Measurements of High Density Matter at RHIC

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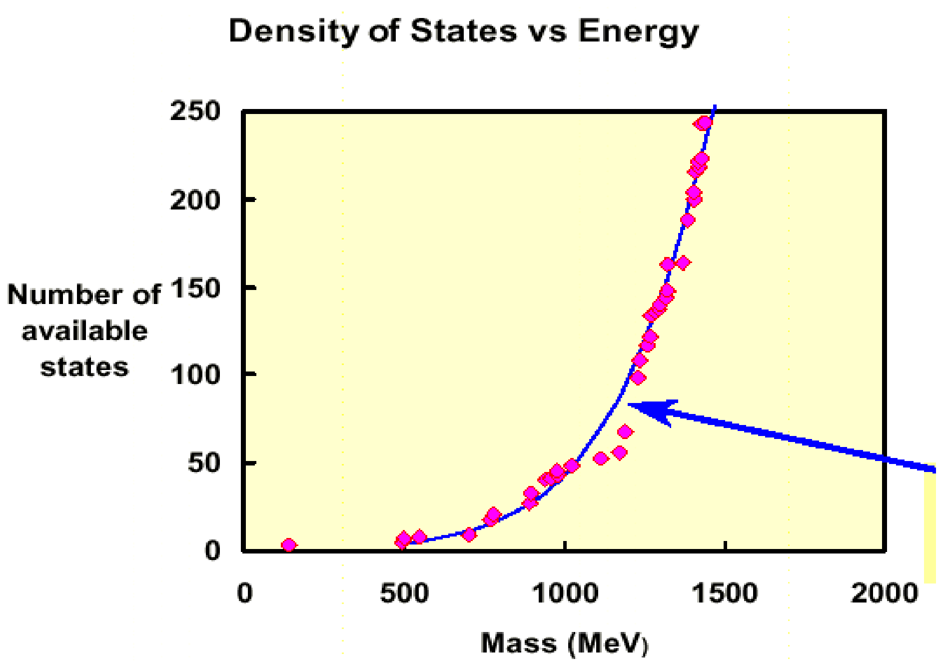
Phase transition in high (energy-) density matter?

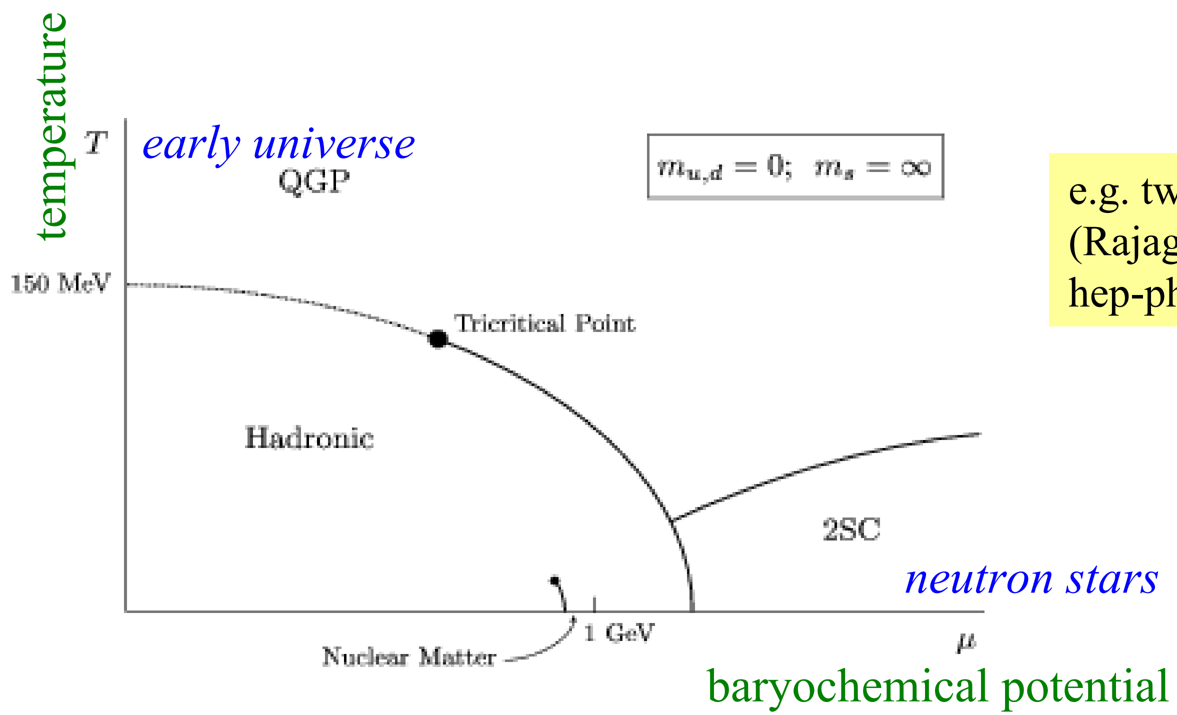
Hagedorn (1960's):

- Spectrum of excited hadronic states: exponentially increasing level density
- Heat a hadron gas ⇒ excite more massive resonances
- Hadronic gas has limiting temperature T ~ 170 MeV



But cannot continue to arbitrary energy density: hadrons have finite size ⇒ transition to phase of hadronic consituents at T~170 MeV?

QCD Phase Diagram



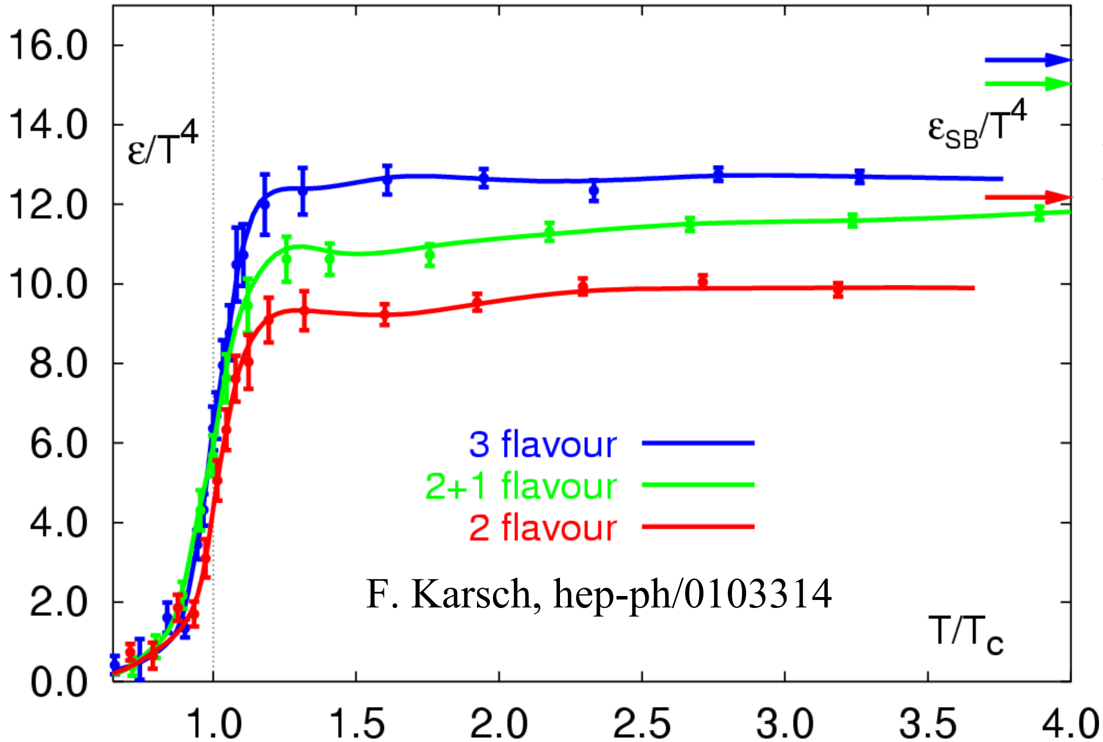
e.g. two massless flavours (Rajagopal and Wilczek, hep-ph/-0011333)

- T >> Λ_{QCD}: weak coupling ⇒ deconfined phase (Quark Gluon Plasma)
- T < Λ_{QCD}: strong coupling ⇒ confinement

⇒phase transition at T~ Λ_{QCD}?

Lattice QCD at Finite Temperature

- Coincident transitions: deconfinement and chiral symmetry restoration
- Recently extended to $\mu_B > 0$



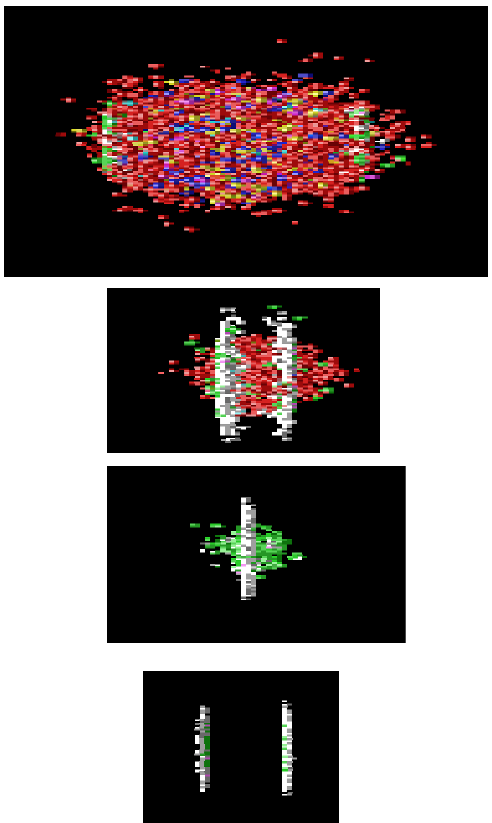
Ideal gas (Stefan-Boltzmann limit)

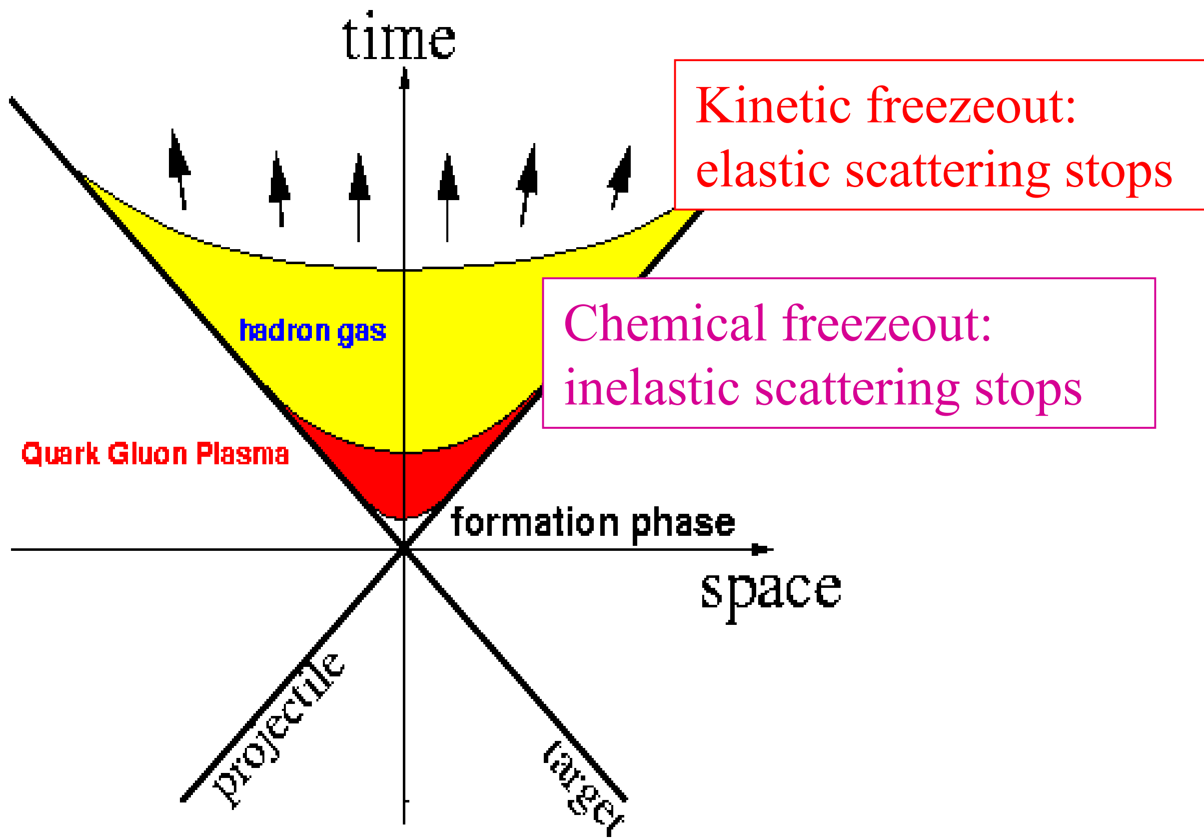
Critical energy density: $\varepsilon_C = (6 \pm 2) T_C^4$

$T_C \sim 175$ MeV $\Rightarrow \varepsilon_C \sim 1$ GeV/fm^3

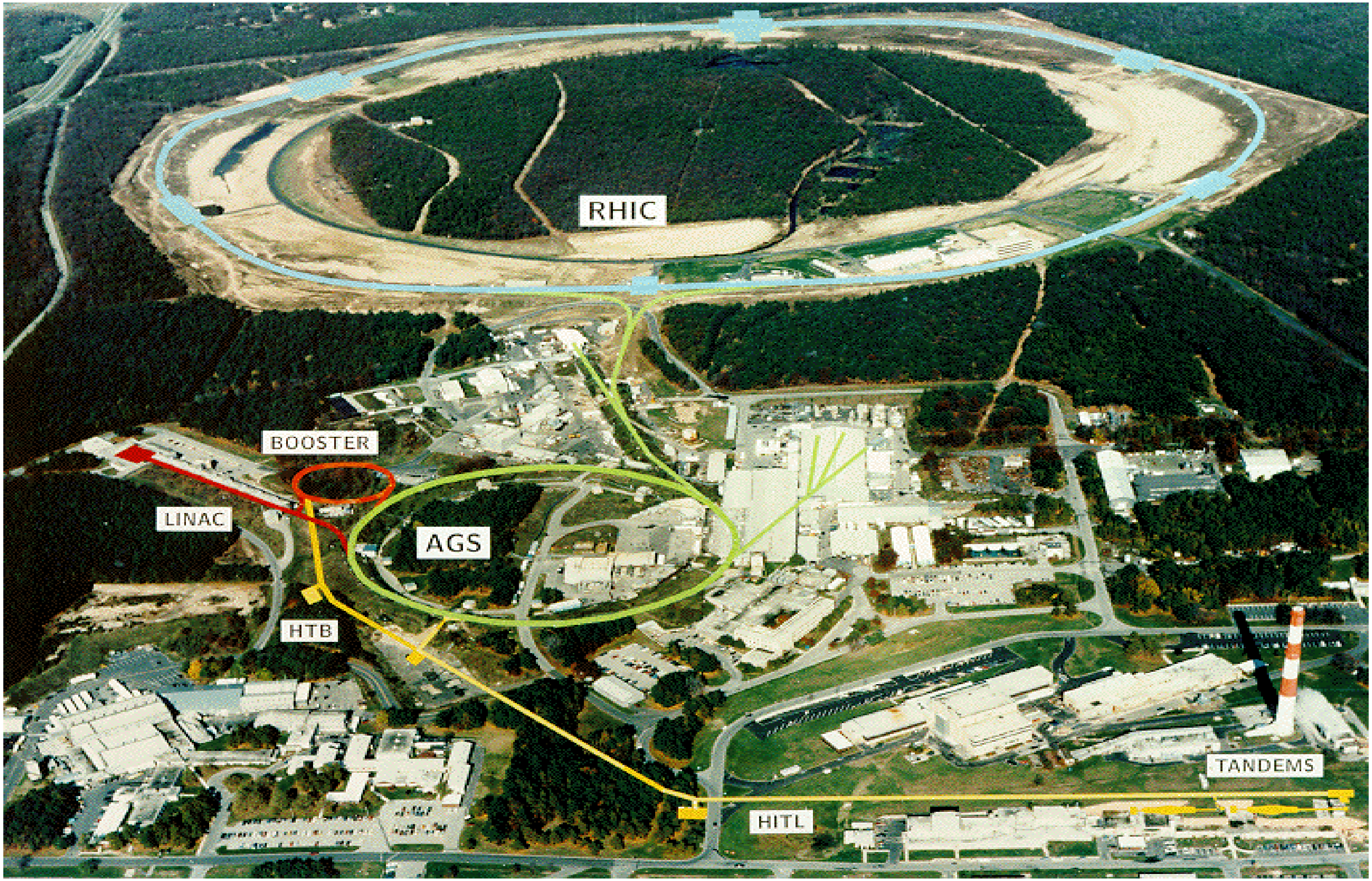
Can we study the QCD Phase Diagram in the Laboratory?

