High p_T Physics in the $Au + Au$ Program with the STAR Experiment at RHIC

$\rightarrow$ In Search of Quark-Gluon Plasma Formation

Dr. Kathleen Turner
Brookhaven National Laboratory

Purdue University
16 November 1999

Will Cover:

- Introduction
- The Relativistic Heavy Ion Collider
- The STAR Physics Program
- The STAR Detector
- Why Do High p_T Physics at RHIC?
- High p_T Physics Measurements with STAR
- Summary & Future

Quark Gluon Plasma

$\Rightarrow$ Quantum Chromodynamics (QCD):

- ◦ "Standard Model" describing strong force between colored objects (quarks and gluons)
- ◦ Requires that partons exist only in color singlets, i.e. inside hadrons

perturbative QCD calculations: applicable only for large momentum transfers, small coupling

lattice gauge theory: numerical calculations of QCD observables in non-perturbative regime
(currently deals with simple systems)

$\star$ Lattice QCD calculations show two expected phase transitions at high energy densities:
energy density $\approx 1\ \mathrm{GeV/fm^3}$
(temperature $T \approx 200$ MeV $= 10^{12}$ K)

- transition to a color-deconfined state of matter:
  Quark Gluon Plasma (QGP)
  $\rightarrow$ quarks and gluons exists freely
- chiral symmetry restoration
  $\rightarrow$ quark masses go to zero

Nuclear Phase Diagram

Understanding the Phase Transition

Simple Examples:

1. squeeze hadrons to about 10 times the normal nuclear density ($= 0.16\ \mathrm{GeV/fm^3}$)
2. increase energy (temperature) of system

Where Can We Find the QGP?

The QGP is predicted to have existed in early universe and may exist today in core of neutron stars.

How do we construct this phase transition to QGP in the laboratory so we can study it?

$\Rightarrow$ Use collisions of nuclei at high energies!

- create hot, dense matter of quarks & gluons
- study how matter behaves in this environment
- do we get phase transition to QGP as predicted?

... at AGS, SPS and now
at the *Relativistic Heavy Ion Collider*
at Brookhaven National Lab!

Relativistic Heavy Ion Collider - RHIC

RHIC will provide collisions of ions from p to Au:

$$p + p, \qquad p + A, \qquad A + A$$

with center of mass energy up to:

p beams: $\sqrt{s} = 500$ GeV (polarized)
Au beams: $\sqrt{s} = 200$ GeV

Why using Gold beams?

- large number of nucleons (197) with energy 100 GeV/nucleon
- large nuclear size

$\longrightarrow$ best hope for volume and energy density needed to create extended QGP state

RHIC Schedule

- RHIC proposed - 1984
- RHIC designed and built throughout 1990's
- RHIC commissioning - Summer 1999
- RHIC operation for physics - begins in Spring 2000

STAR Physics Program

$\longrightarrow$ Study behavior of high temperature, high density nuclear matter created in RHIC collisions

$\longrightarrow$ Search for Quark Gluon Plasma formation - did quarks and gluons become deconfined or stay confined after the collision?

$\star$ Event-by-Event Measurements
- search for nonstatistical fluctuations & unanticipated momentum correlations

$\star$ Low p_T charged particle production
- measurements of energy densities, temp. etc.

- Hadron Spectra (p_T,η) & Strangeness

$\star$ HBT - measurement of space-time characteristics of the high energy density nuclear matter

$\star$ - High p_T hadron and jet production (this talk!)

$\star$ Quarkonium production

$\star$ Peripheral Collisions
- nuclei don't collide - interact via longer range forces (photon & pomeron interactions)

$\star$ Spin Program (using polarized pp running)
- to measure the spin structure of the proton

STAR Detector

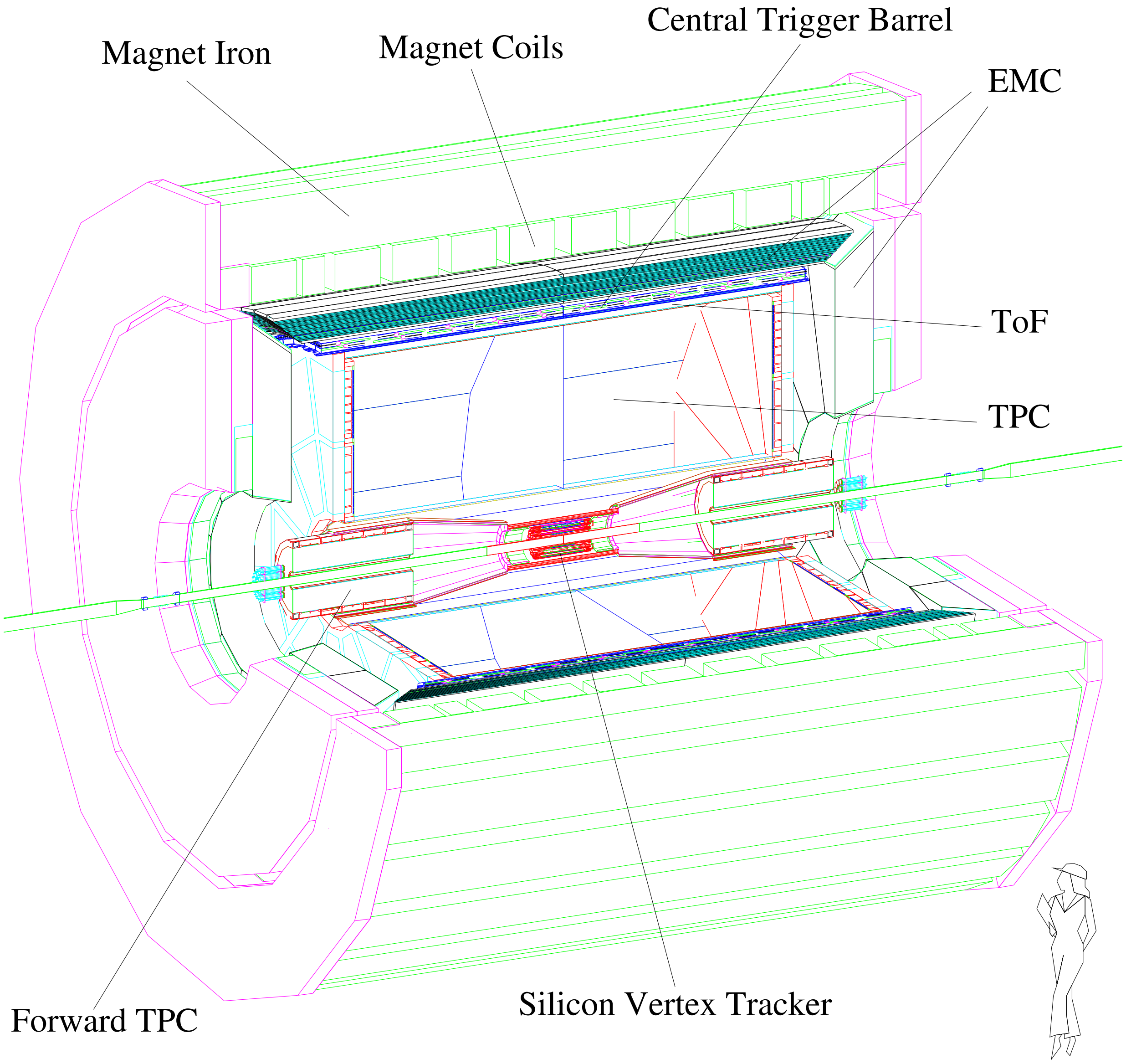
Requirements:

⋆ tracking, momentum measurement and good particle identification of charged particles at mid-rapidity

⋆ accurate primary vertex determination

⋆ EM calorimetry and tracking for high p_T particle and jet measurements

STAR Detector



STAR Detector

STAR has full azimuthal coverage and large η range.
Heart of detector is TPC & 0.5 Tesla solenoidal magnet.

