The J/ψ way to nuclear structure

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Brookhaven, 18th of June 2009

Why eA physics with J/ψ's?:

Because:

Physics of nuclei is still poorly understood

from the perspective of QCD it is not clear

- what gives proton or neutron its mass and size,
- why nuclear radius grows with $A^{1/3}$

  (atomic radius remains ~ constant with Z)
- why quarks and gluons contained in different nucleons are not merging into a common bag in a nucleus

  (common bag = delocalization = energy saving)

Textbook knowledge:

lack of good probe to view inside nuclei

electrons can only see the electric charge distribution

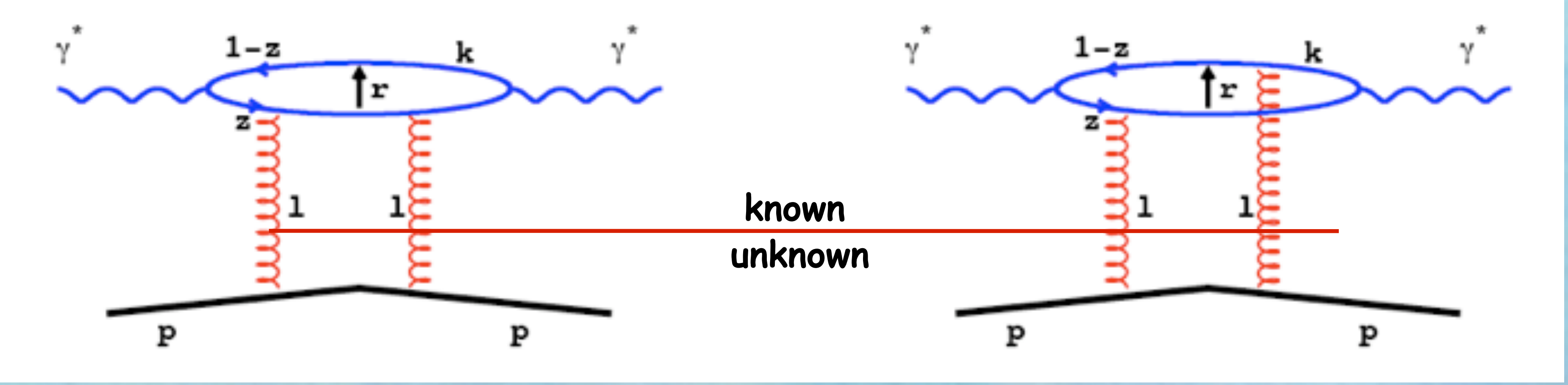
protons are not simple probes

Feynman: scattering of hadrons on hadrons is like colliding Swiss watches to find out how they are build

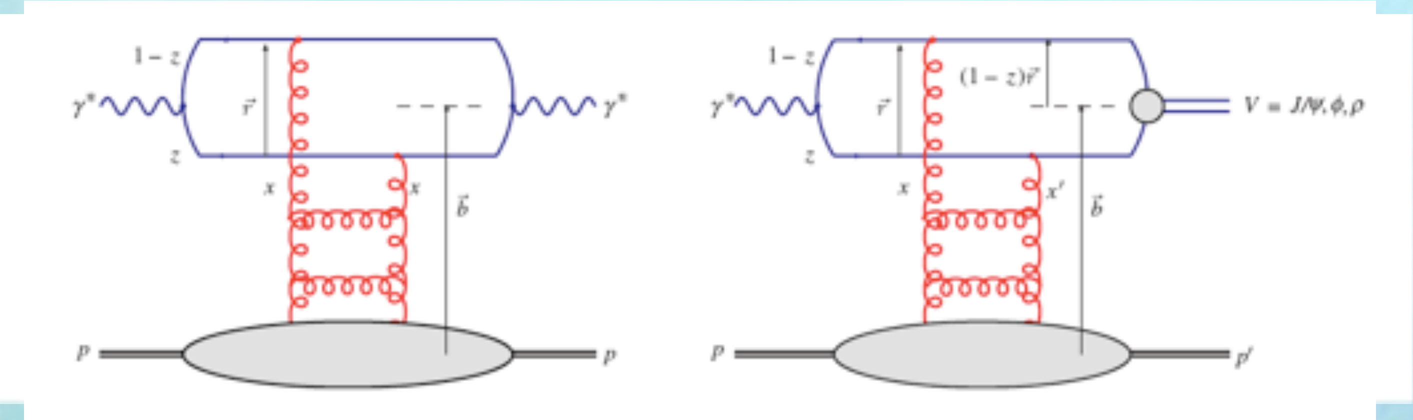
A novel tool to investigate nuclei: Quark-antiquark color dipoles

Dipoles interact strongly with the nuclear matter but the interaction is well understood in QCD

QCD in LO



dipole life time ≈ $1/m_p x$ → 20 to 2000 fm, for x^{-2} to x^{-4}



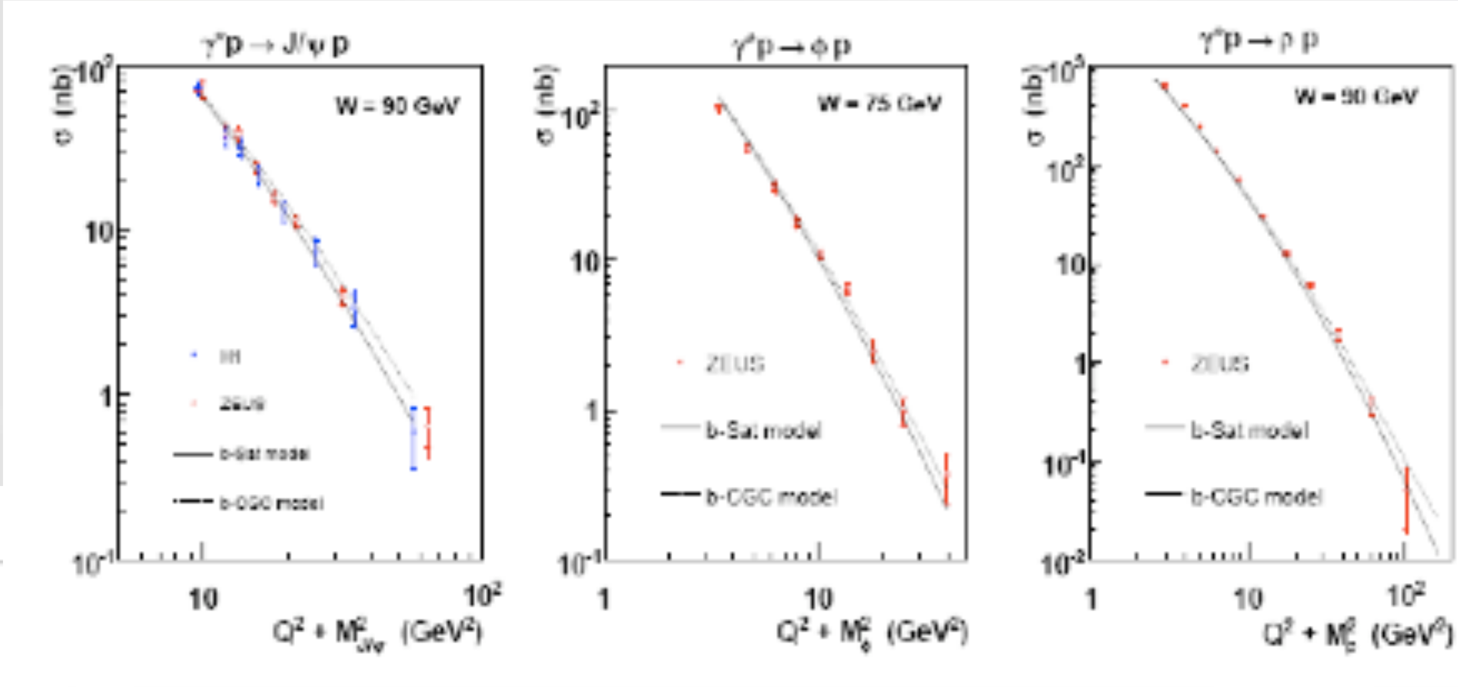
$$\sigma_{tot}^{\gamma^* p} = \int \Psi^* \sigma_{q\bar{q}} \Psi$$ ← **Optical Theorem** → $$\frac{d\sigma_{VM}^{\gamma^* p}}{dt} \sim \left| \int \Psi_{VM}^* \frac{d\sigma_{q\bar{q}}}{d^2 b} \sigma_{q\bar{q}} \Psi e^{-i\vec{b}\vec{\Delta}} \right|^2$$

$$\frac{d\sigma_{q\bar{q}}}{d^2 b} \sim r^2 \alpha_S x g(x, \mu^2) T(b)$$

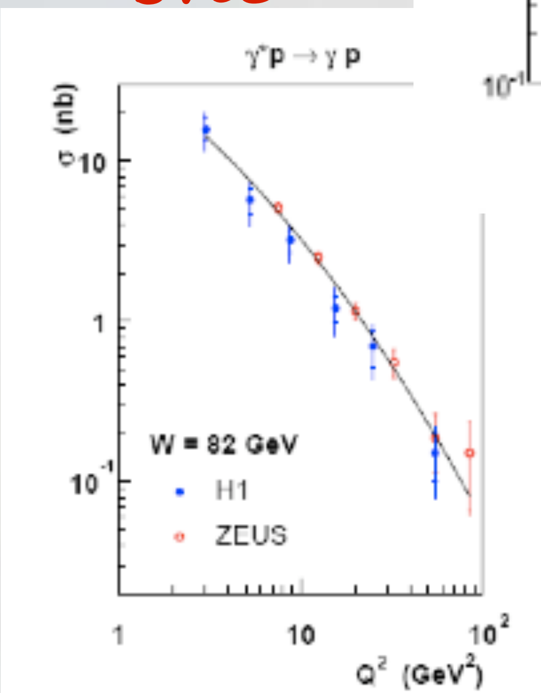
The same, universal, gluon density describes
the properties of many reactions measured at HERA:

F_2 , inclusive diffraction,
exclusive J/Psi, Phi and Rho production
DVCS, diffractive jets

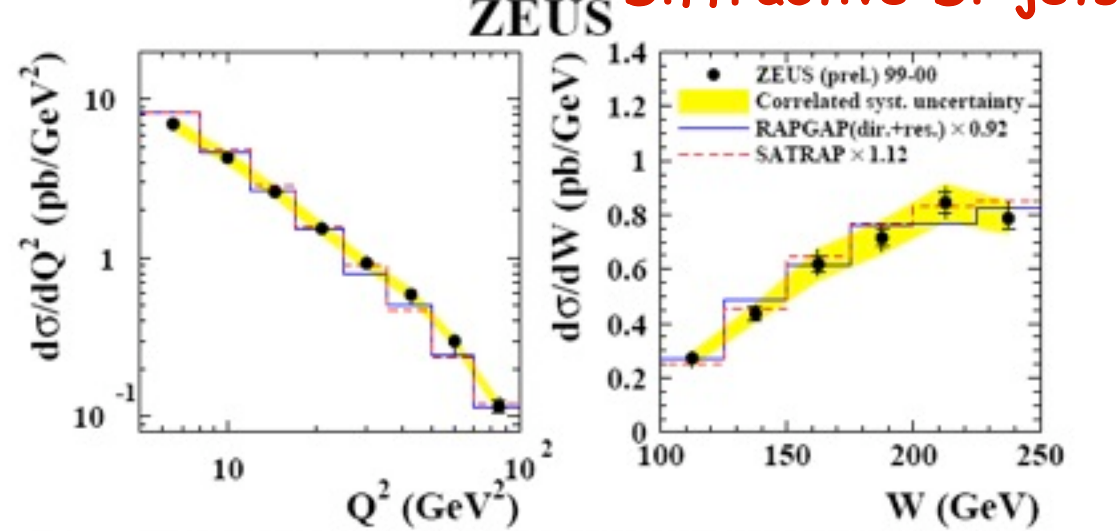
Vector Mesons



DVCS

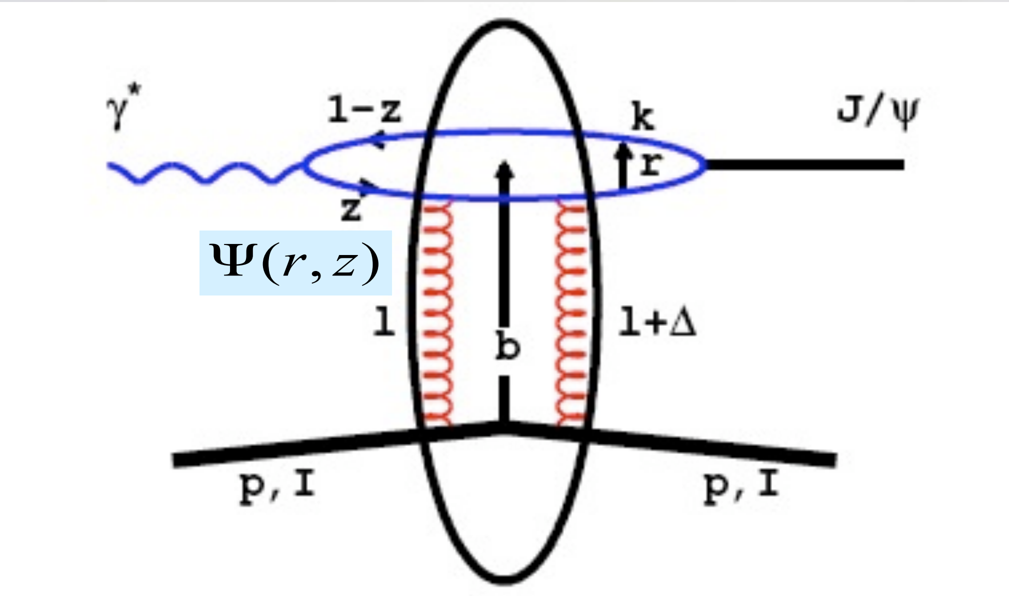


Diffractive Di-jets



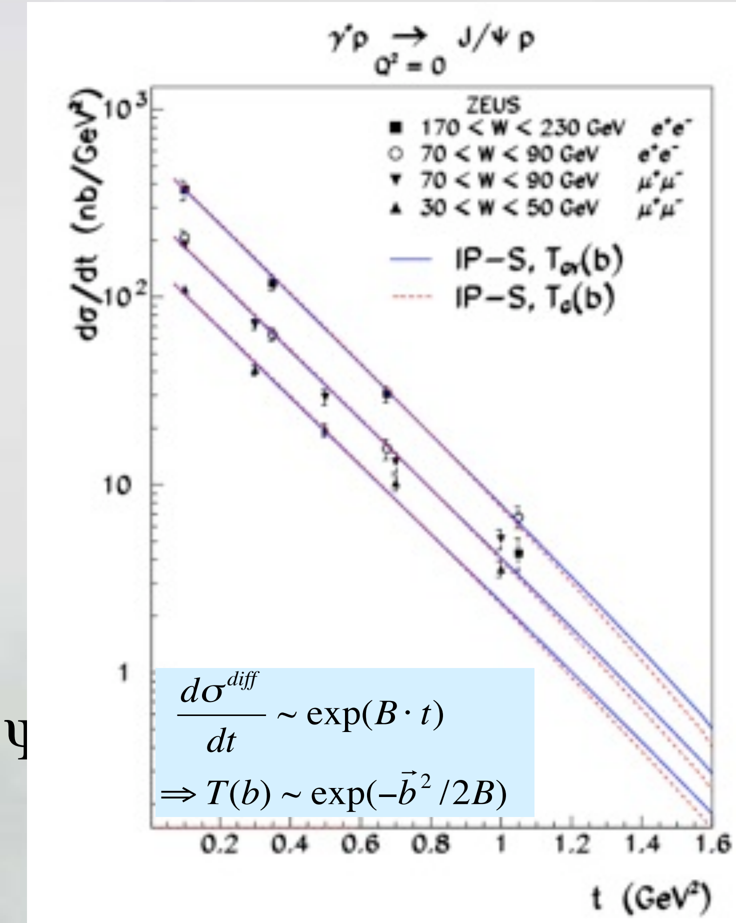
Note: educated guesses for VM wf are working very well

Extracting Proton Shape using dipoles



$$\frac{d\sigma^{\gamma^* p}_{VM}}{dt} = \frac{1}{16\pi} \left| \int e^{-i\vec{b}\cdot\vec{\Delta}} \Psi^*_{VM}\, 2\left\{ 1 - exp(-\frac{\Omega}{2}) \right\} \Psi \right.$$

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



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

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

KT, KMW

T(b)-proton shape

Two main fields of dipole investigations

Saturation of gluon density

high density gluon state with small coupling const.

