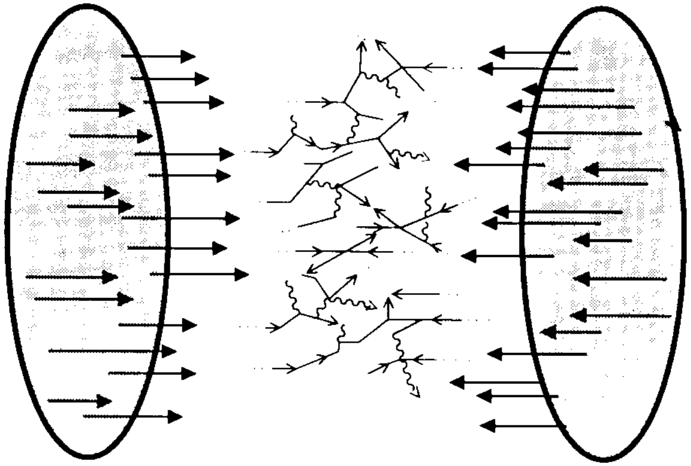
Extreme QCD with the PHENIX Experiment at RHIC



James Nagle

University of Colorado at Boulder

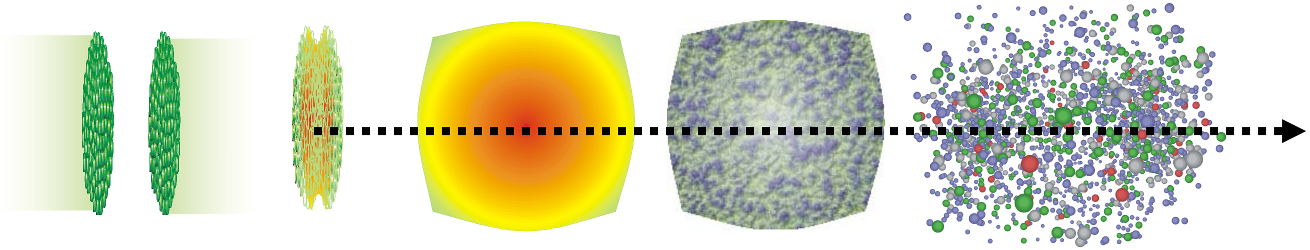
Outline

Quantum Chromodynamics (QCD)

QCD Under Conditions of Extreme Temperature and Density

Relativistic Heavy Ion Collisions

How does a parton propagate through different systems?

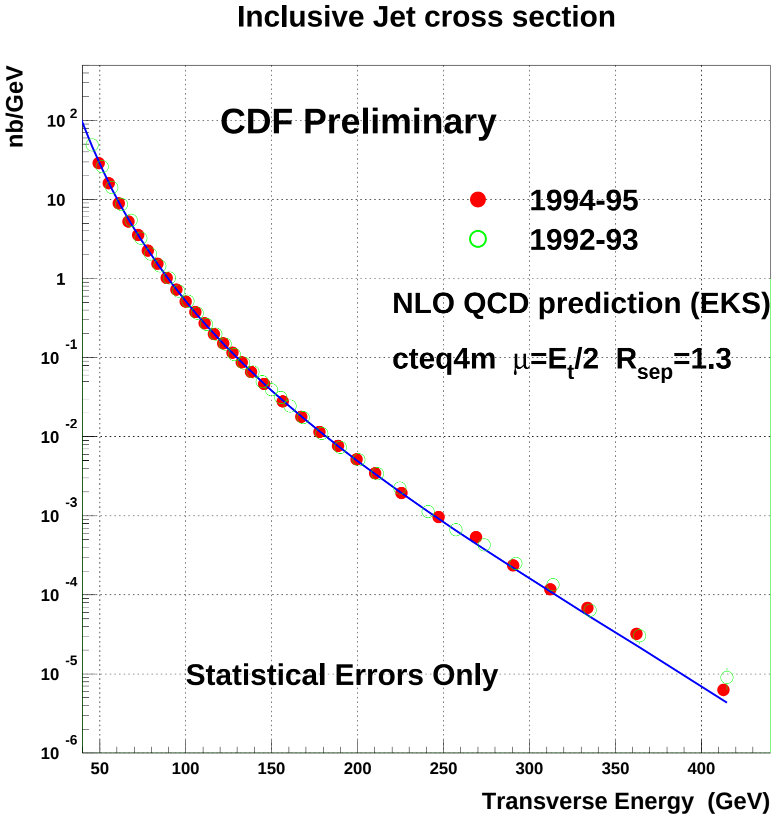


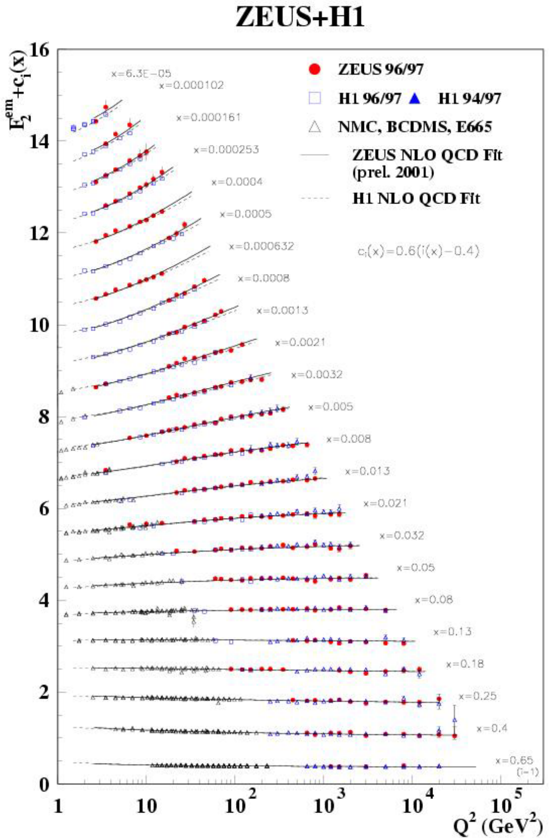
Quantum Chromodyanmics

Most of us believe that QCD is the correct theory of strong interactions. Why do we believe this?

High Energy Jet Observations

Deep Inelastic Scattering Observations





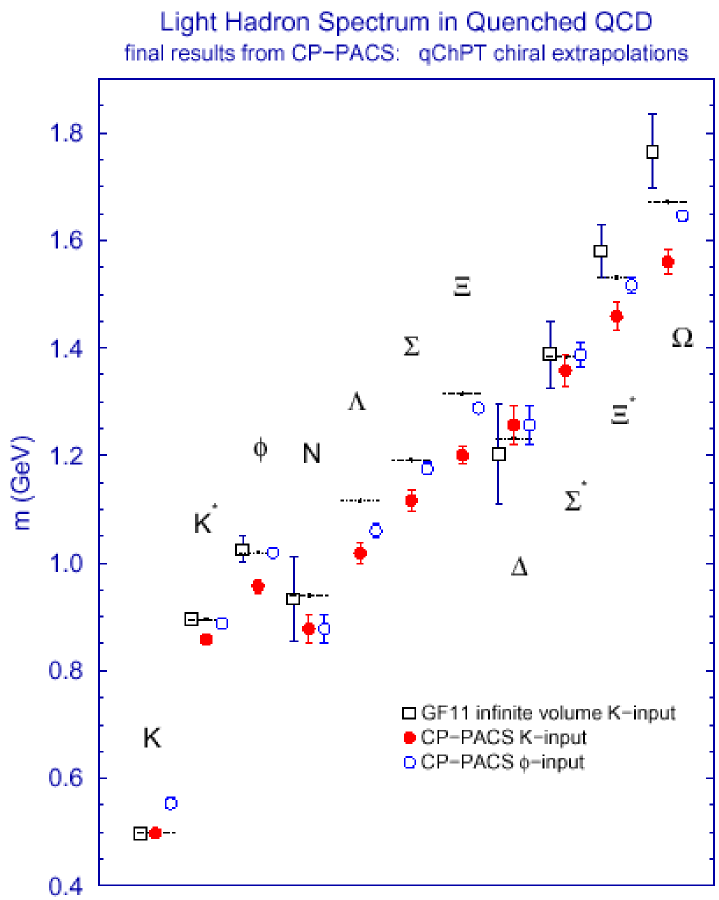
Quantum Chromodynamics II

The previous examples were Next-to-Leading-Order (NLO) perturbative calculations that are applicable at large Q^2.

What about the non-perturbative world around us?

Using lattice QCD we can calculate the various hadron masses.

Agreement at 10% level, excluding π^0.



Lattice QCD

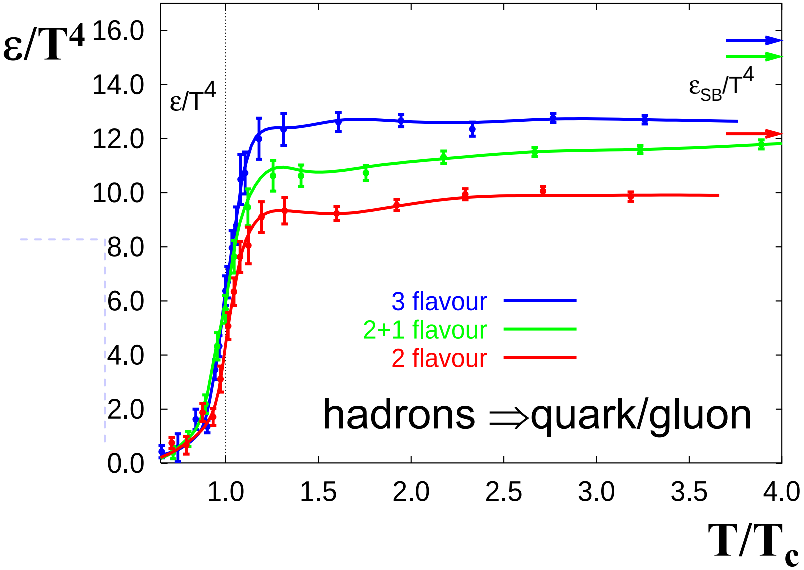
Lattice QCD also predicts a phase transition to a Quark-Gluon Plasma at high temperature where the number of degrees of freedom is significantly increased.

Phase Transition:

T = 150-200 MeV ~ 10^{12} ^{0}F

$\varepsilon \sim$ 0.6-1.8 GeV/fm^3

Assumes thermal system.



(F. Karsch, hep-lat/0106019)

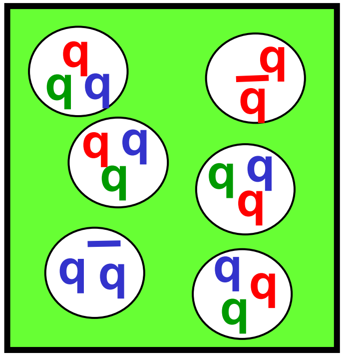
Deconfinement

QCD in Vacuum

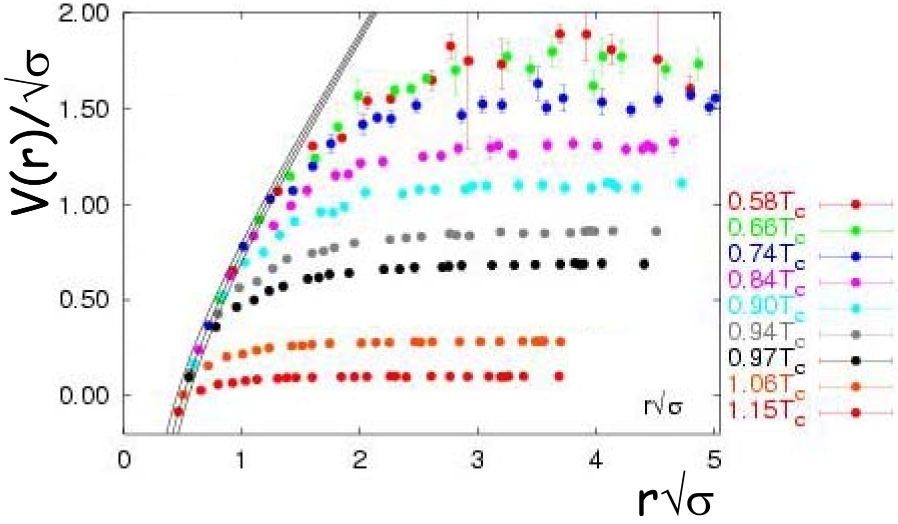
- linear increase with distance from color charge
- strong attractive force
- **confinement of quarks** to hadrons baryons (qqq) and mesons ($q\bar{q}$)

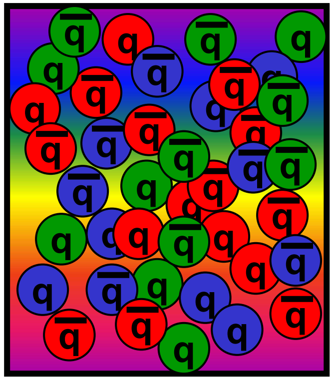
QCD in dense and hot matter

- screening of color charges
- potential vanishes for large distance scales
- restoration of approximate chiral symmetry
- **deconfinement of quarks and gluons !**

