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

talk by Henri Kowalski,
based on the paper with A. Caldwell
+ Al Mueller, T. Lappi, R. Venugopalan, M. Diehl, ...

LHeC Workshop
Divonne 2nd of September 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)

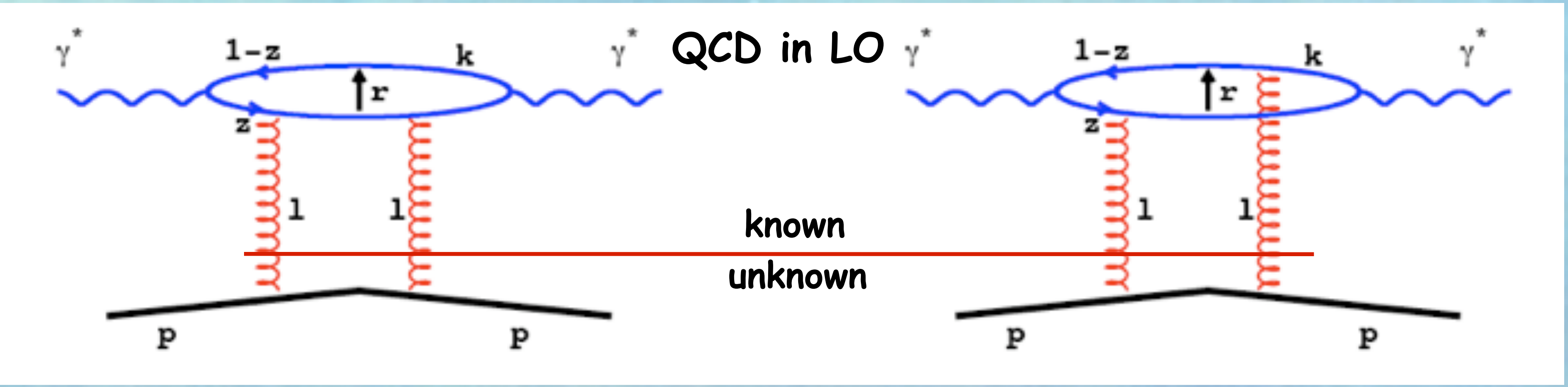
Lattice Gauge Theory has proven that QCD is the correct theory of strong interactions at large distances
Its application to hadronic interactions are only now being developed

Nuclei are difficult to investigate because of a lack of proper tools to view inside nuclei

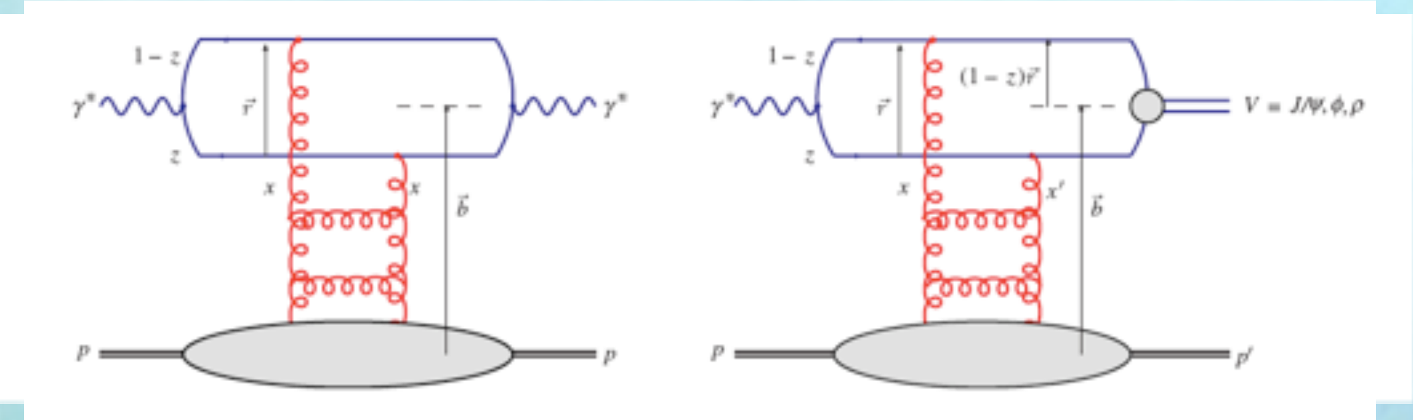
electrons can only see the electric charge distribution
protons are not simple probes

the novel probe to investigate nuclei:

Quark-antiquark color dipoles
Dipoles interact strongly with the nuclear matter
but the interaction is well understood in QCD



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 →

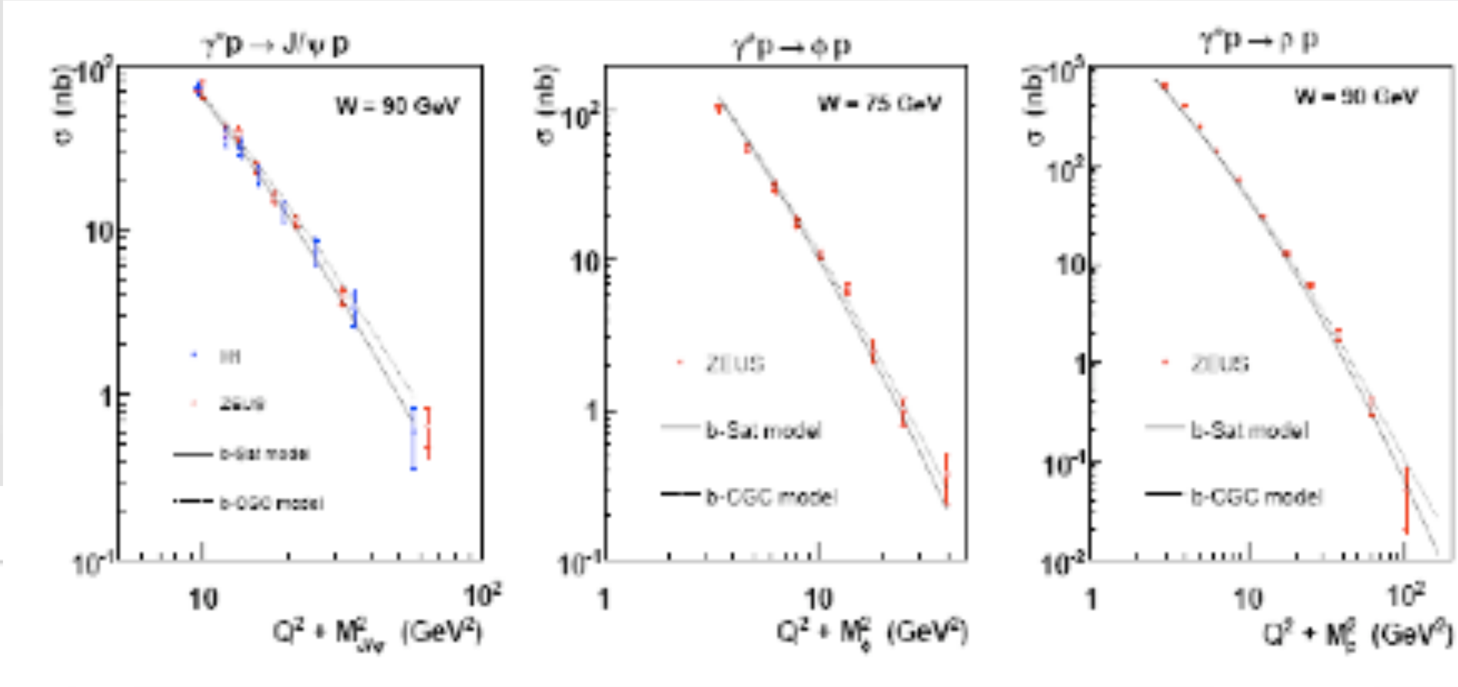
$$\frac{d\sigma_{VM}^{\gamma^* p}}{dt} \sim \left| \int \Psi_{VM}^* \frac{d\sigma_{q\bar{q}}}{d^2 b} \sigma_{q\bar{q}} \Psi e^{-i\vec{b}\vec{\Delta}} \right|^2$$

