Results from PHENIX experiment at RHIC

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Outline

- RHIC and PHENIX experiment
- Results from Run-1 (2000) and Run-2(2001)
  - Soft Physics
    - Global observables
    - Hadron spectra and ratios (Thermal model works)
    - Two particle correlation (HBT puzzle. Quick de-coupling?)
    - Elliptic Flow (Early thermalization?)
  - Hard Scattering
    - Discovery of high pt suppression (energy loss of quark and gluons)
    - Evidence for jets at RHIC
    - High pt particle ratios (source of high pt baryons?)
  - Lepton measurement
    - Single electron and charm (scaling with number of collisions)
    - J/Ψ measurement (suppression or enhancement?)
- Summary

- For more…
  - RHIC http://www.rhic.bnl.gov
  - PHENIX http://www.phenix.bnl.gov
  - QM2002 http://alice-france.in2p3.fr/qm2002

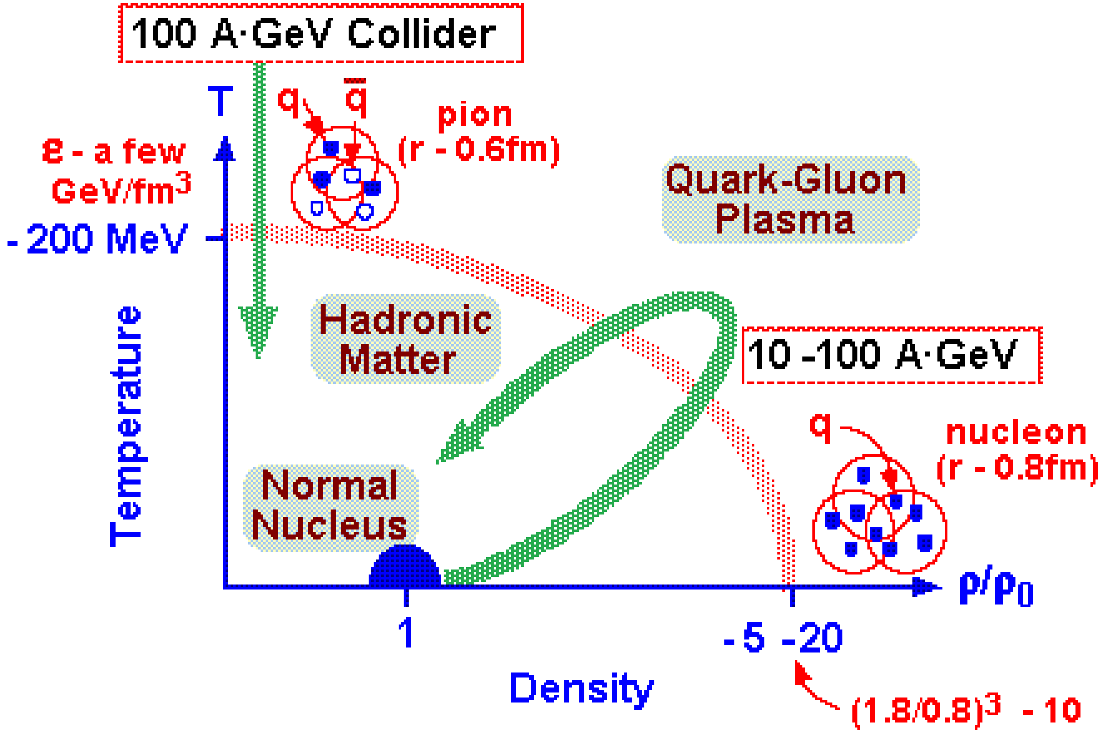
PHENIX

Q: Why RHIC?
A: Quark Gluon Plasma

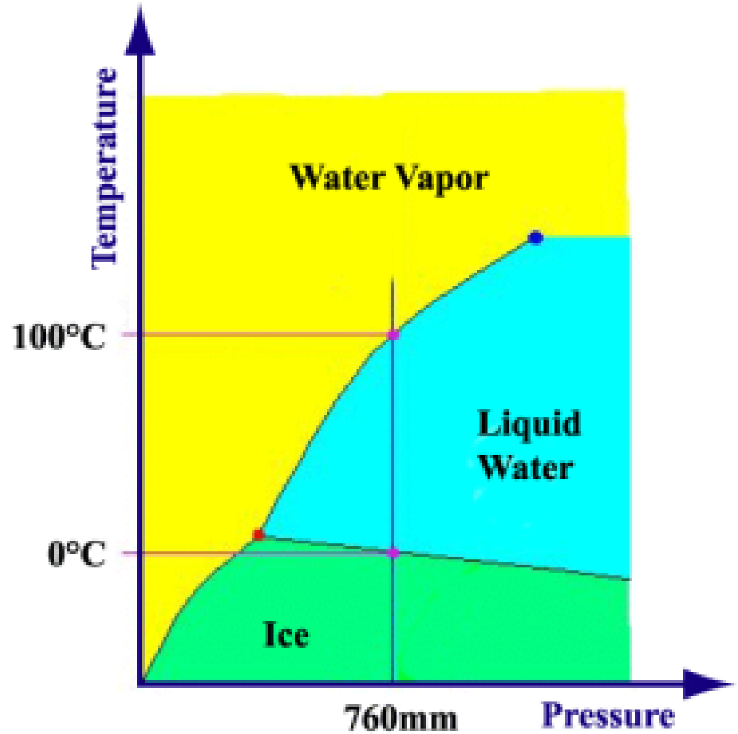
In cold matter: quark and gluons are confined in nucleon

In hot matter: quarks are de-confined.

Lattice QCD predicts that the de-confinement phase transition at T~170 MeV and ε_{crit}~1GeV/fm^3

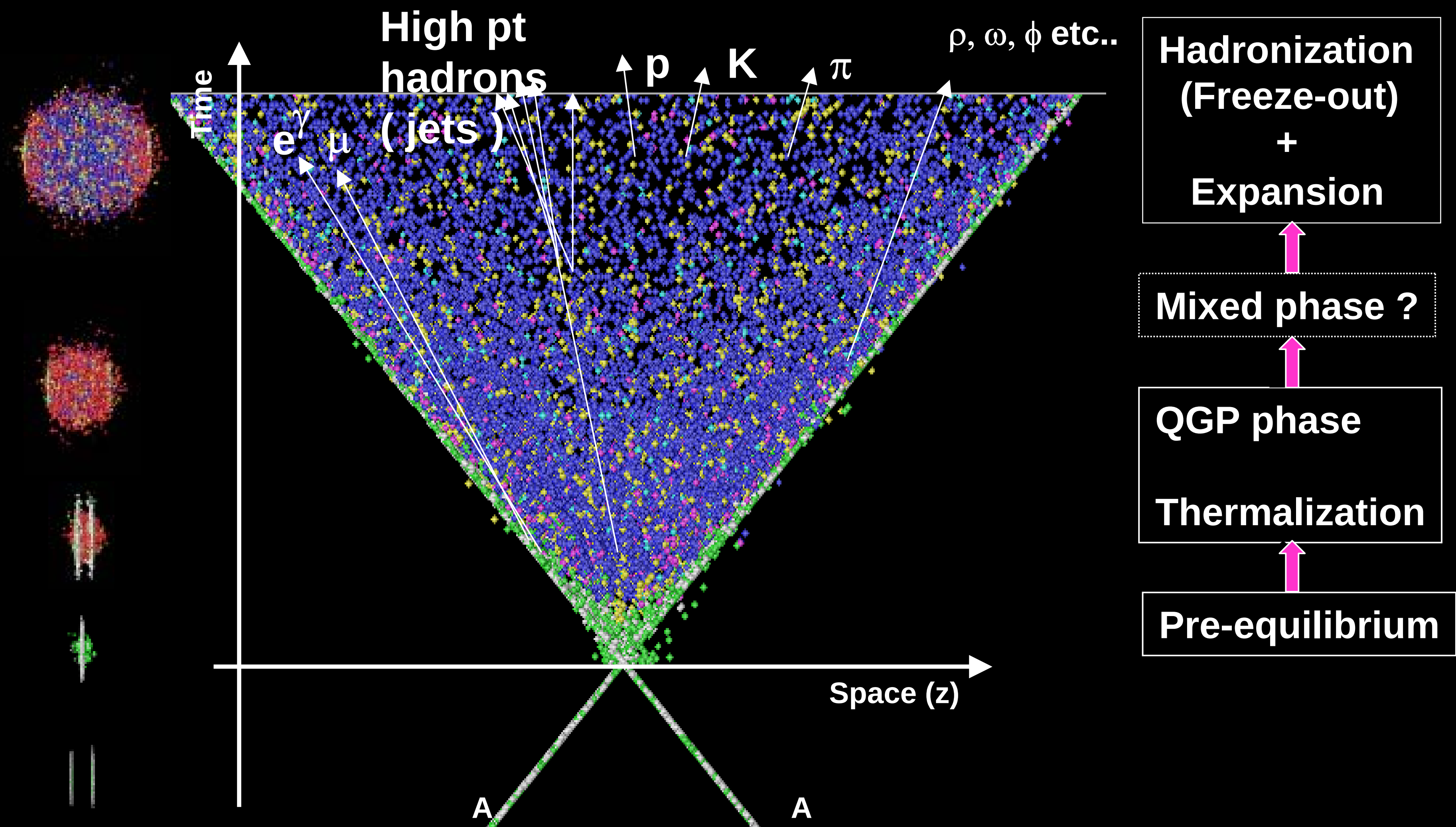


Nuclear Matter



Water

Space-time Evolution of A+A collision



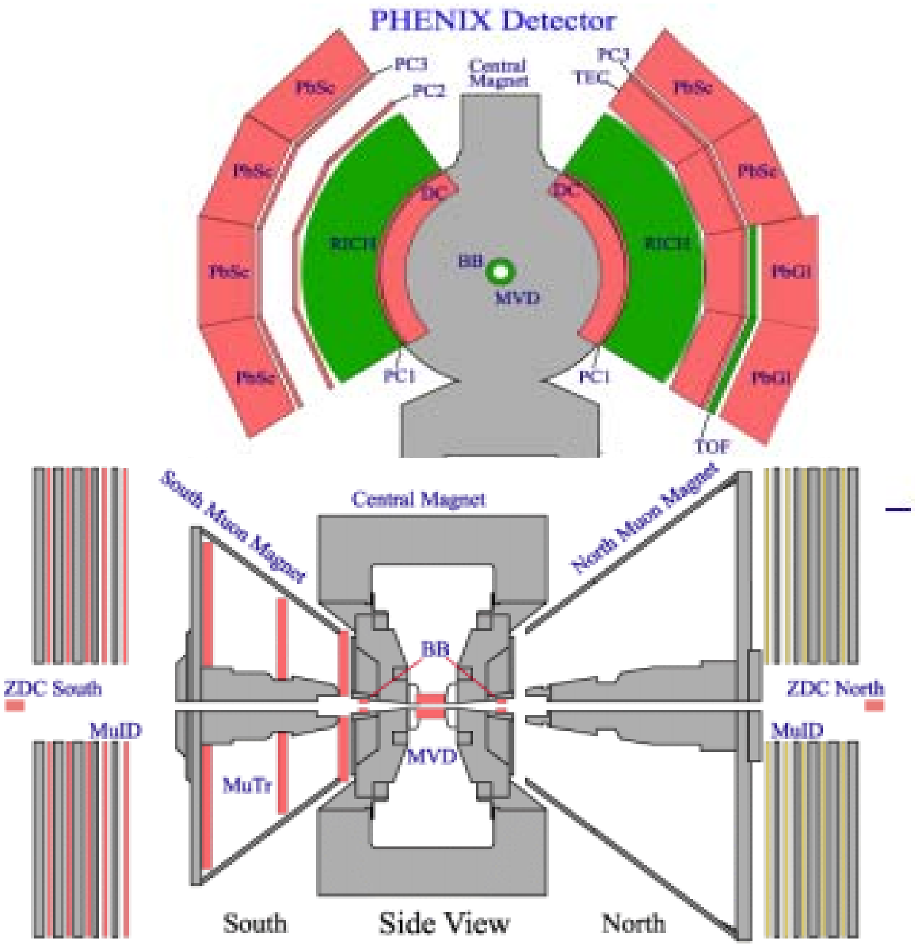
- Create QGP phase by colliding heavy nuclei at high energy
- Reconstruct the space/time evolution from many observable

Relativistic Heavy Ion Collider

- Located at BNL
- The first collider of heavy ion
- Two super-conducting rings
  - 3.83 km circumference
  - 120 bunches/ring
  - 106 ns bunch crossing time
- Top Energy:
  - ➔ $s^{1/2} = 500$ GeV for p-p
  - ➔ $s_{NN}^{1/2} = 200$ GeV for Au-Au
    (total $s^{1/2} = 40$ TeV for Au+Au)
- Luminosity
  - Au-Au: $2 \times 10^{26}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
  - p-p : $2 \times 10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (*polarized*)
- Started physics run in spring 2000

PHENIX detector

- Two central arms to measure e, γ, and hadron
  - $|y|<0.35$ and $\Delta\phi = \pi/2 \times 2$
- Two forward muon arms
  - $1.2<|y|<2.2$ and $\Delta\phi=2\pi$
    (* one muon arm operational in RUN-2)
- Good PID capability
  - Electron
  - Photon and π^0
  - Hadron
    - π/K in pt<2 GeV/c (TOF)
    - p, pbar in pt<4GeV/c (TOF)
    - π in pt>5.5 GeV/c (RICH)
  - Muon
- High speed DAQ and trigger
  - Logging rate 30 – 60 MB/s (RUN-2)
  - LVL-2 trigger (~1K Hz Au+Au)
- Participation from Japan
  - RICH (electron ID: Japan/US)
  - TOF (Hadron PID: Japan/US)
  - BBC (trigger, centrality: Japan/US)
  - Muon arm (part: RIKEN)



RHIC operation

Completed and started physics in 2000

- RUN-1 (August – September, 2000)
  - Au + Au at $s_{NN}^{1/2}$ = 130 GeV
  - Achieve ~10% of design luminosity
  - PHENIX recorded ~5 M triggers (About 1.5 M useful events)
- RUN-2 (August 2001 – January 2002)
  - Au + Au at $s_{NN}^{1/2}$ = 200 GeV
    - Achieve design luminosity
    - PHENIX recorded ~24/μb of Au+Au (~1/pb of N-N)
  - short (1 day) run Au+Au at $s_{NN}^{1/2}$ = 22 GeV
  - First polarized p+p run at $s^{1/2}$ = 200 GeV
    - PHENIX recorded ~150/nb of pp collision.
- RUN-3 (January 2003 – June 2003)
  - d+Au at $s_{NN}^{1/2}$ = 200 GeV (11 weeks + setup)
  - ploarized p+p at $s_{NN}^{1/2}$ = 200 GeV (3 weeks + setup)
- Next long Au+Au run is expected in RUN-4 (US FY04)

Run-1 (130 GeV)Results of PHENIX

- Global Measurements
  - Charged Multiplicity — PRL 86, 3500 (2001)
  - Transverse Energy — PRL 87, 052301 (2001)
- Elliptic flow measurement — nucl-ex/0204005, accepted in PRL.
- Event fluctuation
  - Charge fluctuation — PRL 89, 082301 (2002)
  - <Pt>, <et> fluctuation — PRC 66, 024901 (2002)
- Two particle correlation — PRL 88, 192302 (2002)
- Hadron production
  - K,π,p spectra — PRL 88, 242301 (2002), full paper in preparation
  - Particle ratios — paper in preparation
  - Λ production — PRL 89, 092302 (2002)
- High pt particle production
  - Suppression of high pt hadrons — PRL 88, 022301 (2002)
  - Centrality dependence — nucl-ex/0207009, submitted to PLB
- Electron and charm — PRL 88, 192303 (2002)

Results from RUN-2 (200 GeV) (presented in QM2002)

- **Global/hadron**

Hadron spectra	Chujo	nucl-ex/0209027
dN/dh, dEt/dh	Bazilevsky	nucl-ex/0209025
Thermal fit to spectra and HBT	Burward-hoy	nucl-ex/0210001
Two particle correlation	Enokizono	nucl-ex/0209026
Elliptic flow	Esumi	nucl-ex/0210012
Flow at high pt	Ajitanand	nucl-ex/0210007
Fluctuation	Nystrand	nucl-ex/0209019

- **High pt**

High pt summary	Mioduszewski	nucl-ex/0210021
High pt charged	Jia	nucl-ex/0209030
High pt π^0 in Au+Au	d'Enterria	hep-ex/0209051
Evidence for jets in Au+Au	Chiu	
Particle ratio at high pt	Sakaguchi	nucl-ex/0209030
Inclusive photon	Reygers	nucl-ex/0209021
High pt π^0 in pp	Torii	nucl-ex/0210005

- **Leptons**

Lepton result summary	Nagle	nucl-ex/0209015
J/Ψ	Frawley	nucl-ex/0210013
Single electron and charm	Averbeck	nucl-ex/0209016
$\phi \rightarrow KK$ and $\phi \rightarrow ee$	Mukhopadhyay	nucl-ex/0209028

Basics: N_{part}, N_{coll}

- Geometrical Model (Glauber Model)
  - Number of collsion (N_{coll})
  - Participants (N_{part})
    - Nucleons that collide with nucleus
  - Spectators ($2A - N_{part}$)
    - Nucleons that do not collide
- p+p: $N_{part} = 2$, $N_{coll} = 1$
- p+A: $N_{part} = N_{coll} + 1$

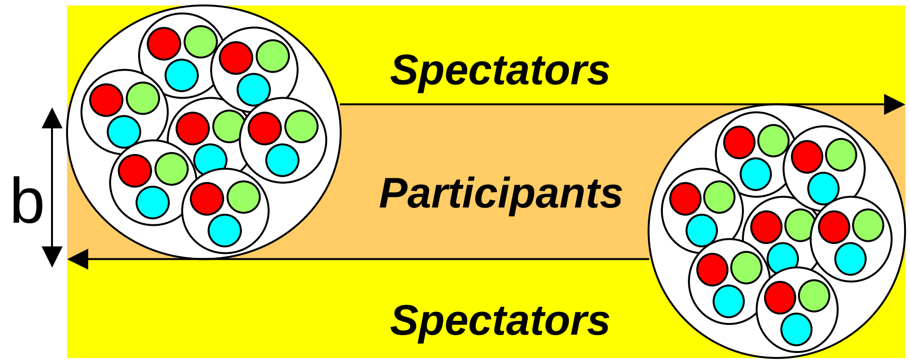
  (N_{part} ~ 6 for Au)
- A+A: $N_{coll} \propto N_{part}^{4/3}$

