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, arXiv 0909.1254
+ Al Mueller, T. Lappi, R. Venugopalan, M. Diehl, ...

Alfest
New York 24th of Oct 2009

Why eA physics with J/ψ's?:

Because:

From the perspective of QCD the physics of nuclei is poorly understood

- what gives proton or neutron its mass and size,
- compressibility of nuclear matter
  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

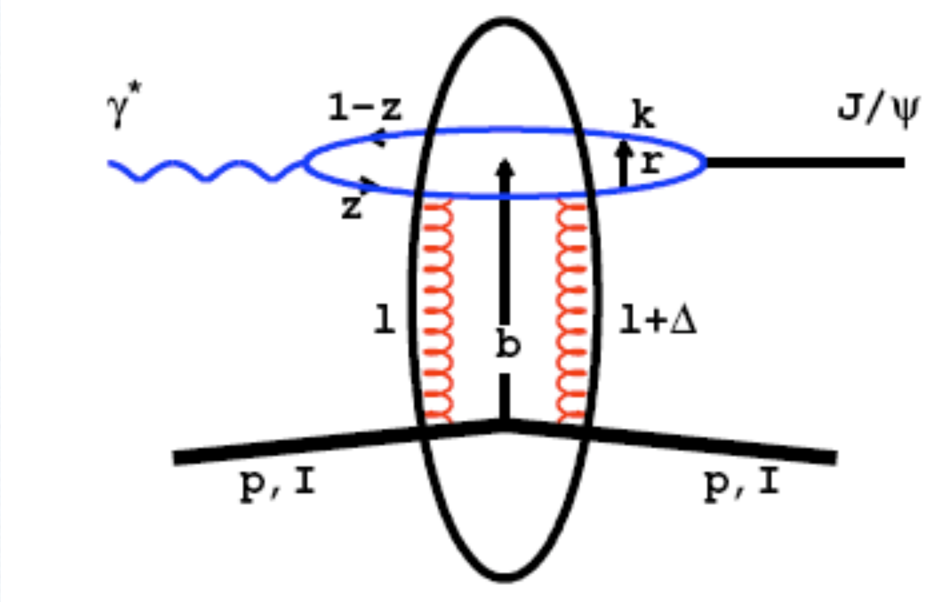
electrons can only see the electric charge distribution

protons are not simple probes

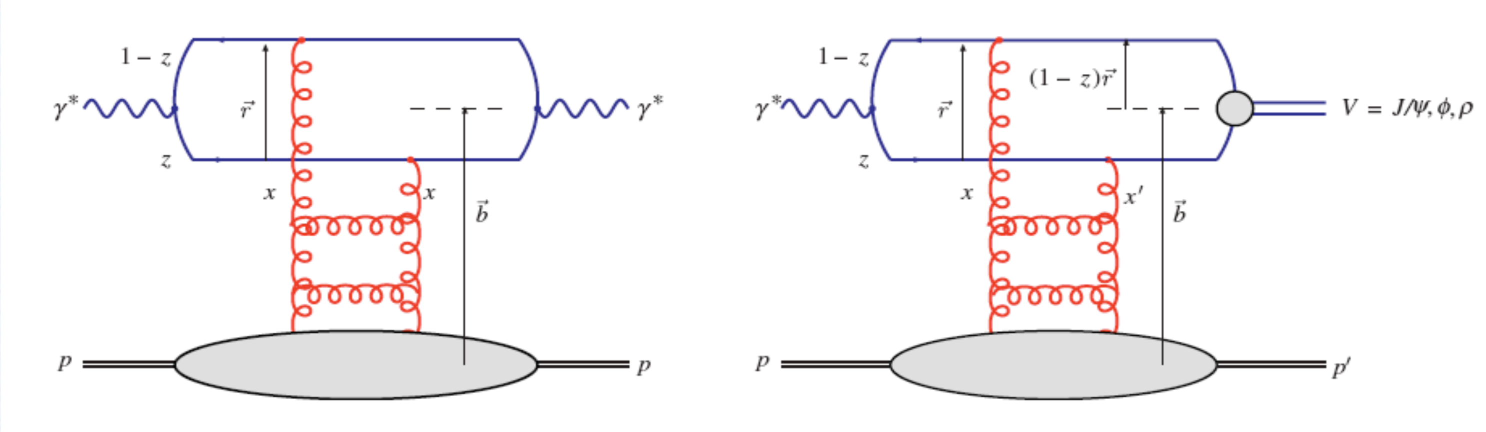
The novel probe to investigate nuclei: Small quark-antiquark color dipole.

In leading order QCD a small dipole interacts with the nucleus by the exchange of two gluons. Both gluons have high transverse momenta but the net momentum transfer to the nucleus can be small.

Therefore,the reaction leaves frequently the target intact.



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



$$\sigma^{\gamma^* p}_{tot} = \int \Psi^* \sigma_{q\bar{q}} \Psi$$

← **Optical Theorem** →

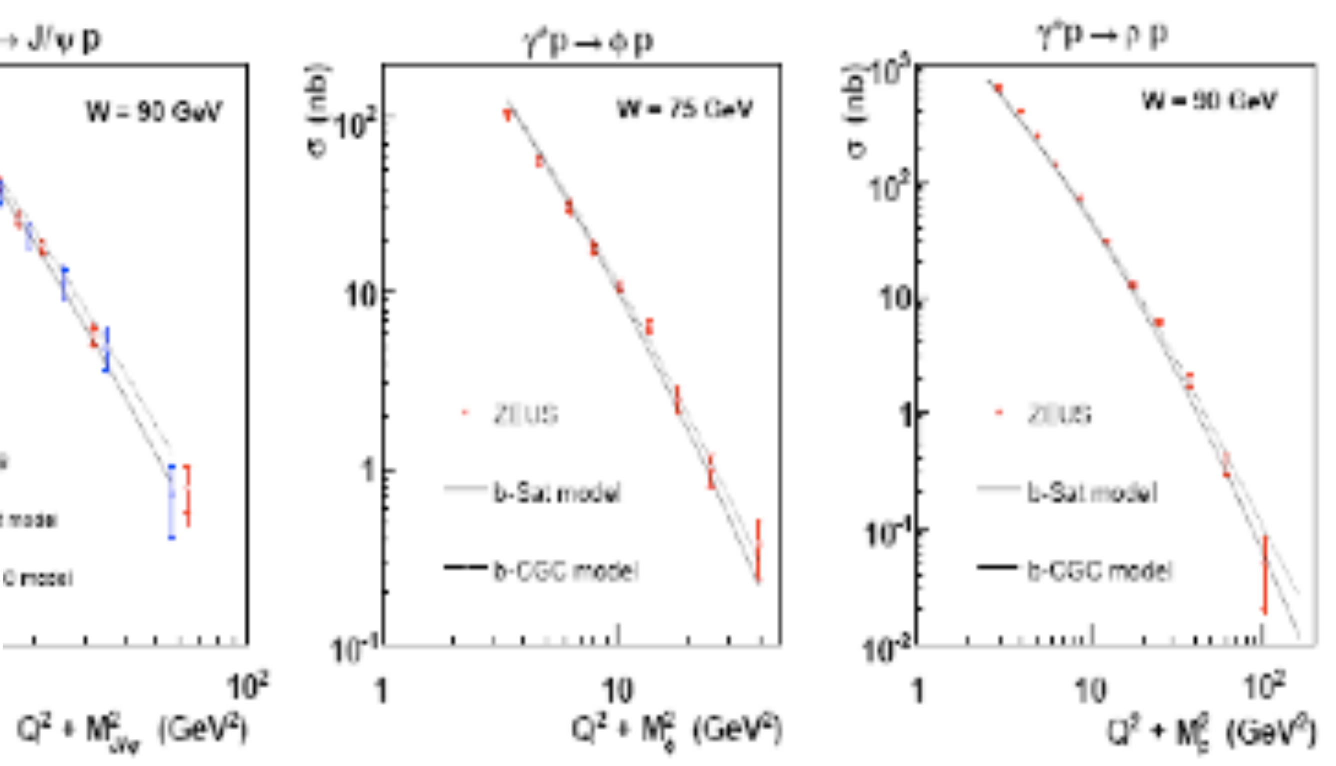
$$\frac{d\sigma^{\gamma^* p}_{VM}}{dt} \sim \left| \int \Psi^*_{VM} \frac{d\sigma_{q\bar{q}}}{d^2 b} \sigma_{q\bar{q}} \Psi e^{-i\vec{b}\vec{\Delta}} \right|^2$$

