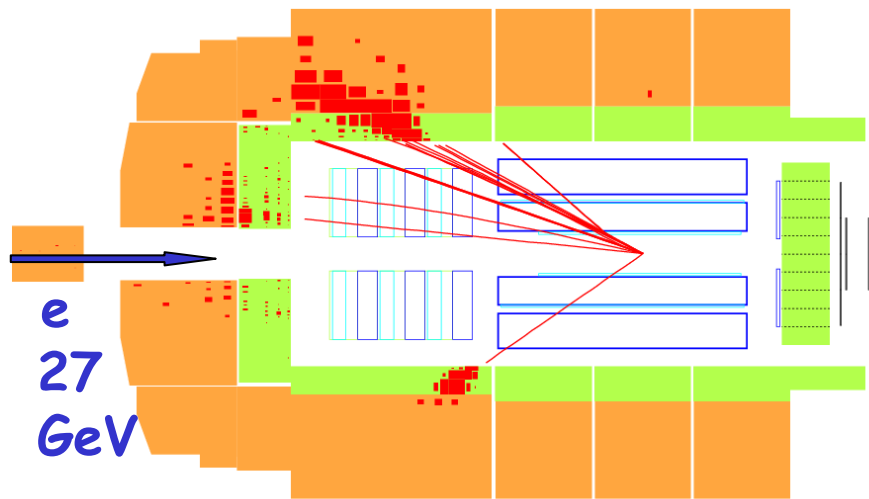
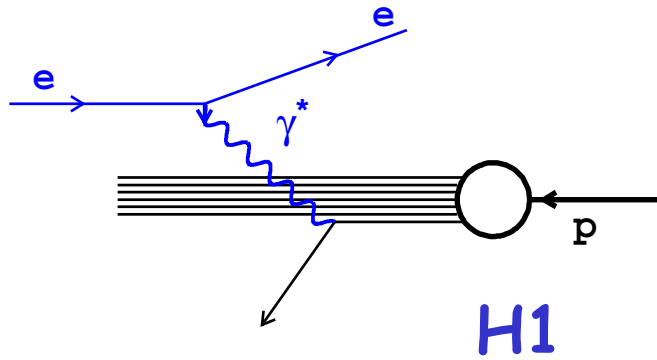


Introduction to Small- x and Diffraction at HERA and LHC

Henri Kowalski
DESY

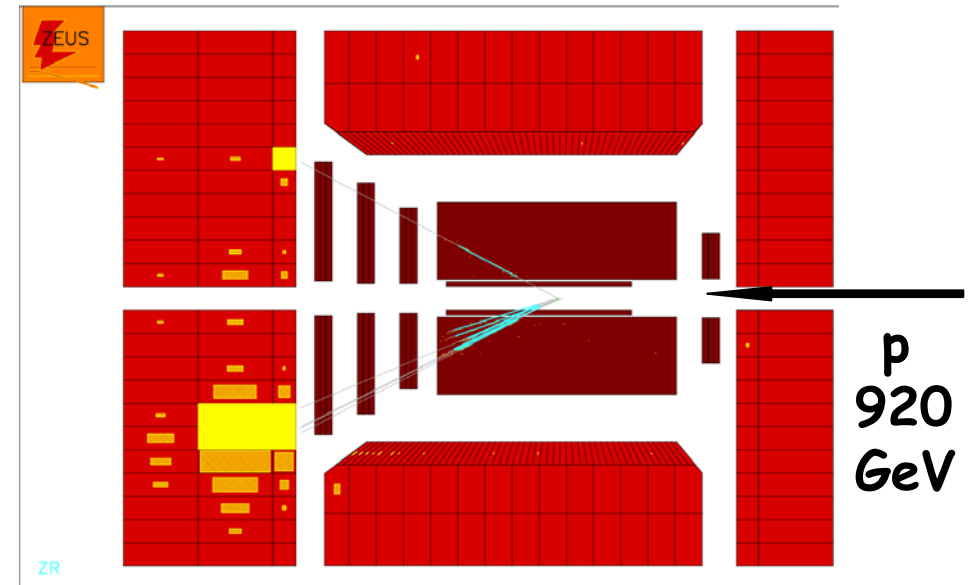
Photon 2005
Warszawa
1st of September

HERA - ep Collider



Liquid Argon Calorimeter

ZEUS



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 $x \sim Q^2/W^2$

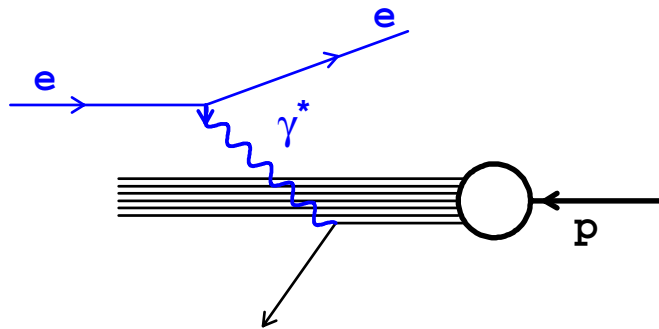
$$\frac{d^2\sigma^{eP}}{dx dQ^2} = \frac{2\pi\alpha_{em}^2}{xQ^4} \cdot [Y_+ F_2(x, Q^2) - Y_- xF_3(x, Q^2) - y^2 F_L(x, Q^2)]$$

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

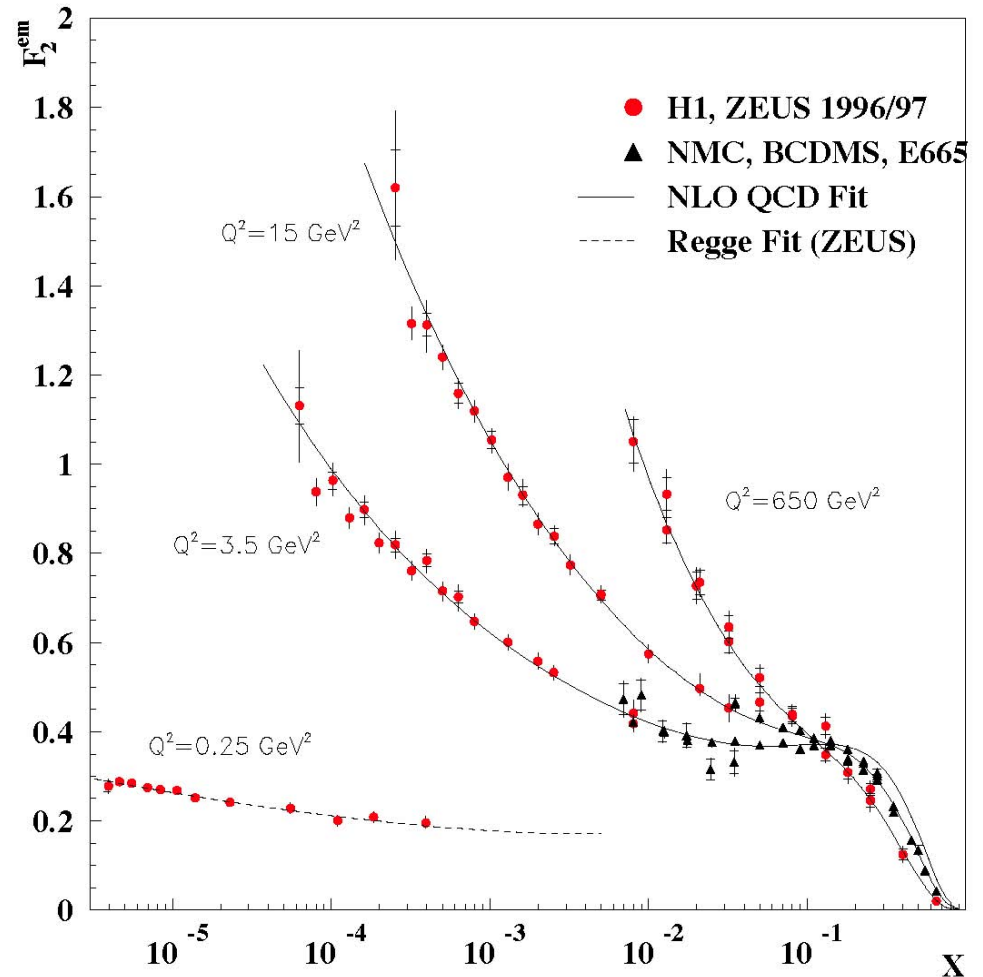
y - inelasticity
 $Q^2 = sxy$

Infinite momentum frame

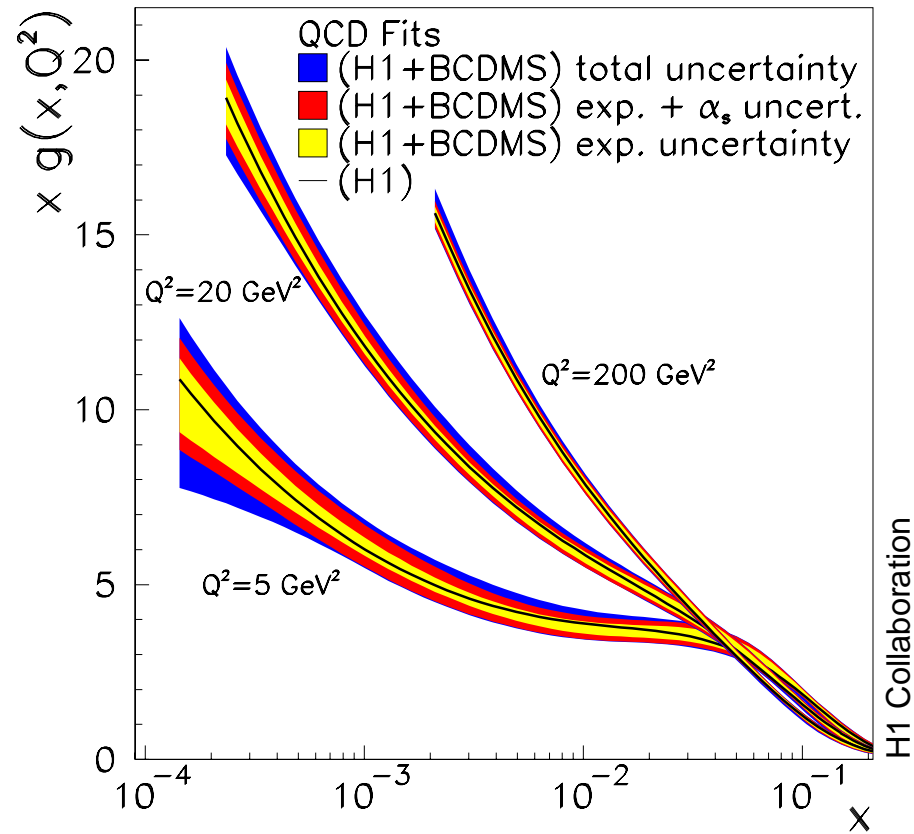
Proton looks like a cloud of non-interacting quarks and gluons