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

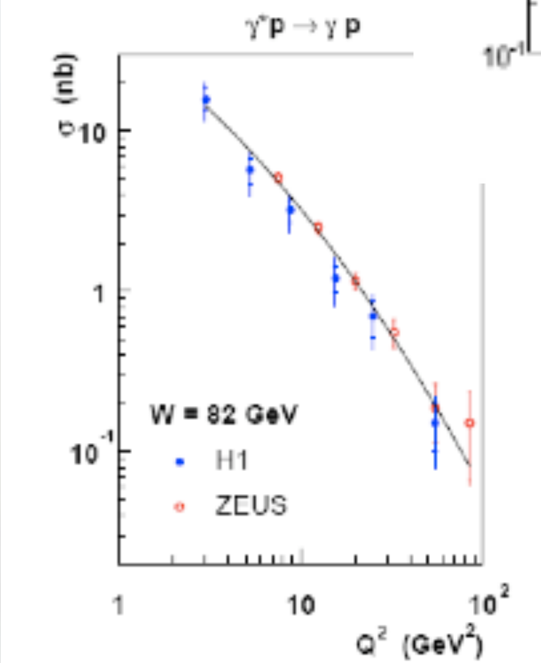
The same, universal, gluon density describes
the properties of many reactions measured at HERA:

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

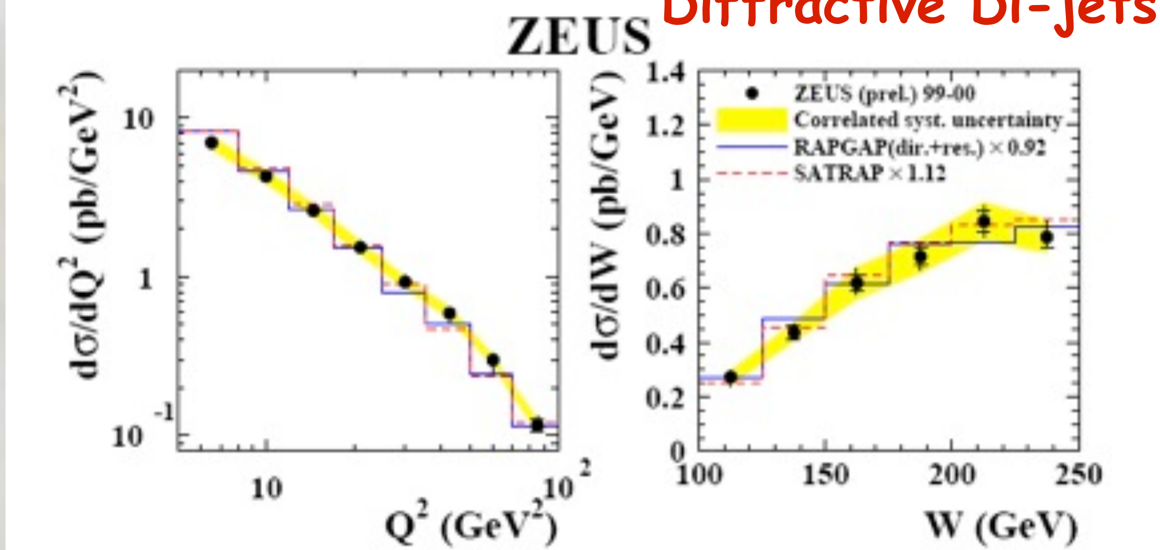
Vector Mesons



DVCS

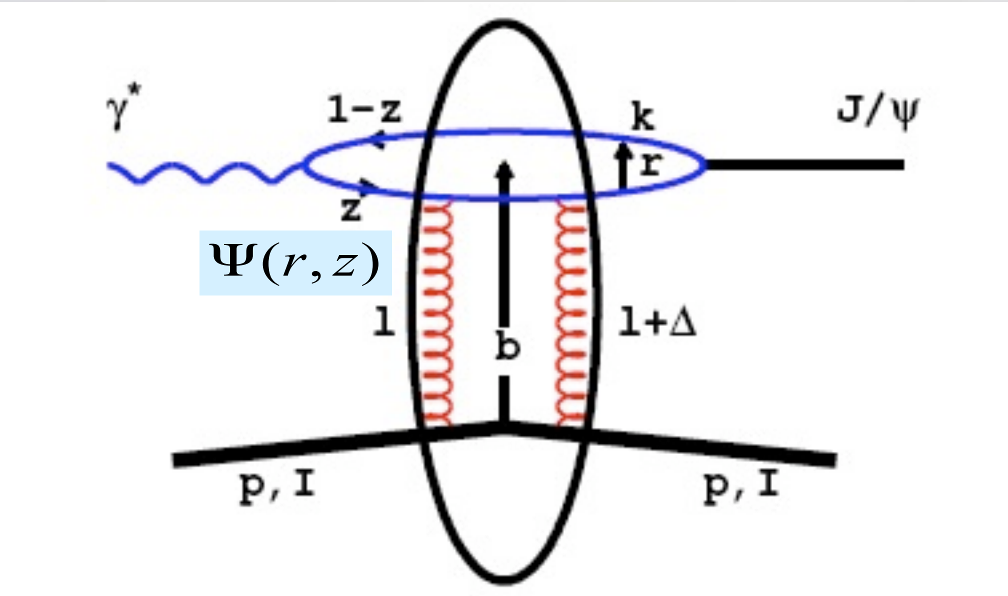


Diffractive Di-jets



Note: educated guesses for VM wf are working very well

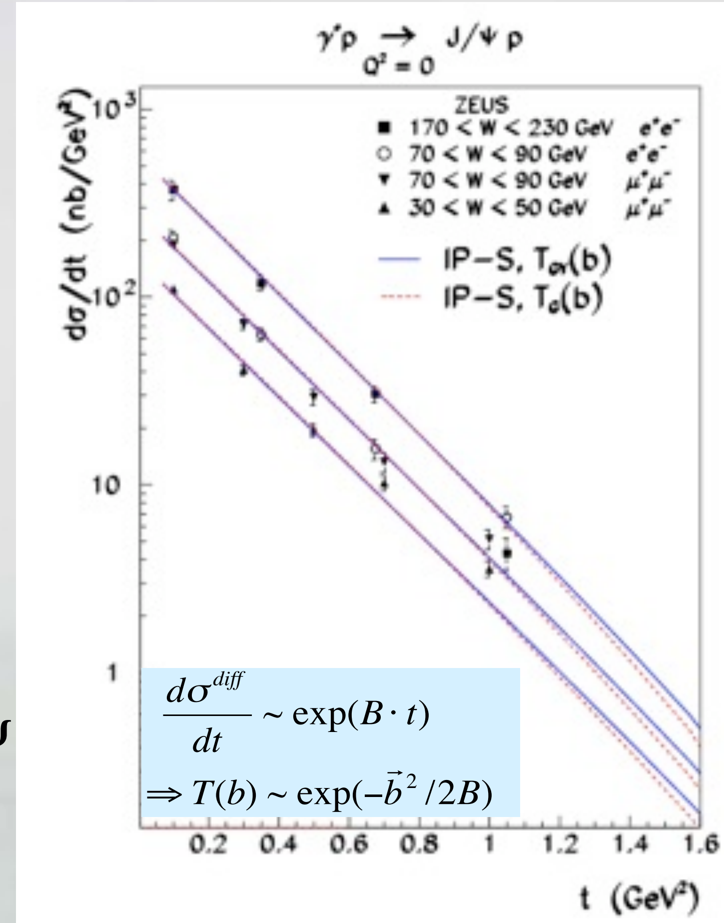
Extracting Proton Shape using dipoles



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

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

T(b)-proton shape



KT, KMW

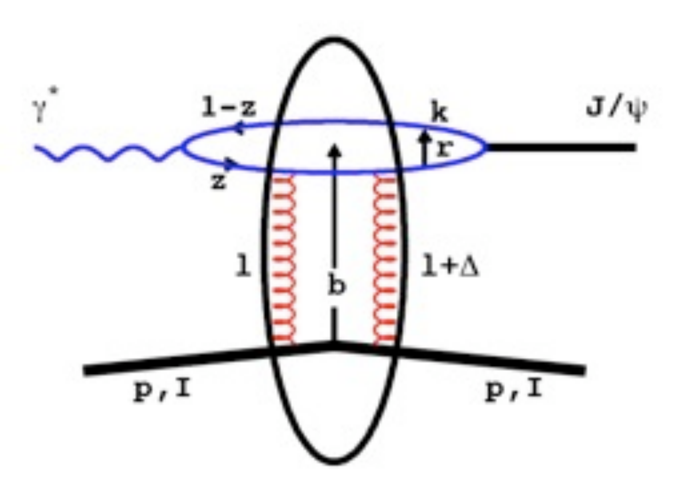
J/ψ as a probe of proton and nuclei

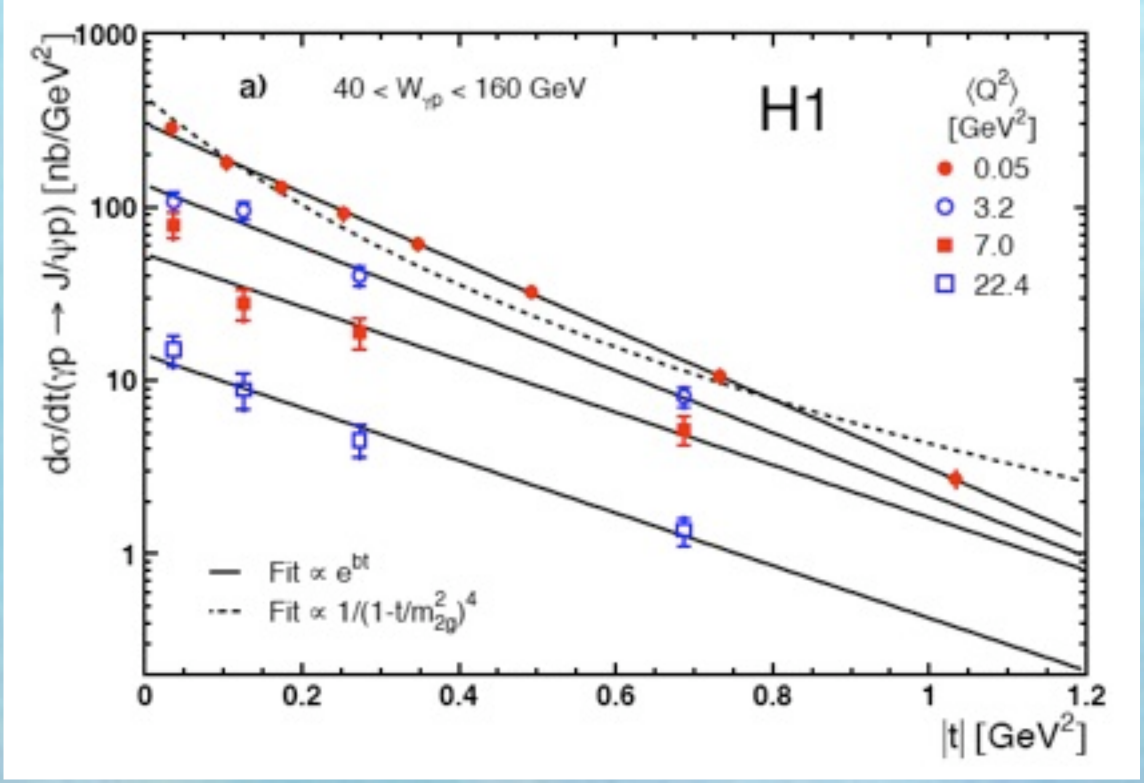
Ideal probe:

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





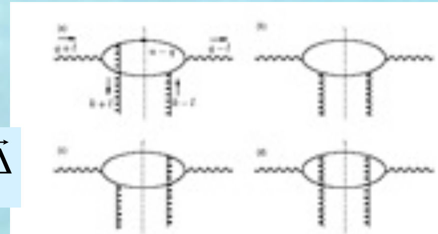
Exponential behavior ➔ B_D size of the interaction region

