

International Spring School of the GDR PH-QCD

QCD prospects for future ep and eA colliders

LECTURERS:

Alfred Mueller High energy ep and eA scattering

Piet Mulders TMDs: theory and phenomenology

George Sterman Factorization of hard processes

Marc Vanderhaeghen GPDs and spatial structure of hadrons



ORSAY 4-8 June 2012

Amphi I, Laboratoire de Physique Théorique,
bâtiment 210, Université d'Orsay

<http://indico.in2p3.fr//event/QCD-ep-eA-colliders>

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Sponsors:



GPDs & spatial structure of hadrons

Part 4

Marc Vanderhaeghen
Johannes Gutenberg
Universität, Mainz

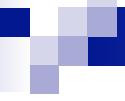
Outline

→ What is the physics contained in GPDs ?

- GPDs: basic definitions and properties
- 3D imaging of the nucleon: link between elastic nucleon Form Factors and GPDs, connection between longitudinal momentum and transverse position
- Generalizations: Wigner distributions
- GPDs and nucleon spin
- Hard exclusive processes : DVCS, hard meson production, $N \rightarrow \Delta$ DVCS, ...

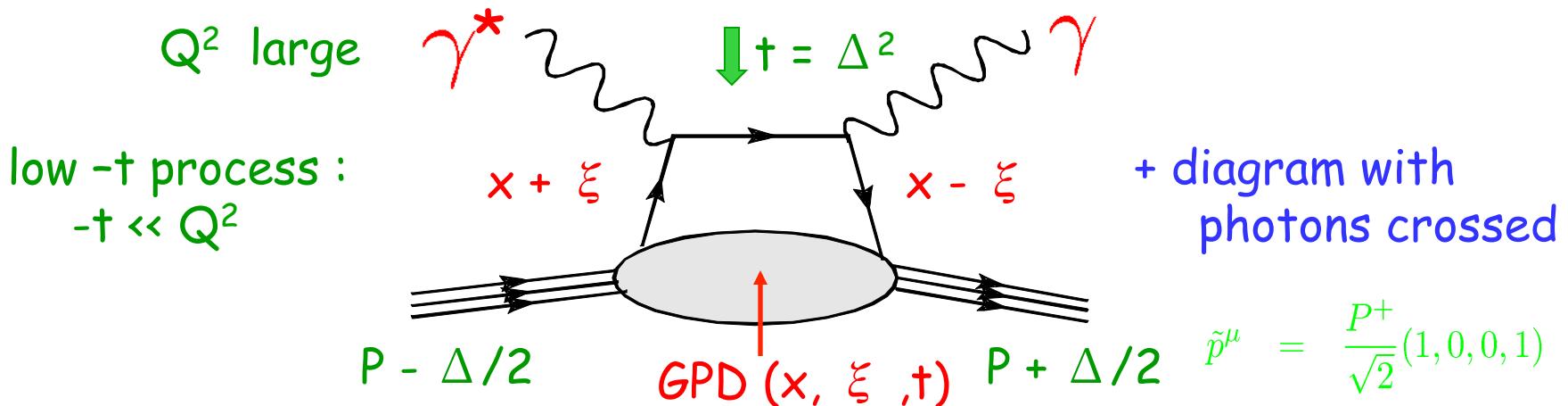
Reviews on GPDs

- > Goeke, Polyakov, Vdh : Prog.Part.Nucl.Phys. 47, 401 (2001)
- > Diehl : Phys.Rept. 388, 41 (2003)
- > Ji : Ann.Rev.Nucl.Part.Sci 54, 413 (2004)
- > Belitsky, Radyushkin : Phys.Rept. 418, 1 (2005)
- > Boffi, Pasquini : Riv.Nuovo.Cim. 30, 387(2007)



Deeply virtual Compton scattering (DVCS)

Deeply Virtual Compton Scattering



$$\begin{aligned}
 & H_{L.O. \text{ DVCS}}^{\mu\nu} \\
 &= \frac{1}{2} [\tilde{p}^\mu n^\nu + \tilde{p}^\nu n^\mu - g^{\mu\nu}] \int_{-1}^{+1} dx \left[\frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right] \\
 & \quad \times \left[H_{DVCS}^p(x, \xi, t) \bar{N}(p') \gamma \cdot n N(p) + E_{DVCS}^p(x, \xi, t) \bar{N}(p') i\sigma^{\kappa\lambda} \frac{n_\kappa \Delta_\lambda}{2m_N} N(p) \right] \\
 &+ \frac{1}{2} [-i\varepsilon^{\mu\nu\kappa\lambda} \tilde{p}_\kappa n_\lambda] \int_{-1}^{+1} dx \left[\frac{1}{x - \xi + i\epsilon} - \frac{1}{x + \xi - i\epsilon} \right] \\
 & \quad \times \left[\tilde{H}_{DVCS}^p(x, \xi, t) \bar{N}(p') \gamma \cdot n \gamma_5 N(p) + \tilde{E}_{DVCS}^p(x, \xi, t) \bar{N}(p') \gamma_5 \frac{\Delta \cdot n}{2m_N} N(p) \right]
 \end{aligned}$$

$$\begin{aligned}
 \tilde{p}^\mu &= \frac{P^+}{\sqrt{2}} (1, 0, 0, 1) \\
 n^\mu &= \frac{1}{P^+ \sqrt{2}} (1, 0, 0, -1)
 \end{aligned}$$

DVCS (continued)

→ $H_{DVCS}^p(x, \xi, t) = \frac{4}{9} H^{u/p} + \frac{1}{9} H^{d/p} + \frac{1}{9} H^{s/p}$

and similarly for \tilde{H}_{DVCS} , E_{DVCS} , \tilde{E}_{DVCS}

→ twist-2 DVCS amplitude independent of $Q \rightarrow SCALING!$

→ DVCS amplitude is **complex** : imaginary part $\rightarrow x = \xi$

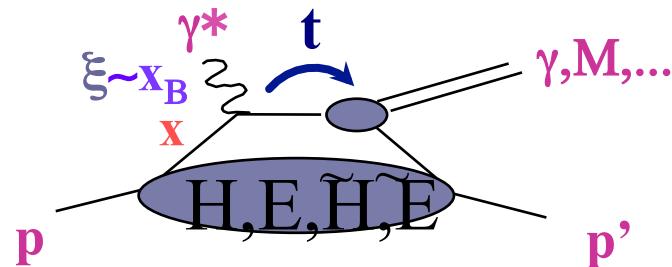
→ Q^2 , ξ , and t are kinematic variables

with $\xi = \frac{x_B/2}{1 - x_B/2}$ and $x_B = \frac{Q^2}{2p \cdot q}$

→ variable x is integrated over ($x \neq x_B$!)

DVCS amplitude is sensitive to GPDs weighted
with coefficient functions

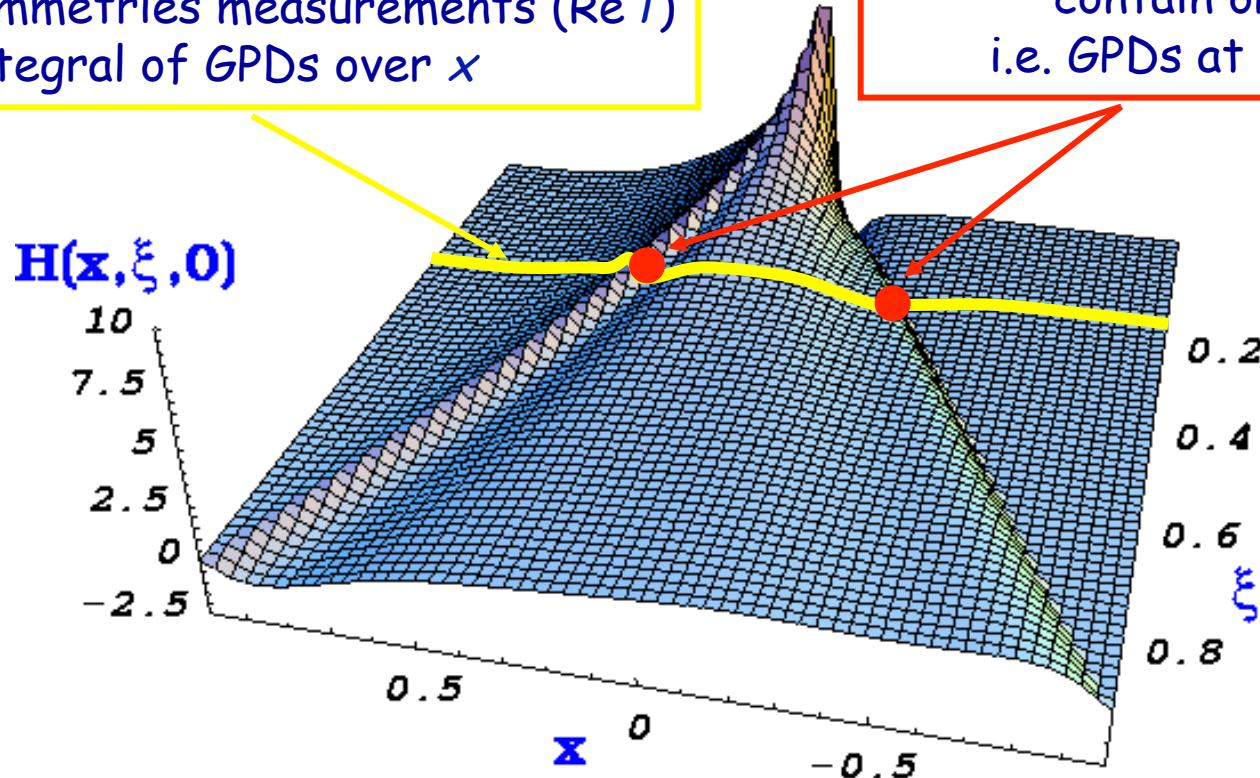
link GPDs and observables



$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x, \xi, t)}{x \pm \xi + i\epsilon} dx + \dots \sim P \int_{-1}^{+1} \frac{H(x, \xi, t)}{x \pm \xi} dx - i\pi H(\pm \xi, \xi, t) + \dots$$

Cross sections and
charge asymmetries measurements ($\text{Re } T$)
Integral of GPDs over x

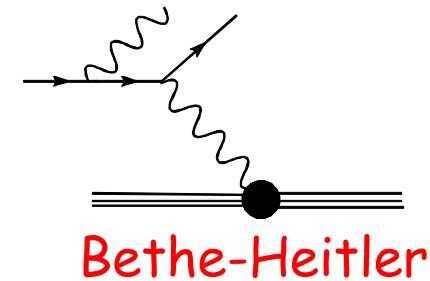
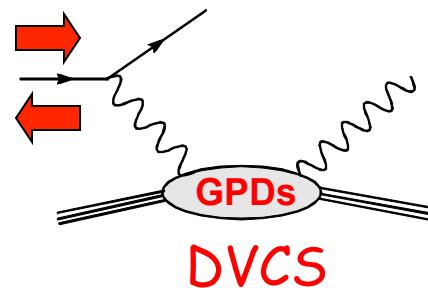
Beam or target spin asymmetries
contain only $\text{Im } T$,
i.e. GPDs at $x = \xi$ and $-\xi$



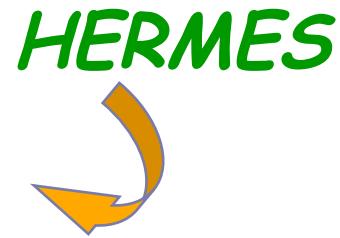
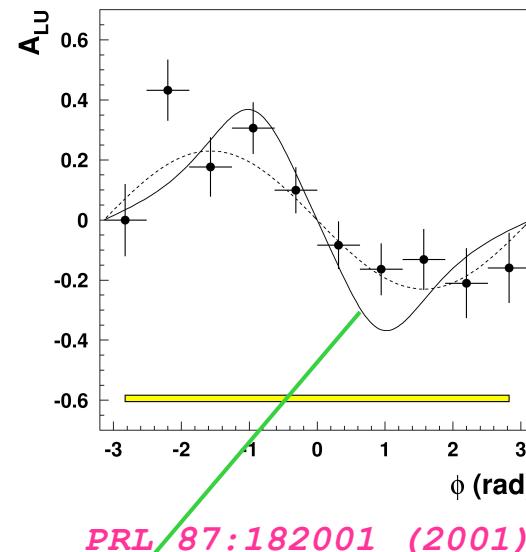
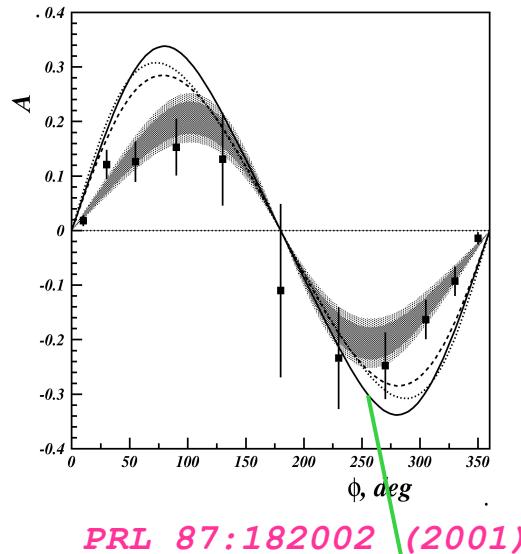


