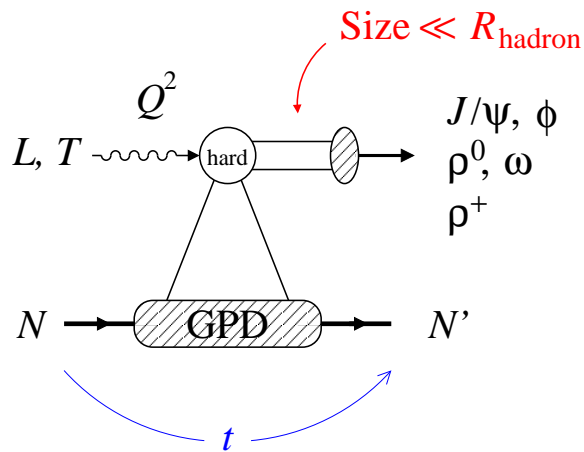


# Mechanism of vector meson production at low $W$

C. Weiss (JLab), INT Workshop "Orbital angular momentum," Seattle, 14-Feb-12



Phenomenological approach based on parton picture

Contains asymptotic pQCD mechanism but more general:  
finite-size/higher-twist effects  
non-perturbative interactions

Suggests experimental tests of reaction mechanism

- Small-size configurations

Example: Pion form factor

Model-independent analysis

Dynamical origin: pQCD interactions, QCD vacuum structure

- Vector meson production at high  $W$  ( $\gtrsim 5$  GeV)

Tests of approach to small-size regime:  
 $t$ -slopes,  $Q^2$ ,  $W$ -dependence,  $\phi/\rho^0$  ratio  
HERA, HERMES, COMPASS, EIC

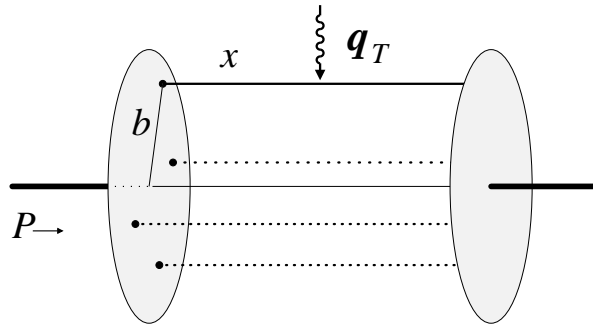
- Vector meson production at low  $W$

Existing data: Kinematic dependences, comparison of channels  
Cornell, JLab 6 GeV

Speculation:  $q\bar{q}$  pair knockout in  $\rho^0$

Experimental tests  
JLab 12 GeV

# Small-size configurations: Elastic form factors



- Parton picture  $P \rightarrow \infty$ ,  $\mathbf{q}_T$  transverse

Current cannot produce pairs

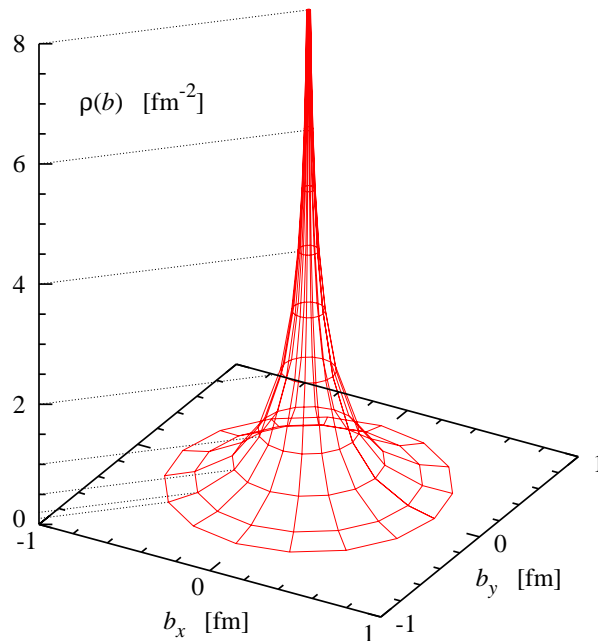
Wave function overlap representation

$$F(q^2) = \sum_n \int dx d^2k_T \psi_n^*(x, k_{T1}, \dots) \psi_n(x, k_{T2}, \dots)$$

Configurations with different particle number and transverse size

Expect that large  $|\mathbf{q}_T|$  “select” small sizes

How to quantify it?



