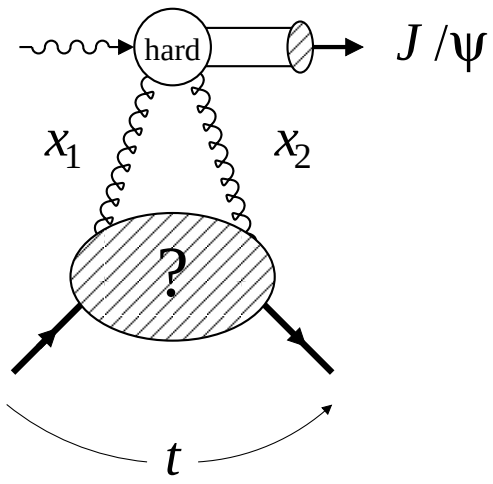
Exclusive J/ψ production and gluonic structure

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/ψ photo/electroproduction at $W \gg W_{\rm th}$
  FNAL, COMPASS, HERA, EIC

  Space–time picture in rest frame

  GPD as color dipole moment of nucleon

  "Gluon imaging" of nucleon

- J/ψ photo/electroproduction near threshold
  Cornell, SLAC, JLab 12 GeV

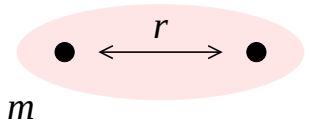
  Kinematics of large $t_{\rm min}, x$

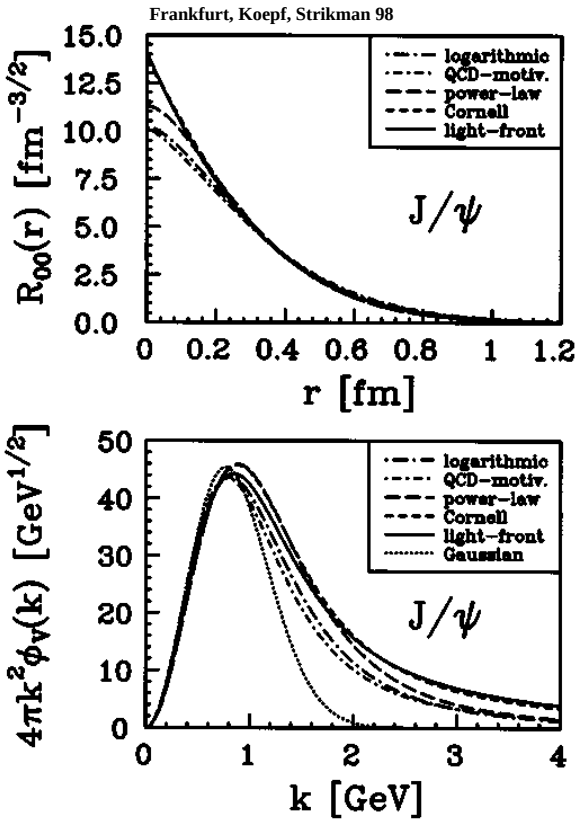
  Gluonic form factor of nucleon

  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, $v \sim \alpha_{\rm em}$

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

mass — momentum, inv. size — 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

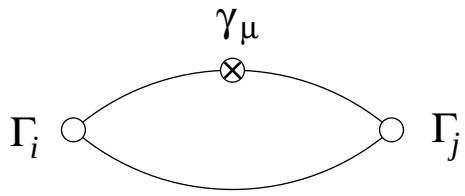
Typical $c\bar{c}$ distances $r \sim$ 0.2–0.3 fm $\ll$ 1 fm

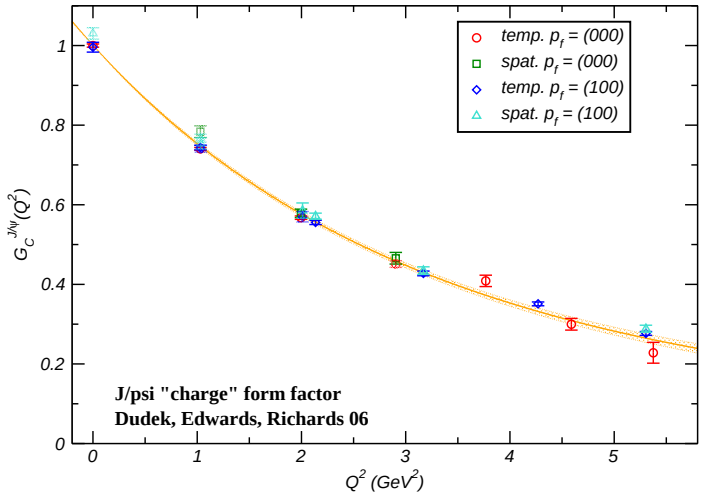
Transverse size in light–cone wave function
$\langle r_T^2 \rangle = 2/3 \, \langle r^2 \rangle$

