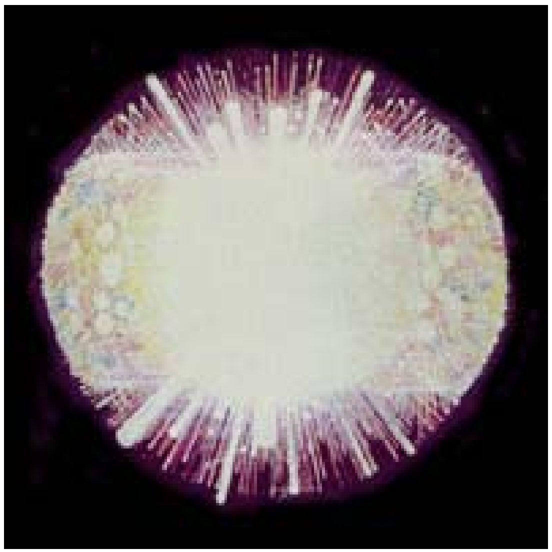
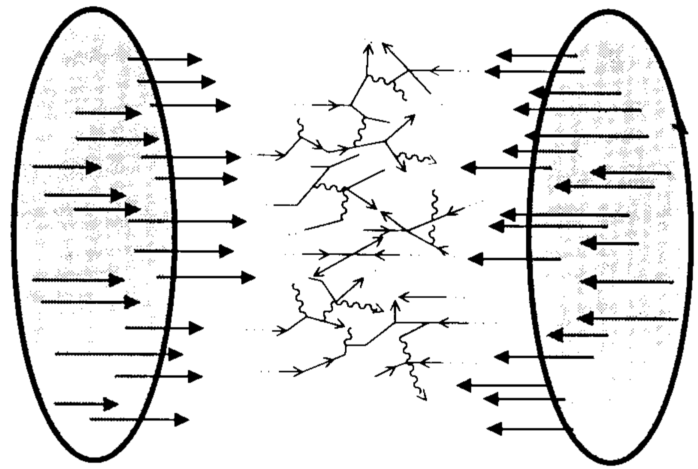
Experimental Probes of Quark-Gluon Plasma





Jamie Nagle
University of Colorado at Boulder
Quark Matter 2004

The Dark Side of Heavy Ion Physics

What they won't tell you at the Quark Matter Conference ?

But you should ask !

Jamie Nagle
University of Colorado at Boulder
Quark Matter 2004

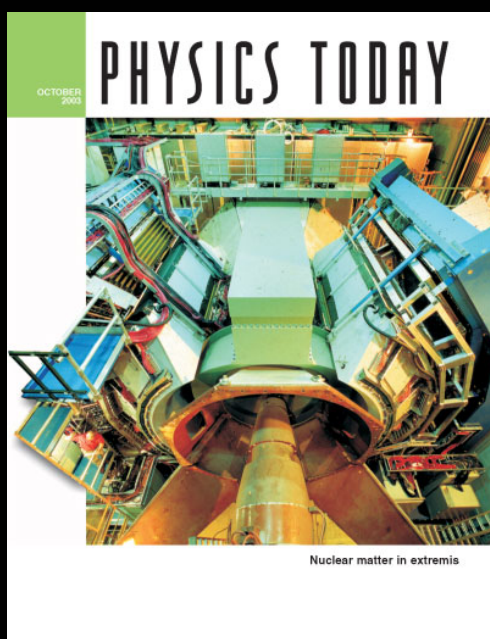
Why are we here?

The purpose of the field of Relativistic Heavy Ions is to observe and understand the nature of Quantum Chromodynamics (QCD) under extreme and novel conditions.

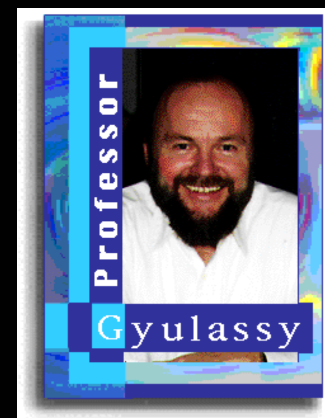
- Can we understand characteristics of the matter that dominated the very earliest stages of the universe?
- Can we observe characteristics of hot and dense nuclear matter in the laboratory with relativistic heavy ion collisions?
- Can these observations give us insight about the transition to deconfinement and approximate chiral symmetry restoration?

Discovery Physics !

http://www.bnl.gov



"It's a Quark-Gluon Plasma. Period."

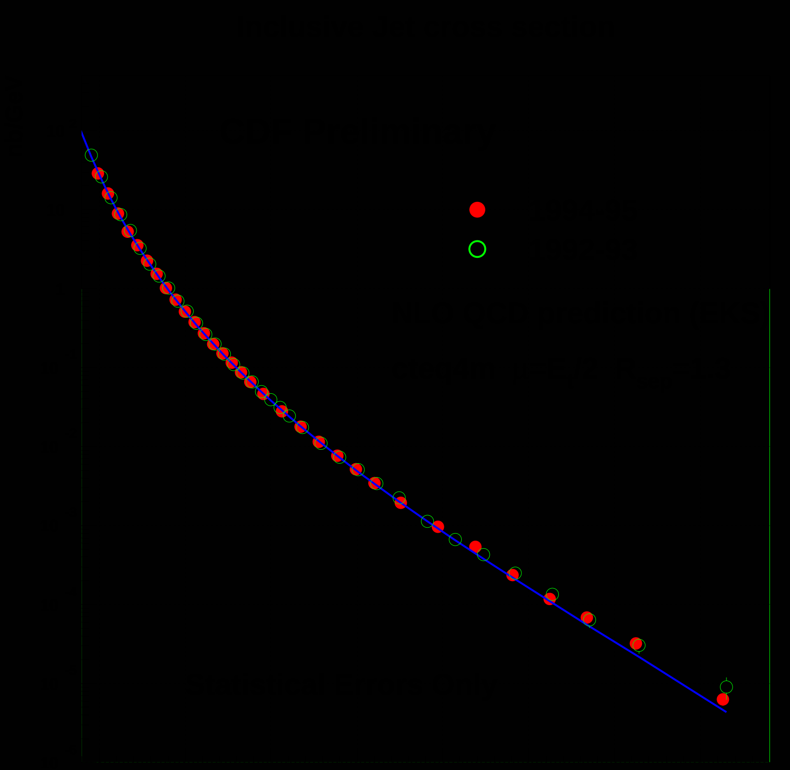


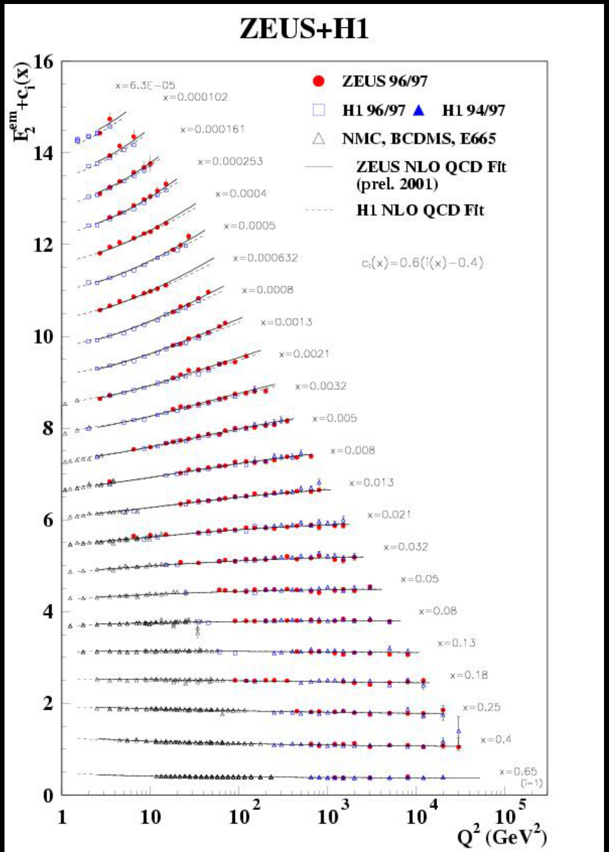
"But, What Have You Learnt?"

Quantum Chromodynamics (QCD)

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 DGLAP





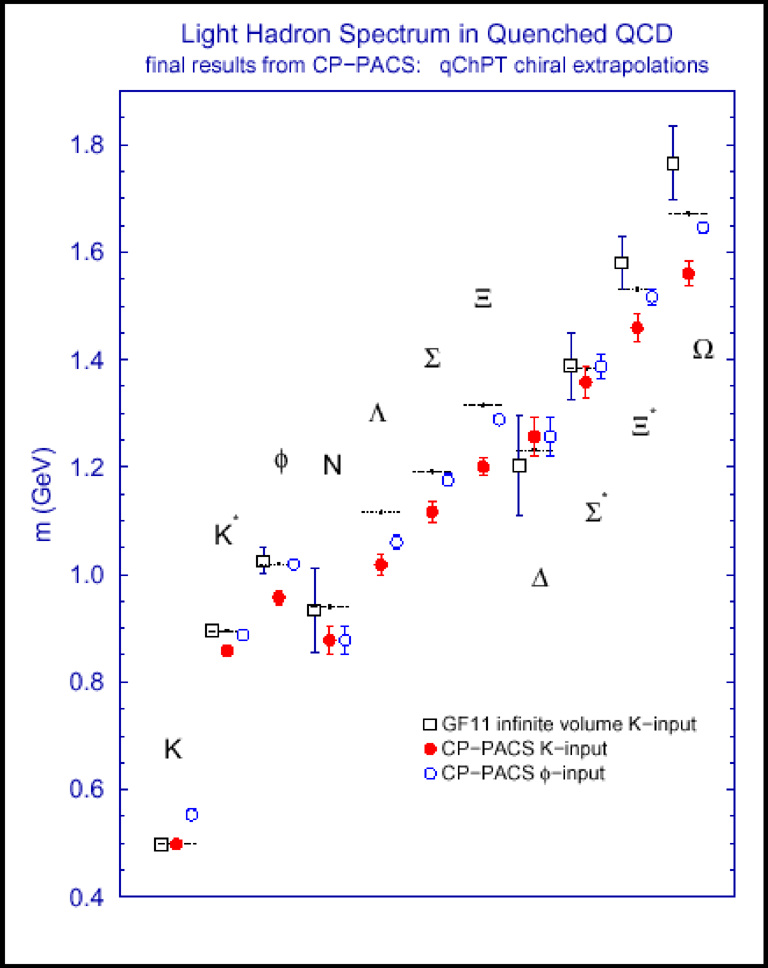
What about other cases?

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

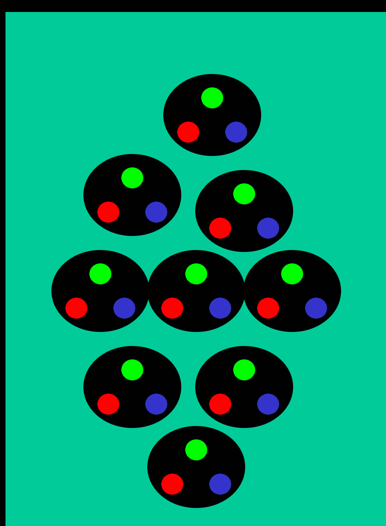
QCD in Vacuum

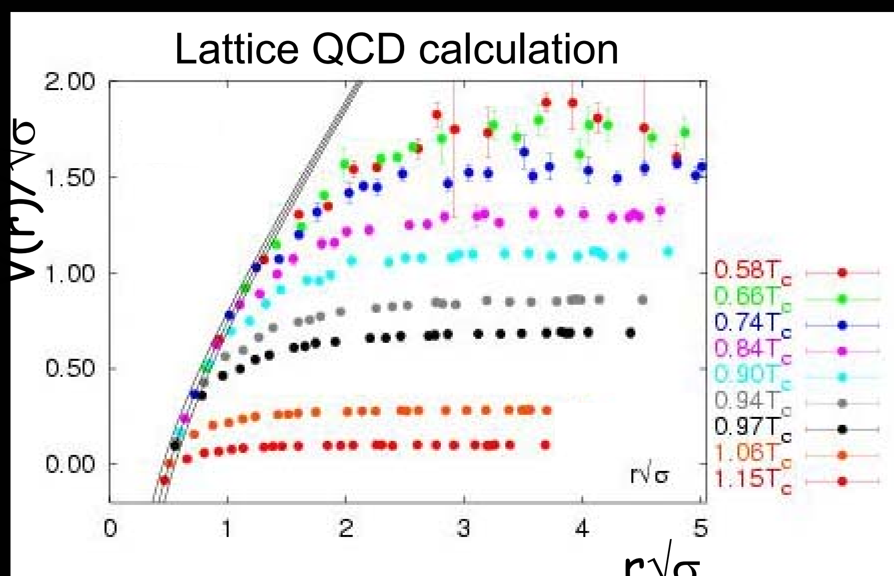
linear increase in potential with distance from color charge

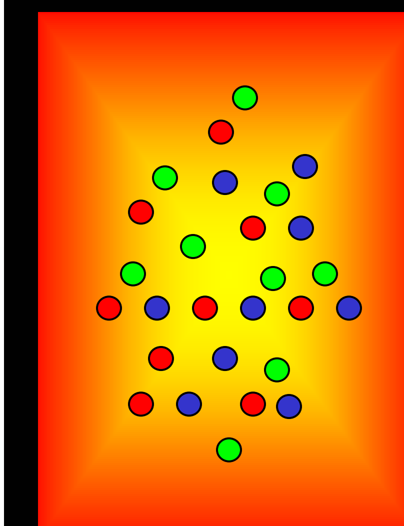
- strong attractive force
- **spontaneous breaking of chiral symmetry**
- **confinement of quarks** to hadrons baryons (qqq) and mesons (qq)

QCD in dense and hot matter

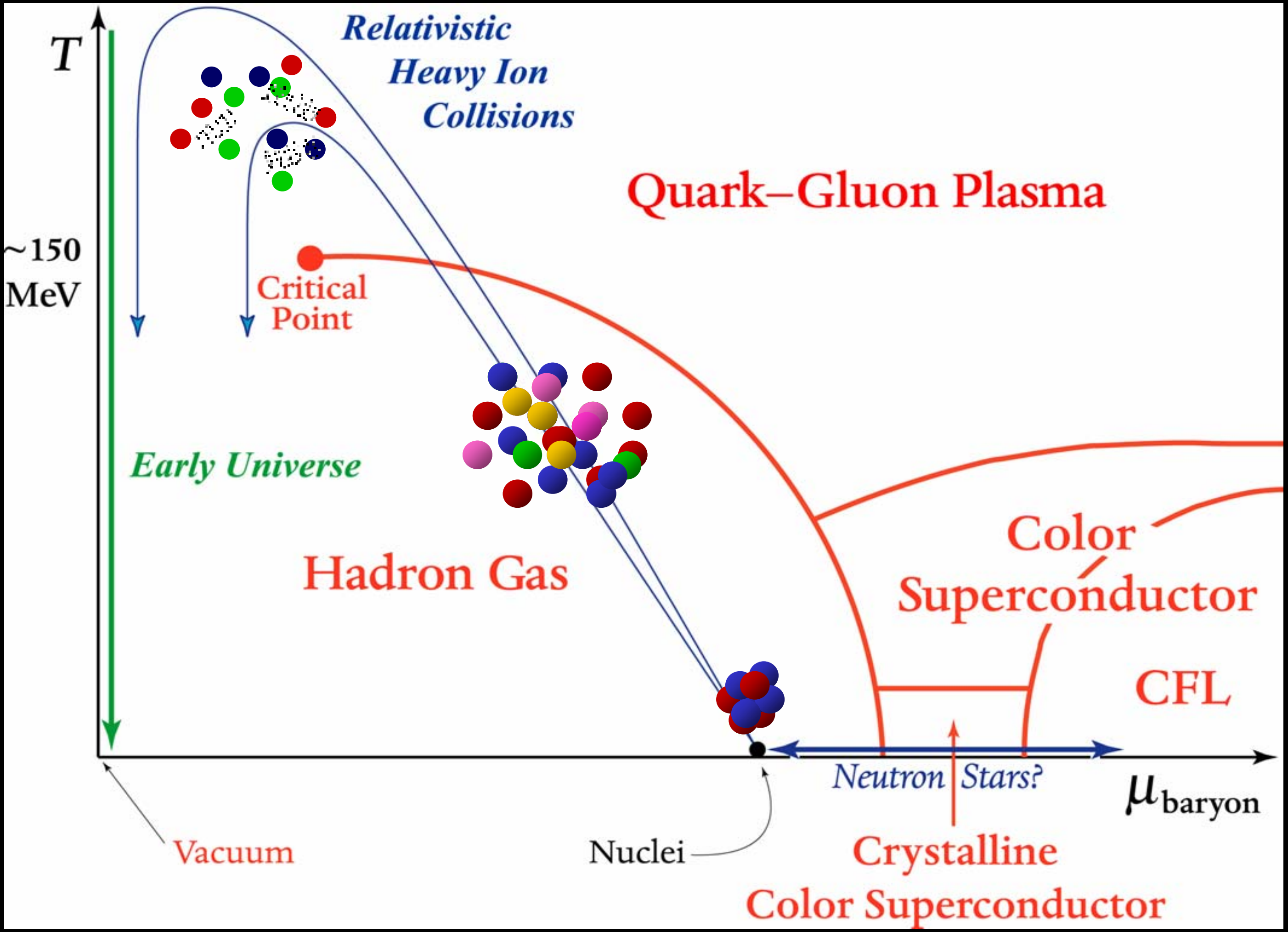
- screening of color charges
- potential vanishes for large distance scales
- **restoration of approximate chiral symmetry** as quarks act as nearly massless particles
- **deconfinement of quarks !**







QCD Phase Diagram

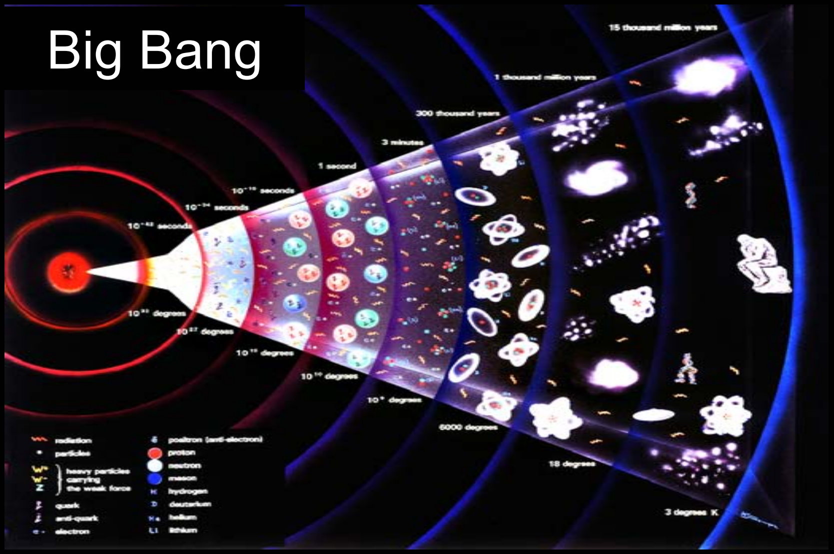


Quark Gluon Plasma

If the plasma-to-hadrons transition were strongly first order, bubble formation could lead to an inhomogeneous early universe, thus impacting big bang nucleosynthesis (BBN).

Are the bubbles too small and close together such that diffusion before nucleosynthesis erases the inhomogeneities? (200 MeV to 2 MeV)

This line of investigation was quite active when the dark matter issue raised questions about the implied baryon content in the universe from BBN.

