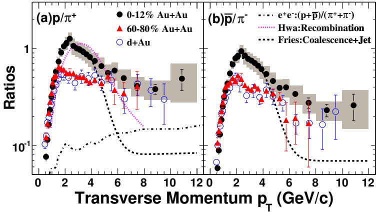
- Scattering in the QGP can change the flavor of a fast parton
  - Annihilation
    $q + \bar{q} \leftrightarrow g + g$
  - Compton scattering
    $q + g \leftrightarrow g + q$
- Differences between energy loss may be mitigated



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

Our good friends in STAR

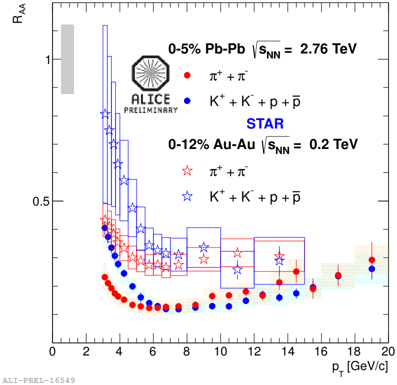


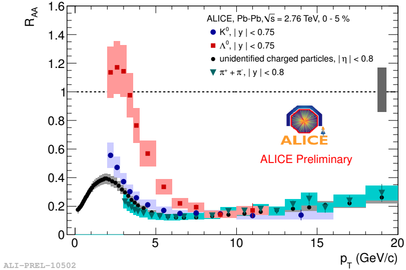


STAR, Phys. Rev. Lett. 97, 152301 (2006)

- 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



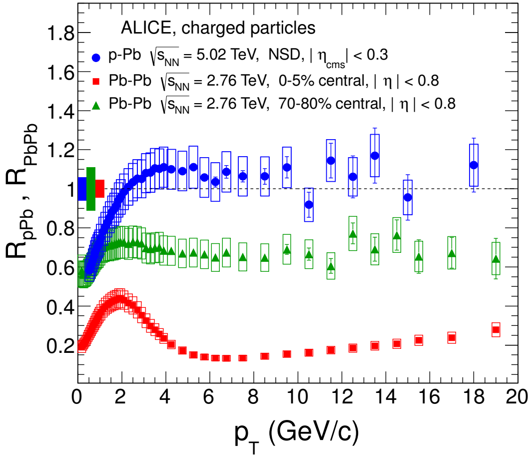


ALICE, arXiv:1208.5368

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



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 described in a single theoretical framework
- Further theoretical investigation is warranted!

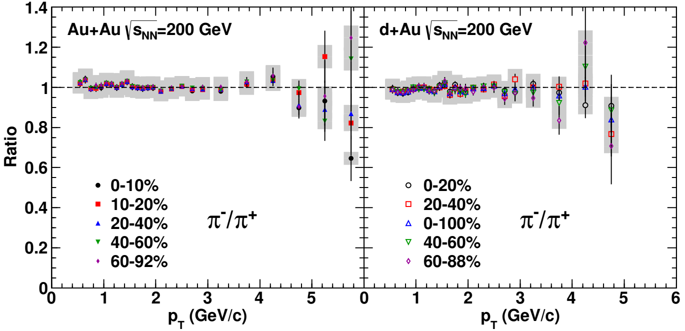
Final thoughts

- Heavy ion physics is an increasingly quantitative testing ground for QCD
- I very much look forward to theoretical investigations of the present work
- Highly detailed, precise, and systematic studies like this one are essential to furthering our understanding of the strong interaction