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



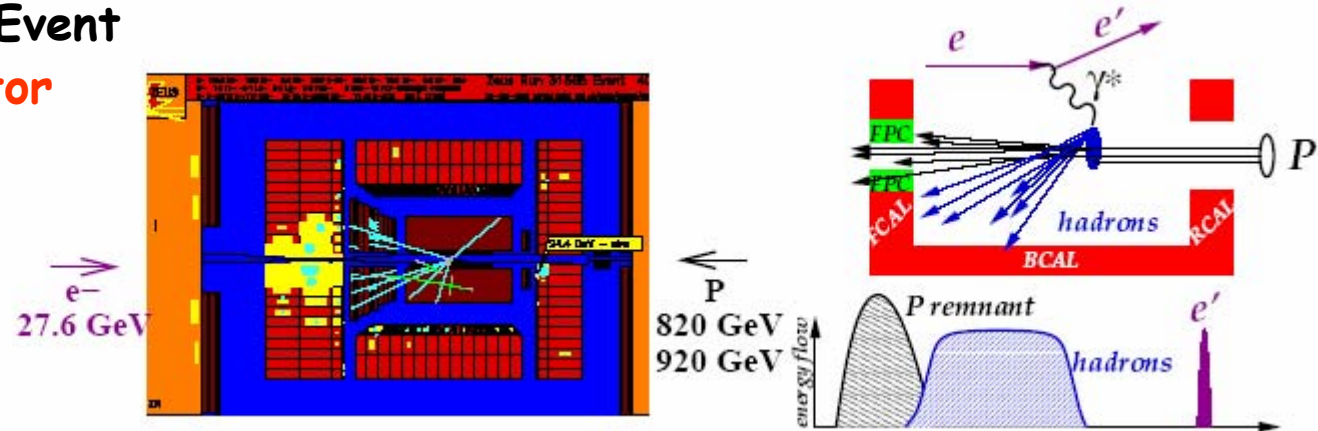
Gluon density



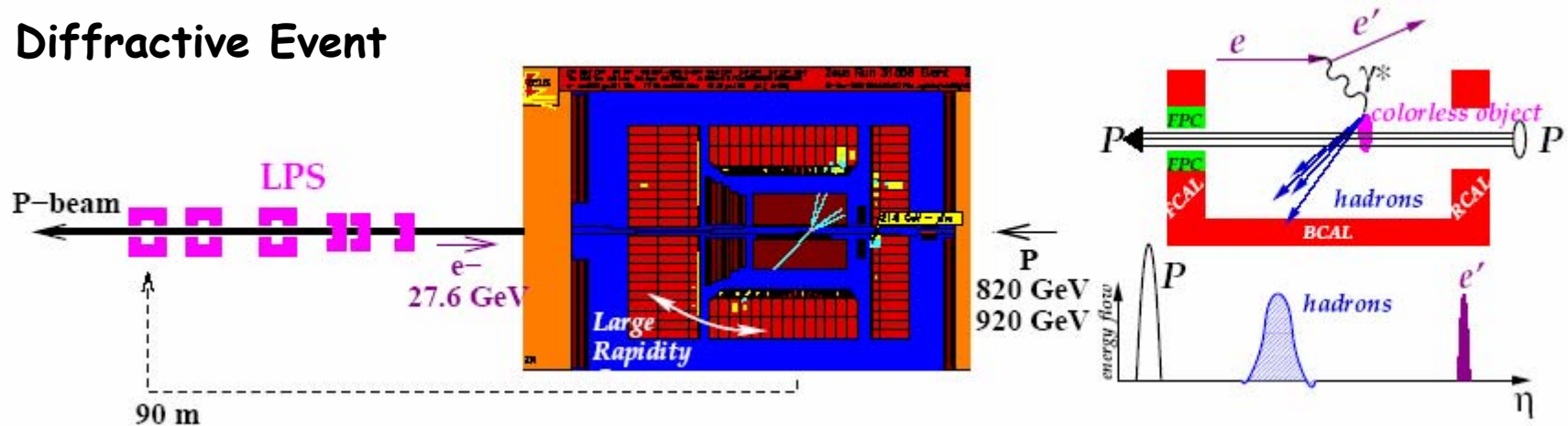
Gluon density dominates F_2 for $x < 0.01$

Diffraction Scattering

Non-Diffractive Event ZEUS detector



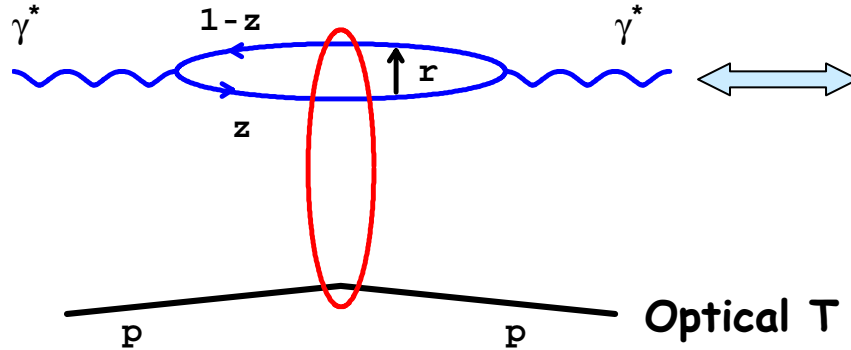
Diffraction Event



- 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



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

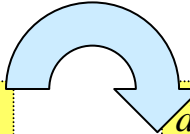
$$|\Psi_L^f|^2 = \frac{3\alpha_{em}}{2\pi^2} e_q^2 \{ 4Q^2 z^2 (1-z)^2 K_0^2(\varepsilon r) \}$$

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

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

Mueller, Nikolaev, Zakharov

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



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

GBW - first Dipole Saturation Mode (rudimentary evolution)

Golec-Biernat, Wuesthoff

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

BGBK - DSM with DGLAP

Bartels, Golec-Biernat, Kowalski

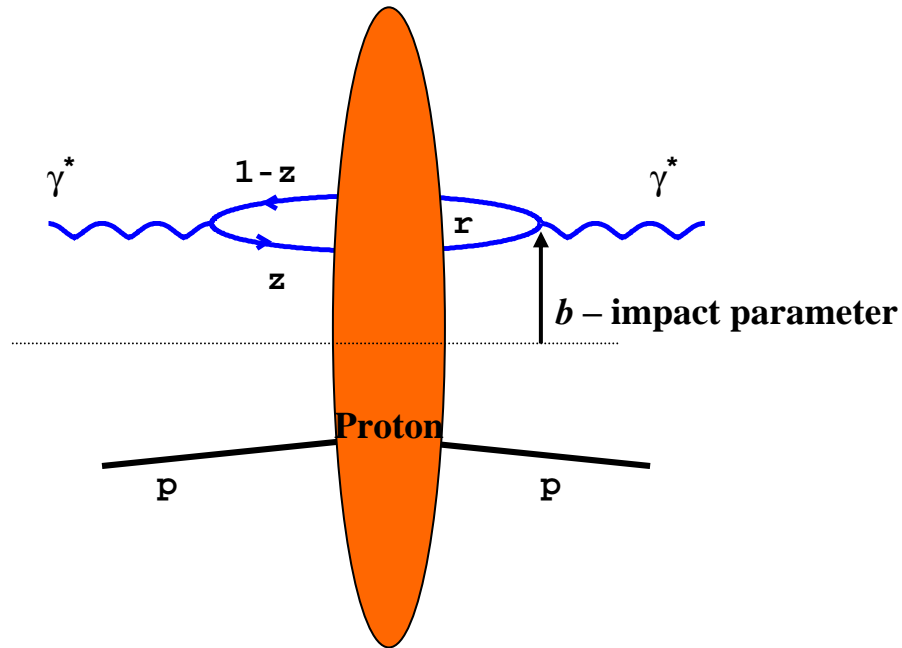
$$\sigma_{qq}(x, r) \approx \sigma_0 (1 - \exp(-\frac{\pi^2}{3\sigma_0} r^2 \alpha_s x g(x, \mu^2 = C/r^2 + \mu_0^2)))$$



