High Energy Heavy Ion Collisions:

The Physics of Superdense Matter

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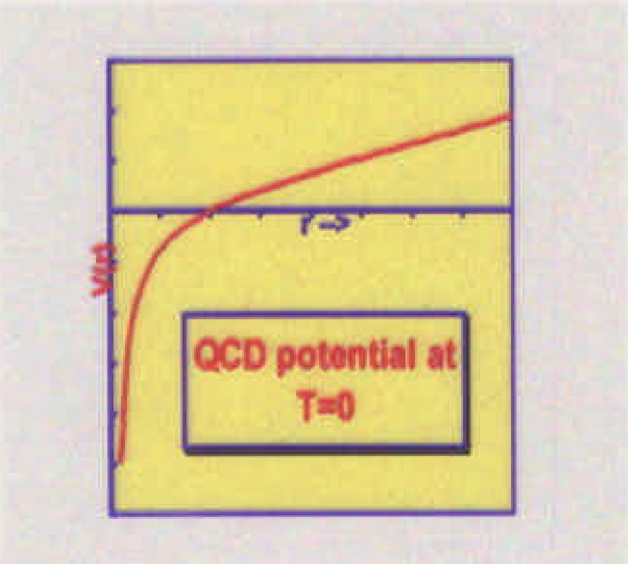
outline

- why study superdense matter
- physics at different stages in a heavy ion collision
- predicted quark gluon plasma signatures and observations at CERN
- roadmap to demonstrate QGP and its properties
- new regime at RHIC + first glimpse of results

2 Mysteries in QCD

- hadron properties governed by QCD
  force between quarks :
  exchange of colored gluons



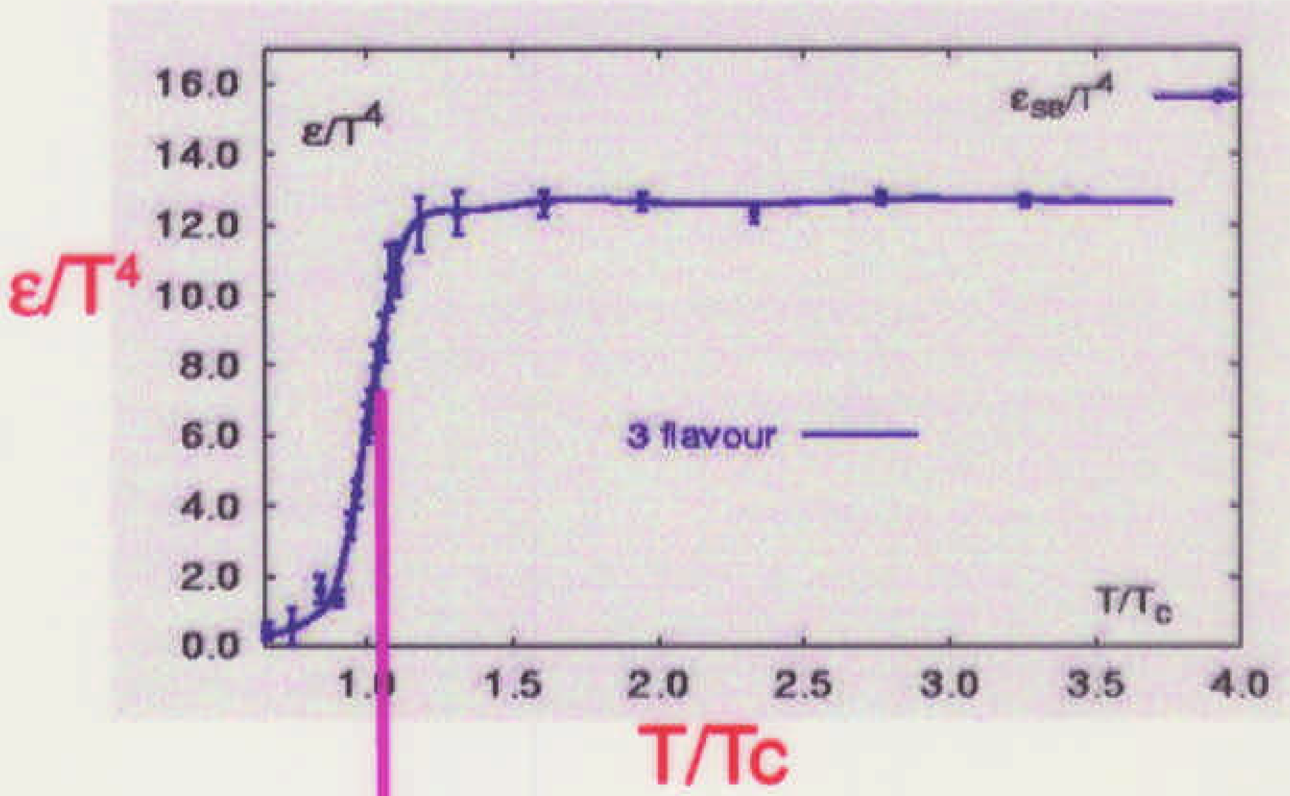
theory is non-abelian
gluons can interact with gluons

@ short distance: force is weak
probe with high Q^2
@ long distance: force is strong
probe with low Q^2

- 2 fundamental puzzles of QCD
  => confinement of quarks & gluons
  => broken chiral symmetry
  (gives hadrons their mass)

QCD on the lattice

Karsch, Laermann, Peikert '99



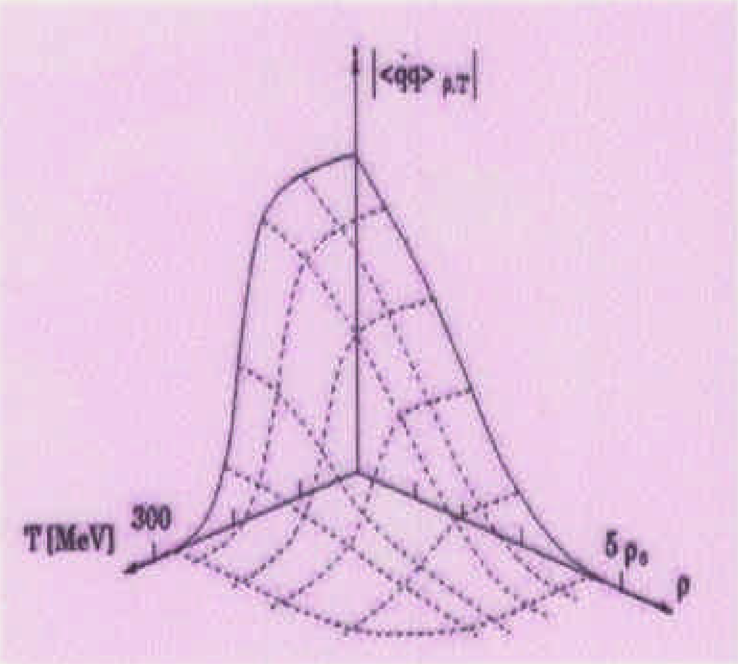
Tc ~ 170 +/- 10 MeV
ε ~ 3 GeV/fm^3

(for 2 massless + 1 strange quark, ε decreases by 15%)

At high T (or density, ρ) the QCD puzzles are resolved

Chiral Symmetry

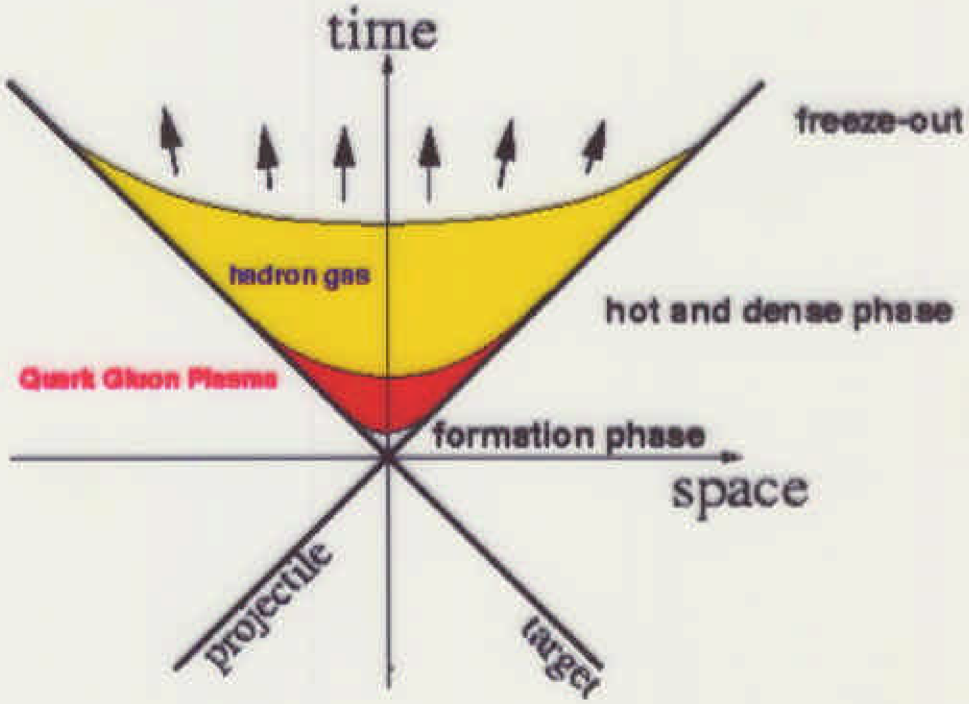
- Fundamental symmetry of QCD
  with 3 massless quarks
  $SU(3)_R \times SU(3)_L$
- Non-zero quark masses explicitly break it
  (a little bit - treat as perturbation)
- Normal matter: symmetry spontaneously broken
  $<q\bar{q}>$ ~ 230 MeV (chiral condensate)
  constituent quarks have mass



approach to chiral symmetry restore should strongly modify hadron properties (mass and width)

Create highly excited matter in the lab

- Collide HEAVY ions
  large volume for maximum time



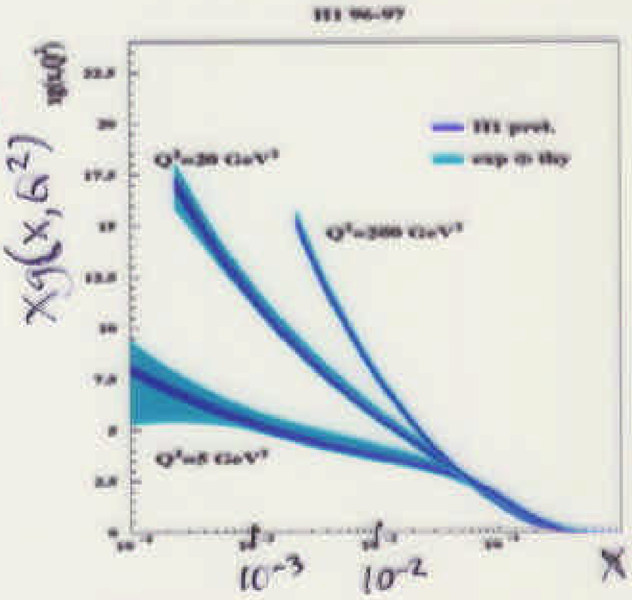
- AGS (BNL), SPS (CERN), RHIC(BNL)
  cm energy per nucleon:
  11-14 GeV, 20 GeV, 200 GeV

