EIC, JLab12 and the Quarkonia

Z.-E. Meziani

Temple University

Outline

- Introduction
- Quarkonia at an EIC as a 2D+1 imaging probe of the glue in the nucleon and nuclei.
- Quarkonia at JLab12 as a probe of non-perturbative gluonic physics—Color Van-der Waal force, Trace Anomaly….
- Summary

The Science Problem ?

- The structure of all nuclear matter in Quantum Chromodynamics (QCD) and ultimately confinement

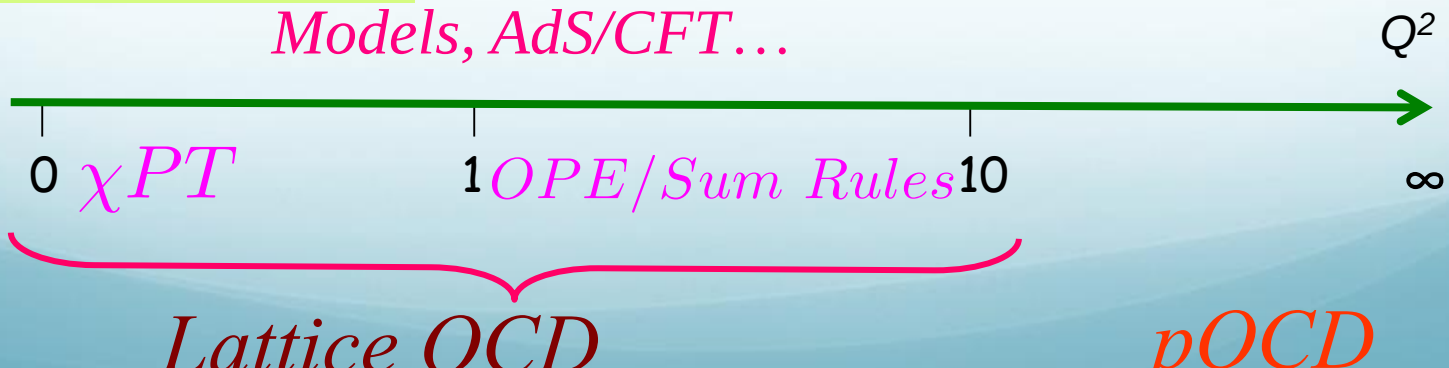
What do we know?

- QCD successes in the perturbative regime are impressive, many experimental tests led to this conclusion

But

- Many non-perturbative aspects of QCD including confinement are still puzzling. Confinement has been identified as one of the top millenium problems in Physics! (Gross, Witten,….) Many conferences have been devoted to this problem

Present theoretical tools:



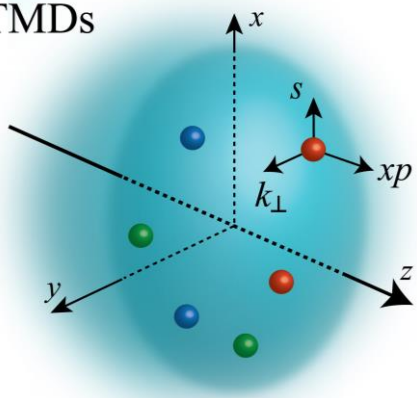
Unified View of Nucleon Structure

$W_p^u(x,k_T,r_T)$ *Wigner distributions*

5D Dist.

Transverse Momentum Dist.

TMDs

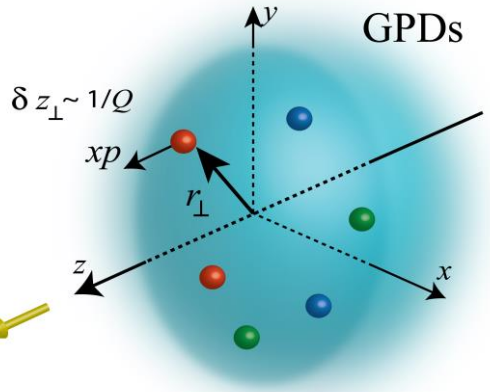


dr_T

d^2k_T

Generalized Parton Dist.

