From RHIC to the EIC:
Seeing through the (Colored) glass less darkly

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Preliminaries

The Big Picture

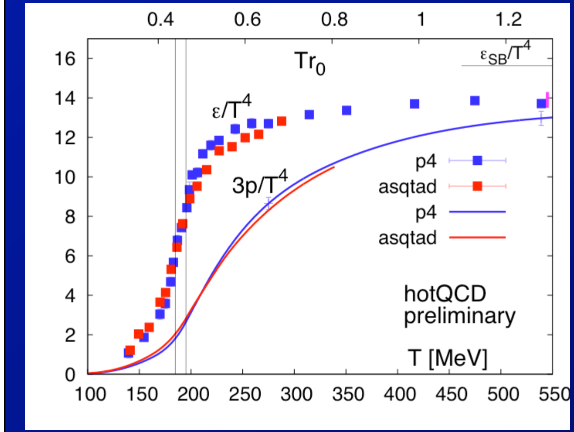
- My view:
  - The primary goal of the RHIC program is the study of the consequences of QCD

$$L_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} - \sum_n \bar{\psi}_n \left(\not{\partial} - ig\gamma^\mu A^a_\mu t_a - m_n \right) \psi_n$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

  ⇒Particularly asymptotic freedom
  - In a regime in which the physics is not described by "ordinary" pQCD
  - But where QCD nonetheless exhibits some understandable, calculable, and/or universal behavior.

QCD: Hadron to QGP Transition

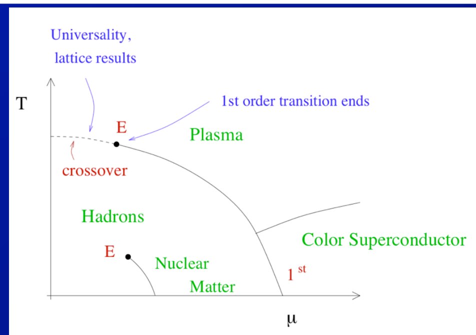


First-principles calculation from fundamental QCD Lagrangian using a (increasingly) controlled set of approximations.

- **The QGP is interesting to me not simply because it is a unique state of matter, but because it properties are determined by**

$$L_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a - \sum_n \bar{\psi}_n \left(\partial\!\!\!/ - i g \gamma^\mu A^a_\mu t_a - m_n \right) \psi_n$$

QCD: Phase Diagram & Critical Point



From A. Schaefer Quark Matter Student talk

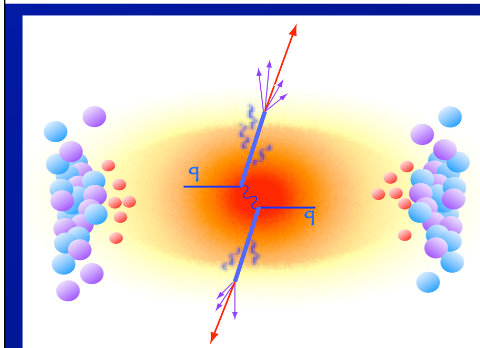
From INT "QCD Critical Point" workshop introduction page

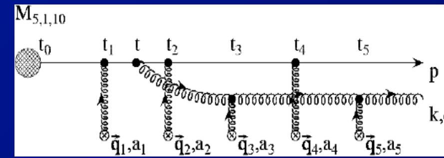
The purpose of this program is to bring together theorists and experimentalists to assess possibilities to discover the QCD critical point in relativistic heavy ion collisions. Specifically, the program goals are to:

- Summarize the present status of Lattice QCD studies locating the QCD critical point. We envisage a forum in which the advantages and limitations of various approaches will be discussed by the experts with the aim to further develop existing methods as well as to conceive radically new approaches.
- Facilitate development of reliable models which are anchored in Lattice QCD, take maximum advantage of the first-principle knowledge of QCD dynamics, including perturbative QCD and low energy theorems, and/or based on recent theoretical developments, such as random matrices or holographic correspondence. A particular emphasis should be given to approaches which are suitable for modeling dynamical real-time processes necessary for the description of the heavy ion collisions.
- Make maximum use of the knowledge of the critical-point phenomena gained in other branches of physics, both theoretical and experimental, such as condensed matter physics and the nuclear liquid-gas phase transition studies.

