Exclusive Physics at HERMES and COMPASS

- Hard exclusive reactions and GPDs
- The experiments
- DVCS
- DMVP
- Outlook

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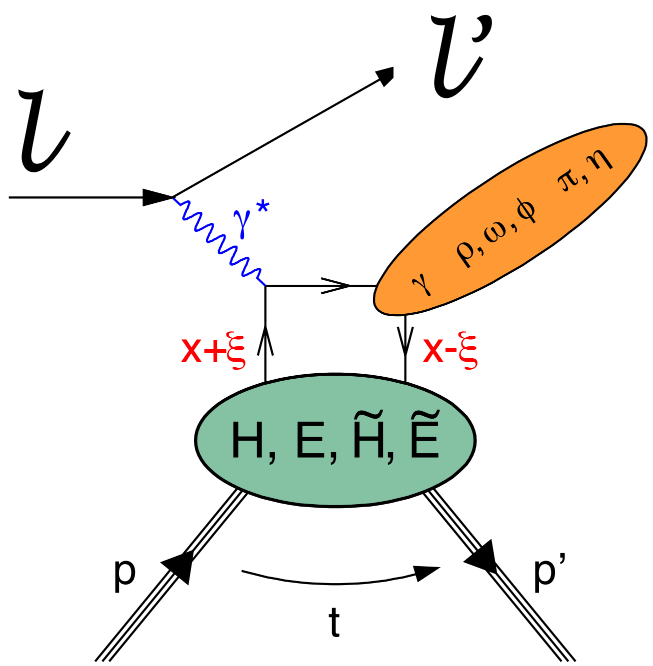
EDS Blois 2015, 16th International Conference on Elastic and Diffractive Scattering
Borgo-Corsica, June 29 - July 3, 2015



Hard-exclusive reactions

$lp \rightarrow lp\gamma$ Deeply Virtual Compton Scattering (**DVCS**)

$lp \rightarrow lpM$ Deeply Virtual Meson Production (**DVMP**)

Generalized Parton Distributions

4 chiral-even quark GPDs	flips nucleon helicity	conserves nucleon helicity
does not depend on quark helicity	**E** ↔ Sivers	**H** →q(x)
		forward limit
depends on quark helicity	$\tilde{\mathbf{E}}$	$\tilde{\mathbf{H}}$ →Δq(x)

@leading twist for a spin-½ target

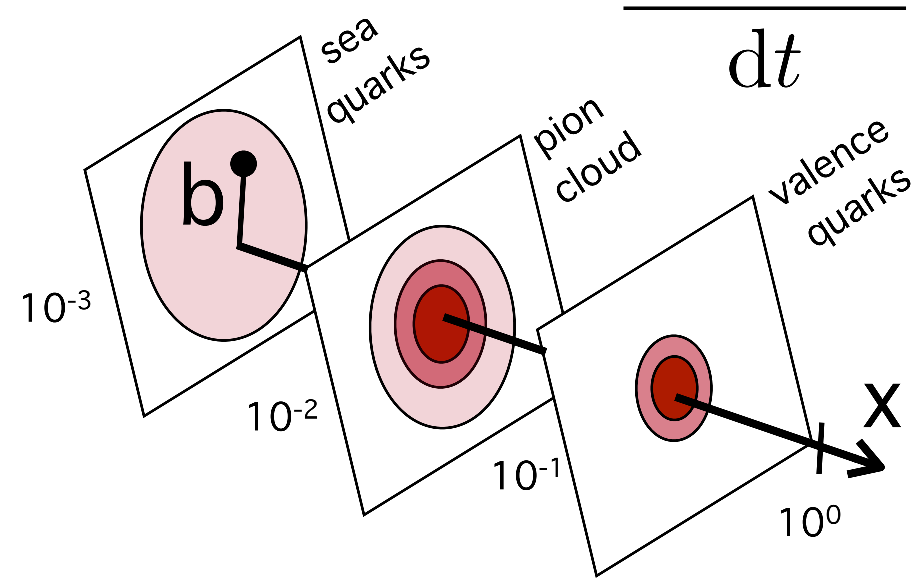
4 chiral-odd quark GPDs
H_T ↔ transversity TMD
$2\tilde{H}_T + E_T$ ↔ Boer-Mulders
$\tilde{E}_T$

GPD E and Sivers function involve switch of nucleon helicity: related to OAM

Transverse imaging: transverse size of nucleus

b = "t-slope" = average impact parameter

$$\frac{d\sigma^{\mathrm{DVCS}}}{dt} \propto e^{-b|t|}$$

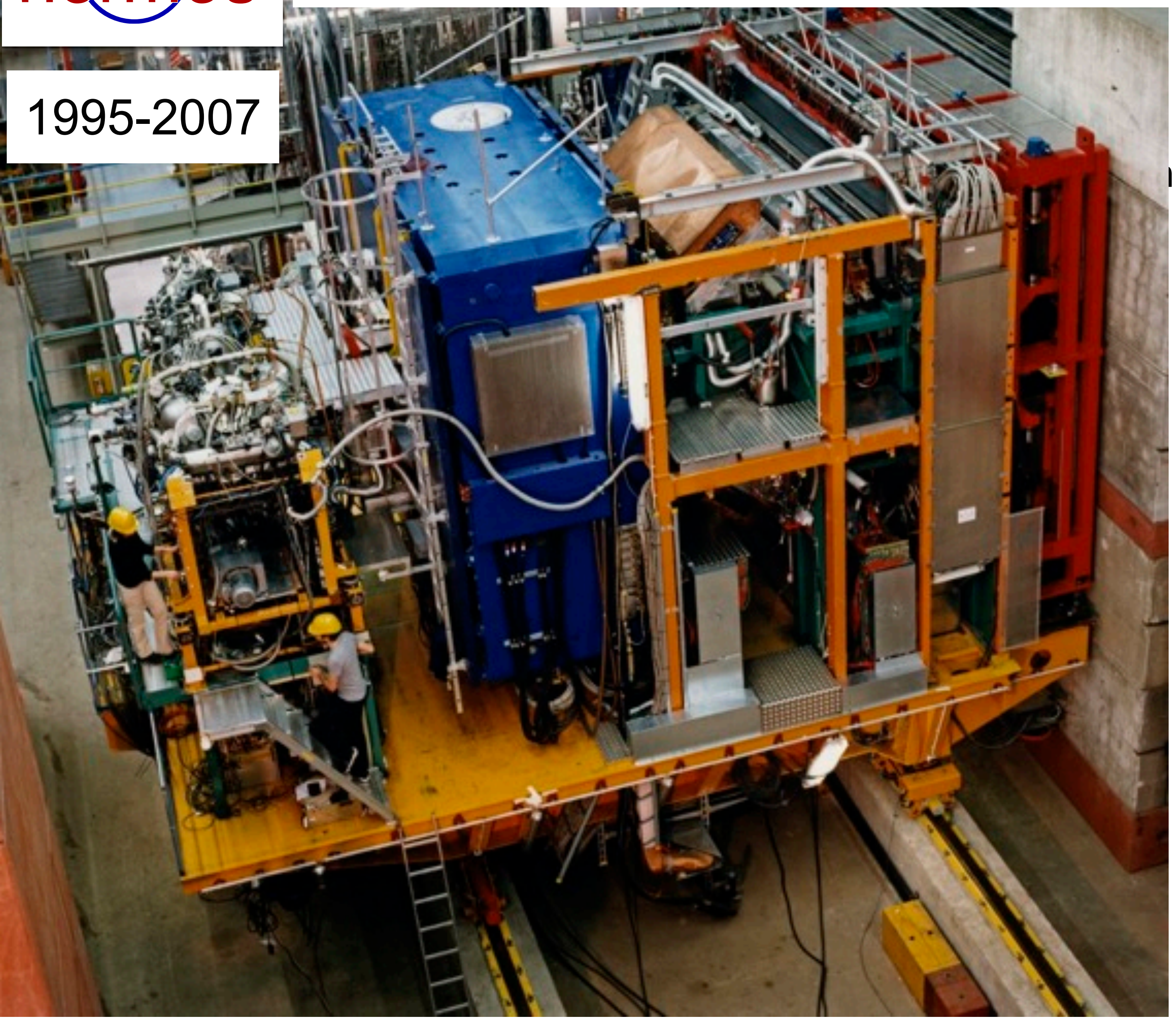


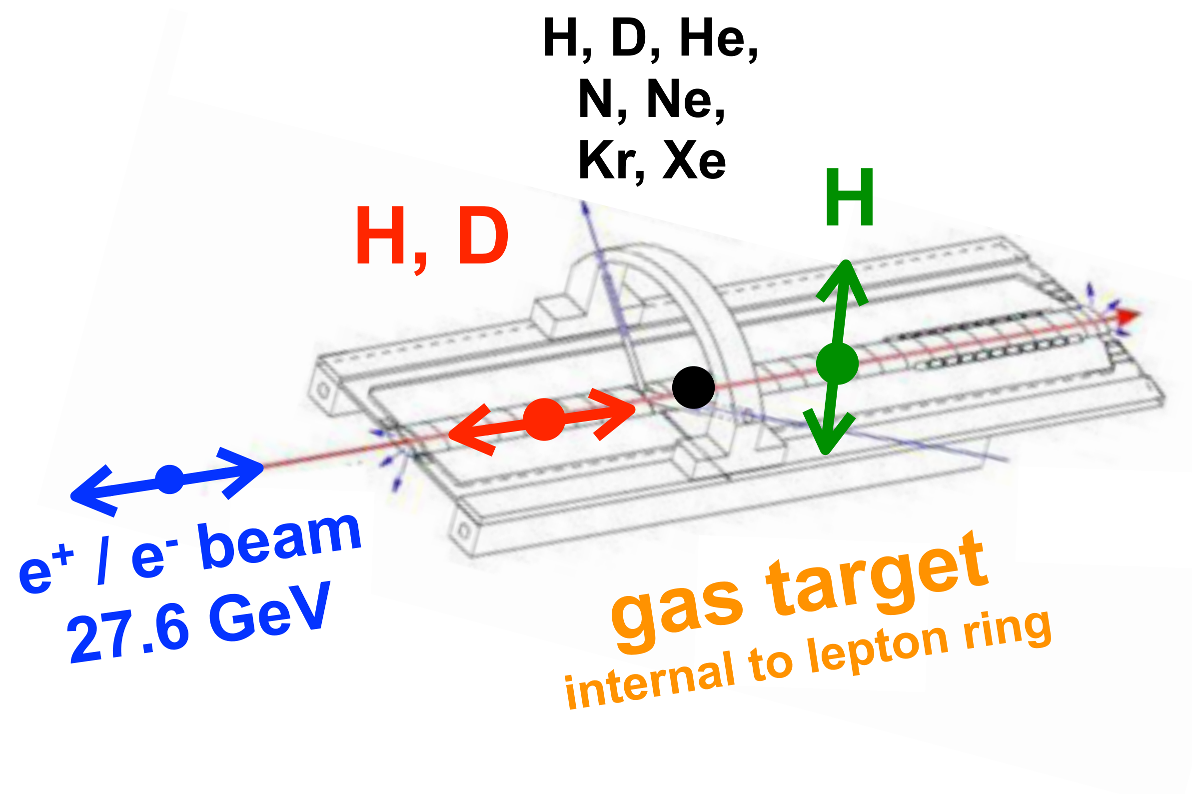
"tomographic images" of the nucleon

impact-parameter representation: $q^f(x, \boldsymbol{b}_\perp) = \int \frac{d^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} H^f(x, 0, -\boldsymbol{\Delta}_\perp^2)$

Burkardt, Int. J. Mod. Phys. A18 (2003) 173

hermes at DESY: exclusive measurements





- 1996-2007: **H, D, *He, N, Ne, Kr, Xe***
- 2006/2007: **H, D** with recoil
- 1996/97: **H→**
- 1999/2000: **D→**
- 2002-2005: **H↑**

at CERN

since 2002

$\mu^{\pm\leftrightarrows}$ beam: 160/200 GeV,

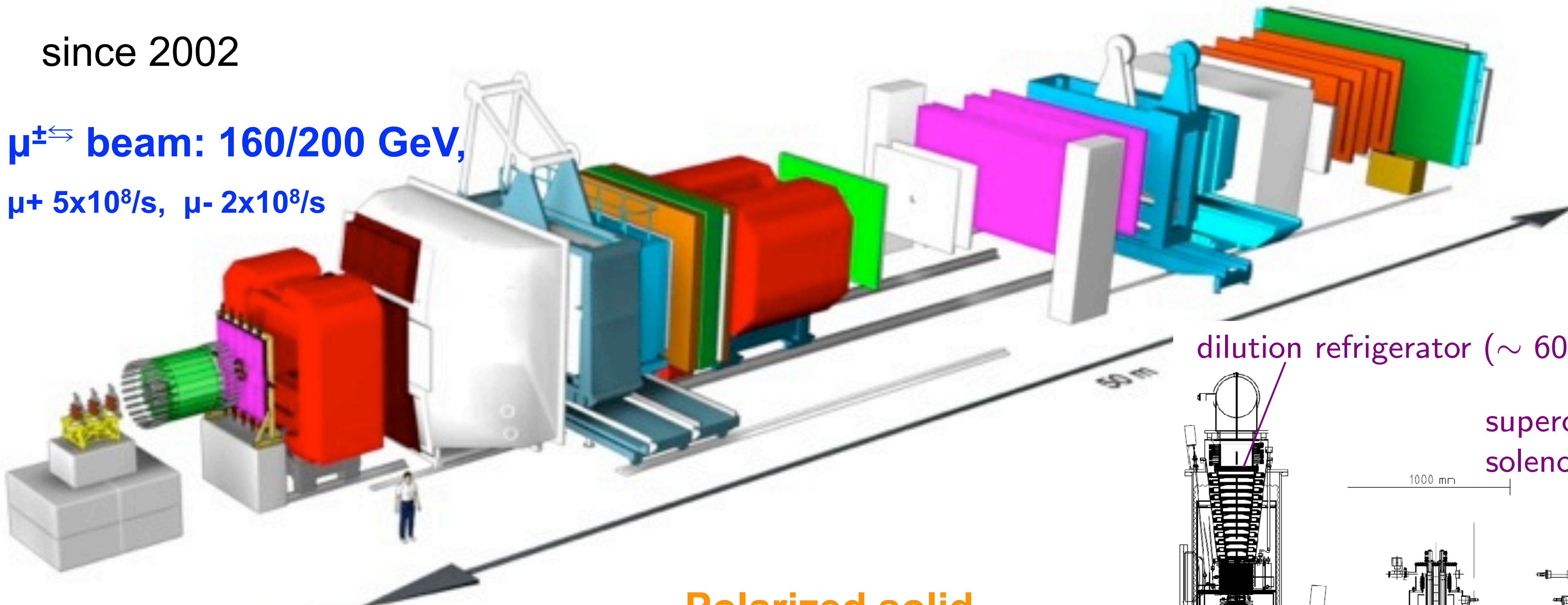
$\mu+$ $5x10^8$/s, $\mu-$ $2x10^8$/s

DVMP:

- 2002/03: D→ (ρ)
- 2002-2004: D↑ (ρ)
- 2007/2010: H↑ (ρ, ω)

DVCS:

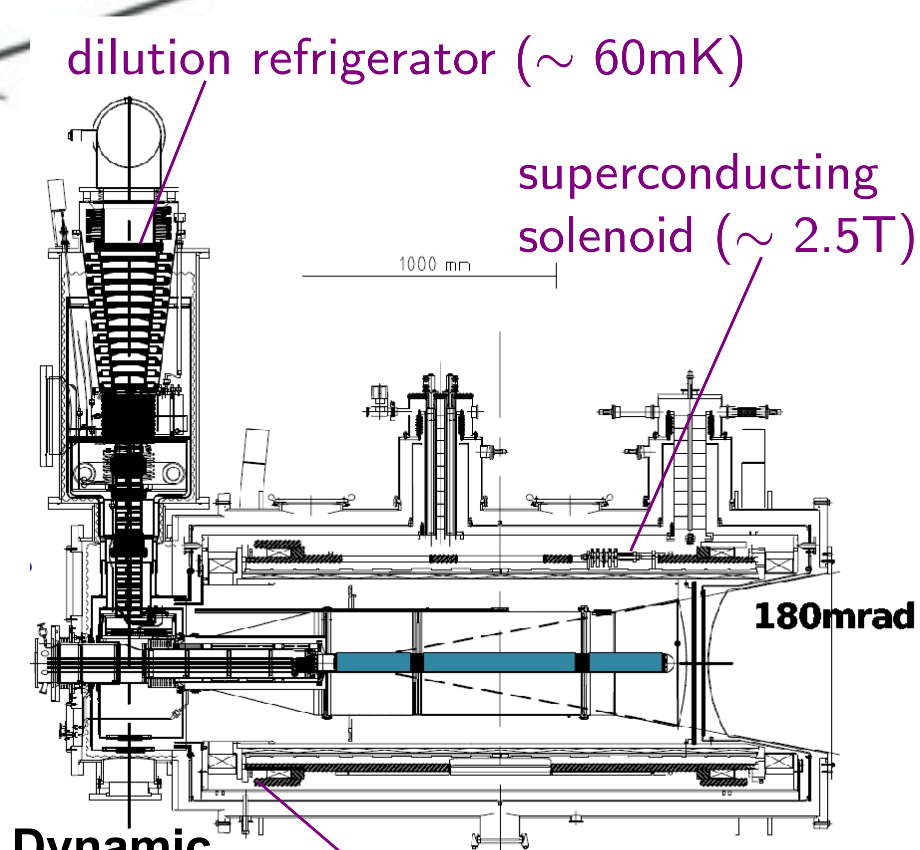
- 2008/09: H with short recoil (test run)
- 2012: H with long recoil (pilot run)
- **2016/17:** H with long recoil



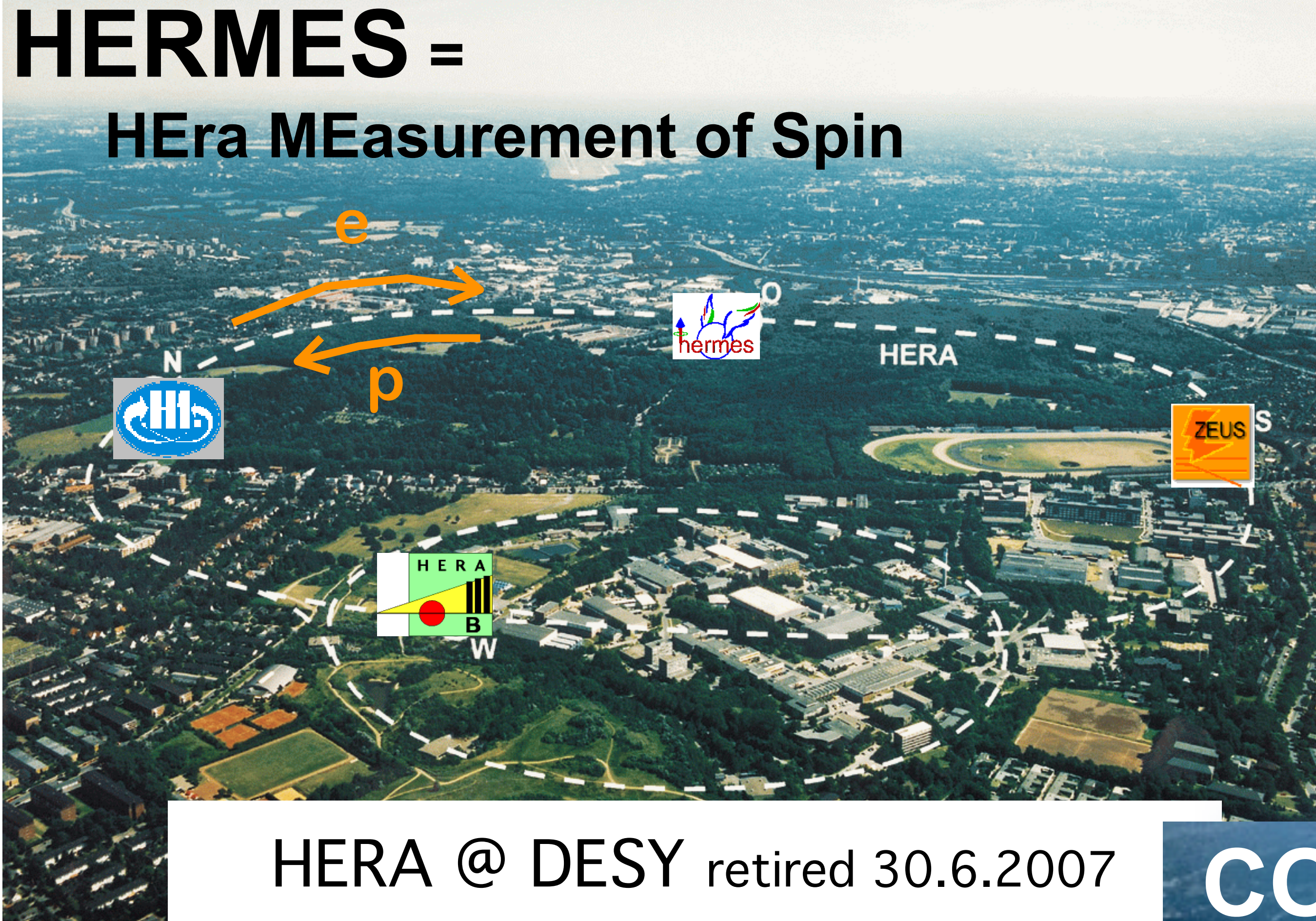
More than 300 tracking planes

18 mrad < θ_μ < 180 mrad

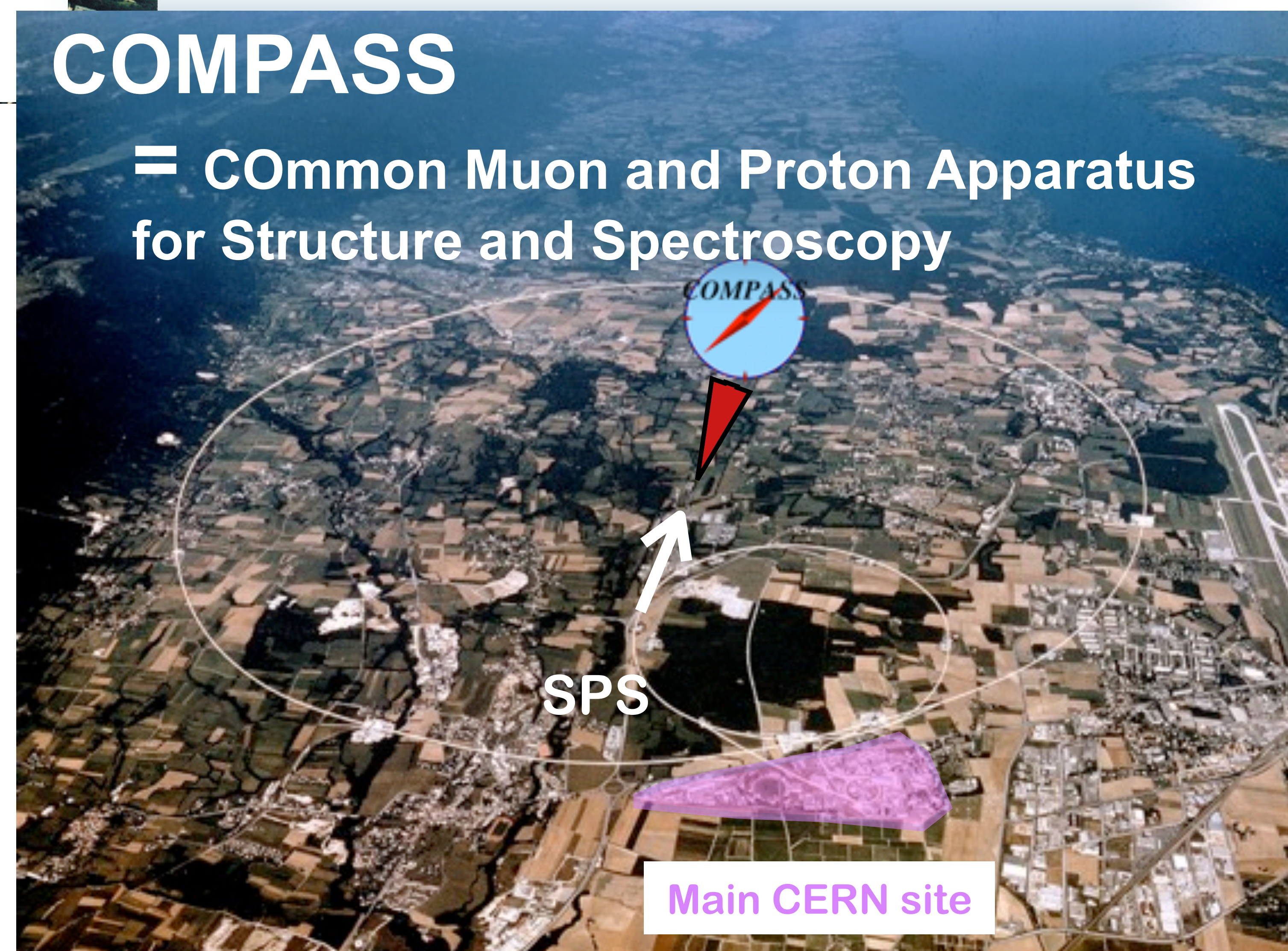
Polarized solid NH_3 & ^6LiD *or* unpolarized liquid NH_2



Dynamic Nuclear Polarization



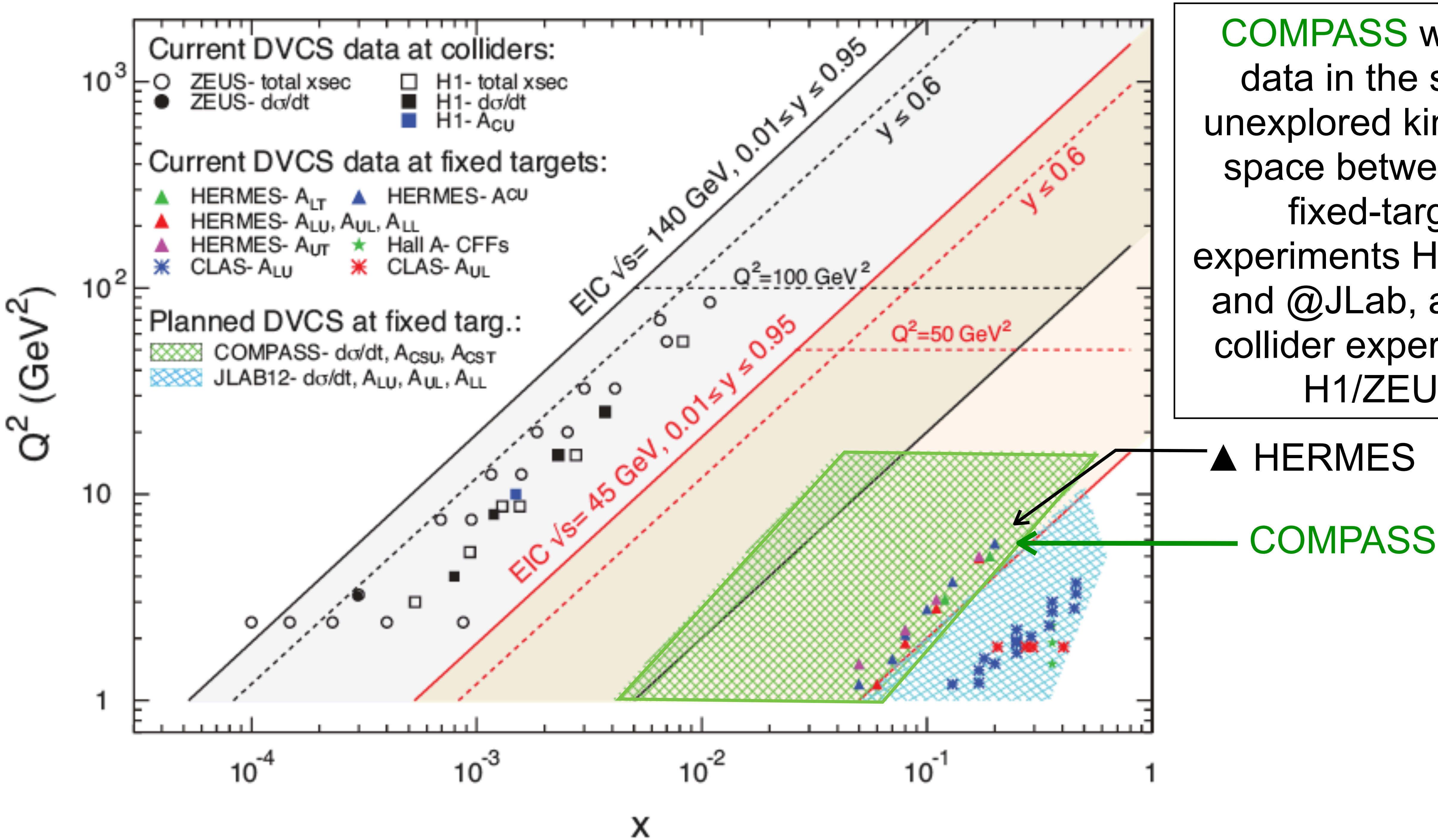
Hamburg,
Germany



Geneva,
Switzerland /

Prevessin,
France

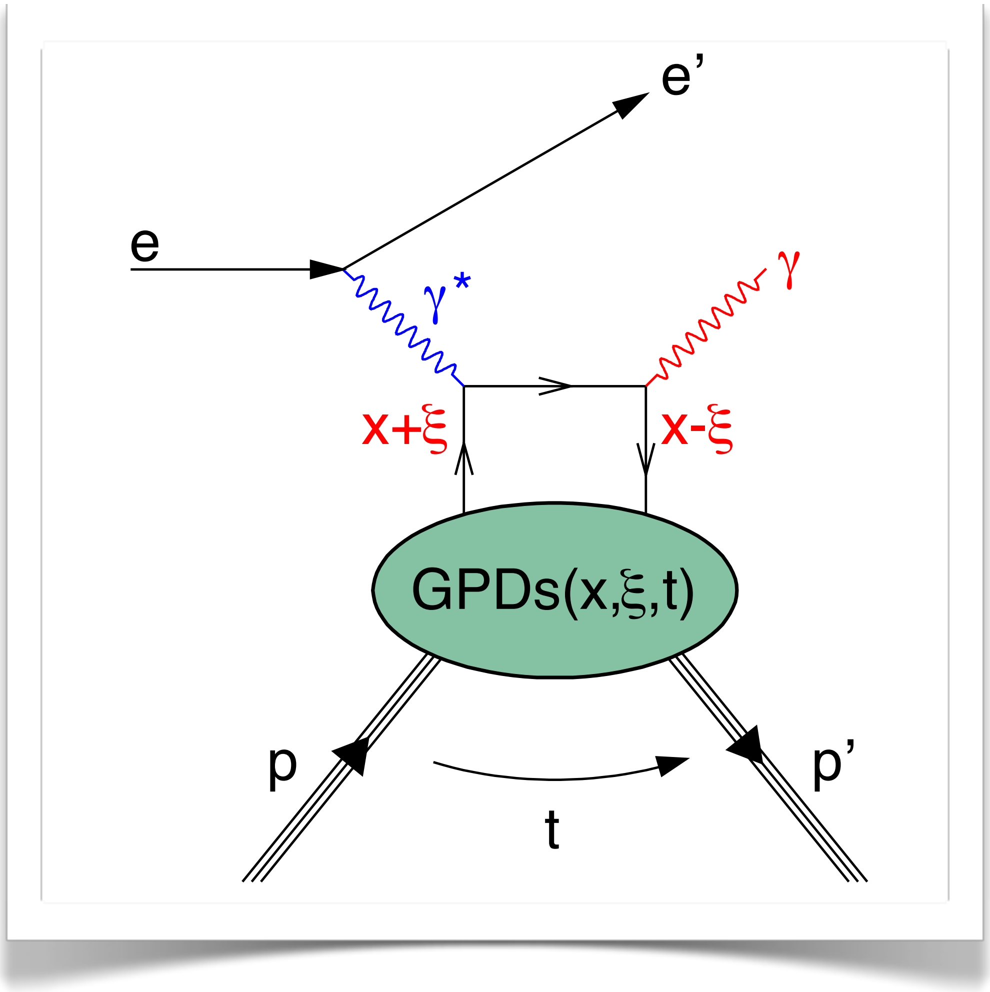
DVCS: kinematic coverage



COMPASS will add data in the so-far unexplored kinematic space between the fixed-target experiments HERMES and @JLab, and the collider experiments H1/ZEUS

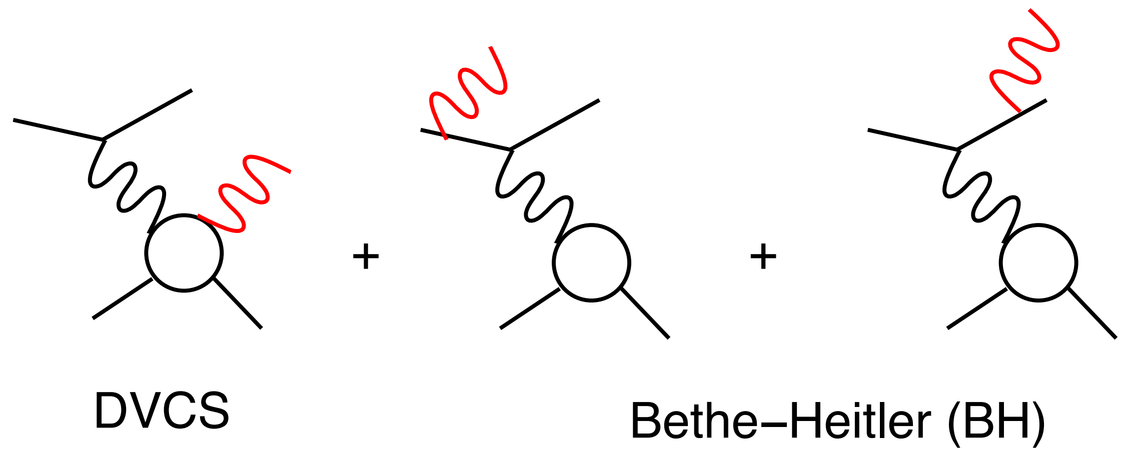
"Deeply Virtual Compton Scattering at a Proposed High-Luminosity Electron-Ion Collider", E.-C. Aschenauer, S. Fazio, K. Kumericki and D. Mueller, arXiv:1304.0077

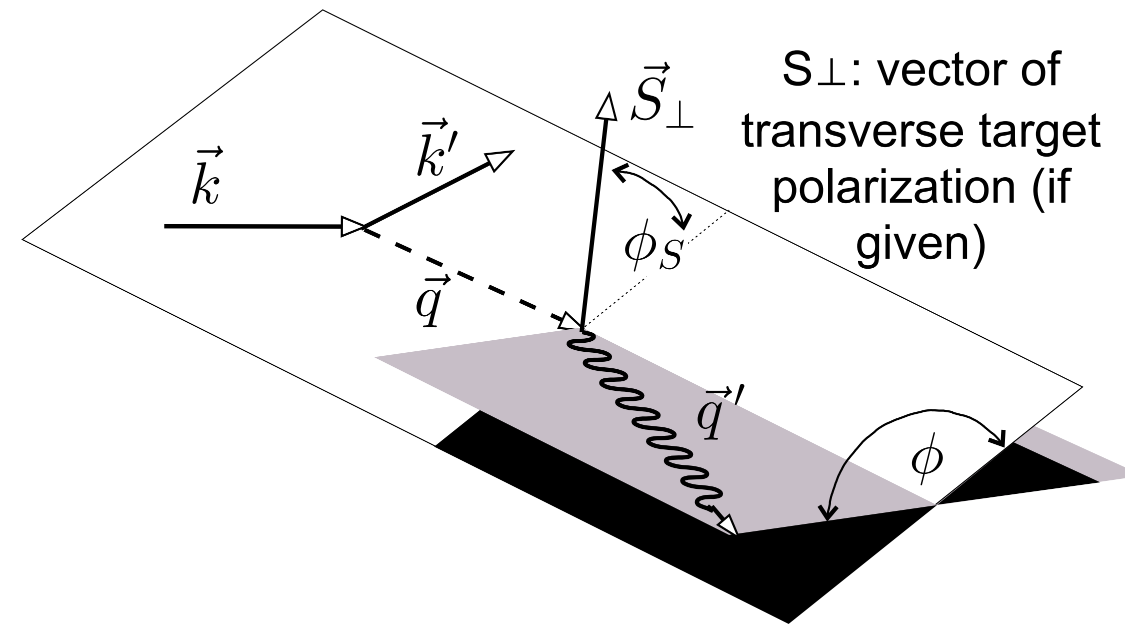
Deeply Virtual Compton Scattering



The γ*N→γN cross section

Lepton beam k with charge C_B and helicity P_B

$\sigma_{\gamma^*\gamma N} \sim \Big|$  $\Big|^2$



S⊥: vector of transverse target polarization (if given)

$$= |\mathcal{T}_{\rm BH}|^2 + (\mathcal{T}_{\rm DVCS}\mathcal{T}^*_{\rm BH} + \mathcal{T}^*_{\rm DVCS}\mathcal{T}_{\rm BH}) + |\mathcal{T}_{\rm DVCS}|^2$$

➜ expand as harmonic series in ϕ (and ϕ_S).

