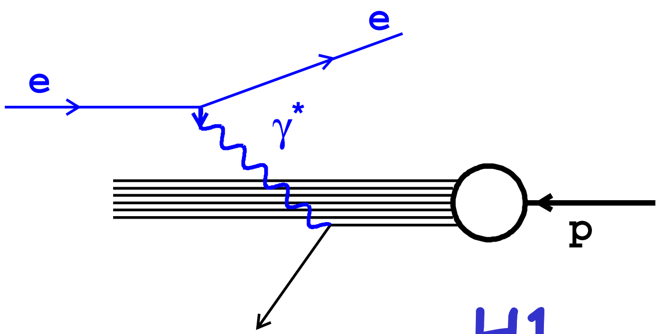
Introduction to Small-x and Diffraction at HERA and LHC

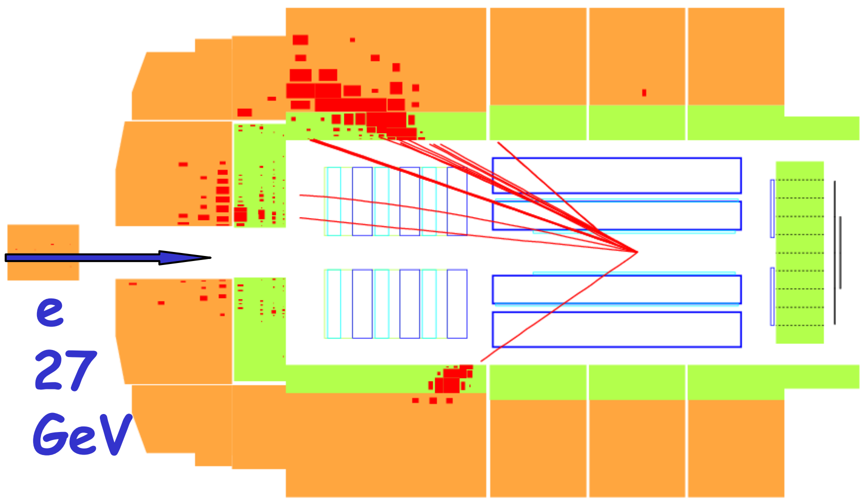
Henri Kowalski
DESY

Photon 2005
Warszawa
1st of September



HERA – ep Collider

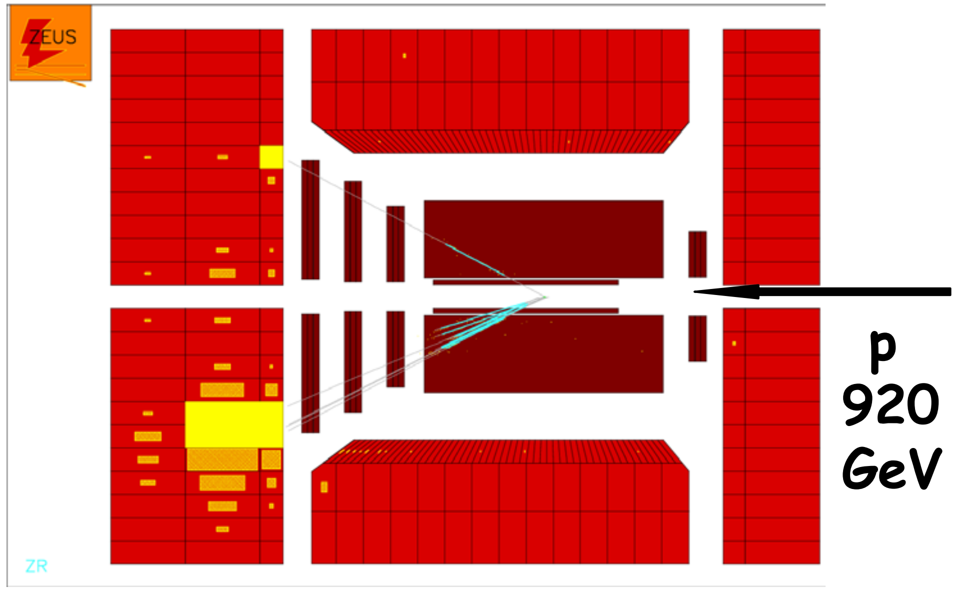
H1



e
27
GeV

Liquid Argon Calorimeter

ZEUS



p
920
GeV

Uranium-Scintillator Calorimeter

Q^2 - virtuality of the incoming photon

W - CMS energy of the incoming photon-proton system

x - Fraction of the proton momentum carried by the struck quark $x \sim Q^2/W^2$

$$\frac{d^2\sigma^{eP}}{dxdQ^2} = \frac{2\pi\alpha_{em}^2}{xQ^4} \cdot [Y\_F_2(x,Q^2) - Y\_xF_3(x,Q^2) - y^2 F_L(x,Q^2)]$$

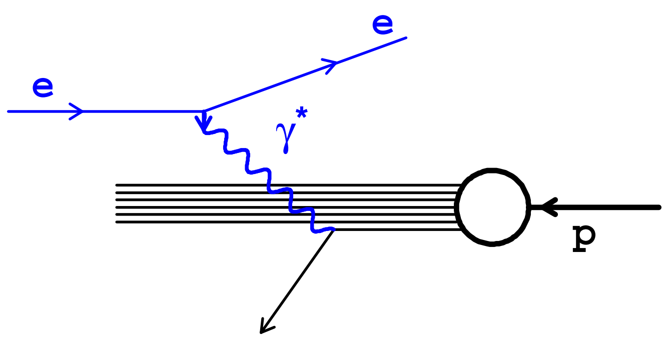
$$Y_{\pm} = 1 \pm (1-y)^2$$

y – inelasticity

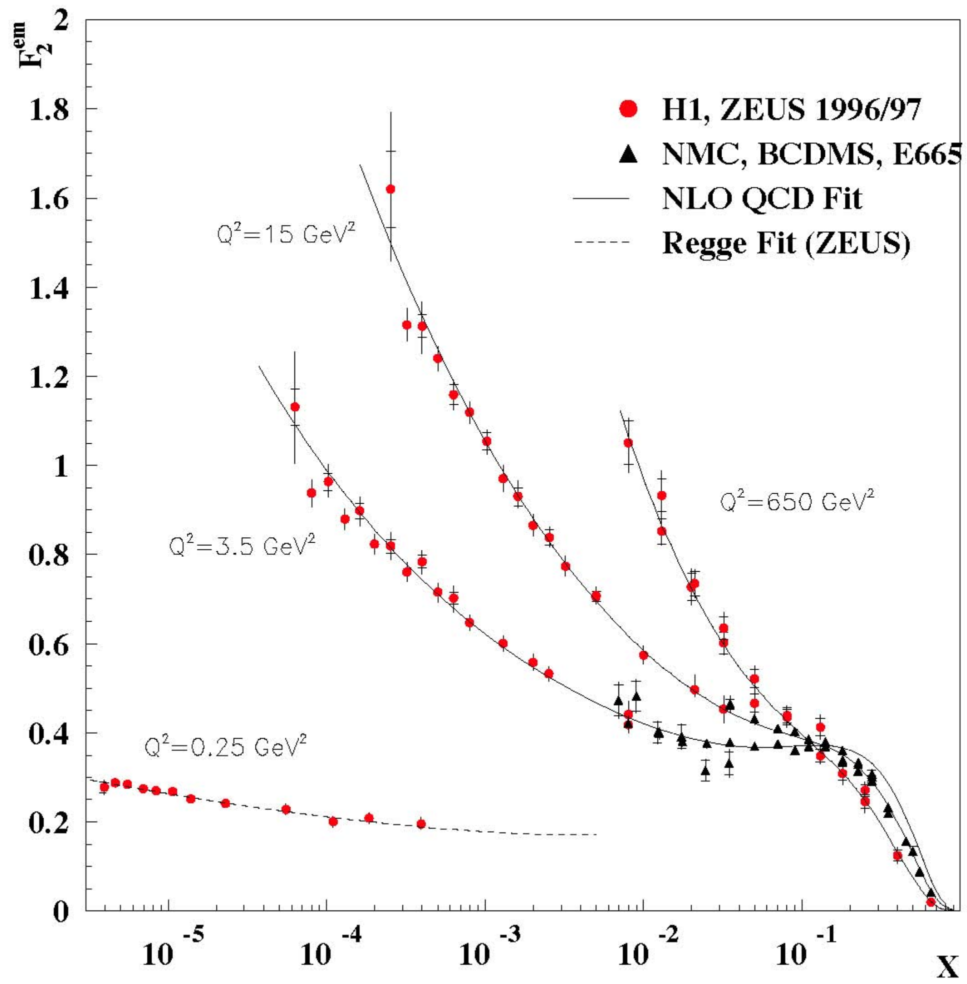
$Q^2 = sxy$

Infinite momentum frame

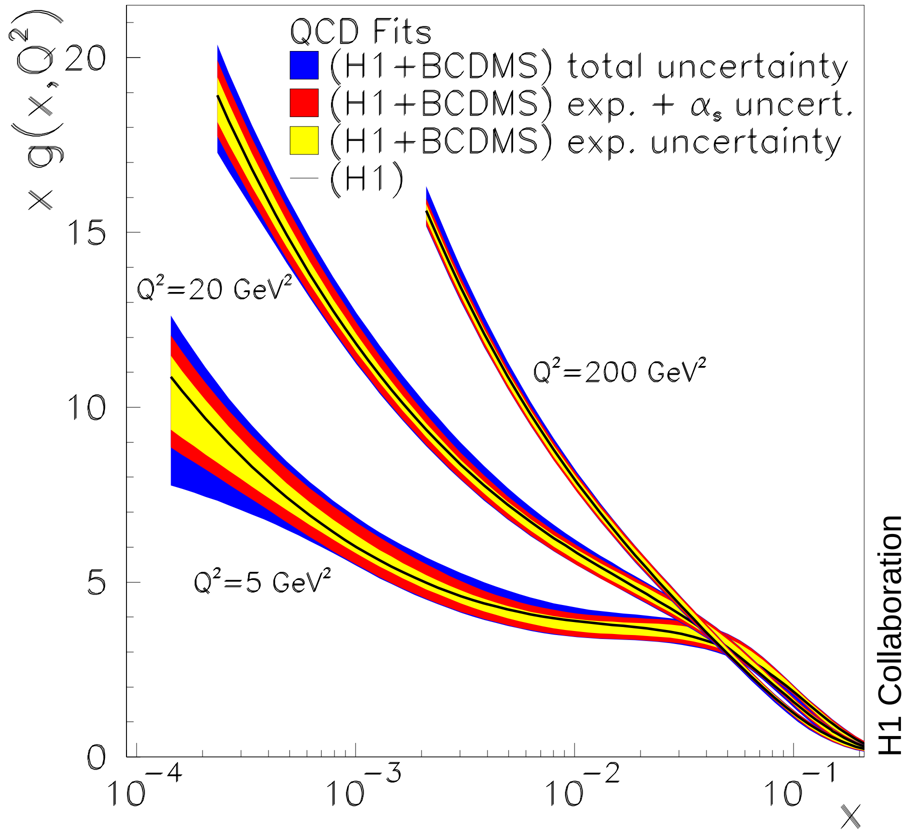
Proton looks like a cloud of non-interacting quarks and gluons