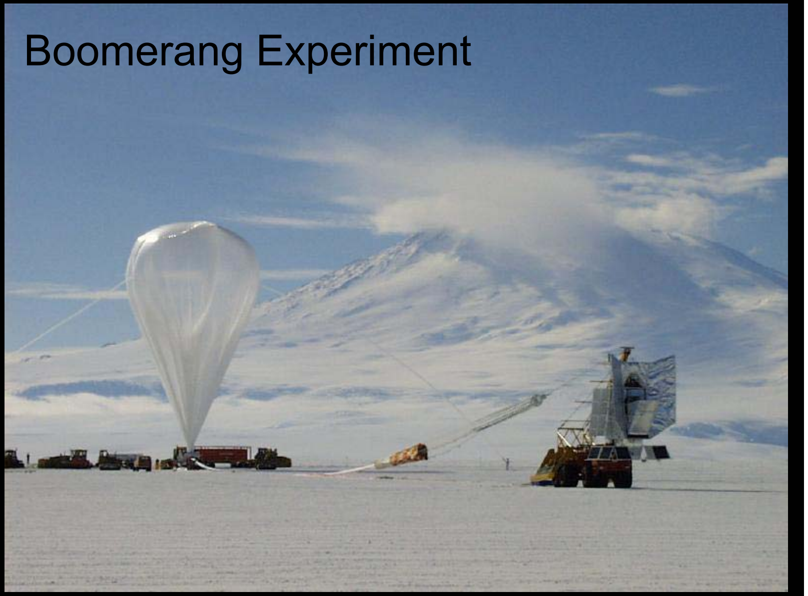


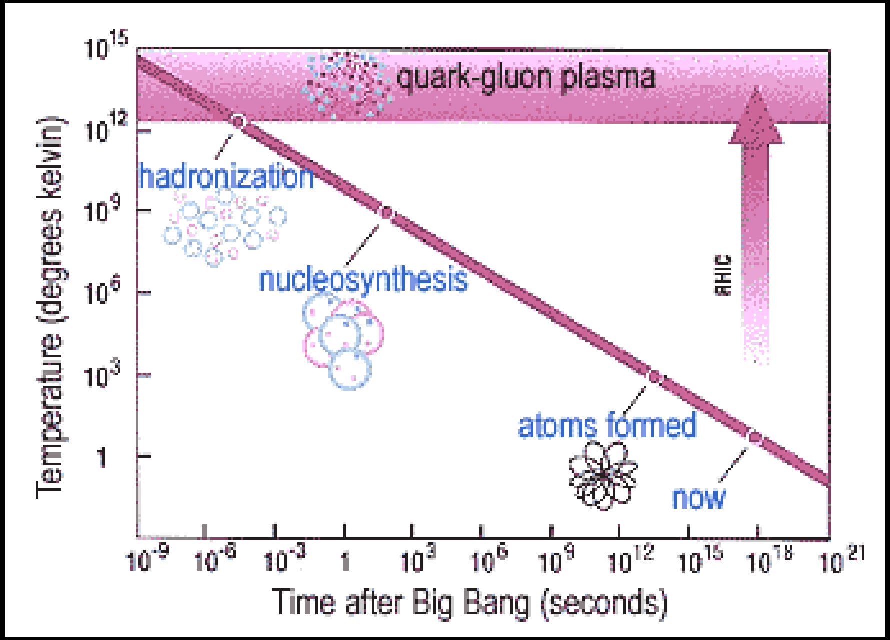
Other Experimental Observations

Physics Today, July 2001: Cosmic Microwave Background Observations

"The value deduced from the second harmonic in the acoustic oscillations for $\Omega_B=0.042 \pm 0.008$ (cosmic baryon mass density) is in very good agreement with the value one gets by applying the theoretical details of primordial big bang nucleosynthesis to the observations of cosmic abundances of deuterium."

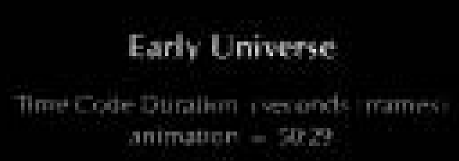
However, this confirmation of BBN does not rule out a first order phase transition in QCD because of the diffusion issue.

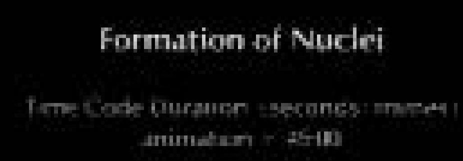




Laboratory Study is Crucial

"A first-order QCD phase transition that occured in the early universe would lead to a surprisingly rich cosmological scenario." Ed Witten





But, it does not seem like it did. Thus, we must study this aspect of QCD with accelerators.

Initial State Physics

Parton Distribution Functions

Saturation Physics

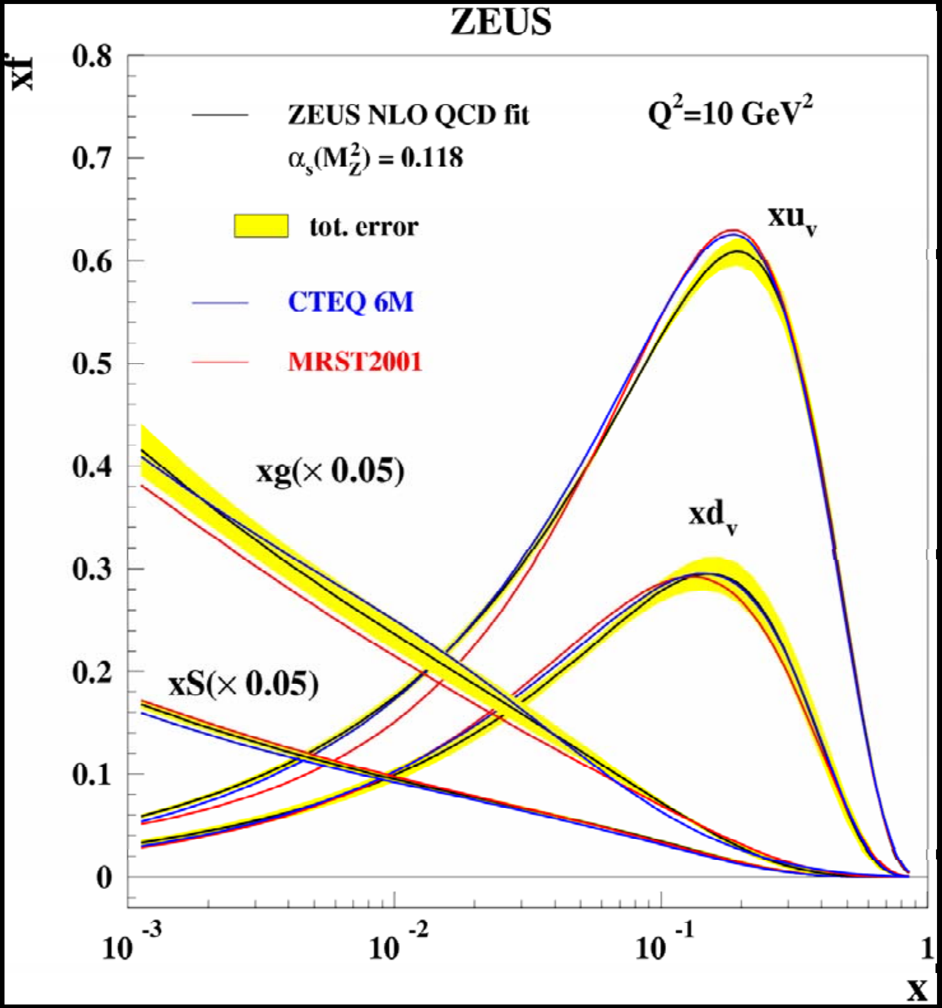
Color Glass Condensate

Partonic Structure

NLO DGLAP fits can follow the data accurately, yield parton densities. BUT:

• Many free parameters (18-30)

• Form of parametrization fixed (not given by theory)



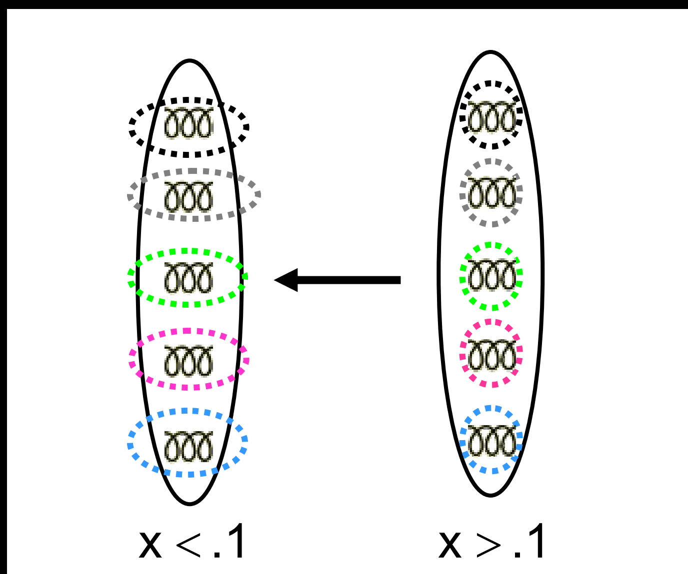
See breakdown of NLO DGLAP approach ...

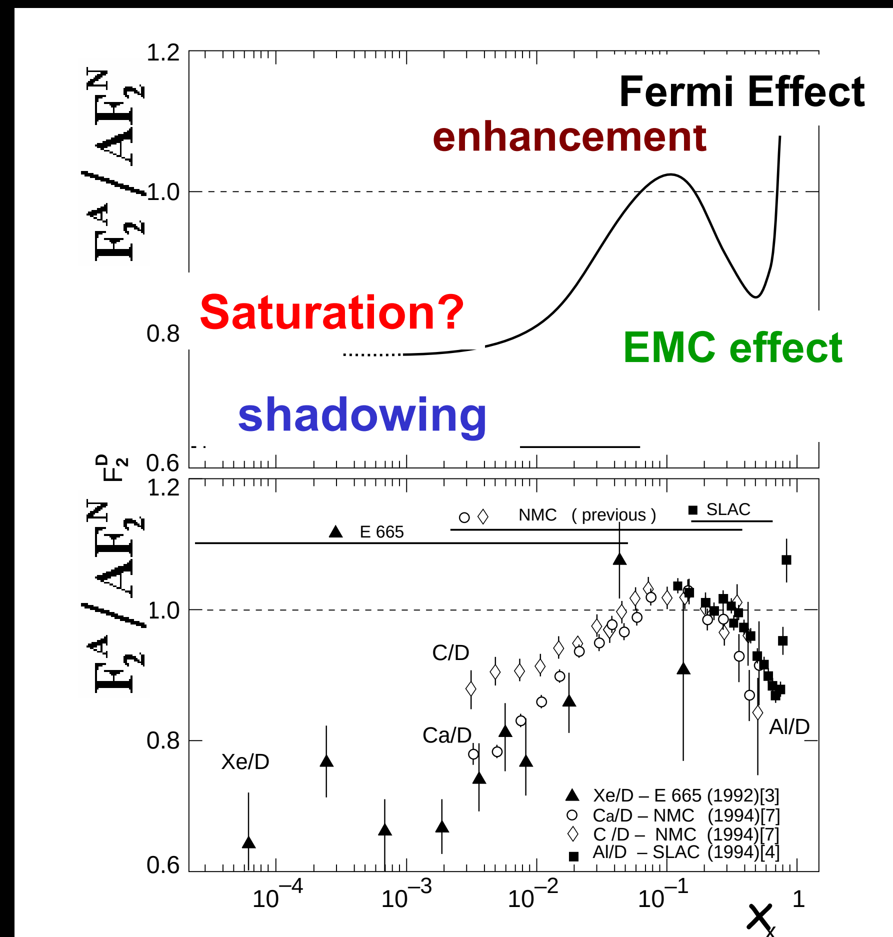
Gluon density known with good precision at larger Q^2. For Q^2=1, gluons go negative.

What About in Nuclei?

Nucleon structure functions are known to be modified in nuclei.

Can be modeled as recombination effect due to high gluon density at low x (in the frame where the nucleus is moving fast).



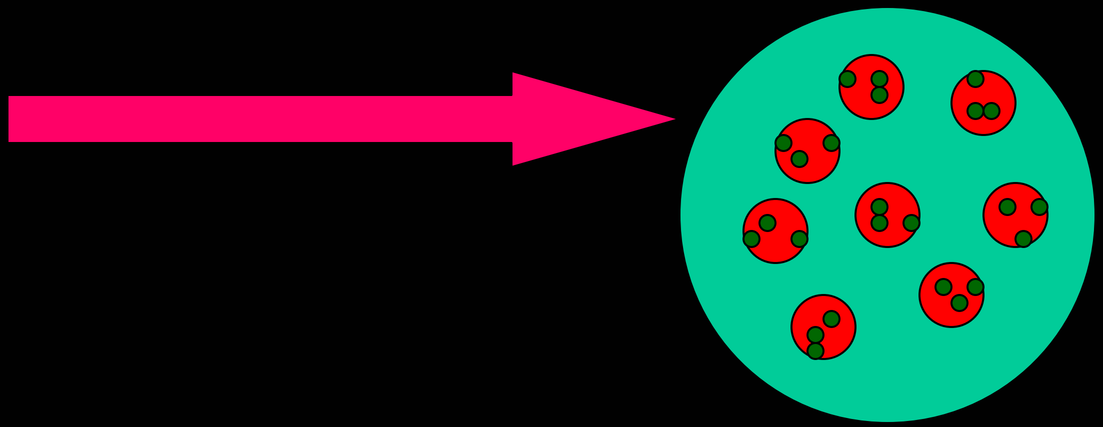


RHIC probes $\mathbf{x \approx \frac{2p_T}{\sqrt{s}} > 10^{-2}}$

Lower x at forward rapidity

How Different Are Nuclei?

Enhancement of possible nonlinear effects (saturation)



At small x, the scattering is coherent over nucleus, so the diquark sees much larger # of partons:

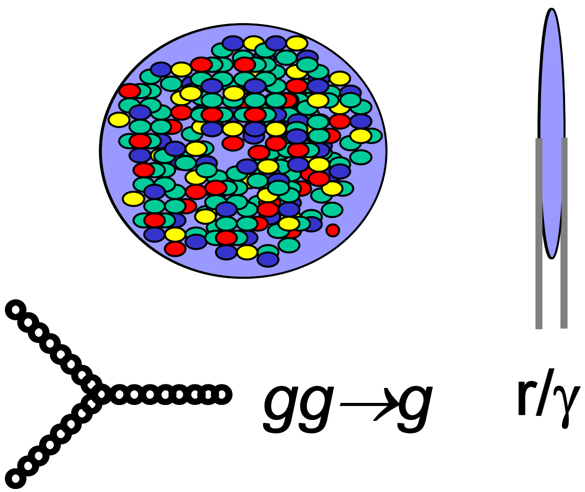
$xg(x_{eff},Q^2) = A^{1/3}\, xg(x,Q^2)$, at small-x, $xg \propto x^{-\lambda}$, so

$x_{eff}^{-\lambda} = A^{1/3}x^{-\lambda}$ so $x_{eff} \approx xA^{-1/3\lambda}$ $= xA^{-3}$ ($Q^2 < 1$ GeV^2)

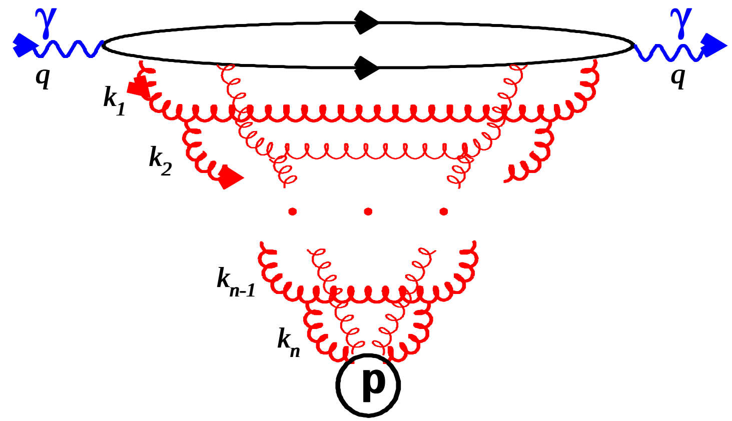
$= xA^{-1}$ ($Q^2 \approx 100$ GeV^2)

What Gauge Are You In?

probe rest frame



target rest frame



Transverse size of the quark-antiquark cloud is determined by $r \sim 1/Q \sim 2\ 10^{-14}\mathrm{cm}/\ Q\ (GeV)$

Wavefunction of low x gluons overlap and the self-coupling gluons fuse, thus saturating the density of gluons in the initial state

Fluctuations from dipole increase and the unitary limit of the photon cross section in deep inelastic scattering is the equivalent to saturation.

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

Color Glass Condensate

Excellent aspect of QCD solvable as wave solutions to Yang-Mills equation in the infinite momentum frame.

It is relevant for low-x, but often applied to larger x values.

Analogy: QCD in low temperature, infinite density limit has a very beautiful solution (Color Superconductivity). We can apply it to neutron stars and see if any predictions agree with experiments.

CGC predictions are extrapolating very far, and thus any tuning with data really jeopardizes progress.

"Our approach will be somewhat academic: we will not include explicitly all effects related to the fact that high k_T particles corresponds to rather large Bjorken x, x~0.1 may be too large for the small-x treatment we present." Kharzeev *et al.*

Looks Like a Phase Diagram, but Isn't

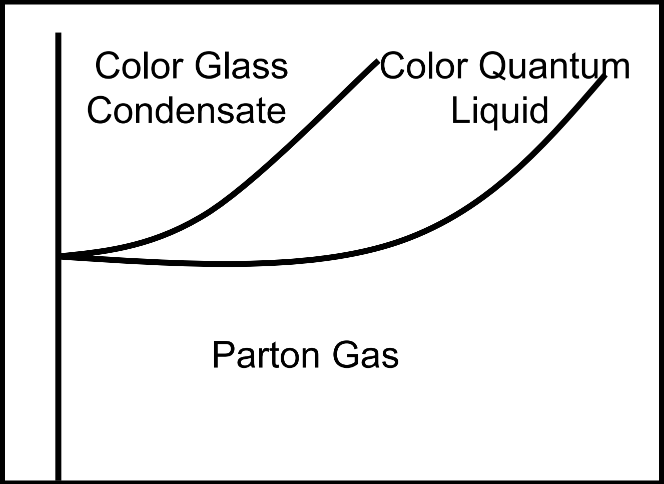
At low x the gluon density may be so high that it saturates.

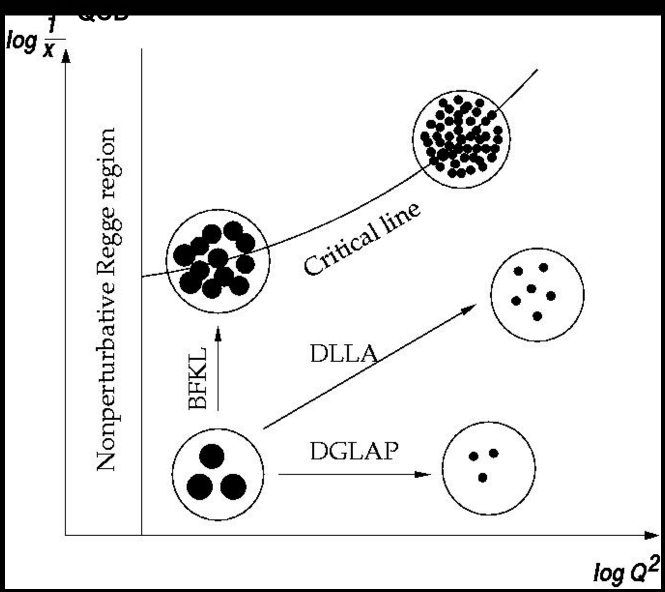
Gluon density is increased in a nucleus relative to the proton by $A^{1/3}$

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.

CGC is not a state of matter like QGP, it is a Fock state of the wavefunction. (DGLAP matter)



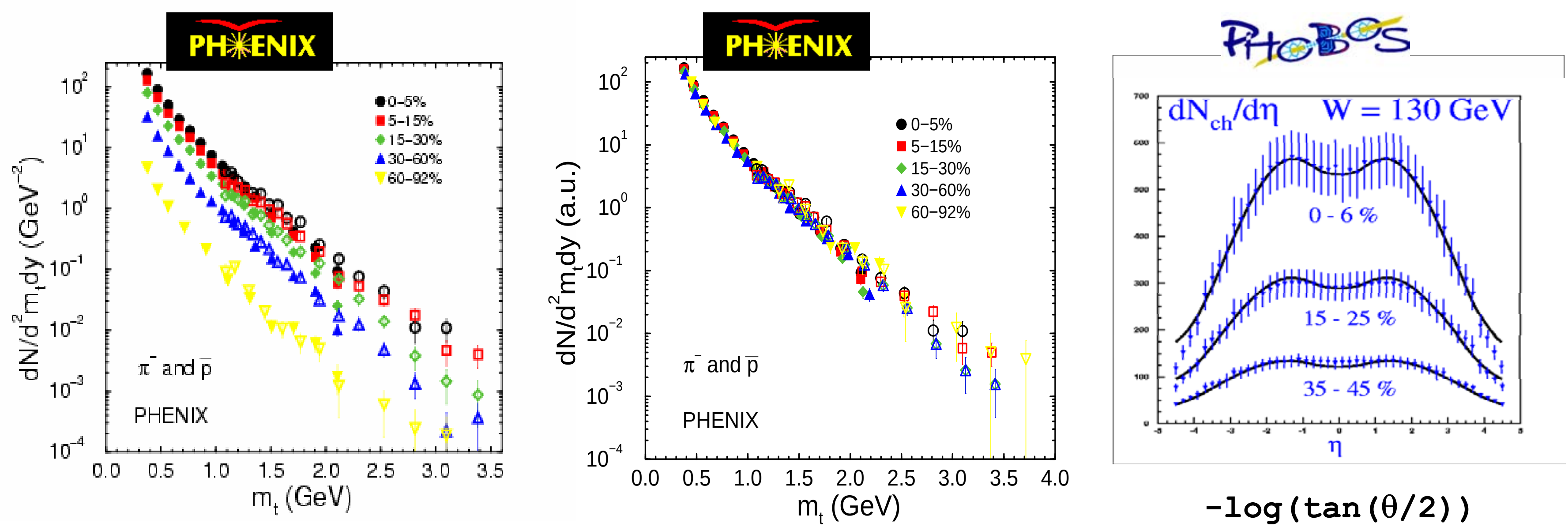


[1] J.P Blaizot, A.H. Mueller, Nucl. Phys. B289, 847 (1987).

