Color Glass Condensate at RHIC

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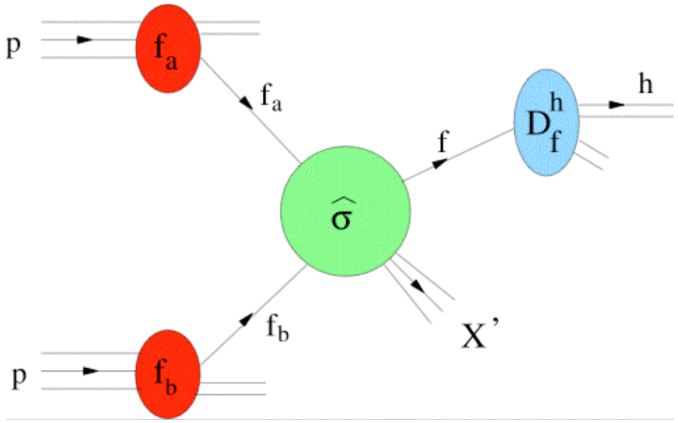
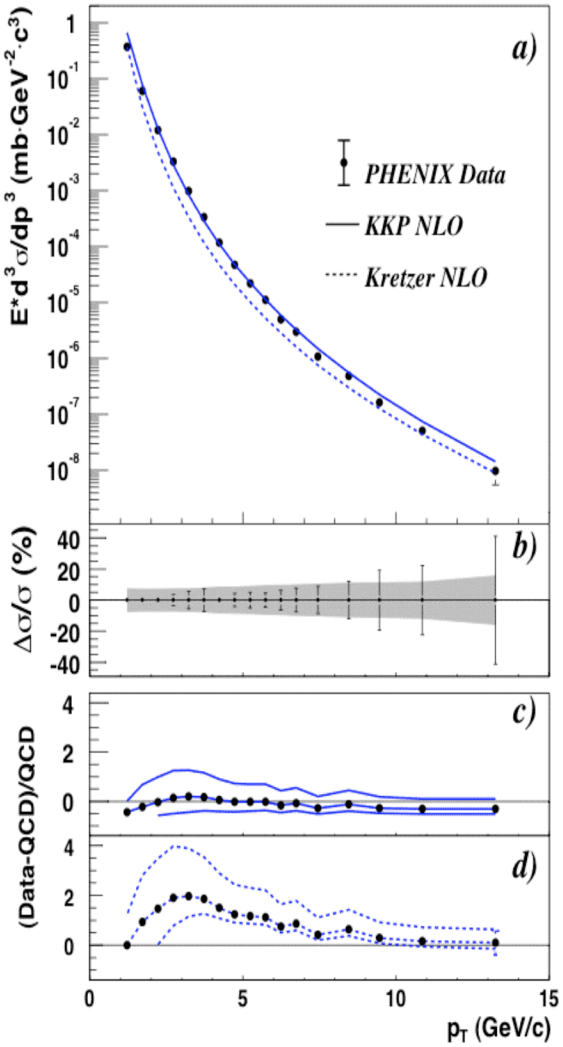
OUTLINE

- Quantum Chromo Dynamics
  - Perturbative QCD
    - Parton Model
  - Semi-Classical QCD
    - Color Glass Condensate
    - Color Quantum Fluid
- Semi-Classical QCD at RHIC
  - Indications
  - Tests

Perturbative QCD

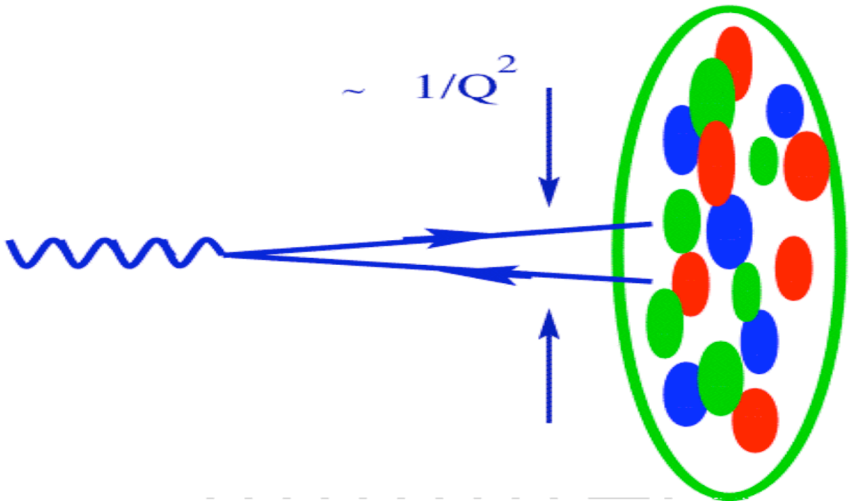


- Quarks, gluons (x, Q^2)
- Weak coupling ($\alpha_s << 1$)
- Collinear factorization
- Incoherence
- *Dilute* systems