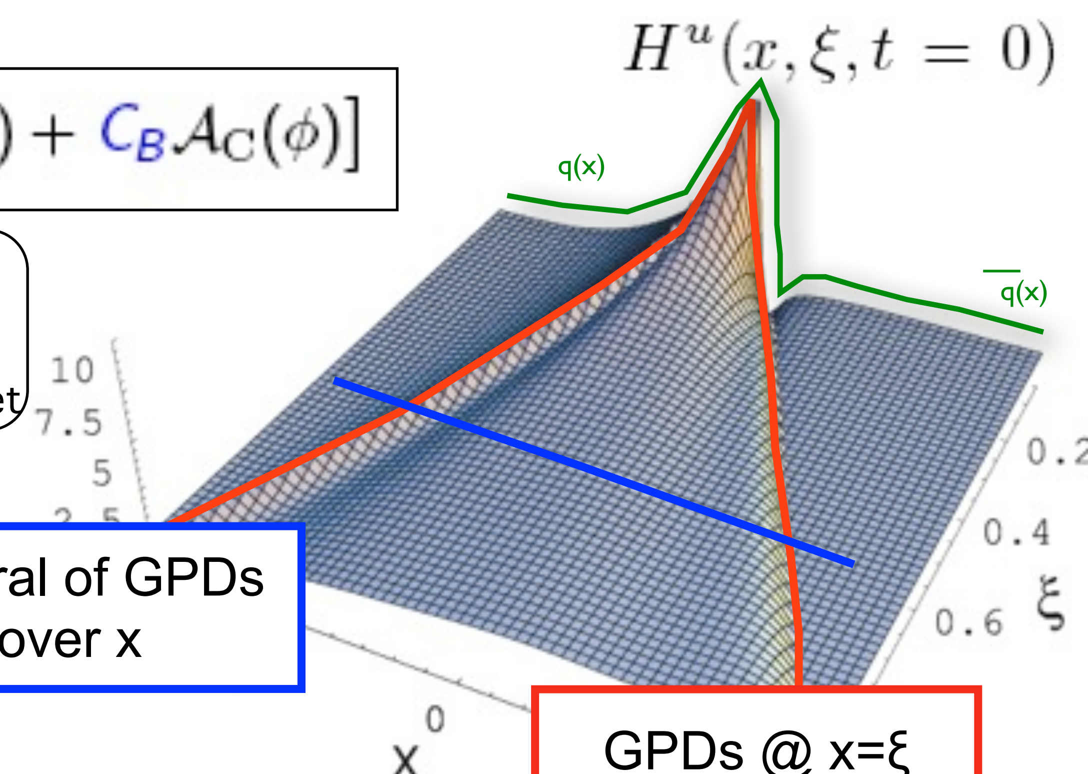
☛ Experimental access: through azimuthal asymmetries

$$\sigma(\phi; P_B, C_B) = \sigma_{\rm UU}(\phi)\cdot\left[1 + P_B\mathcal{A}^{\rm DVCS}_{\rm LU}(\phi) + C_B P_B \mathcal{A}^{\mathcal{I}}_{\rm LU}(\phi) + C_B\mathcal{A}_{\rm C}(\phi)\right]$$

$\mathcal{A}_{\rm LU}$: Beam, Target

☛ Compton Form Factors

$$\mathcal{F}(\xi,t) = \sum_q \int_{-1}^{1} {\rm d}x\; C_q^{\mp}(\xi,x)F^q(x,\xi,t)$$



integral of GPDs over x

GPDs @ x=ξ

Azimuthal asymmetries and GPDs

$\mathcal{A}_{\mathrm{LU}}$ (L: Beam, U: Target)

Best access

☞ unpolarized target:

$$F_1\mathcal{H} + \frac{x_B}{2-x_B}(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$

$\mathcal{H}$: dominant for the proton

$\mathcal{E}$: dominant for the neutron

$$\mathcal{A}_{\mathrm{LU}}(\phi) \equiv \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}}$$

Beam-helicity asymmetry

More Fourier coefficients accessible with 2 beam charges

Im($\mathcal{H}$)

$$\mathcal{A}_{\mathrm{C}}(\phi) \equiv \frac{d\sigma^{+} - d\sigma^{-}}{d\sigma^{+} + d\sigma^{-}}$$

Beam-charge asymmetry

Re($\mathcal{H}$)

☞ longitudinally polarized target:

$$\frac{x_B}{2-x_B}(F_1+F_2)\left(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\right)$$

$$+F_1\widetilde{\mathcal{H}} - \frac{x_B}{2-x_B}\left(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2\right)\widetilde{\mathcal{E}}$$

$\mathcal{A}_{\mathrm{UL}}(\phi, e_\ell) \equiv$ **Longitudinal target-spin asymmetry**

$$\frac{[\sigma^{\leftarrow\Rightarrow}(\phi,e_\ell) + \sigma^{\rightarrow\Rightarrow}(\phi,e_\ell)] - [\sigma^{\leftarrow\Leftarrow}(\phi,e_\ell) + \sigma^{\rightarrow\Leftarrow}(\phi,e_\ell)]}{[\sigma^{\leftarrow\Rightarrow}(\phi,e_\ell) + \sigma^{\rightarrow\Rightarrow}(\phi,e_\ell)] + [\sigma^{\leftarrow\Leftarrow}(\phi,e_\ell) + \sigma^{\rightarrow\Leftarrow}(\phi,e_\ell)]}$$

analog: **Double-spin (LL) asymmetry**

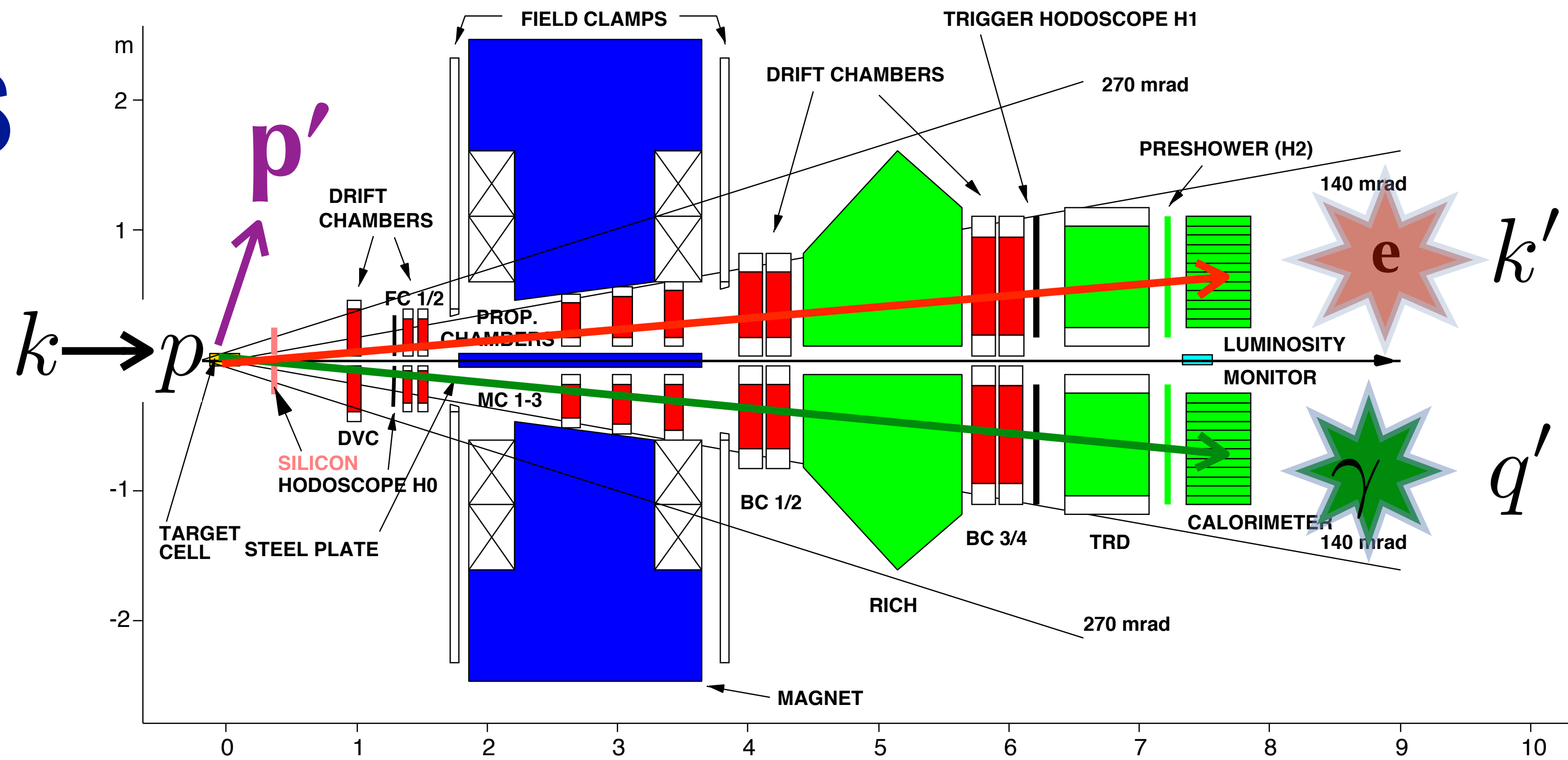
☞ transversely polarized target:

$$\frac{t}{4M^2}\left[(2-x_B)F_1\mathcal{E} - 4\frac{1-x_B}{2-x_B}F_2\mathcal{H}\right]$$

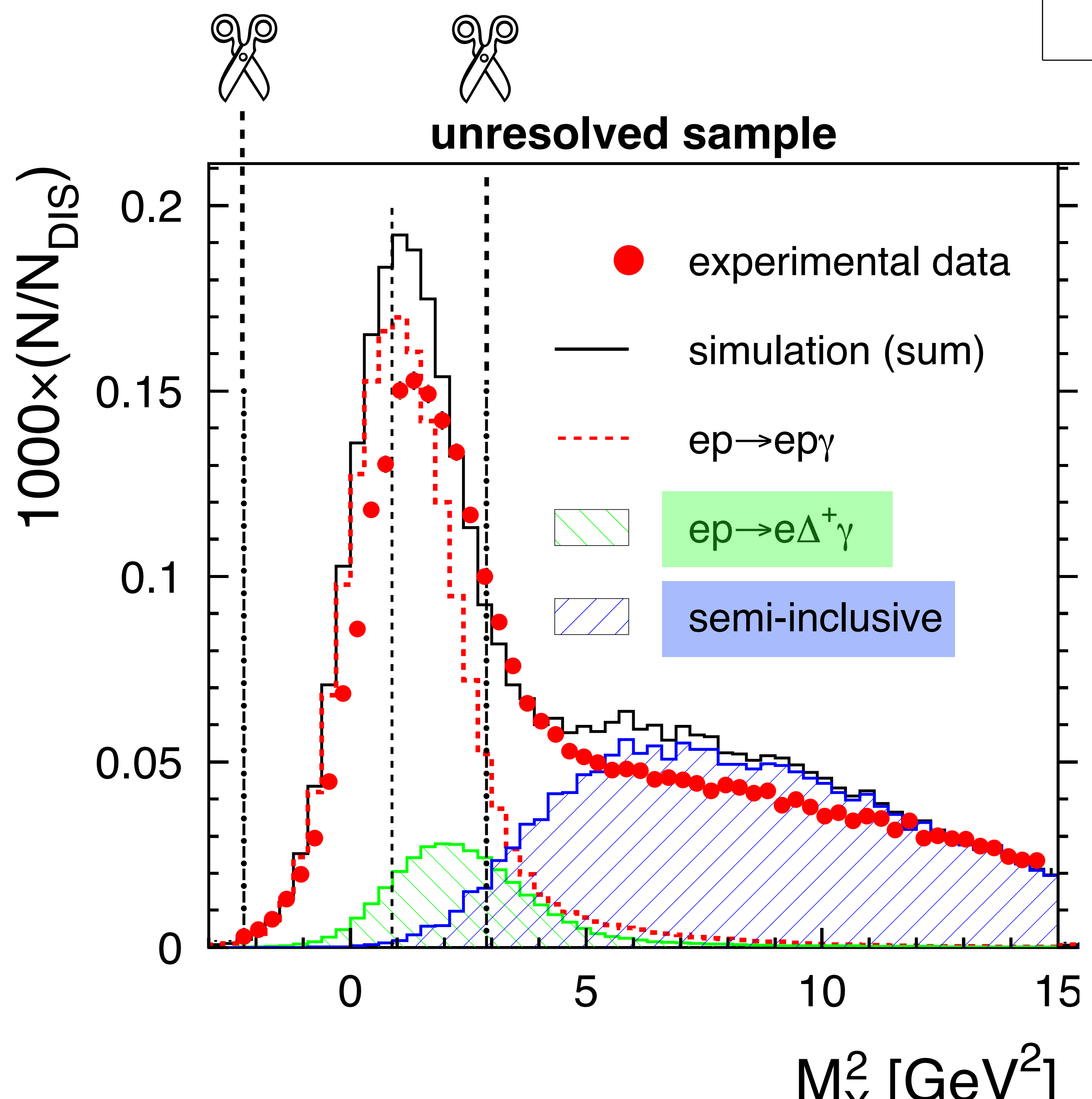
$\mathcal{A}_{\mathrm{UT}}^{\mathrm{DVCS}}(\phi,\phi_S)$ $\mathcal{A}_{\mathrm{UT}}^{\mathrm{I}}(\phi,\phi_S)$ — **Transverse target-spin asymmetry**

$\mathcal{A}_{\mathrm{LT}}^{\mathrm{I}}(\phi,\phi_S)$ $\mathcal{A}_{\mathrm{LT}}^{\mathrm{BH+DVCS}}(\phi,\phi_S)$ — **Double-spin (LT) asymmetry**

"Traditional" DVCS Analysis at HERMES



"exclusive region" in (missing mass)^2



- No other charged tracks reconstructed
- No other untracked clusters in the calorimeter

Missing-mass technique

$$M_X^2 = (k + p - k' - q')^2$$

ep ➔ eXγ sample

about 12%

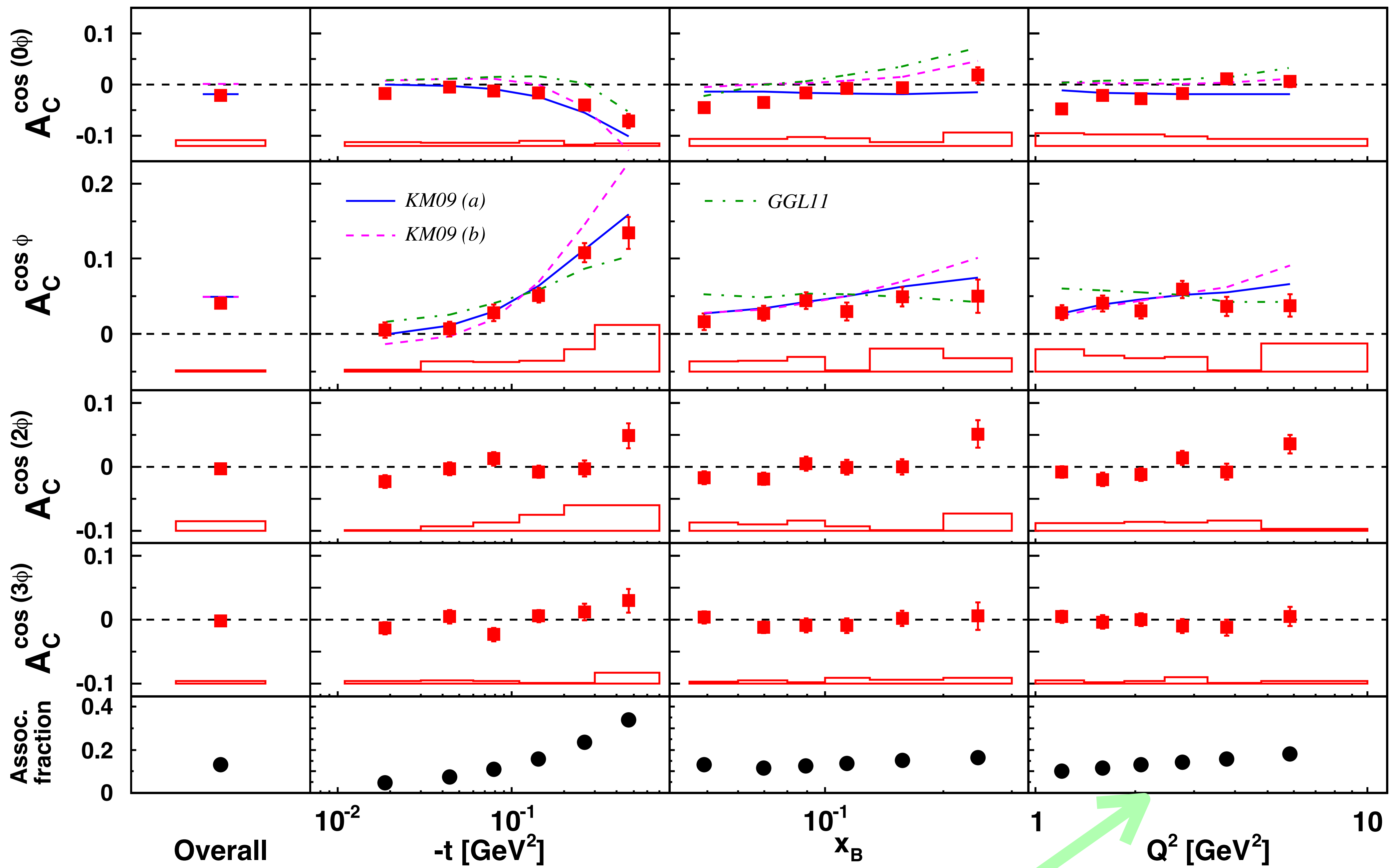
✘ Unresolved for associated production

✔ Semi-inclusive neutral pion production corrected for

about 3%

HERMES: beam-charge asymmetry

GPD H
Re(τ_{DVCS})
BCA



☆ KM10
Global fit
including data from JLab, HERMES and HERA colliders
(dashed excludes JLab Hall A cross section)
K. Kumericki and D. Müller, Nucl. Phys. B 841 (2010) 1

☆ GGL11
Model calculation
G. Goldstein, J. Hernandez and S. Liuti, Phys. Rev. D 84 034007 (2011)

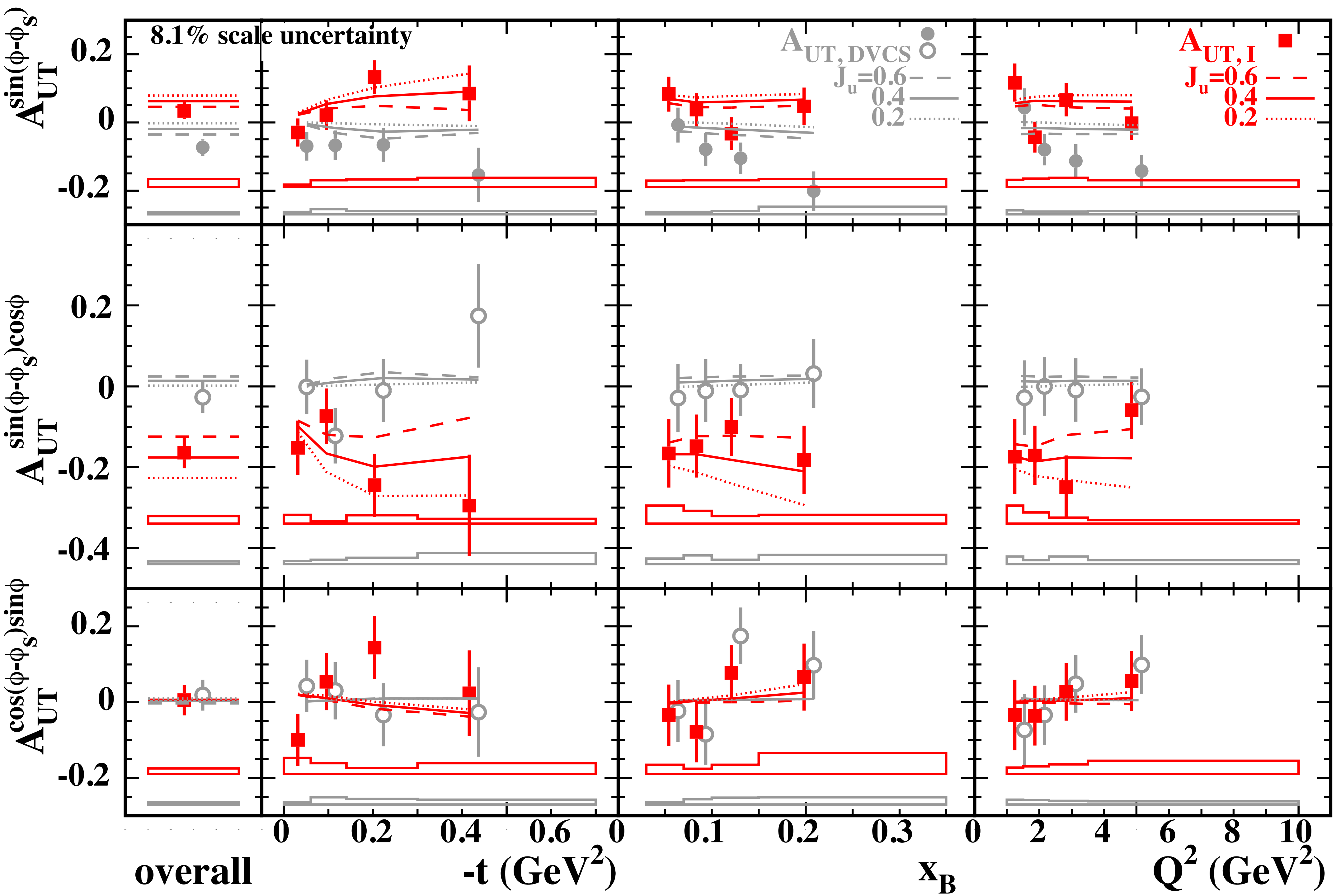
All 1996–2007 proton data.
No recoil-proton detection

Associated fraction $ep \to e\Delta^+\gamma$
(from MC simulation)

HERMES: JHEP 07 (2012) 032

GPD E

HERMES: transverse target-spin asymmetry



Model curves:
VGG Regge, no D-term
3 different values for J_u
fixed J_d=0
Eur. Phys. J C46 (2006) 729

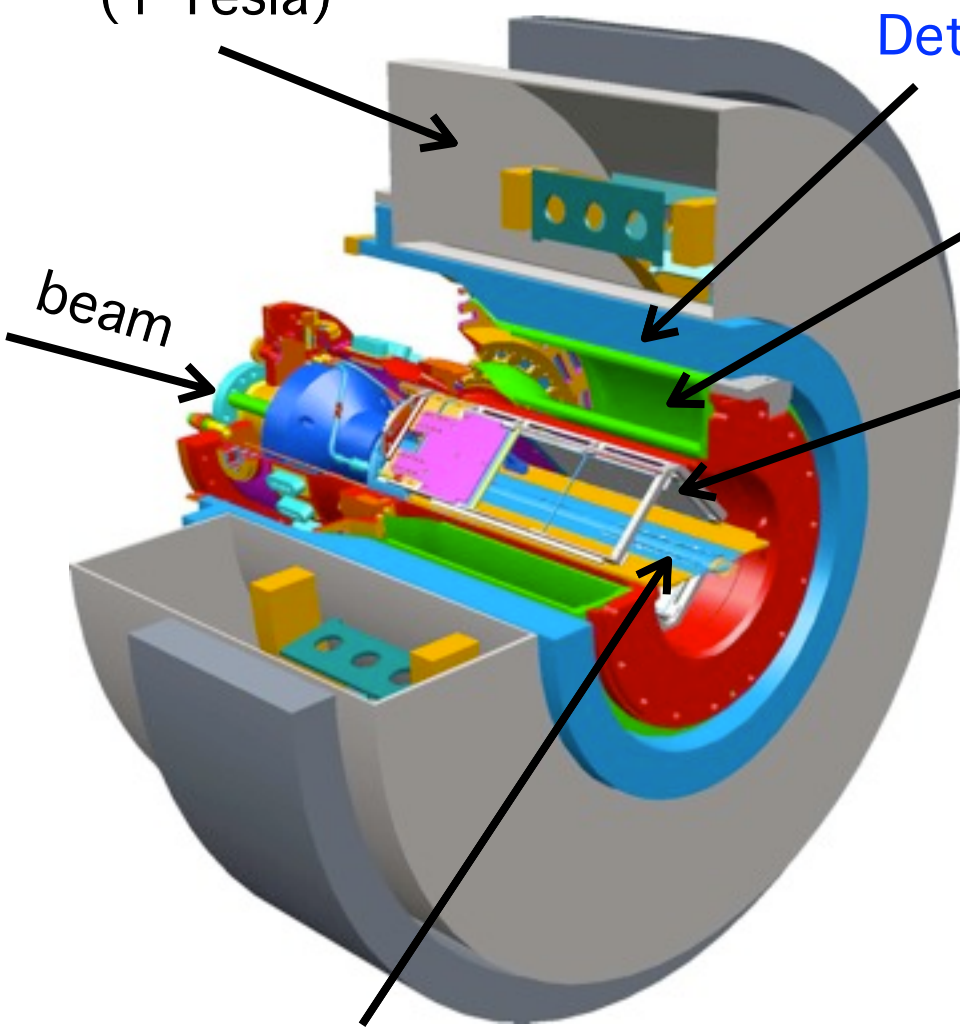
HERMES: JHEP 06 (2008) 066

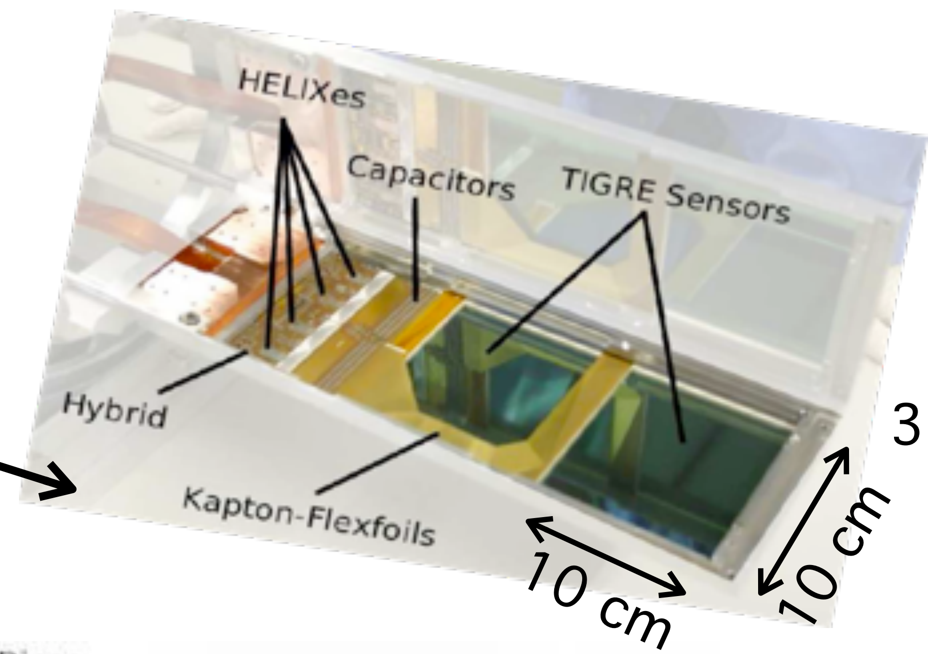
The HERMES Recoil Detector

2006/2007 unpolarized proton and deuteron data

purpose: tagging of exclusive events

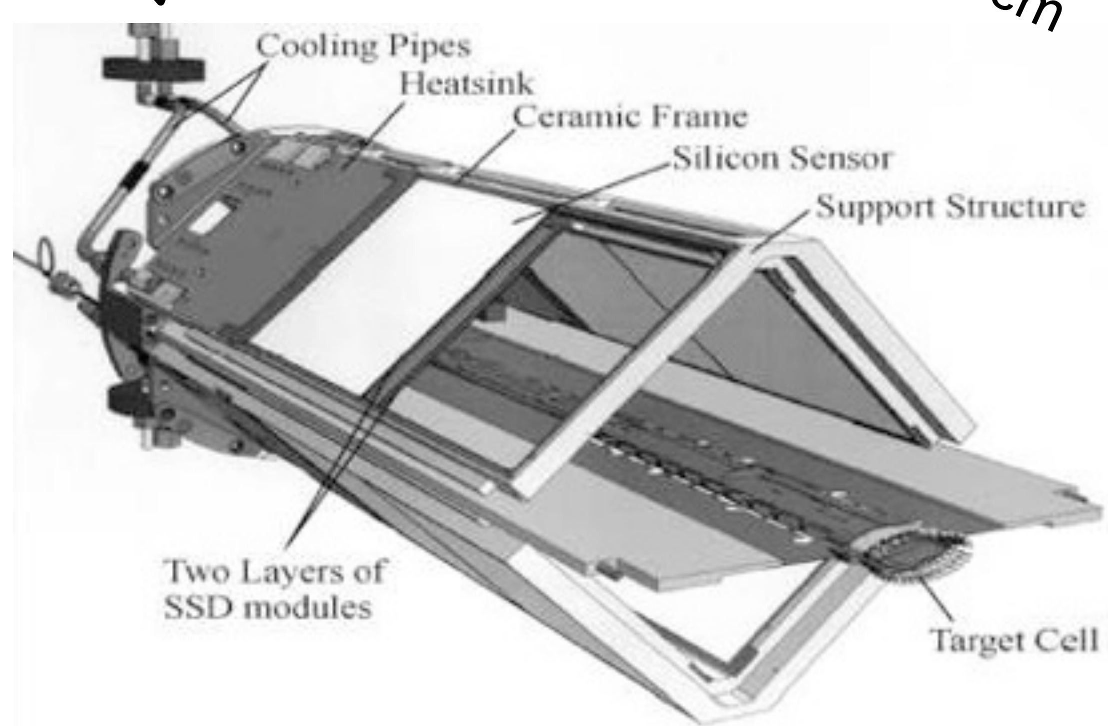
Momentum reconstruction down to 125 MeV (protons).
Want as low -t as possible!
(corresponds to -t=0.016 GeV²)