Extra Material

Extra Material

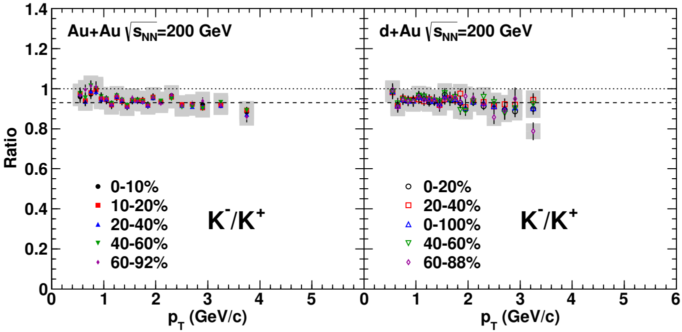
Ratio π^-/π^+



PHENIX, in preparation (R. Belmont and C. Aidala)

- 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

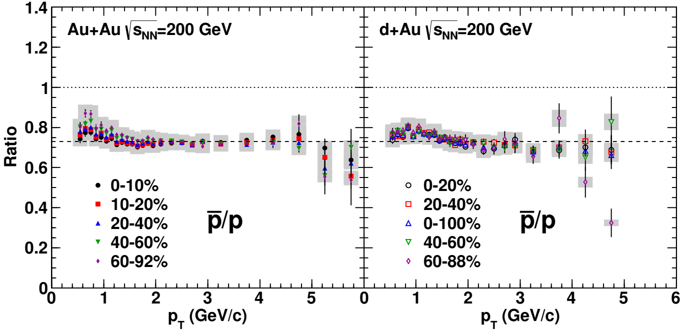
Ratio K^-/K^+



PHENIX, in preparation (R. Belmont and C. Aidala)

- 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 $p+p$

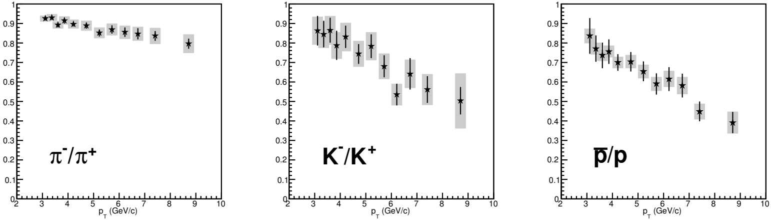
Ratio $\bar{p}/p$



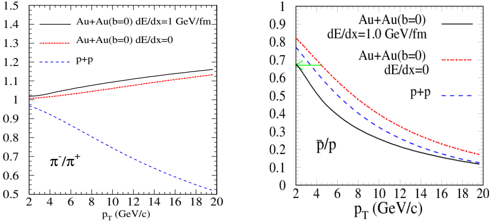
PHENIX, in preparation (R. Belmont and C. Aidala)

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

Antiparticle/particle ratios in $p+p$



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

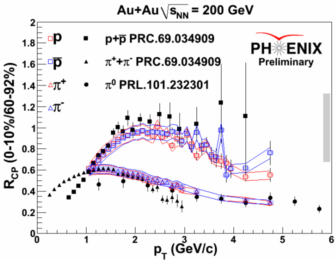


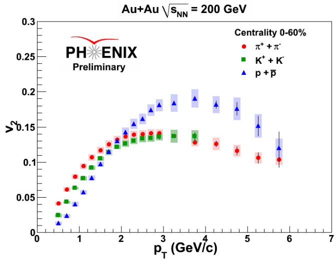
X.-N. Wang, Phys. Rev. C58, 2321 (1998)

What did we learn from antiparticle/particle ratios?

- The most boring result ever? No dependence on p_T, centrality, or collision species...
- But the result is completely 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 apparently much higher than in $p+p$

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

Can you make a QGP in $\bar{p}+p$ and $p+p$ collisions?

