

# Hard exclusive meson production with 12 GeV: Theory Overview

C. Weiss (JLab), Hall C Summer Workshop, 19–Aug–2011

$\gamma^* N \rightarrow M + B$		
$W$	$\sim$	$2 - 4 \text{ GeV}$
$Q^2$	$\lesssim$	$10 \text{ GeV}^2$
$ t - t_{\min} $	$\lesssim$	$1 \text{ GeV}^2$ low
		$10 \text{ GeV}^2$ high

## Unifying framework

Small-size  $q\bar{q}$  configurations

Generalized parton distributions

Address specific questions  
in nucleon/meson structure

- **Vector mesons** [PR12-11-103, LOI-10-002](#)
  - $\phi$  Transverse gluon imaging of nucleon
  - $\rho^0, \rho^+, \omega$  Quark–antiquark correlations
- **Pseudoscalar mesons** [E12-07-105, E12-06-101, E12-06-108](#)
  - $\pi^+$  Pion FF
  - $\pi^0, \eta$  Transversity GPDs
- **Strange mesons** [E12-09-011, LOI12-07-101](#)
  - $K\Lambda, K\Sigma$  Flavor structure of GPDs
  - $K^*\vec{\Lambda}$  Helicity structure w. recoil pol.
- **High- $t$  and backward region** [PR12-11-103](#)
  - Small-size  $qqq$  configurations, transition distribution amplitudes

# Exclusive meson production: High $Q^2$

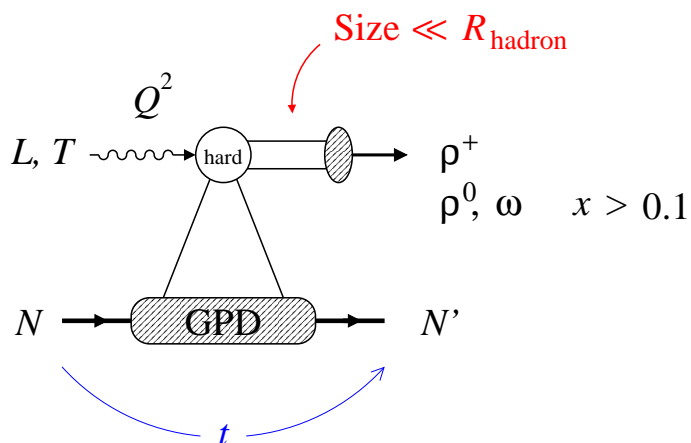
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- Meson produced in small-size configuration

$Q^2 \rightarrow \infty$ :  $q\bar{q}$  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  
 $\leftrightarrow$  DVCS, other processes, lattice QCD



- Select specific flavor/spin components

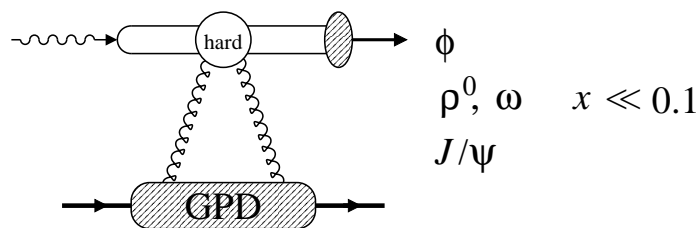
$\phi, J/\psi$	gluons
$\rho^+$	quarks $u - d$
$\rho^0, \omega$	quarks $2u \pm d$ + gluons

Pseudoscalars: Quark helicity structure

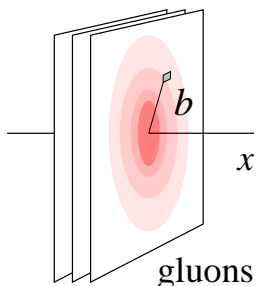
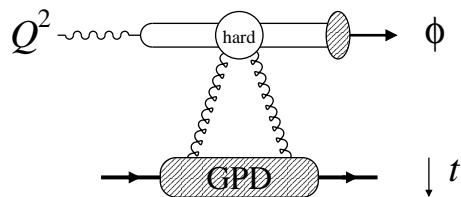
- Two-stage analysis

Verify approach to small-size regime: Kinematic dependences, comparison of channels, nuclear transparency  
 Quantitative questions: What are the effective sizes?

