Studying QCD @ RHIC, e-RHIC, and the LHC

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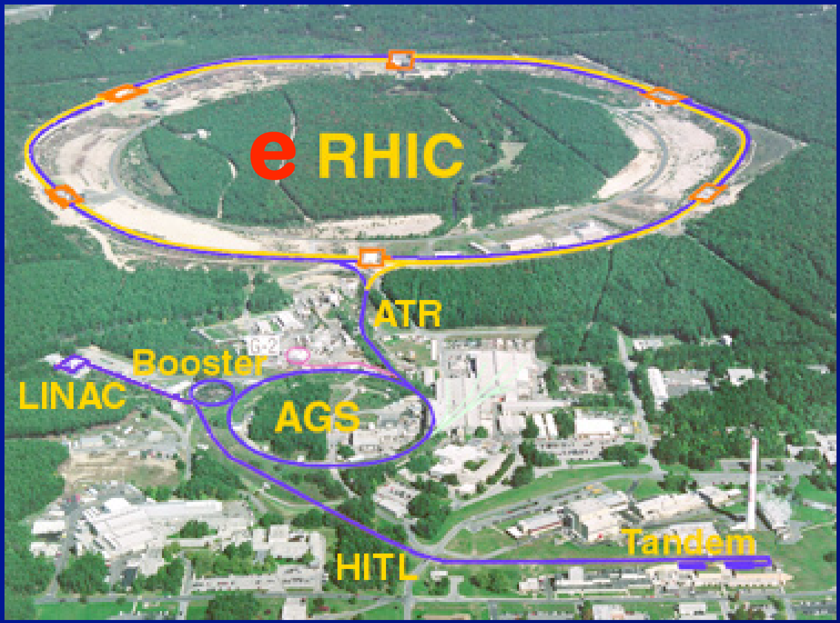

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= Coherent program providing new insight on fundamental aspects of QCD

The Big Picture

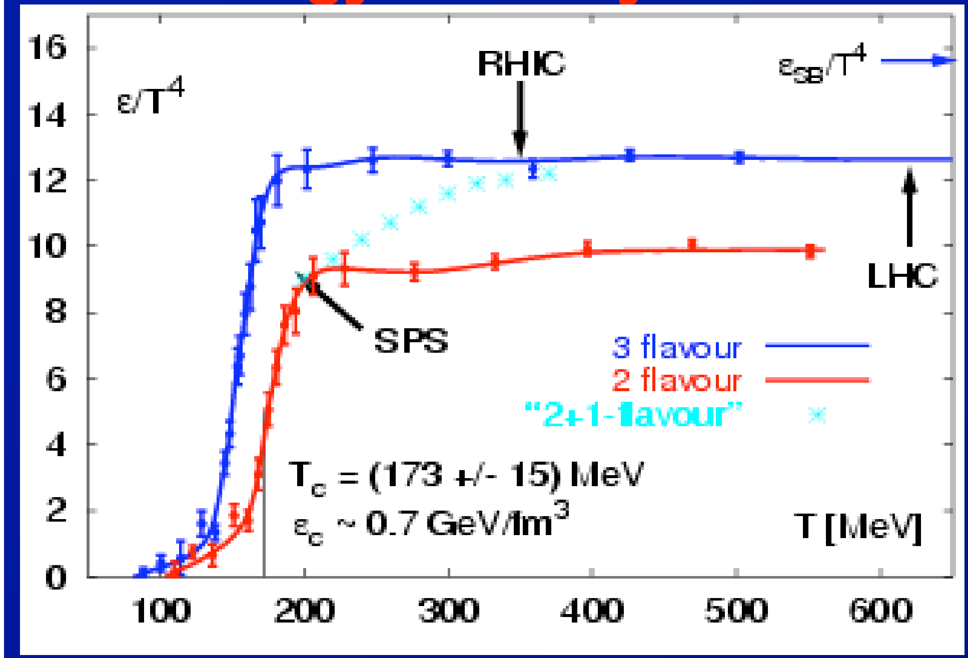
- The RHIC, e-RHIC, and LHC (heavy ion) programs will allow us to study how QCD

$$L_{QCD} = -\frac{1}{4} F^{\alpha}_{\mu\nu} F^{\mu\nu}_{\alpha} - \sum_{n} \overline{\psi}_n \left(\partial\!\!\!/ - ig\gamma^{\mu} A^{\alpha}_{\mu} t_{\alpha} - m_n \right) \psi_n$$

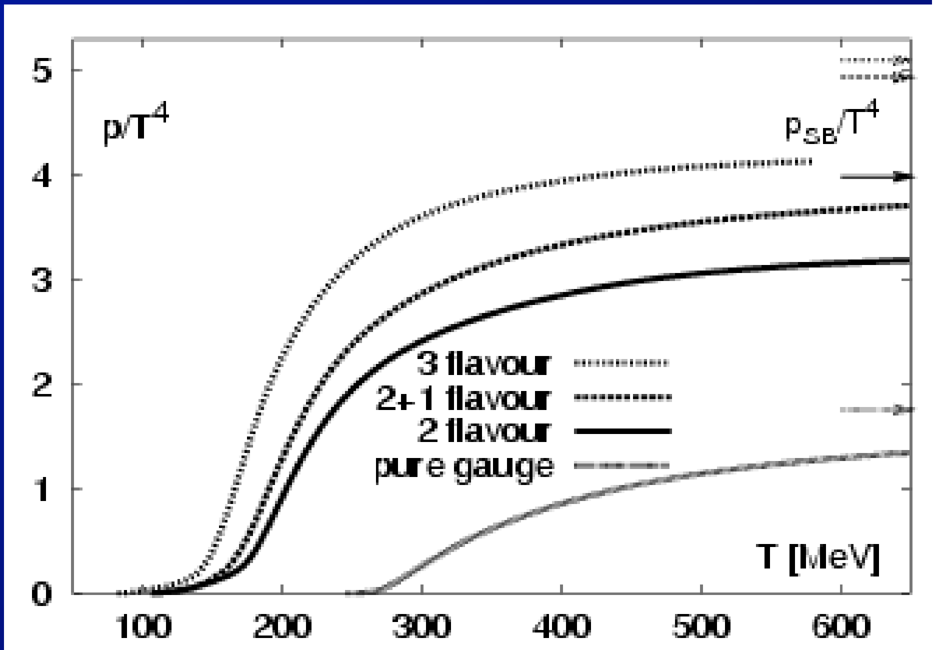
  - Determines properties of deconfined matter
    - ⇒ "Quark Gluon Plasma (QGP)"
    - ⇒ **Only** matter we can create in the laboratory whose properties are entirely determined by a *fundamental*, *non-Abelian* interaction
  - Behaves for strong, coherent (nearly classical?) gluon fields generated by ultra-relativistic nuclei
    - ⇒ "Color Glass Condensate (CGC)"

QCD Thermodynamics (on Lattice)

Energy Density / T^4



Pressure / T^4

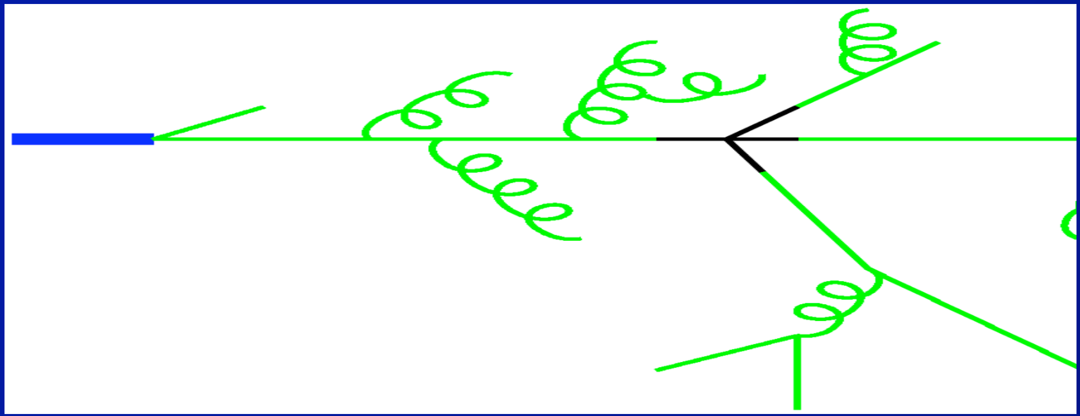


- Rapid cross-over from "hadronic matter" to "Quark-Gluon Plasma" at T ~ 170 MeV

  ⇒Energy density, $\varepsilon \sim 1$ GeV/fm^3.

- Only fundamental "phase transition" that can be studied in the laboratory.
  - Direct consequence of asymptotic freedom.

Radiation from Accelerated (Color) Charge

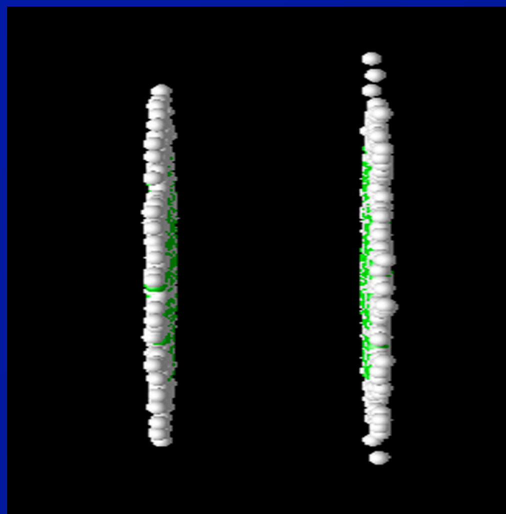


One of the most fundamental problems in physics

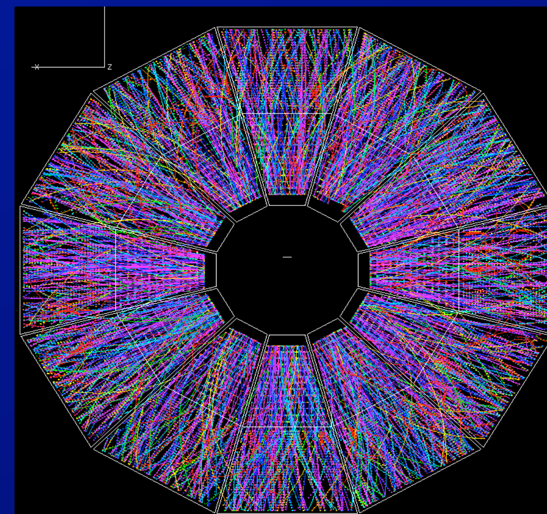
- QCD is unique among fundamental theories by having large coupling, massless boson
  - ⇒Copious radiation
  - ⇒Responsible for evolution of PDFs
  - ⇒And final-state parton showers
- @ RHIC, e-RHIC, LHC collisions we can modify QCD radiation processes in controlled way
  - PDFs: change initial condition ($p \rightarrow A$), x
  - Parton shower: embed in medium (QGP)

Heavy Ion Collisions – Fundamental??

- Can we really understand how to go from



to

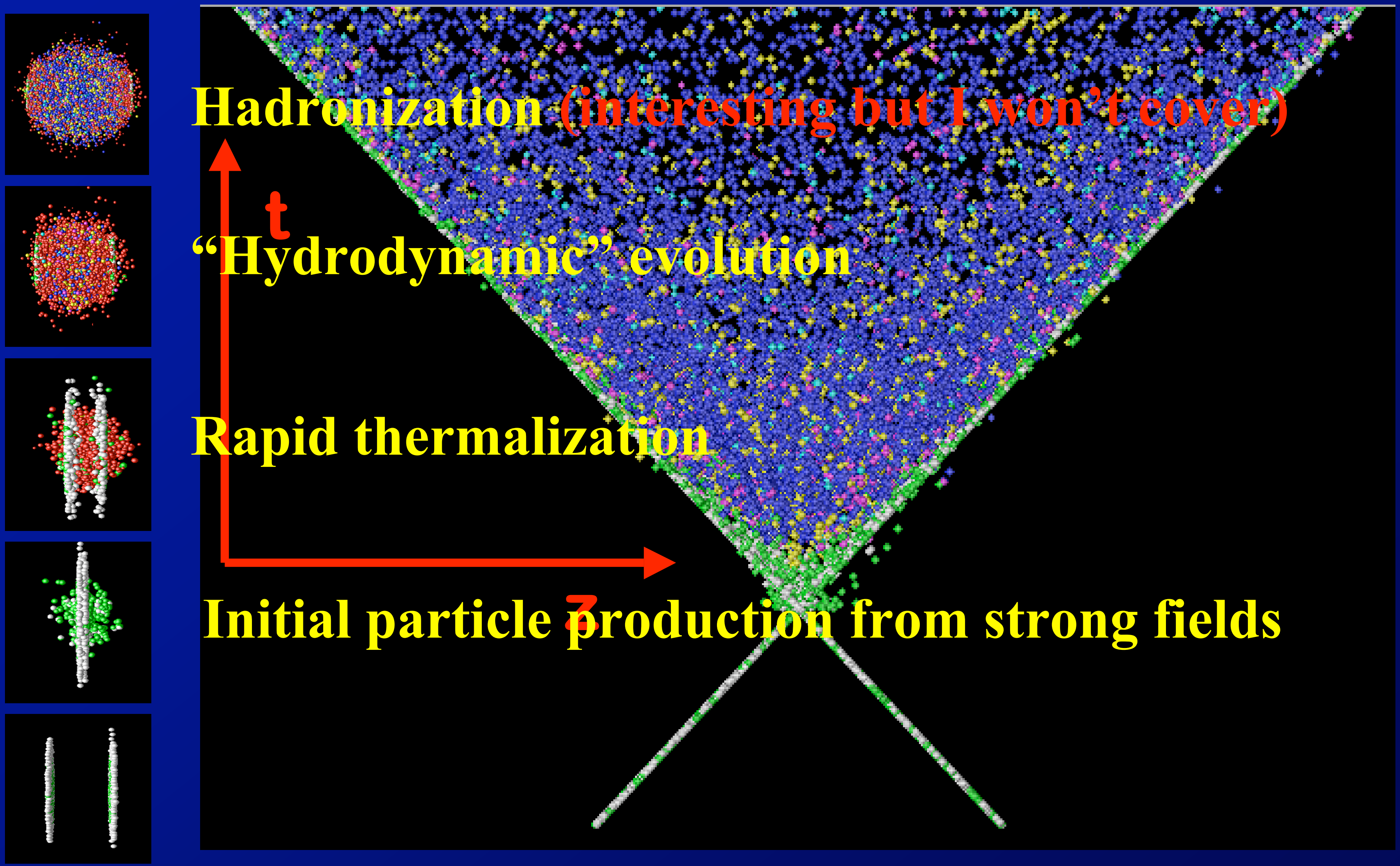


from first principles? Maybe, almost

- At the very least, we are much closer than we ever have been before. Why?
  - Initial particle production from saturated state
  - Rapid thermalization of QGP (best hypothesis)
- With the right probes, we may not need to

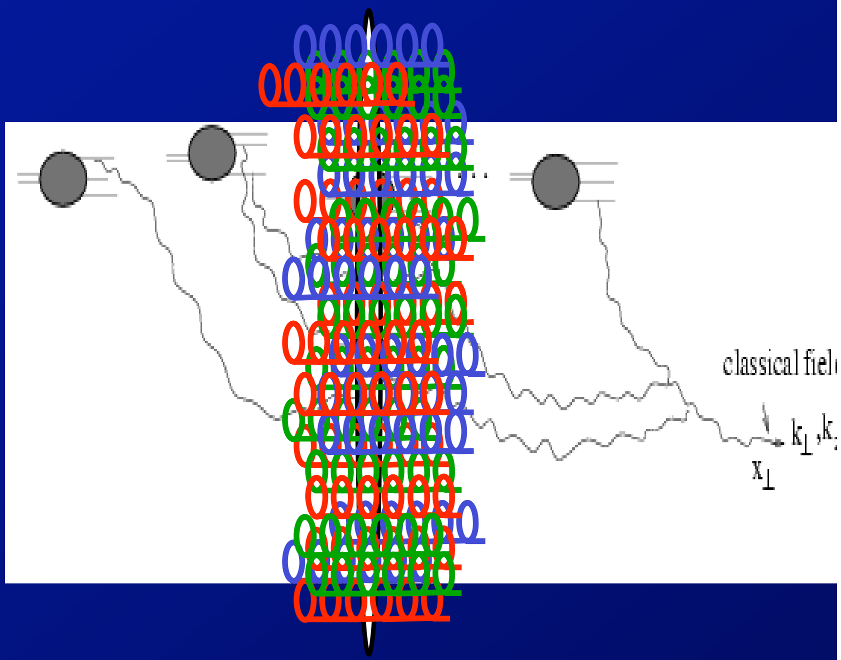
Heavy Ion Collision Time History

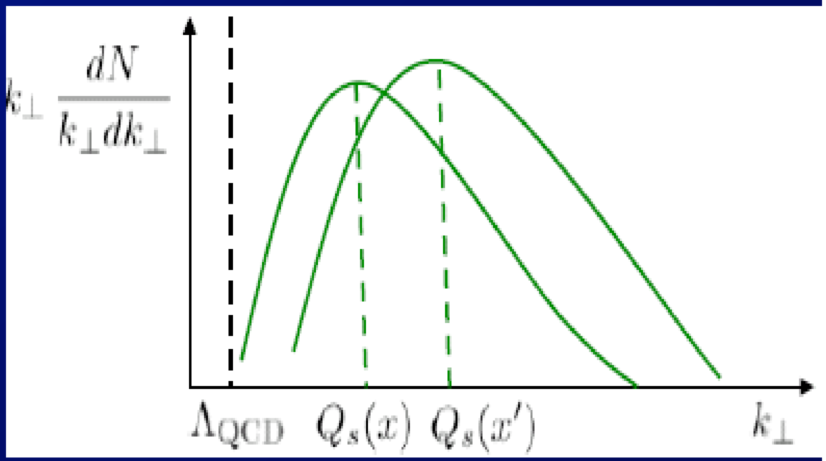
RHIC collision space-time history in “parton cascade” model