Initial Stage

- N-N collisions: known from p-p, $\bar{p}$-p data

  calculate with parton structure functions

  known from e-p, pA



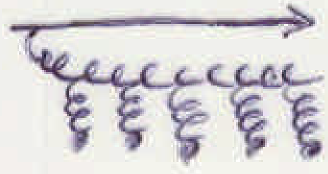
- structure functions modified in nuclei

  especially shadowing in small-x region

$$\frac{F_2^A(x)}{AF_2^N(x)}$$

Form a Dense Medium

- Multiple parton scattering
  - visible already in pA as Cronin effect
  - higher density in AA drives system
    - toward thermal equilibrium
  - -> thermalize mini-jets
    - increase soft N_{ch}
- Medium induced energy loss of partons
  - Gyulassy & Wang '94, BDMPS '96
  - energy loss of fast quark increases due to accumulated q_T transfer



dE/dx > 1 GeV/fm

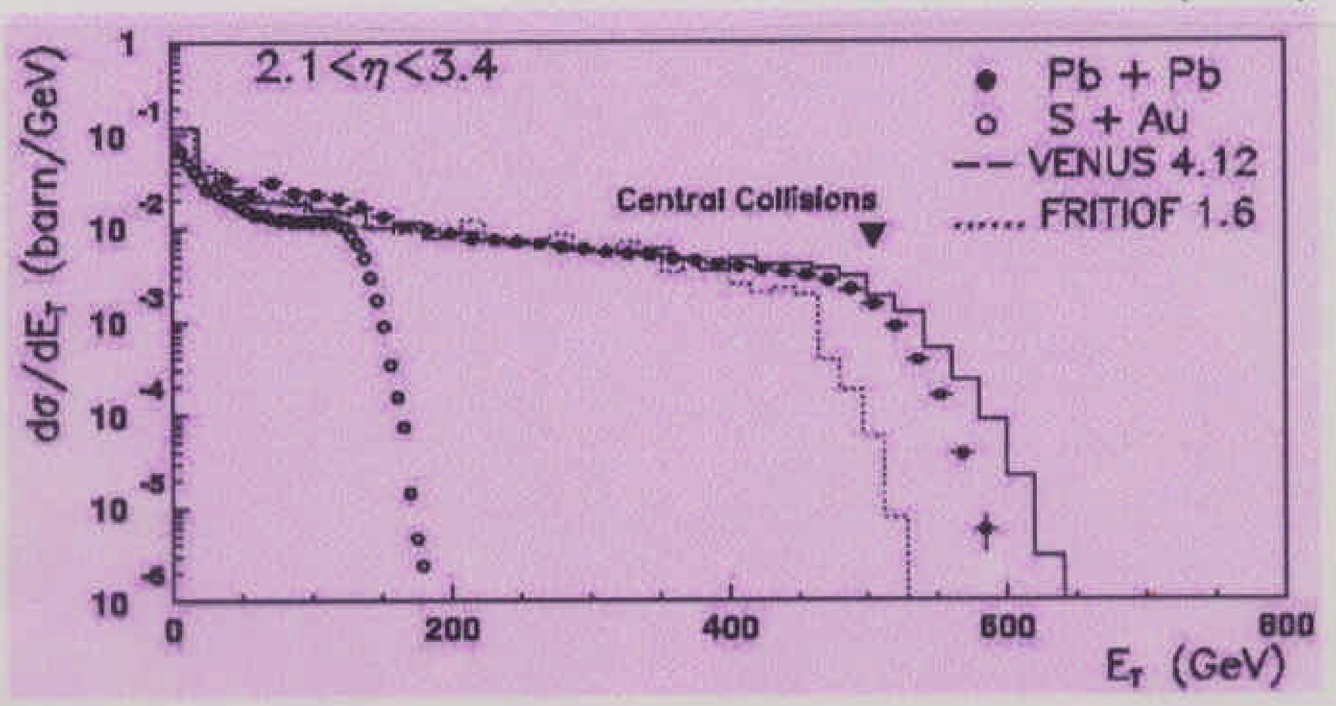
up to 3(L/10fm) GeV/fm at T=250 MeV!

Expected Quark Gluon Plasma Signatures

- Probes of the medium
  - J/Ψ suppression due to Debye screening
  - Jet quenching from large energy loss
- Strangeness enhancement
- Thermal radiation
- Chiral symmetry restoration
  - predicted by QCD
  - observable when partial restoration
    - -> modification of hadron properties
      - mass, width, decays

Was the energy density high enough?

PRL 75, 3814 (1995)



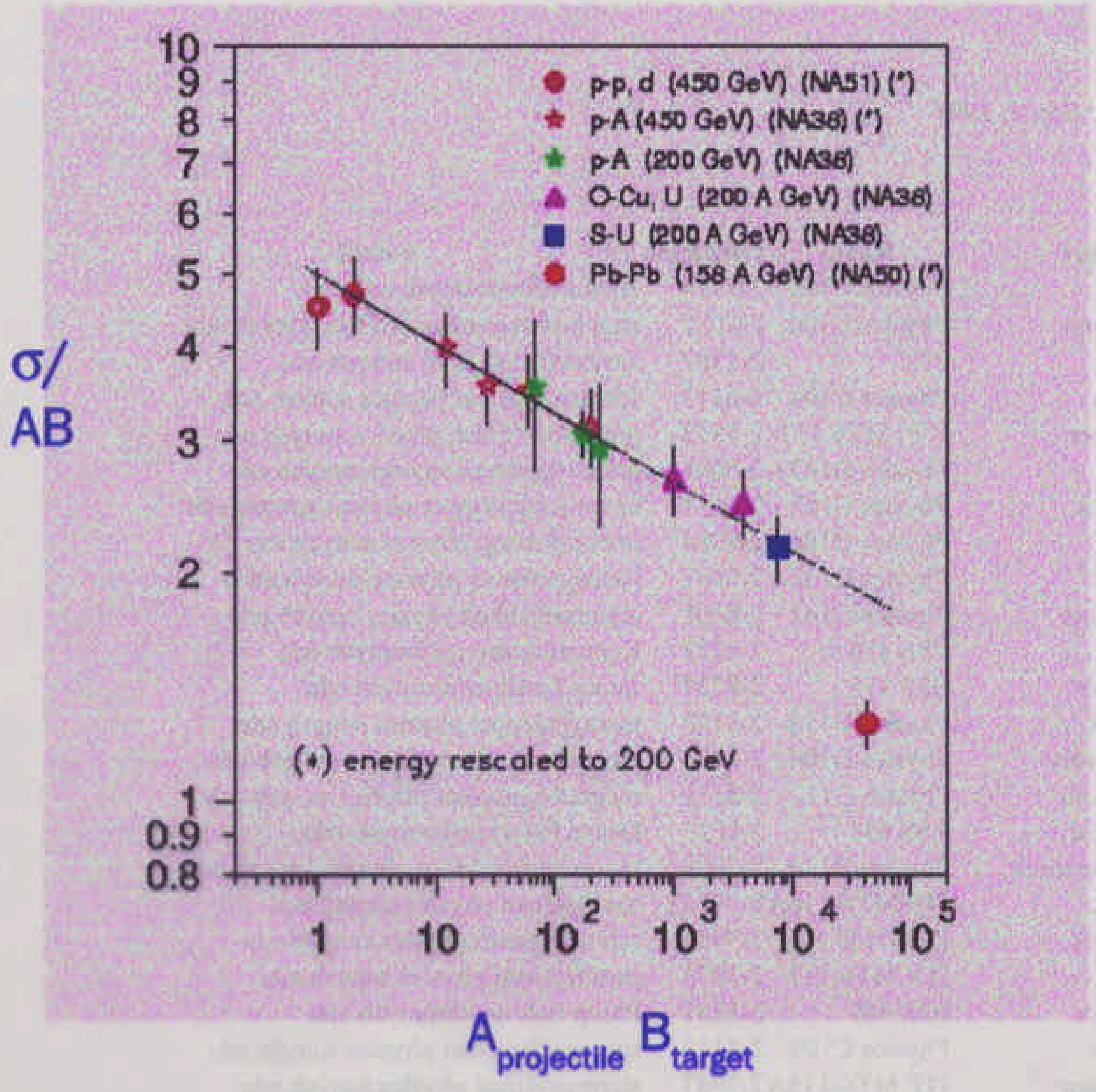
- Energy transverse to beam measures available energy
- scaling longitudinal expansion (Bjorken)
  - $\varepsilon = dE_T/d\,\eta$ * 1/volume
  - volume = (πR^2) * τ
  - $R = 1.2\,A^{1/3}$ (0.9) ← definition of central collision
- initial energy density $\varepsilon \sim 3.2$ GeV/fm^3

Screening by QGP

Matsui + Satz '86

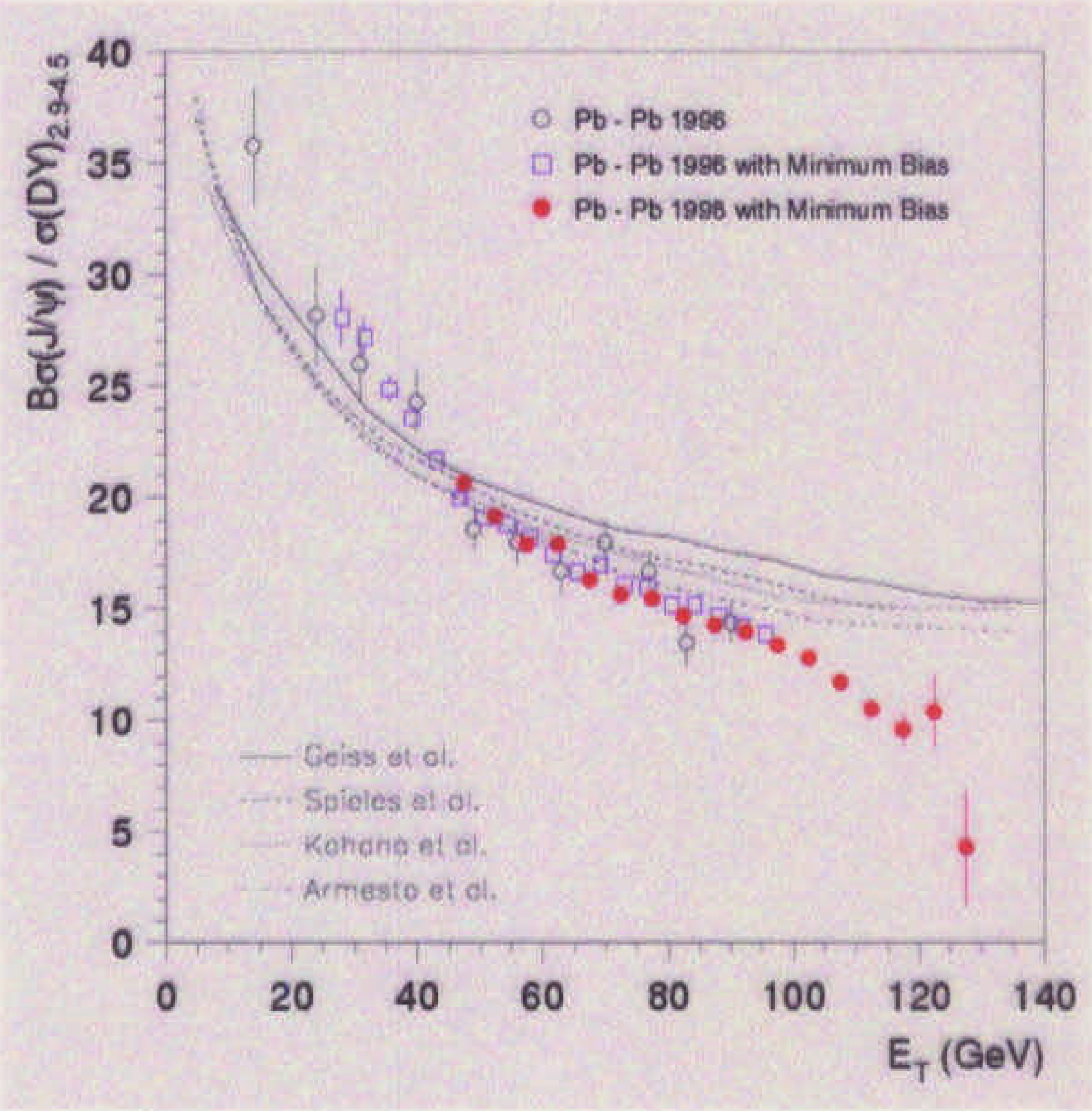
- J/Ψ is $c\bar{c}$ bound state ; formed early
  binding energy ~ 650 MeV, r ~ 0.29 fm
- c and $\bar{c}$ are screened in color field of QGP
  -> J/Ψ unbound
  Debye screening length is function of T
  λ ~ 0.4 fm at T=200 MeV
  Ψ' even easier to break up
  BE ~ 60 MeV, r ~ 0.56 fm
- use J/Ψ and Ψ' to test screening length (energy density) of matter

