# DVCS Factorization

- Works great for  $Q^2$  ≥ 20 GeV<sup>2</sup>! (HERA)
	- COMPASS (muons), HERMES(fixed target at HERA), Jlab  $Q^2$  < 10 GeV<sup>2</sup>
	- Even if vector meson content of photon is suppressed, what about higher order perturbative QCD effects.
		- Enter Amplidute with powers  $\lceil \Lambda^2/Q^2 \rceil^{n/2}$
		- Coefficients not known *a priori*. Can be large from Chiral symmetry breaking effects.

# Higher Order qqg Correlations, as corrections to DVCS

• GPD  $\sim 1/Q^2$ 

• *qqg* Correlation *~ 1/[Q2]3/2*

• *qqqq* "Cat's Ears" ~1/Q<sup>4</sup>



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#### What do DVCS experiments measure?

 $d\sigma$ (ep $\rightarrow$ ep $\gamma$ ) = twist-2 (GPD) terms +  $\Sigma_n$  [twist-*n*]/ $Q^{n-2}$ 

• Isolate twist-2 terms  $\rightarrow$  cross sections *vs Q<sup>2</sup>* at fixed ( $x_{Bj}$ , *t);* or

 $\gamma^*$   $\mathcal{Z}_{\mathbf{Z}_2}$   $\mathcal{Z}_{\mathbf{Z}_3}$ 

 $x+\xi$   $x-\xi$ 

•  $\rightarrow$  Multiple beam energies at fixed *(Q<sup>2</sup>, x<sub>Bj</sub>, t)* 

**GPD** terms are `Compton Form Factors'

 $CFF(\xi, \Delta^2) = \int dx$  $GPD(x,\xi,\Delta^2;Q^2)$ 1 ∫

• *Re* and Im parts (accessible via interference with BH): *x* ±ξ = *iε*<br>Pssible via interf

$$
\mathfrak{R}m\Big[CFF(\xi,\Delta^2)\Big] = \pi\Big[GPD(\xi,\xi,\Delta^2) \pm GPD(-\xi,\xi,\Delta^2)\Big]
$$
  

$$
\mathfrak{R}e\Big[CFF(\xi,\Delta^2)\Big] = \mathcal{P}\int dx \frac{GPD(x,\xi,\Delta^2)}{x \pm \xi}
$$
  

$$
\xrightarrow[D,R]{} \mathcal{P}\int d\xi \frac{GPD(\xi^*,\xi^*,\Delta^2)}{\xi^* \pm \xi} + D(\Delta^2)
$$

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### Physical Interpretation of GPDs:

•  $\zeta$ =0: Probability densities of impact parameter **b** relative to Center-of-Momentum of proton:  $\rightarrow$ 

 $H(x,0,\Delta^2) \Leftrightarrow q(x,$ *b*)  $\tilde{H}(x,0,\Delta^2) \Leftrightarrow \Delta q(x,$  $\rightarrow$ *b*)

- $x=\xi$ :  $H(\xi, \xi, \Delta^2) H(-\xi, \xi, \Delta^2)$ , E, *etc.* 
	- 2-d Fourier-transform ∆,  $\leftrightarrow$  **r**
	- Transition amplitude from longitudinal momentum 0 to  $2\xi/(1+\xi)$  at fixed impact parameter **r** relative to CM of *spectators*.
		- Not a positive definite density, but still an image.
	- Directly measurable
	- Expect size shrinks as  $\xi \rightarrow 1$
	- Different profiles for *u*, *d*, *glue*,...

## **Tomography with Generalized** Parton Distributions (M. Burkardt)

*by*

- $H(x,t)\gamma^{\mu} + E(x,t)\sigma^{\mu\nu}\Delta_{\nu}$ 
	- Proton size shrinks as  $x \rightarrow 1$ .
	- Spatial separation of upand down-quarks in a transversely polarized proton
- Spin-Flavor dependence to Proton size & profile.
	- up and down quarks separate in transversely polarized proton

$$
\varepsilon_f(x, b_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{i \Delta_\perp \cdot b_\perp} E_f(x, \Delta_\perp)
$$

$$
q_{X}(x,b_{\perp}) = h_{q}(x,b_{\perp}) + \frac{1}{2M} \frac{\partial}{\partial y} \varepsilon_{q}(x,b_{\perp})
$$



#### Exploiting the harmonic structure of DVCS with polarization

 $\mathbf{X}$ 

Z

 $\vec{k}$ 

 $\varphi$ 

The difference of cross-sections is a key observable to extract GPDs

With polarized beam and unpolarized target: **~**  ${F_1H + \xi(F_1 + F_2)H + (t/4M^2)F_2E}$  $\Delta \sigma_{LU}$  – sin $\varphi$   $\overline{F_1H} + \xi (F_1 + F_2)\overline{H} + (t/4M^2)F_2E$   $\overline{d\varphi}$ 