Extract nucleon structure information:  
 Transverse parton distributions,  $q\bar{q}$  correlations, . . .



# Exclusive $\phi$ : Gluon imaging of nucleon

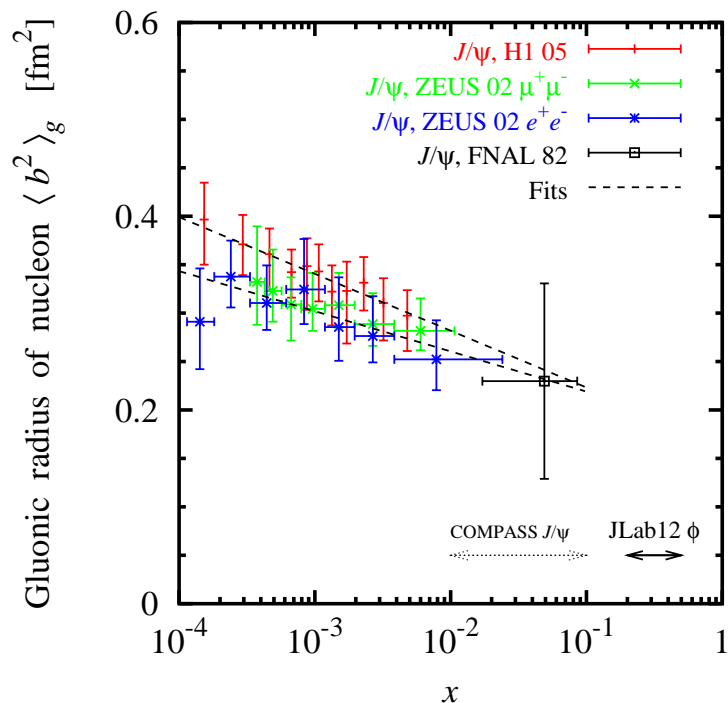


- Exclusive  $\phi$  as clean probe of gluon GPD

Small-size  $q\bar{q}$  pairs dominate at  $Q^2 \sim 10 \text{ GeV}^2$   
 $t$ -slope becomes  $Q^2$ -independent, universal  
 HERA H1/ZEUS 02+

Gluon GPD model describes cross section data from JLab 6 GeV to HERA  
 Goloskokov, Kroll 08; Frankfurt et al. 95

$L/T$  ratio from vector meson decay and  $s$ -channel helicity conservation



- Transverse spatial distribution of gluons in nucleon

Fundamental leading-twist characteristic  
 Cf. charge radii. Needed for jets in  $pp$ @LHC

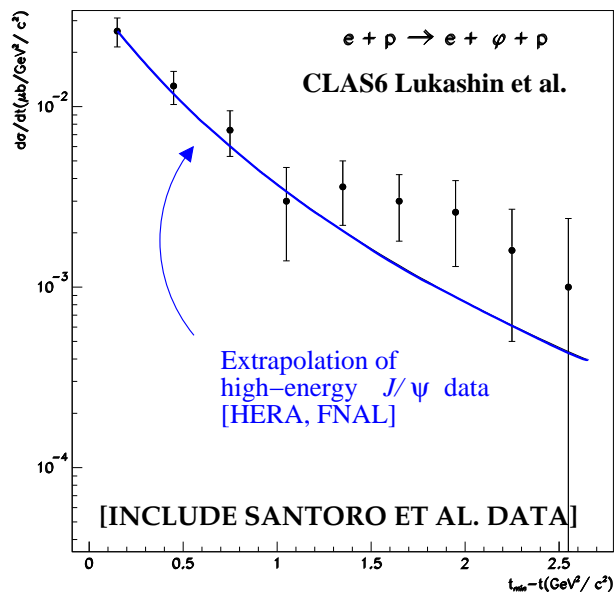
Changes with  $x$ : Non-perturbative dynamics

