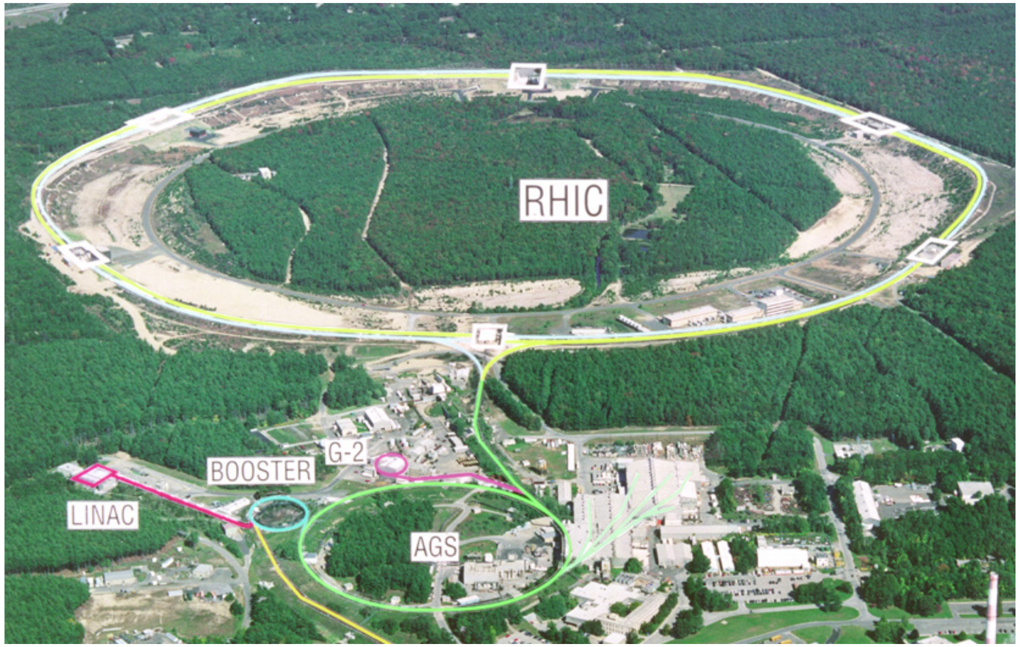
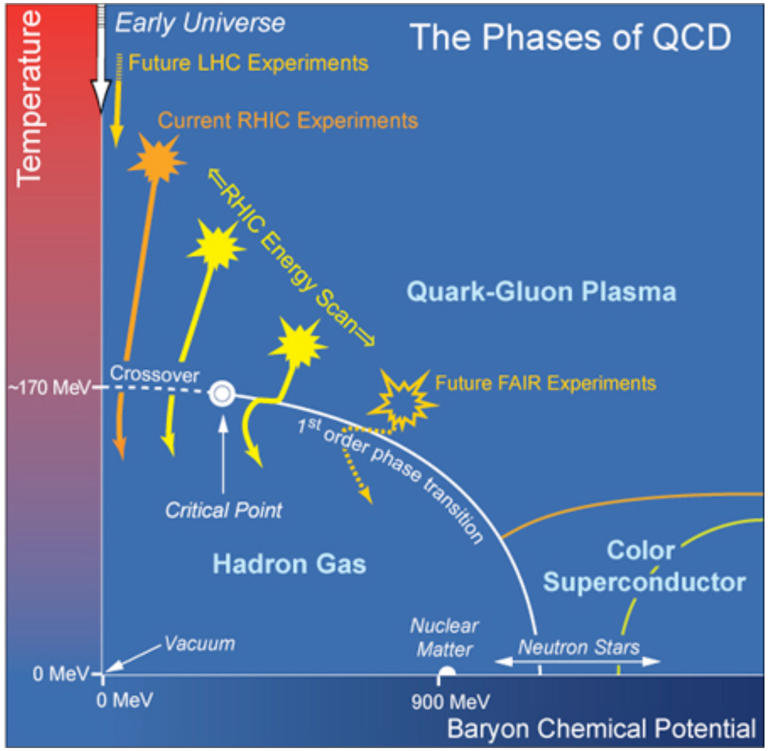
Proving Quark Gluon Plasma via Baryon Production at RHIC





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Outline

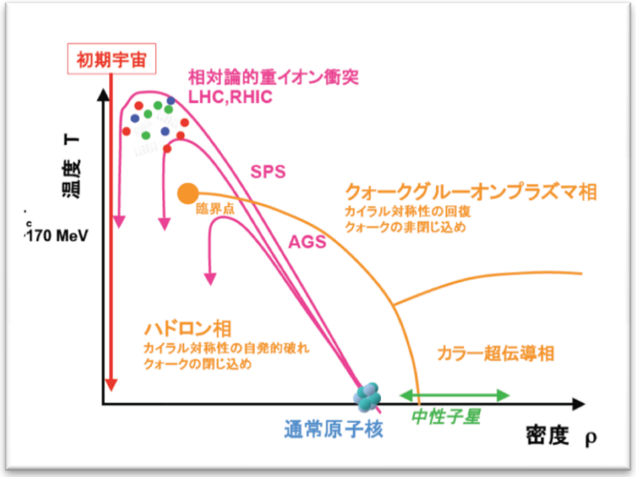
1. Introduction
2. Overview of bulk properties at RHIC
3. Systematic study of baryon enhancement
4. What’s the origin of baryon enhancement?
5. Exploring the QCD phase diagram at RHIC
6. Summary

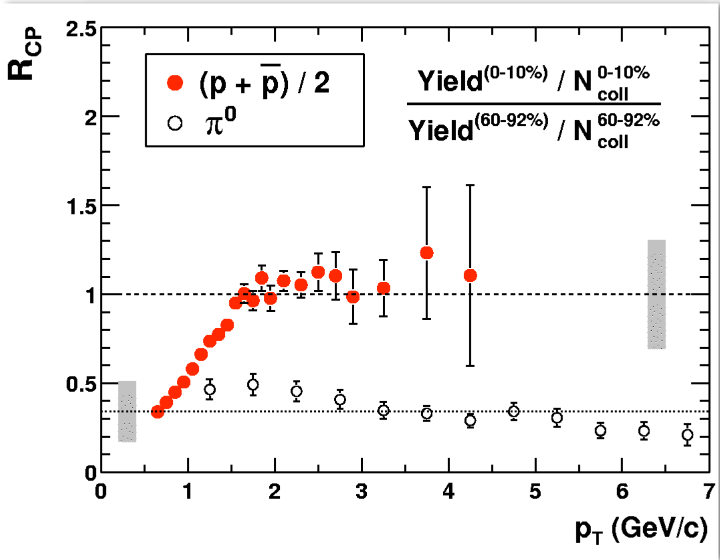
1. INTRODUCTION

Why baryons* ?

(* protons and antiprotons in this talk)

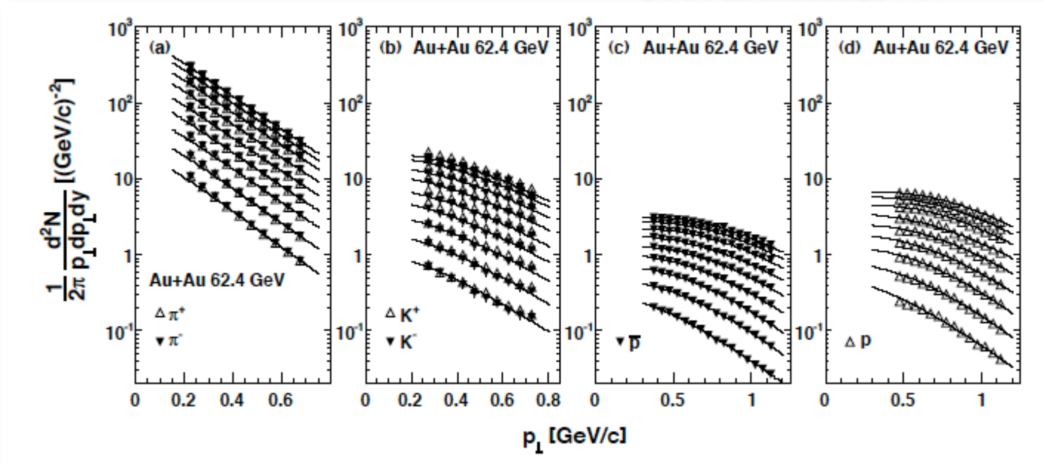
- Heavier mass than the light mesons, sensitive to the **collective phenomena**, such as a radial flow.
- Sensitive to the **baryo-chemical property** of the matter.
- Different number of **constituent quarks** from that for mesons, test of recombination models.





PHENIX: PRL 91, 172301 (2003), PRC 69, 034909 (2004)

STAR: arXiv:0808.2041v1



A lots of data and publications on baryons from RHIC experiments; 1
(spectra, yields, and jet correlations)

- **BRAHMS**
  - Nuclear Stopping in Au+Au Collisions at $\sqrt{s_{NN}}$ = *200 GeV, PRL 93,* 102301 (2004).
- **PHENIX**
  - Scaling Properties of Proton and Antiproton Production in $\sqrt{s_{NN}}$ = *200 GeV Au Au Collisions, PRL 91, 172301 (2003). [TC]*
  - Identified charged particle spectra and yields in Au+Au collisions at $\sqrt{s_{NN}}$=*200 GeV, PRC 69, 034909 (2004). [TC]*
  - Nuclear effects on hadron production in *d + Au collisions at* $\sqrt{s_{NN}}$ = *200 GeV revealed by* comparison with *p + p data, PRC 74, 024904 (2006). [(TC)]*
  - Jet structure of baryon excess in Au+Au collisions at $\sqrt{s_{NN}}$ =*200 GeV, PRC 71, 051902 (R) (2005).*
  - Particle-Species Dependent Modification of Jet-Induced Correlations in Au+Au Collisions at $\sqrt{s_{NN}}$ =*200 GeV, PRL 101, 082301 (2008).*
  - Correlated production of *p and pbar in Au+ Au collisions* at $\sqrt{s_{NN}}$ = *200 GeV, PLB 649 (2007) 359-369.*
  - *Au+Au 62.4 GeV (preliminary) [TC], Cu+Cu 200 GeV (preliminary),*
  - *Cu+Cu 22.5, 62.4 GeV (preliminary) [TC], p+p 62.4 GeV (preliminary) [TC]*
  - *p+p 200 GeV (new data)*

to be published before QM09 (hopefully)

* note: not the complete list.

A lots of data and publications on baryons from RHIC experiments; 2

(spectra, yields, and jet correlations)

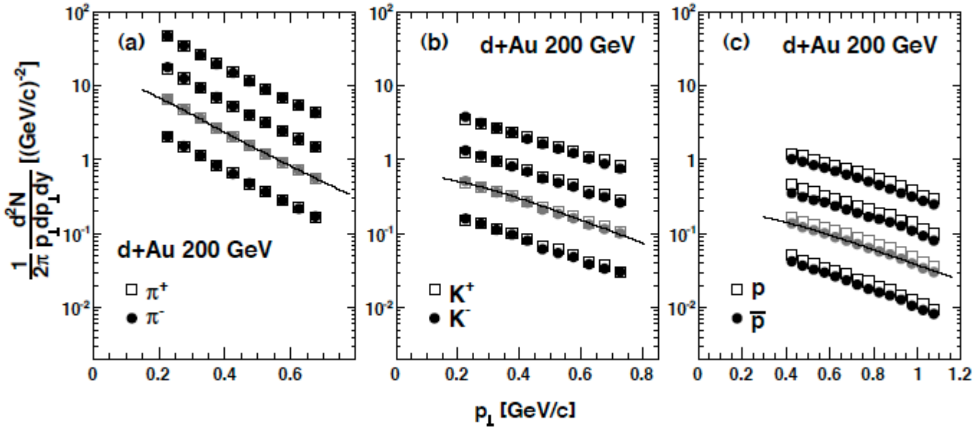
- **PHOBOS**
  - Identified hadron transverse momentum spectra in Au+Au collisions at $\sqrt{s_{NN}}$ = *62.4 GeV, PRC 75, 024910 (2007).*
- **STAR**
  - Identified Baryon and Meson Distributions at Large Transverse Momenta from Au+Au Collisions at $\sqrt{s_{NN}}$ = *200 GeV, PRL 97, 152301 (2006).*
  - Energy dependence of $\pi^{\pm}$, p and p-bar transverse momentum spectra for Au+Au collisions at $\sqrt{s_{NN}}$ = 62.4 and 200 GeV, arXiv:nucl-ex/0703040.
  - Identified hadron spectra at large transverse momentum in *p + p and d + Au collisions at* $\sqrt{s_{NN}}$ = *200 GeV, PLB 637 (2006) 161-169.*
  - Systematic Measurements of Identified Particle Spectra in pp, d+Au and Au+Au Collisions from STAR, arXiv:0808.2041.

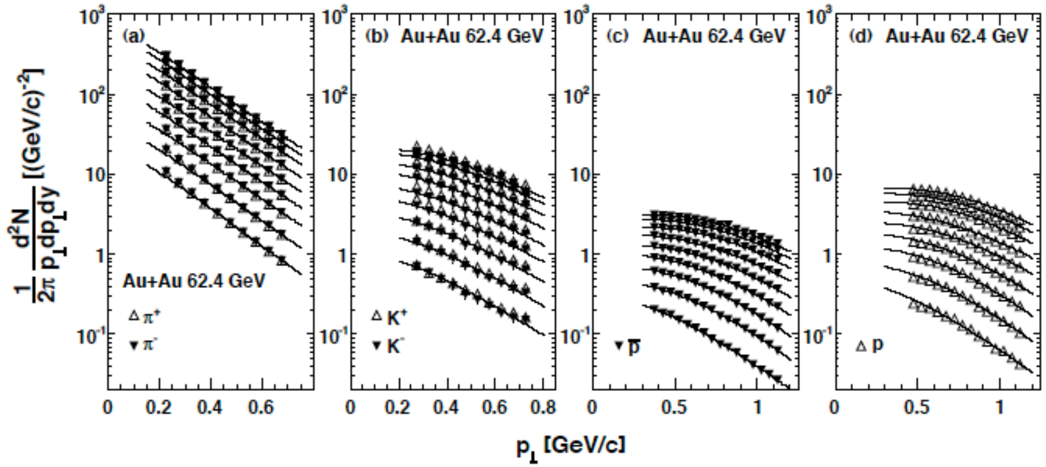
* note: not the complete list.

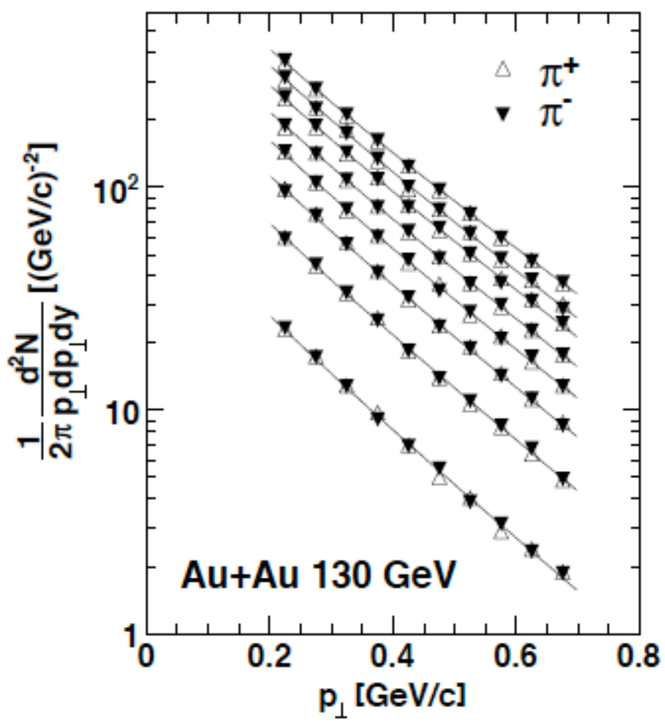
A recent STAR publication

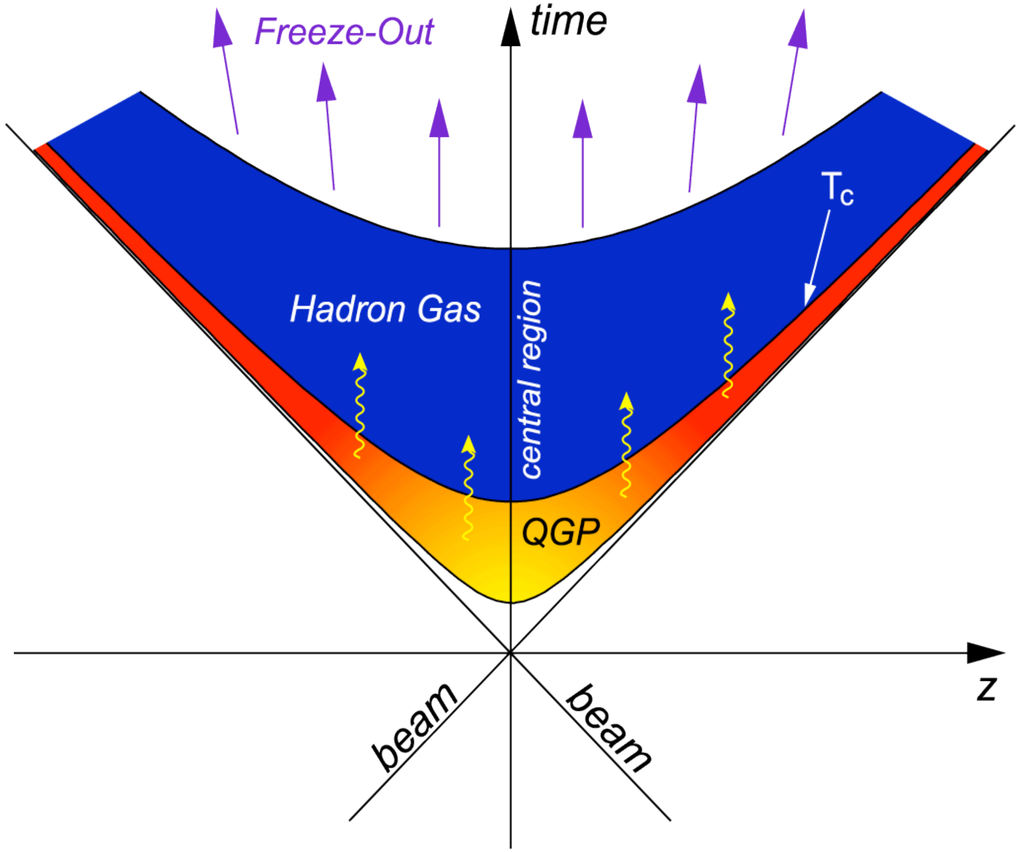
(systematic study of PID spectra in p+p (200 GeV), d+Au (200 GeV), Au+Au (62, 130, 200 GeV), arXiv:0808.2041)

- $\pi^{\pm}$, $K^{\pm}$, p, pbar p_T spectra (low p_T region only, dE/dx by TPC).
- A nice full paper (60 pages)!









2. BULK PROPERTIES AT RHIC

What are the bulk properties (EOS)?

- Energy density (ε)
- Temperature (T):
  - critical temperature (T_c), initial temperature (T_{ini}), chemical freeze-out temperature (T_{ch}), kinetic freeze-out temperature (T_{kin})
- Chemical potential (μ):
  - baryon chemical potential (μ_B), strangeness chemical potential (μ_s), strangeness suppression factor (γ_s)
- Collective flow velocity ($\langle\beta_T\rangle$)
- Pressure gradient (ΔP), particle emission anisotropy (v_2)
- Particle multiplicity (dN/dy, N)
- Transverse energy (dE_T/dy, E_T)
- Transverse momentum distribution (Ed^3N/dp^3)
- Particle abundance and ratio
- Average transverse momentum ($\langle p_T\rangle$)
- HBT radii (R_{out}, R_{side}, R_{long}, λ)
- Velocity of sound (v_s)
- Shear viscosity – entropy ratio (η/s)

….

