Hard Diffraction in Deep Inelastic Scattering at small x

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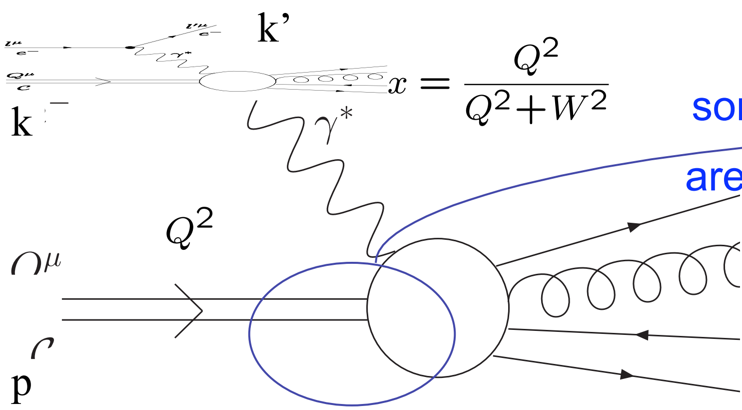
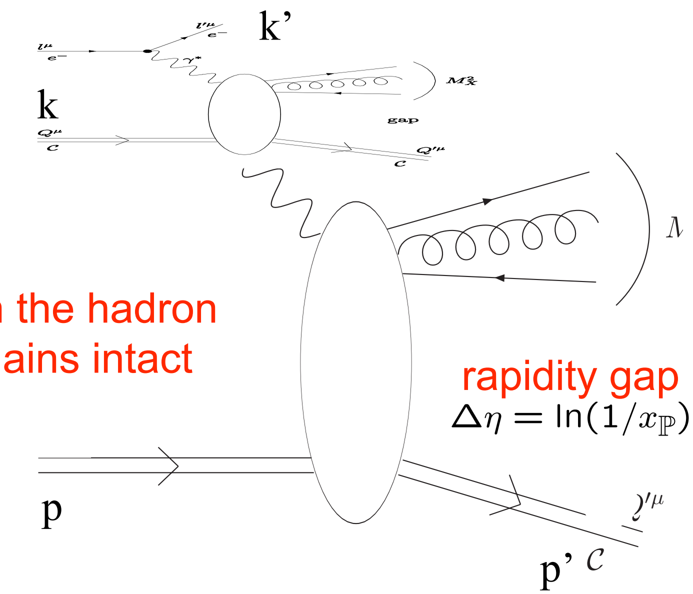
Diffractive processes in DIS

Inclusive diffraction in DIS



some events are diffractive

when the hadron remains intact



rapidity gap
$\Delta\eta = \ln(1/x_{\mathbb{P}})$

diffractive mass

$M_X^2 = (p-p'+k-k')^2$

momentum transfer

$t = (p-p')^2 < 0$

$$\beta = \frac{Q^2}{2(p-p').(k-k')} = \frac{Q^2}{M_X^2 - t + Q^2}$$

$$x_{\mathbb{P}} = x/\beta$$

momentum fraction of the exchanged object (Pomeron) with respect to the hadron

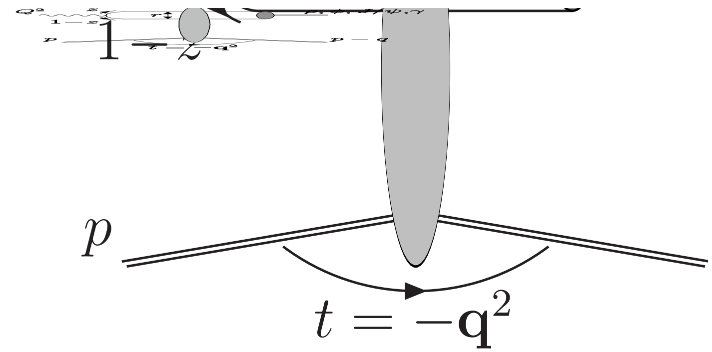
- the measured cross-section

$$\frac{d^4\sigma^{eh\to eXh}}{dx dQ^2 d\beta dt} = \frac{4\pi\alpha_{em}^2}{\beta^2 Q^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2^{D,4}(x,Q^2,\beta,t) - \frac{y^2}{2}F_L^{D,4}(x,Q^2,\beta,t)\right]$$

Less inclusive diffraction

- exclusive diffraction

vector meson production
deeply virtual Compton scattering (DVCS)



measurements:

$$\begin{cases} \dfrac{d\sigma_{VM}^{\gamma^* p\to Vp}}{dt}(W^2, Q^2, t) \\ \sigma_{VM}^{\gamma^* p\to Vp}(W^2, Q^2) \end{cases}$$

determination of the diffractive slope *B*

$$\frac{d\sigma_{VM}^{\gamma^* p\to Vp}}{dt} \propto e^{B(x,Q^2,M_V)t}$$

$k_\perp, y$

- semi inclusive diffraction

diffractive jets, hadron production

The dipole picture and saturation

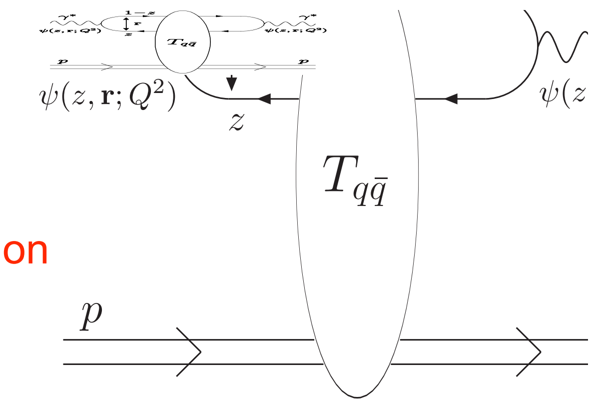
The dipole factorization

- inclusive DIS

$$\sigma_{tot}^{\gamma^* p \to X} = 2 \int d^2r \, dz \sum_\lambda |\psi_\lambda(r,z,Q^2)|^2 \underbrace{\int d^2b \, T_{q\bar{q}}(r,x,b)}$$

dipole-hadron cross-section

overlap of $\gamma^* \to q\bar{q}$
splitting functions



at small *x*, the dipole cross section is comparable to that of a pion, even though $r \sim 1/Q << 1/\Lambda_{QCD}$

