Color Glass Condensate

in

dA collisions at RHIC

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Work done with A. Dumitru and F. Gelis

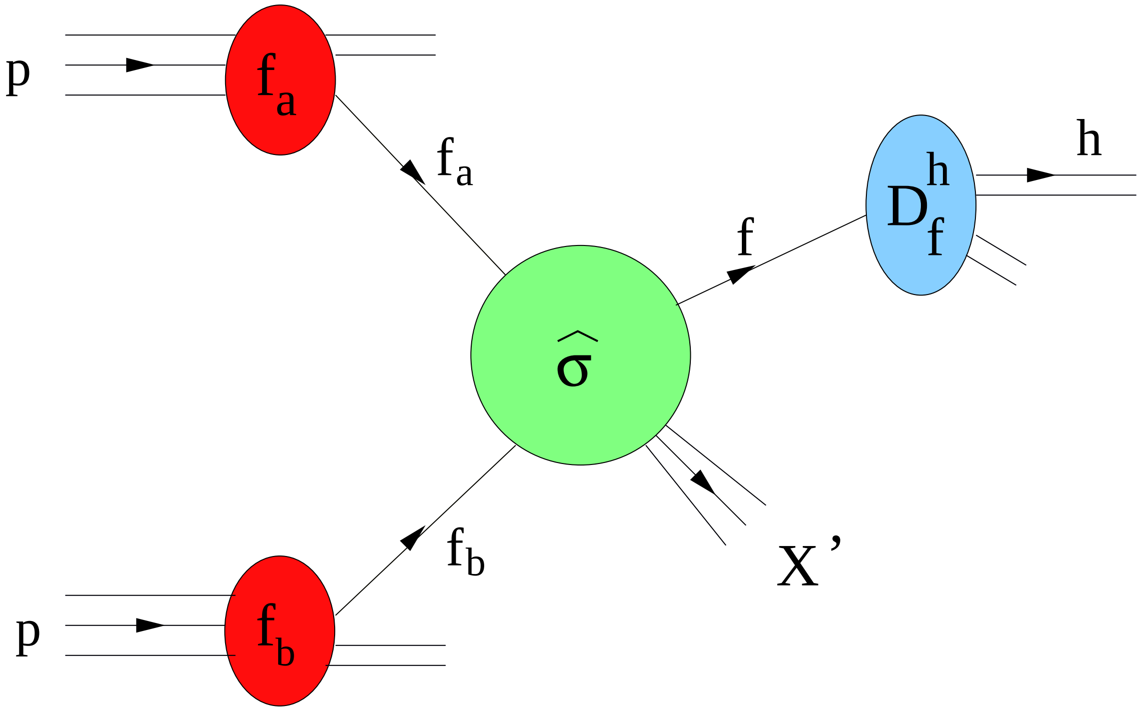
OUTLINE

- The NEED for dA
  - AA: Initial or final state interactions?
  - Do we understand dA?
- PQCD in pp
  - Collinear factorization
  - Very successfull
- "Common" approach to dA
  - Shadowing $+$ Cronin
  - Many poorly understood components
- C G C approach to dA
  - Deuteron: quarks and gluons
  - Nucleus: C G C
  - Same ingredient as DIS: dipoles
  - A unified description $\rightarrow$ predictability

PQCD in pp

- Collinear factorization

$$\sigma^{pp\to h\,X} = f_{a/p} \otimes f_{b/p} \otimes \sigma^{ab\to fx} \otimes D_{f/h} + O(\frac{1}{Q^2})$$



  - $f_{a/p}$ measured in DIS $e\,p$
  - $D_{f/h}$ measured in $e^+\,e^-$

(universality $\rightarrow$ predictability)

- Extremely successfull

“Common” approach to dA

- Collinear factorization

- Nuclear Modifications

  - Shadowing $f_{a/A} \neq A\, f_{a/p}$

    * Gluon shadowing ?

