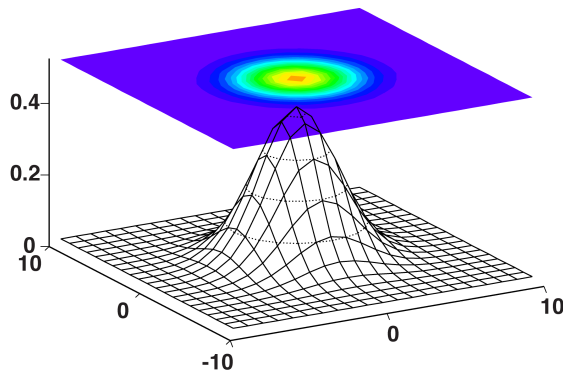


From Hard Exclusive meson electroproduction to deeply virtual Compton scattering

Franck Sabatié
CEA Saclay

in collaboration with P. Kroll and H. Moutarde

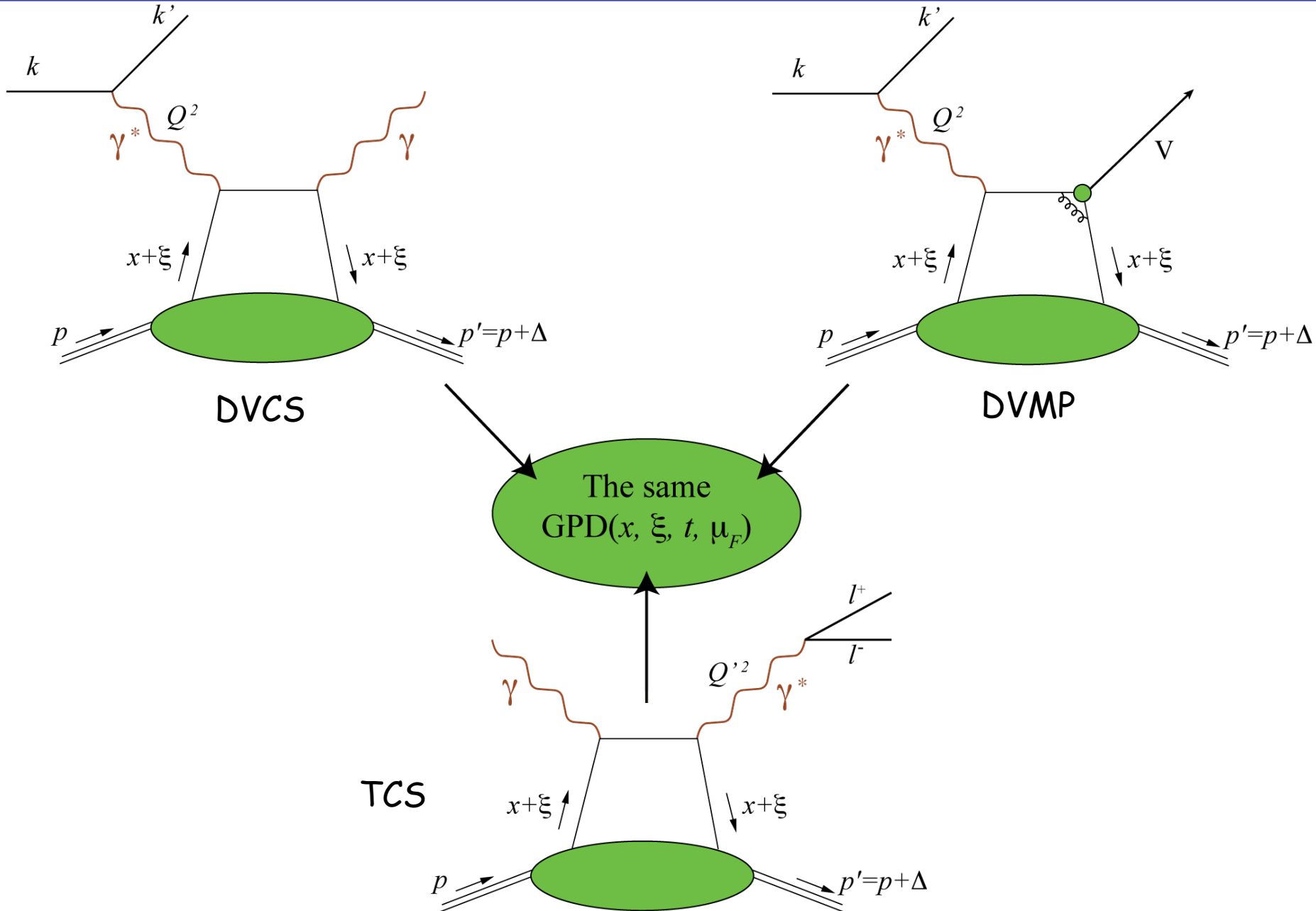
Eur. Phys. J. C (2013) 73:2278 [arXiv:1210.6975]



- > Generalized Parton Distributions and universality
- > The Goloskokov-Kroll GPD model
- > Deeply Virtual Compton Scattering
- > Confrontation with DVCS data
- > Potential extensions
- > Conclusion

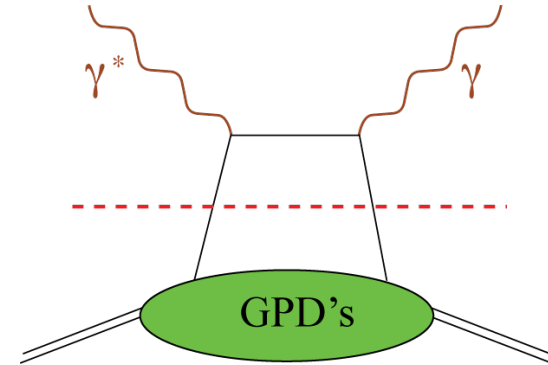


Generalized Parton Distributions are **Universal** !



Factorization and Universality

The partonic interpretation of all these hard exclusive processes relies on collinear *factorization theorems* valid in the Bjorken limit of large Q^2 and W , fixed $x_B \approx 2\xi / (1+\xi)$



The GPD's then depend on an arbitrary factorization scale μ_F which is the separation scale between soft and hard parts

The soft part, *i.e.* GPD's, should be the same for DVCS, DVMP, TCS, ... :

Not only is **Universality an essential property**
But we *need* it to **Explore the whole GPD landscape**

(indeed, all those processes have different dependences wrt the GPD's and quark flavors/gluons)

Different Hard Processes : different advantages

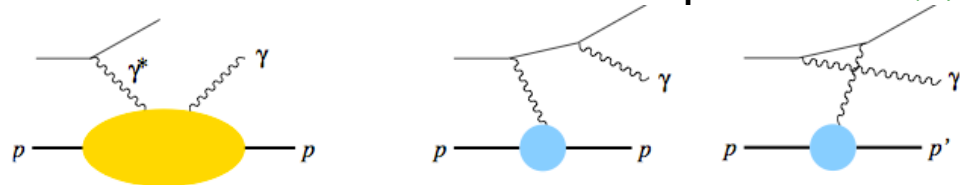
Deeply Virtual Compton Scattering

- Theory is under control : up to α_S^2 , twist-3, target mass corrections, etc Müller et al, Braun et al
- Sensitive to the quark combination : $\frac{4}{9}u + \frac{1}{9}d + \frac{1}{9}s$
- At JLab/HERMES energies, mostly sensitive to valence and sea quarks
- Sensitive to gluon GPDs through scale dependence at NLO or beyond

Direct access to the Re and Im part of Compton Form Factors \mathcal{H}, \dots

through interference with known **Bethe-Heitler** process

Diehl, Gousset, Pire, Ralston, ...



Hard Meson Electroproduction

- Many channels available for flavor separation ($\rho^0, \rho^+, \pi^0, \pi^+, \phi, \dots$)
- J/Ψ and ϕ are especially interesting to access gluon GPDs (H and even E)
- Theory less under control : convolution with (unknown) meson WF, very slow scaling, large power and NLO corrections

The GK parametrization of GPDs

Goloskokov & Kroll, 2005-2011

Double Distribution ansatz (Radyushkin, '96 and later) :

$$F_i(x, \xi, t) = \int_{-1}^{+1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \delta(\beta - \alpha\xi - x) f_i(\alpha, \beta, t) + \underbrace{D_i \Theta(\xi^2 - x^2)}_{\text{D-term}}$$

$f_i(\alpha, \beta, t) =$ zero-skewness GPD x weight fct. (generates ξ dependence)

$$F(\rho, \xi = 0, t) = f(\rho) \exp[(b_f + \alpha'_f \ln(1/\rho))t] \quad (\text{Regge-like } t\text{-dependence})$$

$$f = q, \Delta q, \delta^q \text{ for } H, \tilde{H}, H_T \text{ or } c\rho^{-\alpha_f(0)}(1 - \rho)^{\beta_f}$$

D-term largely *unknown*, neglected in GK parametrization

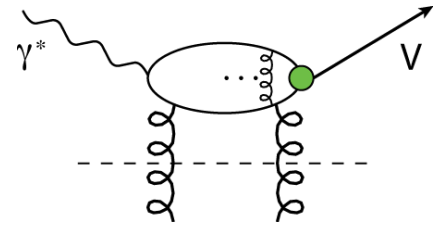
Advantages of DD's: - polynomiality of GPD moments automatically satisfied
- parametrization in terms of PDF is easy

Drawbacks of DD's: been shown to lack flexibility, skewness-ratio problem

More on DD ? See C. Mezrag's talk on Friday in the DPWG !