- exclusive diffraction

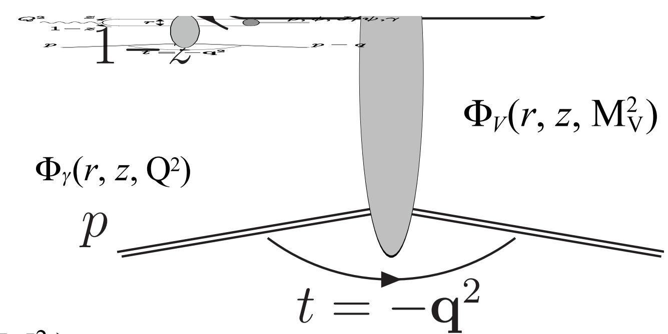
$$\frac{d\sigma_{VM}^{\gamma^* p \to Vp}}{dt} = \frac{1}{16\pi} \left| \int d^2r \int d^2b \; T_{q\bar{q}}(r,b;x_V) e^{iq.b} \varphi(r, \mathrm{Q}^2, \mathrm{M}_\mathrm{V}^2) \right|^2$$

$T_{q\bar{q}}$
instead of
$\int d^2b \; T_{q\bar{q}}$

the overlap function:

$$\varphi(r, \mathrm{Q}^2, \mathrm{M}_\mathrm{V}^2) = \int dz \, \Phi_\gamma(r, z, \mathrm{Q}^2) \, \Phi_V(r, z, \mathrm{M}_\mathrm{V}^2)$$

$\Rightarrow$ access to impact parameter



$$x_V = \frac{Q^2 + M_V^2}{Q^2 + W^2}$$

The dipole picture for F_2^D

the diffractive final state is decomposed into $q\bar{q},\ q\bar{q}g,\ \ldots$ contributions

- the $q\bar{q}$ contribution

double differential cross-section (proportional to the structure function) for a given photon polarization:

comes from $M_X^2 > 4m_f^2$

Fourier transform to M_X^2: $\boldsymbol{\kappa}_f^2 = z(1-z)Q^2(1-\beta)/\beta - m_f^2$

$$\frac{d\sigma_\lambda^{\gamma^* p\to Xp}}{d\beta\ dt}(\beta, x_{\mathbb{P}}, Q^2, t) = \frac{Q^2}{4\beta^2}\sum_f \int \frac{d^2r}{2\pi}\int \frac{d^2r'}{2\pi}\int_0^1 dz z(1-z)\Theta(\boldsymbol{\kappa}_f^2)\ e^{i\boldsymbol{\kappa}_f.(\mathbf{r}'-\mathbf{r})}$$

$$\phi_\lambda^f(z, \mathbf{r}, \mathbf{r}'; Q^2)\int d^2b\ d^2b'\ e^{i\boldsymbol{\Delta}.(\mathbf{b}'-\mathbf{b})}\underbrace{T_{q\bar{q}}(\mathbf{r}, \mathbf{b}; x_{\mathbb{P}})T_{q\bar{q}}(\mathbf{r}', \mathbf{b}'; x_{\mathbb{P}})}$$

overlap of wavefunctions

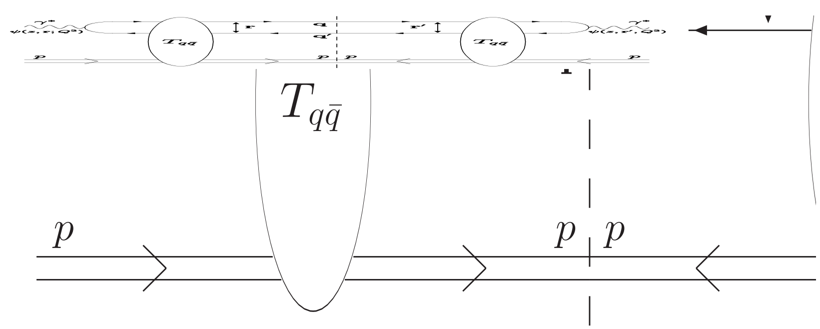
Fourier transform to t: $t = -\boldsymbol{\Delta}^2$

dipole amplitudes

- higher Fock states

contribute to F_2^D but also to semi inclusive diffraction

also taken into account with dipoles



Hard diffraction and saturation

- the total cross sections

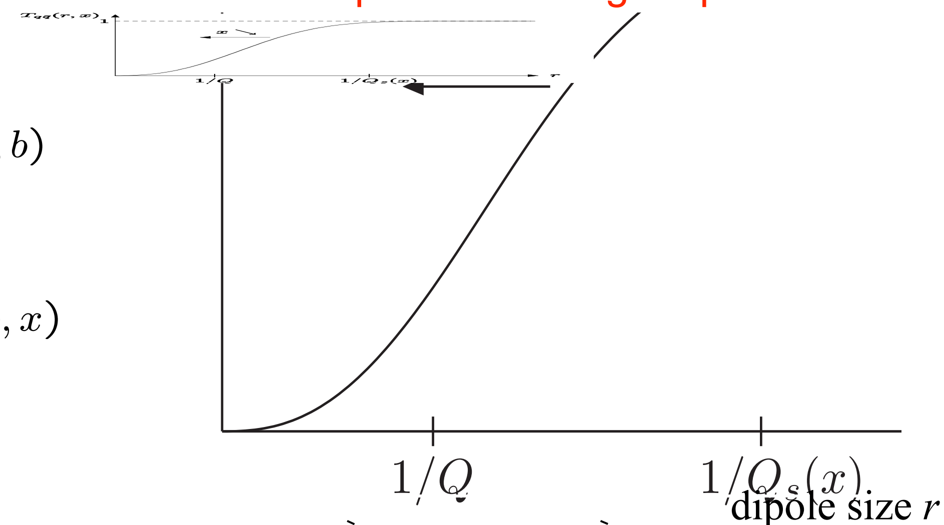
in DIS

$$\int d^2r\ dz\ \sum_\lambda |\psi_\lambda(r,z,Q^2)|^2 \int d^2b\ T_{q\bar{q}}(r,x,b)$$

in DDIS

$$\int d^2r\ dz\ \sum_\lambda |\psi_\lambda(r,z,Q^2)|^2 \int d^2b\ T^2_{q\bar{q}}(r,b,x)$$

the dipole scattering amplitude



- diffraction directly sensitive to saturation

contribution of the different r regions in the hard regime

$Q^2 > Q_S^2$

$$\int rdr|\psi|^2 T_{q\bar{q}} \rightarrow \quad Q^2\sigma_{DIS} \approx \quad 1 \quad + \quad \ln(Q^2/Q_S^2) \quad + \quad 1$$

