Low-x and diffractive physics at future electro proton/ion colliders

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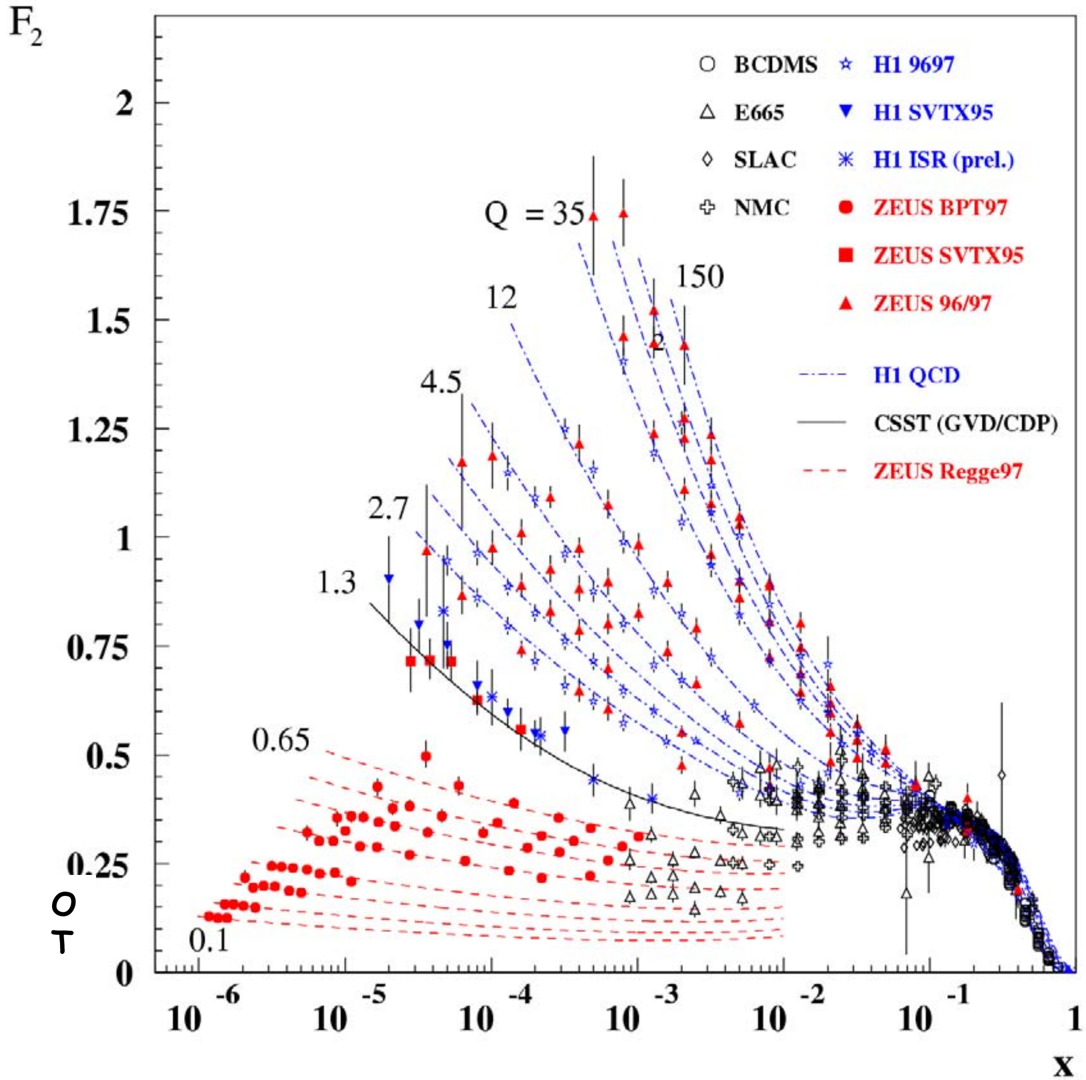
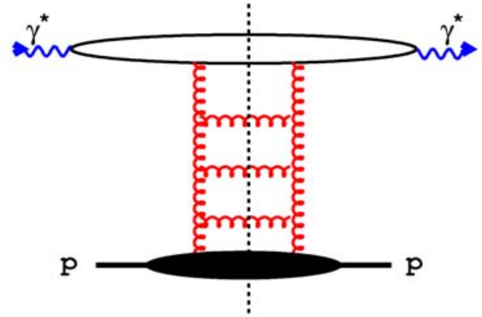
DESY Hamburg, 25th of May 2007

HERA – what have we learned, what is missing

Future facilities
- high luminosity, precise, electron-proton/ion scattering
  EIC ~ ½ of HERA CMS energy, similar x- range
  LHeC ~5 x HERA CMS energy, x – range extended by factor ~100

➔
Saturated gluon densities
Nuclear tomography
Pomeron-Graviton correspondence





$$\sigma_{tot}^{\gamma p} = \frac{1}{W^2} Im A_{el}(W^2, t = 0)$$

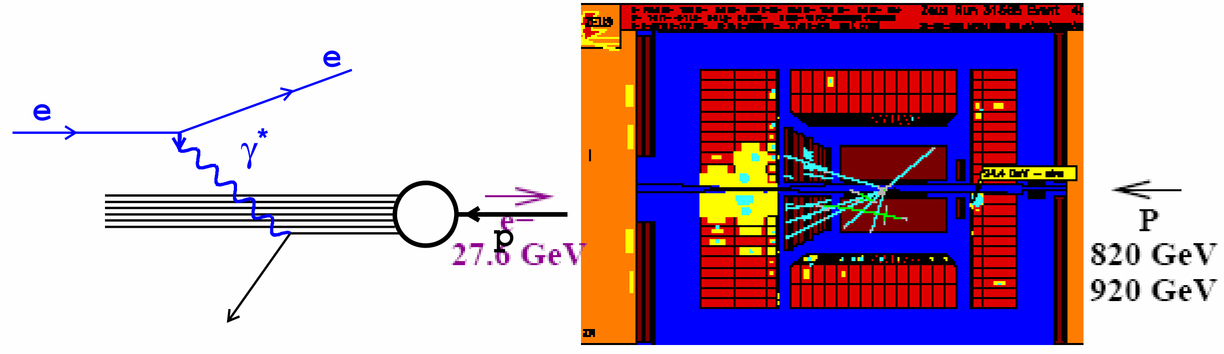
$$F_2(x,Q^2) = \frac{Q^2}{4\pi^2 \alpha_{em}} \cdot \sigma_{tot}^{\gamma^* P}(W,Q^2) \qquad x \approx \frac{Q^2}{W^2}$$

Behavior of F_2 is dominated by gluon density at small-x

gluon density is determined from fits to F_2

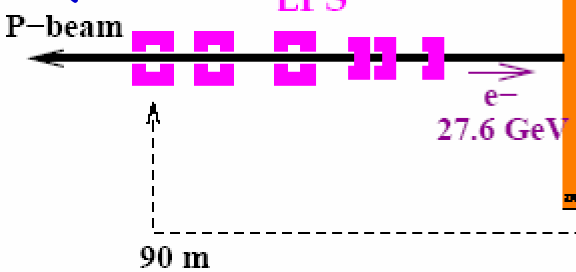
Hard Diffraction – the HERA surprise

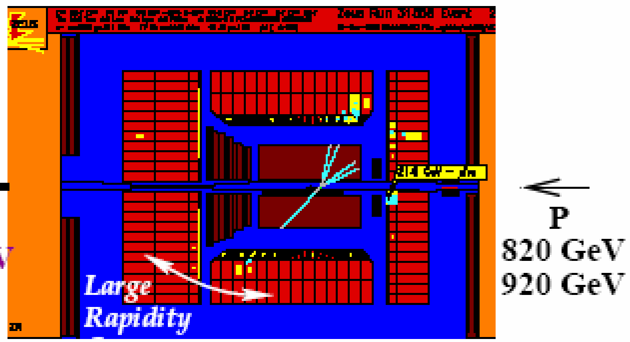
Non-Diffractive Event

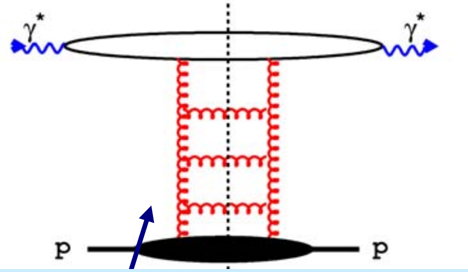


Diffractive Event

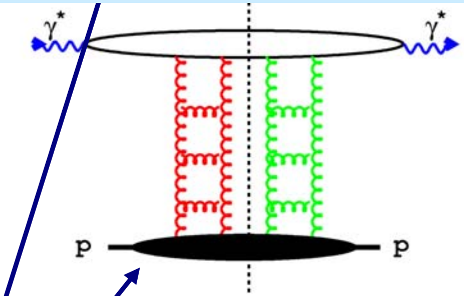
expected before HERA
<0.01%, seen over 10%
at Q^2=10 GeV^2







$$\tau_{qq} \approx \frac{1}{\Delta E} \approx \frac{1}{m_p x} \approx 10 - 1000 \ \ \text{fm}$$



Diffraction at HERA is so large because it is a shadow of DIS (i.e. inelastic processes) ➔ dipole picture

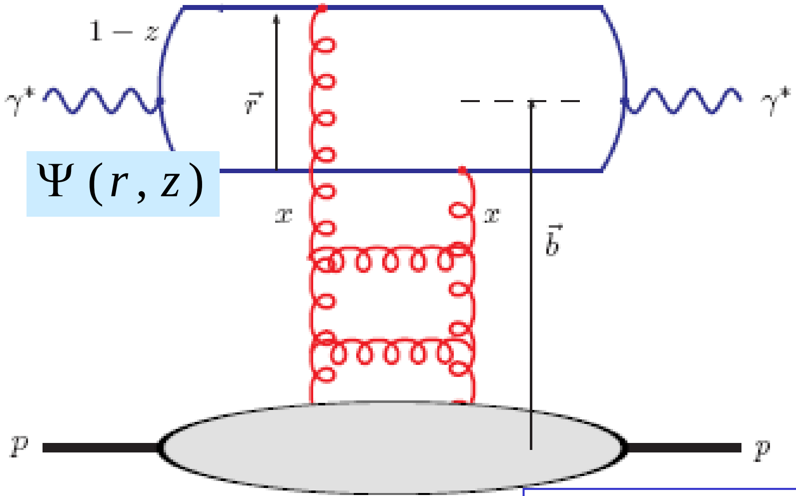
$$\sigma_{tot}^{\gamma^* p} = \frac{1}{W^2} Im A_{el}(W^2, t = 0)$$

$$\sigma_{tot}^{\gamma p} = \frac{1}{W^2} ImA_{el}(W^2, t=0)$$

Dipole Models

equivalent to LO perturbative QCD for small dipoles

NNPZ, GLM, FKS, GBW, MMS
DGKP, BGBK, IIM, FSS……
KT - Kowalski, Teaney
KMW - Kowalski, Motyka, Watt