Space-time Evolution of Heavy Ion Collisions





The Relativistic Heavy Ion Collider at Brookhaven National Laboratory



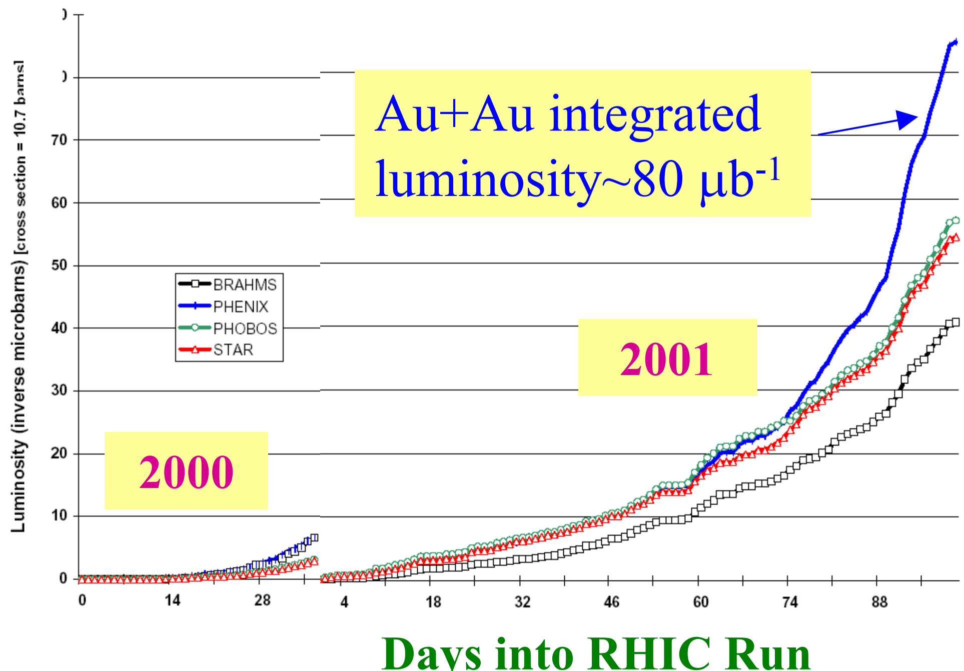
RHIC

- Dedicated collider for heavy ion physics
  - independent superconducting rings
  - enormous flexibility in nuclear beams and energies (incl. p+A)
  - polarized protons

RHIC Design Parameters:

- Au+Au:
  $\sqrt{s_{NN}}$ =200 GeV@L =2x10^{26}/cm^2/s
  Interaction rate ~ 1.4 kHz

- p+p (polarized):
  $\sqrt{s}$ =500 GeV @L=1.4x10^{31} /cm^2/s
  Interaction rate ~ 300 kHz

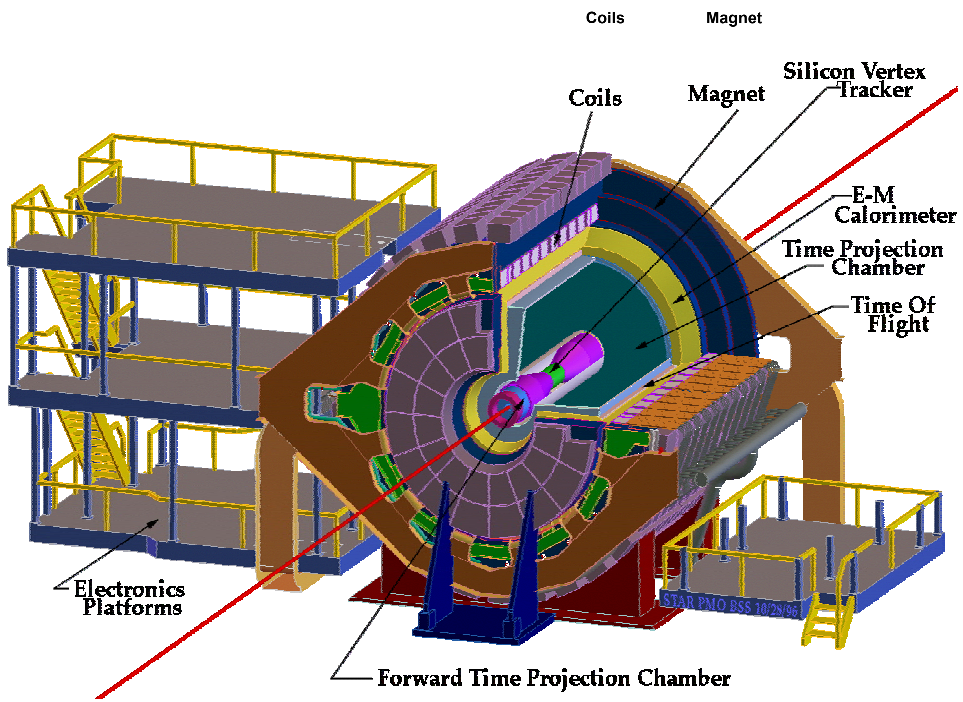


- 2000 run: Au+Au @ $\sqrt{s_{NN}}$=130 GeV
- 2001 run: Au+Au @ $\sqrt{s_{NN}}$=200 GeV (80 μb^{-1}); polarized p+p @ $\sqrt{s}$=200 GeV (~15% polarization, ~1 pb^{-1})

The Two Large Detectors

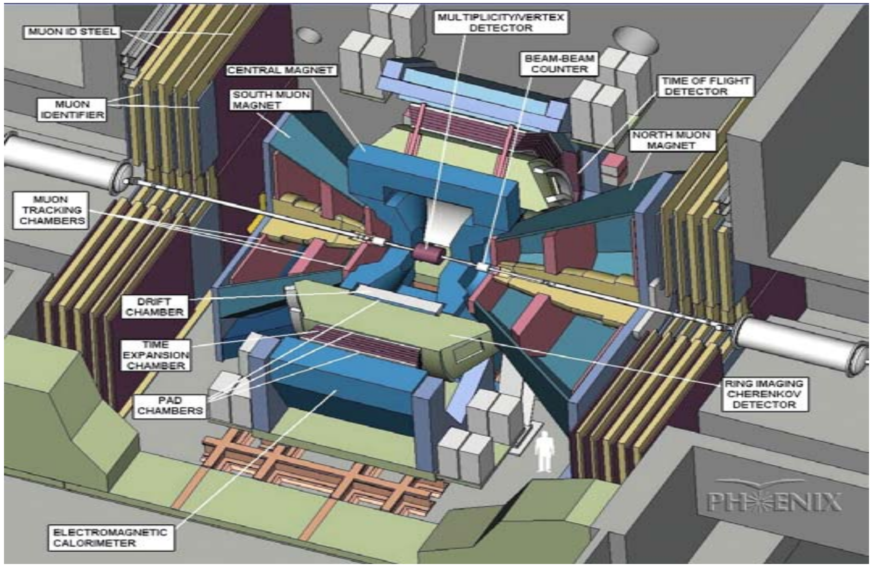
STAR

Solenoidal field, large-Ω tracking
TPC's, Si-vertex tracking
RICH, TOF, large EM Cal
~420 participants



PHENIX

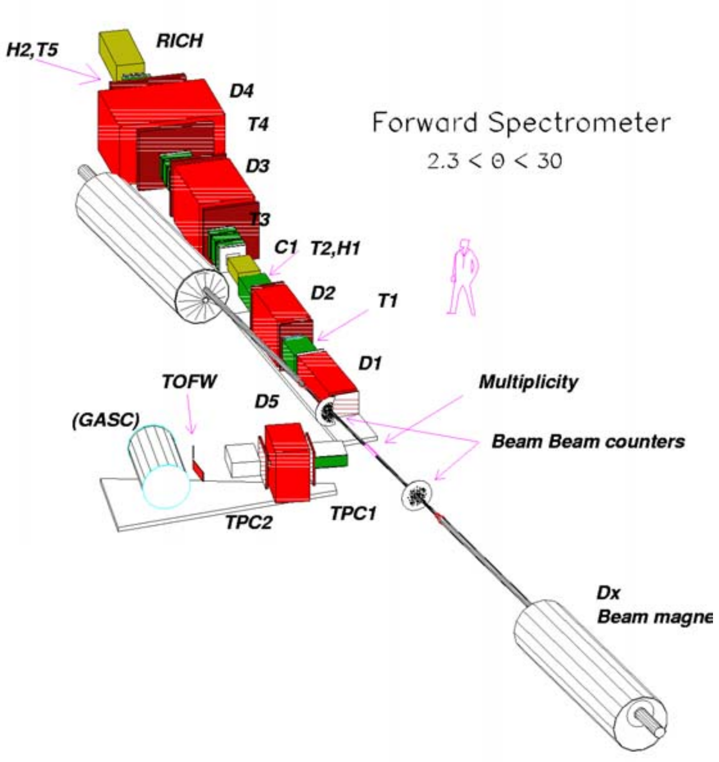
Axial field, high resolution & rates
2 central arms, 2 forward muon arms
TEC, RICH, EM Cal, Si, TOF, μ-ID
~450 participants



The Two Small Detectors

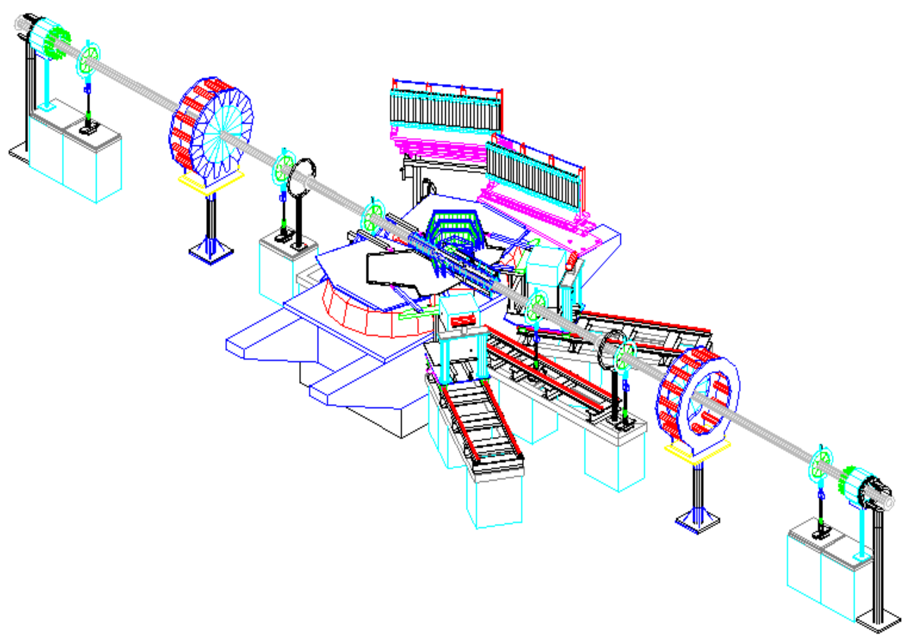
BRAHMS

2 “conventional” spectrometers
full phase space coverage
Magnets, TPCs, TOF, RICH
~40 participants



PHOBOS

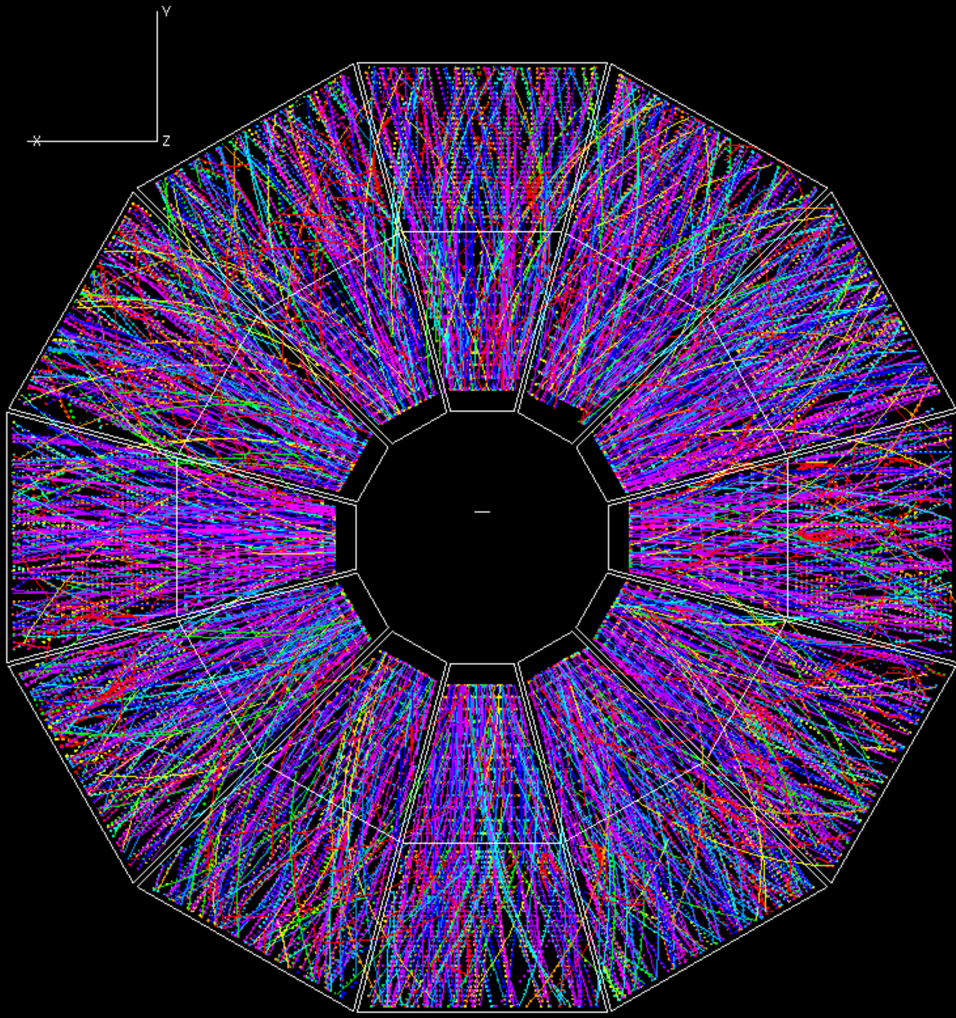
“Table-top” 2-arm spectrometer
full phase space multiplicity measurement
Magnet, Si μ-strips, Si multiplicity rings, TOF
~80 participants

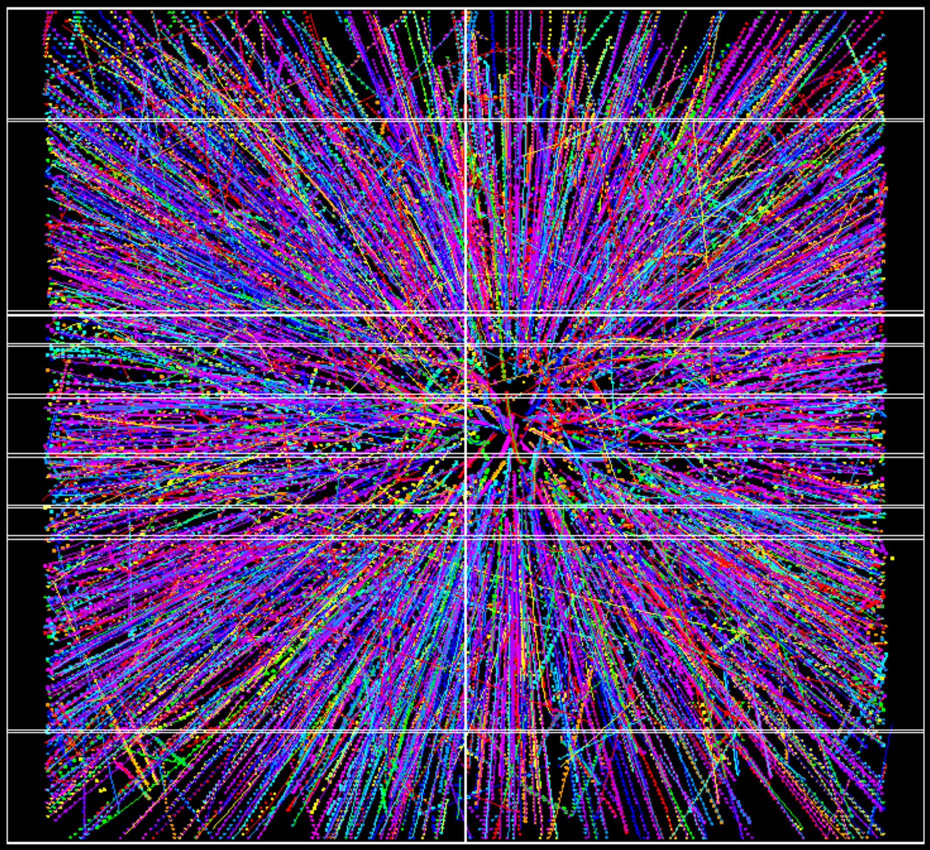


STAR

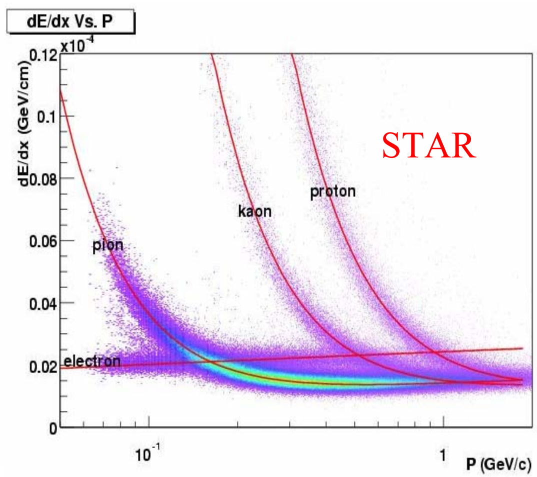
High Multiplicity Au+Au Collision at $\sqrt{s_{NN}}$=130 GeV

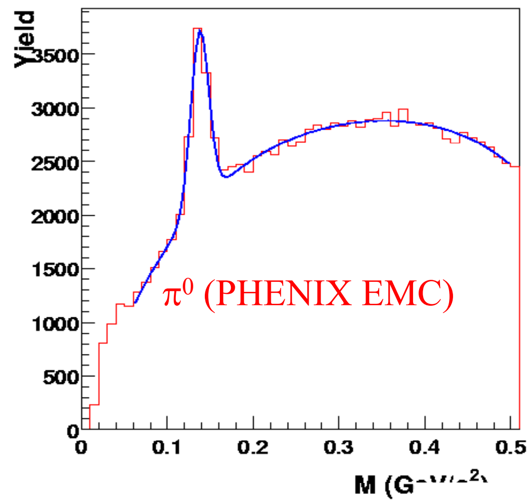
colors ~ momentum: low - - - high



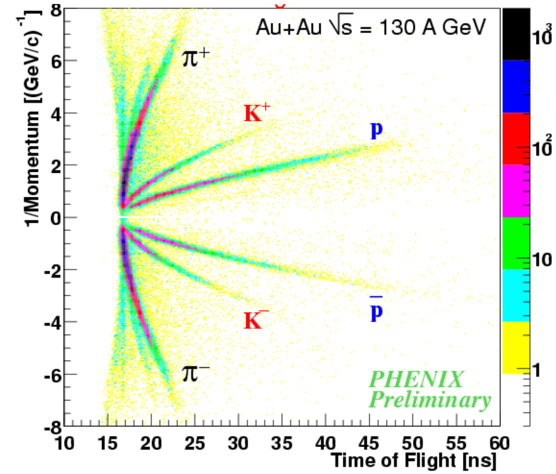


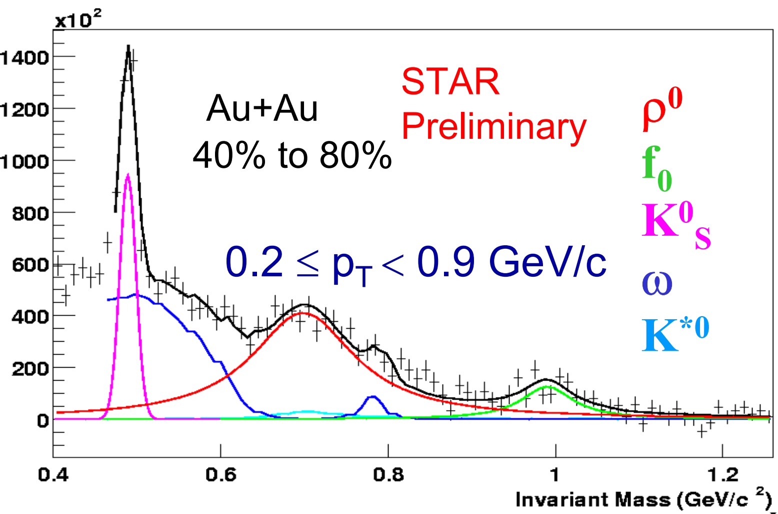
Particle Identification in Heavy Ion Events