Intriguing, but Not Compelling

Saturation models predict the angular distribution and transverse momentum distribution of initial gluons.

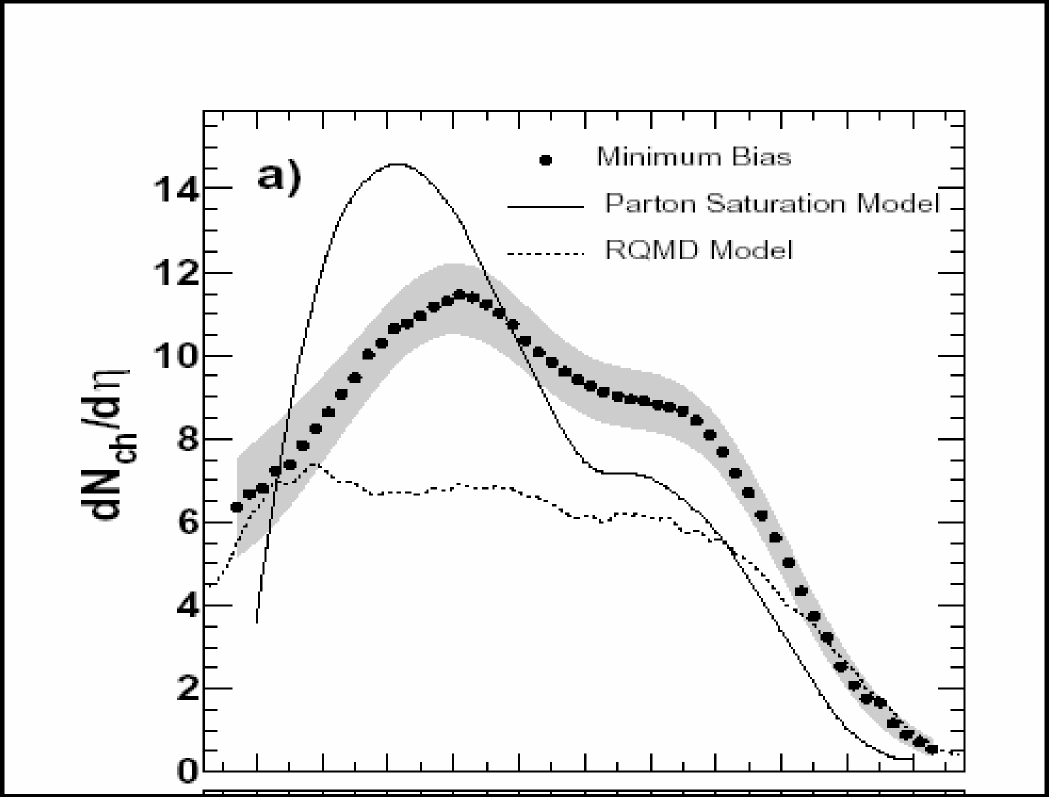
$$\frac{dN}{d\eta} = \frac{\cosh y}{\sqrt{m_T^2/p_T^2 + \sinh^2 y}} \times cN_{part}\left(\frac{s}{s_o}\right)^{\frac{\lambda}{2}} \times e^{-\lambda|y|} \ln\left(\frac{Q_s^2 e^{-\lambda|y|}}{\Lambda_{QCD}^2}\right) \times \left[1+\lambda|y|\left(1-\frac{Q_s}{\sqrt{s}}e^{\lambda|y|/2}\right)^4\right]$$



-log(tan(θ/2))

Predictions

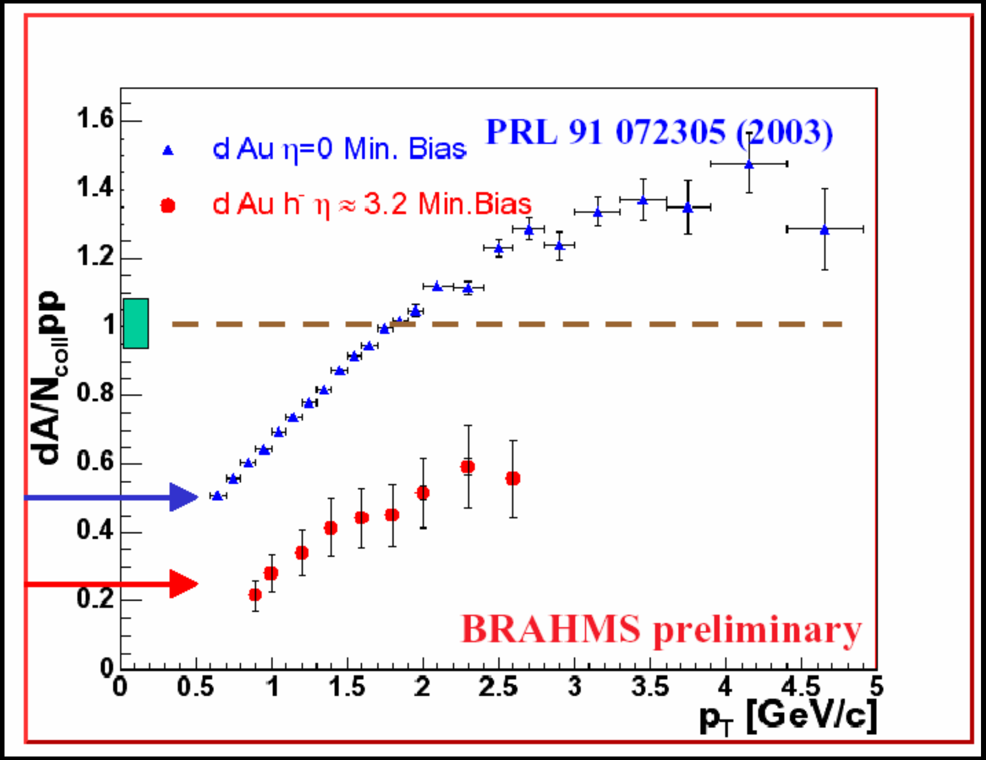
Since CGC calculations are extrapolating to a regime that may be not applicable it is critical to view predictions with caution.



We must resolve all observables. What about the factor of 3 transverse energy problem?

Look for new PHOBOS data with centrality dependence at QM2004.

BRAHMS Beautiful Music



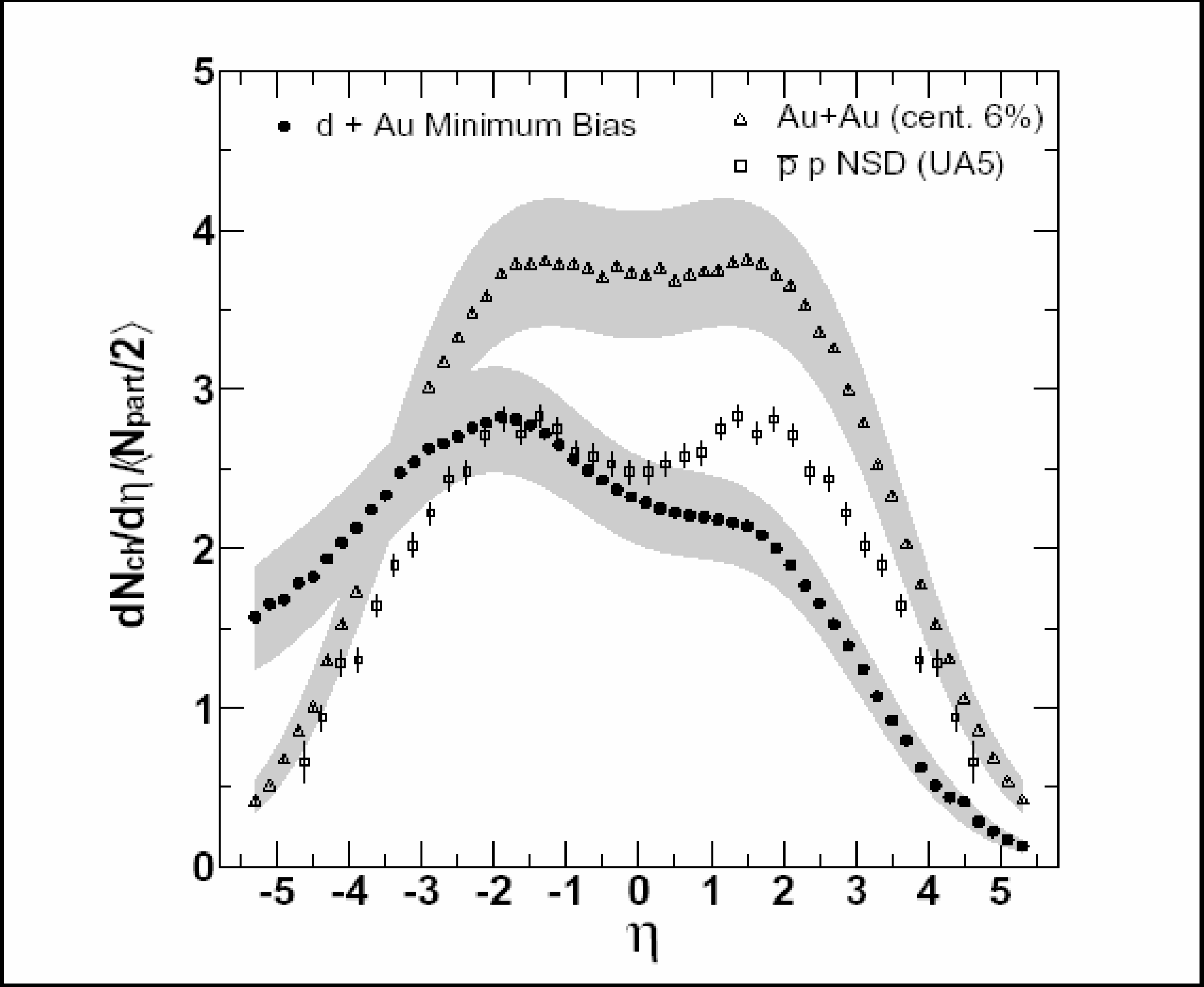
How many people "see" the Color Glass?

Some CGC calculations have a sum-rule and thus the suppression of low x gluons leads to enhancement of high x gluon (anti-shadowing)

Beware the difference of R(dAu/pp) versus R(dAu-cent / dAu-perip)

Soft versus Hard Regime?

PHOBOS data and at lower energy shows soft particle production shifted to backward pseudorapidity.



$R(\eta=-3) \sim 0.6$
$R(\eta=0) \sim 0.4$
$R(\eta=+3) \sim 0.3$

We need to see the centrality dependence.

Hydrodynamics

3-d Hydrodynamics may hold the most promise for learning about QCD (Equation of State)

"RHIC data is well described by hydrodynamics with expected Equation of State." Ed Shuryak (and many others)

Hydrodynamics

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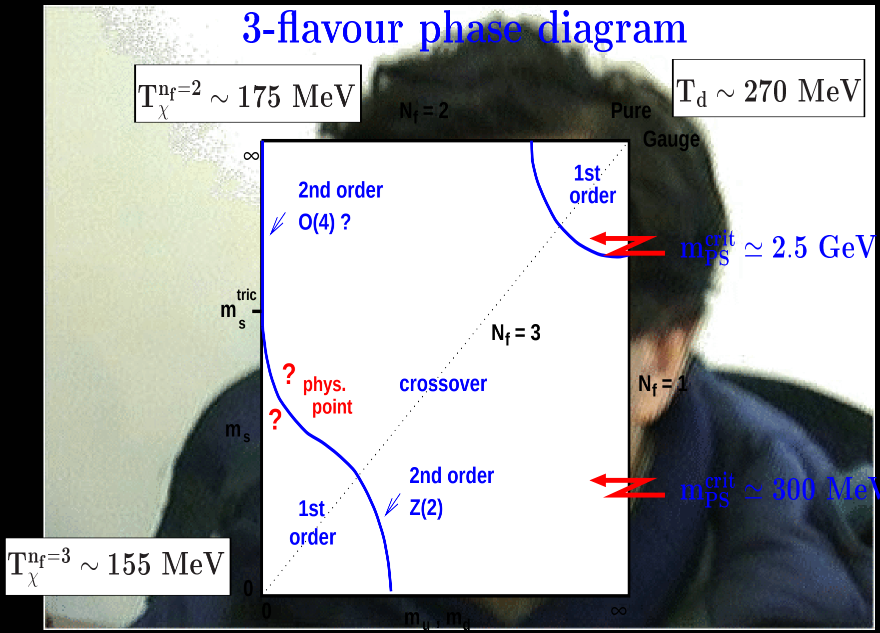
"RHIC data is well described by hydrodynamics with expected Equation of State." Ed Shuryak (and many others)

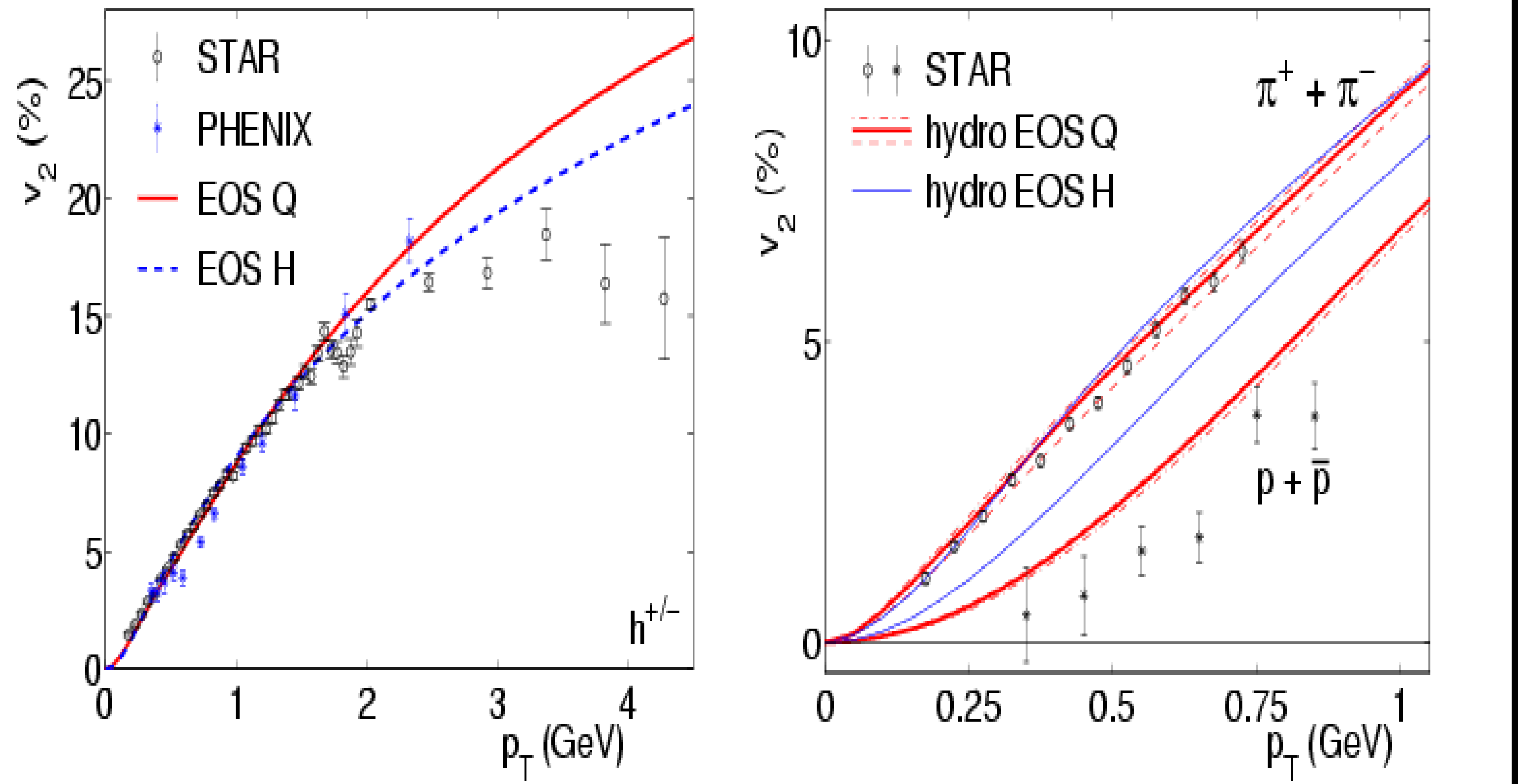
What is the expected Equation of State?

I thought that was what we were trying to determine experimentally?



First Order Phase Transition?

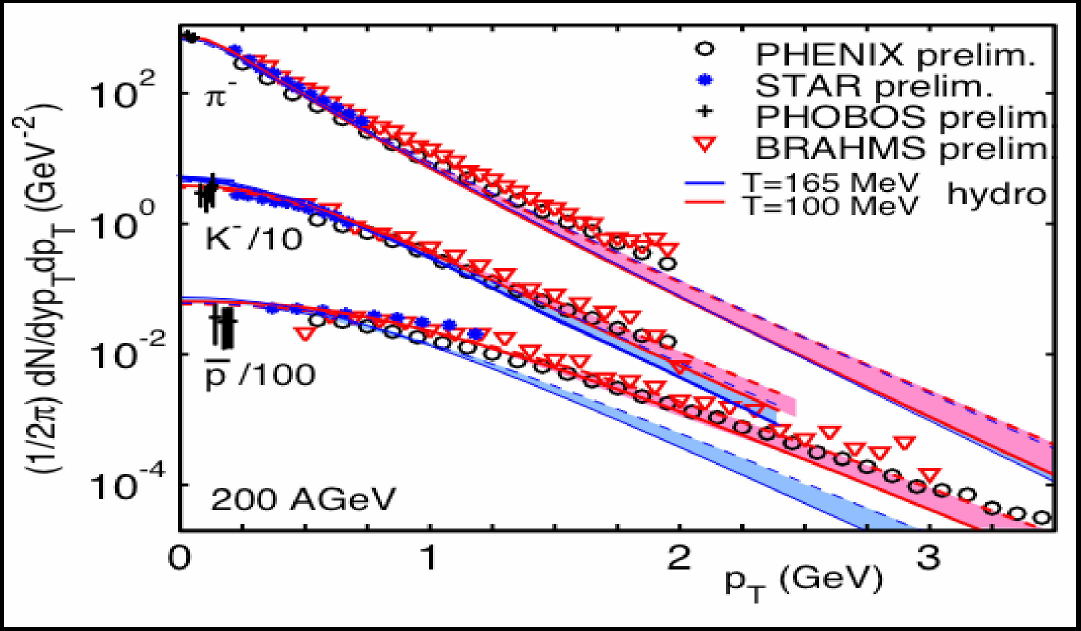
Experimental data seem to favor an EOS with a phase transition with a mixed phase.



STAR Coll., PRL 86 (2001) 402; 87 (2001) 182301; PHENIX Coll., nucl-ex/020400512 and QM 2001

Repeat After Me...