GPDs



TMD $f_1^u(x,k_T)$, $h_1^u(x,k_T)$

GPD

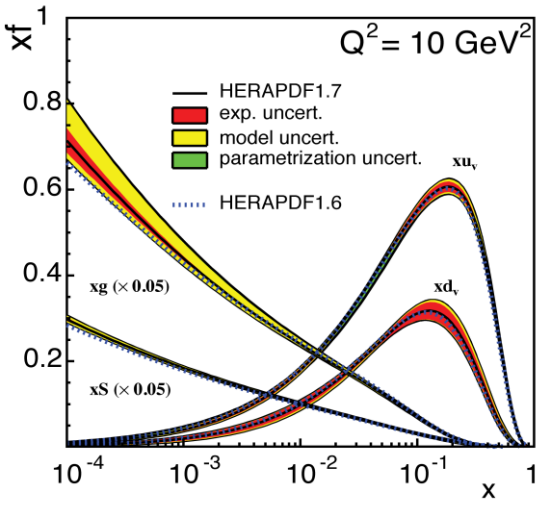
"3D" imaging

d^2k_T

d^2r_T

dx &Fourier Transformation

Parton Distribution Functions

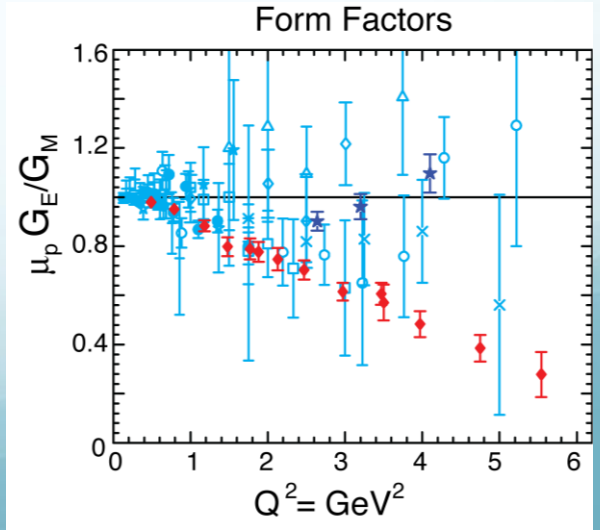


PDFs
$f_1^u(x)$, ..
$h_1^u(x)$

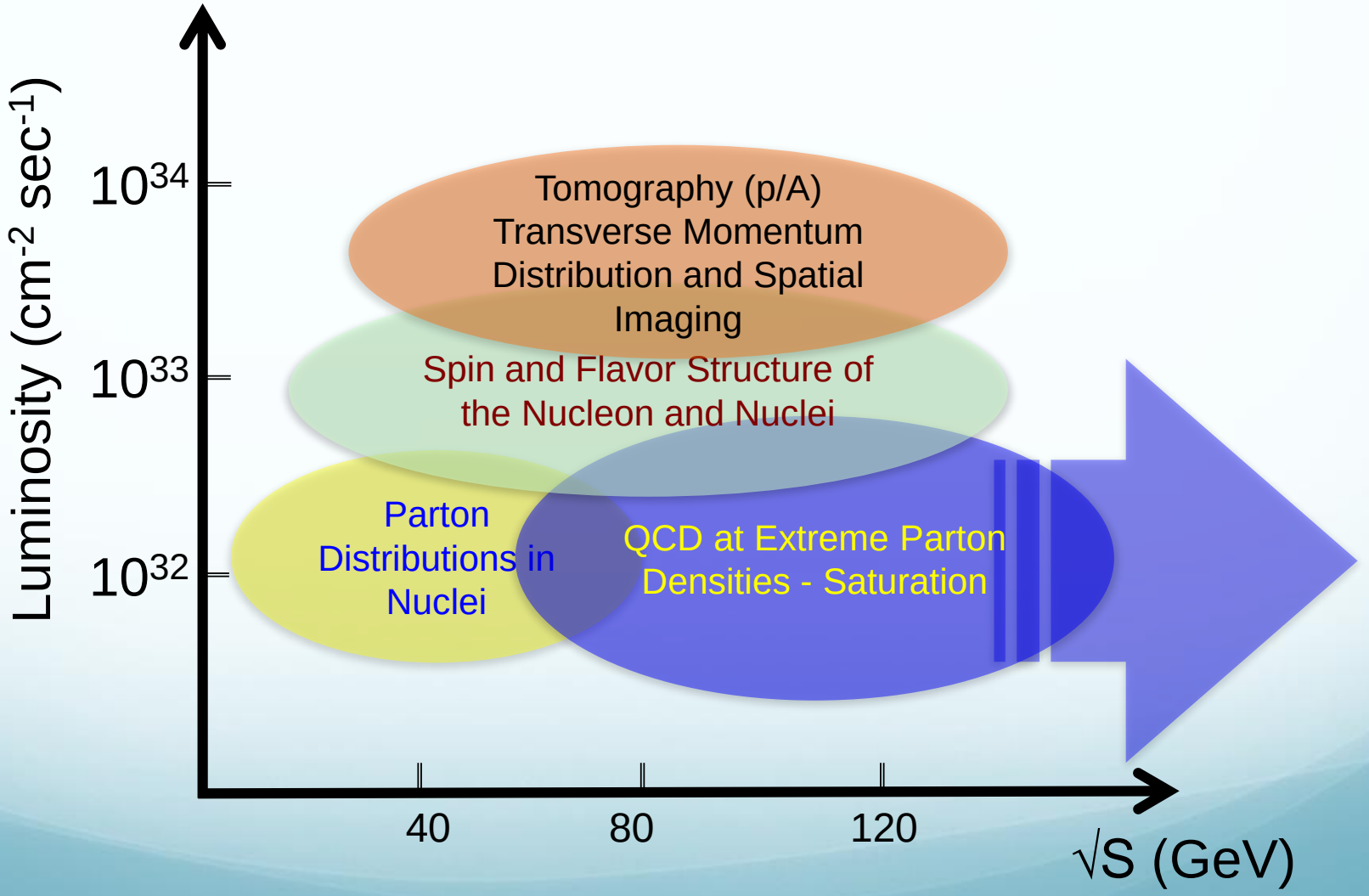
1D

Form Factors
$G_E(Q^2)$,
$G_M(Q^2)$

Form Factors

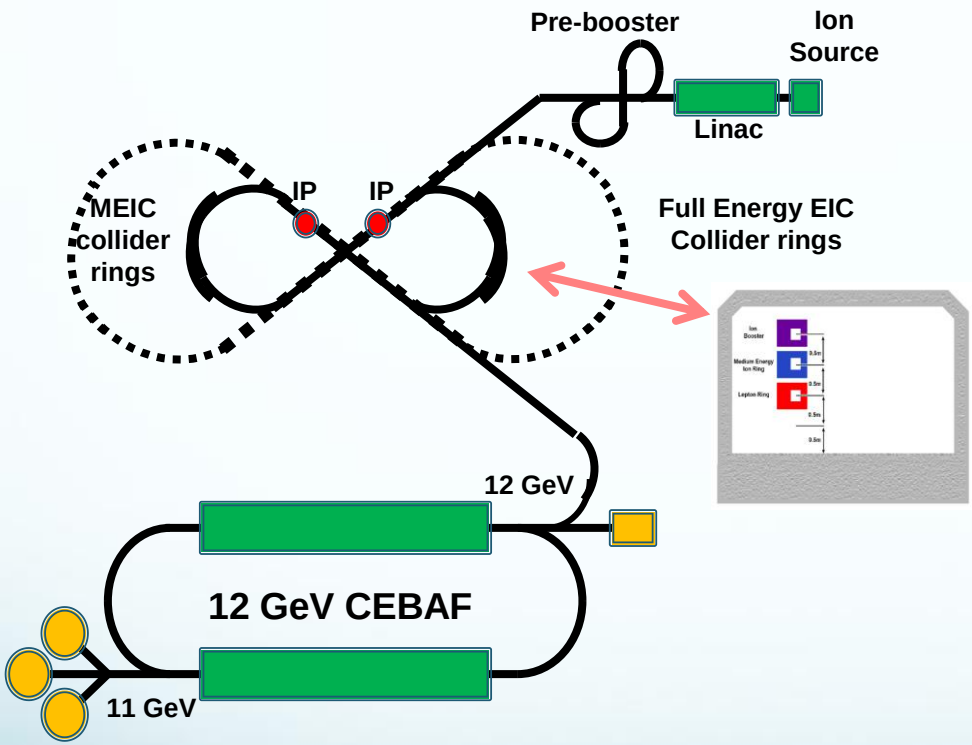


Physics vs. Luminosity & Energy

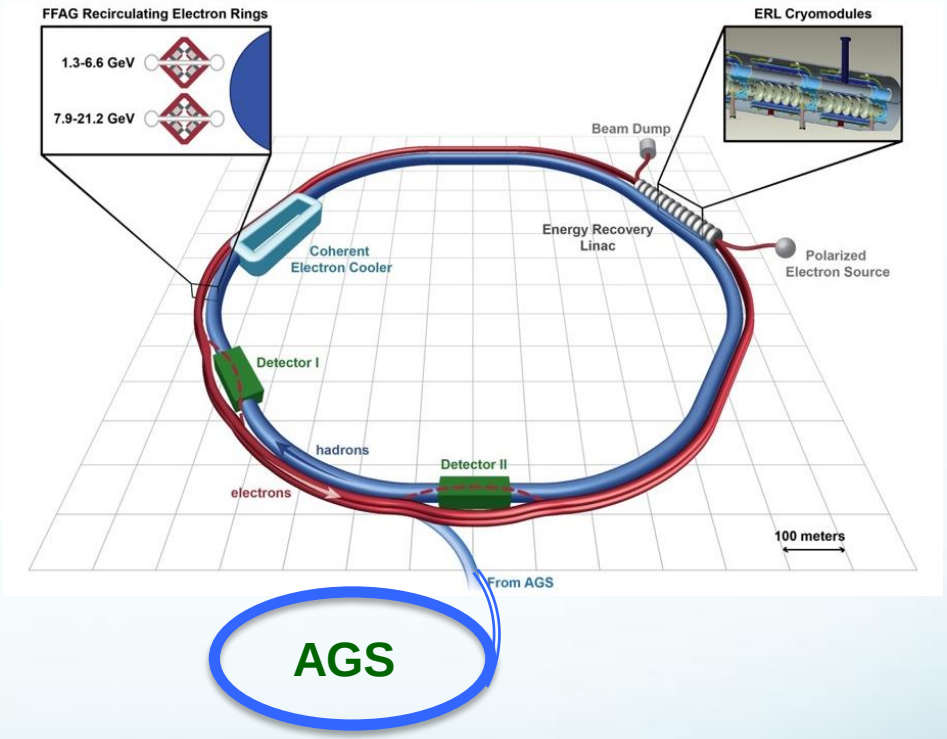


U.S.-based EICs – the Machines

JLEIC (JLab)