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

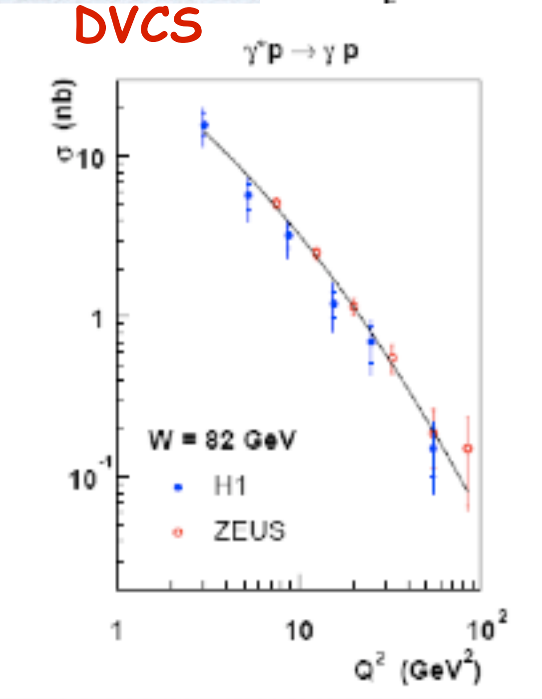
The same, universal, gluon density describes
the properties of many reactions measured at HERA:

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

Vector Mesons

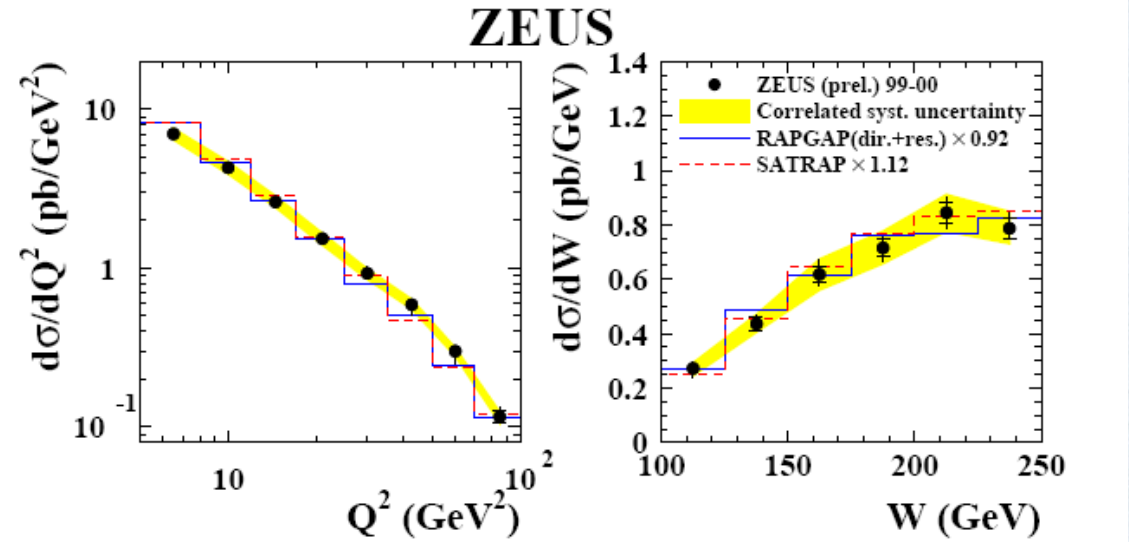


DVCS

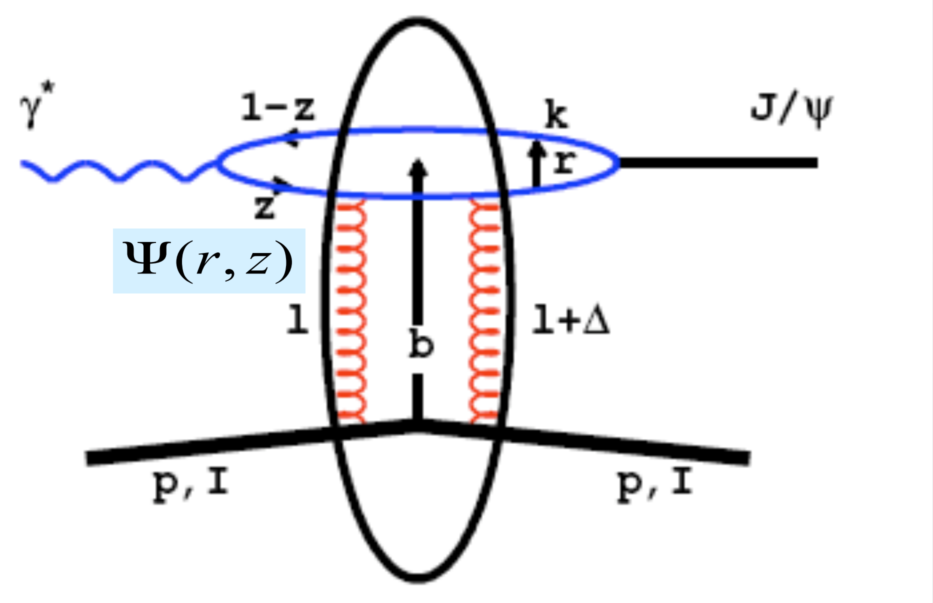


Note: educated guesses for VM wf are working very well

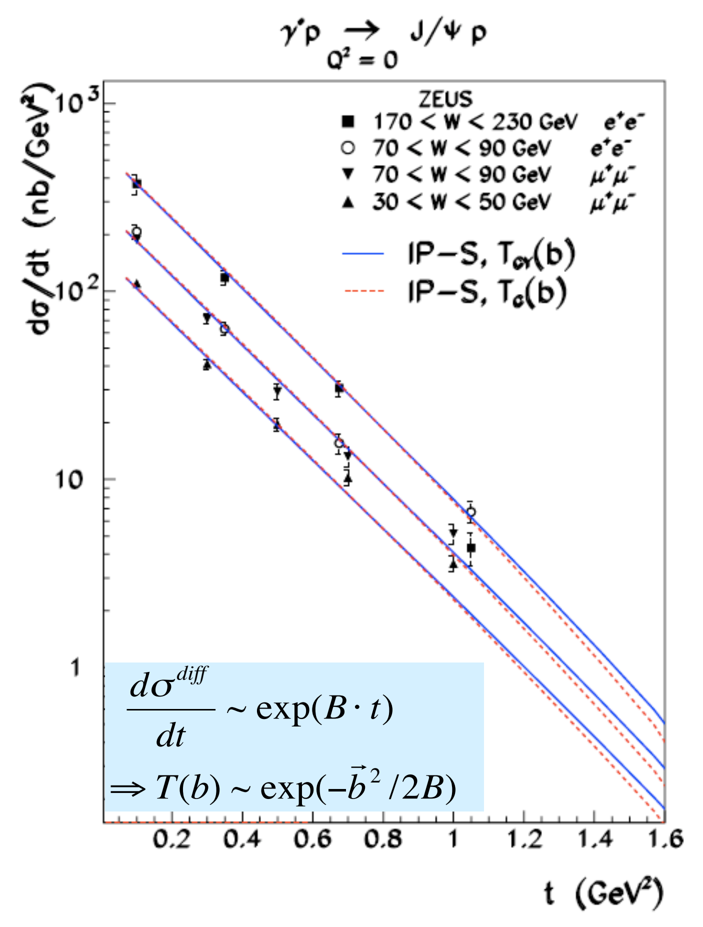
Diffractive Di-jets



Extracting Proton Shape using dipoles



$\Psi(r,z)$



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

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

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

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

KT, KMW

T(b)-proton shape

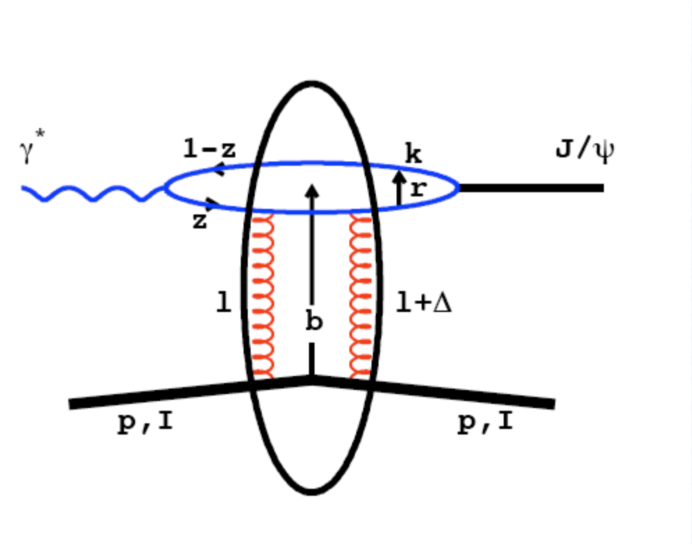
J/ψ as a probe of proton and nuclei

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

J/ψ p_T resolution at EIC or LHeC



J/psi p_T is determined from p_T of ee or μμ decay pair

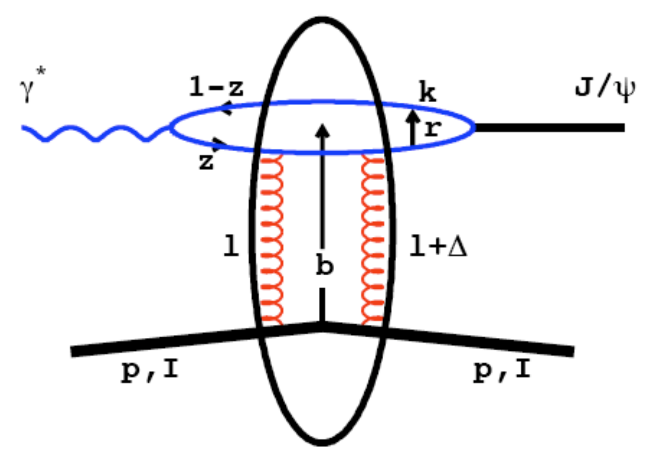
p_T resolution for J/psi - O(1) MeV for a TPC with 2m radius

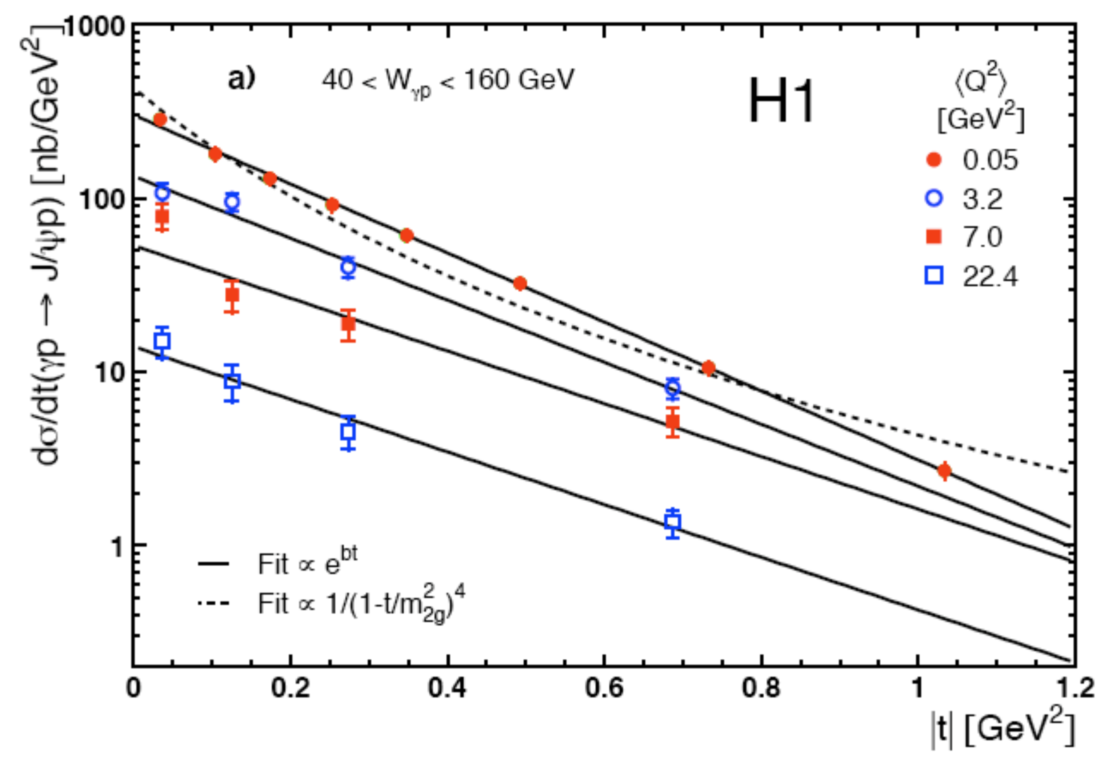
no measurement of a proton or ion momentum necessary

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

Proton shapes from exclusive J/ψ





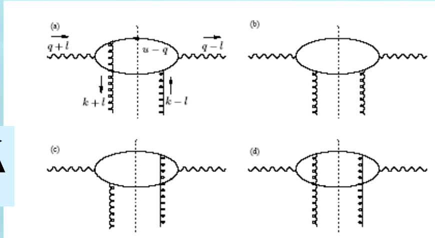
Exponential behavior ➔ B_D size of the interaction region

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

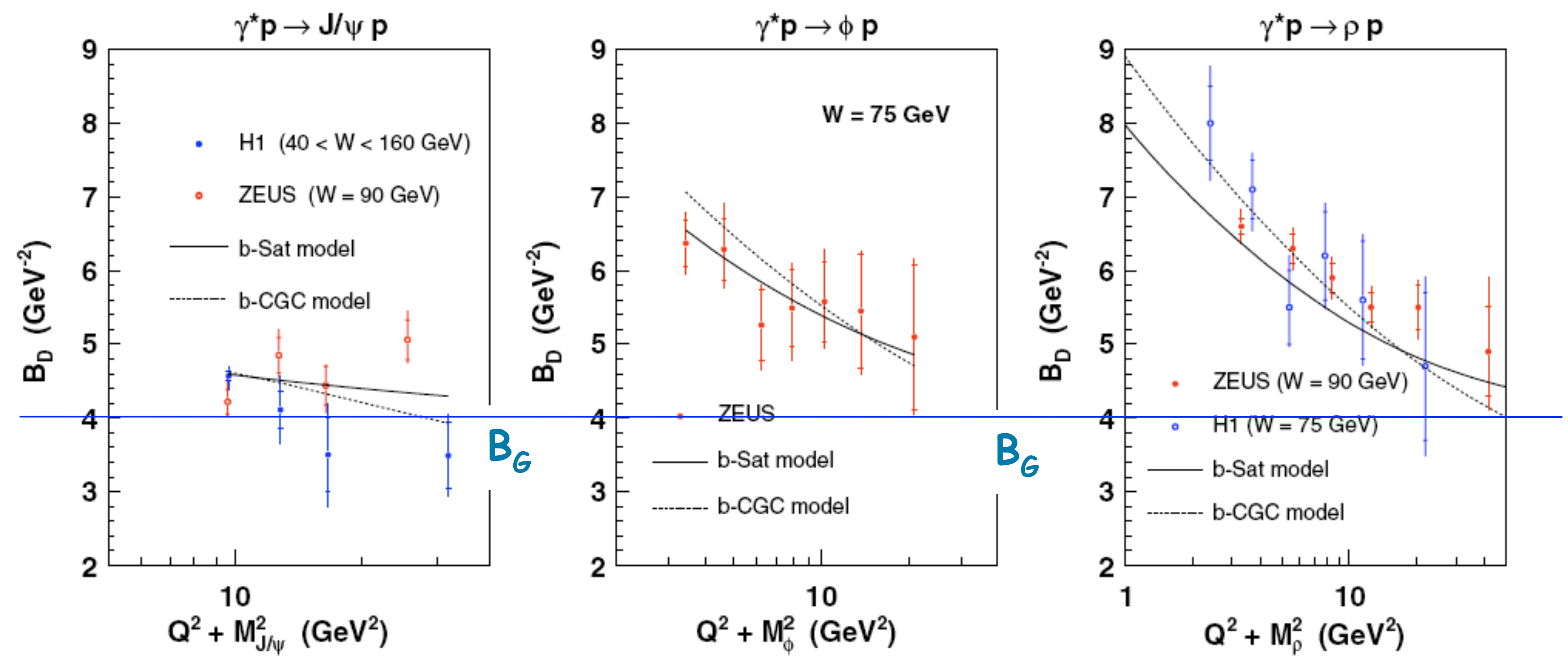
The size of interaction region B_D for various VM