F_2 measures parton density in the proton at a scale Q^2



Gluon density

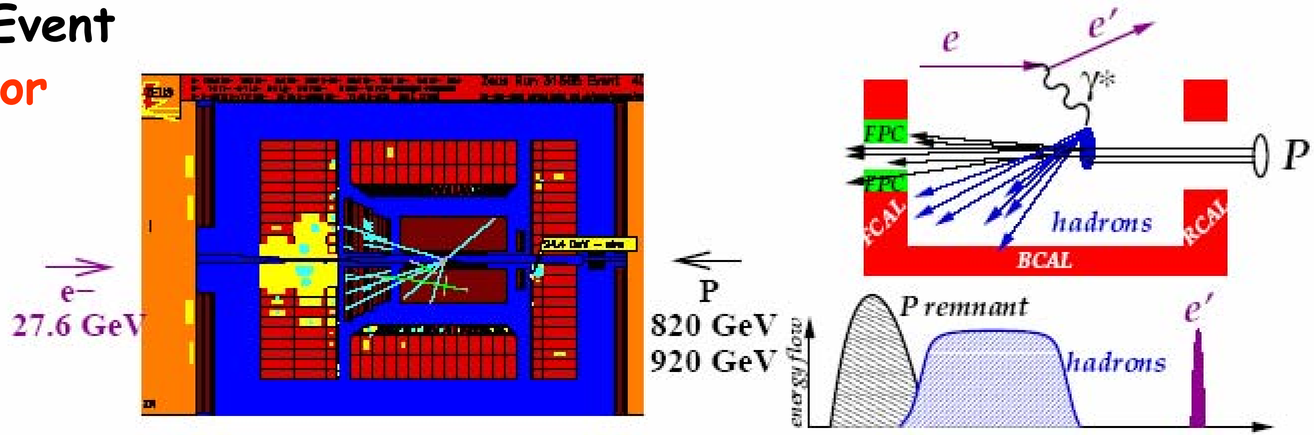


Gluon density dominates F_2 for *x* < 0.01

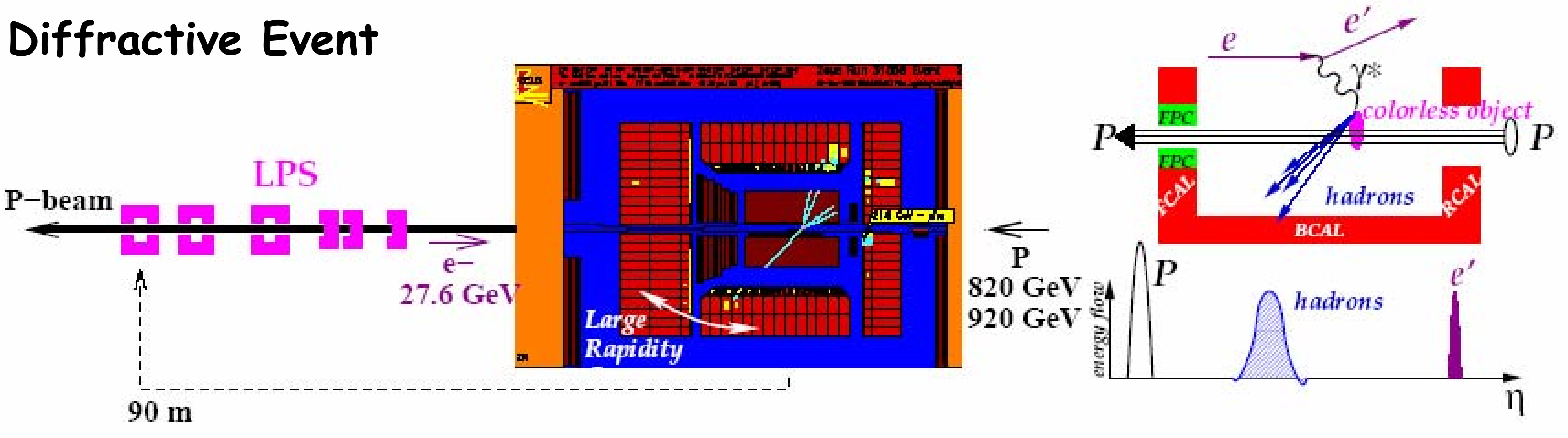
Diffractive Scattering

Non-Diffractive Event

ZEUS detector



Diffractive Event



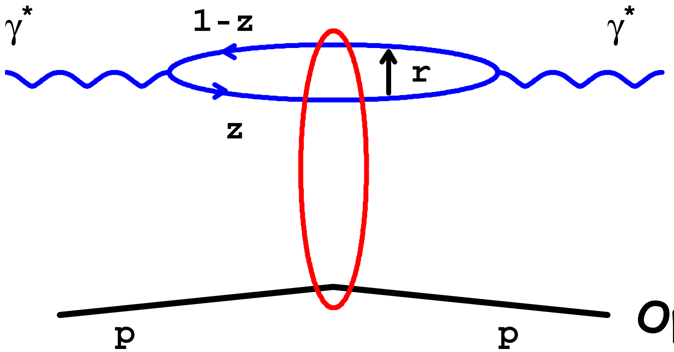
M_X - invariant mass of all particles seen in the central detector

t - momentum transfer to the diffractively scattered proton

t - conjugate variable to the impact parameter

Dipole description of DIS

equivalent to Parton Picture in perturbative region



$$|\Psi_T^f|^2 = \frac{3\alpha_{em}}{2\pi^2} e_q^2 \{[z^2 + (1-z)^2]\varepsilon^2 K_1^2(\varepsilon r) + m_q^2 K_0^2(\varepsilon r)\}$$

$$|\Psi_L^f|^2 = \frac{3\alpha_{em}}{2\pi^2} e_q^2 \{4Q^2 z^2 (1-z)^2 K_0^2(\varepsilon r)\}$$

$$\varepsilon^2 = z(1-z)Q^2 + m_q^2$$

$\varepsilon r << 1$
$Q^2 \sim 1/r^2$

Optical T

Mueller, Nikolaev, Zakharov

$$\sigma_{tot}^{\gamma^* p} = \int d^2\hat{\vec{r}} \int_0^1 dz \Psi^* \sigma_{q\bar{q}}(x, r^2) \Psi$$

$$\frac{d\sigma_{diff}^{\gamma^* p}}{dt}\Big|_{t=0} = \frac{1}{16\pi} \int d^2\vec{r} \int_0^1 dz \Psi^* \sigma_{q\bar{q}}^2(x, r^2) \Psi$$

GBW – first Dipole Saturation Mode (rudimentary evolution)

Golec-Biernat, Wuesthoff

$$\sigma_{qq}(x,r) \approx \sigma_0 (1 - \exp(-\frac{r^2}{R_0^2})); \qquad R_0^2 = \frac{1}{GeV^2}\left(\frac{x}{x_0}\right)^{\lambda_{GBW}}$$

BGBK – DSM with DGLAP

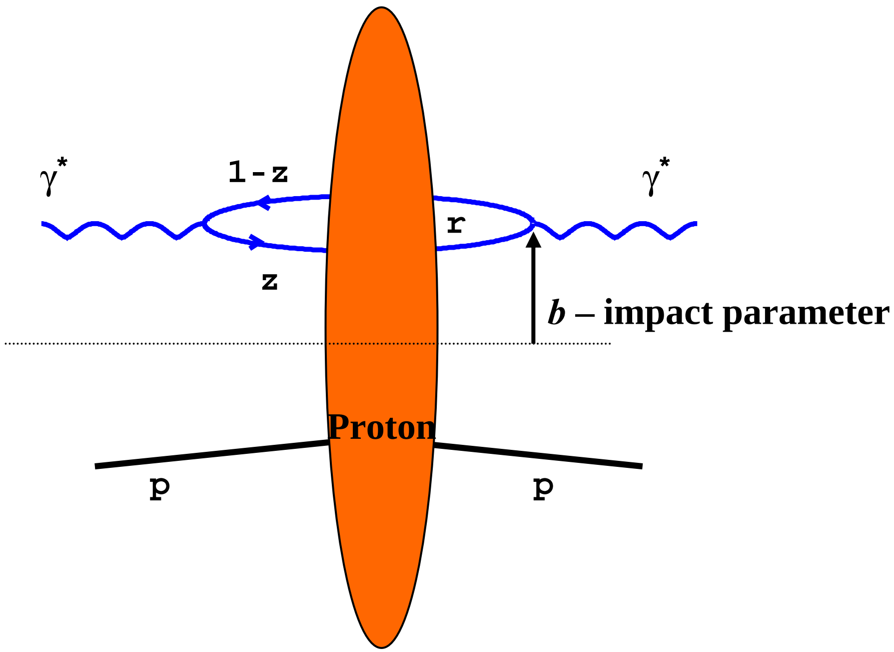
Bartels, Golec-Biernat, Kowalski

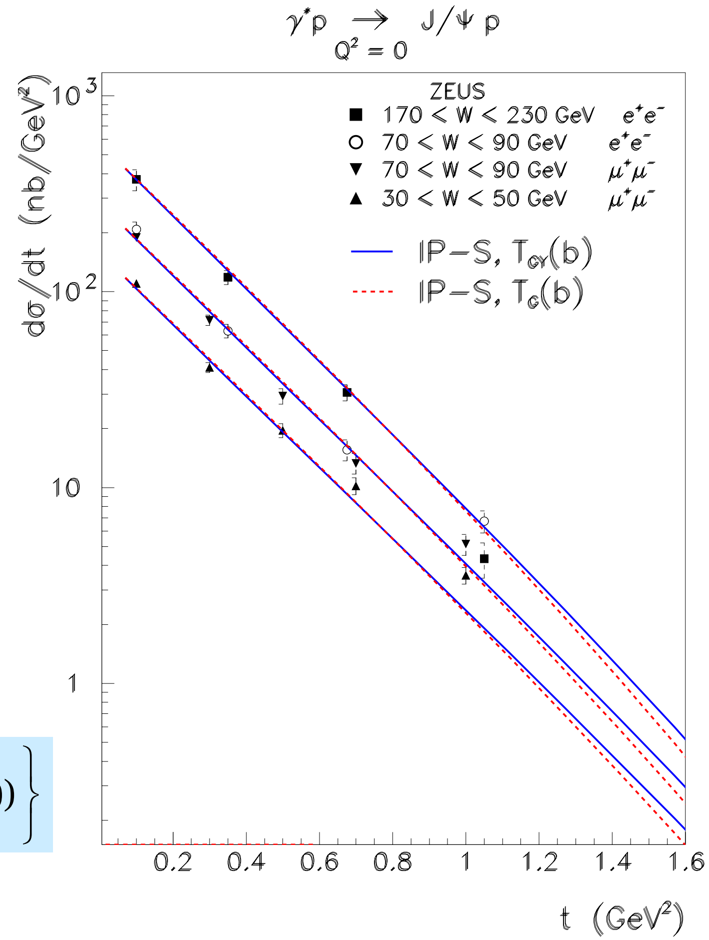
$$\sigma_{qq}(x,r) \approx \sigma_0 (1 - \exp(-\frac{\pi^2}{3\sigma_0} r^2 \alpha_s x g(x, \mu^2 = C/r^2 + \mu_0^2)))$$

