The Physics of RHIC

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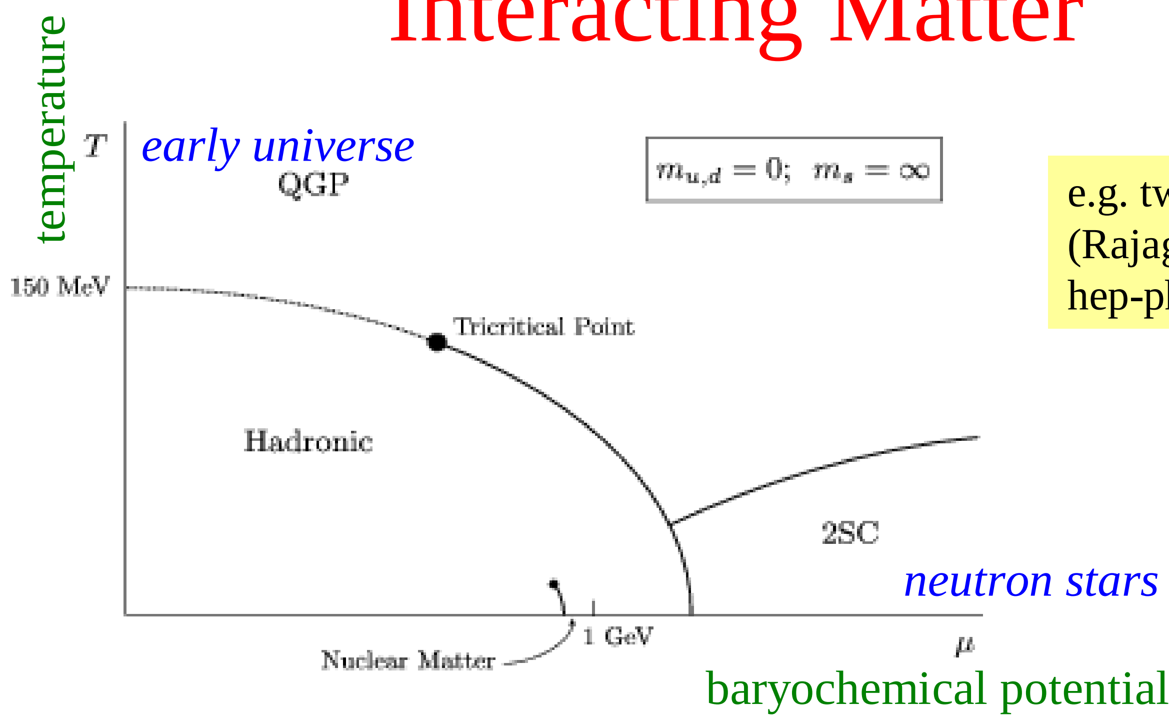
- Why collide nuclei at high energy?
- RHIC: machine and experiments
- Physics from the first year of RHIC
- Outlook

Schematic Phase Diagram of Strongly Interacting Matter



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

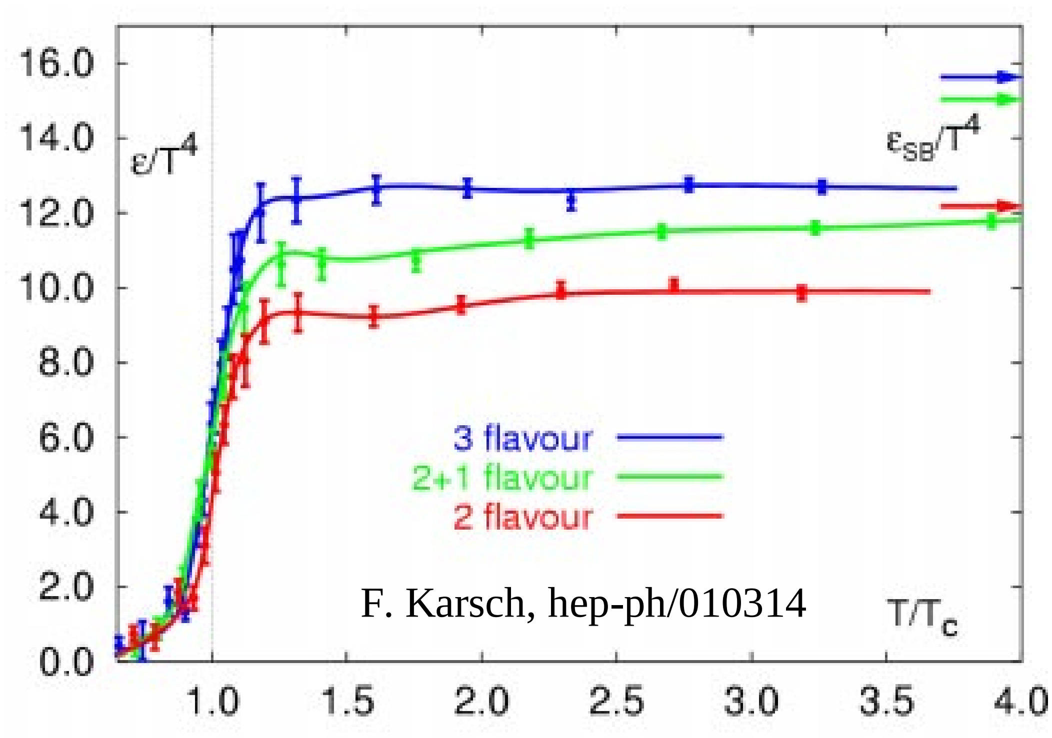
- $T \gg \Lambda_{QCD}$: weak coupling ⇒ deconfined phase (Quark Gluon Plasma)
- $T < \Lambda_{QCD}$: strong coupling ⇒ confinement

⇒phase transition at $T \sim \Lambda_{QCD}$?

- Similar arguments for squeezing cold matter (increasing μ_B)

Lattice QCD at Finite Temperature

- Coincident transitions: deconfinement and chiral symmetry restoration
- Currently only for μ_B=0 (but some recent developments…)



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

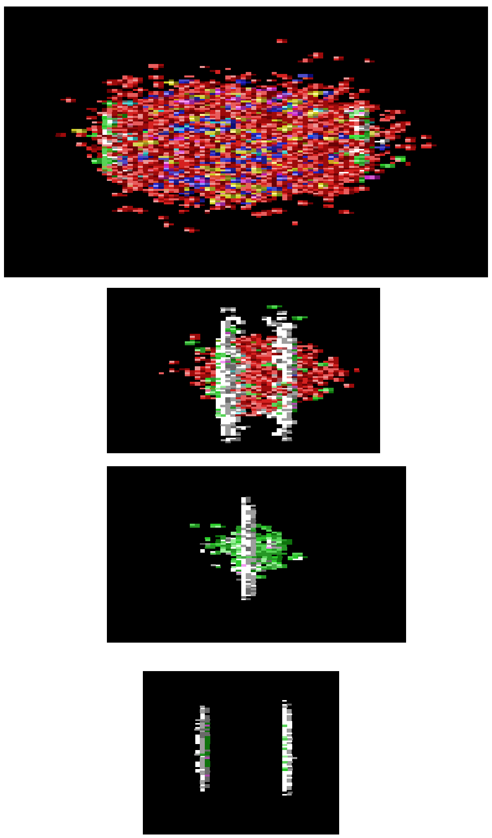
Order of the Phase Transition

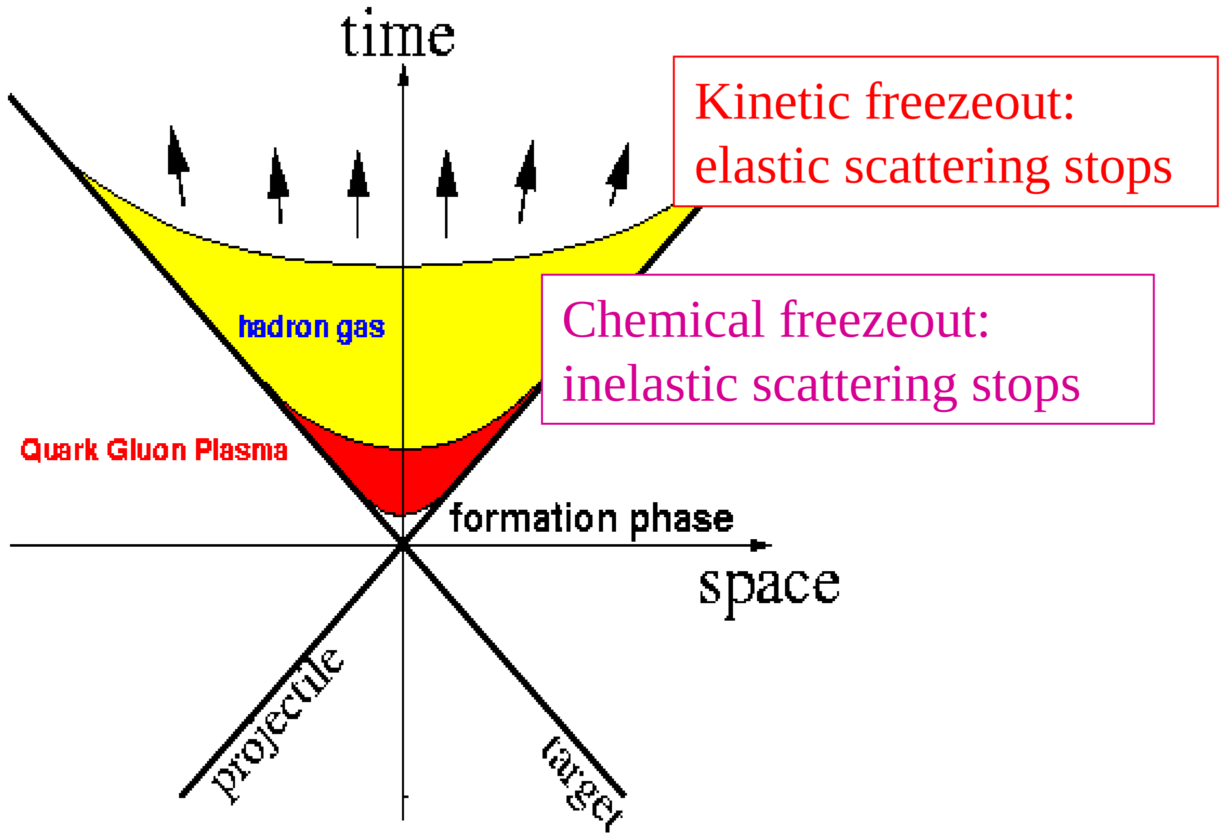
- Only partially understood:
  - Three massless flavours: first order
  - Two massless flavours: second order
  - Two light and one heavy: probably second order
  - μ_B=0, physical strange quark mass: rapid cross over?

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

Can we study the QCD Phase Diagram in the Laboratory?

Space-time Evolution of Heavy Ion Collisions





Observables of the QGP in Nuclear Collisions

- Nuclear collisions are highly dynamic, no first-principles theory
- Some tools to distinguish deconfined QGP from dense hadron gas:
  - Direct observation of deconfinement: suppression of J/ψ
  - High energy density: interaction of jets with medium
  - High temperature: direct photons
  - Non-hadronic degrees of freedom: charge fluctuations
  - Quasi-equilibrium at early stage: flow
  - Rapid equilibration, mass shifts: strangeness enhancement
  - Threshold behaviour: must be able to turn effects off

    ⇒ $\sqrt{s}$, centrality of collision, mass of system

Smoking gun? More likely scenario: QGP is most reasonable picture from many different observables simultaneously

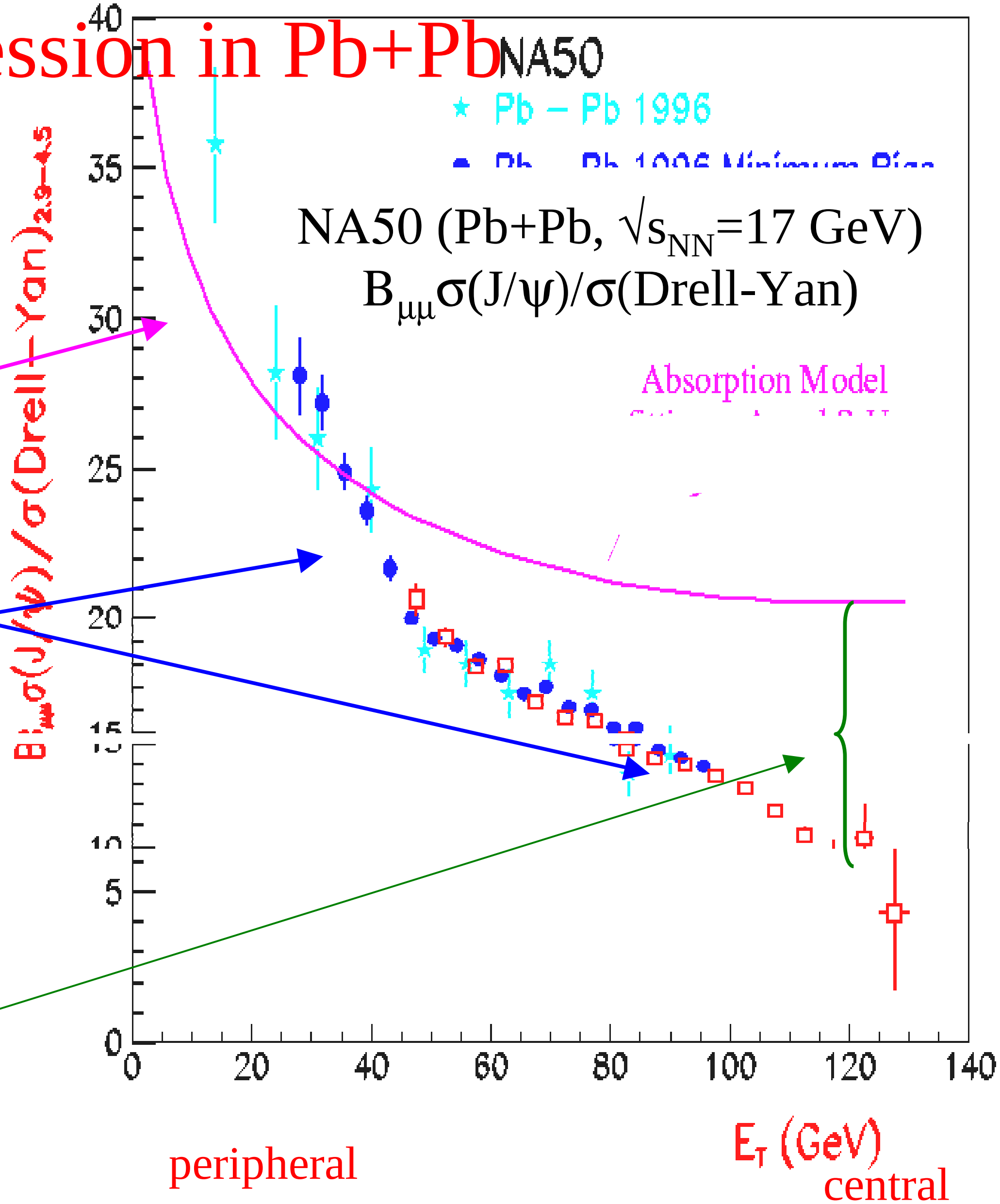
Digression to the SPS fixed target: Charmonium Suppression in Pb+Pb

Matsui and Satz ’86: color Debye screening in plasma prevents formation of c-cbar resonances

Absorption in cold nuclear matter

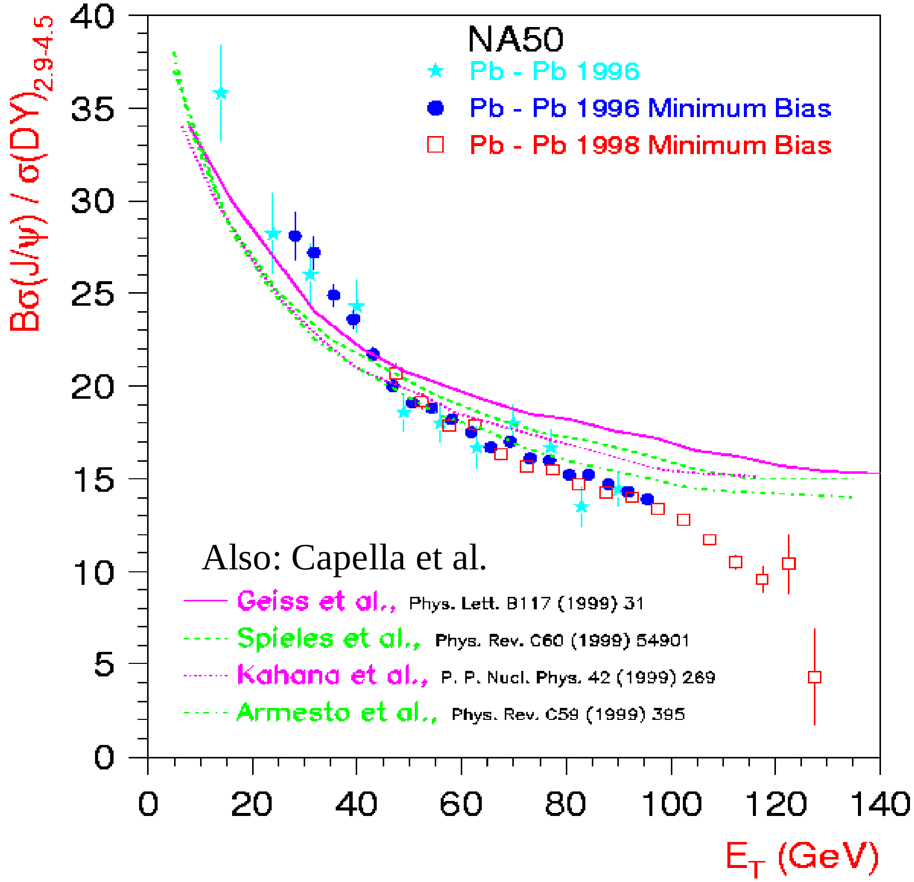
changes in slope: energy density threshold? ⇒successive melting of ψ‘, χ_c, J/ψ

Anomalous absorption for central collisions (high energy density)