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

J/ψ "moderately small," relativistic

Heavy quarkonium: Size from lattice QCD





- Charmonium form factors

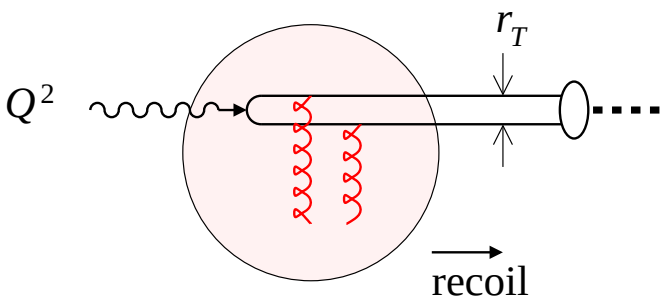
  Separate ground $\leftrightarrow$ excited states using matrix of correlation functions
  Dudek et al. 06 $\rightarrow$ Light quarks, hybrid mesons

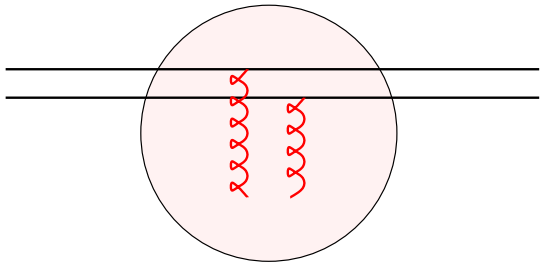
  Artificial J/ψ "charge form factor" from current with $c \neq \bar{c}$ coupling

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

  Also η_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 + . . .

- Exclusive photo/electroproduction

  Target recoils: Gluonic form factor

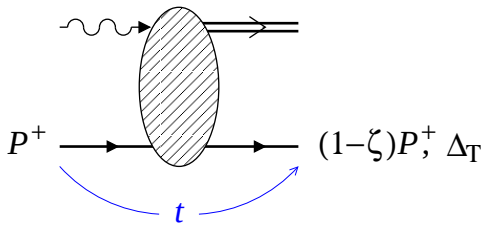
  Q^2 tests/changes "mix" of $Q\bar{Q}$ sizes

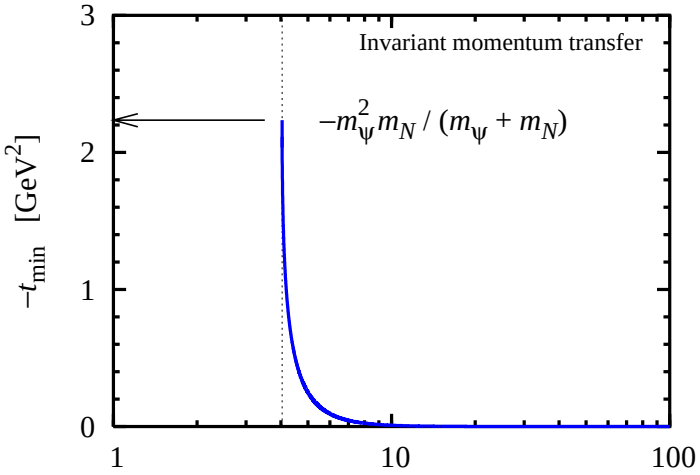
  Theoretical challenges!
  Separate structures of target and probe (factorization),
  model gluonic structure of target