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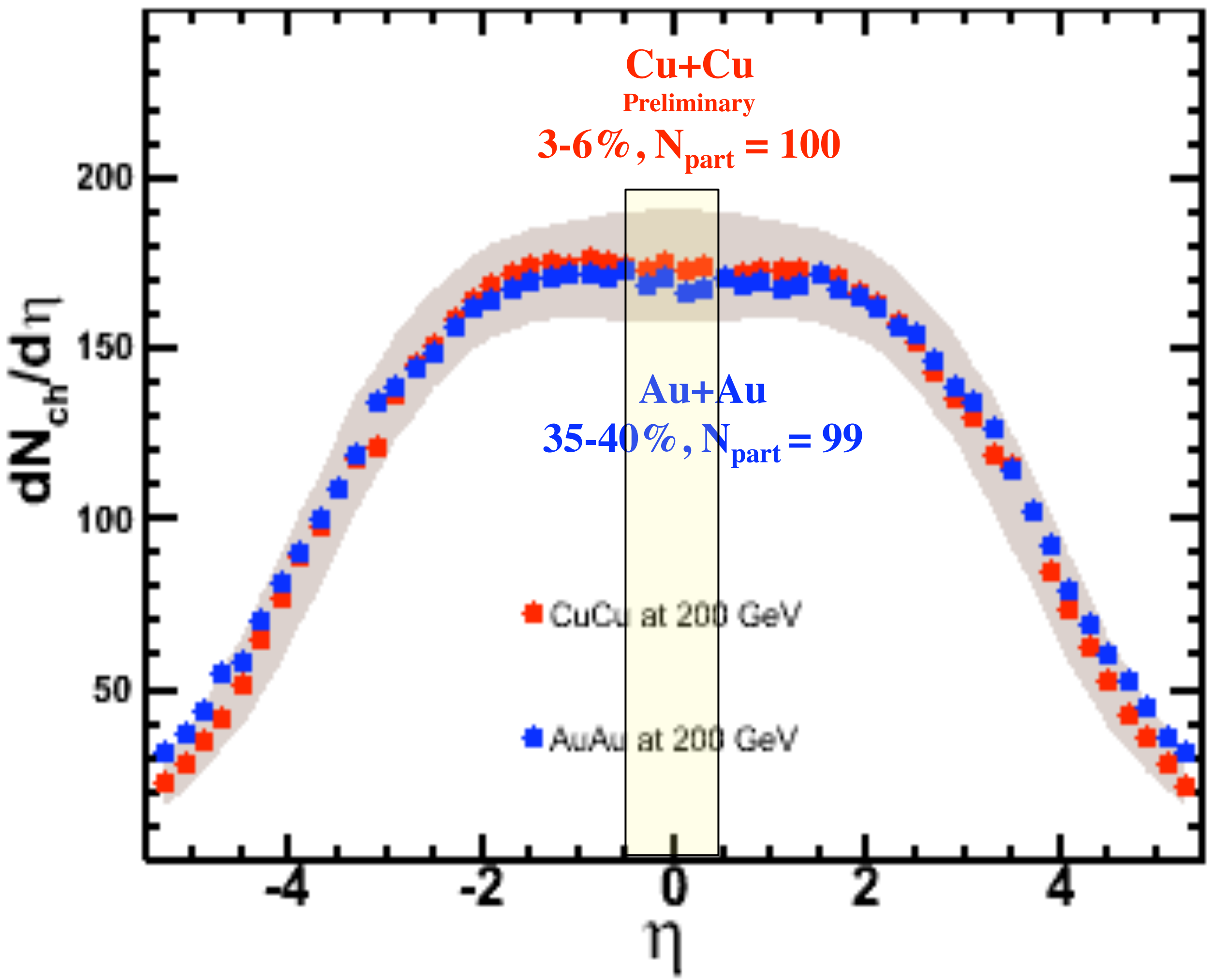
…

- **red:** directly measured by p_T spectra
- **pink:** indirectly measured by p_T spectra

How the bulk properties change as a function of centrality, system and beam energy?

Charged particle multiplicity at RHIC

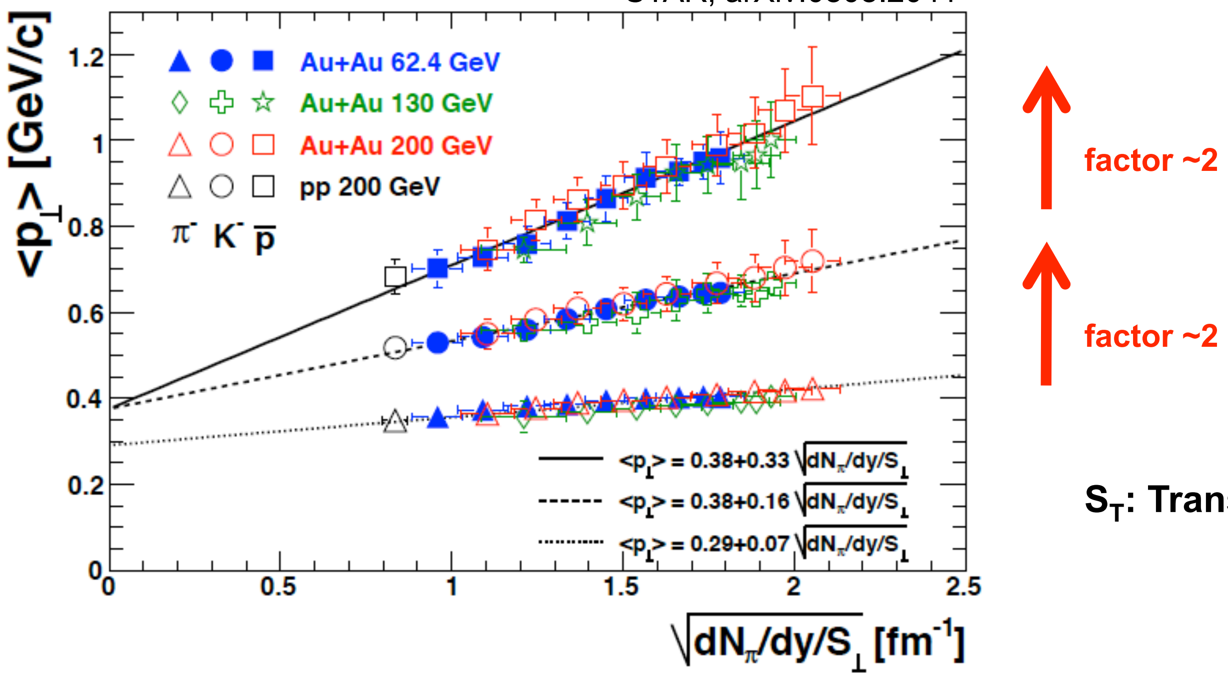
PHOBOS

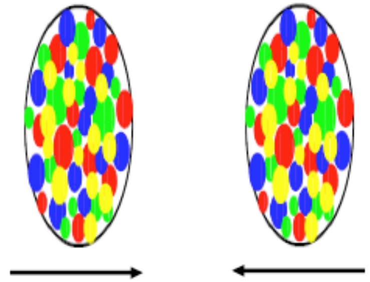


- Same number of participants, ~same number of charged particle density at RHIC.
- Focus at the mid-rapidity to study the multiplicity scaling of bulk properties.

Average p_T vs. N_{ch}

STAR, arXiv:0808.2041



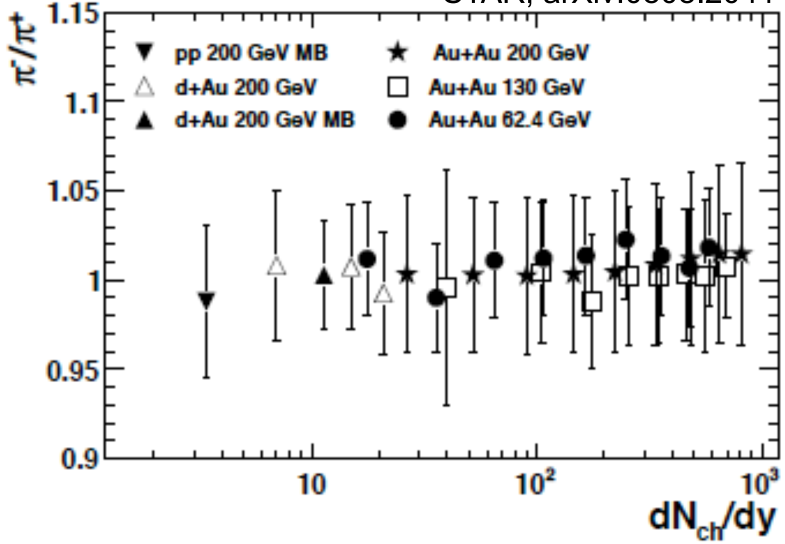


S_T: Transverse overlap area [fm^2]

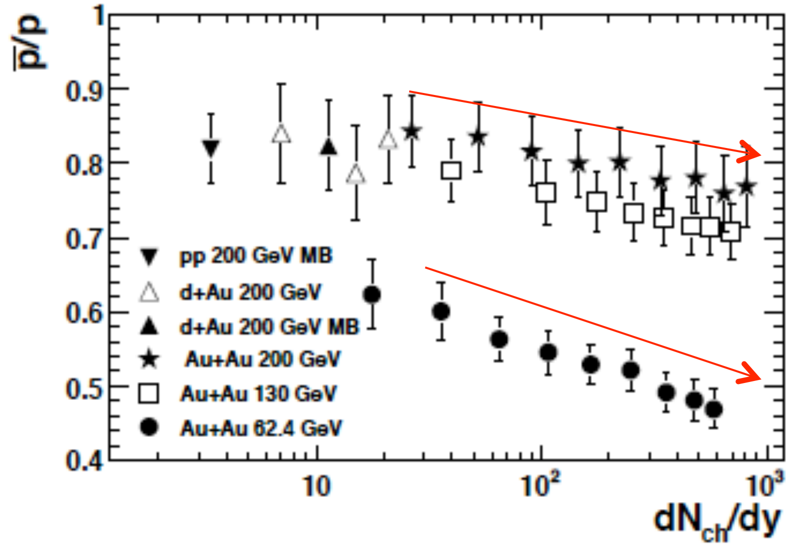
- $<p_T>$ scales with $\sqrt{((dN_\pi/dy)/S)}$, p+p 200 GeV, Au+Au 62.4, 130, 200 GeV data.
- Suggests that the kinetic freeze-out properties in Au+Au collisions are **energy independent**.
- **CGC (gluon saturation)**: small x gluons overlap and recombine, reducing the total number of gluons and increasing their transverse energy.
  - **Predicts a lower particle multiplicity and larger $<p_T>$.**
  - In CGC, $<p_T>$ scales with $\sqrt{((dN_\pi/dy)/S)}$.
  - Data is consistent with CGC picture.

Antiparticle-to-Particle Ratios vs. N_{ch}

STAR, arXiv:0808.2041



STAR, arXiv:0808.2041



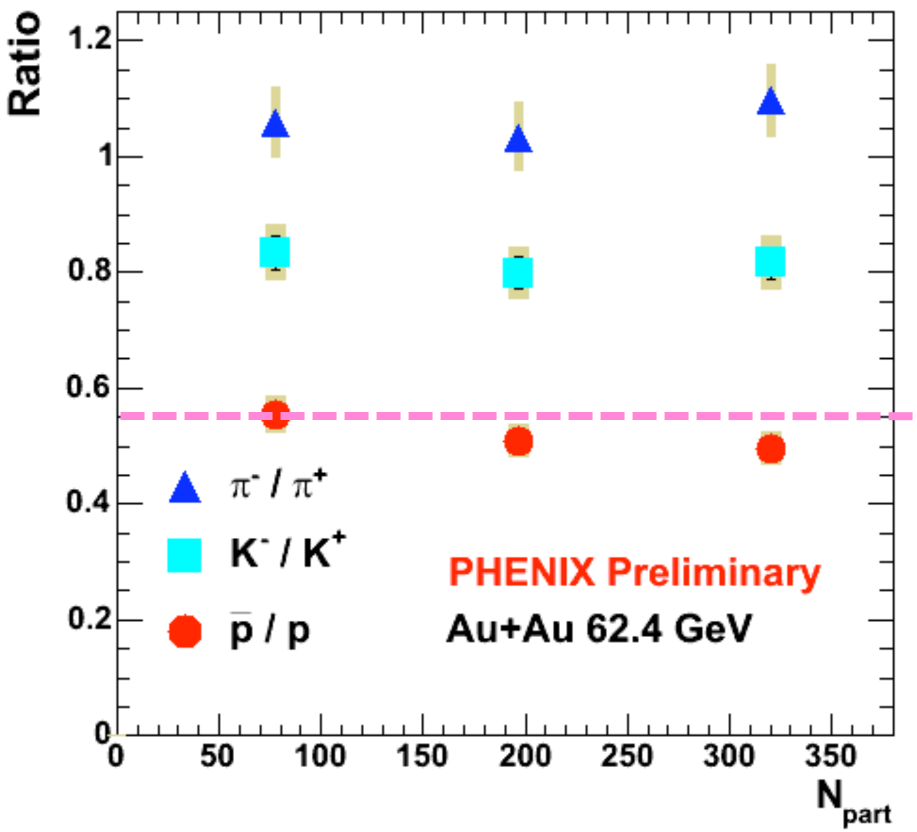
π^-/π^+: Flat and unity.

pbar/p:

- A slight decrease with centrality (130, 200 GeV)
- Considerable drop with centrality (62 GeV)

→ indicating that **larger baryon stopping in central collisions.**

PHENIX 62.4 GeV Au+Au



Hum…

pbar/p ratio: seems decreasing with N_{part} in PHENIX data too.

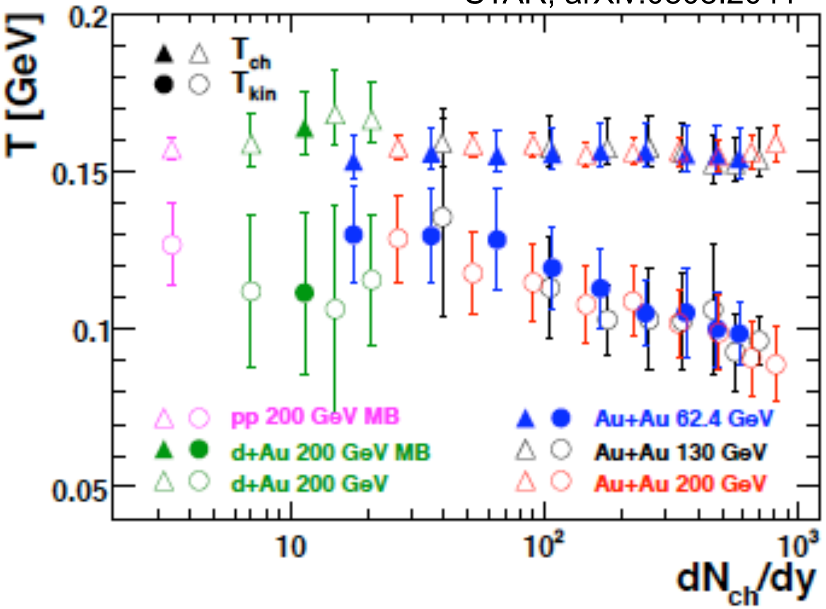
DNP2004 (TC)

Bulk properties vs. N_{ch} (1)

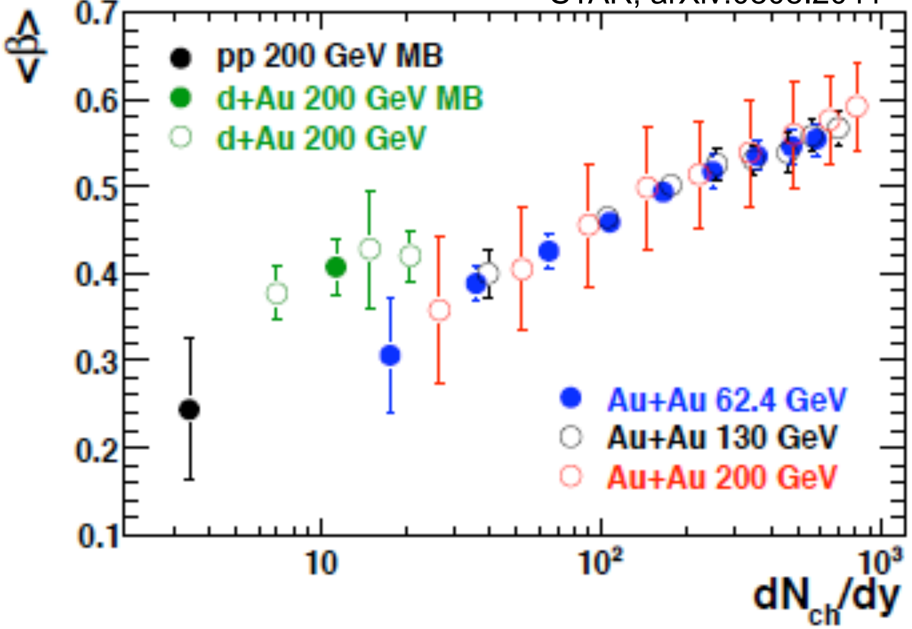
T_{ch}, T_{kin}

$\langle \beta_T \rangle$

STAR, arXiv:0808.2041



STAR, arXiv:0808.2041



T_{ch}: constant with dN_{ch}/dy.
close to the lattice QCD: Tc ~160 MeV.
universality at RHIC energies.
T_{kin}: decreasing with dN_{ch}/dy.
same trend for all systems at RHIC (with dN_{ch}/dy)
indicating strong expansion and cooling?

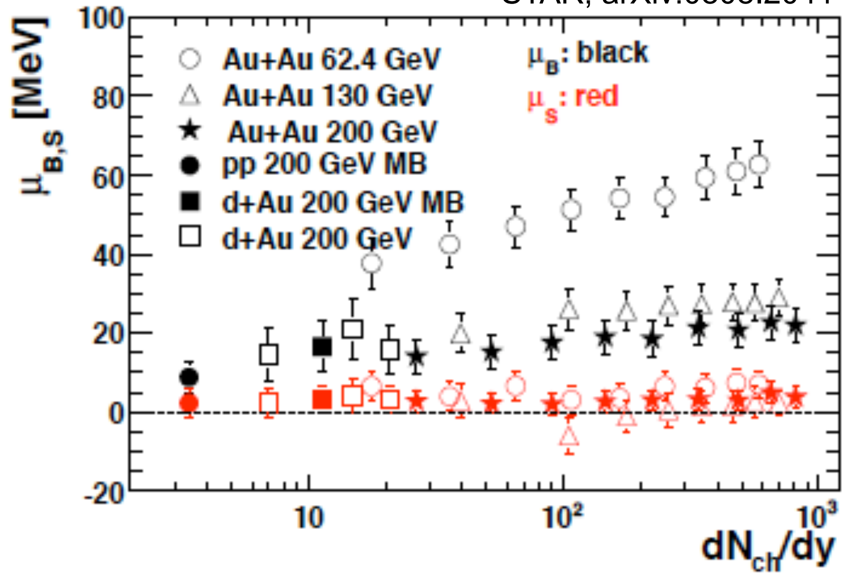
$\langle\beta\rangle$: incleasing with dN_{ch}/dy.

Bulk properties vs. N_{ch} (2)

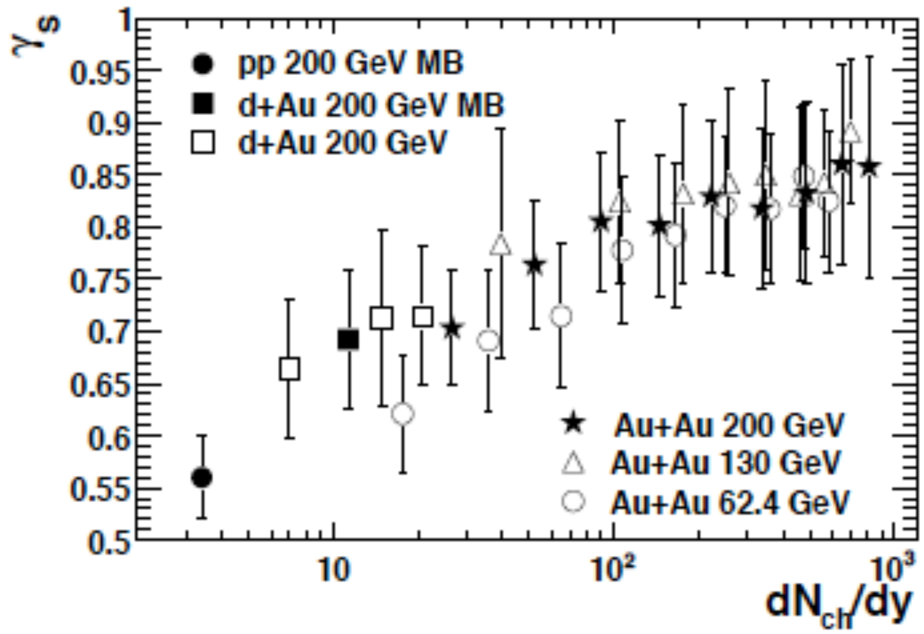
$\mu_{B,s}$

γ_s

STAR, arXiv:0808.2041



STAR, arXiv:0808.2041



- μ_B: finite value, weak centrality dependence (baryon stopping at central)
- μ_s: close to zero.

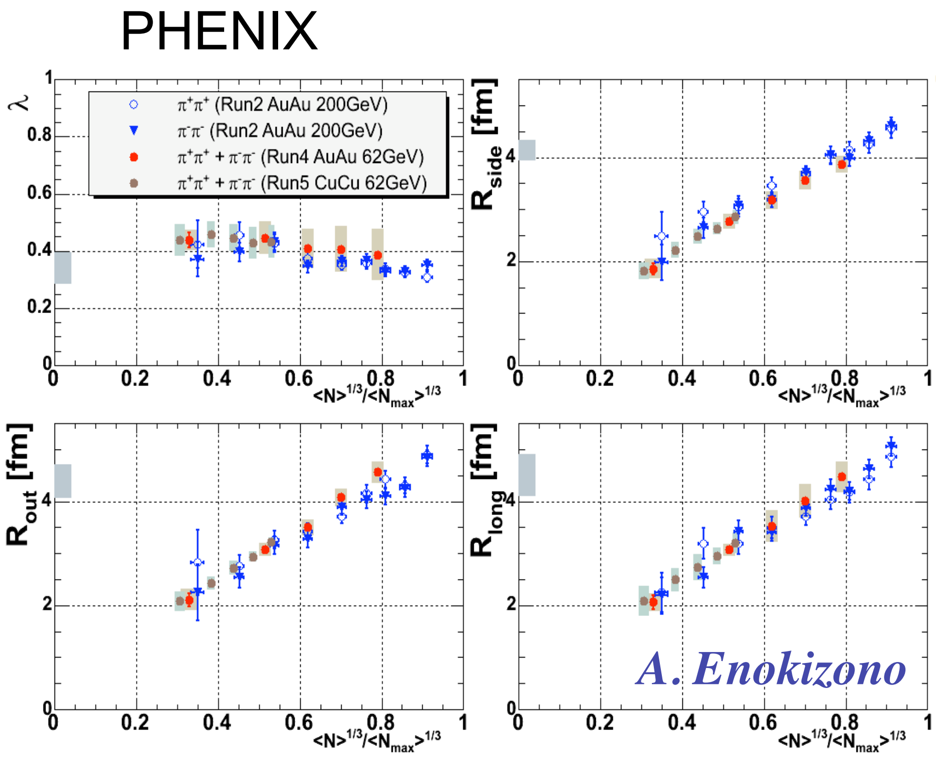
- γ_s: approaching to unity with dN_{ch}/dy.