Particularly simple limes of QCD (McLerran,Venugopalan)

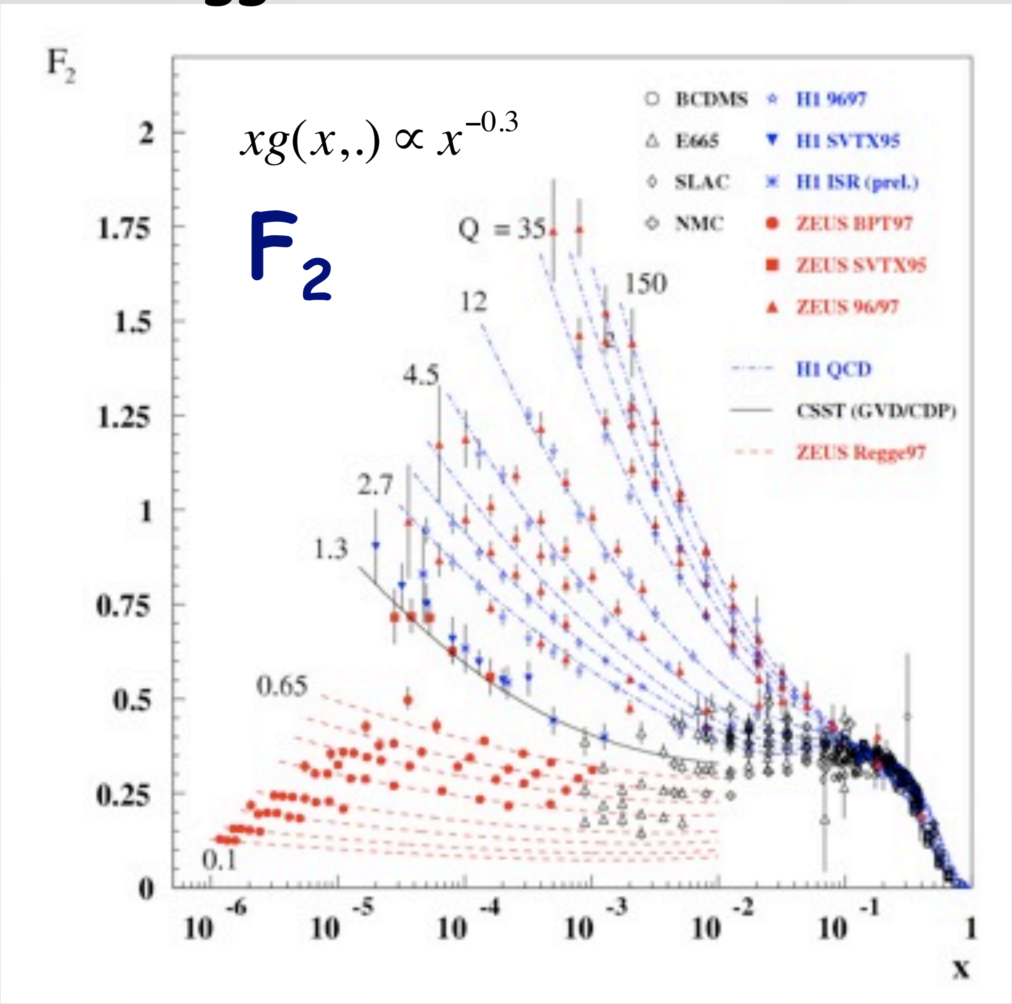
Determination of the gluonic shape of the proton

Measurement of the gluonic proton radius

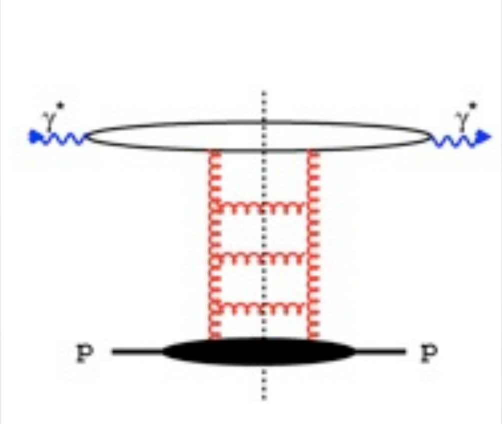
Structure of nuclei

Fast rise of the proton structure function

➔ Suggestion of saturation



F_2 is dominated by gluon density at $x < 10^{-2}$

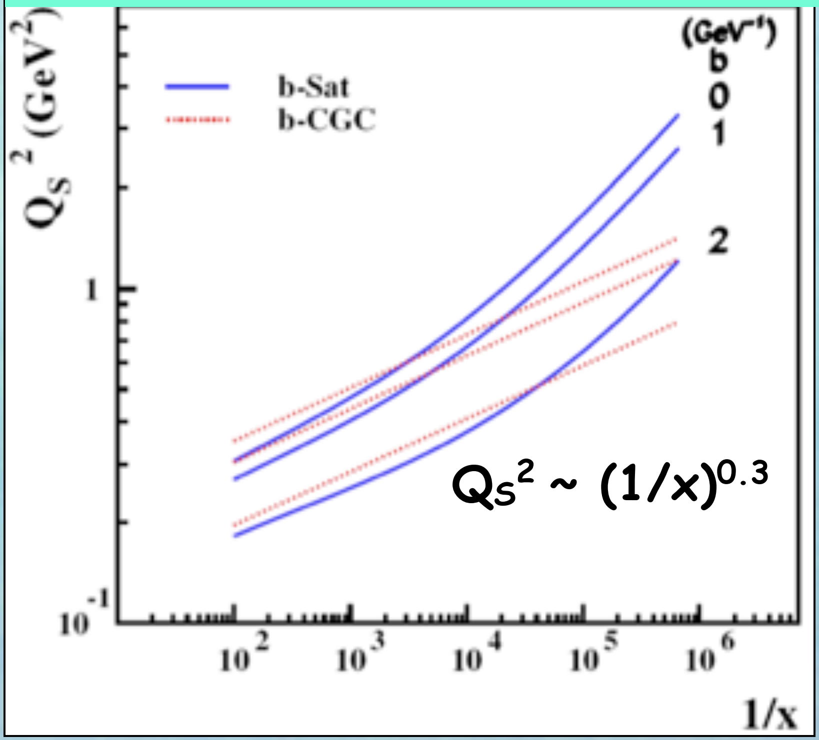


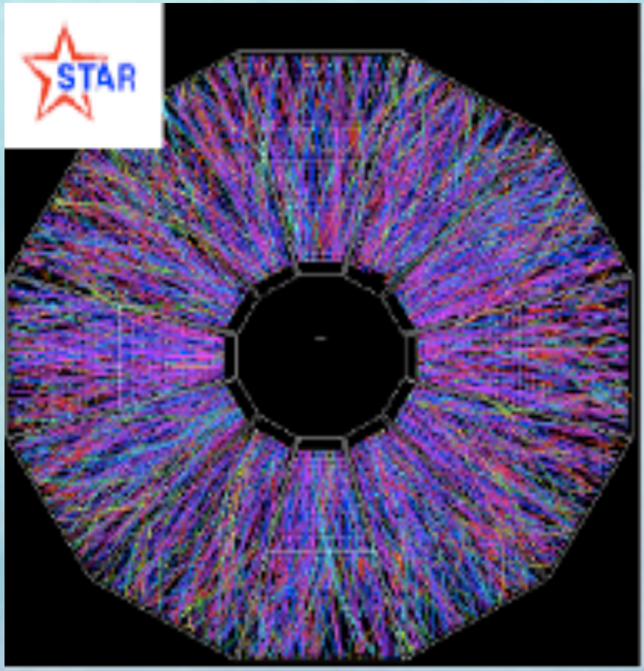
Saturation

Q_S - measure of gluon density at which a dipole r_S starts to be absorbed; $Q_S=2/r_S$

$$\frac{d\sigma_{q\bar{q}}(x, r_S, b)}{d^2b} = 2(1 - \exp(-1/2)) \approx 0.8.$$

a small dipole sneaks through the gluon cloud because of r^2 dependence

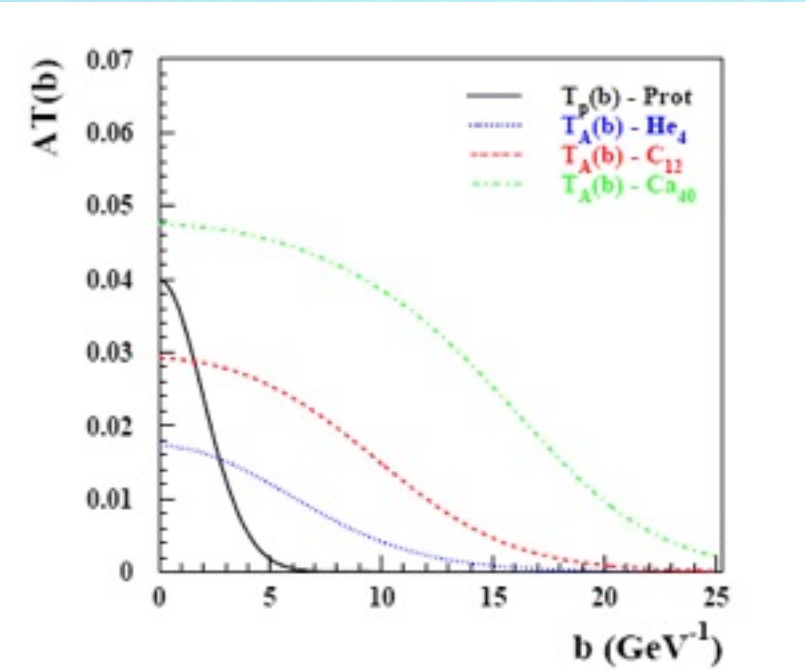


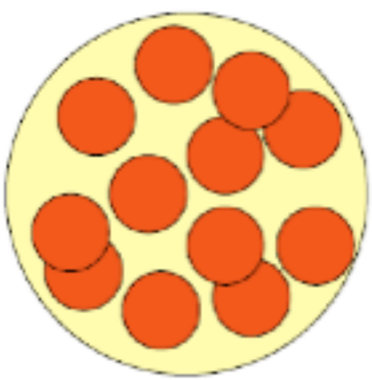


$Q_S^{HERA}(x=10^{-4}) \sim Q_S^{RHIC}\ (x=10^{-2})$

DIS on Nuclei

$$\frac{\mathrm{d}\sigma^A_{q\bar{q}}}{\mathrm{d}^2\vec{b}} = 2\left[1-\left(1-\frac{T_A(b)}{2}\sigma^p_{q\bar{q}}\right)^A\right]$$