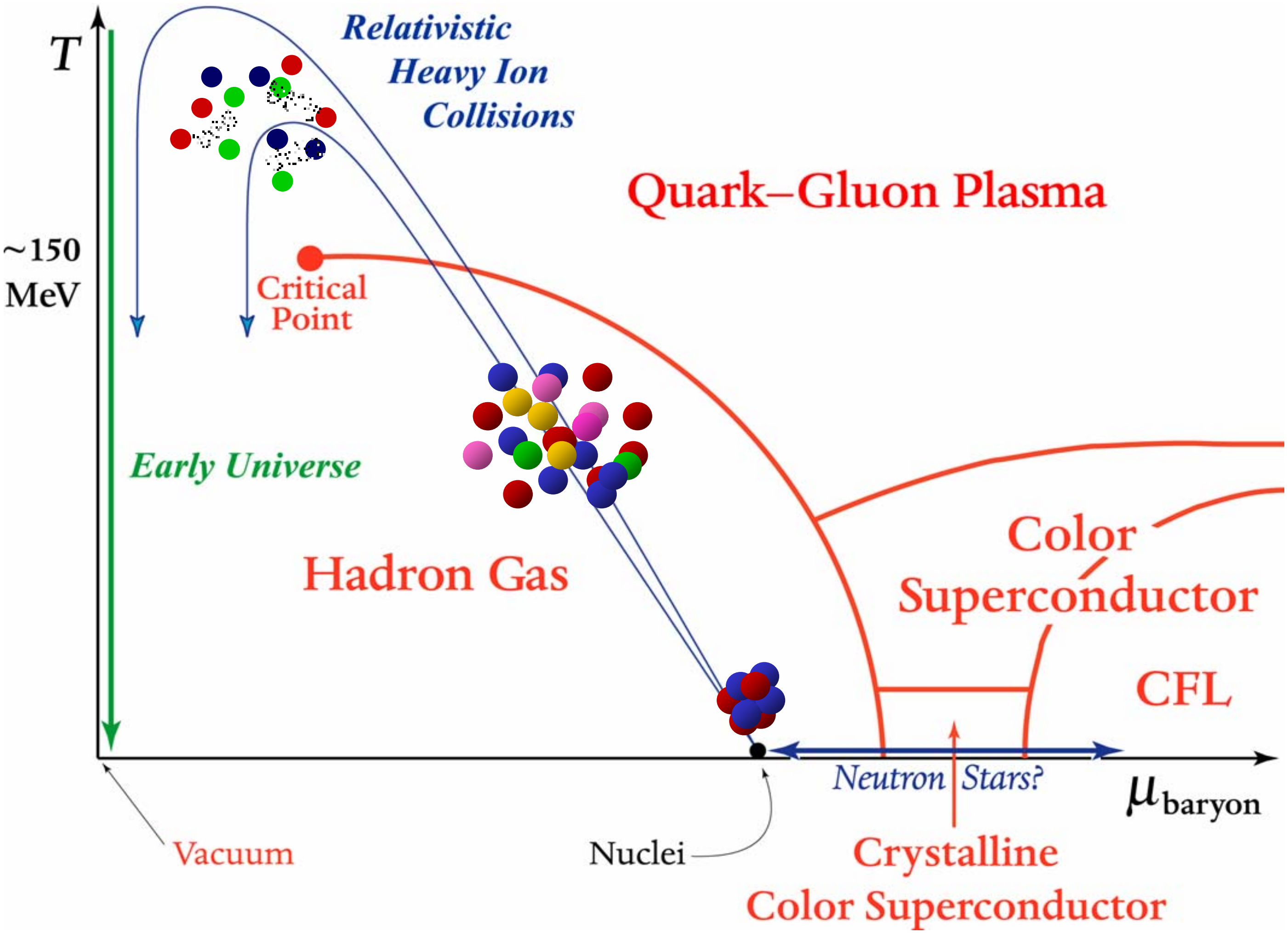


Lattice QCD calculation



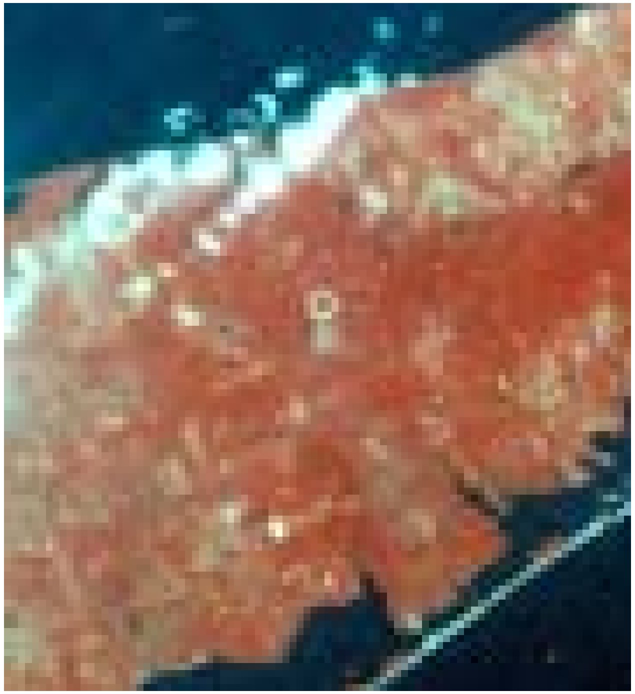


Phase Diagram

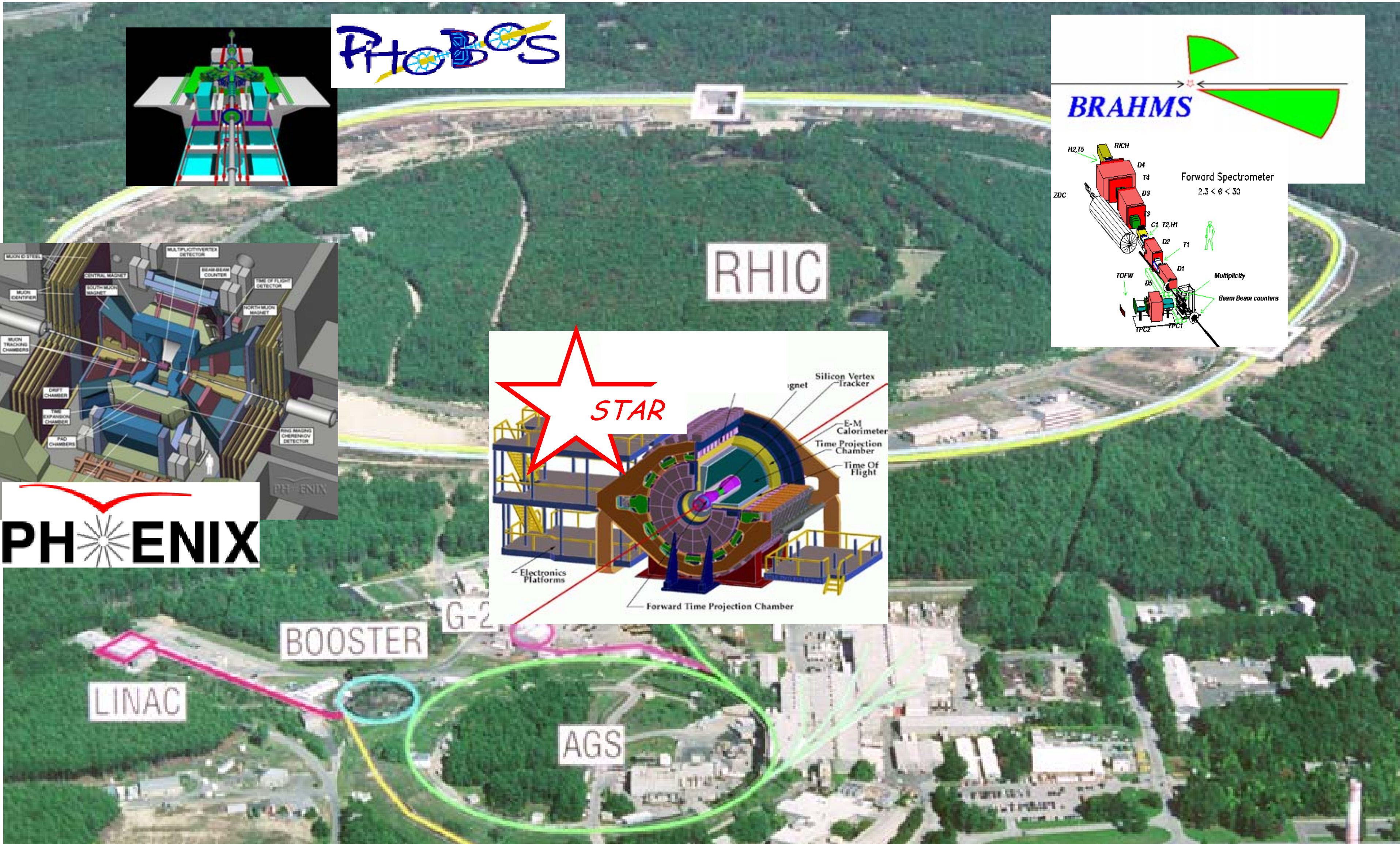


Relativistic Heavy Ion Collider

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



Four Experiments



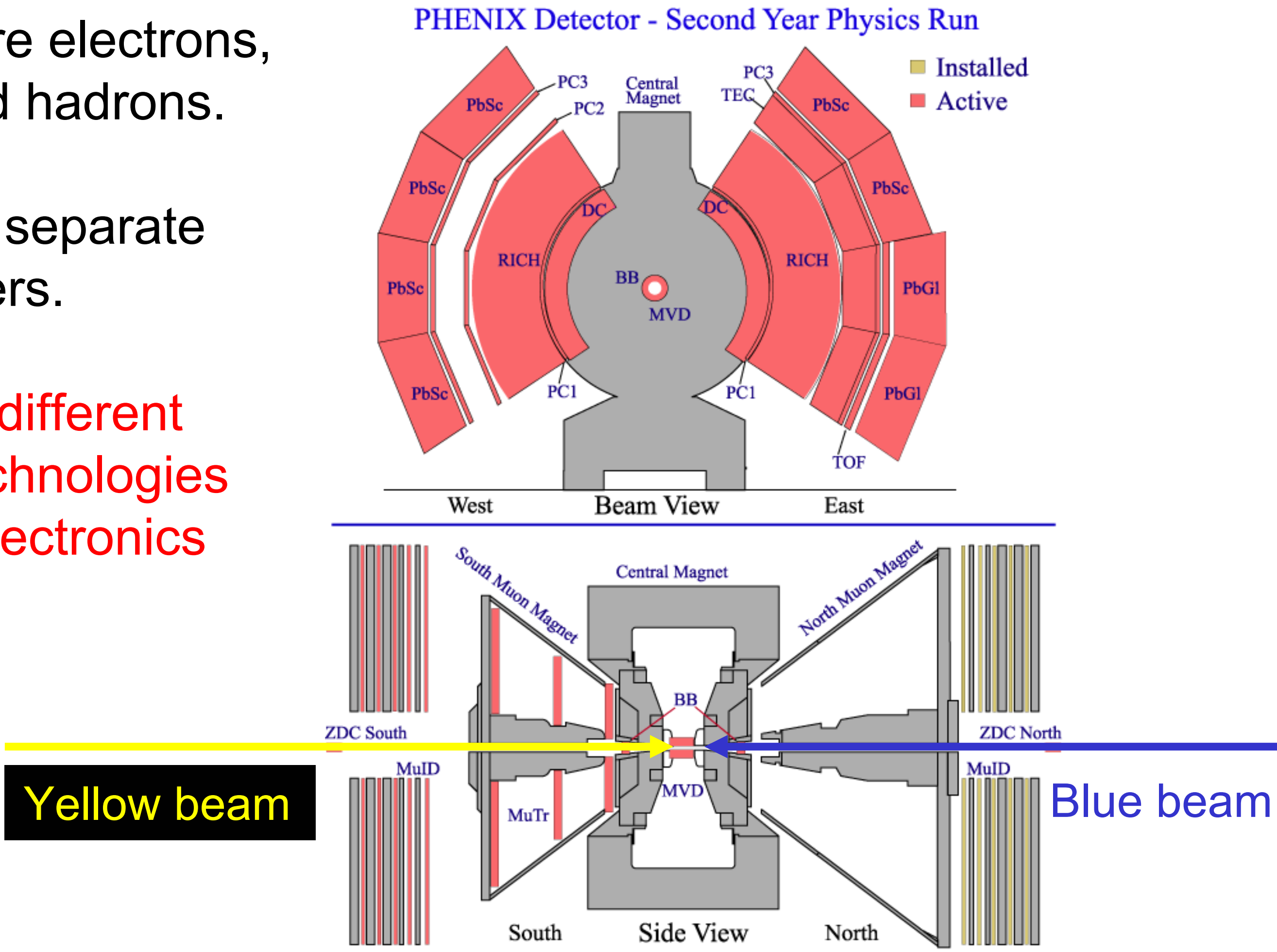
PHENIX

Pioneering High Energy Ion eXperiment

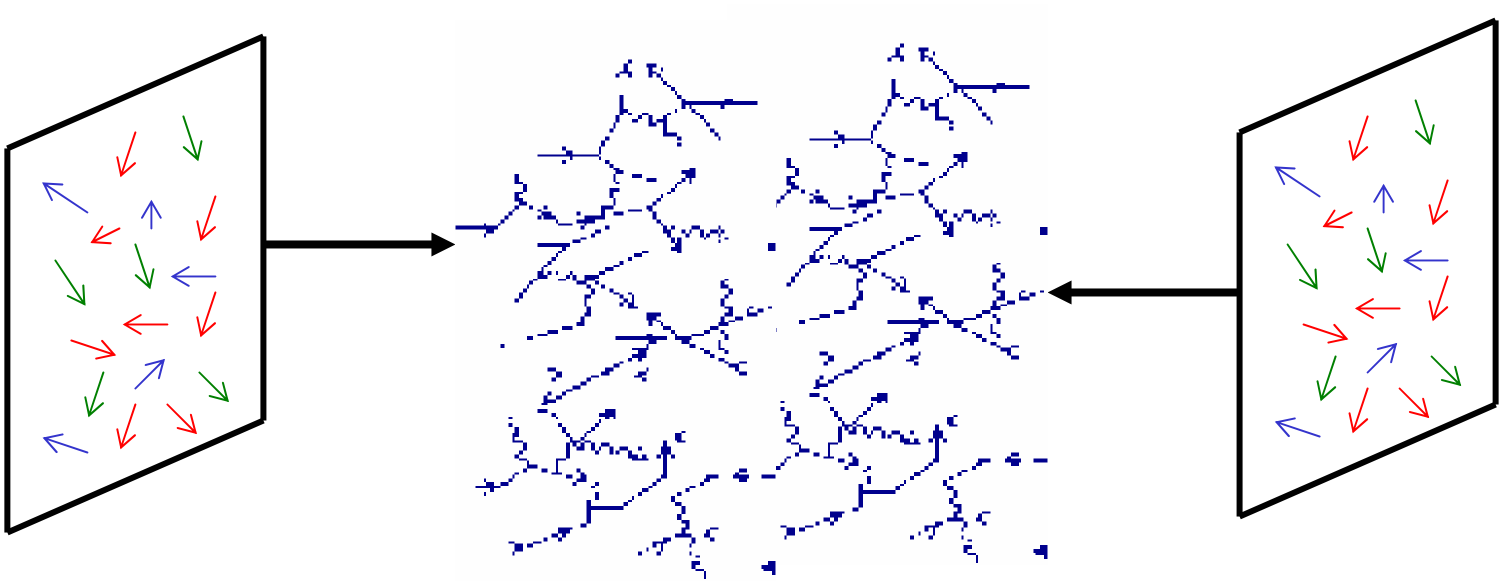
Designed to measure electrons, muons, photons and hadrons.

Complex set of four separate particle spectrometers.

This requires many different types of detector technologies and an integrated electronics readout.

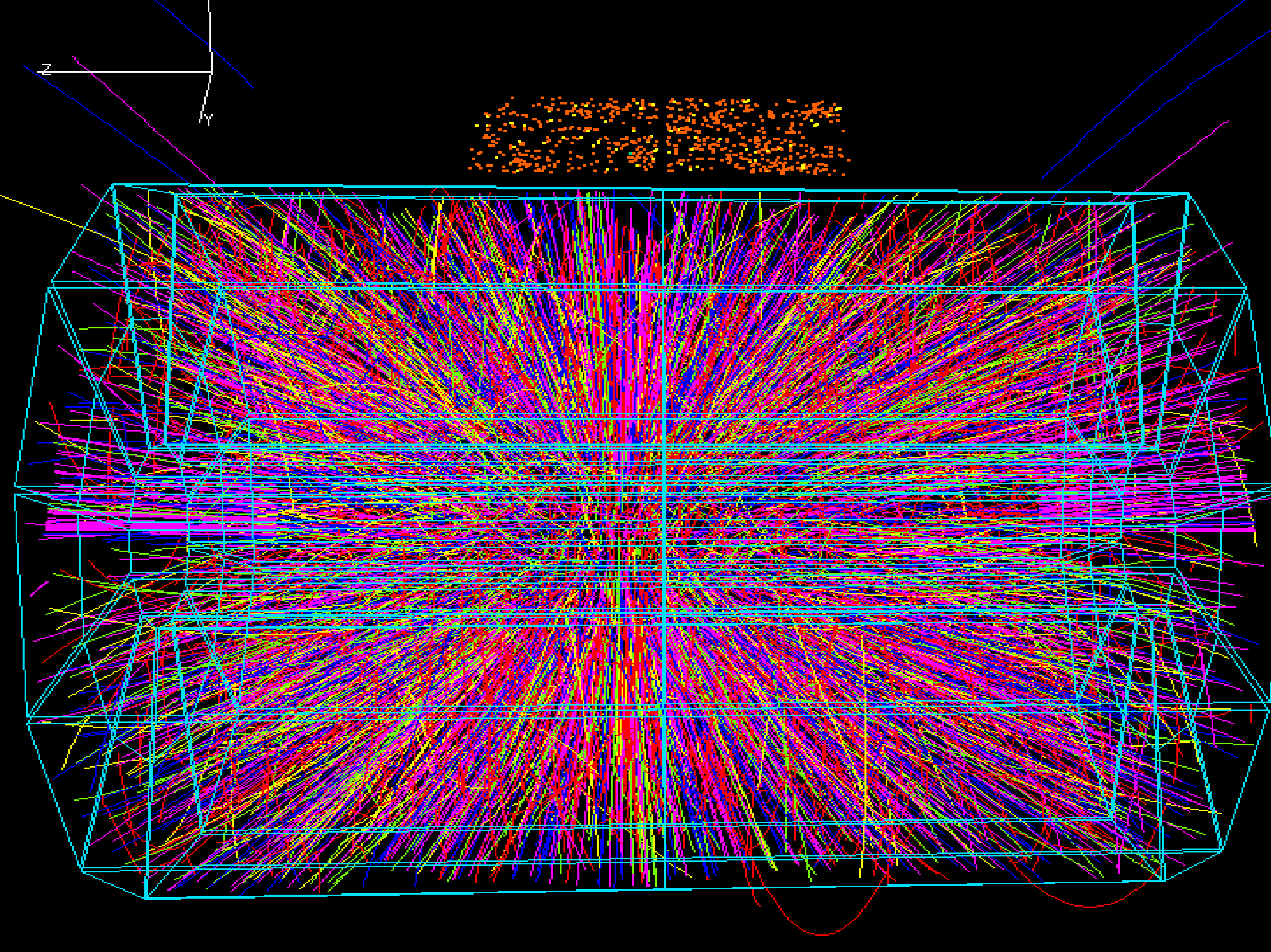


Complex System



10,000 gluons, quarks, and antiquarks
from the nuclear wavefunctions
are made physical in the laboratory !

What is the nature of this ensemble of partons?


Z
Y

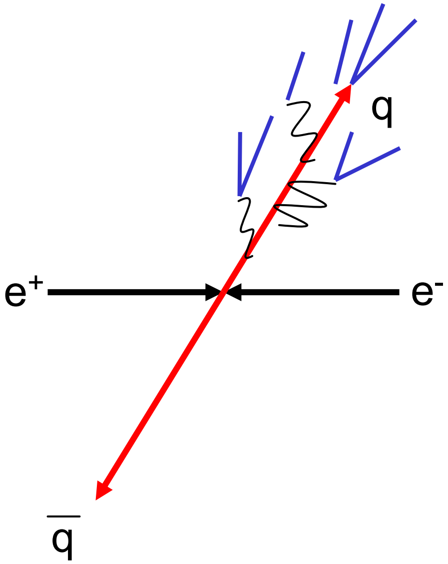
How to Study QCD in this Environment?

Two general categories of observables.

1. Bulk Effects
    - Collective motion
    - Particle production (mostly low momentum)
    - Particle ratios and correlations

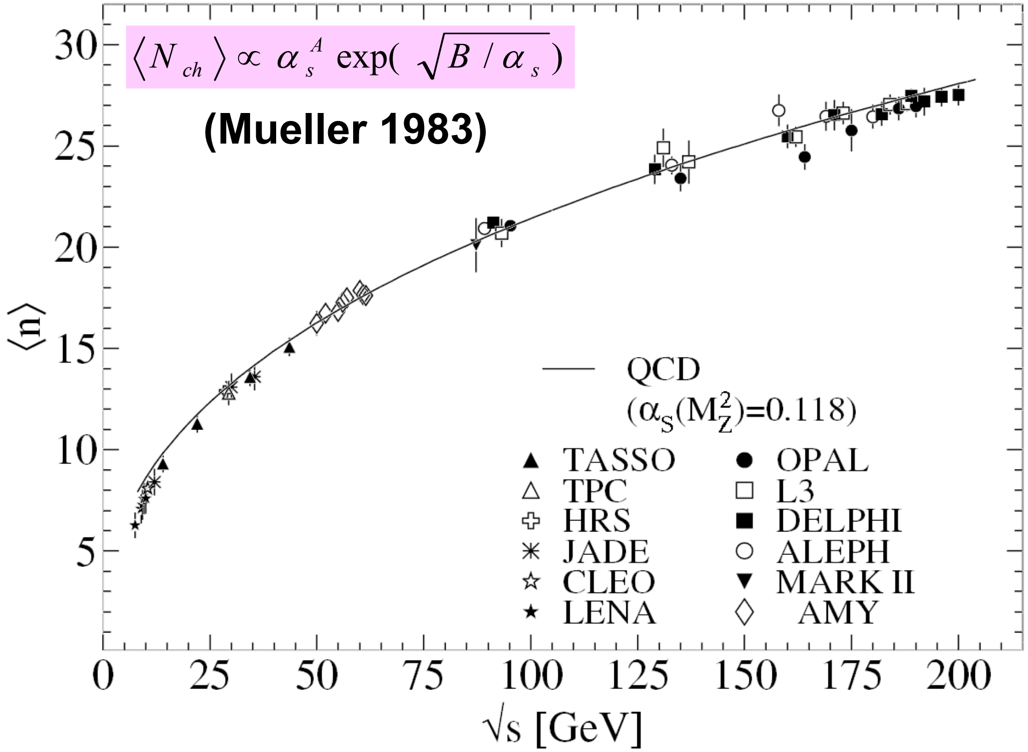
2. Probes of the System
    - Hard scattered partons propagating in medium
    - Quark-Antiquark pairs propagating in medium

Parton Propagating in Vacuum



Quark radiates gluons and eventually forms hadrons in a jet cone.

QCD calculation of gluon multiplicity times a hadron scale factor gives excellent agreement with data.

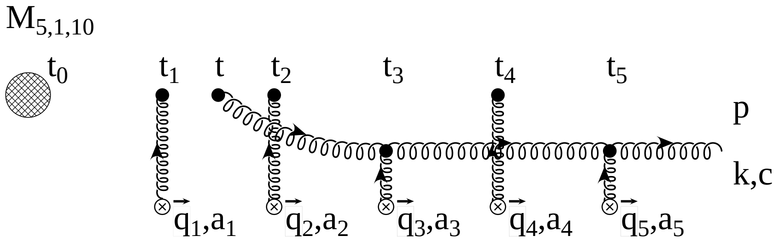

$\langle N_{ch} \rangle \propto \alpha_s^A \exp(\sqrt{B/\alpha_s})$

(Mueller 1983)

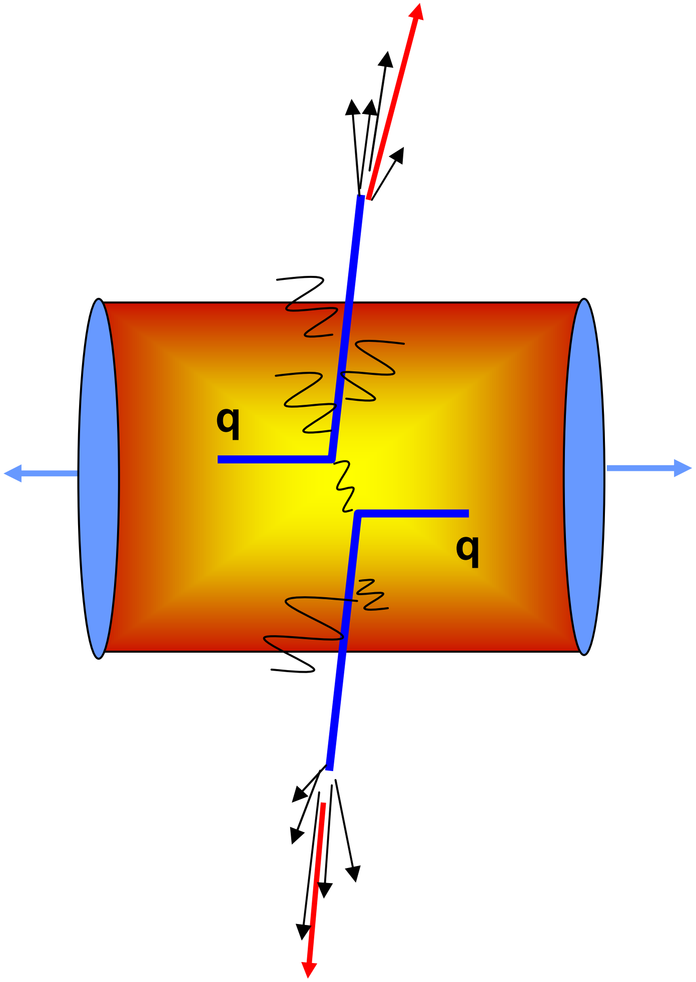
Induced Gluon Radiation

Partons are expected to lose additional energy via induced gluon radiation in traversing a dense partonic medium.

Coherence among these radiated gluons leads to ΔE a L^2



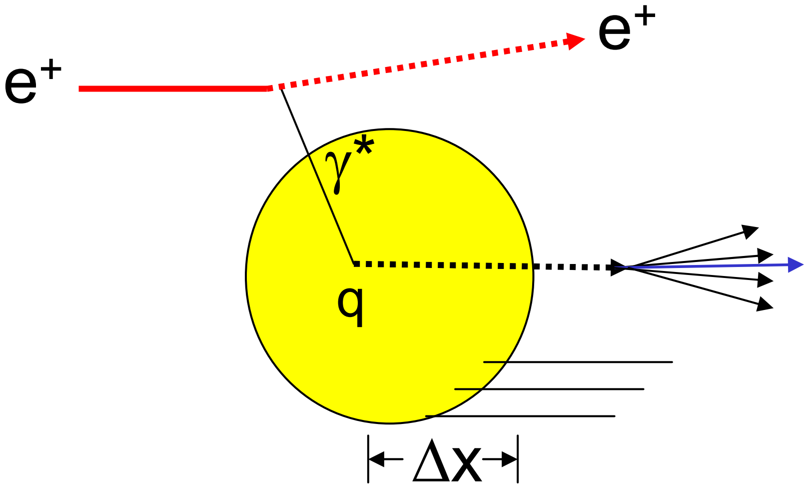
Look for an increase in multiplicity and a suppression of high z (momentum fraction) hadrons from jet fragmentation.