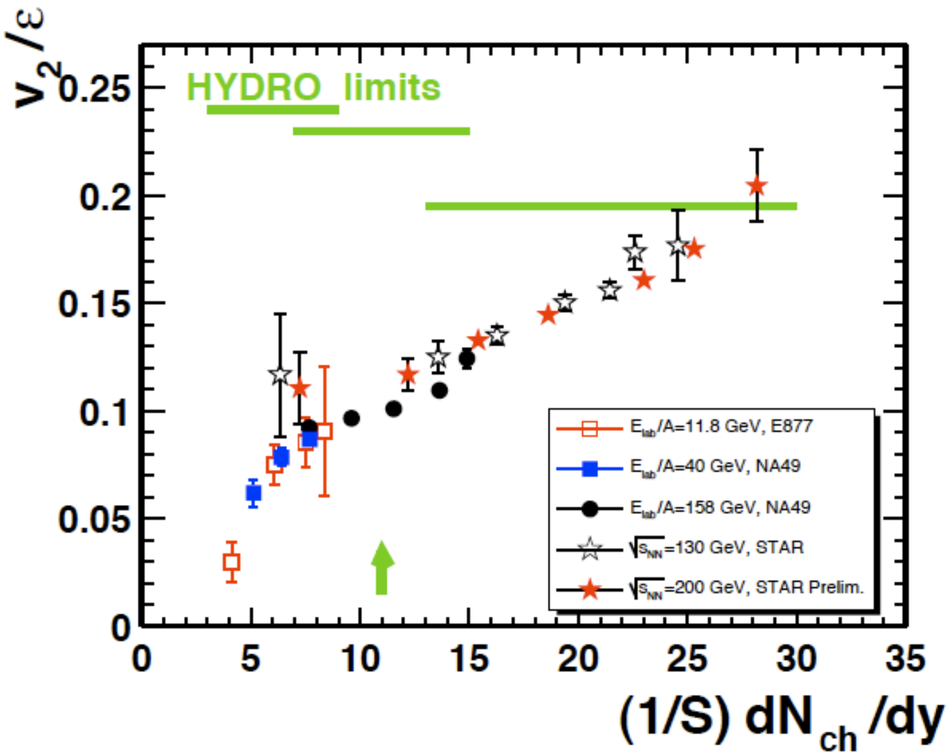
Strangeness production is strongly suppressed in p+p, dAu, peripheral Au+Au. In central Au+Au, implying that strangeness is as equally equilibrated as light quarks.

Bulk properties vs. N_{ch} (3)

HBT

v_2/ε

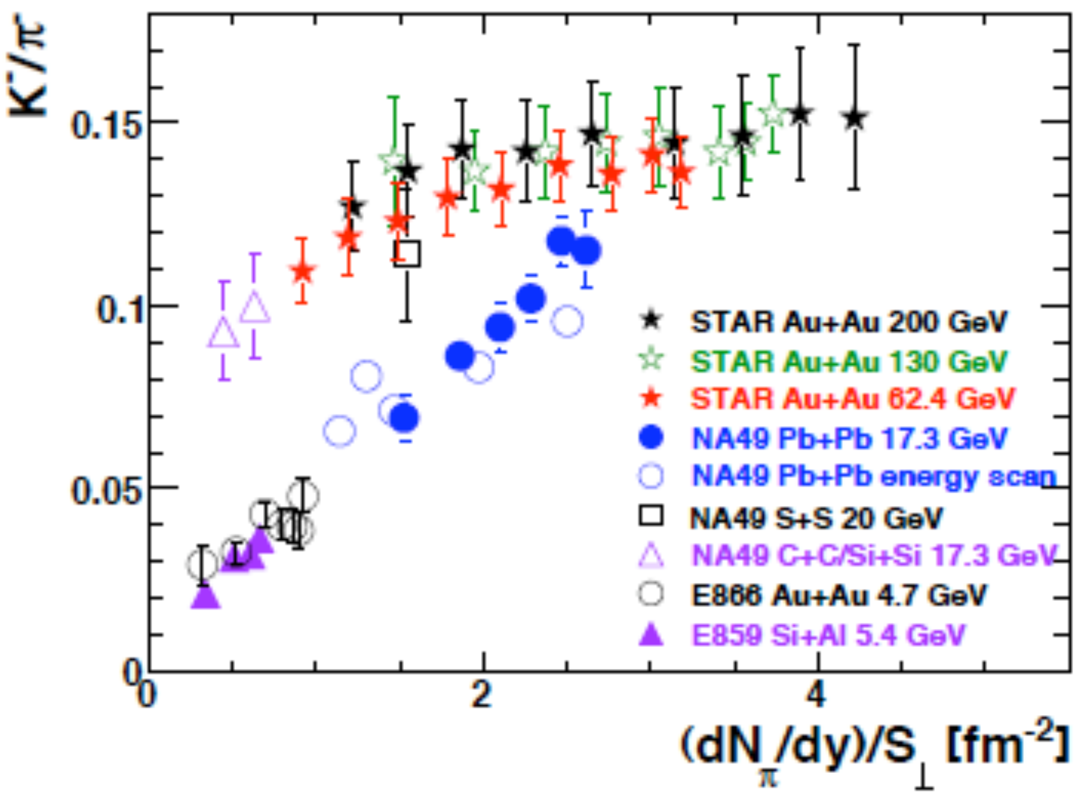




Bulk properties vs. N_{ch} (4)

K^-/π^-

STAR, arXiv:0808.2041



"Only" N_{ch} (or initial energy density) determines the bulk properties at RHIC?

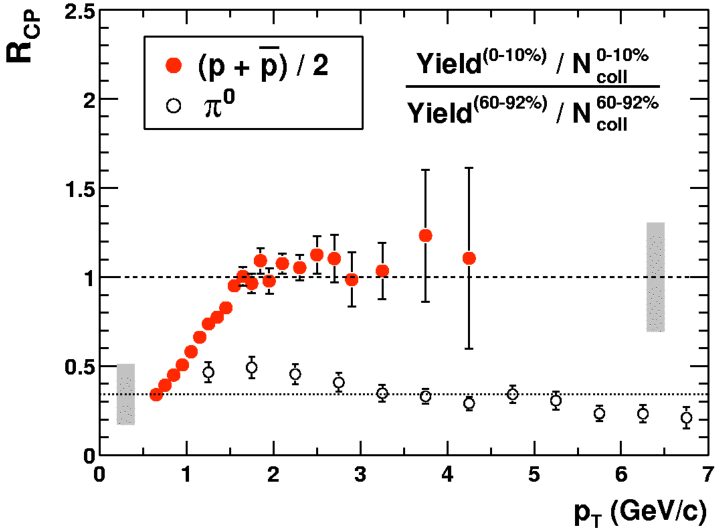
Run	Year	Species	$\sqrt{s_{NN}}$ (GeV)	$\int L\,dt$	N_{Tot}	p+p Equivalent	Data Size
01	2000	Au+Au	130	1 μb^{-1}	10M	0.04 pb^{-1}	3 TB
02	2001/2002	Au+Au	200	24 μb^{-1}	170M	1.0 pb^{-1}	10 TB
		p+p	200	0.15 pb^{-1}	3.7G	0.15 pb^{-1}	20 TB
03	2002/2003	d+Au	200	2.74			
		p+p	200	0.35			
04	2004/2004	Au+Au	200	241			
		Au+Au	62.4	9			
05	2004/2005	Cu+Cu	200	3			
		Cu+Cu	62.4	0.19			
		Cu+Cu	22.5	2.7			
		p+p	200	3.8			
06	2006	p+p	200	10.7			
		p+p	62.4	0.1			
07	2007	Au+Au	200	0.813			
08	2008	d+Au	200	80			
		p+p	200	5.2			

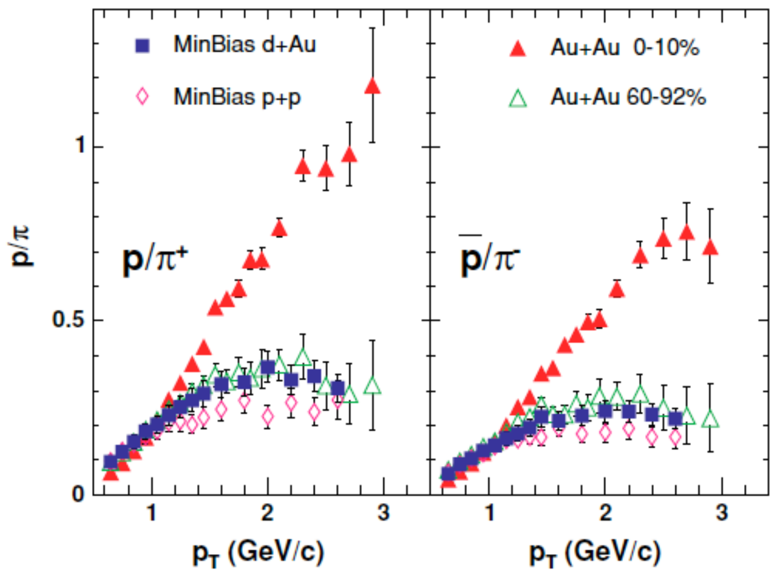
Fiscal Year	Colliding Beam Species/Energy	Comments
2009	500 GeV p+p	Assuming ~April 1 start, about 5-6 physics weeks to commission collisions, work on polarization & luminosity and obtain first W production signal to meet RIKEN milestone
2010	200 GeV p+p	~12 physics weeks to complete 200 GeV A_{LL} measurements – could be swapped with 500 GeV Run 9 if Run 9 can start by March 1, 2009; STAR DAQ1000 fully operational
	200 GeV Au+Au	9-10 physics weeks with PHENIX HBD, STAR DAQ1000 & TOF permits low-mass dilepton response map and 1st collision test of transverse stochastic cooling (one ring)
2011	Au+Au at assorted low E	1st energy scan for critical point search, using top-off mode for luminosity improvement – energies and focus signals to be decided; commission PHENIX VTX (at least prototype)
	200 GeV U+U	1st U+U run with EBIS, to increase energy density coverage
2012	500 GeV p+p	1st long 500 GeV p+p run, with PHENIX muon trigger and STAR FGT upgrades, to reach ~100 pb^{-1} for substantial statistics on W production and ΔG measurements
	200 GeV Au+Au	Long run with full stochastic cooling, PHENIX VTX and prototype STAR HFT installed; focus on RHIC-II goals: heavy flavor, γ-jet, quarkonium, multi-particle correlations
2013	500 GeV p+p	Reach ~300 pb^{-1} to address 2013 DOE performance milestone on W production
	200 GeV Au+Au or 2nd low-E scan	To be determined from 1st low-E scan and 1st upgraded luminosity runs, progress on low-E e-cooling, and on installation of PHENIX FVTX and NCC and full STAR HFT
2014	200 GeV Au+Au or 2nd low-E scan	Run option not chosen for 2013 run – low-E scan addresses 2015 DOE milestone on critical point, full-E run addresses 2014 (γ-jet) and 2016 (identified heavy flavor) milestones. Proof of principle test of coherent electron cooling.
	200 GeV p+p	Address 2015 DOE performance milestone on transverse SSA for γ-jet; reference data with new detector subsystems; test e-lenses for p+p beam-beam tune spread reduction

3. SYSTEMATIC STUDY OF BARYON ENHANCEMENT

Baryon enhancement at RHIC

PHENIX: PRL 91, 172301 (2003), PRC 69, 034909 (2004),
PRC 74, 024904 (2006)

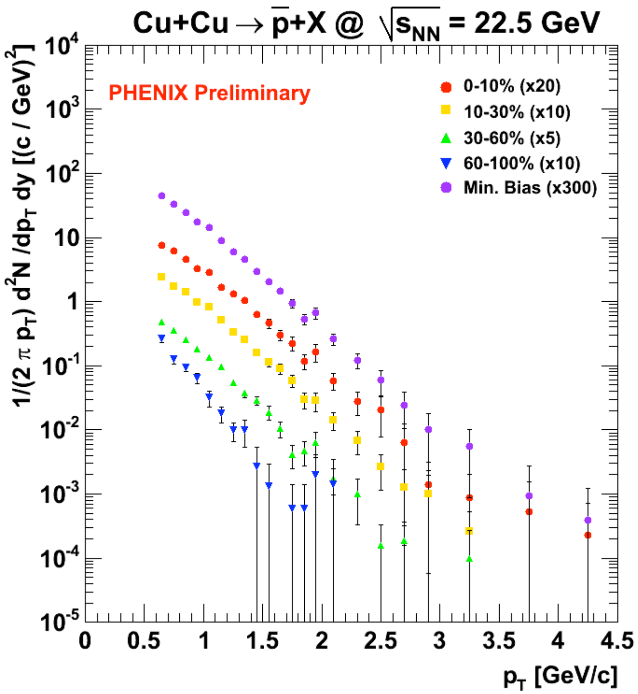


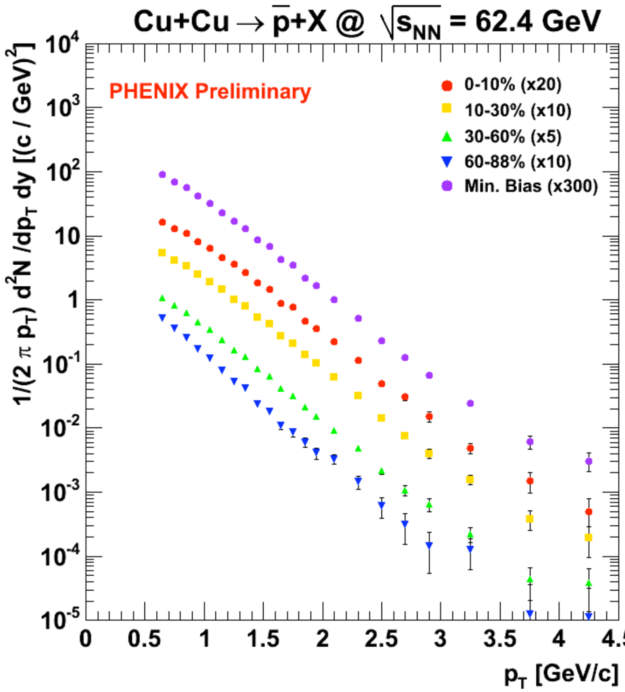


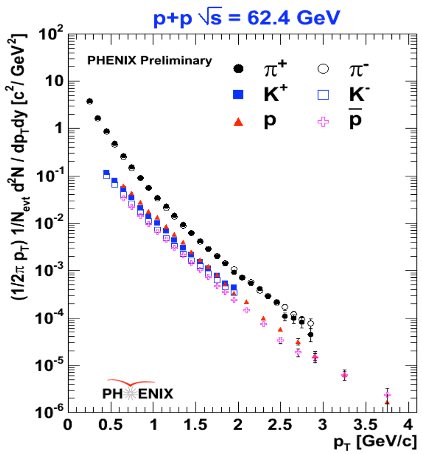
In Au+Au $\sqrt{s_{NN}}$ = 200 GeV central collisions:

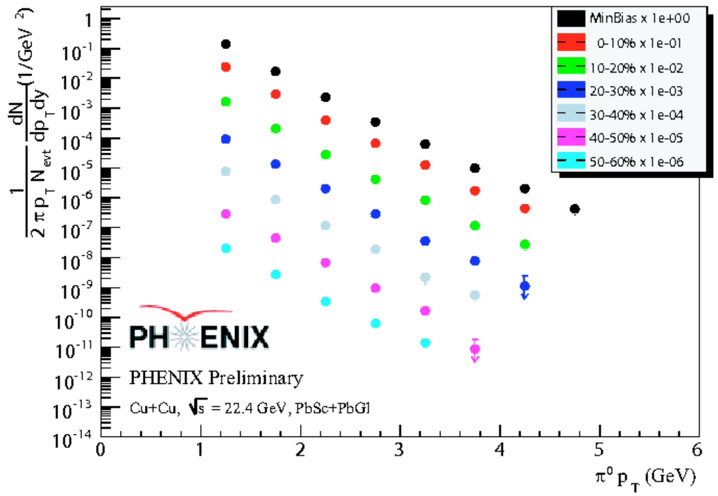
- R_{CP} (or R_{AA})
  - Pions: Strong suppression of yields above p_T ~ 2 GeV/c, due to jet quenching.
  - **Protons: No suppression at intermediate p_T (2-5 GeV/c).**
- p/π and pbar/π ratios
  - **Factor ~3 more (anti) protons** than pions at intermediate p_T (2-5 GeV/c).
  - Strong centrality dependence.

Systematic study of PID spectra:
Au+Au, Cu+Cu, p+p at $\sqrt{s_{NN}}$ = 22.5, 62.4, 200 GeV



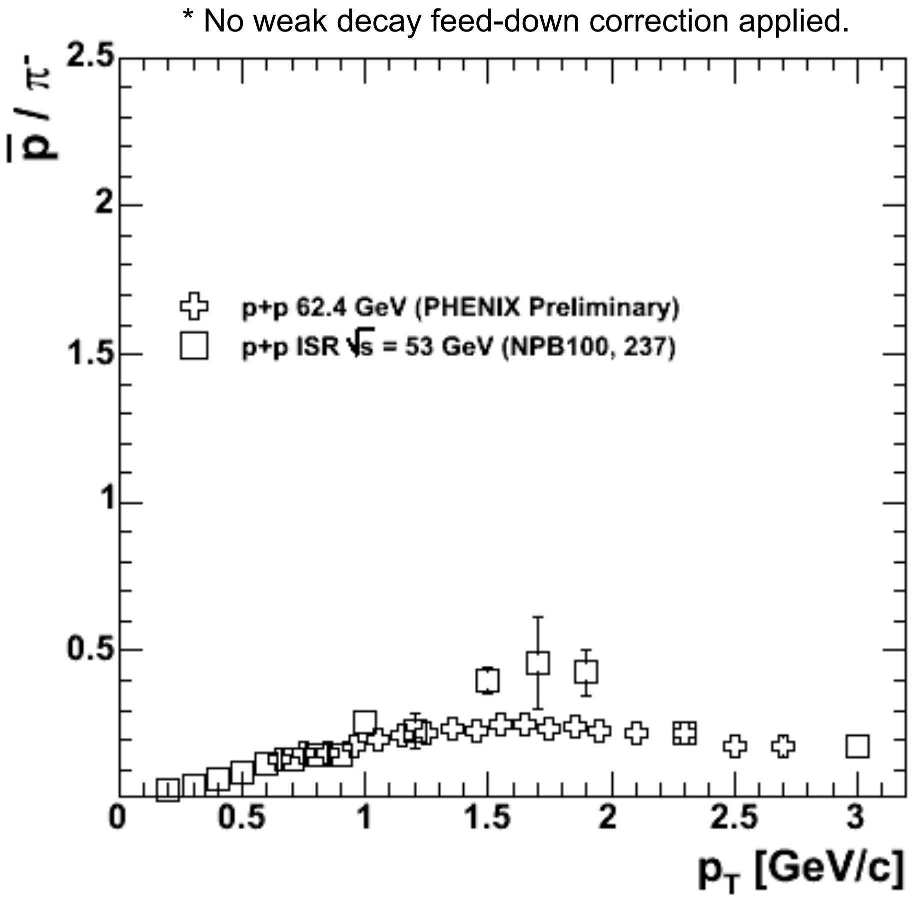






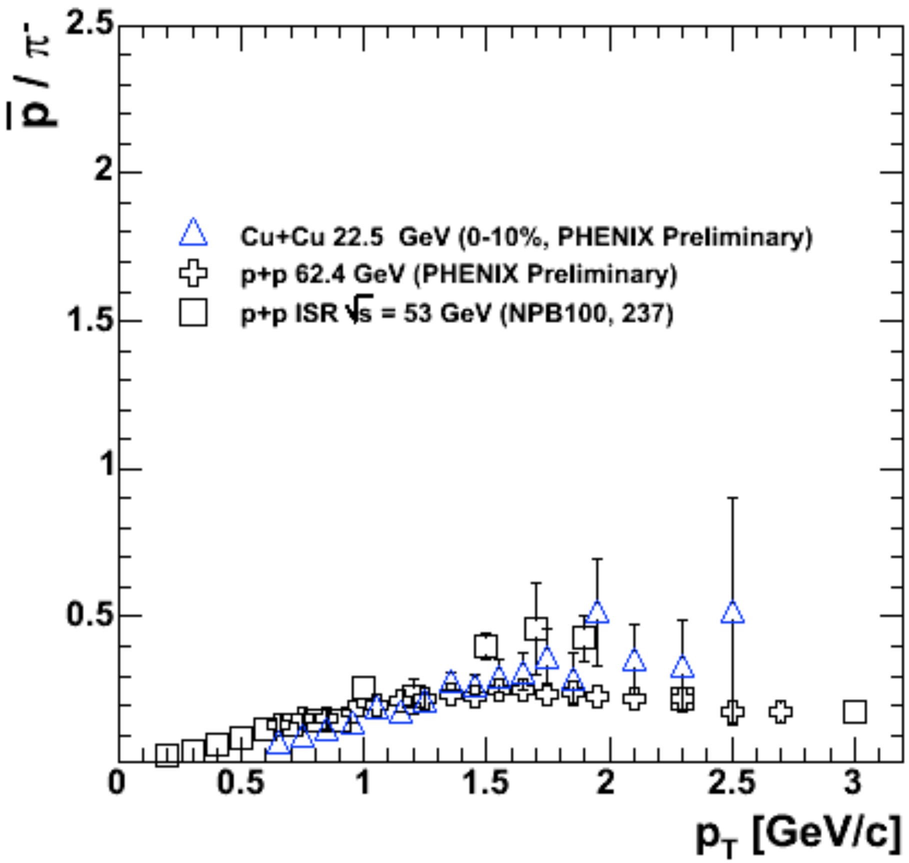
π^0 p_T spectra
in Cu+Cu 22.5 GeV

√s dep. of pbar/π⁻ ratio (central)



