Studying the Glue which binds us all

EIC

A High Luminosity Electron-Ion Collider to Study the Fundamental Structure of Matter

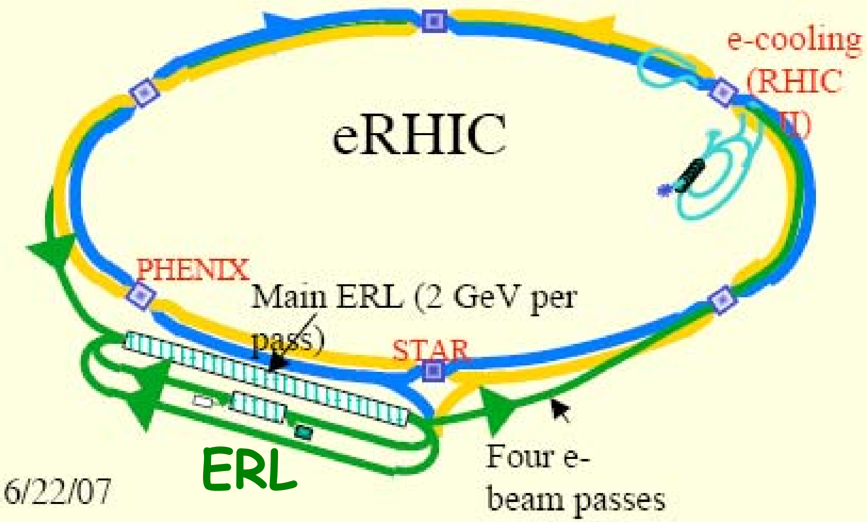
Henri Kowalski, DESY
EINN 2007, September 2007

What is EIC?

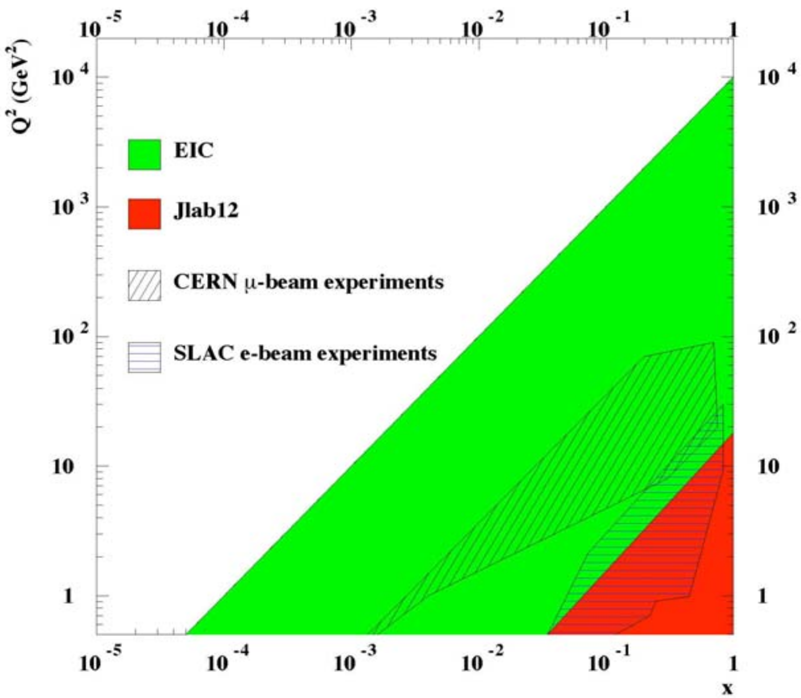
HERA Physics – what have we learned, what is missing
Highlights of EIC Physics →
- precise measurement of gluon densities, F_L
  - enhancement of saturation in nuclei
- Nuclear tomography
- Spin Physics

Electron Ion Collider

- Addition of a high energy polarized electron beam facility to the existing RHIC will drastically enhance our ability to study fundamental and universal aspects of QCD [**eRHIC**]
  - **Alternatively, one could add a high energy hadron/nuclear beam facility at Jefferson Laboratory [<u>EL</u>ectron <u>I</u>on <u>C</u>ollider: ELIC]**



EIC Design Parameters



- E_e=5-10 (20) GeV
- E_p=30-250 GeV
- $s^{\frac{1}{2}}$=25-100 (140) GeV
- $x_{Bj}=10^{-4}$ to 0.7
- $Q^2=0$ to 10^4 $(GeV/c)^2$
- polarization of $e^{\pm}$, p, ^3He ~ 70%
- heavy ion beams of all elements
- high luminosity ~ 10^{33} cm^{-2} s^{-1}
- 50 fb^{-1} integrated luminosity over a decade, i.e. x 100 above HERA

Unanimous recommendation of the QCD Town Meeting Rutgers University, New Jersey January 13th 2007

A high luminosity Electron-Ion Collider (EIC) is the highest priority of the QCD community for new construction after the JLab 12 GeV and RHIC II luminosity upgrades. EIC will address compelling physics questions essential for understanding the fundamental structure of matter:

- Precision imaging of the sea-quarks and gluons to determine the spin, flavor and spatial structure of the nucleon;

- Definitive study of the universal nature of strong gluon fields in nuclei.

This goal requires that R&D resources be allocated for expeditious development of collider and detector design.

EIC Recommendation
NSAC LRP, May 4, 2007

We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton.

Without gluons there are no protons, no neutrons, and no atomic nuclei. Interactions among gluons determine the unique features of strong interactions. However, gluon properties in matter remain largely unexplored. Recent theoretical breakthroughs and experimental results suggest that both nucleons and nuclei when viewed at high energies appear as dense systems of gluons, creating the strongest fields in nature. The emerging science of this universal gluonic matter drives the development of a next generation high luminosity electron ion collider. Polarized beams in the EIC will give unprecedented access to the spatial and spin structure of gluons in the proton. The EIC embodies our vision for reaching the next QCD frontier. Realization of an EIC will require advancements in accelerator science and technology, detector R&D, and continued theoretical development.

The EIC Collaboration/Working Group

http://www.bnl.gov/eic & http://web.mit.edu/eicc

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EIC Steering Committee

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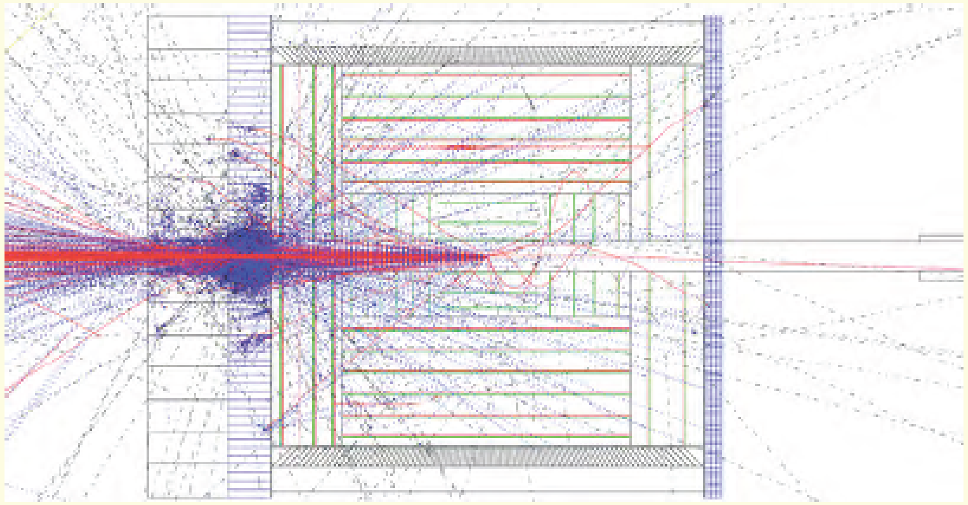
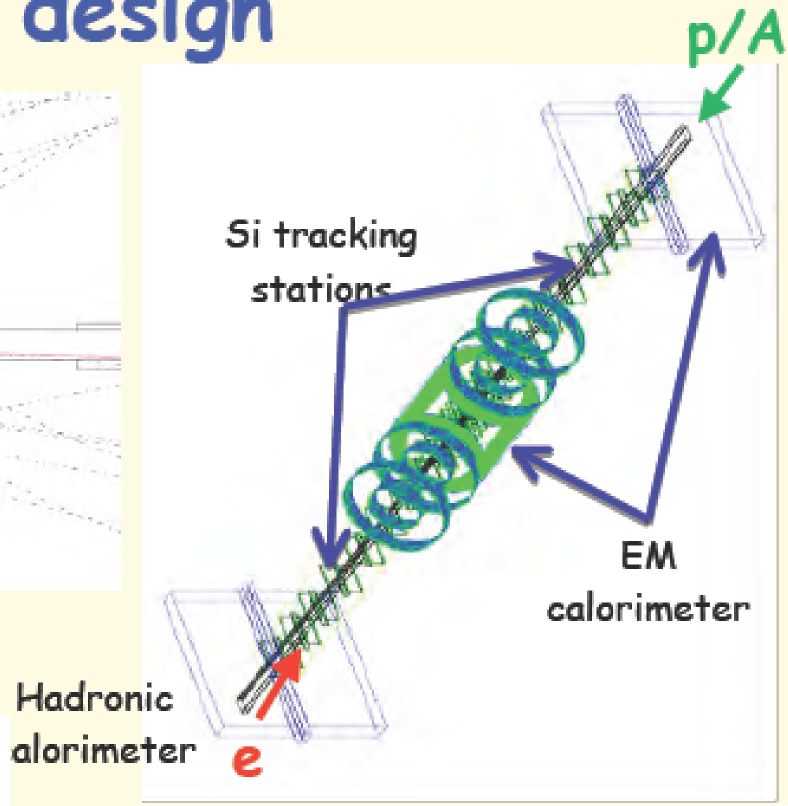
Detector design