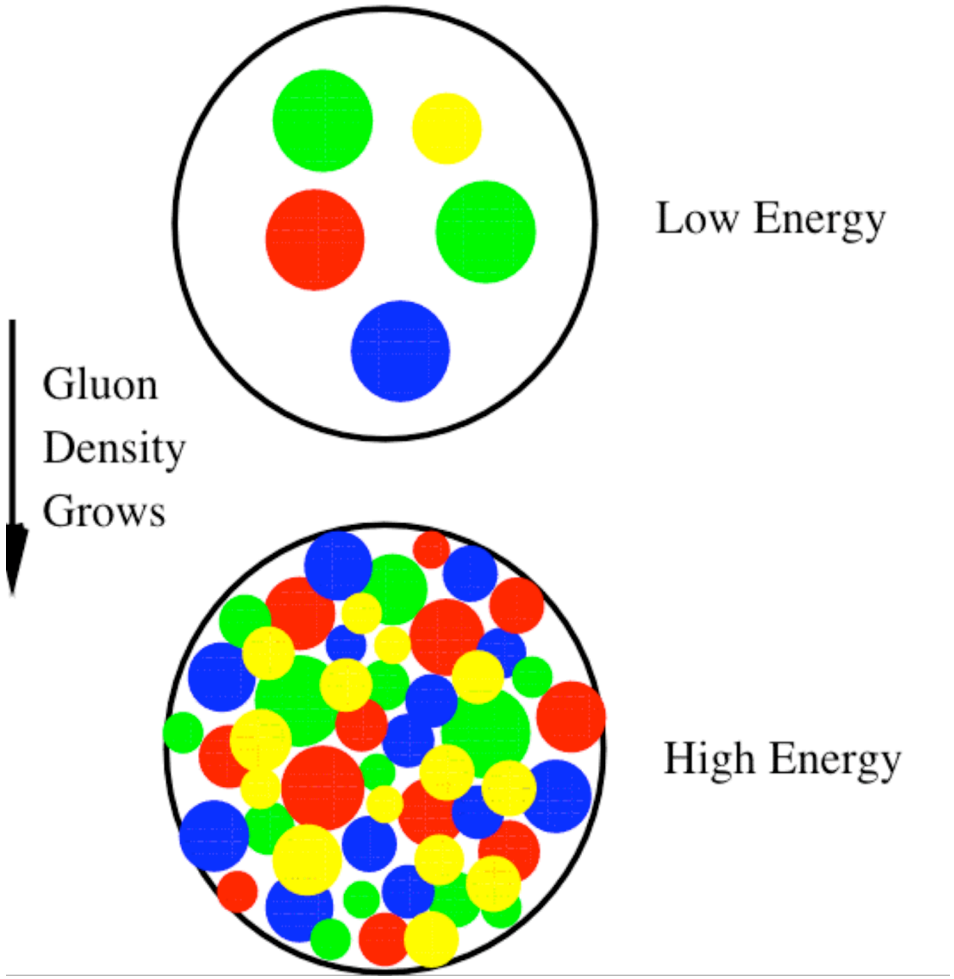
Semi-Classical QCD

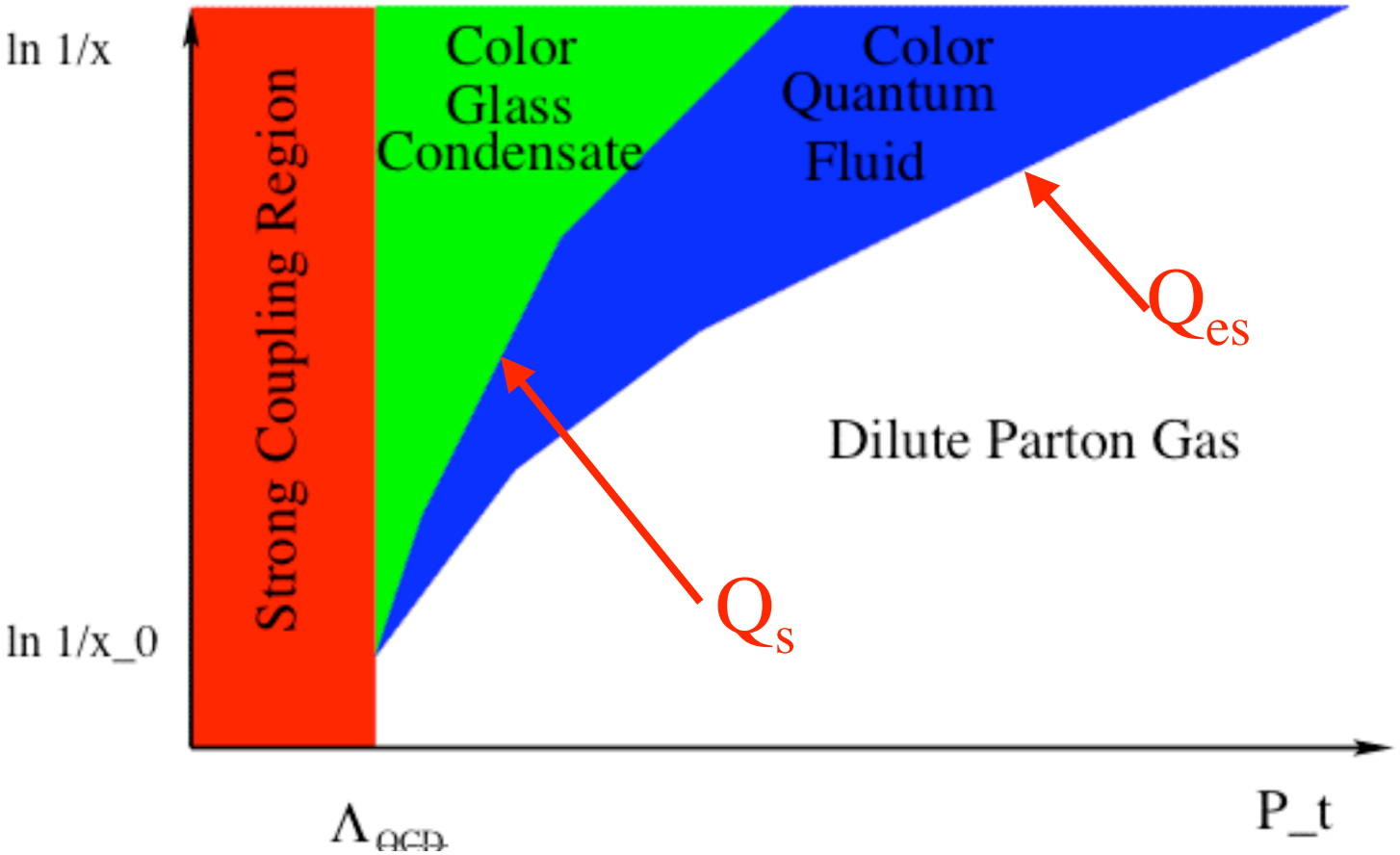
- Wilson lines
- Weak coupling ($\alpha_s << 1$)
- Classical fields + renormalization group
- Coherence (longitudinal): $l_c \sim 1/m_N\, x$
- Dense systems



Gluon Saturation

- Small X/Large A
- *Large occupation number*
- *Coherent state*
- *Saturation momentum* Q_s (x)