- **The QCD critical point is important because it provides unique insight on the physics of hadronization**
  - **⟹ Fundamental problem in QCD**

QCD: Jet Quenching in QGP



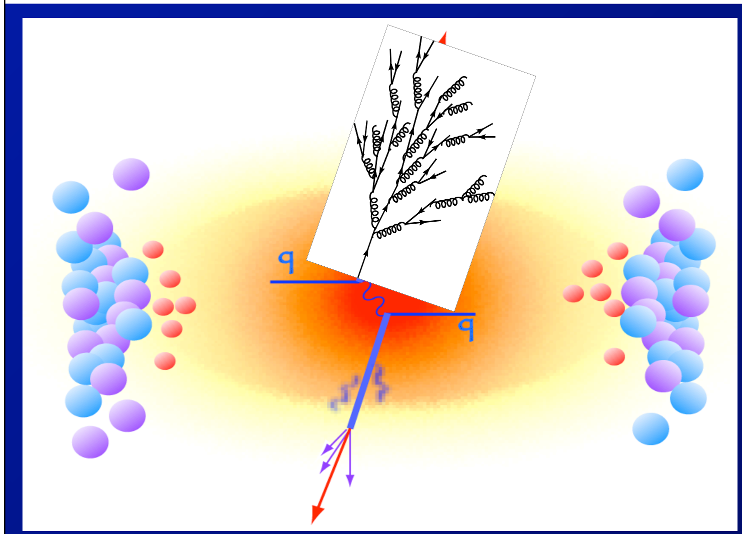


(GLV) Diagram for medium induced gluon radiation

- Why is this physics so interesting to me?
  - Interaction of fundamental charges in QCD with a medium composed of same fundamental charges.
- In principle, calculable:
  - Weak coupling (pQCD)
  - Strong coupling (AdS/CFT?)

    ⇒Direct test of our understanding of QCD

QCD: Jet Quenching in QGP (2)



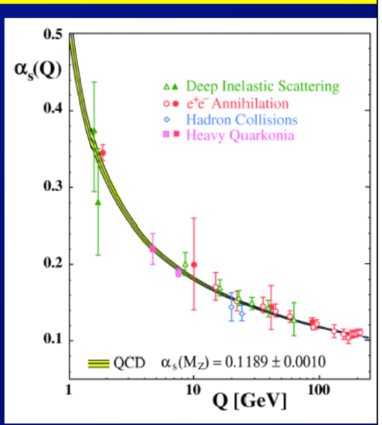
- **Another view of quenching:**
  - Modification of **time-like** parton shower in a medium of high unscreened color density.

Low-x, saturation

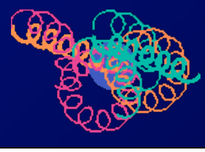
QCD and Asymptotic Freedom

- QCD is unique among the four fundamental interactions
  - Unbroken non-Abelian gauge symmetry and massless gluons.

    ⇒Asymptotic freedom
- The discovery of asymptotic freedom in QCD was a major breakthrough in particle physics.
  - Resolved serious theoretical issues w/ field theory @ short-distances.
  - Negative β function due to anti-screening @ short-distances
- But, there is more than one "high-energy" limit in QCD
  - And another fundamental problem to be understood.

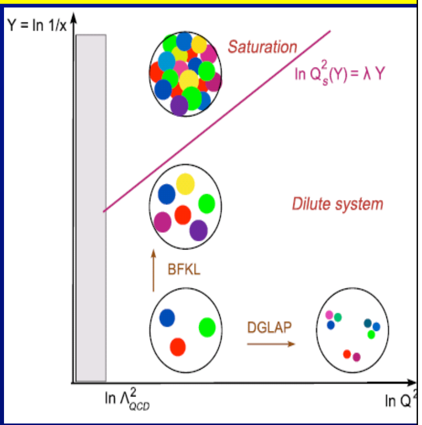


$$\beta(\alpha_s) = -\frac{\alpha_s^2}{2\pi}\left(\frac{11}{3}N_c - \frac{2}{3}N_f\right)$$



pQCD at low x

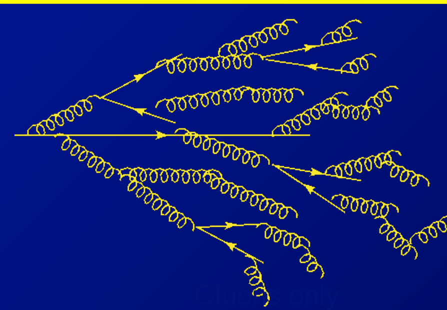
- pQCD has a built-in high energy "catastrophe"
  - Violation of unitarity
  - From rapid growth of gluon density @ low x
- Theoretical solution
  - Tamed by recombination of virtual gluons?
  - Generation of new scale Q_s
    - ⇒ Gluon screening of long-distance physics
    - ⇒ Another manifestation of asymptotic freedom