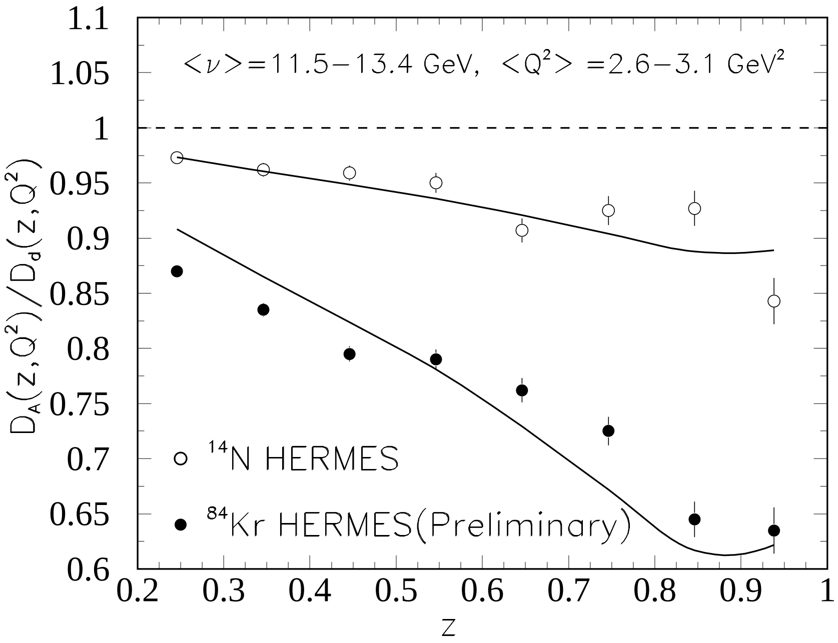


Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267
Gyulassy, Levai, Vitev, hep-pl/9907461
Wang, nucl-th/9812021
and many more…..

Partons in Cold Nuclear Matter

HERMES Experiment





Measure quark energy from electron scattering off nuclei.

Measure hadron fragmentation function D(z).

Larger nuclei show fewer high z hadrons in fragmentation.

Calculations of Wang *et al.* indicate radiative energy loss α L^2 and for Kr target <dE/dx> ~ 0.3 GeV/fm

HERMES - Eur. Phys. J. C20, 479 (2001).
Wang et al., hep-ph/0202105

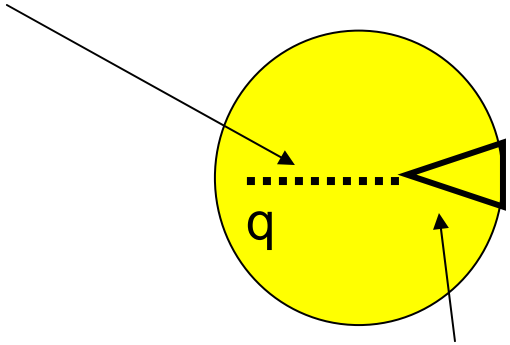
Hadronization Time

Alternative description also considered by HERMES.

Suppression due to quark-nucleon scattering ($t < t^{\pi}_{f}$) and hadron-nucleon scattering ($t > t^{\pi}_{f}$).

$$\boxed{t_f^{\pi} = c_{\pi}(1-z)\nu}$$

$$\sigma_{q-N} = 0.0 \pm 0.2mb$$



$$\sigma_{h-N} = 25.0mb$$

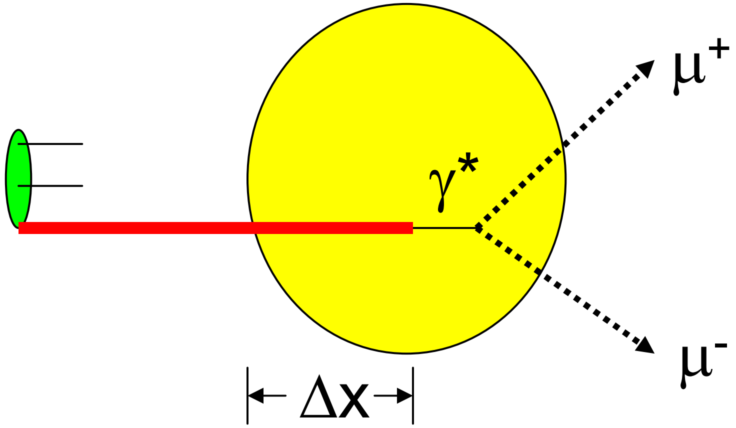
A hadron with large z originates from a quark emitting only a few gluons. The emission of only a few gluons corresponds to a small formation time.

They consider good agreement with N^{14} data in a model in which the “interaction of the struck quark with the nuclear medium is very small.”

hep-ex/0012049

Incoming Parton Energy Loss

Drell-Yan production in proton-nucleus collisions is sensitive to parton energy loss..



Must carefully separate nuclear shadowing effects and energy loss effects both of which lead to suppression of Drell-Yan pairs.

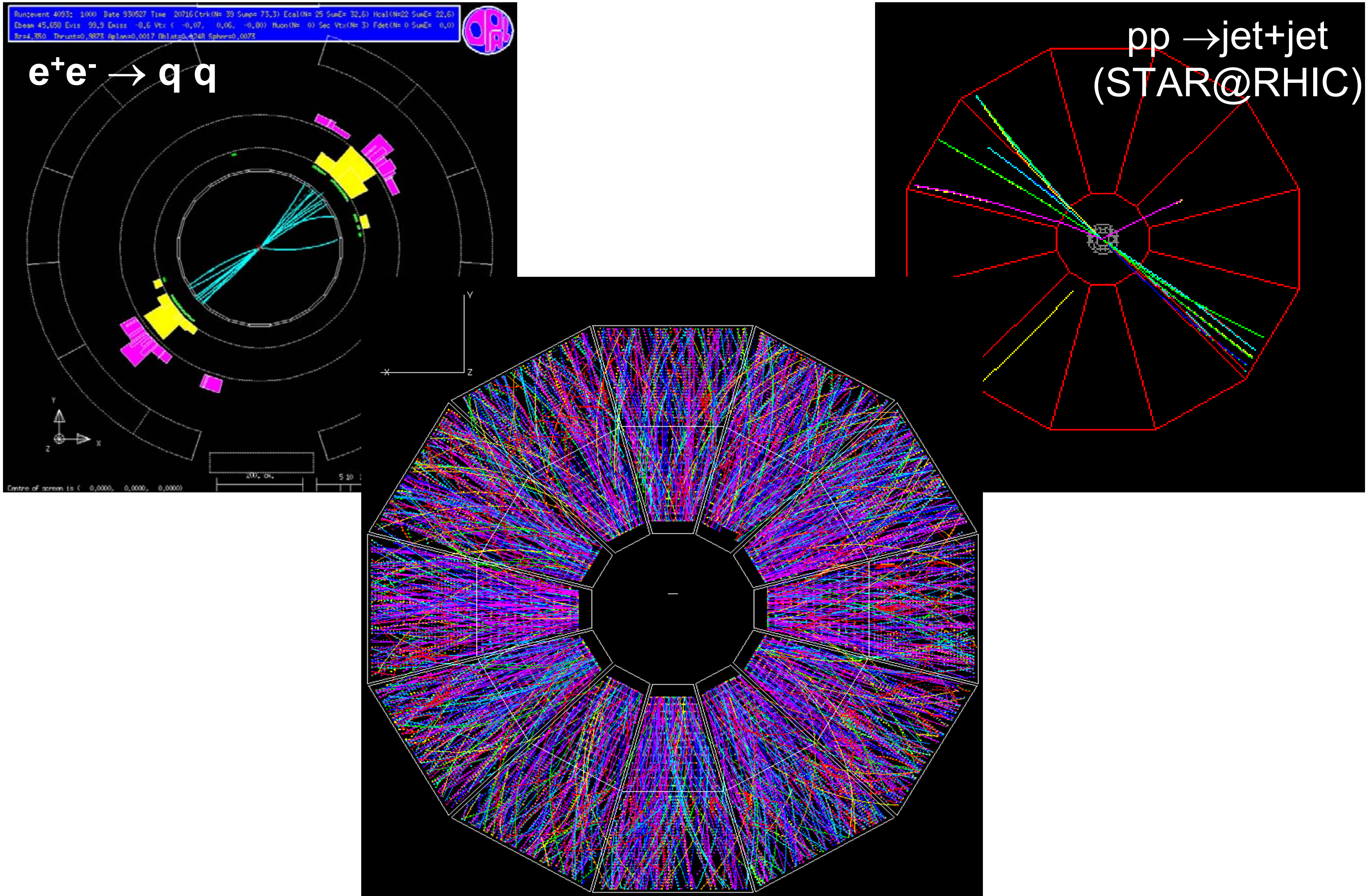
E772 and E866 at Fermilab

dE/dx = 2.73 ± 0.37 ± 0.5 GeV/fm (from hadronization due to confinement)
dE/dx ~ 0.2 GeV/fm (from gluon radiation due to nuclear environment)

“This is the first observation of a non-zero energy loss effect in such experiments.”

Johnson, Kopeliovich, Potashnikova, E772 et al.
Phys. Rev.C 65, 025203 (2002) hep-ph/0105195
Phys. Rev. Lett. 86, 4487 (2001) hep=ex/0010051

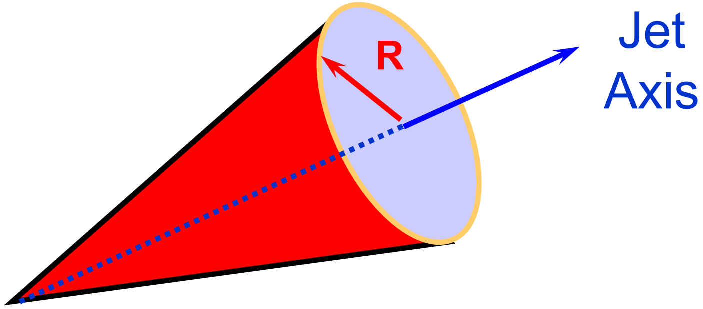
What about in Hot Nuclear Matter?

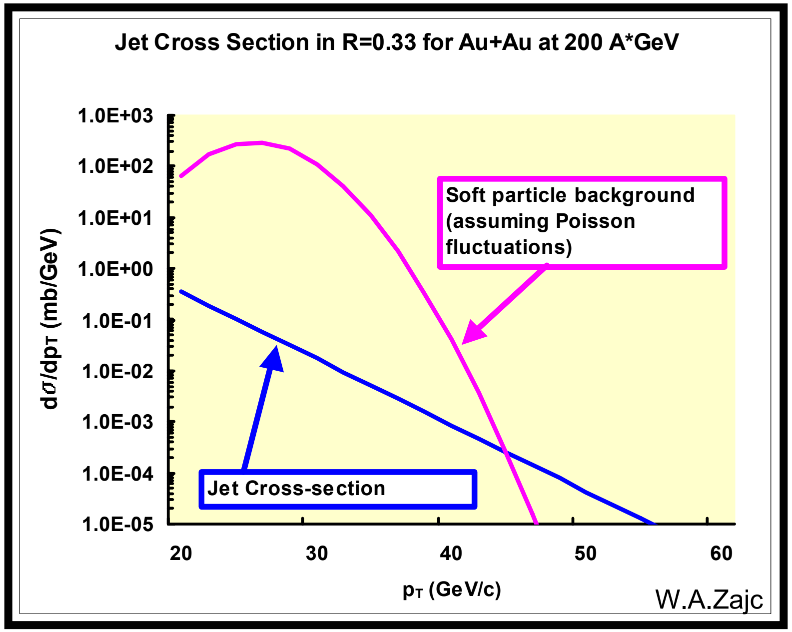


Jets and Underlying Event

“Traditional” jet methodology fails at RHIC because jets are dominated by the soft background.

For a typical jet cone R = 0.33




Jet Cross Section in R=0.33 for Au+Au at 200 A*GeV

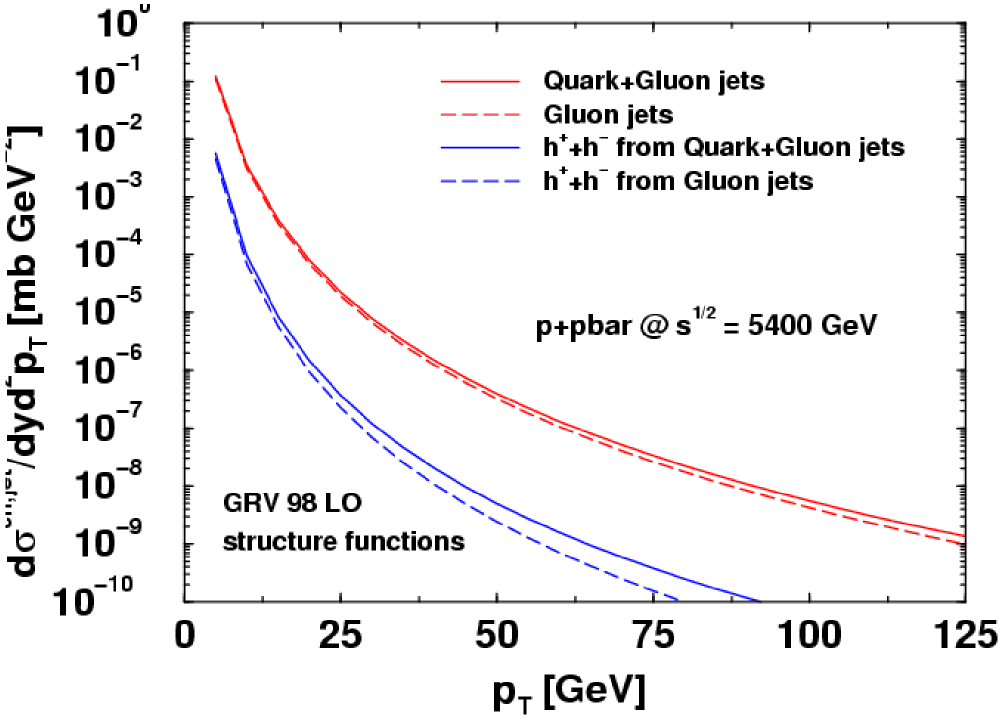
W.A.Zajc

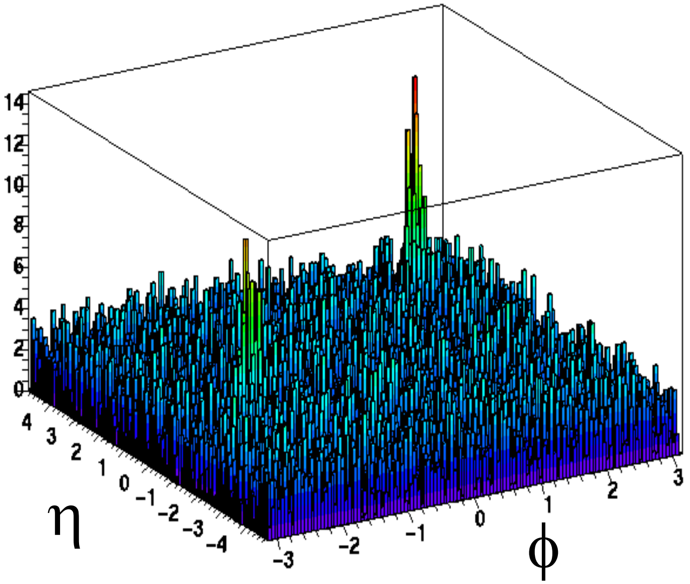
Fluctuations in this soft background swamp any jet signal for $p_T < \sim 40$ GeV

Note that Jet measurements at Tevatron below 50 GeV are still very challenging.

Jets in ATLAS at LHC

Although the soft background is increased at LHC energies, the jet cross sections are so large that truly high p_T (> 70 GeV) jets may be observed.



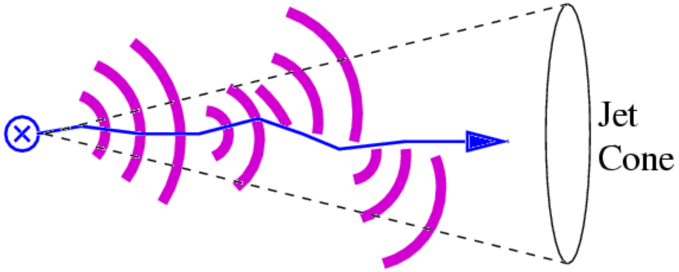


200 GeV jet event overlay on central Pb-Pb event with ATLAS calorimter segmentation

ATLAS Heavy Ion Letter of Intent [nucl-ex/0212016]

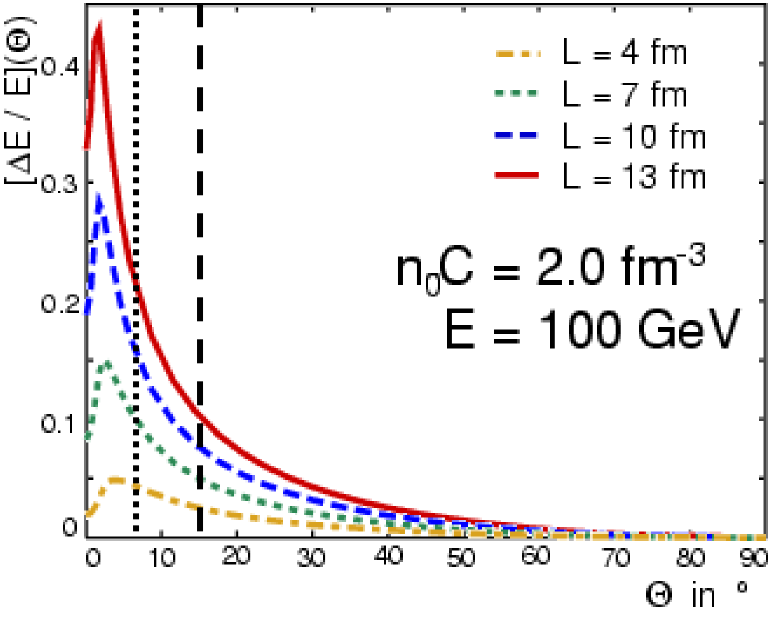
Jet Broadening

The induced gluon radiation may be measurable due to the broader angular energy distribution than from the jet.



$\theta<20^0$ - 80% of jet energy contained
5% loss of energy outside

$\theta<12^0$ - 70% of jet energy contained
8% loss of energy outside



Possible observation of reduced “jet” cross section from this effect.
This is not going to be easy at RHIC or LHC.

U.A. Wiedemann, hep-ph/0008241.
BDMS, hep-ph/0105062.