DVCS asymmetries: first observations

$$A_{LU} = \frac{(BH) * \text{Im}(DVCS) * \sin \Phi}{(BH^2 + DVCS^2)}$$



$Q^2 = 1.25 \text{ GeV}^2$,
 $x_B = 0.19$,
 $-t = 0.19 \text{ GeV}^2$



$Q^2 = 2.6 \text{ GeV}^2$,
 $x_B = 0.11$,
 $-t = 0.27 \text{ GeV}^2$

twist-2 + twist-3

Vdh, Guichon, Guidal (1999)
Kivel, Polyakov, Vdh (2000)

Extracting GPDs from DVCS observables

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

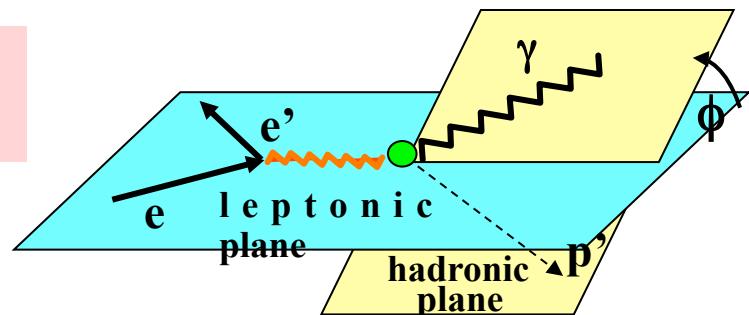
$$\xi = x_B/(2-x_B)$$

$$k = -t/4M^2$$

Polarized beam, unpolarized proton target:

$$\Delta\sigma_{LU} \sim \sin\phi \operatorname{Im}\{F_1 H + \xi(F_1 + F_2) \tilde{H} + kF_2 E\} d\phi$$

Kinematically suppressed



$$H_p, \tilde{H}_p, E_p$$

Unpolarized beam, longitudinal proton target:

$$\Delta\sigma_{UL} \sim \sin\phi \operatorname{Im}\{F_1 \tilde{H} + \xi(F_1 + F_2)(H + \dots)\} d\phi$$

$$H_p, \tilde{H}_p$$

Unpolarized beam, transverse proton target:

$$\Delta\sigma_{UT} \sim \sin\phi \operatorname{Im}\{k(F_2 H - F_1 E) + \dots\} d\phi$$

$$H_p, E_p$$

Polarized beam, unpolarized neutron target:

$$\Delta\sigma_{LU} \sim \sin\phi \operatorname{Im}\{F_1 H + \xi(F_1 + F_2) \tilde{H} - kF_2 E\} d\phi$$

Suppressed because $F_1(t)$ is small

Suppressed because of cancellation between PPD's of u and d quarks

$$H_p(x, \xi, t) = \frac{4}{9} H_u(x, \xi, t) + \frac{1}{9} H_d(x, \xi, t)$$

$$H_n(x, \xi, t) = \frac{1}{9} H_u(x, \xi, t) + \frac{4}{9} H_d(x, \xi, t)$$

Compton Form Factors (CFFs)

In hard exclusive process @ leading twist: one accesses 8 CFFs

REAL parts of CFF

IMAG parts of CFF

$$\left\{
 \begin{array}{l}
 P \int_0^1 dx [H(x, \xi, t) - H(-x, \xi, t)] C^+(x, \xi), \quad (1) \\
 P \int_0^1 dx [E(x, \xi, t) - E(-x, \xi, t)] C^+(x, \xi), \quad (2) \\
 P \int_0^1 dx [\tilde{H}(x, \xi, t) + \tilde{H}(-x, \xi, t)] C^-(x, \xi), \quad (3) \\
 P \int_0^1 dx [\tilde{E}(x, \xi, t) + \tilde{E}(-x, \xi, t)] C^-(x, \xi), \quad (4) \\
 H(\xi, \xi, t) - H(-\xi, \xi, t), \quad (5) \\
 E(\xi, \xi, t) - E(-\xi, \xi, t), \quad (6) \\
 \tilde{H}(\xi, \xi, t) + \tilde{H}(-\xi, \xi, t), \quad (7) \\
 \tilde{E}(\xi, \xi, t) + \tilde{E}(-\xi, \xi, t) \quad (8)
 \end{array}
 \right.$$

with

$$C^\pm(x, \xi) = \frac{1}{x - \xi} \pm \frac{1}{x + \xi} \quad (9)$$

which we can call, respectively, in a symbolic notation,
 $Re(H)$, $Re(E)$, $Re(\tilde{H})$, $Re(\tilde{E})$, $Im(H)$, $Im(E)$, $Im(\tilde{H})$
and $Im(\tilde{E})$.

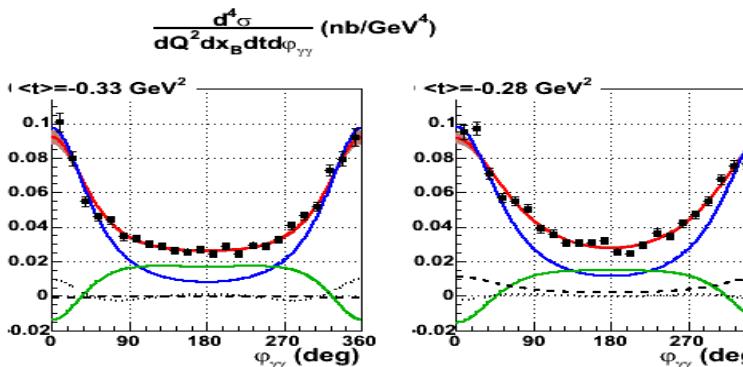
DVCS: observables

Jlab/Hall A



Bethe-Heitler

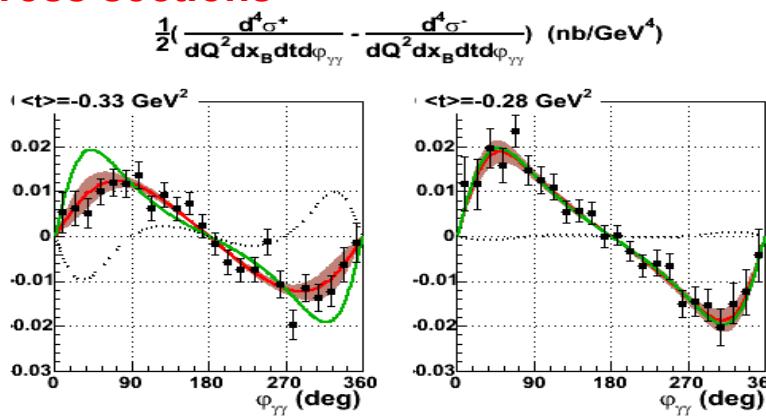
Unpolarized cross sections



E00-110
Fit
 $1-\sigma$

BH
Re (C_1^l)
Re ($C_1^l + \Delta C_1^l$)
Re (C_{eff}^l)

Difference of polarized cross sections



E00-110
Fit
 $1-\sigma$

Im (C_1^l)
Im (C_{eff}^l)

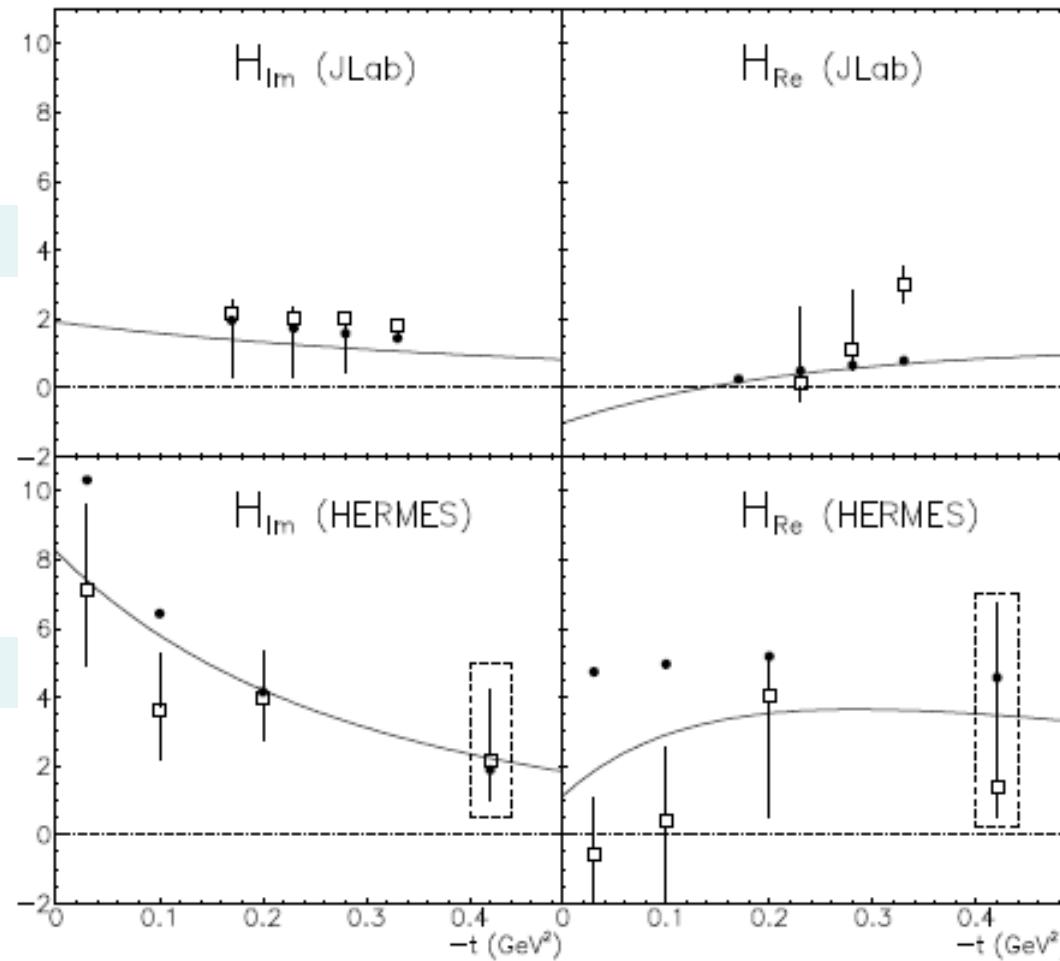
CFFs from DVCS: model independent fit extractions (I)

JLab

$x_B=0.36, Q^2=2.3$

HERMES

$x_B=0.09, Q^2=2.5$



as energy increases:

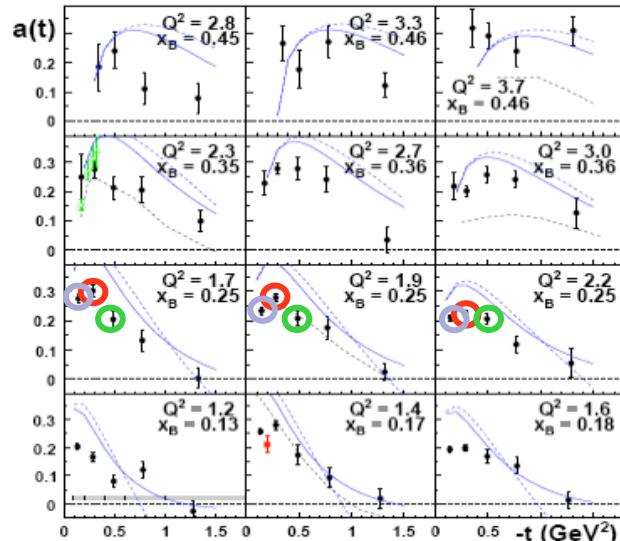
- « Shrinkage » of $\text{Im}(H)$
- $\text{Im}(H) > \text{Re}(H)$

→ different t -behavior for $\text{Im}(H)$ & $\text{Re}(H)$

solid circles :
VGG(1998)

model dependent fit
of
D. Muller,
K. Kumericki (2009)

