

Probing color fields with heavy quarkonia

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- Quarkonium size and structure

Parametric: Dynamical scales

Numerical: Potential models, Lattice QCD

- J/ψ 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

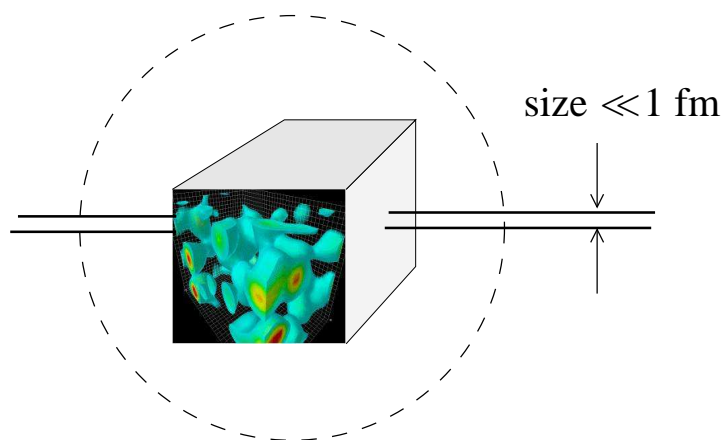
- J/ψ photo/electroproduction near threshold
Cornell, SLAC, JLab 12 GeV

Kinematics of large t_{min}, x

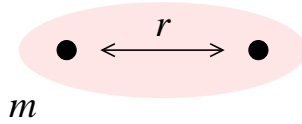
Gluonic form factor of nucleon

Nuclear targets → Talk Strikman

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

→ Talks Butenschoen, Gay Ducati

- Numerical: Potential models

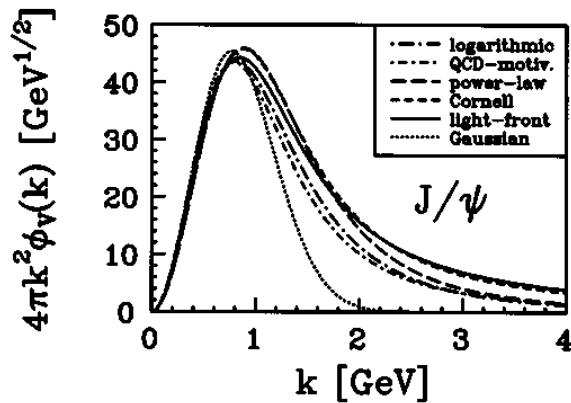
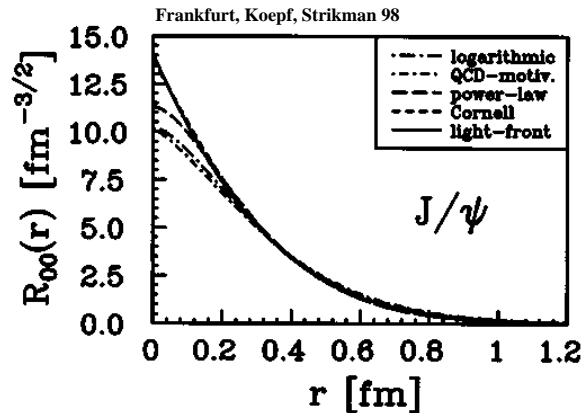
Eichten et al. 75; Quigg, Rosner 77

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

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

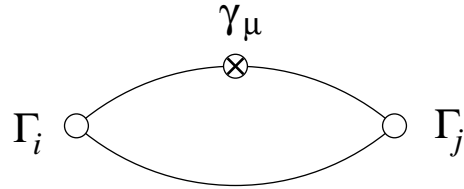
High-momentum components with $k \gtrsim m$
account for $\sim 30\%$ of $R_{00}(r=0)$