- In principle, yes!
- BFKL and DGLAP: lots of virtual partons, thus participants, thus possibility for collective behavior... QGP!
- E735 at Tevatron: Inconclusive—looked at multiple signals, including dN/dy and $\langle p_T \rangle$ of strange particles, HBT source radii (QM correlations), etc.
  Reference: Nucl. Phys. A544 (1992) 343-356
- CMS at LHC: Maybe—first observation of long range correlations in $p+p$ collisions, had previously been seen in heavy ions.
  Reference: JHEP 1009 (2010) 091

Some info on RHIC Runs

Run Number	Collisions species and energies
1	Au+Au 130 GeV
2	Au+Au 200 GeV, p+p 200 GeV
3	d+Au 200 GeV, p+p 200 GeV
4	Au+Au 200, 62.4 GeV
5	Cu+Cu 200, 62.4, 22.5 GeV, p+p 200 GeV
6	p+p 200, 62.4 GeV
7	Au+Au 200 GeV
8	d+Au 200 GeV, p+p 200 GeV
9	p+p 500, 200 GeV
10	Au+Au 200, 62.4, 39.0, 7,7, 5.0, 11.5 GeV
11	p+p 500, Au+Au 19.6, 200, 27.0 GeV
12	p+p 510, 200 GeV, U+U 192 GeV, Cu+Au 200 GeV, Au+Au 5.0 GeV

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

Hadronization by Recombination

For recombination in heavy ion collisions, we can use a very similar formulation as for fragmentation shown above.

For mesons:

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

For baryons:

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

Note that in place of the Wigner function for a single quark and the fragmentation function, we have a Wigner function for each of the valence quarks and the hadron wave function ϕ.

Fragmentation and Recombination

Fragmentation:

$$E\frac{d^3N_h}{d^3P} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3}\sum_{\alpha}\int dz\ z^{-3}\ w_\alpha(P/z)\ D_{\alpha\to h}(z)$$

Recombination for mesons:

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

Recombination for baryons:

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

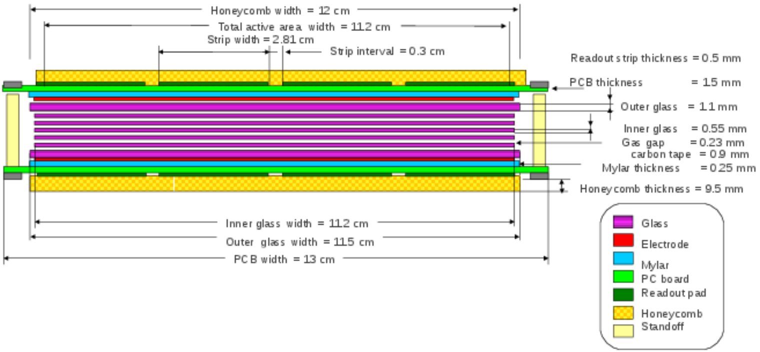
A little group theory...

- Elements of a group can be written as a linear combination of the generators: $\forall\ X \in \mathcal{G},\ X = x^a G^a \mid x^a \in \mathbb{C},\ G^a \in \mathcal{G}$
- Infinitesimal rotations: $1 + i\theta^a t^a$, with infinitesimal generators t^a.
- Arbitrary rotations: $V = e^{i\theta^a t^a}$
- Infinitesimal generators for group $SU(N)$ define associated Lie algebra $\mathfrak{su}(N)$ through commutation relation $[t^b, t^c] = if^{abc}t^a$, where f are the structure constants, with indices $a, b, c = 1, ..., N^2 - 1$.
- The t^a are $N \times N$ and form the fundamental representation, the adjoint representation can be constructed $(\hat{t}^a)_{ij} = -if^{aij}$, where $a, i, j = 1, ..., N^2 - 1$ and i and j indicate the elements of the adjoint matrix $\hat{t}^a$, meaning the matrices of the adjoint representation are $N^2 - 1 \times N^2 - 1$
- The adjoint generators obey the same commutation relation as the fundamental operators, $[\hat{t}^b, \hat{t}^c] = if^{abc}\hat{t}^a$
- Fundamental Casimir: $(t^a t^a)_{ij} = \delta_{ij} C_F \to t^a t^a = C_F$
- Adjoint Casimir: $(\hat{t}^a \hat{t}^a)_{ij} = \delta_{ij} C_A \to \hat{t}^a \hat{t}^a = C_A$
- For $SU(N)$, $\quad C_F = \frac{N^2-1}{2N}, \quad C_A = N$