- TPC:
  - tracking and individual track PID
  - $|\eta| < 1.7$, $\Delta\phi = 2\pi$
  - momentum resolution: $\sigma_p/p \leq 1\%$ for $p < 5$ GeV
- RICH:
  - limited angular coverage
  - $0 < \eta < 0.3$, $\Delta\phi \approx 20°$
  - extends PID to $\approx 3 - 5$ GeV
- SVT:
  - vertex tracking, PID
- FTPC:
  - $2.4 < |\eta| < 4.0$
  - 1 side in first year
- EMC:
  - Pb-scintillator sampling EM calorimeter, $+$ preshower & shower max detector
  - segmentation 0.05×0.05 in $\Delta\eta \times \Delta\phi$
  - resolution $\approx 15\%/\sqrt{E}$
  - 4800 projective towers
  - 36,000 shower max pads at $5X_\circ$
  - barrel: $|\eta| < 1$, $\Delta\phi = 2\pi$ (10% in Year1 $+30\%$ added each year)
  - endcap: $1.05 < \eta < 2$, $\Delta\phi = 2\pi$ ($>$ Year2)

Hard Probes for QGP

Need probes which:

· are present in *early* stages of collision evolution

· are able to *distinguish* between confined and deconfined states

· retain information about the initial state of matter through to the final state

Two types of hard probes:

⋆ High p_T hadron (jet) production

This Talk!

⋆ Quarkonium Production (J/ψ)

(STAR is investigating this signal too)

Why Study High p_T Production?

· Large momentum transfer
  $\Rightarrow$ probe small (sub-hadronic) distances
  $\Rightarrow$ formed at earliest time after collisions
    (high temperature, gluon-dominated,
    pre-equilibrium stage of collision)

· high p_T partons travel thru dense matter and lose energy
  $\Rightarrow$ probes full extent of the QGP system

· hadronize (fragment) outside collision zone

· retain information during hadronization

High p_T Production at RHIC

At RHIC energies ($\sqrt{s} = 200$ GeV), $\approx 50\%$ of energy produced is due to partonic processes that are calculable with perturbative QCD.

$\Rightarrow$ can make predictions for high p_T production using pQCD + addition of known nuclear effects as input:

- initial k_T
- k_T broadening due to multiple initial state scattering (Cronin effect)
- structure function modification (shadowing)

For the first time in relativistic heavy ion physics, accurate predictions and comparisons with data become possible!

High p_T Charged Hadron Production from pp Collisions

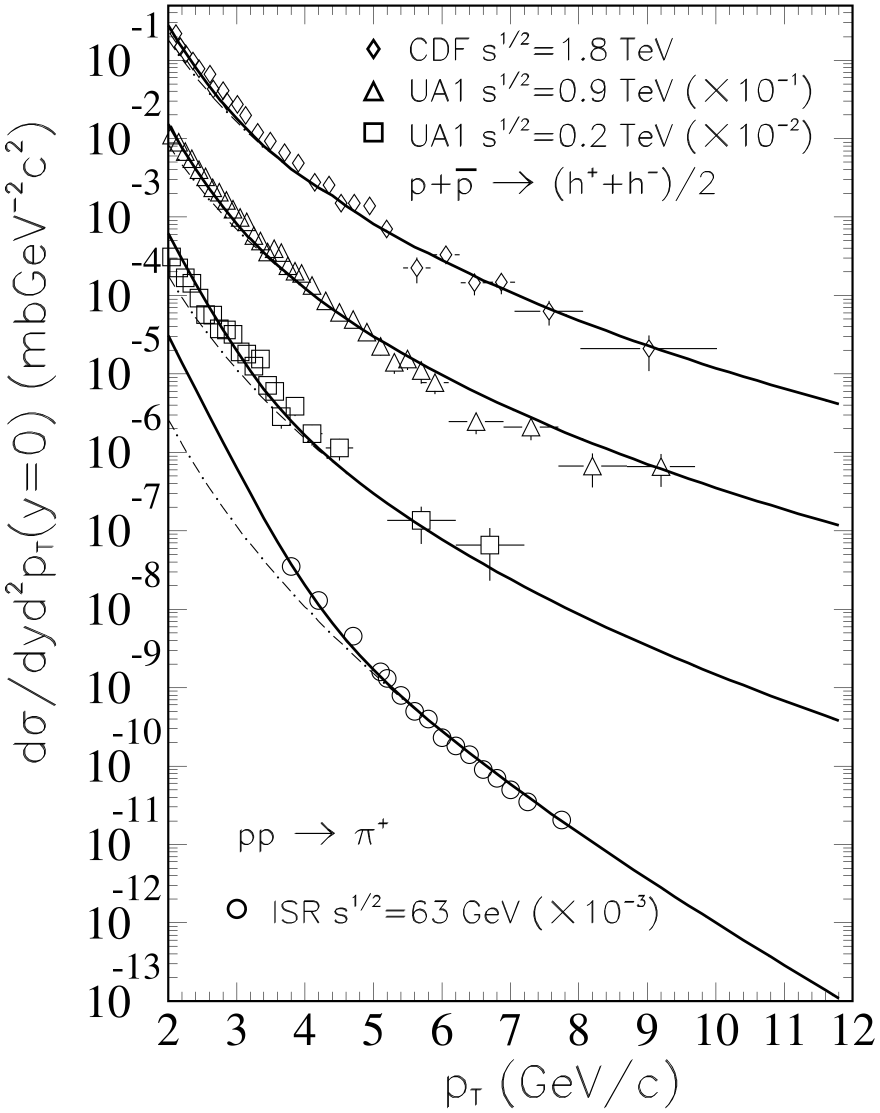


Figure 1: From pQCD calculation - Wang, Phys Rev **C58** (1998)2321.

Shows that pQCD predictions are accurate at RHIC energies for nucleon-nucleon collisions

Search for Quark Gluon Plasma Formation using High p_T Production

What are we looking for?