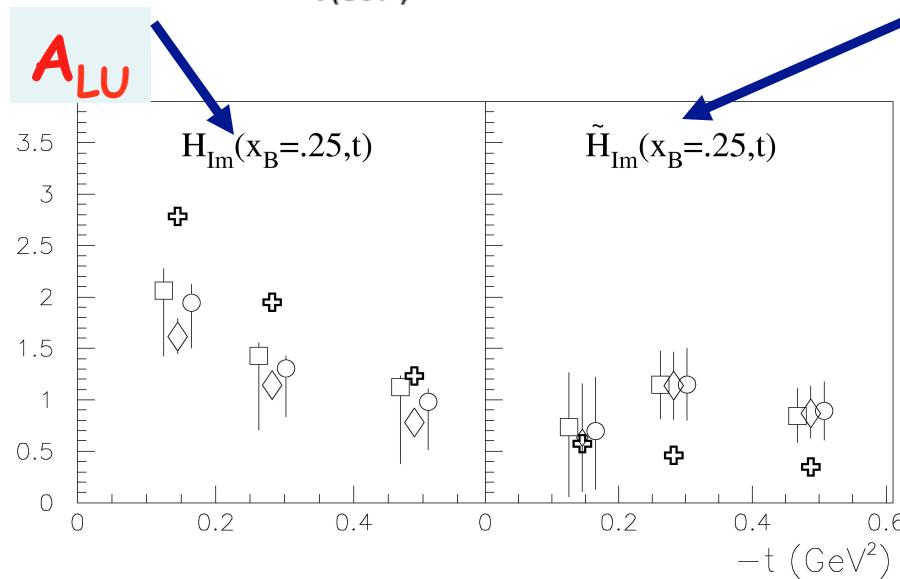
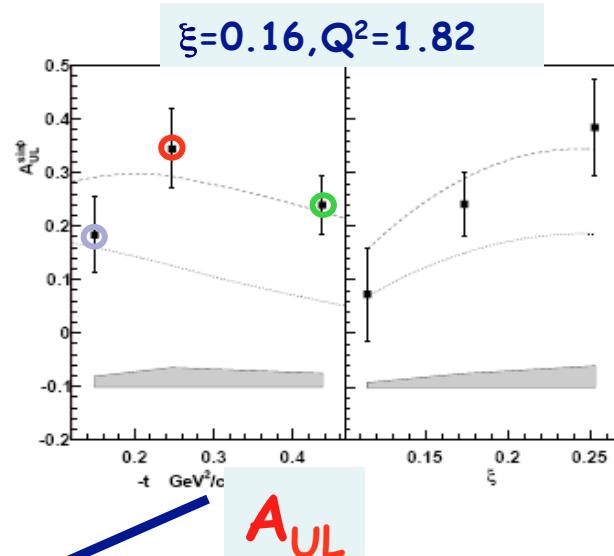
CFFs from DVCS: fits (II)



Jlab/CLAS

Girod et al.
(2006)

Chen et al.
(2008)



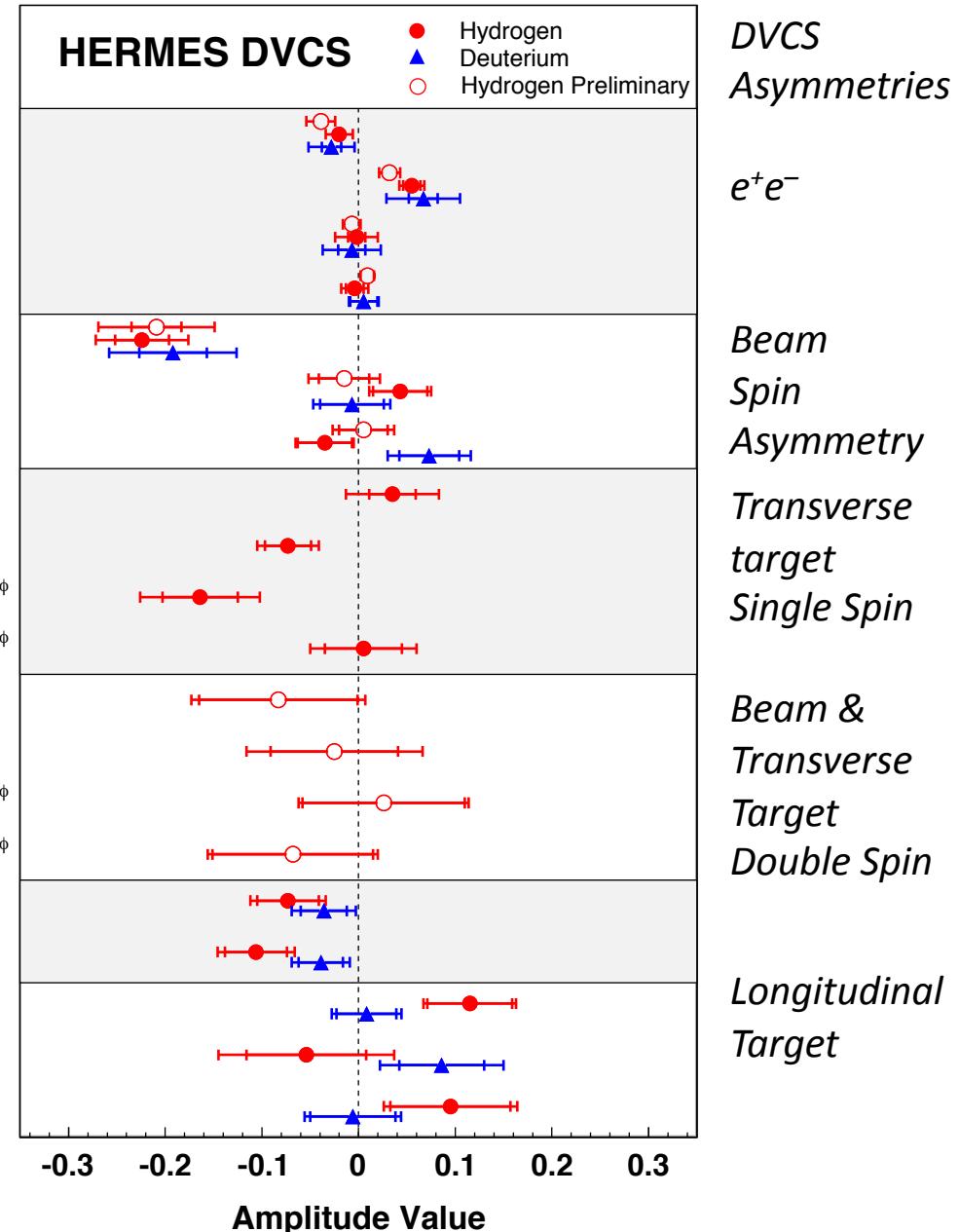
- Fit with 7 CFFs
(bounds 5xVGG CFFs)
- Fit with 7 CFFs
(bounds 3xVGG CFFs)
- Fit with ONLY \tilde{H} and H CFFs
- VGG prediction

Guidal (2010)

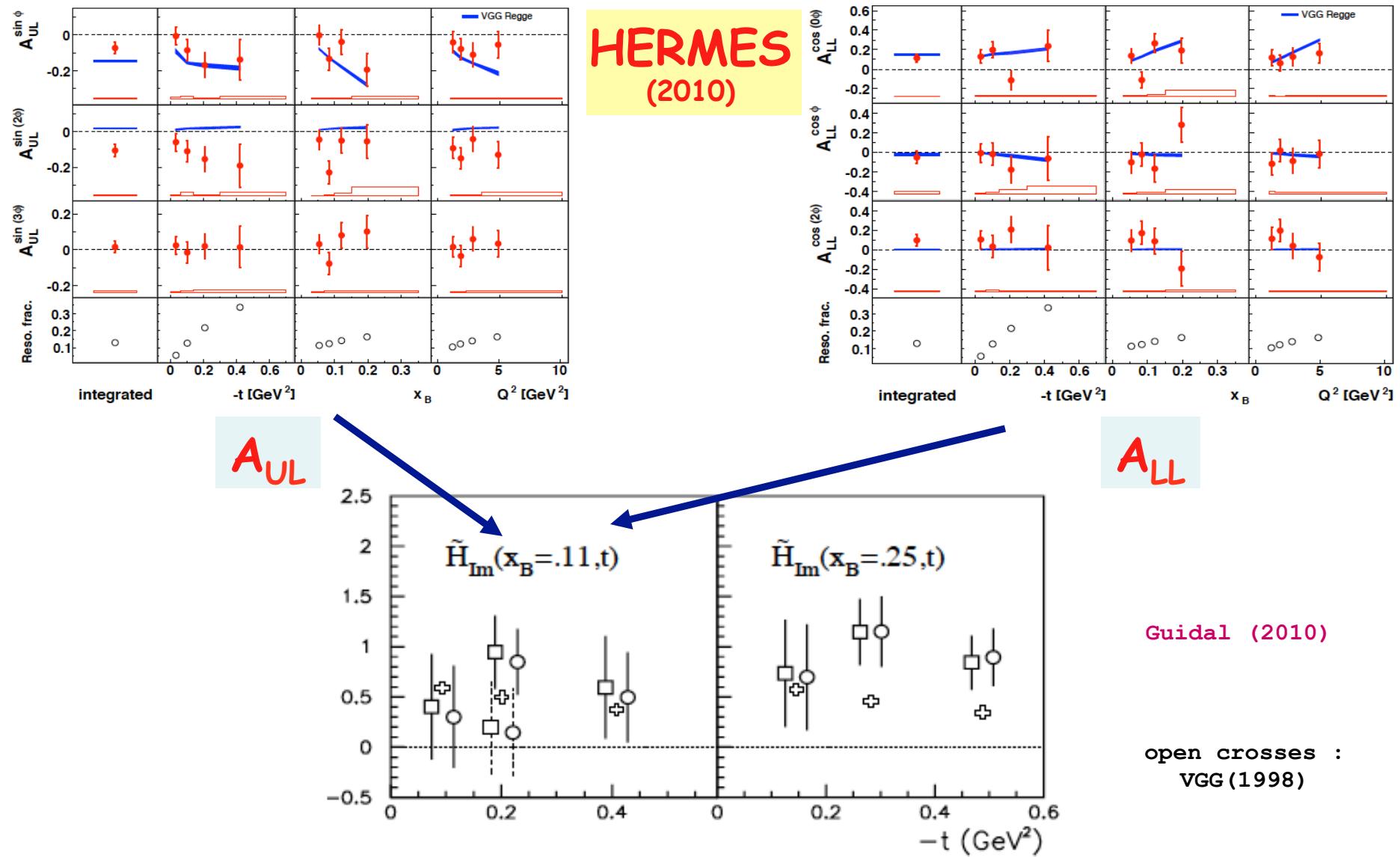
DVCS: asymmetries



summary 2011



CFFs from DVCS: fits (III)

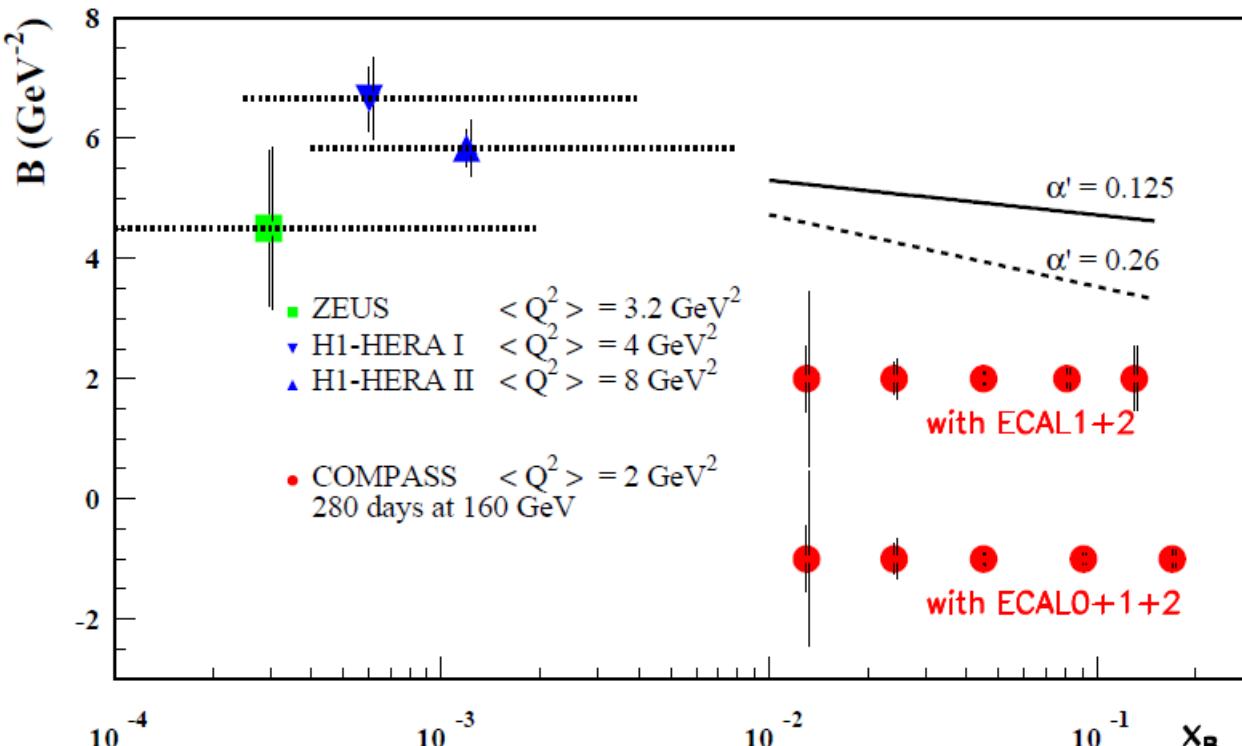


DVCS: transverse imaging

$$d\sigma^{DVCS} / dt \sim \exp(-B |t|)$$

$$B(x_B) = \frac{1}{2} \langle r_\perp^2(x_B) \rangle$$

r_\perp transverse size of nucleon

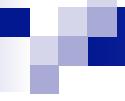


2 years of data
 160 GeV muon beam
 2.5m LH₂ target
 $\epsilon_{\text{global}} = 10\%$