x2 x4

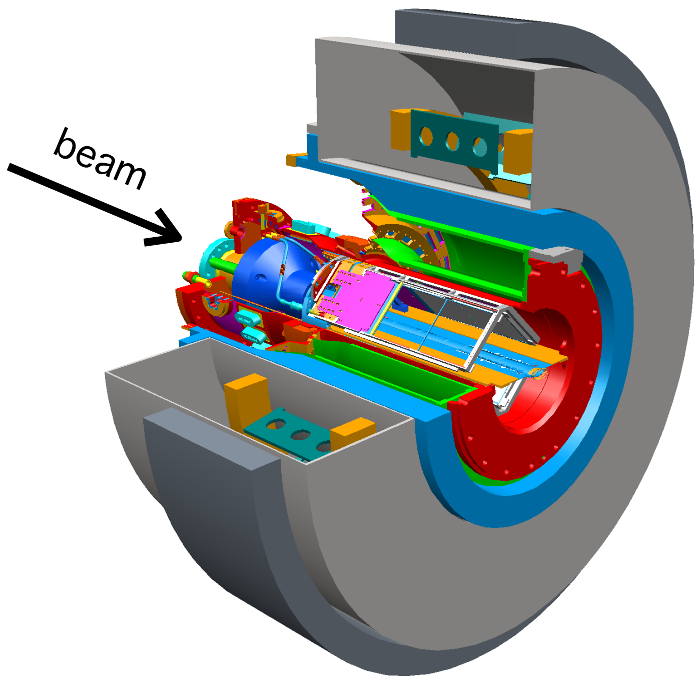
300 μm thick



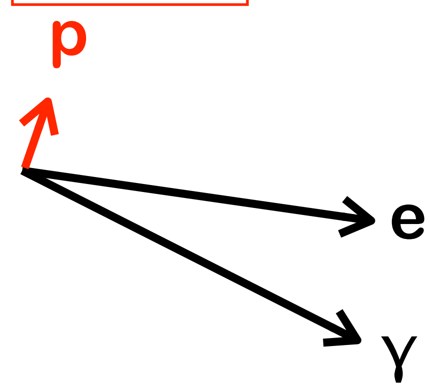
JINST 8 (2013) P05012

Improvement by recoil detector

Adding the Recoil Proton



Recoil detector



Forward tracking

ECal

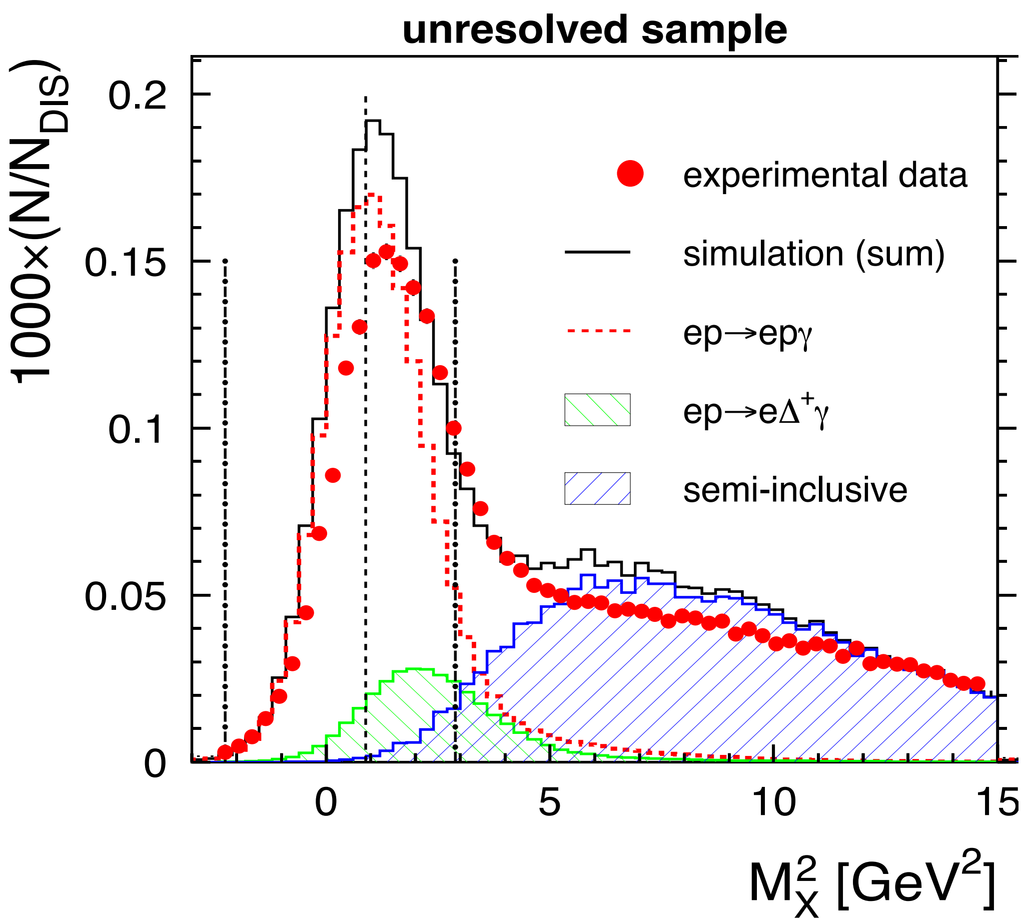
Kinematic event fitting

$$\chi^2_{\text{pen}} = \sum_{i=1}^{9} \frac{(r_i^{\text{fit}} - r_i^{\text{meas}})^2}{\sigma_i^2} + T \cdot \sum_{j=1}^{4} \frac{\left[f_j(r_1^{\text{fit}}, \ldots, r_9^{\text{fit}})\right]^2}{(\sigma_j^f)^2}$$

f_j: 4 constraints of 4-momentum conservation & assuming proton mass

Hypothesis: ep→epγ event
⇒ require: $\chi^2 < 13.7$

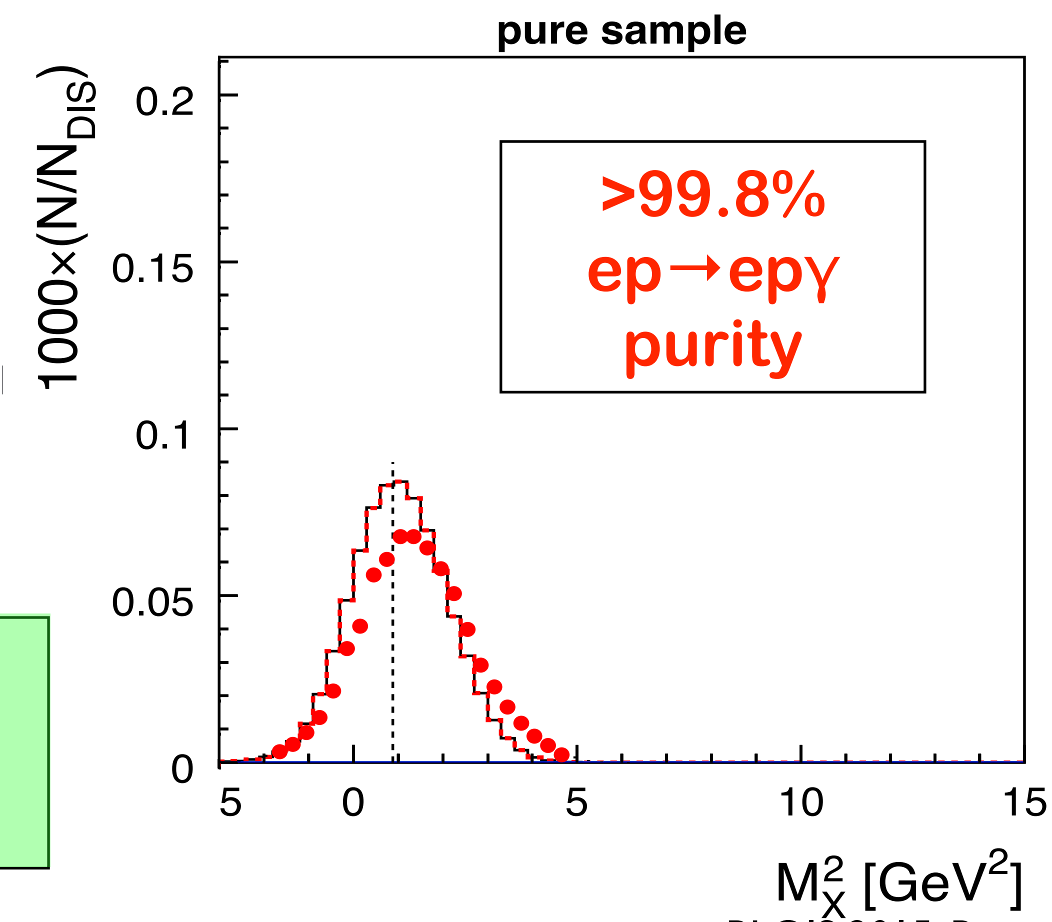
Only eγ detection



unresolved for Δ⁺

~88% ep→epγ purity

epγ detection

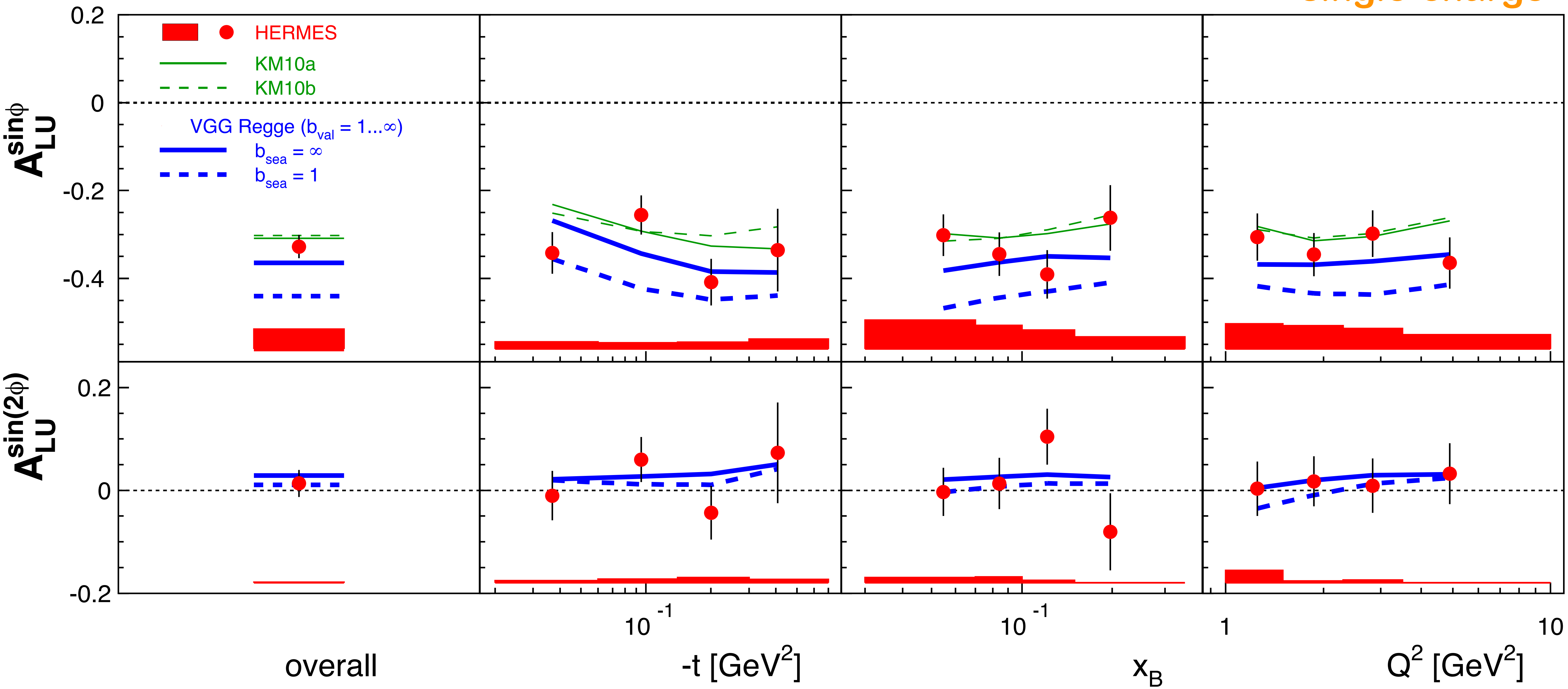


>99.8% ep→epγ purity

HERMES (with recoil proton): beam-helicity asymmetry

GPD H
Im($\mathcal{H}_{DVCS}$)
BSA

single-charge



Global fit of world data
JLab, HERMES and HERA,
dashed excludes JLab Hall A cross section
K. Kumericki and D. Müller, Nucl. Phys. B 841 (2010) 1

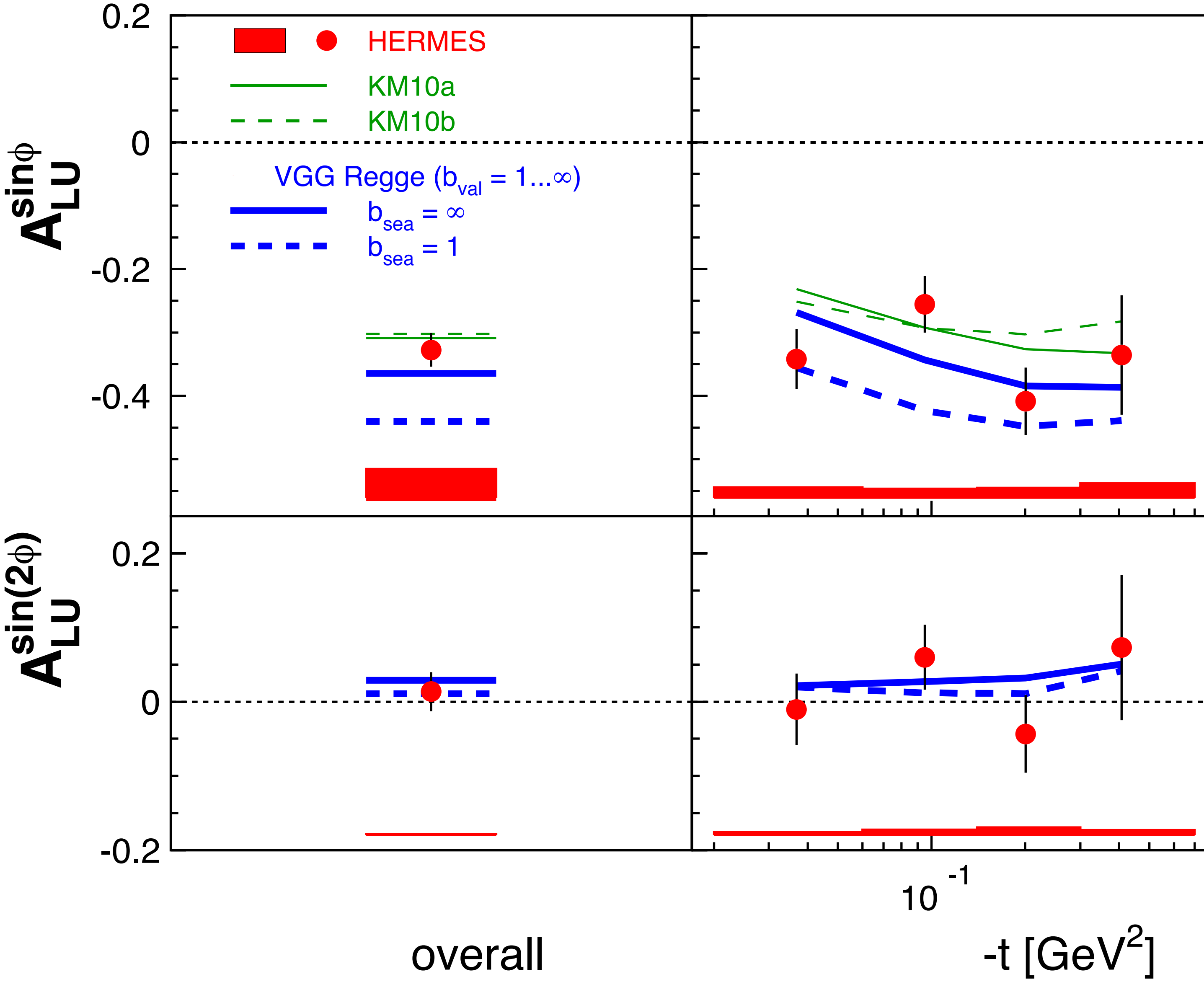
GPD model calculation "VGG Regge"
Phys.Rev. D60 (1999) 094017 and Prog.Nucl.Phys. 47 (2001) 401

HERMES: JHEP 10 (2012) 042

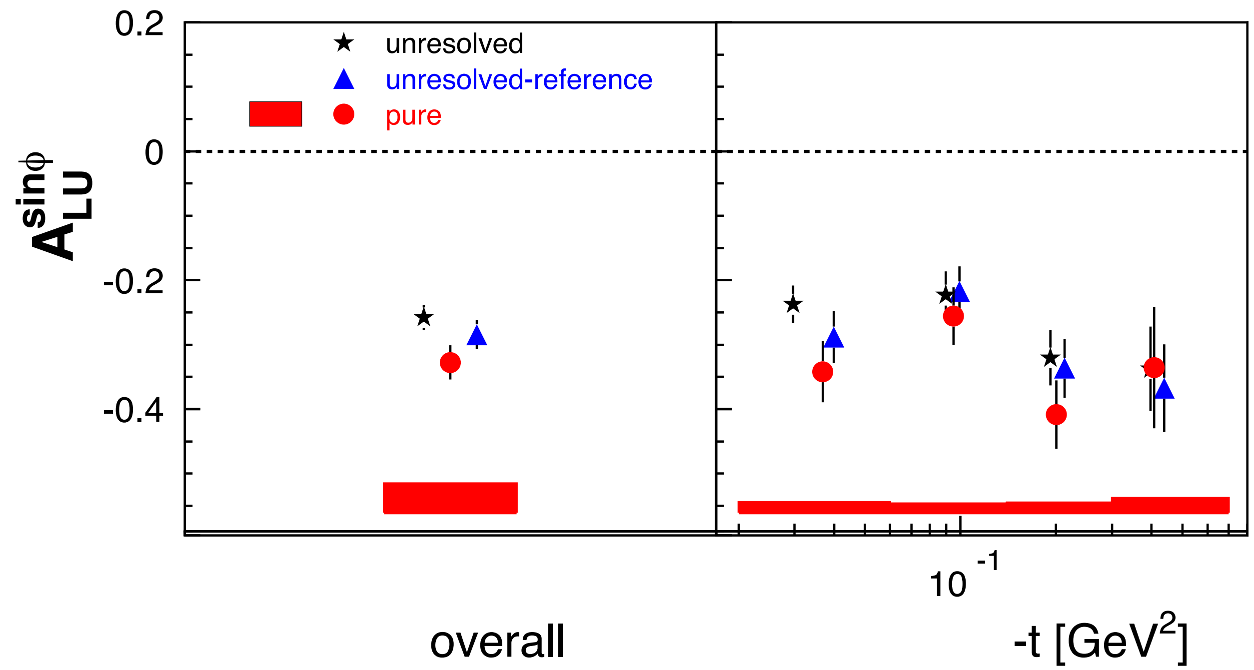
GPD H
$Im(\mathcal{T}_{DVCS})$
BSA

HERMES (with recoil proton): beam-helicity asymmetry

single-charge



- epγ detection: >99.8% purity of ep→ epγ
- ★ eγ detection: sample unresolved for 12% resonant production, e.g. ep→ $e\Delta^+\gamma$
- ▲ eγ detection in recoil acceptance (reference)



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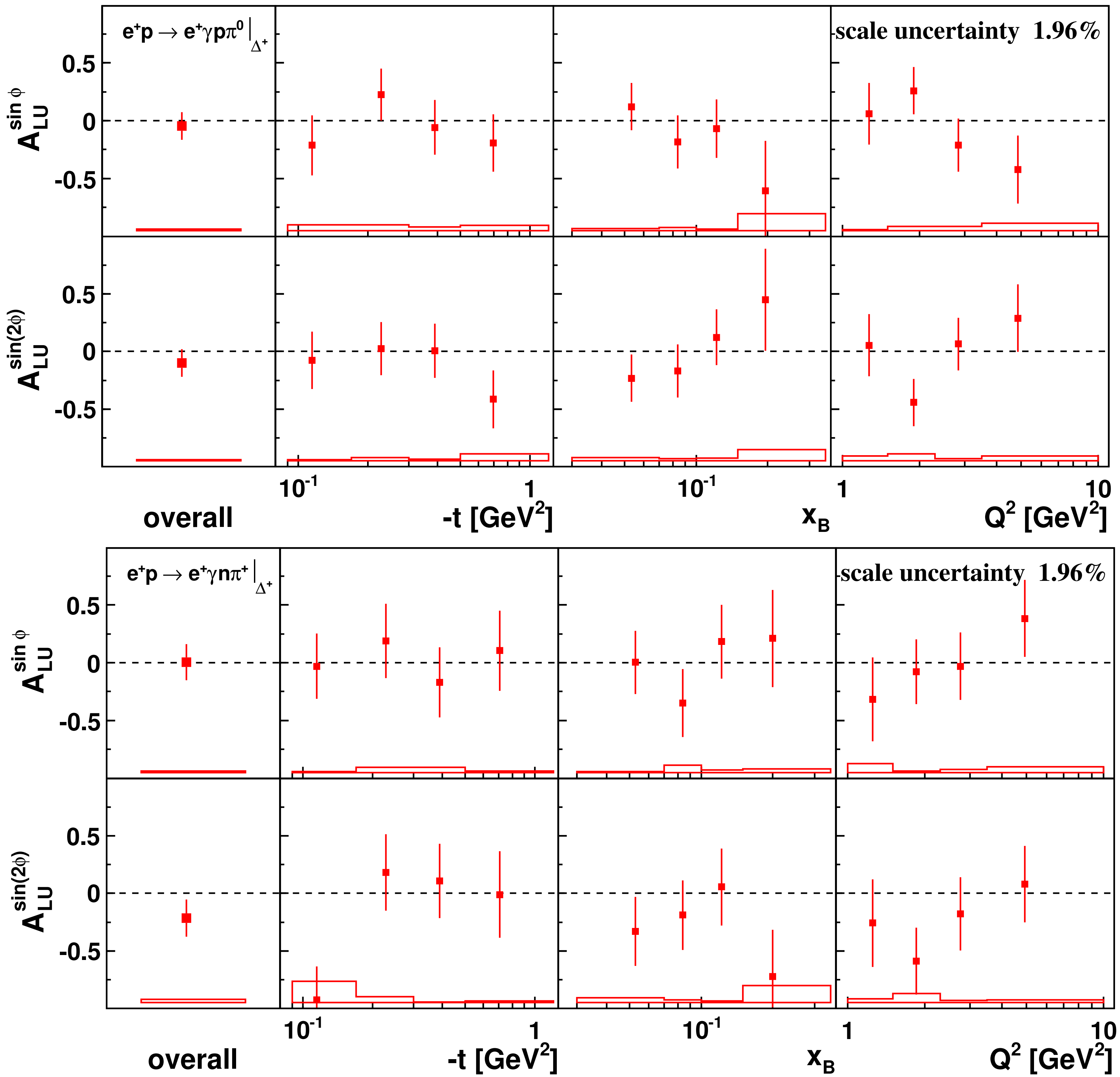
Phys.Rev. D60 (1999) 094017 and Prog.Nucl.Phys. 47 (2001) 401

HERMES: JHEP 10 (2012) 042

HERMES: beam-helicity asymmetry

in $ep \rightarrow e\gamma(\pi N)$ in the Δ-resonance region

(transition GPDs)



☛ The charged particle of (πN) reconstructed by the recoil detector.

☛ This result is consistent with the slight increase of the beam-helicity asymmetry amplitude with recoil proton.

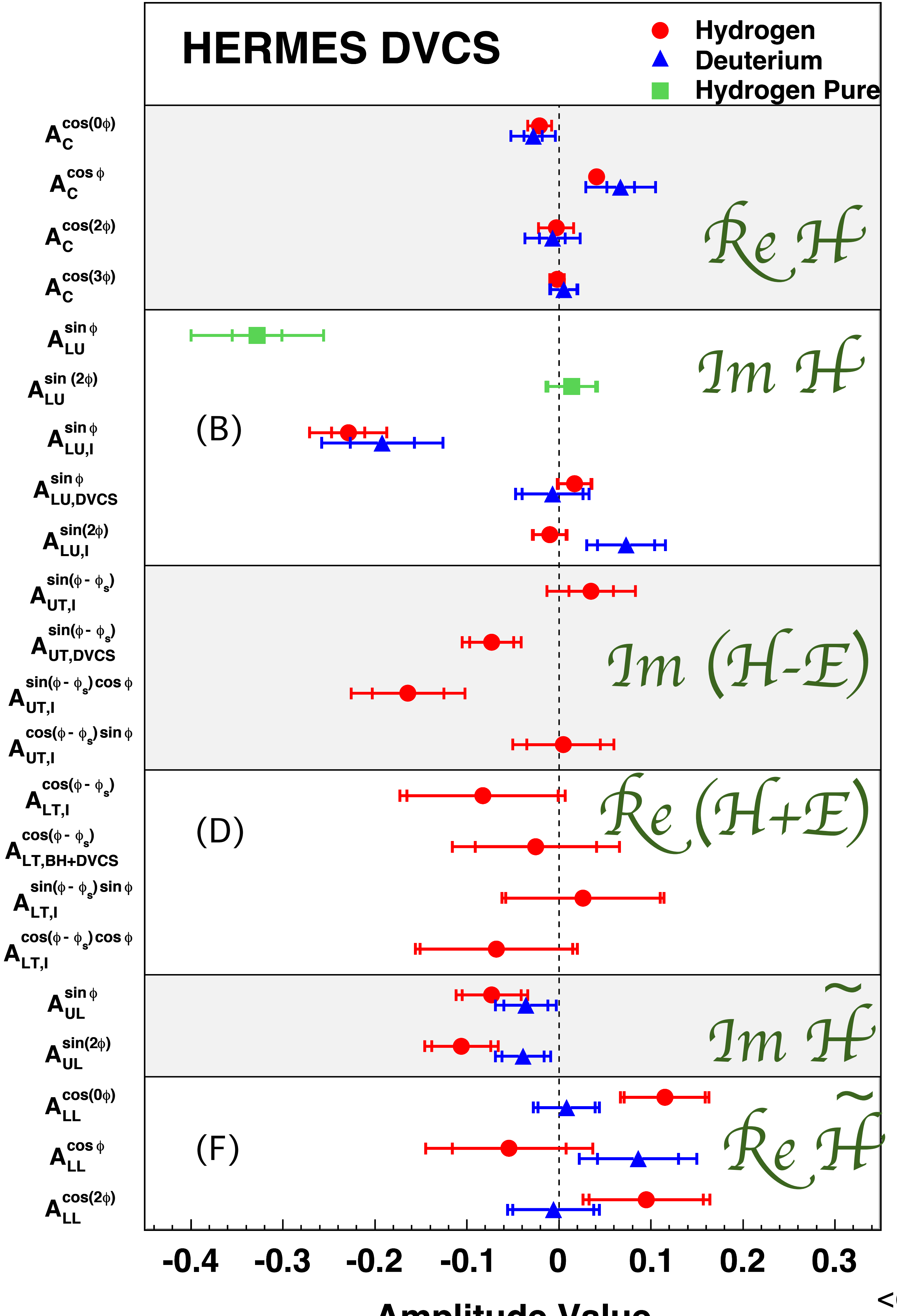
☛ Associated process acts as small dilution in the asymmetries for the unresolved sample.

☛ Only existing model prediction for sinϕ amplitude: π^0p: -0.15, π^+n: -0.10

P.A.M. Guichon, L. Mossé, M. Vanderhaeghen: Pion production in deeply virtual Compton scattering, Phys. Rev. D68, 034018 (2003).

