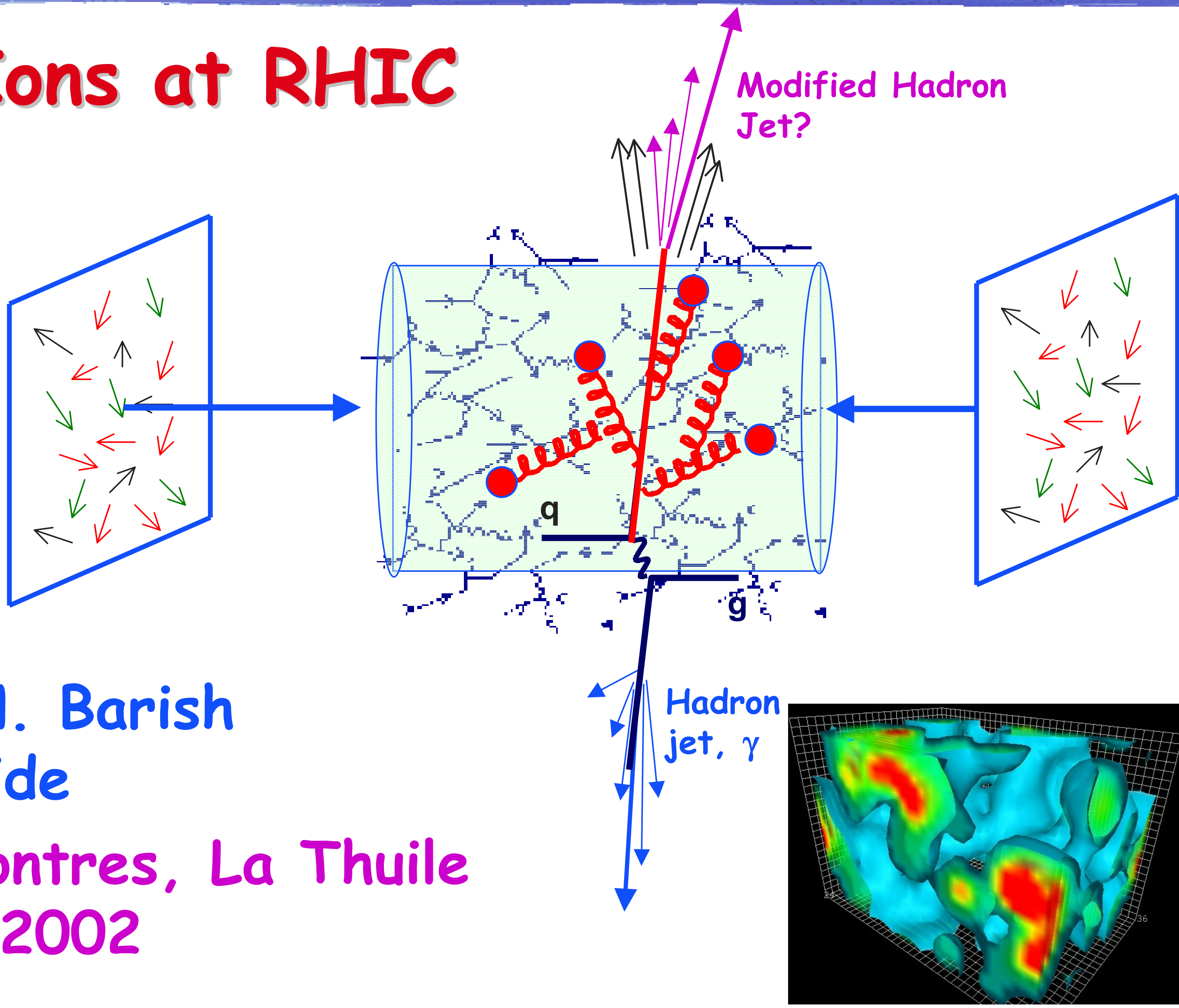
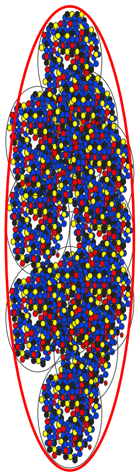
Heavy Ions at RHIC



Kenneth N. Barish
UC Riverside

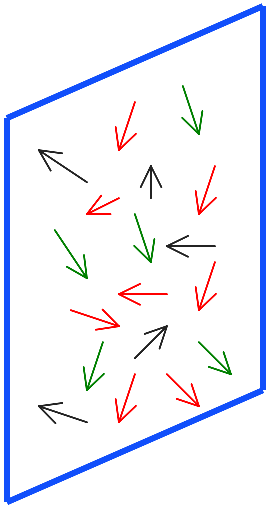
XVI Rencontres, La Thuile
5 March, 2002

Color Glass Condensate

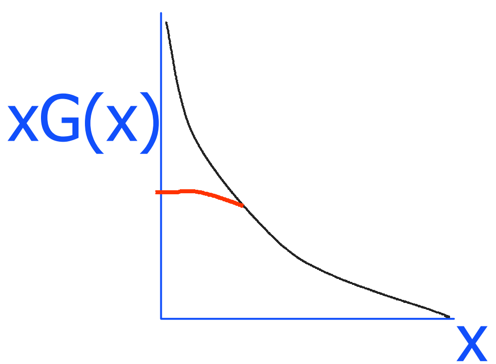


Put many nucleons into a nucleus and Lorentz boost to the infinite momentum frame

Creates a 2-dimensional sheet of very high density color charges.



High density of gluons (saturation) allows for the simplification of Quantum Chromodynamics



Gluons fill up available states, fixing up unitarity for fixed Q^2

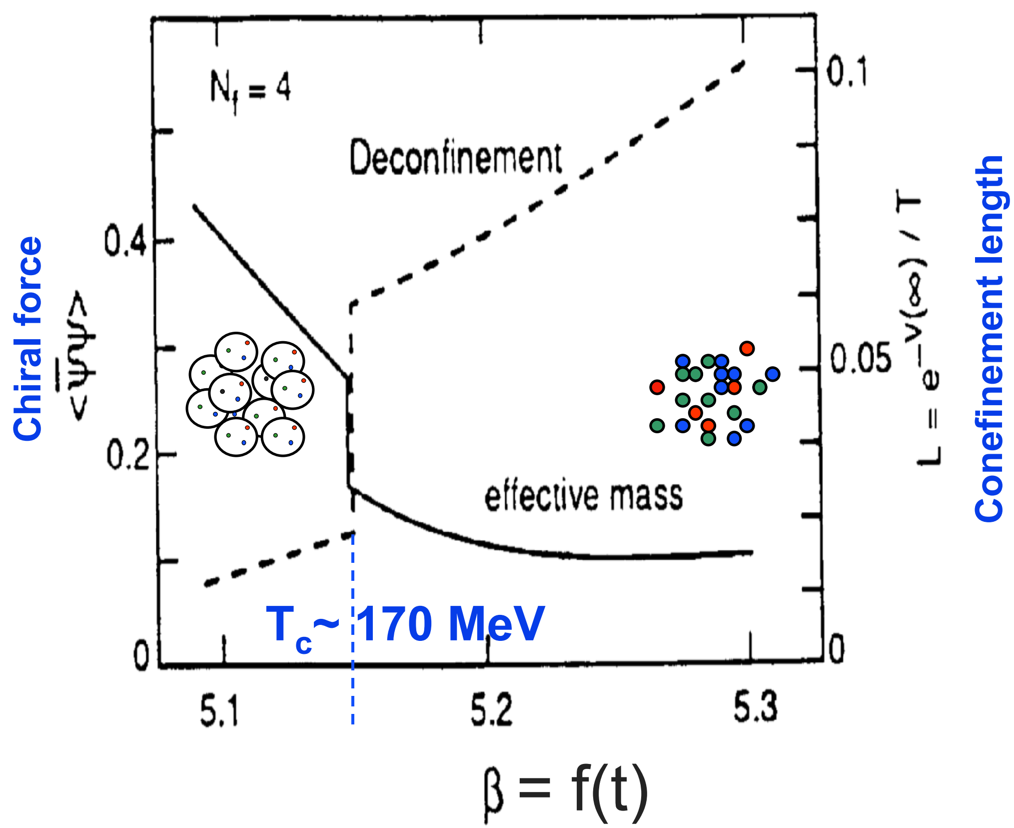
QCD Calculations on the Lattice

- **Calculations on lattice**
  - Predict transition temperature (T_c) from hadronic to QGP -- guides experiments
  - Indicate **deconfinement** and **chiral symmetry restoration**

Phase Transition:

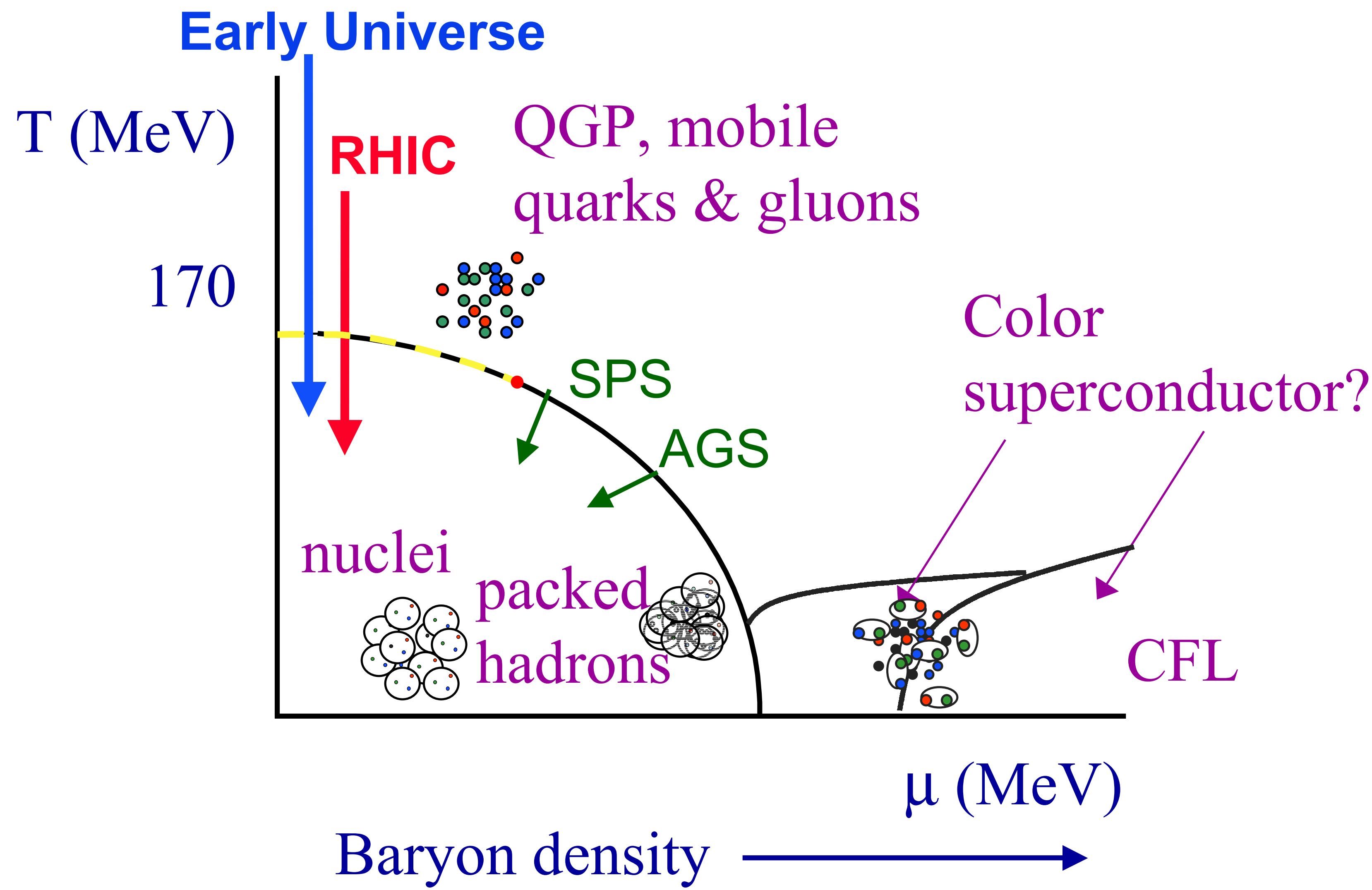
T = 170 ± 15% MeV
ε ~ 0.6 GeV/fm³

Assumes thermal system.



F. Karsch, Nucl. Phys. B (proc Suppl.) 83-84 (2000) 14.
calculation with 3 dynamical light quarks

Phases of Nuclear Matter



Relativistic Heavy Ion Collider

Year-1 Data Taking

- ✓ PHENIX Recorded ~5M minimum bias events
  ~ 3TB of data !
- ➢ Collisions from 15-Jun-00 to 04-Sep-00

Performance	Au + Au	RHIC Design
$\sqrt{s_{nn}}$	130 GeV	200 GeV
L [cm^{-2} s^{-1}]	~ 2 x 10^{25}	2 x 10^{26}
Interaction rates	~ 100 Hz	1400 Hz

RHIC Capabilities

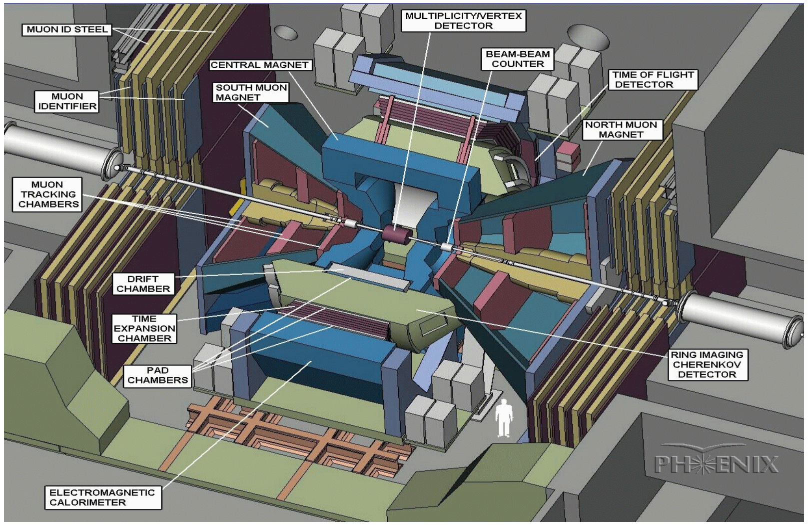
- ✓ Au + Au collisions at **200** GeV/u
- ✓ p + p collisions at 500 GeV
- ✓ spin polarized protons
- ✓ lots of combinations in between

Two Large Experiments

PHENIX

Electrons, Muons, Photons and Hadrons Measurement Capabilities
Focus on Rare Probes: J/ψ, high-p_T

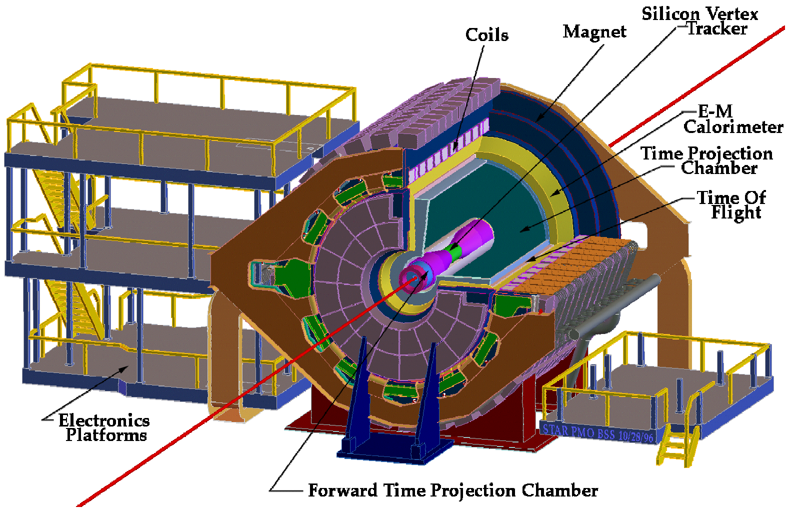
Two central spectrometers with tracking and electron/photon PID
Two forward muon spectrometers



STAR

Hadronic Observables over a Large Acceptance
Event-by-Event Capabilities

Solenoidal magnetic field
Large coverage Time-Projection Chamber
Silicon Tracking, RICH, EMC, TOF

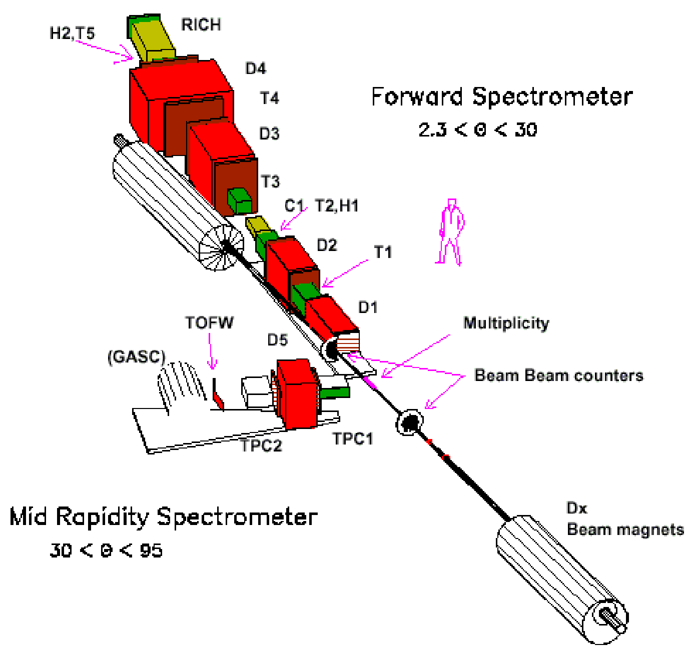


Two Small Experiments

BRAHMS

Hadron PID over broad rapidity acceptance

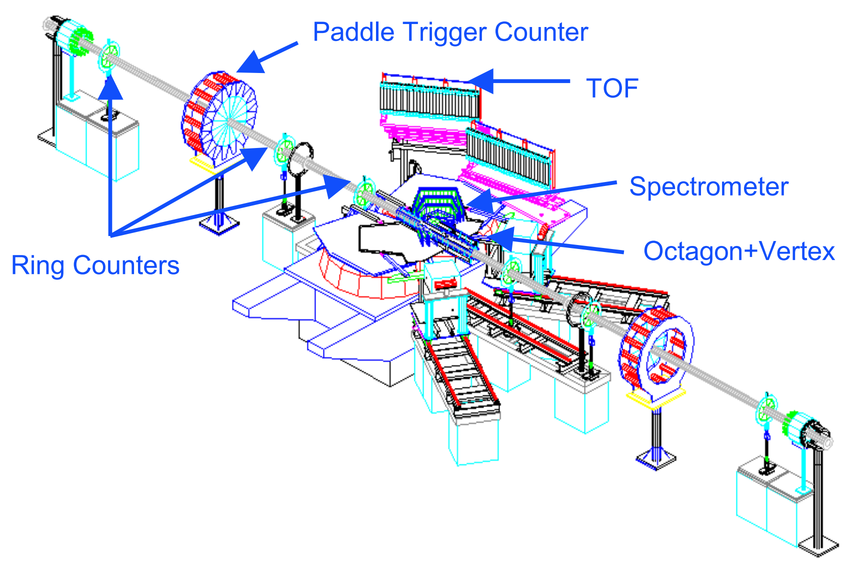
Two conventional beam line spectrometers
Magnets, Tracking Chambers, TOF, RICH