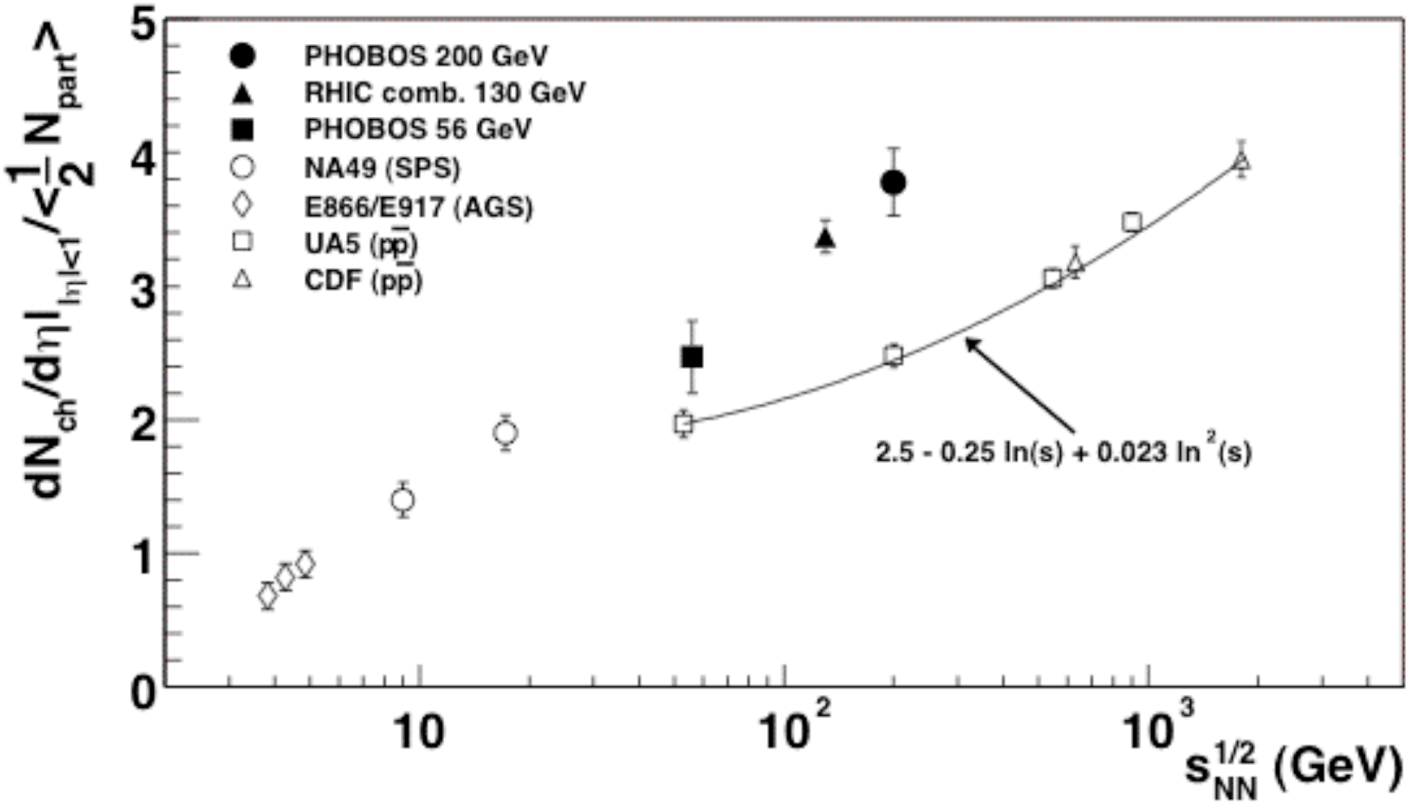
- Color Glass Condensate $P_t < Q_s(y)$
- Color Quantum Fluid $Q_s(y) < P_t < Q_{es}(y)$
- Dilute Parton Gas $P_t > Q_{es}(y)$
- Where is RHIC?

QCD: Kinematic Regions

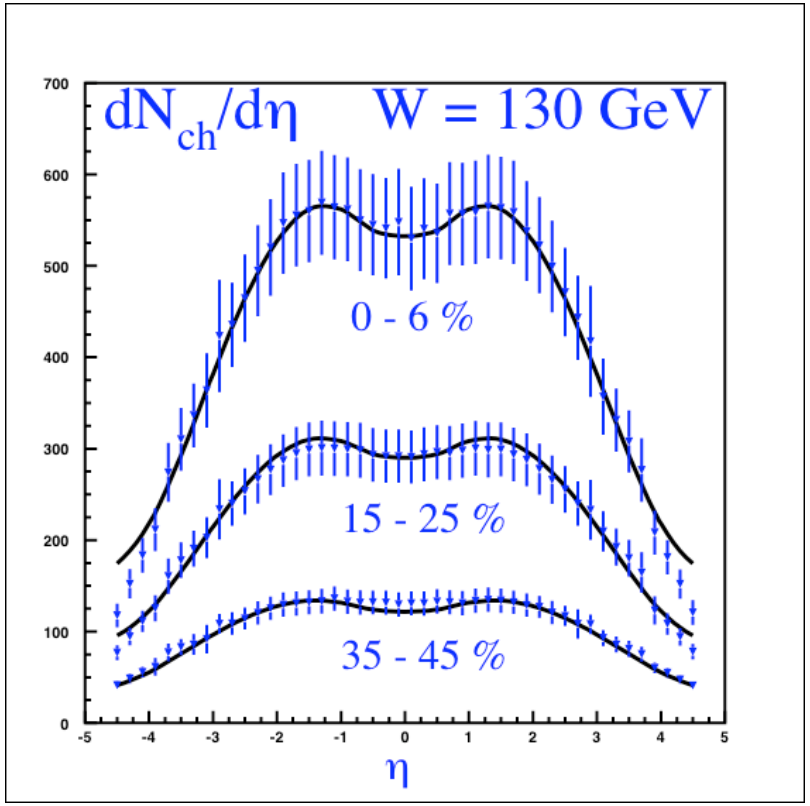
- Color Glass Condensate
  - High gluon density
  - Strong classical fields
  - Non-Linear evolution: JIMWLK (BK at large N_c)
- Color Quantum Fluid
  - Low gluon density
  - Linear evolution: BFKL
  - Anomalous dimension (k_t factorization)
- Dilute Parton Gas
  - Low gluon density
  - Linear evolution: DGLAP
  - No anomalous dimension (collinear factorization)

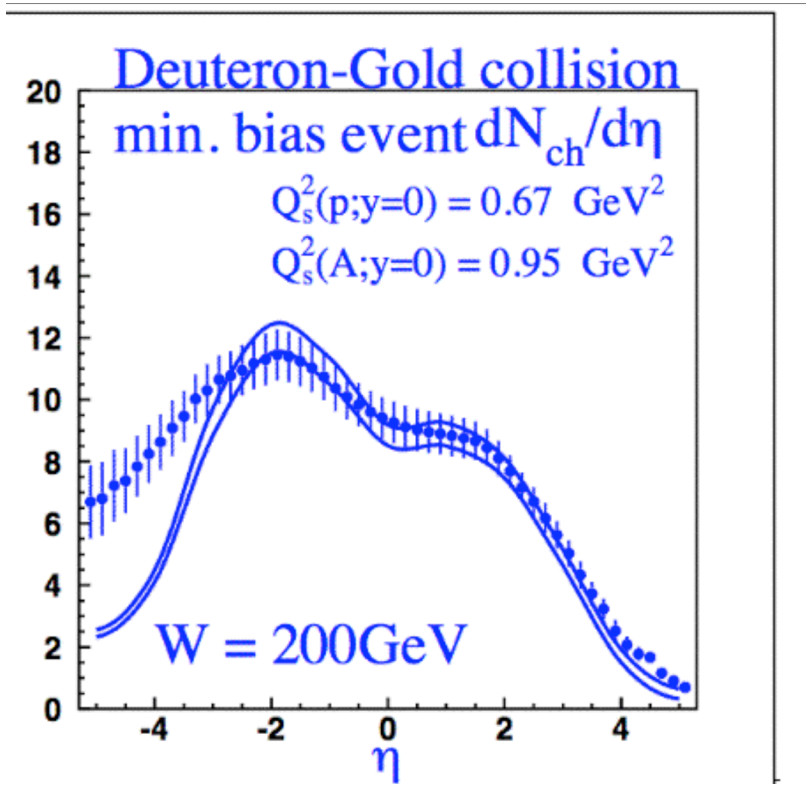
Coherence at RHIC

- Multiplicity growth: from pp to AA
  - Incoherent scattering ~3
  - Coherent scattering ~ 50%