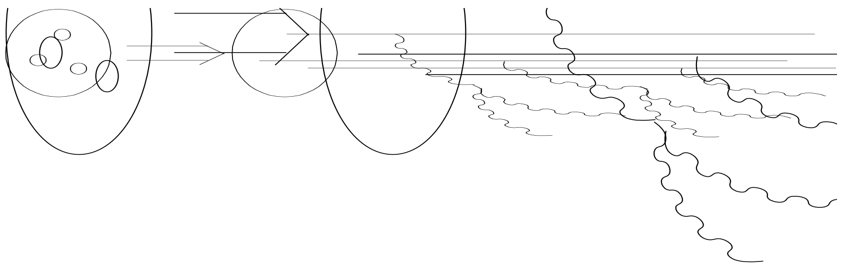
$$\int rdr|\psi|^2 T^2_{q\bar{q}} \rightarrow \quad Q^2\sigma_{DDIS} \approx \quad \frac{1}{Q^2} \quad + \quad 1 \quad + \quad 1$$

σ_{DIS} dominated by relatively hard sizes $1/Q < r < 1/Q_S$

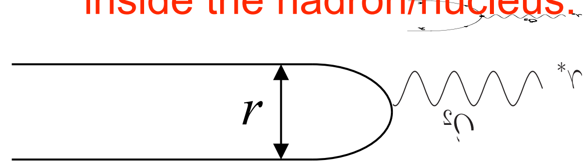
σ_{DDIS} dominated by semi-hard sizes $r \sim 1/Q_S$

What about geometric scaling

geometric scaling can be easily understood as a consequence of large parton densities



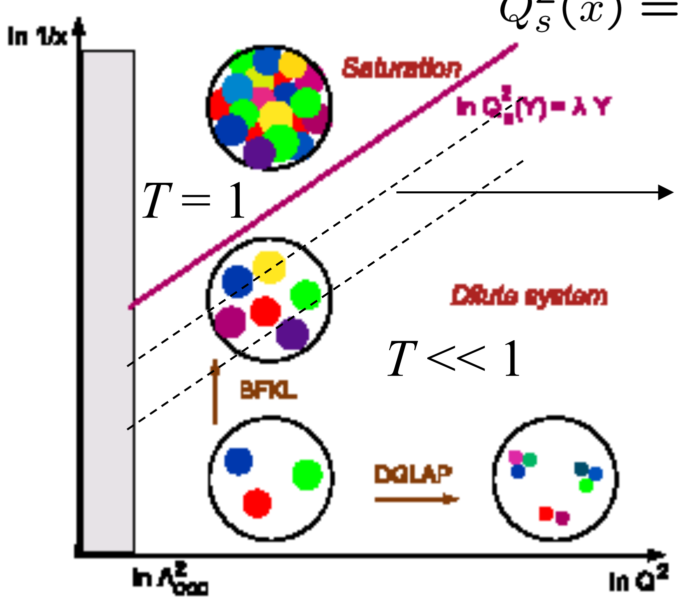
the dipole is probing small distances inside the hadron/nucleus: $r \sim 1/Q$



what does the proton look like in (Q^2, x) plane:

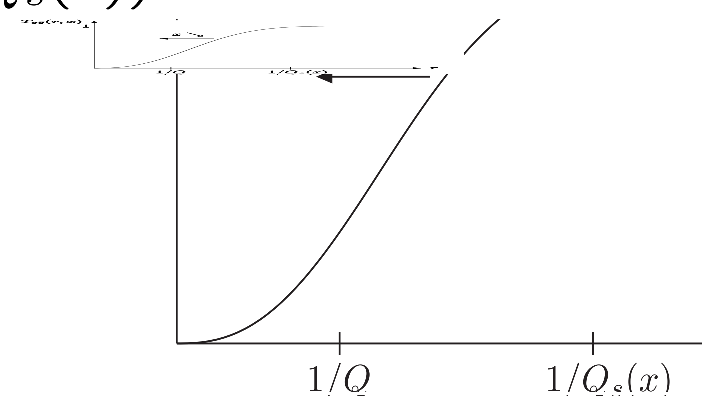
$$Q_s^2(x) = Q_0^2\, x^{-\lambda}$$

$$\lambda \simeq 0.3$$



lines parallel to the saturation line are lines of constant densities along which scattering is constant