Modification by Bartels, Golec-Biernat, Peters

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

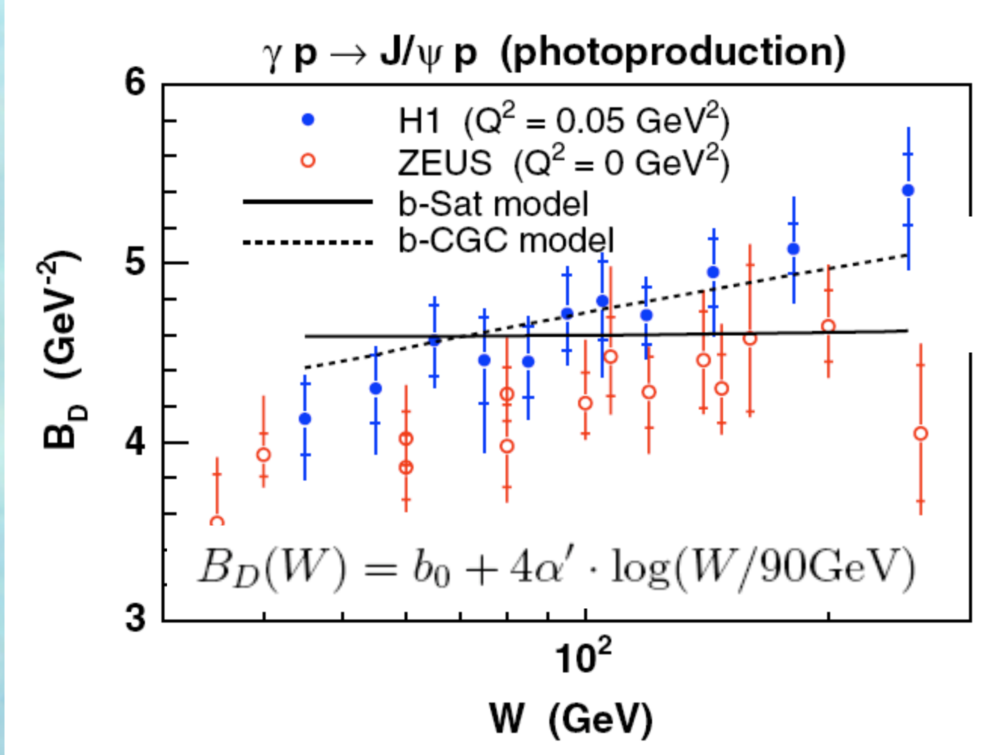


KMW



For J/ψ $B_D - B_G = 0.6 +/- 0.2$ 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

Expected EIC improvements

Hera diffractive measurements were made with the luminosity of O(100) pb^{-1} and the t-range 0 - 0.6 GeV^2

EIC measurements can reduce the errors by a factor of ~10 and extend the t-range to 2 GeV^2

➤ precise measurement of α' becomes possible,
determine the properties of the hard, BFKL-Pomeron,
i.e; energy dependence of the Pomeron trajectories

physics goal: Pomeron-Graviton correspondence

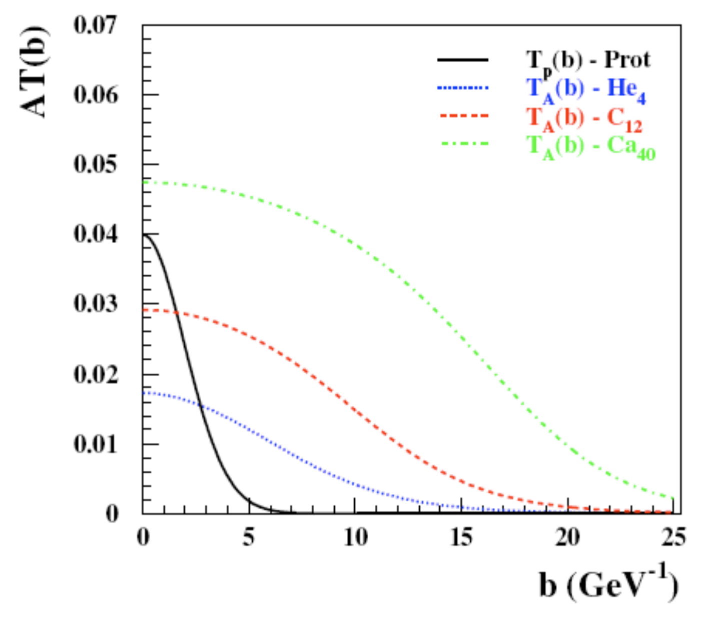
X-sections for nuclear J/ψA production

Conventional assumption: charmed dipole scatters on individual nucleons

Amplitude for scattering on a configuration {b_i}:

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

Assumption: One nucleon distribution given by the Woods-Saxon distr.



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

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

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

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

Fourier transform the amplitude for the scattering on a configuration:

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

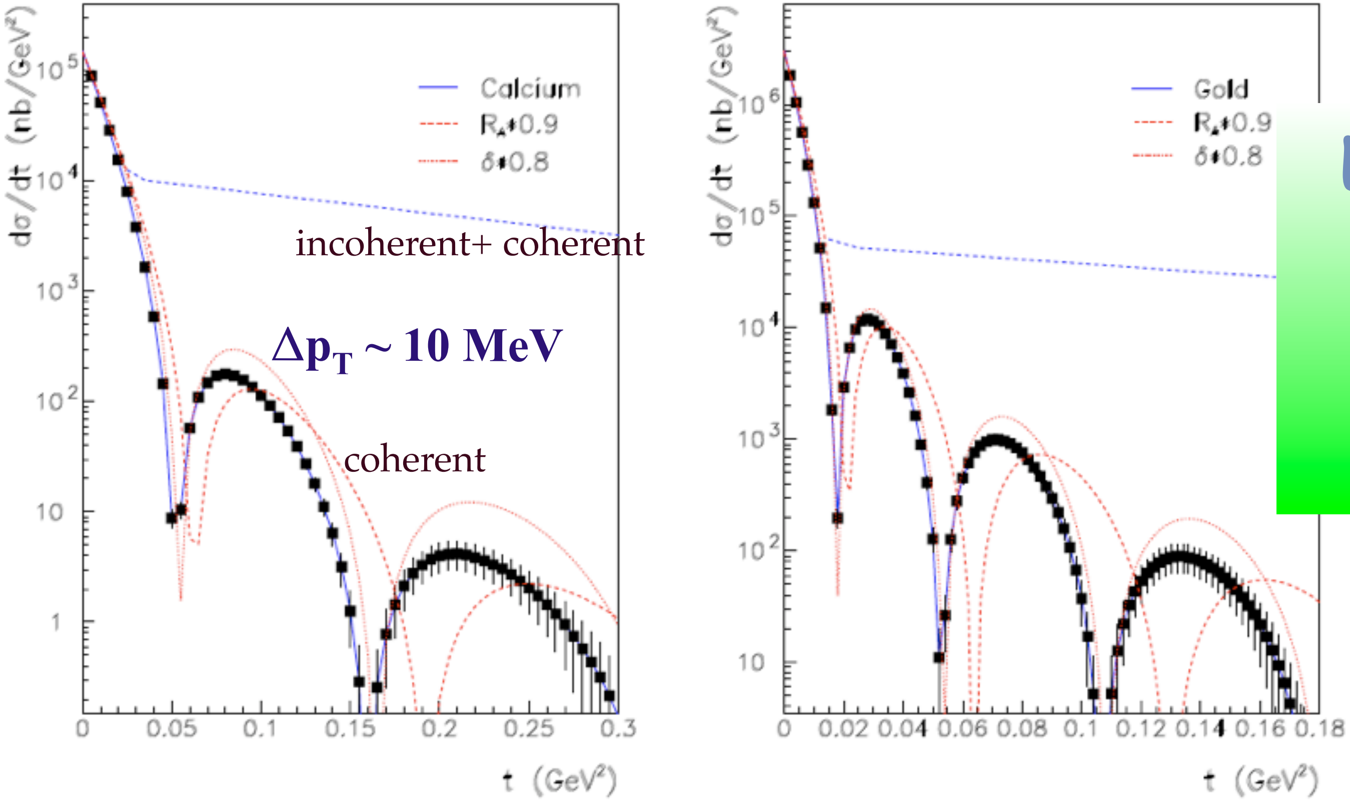
compute xsections, apply completeness relation