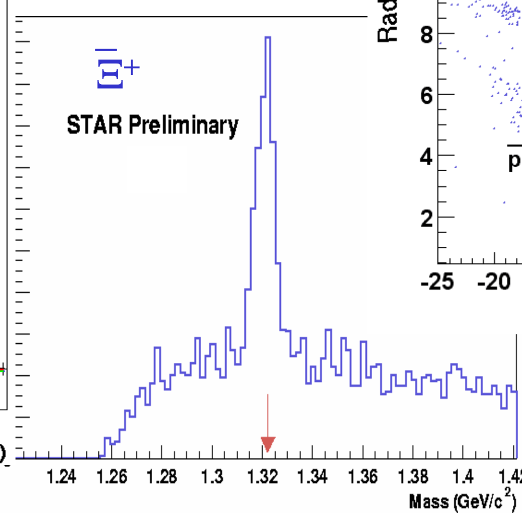


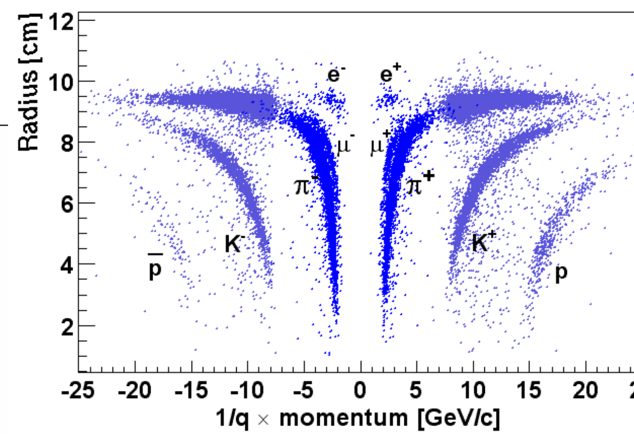


PHENIX TOF





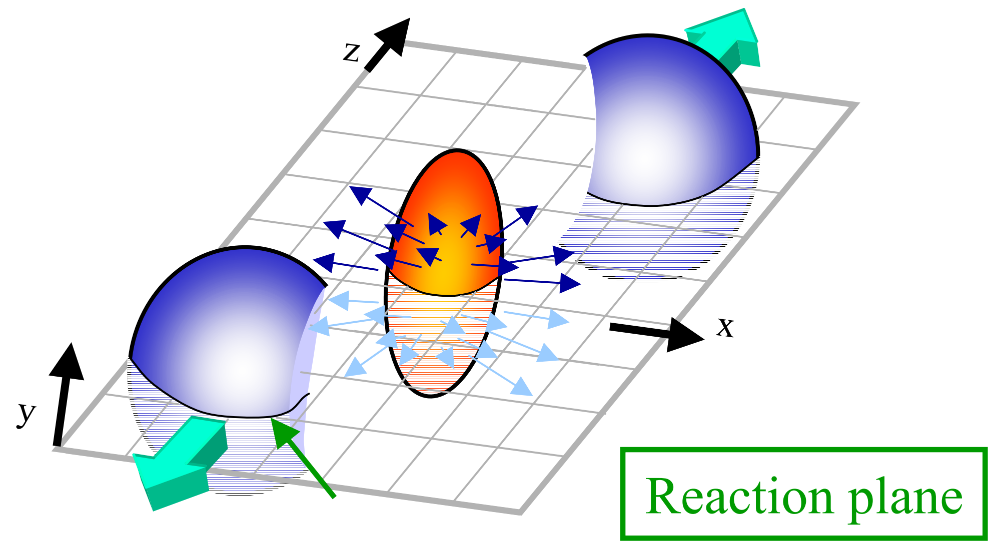




BRAHMS

Geometry of Heavy Ion Collisions

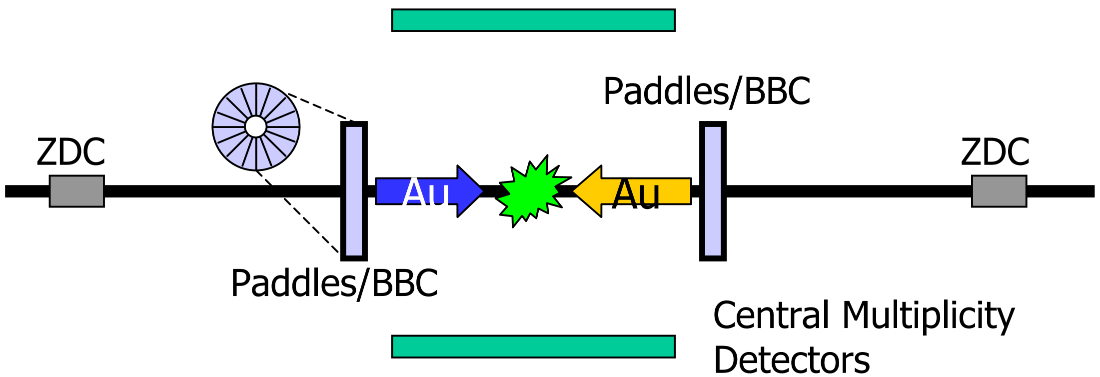
Non-central Collisions

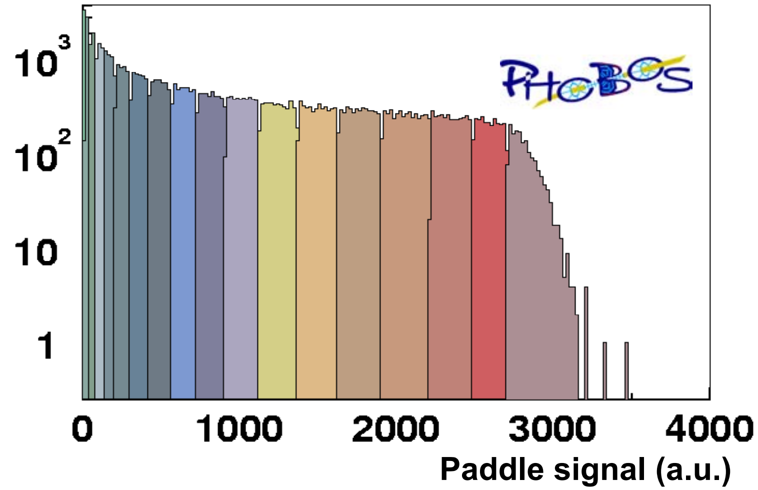


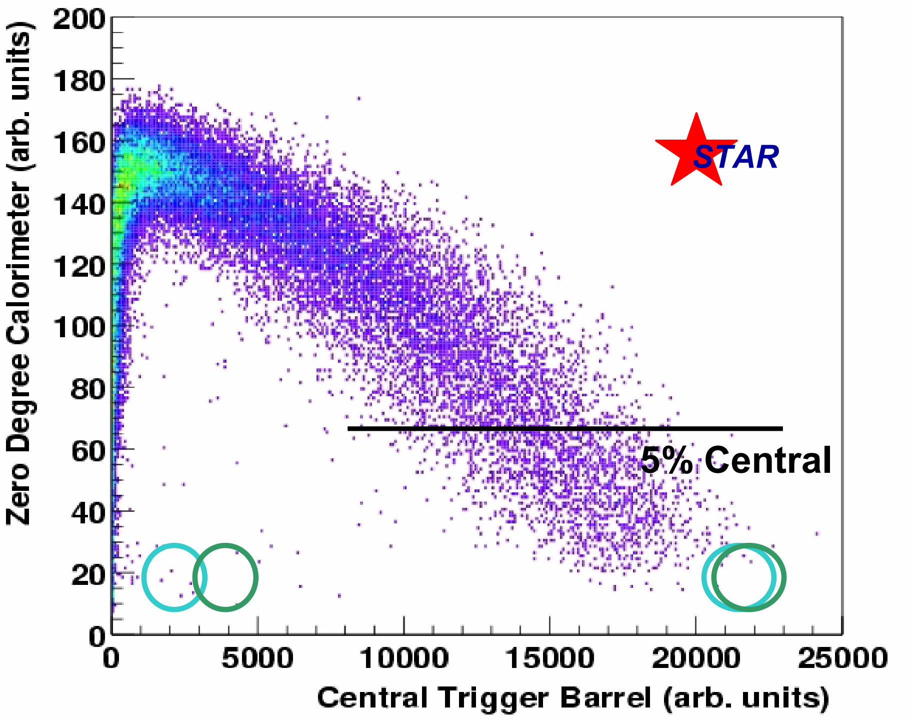
Number of participants: number of incoming nucleons (participants) in the overlap region

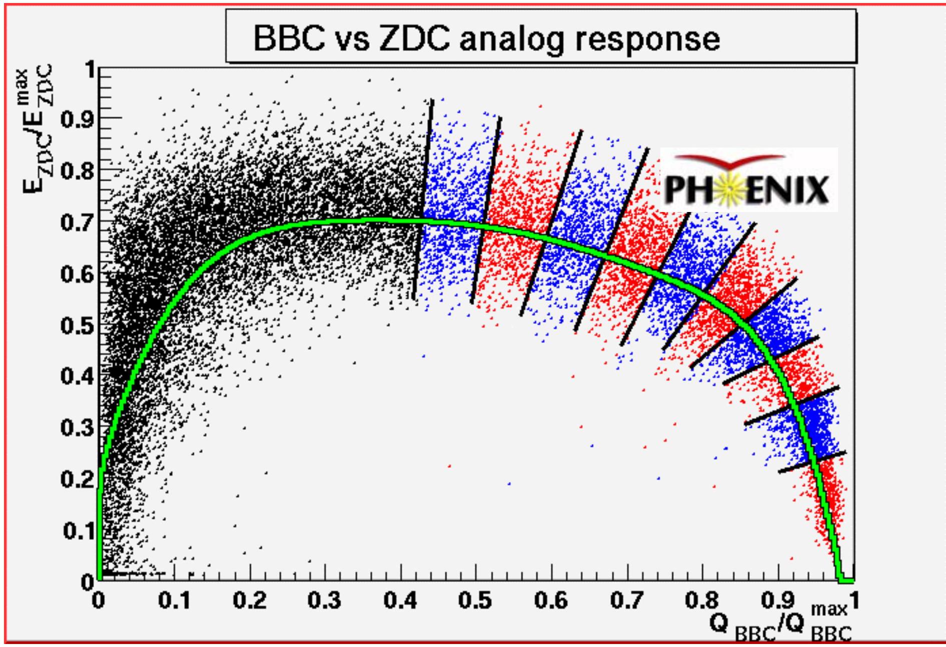
Number of binary collisions: number of equivalent inelastic nucleon-nucleon collisions

Experimental Determination of Geometry



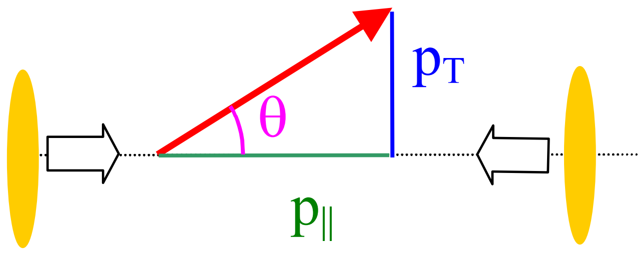




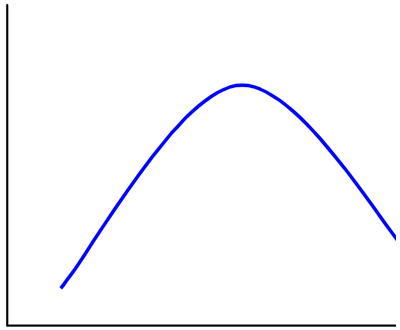


Kinematics for Inclusive Reactions

Rapidity: $$y = \tfrac{1}{2}\ln\left(\frac{E + p_{\parallel}}{E - p_{\parallel}}\right)$$



Boost invariance: $$\delta y \sim \frac{\delta p_{\parallel}}{E} \quad \Rightarrow$$

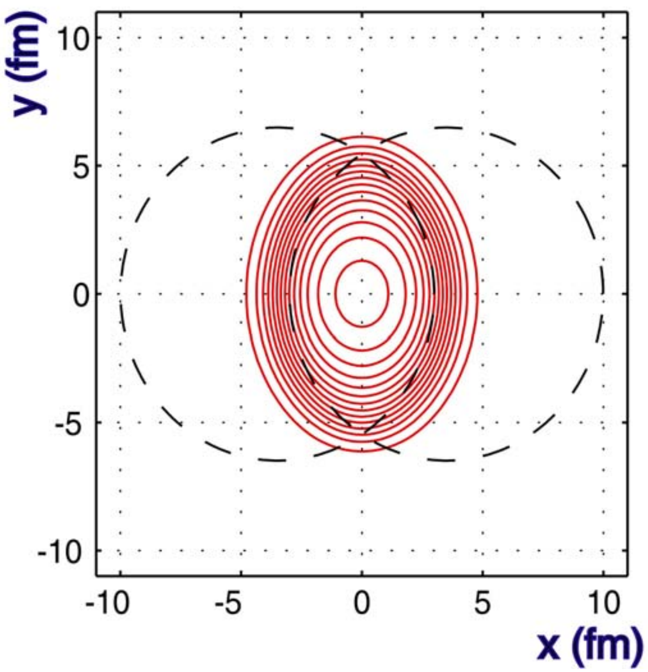


Invariant cross section: $$E\frac{d^3\sigma}{d^3p} = \frac{d^2\sigma}{2\pi p_T\, dy\, dp_T}$$

Pseudo-rapidity: $$y \rightarrow \eta = -\ln\left[\tan\left(\theta/2\right)\right]$$ for m/p << 1

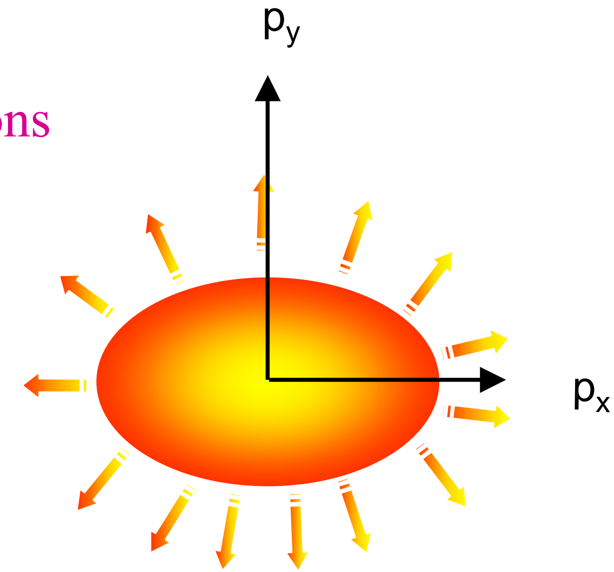
Elliptic Flow in Non-central Collisions

Coordinate space:
initial asymmetry



multiple collisions
(pressure)

Momentum space:
final asymmetry

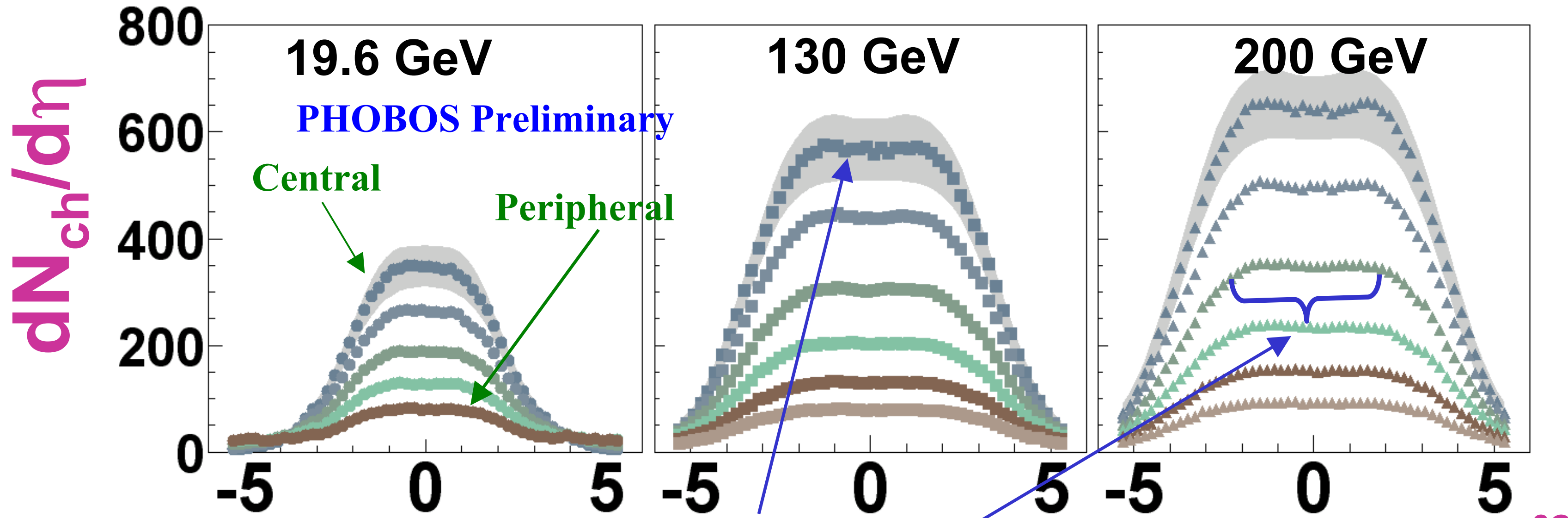


- Asymmetry generated early in collision, quenched by expansion

⇒ observed asymmetry emphasizes early time

Second Fourier coefficient v_2: $v_2 = \langle \cos 2\phi \rangle$ $\phi = \mathrm{atan}\,\frac{p_y}{p_x}$

Charged Particle and E_T Production



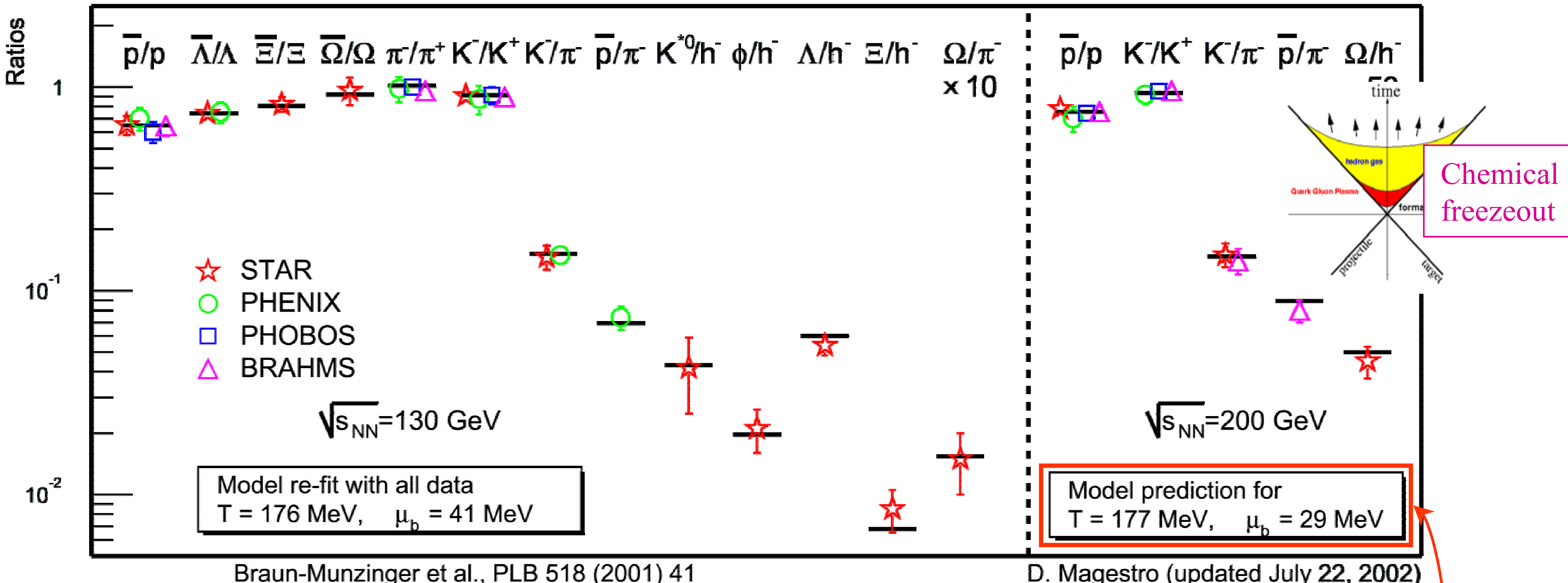
- Central collisions at 130 GeV: 4200 charged particles (!)
- mid-rapidity: ~ boost invariance
- Energy density: boost invariant hydrodynamics (Bjorken)

$$\varepsilon = \frac{1}{\pi R^2 \tau}\frac{dE_T}{dy} \approx \frac{1}{\pi R^2 \tau}\langle p_T \rangle \frac{3}{2}\frac{dN_{ch}}{d\eta}$$

($R \sim A^{1/3}$, $\tau = 1$ fm/c)

PHENIX (Central Au+Au at 130 GeV): $\varepsilon = 4.6$ GeV/fm^3
(nucl-ex/0104015)

Chemical equilibrium?