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

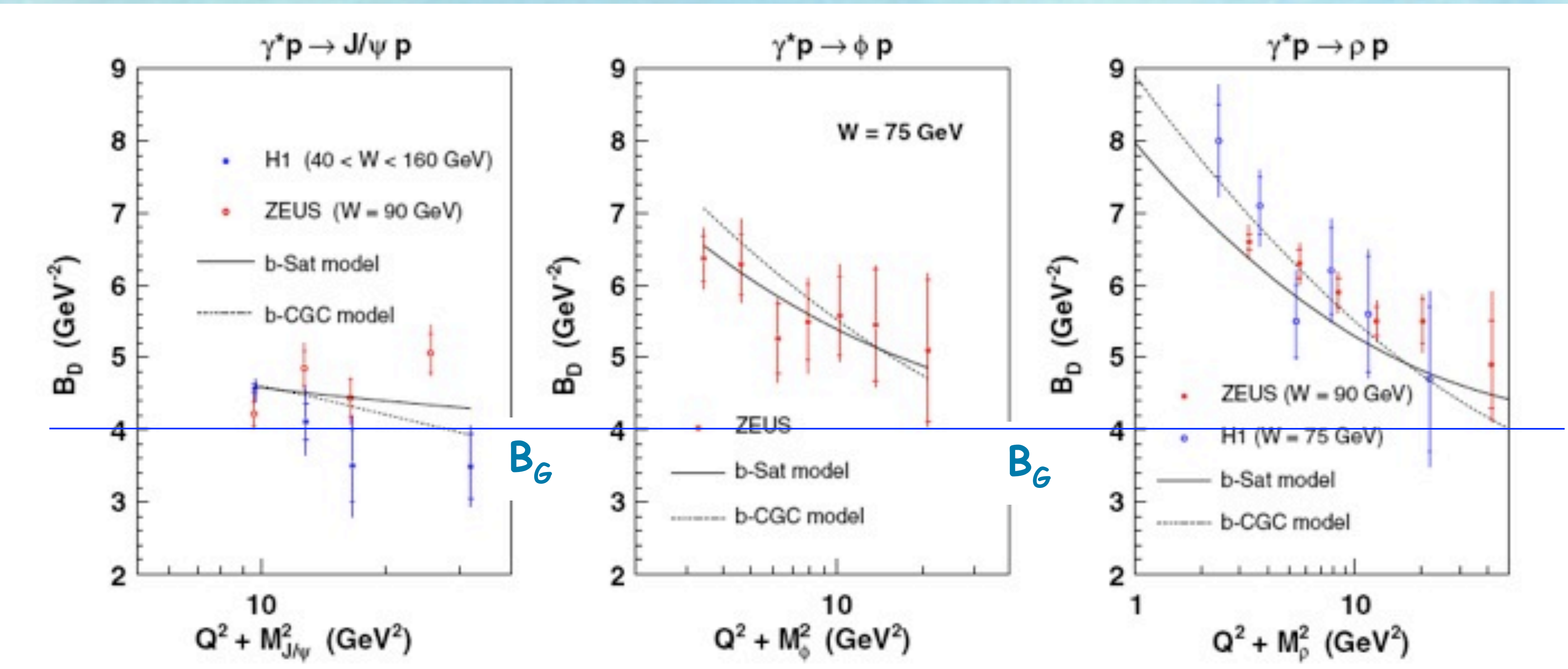
The size of interaction region B_D for various VM

Modification by Bartels, Golec-Biernat, Peters

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

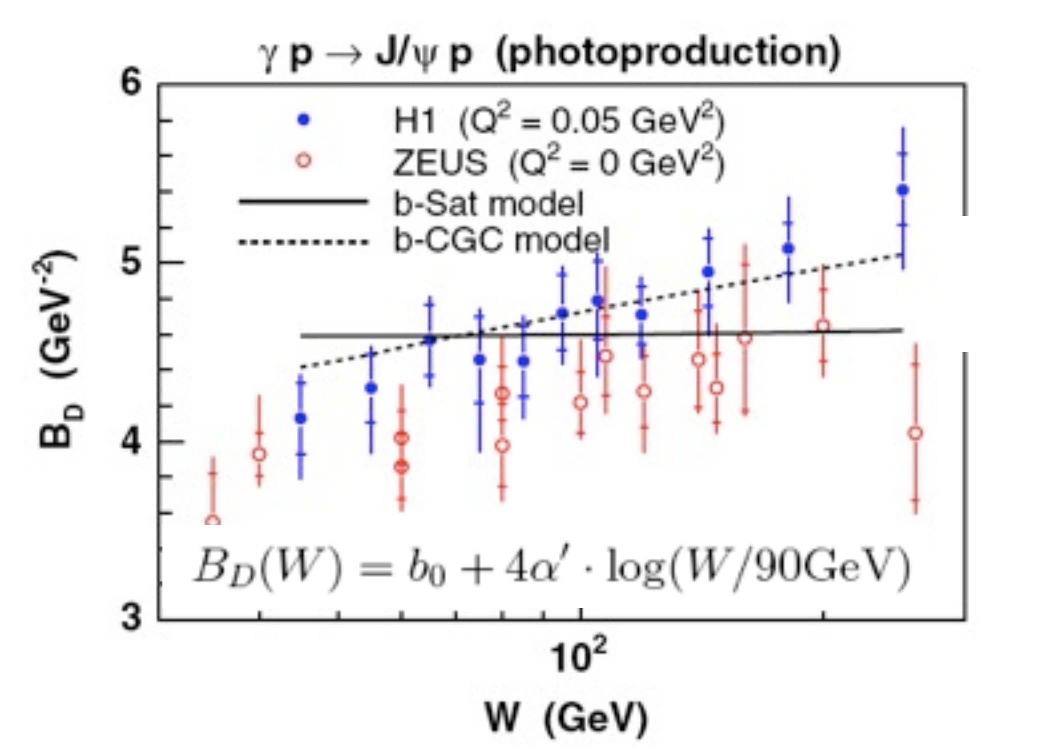


KMW



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

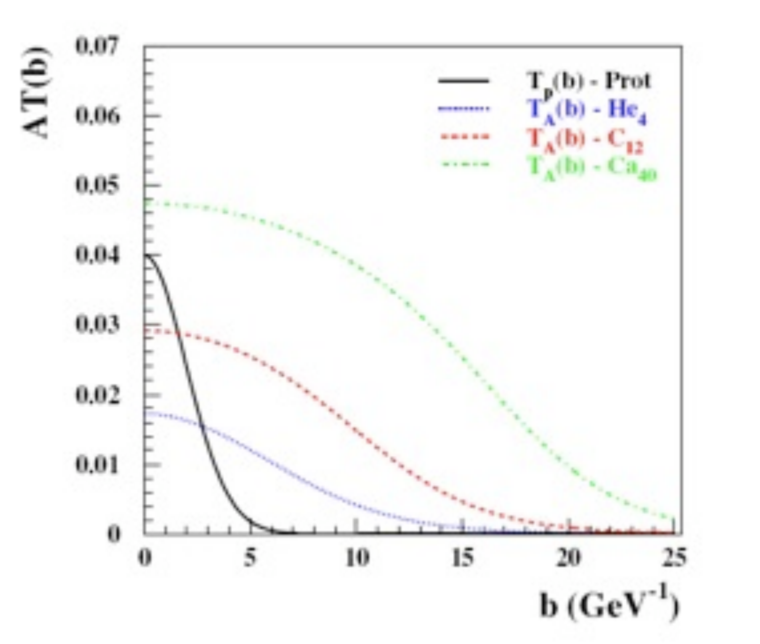
the gluonic proton radius is smaller than the quark radius

