The J/ψ way to nuclear structure
at EIC and LHeC

EIC - ep or eI, E_e = 4-20 GeV, E_I =100 GeV
LHeC - ep or eI, E_e = 5-150 GeV, E_I =3 TeV

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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

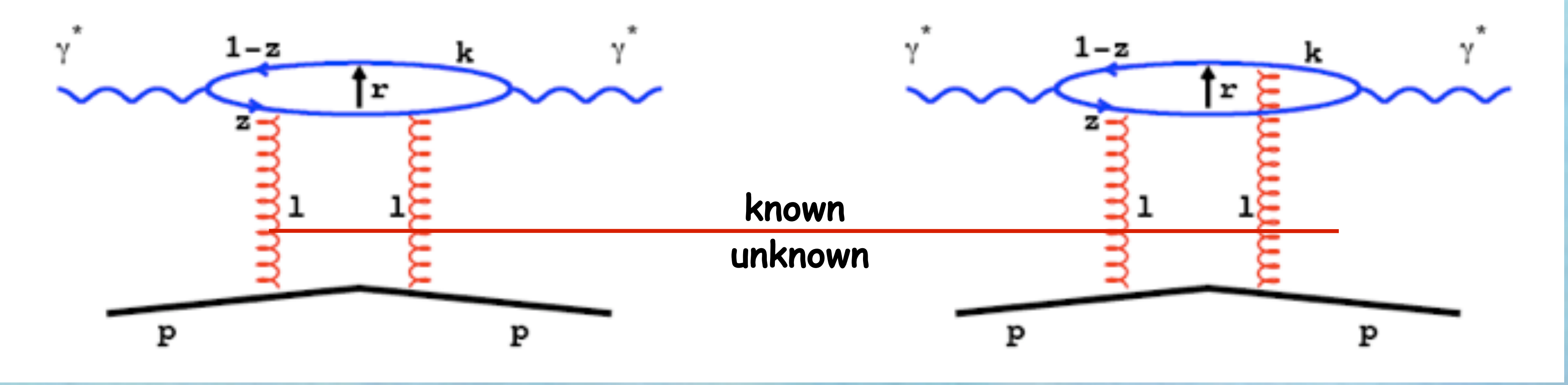
protons are not simple probes

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

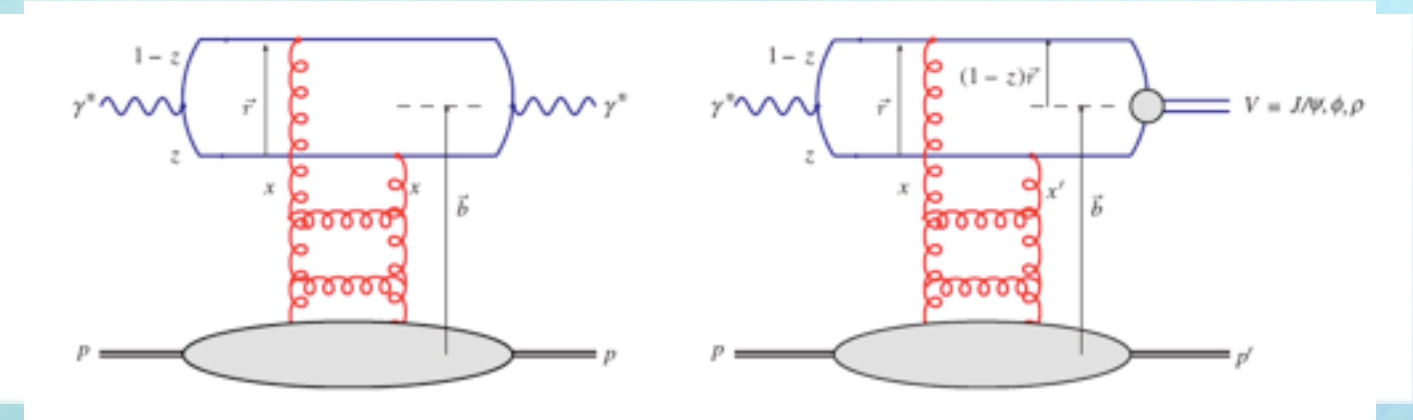
A novel tool to investigate nuclei:
Quark-antiquark color dipoles

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}



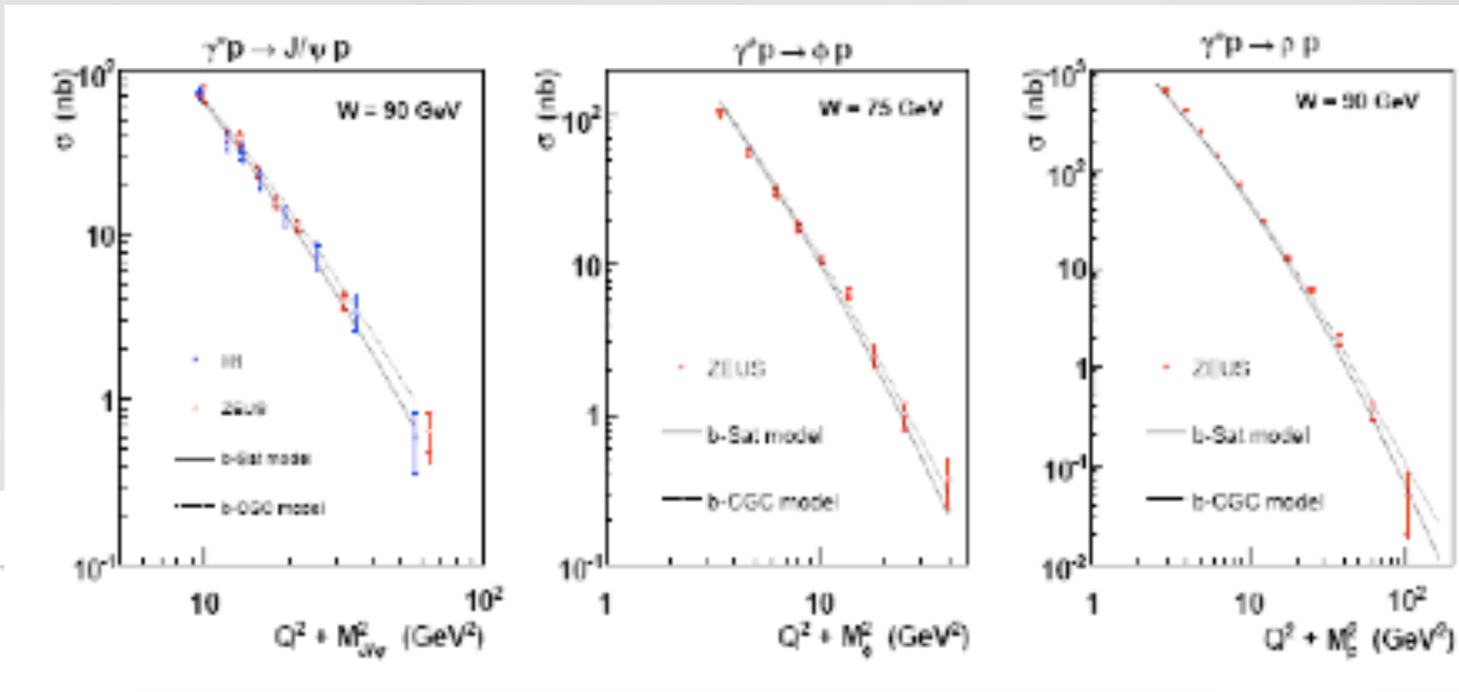
$$\sigma_{tot}^{\gamma^* p} = \int \Psi^* \sigma_{q\bar{q}} \Psi$$ ← Optical Theorem → $$\frac{d\sigma_{VM}^{\gamma^* p}}{dt} \sim \left| \int \Psi_{VM}^* \frac{d\sigma_{q\bar{q}}}{d^2 b} \sigma_{q\bar{q}} \Psi e^{-i\vec{b}\vec{\Delta}} \right|^2$$