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

Subtract ground state ➡ Incoherent scattering

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

Nuclear gluonic shapes Coherent and incohernt eA → J/ψA photoproduction



incoherent+ coherent

$\Delta p_T \sim 10$ MeV

coherent

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 the incoherent production

Break up: large rapidity gap with some particles in the forward neutron and proton detectors

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

Experimental signature of the 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

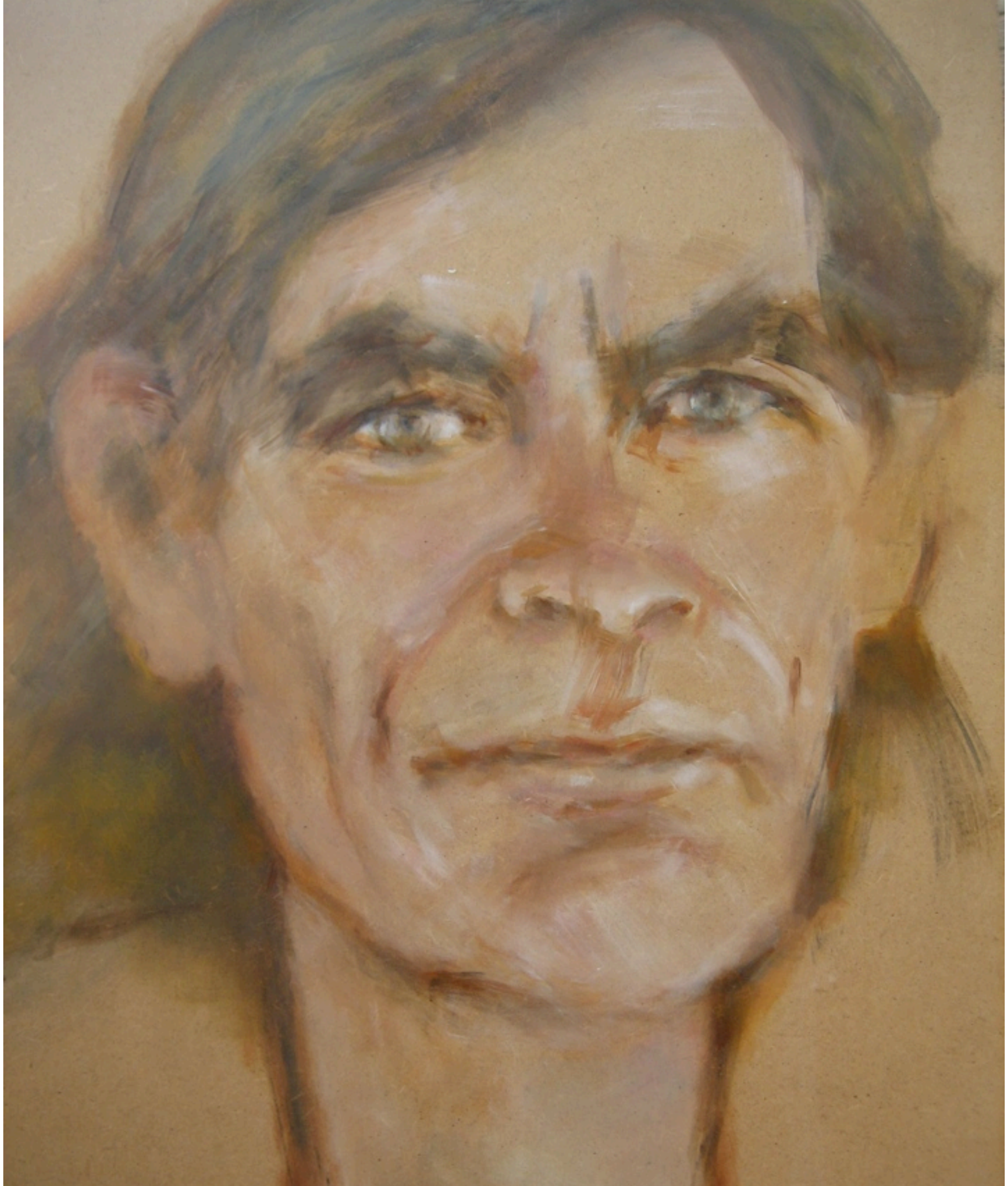
Conclusions

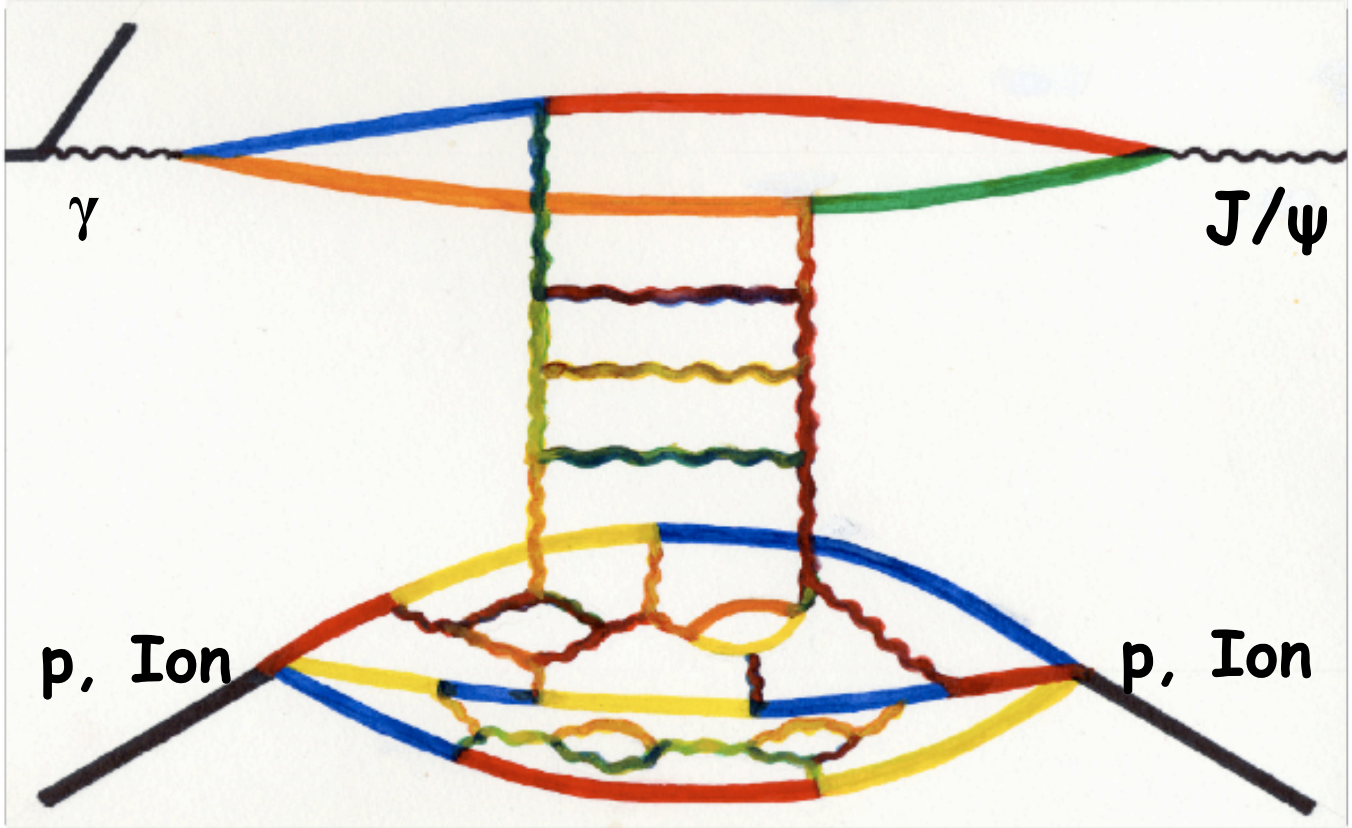
We have an ideal tool to investigate at EIC the
gluonic structure of nuclear matter with a pure QCD probe

