Gluonic structure of the nucleon

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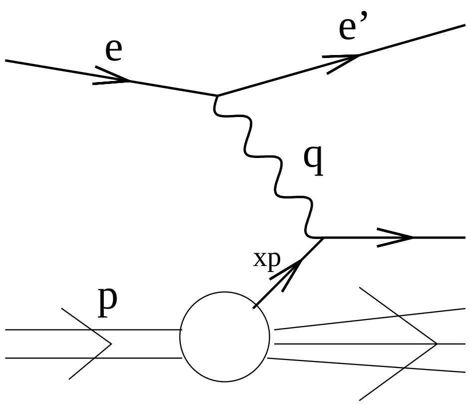
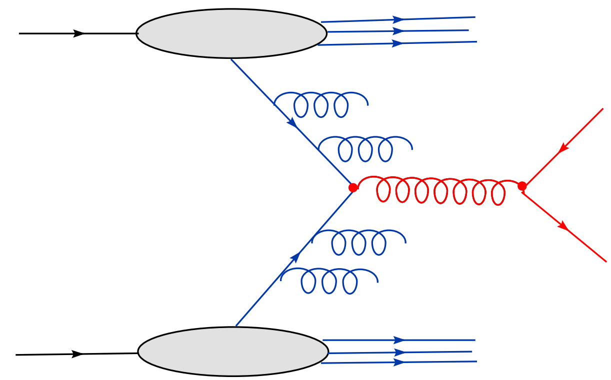
Plan

- Parton distributions and QCD
- Gluon distribution at small x
- Color Glass Condensate and heavy-ion collisions

Hard processes

- Quarks and gluons in a nucleon are seen through hard processes - hard scale $Q \gg \Lambda_{QCD} \sim 200 - 400 \text{ MeV}$





DIS: $Q = \sqrt{-q^2}$

pp: $Q = E_T$

- Hard scattering cross sections:

$$\sigma_{AB} = \int dx_a dx_b \, f_{a/A}(x_a, Q) \{\hat{\sigma}_0 + \alpha_s(Q)\hat{\sigma}_1 + \ldots\} f_{b/B}(x_b, Q)$$

Parton distribution functions

- pdfs: $\{u,\ d,\ s,\ \bar{u},\ \bar{d},\ \bar{s},\ G\}\,(x,Q)$
- valence quarks and sea quarks:

$$u = u_{val} + u_{sea} \qquad d = d_{val} + d_{sea} \qquad s = s_{sea}$$

$$\bar{u} = u_{sea} \qquad \bar{d} = d_{sea} \qquad \bar{s} = s_{sea}$$

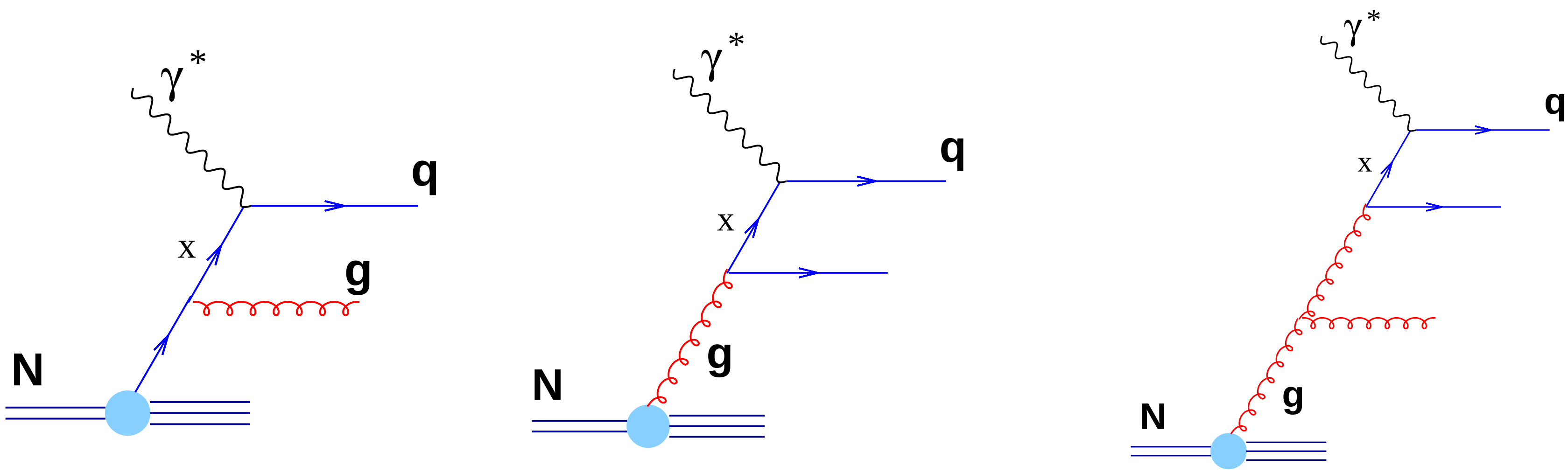
- number of valence quarks sum:

$$\int_0^1 dx\, u_{val}(x,Q) = 2 \qquad \int_0^1 dx\, d_{val}(x,Q) = 1$$

- momentum sum:

$$\int_0^1 dx\, x\,\{u + \bar{u} + d + \bar{d} + s + \bar{s} + G\}\,(x,Q) = 1$$

QCD fits



- Altarelli-Parisi (DGLAP) evolution equations

$$\frac{\partial\, q(x,Q)}{\partial \ln Q} = \int_x^1 \frac{dz}{z}\, P_{qq}(z,\alpha_s)\, q\left(\frac{x}{z},Q\right) + P_{qG}\otimes G$$