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

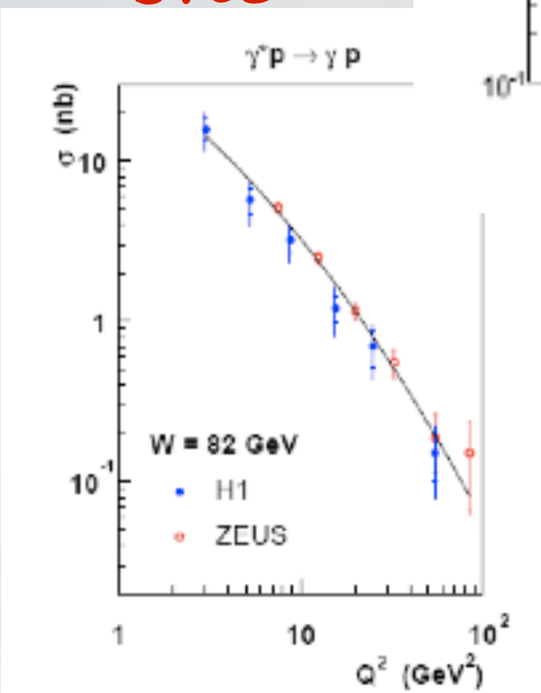
The same, universal, gluon density describes
the properties of many reactions measured at HERA:

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

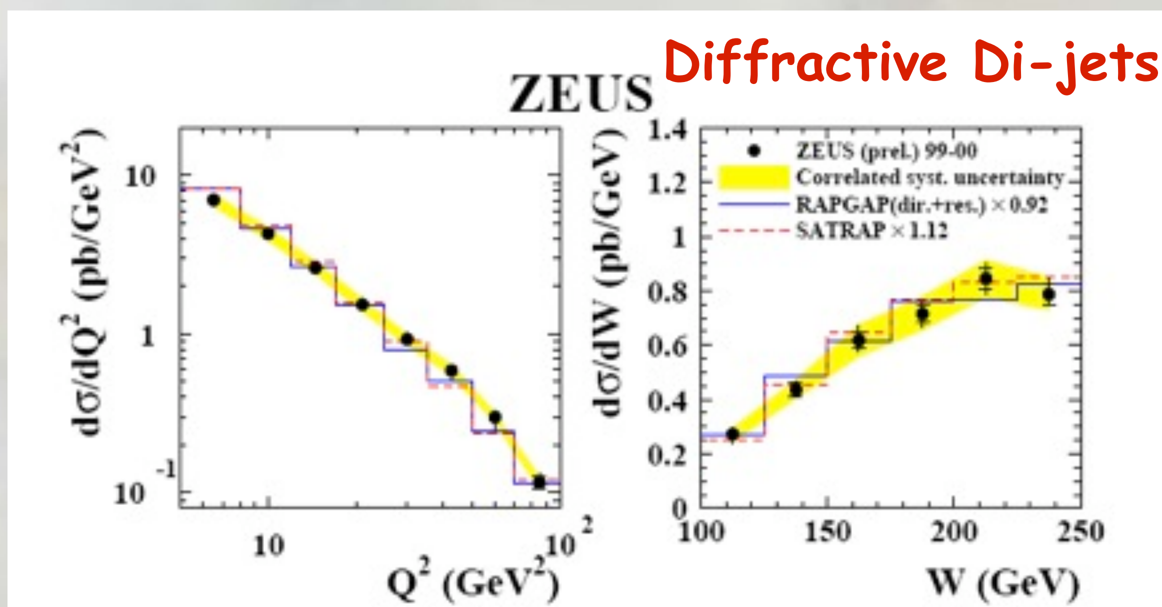
Vector Mesons



DVCS

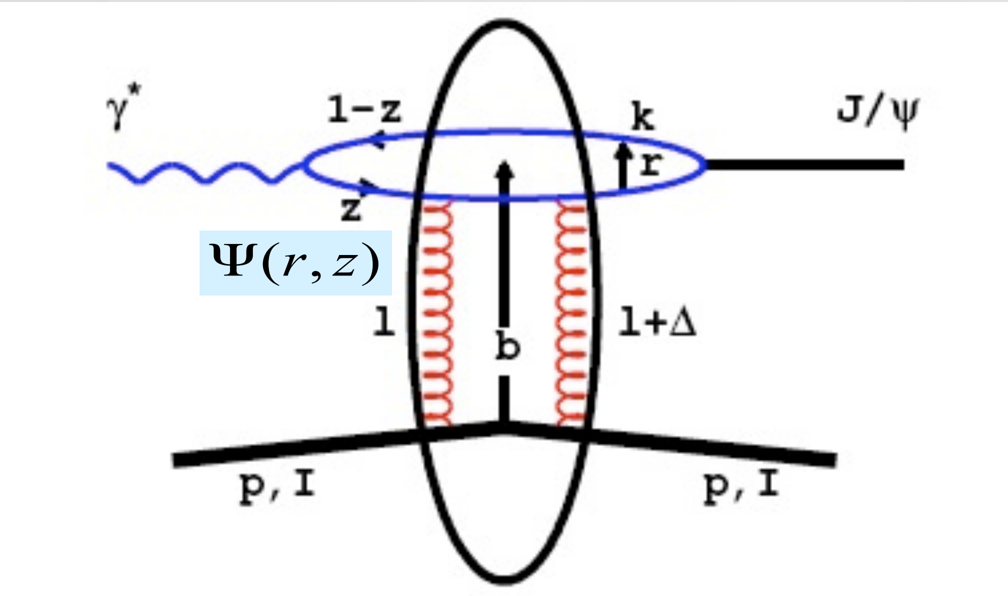


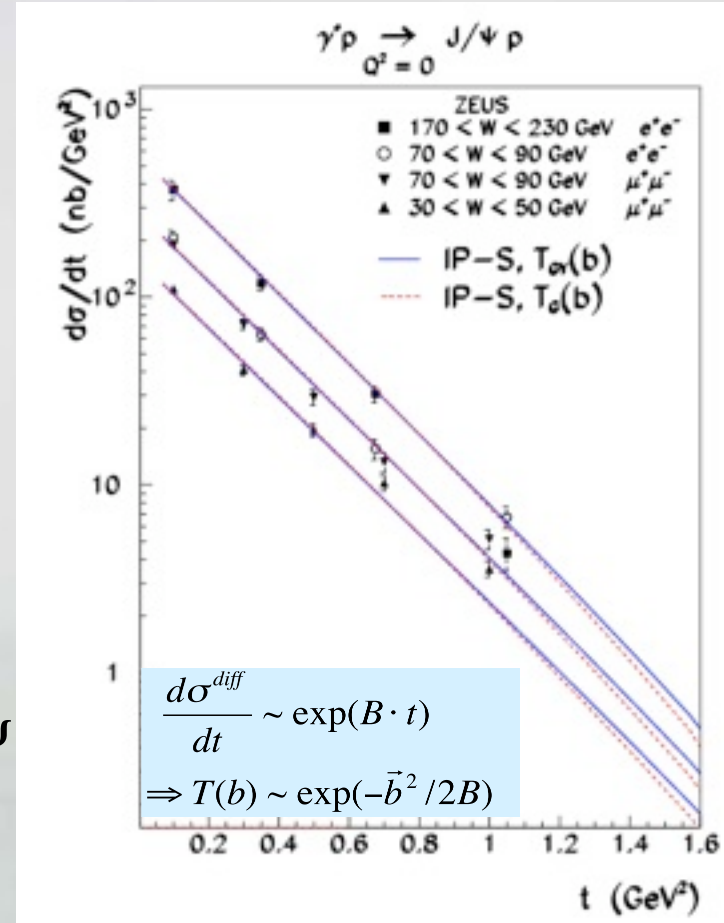
Diffractive Di-jets



Note: educated guesses for VM wf are working very well

Extracting Proton Shape using dipoles





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

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

KT, KMW