- Transverse density Soper 76, Miller 07

$$F(q^2) = \int d^2b e^{i\mathbf{q}_T \cdot \mathbf{b}} \rho(b) \quad \text{2D Fourier}$$

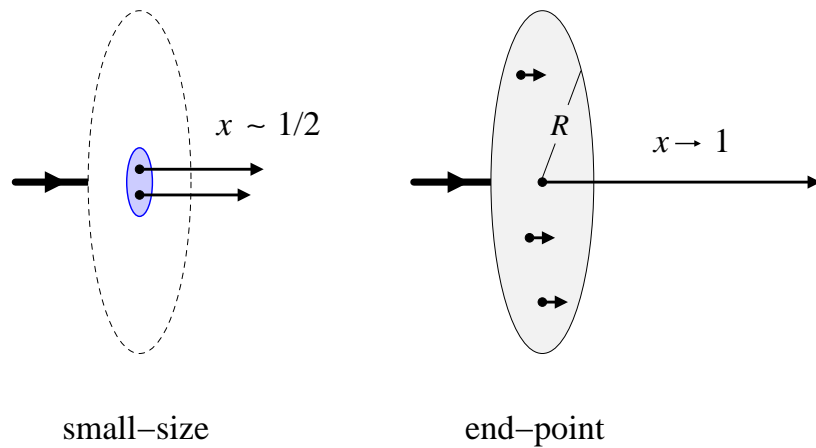
Cumulative charge/current of constituents at transverse position  $\mathbf{b}$

- Empirical charge density in pion

Dispersion integral over timelike FF  $e^+e^-$  data

High density at  $b \rightarrow 0$ : Small-size configurations?

# Small-size configurations: Pion



- Two sources of small- $b$  density

$x \sim 1/2$	size $\ll R$	small-size	mostly $q\bar{q}$
$x \rightarrow 1$	size $\sim R$	end-point	multiparticle, soft gluons

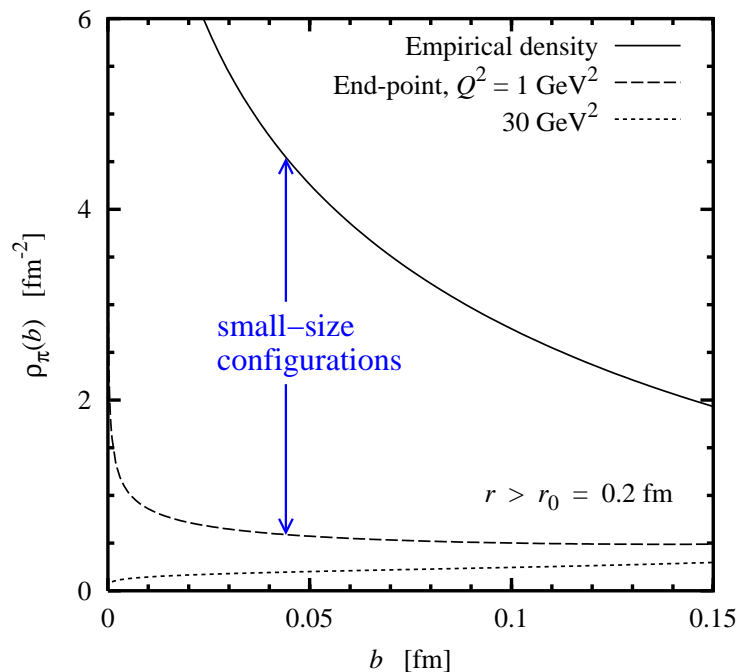
Dynamical question!

- Density in center of pion mostly from small-size configurations

End-point contribution constrained by quark density in pion at  $x \rightarrow 1$

Miller, Strikman, CW 10.  $\pi A$  Drell-Yan data.