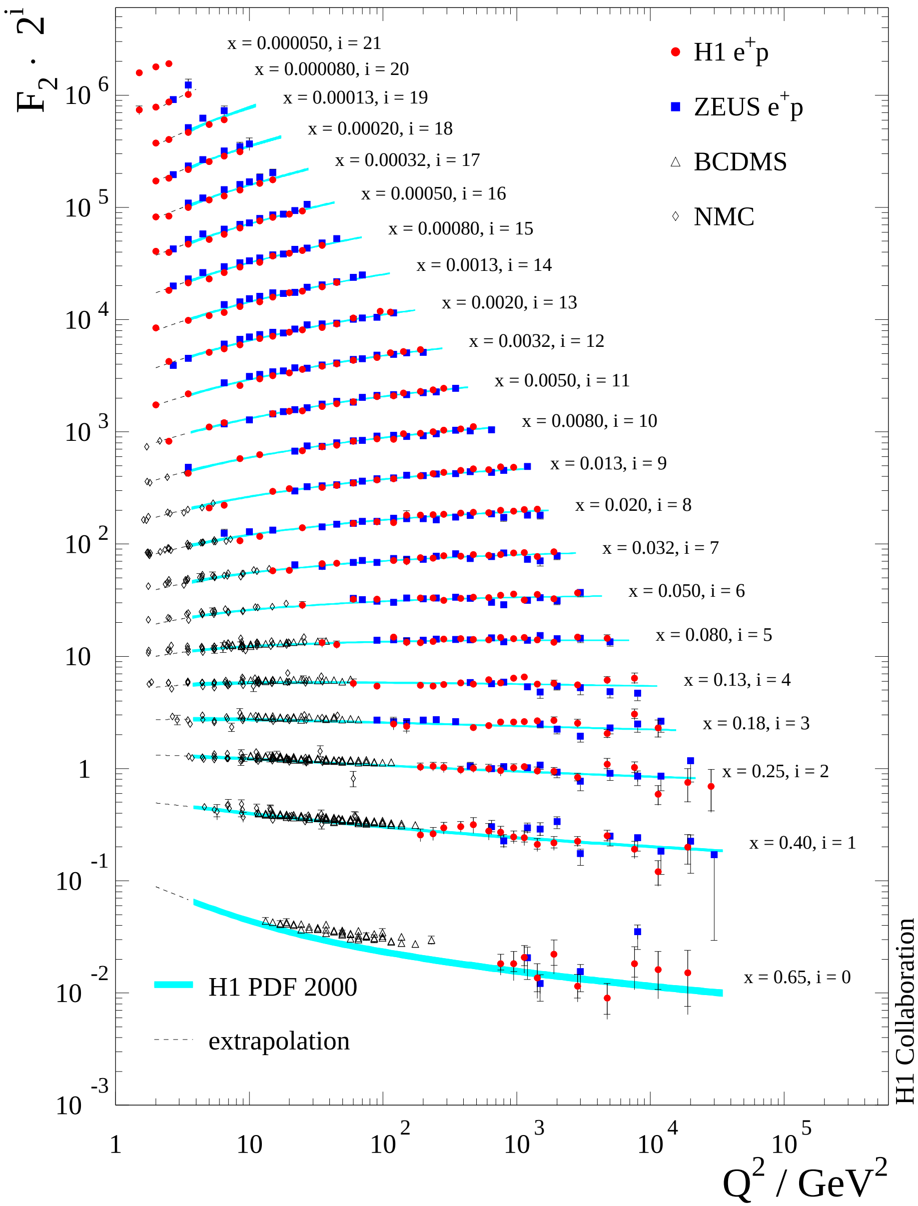
$$\frac{\partial\, G(x,Q)}{\partial \ln Q} = P_{GG}\otimes G + \sum_q P_{Gq}\otimes q$$

- Fit of initial conditions: $q(x,Q_0)$, $G(x,Q_0)$.

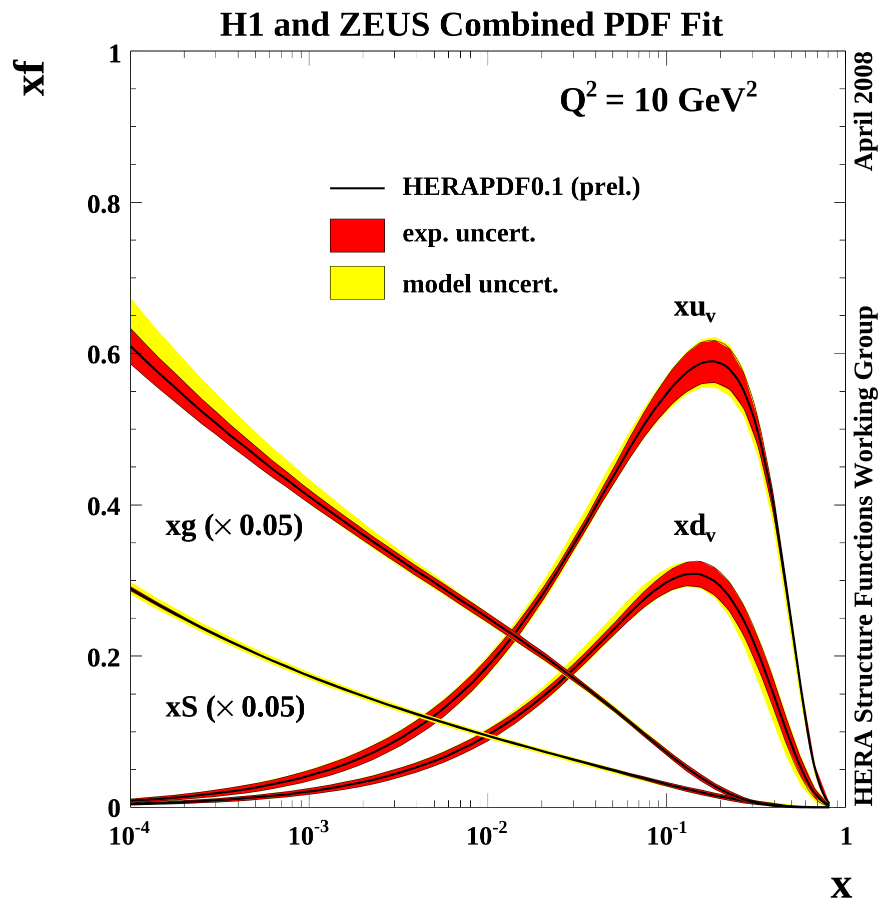
Physical processes

H1, ZEUS	$F_2^{e^+p}(x,Q^2)$, $F_2^{e^-p}(x,Q^2)$ NC + CC
BCDMS	$F_2^{\mu p}(x,Q^2), F_2^{\mu d}(x,Q^2)$
NMC	$F_2^{\mu p}(x,Q^2), F_2^{\mu d}(x,Q^2), F_2^{\mu n}(x,Q^2)/F_2^{\mu p}(x,Q^2)$
SLAC	$F_2^{e^-p}(x,Q^2), F_2^{e^-d}(x,Q^2)$
E665	$F_2^{\mu p}(x,Q^2), F_2^{\mu d}(x,Q^2)$
CCFR, NuTeV, CHORUS	$F_2^{\nu(\bar\nu)N}(x,Q^2), F_3^{\nu(\bar\nu)N}(x,Q^2)$
	$\rightarrow$ q, $\bar q$ at all x and g at medium, small x
H1, ZEUS	$F_{2,c}^{e^\pm p}(x,Q^2), F_{2,b}^{e^\pm p}(x,Q^2) \rightarrow c, b$
E605, E772, E866	Drell-Yan $pN \rightarrow \mu\bar\mu + X \rightarrow \bar q$ (g)
E866	Drell-Yan p, n asymmetry $\rightarrow \bar u, \bar d$
CDF, D0	$W^\pm$ rapidity asymmetry $\rightarrow u/d$ ratio at high x
CDF, D0	Z^0 rapidity distribution $\rightarrow u, d$
CDF, D0	inclusive jet data $\rightarrow g$ at high x
H1, ZEUS	DIS $+$ jet data $\rightarrow g$ at medium x
CCFR, NuTeV	dimuon data $\rightarrow$ strange sea s, $\bar s$