HERMES: JHEP01 (2014) 077

DVCS Amplitudes



(A) Beam-charge asymmetry:
GPD H
[JHEP 07 (2012) 032 - Nucl. Phys. B 829 (2010) 1-27]

(B) Beam-helicity asymmetry:
GPD H
[JHEP 07 (2012) 032 - Nucl. Phys. B 829 (2010) 1-27 - JHEP10 (2012) 042]

(C) Transverse target-spin asymmetry:
GPD E
[JHEP 06 (2008) 066]

(D) Double-Spin (LT) asymmetry: **GPD E**
[*Phys. Lett. B 704 (2011) 15-23*]

Unique & complete set

Variety highly welcome by global fitters

(E) Longitudinal target-spin asymmetry:
GPD H~
[JHEP 06 (2010) 019 - Nucl. Phys. B 842 (2011) 265-298]

(F) Double-spin (LL) asymmetry:
GPD H~
[JHEP 06 (2010) 019 - Nucl. Phys. B 842 (2011) 265-298]

$<Q^2>=2.46$ GeV^2, $<x_B>=0.10$, $<-t>=0.12$ GeV^2

DVCS on hadrons other than the proton

Coherent and tensor signatures; nuclear medium

Spin-1	$H_1, H_2, H_3, H_4, H_5,$ $\tilde{H}_1, \tilde{H}_2, \tilde{H}_3, \tilde{H}_4$

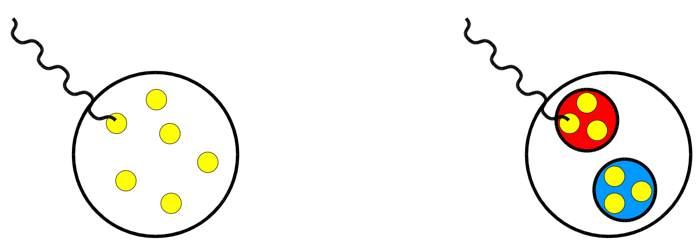
$H_5 \rightarrow$ **$b_1(x)$** **tensor structure function**

- **9** chiral-even quark GPDs at LT
- H_3, H_5 associated with 5% D-wave component of deuteron wave function

Coherent scattering

Deuteron: probe spin-1 object

Nucleon: probe spin-1/2 object



coherent **incoherent**

Kinematic cut in ***-t*** determines the domain: **"coherent enriched"** and **"incoherent enriched"** data samples

Tensor polarized deuteron

- Vector polarization $P_z \approx 0.85$
- Tensor polarization $P_{zz} \approx 0.83$
- Dedicated data set with with $P_{zz}=-1.656$ && $P_z \approx 0$

$$P_z = \frac{n^+ - n^-}{n^+ + n^- + n^0}$$

$$P_{zz} = \frac{n^+ + n^- - 2n^0}{n^+ + n^- + n^0}$$

Spin-1 particle with Λ=-1,0,+1

Nuclear targets

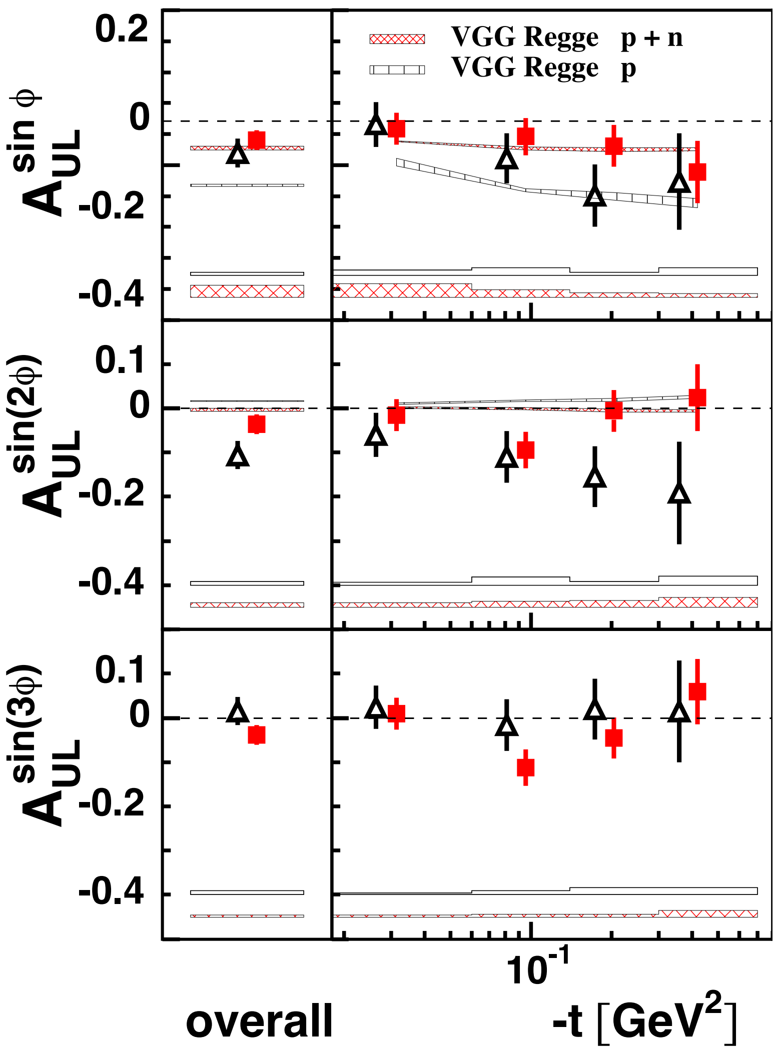
Target	Spin	L (pb^{-1})
^1H	1/2	227
He	0	32
N	1	51
Ne	0	86
Kr	0	77
Xe	0, 1/2, 3/2	47

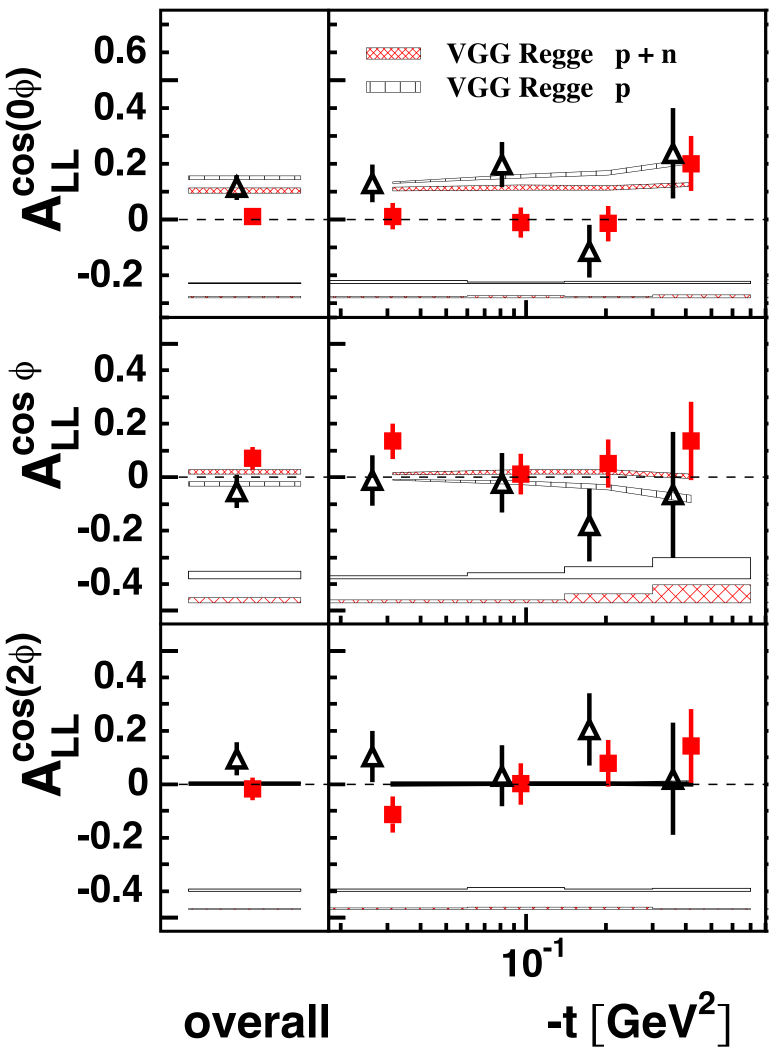
GPD $\tilde{H}_1$

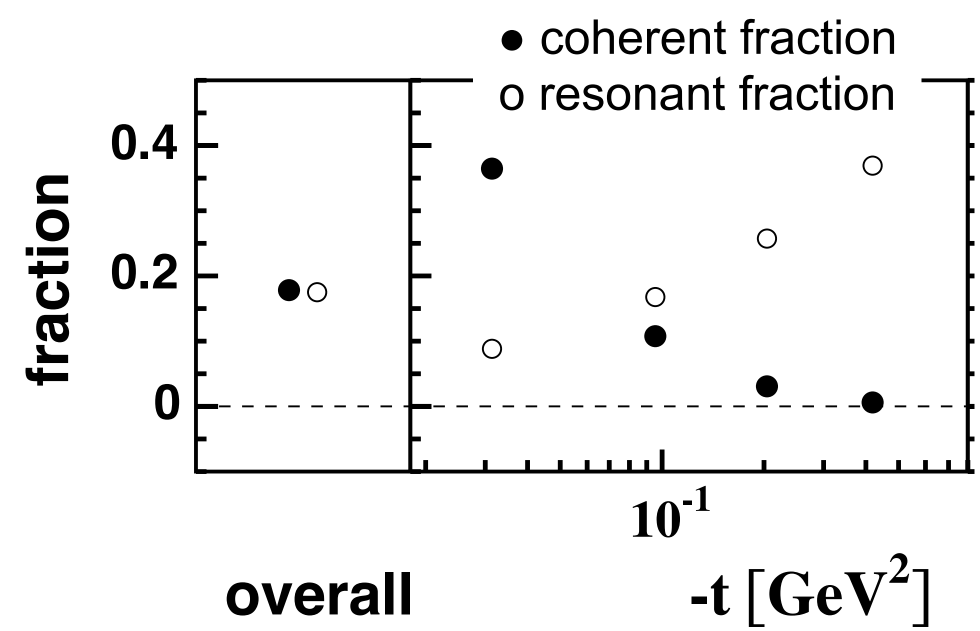
Target-Spin Asymmetry on p and d

Search for coherent signature

1998-2000 longitudinally polarized deuteron data







□ **Proton:**

$\mathcal{R}e(\tilde{\mathcal{H}})$ (incoherent)

■ **Deuteron:**

$\mathcal{R}e(\tilde{\mathcal{H}}_1)$ (coherent @low -t)

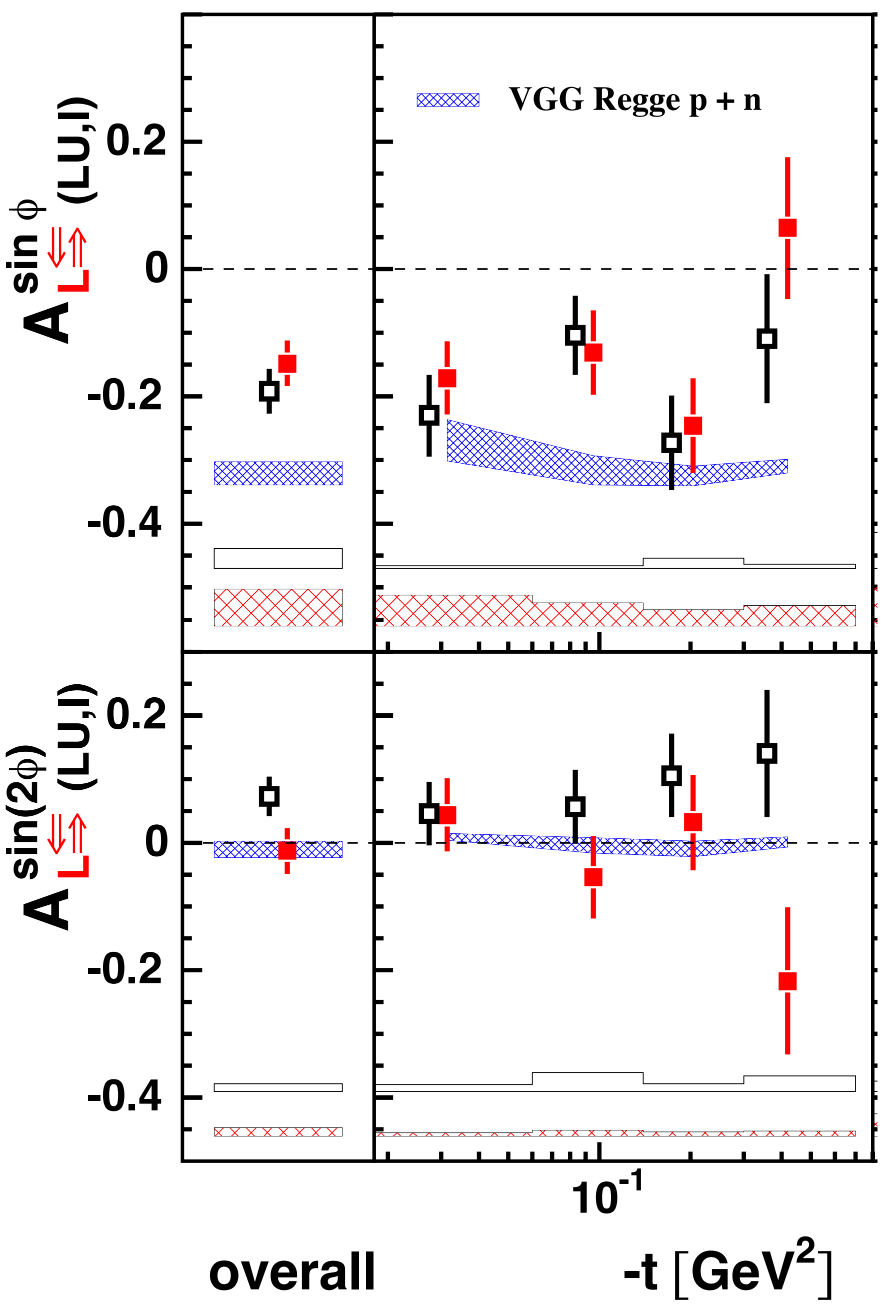
$\mathcal{R}e(\tilde{\mathcal{H}})$ (incoherent @larger -t)

Nucl. Phys. B 842 (2011) 265-298

Beam-Helicity Asymmetry on p and d

Search for tensor signature

1998–2000 longitudinally polarized deuteron data



□ unpolarized: Re(H_1)

■ tensor-polarized (P_{zz}=0.827): Re(H_1-⅓H_5)

for coherent scattering at low values of -t

$\mathcal{H}_5$

≡ tensor structure function in the forward limit

DVCS A_{LZZ} (tensor asymmetry) sinϕ amplitude:

0.074 ± 0.196 ± 0.022

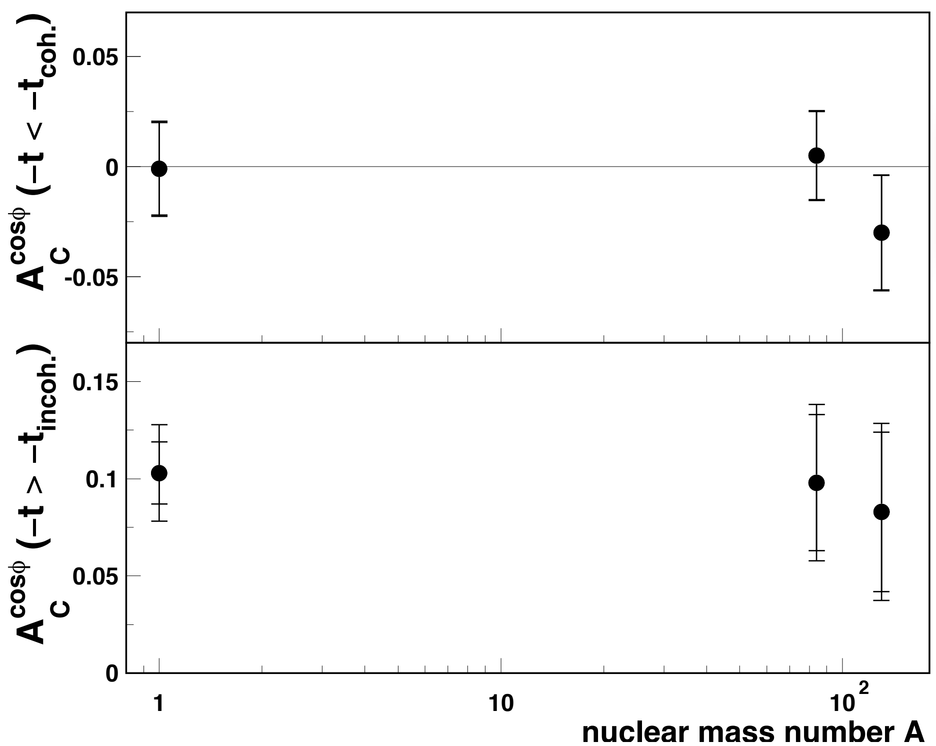
(-t<0.06 GeV^2, 40% coherent)

Nucl. Phys. B 842 (2011) 265-298

DVCS Nuclear Mass Dependence

Nuclear medium

$A_C^{\cos\phi}$ vs. A

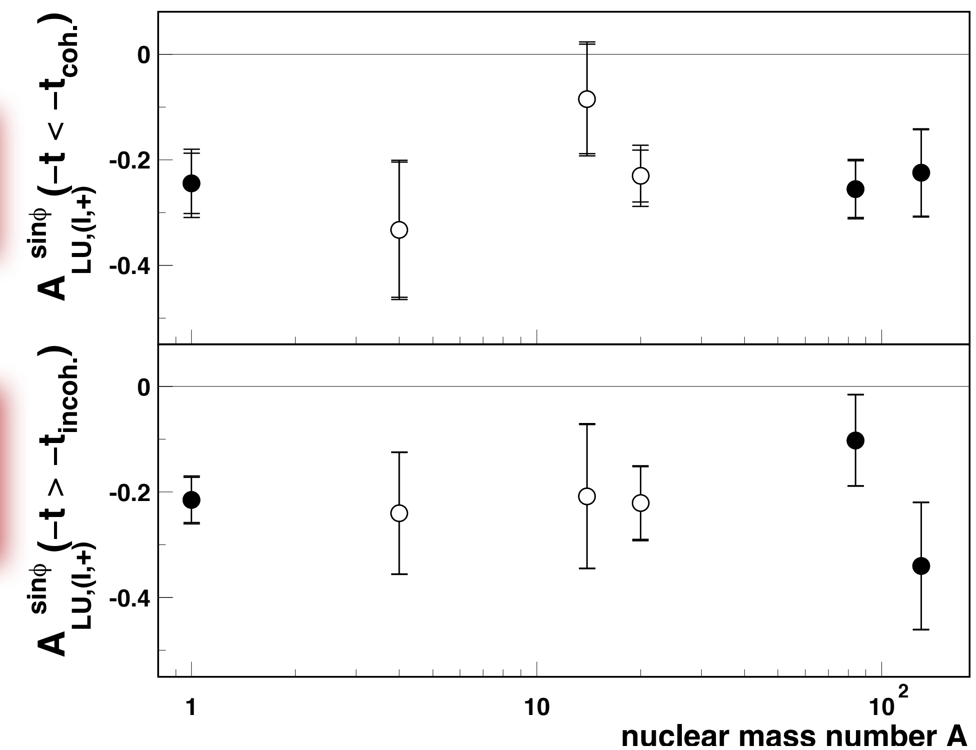


coherent enriched

incoherent enriched

Beam-charge asymmetry

$A_{LU}^{\sin\phi}$ vs. A



Beam-helicity asymmetry

Average A_{LU}^{A} / A_{LU}^{H}:

0.91±0.19
0.93±0.23

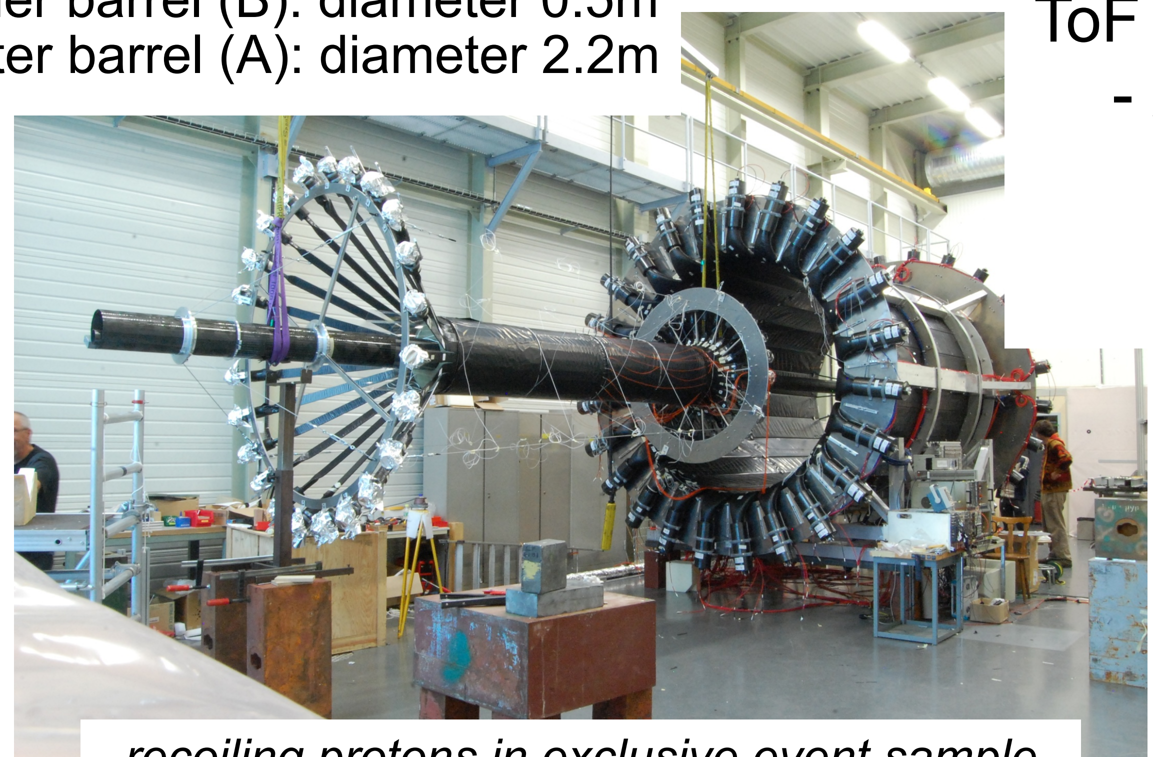
Normalization to hydrogen ^{1}H

- How does the nuclear medium modify parton-parton correlations?
- How do the nucleon properties change in the nuclear medium?
- Is there an enhanced 'generalized EMC effect', which could be revealed through the rise of τ_{DVCS} with A?

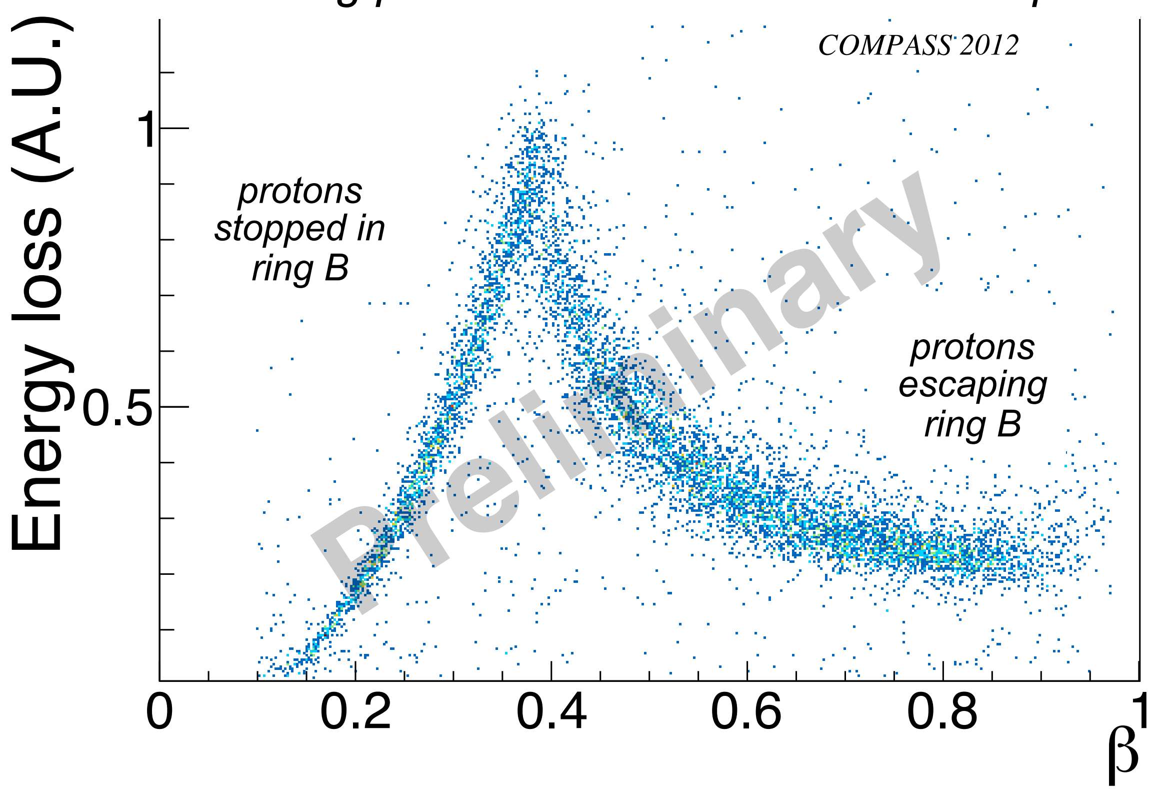
Phys. Rev. C 81 (2010) 035202

COMPASS upgrade for GPD run 2016/17

inner barrel (B): diameter 0.5m
outer barrel (A): diameter 2.2m



recoiling protons in exclusive event sample

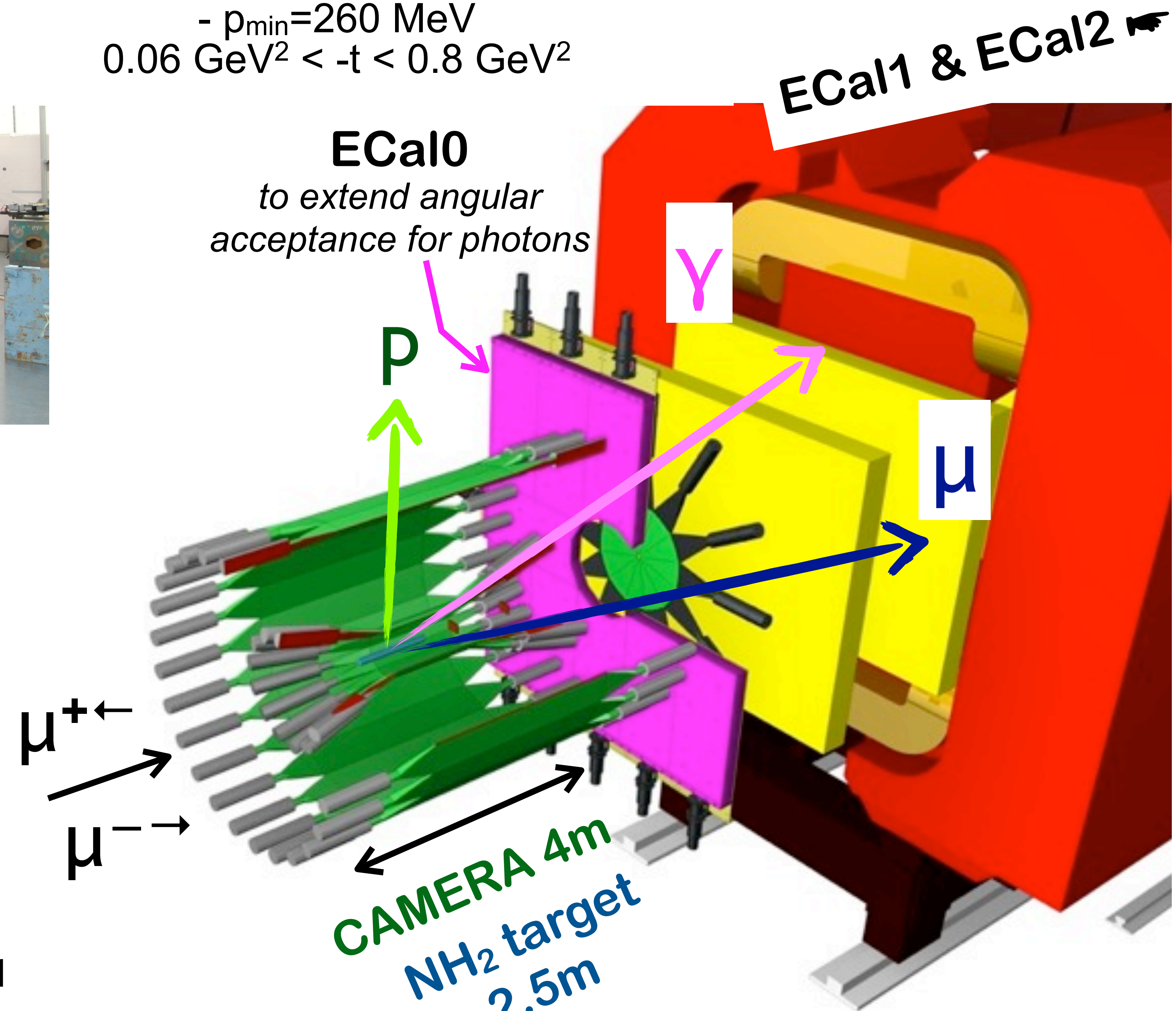


Long recoil detector CAMERA

ToF between 2 rings of scintillators

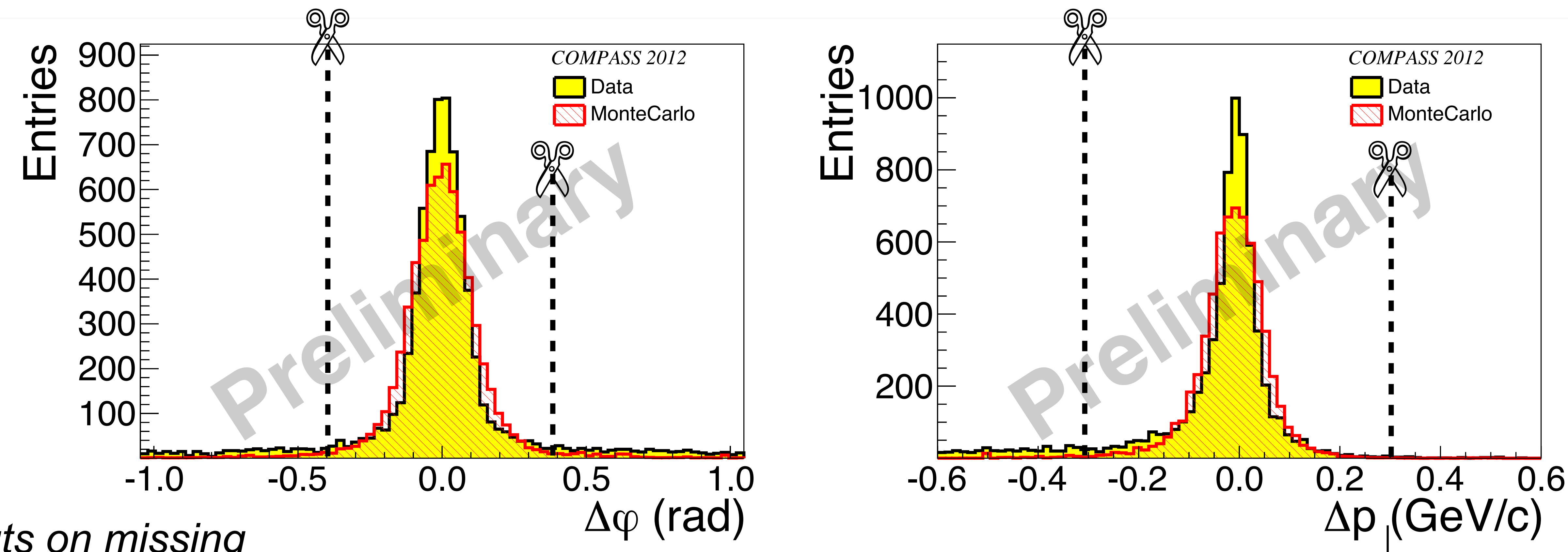
- 24 inner and 24 outer scintillators
- ToF resolution 300 ps
- p_{min}=260 MeV

$0.06\ GeV^2 < -t < 0.8\ GeV^2$



COMPASS DVCS pilot run 2012

- Full-scale recoil CAMERA detector *and only central part of ECal0 installed = 25%*



+cuts on missing mass w/o proton, ΔE, and ΔZ

Expected minus measured kinematics

from forward spectrometer

recoil in CAMERA

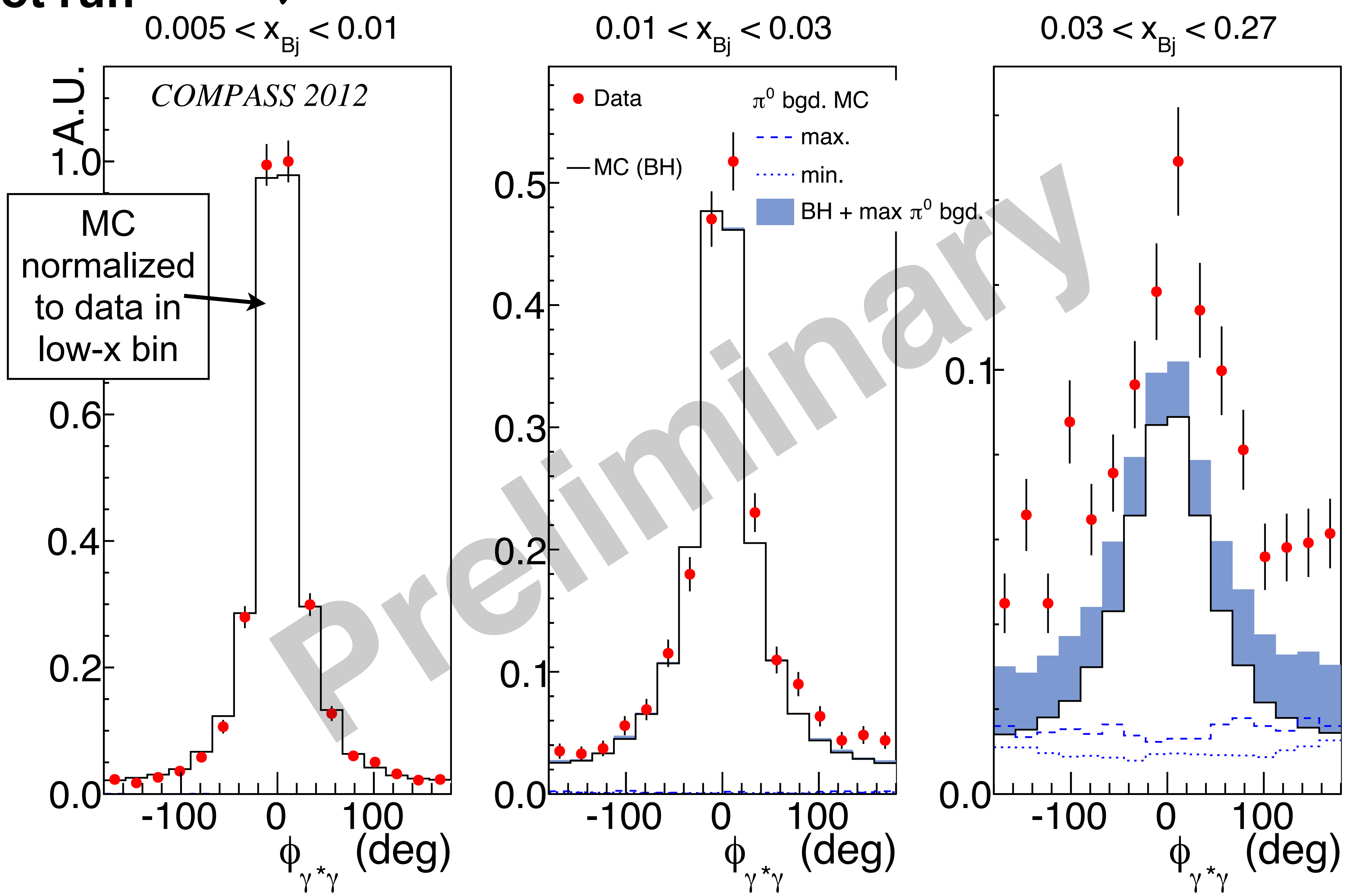
***MC**: HEPGEN/BH + DVCS/2 with GEANT4 simulation of detectors & full COMPASS reconstruction chain.*