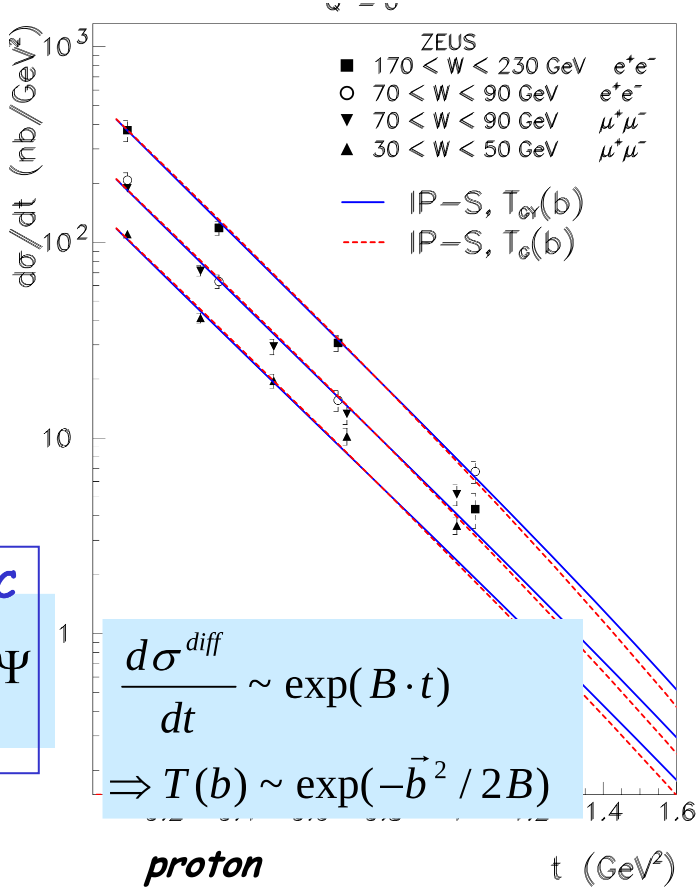
G-M or classical CGC

$$\sigma_{tot}^{\gamma^* p} = \int d^2\vec{r} \int_0^1 dz \int d^2 b \Psi^* \cdot 2\left\{1 - \exp\left(-\frac{\Omega}{2}\right)\right\}\Psi$$

Optical Theorem

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

$$\frac{d\sigma_{VM}^{\gamma^* p}}{dt} = \frac{1}{16\pi} \left| \int d^2\vec{r} \int d^2 b e^{-i\vec{b}\cdot\vec{\Delta}} \int_0^1 dz \Psi_{VM}^* \; 2\left\{1 - \exp\left(-\frac{\Omega}{2}\right)\right\}\Psi \right|^2$$



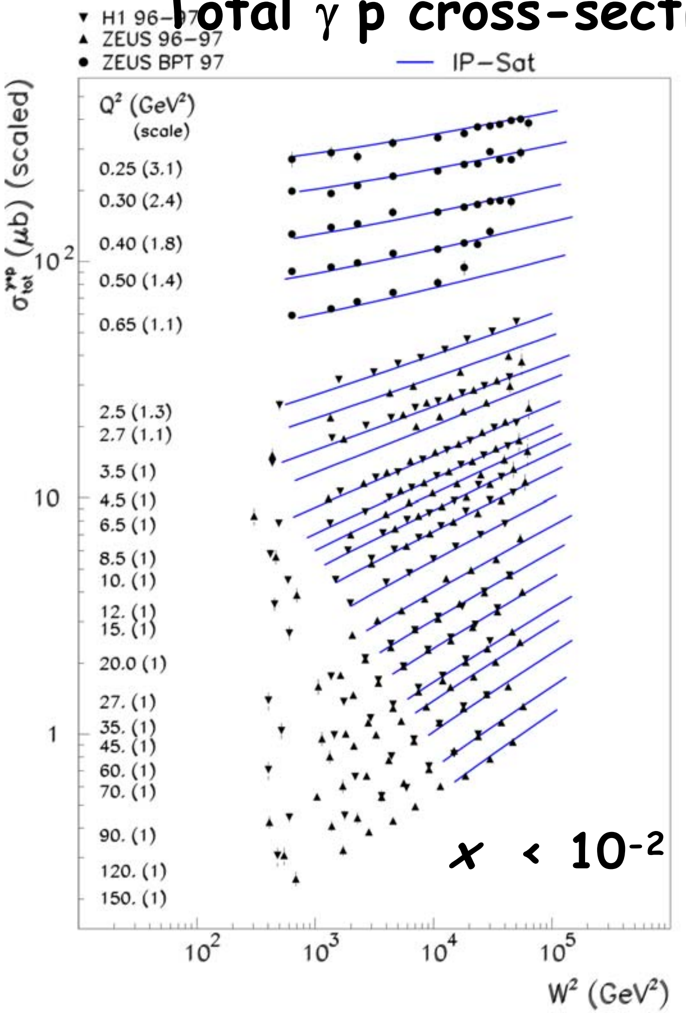
$$\frac{d\sigma^{diff}}{dt} \sim \exp(B \cdot t)$$

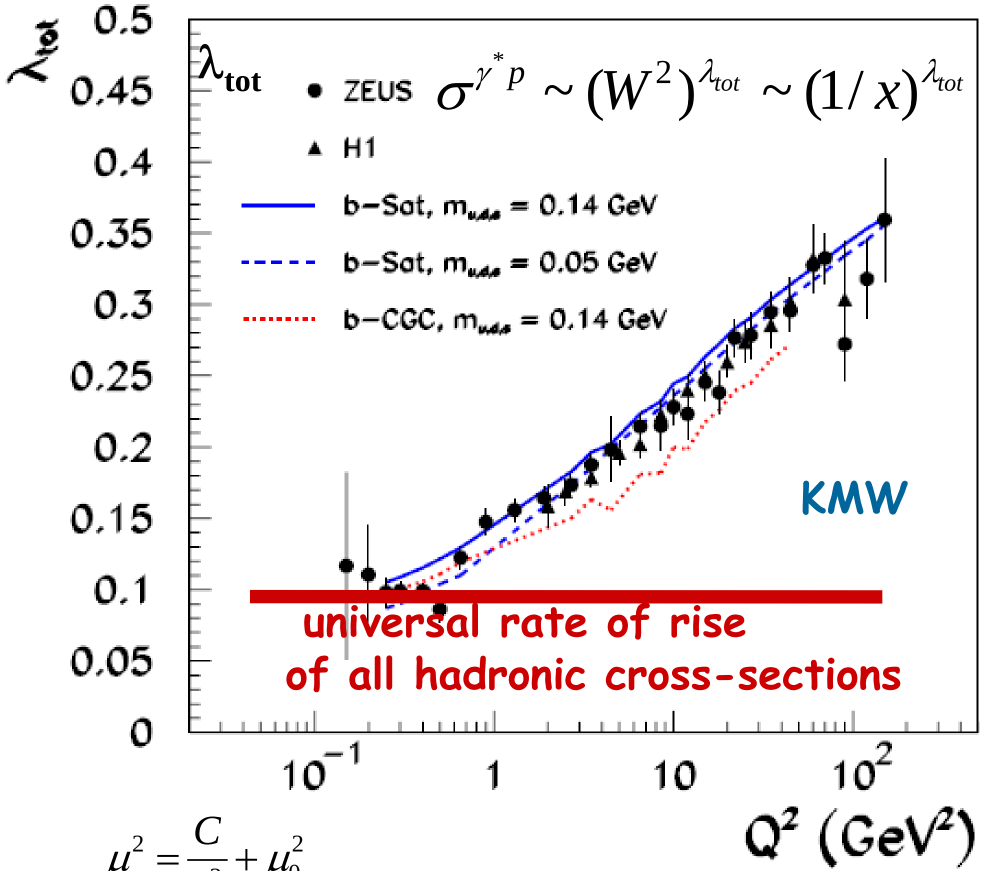
$$\Rightarrow T(b) \sim \exp(-\vec{b}^2 / 2B)$$

proton shape

KT

Total $\gamma^* p$ cross-section





$$\mu^2 = \frac{C}{r^2} + \mu_0^2$$

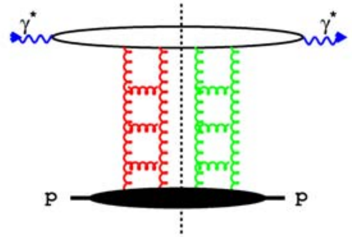
$$\frac{d\sigma_{q\bar{q}}}{d^2 b} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2) x g(x,\mu^2) T(b)\right)\right] \quad xg(x,\mu_0^2) = A_g \left(\frac{1}{x}\right)^{\lambda_g} (1-x)^{5.6}$$

b-Sat

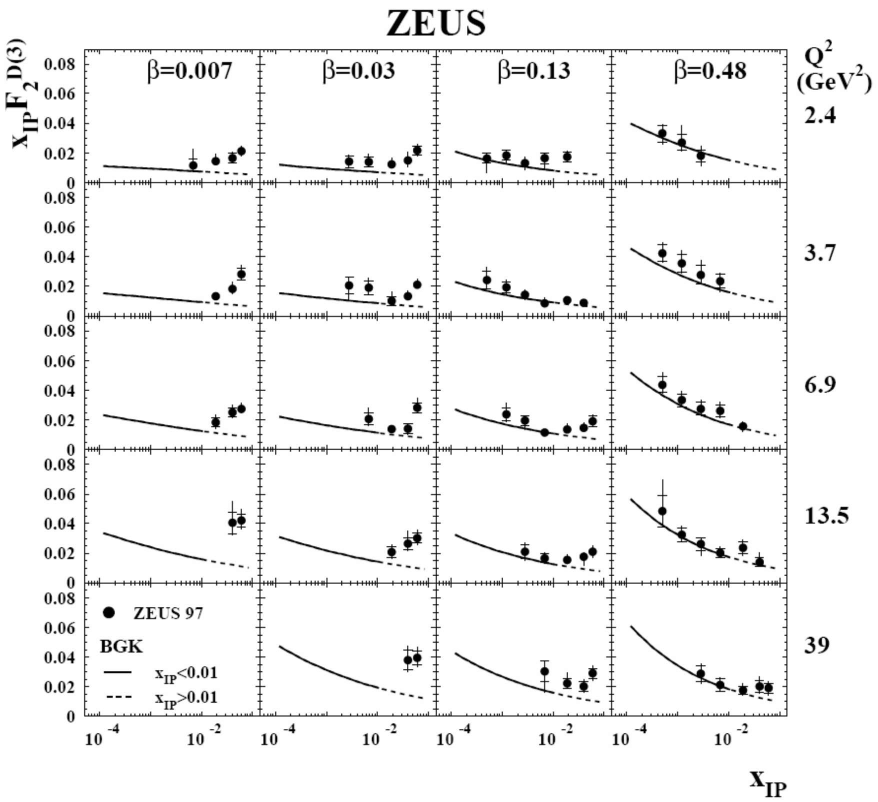
$$\frac{d\sigma_{q\bar{q}}}{d^2 b} \equiv 2\mathcal{N}(x,r,b) = 2 \times \begin{cases} \mathcal{N}_0 \left(\frac{rQ_s}{2}\right)^{2\left(\gamma_s + \frac{1}{\kappa\lambda Y}\ln\frac{2}{rQ_s}\right)} & : \quad rQ_s \le 2 \\ 1 - e^{-A\ln^2(BrQ_s)} & : \quad rQ_s > 2 \end{cases}$$

b- CGC or quantum-CGC

Dipole Model - gluon density convoluted with dipole wave functions simultaneous prediction/description of many reactions

