Hadron Production at RHIC

- Proving Hot and Dense Matter -

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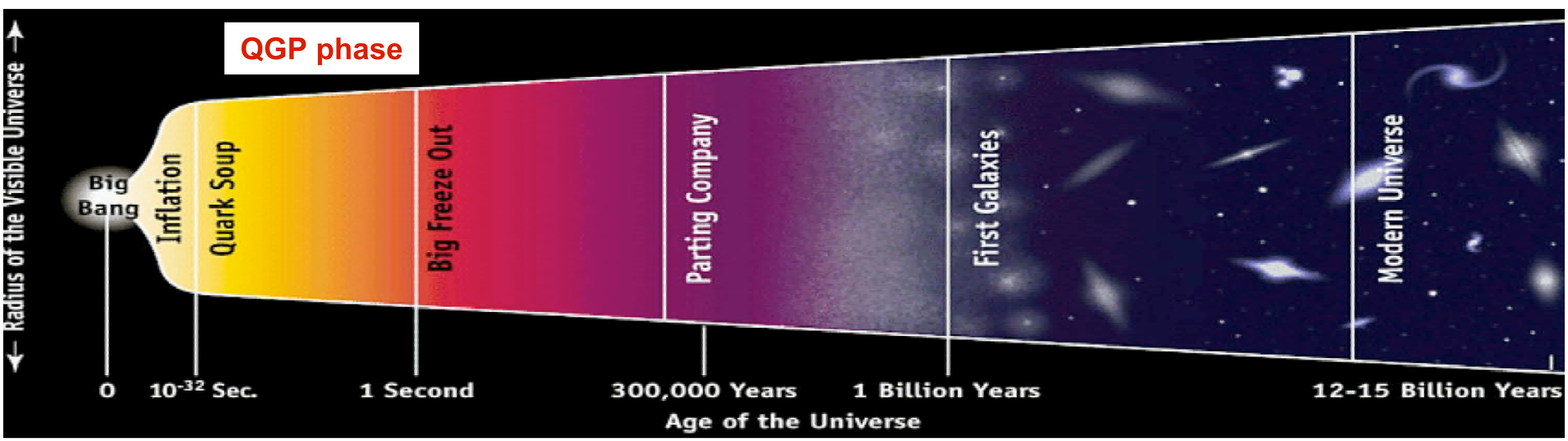
for the PHENIX Collaboration

Heavy-Ion Program at RHIC

PHENIX

- Lattice QCD predicts transition to deconfinement sate of quarks and gluons occurs at:
  - **$T_c \sim 170 \pm 10$ MeV (10^{12} °K) and $\varepsilon_c \approx 1$ GeV/fm^3.**
  - **As existed ~ 1 micro sec after the Big Bang.**

- RHIC is designed to create very high temperature and density matter in the laboratory.



First three years of RHIC run

- **High quality hadron data from RHIC experiments!**

$\pi^{\pm}$, π^0, $K^{\pm}$, K^{*0}, K_s^0, p, d, ρ^0, ϕ, Λ, Ω, Ξ (+ anti-particles) …

- ***Hadron Measurements***
  - Particle ratio, yield, <p_T>.
  - p_T distribution (soft and hard process).
  - HBT correlations.
  - Event anisotropy (v_2).
  - Jet physics.

  etc …

2000 summer (Run-01):	**Au+Au**	**130 GeV**
2001/2002 (Run-02):	**Au+Au**	**200 GeV**
	p+p	**200 GeV**
2002/2003 (Run-03):	**d+Au**	**200 GeV**
	p+p	**200 GeV**


PHENIX
I'm here

PHENIX

Brazil University of São Paulo, São Paulo

China Academia Sinica, Taipei, Taiwan
China Institute of Atomic Energy, Beijing
Peking University, Beijing

France LPC, University de Clermont-Ferrand, Clermont-Ferrand
Dapnia, CEA Saclay, Gif-sur-Yvette
IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
SUBATECH, Ecòle des Mines at Nantes, Nantes

Germany University of Münster, Münster

Hungary Central Research Institute for Physics (KFKI), Budapest
Debrecen University, Debrecen
Eötvös Loránd University (ELTE), Budapest

India Banaras Hindu University, Banaras
Bhabha Atomic Research Centre, Bombay

Israel Weizmann Institute, Rehovot

Japan Center for Nuclear Study, University of Tokyo, Tokyo
Hiroshima University, Higashi-Hiroshima
KEK, Institute for High Energy Physics, Tsukuba
Kyoto University, Kyoto
Nagasaki Institute of Applied Science, Nagasaki
RIKEN, Institute for Physical and Chemical Research, Wako
RIKEN-BNL Research Center, Upton, NY
University of Tokyo, Bunkyo-ku, Tokyo
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University of Tsukuba, Tsukuba
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S. Korea Cyclotron Application Laboratory, KAERI, Seoul
Kangnung National University, Kangnung
Korea University, Seoul
Myong Ji University, Yongin City
System Electronics Laboratory, Seoul Nat. University, Seoul
Yonsei University, Seoul

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Joint Institute for Nuclear Research, Dubna
Kurchatov Institute, Moscow
PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
St. Petersburg State Technical University, St. Petersburg

Sweden Lund University, Lund

*12 Countries; 57 Institutions; 460 Participants**

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Columbia University, Nevis Laboratories, Irvington, NY
Florida State University, Tallahassee, FL
Georgia State University, Atlanta, GA
University of Illinois Urbana Champaign, Urbana-Champaign, IL
Iowa State University and Ames Laboratory, Ames, IA
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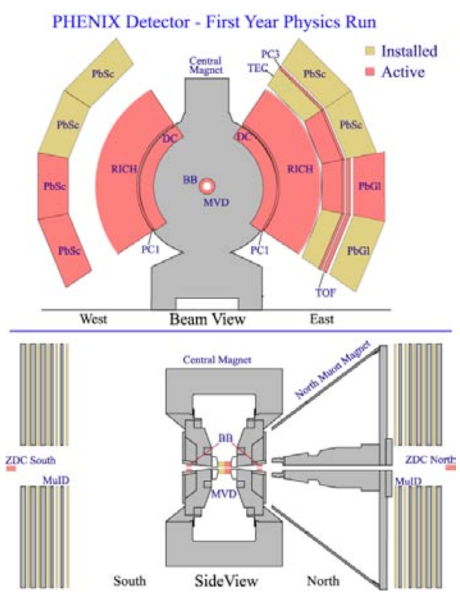
*as of July 2002

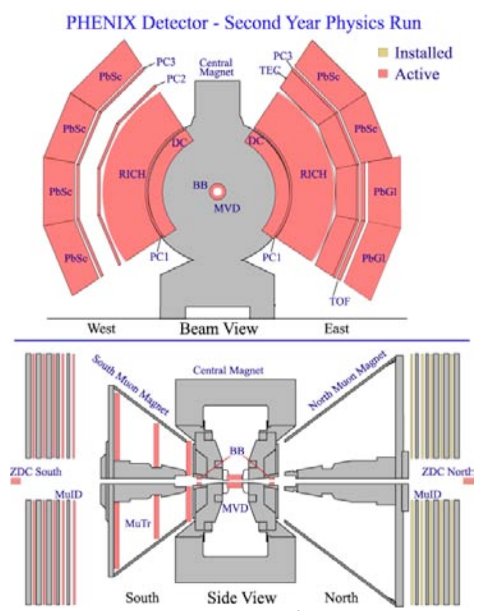
PHENIX Run History

Run	Year	Species	$s^{1/2}$ [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 nb^{-1}	5.5G	1.1 pb^{-1}	46 TB
		p-p	200	0.35 pb^{-1}	6.6G	0.35 pb^{-1}	35 TB

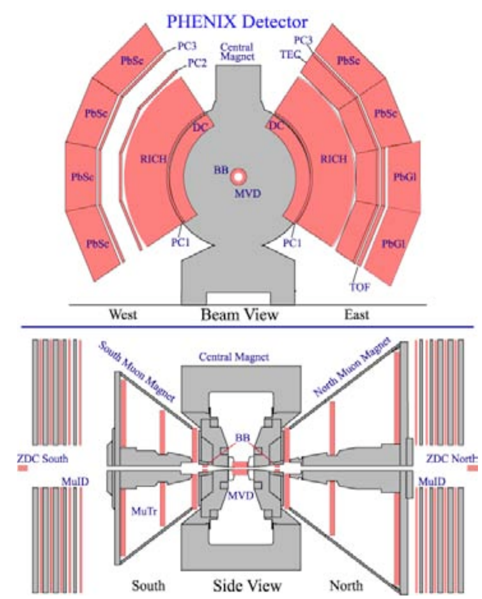
Run-1



Run-2



Run-3



PHENIX Goals and Achievements

- Goal: To measures all possible signatures at once for proving **QGP**.
  - Hadrons, leptons and photon.
- Accomplished baseline measurements by 3 RHIC runs.
  - 22 publications (including e-print, as of Oct. 27. 2003)
  - Much remains
    - Truly rare probes in Au-Au, Species & energy scans.

Conceptual Design Report (29-Jan-1993)

Quantity to be Measured	Category*	Physics Objective
e^+e^-, $\mu^+\mu^-$		
• $\rho \to \mu^+\mu^- / \rho \to \pi\pi$, $d\sigma/dp_\perp$	BCD	Basic dynamics (T, τ, etc.,) for a hot gas,
$\omega \to e^+e^- / \omega \to \pi\pi$, $d\sigma/dp_\perp$		transverse flow, etc.
• ϕ-meson's width and $m_{\phi\to e^+e^-}$	QGP	Mass shift due to chiral transition (C.T.) [2]
$\phi \to e^+e^- / \phi \to K^+K^-$	QGP	Branching ratio change due to C.T. [3]
ϕ-meson yield (e^+e^-)	ES	Strangeness production ($gg \to s\bar{s}$)
• $J/\psi \to e^+e^-, \mu^+\mu^-$	QGP, QCD	Yield suppression and the distortion
$\psi' \to \mu^+\mu^-$		of p_T spectra due to Debye screening
$\Upsilon, \to \mu^+\mu^-$		in deconfinement transition (D.T.) [4]
• $1 < m_T(l^+l^-) < 3$ GeV	ES, QGP	Thermal radiation of hot gas, and
(rate and shape)		effects of QGP [5, 6, ?]
• $m_{l^+l^-} > 3$ GeV $\to \mu^+\mu^-$	QCD	A-dependence of Drell-Yan, and
	QGP	thermal $\mu^+\mu^-$ [5, 6, 7, 8]
• $\sigma \to \pi\pi, e^+e^-, \gamma\gamma$	QGP	Mass shift, narrow width due to C.T. [2]
$e\mu$ coincidence		
• $e\mu$, $e(p_T > 1$ GeV/c$)$	QCD, QGP	$c\bar{c}$ background, charm cross section [9]
Photons		
• $0.5 < p_T < 3$ GeV/c γ	ES, QGP	Thermal radiation of hot gas, and
(rate and shape)		effect of QGP [6, 7]
• $p_T > 3$ GeV/c γ	QCD	A-dependence of QCD γ
• π^0, η spectroscopy	BCD	Basic dynamics of hot gas, strangeness in η
• $N(\pi^0)/N(\pi^+ + \pi^-)$ fluctuations	QGP	Isospin correlations and fluctuations [10, 11]
• High p_T π^0, η from jet	QGP	Reduced dE/dx of quarks in QGP [12]
Charged Hadrons		
• p_T spectra for $\pi^\pm$, $K^\pm$, p, $\bar{p}$	BCD	Basic dynamics, flow, T, baryon density,
		stopping power, etc.
	QGP	Possible second rise of $< p_T >$ [13]
• $\phi \to K^+K^-$	ES, QGP	Branching ratio, mass width [3, 14]
• K/π ratios	ES	Strangeness production
• $\pi\pi$ + KK HBT	BCD	Evolution of the collision, $R_\perp$
	QGP	Long hadronization time ($R_{out} \gg R_{side}$) [15]
• Antinuclei	QGP	High baryon susceptibility due to C.T.? [16]
• high p_T hadrons from jet	QGP	Reduced dE/dx of quarks in QGP [12]
Global		
• N_{tot} (total multiplicity)	BCD	Centrality of the collision
• $dN/d\eta, d^2N/d\eta d\phi, dE_T/d\eta$	BCD	Local energy density, entropy
	QGP	Fluctuations, droplet sizes [17]

* BCD = Basic collisions dynamics. ES = Thermodynamics at early stages.
QGP = Effect of QGP phase transition. QCD = Study of basic QCD processes.

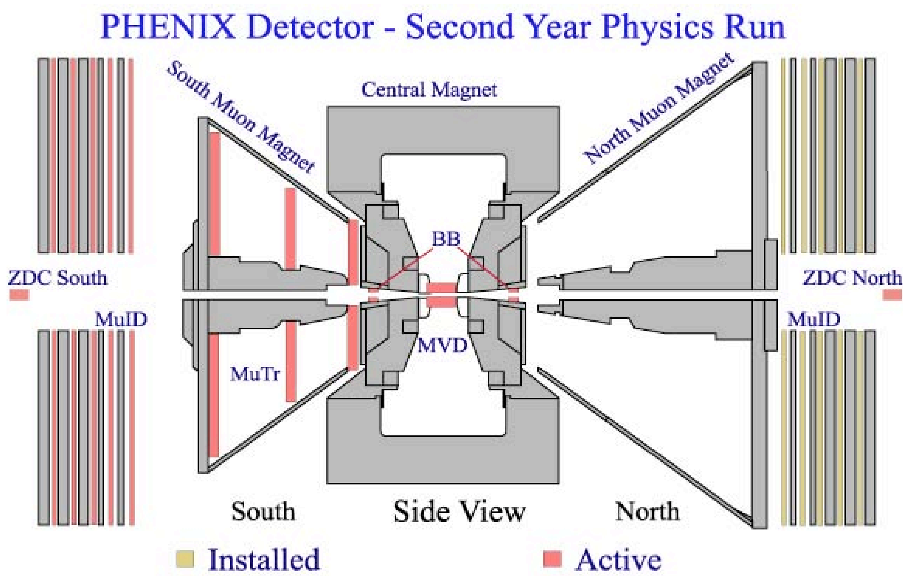
Outline of this talk

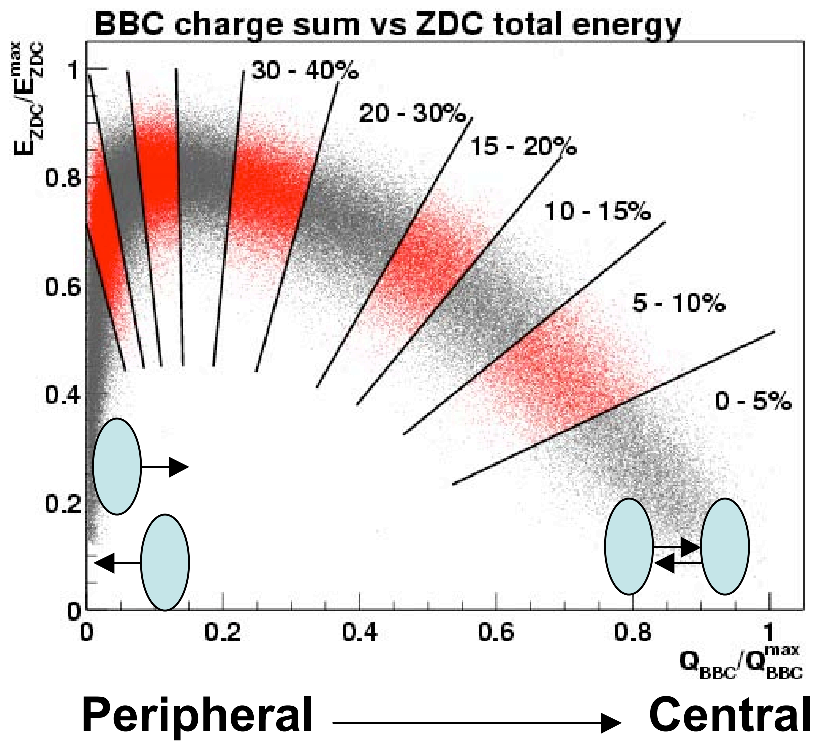
We present the results on hadron production (mainly from PHENIX experiment) and overview the current understanding of hot and dense matter produced at RHIC from hadron production viewpoint.

- Physics Topics (in different p_T regions) -

- **Low p_T (< 2 GeV/c)**
  - Bulk properties : Energy density and charged multiplicity.
  - Hydrodynamical behavior and chemical properties in AuAu.
  - Space-time evolution of the system (HBT correlation).
  - Event anisotropy (elliptic flow v_2).
- **High p_T (5 > GeV/c)**
  - Jet quenching in Au+Au
  - d+Au experiment
- **Intermediate p_T (2 - 5 GeV/c)**
  - Scaling behavior of baryon and particle compositions.

PHENIX Event Characterization



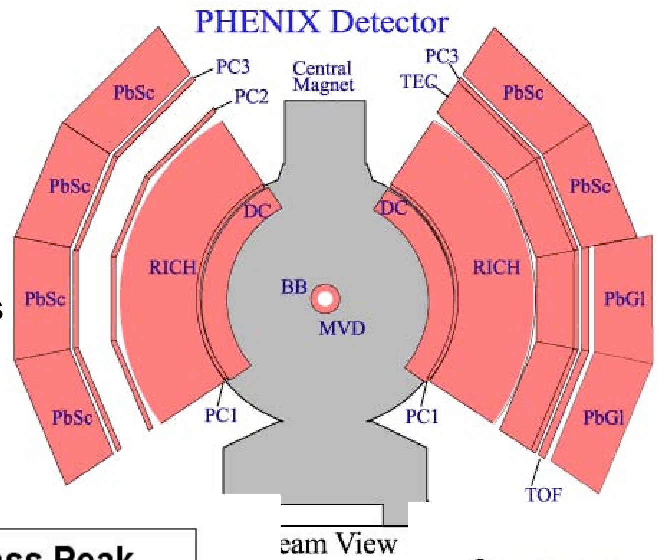


- Centrality selection : Used charge sum of Beam-Beam Counter (**BBC**, $|\eta|$=3~4) and energy of Zero-degree calorimeter (**ZDC**) in minimum bias events (92% of total inelastic cross sections).
- Extracted $\mathbf{N}_{\mathbf{coll}}$ and $\mathbf{N}_{\mathbf{part}}$ based on Glauber model.

PHENIX Hadron PID

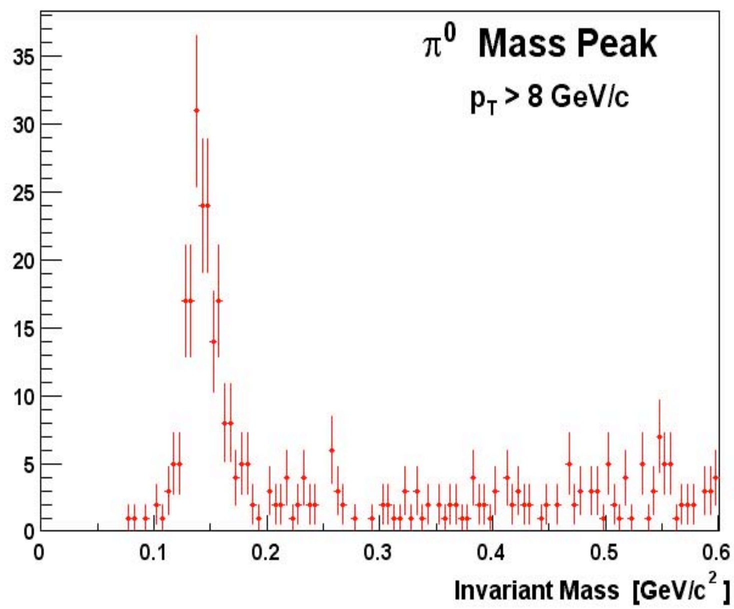
π^0 PID by EMCal

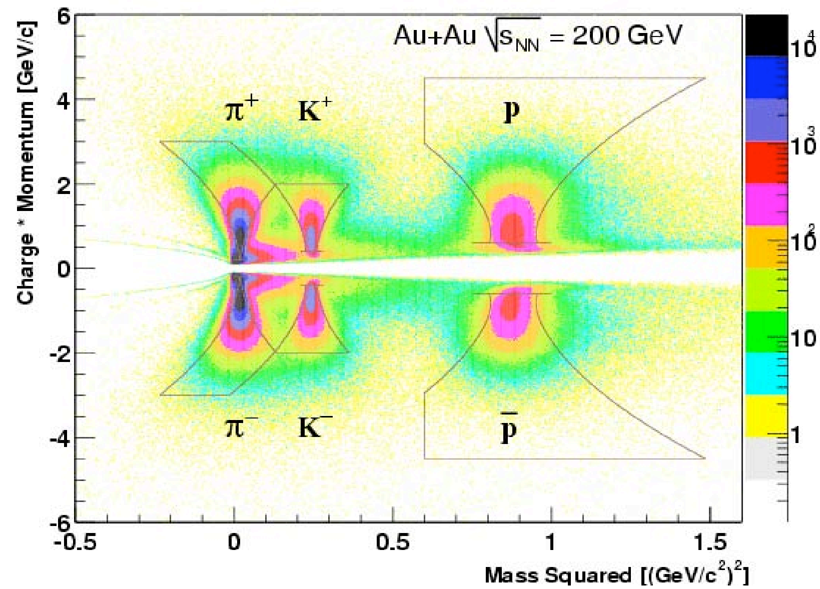
via $\pi^0 \rightarrow \gamma\gamma$ ($1<p_T<10$GeV/c)
6 lead- Scintillator (PbSc) sectors
2 lead- glass (PbGl) sectors
$\Delta\phi = \pi$
$\Delta\eta = 0.7$