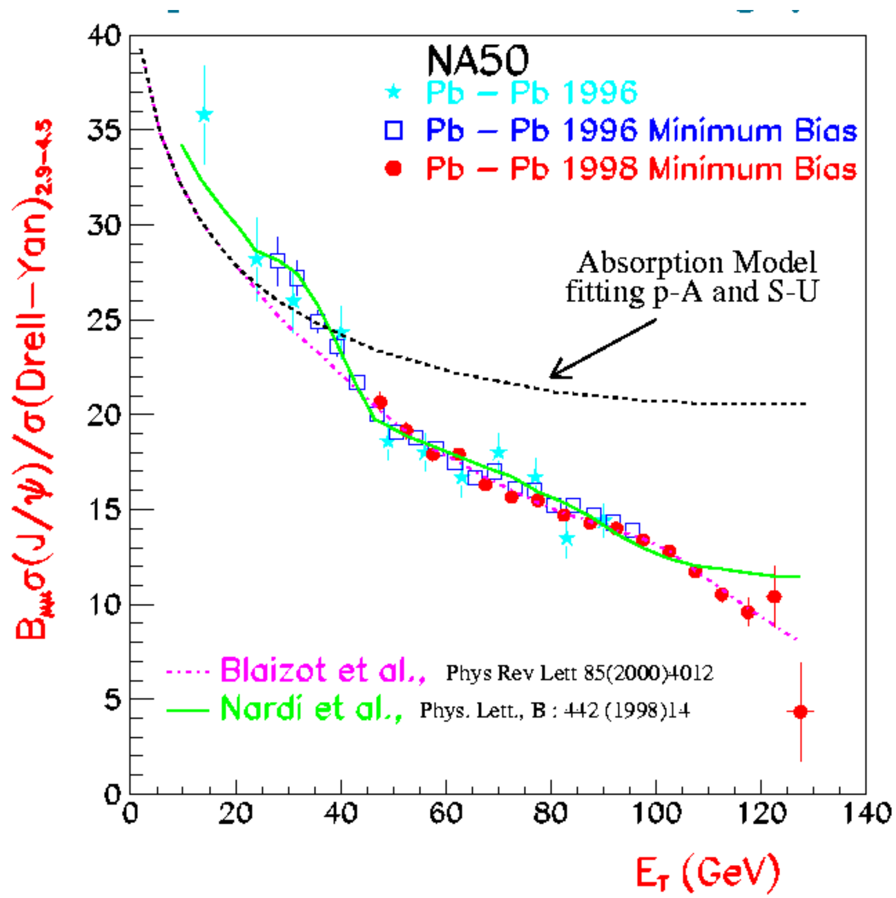


Charmonium Suppression: compare to models

Hadronic models: cold nuclear + "comover" dissociation



QGP models: energy density thresholds + E_T fluctuations



⇒"thresholds" and high E_T behavior favour QGP models

Summary of Pb+Pb Collisions at the SPS

- hadron thermodynamics:
  - Baryon-rich system at y~0
  - high initial energy density ($\varepsilon \sim 3$ GeV/fm^3 ?)
  - early equilibration ?
- low mass enhancement of di-electrons: chiral symmetry restoration?
- direct photons beyond hadronic sources: radiation from plasma?

- multistrange baryon enhancement
- charmonium suppression

} difficult to explain by dense hadronic gas

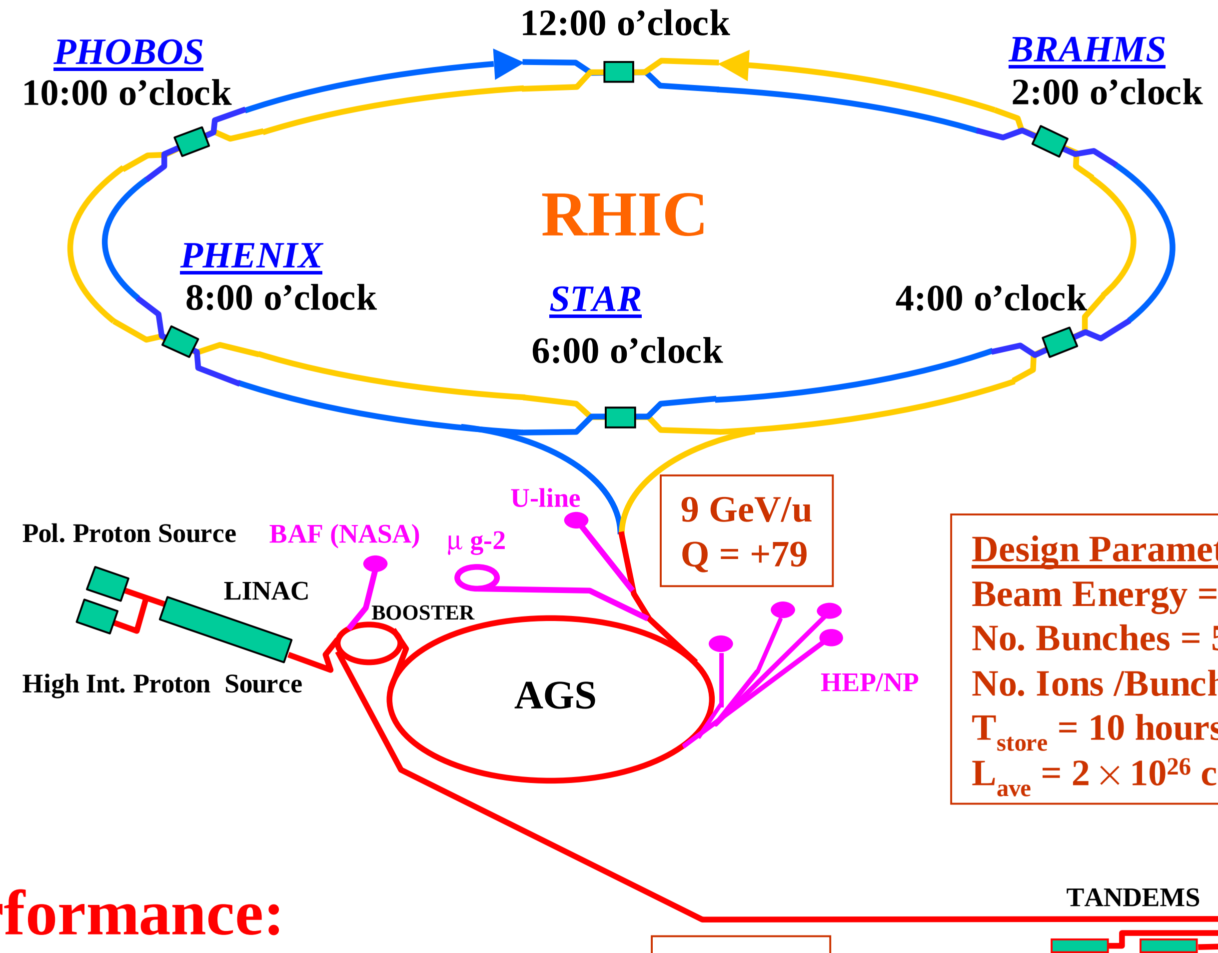
Evidence for deconfinement at the SPS is suggestive but not definitive:
- theoretical ambiguities: dense hadron gas vs QGP effects
- if deconfinement indeed seen at top SPS energy, how to turn it off? (⇒lower energy running)

The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

- Dedicated collider for heavy ion physics:
  - Au+Au up to $\sqrt{s_{NN}}$ =200 GeV (SPS: $\sqrt{s_{NN}}$ = 17-20 GeV)
  - (polarized) p+p up to $\sqrt{s}$ = 450 GeV
- great flexibility in beams and energies: extensive reference data
- What is new relative to fixed target experiments?
  - higher initial energy density $\Rightarrow$ longer-lived hot phase
  - (much) lower baryon density
  - new physics channels: jets, B-production,…
  - much higher statistics: more detailed studies

- First physics run June-Aug ’00: Au+Au at $\sqrt{s_{NN}}$ =130 GeV

Gold Ion Collisions in RHIC



Design Parameters:
Beam Energy = 100 GeV/u
No. Bunches = 57
No. Ions /Bunch = 1×10^9
T_{store} = 10 hours
$L_{ave} = 2 \times 10^{26}$ cm^{-2} sec^{-1}

Year 1 Performance:

- $\gamma = 70 \Rightarrow \sqrt{s_{NN}} = 130$ GeV
- $L = 2 \times 10^{25}$ cm^{-2} s^{-1}
- Integrated L ~ few μb^{-1}

Oct. '01: 2x10^{26} (design) achieved

The Two Large Detectors

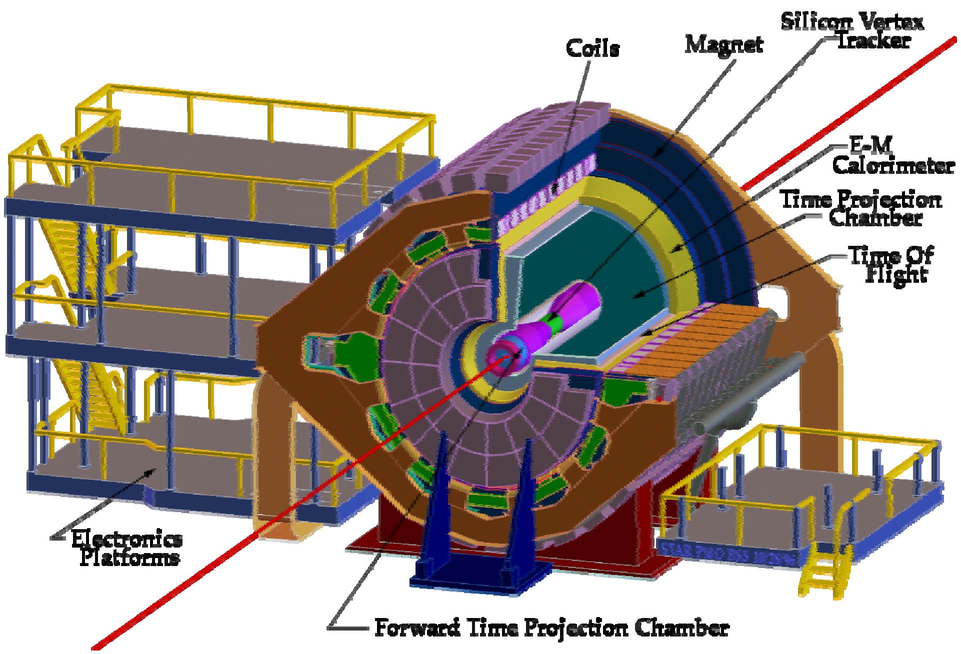
STAR

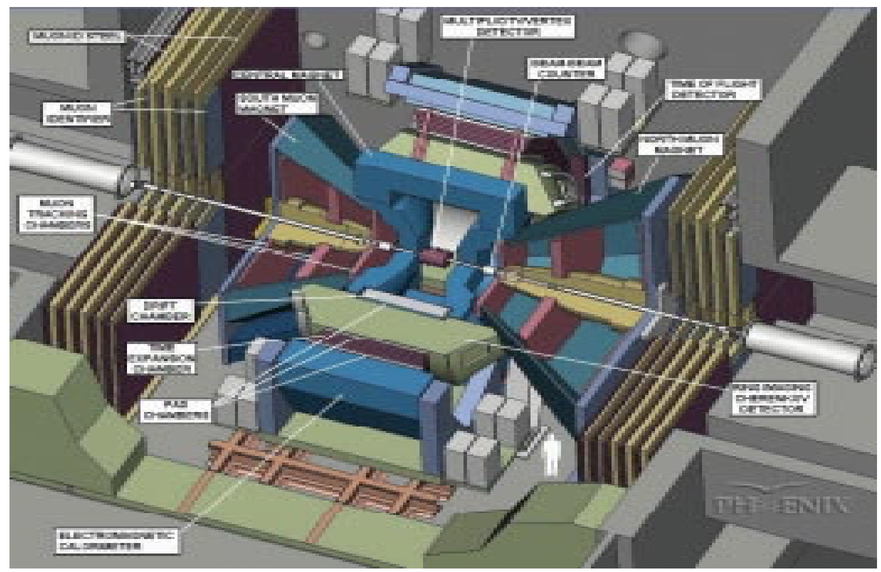
Solenoidal field, large-Ω tracking
TPC's, Si-vertex tracking
RICH, TOF, large EM Cal
~420 participants

PHENIX

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

Coils Magnet





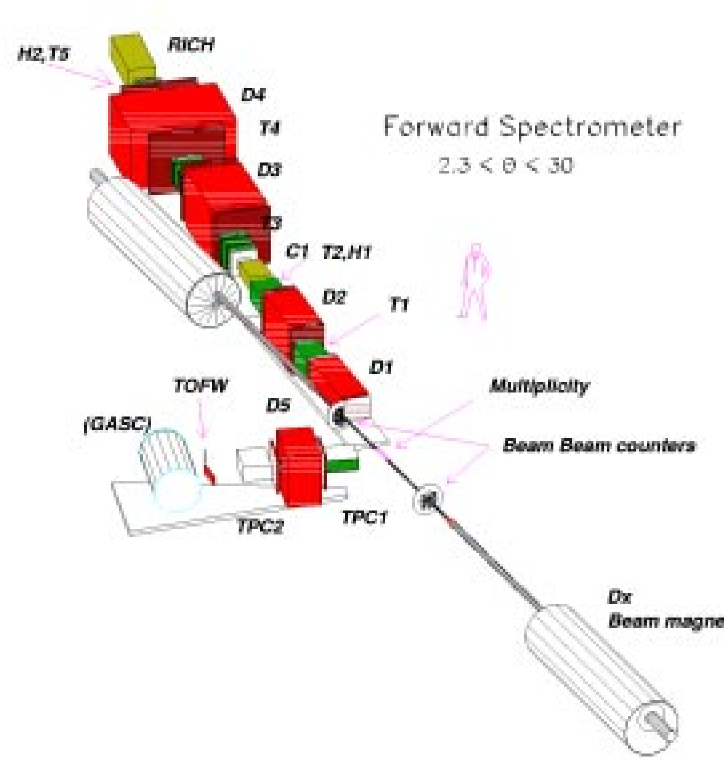
The Two Small Detectors

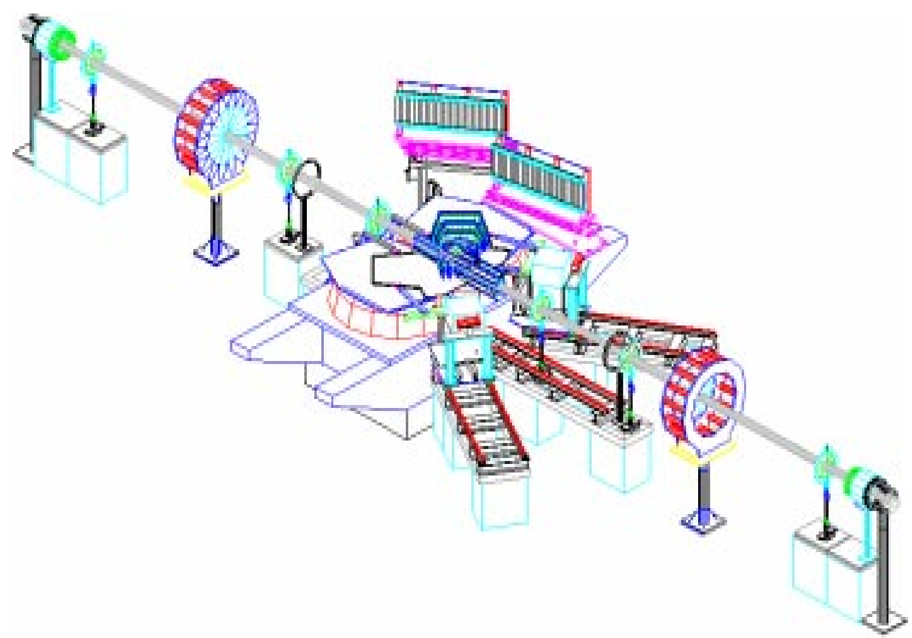
BRAHMS

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

PHOBOS

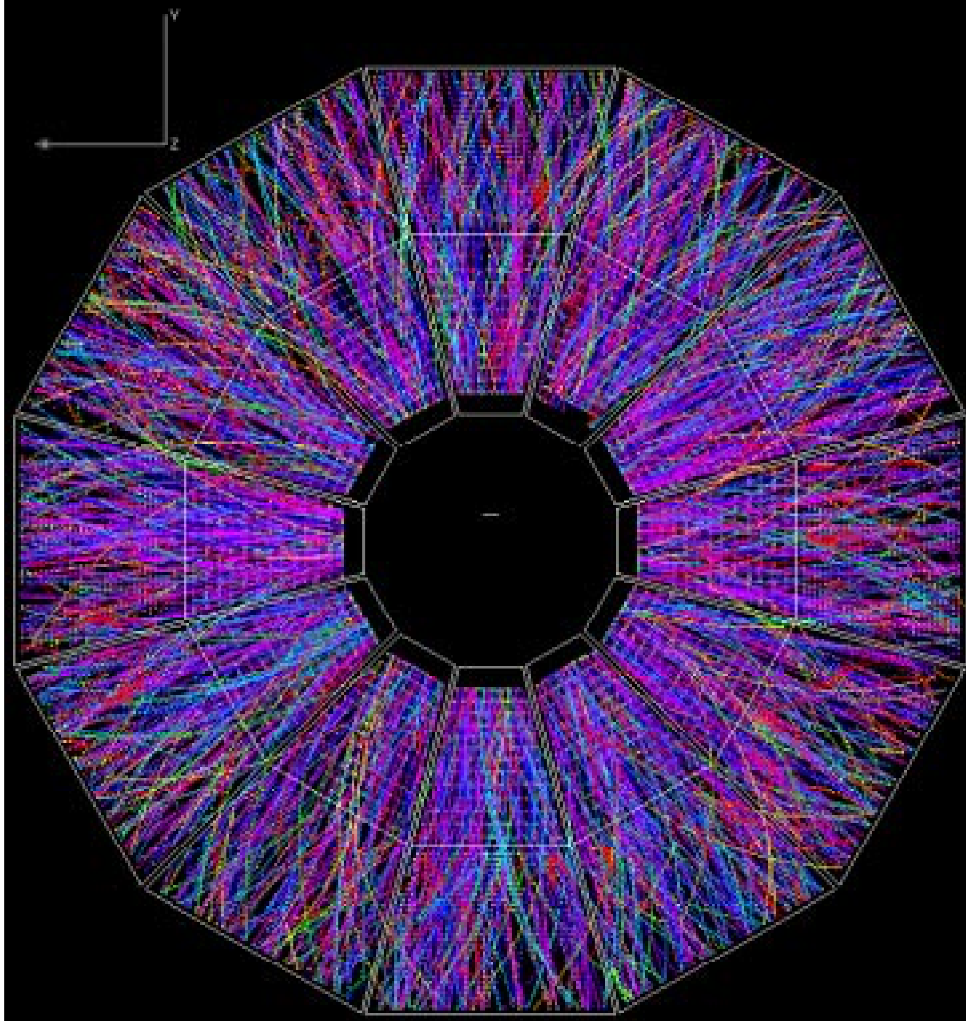
“Table-top” 2-arm spectrometer
full phase space multiplicity measurement
Magnet, Si μ-strips, Si multiplicity rings, TOF
~80 participants