Iancu, Itakura, Mounier
BFKL-CGC motivated ansatz

Impact Parameter Dipole Saturation Model

Kowalski
Teaney

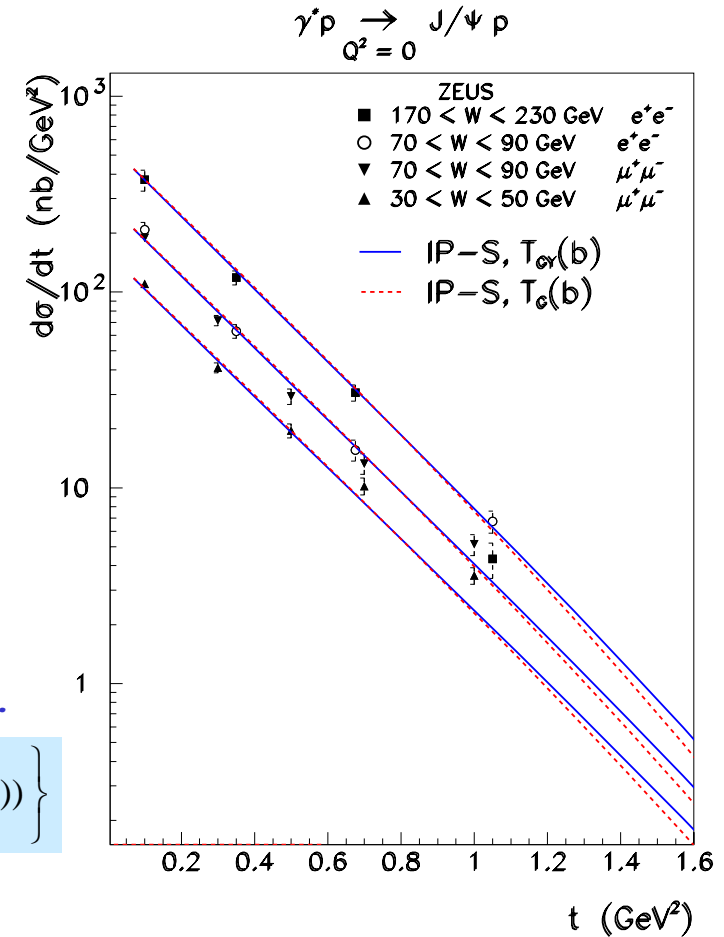


Glauber-Mueller, Levin, Capella, Kaidalov...

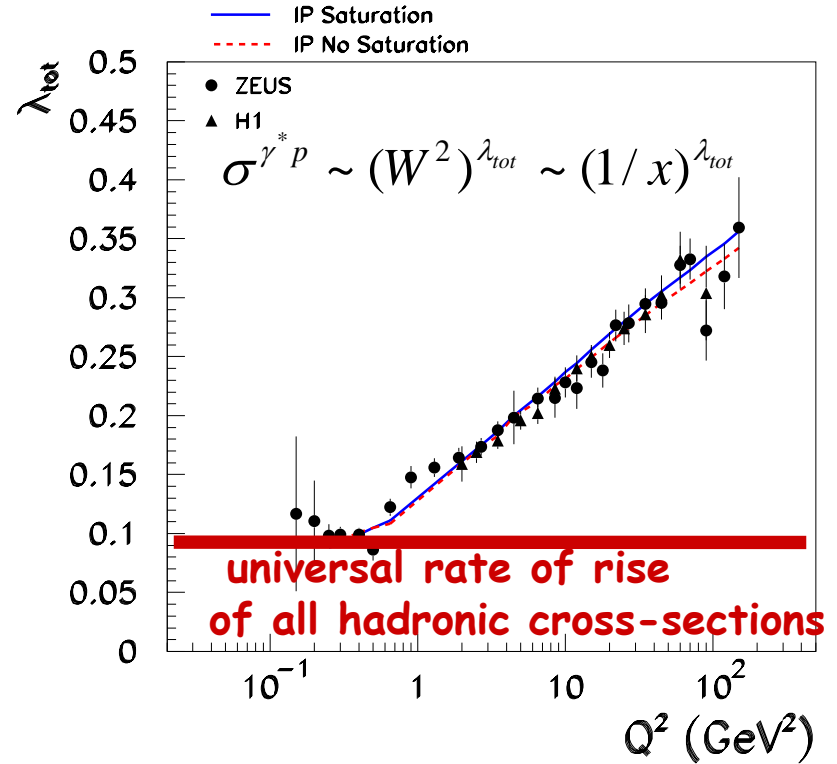
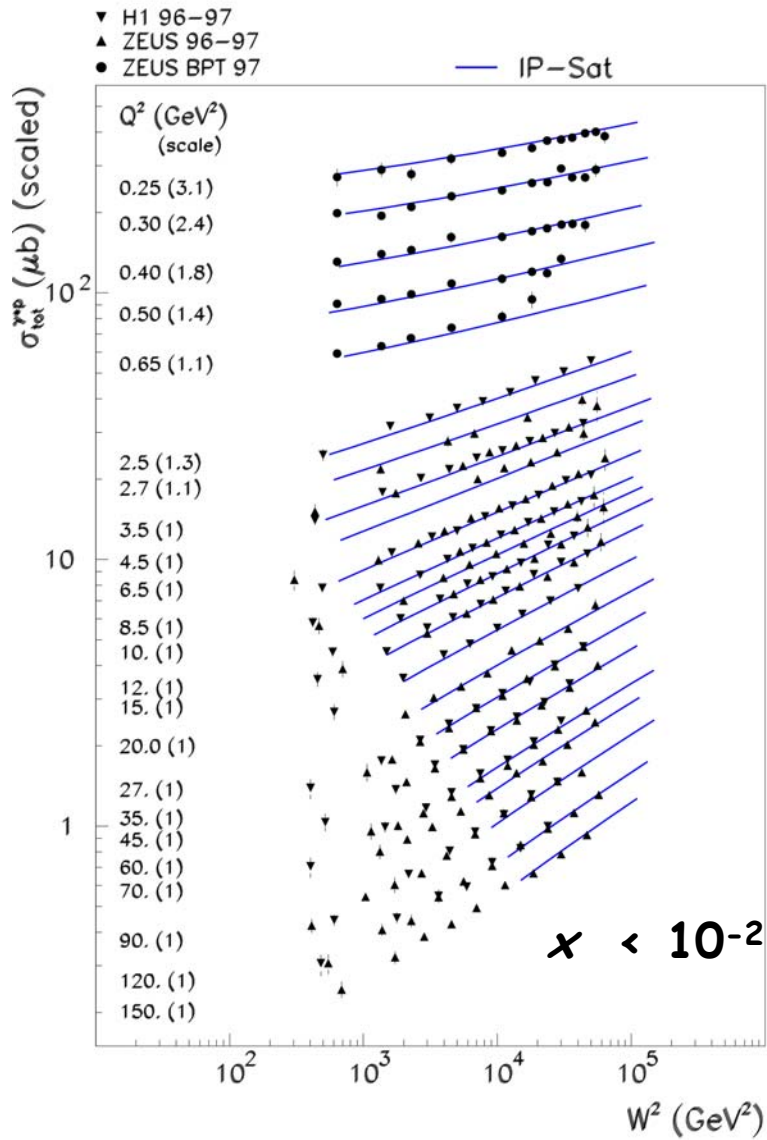
$$\frac{d\sigma_{qq}(x, r)}{d^2b} = 2 \cdot \left\{ 1 - \exp\left(-\frac{\pi^2}{2 \cdot 3} r^2 \alpha_s(\mu^2) x g(x, \mu^2) T(b) \right) \right\}$$

$T(b)$ - proton shape

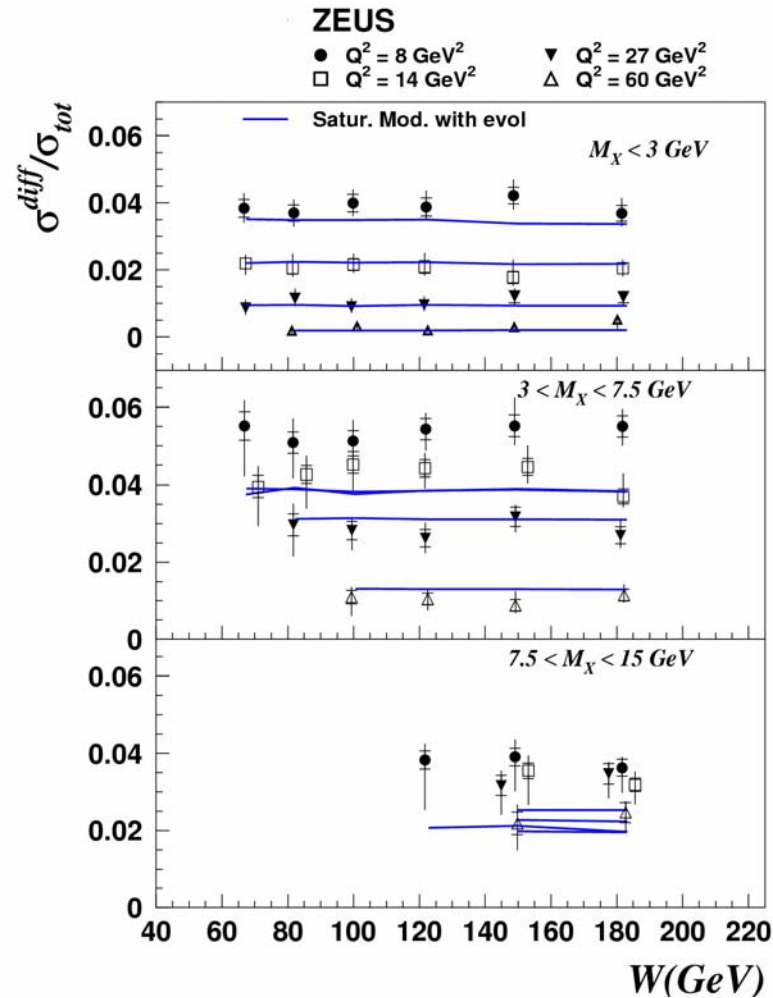
$$\frac{d\sigma^{diff}}{dt} \sim \exp(B \cdot t) \Rightarrow T(b) \sim \exp(-\bar{b}^2 / 2B)$$



Total γ^*p cross-section



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



2005 measurements:

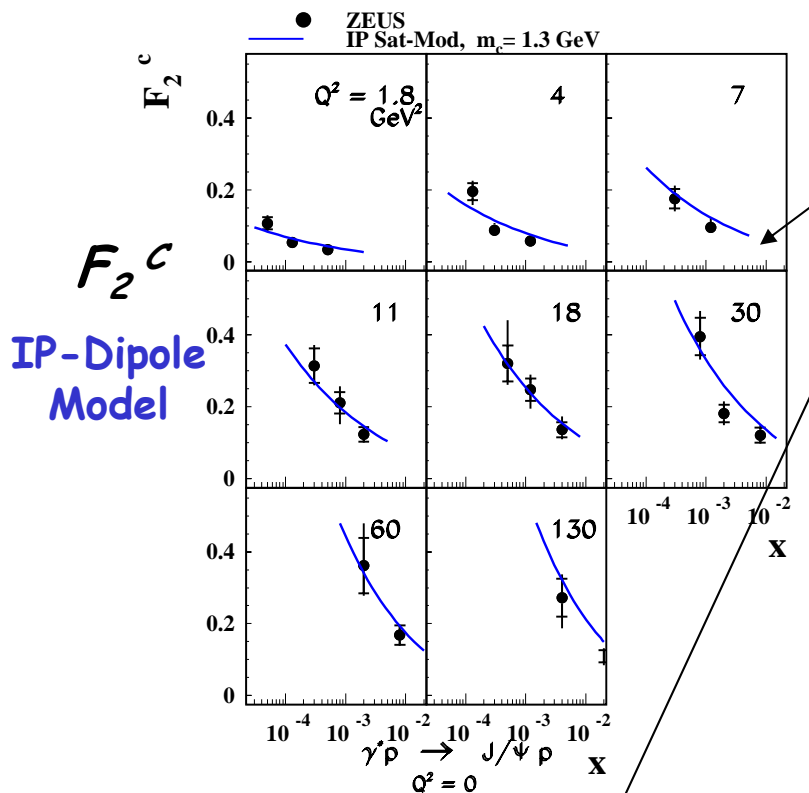
$$\sigma^{diff} / \sigma^{tot}$$

integrated over all masses

16% at $Q^2 = 4 \text{ GeV}^2$

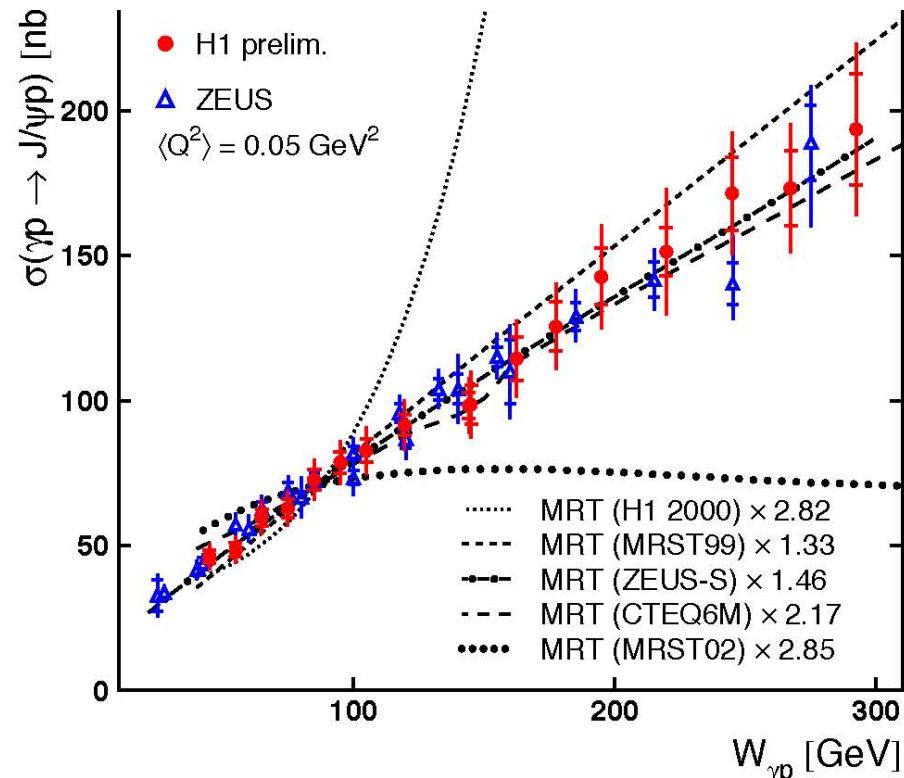
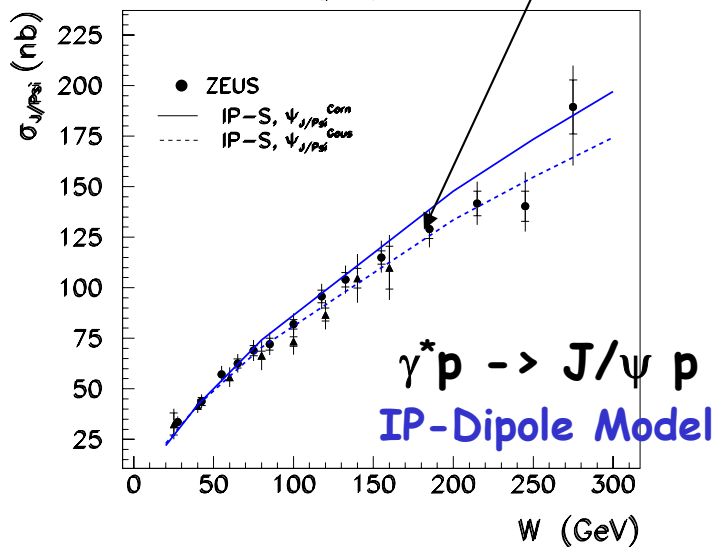
10% at $Q^2 = 27 \text{ GeV}^2$

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

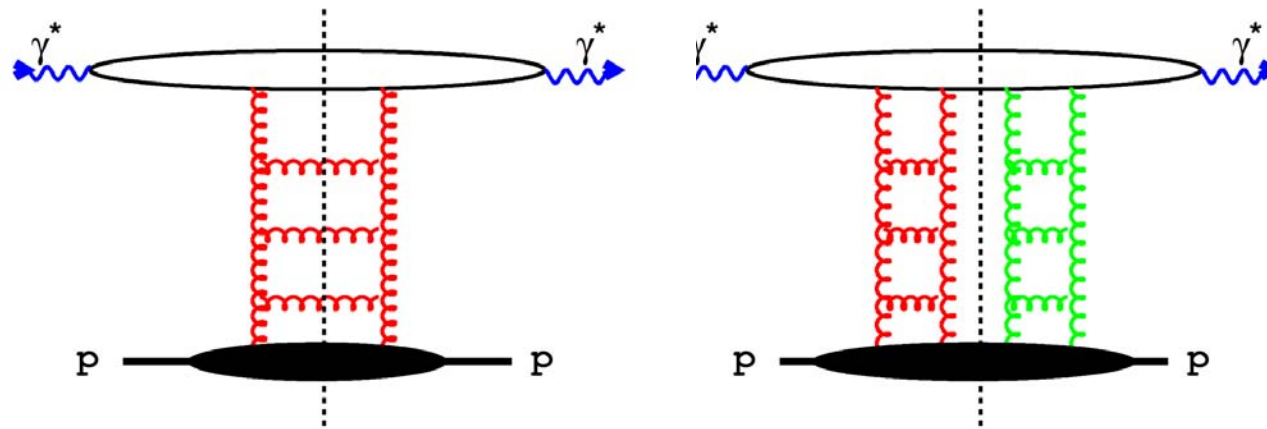


Dipole cross section determined
by fit to F_2 \rightarrow
Simultaneous description of many
reactions

