

# Exclusive $J/\psi$ production and gluonic structure

C. Weiss (JLab), Nuclear Photoproduction with GlueX, JLab, 28–29 Apr 2016

- Quarkonium size and structure

Parametric: Dynamical scales

Numerical: Potential models, Lattice QCD

- $J/\psi$  photo/electroproduction at  $W \gg W_{\text{th}}$   
FNAL, COMPASS, HERA, EIC

Space–time picture in rest frame

GPD as color dipole moment of nucleon

“Gluon imaging” of nucleon

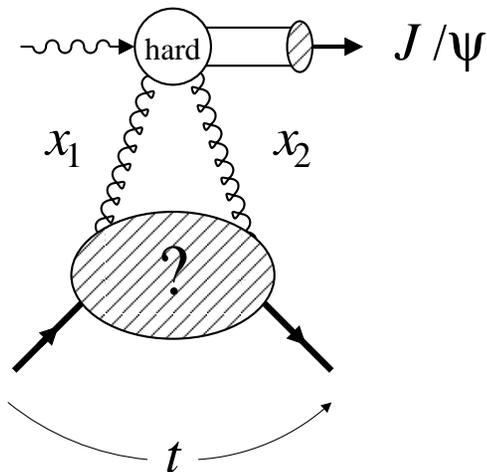
- $J/\psi$  photo/electroproduction near threshold  
Cornell, SLAC, JLab 12 GeV

Kinematics of large  $t_{\text{min}}, x$

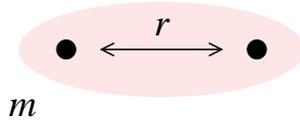
Gluonic form factor of nucleon

Nuclear targets

Connections: Small–size configurations, high- $Q^2$  meson production, high- $t$  form factors, color transparency . . .



# Heavy quarkonium: Scales and size



- Parametric: Non-relativistic system

Cf. Positronium in QED,  $v \sim \alpha_{em}$

$$m \gg mv \gg mv^2$$

mass            momentum,            binding  
                  inv. size                energy

Effective field theory approach:  
Non-relativistic QCD,  $mv^n$  expansion

Lepage et al 92; Manohar 97; Brambilla 2000; Kniehl et al. 2002

- Numerical: Potential models

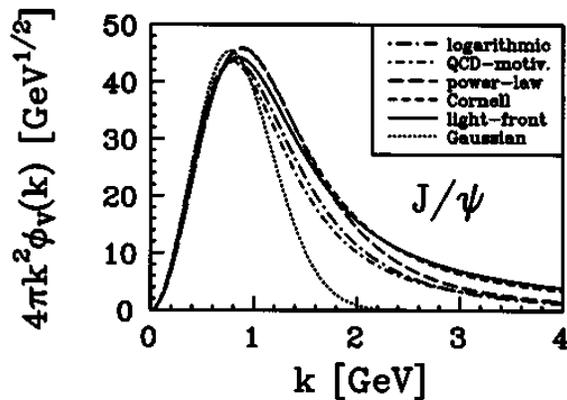
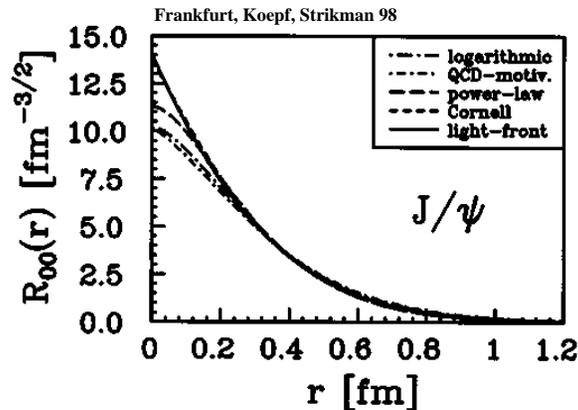
Eichten et al. 75; Quigg, Rosner 77

Typical  $c\bar{c}$  distances  $r \sim 0.2-0.3 \text{ fm} \ll 1 \text{ fm}$

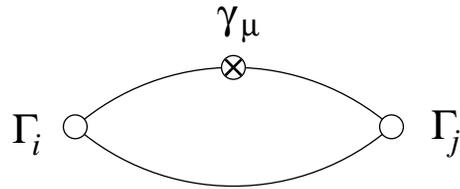
Transverse size in light-cone wave function  
 $\langle r_T^2 \rangle = 2/3 \langle r^2 \rangle$

