The Physics of Relativistic Heavy Ion Collisions

18th National Nuclear Physics Summer School

July 23 - August 5, 2006

Indiana University, Bloomington, IN

Lecture #4

18th National Nuclear Physics Summer School
Lectures July 31-August 3, 2006

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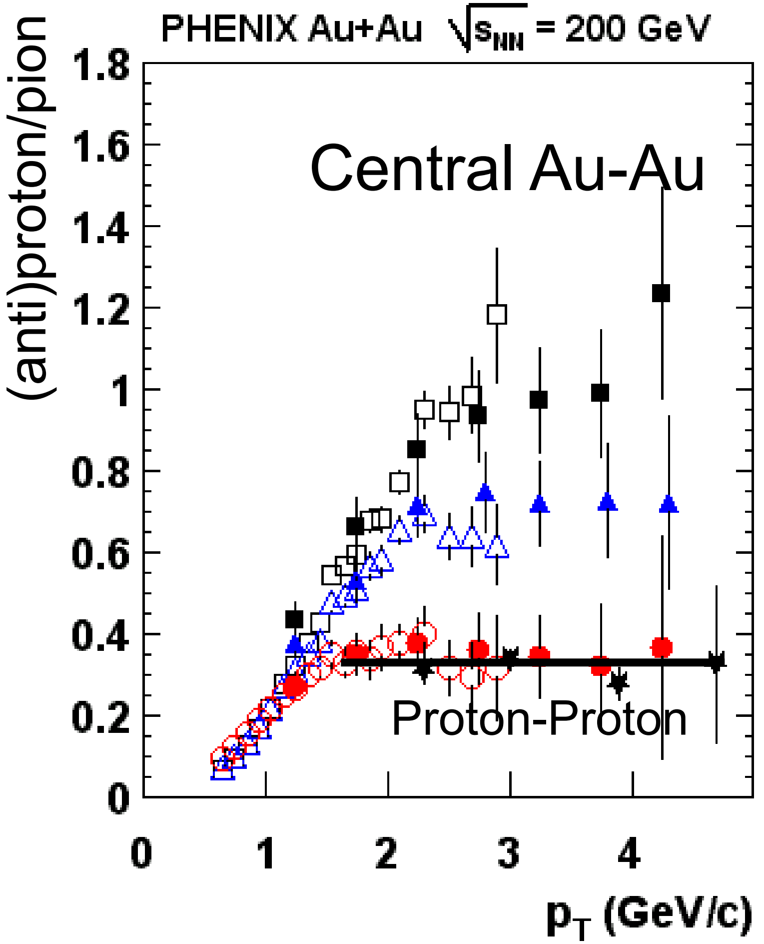
University of Colorado, Boulder

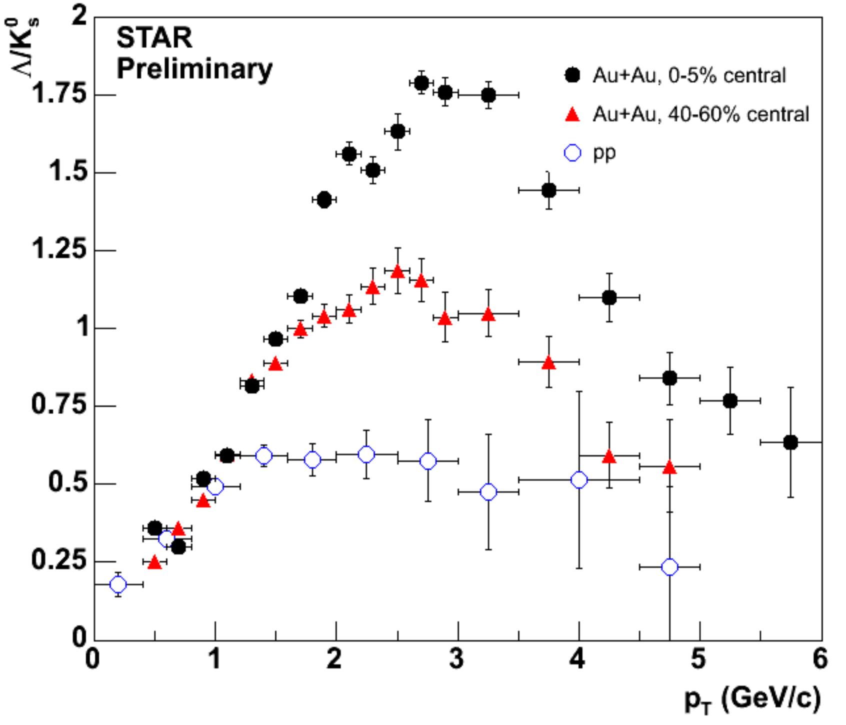
Hadron Formation
Recombination

Baryon Anomaly

In proton proton and e^+e^- reactions at moderate pT, baryons and antibaryons are suppressed relative to mesons.

In heavy ion reactions, there is anomalous baryon production.

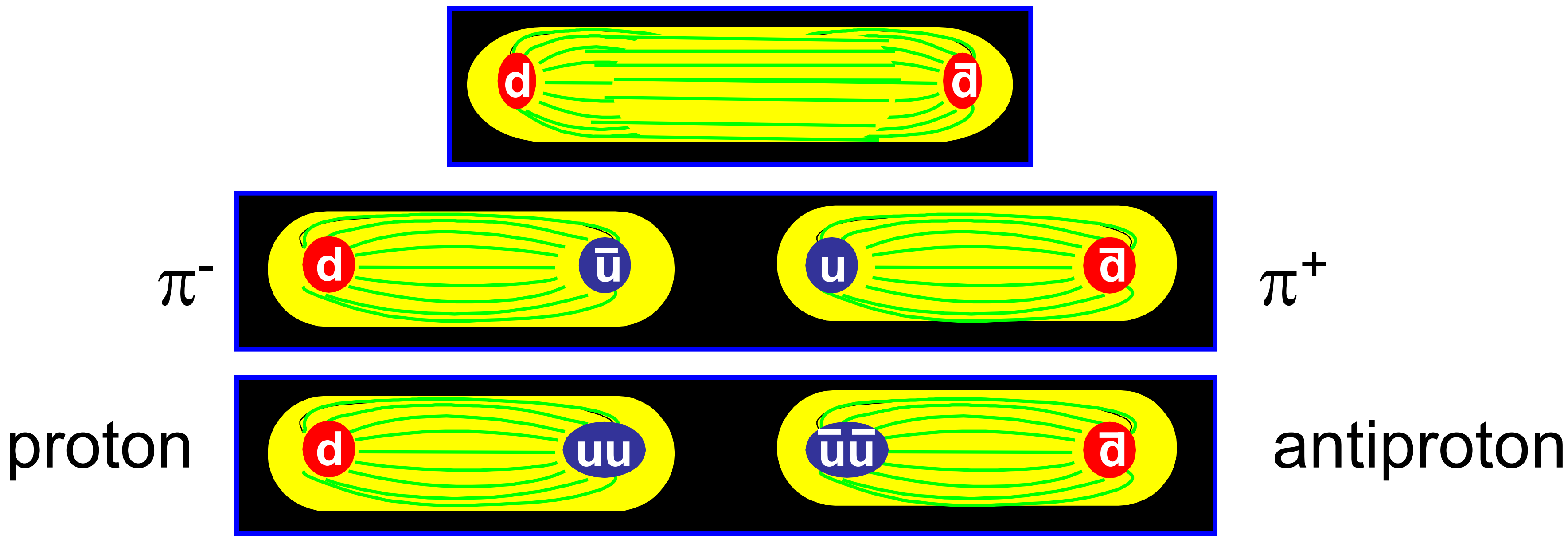




Baryons via Jet Fragmentation

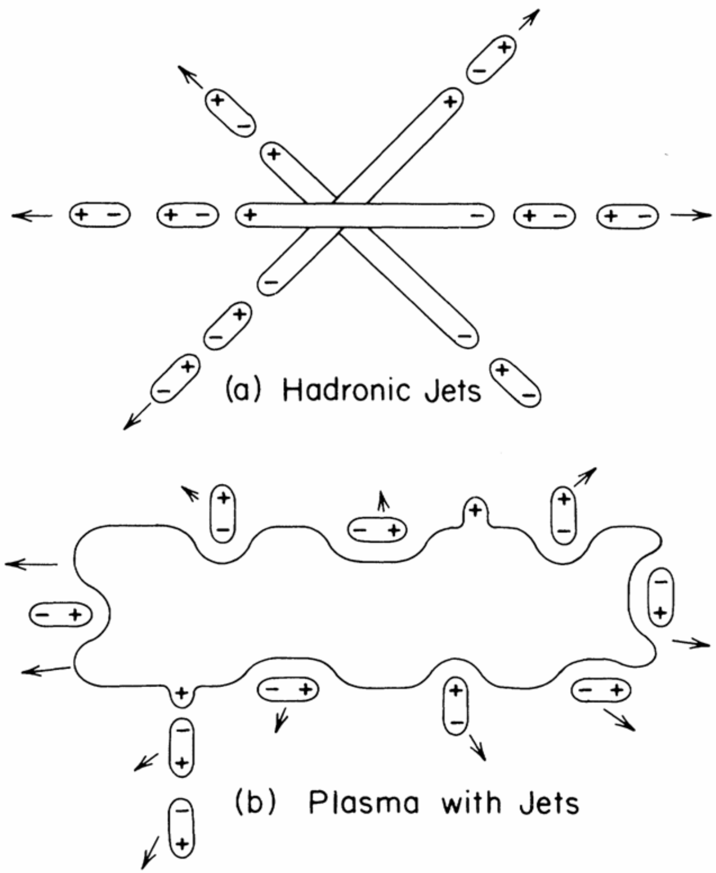
Jet fragmentation occurs when particle pairs tunnel out of the vacuum from the flux tube potential energy. Analogous to Schwinger mechanism in QED.

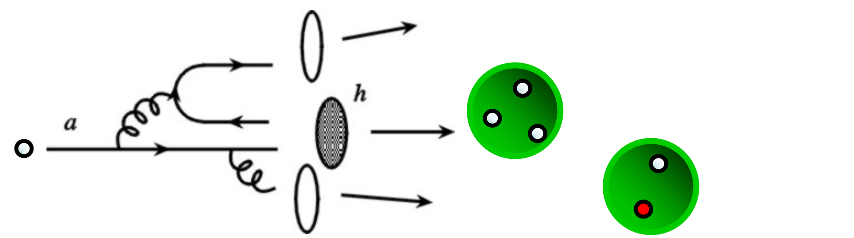
Production of $q\bar{q}$ leading to pions is much more likely than $qq\,\overline{qq}$ (diquark antidiquark) leading to protons and antiprotons.

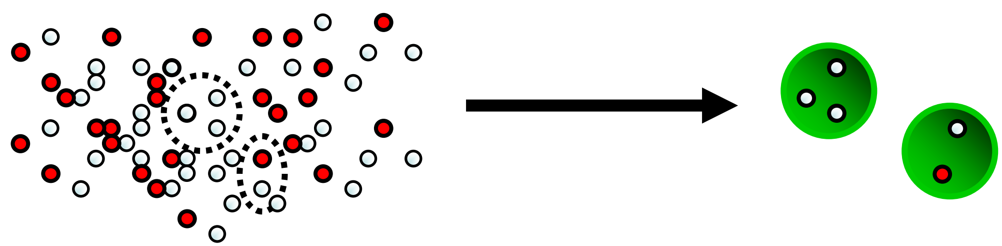


Color Recombination

Factorization assumption of jet fragmentation completely breaks down. New hadronization mechanism.

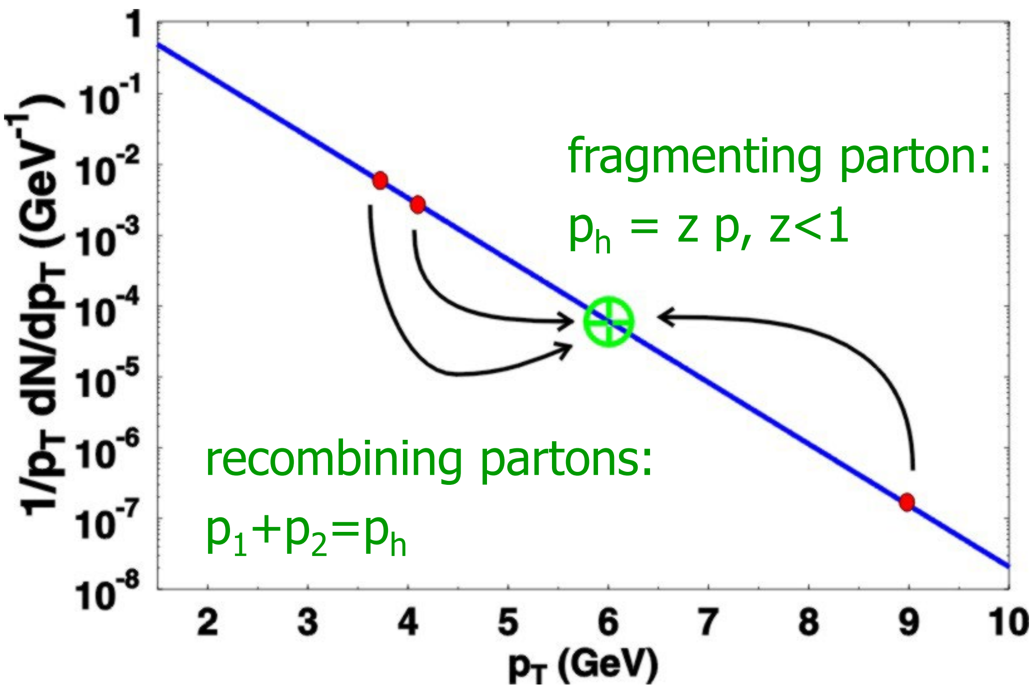


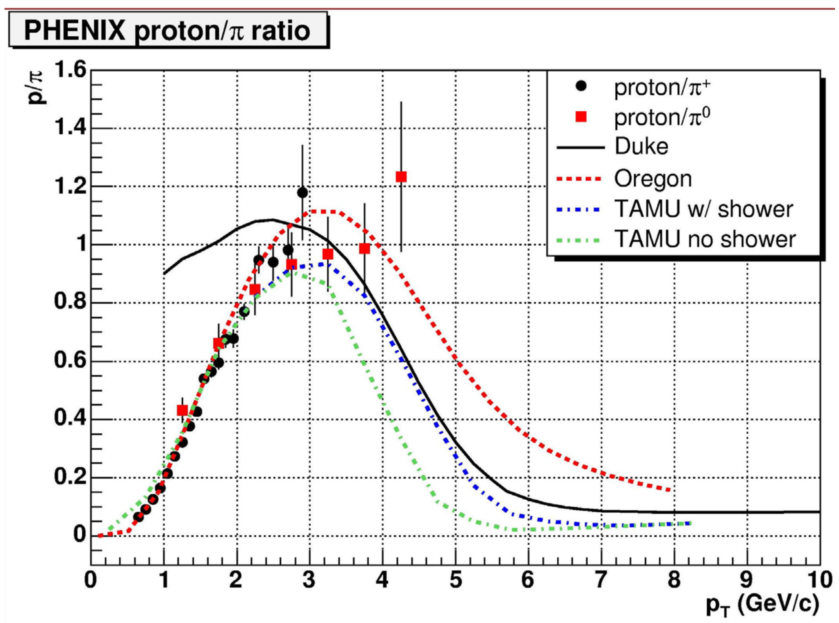




From Above or Below?

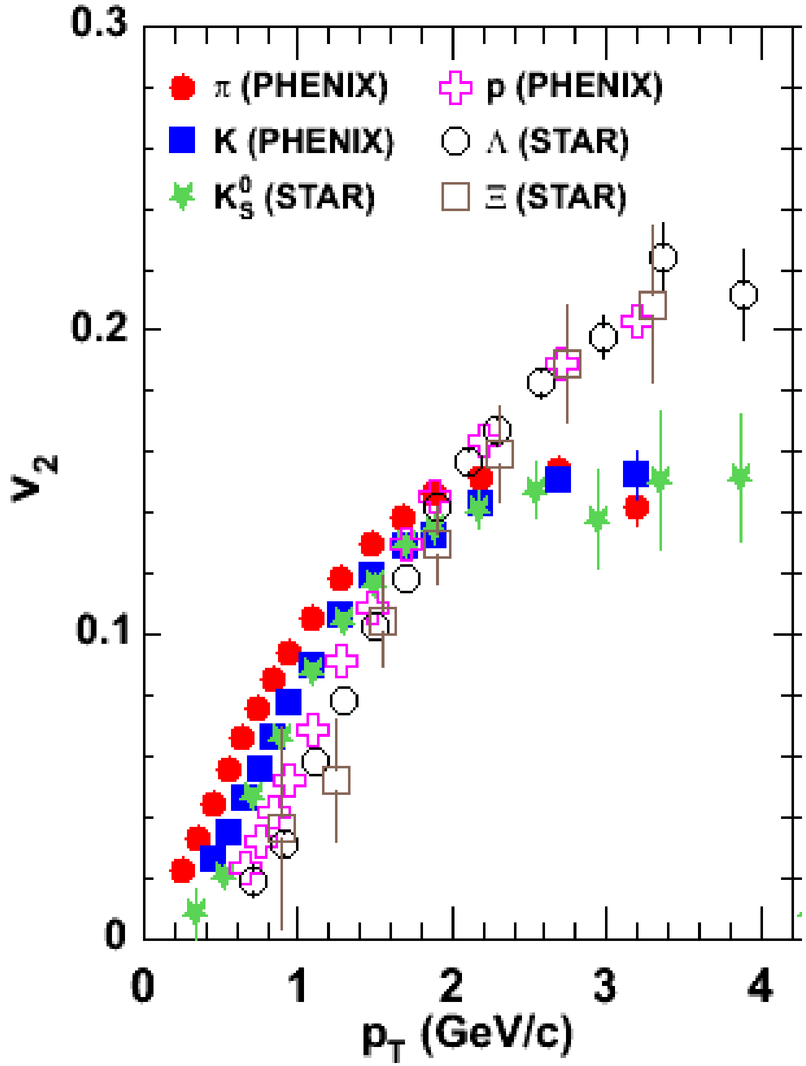
Lower pT partons combine to form higher pT hadrons, instead of higher pT partons fragmenting into lower pT hadrons.





Baryon Issue in Elliptic Flow

v_2 results at low pT agreed reasonably with hydrodynamic calculations, but at higher pT there is a split of mesons and baryons.