$x < 0.01$  measured: HERA H1/ZEUS

$x > 0.1$  practically unknown:  $\phi$  with JLab12

DIS: Lots of gluons above  $x > 0.1$ , carry  $\sim 30\%$  of nucleon's momentum

# Exclusive $\phi$ : JLab12



- $t$ -dependence of 6 GeV  $\phi$  data consistent with gluonic radius measured at high energies  
Extrapolation of HERA, FNAL  $J/\psi$  results

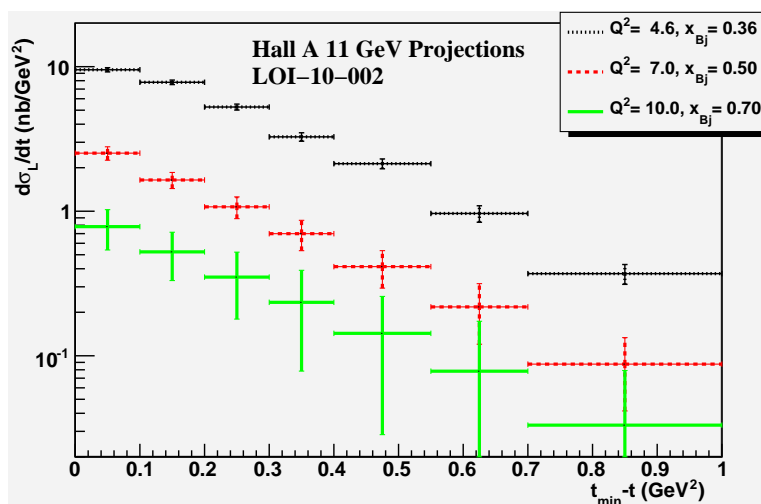
- JLab12: Test reaction mechanism and harden GPD-based description  
CLAS12 PR12-11-103: Wide kinematic coverage  $\rightarrow$  Talk Stoler

When does  $t$ -slope become independent of  $Q^2$ ?

How does  $W$ -dependence change with  $Q^2$ ?

- JLab12: Extract  $t$ -dependence of gluon GPD at  $x = 0.2 - 0.5$   
Hall A LOI-10-002, CLAS12 PR12-11-103  $\rightarrow$  Stoler

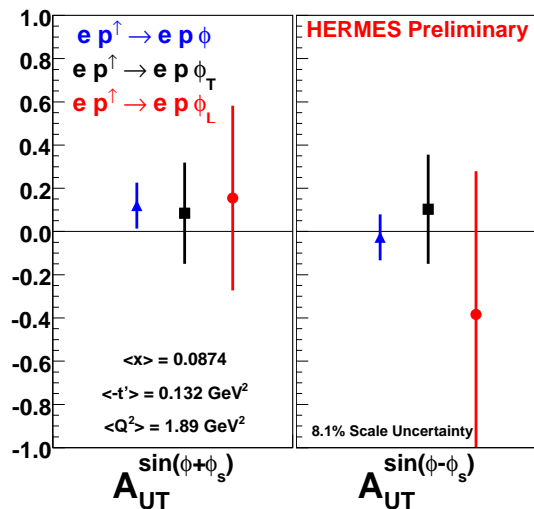
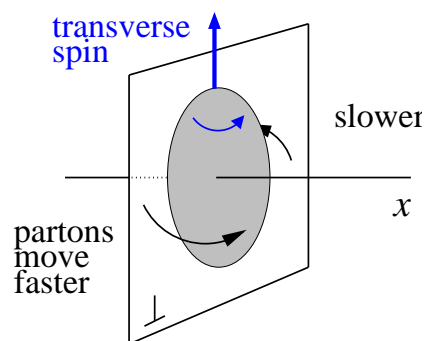
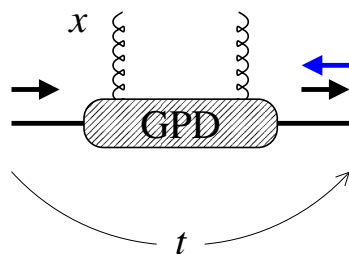
Obtained from relative  $t$ -dependence of  $d\sigma_L/dt$