Main detector: Top view

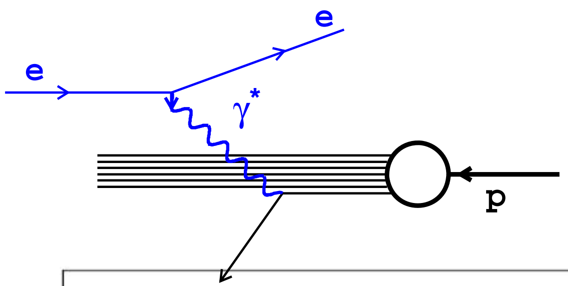


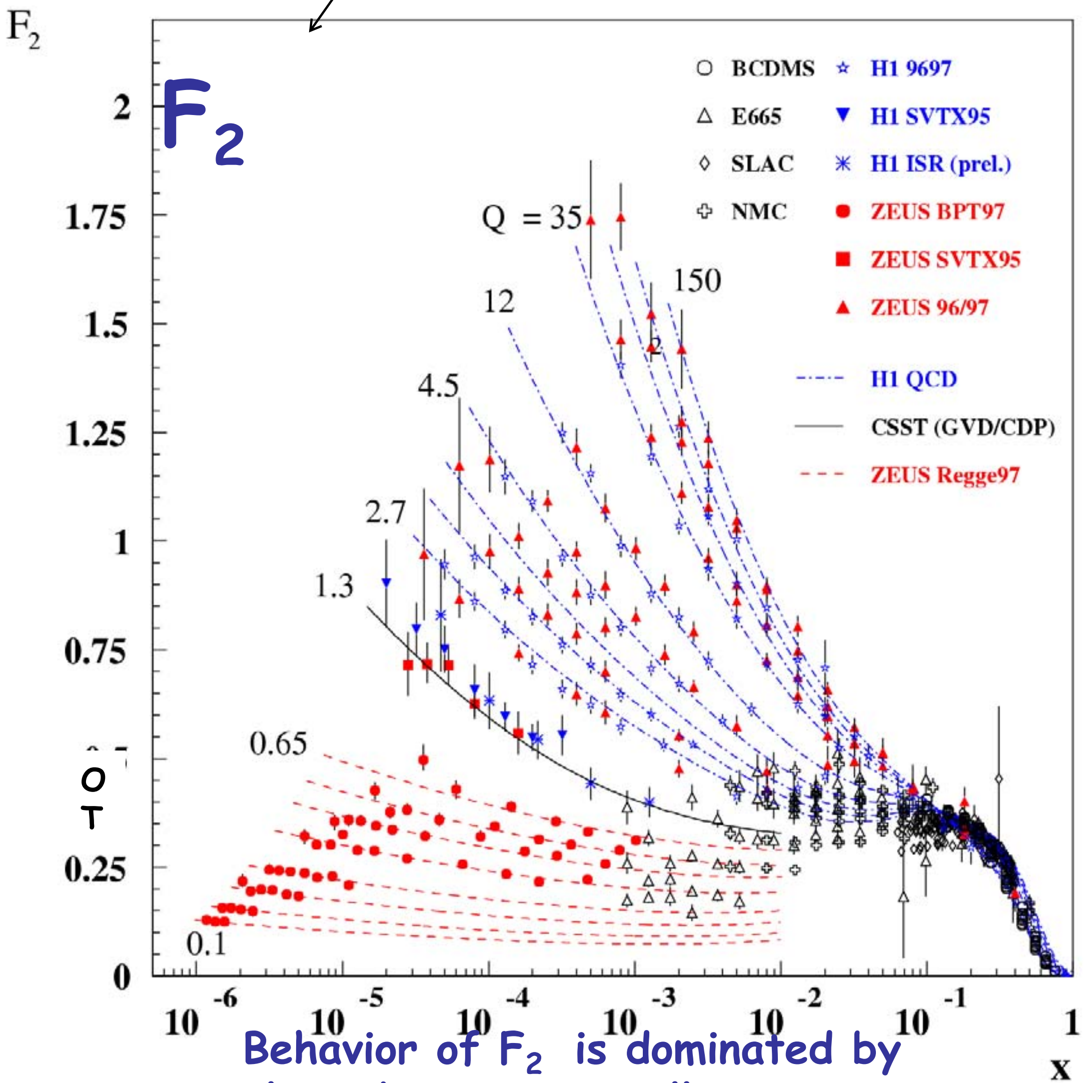
Multipurpose detector similar to ZEUS and H1 with addition of forward detectors, B. Surrow

Hera III detector design
MPI Munich

➔ **Particle detection in the full rapidity range** ←

HERA

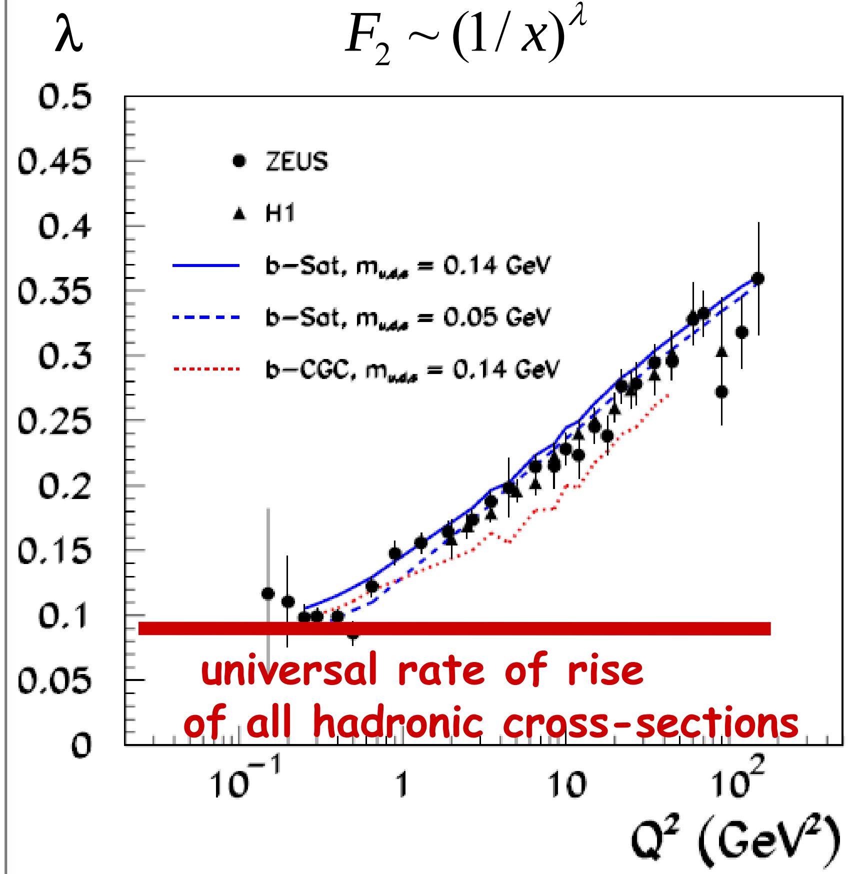




Behavior of F_2 is dominated by gluon density at small-x

rate of rise of F_2 at small-x

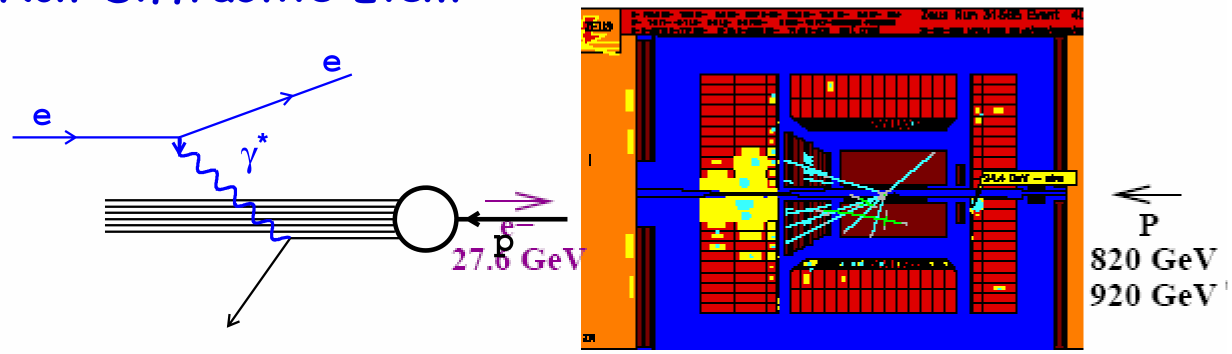
$$F_2 \sim (1/x)^{\lambda}$$

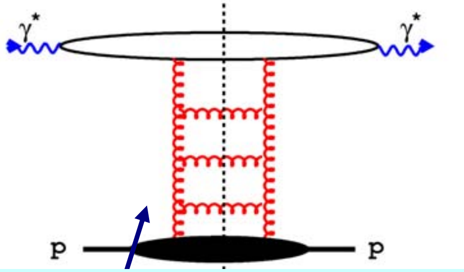


universal rate of rise
of all hadronic cross-sections

Hard Diffraction – the HERA surprise

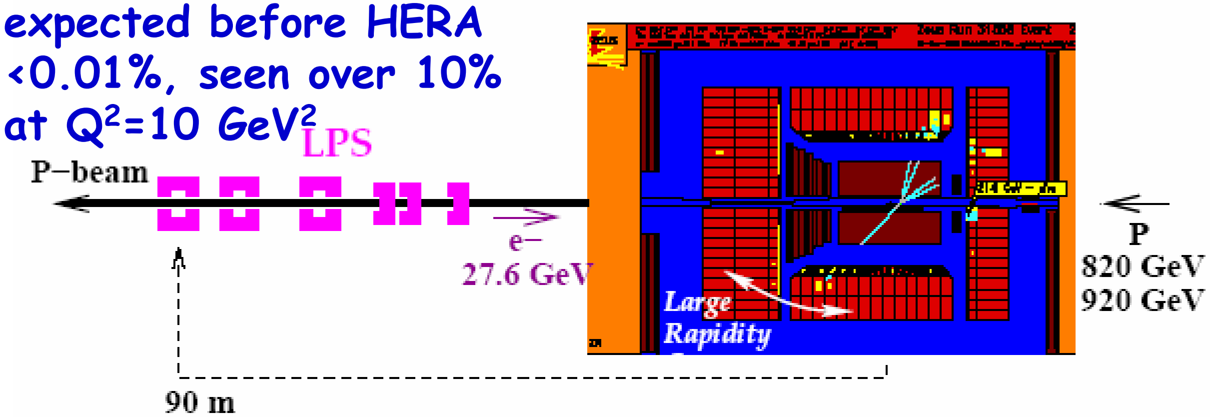
Non-Diffractive Event

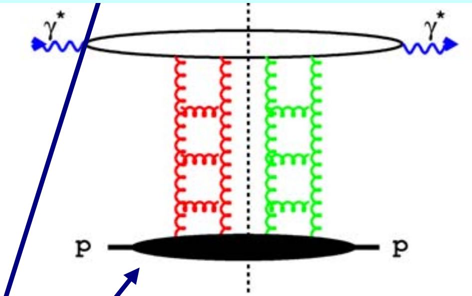




$$\tau_{qq} \approx \frac{1}{\Delta E} \approx \frac{1}{m_p x} \approx 10 - 1000 \ \text{fm}$$

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

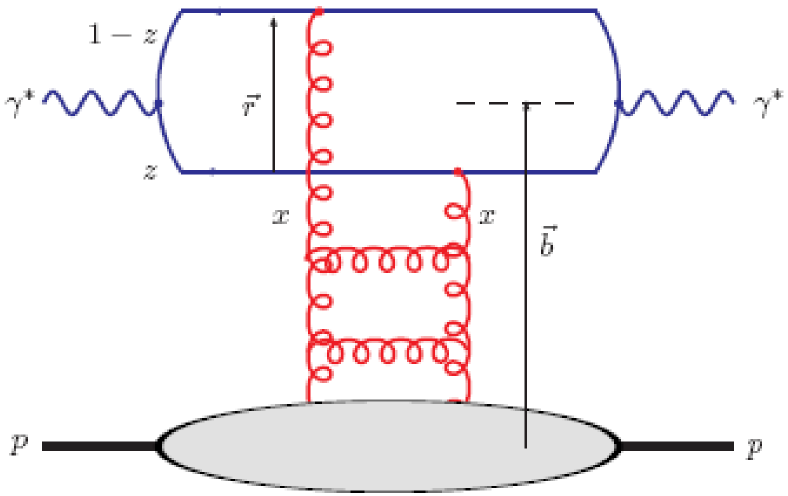




Diffraction at HERA is so large because it is a shadow of DIS (i.e. inelastic processes) ➔ dipole picture