J/psi suppression



NA50

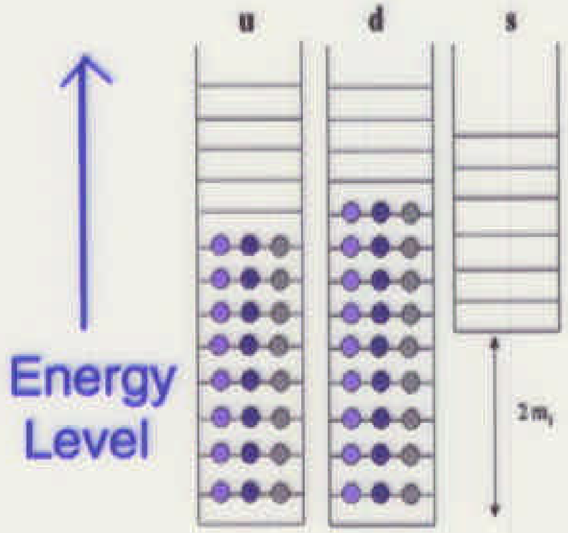
suppression beyond conventional explanations



peripheral <--- b central

Strangeness enhancement

- Strangeness equilibration (enhanced vs. pp collisions)
  Rafelski & Mueller, PRL 48, 1066 (1982)
  deconfinement -> increased g+g -> increased $s+\bar{s}$

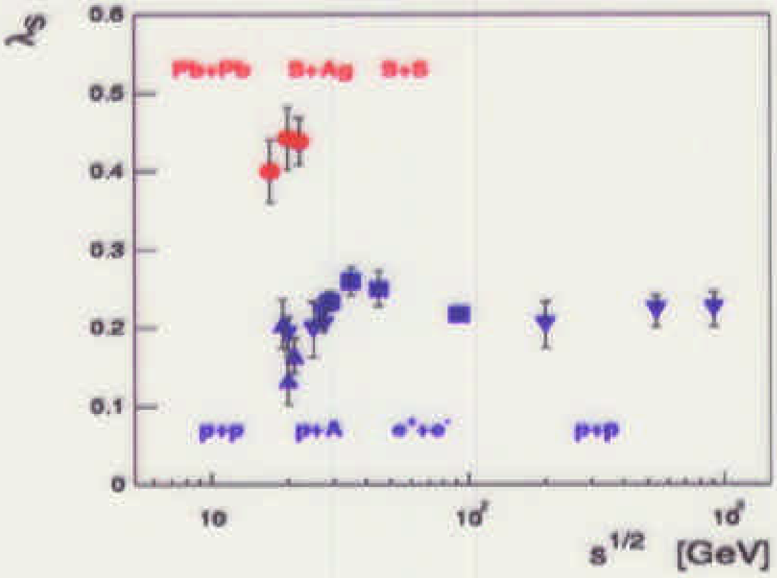


in elementary p-p collision:
u,d quark levels are empty
s quark levels have large energy gap
-> strangeness suppressed

in A-A with QGP:
u,d quark levels occupied
s quark levels have gap

-> strangeness enhanced

enhancement observed



enhancement observed!

but can happen in dense hadron gas too!

via π+N -> K+Λ

- strange hadrons (1 s) enhanced AGS & SPS

  hadron gas can equilibrate strangeness
  requires ~ 10 fm/c
  likely at AGS and also SPS

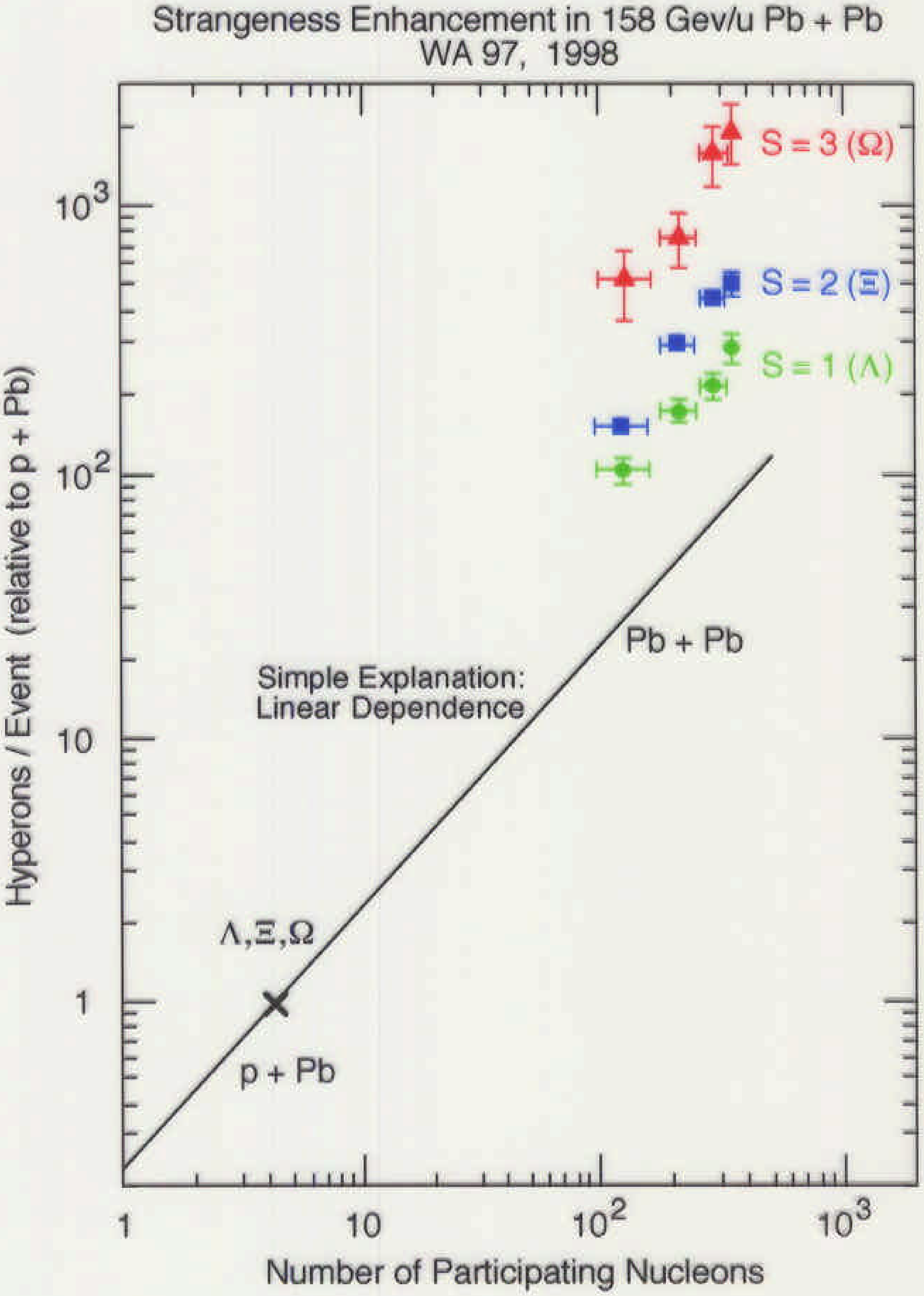
  -> not simple superposition of NN!!

  dense matter, but confined or deconfined?

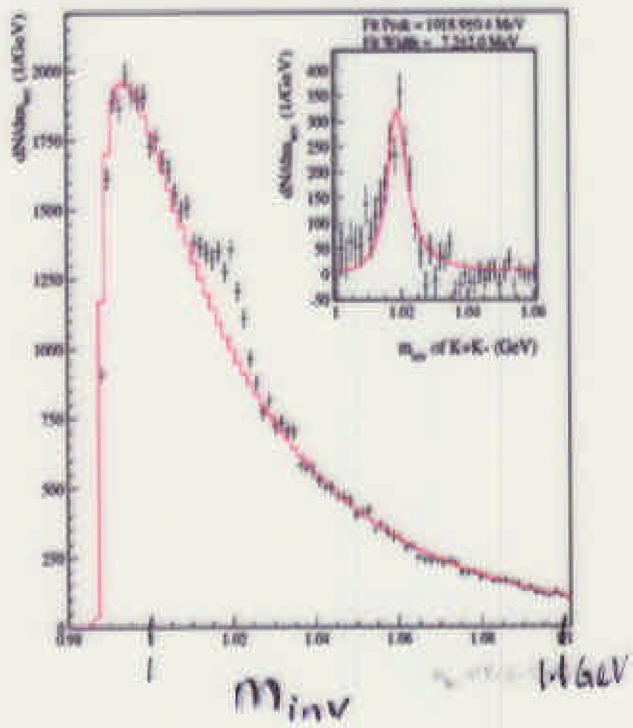
- so, look at multi-strange baryons

  would need ~100 fm/c to equilibrate
  system doesn't last that long!

ANL-P-22,595

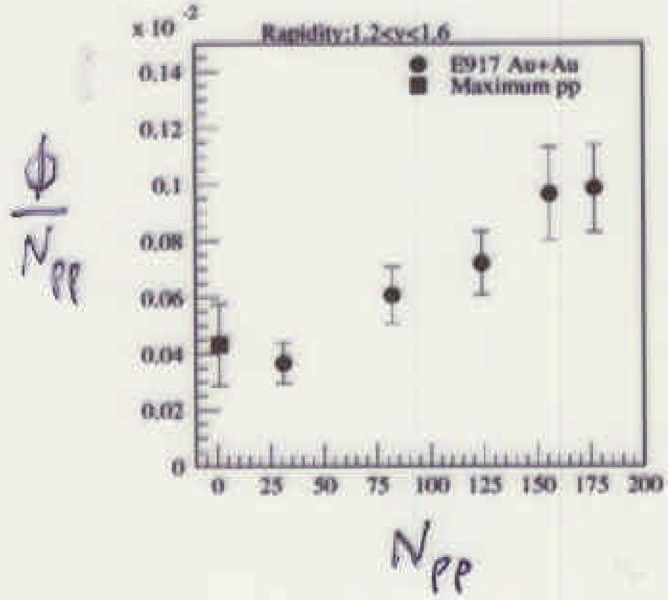

Strangeness Enhancement in 158 Gev/u Pb + Pb
WA 97, 1998
S = 3 (Ω)
S = 2 (Ξ)
S = 1 (Λ)
Pb + Pb
Simple Explanation:
Linear Dependence
Λ,Ξ,Ω
p + Pb
Hyperons / Event (relative to p + Pb)
Number of Participating Nucleons
1
10
10^2
10^3

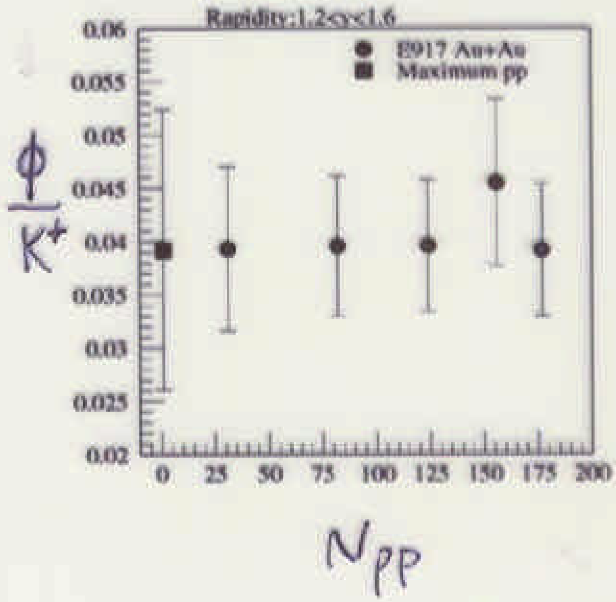
E917 at AGS (11 GeV/A)



measure φ -> KK as a function of participant nucleon number (i.e. centrality)

φ is enhanced at same rate as K+
associated production?
φ dynamics more complicated!