With unpolarized beam and Long. polarized target:  $\Delta \sigma_{UU}$  =  $\sin \varphi$   $\{F_1\tilde{H} + \xi(F_1 + F_2)H + (t/4M^2)F_2E\}$  $\Delta \sigma_{UU}$   $\sim$  sin $\varphi$  {F<sub>1</sub>H +  $\xi$ (F<sub>1</sub> + F<sub>2</sub>)H + († / 4M<sup>2</sup>)F<sub>2</sub>E \d  $\varphi$  $\widetilde{\bm{f}}$ 

With unpolarized beam and Transversely polarized target:

$$
\Delta \sigma_{UT} \sim \cos \varphi \sin(\phi_s - \varphi) \left\{ (t/4M^2) F_z H - (t/4M^2) F_1 E + ... \right\} d\varphi
$$

Separations of CFFs  $H(\pm \xi,\xi,t)$ ,  $H(\pm \xi,\xi,t)$ ,  $E(\pm \xi,\xi,t)$ , … \_<br>C

# Measuring GPDs

- HERA  $(2001 - 2007)$
- HERMES  $(2001 - 2007)$
- JLab 6 GeV  $(2001 - 2012)$
- JLab 12 GeV  $(2014 -$
- COMPASS  $(2016 -$
- EIC (2025+?



 $e p \rightarrow e p \gamma$ 

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# HERMES overview

#### 27.6 GeV e+/e- HERA beam Access to valence and sea Electron and Hadron ID





# **HERMES** summary

- averaged over  $Q^2$  and  $t$
- Transversely polarized H*–* target  $\rightarrow$ sensitivity to  $E(\xi,\xi,\Delta^2)$ , x*≈*0.1



#### DVCS: JLab Hall A 2004, 2010, 2014-2016  $L \ge 10^{37}$  cm<sup>2</sup>/s

(e,e')X HRS trigger

Digital Trigger 208 PbF<sub>2</sub>

**Validation** 

 $\rightarrow$ e-

Precision cross sections

- •Test factorization
- •Calibrate Asymmetries



# Hall A Results: Scaling Tests

•  $Q^2$ =2.3 GeV<sup>2</sup>,  $x_{Bj}$ =0.36, *t=–0.23 GeV2*



. The error bars on the data points are statistically defined as

PRL**97**:262002 (2006) **C. Muñoz Camacho, et al.,** PRC 92, 055202 (2015) M.Defurne, et al., Re

- **A. Scan in** *Q***<sup>2</sup>** • Empirical extraction extracted from the fitting procedure for Kin1–3 using the
- **formalism developed in Ref. [41] and integrated in Ref. [41] and integrated over**  $\mathbf{f}$  **are shown integrated over**  $\mathbf{f}$  **and integrated over**  $\mathbf{f}$  **and integrated over**  $\mathbf{f}$  **and integrated over**  $\mathbf{f}$  **and integ Example 23. With the choice of parameters used to descript the choice of parameters used to descript the choice of parameters used to describe the choice of parameters used to describe the choice of the choice of the choi**
- $Hichor$  twict torrow **EXEC. IV FINDER**<br>Sec. 2 Terms
- $I_{\text{ext}}$  The  $\Omega$  independent • Test *Q<sup>2</sup>*-independence  $\mathbf{f} \cap \mathbf{D}$  to be small, with  $\mathbf{f} \cap \mathbf{D}$ uncertainties of GPD terms



close to 0◦, which increases the correlation between the correlation between the correlation between the correlation

−**t** = 0 °C GeV20 GeV20 GeV<br>−

APCTP-2018 **C.** Hyde — Lecture 1 32  $\frac{1}{2}$  Fig. 23. (Color online) CFFs extracted from the fitting procedure described in Sec. IV F using the formalism procedure described in Sec. IV F using the formalism procedure described in Sec. IV F using the formal developed in Ref. [41], integrated over *t* and plotted as a function of *Q*2. The top three plots show the effective CFFs resulting from

the unit (Kin2 and Kin3), whereas the bottom plots show the effective CFFs resulting from the helicity-dependent

Hall A:  $H(e,e'\gamma)$  $x_B$  = 0.36, Q<sup>2</sup>=1.5, 1.75, 2.0 GeV<sup>2</sup> M.Defurne et al., "A Glimpse of Gluons", Nat. Comm.8 (2017)

 $\triangleleft Q^2 = 1.75$ 

- $\div$  E<sub>e</sub> = 4.455 (left), 5.55 (right) GeV
- $\triangleleft d^4\sigma/[dQ^2dx_Bdt d\phi_{\gamma\gamma}]$  $\Delta^4 \sigma = d^4 \sigma (h=+)-d^4 \sigma (-)$
- $\blacklozenge$  Solid Grey Line = KM2015
- ◆ Dashed: Leading Twist / Leading Order (LT/LO) fit with V. Braun Kinematic Twist-4  $(t/Q^2)$ constrained by LO/LT:
	- **► Global fit at each –t :** *3*⊗*Q2 & 2*⊗*Ee*