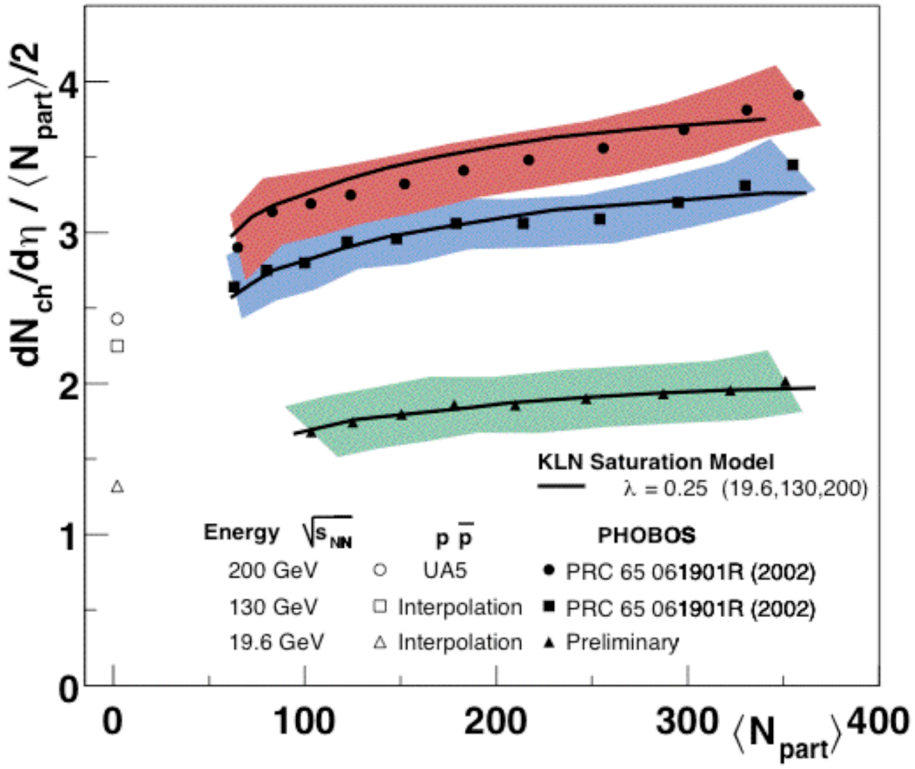
Color Glass Condensate at RHIC





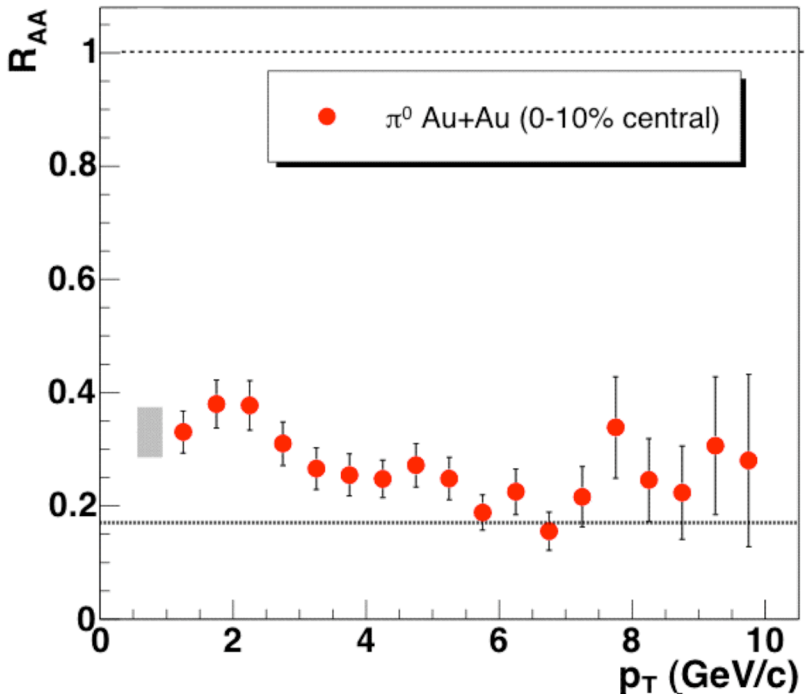
- Gluon production
- Multiplicities are correctly predicted
- Beware of the fragmentation region

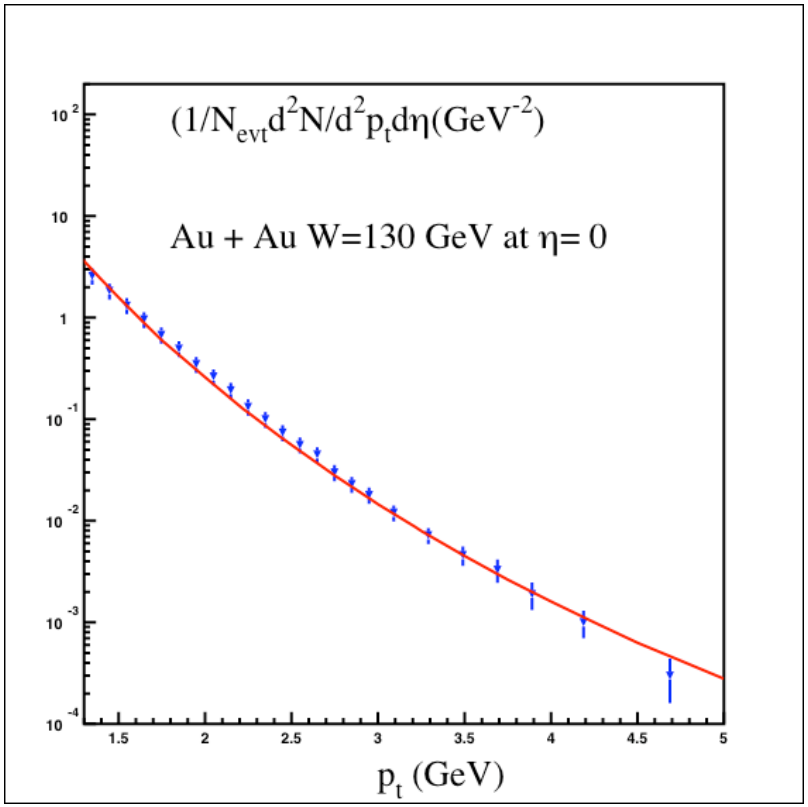
Color Glass Condensate at RHIC



- Energy, N_{part} dependence: OK
- Warning: saturation at $\sqrt{s} \sim 20$ GeV !