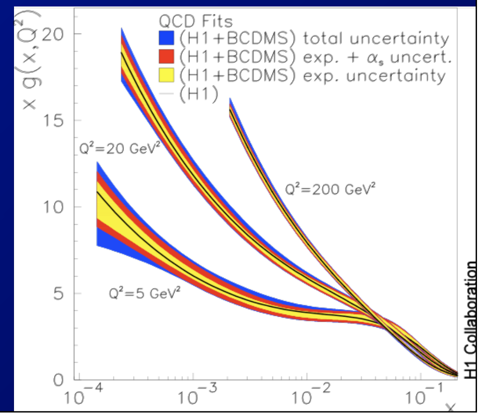


Verification and clarification of saturation (one of) most fundamental outstanding problem(s) in QCD

Radiation (Evolution) in QCD

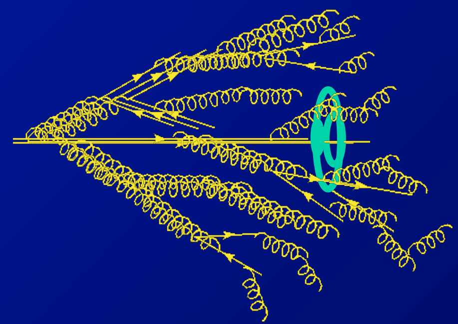
- Copious radiation from color charges in QCD
  - Initial state evolution of parton dist's
  - Final state parton showers
- PDF evolution
  - Increasing Q^2
  - Decreasing x
- What happens when gluon (parton) density becomes very large?

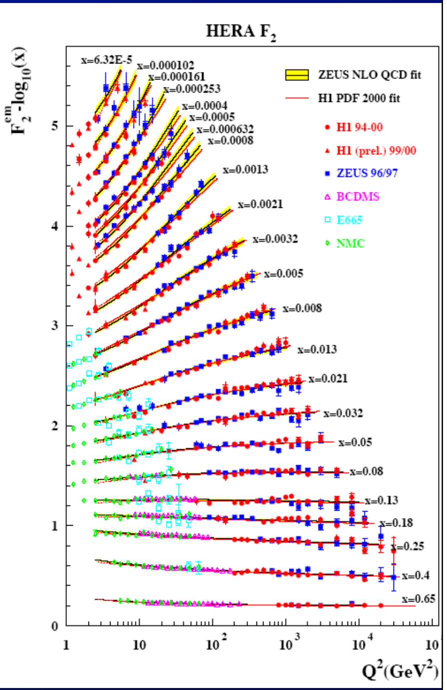




Two Kinds of Evolution (Q^2 vs x)

- DGLAP evolution (in Q^2)
  - With increasing resolution (Q^2) strip away more and more of virtual parton cloud
  - Well describes scaling violations in DIS (e.g. Hera)

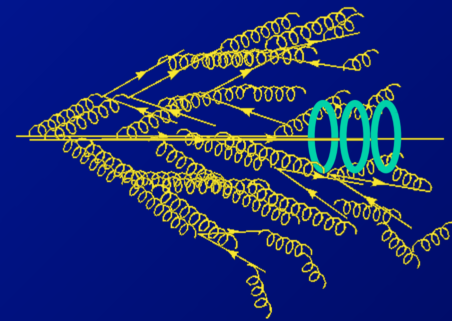




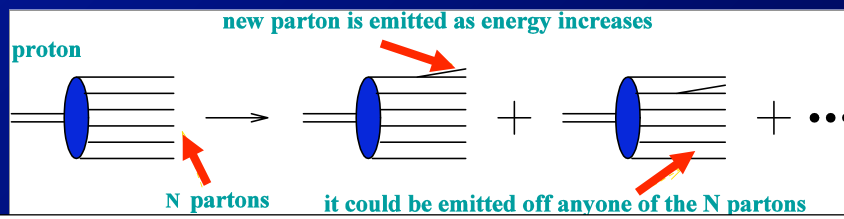
Two Kinds of Evolution (Q^2 vs x)