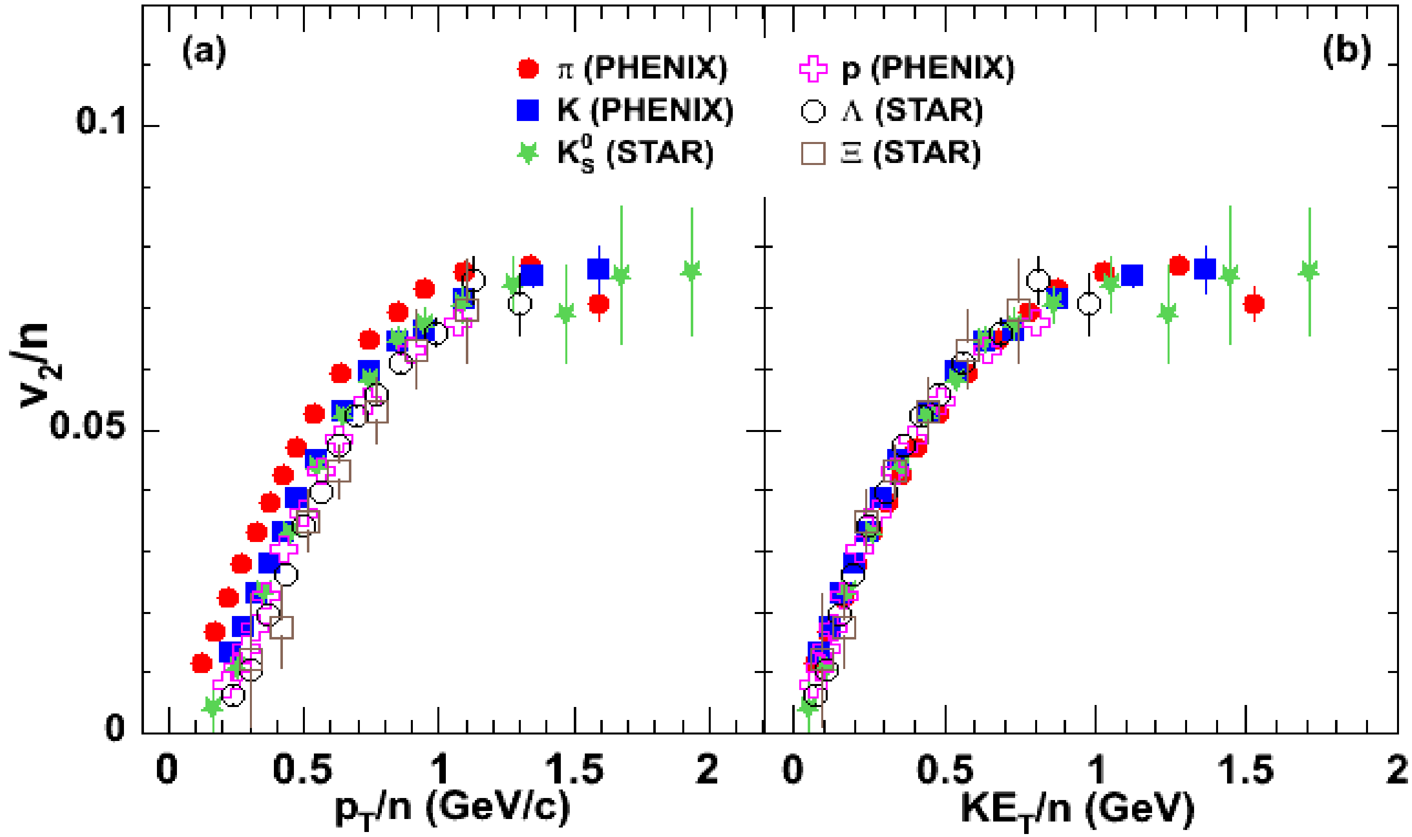


Baryons

Mesons

Rescaling by Valence Quarks

If one rescales the data by the number of valence quarks (2 for mesons and 3 for baryons), one sees a remarkable scaling! Is this another indication for recombination?

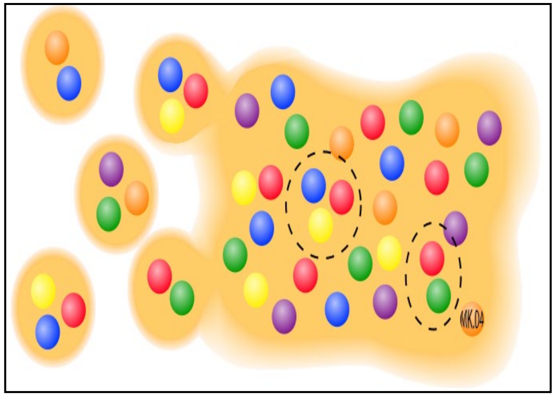


Contrast Deuteron Coalescence

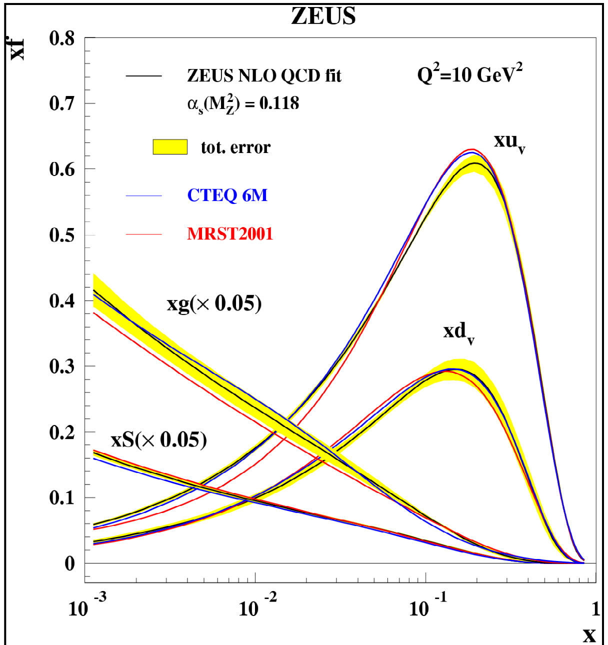
In BBN, deuteron coalescence process is well know n+p→d+γ. In heavy ion reactions, we can have off-shell n+p→d and we know the deuteron wavefunction.

What is the required space and momentum distribution of partons to form a hadron?

Very Simple Picture



Not so Simple Picture



Conclusions and Terminology

Perhaps at moderate pT hadrons are formed from localized distribution of uncorrelated partons.

Some call it coalescence of constituent quarks?
What is a constituent quark outside a hadron? Mass?

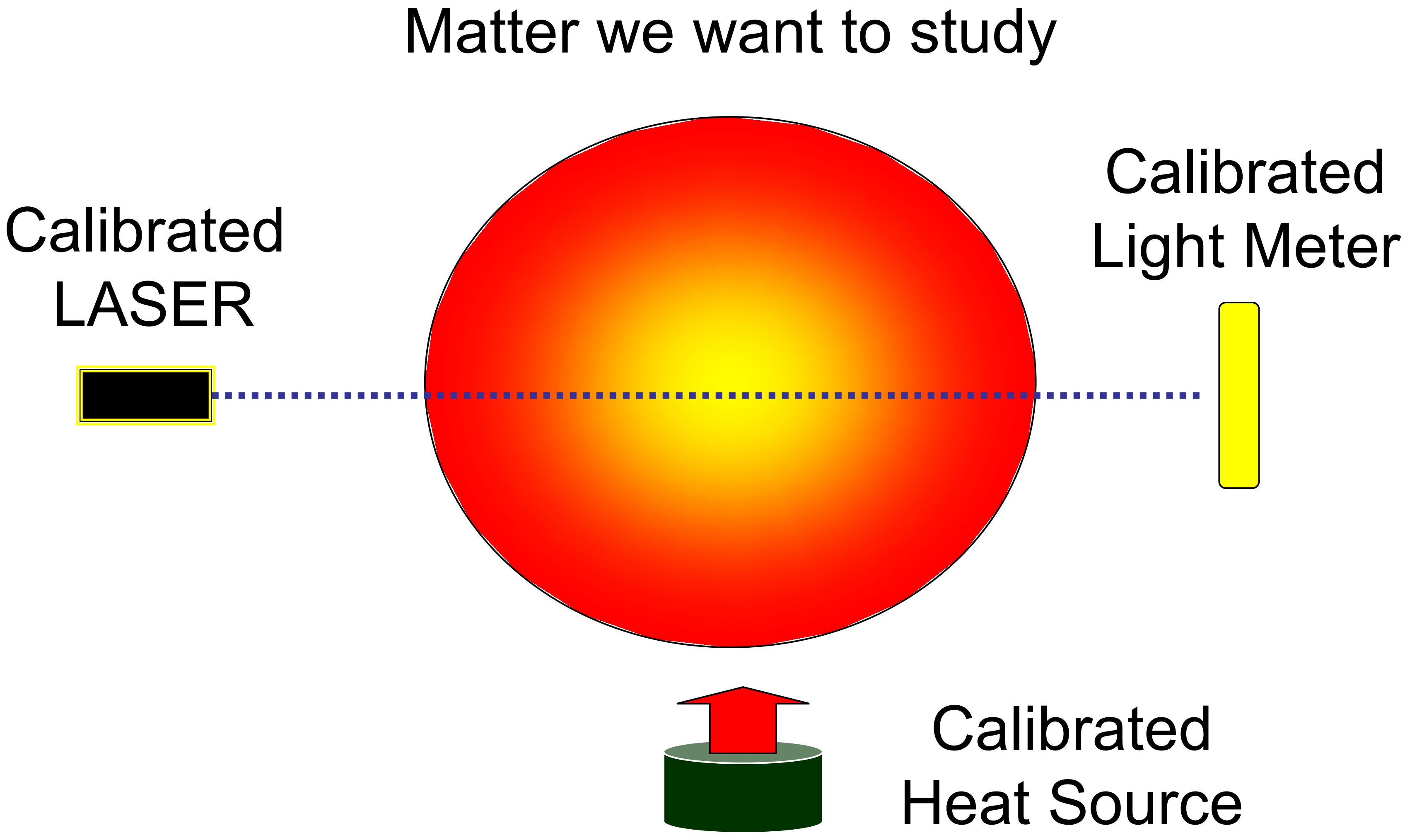
Some call it coalescence of valence quarks?
What is a valence versus a sea quark outside a hadron?

What is true is that you need a certain minimum number of objects (partons?) to have the right quantum numbers in some region of real and momentum space to form the hadron.

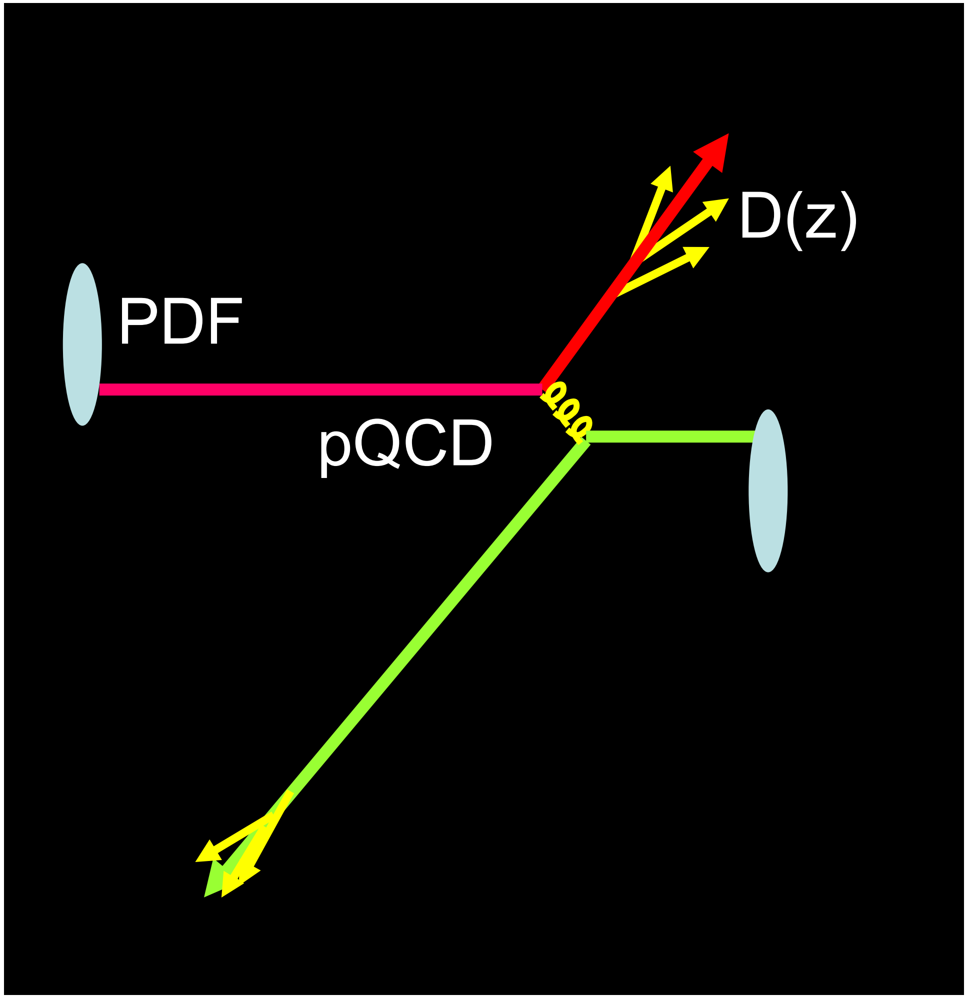
We still need to understand the full implications.

Jet Quenching

Probing the Matter



Autogenerated Quark "LASER"



$$\frac{d\sigma_{pp}^{h}}{dyd^{2}p_{T}} = K\sum_{abcd}\int dx_{a}dx_{b}f_{a}(x_{a},Q^{2})f_{b}(x_{b},Q^{2})\frac{d\sigma}{d\hat{t}}(ab\rightarrow cd)\frac{D_{h/c}^{0}}{\pi z_{c}}$$

Fermi National Accelerator Laboratory

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

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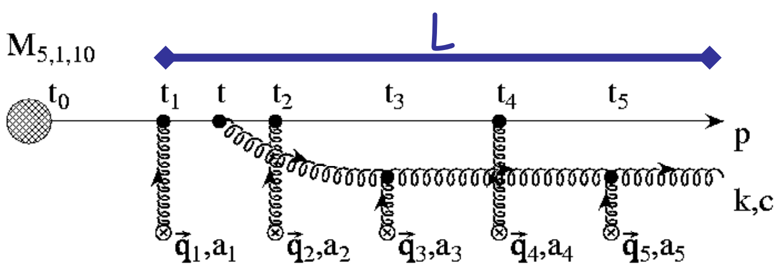
Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

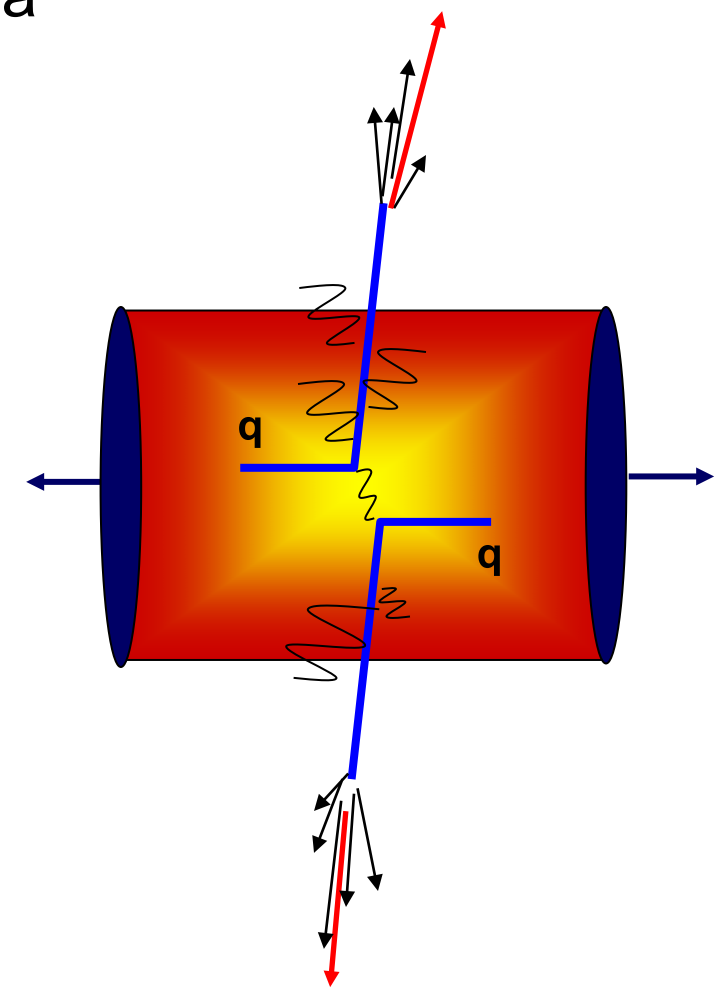
Gluon Radiation

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

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

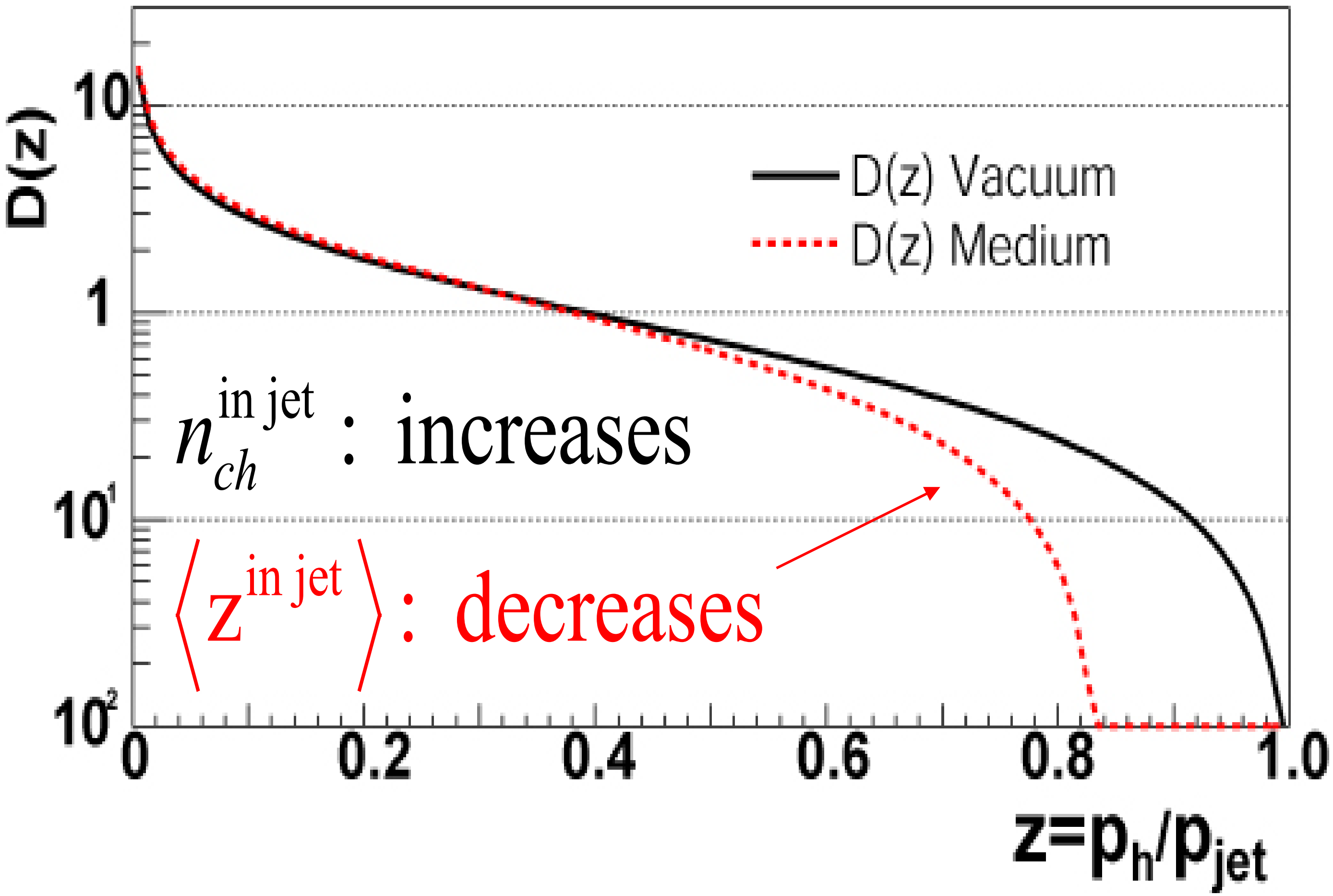


Look for an effective modification in the jet fragmentation properties.