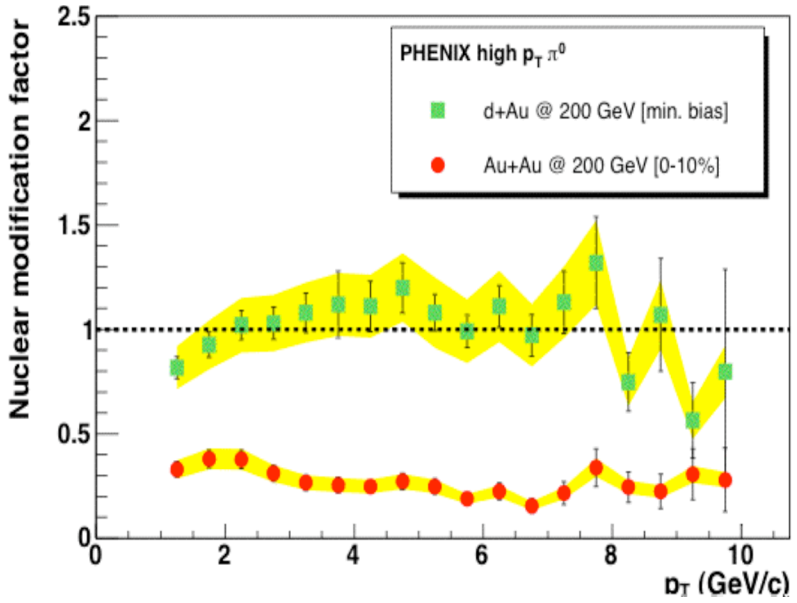
Color Quantum Fluid at RHIC?

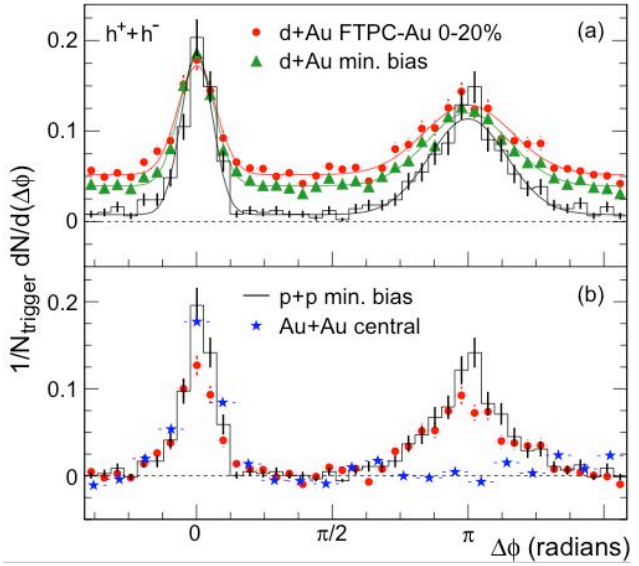




- $R_{AA} < 1$: initial state?
  - BFKL anomalous dimension: $1/Q^2$ ---> $(1/Q^2)^{0.6}$
  - Approximate N_{part} scaling
- 2 ---> 1 processes (reduced back to back correlations)

dA:Mid Rapidity





- R_dA ($p_t > 2$ GeV)
  - Quantum evolution: not the dominant physics
  - Classical: MV model (Cronin effect)?
- Correlations ($p_t > 4$ GeV)
  - CGC: not the dominant physics

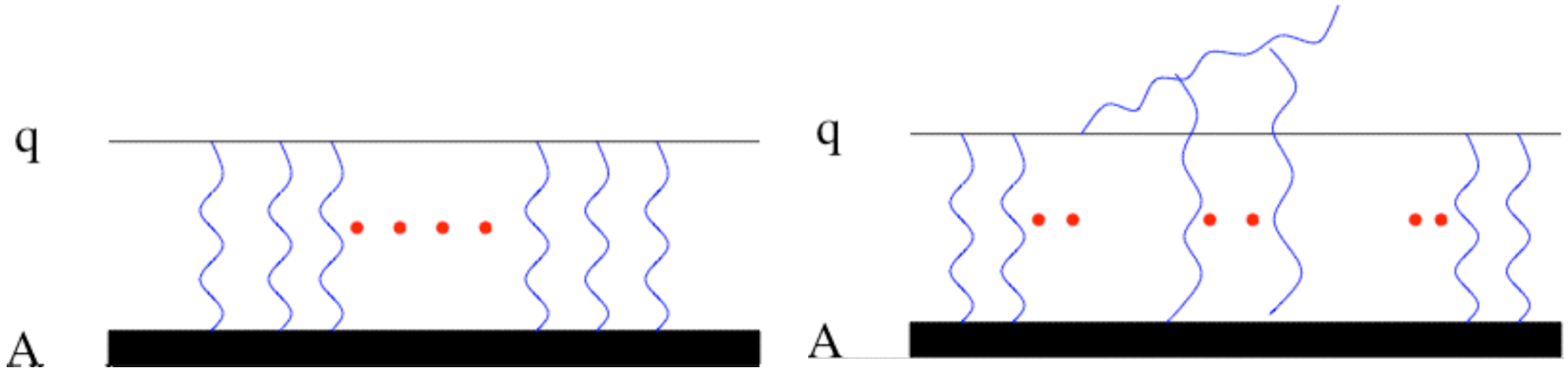
RHIC: Color Glass Condensate?

- HERA (protons): $X \leq 0.01$
- Mid rapidity RHIC (AA):
  - $P_t \sim 5$ GeV --> $X \sim 0.1$
  - $P_t \sim 1$ GeV --> $X \sim 0.01$
  - Multiplicity (P_t < 1 GeV): *OK*
  - High P_t spectra: *X is too large*
- Color Glass Condensate provides the initial conditions, but the physics of high p_t is that of final state rescattering, energy loss, ….
- Look forward in dA

dA: The Common Approach

- Two main effects
  - Cronin
    - Intrinsic momentum
      - $F(x, Q^2)$ --> $F(x, k_t^2, Q^2)$
      - $\langle k_t^2 \rangle_{pA} = \langle k_t^2 \rangle_{pp} + k\, H[\nu]$
      - Parameters from fitting data at low energy
  - Shadowing
    - Parameterize the data on structure functions
    - Gluon shadowing?
- Phenomenological models
  - Parameters are process, energy, etc. dependent
  - **No Universality ---> Predictability ?**

dA: The CGC Approach



- Quark "production"

$$\frac{d\sigma^{pA}}{dy\, d^2b_t\, d^2k_t} \sim \int d^2r_t\, e^{ik_t\cdot r_t}\, \sigma_{dipole}(x, r_t, b_t)$$