Iancu, Itakura, Mounier
BFKL-CGC motivated ansatz

Impact Parameter Dipole Saturation Model

Kowalski
Teaney





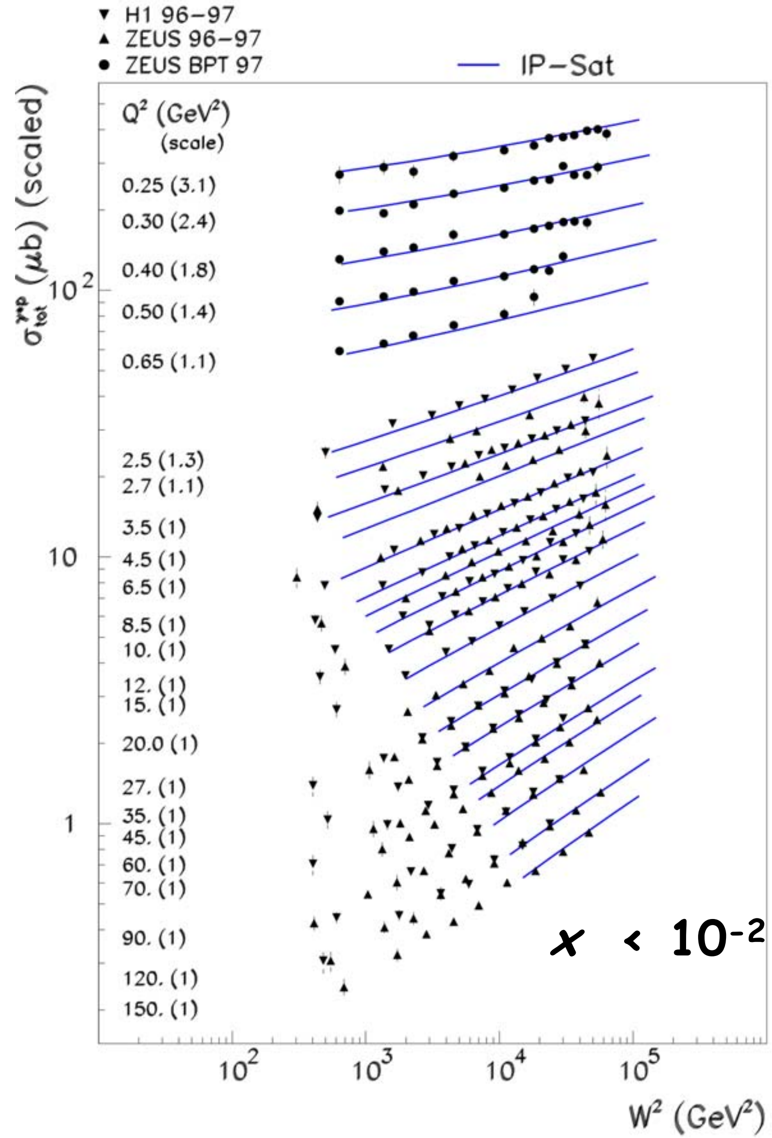
Glauber-Mueller, Levin, Capella, Kaidalov…

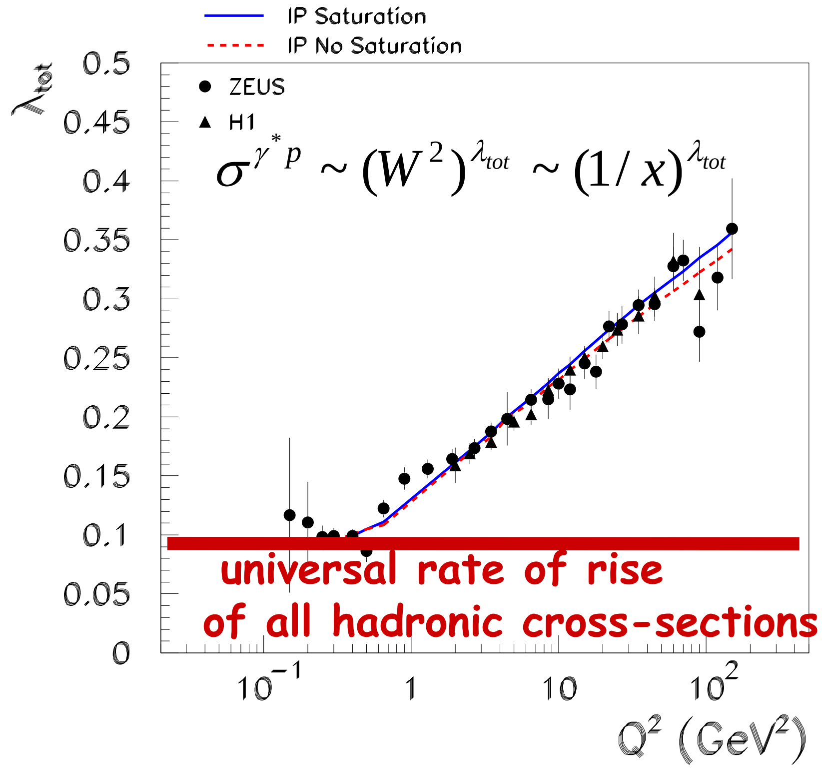
$$\frac{d\sigma_{qq}(x,r)}{d^2b} = 2\cdot\left\{1-\exp\left(-\frac{\pi^2}{2\cdot 3} r^2 \alpha_s(\mu^2) xg(x,\mu^2) T(b)\right)\right\}$$

T(b) **- proton shape**

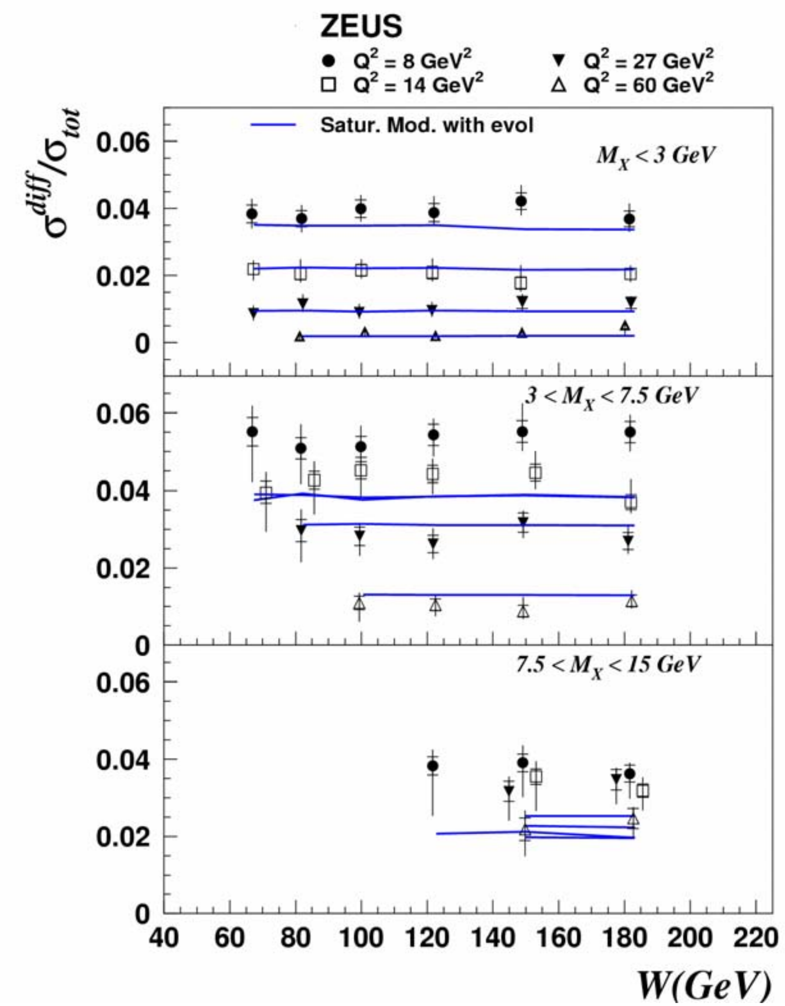
$$\frac{d\sigma^{diff}}{dt} \sim \exp(B\cdot t) \Rightarrow T(b) \sim \exp(-\vec{b}^2/2B)$$

Total $\gamma^* p$ cross-section





from fit to σ_{tot} predicts σ^{diff}
GBW, BGBK ...