"99% of all particle production is perfectly described by hydrodynamic calculations." (99% of the people in the field)



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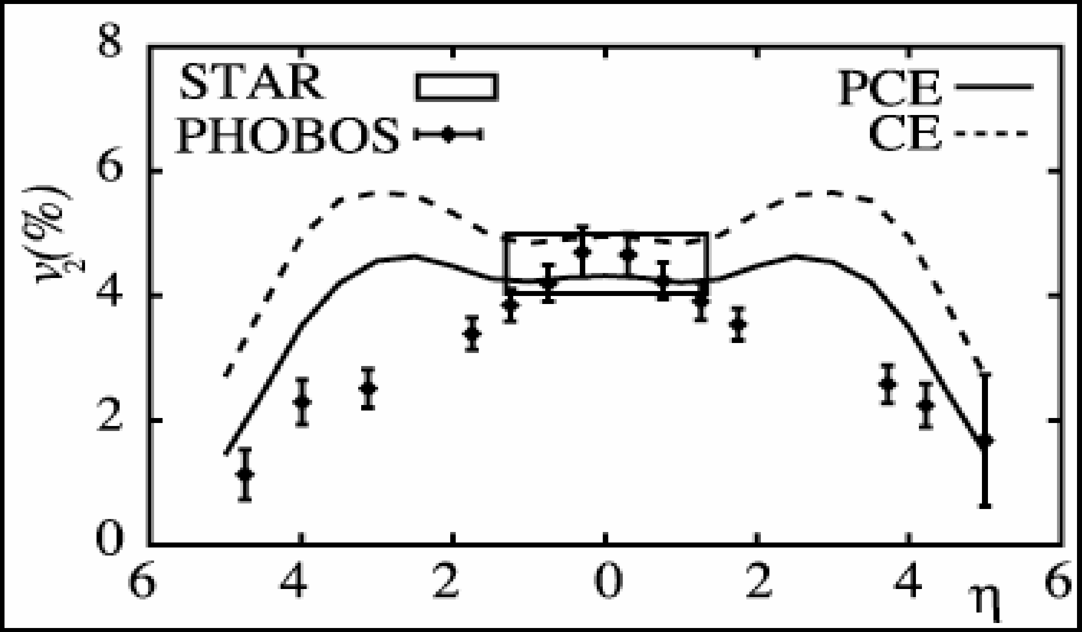
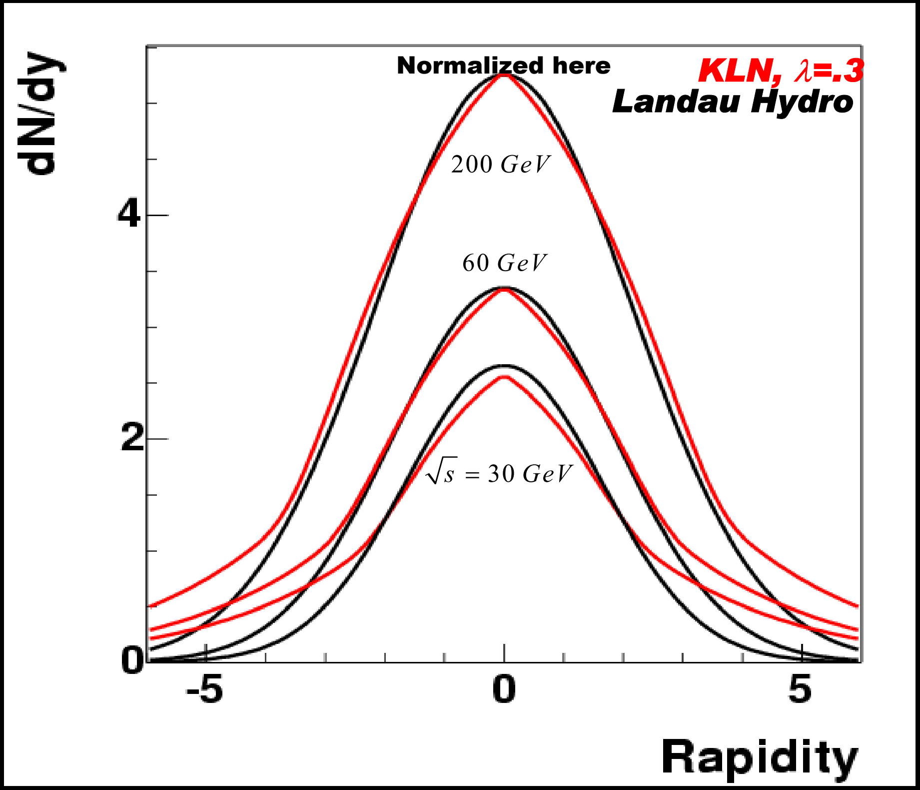
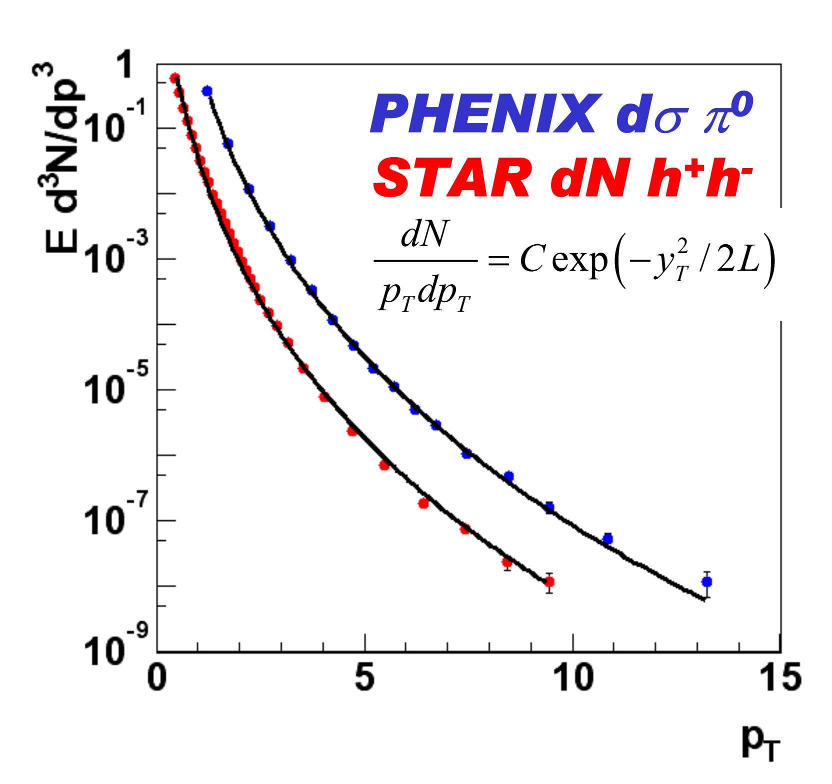


“Acutally we do not yet know the pre-hydro initial stage well even now, so longitudinal hydro has little predictive power.” Shuryak
“Boost invariance is reasonable over +/- 1.5 units of rapidity” Kolb
“3-d and 2+1-d with boost invariance are not the same.” Nagle

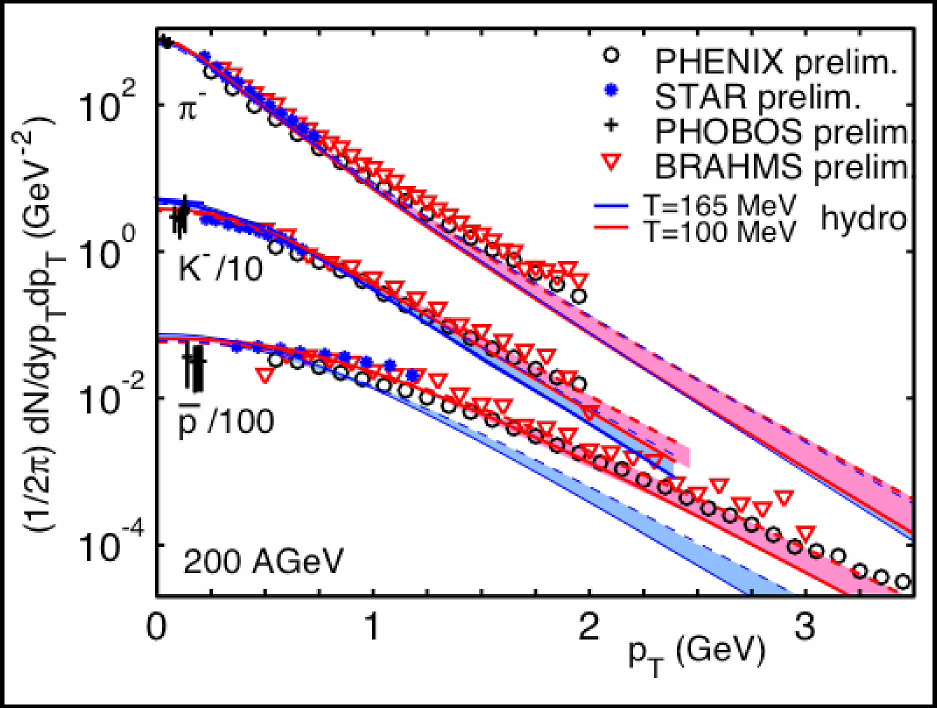
Landau-Peter Steinberg

How does the hydrodynamics and implications change with modification of boost invariant assumption? Landau fireball may not be a poor second choice.



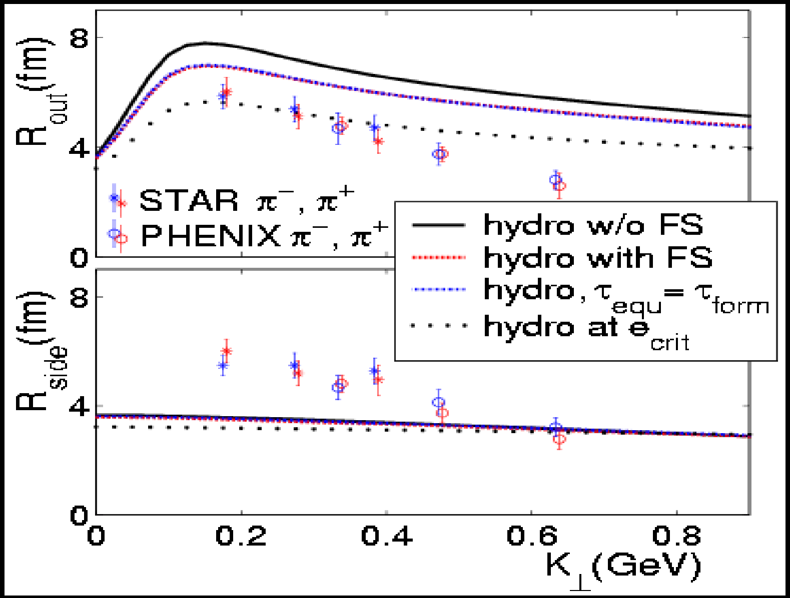


What About the Lifetime? HBT Puzzle?



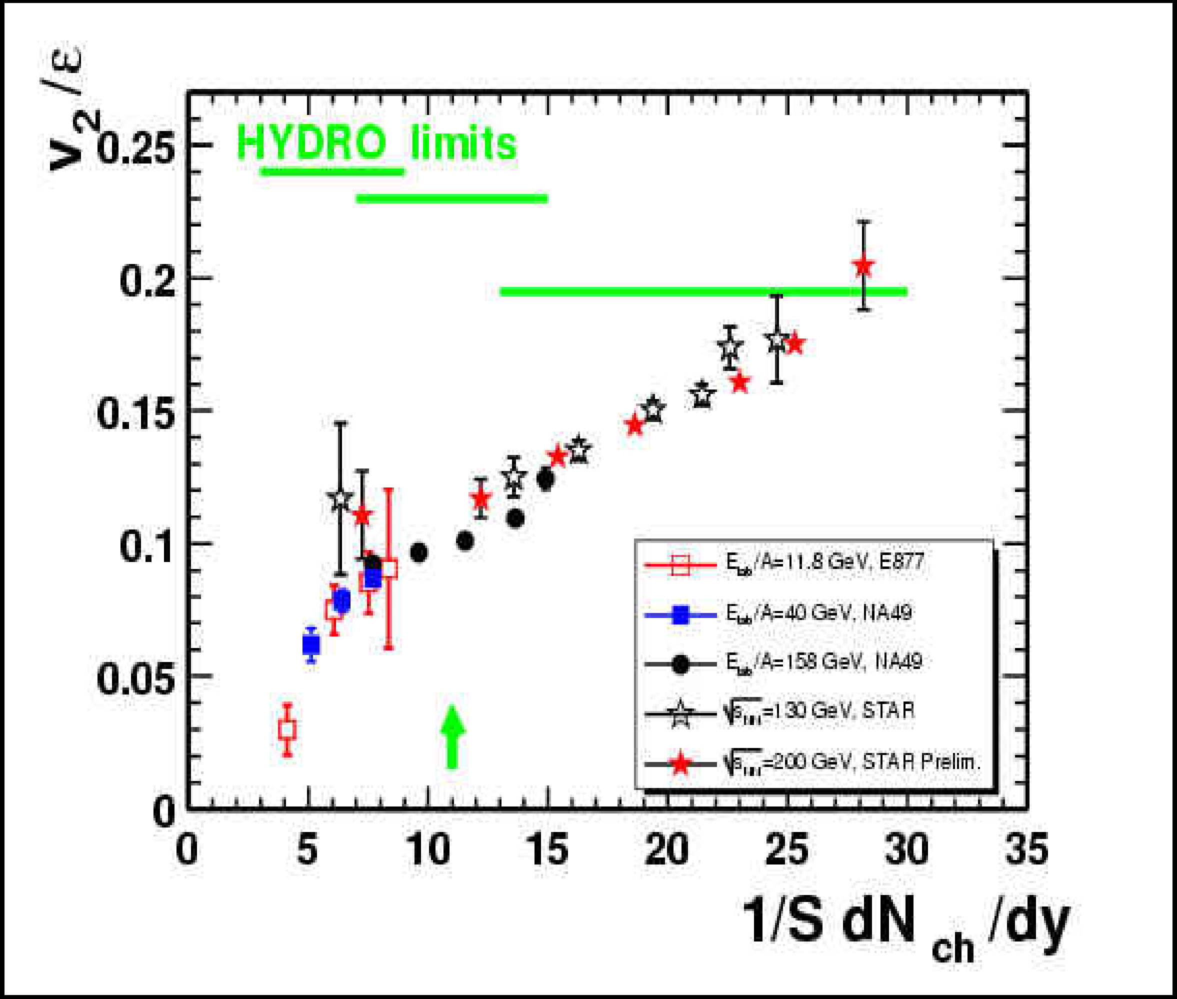
The mixed phase in the EOS gives reasonable agreement with data, but makes the system lifetime significantly longer.

However, lifetimes implied by HBT are essentially the same as at lower energies. Perhaps hadronic resonances can shed more light on this.



Very, Very Promising, But Not Done!

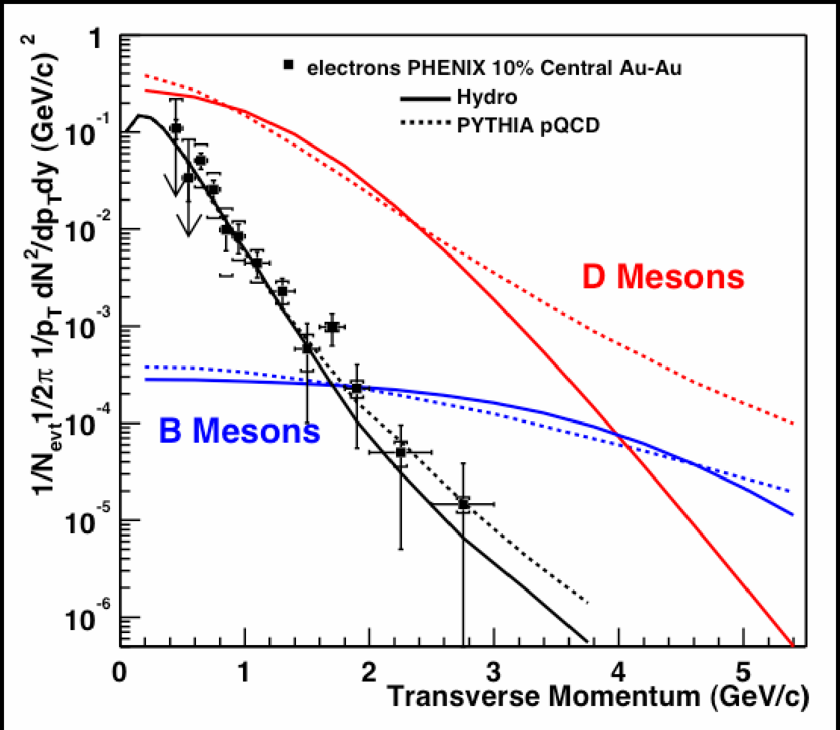
$v_2(E_{cm})$ → QGP hydro for the *FIRST* time at RHIC!

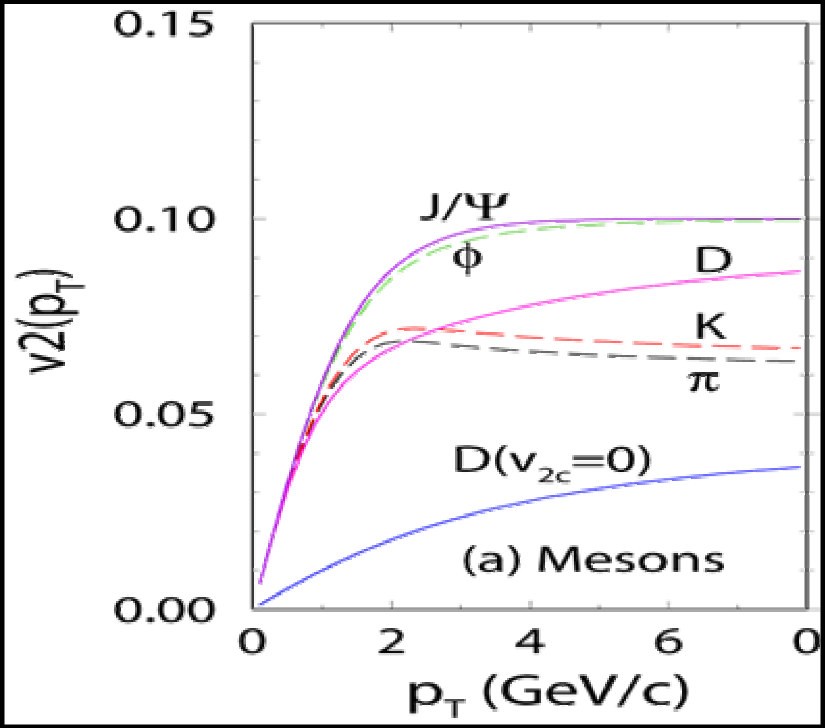


Charm Flow

Perhaps even charm quarks follow hydrodynamics?

There is a lot of charm physics to be studied even before RHIC detector upgrades for displaced vertex reconstruction.





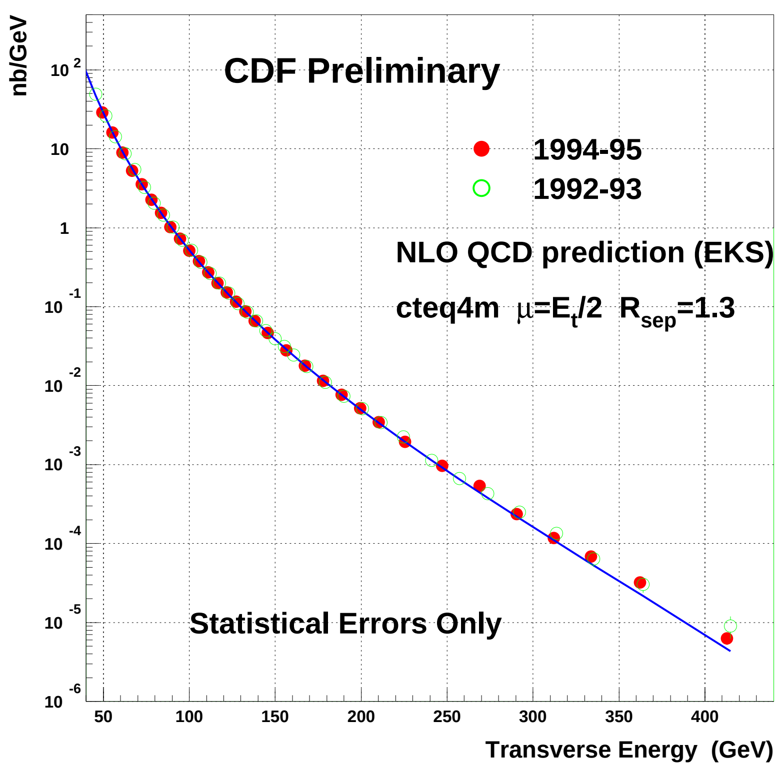
PLB 2002, Batsouli, Kelly, Gyulassy, Nagle

Molnar, Lin et al.