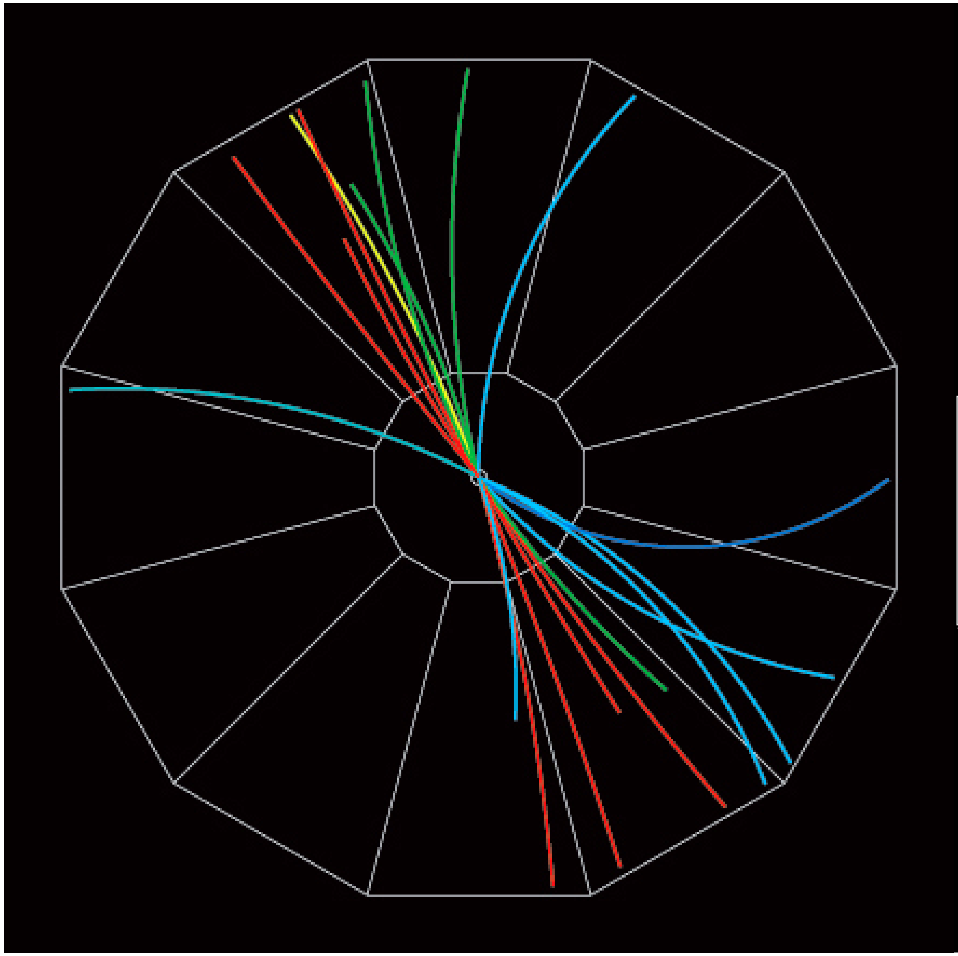


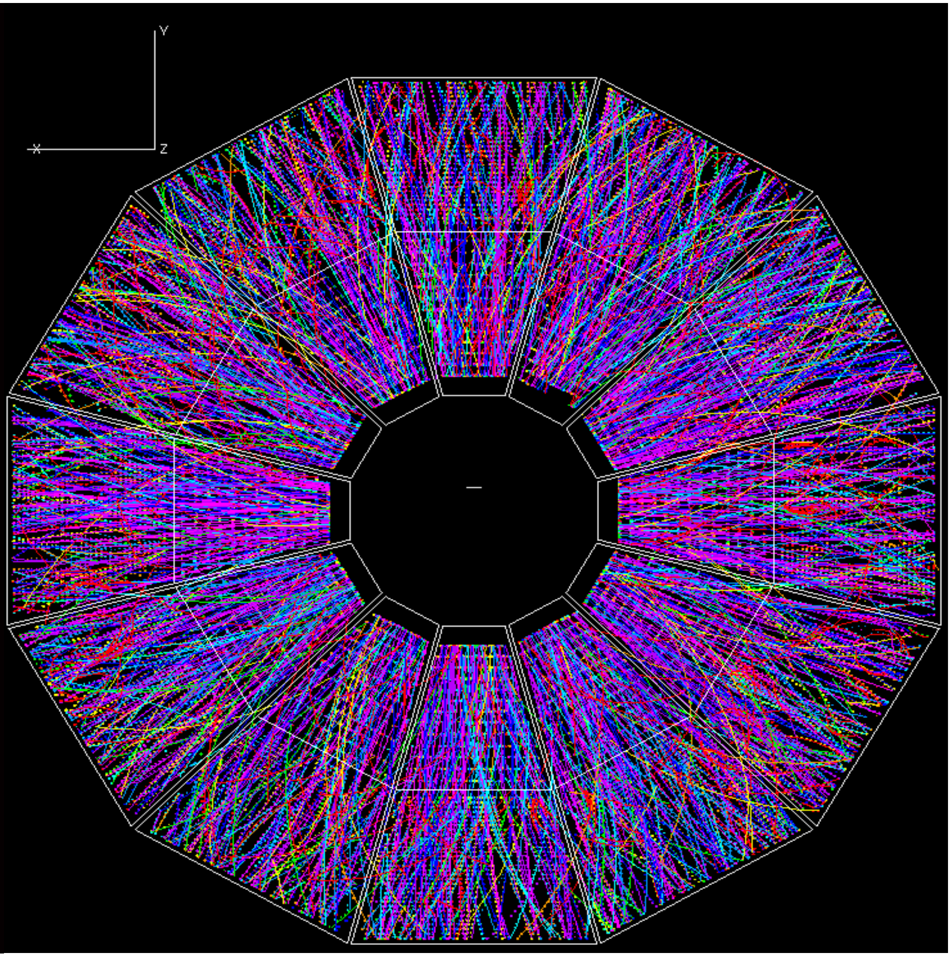
Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267
Gyulassy, Levai, Vitev, hep-pl/9907461
Wang, nucl-th/9812021
and many more…..

Modified Fragmentation



STAR Event Displays

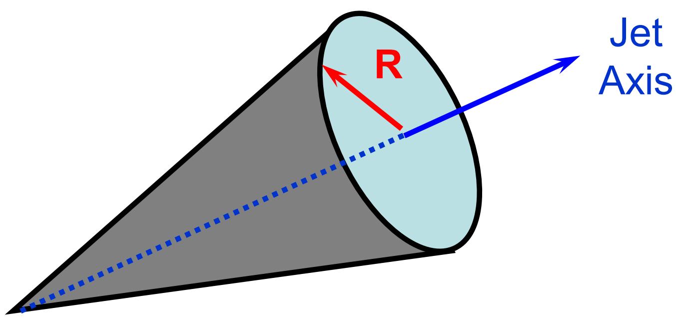


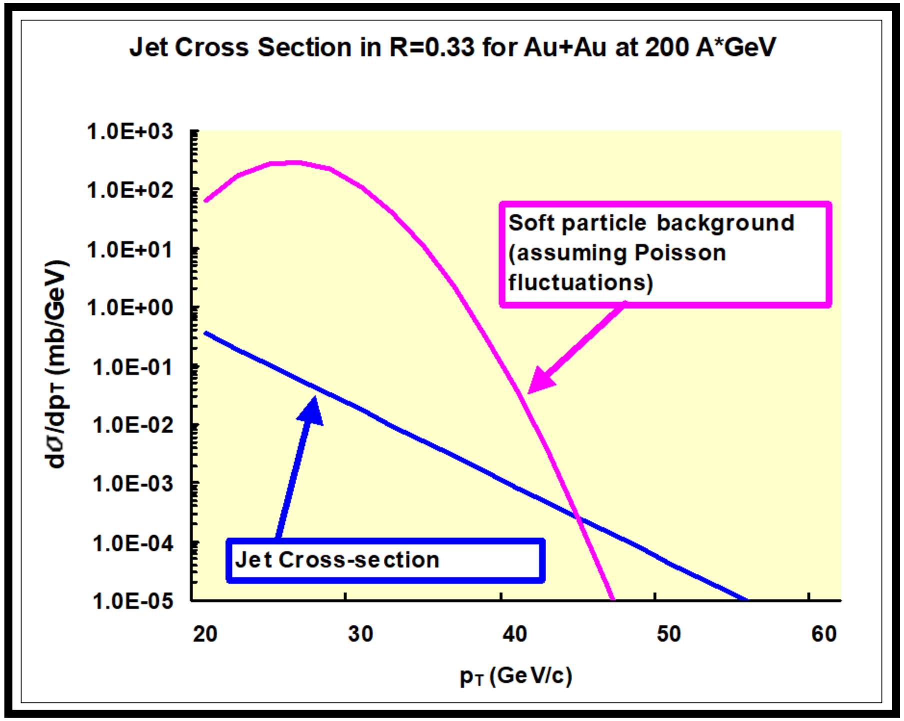


Energy and Fragmentation

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

For a typical jet cone R = 0.33

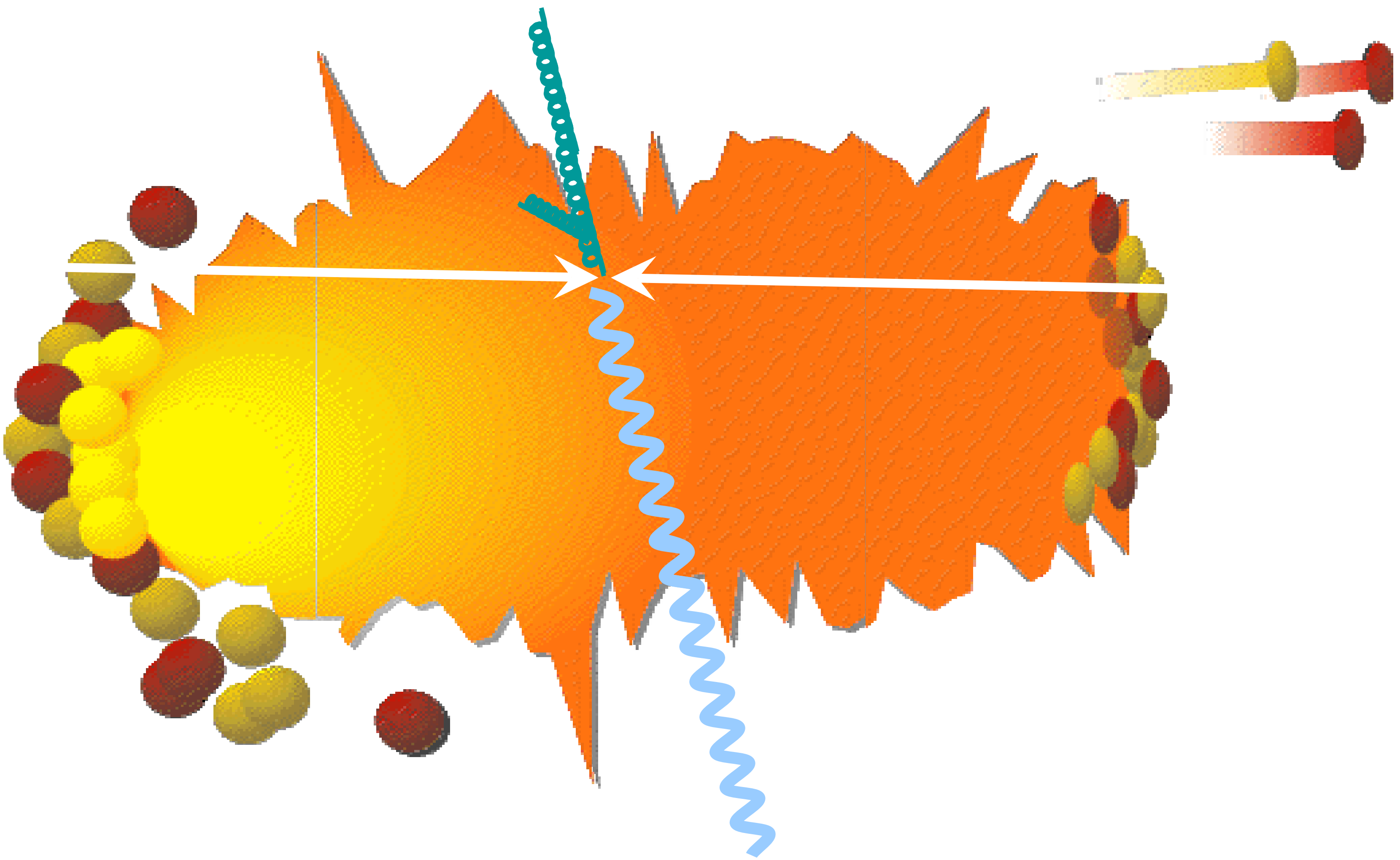




Fluctuations in this soft background swamp any jet signal for pt < ~ 40 GeV

Probes of the Medium

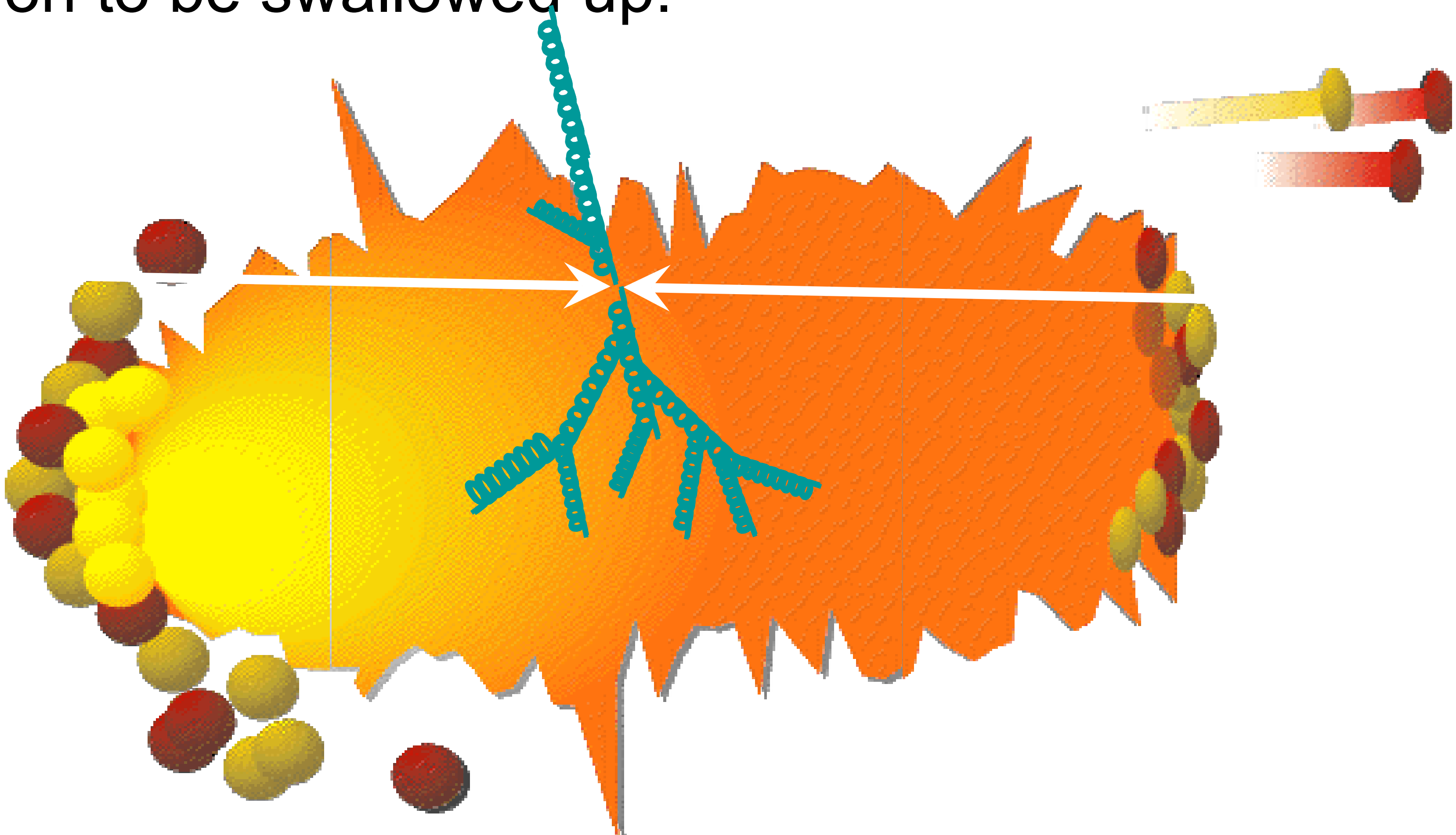
Sometimes a high energy photon is created in the collision. We expect it to pass through the plasma without pause.