First accurate gluonic image of nucleon at large  $x$ !

# Exclusive $\phi$ : Gluonic Pauli form factor

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- Helicity–flip gluon GPD: Gluonic Pauli FF

Distortion of gluons' spatial distribution by transverse spin of nucleon Burkardt 03

Reveal coupling of non-perturbative gluon fields to valence quarks

- Exclusive  $\phi$  transverse target asymmetry  $A_{UT}$

Constrains ratio  $E_g/H_g = \text{Pauli/Dirac GPD}$

HERMES 08 data, large errors see e.g. Gliske, Lorenzon 08

Accurate measurement with JLab 12 Hall A?

- Gluon spin through Ji sum rule Ji 96

$$J_g = \int_0^1 dx x [H_g + E_g](x, \xi = 0, t = 0)$$

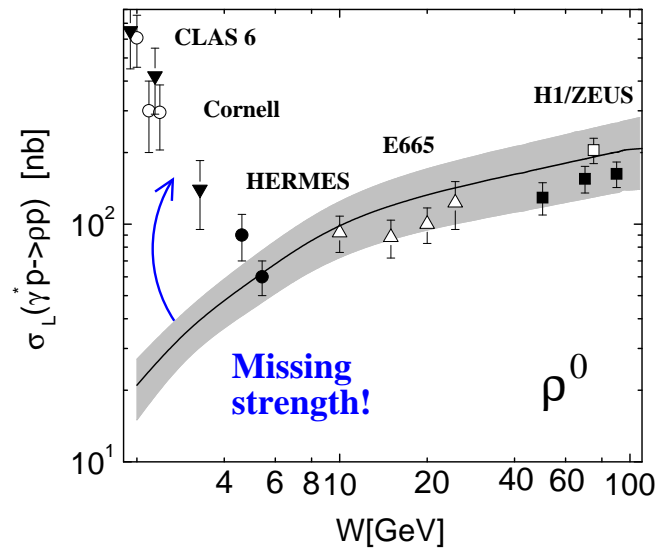
$E_g$  contribution expected to be small, but should be measured

Positivity bounds: Diehl et al. 04; Goloskokov, Kroll 08

“Next step” after establishing GPD description

# Exclusive $\rho^0, \rho^+, \omega$ : Quark–antiquark correlations

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- Exclusive  $\rho^0$  at  $W = 2 - 4$  GeV must come from quark GPDs

$\rho^+ > \rho^0$  consistent with  $u$ -quark dominance  
CLAS 6 Morrow et al. 08, Fradi et al. 10

Present quark GPD models fall short by an order of magnitude. . . missing strength!  
Goloskokov, Kroll 08; Vanderhaegen, Guichon, Guidal 99

- Correlated  $q\bar{q}$  pairs in nucleon?  
Guidal, Morrow 08

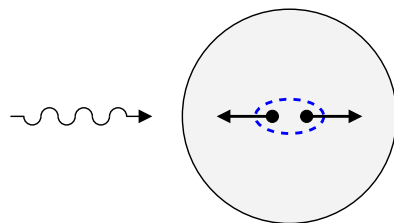
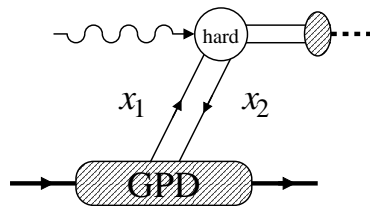
Supplied by non-perturbative QCD vacuum:  
Dynamical chiral symmetry breaking