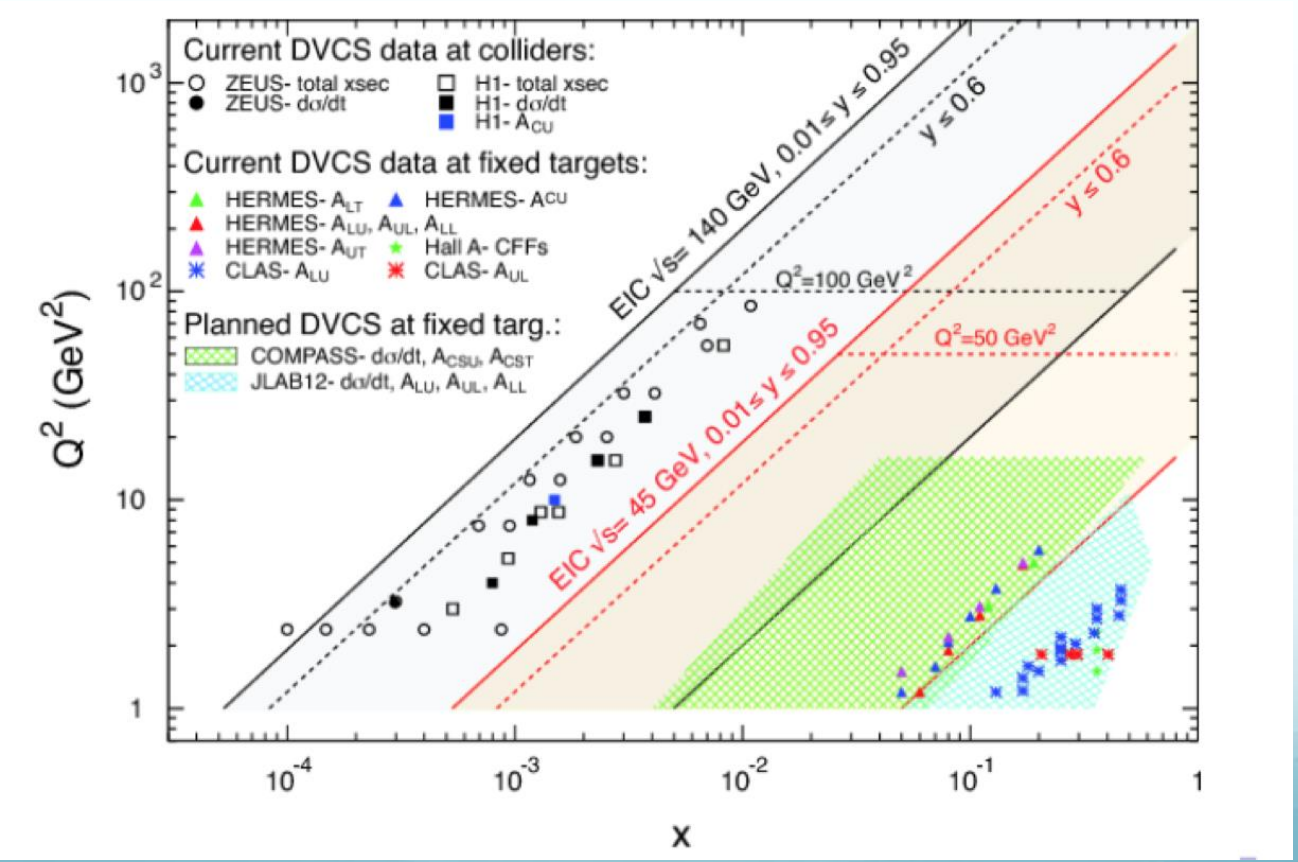
eRHIC (BNL)



- First polarized electron-proton/light ions collider in the world
- First electron-nucleus (various species) collider in the world
- Both cases make use of existing facilities

Kinematics and machine properties for e-N collisions

- ✓ First polarized e-p collider
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ **Luminosity L_{ep} ~ $10^{33\text{-}34}$ cm^{-2}s^{-1}**, HERA luminosity ~ 5x10^{31} cm^{-2} s^{-1}



Physics opportunities at EIC

➢ Machine parameters

- ✧ Collision energy: $\sqrt{s} \sim 20 - 100$ GeV Upgradable to ~ 150 GeV
- ✧ Luminosity: **$10^{33\text{-}34}$ cm^{-2} s^{-1}** (compare to **HERA luminosity ~** 5x10^{31} **cm^{-2} s^{-1}**)
- ✧ Polarized proton and various nuclei

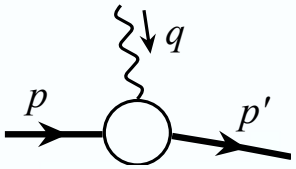
➢ Key Deliverables

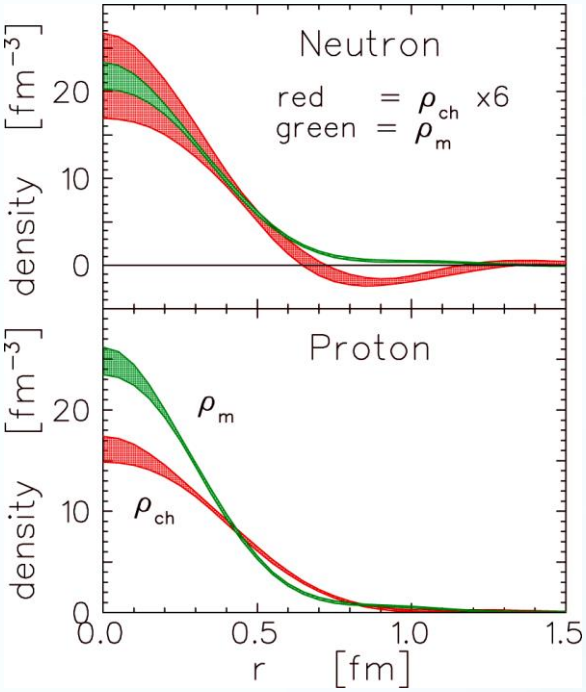
Deliverables	Observables	What we learn
Sea/gluon x~10^{-2} -10^{-4} S.F.	Inclusive DIS at low-x, in e-p	**Sea/gluon contrib. to proton spin, flavor separation**
Polarized and unpolarized TMDs	SIDIS e-p, single hadron, Dihadron and heavy flavors	**3D momentum images of quarks and gluons**
Sea quarks and gluon GPDs	DVCS, Exclusive J/Ψ, ρ,φ production	**Spatial images of sea and gluon, angular mom. J_q , J_g**
Weak mixing angle	PV asymmetries in DIS	**EW symmetry breaking, BSM**

How is color distributed inside the proton?

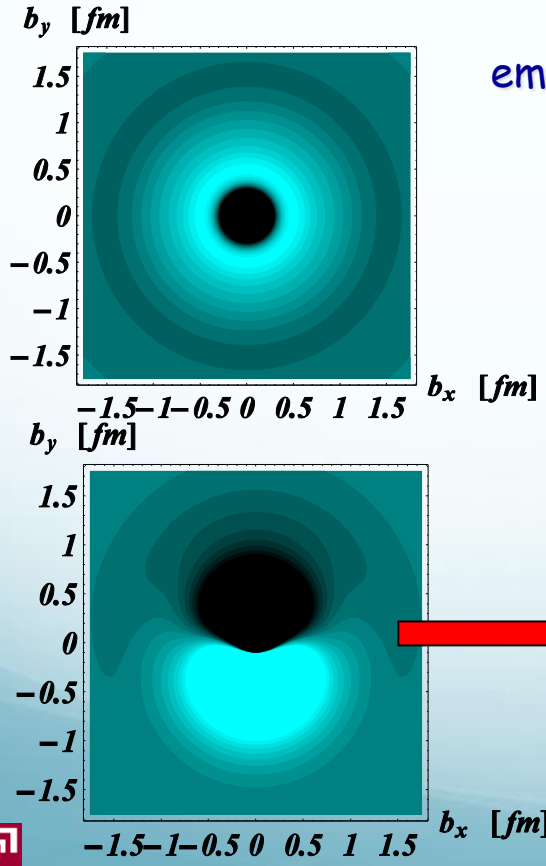
➢ Electric charge distribution:

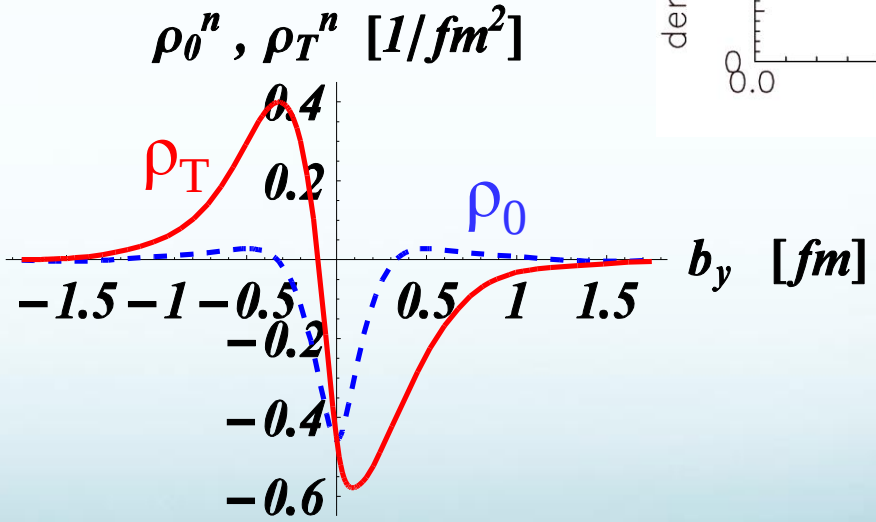
Elastic electric form factor
➡ Charge distributions





empirical quark transverse densities in Neutron





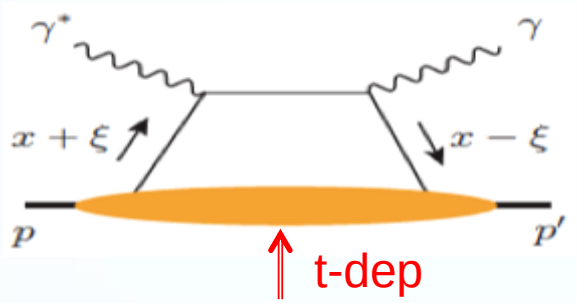
densities : Miller (2007); Carlson, Vanderhaeghen 2007)

induced EDM : $d_y = F_{2n}(0) \cdot e / (2 M_N)$

Spatial imaging of sea quarks

EIC: Sea quarks

- **Exclusive processes - DVCS**:



$$\frac{d\sigma}{dx_B dQ^2 dt}$$

$$t = (p' - p)^2$$

$$\xi = (P' - P) \cdot n/2$$

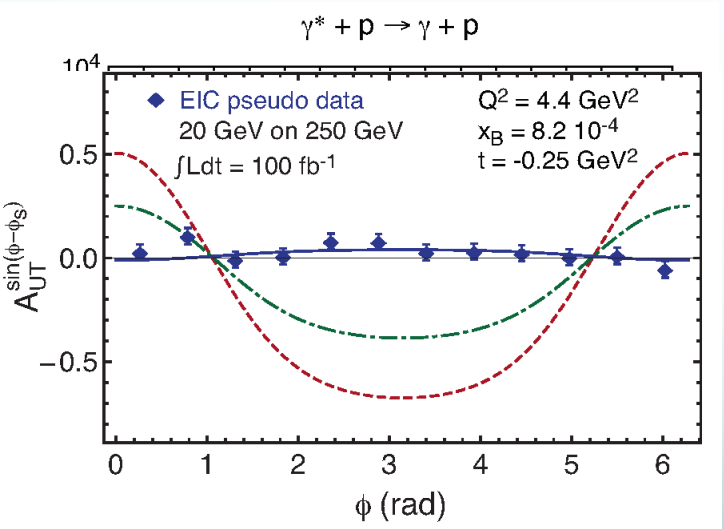
CFFs→GPDs

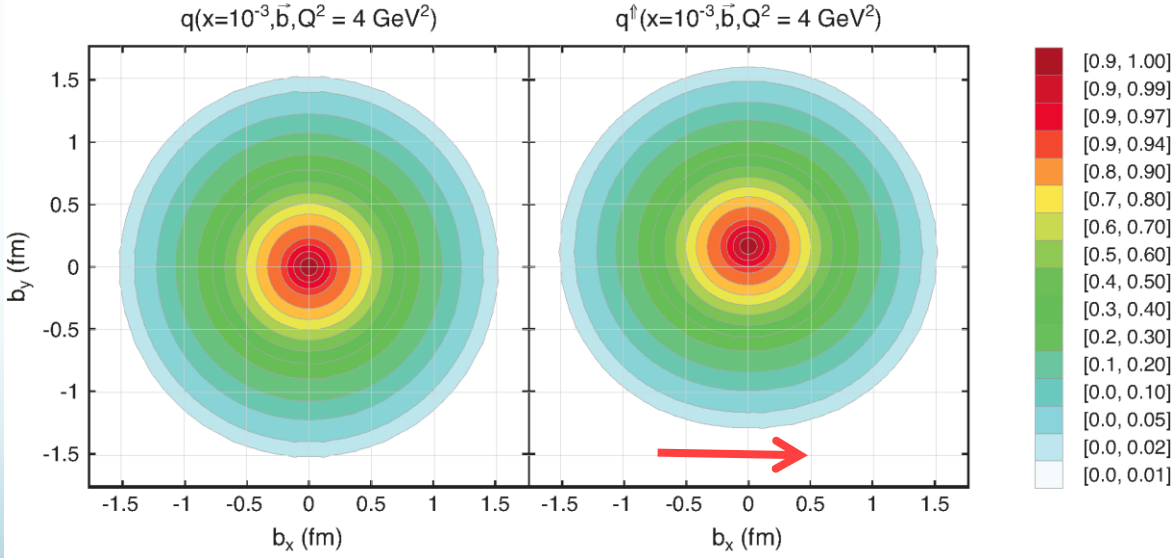
$$H_q(x,\xi,t,Q), E_q(x,\xi,t,Q), \ldots$$

F.T. of t-dep → Spatial distributions

JLab 12: Valence quarks

EIC: Sea quarks

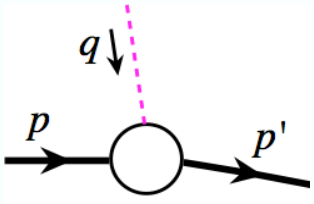




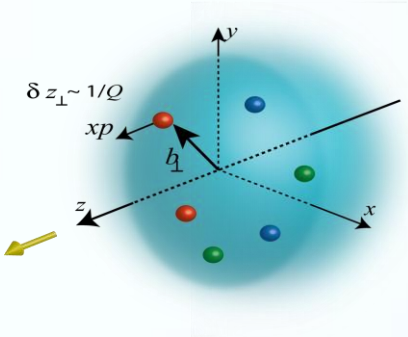
How about the glue?