Soft-gluon resummation  $\rightarrow$  Talk Vogelsang

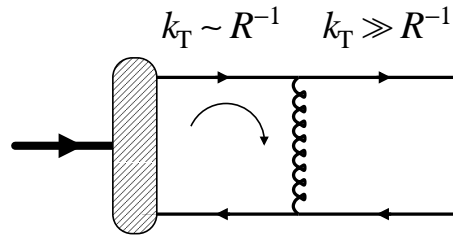


- Alt. picture: Rest frame

Photon reverses quark in pair with momenta back-to-back along reaction axis

Model-independent statement on small-size configurations!

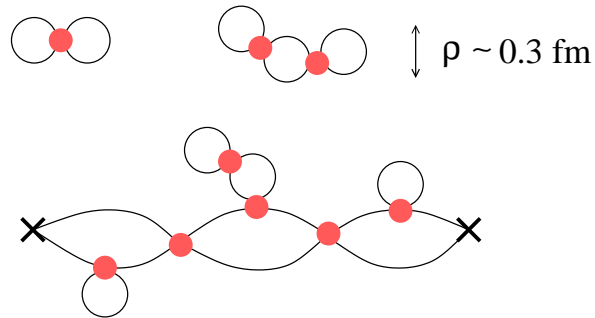
# Small-size configurations: Dynamical origin



- Perturbative interactions

High-momentum component of wave function  
 $k_T \sim R^{-1}$  wave function as source,  $\int d^2 k_T$

Responsible for leading  $Q^2 \rightarrow \infty$  asymptotics  
of pion FF [Efremov, Radyushkin 77+](#); [Brodsky Lepage 80](#)



- QCD vacuum structure

Strong non-perturbative gluon fields  
of size  $\rho \sim 0.2-0.3 \text{ fm}$

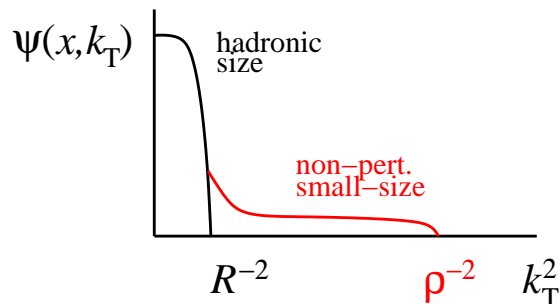
Objective measure: Average quark virtuality  
 $\langle \bar{\psi} \nabla^2 \psi \rangle / \langle \bar{\psi} \psi \rangle > (0.7 \text{ GeV})^2$

Lattice: [Teper 87](#), [Doi 02](#), [Chiu 03](#)

Non-perturbative semi-hard component of WF

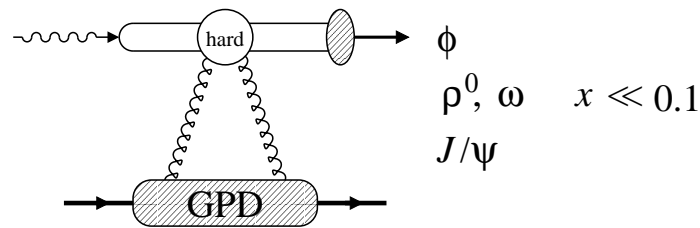
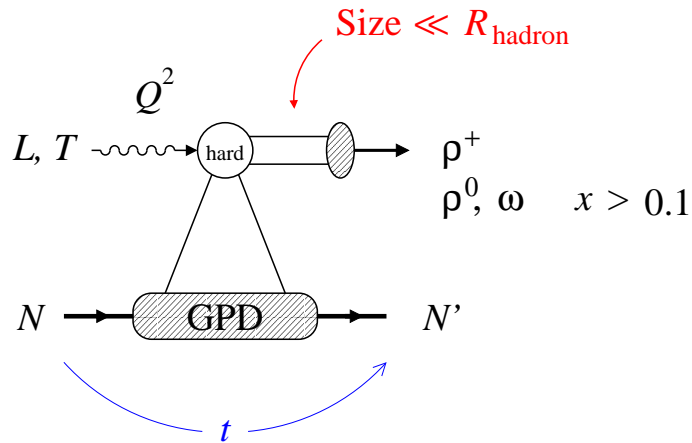
Cf. [short-range correlations in nuclei](#)

Chiral anomaly?  $\gamma^* \gamma \rightarrow \pi^0$  puzzle



Evidence for non-perturbative  
small-size configurations!