Gluon density test?
Teubner
 $\gamma^* p \rightarrow J/\psi p$



Saturation and Absorptive corrections



$$F_2 \sim \text{Single inclusive pure DGLAP} - \text{Diffraction}$$

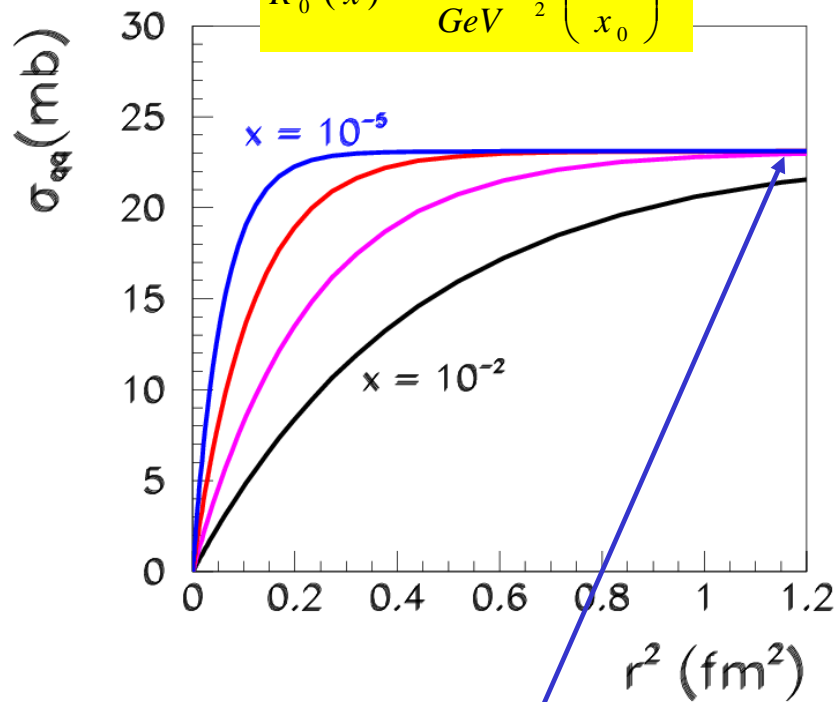
Example in Dipole Model

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

GBW Model

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

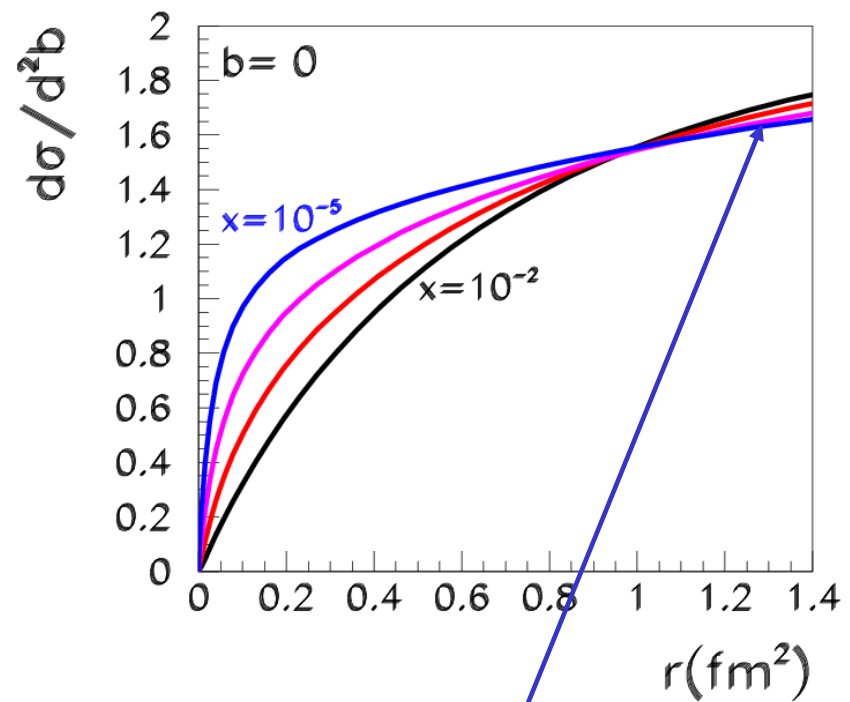
$$R_0^2(x) = \frac{1}{\text{GeV}^2} \left(\frac{x}{x_0} \right)^\lambda$$



strong saturation

IP Dipole Model

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



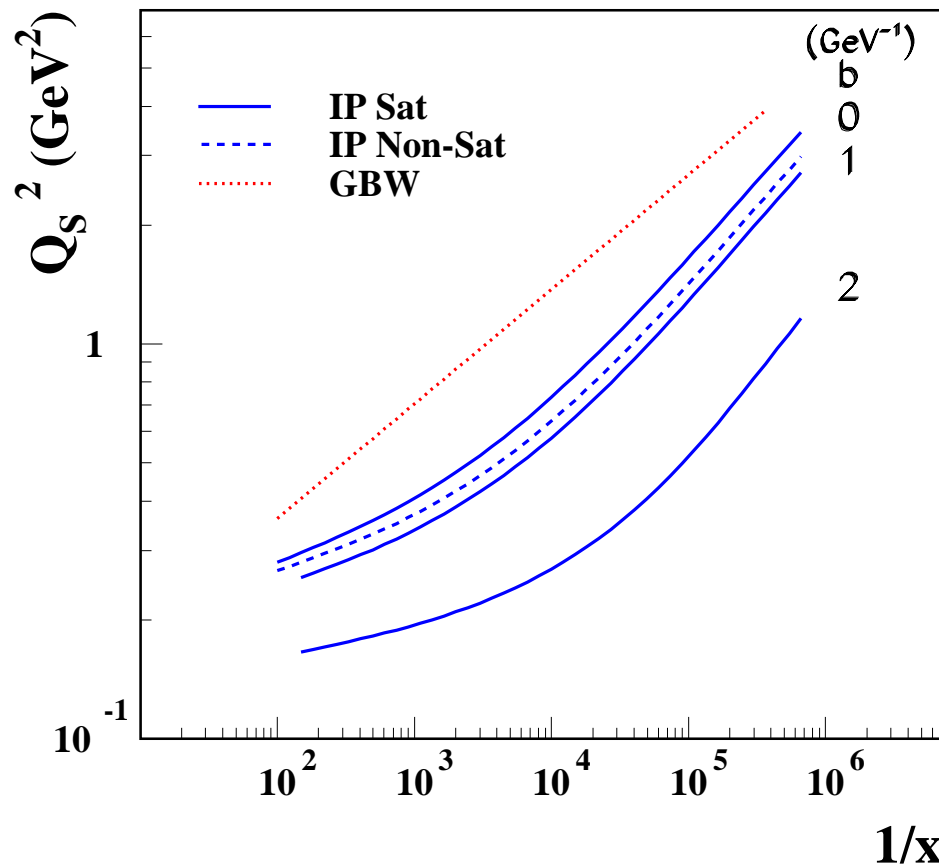
less saturation
(due to IP and charm)

Saturation scale (a measure of gluon density)

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

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

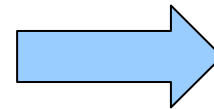
RHIC



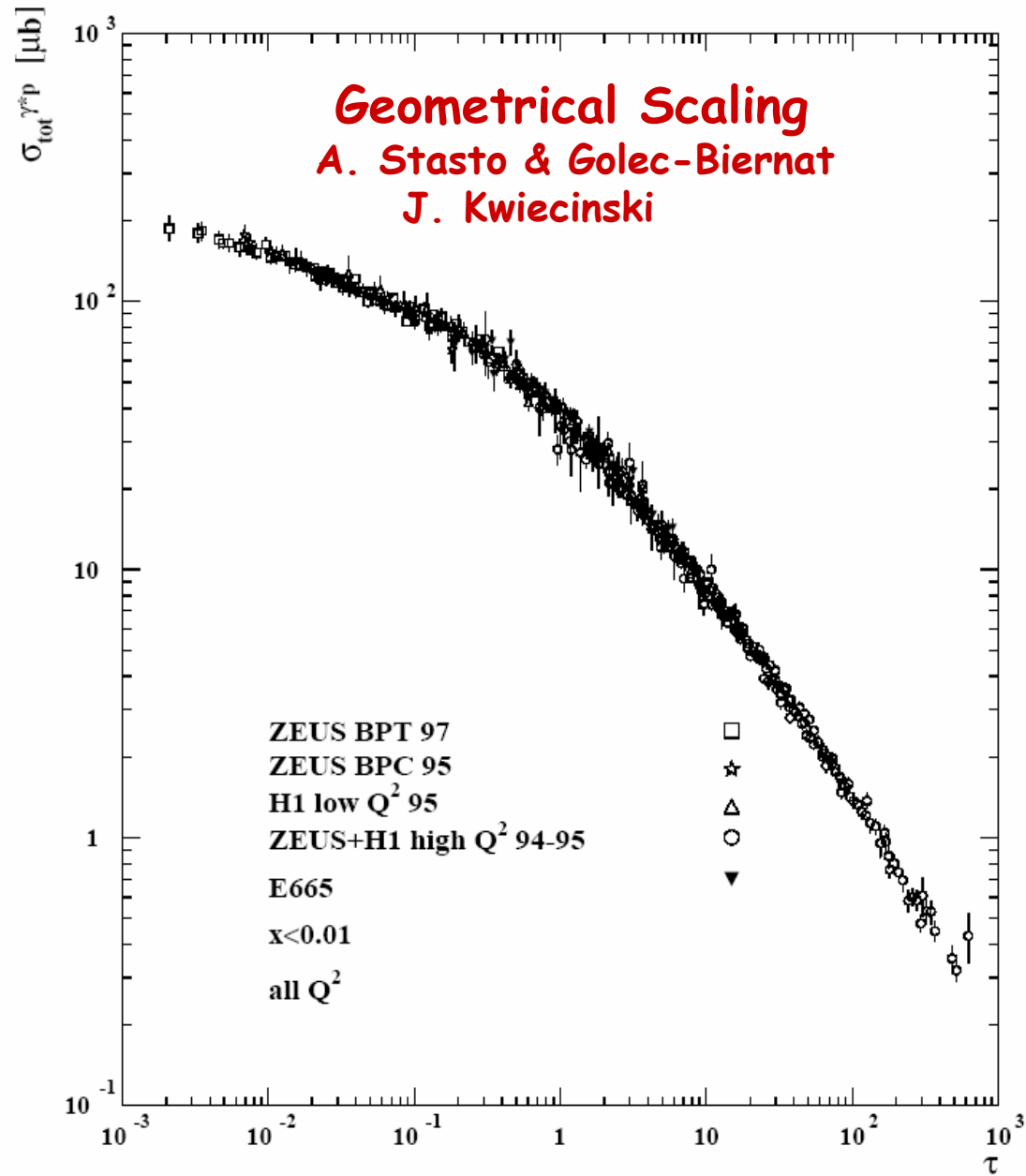
$$Q_S^2 = \frac{4\pi^2 \alpha_s N_C}{N_C^2 - 1} \frac{1}{\pi R^2} \frac{dN}{dy}$$

$$\frac{dN}{dy} \approx 1000 \quad R \approx 7 \text{ fm}$$

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



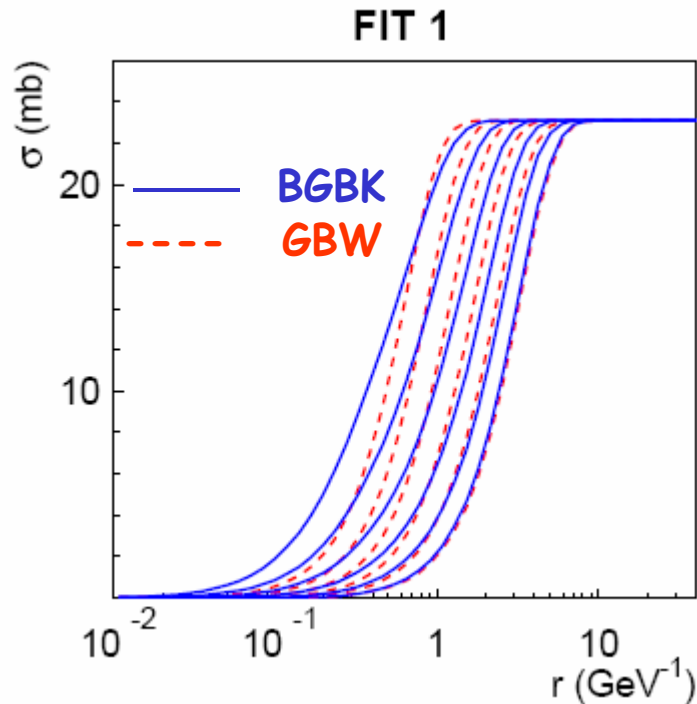
$$Q_S^{\text{RHIC}} \sim Q_S^{\text{HERA}}$$