Analysis of Deep Virtual Meson Production

Goloskokov & Kroll, 2005-2011

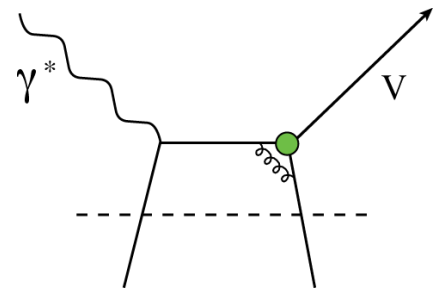


Subprocess amplitude via **Modified Perturbative Approach**

Sterman et al, 92

LO pQCD + quark k_{\perp} + Sudakov suppression

(large transverse separation)



On the proton side, partons are emitted/absorbed collinearly

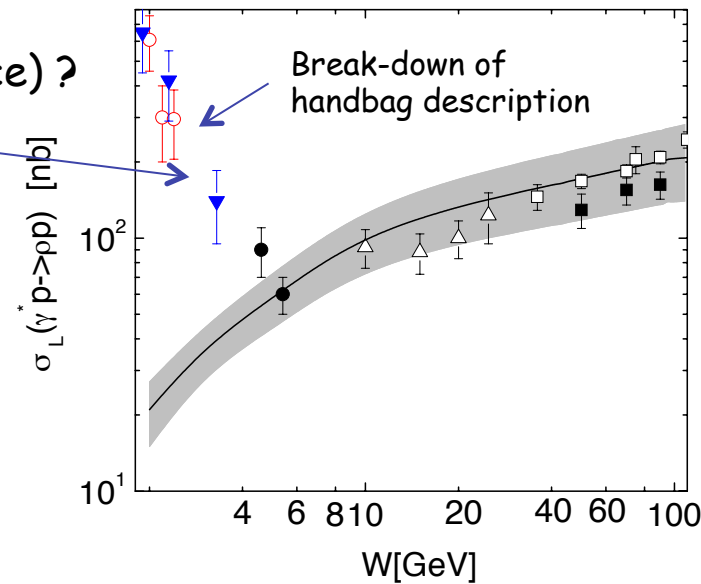
Meson wave function are gaussians : $\Psi_M(\tau, \mathbf{k}_{\perp}) \propto \exp[-a_M^2 \mathbf{k}_{\perp}^2 / (\tau \bar{\tau})]$

Fit to all meson data from H1, ZEUS, E665, HERMES, COMPASS

Large range of x_B (10^{-4} -0.1), Q^2 (3-100 GeV^2) and W (5-180 GeV)

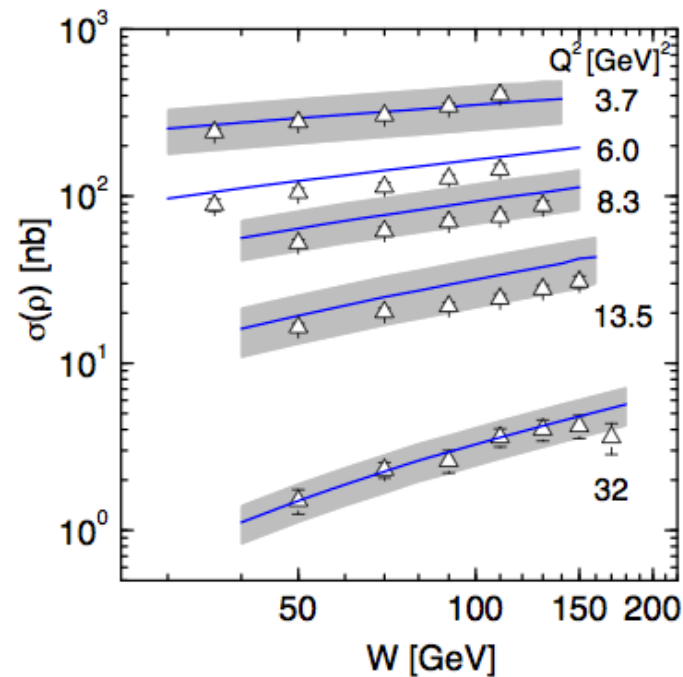
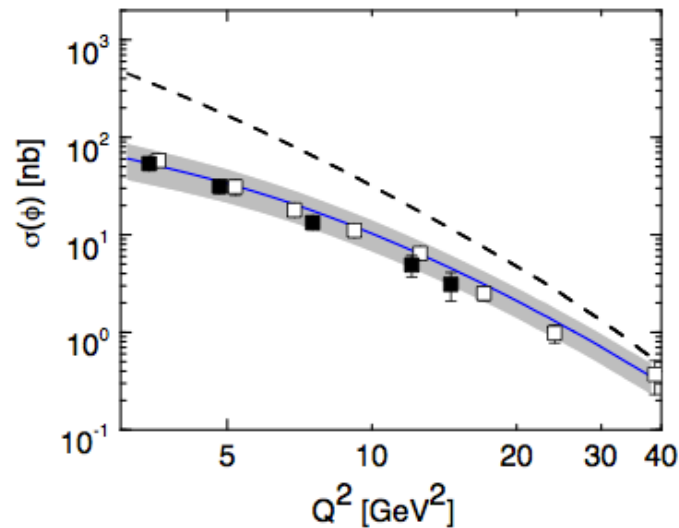
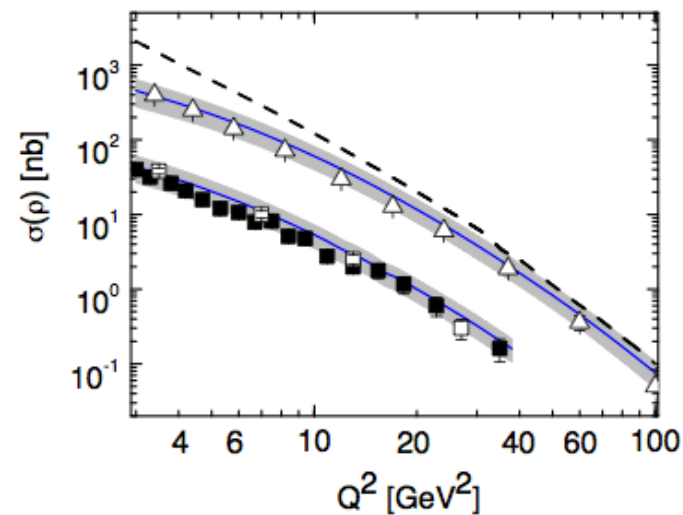
Why not **CLAS data** (on ρ^0 for instance) ?

Consequence: model tuned for rather low values of x_B



Example of fits to ρ and ϕ cross-section HERA data

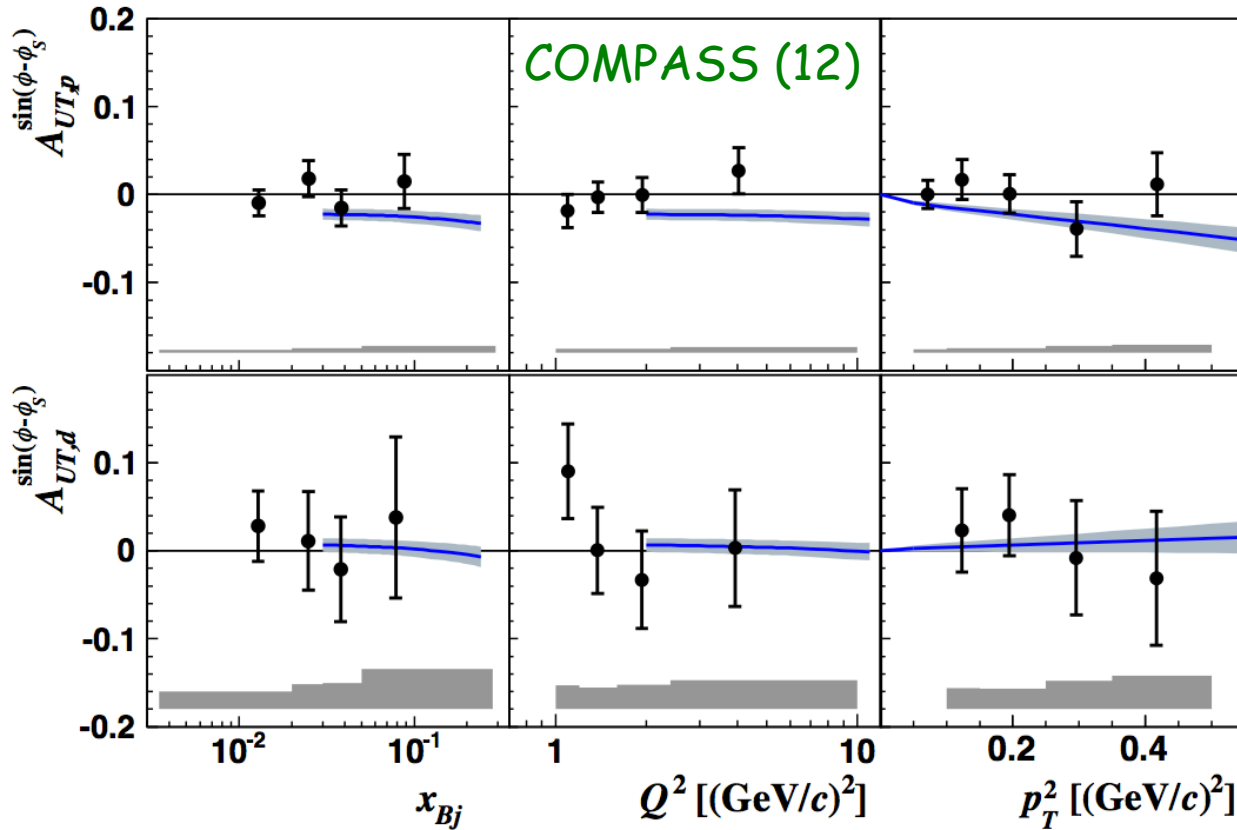
Goloskokov & Kroll, 2005-2011



Excellent agreement over large kinematical range

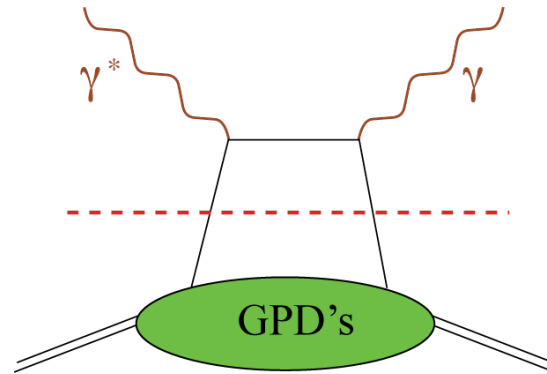
Transverse target spin asymmetry for ρ^0