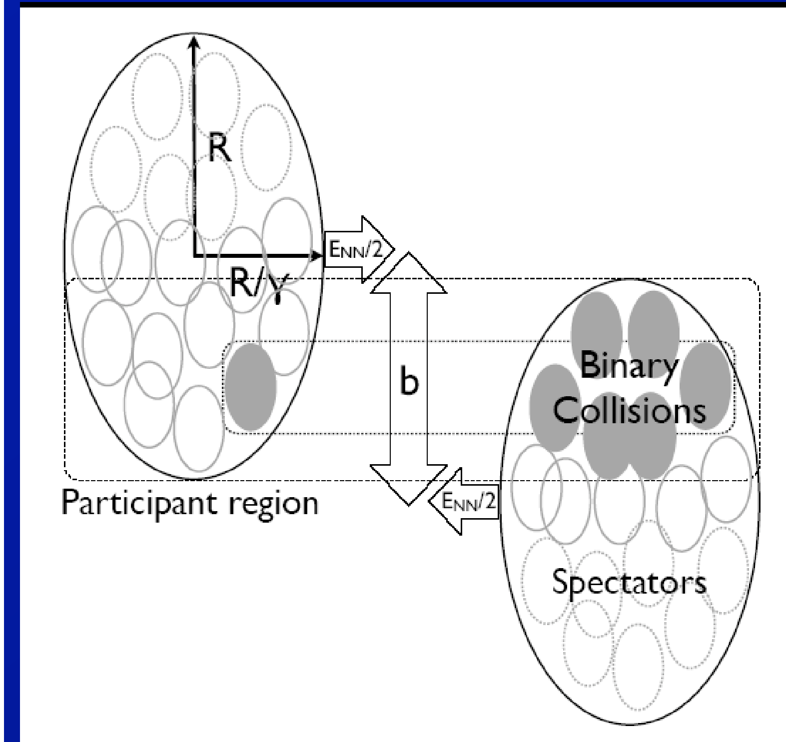
"Saturation" @ low x

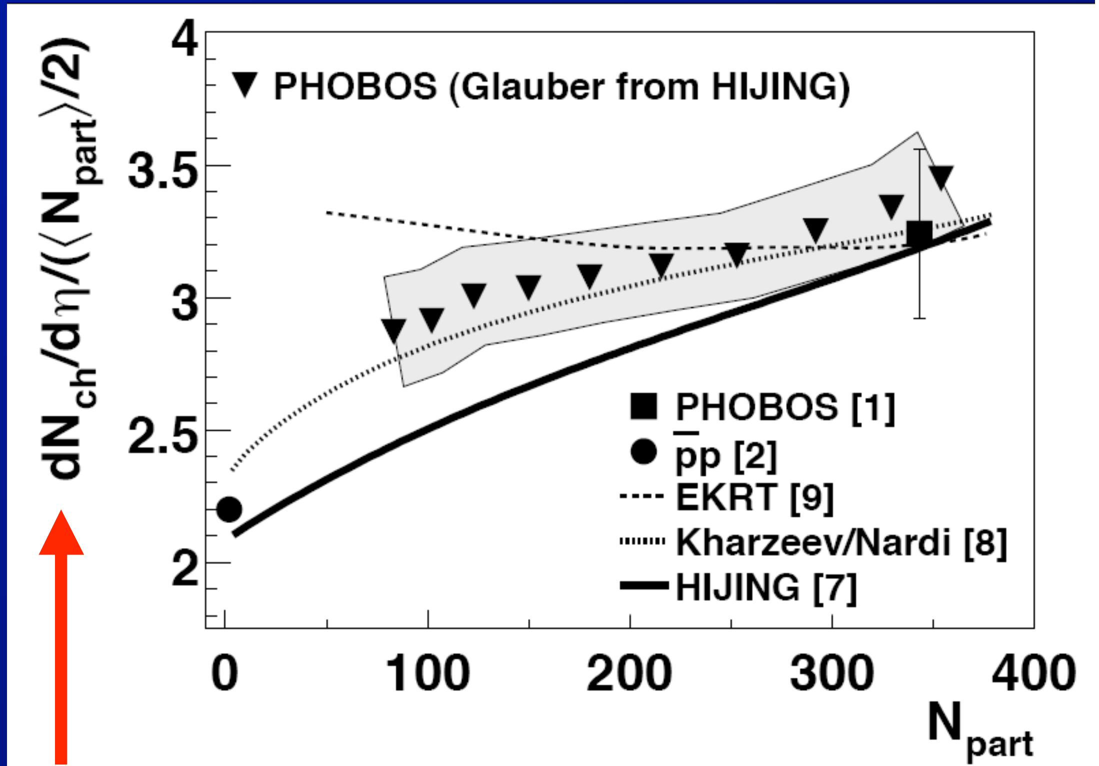
- @ High energy nuclei are highly Lorentz contracted
  - Except for soft gluons
  - Which overlap longitudinally
  - And recombine producing broadened k_T distribution
    - ⇒Generates a new scale: Q_s
    - ⇒Typical k_T of gluons
- If $Q_s >> \Lambda_{QCD}$, perturbative calculations possible.
  - ⇒Large occupation #s for $k_T < Q_s$ ⇒ classcial fields
- Saturation is a result of unitarity in QCD





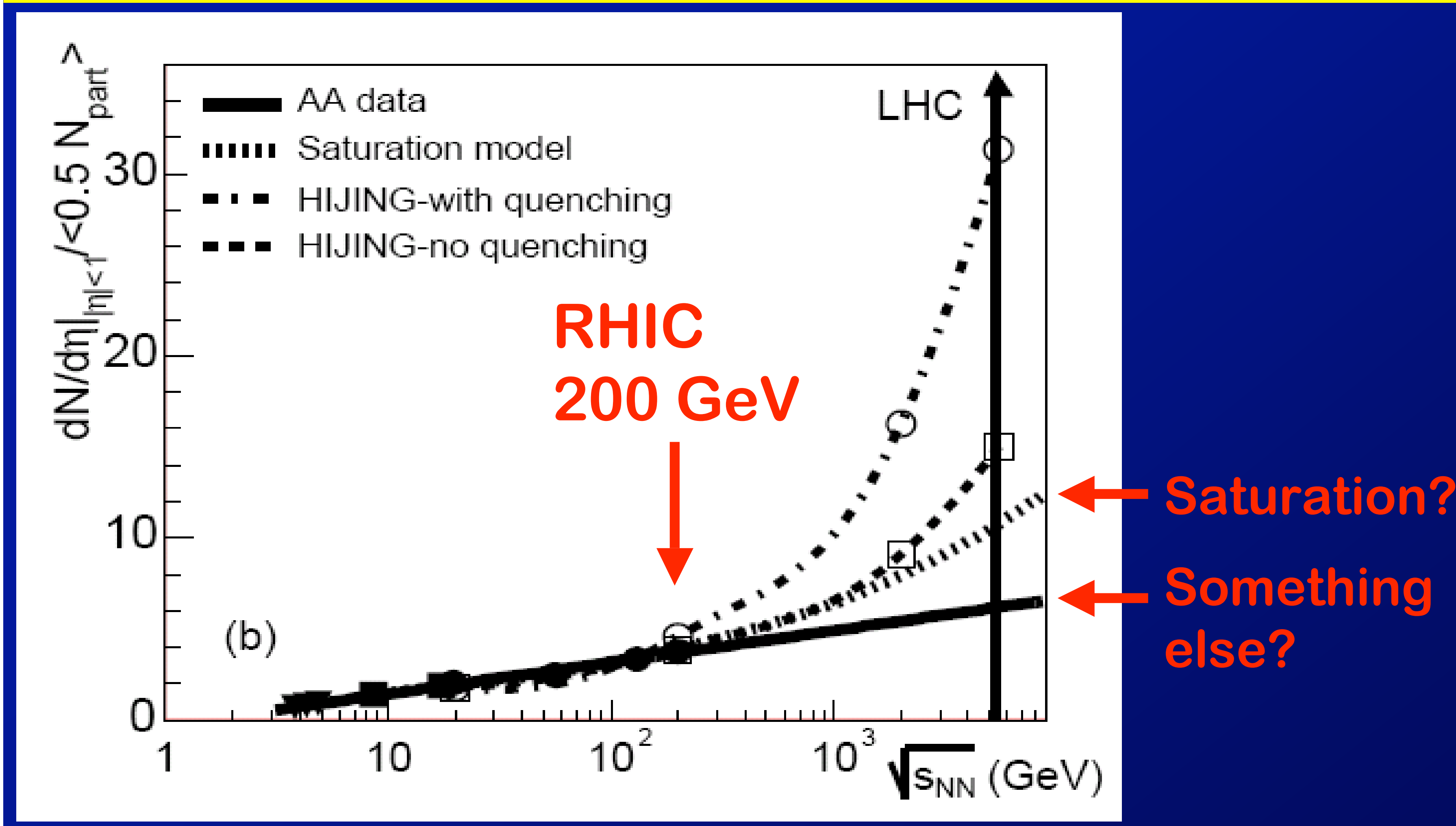
RHIC Particle Multiplicities





- Multiplicity @ RHIC on low end of predicted range
- Slow growth with impact parameter (N_{part})
  - Inconsistent with factorized mini-jet production
  - Best described by saturation model

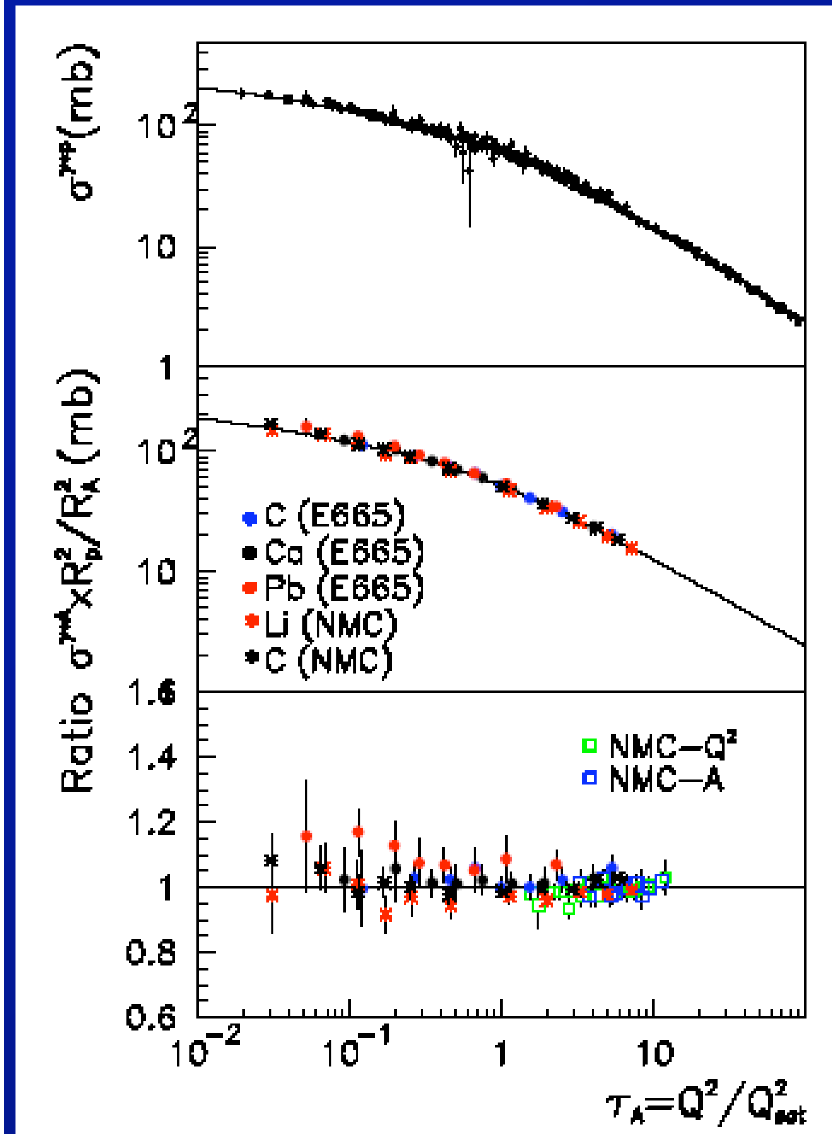
A+A Multiplicity @ LHC



- LHC measurements will provide an essential test of whether we understand the mechanism responsible for bulk particle production.
  - e.g. does saturation correctly extrapolate?

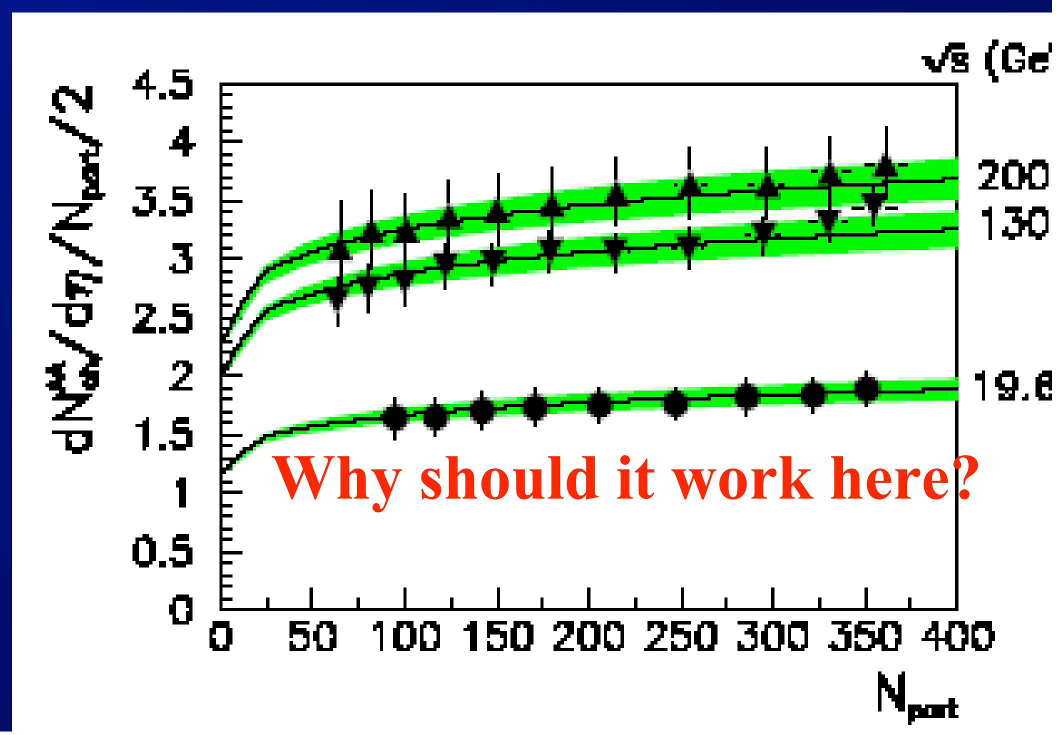
Saturation: Geometric Scaling to A-A?

Armesto, Salgado, Wiedemann
Phys. Rev. Lett. 94 :022002,2005

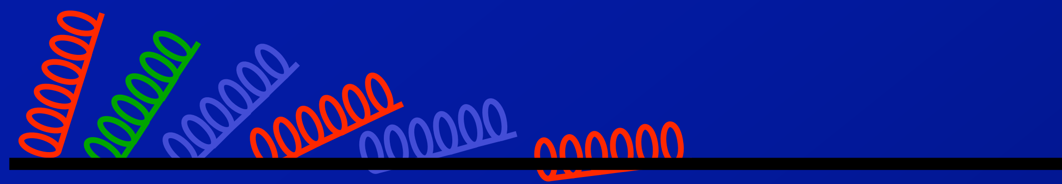


- Extension of GBW analysis to NMC nuclear targets
- Using k_T factorization calculate mult. **(parton-hadron duality)**
- Compare to PHOBOS data

$$Q^2_{\mathrm{sat,A}} = Q^2_{\mathrm{sat,p}} \left(\frac{A \pi R_p^2}{\pi R_A^2} \right)^{\frac{1}{\delta}}$$



(Quantum) Evolution of the CGC

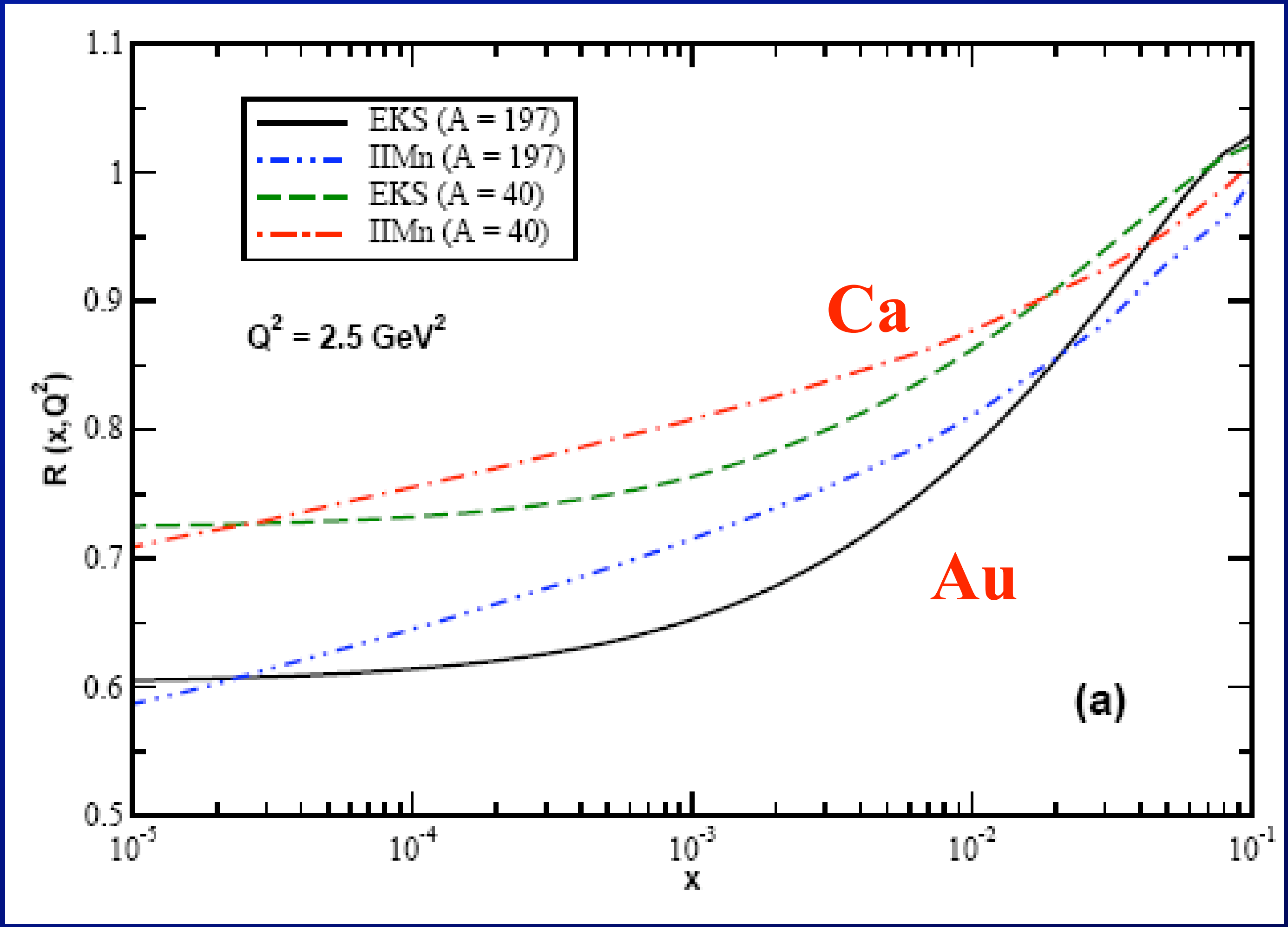


- Coherent emission of multiple gluons in QCD can be approximated by angular ordering of successive radiation
  - For large Q^2 processes, ordering in k_T (DGLAP)
  - For low-x, moderate Q^2, ordering in x (BFKL)
- Relevance of BFKL to available data (e.g. HERA) is controversial.
- But BFLK evolution is a critical component of most saturation calculations.
  - Natural framework for including recombination
- Saturation + BFKL evolution ⇒ shadowing