ansatz at small x_B
 inspired by
 Regge Phenomenology:

$$B(x_B) = b_0 + 2 \alpha' \ln(x_0/x_B)$$

α' slope of Regge trajectory



Dispersion Formalism for DVCS (twist-2)

helicity averaged twist-2 DVCS amplitude

- twist-2 DVCS amplitude for GPD H : convolution integral

$$A(\xi, t) \equiv - \int_0^1 dx H^{(+)}(x, \xi, t) \left[\frac{1}{x - \xi + i\varepsilon} + \frac{1}{x + \xi - i\varepsilon} \right]$$

involves singlet GPD $H^{(+)}(x, \xi, t) \equiv H(x, \xi, t) - H(-x, \xi, t)$

- SSA measures Im part : $Im A(\xi, t) = \pi H^{(+)}(\xi, \xi, t)$
- Re part involves convolution integral :

$$Re A(\xi, t) \equiv -PV \int_0^1 dx H^{(+)}(x, \xi, t) \left[\frac{1}{x - \xi} + \frac{1}{x + \xi} \right]$$

dispersion relation for helicity- averaged twist-2 DVCS

- energy variables $\nu = \frac{Q^2}{4M_N\xi}, \quad \nu' = \frac{Q^2}{4M_Nx}$
- helicity averaged ampl : even in $\nu \quad \bar{A}(\nu, t) = \bar{A}(-\nu, t)$
- once subtracted fixed-t dispersion relation (analyticity, crossing)

$$Re\bar{A}(\nu, t) = \bar{A}(0, t) + \frac{\nu^2}{\pi} \int_{\nu_0}^{\infty} \frac{d\nu'^2}{\nu'^2} \frac{Im\bar{A}(\nu', t)}{\nu'^2 - \nu^2}$$



subtraction
at $\nu = 0$

$$\begin{aligned} \nu = \nu_0 &= \frac{Q^2}{4M_N} \longrightarrow \xi = 1 \\ \nu = 0 &\longrightarrow \xi \rightarrow \infty \\ \nu \rightarrow \infty &\longrightarrow \xi = 0 \end{aligned}$$

DR for DVCS (cont'd)

→ once subtracted fixed-t dispersion relation in variable x

$$ReA(\xi, t) = \Delta(t) + \frac{2}{\pi} PV \int_0^1 \frac{dx}{x} \frac{ImA(x, t)}{(\xi^2/x^2 - 1)}$$

Subtraction function

accessible through spin asymmetries

→ link with twist-2 GPD : $ImA(x, t) = \pi H^{(+)}(x, x, t)$

$$ReA(\xi, t) = \Delta(t) - PV \int_0^1 dx H^{(+)}(x, x, t) \left[\frac{1}{x - \xi} + \frac{1}{x + \xi} \right]$$

DR for DVCS amplitudes (in terms of GPDs)

Anikin, Teryaev (2007) Diehl, Ivanov (2007)

Polyakov, Vdh (2008)

Kumericki-Passek, Mueller, Passek (2008)

Goldstein, Liuti (2009)

...

subtraction function for DVCS

- difference between convolution and DR integrals :

$$\Delta(t) = PV \int_0^1 dx \left[H^{(+)}(x, \xi, t) - H^{(+)}(x, x, t) \right] \left[\frac{1}{\xi - x} - \frac{1}{\xi + x} \right]$$

- Subtraction function is independent of ξ → formally put $\xi = 0$

$$\Delta(t) = -PV \int_{-1}^1 dx \frac{1}{x} \left[H^{(+)}(x, 0, t) - H^{(+)}(x, x, t) \right]$$

- time reversal : GPD even in ξ (2nd argument)

$$H(x, -x, t) = H(x, x, t)$$

$$\boxed{\Delta(t) = -2 PV \int_{-1}^1 dx \frac{1}{x} [H(x, 0, t) - H(x, x, t)]}$$

subtraction function for DVCS: relation with D-term (I)

→ Lorentz invariance → polynomiality of Mellin moments of GPDs

$$\int_{-1}^1 dx \, x \, H(x, \xi, t) = A(t) + C(t) \, \xi^2$$

$$\int_{-1}^1 dx \, x^n \, H(x, \xi, t) = h_0^{(n)}(t) + h_2^{(n)}(t) \, \xi^2 + \dots + h_{n+1}^{(n)}(t) \, \xi^{n+1}$$

→ highest moment generated by
Polyakov-Weiss D-term contribution to GPD

$$h_{n+1}^{(n)}(t) = \frac{1}{N_f} \int_{-1}^1 dz \, z^n \, D(z, t)$$

subtraction function for DVCS: relation with D-term (II)

$$\begin{aligned} & \int_{-1}^1 \frac{dx}{x} [H(x, \xi + x, t) - H(x, \xi, t)] \\ = & \int_{-1}^1 \frac{dx}{x} \sum_{n=1}^{\infty} \frac{x^n}{n!} \frac{\partial^n}{\partial \xi^n} H(x, \xi, t) \\ = & \sum_{n=0}^{\infty} \frac{1}{(n+1)!} \int_{-1}^1 dx x^n \frac{\partial^{n+1}}{\partial \xi^{n+1}} H(x, \xi, t) \\ = & \sum_{\substack{n=odd}}^{\infty} h_{n+1}^{(n)}(t) \\ = & \frac{1}{N_f} \int_{-1}^1 dz \frac{D(z, t)}{1-z} \equiv \frac{2}{N_f} D(t) \end{aligned}$$

subtraction function for DVCS: relation with D-term (III)

→ $\Delta(t) = -2 \text{ } PV \int_{-1}^1 dx \frac{1}{x} [H(x, 0, t) - H(x, x, t)]$

$$\Delta(t) = \frac{4}{N_f} D(t) \quad \text{with} \quad D(t) \equiv \frac{1}{2} \int_{-1}^1 dz \frac{D(z, t)}{1 - z}$$

→ Gegenbauer expansion of D-term

$$D(z, t) = (1 - z^2) \sum_{\substack{n=1 \\ n \text{ odd}}}^{\infty} d_n(t) C_n^{(3/2)}(z)$$

Gegenbauer polynomials

 $C_1^{(3/2)}(z) = 3z$

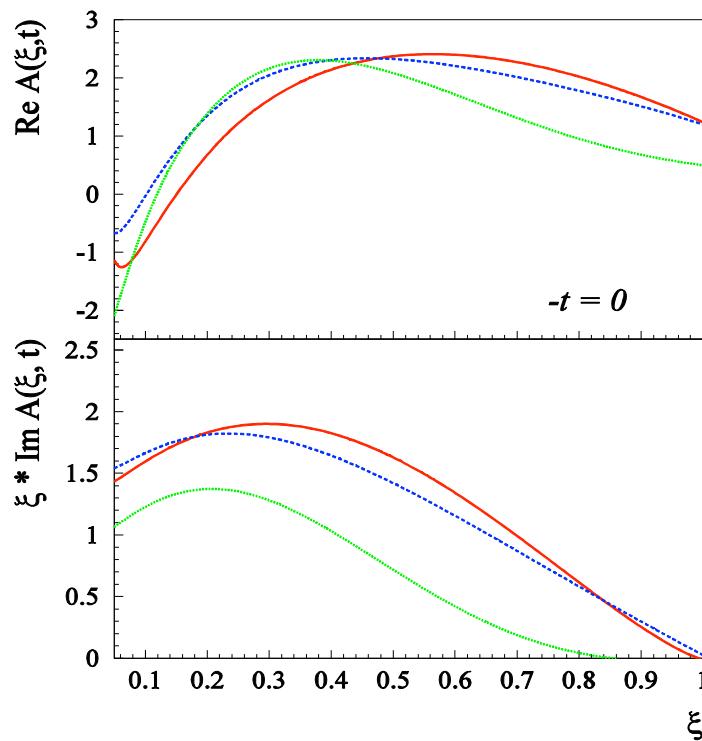
$$D(t) = \sum_{n=1}^{\infty} d_n(t)$$

in χ QSM at $t = 0$: $d_1 = -4.0$, $d_3 = -1.2$, $d_5 = -0.4$

Goeke, Polyakov, Vdh (2001)

also calculable in lattice QCD

dispersion analysis for DVCS: GPD H



Double Distribution model

$$---- \quad b_v = b_s = 1$$

..... $b_y = b_s = 20$

Dual model

_____ based on same forward distr.

result for real part shown for $\Delta = 0$

Polyakov, vdh (2008)

experimental strategy :

measurement of **imaginary parts** : single polarization observables
over sufficiently broad range in ξ

real parts : fix the subtraction constants, **cross check** by extracting constants at same t for different values of ξ

DR for DVCS amplitudes involving GPD H-tilde

- Under crossing : amplitude odd in ν $\bar{A}(\nu, t) = -\bar{A}(-\nu, t)$
- assume unsubtracted dispersion relation (cfr. Bjorken sum rule, GDH sum rule,... in forward case)

$$Re \bar{A}(\nu, t) = \frac{2\nu}{\pi} PV \int_{\nu_0}^{\infty} d\nu' \frac{Im \bar{A}(\nu', t)}{\nu'^2 - \nu^2}$$

$$Re \tilde{A}(\xi, t) = -\frac{1}{\pi} PV \int_0^1 dx Im \tilde{A}(x, t) \left[\frac{1}{x - \xi} - \frac{1}{x + \xi} \right]$$

- link with GPD

$$\begin{aligned} Im \tilde{A}(x, t) &= \pi \tilde{H}^{(+)}(x, x, t) \\ \tilde{H}^{(+)}(x, \xi, t) &\equiv \tilde{H}(x, \xi, t) + \tilde{H}(-x, \xi, t) \end{aligned}$$

DR for DVCS amplitudes involving GPDs E and E-tilde

→ GPD E : once-subtracted DR

GPD (H + E) is unsubtracted

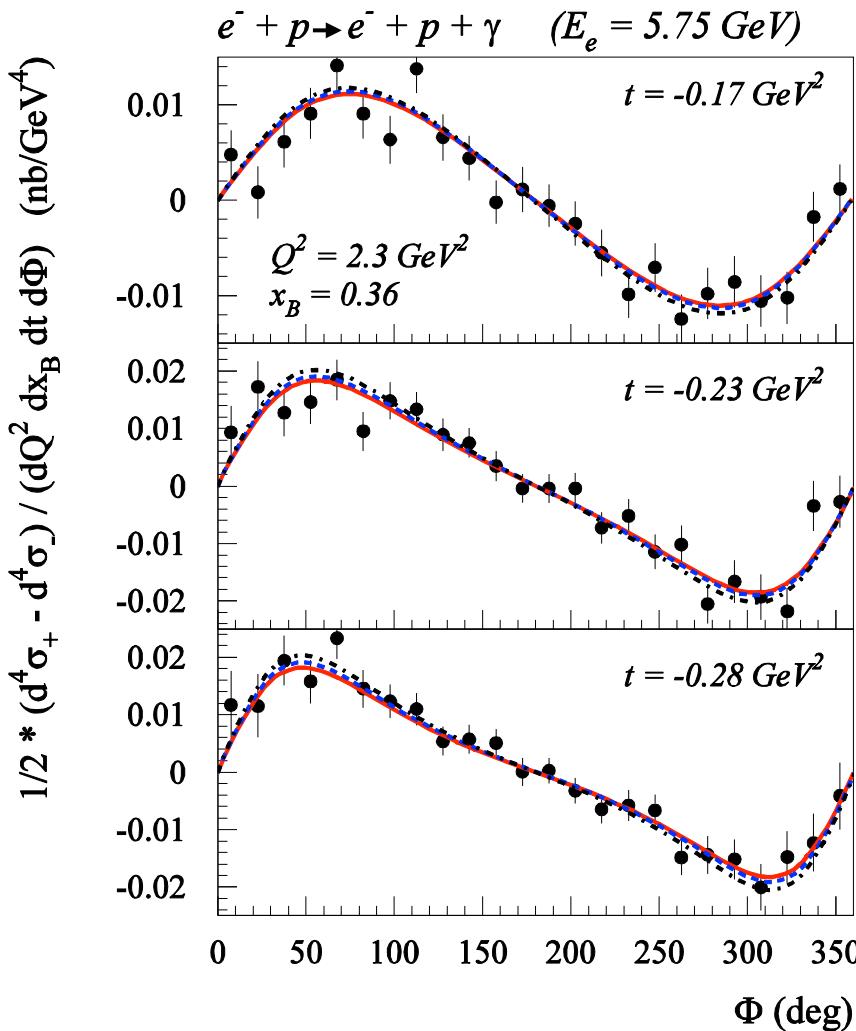
subtraction constant for GPD E is → - $\Delta(t)$
(cfr. - D-term)