Perturbative QCD Probes

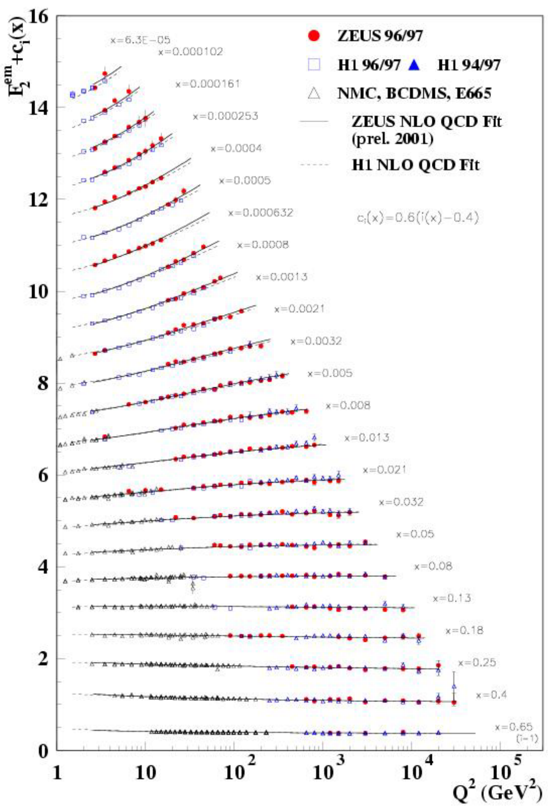
High Energy Jet Observations

Inclusive Jet cross section



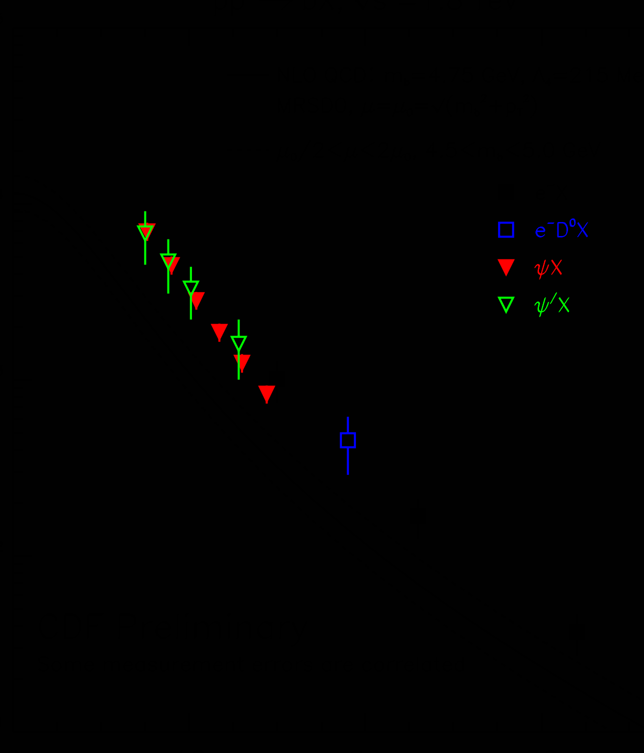
Deep Inelastic Scattering DGLAP Evolution

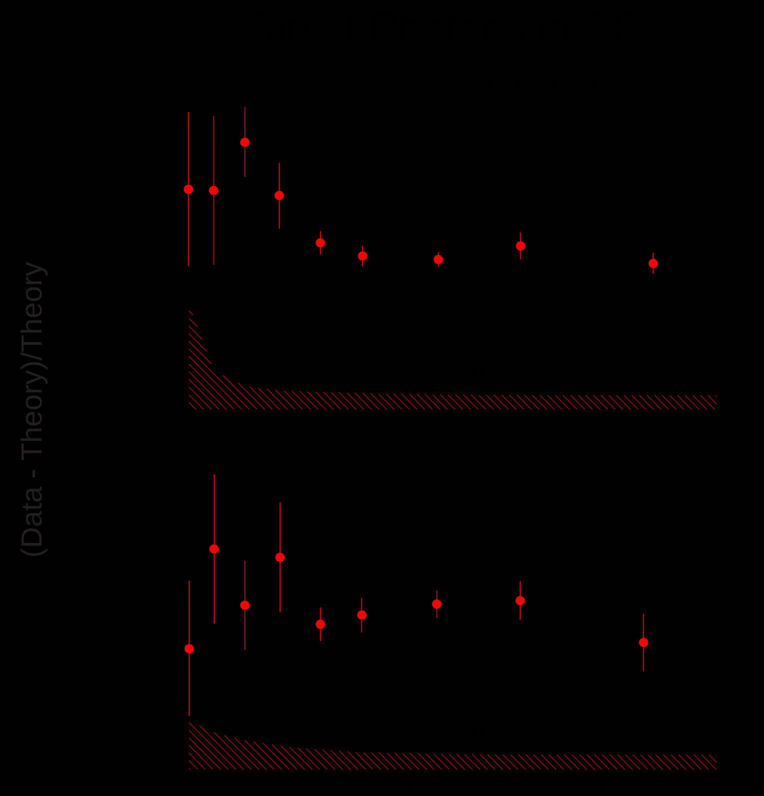
ZEUS+H1



Warning About pQCD

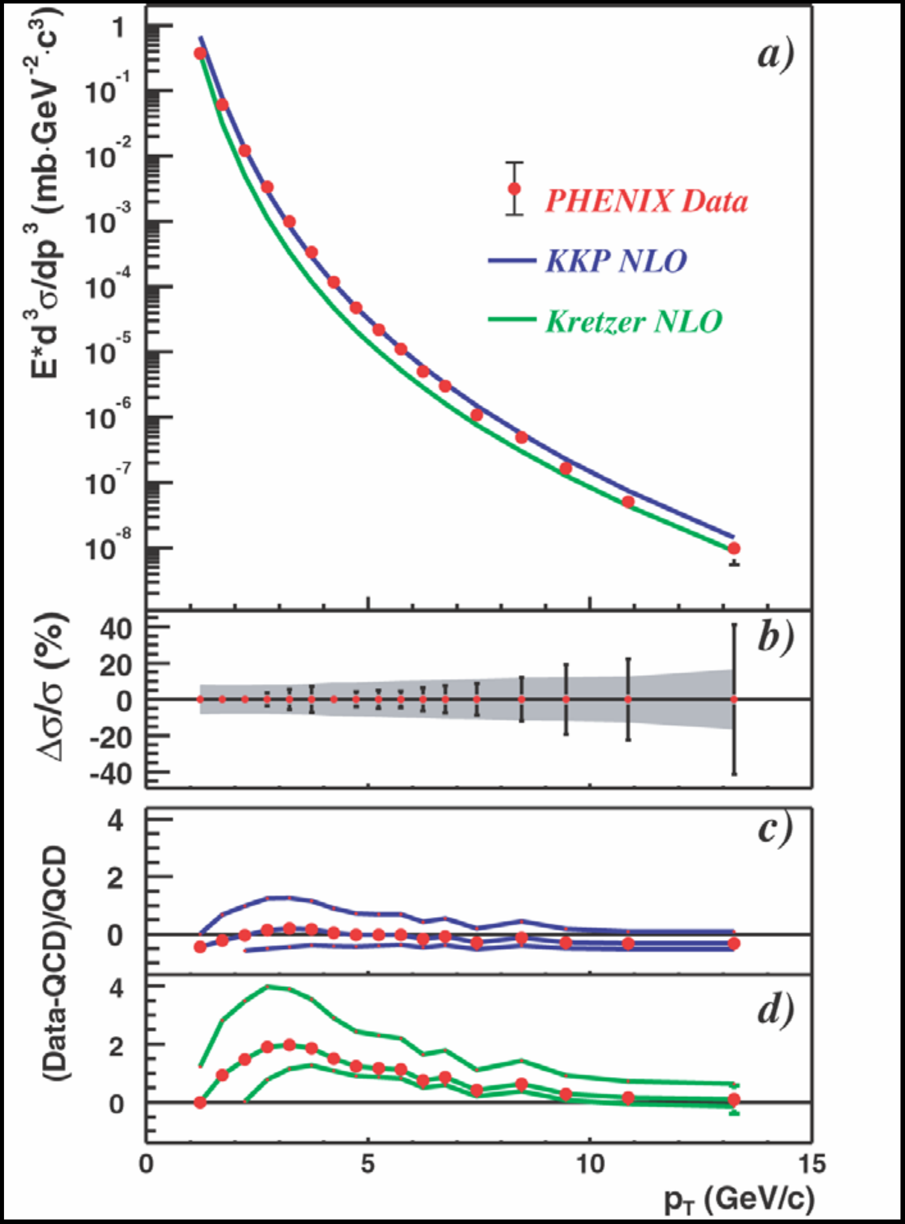
- pQCD calculations have many open issues at p_T < 50 GeV.
- For example, currently there is poor agreement with beauty production and direct photon observations.





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

Sensitivity of pQCD



Agreement of pQCD with pion spectra from 1.5 – 13 GeV is quite amazing.

This is particularly encouraging for spin program.

However, sensitive to uncertainty in gluon fragmentation function at the level of factor of 2.

Factorization and Universality

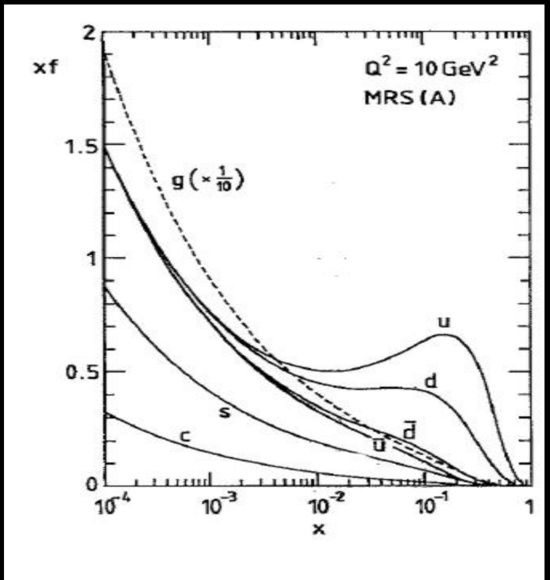
In heavy ion collisions we can calculate the yield of high p_T hadrons

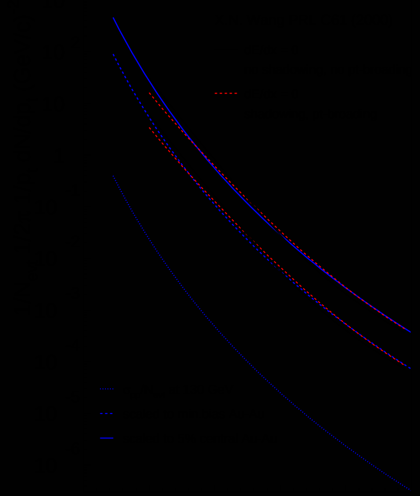
$$E_h \frac{d\sigma_h^{pp}}{d^3p} = K \sum_{abcd} \int dz_c\, dx_a\, dx_b \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} f(\mathbf{k}_{Ta}) f(\mathbf{k}_{Tb}) f_{a/p}(x_a, Q_a^2) f_{b/p}(x_b, Q_b^2)\; D_{h/c}(z_c, Q_c^2) \frac{\hat{s}}{\pi z_c^2} \frac{d\sigma^{(ab\to cd)}}{d\hat{t}} \delta(\hat{s}+\hat{u}+\hat{t})$$

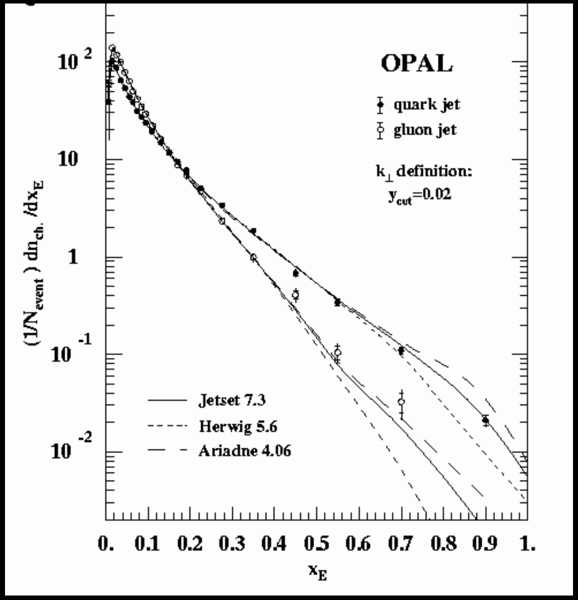
Flux of incoming partons (structure functions) from Deep Inelastic Scattering

Perturbative QCD

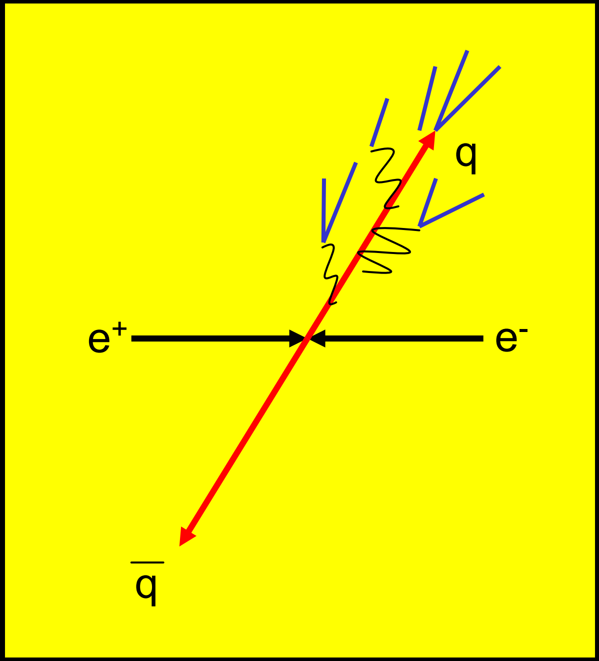
Fragmentation functions D(z) in order to relate jets to observed hadrons





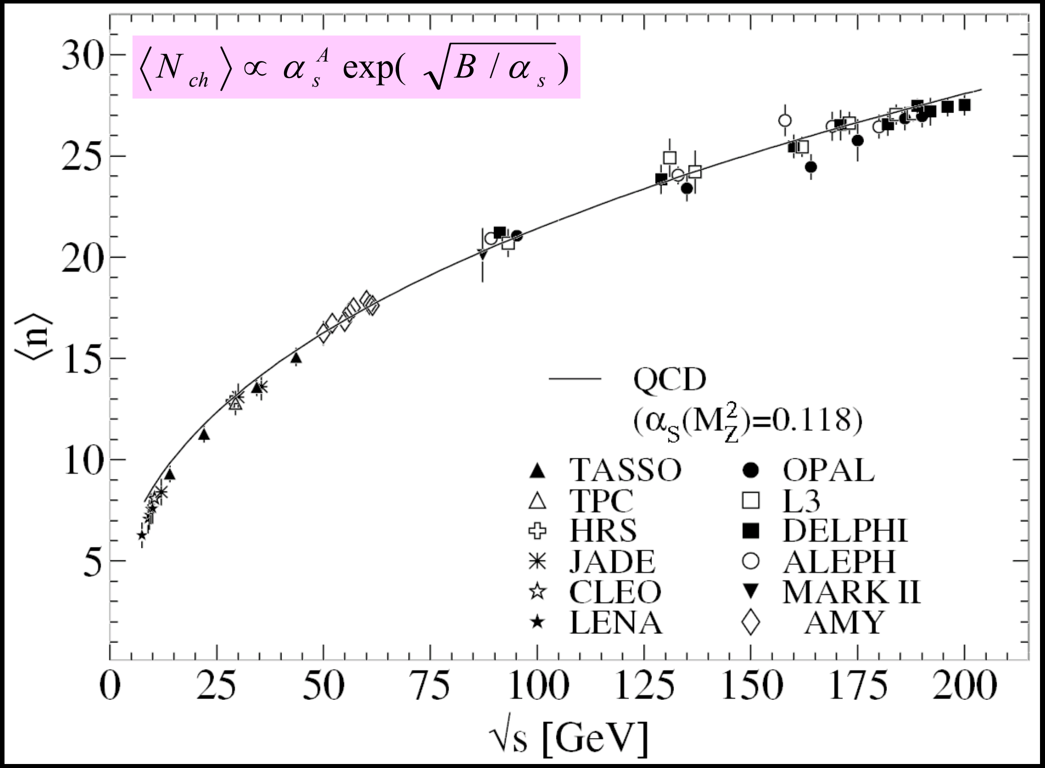


Off-Shell Parton Radiation (0^{th} Order)



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

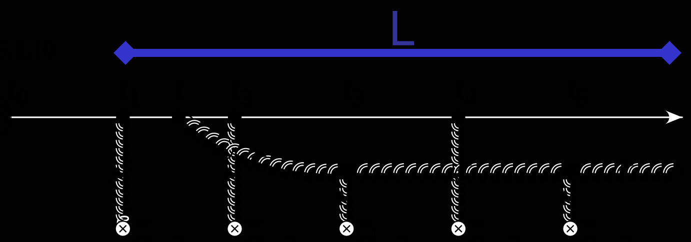
QCD calculation of gluon multiplicity times a hadron scale factor gives excellent agreement with data.



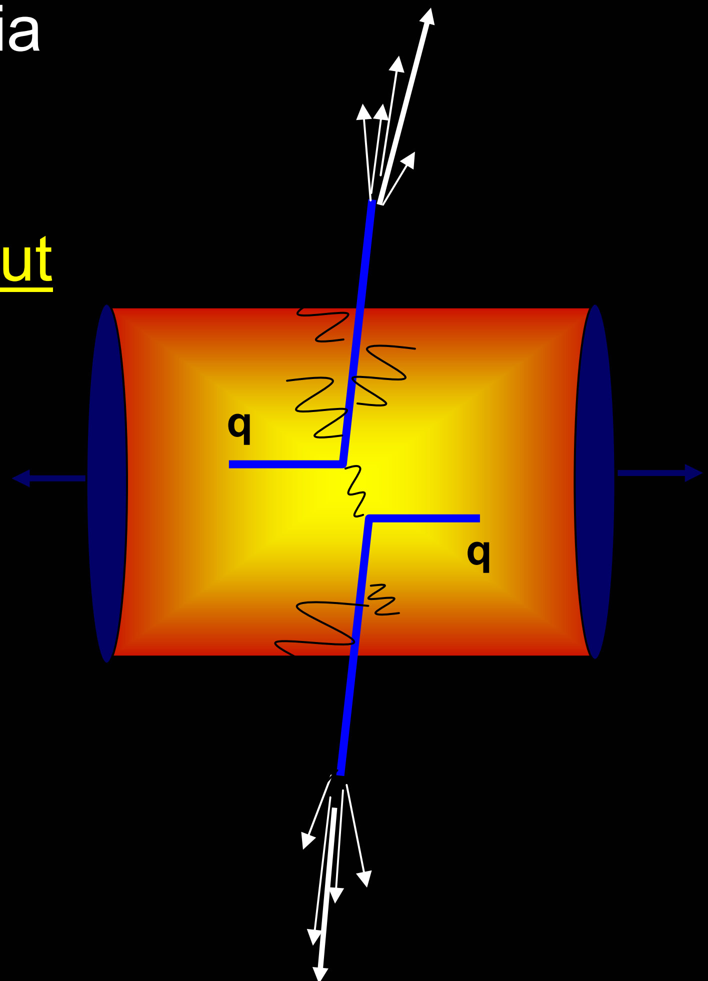
Medium Induced (1st Order) Parton Energy Loss

Partons are expected to lose energy via induced gluon radiation in traversing a dense partonic medium.
Not very sensitive to deconfinement, but only to the color charge density!

Coherence among these radiated gluons leads to $\Delta E \propto L^2$

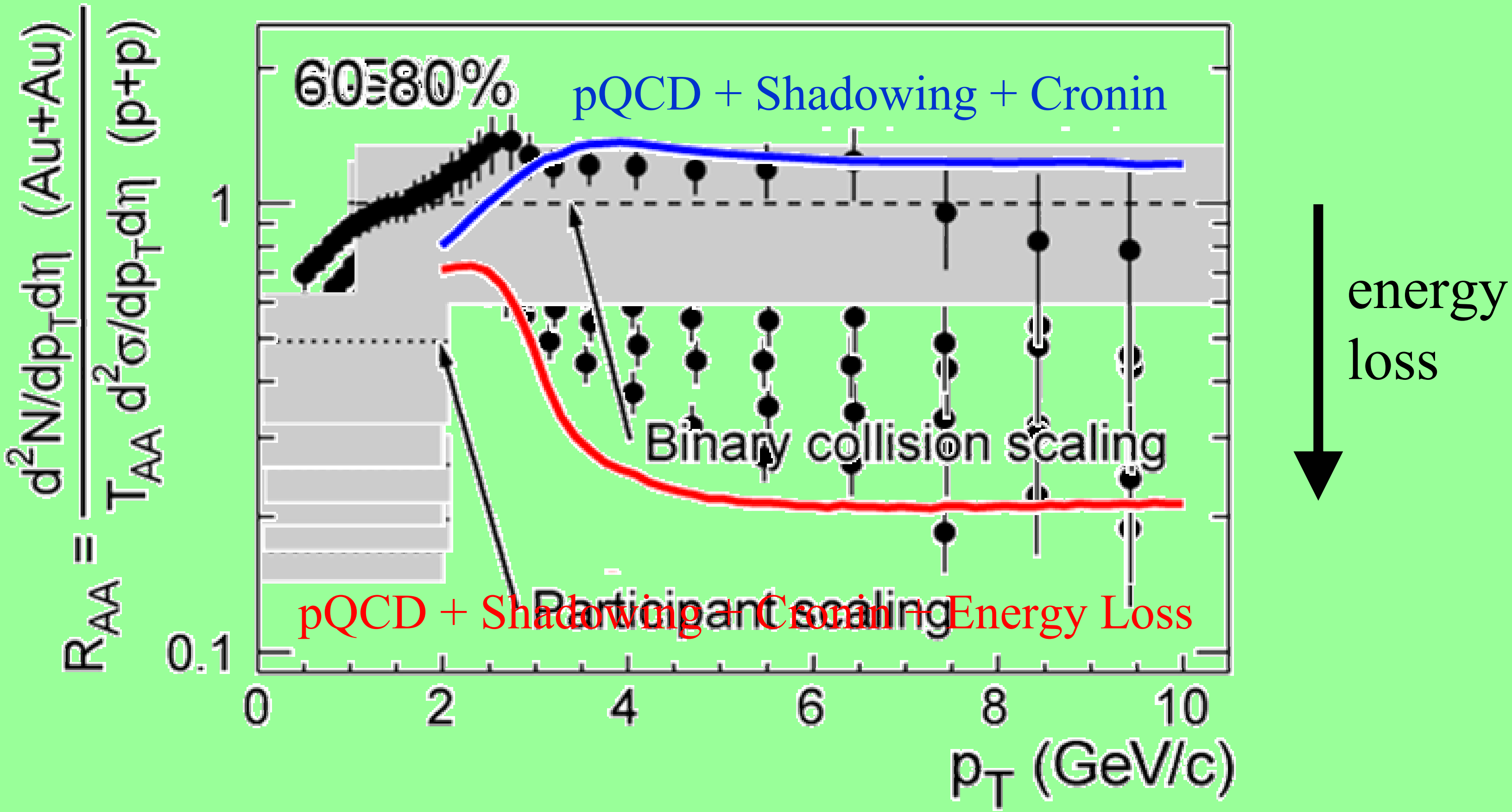


Look for an effective modification in the jet fragmentation properties.