# Exclusive meson production: High $Q^2$



Pseudoscalars  $\pi, \eta$ : Quark helicity/transversity structure

→ Talks Kroll, Liuti

- Meson produced in small-size configuration

$Q^2 \rightarrow \infty$ :  $q\bar{q}$  pointlike, pQCD interactions  
QCD factorization for  $\sigma_L$ : Collins, Frankfurt, Strikman 96

$Q^2 \sim \text{few GeV}^2$ :  $q\bar{q}$  has small size, but non-perturbative interactions possible

Recent progress: Sudakov suppression. Goloskokov, Kroll 08/10

Nucleon structure in GPDs: Quark/gluon form factors, universal, process-independent

↔ DVCS, other processes, lattice QCD

- Meson selects flavor/spin component

$\phi, J/\psi$	gluons
$\rho^+$	quarks $u - d$
$\rho^0, \omega$	quarks $2u \pm d$ + gluons

- Two-stage analysis

Verify approach to small-size regime:

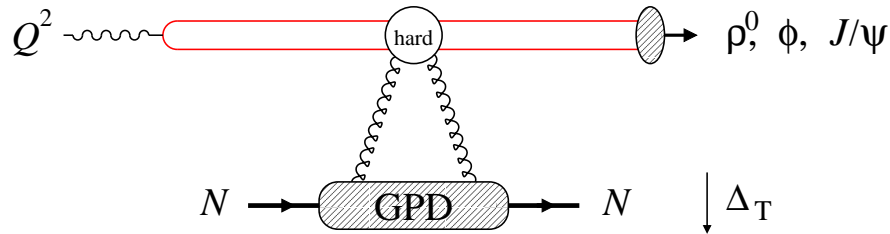
Kinematic dependences, comparison of channels

Quantitative questions: Effective sizes? Dominant amplitudes?

Extract nucleon structure information:

Transverse parton distributions,  $q\bar{q}$  correlations, . . .

# High $W$ : Approach to small-size regime I



- Simplifications at high  $W$

Gluon exchange dominant in  $\rho^0$ , similar to  $\phi, J/\psi$

Coherence length  $\gg 1$  fm:  
Dipole picture in nucleon rest frame

$\text{Im } A \gg \text{Re } A$ : DGLAP region of GPD

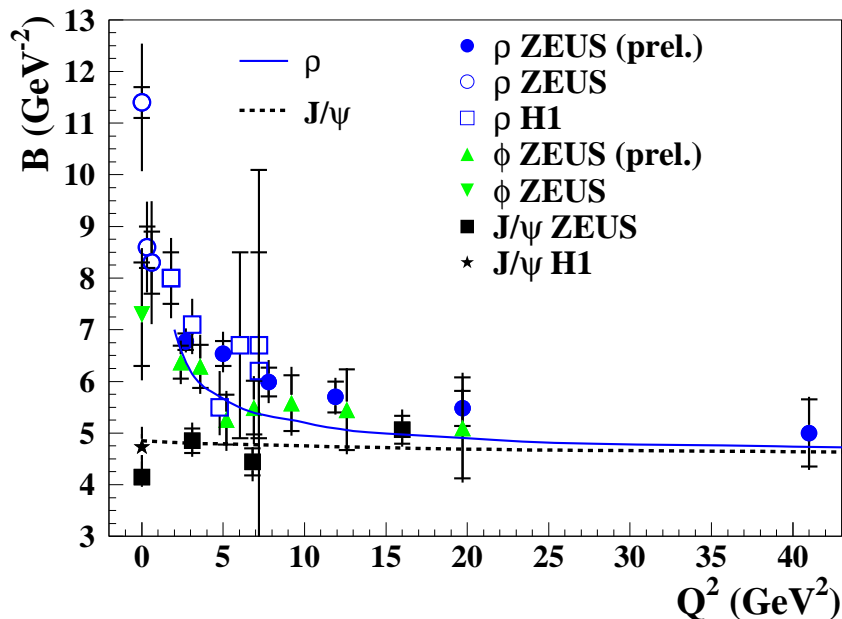
Test approach to small-size regime!

- Universality of  $t$ -slopes at high  $Q^2$

$\Delta_T^2$  slope measures transverse size of interaction region = size of target and meson configurations

Decreases at large  $Q^2$ , becomes universal:  
Approach to small-size regime  
Contradicts Regge factorization!