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



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

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

Fourier transform of the amplitude

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

Coherent: scattering on nucleus in the ground state

$$-iA^{q\bar{q}}_{A_0\to A_0} = \sigma_p e^{-B_p\cdot\Delta^2/2} \sum_{i=1}^{A} \int d^2\vec{b}_1 ... d^2\vec{b}_A \Psi^*_{A_0}(\vec{b}_1 ... \vec{b}_A)\Psi_{A_0}(\vec{b}_1 ... \vec{b}_A) \cdot e^{-i\vec{b}_i\cdot\vec{\Delta}}$$

definition of one nucleon distribution

$$\int d^2\vec{b}_2 ... d^2\vec{b}_A d^2\Psi^*_{A_0}(\vec{b}_1 ... \vec{b}_A)\Psi_{A_0}(\vec{b}_1 ... \vec{b}_A) = T_A(b_1)$$

assumption $T_A(b_1) = T_A(b_i).$

$$\frac{d\sigma^{q\bar{q}}_{A_0\to A_0}}{dt} = \frac{A^2\sigma_p^2}{16\pi} e^{-B_p\cdot\Delta^2} \cdot \left|\int d^2b\, T_A(b) e^{-i\vec{b}\cdot\vec{\Delta}}\right|^2,$$

KT & KLV

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

Fourier transform the amplitude for the scattering on a configuration:

$$-iA^{q\bar{q}}_{A_0\to A_n} = \sigma_p e^{-B_p\cdot\Delta^2/2}\sum_{i=1}^{A}\int d^2\vec{b}_1 ... d^2\vec{b}_A \Psi^*_{A_n}(\vec{b_1}...\vec{b_A})\Psi_{A_0}(\vec{b_1}...\vec{b_A})\cdot e^{-i\vec{b_i}\cdot\vec{\Delta}}$$

compute xsections, apply completeness relation

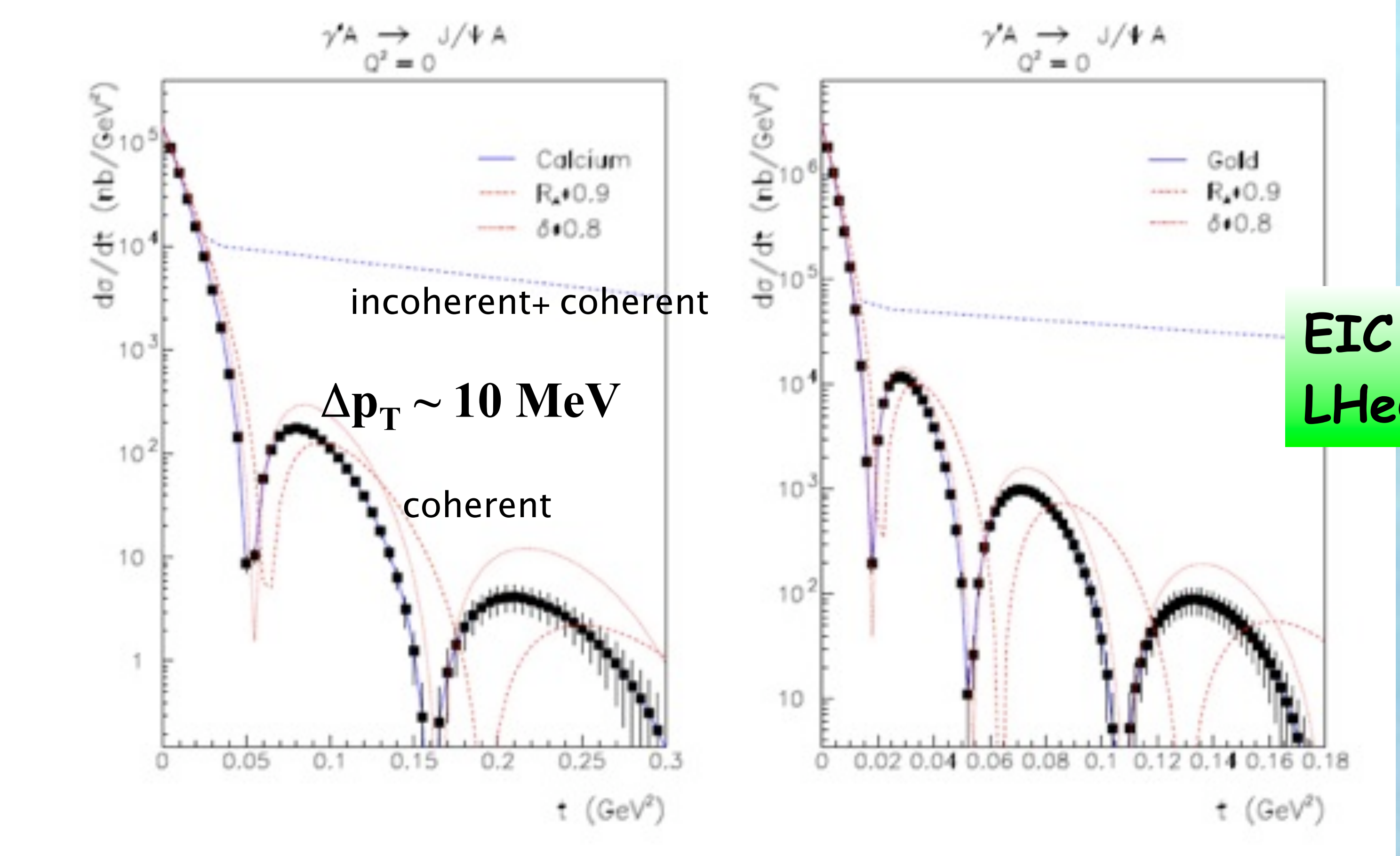
$$\sum_n \frac{d\sigma^{q\bar{q}}_{A_0\to A_n}}{dt} = \frac{\sigma_p^2}{16\pi}e^{-B_p\Delta^2}\sum_i^A\sum_j^A\int d^2\vec{b}_1 ... d^2\vec{b}_A \Psi^*_{A_0}(\vec{b_1}...\vec{b_A})\cdot\Psi_{A_0}(\vec{b_1}...\vec{b_A})\cdot e^{-i(\vec{b_i}-\vec{b_j})\cdot\vec{\Delta}}$$

Subtract ground state ➡ Incoherent scattering

$$\sum_{n\neq 0} \frac{d\sigma^{q\bar{q}}_{A_0\to A_n}}{dt} = \frac{\sigma_p^2}{16\pi}e^{-B_p\Delta^2}\int d^2\vec{b}_1 d^2\vec{b}_2 \left\{A\ \left(T_A(b_1)T_A(b_2) - T_A^{(2)}(\vec{b}_1,\vec{b}_2)e^{-i(\vec{b}_1-\vec{b_2})\cdot\vec{\Delta}}\right)\right.$$
$$\left. +\ A^2\left(T_A^{(2)}(\vec{b}_1,\vec{b}_2) - T_A(b_1)T_A(b_2)\right)e^{-i(\vec{b}_1-\vec{b_2})\cdot\vec{\Delta}}\right\}$$

Nuclear gluonic shapes

Coherent and incohernt eA → J/ψA production



EIC ~ x^{-3}

LHeC ~x^{-5}

Coherent - nucleus remains in the ground state

incoherent - nucleus gets excited or breaks up, no additional particles are produced

Experimental signature of incoherent production

Break up: large rapidity gap with some particles in the forward neutron and proton detectors (for A~200, 4 neutrons and 3 protons expected)

Excited state without breakup: low energy photons (electrons) in the final state

Experimental signature of coherent production

large rapidity gap with no particles in the forward em, neutron or proton detectors

Breakup reactions can be well identified by the forward proton and neutron detectors,

Excited states without breakup can be partly identified by the forward em calorimeters.