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

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




γ
J/ψ
p, Ion
p, Ion

BACK UP SLIDES

Dynamics of nuclear disintegration,

first attempt of a review, no claim to completeness

Based on

- the discussions with W. Scobel, Prof. Emeritus of Hamburg Univ.
- Review of "Quantum Molecular Dynamics" by J. Aichelin,
  Phys. Reports 202, p233 (1991)
- papers by Niita et al. Phys Rev C 52, p2620 (1995)
  Marcusi et al. Phys Rev C 79, 014614 (2009)

physics interest: understanding of fission
compressibility of nuclear matter,
supernova explosions, giant resonances
heavy ion reactions

VOLUME 62, NUMBER 10 PHYSICAL REVIEW LETTERS 6 MARCH 1989

Observation of Cold Scission of Highly Excited Fissioning Nuclei

D. Hilscher, H. Rossner, B. Cramer, B. Gebauer, U. Jahnke, M. Lehmann, E. Schwinn, M. Wilpert, and Th. Wilpert
Hahn-Meitner-Institut Berlin, 1000 Berlin 39, Federal Republic of Germany

H. Frobeen, E. Mordhorst, and W. Scobel
Universität Hamburg, 2000 Hamburg 50, Federal Republic of Germany
(Received 28 November 1988)

Nuclear fission at temperatures up to 2.7 MeV is very slow, about 10^{-20} s. Fission occurs at the very end of the nuclear deexcitation chain.

neutrons emitted before scission are in the statistical equilibrium (there is enough time to equilibrate the system)

W. Scobel: O(10) MeV of kin. energy is sufficient to liberate a neutron or proton.

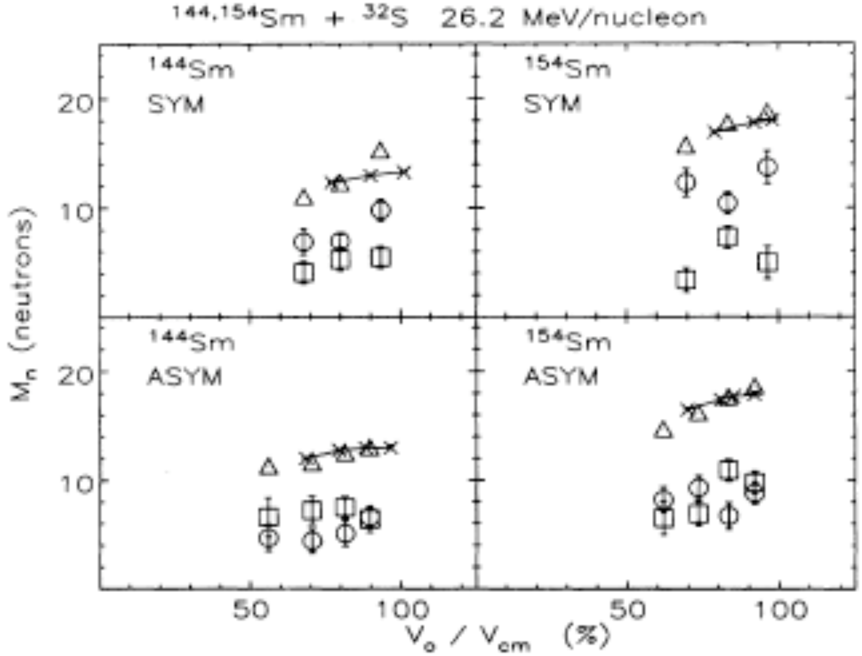


FIG. 2. Multiplicity of neutrons emitted prior to (circles) and after (squares) scission and the sum of both (triangles) for symmetric (SYM: $\langle A_1\rangle=\langle A_2\rangle=76-120$) and asymmetric (ASYM: $A_1=20-75$ and $A_2=121-160$) mass splits. The

Quantum Molecular Dynamics

J. Aichelin, Phys. Reports.

Microscopical dynamical n-body theory:
Starting from the n-body Schroedinger eq. time evolution determined from the Wigner transform of the n-body transition matrix.

Several simplified assumptions:

- scattering of the nucleons can be treated as if they are free
- interference between two different sequences vanishes
- replacement of the real part of the transition matrix by an eff. interaction
  eff. interaction = local (Skyrme type) + Yukava + Coulomb

PHYSICAL REVIEW C VOLUME 52, NUMBER 5 NOVEMBER 1995

Analysis of the (N,xN') reactions by quantum molecular dynamics plus statistical decay model

Niita et al.

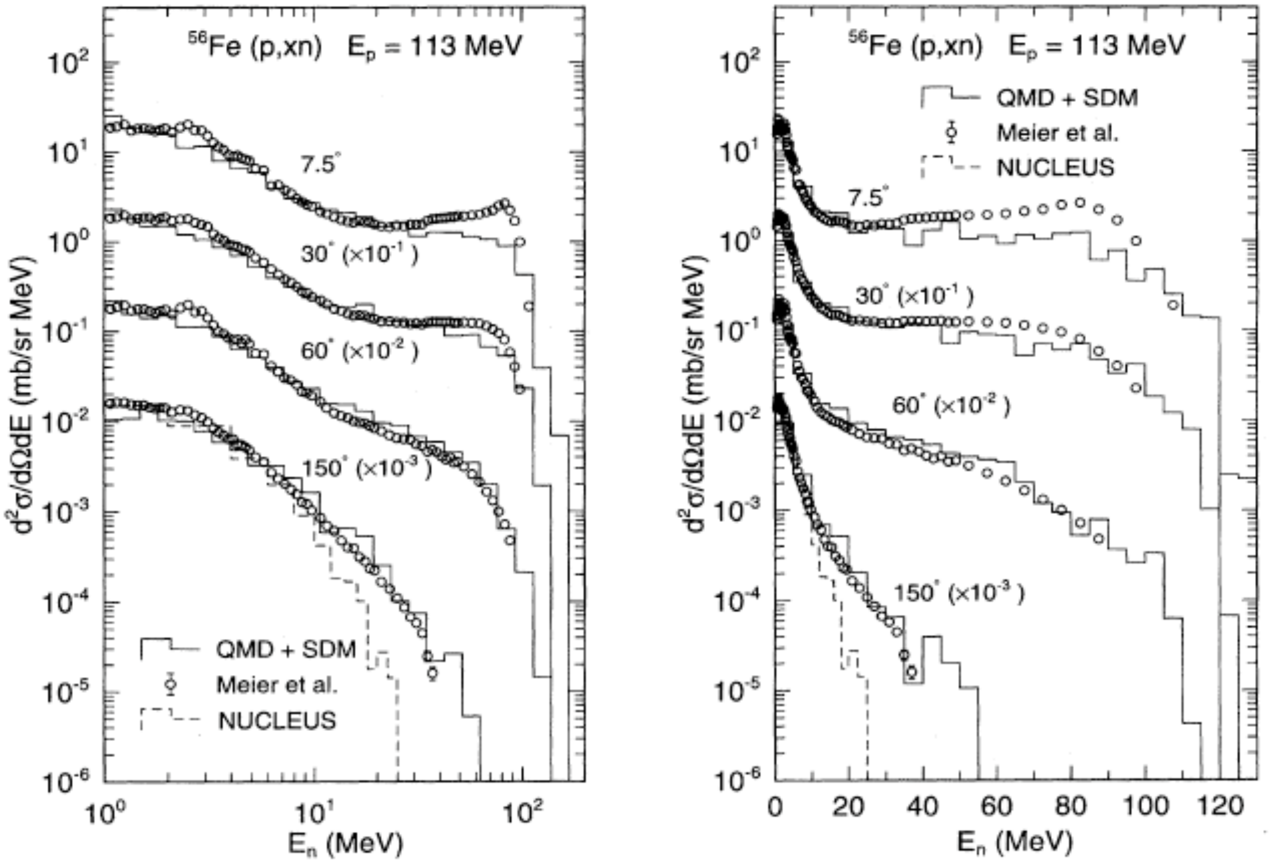


FIG. 10. Neutron energy spectra for the reaction p (113 MeV) + ^{56}Fe at different laboratory angles as indicated in the figure. The x axis is plotted in a logarithmic scale on the left-hand side, and a linear scale on the right-hand side. The solid histograms are the results of QMD + SDM and the open circles with error bars denote the experimental data taken from Ref. [26]. The dashed histograms denote the results of NUCLEUS [27] at the 150° laboratory angle.