Charged PID by TOF

(DCH+PC1+TOF+BBC)
π/K < 2 GeV/c, K/p < 4 GeV/c
$\Delta\phi = \pi/8$

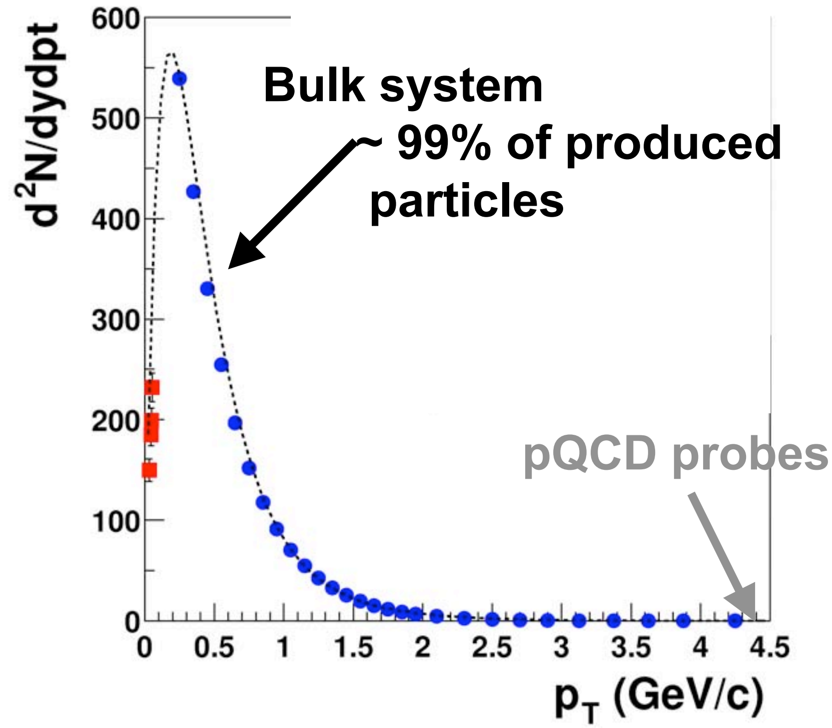




(1) Particle Production at low p_T - Soft Physics -

Bulk Effects

- Equilibration
- Equation of State
- Spatial and Temporal extents

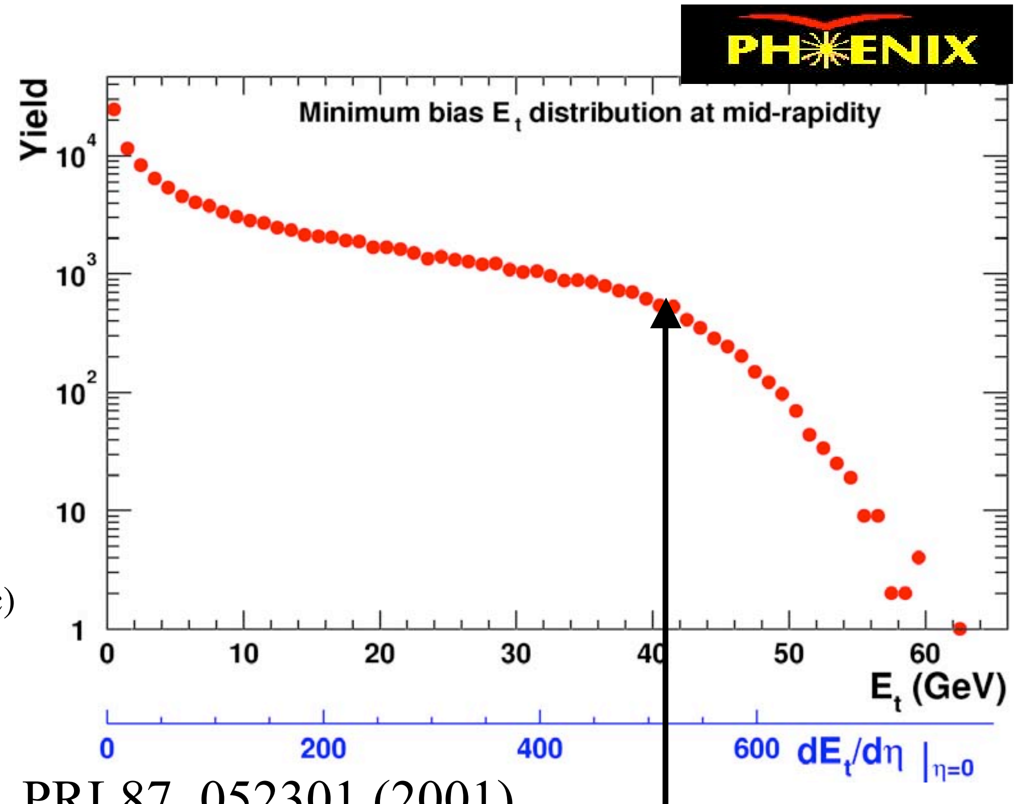


Energy Density High Enough?

Bjorken Formula:

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{c\tau_0} \frac{dE_T}{dy}$$
$$\approx 4.6 \mathrm{GeV/fm}^3$$
$$> \varepsilon_c \approx 0.6 - 1.2 \mathrm{GeV/fm}^3$$

* τ_0: Effective thermalization time (0.2 - 1.0 fm/c)



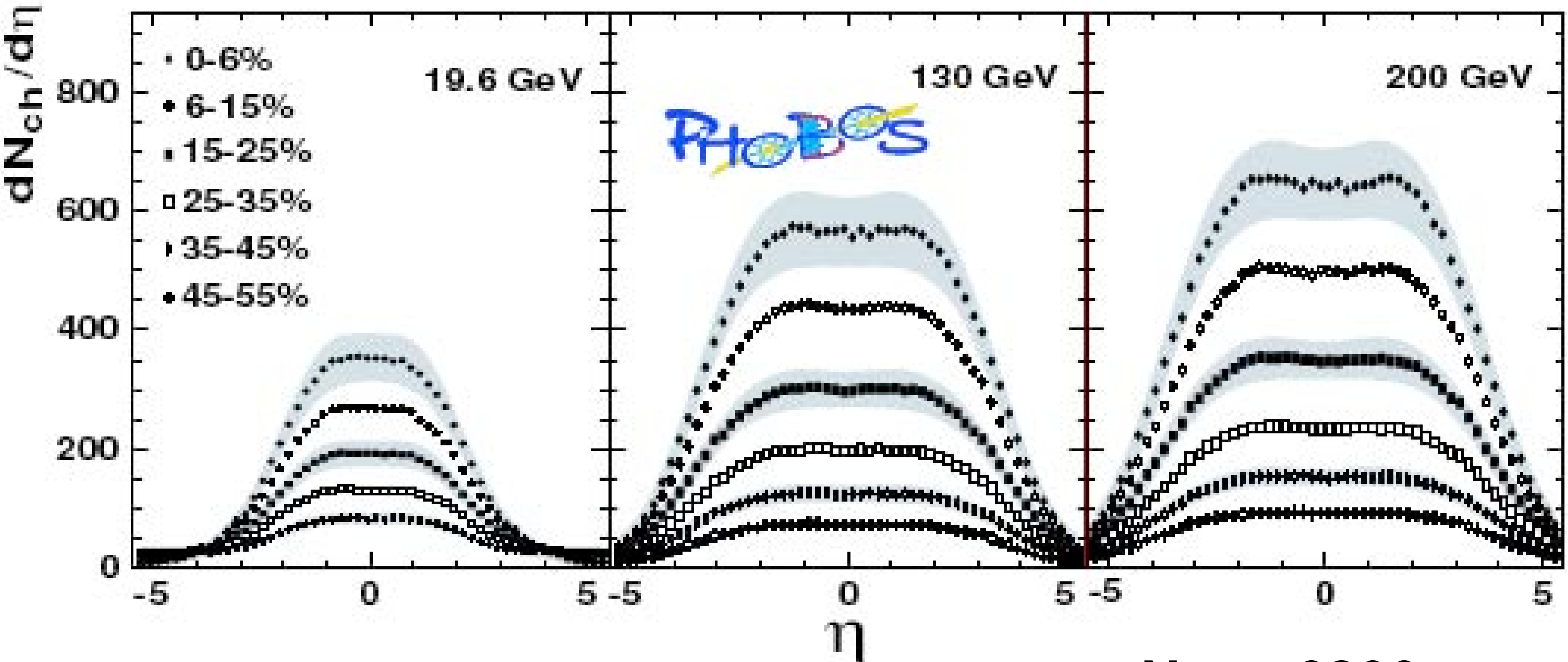
PRL87, 052301 (2001)

→ $\varepsilon \geq$ 4.6 GeV/fm³ (130 GeV Au+Au)

5.5 GeV/fm³ (200 GeV Au+Au)

Well above predicted transition!

Charged Particle Multiplicity



N_{tot} = 5000
(Au+Au 130 GeV, central)

N_{tot} = 6200
(Au+Au 200 GeV, central)

In initial volume ~ $V_{nucleus}$
Rescattering should be important!

PID p_T Spectra

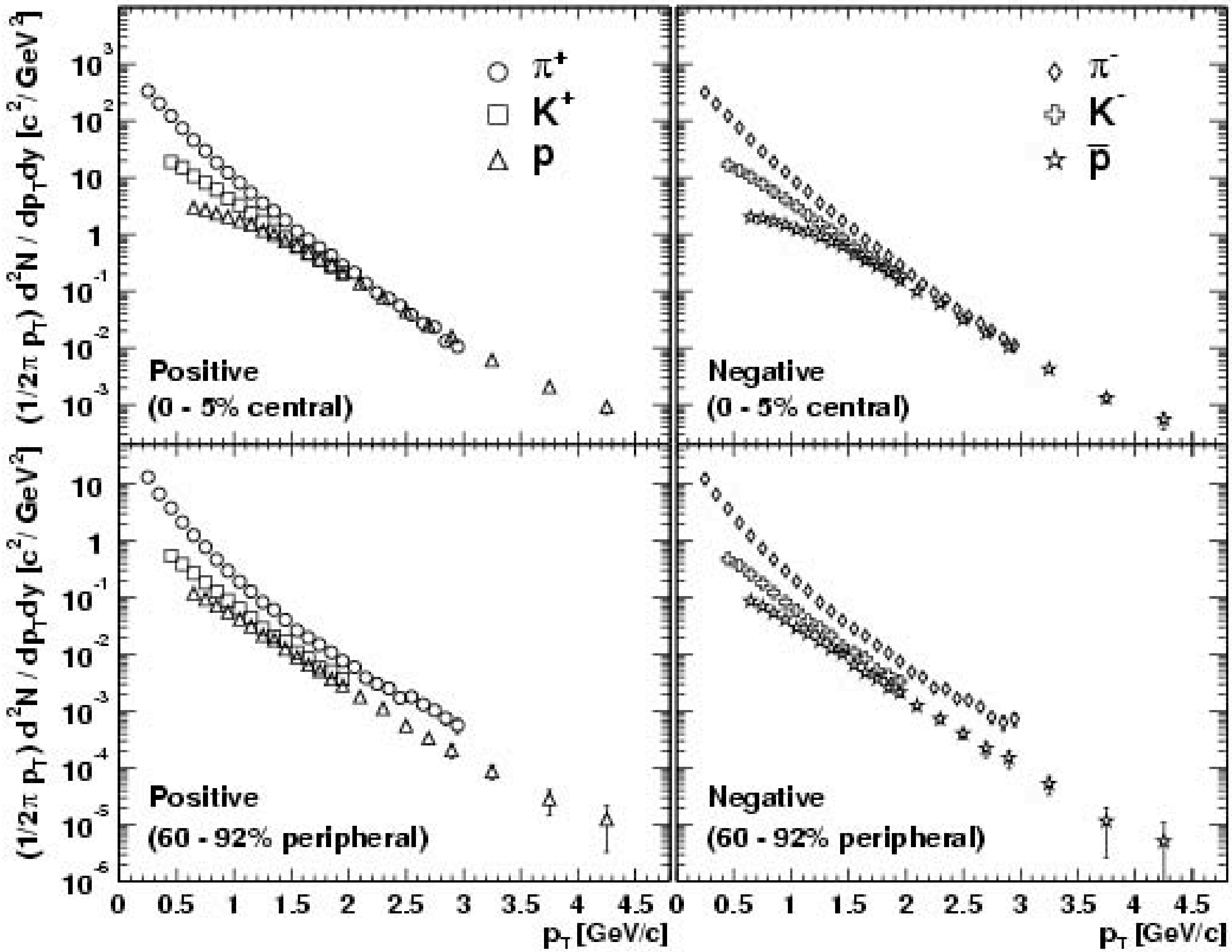
Central

- low p_T slopes increase with particle mass
- proton and anti-proton yields equal the pion yield at high p_T.

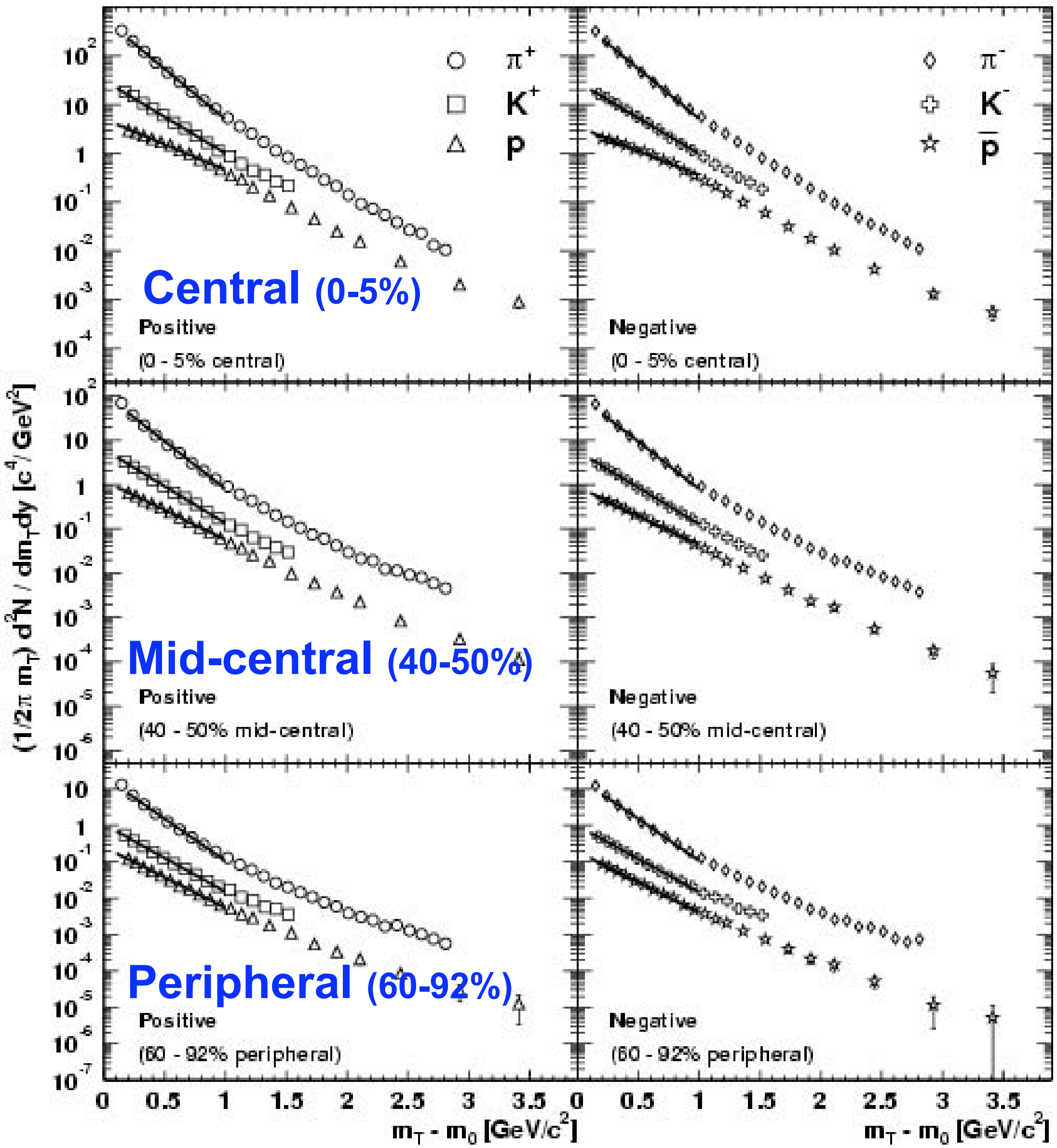
Peripheral

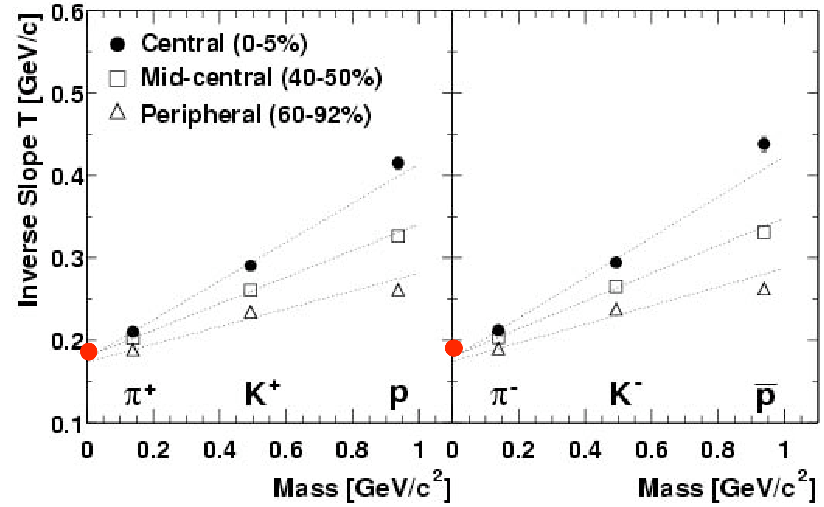
- mass dependence is less pronounced
- similar to pp

PHENIX: PRC accepted, nucl-ex/0307022



m_T - m_0 Spectra





- **Clear mass and centrality dep. in slope parameter *T*.**
- **Consistent with collective flow picture.**

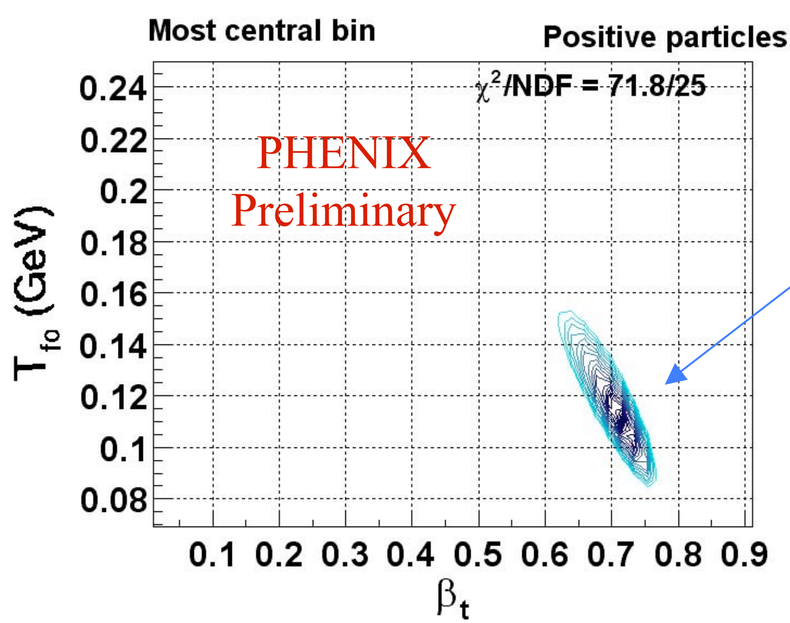
PHENIX: PRC accepted,
nucl-ex/0307022

Blast-wave fit and kinetic freeze-out

E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. C 48, 2462 (1993)

$$\frac{dN}{m_T dm_T} \propto \int_0^R r \cdot dr \cdot m_T \cdot I_0\left(\frac{p_T sinh\rho}{T}\right) \cdot K_1\left(\frac{m_T sinh\rho}{T}\right)$$

$$\beta = \beta_{\max}\left(\frac{r}{R}\right)^{1,2} \qquad \rho = \tanh^{-1}\beta$$



QM02 talk, J. Burward-Hoy

Au+Au 200 GeV (central)

Freeze-out Temperature

T_{fo} = 110 ± 23 MeV

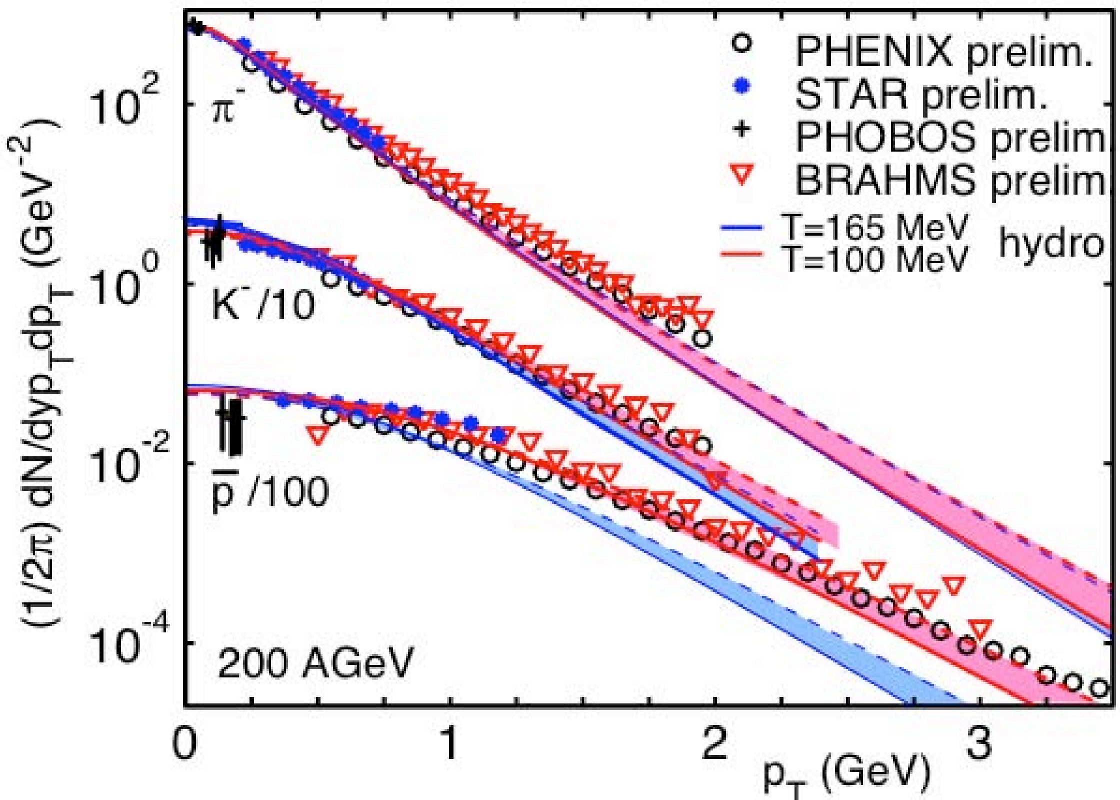
Transverse flow velocity

β_T = 0.7 ± 0.2

($\langle\beta_T\rangle$= 0.47)

p_T Spectra for All 4 Experiments and Hydrodynamical Model

Data: PHENIX: NPA715(03)151; STAR: NPA715(03)458; PHOBOS: NPA715(03)510; BRAHMS: NPA715(03)478
Hydro-calculations including chemical potentials: P.Kolb and R. Rapp, Phys. Rev. C 67 (03) 044903



* Note: all data points are preliminary results (QM02).