    * Limited Q^2 coverage

    * Leading vs. higher twist

    * Electron Ion Collider

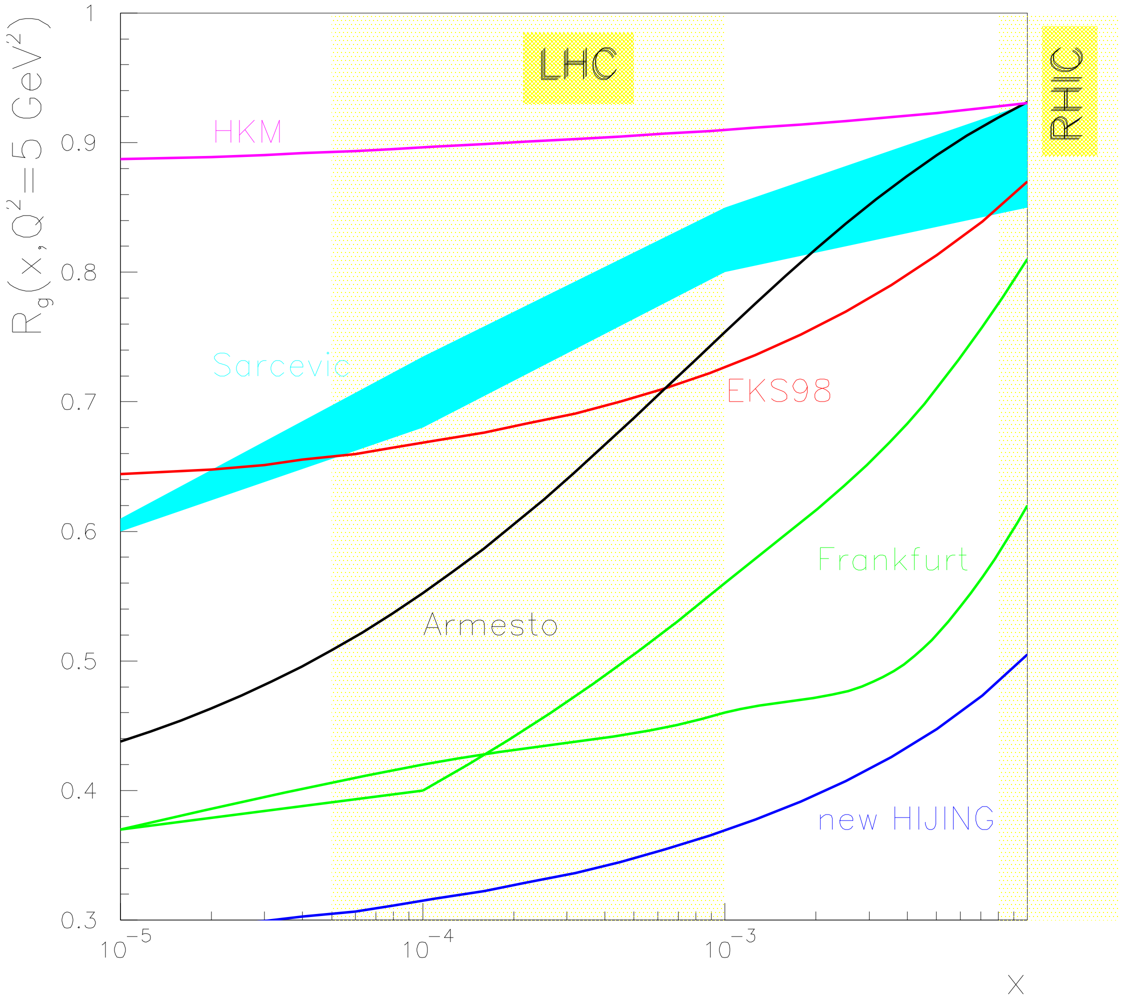
  - Cronin effect

    * Intrinsic p_t

    * p_t broadening

    * $\cdots\cdots$

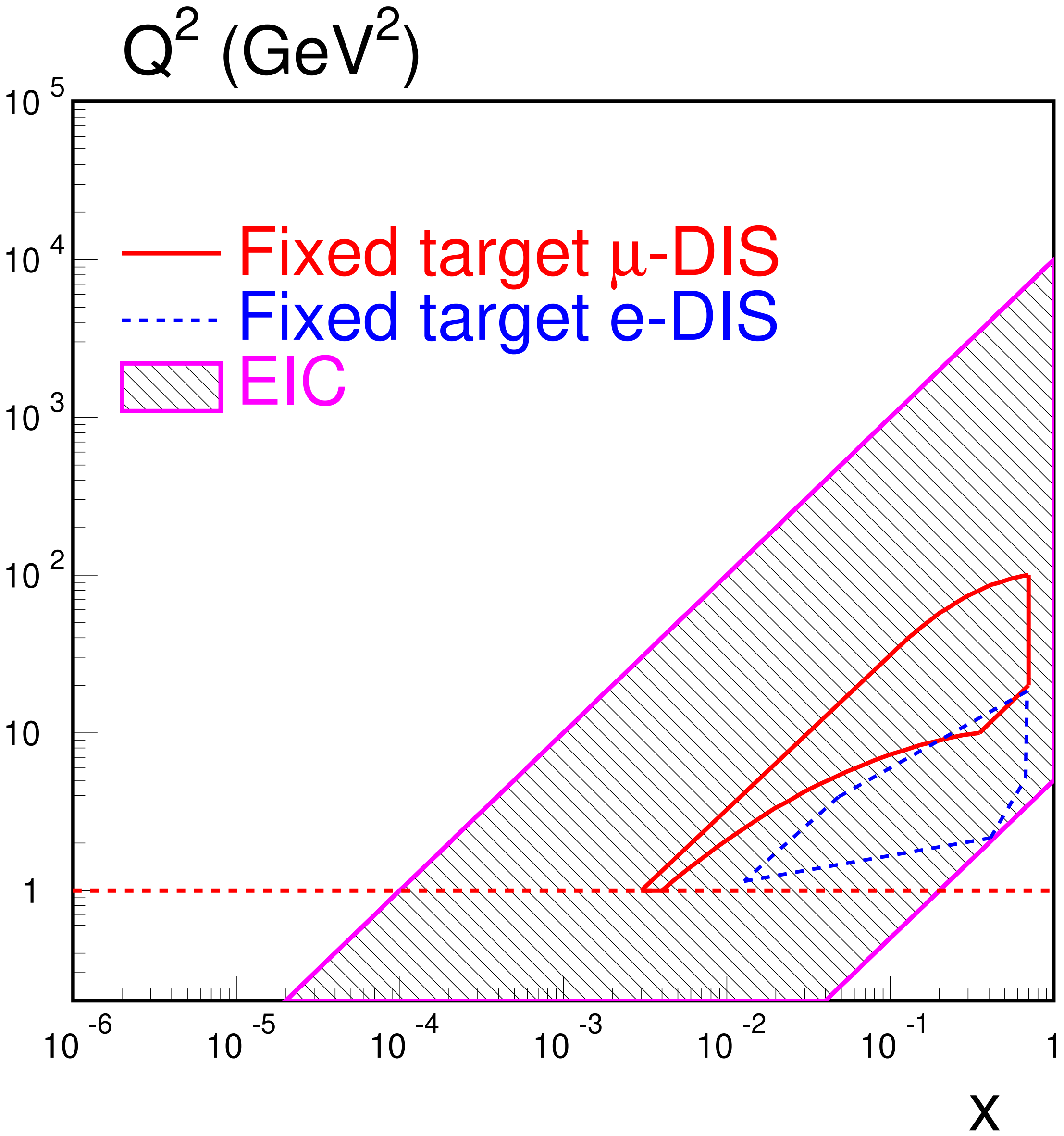
Nuclear Shadowing



From N. Armesto and C.A. Salgado (hep-ph/0301200)

Electron Ion Collider

- 5 – 10 GeV electron on 100 GeV ion (figure from A. Deshpande)
- Wide coverage in x, Q^2
- Complementary to RHIC



Cronin effect in dA

- Models of Cronin effect
  - Intrinsic momentum $\langle k_t^2 \rangle_{pp} \sim 1 - 5 GeV^2$
    - Soft/collinear gluon resummation
    - Phenomenology: $f(x, Q^2) \rightarrow f(x, Q^2, k_t^2)$
    - pp at RHIC: NLO pQCD works fine ($p_t \geq$ 3 GeV)
  - p_t broadening due to multiple scattering

$$\langle k_t^2 \rangle_{pA} \equiv \langle k_t^2 \rangle_{pp} + \kappa\, F[\nu(b_t)]$$