Look for differences in production due to
changes in *parton energy loss*:

$\longrightarrow$ gives changes in fragmentation, $z = E_{\mathrm{hadron}}/E_{\mathrm{parton}}$

- softening of p_T spectum of hadrons and jets (jet quenching)
- changes in jet profiles (distribution of energy in jet may change)

Partons in High Energy Density Environment

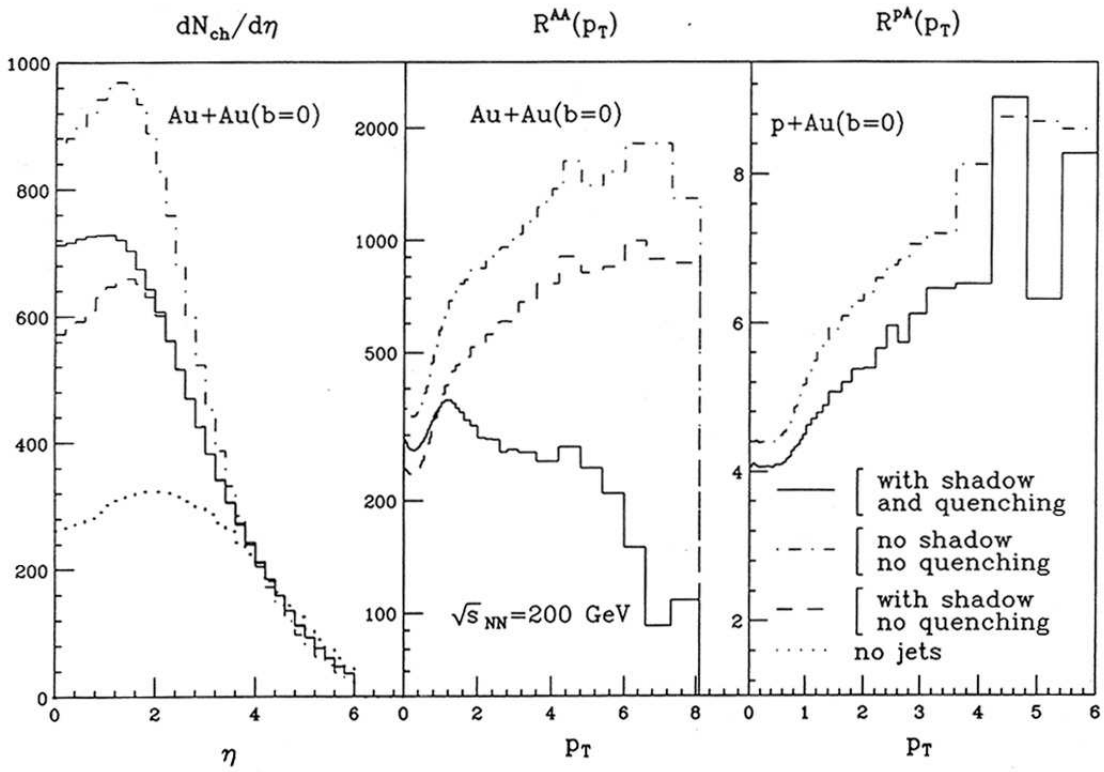


Figure 2: Inclusive charged particle spectra (HIJING) dependence on mini-jet production. R is ratio of nucleus-nucleus collisions to *pp* collisions. Gyulassy & Wang, PRL **68** (1992) 1480.

Search for Quark Gluon Plasma Formation using High p_T Production

$\Rightarrow$ Use pQCD calculation with added known nuclear effects as input.

$\Rightarrow$ Must know nuclear modifications well!
- use pp & pA data as baselines

Measure in data:

$\star$ hadron spectra

$\star$ jet spectra

$\star$ angular correlations (jets produced $180°$ apart?)

$\star$ particle vs. anti-particle differences (q vs. g)

- at this $\sqrt{s}$, more gluons than quarks
- g's $\rightarrow$ equal # of particles & antiparticles
  q's $\rightarrow$ particles
- difference in g and q fragmentation (gluons will lose more energy propagating thru dense matter)

$\star$ distribution of energy in jets (jet shapes)

$\Rightarrow$ Compare prediction with and without added parton energy loss (due to QGP formation) to data.

Prediction for Ratio $AuAu$ to pp inclusive hadron spectra

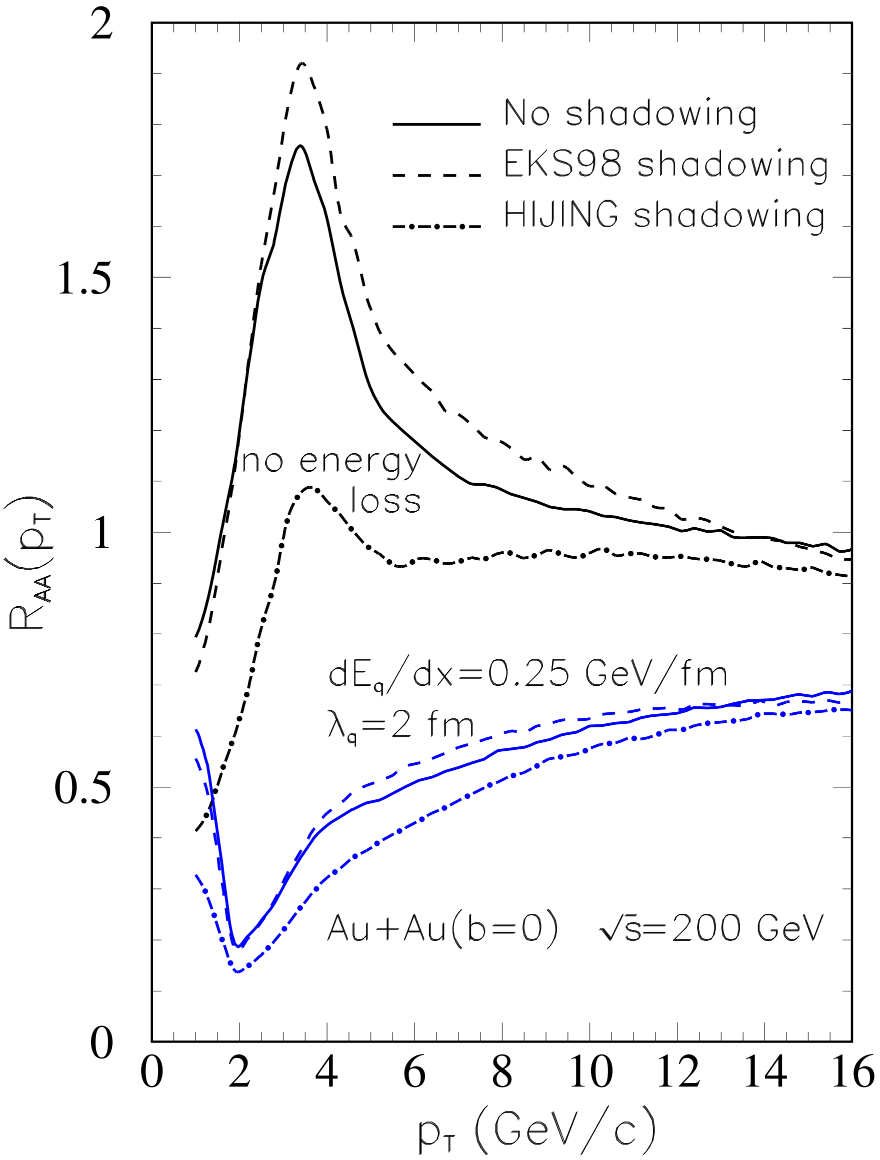


Figure 3: pQCD prediction of ratio of hadron spectra in central $Au + Au$ to pp collisions at $\sqrt{s} = 200$ GeV vs p_T. Nuclear effects included. Effects of different parameterizations of modification of gluon distribution (shadowing) and parton energy loss shown. Wang, nucl-th/9812021.

See suppression of high p_T spectra from $AuAu$ relative to pp collisions due to parton energy loss in QGP.