Goloskokov & Kroll, 2005-2011



- Small asymmetry measured by both COMPASS and HERMES
- In GK model, gluon and sea contributions for E cancel each other for ρ^0
- Dominated by valence quark contributions from E but small at these x_B values

GPD's enter DVCS through Compton Form Factors



$$\underbrace{\mathcal{F}(\xi, t, Q^2)}_{\text{Compton Form Factor (CFF)}} = \int_{-1}^{+1} dx \underbrace{C\left(x, \xi, \alpha_S(\mu_R), \frac{Q}{\mu_F}\right)}_{\text{Integration Kernel}} \underbrace{F(x, \xi, t, \mu_F)}_{\text{GPD's}}$$

Compton Form Factor (CFF)
CFF are *complex* functions!

Integration Kernel has been worked out up to NLO

Müller et al
and many others

GPD's
Factorization scale dependence through evolution equations

$$\xi \simeq \frac{x_B}{2 - x_B}$$

More on DVCS@NLO?
See H. Moutarde's talk on Friday in the DPWG!

Definition of DVCS observables

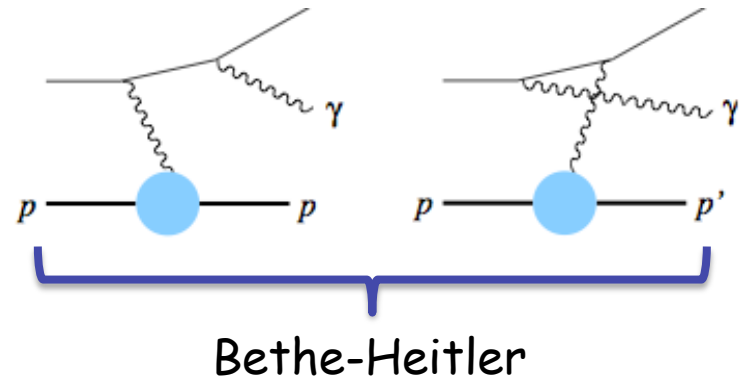
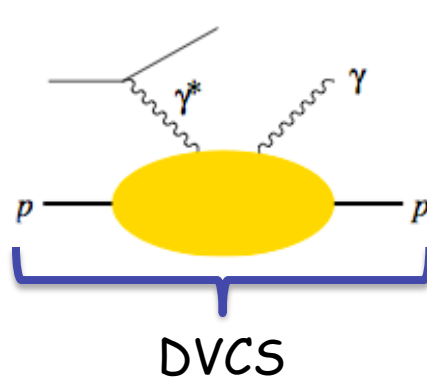
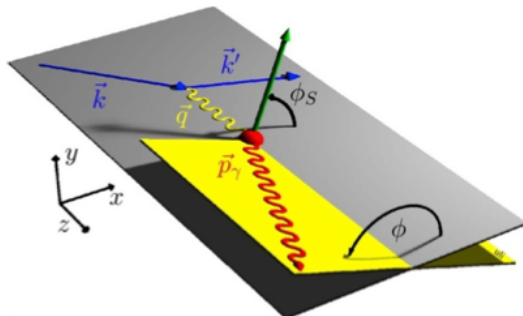
In the one-photon exchange approximation of QED,
the BH, DVCS and interference parts of the $ep \rightarrow ep\gamma$ cross section read :

Diehl et al

$$|\mathcal{M}_{\text{BH}}|^2 \propto \frac{1}{|t|} \frac{1}{P(\cos \phi)} \sum_{n=0}^3 [c_n^{\text{BH}} \cos(n\phi) + s_n^{\text{BH}} \sin(n\phi)]$$

$$|\mathcal{M}_{\text{DVCS}}|^2 \propto \sum_{n=0}^3 [c_n^{\text{DVCS}} \cos(n\phi) + s_n^{\text{DVCS}} \sin(n\phi)]$$

$$\mathcal{M}_{\text{I}} \propto \frac{1}{|t|} \frac{1}{P(\cos \phi)} \sum_{n=0}^3 [c_n^{\text{I}} \cos(n\phi) + s_n^{\text{I}} \sin(n\phi)]$$



Definition of DVCS observables

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$$\mathcal{M}_{\text{I}} \propto \frac{1}{|t|} \frac{1}{P(\cos \phi)} \sum_{n=0}^3 [c_n^{\text{I}} \cos(n\phi) + s_n^{\text{I}} \sin(n\phi)]$$

All the observables' evaluations in this talk are achieved using an **exact treatment of all contributions** apart from the OPE in the hadronic tensor, done at leading twist (only **twist-2 GPD's** are considered)

Guichon, Vanderhaeghen

Definition of DVCS observables

The $lp \rightarrow lp\gamma$ cross section on an unpolarized target for a given beam charge e_l and beam helicity $h_l/2$ can be written as :

$$d\sigma^{h_l, e_l}(\phi) = d\sigma_{UU}(\phi) [1 + h_l A_{LU, DVCS}(\phi) + e_l h_l A_{LU, I}(\phi) + e_l A_C(\phi)]$$

If one has access to both **different beam charges and helicities**, one can extract :

$$A_C(\phi) = \frac{1}{4d\sigma_{UU}(\phi)} \left[(d\sigma^{\rightarrow\rightarrow} + d\sigma^{\leftarrow\leftarrow}) - (d\sigma^{\rightarrow\leftarrow} + d\sigma^{\leftarrow\rightarrow}) \right]$$
$$A_{LU, I}(\phi) = \frac{1}{4d\sigma_{UU}(\phi)} \left[(d\sigma^{\rightarrow\rightarrow} - d\sigma^{\leftarrow\leftarrow}) - (d\sigma^{\rightarrow\leftarrow} - d\sigma^{\leftarrow\rightarrow}) \right]$$
$$A_{LU, DVCS}(\phi) = \frac{1}{4d\sigma_{UU}(\phi)} \left[(d\sigma^{\rightarrow\rightarrow} - d\sigma^{\leftarrow\leftarrow}) + (d\sigma^{\rightarrow\leftarrow} - d\sigma^{\leftarrow\rightarrow}) \right]$$

If one only has access to **different beam helicities**, one can extract :

$$A_{LU}^{e_l}(\phi) = \frac{d\sigma^{\rightarrow e_l} - d\sigma^{\leftarrow e_l}}{d\sigma^{\rightarrow e_l} + d\sigma^{\leftarrow e_l}} = \frac{e_l A_{LU, I}(\phi) + A_{LU, DVCS}(\phi)}{1 + e_l A_C(\phi)}$$

(equivalent expressions for polarized target case)

Definition of DVCS observables

Finally, experiments sometimes prefer to publish Fourier Harmonics of the asymmetries which are linked to the CFF's.

Taking the charge asymmetry for instance, it is evaluated this way :

$$A_C^{\cos(n\phi)} = N \int_0^{2\pi} d\phi A_C(\phi) \cos(n\phi)$$

N is $1/2\pi$ in the case $n = 0$ and $1/\pi$ for $n \geq 1$

In the BMK approximation, a few different harmonics read :

$$A_C^{\cos \phi} \propto \text{Re} \left[F_1 \mathcal{H} + \xi(F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4m^2} F_2 \mathcal{E} \right]$$

$$A_{LU,I}^{\sin \phi} \propto \text{Im} \left[F_1 \mathcal{H} + \xi(F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4m^2} F_2 \mathcal{E} \right]$$