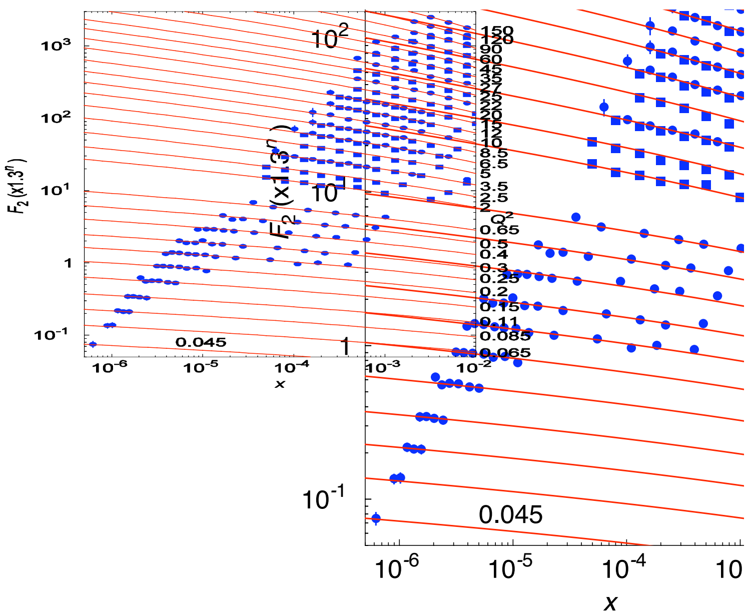
$$T_{q\bar{q}} = T(rQ_s(x))$$



What we learned from HERA

Inclusive DIS

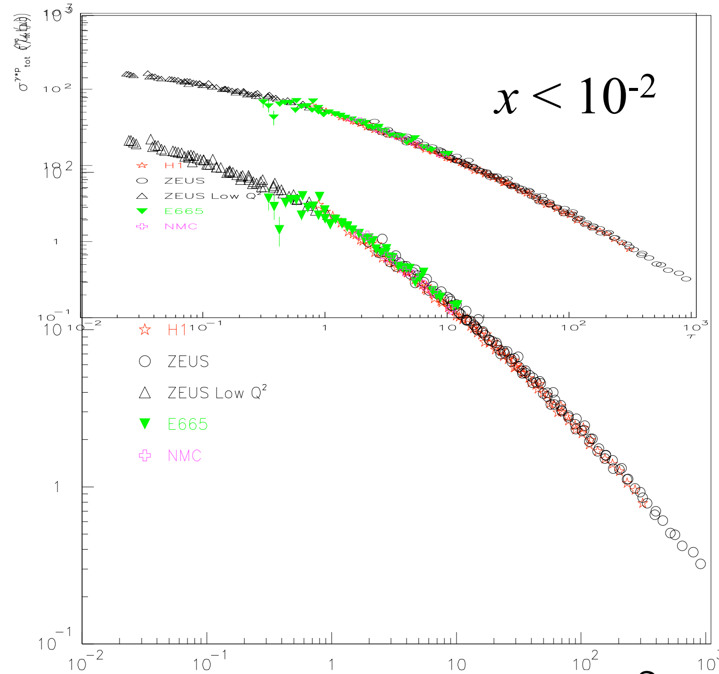
Soyez (2007)



IIM fit (~250 points) $\chi^2/\text{dof} = 0.9$

Stasto, Golec-Biernat and Kwiecinski (2001)

$$\sigma_{tot}^{\gamma^* h \to X}(x, Q^2) = \sigma_{tot}^{\gamma^* h \to X}(Q^2/Q_s^2(x))$$

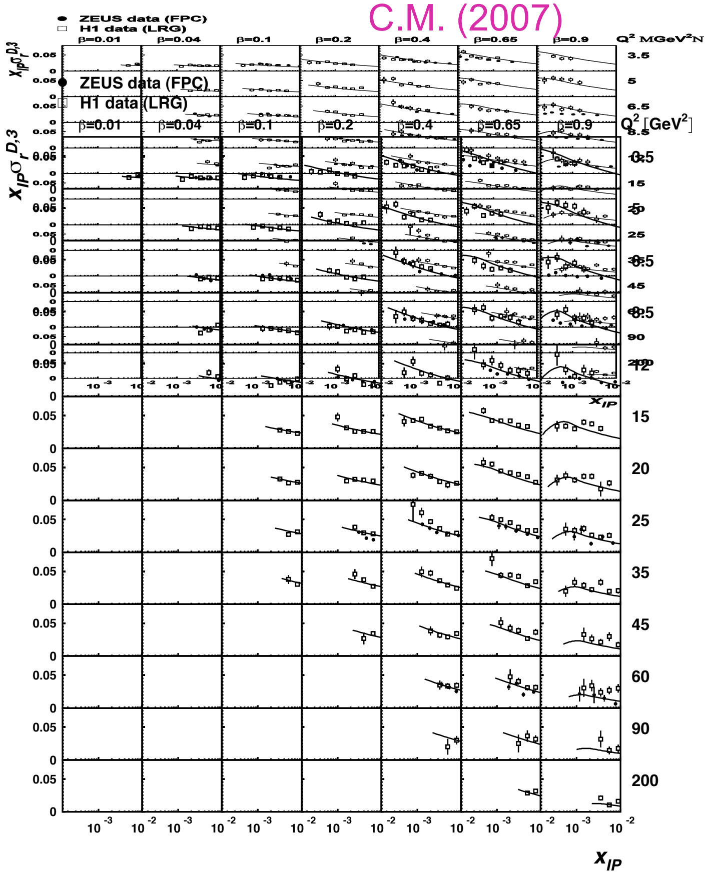


$$\tau \equiv Q^2/Q_s^2(x)$$

geometric scaling seen in the data, but scaling violations are essential for a good fit

Inclusive Diffraction

C.M. (2007)

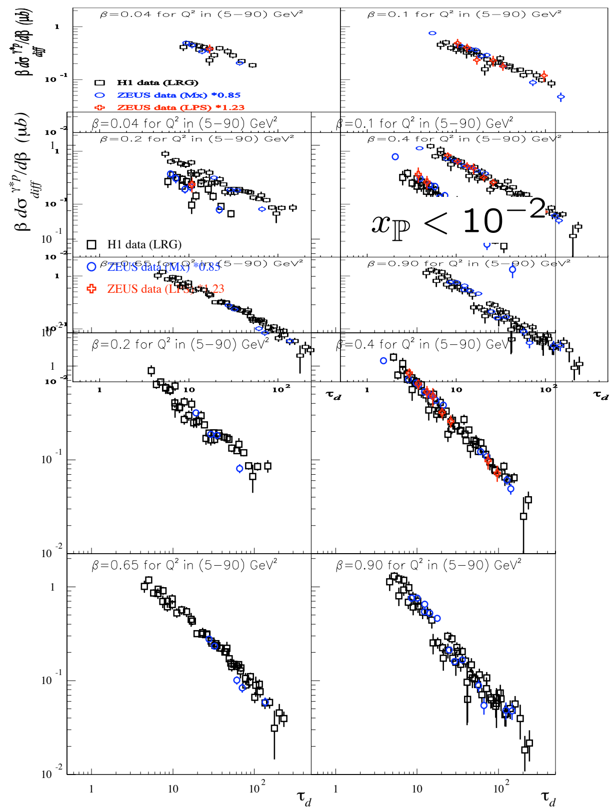


parameter-free predictions
with IIM model

(~450 points) $\chi^2/\text{points} = 1.2$

C.M. and Schoeffel (2006)