Heavy Ion vs. *pp* Interactions

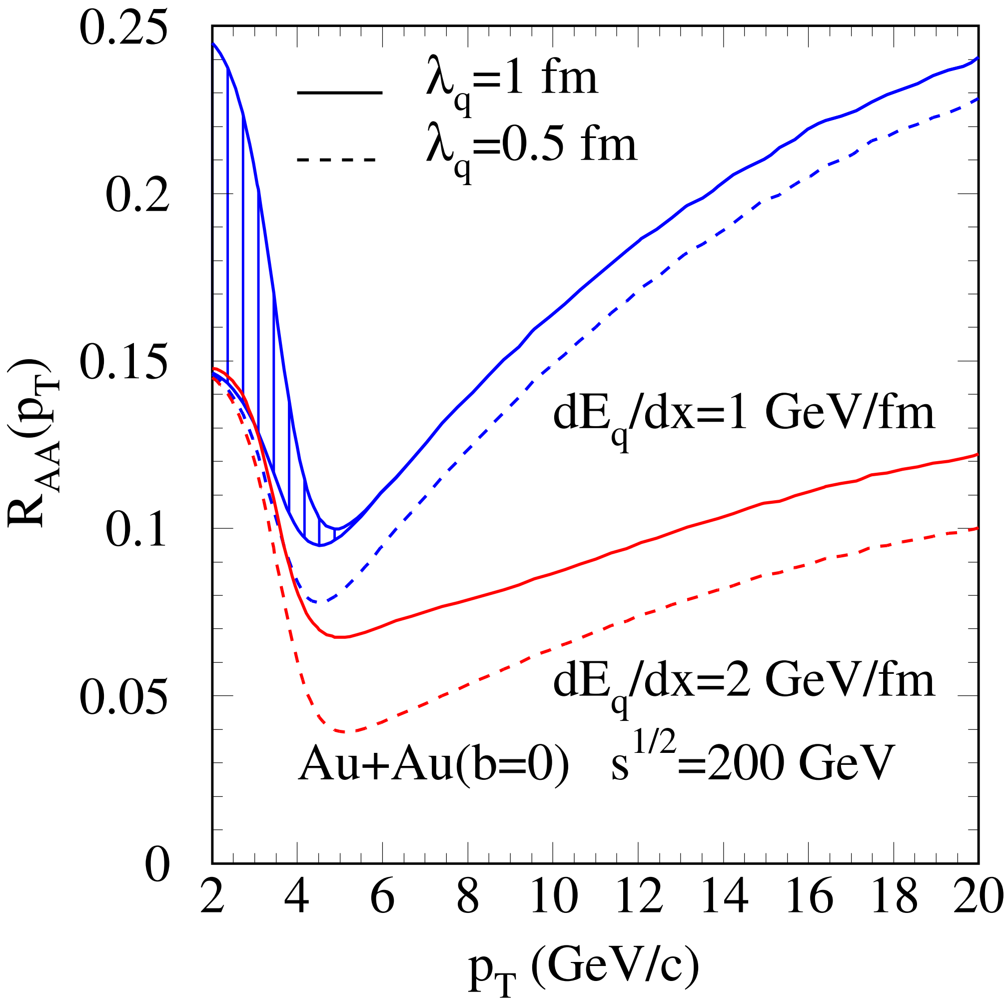


Figure 4: pQCD calculation showing ratio of charged particle P_T spectrum in central AuAu vs. pp at $\sqrt{s}$ = 200 GeV,normalized to effective total number NN collisions in a central AA collision (this is effectively the suppression). If nuclear effects (shadowing & jet quenching) are not taken into account, ratio $\approx$ 1 at large P_T. Wang, Phys. Rev. **C58**(1998)2321.

See variation in suppression of spectra at large p_T due to different amounts of parton energy loss in QGP.

Prediction for Charged Particle Multiplicity in $AuAu$ Collisions

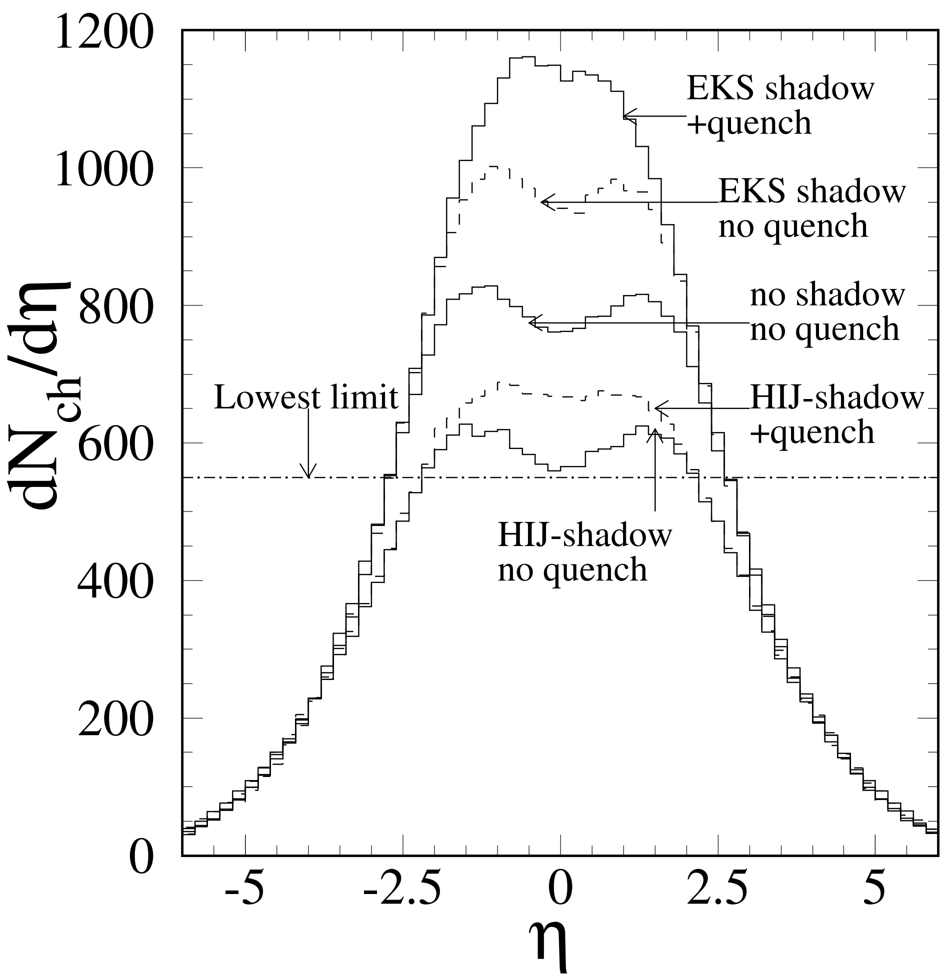


Figure 5: Multiplicity in central $Au + Au$ collisions vs η from pQCD prediction. Nuclear effects included. Effects of different parameterizations of modification of gluon distribution (shadowing) and parton energy loss ($dE/dx = 1$ GeV/fm) shown. Wang, nucl-th/9907090.

See change in charged particle multiplicity vs η due to parton energy loss and to different models of structure function modification.