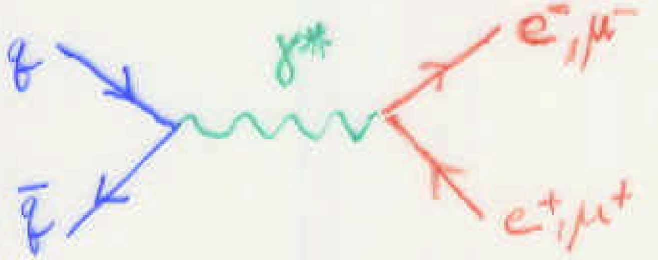




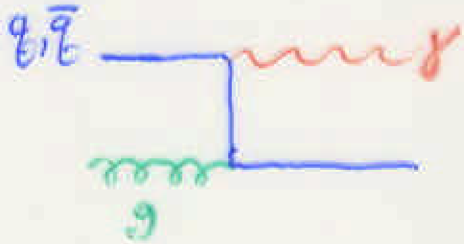
Thermal Radiation

- Measurable rate predicted by Shuryak, Ruuskanen, Kajantie, others

thermal dileptons



thermal photons



thermal rate ~ T^4, dominated by T_{init}

distribution ~ $e^{-M/T}$

bremsstrahlung in QGP important too

qq(g) -> qq(g) γ

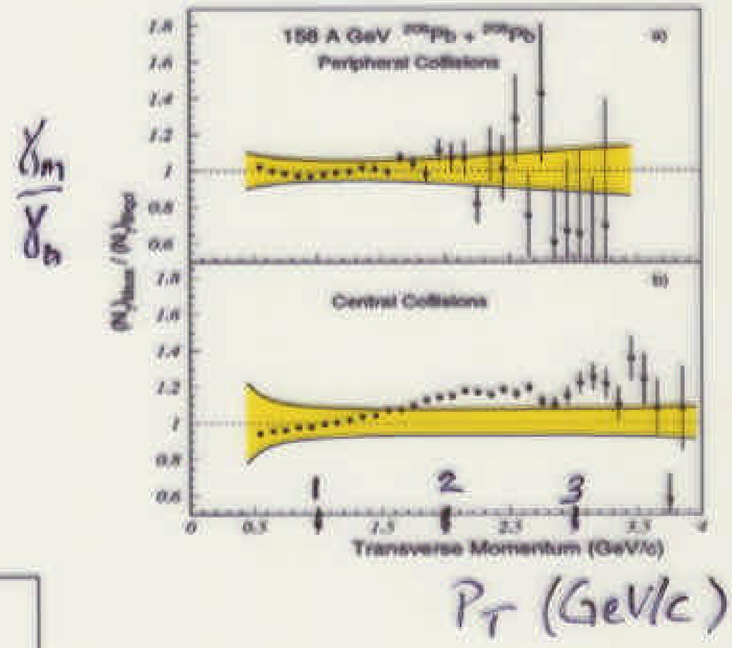
- But hadron gas radiates as well

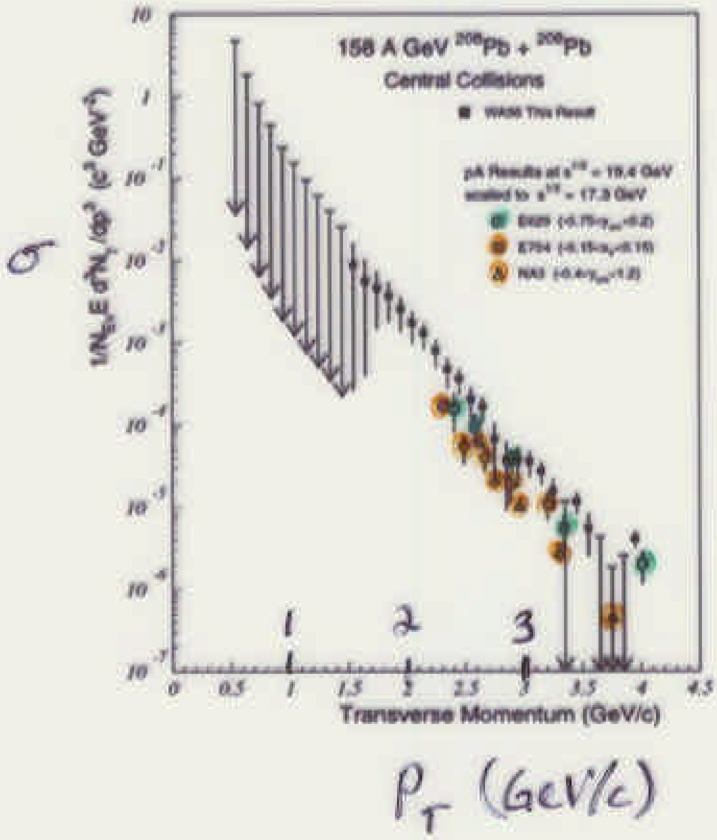
radiation indicates T_{init}, not phase

measure and compare with T_C

Direct photons seen by WA98

Excess photons beyond hadronic decays





does slope differ from p-p?

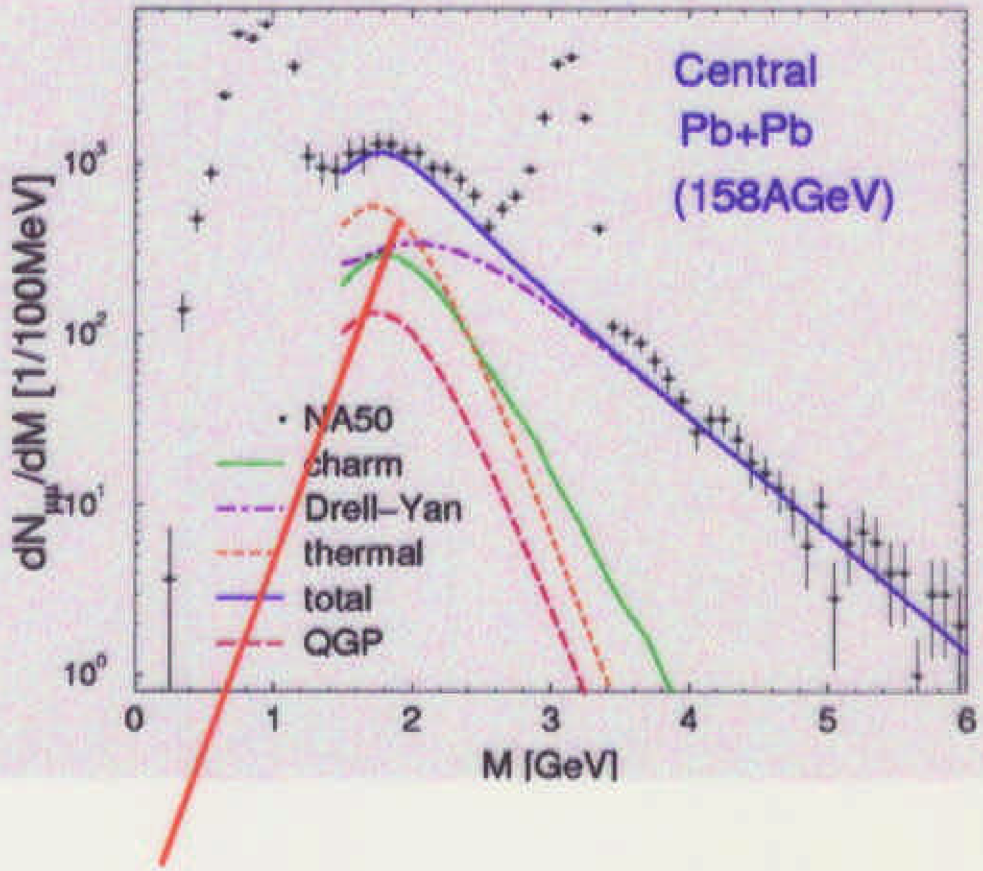
mix of hadron & QGP contributions?

consistent with $T_{init} > T_c$

Are thermal leptons seen?

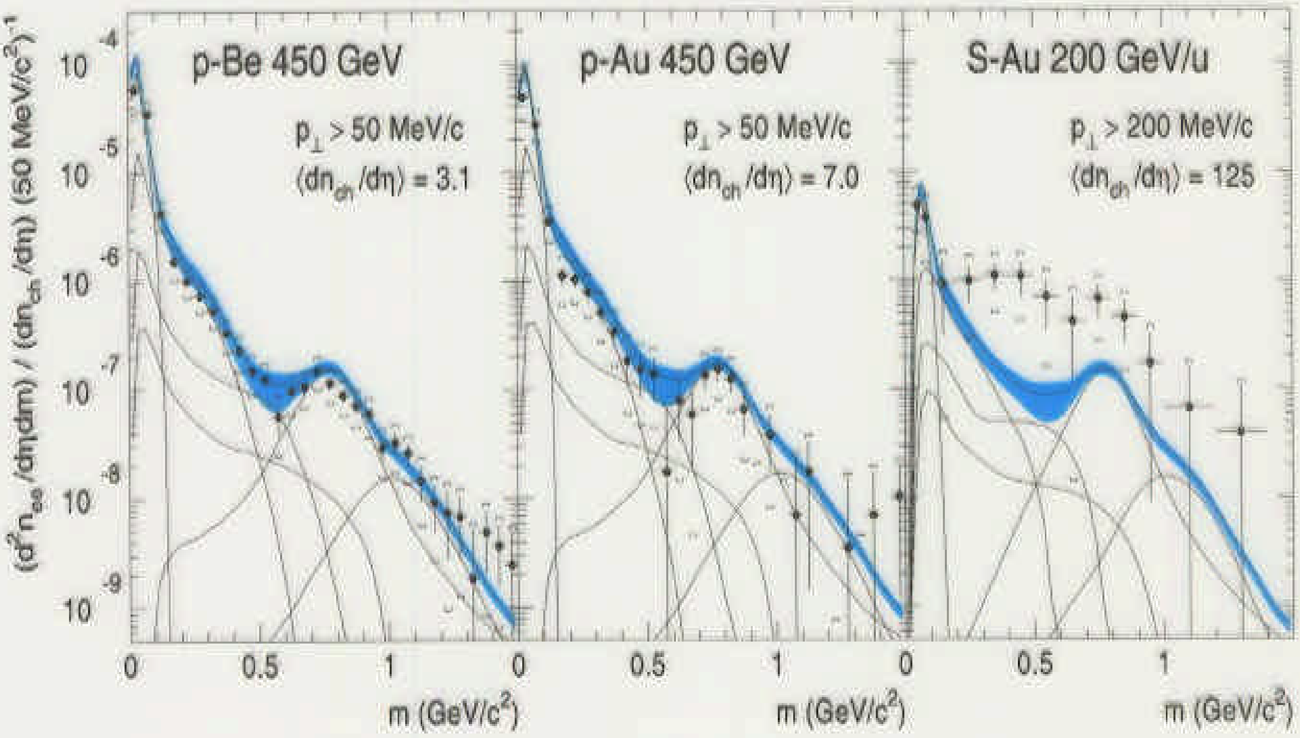
NA50 measures $\mu\mu$ pairs at $1 < m < 3$ GeV

Rapp & Shuryak, Phys. Lett. B473, 13 (2000)



thermal radiation $T_i \sim 200$ MeV
from QGP + hadronic phase
rates dual at same T
integrate over collision time & expansion