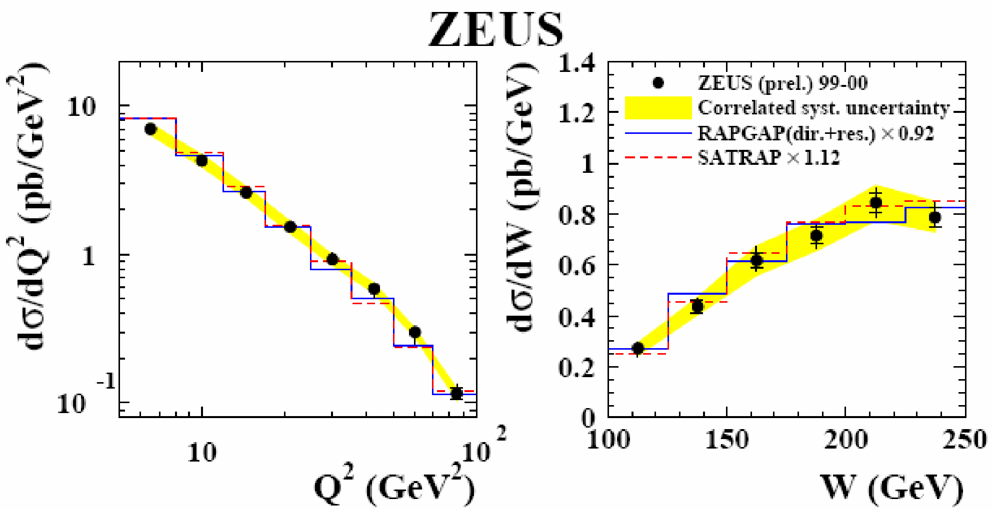


Inclusive Diffractive Cross Section



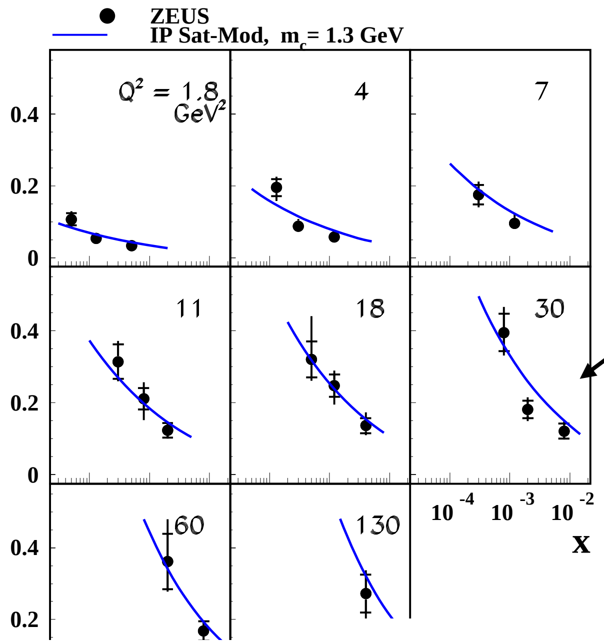
Diffractive Di-jets

Q^2 > 5 GeV^2

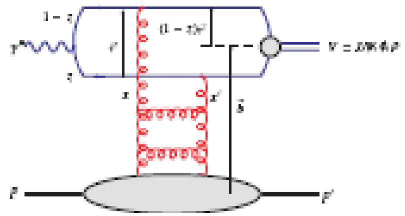


KT

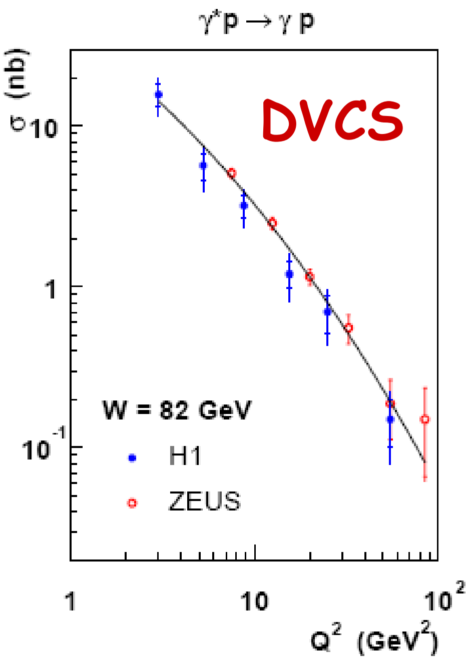
$F_2{}^c$

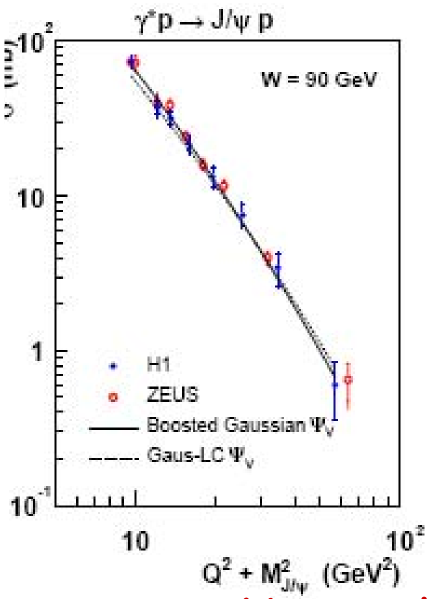


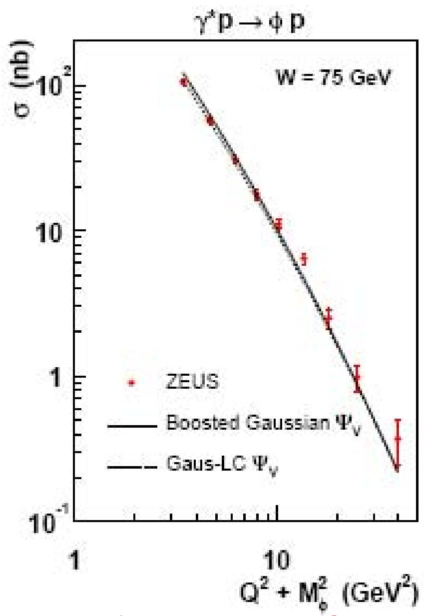
from gluon density convoluted with dipole wave functions we obtain simultaneous prediction/description of many reactions