Prediction for Ratio π^-/π^+ Production from pp and $AuAu$ Collisions

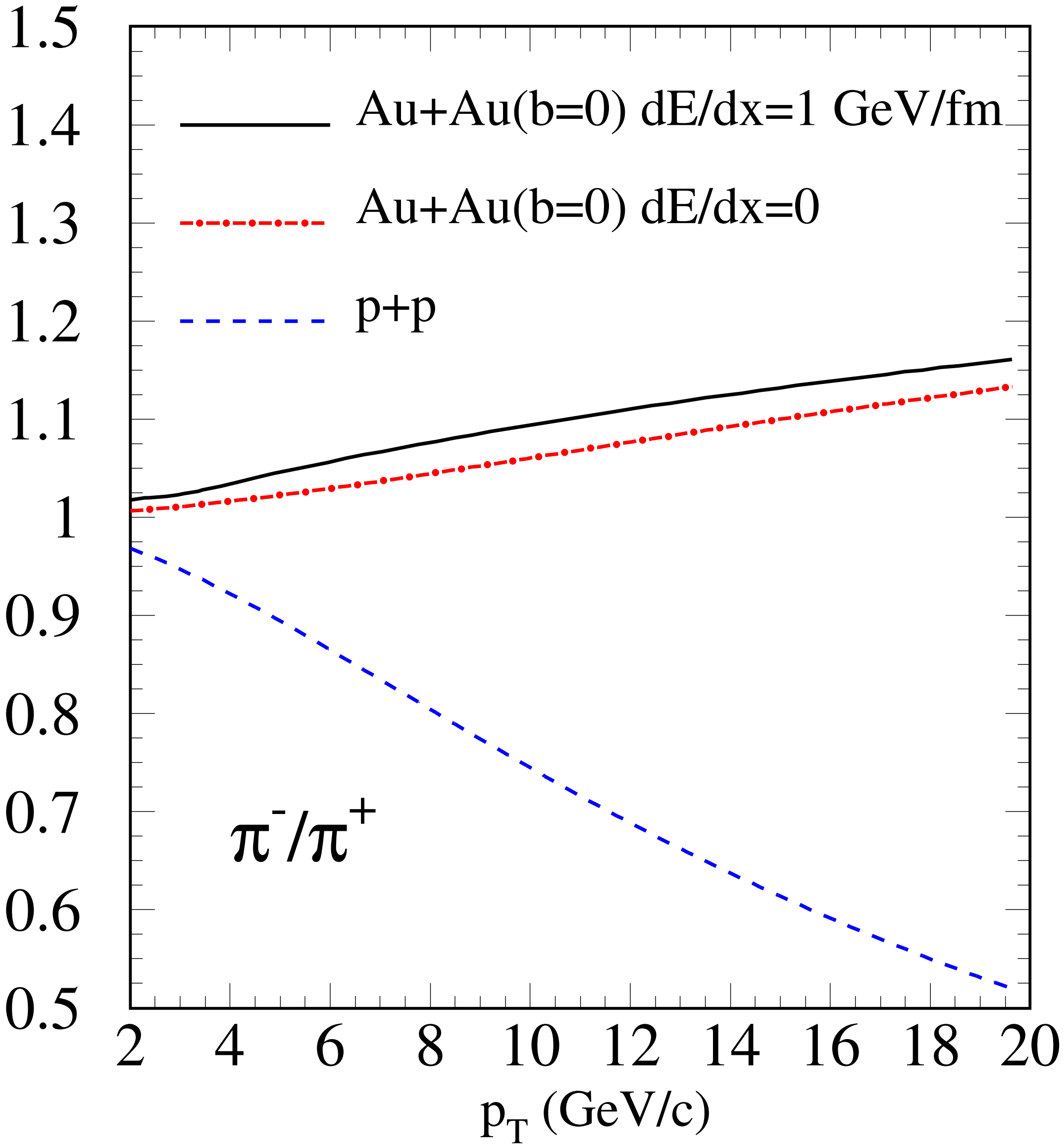


Figure 6: Ratio of charged π to $\bar{\pi}$ production vs. p_T from pp collisions and $AuAu$ collisions with different energy loss schemes. From pQCD calculation by Wang, Phys. Rev.**C58**(1998)2321.

See non-unity ratio and variation with p_T due to differences in contributions from q and g jets and also in q and g fragmentation.

π^0 Production from nucleus-nucleus Collisions - Experimental Results vs. pQCD Predictions

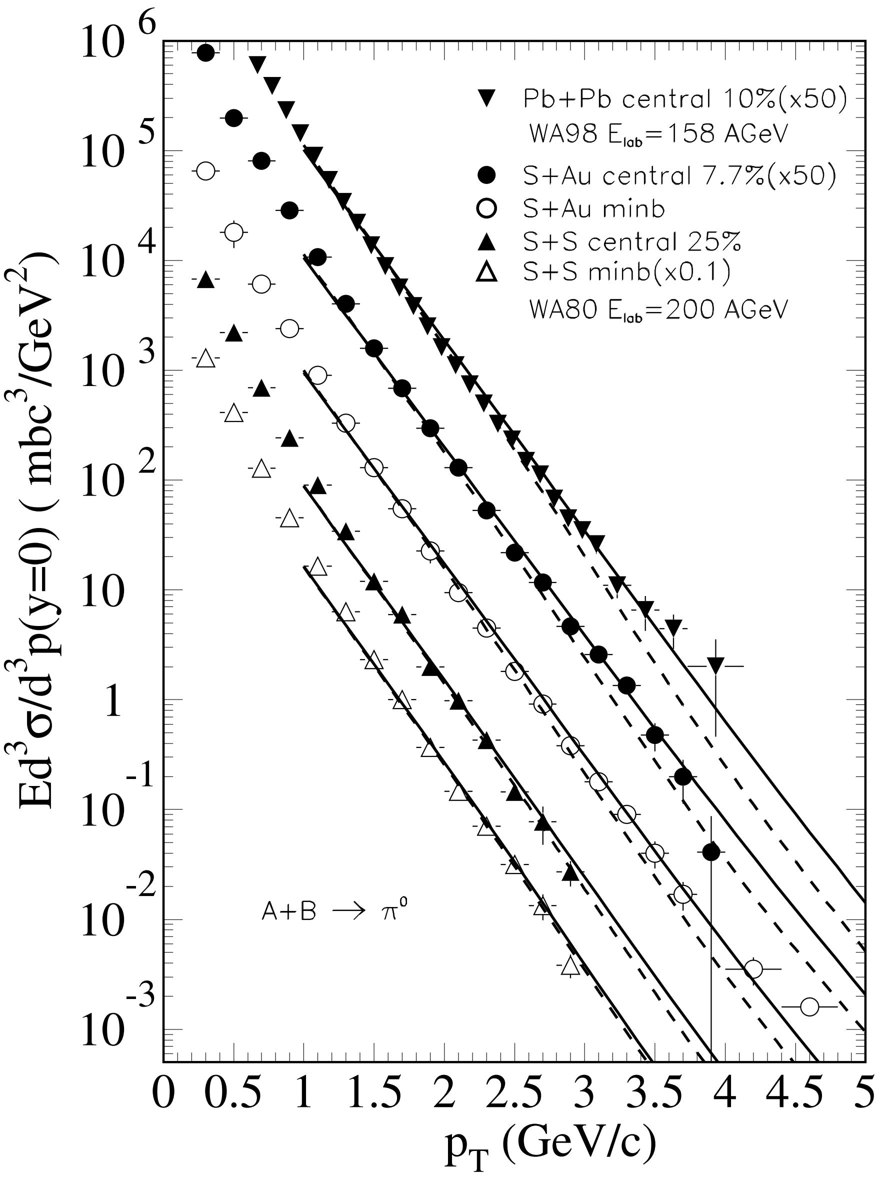


Figure 7: Production of π^0 at CERN SPS compared to pQCD with nuclear effects added. Predictions shown with and without nuclear modification of parton distributions. No parton energy loss added. Wang, nucl-th/9907093.

