Exclusive $J/\psi$ production and gluonic structure

C. Weiss (JLab), Exclusive Meson Production Workshop, JLab, 22–24 Jan 2015

- Quarkonium size and structure
  Parametric: Dynamical scales
  Numerical: Potential models, Lattice QCD

- $J/\psi$ photo/electroproduction at $W \gg W_{th}$
  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 \quad momentum, \quad inv. size \quad binding 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 \( R_{00}(r = 0) \)
  \( \rightarrow \) Decays

  \( J/\psi \) “moderately small,” relativistic
Heavy quarkonium: Size from lattice QCD

- Charmonium form factors

Separate ground ↔ excited states using matrix of correlation functions
Dudek et al. 06 → 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

- 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 $+$ \ldots

- 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!
Photoproduction: Kinematics

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

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

- 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

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

  $W \gg W_{\text{th}}$ \hspace{1cm} $t_{\text{min}}$ negligible, $\zeta \ll 1$
  cf. diffractive processes
  FNAL, COMPASS, HERA, EIC
**High $W$: QCD factorization and dipole picture**

- **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

- **Space–time picture in rest frame**
  Brodsky et al. 94

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

  $A = \int d^2 r_T \psi_\gamma(r_T) A_{QQN}(r_T) \psi_{J/\psi}(r_T)$

  $\propto r_T^2 \alpha_s \text{GPD}(\text{Scale } \propto r_T^{-2})$

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

  Cf. Color transpareny

  GPD as transition color dipole moment

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

$z^2 = 0$ light–like distance

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**Integrand**

Size distribution in integral, McDermott et al. 00

Small sizes $\sim 0.1$ fm

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Run fixed mass

Running mass

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$N \rightarrow \text{GPD} \rightarrow N$
High $W$: Data and interpretation

- $J/\psi$ photo/electroproduction at high $W$ well understood HERA data, extensive literature

  Experimental tests of small–size regime
  Universality of $t$–slopes above $Q^2 \approx 10 \text{ GeV}^2$

  GPD/dipole calc’s describe cross sections
  Frankfurt et al. 95; Goloskokov, Kroll 08+; . . .

- Transverse spatial distribution of gluons
  
  Fourier $\Delta_T \to b$ 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

Frankfurt, Strikman, CW 11, $Q^2 \approx 3 \text{ GeV}^2$
Near threshold: Reaction mechanism

- Near–threshold kinematics
  Large $|t_{\text{min}}|$, up to 2.2 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 $R_{\text{nucl}} \sim 1$ fm
  Amp $\sim CF_{gg}(t)$ local gluonic form factor.
  Energy dependence through $F_{gg}(t_{\text{min}})$
  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
Near–threshold: Nuclei and $\psi N$ interaction

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

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

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

- \( J/\psi \) 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
  
  How to study low–energy \( \psi N \) interaction, bound states?

- Connections with other JLab 12 GeV experiments
  
  Small–size \( q\bar{q} \) configurations in high–\( Q^2 \) meson production
  
  High–\( t \) form factors — gluon vs. quark operators?
  
  Color transparency — different probes
  
  Nuclear short–range correlations — high–momentum components in WF