Seen in HERA data!



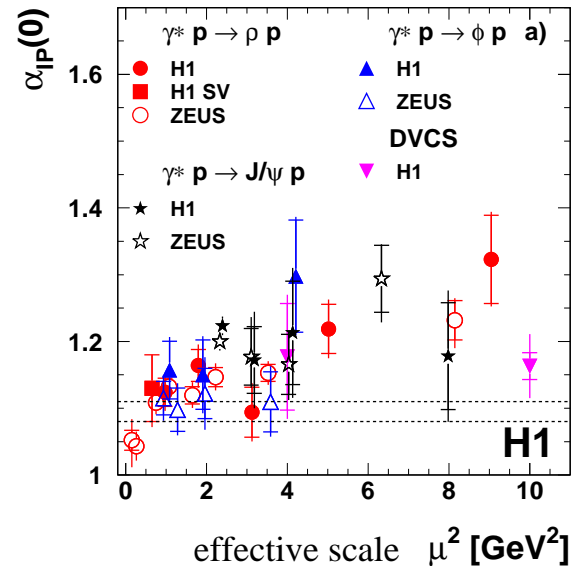
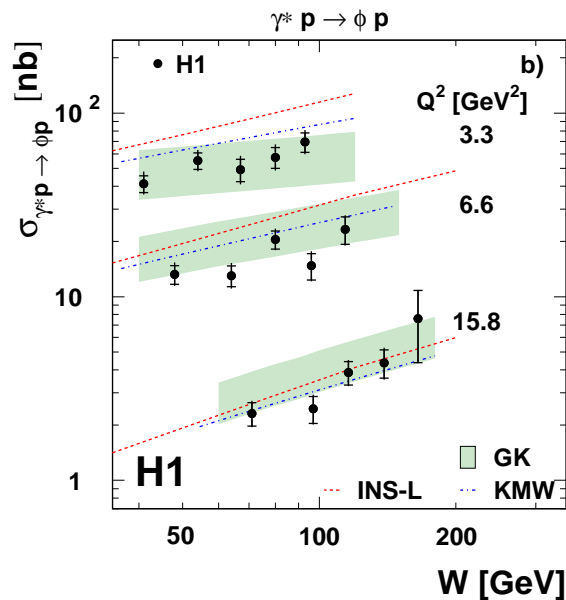
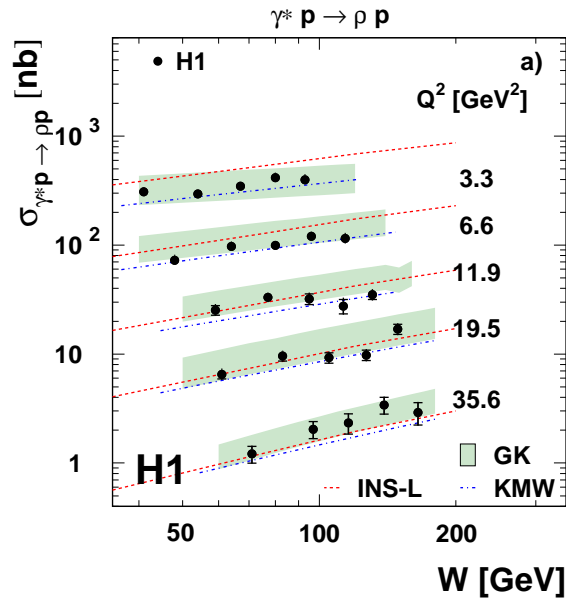
# High $W$ : Approach to small-size regime II