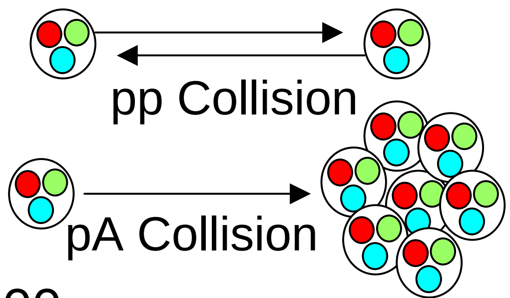
Soft physics ~ N_{part}

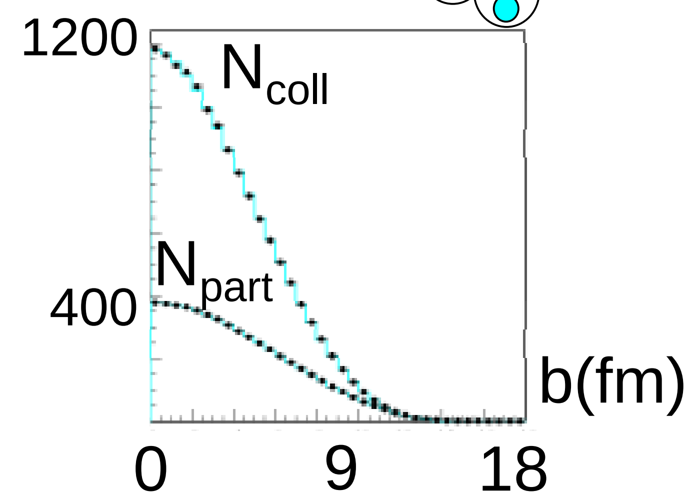
dN/dy, dN/dpt in low pt, etc

Hard phyiscs ~ N_{coll}

dN/dpt at high pt, J/PSI, direct photon, charm, etc

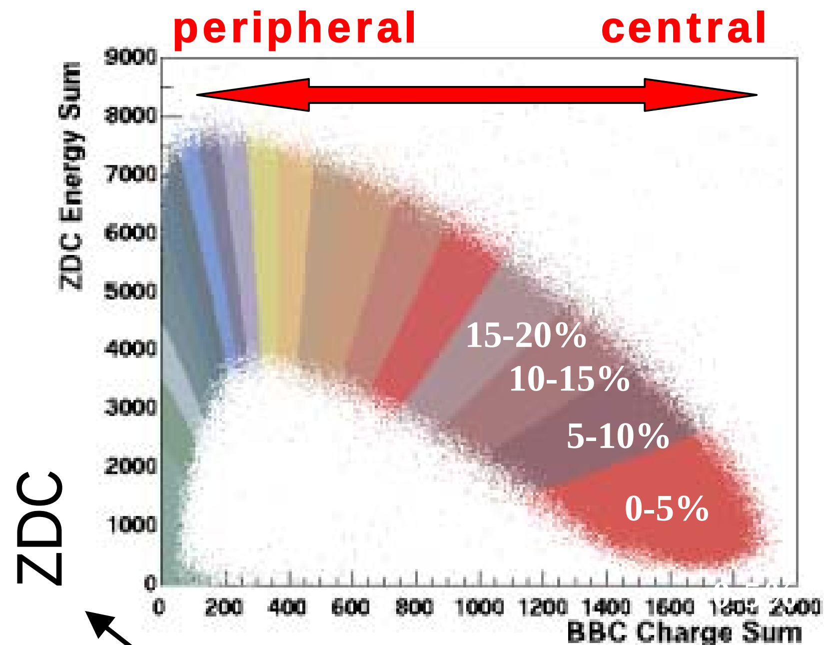


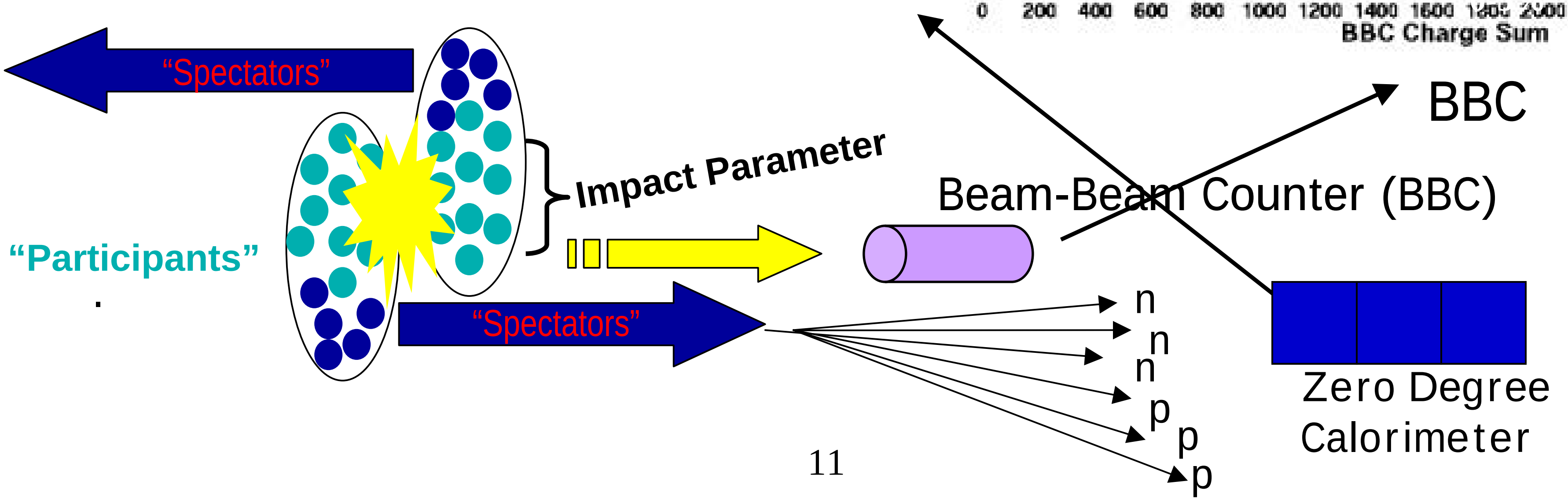




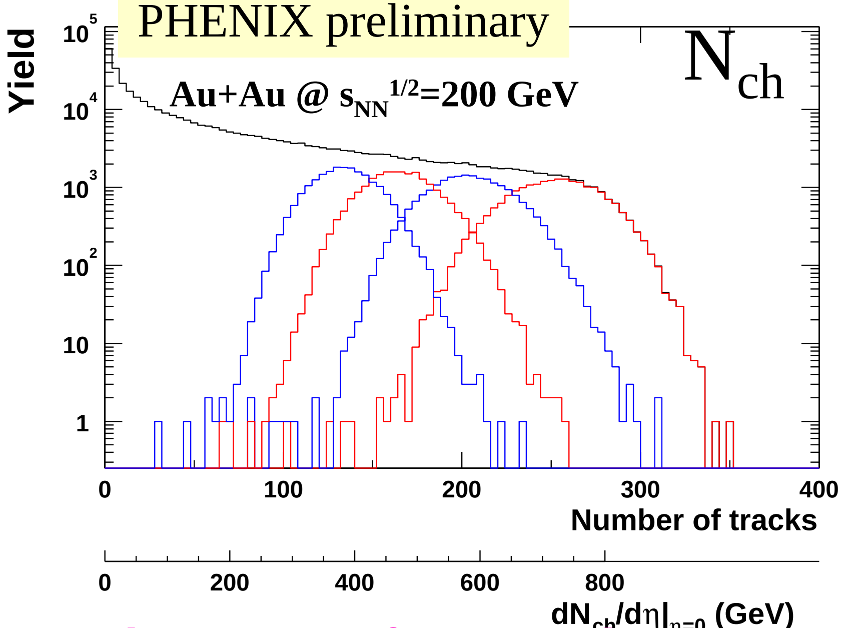
Determining N_{part} and N_{coll}

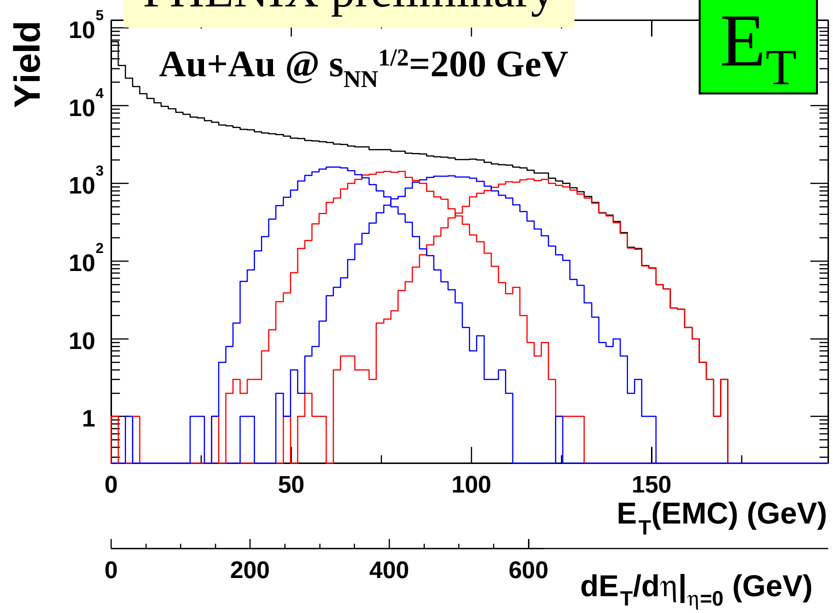
- Use combination of ZDC and BBC
  - ZDC measures number of spectator neutrons
  - BBC measures charged multiplicity (~ # of participants)
- Use Glauber model (geometrical model) to determine N_{part} and N_{coll} in each centrality classes





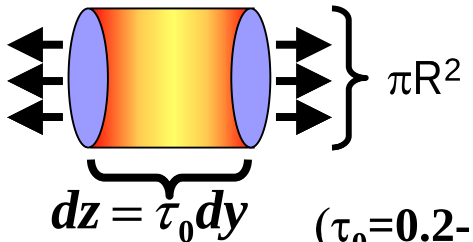
dN/dh, dEt/dη measurement





Bjorken estimate for energy density

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{c\tau_0} \left(\frac{dE_T}{dy} \right)$$



(τ_0=0.2-1.0 fm/c)

Estimated energy density in top 2% central collision (with τ_0 = 1fm/c)

ε_{BJ} ~4.6 GeV/fm³ (@130GeV)

ε_{BJ}~ 5.5 GeV/fm³ (@200 GeV)

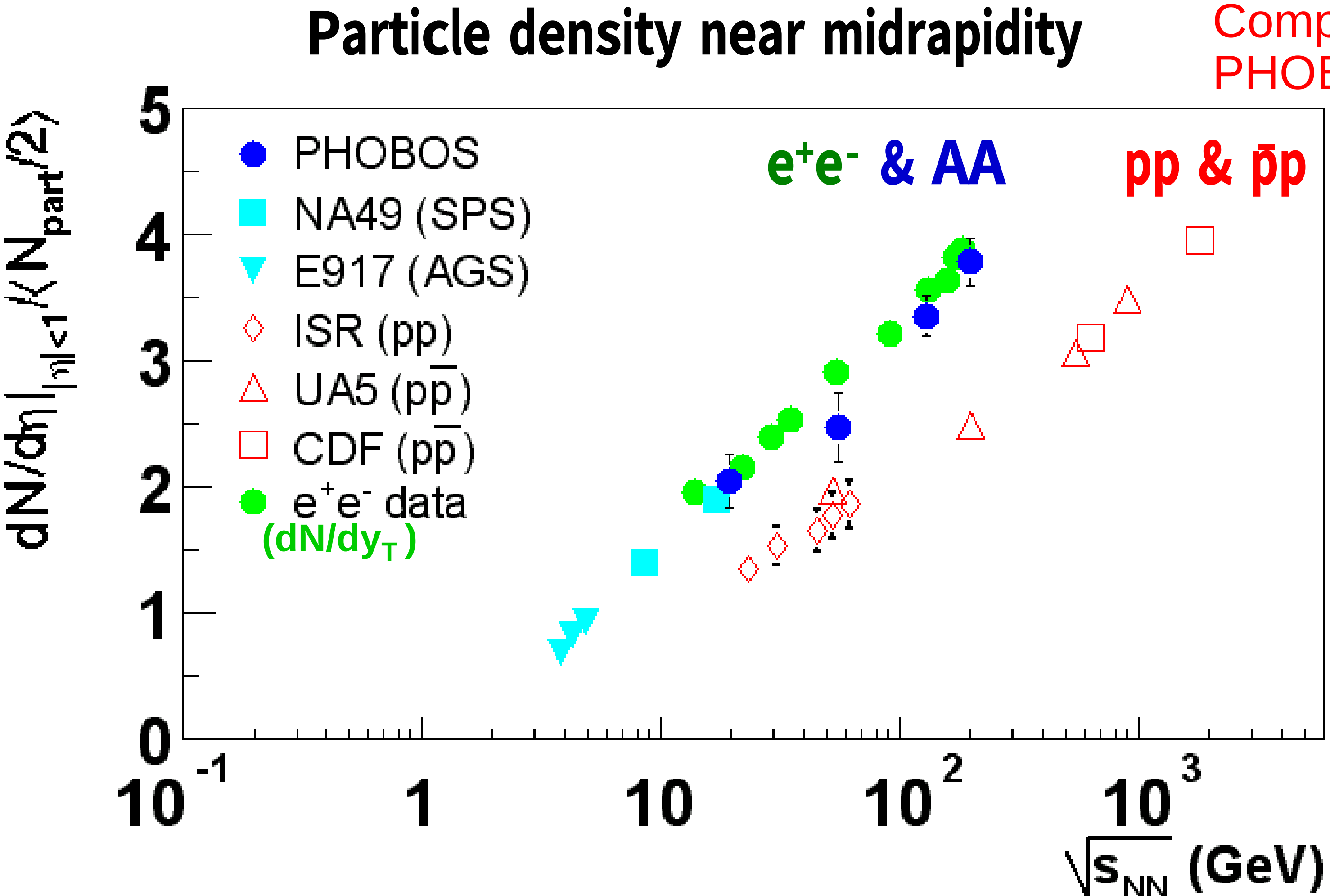
ε is well beyond ε_{crit} ~ 1 GeV/fm³

ε can be much higher for shorter τ_0

nucl-ex/0209025

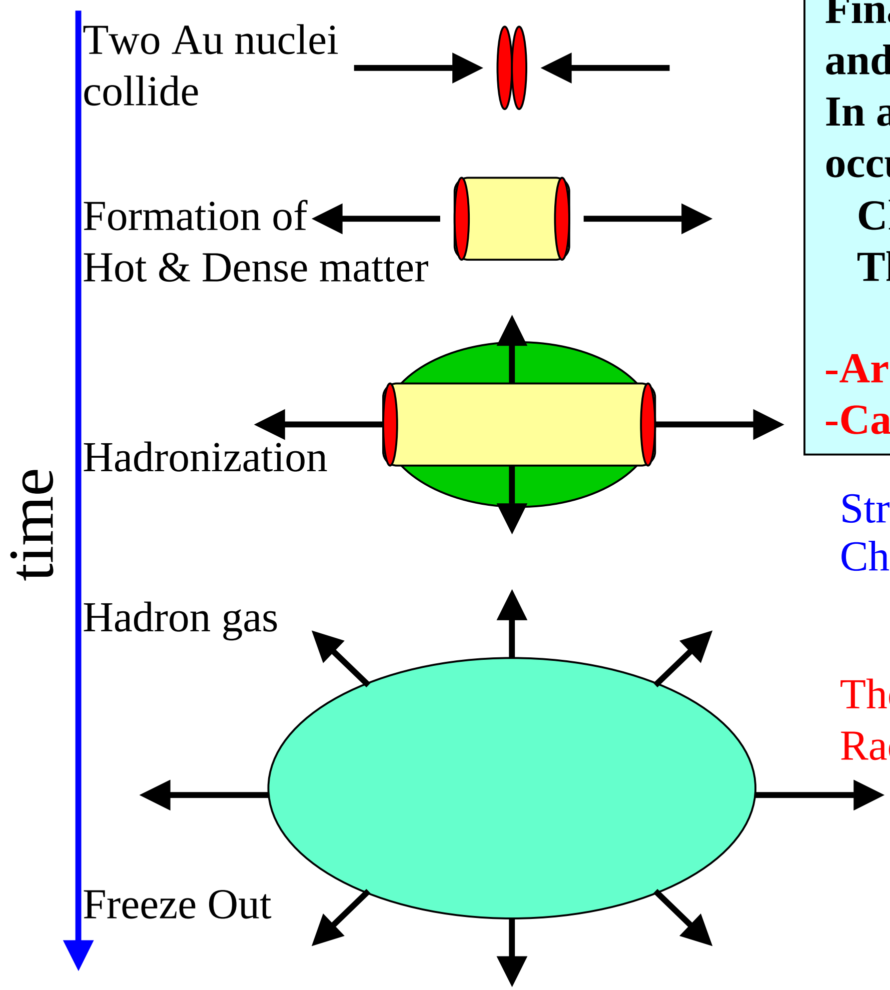
Nch vs $\sqrt{s_{NN}}$

Compilation by PHOBOS



- $dN/d\eta$ in AA is by 60-70% higher than pp
- $dN/d\eta$ in AA is similar to e^+e^-

Hadron measurements



Final stages of the collision is study by hadron spectra and hadron yield.
In a popular picture of A+A collision, the freeze-out occurs in two step:

Chemical freeze-out (T_{ch}, μ_B) ←→ hadron yield
Thermal freeze-out (T_{th}, <β>) ←→ hadron spectra

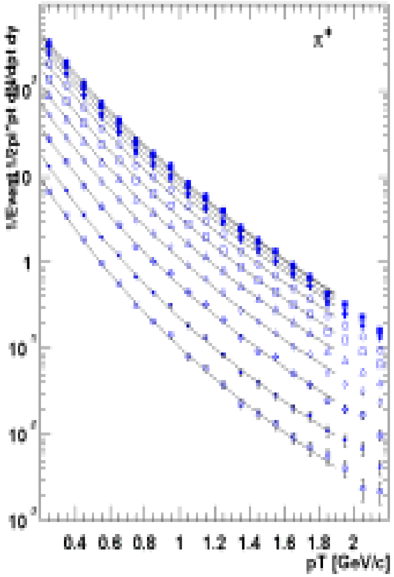
-Are RHIC data consistent with (local) thermalizaton?
-Can those thermal models describe RHIC data?

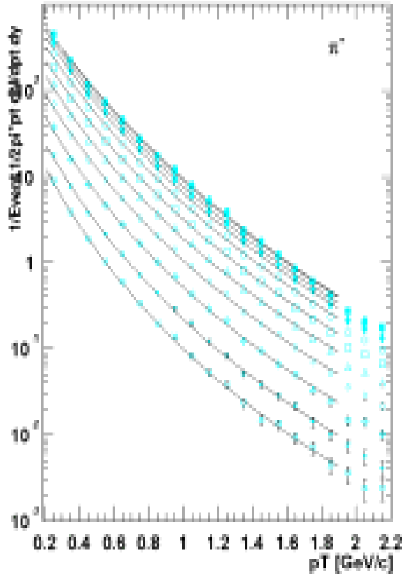
Strangeness production
Chemical freeze-out ←→ dN/dy of K,π,p,Λ,Ξ,Ω
Thermal fit (T_{ch}, μ_B)

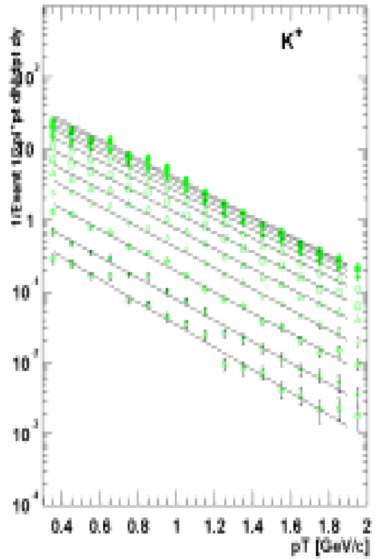
Thermal freeze-out
Radial flow ←→ dN/dpt of K, π, p, Λ, etc
Hydrodynamic model fit (T_{th}, β_t)

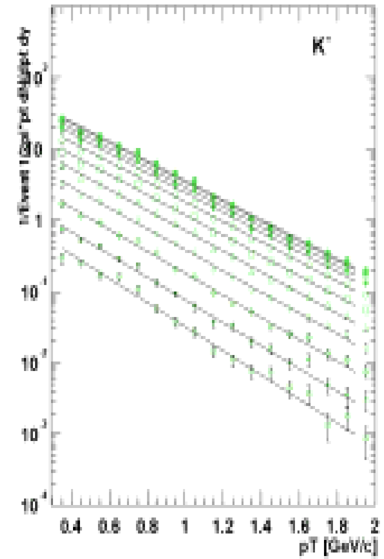
Single particle p_T spectra

Au+Au at $\sqrt{s}$ = 200 GeV PHENIX preliminary



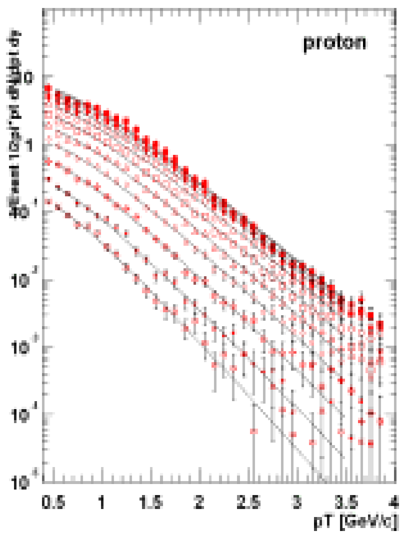


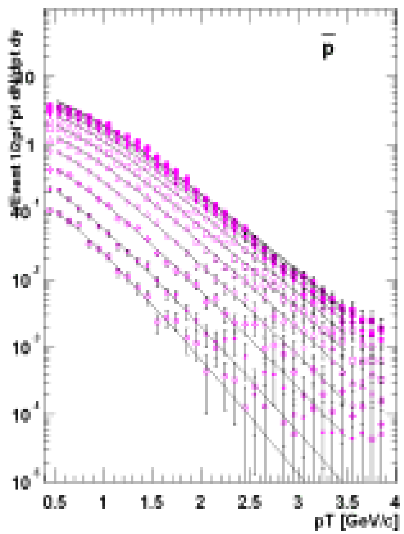




centralities

0 – 5 %
5 – 10 %
10 – 15 %
15 – 20 %
20 – 30 %
30 – 40 %
40 – 50 %
50 – 60 %
60 – 70 %
70 – 80 %
80 – 93 %

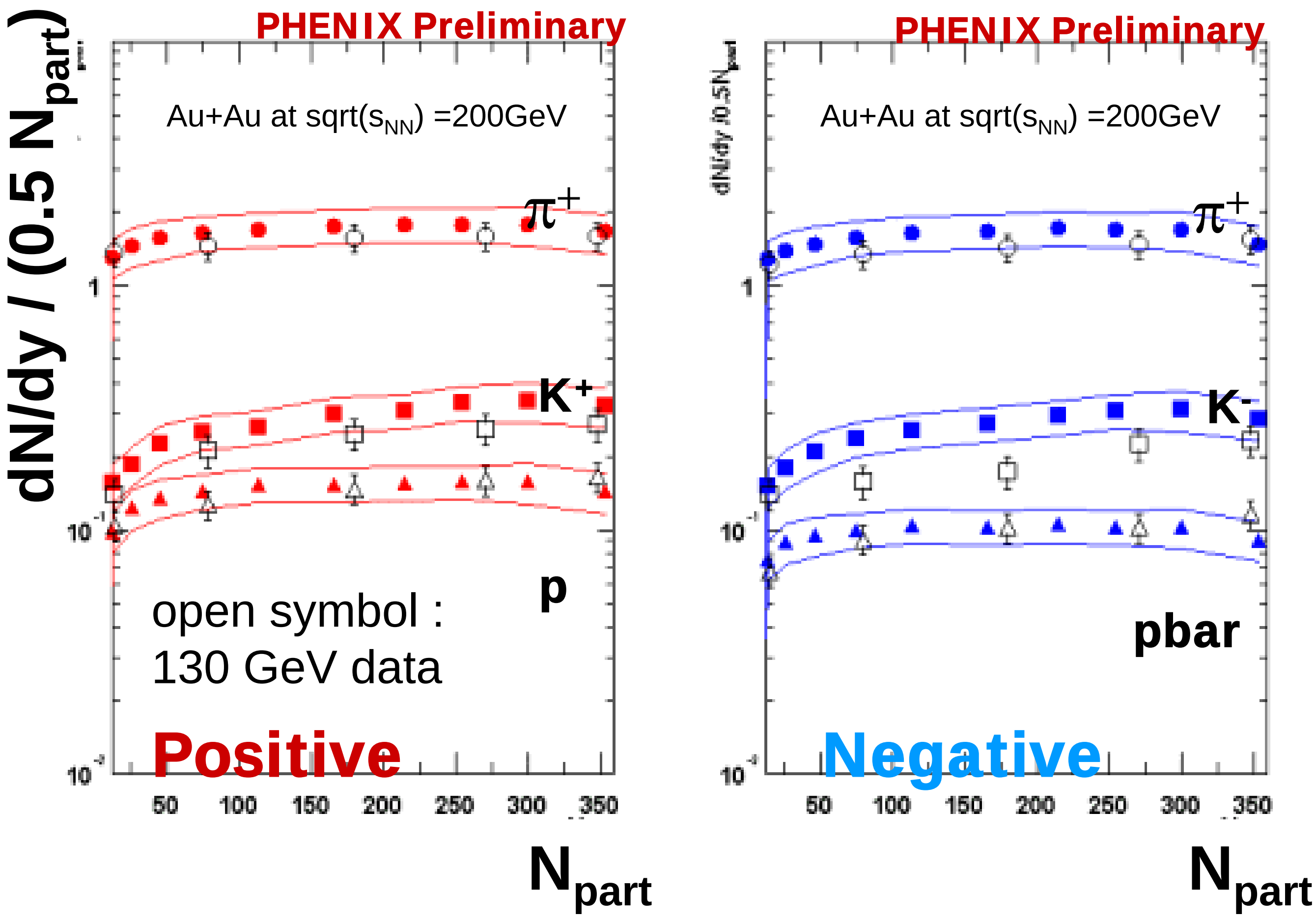




$\pi^{\pm}$: 0.2<p_T<2.0 GeV/c
$K^{\pm}$: 0.3<p_T<2.0 GeV/c
$p^{\pm}$: 0.4<p_T<4.0 GeV/c

nucl-ex/0209027

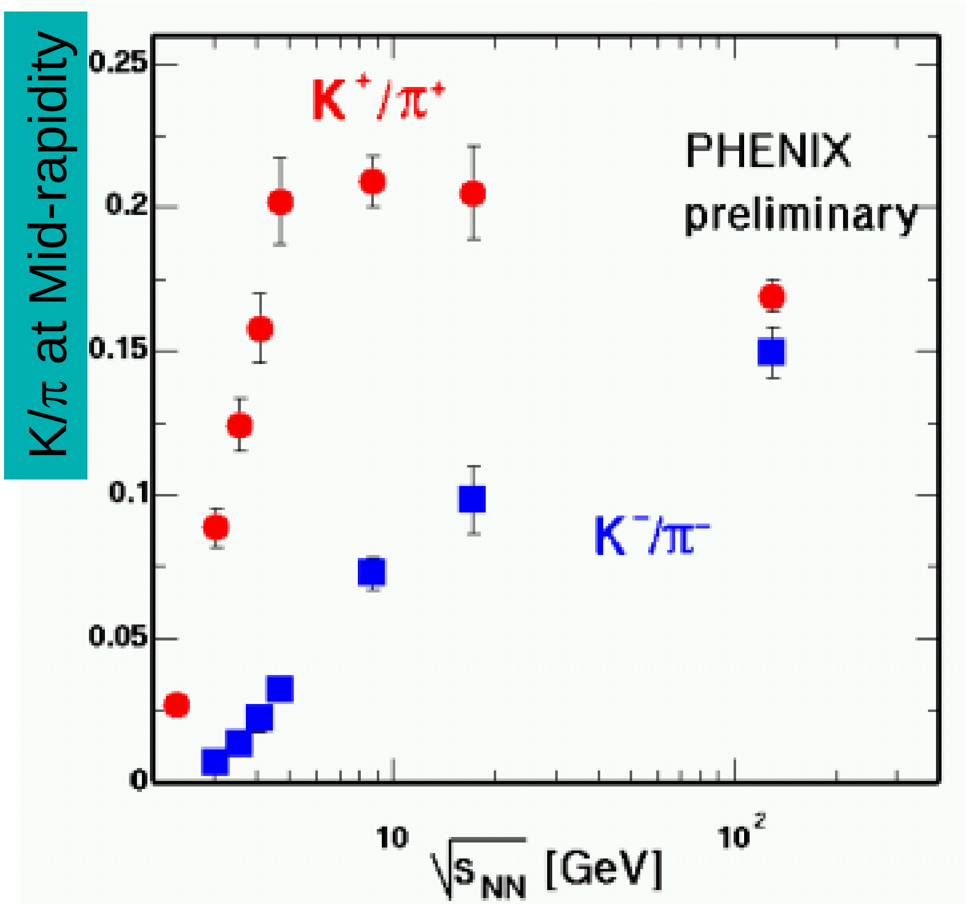
dN/dy vs Npart



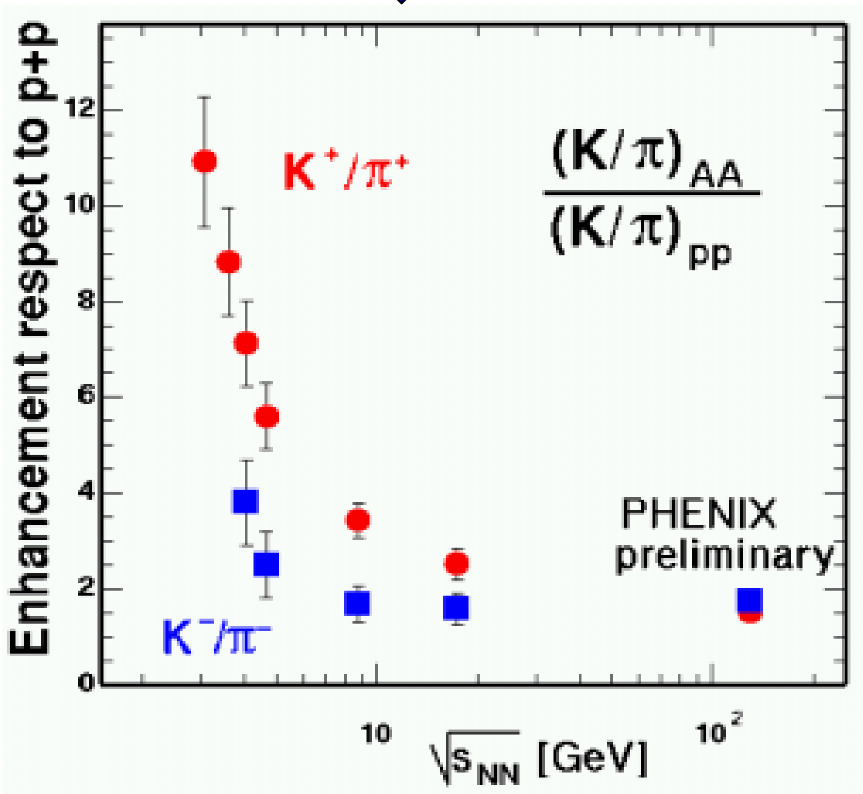
- (dN/dy)/Npart increases slowly with Npart
- Faster increase of kaon than π,p

hep-ex/0209027

K/π ratio in central collisions vs $\sqrt{s_{NN}}$



- Strangeness enhancement with respect to p+p collisions



- K+/π+ : Slightly decreases from top SPS energy.
- K-/π- : monotonically increases from AGS/SPS

