Ultrahigh Energy Neutrino Nucleon Cross Sections

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Neutrino Nucleon Cross Sections

$$\sigma_{total}^{\nu N \to X}(s) = \int_0^1 dx \int_0^{xs} dQ^2 \frac{d\sigma^{\nu N \to X}}{dx dQ^2}$$

$$\frac{d\sigma^{\nu N \to X}}{dx dQ^2} = \frac{G_F^2}{\pi}\left(\frac{M_W^2}{Q^2 + M_W^2}\right)^2 [q(x,Q^2) + (1-y)^2 \bar{q}(x,Q^2)]$$

$q(x,Q^2)$, $\bar{q}(x,Q^2)$ from DGLAP

$Q \sim M_W$ dominates the cross section

$$\sigma_{total}^{\nu N \to X}(s) \simeq \int_0^1 dx \left[\left(\frac{\hat{s}}{1+\hat{s}}\right) q(x) + \left(1 + \frac{2}{\hat{s}} - 2\left(\frac{1+\hat{s}}{\hat{s}^2}\right) \ln(1+\hat{s})\right) \bar{q}(x)\right]$$

with $\hat{s} \equiv \frac{xs}{M_W^2}$

x dependence of PDF's determines the cross section

Neutrino Nucleon Cross Sections

- Contribution of small x partons

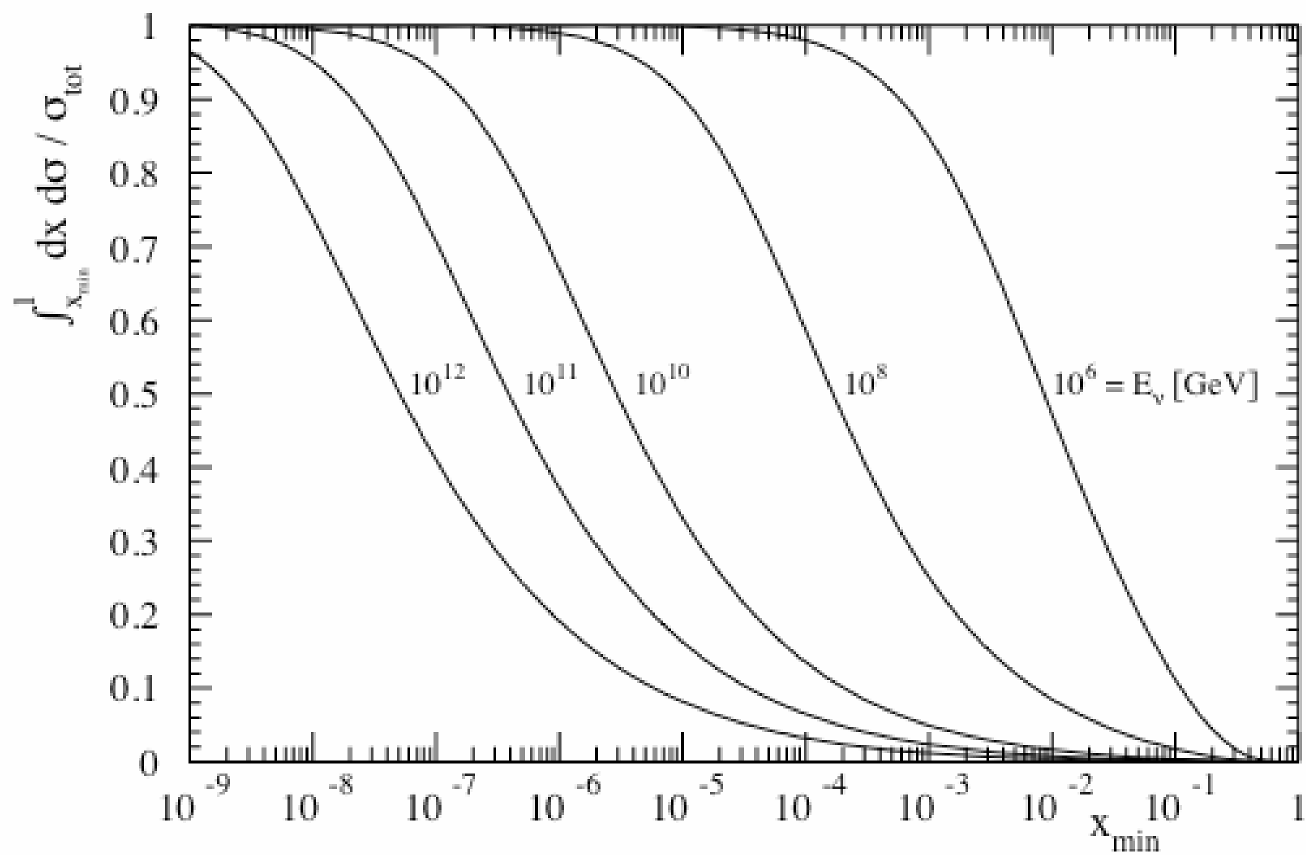
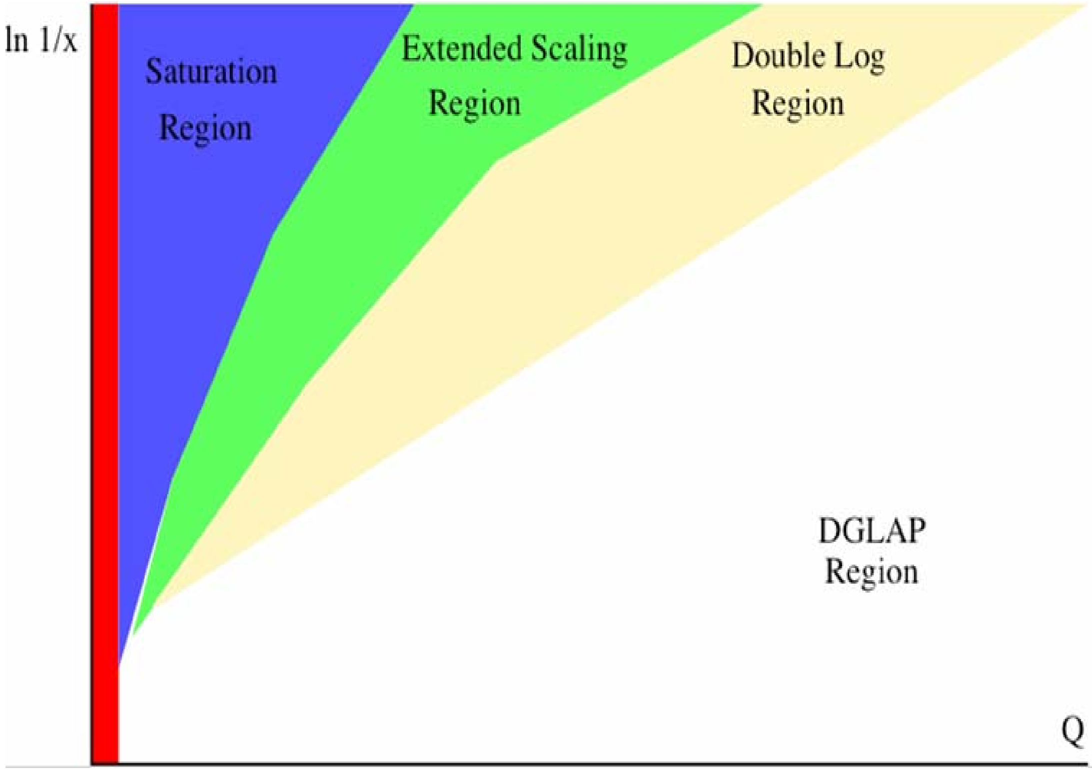
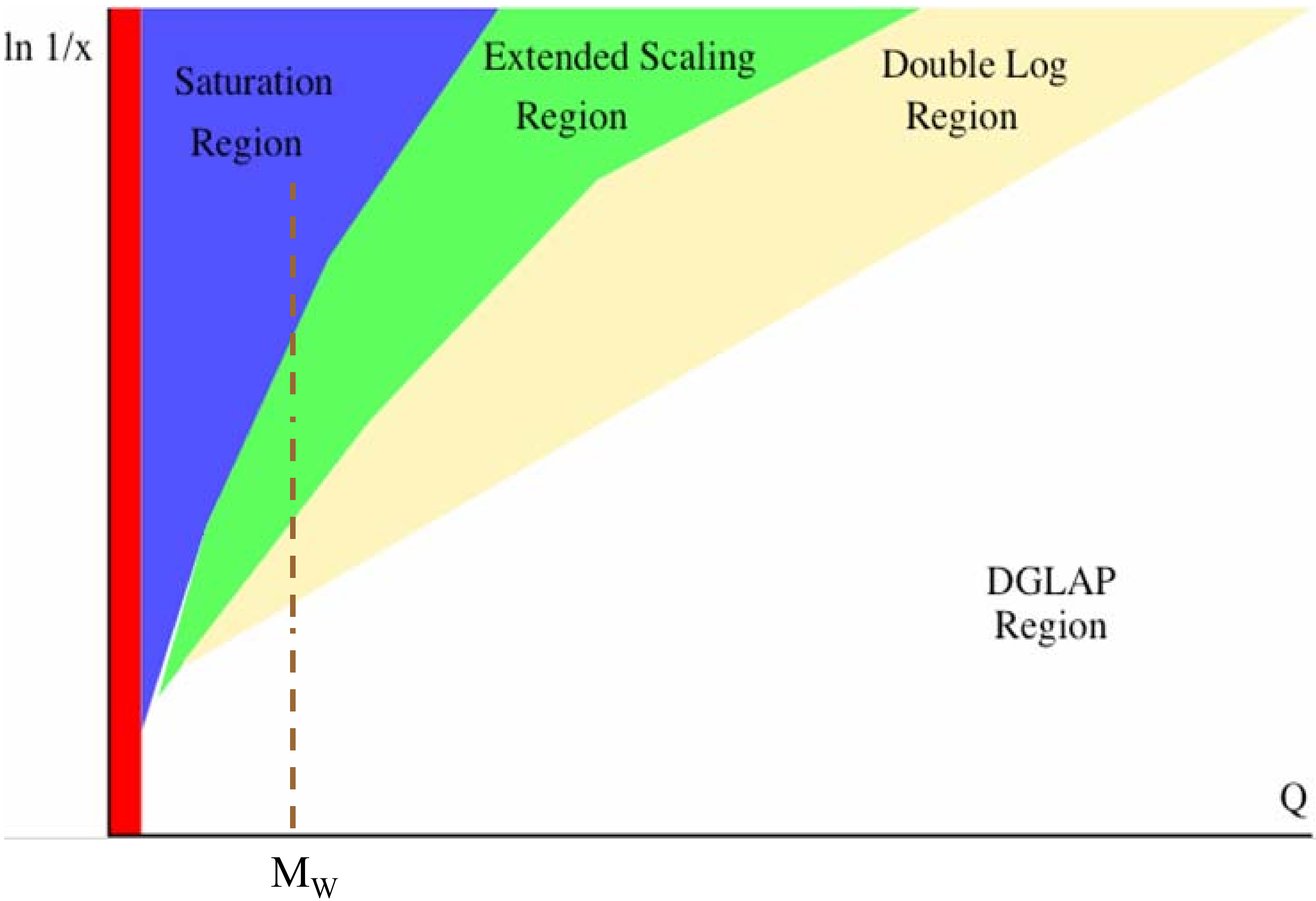