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

Dipole picture of DIS equivalent to LO QCD for small dipoles

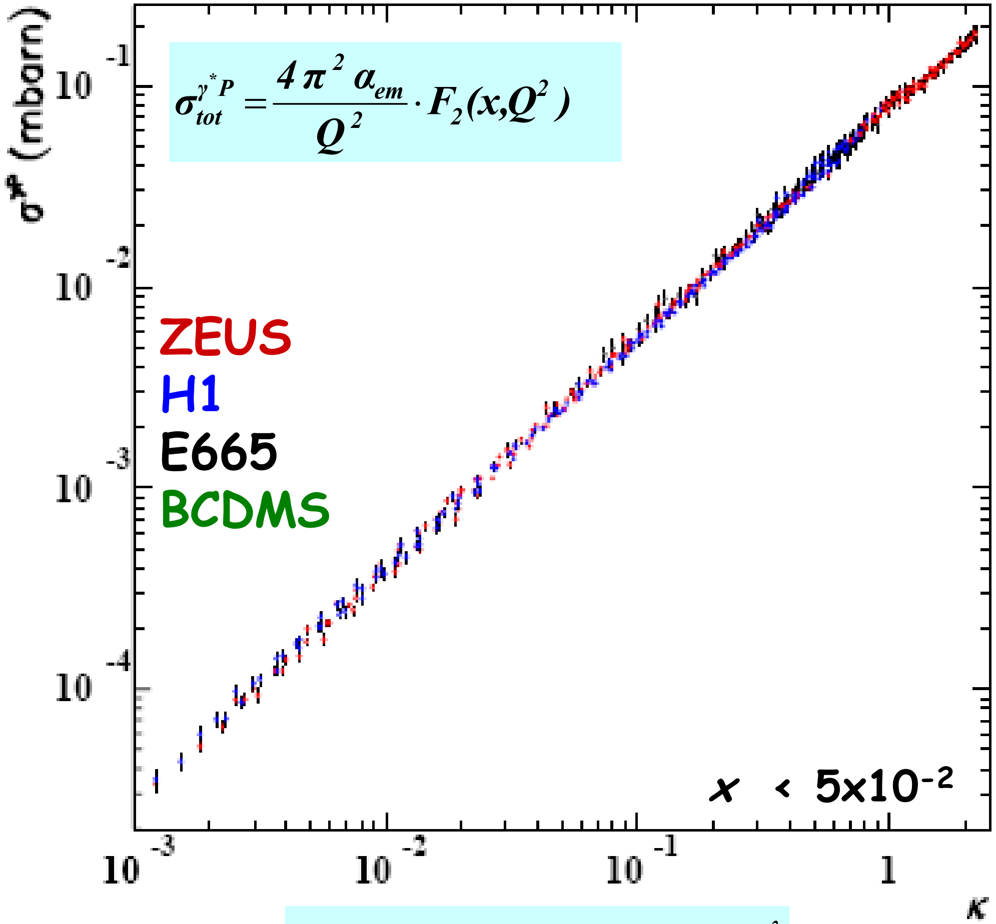


$$\sigma_{tot}^{\gamma^* p} = \int \Psi^* \sigma_{dip} \Psi$$

for small dipoles

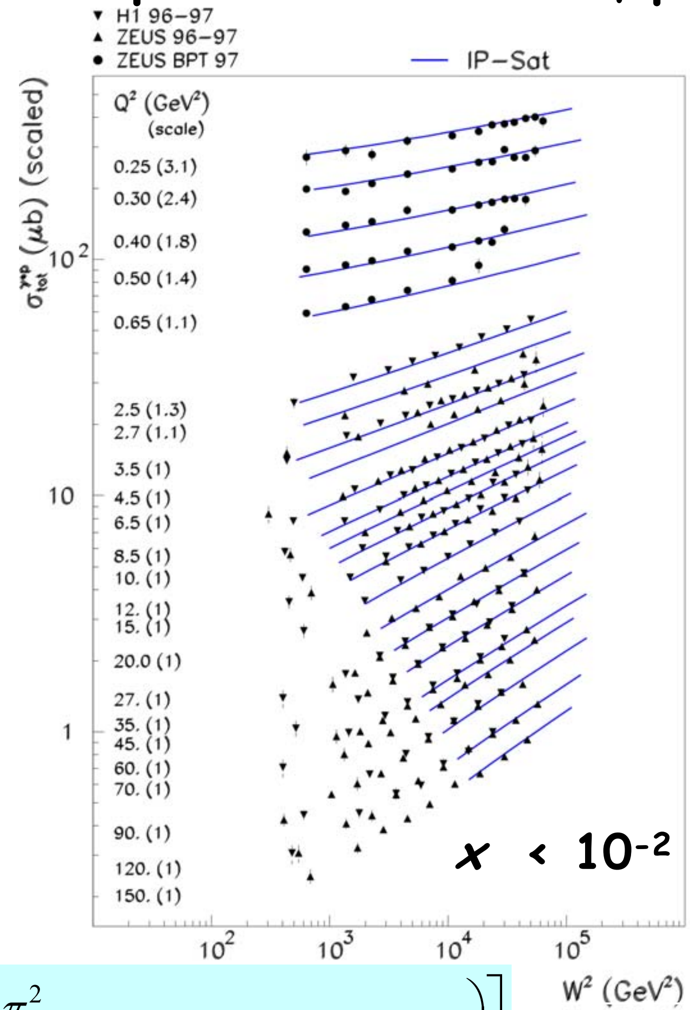
$$\sigma_{dip} = \frac{\pi^2}{N_C} r^2 \alpha_s(\mu^2) x g(x,\mu^2) T(b)$$

remarkable simplicity of DIS data



$$\sigma_{tot}^{\gamma^* P} \propto \kappa = \frac{1}{Q^2 + m_\rho^2} \cdot \left(\frac{1}{x}\right)^{\lambda}$$

Dipole description of the total $\gamma^* p$ cross-section



KMW

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

$$\frac{d\sigma_{dip}}{d^2 b} = 2\left[1 - \exp\left(\frac{\pi^2}{2N_C} r^2 \alpha_s(\mu^2) x g(x,\mu^2) T(b)\right)\right]$$

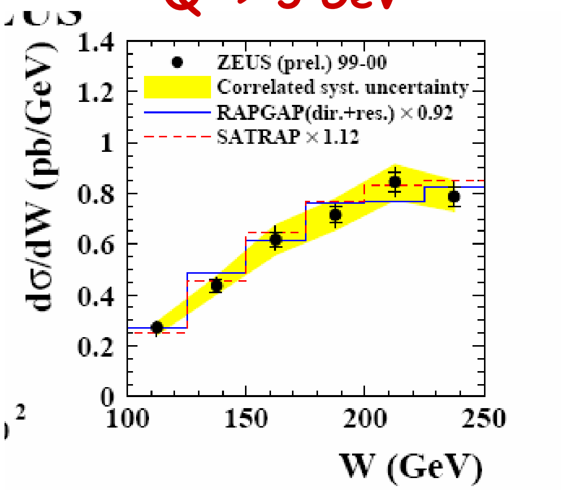
b-Sat with DGLAP ev. for xg(x,.)

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

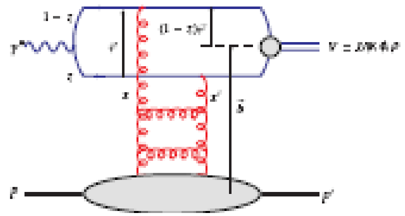
b- CGC or quantum-CGC

Diffractive Di-jets

$Q^2 > 5\ GeV^2$

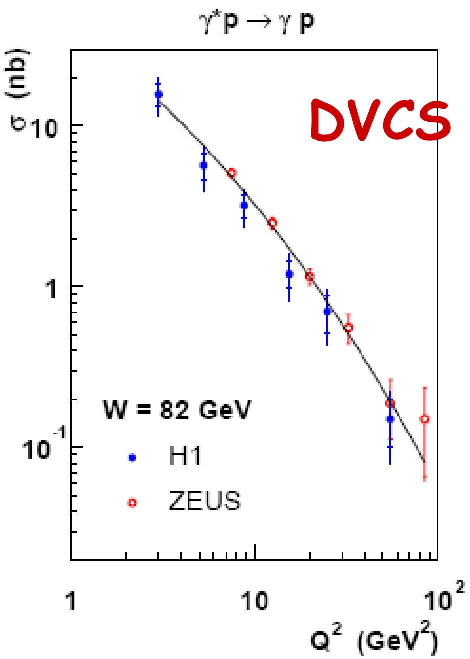


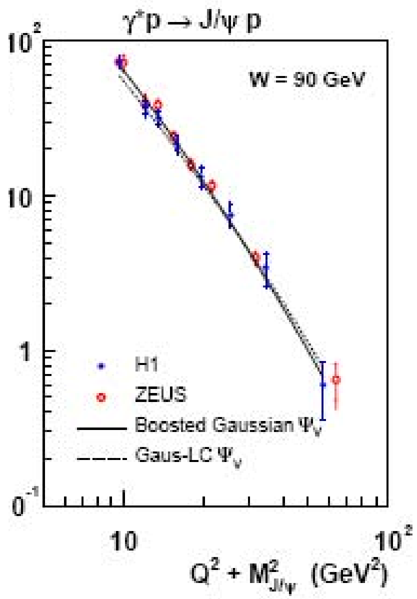
from gluon density convoluted with dipole wave functions we obtain simultaneous prediction/description of many reactions

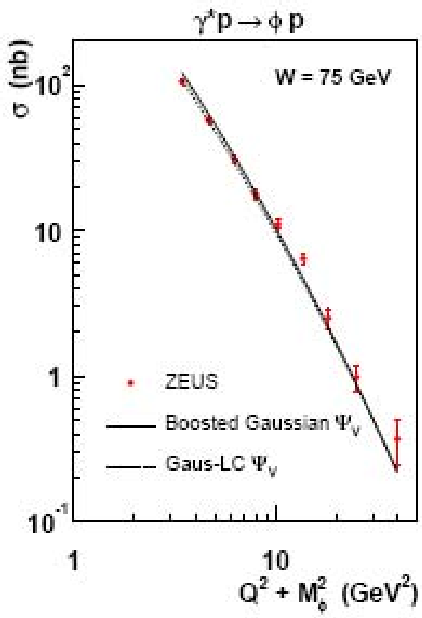


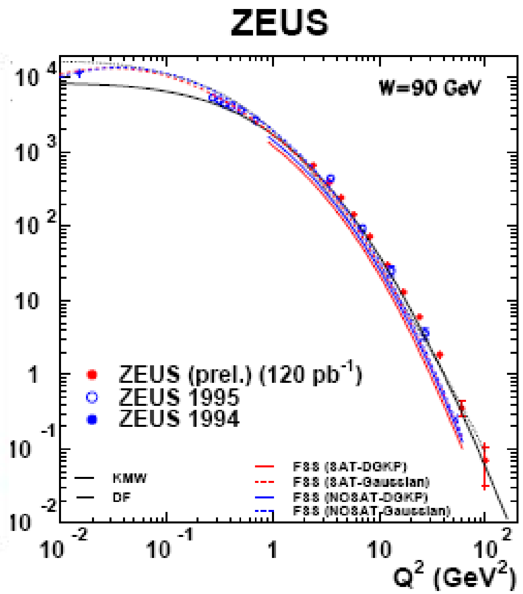
Vector Mesons

DVCS





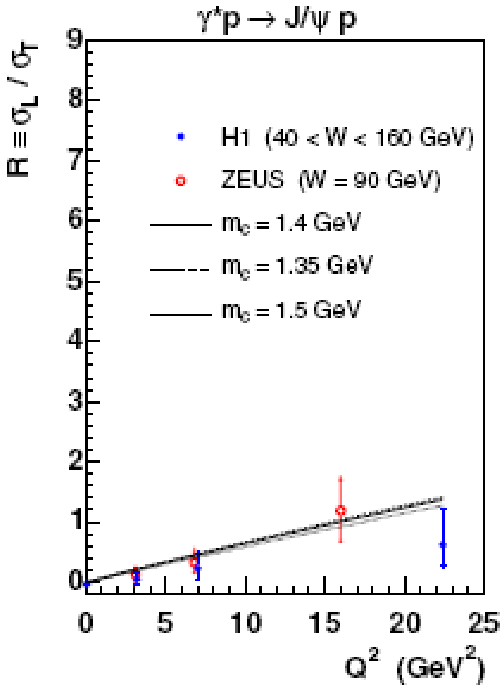


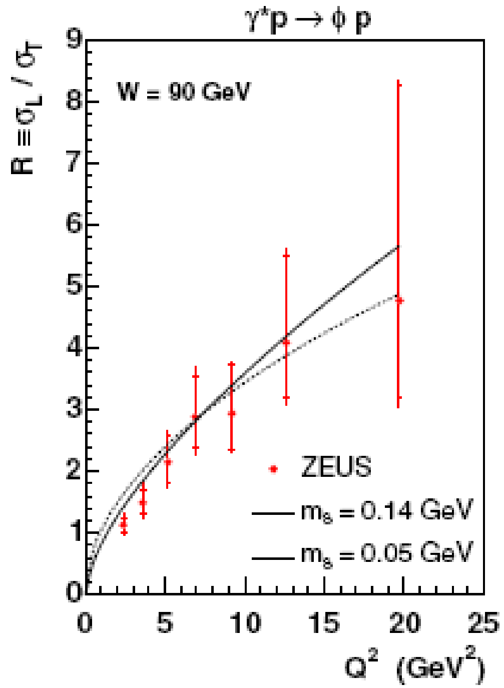


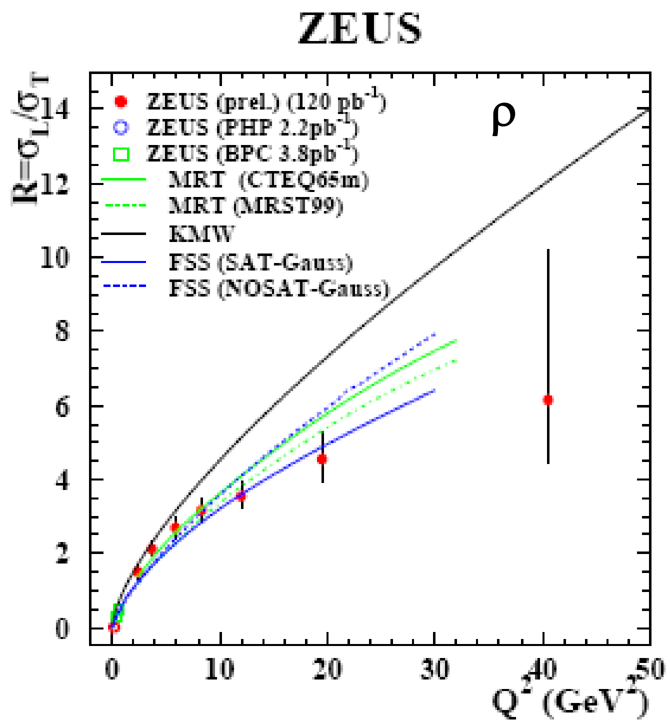
Note: educated guesses for VM wf work very well