Paper in preparation

Thermal fit to particle ratios

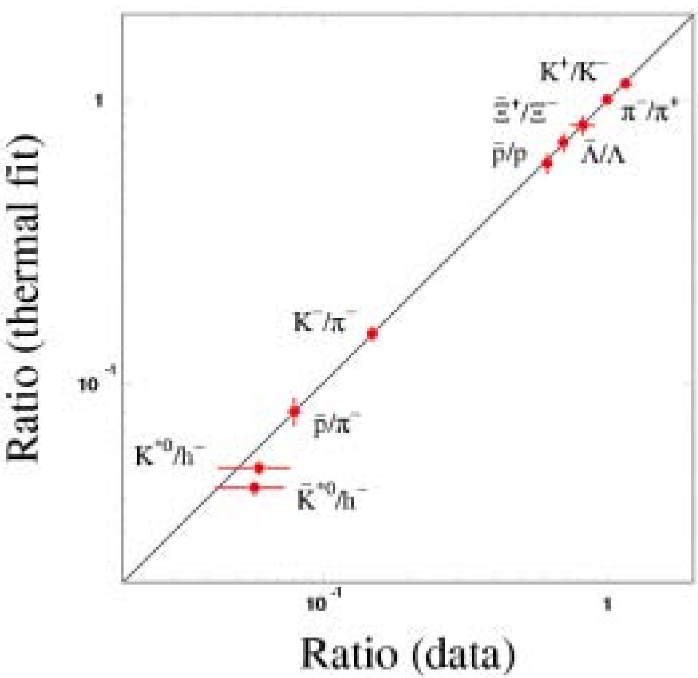
Hadron resonance ideal gas

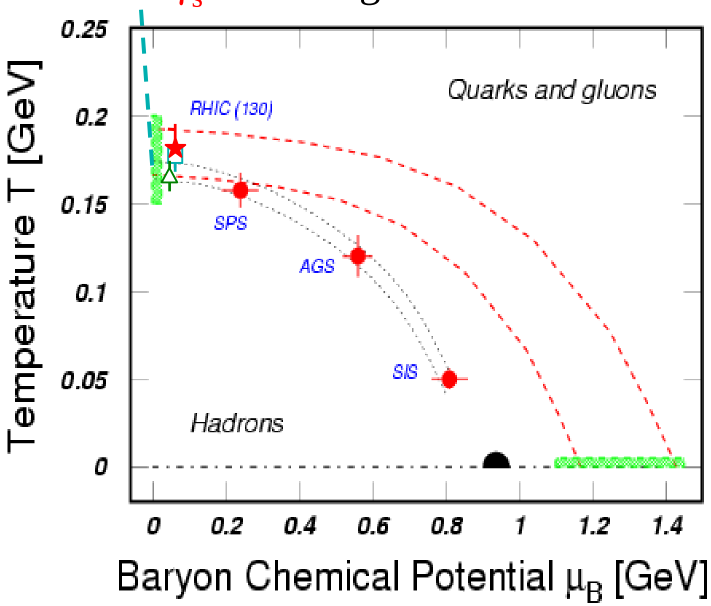
Refs. J.Rafelski PLB(1991)333
J.Sollfrank et al. PRC59(1999)1637

$$\rho_i = \gamma_s^{|s_i|} \frac{g_i}{2\pi^2} T_{ch}^{\ 3} \left(\frac{m_i}{T_{ch}}\right)^2 K_2(m_i/T_{ch})\ \lambda_q^{\ Q_i}\ \lambda_s^{\ s_i}$$

$$\lambda_q = \exp(\mu_q/T_{ch}), \quad \lambda_s = \exp(\mu_s/T_{ch})$$

T_{ch} : Chemical freeze-out temperature
μ_q : light-quark chemical potential
μ_s : strangeness chemical potential
γ_s : strangeness saturation factor

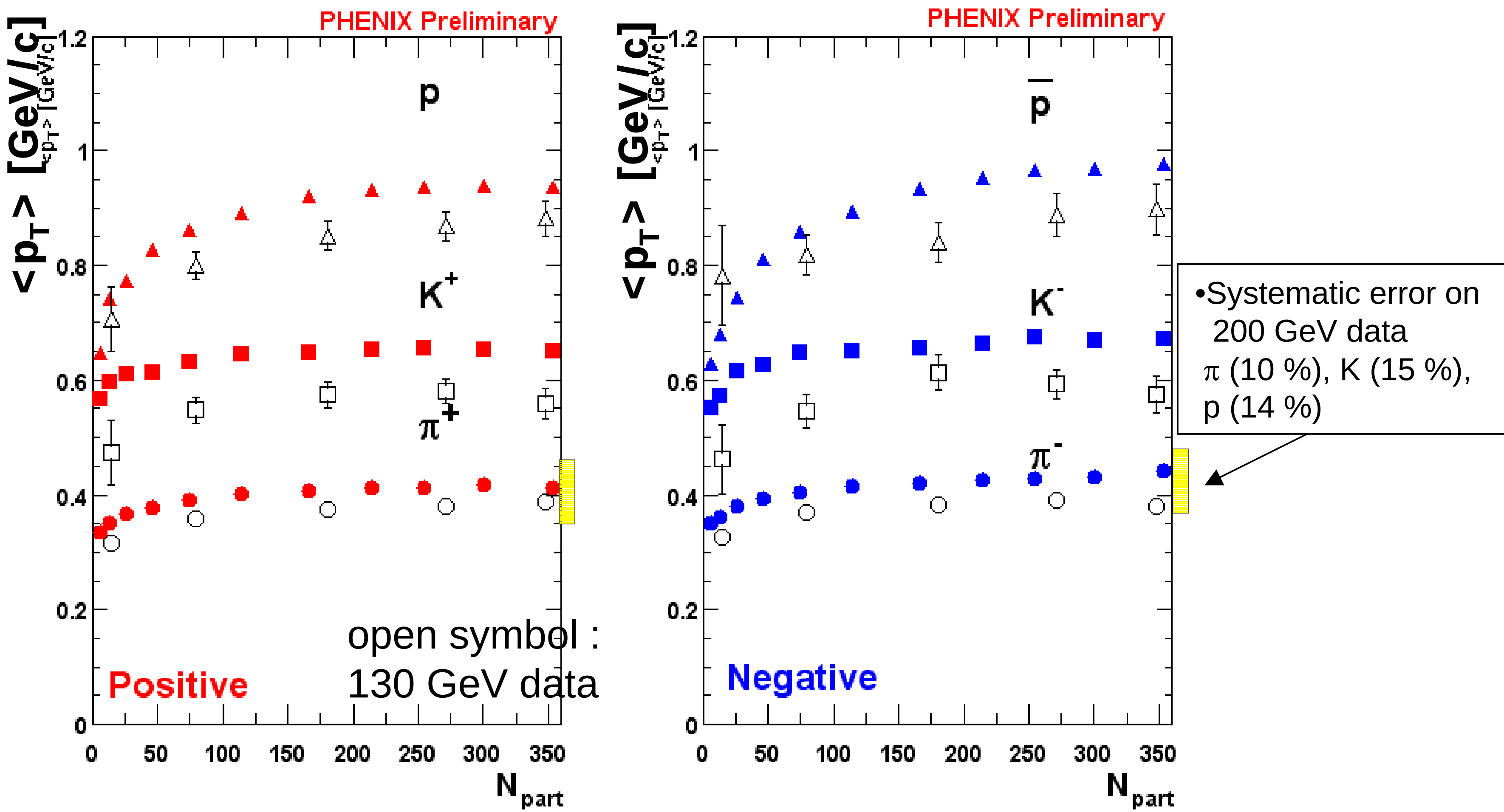




Fit by M. Kaneta to RHIC data
Similar fits by other groups

- Fit results:
  T_{ch}~170MeV~$T_{crit,}$
  μ_B ~ 40 MeV@130GeV
  ~ 30 MeV @200GeV
  γ_s ~ 1.0 (strangeness saturation)

$\langle p_T \rangle$ vs. N_{part}

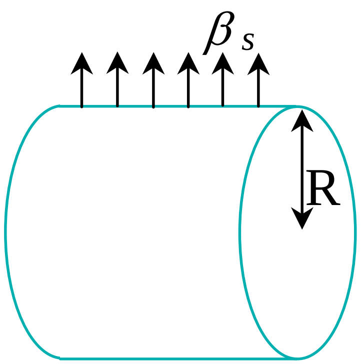


- $\langle p_T \rangle$ increases with N_{part} and particle mass => radial expansion.
- Consistent with hydrodynamic expansion picture.

nucl-ex/0209027

Hydrodynamics model (blast-wave)

Local thermalized fluid with radial expanding flow



$$E\frac{d^3n}{dp^3} \propto \int_\sigma e^{-(u^\nu p_\nu)/T_{th}} p^\lambda d\sigma_\lambda$$

$$u^\nu(t,r,z=0) = (\cosh\rho, e_r \sinh\rho, 0)$$

$$\rho = \tanh^{-1}\beta_r \qquad \beta_r = \beta_s \ f(r)$$

Integral over fluid volume

$$\frac{dn}{m_T dm_T} \propto \int_0^R r\,dr\, m_T K_1\left(\frac{m_T \cosh\rho}{T_{th}}\right) I_0\left(\frac{p_T \sinh\rho}{T_{th}}\right)$$

Ref. : E.Schnedermann et al, PRC48 (1993) 2462

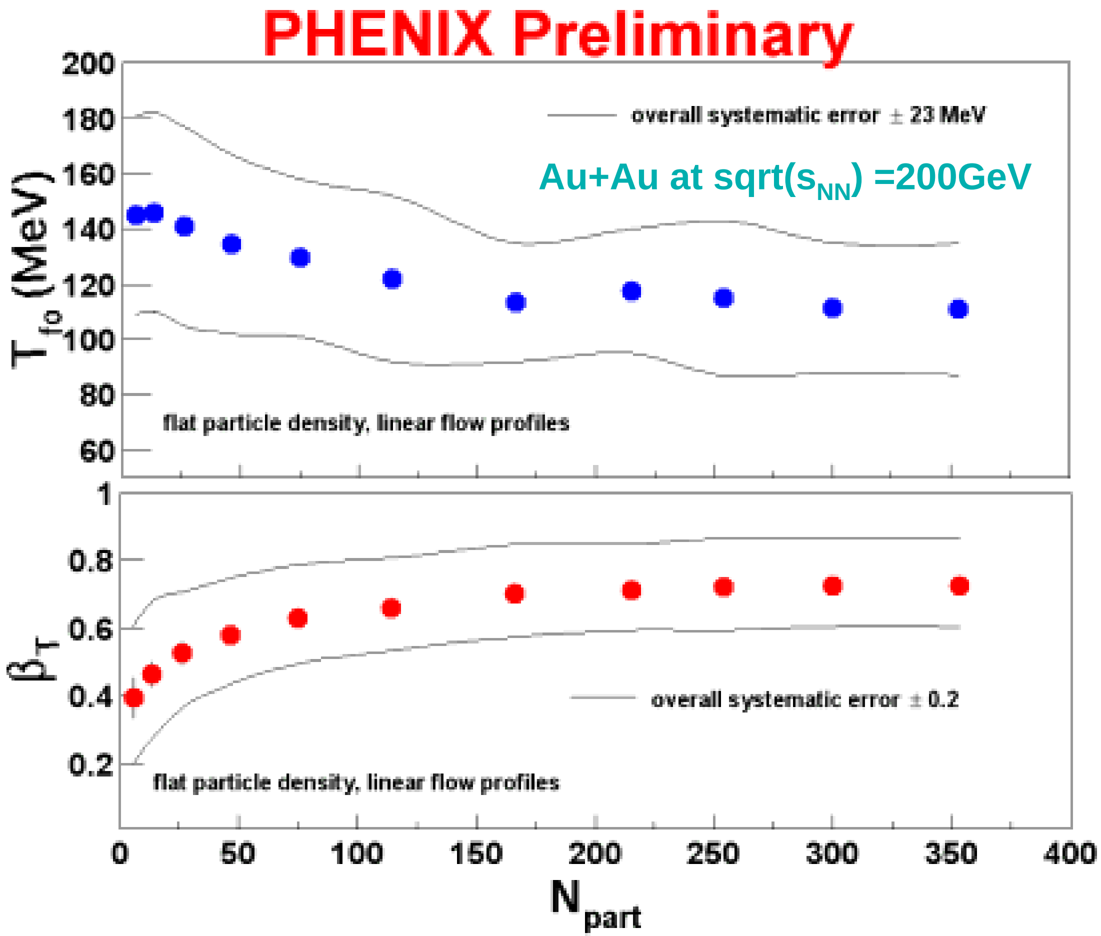
Flow profile used

$(\beta_r = \beta_s (r/R_{max}))$

This simple model predicts the shapes of Mt distribution of π, K, p, Λ, etc for only two parameters (T_{th}, β_s) (if you chose a profile)

Can model describe the data?

Result of hydrodynamic model fit



Most central collisions for 200 GeV data

Freeze-out Temperature(*)

T_{fo} = 110 ± 23 MeV

Transverse flow velocity(*)

β_T = 0.7 ± 0.2

($\langle\beta_T\rangle$ = **0.5** ± **0.15**)

(*) Resonance feed down is not corrected.

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

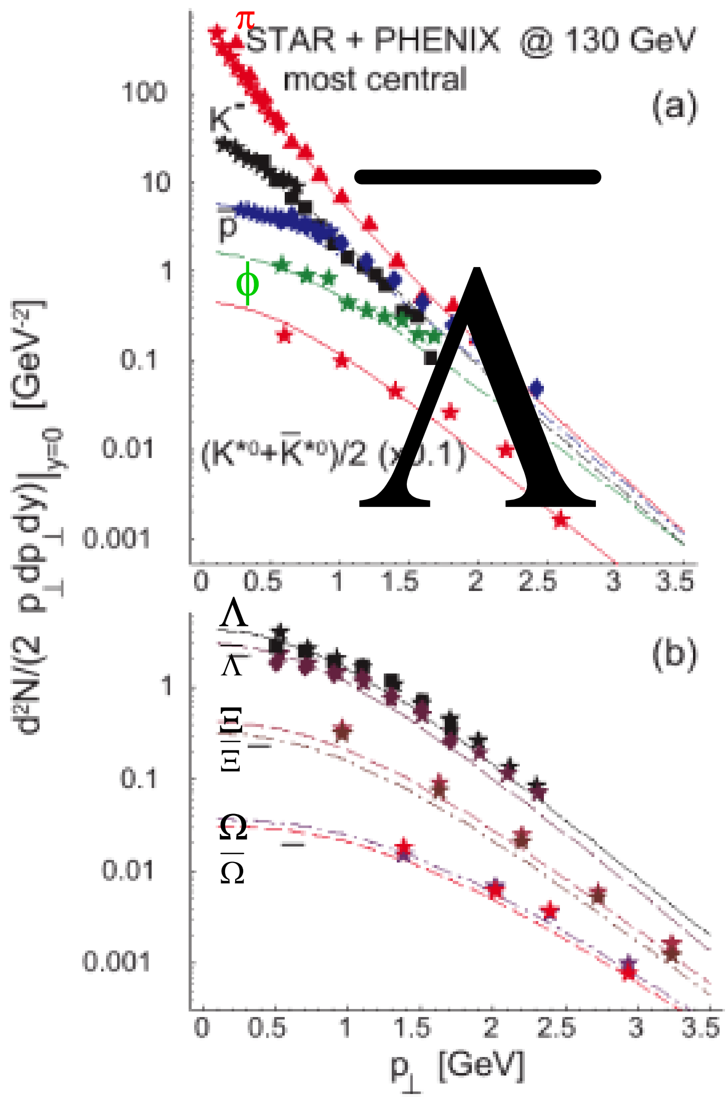
- β_T increases from peripheral to mid-central (N_{part} < 150) and tends to saturate for central collisions.

nucl-ex/0209027 and nucl-ex/0210001

Single Freeze-Out Model

- In “standard” scenario, there are two different freeze-out, chemical freeze out(T_{ch}) and thermal freeze-out (T_{fo}).
  T_{ch} ~ 170 MeV
  T_{fo} ~ 110 MeV
- Recently, model with single freeze-out ($T_{ch}=T_{fo}$) is proposed.
- The model by Broniowski et al. include effects of resonance feed-down and strong radial expansion. They fit all single particle spectra measured by PHENIX and STAR with only 4 parameters:
  - T : freeze-out temperature
  - μ_B : baryon chemical potential
  - τ : **system life time**
  - ρ_{max}: system transverse size

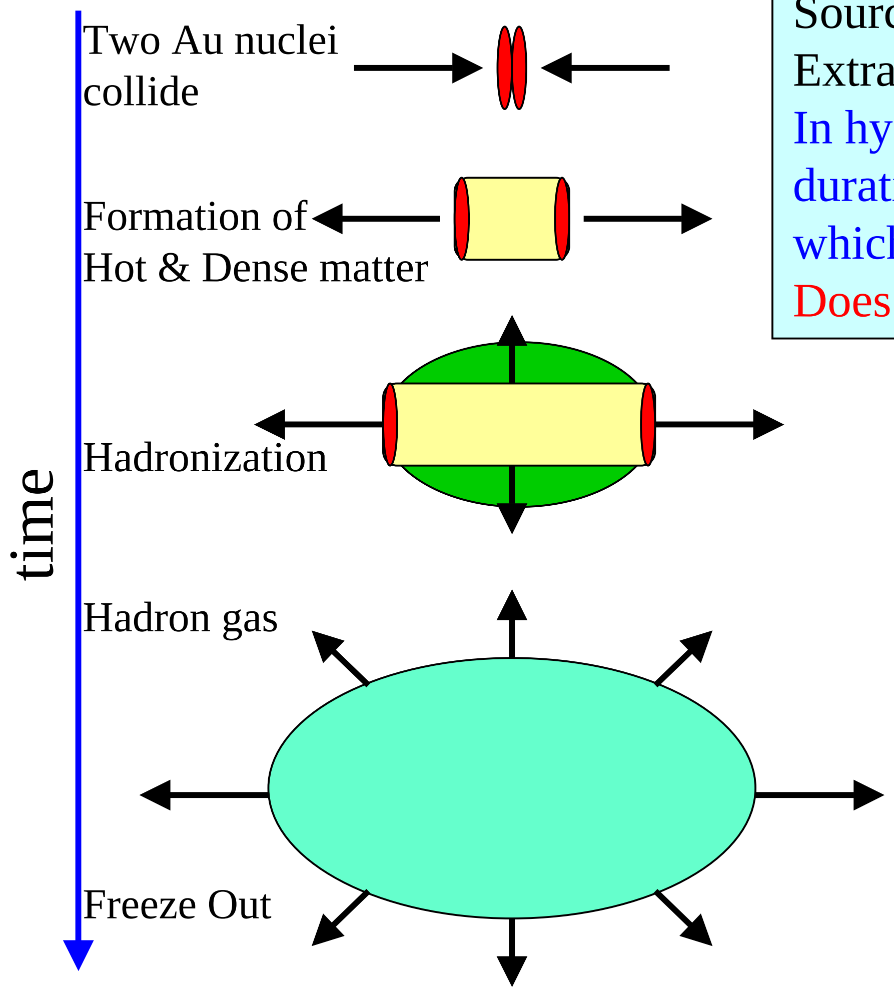
  T=165±7MeV, μ=41±5MeV
- Recent hydrodynamic calculation by Ruusukaen et al. also shows that T_{fo} is close to T_{ch}, if resonances are included.



W. Broniowski and W. Florkowski
PRC66, 064905 and QM2002

Two particle correlation

Source size and duration time of freeze-out can be Extracted from two particle interference measurement.
In hydrodynamic models, it is expected that long duration of fzeeze-out causes a large freeze-out volume, which can be observed in two particle correlation.
Does it observed at RHIC?



1st order phase transition?