T(b)-proton shape

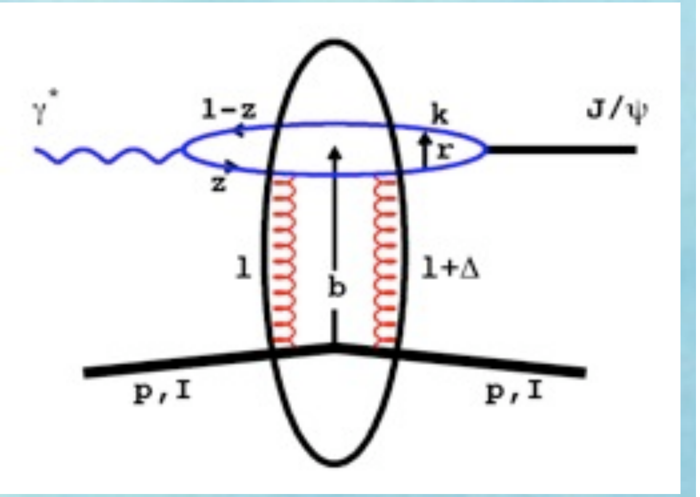
J/ψ as a probe of proton and nuclei

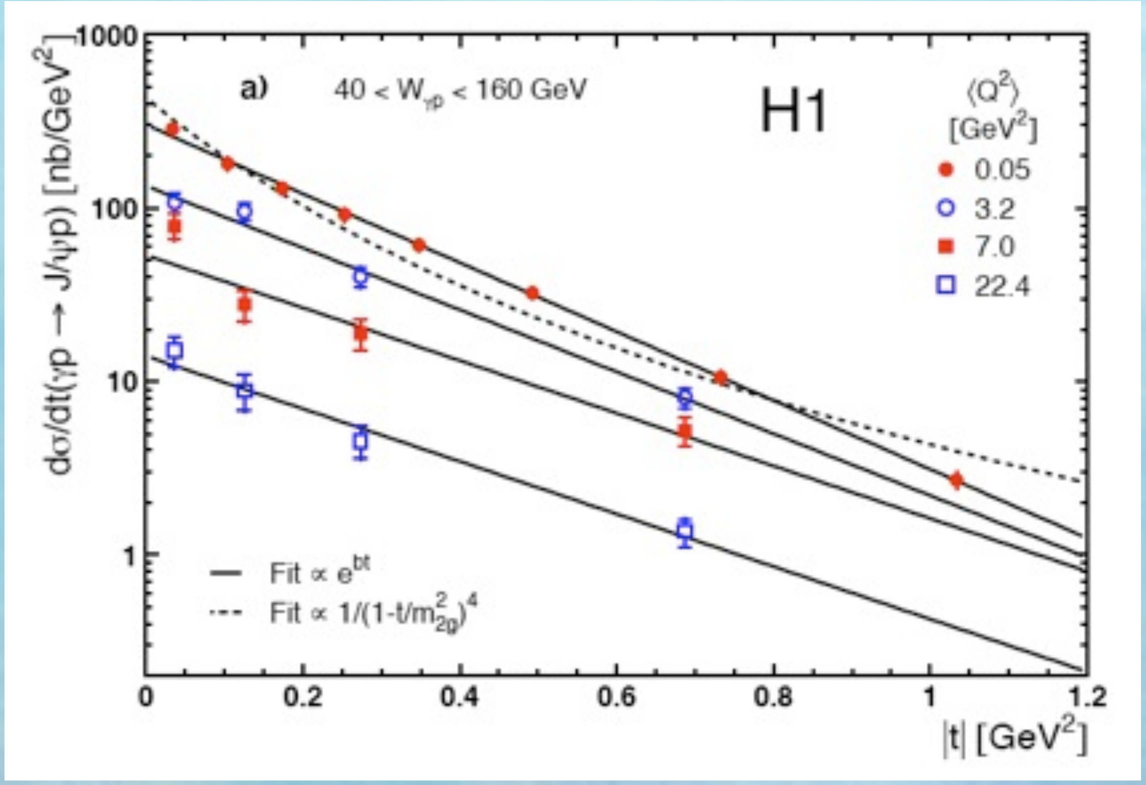
Ideal probe:

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





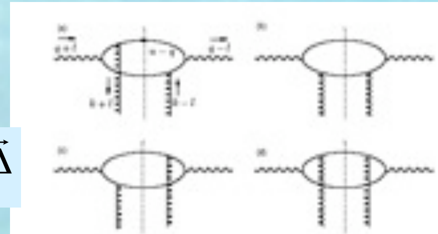
Exponential behavior ➔ B_D size of the interaction region

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

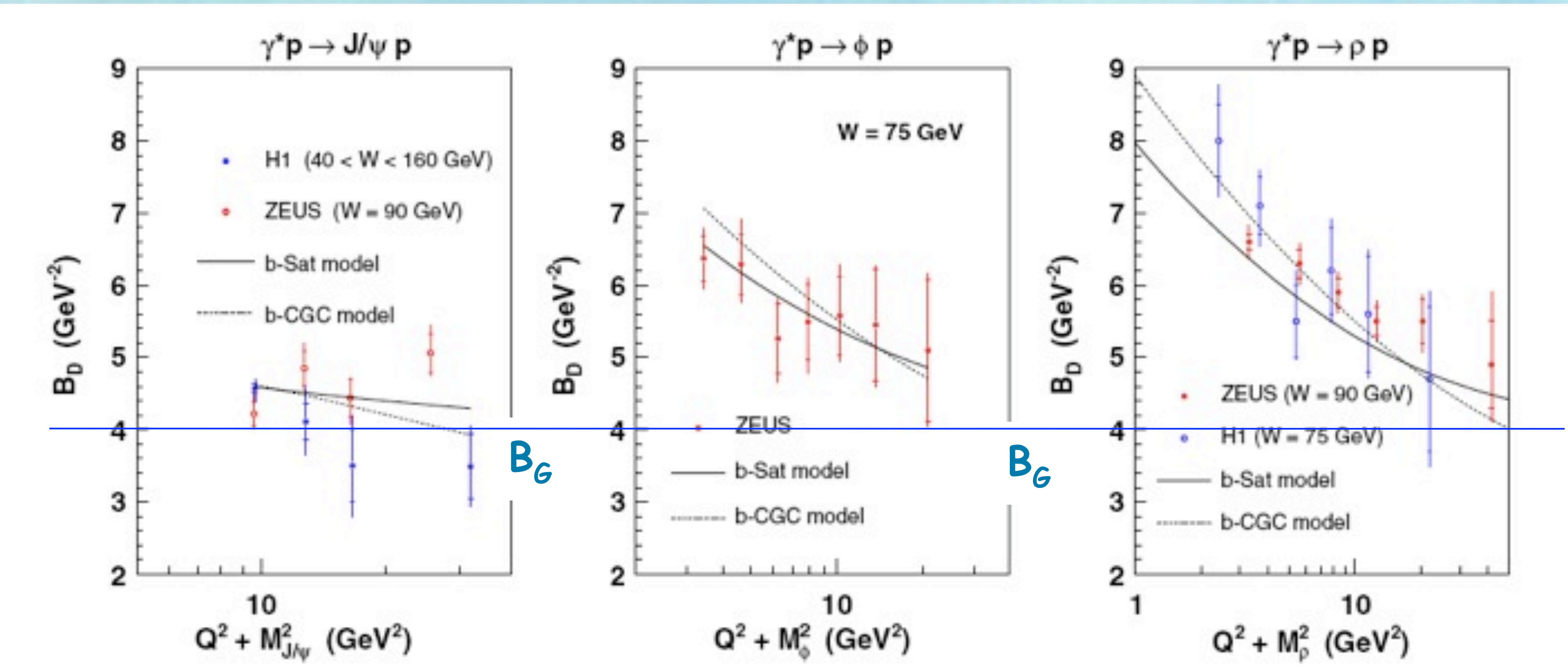
The size of interaction region B_D for various VM