Deconvolution from Final Hadrons

In hadron-hadron, we can calculate the yield of high p_T hadrons

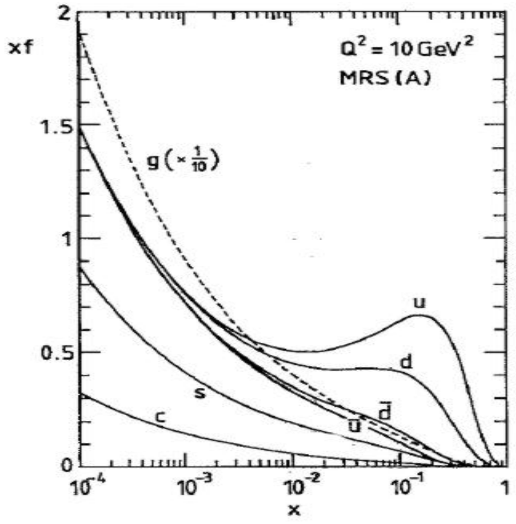
$$E_h \frac{d\sigma_h^{pp}}{d^3p} = K \sum_{abcd} \int dz_c\, dx_a\, dx_b \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} f(\mathbf{k}_{Ta}) f(\mathbf{k}_{Tb}) \underline{f_{a/p}(x_a, Q_a^2) f_{b/p}(x_b, Q_b^2)}\; \underline{D_{h/c}(z_c, Q_c^2)} \frac{\hat{s}}{\pi z_c^2} \underline{\frac{d\sigma^{(ab\to cd)}}{d\hat{t}}} \delta(\hat{s}+\hat{u}+\hat{t})$$

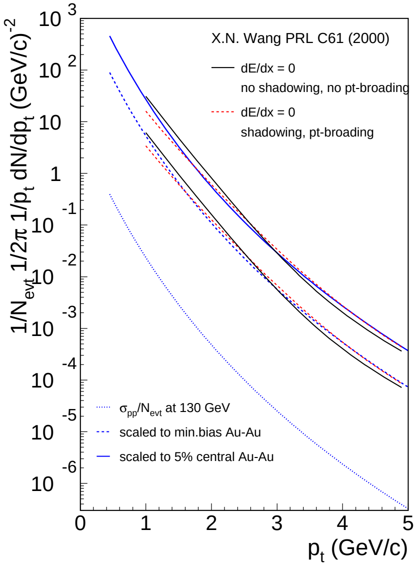
Flux of incoming partons (structure functions) from Deep Inelastic Scattering

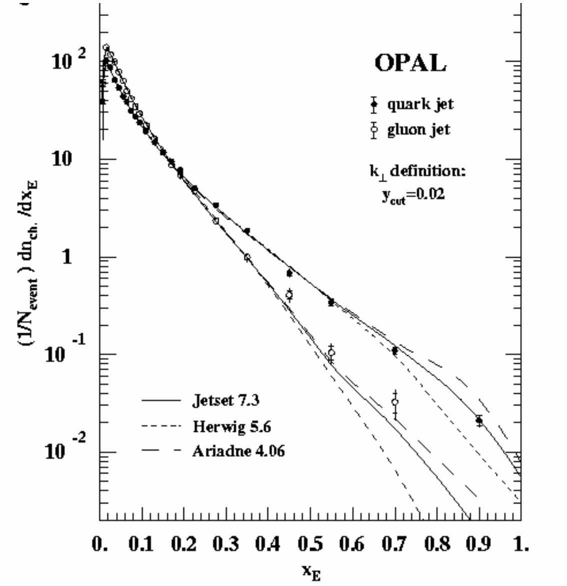
Perturbative QCD

$$\sigma_{AA}(b_c) = \sigma_{pp} \int_0^{b_c} db^2 \underline{T_{AA}}$$

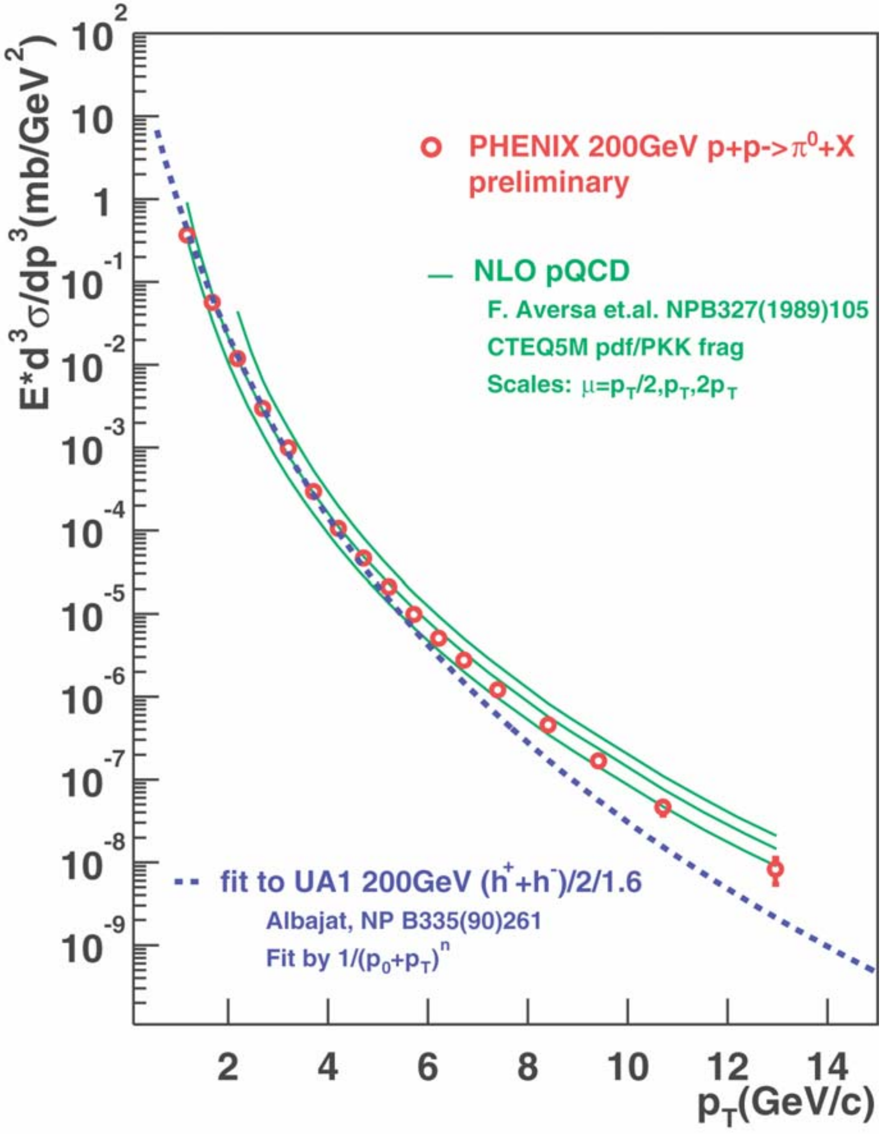
Fragmentation functions D(z) in order to relate jets to observed hadrons





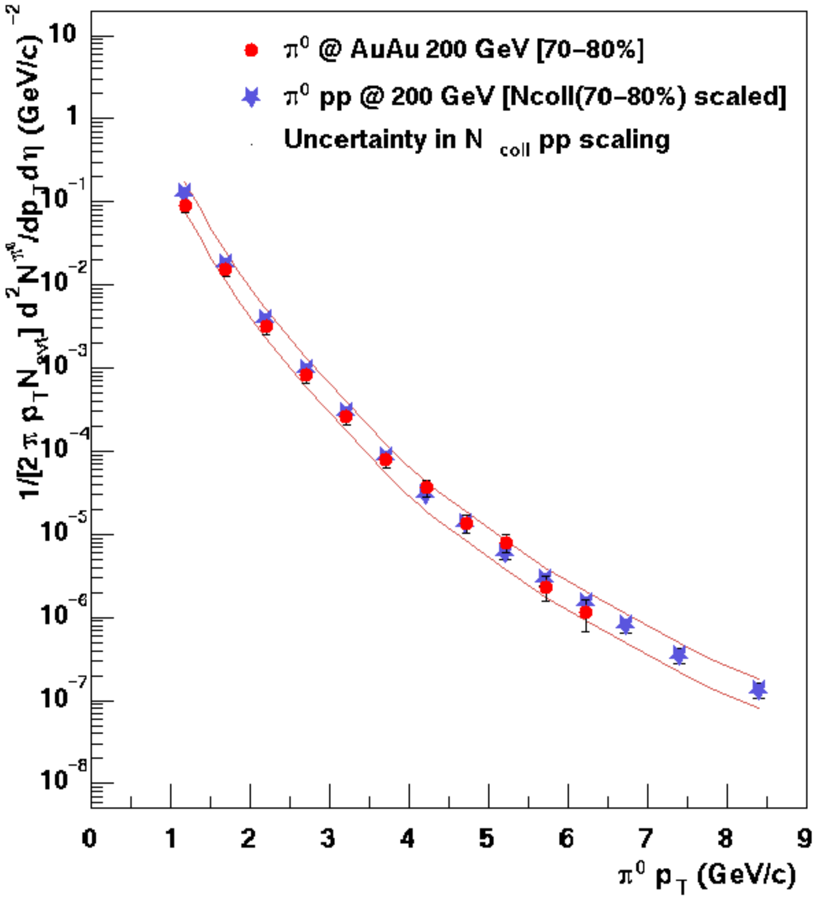


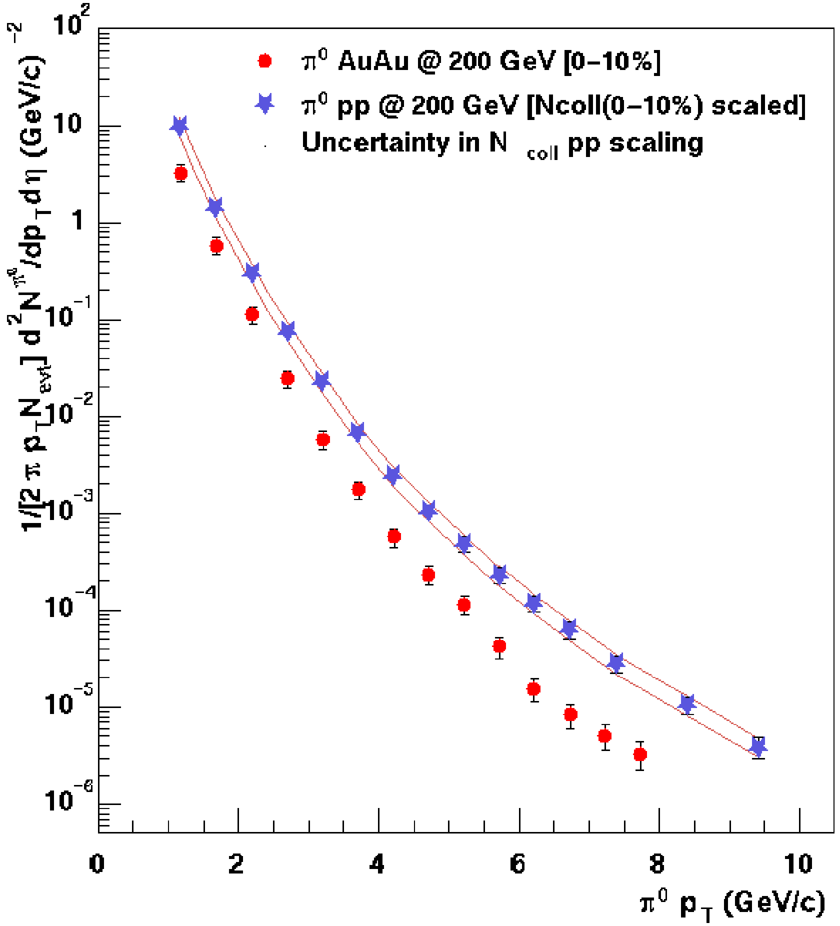
PHENIX pp→ π^0 + X Baseline



Au+Au $\rightarrow \pi^0 + X$

Peripheral Au+Au collisions appear as superposition of proton-proton reactions. Central Au+Au collisions show a significant suppression relative to naïve expectations (binary collision scaling of hard processes).





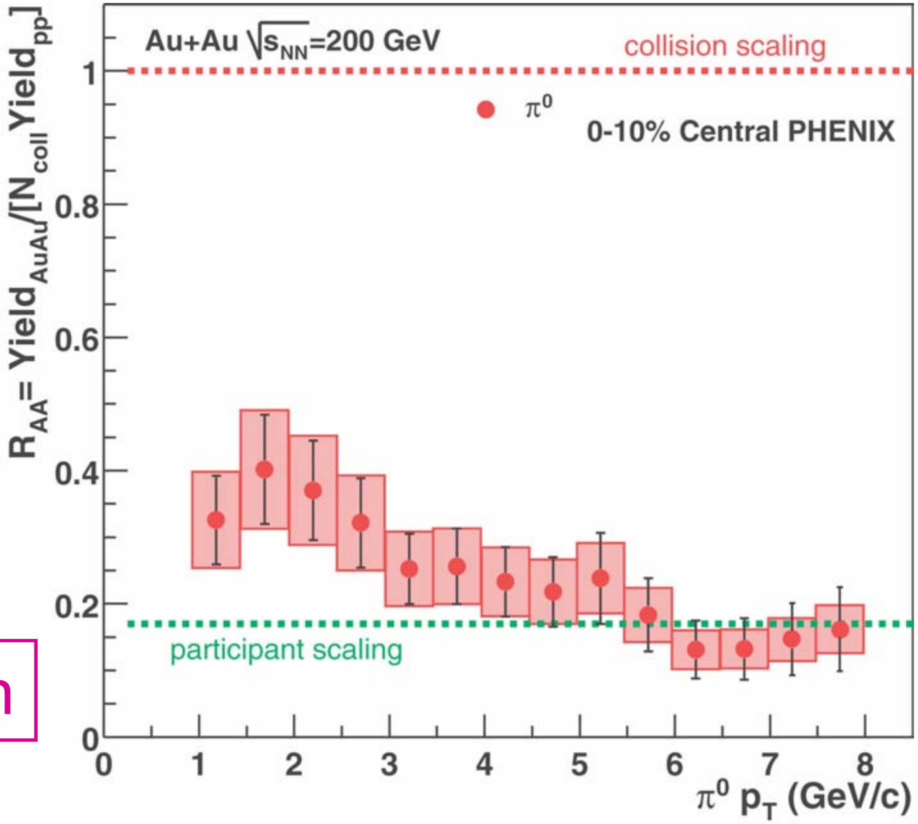
Very Large (x5)
Final or Initial State Effect !

Nuclear Modification Factor:

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

$<N_{binary}>/\sigma_{inel}^{p+p}$

N-N cross section



$$E_h \frac{d\sigma_h^{pp}}{d^3p} = K \sum_{abcd} \int dz_c\, dx_a\, dx_b \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} f(\mathbf{k}_{Ta}) f(\mathbf{k}_{Tb}) \underline{f_{a/p}(x_a, Q_a^2) f_{b/p}(x_b, Q_b^2)}\; \underline{D_{h/c}(z_c, Q_c^2)}\, \frac{\hat{s}}{\pi z_c^2} \underline{\frac{d\sigma^{(ab\to cd)}}{d\hat{t}}} \delta(\hat{s}+\hat{u}+\hat{t})$$

Induced Parton Energy Loss

Energy Loss Calcultions:

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

dE/dx = 0

dE/dx = 0.25 GeV/fm

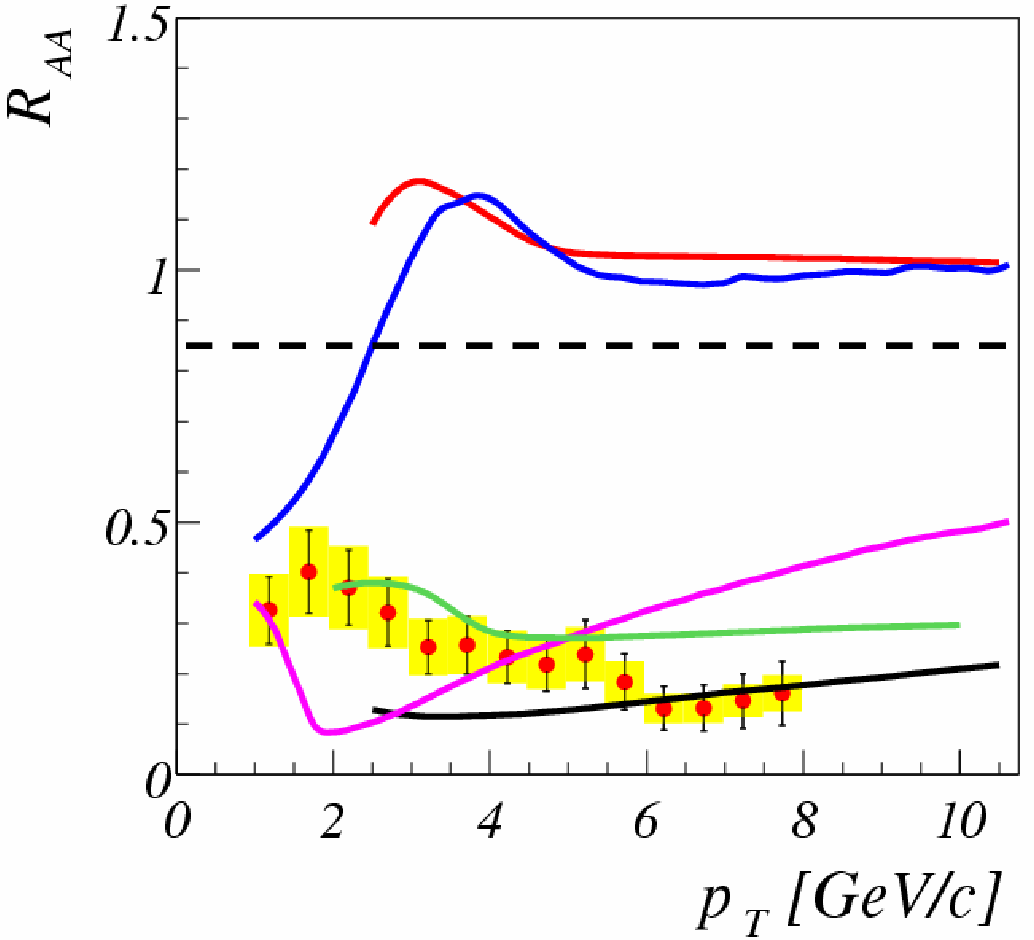
Gyulassy, Levai, Vitev: Nuclear Physics A698 (2002) 631.

Levai L/λ = 0

L/λ = 4

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

$dN^g/dy = 900$

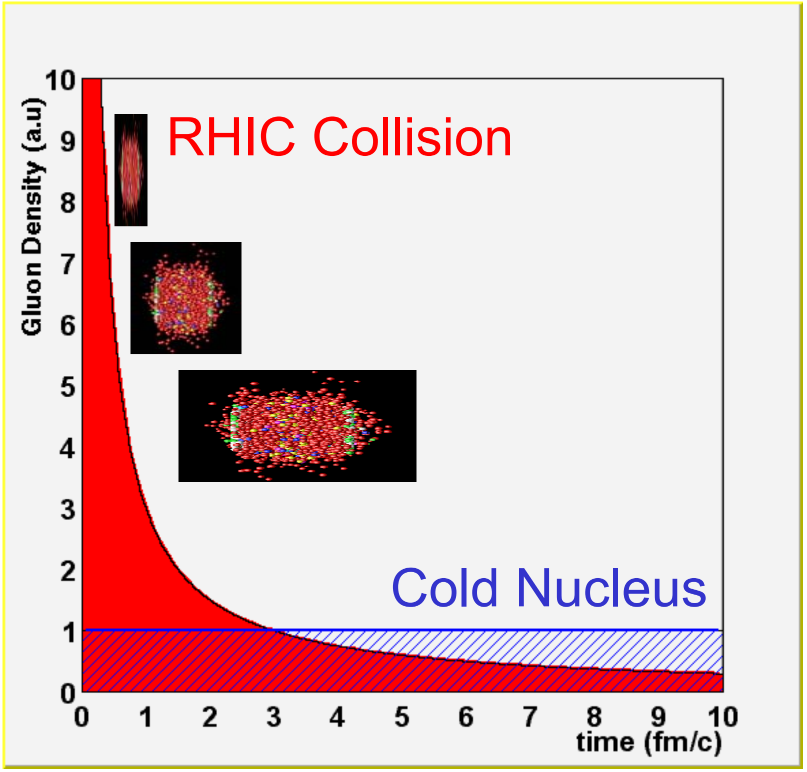


- Calculations sensitive to infrared cutoff (Mueller *et al.*)
- Only indicative of gluon density, no quark-gluon plasma

Expanding System Problem

Calculation of X.N. Wang implies <dE/dx> = 0.25 GeV/fm in hot nuclear matter (RHIC) and <dE/dx> = 0.3 GeV/fm in cold nuclear matter (HERMES)

Longitudinal expansion in RHIC collisions leads to a dissipating gluon dense medium.