properties of wave functions

Ratios of longitudinal/transverse x-sections







good description of J/Ψ and ϕ ratios

KMW

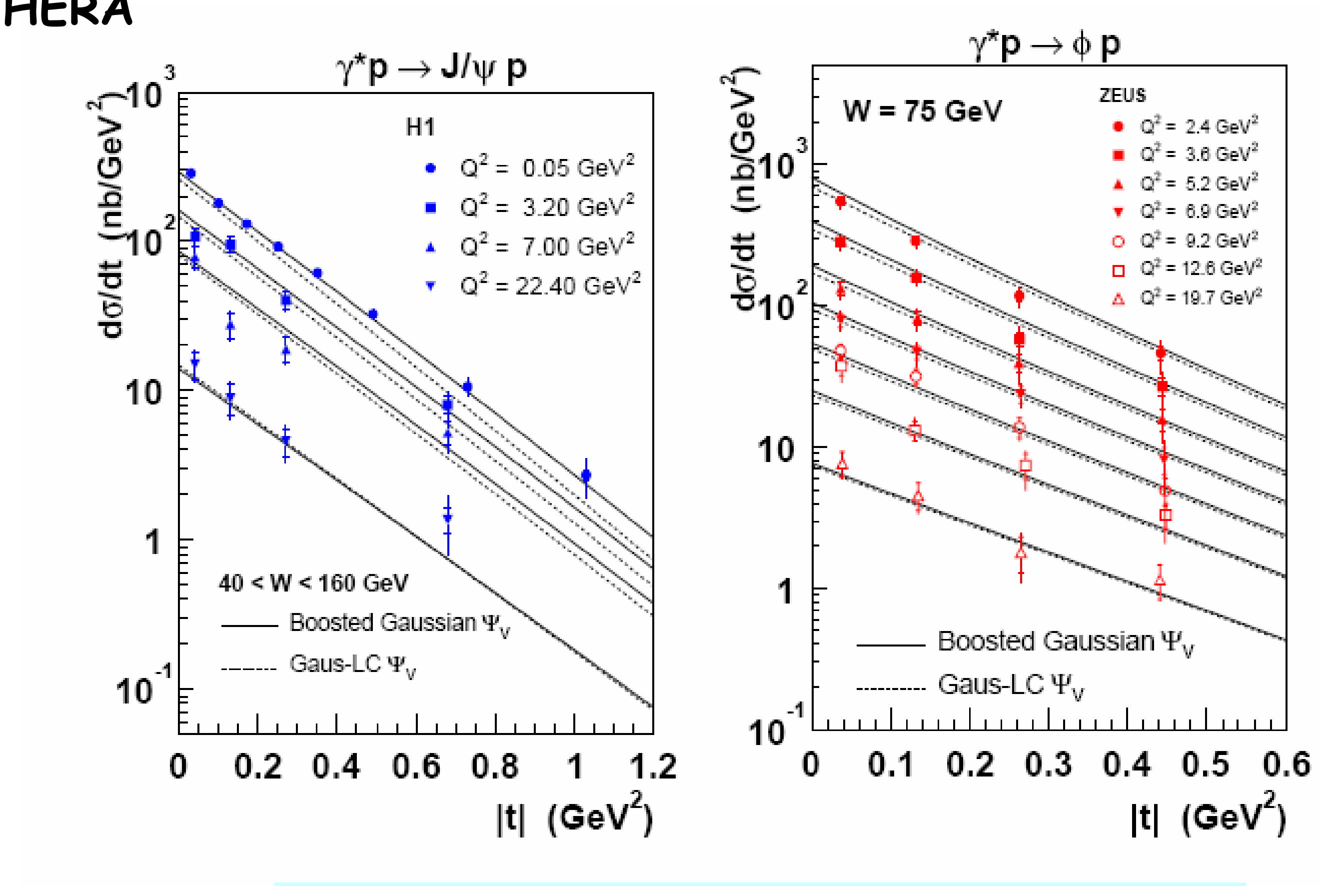
ρ is more difficult

wave function?

unnatural parity exchange?

Nuclear tomography

t-distributions
at HERA



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

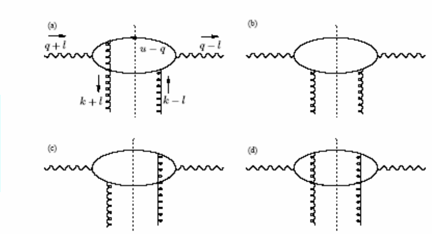
➔ **gaussian shape of the proton in the impact parameter b**

Description of the size of interaction region B_D

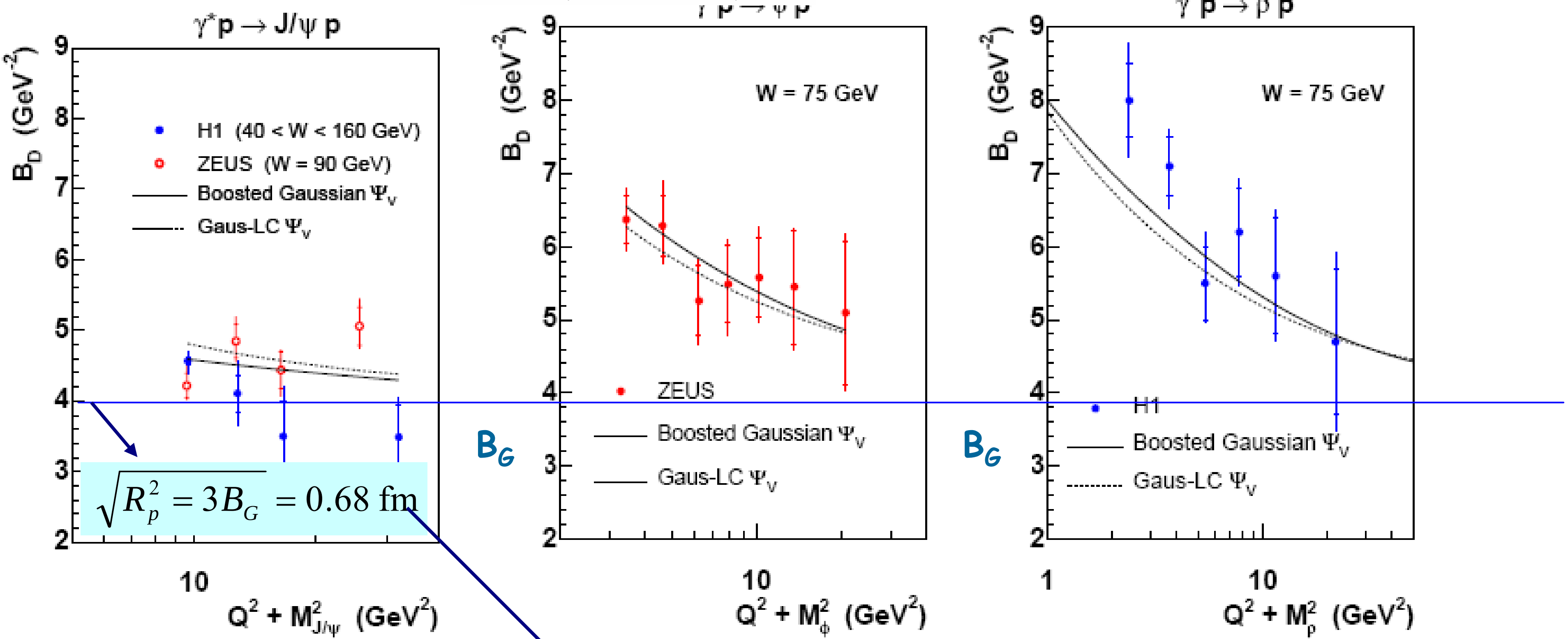
$$\frac{d\sigma^{diff}}{dt} \sim \exp(B_D \cdot t) \qquad \Rightarrow T(b) \sim \exp(-\vec{b}^{\,2}/2B_G)$$