High-momentum components with  $k \gtrsim m$   
account for  $\sim 30\%$  of  $R_{00}(r=0)$

→ Decays

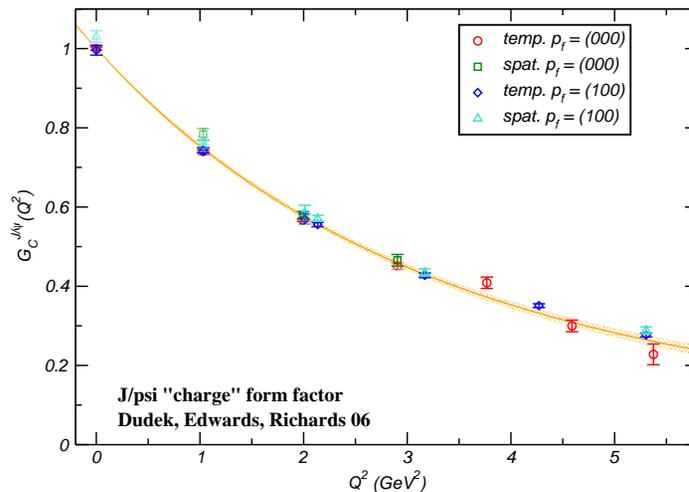


$J/\psi$  “moderately small,” relativistic



- Charmonium form factors

Separate ground  $\leftrightarrow$  excited states using matrix of correlation functions  
 Dudek et al. 06  $\rightarrow$  Light quarks, hybrid mesons



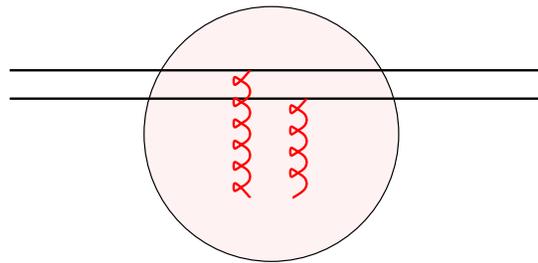
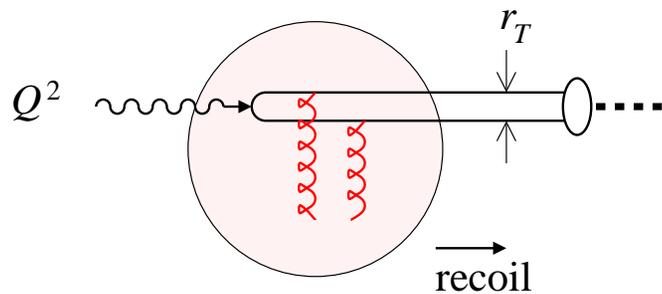
Artificial  $J/\psi$  "charge form factor" from current with  $c \neq \bar{c}$  coupling