CGC: Gluon Shadowing

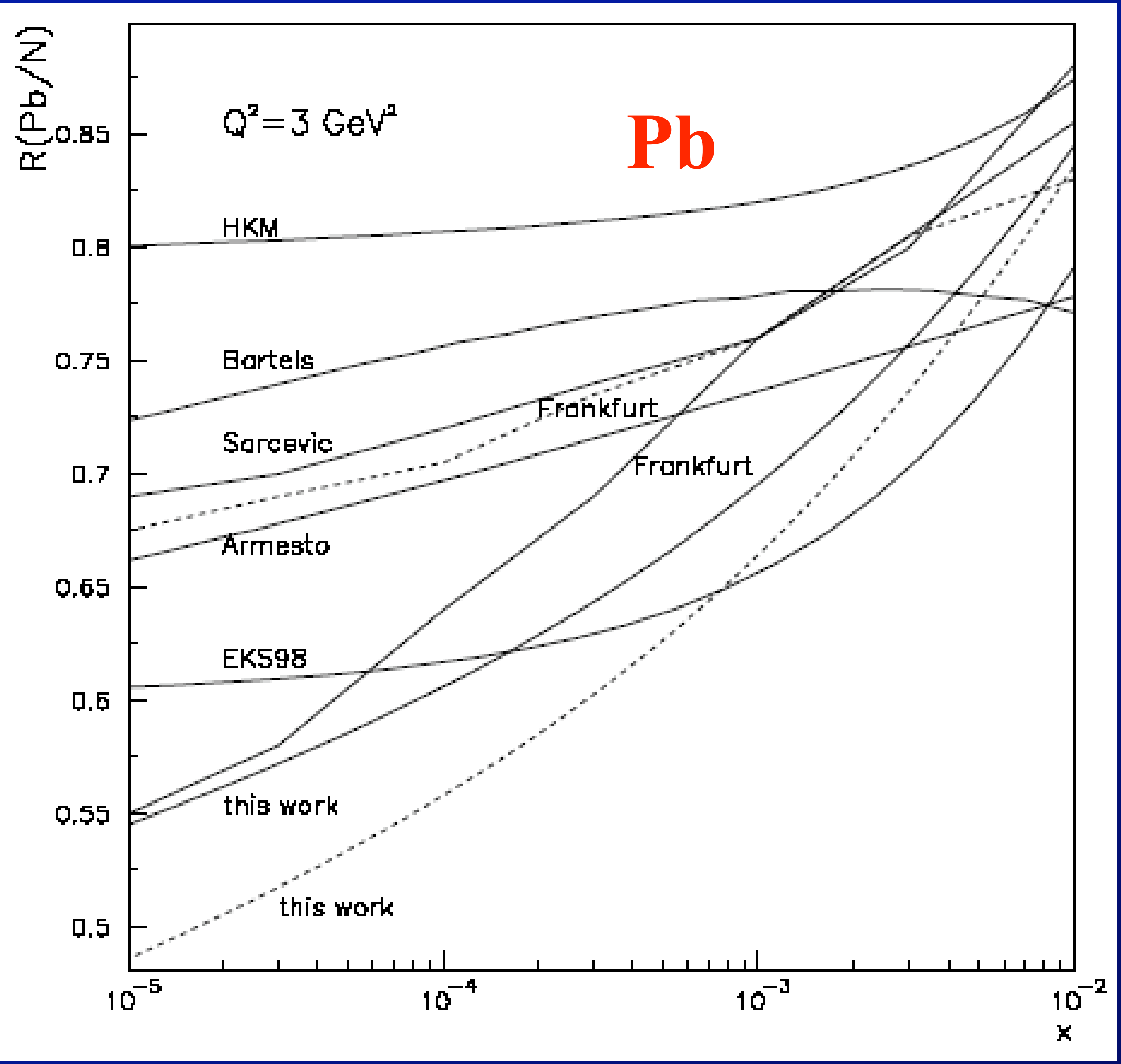
Saturation calculation by Kugeratski et al, hep-ph/058255

$$R = \frac{F_2^A}{AF_2^p}$$



- Given a saturation parameterization of proton DIS data and $Q_s^A \Rightarrow$ prediction of shadowing.

Many Shadowing Prescriptions



Compilation by Armetso, hep-ph/0604108

Many alternative approaches to understanding shadowing

All imply unitarity corrections

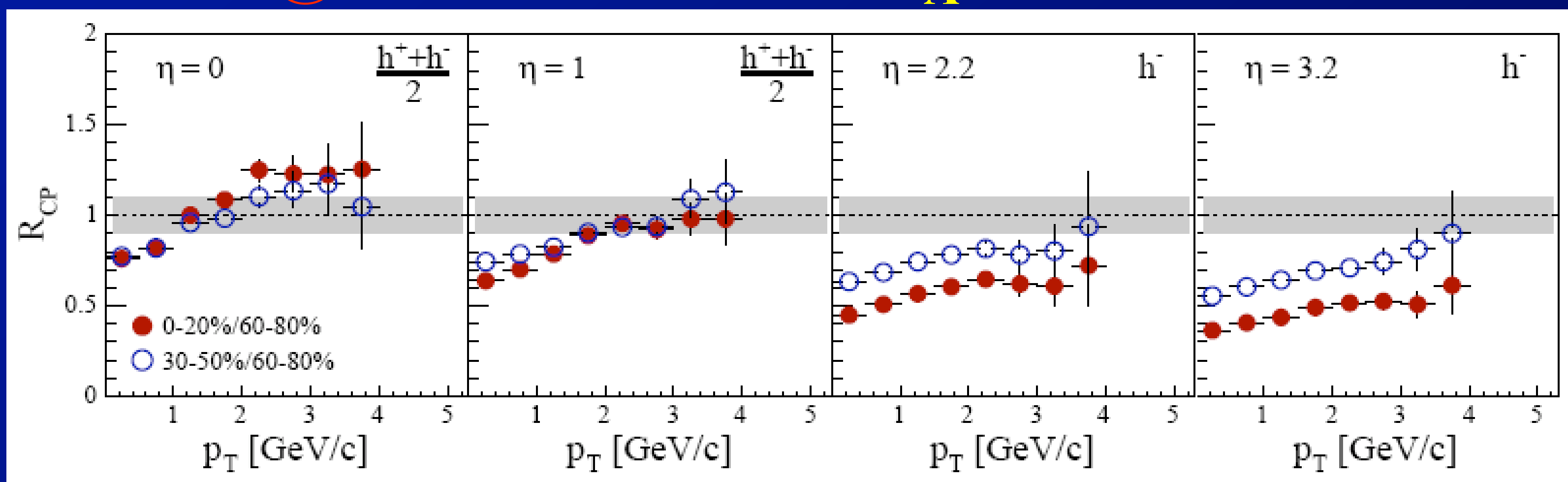
- **Huge disagreements for $x < 10^{-3}$**
  - **All nominally consistent w/ nuclear DIS data!**

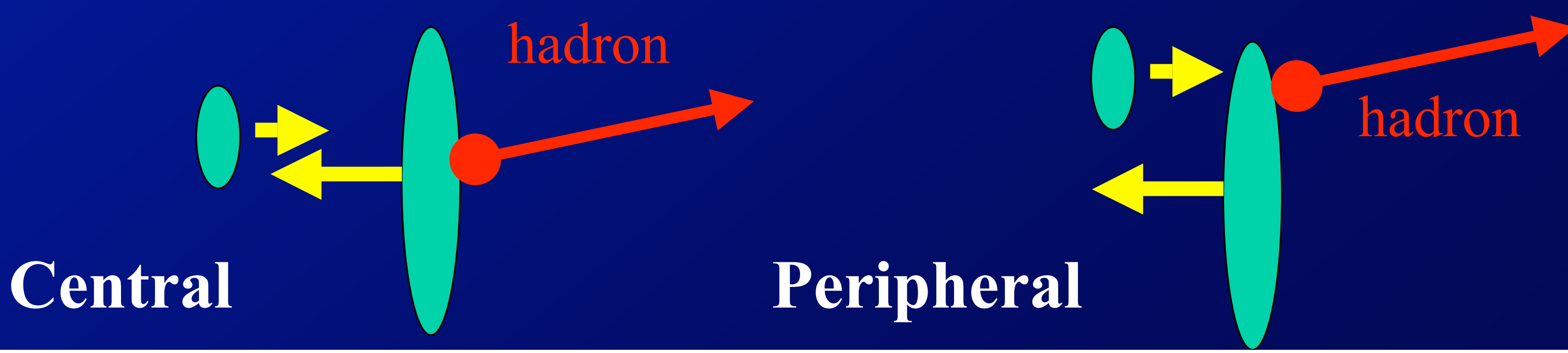
Saturation: proton(deuteron)-A

- p/d-A collisions provide an alternative way to study low-x processes in nuclei.
  - hadron production @ large rapidity **(small x_A)**

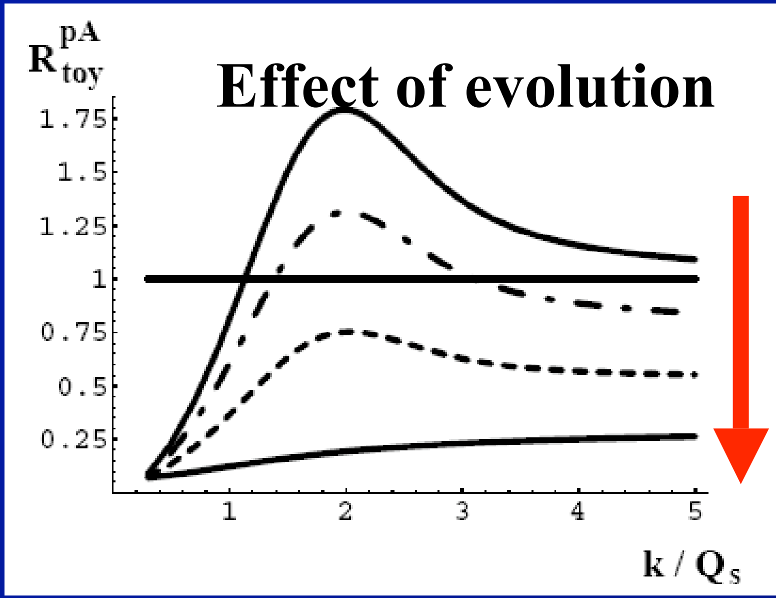
Brahms Data@ RHIC Smaller x_A →

Central to peripheral ratio

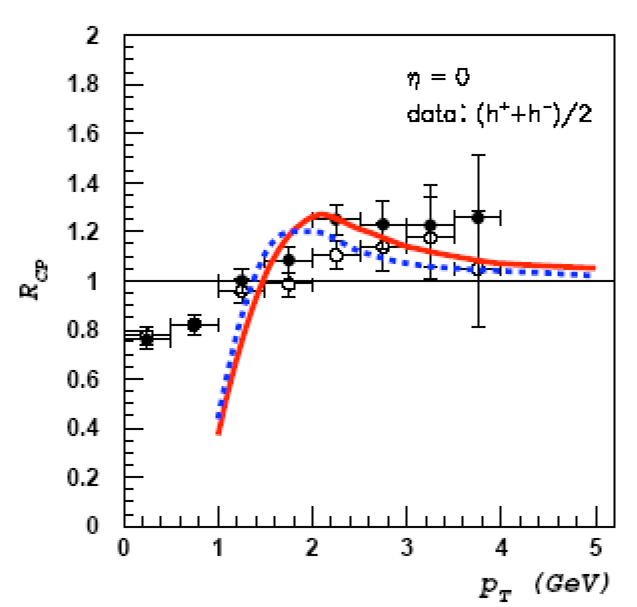


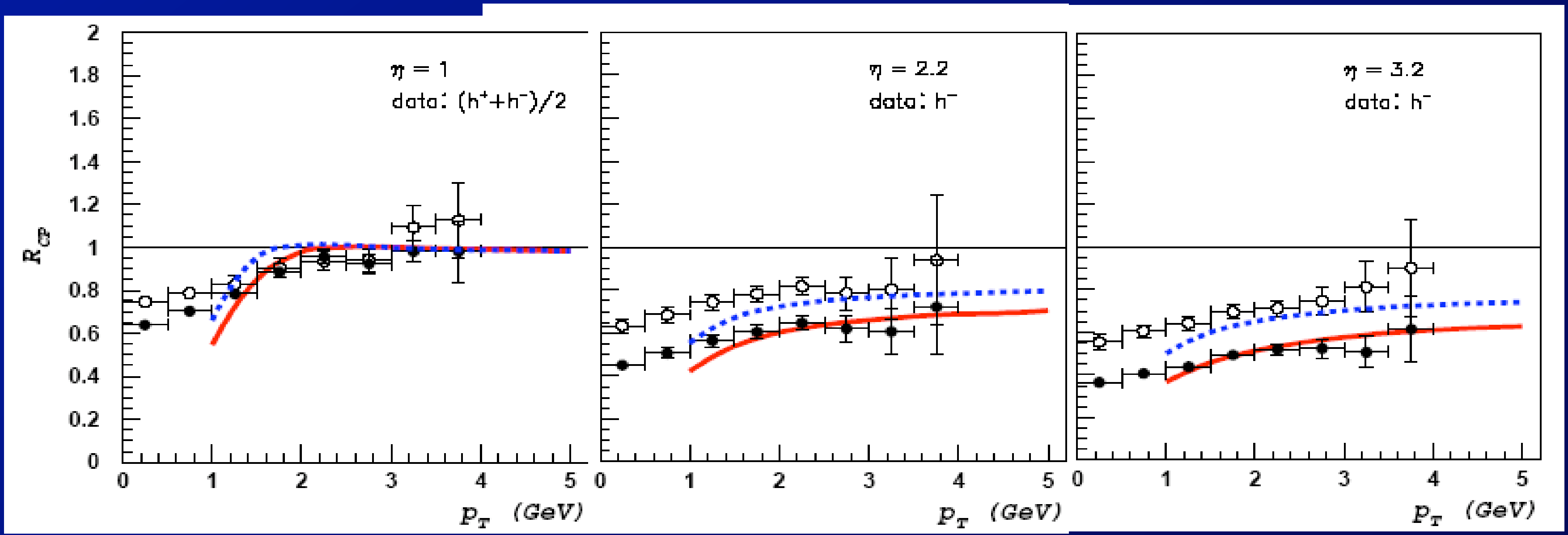


CGC w/ Evolution Compared to Data



Larger η, Lower x



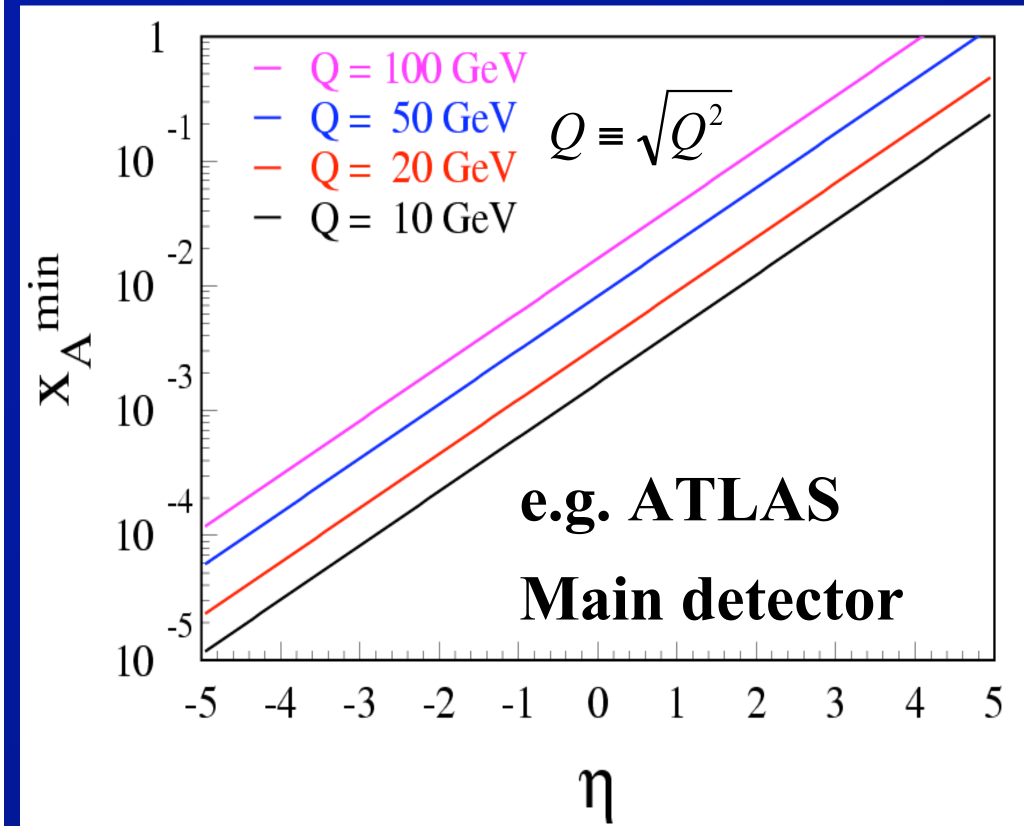


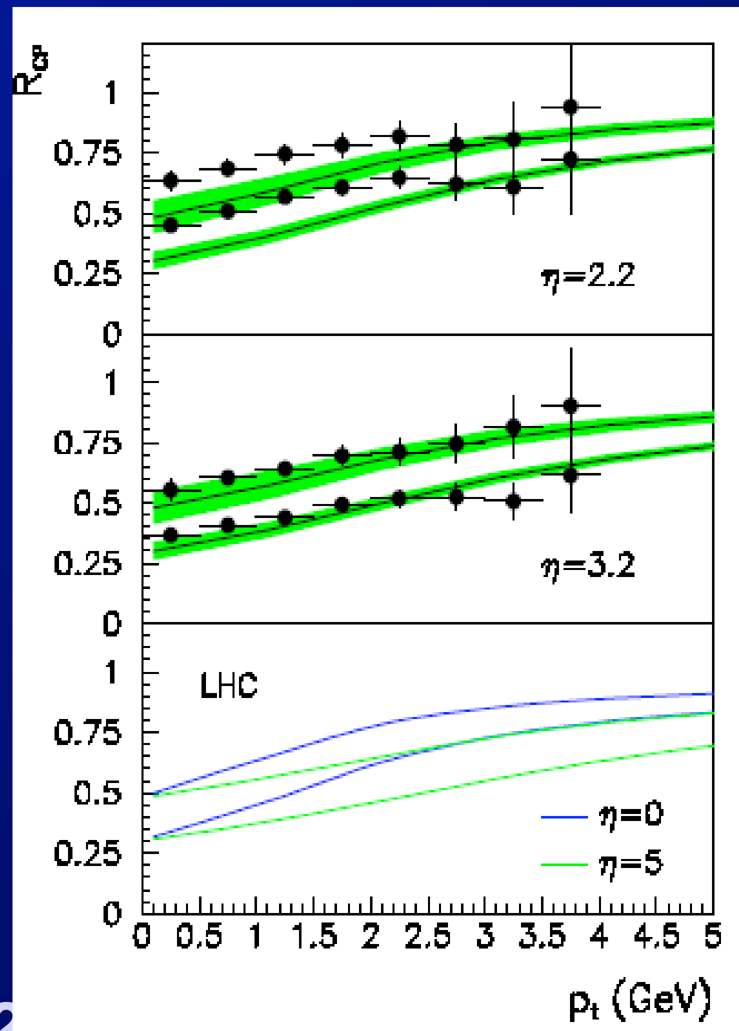
Are we seeing evolved CGC in d-A @ RHIC? Unclear

(Very) low x / Saturation @ LHC

Minimum accessible x (collinear kinematics)

Armesto, Salgado, Wiedemann,
Phys. Rev. Lett. 94:022002 (2005)