Modification by Bartels, Golec-Biernat, Peters

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



KMW

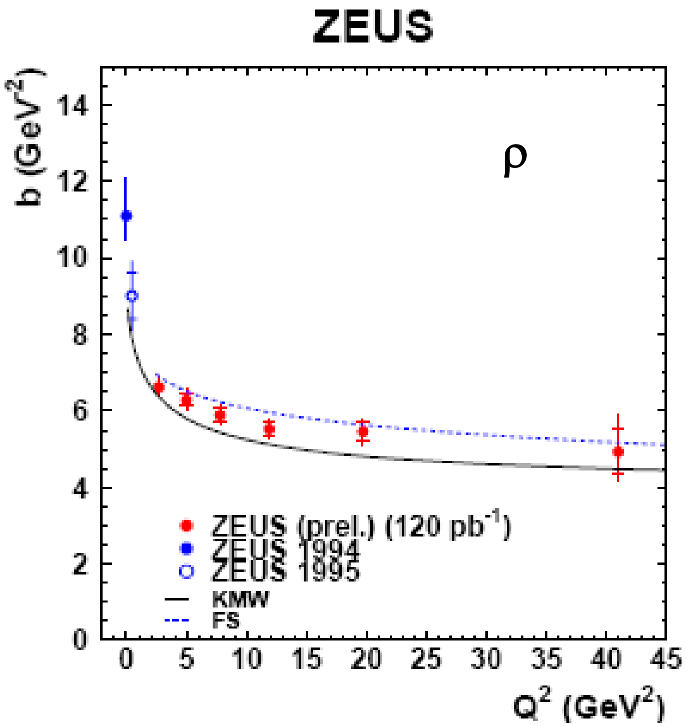


$$\sqrt{R_p^2 = 3B_G} = 0.68 \text{ fm}$$

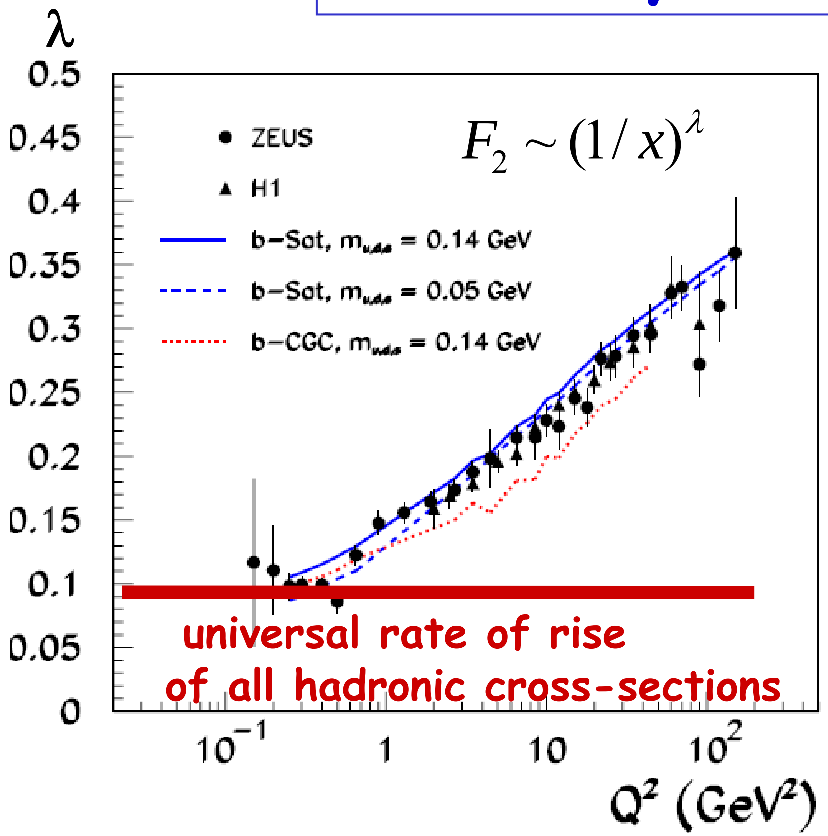
$$R_p = 0.870 \pm 0.008 \text{ fm}$$

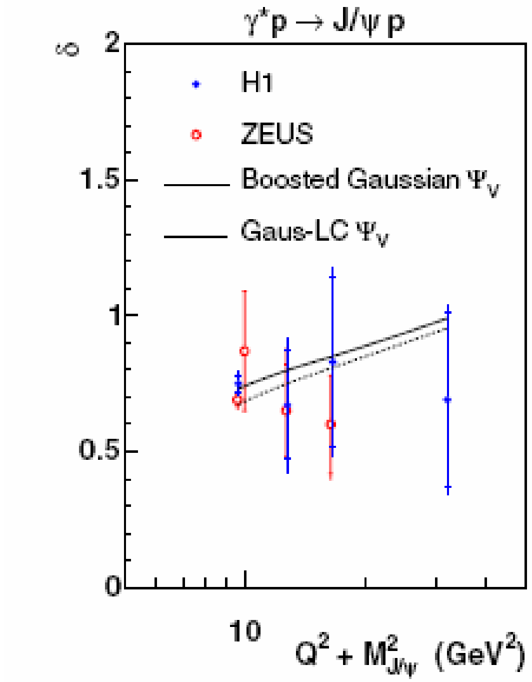
$$\Rightarrow B_G = 6.48 \text{ GeV}^2$$

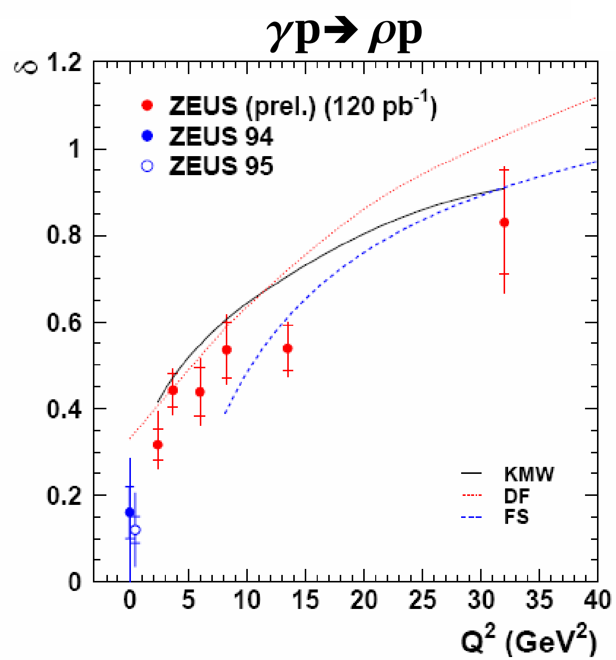
the gluonic proton radius smaller than the quark radius


ZEUS
b (GeV^2)
ρ
ZEUS (prel.) (120 pb^-1)
ZEUS 1994
ZEUS 1995
KMW
FS
Q^2 (GeV^2)

Discovery of HERA







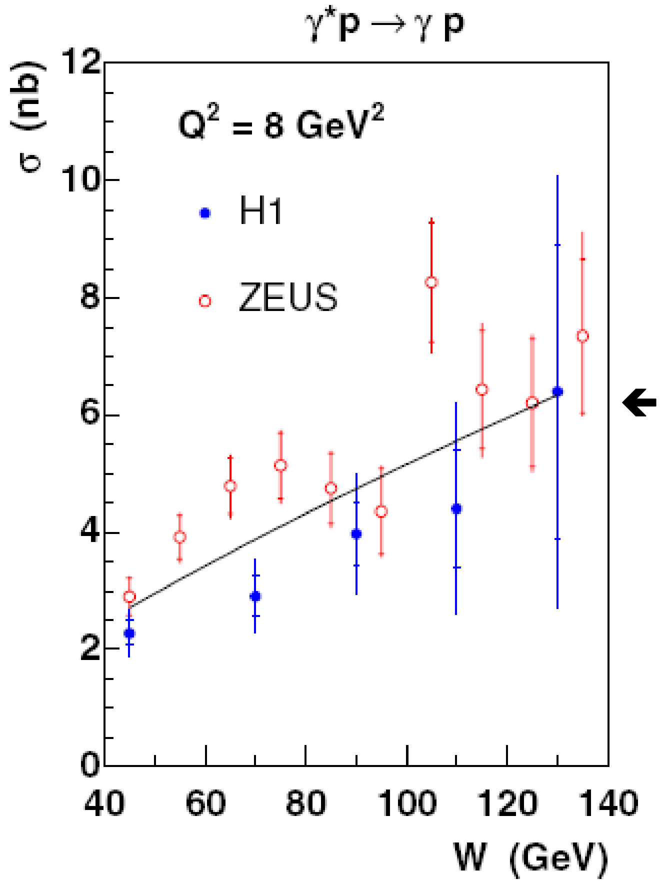
Universality of the observed intercepts

$$\alpha(Q^2) = 1 + \lambda = 1 + \delta/2$$

➔ **Pomeron is a fundamental QCD object**
soft and hard *IP* join together

Pomeron at work

Rise of the DVCS cross-sections



➔ b-Sat or IP-Sat

At EIC it should be possible to reduce the errors by a large factor, O(100), ➔ study of t-dependent rate of rise

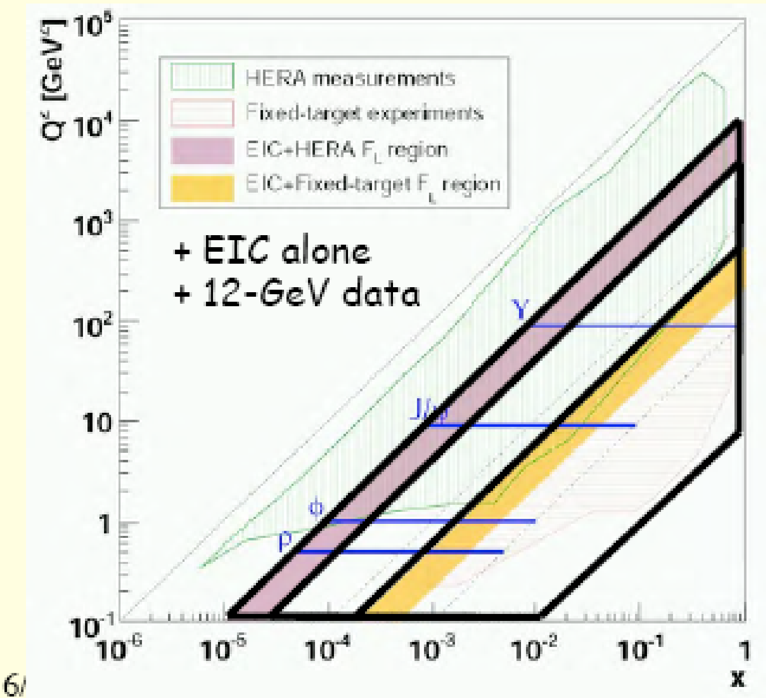
➔

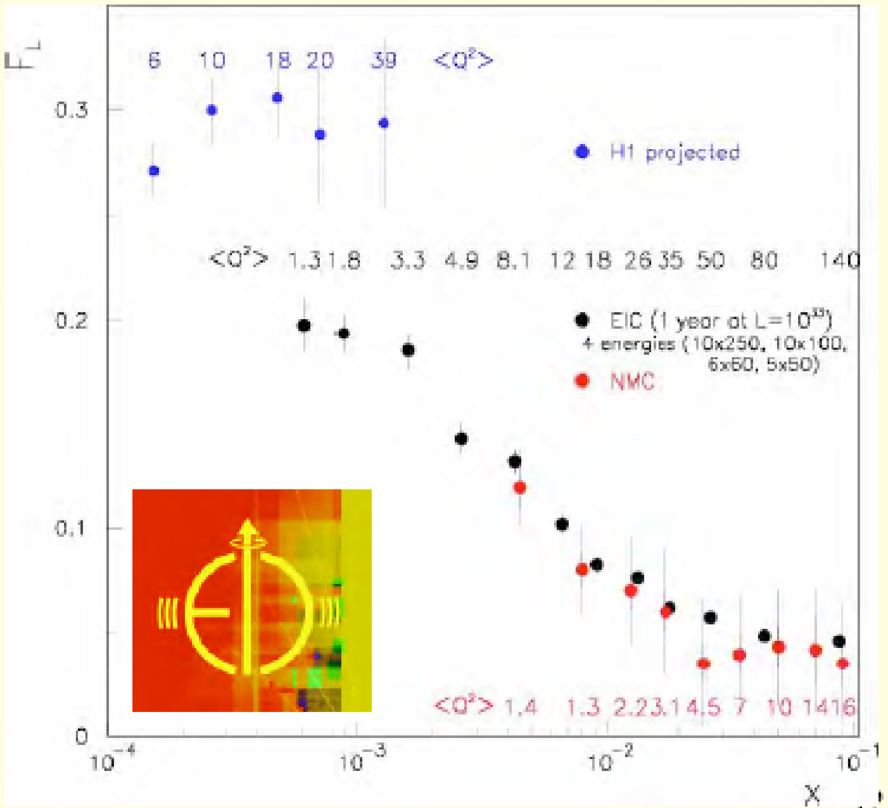
study of b-dependent Pomeron evolution

– direct insight into saturation inside the proton or nuclei

Longitudinal Structure Function F_L

- Requires energy variability of collider beam with minimal loss of luminosity
- Highly sensitive to effects of gluon, and an independent method to get to gluon distribution