$J/\psi$  charge radius  $\langle r^2 \rangle^{1/2} \approx 0.26$  fm

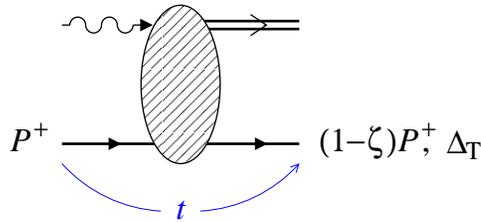
Also  $\eta_c$ , radiative transitions

# Heavy quarkonium: Probe of color field

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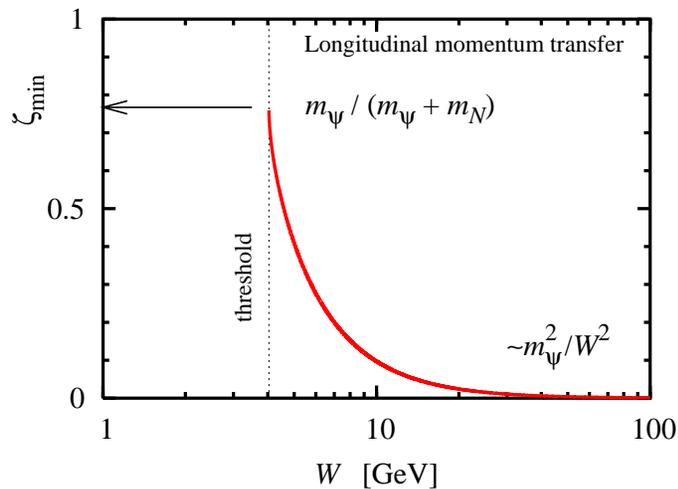
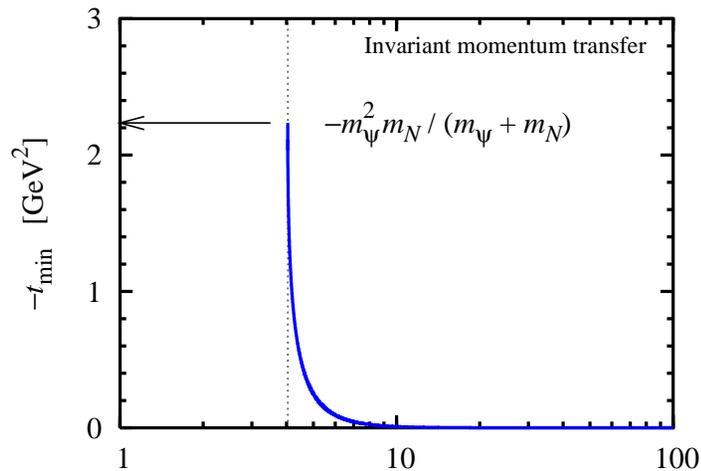


- Use heavy quarkonium as probe of color fields in light hadrons
  - Fields change with incident energy, size of  $Q\bar{Q}$  configurations
  - Multipole expansion: Dipole + . . .
- Exclusive photo/electroproduction
  - Target recoils: Gluonic form factor
  - $Q^2$  tests/changes "mix" of  $Q\bar{Q}$  sizes
  - Theoretical challenges!  
Separate structures of target and probe (factorization),  
model gluonic structure of target
- Quarkonium-hadron rescattering
  - Theoretically simpler, but difficult to realize at low energies!



- Exclusive production  $\gamma N \rightarrow J/\psi + N$

Invariant momentum transfer grows near threshold  $|t_{\min, \text{th}}| = 2.2 \text{ GeV}^2$



- Light-cone variables

$\zeta$  “Plus” momentum transfer, cf.  $x_B$  large near threshold, but not  $x \rightarrow 1$ !

$\Delta_T$  Transverse momentum transfer

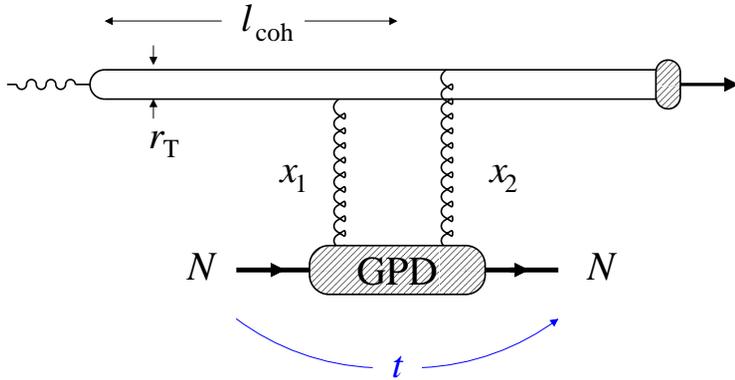
$$t = -(\zeta^2 m_N^2 + \Delta_T^2) / (1 - \zeta)$$

- Two regimes

$W \approx W_{\text{th}}$   $t_{\min} = 1\text{--}2 \text{ GeV}^2$ ,  $\zeta$  large  
cf. nucleon elastic form factors  
Cornell, SLAC, JLab 12 GeV

$W \gg W_{\text{th}}$   $t_{\min}$  negligible,  $\zeta \ll 1$   
cf. diffractive processes  
FNAL, COMPASS, HERA, EIC

# High $W$ : QCD factorization and dipole picture 6



- QCD factorization theorem

Collins, Frankfurt, Strikman 96

Collinear factorization of amplitude  
 GPD  $\times$  Hard scattering  $\times$  Meson dist. amp.

