Hard exclusive meson production: Space–time picture and QCD factorization

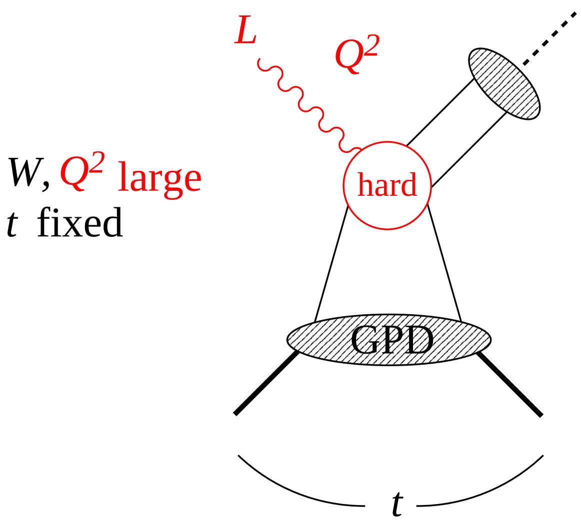
Ch. Weiss [with M. Strikman], Exclusive Reactions, JLab, May 21–24, 2007

Space–time evolution of hard processes in target rest frame

- QCD factorization $\leftrightarrow$ Color Transparency
- Physical picture of "higher twist"
- Model–independent tests of reaction mechanism
- Interesting! QM motion . . .

$$\boxed{\text{Small } x} \Big\downarrow \boxed{\text{Large } x}$$

QCD factorization [Collins, Frankfurt, Strikman 96; . . .]



$J/\psi, \phi$	G
ρ^0	$G, u+d$
$\rho^\pm$	u, d
K^*	u, d, s
π, η	$\Delta u, \Delta d$
K	$\Delta u, \Delta s$

- Qualitative implications of factorization:

  GPDs universal, process–independent

  t–dependence only from GPD,
  no change with Q^2

  Dominance of L polarization
  $\sigma_L \gg \sigma_T,\ \sigma_{LT},\ \sigma_{LT'}, \ldots$

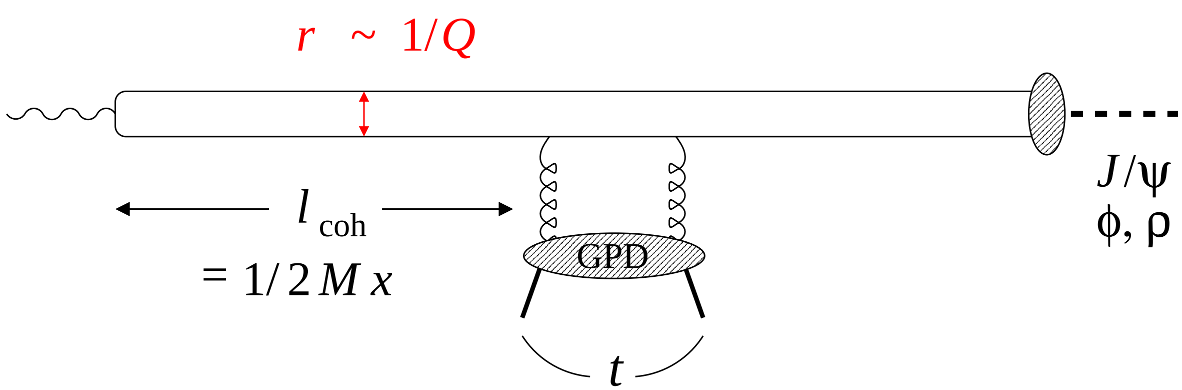
- Quantitative questions:

  "When" does it start to work?

  How include subasymptotic effects?

Space–time picture: Small x

[Brodsky et al 94;
Frankfurt, Radyushkin, Strikman 96]



- Scattering of small–size $q\bar{q}$ pair from nucleon

- $q\bar{q}$–nucleon scattering amplitude in leading–log approximation

$$A^{q\bar{q}}(r) \quad = \quad r^2 \, \alpha_s \, x \, G(x, t; \; Q^2_{\text{eff}})$$