If the density were maintained at the initial level, calculations indicate equivalent energy loss

<dE/dx> ~ 7 GeV/fm

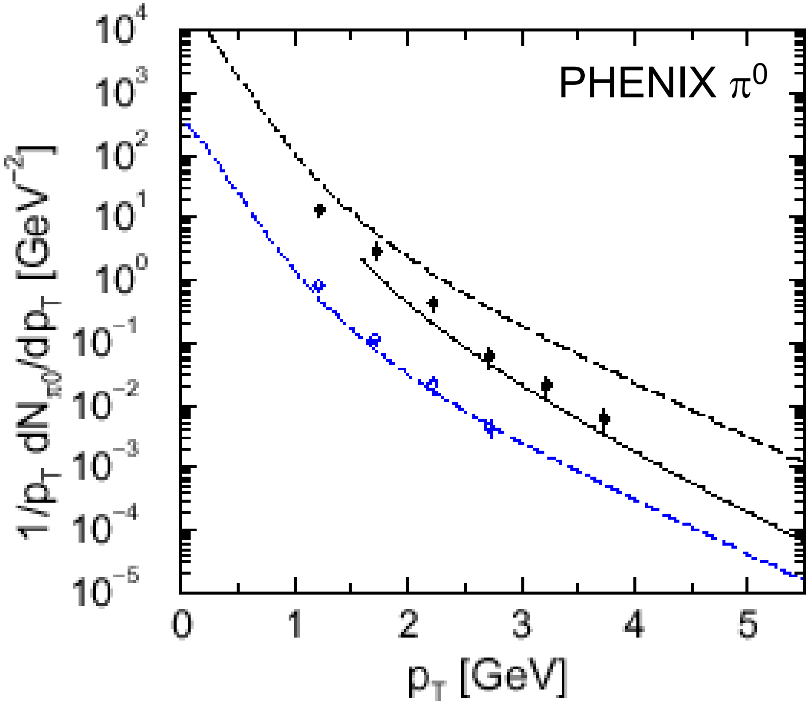
Over an order of magnitude higher than in cold nuclear matter !

Should it worry us that the large energy loss does not occur, but would have occurred if the system were static?

Formation Time

What if the quark or gluon jet begins to fragment inside the medium?

Then the fragmented hadrons can interact with other hadrons and thus suppress high momentum hadrons.



Gallmeister model:
Formation time is the time to build up the hadronic wavefunction and is proportional to energy from γ boost

$\tau_f \sim 1.2$ (E/GeV) * fm/c

This model should see the suppression go away at high p_T.
As one moves up in p_T, z is always ~ 0.6-0.7, but γ boost increases.

$\boxed{t_f^\pi = c_\pi (1-z)\nu}$

Gallmeister et al., nucl-th/0202051

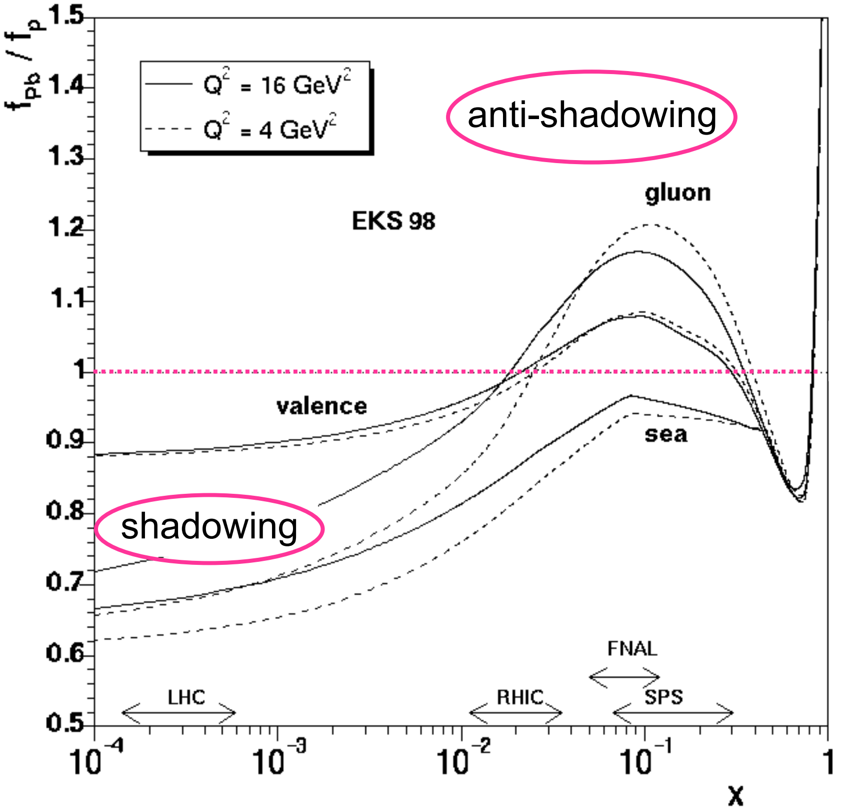
Initial State Effects

The probabilities of finding a parton at a given *x* are different if the proton is inside a nucleus.

$$E_h \frac{d\sigma_h^{pp}}{d^3p} = K \sum_{abcd} \int dz_c dx_a dx_b \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} f(\mathbf{k}_{Ta}) f(\mathbf{k}_{Tb}) \underline{f_{a/p}(x_a, Q_a^2) f_{b/p}(x_b, Q_b^2)}\ \underline{D_{h/c}(z_c, Q_c^2)} \frac{\hat{s}}{\pi z_c^2} \underline{\frac{d\sigma^{(ab\to cd)}}{d\hat{t}}} \delta(\hat{s}+\hat{u}+\hat{t})$$

Nuclear shadowing naturally leads to a suppression of high p_T hadrons.

However, at p_T ~ 7 GeV, the dominant x ~ 2 p_T/sqrt(s) ~ 0.1 which is in the anti-shadowing region.



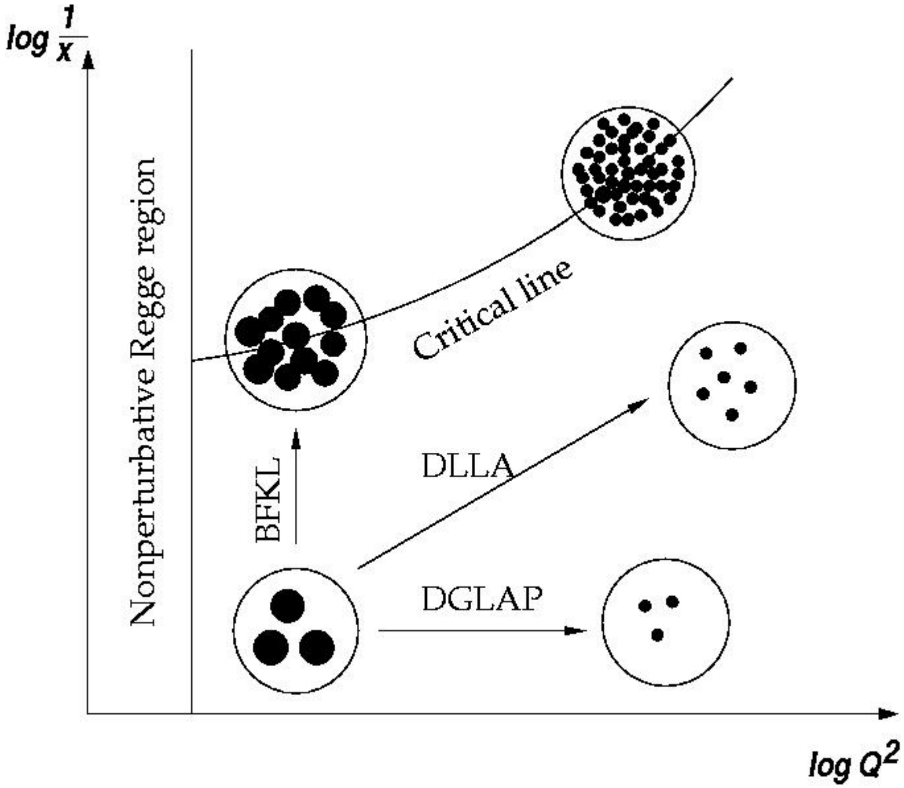
Extreme Initial State Effects

At low x the gluon density may be so high that it saturates.

Gluon density is increased in a nucleus relative to the proton by $A^{1/3}$

McLerran *et al.* show that in this limit, factorization breaks down and one can describe the proton or nucleus in terms of classical gluon fields (Color Glass Condensate).

Mueller has shown that this is isomorphic to the color dipole cross section approaching the unitarity limit in DIS.

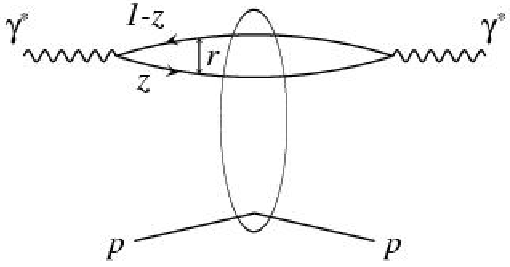


Critical line indicates region above which saturation will occur – gluons overlap – nonlinear evolution

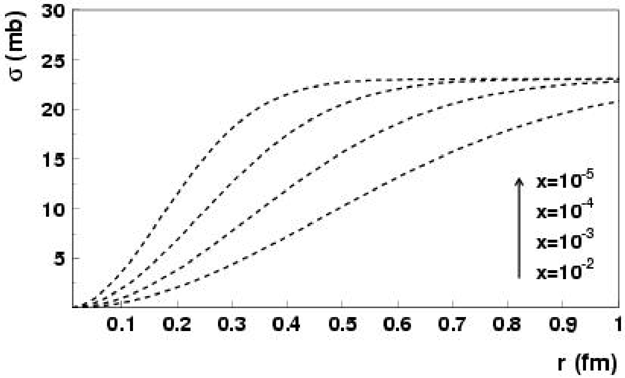
[1] J.P Blaizot, A.H. Mueller, Nucl. Phys. B289, 847 (1987).

Saturation Effects in the Proton

$$\sigma_{\gamma^* P} = \int d^2r\, dz\, \Psi^*_{\gamma^*}(r,z,Q^2)\, \sigma_{qq}(x,r)\, \Psi_{\gamma^*}(r,z,Q^2)$$



$$\sigma_{qq}(x,r) = \sigma_0 \left\{ 1 - \exp(-r^2/4R_0^2(x)) \right\}; \qquad R_0(x) = (x/x_0)^{\lambda/2}$$



$r \ll R_0 \qquad \sigma_{qq} \propto r^2 x^{-\lambda}$

$r \gg R_0 \qquad \sigma_{qq} \propto \sigma_0$

Unitarity bound built in and approach controlled by $R_0(x)$ – saturation radius

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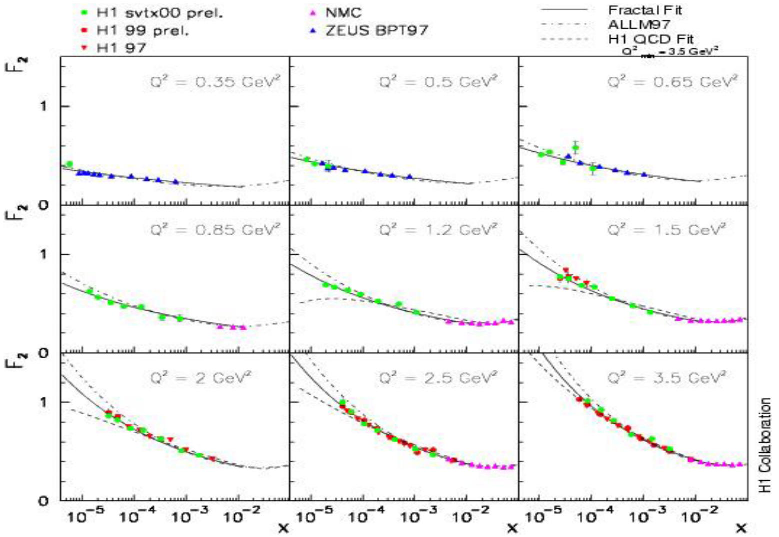


Jury is still out….

Color Dipole Model with Saturation shows excellent agreement with data, but

Standard NLO DGLAP fits also describe data at low *x* down to $Q^2 \sim 1.5$ GeV^2

Golec-Biernat and Wuesthoff

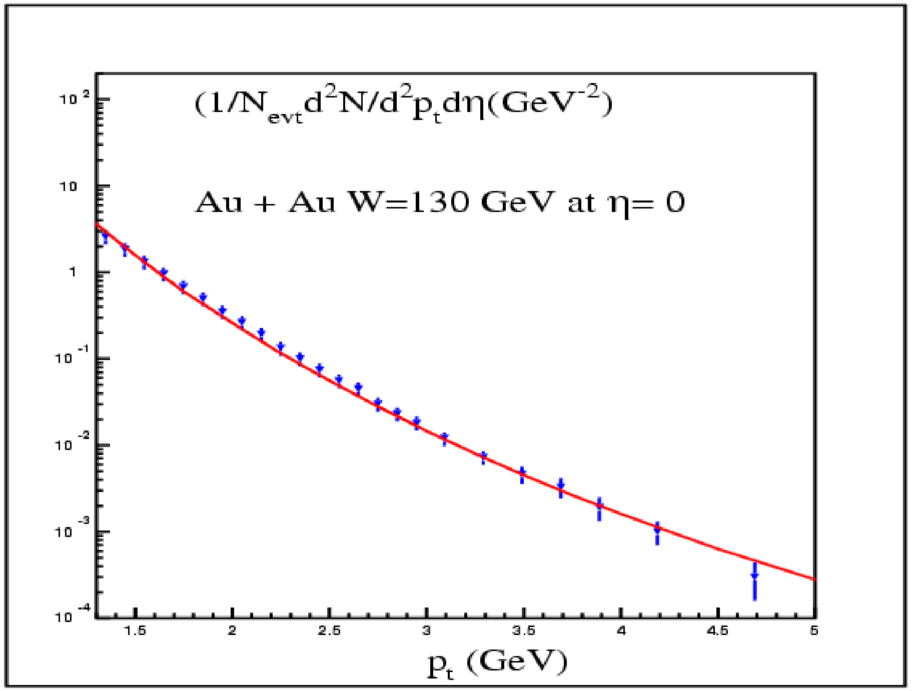
Extreme Initial State Effects

If saturation is the relevant physics in the proton at x ~ 10^{-4} to 10^{-5}, then it may play a role in heavy nuclei at x ~ 10^{-2} to 10^{-3}.

Kharzeev, Levin, and McLerran have extended the saturation model and get reasonable agreement with PHENIX spectra up to 4 GeV/c.

Statement is that hard scattering as calculated via factorization is massively suppressed and that the hadron spectra only represents the freed gluon distribution from the nuclear wavefunction.

My opinion is that this really pushes the saturation effect into an x and Q^2 range that is very questionable.



hep-ph/0210032

Deuteron-Nucleus Collisions

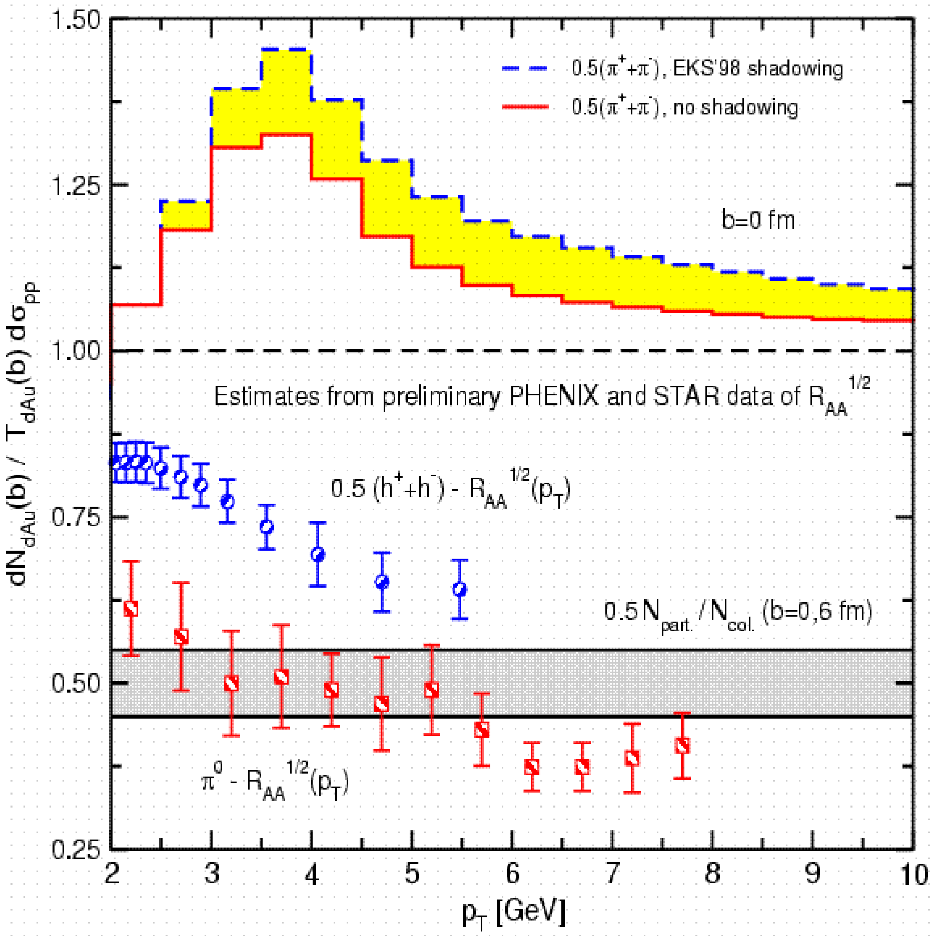
Two extreme opposite interpretations of RHIC data exists:

1) Evidence for opaque
   100 x nuclear density matter

2) Evidence for deep gluon
   shadowing (saturation)

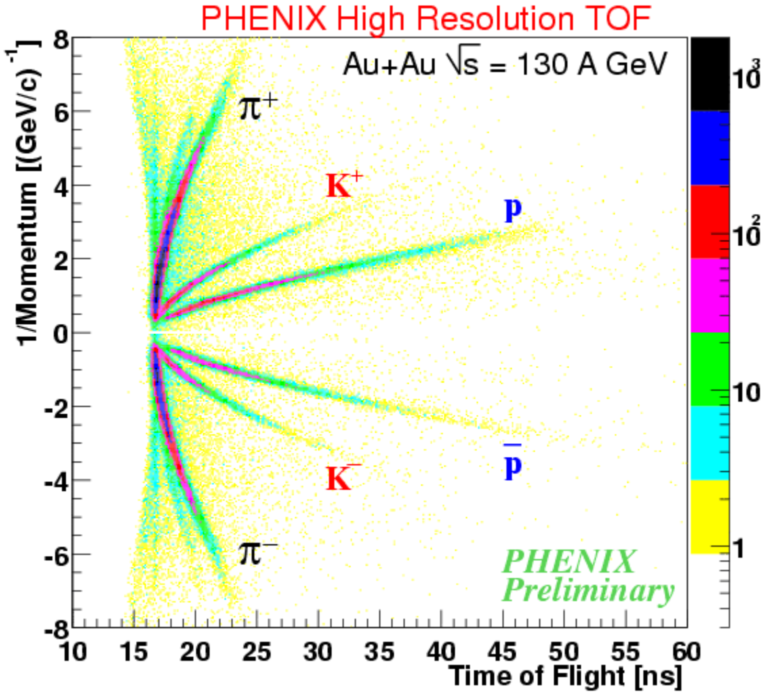
Deuteron-Nucleus data taken by PHENIX this winter should resolve the issue.

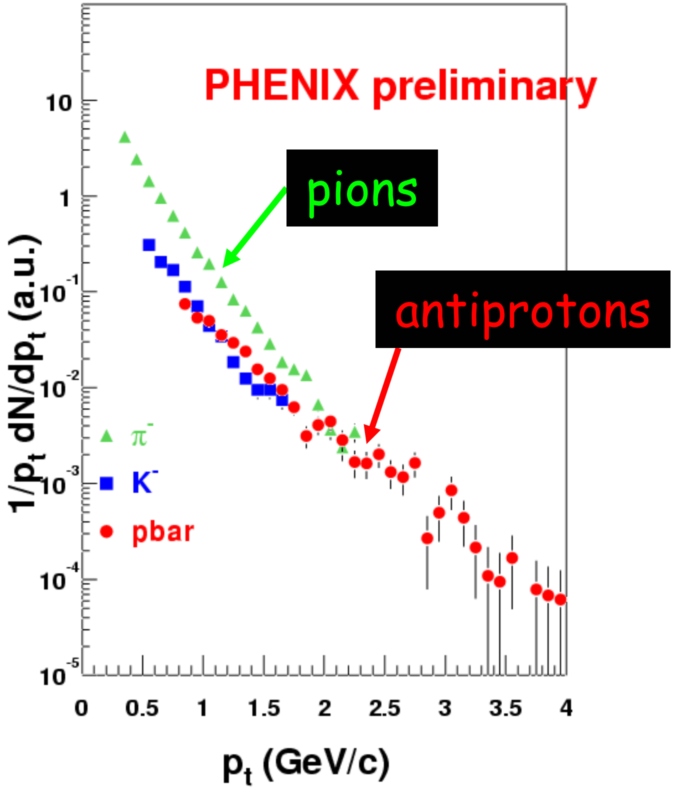
Another discriminator are direct photons (Justin Frantz thesis work).