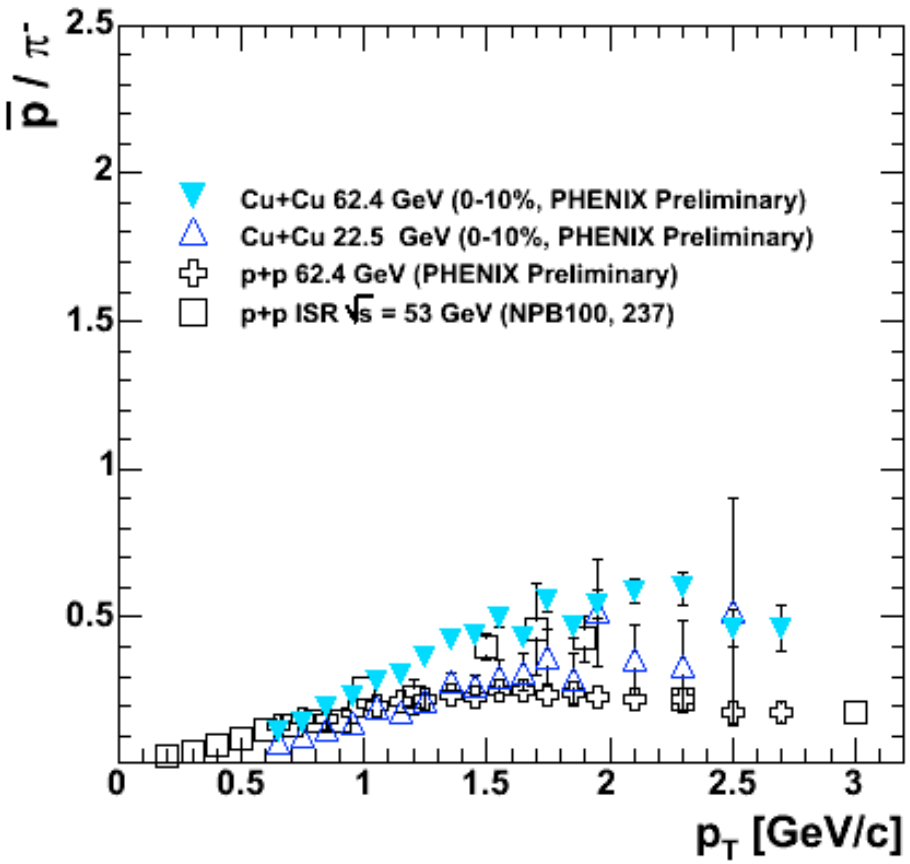
p+p 62.4 GeV, set the baseline for HI data. PHENIX data agrees with ISR data.

√s dep. of pbar/π⁻ ratio (central)



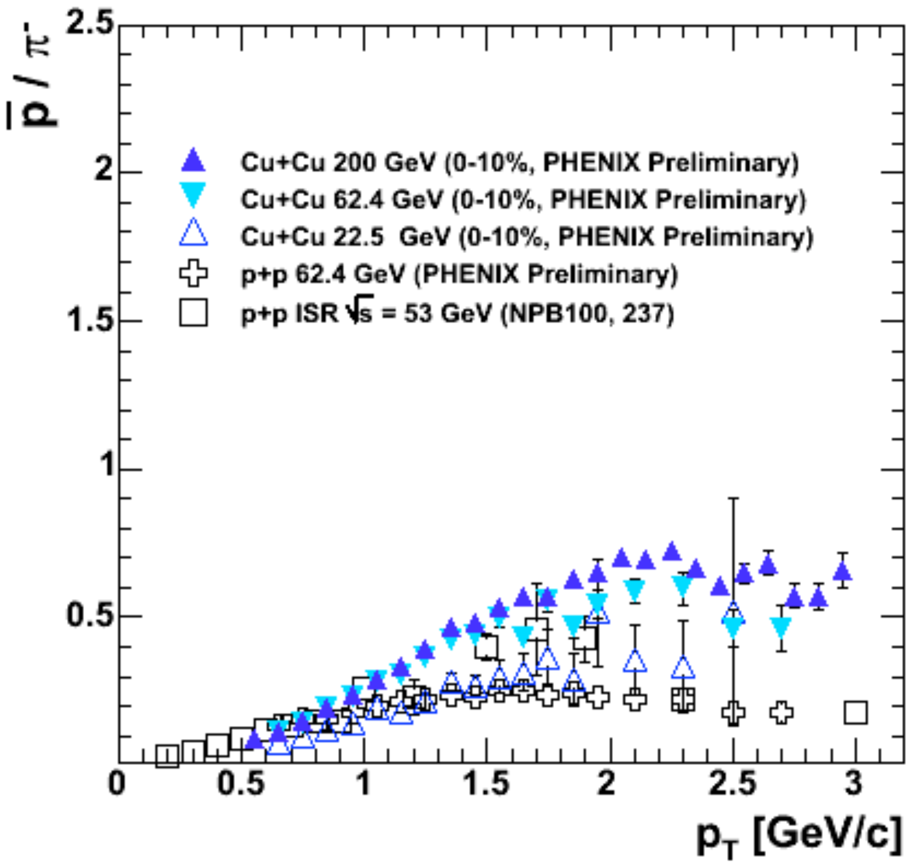
Cu+Cu 22.5 GeV, pbar/π⁻ ratio in central agrees with p+p.

√s dep. of pbar/π^- ratio (central)



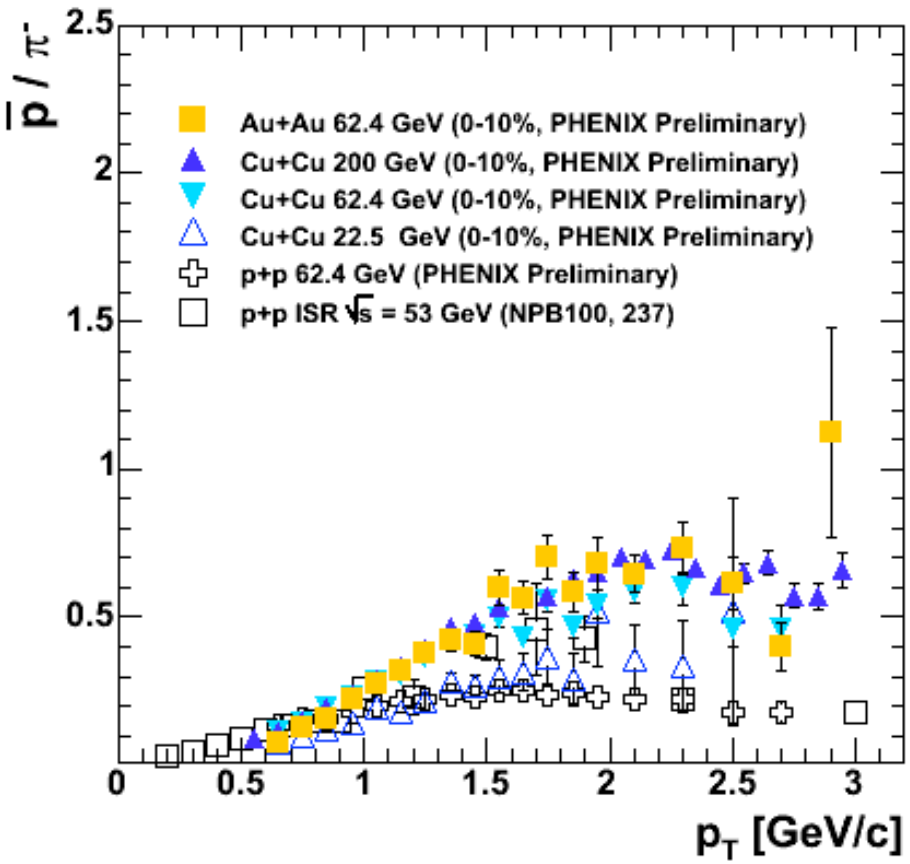
Cu+Cu 62.4 GeV, pbar/π^- ratio larger than those in p+p and Cu+Cu 22.5 GeV.

√s dep. of pbar/π^- ratio (central)



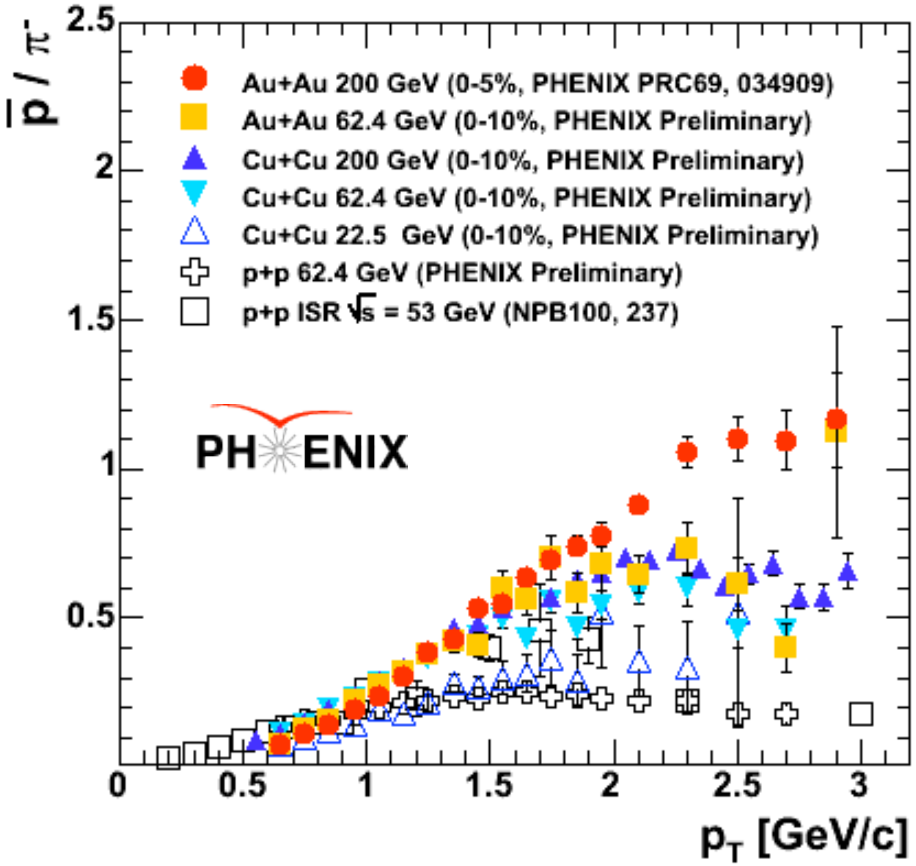
Cu+Cu 200 GeV, similar to those in Cu+Cu 62.4 GeV.

√s dep. of pbar/π^- ratio (central)



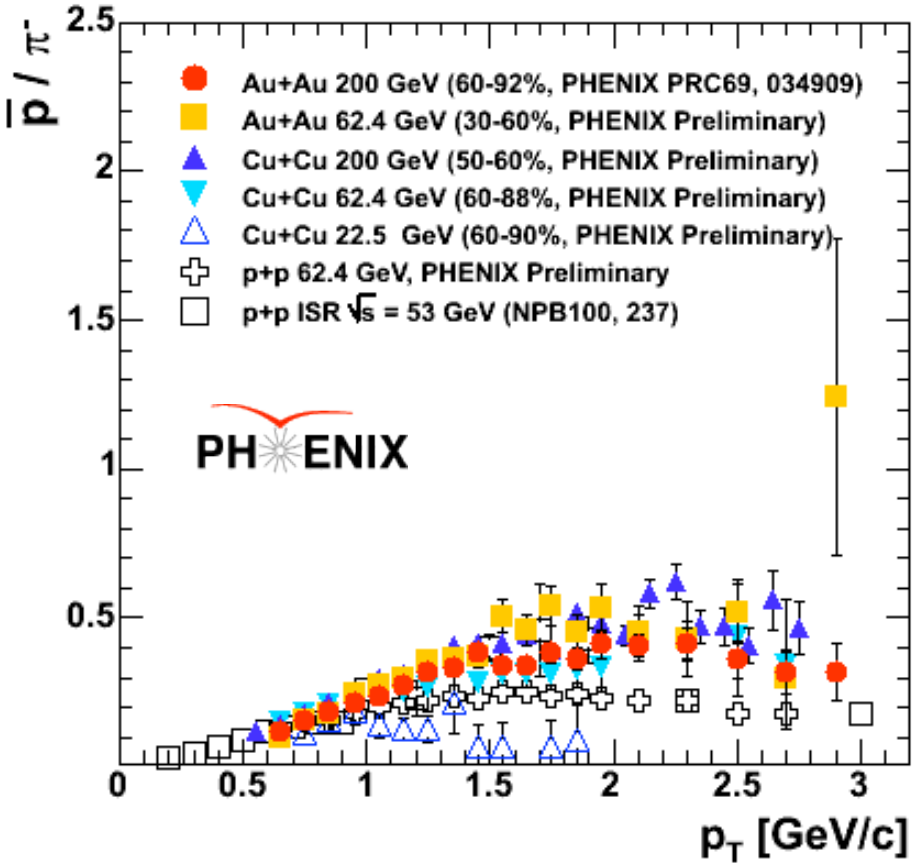
Au+Au 62 GeV, pbar/π^- is unchanged from Cu+Cu 200 GeV

√s dep. of pbar/π⁻ ratio (central)



Au+Au 200 GeV, p-bar/π⁻ is enhanced.

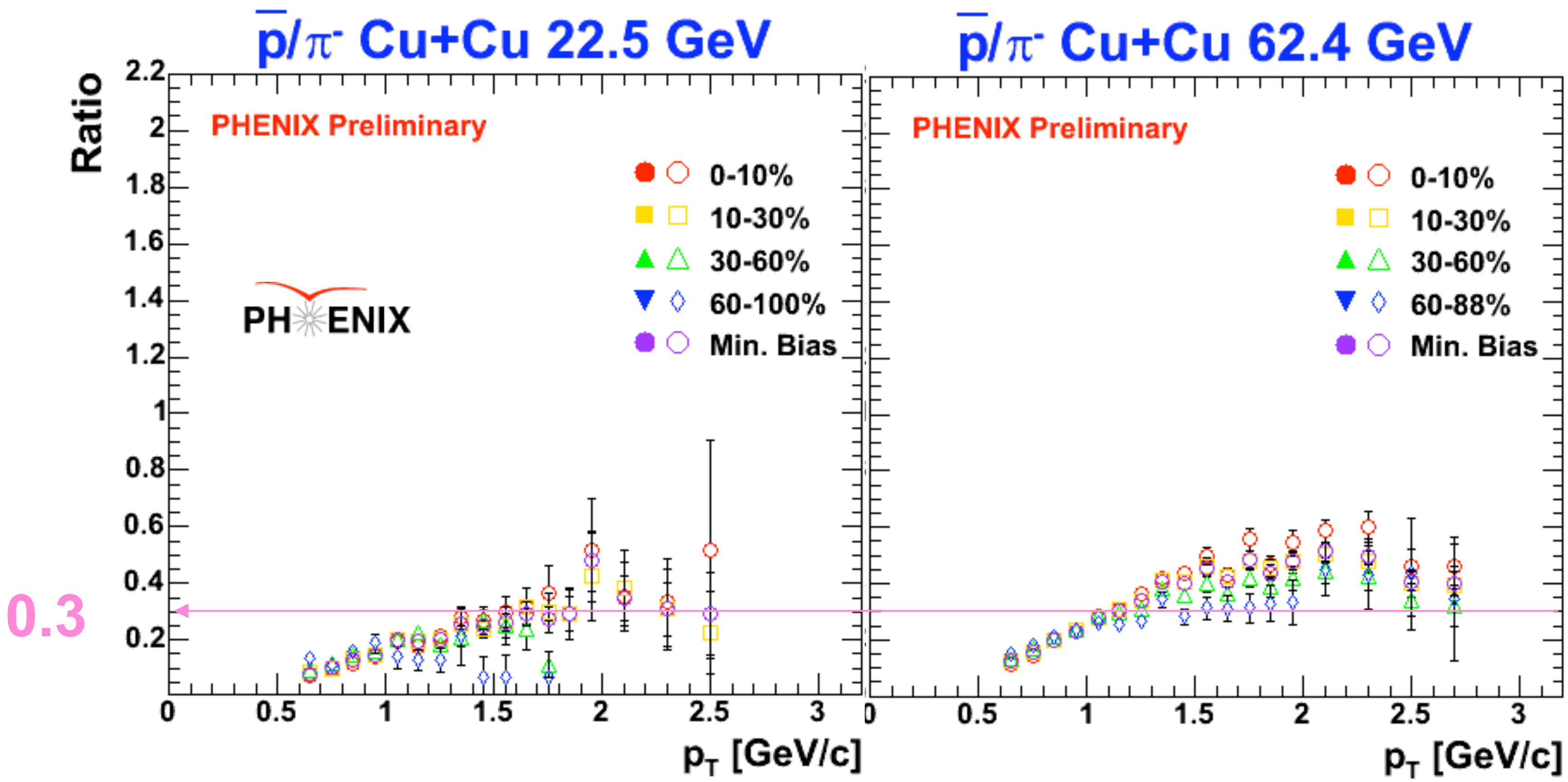
√s dep. of pbar/π^- ratio (peripheral)



Peripheral collisions for all systems

Conversing to the same line

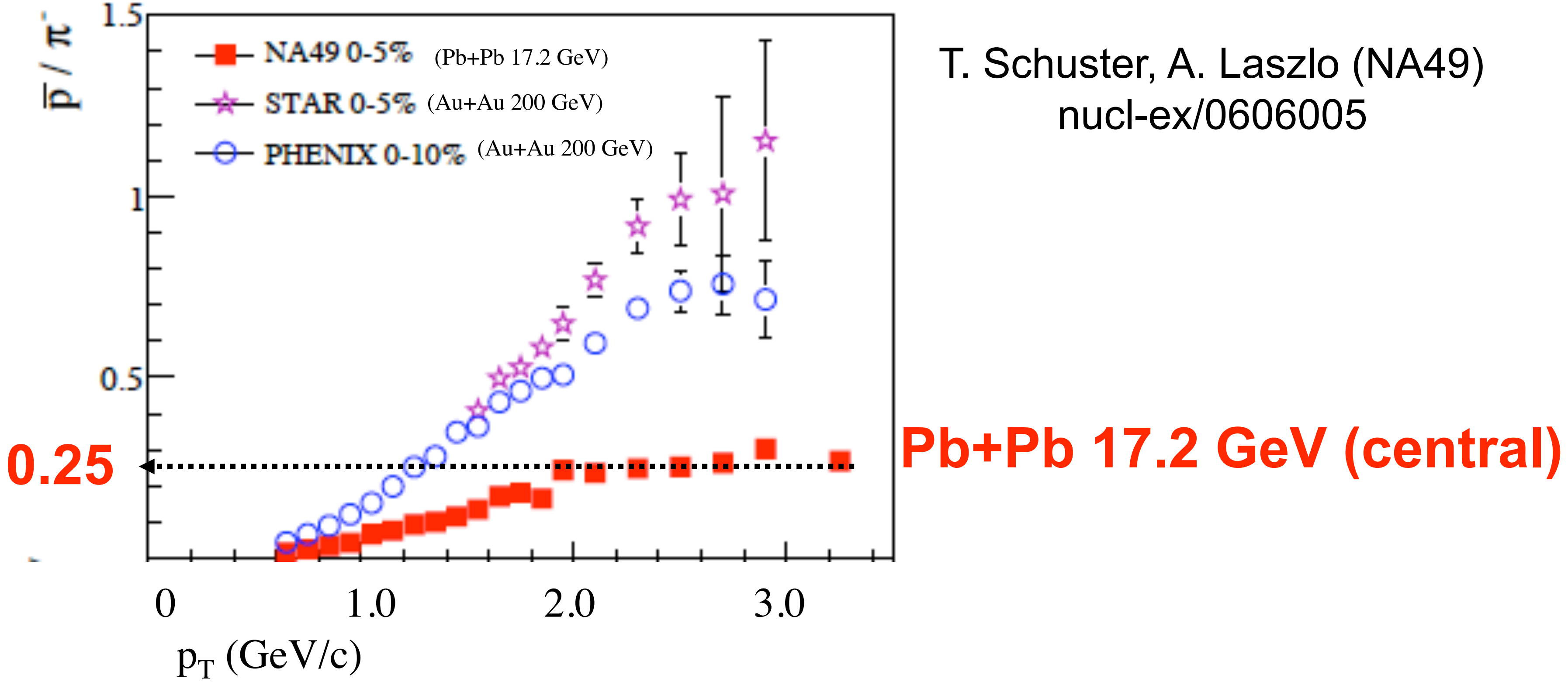
Centrality dep. of pbar/π^- (22 GeV vs. 62 GeV)



* No weak decay feed-down correction applied.