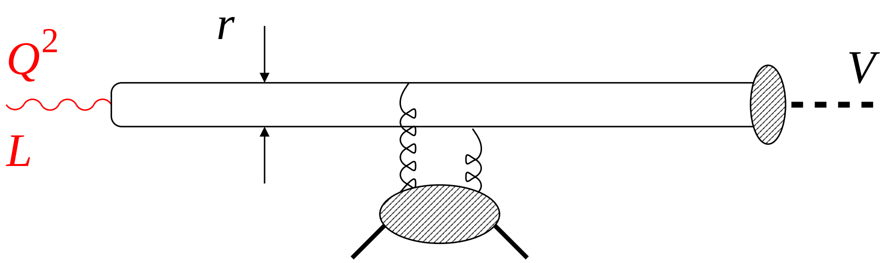
$$\text{Scale} \;\; Q^2_{\text{eff}} \; \propto r^{-2}$$

QCD factorization $\longleftrightarrow$ Color transparency

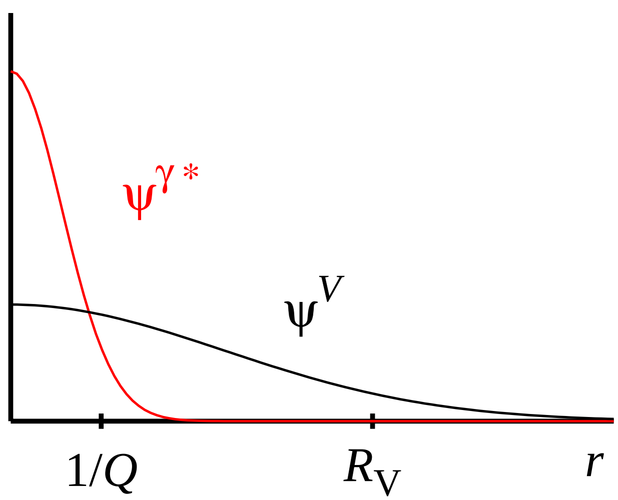
Gluon GPD $\longleftrightarrow$ Color dipole moment of nucleon

Small and large–size configurations

[Frankfurt, Koepf, Strikman 96]



$$\text{Amp} = \int d^2r\ \psi^{\gamma*}(r, Q^2)\ A^{q\bar{q}}(r)\ \psi^V(r)$$



- Broad distribution of transverse $\bar{q}q$ sizes

$$\begin{array}{lll} r \sim & 1/Q & \text{“small”} \\ & R_V & \text{“large”} \end{array}$$

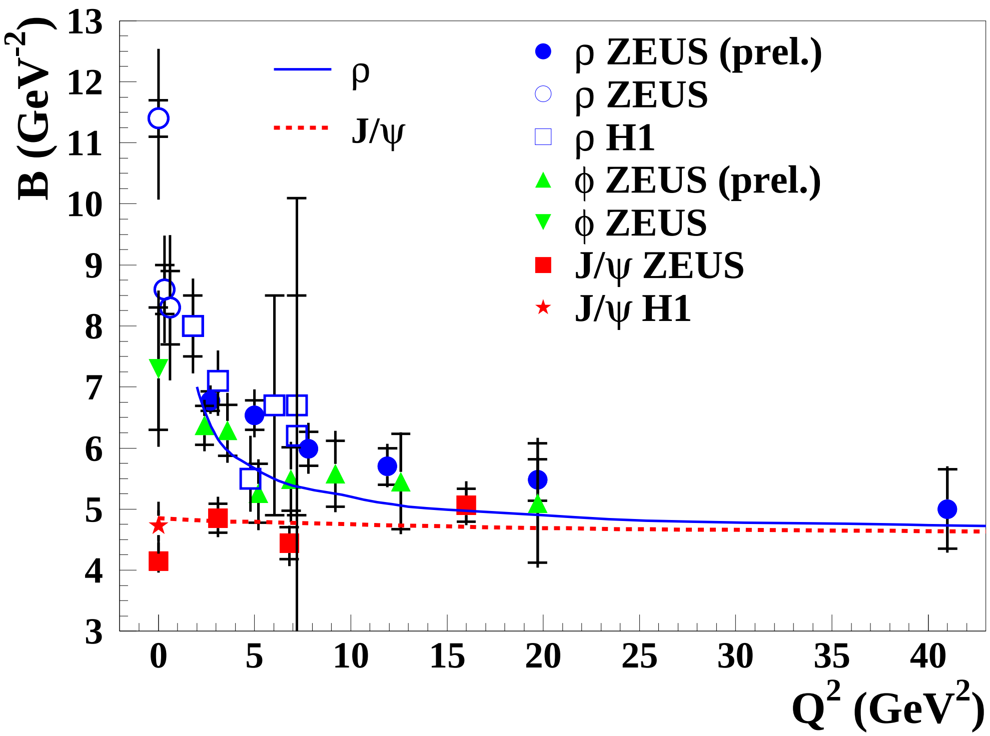
- Large Q^2 required for dominance of small sizes

$$\begin{array}{llll} <r> = & 0.4 \text{ fm} & Q^2 = & 2 \text{ GeV}^2 \\ & 0.25 & & 20 \end{array}$$