at fixed β , the scaling variable is $Q^2/Q_s^2(x_{\mathbb{P}})$



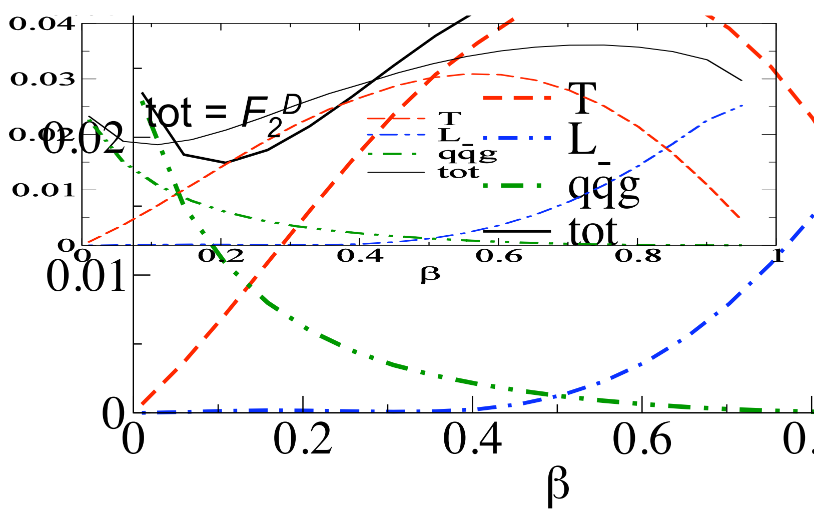
$$\beta\frac{d\sigma}{d\beta}(\beta, \tau_d \equiv Q^2/Q_s^2(x_{\mathbb{P}}))$$

Important features

- the β dependence

contributions of the different final states to the diffractive structure function:

$$x_{\mathbb{P}} F_2^{D,3}(\beta, Q^2 = 5\ \text{GeV}^2, x_{\mathbb{P}} = 0.001)$$

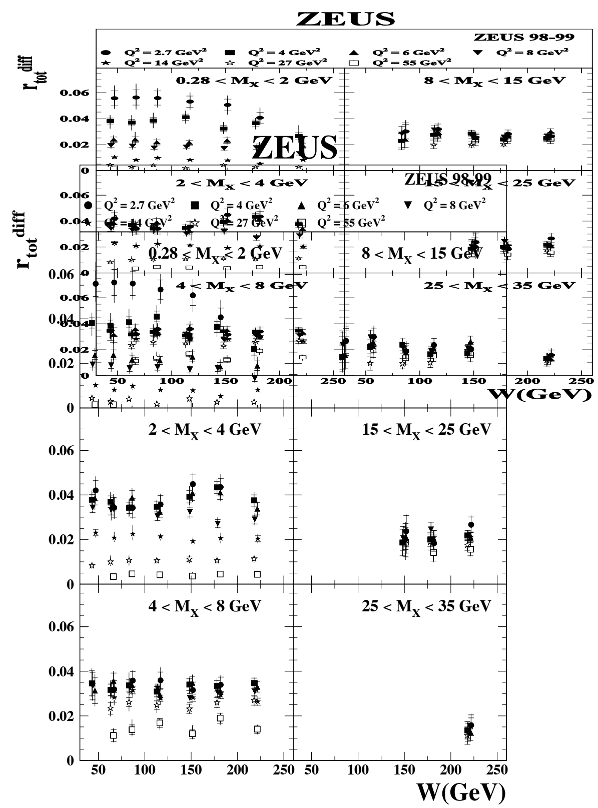


at small β : quark-antiquark-gluon

at intermediate β : quark-antiquark (T)

at large β : quark-antiquark (L)

- the ratio $F_2^{D,A} / F_2^{\,A}$



saturation naturally explains the constant ratio

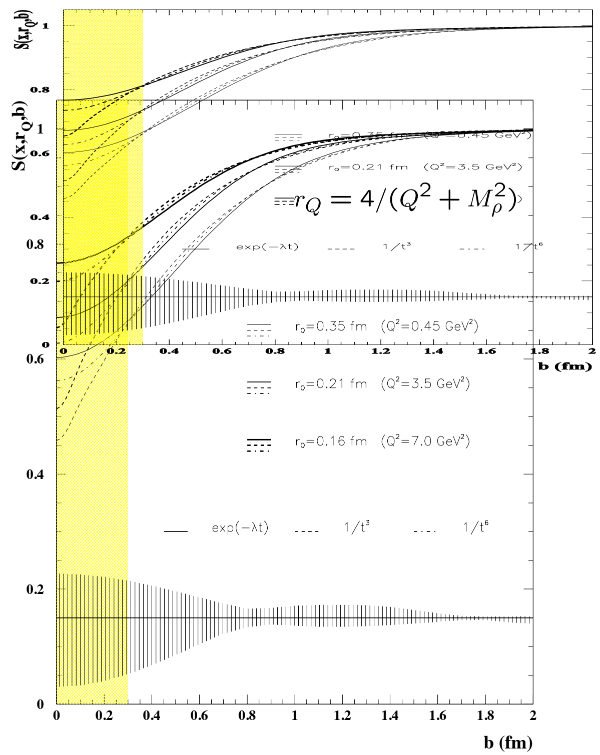
$$r_{tot}^{diff}(x, Q^2) = \frac{\int_{M_<}^{M_>} d\beta \, \frac{d\sigma_{diff}^{\gamma^* h \to Xh}}{d\beta}}{\sigma_{tot}^{\gamma^* h \to X}}$$