PHOBOS

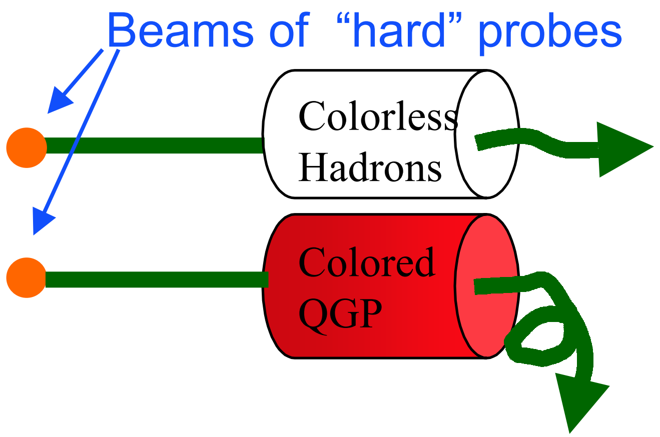
Charged Hadrons in Central Spectrometer
Nearly 4π coverage multiplicity counters

Silicon Multiplicity Rings
Magnetic field, Silicon Strips, TOF

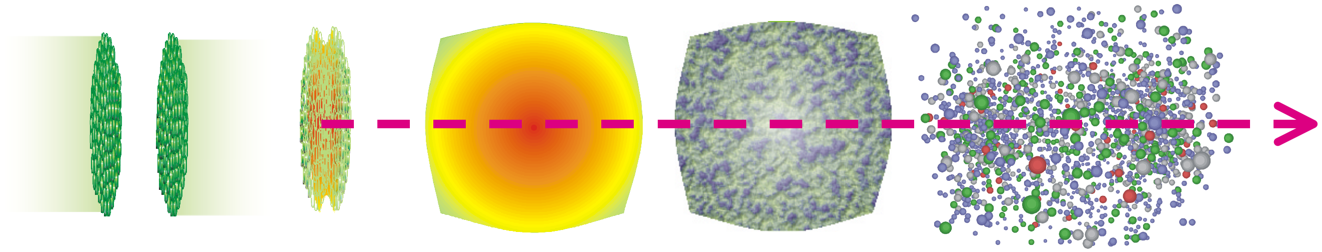


(I) Plasma Probes

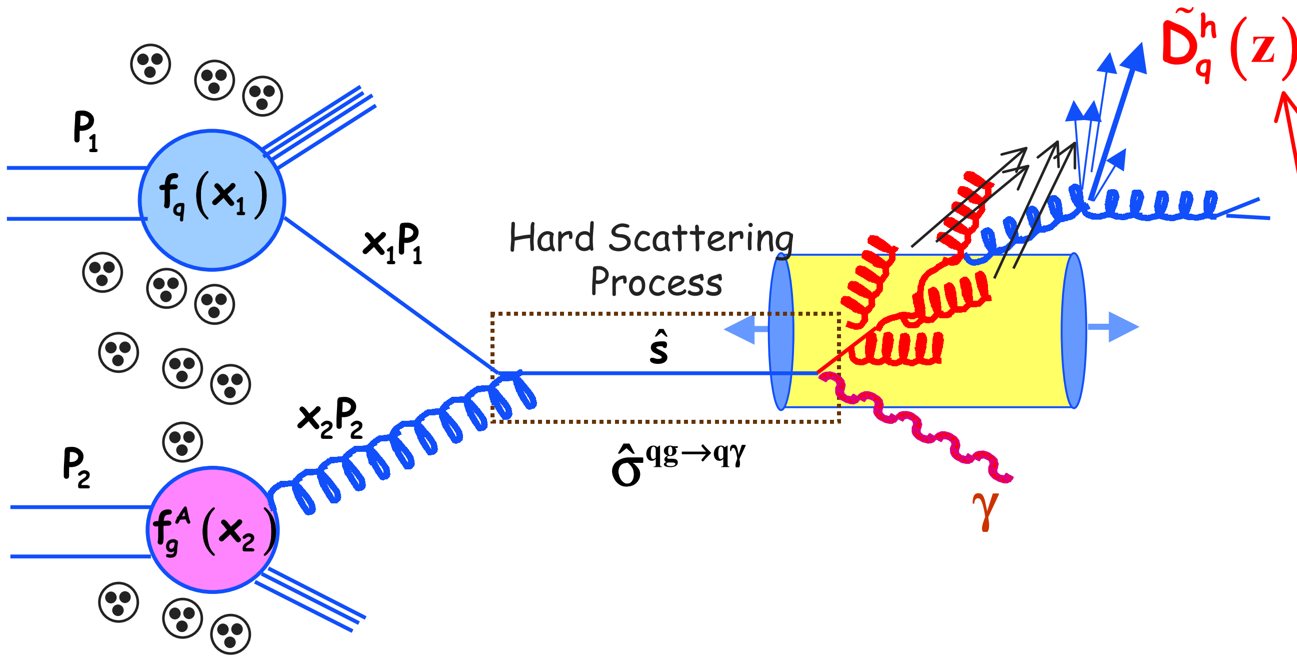
We expect quarks and quarkonium states to ***respond differently*** to a plasma compared to ordinary nuclear matter



All probes must be auto-generated



Hard Scattering Processes in AA

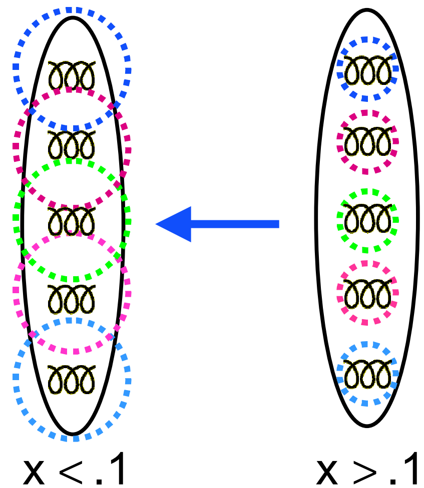


$$\sigma(AA \to hX) \sim f_q^A(x_1) \otimes f_g^A(x_2) \otimes \hat{\sigma}^{qg\to q\gamma}(\hat{s}) \otimes \tilde{D}_q^h(z)$$

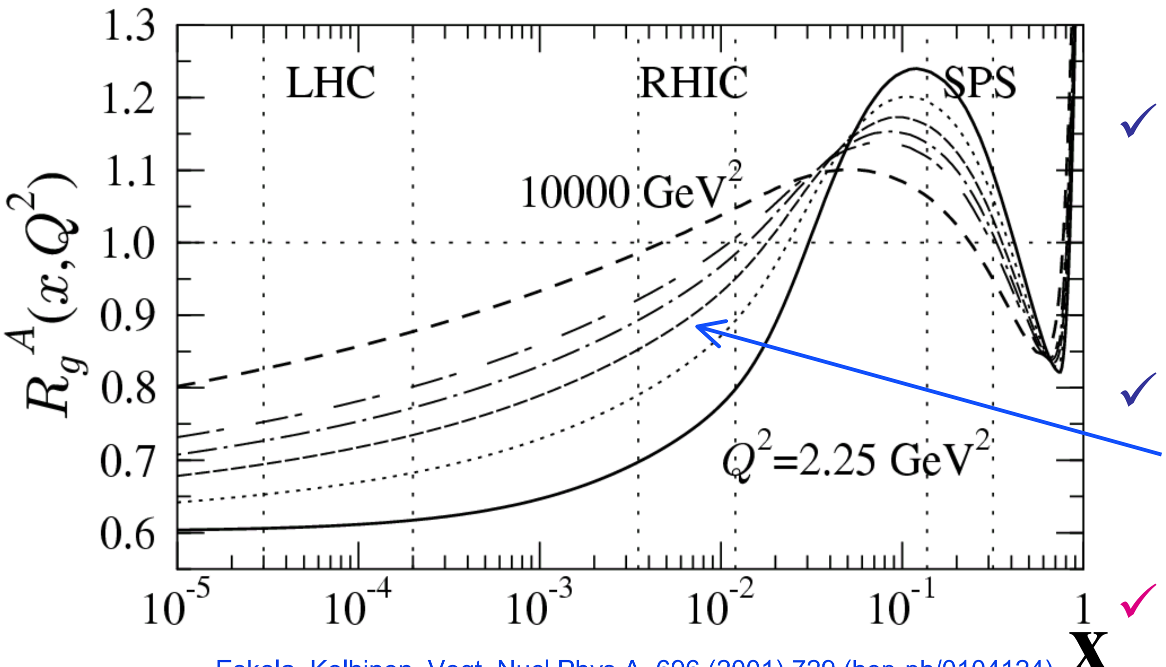
Look for an effective change in the jet fragmentation function due to energy loss in the parent parton due to gluon radiation

Nuclear Shadowing of quarks and gluons

- ✓ Nucleon structure functions are known to be modified in nuclei.
- ✓ Can be modeled as a recombination effect due to high gluon # density at low x (in frame where nucleon is moving fast)



$$x \simeq \frac{1}{2m\ell_c} \approx 0.1$$



Eskola, Kolhinen, Vogt, Nucl Phys A. 696 (2001) 729 (hep-ph/0104124)

- ✓ Quark shadowing is measured and is expected to be a small (~10%) effect at RHIC energies.
- ✓ Gluon shadowing is not measured, but will clearly play a role at RHIC & LHC
- ✓ pA running is needed at RHIC and LHC energies.