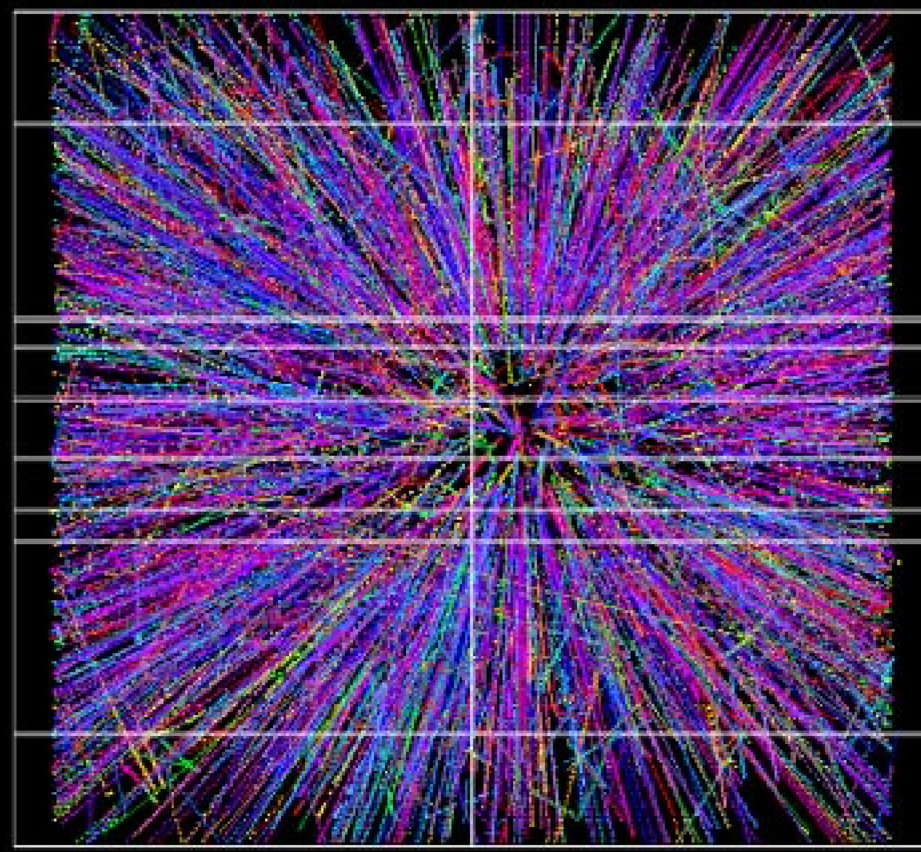


STAR

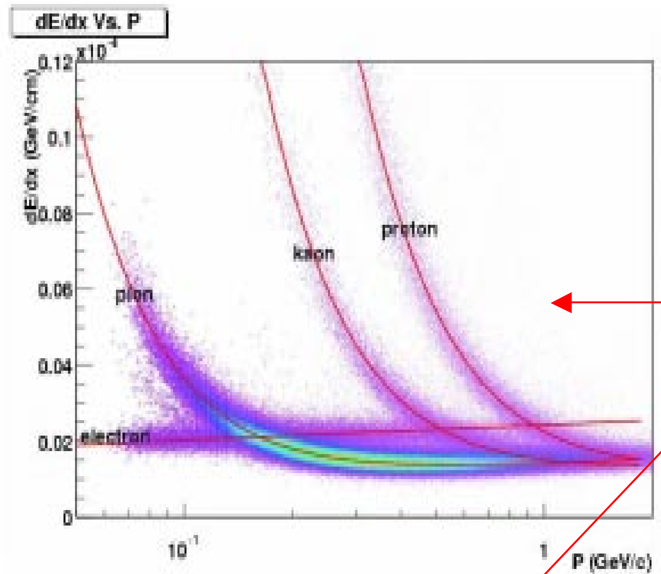
High Multiplicity Au+Au Collision at $\sqrt{s_{NN}}$=130 GeV



colors ~ momentum: low - - - high

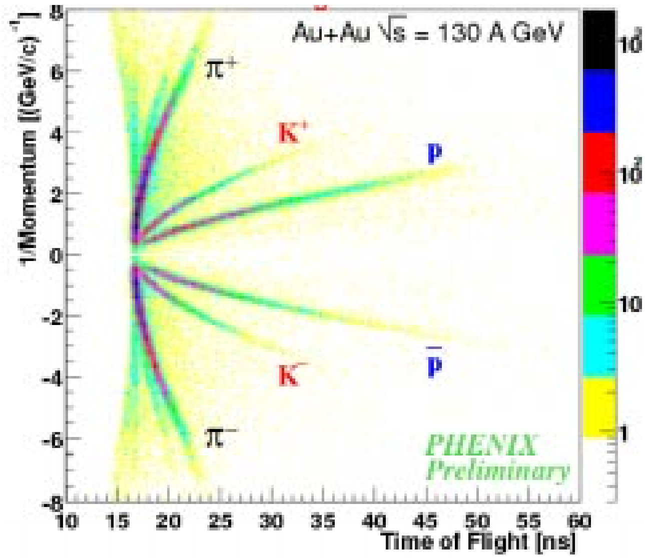


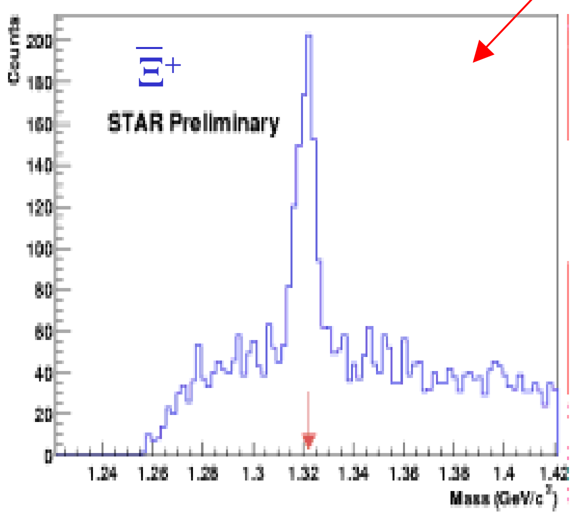
Particle Identification in Heavy Ion Events



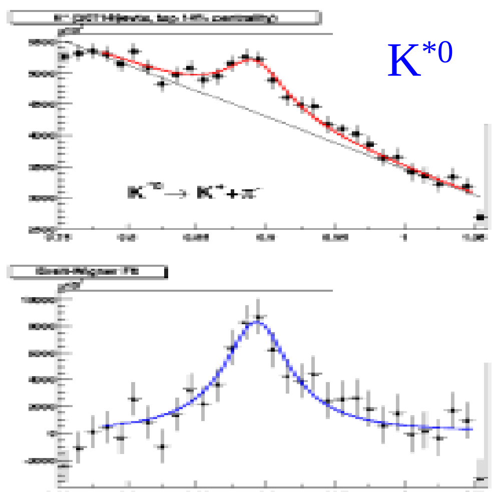
STAR TPC

PHENIX TOF

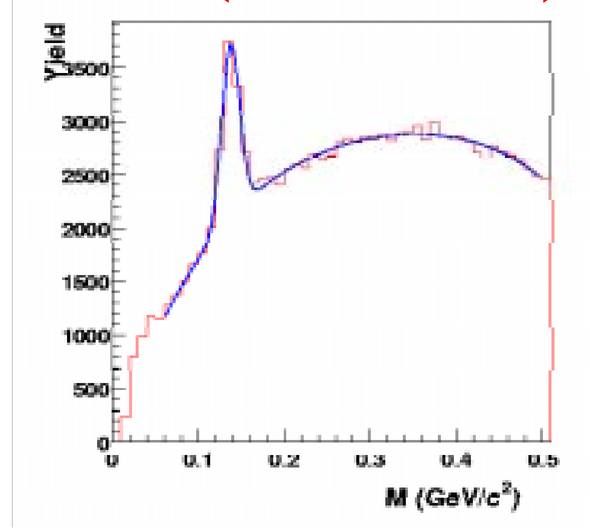




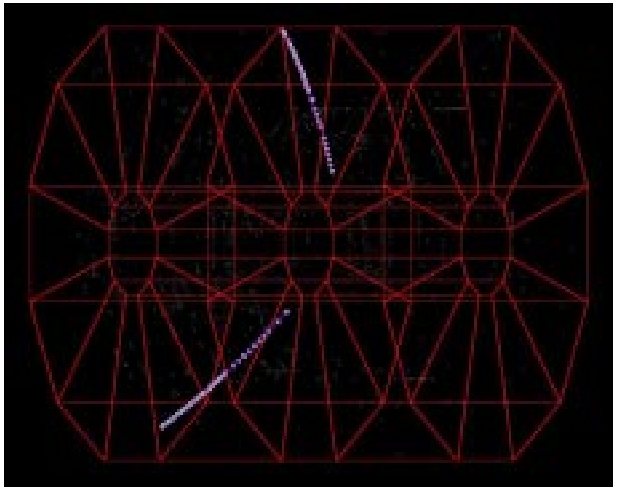
K^{*0}



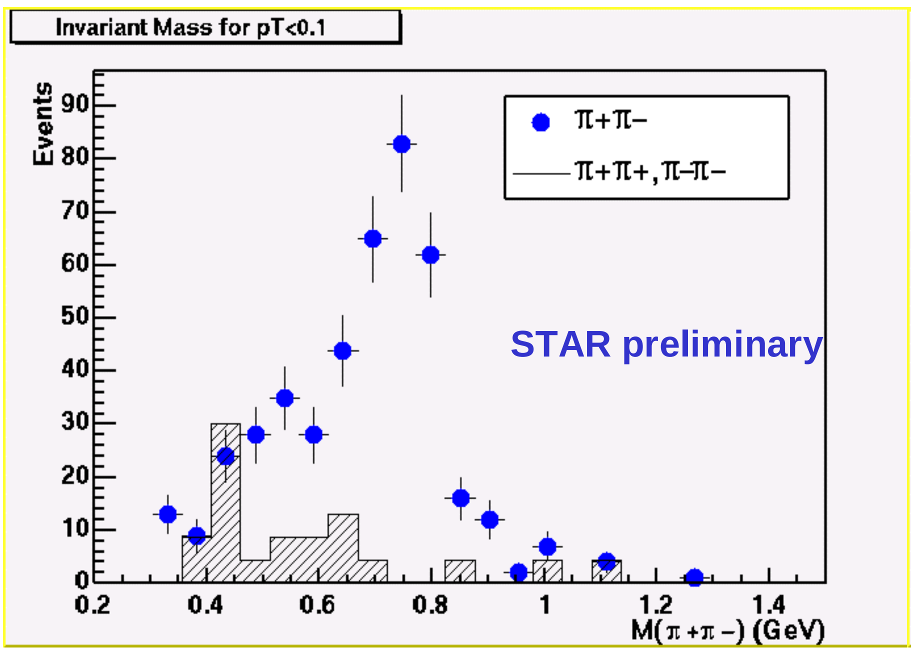
π^0 (PHENIX EMC)

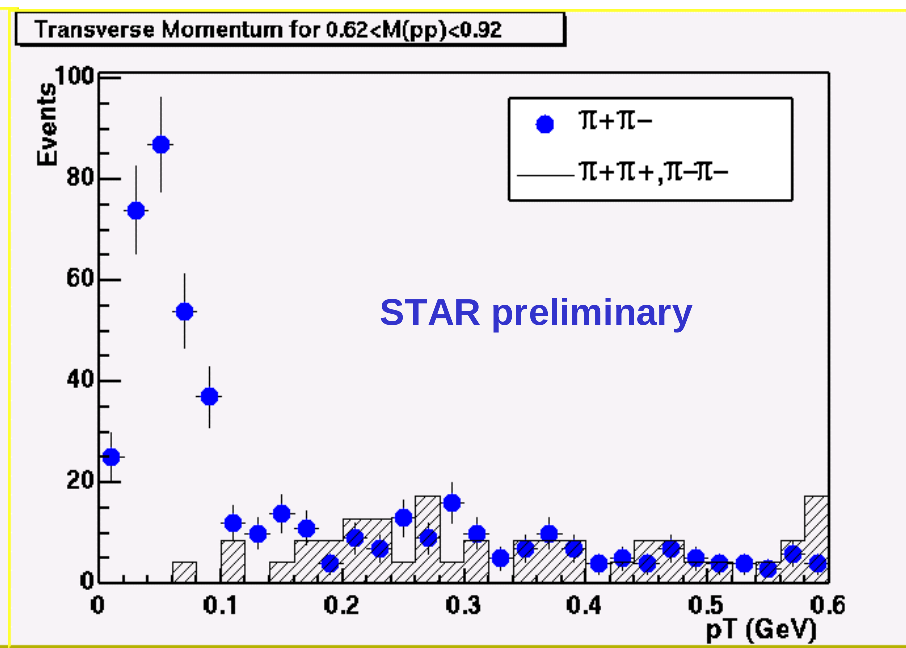


Digression: ultra-peripheral collisions



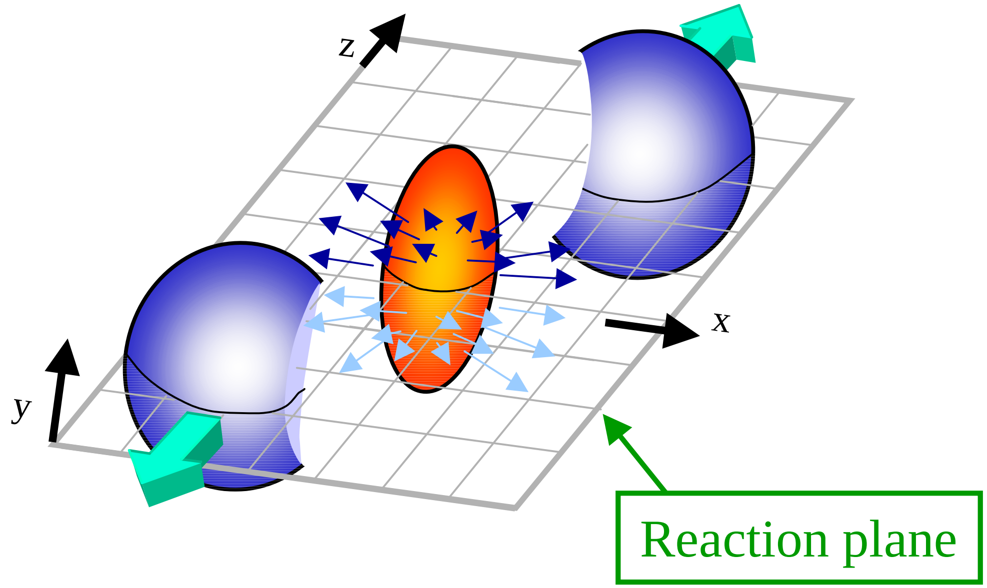
- $\gamma\gamma$, γ-Pomeron interactions
- Signature: back-to-back opposite charges
- Au+Au $\rightarrow$ Au+Au + ρ^0