- Visible π^0 background (2 photons reconstructed): measured and corrected for
- Invisible π^0 background (1 photon escapes): estimated by MC. SIDIS: LEPTO; exclusive: HEPGEN/π^0

DVCS vs. BH at COMPASS

2012 DVCS pilot run

$$|\mathcal{T}_{\mathrm{BH}}|^2 + (\mathcal{T}_{\mathrm{DVCS}}\mathcal{T}^*_{\mathrm{BH}} + \mathcal{T}^*_{\mathrm{DVCS}}\mathcal{T}_{\mathrm{BH}}) + |\mathcal{T}_{\mathrm{DVCS}}|^2$$



BH reference yield	**DVCS amplitude:** Φ-modulations in cross section	**Transverse imaging:** Φ-integrated cross section

High-x bin:

- Largest fraction of π^0 background
- Pure DVCS events after subtraction of (BH + measured SIDIS π^0 + max. simulated exclusive π^0) ⇒ excess

DVCS at COMPASS-II

$$\mathcal{S}_{CS,U} \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}} = 2(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \boxed{\mathrm{Im}\,\mathcal{I}})$$

$$\mathcal{D}_{CS,U} \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}} = 2(P_\mu d\sigma^{DVCS}_{pol} + e_\mu \boxed{\mathrm{Re}\,\mathcal{I}})$$

@COMPASS:
H-dominance

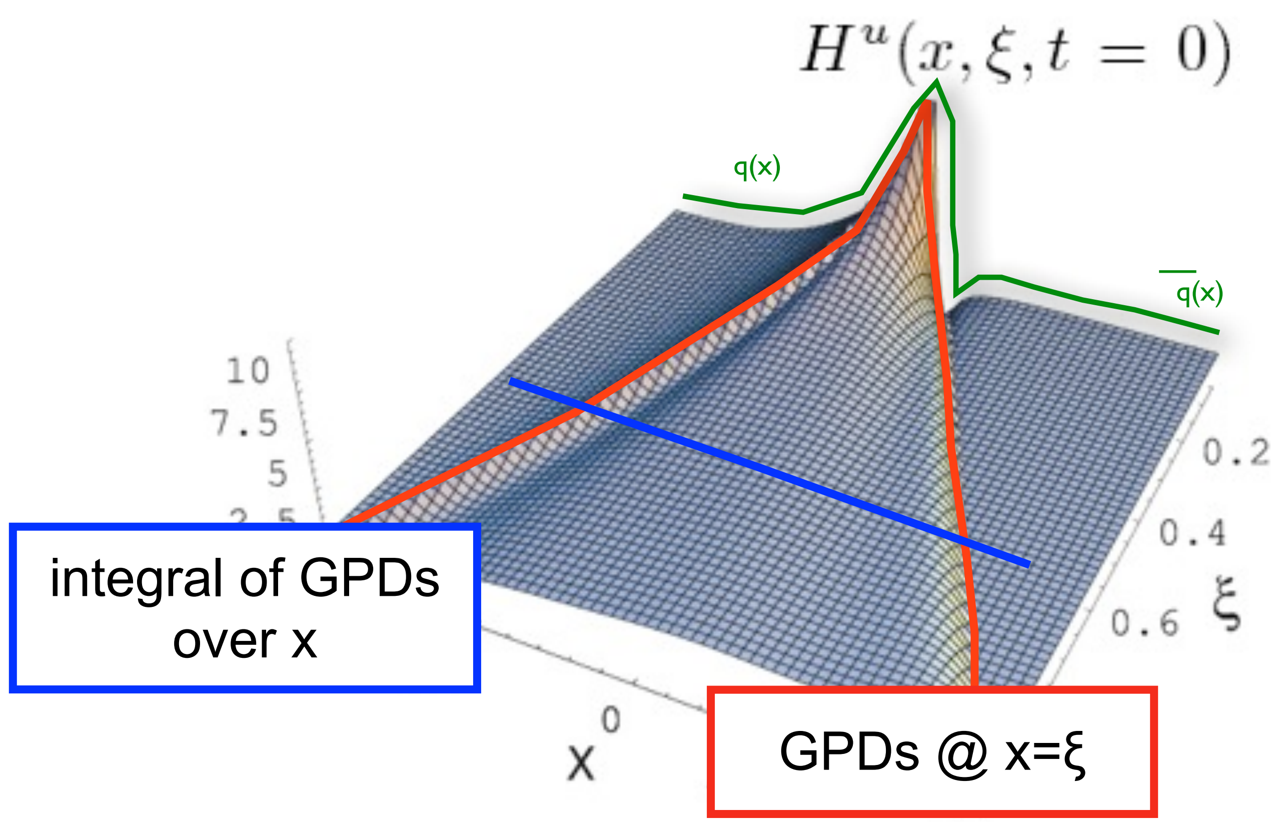
$$\mathrm{Im}\,\mathcal{H}(\xi,t,Q^2) \overset{LO}{=} \pi \sum_f e_f^2 \left(H^f(\xi,\xi,t,Q^2) \mp H^f(-\xi,\xi,t,Q^2)\right)$$

$$\mathrm{Re}\,\mathcal{H}(\xi,t,Q^2) \overset{LO}{=} \sum_f e_q^2 \left[\mathcal{P}\int_{-1}^{1} dx\ H^f(x,\xi,t,Q^2)\left(\frac{1}{x-\xi} \mp \frac{1}{x+\xi}\right)\right]$$

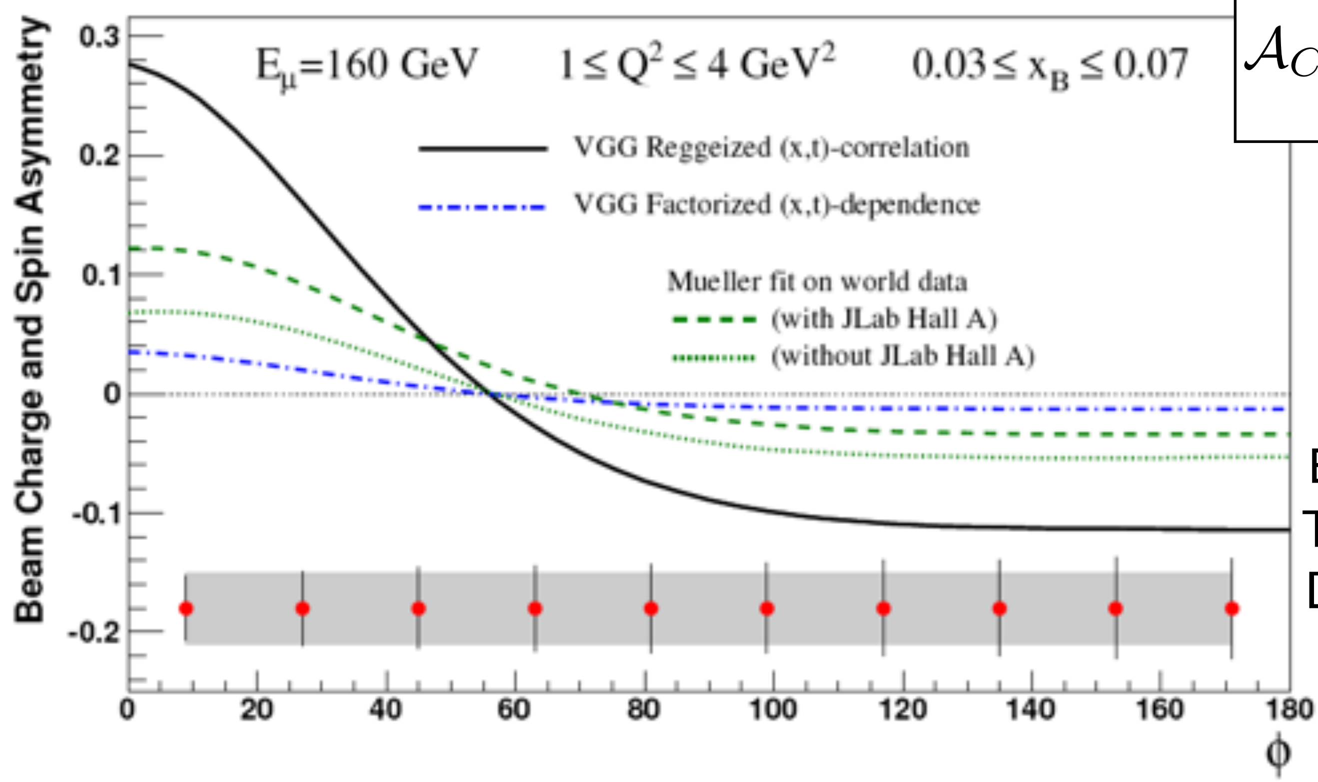
+ link to D-term

Kinematic range
(DVCS 2012 pilot run):

$1\ \mathrm{GeV}^2 < Q^2 < 20\ \mathrm{GeV}^2$
$0.005 < x_{Bj} < 0.27$
$0.06 < |t| < 0.64\ \mathrm{GeV}^2$

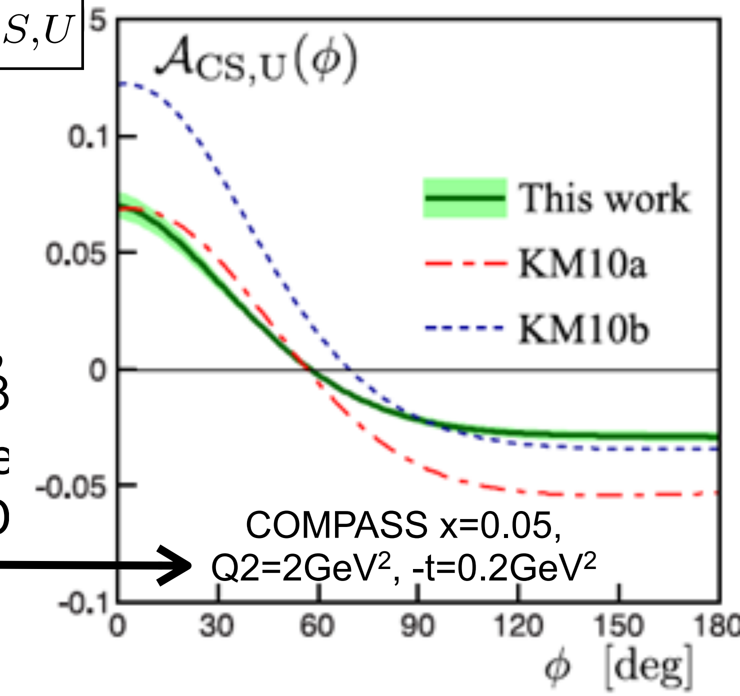


COMPASS-II projections for spin & charge asym.

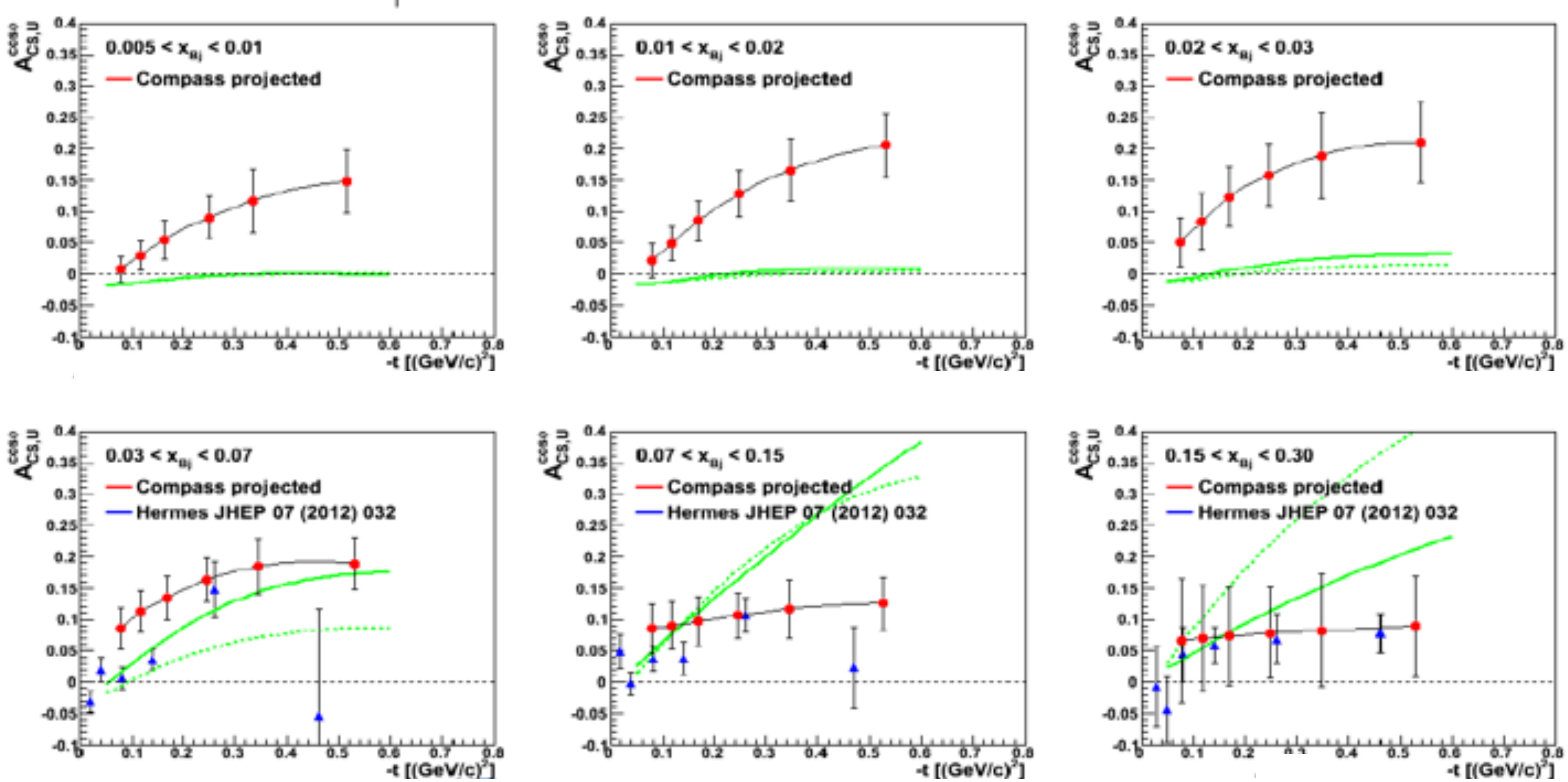


$$\mathcal{A}_{CS,U} \equiv \frac{d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}}{d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}} = \frac{\mathcal{D}_{CS,U}}{\mathcal{S}_{CS,U}}$$

Kroll, Moutarde, Sabatié,
Eur. Phys. J. C (2013) 73:2278
Test of GPD universality: use DVMP data to constrain GPD params



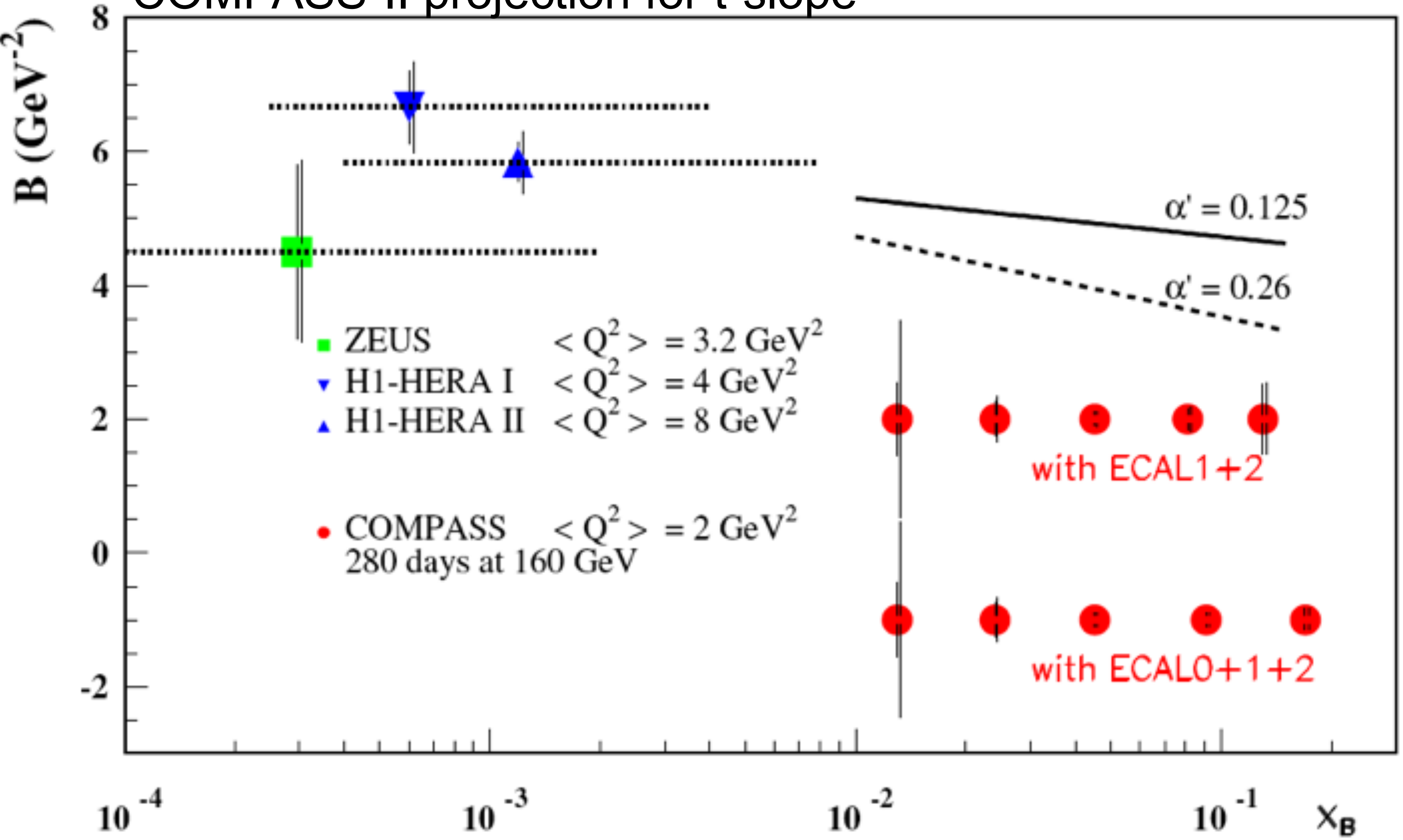
- Projection compared with HERMES beam-charge asymmetry's cosΦ-modulation
- Question: magnitude of cosΦ-modulation in COMPASS data?
- Changes sign in between H1 and HERMES!



Transverse imaging from DVCS and DVMP

$$\frac{d\sigma^{\mathrm{DVCS}}}{dt} \propto e^{-b|t|}$$

COMPASS-II projection for t-slope



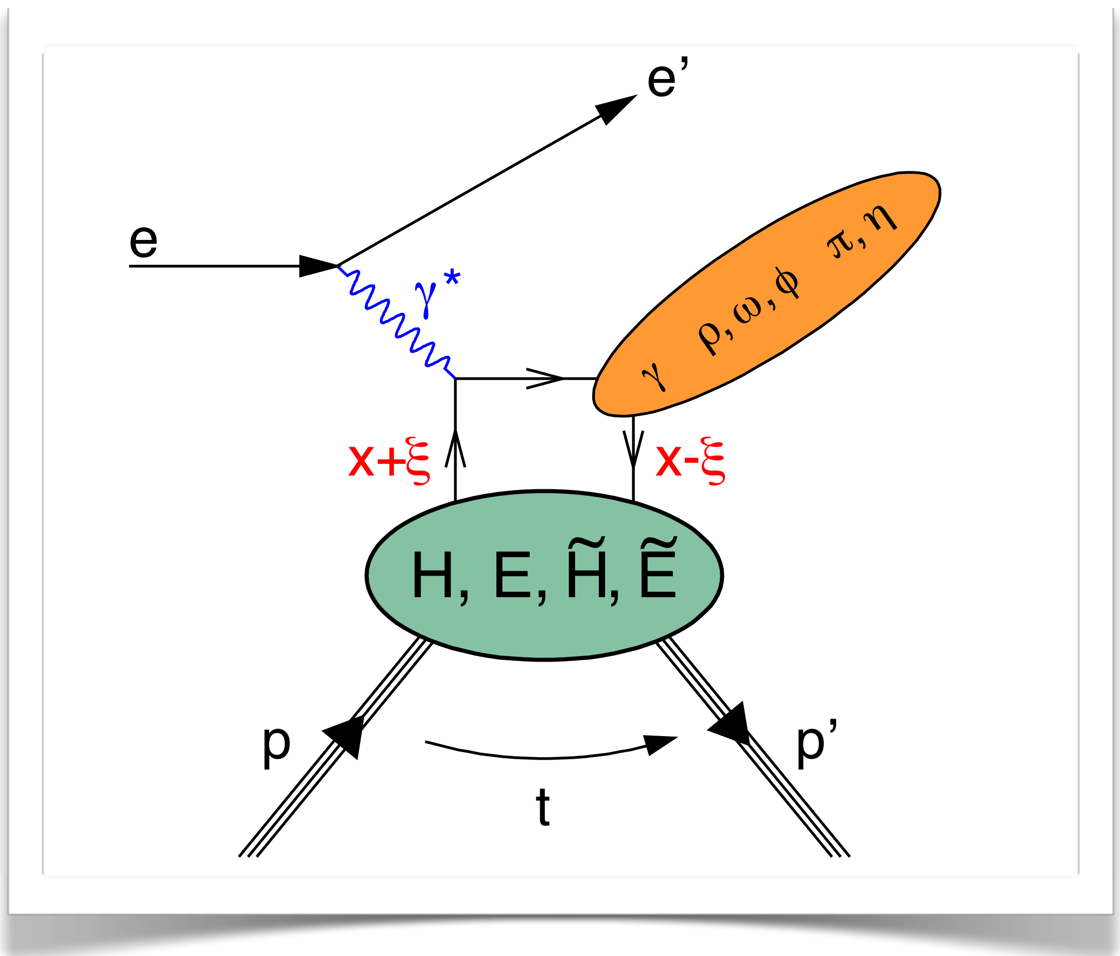
2 years of data
beam energy 160 GeV
$4{\cdot}10^8$ μ^+/spill (μ^- 2.6x less)
duration 9.6s every 48s
2.5m target
Lumi=10^{32} cm^{-2}s^{-1}
ε_{global} =10%

Regge-trajectory ansatz
$b(x_B) = b_0 + 2\boldsymbol{\alpha}'\ln(x_0/x_B)$

$\alpha' \simeq 0.25$ GeV^{-2}
soft pomeron

1-bin-extraction already possible from DVCS test in 2012

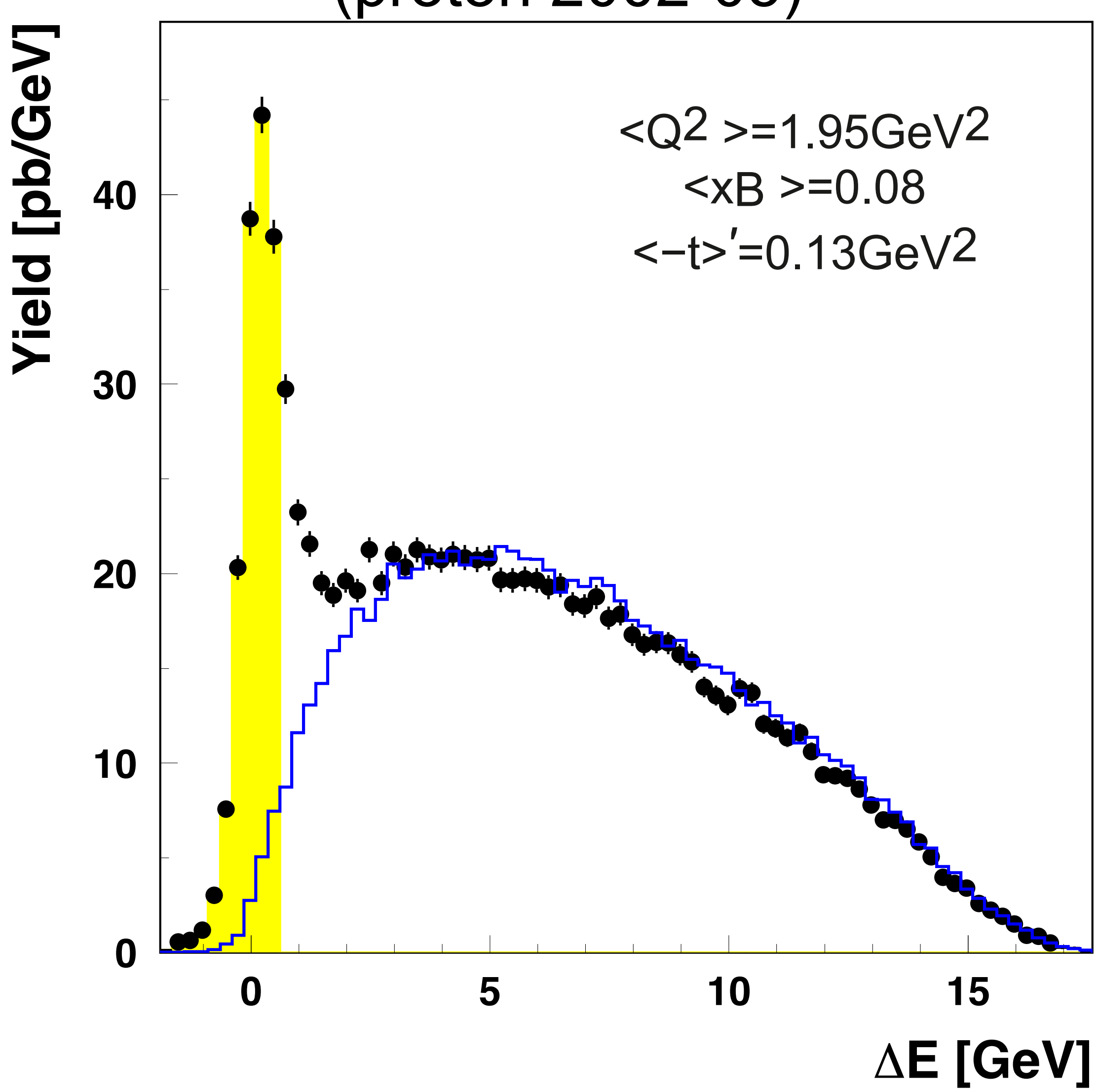
Deeply Virtual Meson Production



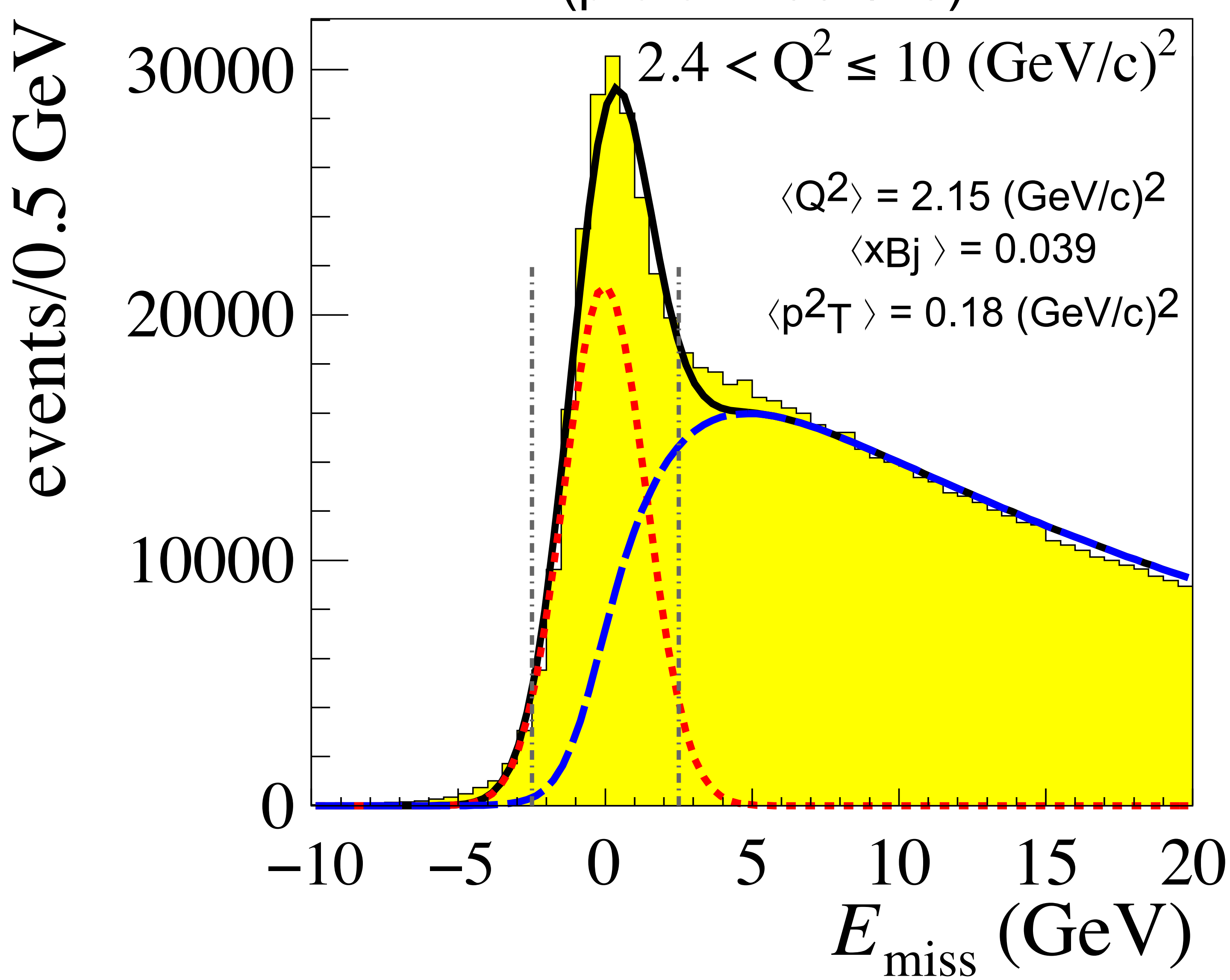
Selection of exclusive meson sample

- No recoil proton detection: missing-energy technique assuming proton mass
- MC simulation of non-exclusive background and subtraction in exclusive ΔE bin (11% HERMES, 35% COMPASS))

HERMES exclusive ρ^0
(proton 2002-05)

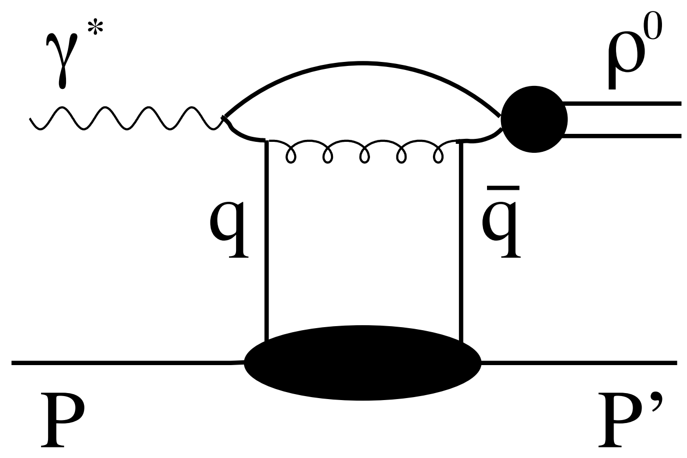


COMPASS exclusive ρ^0
(proton 2007/10)



lp→lpV: Exclusive vector meson production

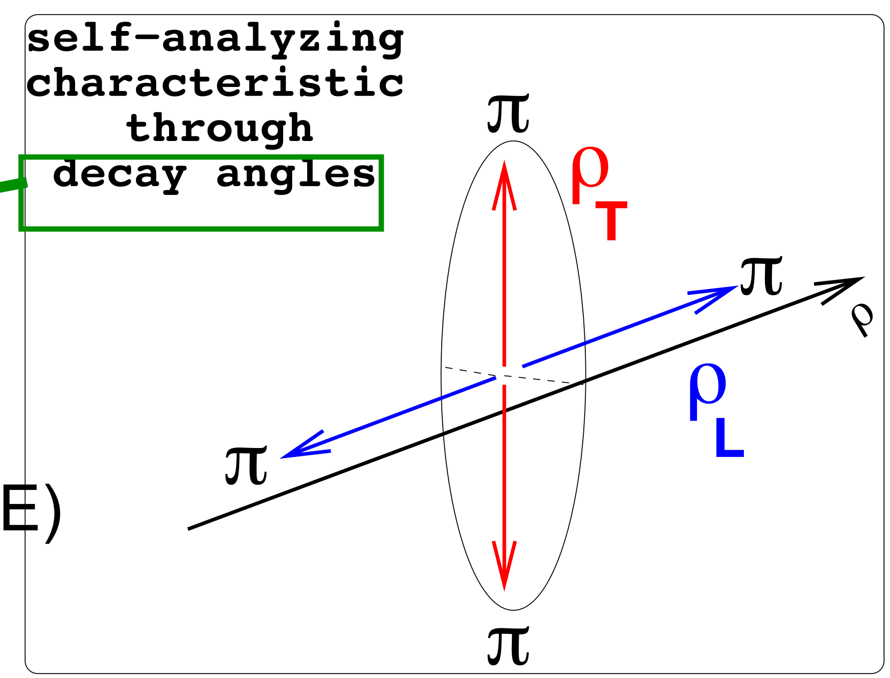
- pQCD at sufficiently large Q^2 and W: 1. γ*→(qqbar) 2. (qqbar) scatters off nucleon 3. formation of observed vector meson.