2005 measurements:
σ^{diff} / σ^{tot}
integrated over all masses

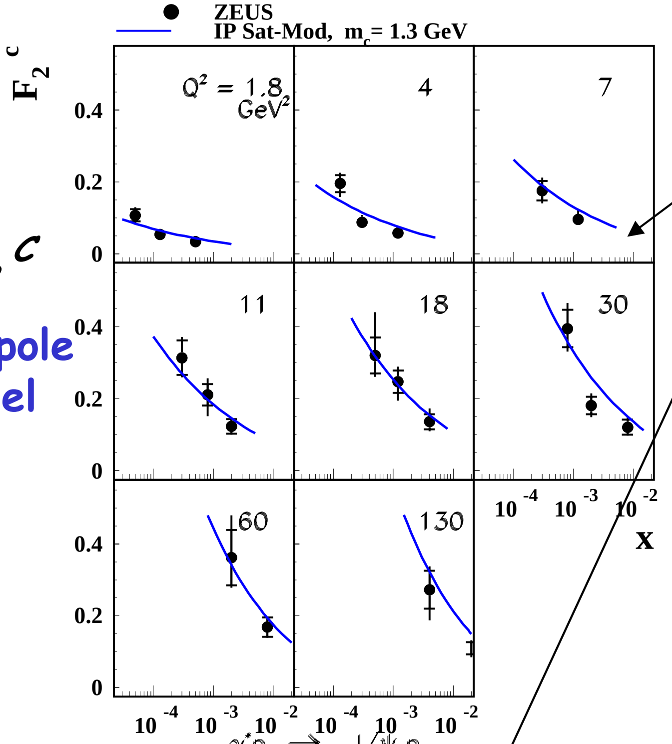
16% at Q^2 = 4 GeV^2
10% at Q^2 = 27 GeV^2

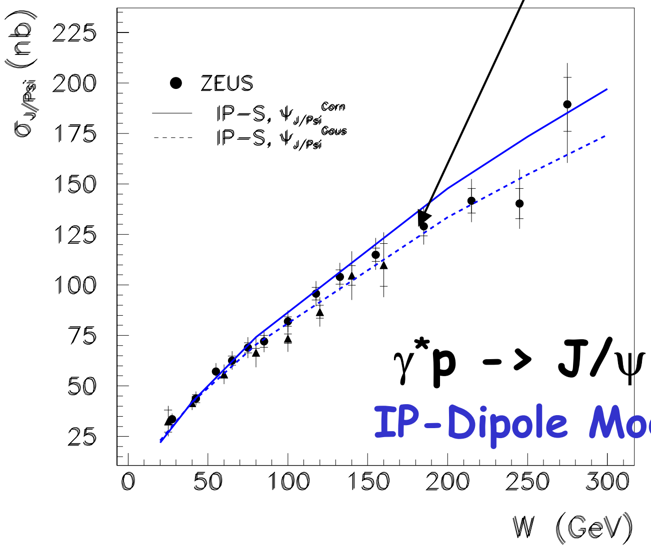
logarithmic drop of diffractive contribution with Q^2
(in agreement with DSP)

Dipole cross section determined by fit to F_2 → Simultaneous description of many reactions

$F_2{}^c$

IP-Dipole Model





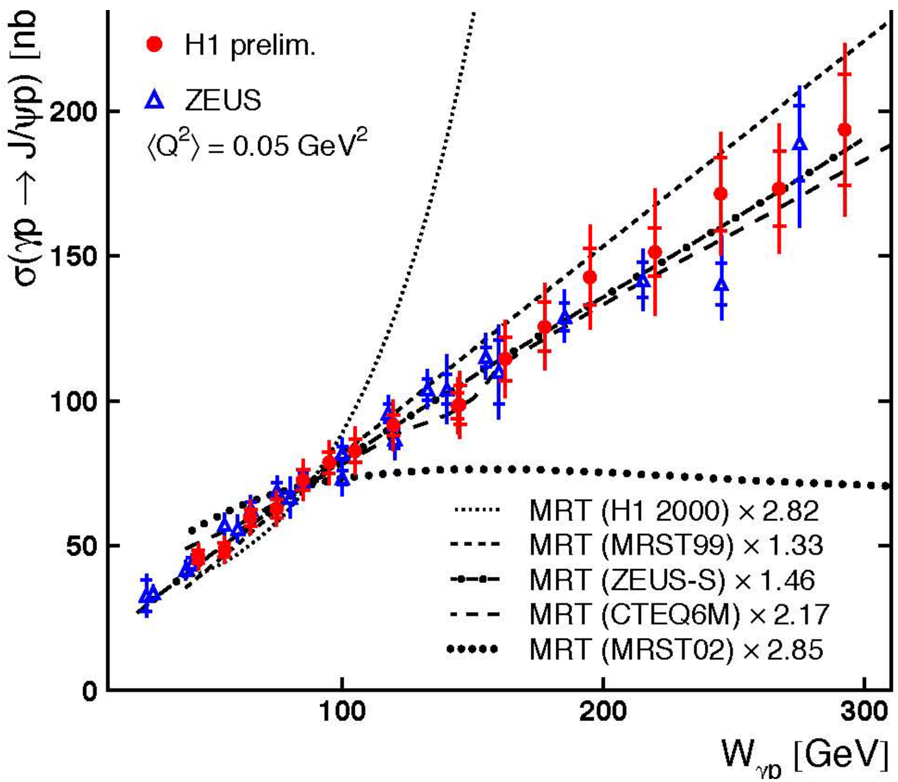
γ^*p -> J/ψ p

IP-Dipole Model

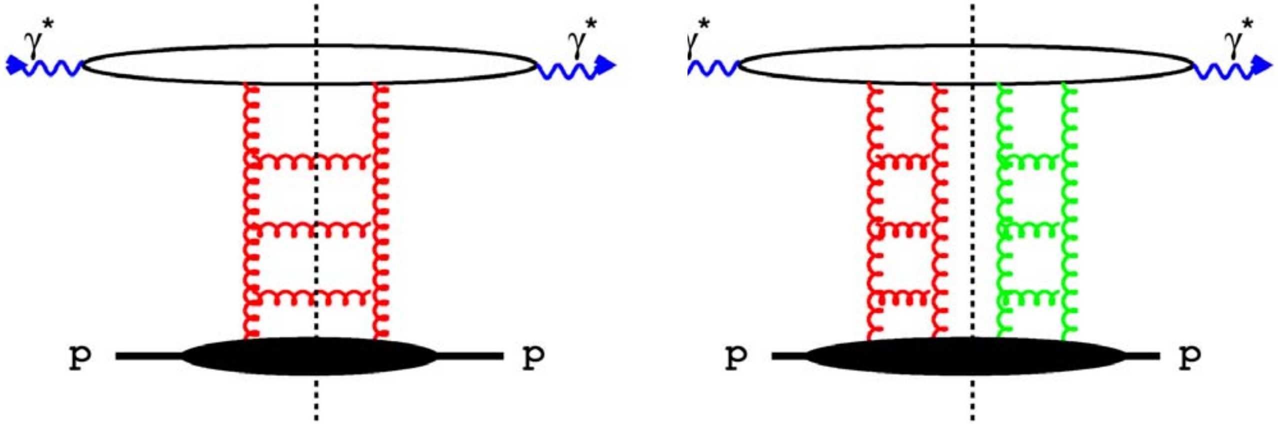
Gluon density test?

Teubner

γ^*p -> J/ψ p



Saturation and Absorptive corrections



F₂ ~ ***Single inclusive*** **pure DGLAP** - ***Diffraction***

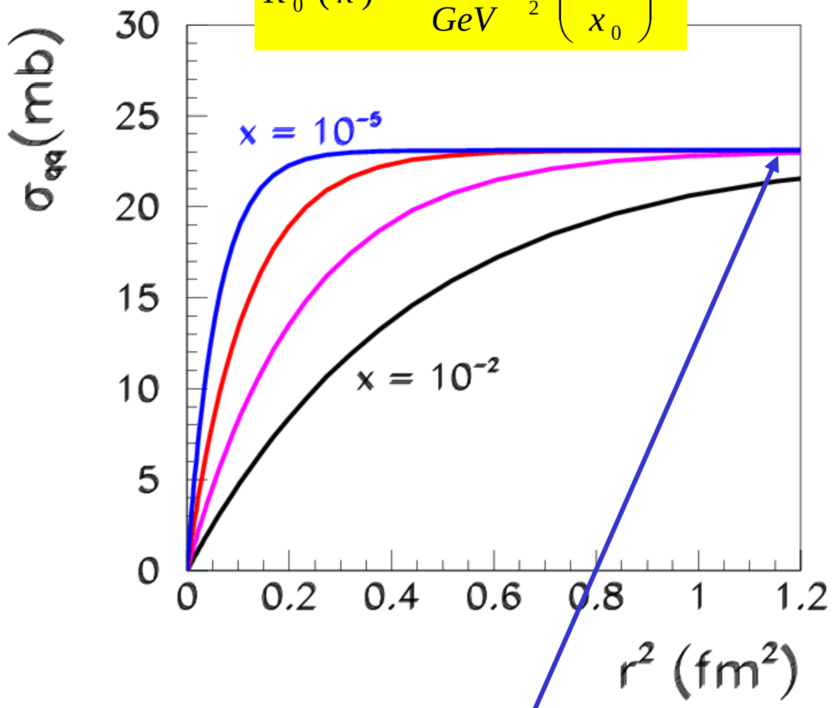
Example in Dipole Model

$$\frac{d\sigma}{d^2b} = 2(1-\exp(-\Omega/2)) = \Omega - \Omega^2/4 + ...$$

GBW Model

$$\sigma_{qq}(x,r) = \sigma_0[1-\exp(-\frac{r^2}{4R_0^2})]$$

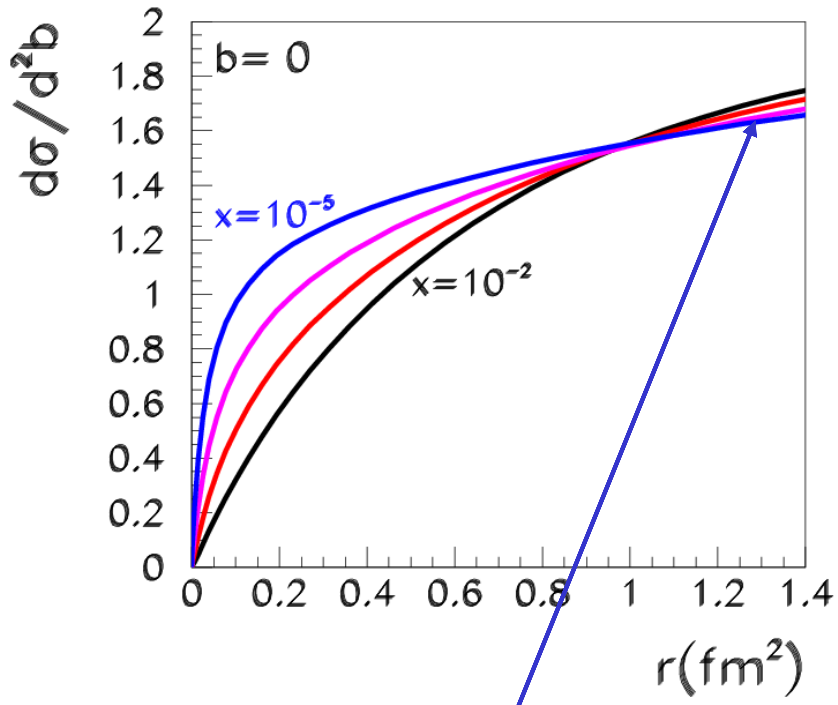
$$R_0^2(x) = \frac{1}{GeV^2}\left(\frac{x}{x_0}\right)^{\lambda}$$



strong saturation

IP Dipole Model

$$\frac{d\sigma_{qq}(x,r)}{d^2b} = 2\cdot\left\{1-\exp(-\frac{\pi^2}{2\cdot 3}r^2\alpha_s xg(x,C/r^2+Q_0^2)T(b))\right\}$$