→ GPD Etilde : once-subtracted DR

subtraction constant for GPD Etilde → sum of pseudoscalar meson poles
 (π^0, η, \dots)

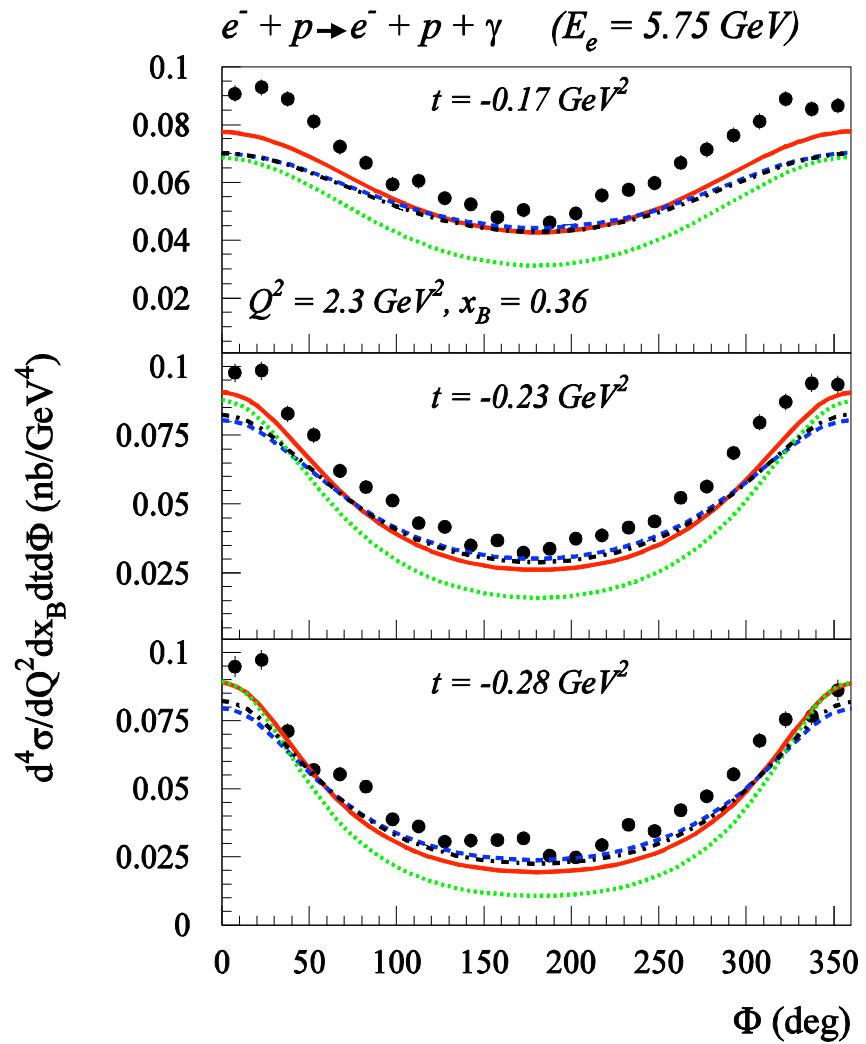
DVCS cross sections

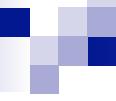
polarized



data : JLab/Hall A

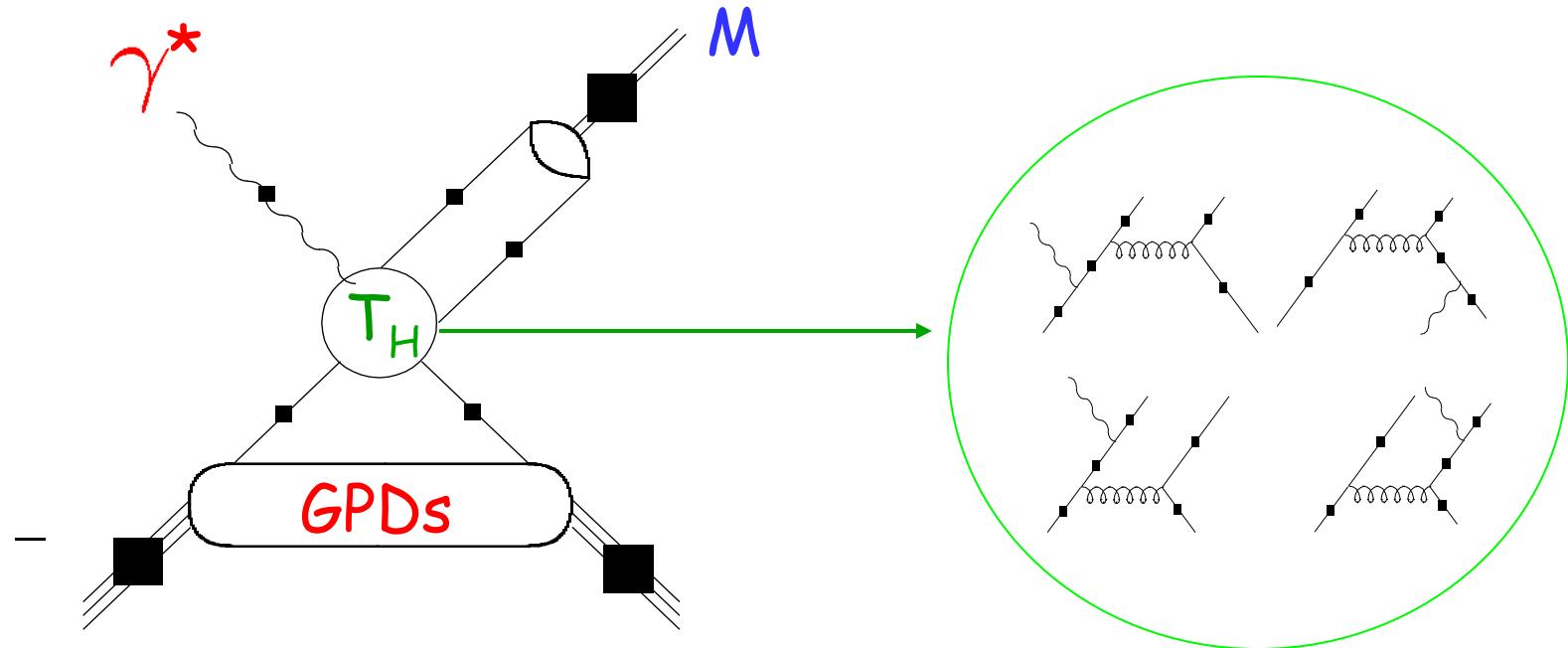
unpolarized





Hard meson electroproduction

hard electroproduction of mesons $(\rho^{0,\pm}, \omega, \phi, \pi, \dots)$



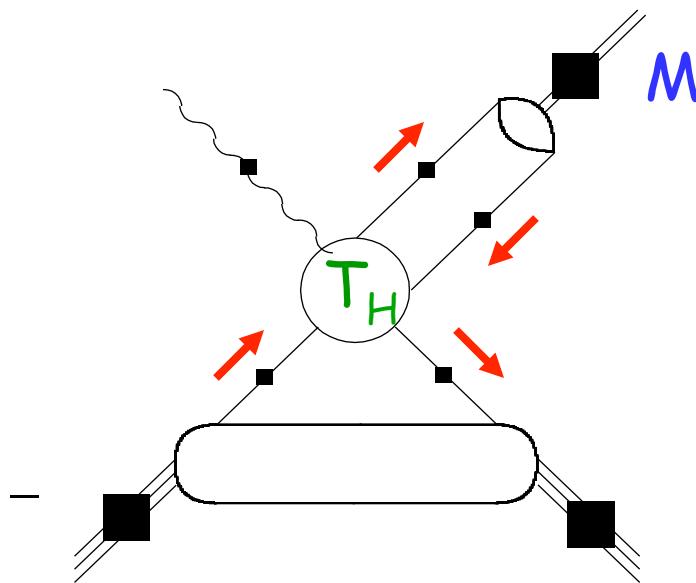
Factorization theorem shown for
longitudinal photon

hard scattering
amplitude

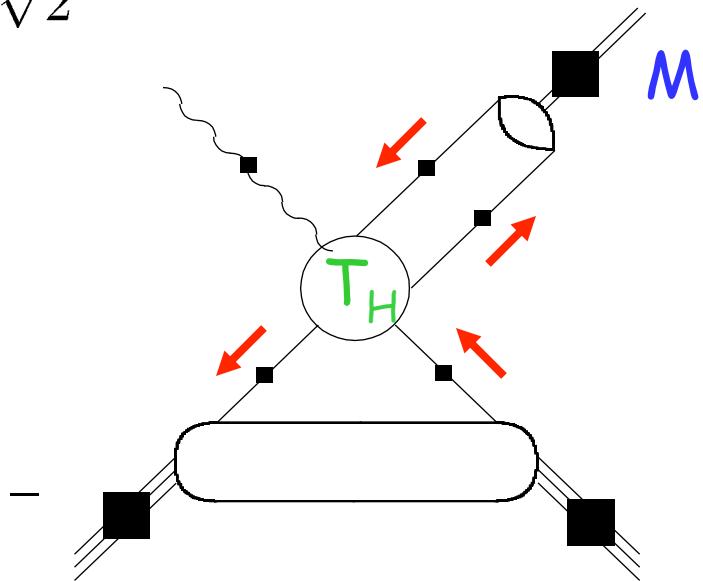
meson acts as helicity filter

longitudinally pol. Vector meson $|\rho_L\rangle = \frac{1}{\sqrt{2}} |\uparrow\downarrow + \downarrow\uparrow\rangle$

PseudoScalar meson $|\pi\rangle = \frac{1}{\sqrt{2}} |\uparrow\downarrow - \downarrow\uparrow\rangle$



\pm



→ Vector meson : accesses unpolarized GPDs H and E

→ PseudoScalar meson : accesses polarized GPDs \tilde{H} and \tilde{E}

hard electroproduction of vector mesons ($\rho^{0,\pm}$, ω , ϕ)

→ amplitude for longitudinally polarized vector meson

$$\begin{aligned}\mathcal{M}_{V_L}^L &= -ie \frac{4}{9} \frac{1}{Q} \left[\int_0^1 dz \frac{\Phi_{V_L}(z)}{z} \right] \frac{1}{2} (4\pi\alpha_s) \\ &\times \left\{ A_{V_L N} \bar{N}(p') \gamma \cdot n N(p) + B_{V_L N} \bar{N}(p') i\sigma^{\kappa\lambda} \frac{n_\kappa \Delta_\lambda}{2m_N} N(p) \right\}\end{aligned}$$

→ leading (1 gluon exchange) amplitude depends on α_s goes as $1/Q$

→ dependence on meson distribution amplitude Φ_V

$$\Phi_{V_L}(z) = f_V 6z(1-z)$$

with $f_\rho = 0.216$ GeV, $f_\omega = 0.195$ GeV, from $V \rightarrow e^+e^-$

flavor decomposition of the GPDs H and E

ρ^0

$$A_{\rho_L^0 p} = \int_{-1}^1 dx \frac{1}{\sqrt{2}} (e_u H^u - e_d H^d) \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}$$

$$B_{\rho_L^0 p} = \int_{-1}^1 dx \frac{1}{\sqrt{2}} (e_u E^u - e_d E^d) \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}$$

ρ^\pm

$$A_{\rho_L^\pm n} = - \int_{-1}^1 dx (H^u - H^d) \left\{ \frac{e_u}{x - \xi + i\epsilon} + \frac{e_d}{x + \xi - i\epsilon} \right\}$$