Spatial imaging of gluons

- **Need Form Factor of density operator**:

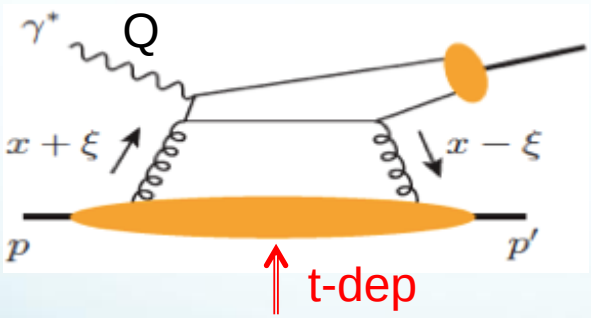


- ✧ Exchange of a colorless “object”
- ✧ “Localized” probe
- ✧ Control of exchanged momentum



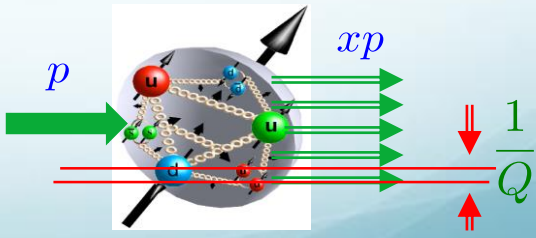
- **Exclusive vector meson production:**

$$\frac{d\sigma}{dx_B dQ^2 dt}$$



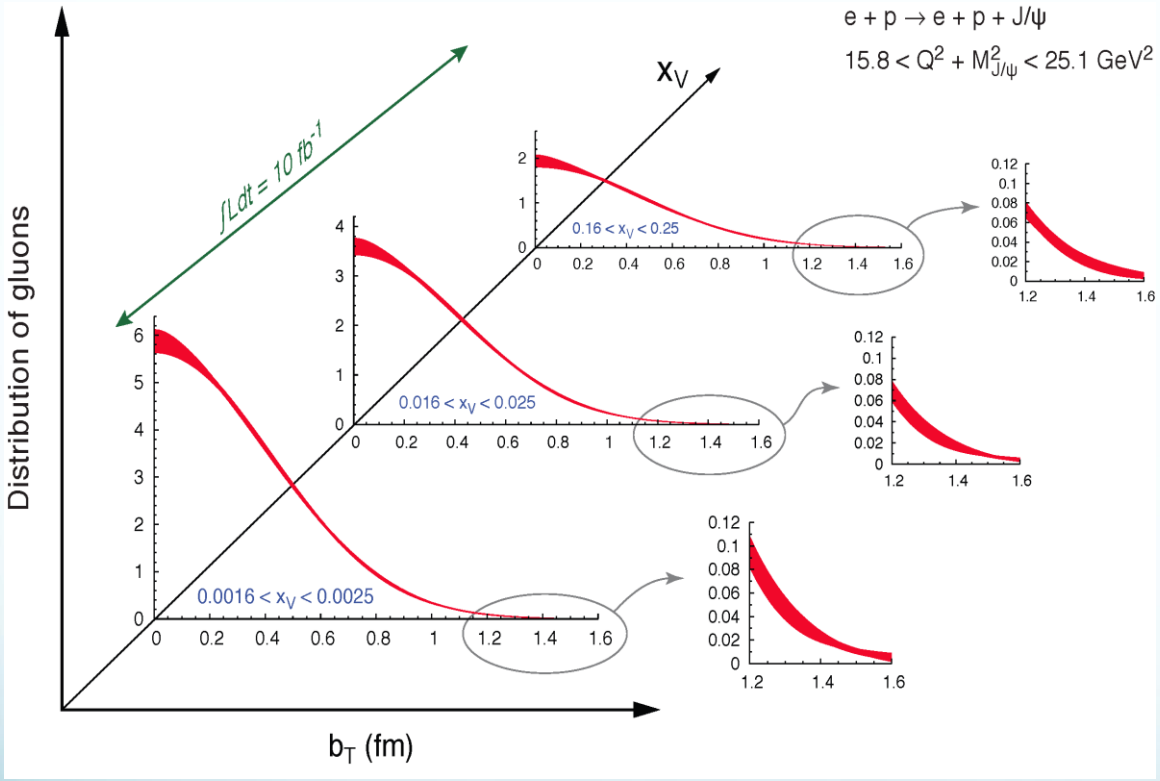
J/Ψ, Φ, …

- ✧ Fourier transform of the t-dep
- ➡ Spatial imaging of glue density
- ✧ Resolution ~ 1/Q or 1/M_Q



Spatial imaging of gluon density

- **Gluon imaging from simulation:**



$$x_V = \frac{M_{J/\psi}^2 + Q^2}{W^2 + Q^2 - M_N^2}$$

$$W^2 = (p+q)^2; \qquad M_N^2 = p^2$$

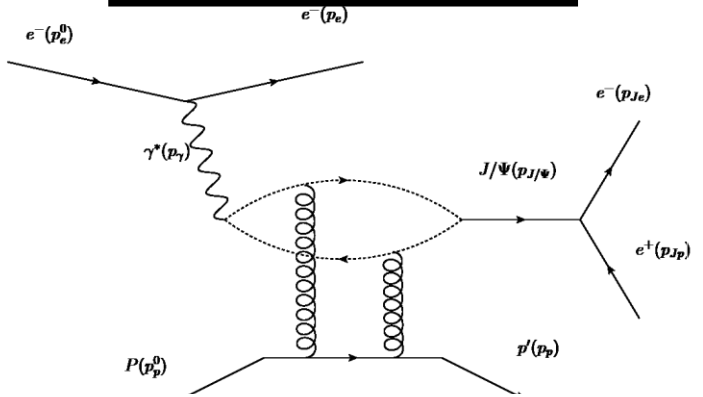
Images of gluons from exclusive J/ψ production

Only possible at the EIC: From the valence quark region deep into the sea quark region

J/ψ @ SoLID

Threshold J/Ψ production, probing strong color field in the nucleon, QCD trace anomaly (important to proton mass budget)