Probes of the Medium

Sometimes we produce a high energy quark or gluon.

If the plasma is dense enough we expect the quark or gluon to be swallowed up.

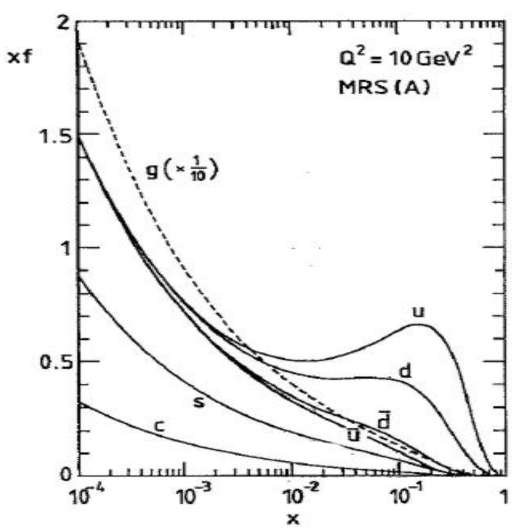


pQCD + Factorization + Universality

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

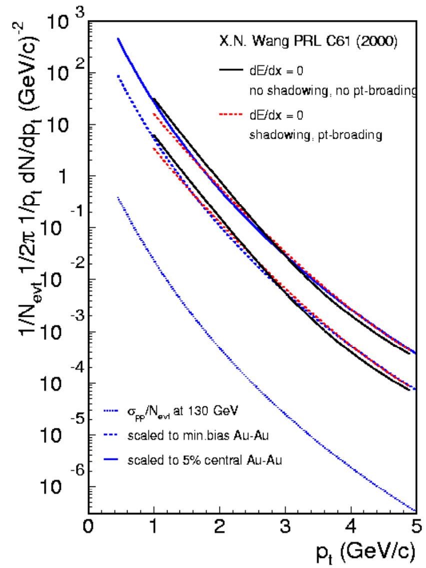
$$E_h \frac{d\sigma_h^{pp}}{d^3p} = K \sum_{abcd} \int dz_c dx_a dx_b \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} f(\mathbf{k}_{Ta}) f(\mathbf{k}_{Tb}) f_{a/p}(x_a, Q_a^2) f_{b/p}(x_b, Q_b^2)\, D_{h/c}(z_c, Q_c^2) \frac{\hat{s}}{\pi z_c^2} \frac{d\sigma^{(ab\to cd)}}{d\hat{t}} \delta(\hat{s}+\hat{u}+\hat{t})$$

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

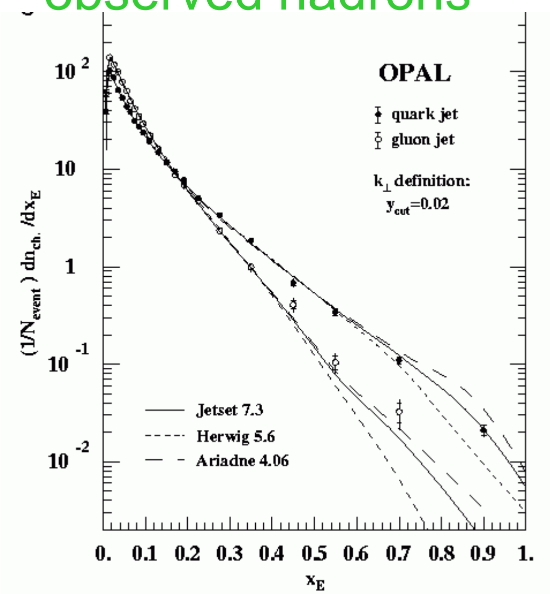


Perturbative QCD

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

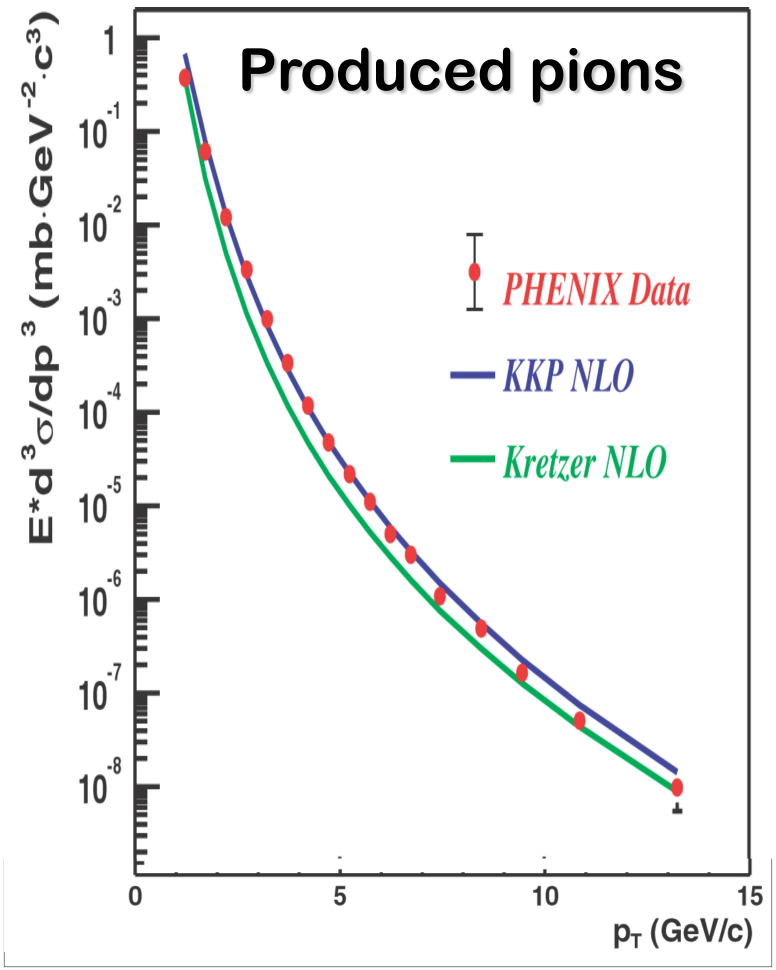


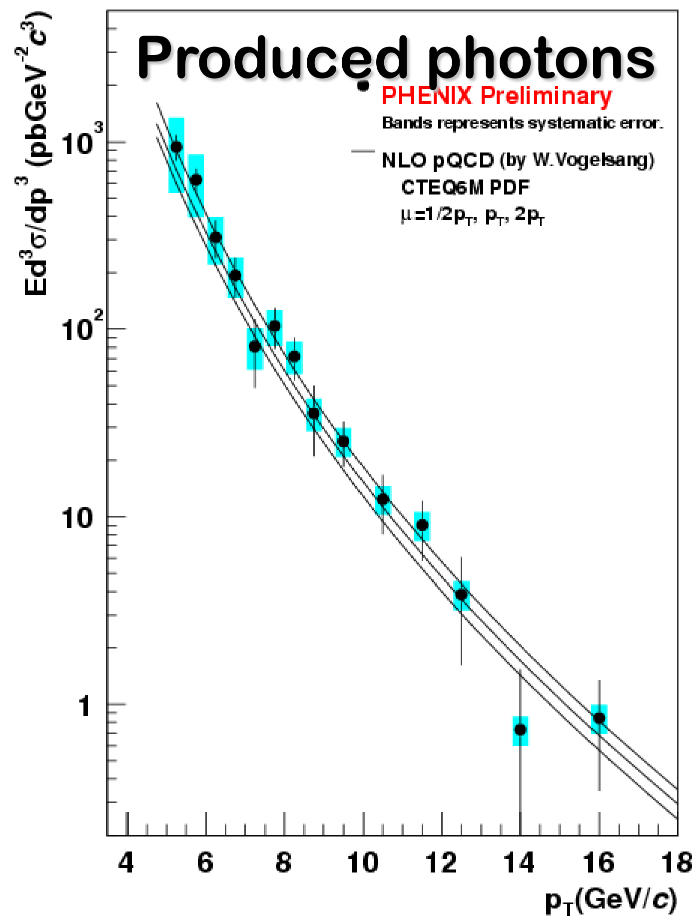
Fragmentation functions D(z) in order to relate jets to observed hadrons



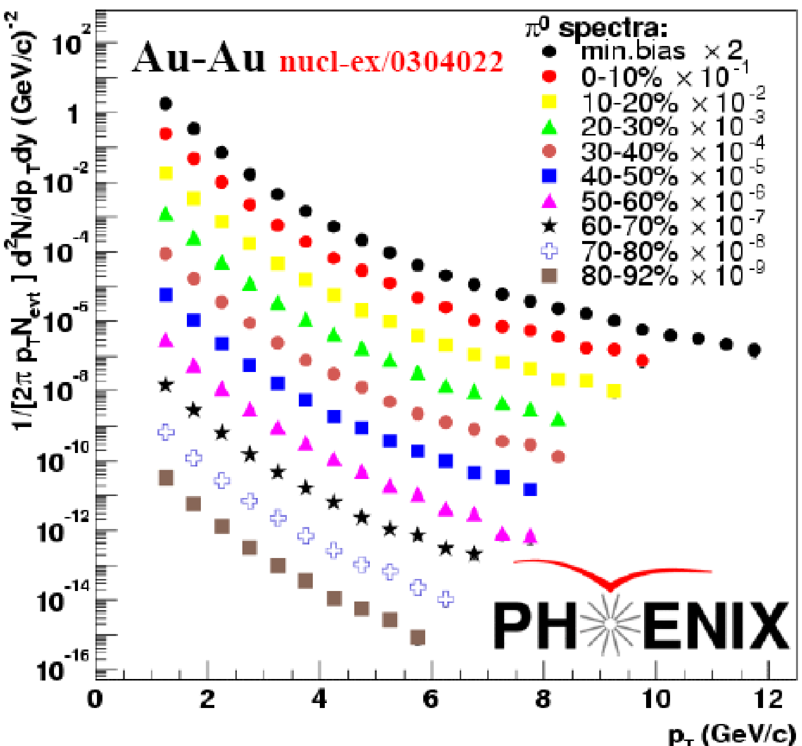
Calibrating Our Probes

High Energy Probes are well described in Proton-Proton reactions by NLO Perturbative QCD.

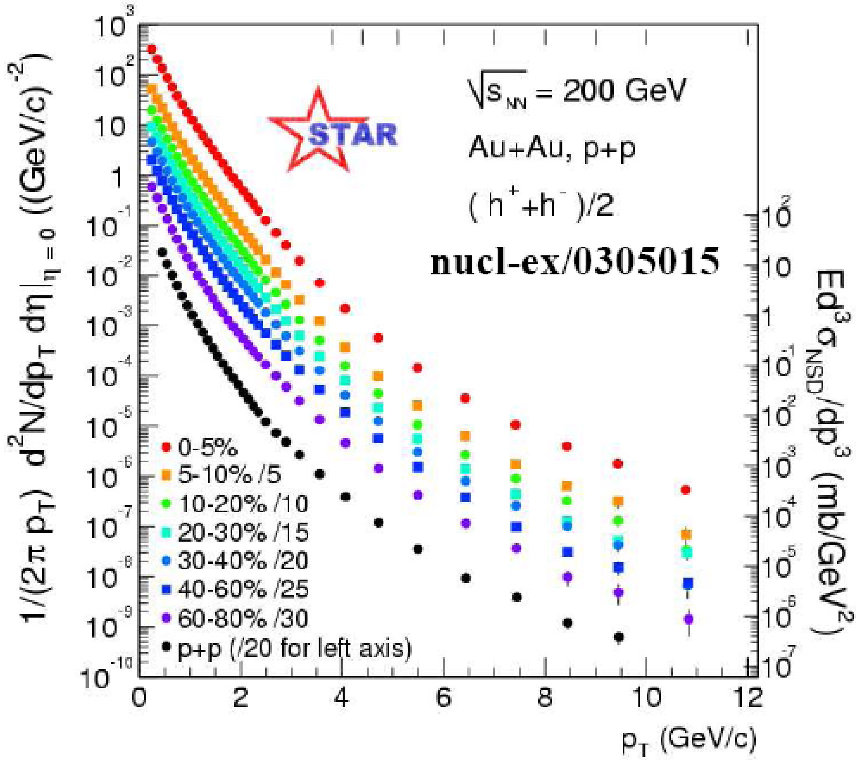




Experimental Measurements



p+p-> π^0 hep-ex/0304038

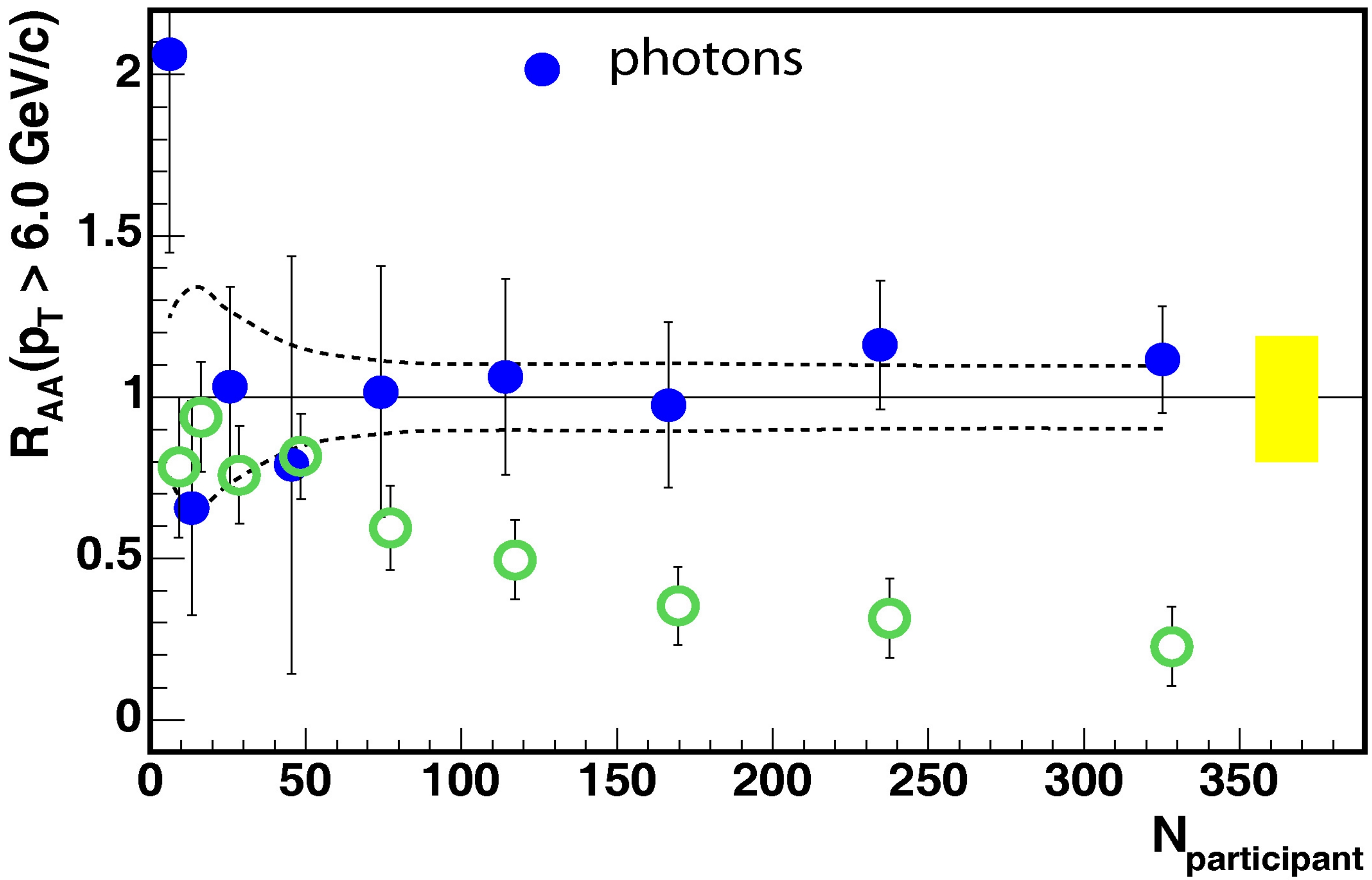


STAR PRL 89, 202301

Experimental Results

Scaling of photons shows excellent calibrated probe. Quarks and gluons disappear into medium, except consistent with surface emission.

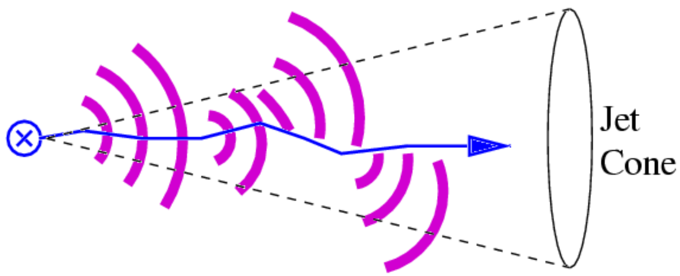
Survival Probability



Size of Medium

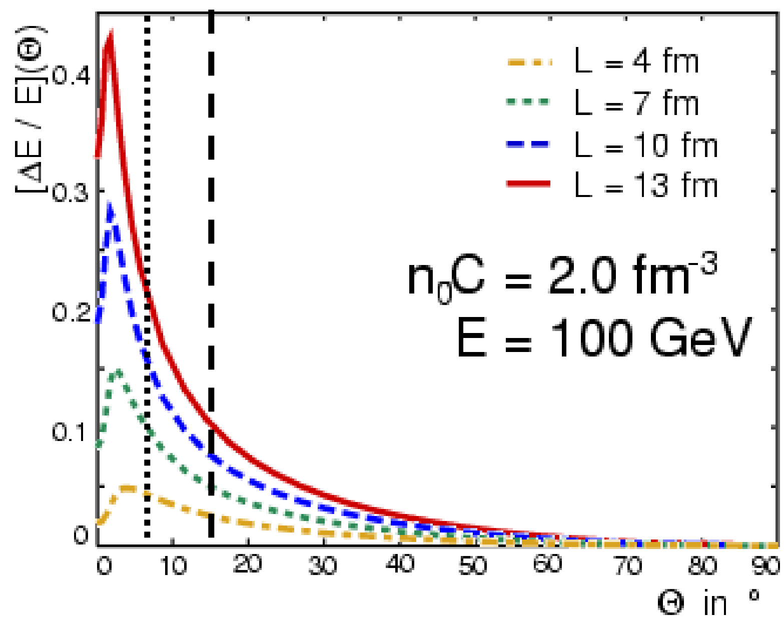
Wider Angular Distribution

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.