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

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

Dipole X-section



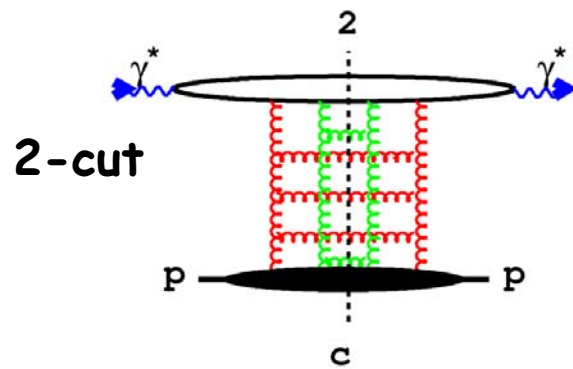
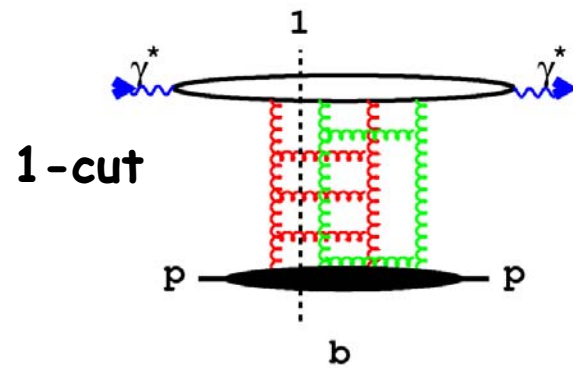
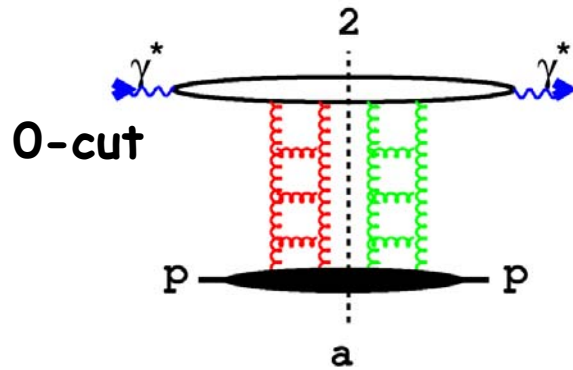
Geometrical Scaling can be derived from traveling wave solutions of non-linear QCD evolution equations

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

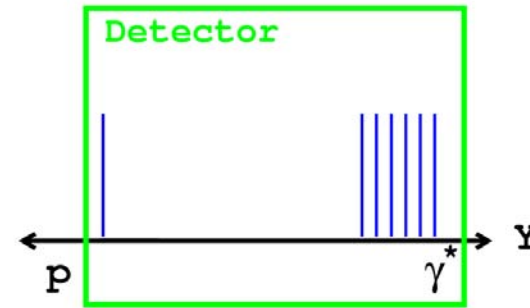
Munier, Peschansk
L. McLerran + ...
Al Mueller + ..

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

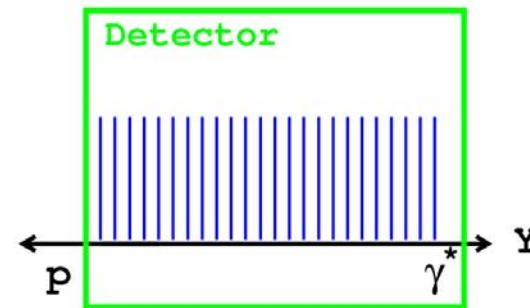
2-Pomeron exchange in QCD



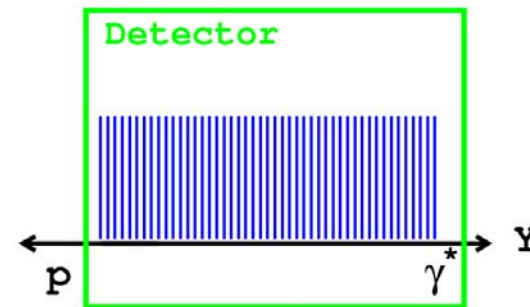
Final States (naïve picture)



Diffraction



$\langle n \rangle$

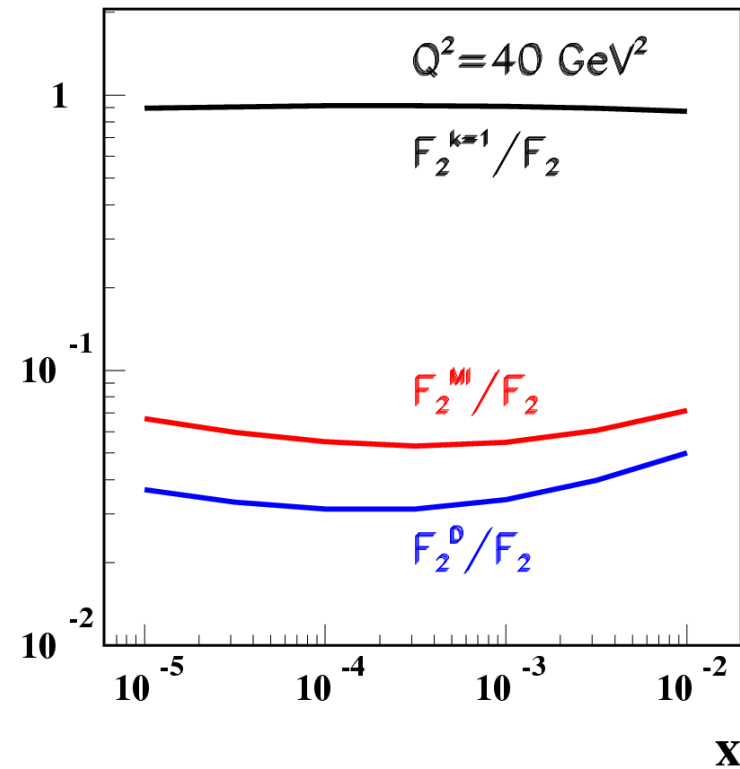
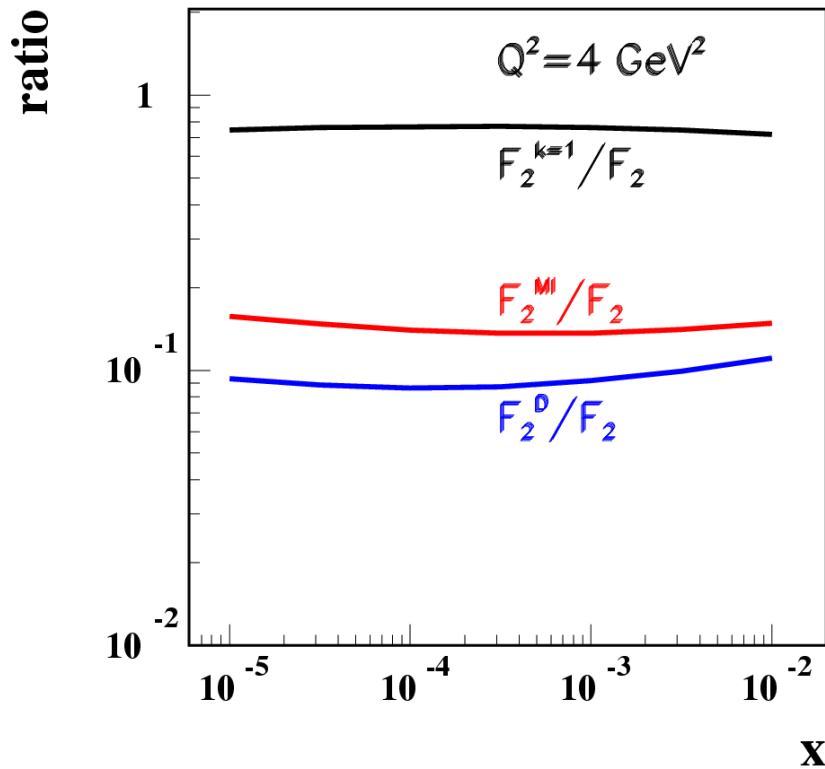