- Hardening of  $W$ -dependence with  $Q^2$

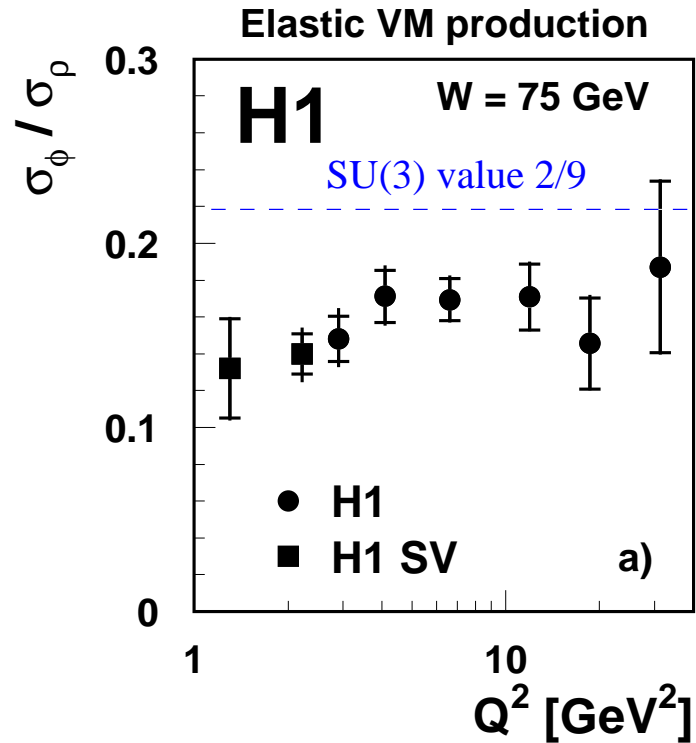
$W$ -dependence becomes steeper with increasing  $Q^2$

Rate of growth reveals effective scale in gluon GPD  $Q_{\text{eff}}^2 \approx \pi^2 / \langle r_{q\bar{q}}^2 \rangle \ll Q^2$

Contradicts Regge factorization  
"Effective" trajectory



# High $W$ : Approach to small-size regime III



- Ratio  $\phi/\rho^0$  constant at high  $Q^2$

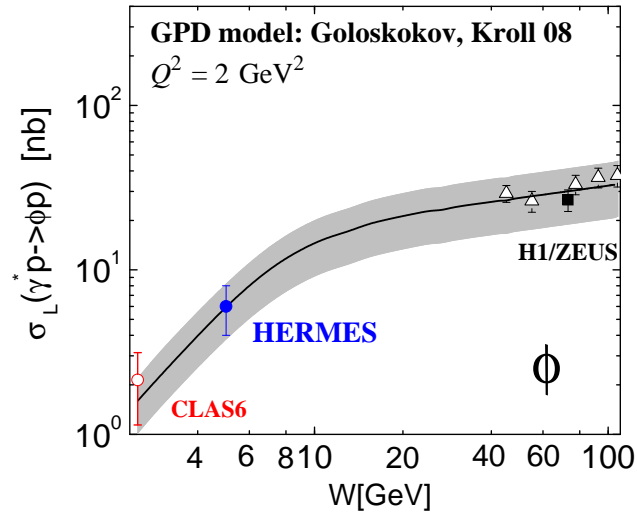
Same spatial size of configurations,  
only difference in quark charges

Consistent with  $SU(3)$  value 2/9



# Low $W$ : Reaction mechanism

- Mechanism of hard exclusive vector meson production more complex at low  $W$



Quark exchange important in  $\rho^0, \omega$ ; cf.  $\rho^+, K^*$

Re/Im could be large: ERBL region of GPDs?

Large skewness  $\xi$ : GPDs not simply related to forward limit

Potentially quark helicity-flip amplitudes, SCHC violation

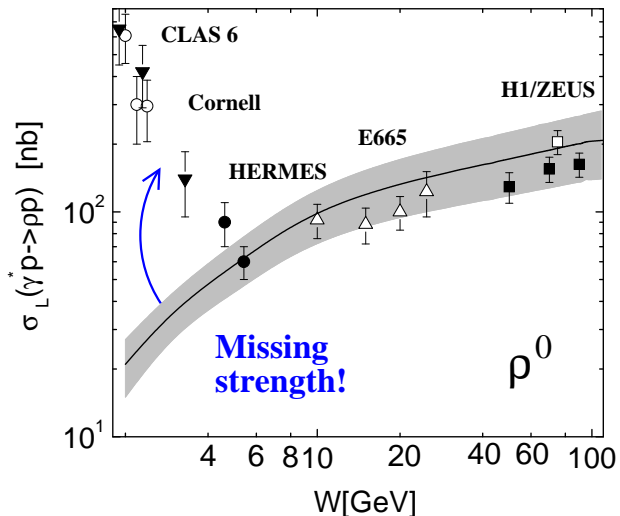
- Present GPD models challenged

$\phi$  overall well described with gluon GPD

Hints of non-uniform  $W$  dependence near threshold.