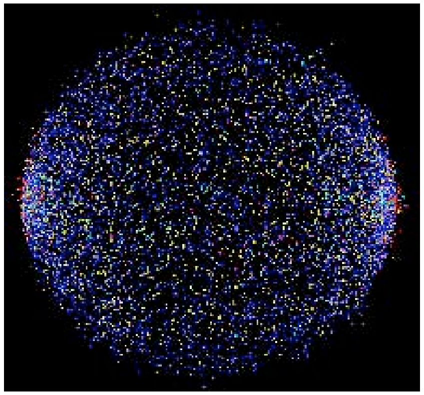
Calculations → too long a system lifetime
Enormous initial pressure, but decouples quickly (~10 fm/c)

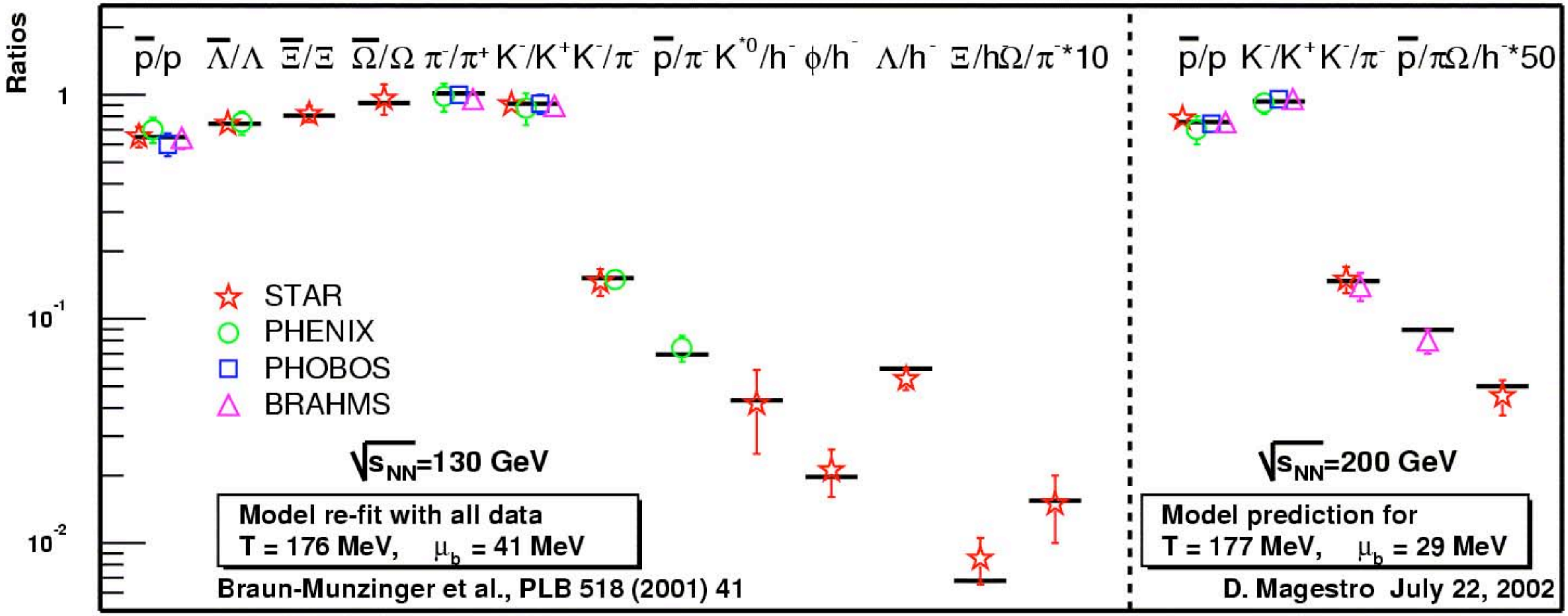
Hydrodynamics describes all p_T spectra up to 2 GeV/c.

Evidence for equilibrated final state

- Almost complete reconstruction of hadronic state when system decouples by the statistical thermal model.

- Fit yields vs. mass (grand canonical ensemble)
  - ➢ T_{ch} = 177 MeV, μ_B = 29 MeV @ 200 GeV central AuAu.





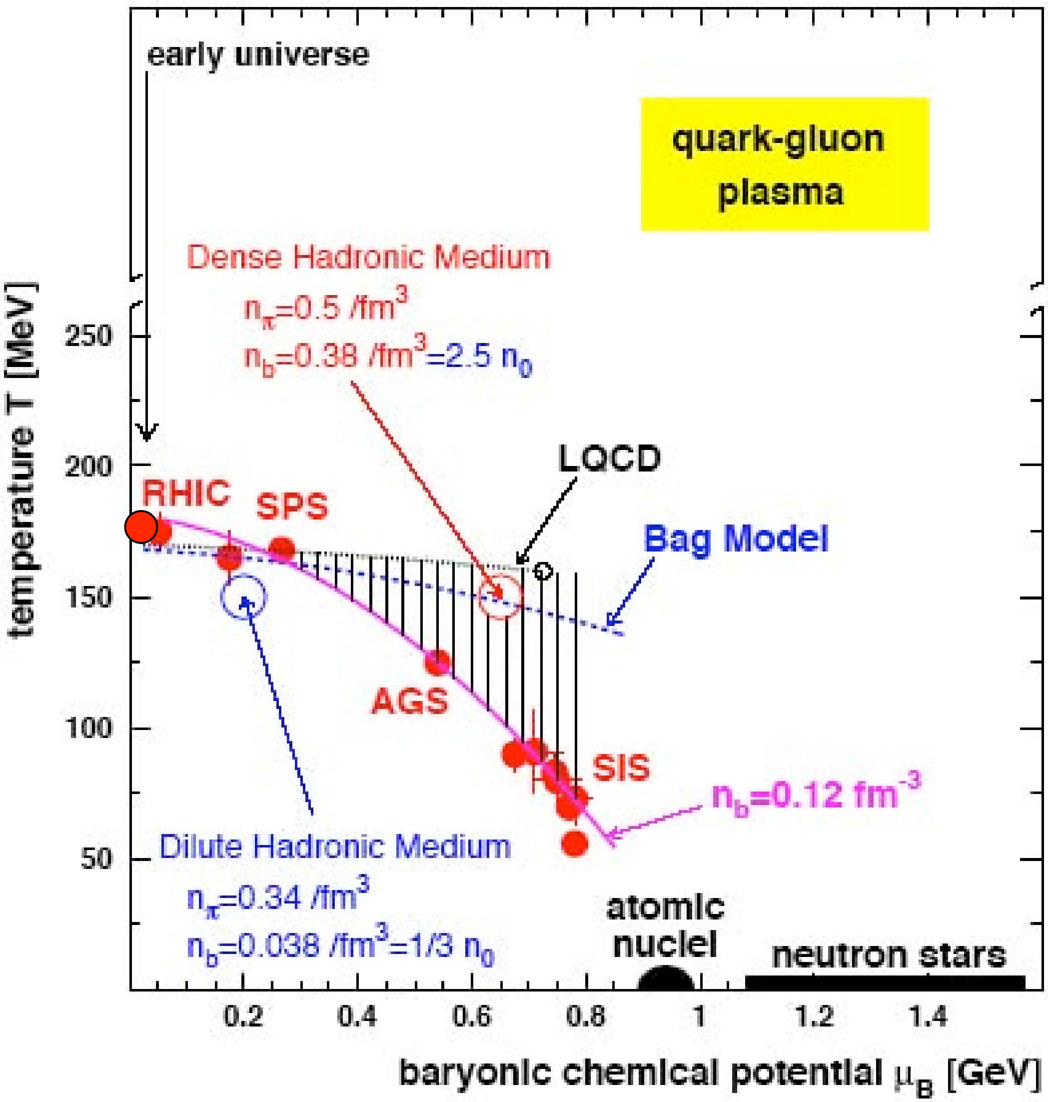
T_{ch} vs. μ_B from thermal model

PBM, J. Stachel, nucl-th/0112051, J. Phys. G28, 1971 (2002)

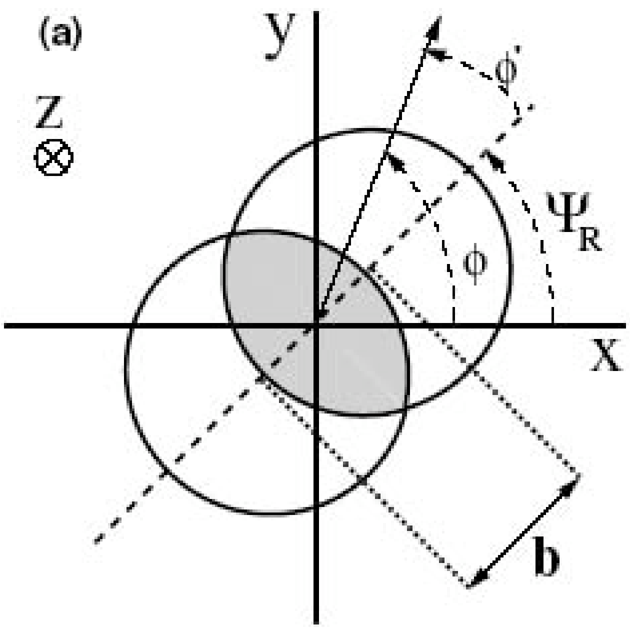
- **Statistical thermal model**

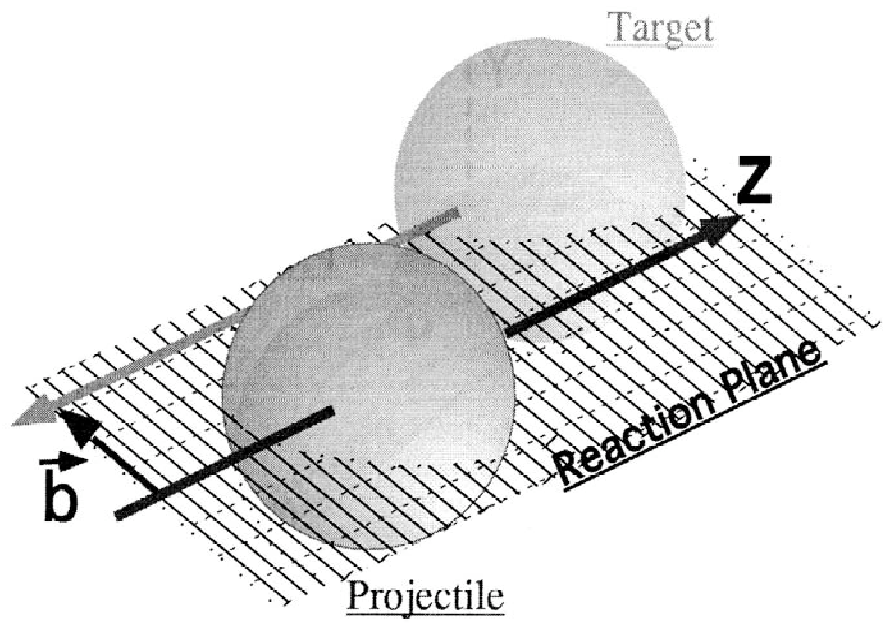
$$\rho_i = \frac{g_i}{2\pi}\int \frac{p^2 dp}{\exp\left(E_i - \mu_i / T_{ch}\right) \pm 1}$$

- **RHIC and SPS points are very close to the phase boundary of lattice QCD.**



• **Elliptic flow is expected to be sensitive to the early stage of the collision.**



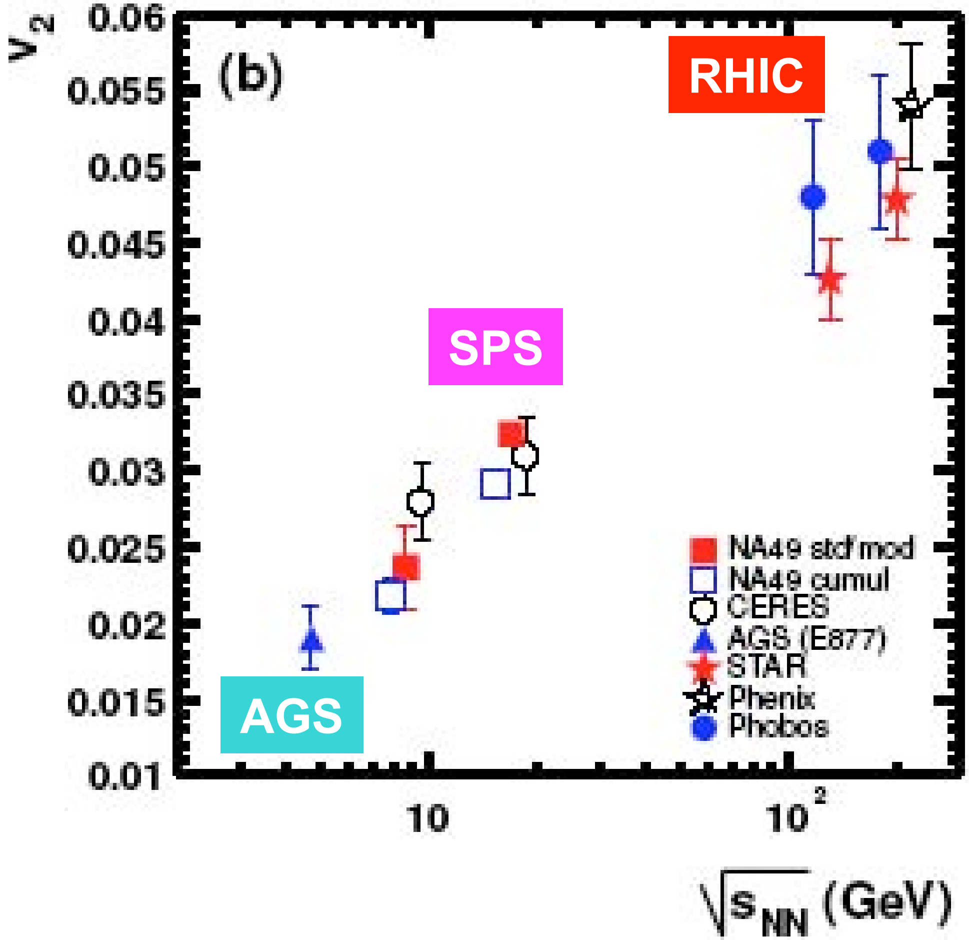


$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_R)$$

v_2: 2nd harmonic coefficient of a Fourier expansion in ϕ.

$\sqrt{s}$ dependence of integrated v_2

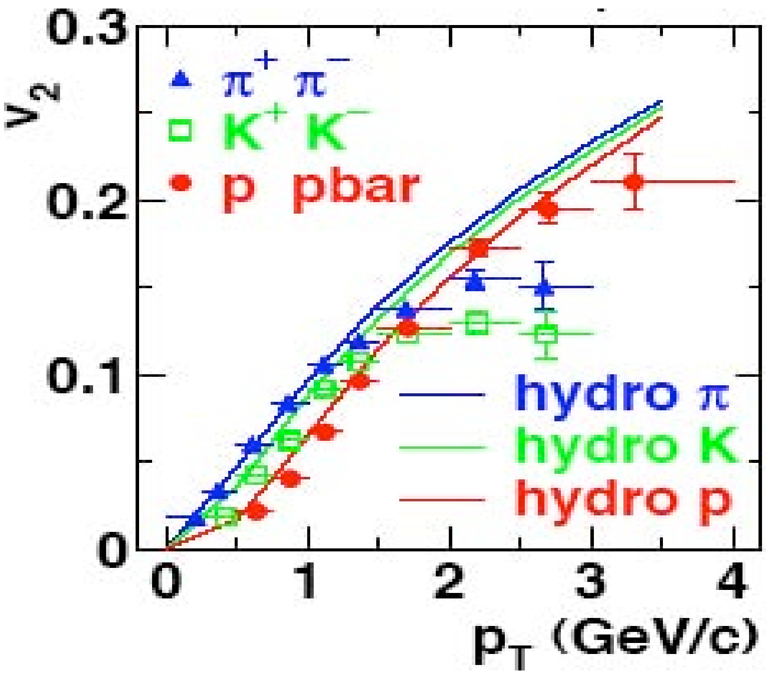
C. Alt et al., PRC 68, 034903 (2003)



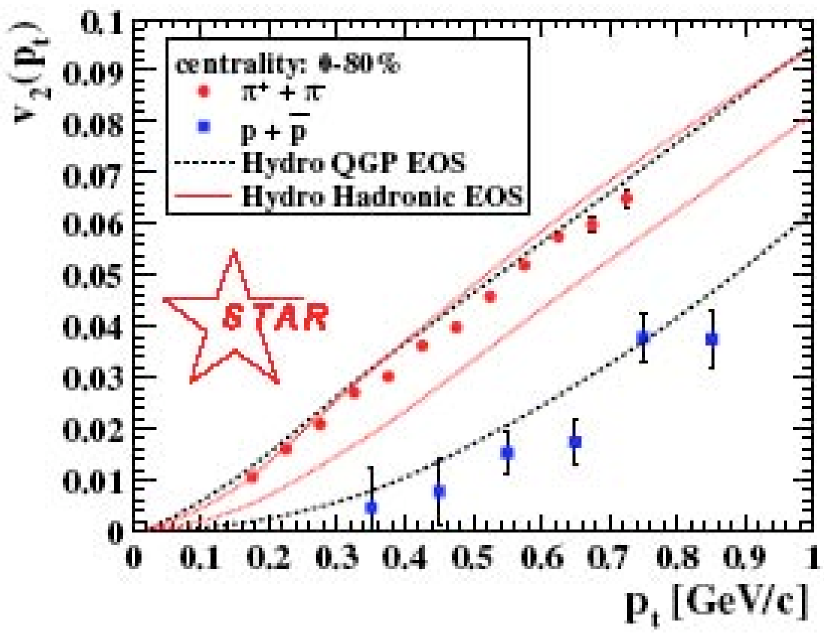
- Smooth increase from AGS-SPS-RHIC.
- Highest v_2 @ RHIC: qualitative agreement with hydro model.

p_T dependence of v_2

PHENIX: nucl-ex/0305013
Au+Au 200 GeV



STAR: PRL 87, 182301 (2001)
Au+Au 130 GeV



- **Good agreement with QGP type EOS at low p_T.**
- **Start to deviate from hydro calc. at p_T > 2 GeV/c.**

  → ***Data shows a different p_T dependence between meson and baryon!***

Universality of $v_2(p_T)$?