- Translated into Regge phenomenology: reggeon exchange with $J^P=0^+, 1^-, 2^+,...$ (Natural Parity Exchange) ↔ **GPDs H, E**
  $J^P=0^-, 1^+,...$ (Unnatural Parity Exchange) ↔ **GPDs H∼, E∼**

- Cross section for exclusive leptoproduction of vector mesons:

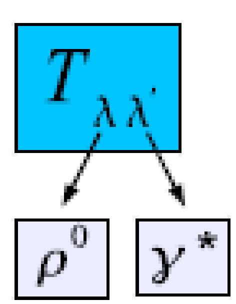
$$\frac{d\sigma}{dx_B\, dQ^2\, dt} W(x_B, Q^2, t, \phi, \phi_S, \varphi, \vartheta)$$



- ***W*** parametrized by Spin Density Matrix Elements (SDME)

- SDME describe the helicity transfer from γ* to V.

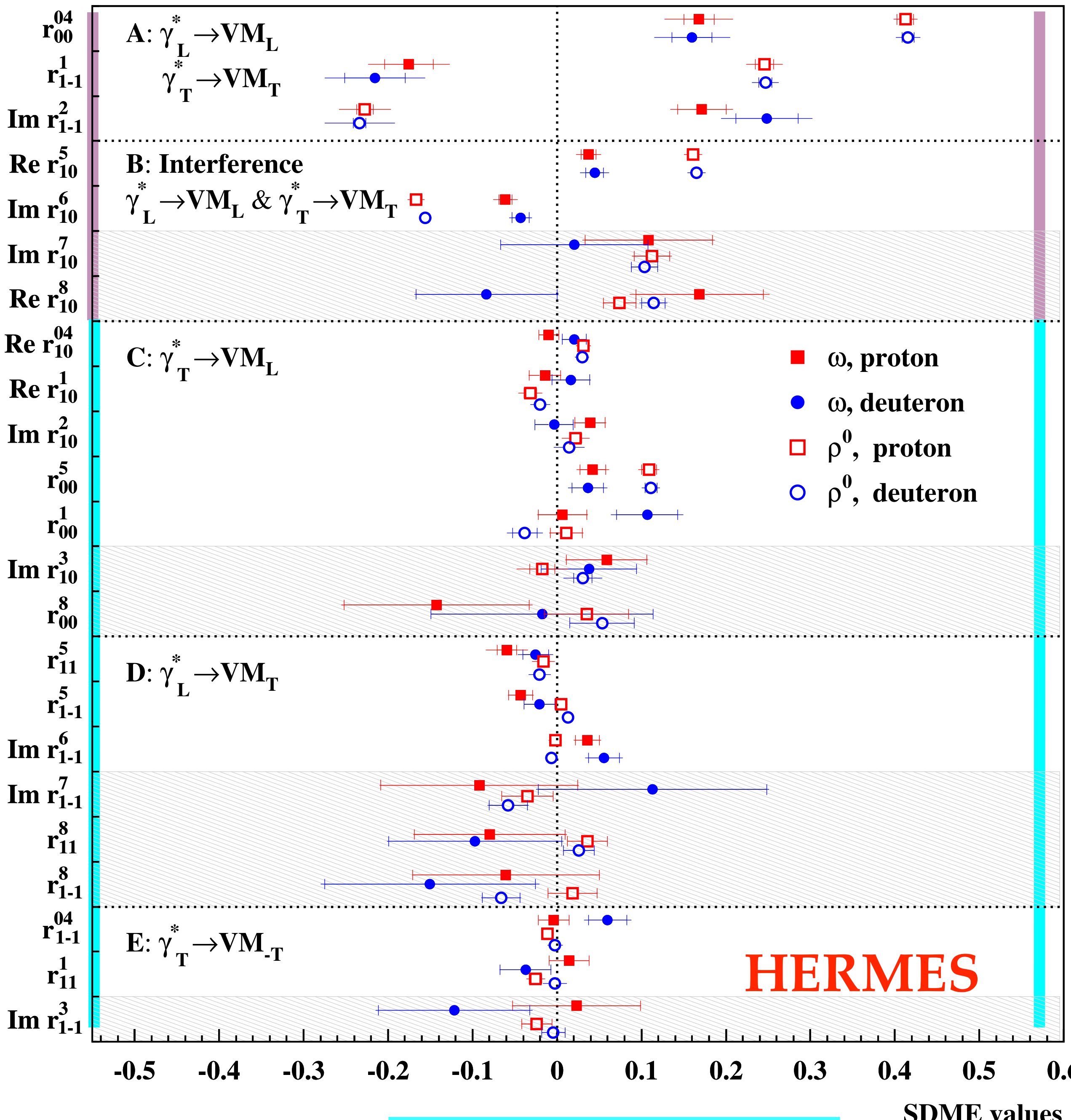
- Hierarchy of helicity amplitudes:
  $|T_{00}| \sim |T_{11}| >> |T_{01}| > |T_{10}| >= |T_{1-1}|$



- s-channel helicity conservation (SCHC) T→T, L→L

- s-channel helicity violation

Rho, Phi, and Omega SDME



$|T_{00}| \sim |T_{11}| >> |T_{01}| > |T_{10}| >= |T_{1-1}|$

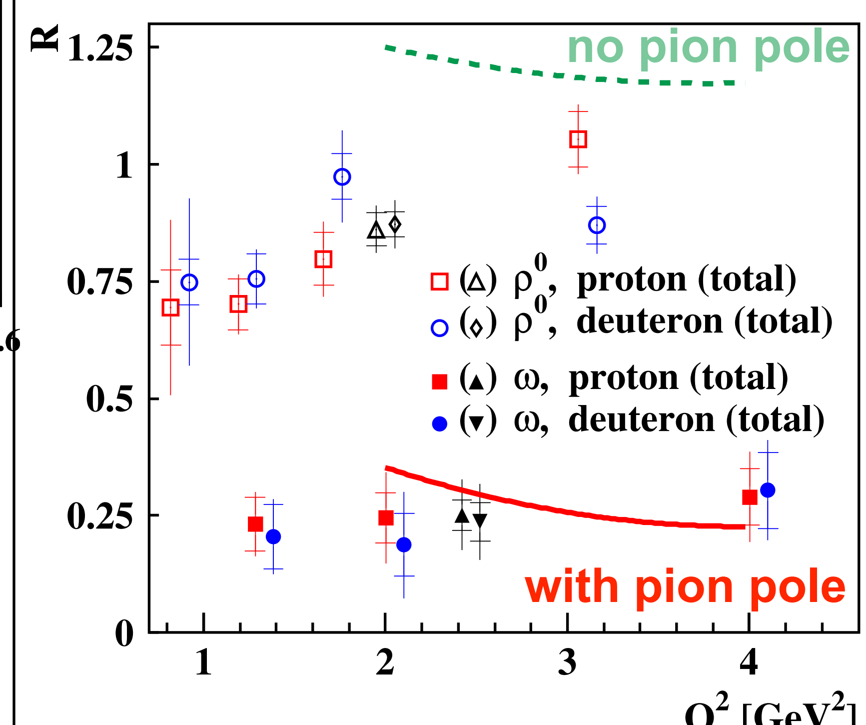
- **ρ^0** *(EPJC 62 (2009) 659-694)*
  - Hierarchy of amplitudes ✔
  - Small deviation from 0 for helicity-flip amplitudes
  - Contributions of UPE

- **ω** *(EPJC 74 (2014) 3110)*
  - Hierarchy of amplitudes ✘
  - Significant role of UPE

- **Φ** *(preliminary analysis)*
  - Hierarchy of amplitudes ✔
  - Helicity-conserving amplitudes 10-20% larger than for ρ^0

- Cross section ratio of longitudinal to transverse vector mesons

$$R(W,Q^2,t) \equiv \frac{d\sigma_L}{dt} / \frac{d\sigma_T}{dt}$$



Goloskokov, Kroll, Eur. Phys. J. A (2014) 50: 146

Analysis of HERMES ω SDMEs using a set of GPDs extracted from ρ^0, Φ, π^+ data.

Importance of pion pole for ω production.

Transverse asymmetry for exclusive ρ^0 & ω

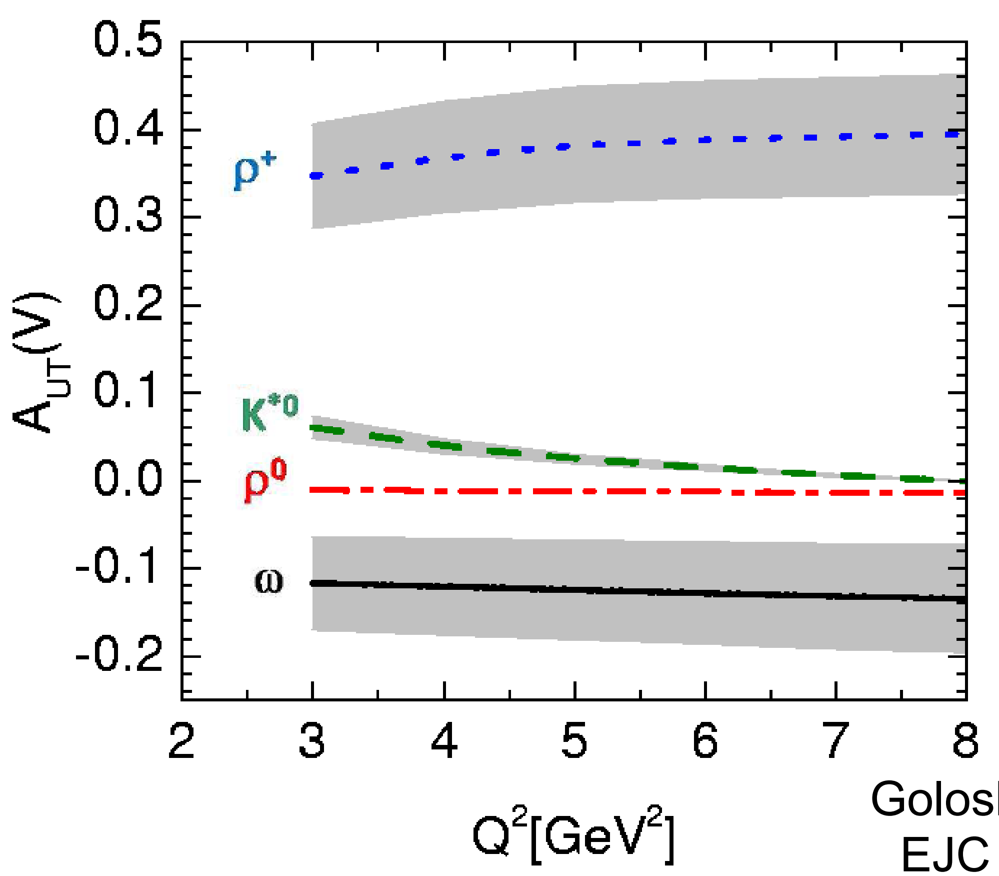
$A_{UT}^{sin(\phi-\phi_S)} \propto \mathrm{Im}\left(\mathcal{E}^\star\mathcal{H}\right)$ GPD ***E*** linked to quark orbital angular momentum.

$A_{\mathrm{UT}}^{\sin\phi_S}$ sensitive to **chiral-odd GPD *H***

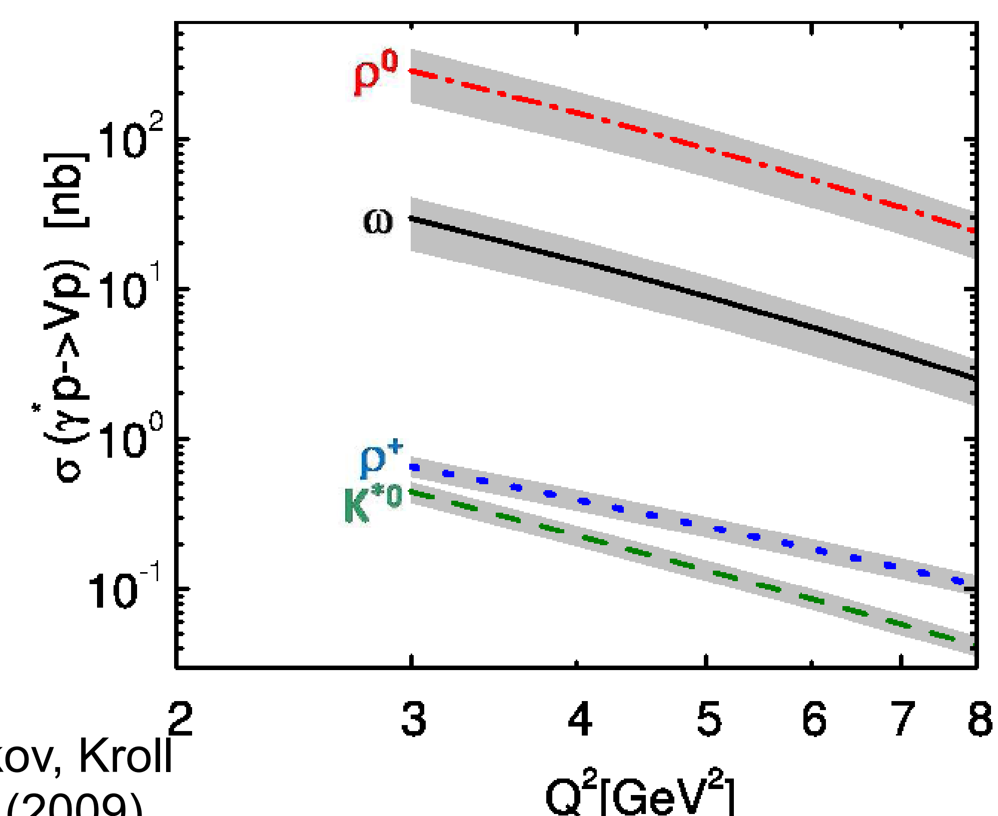
$$E^{\rho^0} = 1/\sqrt{2}(2/3E^u + 1/3E^d + 3/8E^g)$$
$$E^{\omega} = 1/\sqrt{2}(2/3E^u - 1/3E^d + 3/8E^g)$$

Different mesons filter different quark flavors

Cancellation effects expected for ρ production.

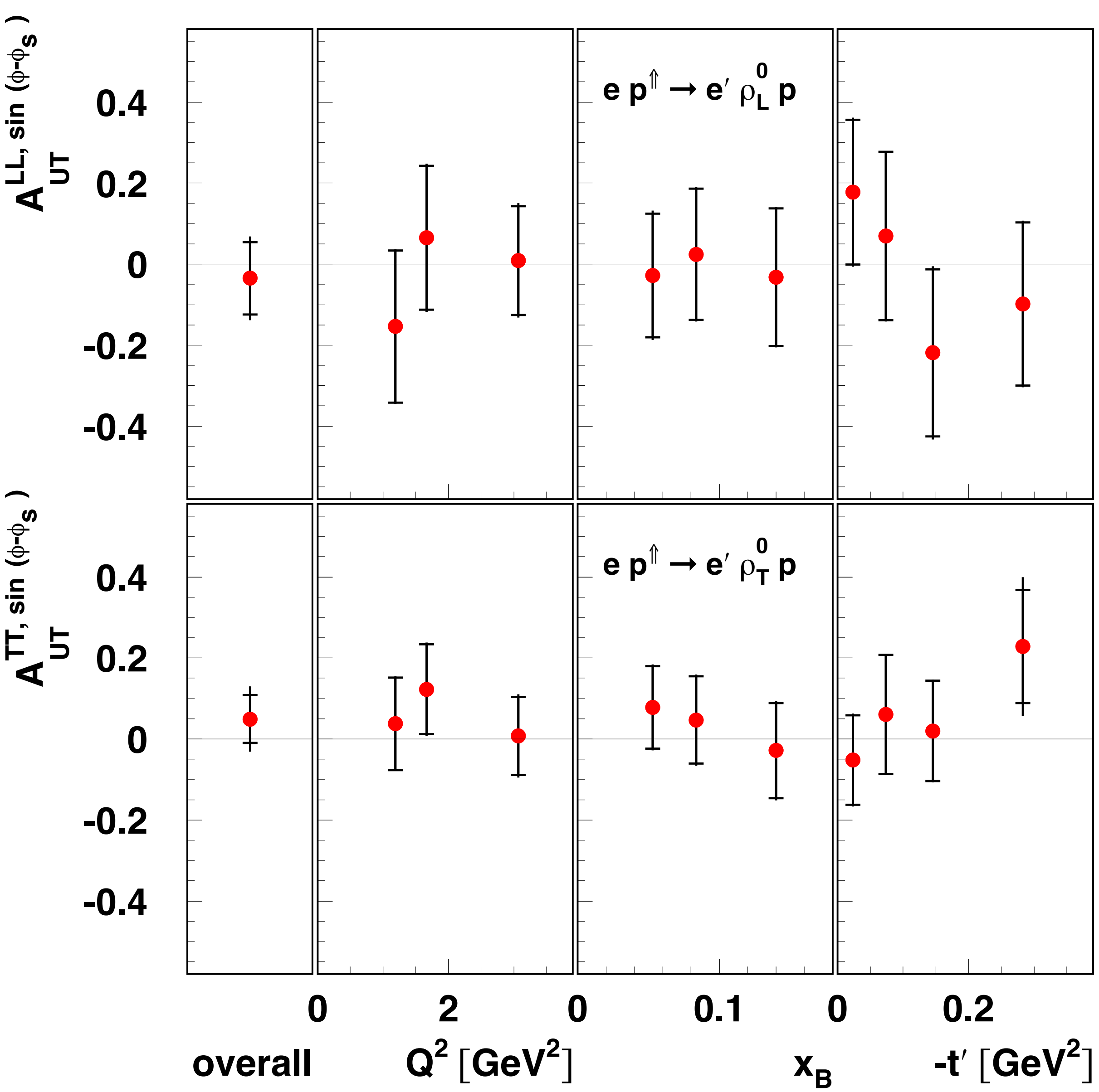


Goloskokov, Kroll
EJC 59 (2009)

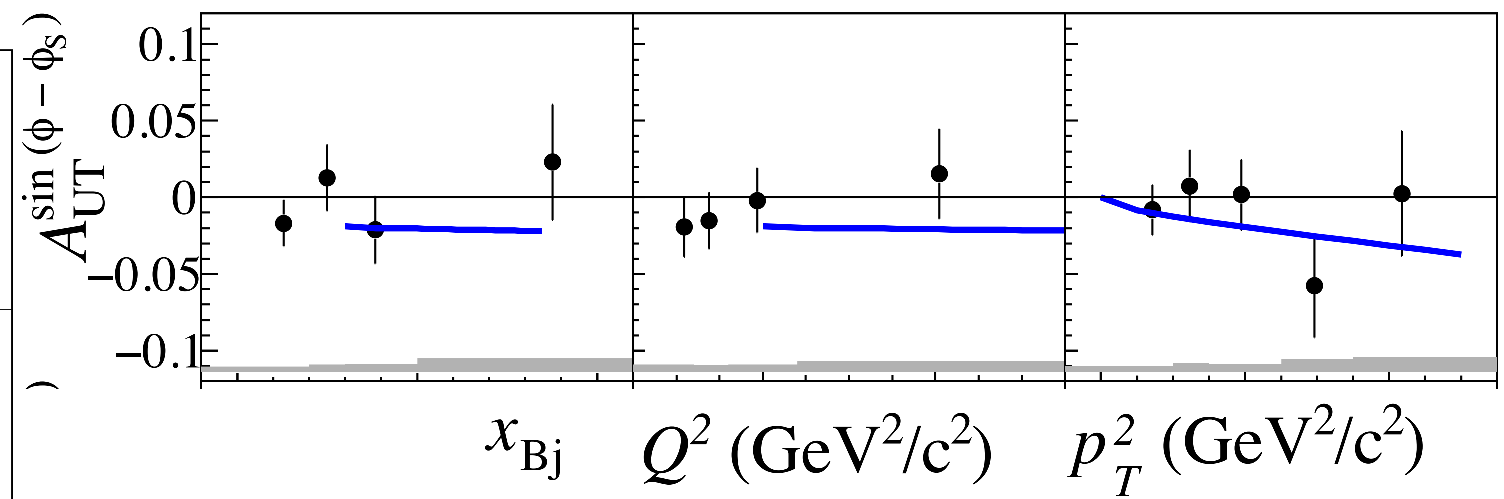


Asymmetry in $lp^{\Uparrow} \rightarrow lp\rho^0$: $\sin(\Phi-\Phi_S)$

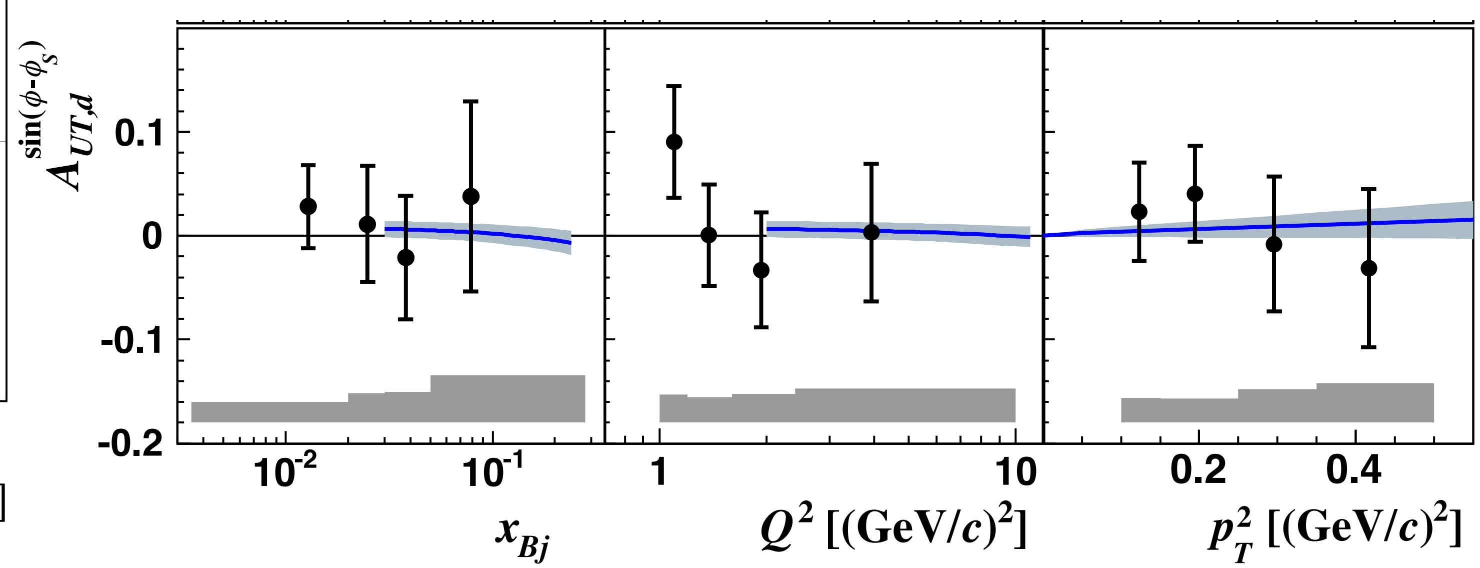
HERMES proton *Phys. Lett. B679 (2009) 100-105*



COMPASS proton *PLB B731 (2014) 19*

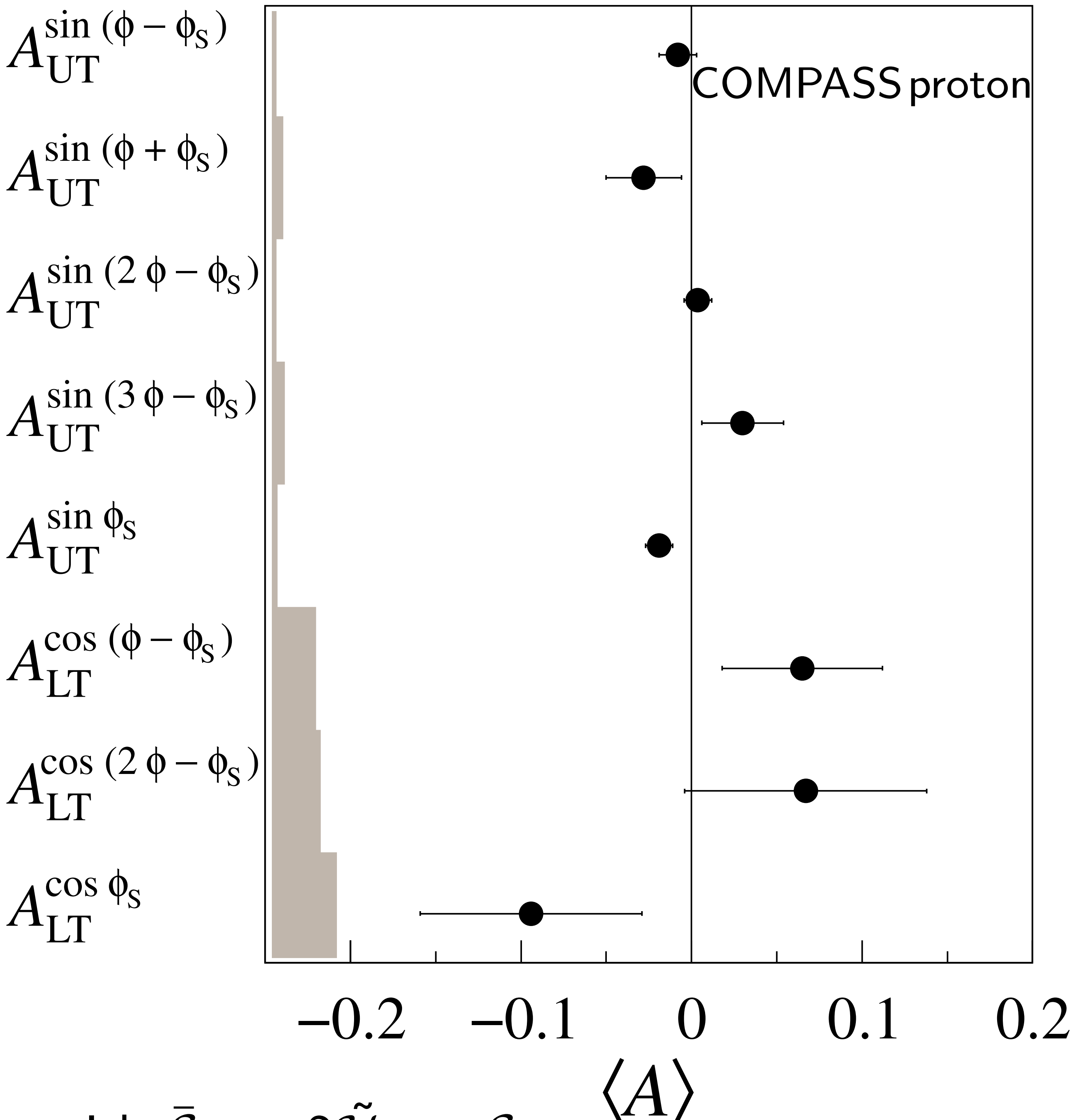


COMPASS deuteron *NPB 865 (2012) 1*



Blue curves: prediction from phenomenological GPD-based **GK model 2009**

COMPASS $\mu p^{\Uparrow} \rightarrow \mu p \rho^0$: all amplitudes



$A_{UT}^{sin(\phi-\phi_S)} \propto \mathrm{Im}\,(\mathcal{E}^*\mathcal{H})$

$A_{UT}^{sin(\phi+\phi_S)} \propto \mathrm{Im}\,(\bar{\mathcal{E}}_T^*\mathcal{H}_T)$

$A_{UT}^{(2\phi-\phi_S)} \propto \mathrm{Im}\,(\bar{\mathcal{E}}_T^*\mathcal{E})$

0

$A_{UT}^{sin\phi_S} \propto \mathrm{Im}\,(\mathcal{H}_T^*\mathcal{H} - \bar{\mathcal{E}}_T^*\mathcal{E})$

$A_{LT}^{cos(\phi-\phi_S)} \propto \mathrm{Re}\,(\mathcal{H}_T^*\bar{\mathcal{E}}_T)$

$A_{LT}^{cos(2\phi-\phi_S)} \propto \mathrm{Re}\,(\bar{\mathcal{E}}_T^*\mathcal{E})$

$A_{LT}^{cos\phi_S} \propto \mathrm{Re}\,(\mathcal{H}_T^*\mathcal{H} - \bar{\mathcal{E}}_T^*\mathcal{E})$

with $\bar{\mathcal{E}}_T = 2\tilde{\mathcal{H}}_T + \mathcal{E}_T$

- Evidence for existence of H_T

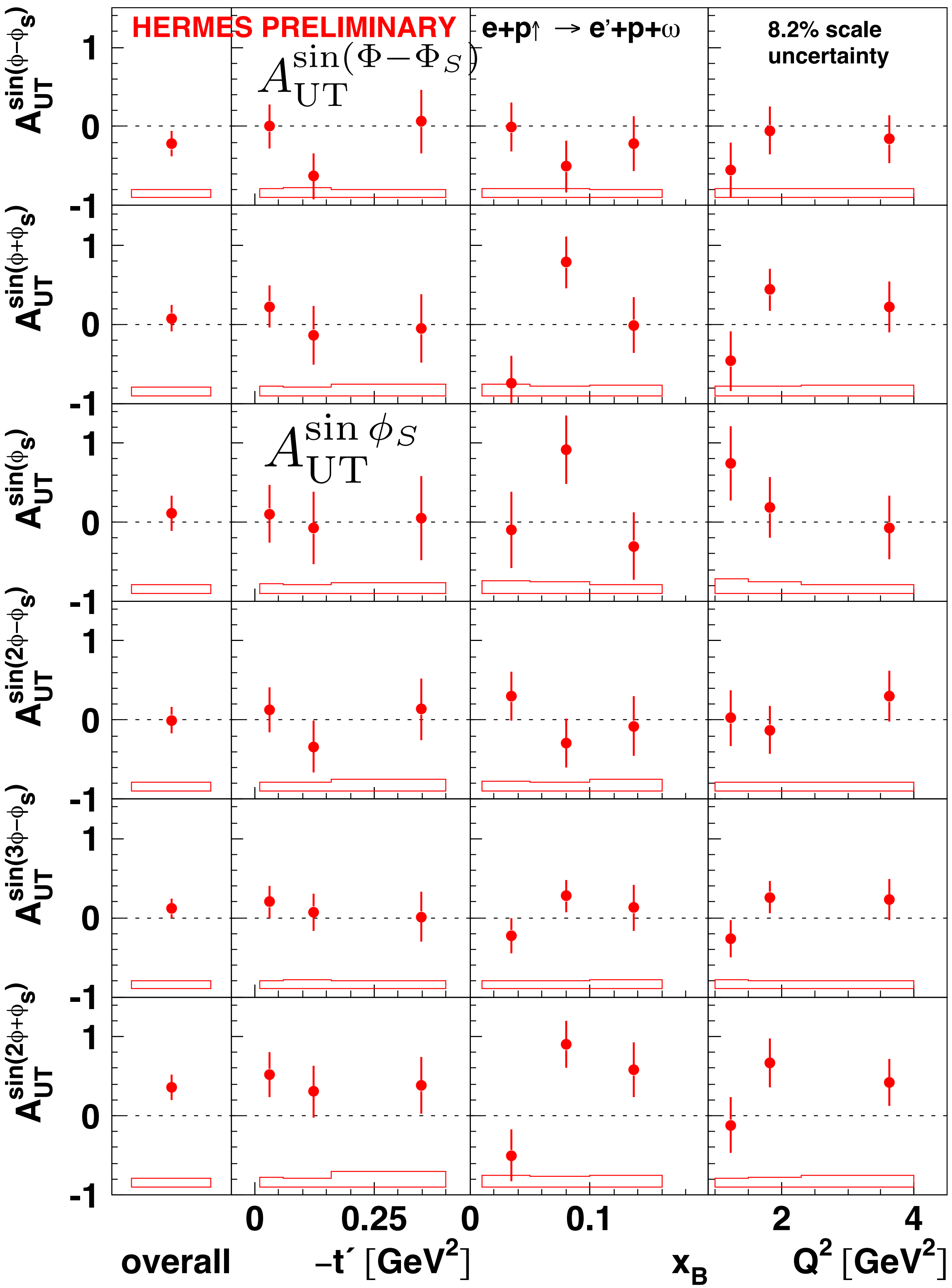
$A^{\sin\phi S}$ = –0.019 ± 0.008(stat.) ± 0.003(syst.)