- **BFKL Evolution (x)**
  - Essentially an evolution in energy (or rapidity).
  - With larger collision energy, "see" more extended showers

    ⇒uncertainty & dilation

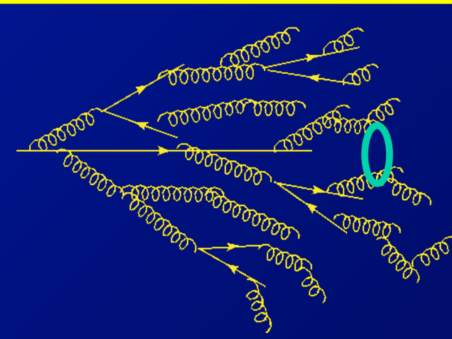


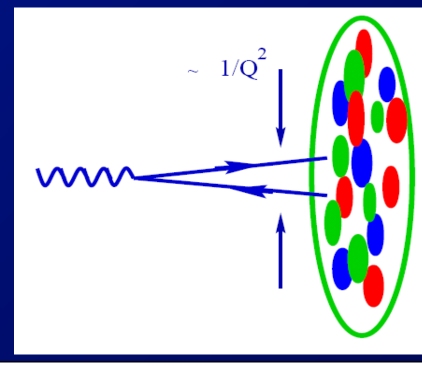
$$\frac{\partial}{\partial \ln(1/x)} N(x,Q^2) = \alpha_S K_{BFKL} \otimes N(x,Q^2) \quad N(x,Q^2) \sim xG \propto \frac{1}{x^\lambda}$$



But, Unitarity!

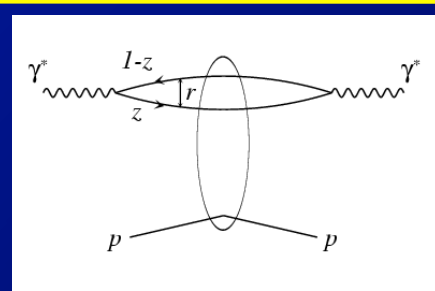
- Perturbative cross sections in QCD usually vary $\propto f(x,Q^2)$ or $xf(x,Q^2)$
  - In dilute (large Q^2) limit, probe sees << 1 parton
  - But what if probe sees ≥ 1 partons?
    - $\Rightarrow$Need modification <u>to preserve unitarity</u>
- Key concept:
  - New dimensionful scale Q^2_s
  - If $Q^2 < Q^2_s$ different physics
  - Interesting if $Q_s >> \Lambda_{QCD}$





Target Rest Frame & Dipole Picture

- Suppose we view DIS in rest frame of target
  - γ^* fluctuation into quark, anti-quark (dipole) frozen
  - w/ radial separation r
  - Dipole interacts with proton



Unitarity diagram: γ^*p A^*A

- Then DIS cross-section

$$\sigma(x,Q^2) = \int dz \int d^2r \left|\psi(r,z,Q^2)\right|^2 \hat{\sigma}(r,x)$$

- Interesting physics in $\hat{\sigma}(r,x)$
- What happens @ large r ? $r \sim h/\sqrt{Q^2}$

"Saturation" @ low x

- In dipole picture suppose $\hat{\sigma}(r,x)$ saturates for $r > R_0 = 1/Q_s$
- And assume

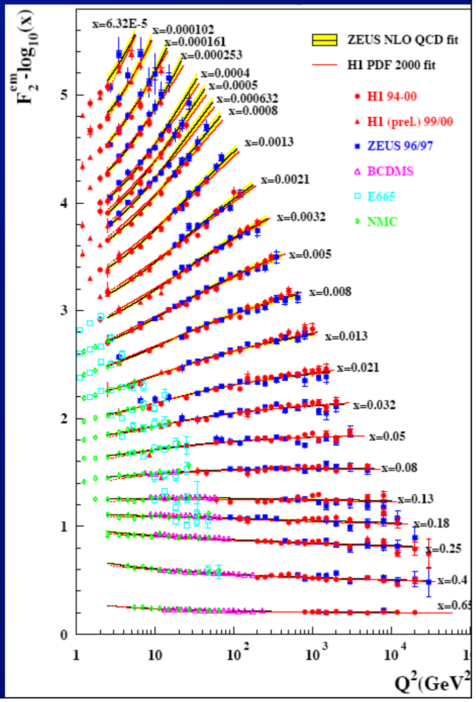
$$\hat{\sigma}(r,x) = g(r\,Q_s)$$

- Use BFKL for x dependence of Q_s

$$Q_s(x) = Q_0\left(\frac{x_0}{x}\right)^{\lambda/2}$$

- Plot

$$\sigma_{tot}^{\gamma^* p}(\tau),\ \tau = \left(Q/Q_s(x)\right)^2$$



Saturation: Empirical evidence?