About the TOFW

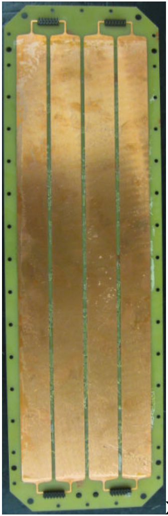
- 4 gas volumes (boxes) in two sectors (W1 north and south, W2 north and south)
- Each box has 32 chambers, with 4 strips per chamber
- There's a total of 128 chambers, 512 strips, 1024 readout channels

More about the TOFW

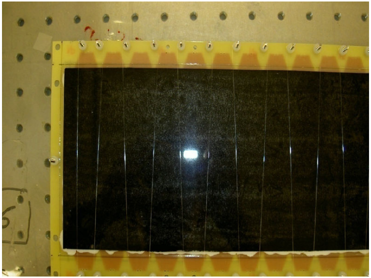


- Each chamber is an MRPC—Multi-gap Resistive Plate Chamber
- MRPCs achieve better timing resolution than single gap RPCs
- The gaps are much smaller than for a single gap RPC, which ensures a smaller charge footprint induced in the strip and therefore better timing resolution
- The smaller gap reduces the signal strength, so multiple gaps are used
- We run in avalanche mode—smaller charge footprint than streamer mode

More about the TOFW

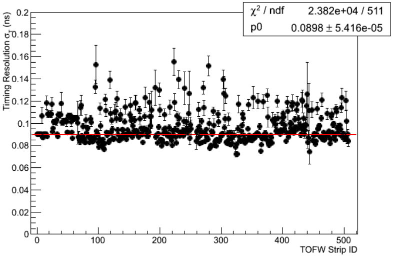


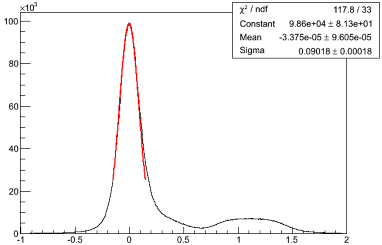
x



- Each strip is 37 cm x 2.8 cm
- Operational voltage 14 kV ($\pm$ 7 kV each electrode)
- Gas mixture—95% R134a and 5% isobutane in 2007; 92% R134a, 5% isobutane, 3% SF_6 now
- Voltage and gas mixture chosen to give good combination of high efficiency and streamer suppression

TOFW Performance





- Timing resolution in situ 90 ps (Run8 d+Au shown, better in Au+Au)
- Intrinsic timing resolution about 75 ps
- That's an average over all strips!

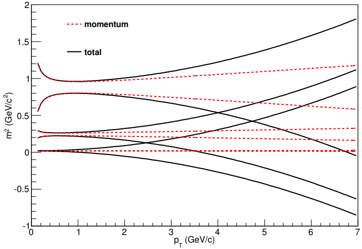
PID by TOFW

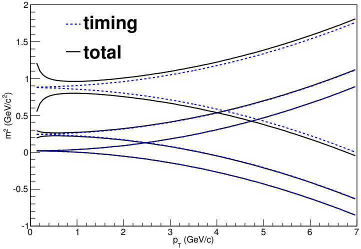
Particles are identified by their mass, and we determine mass from time-of-flight:

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

Parametrize variance of m^2 distribution:

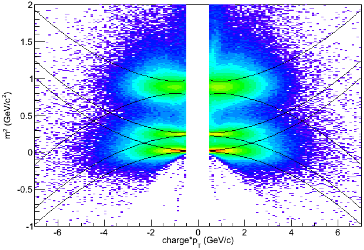
$$\sigma^2_{m^2} = \frac{\sigma^2_\alpha}{K_1^2}\left(4m^4p^2\right) + \frac{\sigma^2_{ms}}{K_1^2}\left(4m^4\left(1+\frac{m^2}{p^2}\right)\right) + \frac{\sigma_t^2c^2}{L^2}\left(4p^2\left(m^2+p^2\right)\right)$$