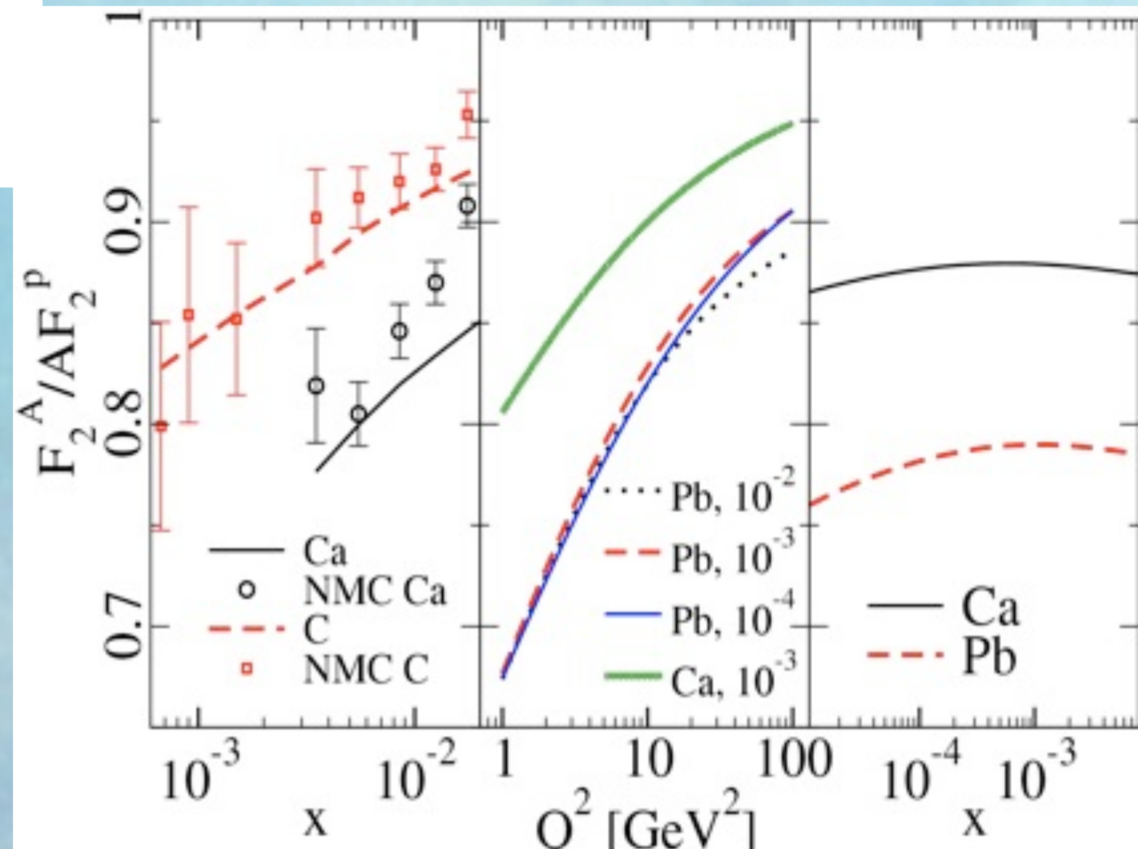


Lumpy Gluon Cloud

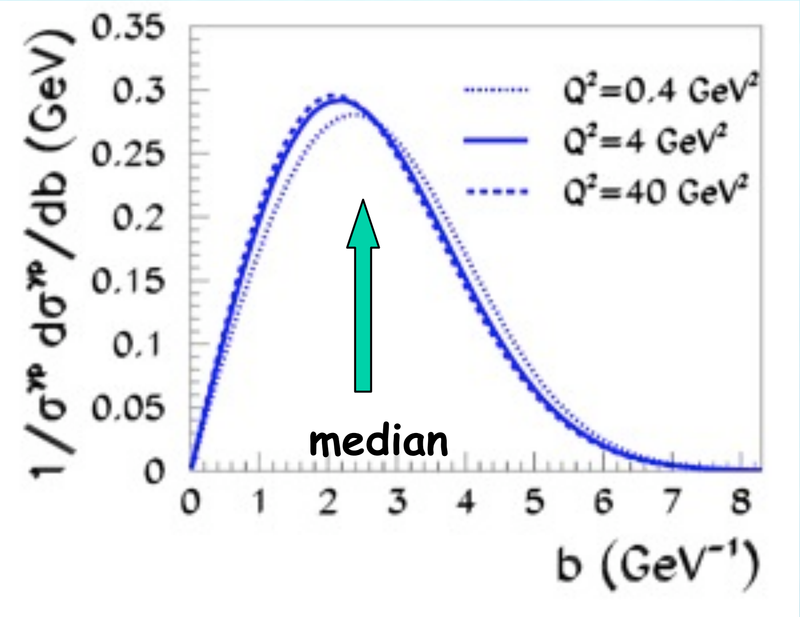
Shadowing in Nuclei

Kowalski Teaney

Kowalsi, Lappi, Venugopalan



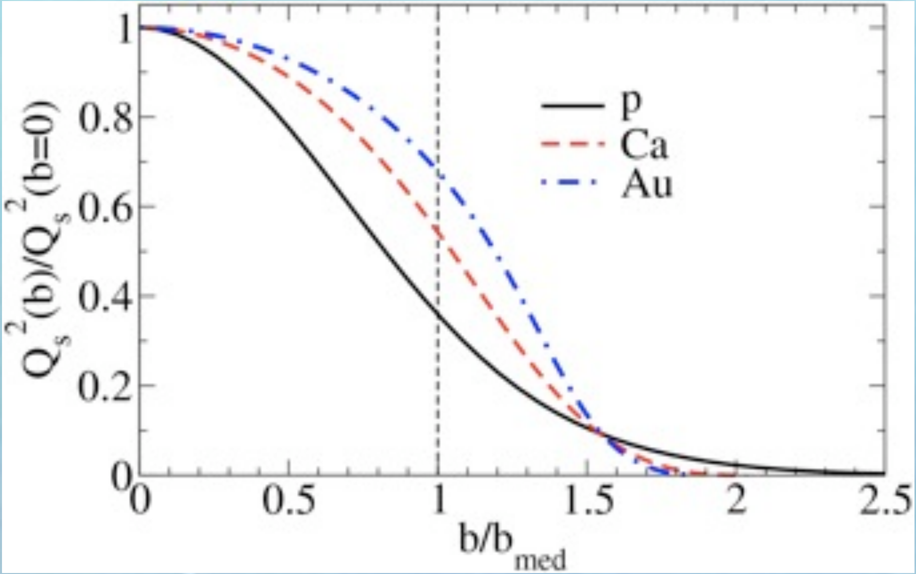
At HERA, large fraction of $\sigma^{\gamma^* p}$ comes from the region of large b where matter density is low



Nuclear enhancement
of universal dynamics
of high parton densities

Kowalski, Lappi, Venugopalan

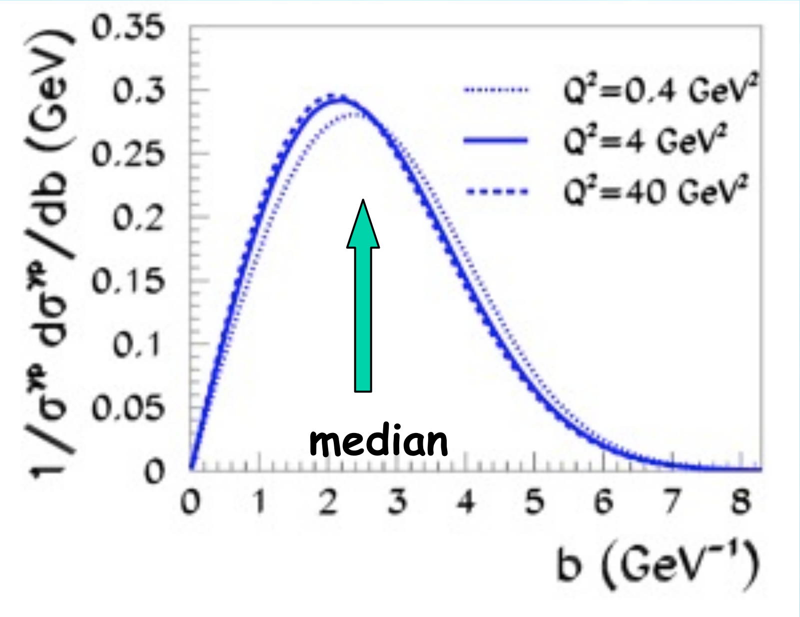
$$\frac{Q^2_{s,A}}{Q^2_{s,B}} = \frac{A}{B}\frac{T_A(\mathbf{b}_\perp)}{T_B(\mathbf{b}_\perp)}\frac{F(x,Q^2_{s,A})}{F(x,Q^2_{s,B})} \sim \frac{A^{1/3}}{B^{1/3}}\frac{F(x,Q^2_{s,A})}{F(x,Q^2_{s,B})}$$



At HERA, large fraction of $\sigma^{\gamma^* p}$ comes from the region of large b where matter density is low

➔ Saturation shapes data in a similar way as DGLAP

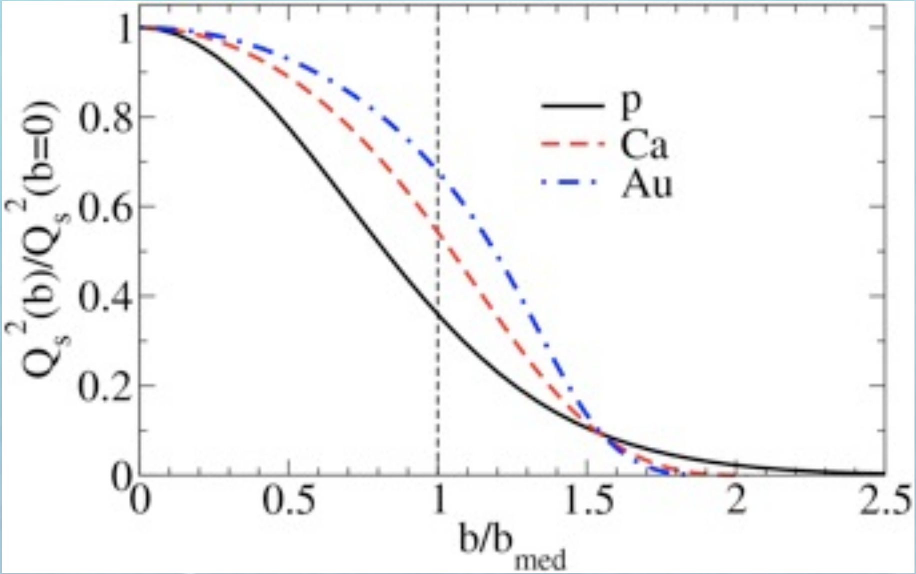
➔ Difficult to distinguish

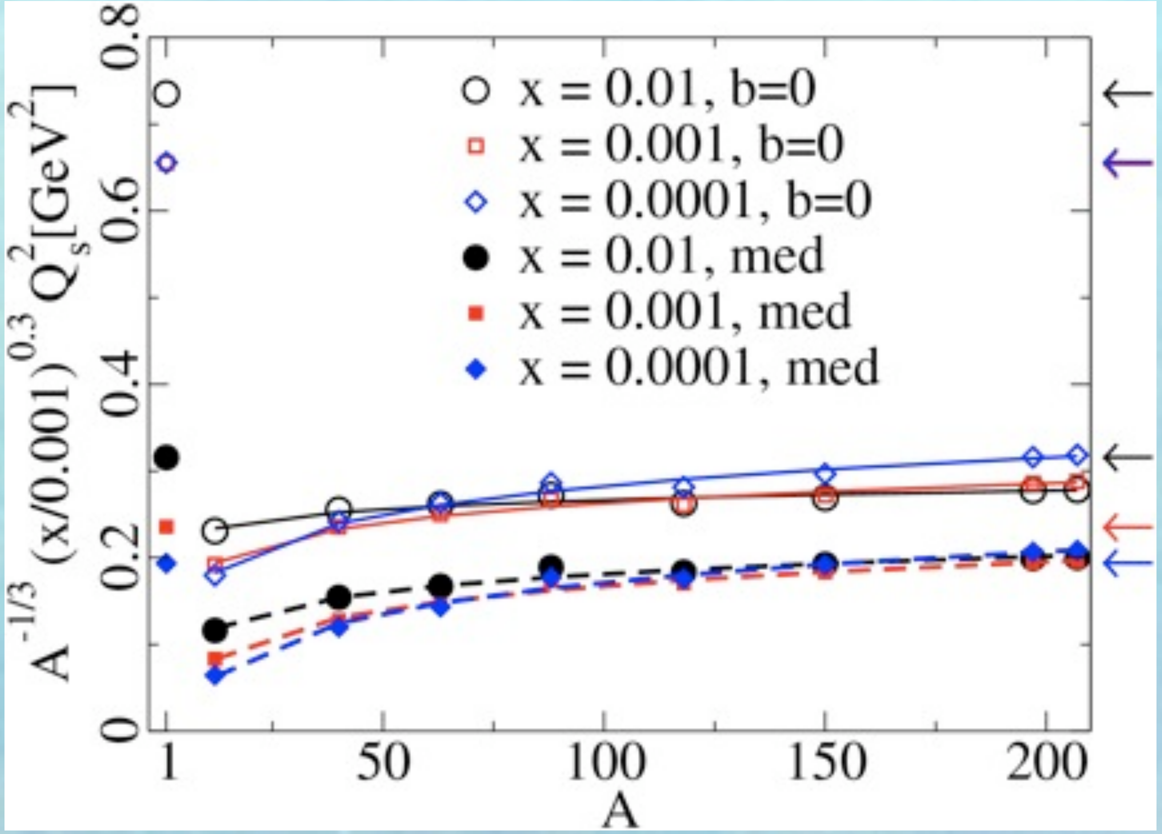


Nuclear enhancement of universal dynamics of high parton densities

Kowalski, Lappi, Venugopalan

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





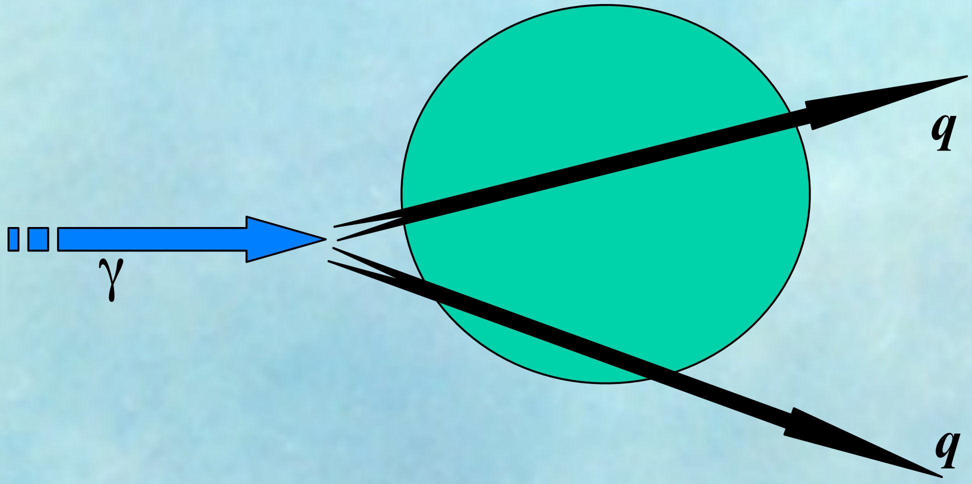
Pocket formula $Q_S \sim (A/x)^{0.3}$

large enhancement of saturation scale in nuclei

$200^{1/3} \sim 6$

Oomph factor

DIS studies of jet quenching in nuclei



Forward vs transverse jet absorption
particles energy loss
photons vs hadron
Diffractive vs inclusive jets