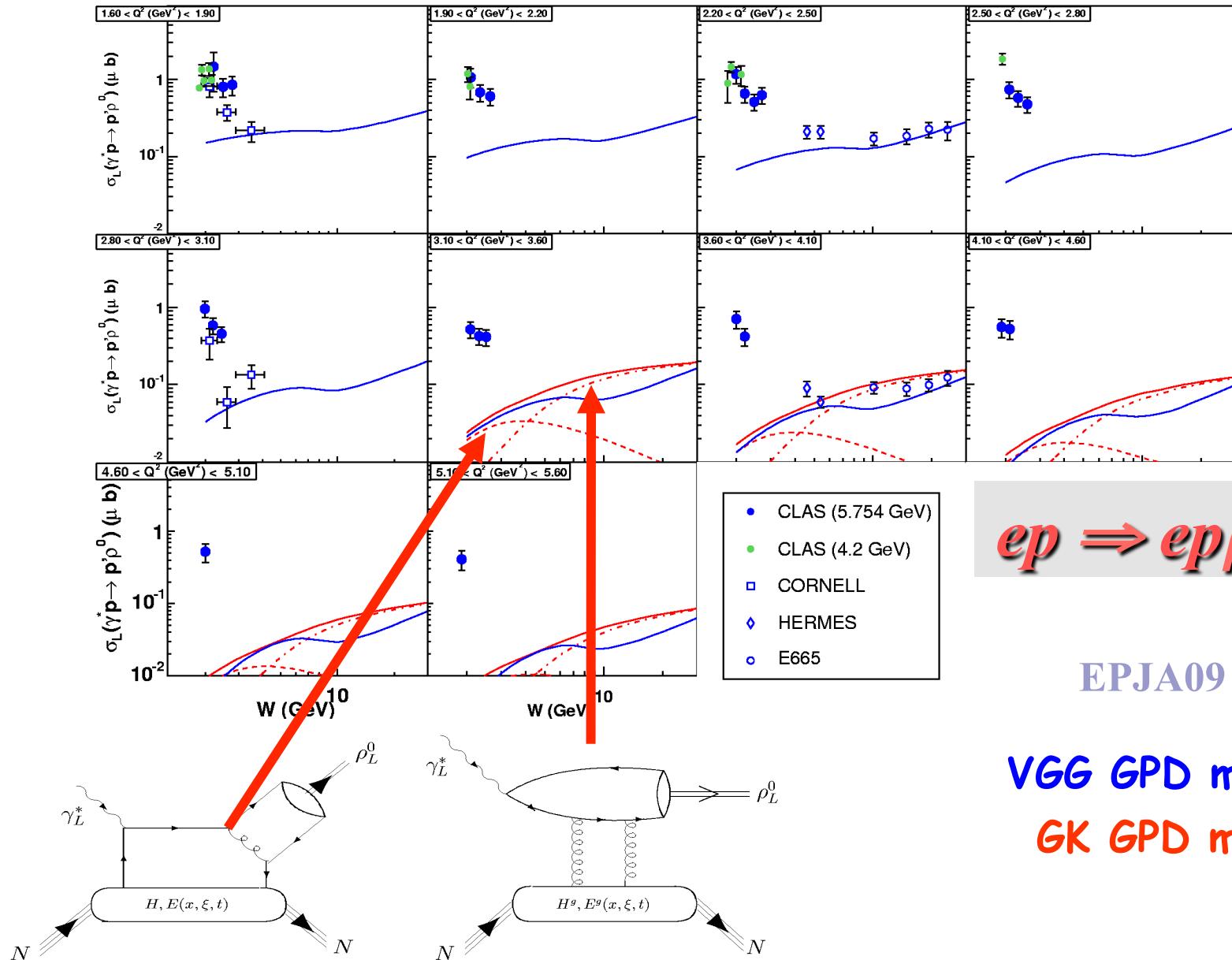
$$B_{\rho_L^\pm n} = - \int_{-1}^1 dx (E^u - E^d) \left\{ \frac{e_u}{x - \xi + i\epsilon} + \frac{e_d}{x + \xi - i\epsilon} \right\}$$

ω

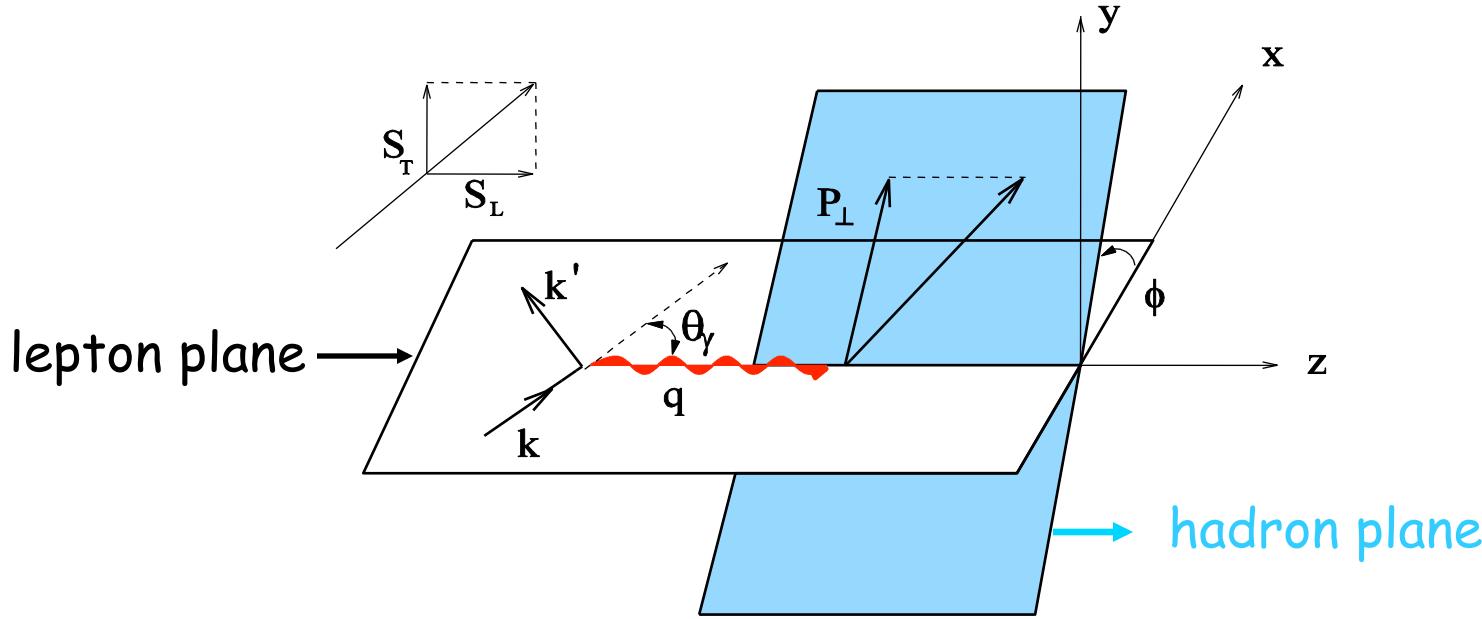
$$A_{\omega_L p} = \int_{-1}^1 dx \frac{1}{\sqrt{2}} (e_u H^u + e_d H^d) \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}$$

$$B_{\omega_L p} = \int_{-1}^1 dx \frac{1}{\sqrt{2}} (e_u E^u + e_d E^d) \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}$$

hard electroproduction of ρ^0 : cross sections



hard electroproduction of mesons: target normal spin asymmetries



in leading order (in Q) \rightarrow 2 observables $\sigma = \sigma_L + P_n \sigma_L^n$

\rightarrow Asymmetry :

$$A = \frac{2 \sigma_L^n}{\pi \sigma_L}$$

Target polarization normal
to hadron plane

hard electroproduction of vector mesons: target normal spin asymmetries

$$\begin{aligned} A_{VN} &= - \frac{2 |\Delta_\perp|}{\pi} \\ &\times \frac{\text{Im}(AB^*) / m_N}{|A|^2 (1 - \xi^2) - |B|^2 (\xi^2 + t/(4m_N^2)) - \text{Re}(AB^*) 2\xi^2} \end{aligned}$$

- $A \rightarrow \text{GPD H}$ $B \rightarrow \text{GPD E}$
- linear dependence on GPD E \longleftrightarrow unpolarized cross section
- ratio : less sensitive to NLO and higher twist effects
- sensitivity to J^u and J^d
measure of TOTAL angular momentum contribution to proton spin

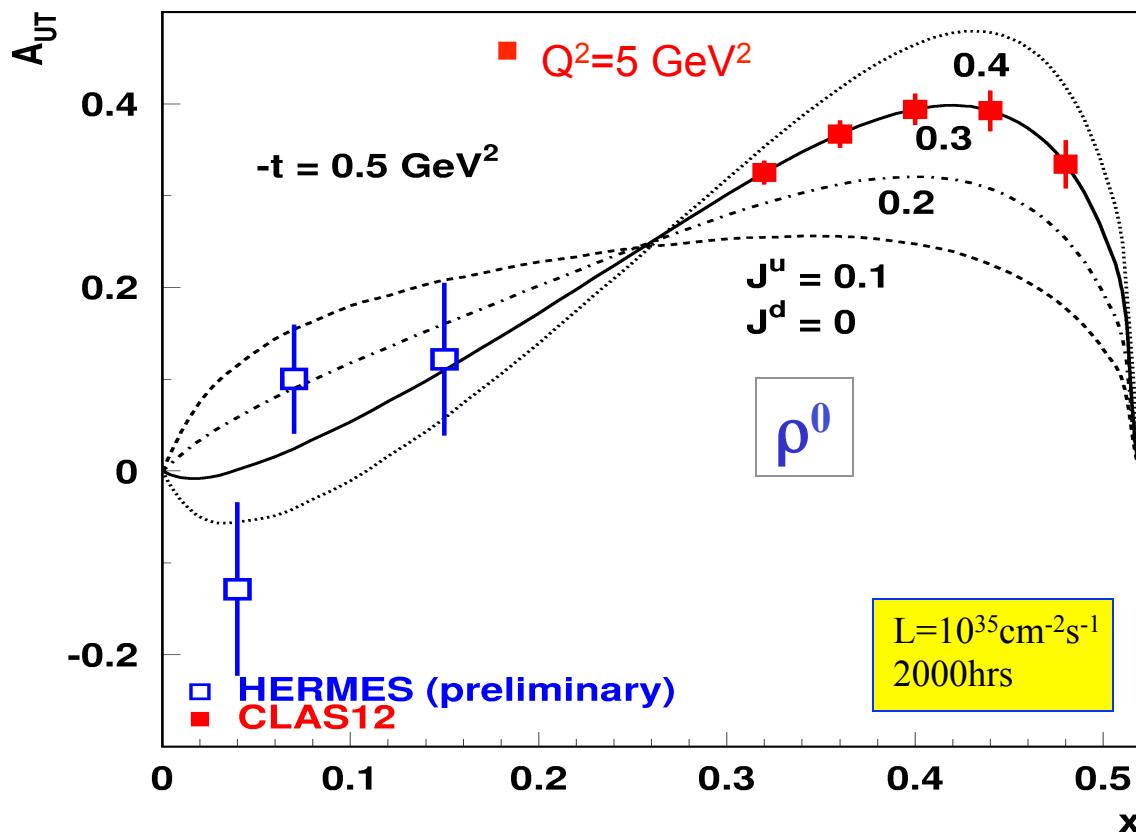
exclusive ρ^0 production: transverse target

$$A_{UT} = - \frac{2\Delta (\text{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \text{Re}(AB^*)2\xi^2}$$

ρ^0

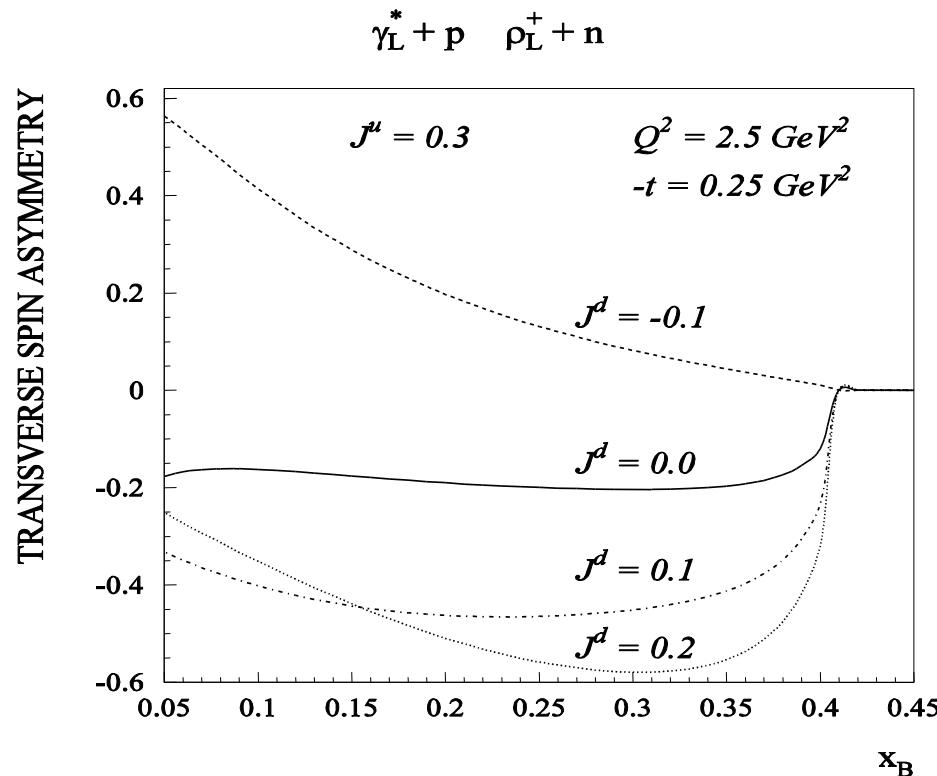
$$A \sim (2H^u + H^d)$$

$$B \sim (2E^u + E^d)$$

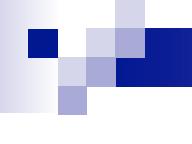


Asymmetry depends linearly on the GPD E , which enters Ji's sum rule.