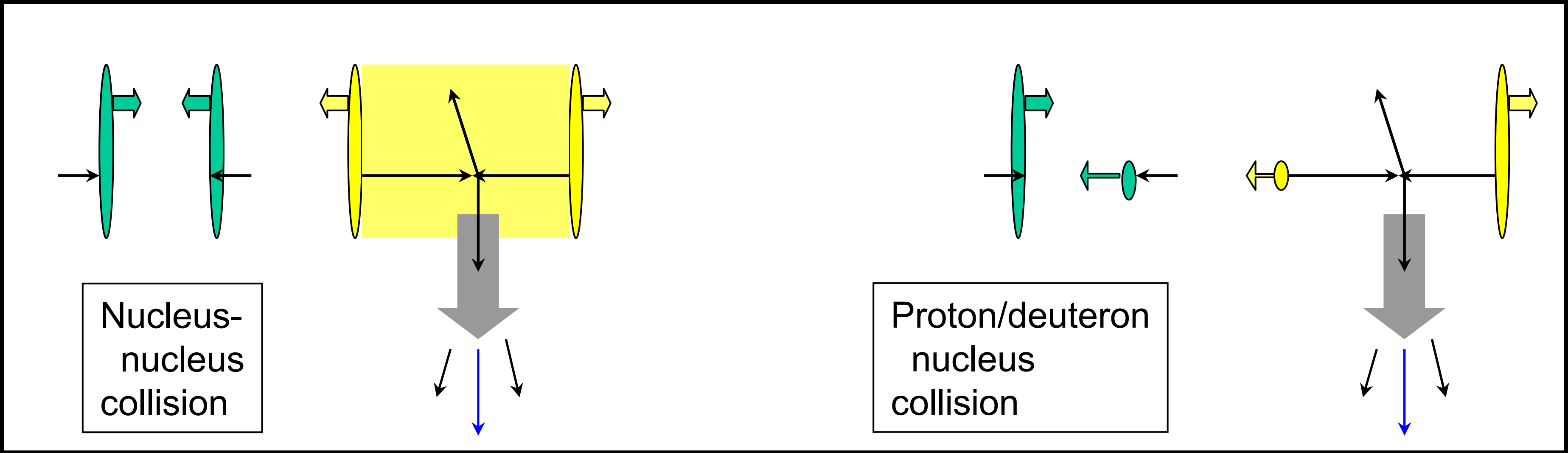
Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267
Gyulassy, Levai, Vitev, hep-pl/9907461
Wang, nucl-th/9812021
and many more…..

Jet Quenching Observed



Seen by all four RHIC experiments.

Deuteron-Gold Control Experiment



- Collisions of small with large nuclei were always foreseen as necessary to quanify cold nuclear matter effects.
- Recent theoretical work on the “Color Glass Condensate” model provides alternative explanation of data:
  - Jets are not quenched, but are a priori made in fewer numbers.
  - Color Glass Condensate hep-ph/0212316; Kharzeev, Levin, Nardi, Gribov, Ryshkin, Mueller, Qiu, McLerran, Venugopalan, Balitsky, Kovchegov, Kovner, Iancu
- Small + Large distinguishes all initial and final state effects:

Qualitative Agreement !

Description of data in approach that combines multiple scattering, initial state shadowing and gluon bremstrahlung in a dense gluonic medium.

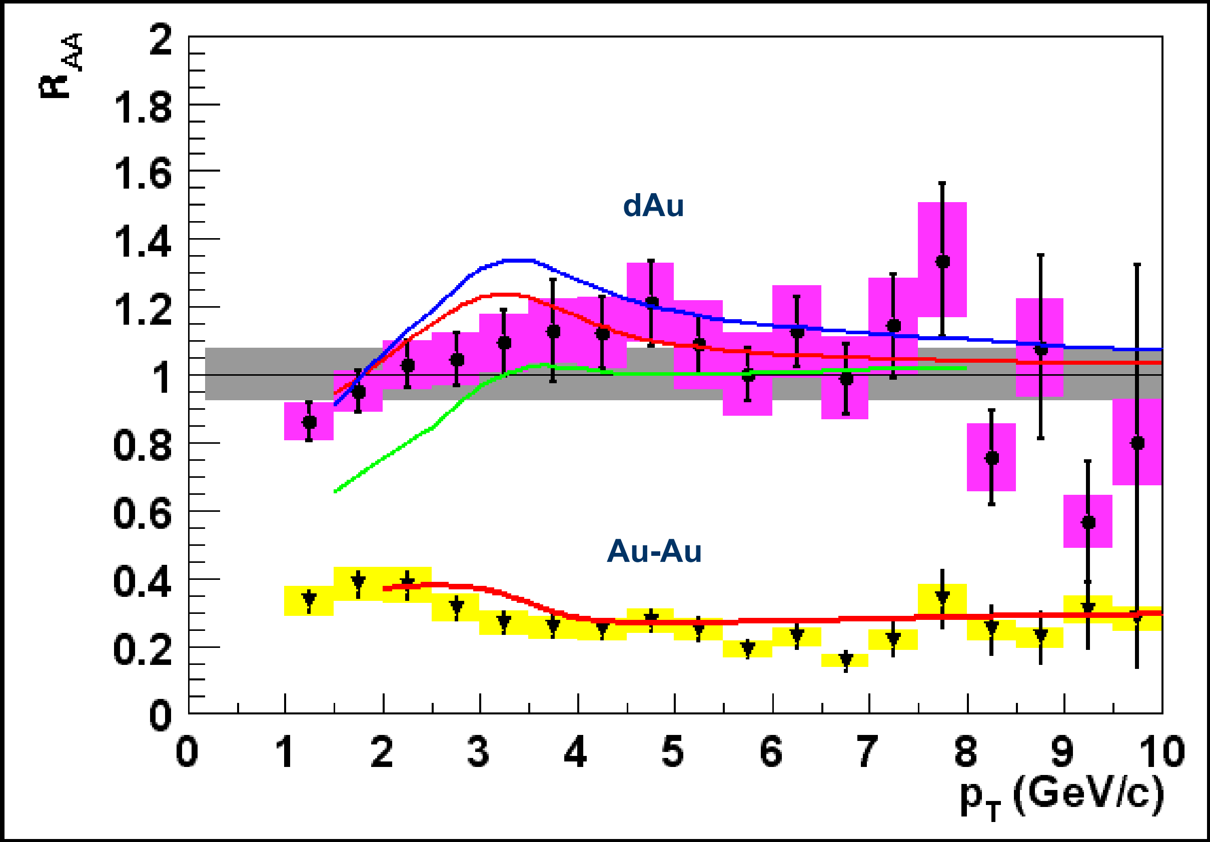
Claim that our high pT probes have been calibrated and give:

$dN_g/dy \sim 1100$

$\varepsilon > 100\ \varepsilon_0$

Agreement with initial energy density needed to drive hydrodynamics.

How exact is that agreement?



Infrared Cutoff Issue

"In the presently available RHIC range p_T < 15 GeV a reliable quantitative prediction of quenching can hardly be page. It is the soft singularity that causes instability of the pQCD description." BDMS

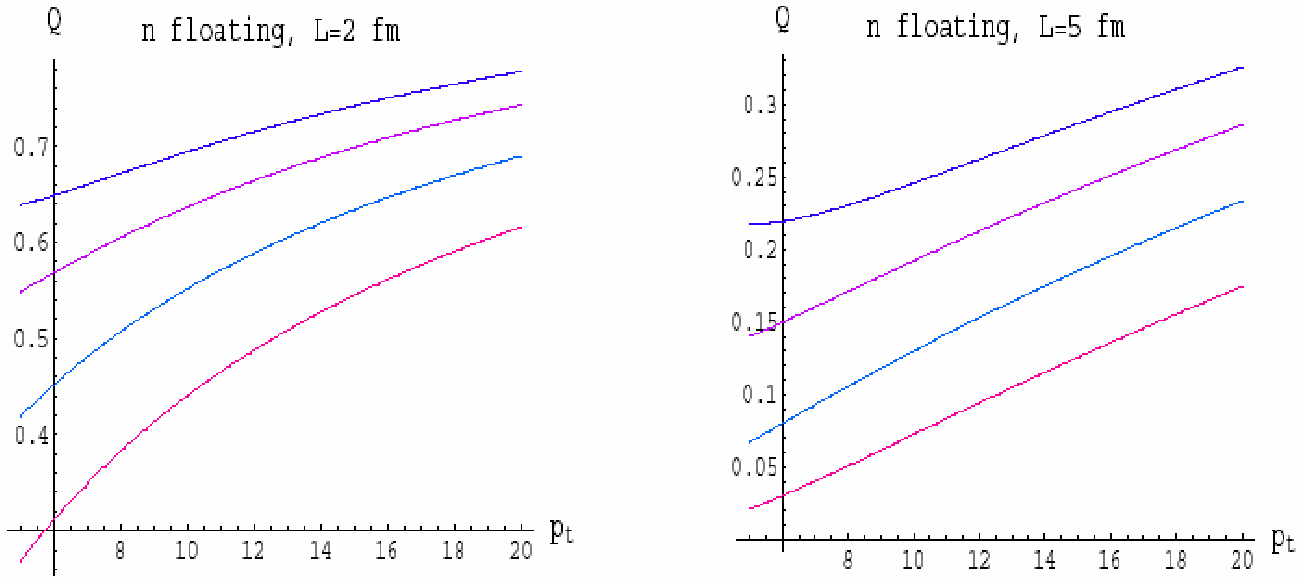


Figure 3: "Infrared" dependence of the quenching factor for hot medium. The curves (from bottom to top) correspond to the gluon energy cuts 0, 100, 300 and 500 MeV.

GLV Formalism

No gluon modes propagate below the plasma frequency.
Provides a potential natural scale for the infrared cutoff.

For a thermally equilibrated medium at temperature T, the color screening mass in pQCD is given by $\mu = 4\pi\alpha_s T^2$. In addition, as in ordinary plasmas, no gluon modes propagate below the plasma frequency, $\omega_{pl} \sim \mu/\sqrt{3}$. In practice, lattice QCD calculations of μ indicate sizable nonperturbative corrections to the pQCD estimates for achievable temperatures. Therefore, we simply take here $\mu \sim \omega_{pl} \sim 0.5$ GeV as a characteristic infrared scale of the medium. In perturbation theory, there is a relation between the screening scale μ and the mean free path λ,

$$\mu^2/\lambda \approx 4\pi\alpha_s^2\rho \tag{4}$$

where ρ is the density of plasma partons weighed by appropriate color factors. Another important scale for our problem is the Bethe-Heitler frequency,

$$\omega_{BH} \equiv \frac{1}{2}\mu^2\lambda \gg \mu \tag{5}$$

in the dilute plasma approximation assumed here.

No gluon modes propagate below the plasma frequency.
This would also then be true for 0^{th} order gluon radiation – normal hadronization process !

Implications for 0th Order Radiation

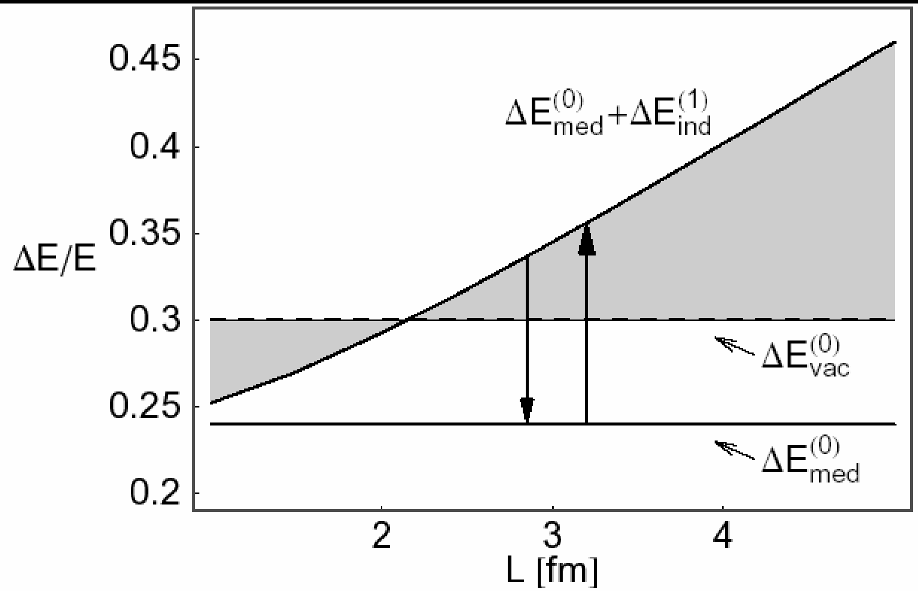
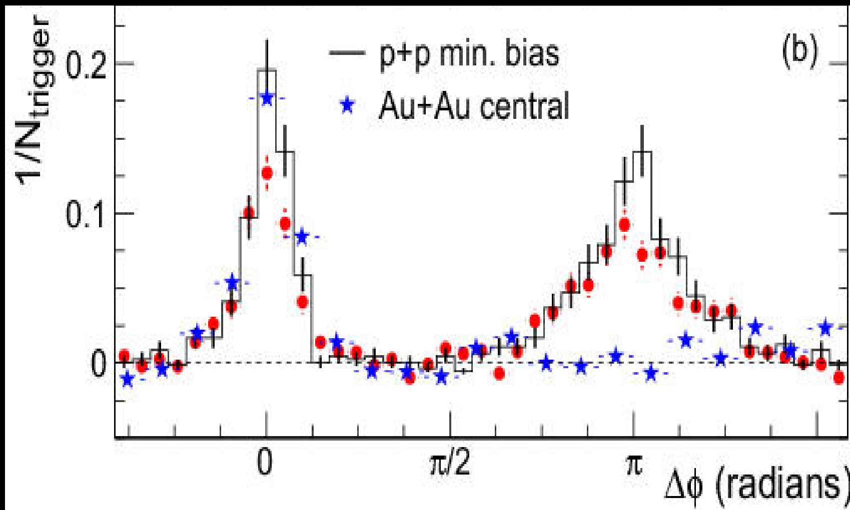


FIG 4. The fractional energy loss for a 10 GeV charm quark is plotted versus the effective static thickness L of a plasma characterized by $\mu = 0.5$ GeV and $\lambda = 1$ fm. The dashed middle horizontal line corresponds to the energy loss in the vacuum taking into account the kinematic dead cone of radiation for heavy quarks [29]. The lower horizontal solid line shows our estimate of the reduction of the zeroth order energy loss due to the QCD analog of the Ter-Mikayelian effect. The solid curve corresponds to the net energy loss, $\Delta E^{(0)}_{med} + \Delta E^{(1)}_{ind}$.

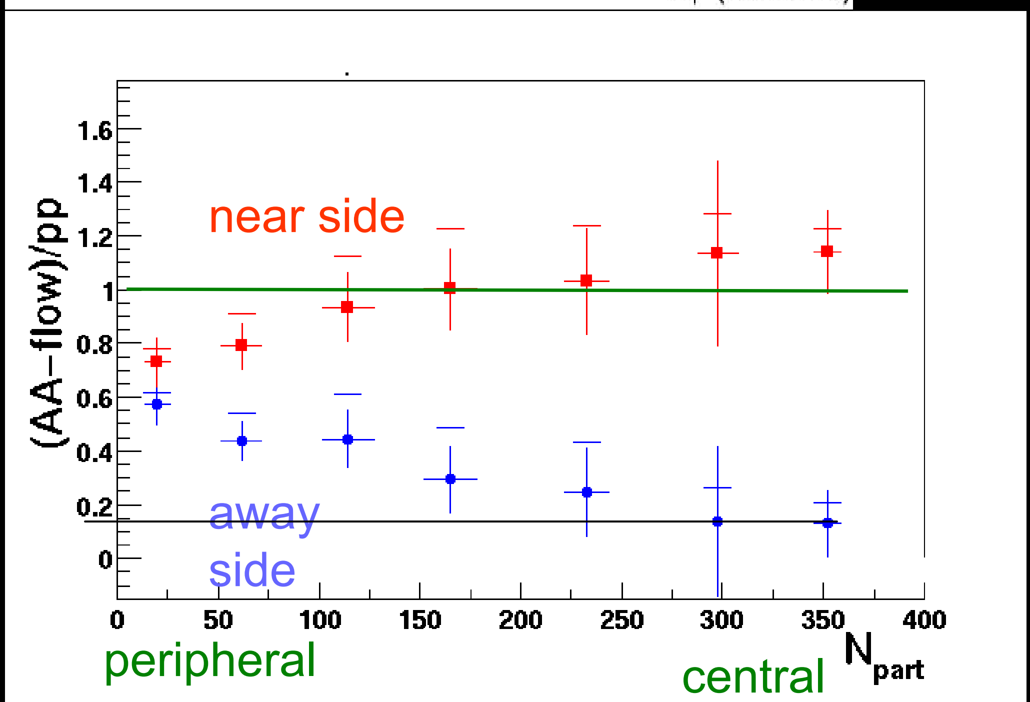
Gyulassy and Djordjevic calculate that suppression of 0^{th} order radiation from charm quarks actually leads to enhancement of high pT D mesons (hardening of fragmentation).

What about the same effect for light quarks? "We cannot calculate that."

Near and Away Side !



Disappearance of the away side jet has caused lots of excitement. Very opaque matter.



Energy conservation precludes disappearance except into Black Hole created at RHIC!

Where did the energy go?

Options:

(1) Hadron angular distribution is so broadened that away side correlation is too wide. - Important implication for LHC detectors.

(2) Hadrons are shifted in energy below experimental p_T cut – Vitev model favors this one.

(3) Hadrons lose so much energy they are completely thermalized in medium.

(4) Black hole.

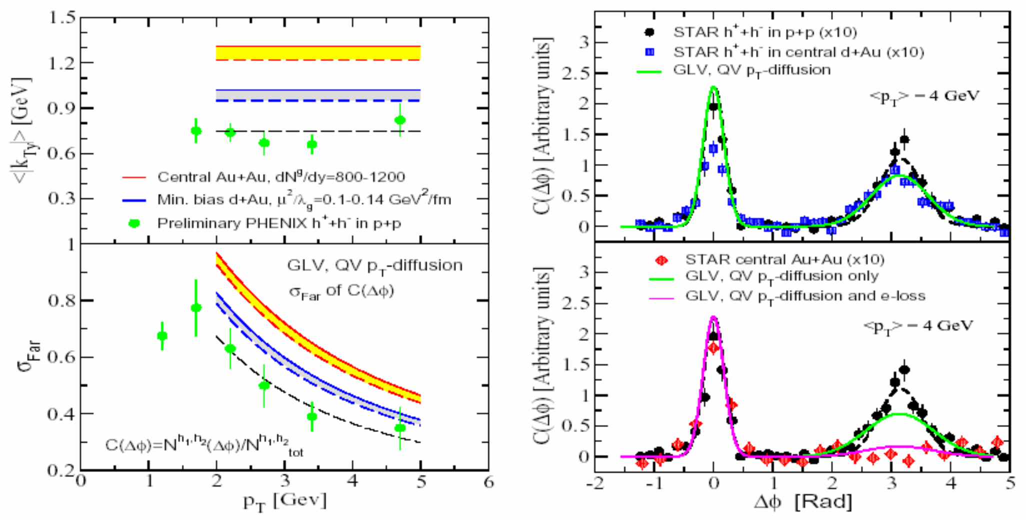


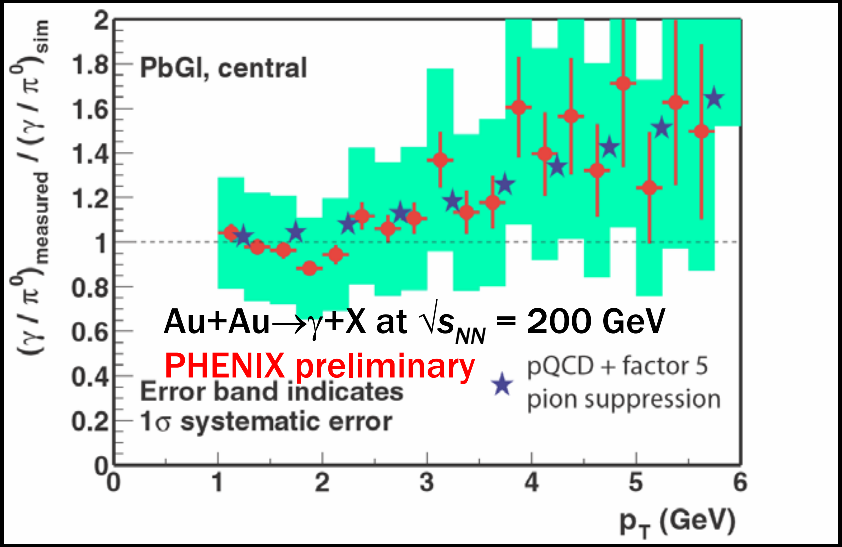
FIGURE 2. Left panel: predicted enhancement of $\langle|\mathbf{k}_{Ty}|\rangle$ and σ_{Far} in minimum bias $d+Au$ and central $Au+Au$ reactions at RHIC from p_T-diffusion [3]. Preliminary $p+p$ data is from PHENIX [10]. Right panel: the broadening of the far-side di-hadron correlation function in central $d+Au$ and $Au+Au$

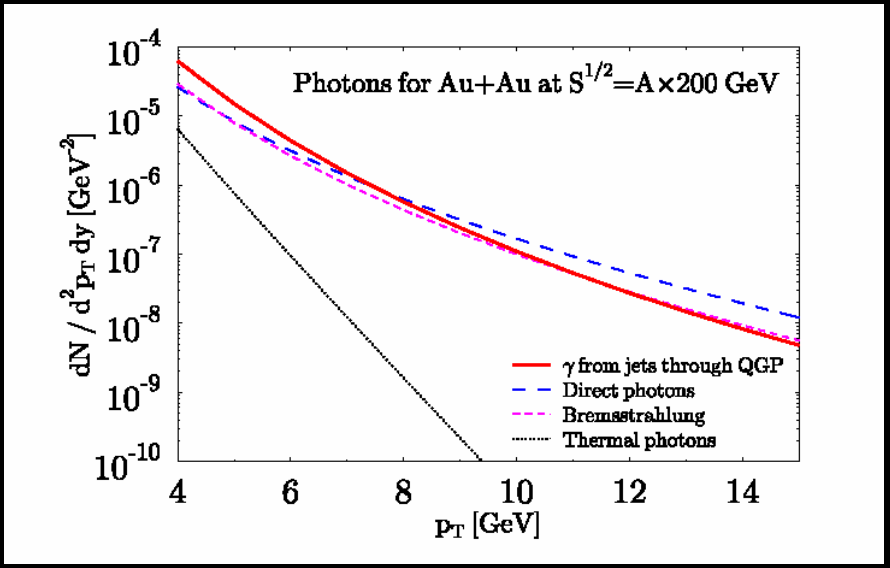
Key experimental results are needed in this area.