- **In 22.5 GeV Cu+Cu: weak centrality dependence, pbar/π^- ratios are ~0.3-0.4 at p_T = 2 GeV/c,** which is close to the value in p+p.
- **In 62.4 GeV Cu+Cu: pbar/π^- ratio in central collisions reaches R=~0.6 at p_T = 2 GeV/c, decreasing towards the peripheral events.**

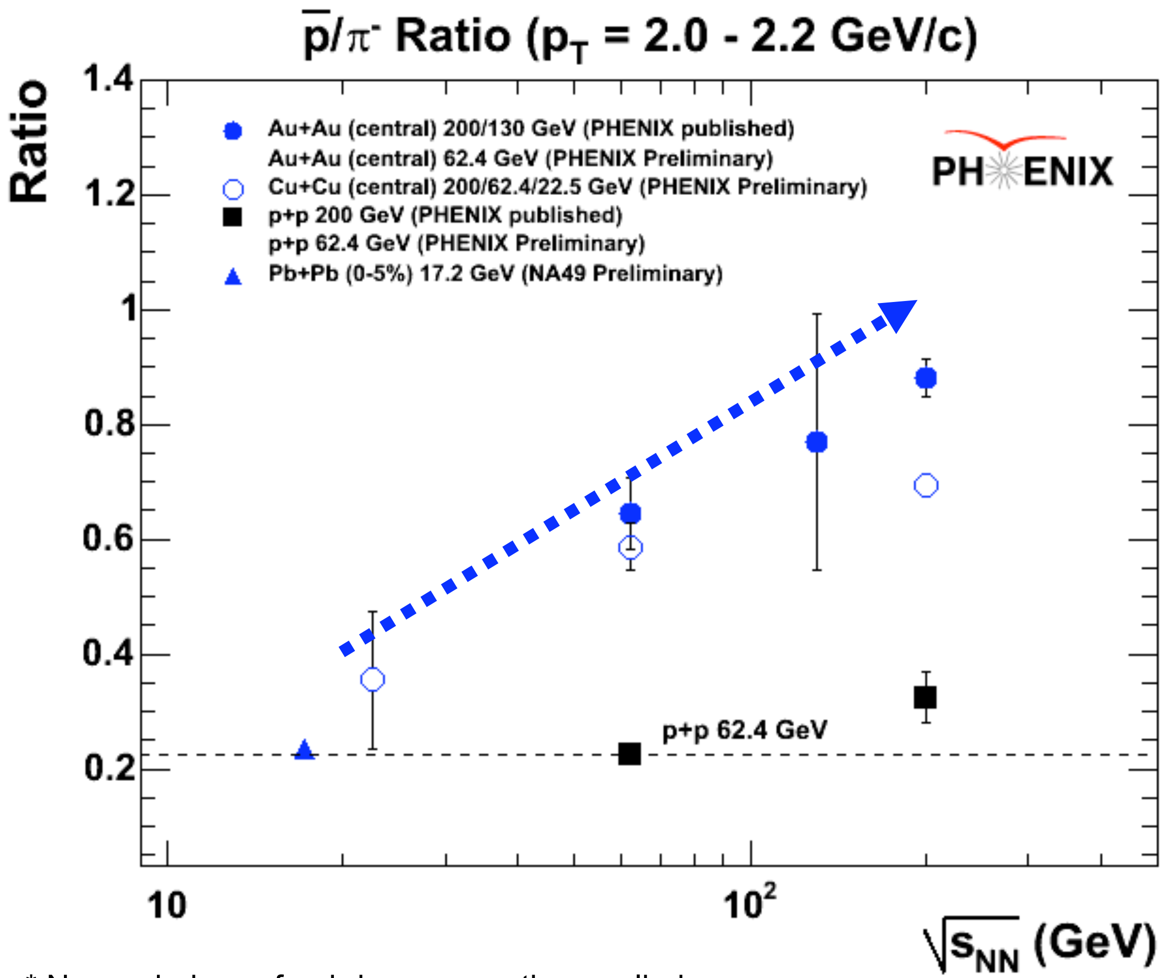
Comparison with SPS data



T. Schuster, A. Laszlo (NA49)
nucl-ex/0606005

SPS Pb+Pb: consistent with Cu+Cu 22.5 GeV pbar/π.

pbar/π^- ratio (central): summary

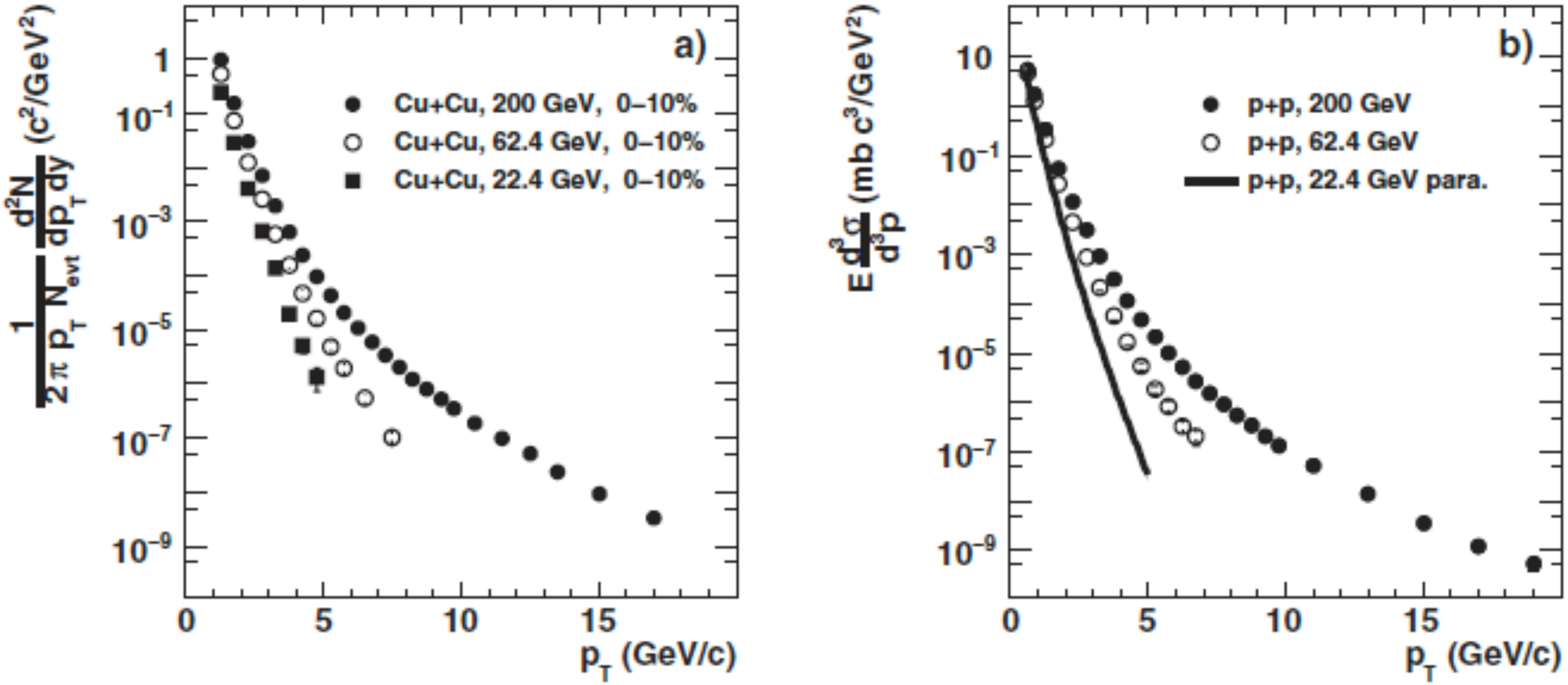


* No weak decay feed-down correction applied.

- Increasing as a function of √s.
- Indicates the onset of baryon enhancement is in between 22 GeV and 62 GeV.

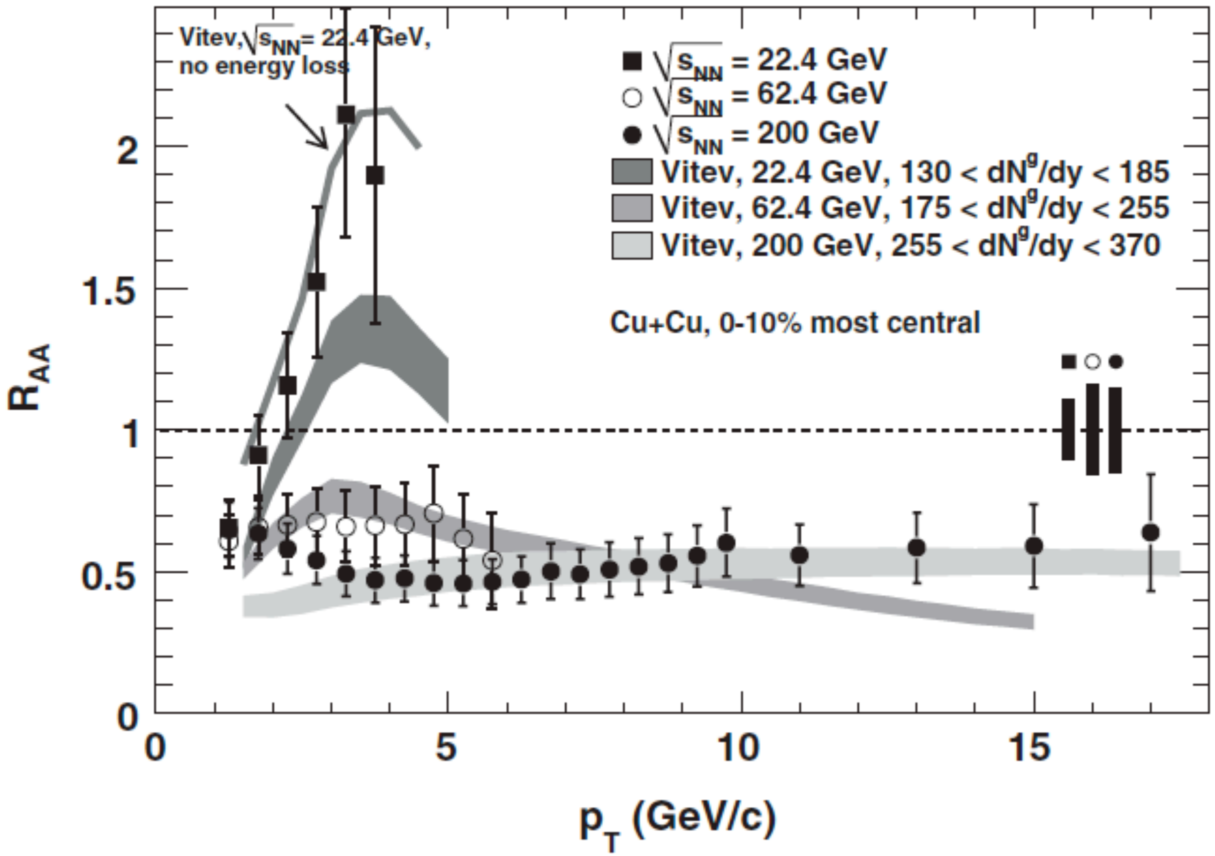
π^0 p_T spectra in Cu+Cu and p+p at 22.4, 62.4, 200 GeV

PHENIX: PRL 101, 162301 (2008)



π^0 R_{AA} in Cu+Cu: energy dep.

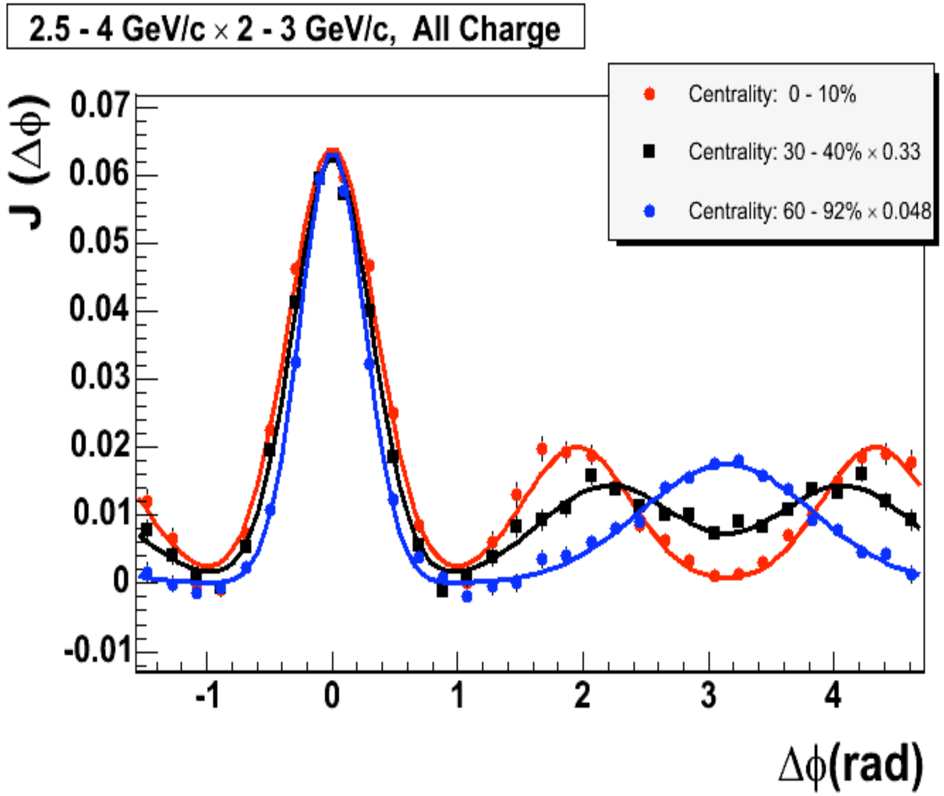
PHENIX: PRL 101, 162301 (2008)



- Enhancement at 22 GeV.
- Consistent with no energy loss model.

4. WHAT'S THE ORIGIN OF BARYON ENHANCEMENT?

Jet induced baryon enhancement?

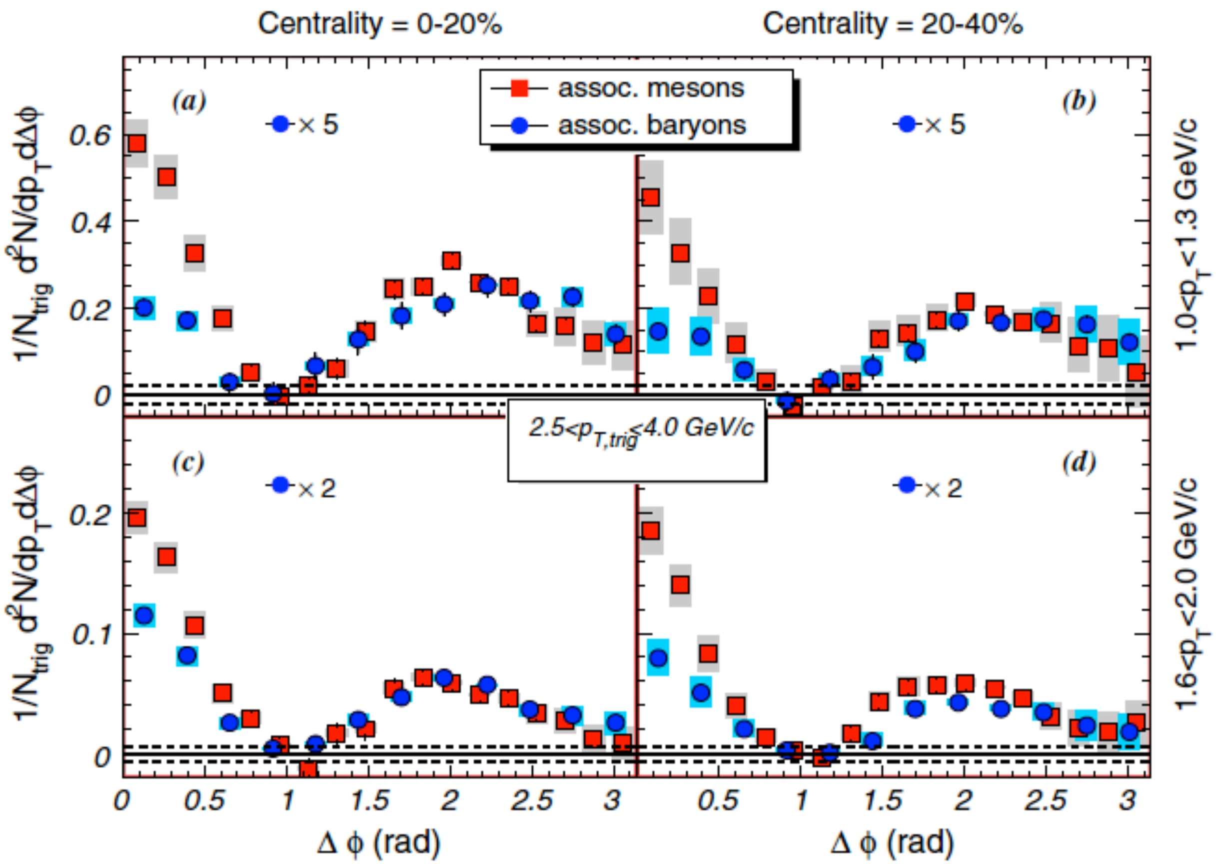


Away side two peaks (shoulder)

Sonic shock wave?
Baryon/Meson effect?

Jet-pair distribution for associated M/B

PHENIX: PRL 101, 082301 (2008)

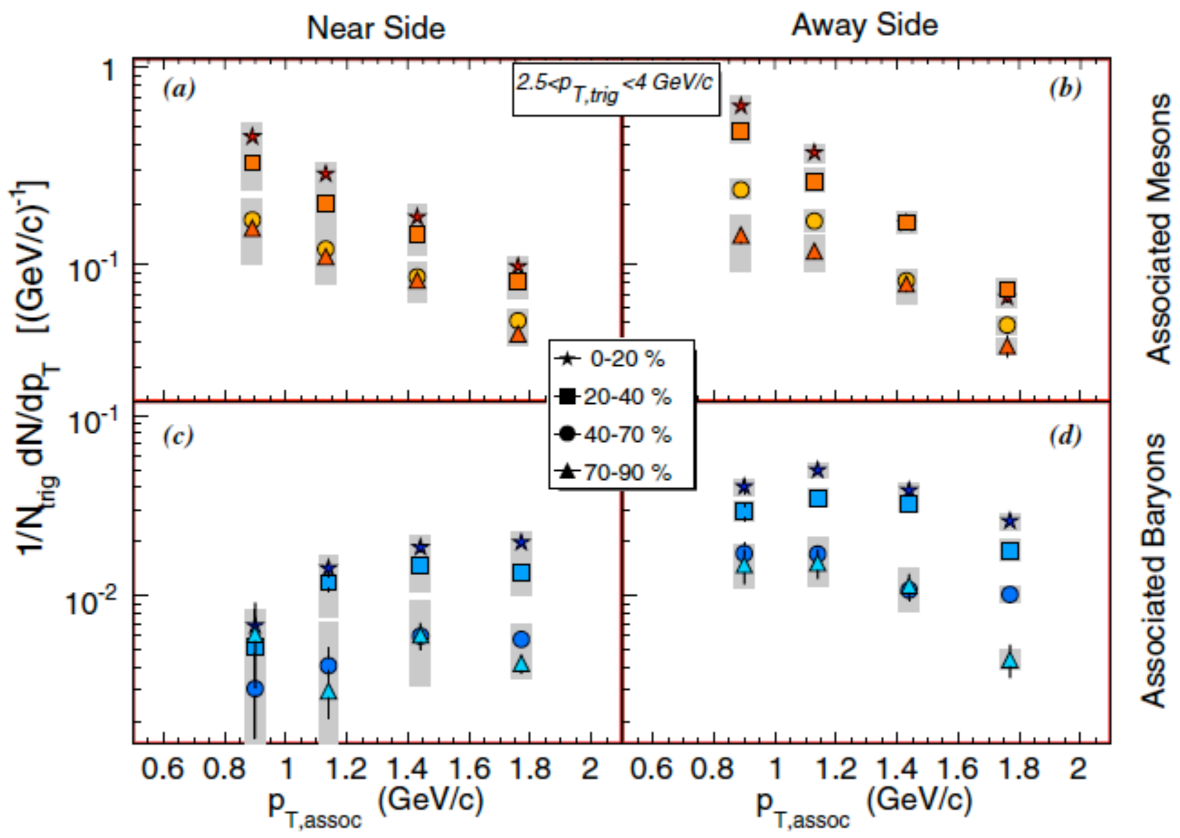


- **Trigger particle**: charged hadron (2.5 <p_T,trig < 4.0 GeV/c)
- **Associate particle**: meson or baryons (1.0 – 2.0 GeV/c).