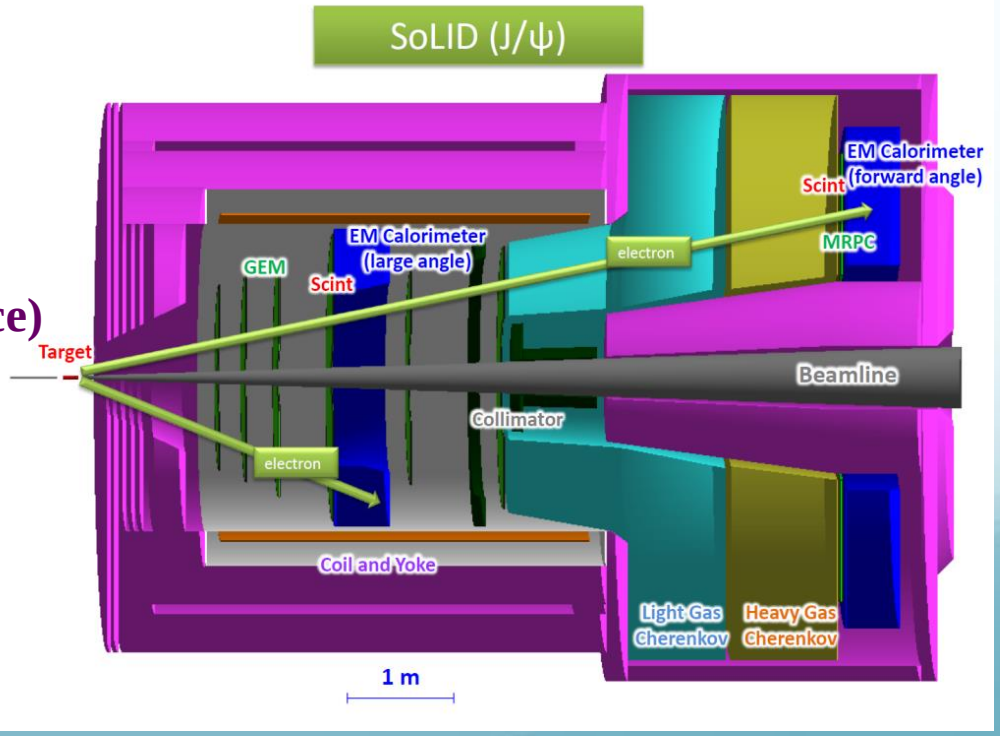
$$\gamma^* + N \rightarrow N + J/\psi$$



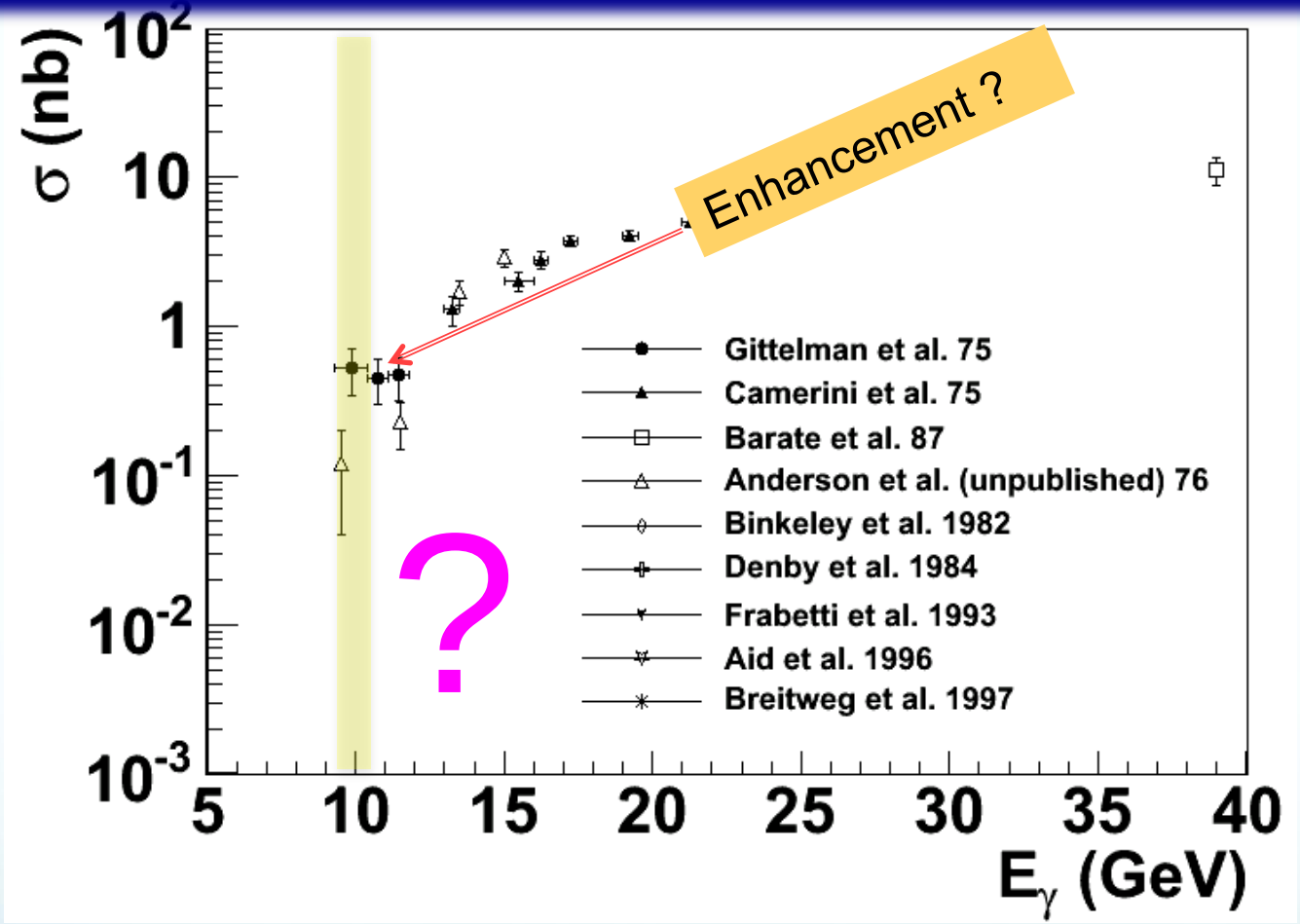
$$e\ p \rightarrow e'\ p'\ J/\psi(e^-\ e^+)$$
$$\gamma\ p \rightarrow p'\ J/\psi(e^-\ e^+)$$

Imaginary part: related to the total cross section through optical theorem

Real part: contains the conformal (trace) anomaly



Near Threshold $\gamma + N \longrightarrow N + J/\Psi$



Intense experimental effort (SLAC, Cornell …) shortly after the discovery of J/ψ

But near threshold not much since (**~40 years till now**)

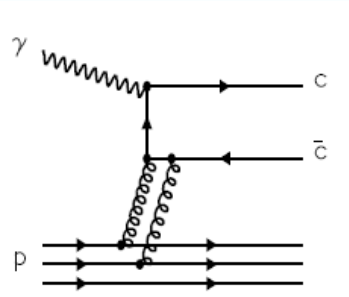
Reaction Mechanism ?

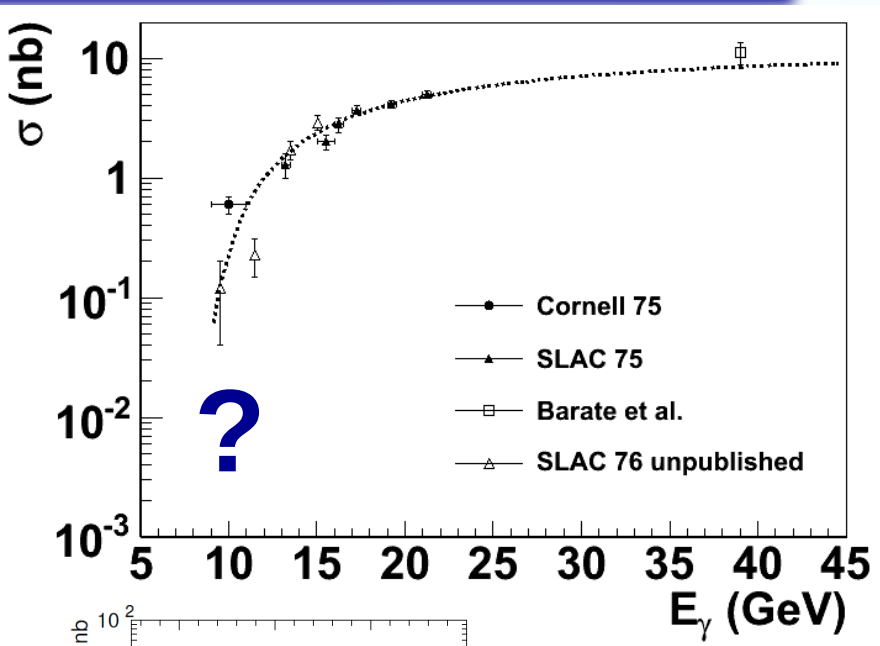
Models-I: Hard scattering mechanism (Brodsky, Chudakov, Hoyer, Laget 2001)

$$2-g:(1-x)^2F(t)$$

$$F(t)\propto \exp(1.13t)$$

$$x=\frac{2M_pM_{J/\psi}+M_{J/\psi}^2}{2E_\gamma M_p}$$

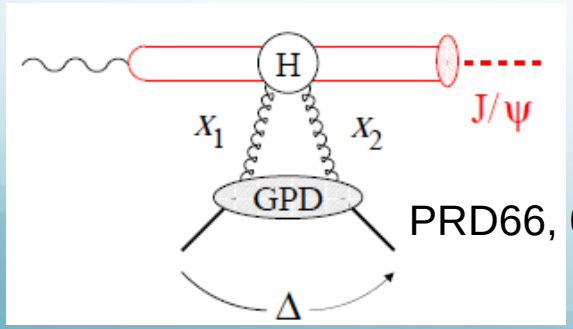




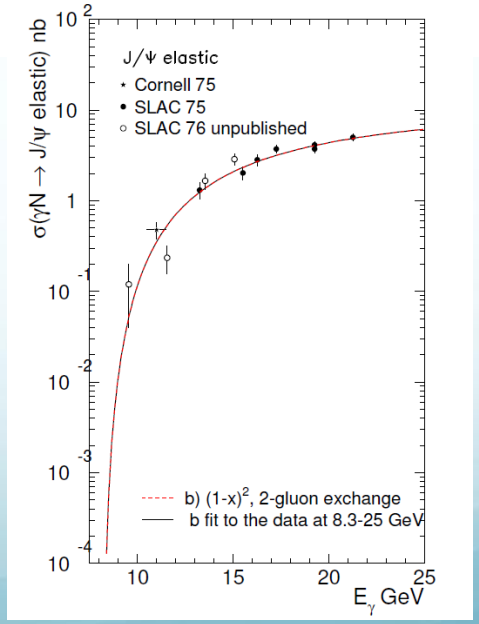
Models -II: Partonic soft mechanism (Frankfurt and Strikman 2002)