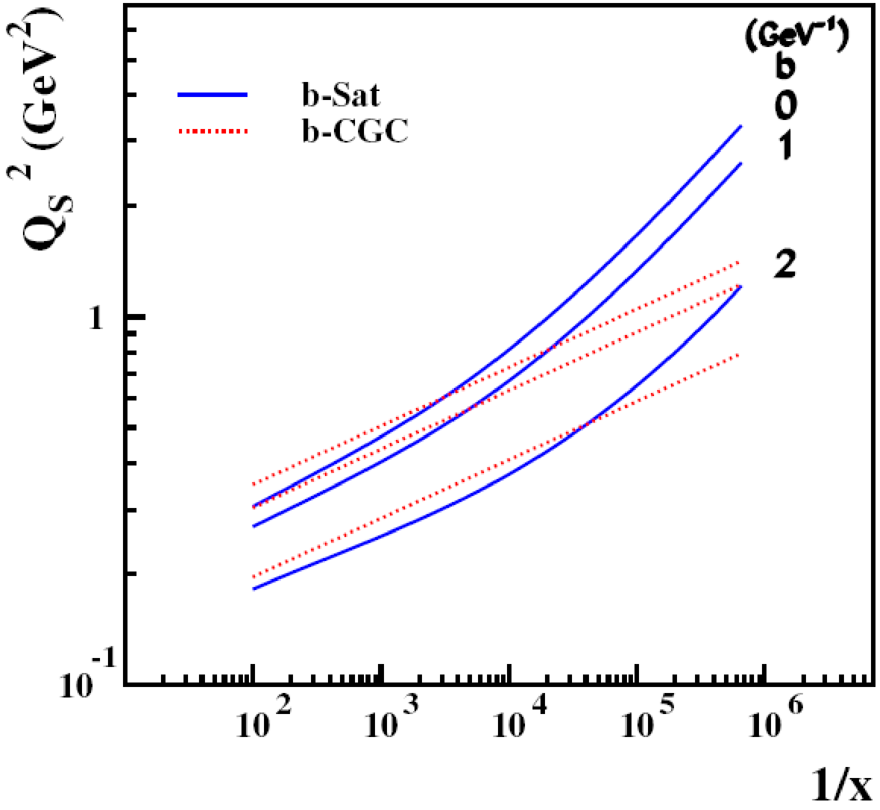


(includes systematic uncertainties)

Saturation scale at HERA

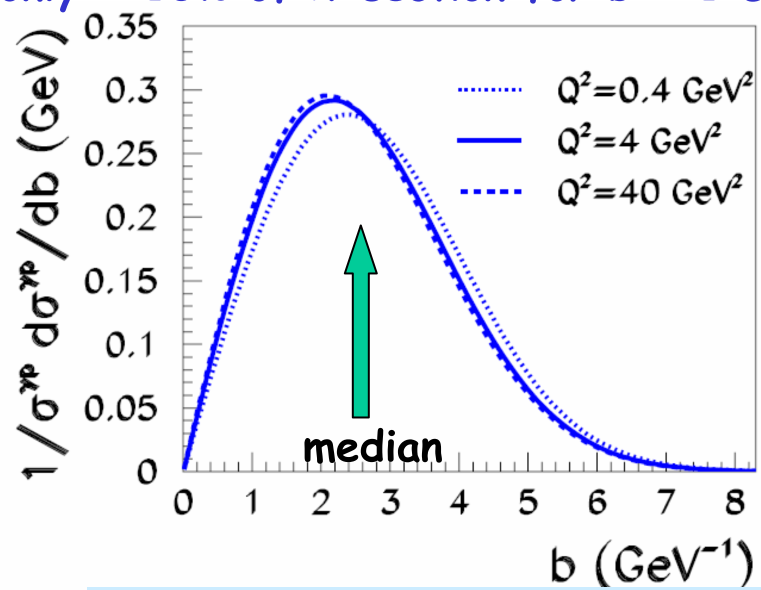
(a measure of gluon density at which gluon re-scattering starts to be substantial)

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



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

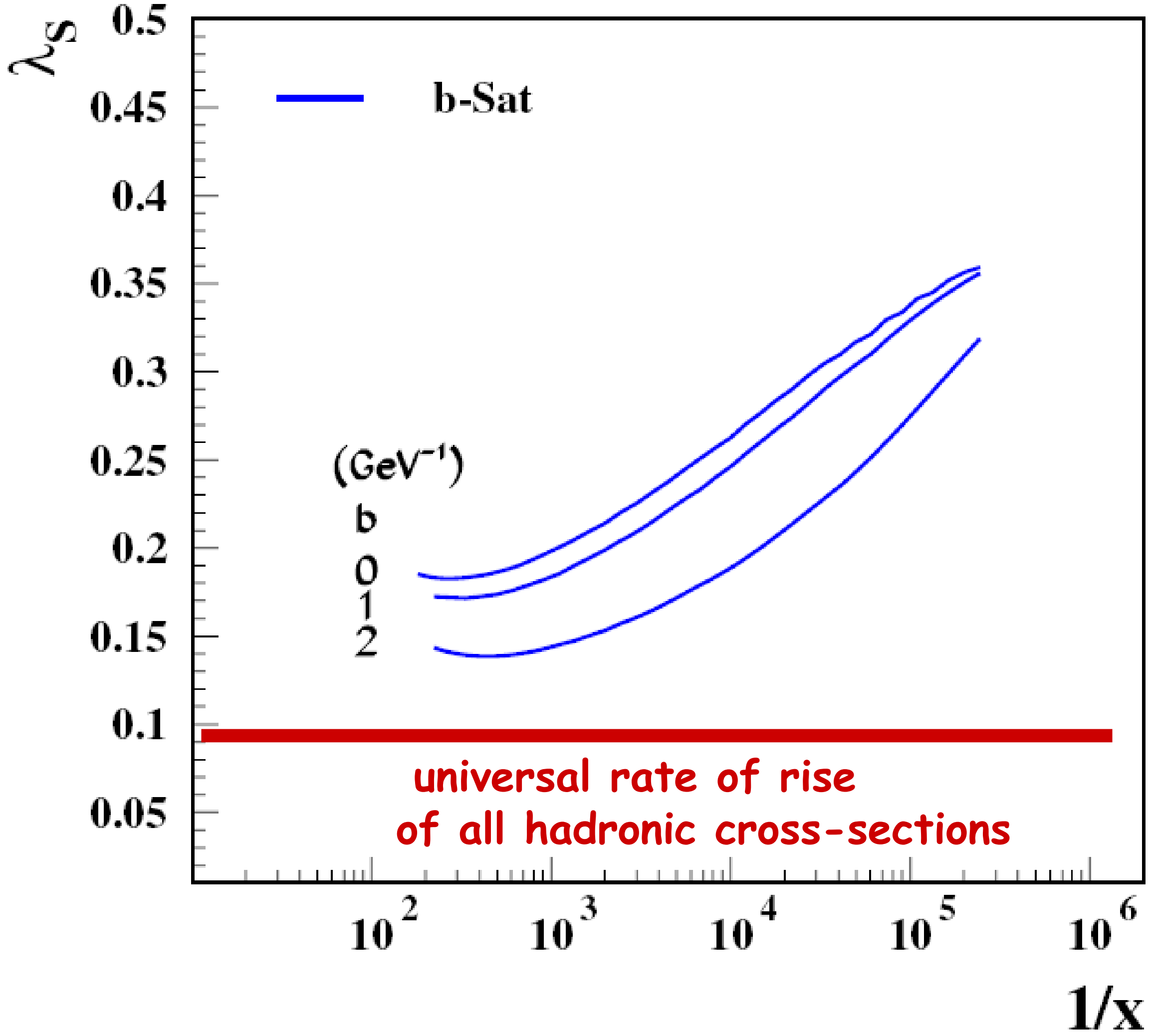
only ~ 10% of x-section for b < 1 GeV^{-1}



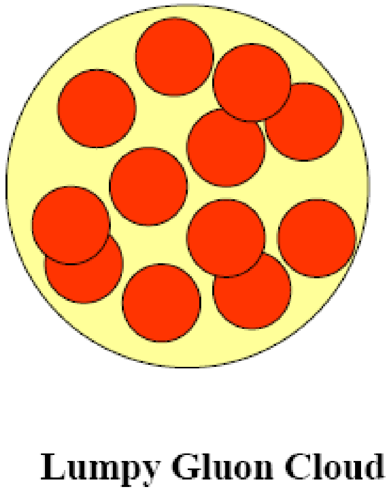
Q_S^{RHIC} ($x=10^{-2}$) ~ Q_S^{HERA}($x=10^{-4}$)

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

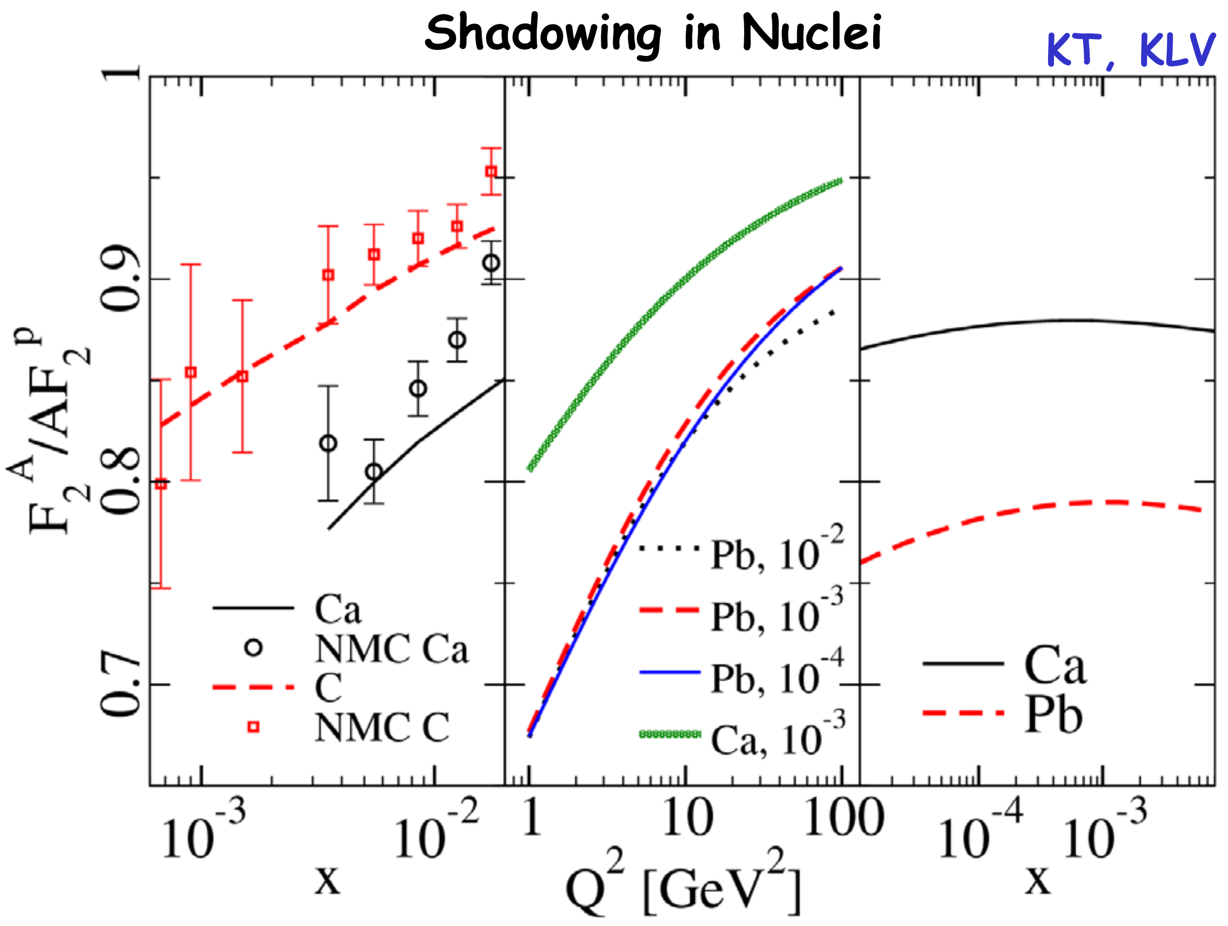
Is saturated state observed at HERA perturbative?