Example:  $D$ -term in GPD  $H$   
Polyakov, CW 99. Seen in DVCS, lattice calculations

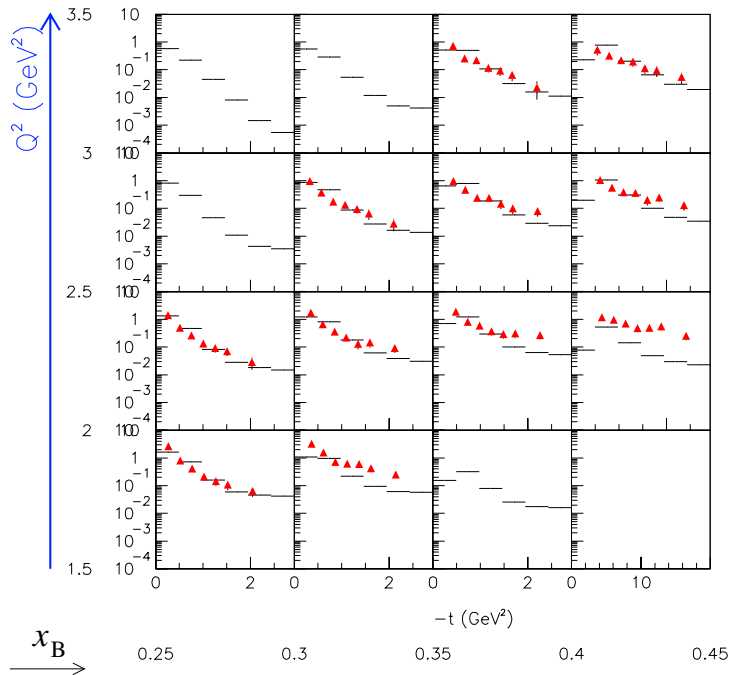
May be more general: Quark helicity flip,  
non-perturbative interactions

Transversity GPDs important in pseudoscalar production.  
Goloskokov, Kroll 11; Goldstein, Liuti 10

Rest frame: “Knockout” of  $q\bar{q}$  pair, analogy with short-range  $NN$  correlations in nuclei  
Strikman, CW; in progress



# Exclusive $\rho^0, \rho^+, \omega$ : JLab12



$d\sigma/dt$  ( $ep \rightarrow e'p\rho^0$ ) CLAS 12 projections CLAS 6 data

- Quantify approach to hard regime in  $u, d$ -quark meson production at  $W = 2 - 4$  GeV

How does  $W$ -dependence change with  $Q^2$ :  
Soft spin-0 exchange  $\rightarrow$  small-size  $q\bar{q}$  pair

Response functions:  $L$  vs.  $T$  amplitudes

Compare  $\rho^0$  and  $\rho^+$ :  
Flavor structure,  $\pi$  vs.  $\sigma$ -like pairs

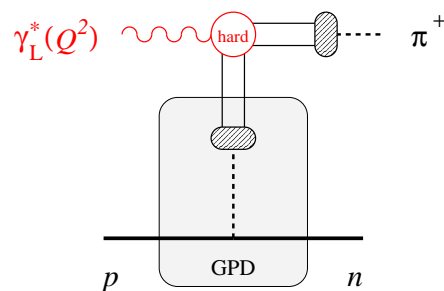
Compare vector and pseudoscalar:  
Chirality of  $q\bar{q}$  pair [E12-06-108](#)

- Explore role of correlated  $q\bar{q}$  pairs in nucleon GPDs

Next-generation quark GPD models:  
in progress

Short-distance manifestation of QCD vacuum structure!