Modification by Bartels, Golec-Biernat, Peters

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

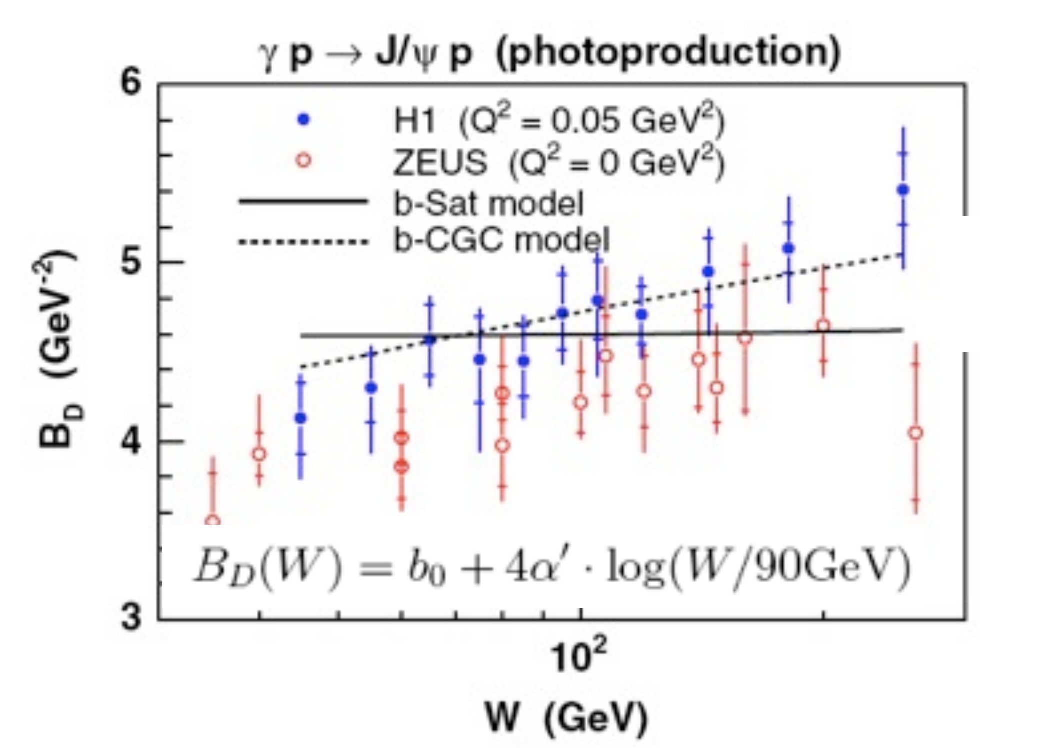


KMW



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

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

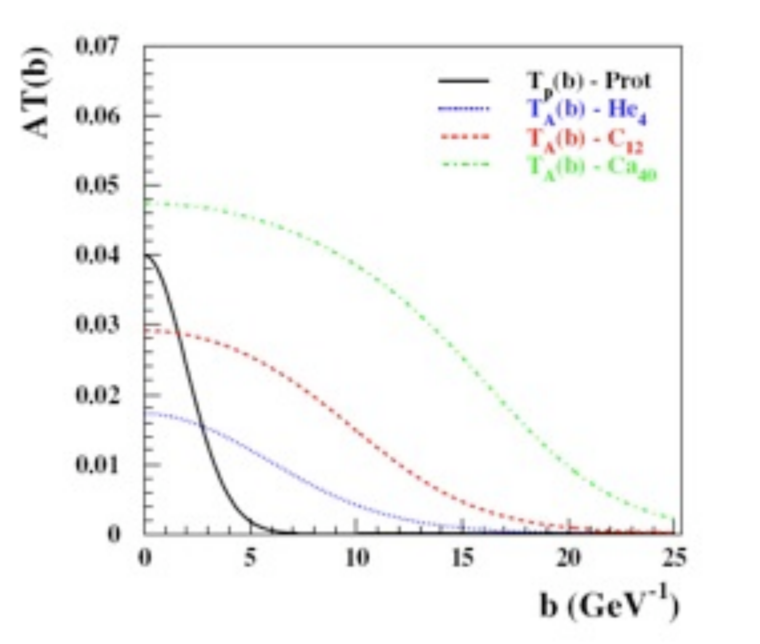
the gluonic proton radius is smaller than the quark radius

X-sections for nuclear J/ψA production

Conventional assumption: charmed dipole scatters on individual nucleons
Amplitude for scattering on a configuration $\{b_i\}$:

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

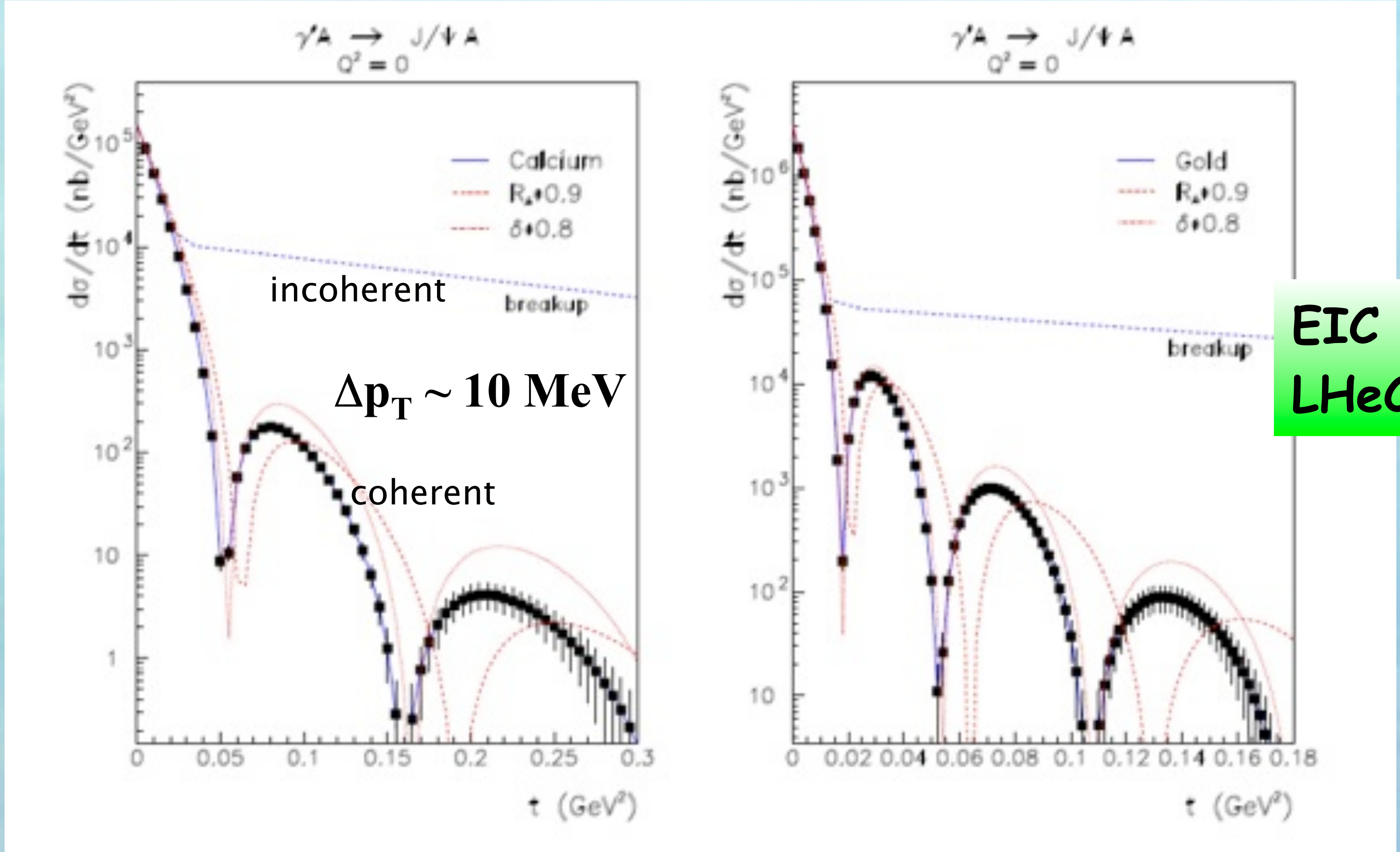
Nucleons distributed within the nucleus of Woods-Saxon shape