GPD as transition matrix element of twist-2 operator: Gluonic form factor of nucleon  
 $x_1 = x_2, t = 0$ : Usual gluon density

$$\langle N' | F_{+i}(0) F_{+i}(z^-) | N \rangle$$

$z^2 = 0$  light-like distance

- Space-time picture in rest frame

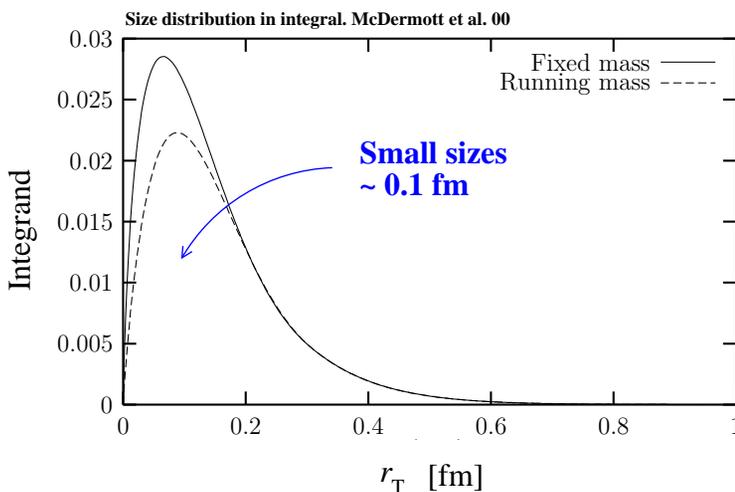
Brodsky et al. 94

Coherence length  $l_{\text{coh}} \gg 1 \text{ fm}$

$$A = \int d^2 r_T \psi_\gamma(\mathbf{r}_T) \underbrace{A_{Q\bar{Q}N}(\mathbf{r}_T)}_{\propto r_T^2 \alpha_s \text{ GPD (Scale } \propto r_T^{-2})} \psi_{J/\psi}(\mathbf{r}_T)$$

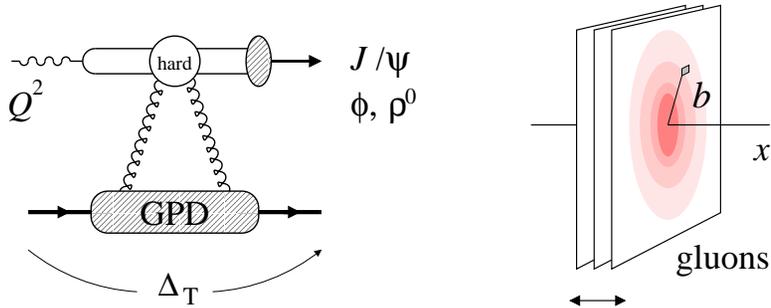
Distribution of  $Q\bar{Q}$  sizes determined dynamically, changes with energy, electroproduction  $Q^2$   
 Cf. Color transparency

GPD as transition color dipole moment



# High $W$ : Data and interpretation

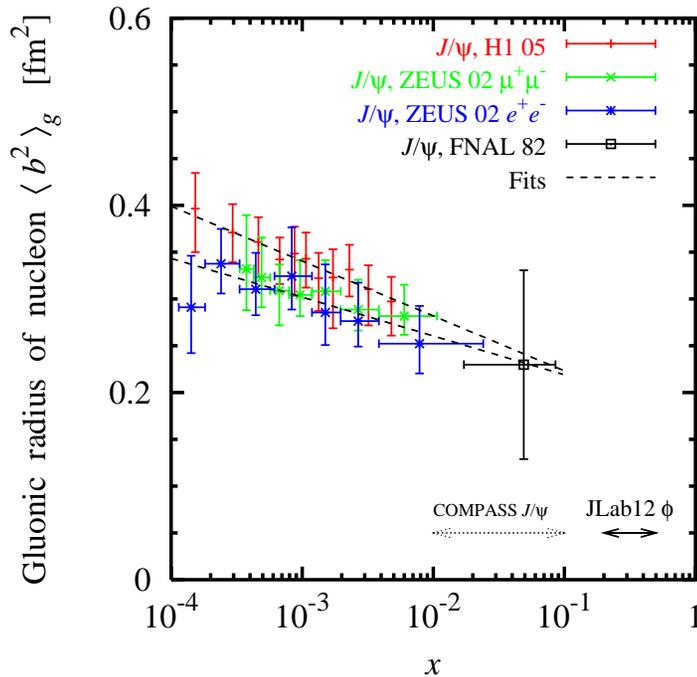
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- $J/\psi$  photo/electroproduction at high  $W$  well understood [HERA data, extensive literature](#)