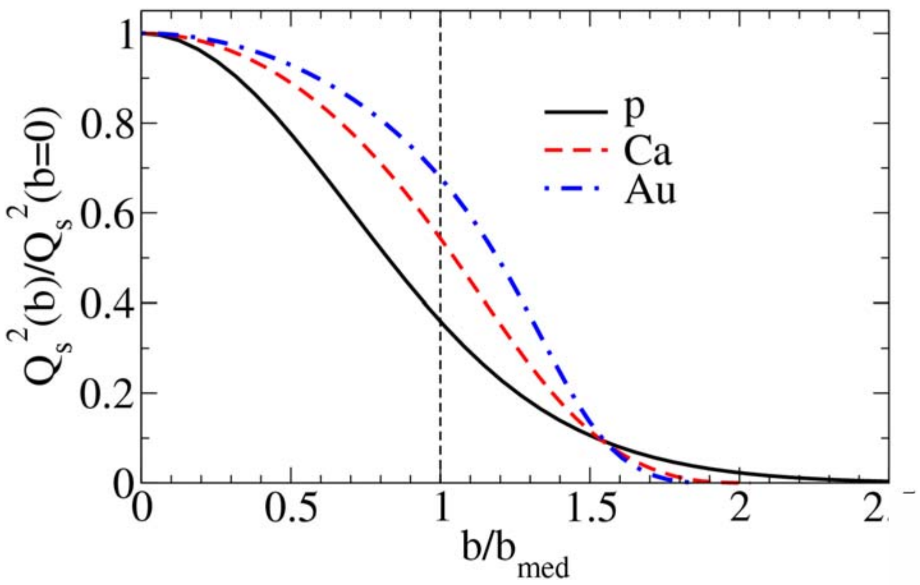


DIS on Nuclei



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



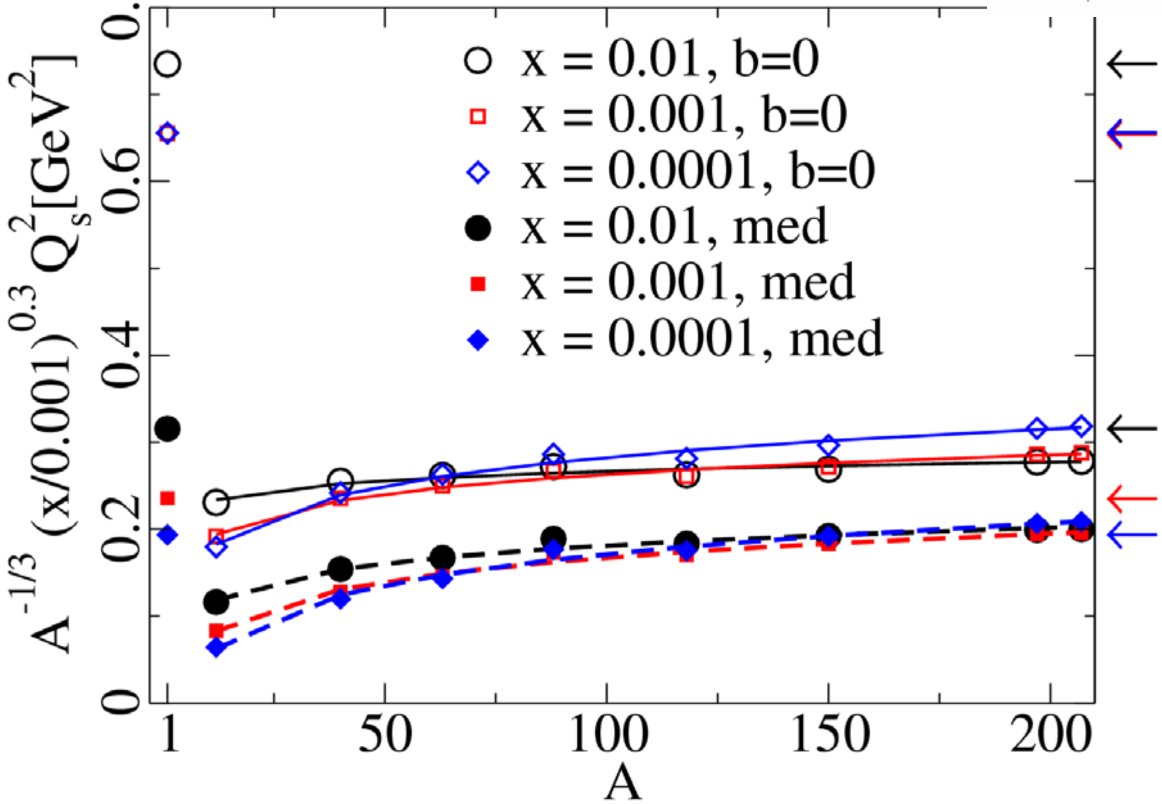


Nuclear enhancement of universal dynamics of high parton densities

Kowalski, Lappi, Venugopalan

hep-ph/0705.3047

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



large enhancement of saturation scale in nuclei

$200^{1/3} \sim 6$ ➔

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

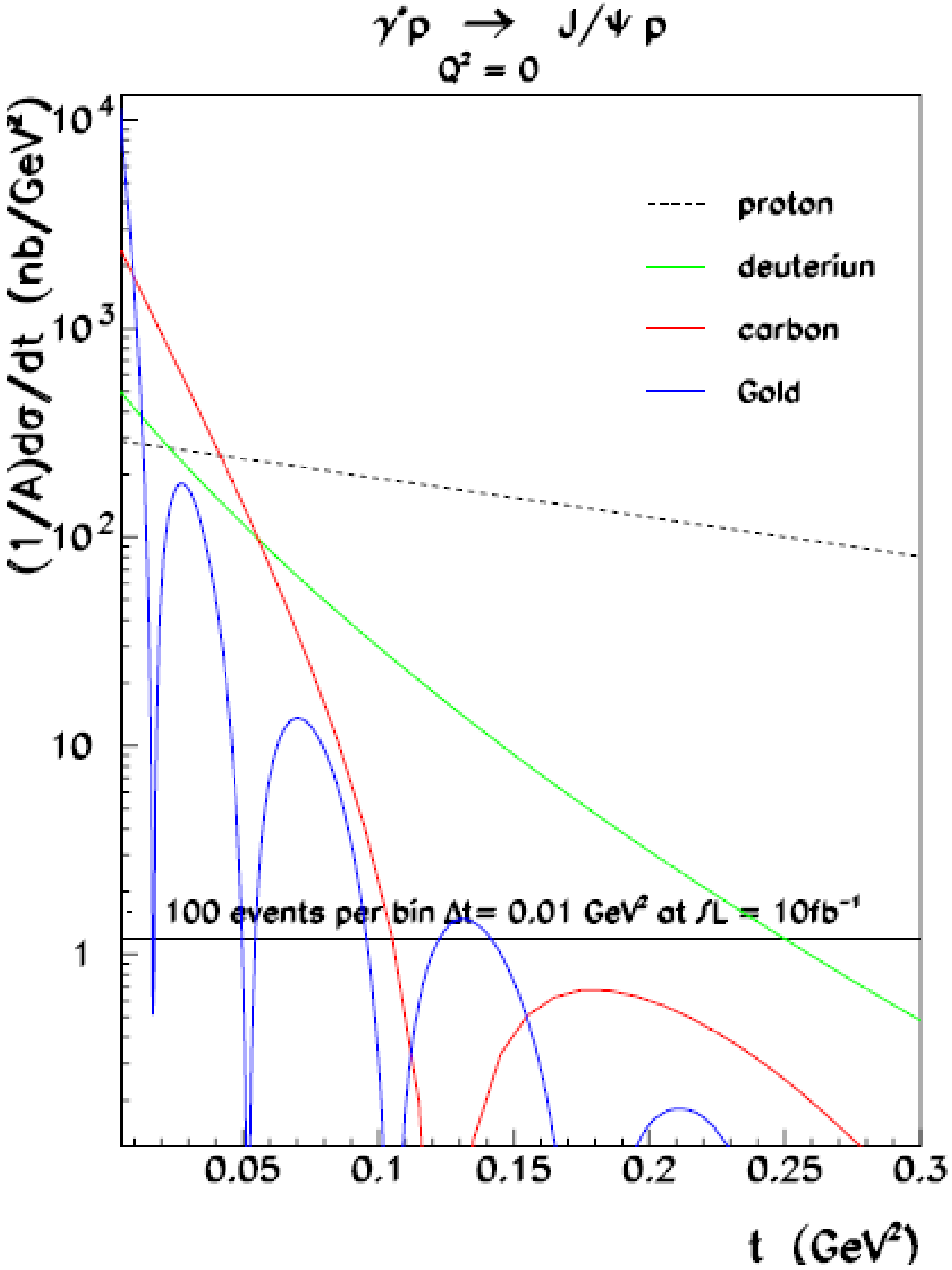
t-distributions for exclusive diffractive meson production on proton and nuclei at EIC

first estimate of the expected measurement precision:

$\Delta p_T < 30$ MeV, $t \sim p_T^2$

$\Delta t < 0.01$ GeV^2

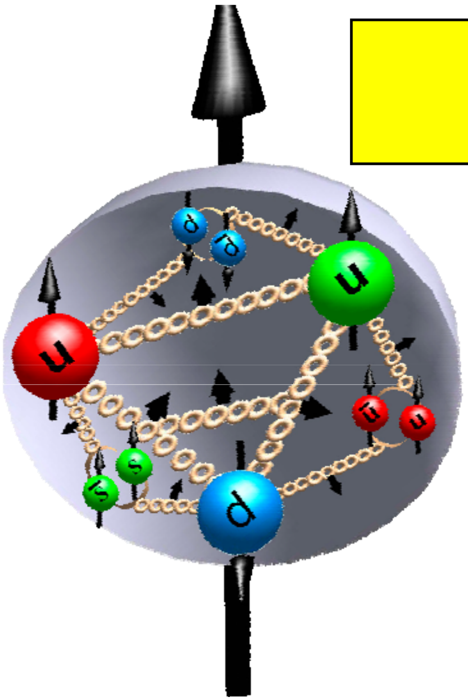
for proton and light nuclei



The Spin Structure of the Nucleon

Most of the mass in the world arises from QCD, ie from a highly relativistic system of spin-$\frac{1}{2}$ quarks interacting via exchange of spin-1 gluons.

It is essential to understand how the proton spin-$\frac{1}{2}$ arises from its quark and gluon constituents and their orbital angular momentum contributions



$$\frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_g$$

- quark contribution $\Delta\Sigma \approx 0.25$
- gluon contribution $\Delta G \approx 1 \pm 1$
- valence quark polarizations as expected
- measured anti-quark polarizations are consistent both with zero and also with sizable negative sea polarization

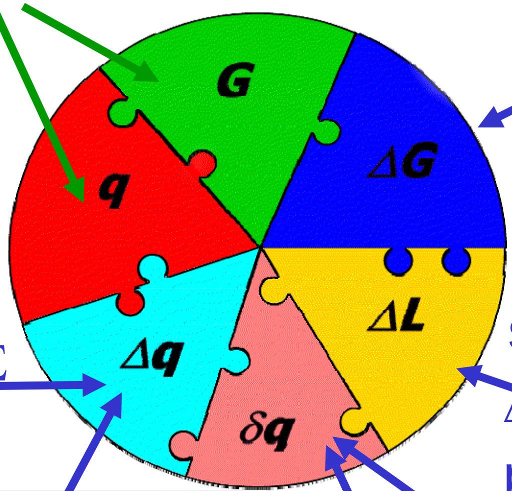
➔ significantly more precise data required

View at the nucleon structure

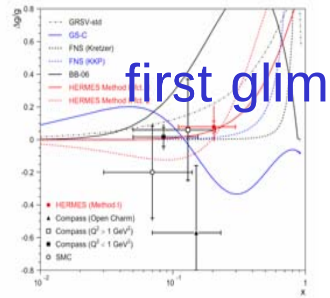
with help of Delia Hasch

from unpolarised DIS

polarised DIS

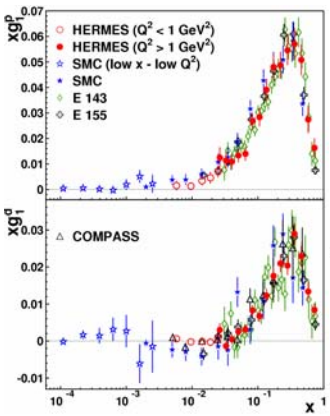


evolution
diffractive J/Psi
charm, ...