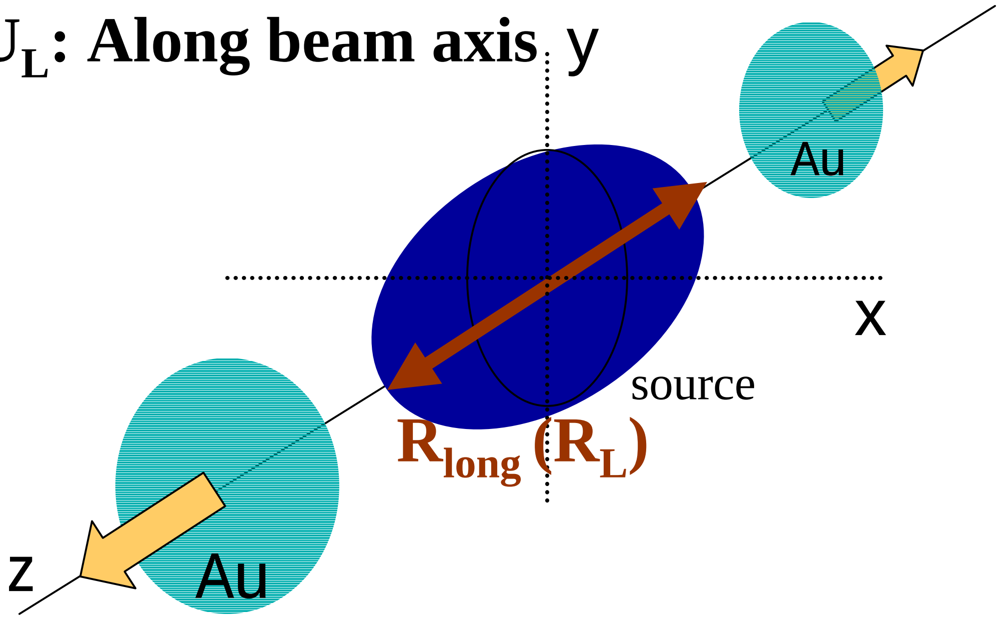
Duration time
and
Source size ↔ Two particle correlation measurement (HBT)
at
Freeze-out

3D HBT analysis in Bertsch-Pratt frame

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

In LCMS frame

U_L: Along beam axis

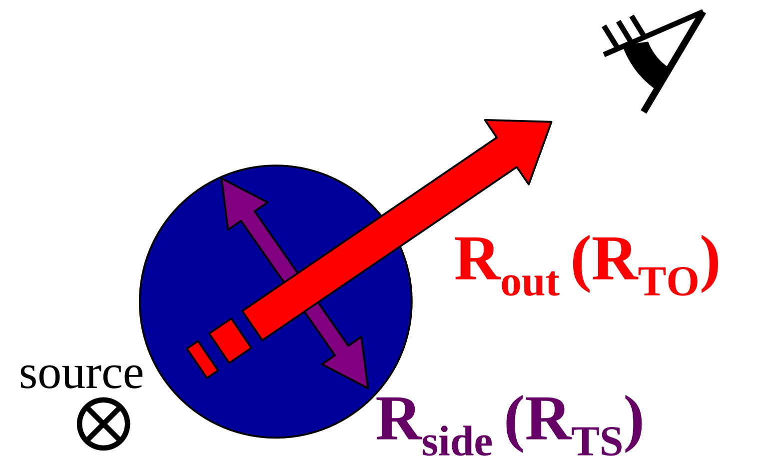


Beam axis

U_{out}: towards detector

U_{side}: U_{out} x U_L

Detector



Beam axis

R_{long} ~ source size along the beam axis
sensitive to freeze-out time τ

R_{side} ~ transverse source size

R_{out} = mixture of geometry and duration
time of particle emission

For static, transparent Source, the duration time $\Delta\tau$ can be measured as

$$\Delta\tau = \sqrt{R_{TO}^2 - R_{TS}^2} / \beta$$

2 π HBT results @ 130 GeV and lower energy

	$\sqrt{s_{NN}}$
PHENIX,STAR	130GeV
NA44,NA49,CERES	17.2GeV
AGS-E866	4.6GeV

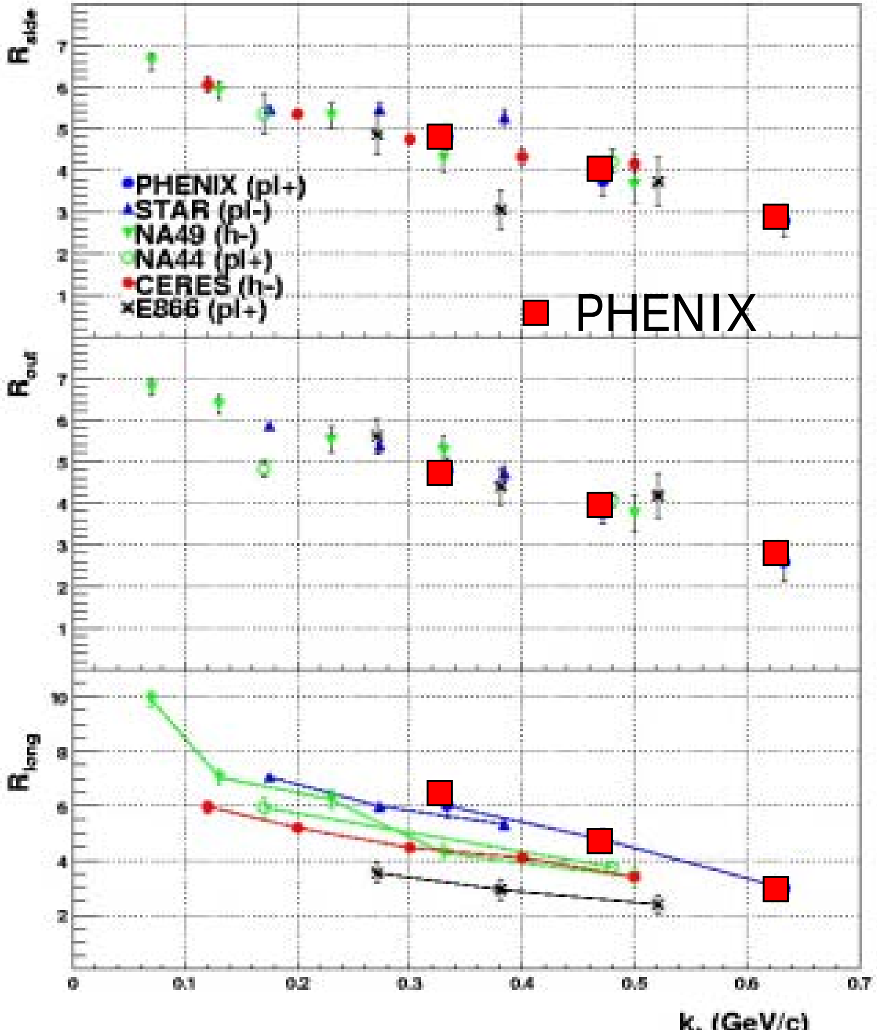
- Radii parameters depend on K_T due to radial expansion

- Transverse radii (R_{side} and R_{out}) have very *little* dependence on beam energy

  naïve expectation: R increase with multiplicity

- Almost all energy dependence is in longitudinal radius (R_{long})

PRL88,192302



K_t = average transverse momentum of the pair

HBT puzzle

In Hydrodynamical models

1st order phase transition → long duration time $\Delta\tau$

For *static* and *transparent* source

$\Delta\tau = (R_{out}^2 - R_{side}^2)^{1/2}$

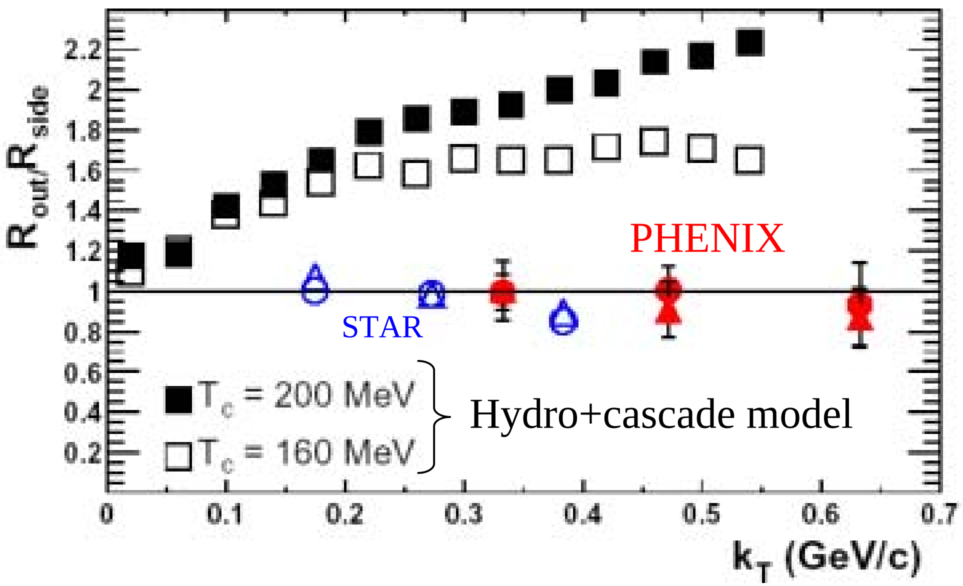
→ Prediction:

$R_{out} >> R_{side}$

PHENIX and STAR data:

Rout ~ Rside

→Naïve hydrodynamic models are excluded



Possibile solutions to the puzzle

- Dynamic effects
- Opacity? (reduce Rout)
- Frame dependence?

PRL88, 192302

HBT result @ 200 GeV

PHENIX two pion HBT data at 200 GeV are compared with a recent hydrodynamic calclulation with two different conditions:

Standard initial condition

Assume early freeze-out at Hadronization point

Data favors early freeze-out scenario, but both scenarios can not explain large R_{side}

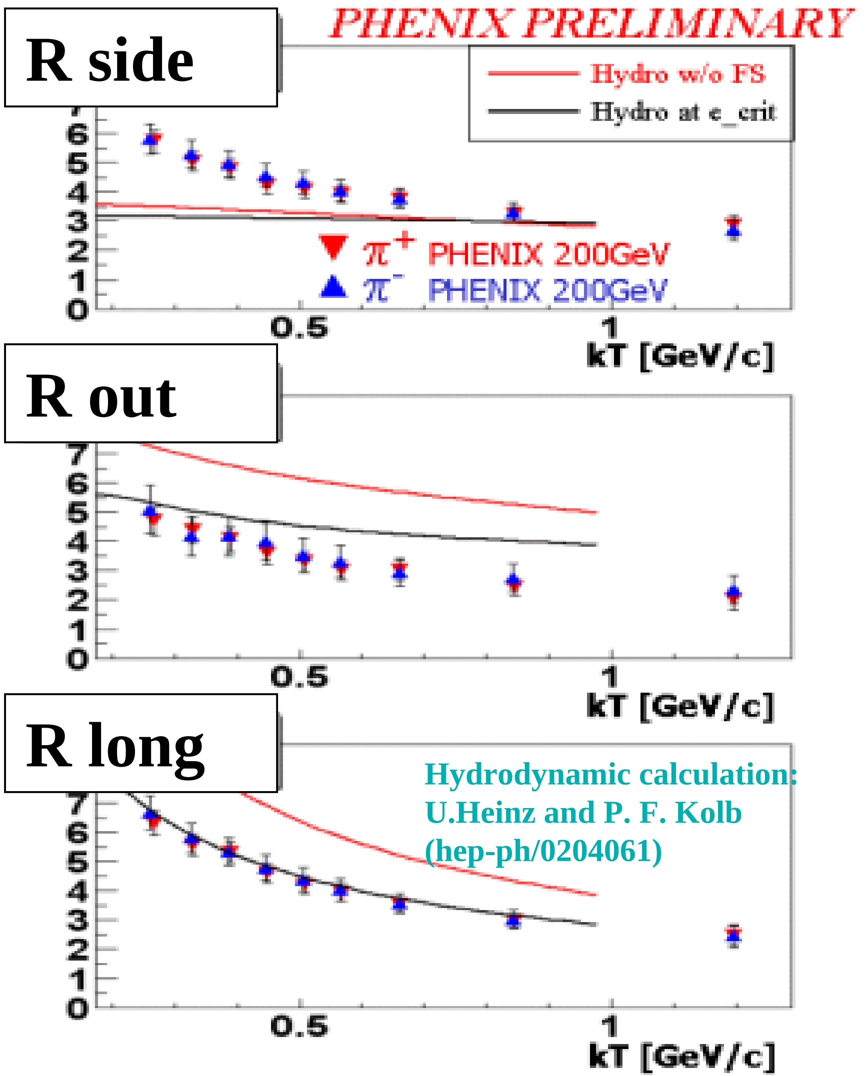
Many theoretical attempts are made to explain RHIC HBT data, but they are so far *not* successful.

The data suggests early freezeout (τ~10fm/c) and short duration time ($\Delta\tau \sim 0$)

- super-cooling?
- very stiff EOS?
- treatment of freeze-out in theory?

nucl-ex/0209026

Centrality is in top 30%

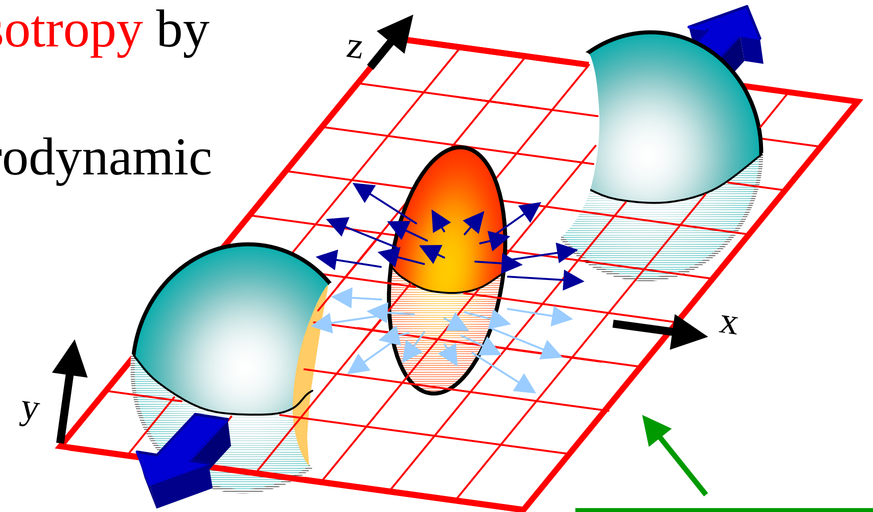


k_T: average transverse momentum of the pair

Elliptic Flow

- In non-central A+A collisions, “flow” effect has been observed.
- The flow effect is caused by conversion of spatial anisotropy to momentum anisotropy by particle re-scattering
- The flow becomes strong in the hydrodynamic limit (strong re-scattering limit).

Non-central Collisions



Reaction plane

Early thermalization and Hydrodynamical expansion → Strong elliptic flow

$dN/d\phi = N\,[\,1 + \Sigma\, 2v_n \cos(n\phi)\,]$

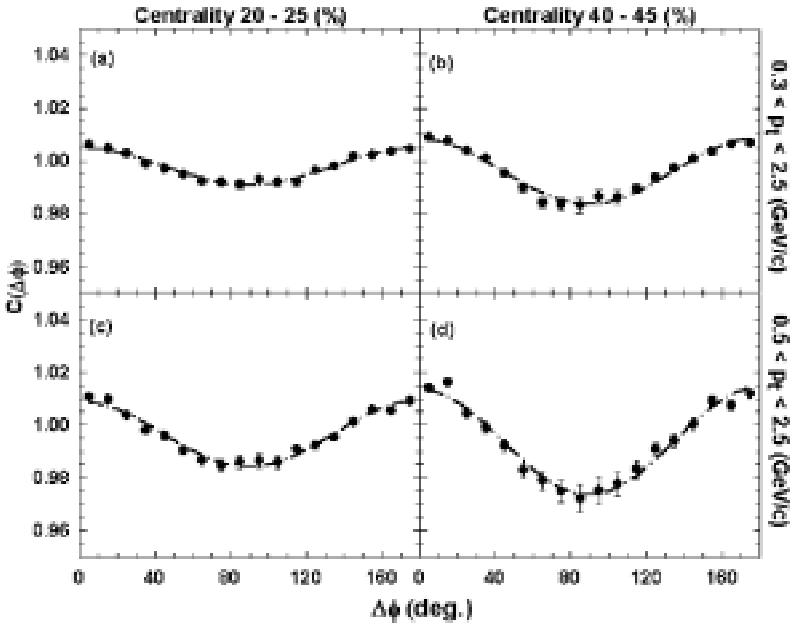
ϕ : azimuthal angle for measured particles from a reaction plane

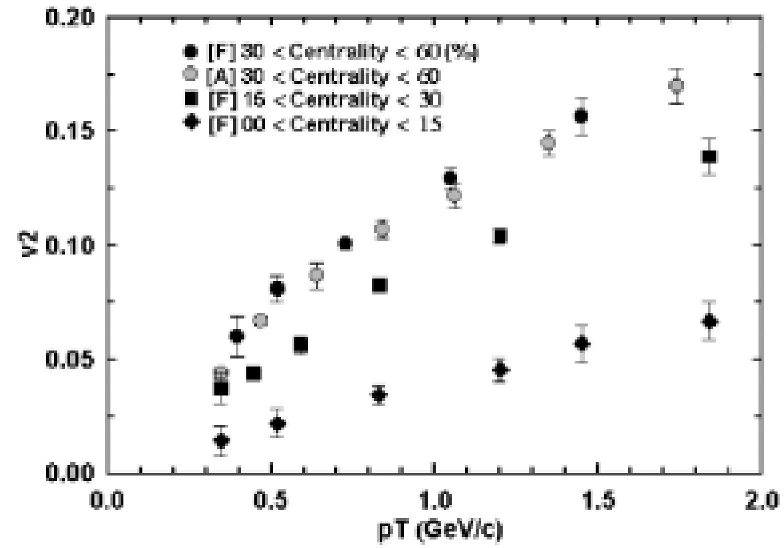
v_n : anisotropy parameter

v_1 := Directed flow

v_2 := Elliptic flow

Elliptic flow measurement in RUN-1





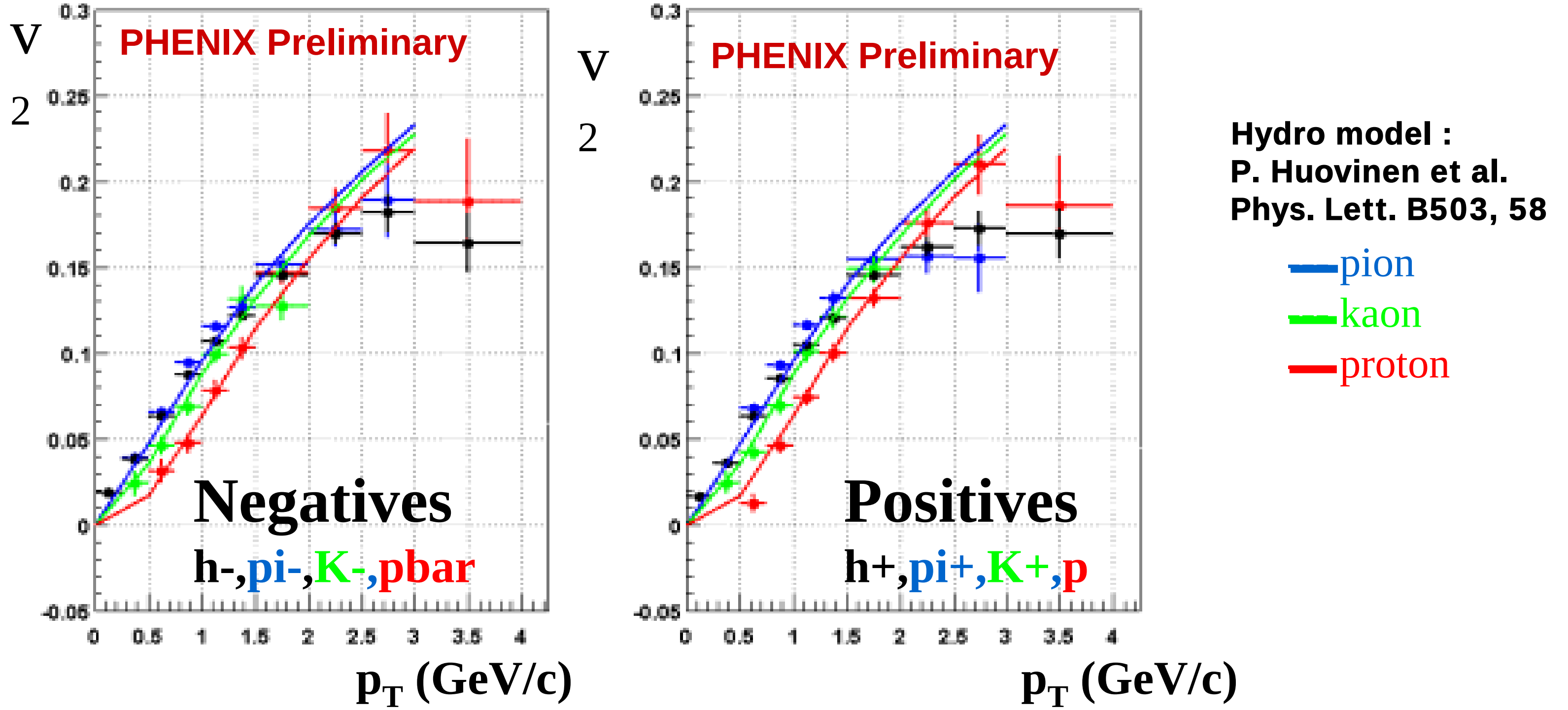
In RUN-1 (@130GeV) PHENIX measured Elliptic flow by two particle correlatoin.
Strong Elliptic flow (v_2) signal is observed
The flow signla increase with pt. The value of v_2 reaches to about 20% in high pt.

Strong elliptic flow requires that the flow develops while the system still has a large spatial anisotropy. This suggests an early thermalization at RHIC.

nucl-ex/0204005, accepted in PRL

v_2 of identified hadrons (π, K, p) in RUN-2 (@ 200 GeV)

Au+Au at sqrt(s_{NN}) =200GeV, Minimum bias



In RUN-2, BBC(|η|<3-4) is used to determine reaction plane.

v_2 saturates in p_T > 2GeV/c.

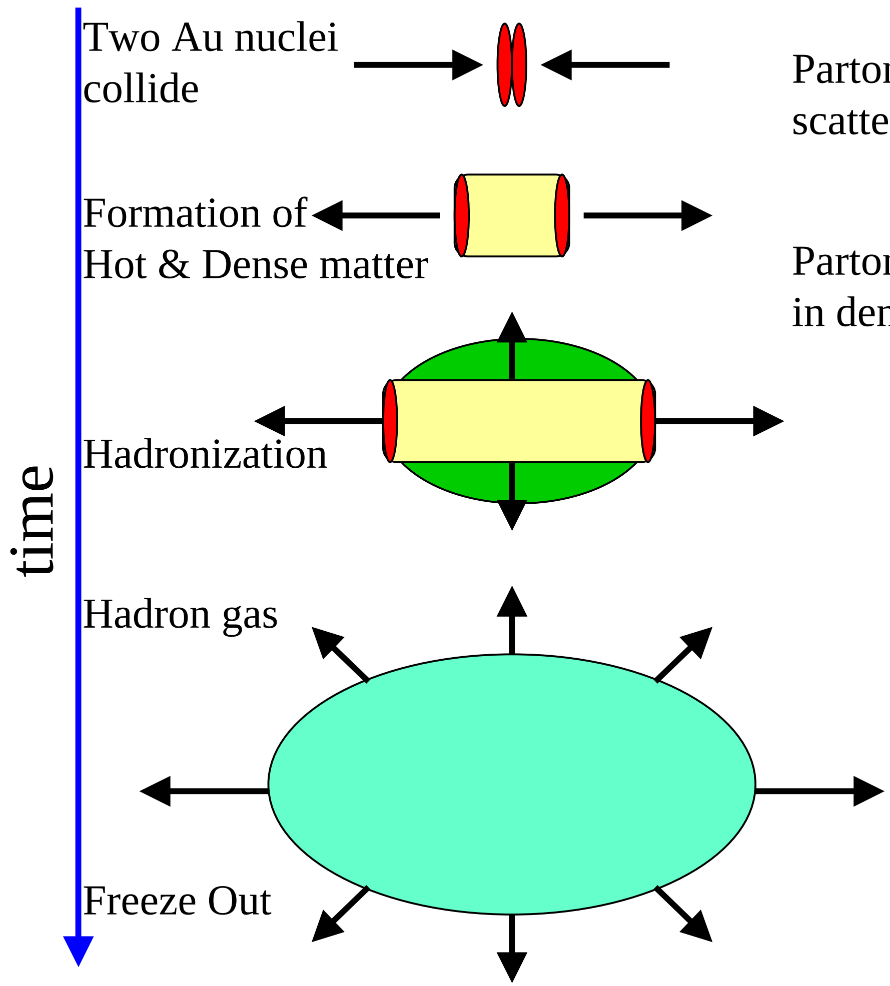
A hydrodynamic model agrees with data in p_T<2GeV/c.