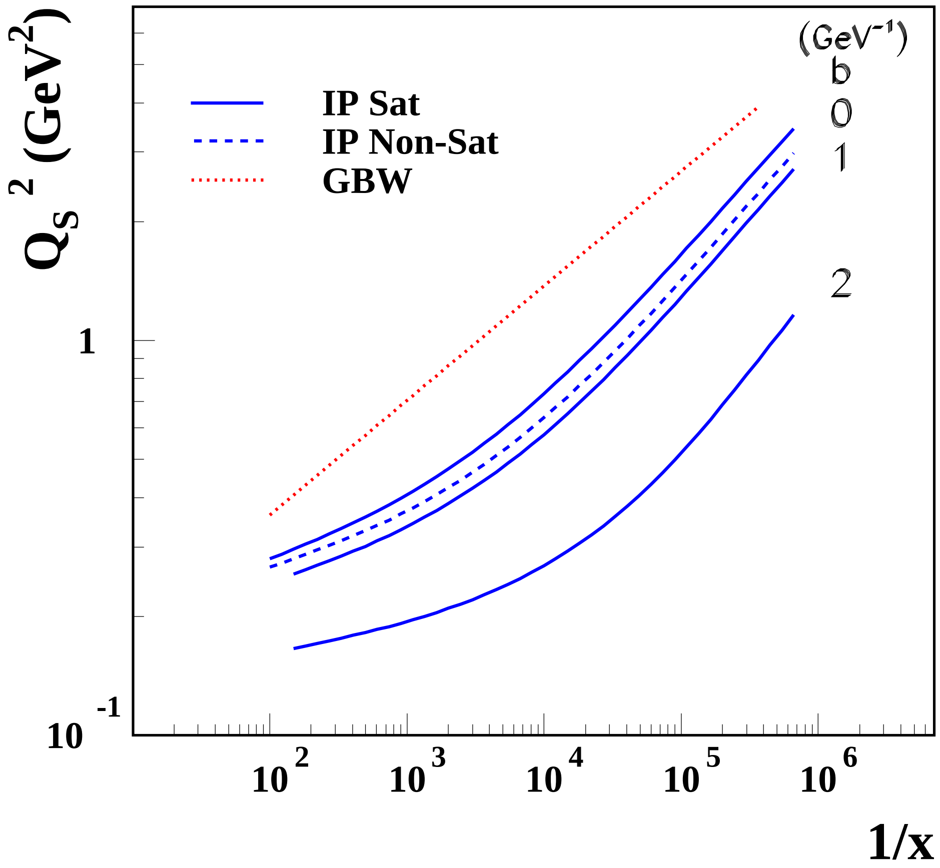


less saturation
(due to IP and charm)

Saturation scale
(a measure of gluon density)

$$Q_S^2 = \frac{2}{r_S^2}$$

$$(Q_S^2)_g = \frac{N_C}{C_F}(Q_S^2)_q = \frac{9}{4}(Q_S^2)_q$$



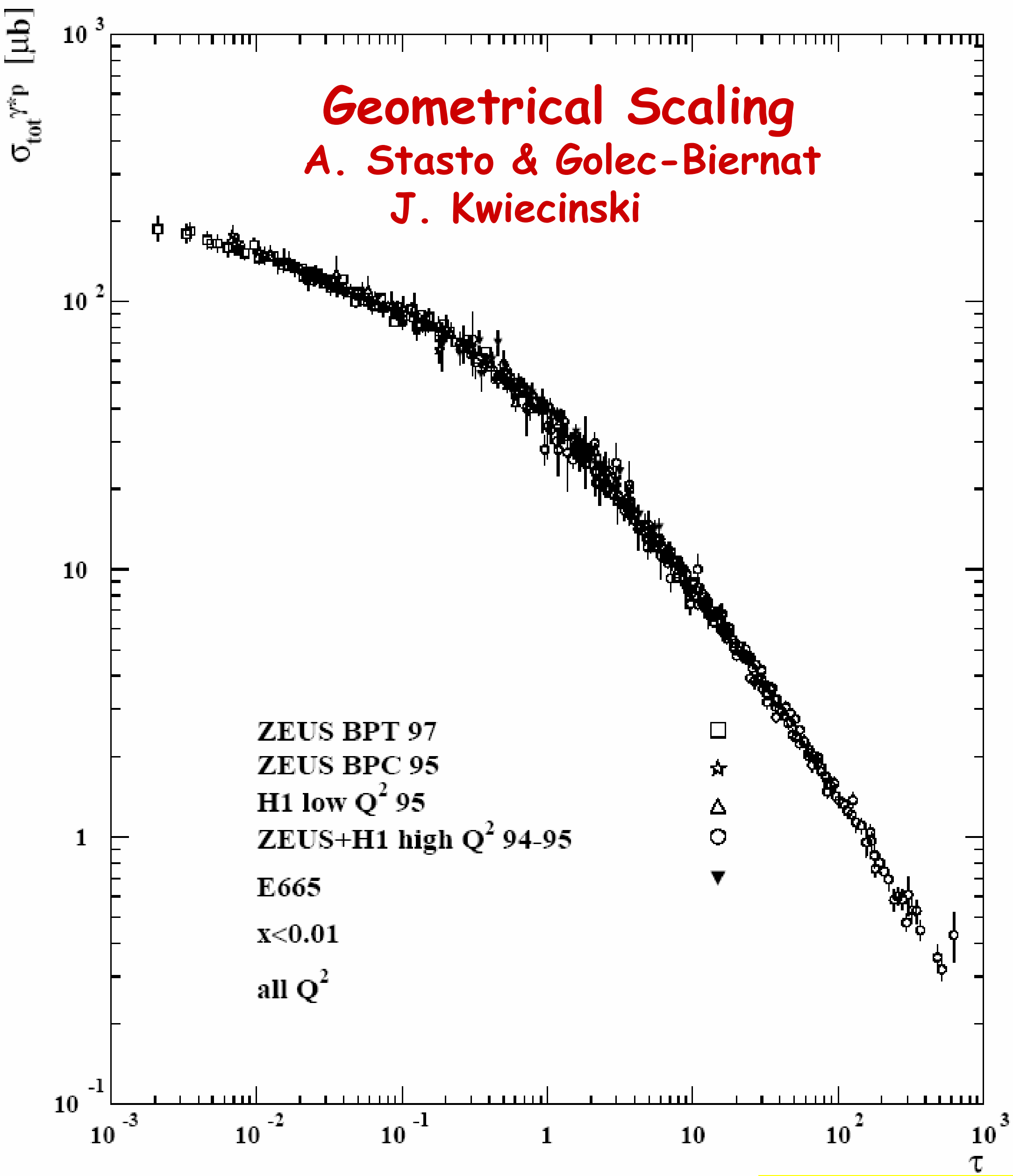
RHIC

$$Q_S^2 = \frac{4\pi^2\alpha_s N_C}{N_C^2-1}\frac{1}{\pi R^2}\frac{dN}{dy}$$

$$\frac{dN}{dy} \approx 1000 \qquad R \approx 7\ \mathrm{fm}$$

$$Q_S^2 \approx 1\ \mathrm{GeV}^2$$

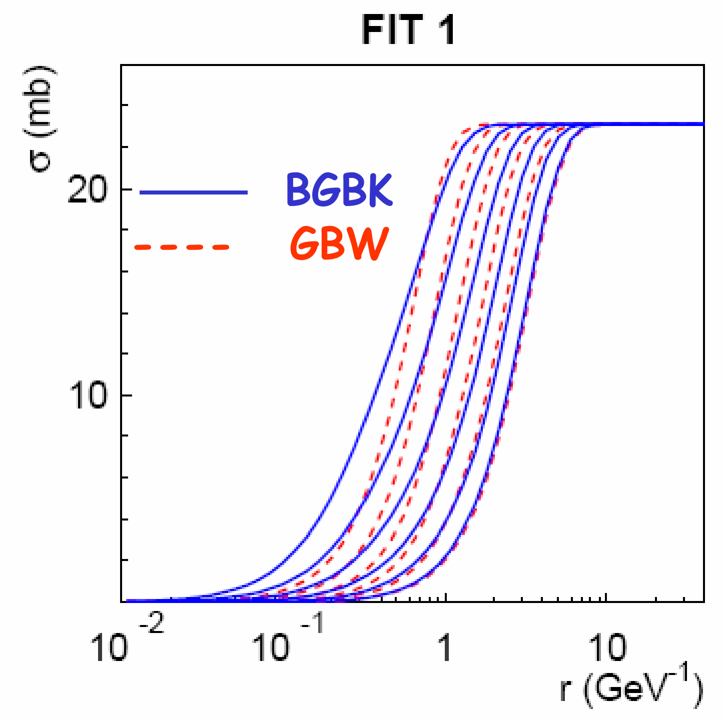
$$\boxed{Q_S^{RHIC} \sim Q_S^{HERA}}$$



$$R_0^2(x) = \frac{1}{GeV^2}\left(\frac{x}{x_0}\right)^{\lambda}$$

$$\tau = Q^2 R_0^2(x)$$

Dipole X-section



Geometrical Scaling can be derived from traveling wave solutions of non-linear QCD evolution equations

⇒Velocity of the wave front gives the energy dependence of the saturation scale

Munier, Peschansk
L. McLerran +…
Al Mueller + ..

Question:
Is GS an intrinsic (GBW) or effective (KT) property of HERA data?