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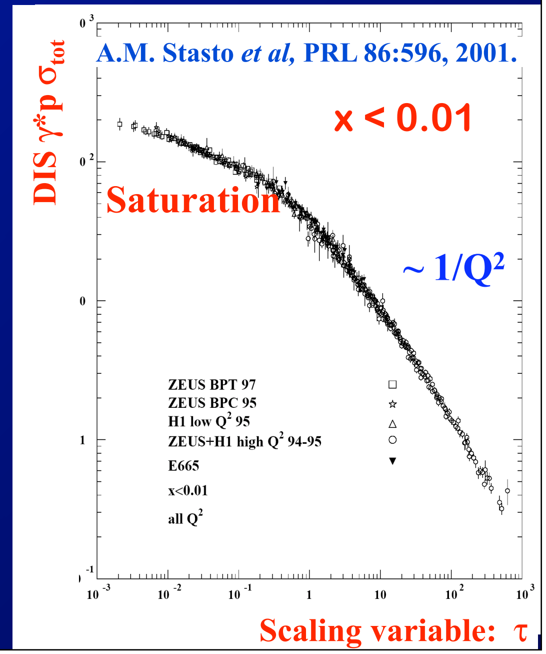
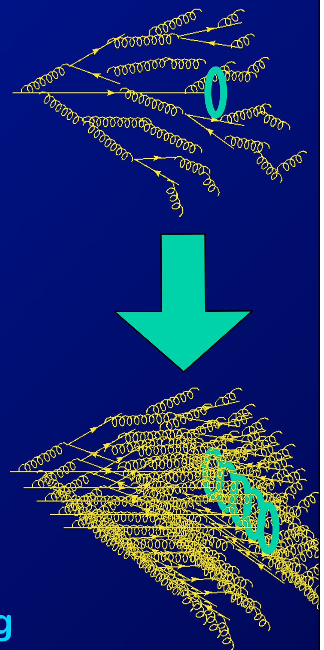
"Geometric Scaling"



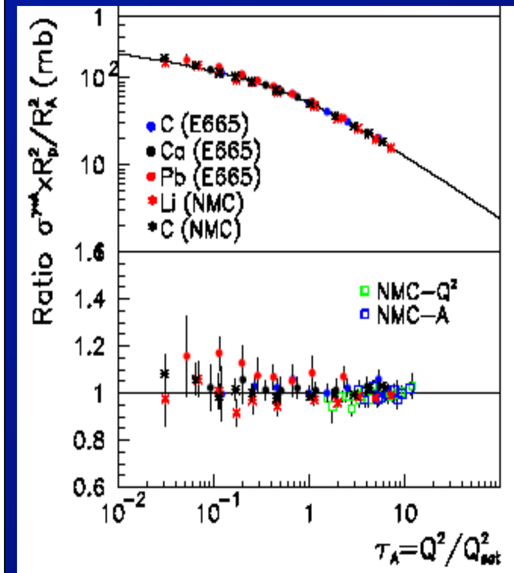
Testing Saturation

- **Ideas re: saturation have been around for >~ 1.5 - 2 decades.**
  - Lots of theoretical progress.
  - Tantalizing hints from HERA.
  - Insight from RHIC A+A data(?)
- **But still ∄ consensus re: saturation**
  - At what x or $\sqrt{s}$ is it important
  - Do we have a correct theoretical description?
- **Need controlled "experiment"**
  - ⇒Increase the gluon density by a known factor using nucleus.
  - ⇒Direct test of our understanding of QCD (evolution).



Saturation in nuclei, hints?