At SPS energies, predictions w/o added parton energy loss match data well. Deviations at RHIC will be striking evidence of different initial state conditions (QGP?)!

High p_T using STAR Detector

Year 1:

◦ inclusive charged particles (h^+, h^-) to high p_T
 $\rightarrow$ TPC

◦ identified π's, K's to ≈ 3 GeV, p's to ≈ 5 GeV
 $\rightarrow$ RICH

◦ single neutral hadrons ($\pi^0 \rightarrow \gamma\gamma$):
 $\rightarrow$ EMC

◦ K and Λ to high p_T:
 $\rightarrow$ TPC, using topological constraints on decays

Year 2 and beyond:

· better identification and momentum resolution of charged hadrons using SVT+SSD

· e, direct-γ
 $\rightarrow$ EMC + TPC

· jets and/or leading hadrons $\rightarrow$ EMC + tracking

Basic Program using High p_T production

$\longrightarrow$ Measure hadron production and compare to predictions using pQCD + known nuclear modifications

$\longrightarrow$ do predictions with and without added parton energy loss due to QGP formation

$\star$ To fully untangle contributions from known nuclear effects, must use pp and pA data as baseline measurements

$\longrightarrow$ In the meantime ... to see effects of dense environment, measure production relative to

- how much dense matter it's gone thru (i.e. centrality)
- different types of beams: $AuAu$, $SiSi$ ... pp
- different beam energies

Lots of measurements that could indicate QGP formation in first year of data!

Data Collection

Triggers:

L0: hardware multiplicity trigger

L3: software, using TPC tracking, EMC info, ready in Year2?
- needed for J/ψ & enhances high p_T rate

Rates:

- Max Central Collision Rate ≈ 100 Hz
  ($\approx 5\%$ of collisons are central)
- DAQ rate to tape ≈ 1 Hz
- rate of π^0's above $p_T = 7$ GeV ≈ 0.0001 Hz

Year 1: 10% of design luminosity by end of year
$\rightarrow$ run $AuAu$ collisions
$\rightarrow$ possible beam or energy change (pp, $SiSi$?)

Year 2: expect full design luminosity by end of year
$L = 2 \cdot 10^{26}$ cm^{-2}/s^{-1}
$\longrightarrow \approx$ 2000 collisions/sec (minbias)

π^0 Spectra

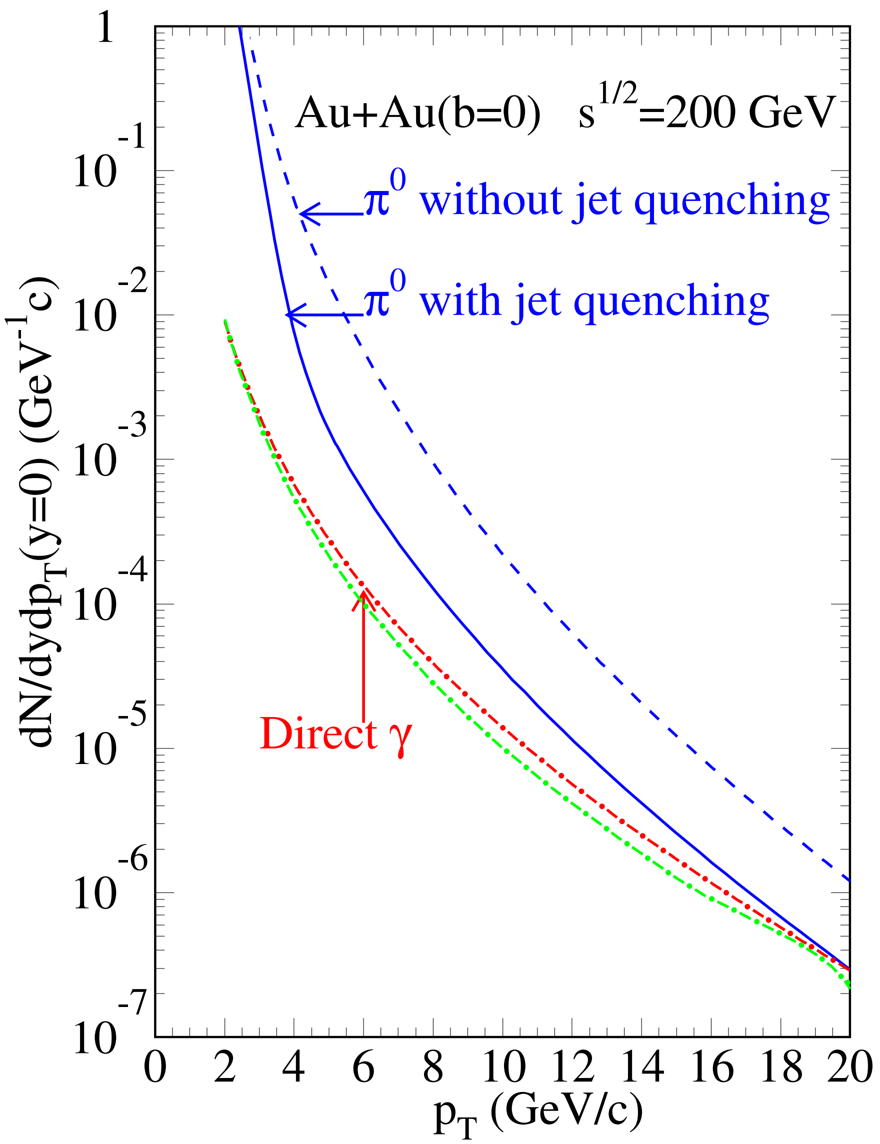
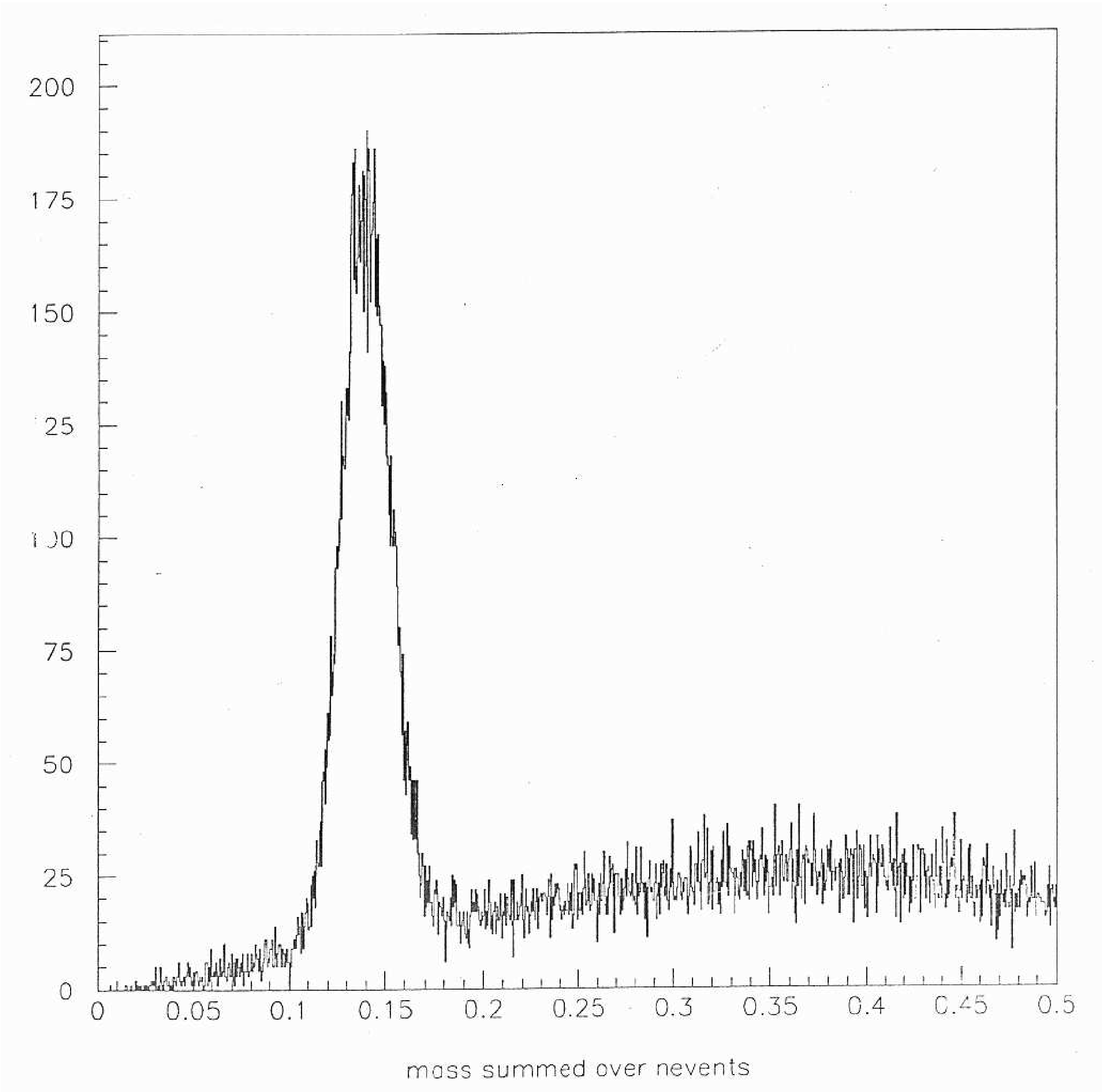