- Near side: substantially weaker for associated baryons.
- Away side: similar for associated mesons and baryons. "Shoulder" structure appeared.

Conditional jet yields for M/B

PHENIX: PRL 101, 082301 (2008)

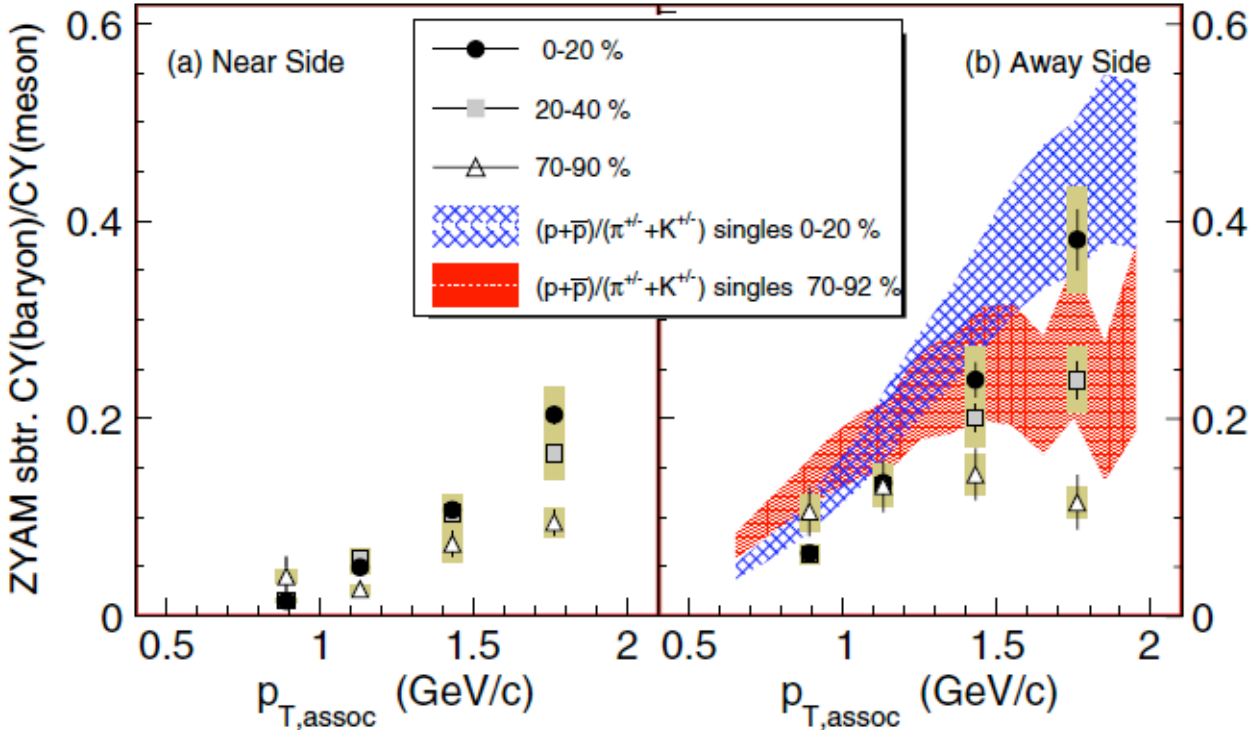


- **Mesons:**
  - exponential decrease with increasing p_T, assoc.
  - Yield increase from peripheral to central, with different slope
  - Incompatible with in-vacuum fragmentation
  - Due to contribution from correlated soft partons, softening of FF, recombination, energy loss, etc… ?

Baryons:
  - different strongly from those for mesons.
  - Not exponential shape.
  - Yield (away) > Yield (near).
  - Much stronger increase with centrality than those for mesons.
  - Might be due to the correlated soft parton recombination.

Baryon/meson ratios associated with high p_T hadron trigger ($2.5 < p_T < 4$GeV/c)

PHENIX: PRL 101, 082301 (2008)



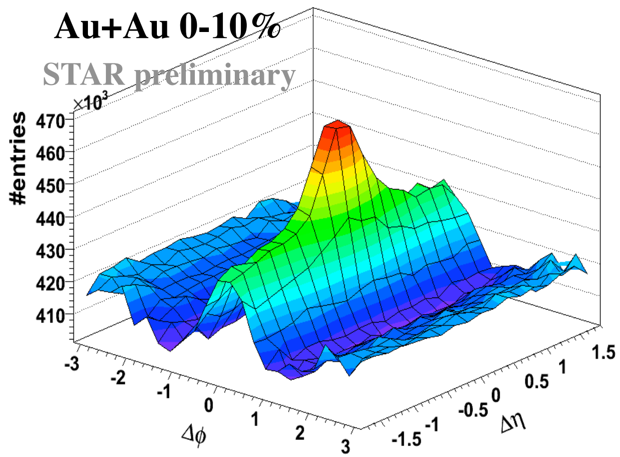
- Peripheral ratios ~ vacuum fragmentation
- In-jet ratios ~ inclusive $p/(\pi+K)$

Away-side "shoulder", and baryon enhancement in single spectra: might be the common origin.

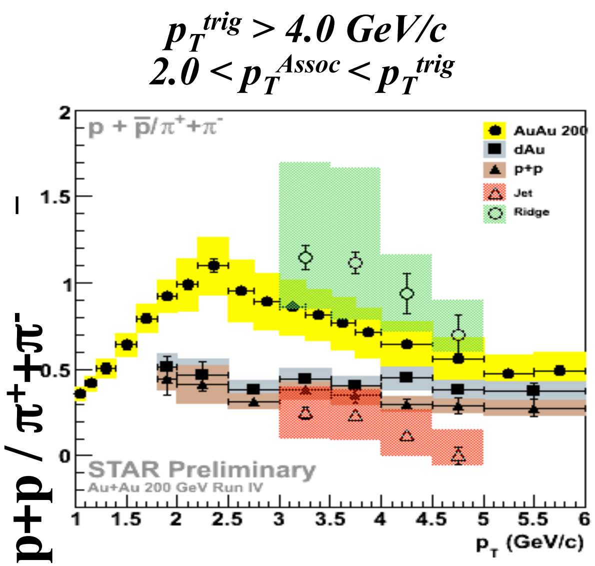
*** Recombination of correlated soft partons induced via strong parton medium interactions?**

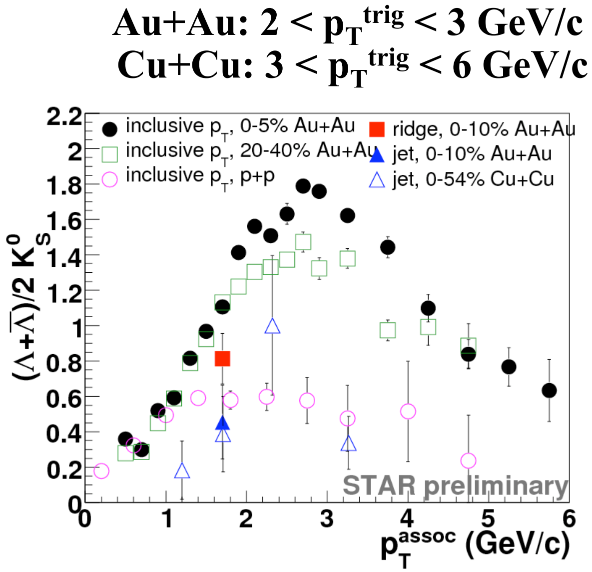
Intermediate p_T ridge & Jet (near side only)

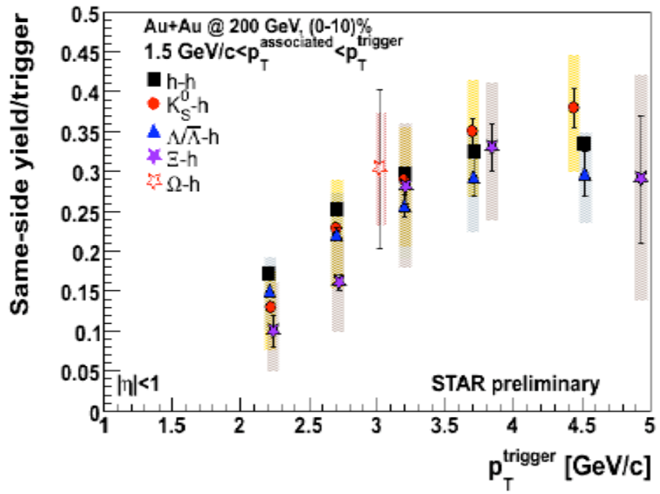
(from SQM08, O. Barannikova, STAR)



$3 < p_{t,trig} < 4$ GeV/c
$p_{t,assoc.} > 2$ GeV/c

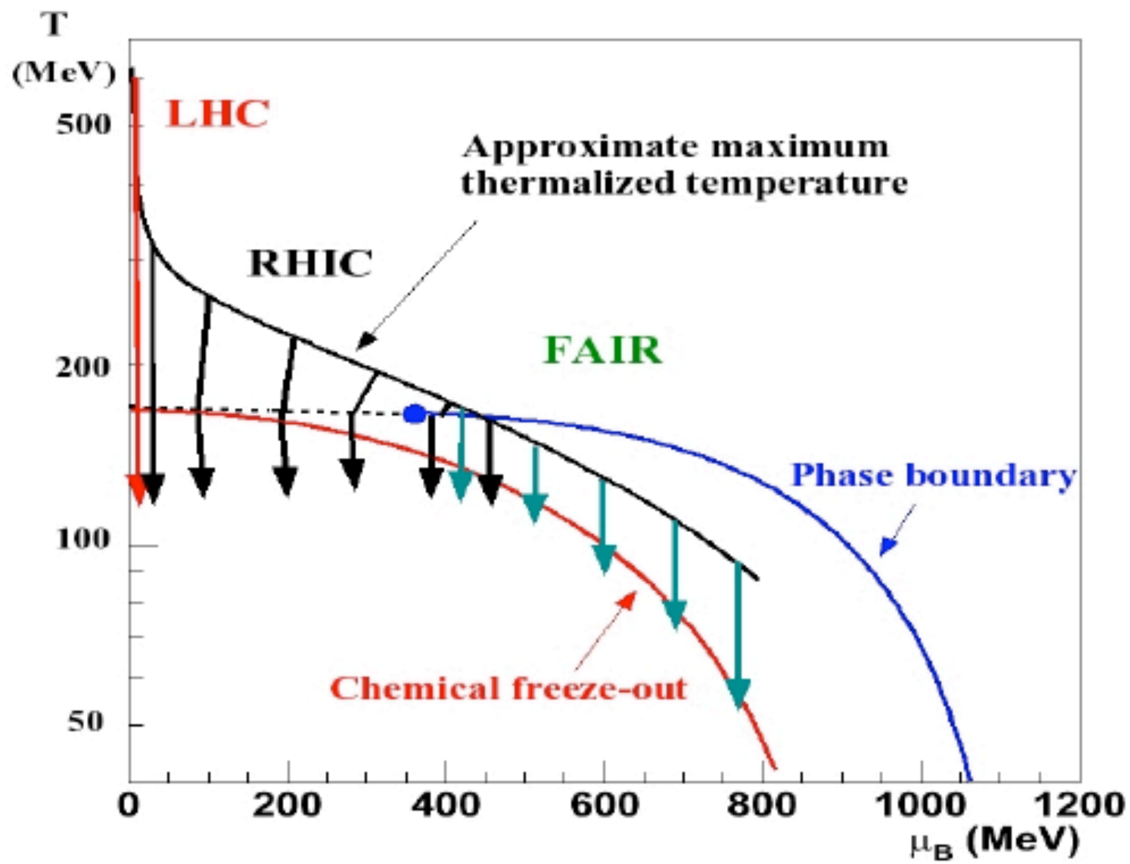






- **Jet+ridge yields follow similar trend in p_T for all trigger types (left bottom)**
- **Production mechanisms for jet and ridge are different (p/π, Λ/K)**

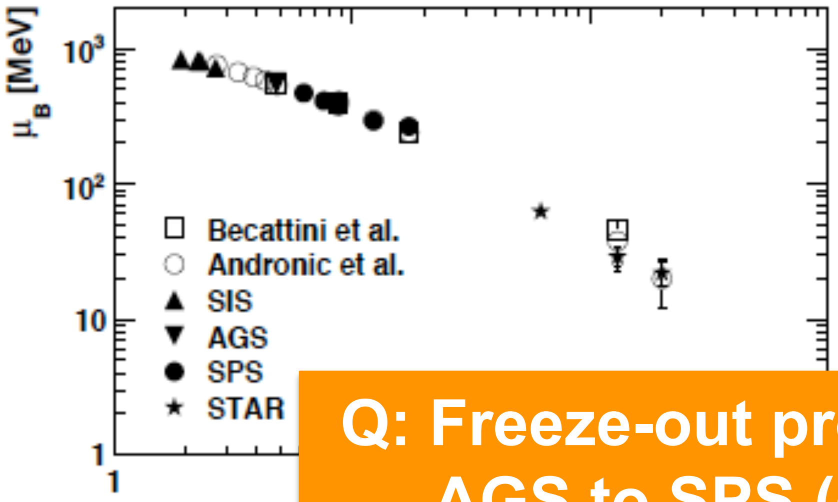
Figure from "Future Science at the Relativistic heavy ion Collider (Aug. 25, 2006 version)", by RHIC II Science Working Groups

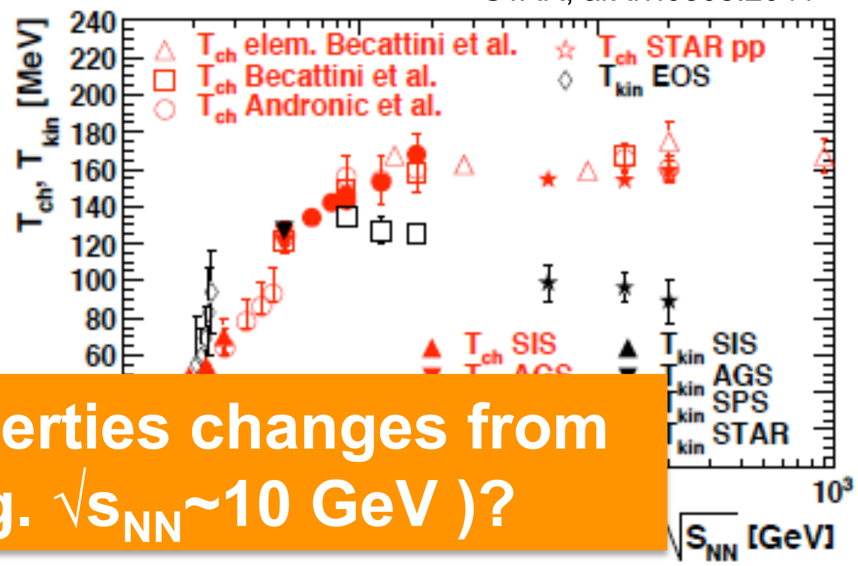


5. EXPLORING THE QCD PHASE DIAGRAM AT RHIC

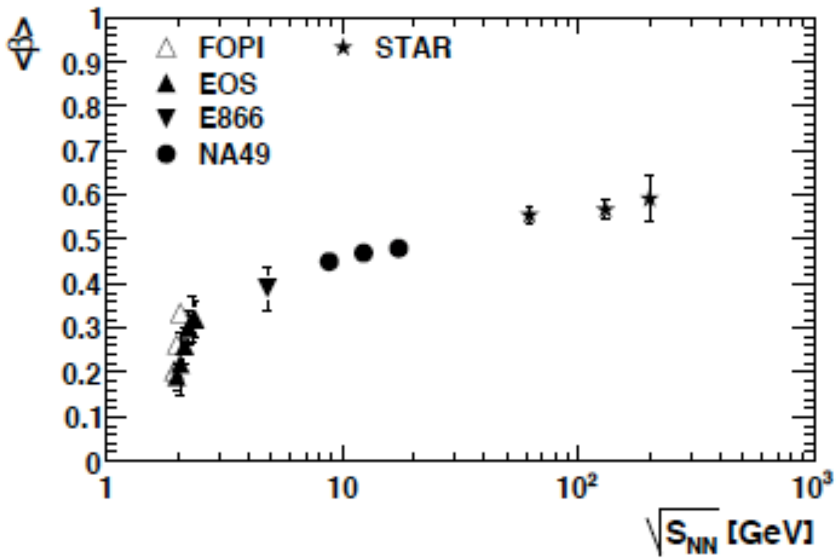
Excitation functions of freeze-out properties

STAR, arXiv:0808.2041





Q: Freeze-out properties changes from AGS to SPS (e.g. $\sqrt{s_{NN}}$~10 GeV)?



- μ_B: falls monotonically.

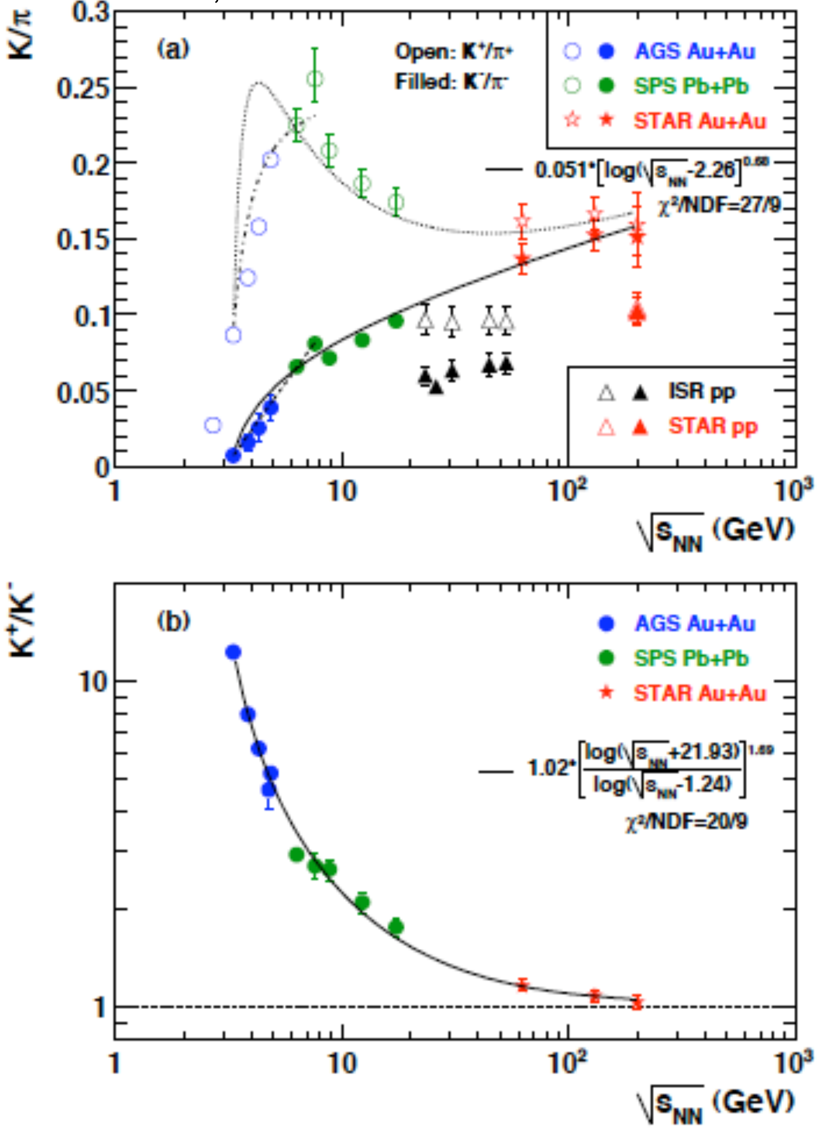
- T_{ch}: rapidly rises at SIS and AGS energy, saturates at SPS and RHIC energies (a unique T_{ch} ~ T_c from lattice QCD).

- T_{kin}: decoupled at $\sqrt{s_{NN}}$~10 GeV from T_{ch}. Due to the strong collective flow, matter is cooled → prolong period of chemical freeze-out and kinetic freeze-out.

- $\langle\beta_T\rangle$: rapid increase from SIS to AGS, increasing slowly from SPS to RHIC.

“hone” at SPS is true?