→ Decays



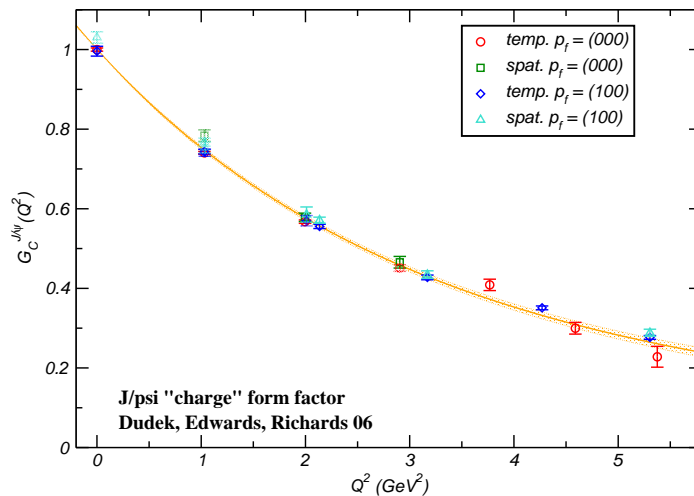
J/ψ “moderately small,” relativistic

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

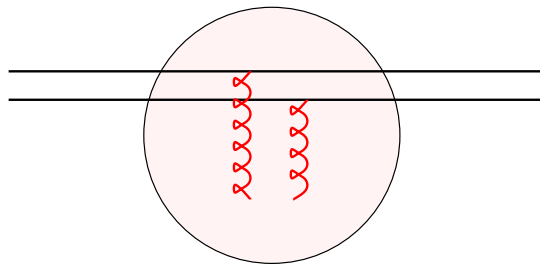
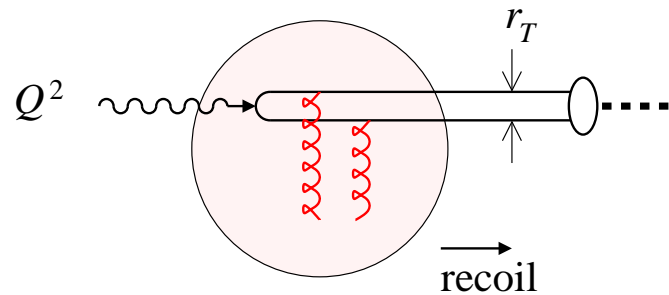


Artificial J/ψ "charge form factor" from current with $c \neq \bar{c}$ coupling

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
Also: Rescattering

Target recoils: Gluonic form factor

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

- Theoretical challenges

Separate structures of target and probe:

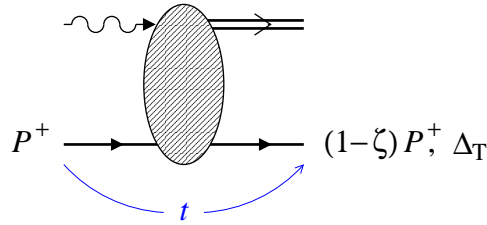
Operator methods, factorization

Space-time picture, light-front quantization

Model gluonic structure of target

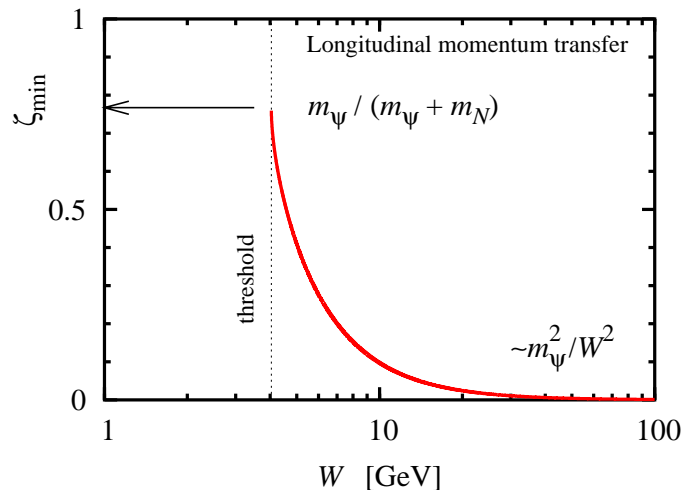
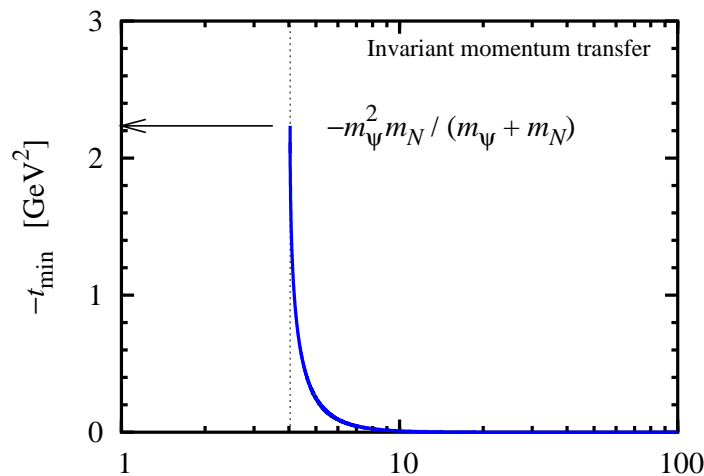
Unique small-size probe of gluon fields