Other Observations: Jet Fragmentation?

PHENIX identifies other hadrons via their time-of-flight. Pions are suppressed as seen before, but protons and antiprotons are not.



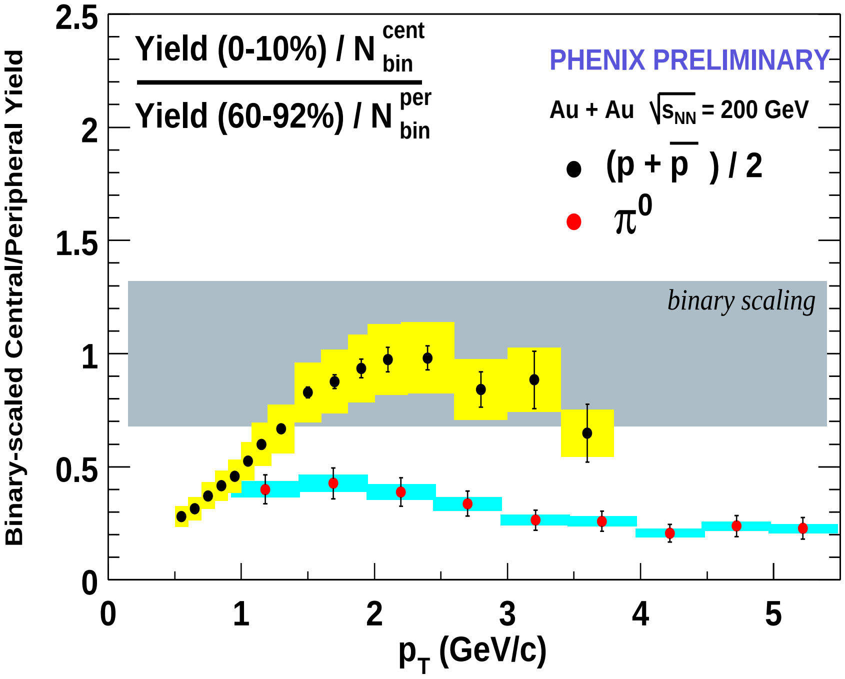


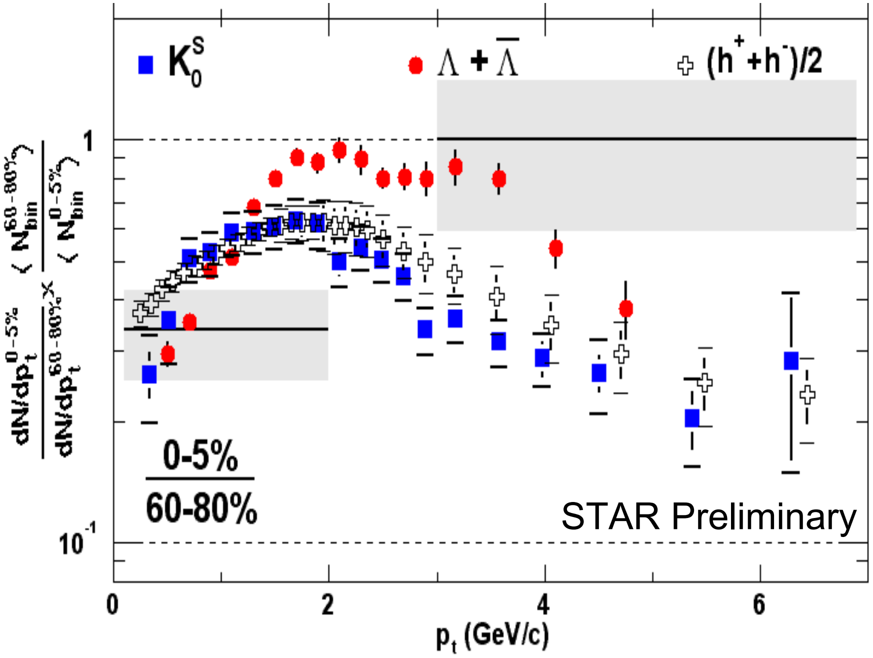
This is not the expected jet fragmentation function D(z).

Excess of Baryons at p_T ~ 1-4 GeV

Large ratio of baryons to mesons in the intermediate p_T
Opposite of fragmentation functions in e^+e^- and p-p(bar).

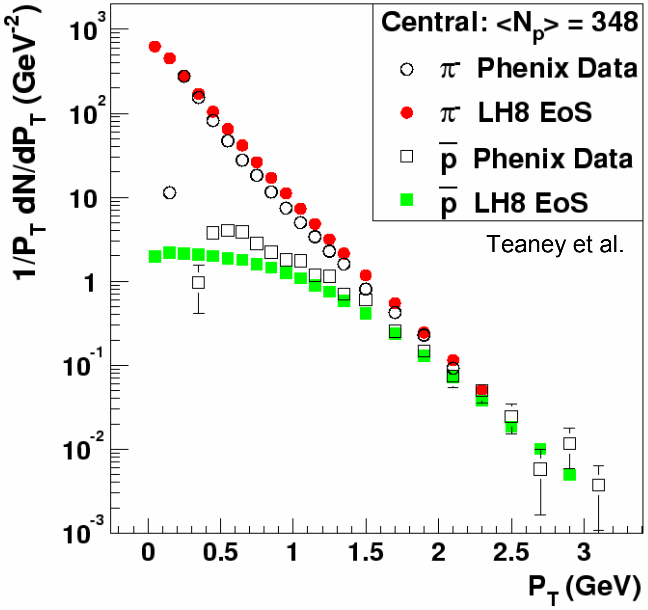
This baryon excess appears to go away at higher p_T.

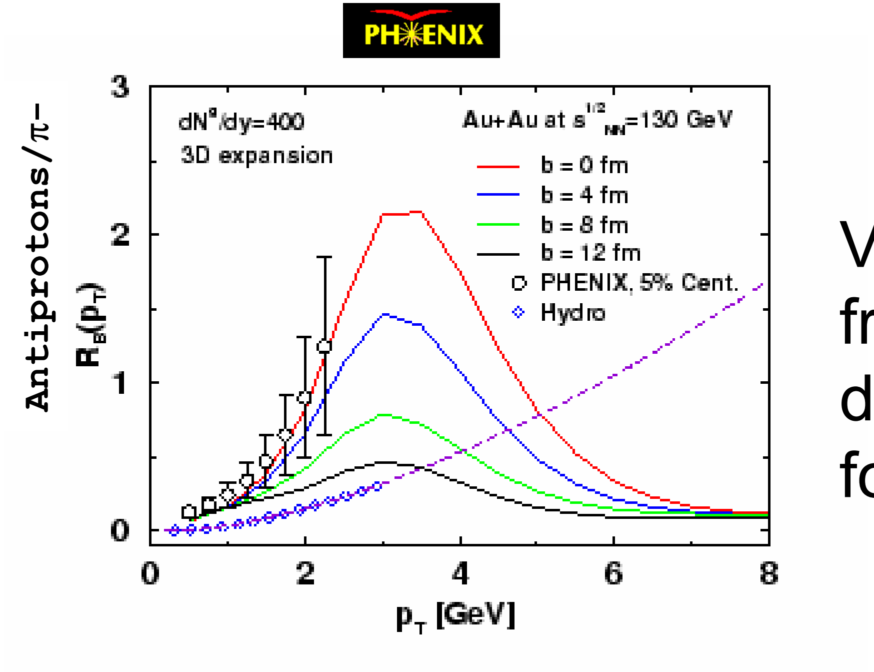




Boosted “Soft” Physics

Hydrodynamic expansion may boost “soft” physics into what was previously thought to be only “hard” physics p_T region.





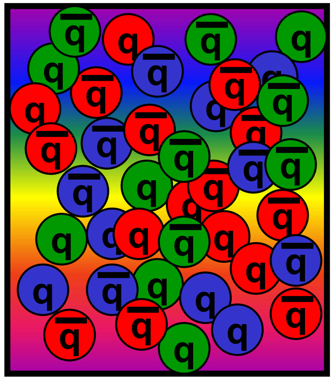
Vitev *et al.* predict that “hard” jet fragmentation eventually dominates over hydrodynamics for antiprotons above p_T~6 GeV

Recombination vs. Fragmentation

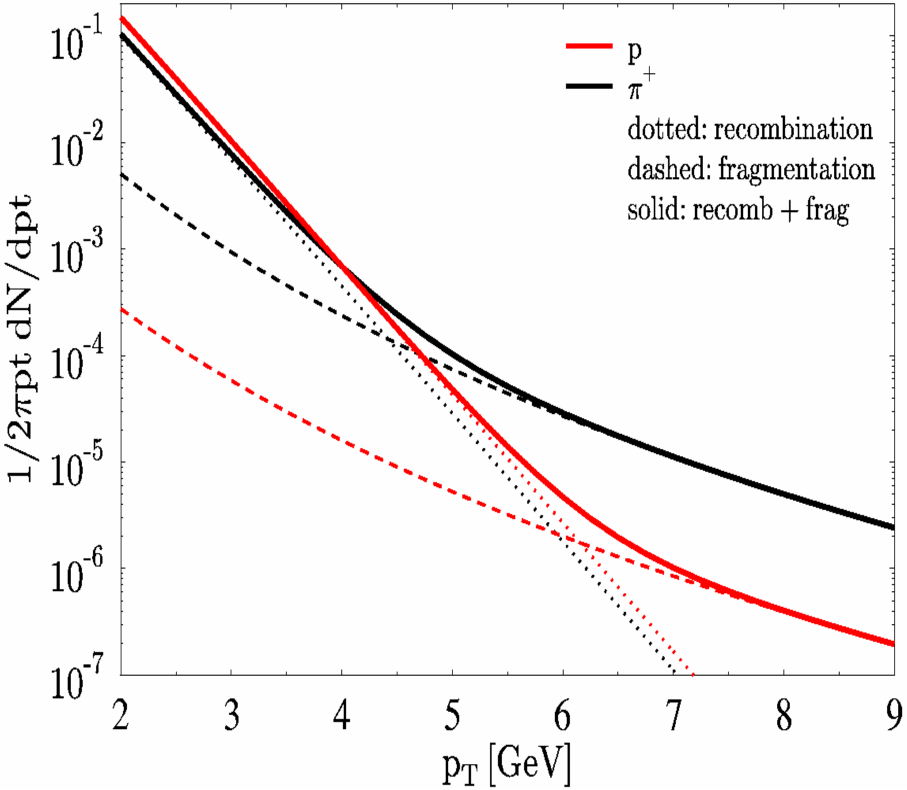
New picture put forth by D.Molnar *et al.* and B. Muller *et al.* speculate that in this dense partonic medium, color recombination dominates over hadron formation via fragmentation at intermediate p_T.

Fragmentation has scattered quark pairing with quark-antiquark or diquark-antidiquark pair from vacuum (B/M << 1).

Recombination has scattered quark pairing with other partons in medium (B/M ~ 1).



B.Muller. et al. nucl-th/0301087



Similar recombination models used to describe forward D meson production at FNAL. Not conclusive yet due to excited D state feed-down.

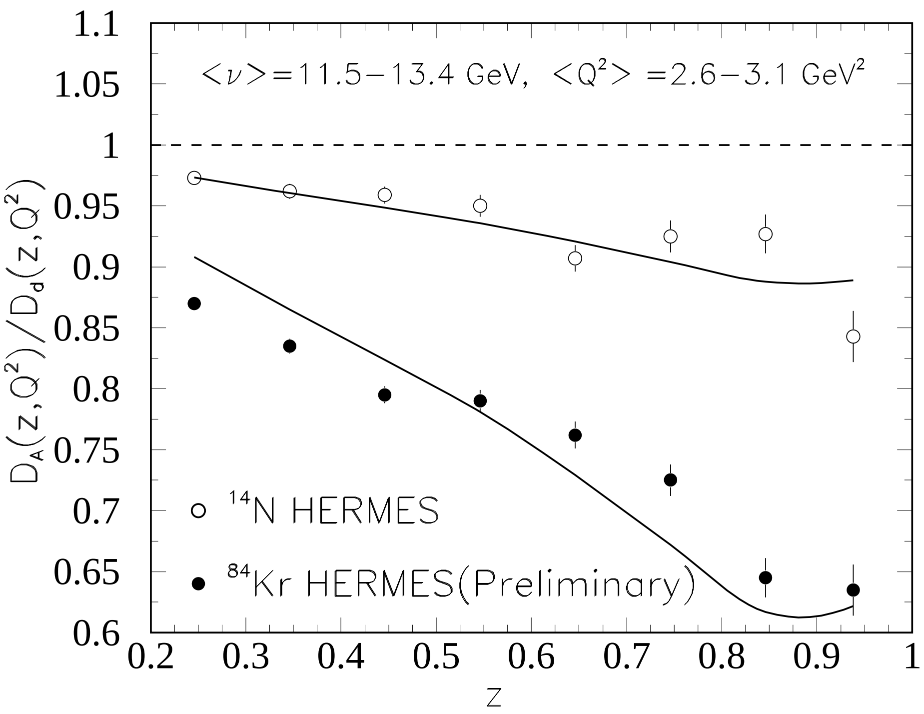
Different Formation Times

HERMES data indirectly indicate smaller D(z) modification for baryons compared to pions.

Could the formation time for baryons be larger than mesons?

Could this explain the large B/M ratio at RHIC?

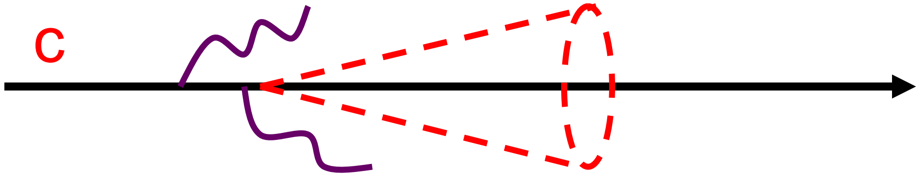
If so, the fact that the B/M ratio drops above p_T ~ 4 GeV is very interesting!

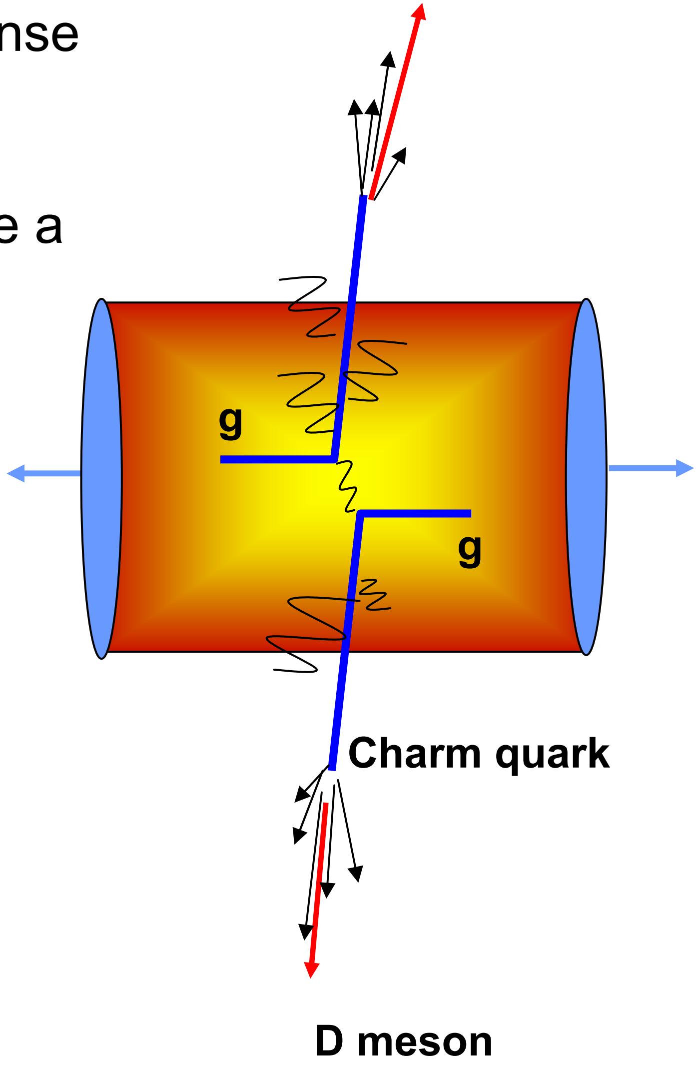


Heavy Quark Propagating

Heavy quarks should also lose energy in a dense gluonic medium.

However, due to their finite velocity, they have a forward "dead-cone" where gluon radiation is not allowed.

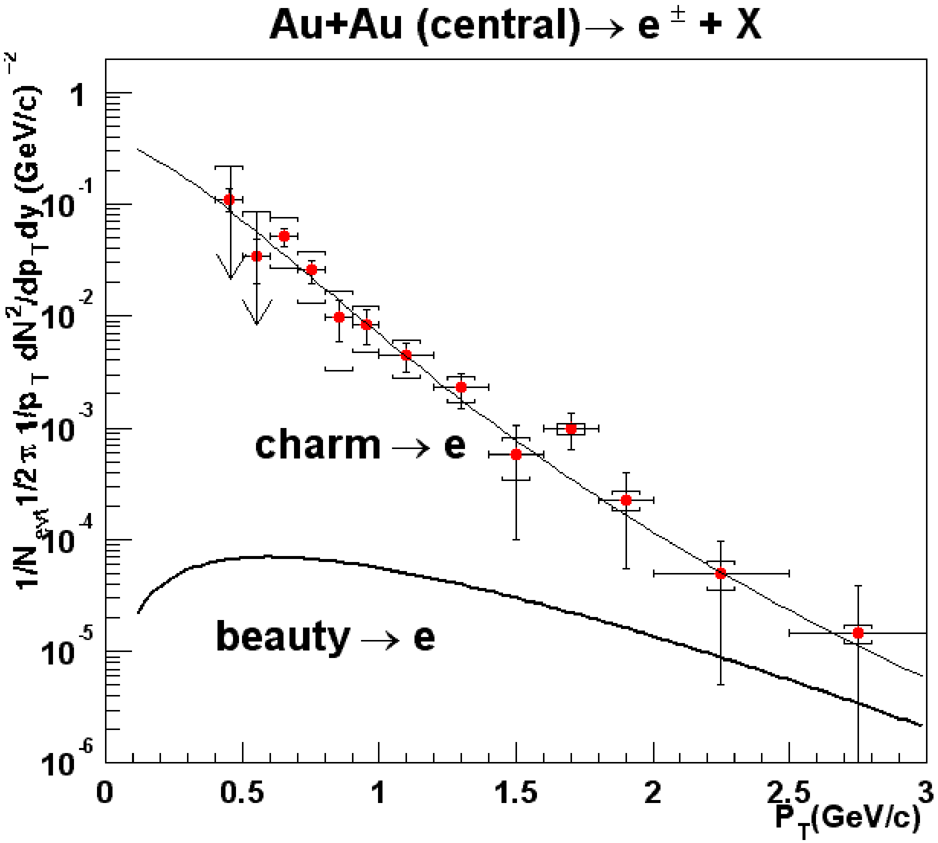




Z. Lin et al., Phys. Rev. C 57, 899, 1992.
Y.L. Dokshitzer and D.E. Kharzeev, hep-ph/0106202
M. Djordjevic and M. Gyulassy, nucl-th/0302069
Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267
Gyulassy, Levai, Vitev, hep-pl/9907461
X.N. Wang, nucl-th/9812021

Charm Results

PHENIX measures single electrons, and after subtracting off Dalitz, conversion and other decay contributions, the remaining signal is dominated by D and B meson semi-leptonic decays.