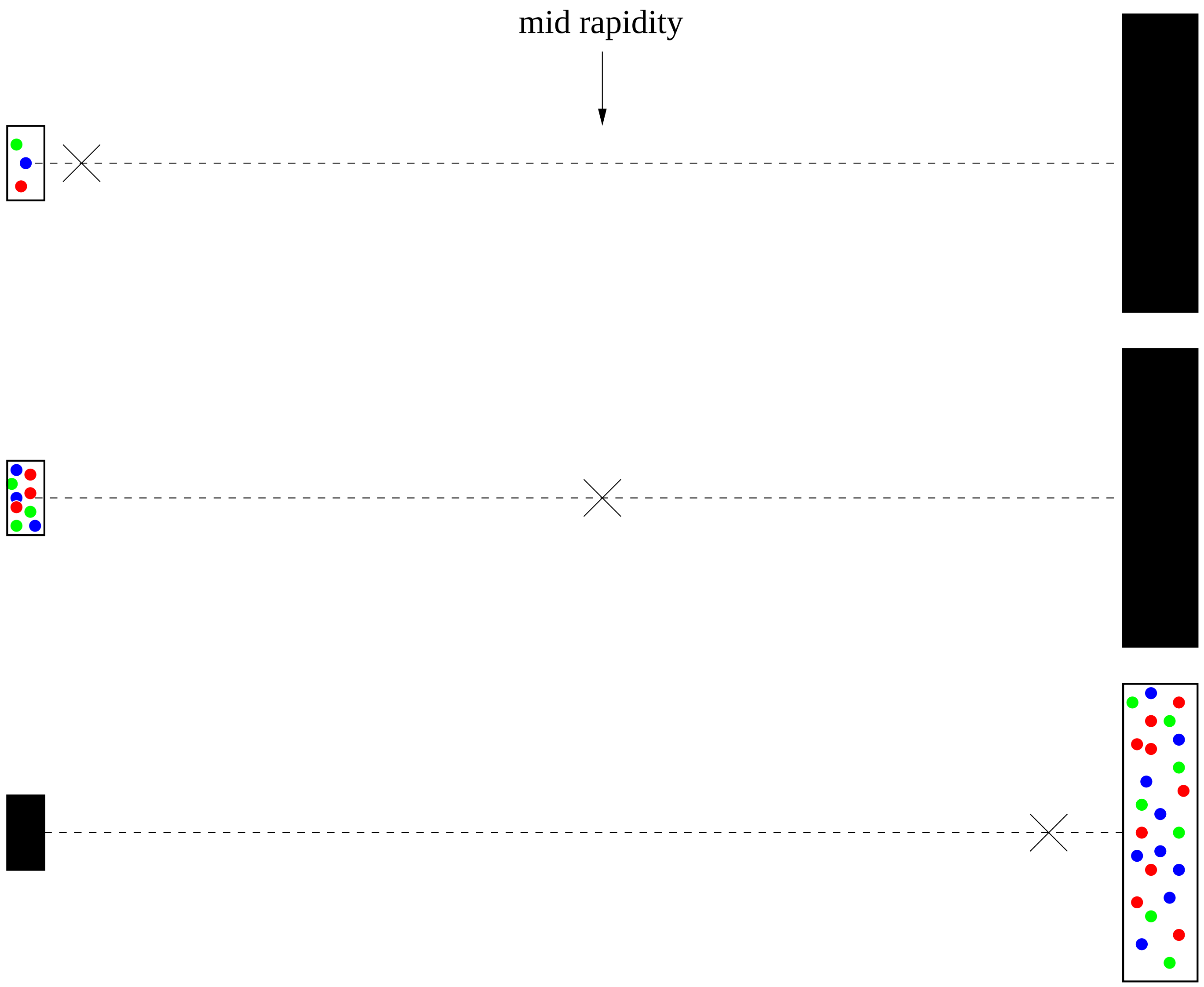
    - $\kappa(Q^2)$: average kick per collision
    - $\nu(b_t)$: number of scatterings inside the target
- Parameters are fit to data

Universality is lost

C G C approach to dA

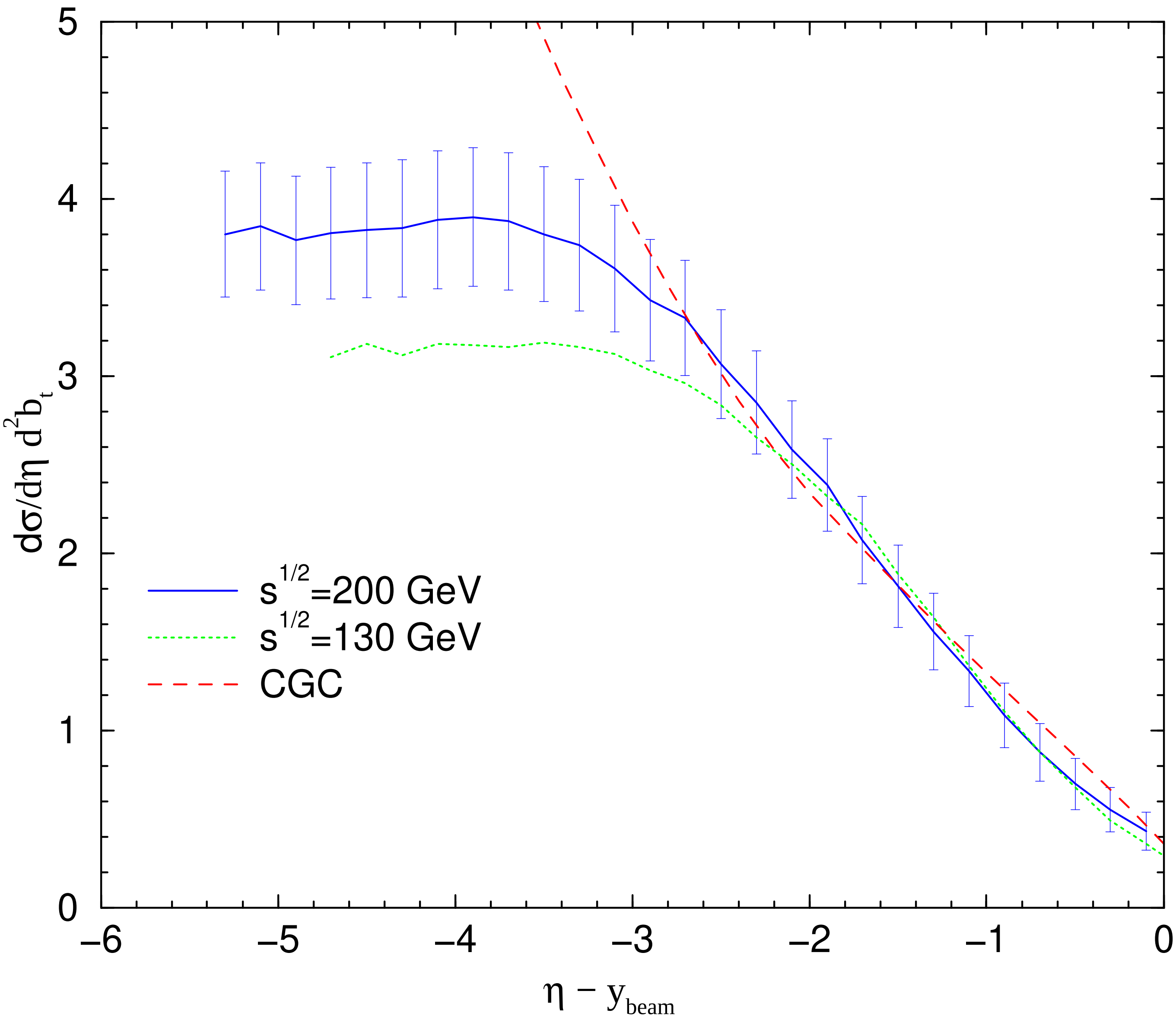
- Deuteron: dilute system of quarks and gluons
  - Collinear factorization
- Nucleus: dense system of gluons C G C
  - Nucleus is described by a classical field
- Scattering of quarks and gluons from the classical field of the nucleus
  - Quark anti-quark (gluon-gluon) dipole
- Vacuum fragmentation into hadrons
- Mid to forward dA, very forward AA or pp