Fig. from Gluck, Kretzer and Reya, Astropart. Phys.11 (1999) 327

QCD Kinematic Regions



- DGLAP ($\alpha_s \, lnQ^2$)[leading twist, no Anomalous Dimension]
  - Double Log ($\alpha_s \, lnQ^2 \, ln1/x$)
- Extended scaling ($\alpha_s \, ln1/x$)[leading twist, BFKL, Ano. Dim.]
- Saturation region ($\alpha_s \, \rho \, ln1/x$)[all twist, JIMWLK (BK)]



ln 1/x
Saturation
Region
Extended Scaling
Region
Double Log
Region
DGLAP
Region
Q
M_W

QCD Effective Action at Small x

McLerran & Venugopalan 93
JJM et al. 96

$$S = -\frac{1}{4}\int d^4x\, G_a^{\mu\nu} G^a_{\mu\nu}$$
$$+ \quad \frac{i}{N_c}\int d^2x_t dx^- \delta(x^-) \mathrm{Tr}\rho(x_t) W_{-\infty,\infty}[A^-](x^-, x_t)$$
$$+ \quad i\int d^2x_t F[\rho^a(x_t)]$$

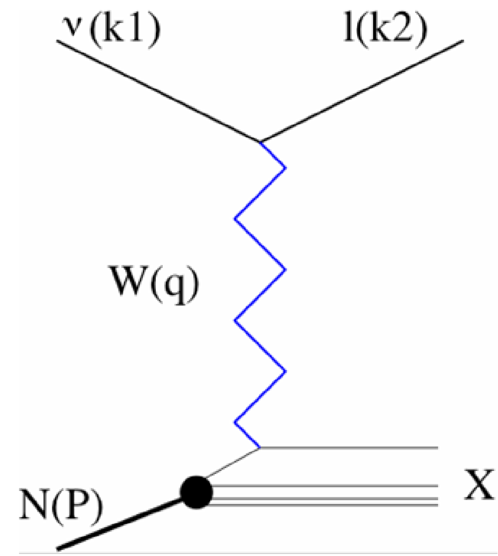
with

$$W_{-\infty,\infty}[A^-](x^-, x_t) = \hat{P}exp\left[- ig \int_{-\infty}^{\infty} dx^+ \, A_a^-(x)\, T_a \right]$$

and

$$< O(A) >\equiv \frac{\int [D\rho^a][DA_a^\mu] O(A) \;\; \exp\{iS[\rho, A]\}}{\int [D\rho^a][DA_a^\mu] \exp\{iS[\rho, A]\}}$$

Neutrino-Nucleon DIS: Charged Current



$$\nu_l(k_1)\, N(P) \rightarrow l(k_2) X$$

$$\begin{aligned} s &\equiv (k_1+P)^2 \qquad q \equiv k_1 - k_2 \\ x &\equiv -\frac{q^2}{2P\cdot q} \qquad Q^2 \equiv -q^2 \\ y &\equiv \frac{P\cdot q}{P\cdot k_1} = \frac{Q^2}{xs} \end{aligned}$$