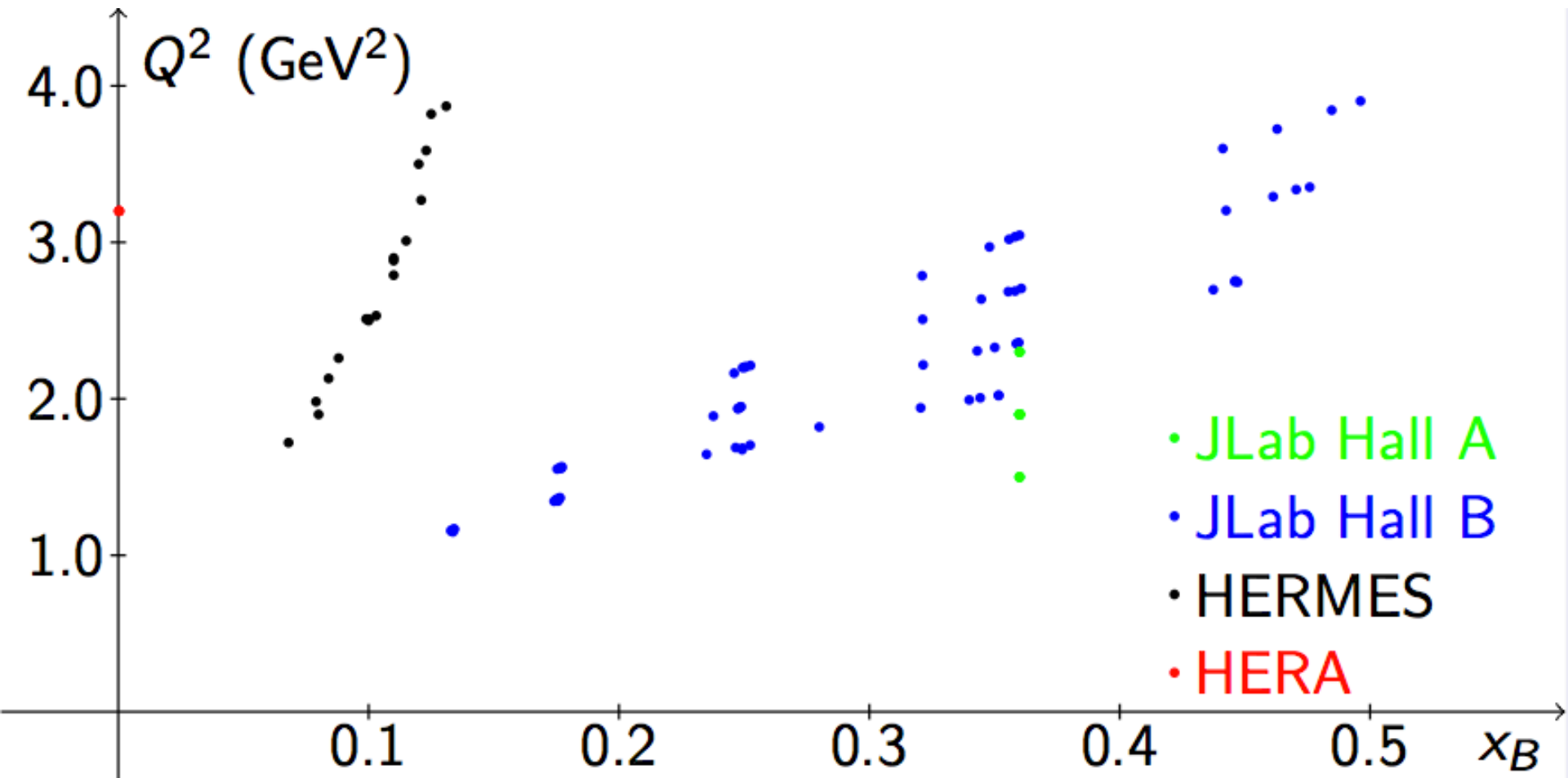
$$A_{UL,I}^{\sin \phi} \propto \text{Im} \left[\xi(F_1 + F_2) \left(\mathcal{H} + \frac{\xi}{1 + \xi} \mathcal{E} \right) + F_1 \tilde{\mathcal{H}} - \xi \left(\frac{\xi}{1 + \xi} F_1 + \frac{t}{4M^2} F_2 \right) \tilde{\mathcal{E}} \right]$$

$$A_{LL,I}^{\cos \phi} \propto \text{Re} \left[\xi(F_1 + F_2) \left(\mathcal{H} + \frac{\xi}{1 + \xi} \mathcal{E} \right) + F_1 \tilde{\mathcal{H}} - \xi \left(\frac{\xi}{1 + \xi} F_1 + \frac{t}{4M^2} F_2 \right) \tilde{\mathcal{E}} \right]$$

DVCS data set worldwide

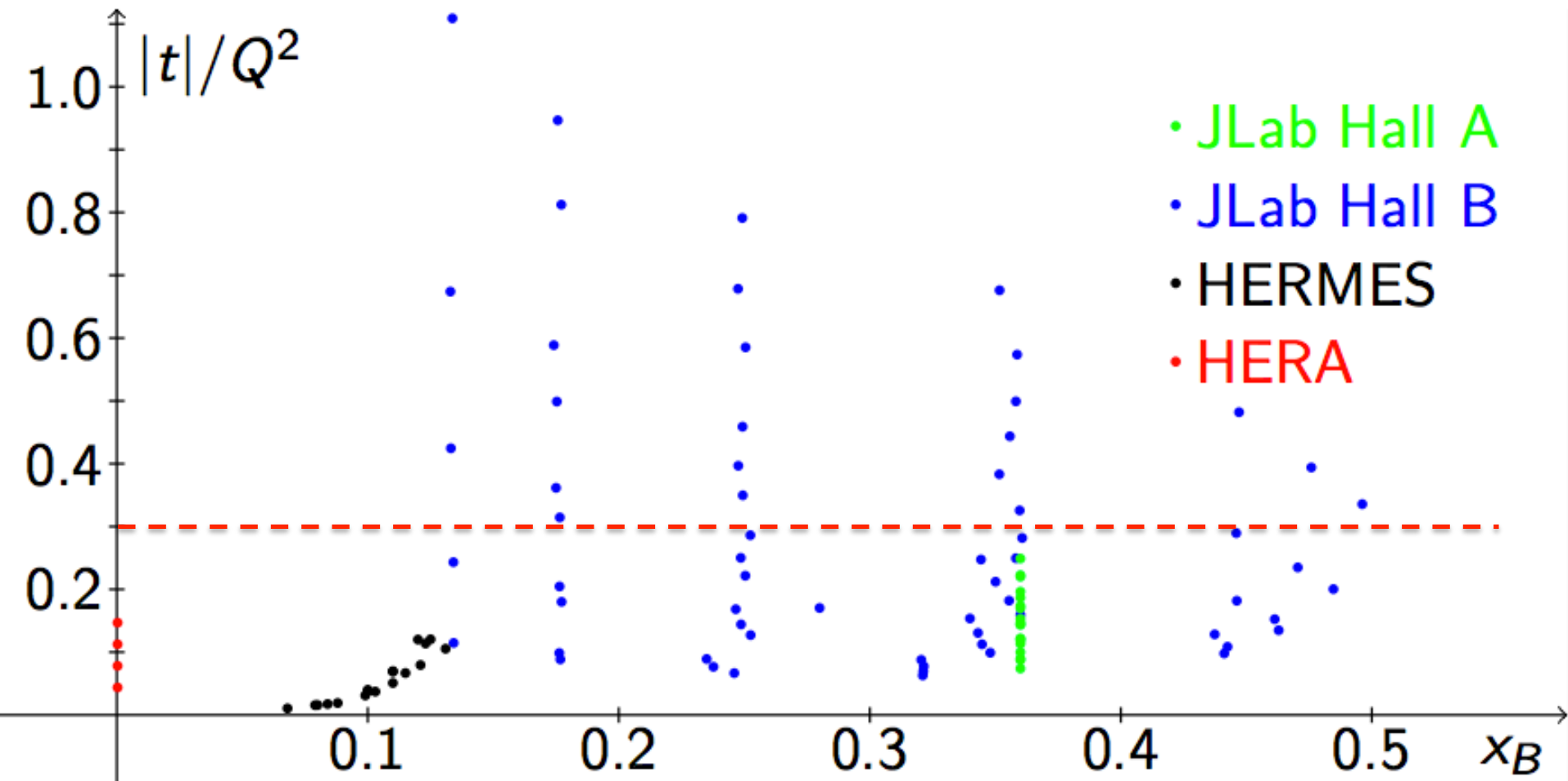
Experiment	
HERMES	Various asymmetries with beam helicity, charge and target L and T polarizations
CLAS	Various asymmetries with beam helicity and target L polarization
HALL A	Helicity-dependent cross sections
HERA	DVCS cross sections and charge asymmetry