C G C approach to dA



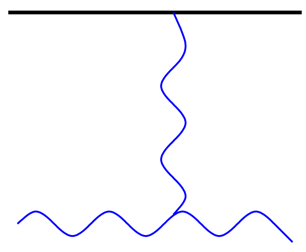
C G C in very forward AA

- Limiting fragmentation
  J.J-M (nucl-th/0212018)



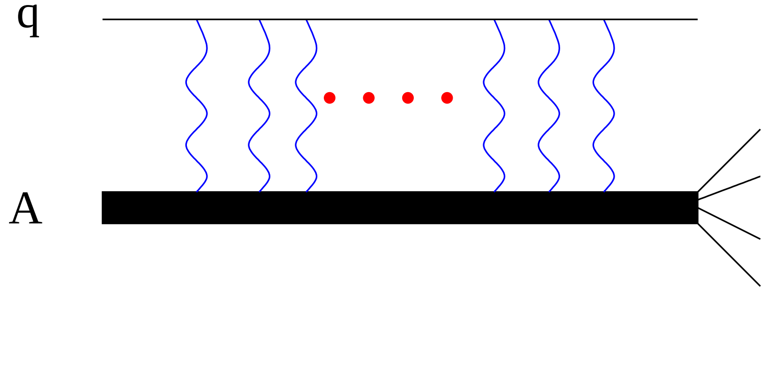
C G C approach to dA

- Scattering of quarks from the nucleus (A.D. + J.J-M., $PRL 89 : 022301, 2002$)
  - pQCD $q\,g \to q\,g$



  - C G C

$$q\;A \to q\;X$$



C G C approach to dA

- Scattering cross section

$$\frac{d\sigma^{qA\to qX}}{dq^- \, d^2q_t \, d^2b_t} \sim \tilde{\sigma}_{\text{dipole}}(x, q_t, b_t)$$

$$\sigma_{dipole}(x, r_t, b_t) \equiv \frac{1}{N_c} Tr\Big\langle 1 - V(b_t + \frac{r_t}{2})\, V^\dagger(b_t - \frac{r_t}{2})\Big\rangle_\rho$$

$$V(z_t) \equiv \hat{P} \exp\Big[- ig^2 \int_{-\infty}^{+\infty} dz^- \frac{1}{\partial_t^2} \rho_a(z^-, z_t) t_a \Big]$$

- $V(z_t)$ includes multiple (eikonal) scatterings of the quark on the nucleus

C G C approach to dA

- Differential cross section
  - pQCD when $q_t^2 \gg Q_s^2$

$$\frac{d\sigma}{d^2q_t} \sim \frac{1}{q_t^4} \quad (\sim A)$$

  - *Enhancement* when $q_t^2 > Q_s^2$

$$\frac{d\sigma}{d^2q_t} \sim \frac{\pi R^2 Q_s^2}{q_t^4}\left[1 + \frac{Q_s^2}{q_t^2}\right] \quad (\sim A^{1+\alpha} \quad \alpha > 0) \quad \mathit{Cronin}$$

  - *Suppresion* when $q_t^2 < Q_s^2$

$$\frac{d\sigma}{d^2q_t} \sim \frac{\pi R^2}{Q_s^2} \quad (\sim A^{1-\alpha} \quad \alpha > 0)$$