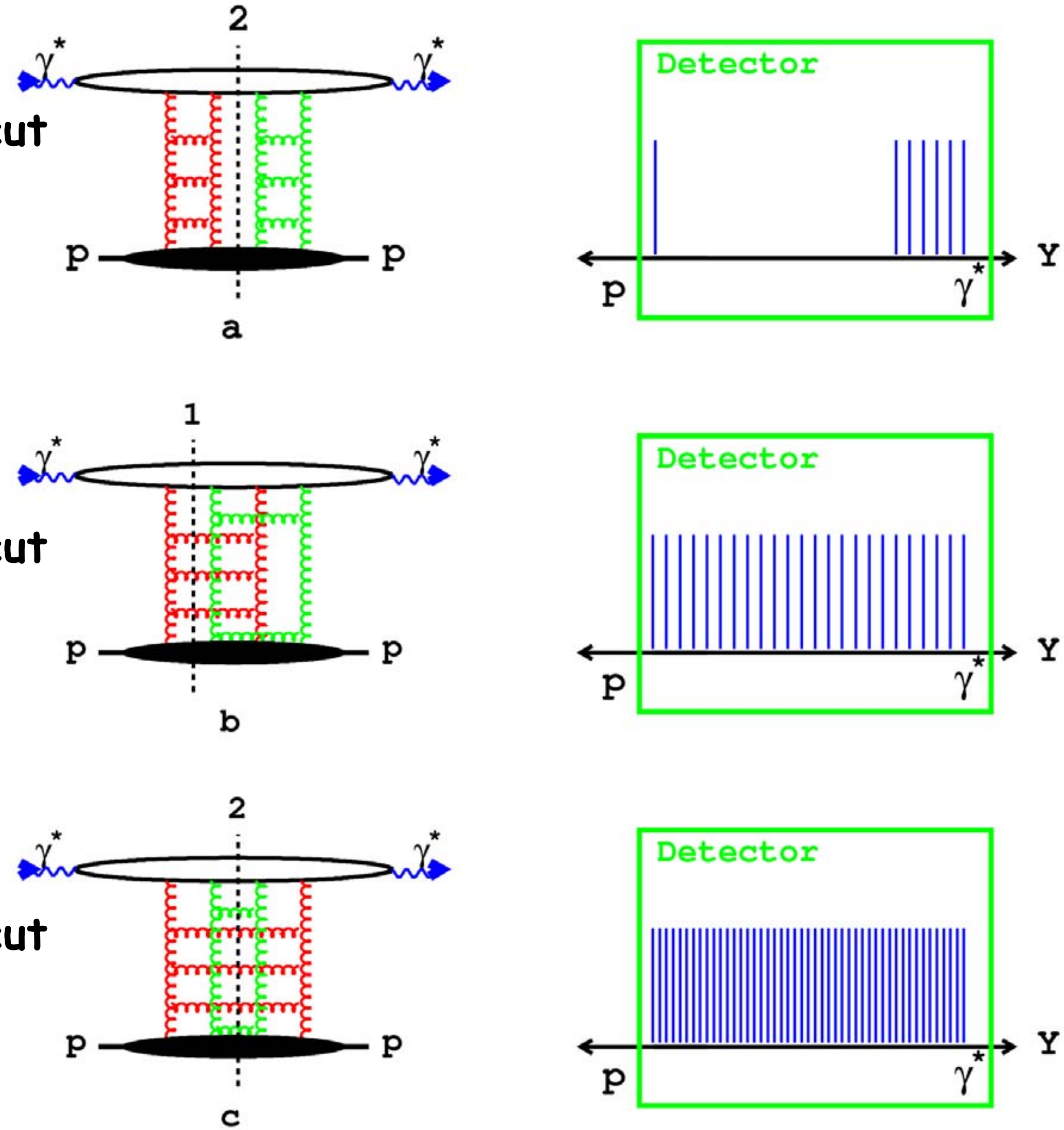
2-Pomeron exchange in QCD

Final States (naïve picture)

0-cut

1-cut

2-cut



Diffraction

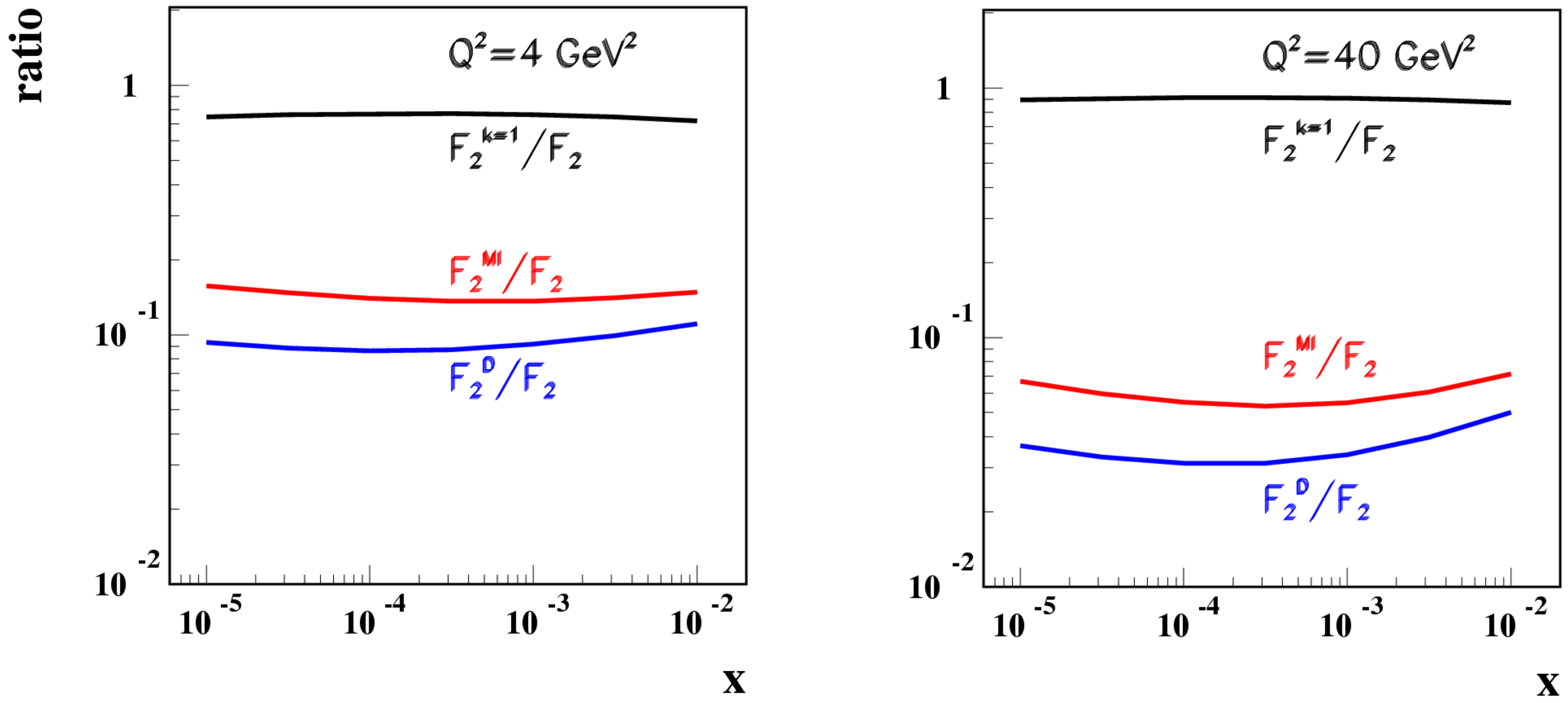
<n>

<2n>

AGK rules in the Dipole Model

$$\frac{d\sigma_k}{d^2b} = \frac{\Omega^k}{k!}\exp(-\Omega)$$

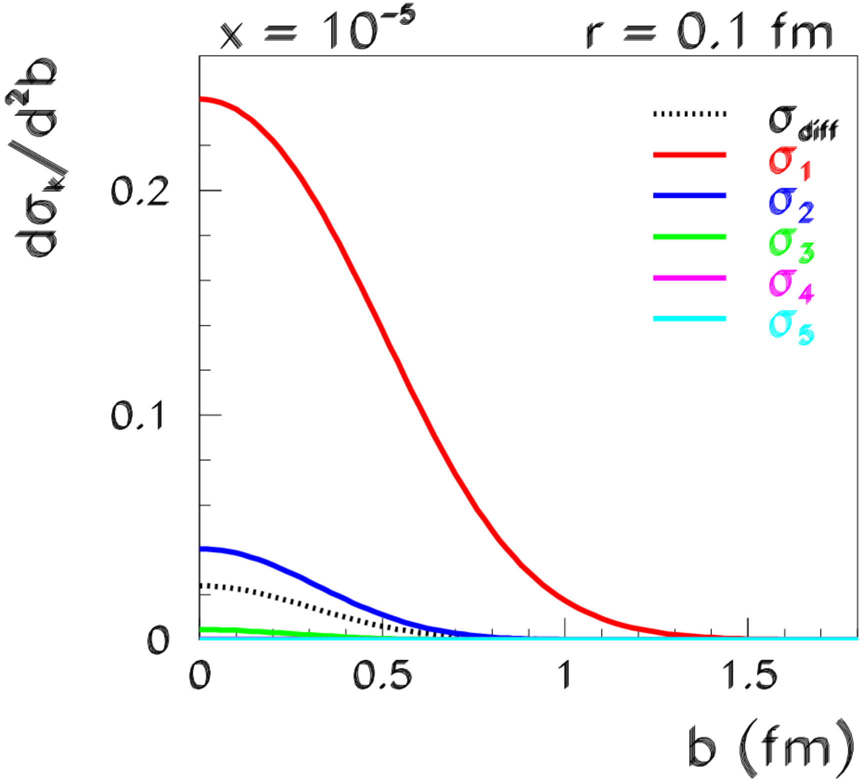
$$\Omega = \frac{\pi^2}{N_C} r^2 \alpha_s(\mu^2) x g(x,\mu^2) T(b)$$