Leading Particles as a Probe

Advantage

- ✓ Can avoid soft background in a jet cone by letting R→0

Requirement

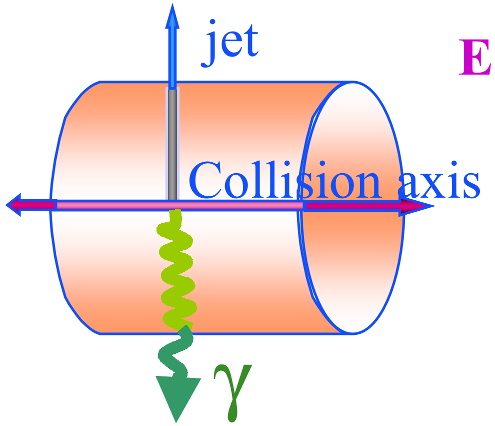
- ✓ Need *fine-grained* calorimeter like PHENIX

Disadvantage

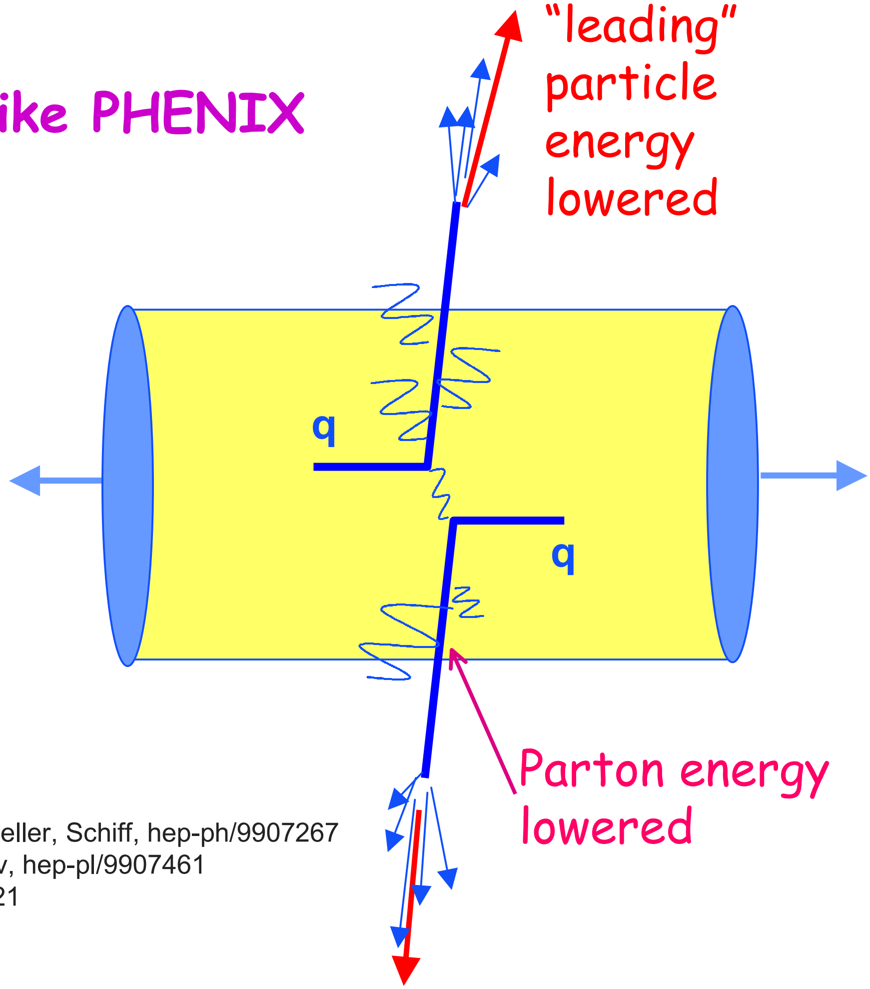
- ✓ Parent parton energy uncertain

Eventual Solution

- ✓ Use γ-jet events



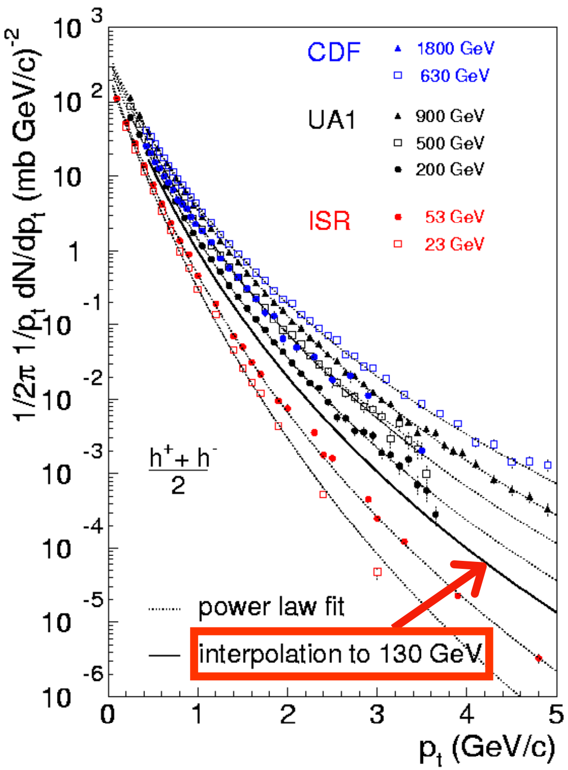
$E_{jet} \sim E_{\gamma}$

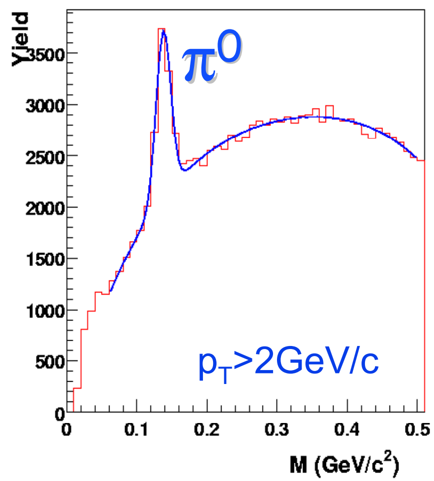


Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267
Gyulassy, Levai, Vitev, hep-pl/9907461
Wang, nucl-th/9812021
and many more…..

PHENIX Year-1 Data

PHENIX measures π^0 with two types of calorimeters (PbSc & PbGl)

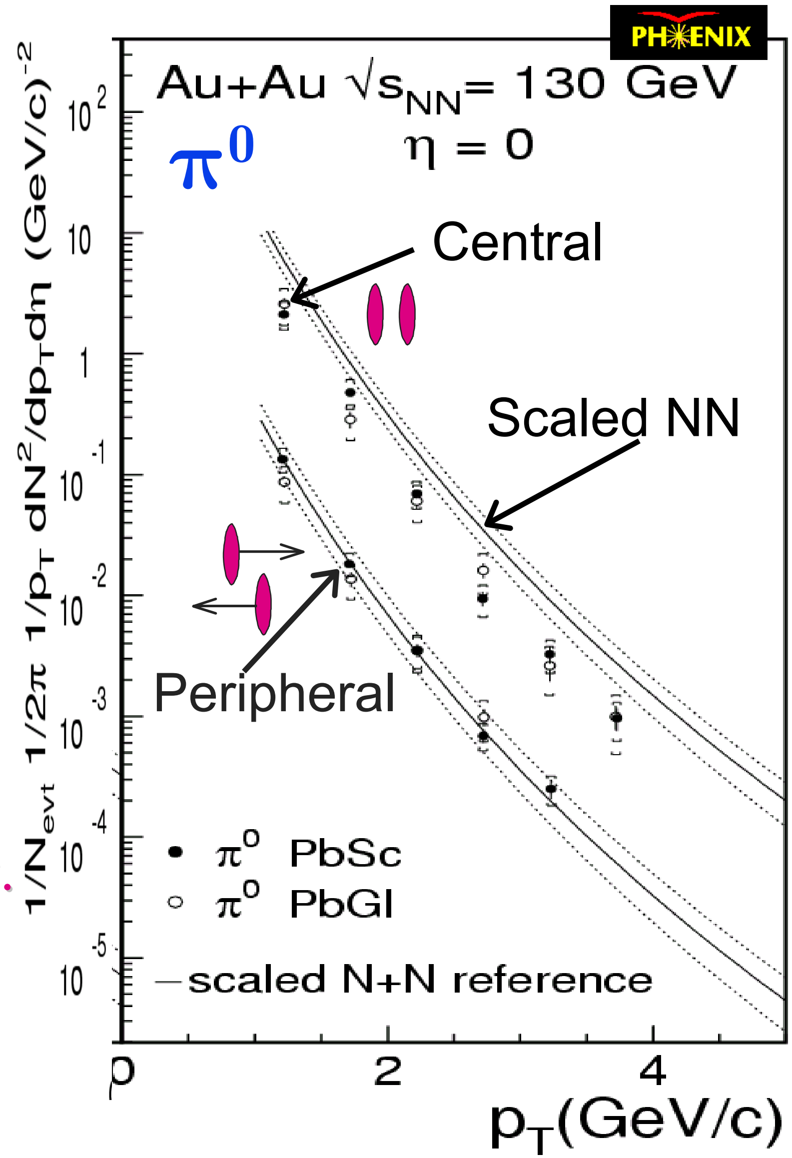




Scale p-p data by the number of binary collision in central and peripheral collisions.