Quantum Molecular Dynamic,

J. Aichelin

Initial Wigner densities:

$$\prod_{i=1}^{n} \frac{1}{\pi^3} \exp(-(\vec{r}_i - \vec{r}_{i0})^2 / 2L) \cdot \exp(-(\vec{p}_i - \vec{p}_{i0})^2 \cdot 2L)$$

r_{i0}'s randomly chosen in a sphere of radius 1.12 $A^{1/3}$

but rejected if $(r_{i0}-r_{j0})$ < 1.5 fm

local Fermi momenta $p_F(r_{i0})$ determined from the effective potential energy of particle i.

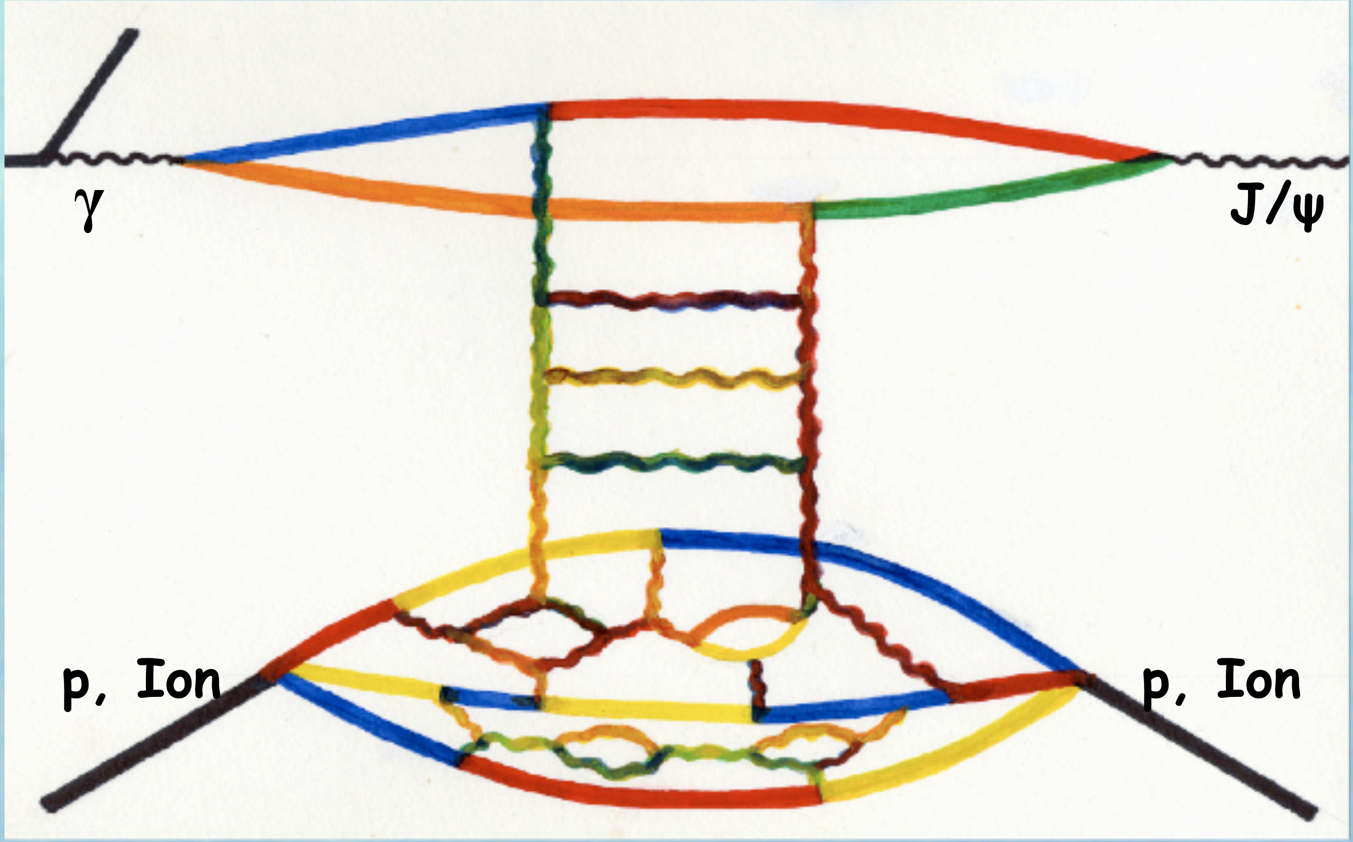
choose p_{i0}'s randomly between 0 and $p_F(r_{i0})$,

Reject all configuration with $(\vec{r}_i - \vec{r}_{i0})^2 \cdot (\vec{p}_i - \vec{p}_{i0})^2 < d_{\min}$

➤ Stable nucleus with proper size, right compressibility, binding energies etc

Nucleus is similar to a lattice with wave function located around the sites

eA Physics with EIC



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

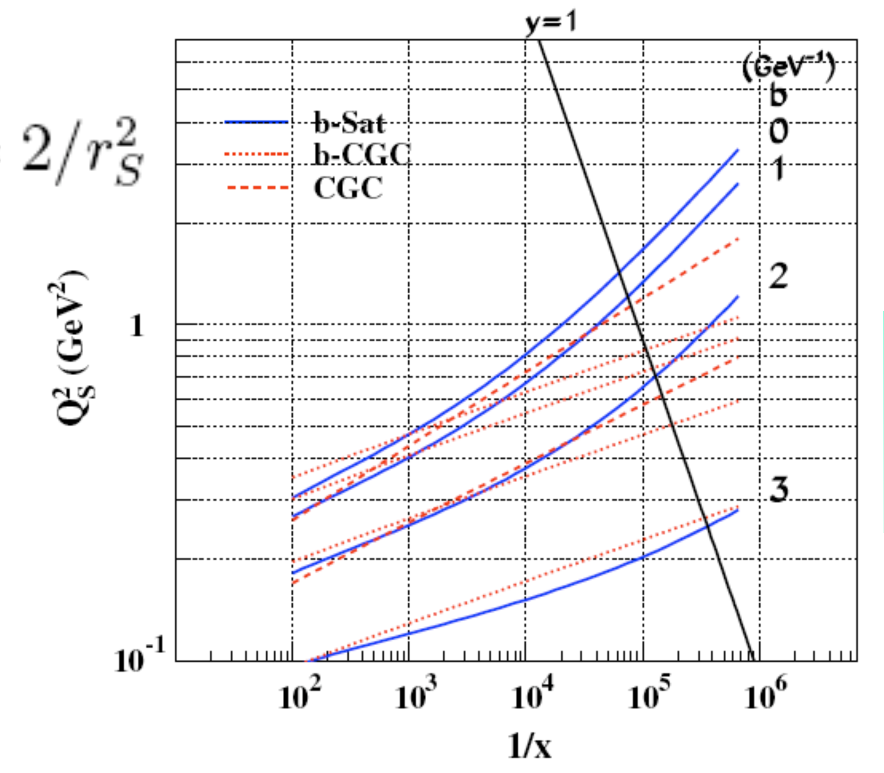
example: 1 MeV gluon kick vs n neutrons, n protons with p_T
10 MeV gluon kick " "
100 Mev gluon kick " "