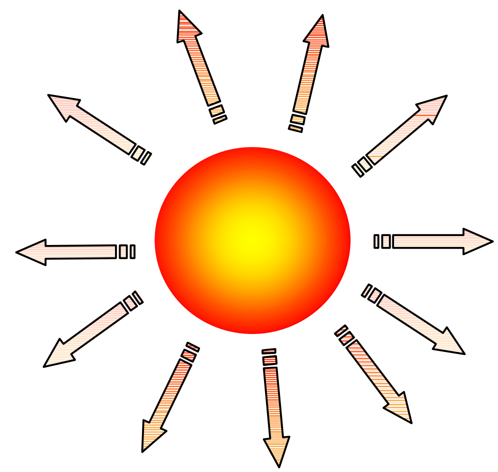


Geometry of Heavy Ion Collisions

Non-central Collisions

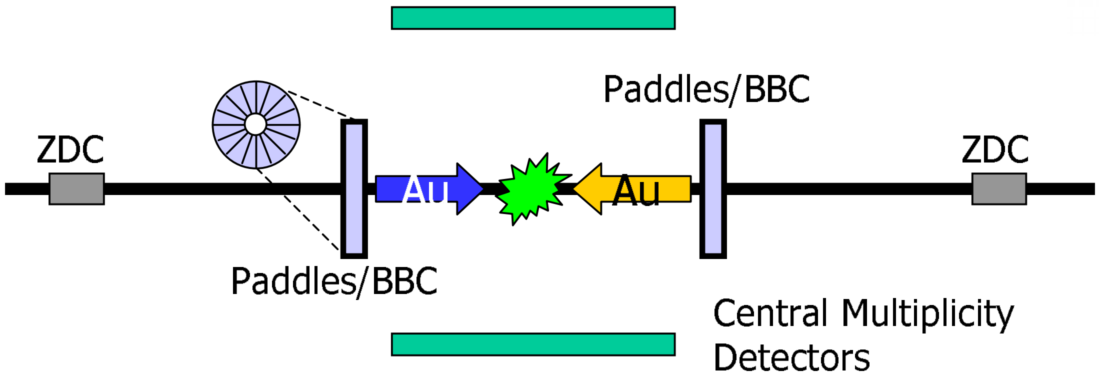


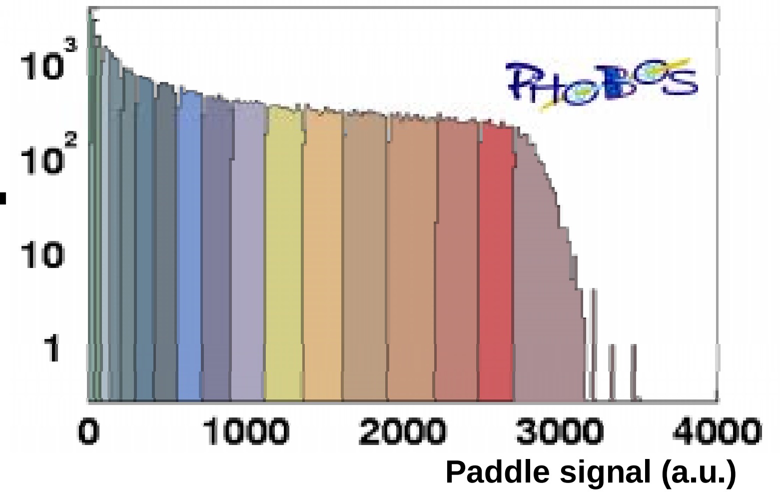
Central Collisions

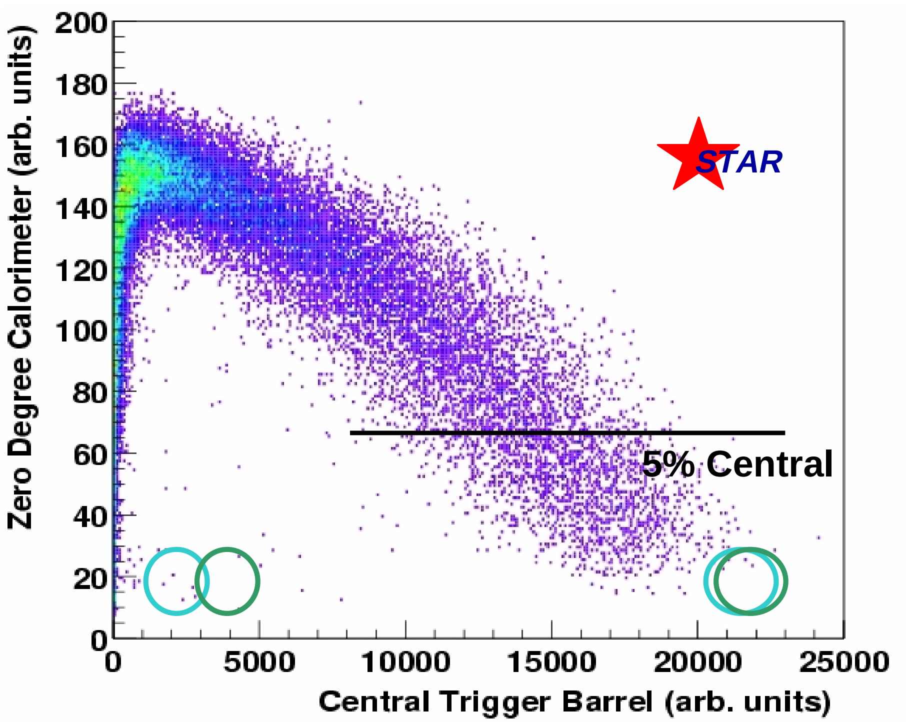


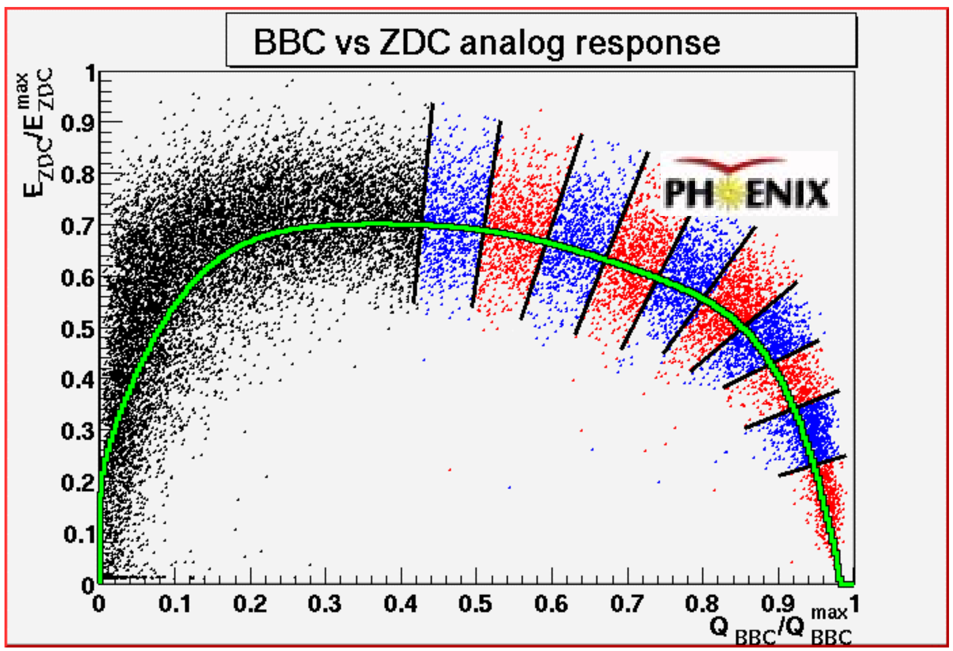
Nparticipant: number of incoming nucleons (participants) in the overlap region
Nbinary: number of equivalent inelastic nucleon-nucleon collisions

Experimental Determination of Geometry



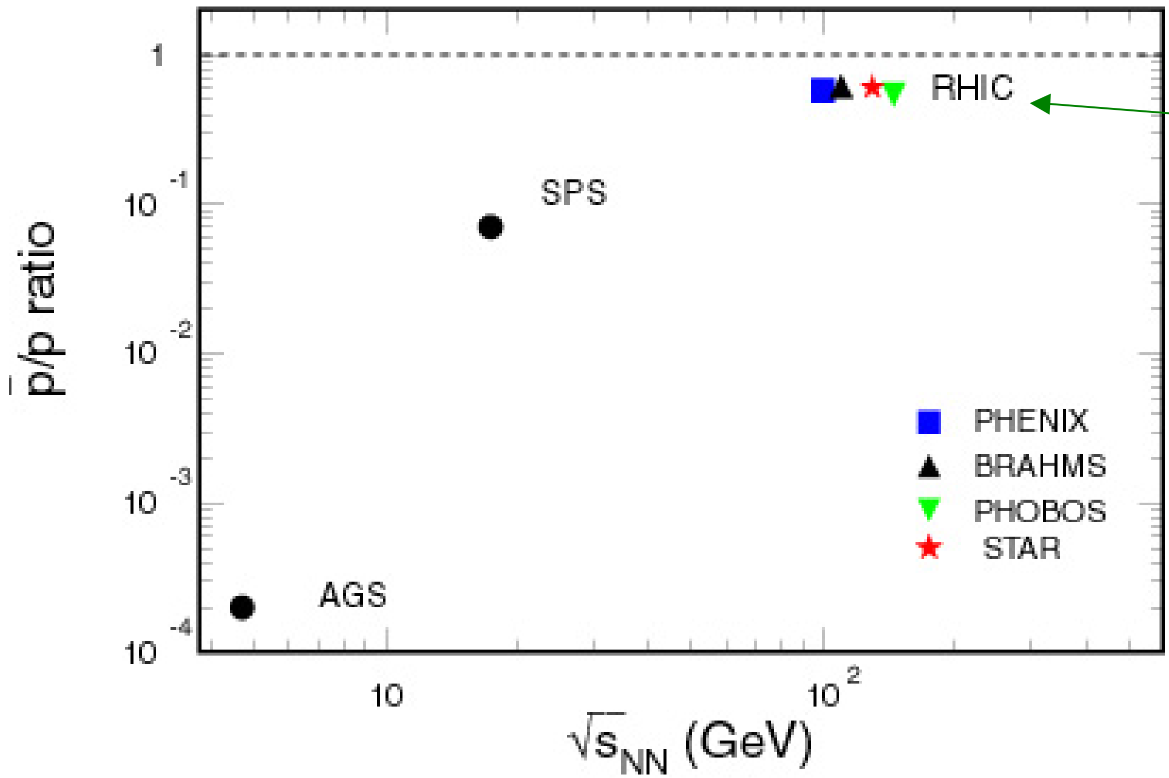






Baryon Density at Midrapidity

pbar/p vs √s, central collisions of heavy nuclei



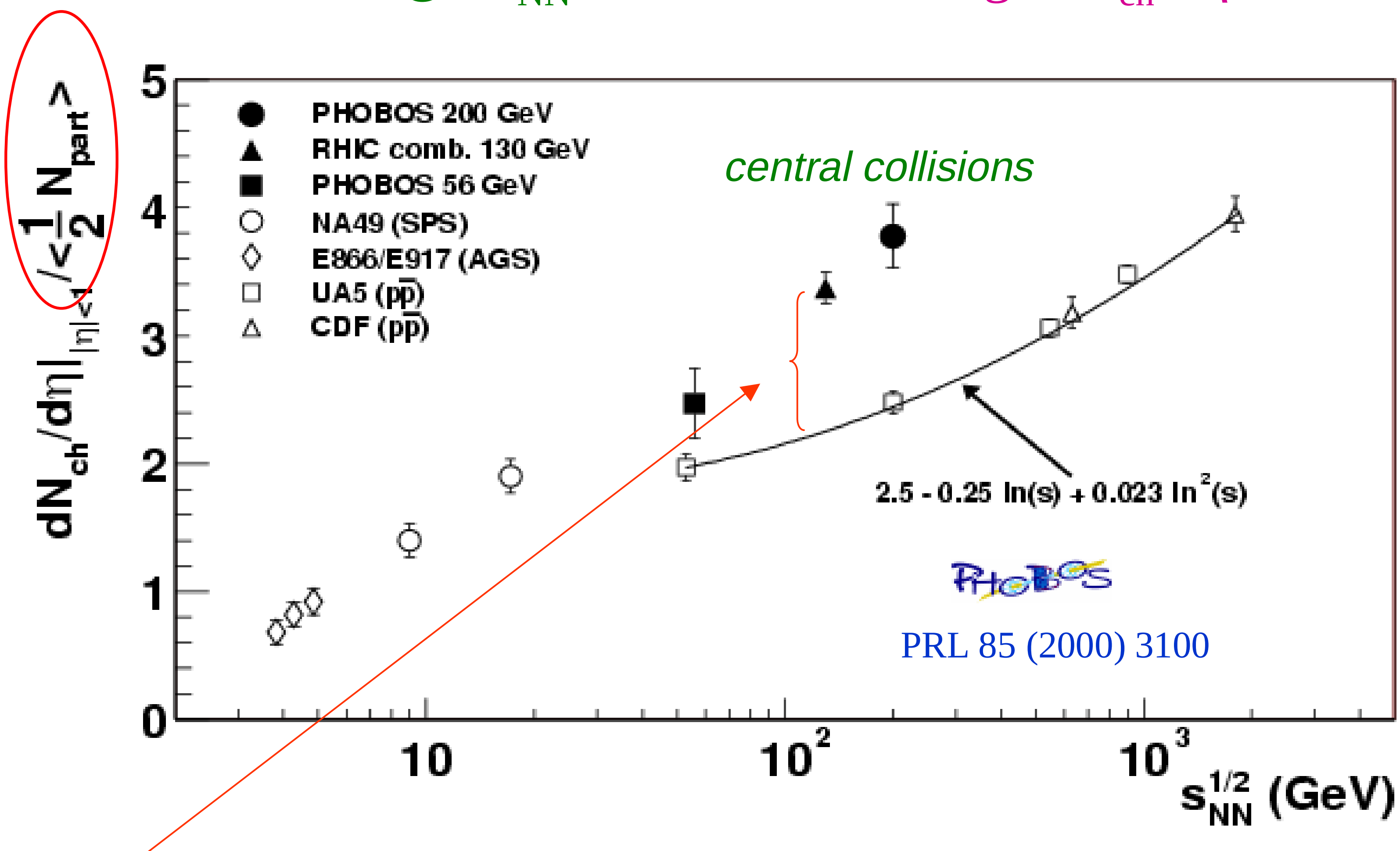
All four experiments: pbar/p ~ 0.6-0.7

STAR:
Λbar/Λ ~ 0.7
Ξbar/ Ξ ~ 0.8

- Approaching baryon-free environment
- But net baryon number still finite (baryon transport over Δy~5.5)

Charged particle production (η=0)

Central Au+Au @ $\sqrt{s_{NN}}$=130: world average $dN_{ch}/d\eta$ =584±18

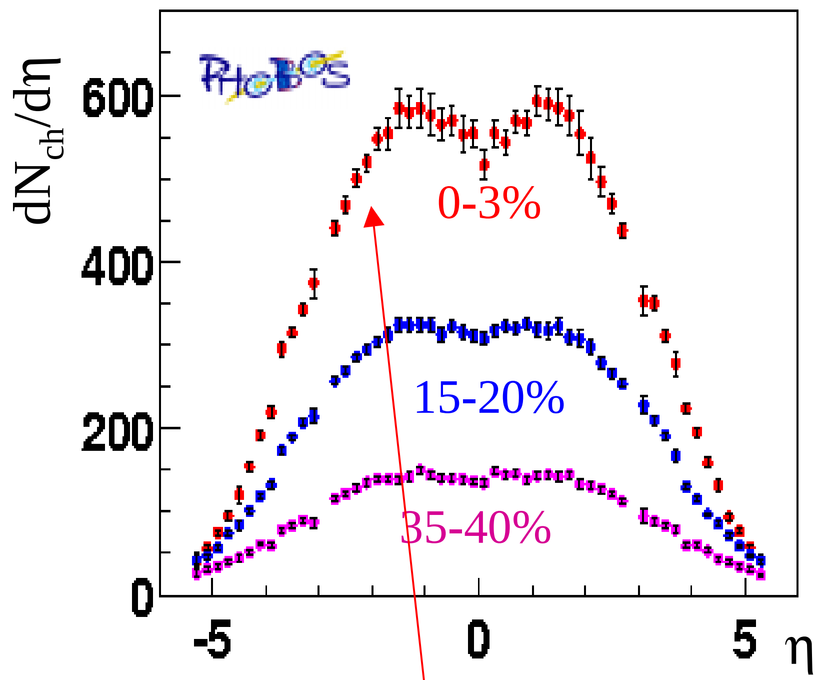


- 40% increase relative to p+pbar: Au+Au is not a simple superposition
- grows faster with √s than p+pbar: onset of hard scattering? (~Nbinary)

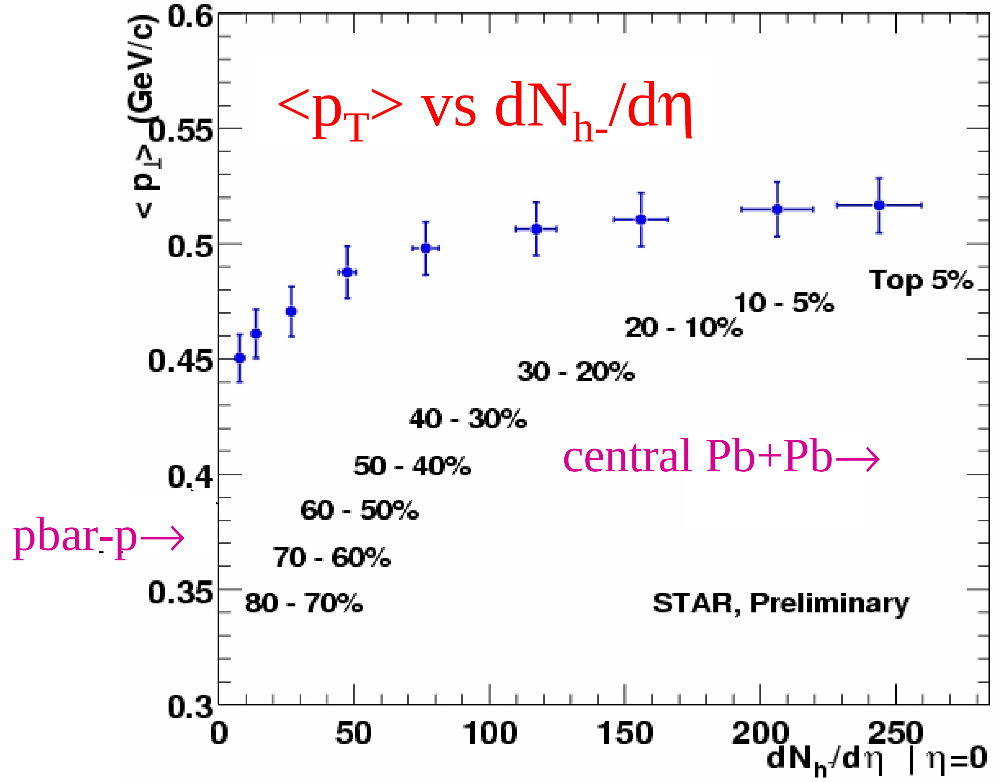
Particle Production vs. Collision Centrality

Rapidity dependence

PHOBOS: nucl-ex/0106006



Total charged particles for central collisions: 4200±470!

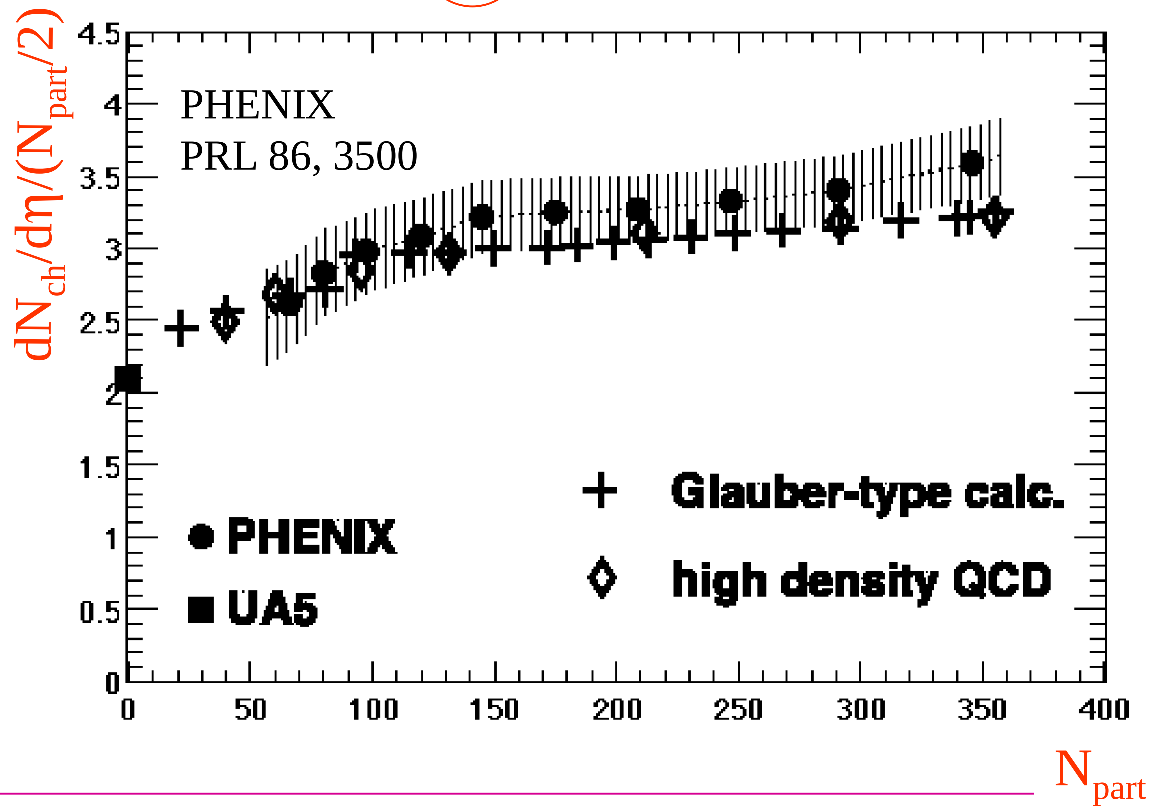


Mean transverse momentum:

- spectrum much harder than for pbar-p, Pb+Pb@ SPS
- harder for more central collisions

Sensitive to gluon saturation?