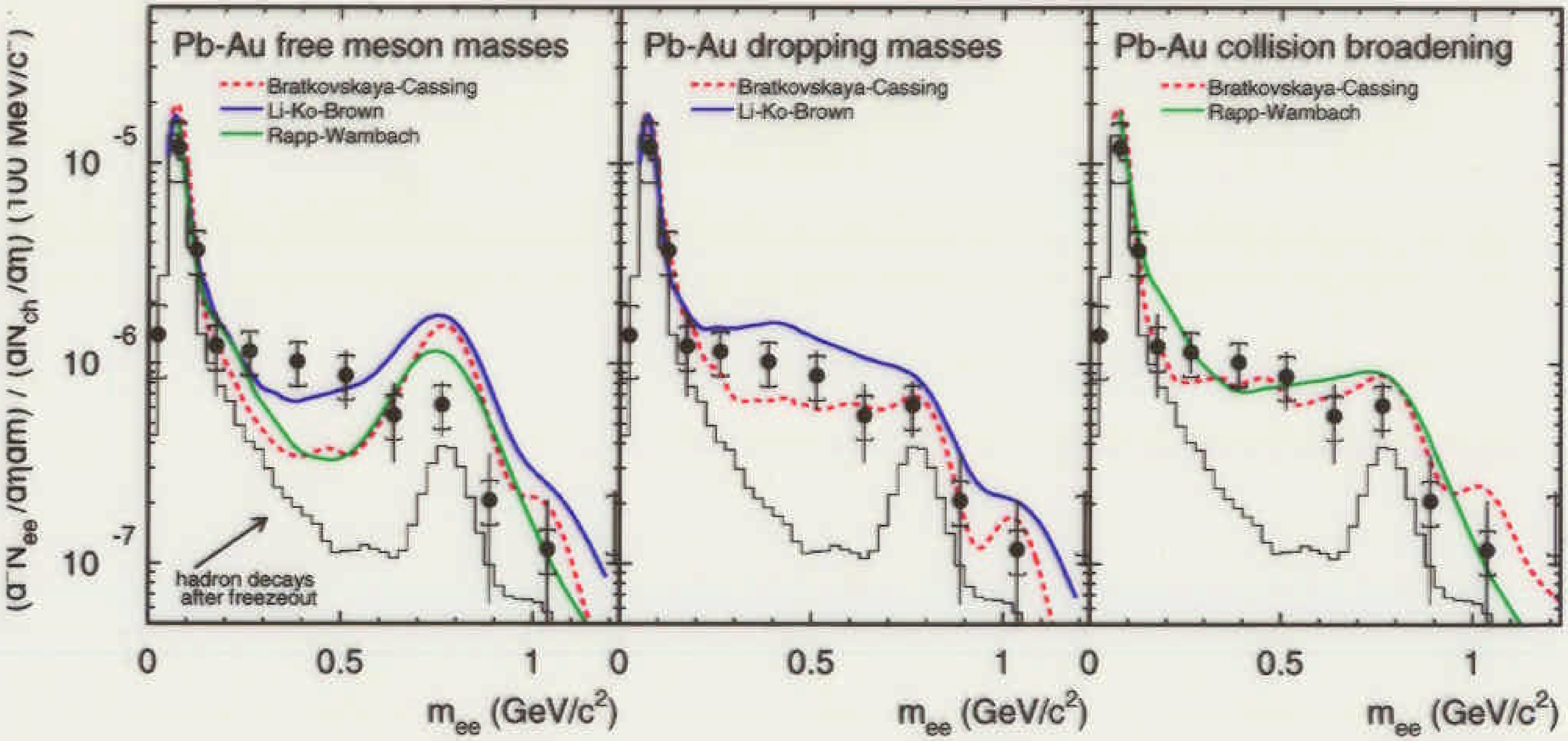
enhanced lepton pairs



CERES collaboration

Predictions for Pb-Pb Collisions

rescaled calculation to fit experimentally observed dN_{ch}/dy



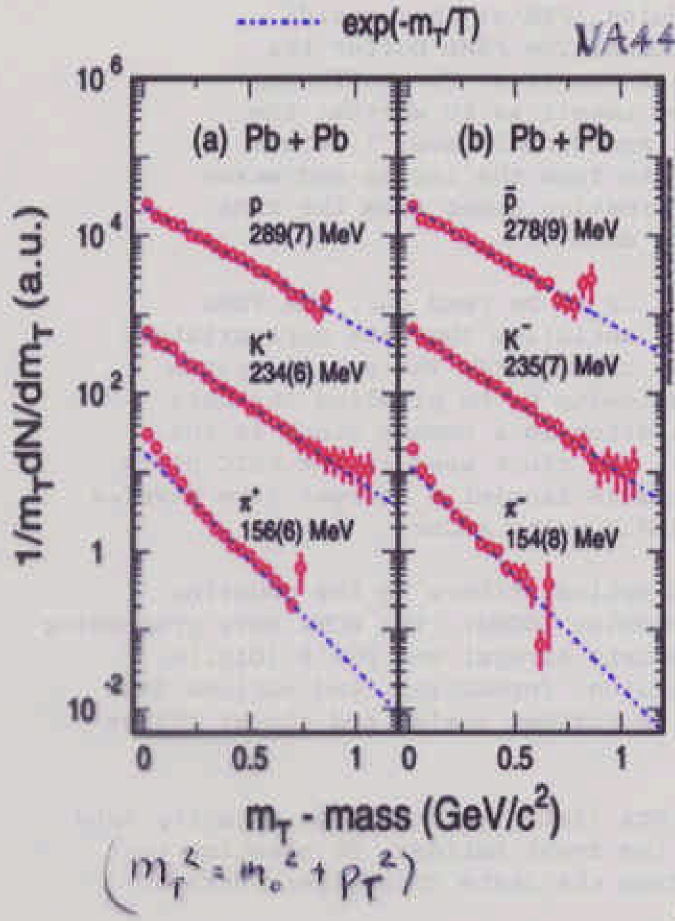
- same situation as for S-beam data
- dropping masses and collision broadening is not distinguished

Hadron gas stage

- Dense system expands and cools
  when $T < T_c$ hadrons form
  hadron gas is still very hot and dense
- Collective expansion boosts particle kinetic energies
  $T_{apparent} \sim T + (1/2)\, m_0 \langle v_T \rangle^2$
  boost depends on m_0
- hadrons radiated at late stage
  $dN/dp_T^2 \sim \exp(-p_T/T)$
  particle masses differ, so instead of p_T
  use $m_T = (p_T^2 + m_0^2)^{1/2}$
- hadronic observables reflect freezeout
  i.e. mean free path > system size

- hadrons -> collision dynamics
  hadron gas phase affect QGP signatures

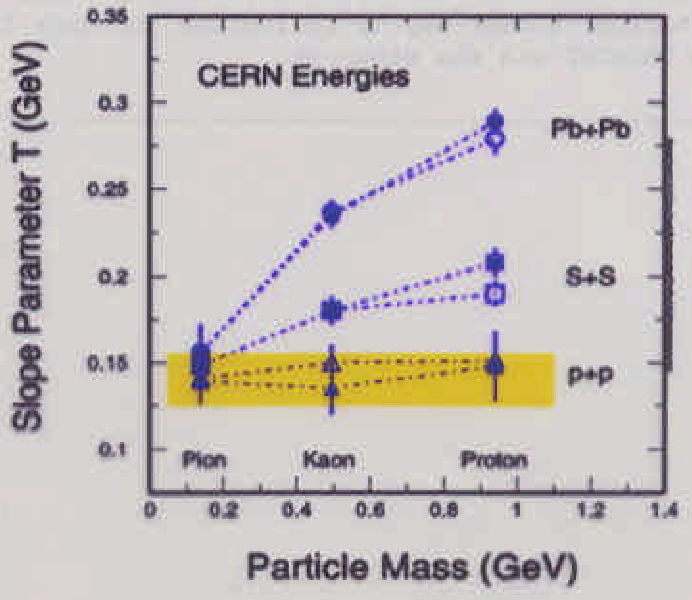
160 GeV/A Pb + Pb



Hadron spectra reflect thermodynamics of the system at freezeout

spectra are convolution of thermal and collective motion

observe increasing radial expansion for larger systems



Bose Einstein Correlations

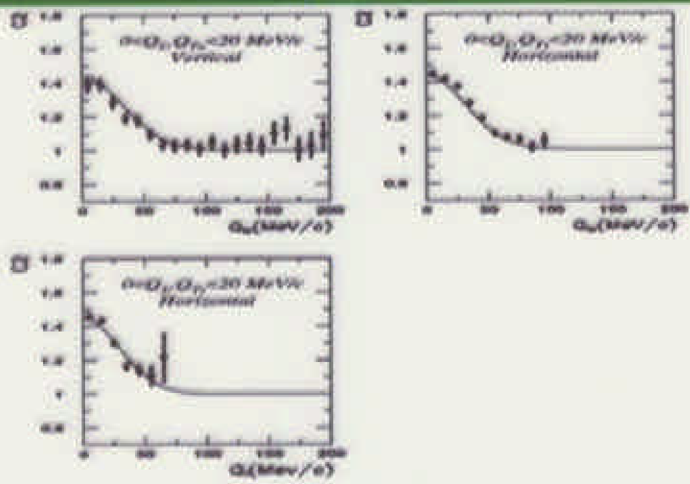


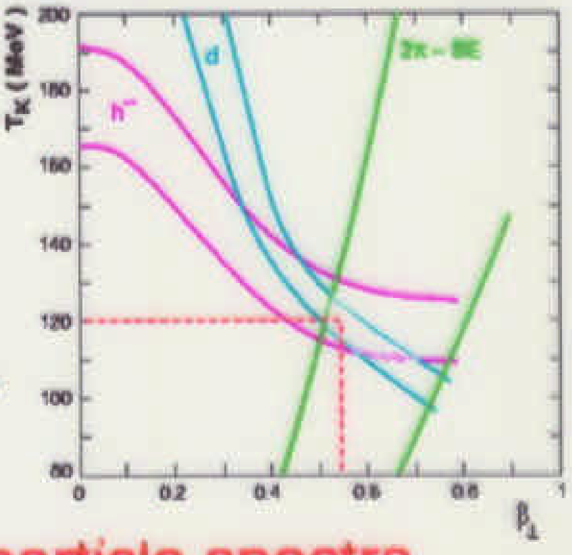
Figure 3: $\pi^+\pi^+$ correlations of S + Pb interaction.