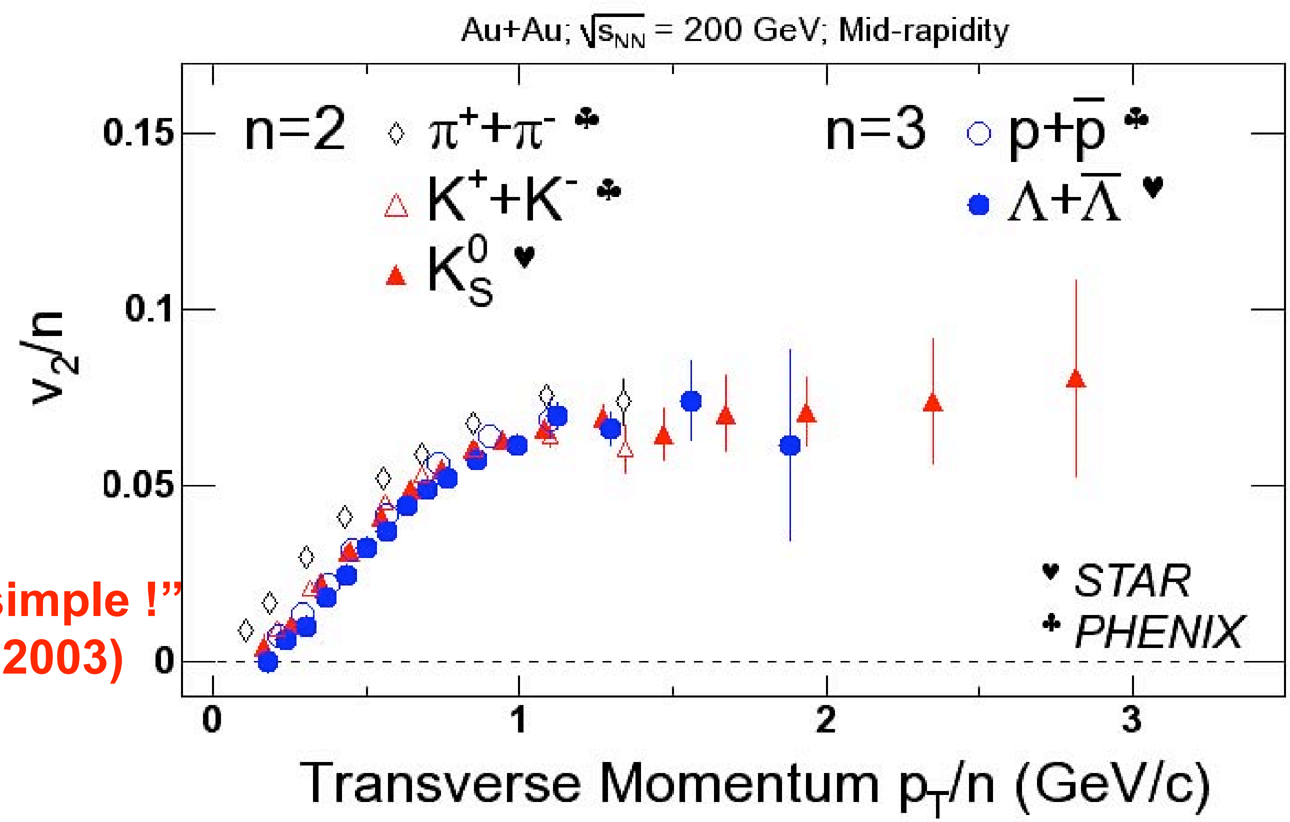
The *complicated* observed flow pattern in $v_2(p_T)$ is predicted to be *simple* at the quark level under

$p_T \rightarrow p_T / n$, $v_2 \rightarrow v_2 / n$, n = 2,3 for meson,baryon

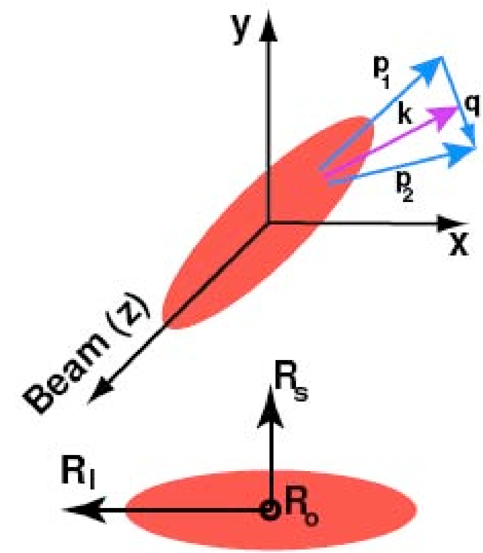
***if* the flow pattern is established at the quark level**

Compilation courtesy of H. Huang

"RHIC Physics is simple !"
(B. Muller, CIPANP2003)



- **Proving the spatial and temporal extents of source: HBT correlation.**



Bertsch-Pratt parameterization

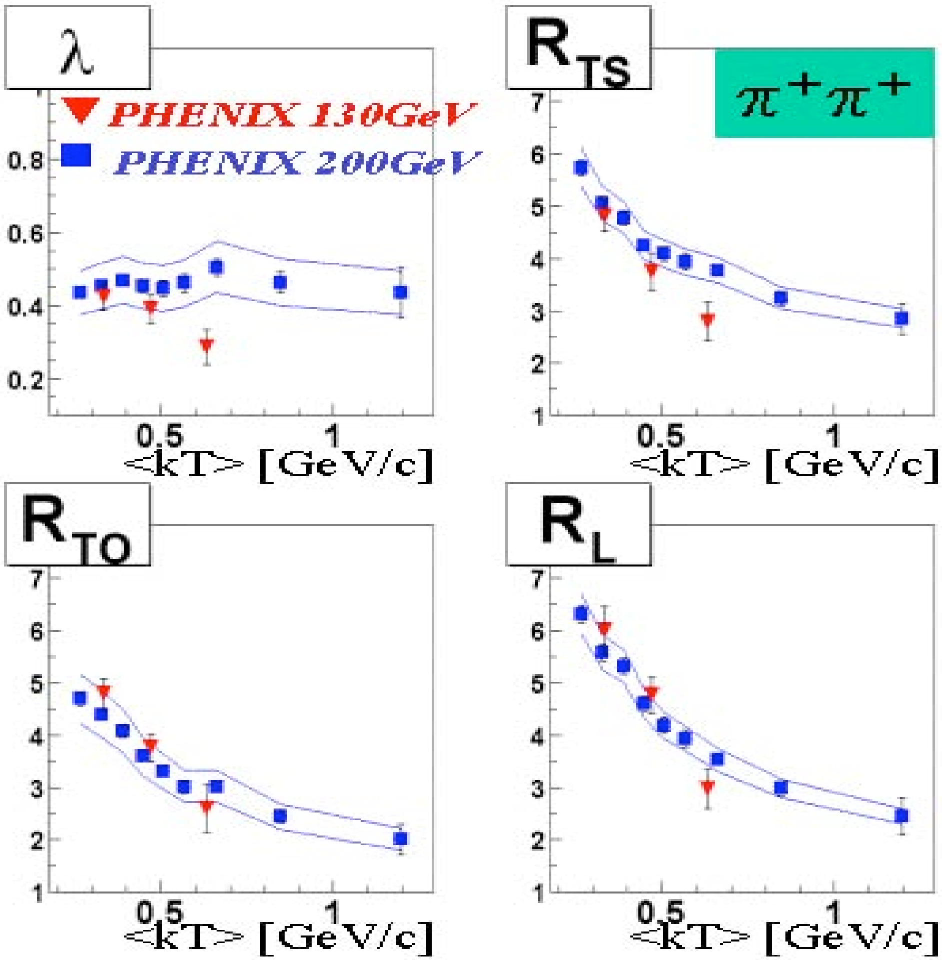
$$C_2 = 1 + \lambda \exp\left(- R_{\text{side}}^2 q_{\text{side}}^2 - R_{\text{out}}^2 q_{\text{out}}^2 - R_{\text{long}}^2 q_{\text{long}}^2\right)$$

$$R_{\text{out}} = \left\langle (\tilde{x} - \beta_\perp \tilde{t})^2 \right\rangle^{1/2}$$

$$R_{\text{side}} = \left\langle \tilde{y}^2 \right\rangle^{1/2}$$

$$R_{\text{long}} = \left\langle \tilde{z}^2 \right\rangle^{1/2}$$

K_T dependence of R



Au+Au central 0-30%

QM02 talk, A. Enokizono

- **Applied the standard full Coulomb correction.**
- **All R parameters decrease as a function of k_T**
  ⇒ consistent with collective expansion picture (x-p correlation with collective flow).

However…

k_T : average momentum of pair

Comparison with hydrodynamic model

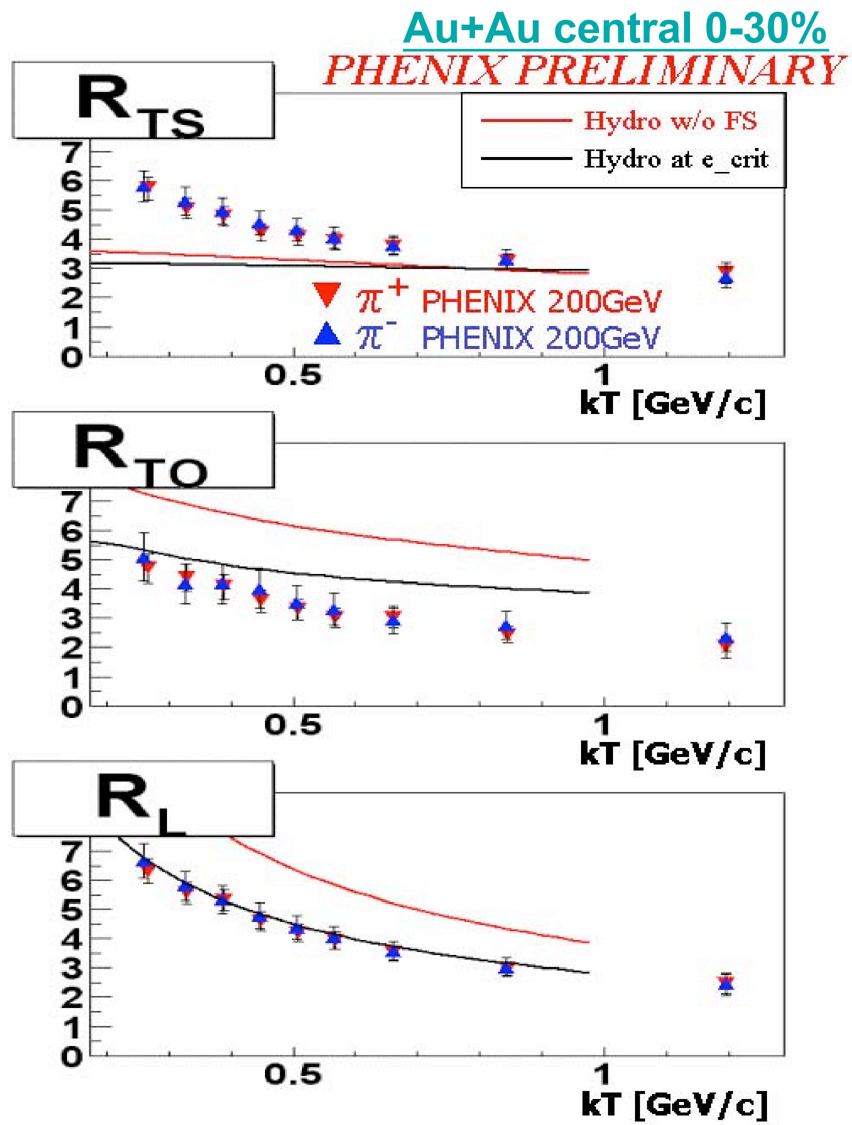
Hydrodynamic calculation by U.Heinz and P. F. Kolb (hep-ph/0204061)

Hydro w/o FS

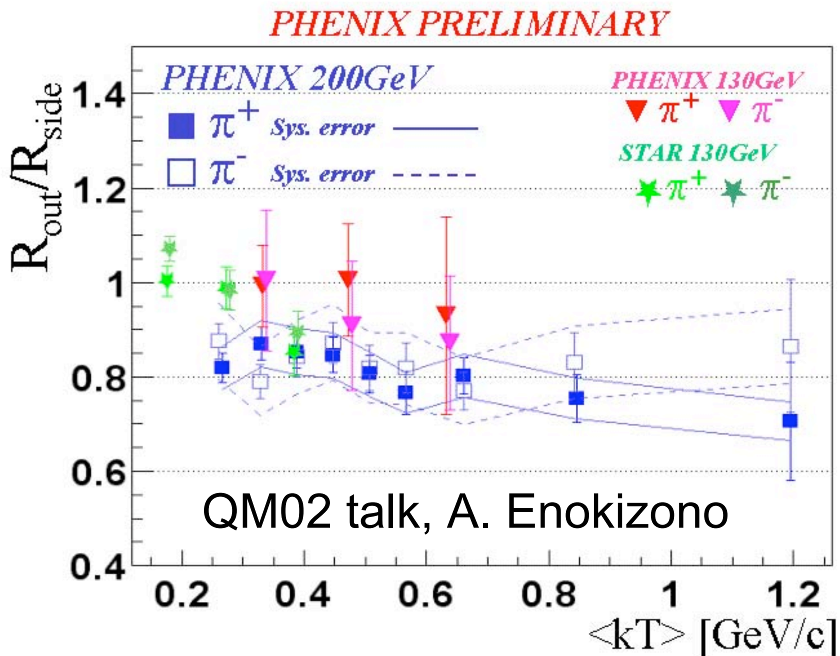
• Standard initialization and freeze out which reproduce single particle spectra.

Hydro at e_{crit}

• Assuming freeze out directly at the hadronization point. ($e_{dec} = e_{crit}$)

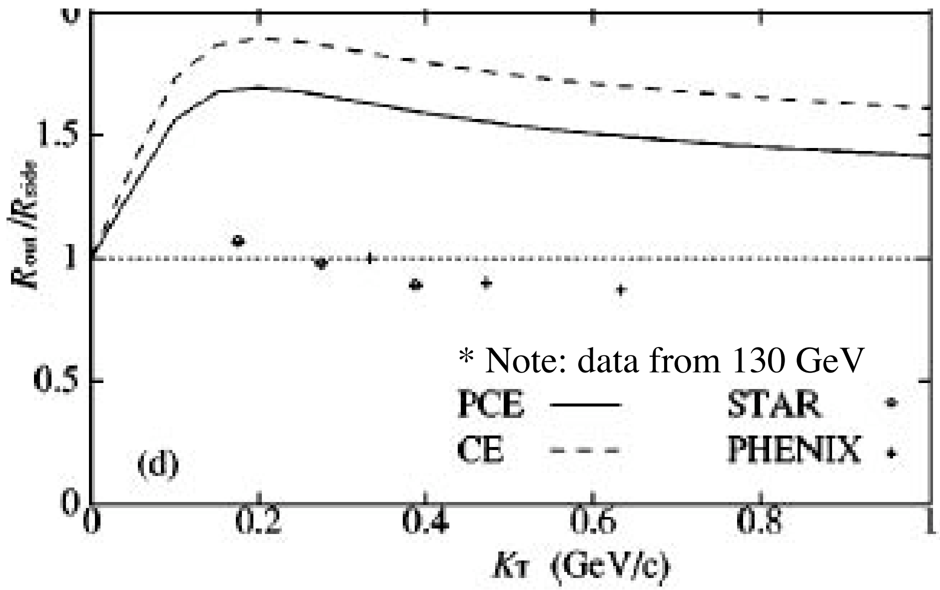


R_{out}/R_{side} vs. K_T



* Standard full Coulomb correction

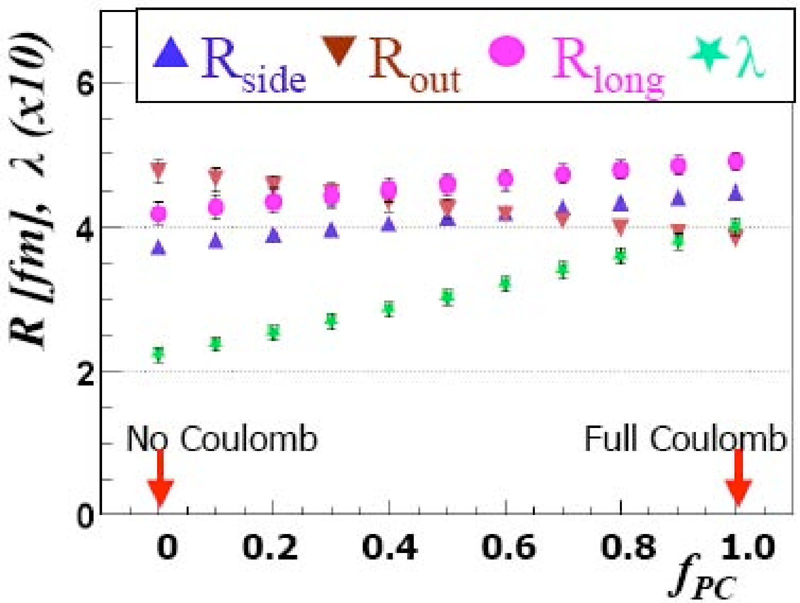
Hirano & Tsuda, PRC, 054905 (2002).

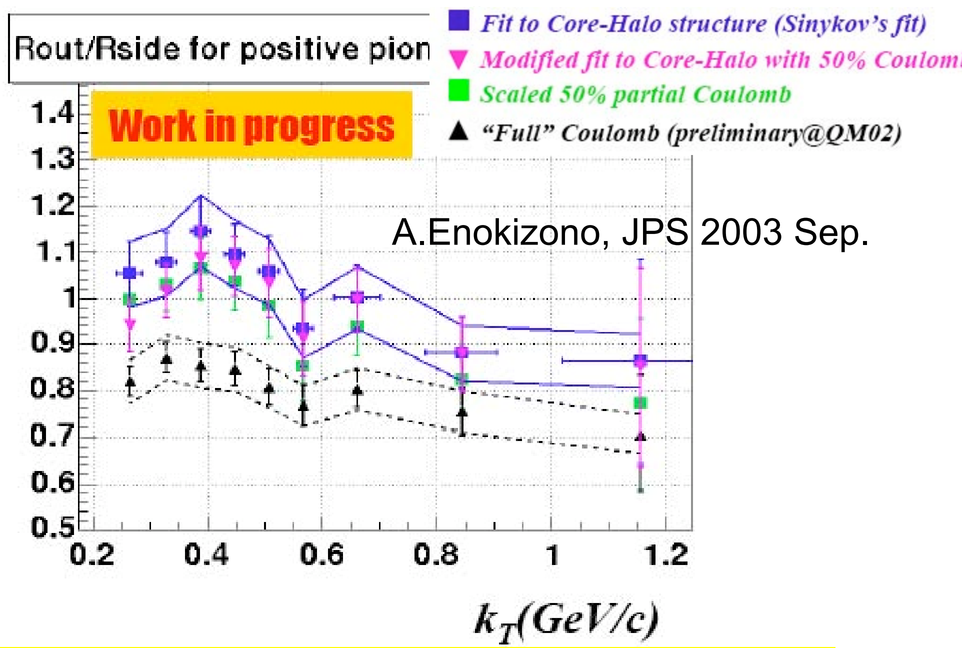


- Data shows $R_{out}/R_{side} \leq 1$, and constant with k_T.
- Hydro calculation predicts **$R_{out}/R_{side} \sim 1.5$.**

"HBT puzzle"

Revisit Coulomb Corrections!





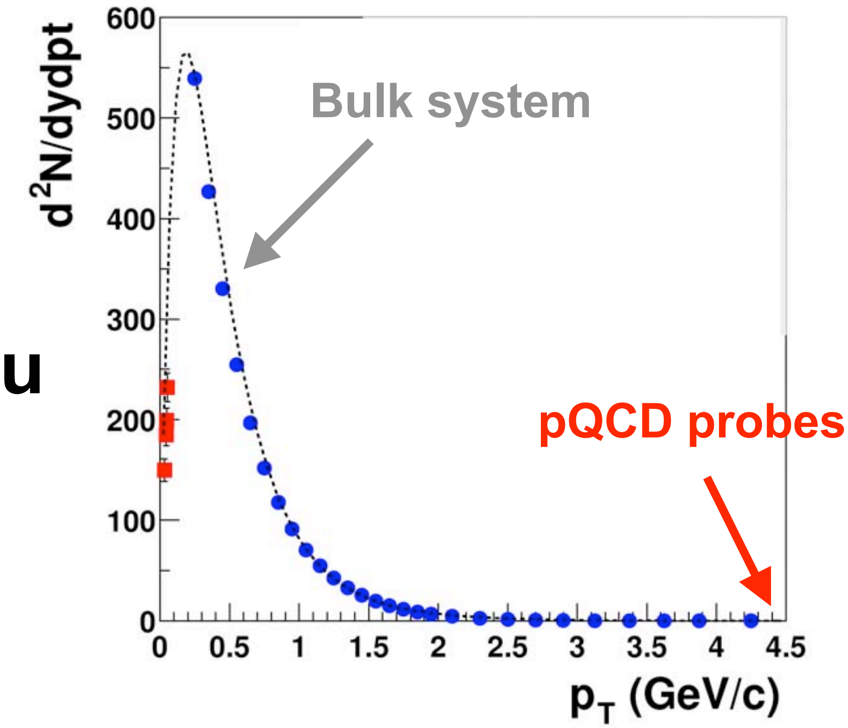
- Taking into account the contribution from the long-lived resonance.
  → **"Core-Halo" source picture** ("Sinyukov's fit").
  → Fraction of coulomb corr. can be determined by data ($\pi^+\pi^-$ correlation).