Elliptic flow remain very strong at 200 GeV. Such strong flow suggests an *early thermalization* at RHIC.

nucl-ex/0210001

PHENIX

High Pt particle production



Parton-parton scattering ↔ High pt particle production

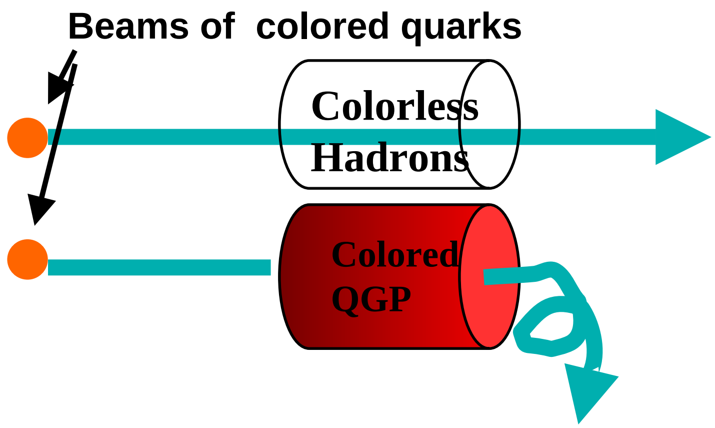
Parton energy loss in dense matter ↔ Suppression of high pt particles (jet quenching)

High pt particles are produced by fragmentation of jets, and they carry information of early stage of collision.

In high density matter, it is expected that quark and gluons loose energy by gluon radition, causing suppression of high pt particle (jet quenching).

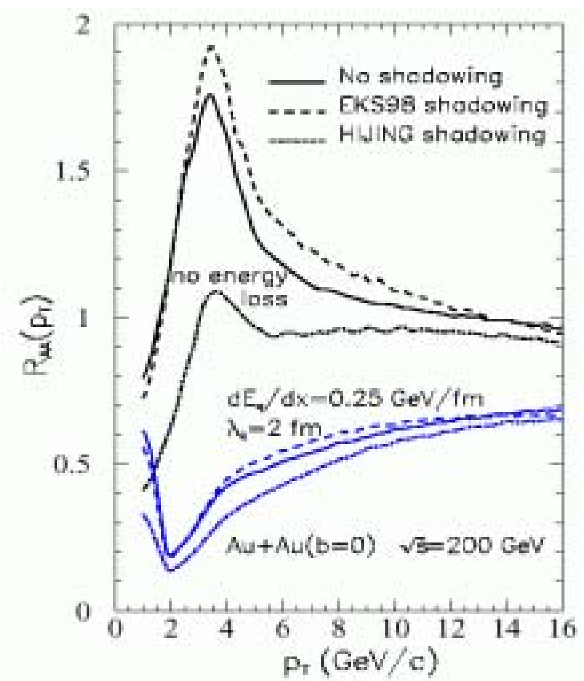
Are high pt particles suppressed at RHIC?

Jet Quenching



Little energy loss of quarks and gluons in ordinary nuclear matter

A large energy loss due to gluon radiation in high density matter is predicted
→Jet Quenching



At RHIC, jet quenching can be observed as suppression of high pt particle production.

A prediction of jet quenching at RHIC (X.N.Wang)
The yield of hadrons in pt=2-6 GeV/c is suppressed relative to scaling with number of binary collisions

Nuclear effects in high pt particle production

In the absence of nuclear effects, high pt particle production should scale with number of binary collisions (Ncoll).

$$R_{AA} = \frac{1}{Ncoll}\frac{Yield(AA)}{Yield(NN)} = 1$$

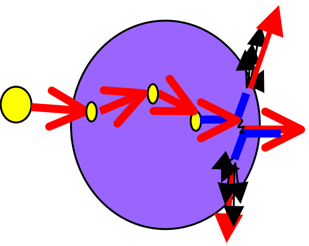
A+A

$$R_{pA} = \frac{1}{A}\frac{\sigma(pA)}{\sigma(pp)} = 1$$

p+A

Known nuclear effects

Cronin Effect



Multiple scattering of partons
→Increase of high pt particle
→$R_{AA}>1$

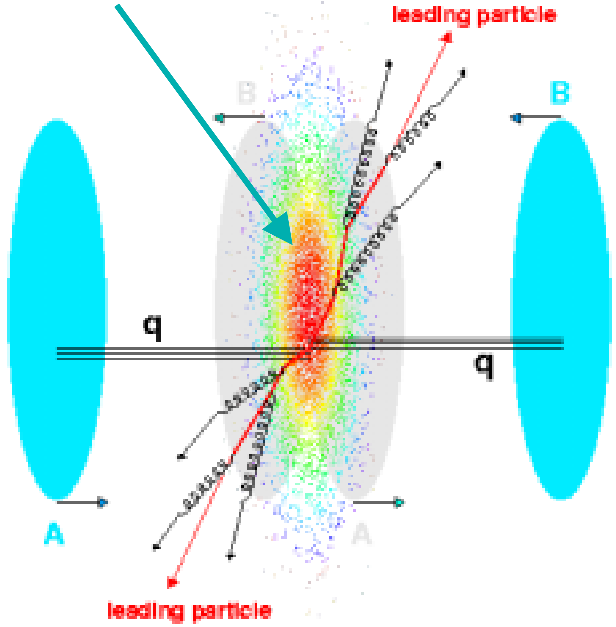
Nuclear Shadowing

Reduction of parton density q(x),G(x) in nucleus.
→ $R_{AA}<1$

- All p+A data shows that high pt particle production in nuclear target is larger than the binary (Ncoll) scaling. This implies that the Cronin effect is greater than the nuclear shadowing.

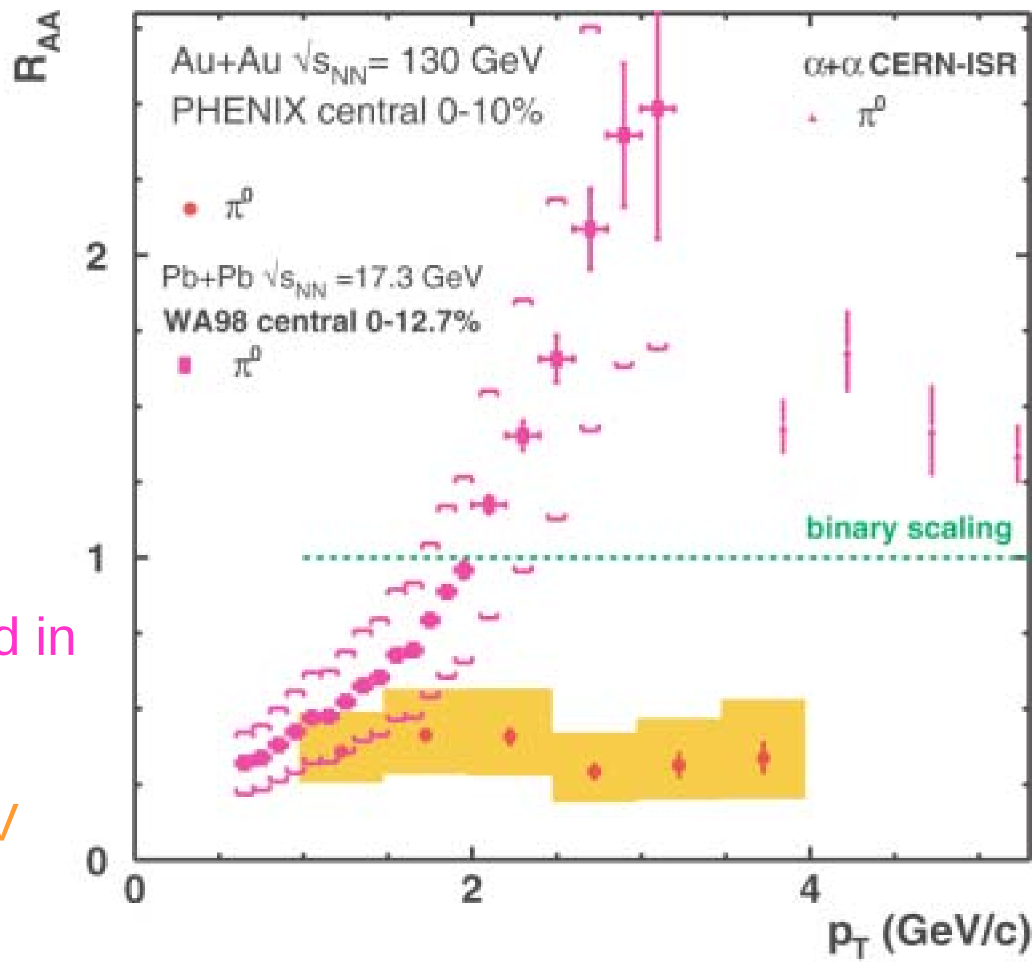
Run-1 result: Discovery of high p_T Suppression

Medium effect



Nuclear Modification Factor

$$R_{AA} \equiv \frac{d^2N^{AA}/dydp_T}{d^2N^{pp}/dydp_T \cdot \langle N_{coll}^{AA} \rangle}$$

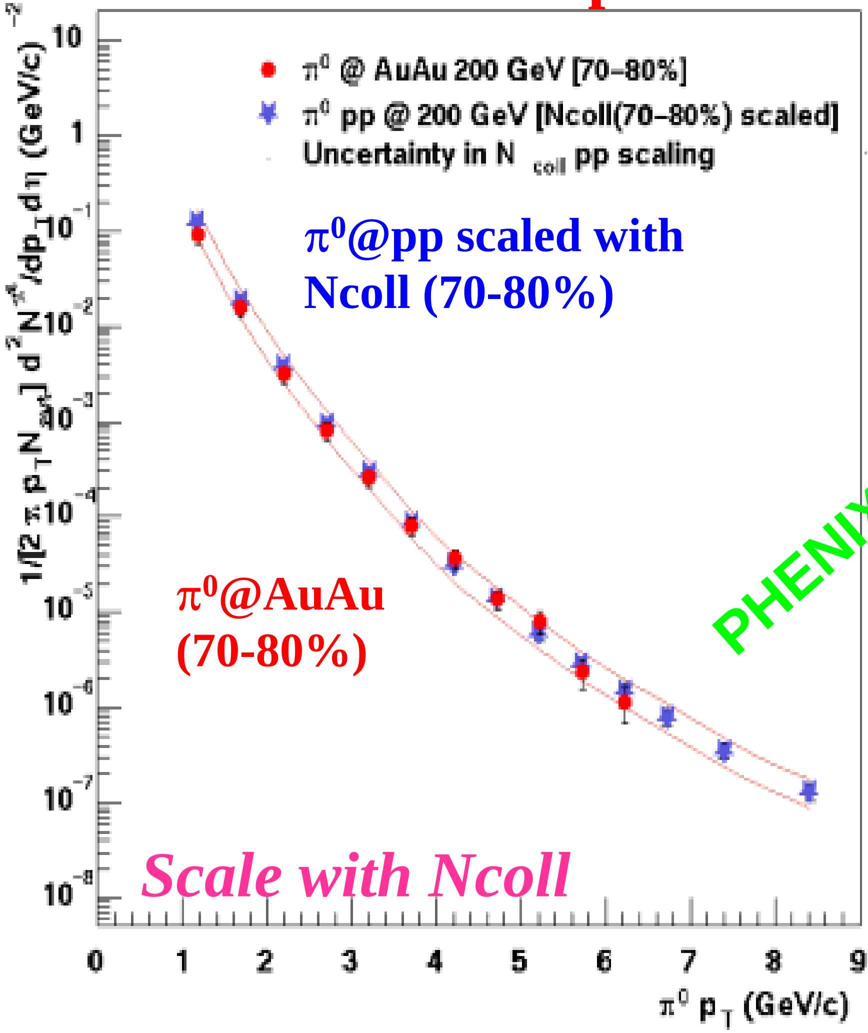


- R_{AA} =1 scale with # of binary collisions
- R_{AA} >1 Cronin effect observed in ISR and SPS
- R_{AA} <1 Suppression was discovered in RHIC@130GeV

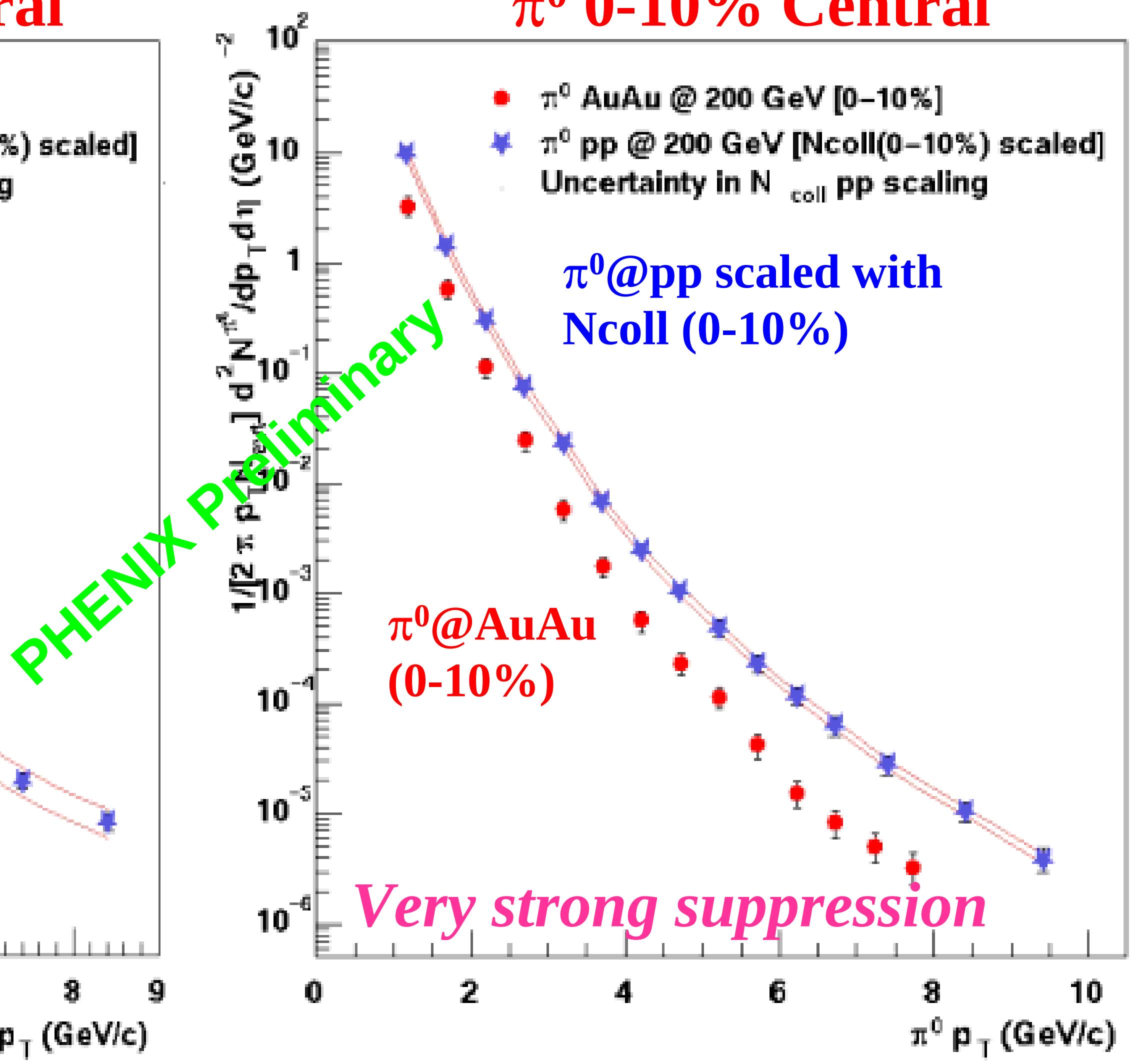
PRL 88, 022301

High Pt suppression @ 200 GeV

π^0 70-80% Peripheral



π^0 0-10% Central

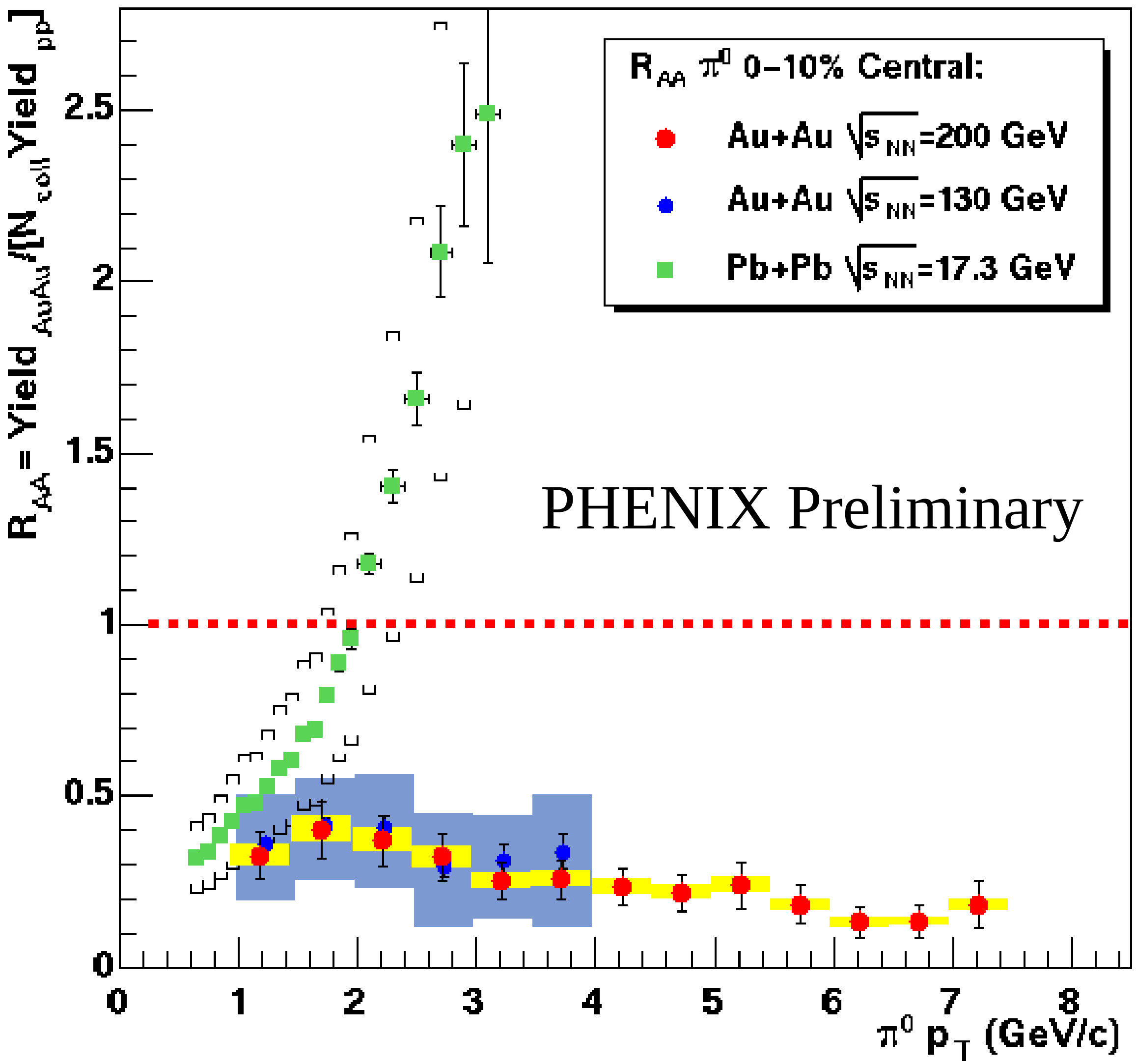


hep-ex/0209051

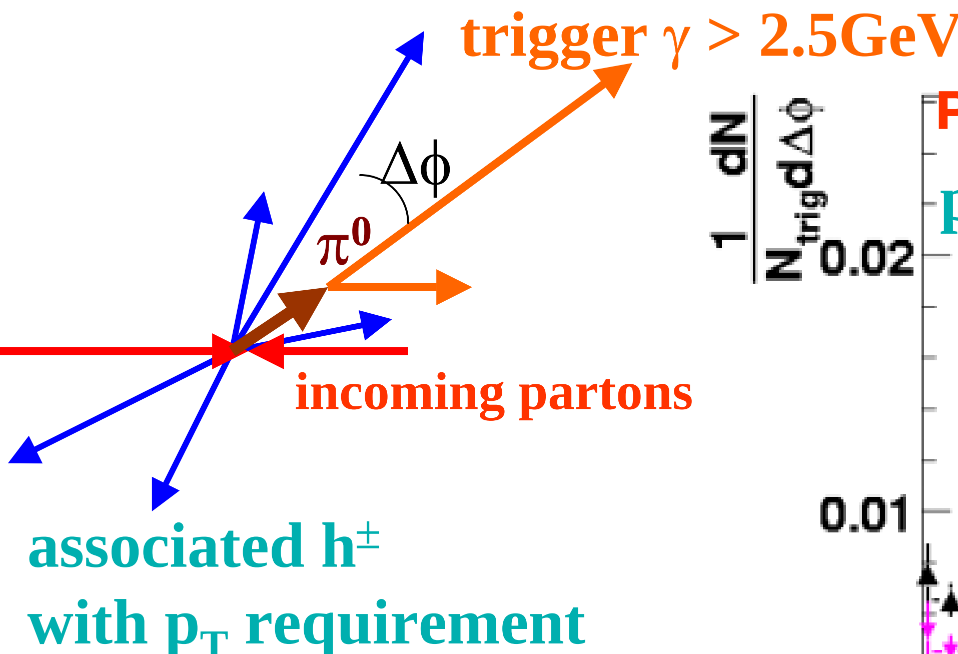
High Pt suppression @200 GeV

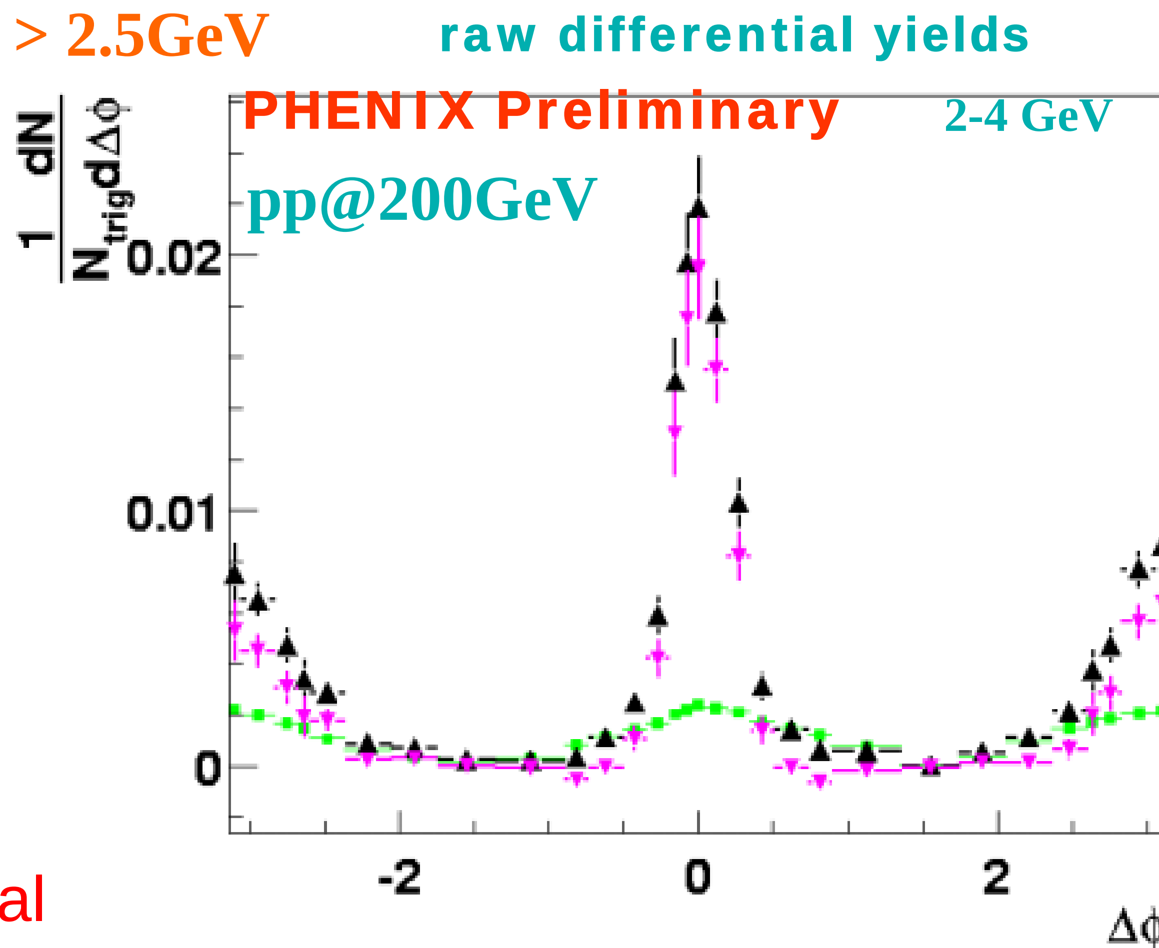
$$\frac{\mathrm{Yield}_{central}/\langle N_{binary}\rangle_{central}}{\mathrm{Yield}_{pp}}$$