Other exchange mechanism?  $s$ -channel hyperon resonances?

Missing strength in  $\rho^0$  — origin?



- Need experimental information

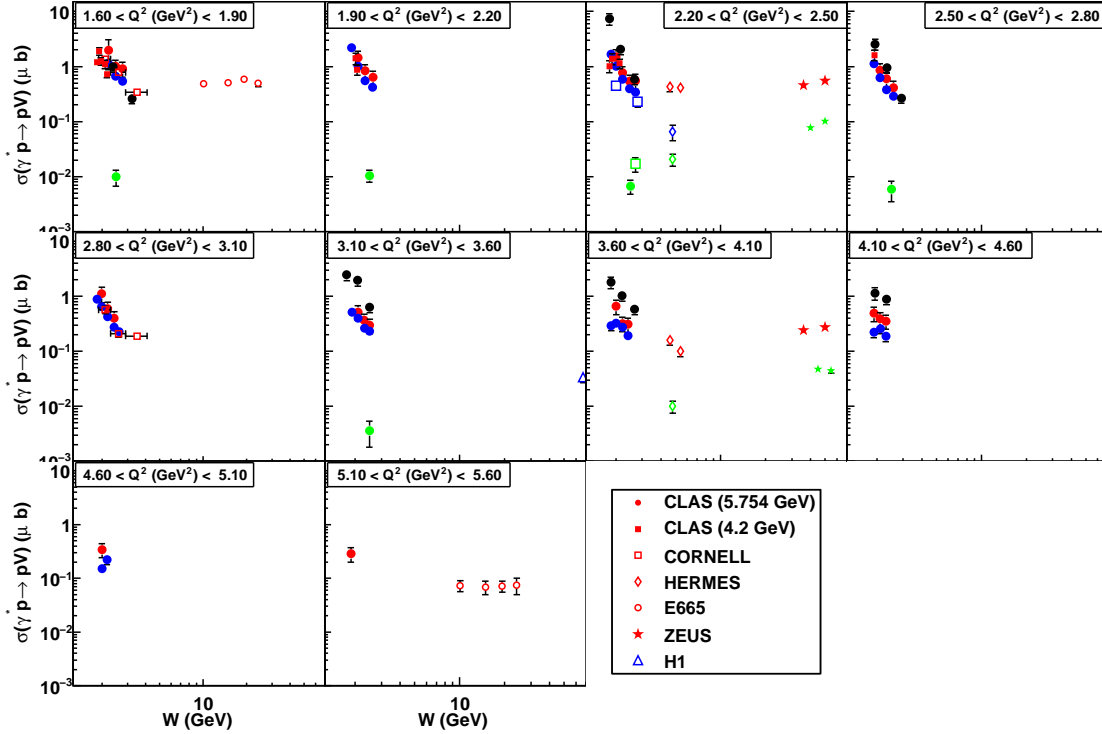
JLab 6 and 12 GeV

Approach to small-size regime?

Type of exchanges/GPDs?

Essential to reduce complexity!

# Low $W$ : Quark vs. gluon exchange



CLAS 09 Fradi et al. **Black**  $\rho^+$ , **Red**  $\rho^0$  **Blue**  $\omega$  **Green**  $\phi$

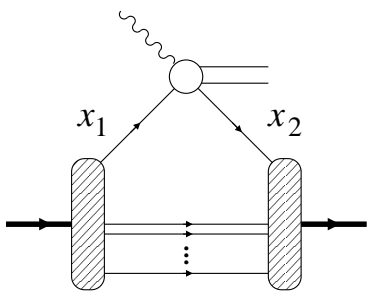
- Comparison  $\rho^+ \leftrightarrow \rho^0 \leftrightarrow \phi$   
 $\rho^0$  comparable to  $\rho^+$ :  
 Quark exchange!  
 Ratios consistent with  $u$ -quark dominance  $\rho^0 : \omega : \rho^+ \sim 1 : 1 : 2$

- Scattering from valence quark or knockout of  $q\bar{q}$  pair?