# Exclusive $\pi^+$ : Pion form factor



- Pion pole in pseudoscalar GPD

Contributes mostly to  $L$  amplitude

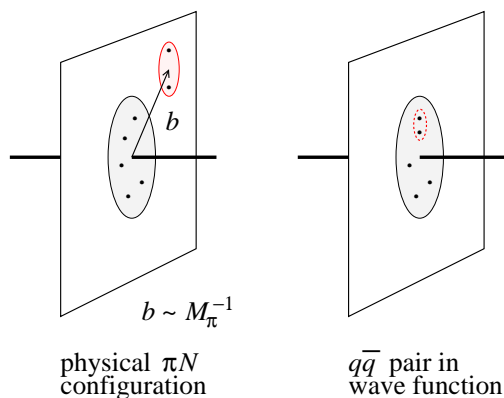
Challenge to separate pion pole from non-pole contributions

Models: Vanderhaeghen et al. 97+, Gallmeister, Mosel, Kaskulov 08+

Impact parameter picture: Peripheral vs. central  $q\bar{q}$  pairs in nucleon light-cone wave function

Partonic content of periphery: Strikman, CW 09

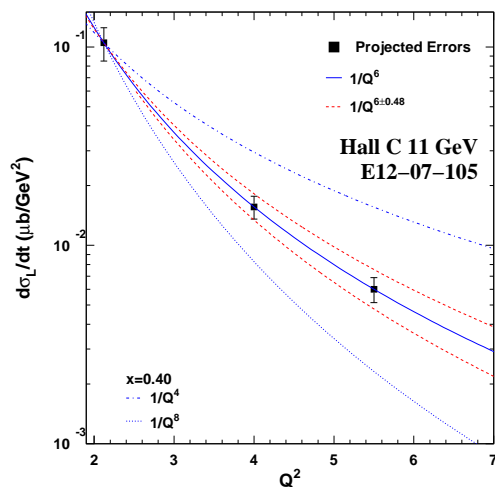
Need to develop model-independent approach!



- JLab12: Detailed studies of  $\pi^+$  production mechanism E12-07-105

$L/T$  separation through multidim. fitting,  $TT$ ,  $LT$  response functions

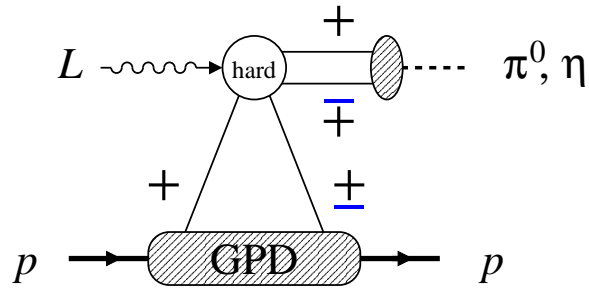
$Q^2$  scaling tests



Control production mechanism at 12 GeV!



# Exclusive $\pi^0, \eta$ : Transversity GPDs



- Quark helicities in pseudoscalar production

Twist-2: Quark helicity-conserving GPDs  
 $\tilde{H} \leftrightarrow \Delta_q, \tilde{E}$

Twist-3: Quark helicity-flip GPDs  
 $H_T \leftrightarrow \Delta_{Tq}, \bar{E}_T \equiv 2\tilde{H}_T + E_T$

Large amplitudes, distinctive  $t$ -dependence  
 Goloskokov, Kroll 10; Ahmad, Goldstein, Liuti 08