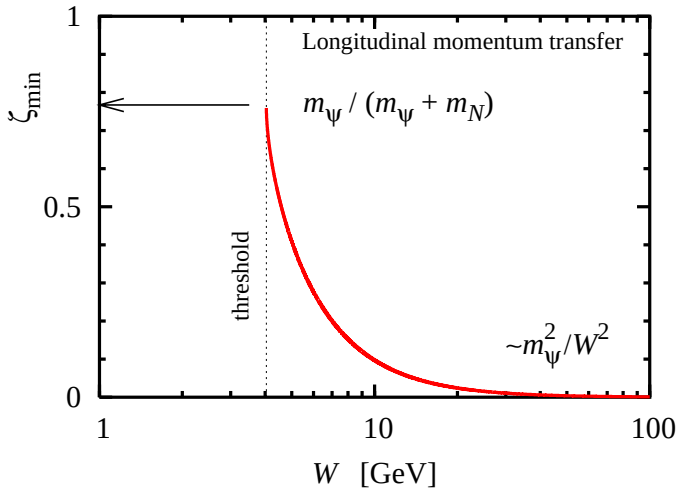
- Quarkonium–hadron rescattering

  Theoretically simpler, but difficult to realize at low energies!

Photoproduction: Kinematics







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

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

- Light–cone variables

  ζ "Plus" momentum transfer, cf. x_B large near threshold, but not $x \to 1$!

  Δ_T Transverse momentum transfer

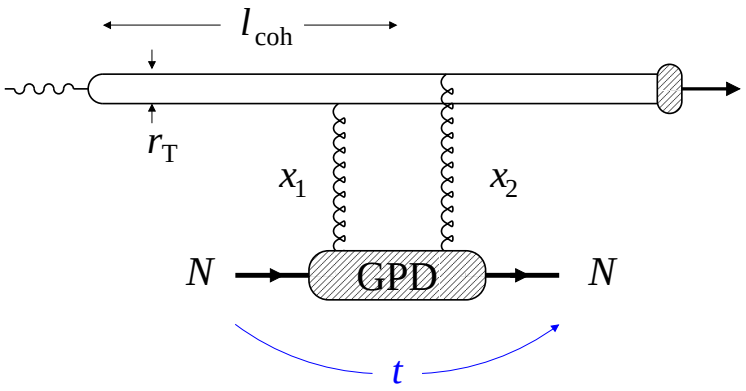
  $t = -(\zeta^2 m_N^2 + \Delta_T^2)/(1-\zeta)$

- Two regimes

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

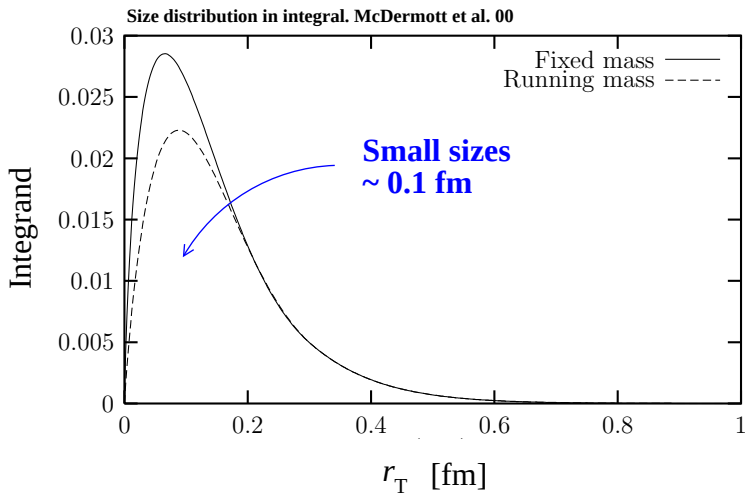
  $W \gg W_{\rm th}$ $t_{\rm min}$ negligible, $\zeta \ll 1$
  cf. diffractive processes
  FNAL, COMPASS, HERA, EIC

High W: QCD factorization and dipole picture



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

$z^2 = 0$ light–like distance



- 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 $l_{\rm coh} \gg 1\,{\rm fm}$

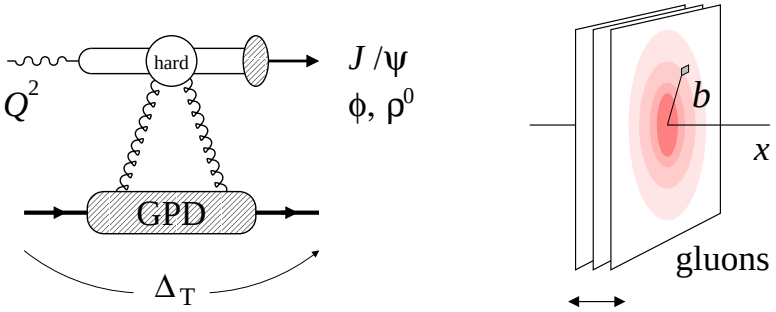
$$A = \int d^2 r_T \; \psi_\gamma(\boldsymbol{r}_{\rm T}) \; \underbrace{A_{Q\bar{Q}N}(\boldsymbol{r}_{\rm T})} \; \psi_{J/\psi}(\boldsymbol{r}_{\rm T})$$

$$\propto \; \boldsymbol{r}_{\rm T}^2 \; \alpha_s \; {\rm GPD}({\rm Scale} \propto \boldsymbol{r}_{\rm T}^{-2})$$