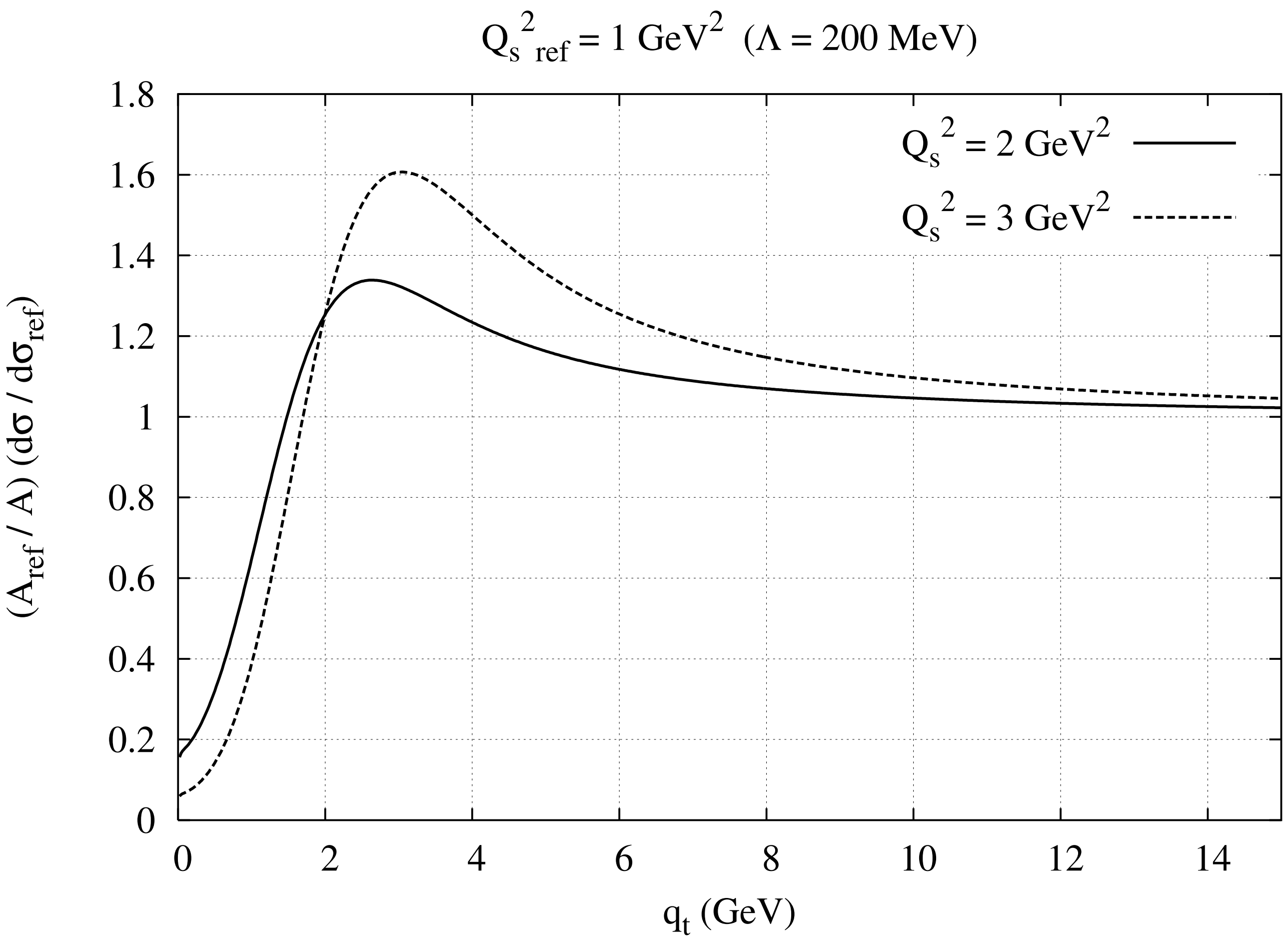
  - Crossover region $q_t^2 \sim Q_s^2$

$$\frac{d\sigma}{d^2q_t} \sim \frac{\pi R^2}{q_t^2}$$

  - Cross section is finite as $q_t \to 0$

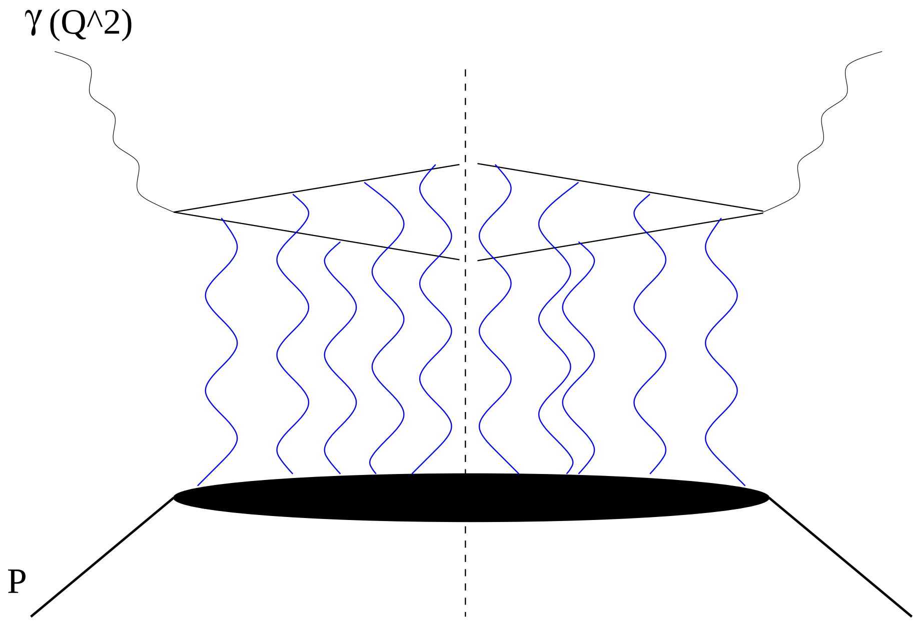
C G C approach to dA

- Illustration
  - Suppression at low p_t
  - Enhancement at intermediate p_t
  - Cross over moves to higher p_t with rapidity



C G C approach to DIS

- Dipoles in Deep Inelastic Scattering (DIS)
- F_2 structure function



$$F_2(x,Q^2) \sim \int dz \int d^2r_t\, |\psi(z,r_t)|^2\, \sigma^{dipole}(x,r_t,b_t)$$

$$\sigma_{dipole}(x,r_t,b_t) \equiv \frac{1}{N_c} Tr\Big\langle 1 - V(b_t+\frac{r_t}{2})\,V^\dagger(b_t-\frac{r_t}{2})\Big\rangle_\rho$$

DIS $\leftrightarrow$ C G C $\leftrightarrow dA$

- Quark-anti-quark (gluon-gluon) dipoles are the universal building blocks

- How do we calculate σ_{dipole}?

  - Exact in RG: correlations (numerical)

  - Gaussian model (analytic $\rightarrow$ "Glauber")