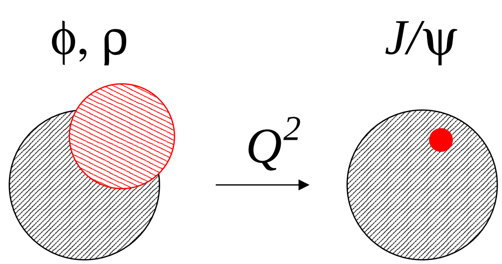
- Duality: Smooth matching of cross sections

$$\begin{array}{lcl} \text{large–size} & \longleftrightarrow & \text{hadronic} \\ \bar{q}q \text{ pairs} & & \rho N \end{array}$$

Small vs. large sizes: Experimental tests



transverse view



[Levy 05; Frankfurt, Strikman, CW 05]

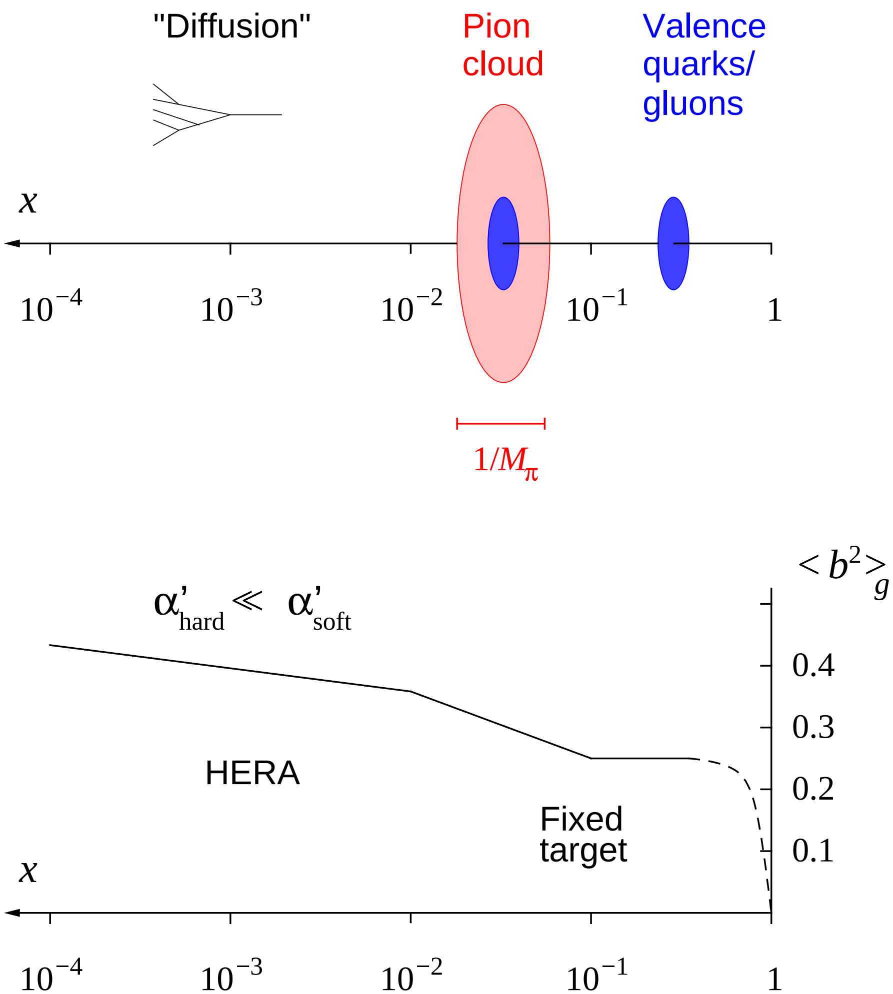
- t–slope measures transverse size of interaction region

  $2\,B \;\approx\; \langle r^2 \rangle_{\mathsf{probe}} + \langle b^2 \rangle_{\mathsf{GPD}}$

- Convergence of t–slopes at large $Q^2 \longrightarrow$ dominance of small–size $q\bar{q}$ configurations

- Other tests (specific to small–x / gluon GPD)
  - x–depend. changes w. Q^2
  - Flavor relations $\rho : \phi : J/\psi$