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

  GPD as transition color dipole moment

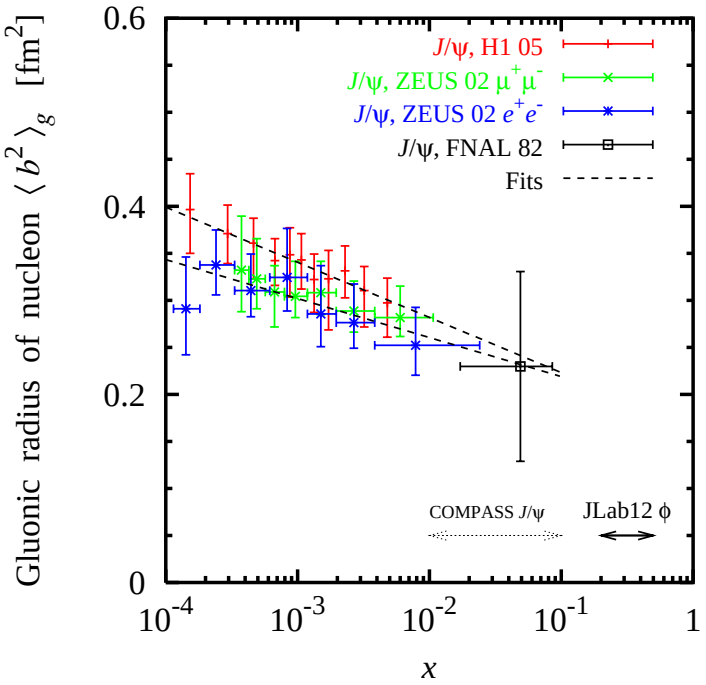
High W: Data and interpretation



- J/ψ photo/electroproduction at high W well understood HERA data, extensive literature

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

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



Frankfurt, Strikman, CW 11, $Q^2 \approx 3\,\mathrm{GeV}^2$

- Transverse spatial distribution of gluons

  Fourier $\boldsymbol{\Delta}_T \to \boldsymbol{b}$ impact parameter

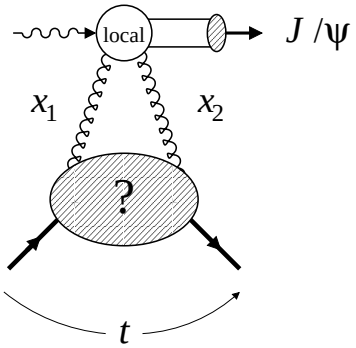
  Distribution changes with x and scale Q^2:
  Parton diffusion, DGLAP evolution

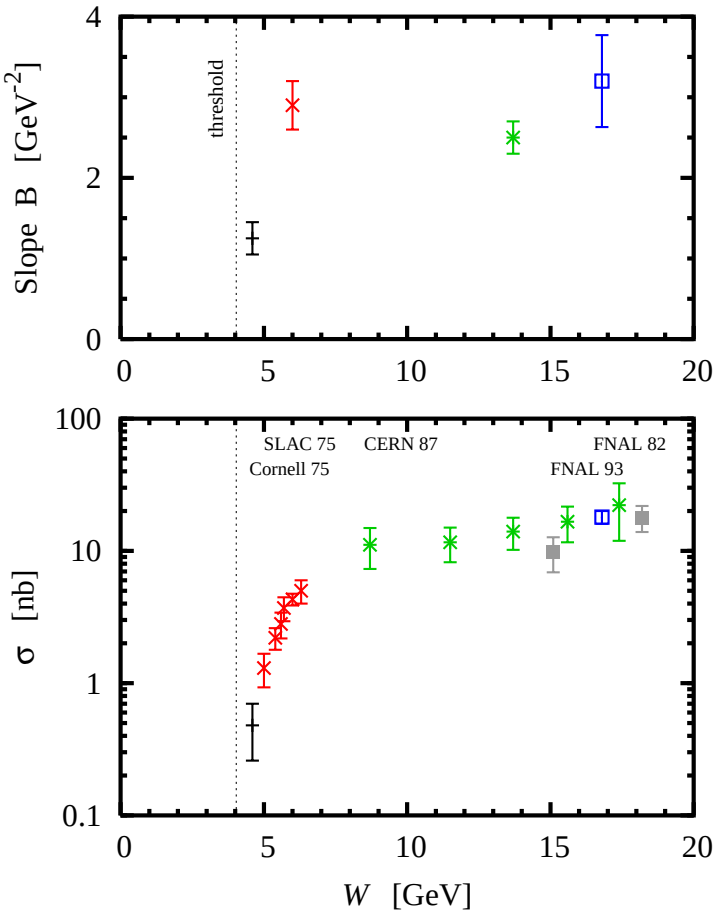
  Fundamental gluonic size of nucleon in QCD:
  Gluon vs. quark radii, non–pert. dynamics