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

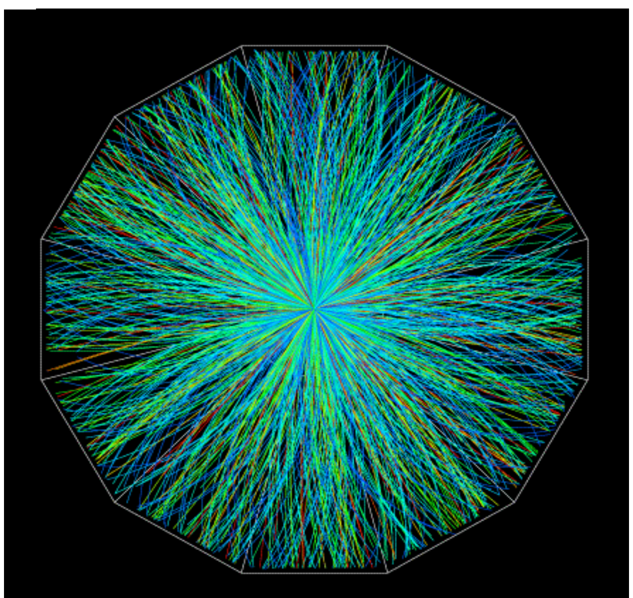
Jet Quenching !

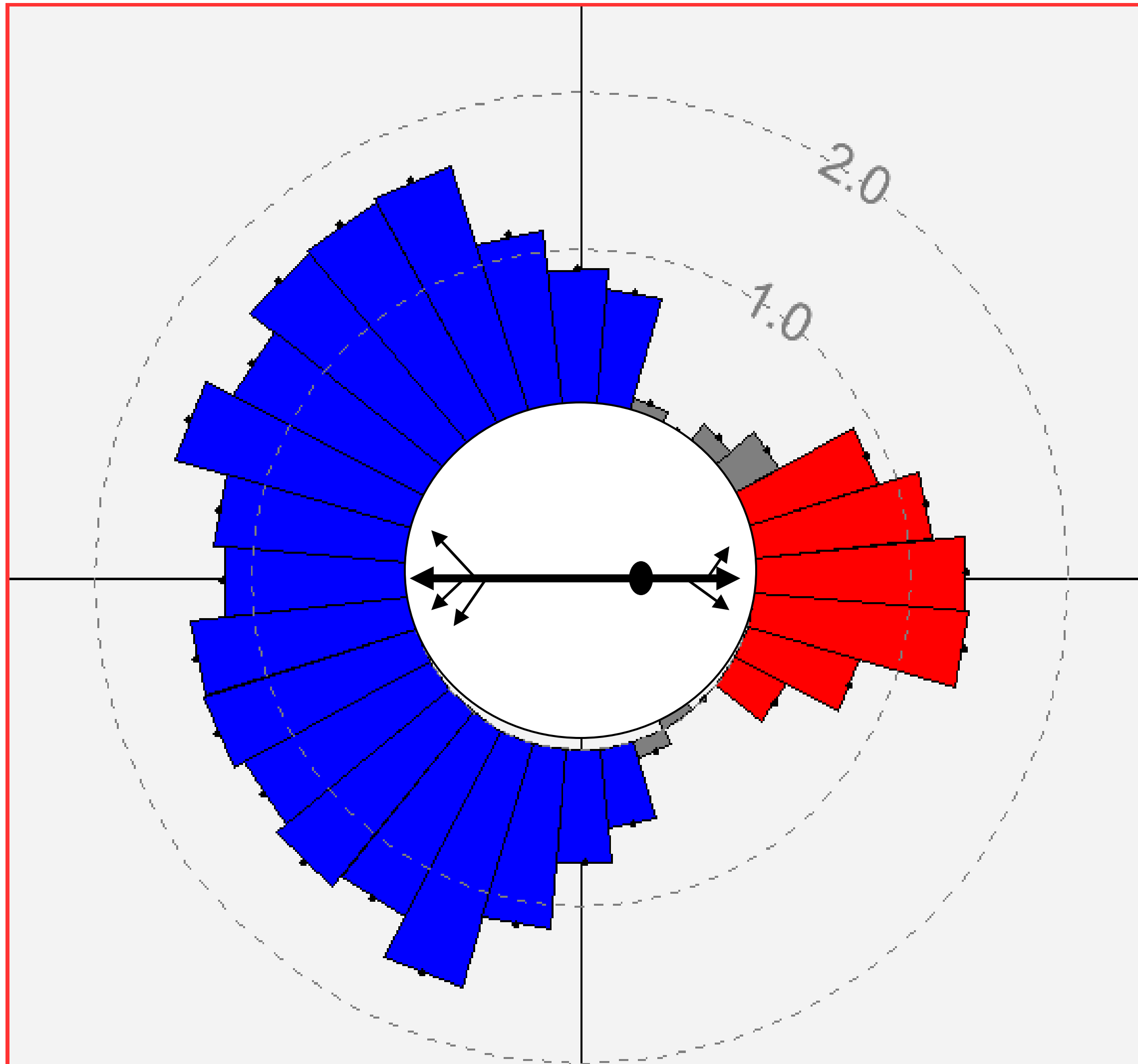
Jet correlations in central Gold-Gold.

Away side jet disappears for particles $p_T > 2$ GeV

Jet correlations in proton-proton reactions.

Strong back-to-back peaks.

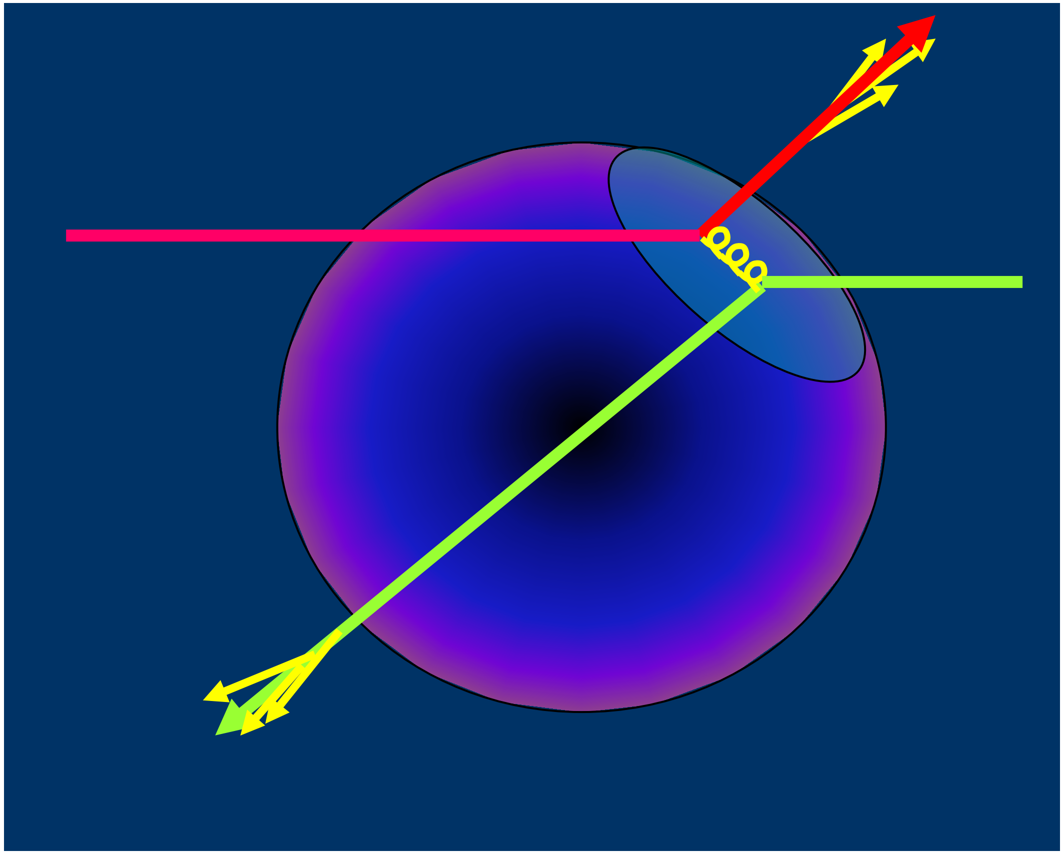




Azimuthal Angular Correlations

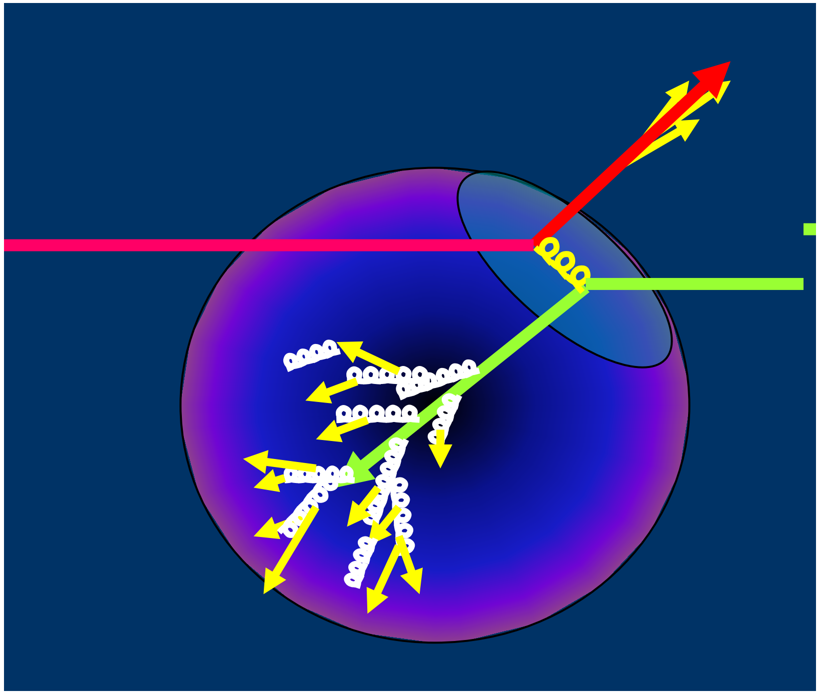
Where is the Energy?

- High p_T trigger hadron selects surface emission.
- Thus, away side partner has maximum path through the medium.



Opaque Medium

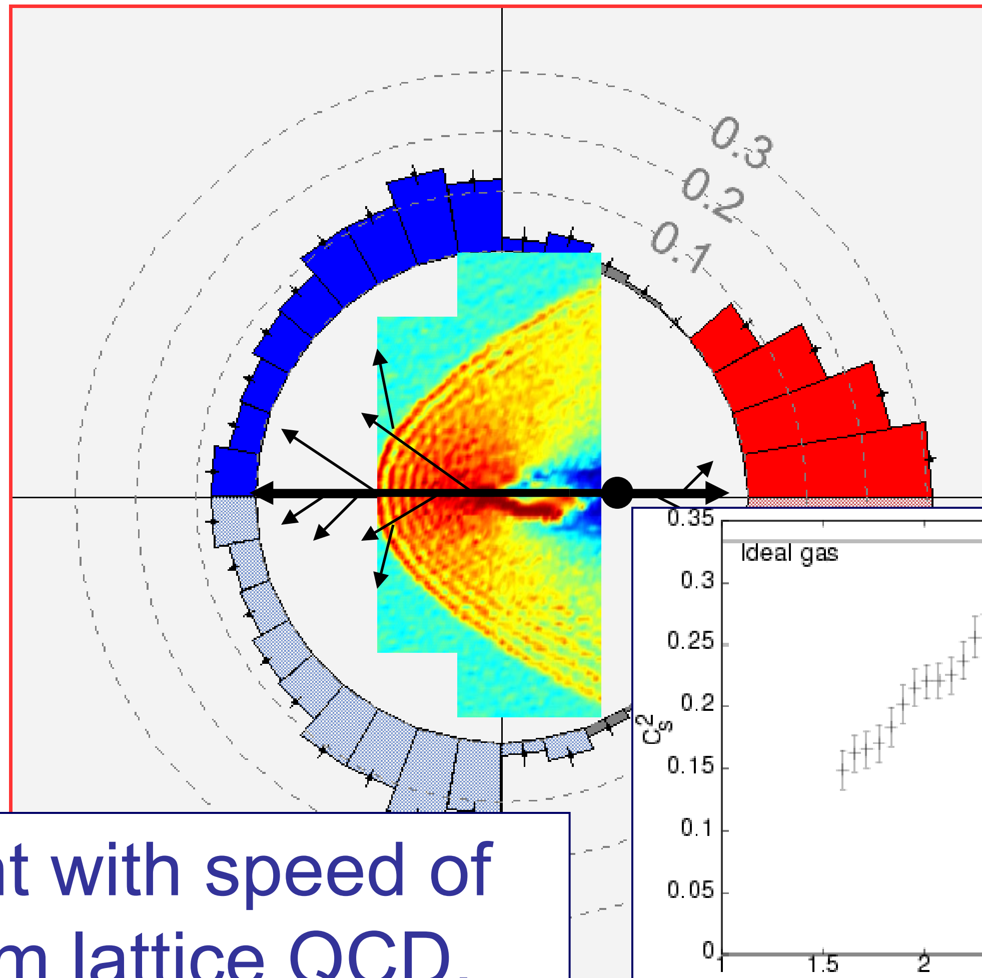
Massive induced gluon radiation thermalizes the parton energy.

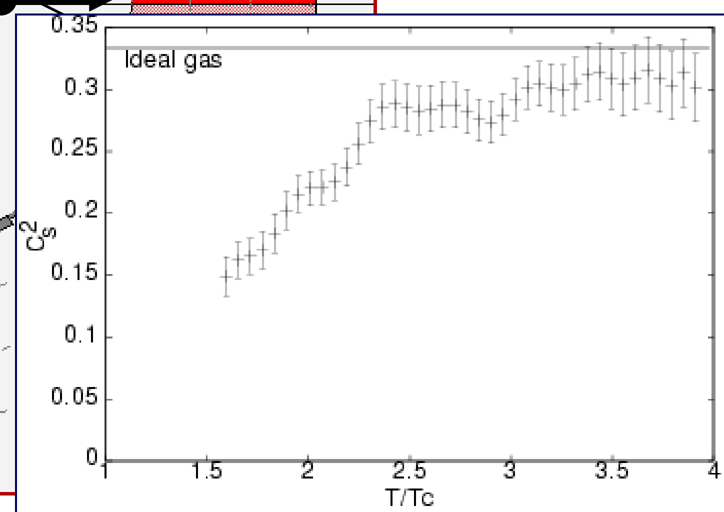


Example – 10 GeV quark shot through medium and comes out the other side as large number of hadrons. Thermalized? or Collective Modes?

Reaction of the Medium

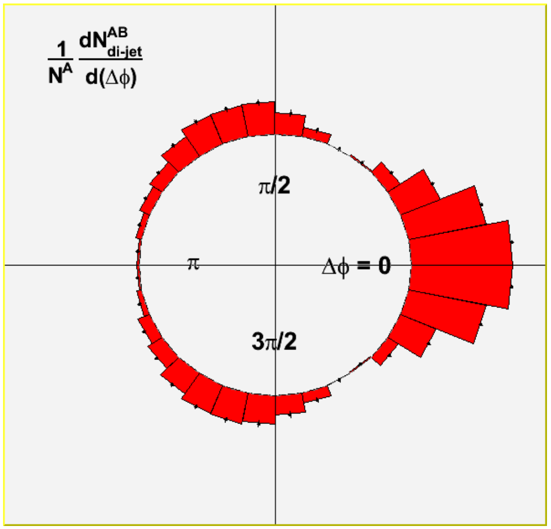
How does the near perfect liquid react to this large energy deposition? Color shock wave? Cherenkov?

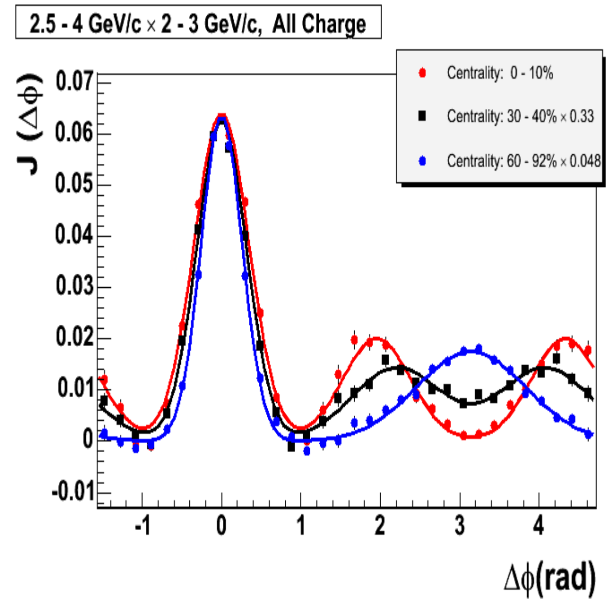




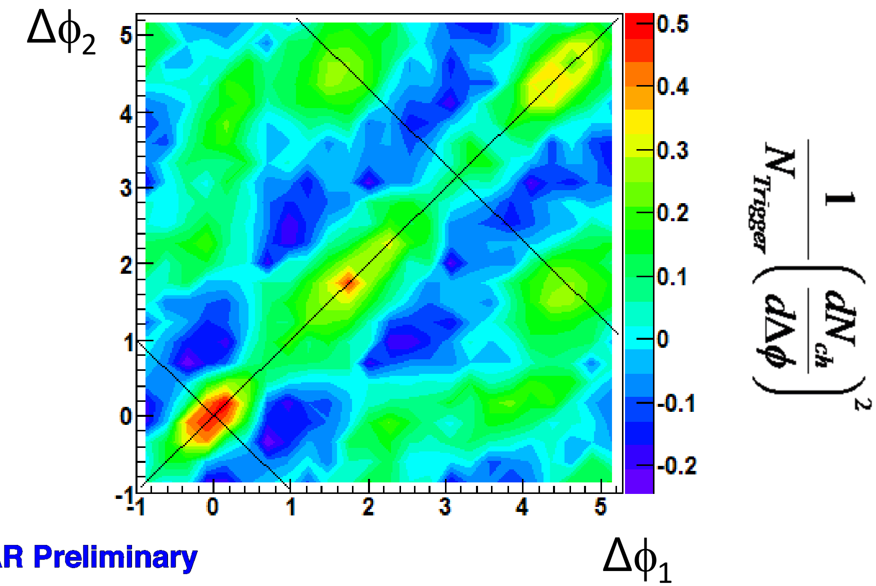
Consistent with speed of sound from lattice QCD.