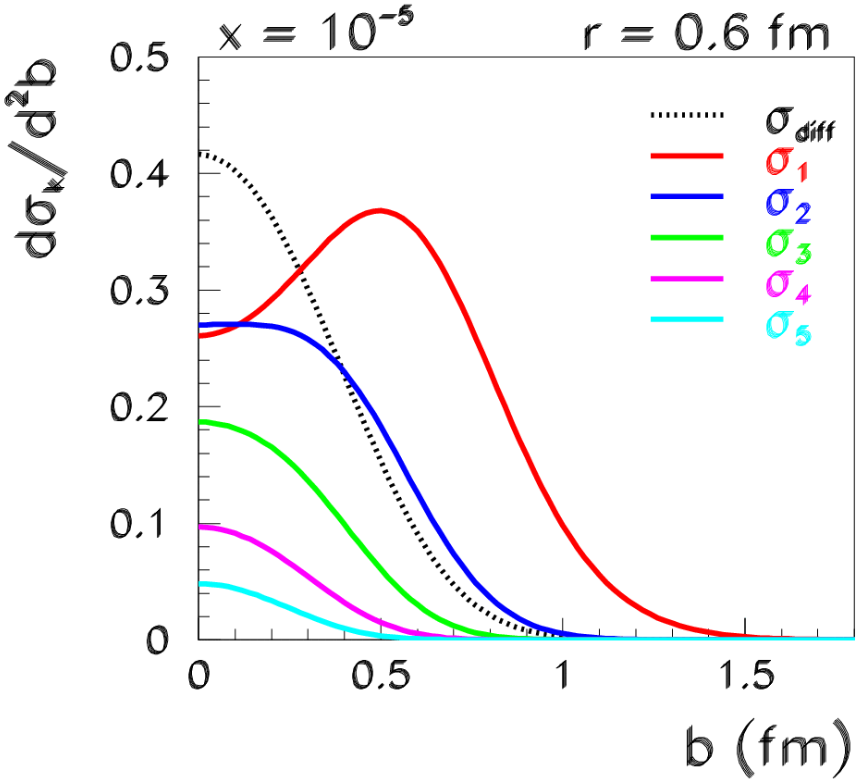


Note: AGK rules underestimate the amount of diffraction in DIS

$$\frac{d\sigma_{qq}}{d^2b} = 2\cdot\left\{1-\exp(-\frac{\Omega}{2})\right\}$$

$$\frac{d\sigma_k}{d^2b} = \frac{\Omega^k}{k!}\exp(-\Omega)$$

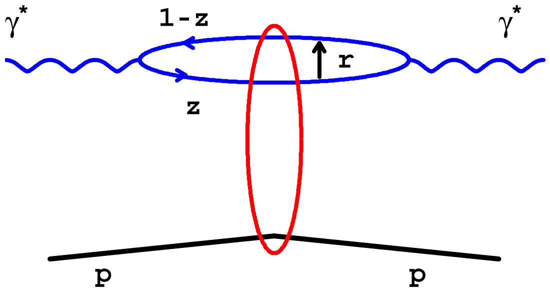




$$\Omega = \frac{\pi^2}{N_C} r^2 \alpha_s(\mu^2)\, x g(x,\mu^2)\, T(b)$$

HERA Result

Unintegrated Gluon Density

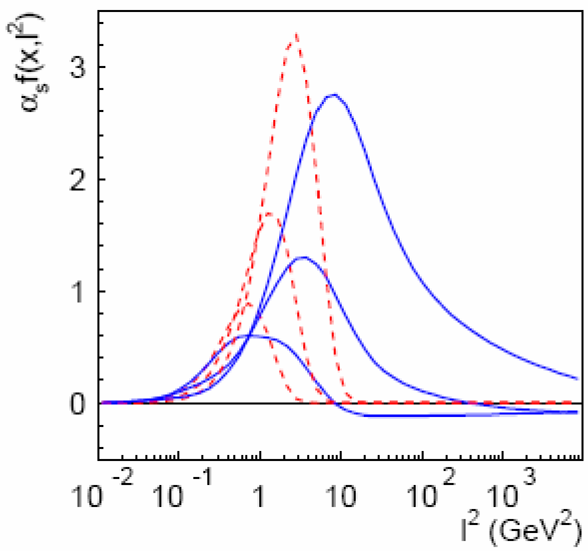


Dipole Model

$$\frac{\alpha_s f(x,l^2)}{l^4} = \frac{3}{8\pi^2}\int_0^\infty dr\, r\, J_0(lr)\, \{\hat{\sigma}_\infty(x) - \hat{\sigma}(x,r)\}$$

$$\alpha_s(Q^2)\, xg(x,Q^2) = \int^{Q^2} \frac{d^2 l}{\pi\, l^2}\, \alpha_s f(x,l^2)$$

Example from dipole model - BGBK



Another approach (KMR)

$$f_g(x,\mu^2) = \beta(t)\cdot \frac{\partial}{\partial \ln Q_t^2}[\sqrt{T(Q_t,\mu)}\cdot xg(x,Q_t^2)]$$

$$T(Q_t,\mu) = \exp\left(-\int_{Q_t^2}^{\mu^2} \frac{\alpha_S(k_t^2)}{2\pi}\frac{dk_t^2}{k_t^2}\int_0^{k_t/(\mu+k_t)} zP_{gg}(z)dz\right)$$

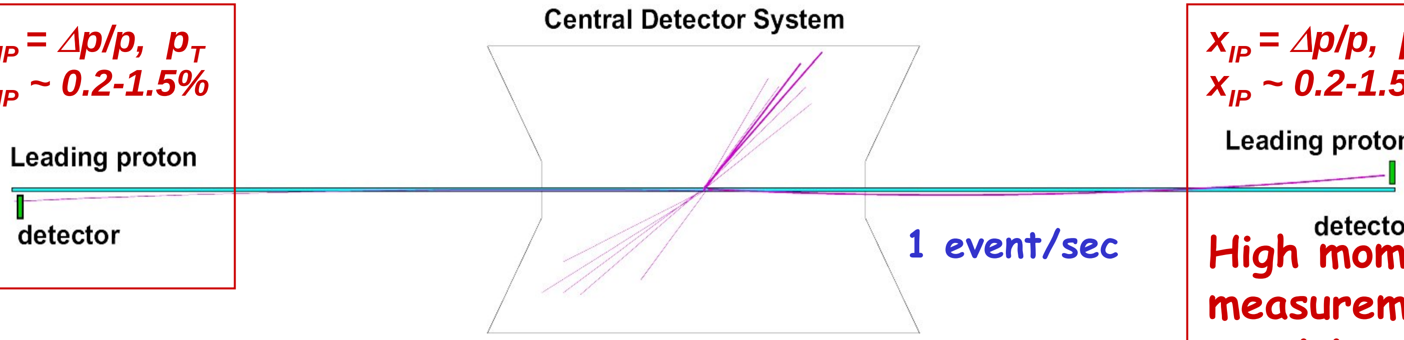
$$f_g(x_1,t,Q_t,\mu) = \beta(t)\, f_g(x_1,t=0,Q_t,\mu) \qquad b(t) = \exp(Bt/2)$$

Active field of study at HERA:

UGD in heavy quark production, new result expected from high luminosity running in 2005, 2006, 2007

Exclusive Double Diffractive Reactions at LHC

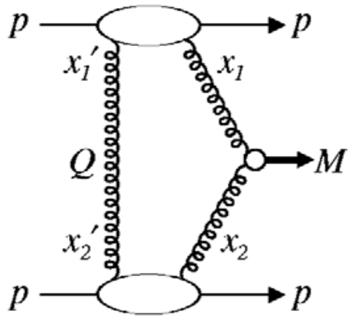
$x_{IP} = \Delta p/p,\ p_T$
$x_{IP} \sim 0.2\text{-}1.5\%$



$x_{IP} = \Delta p/p,\ p_T$
$x_{IP} \sim 0.2\text{-}1.5\%$

1 event/sec

High momentum measurement precision



$$\sigma^{Diff} = \hat{\sigma} \cdot L$$

$$M^2 \frac{\partial L}{\partial \nu \partial M^2} = S^2 O$$

$$O^{exclusive} = \left(\frac{\pi}{(N_c^2 - 1)b} \int \frac{dQ_t^2}{Q_t^4} f_g(x_1, Q_t) f_g(x_2, Q_t) \right)^2$$

low x QCD reactions:

pp => pp + $g_{Jet}\, g_{Jet}$ $\sigma \sim$ 1 nb for M(jj) ~ 50 GeV
$\sigma \sim 0.5$ pb for M(jj) ~ 200 GeV
$\eta_{JET}| < 1$

pp => pp + Higgs $\sigma \sim$ O(3) fb SM
$\sim$ O(100) fb *MSSM*

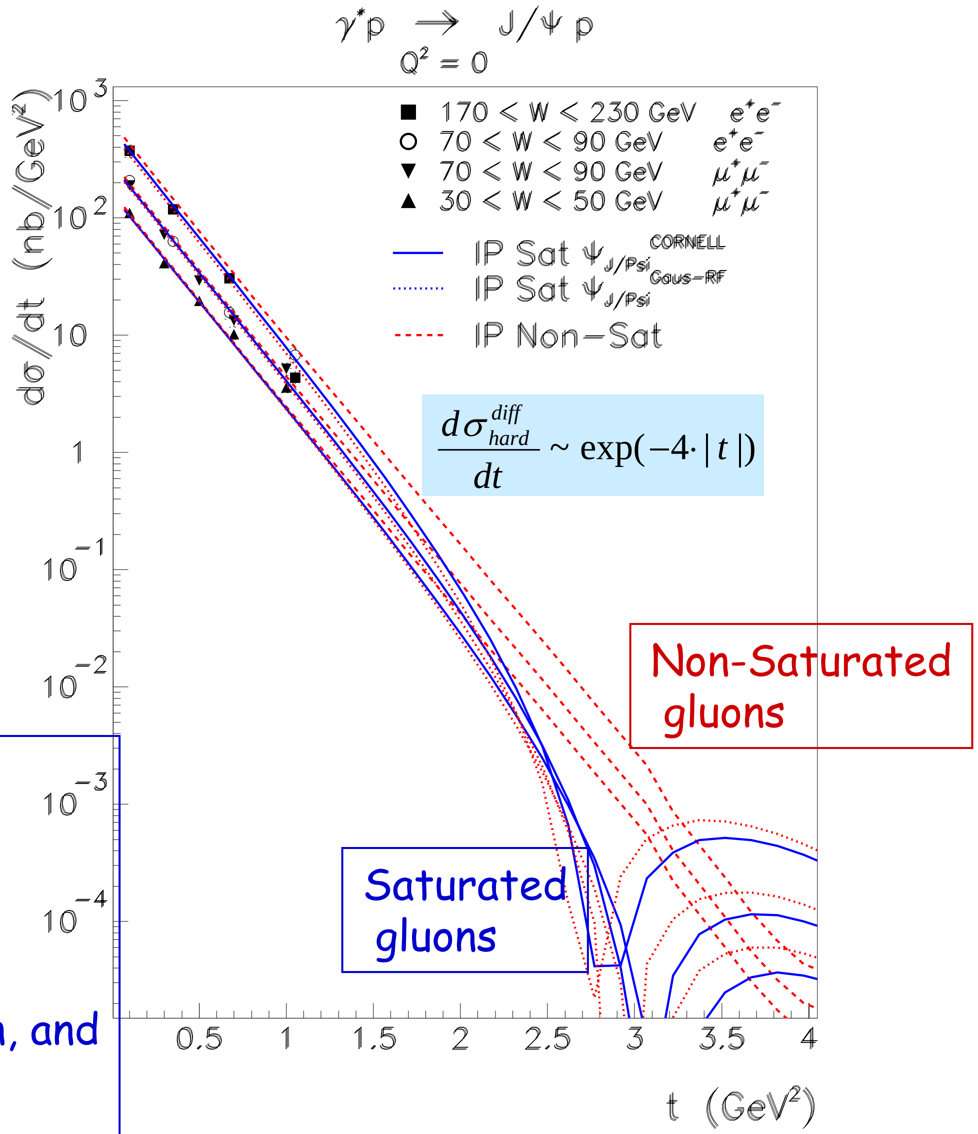
t – distributions at LHC

with the cross-sections of the O(1) nb and L ~ 1 nb^{-1} s^{-1} =>
O(10^7) events/year are expected.