It remains to be determined how well excited and coherent states can be (statistically) separated

Coherent J/ψ production

Study of the gluonic nuclear radius and density

Incoherent J/ψ production

Study of gluonic two body correlations

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

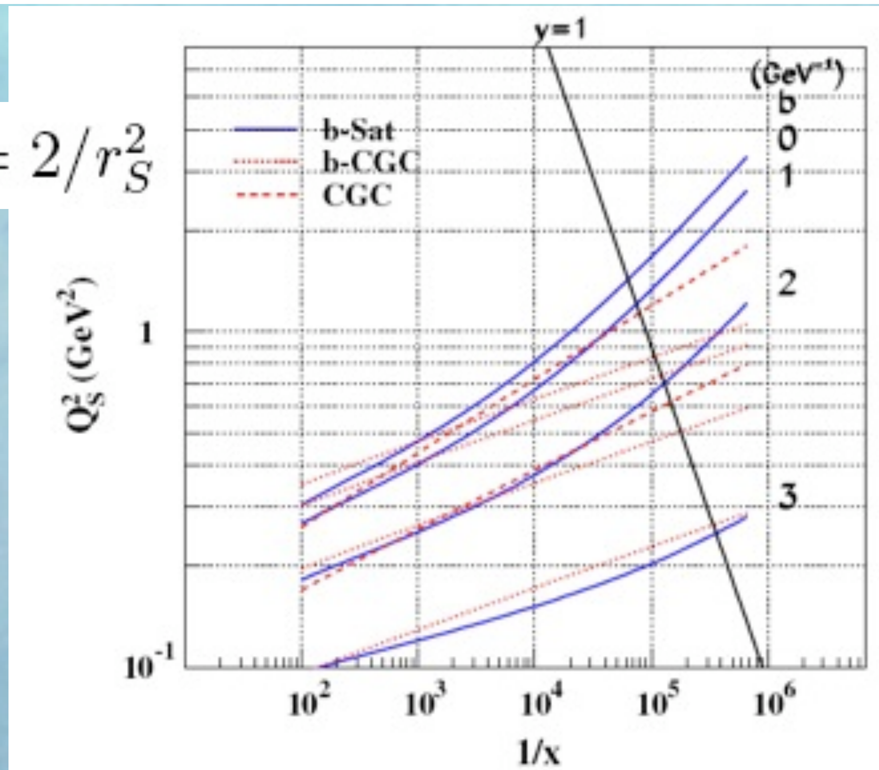
example: 1 MeV gluon kick vs n neutrons, n protons with p_T
10 MeV gluon kick " "
100 Mev gluon kick " "

Saturation

Degree of saturation is characterized by the size of the dipole, r_S which, at a given x, starts to interact multiple times

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

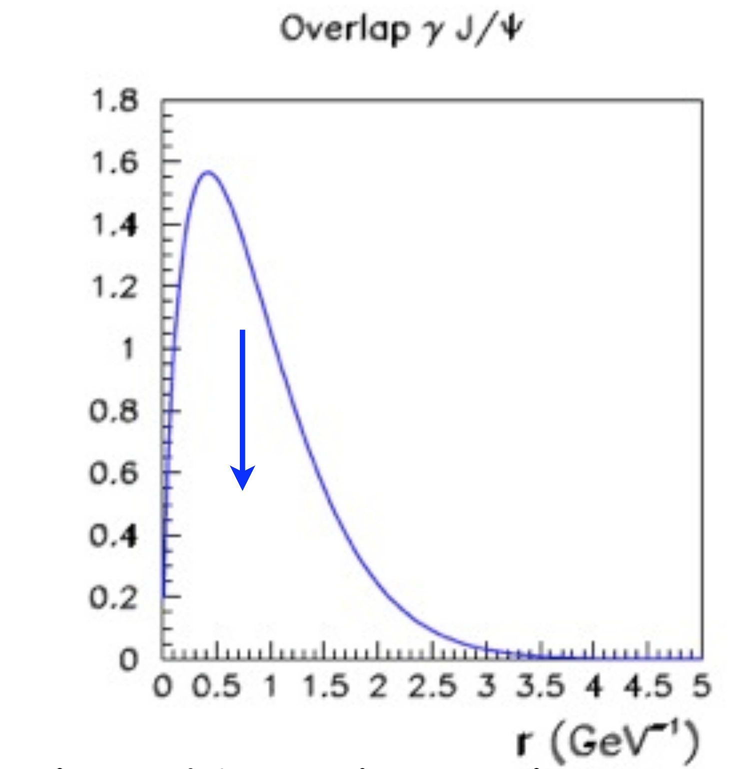
$$Q_S^2 = 2/r_S^2$$

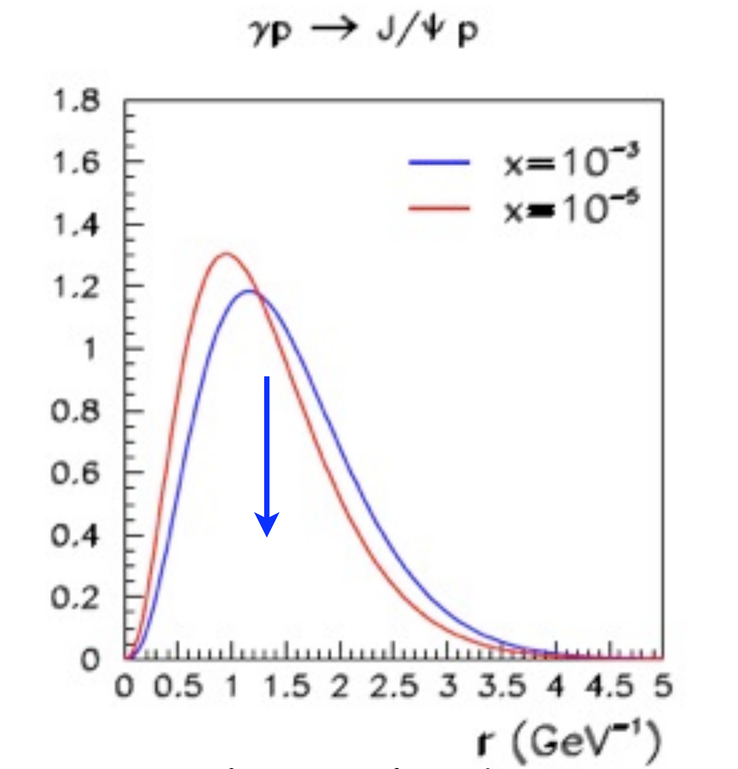


$(Q_S)^2$ =
0.5 GeV^2 at $x=10^{-3}$
0.8-1.8 GeV^2 at $x=10^{-5}$

how xg evolve will be clarified by LHC

Distribution of J/ψ dipole sizes





selected by: the overlap **the amplitude**

$$r \int dz \Psi^*_{J/\psi} \Psi.$$

$$\int \frac{dz}{4\pi} \int d^2b\, \Psi^*_V \Psi \exp(-i\vec{b}\cdot\vec{\Delta}) \frac{d\sigma_{q\bar{q}}}{d^2b}$$