R_{out}/R_{side} (full coulomb) < R_{out}/R_{side} (partial coulomb)

- **Work in progress on pair efficiency correction.**
- **Final results will appear soon!**

(2) High p_T Particle Production
- Hard Process -

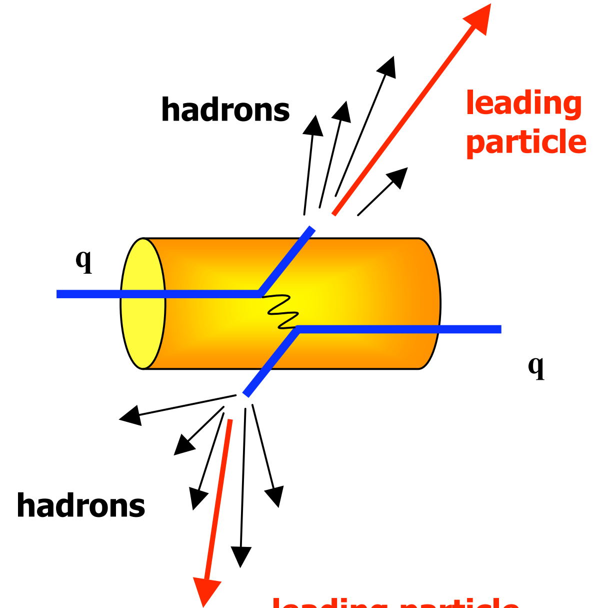
- Jet quenching effect.
- Control experiment: d+Au



Hard Scattered Partons

- Used "calibrated" probe (p+p data).
- Hard scatterings in nucleon collisions produce jets of particles.
  - hadron structure function
  - hard scattering parton (pQCD)
  - fragmentation of partons
- In the presence of a color-deconfined medium, the partons lose their energy (~GeV/fm) via gluon bremsstrahlung.
  - **"Jet Quenching"**
    $\propto$ Color Charge Density

"gluonometer"



PHENIX

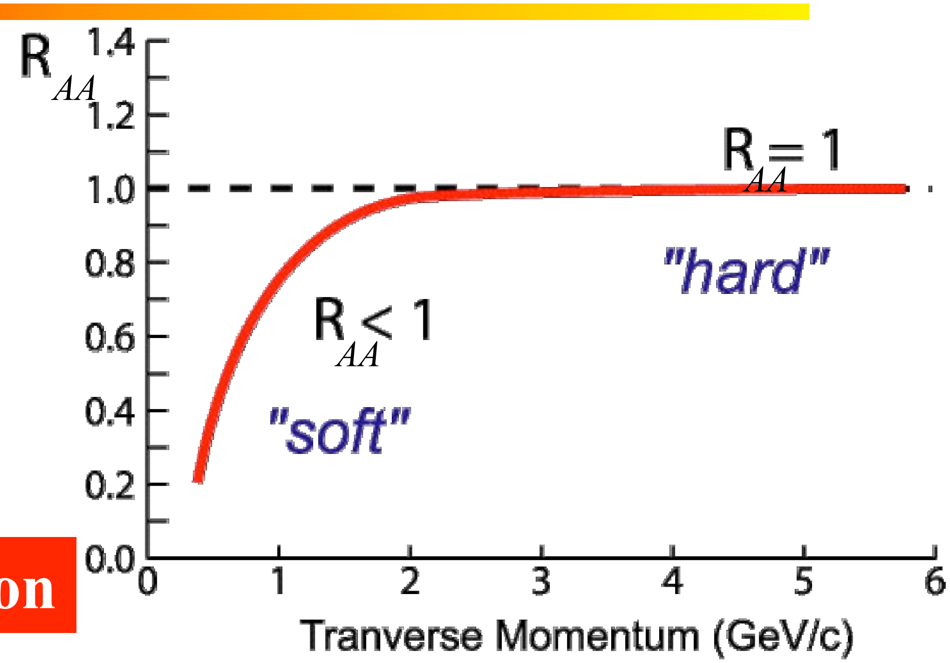
How Quantify the Nuclear Modification

Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA}\, d^2\sigma^{NN}/dp_T d\eta}$$

$\langle N_{binary}\rangle/\sigma_{inel}^{p+p}$

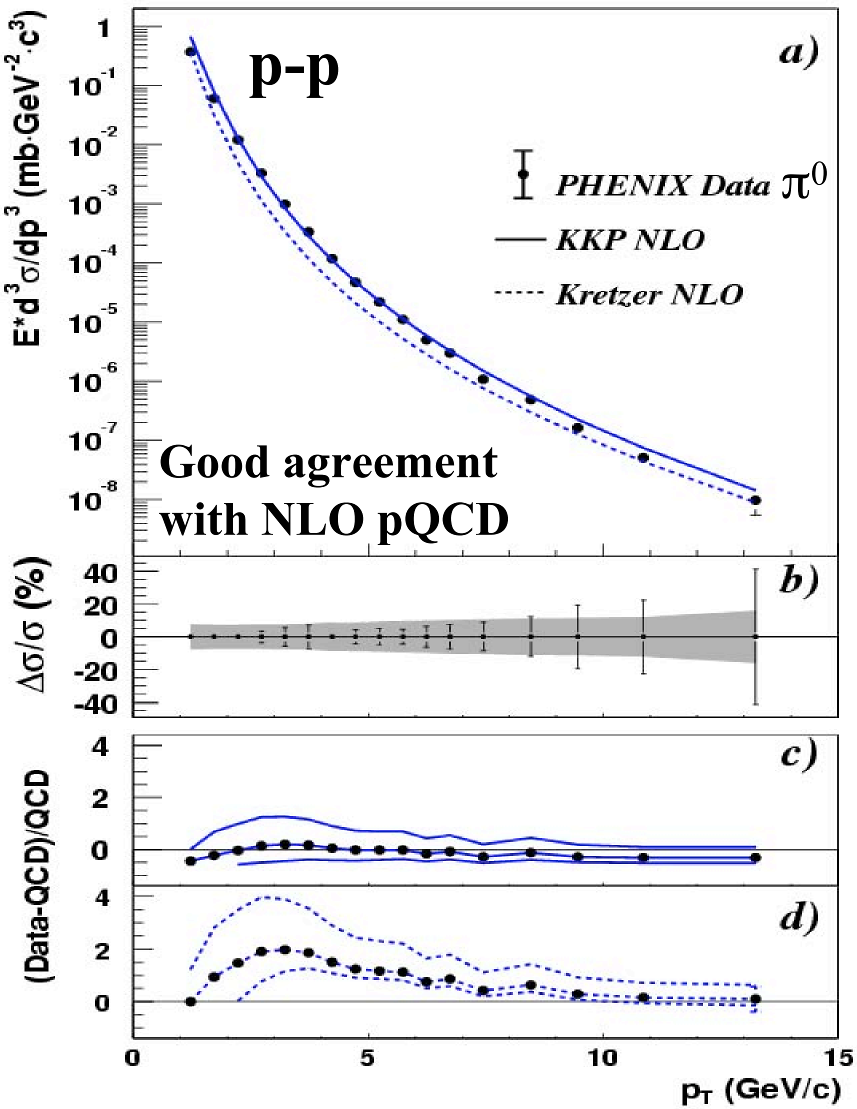
NN cross section



- **Scenario 1 : R_{AA} =1 : Scale with # of binary collisions (N_{coll}).**
- **Scenario 2 : R_{AA} >1 : Cronin effect (observed in ISR and SPS).**
- **Scenario 3 : R_{AA} <1 : Suppression.**

- Any departures from the expected binary collision scaling (N_{coll}) behavior provide the information on the strong interacting medium in *AA* collisions.

π^0 spectra pp @ 200 GeV : Baseline

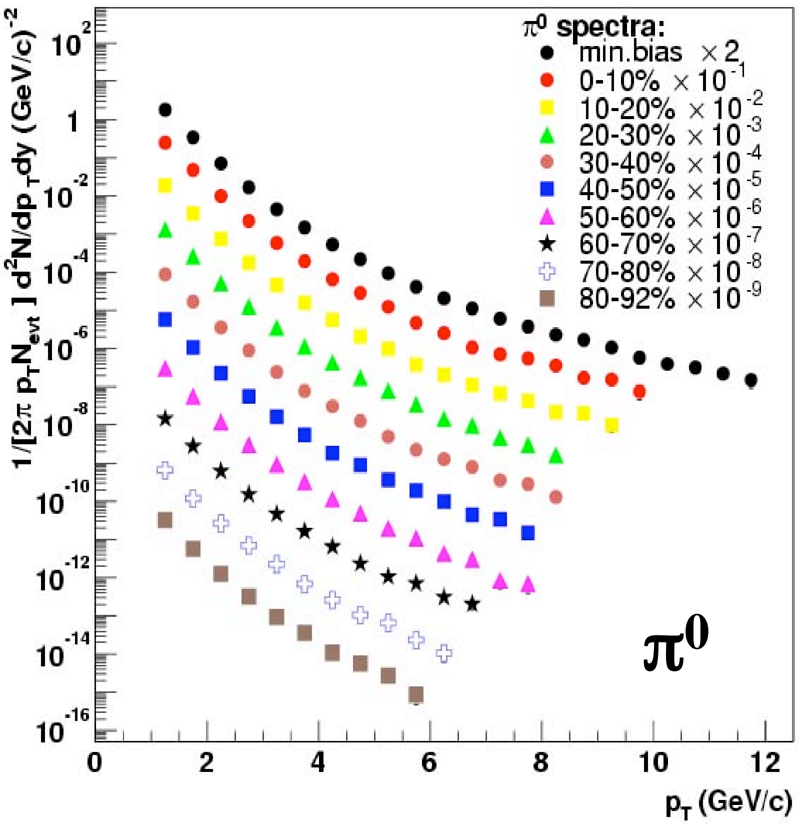


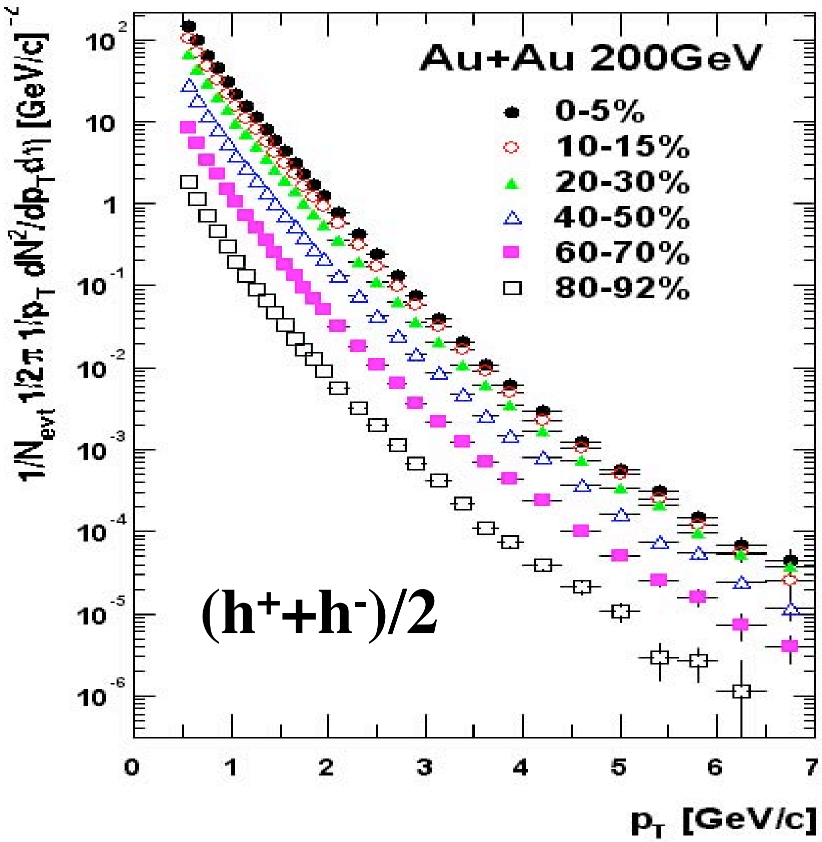
- π^0 measurement in same experiment allows us the study of nuclear effect with less systematic uncertainties.

- Good agreement with NLO pQCD
- **Reference for Au+Au spectra**

PHENIX (p+p)
PRL accepted, hep-ex/0304038

π^0 and *h* spectra AuAu @ 200 GeV





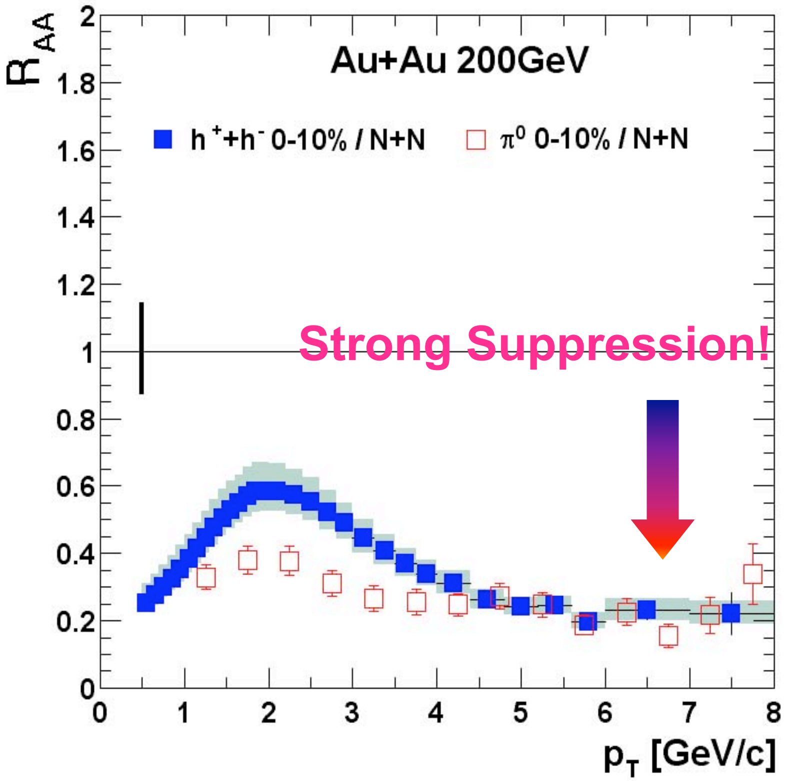
PHENIX AuAu 200 GeV

π^0 data: PRL 91, 072301 (2003), nucl-ex/0304022.

charged hadron: submitted PRC, nucl-ex/0308006.

R_{AA} for π^0 and charged hadron

$$R_{AA} = \frac{\mathrm{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\mathrm{Yield}_{pp}}$$



PHENIX AuAu 200 GeV
π^0 data: PRL 91, 072301 (2003), nucl-ex/0304022.
charged hadron: submitted PRC, nucl-ex/0308006.

- **R_{AA} is well below 1 for both charged hadrons and neutral pions.**
- **The neutral pions fall below the charged hadrons since they do not contain contributions from protons and kaons (will be discussed later).**

Initial state effect

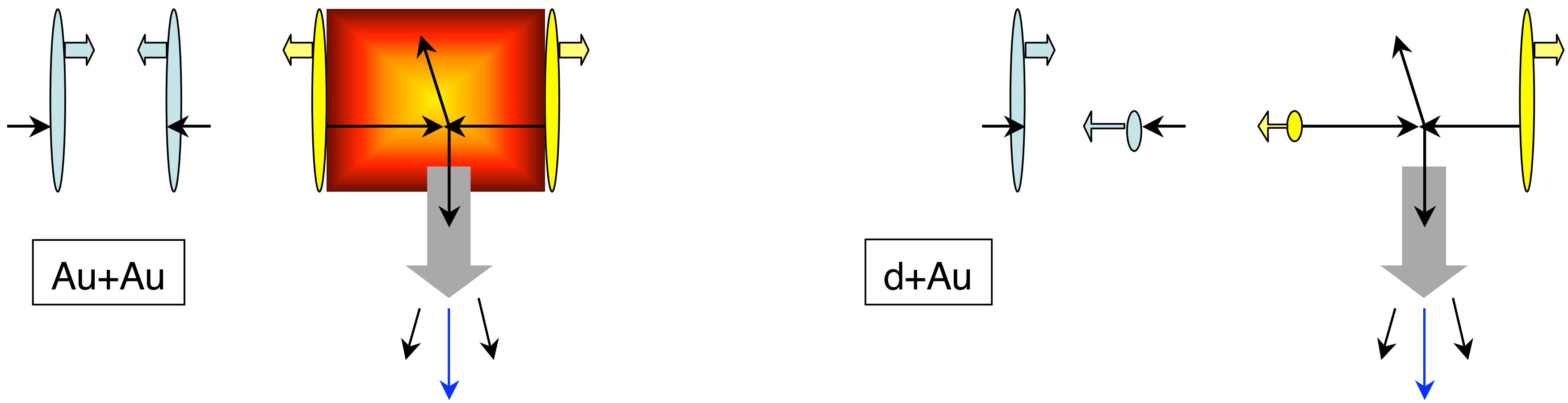
or

Final state effect?

- d+Au Experiment -

PHENIX

d+Au: Control Experiment



= hot and dense medium

Initial + Final State Effects

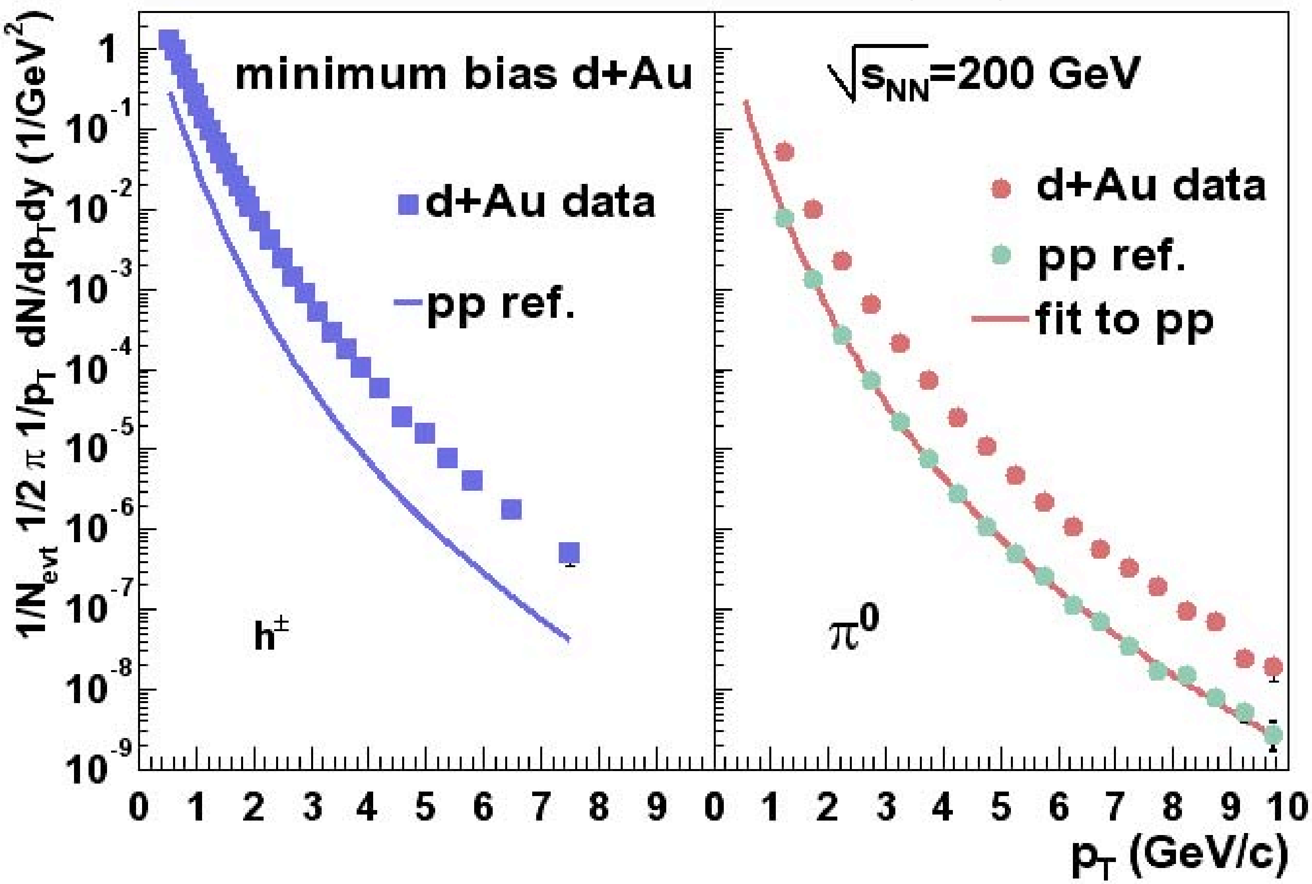
= cold medium

Initial State Effects Only

- The "Color Glass Condensate" model predicts the suppression in **both Au+Au and d+Au** (due to the initial state effect).
- **d+Au experiment can tell us whether the observed hadron suppression at high p_T central Au+A is the final state effect or initial state effect.**

d+Au Spectra

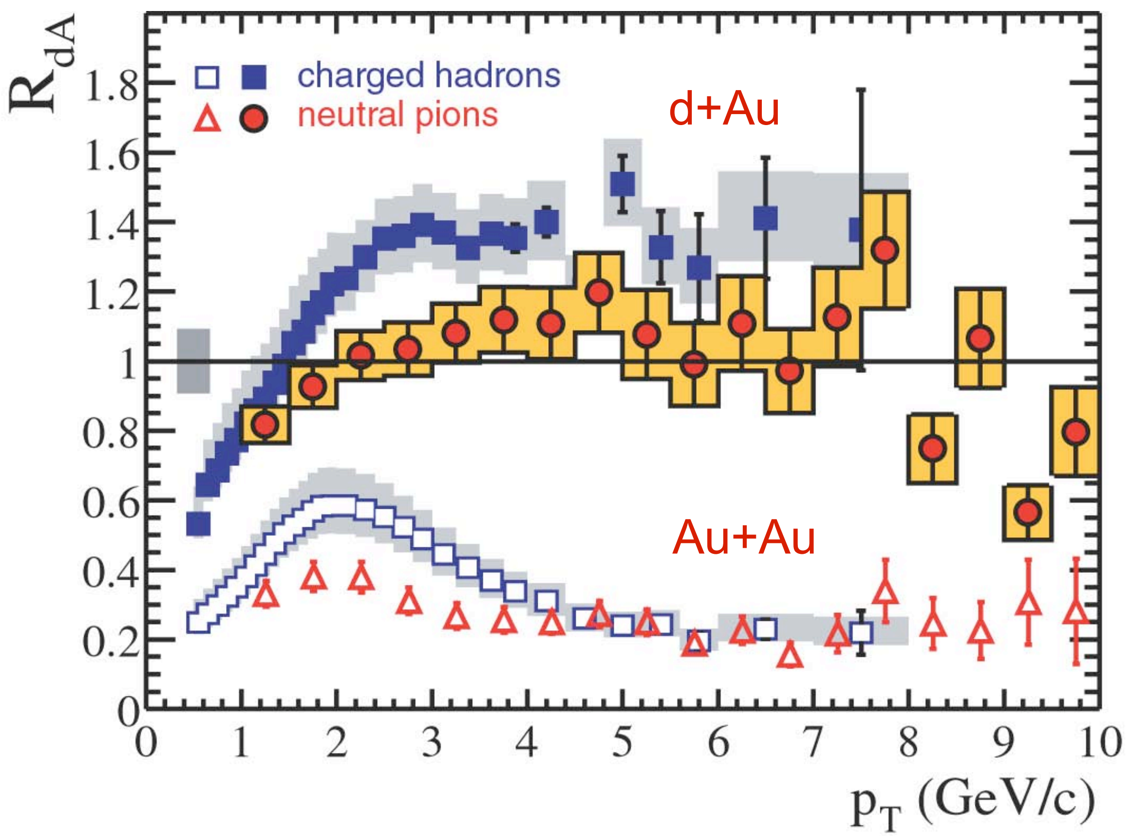
PHENIX: PRL 91, 072303 (2003), nucl-ex/0306021



- Final spectra for charged hadrons and identified pions.
- Data span 7 orders of magnitude.