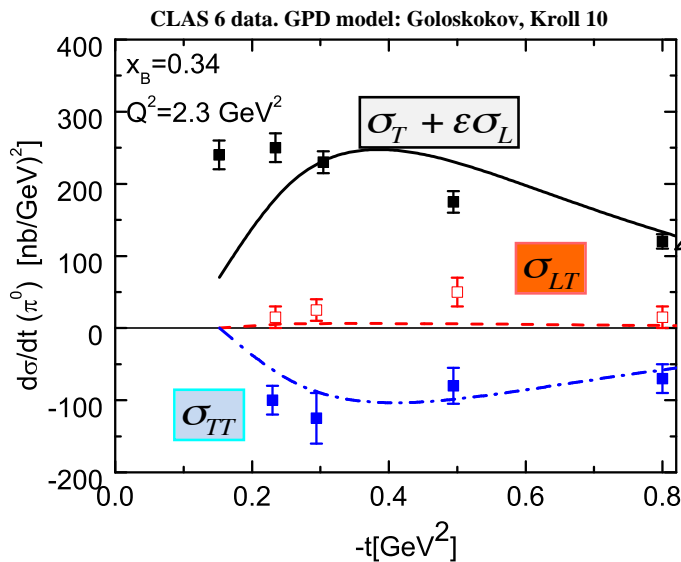
- Realistic description of data 6 GeV data

Cross sections  $\sigma_T + \epsilon\sigma_L, \sigma_{TT}, \sigma_{LT}$

$\pi/\eta$  ratio

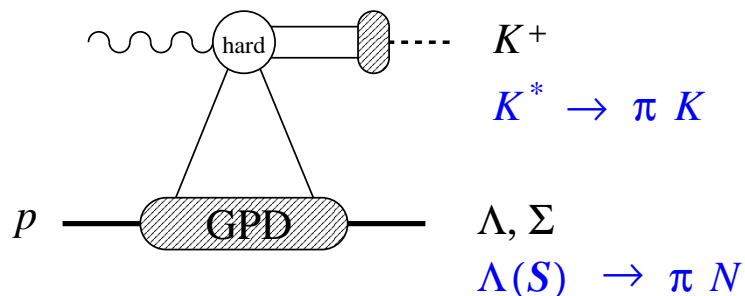
- JLab12: Probe quark transversity in pseudoscalar meson production? E12-06-108

Detailed tests of reaction mechanism:  
 $Q^2$  dependence,  $L/T$  with Rosenbluth



Manifestation of QCD vacuum structure

# Exclusive $K, K^*$ : Flavor and spin



- Exclusive  $K\Lambda, K\Sigma$

Flavor separation of GPDs:  $SU(3)$  symmetry  
 $\langle \Lambda | \bar{s}u | p \rangle = -\frac{1}{\sqrt{6}} \langle p | 2\bar{u}u - \bar{d}d - \bar{s}s | p \rangle$

Test models for pole and non-pole contributions in  $\pi^+$  production

- Exclusive  $K^*\Lambda$  with recoil polarization

LOI12-07-101

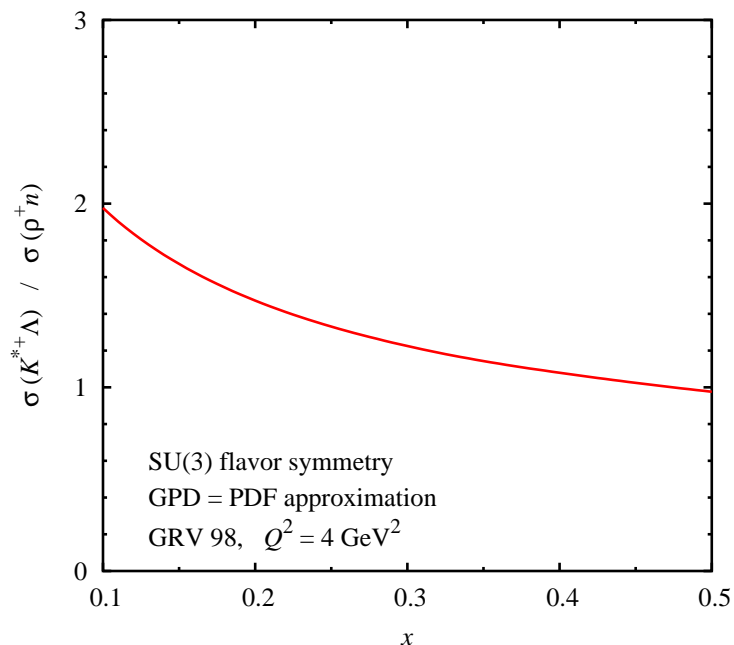
Test role of  $q\bar{q}$  correlations in  $\rho^0, \rho^+$