For hard diffraction this allows to follow the t – distribution to
t_{max} ~ 4 GeV^2

For soft diffraction t_{max} ~ 2 GeV^2

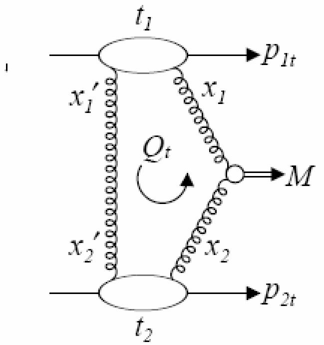
t – distributions at HERA

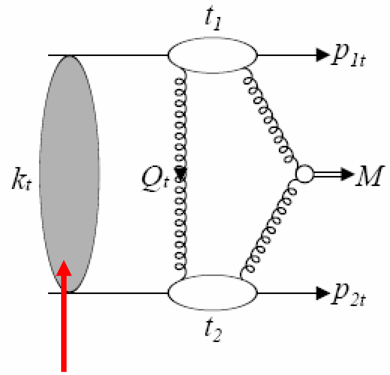


t-distribution of hard processes should be sensitive to the evolution and/or saturation effects

see:
Al Mueller dipole evolution, BK equation, and the impact parameter saturation model for HERA data

Survival Probability S^2





Soft Elastic Opacity

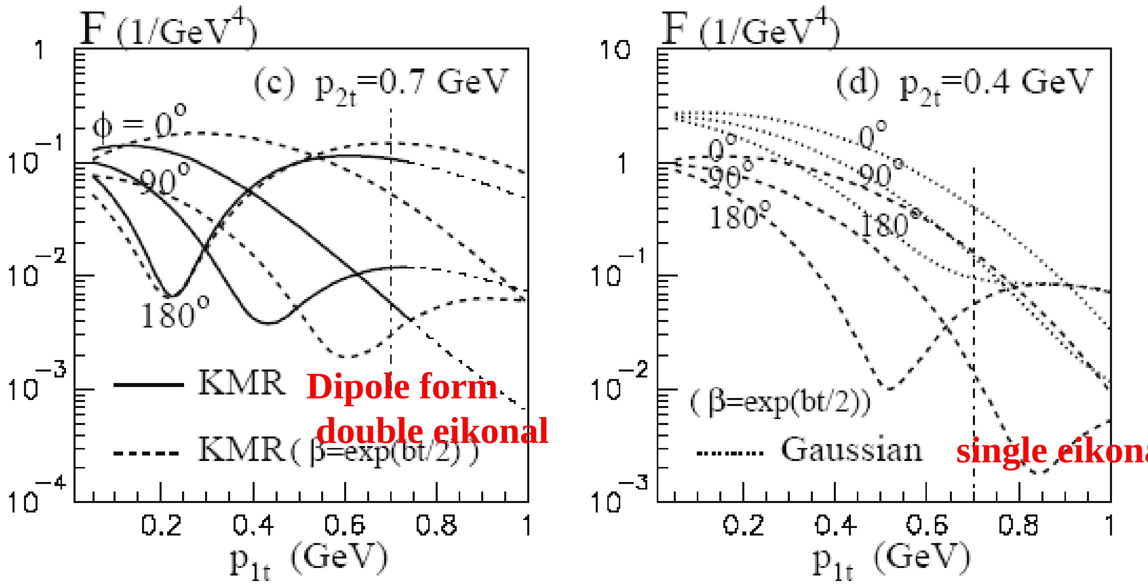
$$S^2 = \frac{\int M^2(s,b)\boxed{e^{-\Omega(s,b)}}d^2b}{\int M^2(s,b)d^2b}$$

$$F(\vec{p}_{1t},\vec{p}_{2t}) = \frac{\beta^2(t_1)\beta^2(t_2)}{< S^2 > \pi^2 / b_0^2} S^2(\vec{p}_{1t},\vec{p}_{2t})$$

***t* – distributions at LHC**

Effects of soft proton absorption modulate the hard *t*- distributions

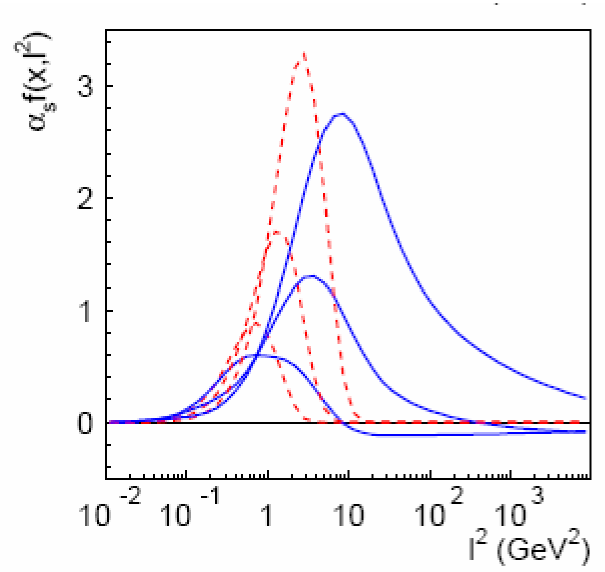
t-measurement will allow to disentangle the effects of soft absorption from hard behavior



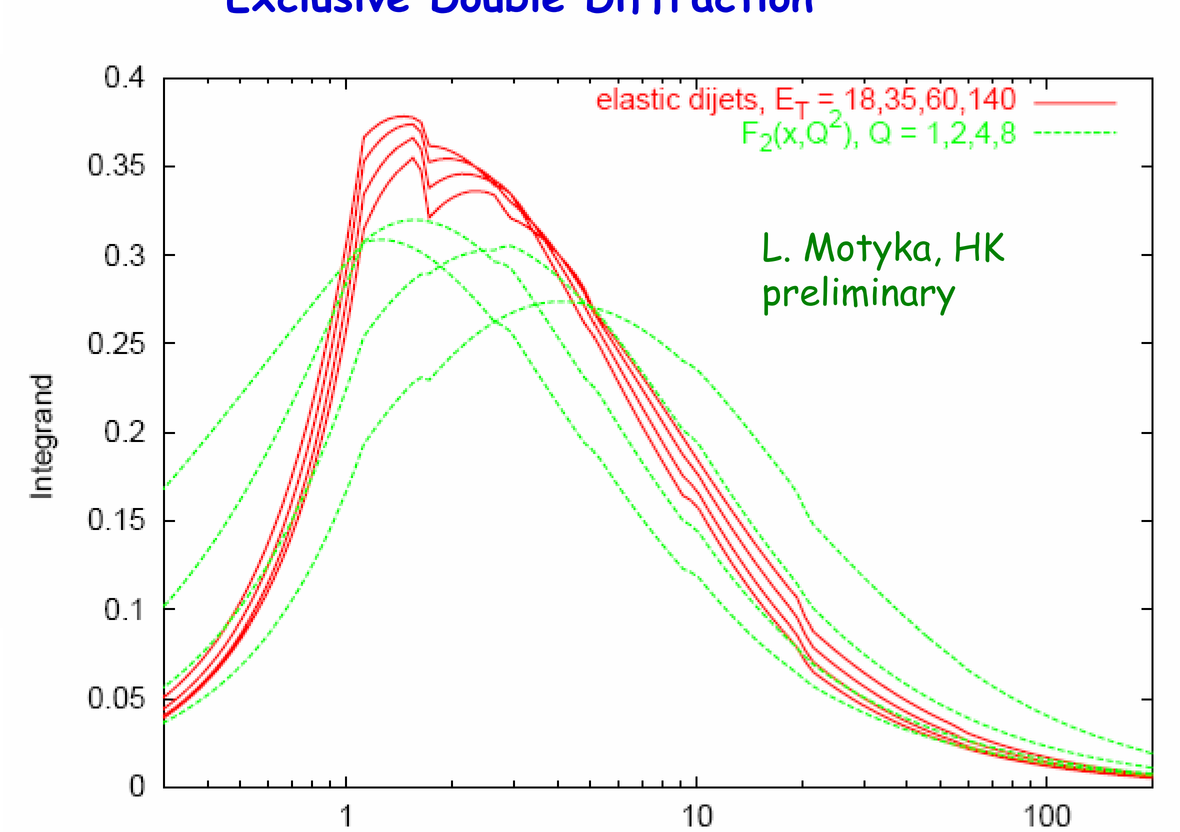
Khoze
Martin
Ryskin

F_2 ⟷ Gluon Luminosity

Dipole Model



Exclusive Double Diffraction



Q_T^2 (GeV^2)

$$\sigma^{Diff} = \hat{\sigma} \cdot L$$

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$$O^{exclusive} = \left(\frac{\pi}{(N_c^2 - 1)b} \int \frac{dQ_t^2}{Q_t^4} f_g(x_1, x_1', t, Q_t, \mu) f_g(x_2, x_2', t, Q_t, \mu) \right)^2$$

f_g – unintegrated gluon densities

Conclusions

We are developing a very good understanding of inclusive and diffractive g*p interactions:

F_2 , $F_2^{D(3)}$, F_2^c , Vector Mesons (J/Psi)….

Observation of diffraction indicates multi-gluon interaction effects at HERA

HERA measurements suggests presence of Saturation phenomena
Saturation scale determined at HERA agrees with RHIC

HERA determined properties of the Gluon Cloud

Diffractive LHC ~ pure Gluon Collider
=> investigations of properties of the gluon cloud in the new region

Gluon Cloud is a fundamental QCD object - SOLVE QCD!!!!

Precise measurement of the Higgs Mass

J. Ellis, HERA-LHC Workshop

Higher symmetries (e.g. Supersymmetry) lead to existence of *several* scalar, neutral, *Higgs states*, H, h, A . . . .   Higgs Hunter Guide, Gunnion, Haber, Kane, Dawson 1990

In MSSM *Higgs x-section* are likely to be much *enhanced* as compared to Standard Model   (tanβ large because M_{Higgs} > 115 GeV)

CP violation is highly probable in MSSM $\longrightarrow$ all *three* neutral Higgs bosons have *similar masses* ~120 GeV $\longrightarrow$

can ONLY be RESOLVED in DIFFRACTION

Ellis, Lee, Pilaftisis Phys Rev D, 70, 075010, (2004) , hep-ph/0502251

Correlation between *transverse momenta* of the tagged *protons* give a handle on the CP-violation in the Higgs sector

Khoze, Martin, Ryskin, hep-ph 040178