$$N^{60-80\%}_{collisions} = 20 \pm 6$$

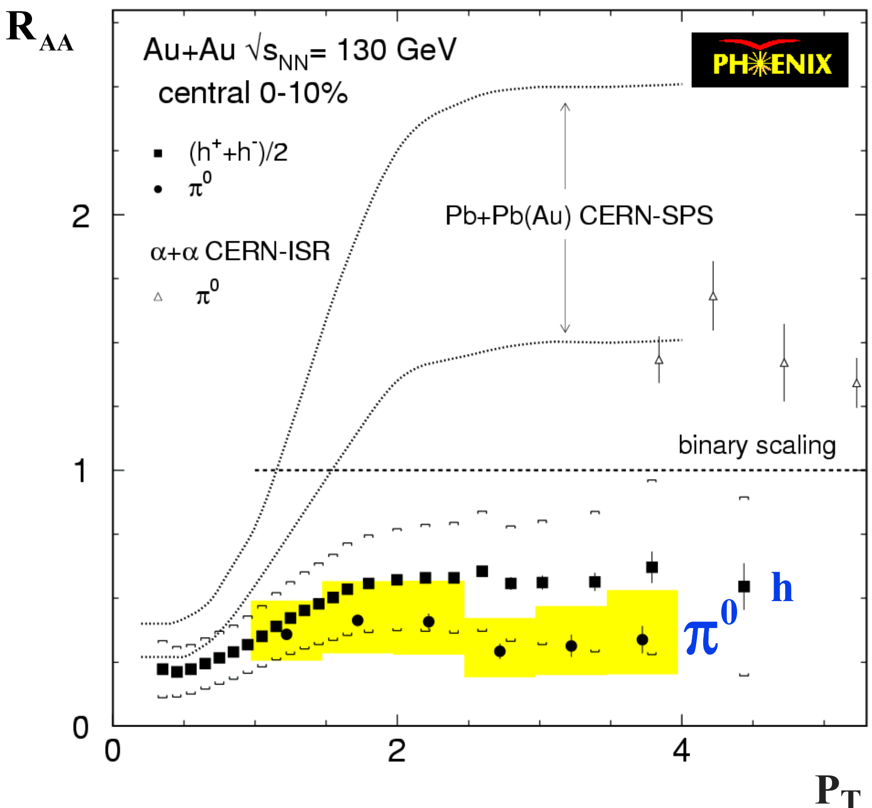
$$N^{0-10\%}_{collisions} = 905 \pm 96$$

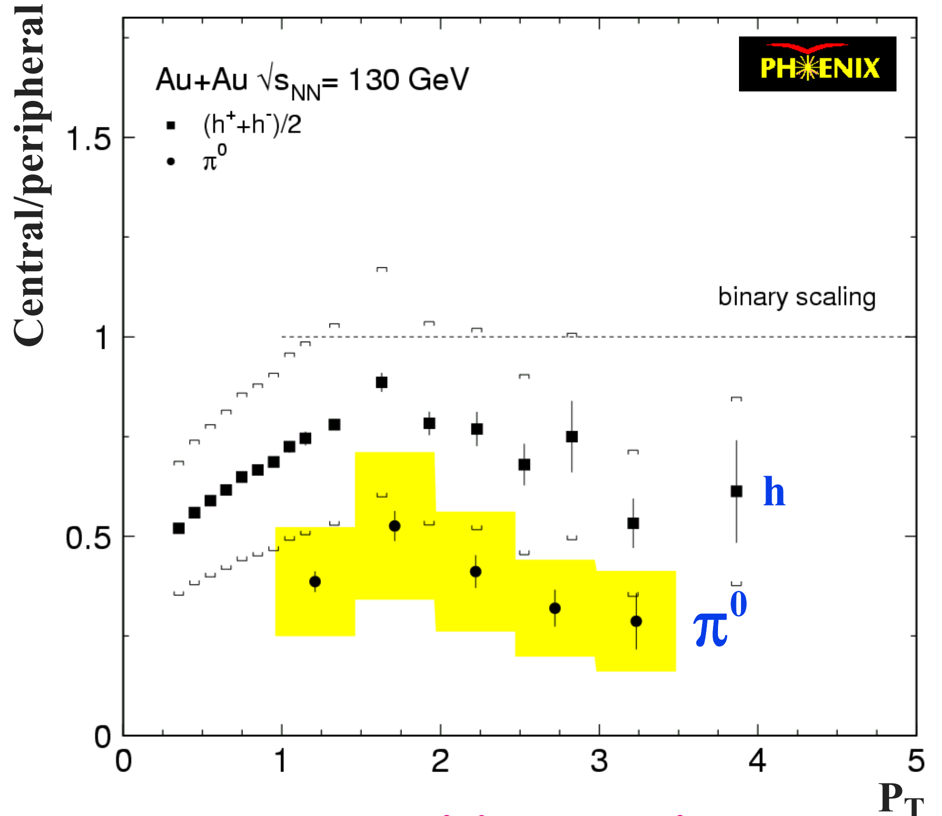


π^0 Ratio's with pp and Peripheral

$$R_{AA} = \frac{\text{Yield}_{\text{central}} / \langle N_{\text{binary}} \rangle_{\text{central}}}{\text{Yield}_{pp}}$$

$$\frac{\text{Yield}_{\text{central}} / \langle N_{\text{binary}} \rangle_{\text{central}}}{\text{Yield}_{\text{peripheral}} / \langle N_{\text{binary}} \rangle_{\text{peripheral}}}$$





Significant suppression relative to point-like scaling is seen. Effect in unidentified is smaller than in π^0.

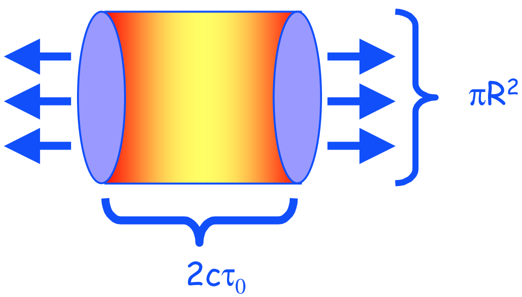
(II) Initial Conditions

- ✓ What is the energy density achieved?
  - » How does it compare to the expected phase transition value from lattice QCD?
- ✓ What is the initial density of created partons?
  - » Does the parton density saturate?

Energy Density

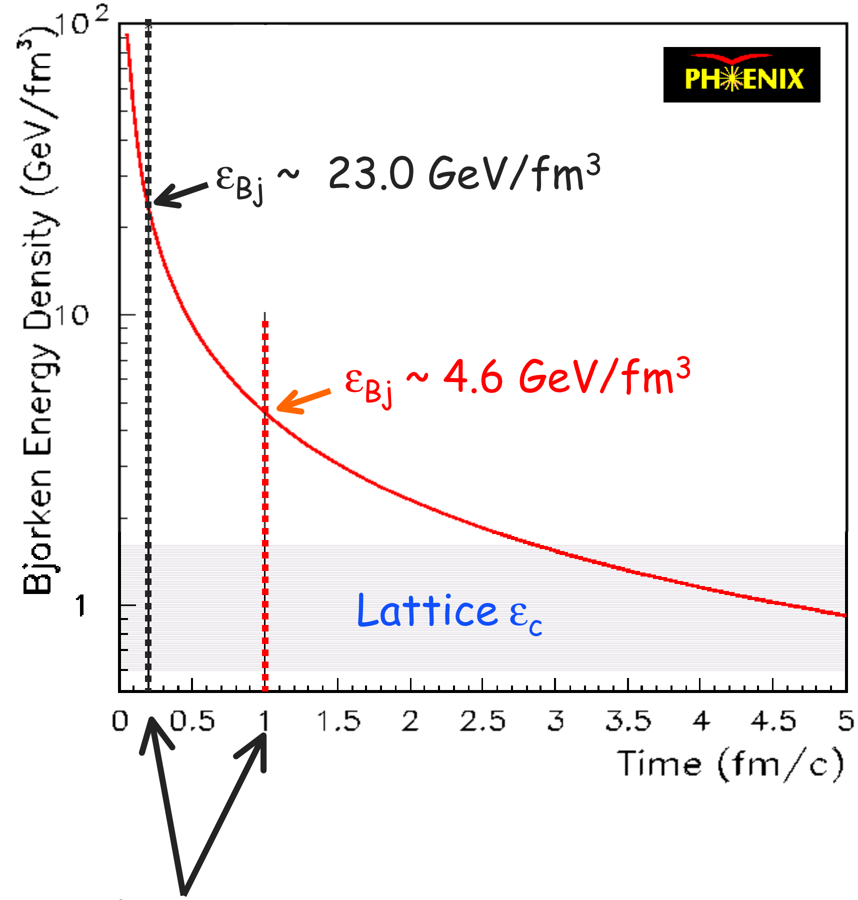
Bjorken formula for thermalized energy density in terms of measured transverse energy E_T

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



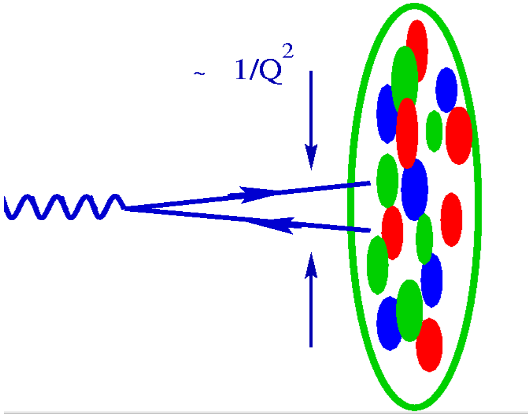
PHENIX: Central Au Au yields

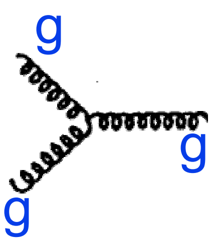
$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\, GeV$$



Thermalization time ?