- High pt suppression confirmed at 200 GeV
- Suppression increases with pt and is strong (R_{AA}~0.2) at high pt (~8 GeV/c)



Jet signal in p+p @ 200 GeV





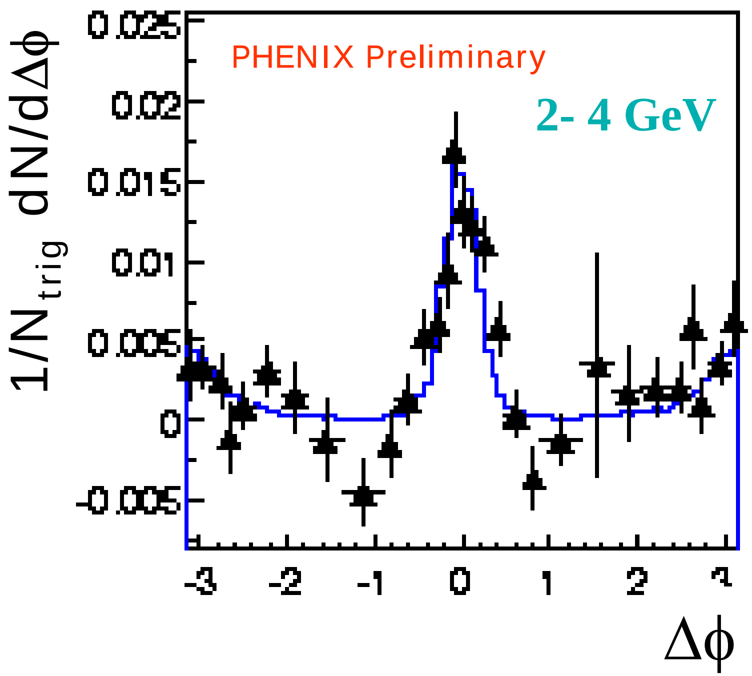
- Jet structure was observed in azimuthal correlation in pp at $s_{pp}^{1/2}$=200GeV.

•black = pair distribution

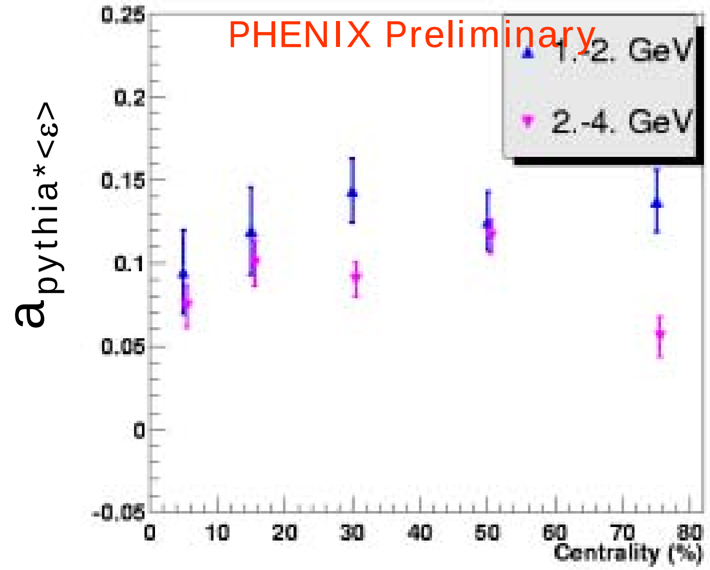
•green = mixed event pair distribution

•purple = bkg subtracted distribution

Evidence for jets in Au+Au



Jet-like signal amplitude vs. centrality



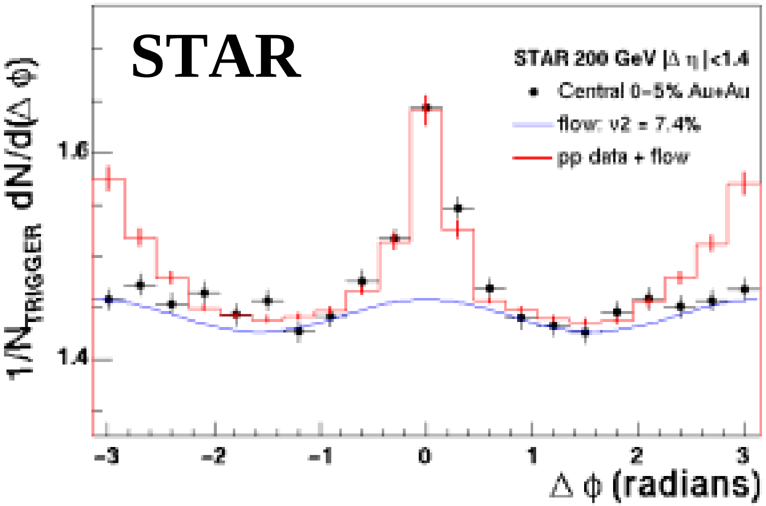
- Use p-p analysis as a reference for Au-Au jet signal
- *Jet-like* narrow angular Correlation seen in $\Delta\varphi$
- This jet-like signal strength is approximately *independent* of centrality (no sys error yet)

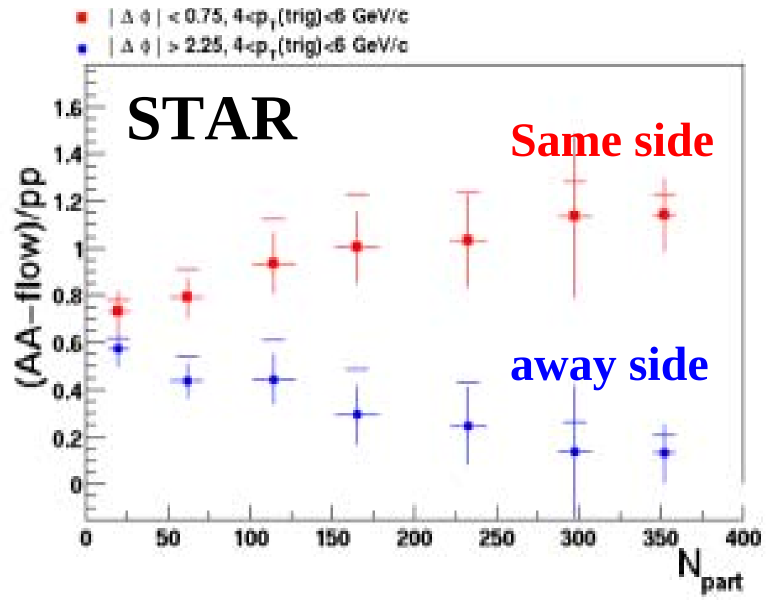
Suppression of away-side jet (STAR)

- STAR observed the signal "away-side" jet in AuAu.

- The strength of the "away-side" signal decrease with centrality.
  - Is the away-side jet suppressed during the propagation through reaction zone?

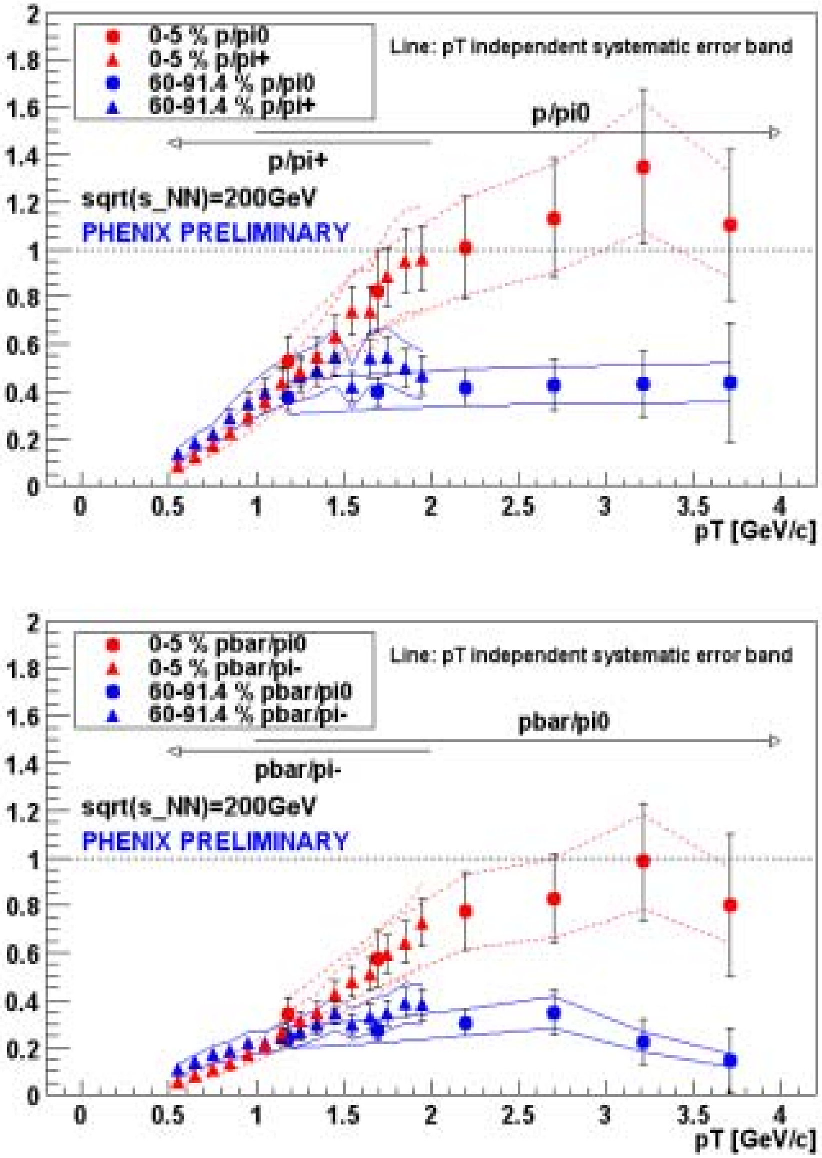
- The strength of "same-side" jet signal is almost independent of centrality. It is almost same as in p+p.
  - Evidence for that the suppression occurs at quark/gluon level?





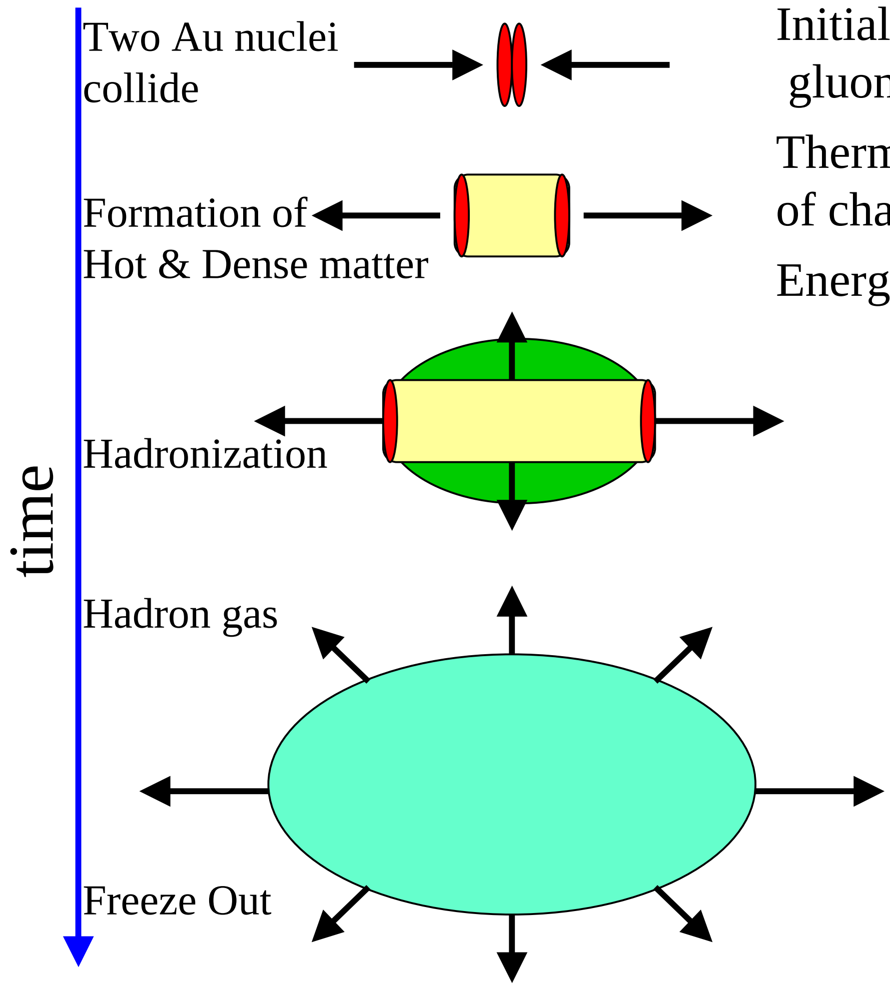
Puzzle: Baryons at high pt

- A puzzle in high pt data:
  p/pbar yield is comparable or higher than pion in 3-4 GeV/c for central collision.
- If pbars are from jet fragments, pbar/π ratio should be small at high pt.
  - Peripheral collision agree with this expectation.
- How those high pt baryons are produce?
  - Very strong radial flow?
  - Gluon junction model?



hep-ex/0209030

Single electron and Charm



Initial gluon density	⟷	Charm cross section
gluon shadowing?	⟷	Charm suppression?
Thermal production of charm	⟷	Charm enhancement?
Energy loss of charm	⟷	Charm pt distribution

Charm is a very good probe of initial stage of heavy ion collisions.

Open charm measurement is important to understand J/Ψ production

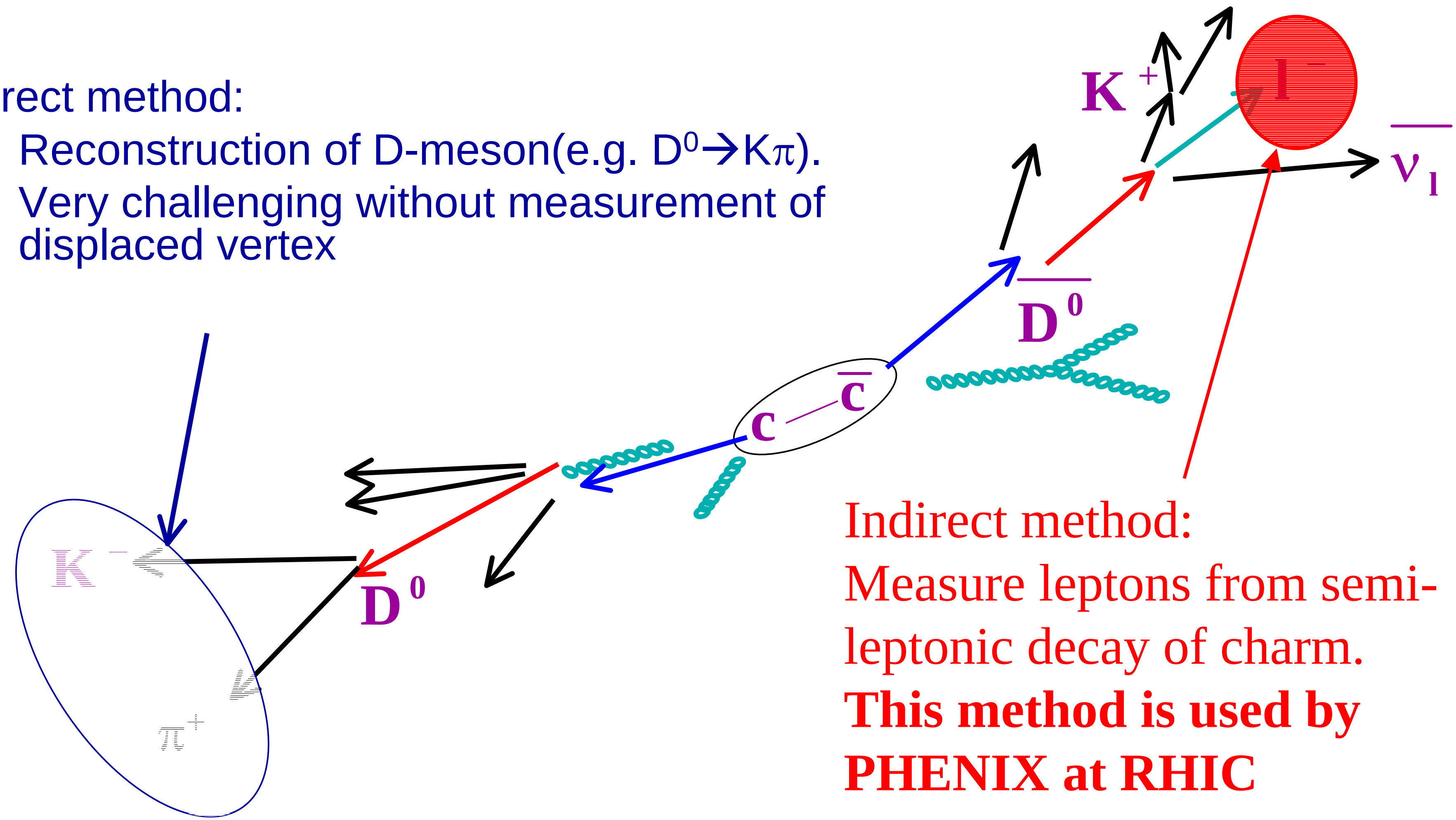
Charm production at RHIC can be studied from its decay to single electrons

Charm measurement

Direct method:

Reconstruction of D-meson(e.g. $D^0 \rightarrow K\pi$).

Very challenging without measurement of displaced vertex

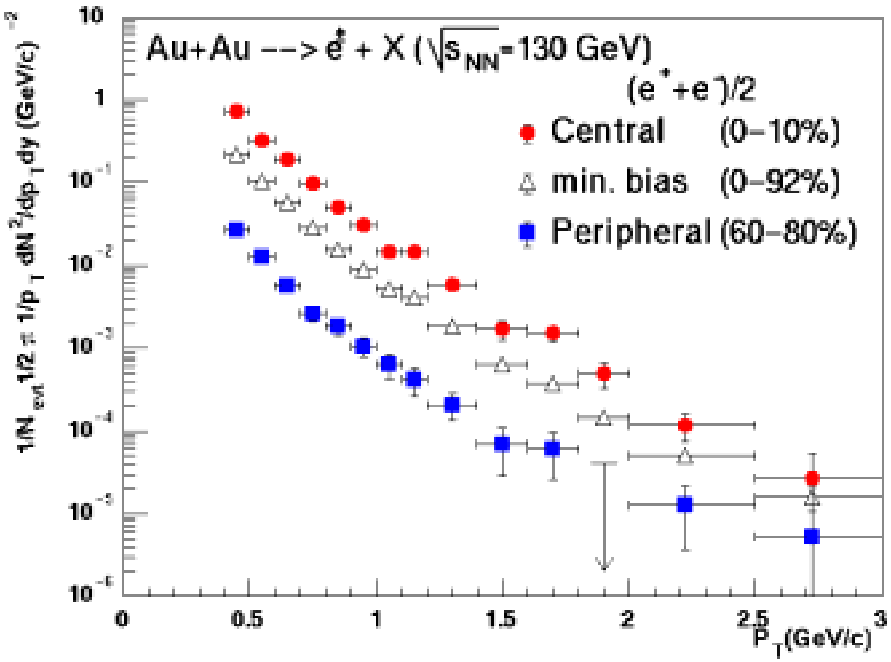


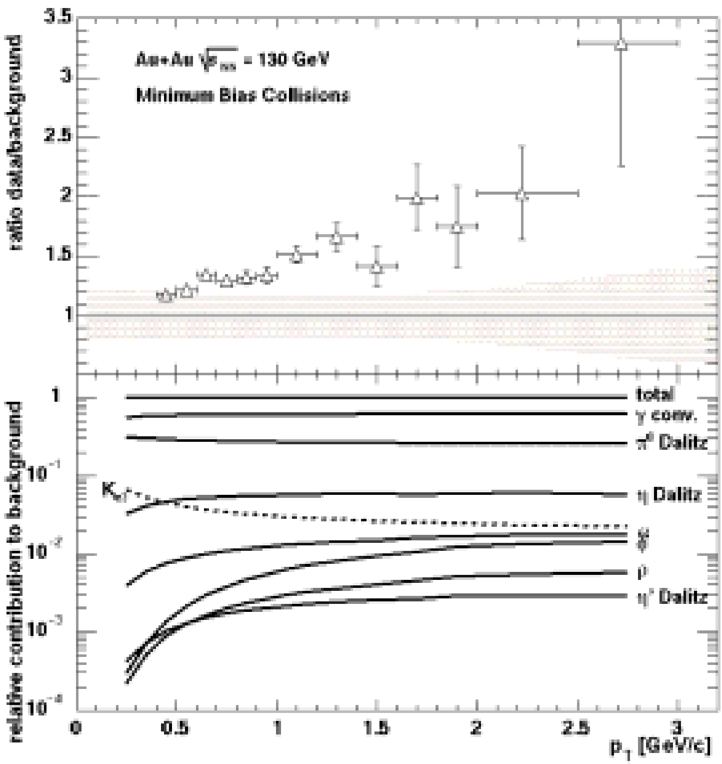
Indirect method:

Measure leptons from semi-leptonic decay of charm.