DVCS data kinematics



□ DVCS data cover complementary kinematical regions

DVCS data kinematics



□ DVCS data cover complementary kinematical regions

□ Warning : $|t|/Q^2$ is not always small, sometimes ~ 1 for CLAS data

DVCS data and their sensitivity to CFF's

Experiment	Observable	Normalized CFF dependence
HERMES	$A_C^{\cos 0\phi}$	$\text{Re}\mathcal{H} + 0.06\text{Re}\mathcal{E} + 0.24\text{Re}\tilde{\mathcal{H}}$
	$A_C^{\cos \phi}$	$\text{Re}\mathcal{H} + 0.05\text{Re}\mathcal{E} + 0.15\text{Re}\tilde{\mathcal{H}}$
	$A_{\text{LU,I}}^{\sin \phi}$	$\text{Im}\mathcal{H} + 0.05\text{Im}\mathcal{E} + 0.12\text{Im}\tilde{\mathcal{H}}$
	$A_{\text{UL}}^{+,\sin \phi}$	$\text{Im}\tilde{\mathcal{H}} + 0.10\text{Im}\mathcal{H} + 0.01\text{Im}\mathcal{E}$
	$A_{\text{UL}}^{+,\sin 2\phi}$	$\text{Im}\tilde{\mathcal{H}} - 0.97\text{Im}\mathcal{H} + 0.49\text{Im}\mathcal{E} - 0.03\text{Im}\tilde{\mathcal{E}}$
	$A_{\text{LL}}^{+,\cos 0\phi}$	$1 + 0.05\text{Re}\tilde{\mathcal{H}} + 0.01\text{Re}\mathcal{H}$
	$A_{\text{LL}}^{+,\cos \phi}$	$1 + 0.79\text{Re}\tilde{\mathcal{H}} + 0.11\text{Im}\mathcal{H}$
	$A_{\text{UT,DVCS}}^{\sin(\phi-\phi_S)}$	$\text{Im}\mathcal{H}\text{Re}\mathcal{E} - \text{Im}\mathcal{E}\text{Re}\mathcal{H}$
	$A_{\text{UT,I}}^{\sin(\phi-\phi_S)\cos \phi}$	$\text{Im}\mathcal{H} - 0.56\text{Im}\mathcal{E} - 0.12\text{Im}\tilde{\mathcal{H}}$
CLAS	$A_{\text{LU}}^{-,\sin \phi}$	$\text{Im}\mathcal{H} + 0.06\text{Im}\mathcal{E} + 0.21\text{Im}\tilde{\mathcal{H}}$
	$A_{\text{UL}}^{-,\sin \phi}$	$\text{Im}\tilde{\mathcal{H}} + 0.12\text{Im}\mathcal{H} + 0.04\text{Im}\mathcal{E}$
	$A_{\text{UL}}^{-,\sin 2\phi}$	$\text{Im}\tilde{\mathcal{H}} - 0.79\text{Im}\mathcal{H} + 0.30\text{Im}\mathcal{E} - 0.05\text{Im}\tilde{\mathcal{E}}$
HALL A	$\Delta\sigma^{\sin \phi}$	$\text{Im}\mathcal{H} + 0.07\text{Im}\mathcal{E} + 0.47\text{Im}\tilde{\mathcal{H}}$
	$\sigma^{\cos 0\phi}$	$1 + 0.05\text{Re}\mathcal{H} + 0.007\mathcal{H}\mathcal{H}^*$
	$\sigma^{\cos \phi}$	$1 + 0.12\text{Re}\mathcal{H} + 0.05\text{Re}\tilde{\mathcal{H}}$
HERA	σ_{DVCS}	$\mathcal{H}\mathcal{H}^* + 0.09\mathcal{E}\mathcal{E}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*$

Our framework

GPD's we used are from **Goloskokov-Kroll model** (fitted to DVMP, PDF, FF data)

GPD's H and \tilde{H} evolutions are therefore done through PDF's at $\mu_F=Q$

GPD's were not adjusted using DVCS data

Kernel is calculated at **Leading-Order of α_s**

Leading-Twist (in the hadronic tensor OPE)

No D-term

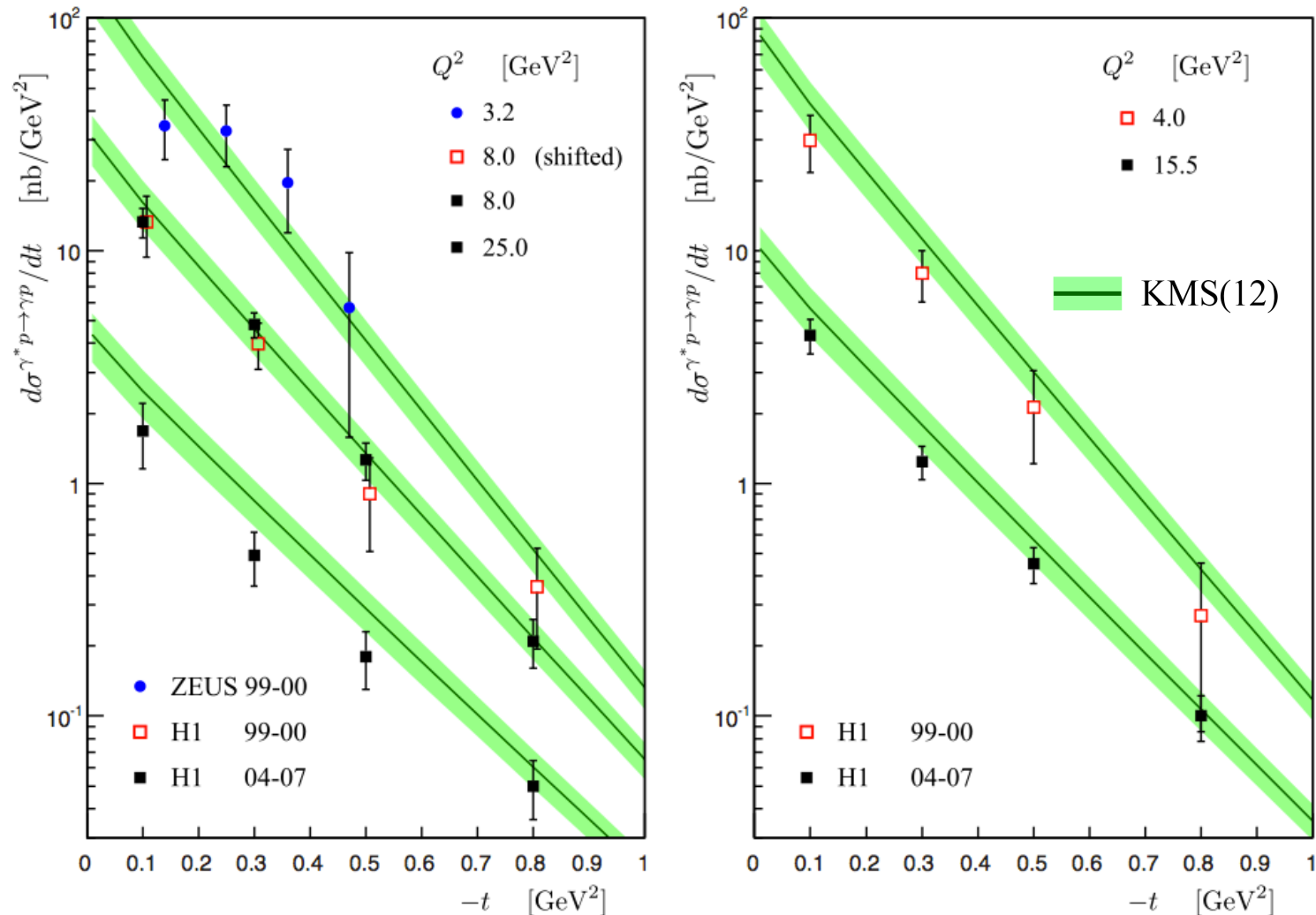
No finite- t or target-mass corrections (Braun et al. recent work)

Exact calculation of all leptonic parts (no $1/Q$ expansion as in BMK, DS)

Error bands are evaluated using polarized and unpolarized PDF errors

Article published in **Eur. Phys. J. C (2013) 73:2278 [arXiv:1210.6975]**

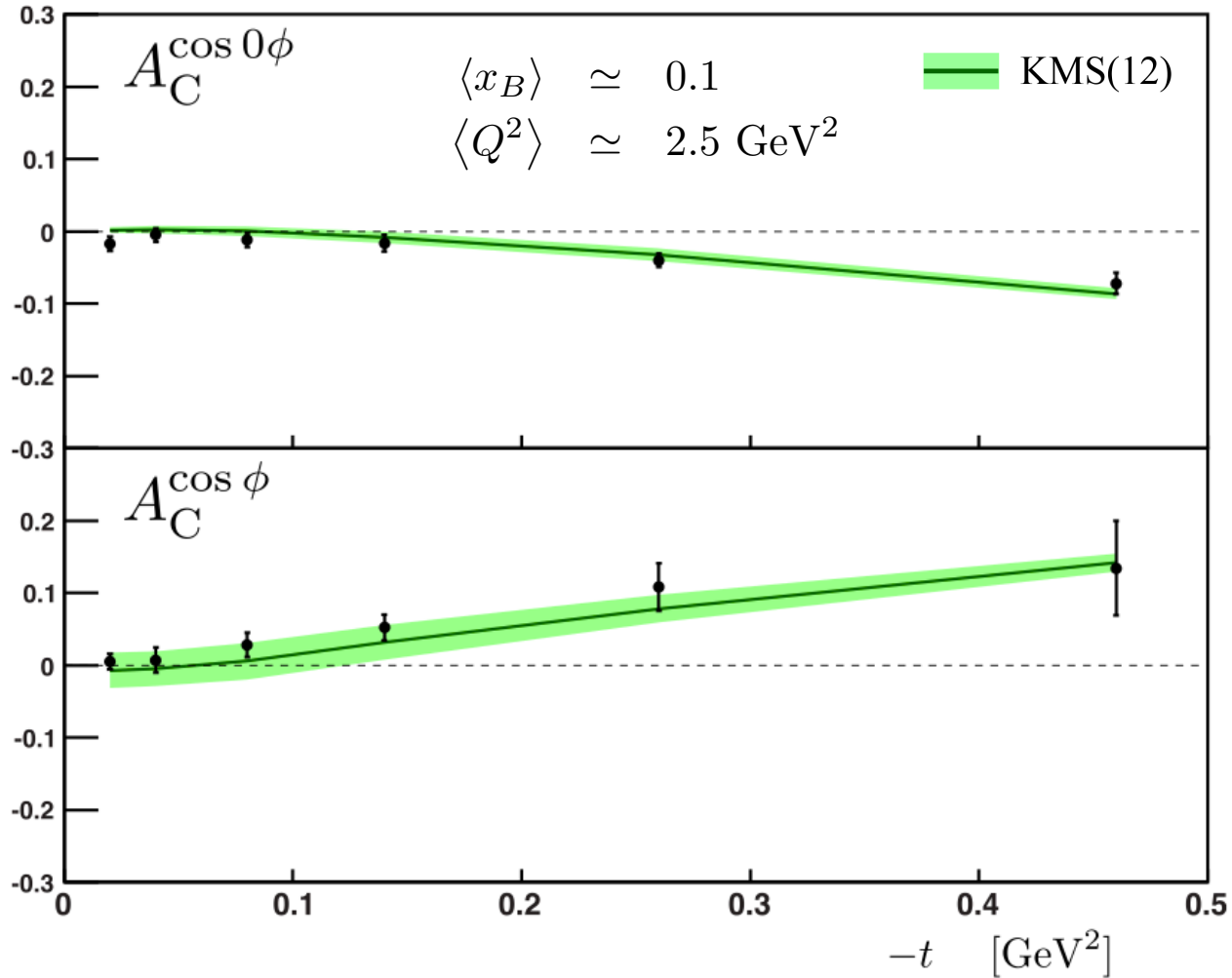
Low- x_B DVCS cross sections (HERA)