Direct Photons

One would like very much to measure some baseline that follows the expectations of pQCD + Factorization + Nuclear Thickness Scaling.

- Direct photons from gluon-Compton?
- Charm production?
- Drell-Yan?

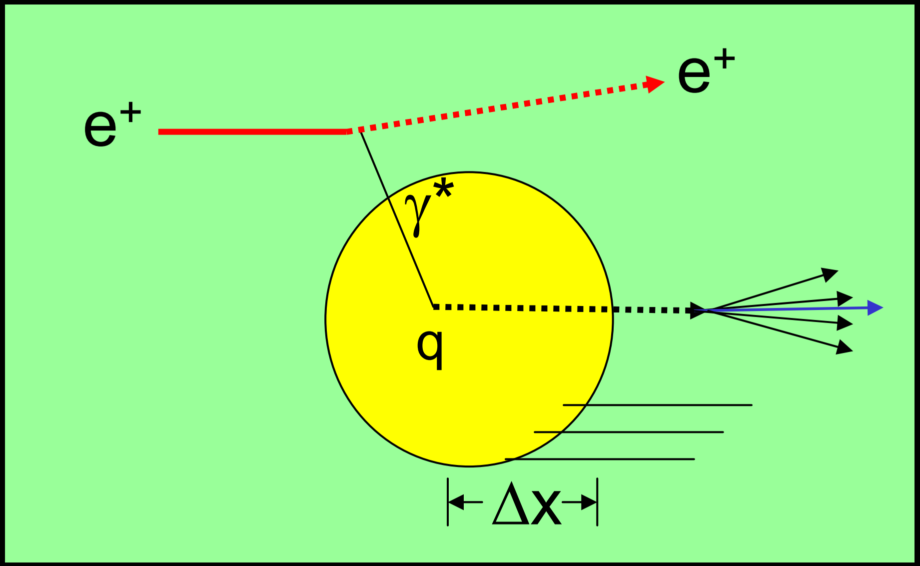




Fries et al. also propose that p_T < 6 GeV may have large contribution of photons from high energy partons losing energy in medium.

Electron-Nucleus Results

HERMES Experiment



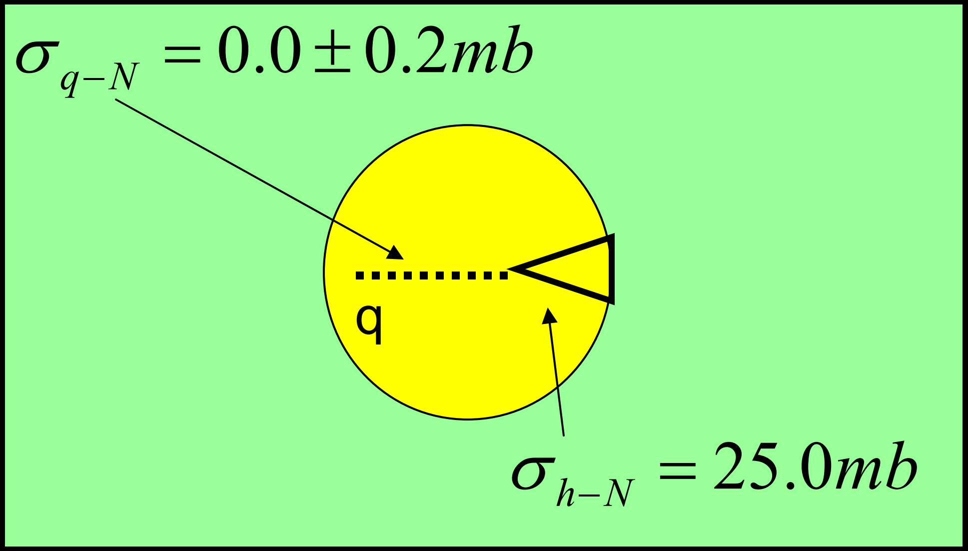
Measure quark energy from electron scattering off nuclei.
Measure hadron fragmentation function D(z).
<u>Larger nuclei show fewer high z hadrons in fragmentation</u>.

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

Formation Time and Other Issues

HERMES considers an alternative description.

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



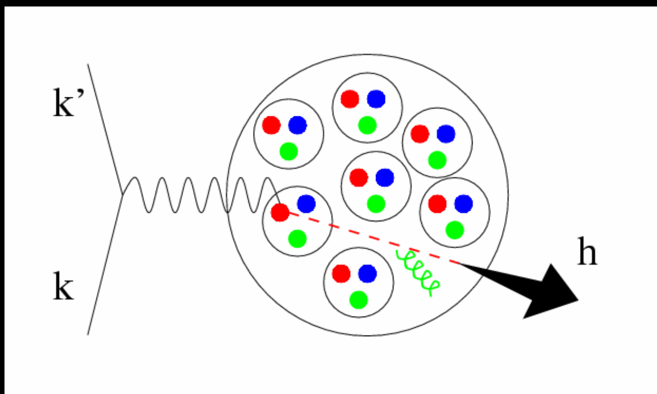
$$t^{\pi}_{f} = c_{\pi}(1-z)\nu$$

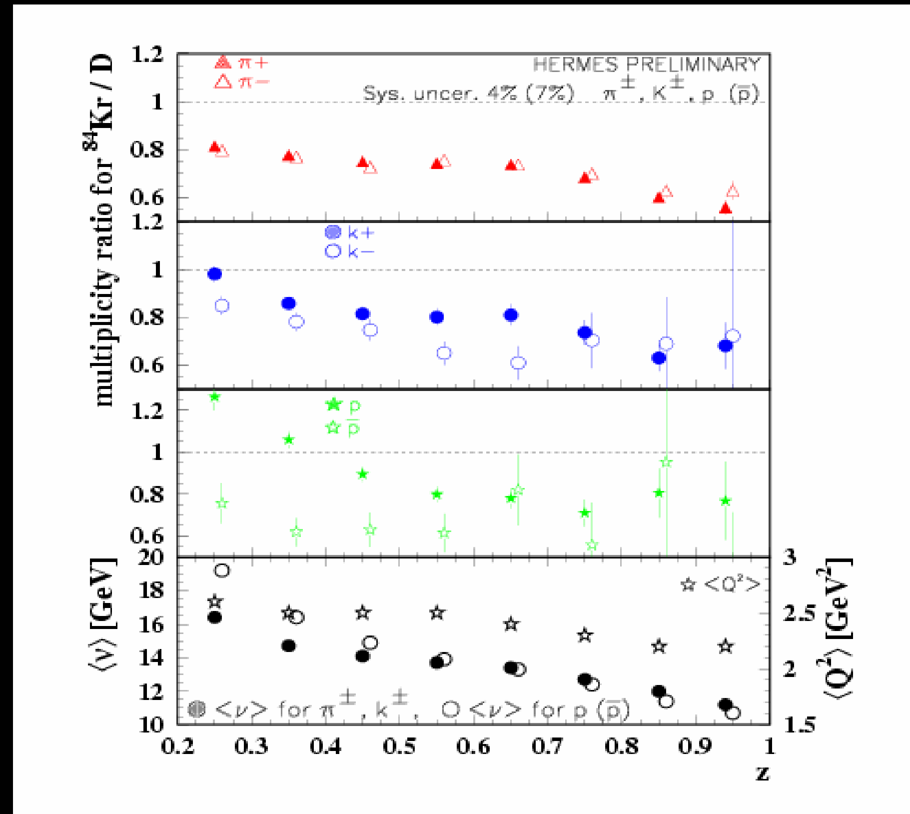
A hadron with large z originates from a quark emitting only a few gluons. The emission of only a few gluons corresponds to a small formation time. Opposite to other models!

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

Hadronic Species Dependence?



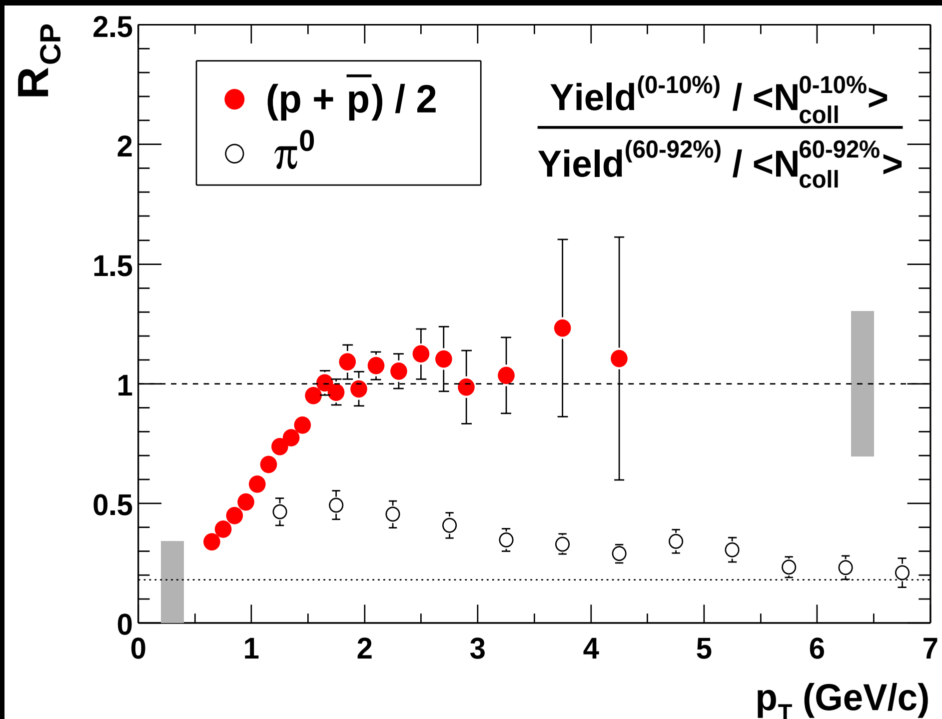


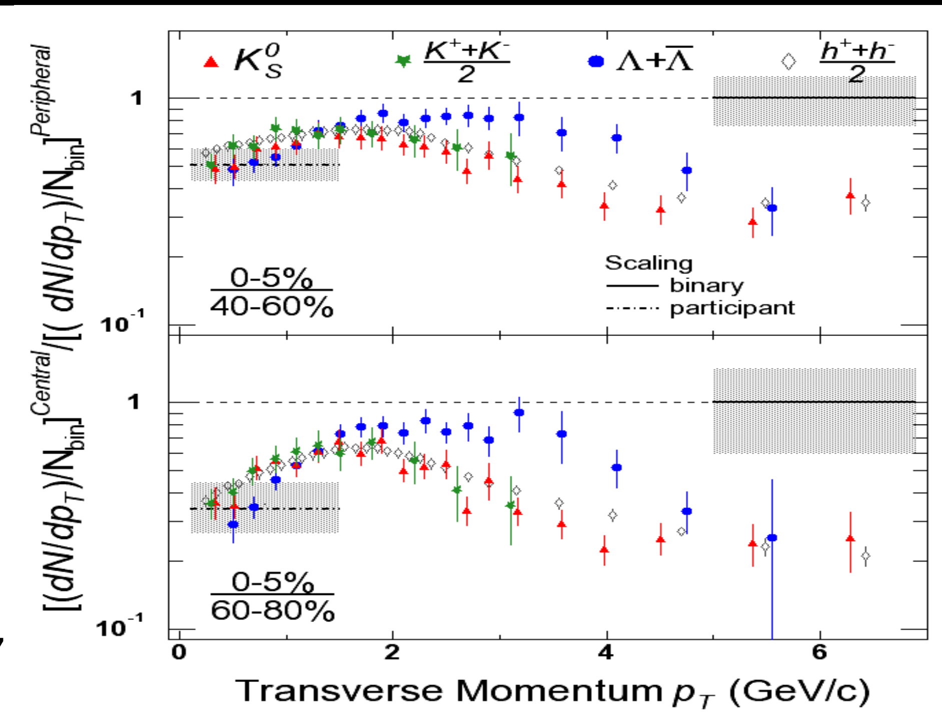
If parton loses energy, but has final fragmentation outside medium, hadron ratios should be unchanged for high z.
This is not what HERMES observes!

Knockout (anti)quark could annihilate with another quark(anti) and be coverted to a gluon. Since nucleus has quarks, antiquark could show more modification (i.e. kaon, pbar difference). X.N. Wang

Jet Fragmentation?

Does not look like hadron ratio in jet fragmentation either.

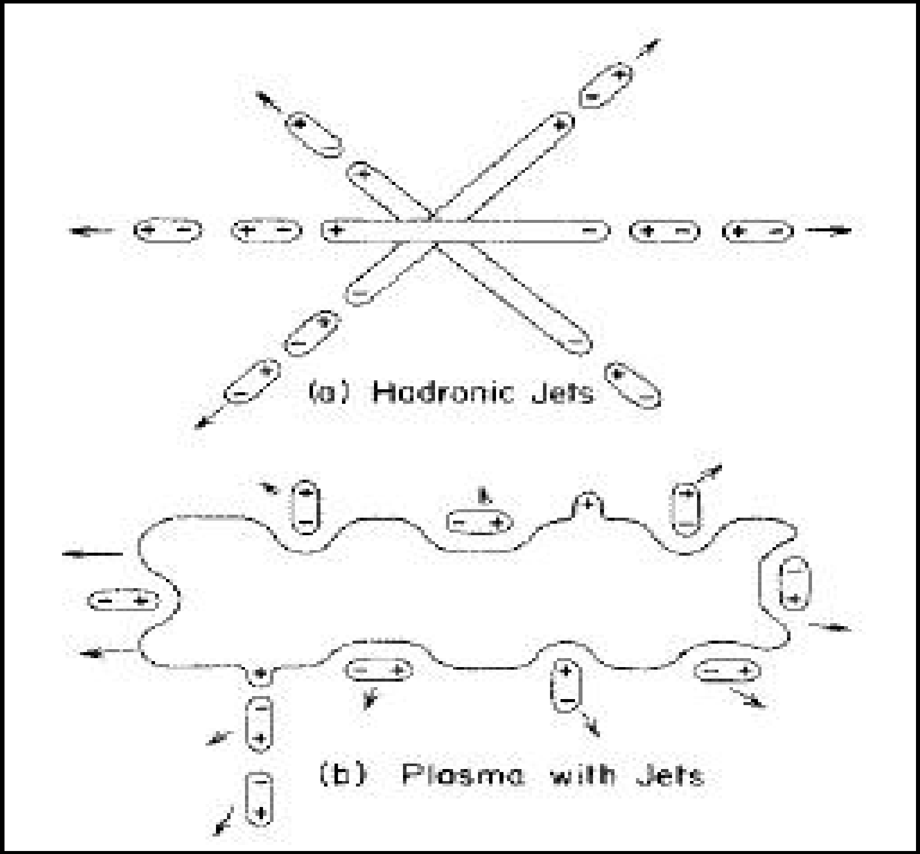


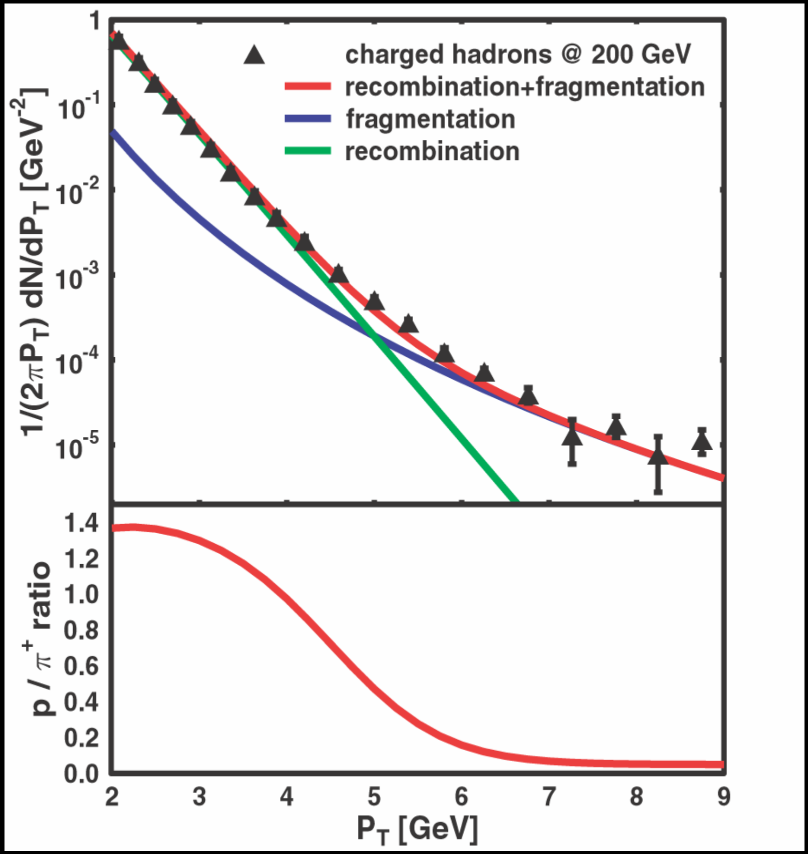


Behaviour of pions and baryons is not the same.

Also, are the pions and kaons following the same trend?

Quark Recombination



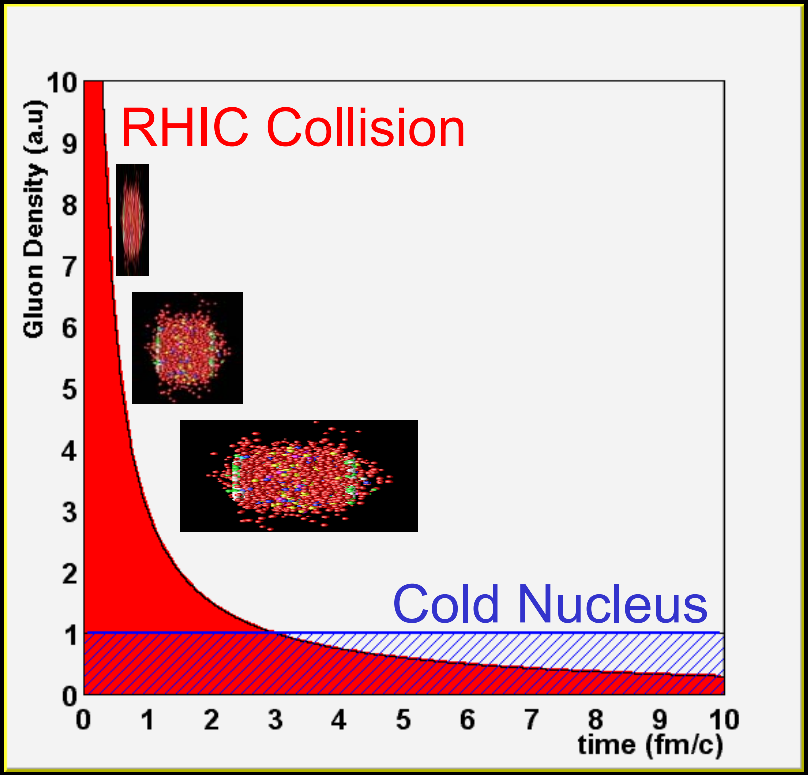


Very appealing qualitatively, but process of recombination ignoring gluons is not complete. Experimental checks with ϕ and charm might help.