$\pi\pi$, KK correlations reflect hadron gas size at freezeout

high statistics data
3-d analysis
function of m_T

<- NA44

NA49 Pb+Pb Hadronic Expansion Dynamics



sensitive to thermal & collective motion

NA49 ->

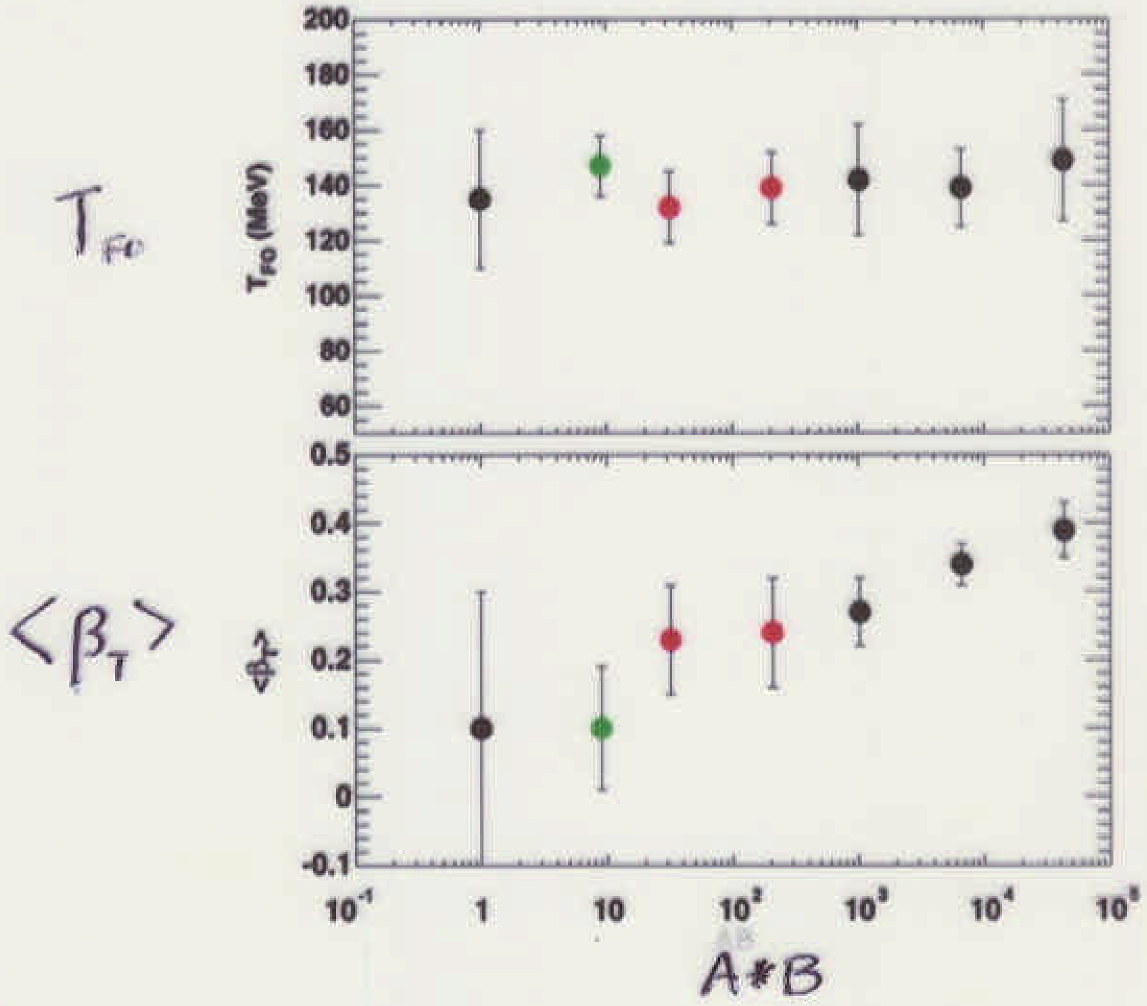
combining with single particle spectra

T_{FO} ~ 100 - 120 MeV

$\langle v_T \rangle$ ~ 0.45 - 0.55c

Expansion increases with system size

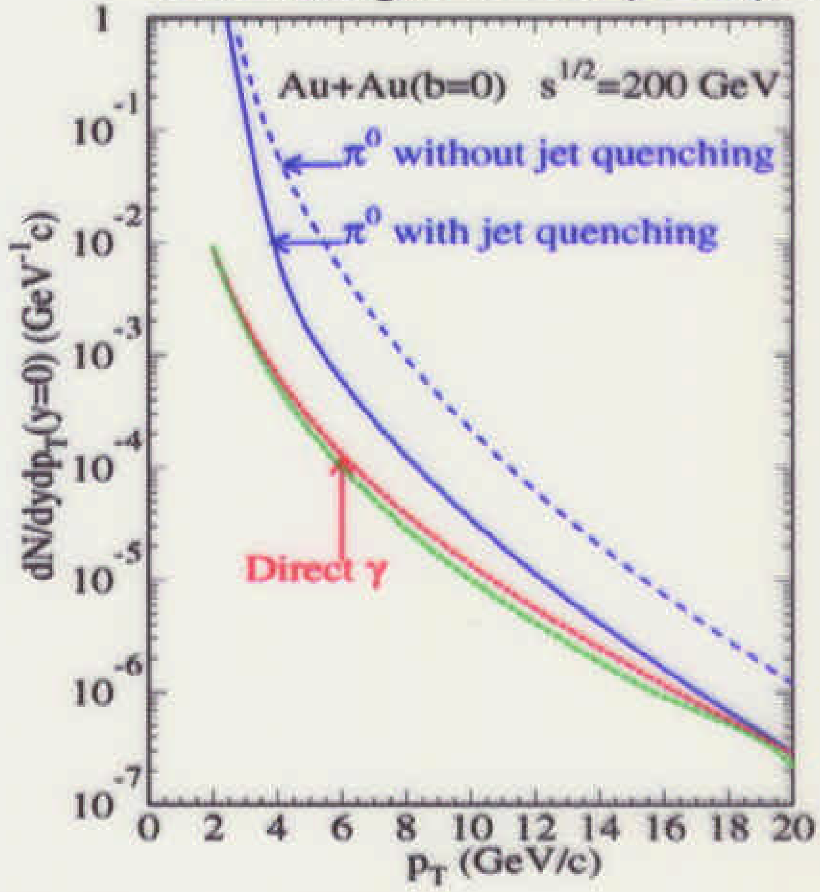
Jane Burward-Hoy



Slopes fitted up to $p_T \sim 1$ GeV/c

Jet quenching

XN Wang, PRC58 (1998) 2321



- Signatures:
  - decreased high p_t tail of π^0
  - increased γ/π^0
- Not observed at CERN!
  - p_t ~ 3-4 GeV/c is mix of hard & soft physics due to boost by radial expansion

IMPORTANT OBSERVABLE AT RHIC!

Nailing down the QGP

- Is quark gluon plasma observed at CERN?

  probably!

  BUT - lack
  - correlated experimental signatures
  - complete, consistent dynamic theory
  - energy threshold for deconfinement
  - characterization of QGP

- Need
  - determination of T_{init} via EM radiation
  - measurement of jet quenching
    - untangle soft vs. hard physics
  - see multiple signatures at same condition
  - signature of the hadronization transition

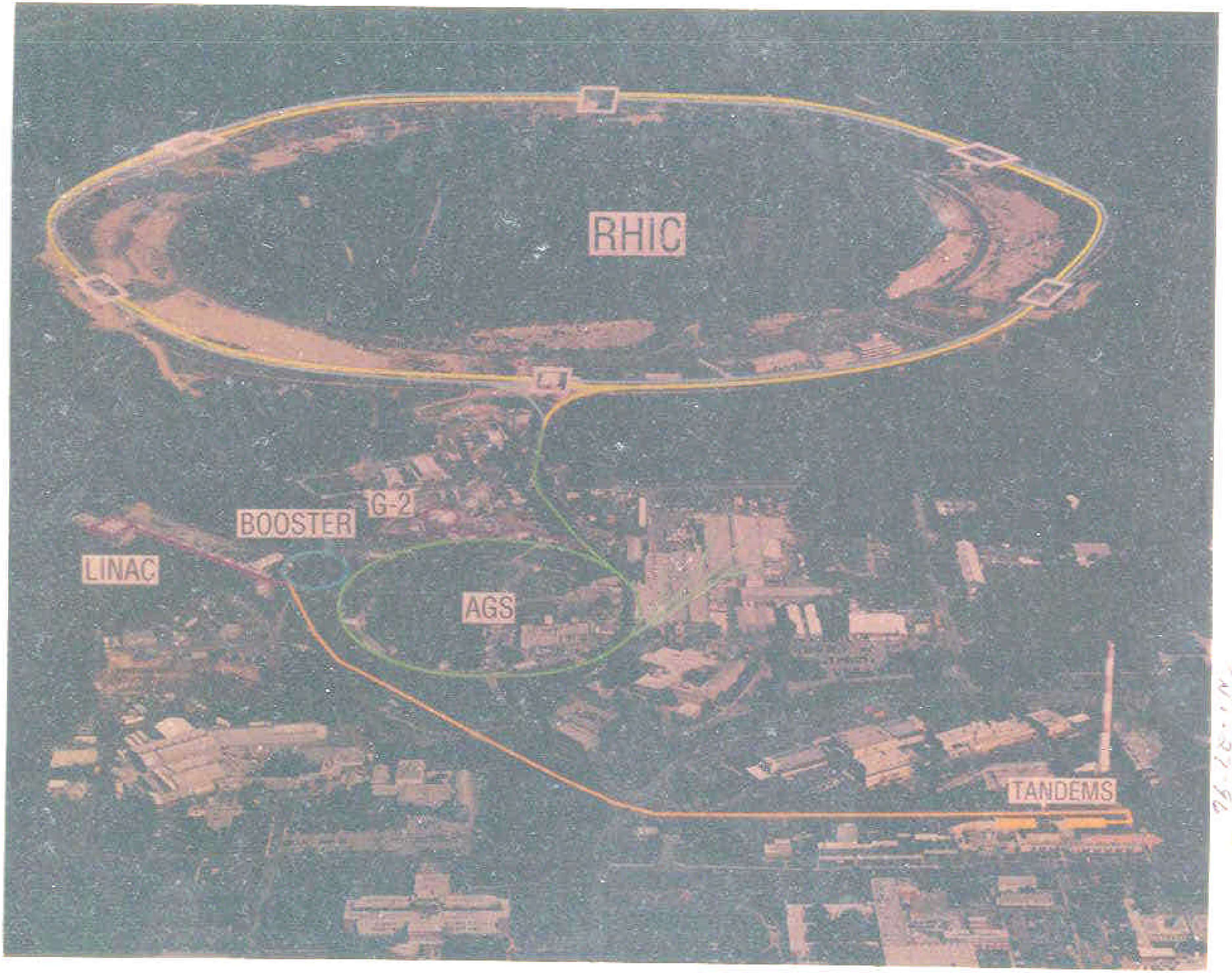
Relativistic Heavy Ion Collider

- 200 GeV/nucleon cm energy
  2 colliding 100 GeV/A beams
  can get up to $\sqrt{s}$ = 500 GeV for p-p

- p-p, p-A, A-A
  accelerate up to Au

- Luminosity
  p-p ~10^{31} $cm^{-2}sec^{-1}$
  p-Au ~10^{29}
  Au-Au ~2 x 10^{26}

- Running now at 65 GeV/A each ring
  $\sqrt{s}$ = 130 GeV/nucleon
  seeing collisions in all 4 experiments
  beam store lifetimes ~ 4 hours