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

Nuclear gluonic shapes

Coherent and incohernt eA → J/ψA production



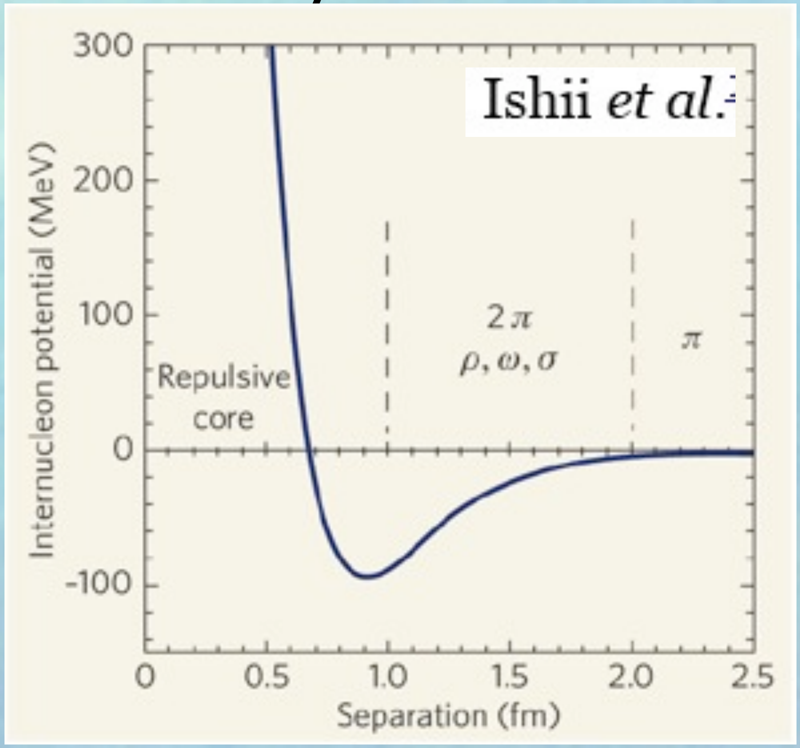
EIC ~ x^{-3}
LHeC ~x^{-5}

Assumption: scattering on configurations of randomly distributed, uncorrelated nucleons within the 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 positions are 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

A more regular nuclear structure?
=> some influence on diffractive patterns is expected

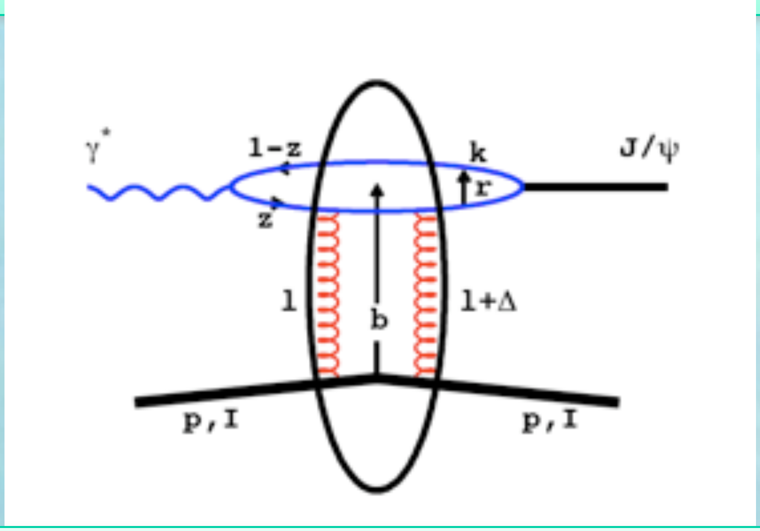
Look into inner arrangements of nucleons in nucleus?