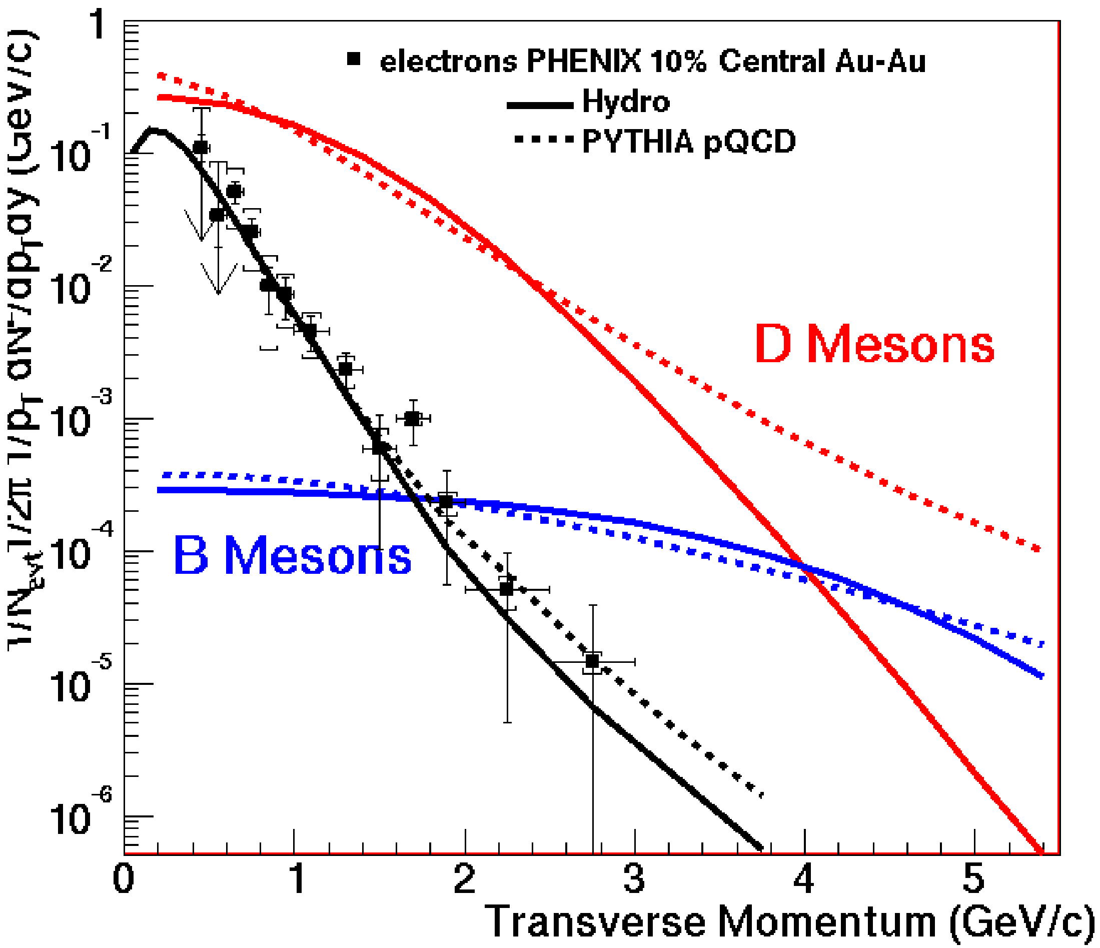


Results are consistent with PYTHIA calculation for charm and beauty tuned to lower energy FNAL data.

Apparent scaling with binary collisions.

No indication of factor of 5 suppression as seen in pions!

Charm Recombination and Flow



What if charm partons hadronize in medium and form D mesons via recombination?

Outward pressure from re-scattering as observed in π, K, protons allows us to predict D, B meson p_T spectra and thus resulting electron spectra.

Amazing ambiguity with previous vacuum fragmentation (PYTHIA) result.

S. Batsouli, S. Kelly, M. Gyulassy, JN, Phys. Lett. B 557, pp 26-32.

Understanding QCD

Frank Wilczek:

“In the quest for evidence of the quark-gluon plasma, there are two levels to which one might aspire. At the first level, one might hope to observe phenomena that are very difficult to explain from a hadronic perspective but have a simple qualitative explanation based on quarks and gluons.

But there is a second, more rigorous level that remains a challenge for the future. Using fundamental aspects of QCD theory, one can make quantitative predictions for the emission of various kinds of “hard” radiation from the quark gluon plasma. We will not have done justice to the concept of weakly interacting plasma of quarks and gluons until some of the predictions are confirmed by experiment.”

The challenge is out there to the people in the field to have this hope realized.

Conclusions

RHIC has passed the first key test.

Nuclear Physics community is capable of constructing and running world class “high-energy” type experiments and re-constructing the physics from the 10,000 particle debris.

The second phase has arrived.

First exciting observations of very large initial or final state medium effects. Key predictions are being tested with more precise data and various colliding systems (deuteron-nucleus).

The third phase is next.

The spin physics program in PHENIX is starting, and will further address basic QCD questions being asked (and hopefully answered).

Run-3 at RHIC

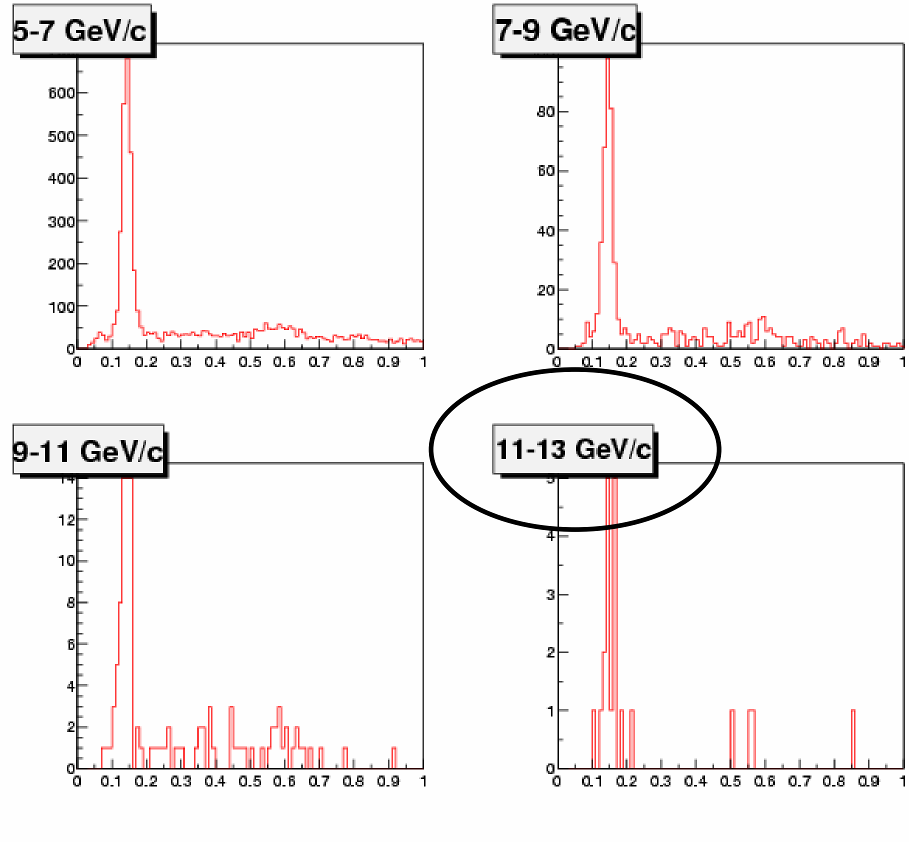
PHENIX is just completing Run-3 at RHIC.

The first phase of deuteron-Au collisions was a great success. Triggers sampling the full luminosity and online reconstruction of key signals.

Excellent data set for high p_T π^0 and heavy quarkonia.

Congratulations to our run coordinator Matthias!

$\pi^0 \rightarrow \gamma\gamma$, 12 % of dataset

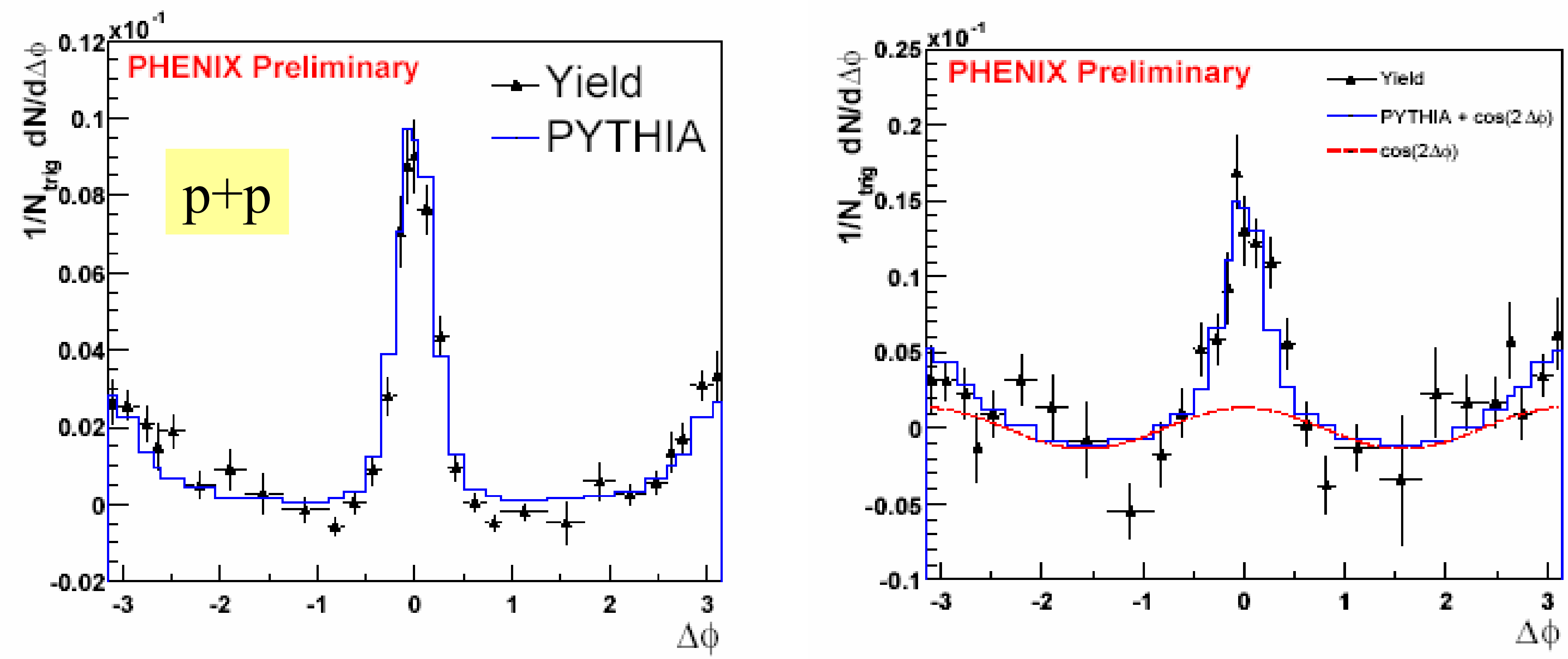


Jet Correlations

Although complete jet reconstruction does not work, we can measure angular correlations from jets.

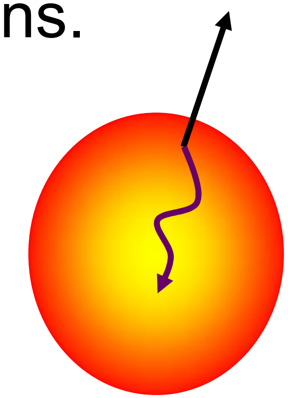
Agreement between PYTHIA model and forward cone ($\Delta\phi \sim 0$) and opposite set cone ($\Delta\phi \sim \pi$) in proton-proton.

Similar behavior in Au-Au. Not sensitive to jet broadening at this level.

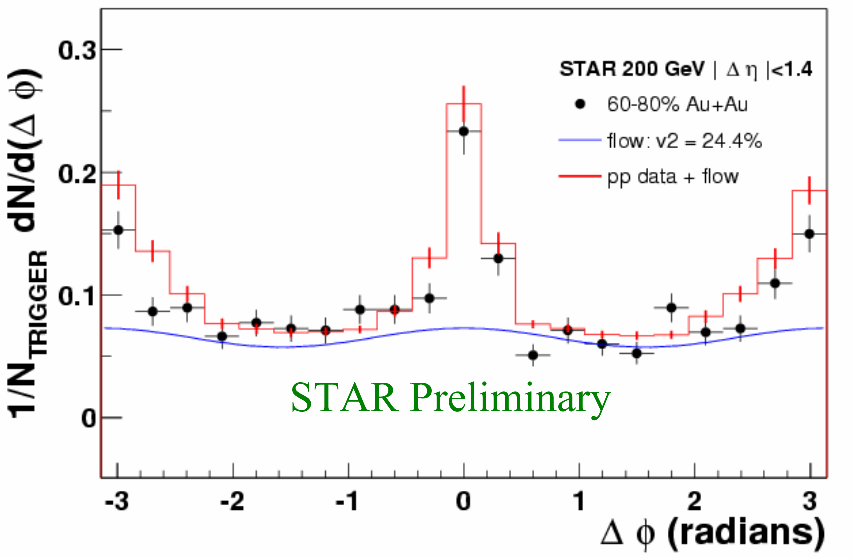


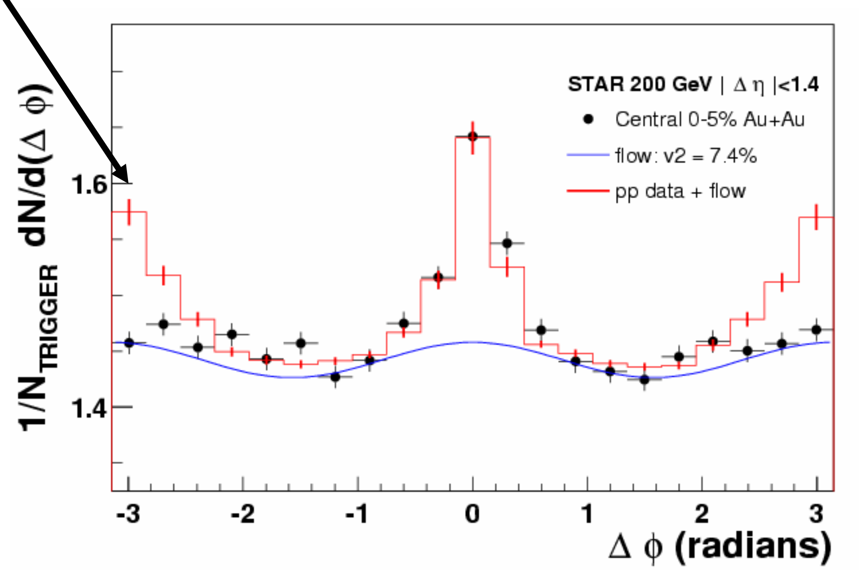
STAR Jet Correlations

STAR with better η and ϕ coverage sees clear disappearance of away side correlation in central Au-Au reactions.



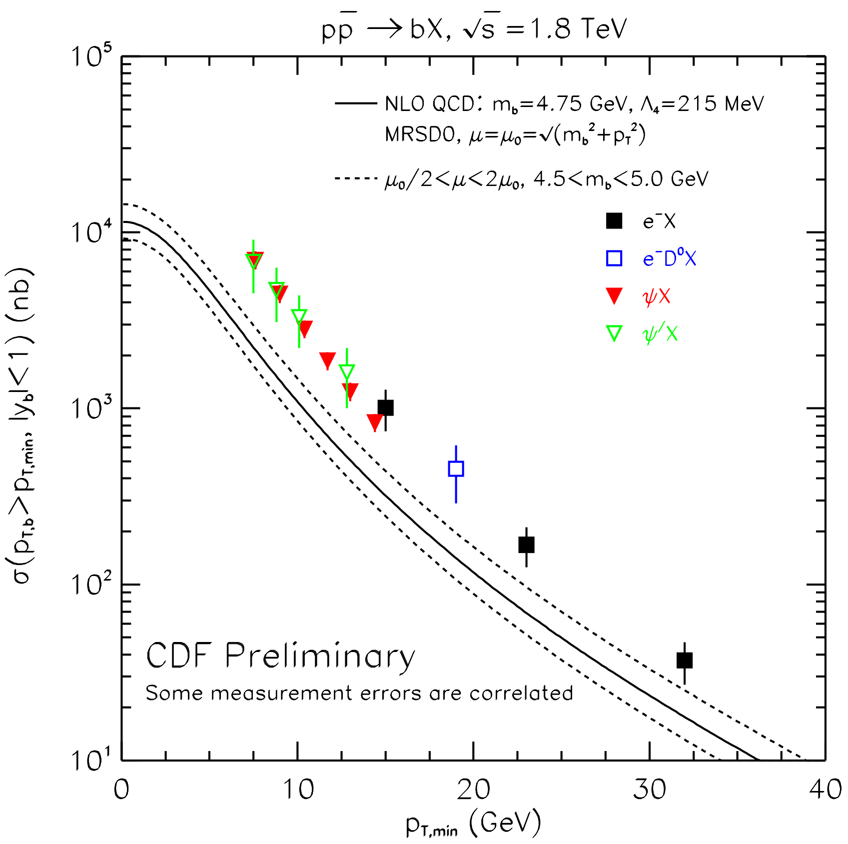
Perhaps the opposite side parton does not emerge?
Or no back-to-back jets at all from saturation model picture?

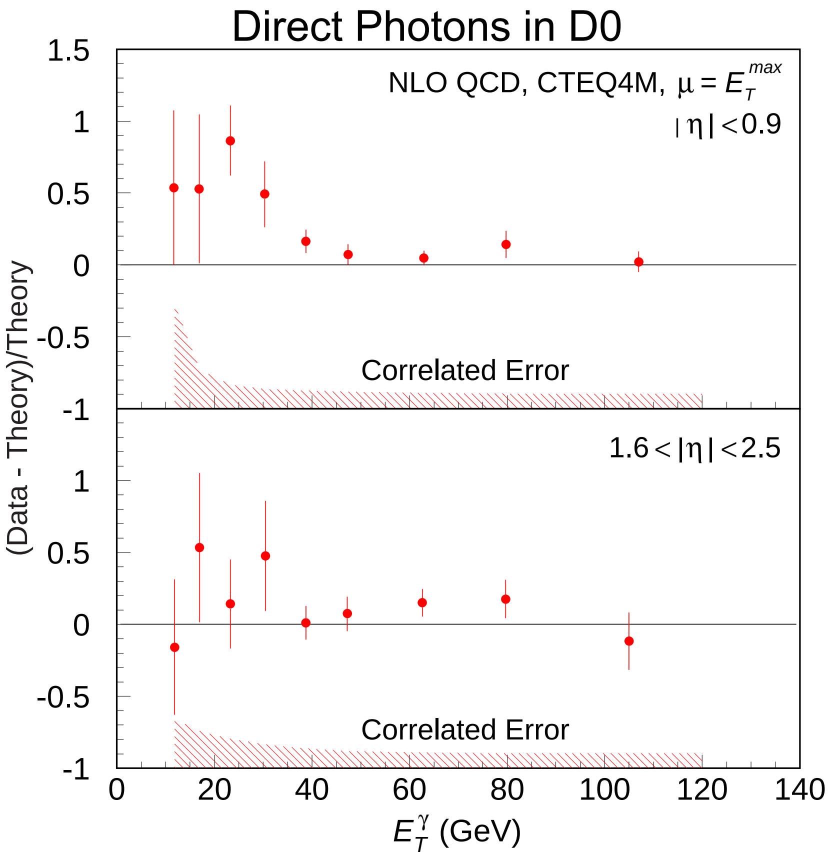




Myth of pQCD

- pQCD calculations have many open issues at $p_T < 50$ GeV.
- For example, currently there is poor agreement with beauty production and direct photon observations.