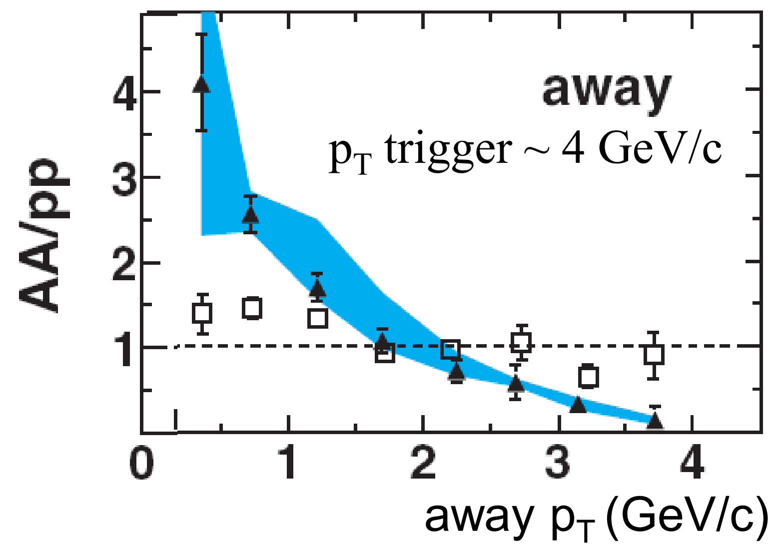
Latest Full Statistics Results





Au+Au Central 0-12% Triggered





STAR Preliminary

STAR, Phys. Rev. Lett. 95 (2005) 152301

What have we learned?

Jet quenching is experimentally so dramatic, sometimes we forget to ask what in detail we have learned.

1. The most basic thing we learn is the time integrated density of color charges for scattering that induces radiation.

$$\Delta E_{GLV} \approx \frac{9}{4} \alpha_s^3 \pi \, C_R \left(\frac{1}{\pi R^2} \frac{dN_g}{dy} \right) \left\{ \mathrm{Log} \frac{2E}{\mu^2 L} \right\} L(\phi)$$

Assuming only radiative energy loss, matching the high pT hadron suppression, indicates dN/dy(gluons) ~ 1000 or possibly dN/dy(quarks,gluons) ~ 2000.

Soft Singularity

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

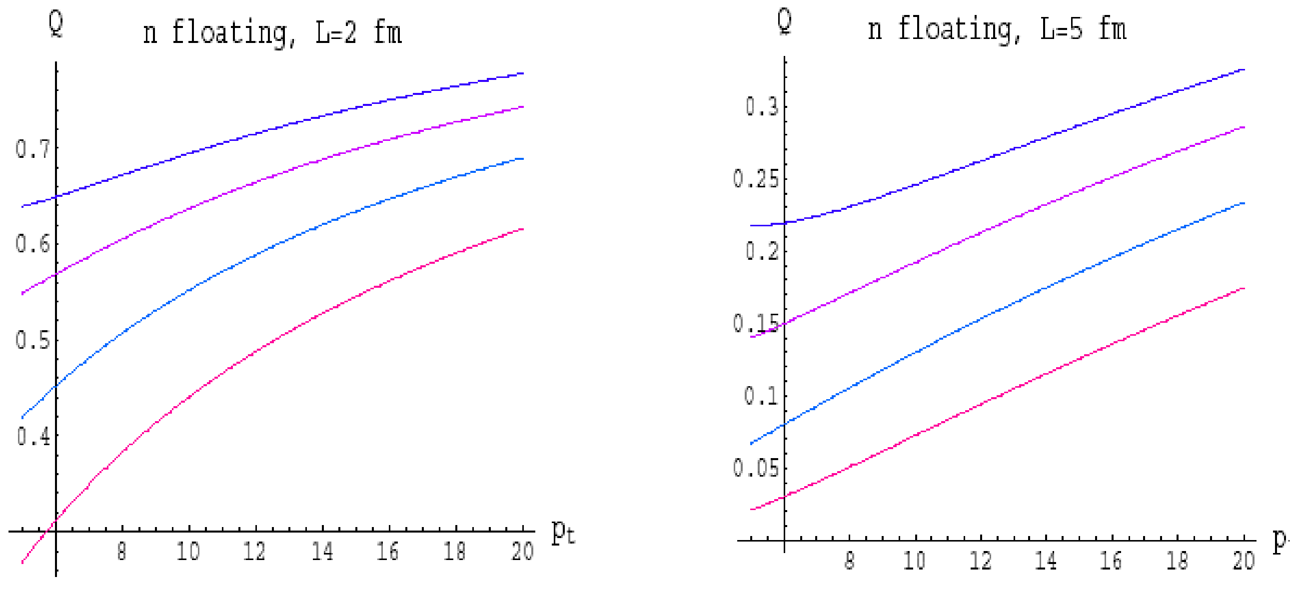


Figure 3: “Infrared” dependence of the quenching factor for hot medium. The curves (from bottom to top) correspond to the gluon energy cuts 0, 100, 300 and 500 MeV.

Plasmon Cutoff

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,

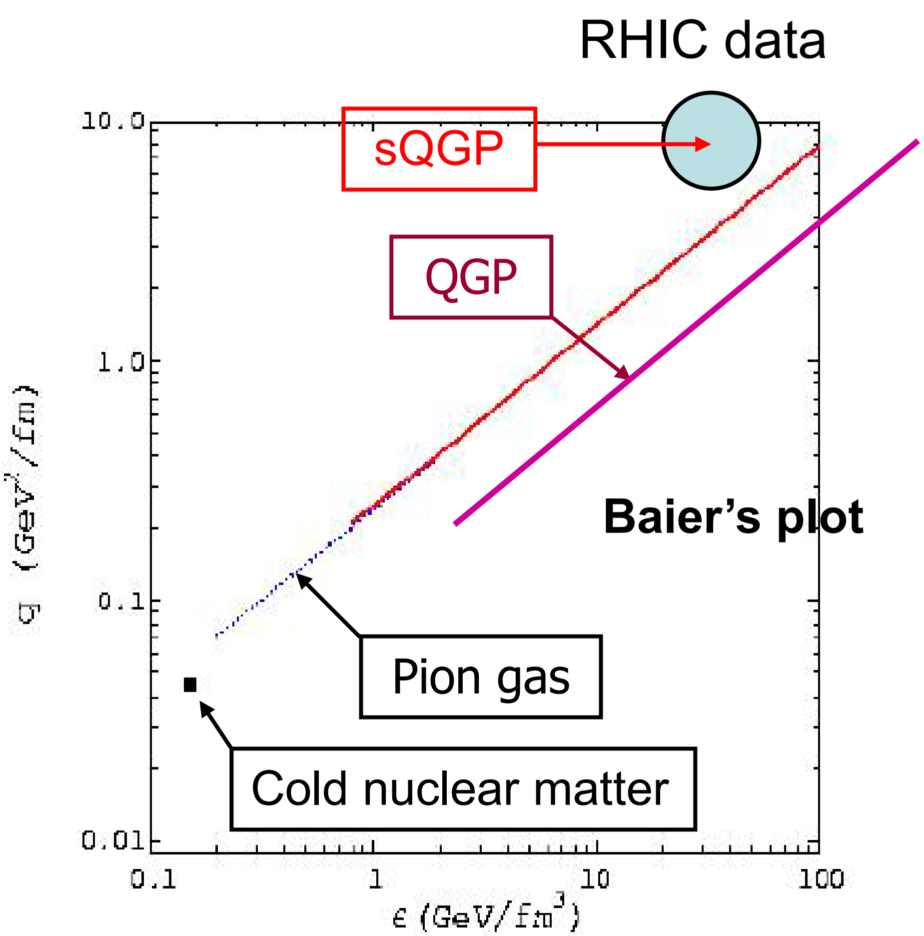
$$\omega_{BH} \equiv \frac{1}{2}\mu^2\lambda \gg \mu \tag{5}$$

in the dilute plasma approximation assumed here.

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

Stronger Coupling

Another possibility is that the pQCD scattering strength is too small (i.e. it is strongly coupled), and thus one overestimates the color charge density.



Density of scatterings

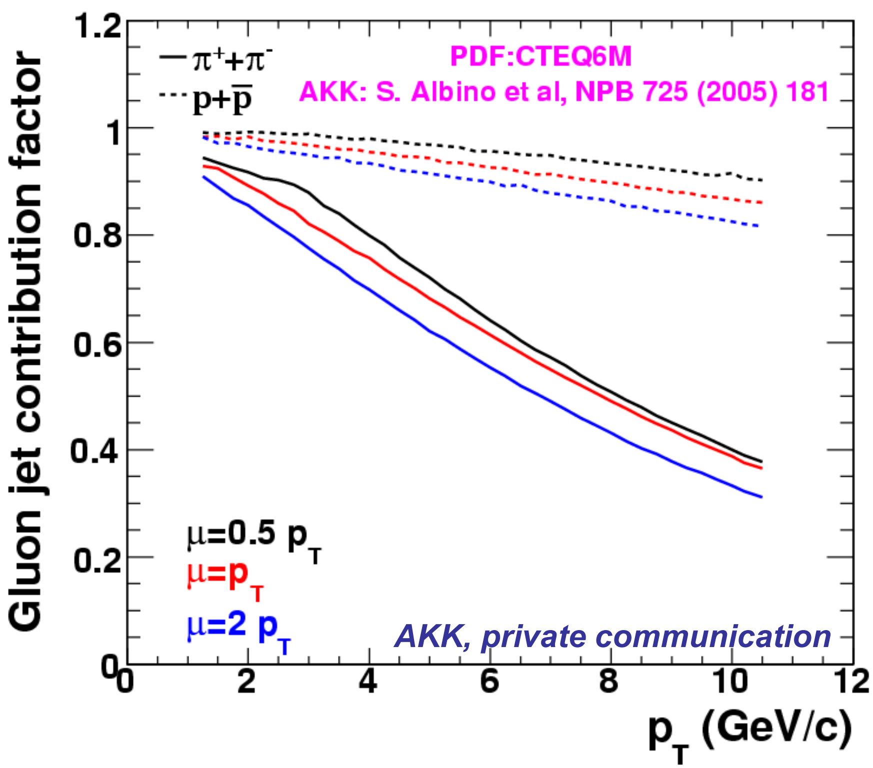
Range of color force

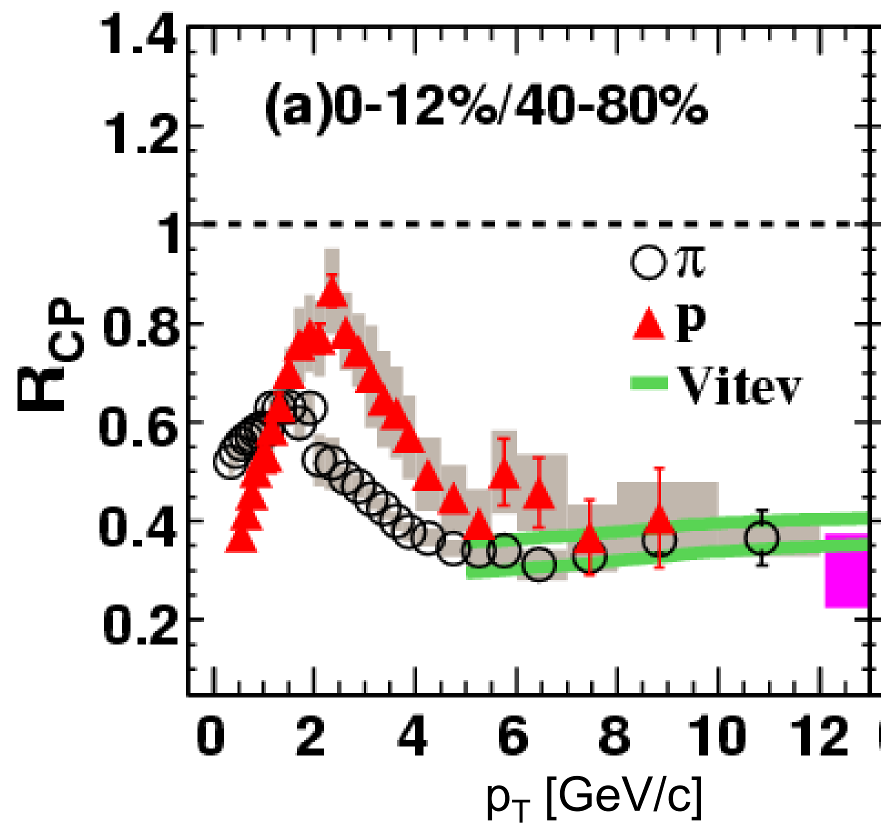
$$\hat{q} = \rho\sigma\left\langle k_T^2 \right\rangle = \frac{\mu^2}{\lambda}$$

$$= 5 - 15\ \mathrm{GeV}^2/\mathrm{fm}$$

Gluon Probes?

Gluons should lose more energy due to their color charge.
Currently we are not observing signs of this effect?

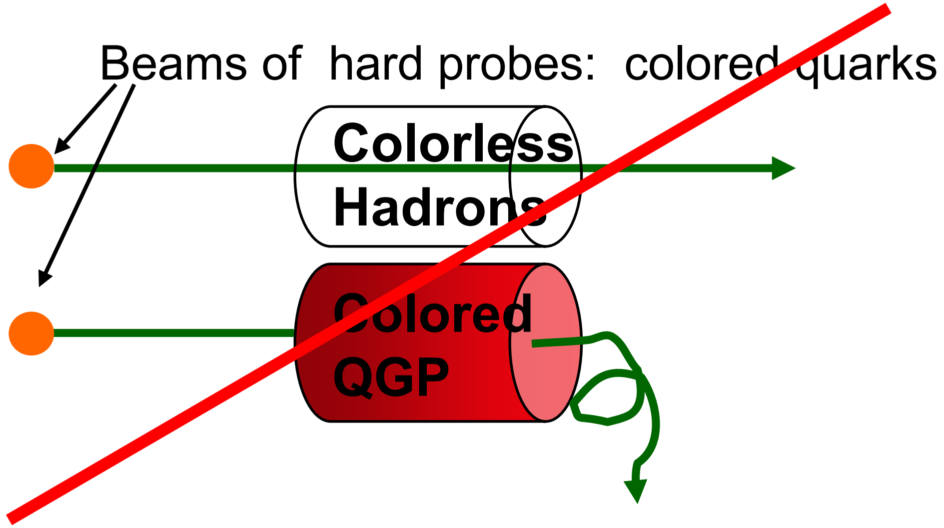




Ruan WW06, I. Vitev, nucl-ex/0603010.

Confined vs Deconfined Color?

Are we sensitive to deconfinement?



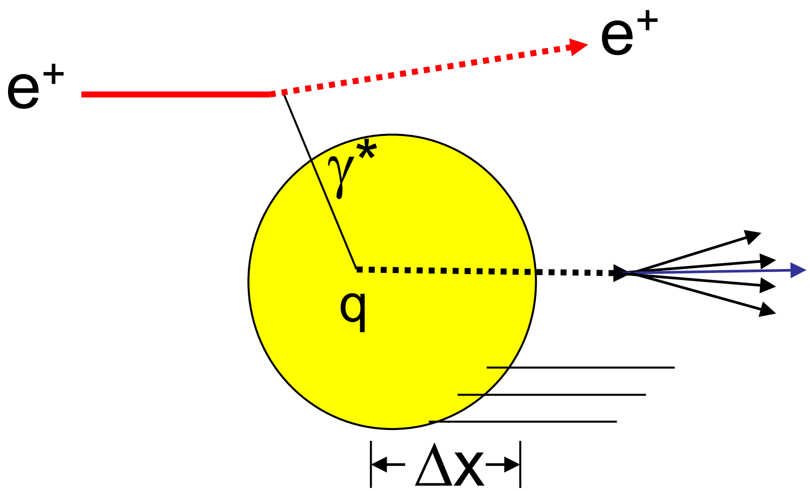
Not really !

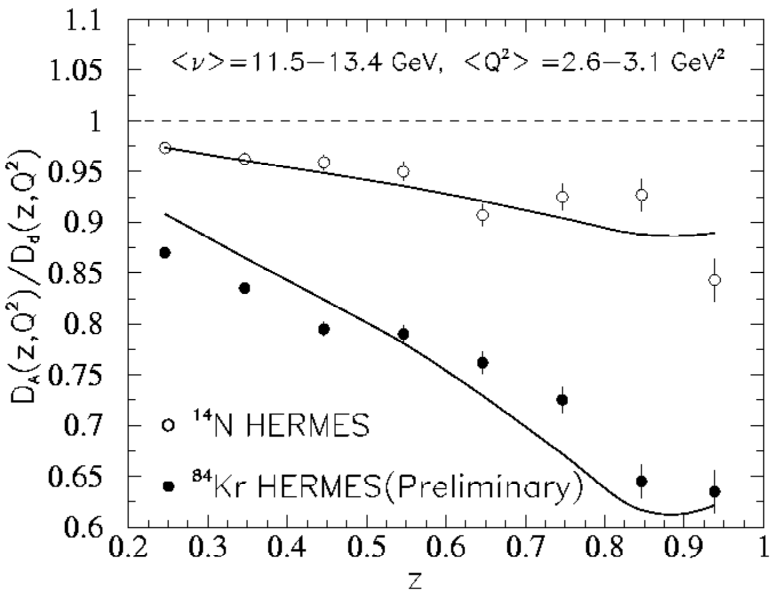
If the coherent energy loss scale is large, then we probe short distances and would “see” the color charges inside hadrons anyway (like in DIS).

Only if the energy loss scale is small would we be sensitive, but this does not seem to be our regime.