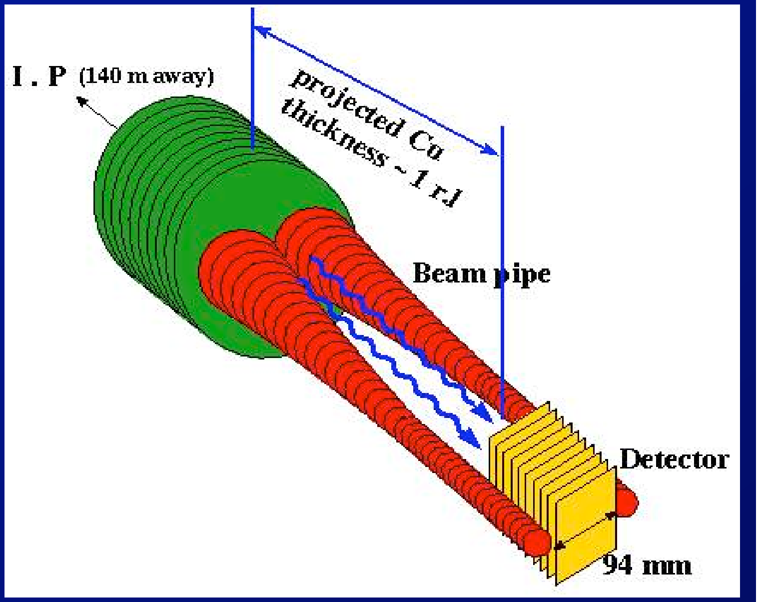
Can reach $x < 10^{-4}$

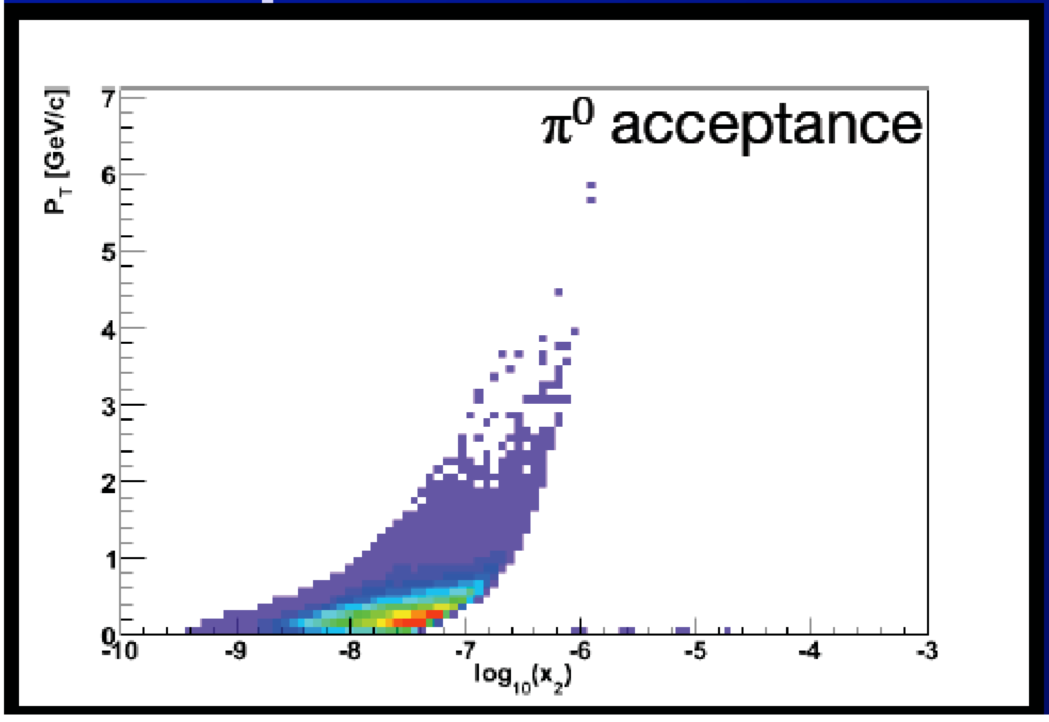
- **with p_T > 20 GeV jets, η < -3**
- **with 5 GeV single hadrons η~2.**

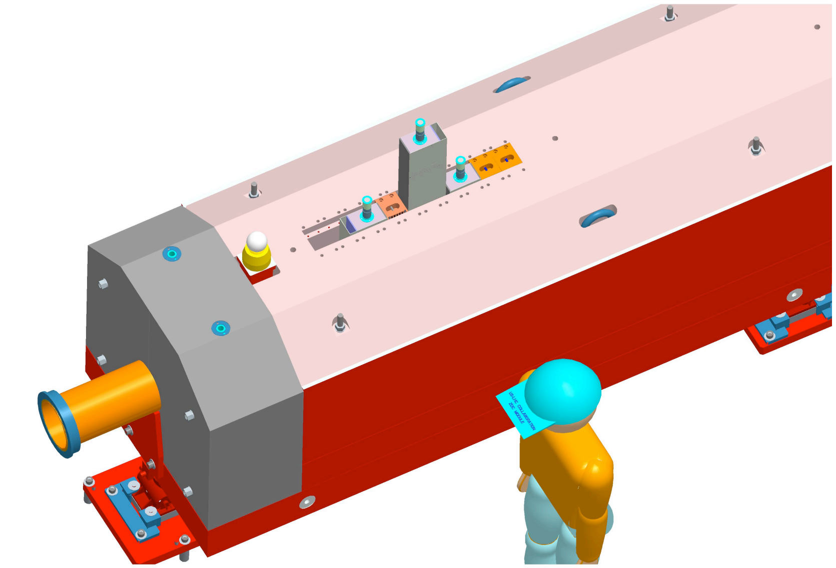
This does not take into account p-A rapidity shift

VERY Low x @ LHC

- e.g. ATLAS will measure π^0's in zero-degree calorimeter
- Coverage down to x ~ 10^{-7} for p_T ~ 2 GeV
- Also very forward acceptance for CMS







Low-x Physics: Motivation

- CGC + Quantum evolution provides compelling framework for analyzing low-x physics
  - New perturbative regime of QCD
  - Quantum evolution from non-Abelian classical fields a fundamental problem in field theory
  - Calculation of heavy ion initial conditions!(?)
- But, we can't yet be certain that it applies to any system that we will study in the laboratory

  ⇒p-p, p-A, A-A measurements @ LHC

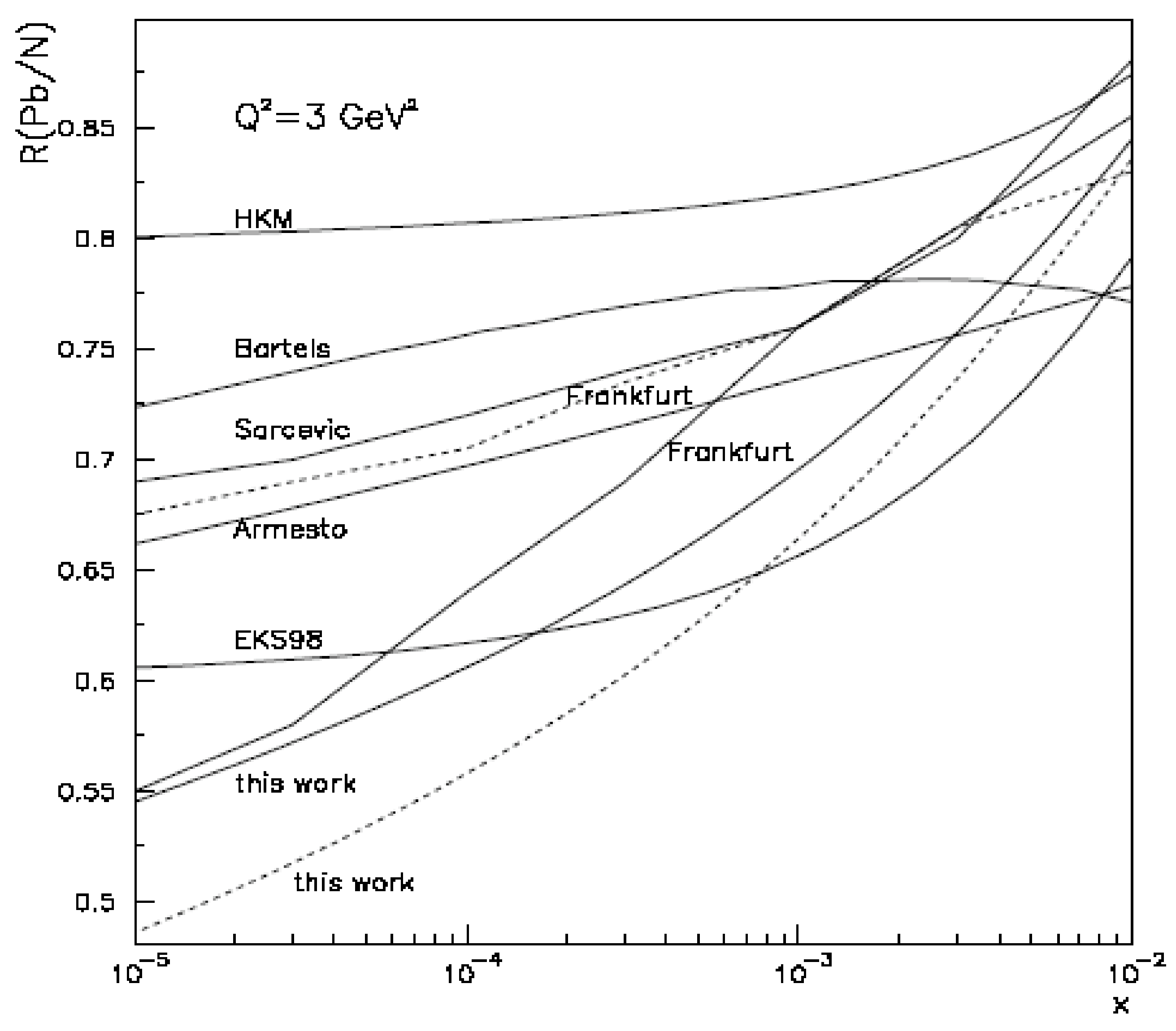
  » Will reach lower x (10^{-7}), but imprecise kinematics

  » Test application of BFKL evolution

  ⇒e-A measurements @ e-RHIC

  » Will reach less extreme x, but precise kinematics

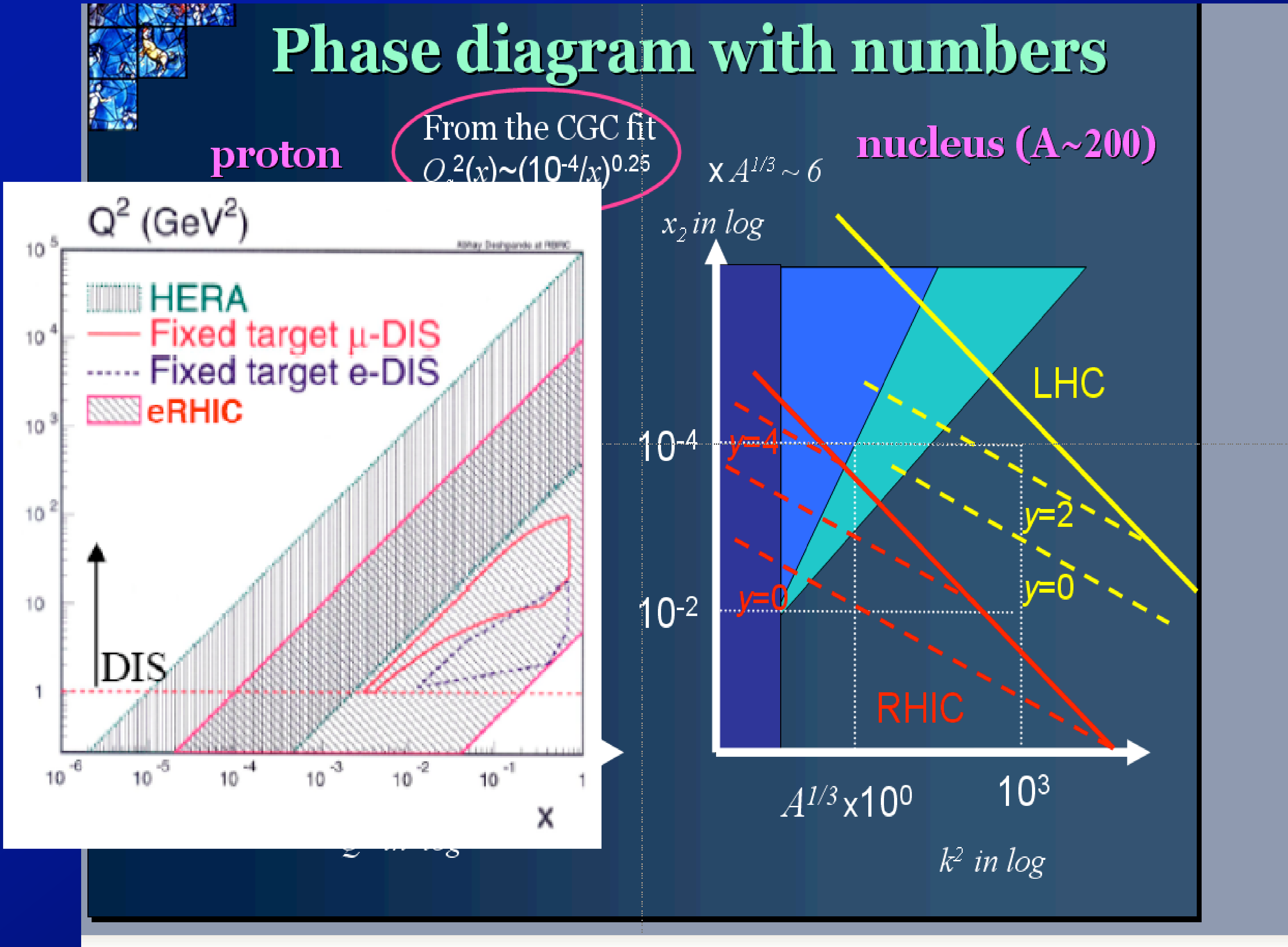
Low-x Physics: Motivation (2)



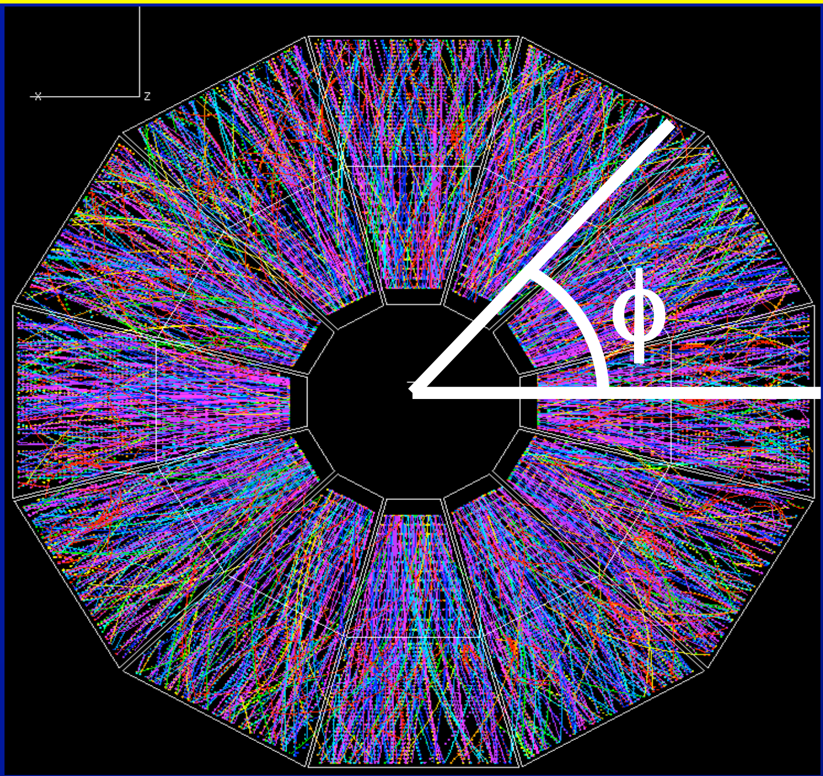
- **This cannot be allowed to persist ...**
- **If not e-RHIC, then how, where ????**

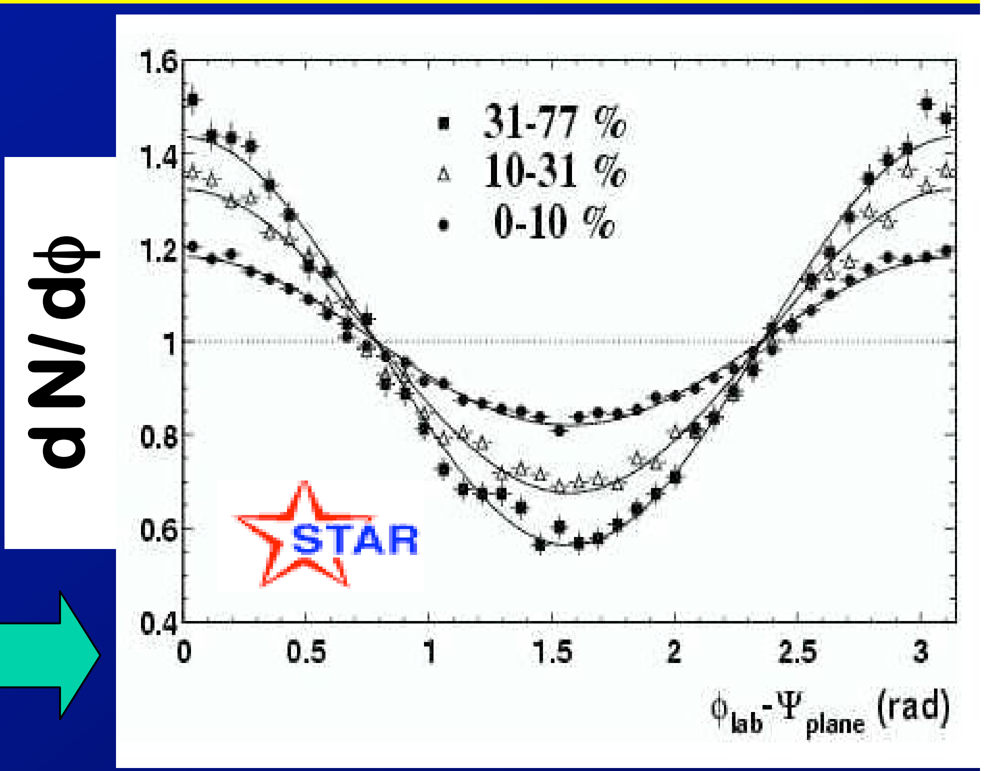
K. Itakura (QM 2005)