- $71 \text{ GeV} \leq W \leq 104 \text{ GeV}$
- Dominated by ImH of sea quarks
- Important evolution effects (Q^2 from 3 to 25 GeV^2)
- Reasonable agreement over the whole data range

DVCS Charge Asymmetry (HERMES)

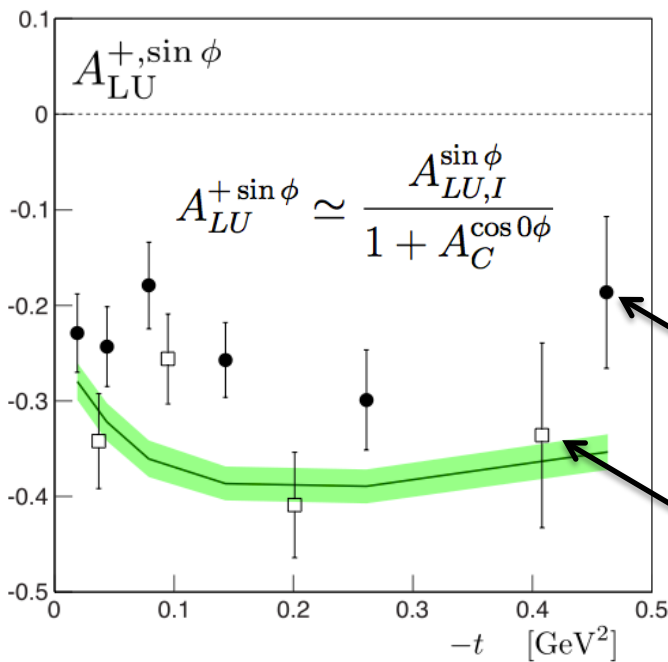
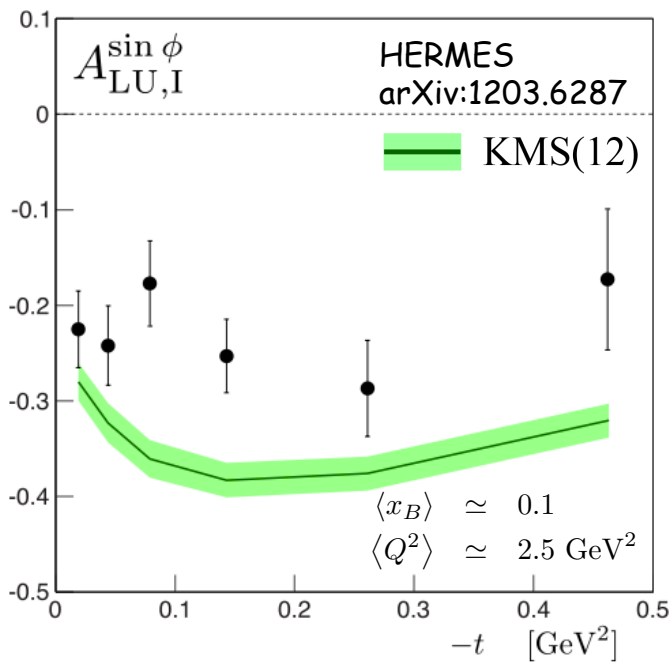
arXiv:1203.6287



☐ Dominated by $\text{Re}H$

☐ In perfect agreement over the whole t -range

DVCS Beam Spin Asymmetries (HERMES, CLAS)



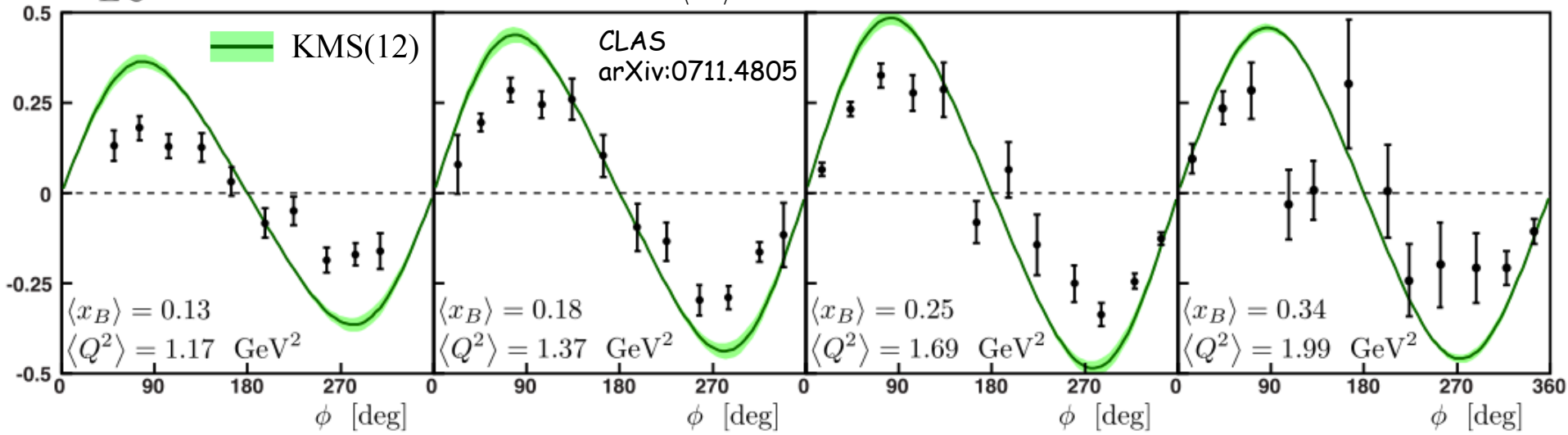
- Dominated by ImH
- In perfect agreement for HERMES recoil data
- Something missing at higher x_B (CLAS)

Non-recoil data from arXiv:1203.6287

Recoil data from arXiv:1206.5683

$A_{LU}^-(\phi)$

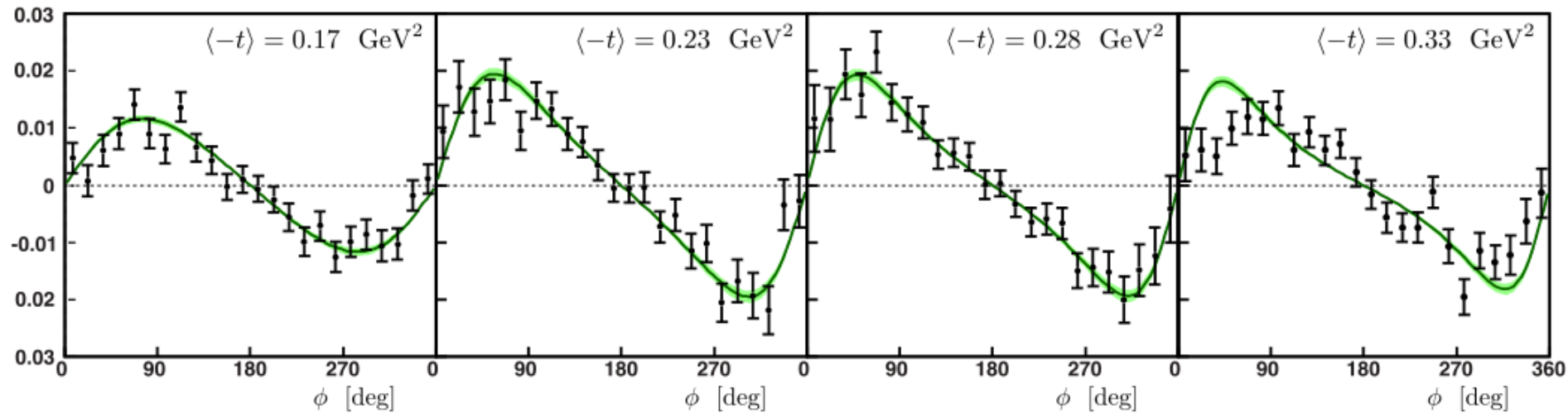
$\langle -t \rangle \simeq 0.3 \text{ GeV}^2$