Slide courtesy Katharina Schmidt (University of Freiburg)

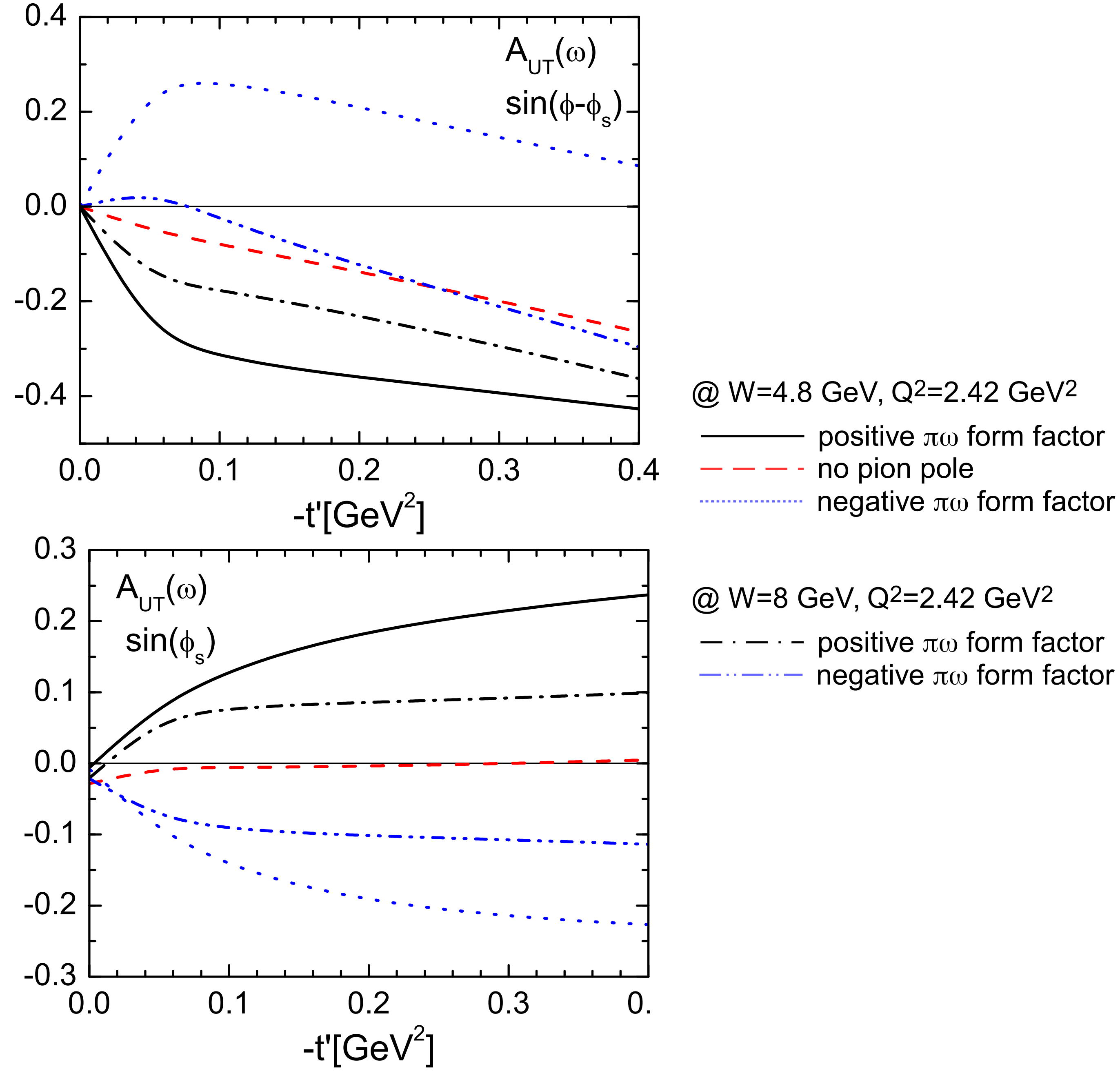
All amplitudes consistent with GK 2014

HERMES: asymmetry in $ep^{\Uparrow} \rightarrow ep\omega$

HERMES proton *publication in preparation*

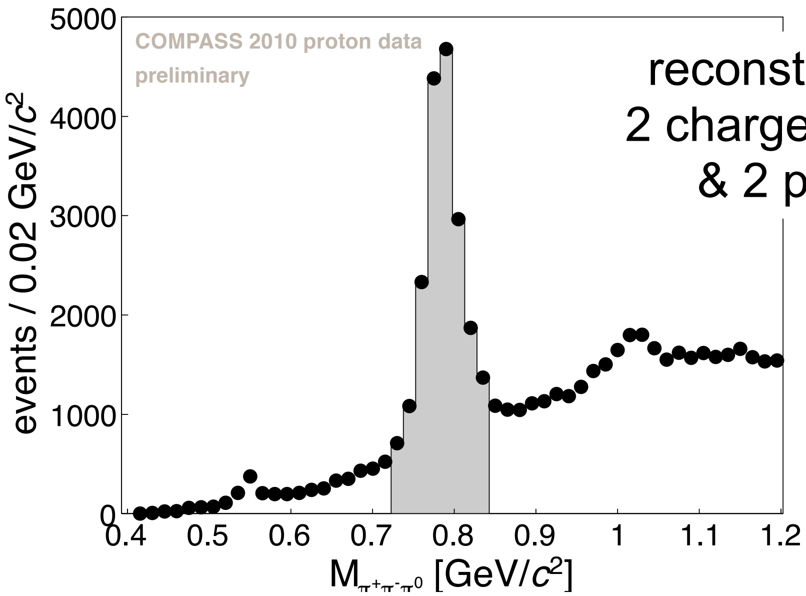


Goloskokov, Kroll, Eur. Phys. J. A (2014) 50: 146

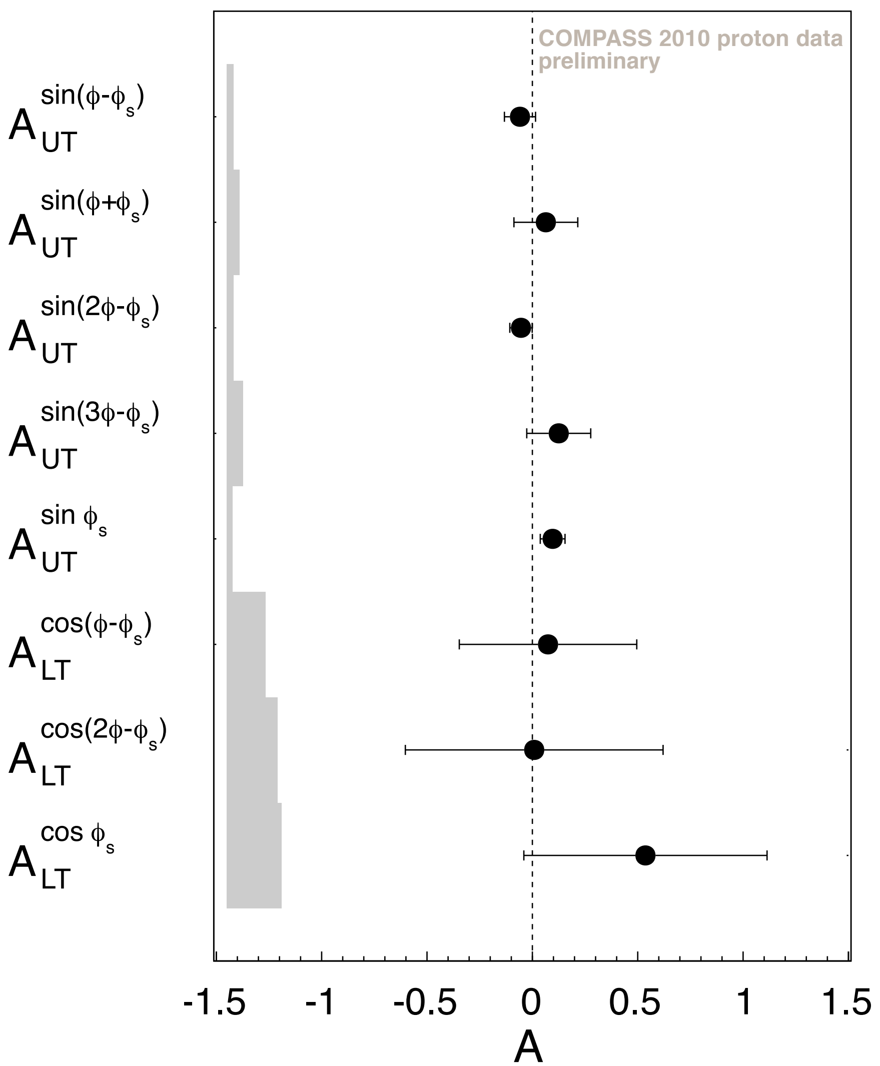


HERMES: too large experimental uncertainties to constrain sign of πω transition form factor.

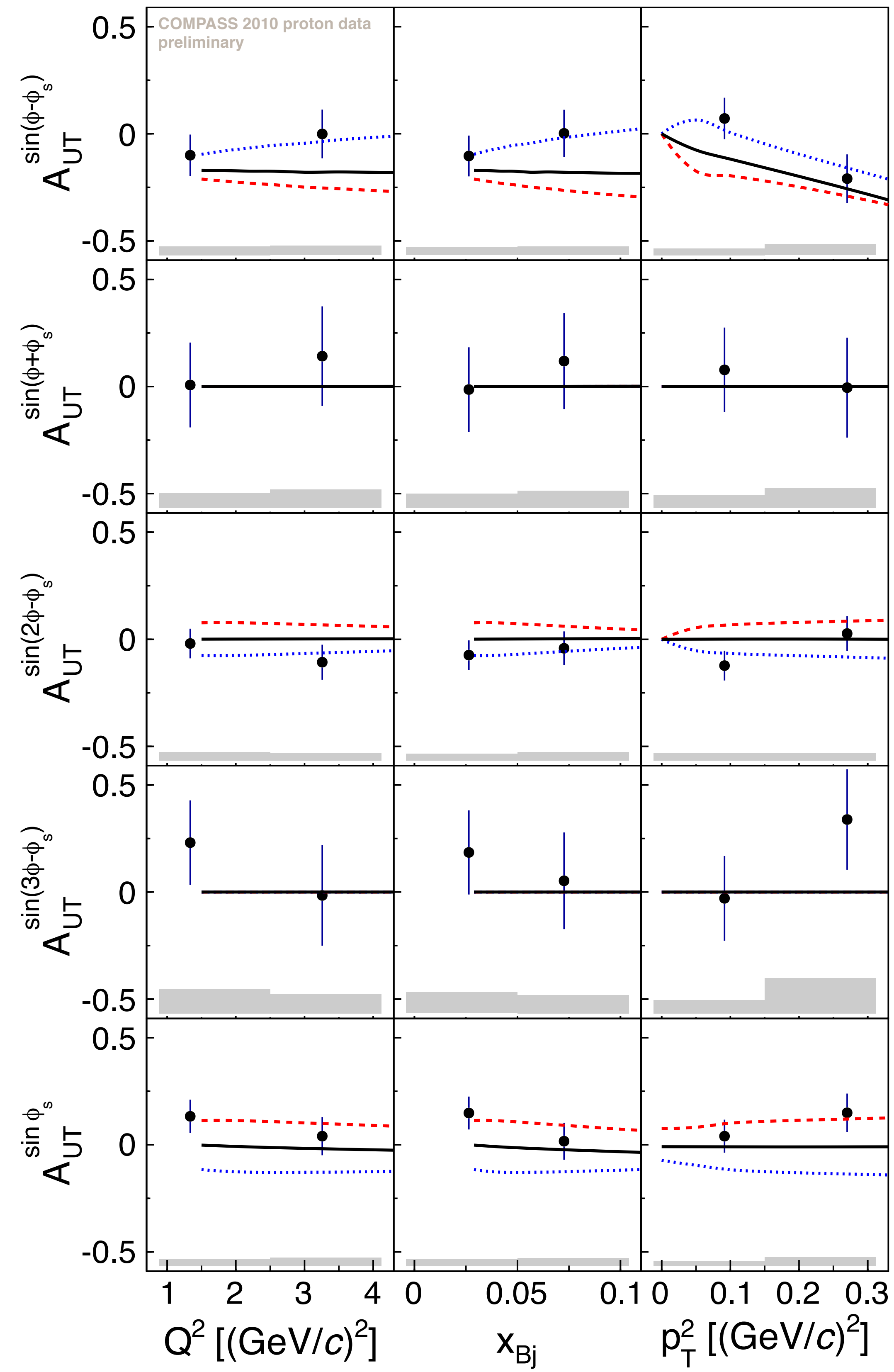
COMPASS: asymmetry in $\mu p^{\Uparrow} \rightarrow \mu p \omega$



reconstruction of
2 charged hadrons
& 2 photons



COMPASS proton *publication in preparation*



GK 2014

positive $\pi\omega$ form factor
no pion pole
negative $\pi\omega$ form factor

COMPASS: results do not allow unambiguous determination of πω transition form factor.

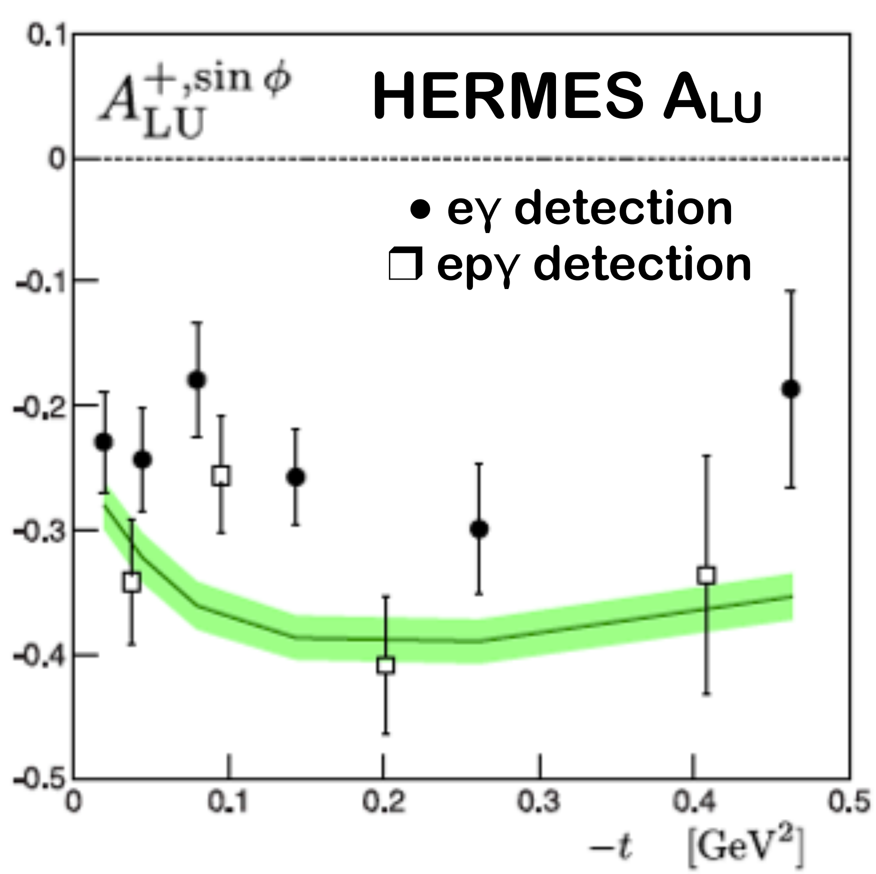
Global analysis of exclusive data

Test of GPD universality

P. Kroll, H. Moutarde and F. Sabatié,
Eur. Phys. J. C (2013) 73:2278

Use **DVMP** data, FF and PDFs to constrain GPD parameters (LO, LT):
GK model

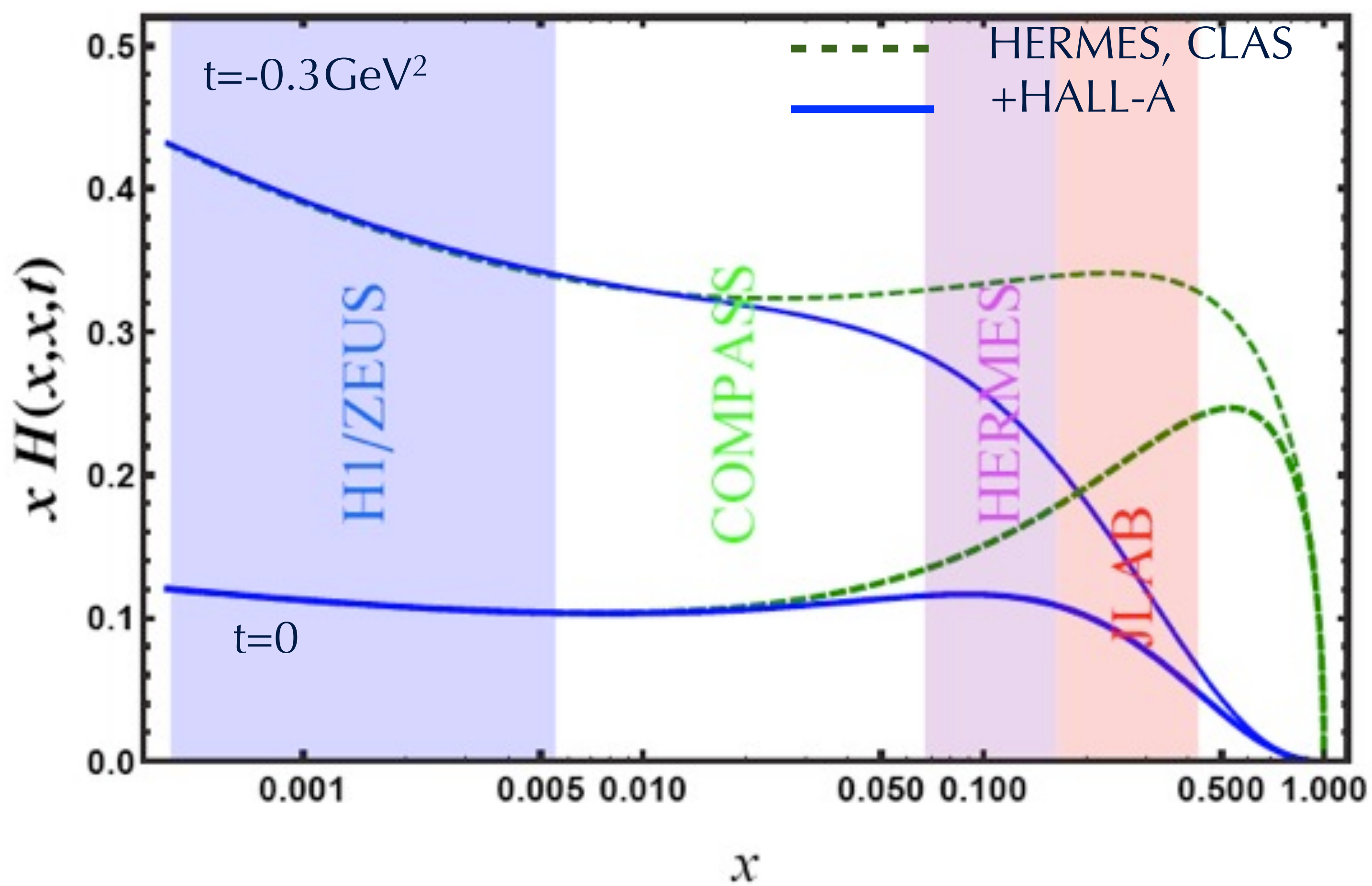
- Compare to **DVCS** observables - good for HERA and HERMES, fair for JLab



Global fit to H(x,ξ=x,t) from DVCS data (NNLO)

Kumericki, Müller
Nucl. Phys. **B**841 (2010) 1-58

- **HERMES** A_C , **CLAS** A_{LU} and **Hall A** x-section.
- Small-x behavior from **HERA collider** data.



Outlook

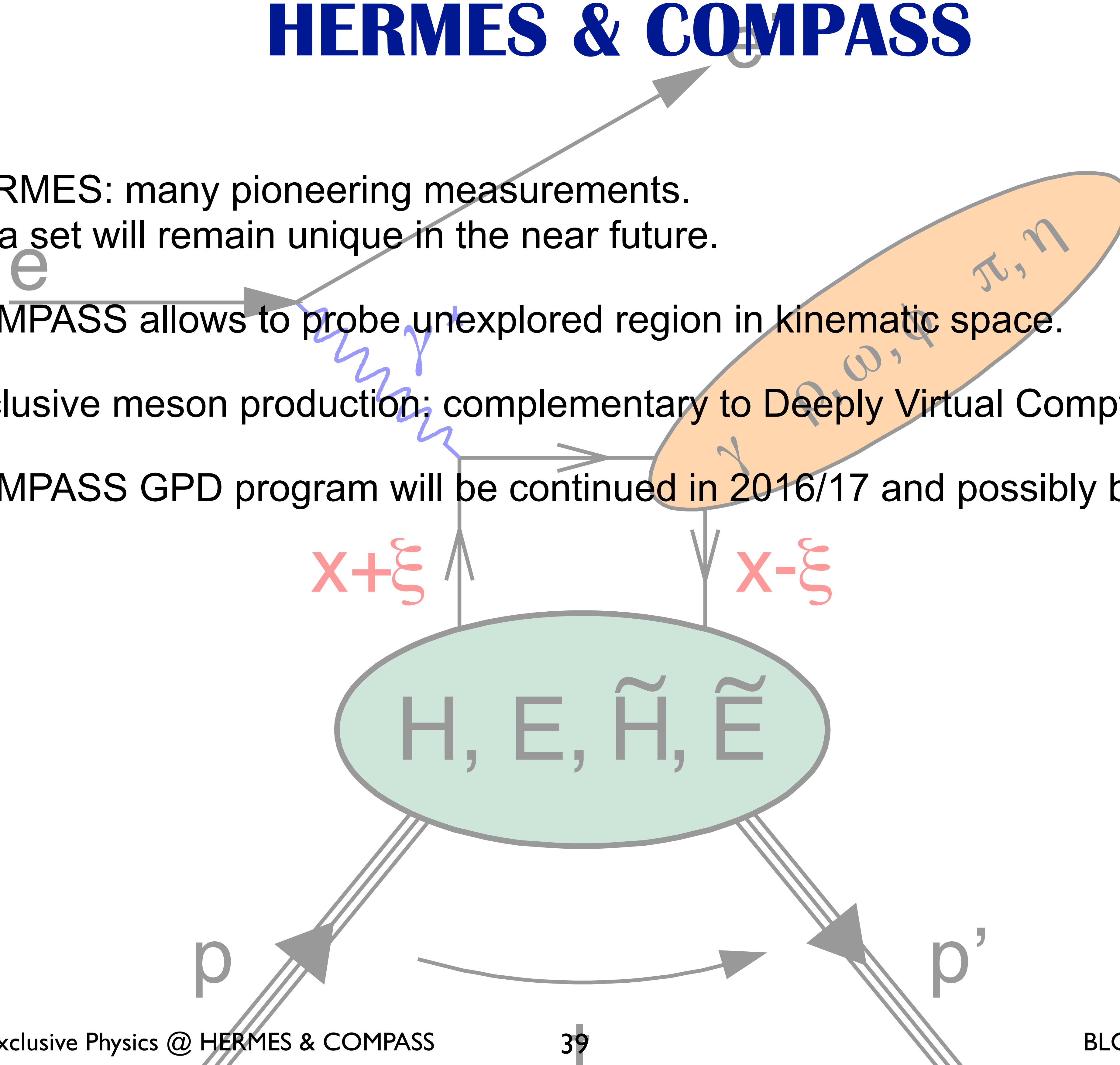
- **COMPASS 2016/17:**
  LH2 target + recoil detector
  - GPD ***H*** from DVCS
  - Transverse imaging of the nucleon from DVCS and DVMP

- **COMPASS >2018 (?)**:
  $NH_3\uparrow$ target + recoil detector
  - GPD ***E*** from DVCS
  - GPD ***E*** and **chiral-odd** GPDs from DVMP
    - vector mesons ρ^0, ρ^+, ω, Φ
    - pseudoscalar mesons π^0

Preparing upgrade of CAMERA recoil proton detector: replace scintillators of inner ring to achieve better attenuation length (2015).

Summary: Exclusive Physics at HERMES & COMPASS

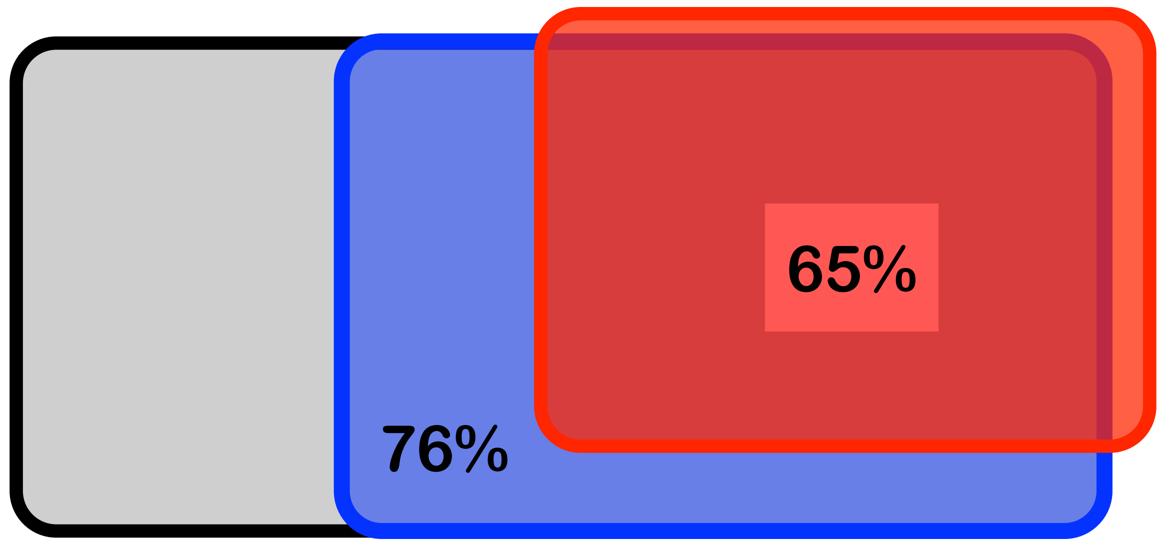
- HERMES: many pioneering measurements.
  Data set will remain unique in the near future.
- COMPASS allows to probe unexplored region in kinematic space.
- Exclusive meson production: complementary to Deeply Virtual Compton scattering.
- COMPASS GPD program will be continued in 2016/17 and possibly beyond 2018.