Poor  $\chi^2$ 



# Two Fit-Scenarios [Using V. Braun et al, PRD 89, 074022 (2014)]

#### $\bigcirc$ LO/LT + Twist-3 + **Kinematic Twist-4**

 $\mathbb{H}(x,\xi,t), \quad \mathbb{H}(x,\xi,t)$ 



#### **CLO+ NLO (gluon** transversity) + Kinematic Twist-4



### `Global' Fit:  $Q^2$ =1.5, 1.75, 2.0 GeV<sup>2</sup> & E<sub>e</sub> = 4.45, 5.55 GeV Displayed at  $Q^2 = 1.75$  for  $-t = 0.030$  GeV<sup>2</sup>

**IPIGEV**  $\cdot$  d $^4\sigma$ - Fit LT/LO  $\Delta^4$  $\sigma$ • Fit HT - KM15  $0.05$ 100 200 300 100 200 300  $\Phi$  (deg)  $\Phi$  (deg)

Identical fit (blue<sup>1</sup>) for either: Twist-3 or NLO (gluon) scenarios. Both fits have Kinematic Twist-4 contribution constrained from Twist-2 component of fit

5

# E07-007 `Global' Fit Separations of Re,Im[DVCS<sup>+</sup>BH], |DVCS|<sup>2</sup>

 $-t = 0.030$  GeV<sup>2</sup> (of three *t*-bins): Displayed at  $Q^2 = 1.75$ 



Total Fit (previous slide blue) 䢕Sum of Pink (LO+NLO) OR 䢕Sum of Cyan (LO+HT)

Model dependence, but full measurement of interference: amplitude & phase

36

# DVCS in CLAS @ 6 GeV

 $H(e,e'\gamma p)$ **Longitudinally** polarized NH<sub>3</sub> target.

• Add:

**5 Tesla Solenoid 420 PbWO<sub>4</sub> crystals :** 

**~10x10x160 mm3 APD+preamp readout Orsay / Saclay / ITEP / Jlab**



 $\epsilon_{\rm{eff}}$ 

Performances:

 $\mathcal{A}$  .

Detection of charged

and neutral particles

 $\mathbb{E}[\mathcal{L}]$ 

#### CLAS 6 GeV: Exclusivity and Kinematics

• H*(e,e'*g*p')x* **Overcomplete** triple 

coincidence







• Example angular distribution of Beam Spin Asymmetry

- •One  $(Q^2, x_B)$  bin
- •Two *t*-bins.

# CLAS DVCS (unpolarized Target)



cross section, i.e., with the introduction, i.e., with the introduction of a strong H $\sim$ 

K.S. Jo, F.-X Girod, *et al.,* Phys.Rev.Lett. 115 (2015) 21, 212003



 $\blacksquare$ **Extraction of the blue solid curves are the VGGG** Model-dependent extraction of **Example 1** Regard Imports of the  $H(\xi \xi t)$ Re and Im parts of the  $H(\xi, \xi, t)$ **point by the eight (unpolarized GPD)** Compton form Factor

FIMORE EN LA CONSTITUCIÓN EN LA CO

1

Lint Q<sup>2</sup> x<sup>B</sup> t Acc Frad

events. We evaluated the contamination from the ep

 $\mathbb{R}^n \to \mathbb{R}$ 

data acquisition dead time, which was deduced from the integrated charge of the beam measured by a Faraday cup. In addition, we applied a global renormalization factor of 12.3%, determined from the analysis of the elas- $\mathbf{b}$  , by comparing the experimental the experimental the experimental  $\mathbf{b}$ cross section to the well-known theoretical one. This factor compensates for various kinematic-independent inef-

### The pressure distribution acting on quarks in the proton



 $\int x \left[ H(x,\xi,t) - H(x,0,t) \right] dx = \frac{4}{5} \xi^2 d_1(t)$ 

*V.Burkert, L.Elourdrhiri, F.X.Girod, Nature* **557** (2018) 396

18 June 2018 **GPDs:** JLab->EIC, C.Hyde



• On to to 11 GeV!

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(black full squares) and *H*˜*Im* (red full circles), which are obtained from the fit of the present data, as a function of *<sup>t</sup>* for each of our 5 *<sup>Q</sup>*<sup>2</sup>-*x<sup>B</sup>* bins. These are the two  $\overline{\phantom{a}}$  that appear to be better constraints by the presentation by the presentation of  $\overline{\phantom{a}}$ results. Given that the size of the error bars reflects the sensitivity of the combination of observables to each CFF, it is evident that is evident that the second that is evident that is evident that is a symmetric area of

The results for *HIm* and *H*˜*Im* confirm what had been  $p$ parison of the *t*-dependence of our TSAs and BSAs in Section VII.2: the *t*-slope of =m*H* is much steeper than that of <sup>=</sup>m*H*˜, hinting at the fact that the axial charge (linked to <sup>=</sup>m*H*˜) might be more "concentrated" in the

the present data, integrated over *Q*<sup>2</sup> and *x<sup>B</sup>* (black circles), the previous CLAS experiment [13] (magenta triangles), and







18 June 2018 **GPDs:** JLab->EIC, C.Hyde

Hall C:NPS

magnet

NSF MRI + JLab

PbWO4 + Sweep