Thermal model: Partition fn with params T, μ_B, μ_s, μ_{I3}

Fit to ratios of antiparticle/particle: π, K, p, Λ, Ξ, K^*_0, ….

Typical fits: T_{ch} = 175~200 MeV, μ_B ~50 MeV, μ_s ~0

Simple "model" fits/predicts alarmingly well: evidence for chemical equilibrium?

p_T< 2 GeV/c: Summary

- Baryon/antibaryon ratios at midrapidity ~ 0.6-1
  - close to baryon-free ~ early universe
  - but not quite (net proton dN/dy~10): baryon transport Δy~5.5
- High apparent energy density ~5 GeV/fm^3 (lattice phase transition ~1 GeV/fm^3, cold matter ~ 0.16 GeV/fm^3)
- Chemical equilibrium: T~170 MeV, μ_b<50 MeV ⇒ near Hagedorn temperature and lattice phase boundary
- Hydrodynamics works very well
- Bose-Einstein correlations: rapid hadronization, no long-lived mixed phase (e.g. from strong 1st order transition)
- Dynamical fluctuations and correlations: in progress
- Gluon saturation effects in A+A?

Overall picture: system appears to be in equilibrium but explodes and hadronizes rapidly ⇒ high initial pressure

Fermi National Accelerator Laboratory

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

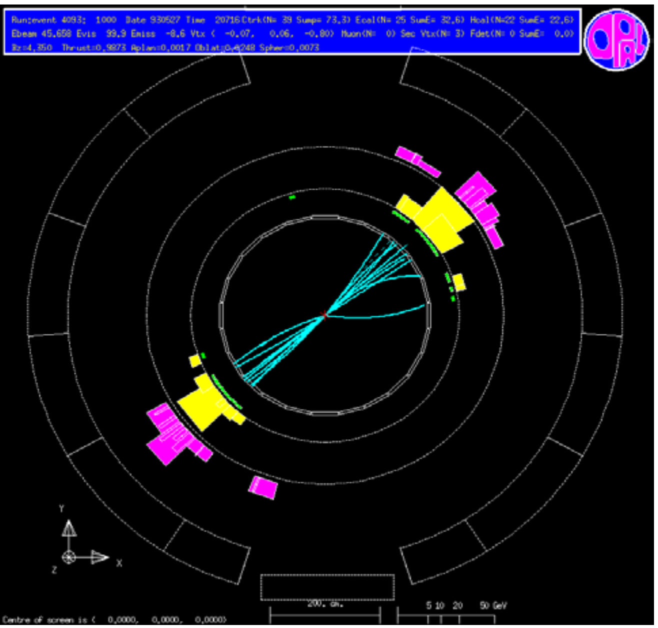
J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Abstract

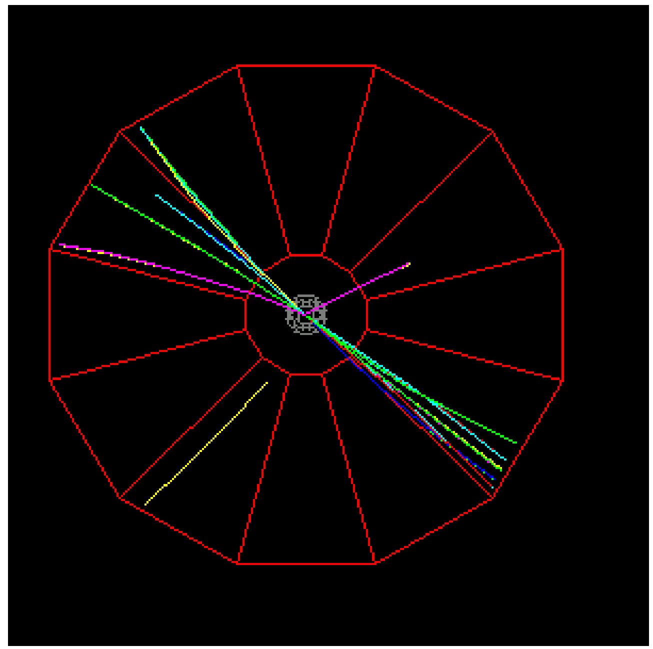
High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For

Jets in heavy ion collisions

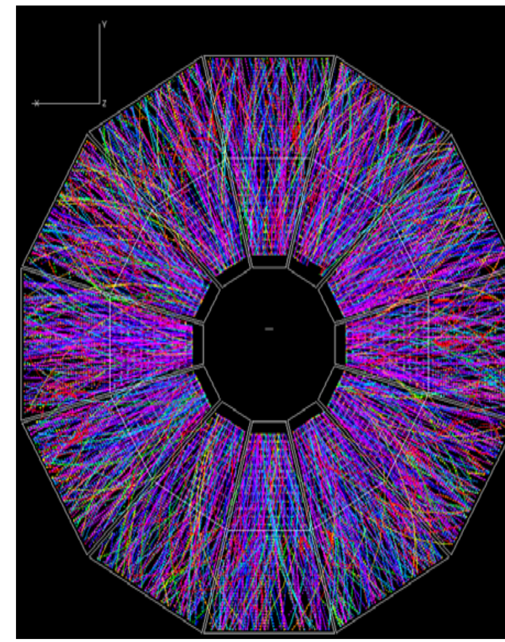
e+e- →qqbar
(OPAL@LEP)



p+p →jet+jet
(STAR@RHIC)

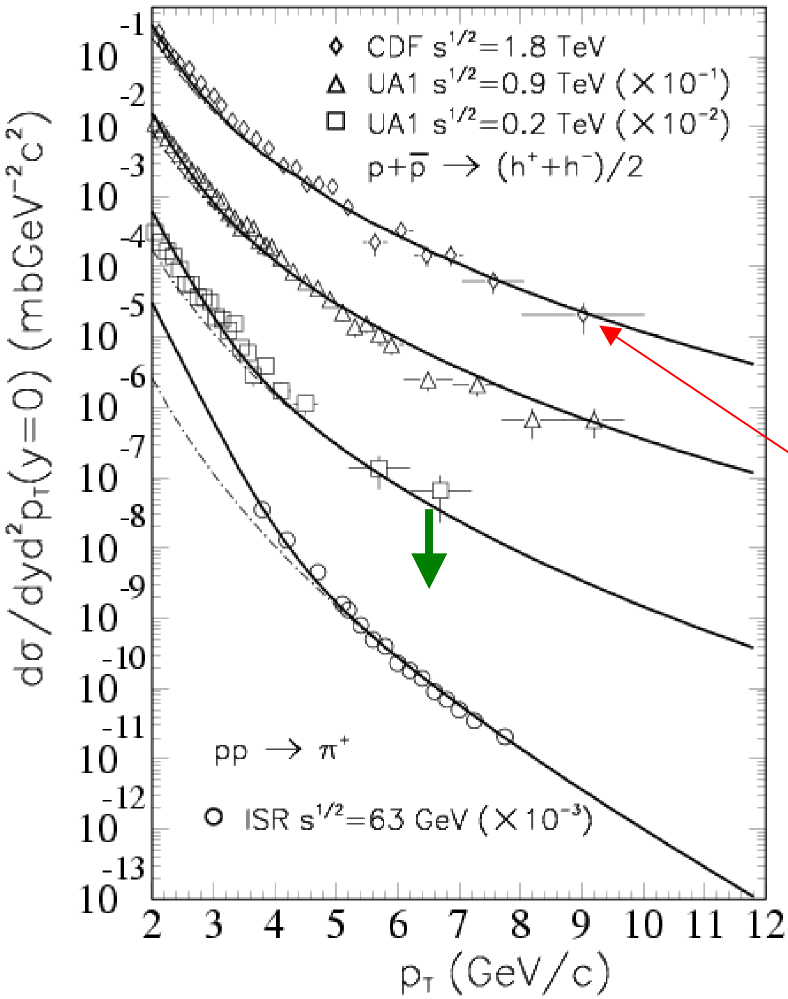


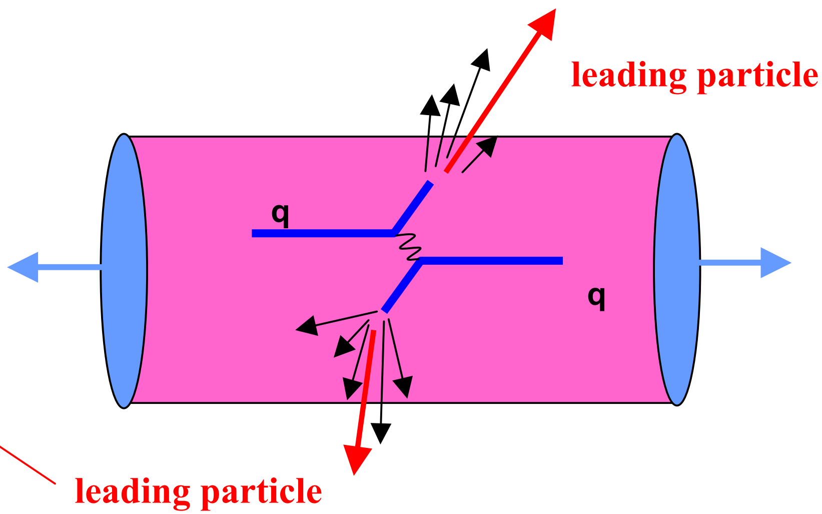
Au+Au →???
(STAR@RHIC)



Hopeless task? No, but a bit tricky…

Jet energy loss via leading hadrons





Wang and Gyulassy: partonic energy loss ⇒effective softening of fragmentation ⇒ suppression of leading hadron yield

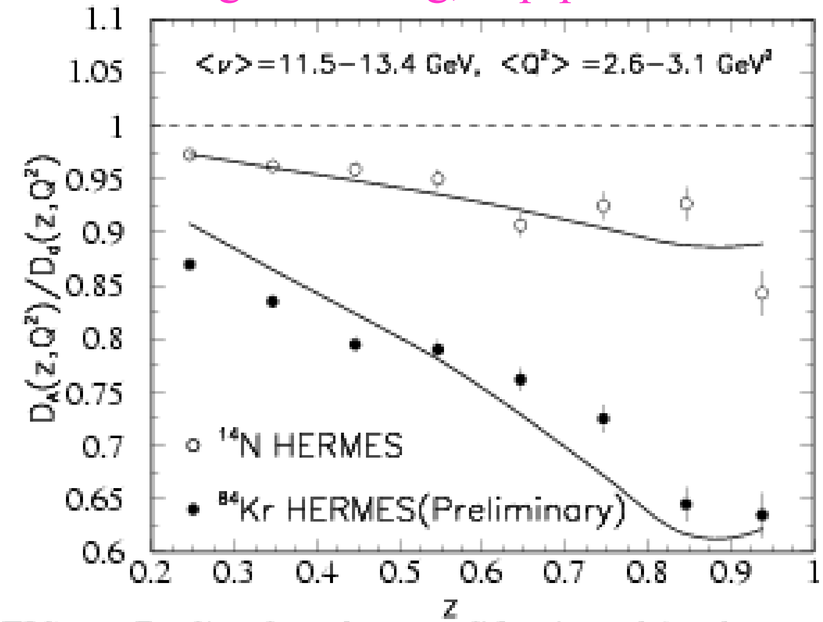
Partonic energy loss: theory

- Elastic scattering (Bjorken): $$-\frac{dE}{dz} \sim \alpha_s^2 \sqrt{\varepsilon} \propto T_{plasma}^2$$
- Gluon radiation is factor ~10 larger:
  - Thick plasma (Baier et al.): $$\Delta E_{BDMS} = \frac{C_R \alpha_s}{4} \hat{q} L^2 \tilde{v}$$ $$\hat{q} = \frac{\mu_{Debye}^2}{\lambda_{glue}} \propto \alpha_S \rho_{glue}$$
  - Thin plasma (Gyulassy et al.): $$\Delta E_{GLV} = C_R \alpha_S^3 \int d\tau \tau \rho_{glue}(\tau, r(\tau)) Log\left(\frac{2E_{jet}}{\mu^2 L}\right)$$

Linear dependence on gluon density ρ_{glue}:
- ΔE measures gluon density
- ΔE is continuous function of energy density $\Rightarrow$ not a direct signature of deconfinement

Energy loss in cold matter

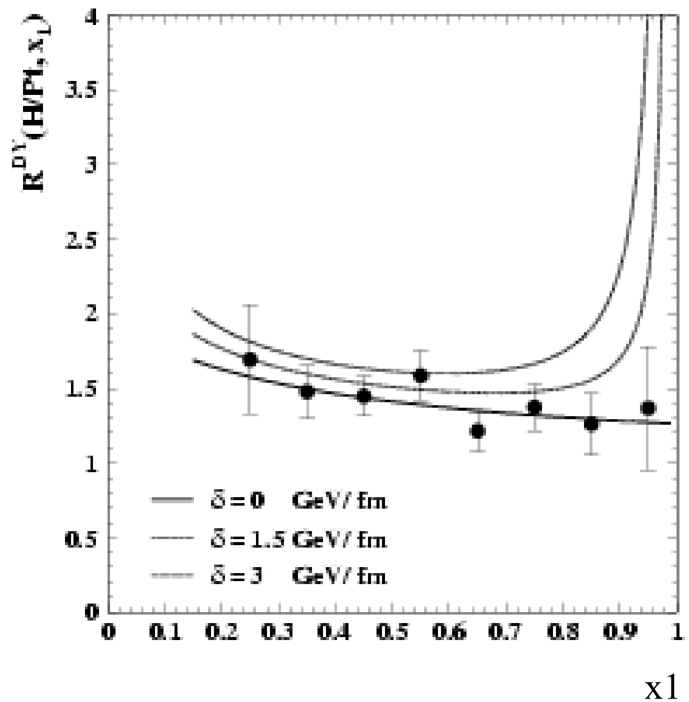
Wang and Wang, hep-ph/0202105



Modification of fragmentation fn in e-Nucleus scattering:

dE/dx ~ 0.5 GeV/fm for 10 GeV quark

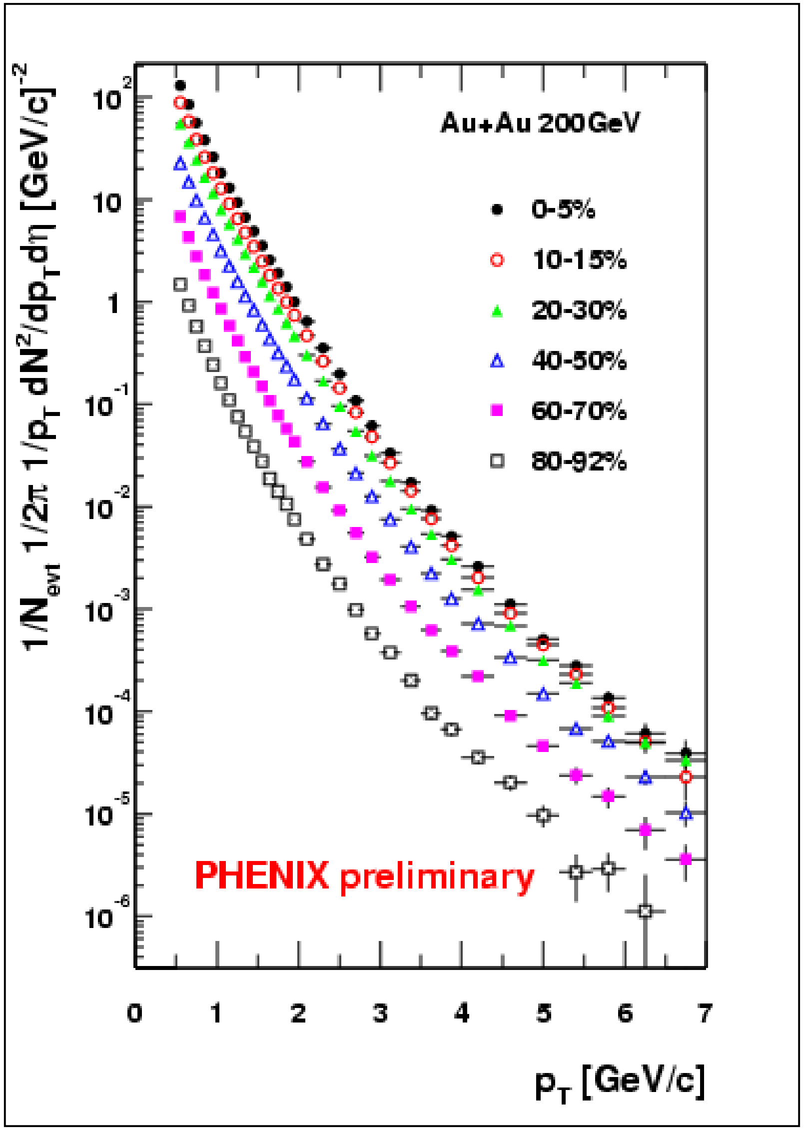
F. Arleo, hep-ph/0201066

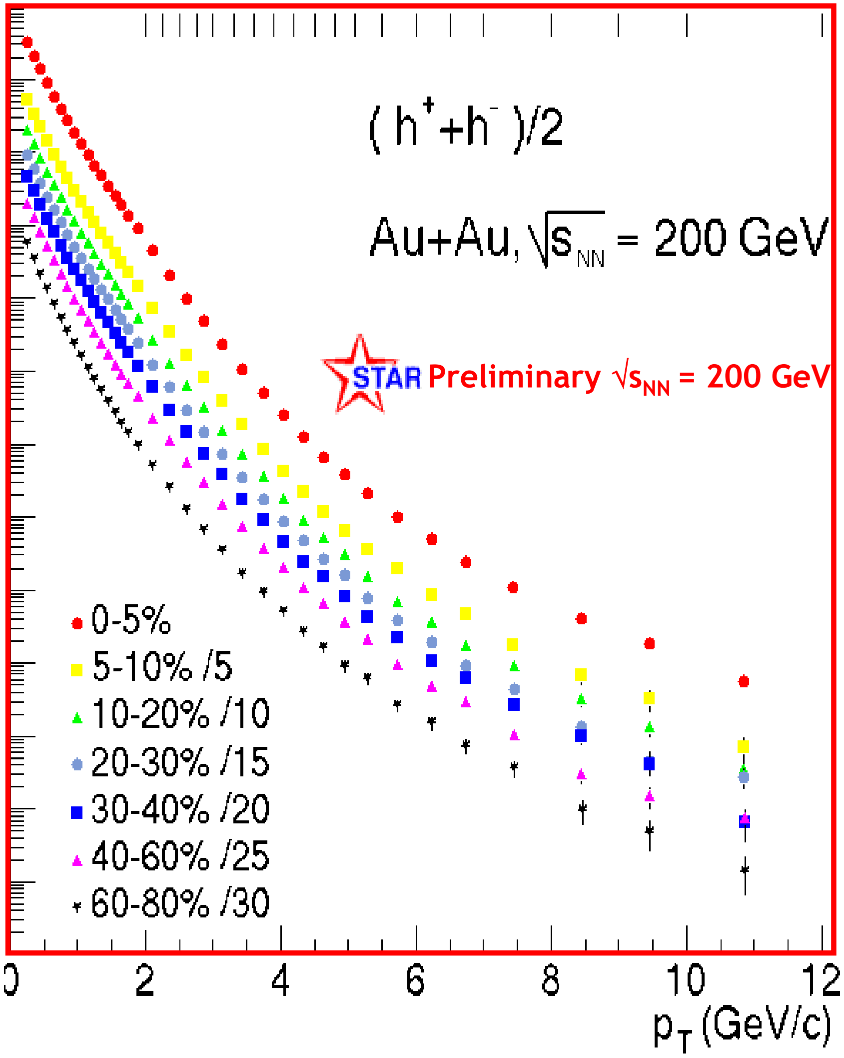


Drell-Yan production in π-Nucleus:

dE/dx <0.2 GeV/fm for 50 GeV quark

High p_T hadrons: Au+Au at RHIC





Measuring hadron suppression

- Nuclear Geometry: number of binary collisions $\langle N_{binary} \rangle$ (Glauber model)
- compare to nucleon-nucleon cross sections:

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

N-N cross section

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

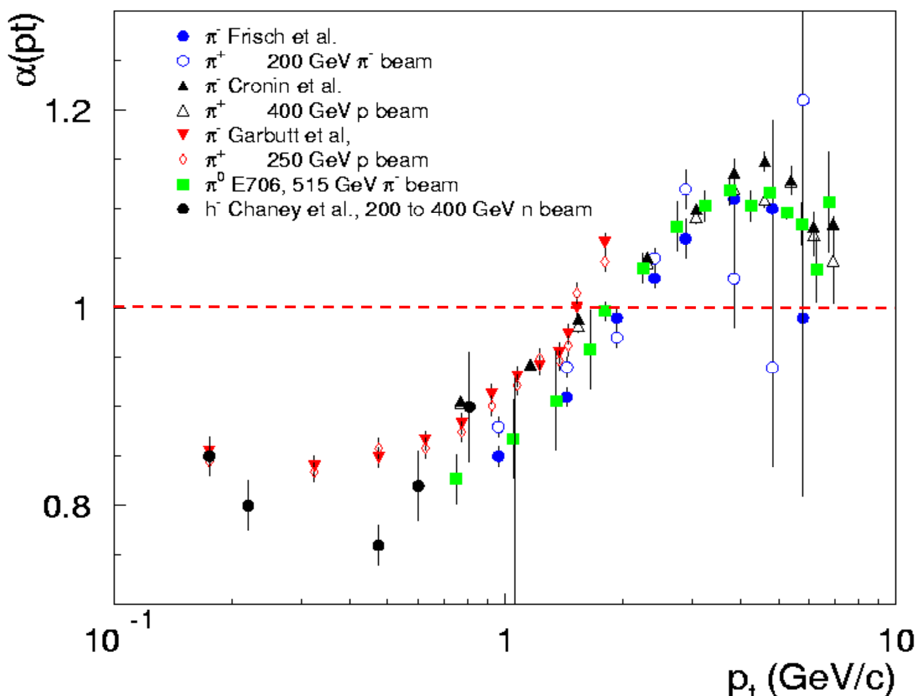
N-N inclusive hadron data:

- pbar-p @200-900 GeV (UA1 @ CERN, 1980's): limited p_T reach at 200 GeV
- Recent 200 GeV p+p @ RHIC

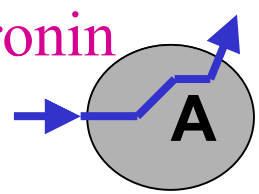
- Au+Au central/peripheral scaled by $\langle N_{binary} \rangle$

Leading Hadrons in Fixed Target Experiments

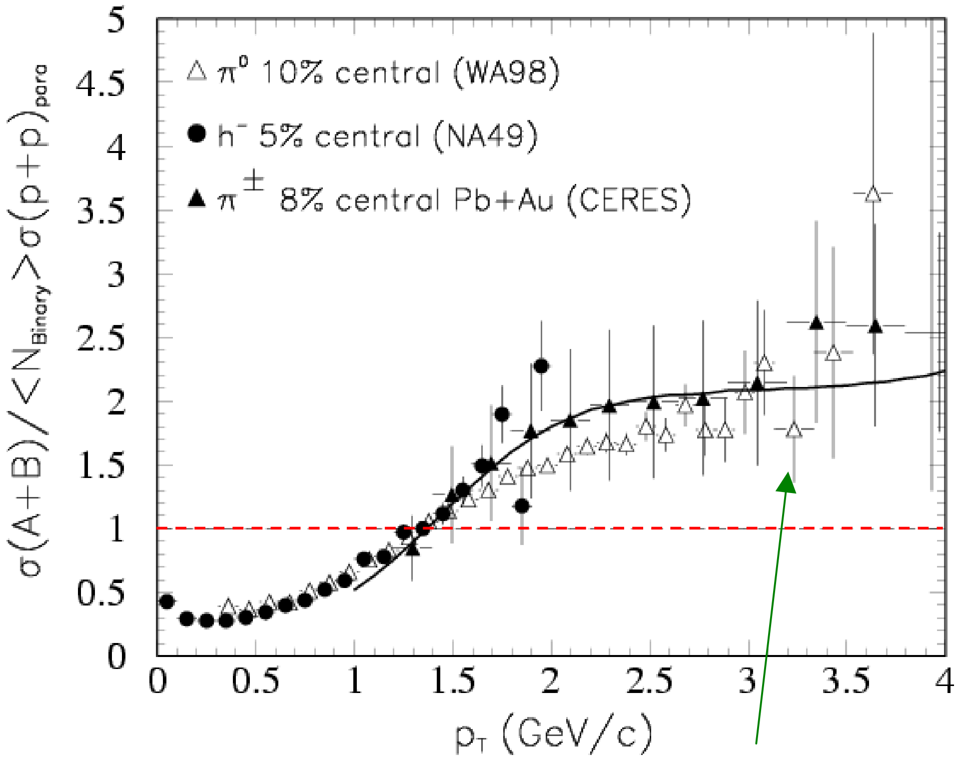
p+A collisions: $\sigma_{pA} = A^{\alpha(p_t)} \sigma_{pp}$



Multiple scattering in initial state("Cronin effect")



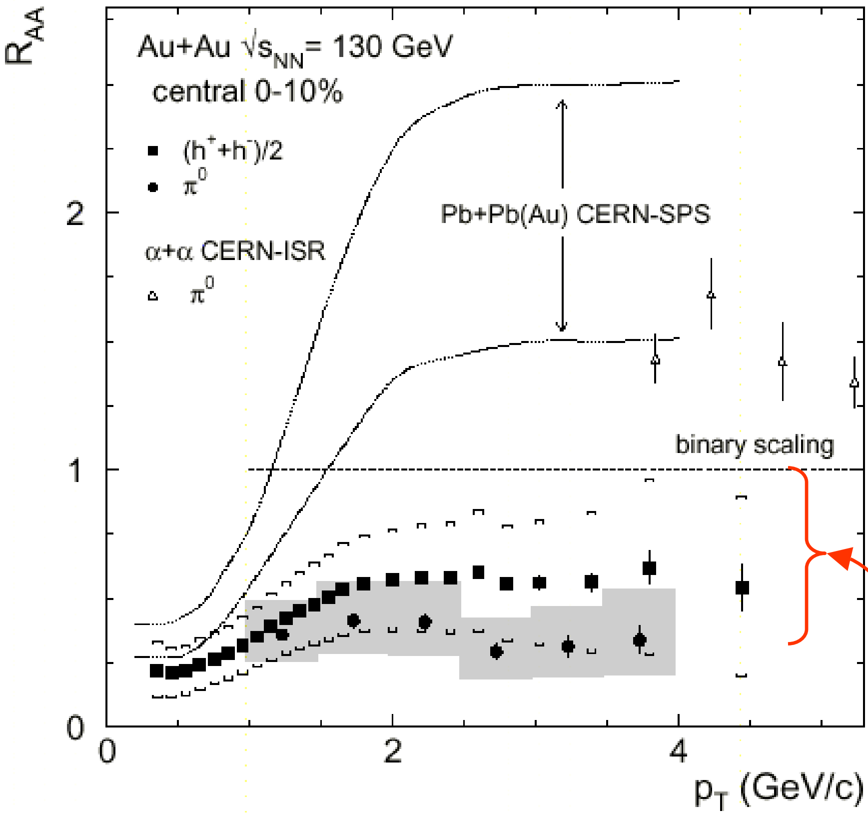
Central Pb+Pb collisions at SPS



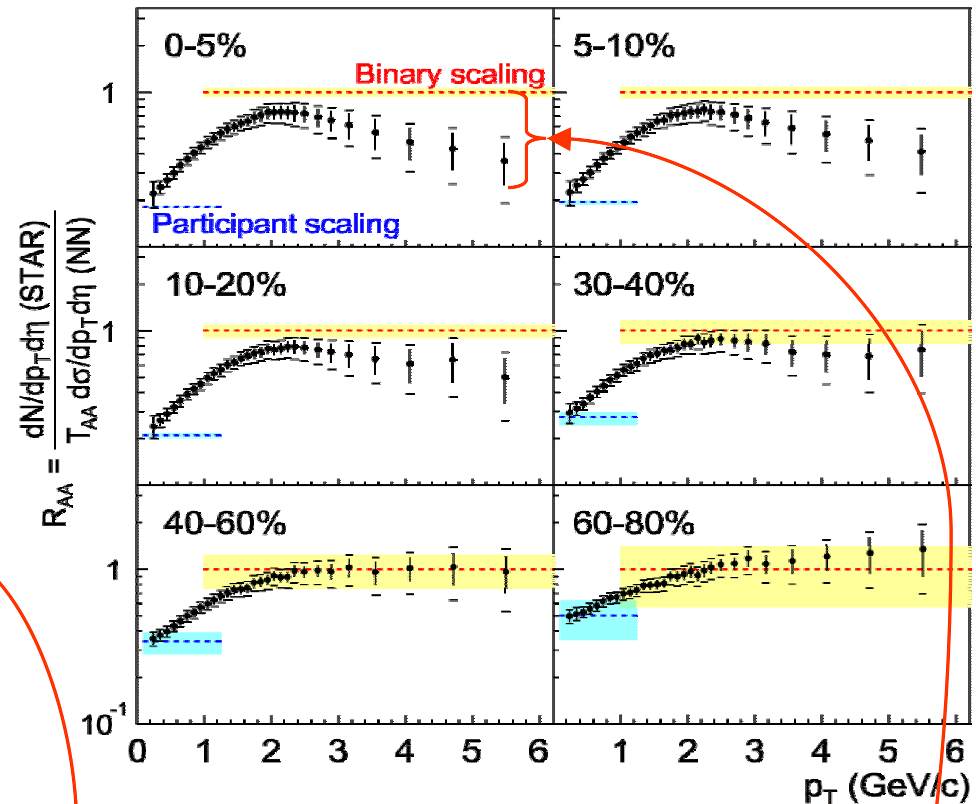
SPS: any parton energy loss effects buried by initial state multiple scattering, transverse radial flow,…

Hadron suppresion:Au+Au at 130 GeV

Phenix: PRL **88** 022301 (2002)
π^0 and charged hadrons, central collisions



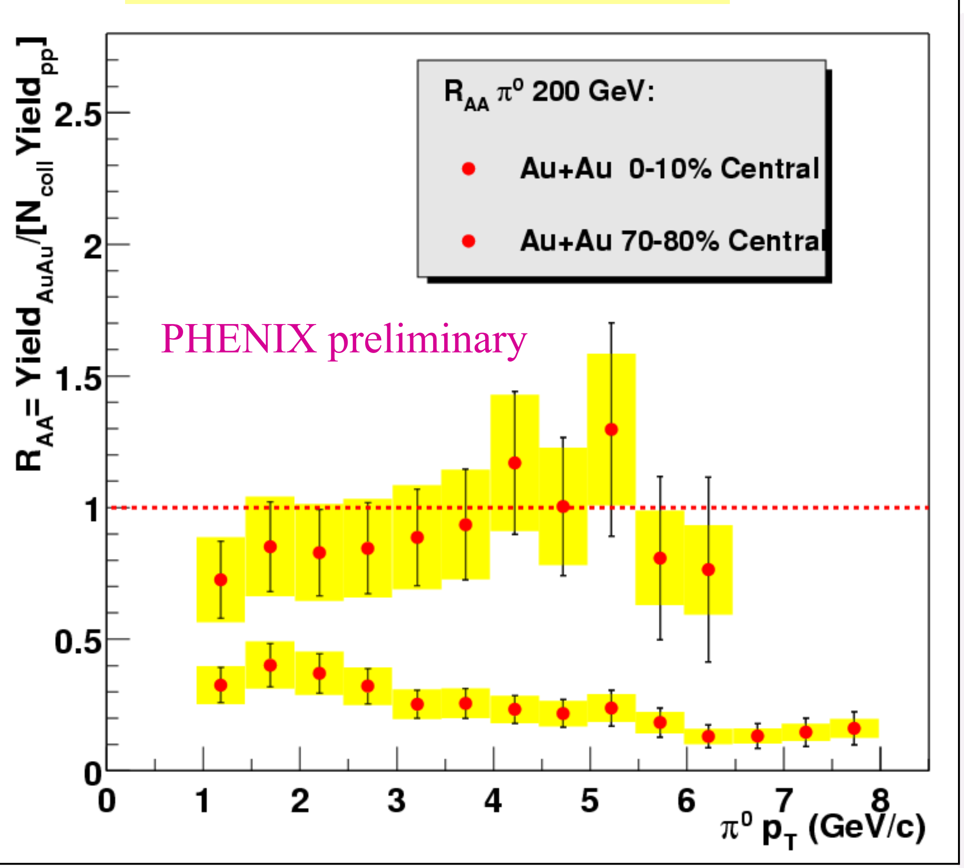
STAR: nucl-ex/0206011
Charged hadrons, centrality dependence



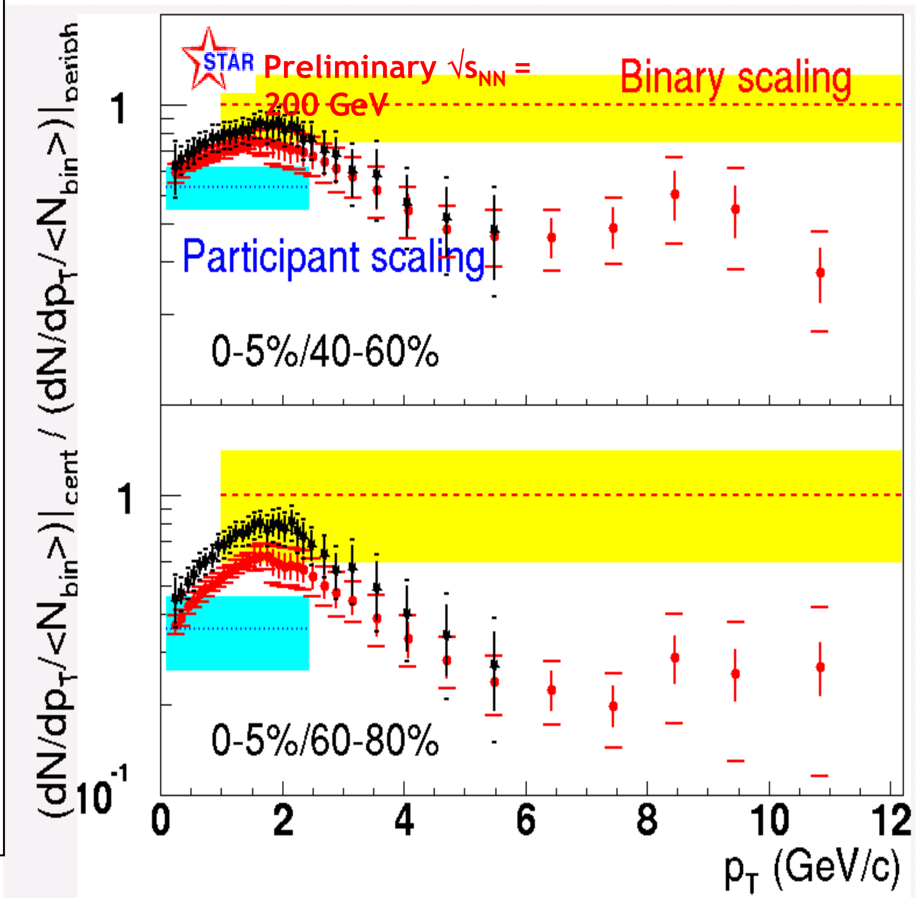
Clear evidence for high p_T hadron suppression in central nuclear collisions

Hadron suppression: Au+Au at 200 GeV

Phenix π^0: peripheral and central over *measured* p+p



STAR charged hadrons: central/peripheral



Quark Matter 2002 preliminary data: suppression of factor 4-5 persists to p_T=12 GeV/c

π^0 suppression: comparison to theory

--- Wang dE/dx = 0

--- dE/dx =0.25 GeV/fm

- Wang: X.N. Wang, Phys. Rev. C61, 064910 (2000).

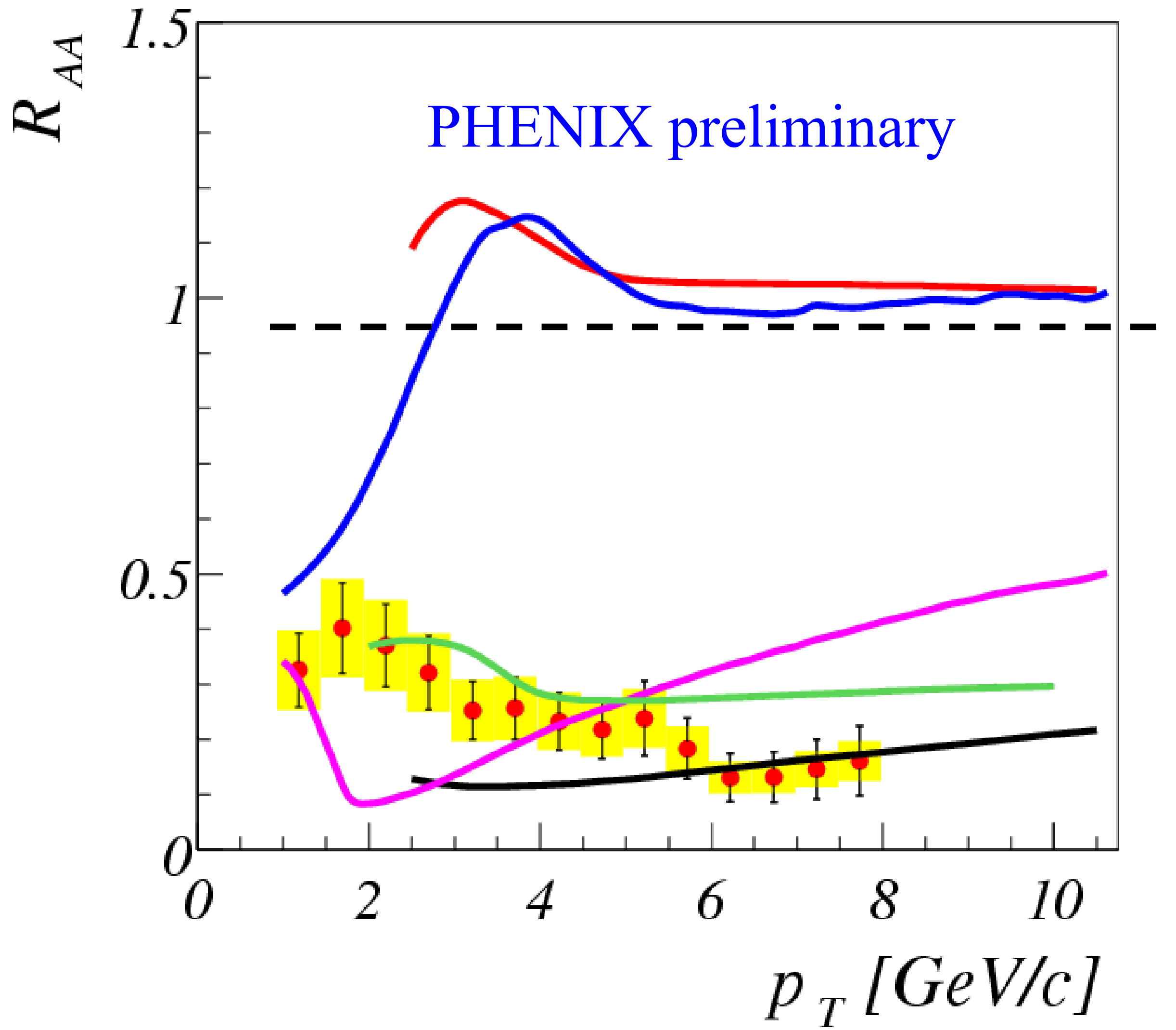
--- Levai L/λ = 0

--- L/λ = 4

- Gyulassy, Levai, Vitev: P.Levai, Nuclear Physics A698 (2002) 631.