Scaling violation of $F_2(x, Q^2)$



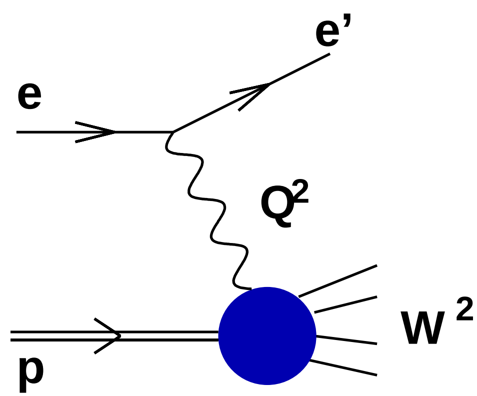
Parton distribution functions



- gluons carry approx. half of the nucleon momentum
- gluons dominate for small momentum fractions x

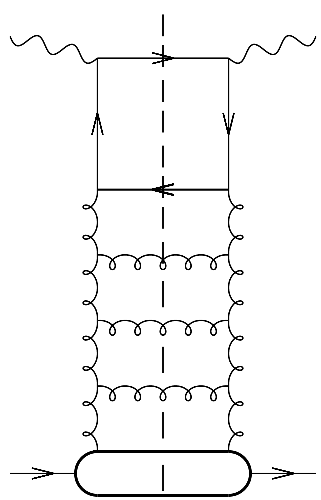
Small x limit

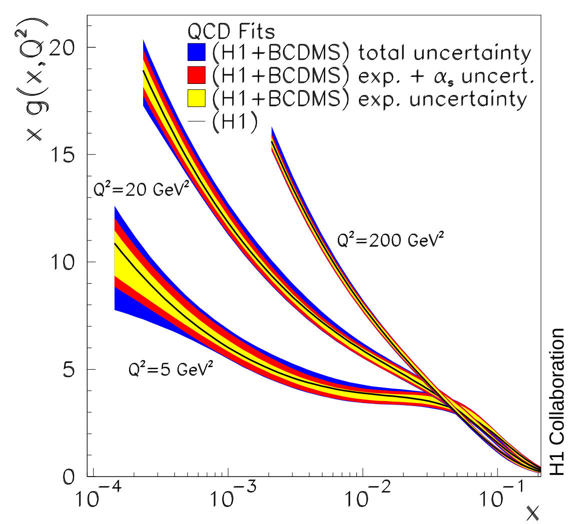
- DIS: Bjorken variable $x \to 0$ => high energy limit



$$x = \frac{Q^2}{Q^2+W^2} \simeq \frac{Q^2}{W^2} \to 0$$

- Regge: highest spin exchanges dominate => spin-1 gluons

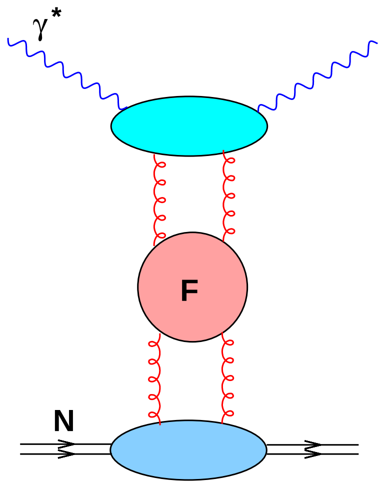




- DGLAP: $P_{GG}(z) \sim 1/z$ => $xG \sim e^{2\sqrt{\bar{\alpha}_s \log(Q^2)\log(1/x)}}$

BFKL pomeron

- Two gluon color singlet compound system exchanged ($s = W^2$)



$$F(s, \ldots) \sim s^{4 \ln 2\, \alpha_s} \approx s^{0.5}$$

- k_T-factorization formula: $s \rightarrow \infty$

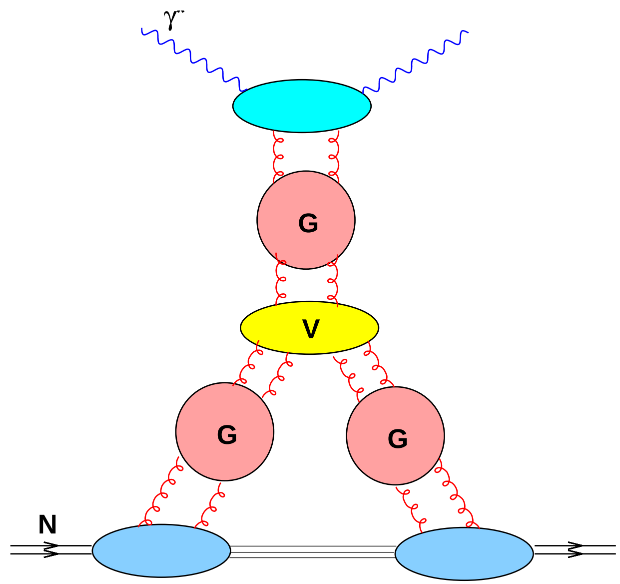
$$\sigma_{AB} = \int d^2 k_{1\perp} \int d^2 k_{2\perp}\ \phi_A(k_{1\perp})\, F(s, k_{1\perp}, k_{2\perp})\, \phi_B(k_{2\perp})$$

- unintegrated gluon distribution:

$$f(x, k_\perp) = \int d^2 k_{2\perp}\ F(x, k_\perp, k_{2\perp})\, \phi_B(k_{2\perp}) \sim x^{-4 \ln 2\, \alpha_s}$$

Parton saturation

- BFKL pomeron violates Froissart bound: $\sigma_{AB} \leq (\pi/m_\pi^2)\log^2 s$
- gluons interact before interaction with a hard probe



- non-linear modification of linear evolution equations (AP or BFKL)

(Gribov, Levin, Ryskin, 83')