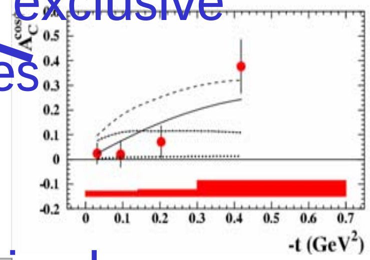
first glimpse

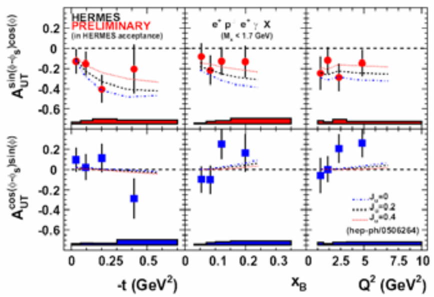
ΔΣ



signals of GPD, ex: DVCS

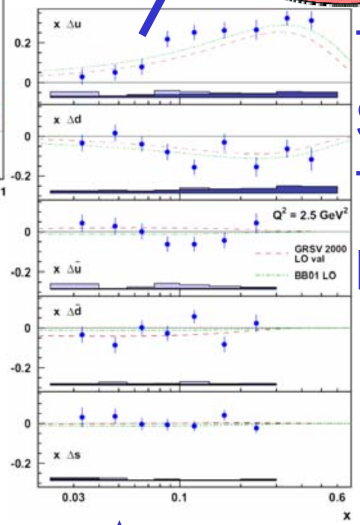
ΔL from exclusive processes

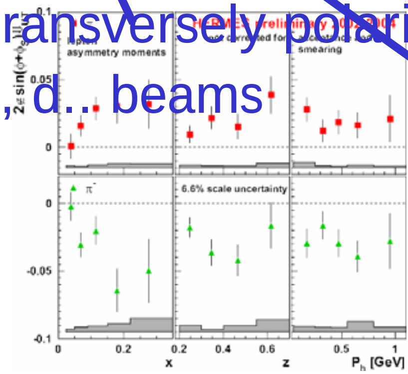


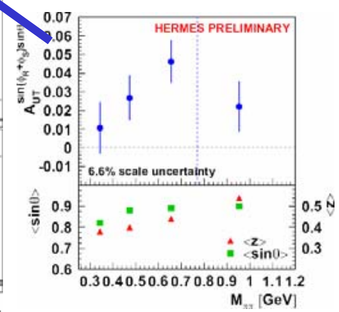


Transverse Structure

Transversely polarized p, d... beams







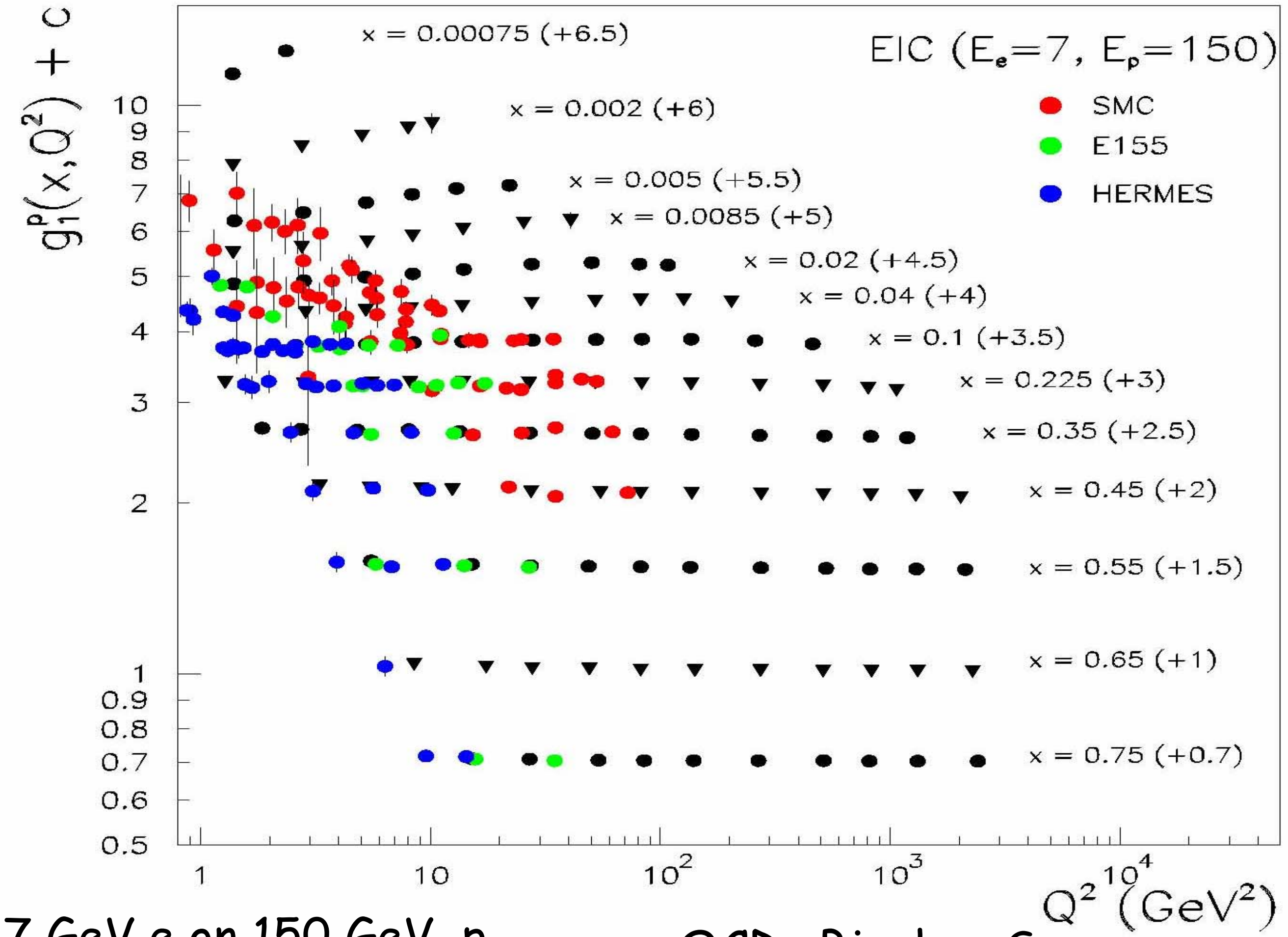
→direct flavour decomp.

→constrain on Δs

→transversity is non-zero!

→first T-odd DF in DIS

EIC will extend reach of spin-dependent inclusive measurements by several orders of magnitude



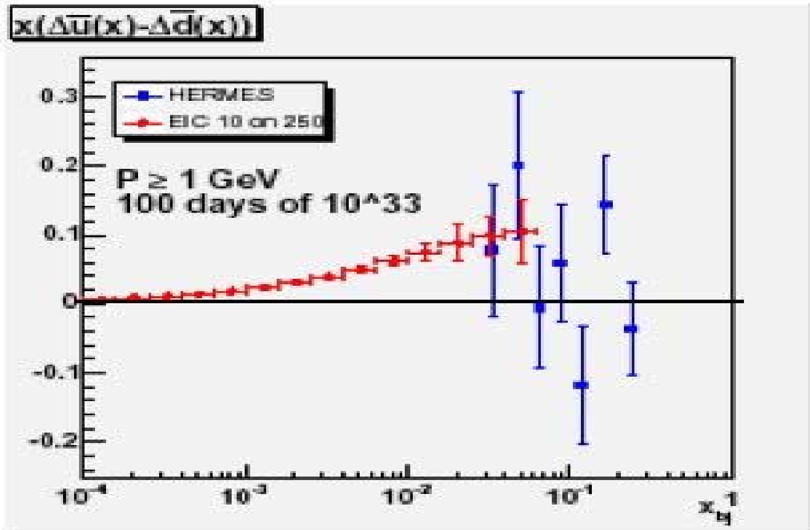
A. Bruell
R. Ent

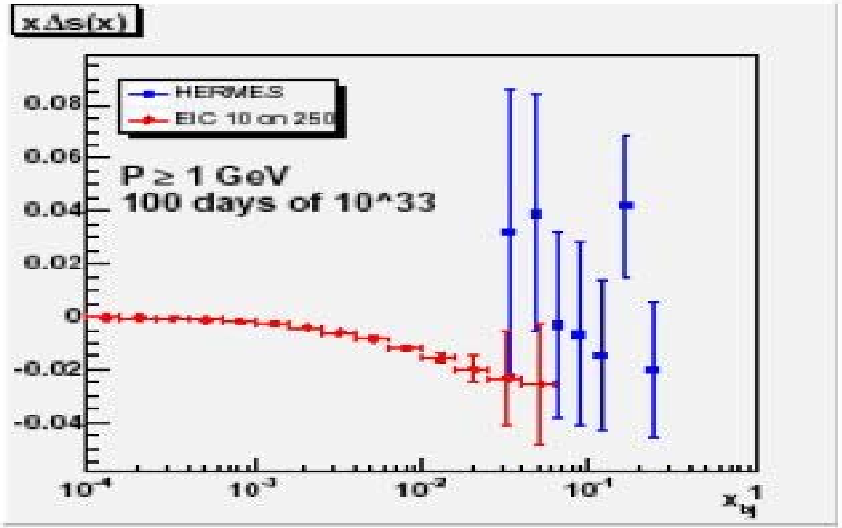
7 GeV e on 150 GeV p
5 fb^{-1} integrated luminosity

QCD Bjorken Sum Rule: $\Gamma_1^p - \Gamma_1^n = 1/6\, g_A [1 + O(\alpha_s)]$
Sum rule verified at present to ±10%→ 1%

EIC determination of polarized quarks and anti-quarks

Hadron identification necessary

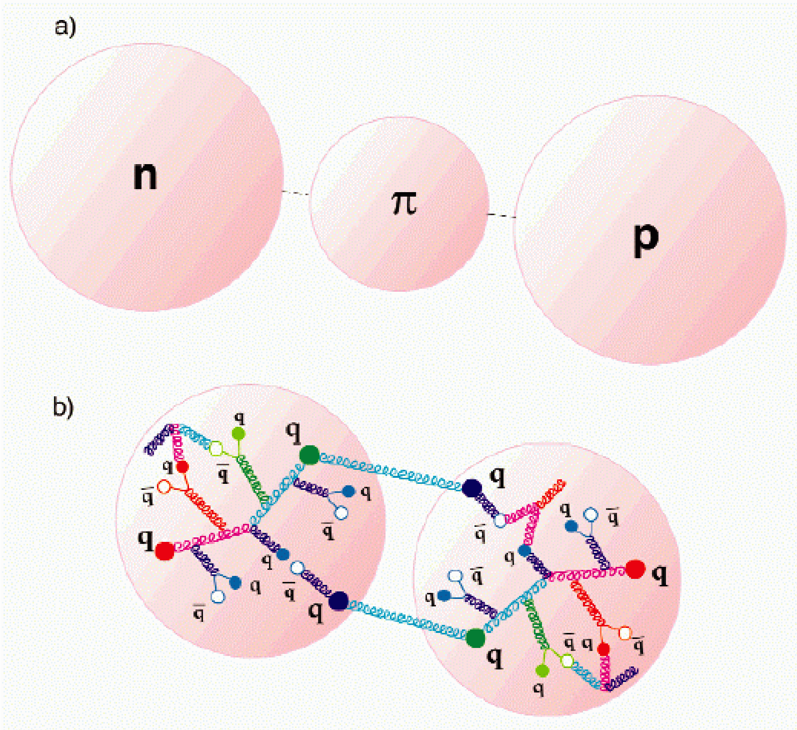




10 GeV e on 250 GeV p
10 fb^{-1} integrated luminosity

E. Kinney et al.

Nuclear Binding



How can one understand nuclear binding in terms of quarks and gluons?

Natural Energy Scale of QCD: O(100 MeV)

Nuclear Binding Scale O(10 MeV)

Does it result from a complicated detail of near cancellation of strongly attractive and repulsive terms in N-N force, or is there another explanation?

Complete spin-flavor structure of modifications to quarks and gluons in nuclear system may be best clue.

DIS is more interesting than we all expected

lets continue !