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 a new source of information about the gluonic nuclear forces

example: 1 MeV gluon kick vs n neutrons, n protons with p_T
10 MeV gluon kick " "
100 Mev gluon kick " "

J/psi p_T resolution at EIC or LHeC



J/psi p_T is determined from p_T of ee or $\mu\mu$ decay pair

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

no measurement of a proton or ion momentum necessary

beam electron p_T < 1 MeV (0.2 with cooling MeV) for E_e < 5 GeV
scattered electron can be easily detected in the forward detector

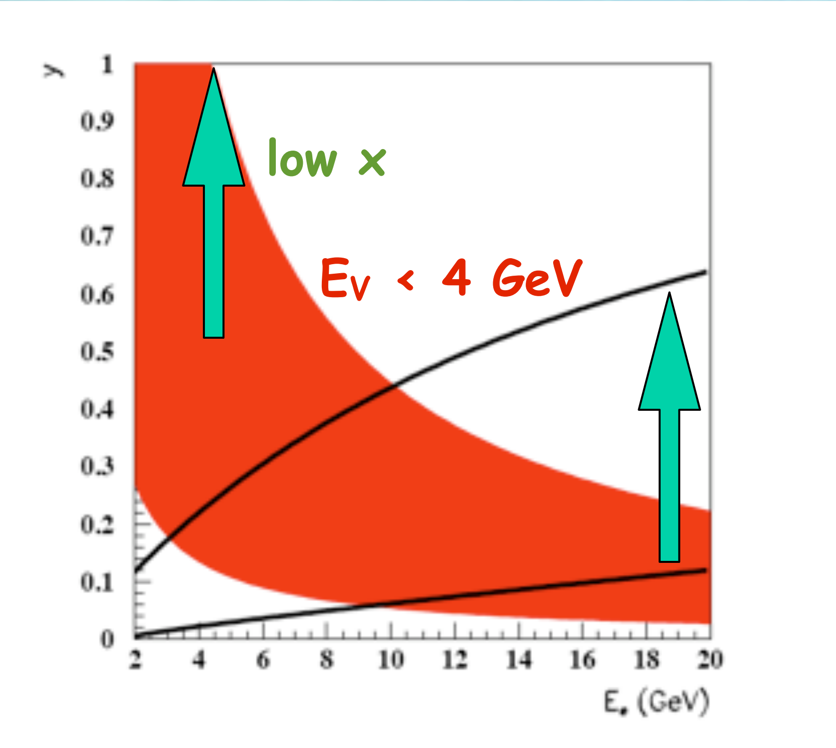
Acceptance and X-sec for elastic J/ψ photoproduction at eRHIC, E_p = 100 GeV

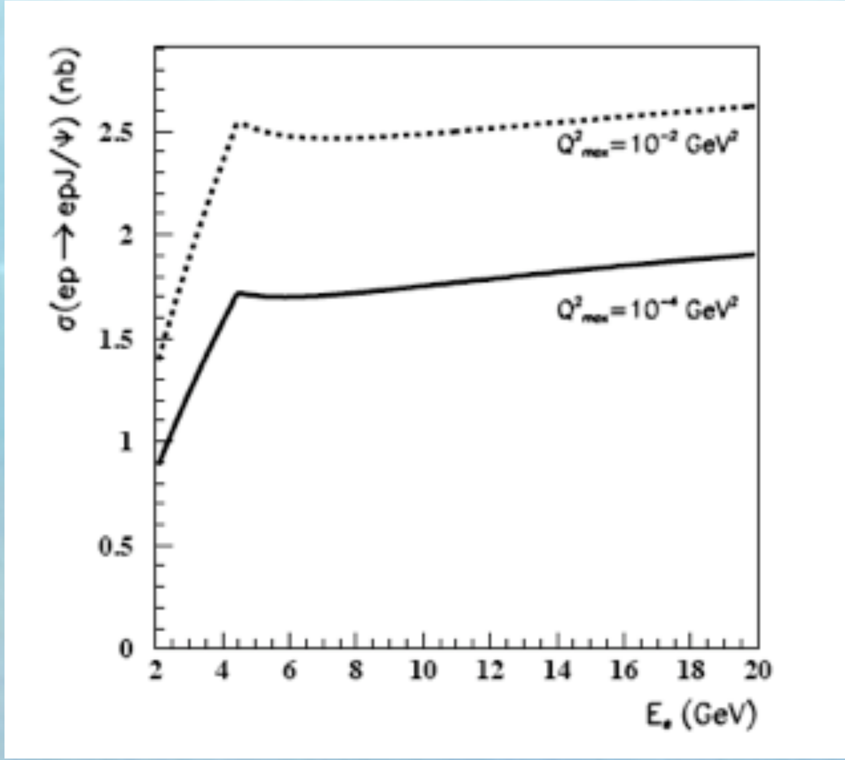
E_V - Energy of J/ψ

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

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

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.

⇐ TPC parameters ⇓

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

⇓

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)

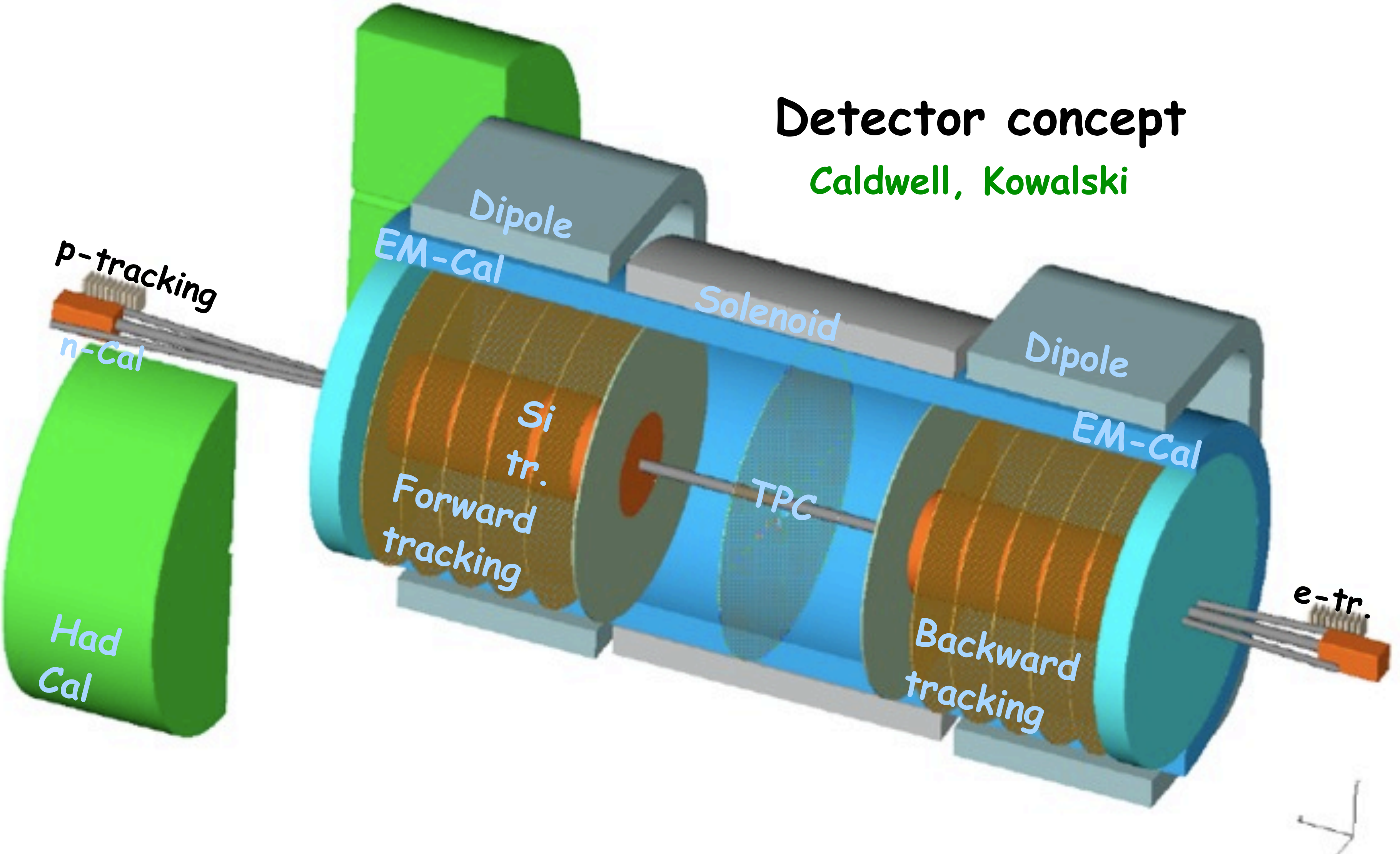
Experimental signature of coherent production