STAR, arXiv:0808.2041

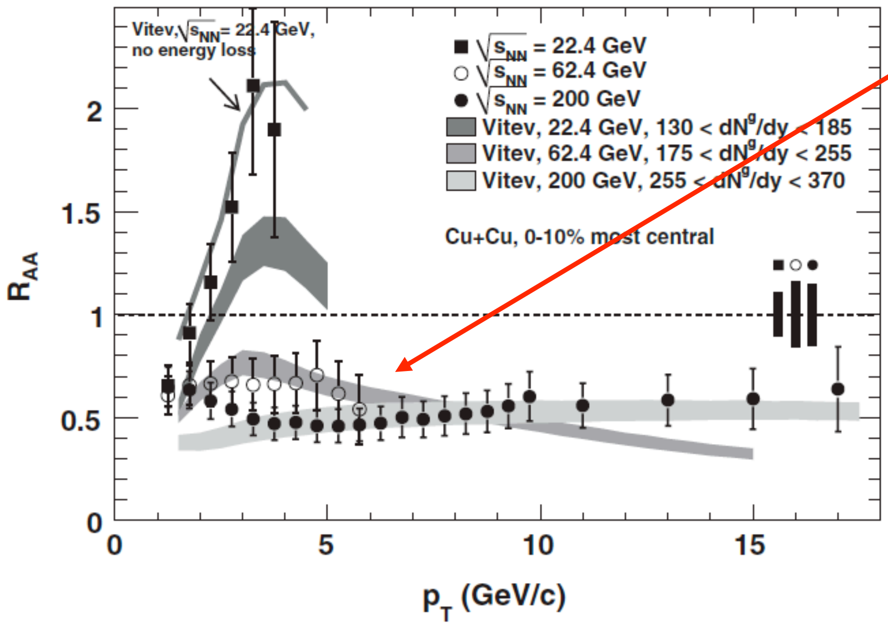


- K^-/π^- ratio : steadily increases with $\sqrt{s_{NN}}$,while K+/π+ sharply increases at low energies.
- A maximum K+/π+ value is reached at about $\sqrt{s_{NN}} \approx 10$ GeV.
- K^+/K^- vs sqrt(s): smooth decrease (log scale).
- using the functional forms for K^+/K^- and K^-/π^-, then make the function for K^+/π^+.
  - Generates a maximum at 10 GeV (“horn”)..
- More detail energy scan is needed.

Yet another onset at RHIC

PHENIX: PRL 101, 162301 (2008)

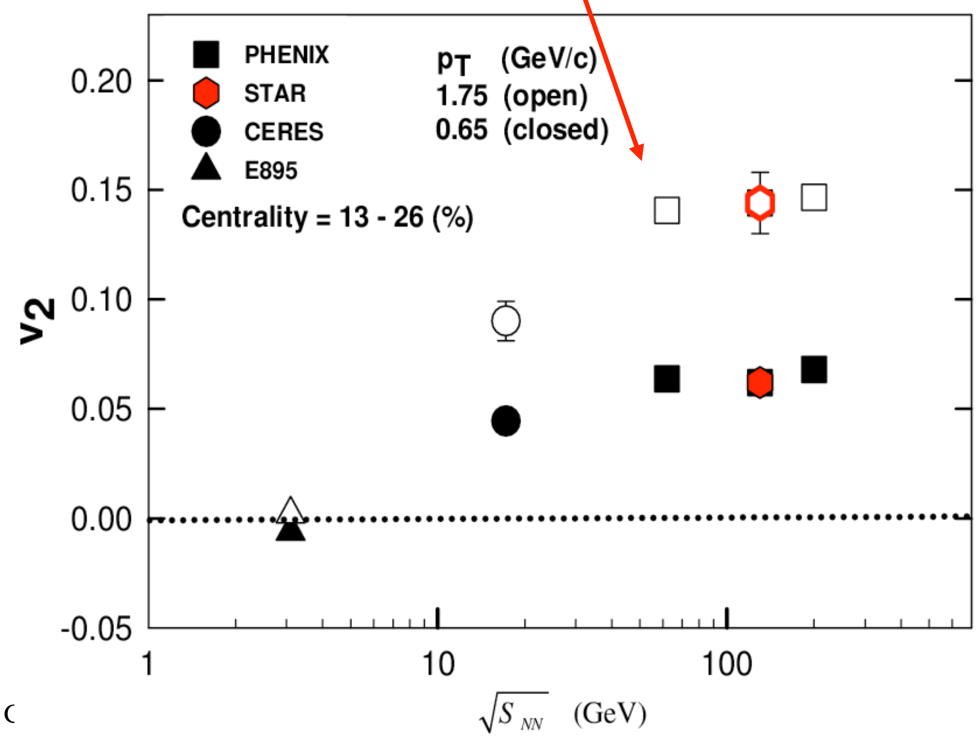
Cu+Cu



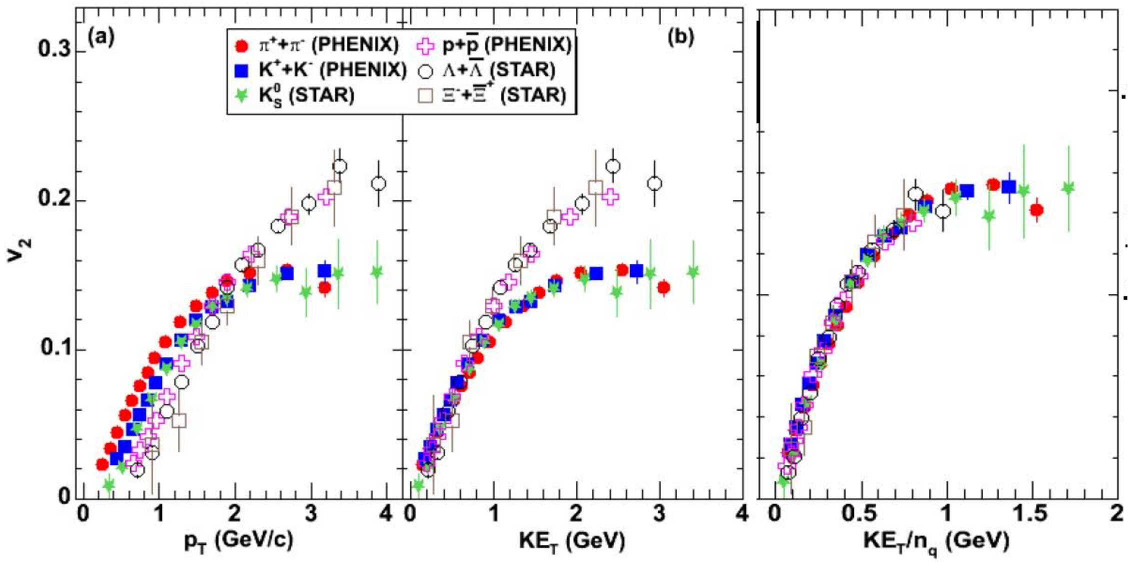
Emergence of opacity

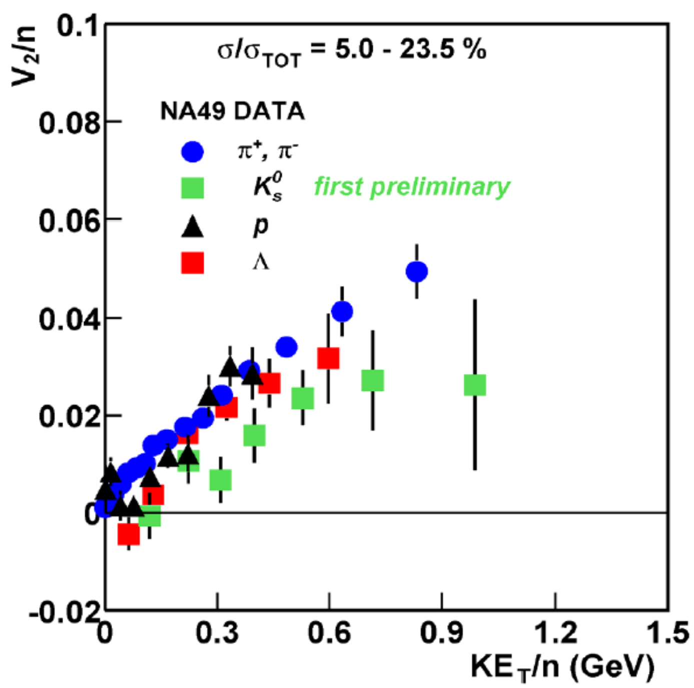
Approach to constant v_2 and hydrodynamic limit?

Au+Au



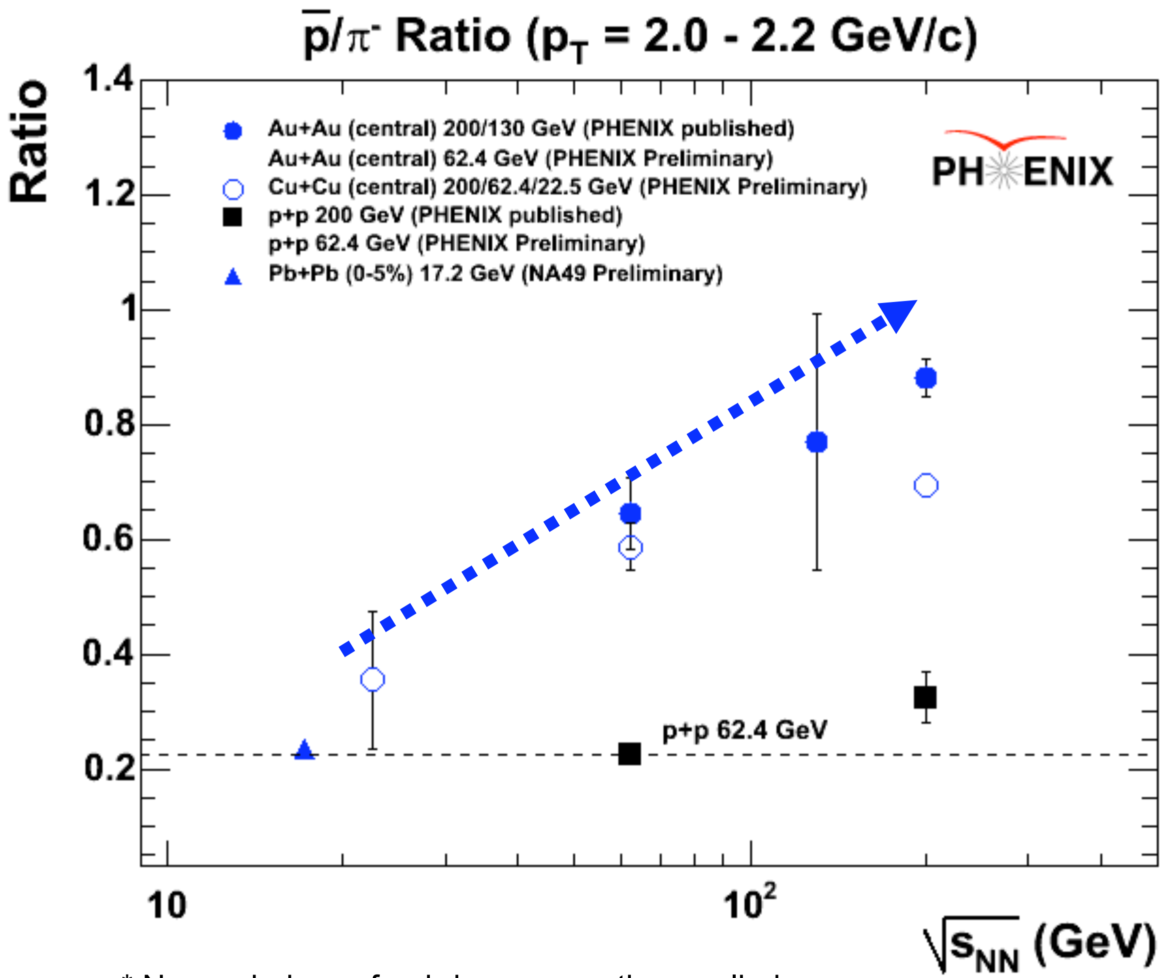
Onset of Quark Number Scaling?





Where is the onset of quark number scaling?
Relationship to quark DOF ?

p-bar/π⁻ ratio vs. √s$_{NN}$



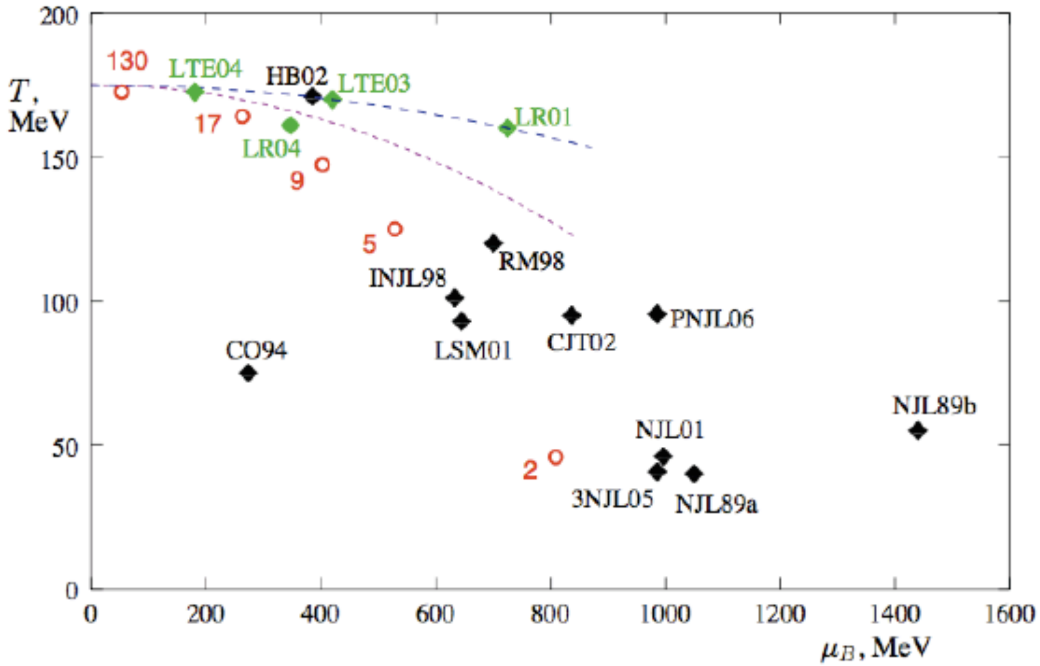
* No weak decay feed-down correction applied.

- Increasing as a function of √s.
- Indicates the onset of baryon enhancement is in **between 22 GeV and 62 GeV**.

Search for QCD Critical Point (QCP)

Where is the QCP?

- **Lattice QCD, Effective models…**



Stephanov,hep-lat/0701002

From C. Nonaka (JPS2008 fall)

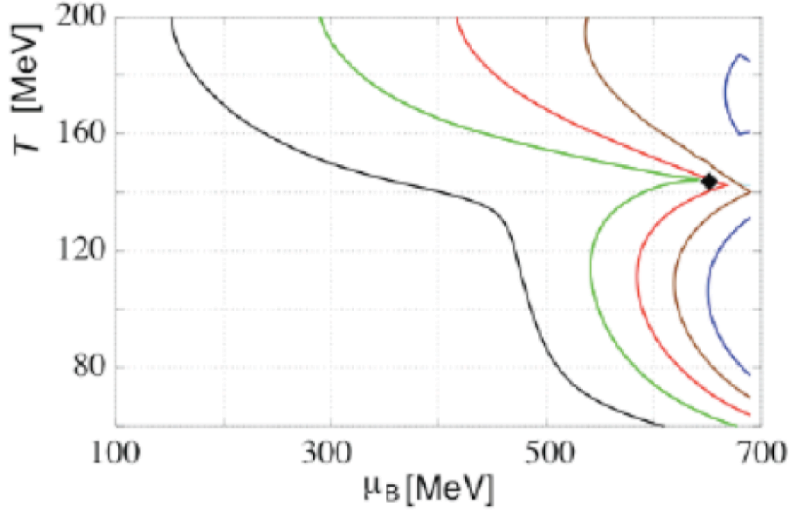
Focusing Effect

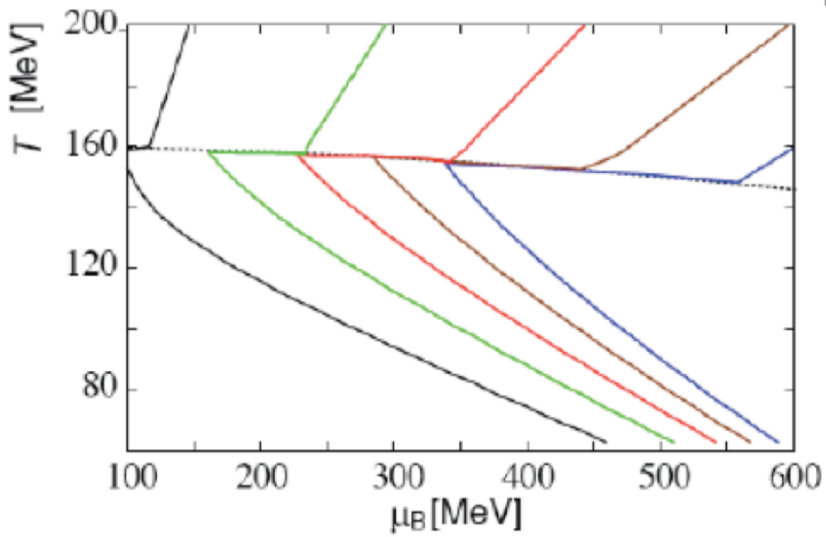
- **Isentropic trajectories on T- μ_B plane**

With QCD critical point

Bag Model +
Excluded Volume Approximation
(No Critical Point)

= Usual Hydro Calculation





Focused

Not Focused

Chiho NONAKA

From C. Nonaka (JPS2008 fall)

Toward Quantitative Analyses

PRC71:044904,2005, arXiv:0803.2449 [nucl-th](PRL)

Realistic Dynamical Model

- 3D Hydro + UrQMD Model

The QCD Critical Point

- Focusing effect near the QCD critical point in isentropic trajectories on the T-μ_B plane

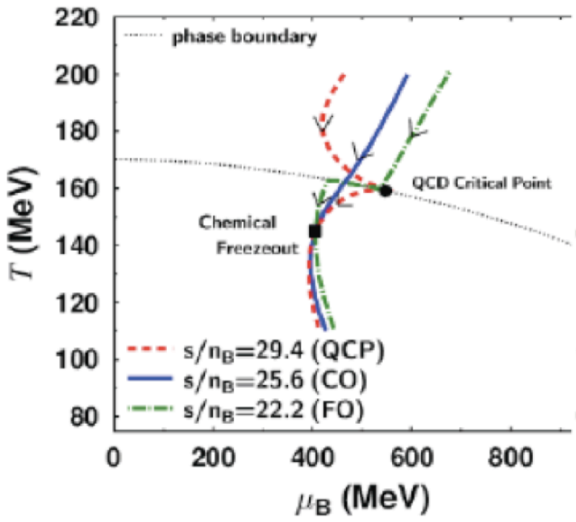
Emission Time Dependence

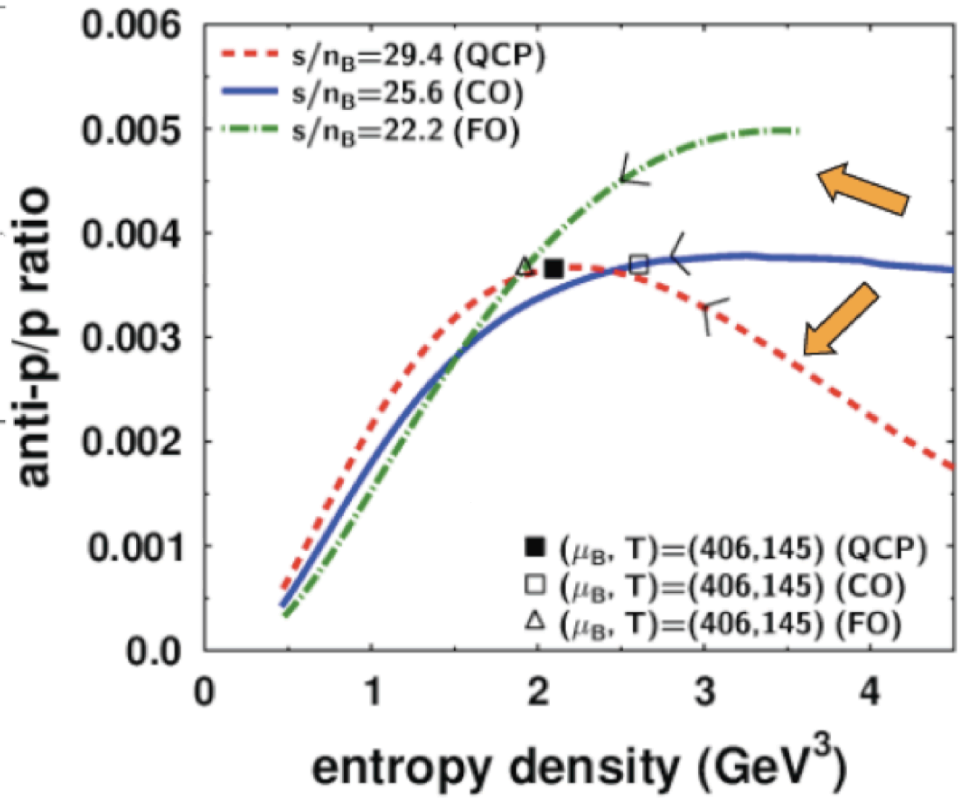
- High P_T particles emit at earlier time

Chiho NONAKA

From C. Nonaka (JPS2008 fall)

Signature of QCP





$$\bar{p}/p \sim \exp\left(-\frac{2\mu_B}{T}\right)$$

- decreases (FO,CO)
- increases (QCP)

with QCP
steeper $\bar{p}$ spectra at high P_T

Chiho NONAKA

Observable: look at pbar/p vs. p_T.