hard electroproduction of vector mesons: target normal spin asymmetries

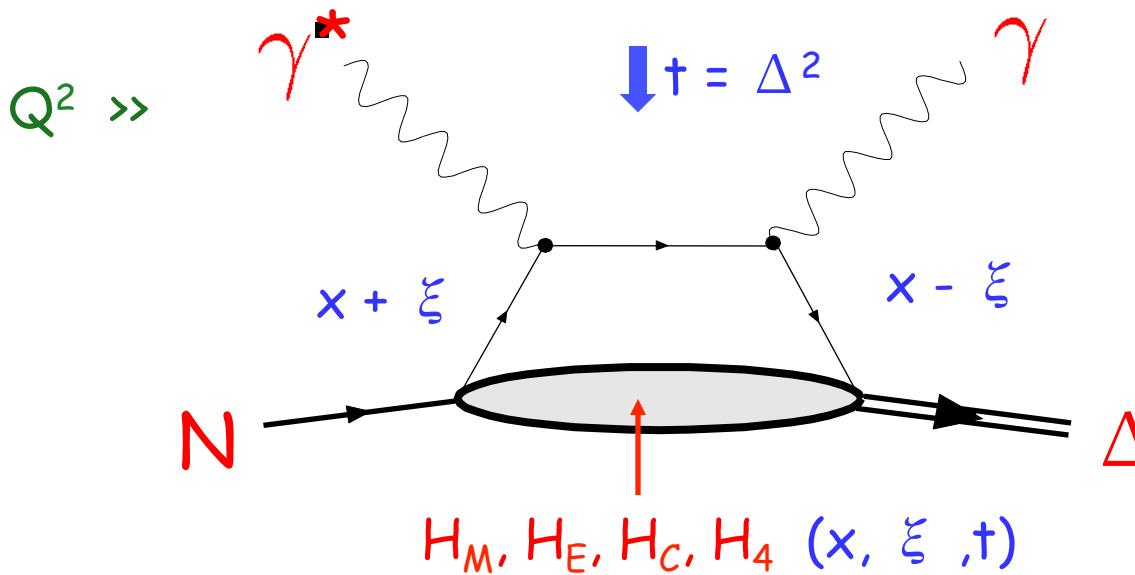


ρ_L^+ sensitive to $(J^u - J^d)$



$N \rightarrow \Delta$ DVCS

$N \rightarrow \Delta$ DVCS and GPDs



low $-t$ process :
 $-t \ll Q^2$



$$\int_{-1}^1 dx H_M(x, \xi, t) = 2 G_M^*(t)$$

$$\int_{-1}^1 dx H_E(x, \xi, t) = 2 G_E^*(t)$$

$$\int_{-1}^1 dx H_C(x, \xi, t) = 2 G_C^*(t)$$

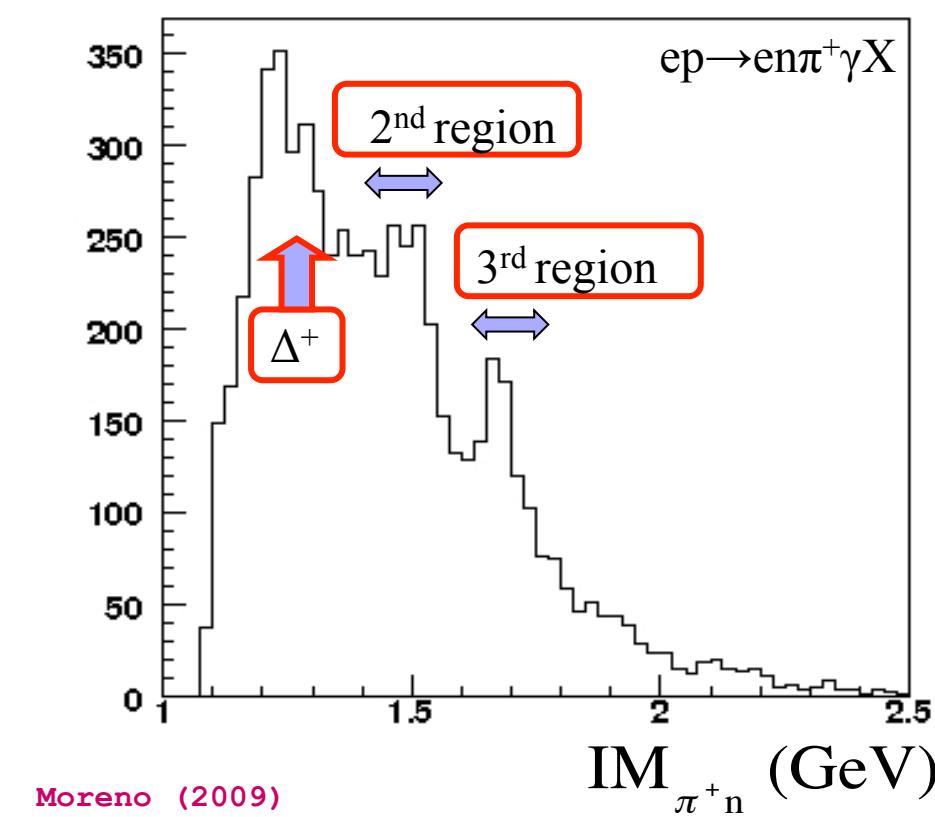
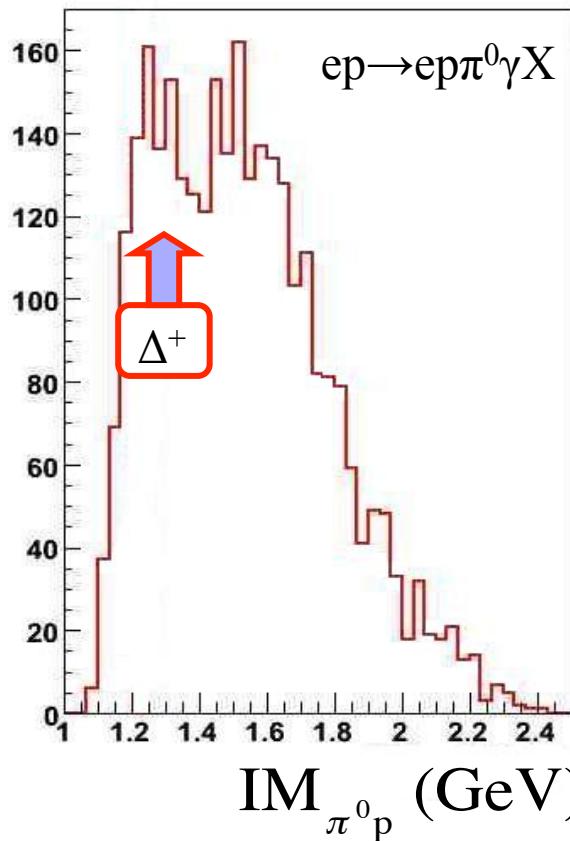
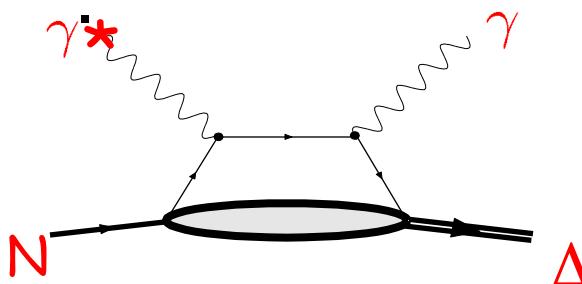
$$\int_{-1}^1 dx H_4(x, \xi, t) = 0$$

Jones-Scadron
 $N \rightarrow \Delta$ form
factors

$N \rightarrow \Delta$ DVCS events in CLAS

$W > 2 \text{ GeV}$

$Q^2 \approx 2.5 \text{ GeV}^2$



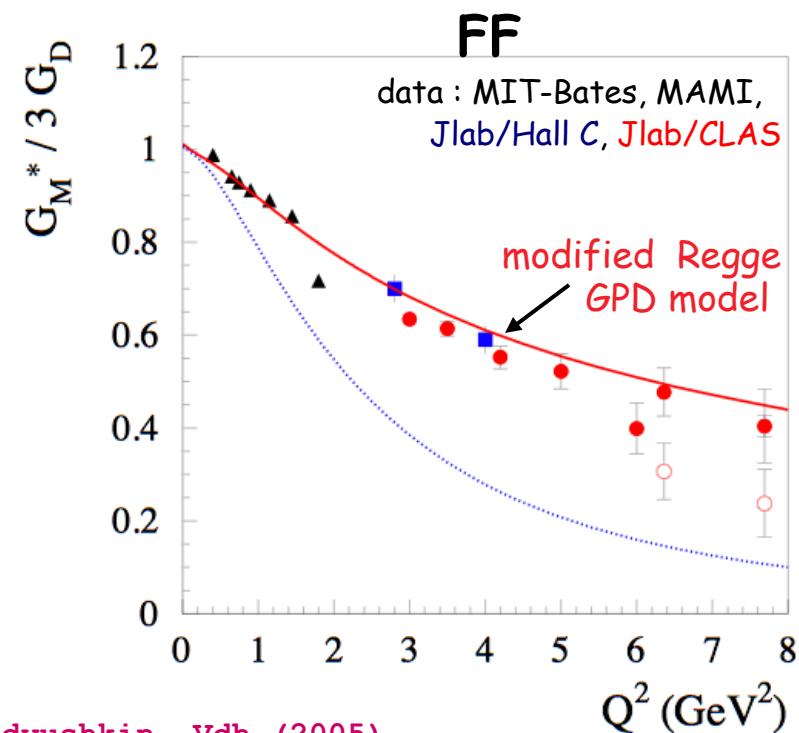
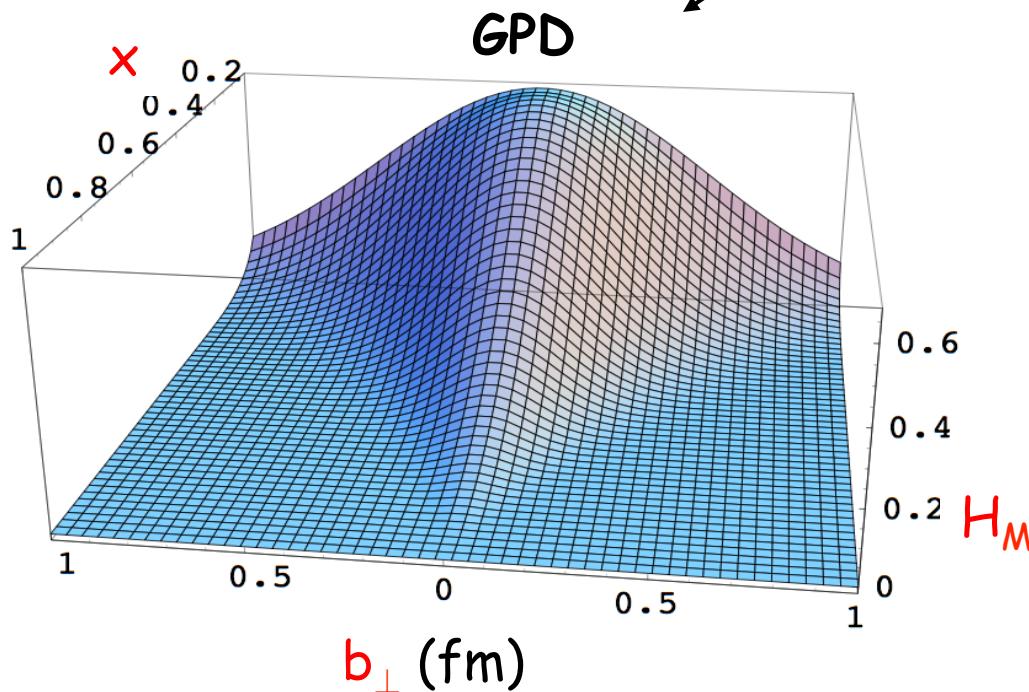
N -> Δ magnetic dipole GPD and FF