McLerran & Venugopalan PRD99
JJM PRD03

$$\frac{d\sigma}{dx dQ^2} = \frac{1}{4\pi}\frac{y}{xs}\frac{G_F^2 M_W^4}{[Q^2+M_W^2]^2} L^{\mu\nu}(k_1,k_2)\, W_{\mu\nu}(q^2, P\cdot q)$$

Neutrino-Nucleon DIS: Charged Current

Leptonic part

$$L^{\mu\nu}(k_1, k_2) = 2[k_1^\mu k_2^\nu + k_1^\nu k_2^\mu - g^{\mu\nu} k_1 \cdot k_2 + i\epsilon^{\mu\nu\rho\sigma} k_{1\rho} k_{2\sigma}]$$

Hadronic part

$$W_{\mu\nu}(q^2, 2P \cdot q) = \frac{\sigma_h}{2\pi} \frac{P^+}{M_h} \mathrm{Im} \int dx^- \int d^4z \, e^{iq \cdot z}$$
$$< T J_\mu^\dagger(x^- + z/2) \, J_\nu(x^- - z/2) >_\rho$$

with

$$J_\mu(x) = \bar{u}(x) \gamma_\mu (1 + \gamma_5) d(x)$$

$\sigma_h, \; M_h$ are the nucleon size and mass

Neutrino-Nucleon DIS: Charged Current

$$< T\, J_\mu^\dagger(x)\, J_\nu(y) >_\rho = \mathrm{Tr}\, \gamma_\mu(1+\gamma_5)\, S_A(x,y)\, \gamma_\nu\, (1+\gamma_5)\, S_A(y,x) + \mathrm{Tr}\, \gamma_\mu(1+\gamma_5)\, S_A(x)\, \mathrm{Tr}\, \gamma_\nu\, (1+\gamma_5)\, S_A(y)$$

where S_A is the quark propagator in the classical gluon field background

$$S_A(x,y) = S_0(x,y) - i \int d^4r\, \delta(r^-) \left[\theta(x^-)\theta(-y^-)[V^\dagger(r_t) - 1] - \theta(-x^-)\theta(y^-)[V(r_t) - 1]\right] S_0(x-r)\, \gamma^-\, S_0(r-y)$$

S_0 is the free quark propagator and

$$V(r_t) \equiv \hat{P} e^{-ig \int dz^- A^+(z^-, r_t)}$$

Neutrino-Nucleon DIS: Charged Current

$$2xF_1 = \frac{N_c Q^2}{4\pi^4} \int_0^1 dz \int d^2b_t\, d^2r_t\, \boxed{\gamma(x, b_t, r_t)}$$
$$a^2[z^2 + (1-z)^2] K_1^2(ar_t)$$

with $a^2 \equiv z(1-z)Q^2$

$$F_2 = \frac{N_c Q^2}{4\pi^4} \int_0^1 dz \int d^2b_t\, d^2r_t\, \boxed{\gamma(x, b_t, r_t)}$$
$$\{4z(1-z)a^2 K_0^2(ar_t) + a^2[z^2 + (1-z)^2] K_1^2(ar_t)\}$$

$$xF_3 = \frac{N_c Q^2}{4\pi^4} \int_0^1 dz \int d^2b_t\, d^2r_t\, \boxed{\gamma(x, b_t, r_t)}$$
$$(1-2z)a^2 K_1^2(ar_t)$$

$$\frac{d\sigma}{dx dQ^2} = \frac{1}{2\pi} \frac{G_F^2}{x[1 + Q^2/M_W^2]^2} \{y^2 xF_1 + (1-y)F_2 + y(1-\frac{y}{2})xF_3\}$$

Dipole Cross Section

$$\gamma(x, r_t, b_t) \equiv \frac{1}{N_c} \mathrm{Tr} < V(b_t + r_t/2)\, V^\dagger(b_t - r_t/2) - 1 >$$

Solution of JIMWLK (BK) non-linear evolution equation:

Rumakainen & Weigert, NPA739 (2004)183
Golec-Biernat & Stasto, NPB668 (2003) 345
Mueller & Triantafyllopoulos NPB640 (2002) 331
Triantafyllopoulos NPB648 (2003) 293
…….

Phenomenological parameterizations:

Golec-Biernat and Wusthoff, PRD59 (1999) 014017
Iancu, Itakura and Munier, PLB590 (2004)199
Kharzeev, Kovchegov and Tuchin, hep-ph/0405045
…….