Transverse gluon imaging of proton



(Scale $Q^2 \approx 3\,\mathrm{GeV}^2$)

- Gluonic transverse size directly from J/ψ t–slope:

$$\langle b^2 \rangle_g = B/2$$

- Increases with decreasing x: Various mechanisms [Frankfurt, Strikman, CW 03/05]

- Detailed gluon imaging (t–profile of GPD, x–dep.) possible with EIC

“Lessons” from small–x space–time picture

- Model–independent tests of size distribution through Q^2–dependence of t–slopes

- Significant large–size contributions (higher twist) in ρ, ϕ production up to $Q^2 \approx 10$ GeV^2

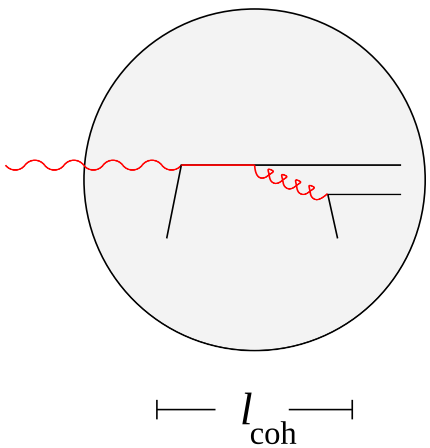
- Good description of absolute cross section & dependences in LO space–time picture with effective scale $Q^2_{\text{eff}} \sim r^{-2} < Q^2$

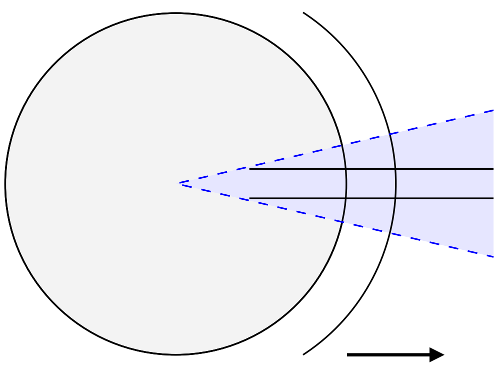
  choice of scale $\longleftrightarrow$ modeling of GPD $\longleftrightarrow$ higher twist . . . related!

- Theory challenge: NLO extension of correspondence QCD factorization $\longleftrightarrow$ space–time picture

  $\rightarrow$ Stability of NLO calculations [Belitsky, Müller 01; Ivanov et al. 04, Diehl et al. (in progress)]

Space–time picture: Large x





- Coherence length

  $l_{\text{coh}} = 1/2Mx \sim R_N.$

  Hard process happens "inside" target

- Identify two "stages"

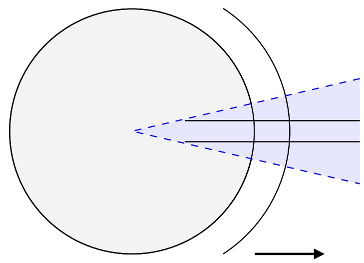
  I) Production of small–size $q\bar{q}$ pair

  II) Formation of final–state meson

- $\xi, t_{\text{min}} \neq 0$: Cannot neglect longitudinal recoil of target

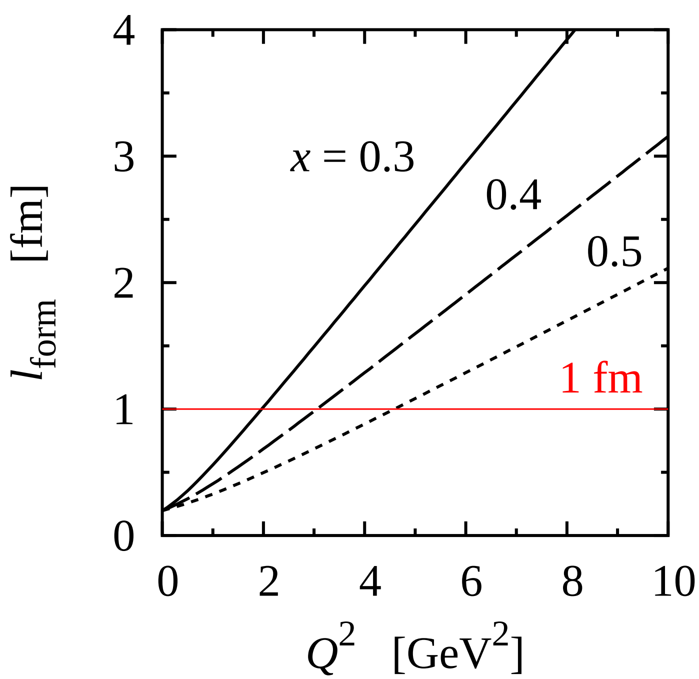
Formation of final–state meson

[Strikman, CW, in progress]