Exclusive diffraction

Munier, Stasto and Mueller (2001)

the scattering probability (S=1-T)
is extracted from the ρ data

S(1/r ≈1Gev, b ≈ 0, x ≈ 5.10^{-4}) ≈ 0.6



⇒ HERA is entering the saturation regime

- success of the dipole models

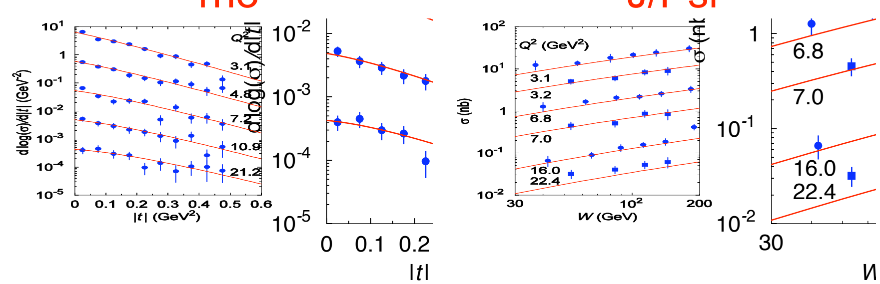
t-CGC $\chi^2/\text{points} = 1.2$

C.M., Peschanski and Soyez (2007)

b-CGC appears to work well
also but no χ^2 given

Kowalski, Motyka and Watt (2006)

rho J/Psi

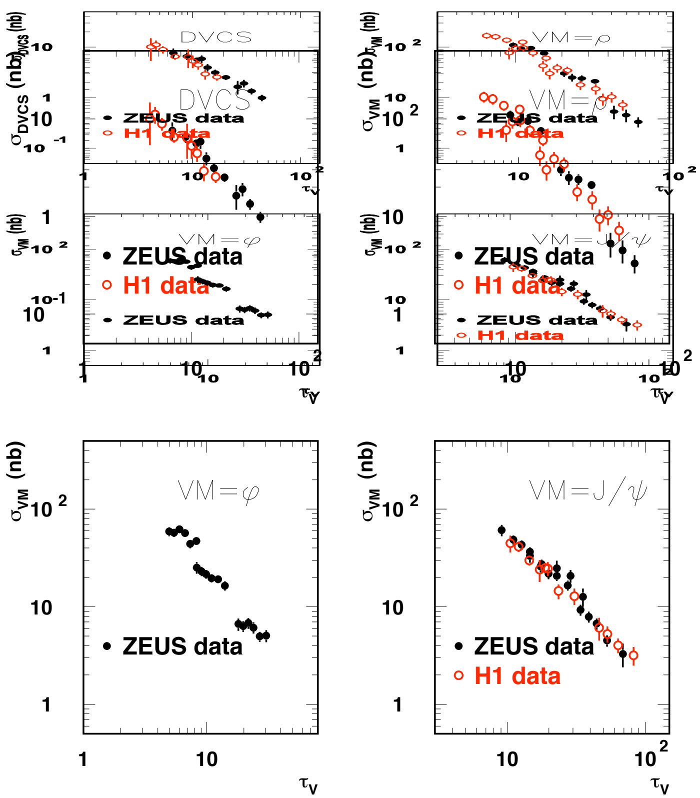


predictions for DVCS are available

Geometric scaling

- for the total VM cross-section

C.M. and Schoeffel (2006)

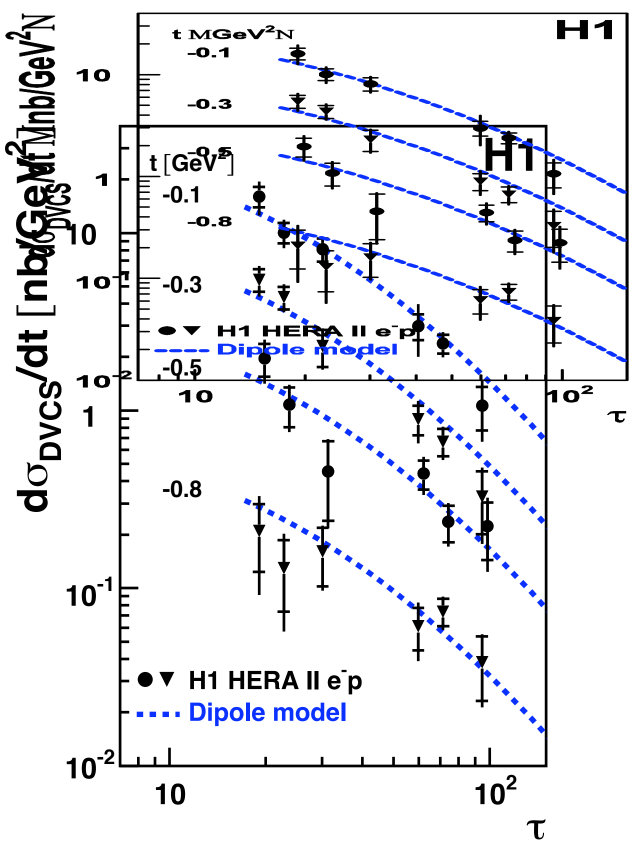


$$\sigma_{VM}(x,Q^2)=\sigma_{VM}(\tau_V\equiv(Q^2+M_V^2)/Q_s^2(x))$$

- scaling at non zero transfer

predicted C.M., Peschanski and Soyez (2005)

checked H1 collaboration (2008)



Hard diffraction off nuclei

From protons to nuclei

- the dipole-nucleus cross-section

Kowalski and Teaney (2003)

$$T^{p}_{q\bar{q}}(r,b,x) = 1 - e^{-f(r,x,b)} \quad \Rightarrow \quad T^{A}_{q\bar{q}}(r,b,x) = 1 - e^{-\sum_i f(r,x,b-b_i)}$$

averaged with the Woods-Saxon distribution $T_A(\{b_i\})$ ← position of the nucleons

$$\langle O \rangle = \int \prod_i d^2 b_i T_A(b_i)\ O(\{b_i\}) \qquad T_A(b) = C \int dz \left\{ 1 + \exp\left[\left(\sqrt{b^2+z^2} - R_A \right)/d \right] \right\}^{-1}$$