Experimental tests of small-size regime  
[Universality of  \$t\$ -slopes above  \$Q^2 \sim 10 \text{ GeV}^2\$](#)

GPD/dipole calc's describe cross sections  
[Frankfurt et al. 95; Goloskokov, Kroll 08+; . . .](#)



- Transverse spatial distribution of gluons

Fourier  $\Delta_T \rightarrow b$  impact parameter

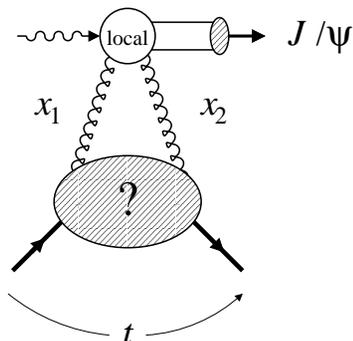
Distribution changes with  $x$  and scale  $Q^2$ :  
 Parton diffusion, DGLAP evolution

Fundamental gluonic size of nucleon in QCD:  
 Gluon vs. quark radii, non-pert. dynamics

Input for small- $x$  physics:  
 Evolution equations, saturation

Needed for pp@LHC: Underlying event,  
 multiparton processes, diffraction

“Gluon imaging” with EIC



- Near-threshold kinematics

Large  $|t_{\min}|$ , up to  $2.2 \text{ GeV}^2$

Large longit. momentum transfer  $x_1 - x_2 = \zeta$

- Reaction mechanism near threshold

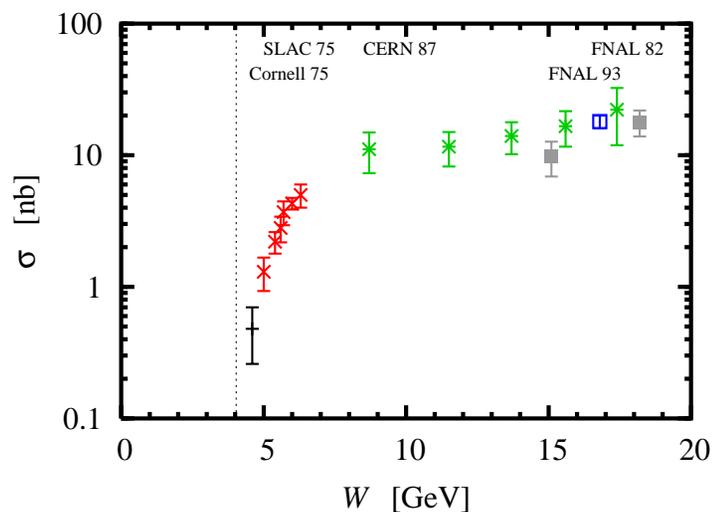
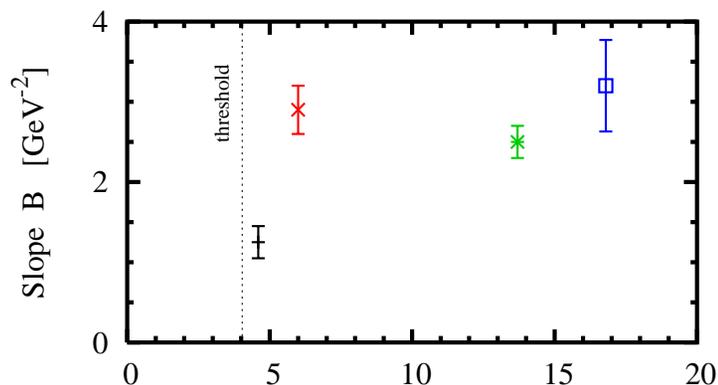
Strikman, CW, in progress

$\gamma gg J/\psi$  vertex local on scale  $R_{\text{nucl}} \sim 1 \text{ fm}$

Amp  $\sim A(s)F_{gg}(t)$  local gluonic form factor.  
Energy dependence through  $F_{gg}(t_{\min})$

Consistent with existing low-energy data.