2-gluon Form Factor

$$F.F.\propto (1-t/1.0\ \mathrm{GeV}^2)^{-4}$$



PRD66, 031502 (2002)



Nucleon Mass Decomposition and the Trace Anomaly

X. Ji PRL 74 1071 (1995)

$$H_{QCD} = \int d^3x \; T^{00}(0, \mathbf{x})$$

$$H_{QCD} = H_q + H_m + Hg + H_a$$

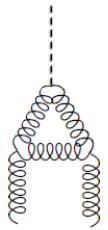
$$H_q = \int d^3x \; \psi^\dagger \left(-i\mathbf{D}\cdot\alpha\right)\psi$$

$$H_m = \int d^3x \; \bar{\psi} m \psi$$

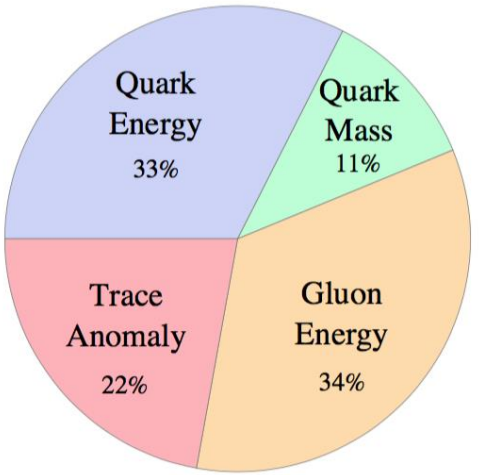
$$H_g = \int d^3x \; \frac{1}{2}\left(\mathbf{E^2} + \mathbf{B^2}\right)$$

$$H_a = \int d^3x \; \frac{9\alpha_s}{16\pi}\left(\mathbf{E^2} - \mathbf{B^2}\right)$$

$$G^{\alpha\beta\gamma} G^{\gamma}_{\alpha\beta}$$



Proton Mass budget



CM Frame
MS at 2 GeV^2

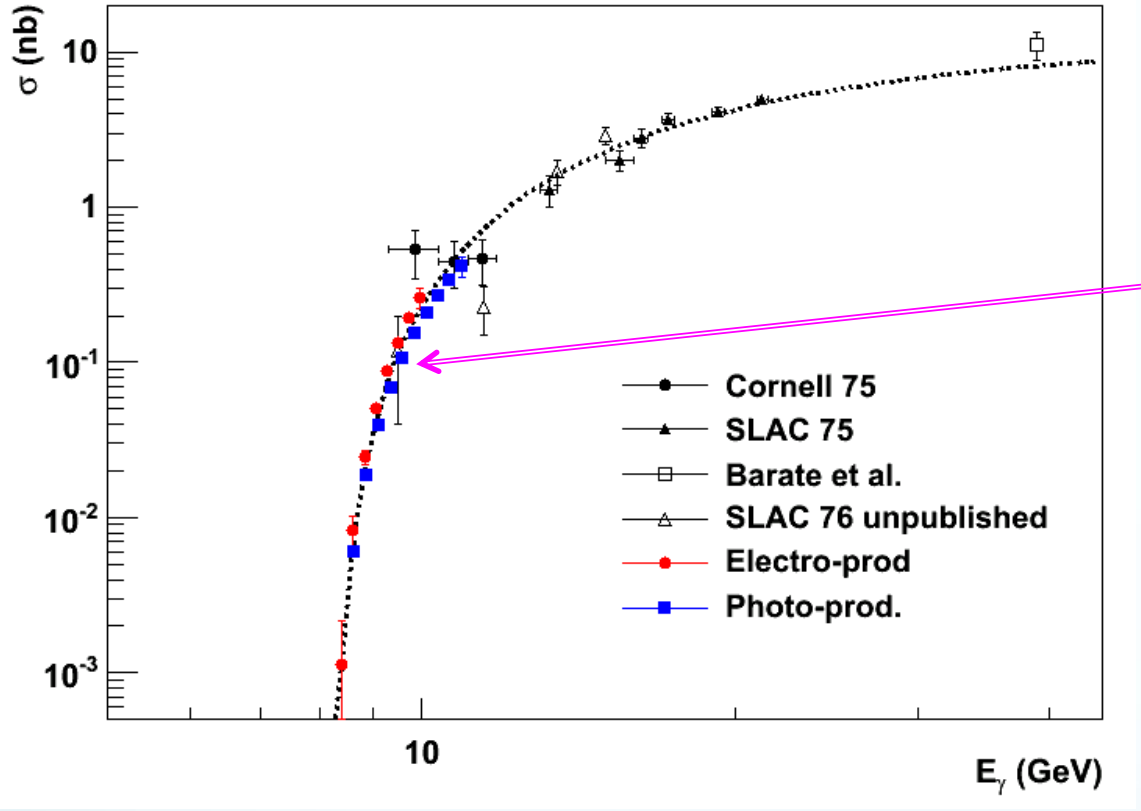
PR12-12-06: Near Threshold J/Ψ Electroproduction

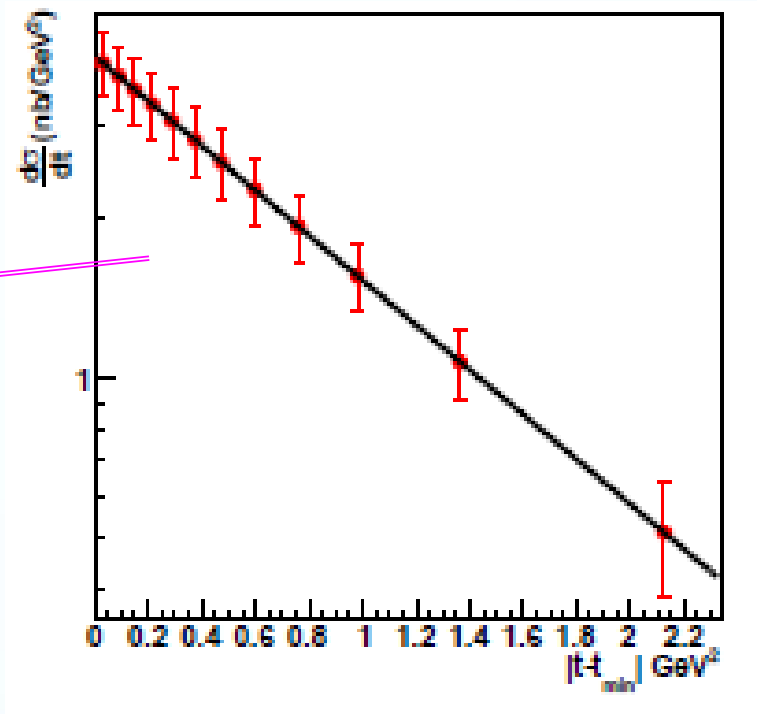
- **Measure the *t* dependence and energy dependence of *J/ψ* cross sections near threshold**
  - Probe the nucleon strong fields in a non-perturbative region
  - Search for a possible enhancement of the cross section close to threshold
  - Shed some light on the conformal/trace anomaly

Establish a baseline for *J/ψ* production in the JLab energy range!