- Meson momentum in rest frame of recoiling nucleon

$$p_M \;=\; \frac{(1-x)\,Q^2}{2Mx}$$ decreases as $x \to 1$



π production

- Formation length of final–state meson

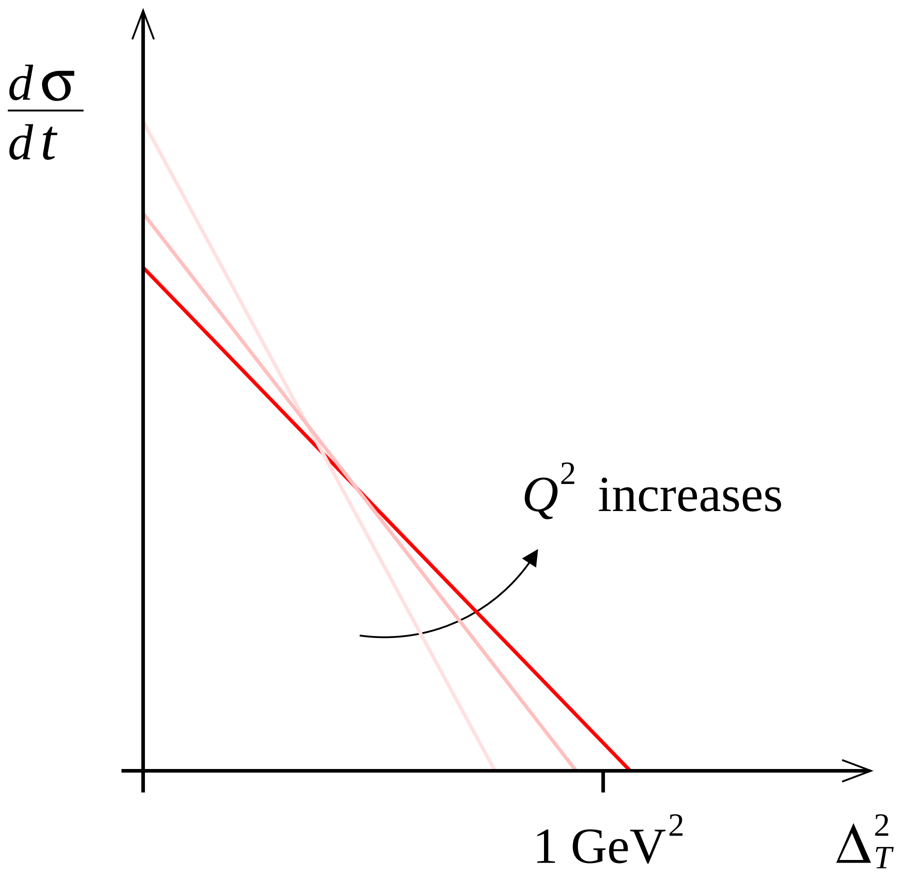
$$l_{\rm form}^{-1} \;\sim\; \sqrt{m_{\rm exc}^2 + p_M^2} - \sqrt{m_{\rm gnd}^2 + p_M^2}$$

Decoherence ground/excited state

- Factorization requires $l_{\rm form} \gg R_N$: Minimum Q^2 increases with x!

$\boxed{\text{“New” source of corrections at large } x}$

Experimental test: t–slope



- Δ_T^2–slope measures transverse size of interacting system

- Approach to factorization: Expect slope to decrease and stabilize with increasing Q^2

- Conversion of slopes

$$t - t_{\text{min}} \ = \ \frac{\Delta_T^2}{1 - \xi^2}$$

$$\xi = \text{function}(x, Q^2, \text{masses})$$

"Independent measure" of size of interacting configurations!

Summary

- Space–time picture in target rest frame helpful for quantifying approach to factorization regime

- t/Δ_T^2–slopes measure transverse size of interacting configurations

- New source of corrections at large x:
  $l_{\text{form}} \propto 1 - x$, meson "cannot escape"

- Need framework/models which consistently combine small– and large–size configurations:

$$\begin{array}{lcl} 1/Q & \longleftrightarrow & \text{GPDs + hard process} \\ R_{\text{had}} & \longleftrightarrow & \text{hadronic interactions} \end{array}$$