➔ Clean studies of nuclear medium properties

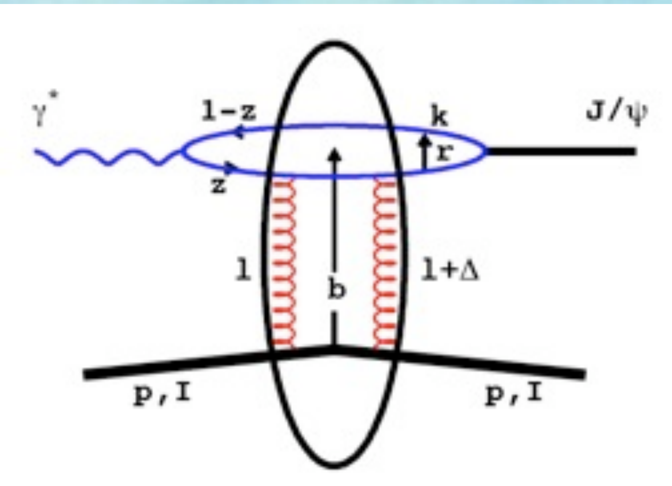
J/ψ as a probe of proton and nuclei

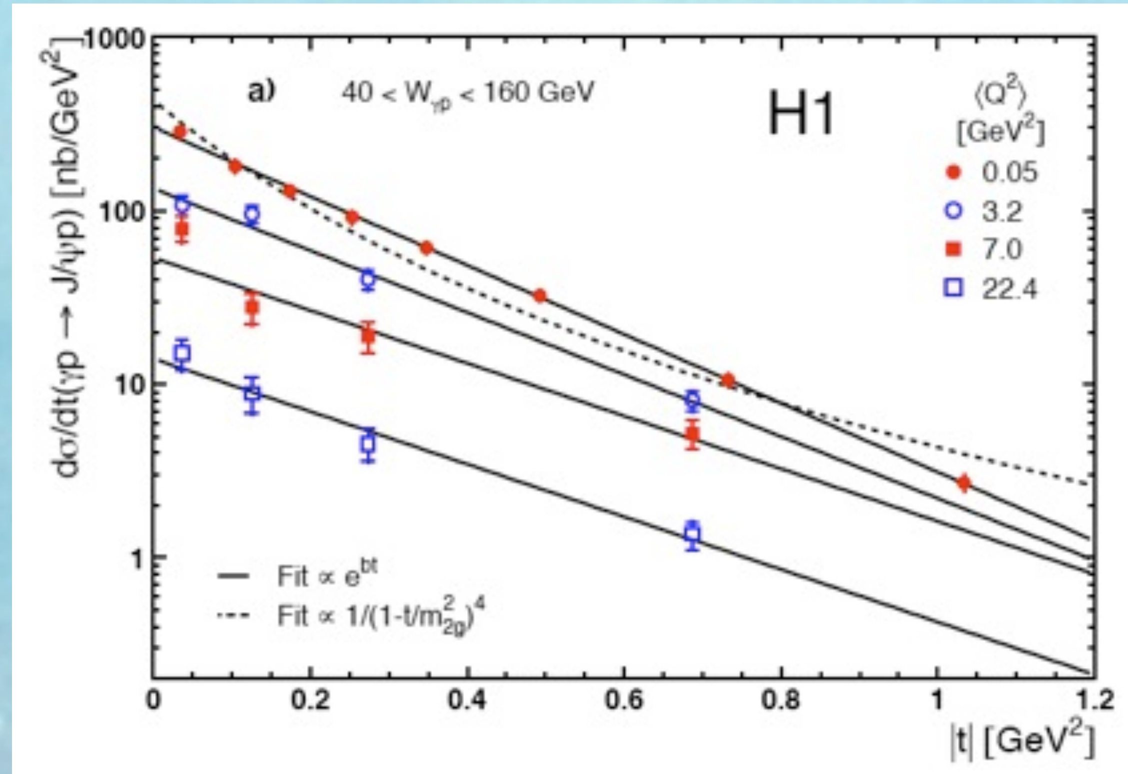
Ideal probe:

large photoproduction cross sections,
easy detection by ee or $\mu\mu$ decay channels
small width ➔ well separated from background
quark dipole annihilates (into leptons)

J/ψ dipole interacts only by 2g exchange at low x
process is well understood in QCD

Proton shapes from exclusive J/ψ





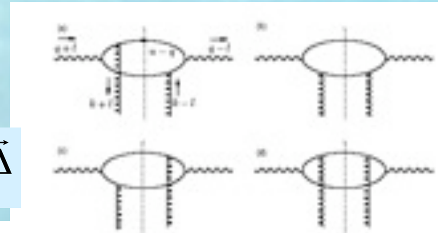
Exponential behavior ➔ B_D size of the interaction region

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

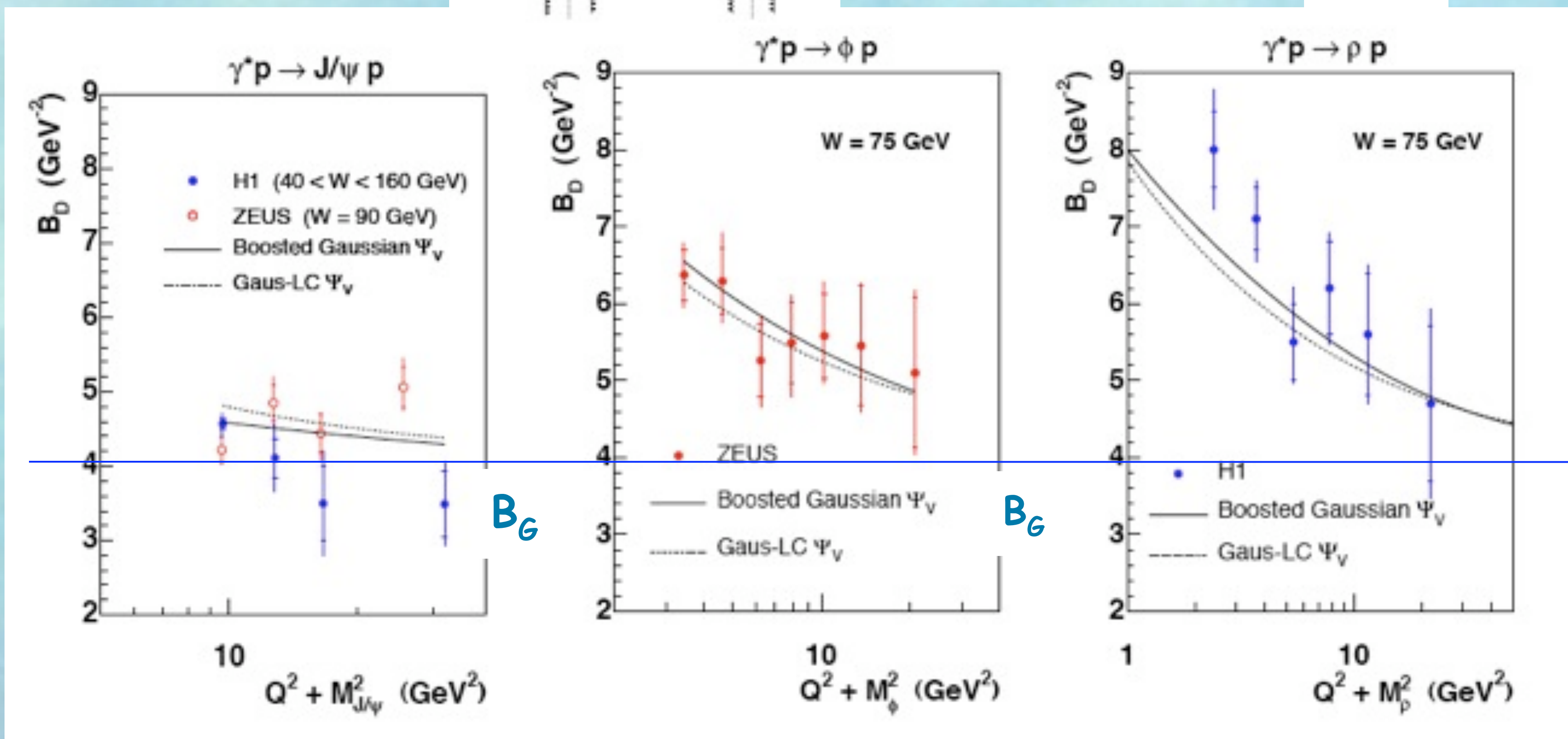
The size of interaction region B_D for various VM

Modification by Bartels, Golec-Biernat, Peters

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

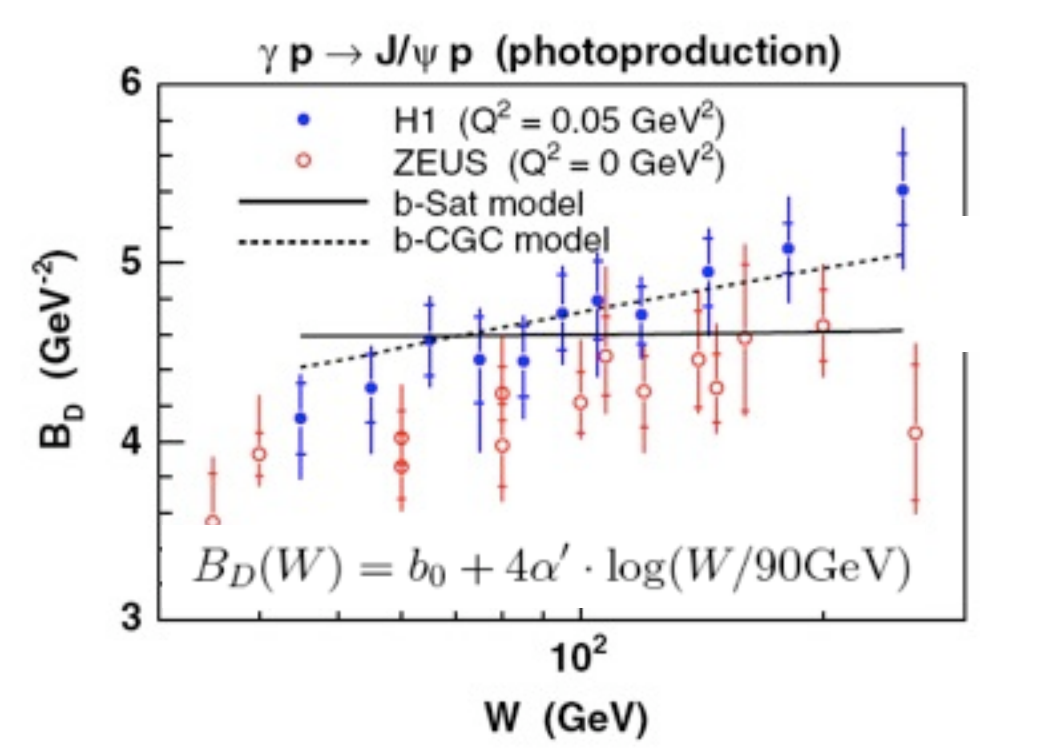


KMW



For J/ψ $B_D - B_G = 0.6 \pm 0.2\ GeV^{-2}$

Proton radius



at W 30 GeV

$$\sqrt{< r_{2g}^2 >} = \sqrt{3 \cdot B_G} = 0.61 \pm 0.04 \text{ fm}$$

$$\sqrt{< r_{2g}^2 >} = \sqrt{3 \cdot B_G} = 0.61 \pm 0.04 \text{ fm}$$

to compare with

$r_p = 0.875 \pm 0.008$ fm electric

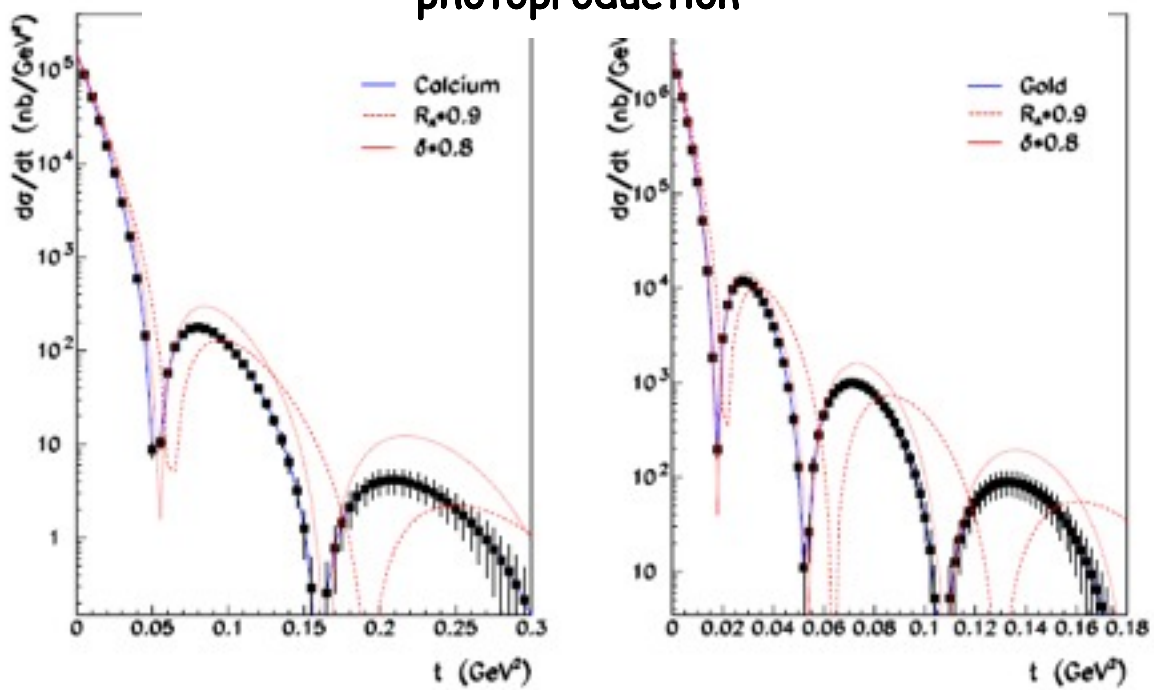
$r_A = 0.675 \pm 0.02$ fm axial

the gluonic proton radius is smaller than the quark radius

Nuclear gluonic shapes at EIC

Coherent eA → $J/\psi A$ production

photoproduction



$\Delta p_T \sim 10$ MeV

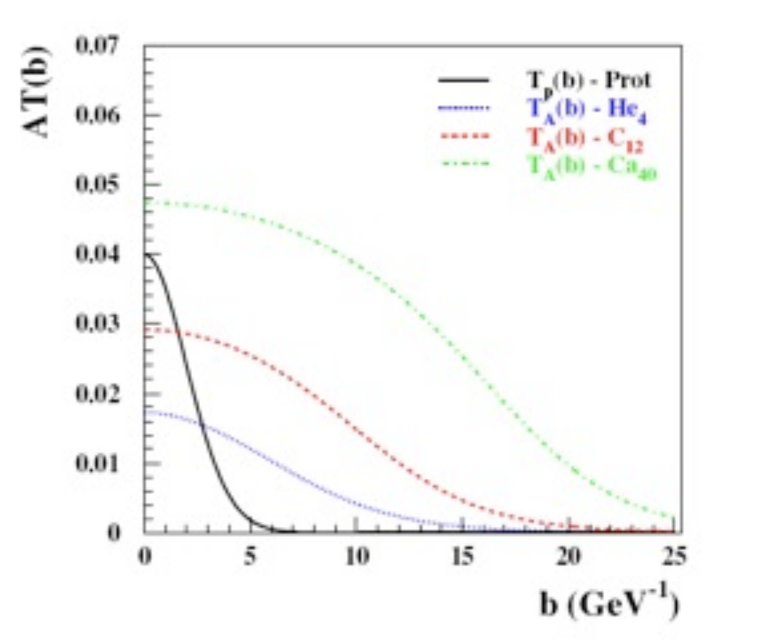
Look into inner arrangements of nucleons in nucleus?