  Input for small–x physics:
  Evolution equations, saturation

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

Near threshold: Reaction mechanism





- Near–threshold kinematics

  Large $|t_{\min}|$, 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 $R_{\mathrm{nucl}} \sim 1\,\mathrm{fm}$

  Amp $\sim C F_{gg}(t)$ local gluonic form factor.
  Energy dependence through $F_{gg}(t_{\min})$
  Consistent with existing low–energy data.

  Can be tested with JLab 12 GeV!

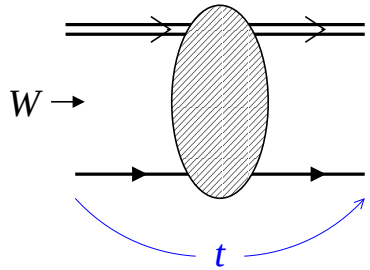
- Theoretical questions

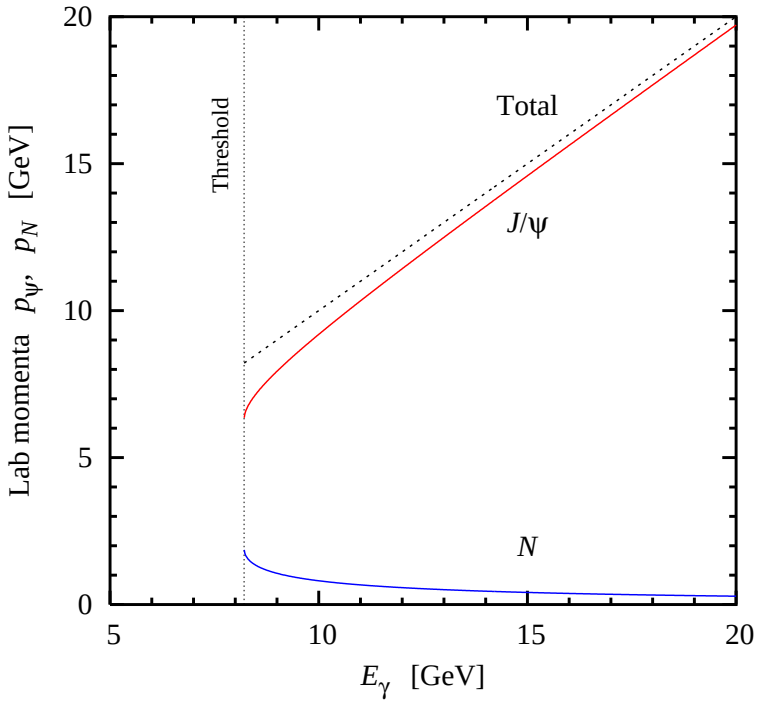
  Matching collinear $\leftrightarrow$ short–distance expansion?

  Quantum numbers of gluonic operator?

  Behavior of two–gluon form factor?
  Correlated configurations in nucleon LCWF?
  Cf. model of Brodsky, Chudakov, Hoyer, Laget 01

Near–threshold: Nuclei and ψN interaction





- Kinematics of ψN scattering

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

  "Ideal process" for probing color fields in hadrons and nuclei!

- Physics of low–energy ψN 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 $\gamma A \to J/\psi + X$

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

Produced J/ψ is fast —
How to study bound states?

Summary

- J/ψ 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/ψ fast in photoproduction

  How to study low–energy ψN 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