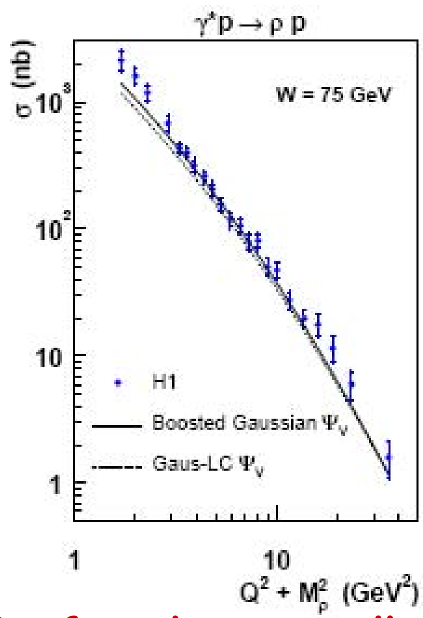


Vector Mesons



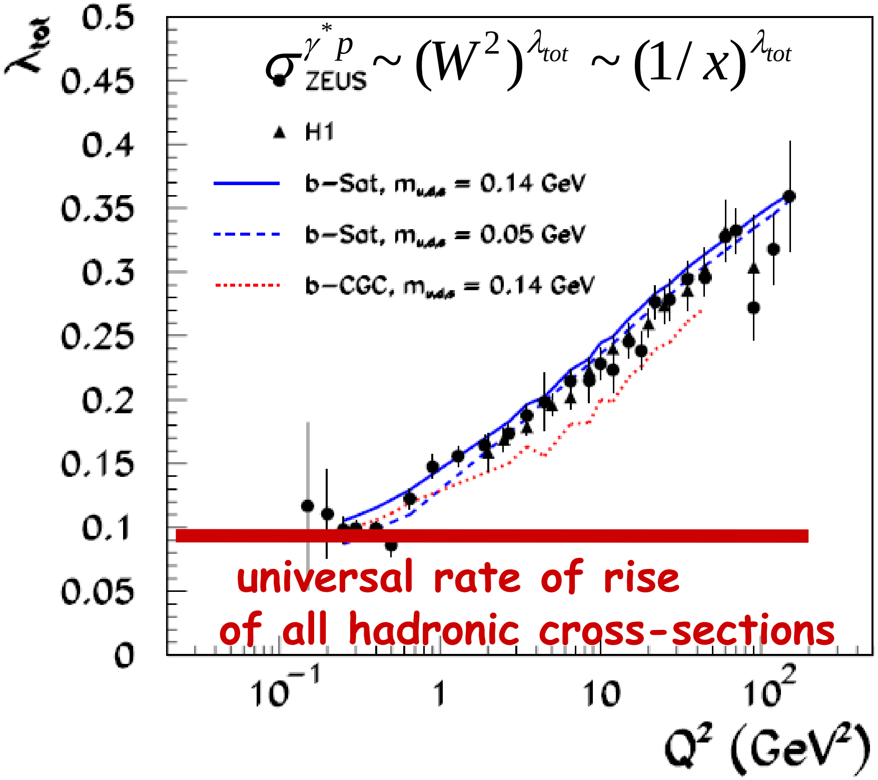


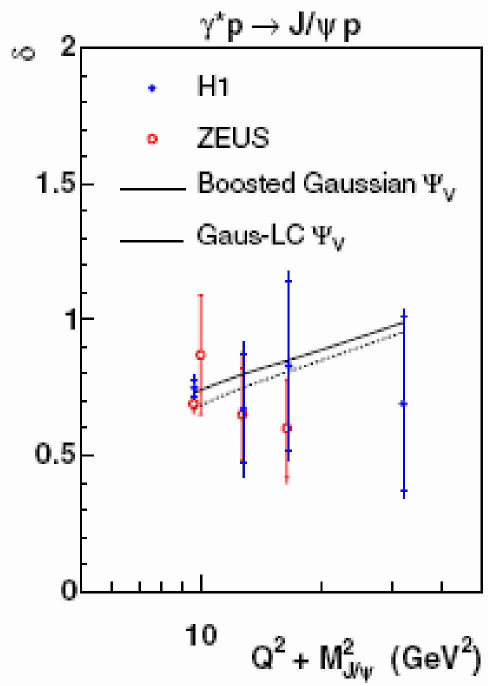


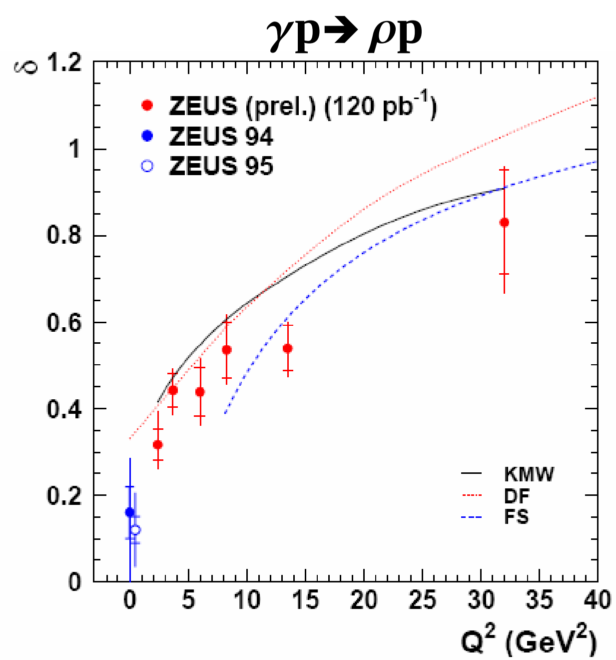


Note: educated guesses for VM wf work very well

Discovery of HERA







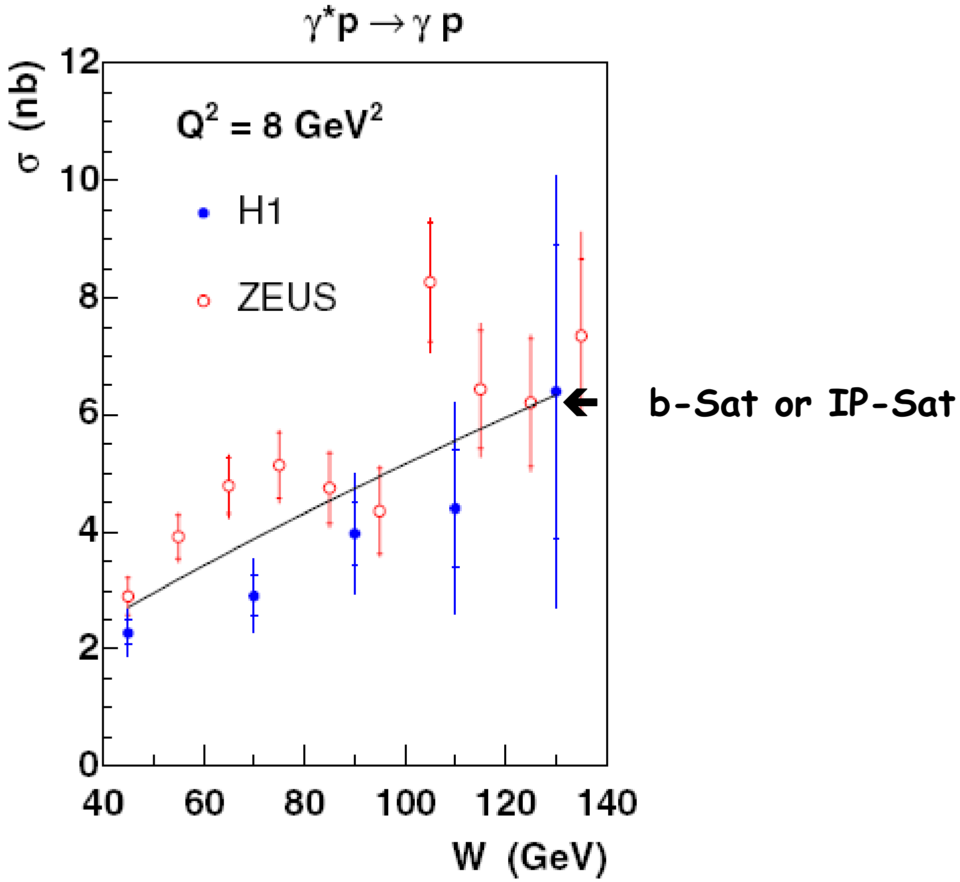
Pomeron is a fundamental QCD object

intercept - $\alpha(Q^2) = 1+\lambda_{tot} = 1+\delta/2$

soft and hard Pomeron join together

Pomeron at work

Rise of the DVCS cross-sections



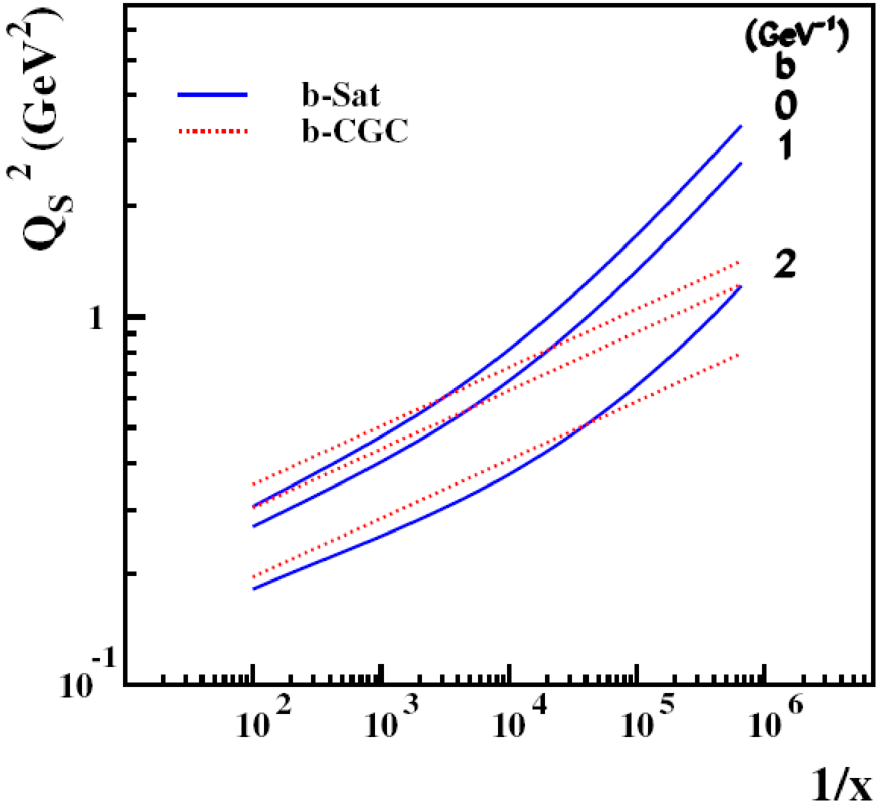
At EIC (LHeC) it should be possible to reduce the errors by a large factor, O(100)

➔ detailed study of the Pomeron possible

Saturation scale at HERA

(a measure of gluon density at which gluon re-scattering starts to be substantial)

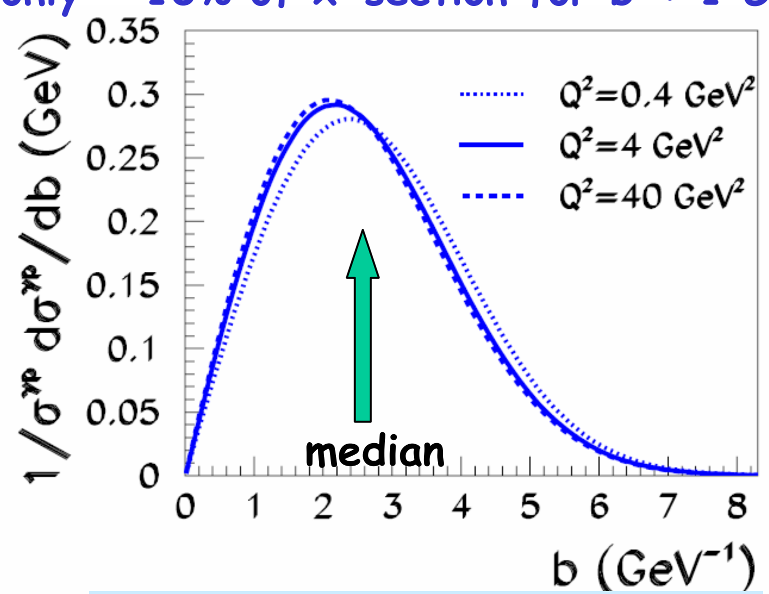
$$\frac{d\sigma_{qq}(x, r^2 = 2/Q_S^2(x,b))}{d^2b} = 2 \cdot \{1 - \exp(-1/2))\}$$