$\langle 2n \rangle$

AGK rules in the Dipole Model \rightarrow

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

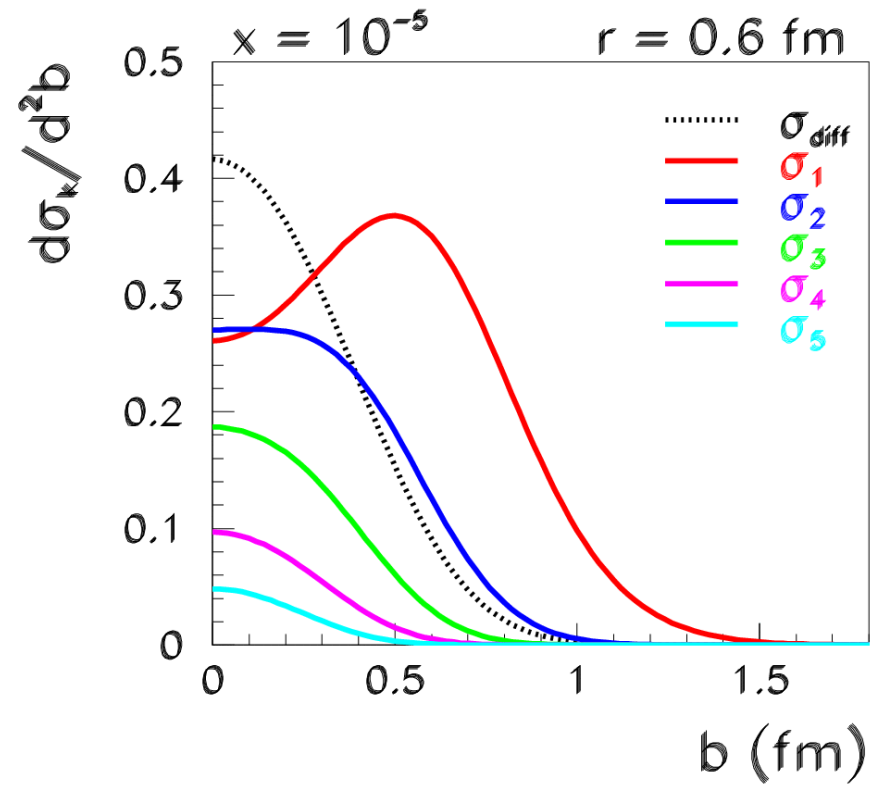
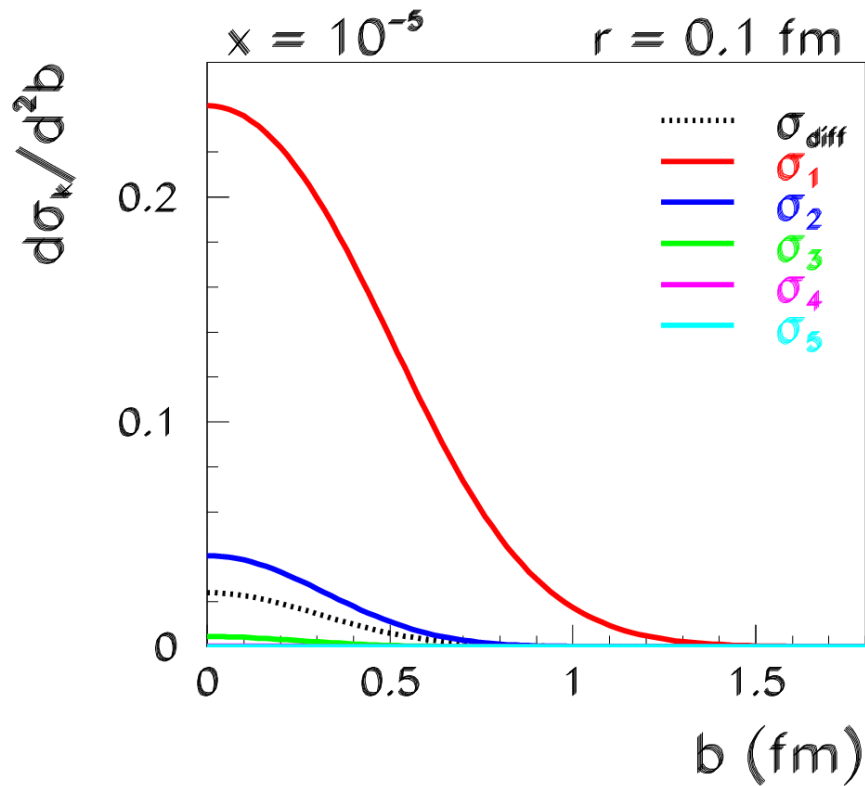
$$\Omega = \frac{\pi^2}{N_c} r^2 \alpha_s(\mu^2) xg(x, \mu^2) T(b)$$



Note: AGK rules underestimate the amount of diffraction in DIS

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

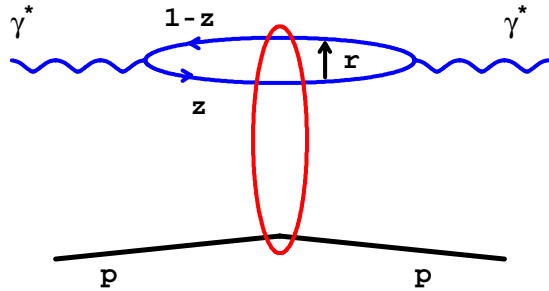
$$\frac{d\sigma_k}{d^2b} = \frac{\Omega^k}{k!} \exp(-\Omega)$$



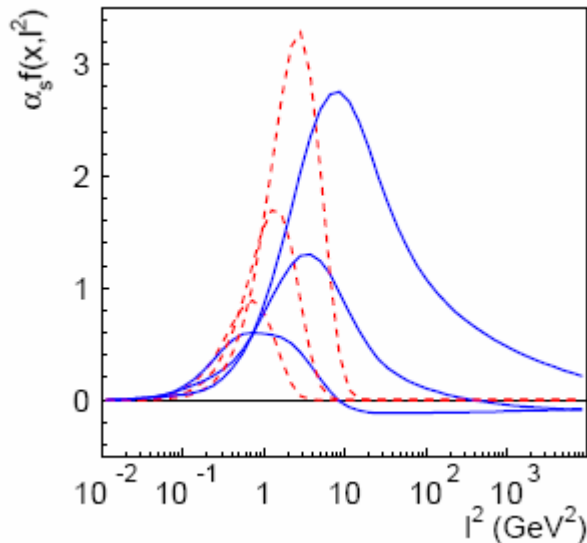
$$\Omega = \frac{\pi^2}{N_C} r^2 \alpha_s(\mu^2) x g(x, \mu^2) T(b)$$

HERA Result

Unintegrated Gluon Density



Example from dipole model
- BGBK



Dipole Model

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

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

Another approach (KMR)

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

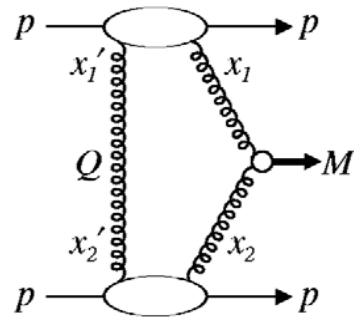
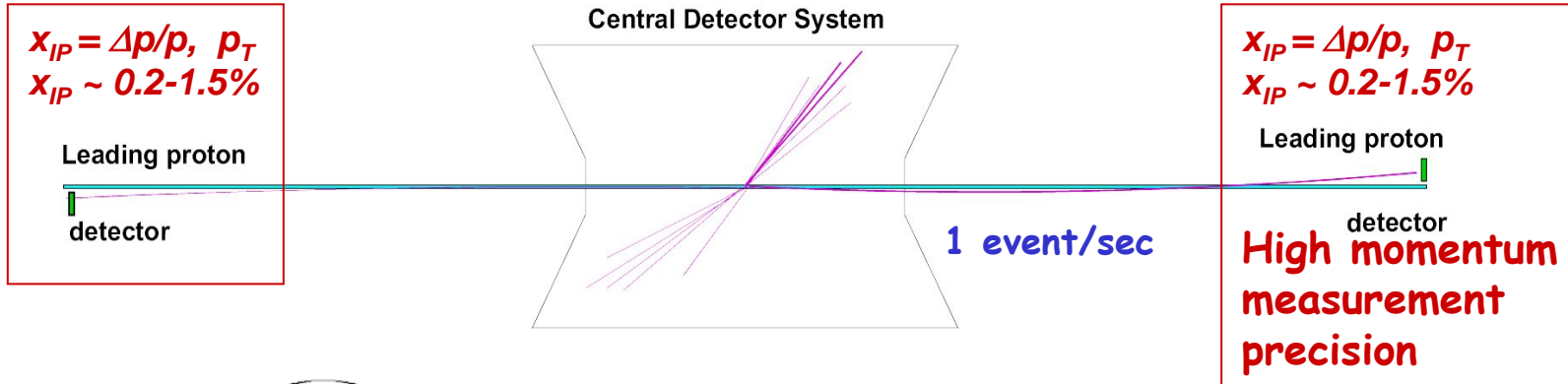
$$T(Q_t, \mu) = \exp \left(- \int_{Q_t^2}^{\mu^2} \frac{\alpha_s(k_t^2)}{2\pi} \frac{dk_t^2}{k_t^2} \int_0^{k_t/(\mu+k_t)} z P_{gg}(z) dz \right)$$

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

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



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

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

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

low x QCD reactions:

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

$pp \Rightarrow pp + \text{Higgs}$ $\sigma \sim O(3) \text{ fb SM}$
 $\sim O(100) \text{ fb MSSM}$

t – distributions at LHC

with the cross-sections of the O(1) nb
and $L \sim 1 \text{ nb}^{-1} \text{ s}^{-1} \Rightarrow$
O(10^7) events/year are expected.