R_{AA} vs. R_{dA} for charged hadrons and π^0

PHENIX: PRL 91, 072303 (2003), nucl-ex/0306021



Initial State Effects Only

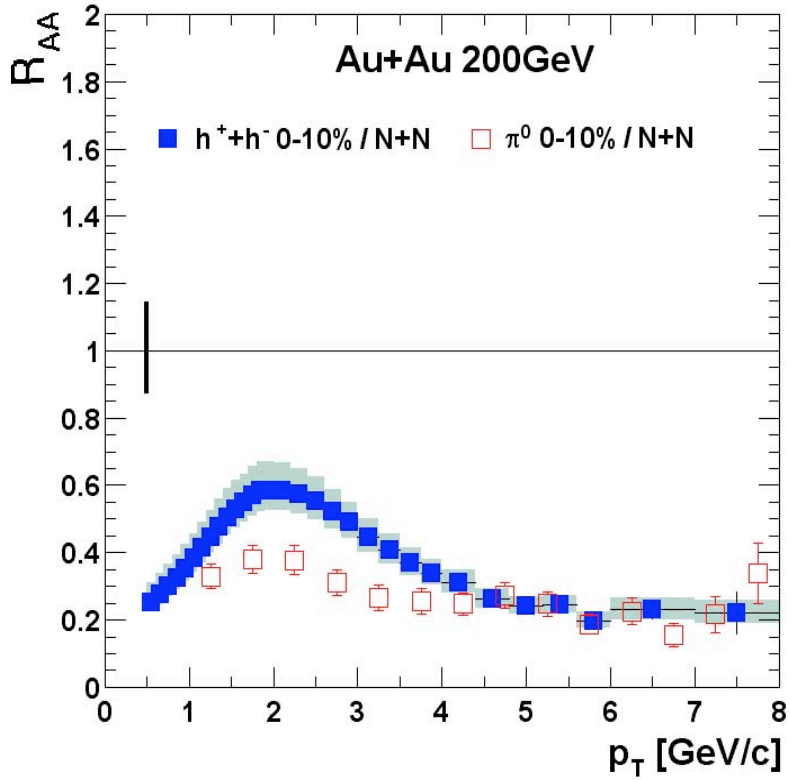
Initial + Final State Effects

No Suppression in d+Au, instead small enhancement observed (Cronin effect)!!

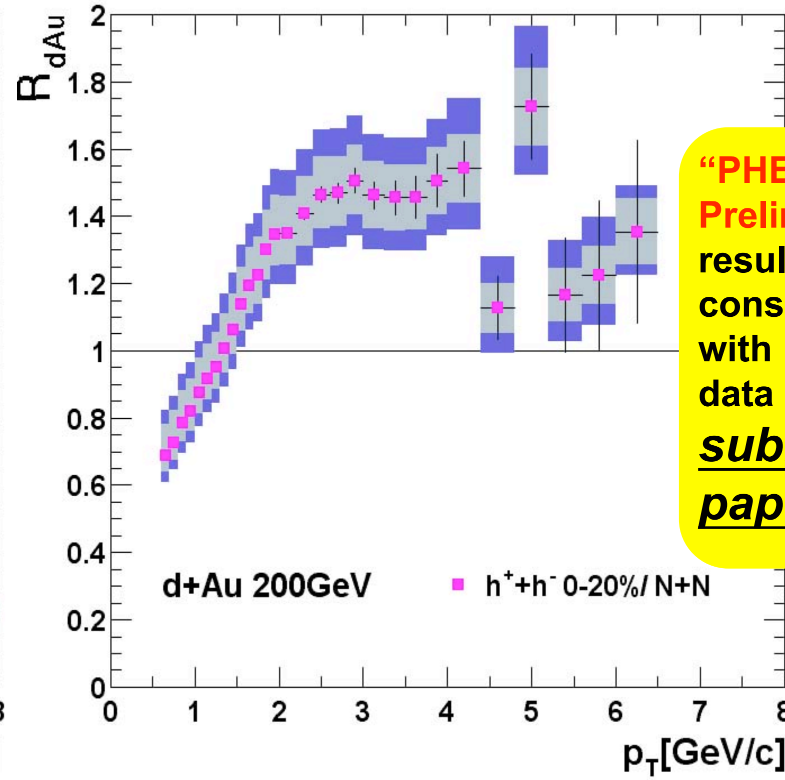
d-Au results rule out CGC as the explanation for high p_T Suppression of hadrons in AuAu central.

Centrality Dependence

Au + Au Experiment



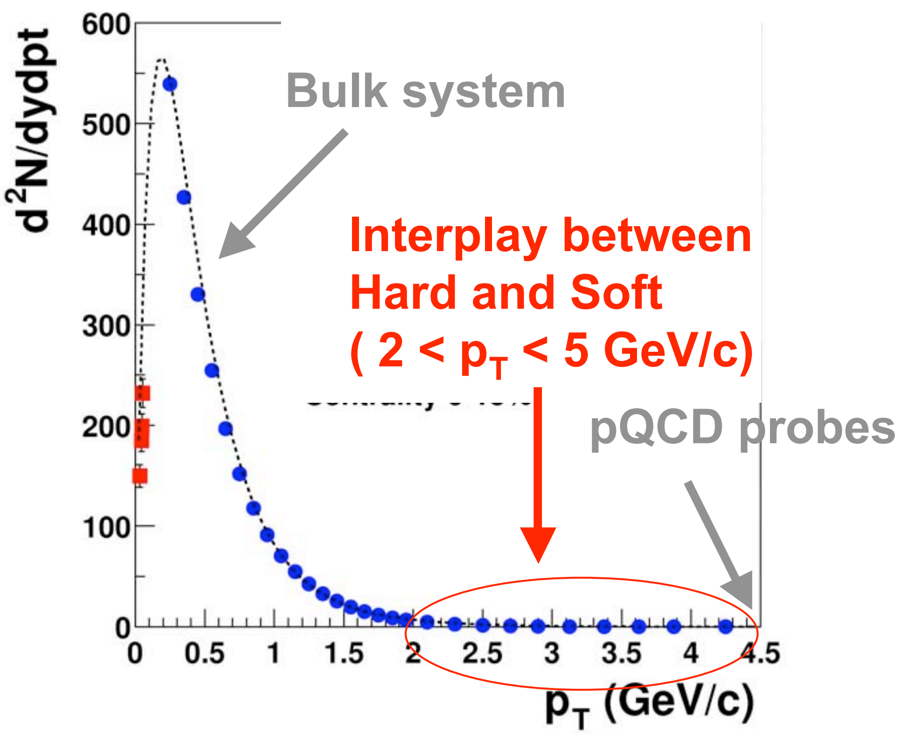
d + Au Control Experiment



"PHENIX Preliminary" results, consistent with PHOBOS data in ***submitted paper***

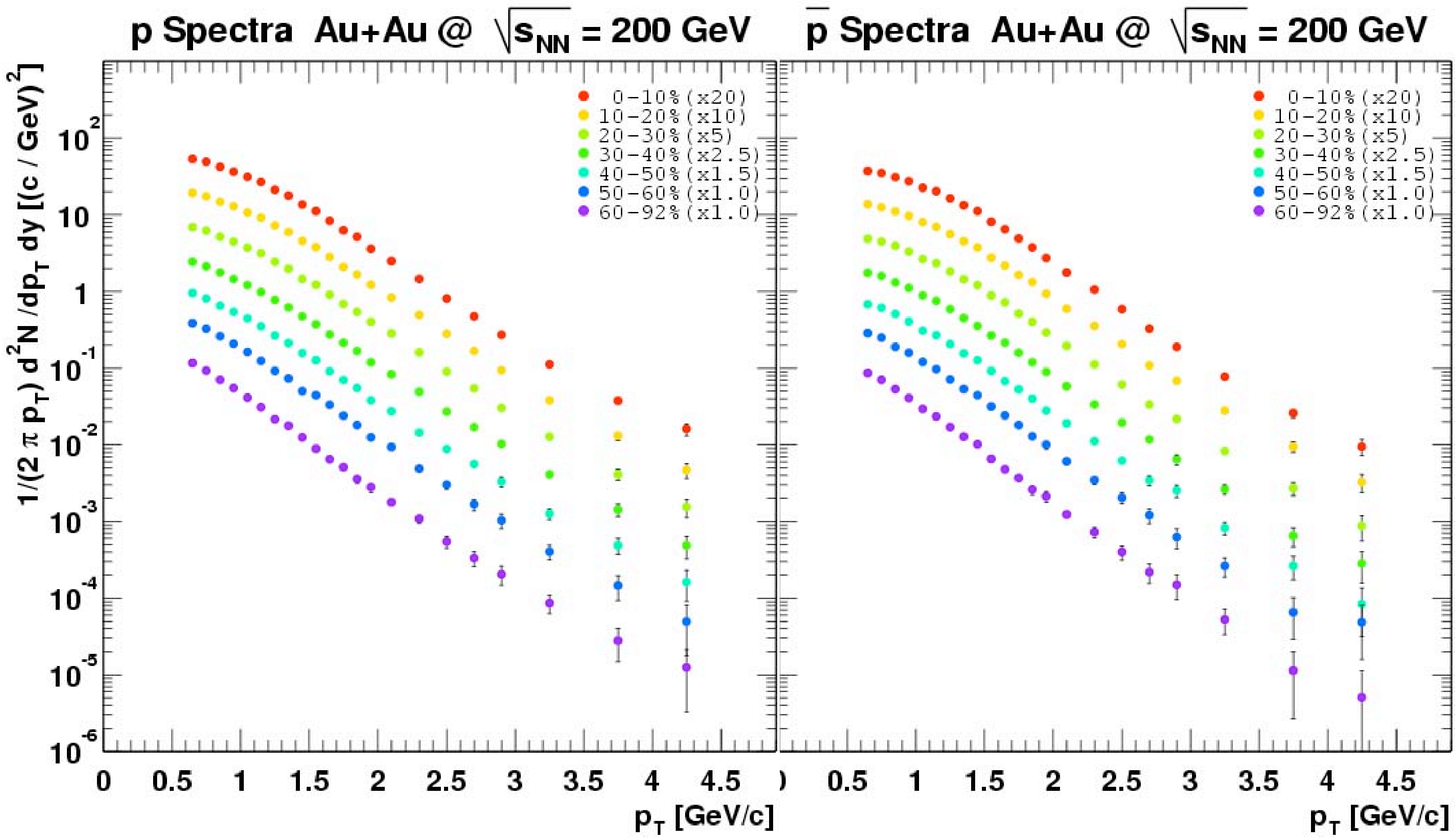
- Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.
- High p_T hadron suppression in AuAu is clearly a final state effect.

(3) Intermediate p_T region



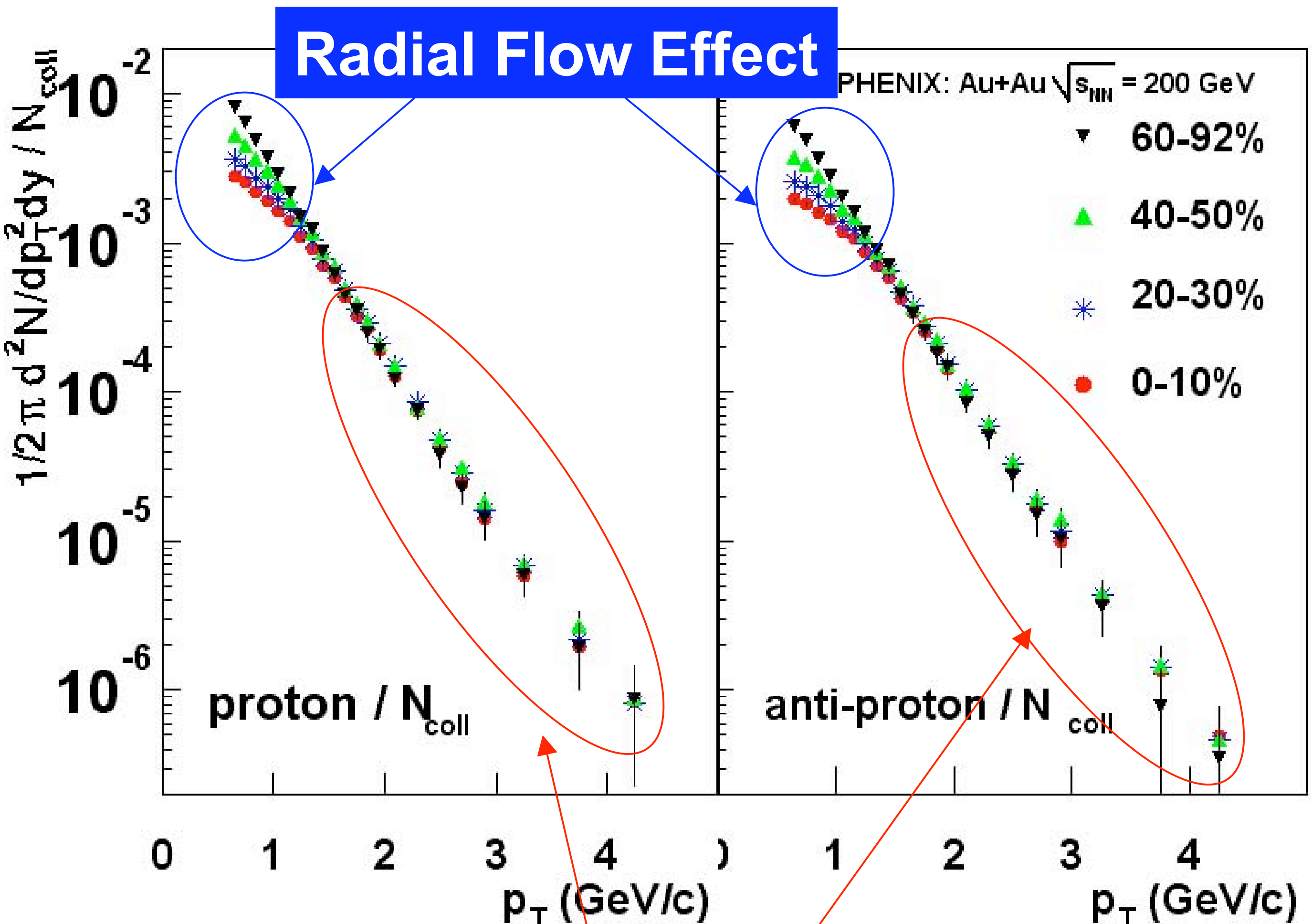
Proton and anti-proton spectra in AuAu at 200 GeV

PHENIX: PRC accepted, nucl-ex/0307022



- Corrected for weak decay feed-down effect (~40% at 0.6 GeV/c, ~25% at 4 GeV/c).
- **Strong centrality dependence in spectra shape at low p_T (< 1.5 GeV/c).**

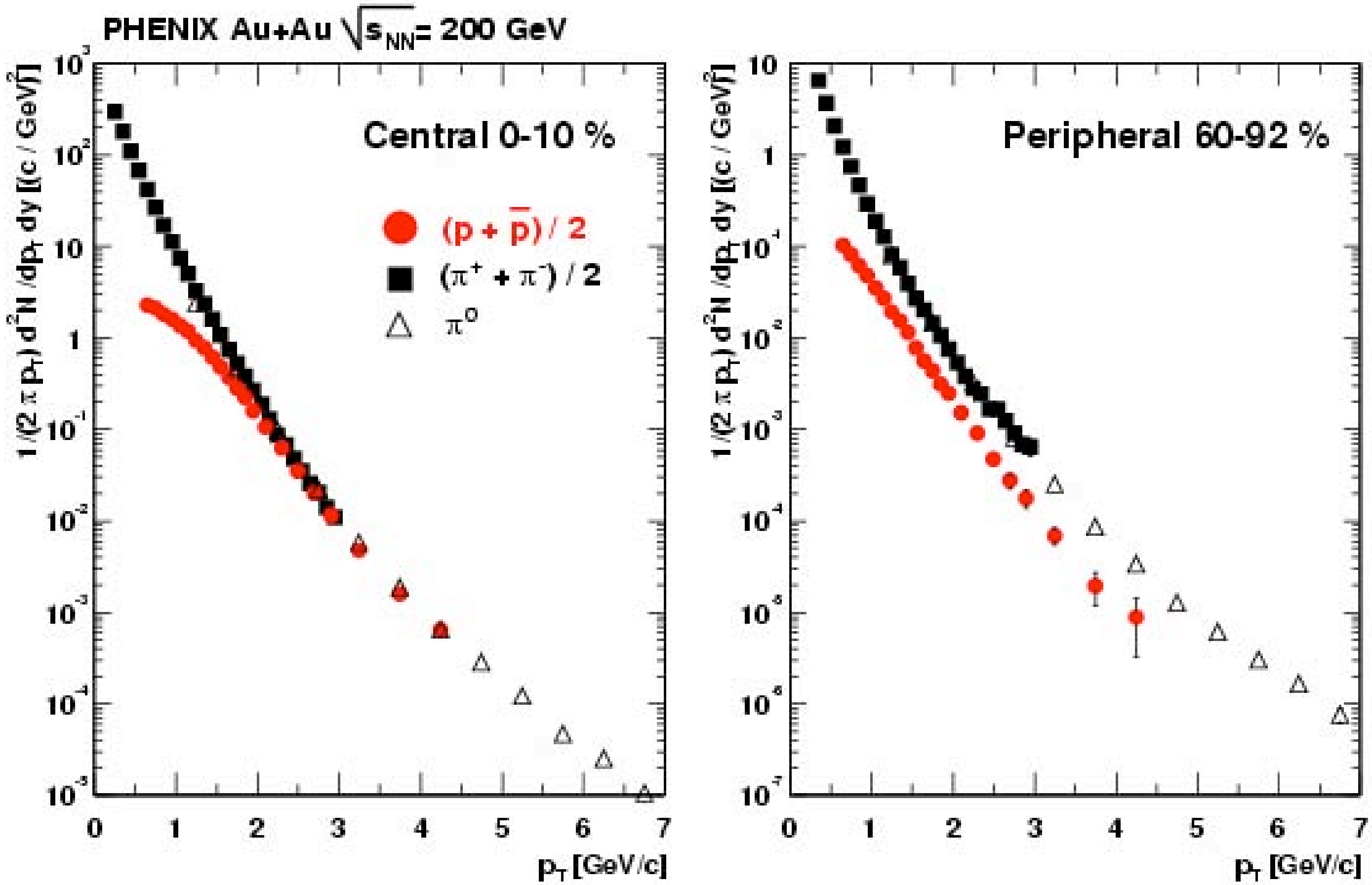
N_{coll} scaled p_T spectra for p and pbar



PHENIX: PRL 91, 172301 (2003), nucl-ex/0307022

Ncoll scaling (p_T > 1.5 GeV) for all centrality bins

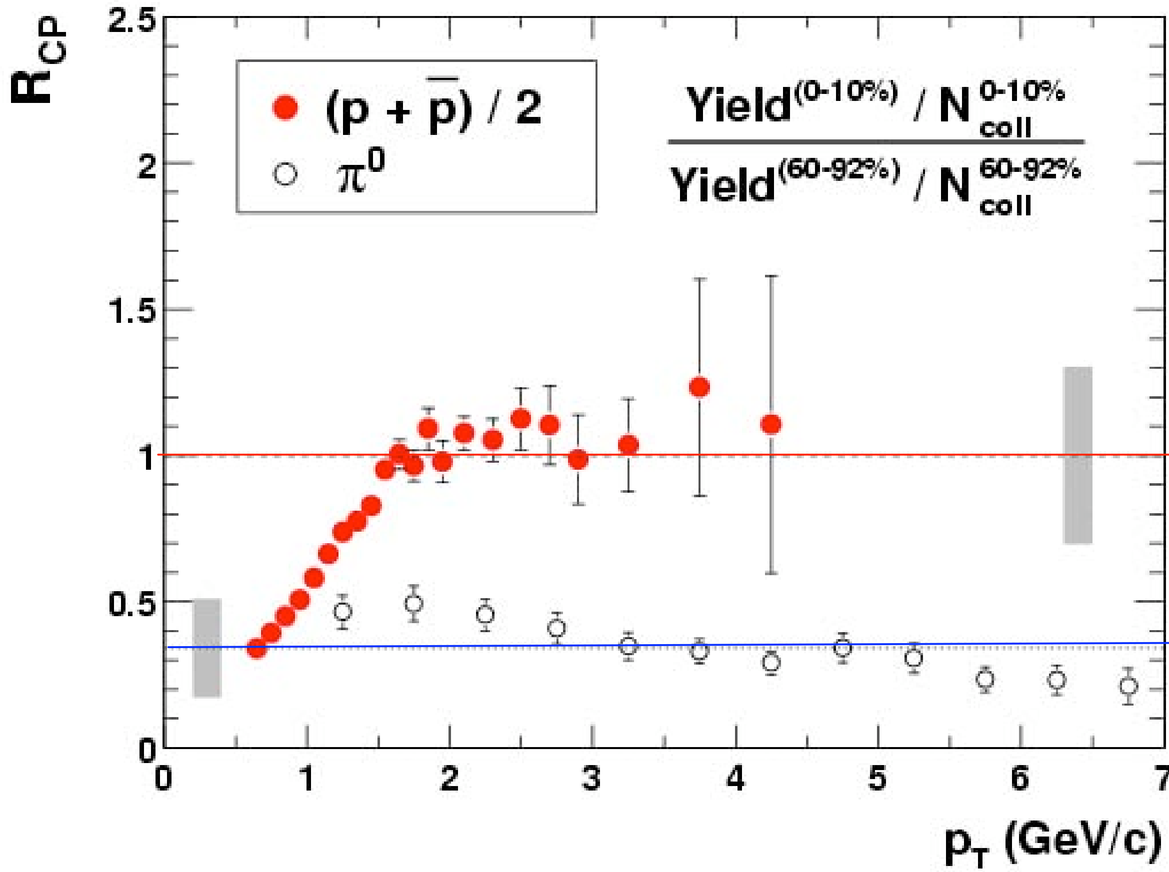
p_T spectra (p vs. π) in Au+Au @ 200 GeV



- Clearly seen p-π merging at p_T ~ 2 GeV/c in central.
- No p-π merging in peripheral.
- Suggested significant fraction of p, pbar at pt = 1.5 - 4.5 GeV/c in central.