$\boxed{Q_S^{RHIC}(x=10^{-2}) \sim Q_S^{HERA}(x=10^{-4})}$

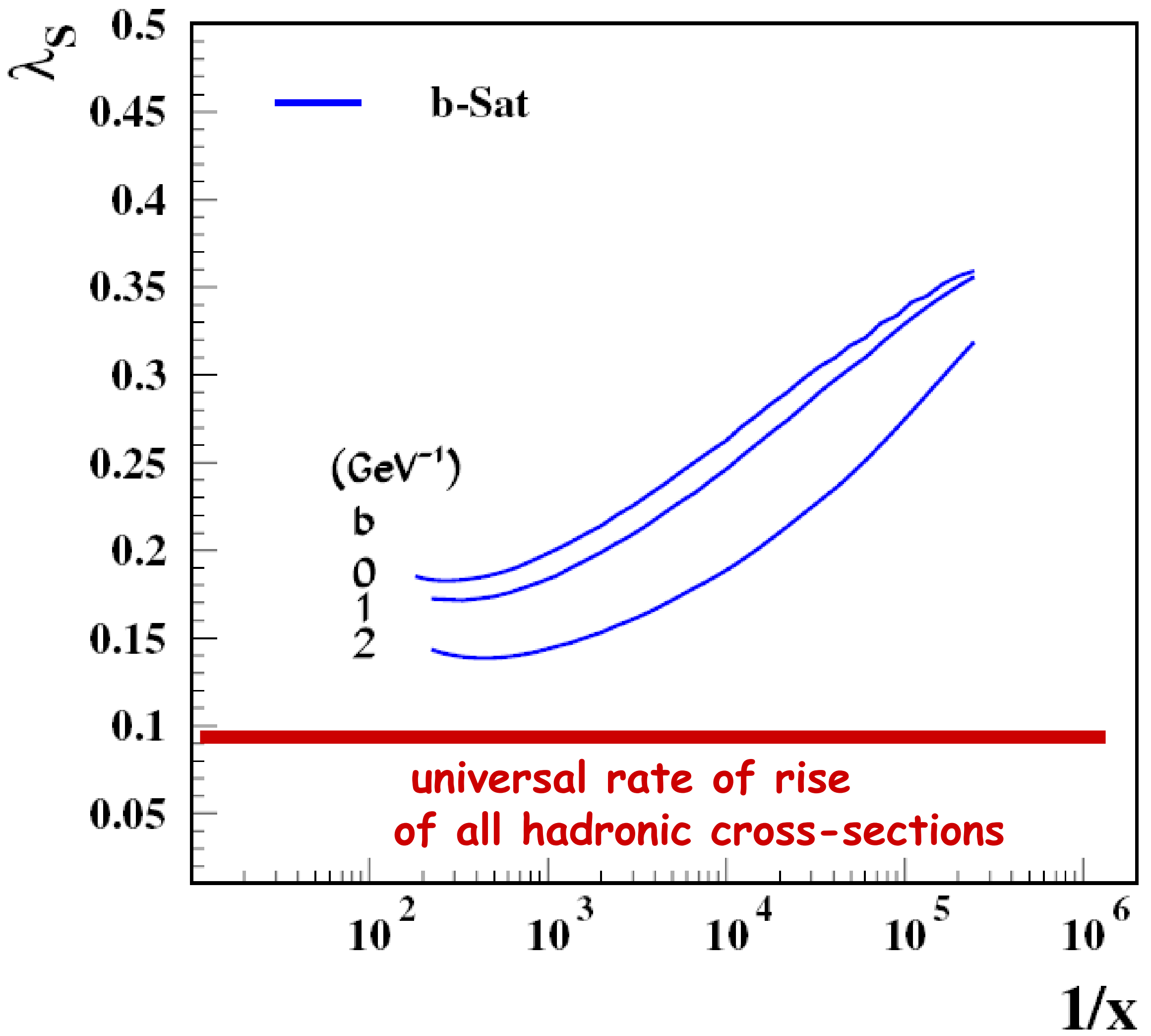
At HERA, the saturation scale can only be determined through dipole model because large fraction of $\sigma^{\gamma^* p}$ comes from the region of large *b* where matter density is low

only ~ 10% of x-section for b < 1 GeV^{-1}



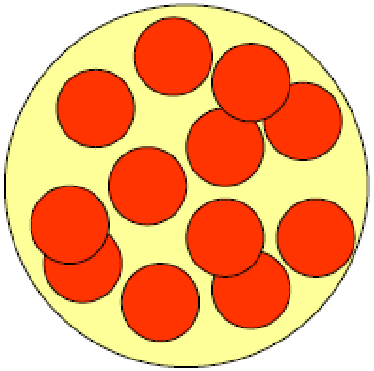
$$T(b) \sim \exp(-b^2_{MEDIAN} / 2 \cdot B_G) \approx 40\%$$

Is saturated state observed at HERA perturbative?



DIS on Nuclei

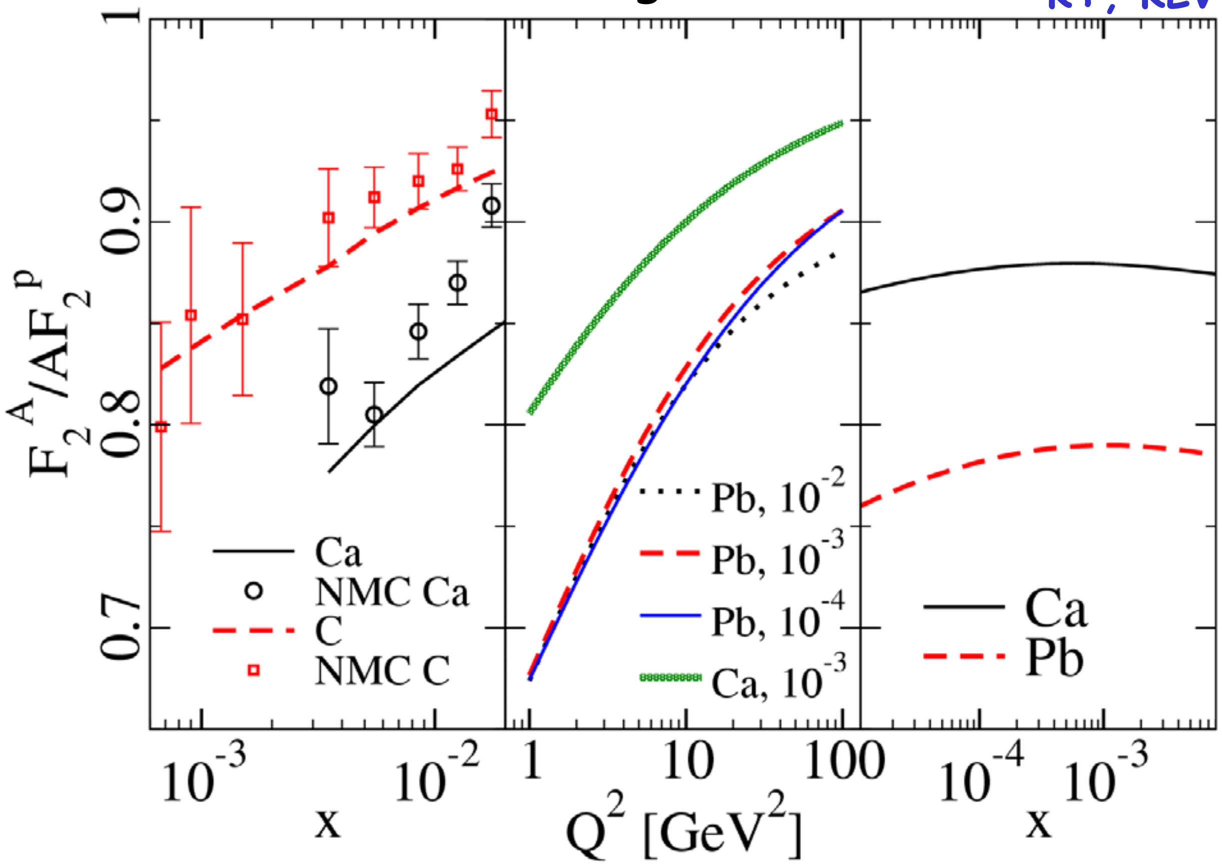
$$\frac{d\sigma^{A}_{qq}(x,r)}{d^{2}b} = \frac{2}{A}\cdot\left\{1-\left(1-T_{WS}(b)\,\sigma_{qq}(x,r)/2\right)^{A}\right\}$$

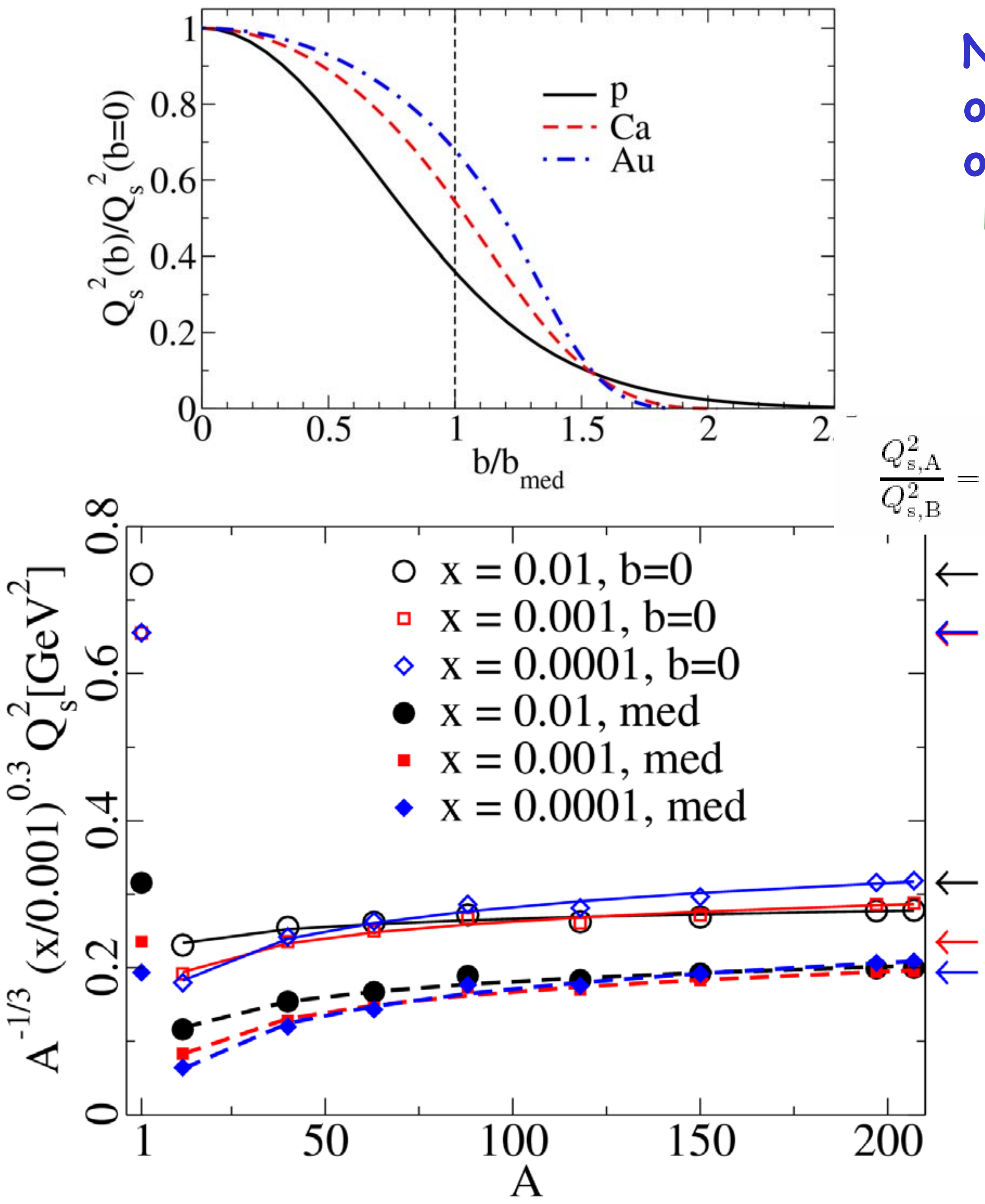


Lumpy Gluon Cloud

Shadowing in Nuclei

KT, KLV





Nuclear enhancement of universal dynamics of high parton densities

Kowalski, Lappi, Venugopalan

hep-ph/0705.3047

$$\frac{Q^2_{s,A}}{Q^2_{s,B}} = \frac{A}{B}\frac{T_A(\mathbf{b}_\perp)}{T_B(\mathbf{b}_\perp)}\frac{F(x,Q^2_{s,A})}{F(x,Q^2_{s,B})} \sim \frac{A^{1/3}}{B^{1/3}}\frac{F(x,Q^2_{s,A})}{F(x,Q^2_{s,B})}$$