Phase diagram with numbers

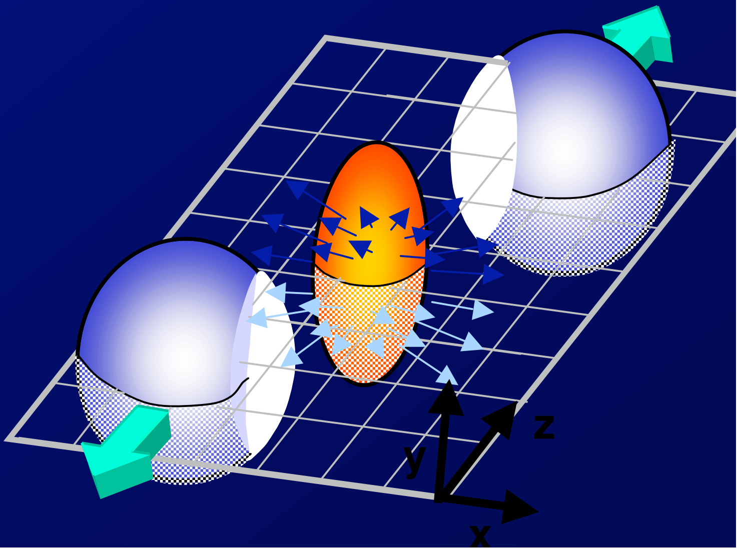


Collective Motion: Elliptic Flow

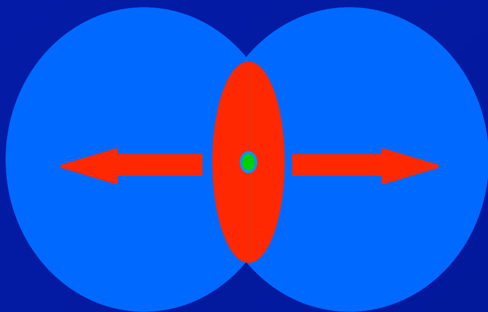




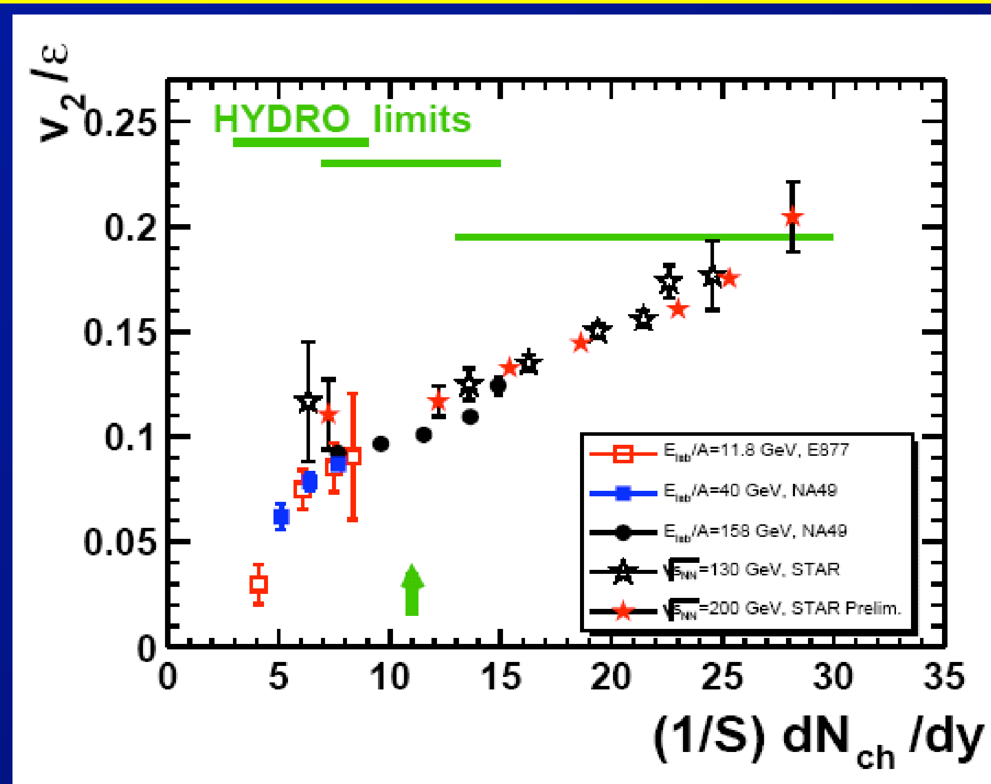
- Pressure converts spatial anisotropy to momentum anisotropy.
- Requires early thermalization.
- **Unique to heavy ion collisions.**



Elliptic Flow Systematics



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



- Quantify azimuthal anisotropy by "v_2"
  - $\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2\phi)$
- Compare to "eccentricity" (ε)
- Plot vs particle density / overlap area
- Data consistent w/ hydrodynamic calculations

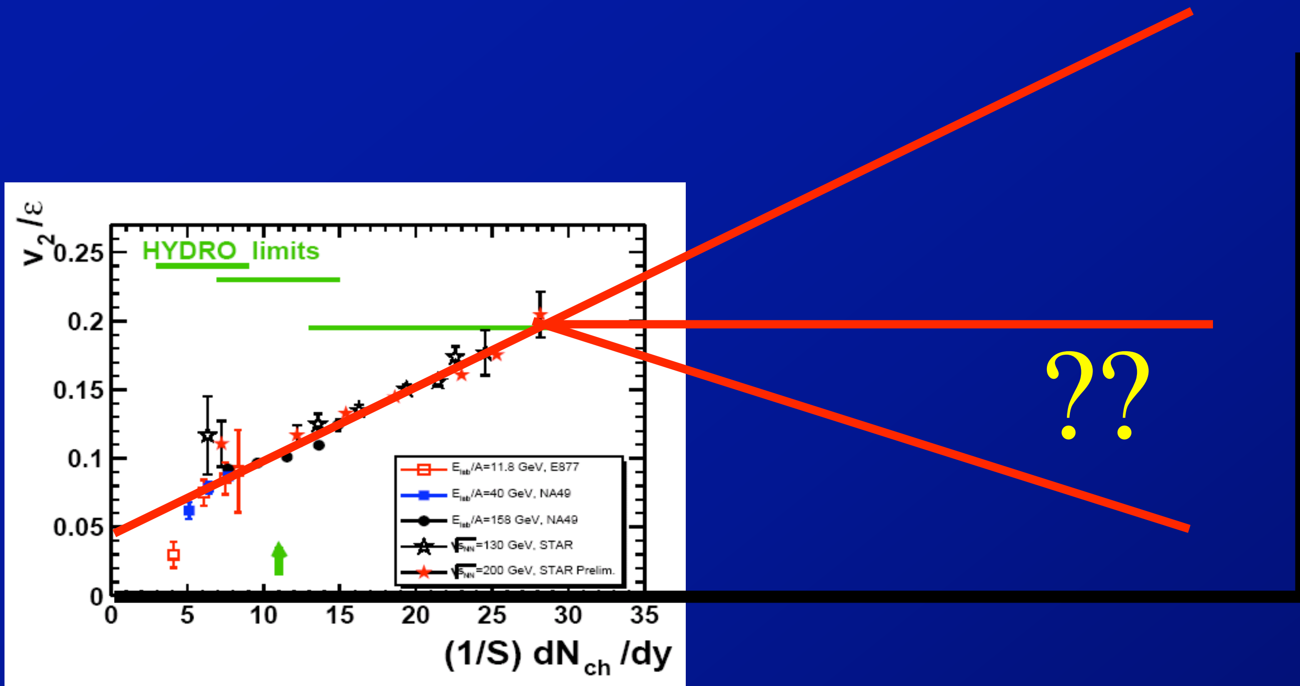
Why is this result so exciting?

- Elliptic flow data ⇒ thermalization in ~ 0.6 fm/c
  - Requires quark/gluon MFP ×10 lower than "expected"
  - Based on perturbative parton-parton cross-sections

    ⇒QGP exhibits non-trivial internal interactions

    ⇒Strongly coupled
- Why is this so important?
  - Unique opportunity to study fundamental theory in the strong coupling limit.
  - May provide an opportunity to test AdS/CFT correspondence (duality between black hole string theory and strongly coupled supersymmetric QCD in 4 dimensions)
  - Or extensions to gauge theories closer to QCD.

Elliptic Flow @ LHC

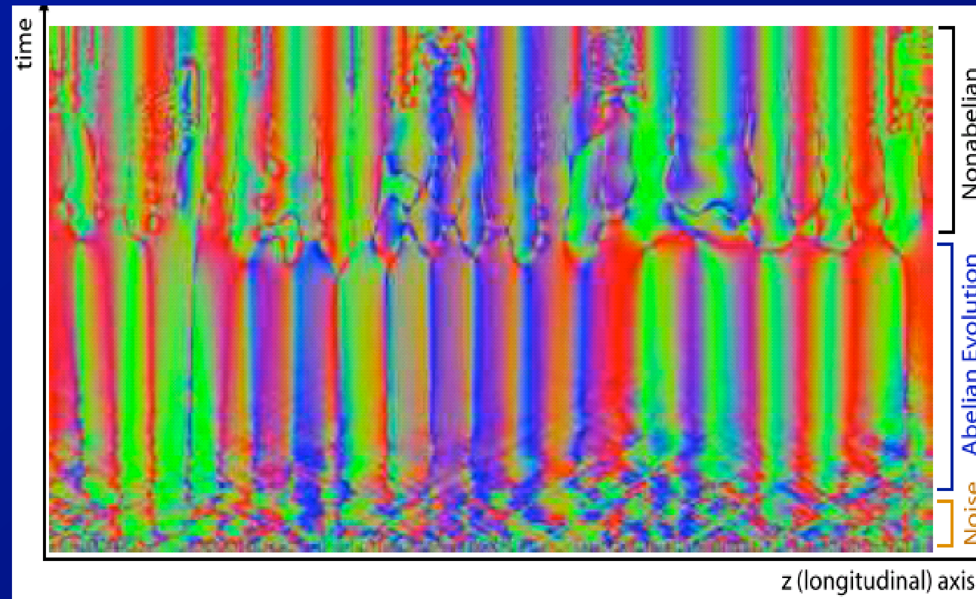


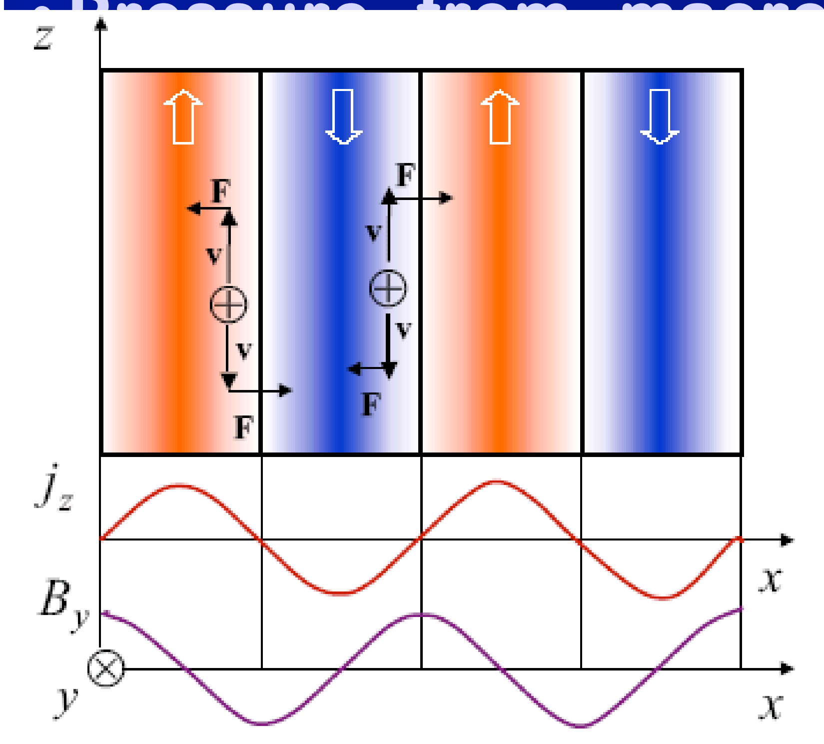
Can change horizontal scale by x2 @ LHC

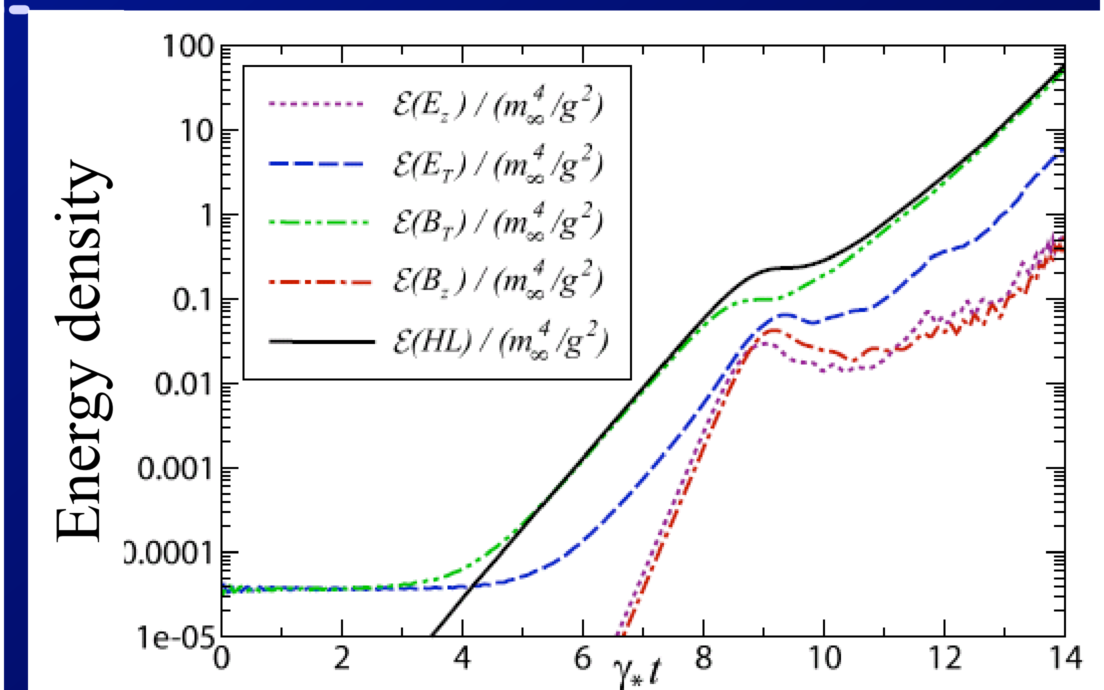
- LHC data will provide an essential test of our understanding of elliptic flow data @ RHIC
  - And test whether QGP is still strongly coupled
- But RHIC measurements may be able to provide unique insight
  - e.g. do thermal photons/di-leptons have flow imprint?

Thermalization via Plasma Instabilities?

- p_T vs p_z anisotropy
  - Generates strong local chromo-magnetic fields
  - Lorentz forces produce rapid isotropization.
- Pressure from macro-

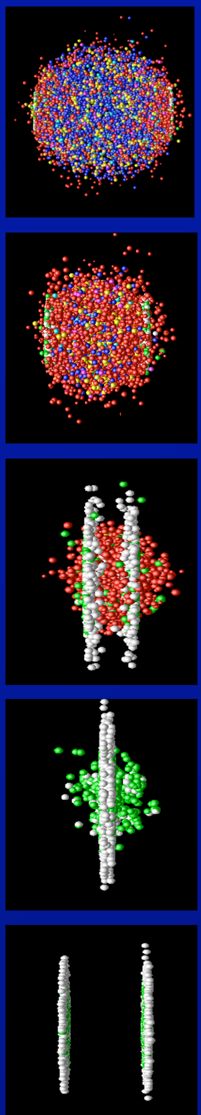


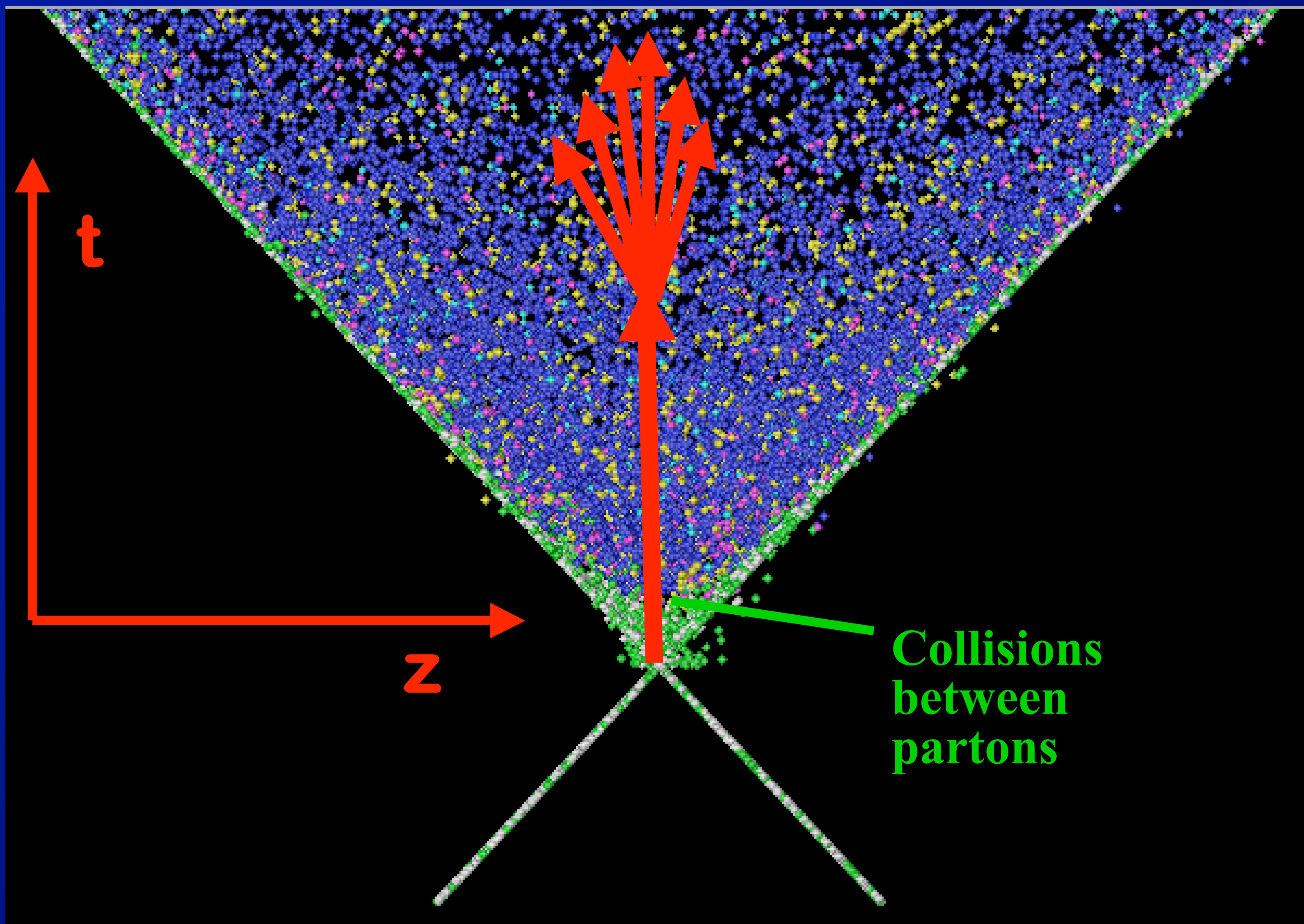




Penetrating Probes

RHIC collision space-time history in "parton cascade" model



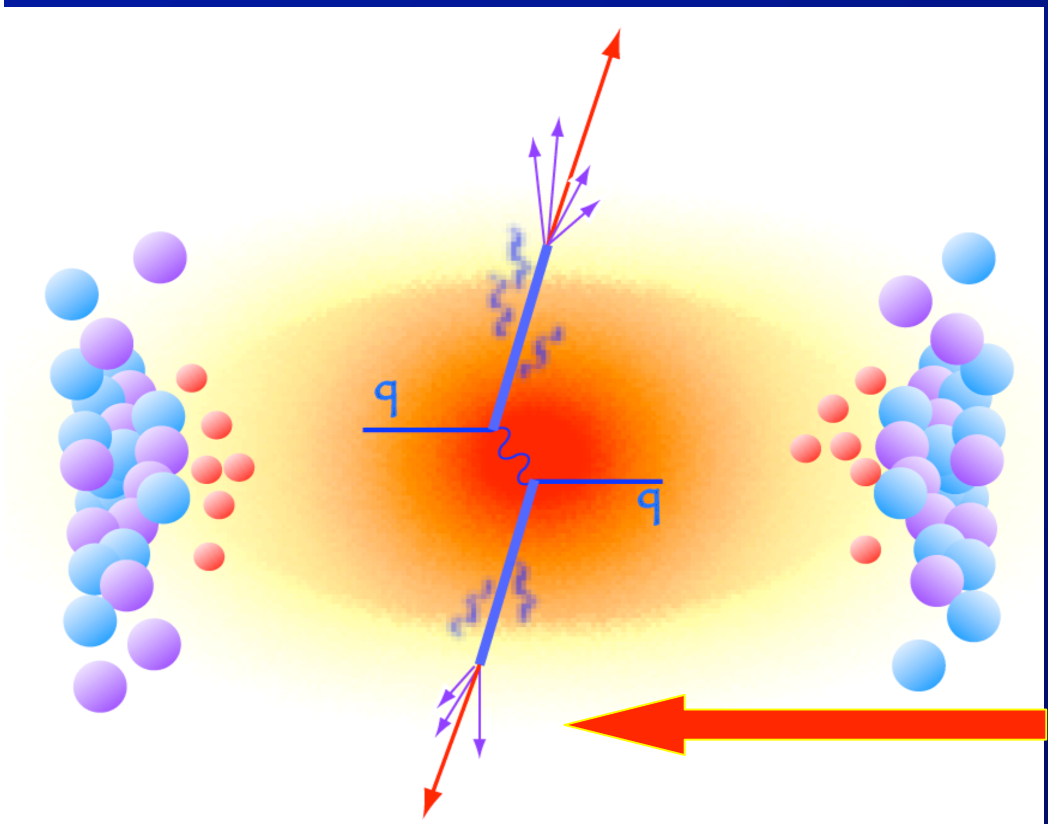


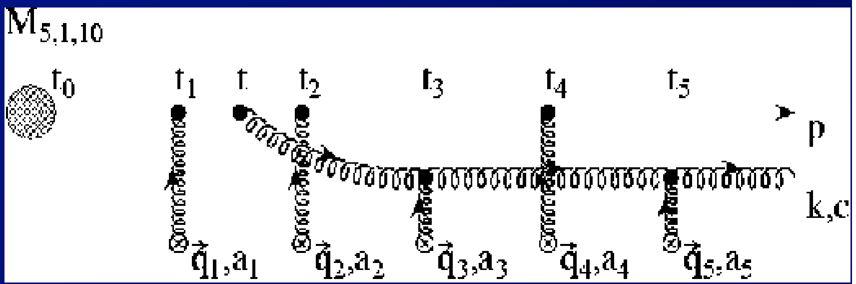
- Use self-generated hard quarks/gluons/photons as probes of initial (early) medium properties