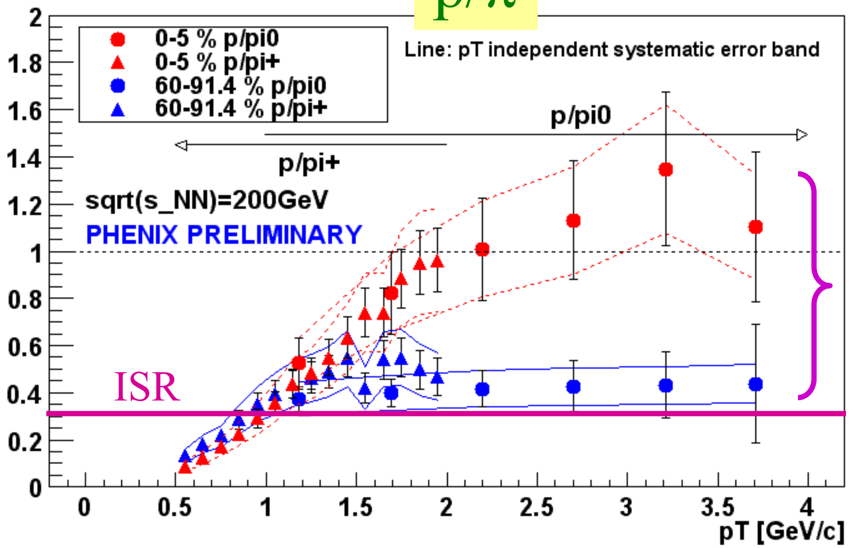
--- Vitev dN^g/dy = 900

- **GLV**, Nucl. Phys. B 594, p. 371 (2001) + work in preparation.



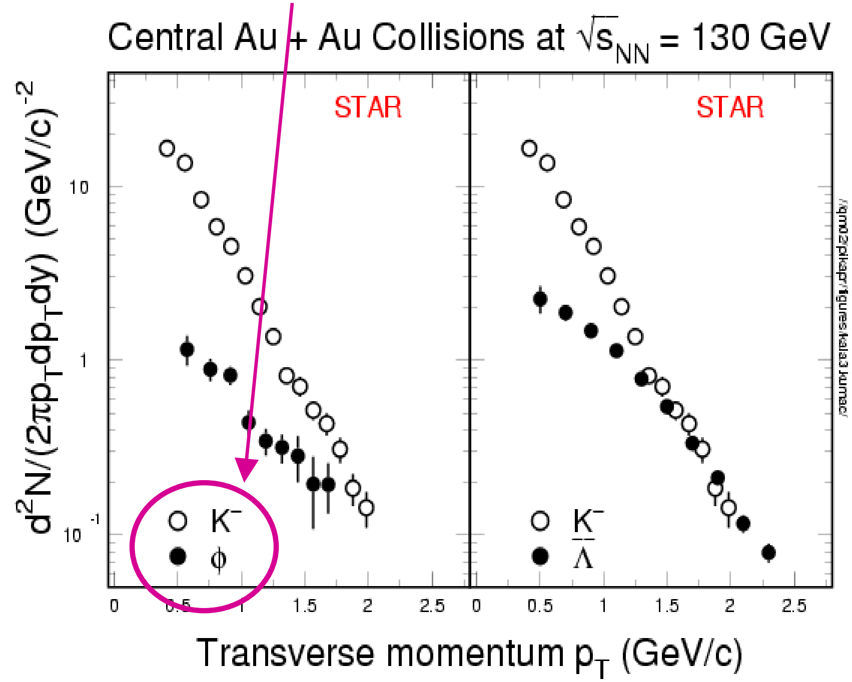
Particle composition at p_T~2-4 GeV/c

p/π



PHENIX: large excess of protons in central collisions relative to p+p at ISR and standard jet fragmentation (p/π~0.3)
Phys. Rev. Lett. 88, 242301 (2002)

STAR: excess also seen in heavy mesons

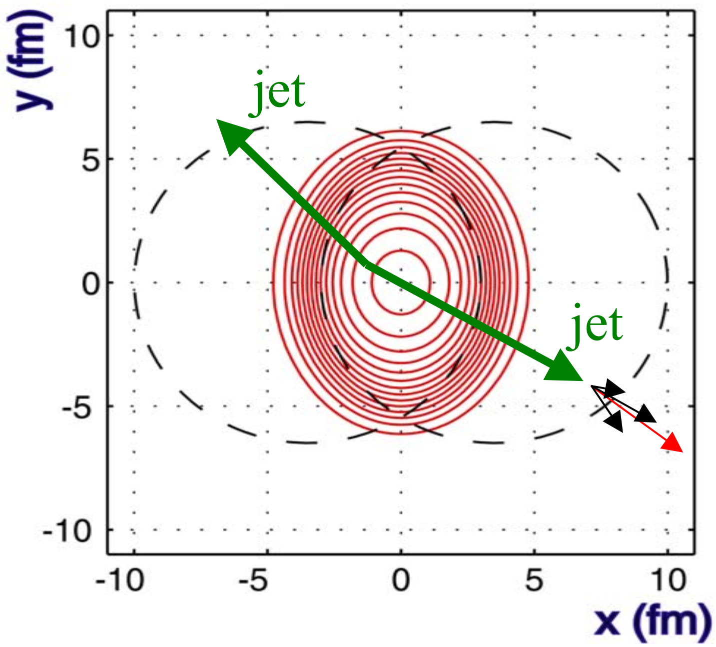


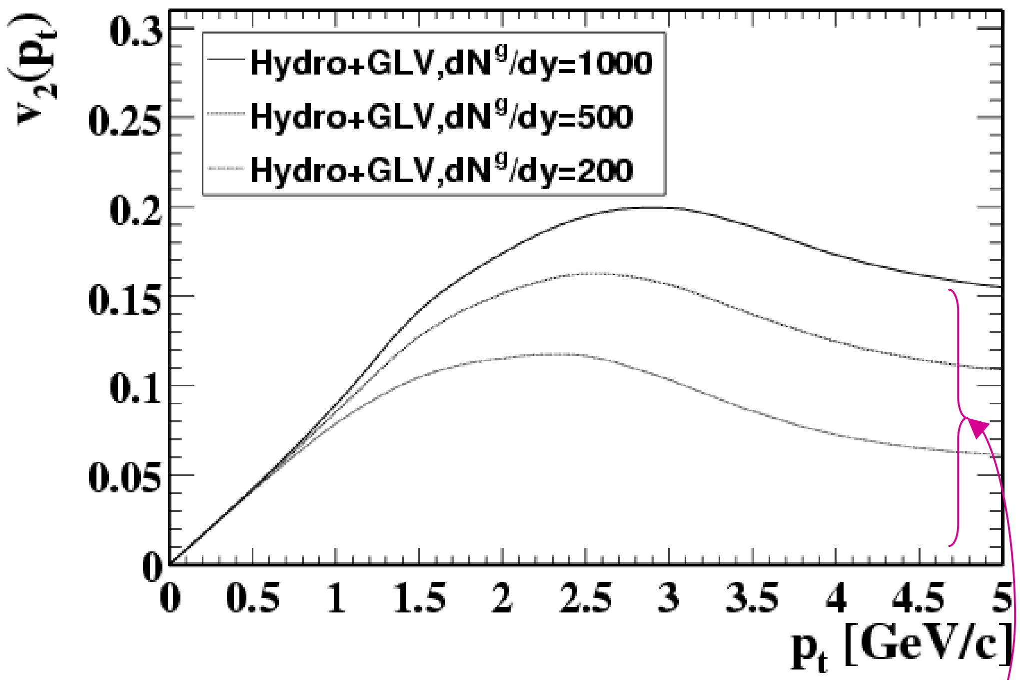
- Exotic explanation: baryon junction interactions enhanced in A+A (Vitev and Gyulassy)
- Mundane explanation: transverse radial flow (common velocity)

Elliptic flow at high p_T: theory

Jet propagation through anisotropic matter (non-central collisions)

Snellings; Gyulassy, Vitev and Wang (nucl-th/00012092)



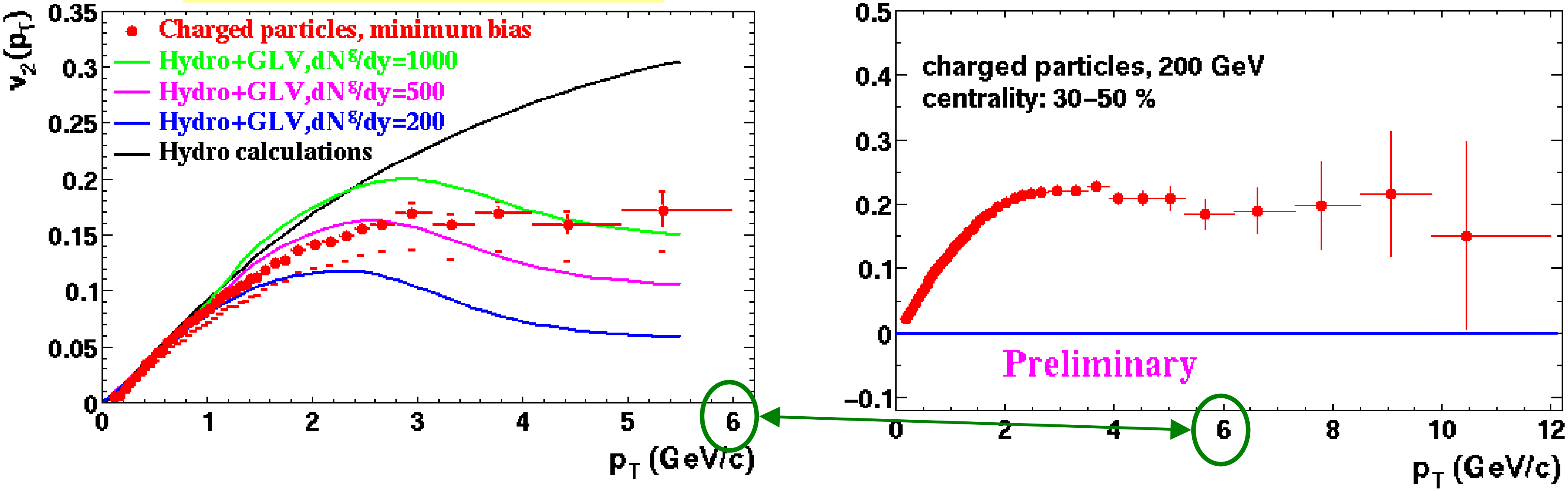


- Finite v_2: high p_T hadron correlated with reaction plane from "soft" part of event (p_T<2 GeV/c)
- Finite asymmetry at high p_T sensitive to energy density

Elliptic flow at high p_T: data

STAR, nucl-ex/0206006
130 GeV

STAR preliminary
200 GeV

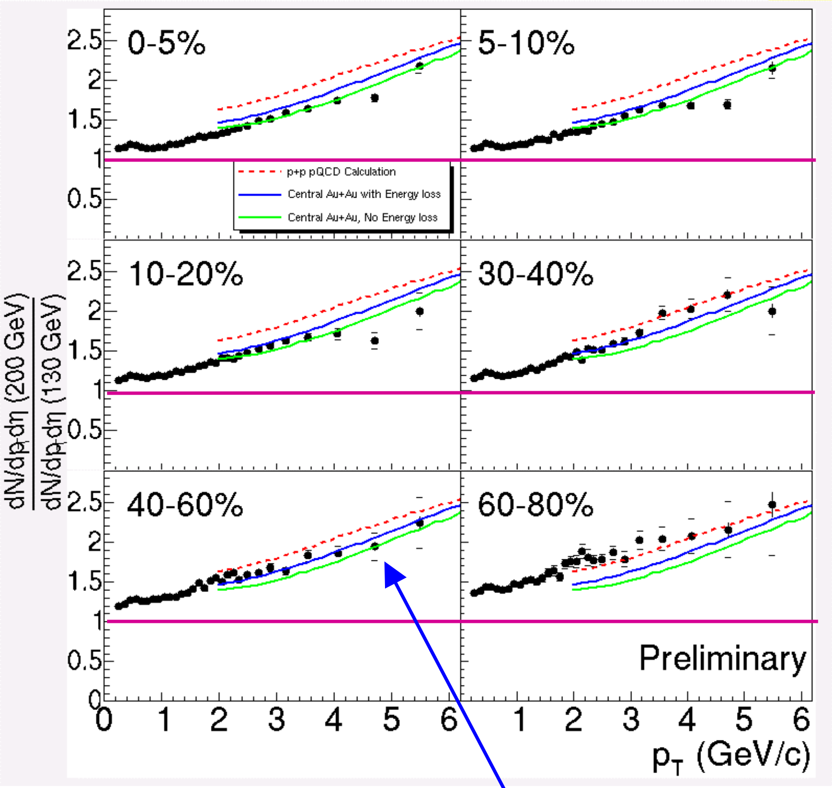


- p_T<2 GeV: detailed agreement with hydrodynamics
- p_T>4 GeV: finite v_2 in qualitative agreement with jet quenching predictions

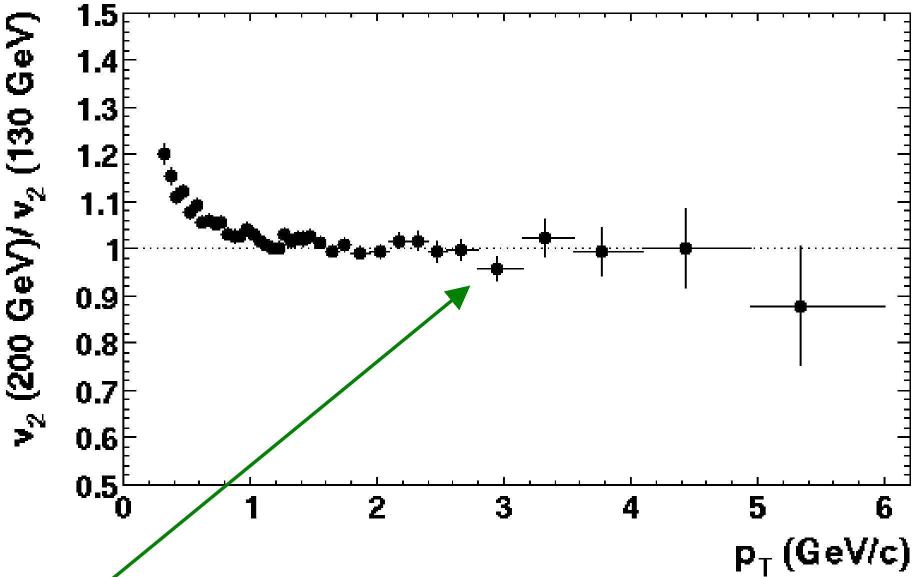
√s dependence at high p_T (200/130)

Ratio of spectra 200/130

STAR preliminary



Ratio of v_2 200/130



- Inclusive spectra follow pQCD prediction (XN Wang)
- minbias v_2 has no energy dependence at p_T>2 GeV

⇒ surface emission at high p_T? (i.e. strong absorption)

Two-particle correlations at high p_T: direct evidence for jets?

- Jet core: $\Delta\phi \times \Delta\eta \sim 0.5 \times 0.5$
  $\Rightarrow$ look at near-side correlations ($\Delta\phi \sim 0$) of high p_T hadron pairs

- Complication: elliptic flow
  - high p_T hadrons correlated with the reaction plane orientation also correlated with each other ($\sim v_2^2$)
  - but elliptic flow has long range correlation ($\Delta\eta >> 0.5$)

- Solution: compare azimuthal correlation functions for $\Delta\eta<0.5$ and $\Delta\eta>0.5$

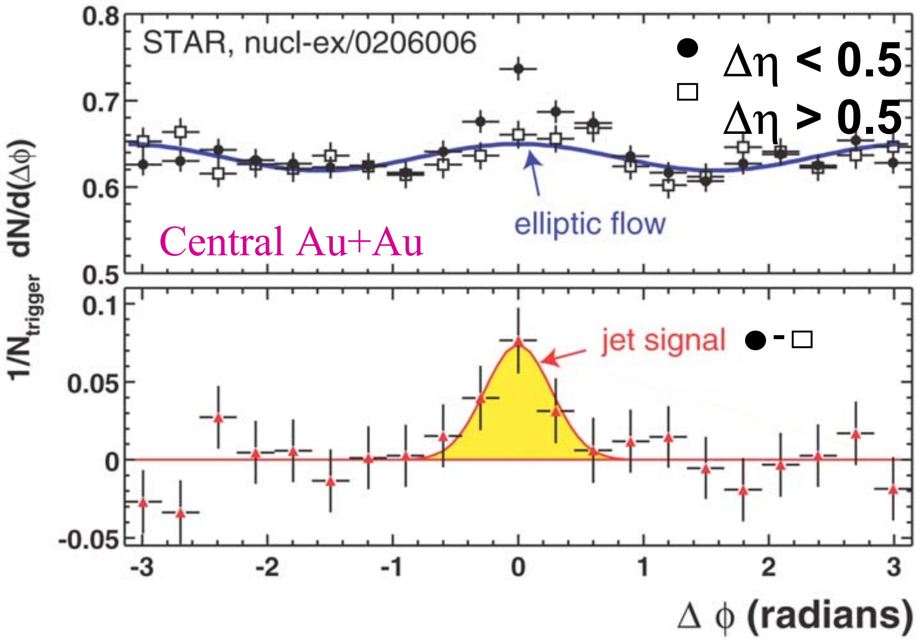
$$C_2(\Delta\phi) = \frac{1}{N_{trigger}} \frac{1}{efficiency} \int d(\Delta\eta) N(\Delta\phi, \Delta\eta)$$

Near-side correlations II

$$C_2(\Delta\phi) = \frac{1}{N_{trigger}} \frac{1}{efficiency} \int d(\Delta\eta) N(\Delta\phi, \Delta\eta)$$

Azimuthal correlation function:

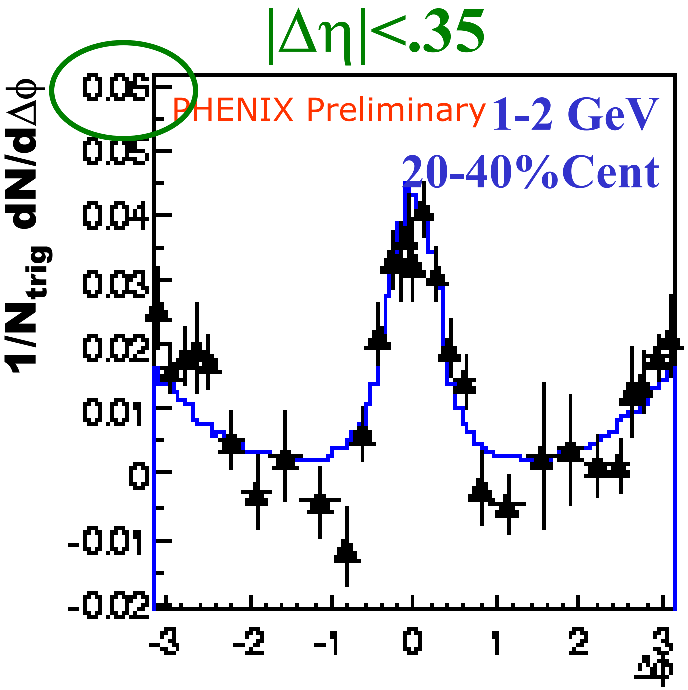
- **Trigger particle $p_T^{trig} > 4$ GeV/c**
- **Associate tracks $2 < p_T < p_T^{trig}$**