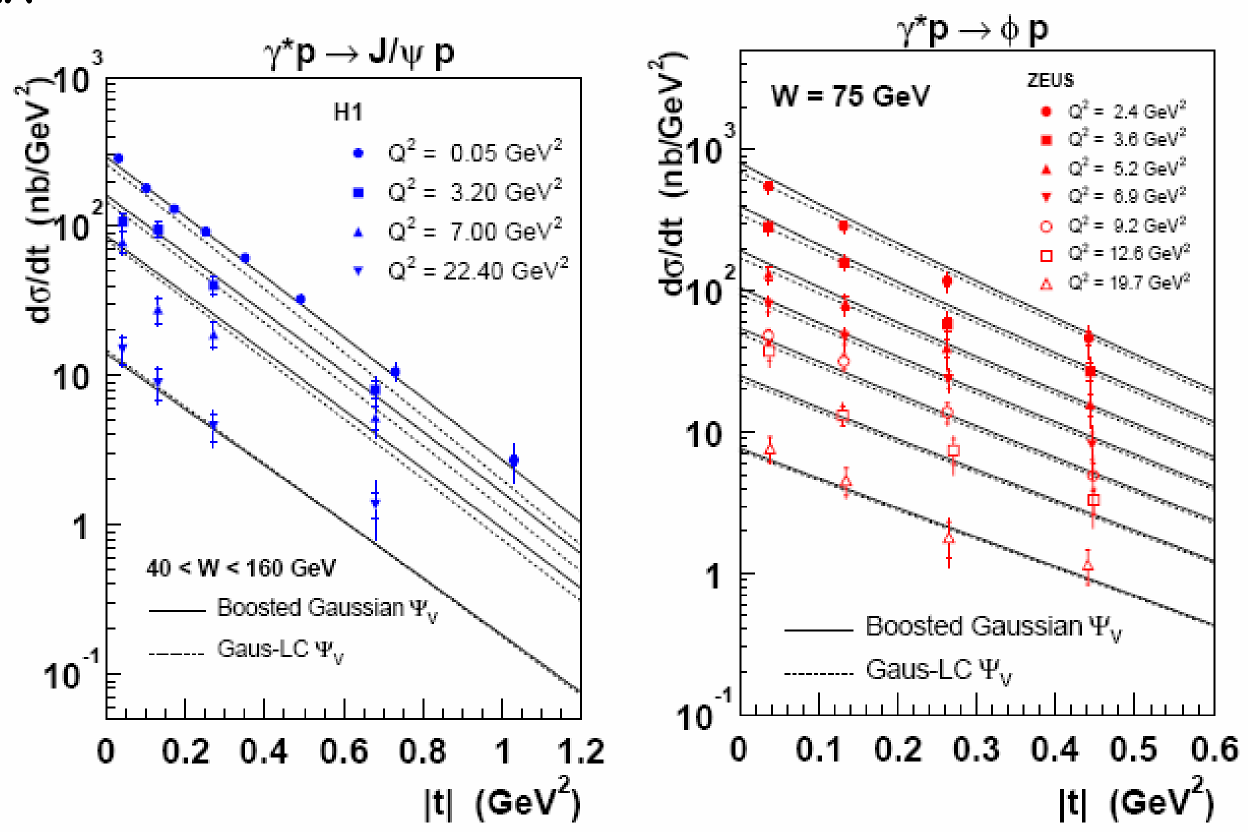
large enhancement of saturation scale in nuclei

$200^{1/3} \sim 6$ ➔

Equivalent center of mass energy ~ 14 time larger than in ep

Nuclear tomography

t-distributions
at HERA



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

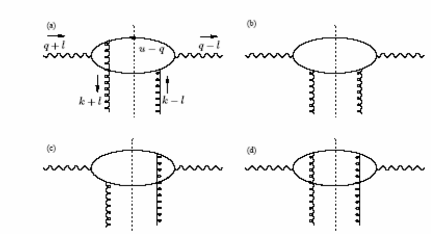
➔ gaussian shape of the proton in the impact parameter b

Description of the size of interaction region B_D

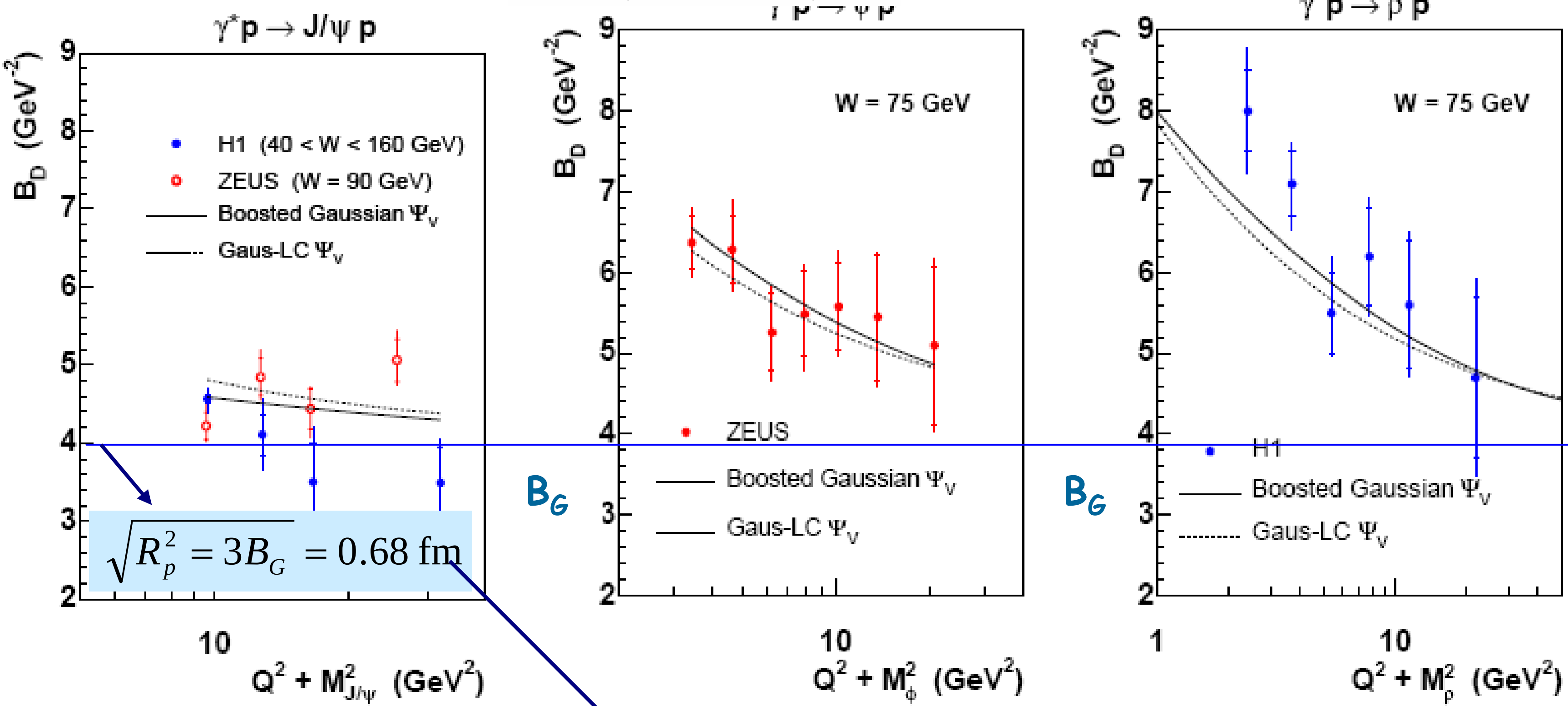
$$\frac{d\sigma^{diff}}{dt} \sim \exp(B_D \cdot t) \qquad \Rightarrow T(b) \sim \exp(-\vec{b}^{\,2} / 2B_G)$$

Modification by Bartels, Golec-Biernat, Peters

$$e^{i\vec{b}\cdot\vec{\Delta}} \rightarrow e^{i(\vec{b}+(1-z)\vec{r})\cdot\vec{\Delta}}$$



KMW



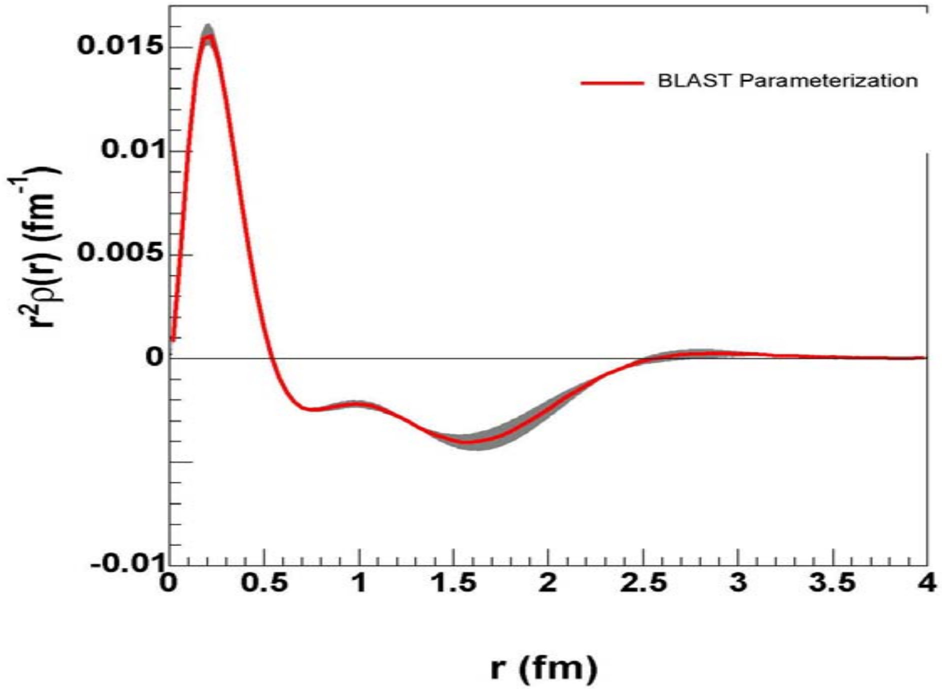
$$\sqrt{R_p^2 = 3B_G} = 0.68 \text{ fm}$$

