# Beam Spin Asymmetries in Exclusive Meson Production with CLAS/CLAS12



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#### **QCD** Science Questions



How can we recover the wellknown characterics of the nucleon from the properties of its colored building blocks?

> Mass? Spin? Charge?

. . .

What are the relevant effective degrees of freedom and effective interaction at large distance?

## The Incomplete Nucleon Spin: Spin Puzzle

- Proton has spin-1/2
- Proton is a composite system consisting of spin-1/2 quarks and spin-1 gluons

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_Q + \Delta G + L_G$$



Possible contributions Quark spin, Quark orbital momentum Gluon spin, Gluon orbital momentum

Classical: L ~ r x p

Needs a cross-product or something three-dimensional!

We need to investigate the 3D nucleon structure!

## **3-Dimensional Imaging of Quarks and Gluons**



**3-Dimensional Imaging of Quarks and Gluons** 



#### **Generalized Parton Distributions (GPDs)**



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## **Study GPDs: Deeply Exclusive Processes**





#### **Deeply Virtual Meson Production**

	Meson	Flavor
H <b>τ</b> ,ε <b>τ</b>	$\pi^+$	$\Delta u - \Delta d$
	<b>π</b> <sup>0</sup>	$2\Delta u + \Delta d$
	$\eta$	$2\Delta u - \Delta d + 2\Delta s$
$\mathcal{H}, \mathcal{E}$	$ ho^+$	u-d
	$ ho^{0}$	2u + d
	ω	2u - d
	$\phi$	g

 $H_{\ensuremath{\mathsf{T}}}$  is related to the protons tensor charge

$$\delta_T^{u,d} = \int dx H_T^{u,d}(x,\xi=0,t=0)$$

- ➔ Absolute magnitude of transversly polarized valence quarks inside a transv. polarized nucleon
  - $\overline{E}_{T}$  is related to the protons anomalous tensor magnetic moment

$$k_T^{u,d} = \int dx \bar{E}_T^{u,d}(x,\xi=0,t=0)$$

## CLAS / CLAS12 in Hall B at Jefferson Lab

• 1995 – 2012, 6 GeV electron beam



2018 – today, 11 GeV electron beam



- ►  $\mathcal{L} = 1 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}$
- Inclusive electron trigger (all reactions will be analyzed in parallel)

$$\rightarrow$$
 I<sub>max</sub> = 90 µA, Pol<sub>max</sub> ~ 90%



#### Unpolarized $\pi^0$ Cross Section and Theory Predictions

#### 2 theoretical models:

Goloskokov, Kroll (GK) Eur. Phys. J. A. 47: 112 (2011)  $\rightarrow$  Chiral odd GPDs parameterized using latest results from lattice QCD and transversity parton distribution functions with emphasis on  $H_T$  and  $\bar{E}_T$ .

Goldstein, Hernandez, Liuti (GGL) Phys. Rev. D 84, 034007 (2011) → Chiral odd GPDs parameterized via linear relations to chiral even GPDs under parity and charge conjugation symmetries in Reggied diquark model





# Pseudoscalar meson electroproduction with CLAS12



From GPDs to Transition Distribution Amplitudes (TDAs)



→ "Backward physics" opens a new window to the 3D nucleon structure! Phys. Rev. Lett. 125, 182001 (2020)

## Exclusive $\rho/\omega$ production with CLAS12, ep-> ep ( $\rho/\omega$ )

$$\sigma_{LT'} \sim r_{00}^8 \sim \operatorname{Im}\left[\langle H_T \rangle^* \langle E \rangle + \langle \bar{E}_T \rangle^* \langle H \rangle\right]$$

Invariant Mass:  $\pi^+ + \pi^-$ 



Invariant Mass:  $\pi^+ + \pi^- + \pi^0$ 





N. Trotta *et al* (UCONN)

## Exclusive $\rho/\omega$ production with CLAS12, ep-> ep ( $\rho/\omega$ )



N. Trotta *et al* (UCONN)

# Exclusive $\phi$ production with CLAS12

Exclusive  $\Phi$  production

![](_page_15_Picture_2.jpeg)

- Exclusive Φ production probes gluon GPDs
- Transverse spatial distribution of gluons
  - x < 0.01 measured at HERA, FNAL
  - x > 0.1 practically unknown

$$A_{LU}^{sin(\phi_t)} \thicksim \operatorname{Im}[\left\langle \bar{E}_T \right\rangle_{LT}^* \left\langle H \right\rangle_{LL} + \frac{1}{2} \left\langle H_T \right\rangle_{LT}^* \left\langle E \right\rangle_{LL}]$$

B. Clary (UConn)

![](_page_15_Figure_9.jpeg)

## From the Ground State Nucleon to Resonances

![](_page_16_Figure_1.jpeg)

How does the excitation affect the 3D structure of the nucleon?

- → Pressure distributions, tensor charge, ... of resonances?
- ➔ Information encoded in transition GPDs

N→∆: 8 helicity non-flip trans. GPDs + 8 helicity flip trans. GPDs

➔ Measurement i.g. with non-diagonal processes (DVCS, DVMP)

![](_page_16_Figure_7.jpeg)

## The N $\rightarrow \Delta^{++}$ DVMP Process

 $ep \rightarrow e\Delta^{++}\pi^{-} \rightarrow ep\pi^{+}\pi^{-}$ 

![](_page_17_Figure_2.jpeg)

## The N $\rightarrow \Delta^{++}$ DVMP Process $ep \rightarrow e\Delta^{++}\pi^- \rightarrow ep\pi^+\pi^-$

![](_page_18_Figure_1.jpeg)

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# $N \rightarrow \Lambda, \Sigma, \Sigma^*$ GPDs in K production with CLAS12

![](_page_19_Figure_1.jpeg)

#### Production mechanism

Same twist-3 mechanism with chiral-odd structures as  $\pi$ ,  $\eta$  production

#### Symmetry relations for strange chiral-odd GPDs

 $N \rightarrow \Lambda, \Sigma$  related to  $N \rightarrow N$ by conventional SU(3) flavor symmetry

 $N \to \Sigma^*$  related to  $N \to N, \Lambda, \Sigma$ by SU(6) spin-flavor symmetry in large- $N_c$  limit

Predictive power; quantitative predictions possible

![](_page_19_Figure_8.jpeg)

![](_page_19_Figure_9.jpeg)

# **Complementary Measurements**

**GPDs** 

**JLAB** 

![](_page_20_Figure_2.jpeg)

![](_page_20_Figure_3.jpeg)

 $\pi^- + p \longrightarrow (\mu^+ \mu^-) + n$ 

![](_page_20_Figure_5.jpeg)

 $e+p \rightarrow e'+K^++\Lambda(\Sigma)$ 

![](_page_20_Figure_7.jpeg)

 $K^- + p \rightarrow (\mu^+ \mu^-) + \Lambda(\Lambda^*)$ 

 $\mu^+$ 

μ

## From CLAS to JLAB to COMPASS to EIC

![](_page_21_Figure_1.jpeg)

→ DVMP/SIDIS at JLAB 22 GeV upgrade / COMPASS and EIC

## **Conclusion and Outlook**

- GPDs provide a unifying framework to study the 3-D quark and gluon structure of the nucleon
- 3-D imaging of nucleons uncovers the rich dynamics of QCD.
- CLAS12 allows high precision measurements of GPDs with large kinematic coverages in the valence quark regime!
- COMPASS, J-PARC, EIC and other experiments will allow complementary measurements in different kinematic regimes.

![](_page_22_Picture_5.jpeg)

![](_page_22_Picture_6.jpeg)