Gluon Saturation





$gg \rightarrow g$

Wavefunction of low x partons overlap and the self-coupling gluons fuse,

thus saturating the density of gluons in the initial state

Gluon number density:

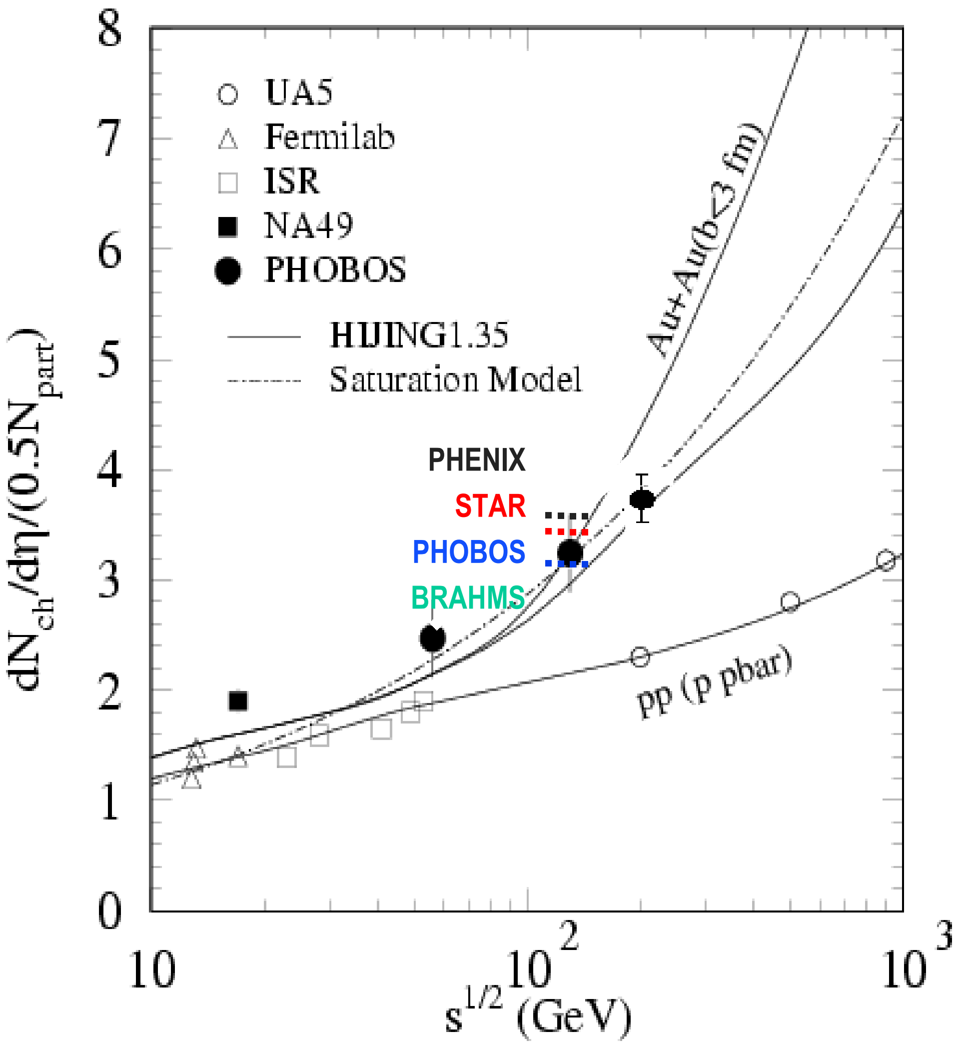
$$\rho_A \sim \frac{xG_A(x,Q^2)}{\pi R_A^2} \sim A^{1/3}$$

Saturation will occur at higher x than in nucleons.

Saturation scale, Q_s, and thus particle production, is a function of s and A.

$$Q_s^2 \sim \alpha_s \frac{xG_A(x,Q_s^2)}{\pi R_A^2} \sim A^{1/3}$$

Charged Particle Multiplicity



Agreement between all four RHIC experiments at 130 GeV

New Result from PHOBOS from Run II at 200 GeV

Particle production rising faster than in pp ($p\bar{p}$)

Over 5000 charged particles produced in central collisions at 200 GeV

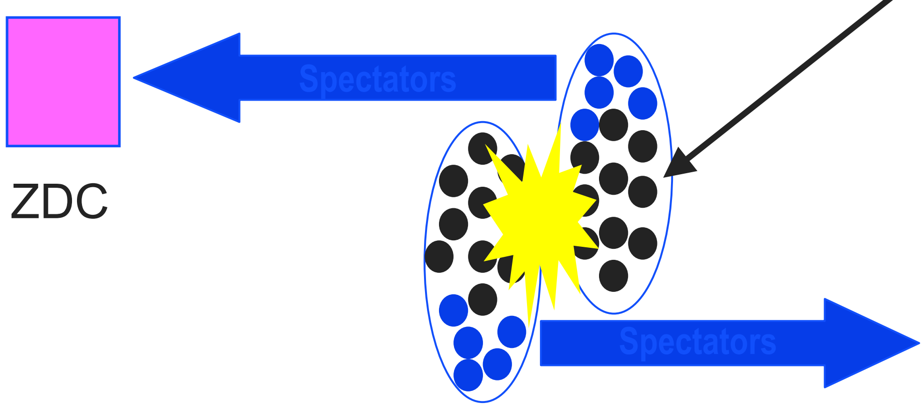
Do we see evidence of gluon saturation in the initial state?

Collision Characterization

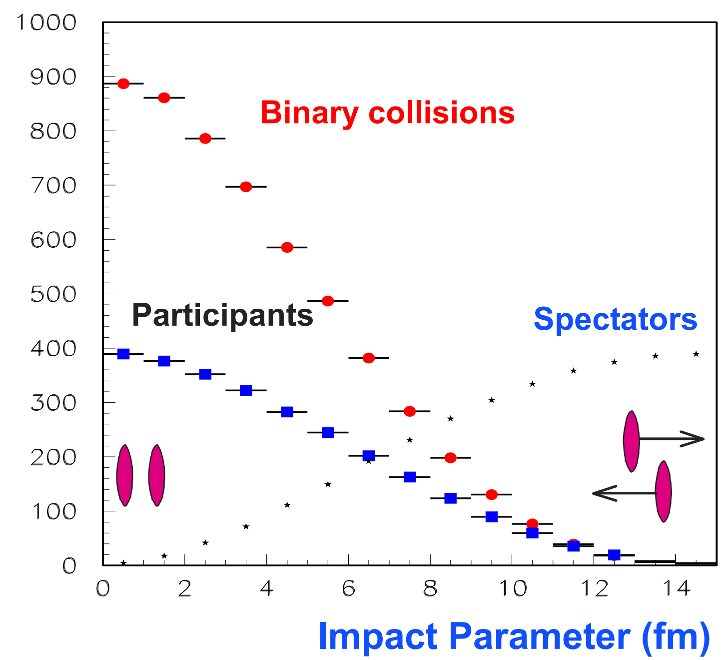
In Run I, we only collided one nuclear species (Gold).

However, we can vary the collision size by selecting different impact parameter events

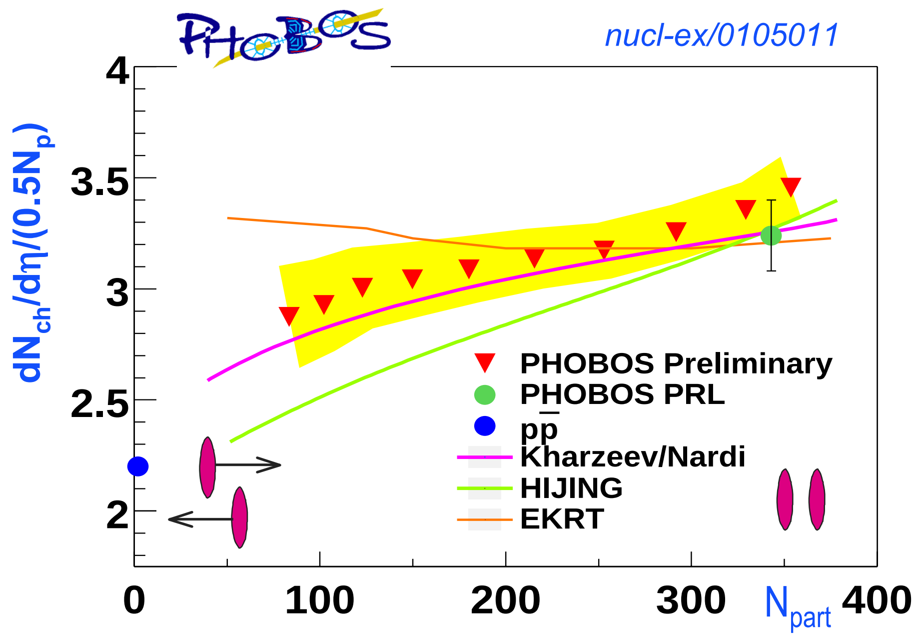
Different number of participating nucleons