large N_c : $G_M^*(0) = \kappa_V / \sqrt{2} = 2.62$

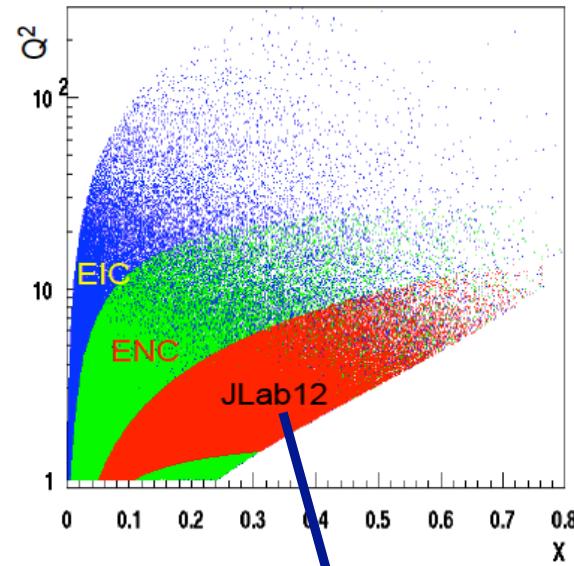
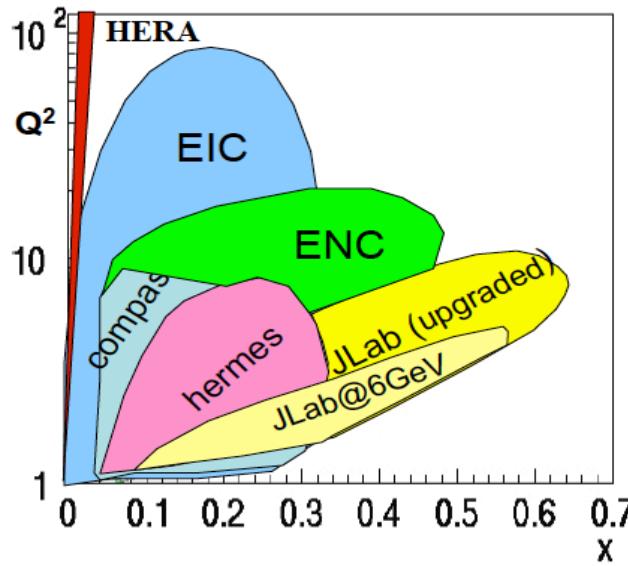
EXP: $G_M^*(0) = 3.02$

large N_c limit

$$G_M^*(t) = \frac{G_M^*(0)}{\kappa_V} \int_{-1}^{+1} dx \left\{ E^u(x, \xi, t) - E^d(x, \xi, t) \right\} = \frac{G_M^*(0)}{\kappa_V} \left\{ F_2^p(t) - F_2^n(t) \right\}$$

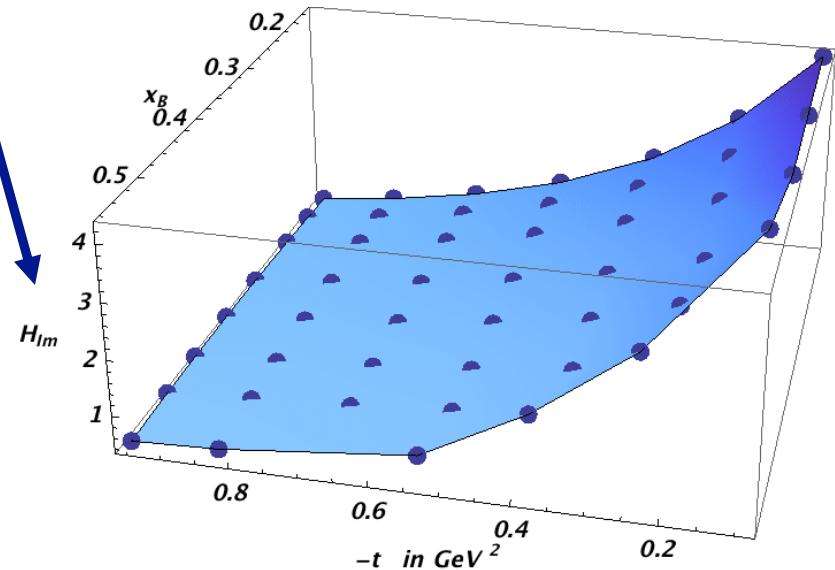


Energy / Luminosity frontier



Jlab 11 GeV projections:
Guidal (2012)

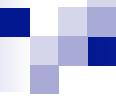
Hard exclusive reactions :
high energy and high luminosity
required + polarization



Summary

Light-front densities provide an imaging of hadrons

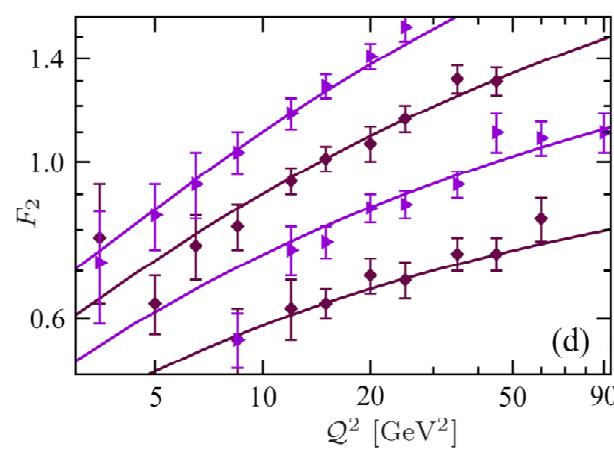
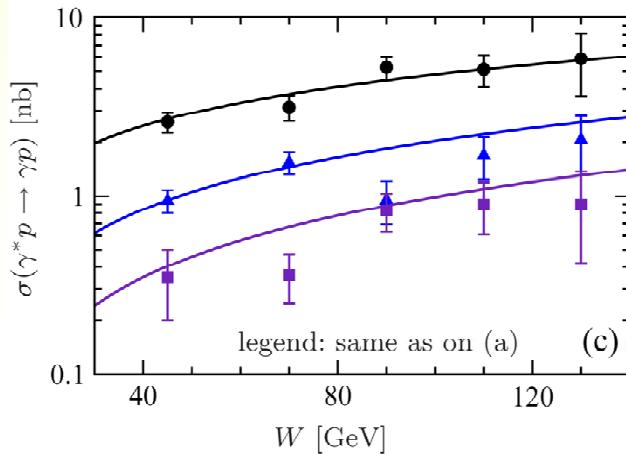
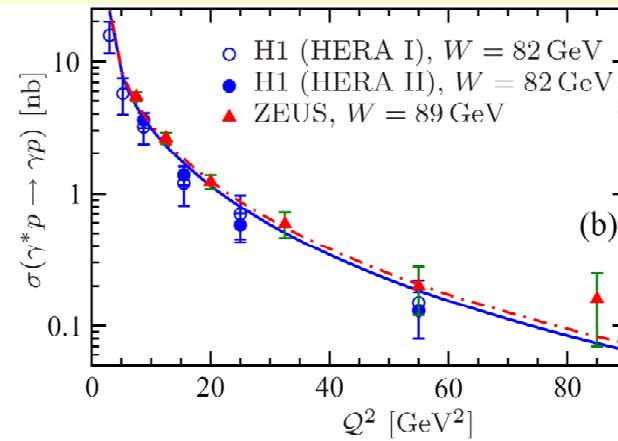
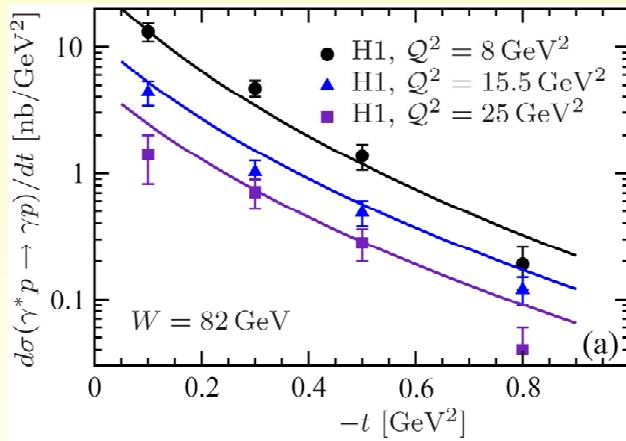
- elastic nucleon form factors : empirical transverse charge densities reveal different spatial distributions of u/d quarks
- shape of hadrons can be understood within relativistic QFT from higher e.m. moments of transverse charge densities as deviations from their "natural" values
- GPDs: 3D picture, densities in longitudinal momentum, transverse position further extensions including transverse momentum d.o.f.
- GPDs allow access to quark & gluon angular momentum contributions
- DVCS extracts Compton Form Factors involving GPDs, new strategies in analysis: model independent fit extractions, dispersion relations
- rich harvest around the corner: Jlab 12 GeV, Compass
Future: sea, gluon region -> high energy + high luminosity: EIC, ENC



Supplementary material

DVCS @ H1 / ZEUS: data

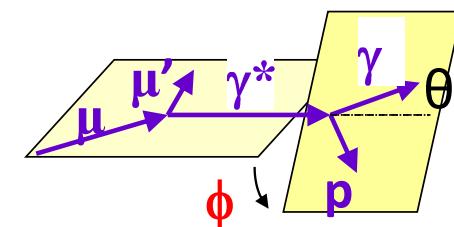
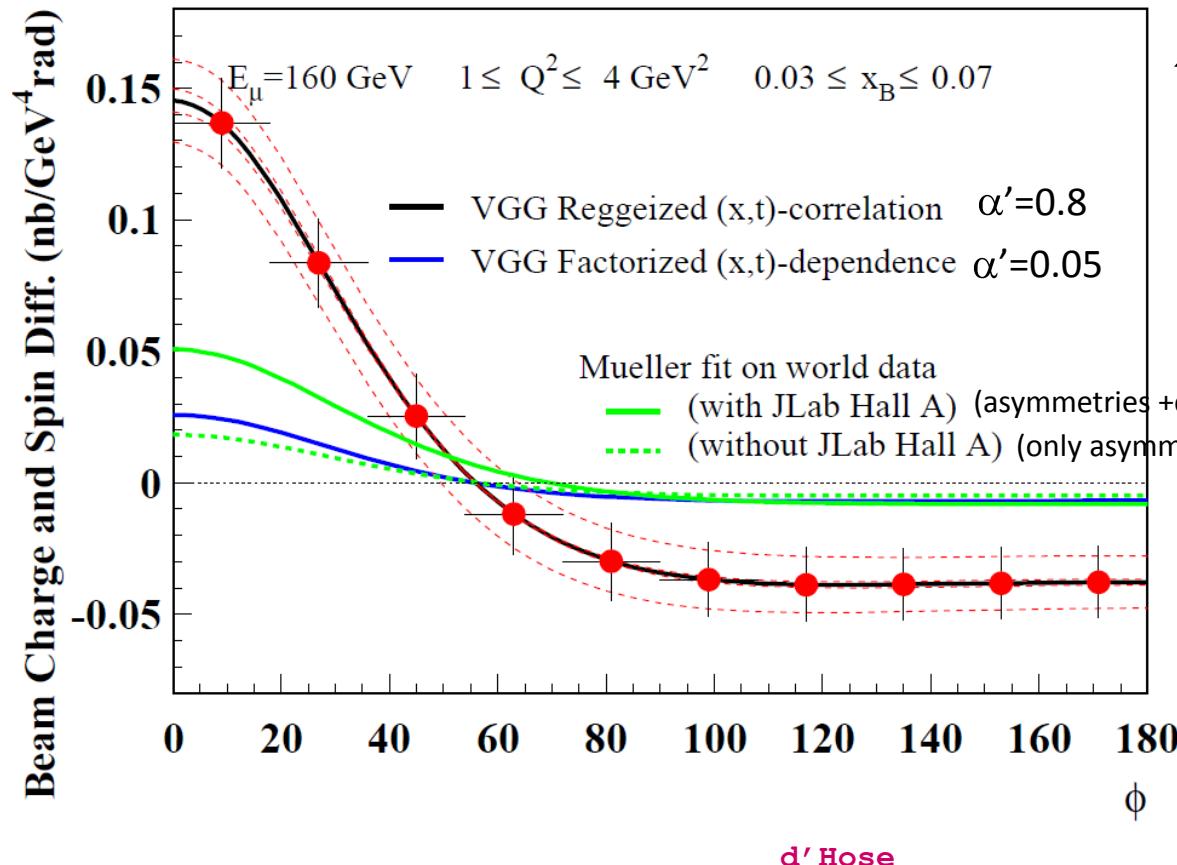
good DVCS fits at LO, NLO, and NNLO with flexible GPD ansatz



DVCS @ COMPASS: projections

beam charge & spin asymmetry

Comparison to different models



2 years of data
160 GeV muon beam
2.5m LH₂ target
 $\varepsilon_{\text{global}} = 10\%$