N1-27-96

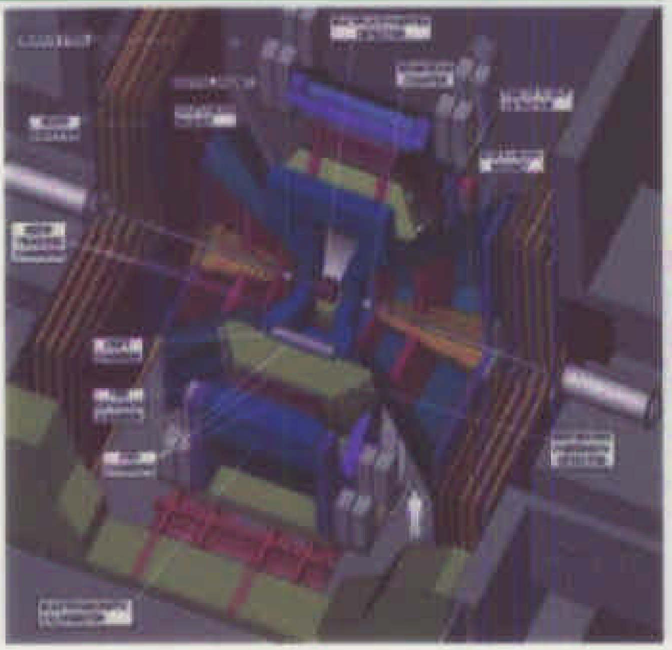
New physics attainable at RHIC

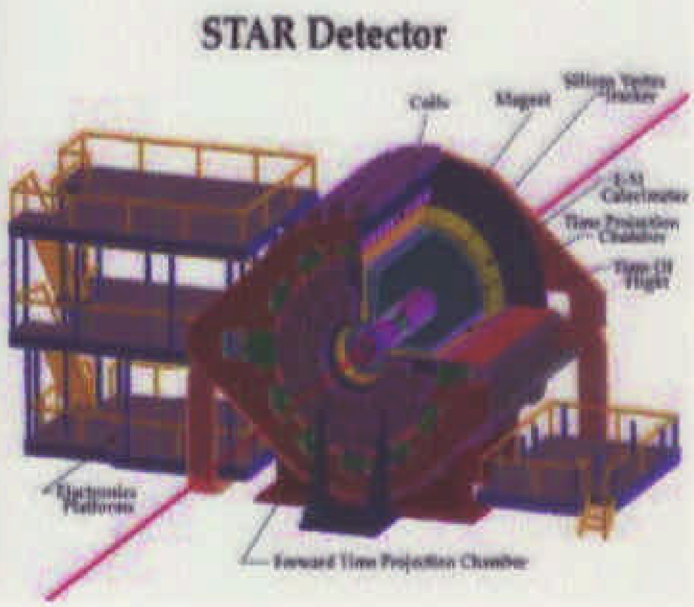
- higher $\sqrt{s}$
  - higher T_{init}
  - longer QGP life (in each collision)
  - higher σ for hard processes
    - jet rate sufficient for energy loss study
  - probe small x partons in nuclei
    - hot glue -> enhanced gluon fusion?
- more running time
  - statistics for J/Ψ, high p_t
- experimental resolution and acceptance
  - ω,ϕ widths, branching ratio
  - event-by-event analyses

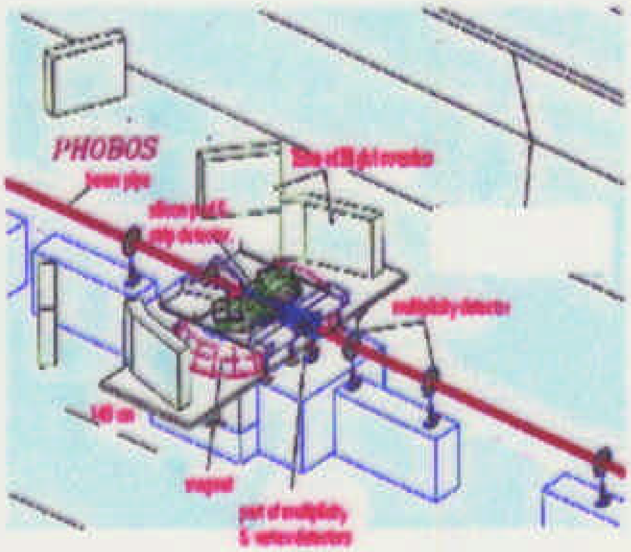
4 Experiments to cover all observables

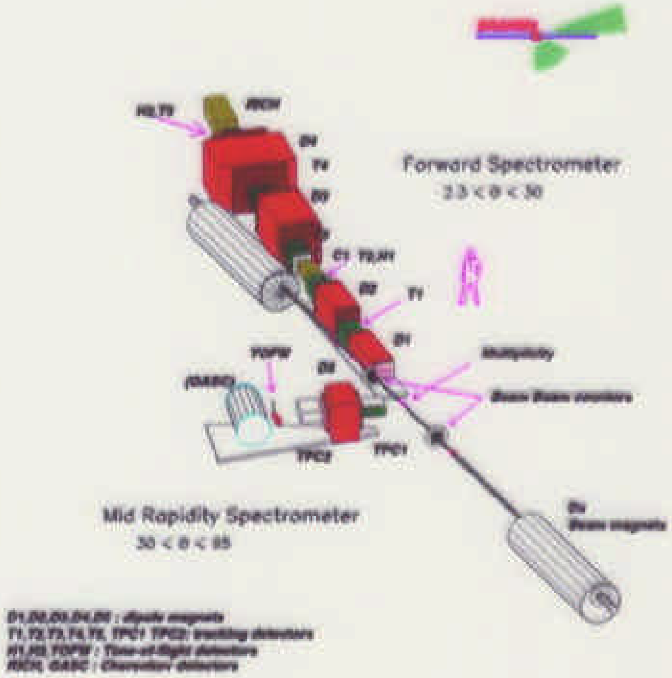
- PHOBOS
  hadrons at low p_t
  DCC search on Day-1
  full coverage multiplicity measurement
- BRAHMS
  identified hadrons over wide y, p_t range
- PHENIX
  leptons, photons and global quantities
  sample hadrons to characterize collisions
  high rate to study rare processes
- STAR
  full azimuth acceptance for hadrons, jets
  triple differential cross sections
  event-by-event analysis
- zero degree calorimeter to provide common event selection

Experiment layout

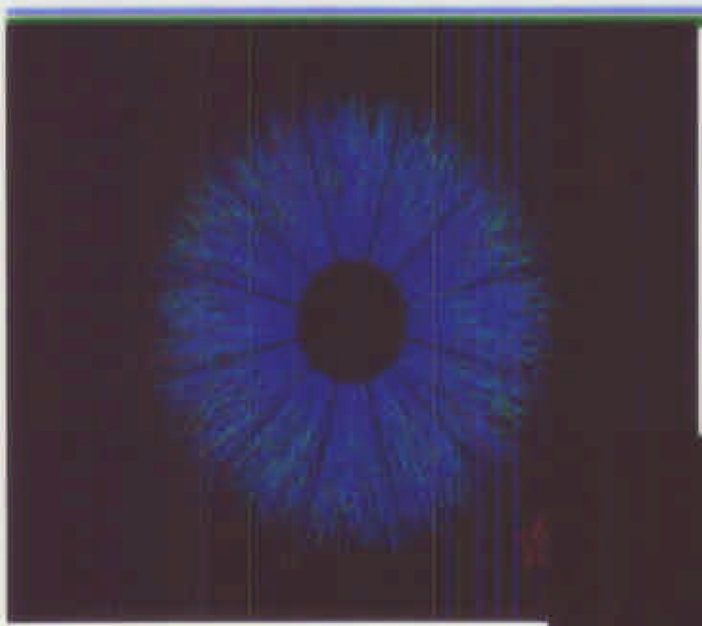




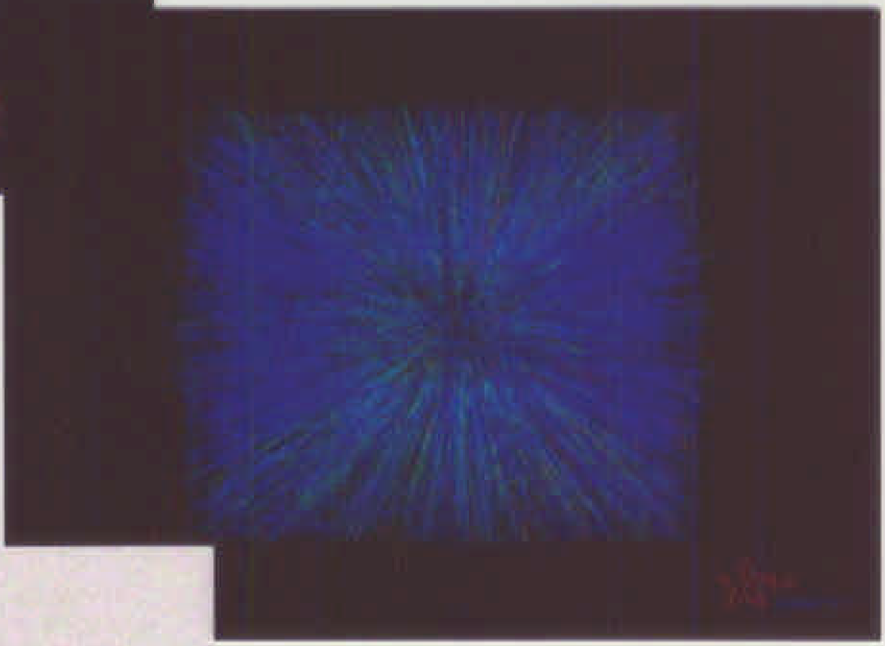


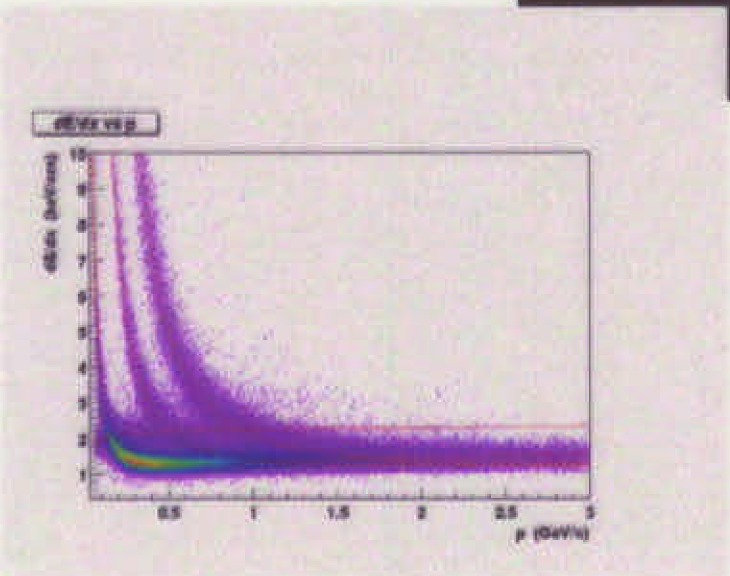


First events in STAR



$\sqrt{s}$ = 130 GeV/A
Au + Au
central collision

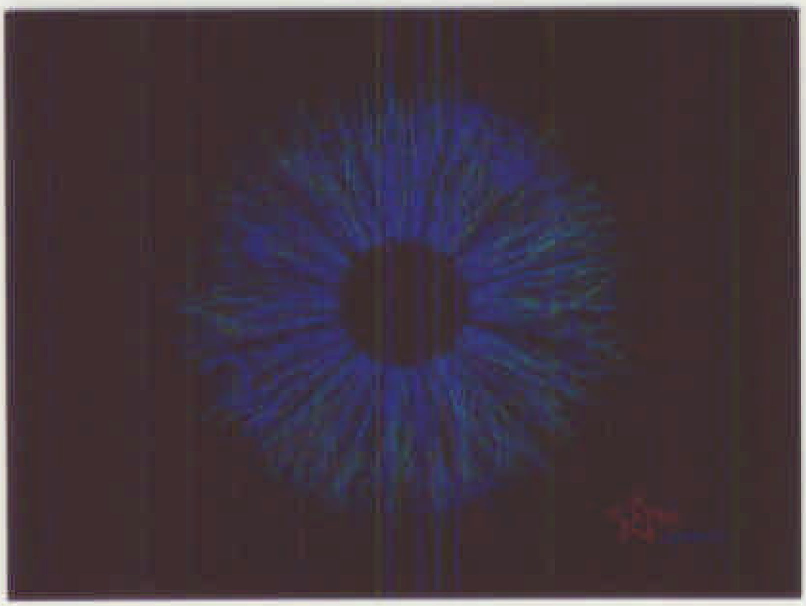




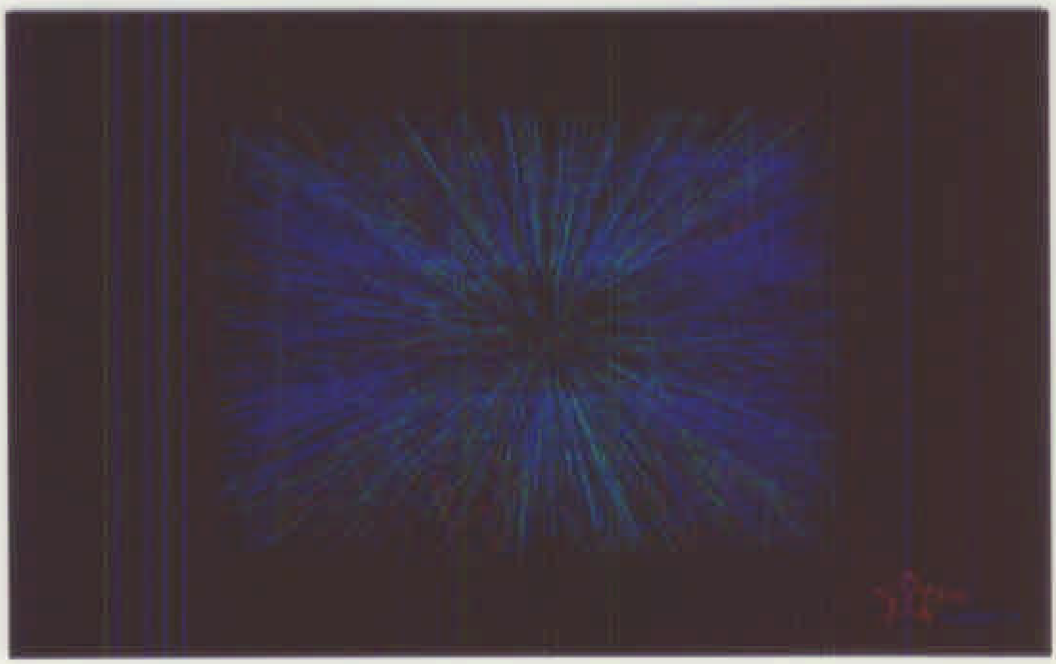
dE/dx in TPC
vs. momentum

PID performance
clear!