- **Bonuses:**
  - Photoproduction data
  - Decay angular distribution of J/ψ
  - Interference with Bethe-Heitler term (real vs. imaginary)
- **Future Plans:**
  - Search for J/ψ-Nuclei bound states
  - J/ψ medium modification

Projection of Differential and Total Cross Section



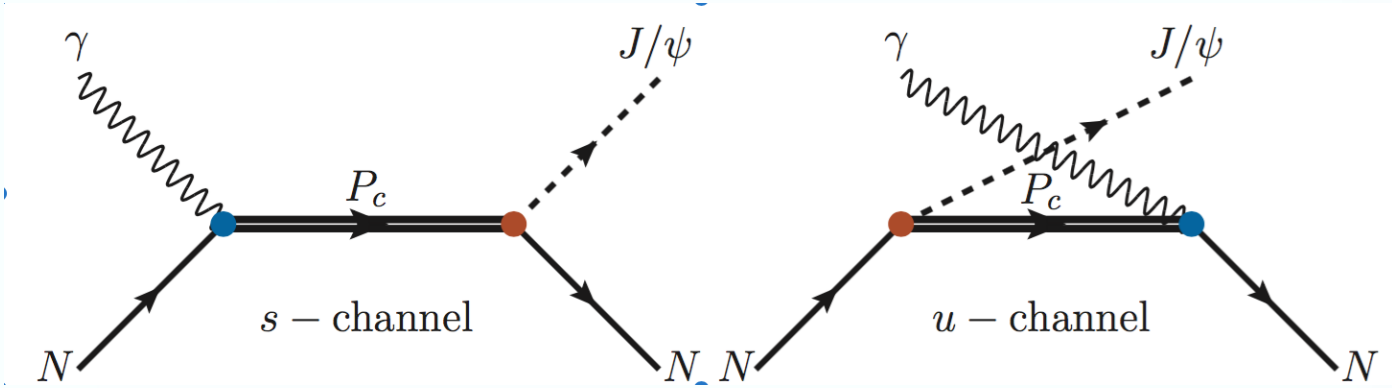


Luminosity 1.2*10^{37}/cm^2/s, 11GeV 3uA e- on 15cm LH2 50 Days

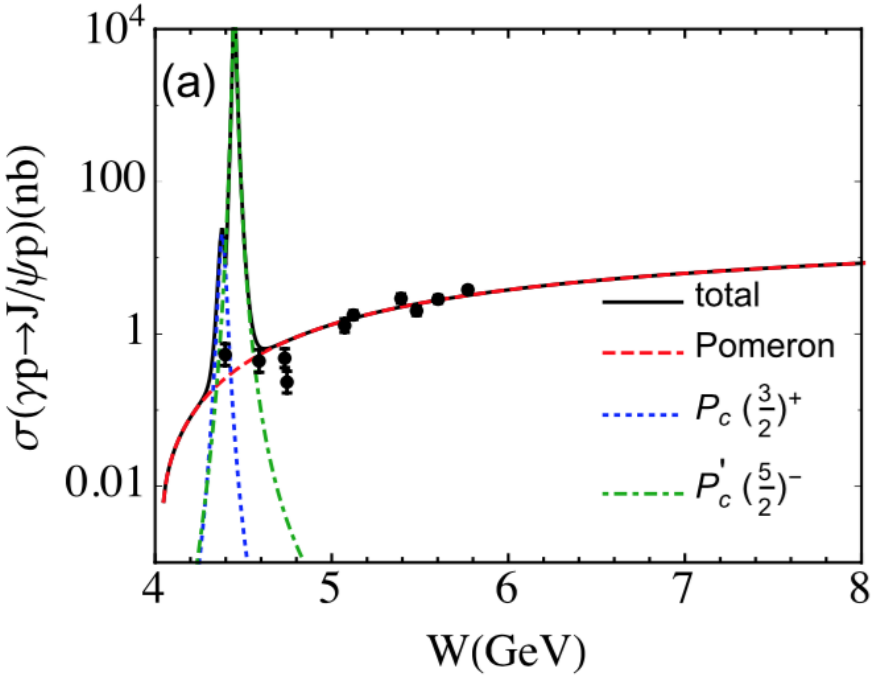
No competition in statistics

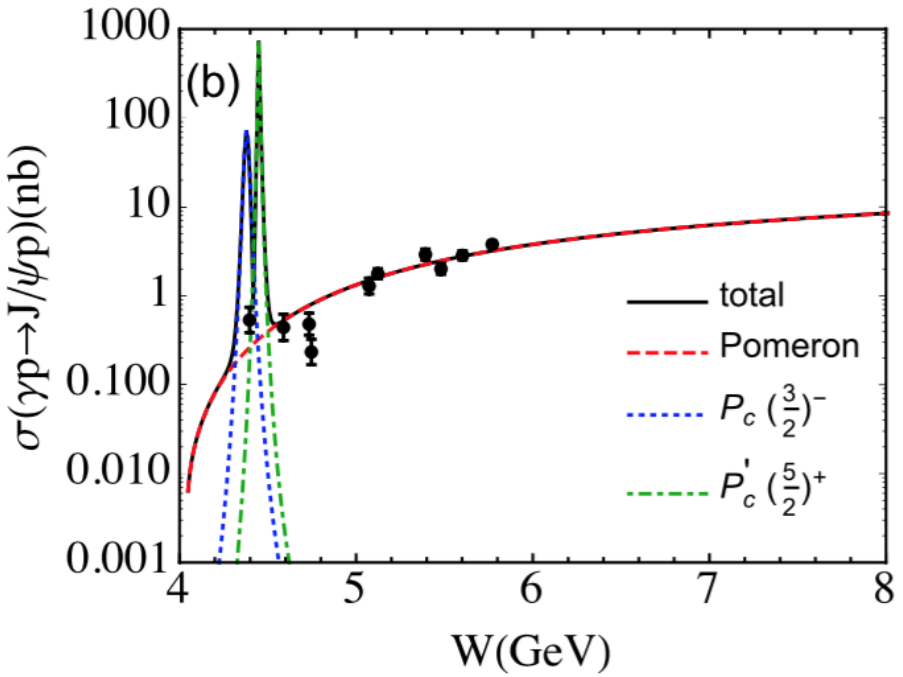
Study the threshold behavior of cross section with high precision **could shed light on the conformal anomaly**

Charm Pentaquark



Qian Wang , Xiao-Hai Liu , and Qiang Zhao Phys. Rev. D 92, 034022 (2015)





Coherent production of ϕ on ^{4}He

- Although the J/Ψ or ϒ are better gluonic probes, we can use the ϕ to probe the gluon density in ^{4}He at JLab
  - Is the diffraction minimum for the charge and gluon distributions the same?
  - If we do not observe a diffraction minimum how is it filled, what are the mechanisms?
  - Are the exchanged gluons probing more then one nucleon at a time?

- Search for bound states near threshold, strong threshold interactions effects might be seen and studied.

Summary

- EIC is “the” machine to probe the glue and the sea and will provide multi-dimensional imaging in momentum an position space.
- Extends the QCD programs developed at BNL and JLab in dramatic and fundamentally important ways
- SoLID at Jlab 12 GeV has a robust science program which includes TMDs, PVDIS and threshold J/Ψ production.
- Charmed Pentaquark can be probed at Jlab
- Ideas to use nuclei are emerging among them
  - ✓ Isovector EMC effect
  - ✓ Accessing nuclei gluon GPDs with phi and J/Ψ
  - ✓ Investigating possible quarkonium-nucleus bound states
  - ✓ Hadronization