This method is used by PHENIX at RHIC

Single electron in RUN-1(130GeV)

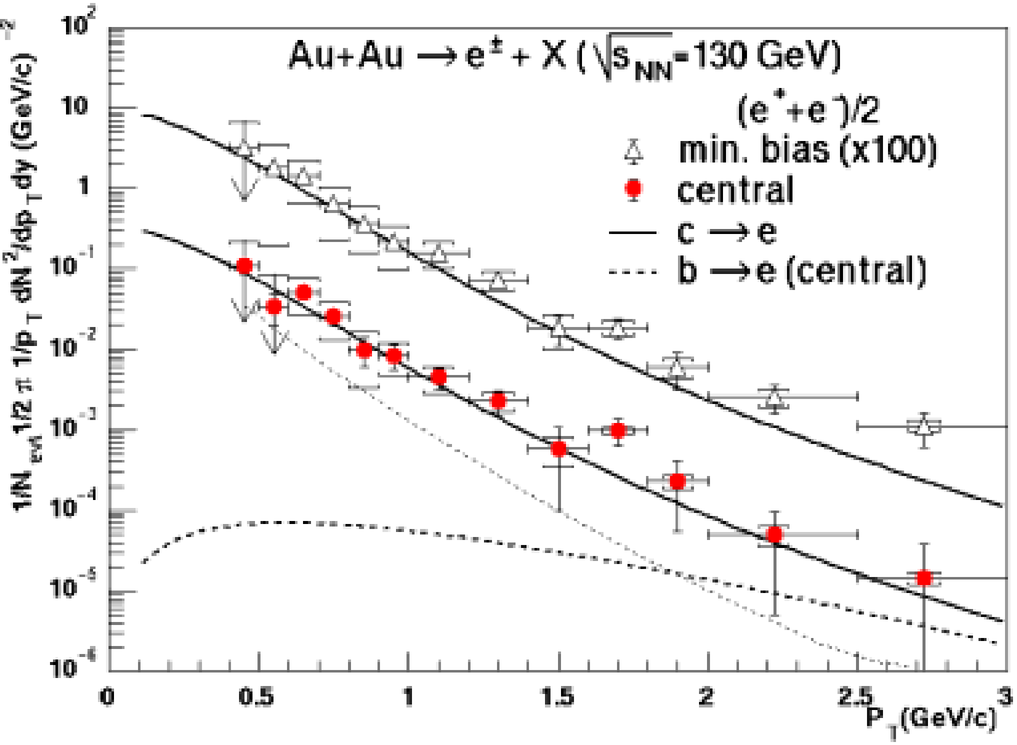




- Inclusive electron spectra are measured at y=0
- The background from π^0 Dalitz, photon conversions, etc are estimated and subtracted.
- Observe excess over background in pt>0.8 GeV/c

PRL 88, 192303

Background-subtracted single electron spectra

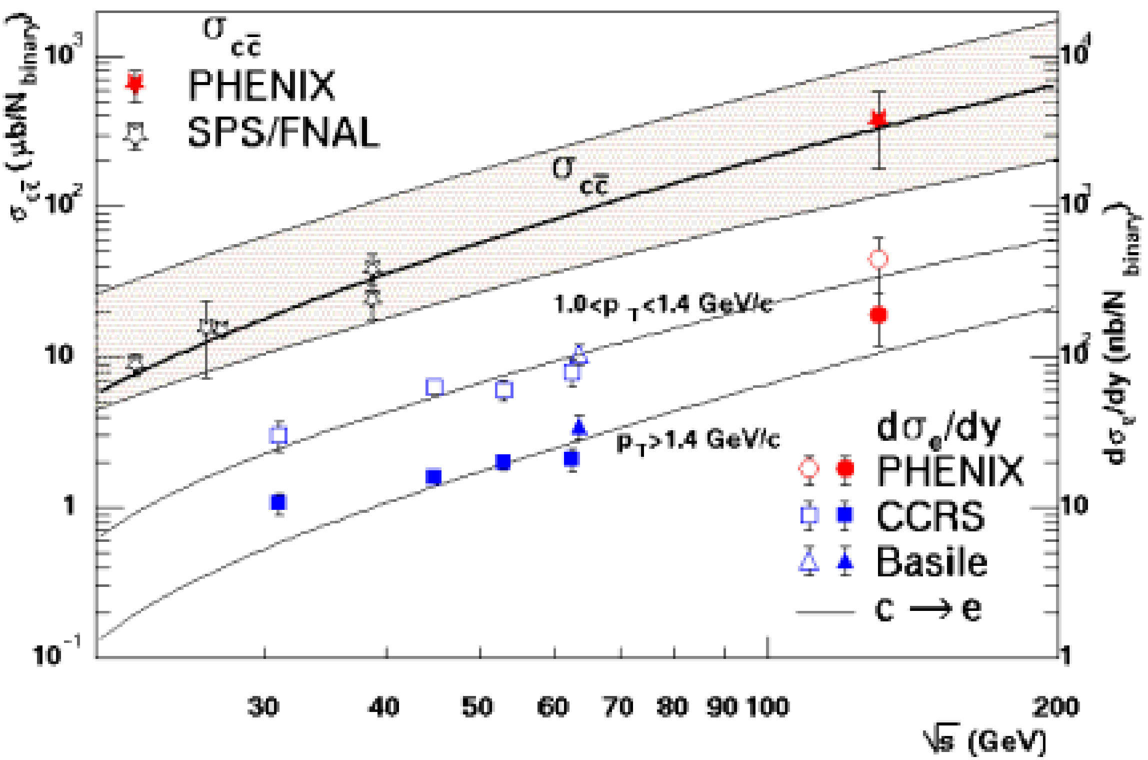


- Background subtracted electron spectra are compared with the charm decay contribution.
- Charm decay contribution is calculated as

  $EdN_e/dp^3 = T_{AA}Ed\sigma/dp^3$
  - T_{AA}: nuclear overlap integral
  - $Ed\sigma/dp^3$: electron spectrum from charm decay calculated using PYTHIA
- From the single electron yield in pt>0.8 GeV/c, charm cross section per binary collision is obtained as
  - $\sigma_{cc} = 380 \pm 60 \pm 200\ \mu b$

PRL 88, 192303

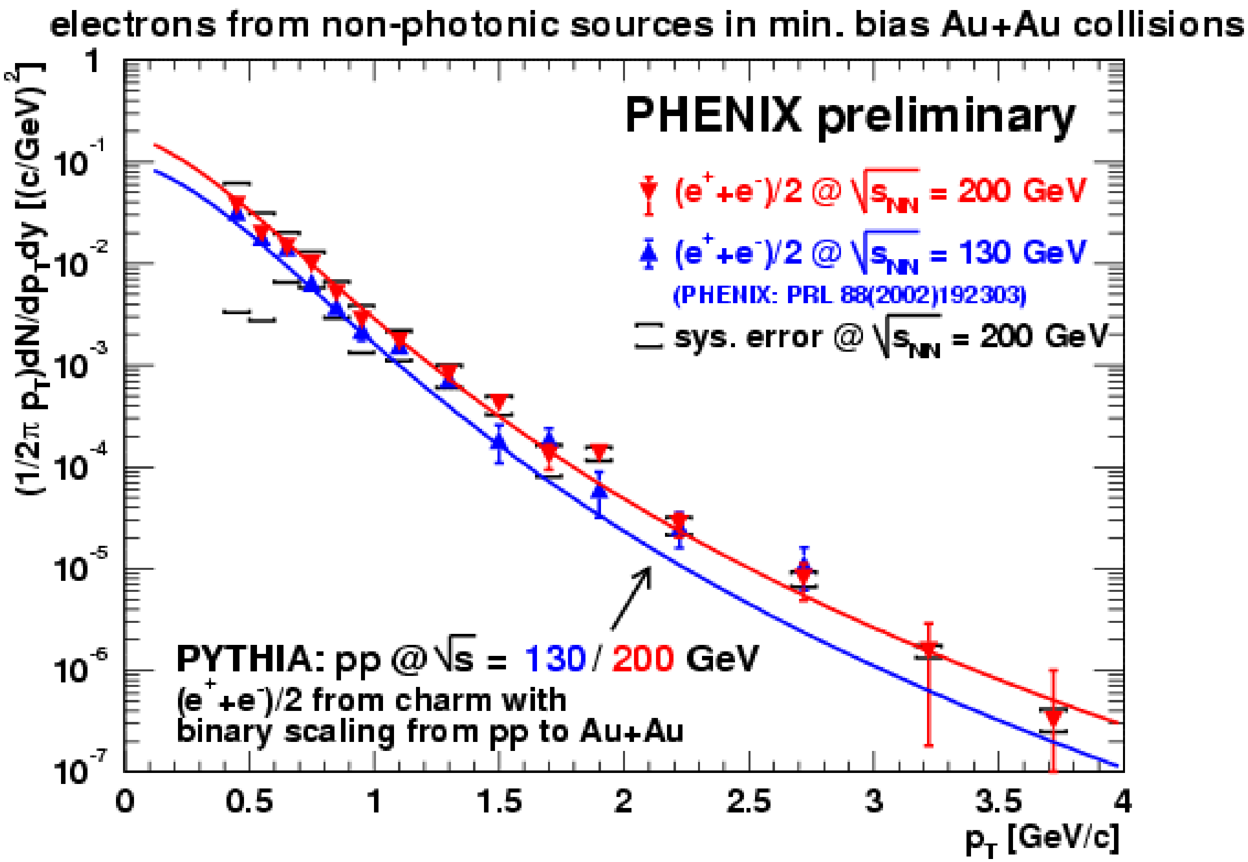
Comparison with other experiments



- PHENIX single electron cross section is compared with the ISR data
- Charm cross section derived from the electron data is compared with fixed target charm data
- Solid curves:
  PYTHIA
- Shaded band:
  NLO pQCD

PRL 88, 192303

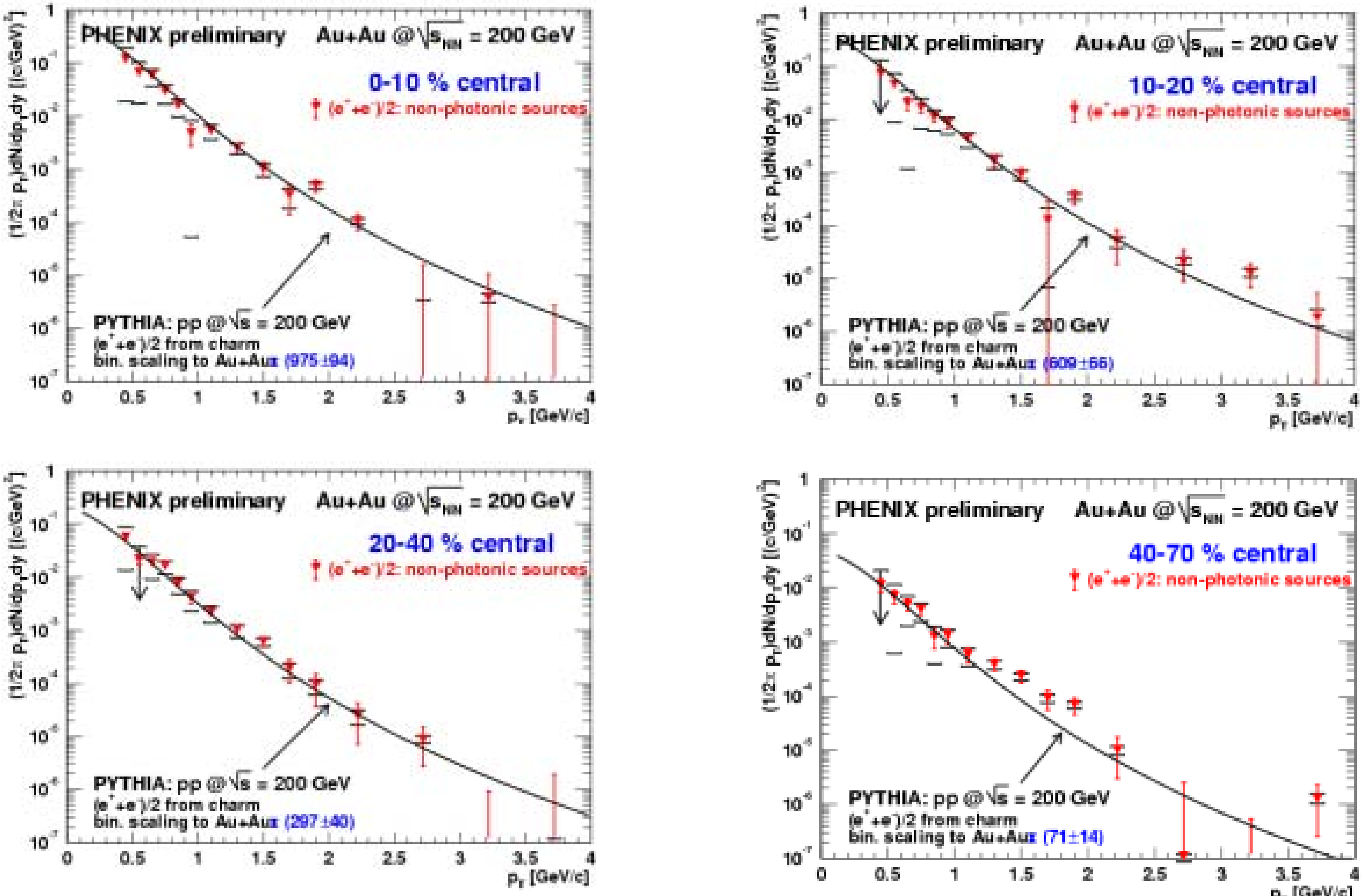
RUN2 single electron result



- The yield of non-photonic electron at 200 GeV is higher than 130 GeV
- The increase is consistent with PYTHIA charm calculation (σ_{cc}(130GeV)=330 μb → σ_{cc}(200GeV)=650 μb)

nucl-ex/0209016

Centrality Dependence

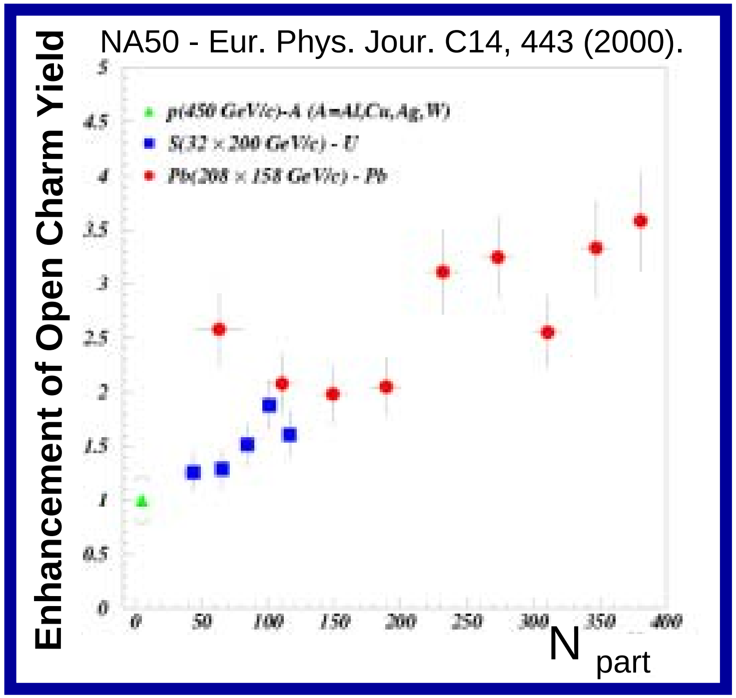


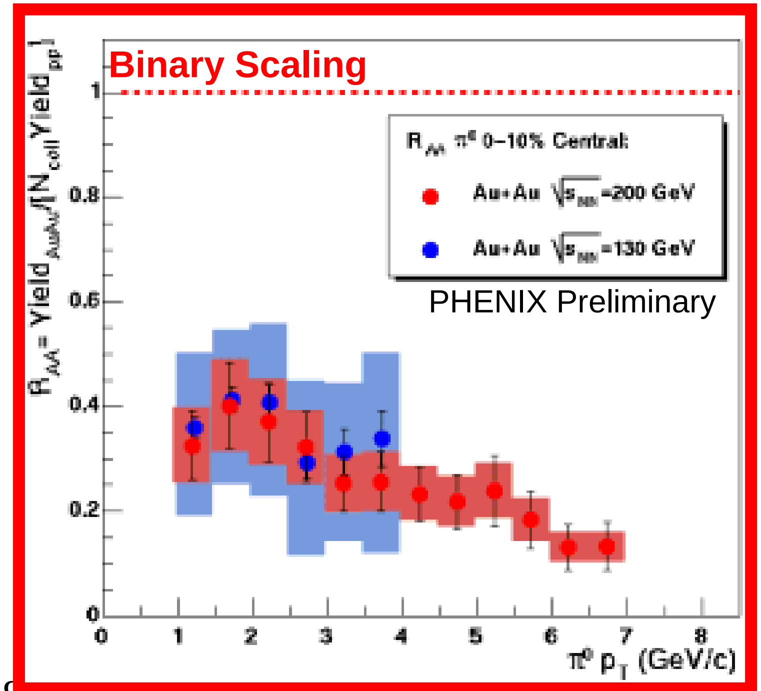
In all 4 centralities, the data are consistent with N_{coll} scaled charm decay contribution calculated by PYTHIA.

nucl-ex/0209016

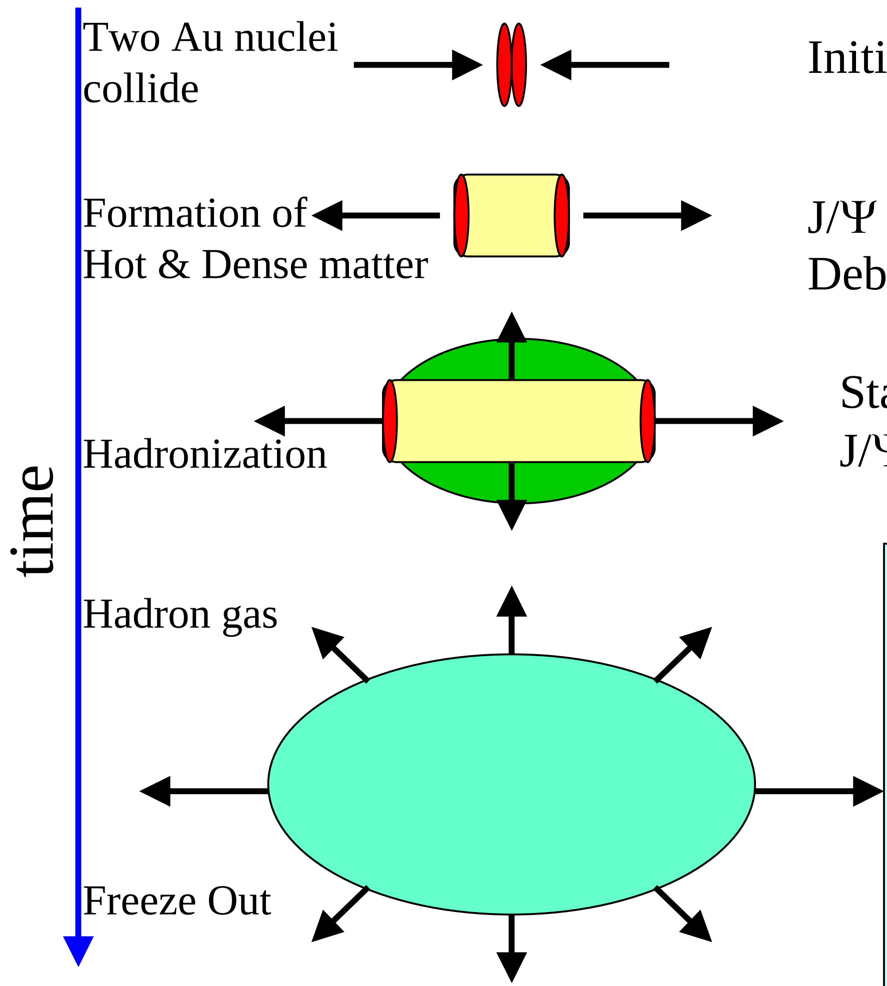
Observations

- PHENIX single electron data are consistent with *binary scaling* within current statistical and systematic errors.
  - Both errors will be much reduced in final RUN-2 result
- NA50 has inferred a factor of ~3 charm *enhancement* at lower energy. We do not see this large effect at RHIC.
- PHENIX observes a factor of ~3-5 *suppression* in high p_T π^0 relative to binary scaling. We do not see this large effect in the single electrons.
  - Initial state high pt suppression is excluded?
  - smaller energy loss for heavy quark ? (dead cone effect)





J/Ψ measurement



Initial ccbar production

J/Ψ can not form due to Debye Screening in QGP → J/Ψ suppression

Statistical formation of J/Ψ from ccbar pair → J/Ψ enhancement at RHIC?!

J/Ψ suppression, predicted by Matsui and Satz and observed by NA50 at SPS, is considered as one of the strongest evidence of QGP formation.

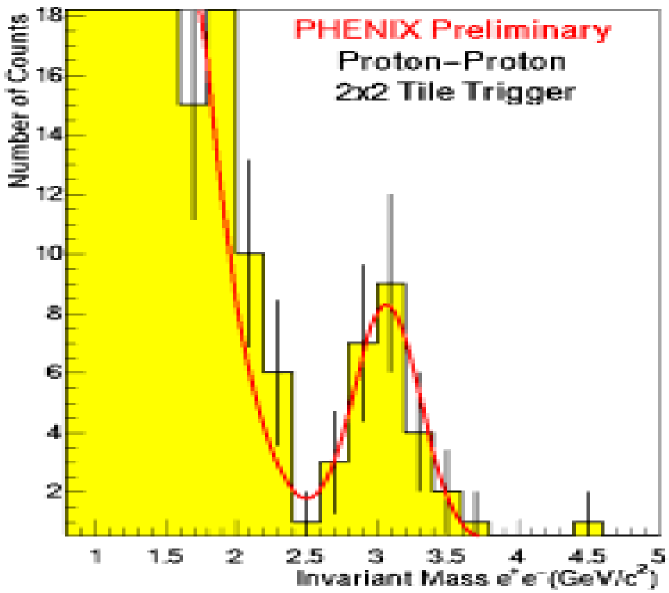
If J/Ψ suppression is due to QGP formation, much stronger suppression is expected at RHIC.