X-sections for nuclear J/ψA production

Conventional assumption: charmed dipole scatters on individual nucleons

$$\frac{d\sigma^A_{q\bar{q}}}{d^2b} = \sigma_p \sum_{i=1}^{A} \frac{e^{-(\vec{b}-\vec{b_i})^2/2B_p}}{2\pi B_p},$$

Shape of the nucleus given by the Woods-Saxon distribution



$$\int d^2b_k T_A(b_k) = 1.$$

X-sections for eA => J/ψA production
Coherent scattering

Simplified assumption:
Random and uncorrelated distribution of nucleons within the nucleus, $\Pi T(b_k)$

$$\left\langle \frac{d\sigma^A_{q\bar{q}}}{d^2b} \right\rangle_N = \sigma_p \int \prod_{k=1}^{A} d^2b_k T_A(b_k) \left(\sum_{i=1}^{A} \frac{e^{-(\vec{b}-\vec{b_i})^2/2B_p}}{2\pi B_p} \right).$$

KT & KLV

Average (sum) over all configurations

$$\left\langle \frac{d\sigma^A_{q\bar{q}}}{d^2b} \right\rangle_N = \sigma_p \left(\sum_{i=1}^{A} \int d^2b_i T_A(b_i) \frac{e^{-(\vec{b}-\vec{b_i})^2/2B_p}}{2\pi B_p} \right) = A\sigma_p \int d^2b' T_A(b') \frac{e^{-(\vec{b}-\vec{b}')^2/2B_p}}{2\pi B_p}.$$

Fourier transform the average

$$\frac{d\sigma_A}{dt} \approx A^2 \sigma_p^2 \left| FT_A(\Delta) \right|^2$$

X-sections for eA => J/ψA production
Incoherent scattering

Fourier transform the dipole cross section:

$$\int d^2b e^{-i\vec{b}\cdot\vec{\Delta}} \frac{d\sigma^A_{q\bar{q}}}{d^2b} = \sigma_p \sum_{i=1}^{A} e^{-i\vec{b_i}\cdot\vec{\Delta}} \cdot e^{-B_p\cdot\Delta^2/2}.$$

KLV

Take a square

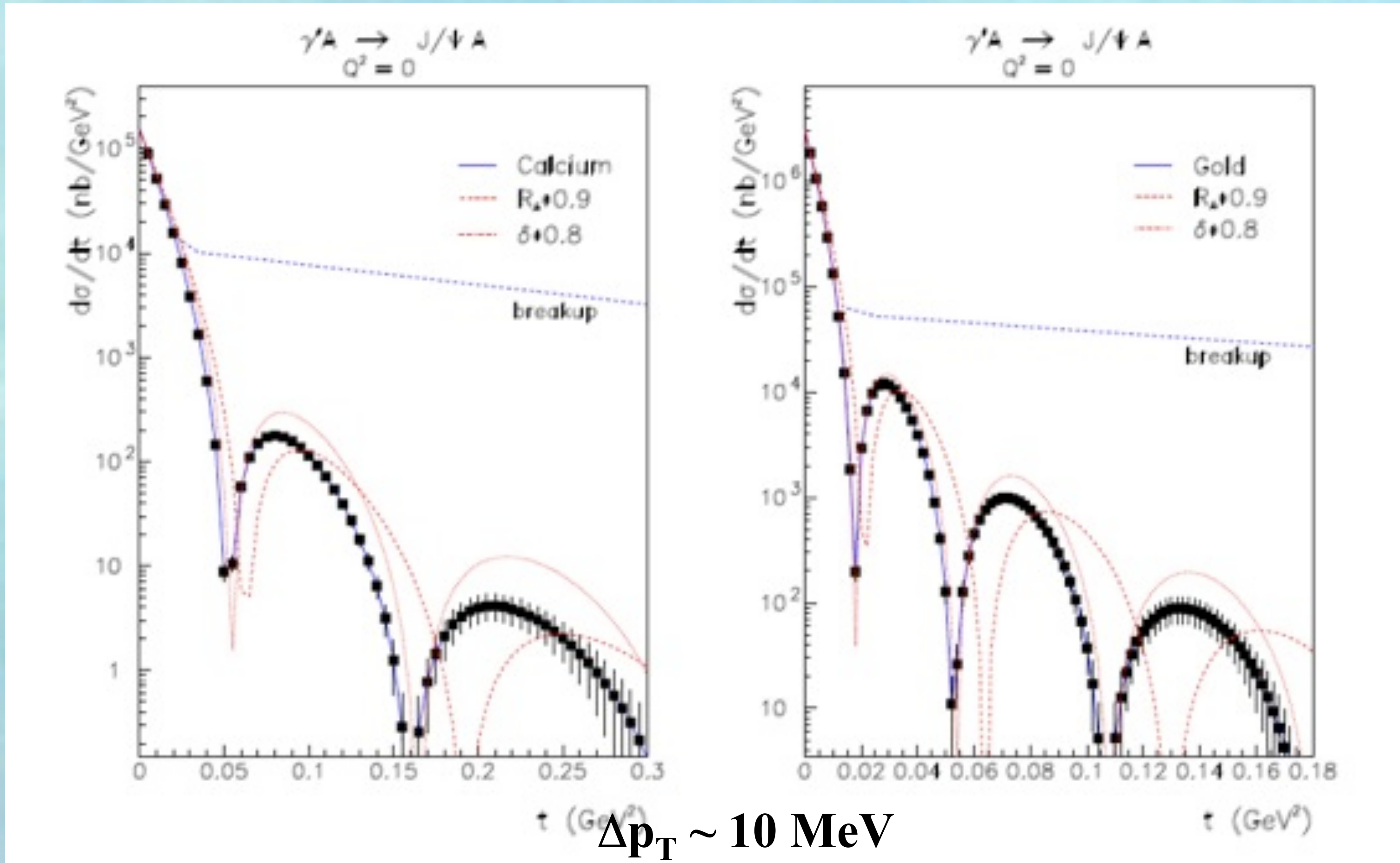
$$\left|\int d^2b e^{-i\vec{b}\cdot\vec{\Delta}} \frac{d\sigma^A_{q\bar{q}}}{d^2b}\right|^2 = \sigma_p^2 \cdot e^{-B_p\cdot\Delta^2} \cdot \left[\sum_{i\neq j}^{A} e^{-i(\vec{b_i}-\vec{b_j})\cdot\vec{\Delta}} + \sum_{k}^{A} 1\right]$$

Average (sum) over all configurations

$$\left\langle\left|\int d^2b e^{-i\vec{b}\cdot\vec{\Delta}} \frac{d\sigma^A_{q\bar{q}}}{d^2b}\right|^2\right\rangle_N = \sigma_p^2 \cdot e^{-B_p\cdot\Delta^2} \cdot \left[A(A-1)|FT_A(\Delta)|^2 + A\right]$$

Nuclear gluonic shapes

Coherent and incohernt eA → J/ψA production

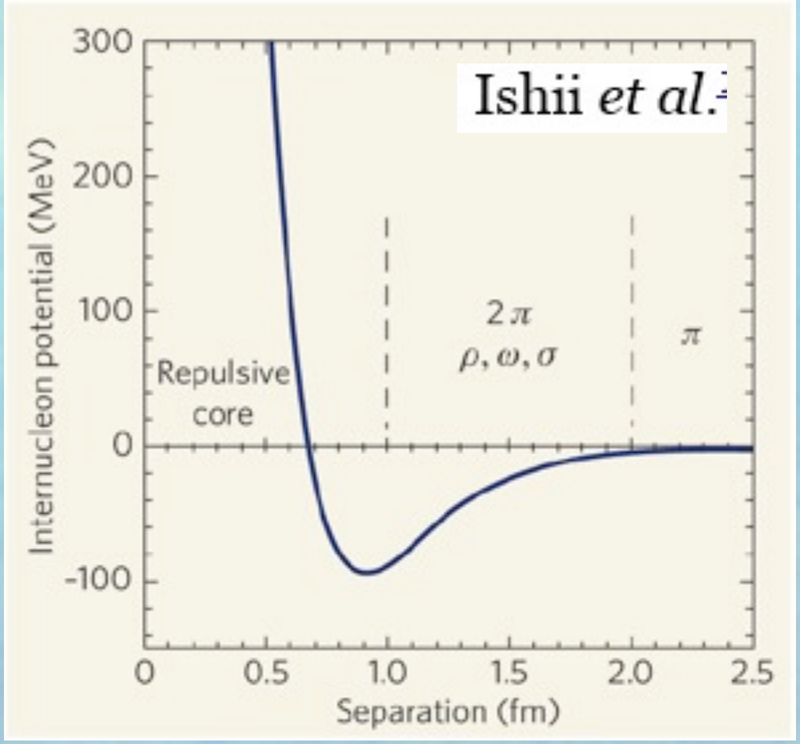


$\Delta p_T \sim 10$ MeV

Look into inner arrangements of nucleons in nucleus?

X-sections for eA => J/ψA production
towards a more realistic investigation

Assumption of uncorrelated nucleon distribution is too simple,
Strong correlation between nucleon position expected
Nuclear Shell model: Nucleons behave like a Fermi gas
Hard Core: any two nucleons are separated by ~1 fm



Lattice calculation
described by F. Wilczek, Nature

Since R_A ~1.2 fm $A^{1/3}$ nucleons cannot move much inside nucleus

Does nucleus look like a crystal?
=> minimal p_T ~ 1/d ?

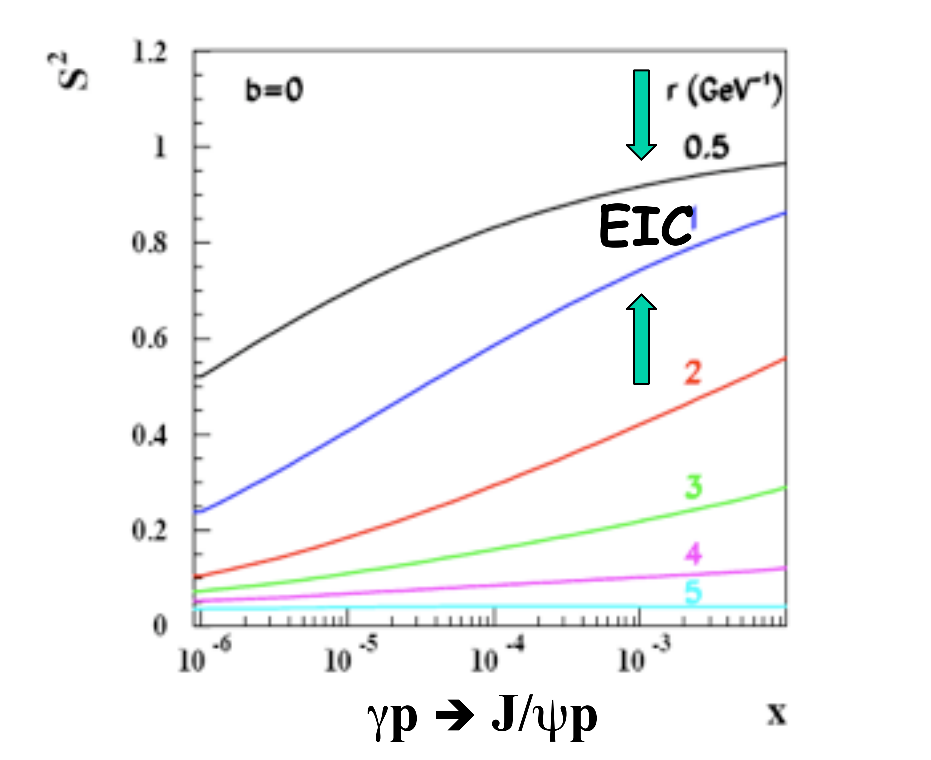
Incoherent exclusive J/ψ production
- Nucleus disintegrates

The measurement of the t-distribution correlated with the number and momenta of the breakup neutrons and protons can become an invaluable source of information about the nuclear forces

Impact dependent saturation studies with J/ψ

Saturation leads to a clear distortion of a proton or nuclear shape

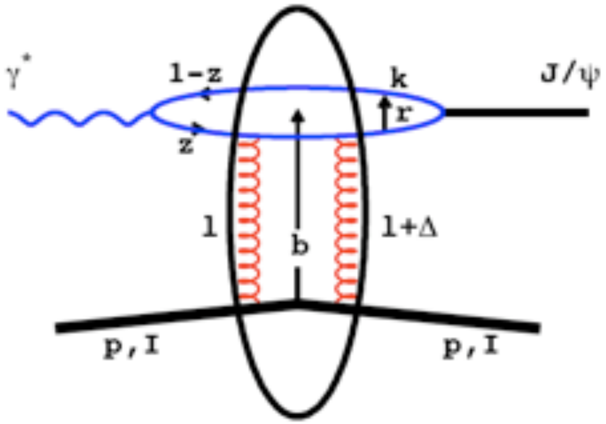
Survival Probability S^2 $\quad d\sigma_{qq}/d^2b = 2[1 - \Re S(b)]$



Munier, Stasto,Mueller
Kowalski,Teaney

Strong inhacement in nuclei?

J/psi p_T resolution



J/psi p_T can be determined from the momentum of ee or μμ decay pair

p_T resolution for J/psi - O(2) MeV for a TPC with 1m of the radius

no measurement of a proton or ion momentum necessary

beam electron p_T < 1 MeV
scattered electron can be easily detected in the forw. det.