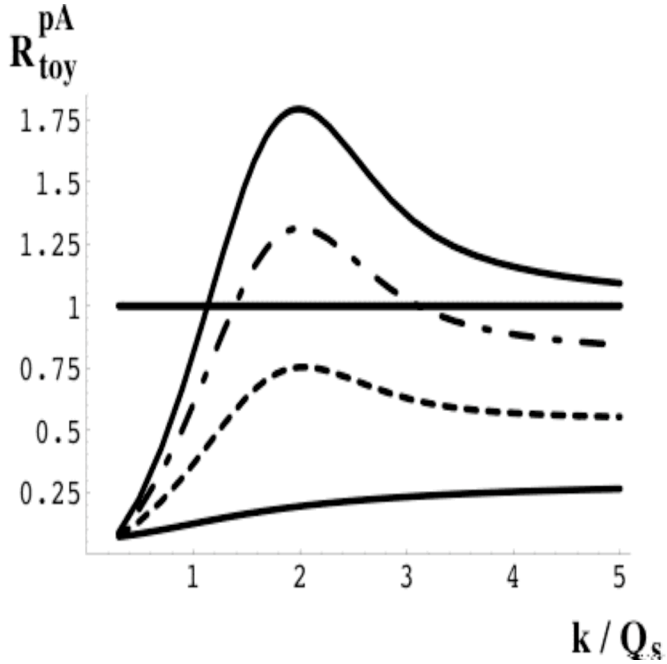
- Gluon production

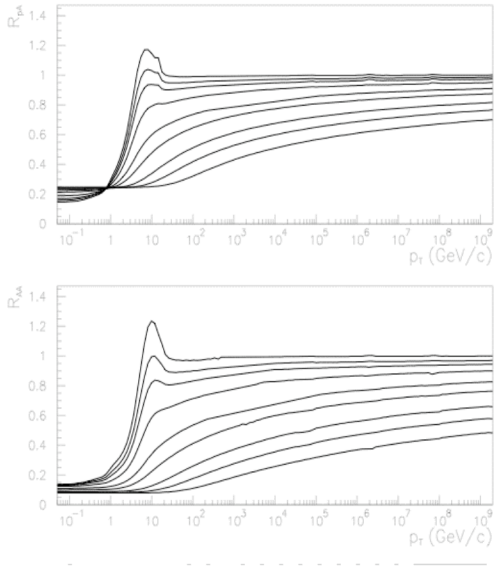
$$\frac{d\sigma^{pA}}{dy\, d^2b_t\, d^2k_t} \sim \int \frac{d^2r_t}{r_t^2}\, e^{ik_t\cdot r_t}\, \sigma_{dipole}(x, r_t, b_t)$$

Going Forward at RHIC

- Assume saturation works for $x \leq x_0$ [$x_0 \sim 10^{-2}$ --> $Q_s(x_0) \sim 1.6$ GeV]
  - For $x \sim x_0$: classical approximation (MV model)
  - Suppression (enhancement) at $p_t <$ (>) Q_s
- Forward: $y = 0 \rightarrow 2 \rightarrow 4$
  - $x \sim 10^{-2} \rightarrow 10^{-3} \rightarrow 10^{-4} << x_0$ ($p_t \sim 2$ GeV)
  - **Quantum evolution becomes essential**
  - $Q_s(y_0) = 1.6$ GeV ---> $Q_s(y=4) = 2.6$ GeV
  - $Q_{es}(y_0) = 1.6$ GeV ---> $Q_{es}(y=4) = 4.2$ GeV
  - Suppression at $p_t < Q_{es}$
  - **Centrality**
  - Reduced correlations (2 ---> 1 processes are dominant)
- Forward rapidity: CGC and CQF regions open up