$$R_p = 0.870 \pm 0.008 \text{ fm}$$

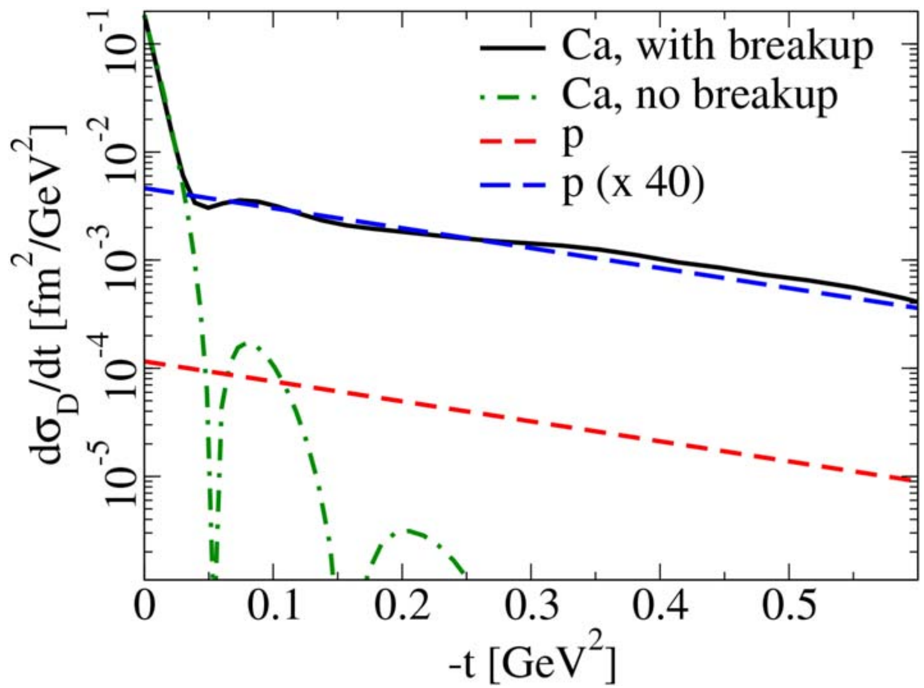
$$\Rightarrow B_G = 6.48 \text{ GeV}^2$$

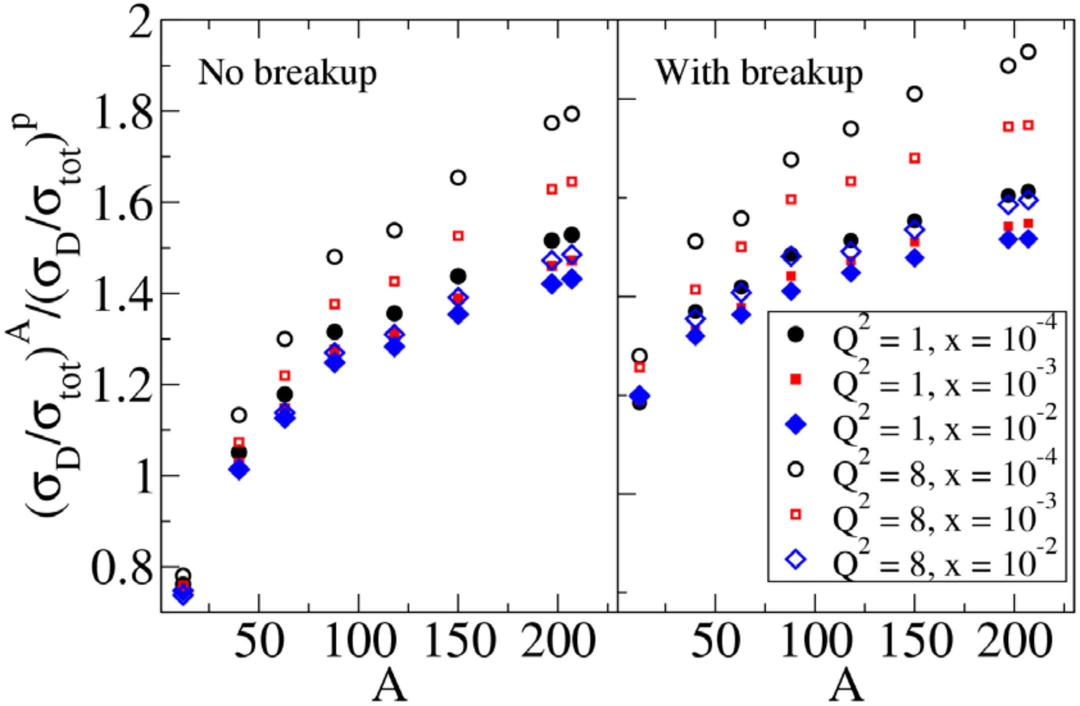
the gluonic proton radius smaller than the quark radius

The Charge Distribution of the Neutron obtained in the BLAST Polarized Deuterium Experiment



Diffractive scattering on nuclei

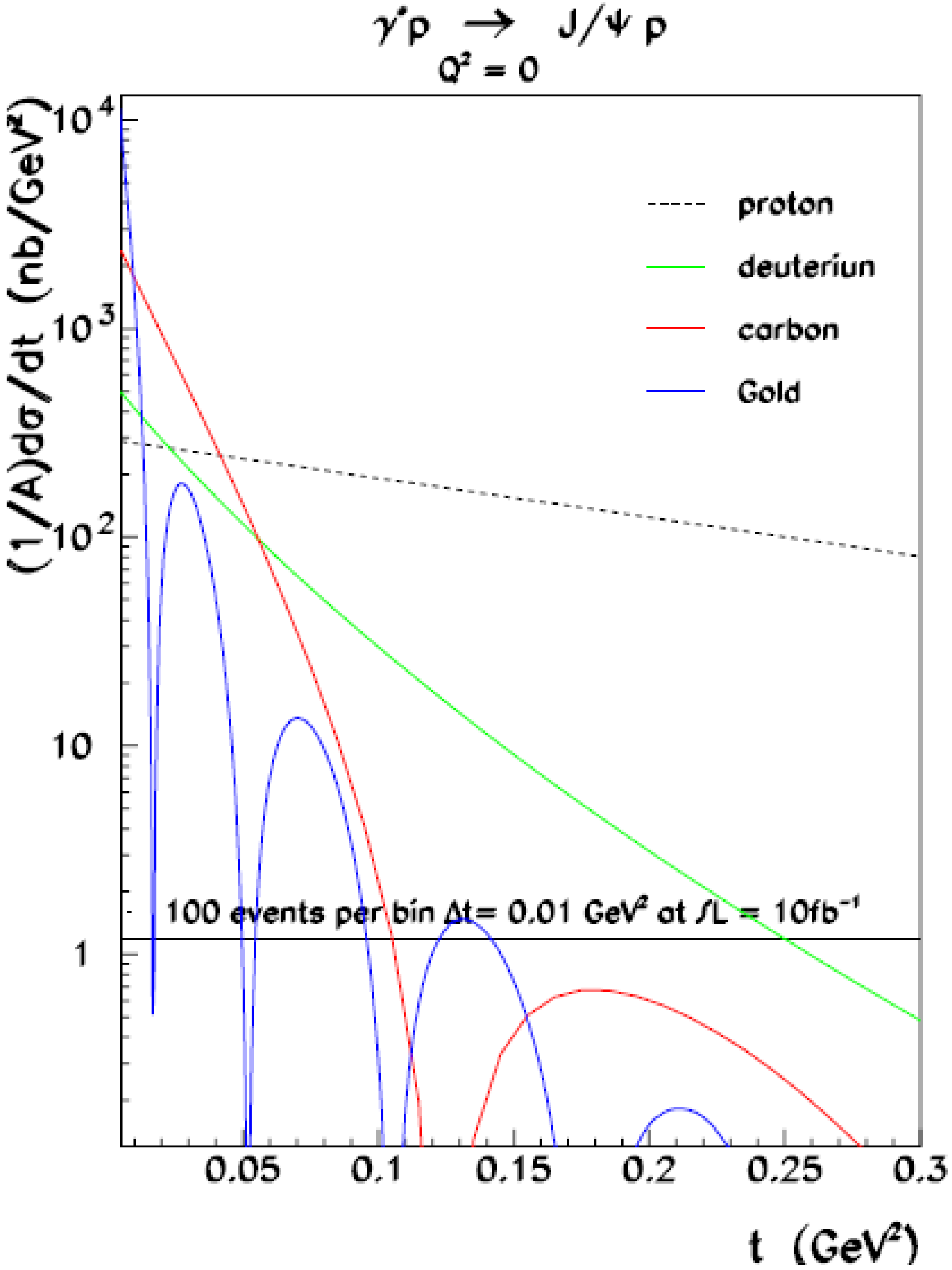




t-distributions for exclusive diffractive meson production on proton and nuclei at EIC

first estimate of the expected measurement precision:

$\Delta p_T < 30$ MeV, $t \sim p_T^2$
$\Delta t < 0.01\ GeV^2$
for proton and light nuclei



Pomeron-Graviton Correspondence

String theory emerged out of
phenomenology of hadron-hadron scattering

Dolan-Horn-Schmid duality between
s-channel and t-channel Regge-pole description
of hadronic X-sections

$$\sum_r \frac{g_r^2(t)}{s-(M_r-i\Gamma_r)^2} \simeq \beta(t)(-\alpha' s)^{\alpha(t)} \,.$$

➔ Veneziano amplitude

$$A_{\pi^+\pi^-\to\pi^+\pi^-}(s,t) = g_o^2\,\frac{\Gamma[1-\alpha_\rho(t)]\Gamma[1-\alpha_\rho(s)]}{\Gamma[1-\alpha_\rho(s)-\alpha_\rho(t)]}$$

generalization of V-amplitude ➔ dual models
➔ mesons are open strings
L - string length, $E = c\,L$, $J = \alpha' E^2$

$\alpha(t) = \alpha_0 + \alpha' t$

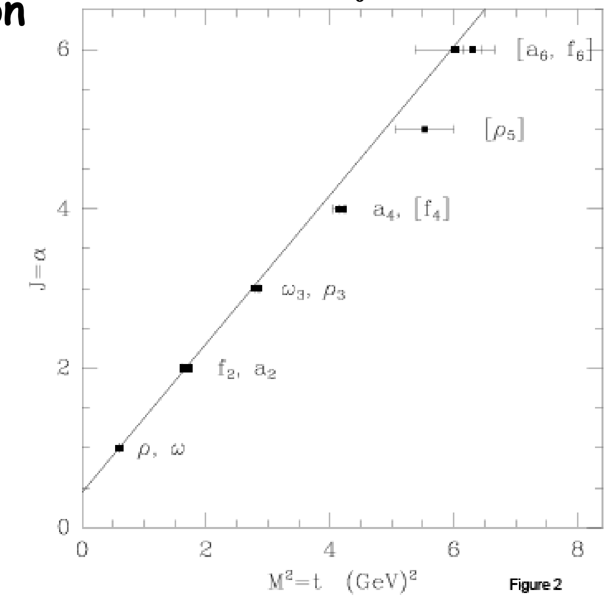


Figure 2

V-amplitude for $\alpha(0)$ = 1 has a pole at $s = t = 0$
with J = 2, a graviton ➔ starting point for theory of quantum gravity

Superstring Theory, Green, Schwarz, Witten (1987)
R. Brower hep-th/0508036

Maldacena Conjecture

from the talk by J. Maldacena

Particle theory = gravity theory

Most supersymmetry QCD theory	=	String theory on $AdS_5 \times S^5$	(J.M.)