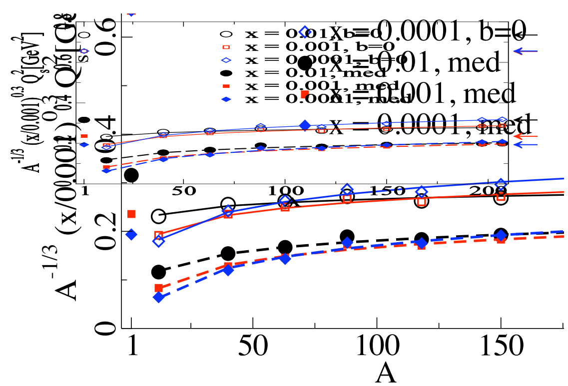
- the Woods-Saxon averaging

averaging $T^{A}_{q\bar{q}}$ allows to evaluate the saturation scale

Kowalski, Lappi and Venugopalan (2007)

in diffraction, averaging at the level of the amplitude corresponds to a final state where the nucleus is intact

averaging at the cross-section level allows the breakup of the nucleus into nucleons



Q_s^2 increases slightly faster than $A^{1/3}$

The ratio $F_2^{D,A}$ / $F_2^{D,p}$

- for each contribution

as a function of β :

quark-antiquark-gluon < 1 and ~ const.

quark-antiquark (T) > 1 and ~ const.

quark-antiquark (L) > 1 and decreases with β

the decrease with (decreasing β) of F_L^D is slower for a nucleus than for a proton

- nuclear effects

enhancement at large β

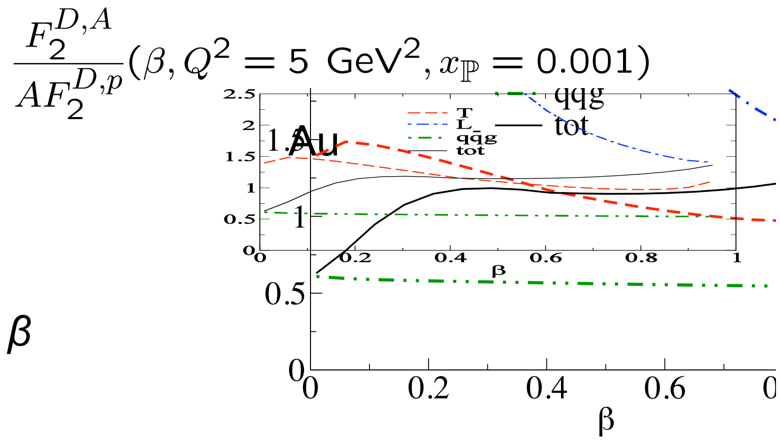
the quark-antiquark contribution dominates

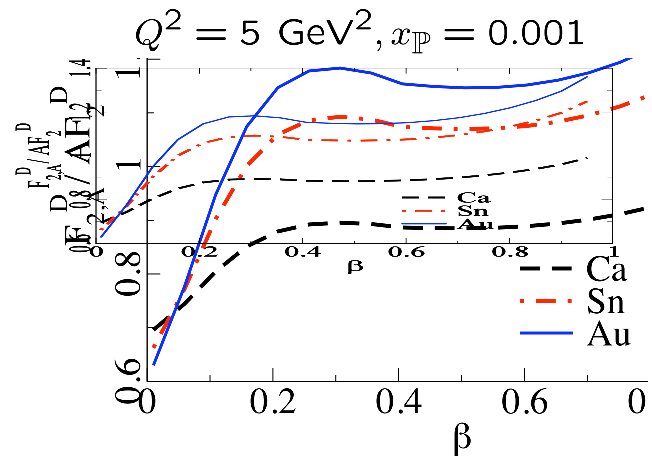
the ratio is almost constant and decreases with A

suppression at small β

the quark-antiquark-gluon contribution dominates

Kowalski, Lappi, C.M. and Venugopalan (2008)





Coherent vs Incoherent diffraction

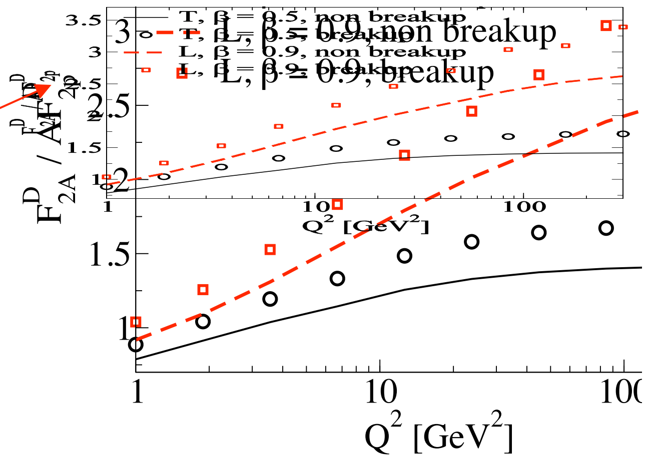
In inclusive diffraction

in this study the breakup of the nucleus into nucleons is allowed

Kowalski, Lappi, C.M. and Venugopalan (2008)

- as a function of Q^2

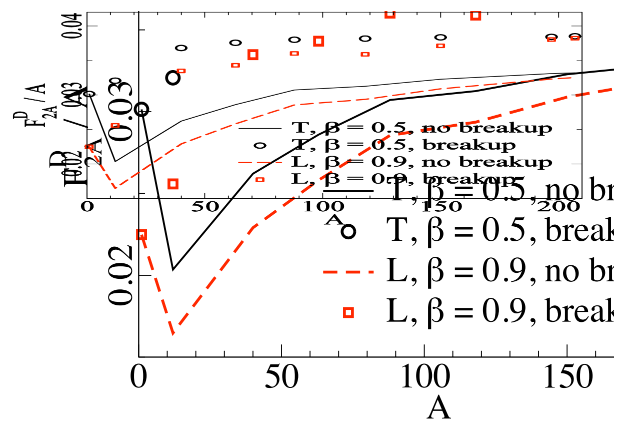
the quark-antiquark contributions
for β values at which they dominate



the decrease (with increasing Q^2) of the diffractive
cross-section is slower for a nucleus than for a proton