Armesto et al
PRL 94:022002, 2005



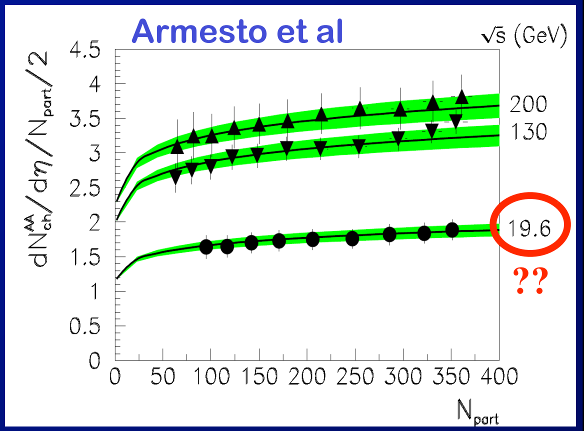
- Armesto et al: nuclear geometric scaling
  - Extension of HERA saturation analysis to nuclear targets

$$Q_s^A = Q_s^p \left(A \frac{R_p}{R_A} \right)^{\lambda}$$

- Good description of 5 different nuclear targets
  - C^{12} - Pb^{208}

A+A Multiplicities from Satuation

- Use nuclear saturation analysis
  - + k_T factorization
  - + Parton-hadron duality
    - ⇒ A+A dN/dη vs centrality, √s
- Describes data (too?) well !



Do we need to be reminded of the importance of saturation physics in (possibly) describing the initial conditions of heavy-ion collisions?

Too important to be left poorly understood ...

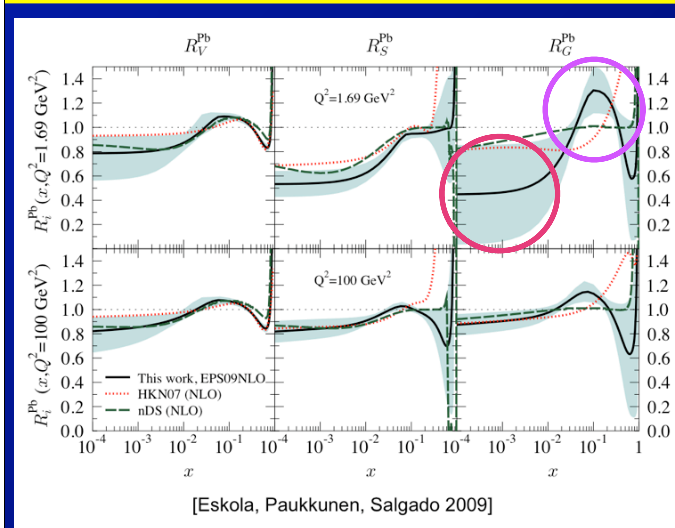
Low-x measurements: Analogies

- Inclusive F_2, F_L ⇔ Multiplicity, dN/dη in A+A
  - Simplest to measure
  - Averages over "details"
  - Sensitive to fundamental changes in dynamics
- Diffraction ⇔ Jets, jet quenching in A+A
  - Harder to measure (rates, selection)
  - Direct sensitivity to large-amplitude effects
- Jet, charm, other semi-inclusive final states ⇔ Measurements w/ particle ID in A+A
- We accept that one observable is not sufficient for "finding" QGP

  ⇒ Same holds for understanding saturation

Beyond Saturation

Nuclear PDFs: New EPS09 (e.g.)



Large anti-shadowing?

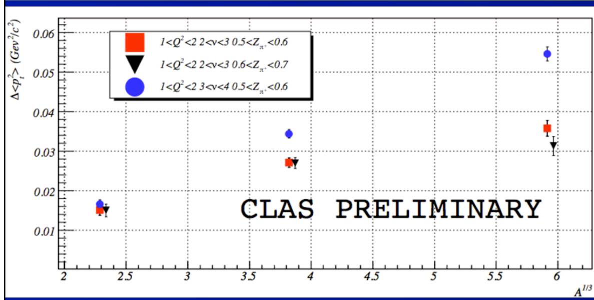
In Gluons?

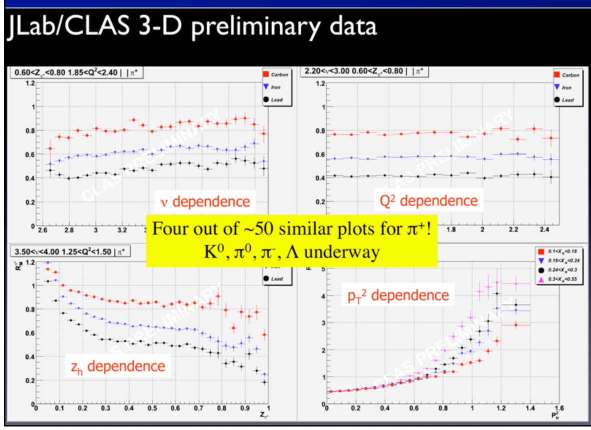
How much shadowing?