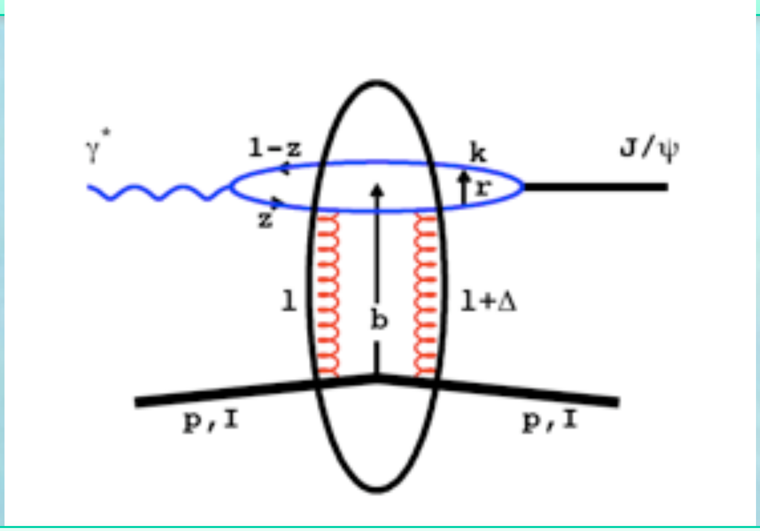
$(Q_{eff})^2$ = 1-1.5 GeV

Saturation effects

at EIC - marginal

at LHeC - substantial

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

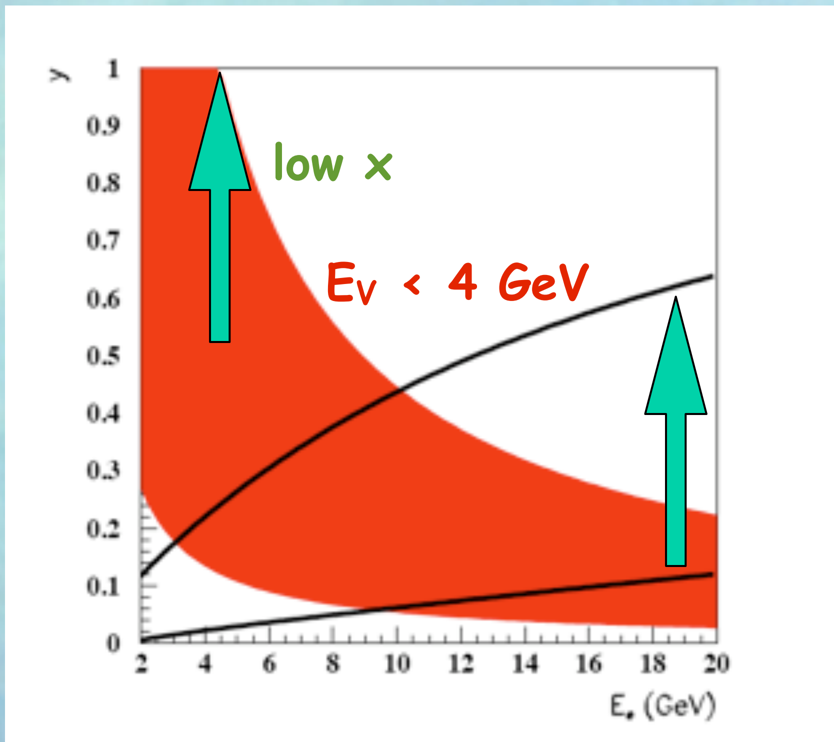
Acceptance and X-sec for elastic J/ψ photoproduction at eRHIC, E_p = 100 GeV