plotting half the TPC



front view

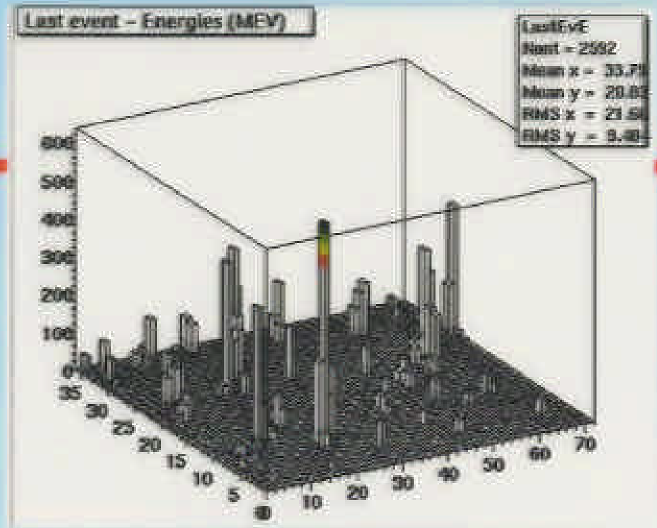


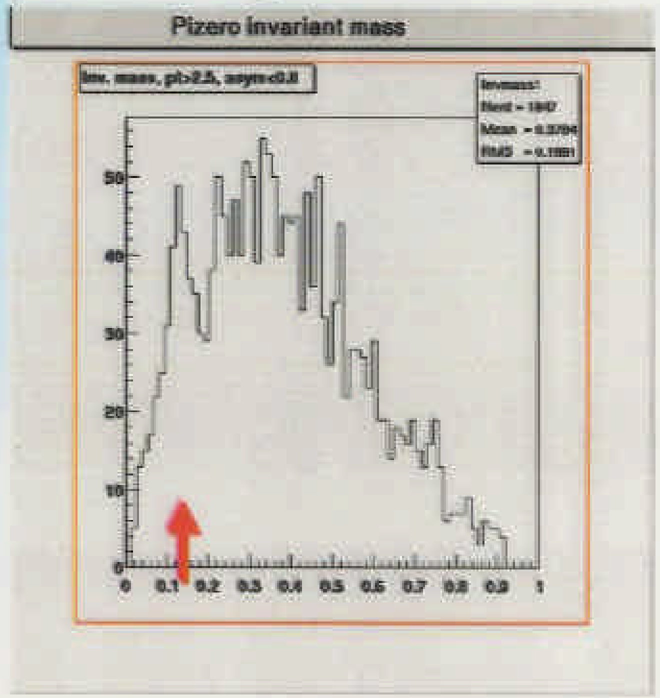
side of TPC nearest the viewer

Calorimetry

- High particle density, broad dynamic range
  - good granularity
    $\Delta\eta = \Delta\phi = 0.01$
  - good energy resolution
    $\sim 8\%/\sqrt{E}$
  - good time resolution
    $\sim 250ps/\sqrt{E}$

Pb-glass + Pb-scintillator
- 25,000 channels



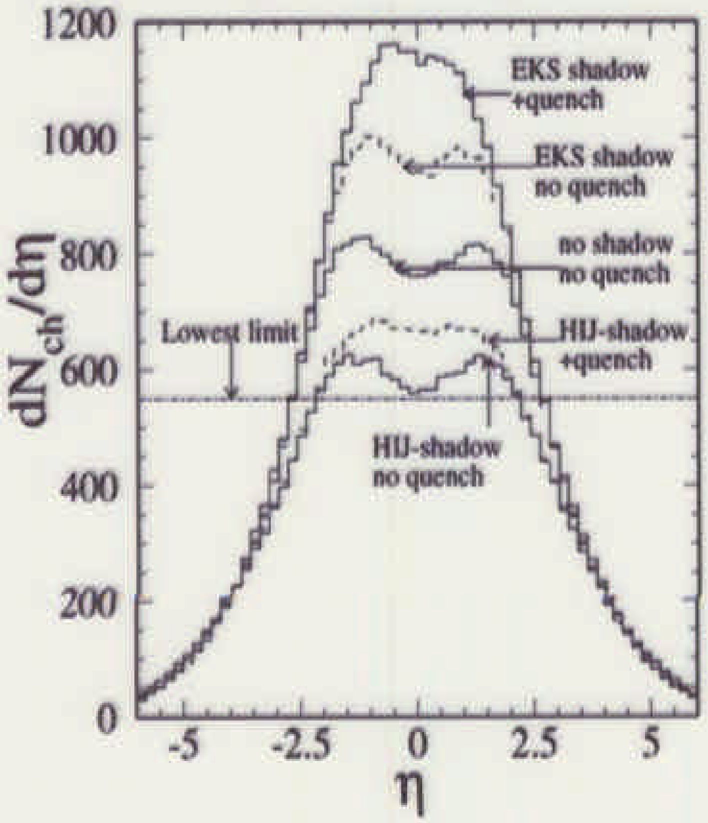


July 27, 2000

BROOKHAVEN NATIONAL LABORATORY

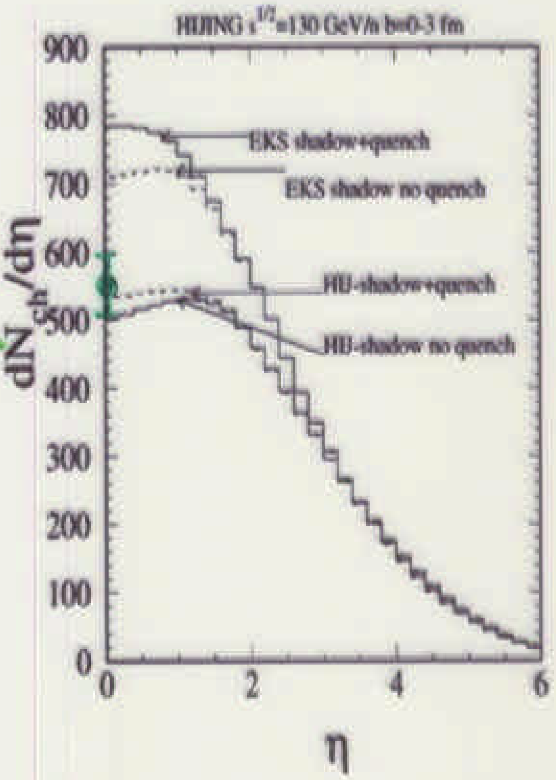
Charged particle multiplicity

XN Wang, Nucl. Phys. A661, 210c (1999)



N_{ch} reflects:
parton mult. scattering
(anti)shadowing
dE/dx (jet quench)

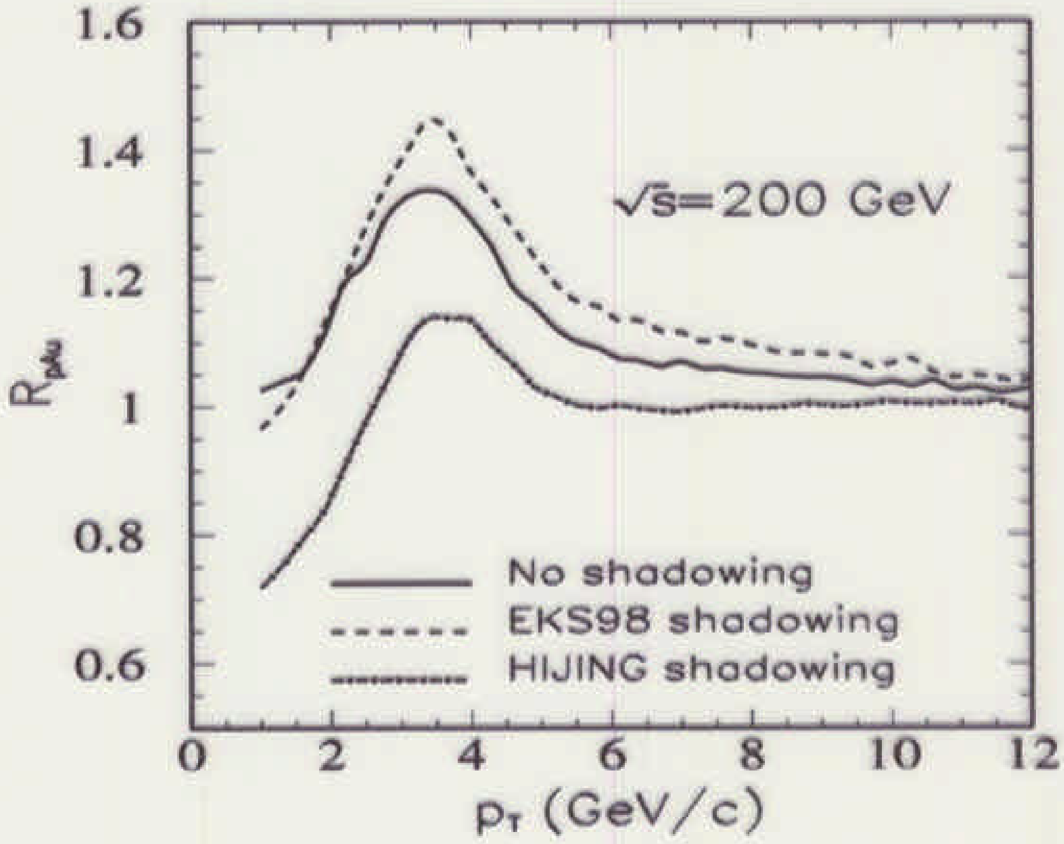
PHOBOS
hep-ex/0007036



looks like no antishadowing at $\sqrt{s}$=130 GeV/A

Uncertainty about shadowing at RHIC

XN Wang, PRC61 (2000) 064910



Will measure using pA collisions!

conclusions

- have produced dense, interacting matter
  - can extract physics from complex events
  - interactions drive equilibration
- ***probably made plasma at CERN!***
  - multiple signals, independent measures
  - BUT lack coherent theoretical description
  - need to characterize T_{init}, properties
- RHIC is up and running!
  - pA -> shadowing -> significant dE/dx!!
  - should reach high T_{init}
    - characterize via EM radiation
    - hard processes & hot glue
  - experimental program with common event selection
    - constrain theory via SUITE of observables