Figure 8: pQCD calculation of inclusive p_T distribution from $Au + Au$ collisions with nuclear effects included. Parton energy loss of $\mathrm{dE_q/dx} = 1\ \mathrm{GeV/fm}$ and mean-free path $\lambda_q = 1\ \mathrm{fm}$ assumed. Wang, Phys. Rev. **C58** (1998) 2321.

$\longrightarrow$ Year1 measurement using EMC:
expect $\approx 2500(25)$ events at $p_T = 5(10)$ GeV

$\longrightarrow$ Also h^+, h^-, production using TPC,
as function of centrality

STAR: $\pi^0 \rightarrow \gamma\gamma$ mass peak - Year1 Statistics



$\longrightarrow$ Year1 measurement using EMC:
expect $\approx 2500, 25$ events at $P_T = 5, 10$ GeV (T. Cormier)

Charged Hadron Ratios

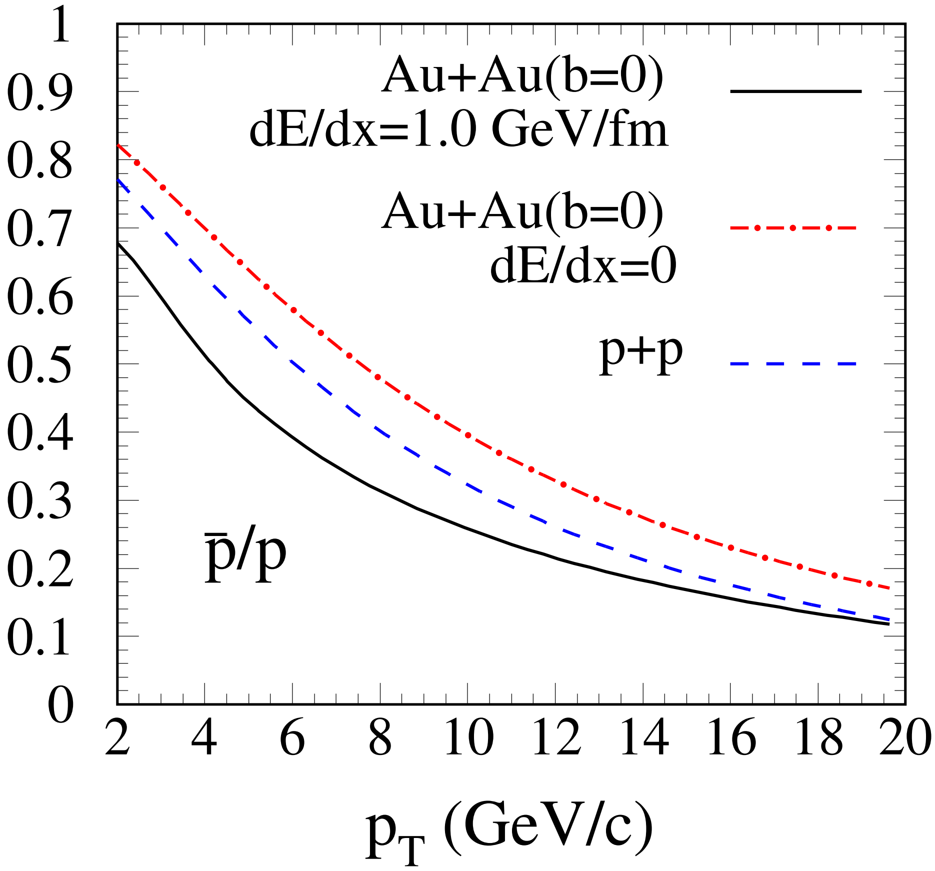


Figure 9: Ratio of $\bar{p}/p$ production vs. p_T from $Au + Au$ collisions. The pQCD predictions with nuclear effects included are shown with and without parton energy loss. Wang, Phys. Rev. **C58** (1998) 2321.

Possible to measure $\bar{p}/p$ ratio at high p_T (also K's, π's, Λ's) with RICH in Year 1. Sensitive to differences in contribution and fragmentation (g,q) and parton energy loss.