Photoproduction: Kinematics



- 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

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

Δ_T Transverse momentum transfer

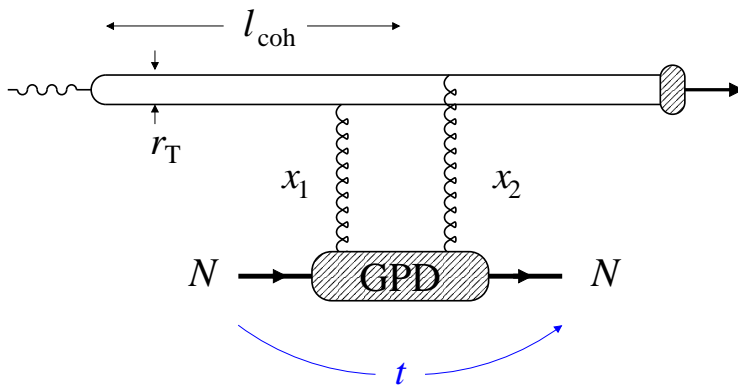
$$t = -(\zeta^2 m_N^2 + \Delta_T^2) / (1 - \zeta)$$

- Two regimes

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

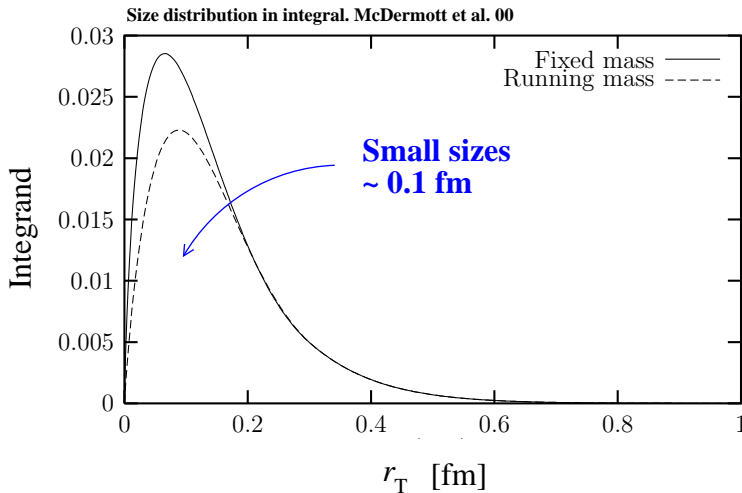
$W \gg W_{\text{th}}$ t_{\min} negligible, $\zeta \ll 1$
cf. diffractive processes
FNAL, COMPASS, HERA, EIC

High W : QCD factorization and dipole picture



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

$z^2 = 0$ 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 $l_{\text{coh}} \gg 1$ fm

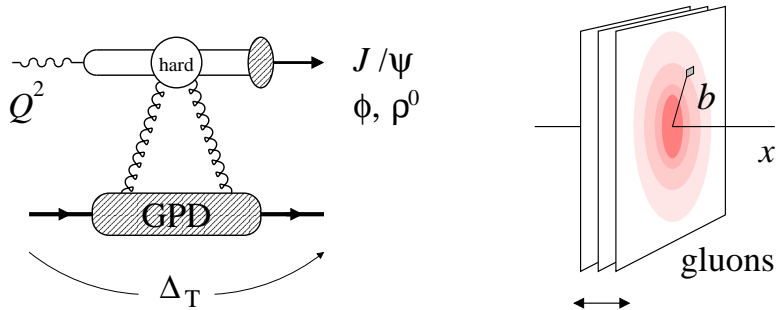
$$A = \int d^2 r_T \psi_\gamma(\mathbf{r}_T) \underbrace{A_{Q\bar{Q}N}(\mathbf{r}_T)}_{\propto r_T^2 \alpha_s \text{ GPD (Scale } \propto r_T^{-2})} \psi_{J/\psi}(\mathbf{r}_T)$$