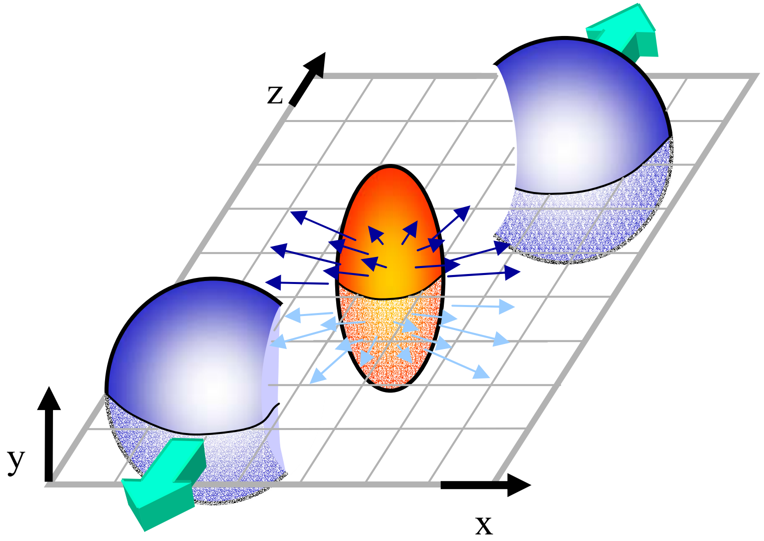


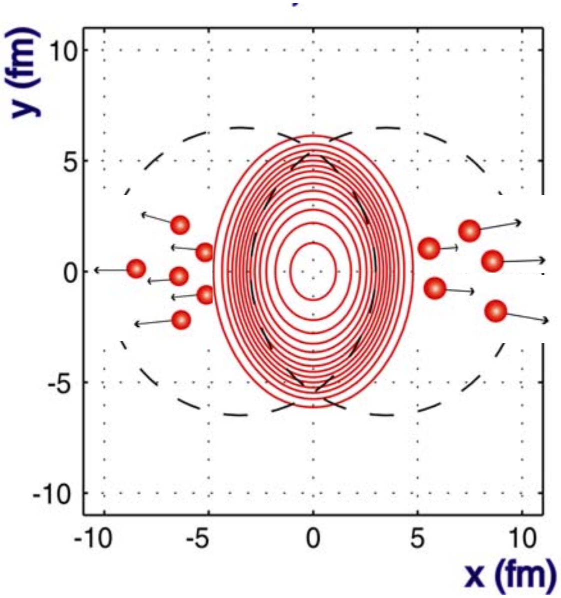


- At RHIC “High” $p_T < 10$ GeV there are many uncertainties. (examples - cutoff scale, Cronin effect, nuclear PDF’s…)

Hydrodynamic Flow

Spatial anisotropy leads to momentum anisotropy in the presence of large re-scattering.



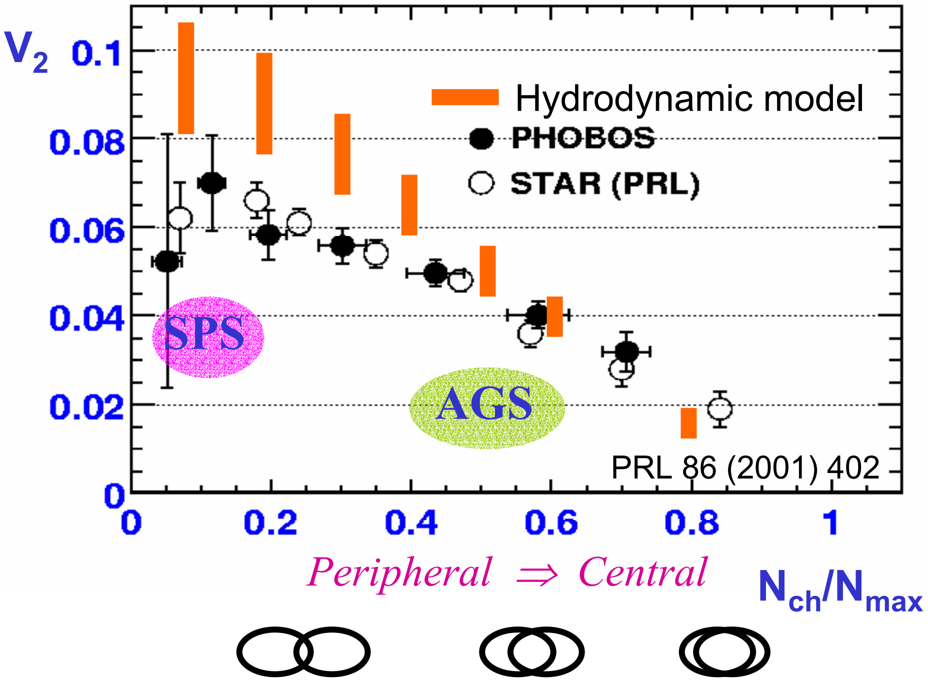


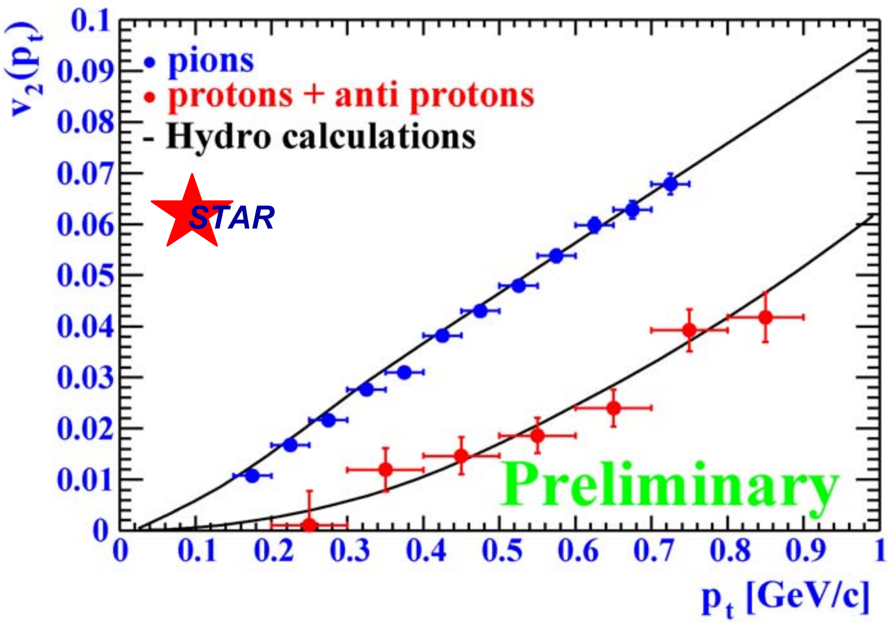
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \longrightarrow \begin{aligned} v_2 &= \langle \cos 2\phi \rangle \\ \phi &= \operatorname{atan} \frac{p_y}{p_x} \end{aligned}$$

v_2: 2nd harmonic Fourier coefficient

Large Parton Re-Scattering

Strong elliptic flow near the hydrodynamic limit





Hadronic re-scattering is insufficient to describe the data.

Implies strong partonic re-scattering and high initial density

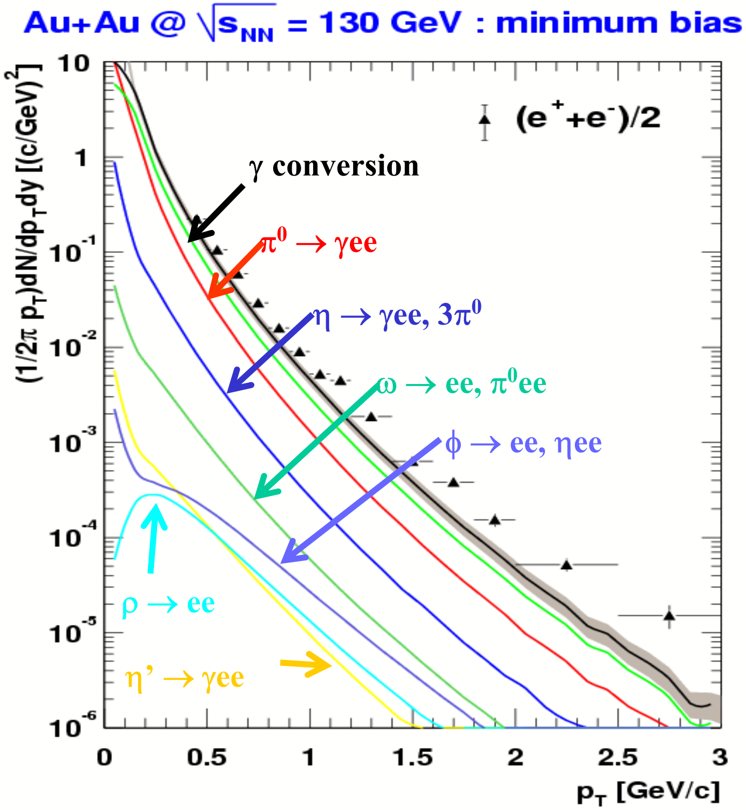
$\varepsilon = 20\ \mathrm{GeV/fm^3}$ and $\tau = 0.6\ \mathrm{fm/c}$

Hydro calculations: P. Huovinen, P. Kolb and U. Heinz

Experimental Results

PHENIX experiment measures single electrons.
After subtracting electrons from Dalitz decays, conversions,…
remaining signal expected from charm and beauty.

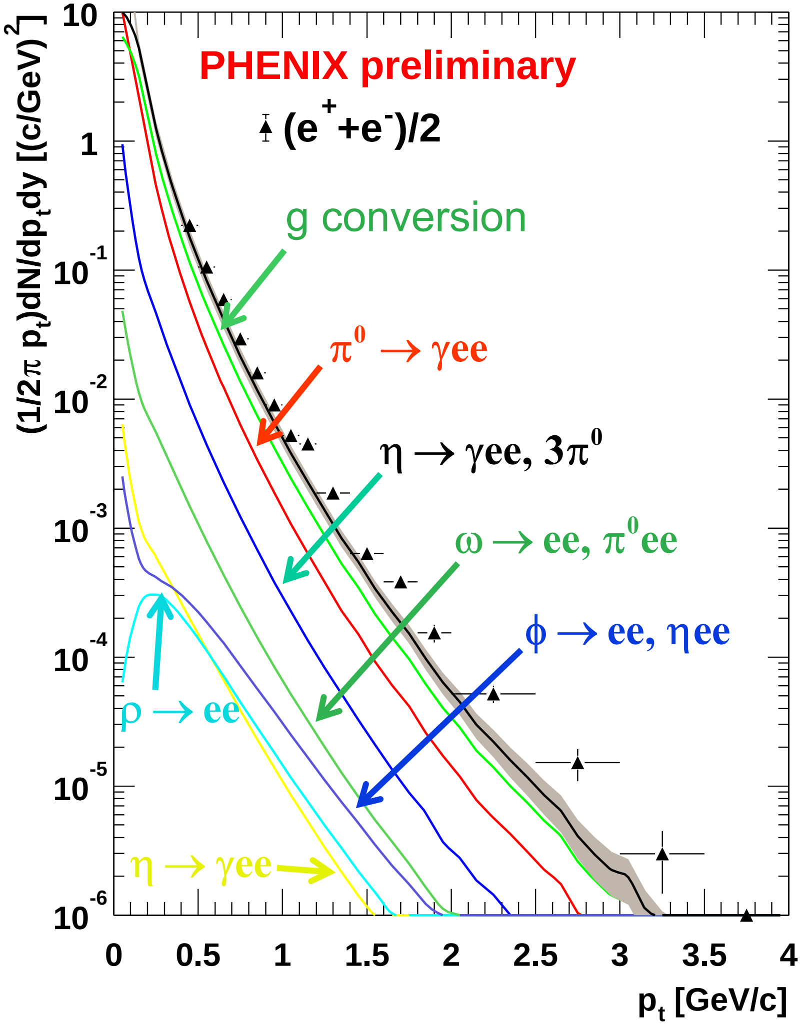
$D \rightarrow e\, K\, \nu \quad B \rightarrow e\, D\, \nu$

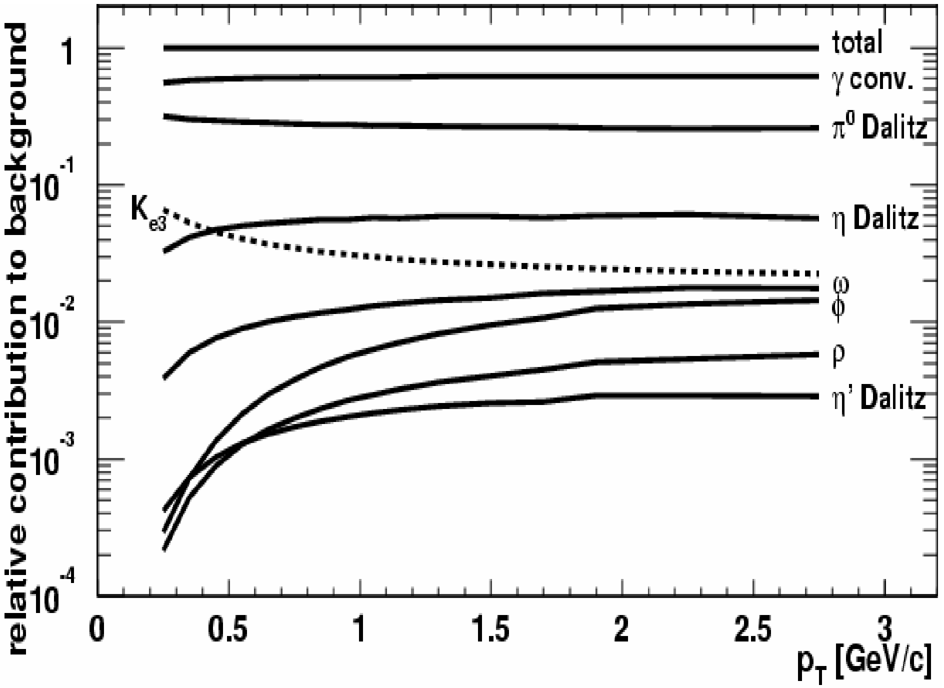


K. Adcox et al., Phys. Rev. Lett. 88, 192303, 2002.

Single Electrons

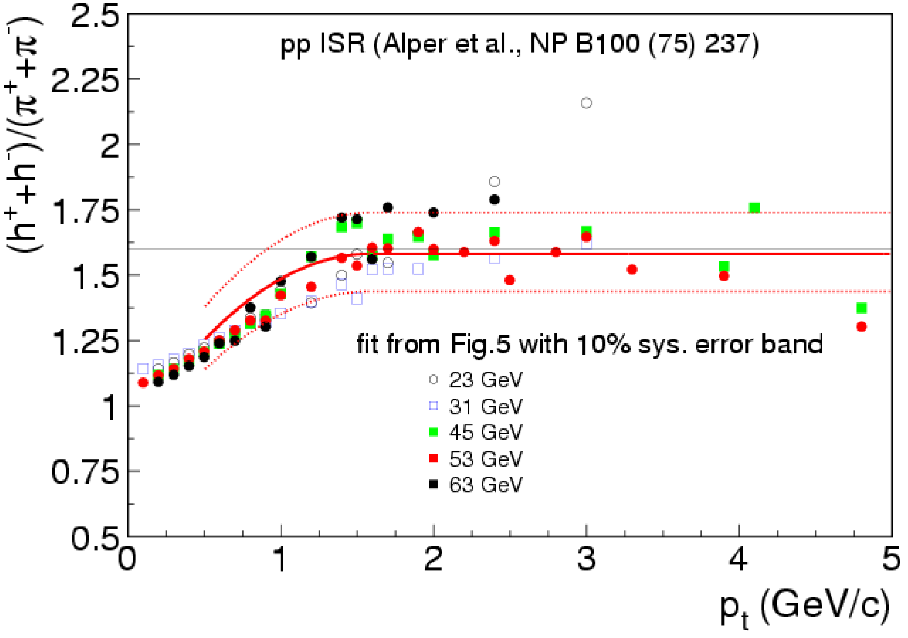
Au+Au @ $\sqrt{s_{NN}}$ = 130 GeV : minimum bias

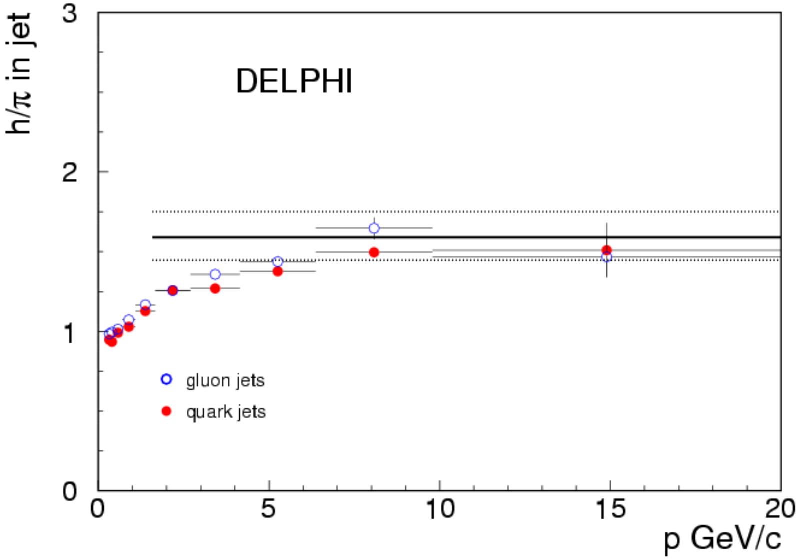




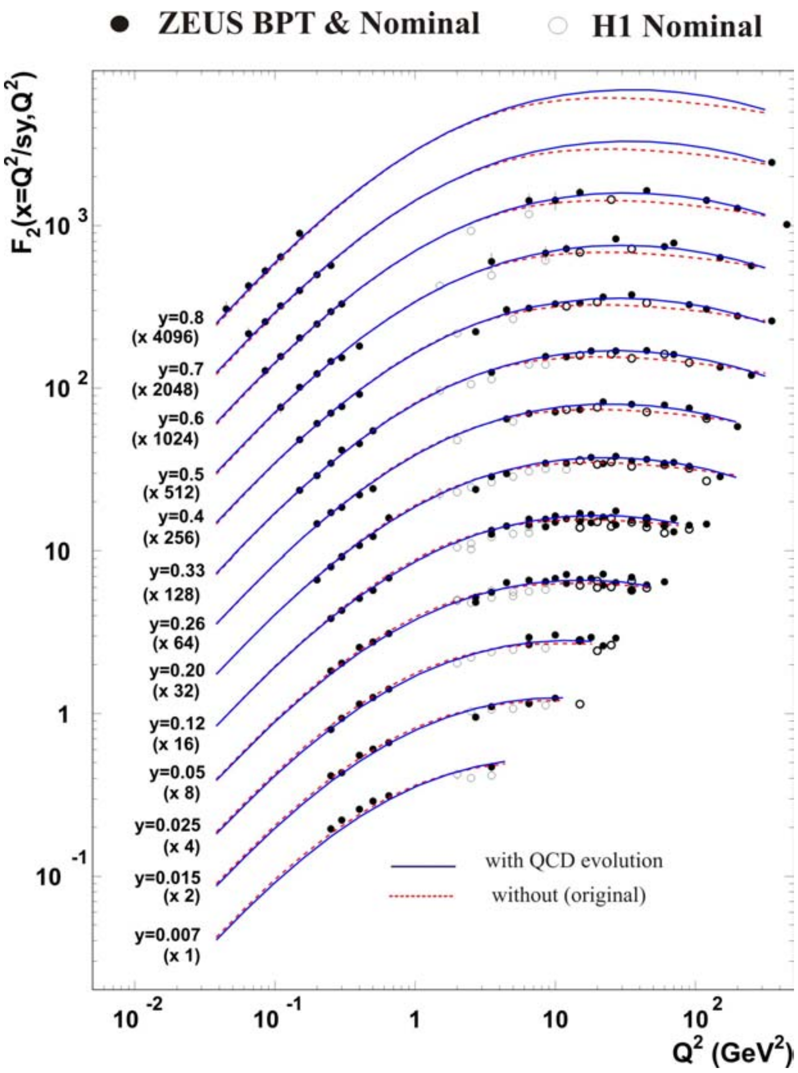
~80% of background from π^0 (either directly from Dalitz decays or indirectly through γ conversion)

Expected Fragmentation





More Saturation…



$$\sigma_{qq}(x,r)=\sigma_0\left\{1-\exp(-r^2/4R_0^2(x)\right\}$$

$$R_0(x)=(x/x_0)^{\lambda/2}$$

Three parameters: λ, x_0, σ_0 to be fitted.

Extension (G-B, Bartels &Kowlaski - DIS02) include QCD evolution by requiring

$$\sigma_{qq}(r,x)=\frac{\pi^2}{3}r^2\alpha_S xg(x,C/r^2),$$ at small r

xg evolves - 5 parameter fit - improves description of high Q^2 data

- Cannot use this agreement as verifying saturation at HERA, as many other models give similar agreement, including non-saturating dipole models.