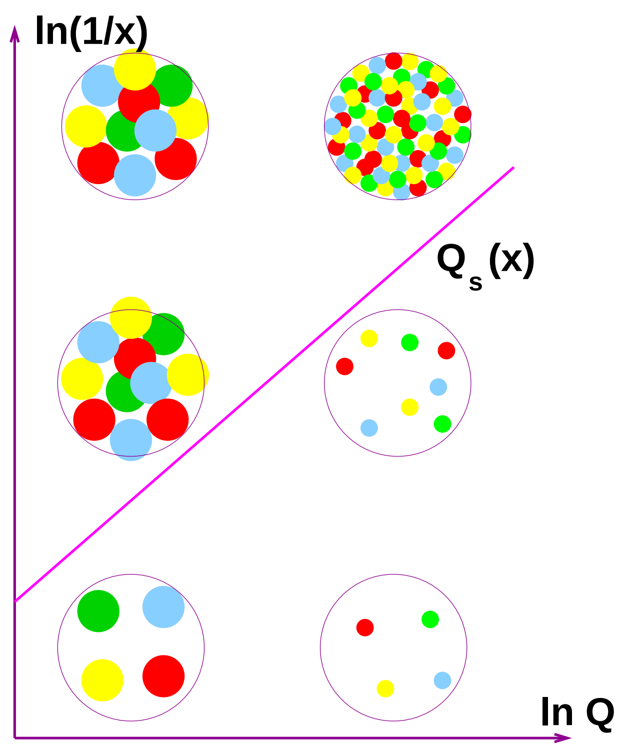
$$\frac{\partial^2 xG(x,Q)}{\partial \ln(1/x)\partial \ln Q^2} = \frac{3\alpha_s}{\pi} xG - \frac{3\alpha_s^2}{\pi^2 R^2}\frac{[xG]^2}{Q^2}$$

Saturation scale

- Saturation of gluon density when nonlinear term ≈ linear term

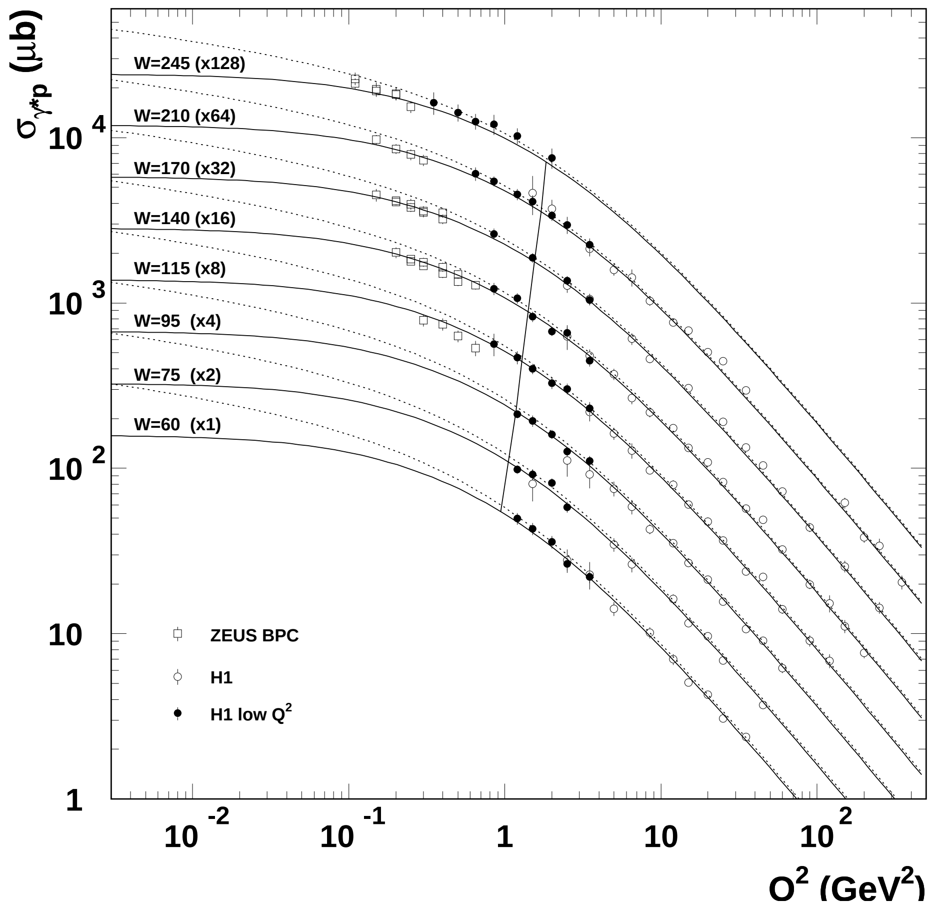
$$\frac{\alpha_s(Q_s)}{Q_s^2}\, xG(x,Q_s) \approx \pi R^2$$

- x-dependent saturation scale $Q_s(x) = Q_0\, x^{-\lambda} \gg \Lambda_{QCD}$ emerges



Saturation scale from HERA data

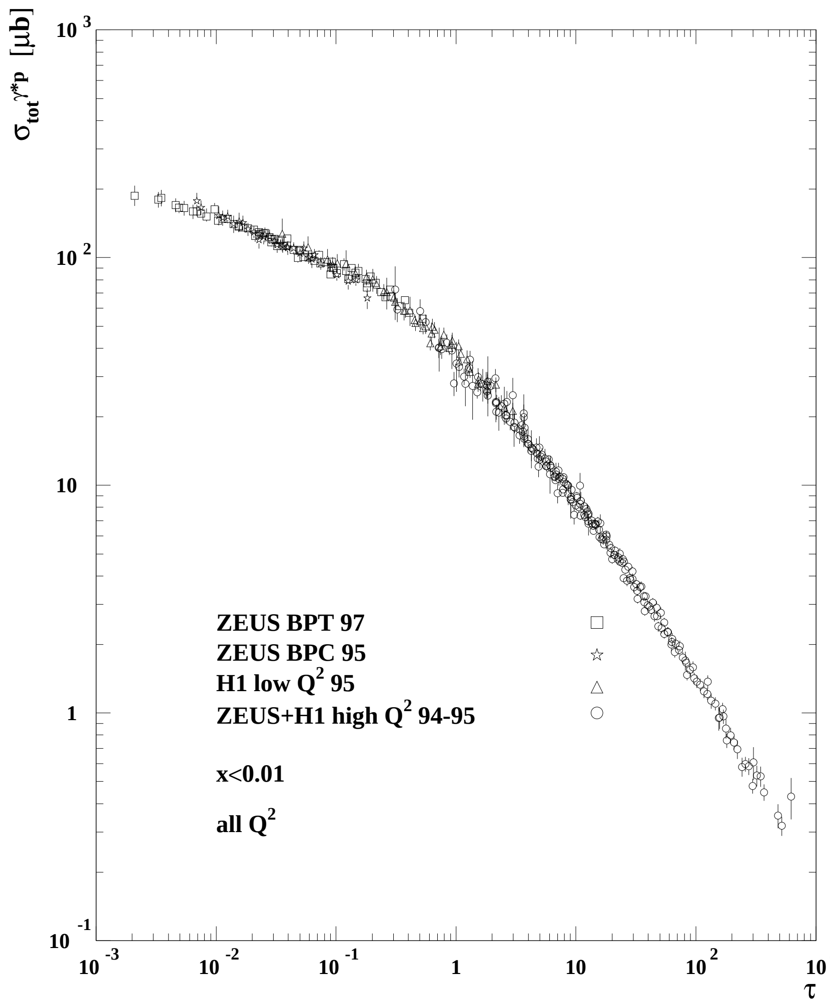
- Transition to low Q^2 as a sign of parton saturation *(GB, Wüsthoff,99')*