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

Response of the Medium

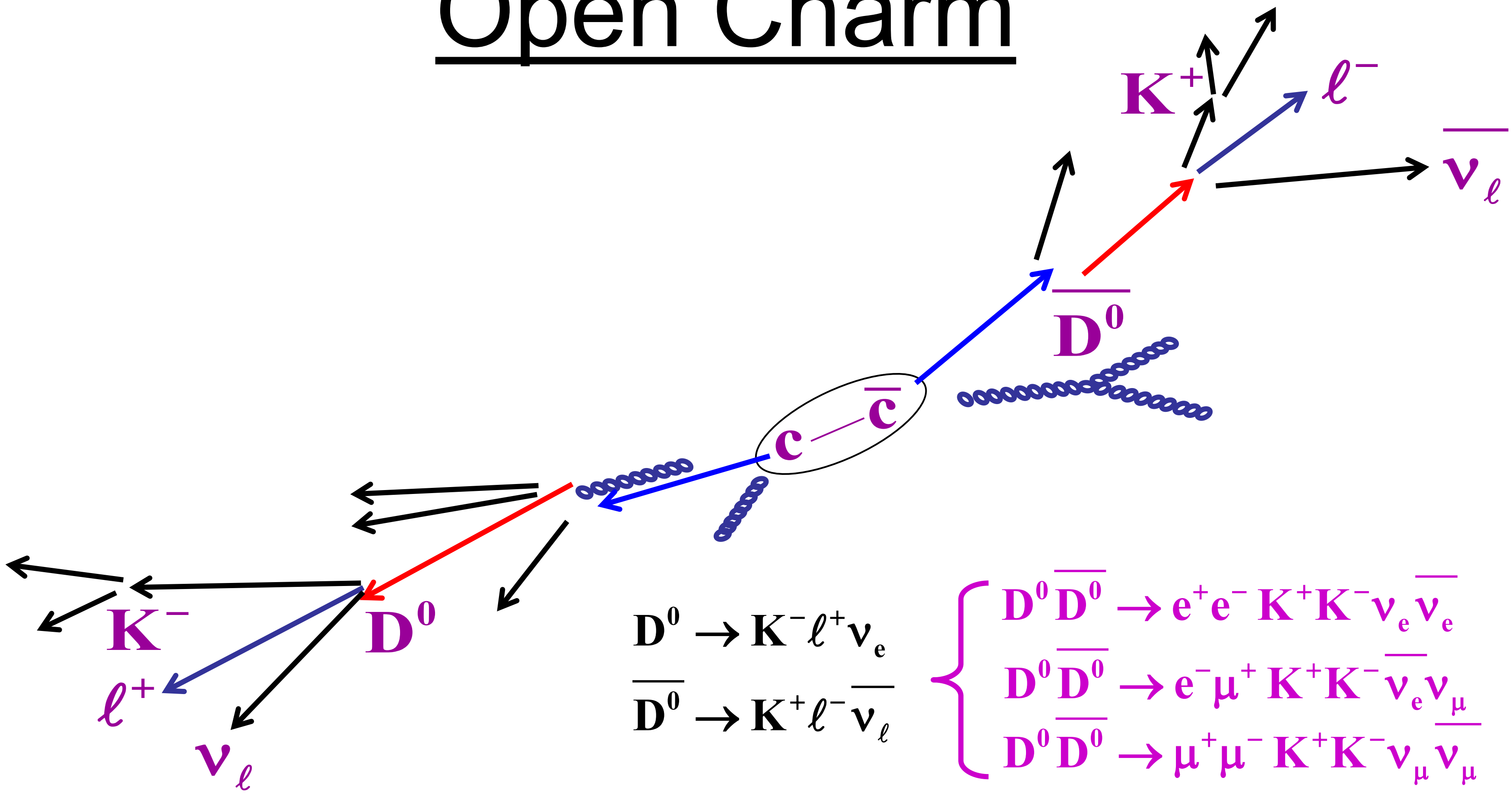
There is a great deal to potentially be learned from the response of the medium (about the medium itself).

If there is a Mach cone → Speed of Sound

If there is a Cherenkov cone → Index of Refraction and ! Proof of Bound States !

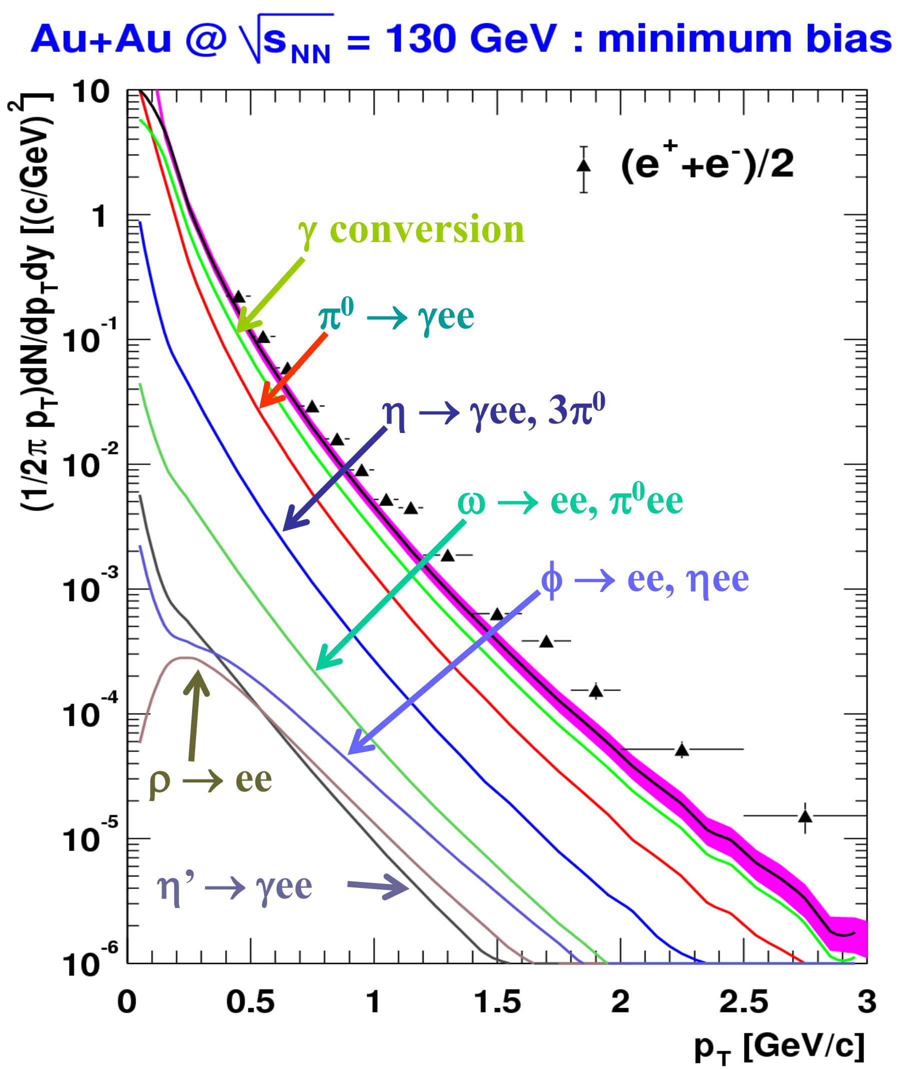
Heavy Quarks and Heavy Quarkonia

Open Charm



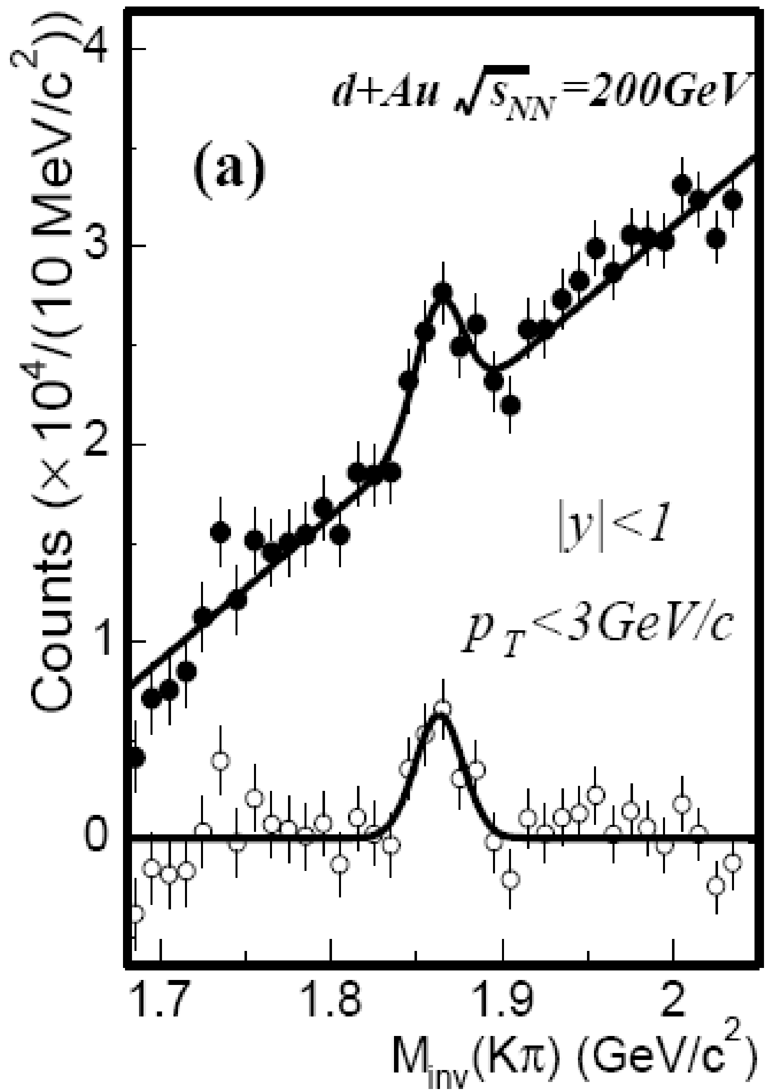
1. Measuring single leptons from semi-leptonic decay of D and B
2. Measuring D→πK and subtract enormous combinatorics
3. Measuring the above two with a displaced vertex measurement (future)

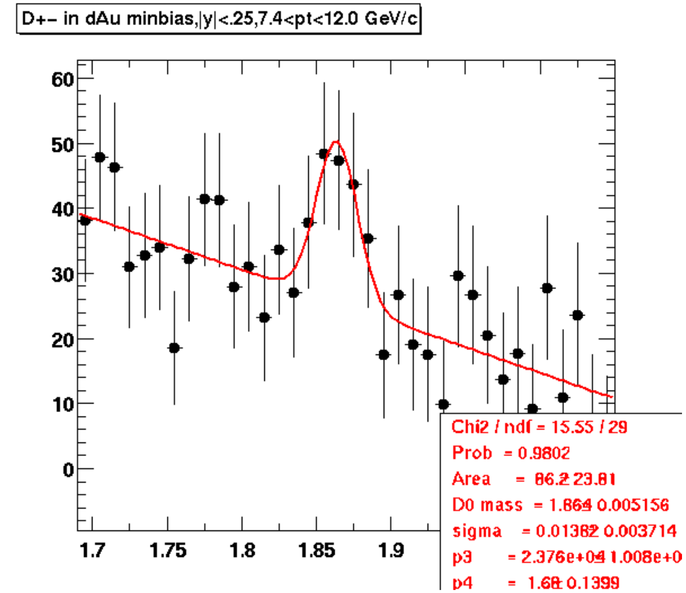
Single Lepton Method

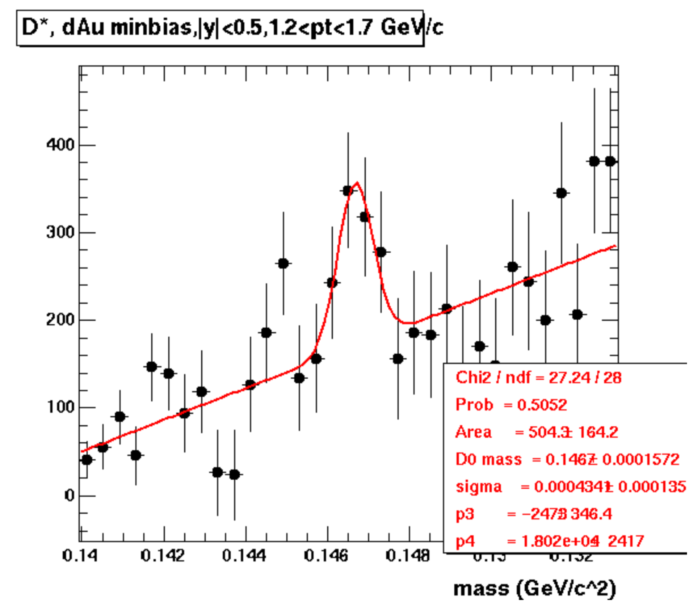


PHENIX: PRL 88(2002)192303

Direct D Reconstruction

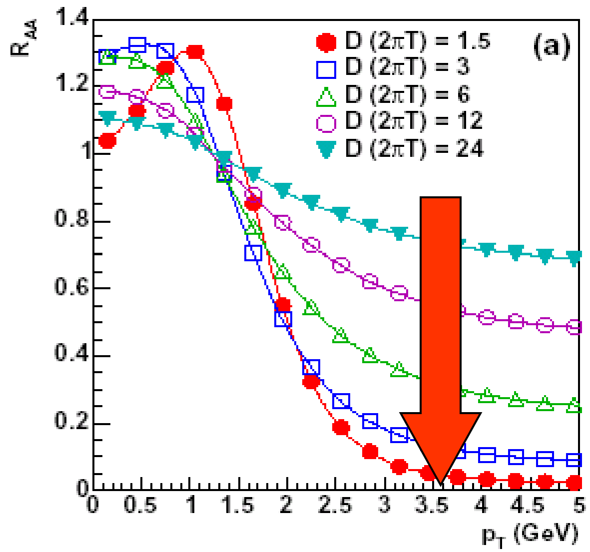


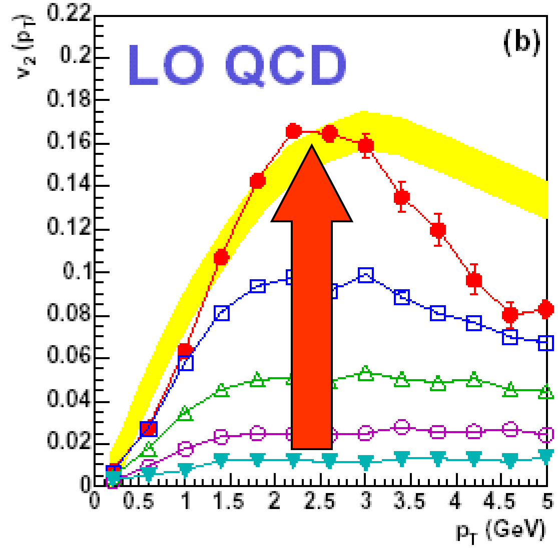




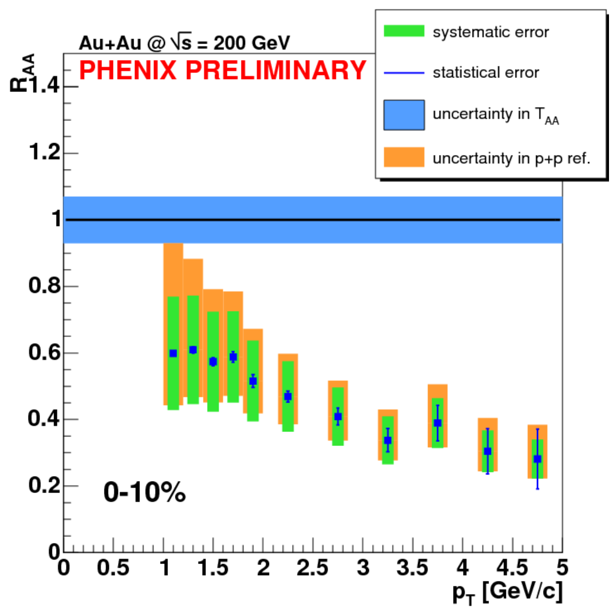
Charm Patterns

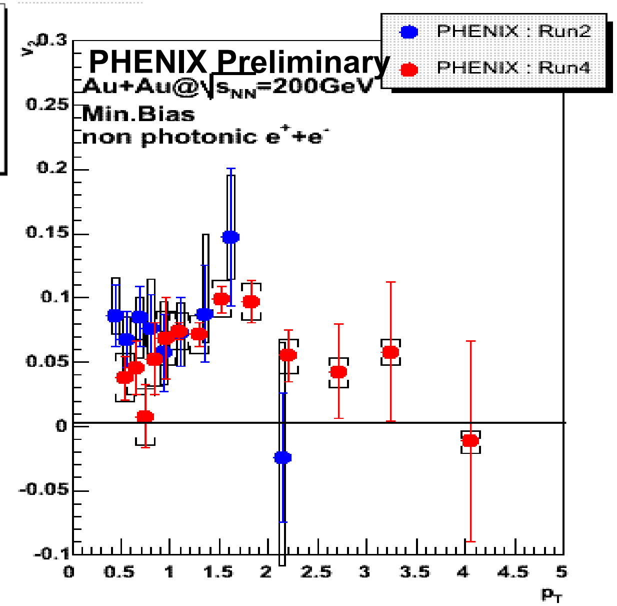
Teaney and Moore





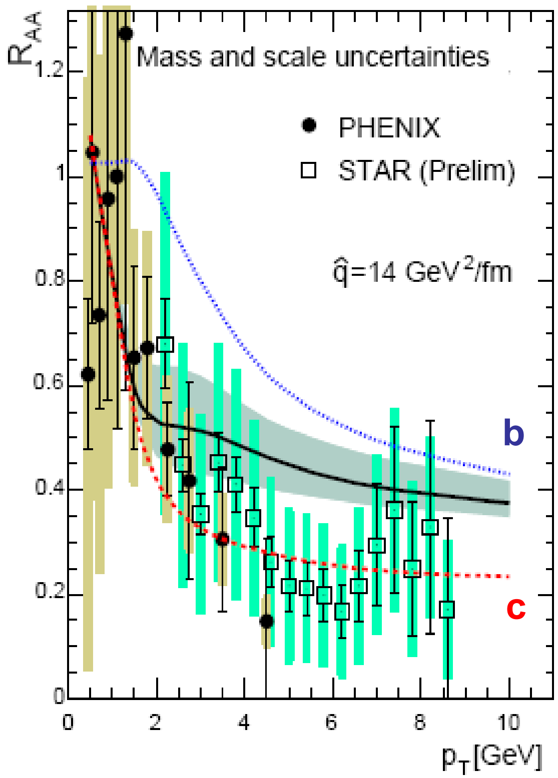
May provide best viscosity constraint!