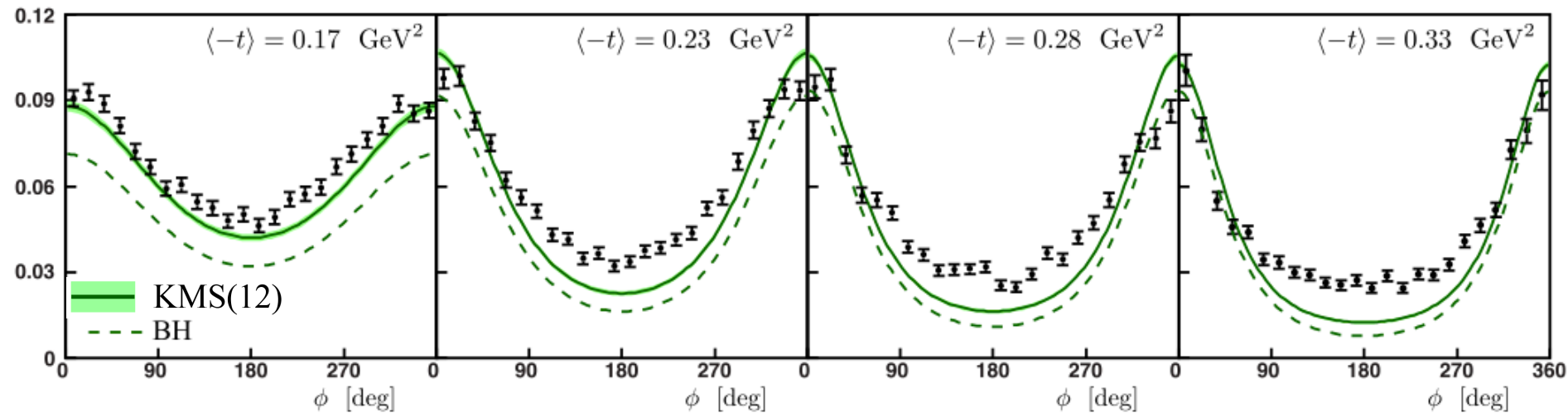
DVCS helicity-dependent cross sections (Hall A)

nucl-ex/0607029

$\Delta\sigma$ [nb/GeV⁴]



$\Sigma\sigma$ [nb/GeV⁴]



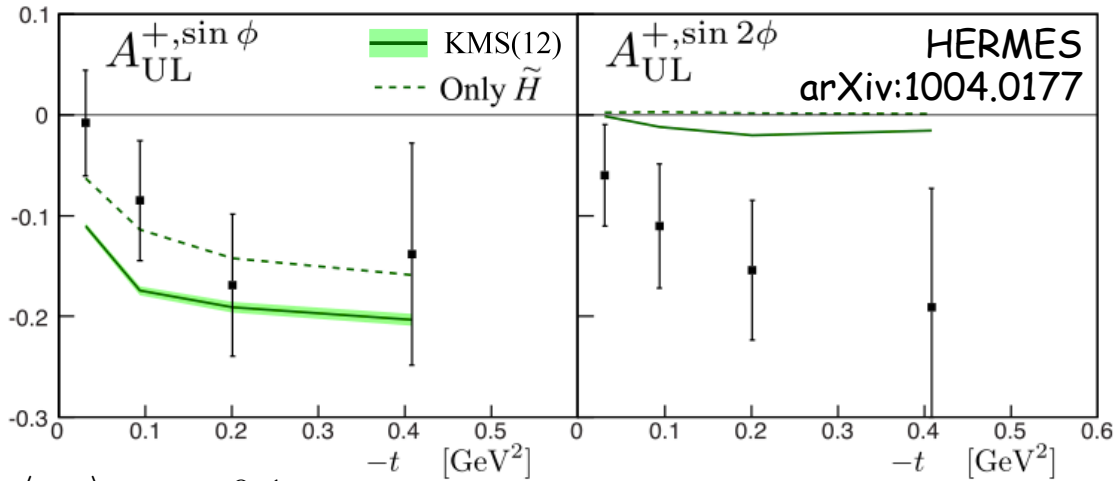
$$\langle x_B \rangle \simeq 0.36$$

□ $\Delta\sigma$ dominated by $\text{Im}H$, in perfect agreement

$$\langle Q^2 \rangle \simeq 2.3 \text{ GeV}^2$$

□ Total cross section more challenging

DVCS L-Target Spin Asymmetries (HERMES, CLAS)



$$\langle x_B \rangle \simeq 0.1$$

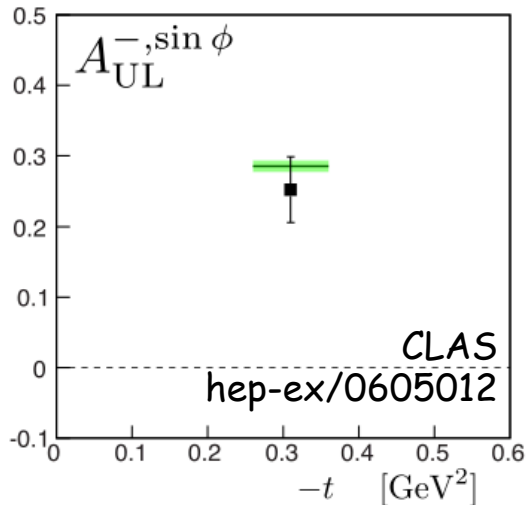
$$\langle Q^2 \rangle \simeq 2.5 \text{ GeV}^2$$

□ Dominated by $\text{Im}\tilde{H}$

□ $\sin\phi$ harmonic in good agreement

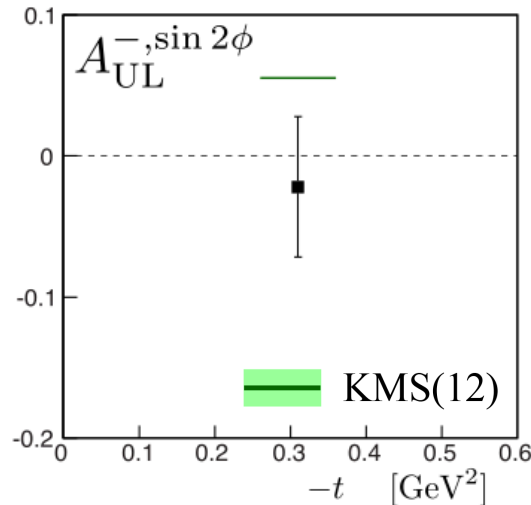
□ HERMES $\sin 2\phi$ unexpectedly large

□ Expect large improvement with recent EG1-DVCS data

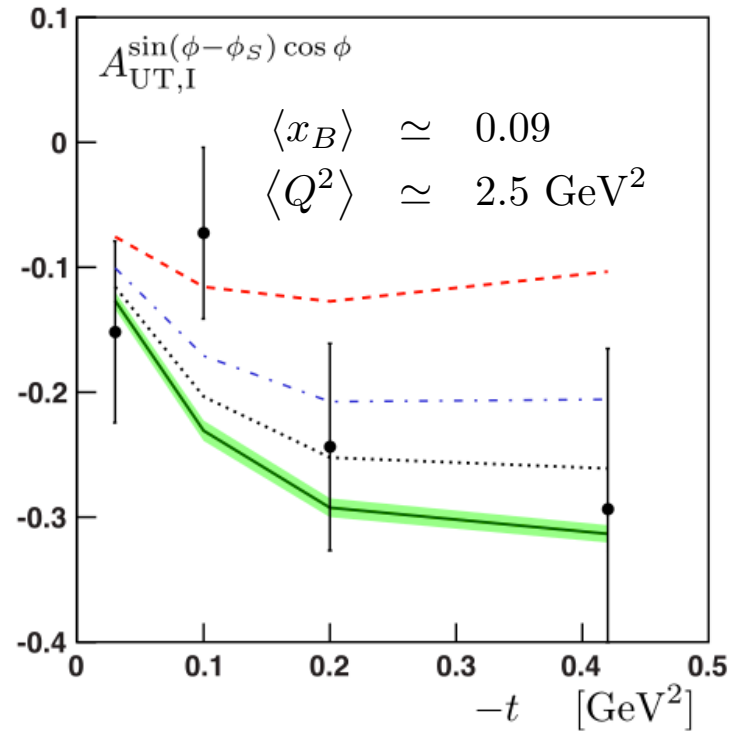
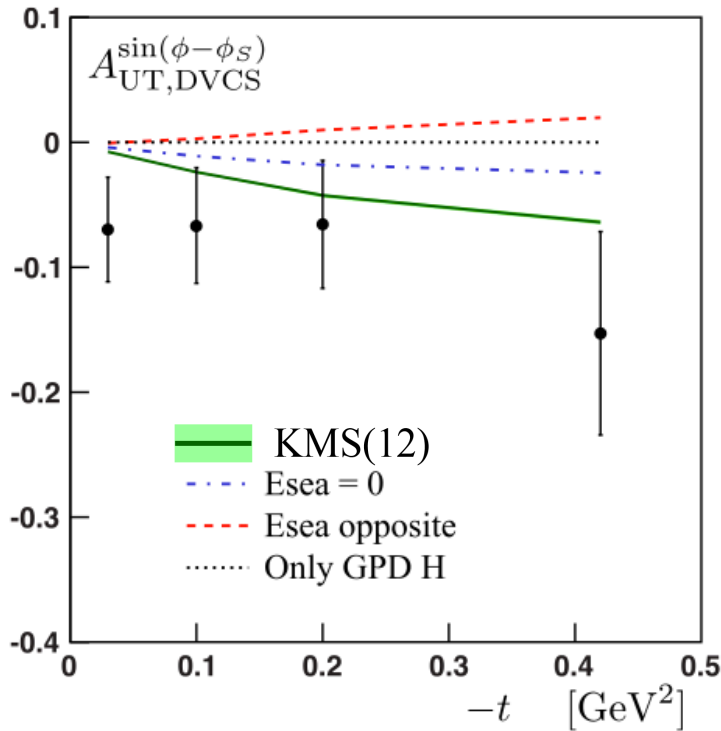


$$\langle x_B \rangle \simeq 0.28$$

$$\langle Q^2 \rangle \simeq 1.82 \text{ GeV}^2$$



DVCS T-Target Spin Asymmetries (HERMES)