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

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

GPD = 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 \text{ GeV}^2\$](#)

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

- Transverse spatial distribution of gluons

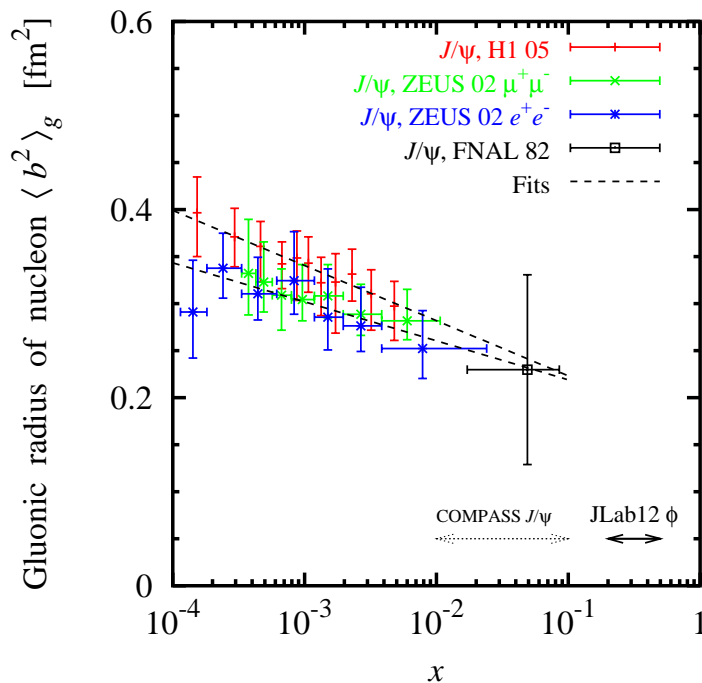
Fourier $\Delta_T \rightarrow b$ impact parameter

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
[Nucleon polarization \$\rightarrow\$ Talk Metz](#)

Input for small- x physics:
 Evolution equations, saturation

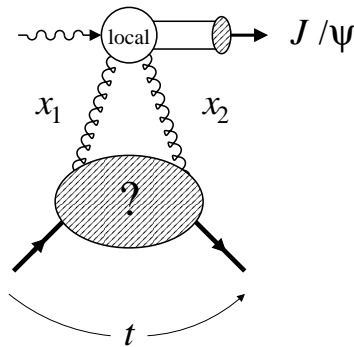
Needed for pp@LHC: Underlying event,
 multiparton processes, diffraction