New theory of J/Ψ formation predicts J/Ψ enhancement at RHIC energy by statistical formation of J/Ψ at hadronizatoin

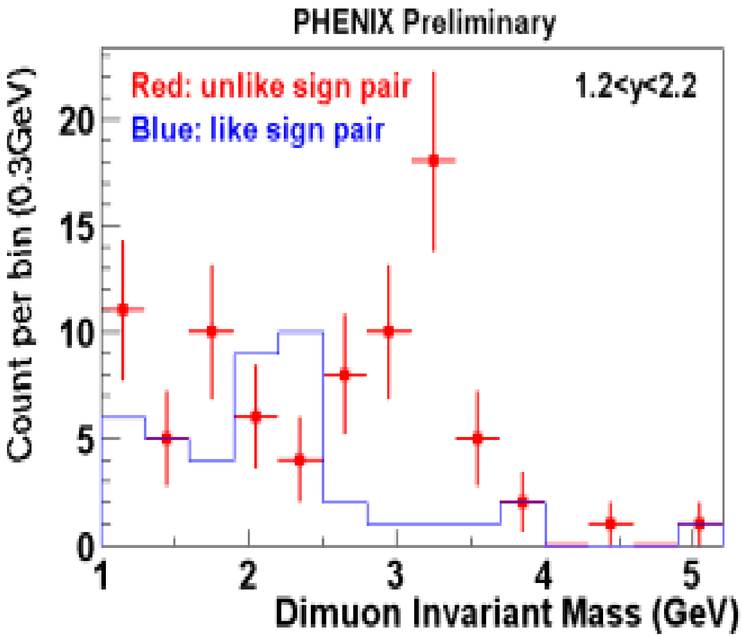
Do we observe J/Ψ *suppression* or *enhancement* at RHIC?

pp→J/Ψ at 200 GeV

pp → e^+e^- X (|y|<0.35)



pp → $\mu^+\mu^-$ X (1.2<y<2.2)



- pp→J/Ψ is measured both in ee and in μμ

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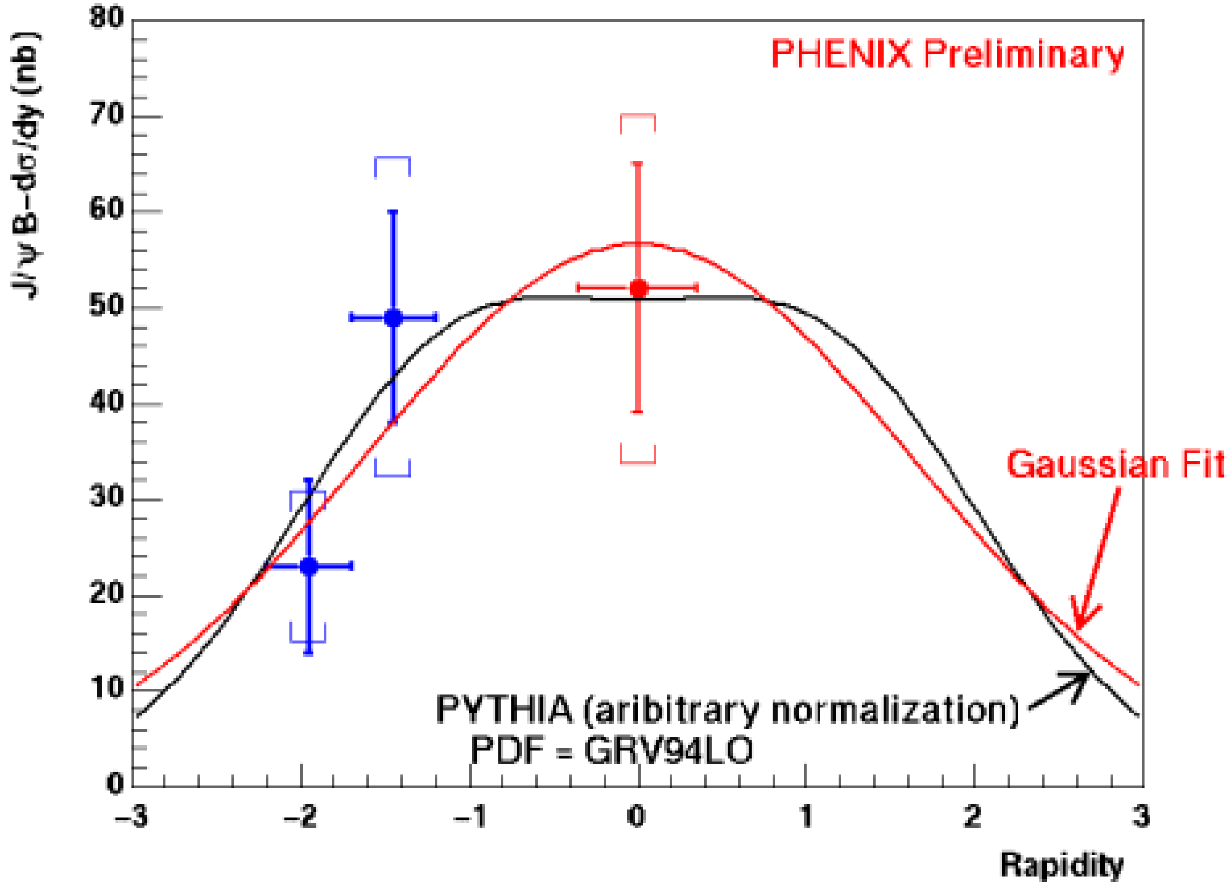
J/Ψ Bdσ/dy in p+p(200GeV)



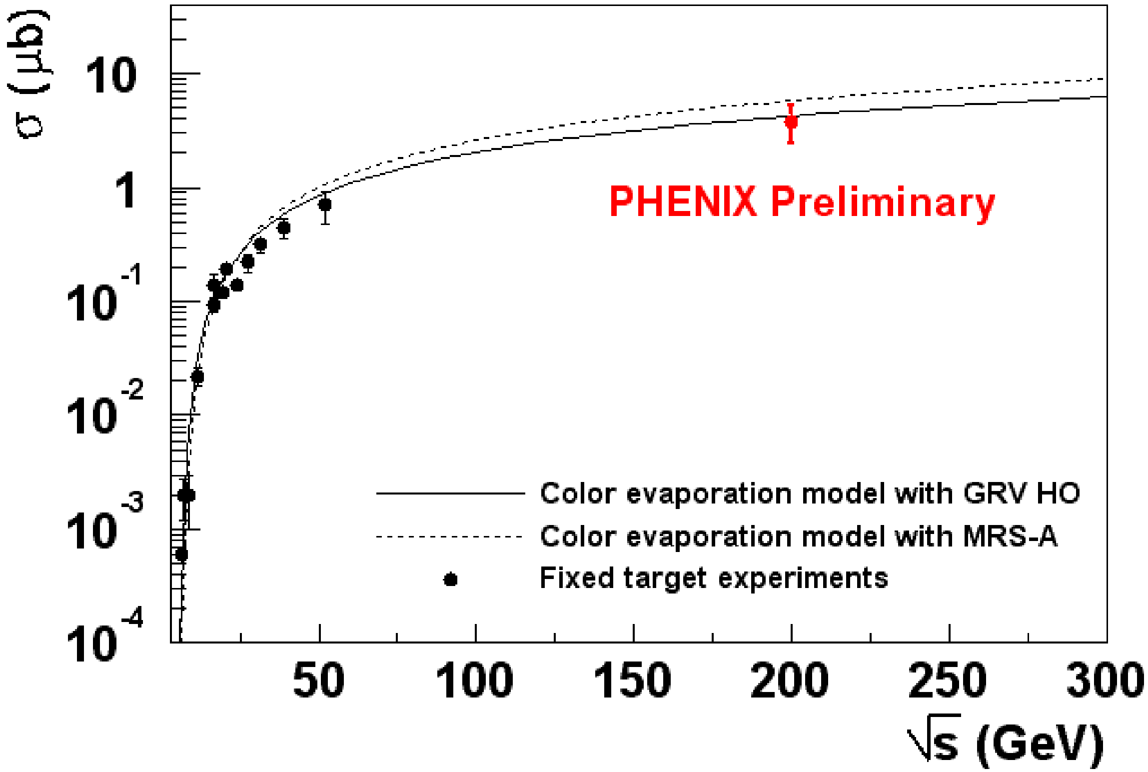
$$B \cdot \sigma(pp \to J/\psi + X) = 226 \pm 36(stat) \pm 79(sys)\ \mathrm{nb}$$
$$\sigma(pp \to J/\psi + X) = 3.8 \pm 0.6(stat) \pm 1.3(sys)\ \mu\mathrm{b}$$

nucl-ex/0210013

Comparison with lower energy

PHENIX preliminary

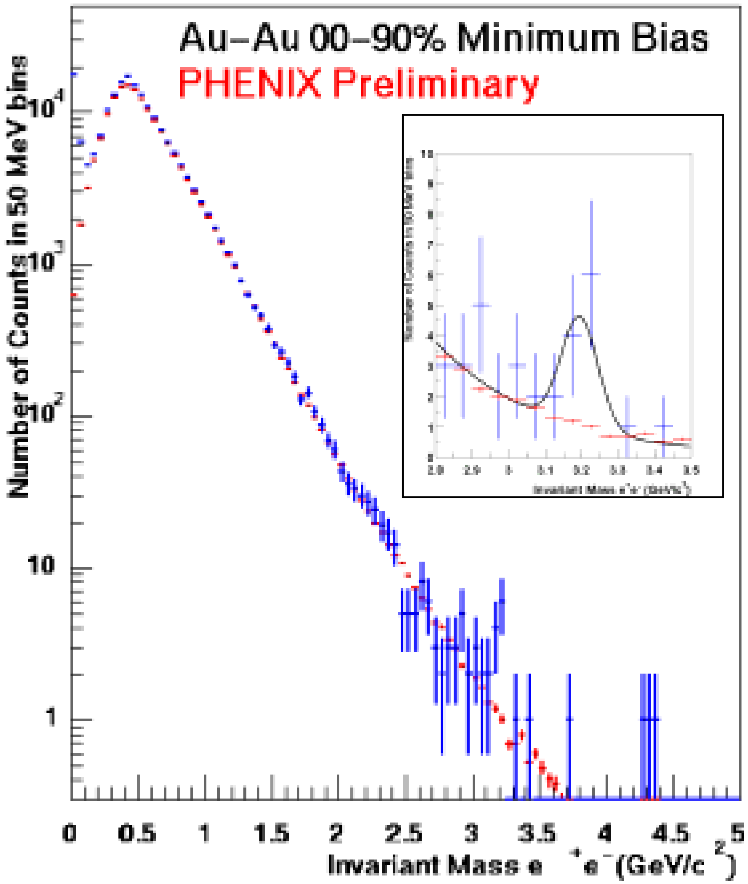
$$\sigma(pp \to J/\psi + X) = 3.8 \pm 0.6(stat) \pm 1.3(sys)\ \mu\text{b}$$



Color evapolation model prediction is consistent with PHENIX data at $s^{1/2}$=200 GeV

$J/\psi \rightarrow e^+e^-$ in Gold-Gold !

- From 26 M min. bias Au+Au collision @ 200 GeV (1/2 – 1/3 of all data)
- $N_{J/\psi}$ in 3 centrality bins.
  - 0-20%:
    $5.9 \pm 2.4(\mathrm{stat}) \pm 0.7(\mathrm{sys})$
  - 20-40%:
    $4.5 \pm 2.1(\mathrm{stat}) \pm 0.5(\mathrm{sys})$
  - 40-90%:
    $3.5 \pm 1.9\ (\mathrm{stat}) \pm 0.5(\mathrm{sys})$



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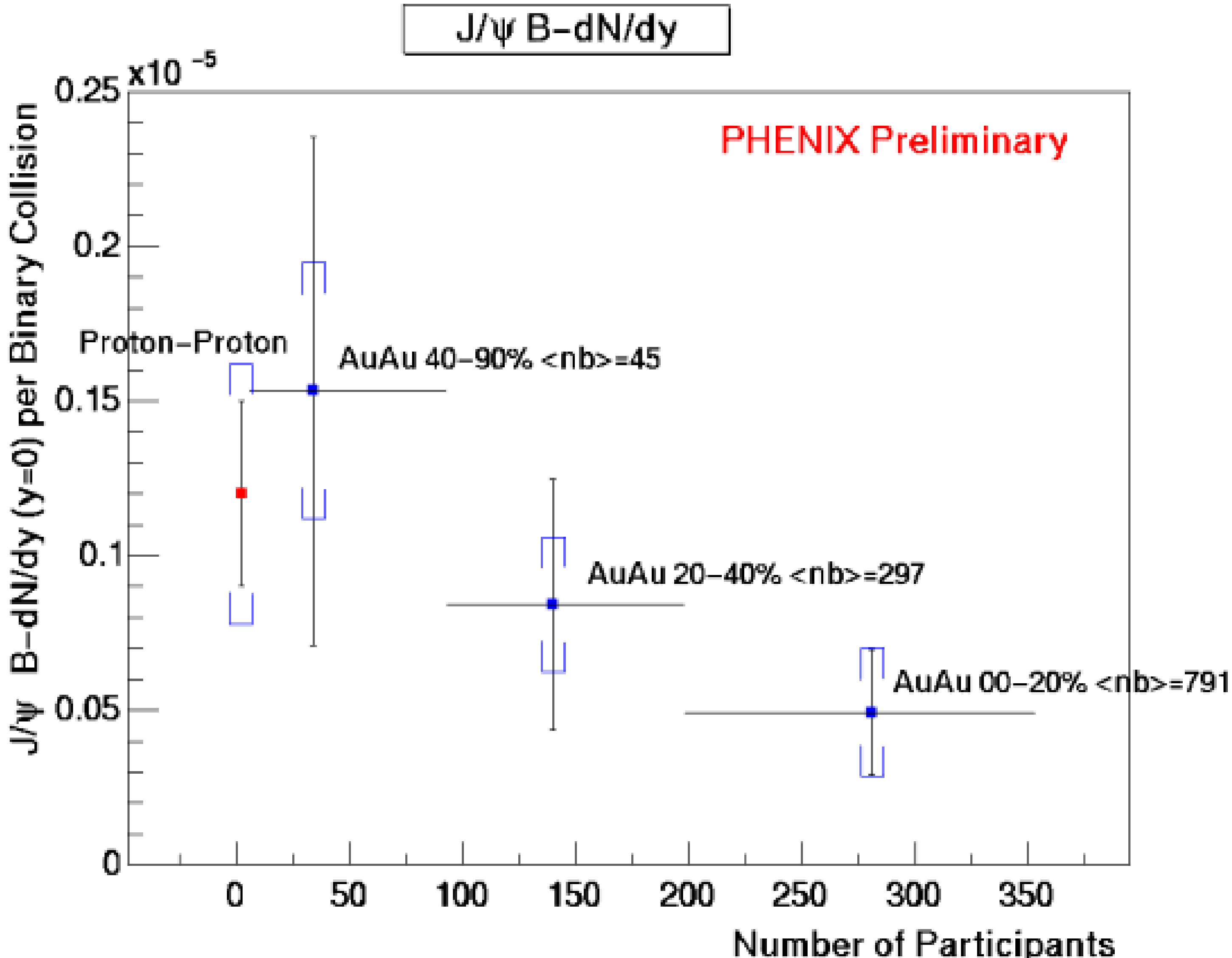
J/ψ B-dN/dy per binary collision



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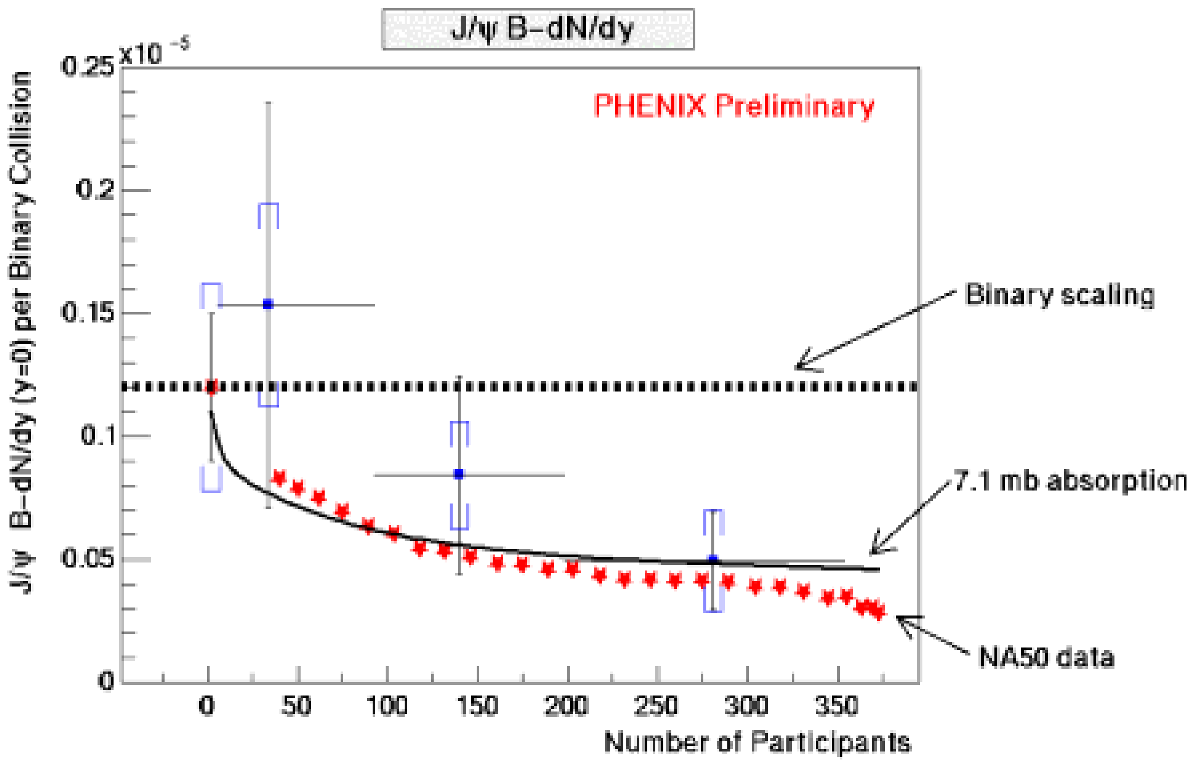
Model Comparisons (1)



(1) J/ψ scale with the number of binary collisions
(2) J/ψ follow normal nuclear absorption with $\sigma_{J\text{-}N}$=7.1 mb
(3) J/ψ follow same pattern as NA50 (J/ψ / DY(mb))[1]

Due to low statistics, our data are compatible all of these models.

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Model comparion(2)
J/Ψ re-generation models

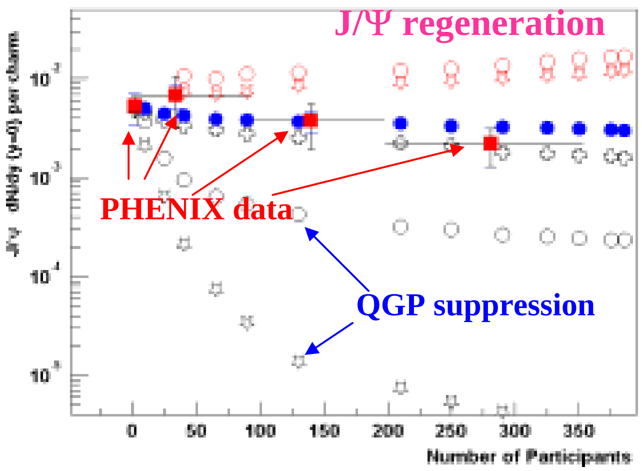
- At RHIC, about 10 ccbar pairs produced in central event.
- They can recombine to form J/Ψ. Those models that assume formation of J/Ψ inside of QGP predict enhanced production of J/Ψ in Au+Au.

  PHENIX data does not favor a large enhancement.
- In QGP suppression model, very strong J/Ψ suppression at RHIC is expected.

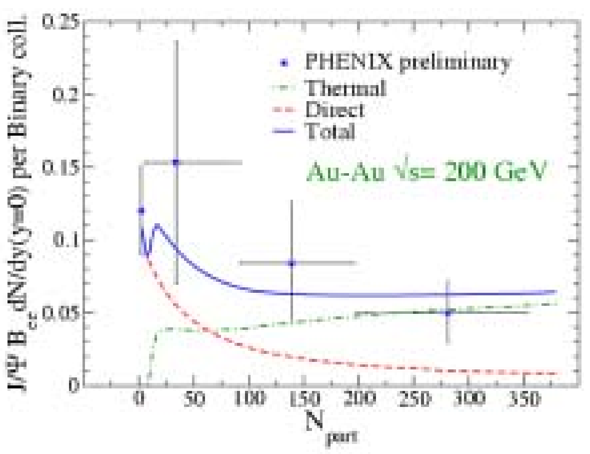
  PHENIX data does not favor a very strong suppression.
- Models of statistical generation of J/Y at hadronization stage predict that J/Y yield in central Au+Au is about half of that of pp.

  A much larger statistics is required to test those models. (→RUN4)

Theory curve from R. L Thews, PRC63,054905



L. Grandchamp and R. Rapp, hep-ph/0209141



Summary(1) Global/hadron

- Transverse energy → ε_{BJ} = 5.5 GeV/fm (>> ε_{crit})
- Charged multiplicity→ N_{ch}/N_{part} ~ 1.6-1.7xN_{ch}(pp)
- Hadron measurements
  - Hadron yield ratios and pt spectra are well described by thermal models.
    - Tch ~170 MeV ~ Tcrit (@chemical freeze-out)
    - T_{th} ~ 110 MeV; $\langle\beta_T\rangle$~ 0.5 (@thermal freeze-out
    - Single freeze-out model with T~170 MeV also seems to work
- Two pion correlation (HBT puzzel)
  - Surprising results:
    Rside and Rout are almost unchanged from SPS energy
    Rout/Rside ~ 1
  - Those results are not explained by theoretical models. The results suggests that the system freeze-out very quickly.
- Elliptic flow
  - Very strong Elliptic flow is observed at RHIC
  - Strong elliptic flow requires a quick conversion of spatial anisotropy to momentum anisotropy. This strongly suggest a very early thermalization.

Summary (2) High pt

- Strong suppression of high pt particles in heavy ion collision is observed
  - Suppression factor R_{AA} ~ 0.2-0.3
  - Suppression continue to the highest p_t measured (p_t ~ 8 GeV/c)
  - Energy loss of quark and gluon in the dense matter?
    - Need d+Au comparison data (RUN-3) to determine “ordinary” nuclear effect
- Signal of Jets in Au+Au collison is observed
  - Same side jets correlation clearly observed by PHENIX and STAR
  - Strength of the same side correlation has little dependence on centralitly
  - The away-side jet signal is suppressed in central collision (STAR)

An interpretation:

High pt particle suppression take place before hadronization of jets?

Summary(3) Leptons

- PHENIX has measured single electrons from charm decay in Au+Au collision at RHIC
- Single electron data is consistent with the binary scaling within (relatively large) errors.
  - No or little nuclear shadowing effect in charm produciton?
  - No or little energy loss for charm quark?
  - Much reduced systematic error is expected for final result.
- PHENIX made the first measurement of J/Ψ in p+p and Au+Au at RHIC
  - Present statistics is too limited to draw any strong conclusion on J/Ψ suppression, but some of extreme models of J/Ψ formation can be excluded.
  - Future high statistics Au+Au run is needed to make a decisive measurement of J/Ψ suppression at RHIC

Outlook

- RUN-2 data
  - "final" results of existing analysis→ publish
  - "new" analysis
    - K* and other short lived resonances
    - jet-like correlation vs particle ID (leading meson vs leading baryon)
    - (search for) thermal direct photon
    - etc
- RUN-3 (US FY03: d+Au and pp)
  - Comparison data in d+Au
  - Study of "ordinary nuclear effect" at RHIC energy
    - Does "high pt suppression" occur in d+Au?
    - "ordinary" nuclear effect in J/Ψ production, direct photon, charm production, etc
- RUN-4 (US FY04: long Au+Au and pp)
  - High pt suppression in pt>10 GeV/c
  - High statistics J/Ψ measurement
  - Search for thermal di-lepton continuum in $0.3<M_{ee}<3$ GeV
  - Search for medium effect in ϕ, ω, $\rho \rightarrow ee$
  - etc