Backup

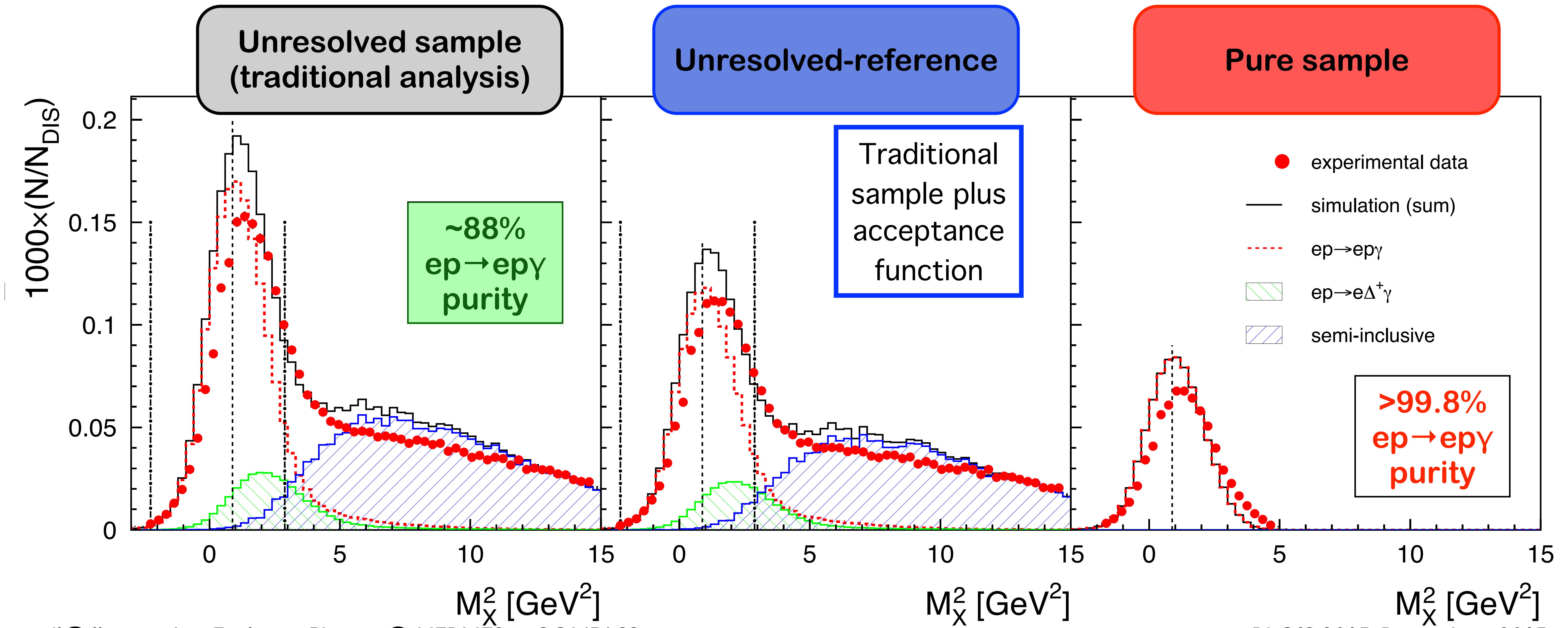
HERMES: unresolved reference sample

Disentangling the effects of recoil-detector acceptance and purification



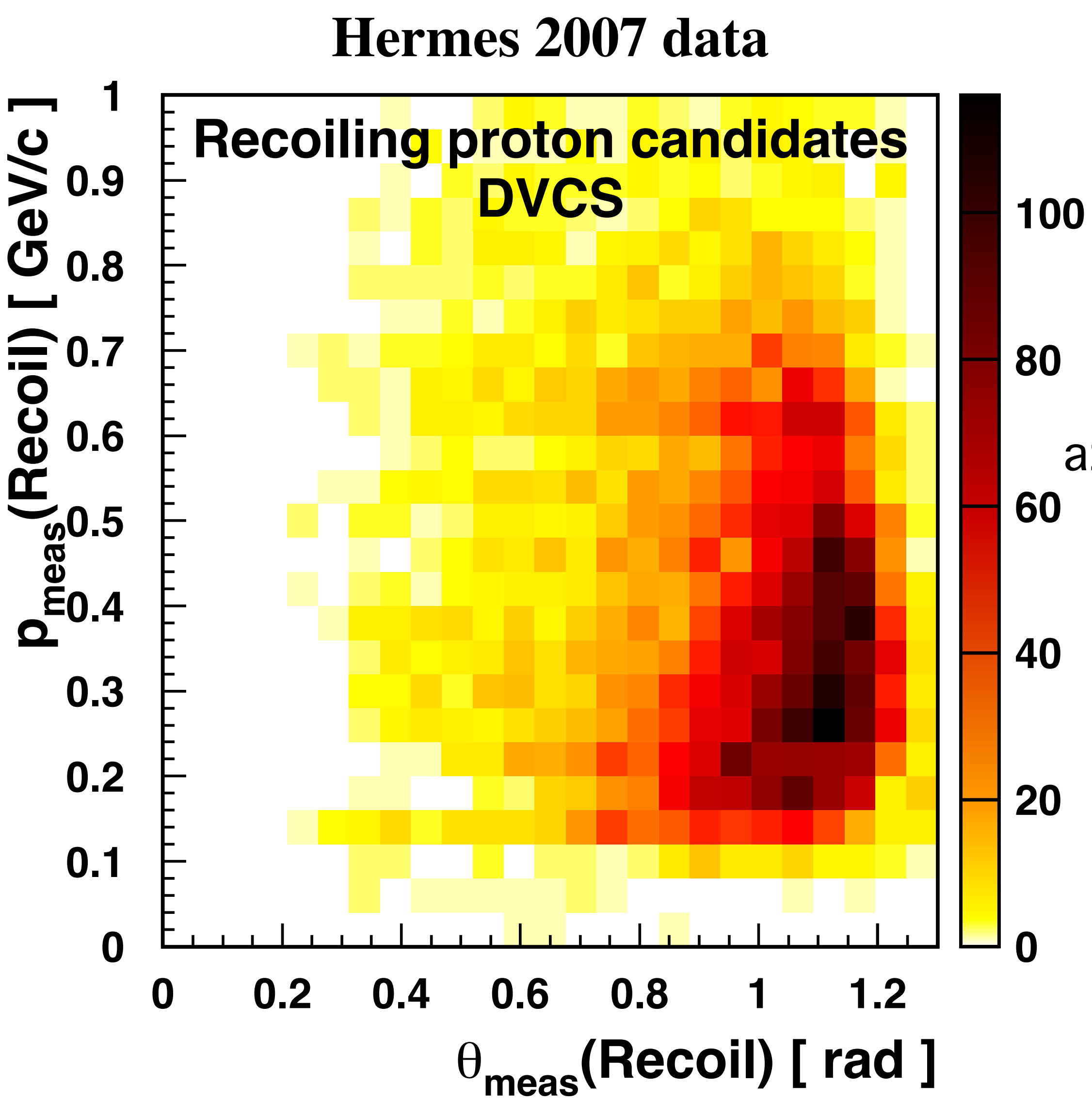
<u>Loss</u> due to
- lower-mom. threshold
- Φ-gaps of SSD

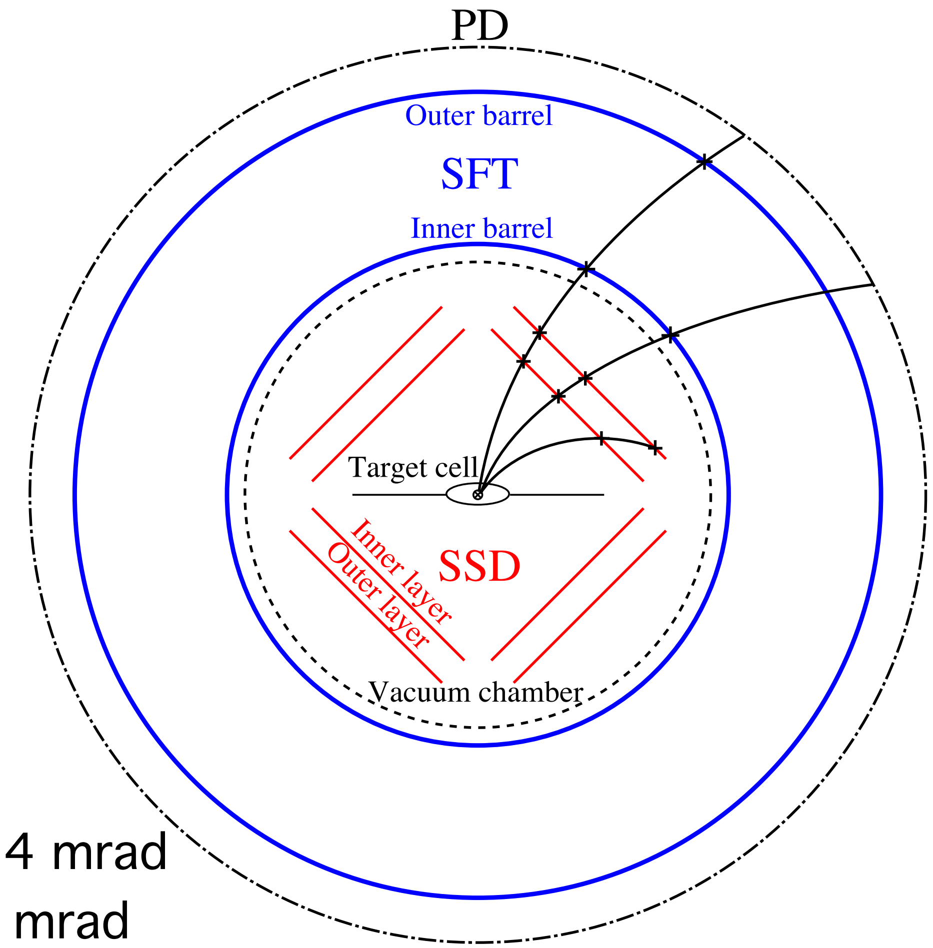
<u>Deficit</u> due to
- removal of background
- inefficiencies of χ^2 cut
- recoil-det. ineffciencies



Track Reconstruction

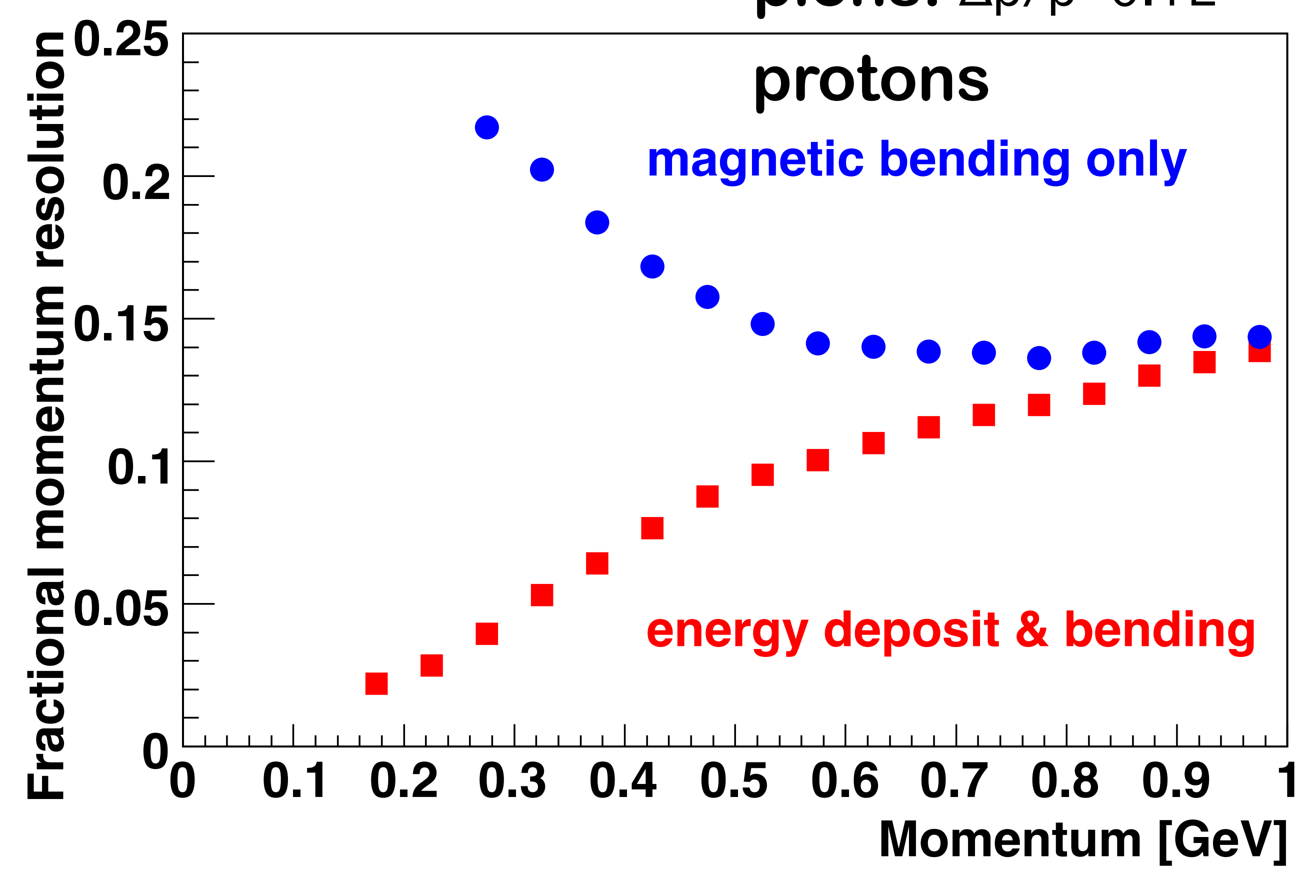
with recoil detector





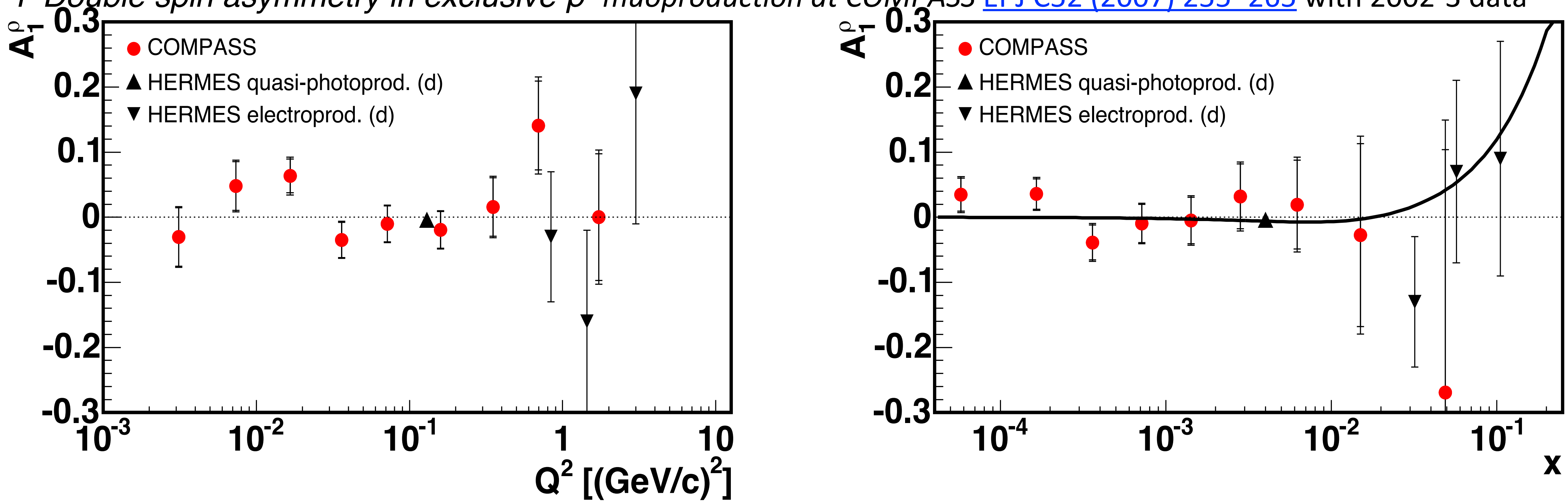
azimuthal-angle resolution: 4 mrad
polar-angle resolution: 10 mrad
(for p>0.5 GeV)

pions: $\Delta p/p=0.12$



Momentum reconstruction down to
125 MeV (protons).
Want as low -t as possible!
(corresponds to $-t=0.016$ GeV^2)

1-Double spin asymmetry in exclusive ρ^0 muoproduction at COMPASS EPJ C52 (2007) 255–265 with 2002-3 data



In the same reference a theoretical prediction for A_1^ρ was presented, which is based on the description of forward exclusive ρ^0 leptoproduction and inclusive inelastic lepton-nucleon scattering by the off-diagonal Generalised Vector Meson Dominance (GVMD) model, applied to the case of polarised lepton–nucleon scattering. At the values of Bjorken variable $x < 0.2$, with additional assumptions [11], A_1^ρ can be related to the A_1 asymmetry for inclusive inelastic lepton scattering at the same x as

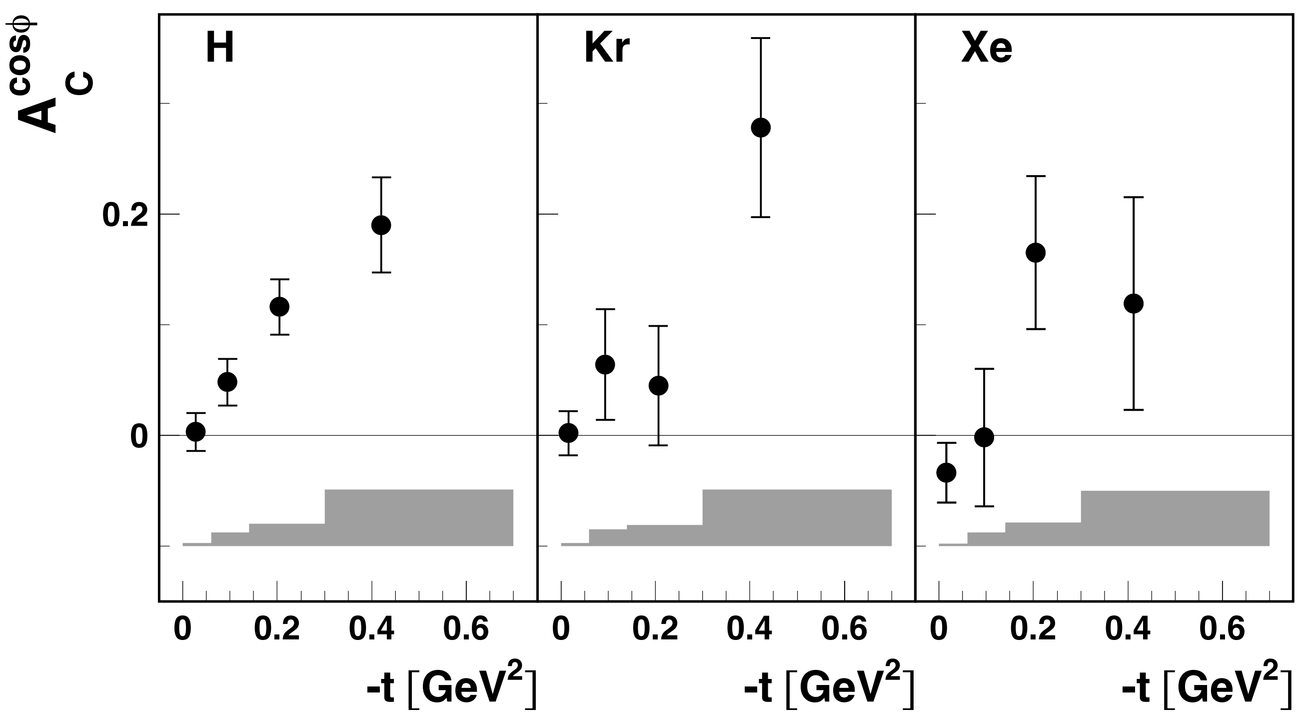
$$A_1^\rho = \frac{2A_1}{1+(A_1)^2}. \quad (4)$$

given by Eq. 4, which relates A_1^ρ to the asymmetry A_1 for the inclusive inelastic lepton-nucleon scattering. To produce the curve the inclusive asymmetry A_1 was parameterised as $A_1(x) = (x^\alpha - \gamma^\alpha) \cdot (1 - e^{-\beta x})$, where $\alpha = 1.158 \pm 0.024$, $\beta = 125.1 \pm 115.7$ and $\gamma = 0.0180 \pm 0.0038$. The values of the parameters have been obtained from a fit of $A_1(x)$ to the world data from polarised deuteron targets [26–31] including COMPASS measurements at very low Q^2 and x [32]. Within the present accuracy the results on A_1^ρ are consistent with this prediction.

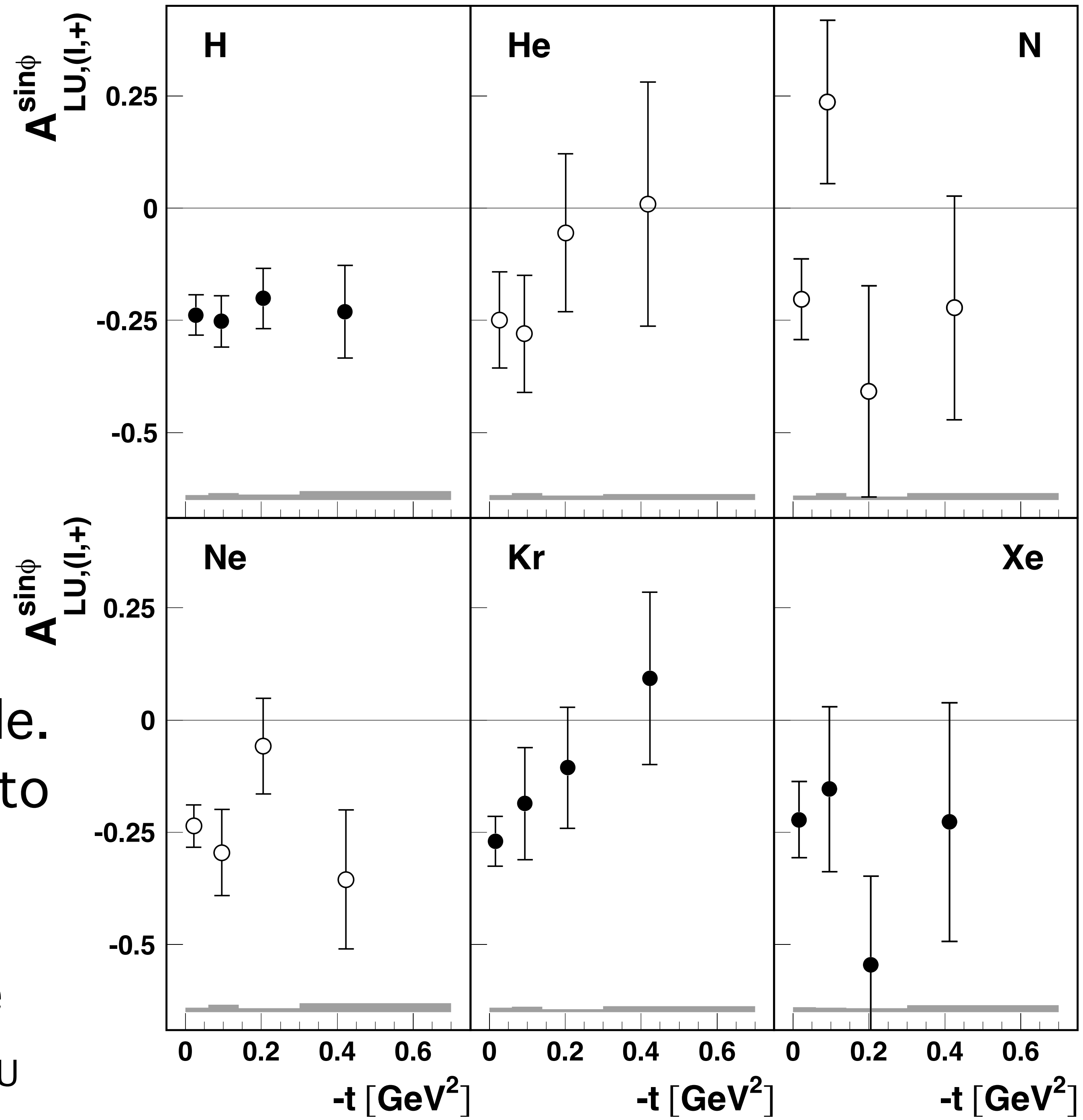
DVCS Asymmetries on Nuclei

1996–2005 nuclear data

Beam-charge asymmetry



Beam-helicity asymmetry



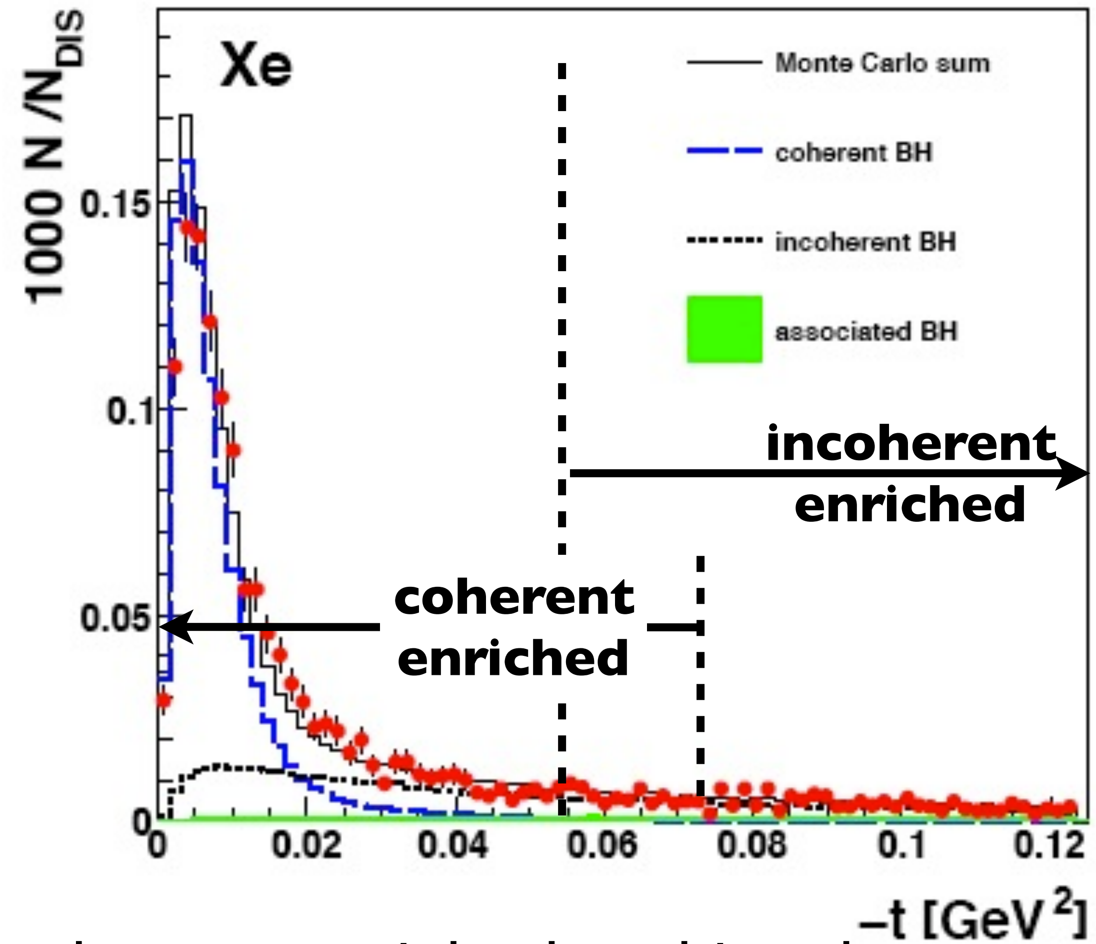
- Targets with 2 beam charges available. A_C and charge-difference A_{LU} sensitive to DVCS-BH interference term

○ Targets with only one beam charge available. No A_C and single-charge A_{LU} with entangled s_1 coefficients

Phys. Rev. C 81 (2010) 035202

HERMES Nuclear Data Sets

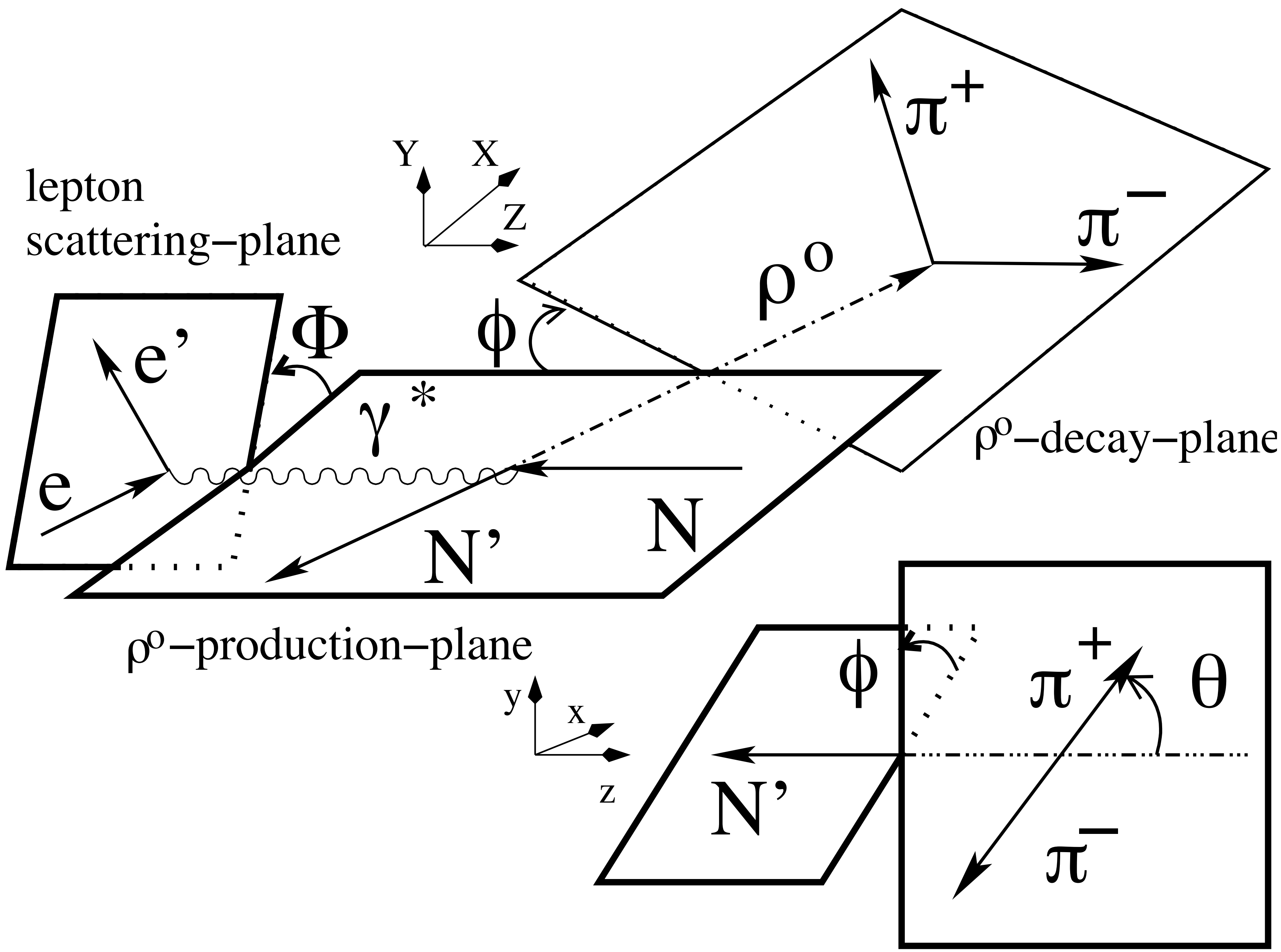
Target	Spin	L (pb^{-1})
^{1}H	1/2	227
He	0	32
N	1	51
Ne	0	86
Kr	0	77
Xe	0, 1/2, 3/2	47



Heavy target data taken at the end of each HERA fill ("high density runs")

- Separation of coherent-enriched and incoherent-enriched data samples by t-cutoff such that ≈same average kinematics for each target.
- Coherent enriched samples: ≈65% coherent fraction
- Incoherent enriched samples: ≈60% incoherent fraction

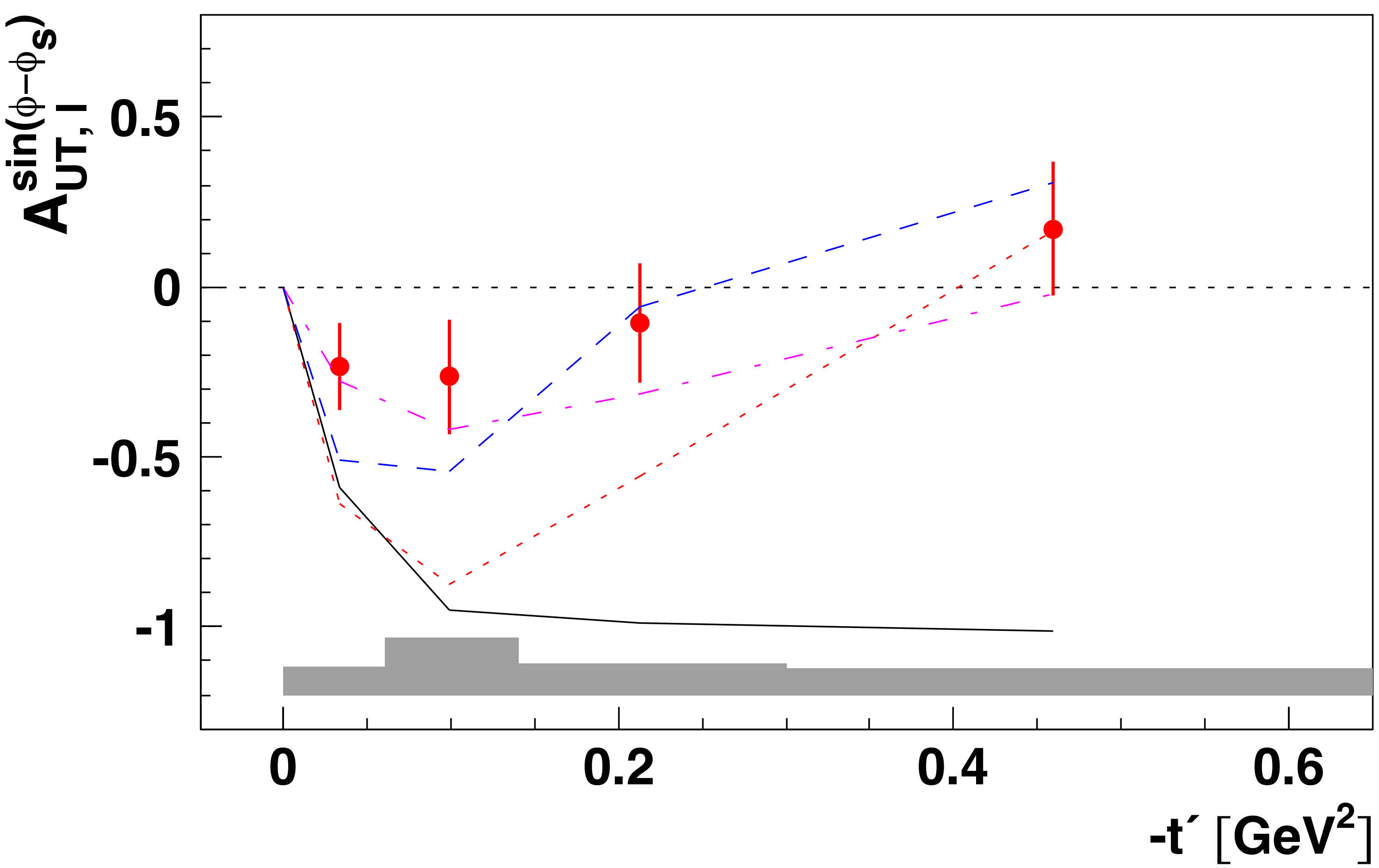
Vector meson production and decay



Exclusive π+ on transversely polarized protons

$$A_{\mathrm{UT},\ell}^{\sin(\phi-\phi_S)} \propto -\frac{\sqrt{-t'}}{M_p}\,\mathrm{Im}(\widetilde{\mathcal{E}}^*\widetilde{\mathcal{H}})$$

- Consistent with zero. A vanishing Fourier amplitude in this model implies the dominance (due to the pion pole) of Etilde over Htilde at low −t′. Excludes a pure pion-pole contribution to Etilde.
- $\sin\Phi_S$ amplitude is large and positive: implies presence of a sizeable interference between contributions from longitudinal and transverse virtual photons.



dashed-dotted: K. Kumericki, D. Müller, and K. Passek-Kumericki, Eur. Phys. J. C 58 (2008) 193.

solid, dashed and dotted: Ch. Bechler and D. Müller, arXiv:0906.2571 [hep-ph]

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