For hard diffraction this allows
to follow the t – distribution to

$$t_{max} \sim 4 \text{ GeV}^2$$

For soft diffraction $t_{max} \sim 2 \text{ GeV}^2$

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

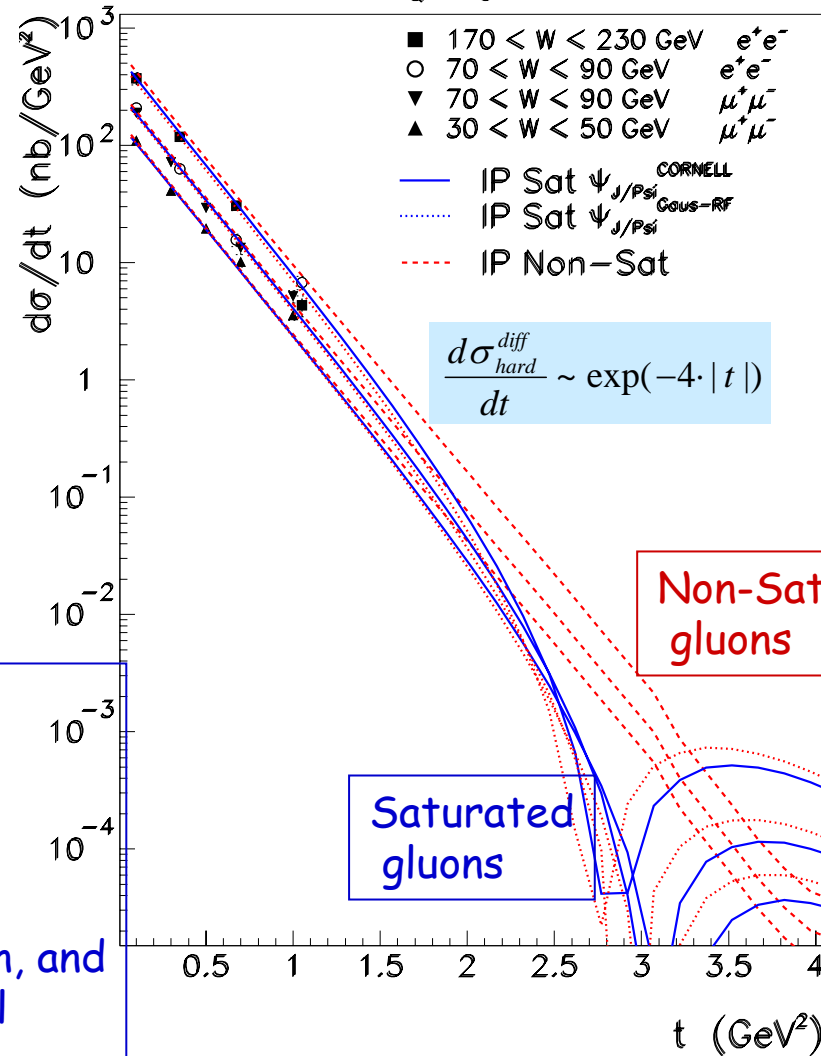
see:

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

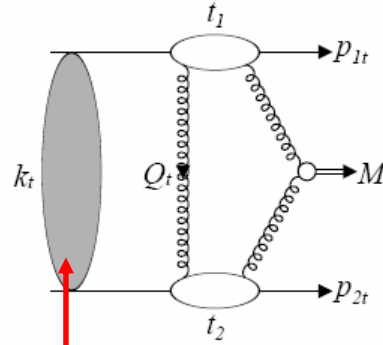
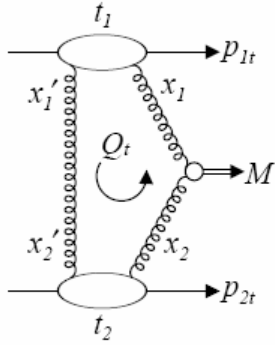
t – distributions at HERA

$$\gamma^* p \rightarrow J/\psi p$$

$$Q^2 = 0$$



Survival Probability S^2



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

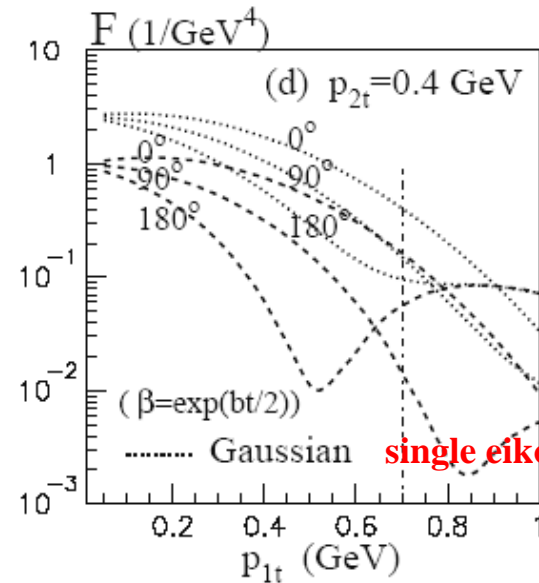
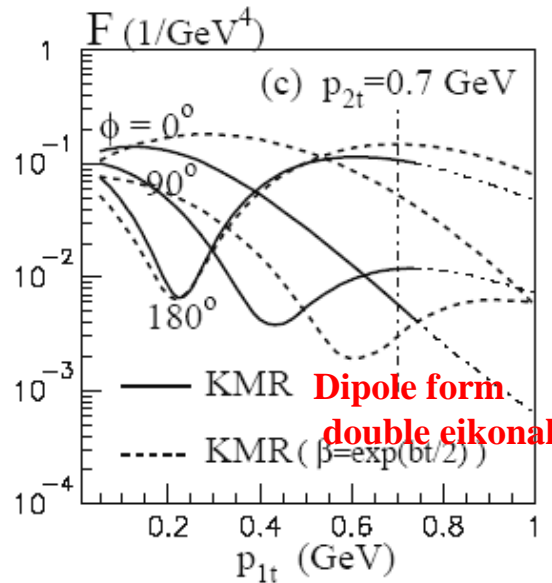
Soft Elastic Opacity

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

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

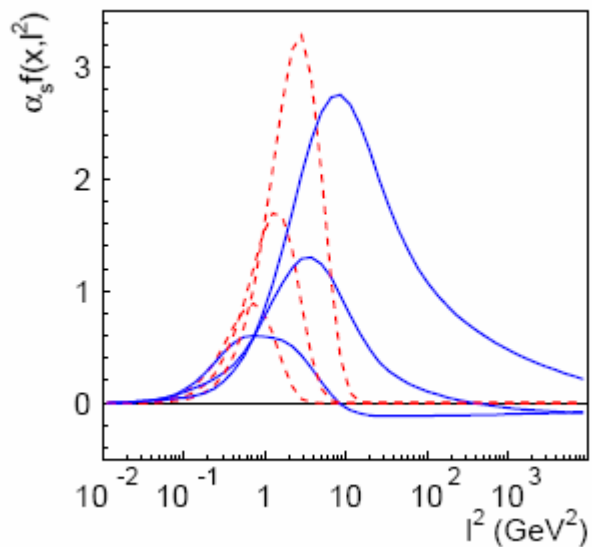


Khoze
Martin
Ryskin

F_2 

Gluon Luminosity

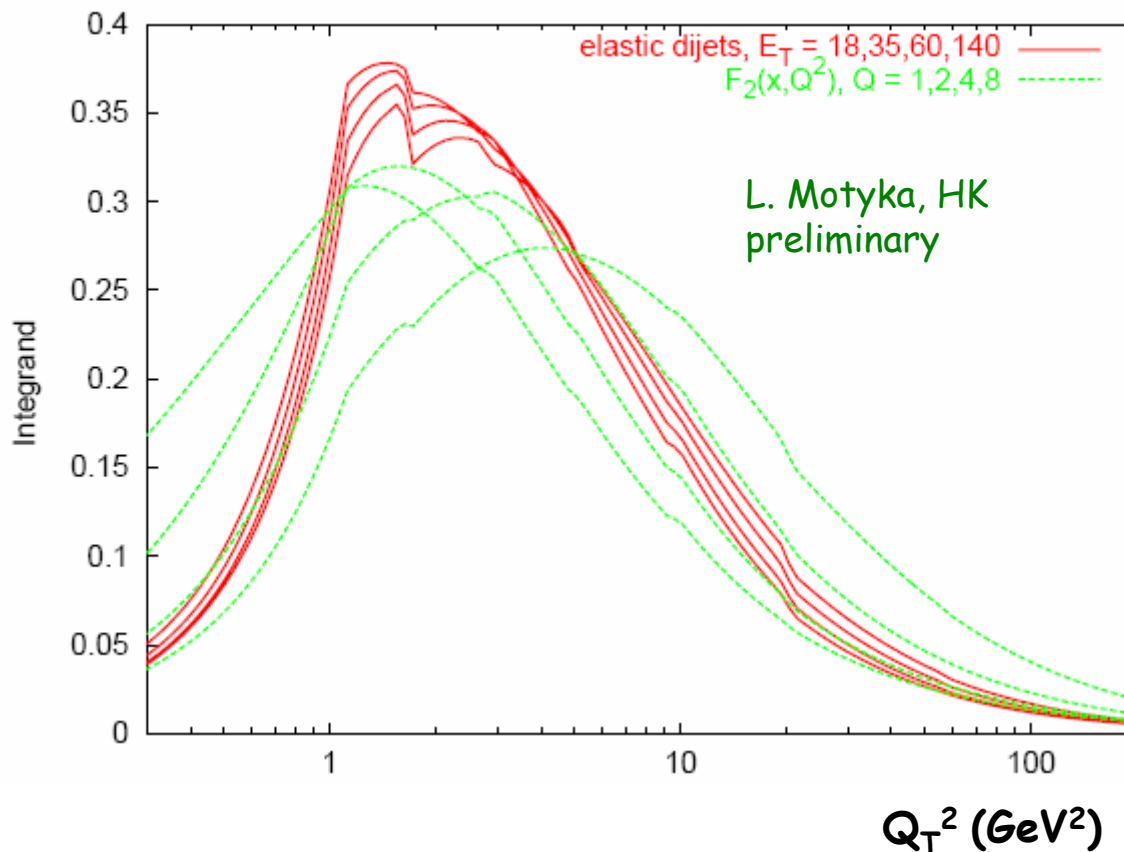
Dipole Model



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

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

Exclusive Double Diffraction



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

 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



New Physics in Diffraction?

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 σ -section are likely to be much *enhanced* as compared to Standard Model ($\tan\beta$ large because $M_{\text{Higgs}} > 115 \text{ GeV}$)

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