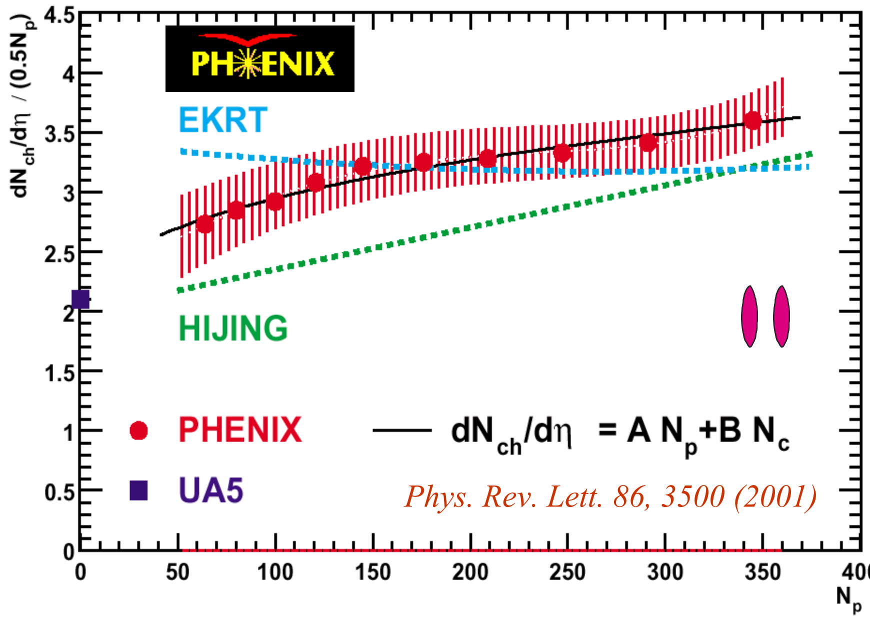


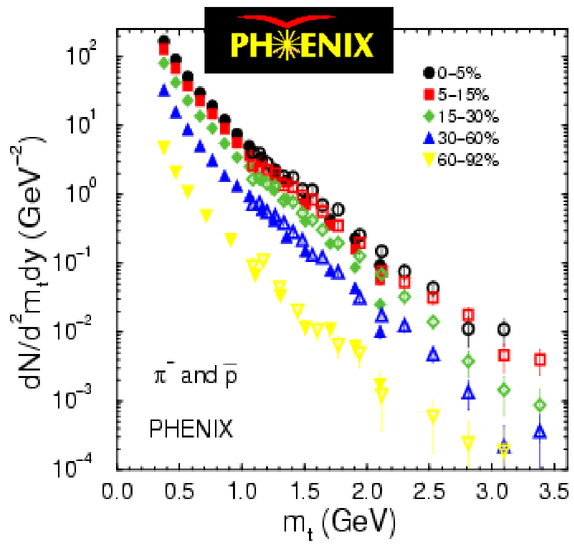
Participants = 2 x 197 - Spectators

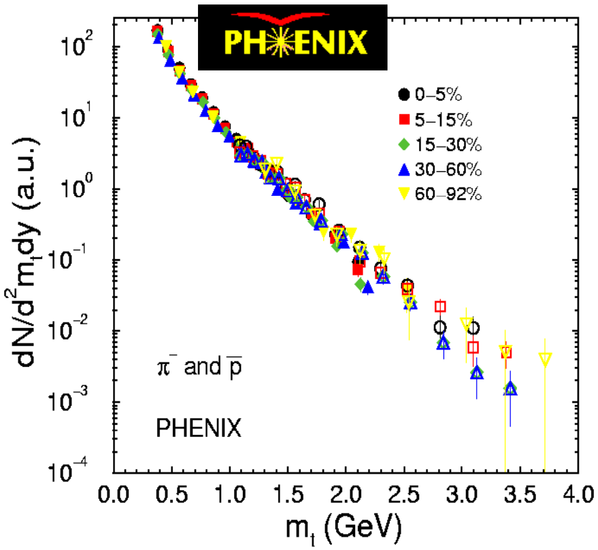


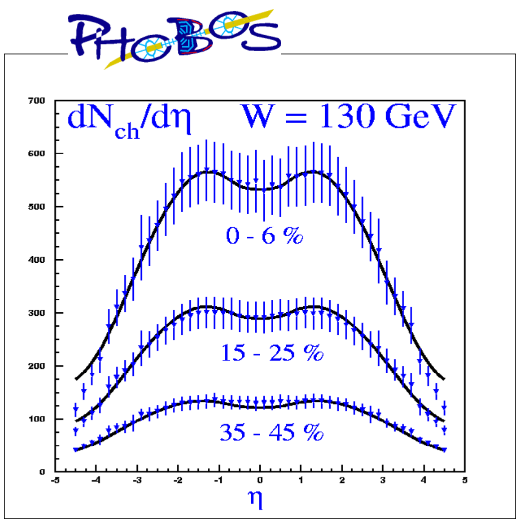
Experimental Tests of Saturation







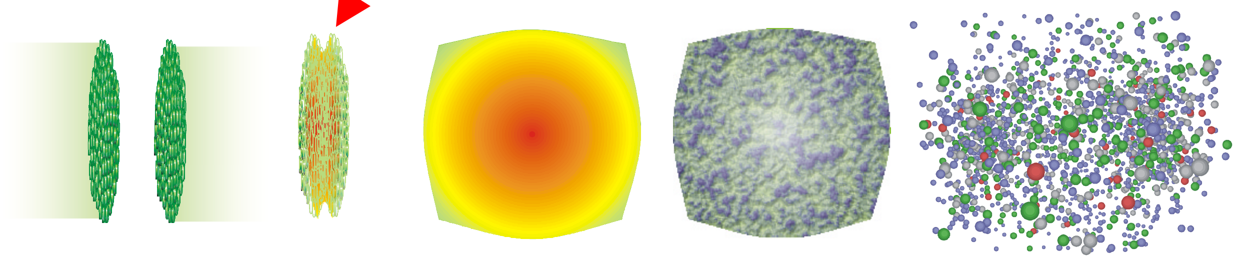




Kharzeev & Levin, nucl-th/0108006
Schaffner-Bielich et al, nucl-th/0108048

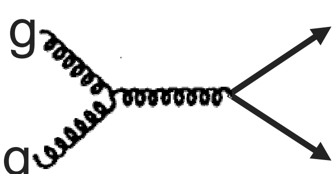
Surprising Agreement

Color Glass Condensate (Saturation) models tell us about the initial density of gluons liberated



Lots of dynamics are simplified into one parameter to relate the gluons to final state hadrons.

Charm couples directly to the initial gluon density. Strong interactions conserve flavor and thus signal is preserved through time evolution.



$gg \rightarrow c\bar{c}$

Charm Production

Heavy quark production measurement in heavy ion collisions is experimentally very challenging.

High transverse momentum single leptons and back-to-back leptons are an excellent signature of charm.

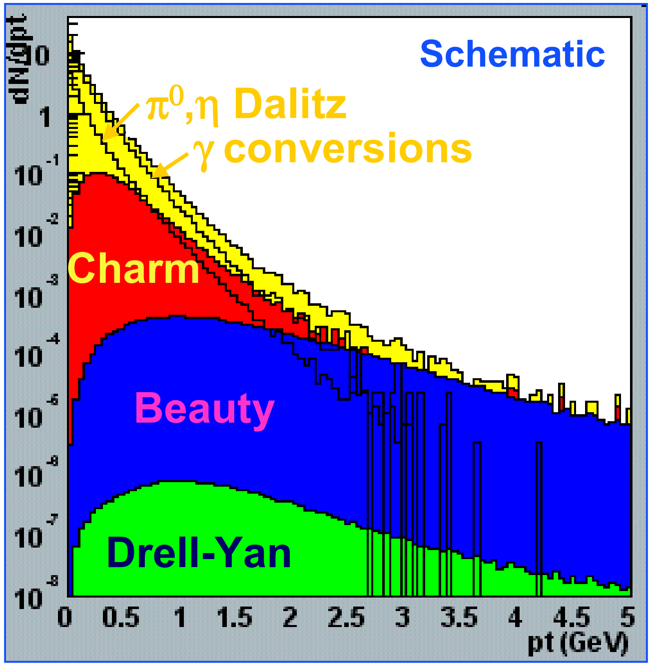
$$D^0 \rightarrow K^- \ell^+ \nu_\ell$$
$$\overline{D^0} \rightarrow K^+ \ell^- \overline{\nu_\ell}$$

One must account for:

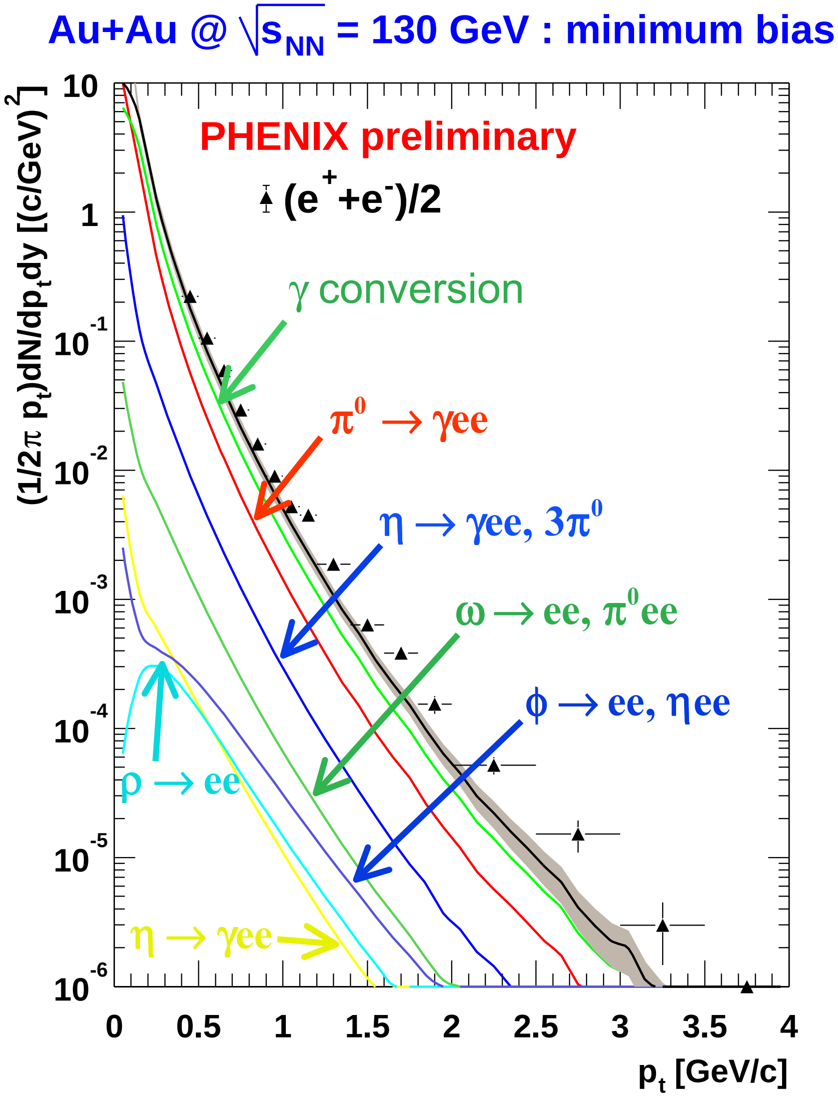
- π^0, η Dalitz
- γ conversions

Remaining signal is then from

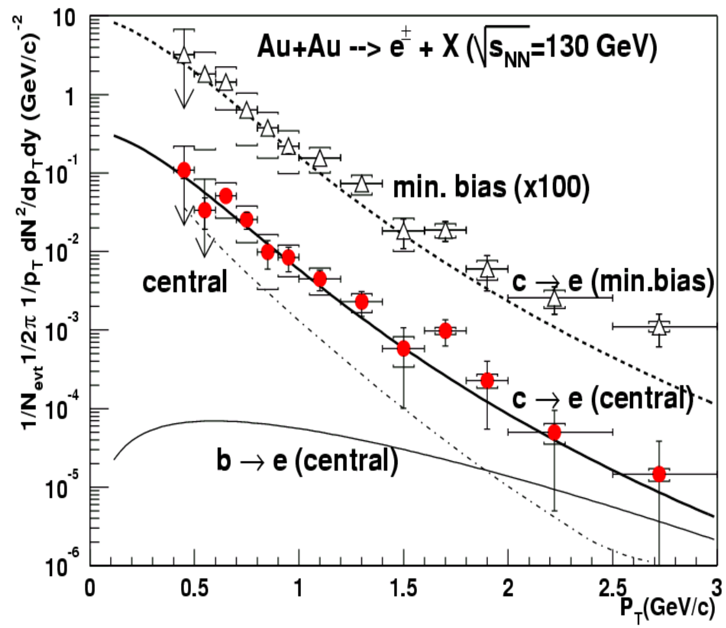
- charm and beauty
- thermal production
- new physics