Can be tested with JLab 12 GeV!



- Theoretical questions

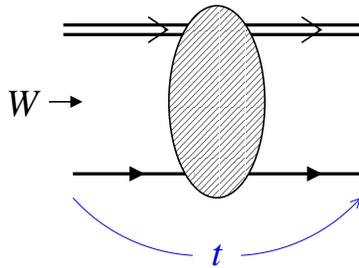
Matching collinear  $\leftrightarrow$  short-distance expansion?

Quantum numbers of gluonic operator?

Behavior of two-gluon form factor?

Correlated configurations in nucleon LCWF?

Cf. model of Brodsky, Chudakov, Hoyer, Laget 01



- Kinematics of  $\psi N$  scattering

$t \approx 0$  accessible at all  $W > W_{\text{th}}$

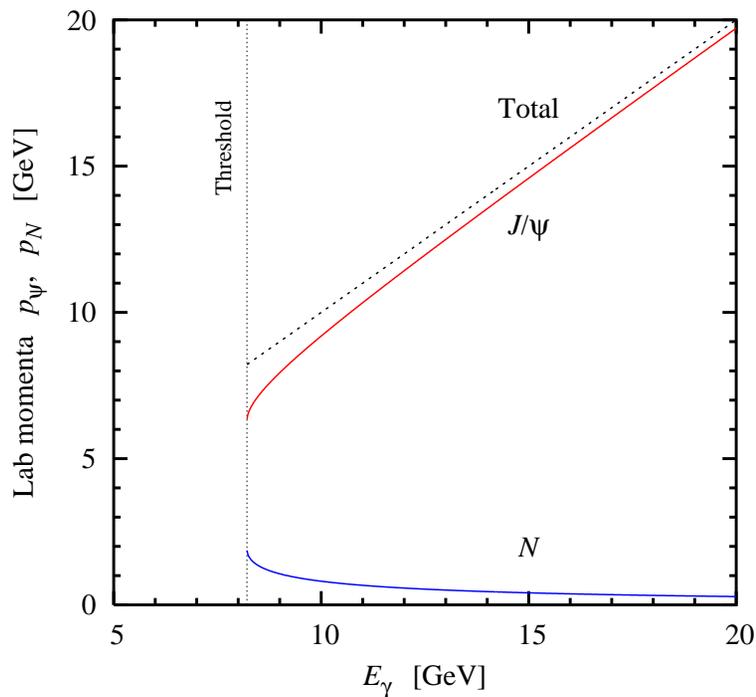
“Ideal process” for probing color fields in hadrons and nuclei!

- Physics of low-energy  $\psi N$  interaction

Operator expansion: Dipole-dipole interaction  
Fuji, Kharzeev 99

Van-der-Waals force of QCD  
Brodsky, Miller 97

Nuclear bound states?  
Brodsky, de Teramond 90; Luke, Manohar, Savage 92



- Near-threshold  $\gamma A \rightarrow J/\psi + X$

$$\frac{p_{\psi}}{m_{\psi}} \approx \frac{m_{\psi}}{2m_N} \quad J/\psi \text{ fast, relativistic!}$$

Produced  $J/\psi$  is fast —  
How to study bound states?

- $J/\psi$  as small-size probe of color fields in hadrons
  - “moderately small,” relativistic
- High- $W$  photo/electroproduction at probes gluon GPD
  - Transverse spatial distribution of gluons at fixed  $x$
- Near-threshold photo/electroproduction probes local gluonic form factor
  - Theory/phenomenology developing
  - “New physics” accessible with JLab 12 GeV!
- $J/\psi$  fast in photoproduction
  - Possible to study transparency,  $\psi N$  interaction
  - How to explore nuclear bound states?
- Open charm production near threshold
  - Extension of “local operator” mechanism at low  $W$ ?
  - Common theoretical description of  $J/\psi$  and  $D\Lambda_c$ ?
  - What can be learned from open charm?