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

Transverse gluon imaging of nucleon

Near threshold: Reaction mechanism



- Near-threshold kinematics

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

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

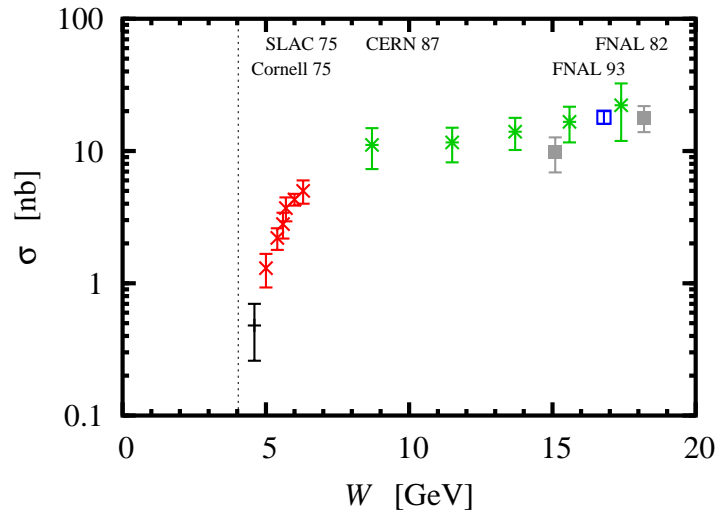
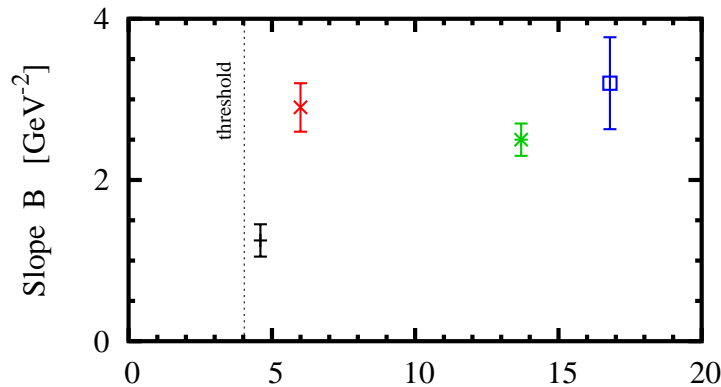
- Reaction mechanism near threshold

Strikman, CW, in preparation → Talk Strikman

$\gamma gg J/\psi$ vertex local on scale $R_{\text{nucl}} \sim 1 \text{ fm}$.
 Normalization fixed by $J/\psi \rightarrow gg\gamma$ decay.

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

Consistent with existing low-energy data.
 Could be tested with JLab 12 GeV



- Theoretical questions

Matching collinear \leftrightarrow short-distance expansion?

Quantum numbers of gluonic operator?

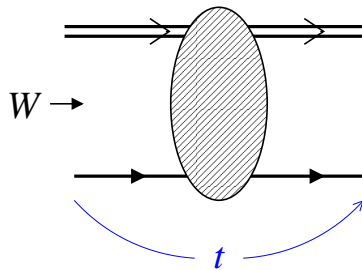
Behavior of two-gluon form factor?

Correlated configurations in nucleon LCWF?

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

“Gluonic form factor” of nucleon!

Near-threshold: Nuclei and ψN interaction



- Kinematics of ψN scattering

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

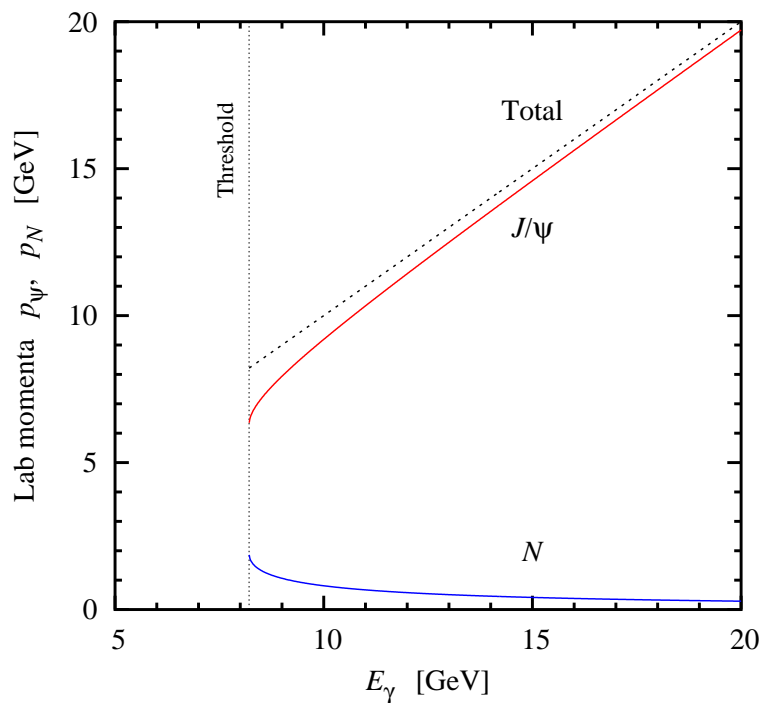
“Ideal process” for probing color fields in hadrons and nuclei!

- Physics of low-energy 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 $\gamma A \rightarrow J/\psi + X$

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

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