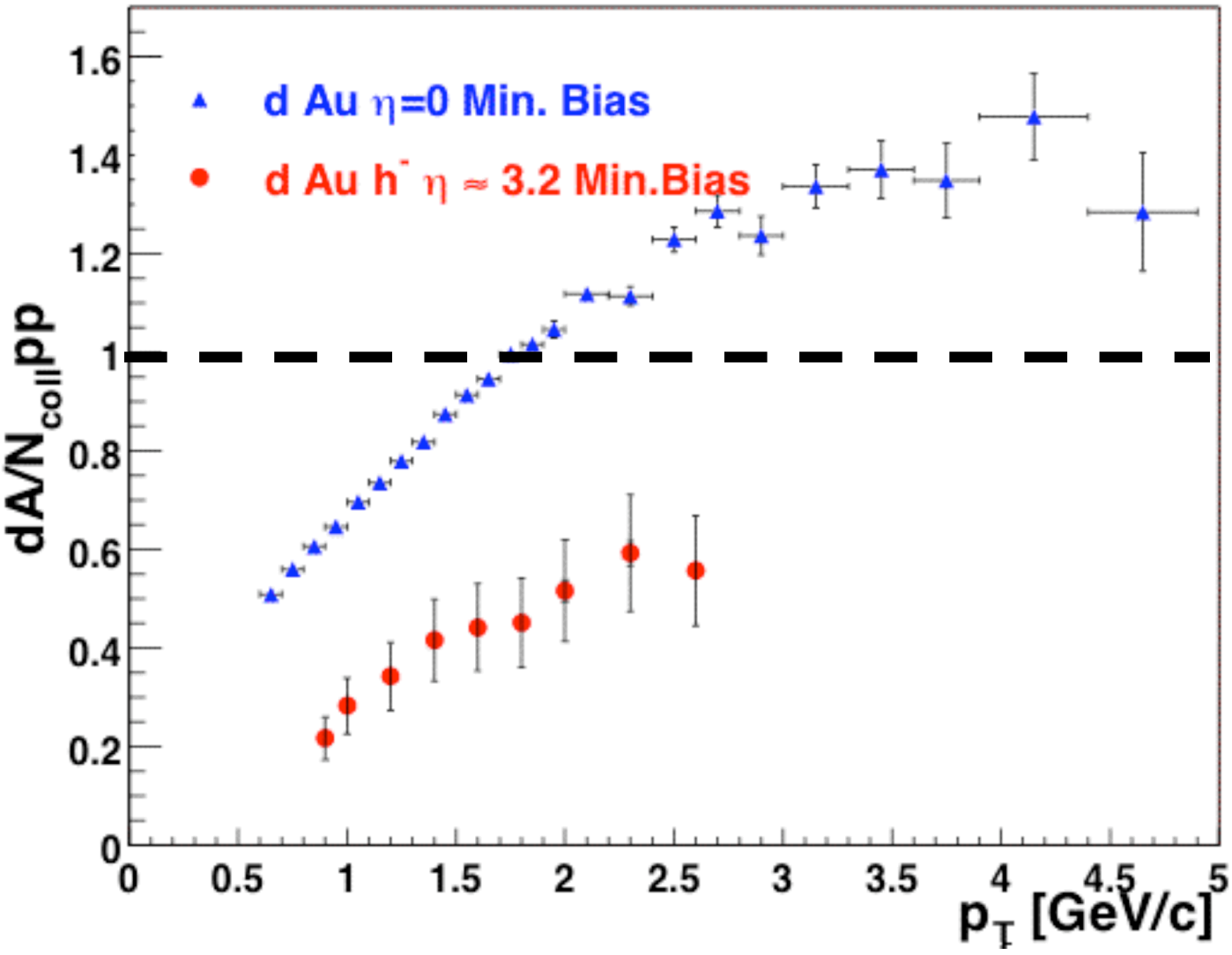
Forward Rapidity dA





- Illustration
- Suppression of R_{dA} as we go forward

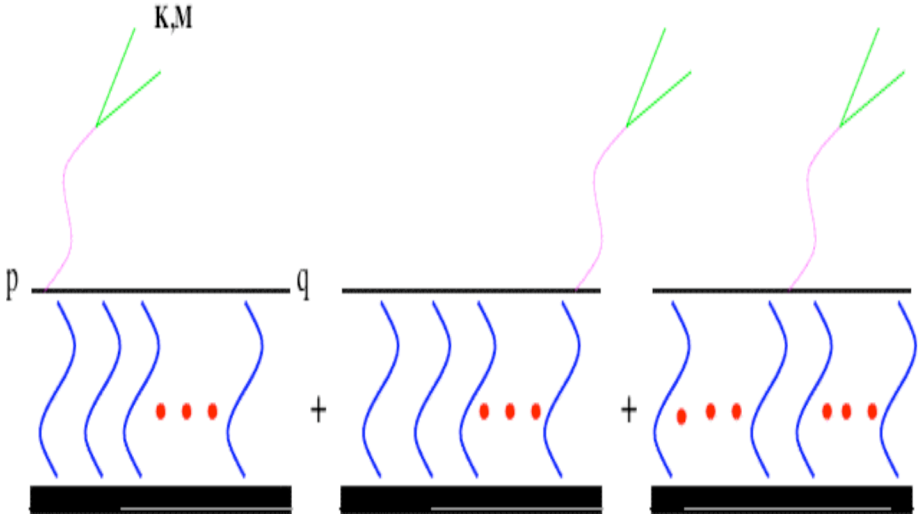
Forward Rapidity dA



Forward Rapidity dA at RHIC

- Deuteron fragmentation region
  - Deuteron: large x_1
  - Nucleus: small x_2
- The experimental coverage
  - STAR: neutral pions at y = 0, 4
  - BRAHMS: charged hadrons at y = 0, 1, 2, 3
  - PHENIX: dileptons at y = 0, 2
- Map out the QCD kinematic regions at RHIC (p_t, y, correlations, **centrality**)
  - Hadrons (Z_{ave} < 1 ---> higher p_t partons)
  - Photons, dileptons, photon + jet

Dilepton Production in dA



$$\frac{d\sigma^{q\,A\to q\,l^+l^-\,X}}{dz\,d^2b_t\,d^2k_t\,d\log M^2} = \frac{2\alpha_{em}^2}{3\pi}\int \frac{d^2l_t}{(2\pi)^4}\,\tilde{\sigma}_{dipole}(x,b_t,l_t)$$

$$\left\{\left[\frac{1+(1-z)^2}{z}\right]\frac{z^2l_t^2}{[k_t^2+M^2(1-z)][(k_t-zl_t)^2+M^2(1-z)]}\right.$$

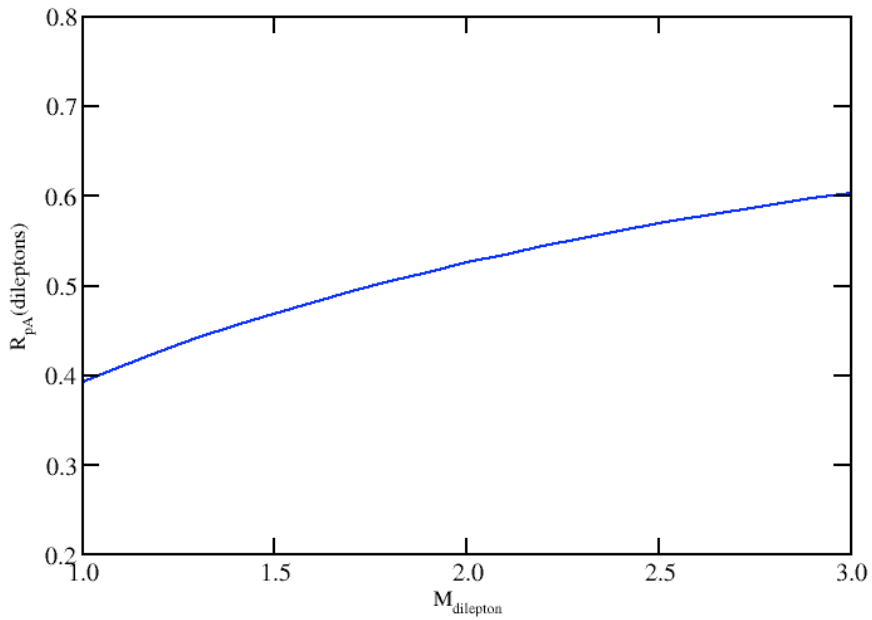
$$\left.-z(1-z)\,M^2\left[\frac{1}{[k_t^2+M^2(1-z)]}-\frac{1}{[(k_t-zl_t)^2+M^2(1-z)]}\right]^2\right\}$$

with $l_t = q_t + k_t$

- No final state interactions
- Dipole cross section
- Additional handle: M^2
- PHENIX: l^+l^- at $y = 1.2 - 2.4$