Probing the Dipole Cross Section

- Inclusive observables
  - Structure functions F_2, F_L
- Single inclusive observables
  - Hadron production in p(d)A
  - Photon, dilepton production in p(d)A
- Double inclusive observables
  - Photon + hadron (jet)
- Correlation studies are excellent probes of CGC but involve higher point functions (quark+gluon, two gluon, quark anti-quark production, …)

Models of the dipole cross section:

Iancu, Itakura and Munier PLB590 (2004) 199

$$\gamma(x, r_t, b_t) \equiv \sigma_0 \mathcal{N}(r_t Q_s, x)$$

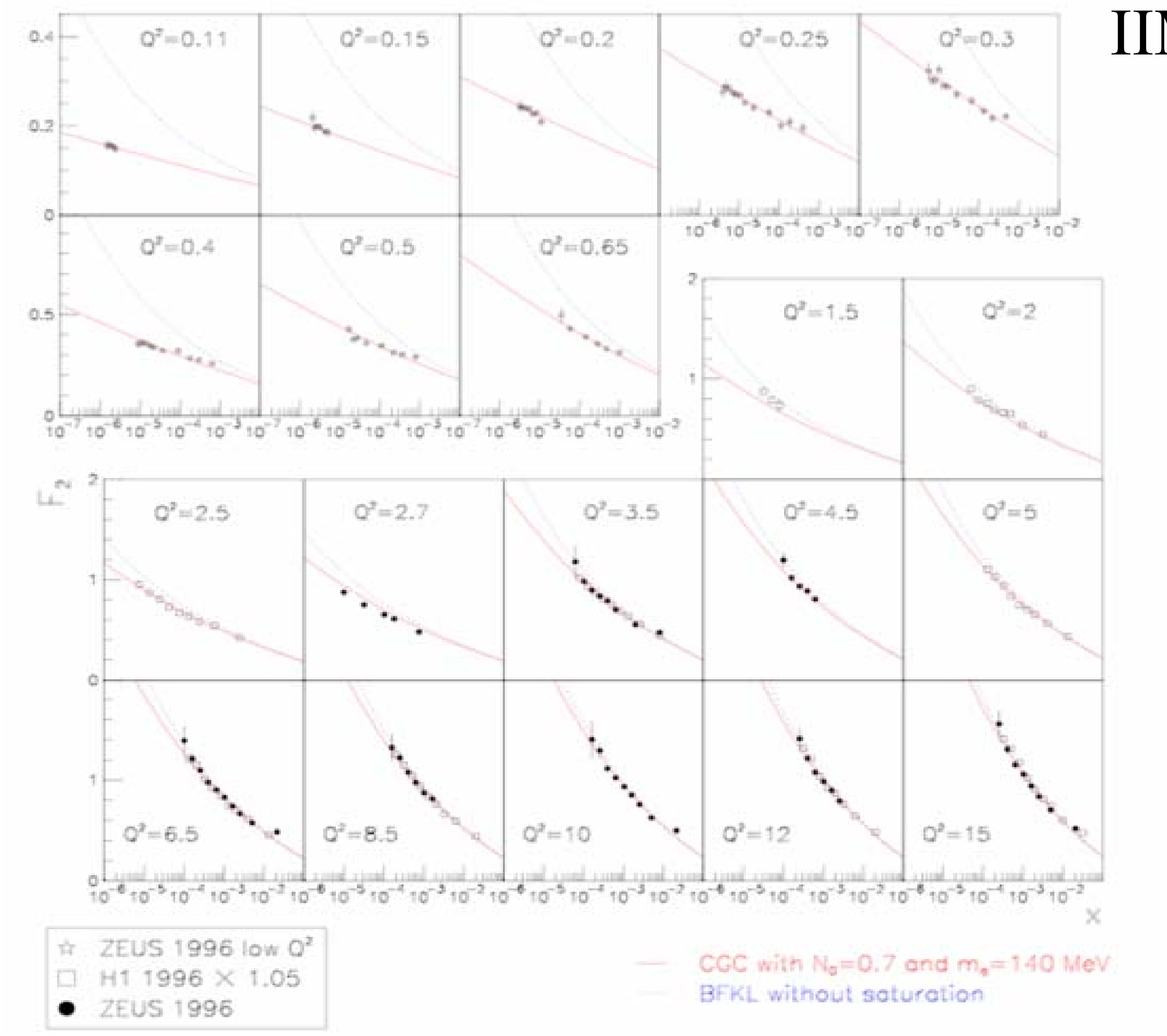
$$\mathcal{N}(r_t Q_s, x) = \mathcal{N}_0 \left[\frac{r_t Q_s}{2}\right]^{2\left(\gamma_s + \frac{\ln(2/R_t Q_s)}{\kappa \lambda y}\right)} \qquad r_t Q_s \leq 2$$