- $\sigma_{\gamma^* p} \sim \log(Q_s^2(x)/Q^2) \rightarrow Q_s^2(x)/Q^2 \qquad Q_s^2 = (x/x_0)^{-0.29}\ \mathrm{GeV}^2$

Geometric scaling

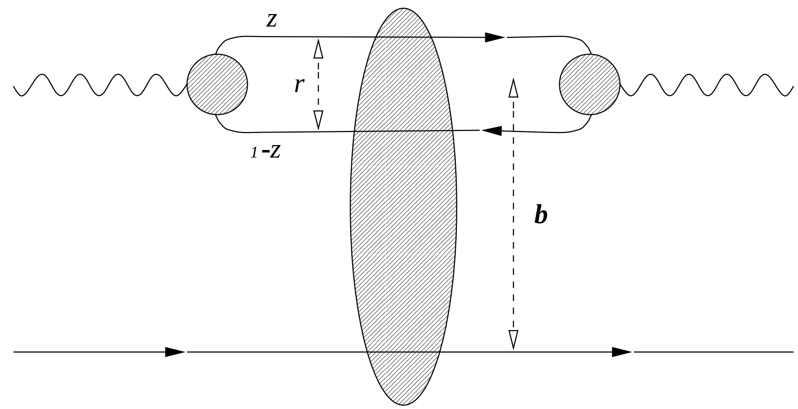
(Stasto, GB, Kwiecinski, 00')



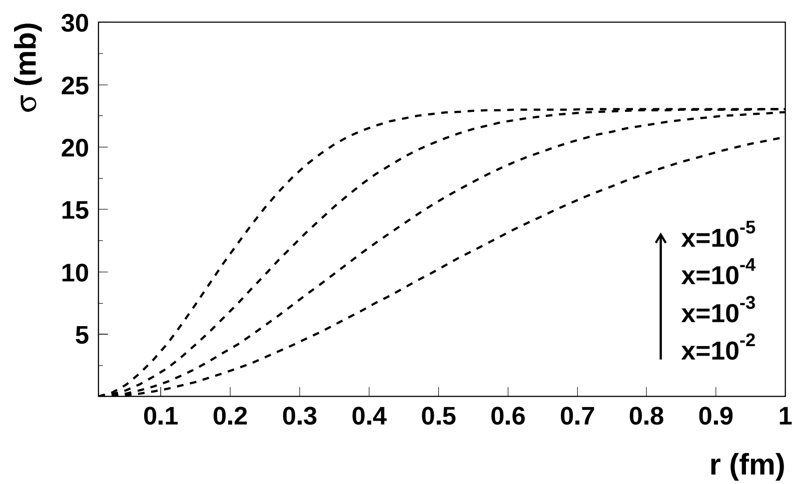
- all DIS data for $x \leq 10^{-2}$: $\sigma_{\gamma^* p}(x, Q^2) = \sigma_{\gamma^* p}(Q^2/Q_s^2(x))$