- **EPS09 Nuclear PDFs with error estimate:**
  - Significan uncertainties in shadowing, anti-shadowing, and EMC regions. Needs data!

    ⇒Important for understanding RHIC results.

SiDIS: Parton Interations in Cold NM





From QM2009 talk by W. Brooks

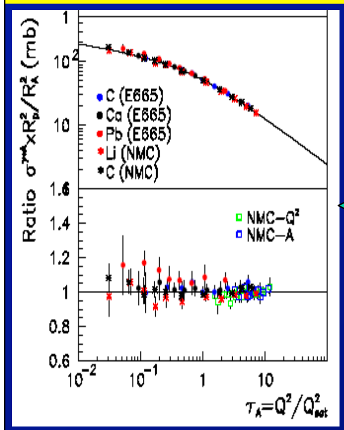
Final-state parton broadening

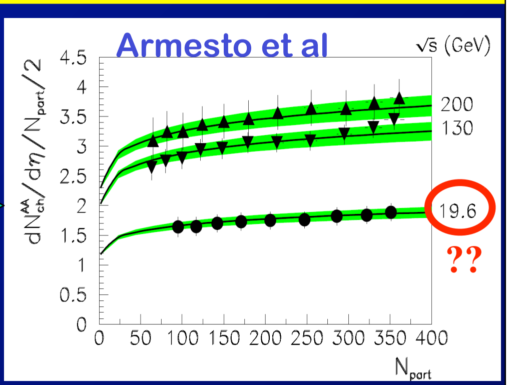
Nuclear multiplicity ratios, multiple observables

- Important control for jet quenching
  - ⇒ But want larger Q^2 and ν range!

Summarizing

RHIC - EIC Physics Connections



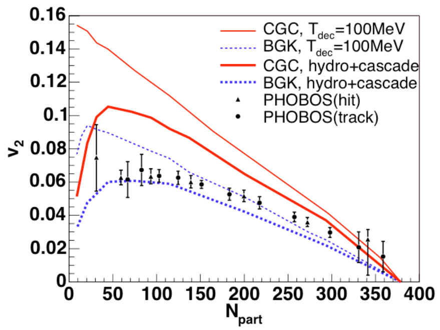


- Understanding of saturation is essential to understanding initial conditions of heavy ion collision

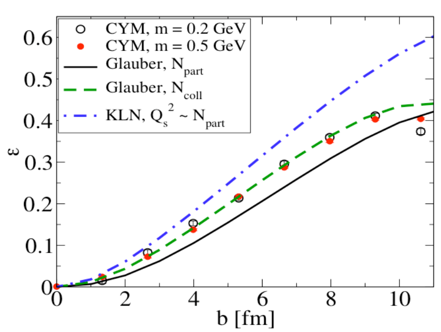
  ⇒And maybe the physics of thermalization

RHIC-EIC Connections(2)

Hirano et al., PLB 636 (2006) 299



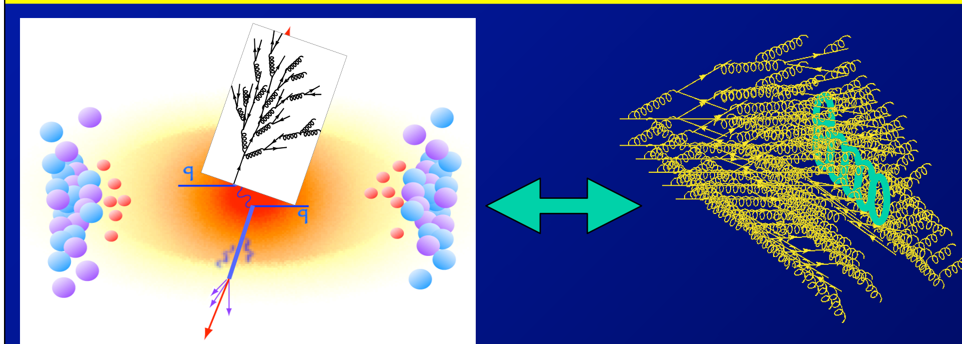
Lappi & Venugopalan, PRC 74 (2006) 054905



- Understanding of initial state tied up in nearly every aspect of A+A measurements.
- e.g. interpretation of elliptic flow & viscosity
  - Significant difference in eccentricity of A+A collision between "non-saturated" and "saturated" initial state.