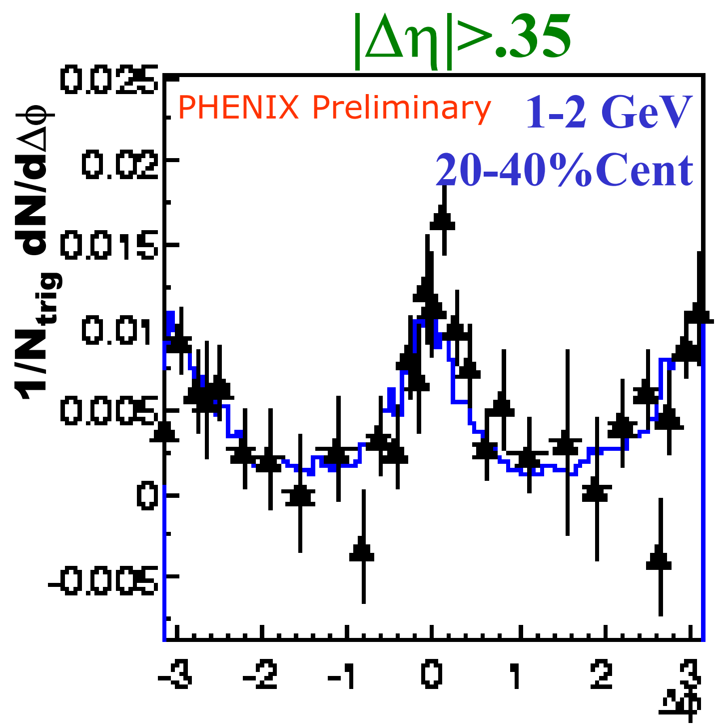


N.B. Away-side jet contribution subtracted by construction, needs different method…

Near-side correlation shows jet-like signal in central Au+Au

Near-side correlations III



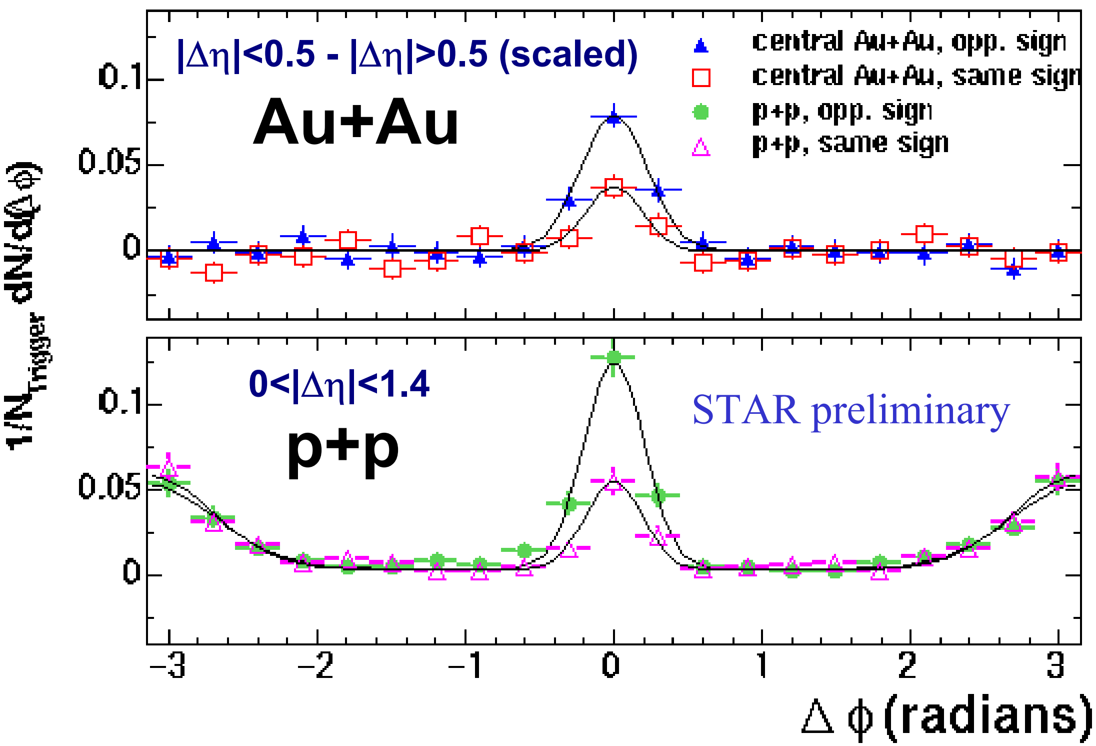


Similar effect seen by PHENIX:

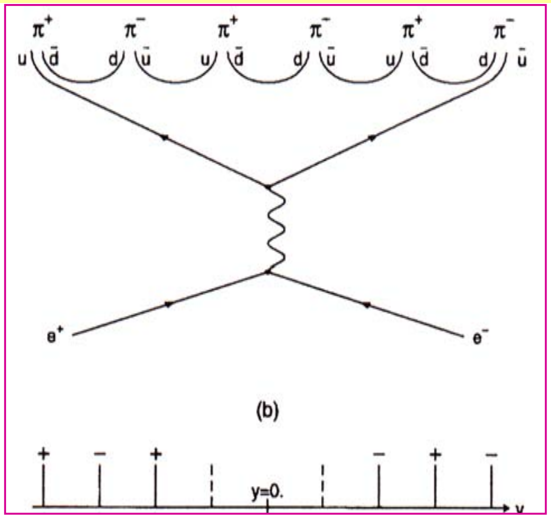
- strong near side correlation
- correlation shape in Au+Au fit by PYTHIA+elliptic flow

Reality check: charge-sign dependence

- Compare same-sign (++, --) and opposite-sign (+-) pairs
- Known jet physics: charge ordering in fragmentation



DELPHI, PL B407, 174 (1997)



System	(+-)/(++ & --)
p+p	2.7+-0.6
0-10% Au+Au	2.4+-0.6
Jetset	2.6+-0.7

Opposite/same correlation strength similar in Au+Au, p+p, JETSET
$\Rightarrow$ p_T~3-4 GeV are jet fragments

Two particle correlations at high p_T: back-to-back jets?

- away-side (back-to-back) jet can be "anywhere" ($\Delta\eta \sim 2.5$)

- p+p measured in RHIC detectors ⇒ assume correlation fn:

high p_T-triggered Au+Au event =
high p_T-triggered p+p event + elliptic flow

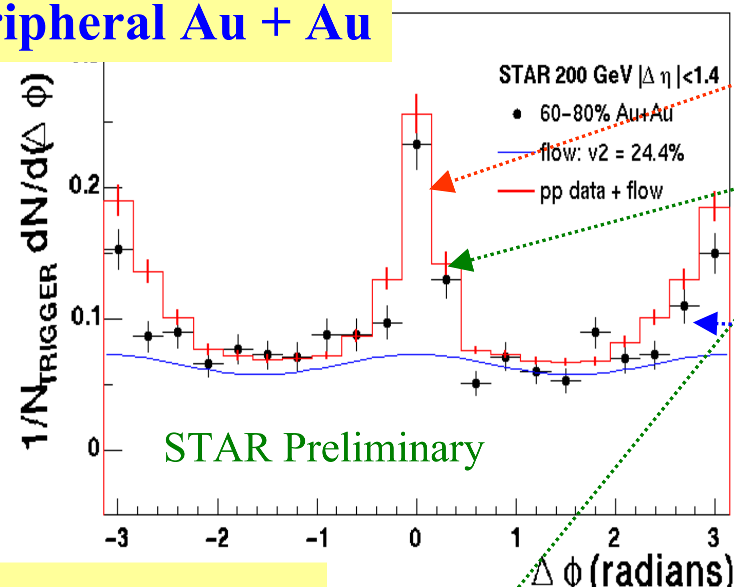
$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$

- A from fit to "non-jet" region $\Delta\phi \sim \pi/2$
- v_2 from reaction plane analysis

Suppression of back-to-back pairs

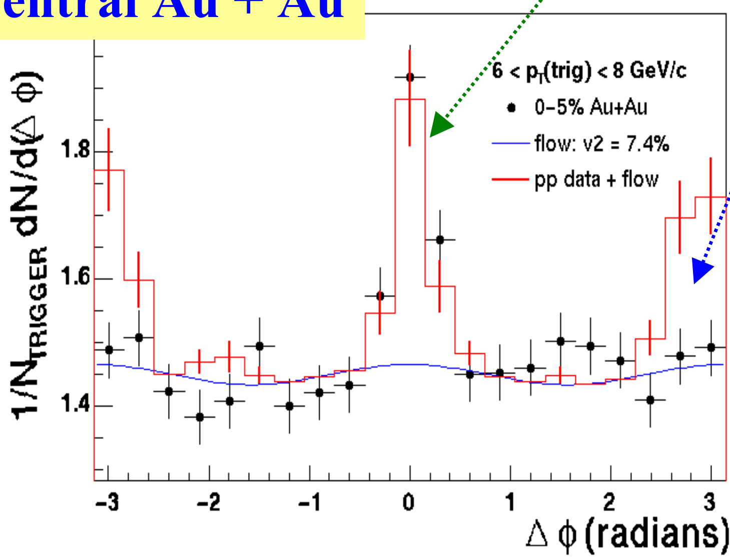
$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$

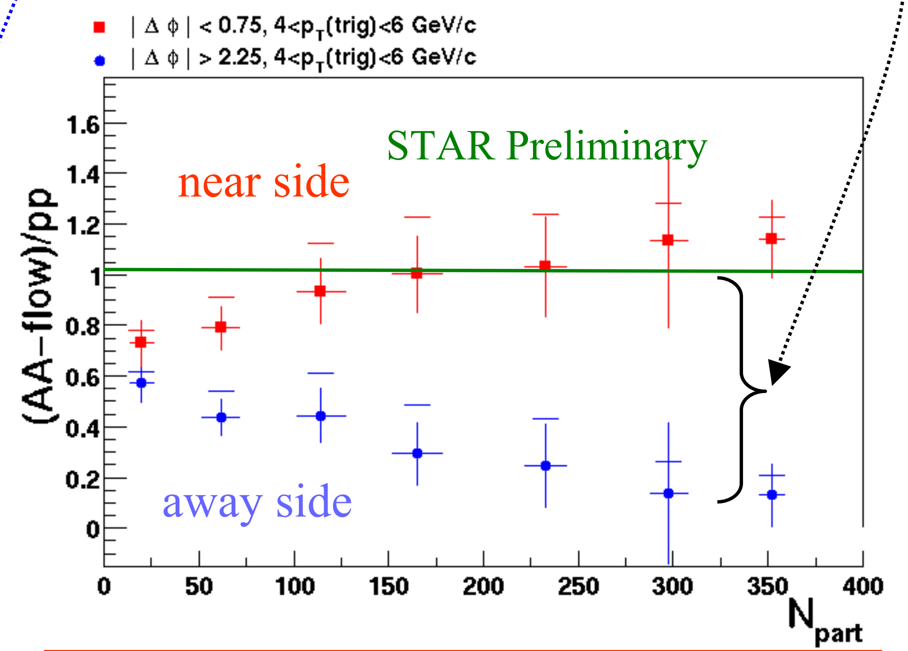
Peripheral Au + Au



- Near-side well-described
- Away-side suppression in central collisions

Central Au + Au



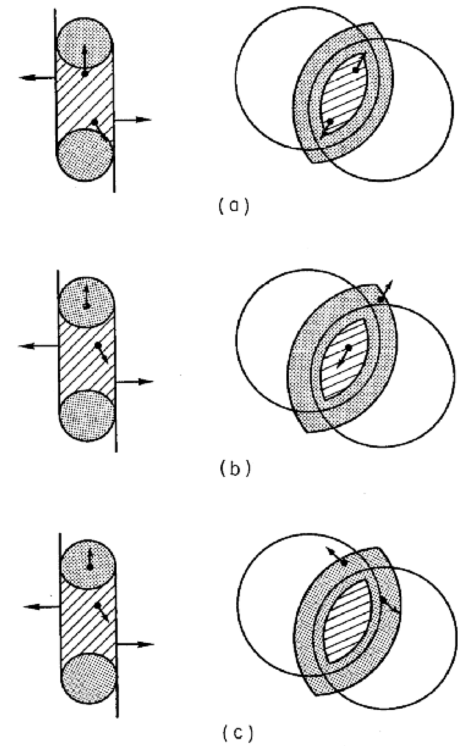


Away side jets are suppressed!

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510



produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

High p_T phenomena: suppression of inclusive rates, finite elliptic flow, suppression of back-to-back pairs
⇒compatible with extreme absorption and surface emission

Summary of Au+Au Collisions at RHIC

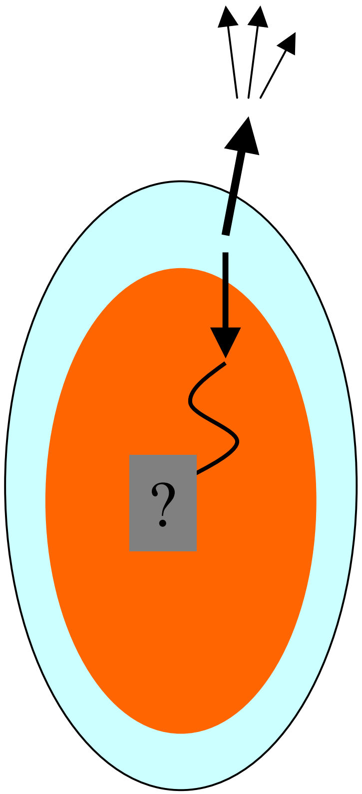
Soft physics:

- Low baryon density
- System appears to be in equilibrium (hydrodynamic behaviour)
- Explosive expansion, rapid hadronization

Hard physics:

- Jet fragmentation observed, agreement with pQCD
- Strong suppression of inclusive yields
- Azimuthal anisotropy at high p_T
- Suppression of back-to-back hadron pairs

$\Rightarrow$large parton energy loss and surface emission?



No strong suppression of open charm (PHENIX):
"dead cone" effect?

Some Coming Attractions

Heavy ions in coming runs:

- d+Au: disentangle initial state effects in jet production (shadowing, Cronin enhancement) $\Rightarrow$ resolution of jet quenching picture
- J/ψ and open charm: direct signature of deconfinement?
  (Charm via single electrons: PHENIX, PRL 88, 192303 (2002))

Heavy ions with detector upgrades:

- Low mass dilepton pairs: chiral symmetry restoration

Polarized protons:

- ΔG (gluon contribution to proton spin)

…Surprises

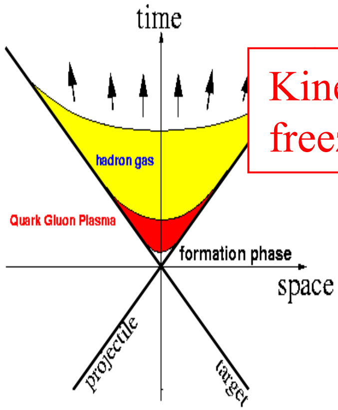
Extra slides…

Order of the Deconfinement Phase Transition

- Only partially understood:
  - Three massless flavours: first order
  - Two massless flavours: second order
  - Two light and one heavy: probably second order
  - μ_B=0, physical strange quark mass: rapid cross over?

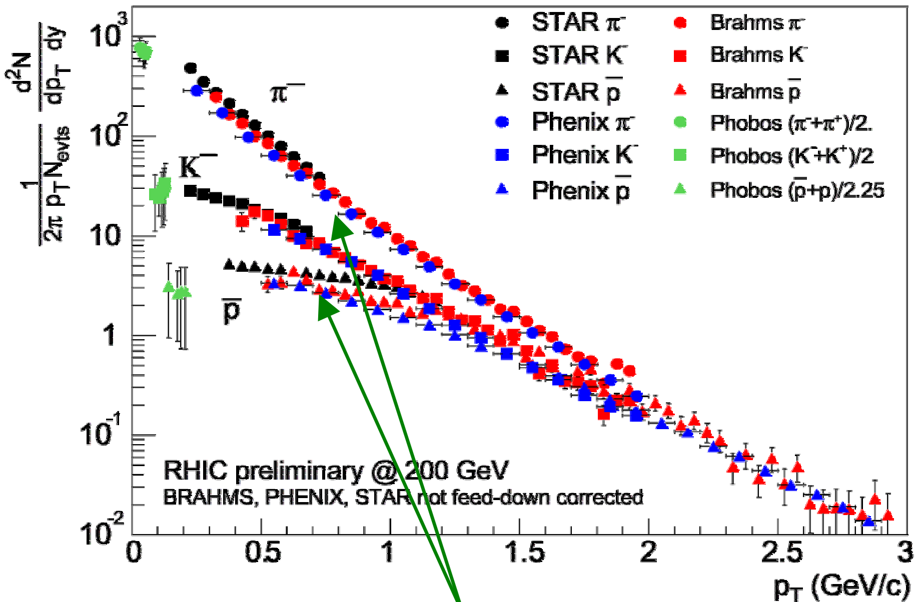
- So what? Early universe (t~10^{-5} sec): strong first order transition may have generated:
  - primordial black holes
  - strange quark nuggets
  - baryon asymmetries ⇒ implications for nucleosynthesis

Kinetic equilibrium?