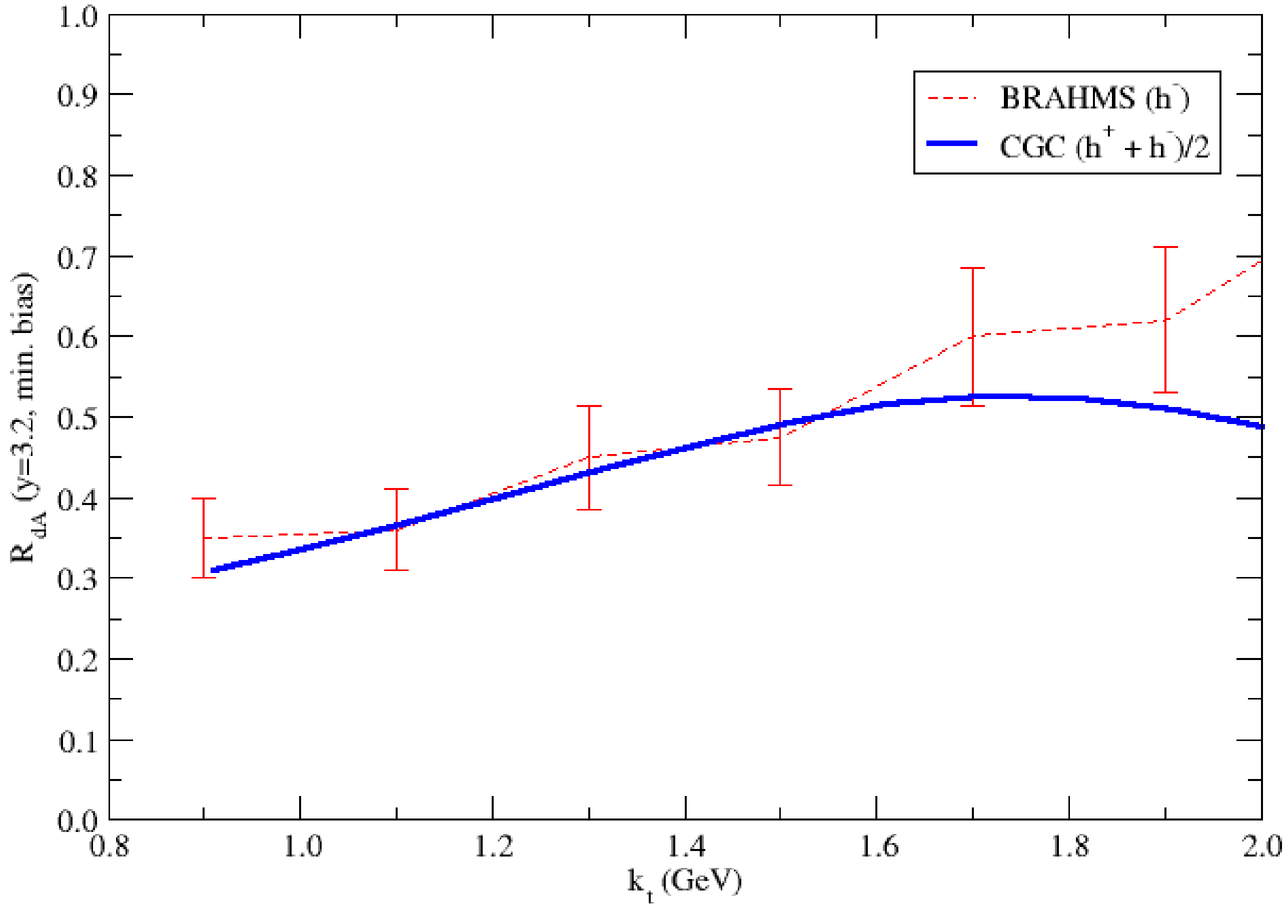
$$\mathcal{N}(r_t Q_s, x) = 1 - e^{-a \ln^2(b r_t Q_s)} \qquad r_t Q_s \geq 2$$

$$Q_s^2(x) = (x_0/x)^\lambda \, GeV^2$$

$$\lambda = 0.25 - 0.3$$

IIM04


Q²=0.11
Q²=0.15
Q²=0.2
Q²=0.25
Q²=0.3
Q²=0.4
Q²=0.5
Q²=0.65
Q²=1.5
Q²=2
Q²=2.5
Q²=2.7
Q²=3.5
Q²=4.5
Q²=5
Q²=6.5
Q²=8.5
Q²=10
Q²=12
Q²=15
F2
x
ZEUS 1996 low Q²
H1 1996 × 1.05
ZEUS 1996
CGC with N0=0.7 and mq=140 MeV
BFKL without saturation



A. Dumitru & JJM 02
JJM 04

Models of the dipole cross section:

Kharzeev, Kovchegov and Tuchin hep-ph/0405045

$$\mathcal{N}(r_t, x) = 1 - e^{-\frac{1}{4}[\frac{C_F}{N_c} r_t^2 Q_s^2]^{\gamma_s(x, r_t^2)}}$$