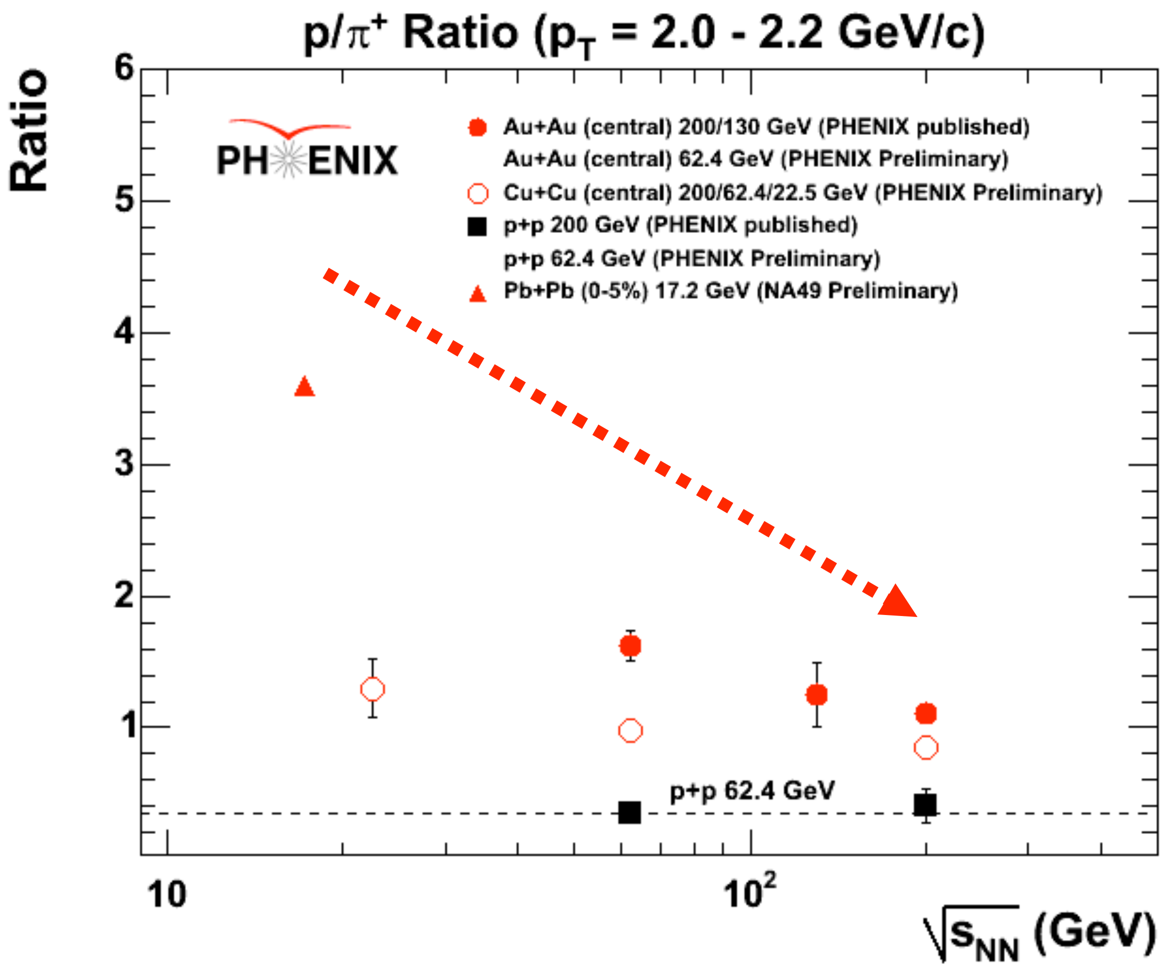
6. Summary

- Baryons (protons and antiprotons) has a unique role to characterize the many bulk properties of matter, hadronization mechanism, and medium response.

- Bulk properties at RHIC (at mid-rapidity) : **governed by the charged particle multiplicity**
  - Relevant to the CGC gluon saturation picture.
- Systematic study of baryon enhancement:
  - qualitative difference between 22 GeV and 62.4 GeV on the property of baryon enhancement (while freeze-out properties seems to be already changed at 10 GeV).
  - Jet correlation: indicating the ***jet induced baryon enhancement.***
- Towards the understanding of QCD phase diagram and **QCP search**.

Backup Slides

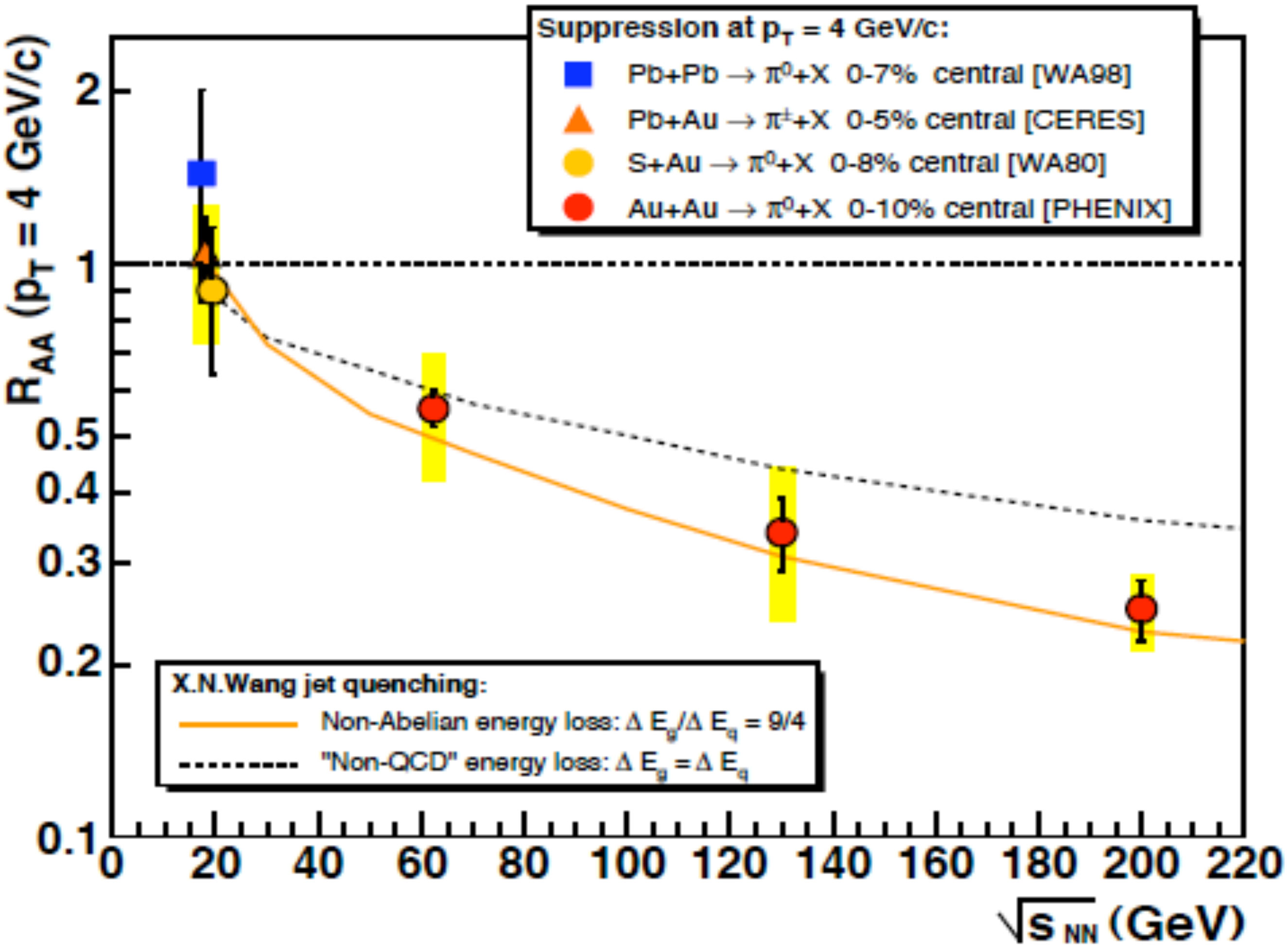
$\sqrt{s_{NN}}$ dep. of p/π^+ ratio (central)



* No weak decay feed-down correction applied.

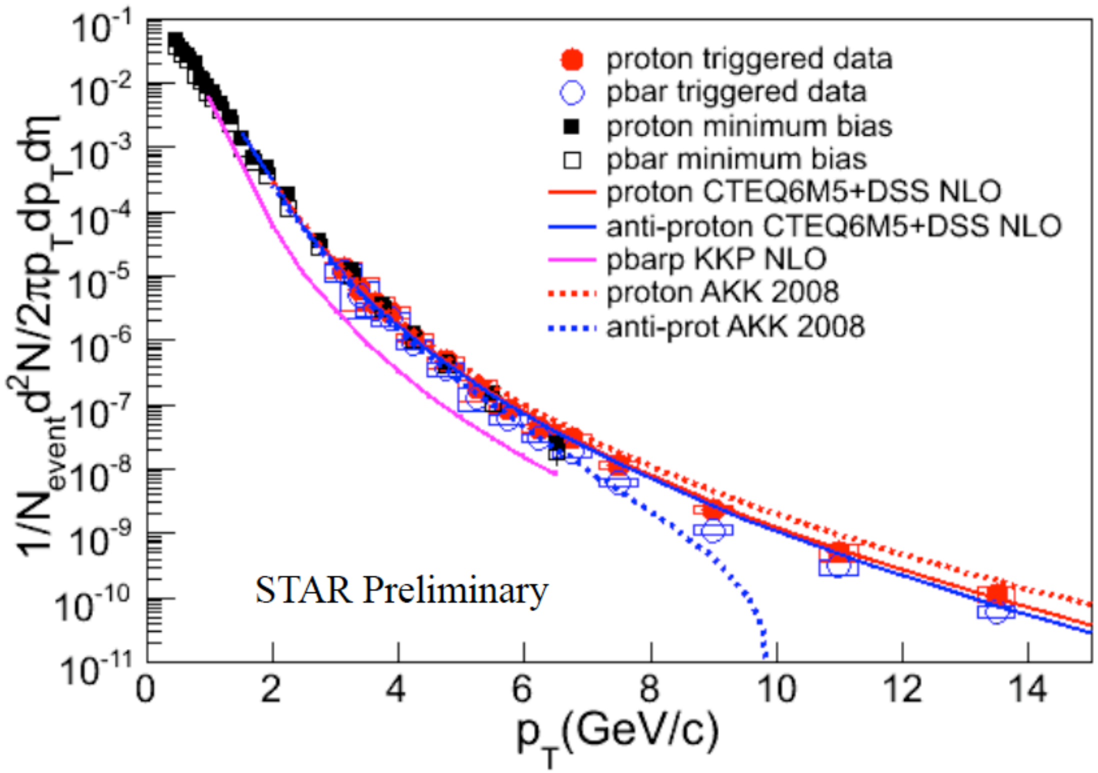
- **decreasing as a function of $\sqrt{s}$.**

π^0 R_{AA} vs. $\sqrt{s_{NN}}$



D. d'Enterria, nucl-ex/0504001

High p_T Results for proton Spectra

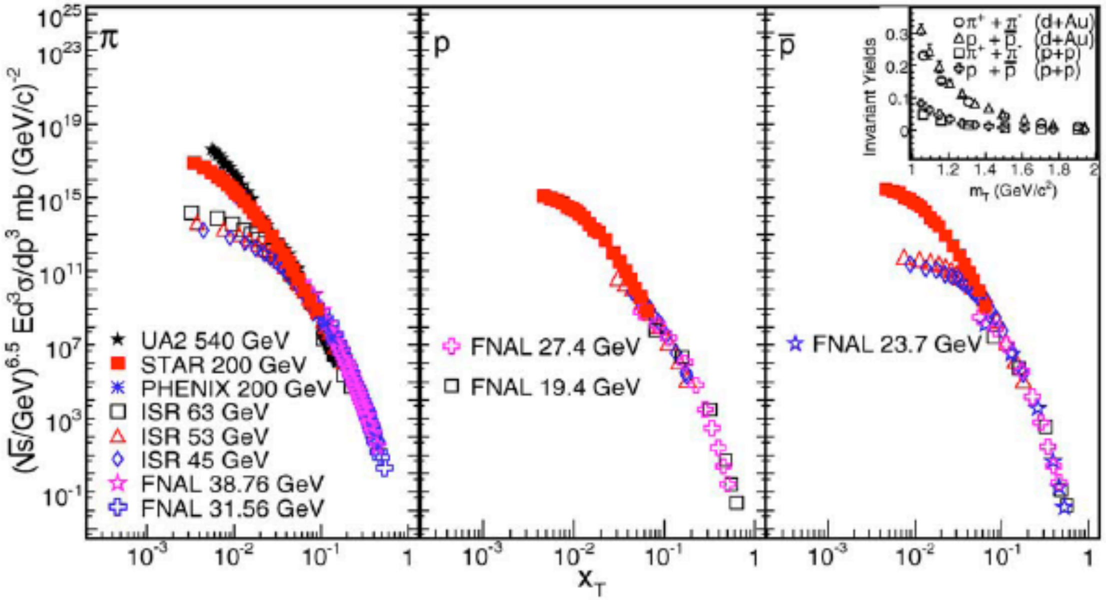


p+p collisions at RHIC:

pQCD based calculations provide a reasonable fit to data

STAR p+p 200 GeV data (x_T scaling)

STAR: PLB 637 (2006) 161-169



- In p+p collisions, x_T (=$2p_T/\sqrt{s}$) scaling works for both inclusive charged hadrons and identified hadrons (pions, protons, and antiprotons).
- Invariant cross sections can be expressed as the following equation:

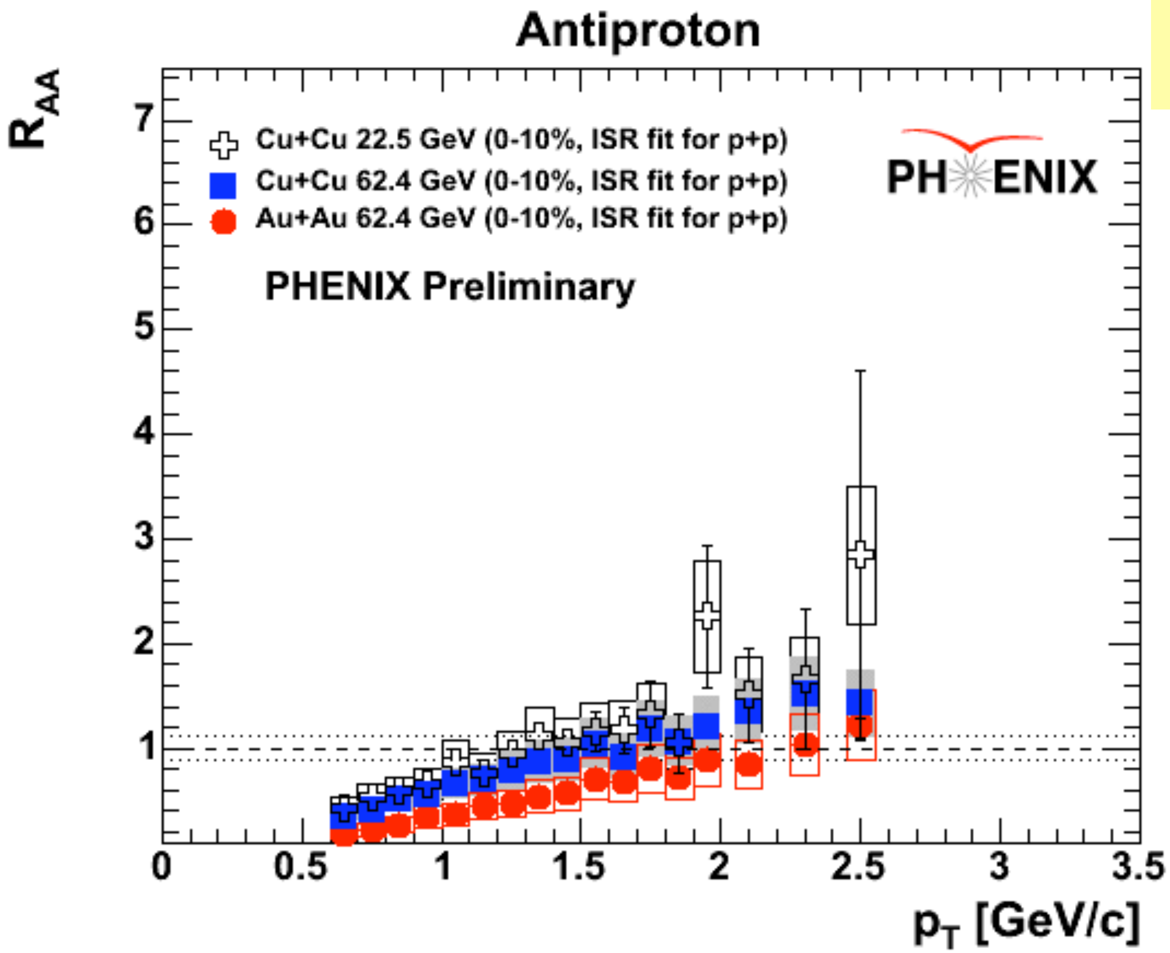
$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{\,n(x_T,\sqrt{s})}}G(x_T)$$

- The power "n" = 6.3-6.5 showed a good scaling in p+p collisions (c.f. PPG023).
- Indicates soft and hard transition by data.

$\sqrt{s_{NN}}$ dep. R_{AA} for antiprotons (by ISR fit)

Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{yield(AuAu)/N_{coll}}{yield(pp)}$$

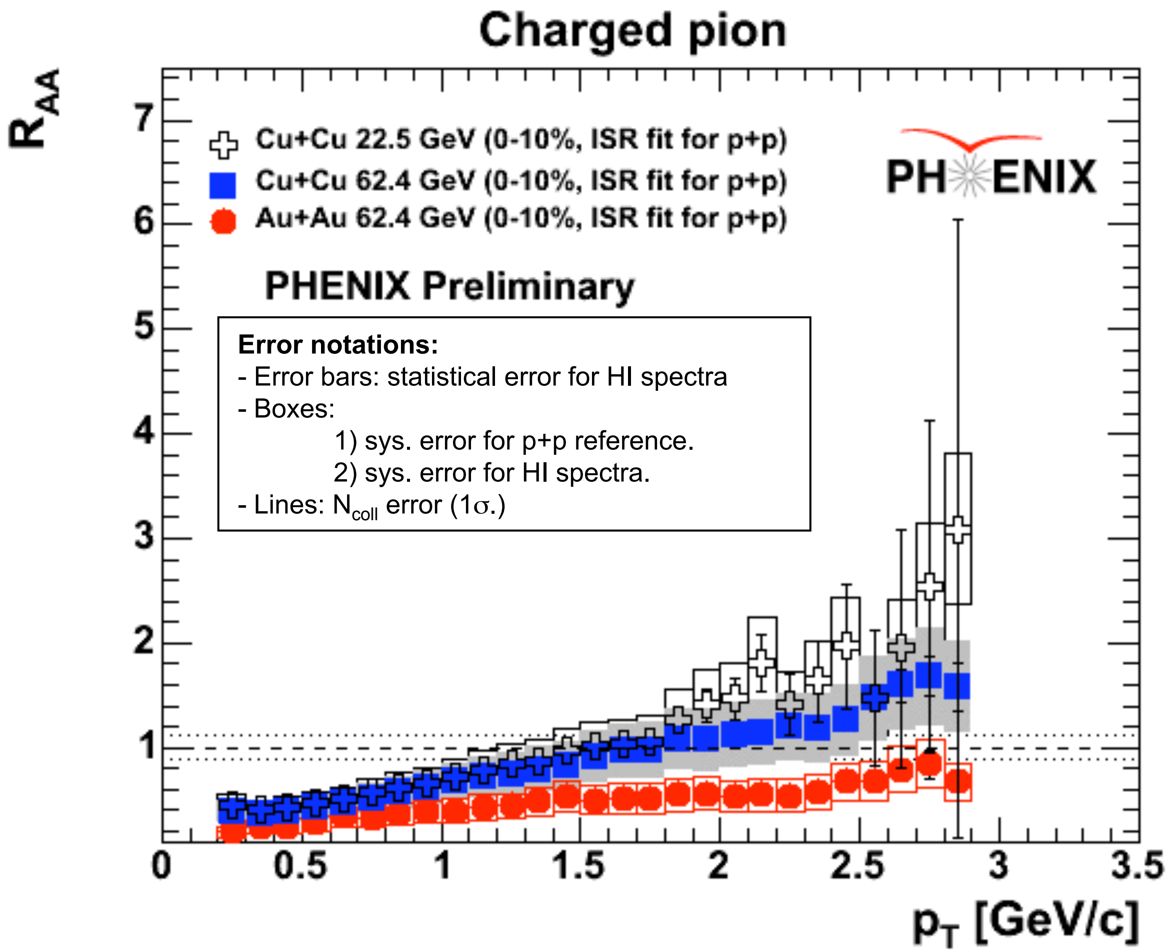


* No weak decay feed-down correction applied.

- Used ISR data at 23 GeV and 63 GeV (Alper. NPB 100, 237) for p+p reference.
- Similar R_{AA} for all three systems.

** Note:*
p+p 62.4 GeV p+p data has been measured by PHENIX, still working on the trigger bias and cross section seen in the detector. Here we use ISR fit to obtain R_{AA}.

$\sqrt{s_{NN}}$ dep. R_{AA} for charged pions (by ISR fit)



* No weak decay feed-down correction applied.

- Used ISR fit (nucl-ex/0411049, D. d'Enteria) for p+p parameterization.
- Moderate suppression for Au+Au 62.4 GeV.
- Greater than unity for Cu+Cu 62/22 GeV (p_T > 2.0 GeV/c).