"Jet Quenching" @ RHIC

- (QCD) Energy loss of (color) charged particle
  - Dominated by medium-induced gluon radiation (??)
  - Strong coherence effects for high-p_T jets

    ⇒Virtual gluons of high-p_T parton multiple scatter in the medium and are emitted



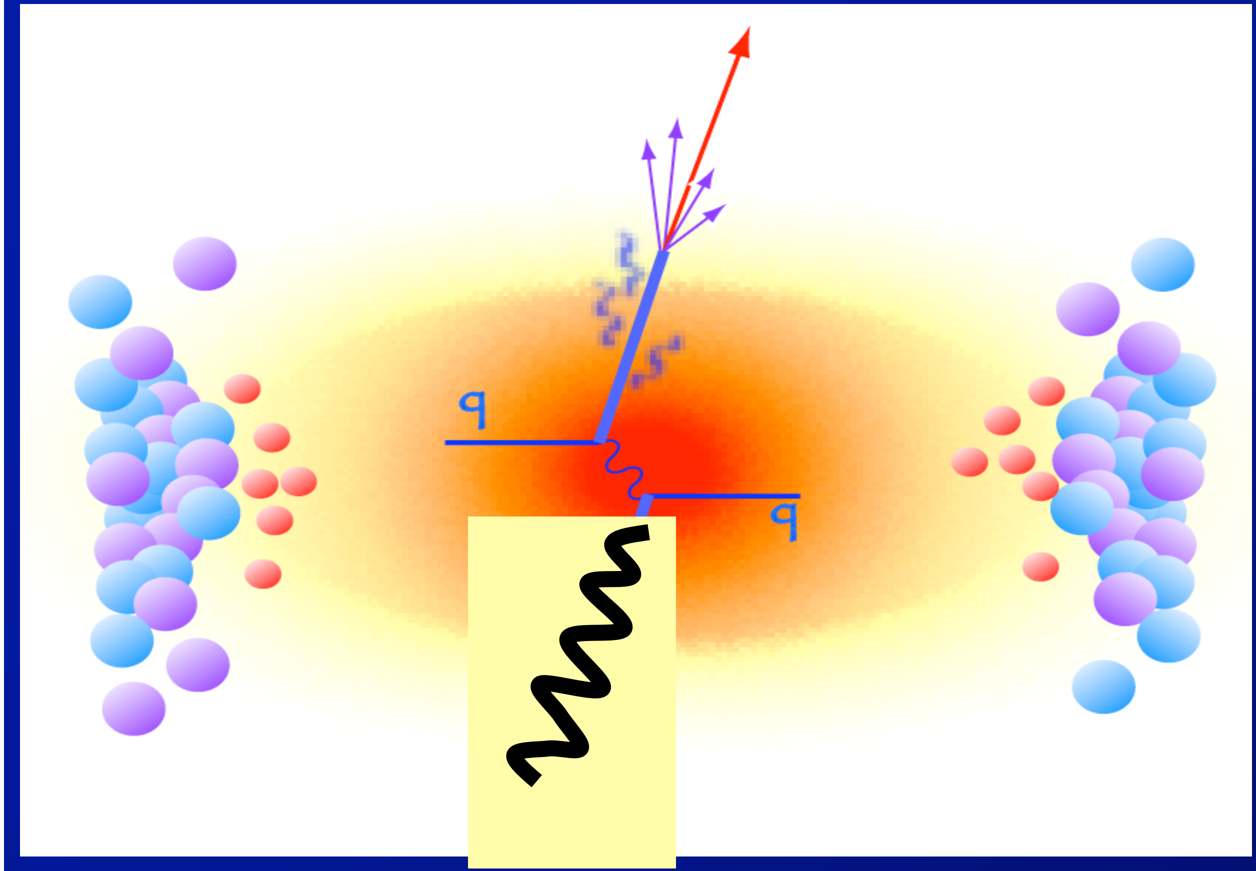


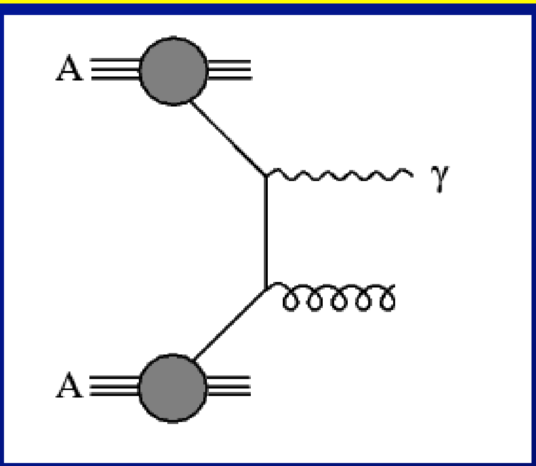
<u>@RHIC measure using:</u>

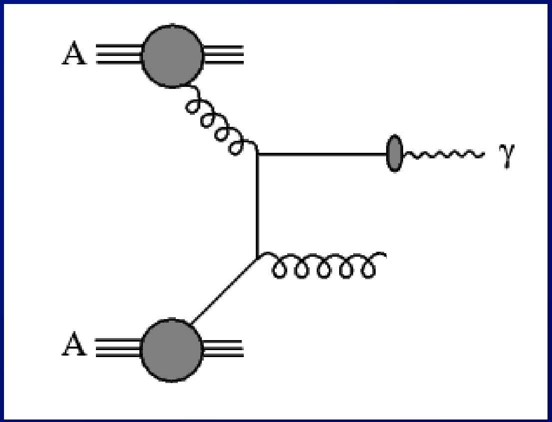
➢(Leading) high-$p_\perp$ hadrons

➢Di-jet correlations

Prompt Photon Production



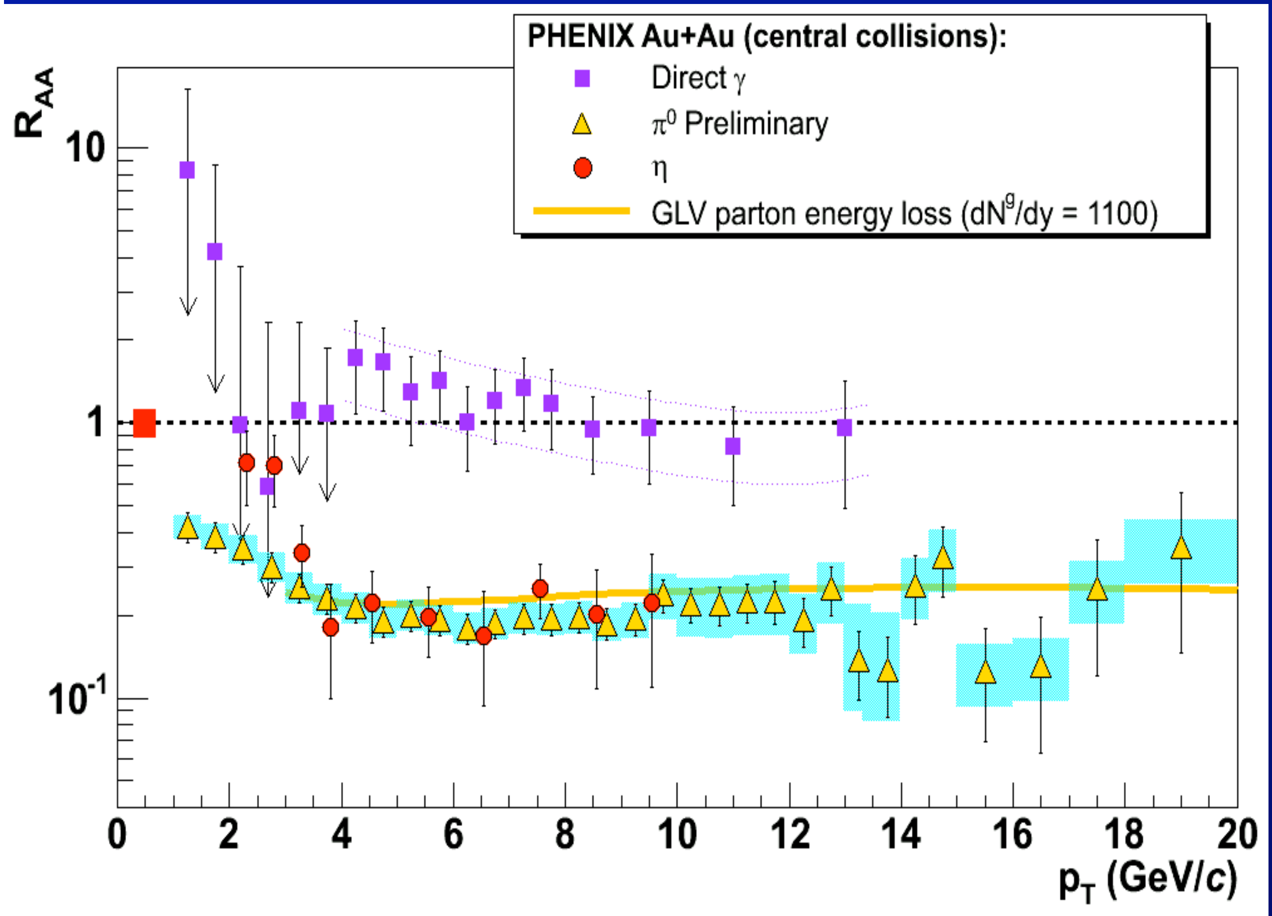




- Prompt photons provide an independent control measurement for jet quenching.
  - Produced in hard scattering processes
  - **But, no final-state effects (?)**

  ⇒ **Talk by Charles Gale on Saturday.**

High-p_T Single Particle Summary



To explain data need:

Unscreened color charge dn/dy~1000

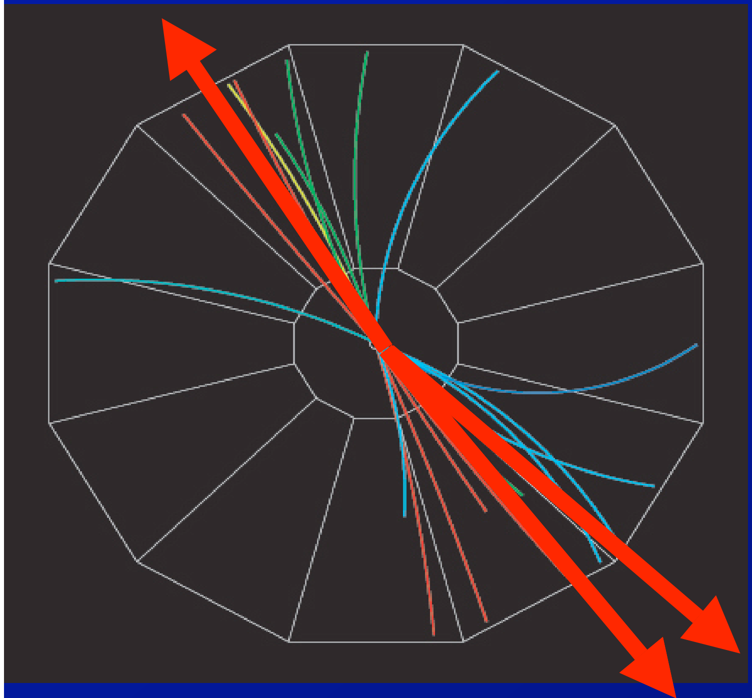
Initial energy density ~15 GeV/fm³

> ×10 "critical" energy density

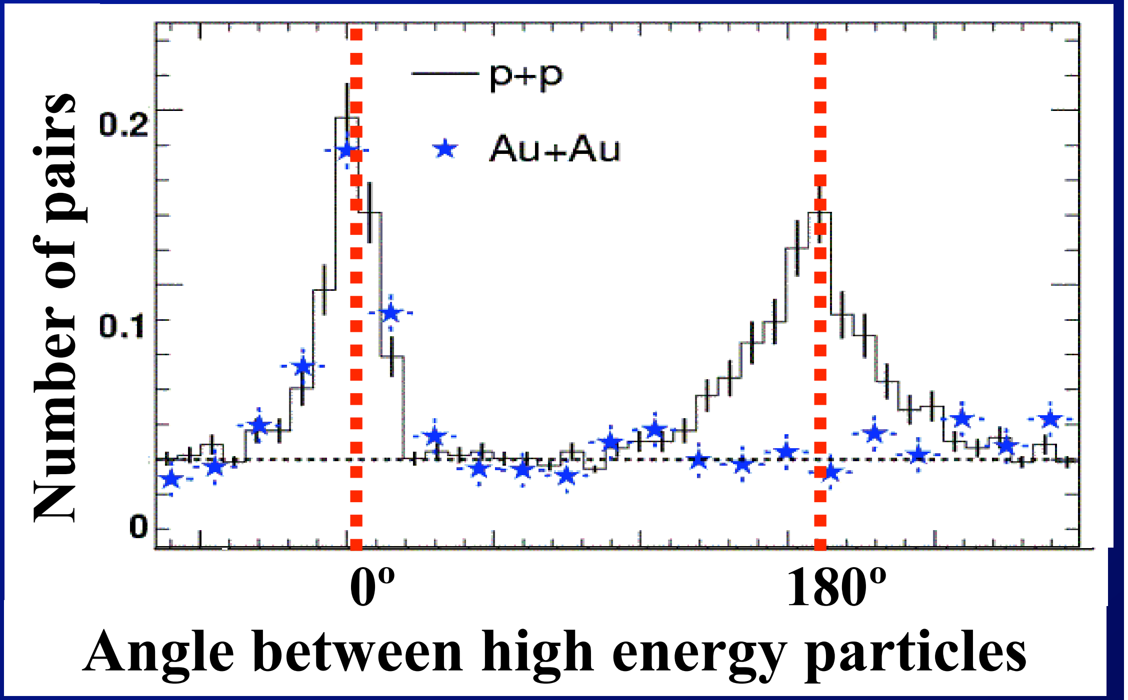
- ×5 violation of factorization up to 20 GeV/c
  - In hadron production (jets), but not prompt γ
    - ⇒Hard scatterings occur at expected rates
    - ⇒Suppression from final-state energy loss

STAR Experiment: Jet Quenching

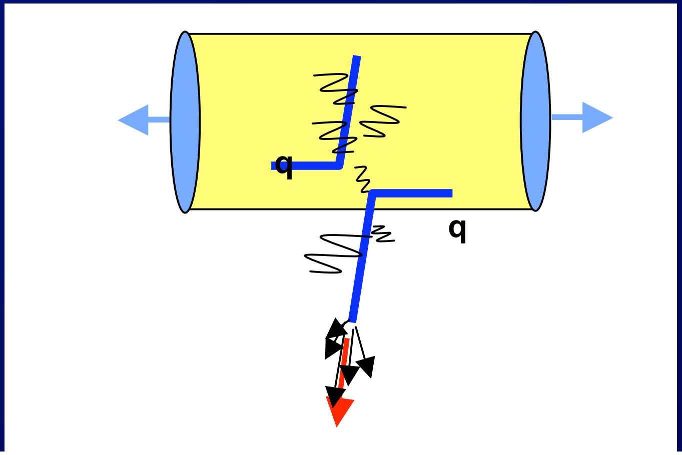
proton-proton jet event



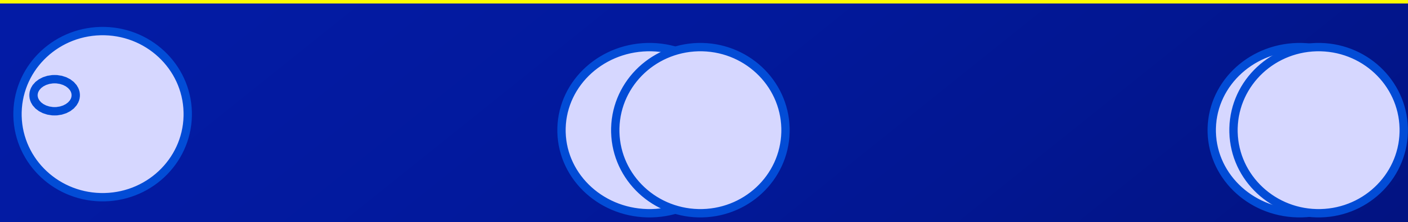
Analyze by measuring (azimuthal) angle between pairs of particles