Central-to-Peripheral Ratio (R_{CP}) vs. p_T

PHENIX: PRL 91, 172301 (2003), nucl-ex/0307022



$\approx R_{AA}$

N_{coll} scaling

N_{part} scaling

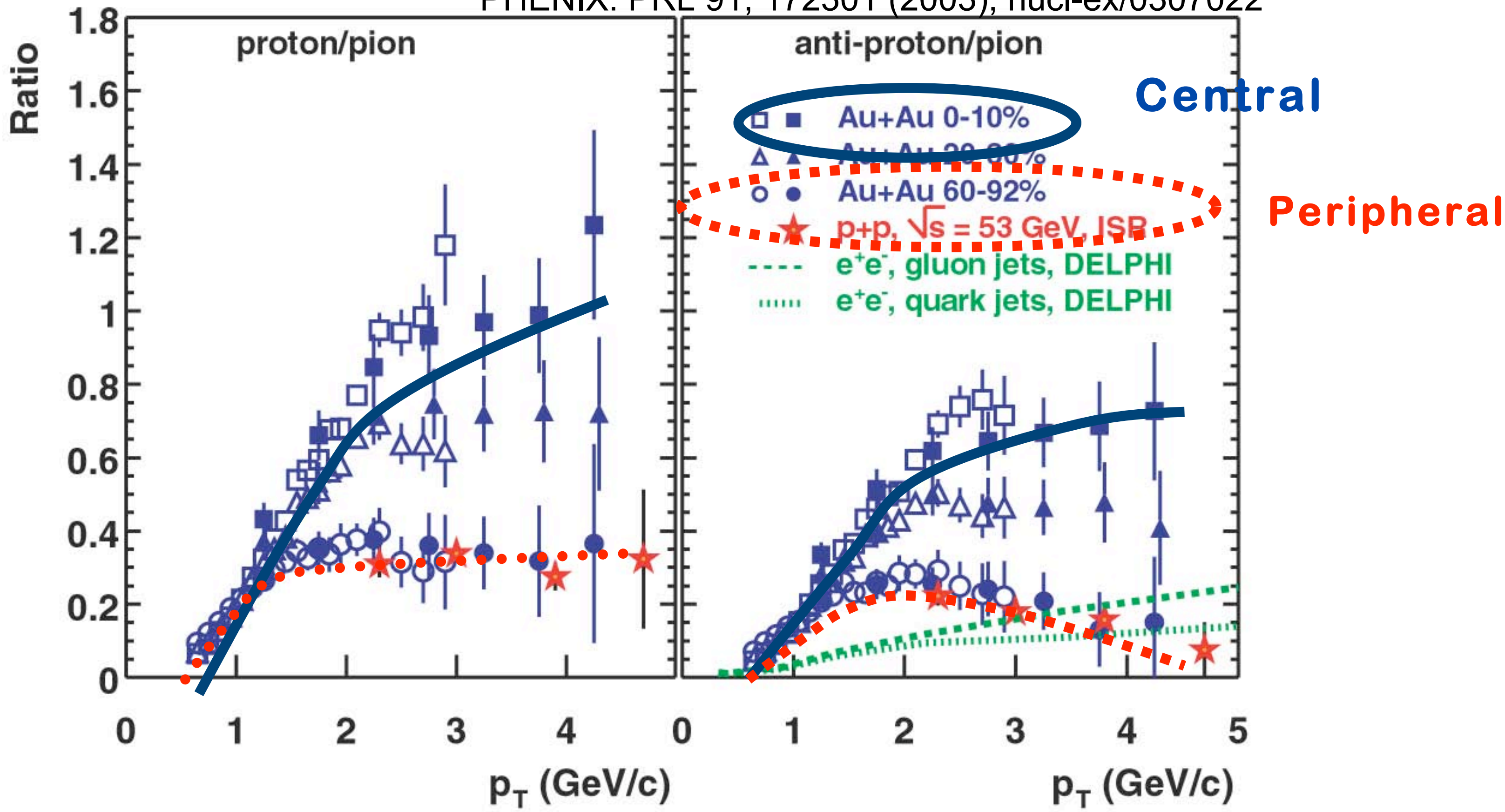
* Shaded boxes : N_{part}, N_{coll} determination errors.

p : No suppression,
N_{coll} scaling at
1.5 GeV - 4.5 GeV

π^0: Suppression
(central > peripheral)

p/π ratio vs. p_T and centrality

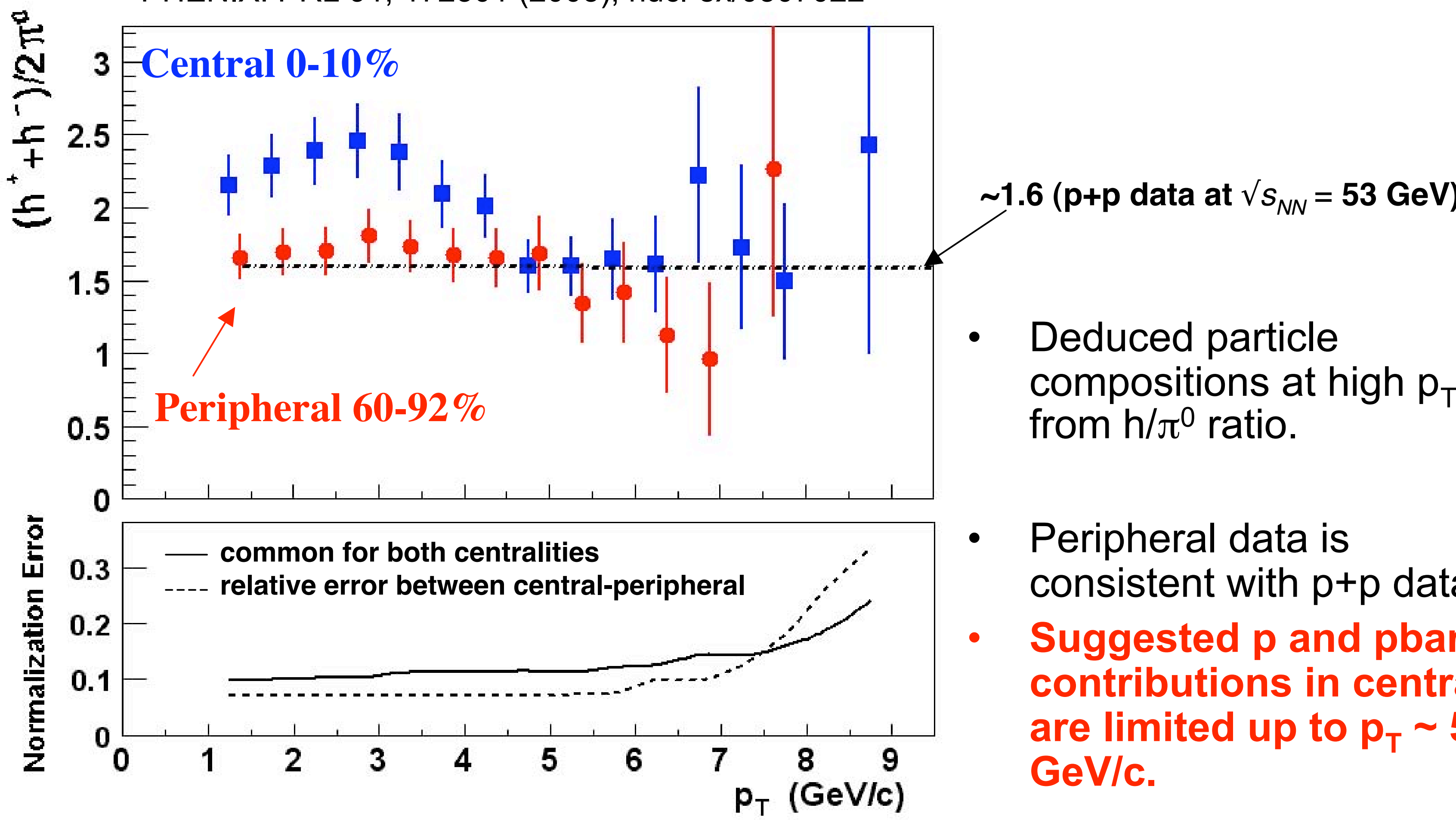
PHENIX: PRL 91, 172301 (2003), nucl-ex/0307022



- **Both p/π and pbar/π ratios are enhanced compared to peripheral Au+Au, p+p and e^+e^- at p_T = 1.5 ~ 4.5 GeV/c.**
- **Consistent with gluon/quark jet fragmentation in peripheral AuAu (> 3 GeV/c).**

Particle composition beyond 5 GeV …

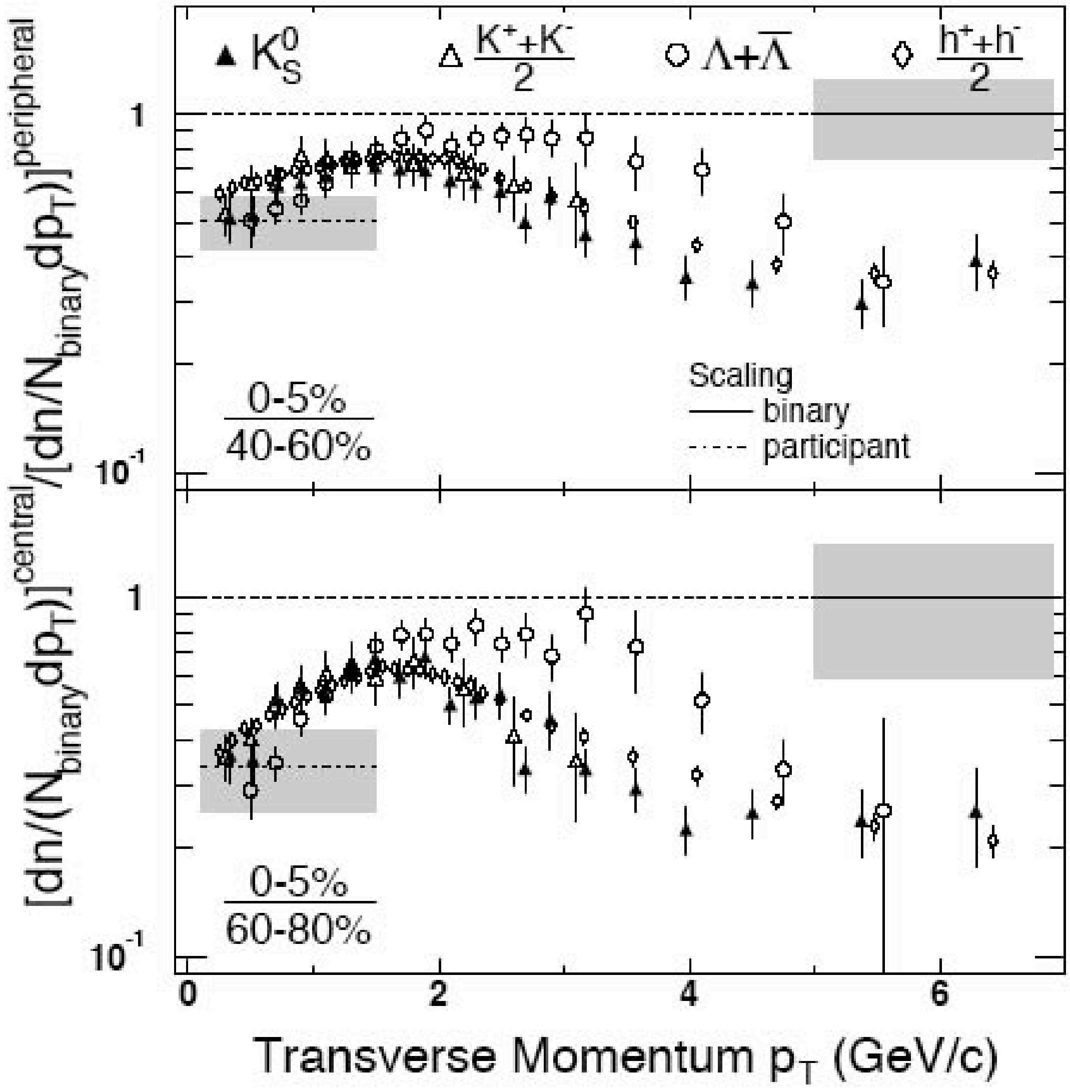
PHENIX: PRL 91, 172301 (2003), nucl-ex/0307022



- Deduced particle compositions at high p_T from h/π^0 ratio.
- Peripheral data is consistent with p+p data.
- **Suggested p and pbar contributions in central are limited up to p_T ~ 5 GeV/c.**

STAR Results

STAR: nucl-ex/0306007



- **Similar behavior has been observed in Λ.**
- **Limited behavior of baryon enhancement (< ~4 GeV/c).**

Recombination/Fragmentation Model

Fragmentation/Recombination model
Fries, Muller, Nonaka, Bass,
nucl-th/0306027

- Quarks and anti-quarks recombine into hadrons locally "at an instant"
  - **qq-bar → Meson**
  - **qqq → Baryon**
- Thermal part (quark only) and power law tail (quarks and gluons) from pQCD.
- Modification of fragmentation function "$D_{i\rightarrow h}(z)$" by energy loss of partons.
- Competition between recombination and fragmentations mechanism.
- **Quark degrees of freedom** play an important role.

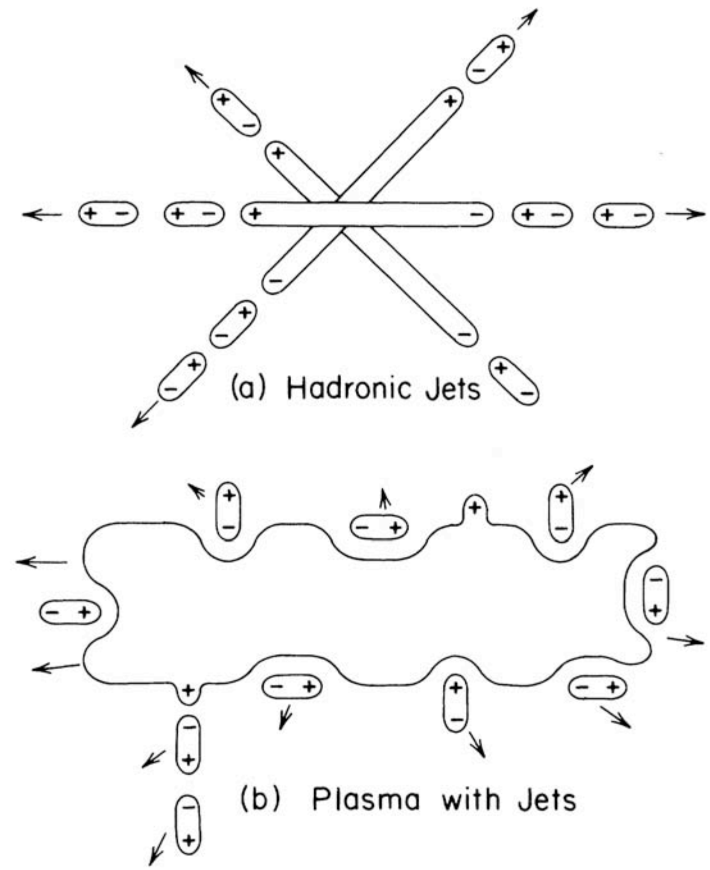
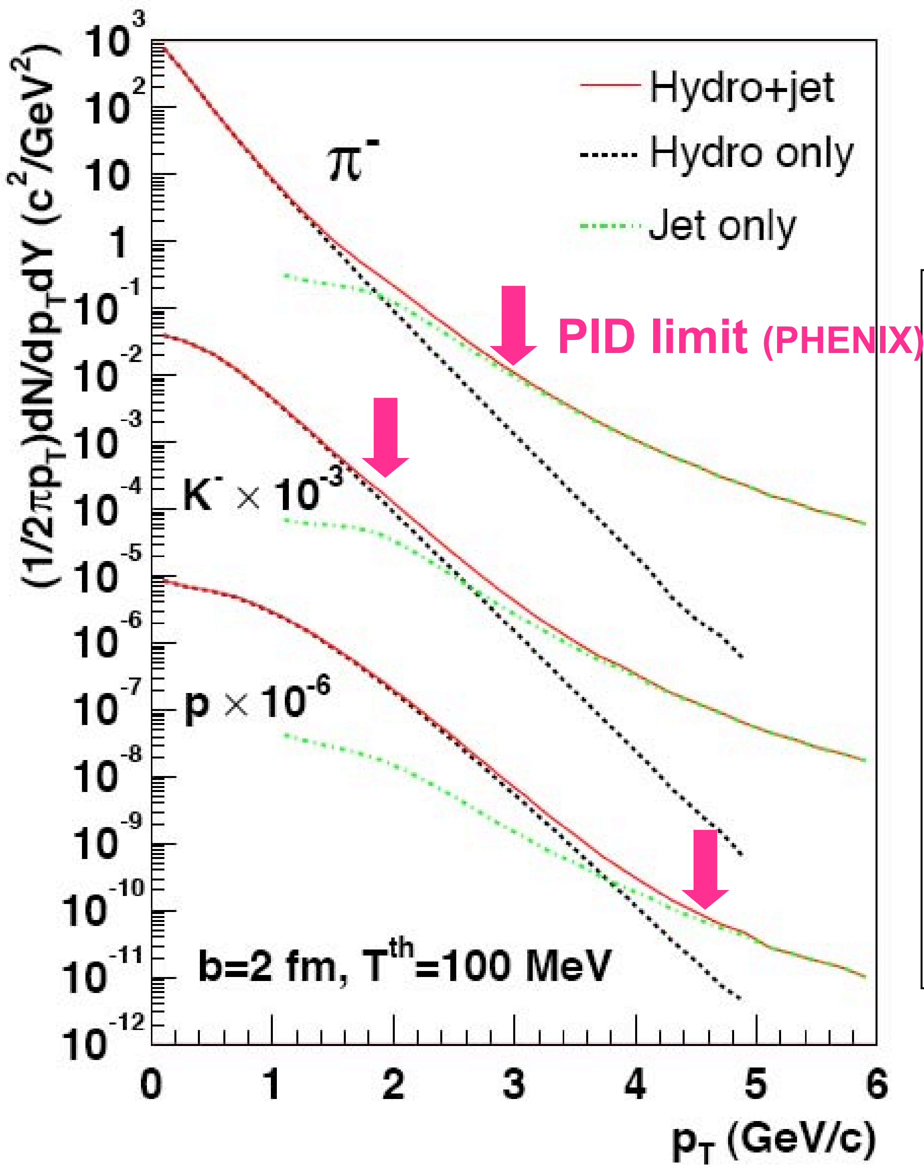


FIG. 1. Schematic conception of contrasting hadronization mechanisms for (a) a superposition of hadronic jets and (b) a plasma with a jet caused by a fast quark escaping.