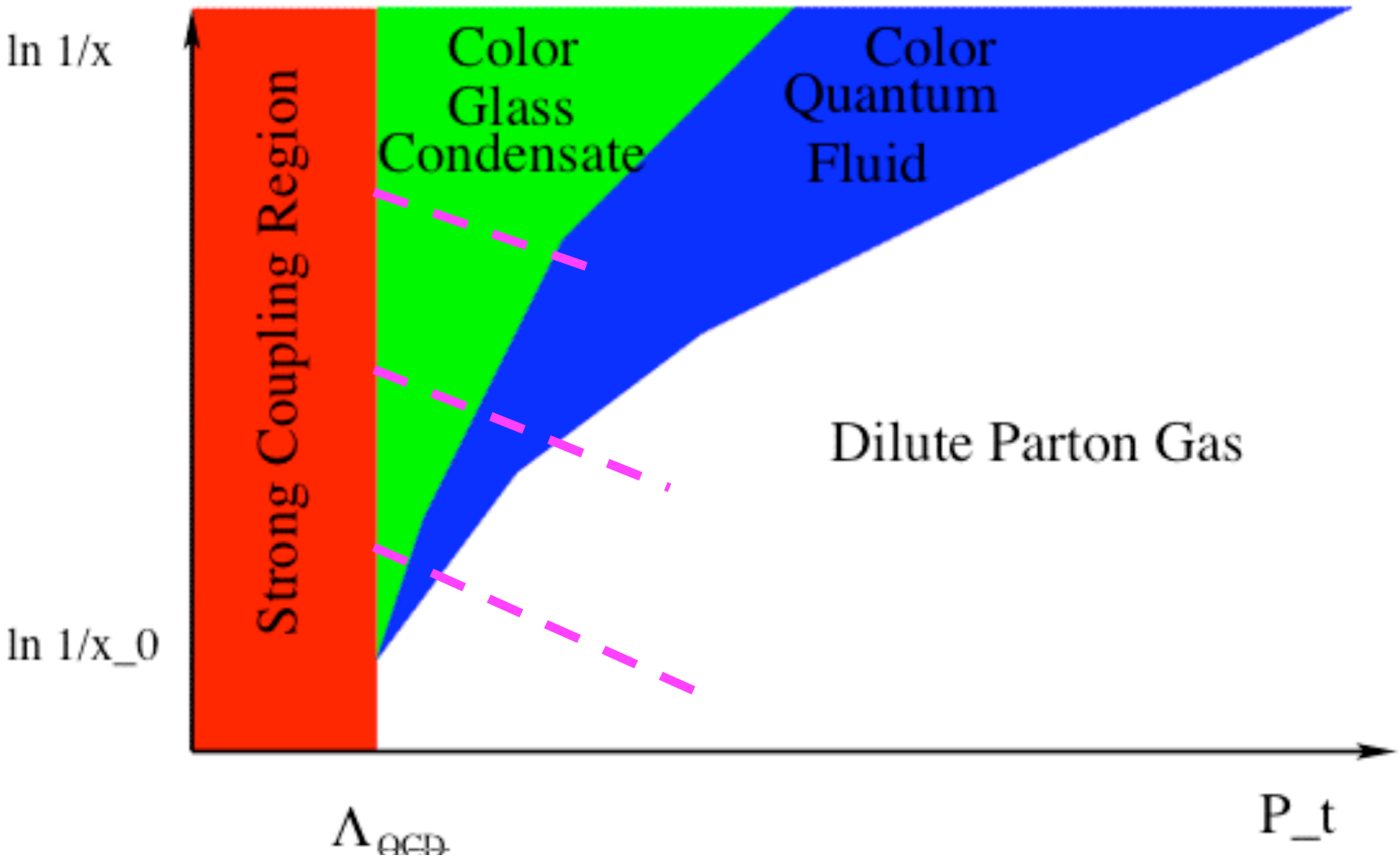
Dilepton Production in dA

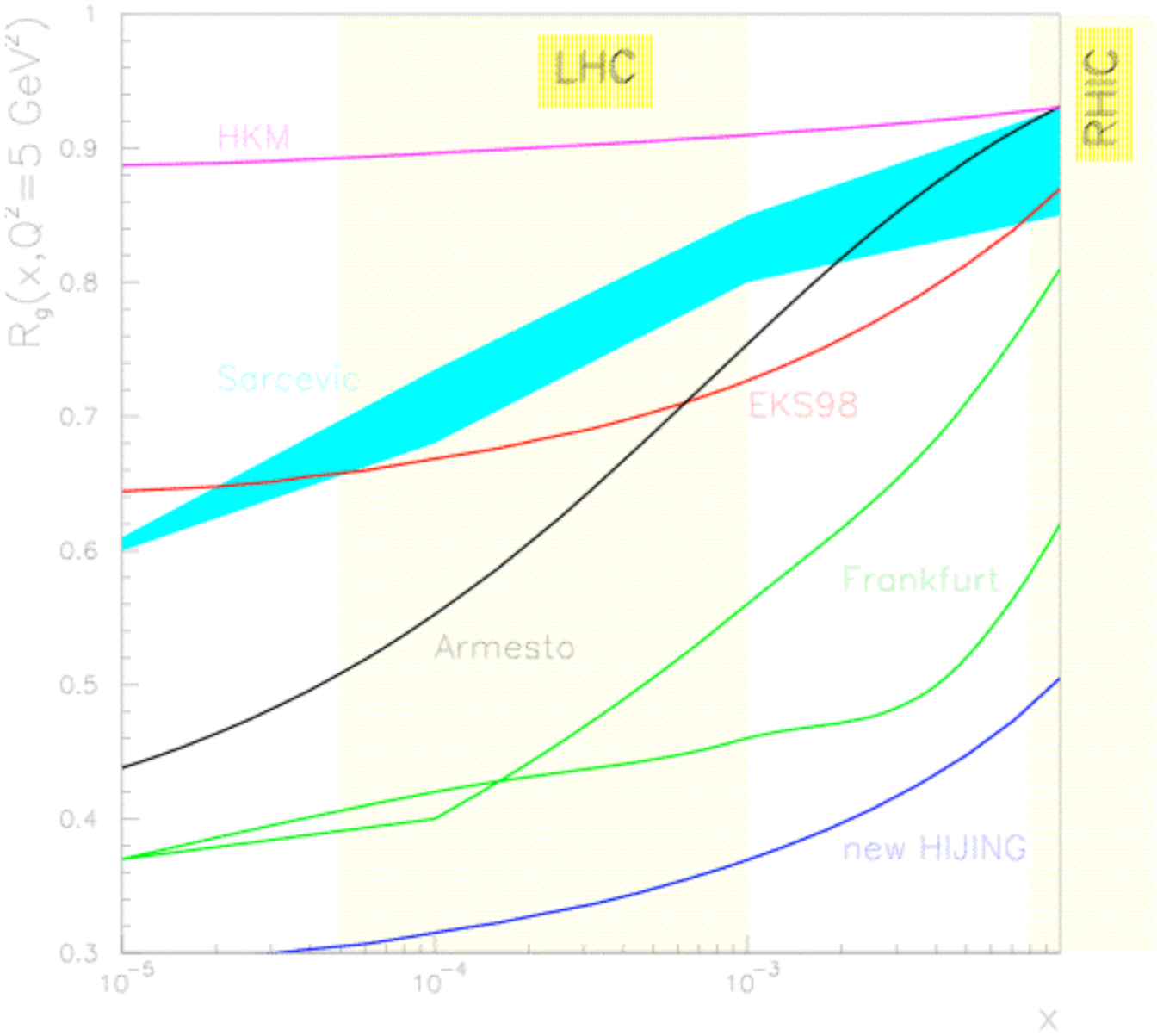
- y = 2.2
- Integrated over p_t
- $R_{dA} < 1$



Summary

- CGC is a new and exciting aspect of QCD
- CGC provides the initial conditions for formation of QGP in heavy ion collisions
- There are strong hints of CGC/CQF at RHIC
  - Multiplicity, energy dependence, forward rapidity spectra, …
- Further tests: electromagnetic signatures, back to back correlations, centrality …
- Forward rapidity region in dA is the best place to explore CGC/CQF at RHIC


ln 1/x
Strong Coupling Region
Color
Glass
Condensate
Color
Quantum
Fluid
Dilute Parton Gas
ln 1/x_0
Λ_{QCD}
P_t


LHC
RHIC
HKM
Sarcevic
EKS98
Armesto
Frankfurt
new HIJING
$R_g(x,Q^2=5\ GeV^2)$
x
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
10^{-5}
10^{-4}
10^{-3}