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 at EIC or LHeC the gluonic structure of nuclear matter with a pure QCD probe

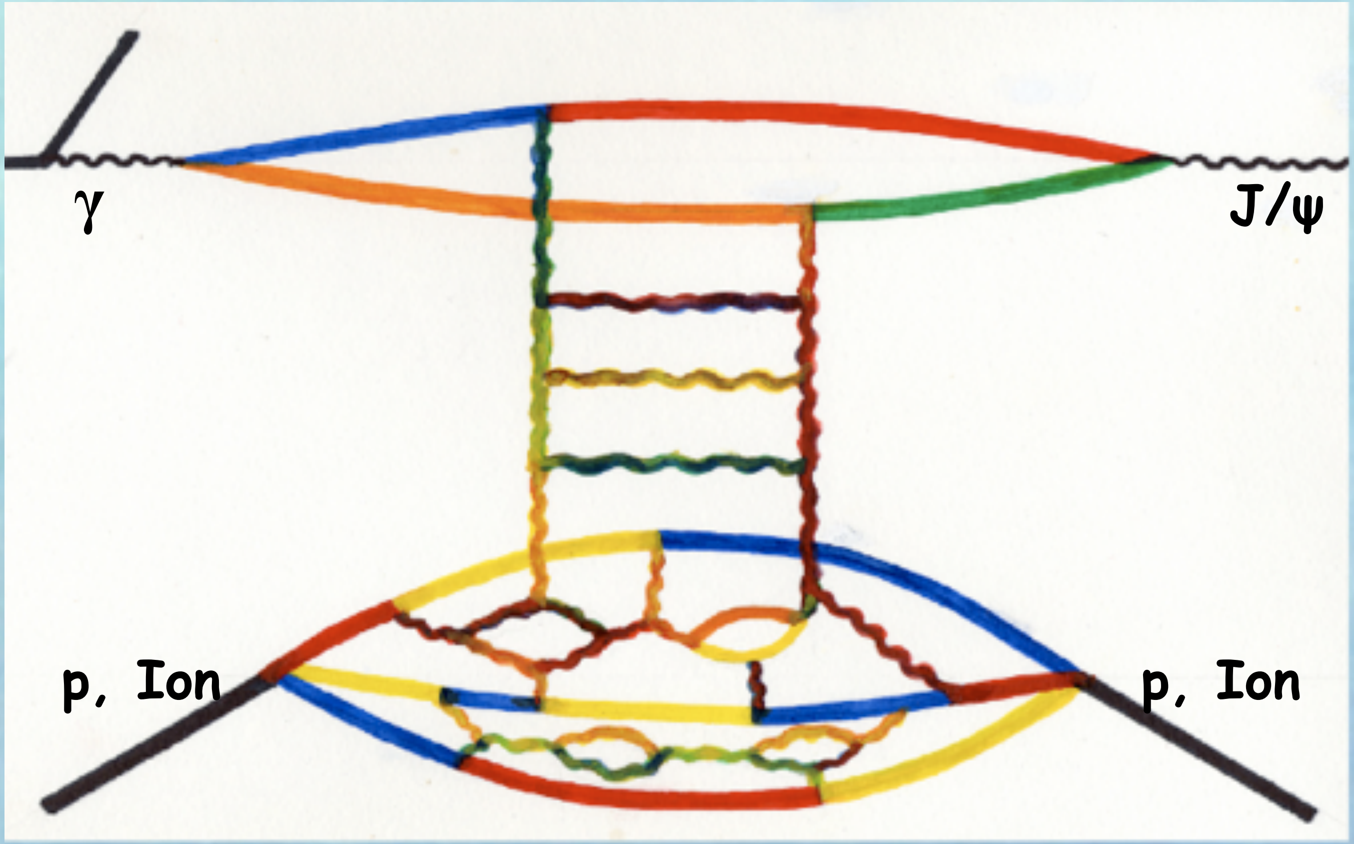
Gluonic radius of the proton is sizably smaller than the quark one

We can investigate the inner structure of nuclear matter by observation of diffractive patterns emerging from densely packed nuclei

LHeC is the ultimate saturation machine

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

eA Physics with EIC and LHEC



BACK UP SLIDES

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 amplitude for the scattering on a configuration:

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

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

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