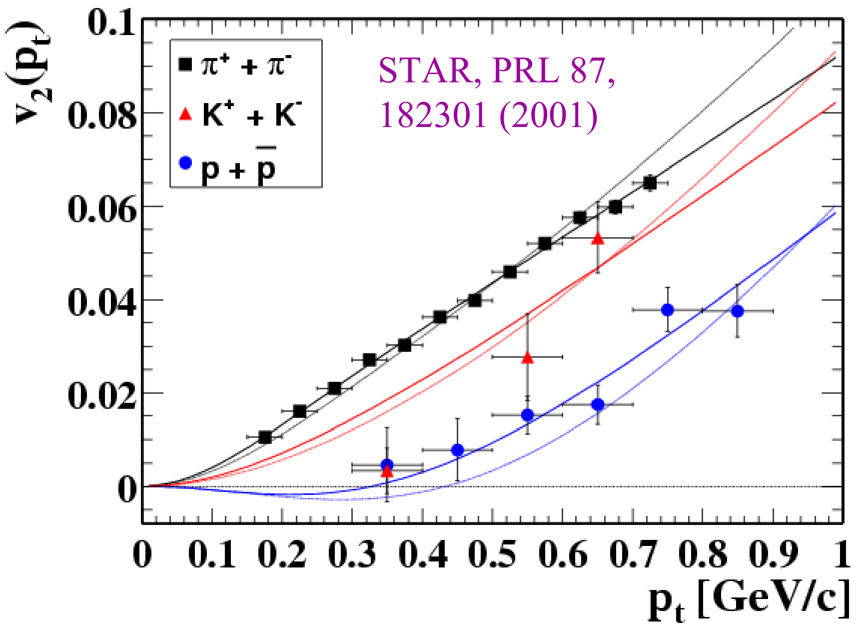
Kinetic freezeout

T. Ullrich and F. Laue



Mass dependence of p_T spectra

- much different than p+p
- common radial velocity profile ⇒ equilibrium

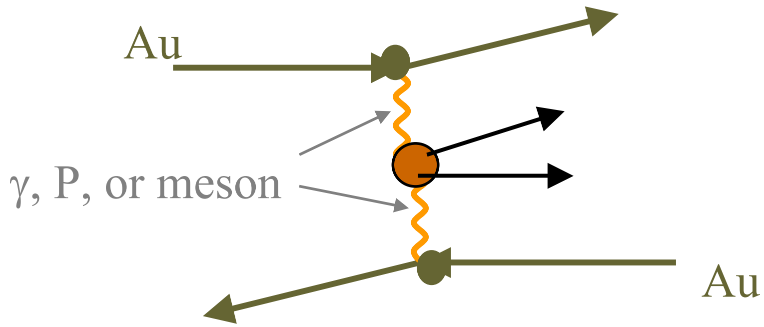


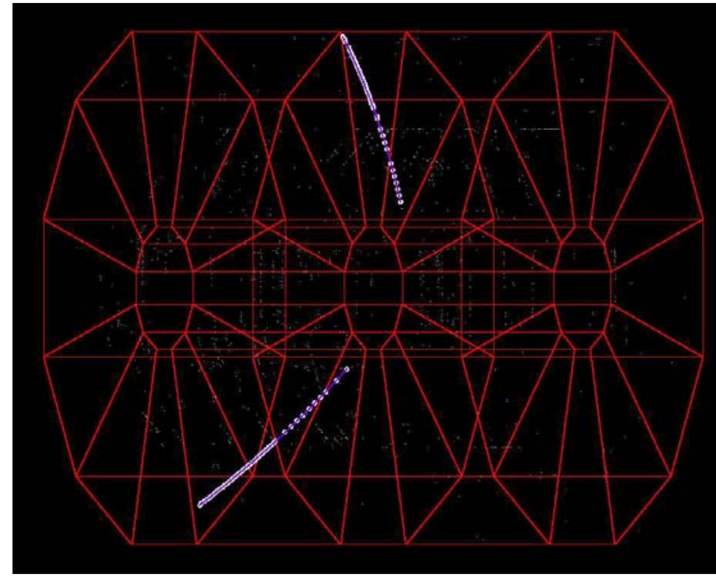
Mass dependence of elliptic flow described by hydrodynamics ⇒ kinetic equilibrium at early time

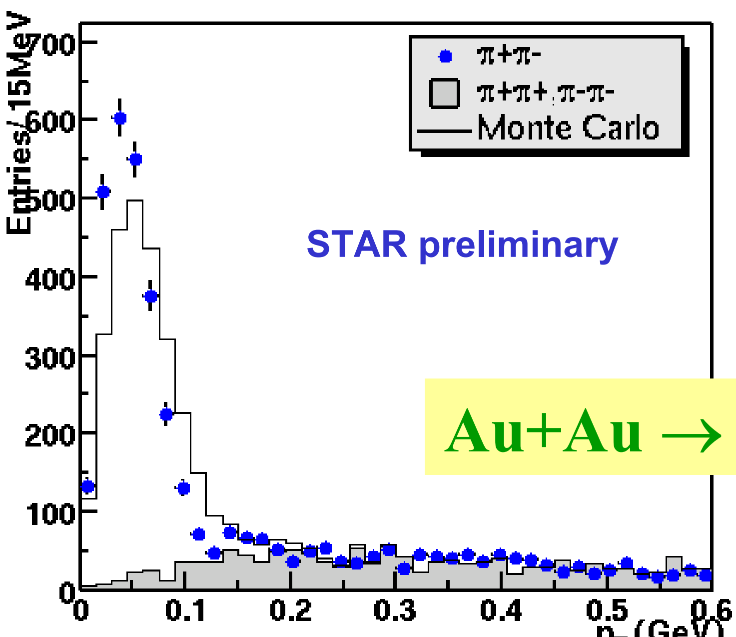
p_T<2 GeV/c: strong evidence for kinetic equilibrium

Digression: ultra-peripheral collisions

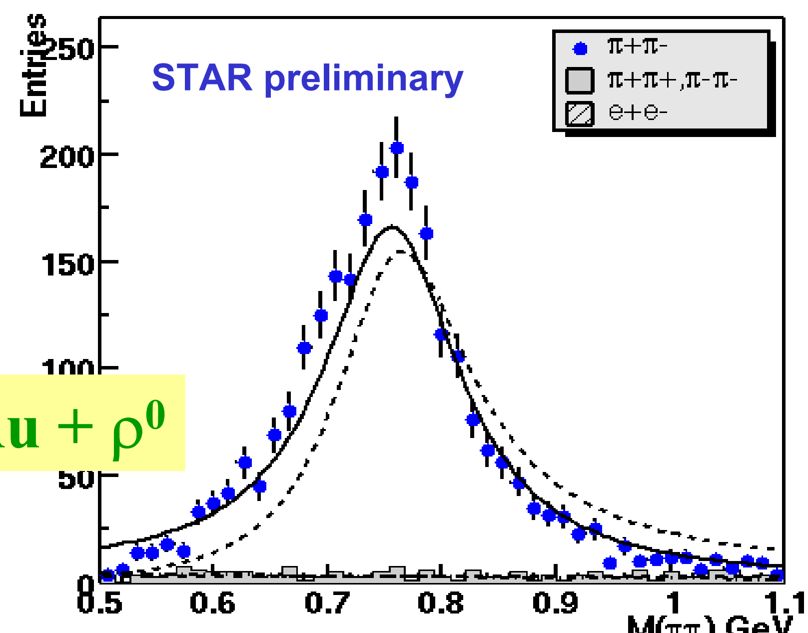
- γγ, γ-Pomeron interactions
- Signature: back-to-back opposite charges







Au+Au → Au+Au + ρ^0

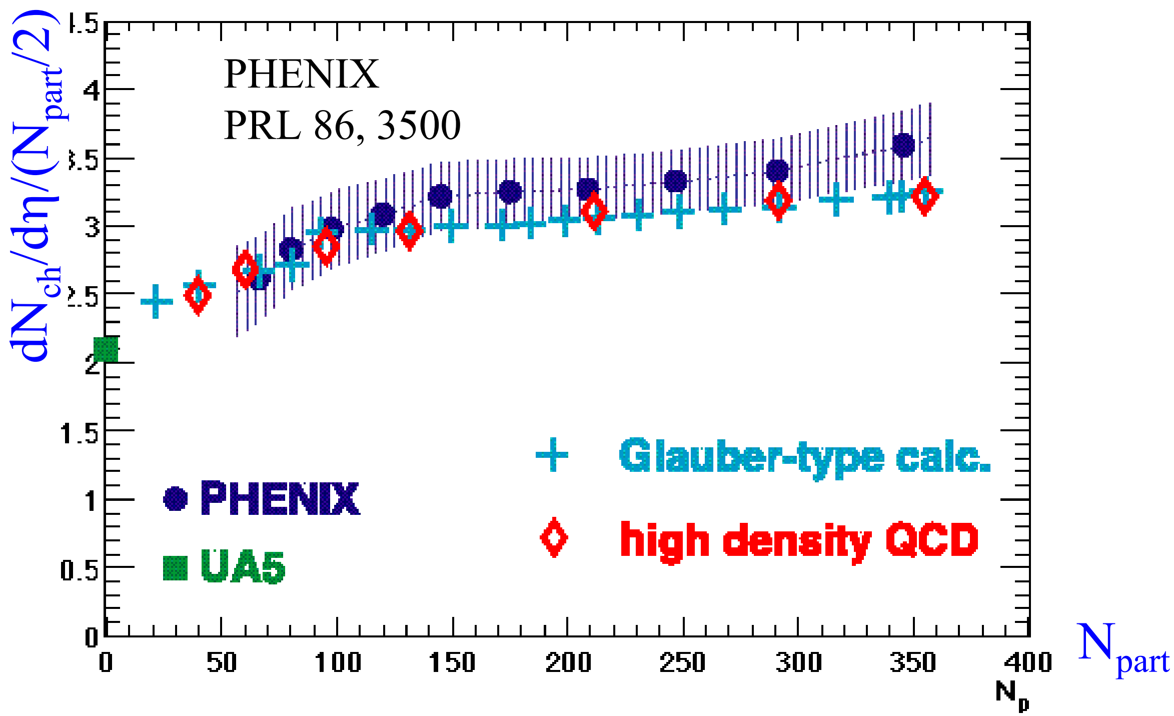


Gluon saturation in A+A?

- High density QCD: $\frac{dN}{d\eta} = cN_{part}xG(x,Q_s^2);Q_s^2 \sim A^{1/3}$

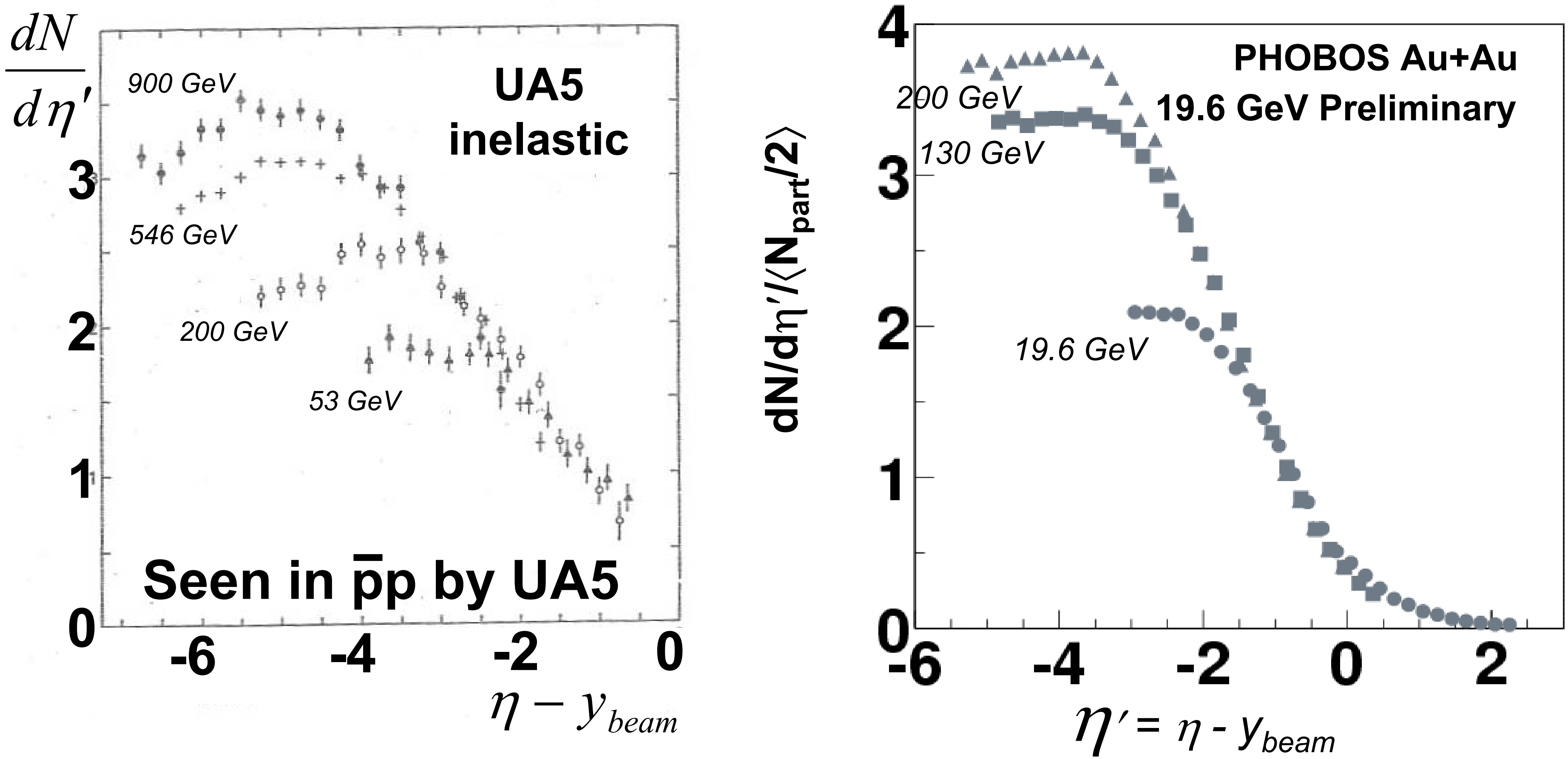
Kharzeev and Nardi,
Phys.Lett. B507 121 (2001)

- vary impact parameter ⇒ vary Q_s^2 ⇒ visible in total multiplicity?



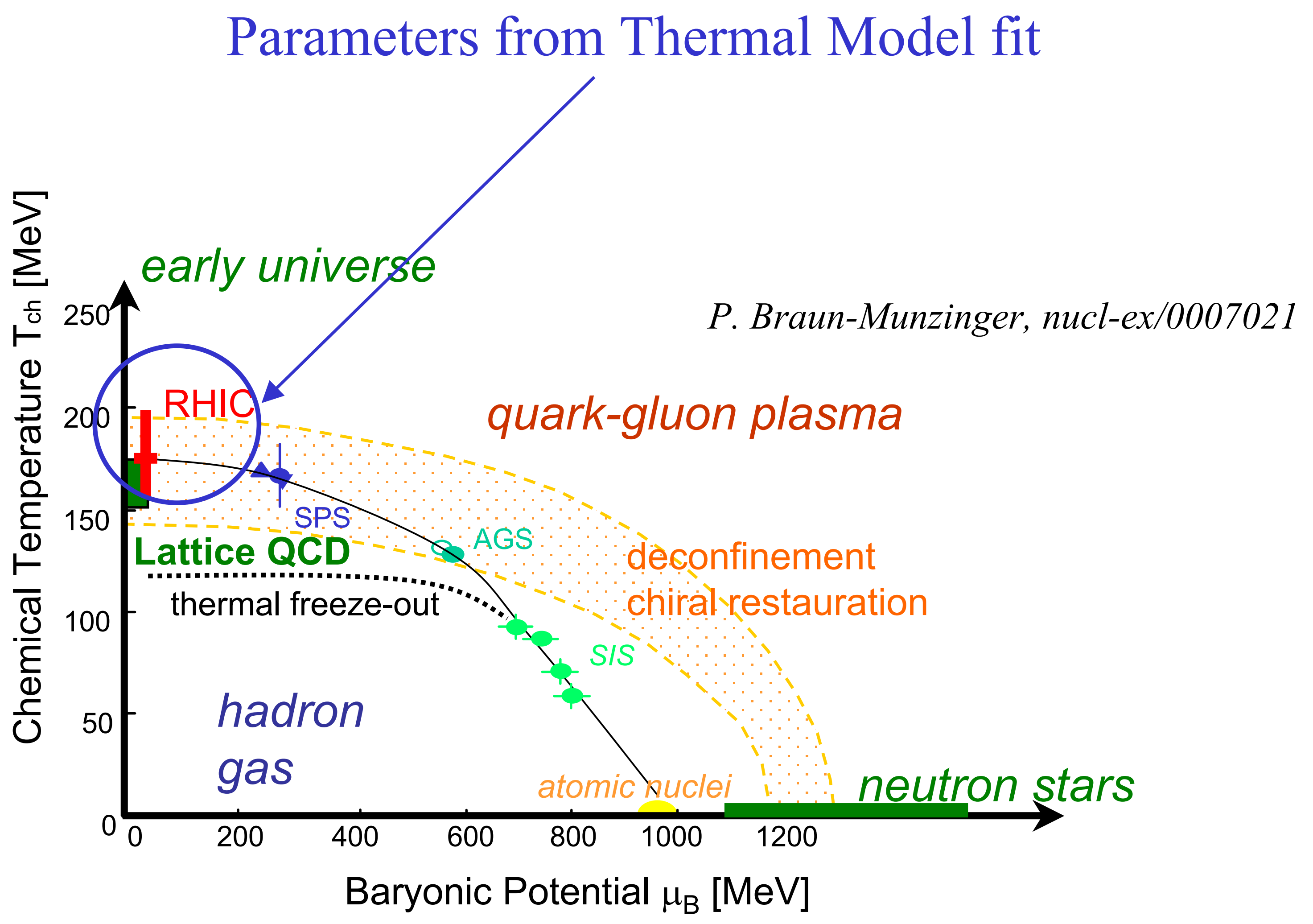
Data agree with both simple Glauber (hard/soft eikonal calculation) and high density QCD ⇒ no clear evidence for/against saturation

Forward rapidity: limiting fragmentation



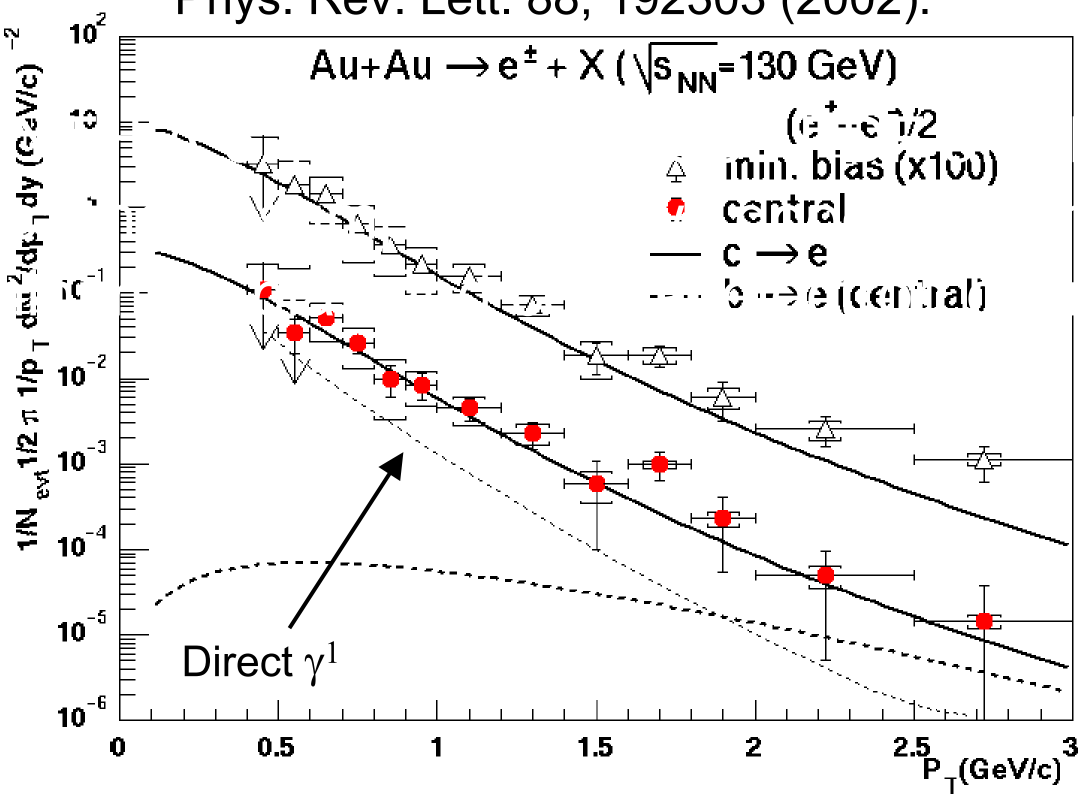
Limiting fragmentation at high rapidity: common features in all hadronic interactions (and $e^+e^- \rightarrow$ jets)

Phase Diagram at Chemical Freezeout



PHENIX: Charm in Au+Au via single electrons

Phys. Rev. Lett. 88, 192303 (2002).



PYTHIA 6.152 with CTEQ5L PDF and binary collision scaling assumption shows good agreement with minimum bias and central electron distributions.