Lepez, Parikh, Siemens, PRL 53 (1984) 1216

Another Approach (Hydro + Jet Model)

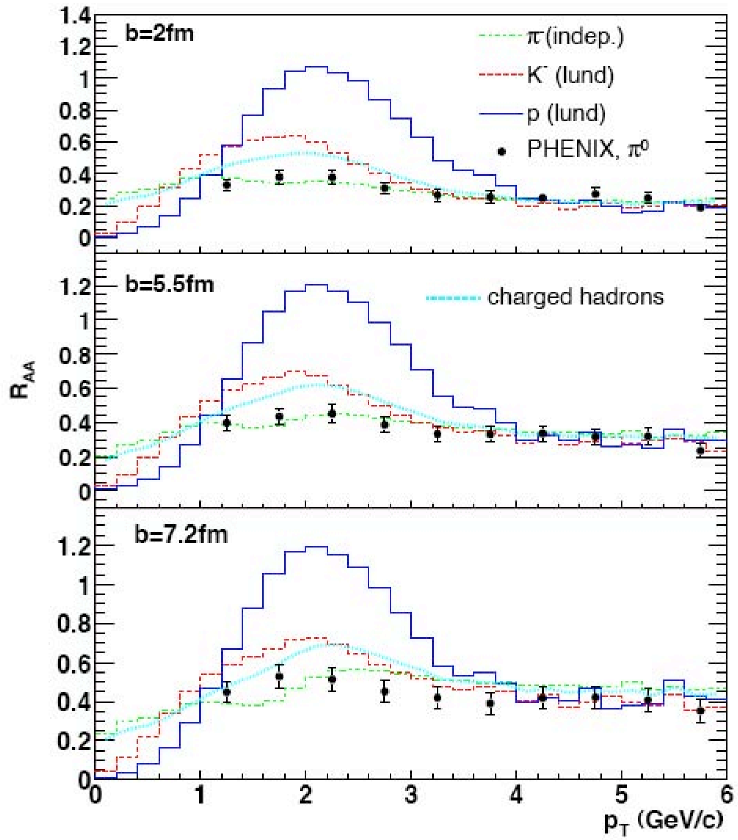


Hydro+Jet Model:
Hirano, Nara,
nucl-th/0307015

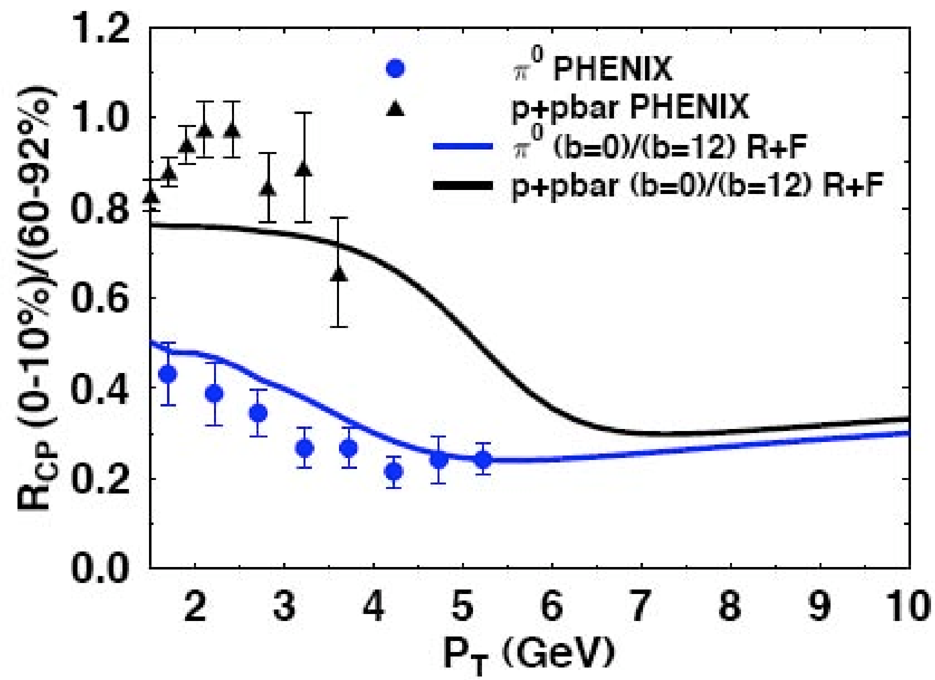
- **Explicit 3D Hydrodynamical calculations (including QGP in EOS).**
- **Tuned jet quenching effect to reproduce the suppression factor in π^0 data.**

- Hydrodynamics can describe p_T spectra up to ~ 2 GeV/c.
- Well described $dN/d\eta$ distributions and v_2 vs. p_T at RHIC.
- **Jet contributions from 2 GeV/c.**

Model Comparison (1) - R_{CP} -



Hirano, Nara (Hydro+Jet model)
nucl-th/0307015



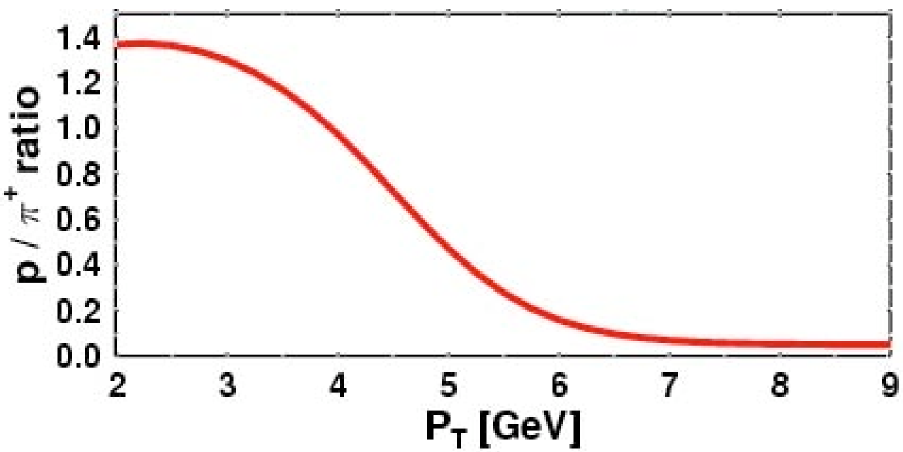
Fries, Muller, Nonaka, Bass
(Fragmentation/Recombination model)
nucl-th/0306027

- **Recombination model, Hydro-jet model**
  ⇒ Predicted baryon enhancement is limited up to ~ 4-5 GeV/c.
- **Qualitative agreement with data for both models.**

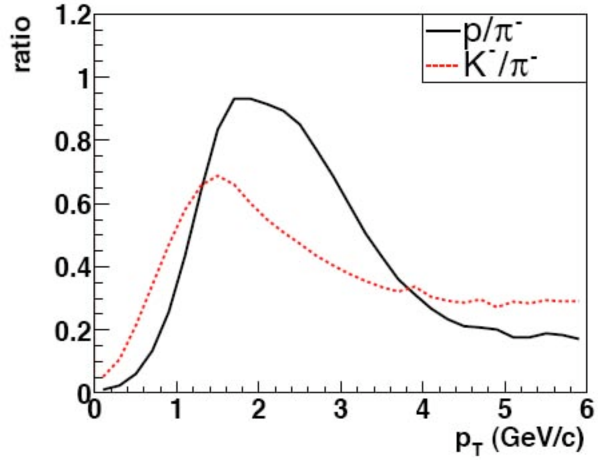
Model Comparison (2) - p/π vs. p_T -

Parton recombination/fragmentation

Fries, Mueller, Nonaka,Bass
nucl-th/0301087



Hydro+Jet Hirano, Nara
nucl-th/0307015



- Both **Parton Recombination** and **Hydro+Jet** models reproduce p/π ratio (p_T and centrality dep.) qualitatively.
- **Both models predict p/π enhancement is limited < 5 GeV/c.**
- Another scenarios: Different formation time between baryons and mesons ?
  or Baryon Junction Mechanism ?
  (Vitev, Gyulassy PRC 65, 041902, 2002)

Summary (1)

E_T, N_{ch}	Above the critical density of deconfined state predicted by the LQCD.
PID spectra	Well described by hydrodynamic model up to 2 GeV/c in p_T.
Particle Yield	Well reproduced by the statistical thermal model. (T_{ch}, μ_B): close to the phase boundary of QGP predicted by LQCD.
Pion HBT	R vs. K_T: consistent with hydro, but large discrepancy in magnitudes. Suggests the importance of partial Coulomb correction.
Elliptic flow	Good agreement with hydrodynamics up to 2 GeV/c. Observed Complicated $v_2(p_T)$ pattern (might be explained by the partonic flow picture).

Summary (2)

High p_T Spectra (Au+Au)	Both neutral and inclusive charged hadrons are largely suppressed in AuAu central collisions.
High p_T Spectra (d+Au)	Suppressions are not observed in d+Au, instead there is a small enhancement, which suggests the suppression in AuAu is the final state effect.
Intermediate p_T in Au+Au	Proton and anti-proton spectra show the different scaling behavior from pions: NO suppression. Strong centrality dependence of p/π ratio. Recombination, Hydro+Jet, (baryon junction) reproduce the data qualitatively.

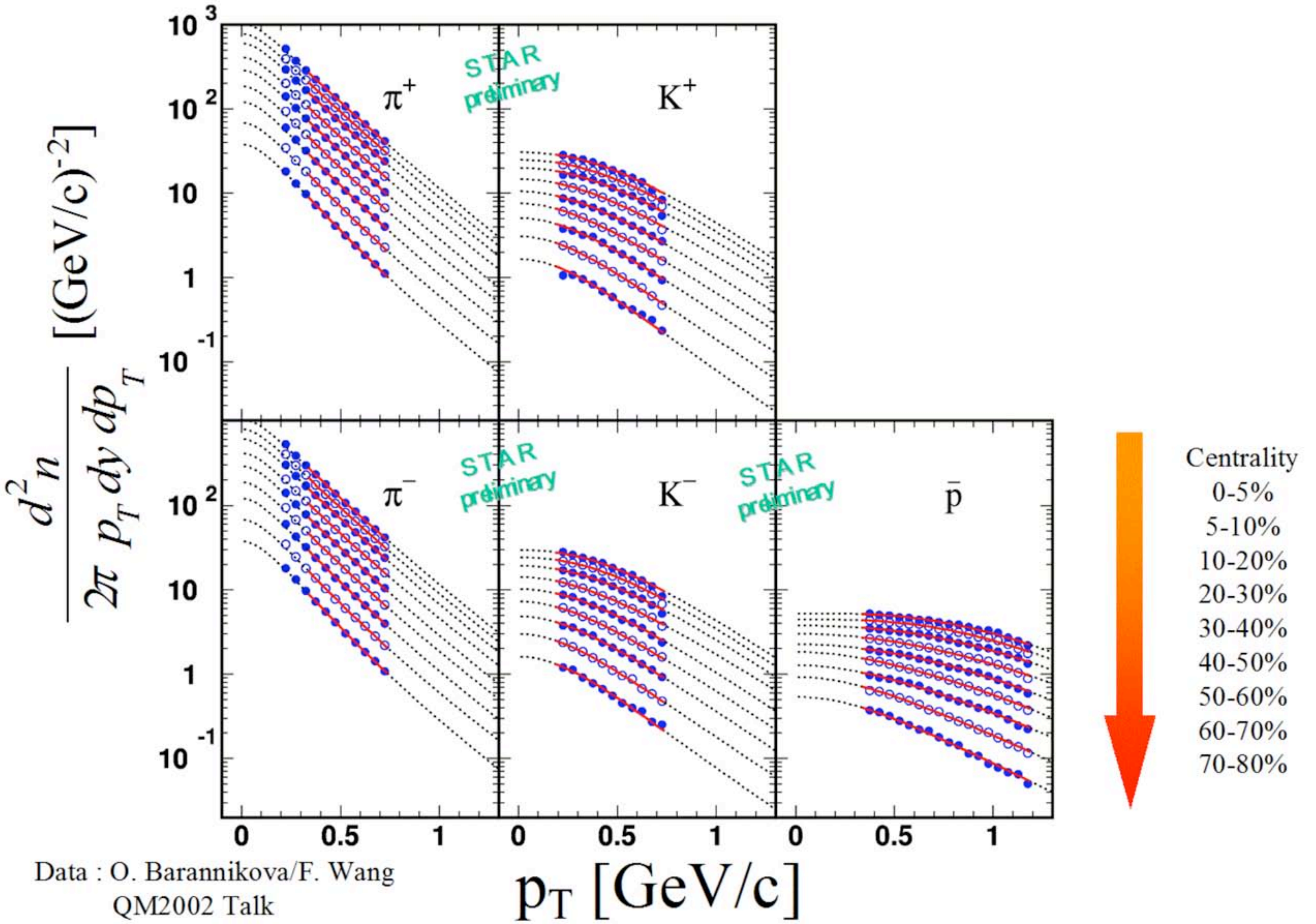
What's Next

- **We must investigate other probes that look deeply into the medium to characterize it.**
- **The Rare Processes Probe the Medium:**
  - **Heavy Quark States**
    - Dissolution of J/Ψ & Ψ', the bound states of charm-anticharm quarks probes quark deconfinement.
  - **Electromagnetic Probes (no strong interaction)**
    - Lack of strong interaction allows them to penetrate the black medium and see through the hadronic veil
    - Direct Photons, e^+e^-, $\mu^+\mu^-$
- **PHENIX plans to make these measurements in the next high luminosity Au+Au run.**

See next talk, K. Shigaki.

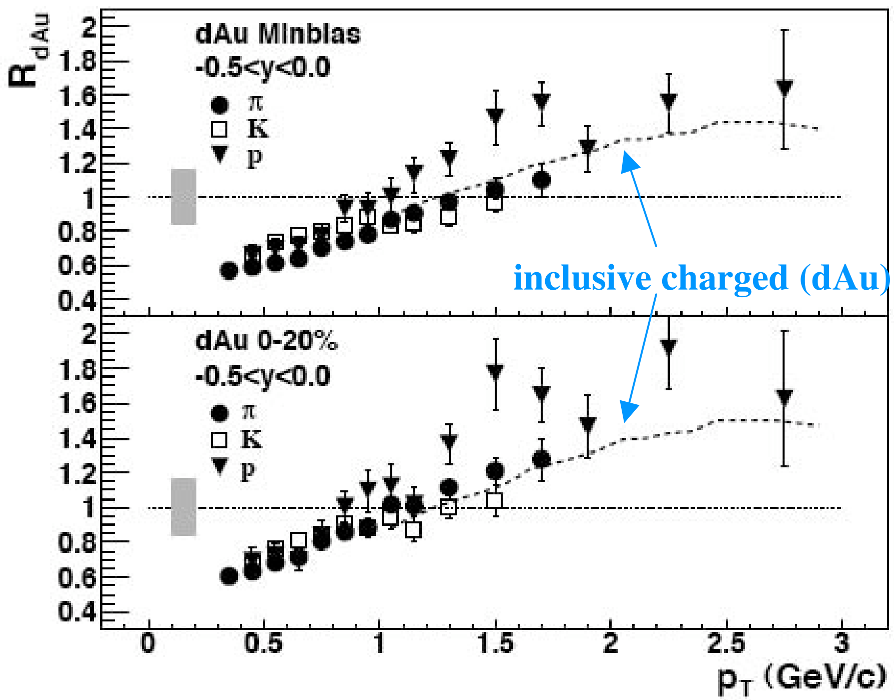
Backup Slides

STAR Blast-wave fit

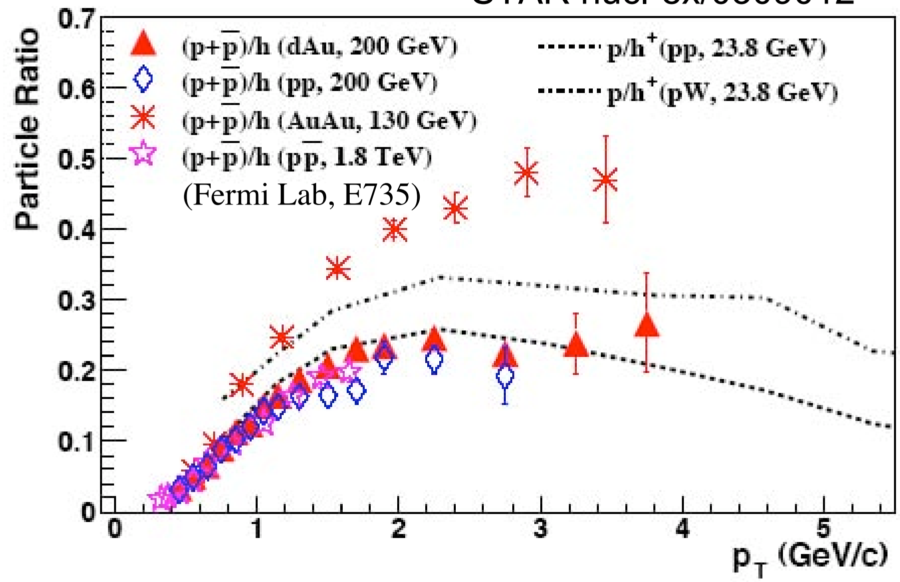


Data : O. Barannikova/F. Wang
QM2002 Talk

R_{dAu} and p/h for π, K, p in d+Au (STAR)



STAR nucl-ex/0309012



- Small particle species dependence of Cronin effect, compared to lower energies.
- Same (p+pbar)/h ratio in dAu as p+p.
- **Indicated the Cronin effect alone is not enough to account for the relative baryon enhancement in AuAu central (discussed later).**

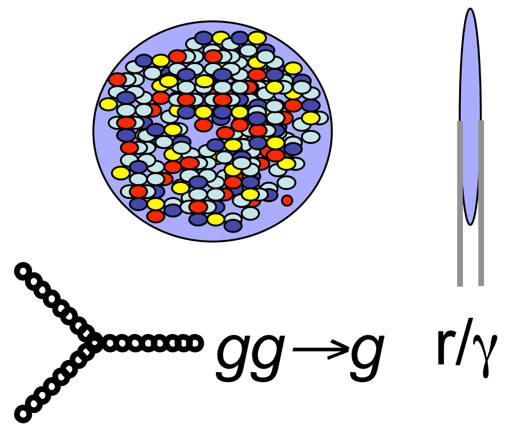
Alternative: Initial Effects

- **Gluon Saturation**
  - **(color glass condensate: CGC)**

Wave function of low x gluons overlap; the self-coupling gluons fuse, saturating the density of gluons in the initial state.

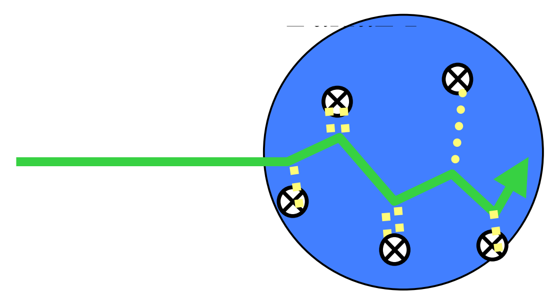
(gets N_{ch} right!)

hep-ph/0212316; D. Kharzeev, E. Levin, M. Nardi



D.Kharzeev et al., PLB 561 (2003) 93

Broaden p_T

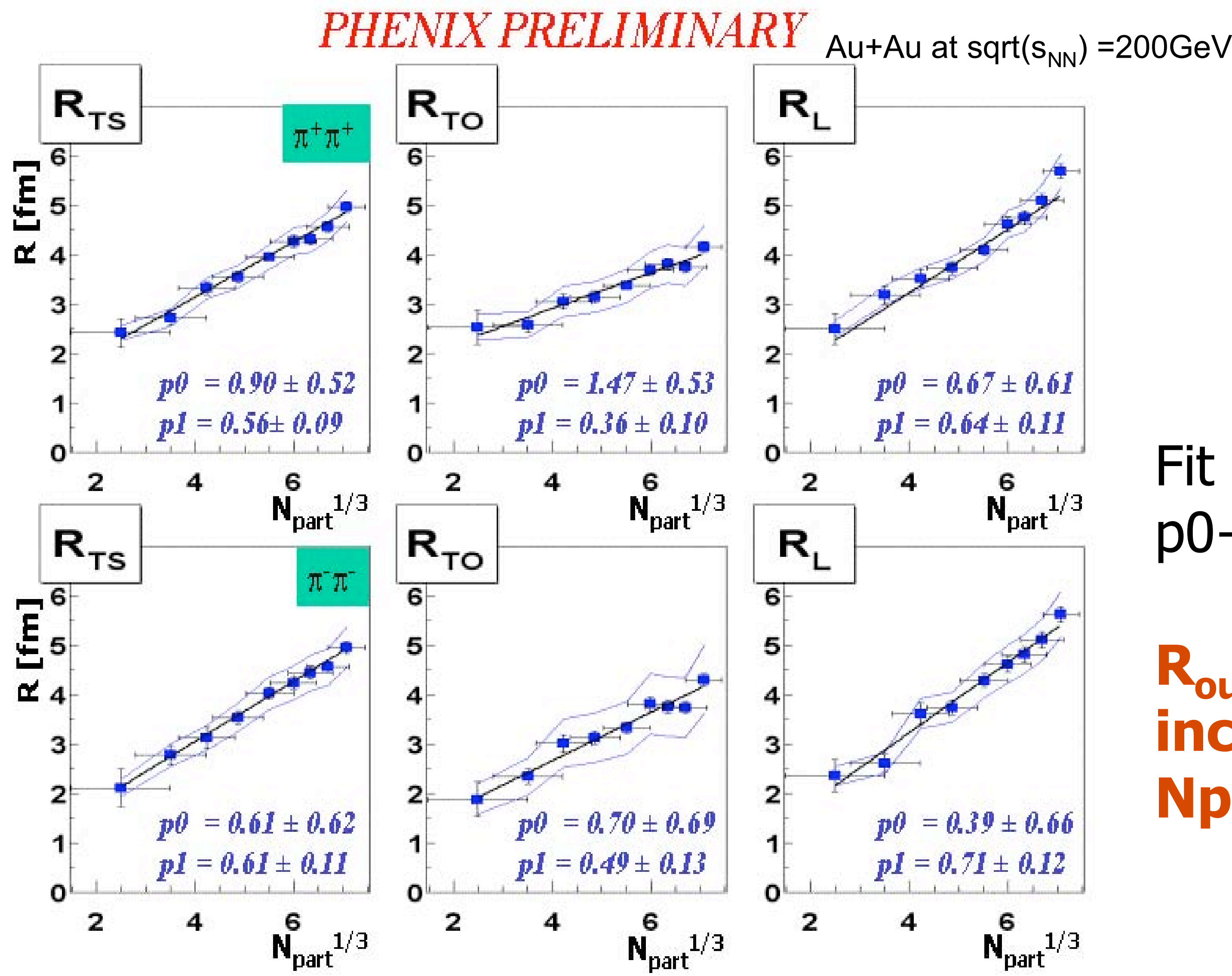


- **Multiple elastic scatterings (Cronin effect)**

  Wang, Kopeliovich, Levai, Accardi

- **Nuclear shadowing**

R vs. $N_{part}^{1/3}$



Fit with
$p0+p1*N_{part}$^1/3

R_{out} weaker increase with Npart