Constrain ratio of nucleon helicity-flip and non-flip quark GPDs

CLAS12: No transversely polarized target

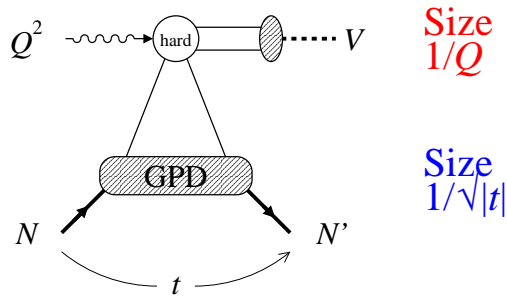
Large rates expected for  $K^*$

Deserves more study!



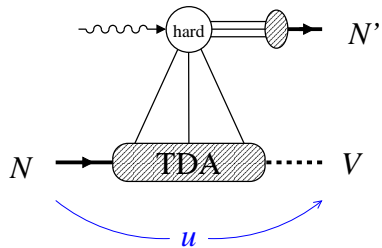
Unravel flavor/spin structure of GPDs

# High- $t$ : Small-size $qqq$ configurations



Size  $1/Q$

Size  $1/\sqrt{|t|}$



- Meson production at  $|t| \gg 1 \text{ GeV}^2$ : Nucleon in small-size configuration

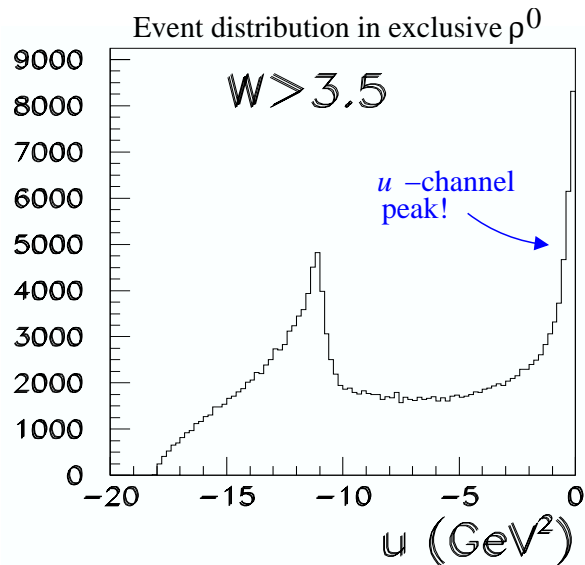
Cf. high- $t$  elastic nucleon form factors

Progress with GPD description of high- $t$  processes  
Kumano, Strikman, Sudoh 10

- Backward production:  $|u| < 1 \text{ GeV}^2$

Knockout of small-size  $qqq$  configuration, mesonic system left behind

Transition distribution amplitude  $\langle V|qqq|N \rangle$   
New information on short-range nucleon structure  
Frankfurt et al. 02; Pire, Semenov-Tian-Shansky, Szymanowski 10/11  
Great interest! Cross section calculations available soon



- CLAS12: Explore high- $|t|$ , high- $Q^2$  region for the first time

New QCD probe of nucleon's valence quark core!

# Summary

- Major progress in theory/phenomenology of hard exclusive meson production

Finite-size effects essential: Physical picture beyond leading twist

Fresh look at quark helicity-flip processes: QCD vacuum structure?

Quantitative GPD-based description looks feasible at 12 GeV

- Meson production addresses specific questions in short-range nucleon and meson structure

GPDs as a practical tool, not abstract object!

Wide choice of final states allows to probe gluons, flavor, spin

Connection with color transparency in nuclei, nuclear short-range correlations

- Data-driven field. . . Looking forward to 12 GeV!