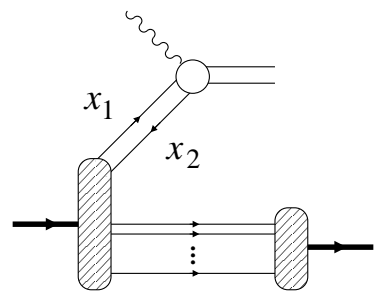
GPDs contain both DGLAP and ERBL regions

$\sigma \sim W^{-4}$  at  $W < 4$  GeV  
 Cf. spin-0 meson exchange in soft regime

Hard regime: Knockout of spin-0  $q\bar{q}$  pair?  
 Guidal, Morrow: Modified D-term in GPD



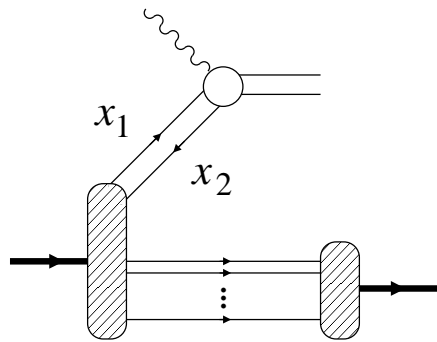
Scattering from quark



Knockout of  $q\bar{q}$  pair

# Low $W$ : $q\bar{q}$ knockout in $\rho$

- Speculation:  $\rho^0$  and  $\rho^+$  at  $W < 4 \text{ GeV}$  dominated by  $q\bar{q}$  knockout



Chiral symmetry breaking produces correlated small-size spin-0  $q\bar{q}$  pairs in nucleon

Light-cone formulation: Schweitzer, Strikman, CW; in progress

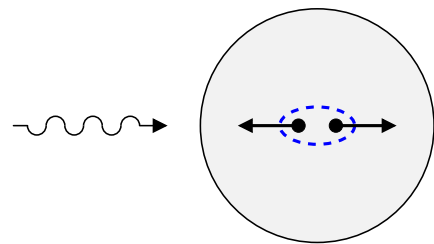
Measured  $\rho^+/\rho^0$  ratio consistent with exchange of  $q\bar{q}$  with pion quantum numbers

Isospin symmetry and  $\rho \rightarrow \gamma\pi$  decay widths

$\rho$  production may involve chirally odd GPDs and distribution amplitudes

Cf. pseudoscalar production  $\rightarrow$  Talks Kroll, Liuti

Challenge to implement quantitative model



- Rest frame picture: Reversal of quark in pair aligned along reaction axis

Analogy with short-range  $NN$  correlations in nuclei

Allows for modeling of non-perturbative interactions

# Low $W$ : Approach to small-size regime

- $Q^2$ -dependence of  $t$ -slopes

$t_{\min}$  large, varies with  $Q^2$

If actual  $t$ -dependence of amplitude is non-exponential, changing  $t_{\min}$  will change effective slope in  $t - t_{\min}$

Need to separate kinematic decrease of slope from actual “squeezing” of  $q\bar{q}$  configurations

- Extensive tests with JLab 12 GeV

$L/T$  ratio from SCHC,  $\phi$ -dependent response functions

Change of  $W$ -dependence with  $t$ : Higher  $|t|$  enhances scattering from valence quarks, suppresses  $q\bar{q}$  knockout

# Summary

- Small-size configurations key concept in phenomenology of hard exclusive processes

More primary than specific interaction models

Encompasses non-perturbative interactions, e.g. chiral symmetry-breaking forces in QCD vacuum

Substantial probability of SSC's in pion from model-independent analysis

Can be probed in other experiments: Nuclear transparency,  $\pi + A \rightarrow 2 \text{ jets}$

- Mechanism of exclusive vector meson production well understood at high  $W$

Model-independent tests of approach to small-size regime

Successful phenomenology based on gluon GPDs

- Challenge to understand reaction mechanism at low  $W$

$\phi$  mostly from gluons — needs closer look near threshold

$\rho^0, \rho^+$  possibly dominated by  $q\bar{q}$  knockout — needs to be quantified

Experimental data essential for deciding between possible scenarios