Single Electron Spectra Results



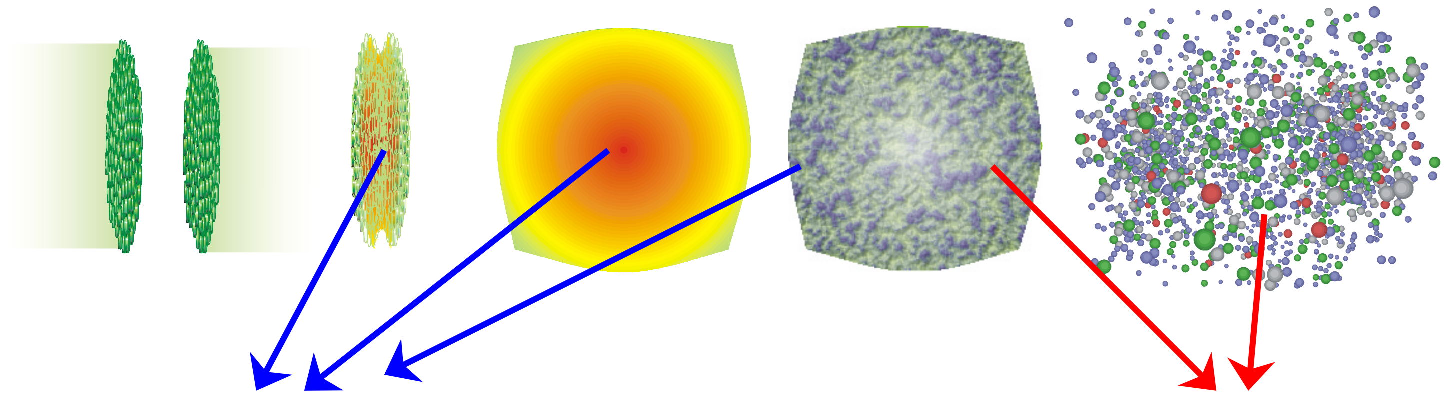
After subtracting the photonic and light hadron decay background, we see a clear electron signal.



Charm cross section
$\sigma_{c\bar{c}} \sim 380 \pm 60 \pm 200\ \mu b$
and binary collision scaling consistent with our data.

(III) Plasma Properties

How can we measure the thermal history?



γ, $\gamma^* \rightarrow$ e^+e^-, $\mu^+\mu^-$

Real and virtual photons from quark scattering is most sensitive to the early stages. Run II measurement.

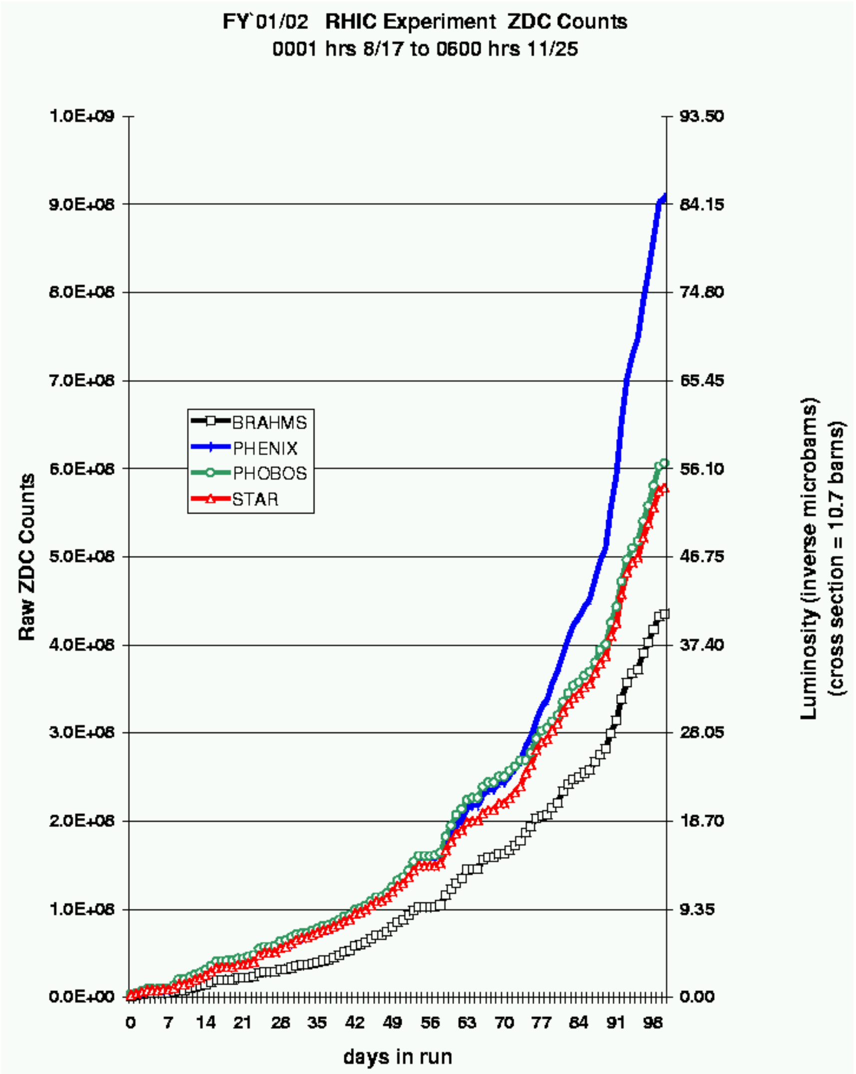
π, **K**, **p**, **n**, ϕ, Λ, Δ, Ξ, Ω, **d**,...

Hadron ratios represent thermal properties when inelastic collisions stop (chemical freeze-out).

Hydrodynamic flow is sensitive to the entire thermal history, in particular the early high pressure stages.

Run II at RHIC

- ✓ RHIC achieved full energy
- ✓ RHIC achieved ~50% of design luminosity in the last two weeks
  - E.g. PHENIX recorded
    - ~ 170 million events
    - ~ 24 μb^{-1}
- ✓ High statistics for charm.
- ✓ Ability to resolve many open issues of parton energy loss.
- ✓ Multistrange baryon measures.
- ✓ First measurement of quarkonia production.



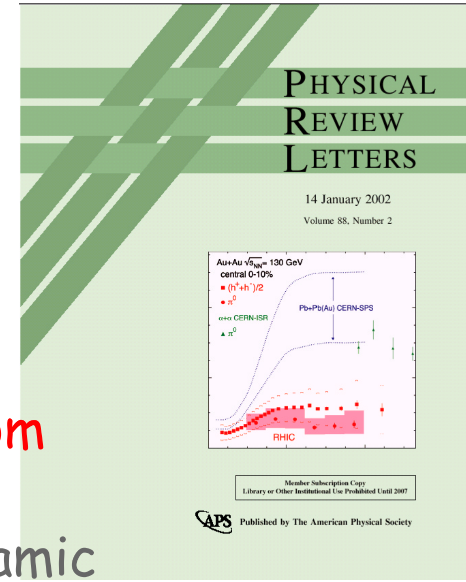
Proton Spin Structure at RHIC

RHIC completed 5 weeks of polarized proton-proton.

Crucial comparison data for the Au-Au program.

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
π^0 Production $A_{LL}(gg, gq \to \pi^0 + X)$ $\pi^{+/-}$ Production $A_{LL}(gg, gq \to \pi^{+/-} + X)$ Heavy Flavors $A_{LL}(gg \to c\bar{c}, b\bar{b} + X)$ Direct Photon $A_{LL}(gq \to \gamma + X)$ Jet Photon $A_{LL}(gq \to \gamma + Jet + X)$ Jet Jet $A_{LL}(gq \to Jet + Jet + X)$	W Production $A_L(u + \bar{d} \to W^+ \to l^+ + \nu_l)$ $A_L(\bar{u} + d \to W^- \to l^- + \bar{\nu}_l)$	Transversity h_1: π^+, π^- Interference fragmentation: $A_T\left(p_\perp p \to (\pi^+, \pi^-) + X\right)$ Single Pion Asymmetries Drell-Yan

Conclusions



RHIC appears to be creating a hot, dense and expanding state of deconfined QCD matter

All results consistent with this interpretation

- ✓ energy density - exceeds lattice QCD expectations
- ✓ initial conditions - saturated gluon distributions from color glass condensate
- ✓ initial state - large parton scattering for hydrodynamic expansion
- ✓ final state - rapidly expanding, thermalized state
- ✓ hard probes - parton energy loss from deconfined medium

Experiments have two orders of magnitude more data in Run II, and with more detector capabilities.

Polarized proton-proton data taking finished.

The future looks bright !