Angular Correlations

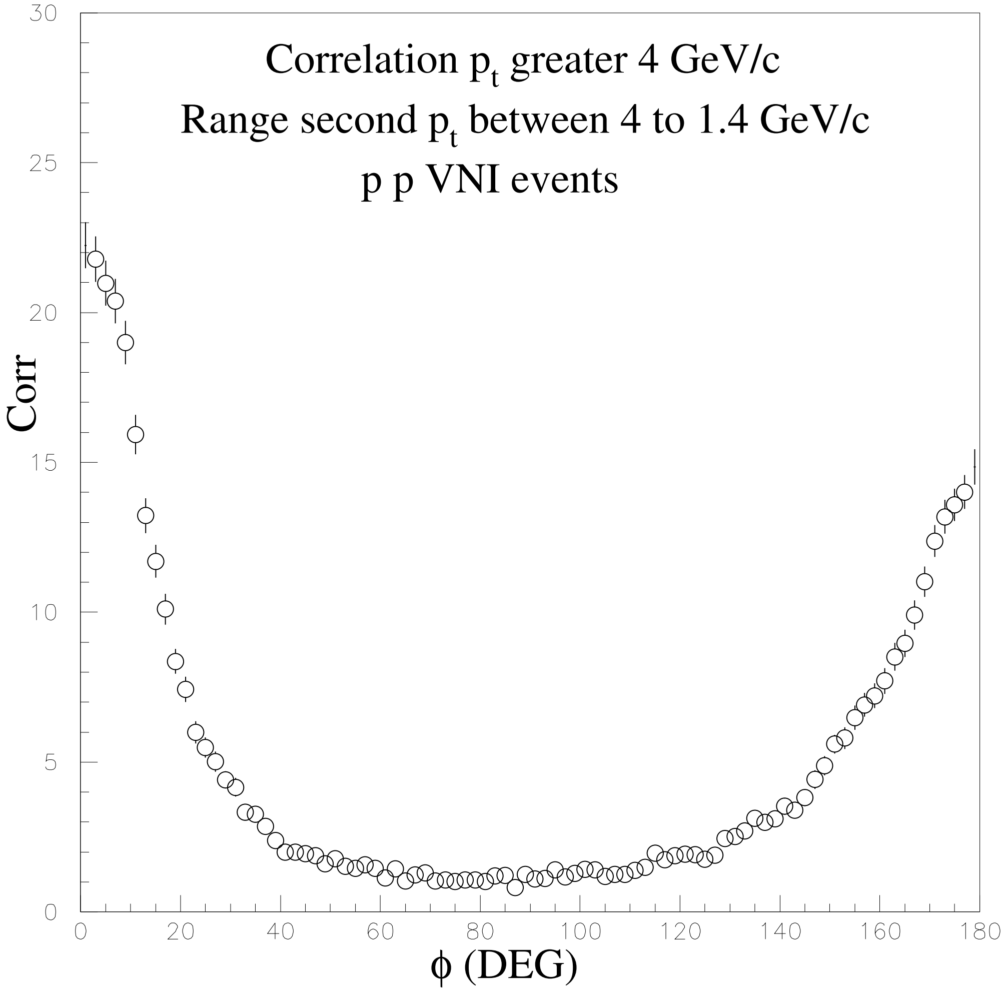


Figure 10: VNI event generator (Klaus Kinder-Geiger), azimuthal angle (ϕ) correlation between high p_T hadrons from pp events. Ron Longacre, 10/99

Shows strong correlations at $0°$ and $180°$ as expected.

Angular Correlations

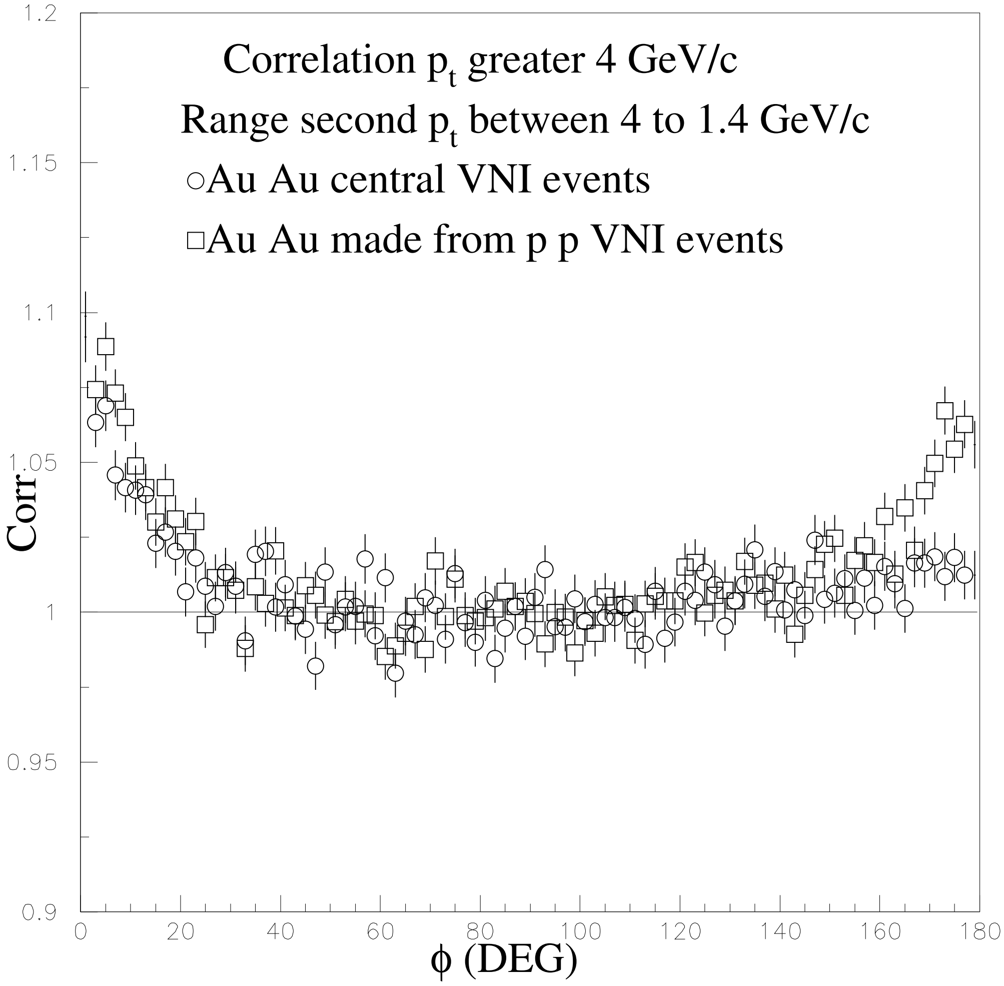


Figure 11: VNI event generator (Klaus Kinder-Geiger), azimuthal angle (ϕ) correlation between high p_T hadrons from $AuAu$ events built from pp events and from $AuAu$ events. Ron Longacre, 10/99

Still have correlations at $180°$ for pp events scaled up to $AuAu$ but the correlation is washed out by the nuclear effects in the $AuAu$ events.

Other High p_T Probes

- ◦ Jet Properties
  - ⋆ sphericity of event
- ◦ Particle Production - first year and future
  - ⋆ J/ψ at high p_T
  - ⋆ leading particle distributions
    $\rightarrow$ may be easier/cleaner to measure than jets
  - ⋆ jet production - more difficult due to large underlying event energies at RHIC (but may be able to do at low multiplicity)
  - ⋆ direct γ's - sensitive to gluon distributions; don't interact with strongly with hadronic matter
  - ⋆ γ+jet events; tag the γ and use to determine jet energy

High p_T Physics Program at STAR

- compare data to pQCD calculations with known nuclear effects and parton energy loss due to QGP added
- to fully determine contributions due to nuclear effects and possible QGP formation, must use pp, pA data and AA measurements as function of centrality, beam energy and beam type in long term

High p_T Physics at STAR in First Year:
(as function of centrality, beam type?, energy?)

⋆ inclusive charged hadron production

- p_T spectra
- multiplicity vs. η

⋆ identified particle production (p, K, π, Λ) and particle/anti-particle ratios vs p_T

⋆ π^0 production p_T spectra

⋆ angular correlations

- Looking forward to Data in 2000

- Many new exciting & unexpected(?) results!!