Energy Loss That Never Occurs !

Wang *et al.* have compared the implied energy loss in RHIC collisions from our π^0 data and the HERMES results.

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

$$\langle dE/dx \rangle \sim 7 \text{ GeV/fm}$$

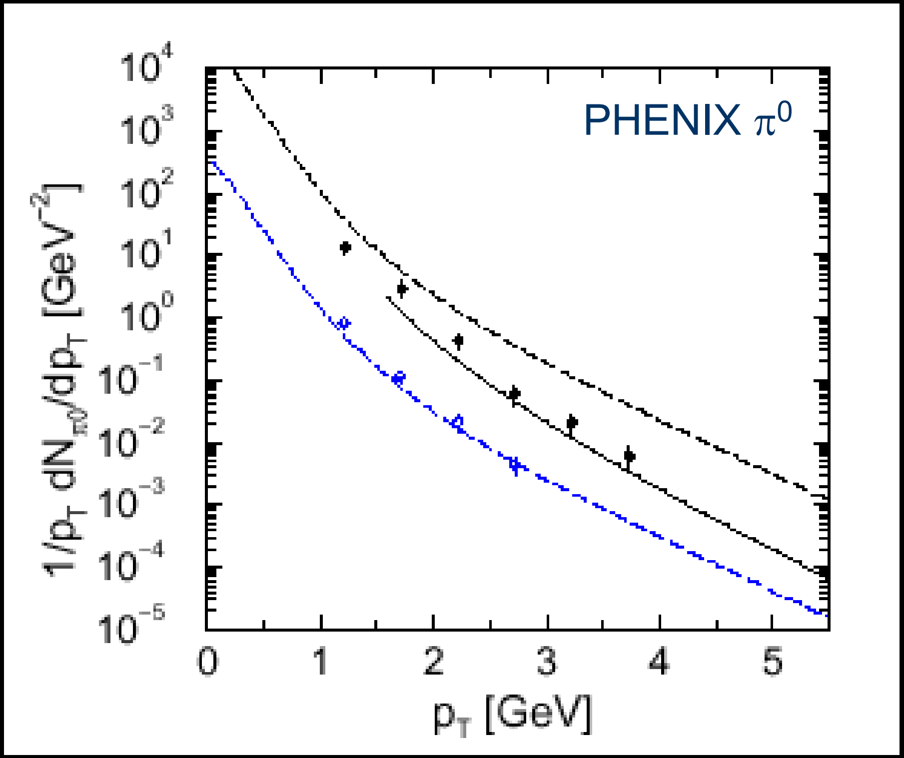
Over an order of magnitude higher than in cold nuclear matter !

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

Back to Formation Time

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

Then the fragmented hadrons can interact with the hadron gas medium, rescatter, 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

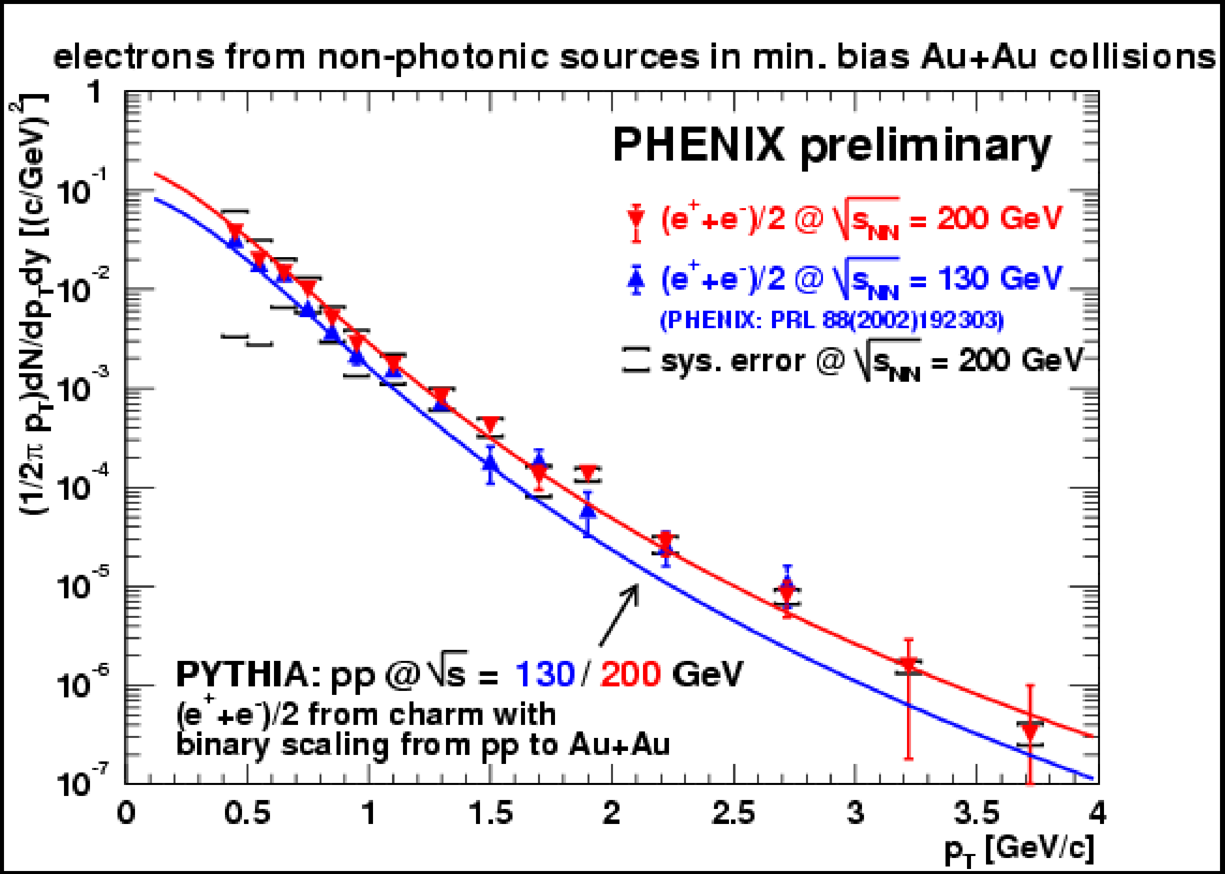
$$\tau_f \sim 1.2\ (E/\mathrm{GeV}) * \mathrm{fm}/c$$

This model should see the suppression go away at high p_T.

Gallmeister et al., nucl-th/0202051

Heavy Flavor Physics

PHENIX has measured charm and beauty contribution via single electrons.
Everyone says it appears to scale with binary collisions.

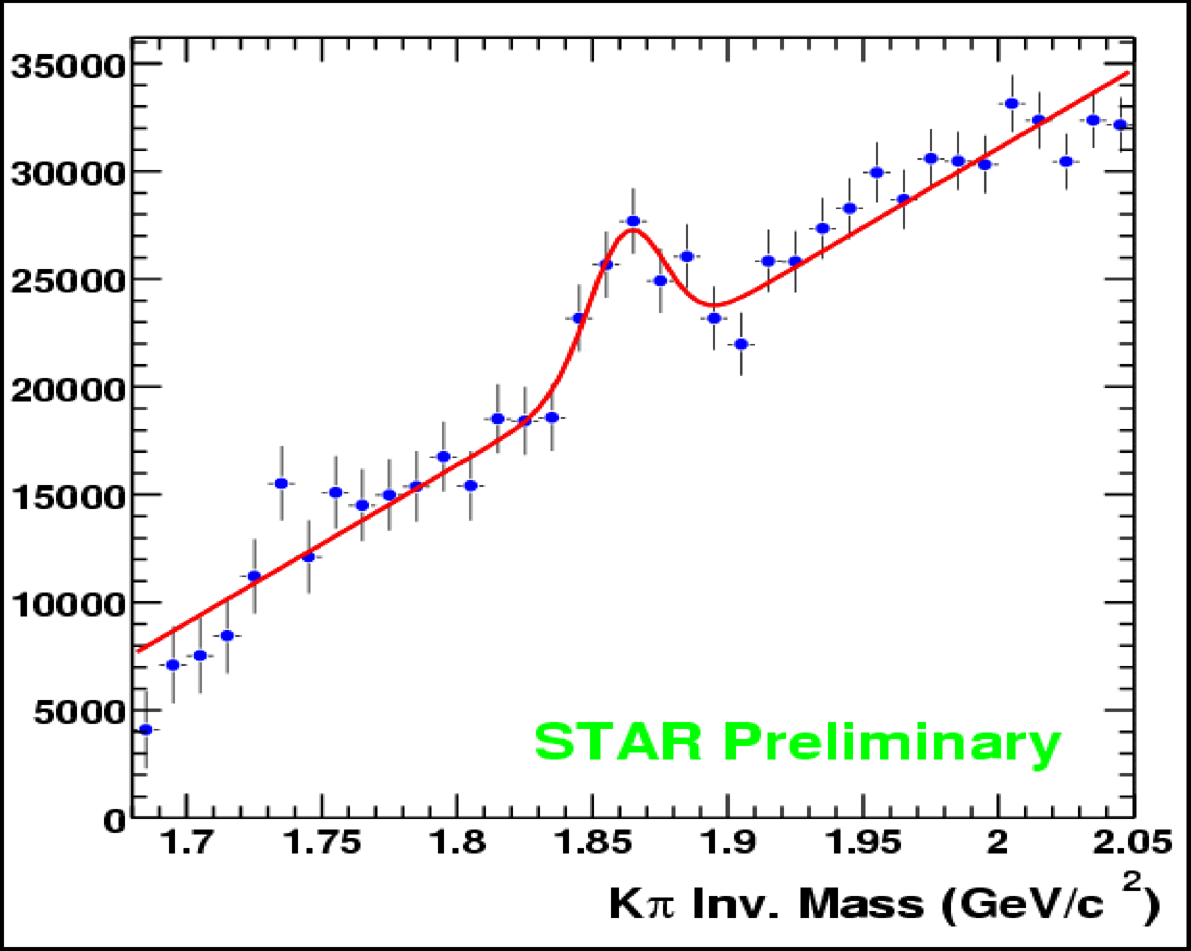


Look for proton-proton measurement for baseline – not PYTHIA.

Does total charm production scale and/or does high p_T charm/beauty scale with binary collisions?

Direct Reconstruciton!

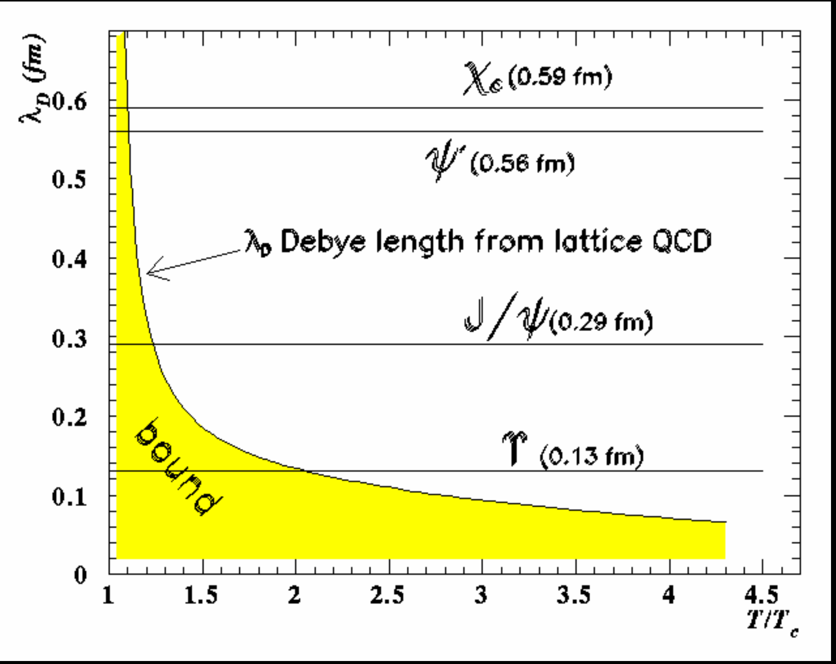
Look for many exciting new results with direct D meson reconstruction from STAR at this conference.



Heavy Quarkonia and Deconfinement

Different states "melt" at different temperatures due to different binding energies.

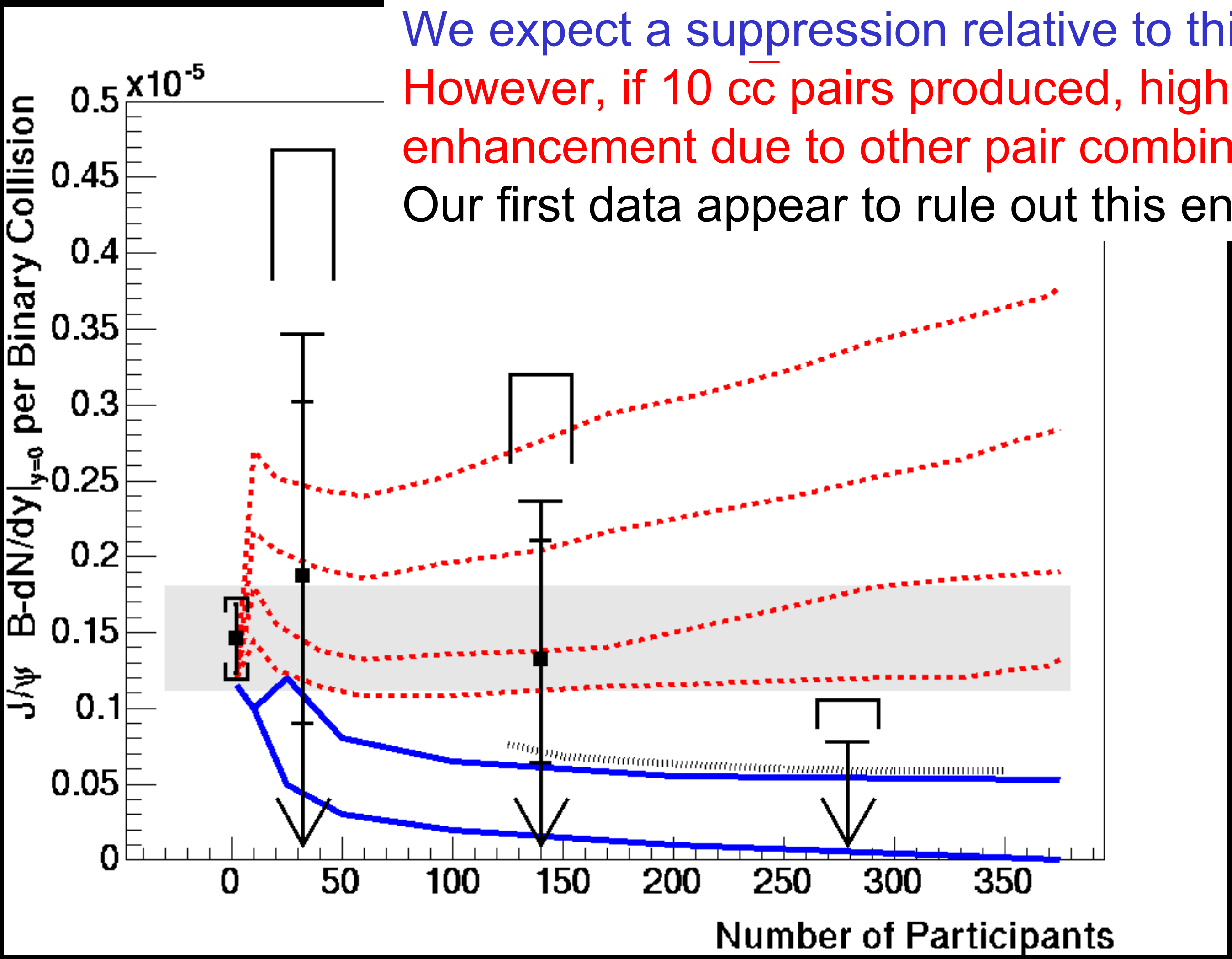
The ψ' and χ_c melt below or at T_c the J/ψ melts above T_c and eventually the Υ(1s) melts.



state	J/ψ	χ_c	ψ'	Υ(1s)	χ_b	Υ(2s)	χ_b'	Υ(3s)
Mass [GeV}	3.096	3.415	3.686	9.46	9.859	10.023	10.232	10.355
B.E. [GeV]	0.64	0.2	0.05	1.1	0.67	0.54	0.31	0.2
T_d/T_c	---	0.74	0.15	---	---	0.93	0.83	0.74

Look for d-Au J/ψ Results at this Conference

First Au-Au results now published.
Each charm-anticharm pair has ~ 1% chance to form J/ψ.
We expect a suppression relative to this rate.
However, if 10 $c\bar{c}$ pairs produced, high mobility could allow enhancement due to other pair combinations.
Our first data appear to rule out this enhancement!



R.L. Thews, M. Schroedter, J. Rafelski Phys. Rev. C63 054905 (2001): Plasma coalesence model for T=400MeV and y_{charm}=1.0,2.0, 3.0 and 4.0.
L. Grandchamp, R. Rapp Nucl. Phys. A&09, 415 (2002) and Phys. Lett. B 523, 50 (2001): Nuclear Absorption+ absoption in a high temperature quark gluon plasma

Conclusions

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 young people in the field to have this hope realized.

Some Pre-Conference Advice

Advice to Experimentalists:

Never let a theorist tell you something is too complicated to explain.

Advice to Theorists:

Never let an experimentalist tell you something is too complicated to explain.

Most all things are really simple once we understand.

How do we make progress?

There is too much repeating of the mantra in this field without additional thinking.

It does not mean the mantra is always false. In this case (QGP), it may well be true. However only by being skeptical and pointing out disagreements can one make scientific progress.

Repeat after me.....

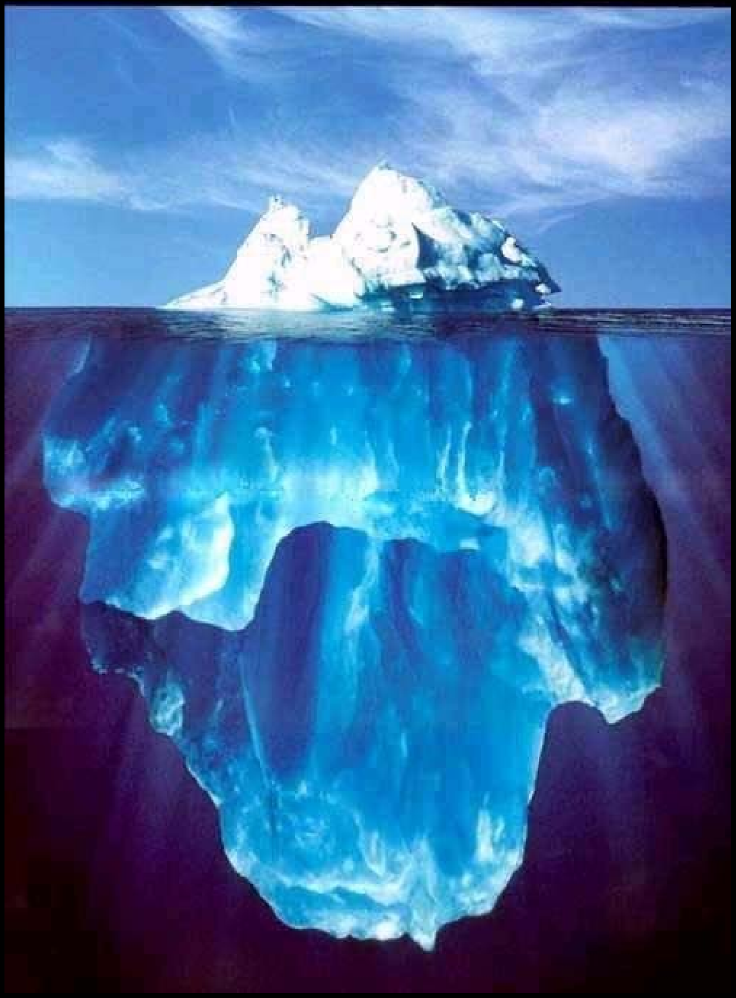
Iraq has weapons of mass destruction.

Iraq has weapons of mass destruction.

Iraq has weapons of mass destruction.

Iraq has weapons of mass destruction.

Potential of the Field



New ideas will come from new minds. Sit in the front row, ask questions, be excited about the discoveries to be made and skeptical at the same time.