X-section for elastic J/ψ photoproduction

$$\frac{d\sigma}{dW^2} = \frac{\alpha}{2\pi}\frac{1}{s}\left[\frac{1+(1-y)^2}{y}\ln\frac{Q^2_{max}}{Q^2_{min}} - \frac{2(1-y)}{y}\left(1-\frac{Q^2_{min}}{Q^2_{max}}\right)\right]\cdot\sigma^{\gamma p}(W^2)\,.$$

$$\sigma^{\gamma p\to J/\psi p}(W^2) \approx 75\text{nb}\cdot\left(\frac{W^2}{8100}\right)^{0.35}$$

ZEUS parametrization

$$Q^2_{min} = \frac{m_e^2 y^2}{1-y}$$

$$Q^2_{max} = 10^{-2}\ \text{GeV}^2.$$

$$E_e + E_p = (1-x)E_p + E'_e + E_V$$

Energy conservation

$$E' = (1-y)E_e$$

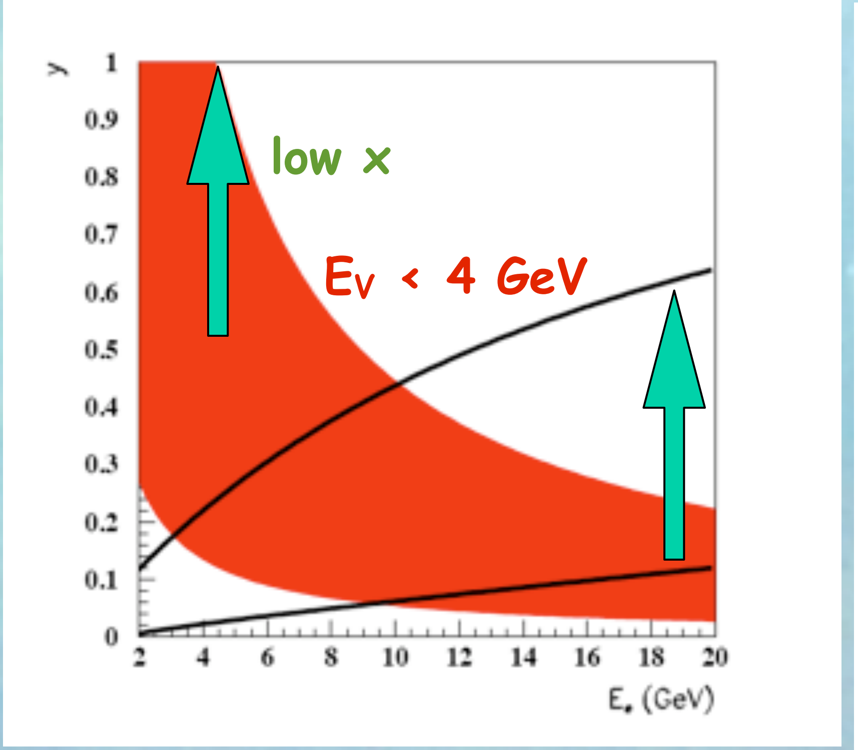
Energy of the scattered electron

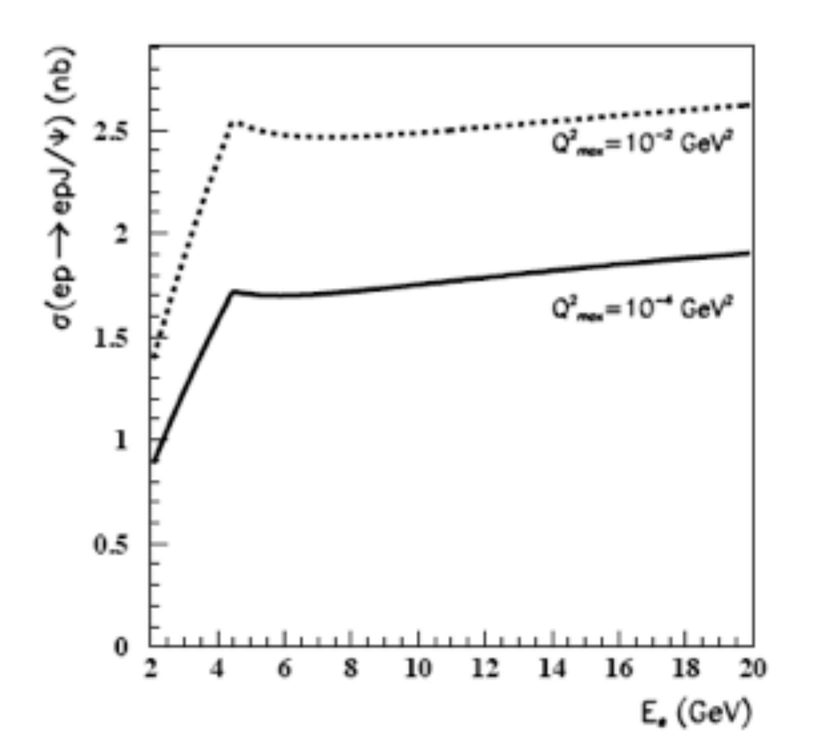
Acceptance and X-sec for elastic J/ψ photoproduction at eRHIC, E_p = 100 GeV

E_V - Energy of J/ψ

$$y_{max} = min\left[1, \frac{E_V + P_V}{2E_e}\right]$$
$$y_{min} = max\left[0, \frac{E_V - P_V}{2E_e}\right]$$

E_V < 4 GeV





Measurement of momenta of J/ψ decay muons

Expected resolution of drift chambers:

$$(\sigma_{p_t}/p_t)_{meas} = \frac{p_t \sigma_{r\phi}}{0.3L^2B}\sqrt{\frac{720}{N+4}}$$

$$(\sigma_{p_t}/p_t)_{MS} = \frac{0.05}{LB\beta}\sqrt{1.43\frac{L}{X_0}[1+0.038\log(L/X_0)]}$$

$$\sigma_{p_t}/p_t = (\sigma_{p_t}/p_t)_{meas} \oplus (\sigma_{p_t}/p_t)_{MS}.$$

1. outer radius $R = 2$ m
2. solenoidal field $B = 3.5$ T
3. gas density $X_0 = 450$ m
4. point resolution $\sigma = 100\ \mu$m
5. measurement $N = 200$ points.

$\Leftarrow$ **TPC parameters** $\Downarrow$

$$\sigma_{p_t}/p_t = 0.005 \cdot p_t \oplus 0.045/\beta\ \%$$

$\Downarrow$

Δp_T < 1 MeV

Experimental signature of incoherent production

large rapidity gap with some particles in the forward neutron and proton detectors (for A~200, 4.3 neutrons and 2.9 protons expected from data on pA etc. scattering, Ranft et. al)

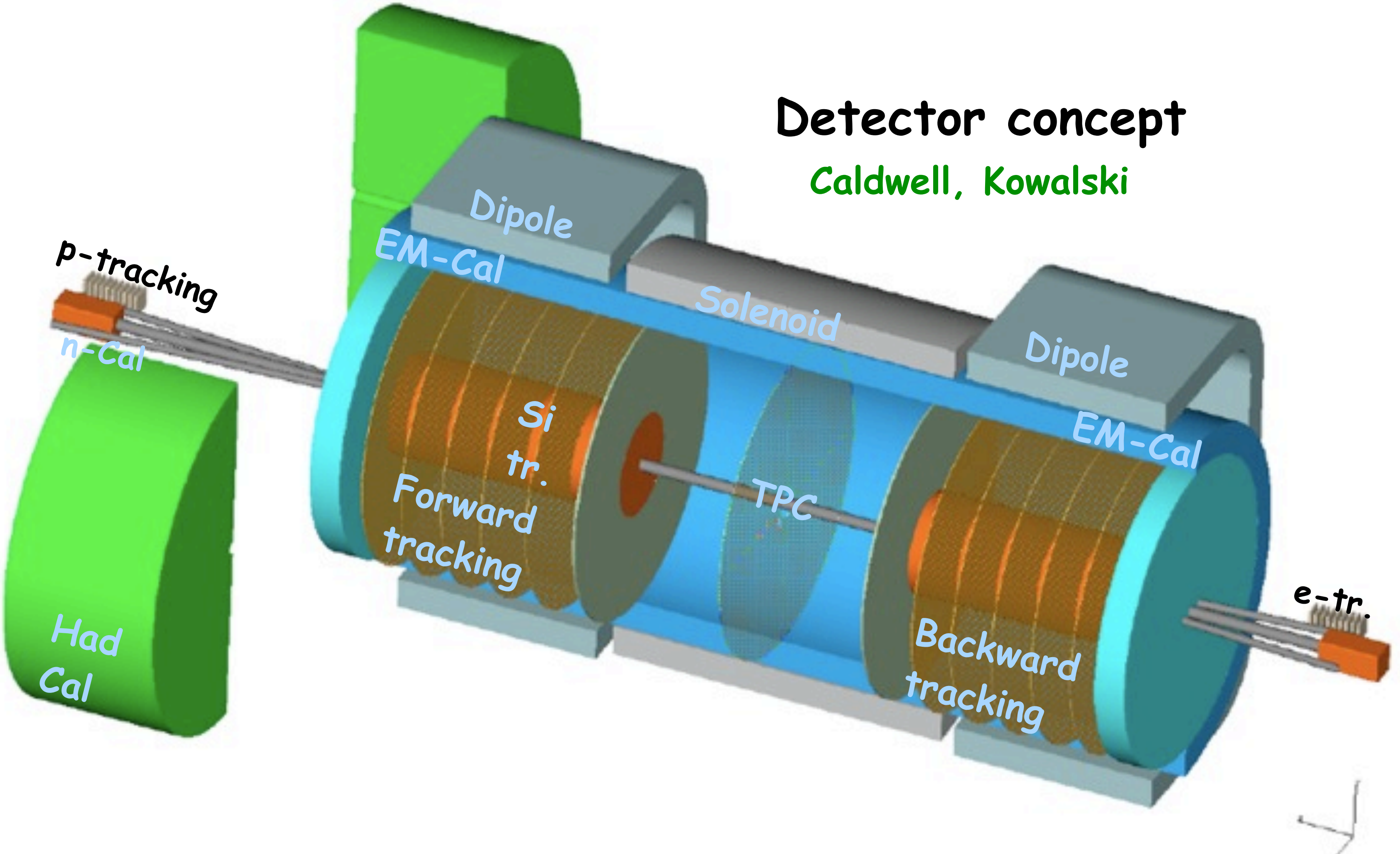
Experimental signature of coherent production

large rapidity gap with no particles in the forward neutron and proton detectors

➤ **Good forward neutron and proton detectors necessary**

Detector concept

Caldwell, Kowalski



Conclusions

We have an ideal tool to investigate the structure of nuclear matter through a well understood QCD process

With EIC we can investigate nuclei in a similar way as molecules are investigated in X-ray crystallography

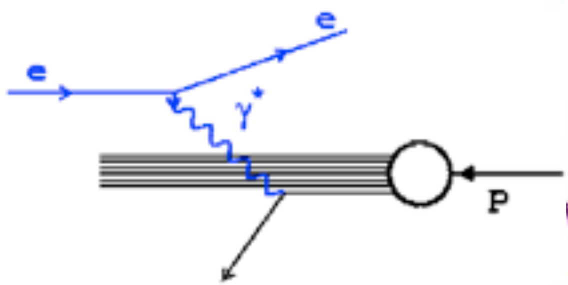
We have a chance to solve the long standing puzzle; how strong interactions are forming the matter

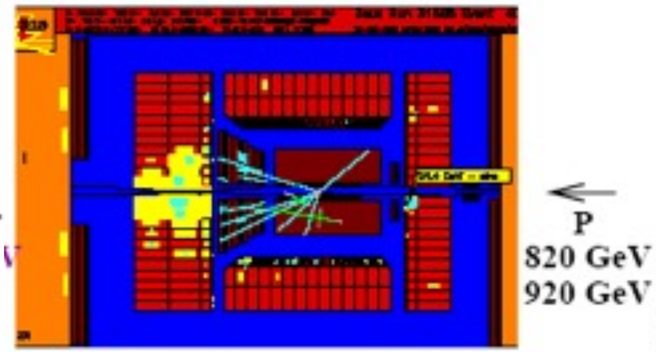
LET US DO IT

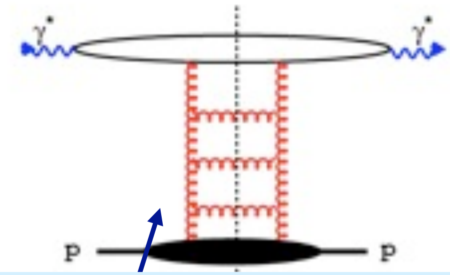
BACK UP SLIDES

Hard Diffraction – the HERA surprise

Non-Diffractive Event



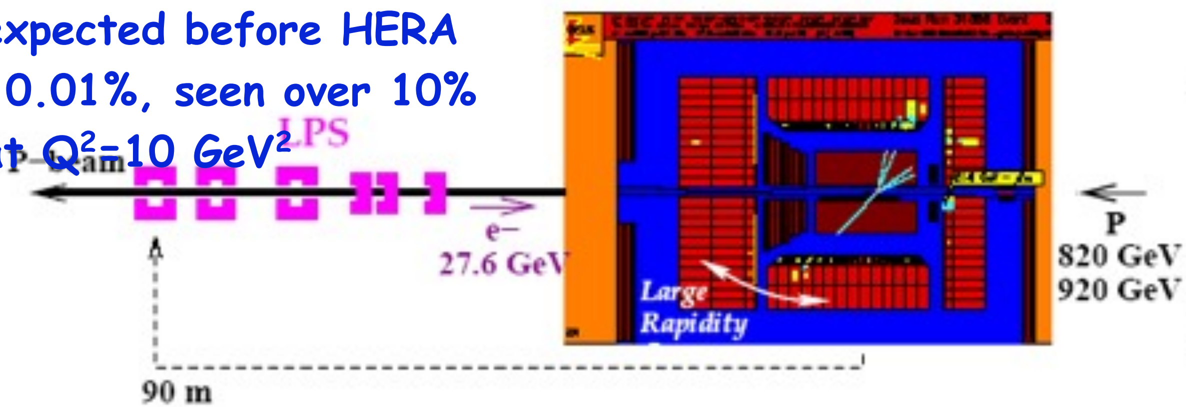


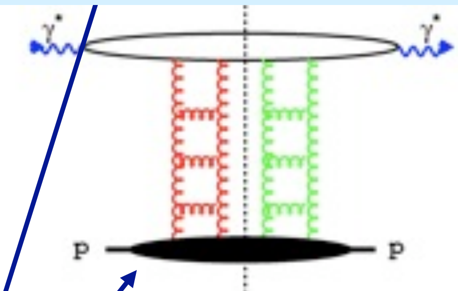


$$\tau_{qq} \approx \frac{1}{\Delta E} \approx \frac{1}{m_p x} \approx 10 - 1000 \text{ fm}$$