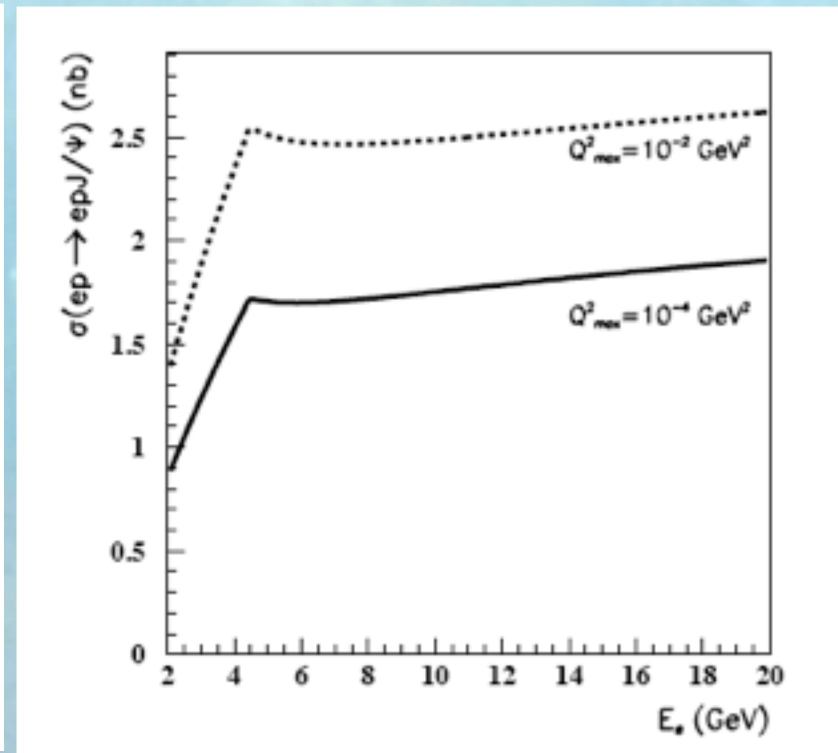
E_V - Energy of J/ψ

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

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

$E_V < 4$ 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** ⇓

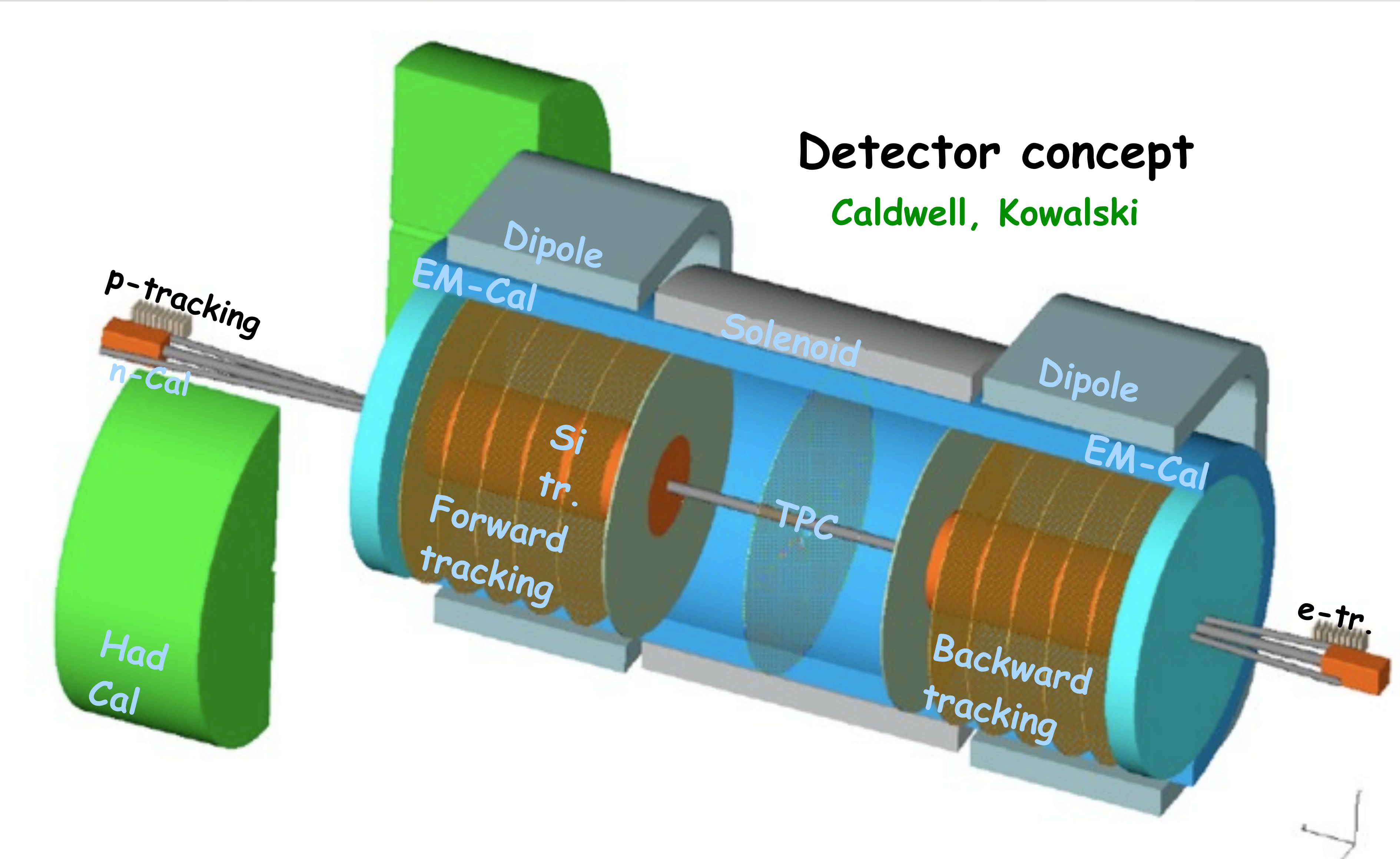
$$\sigma_{p_t}/p_t = 0.005 \cdot p_t \oplus 0.045/\beta\ \%$$

⇓

Δp_T < 1 MeV

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

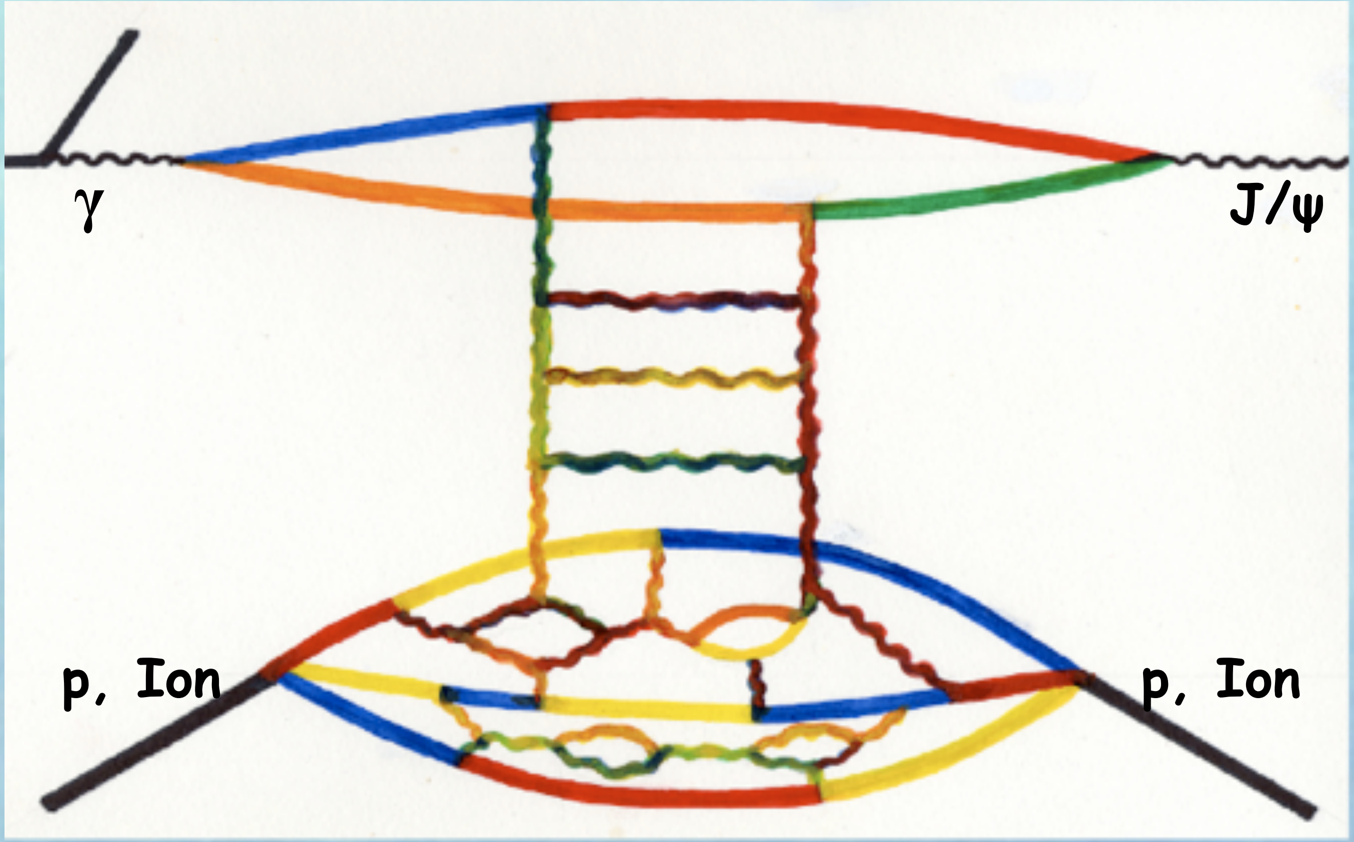
Gluonic radius of the proton is sizably smaller than the quark one

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 form matter

eA Physics with EIC and LHEC



BACK UP SLIDES