Dipole models with saturation

- $q\bar{q}$ pair probes the proton

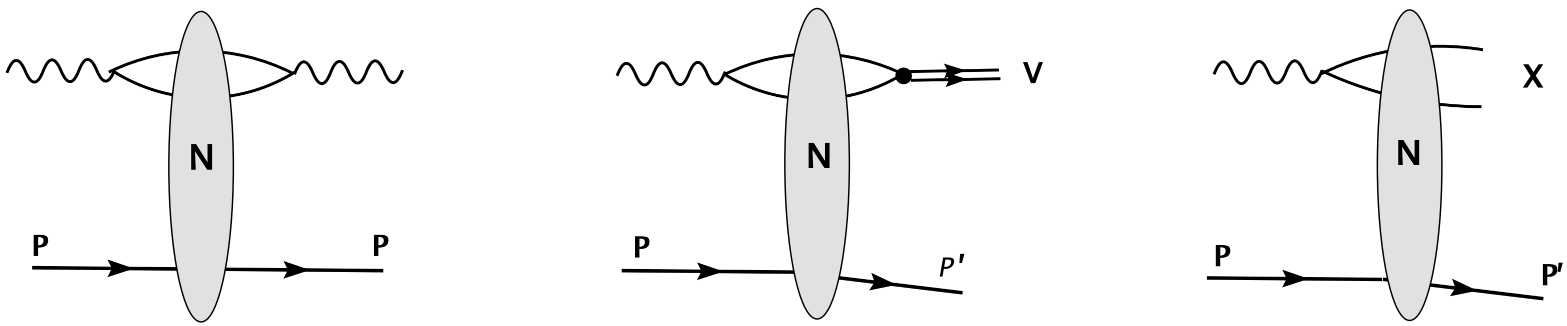


- interaction desribed by a dipole scattering amplitude $N(r, b, x)$



- saturation scale built in: $N(rQ_s(x,b))$ $Q_s \sim x^{-\lambda}$

Description of diffractive processes

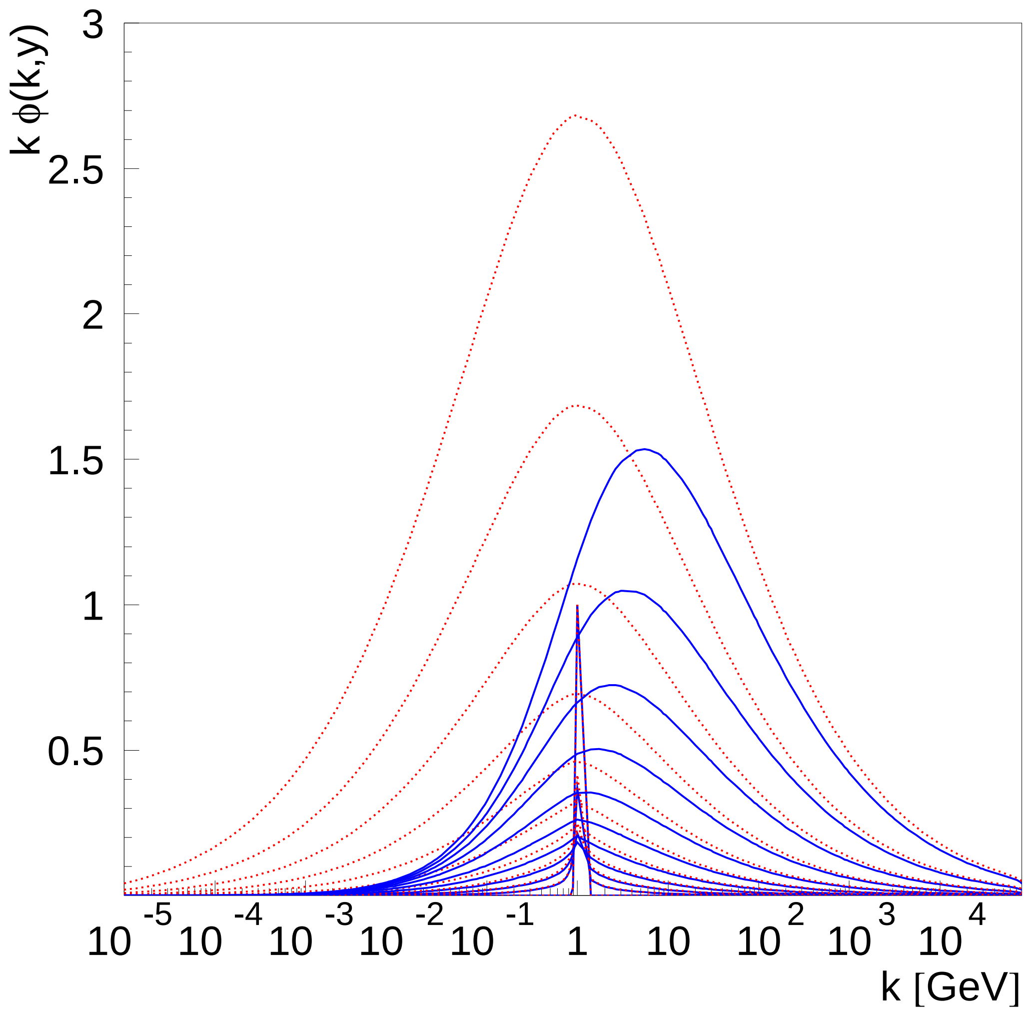


- Scattering amplitude:

$$\mathcal{A}(\gamma^* + p \to A + p) = \int d^2 r dz \, \Psi_A^* \, N \, \Psi_\gamma$$

- Successful description inclusive diffraction, VM production, DVCS
  - energy dependence
  - $t-$dependence
  - Q^2-dependence

Unintegrated gluon distribution



- Saturation scale $Q_s(x)$ screens infra-red region.

Color Glass Condensate

- Effective theory of small-x part of the hadronic wave function
- gluon system becomes dense and respond collectively

$$|h\rangle = |qqq\rangle + |qqqg\rangle + \ldots + |qqqgg\ldots g\rangle \;\rightarrow\; |h\rangle_x = \int DA\,\Phi_x(A)\,|A\rangle$$

- large-x partons are strong color sources $\rho^a \sim 1/g_s$ of low-x gluons described by strong color fields $A^a[\rho] \sim 1/g_s$
- ρ fluctuates stochastically

$$\langle A_\mu(x_\perp)A_\nu(y_\perp)\rangle_x = \int D\rho\,|\Phi_x(A[\rho])|^2 A_\mu[x_\perp,\rho]\,A_\nu[y_\perp,\rho]$$

- x is an arbitrary separation bewteen sources and fields
- JIMWLK equation for $|\Phi_x(A[\rho])|^2 \equiv W_x[\rho]$

Color Glass Condensate and DIS

- Dipole scattering amplitude $N = 1 - S$:

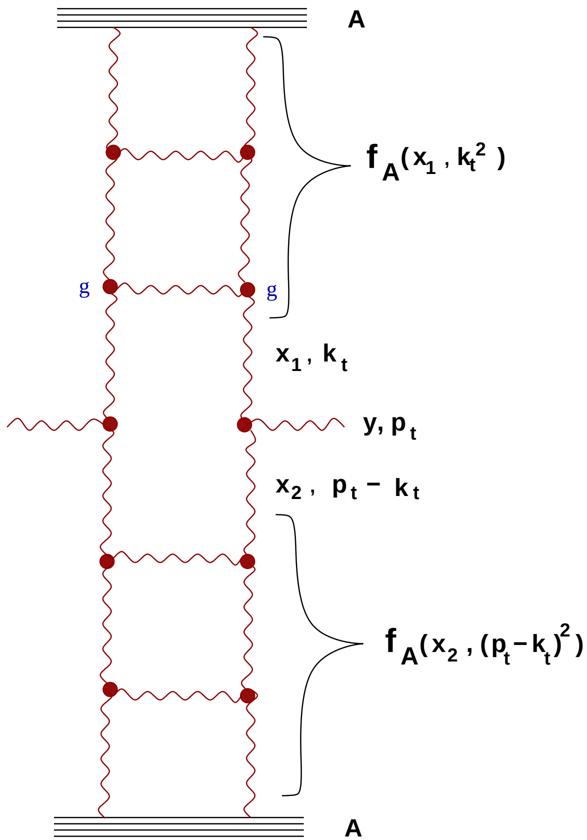
$$S(r,b,x) = \frac{1}{N_c}\left\langle U^\dagger(x_\perp)U(y_\perp)\right\rangle_x \qquad U(x_\perp) = P\exp\{ig\int d\lambda\, A(\lambda u + x_\perp)\}$$

- non-linear Balitsky-Kovchegov equation

$$\frac{\partial S}{\partial \ln x} = K_{BFKL} \otimes S \; - \; S \otimes S$$

- saturation scale and geometric scaling confirmed: $N(rQ_s)$
- problem with impact parameter b: only local unitarity $N(b) < 1$
- unintegrated gluon distribution computed
- in a nucleus gluon distribution enhanced by mass number A