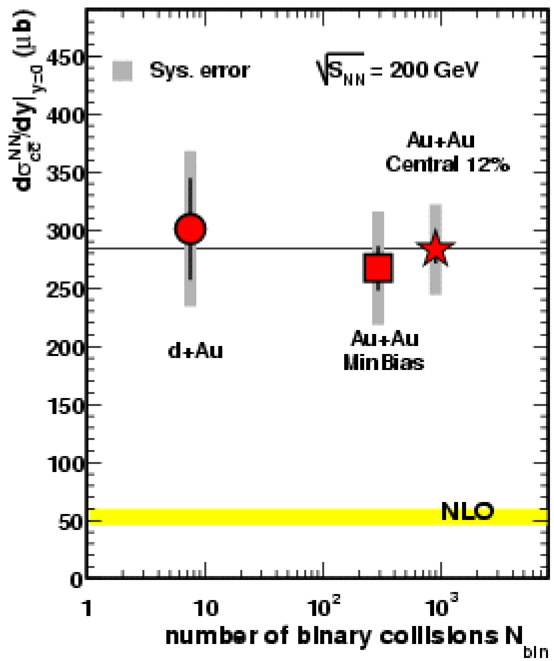


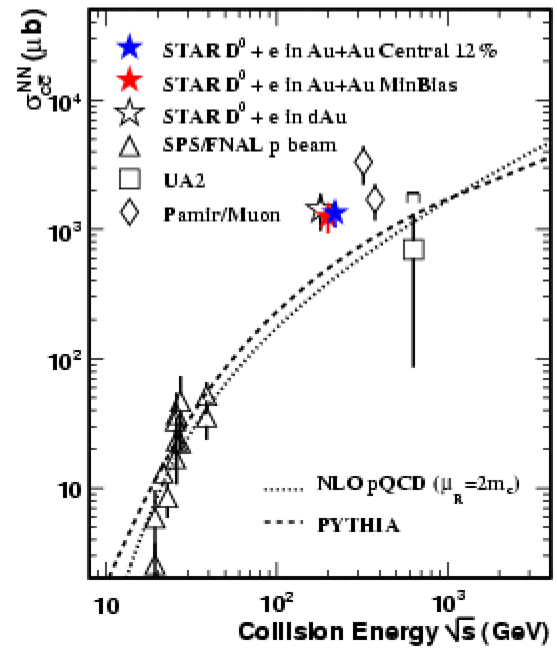


Heavy Flavor Puzzles

N. Armesto et al, nucl-ex/0511257







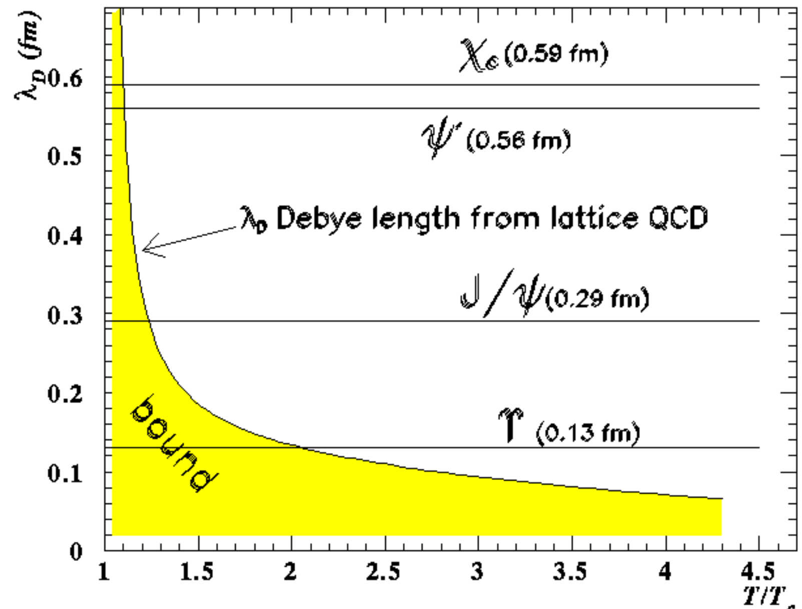
Beauty should start to contribute to single electrons above pT ~ 4 GeV and be less suppressed.

Charm cross sections from STAR and PHENIX disagree. STAR x5 above NLO and PHENIX x2?

Screening Effects

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.

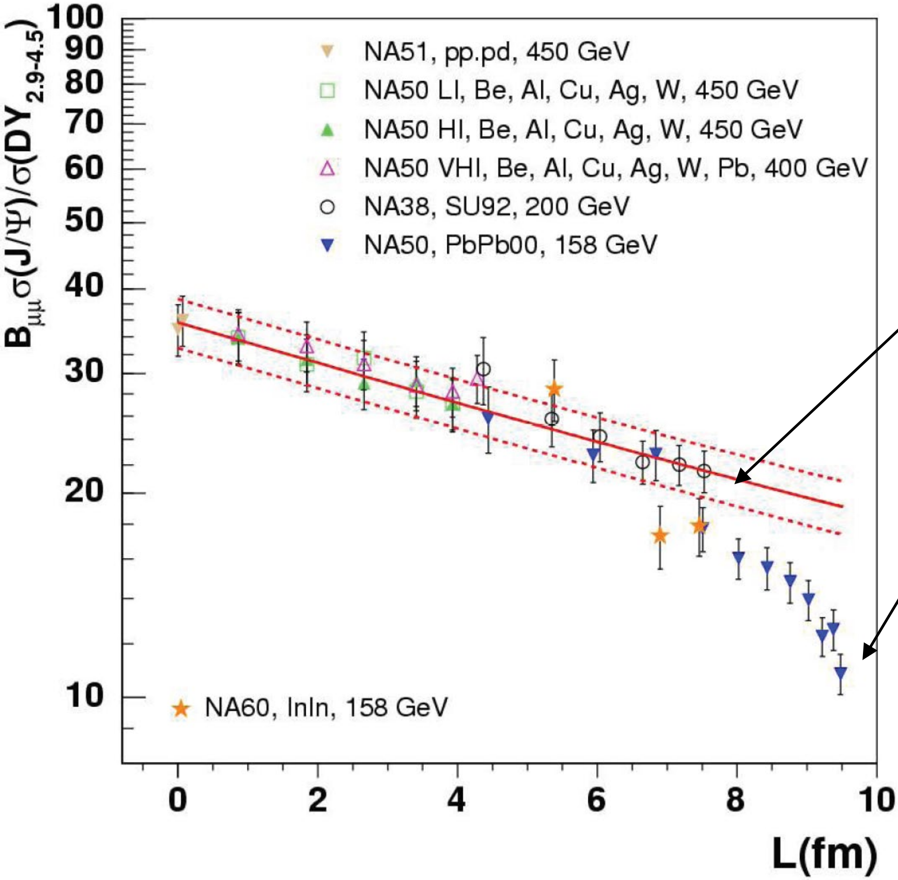


state	J/ψ	χ_c	ψ'	Υ(1s)	χ_b	Υ(2s)	χ_b'	Υ(3s)
Mass [GeV}	3.096	3.415	3.686	9.46	9.859	10.023	10.232	10.355
B.E. [GeV]	0.64	0.2	0.05	1.1	0.67	0.54	0.31	0.2
T_d/T_c	---	0.74	0.15	---	---	0.93	0.83	0.74

hep-ph/0105234 - "indicate ψ' and the χ_c dissociate below the deconfinement point."

Cold and Hot Nuclear Matter

The "L" Plot



Melting of ψ'
(10% contribution to J/ψ)

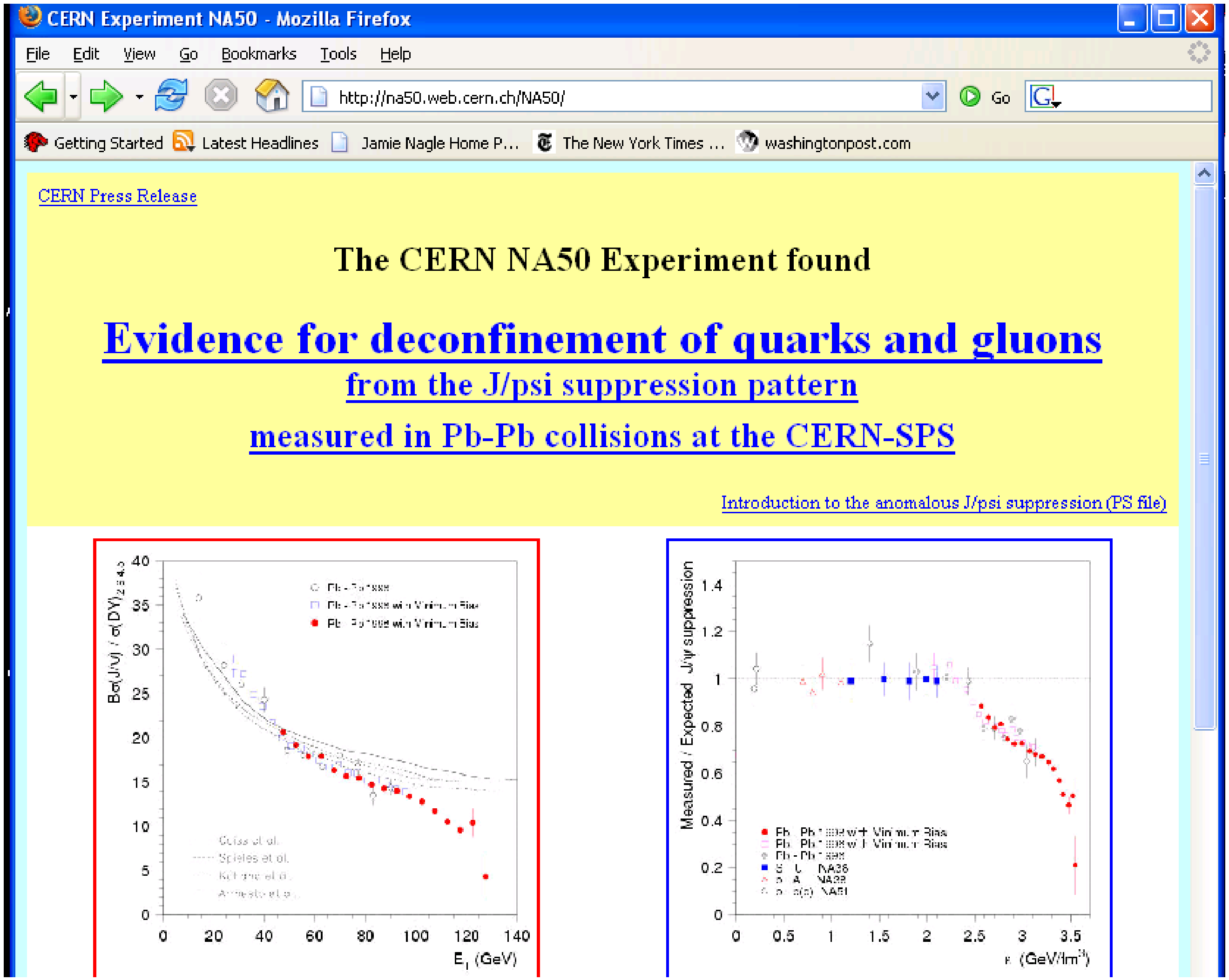
Melting of χc
(40% contribution to J/ψ)

Melting of J/ψ ?

"Strong evidence for the formation of a transient quark-gluon phase without color confinement is provided by the observed suppression of the charmonium states J/ψ, χ_c, and ψ'."

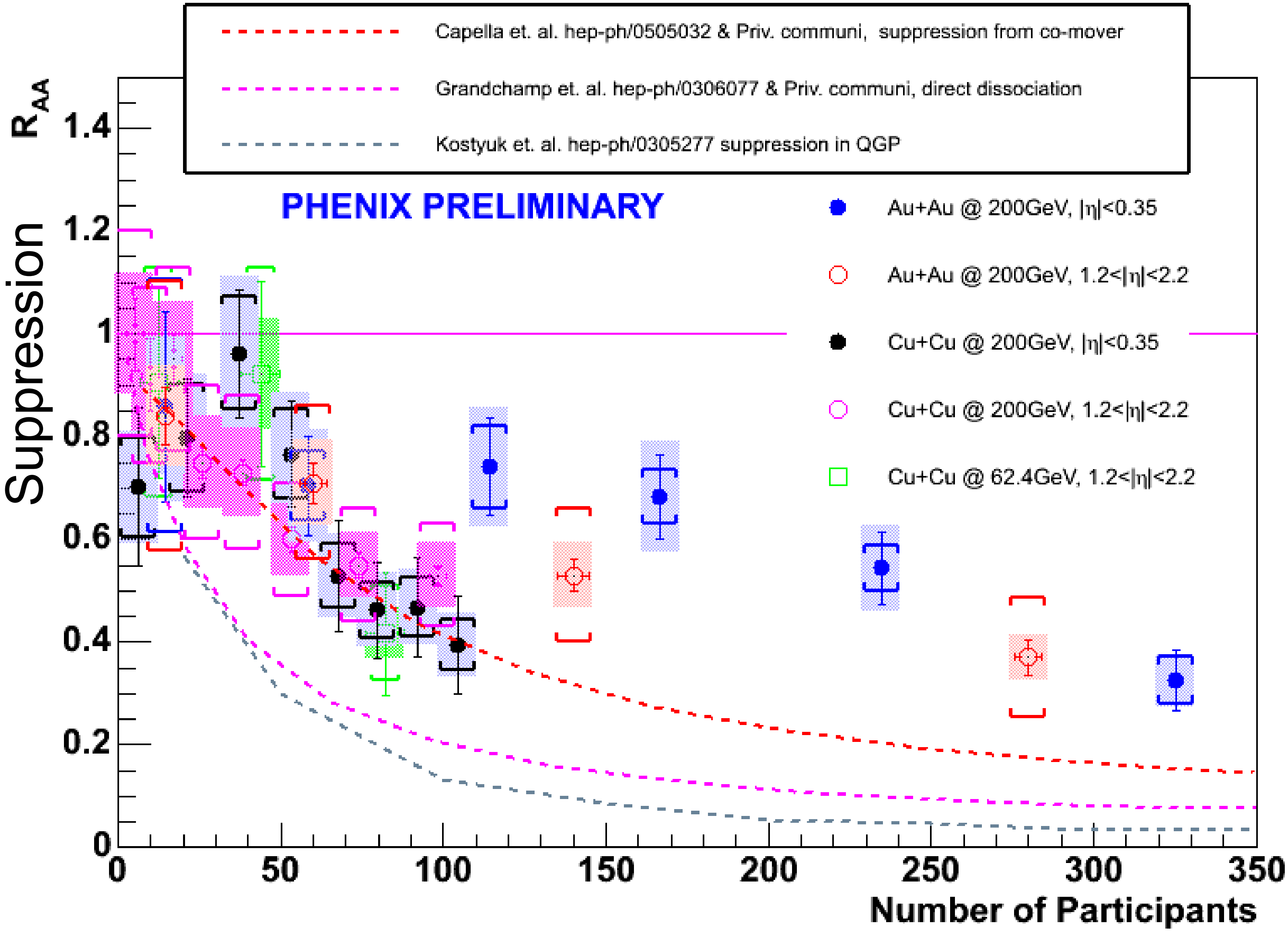
Maurice Jacob and Ulrich Heinz
CERN Press Release 2000

Exciting Lower Energy Result !



Predict a much larger suppression at RHIC!

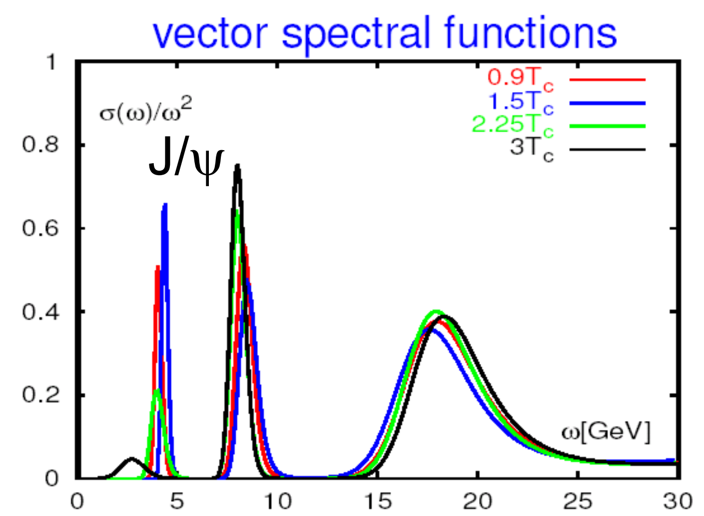
RHIC Preliminary Results



New Ideas

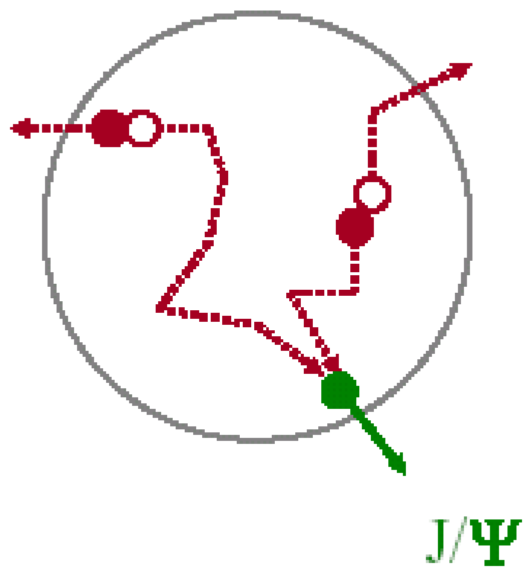
Recent Lattice QCD results indicate J/ψ spectral function may persist up to 3 T_c.

Temperature Bound < 3 T_c (?)



Perhaps charm recombination creates new J/ψ later.

Data to prove or disprove this explanation is on tape.



The Future

QGP?

QGP defined theoretically by lattice QCD.

Many fascinating phenomena discovered and studied at RHIC.

We are starting to attack the problem of quantitatively estimating some fundamental quantities.

Note that even the best experimental probes span a range of times in the evolution of the collision system. Thus, there is inevitably a model used to map the T, S, viscosity, size, time dependence onto observables. Major breakthrough on the theory side is needed to have a “high confidence” space-time framework for studying many probes in a consistent picture. Hydrodynamics is a good start, but needs coupling to non-equilibrium models.

RHIC II and LHC

Exciting future that is bound to make more splashes!