Diffractive Event

expected before HERA <0.01%, seen over 10% at Q^2=10 GeV²





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

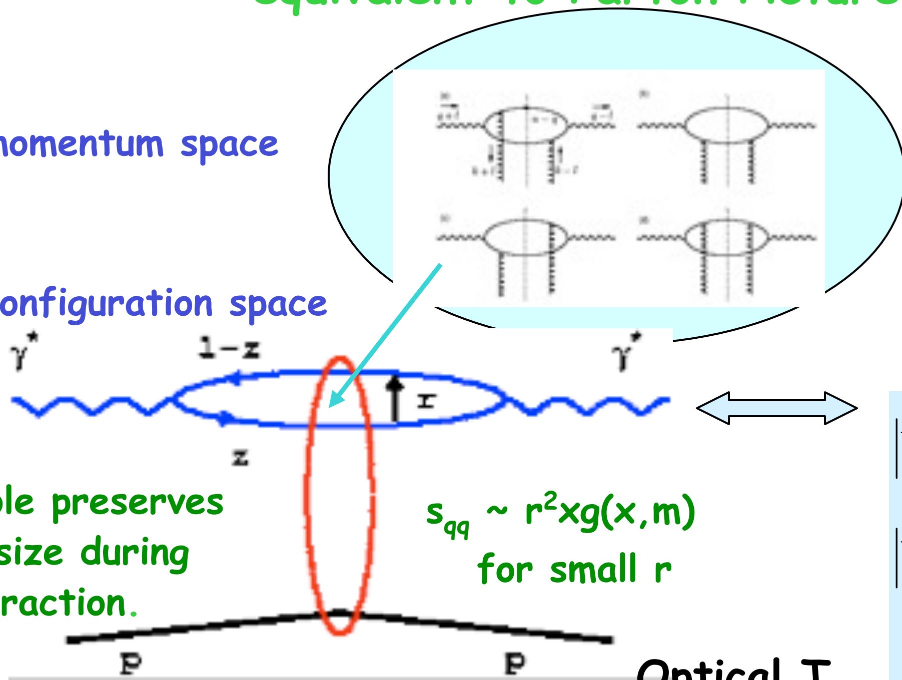
$$\sigma_{tot}^{\gamma^* p} = \frac{1}{W^2} Im A_{el}(W^2, t = 0)$$

Dipole description of DIS

equivalent to Parton Picture in the perturbative region

momentum space

configuration space



dipole preserves its size during interaction.

$s_{qq} \sim r^2 xg(x,m)$ for small r

Optical T

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

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

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

er<<1

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

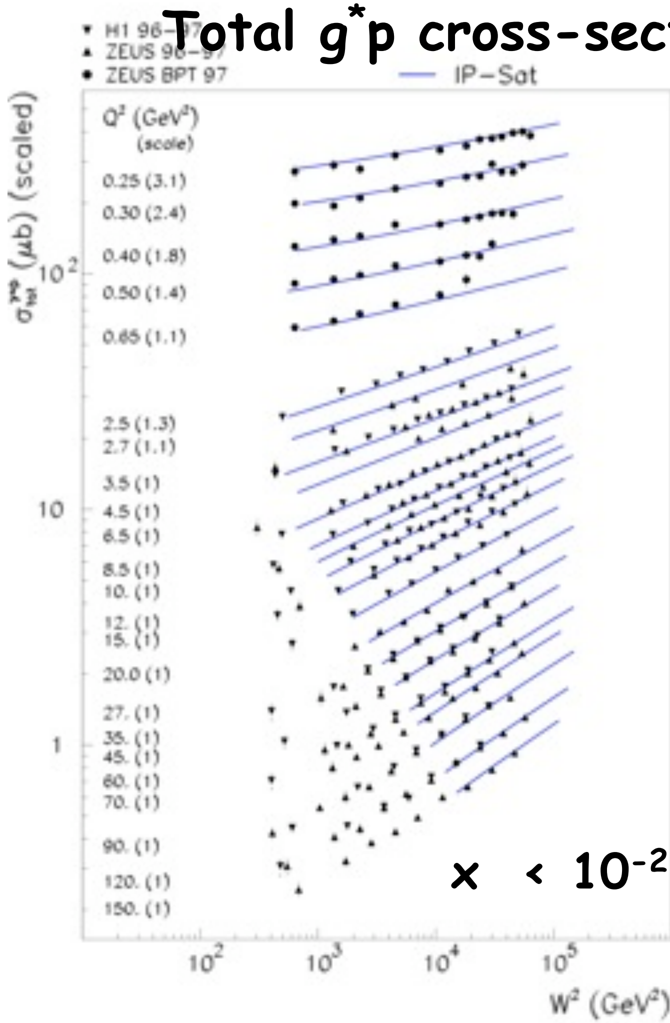
Mueller, Nikolaev, Zakharov

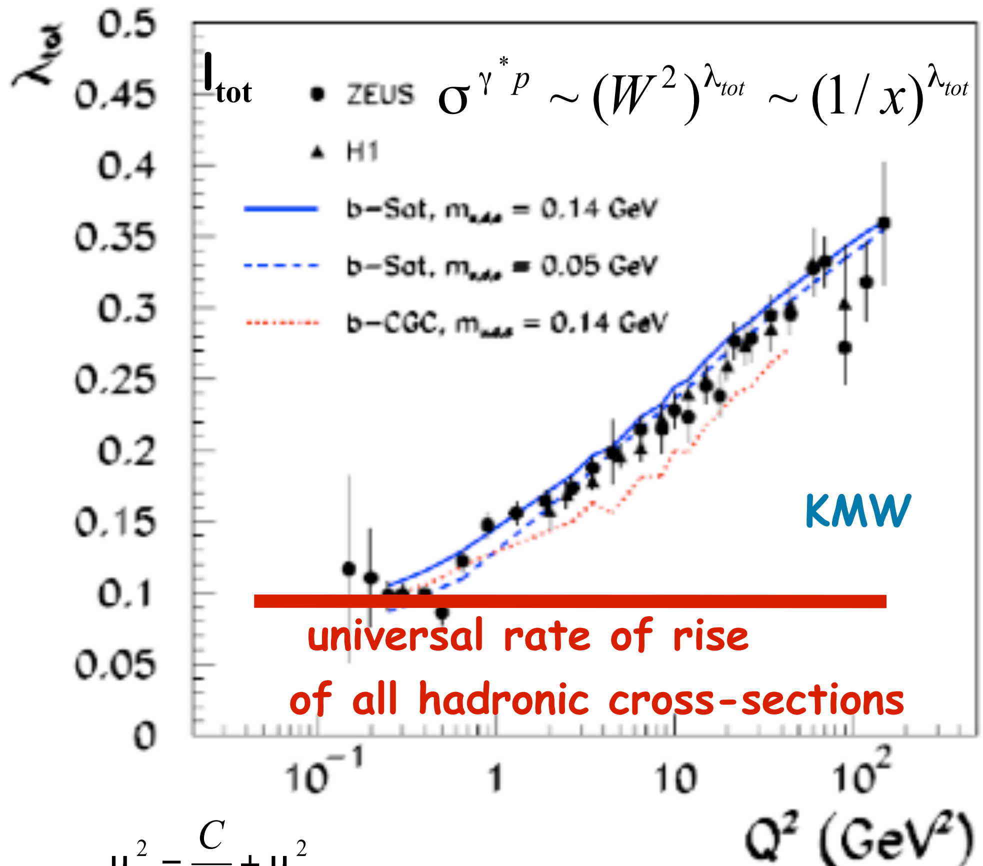
$$\sigma_{tot}^{\gamma^* p} = \int d^2\hat{\vec{r}} \int_0^1 dz \Psi^* \sigma_{q\bar{q}}(x,r^2)\Psi$$

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

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

Total g*p cross-section





$$\sigma^{\gamma^* p} \sim (W^2)^{\lambda_{tot}} \sim (1/x)^{\lambda_{tot}}$$

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

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

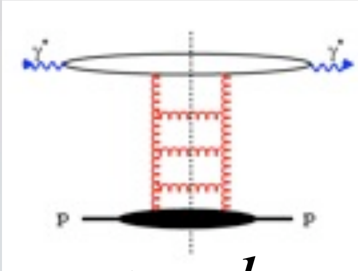
b-Sat

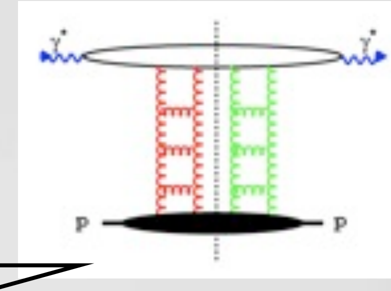
$$\frac{d\sigma_{q\bar{q}}}{d^2 b} \equiv 2\mathcal{N}(x,r,b) = 2 \times \begin{cases} \mathcal{N}_0 \left(\frac{rQ_s}{2}\right)^{2\left(\gamma_s + \frac{1}{\kappa\lambda Y} \ln \frac{2}{rQ_s}\right)} & : \quad rQ_s \le 2 \\ 1 - e^{-A \ln^2 (B r Q_s)} & : \quad rQ_s > 2 \end{cases}$$