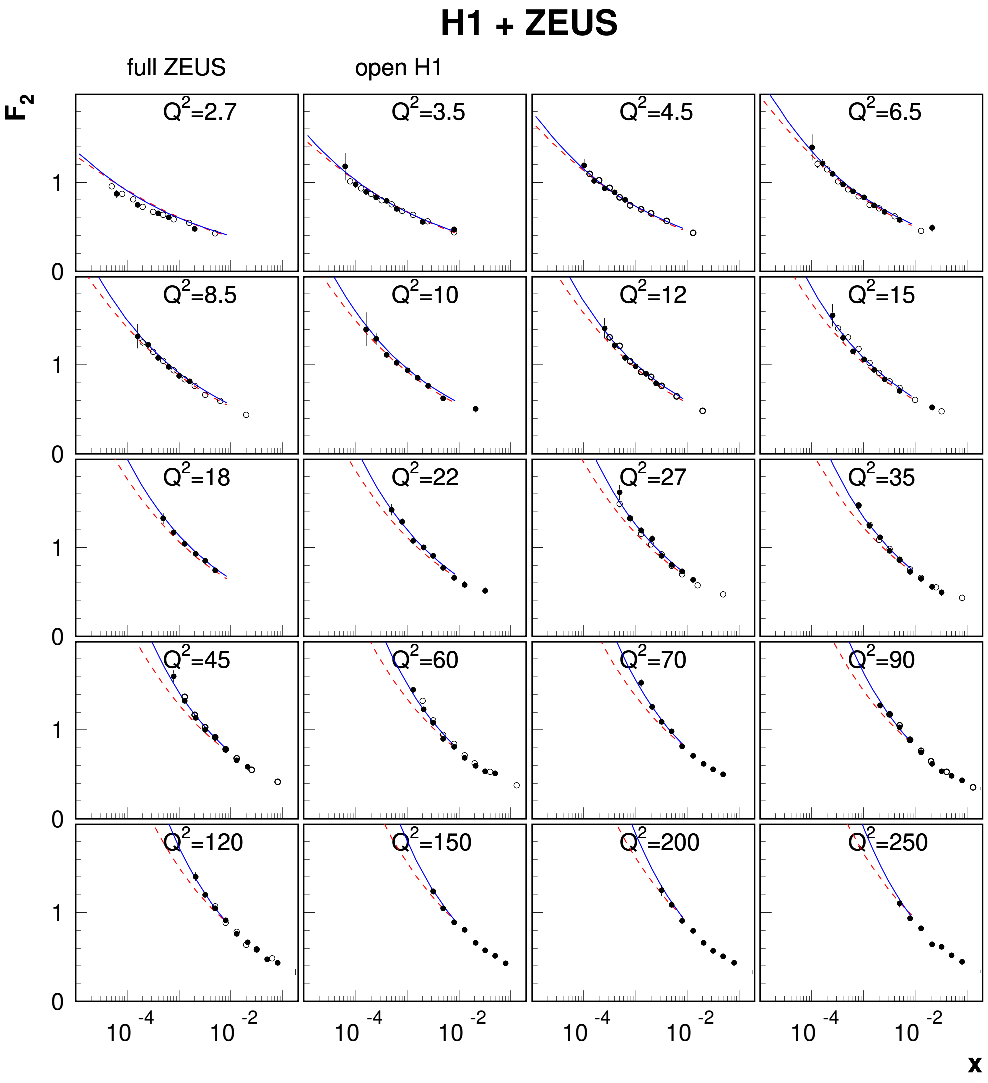
  - Fits to HERA data

    * Golec-Biernat and Wusthoff

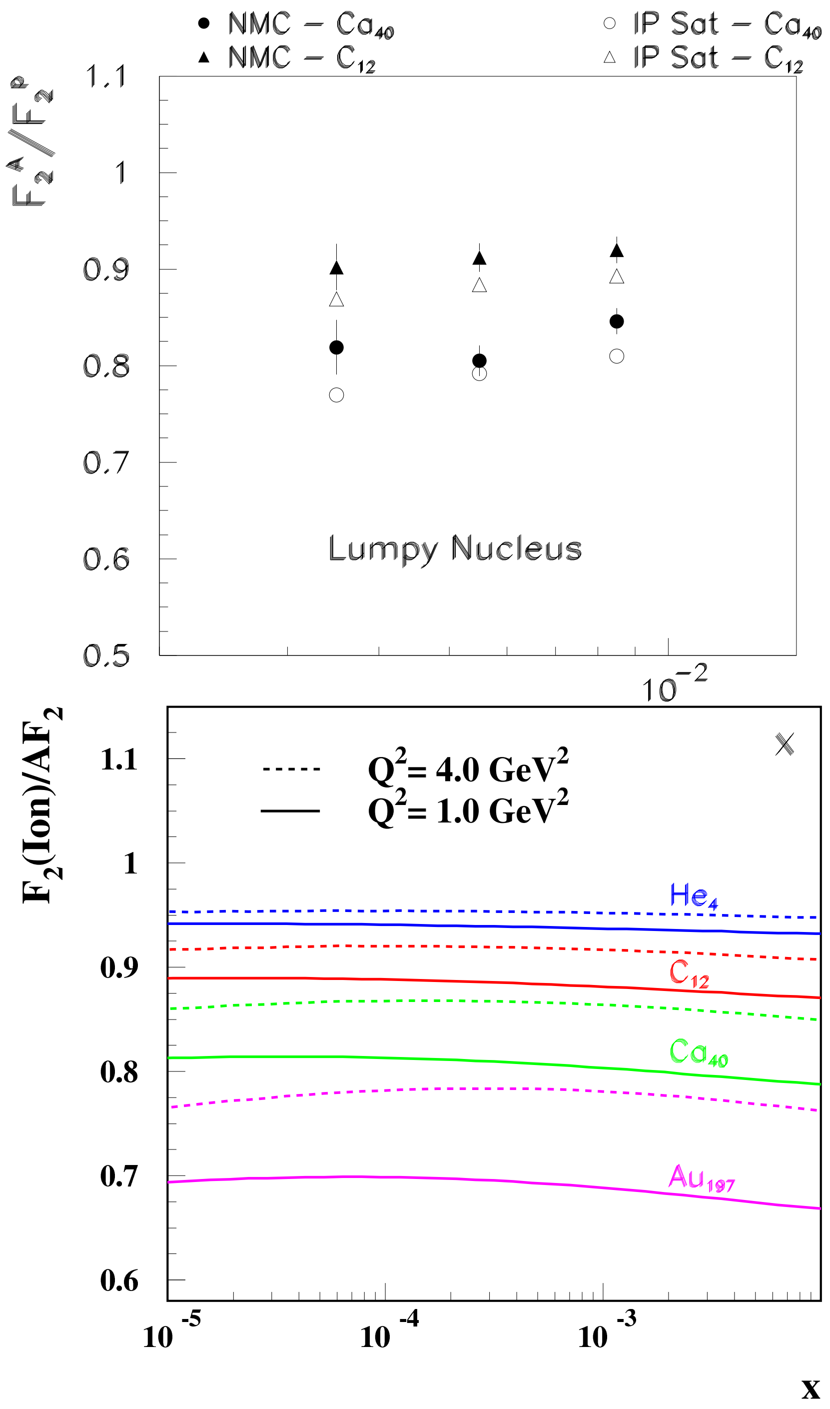
    * DGLAP improved for high p_t by BG-BK