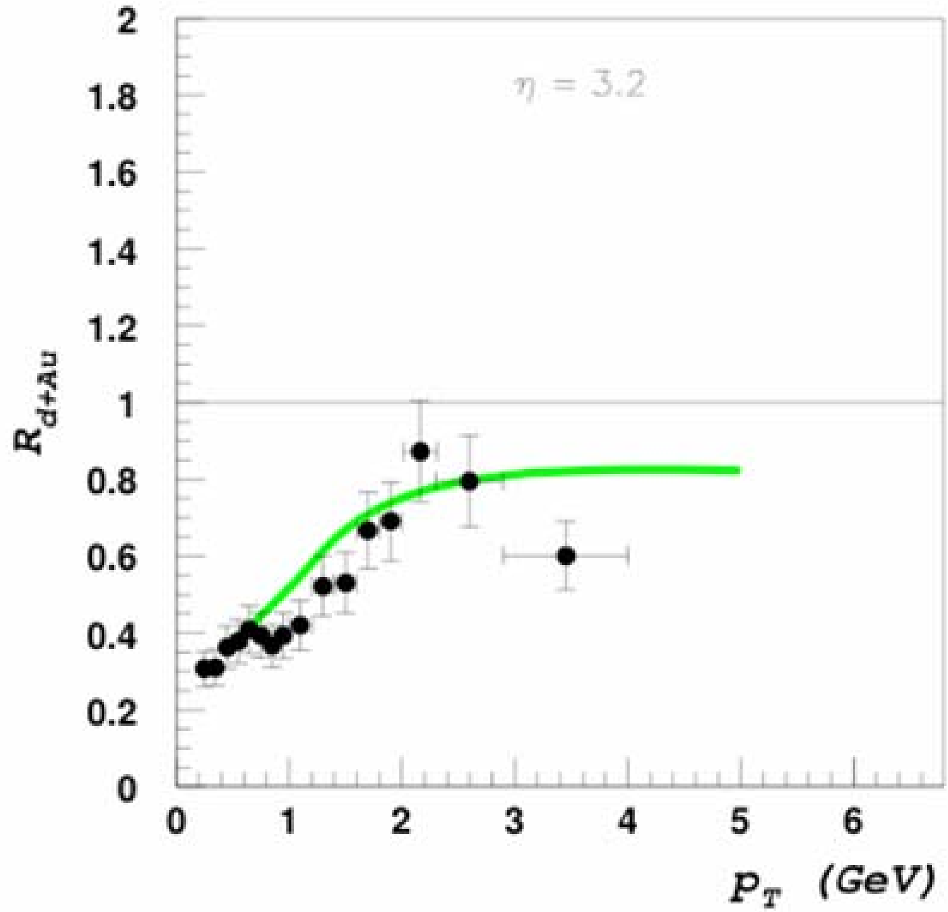
$$\gamma_s(x, r_t) = \frac{1}{2}\left[1 + \frac{\xi(x, r_t)}{\xi(x, r_t) + \sqrt{2\xi(x, r_t)} + 7\, c\, \zeta(3)}\right]$$