CGC and RHIC data - I

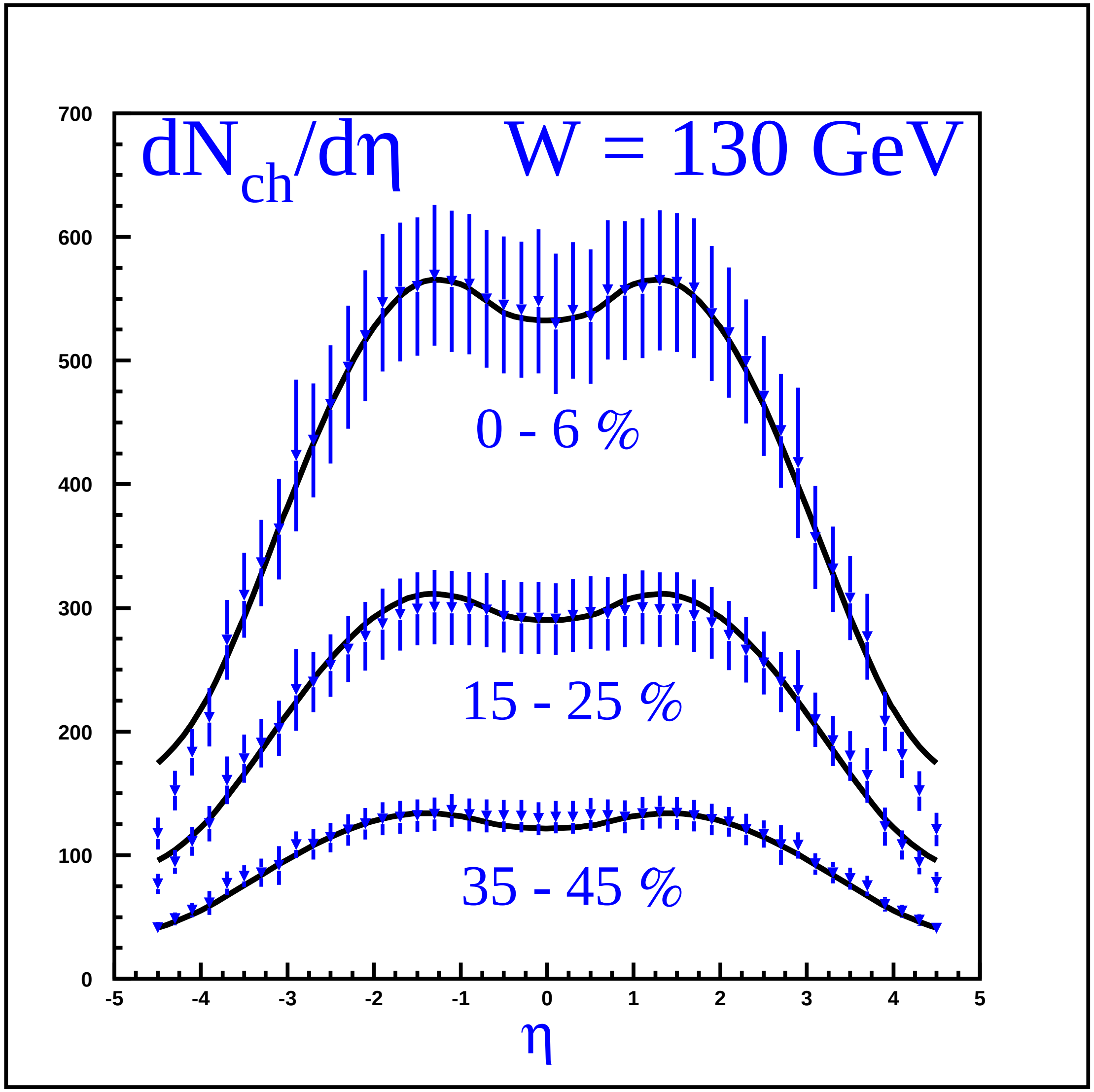


(Kharzeev, Levin, Nardi, 01'-02')

- central rapidities: energy deposited in form of gluons
- parton–hadron duality
- final state effects are not important
- $k_\perp$- factorization formula

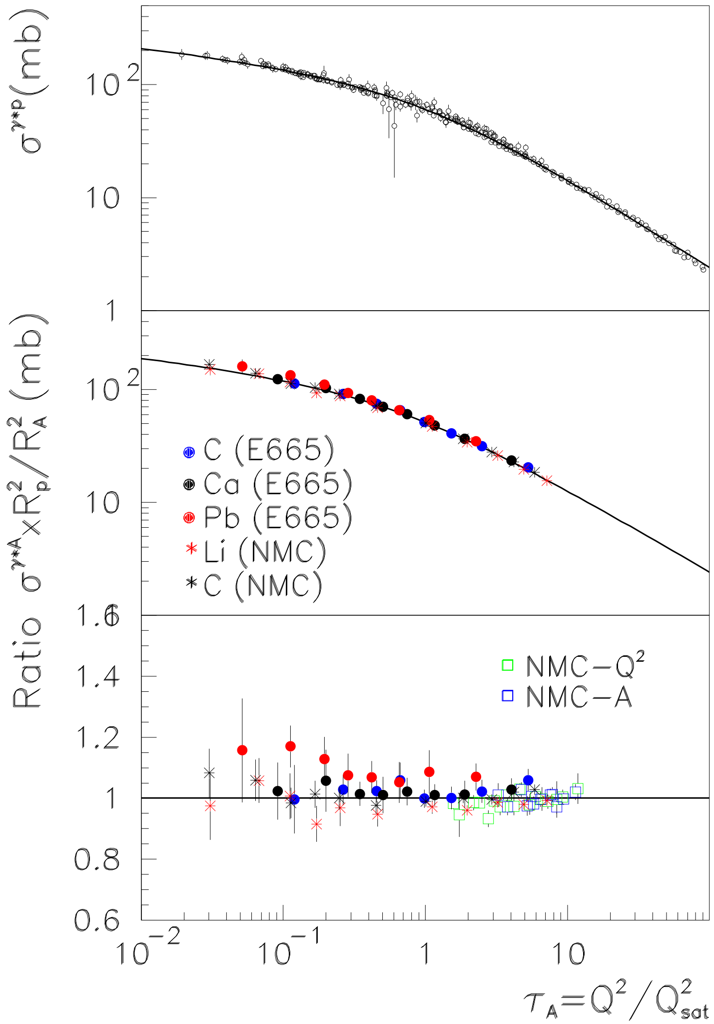
$$\frac{dN}{dy dp_\perp^2} \sim \frac{1}{p_\perp^2} \int d^2k_\perp \, \alpha_s \, f_A(x_1, k_\perp^2) \, f_A(x_2, (p_\perp - k_\perp)^2) \qquad x_{1,2} = \frac{p_\perp}{\sqrt{s}} \mathrm{e}^{\pm y}$$