DIS $\leftrightarrow$ C G C $\leftrightarrow dA$

Guassian Model: Figure from BG-BK
Phys.Rev.D66:014001,2002



A dependence: H. Kowalski and D. Teaney (work in progress)



C G C (qualitative) predictions for dA

- Measure particles in the forward (deuteron fragmentation) region

- $Q_s^2 \sim 2GeV^2$ in mid rapidity and $\sim 10GeV^2$ in the very forward region

- Signatures of C G C

  - P_t distribution at fixed rapidity

    * Suppresion at low p_t, Enhancement at intermediate p_t

  - Rapidity dependence of p_t distribution

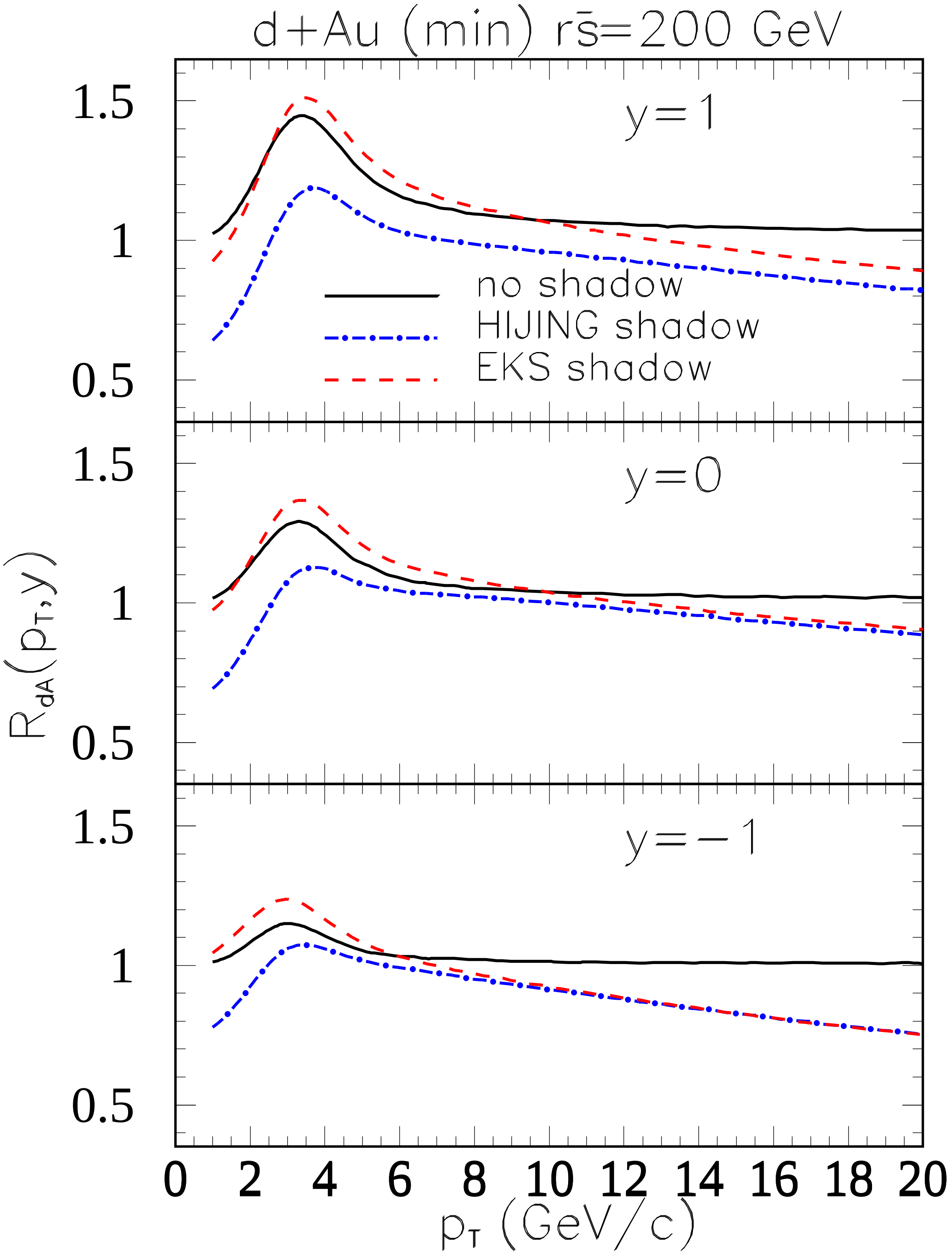
    * Shifting of cross over region to higher rapidity

  - A dependence at different p_t

    * From A^1 to $A^{1+\alpha}$ to $A^{1-\alpha}$

- Quantitative predictions in progress

Figure from X-N. Wang (nucl-th/0303004)