- as a function of A

for a gold nucleus, the diffractive structure function
is 15 % bigger when allowing breakup into nucleons



the proportion of incoherent diffraction decreases with A

In semi-inclusive diffraction

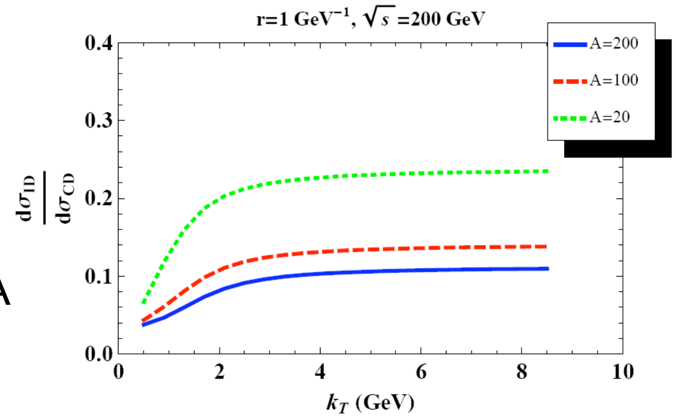
coherent case $eA \to XhA$ studied previoulsy, incoherent case recently adressed

Golec-Biernat and C.M. (2005) Tuchin (2008)

- as a function of p_T of the hadron

results are for pA collisions
but the eA case is very similar

doable at RHIC ?

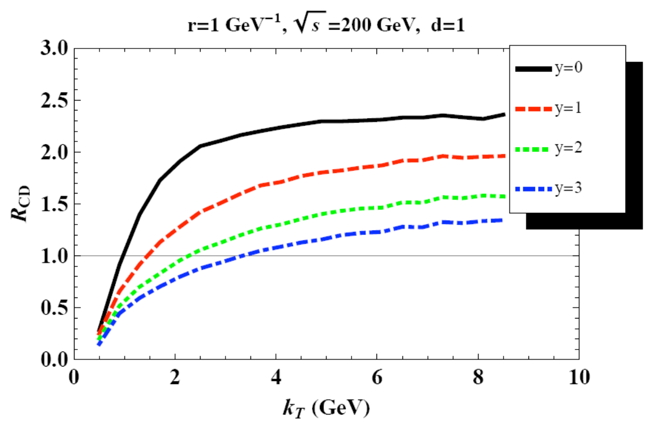


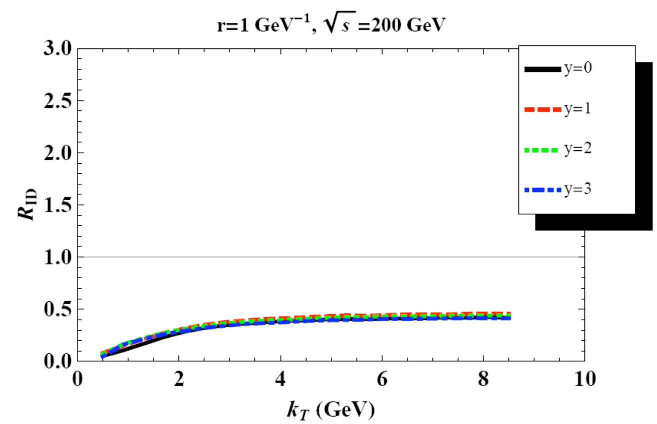
the proportion of incoherent diffraction decreases with A

- nuclear modifications

antishadowing of coherent diffraction

shadowing of incoherent diffraction





In exclusive diffraction

Dominguez, C.M. and Wu, in progress

in this study ($eA \to J/\Psi A$) the breakup of the nucleus into pions is allowed

- as a function of t

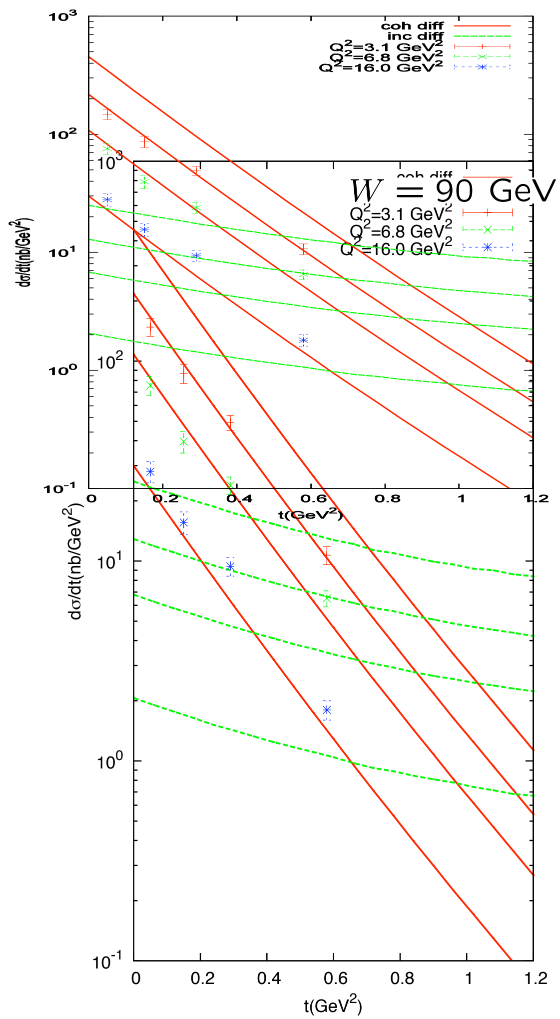
coh diff : the nucleus undergoes elastic scattering
inc diff : the nucleons undergo inelastic scattering

as a illustration, the figure is for ep collisions

incoherent diffraction dominates at large t

In the eA case, there will be three regimes:

coherent diffraction
→ steep exp. fall at small |t|
breakup into nucleons
→ slower exp. fall at $0.05 < -t < 0.7$ GeV^2
incoherent diffraction
→ power-law tail at large |t|



Conclusions

- large parton densities in hadrons/nuclei are probed at small-x and large A

  saturation effect are characterized by $Q_s^2 \simeq \Lambda_{QCD}^2 \, (A/x)^{1/3}$

- diffractive observables at HERA provide several hints that large gluon densities are being probed

  geometric scaling for inclusive, diffractive, exclusive processes
  constant inclusive over diffractive cross-section ratio
  large dipole scattering amplitude close to 0.5

- exploring the saturation regime will be possible with a high-energy electron-ion collider

  diffraction is an important part of the physics program

- ongoing studies of incoherent vs coherent diffraction