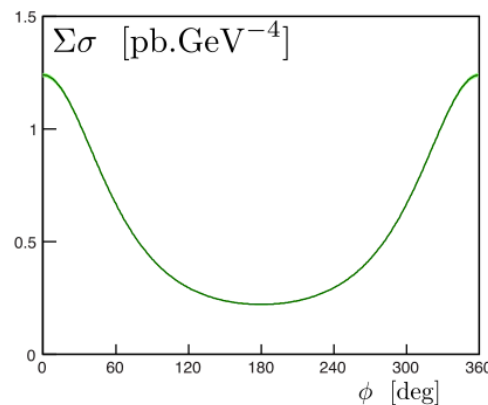
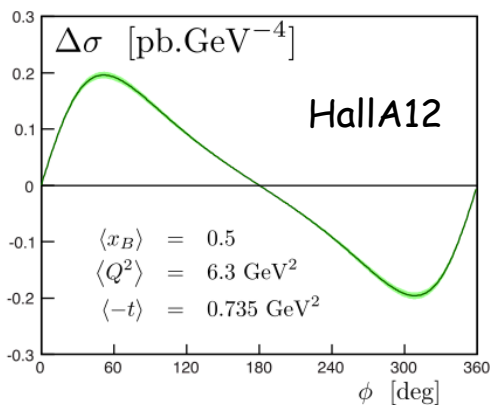
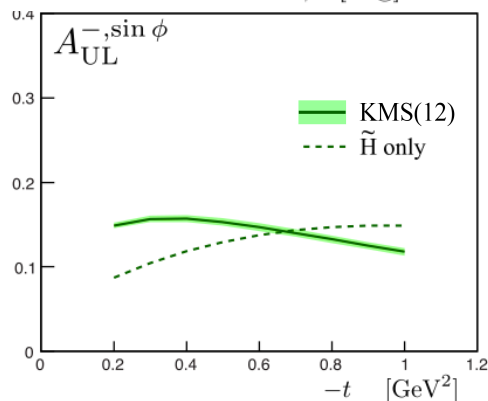
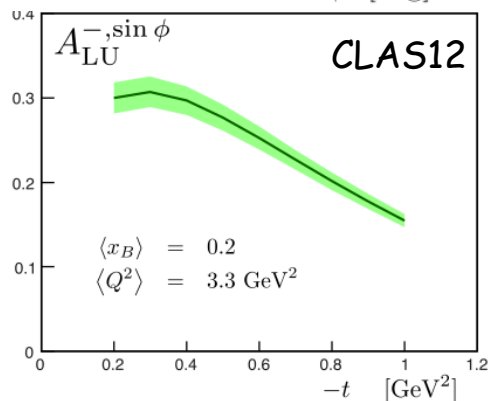
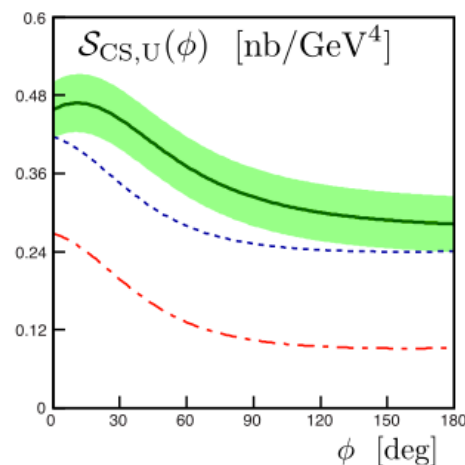
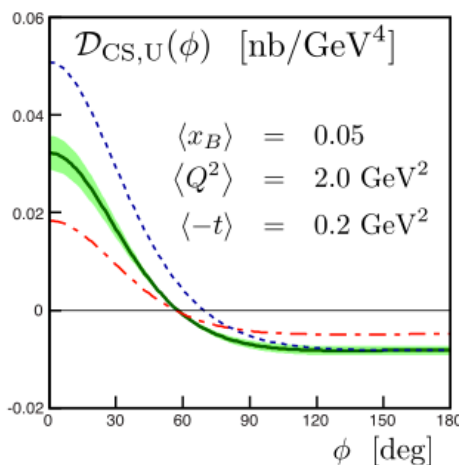
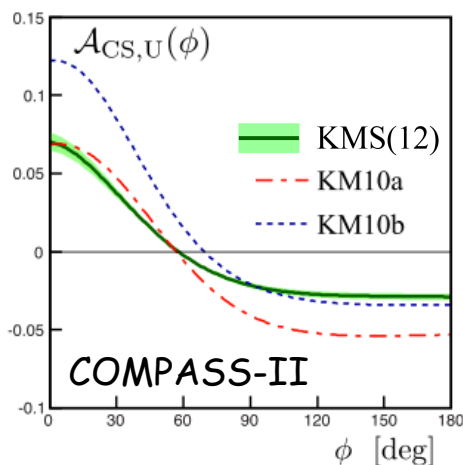
$$A_{UT,DVCS}^{\sin(\phi-\phi_S)} \sim \text{Im}[\mathcal{E}^* \mathcal{H}]$$

$$A_{UT,DVCS}^{\sin(\phi-\phi_S)} \neq 0 \implies \mathcal{E} \neq 0$$

cancellation between \mathcal{E}^s and \mathcal{E}^g does not occur as for ρ^0 asymmetry, DVCS observables are very sensitive to E_{sea}

$E_{sea} < 0$ is favored by DVCS data

Near future : COMPASS-II and JLab12



❑ Mixed charge and spin observables at COMPASS-II

❑ JLab12 : dealing with statistical errors ~1%

❑ x10-100 more data expected in the next few years

Conclusion and outlook

- ❑ Using GPD's fit to low-to-mid- x_B DVMP data (+PDF, FF) we evaluated DVCS observables at LO and Leading-Twist
- ❑ Agreement with data is good for HERA and HERMES, fair for JLab

Possible improvements:

- ❑ NLO kernel + NLO GPD evolution
(Moutarde, Pire, F.S., Szymanowski, Wagner, arXiv:1301.3819, *see DPWG session !*)
- ❑ Modification of the profile function and/or add D-term
(Mezrag, Moutarde, F.S., article in preparation, *see DPWG session !*)
- ❑ Finite- t and target mass corrections
(work in progress based on Braun et al. work, non-trivial)
- ❑ And ... of course, of utmost importance, **add more data** :

CLAS 6 & 12, Hall A 6 & 12, COMPASS-II and ... EIC

Backup Slides

What did we learn about GPD's from DVMP

GPD	probed by	constraints	status
H	ρ^0, ϕ cross sections	PDFs	***
\tilde{H}	$A_{LL}(\rho^0)$	polarized PDFs	*
E	-	sum rule for 2^{nd} moments	*
\tilde{E}, H_T, \dots	-	-	-
H	ρ^0, ϕ cross sections	PDFs, Dirac ff	***
\tilde{H}	π^+ data	pol. PDFs, axial ff	**
E	$A_{UT}(\rho^0, \phi)$	Pauli ff	**
$\tilde{E}^{n.p.}$	π^+ data	pseudoscalar ff	*
H_T, \bar{E}_T	π^+ data	transversity PDFs	*
\tilde{H}_T, \tilde{E}_T	-	-	-

Status of **small-skewness** GPDs as extracted from meson electroproduction data. The upper (lower) part is for gluons and sea (valence) quarks. Except of H for gluons and sea quarks all GPDs are probed for scales of about 4 GeV^2

PDFs *****

Slide from P. Kroll, QCD-N'12 Bilbao

Typical kinematics of experimental data sets

Experiment	Kinematics		
	x_B	Q^2 [GeV ²]	t [GeV ²]
HERMES	0.09	2.50	-0.12
CLAS	0.19	1.25	-0.19
HALL A	0.36	2.30	-0.23
HERA	0.001	8.00	-0.30

What data to be expected in the future?

Short-term (2012-2013) :

- JLab CLAS: Finalized analysis of DVCS cross sections (1st run)
- JLab CLAS: Updated results with 2nd half of DVCS run
- JLab CLAS: Finalized analysis of NH₃ and ND₃ data on DVCS
- JLab Hall A: Rosenbluth separation of DVCS cross section (+ π^0)
- HERMES: Finalized analysis of recoil detector data

Mid-term (2014-2020+) :

- JLab CLAS12: Approved DVCS program (LH2, LD2, NH3) + more to come
- JLab Hall A: Approved DVCS program with up to 11 GeV beam
- COMPASS-II: Short DVCS run in 2012, then 2015 (also DVMP)

Long-term (2025+)

- EIC : DVCS and DVMP, see R. Ent's talk on Friday morning

Conclusion

A sizeable data set to be used for phenomenology

› H1, ZEUS, HERMES, Jlab CLAS + Hall A, COMPASS and more

What we know **experimentally** (with constraints from theory usually !)

› Reasonable idea of the size of H (gluons, sea, valence)

› Rough idea of the size of \tilde{H} and E for valence

› Some limited clues on the size of \tilde{H} and E for sea

› Almost nothing on \tilde{E} and the chiral-odd GPDs, but some progress !

What's next? **Going from a "rough" to a "good" knowledge !**

Clearly, **accurate** data on **cross sections** are **needed** in the next stage
Progress in theory and phenomenology is also needed (corrections, fits, etc)

› COMPASS-II and JLab12 will provide essential new data

› EIC is the ultimate tool for 3D nucleon imaging (and much more)