b- CGC

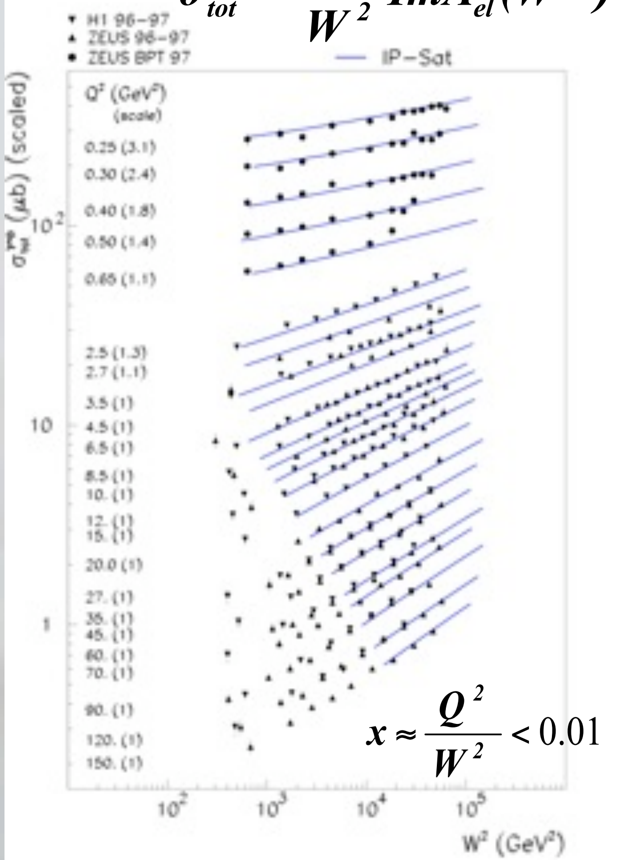
IIM+KMW

Low-x Physics @ HERA





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



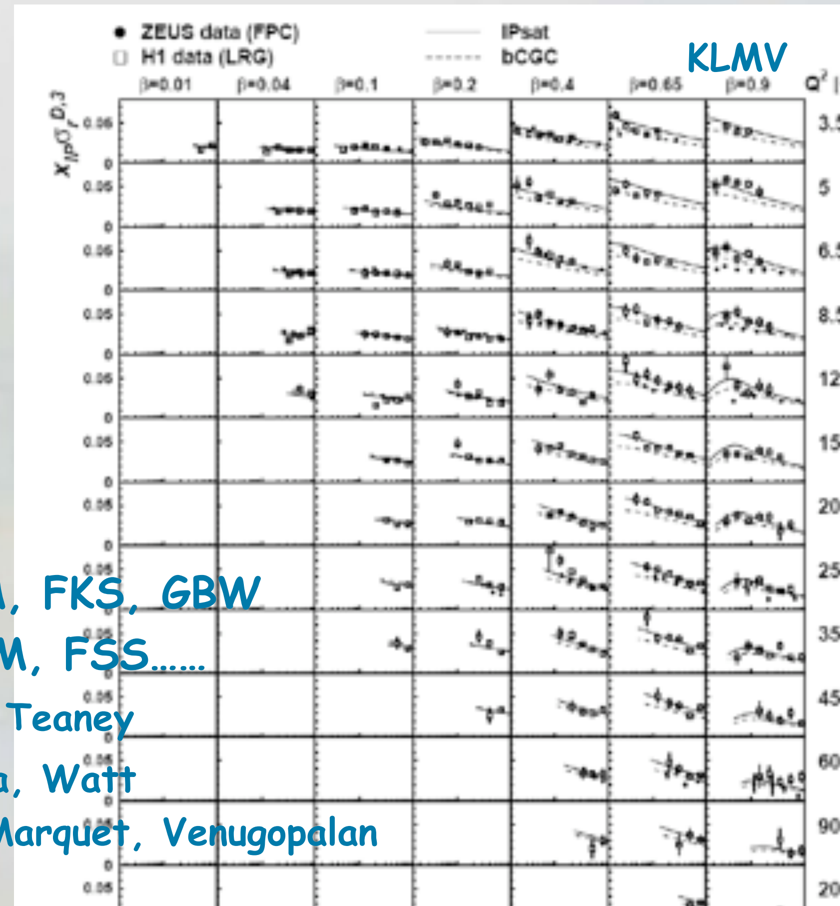
$$x \approx \frac{Q^2}{W^2} < 0.01$$

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

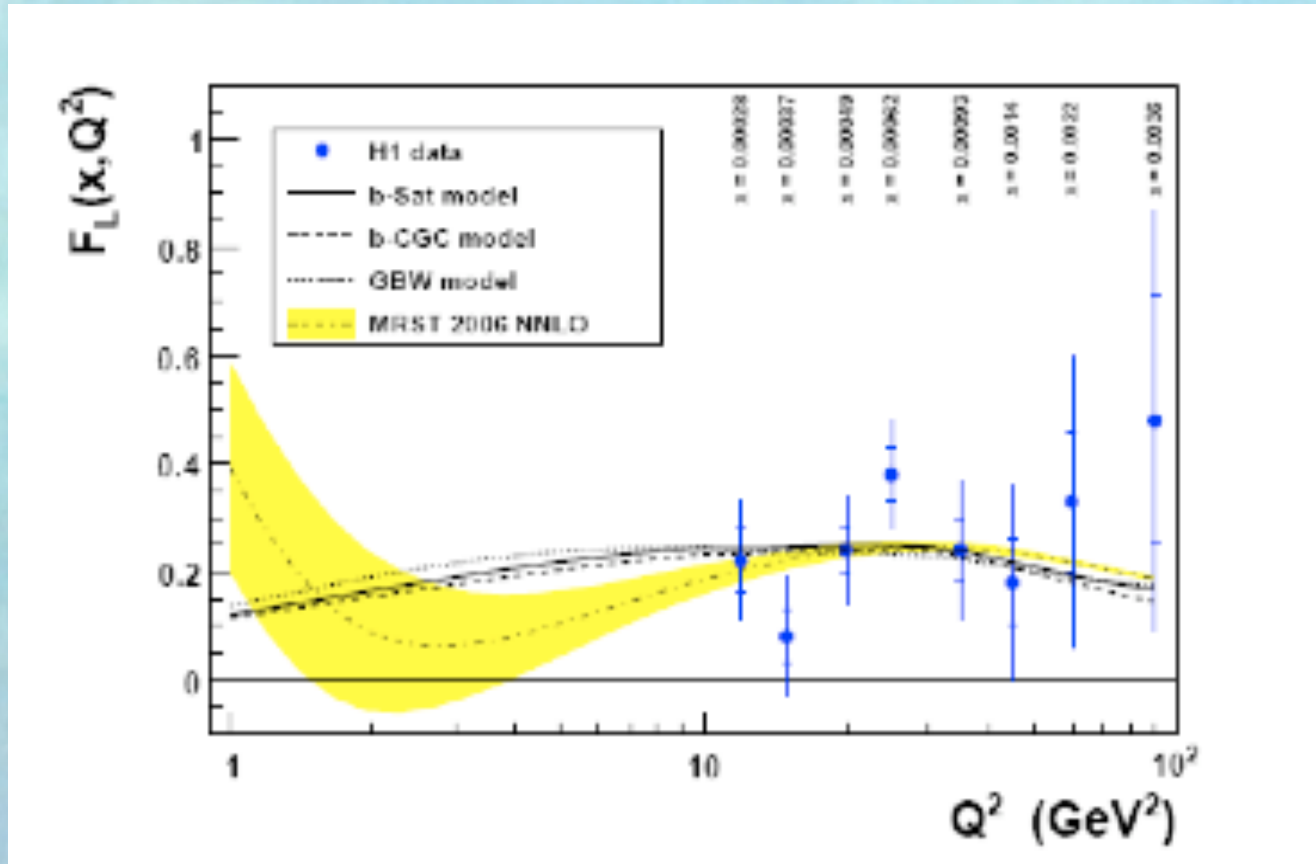
Diffraction at HERA is a shadow of DIS

➔

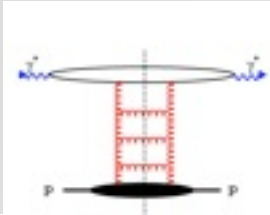
dipole picture,
equivalent to
LO p-QCD
for small
dipoles,
Q~1/r



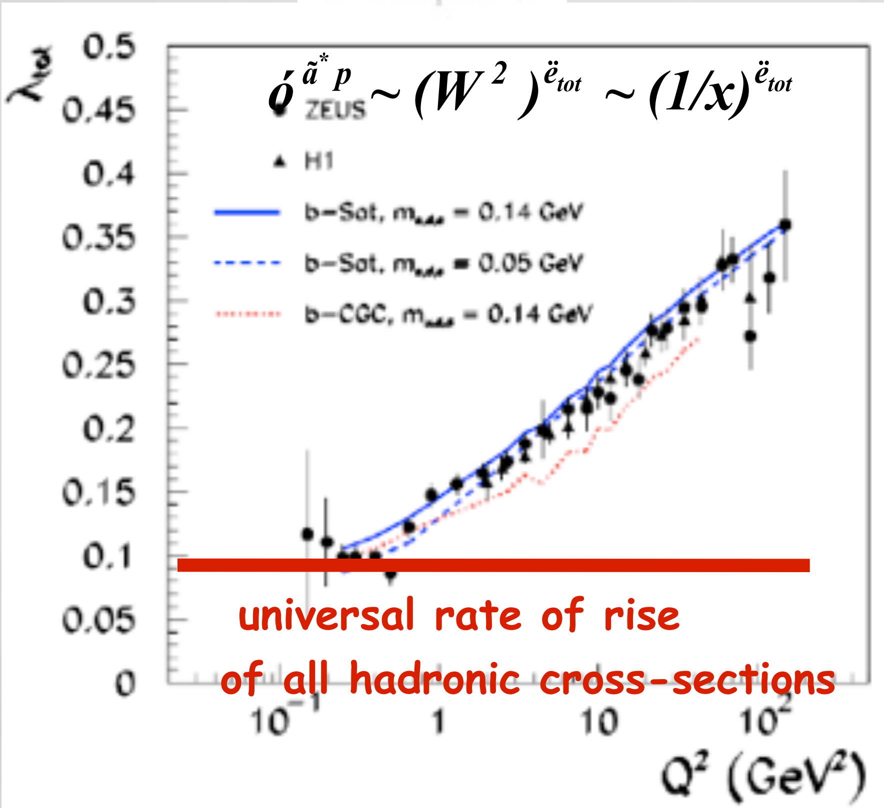
NNPZ, AM, GLM, FKS, GBW
DGKP, BGBK, IIM, FSS……
KT - Kowalski, Teaney
KMW - K, Motyka, Watt
KLMV – K, Lappi, Marquet, Venugopalan

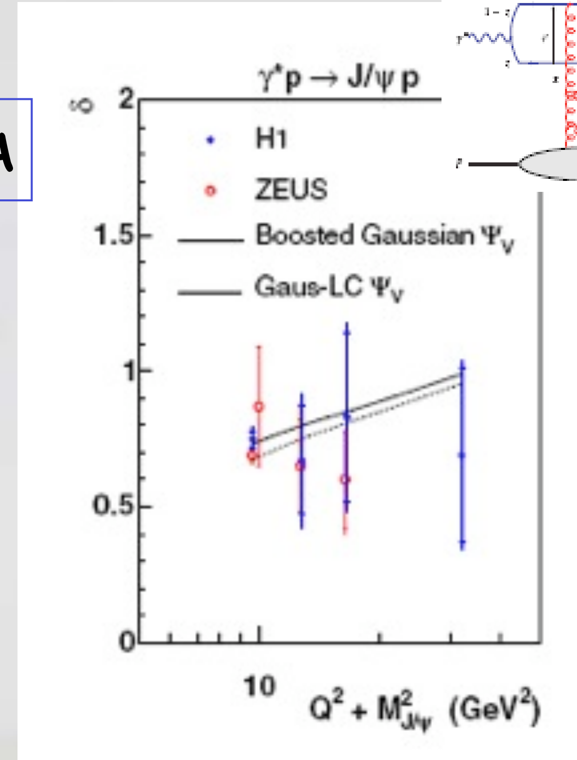

$F_L(x,Q^2)$
H1 data
b-Sat model
b-CGC model
GBW model
MRST 2006 NNLO
1
0.8
0.6
0.4
0.2
0
1
10
10^2
Q^2 (GeV^2)

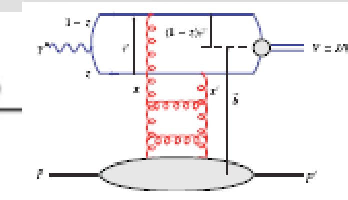
K+Watt



Discovery of HERA

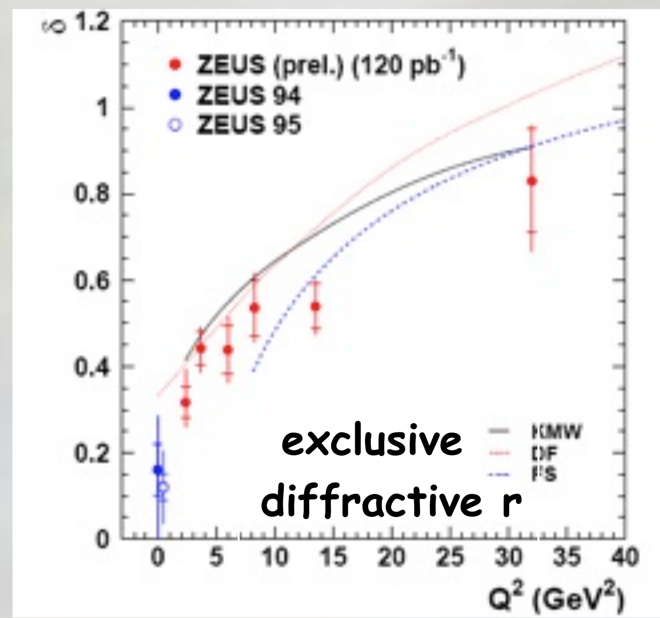






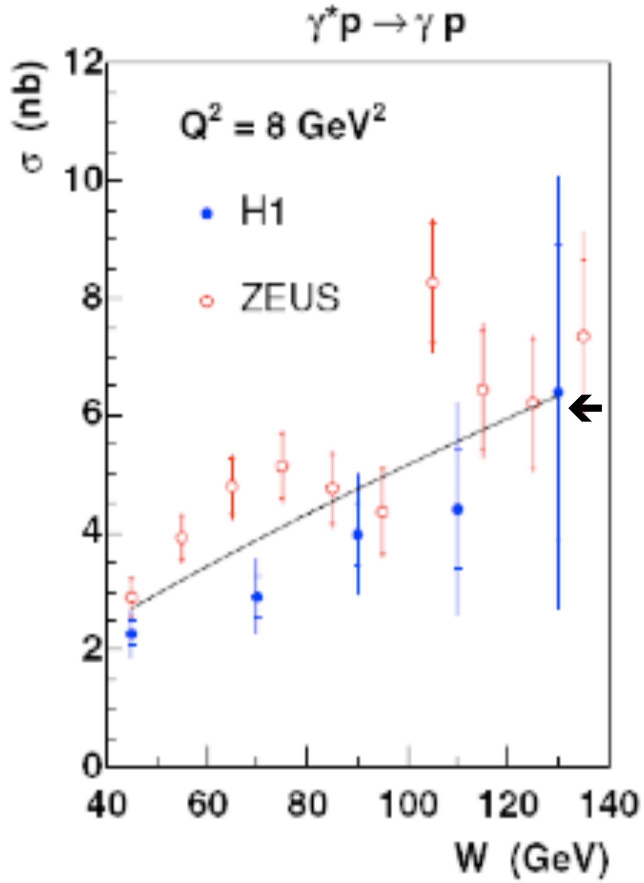
Universality of the observed intercepts

➔ Universal, "Pomeron like" QCD object
soft and hard Pomeron join together



Pomeron at work

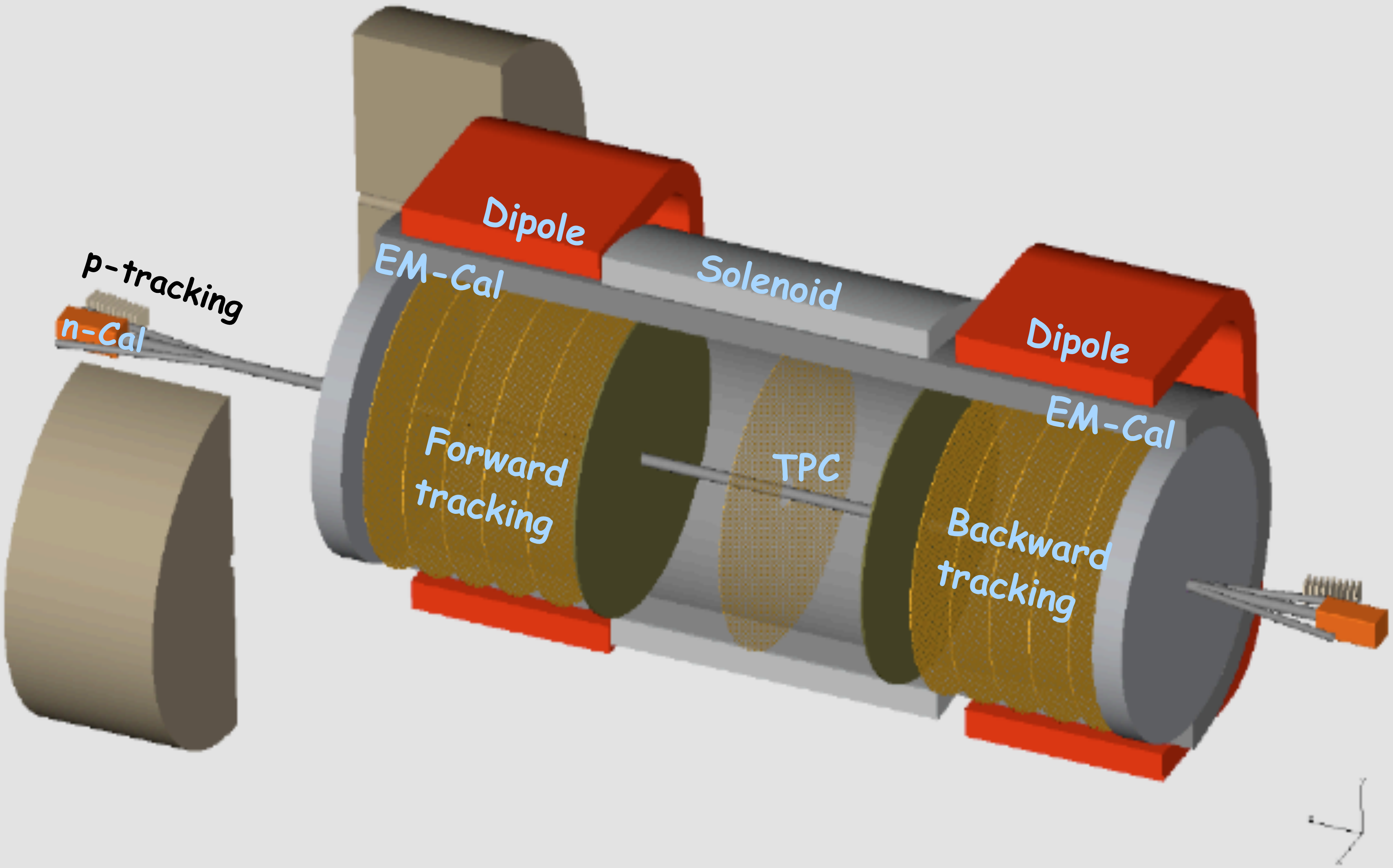
Rise of the DVCS cross-sections



b-Sat or IP-Sat

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

➔ detailed study of the Pomeron possible


p-tracking
n-Cal
Dipole
EM-Cal
Solenoid
Dipole
EM-Cal
Forward
tracking
TPC
Backward
tracking

Detector concept

Caldwell, Kowalski