CGC and RHIC data - II



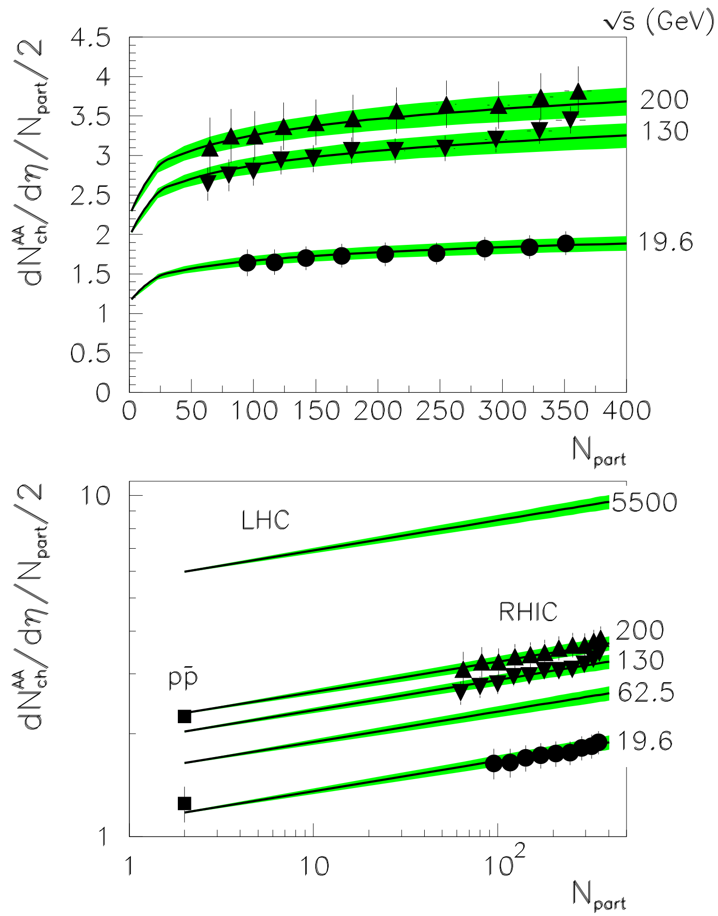
Geometric scaling in $\gamma^* A$ collsion

(Armesto, Salgado, Wiedemann, 04')



- $Q^2_{sA} \sim x^{-\lambda} A^{1/3\delta}$ $\qquad \delta = 0.8 \qquad \lambda = 0.29$

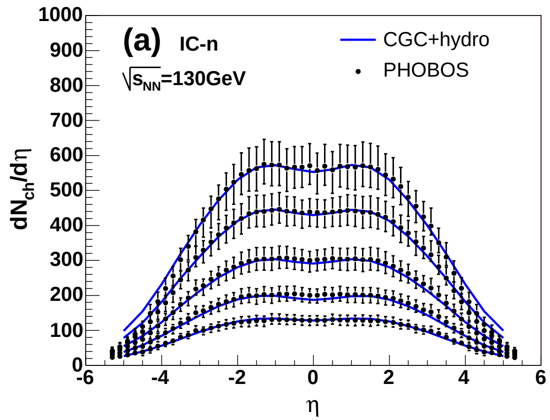
Multiplicity prediction

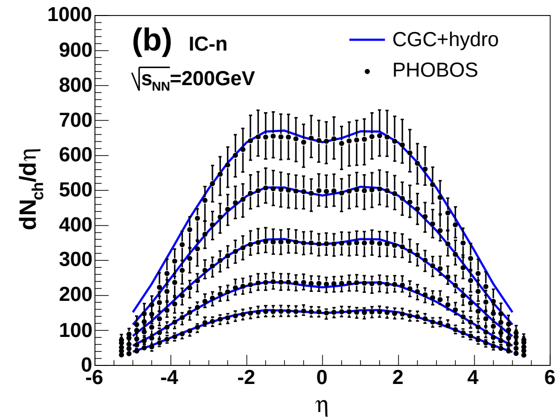


$$\frac{1}{N_{part}}\frac{dN^{AA}}{d\eta}\bigg|_{\eta=0} = N_0\, s^{\lambda/2}\, N_{part}^{(1-\delta)/3\delta}$$

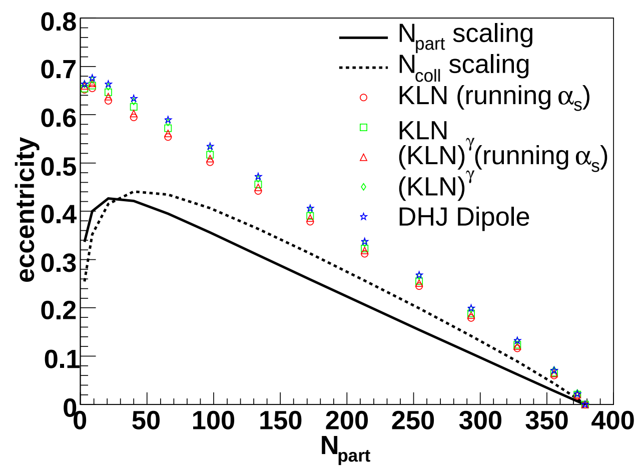
CGC as initial condition

- CGC gives initial conditions for hydro evolution *(Hirano, Nara, 06')*





- harder profile in r leads to stronger initial eccentricity *(Adil, Drescher,Dumitru, Hayashigaki, Nara, 06')*

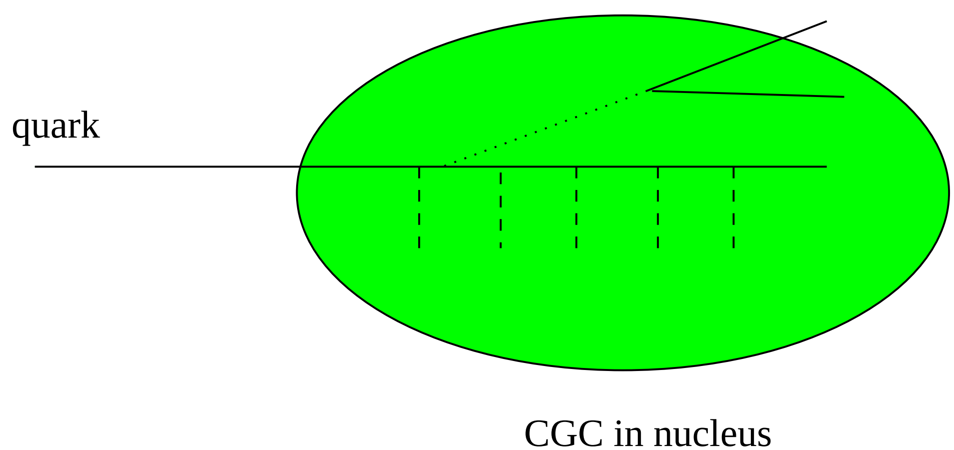


Dedicated processes

Dedicated processes:

- photon production in dA collision
- dilepton production in dA collision
- forward quark jets in dA
- heavy quark production

Quark probe interacting with CGC.



Summary

- Good prospects for looking for parton saturation in pp, pA and AA collisions at the LHC.
- A lot of work to be done.

See you at Epiphany 2009 in Kraków, January 5-7