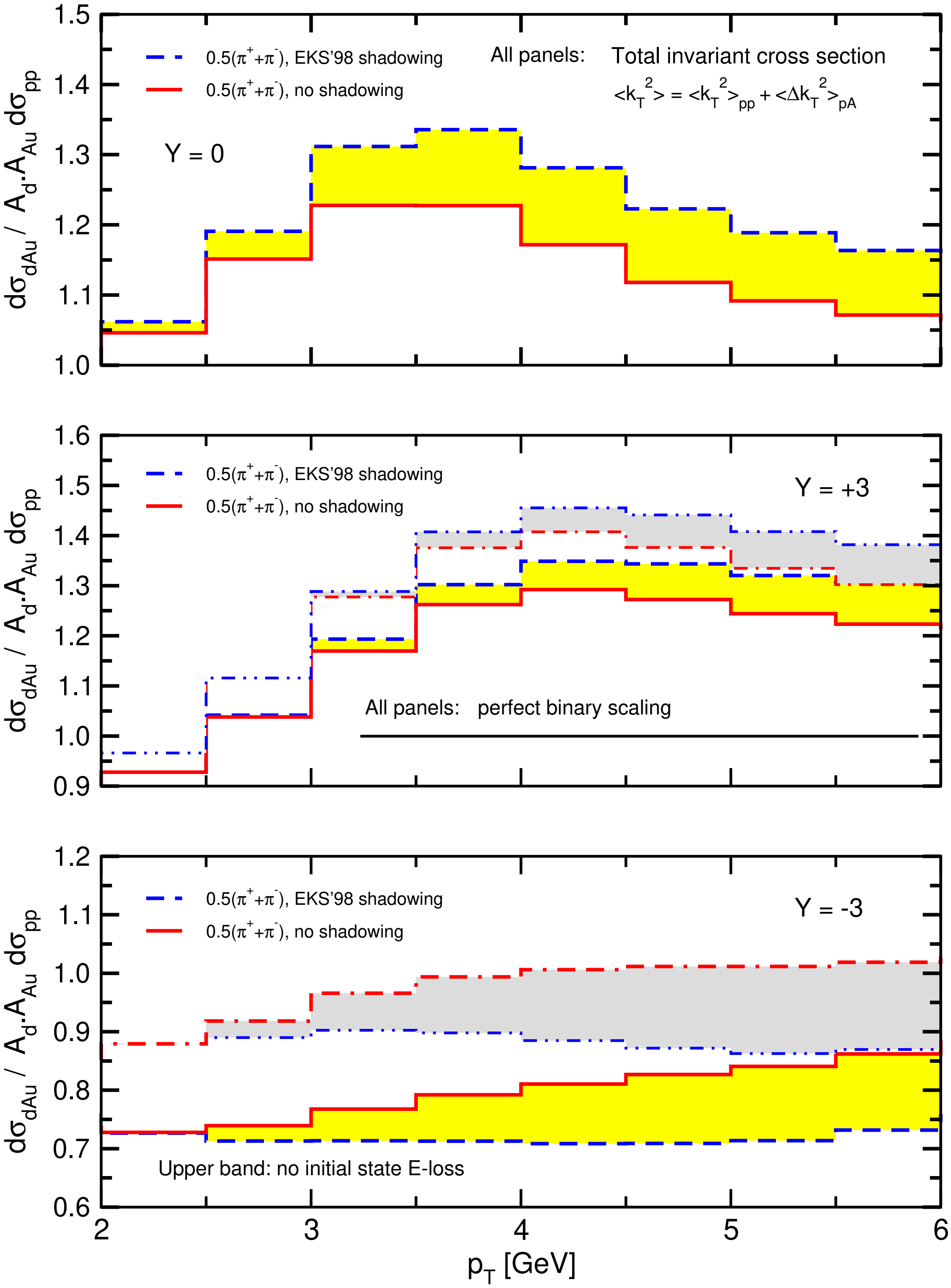
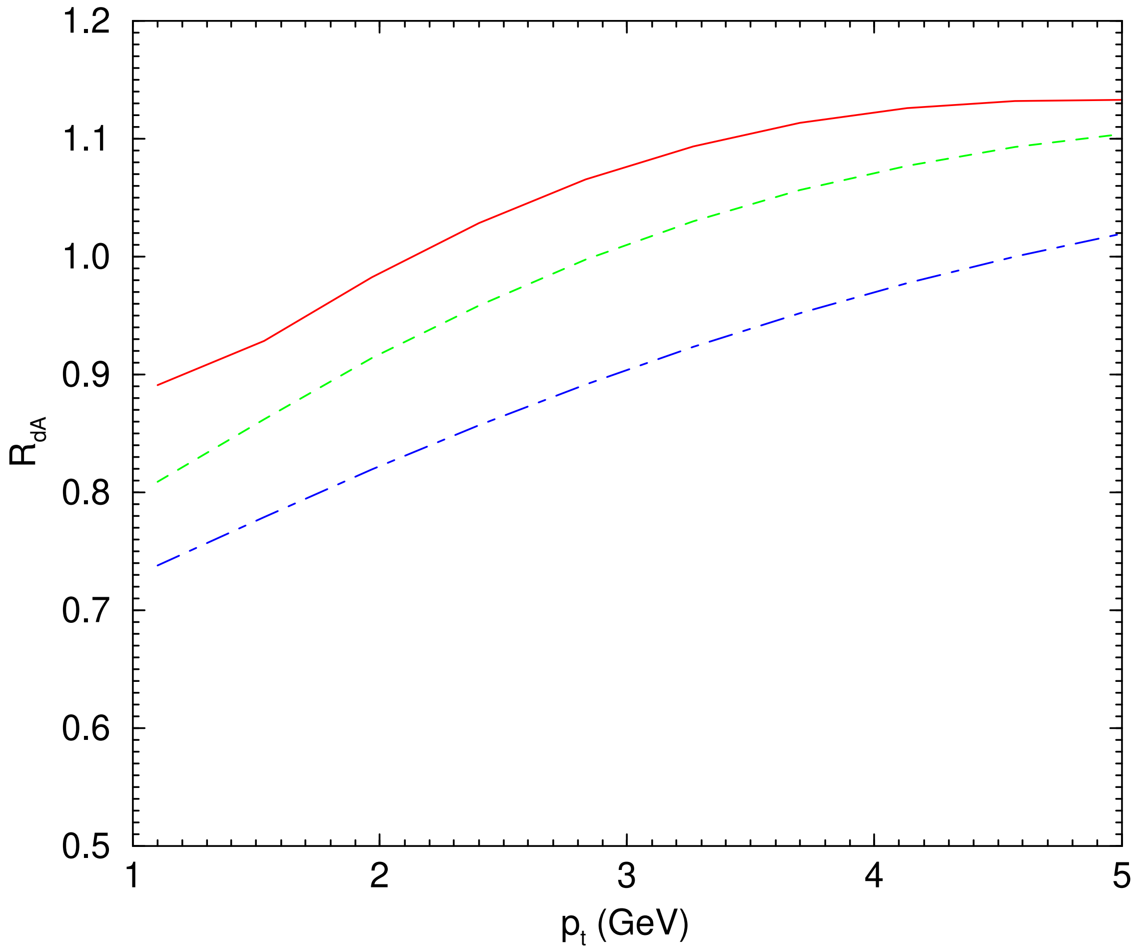


Figure from I. Vitev (nucl-th/0302002)

VERY PRELIMINARY

$R_{dA}(p_t, y)$ at $\sqrt{s} = 200 GeV$ (one quark flavor)

$$\frac{d\sigma^{dA\to\pi^0 X}}{d^2p_t\,dy} \sim q(x,Q^2) \otimes \frac{d\sigma^{qA\to qX}}{d^2p_t\,dy} \otimes D_{q/\pi^0}(z,Q^2)$$



Work in progress (F.G.,J.J-M.,H.K.,D.T.)

Summary

- C G C gives a universal description of DIS and dA at high energy

- Applications of C G C to dA
  - Calculated so far:
    - Hadrons
    - Photons
    - Dileptons

- C G C is magnified in the forward (proton fragmentation) region

C G C in AA ?

look FORWARD in dA