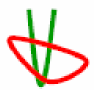
N colors

N = magnetic flux through S^5

Radius of curvature $$R_{S^5} = R_{AdS_5} = \left(g_{YM}^2 \; N\right)^{1/4} l_s$$

Duality:

g^2 N is small → perturbation theory is easy – gravity is bad



g^2 N is large → gravity is good – perturbation theory is hard

Strings made with gluons become fundamental strings.

From the talk by J. Maldacena

Most supersymmetric QCD

Supersymmetry

Bosons $\longleftrightarrow$ Fermions

Ramond
Wess, Zumino

Gluon $\longleftrightarrow$ Gluino

Many supersymmetries

B1 F1
B2 F2

Maximum 4 supersymmetries, $\mathcal{N} = 4$ Super Yang Mills

A_μ	Vector boson	spin = 1
Ψ_α	4 fermions (gluinos)	spin = 1/2
Φ^I	6 scalars	spin = 0

SO(6) symmetry

All NxN matrices

Susy might be present in the real world but spontaneously broken at low energies.

We study this case because it is simpler.

but $\beta = 0$, no asymptotic freedom

Pomeron and Gauge/String Duality

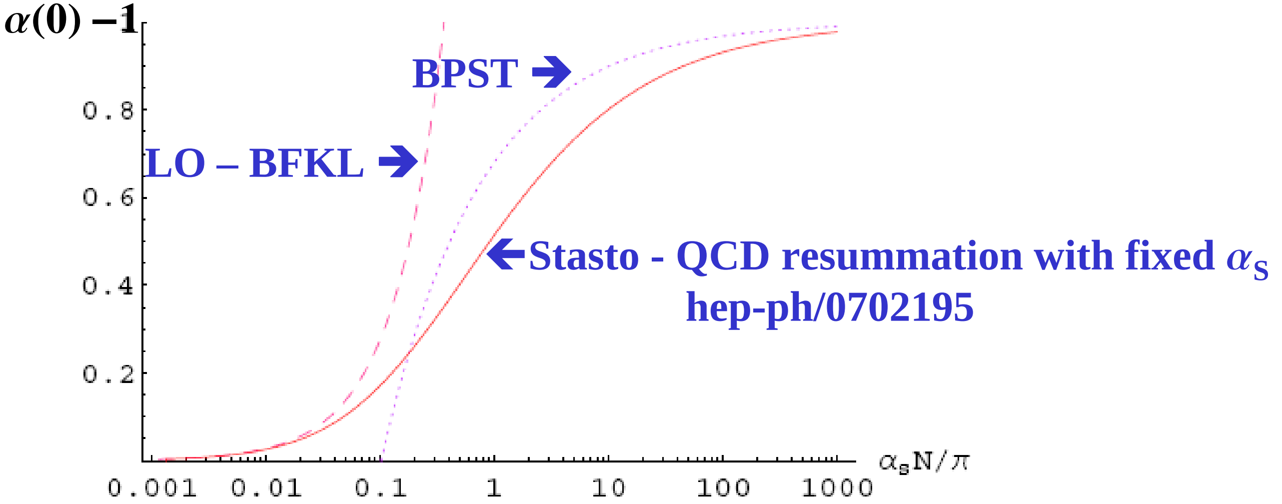
Brower, Polchinski, Strassler, and Tan, hep-th/0603115

Pomeron is a coherent color-singlet object, build from gluons, with universal properties; it is the object which is exchanged by any pair of hadrons that scatter at high energies.
In string theory, it is the object which is exchanged in tree level scattering in the Regge regime, it is not the graviton but the graviton's Regge trajectory (reggeized graviton according to Lipatov)

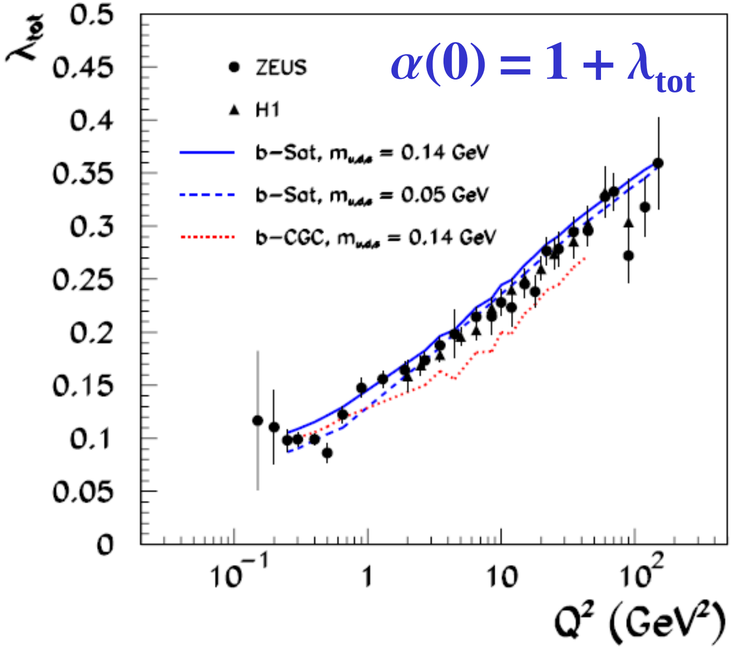
$\alpha(0) = 2 - c/\sqrt{\alpha_S}$ in ADS/CFT

$\alpha(0) = 2 - c/\sqrt{\alpha_S}$ in N=4 YM = Most Supersymmetric QCD

Kotikov, Lipatov, Onishchenko, Velizhanin, Physt. Lett. B 632, 754 (2006)



A Possible Pomeron-Graviton connection in the real world



How to combine Regge theory with DGLAP and BFKL ? Lipatov 1986

$$xg(x,Q^2) \approx \sum_{n=0} (1/x)^{\Delta_n} c_n(Q^2)$$

$$\Delta_n = J_n - 1 = \frac{c}{n+\delta}; \qquad 0 < \delta < 1$$

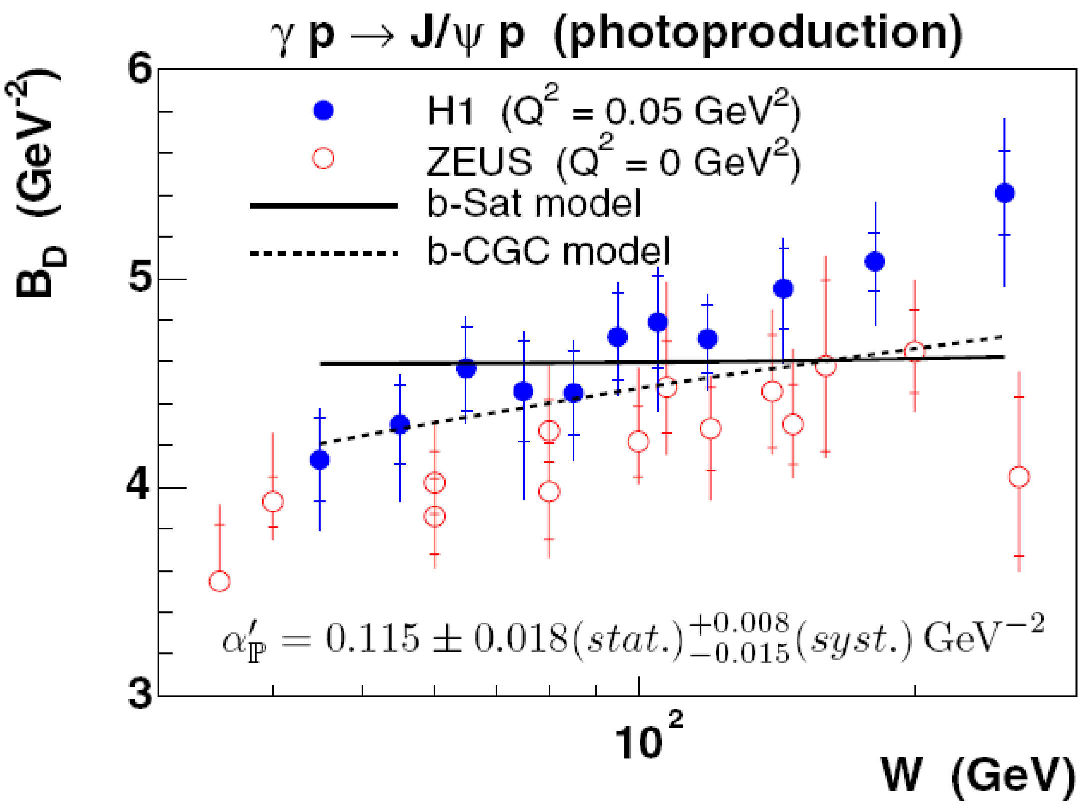
$$c_n \sim (\log Q^2)^{1/\Delta_n}$$

leading intercept $\Delta_0 \geq 0.4$
(no saturation effects)

Lipatov conjecture: quantum properties of the graviton determine the value of the leading pomeron intercept
(leading intercept can be calculated in the gravitational string theory,
it cannot be calculated in the perturbative QCD)

Get the leading intercept from data: determine λ_{tot} as a function of x, Q^2
determine the increase of λ_{tot} with x at fixed Q^2
Necessary conditions: high measurement precision, large range in x (for small x)
Possible at EIC, may be at LHC, best foreseeable machine: LHeC

measurement of α'



Significant slope is expected for a leading pomeron trajectory Lipatov (1986)

$$J_n(t) = 1 + \frac{c}{n + \delta(t)}$$

BPST ➔ $\alpha' = R^2 / g_{YM}\sqrt{N}$

Summary

DIS is more interesting than we all anticipated