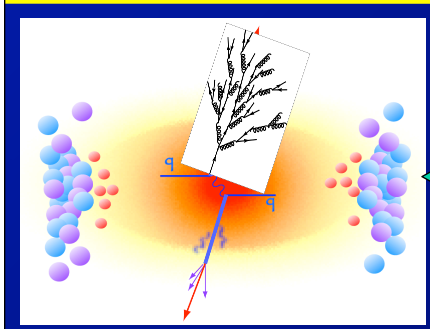
    ⇒ Understanding saturation (or alternative?)

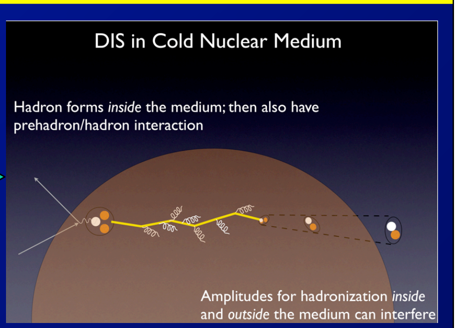
RHIC - EIC Physics Connections (3)



- Parton cascades in “dense” background
  - Jet quenching: time-like shower in QGP
  - Saturation: space-like shower
    - ⇒Self-generated gluon density (very low x, e-p)
    - ⇒Background of other space-like showers (e-A)
      - » Recent work by Iancu et al.

RHIC - EIC Physics Connections (4)

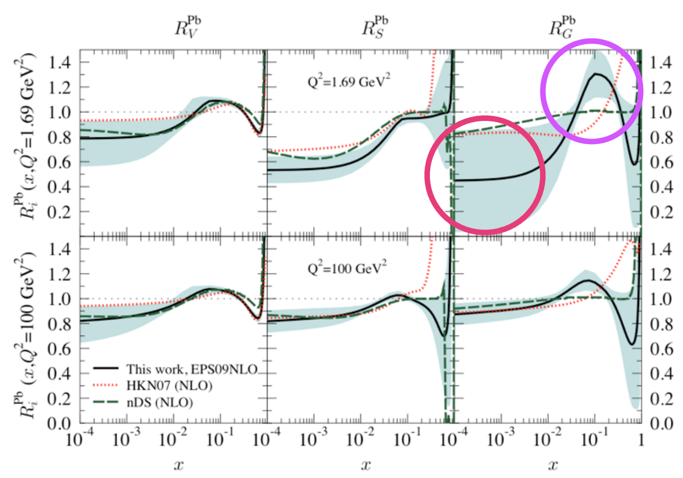




- Two different regimes of final-state parton interactions in “matter” (poor word)
  - Quark gluon plasma (weak/strong coupling?)
  - Nucleus

    ⇒Essential for “calibration” of jet quenching in heavy ion collisions.

RHIC - EIC Physics Connections (5)



[Eskola, Paukkunen, Salgado 2009]

Large anti-shadowing?

In Gluons?

How much shadowing?

- With increasing precision in RHIC measurements we will be more and more limited by knowledge of nuclear PDFs.

EIC and RHIC

- The EIC will provide unique insight crucial to improving our understanding of RHIC and LHC heavy ion measurements.
  - Low energy option already valuable
    - ⇒ Measuring F_2 (F_L ?) in anti-shadowing region ⇒ $f(x, Q^2)$, $g(x, Q^2)$
    - ⇒ Start of SiDIS program measuring parton interactions in nuclei.
- Highly desirable to start EIC program before termination of RHIC, LHC heavy ion programs!

The Big Picture: RHIC and EIC

- The primary goals of **BOTH RHIC and EIC** programs are the study of QCD

$$L_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} - \sum_n \bar{\psi}_n \left(\not{\partial} - i g \gamma^\mu A^a_\mu t_a - m_n \right) \psi_n$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

$\Rightarrow$ **Particularly asymptotic freedom**

- In a regime in which the physics is not described by “ordinary” pQCD
- **But where QCD nonetheless exhibits some understandable, calculable, and/or universal behavior.**

EIC: Low-x Reach