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

Bjorken Energy Density

- Bjorken '83: ideal 1+1 D relativistic hydrodynamics
- boost invariance $\Rightarrow \eta \sim 0$

$$\varepsilon = \frac{1}{\pi R^2 \tau} \frac{dE_T}{dy} \approx \frac{1}{\pi R^2 \tau} \langle p_T \rangle \frac{3}{2} \frac{dN_{ch}}{d\eta} \quad (R \sim A^{1/3},\ \tau = 1\ \text{fm/c})$$

Central Au+Au @ $\sqrt{s_{NN}}$=130:

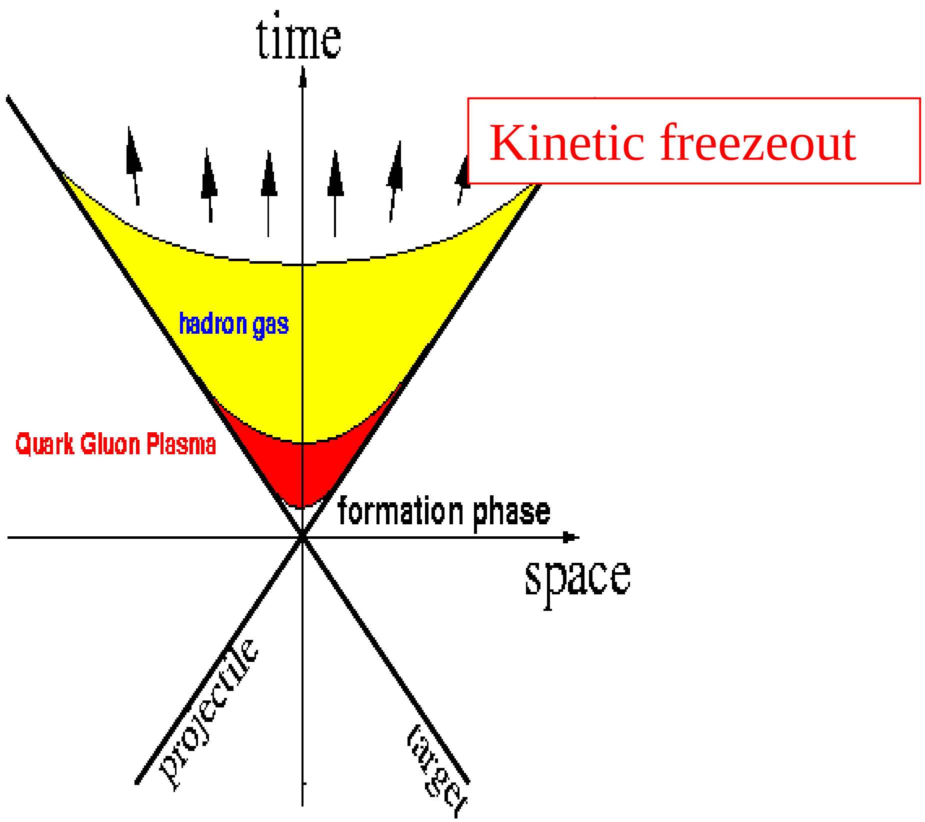
- PHENIX E_T: $\varepsilon = 4.6$ GeV/fm^3 *(nucl-ex/0104015)*
- STAR charged particles: $\varepsilon \sim 4.5$ GeV/fm^3

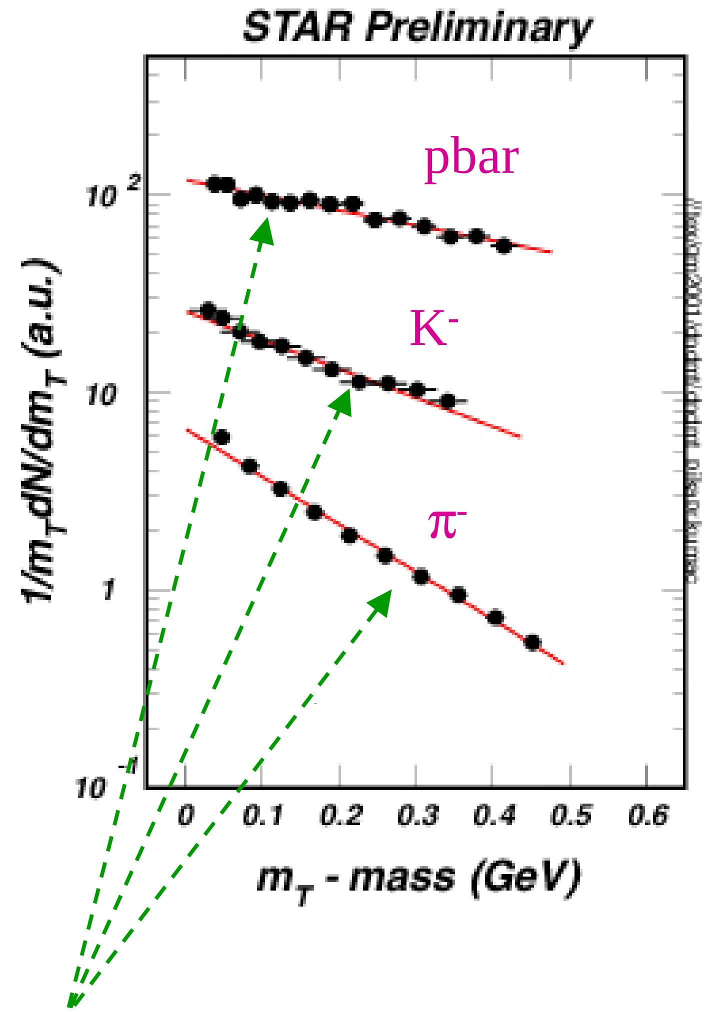
Compare NA49 Pb+Pb@SPS: $\varepsilon \sim 3$ GeV/fm^3 (τ = 1 fm/c)

Critical issues:

- Has equilibrium been achieved? (i.e. hydrodynamics valid?)
- If so, what is formation time τ?

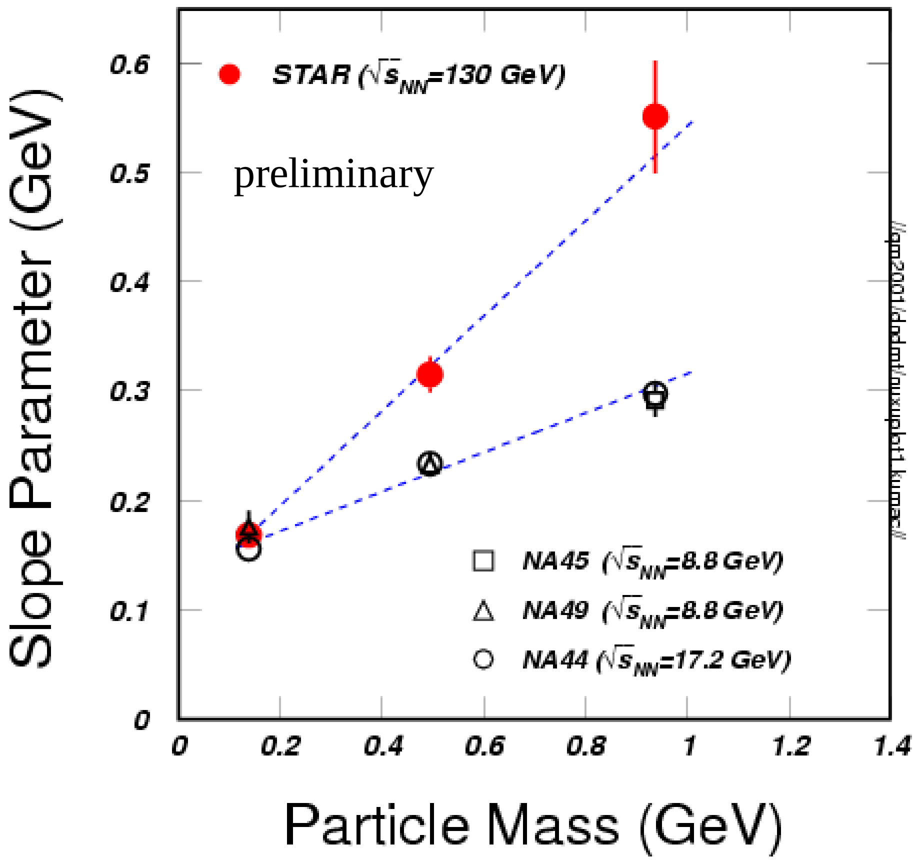
p_T Spectra: central collisions

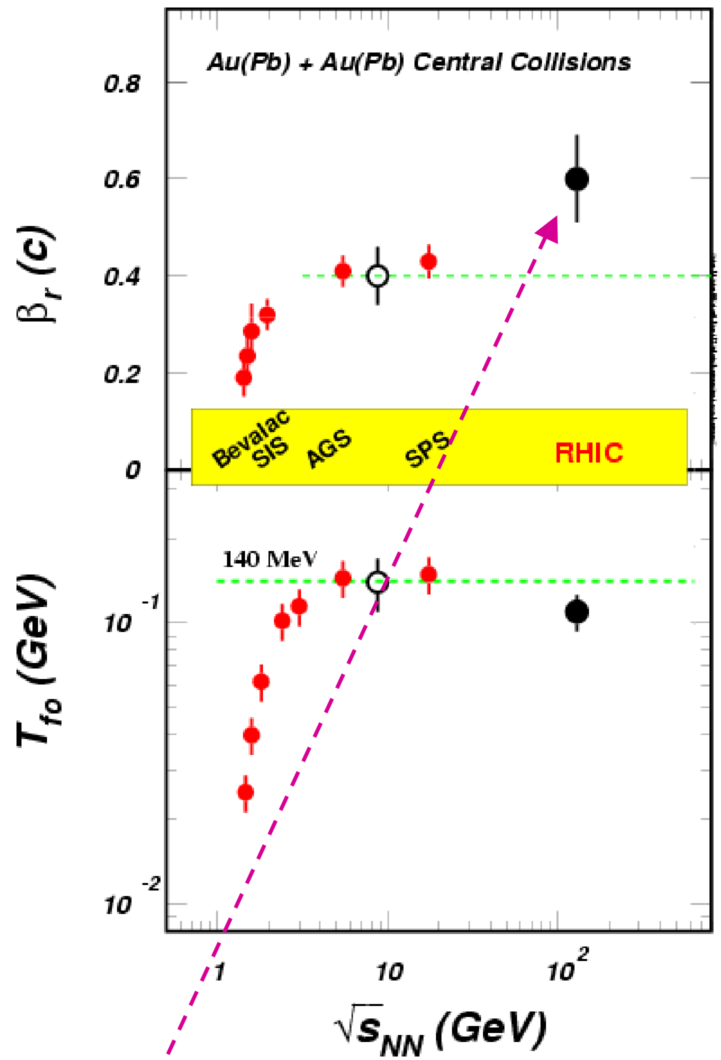




Radial flow of matter: common velocity boost ⇒ stiffer momentum spectrum for more massive particles

p_T Spectra: systematics for $p_T < 1$ GeV/c



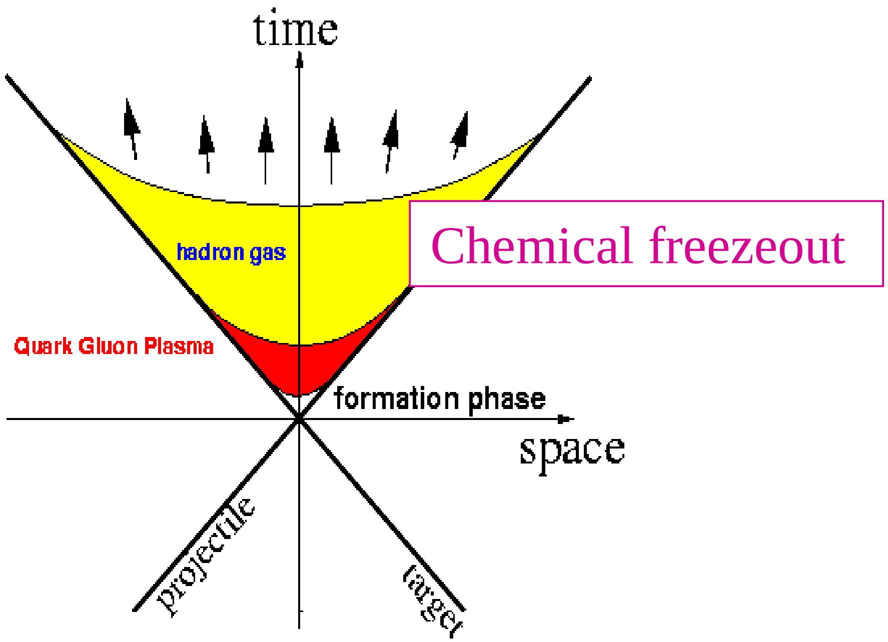


Simple hydrodynamics:

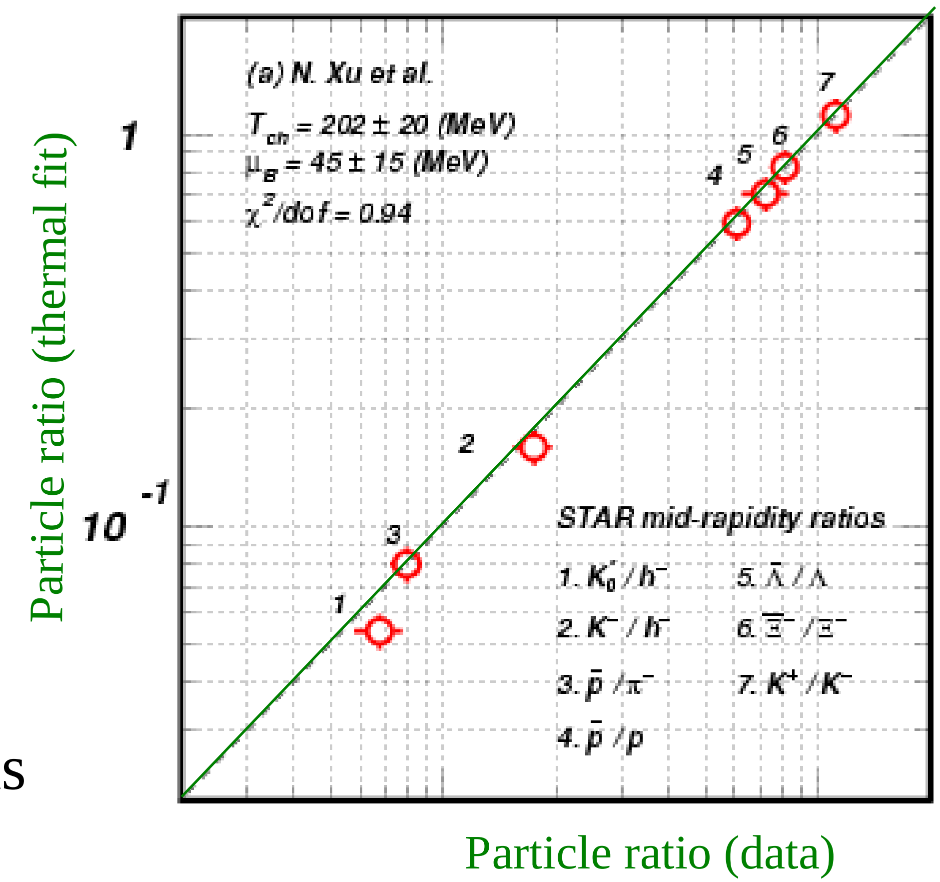
$T_{apparent} = T_{freezeout} + \text{mass} * \beta^2_{RadialFlow}$

explosive radial expansion at RHIC ⇒ high pressure

Particle Ratios in Central Collisions



N. Xu et al.



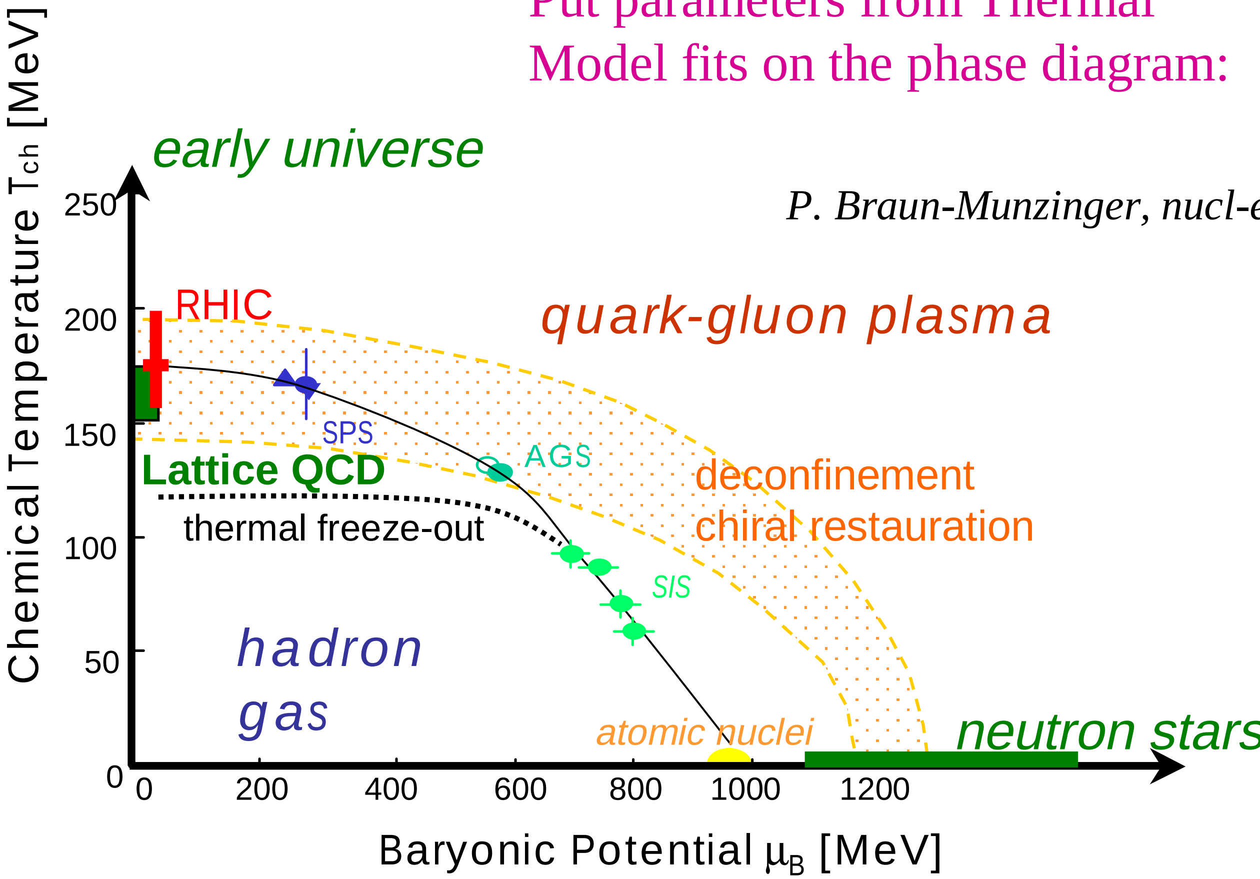
Simple thermal model:

- Partition fn, spectrum of hadrons
- Parameters T, μ_B, μ_s, μ_{I3}
- Fit to ratios of antiparticle/particles: π, K, p, Λ, Ξ, K^*_0

Typical fits: T_{ch} = 175~200 MeV, μ_B ~50 MeV, μ_s ~0
Simple "model" works well: evidence for chemical equilibrium?