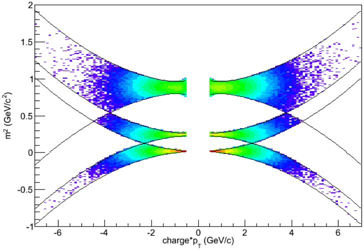




PID by TOFW

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):





Coordinates and Kinematic Variables

- Accelerator based detectors (both collider and fixed target type) have cylindrical geometry, with the z-coordinate being the direction of the beam, and the $r-\phi$ plane being center around the beam pipe
- In this system, we can restrict Lorentz boosts to be along the z-axis
- Based on this construction, any quantity defined in the $r-\phi$ plane is a Lorentz invariant
- The $r-\phi$ plane is called the transverse plane, and variable defined in this plane are called transverse variables
- The magnitude of the projection of the momentum in the transverse plane is p_T is the main kinematic variable, and other Lorentz invariant quantities cane be constructed
- The mass of a particle is a Lorentz invariant (since $p^\mu p_\mu = m^2$), so we can define the invariant transverse energy E_T and transverse mass m_T as $E_T = m_T = \sqrt{p_T^2 + m^2}$ and the invariant kinetic energy as $KE_T = \sqrt{p_T^2 + m^2} - m$
- Oftentimes E_T is used to refer to as the total transverse energy produced in a collision or in a single jet instead of referring to a single particle, while m_T usually refers to an individual particle

Coordinates and Kinematic Variables

- The Lorentz boost parameter, rapidity, is usually denoted as y
- Since we restrict boosts to be along the z-axis, the definition of rapidity is relatively simple:

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

- We can define the related variable, pseudorapidity, as

$$\eta = \frac{1}{2}\ln\frac{p+p_z}{p-p_z}$$

- Using $p_z/p = \cos\theta$ and the trigonometric identity $\tan^2\theta/2 = (1-\cos\theta)/(1+\cos\theta)$, this can be rewritten as $\eta = -\ln(\tan(\theta/2))$, where θ is the polar angle off the z-axis
- For $p_T \gg p_z$ (or equivalently $\theta \approx \pi/2$), $|\eta| \gtrsim |y|$
- Determining the rapidity requires identifying the particle, which is not always possible experimentally, which is why pseudorapidity is often useful

Coordinates and Kinematic Variables

- There are several useful relations that can be determined from the definition of rapidity, by realizing

$$
\begin{aligned}
y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} \quad &\rightarrow \quad e^{2y} = \frac{E+p_z}{E-p_z} \\
&\rightarrow \quad E(e^{2y}-1) = p_z(e^{2y}+1) \\
&\rightarrow \quad \frac{p_z}{E} = \frac{e^{2y}-1}{e^{2y}+1} = \tanh y
\end{aligned}
$$

- This allows us to write

$$
E = m_T \cosh y, \qquad p_z = m_T \sinh y
$$

- Using the fact that $\frac{dp_z}{dy} = E$ and employing the Jacobi determinant for cylindrical coordinates in momentum space, we can rewrite the invariant yield as

$$
E\frac{d^3N}{dp^3} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T\,dy}
$$

Characteristic time

Crossing time

$\sqrt{s_{NN}}$ (GeV)	γ	τ (fm)
200.00	106.38	0.13
100.00	53.19	0.26
62.40	33.19	0.42
27.40	14.57	0.96
17.20	9.15	1.53
12.30	6.54	2.13
8.80	4.68	2.98
7.60	4.04	3.45
6.30	3.35	4.17
5.00	2.66	5.25