Saturation

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

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

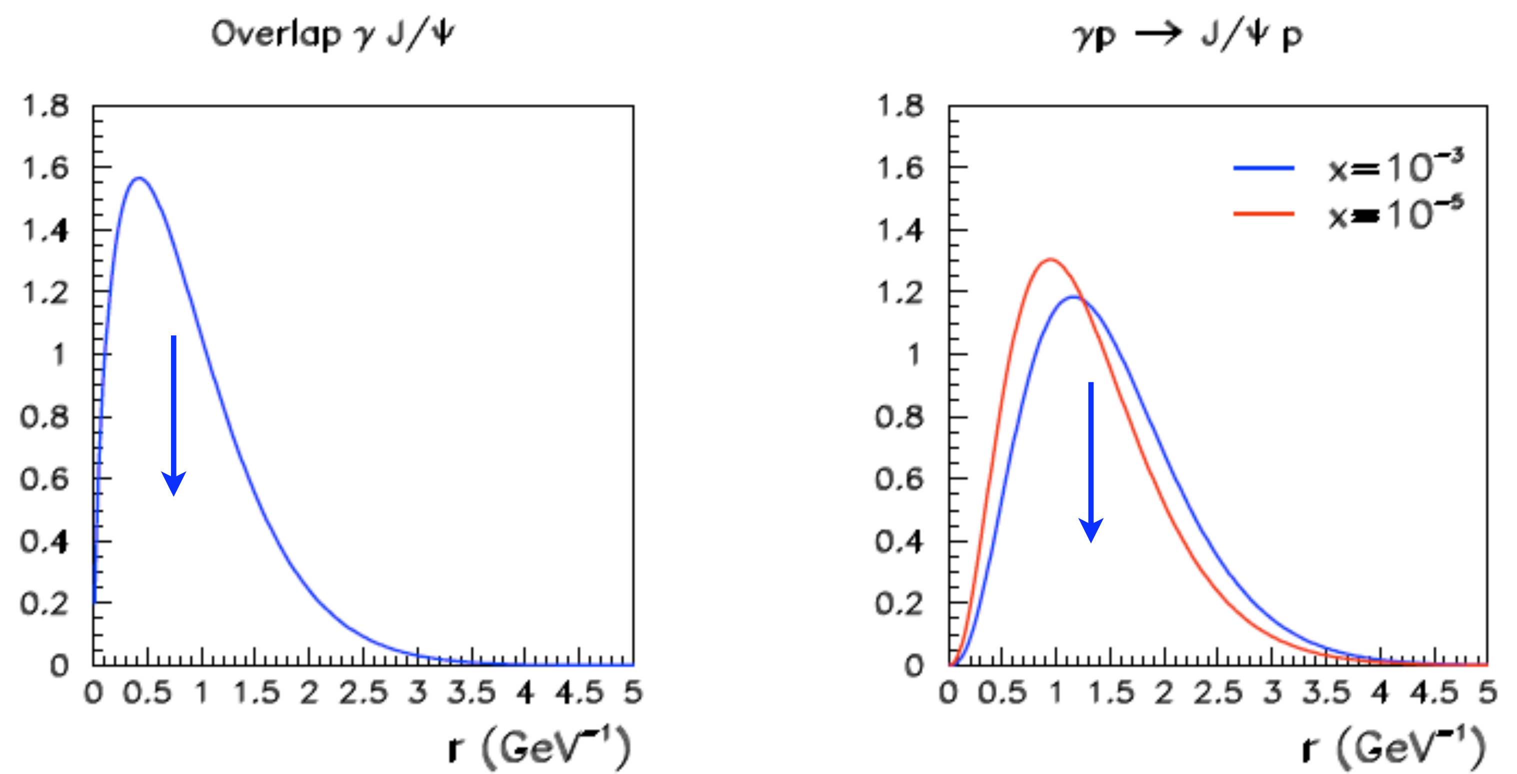
$$Q_S^2 = 2/r_S^2$$



$(Q_S)^2$ =
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

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

the amplitude

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

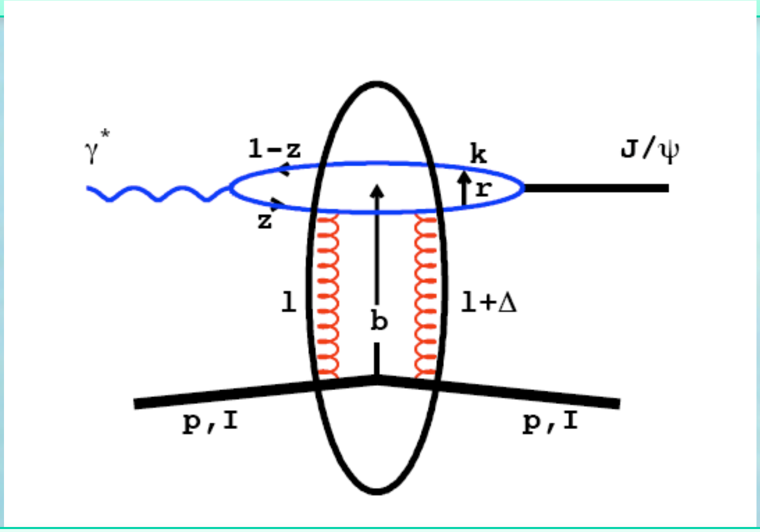
$(Q_{eff})^2$ = 1-1.5 GeV^2

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 μμ 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

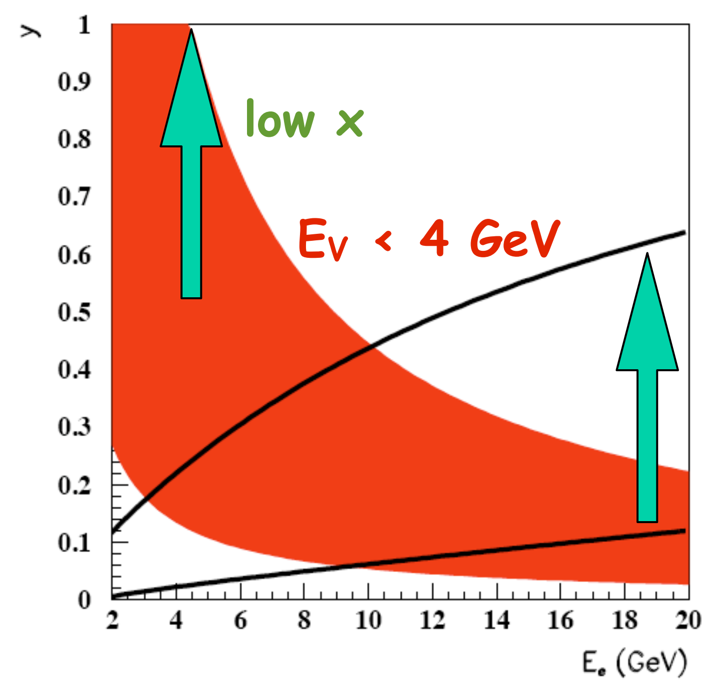
Acceptance and X-sec for elastic J/ψ photoproduction at eRHIC, E_p = 100 GeV

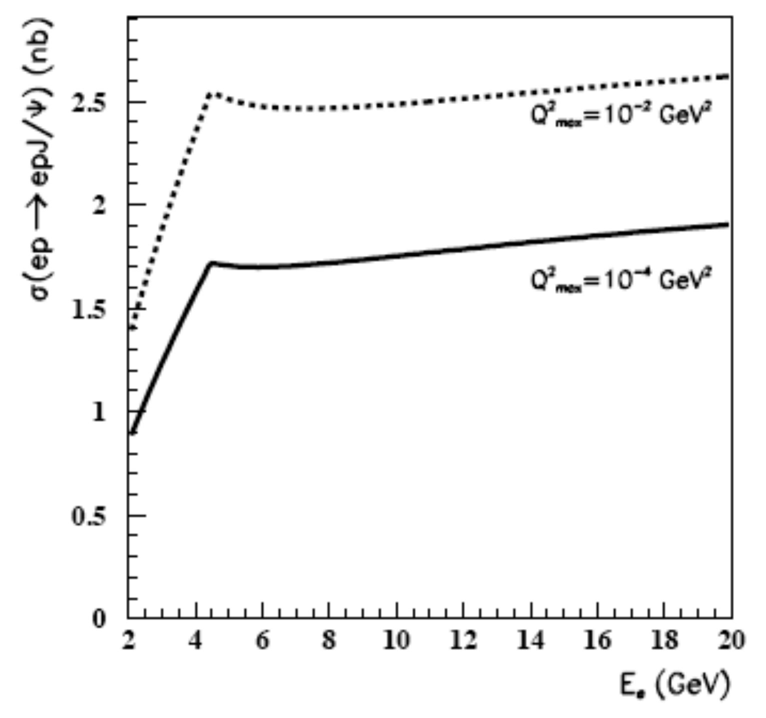
E_V - Energy of J/ψ

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

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

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** ⇓

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

⇓

$\Delta p_T < 1$ MeV

Detector concept

Caldwell, Kowalski