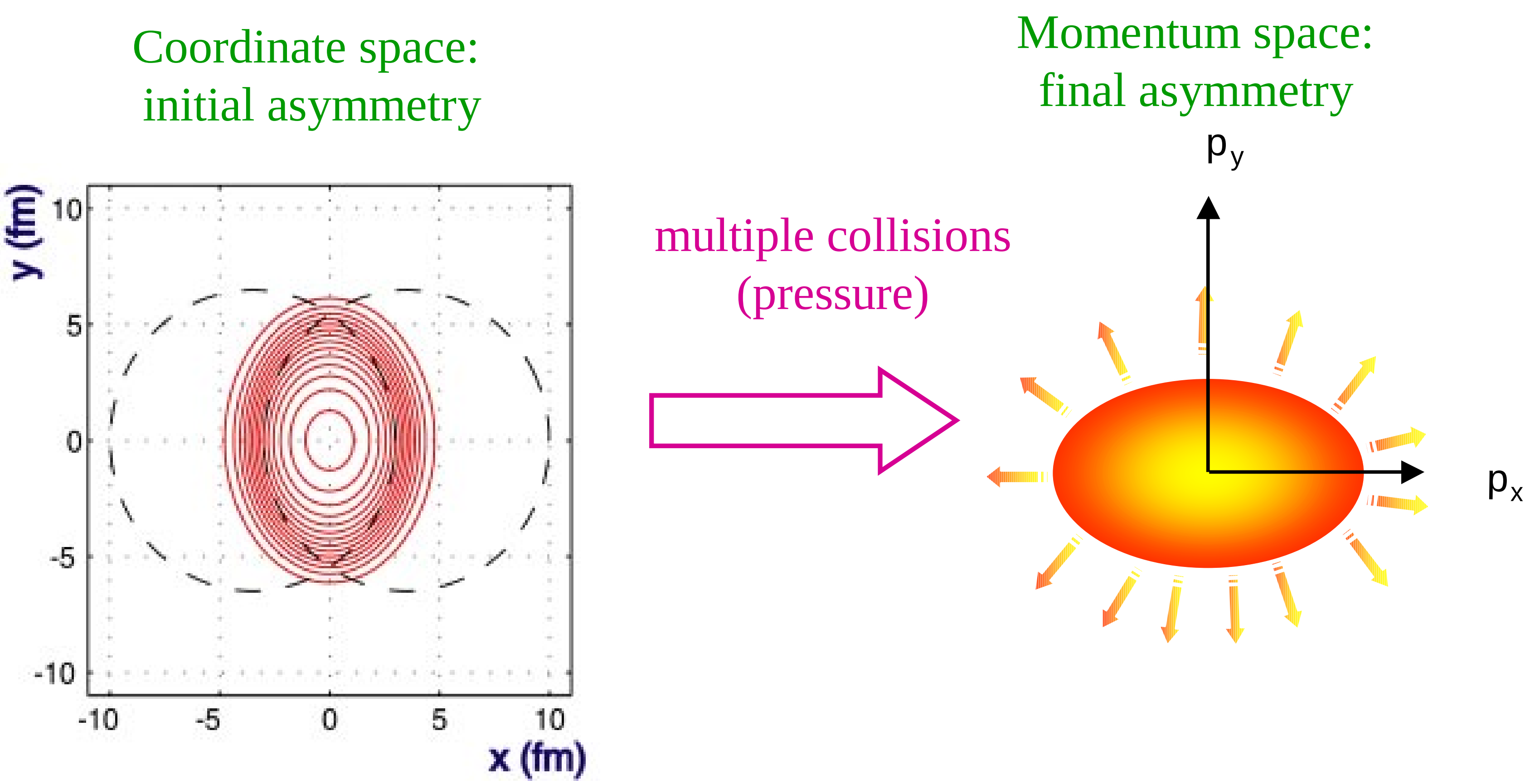
Phase Diagram at Chemical Freezeout

Put parameters from Thermal Model fits on the phase diagram:



- parameters near phase boundary
- (strangeness) equilibration time for hadronic gas very long (~50 fm/c)
- do we have more direct evidence of early equilibration?

Elliptic Flow in Non-central Collisions



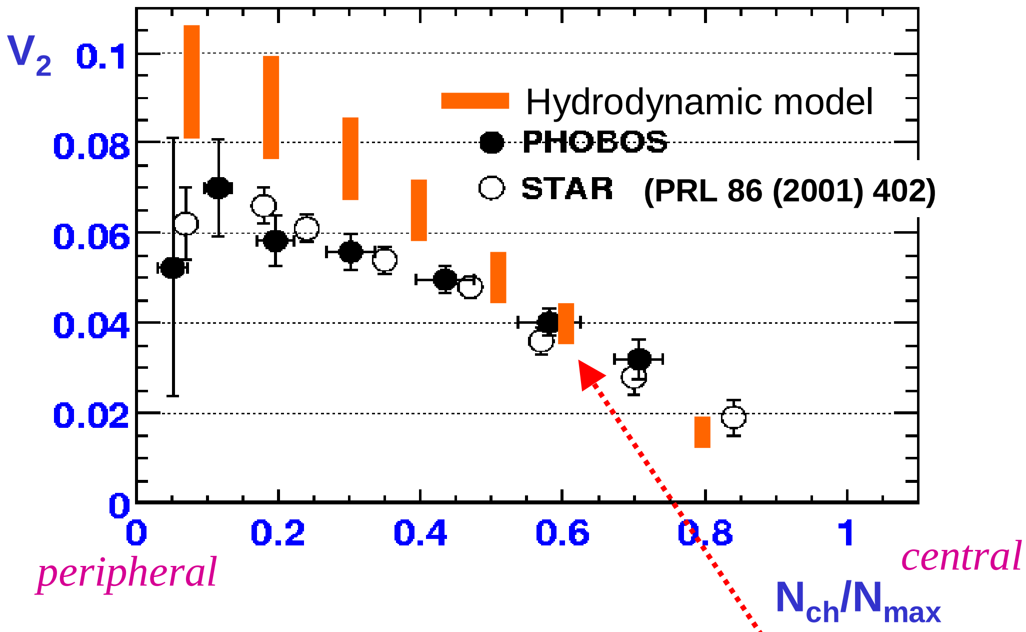
• Asymmetry generated early in collision, quenched by expansion

⇒ observed asymmetry emphasizes early time

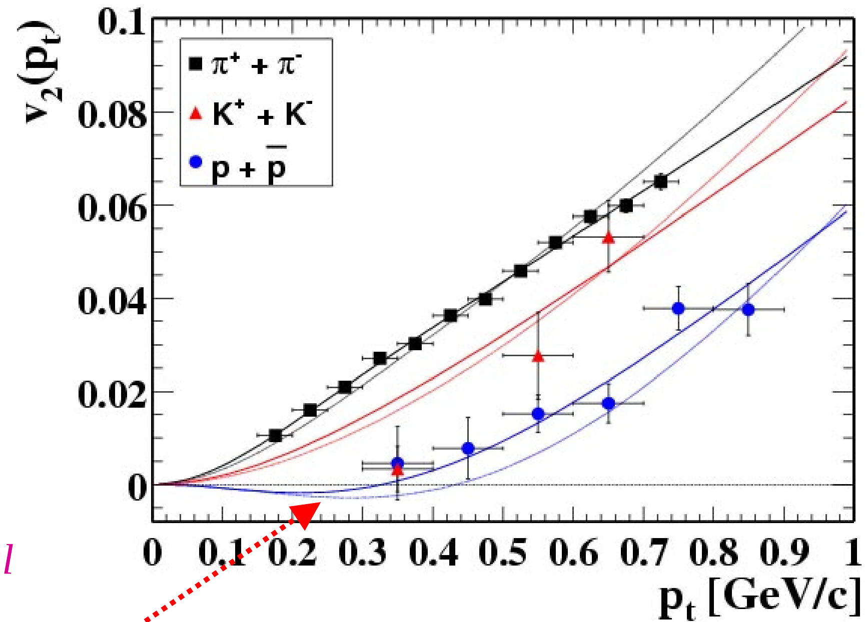
Second Fourier coefficient v2: $v_2 = \langle \cos 2\phi \rangle$ $\phi = \text{atan}\,\frac{p_y}{p_x}$

Elliptic Flow (cont'd)

v2 vs centrality



v2 vs p_T and particle mass



- Hydrodynamic calculations in reasonable agreement

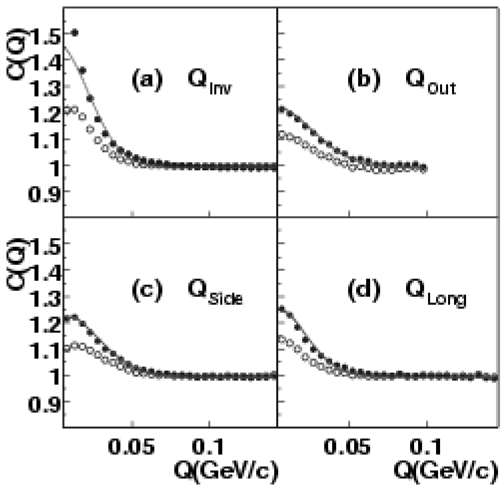
$\Rightarrow$ compatible with early equilibration

- Cascade models require extreme elastic cross sections or huge gluon densities (Molnar and Gyulassy)

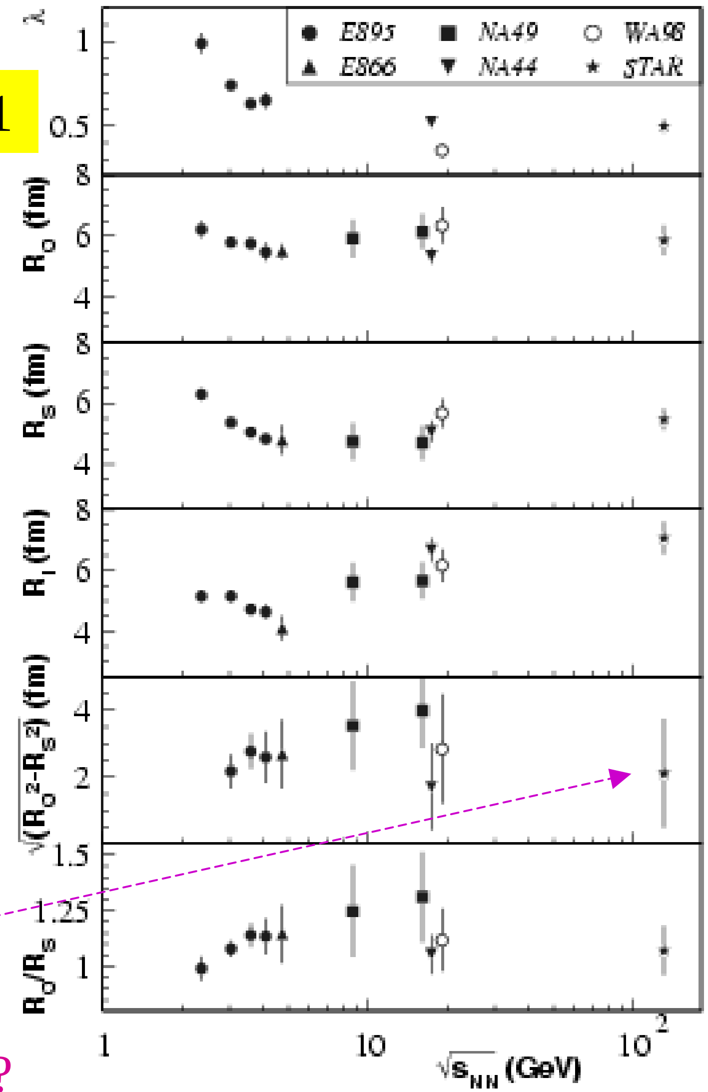
Fly in the Ointment: Pion Interferometry

(GGLP/HBT effect)

π-π- : |y|<0.5
0.125< pT(GeV/c) < 0.225



STAR, PRL 87, 082301



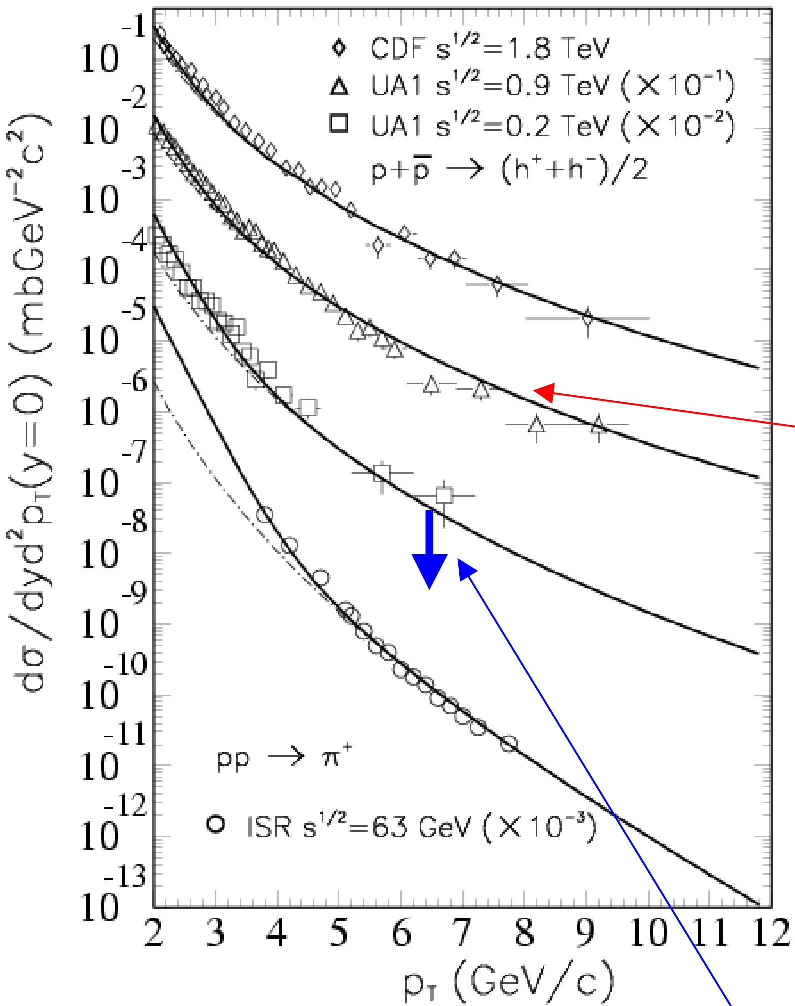
• interference of identical bosons at low relative momentum **q**

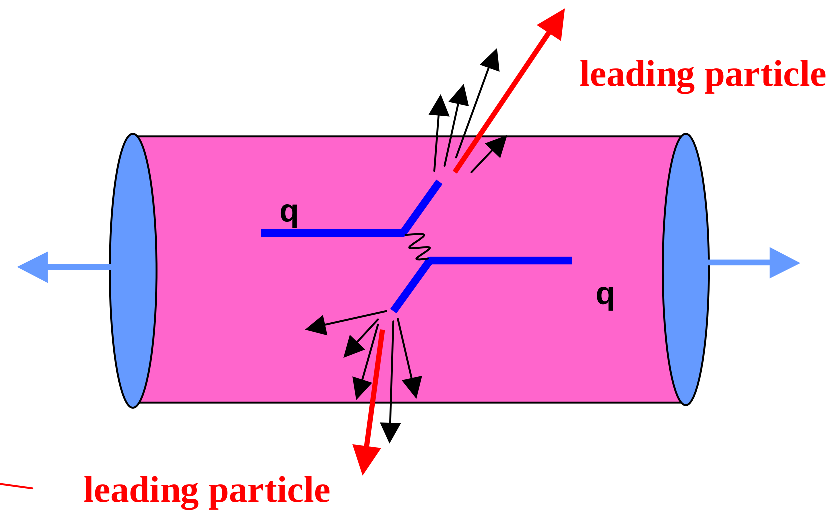
• certain components of **q** sensitive to duration of particle emission

• strong 1st order phase transition ⇒ large latent heat ⇒ long "stall" in expansion ⇒ long lifetime

• No variation with √s seen ⇒ explosive expansion??