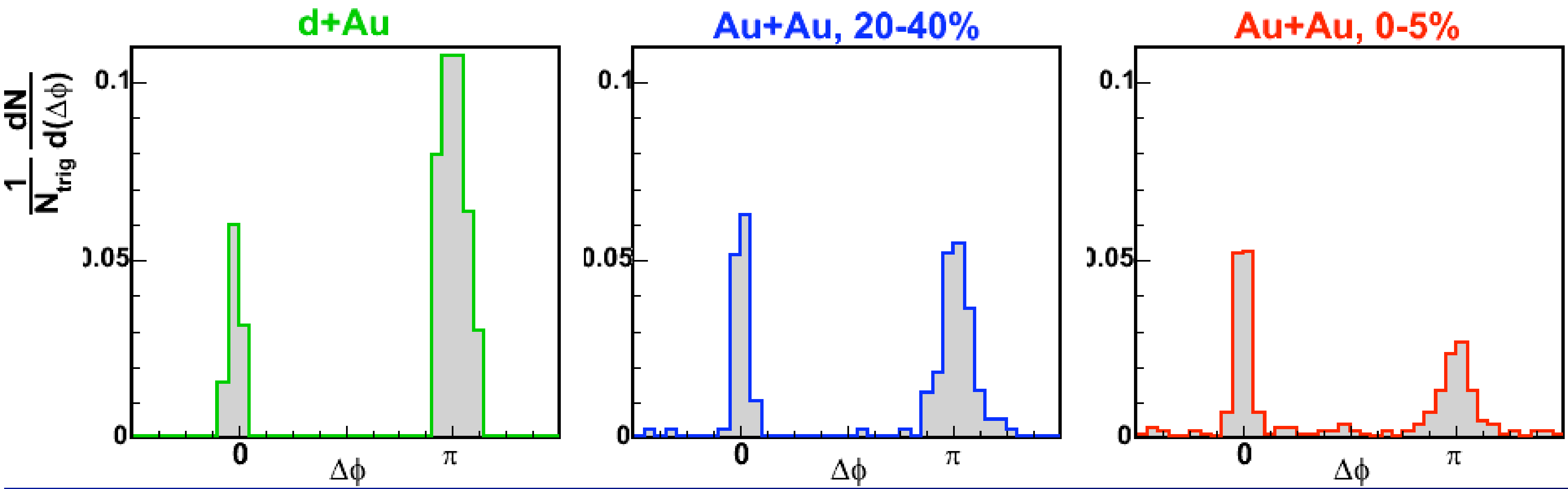


- **In Au-Au collisions we see only one "jet" at a time**
- **Strong jet quenching**
- **Enhanced by surface bias**



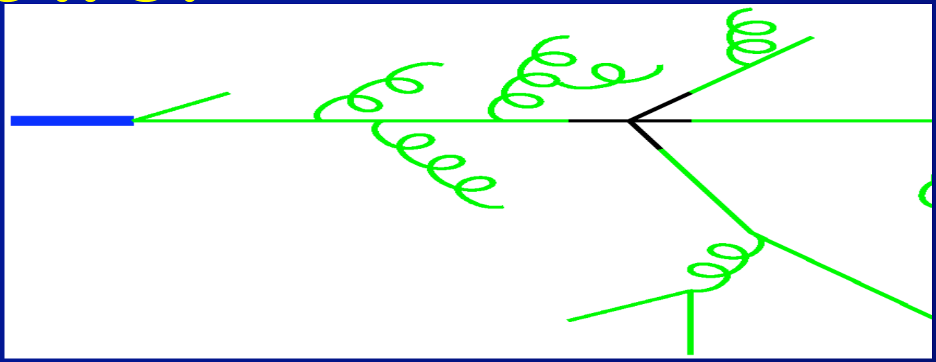
STAR: Jet "Re-emergence" @ High-p_T





- Study 2-hadron $\Delta\phi$ correlations vs system size
  - $p_{T1} > 8$ GeV, $p_{T2} > 6$ GeV $\Rightarrow$ very little background
- "jet" signal strength ~ constant (surface bias?)
- di-jet signal decreases – but doesn't go away.
  - Very important for quantitative analysis of quenching

Jet Quenching as Modified Parton Shower



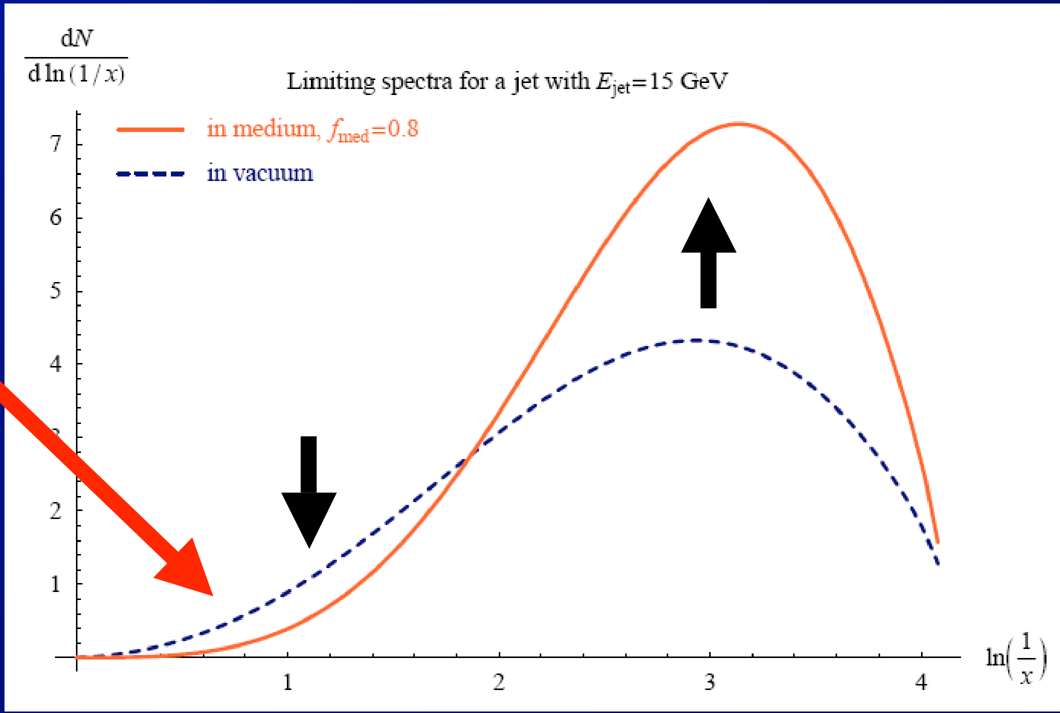
"Hump-back plateau"

Shape from pQCD (MLLA) parton shower calculation

First attempt to apply similar calculation to parton shower in thermal medium

Does angular ordering survive in plasma?

New angular scale?



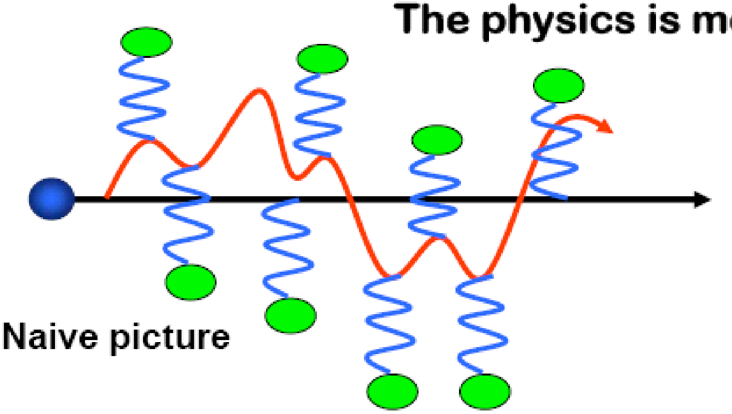
- Fundamental problem in QCD: how does thermal medium "regulate" radiation from quark/gluon?

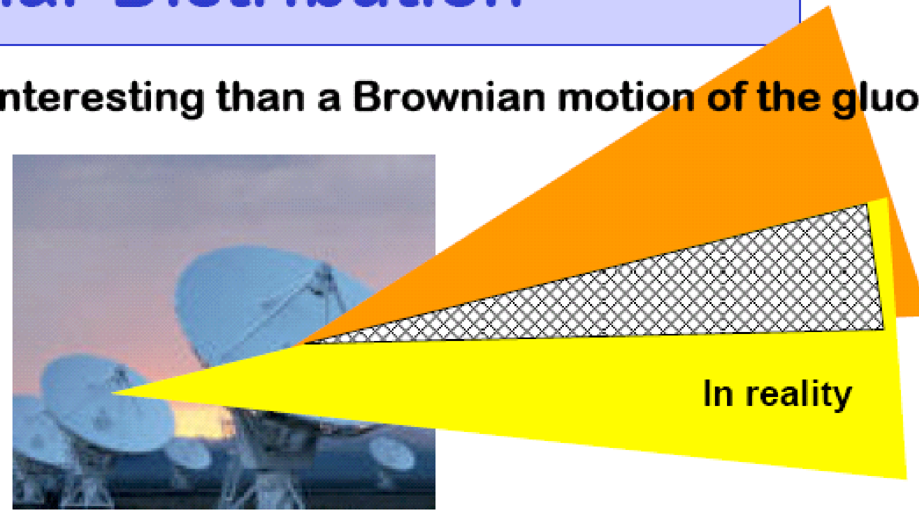
Another Perspective

Los Alamos NATIONAL LABORATORY

Angular Distribution

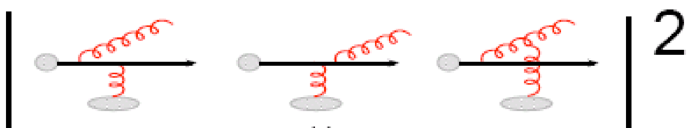
The physics is more interesting than a Brownian motion of the gluon





$i(-i) = 1 \qquad i\ (i) = -1 = \cos(\pi)$

$$\frac{dN^{g}{}_{med}}{d\omega d\sin\theta^{*} d\delta} \propto \left(|M_a|^2 + 2\,\mathrm{Re}\, M_b^{*} M_c \right) + \ldots$$



Solution to first order in the mean # of scatterings

$$\frac{dN^{g}{}_{med}}{d\omega d\sin\theta^{*} d\delta} \approx \frac{2C_R\alpha_s}{\pi^2} \int_{z_0}^{L} \frac{d\Delta z}{\lambda_g(z)} \int_0^{\infty} dq_\perp q_\perp{}^2 \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2 q_\perp}$$

$$\times \int^{2\pi} d\alpha \frac{\cos\alpha}{(\omega^2 \sin^2\theta^{*} - 2q_\perp \omega \sin\theta^{*} \cos\alpha + q_\perp^2)}$$

What happens when we embed a color antenna in a dense colored medium?

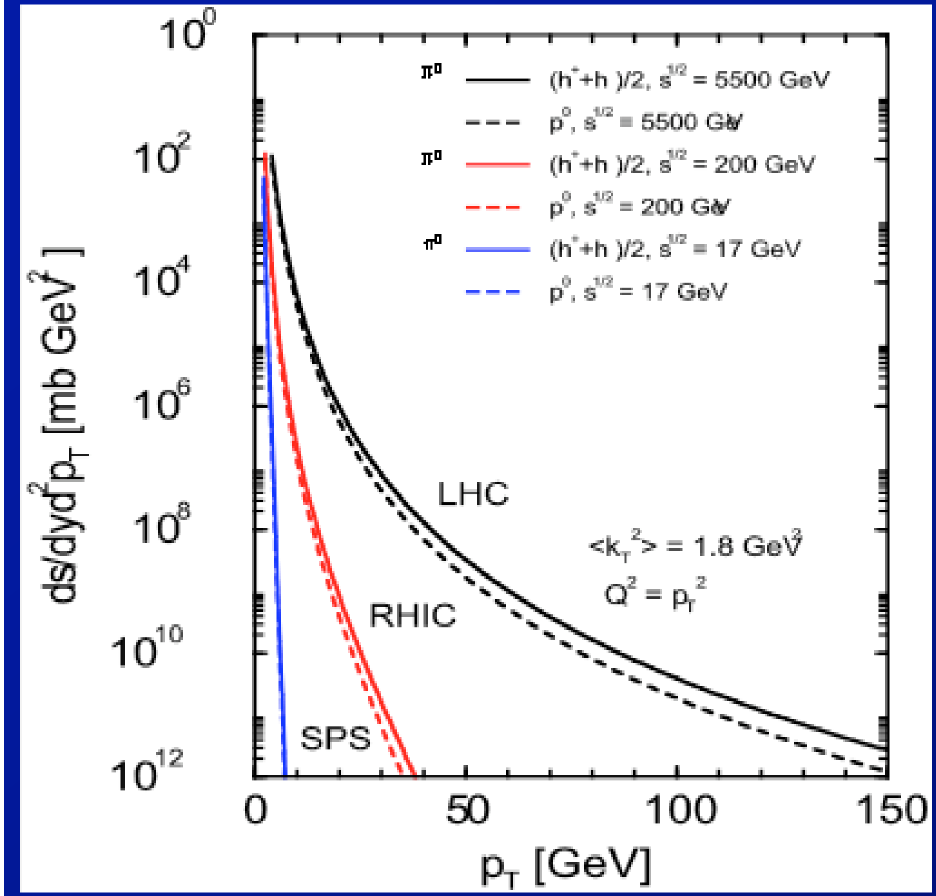
(b) (c)

Why Jets @ LHC?

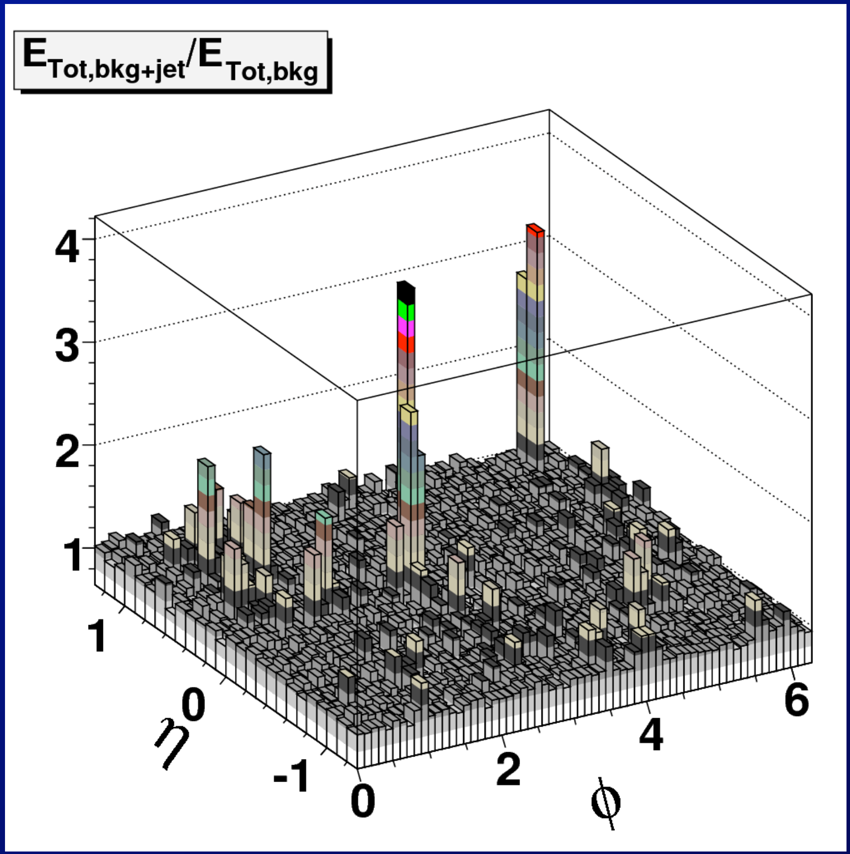
- There are uncertainties in our understanding of jet quenching @ RHIC
  - Role of geometry (geometric fluctuations)
  - Role of fluctuations in # of radiated gluons
  - Thin plasma or thick plasma?
  - Role of radiative energy loss
- Full jet reconstruction will help resolve some of these ambiguities

  ⇒LHC and RHIC II
- Heavy quarks are helping, though we don't yet understand experimental data
  - Too much quenching in data compared to calculations
- But real insight on jet quenching will likely draw on data from both RHIC & LHC

Why Jets @ LHC? Rate @ High p_T



80 GeV Jet in Pb+Pb



- Can access jet energies in excess of 100 GeV
  - Study how jet quenching is "quenched" at large jet energy → restoration of factorization

RHIC, e-RHIC, LHC

- RHIC, e-RHIC, LHC programs are/will address some of the most fundamental outstanding problems in QCD

1) How does QCD manifest itself in deconfined matter?
2) How does non-Abelian, strongly interacting matter behave at different T?
3) How does a (thermal) medium modify the parton shower of an energetic quark or gluon?
4) What happens when we change the initial conditions of PDF evolution at high energy (low x)?
5) Can we use CGC + evolution to predict shadowin, particle production in hadronic scattering, ...

¬ RHIC and LHC address 1-5

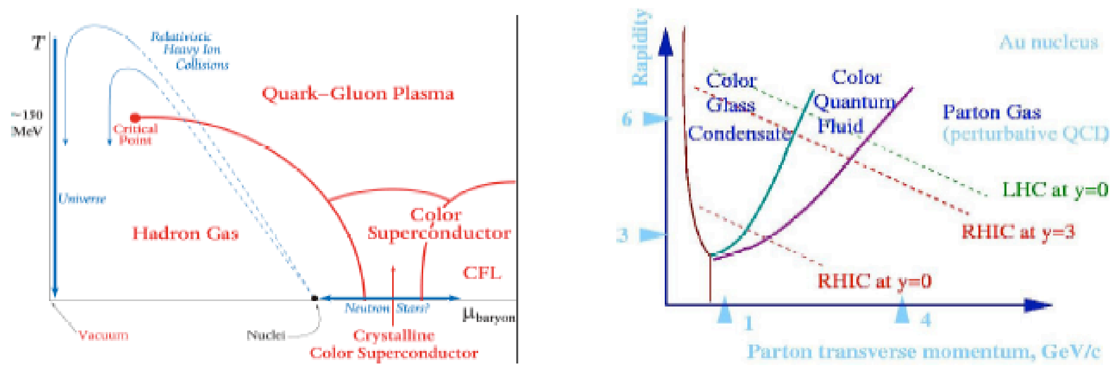
¬ e-RHIC addresses 4, 5 with precision

RHIC II

Science for the Future of RHIC

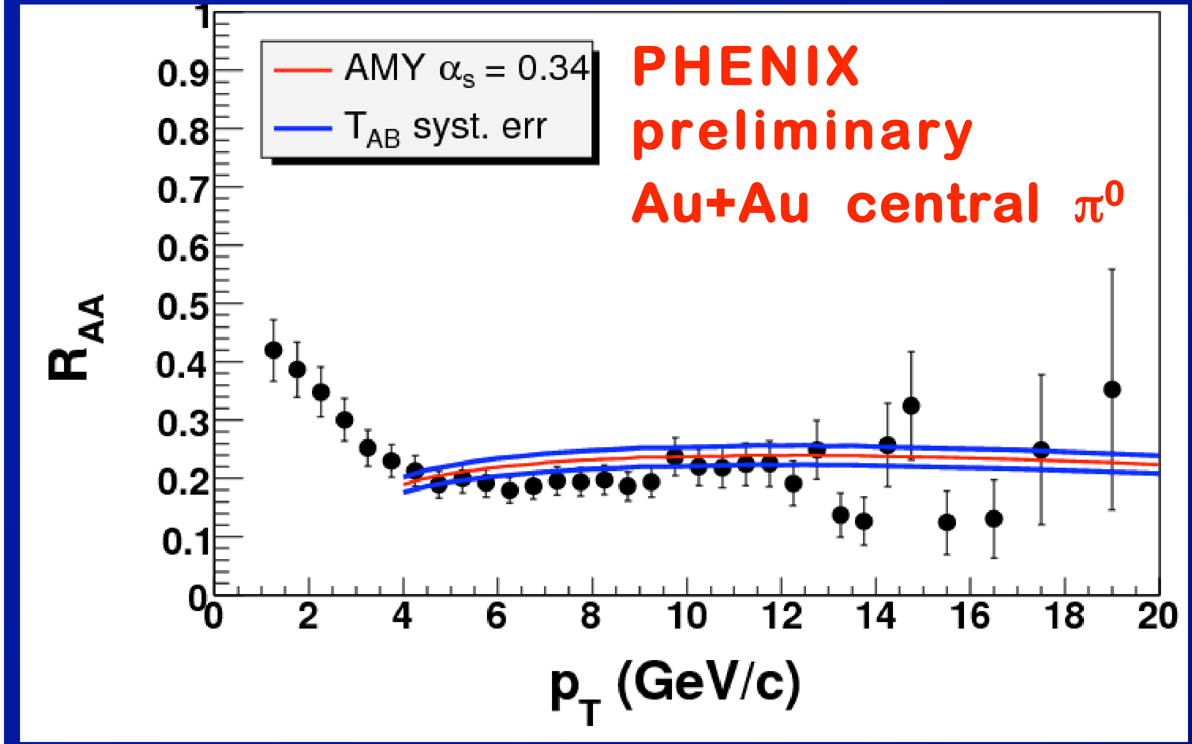
Summary of the RHIC II Science Working Groups