$$\xi(x, r_t) = \frac{2 \ln[1/(r_t^2 Q_{s0}^2)]}{\lambda(y - y_0)}$$

$$Q_s^2 \sim (x_0/x)^\lambda GeV^2$$

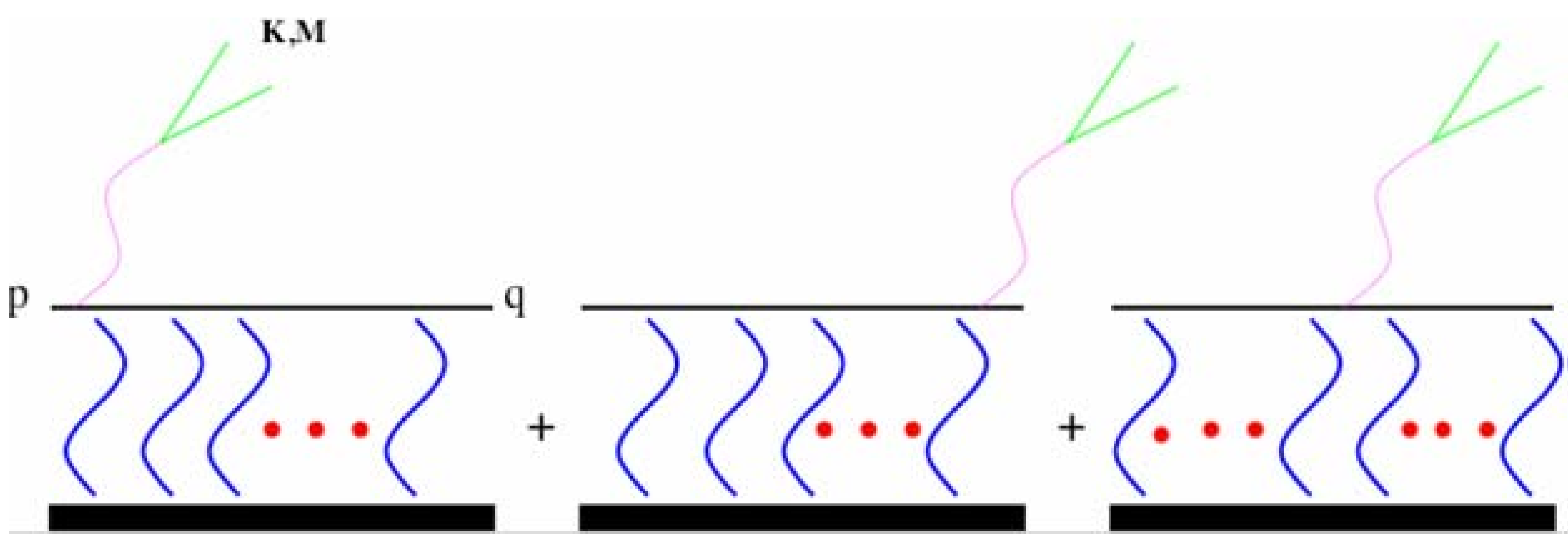
$$\lambda = 0.3$$

KKT04



Probing the Dipole Cross Section

- Electromagnetic signatures: photons and dileptons
  - Cleaner than hadrons but lower rates
- Photon and dilepton production in p(d)A



Probing the Dipole Cross Section:Dileptons

F. Gelis & JJM 02
JJM 04
Baier & Mueller & Schiff 04
Kopeliovich et al

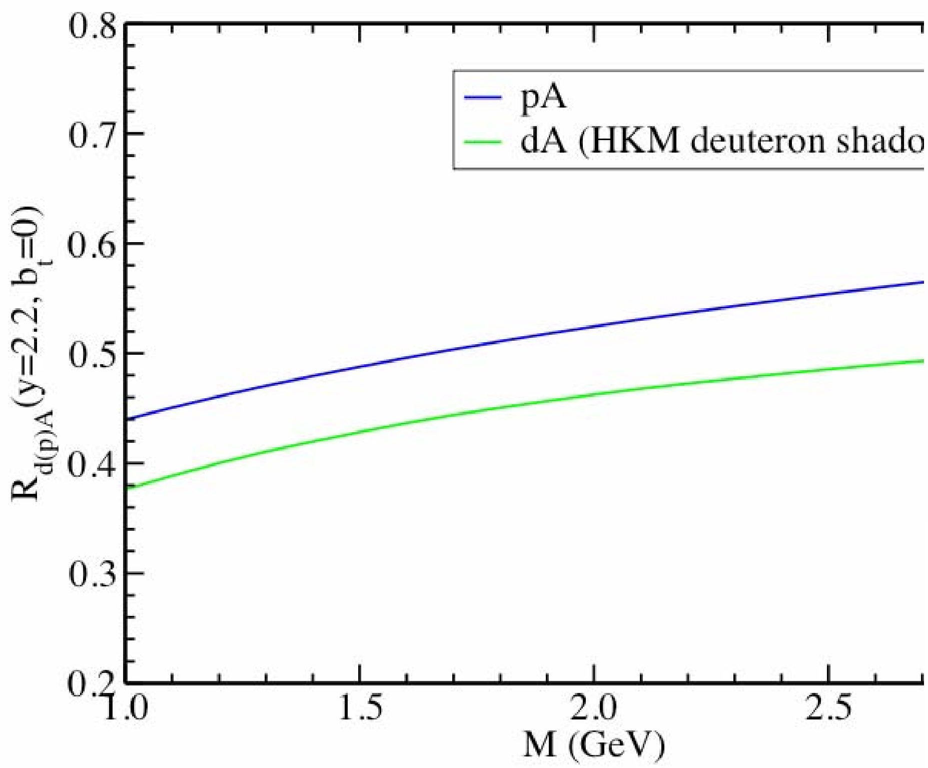
$$\frac{d\sigma^{d(p)\,A\to l^+ l^- \,X}}{d^2b_t\, dM^2\, dx_F} = \frac{\alpha_{em}^2}{6\pi^2}\frac{1}{x_q+x_g}\int_{x_q}^1 dz \int dr_t^2\, \frac{1-z}{z^2}$$

$$F_2^{d(p)}(x_q/z)\,\gamma(x_g, b_t, r_t)$$

$$\left[[1+(1-z)^2]\, K_1^2[\frac{\sqrt{1-z}}{z}Mr_t] \right.$$

$$\left. +2(1-z)\, K_0^2[\frac{\sqrt{1-z}}{z}Mr_t] \right]$$

$$x_F \equiv \frac{M}{\sqrt{s}}[e^y - e^{-y}]$$



Summary

- QCD at high energy ----> CGC
- CGC provides a systematic method to calculate observables at high energies
  - Universal ingredients: Wilson lines
- CGC domain of applicability: need experiments
  - Evidence from forward rapidity region at RHIC?
- CGC wishes/requests for forward rapidity LHC
  - At fixed rapidity: measure p_t spectra of hadrons, photons, dileptons
  - At fixed p_t: measure rapidity spectra
  - Measure correlations: same rapidity, different rapidity
  - ……