High p_T hadrons in Nuclear Collisions





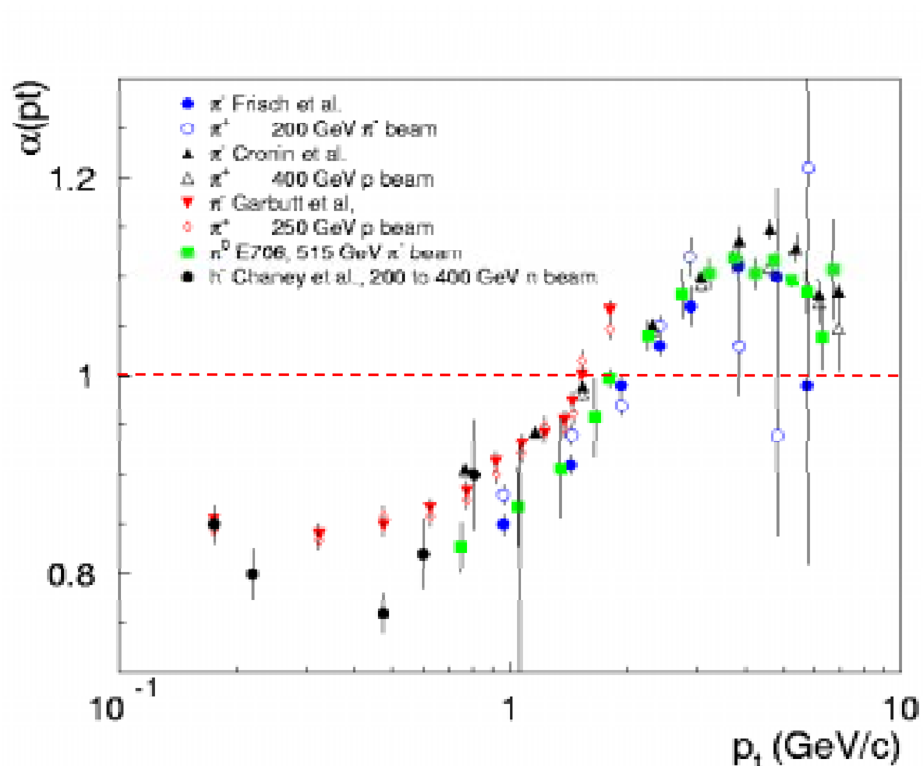
Bjorken, Wang&Gyulassy, Baier et al.:

- dE/dx: parton traversing medium dissipates energy via brehmsstrahlung
- coherence effects: dE/dx ~ x^2
- dE/dx much larger in deconfined medium than hadronic matter

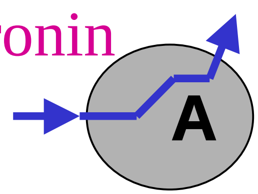
- Full jet reconstruction in Au+Au impossible (underlying event)
- But also not relevant: observable is softening of fragmentation

Leading Hadrons in Fixed Target Experiments

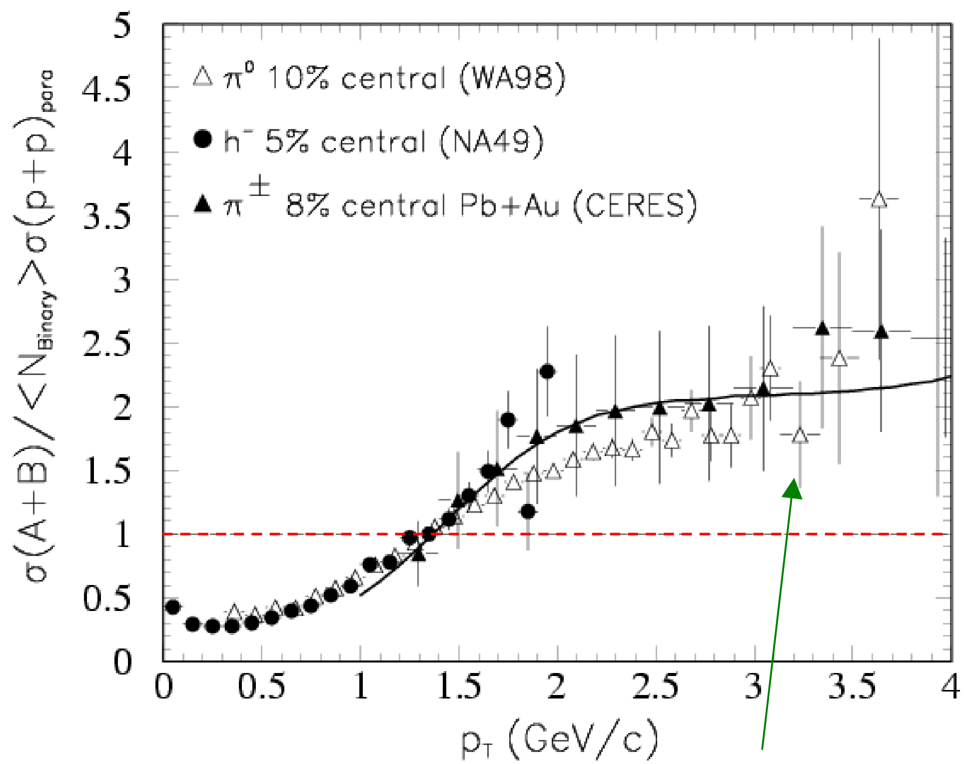
p+A collisions: $\sigma_{pA} = A^{\alpha(p_t)} \sigma_{pp}$



Multiple scattering in initial state("Cronin effect")



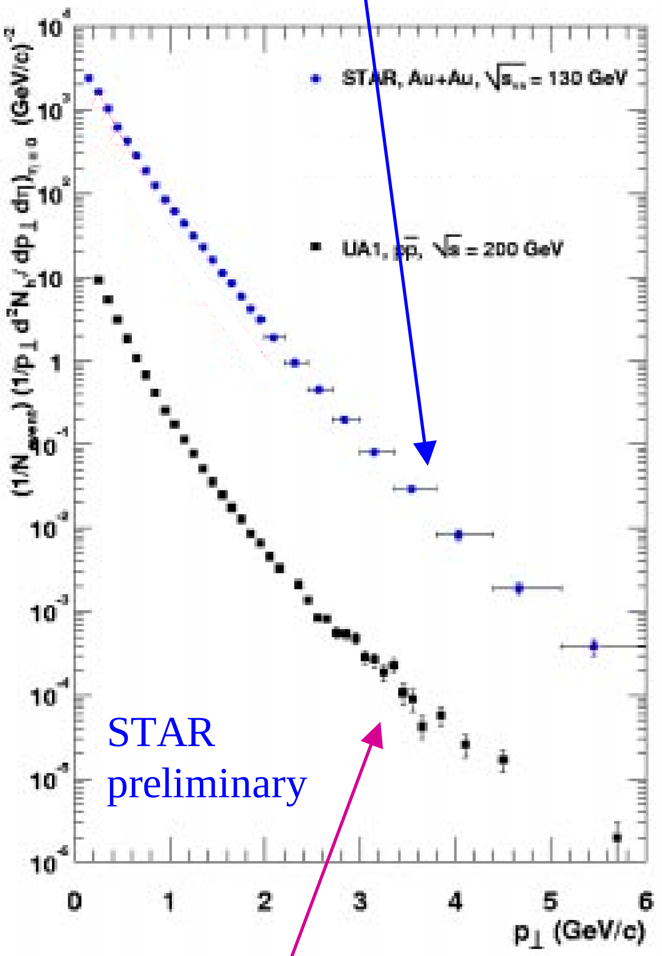
Central Pb+Pb collisions at SPS



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

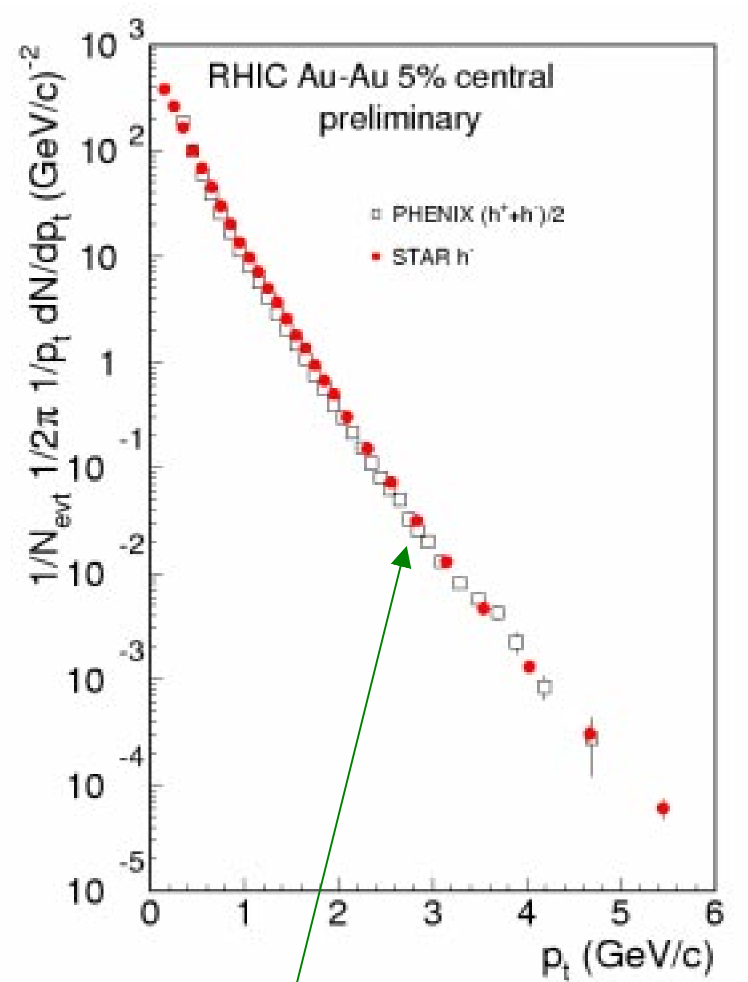
High p_T charged hadrons (central collisions)

STAR negative hadrons



UA1 reference data

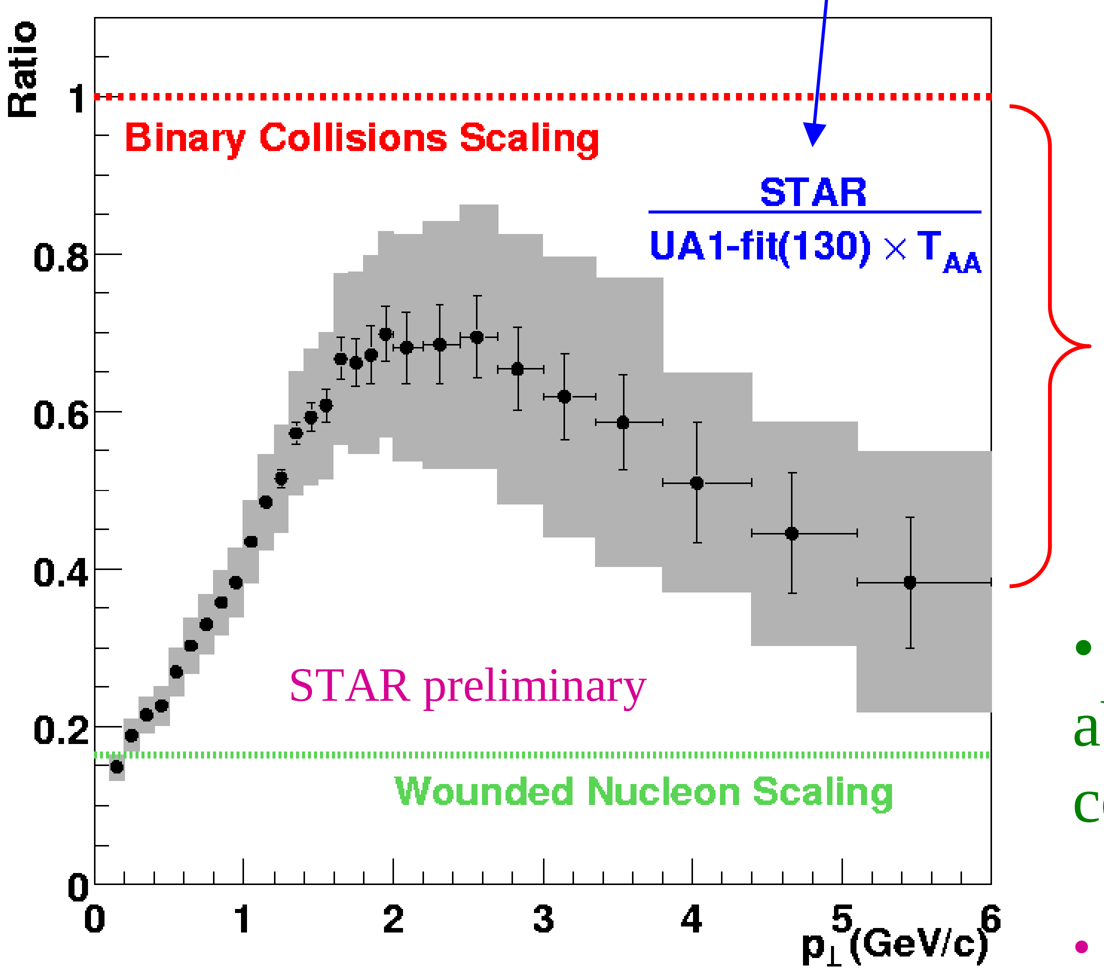
PHENIX vs STAR



Agreement at ~20% level!

Ratio STAR/UA1 vs p_T

Scaling factors: energy dependence, nuclear geometry



Hadron suppression in nuclear collisions at high p_T

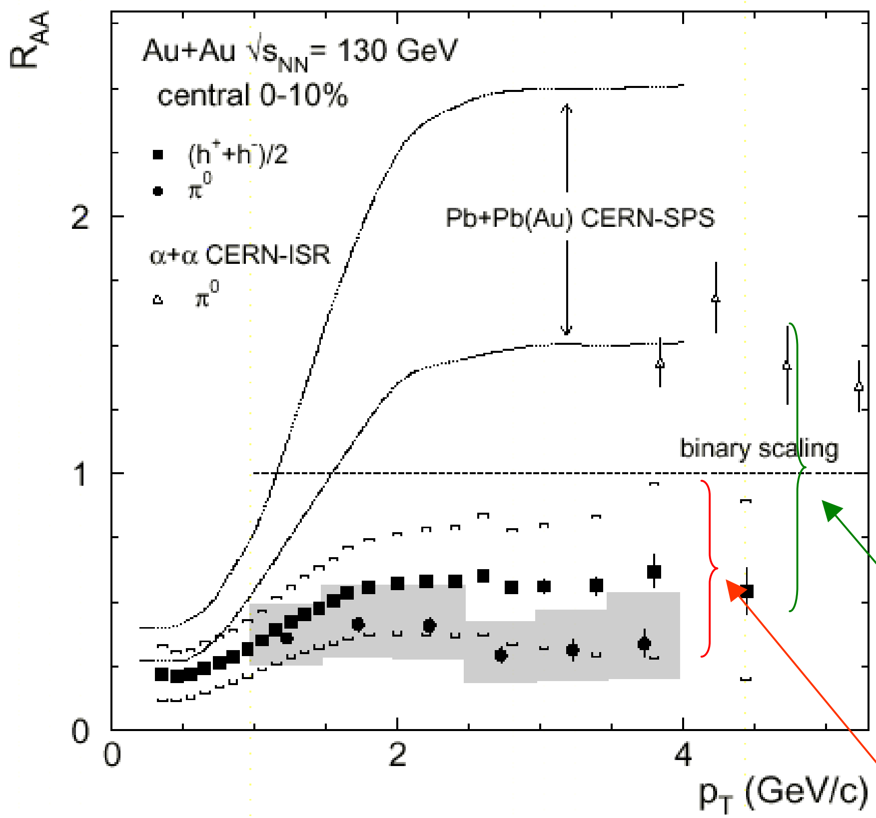
- important open issues about systematics of UA1 comparison