<u>Draft version: June 12, 2006</u>



- RHIC does NOT become irrelevant when LHC starts taking data (probably 2009, maybe 2008)
- Any "Understanding" of LHC results must be tested against RHIC conditions to be robust
- LHC results will stimulate new ideas @ RHIC

Analysis of Single Hadron Data: AMY



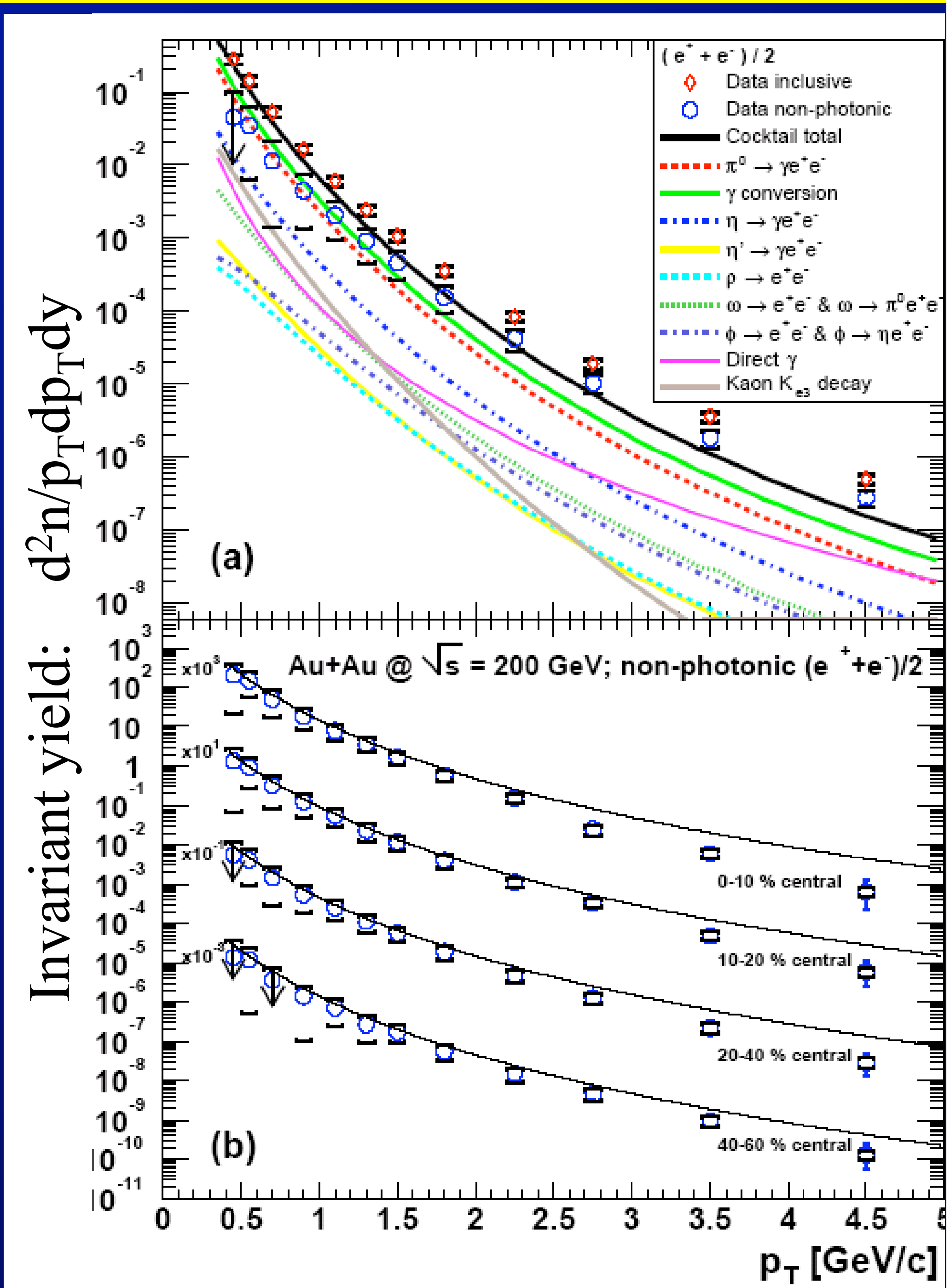
QCD transport calculation by Arnold, Moore, Yaffe (AMY)

Applied to jet quenching by Turbide *et al*, hep-ph/0502248

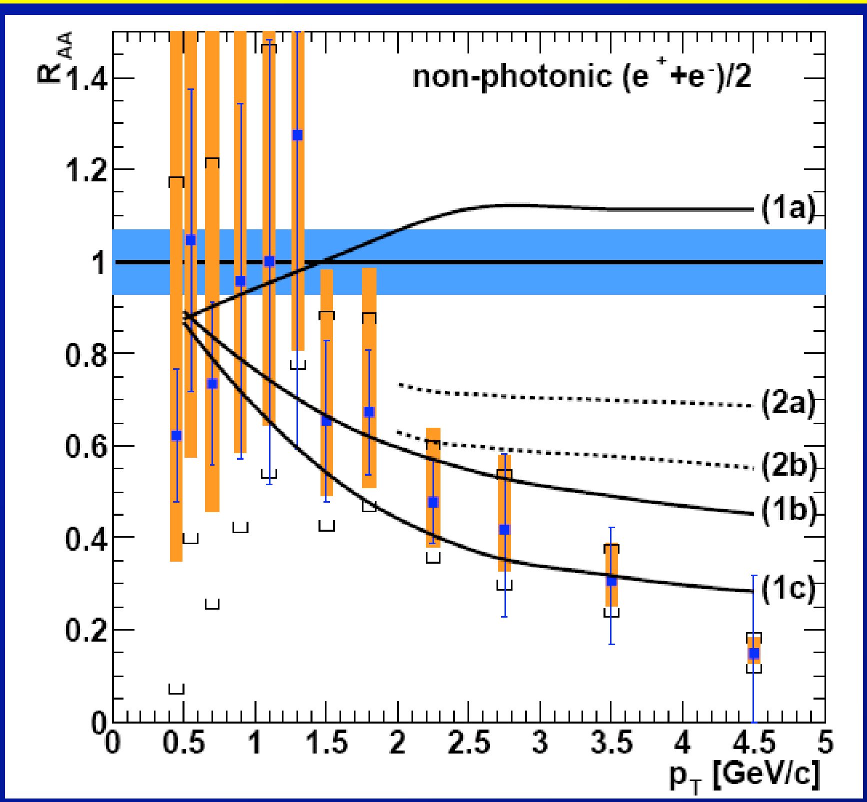
- Numerically solve coupled Langevin equations for quark, gluon distribution functions including quenching.
  - Hard thermal loop re-summed gluon spectral functions.
  - Initial condition (T) fixed by final-state observables
  - Fixed α_s, no other free parameters
  - $\Delta E \leq E$ built in!!

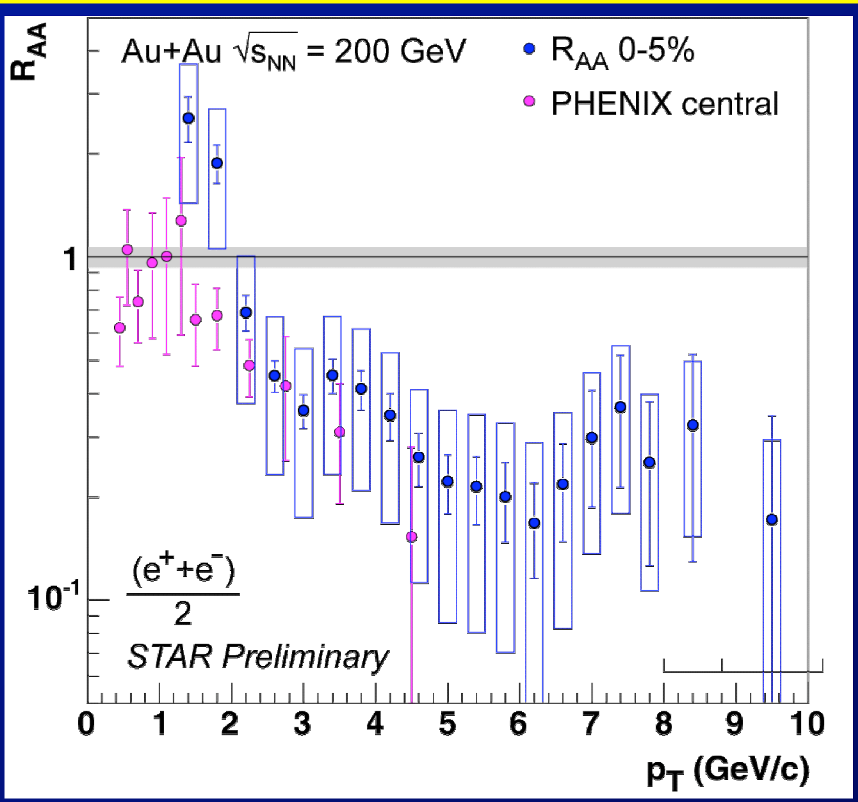
PHENIX: Heavy Quark Quenching

- Measure via semi-leptonic decays
  - Single $e^+ + e^-$ spectrum
- 2 methods to estimate (large) backgrounds
  - Direct estimate of backgrounds (cocktail)
  - Data taken with extra converter material
    - ⇒ Directly measure photon background
  - Background subtracted electron spectra from 2 methods agrees to 10%



Surprise: Strong c (and b?) Energy Loss





- We see substantial suppression of electrons from semi-leptonic c/b decays in central Au+Au collisions.
- This is/was a surprise
  - Expect charm quarks to suffer less radiative dE/dx ?
  - We expect significant b contributions already at 4 GeV/c

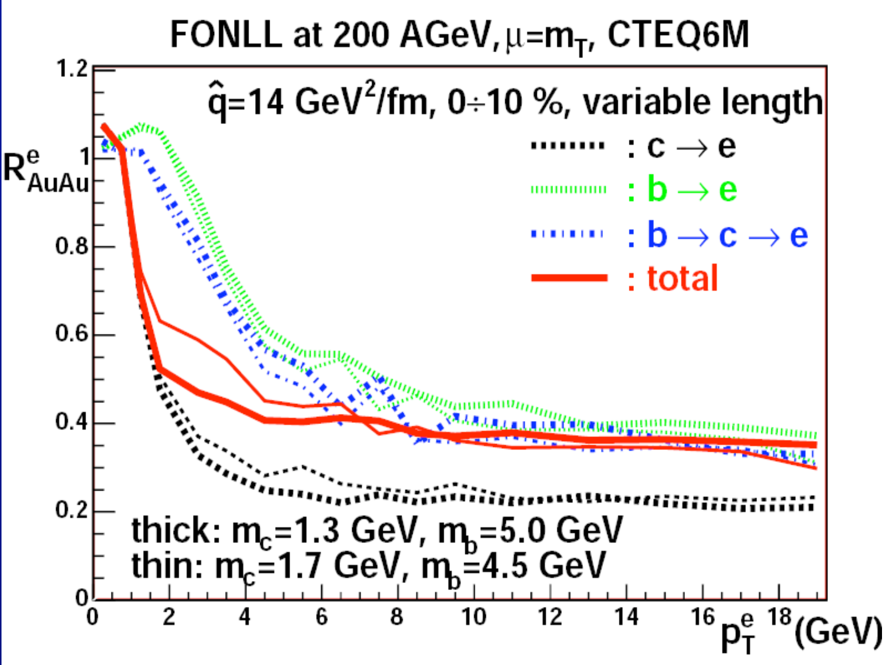
    ⇒ b quark energy loss should be further suppressed.

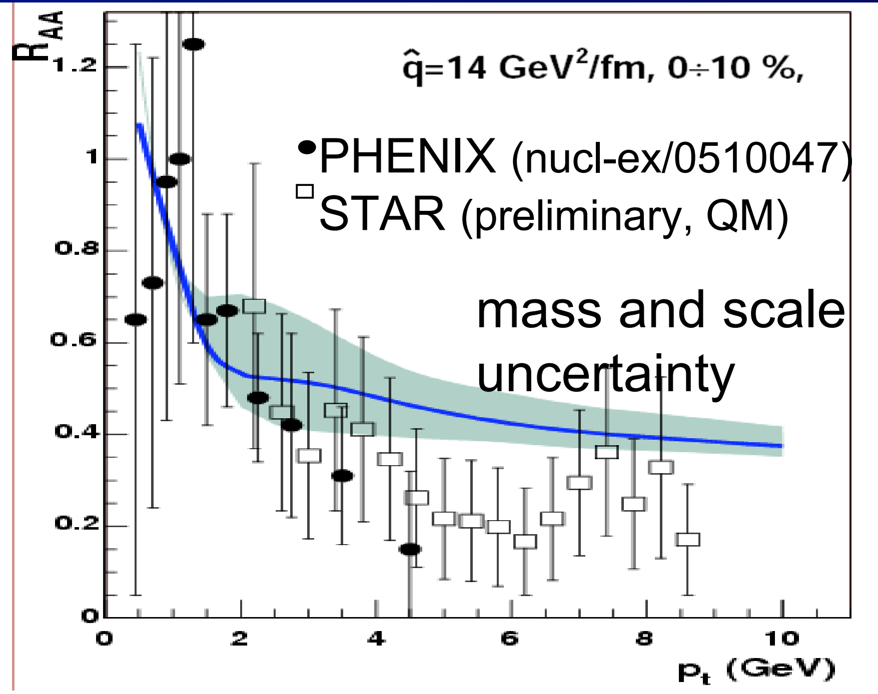
Heavy Quark Energy Loss: Theory(1)

- Calculation uses "thick medium" approximation
  - By Baier, Dokshitzer, Mueller, Peigne, Schiff
  - Improved & implemented by Wiedemann and Salgado
  - Applied to Au+Au in PQM by Dainese, Loizides, Paic.
- Includes **both c, b → e**
- But requires extremely opaque medium

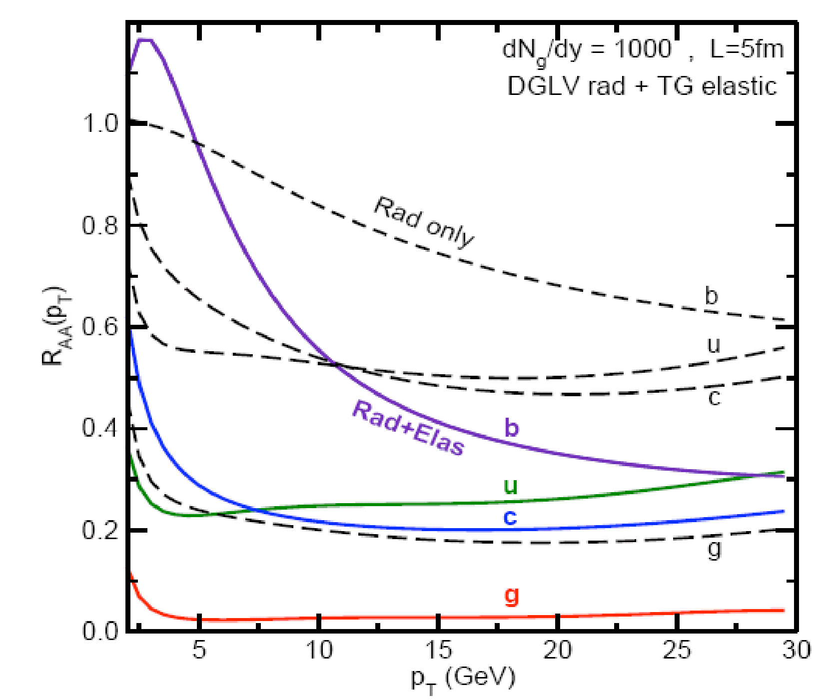
$$\Rightarrow \quad \hat{q} = 14\ \text{GeV}^2/\text{fm}$$

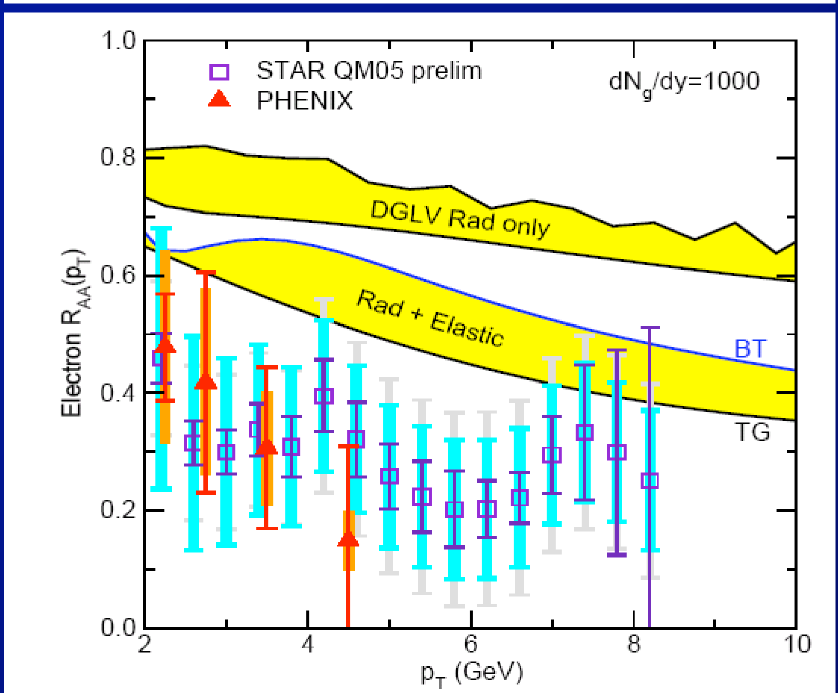
- **And still doesn't quite describe the observed suppression**





Heavy Quark Energy Loss: Theory(2)





- Analysis by Columbia nuclear theory group (Wicks *et al*)
- Includes "new"
  - Collisional dE/dx (significant!)
  - Geometric fluctuations
- Concludes:
  - Collisional dE/dx contributes significantly to quenching.
  - More than expected due to smaller ΔE fluctuations.
- Can come close to data
  - But also cannot quite explain the full observed suppression.
  - But still ∃ uncertainty in the value(s) of α_s