- flavor and isospin are few percent effects

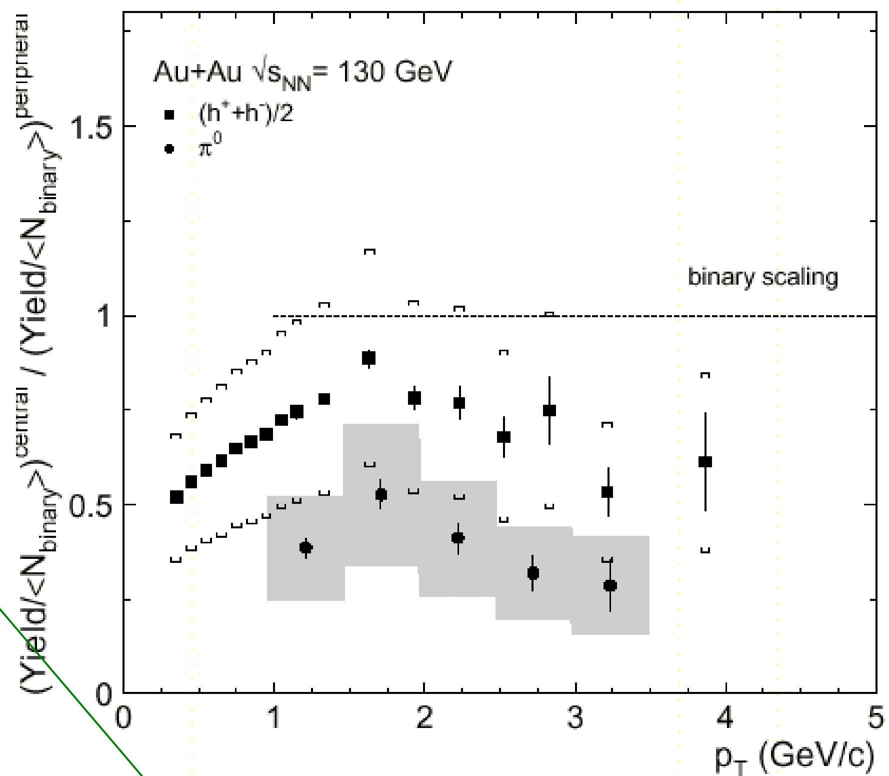
PHENIX: charged hadrons and π^0

nucl-ex/0109003, submitted to PRL

central normalized to p+p/pbar+p



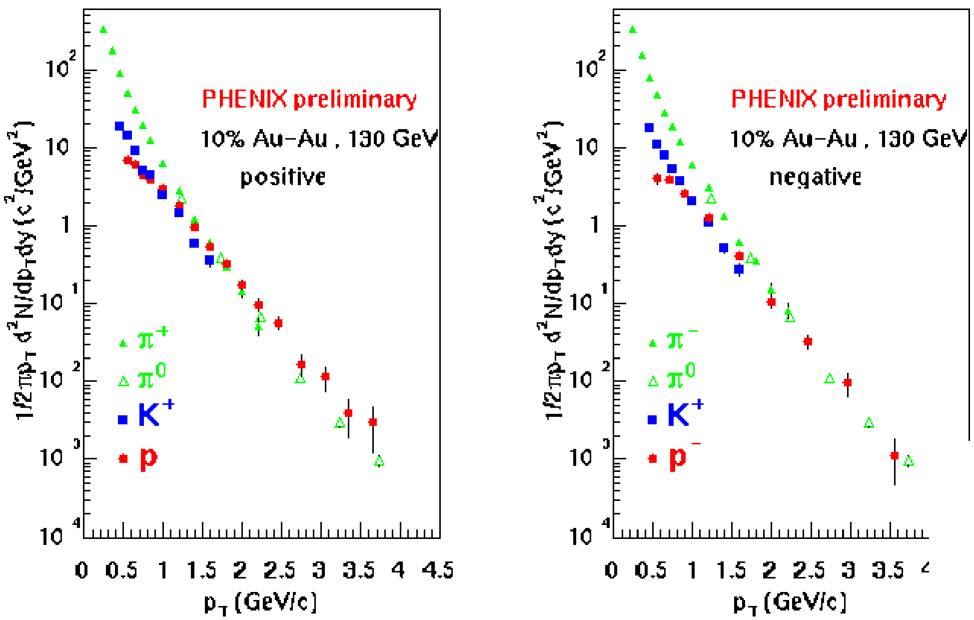
central/peripheral

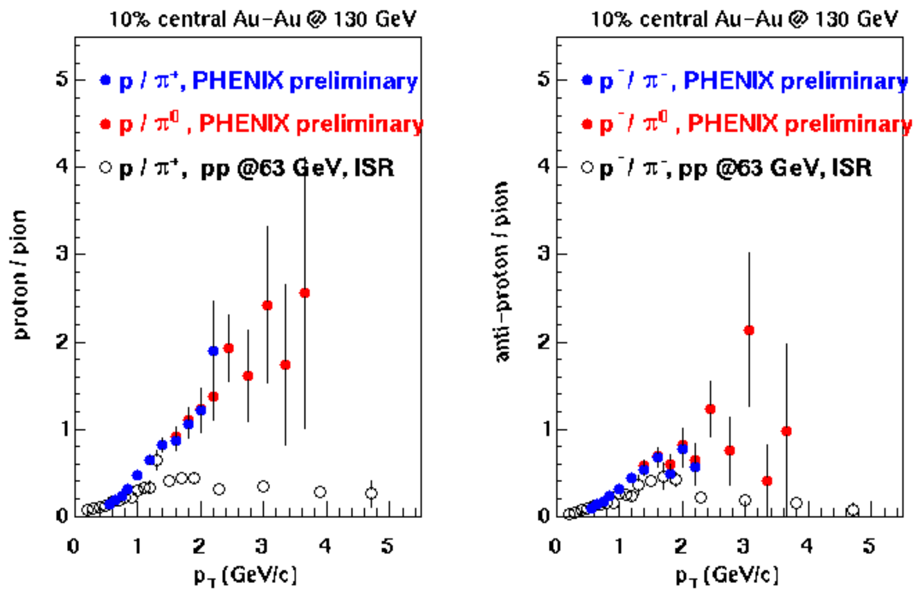


Suppression greater for π^0 than for charged hadrons

Suppression larger if reference includes Cronin effect

PHENIX: π/K/p at high p_T



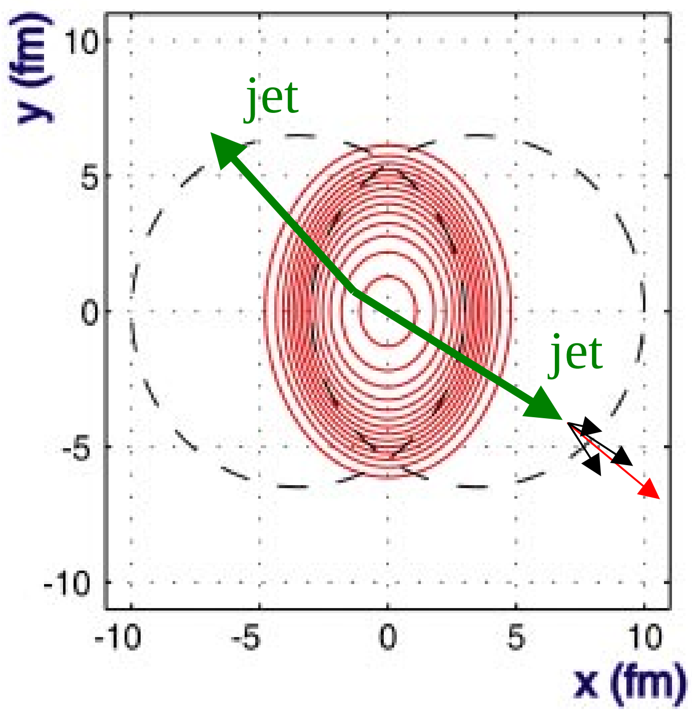


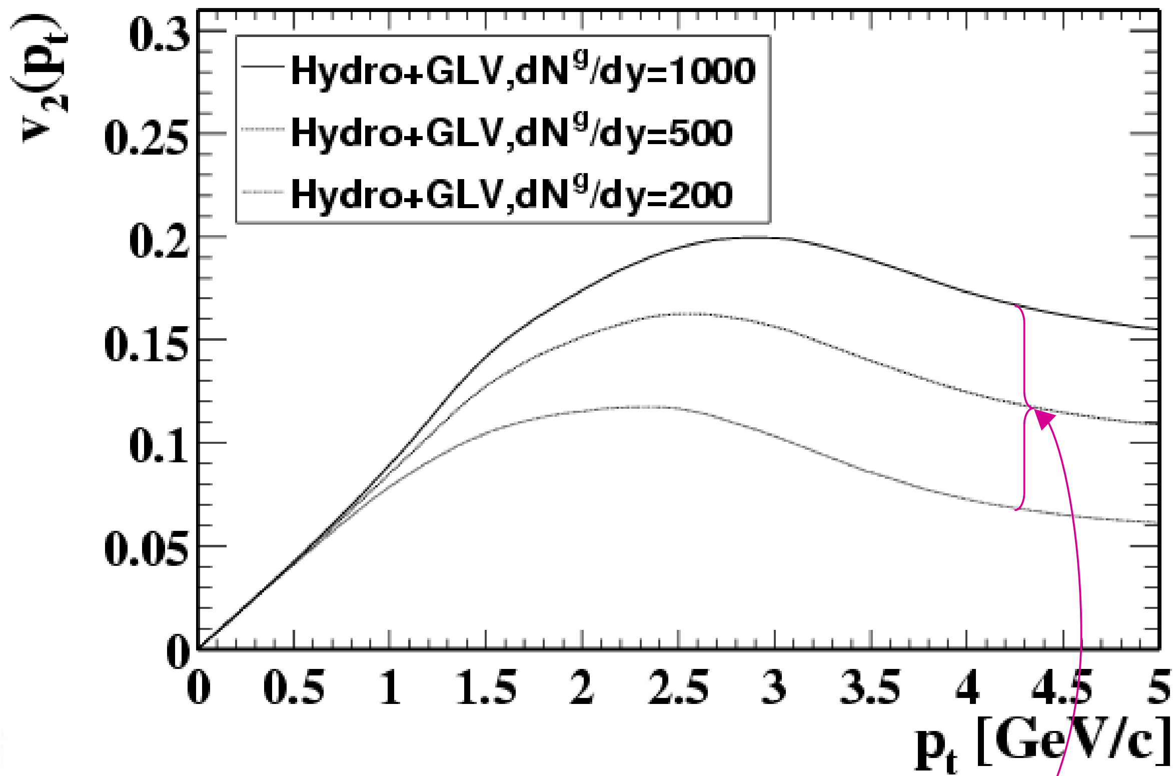
- Central Au+Au@RHIC very different than p+p @ ISR:
  - extreme radial flow?
  - exotic fragmentation?
  - baryon junctions?

Elliptic flow at high p_T : predictions

Jet propagation through anisotropic matter (non-central collisions)

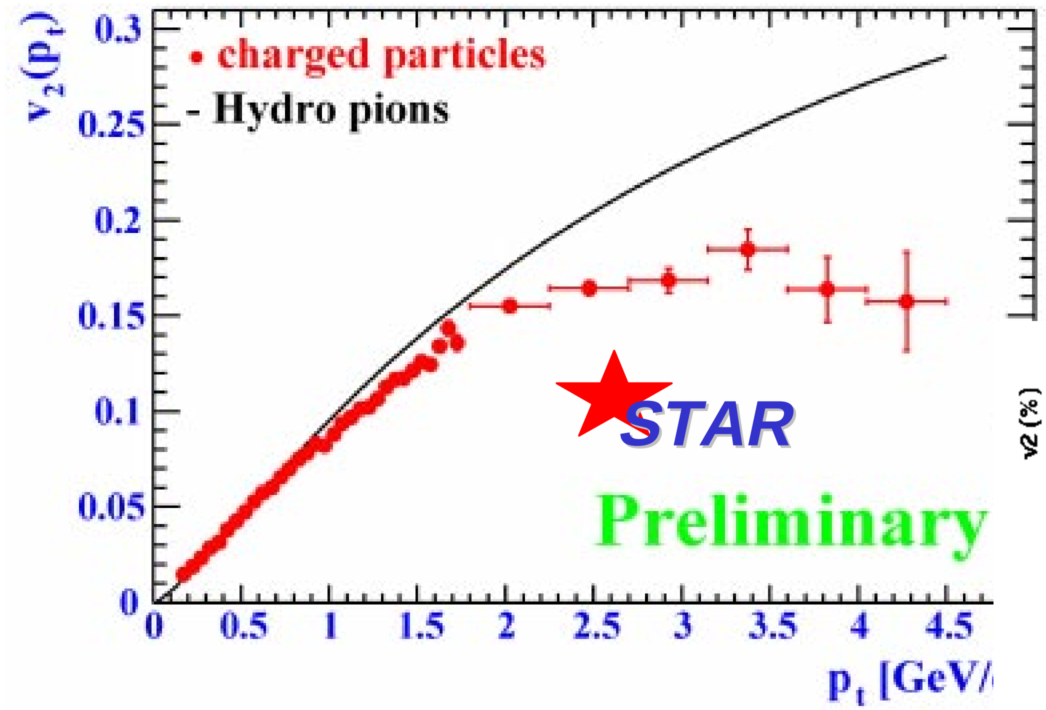
Snellings; Gyulassy, Vitev and Wang (nucl-th/00012092)



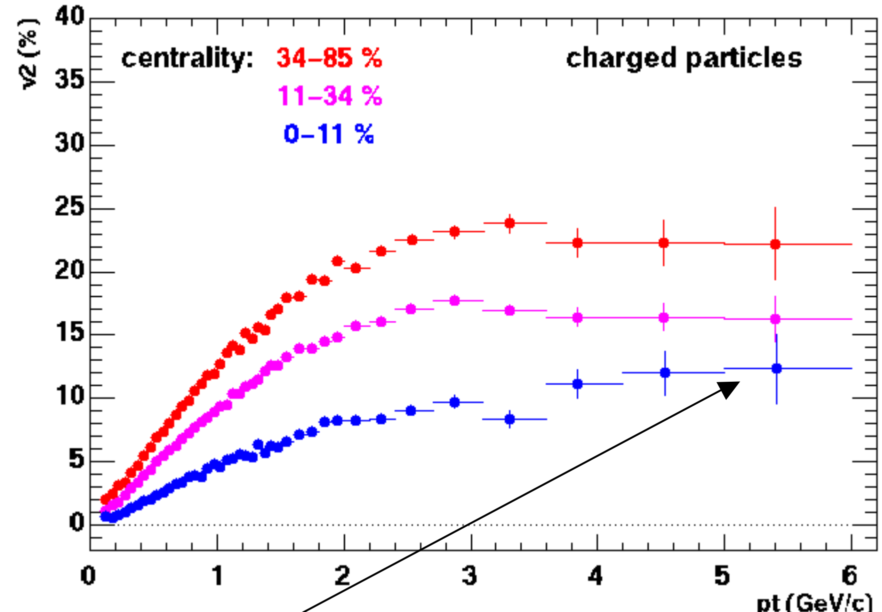


Finite asymmetry at high p_T sensitive to energy density

STAR: Elliptic flow at high p_T



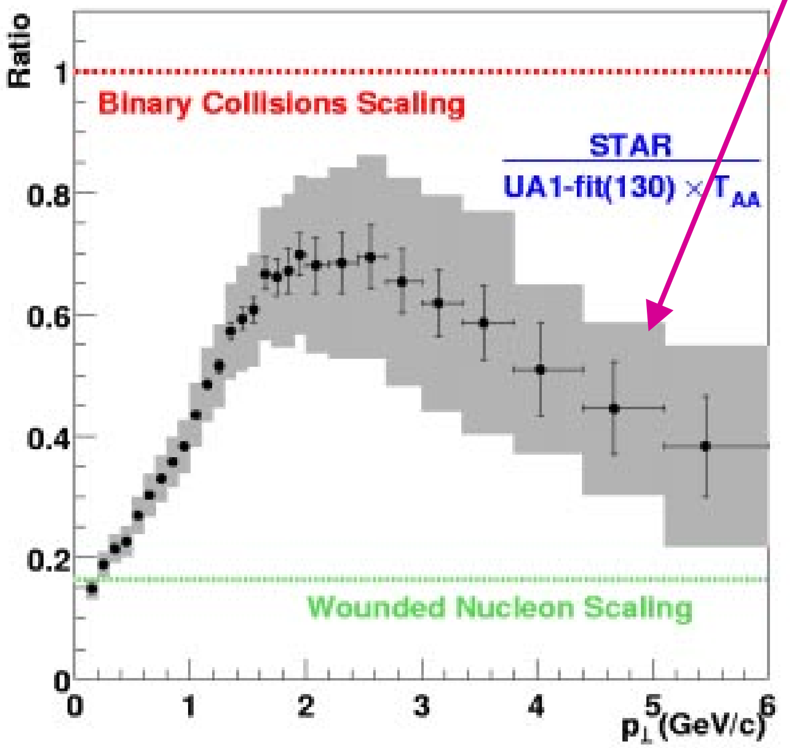
Hydro calculation: P. Huovinen

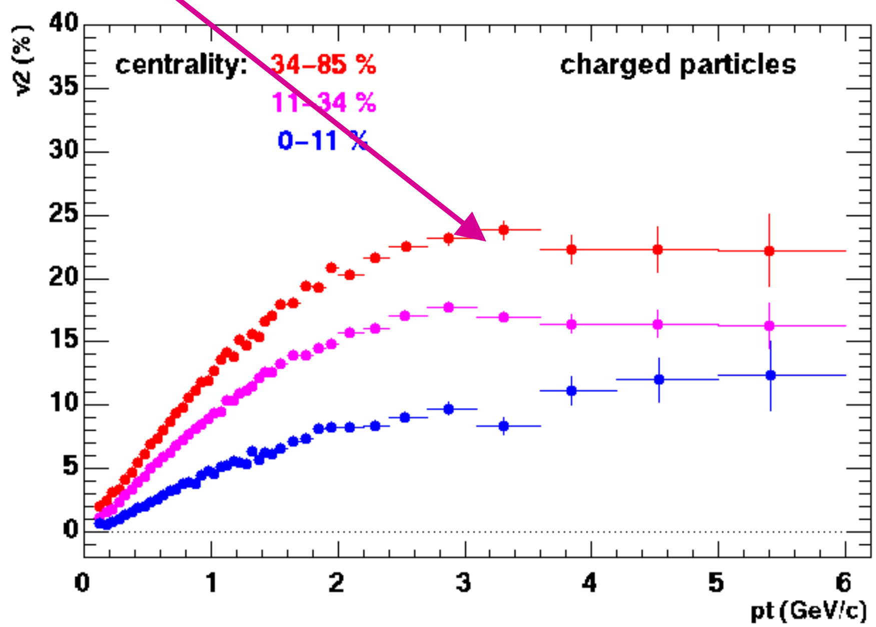


- watch out for autocorrelation: jets distort reaction plane measurement
  - look at v_1 (1st order coeff): effect is negligible
- saturation to 6 GeV: not yet perturbative?? not yet understood

Elliptical flow vs. inclusive hadron spectra

Different views of same physics?





Evidence for hadron suppression at high p_T

Flow or partonic interaction with matter?

Summary of Au+Au Collisions at RHIC

Machine and experiments are working well!

Low p_T hadrons:

- low baryon density at y~0
- strong evidence for early equilibration
- high initial pressure and energy density
  - best estimate: $\varepsilon \sim 4.5$ GeV/fm^3

High p_T hadrons:

- suppression of inclusive yields
- $p/\pi > 1$ at $p_T > 2$ GeV: radial flow or exotic fragmentation?
- elliptic flow persists at high p_T

Most exciting prospect: jet quenching in dense matter?

$\Rightarrow$ direct indicator of deconfinement

$\Rightarrow$ but still a long road: need higher p_T, p+p, p+A, γ+jet measurements

Outlook

- RHIC Year 2:
  - July-Nov: Au+Au @200 GeV (design luminosity reached)
  - Dec-Jan: 5 weeks of polarized protons
- Major detector upgrades in Year 2:
  - STAR: EM calorimeter, inner and forward tracking
  - PHENIX: completed spectrometers, first muon arm
- Year 2 physics:
  - Very high p_T spectra & correlations
  - First charm physics (J/ψ)
  - Many rare probes: detailed dynamics
  - Energy scan: extensive systematics (unique to RHIC)
- Long term: extensive program of pA, AA, polarized protons,…