Opportunities for constraining GPDs at COMPASS after 2020

Image courtesy of https://marlaongtao.files.wordpress.com/2013/11/plato-cave.jpg

- Why GPDs?
- Experimental methods and results
- Global analysis
- Upcoming data
- COMPASS-III

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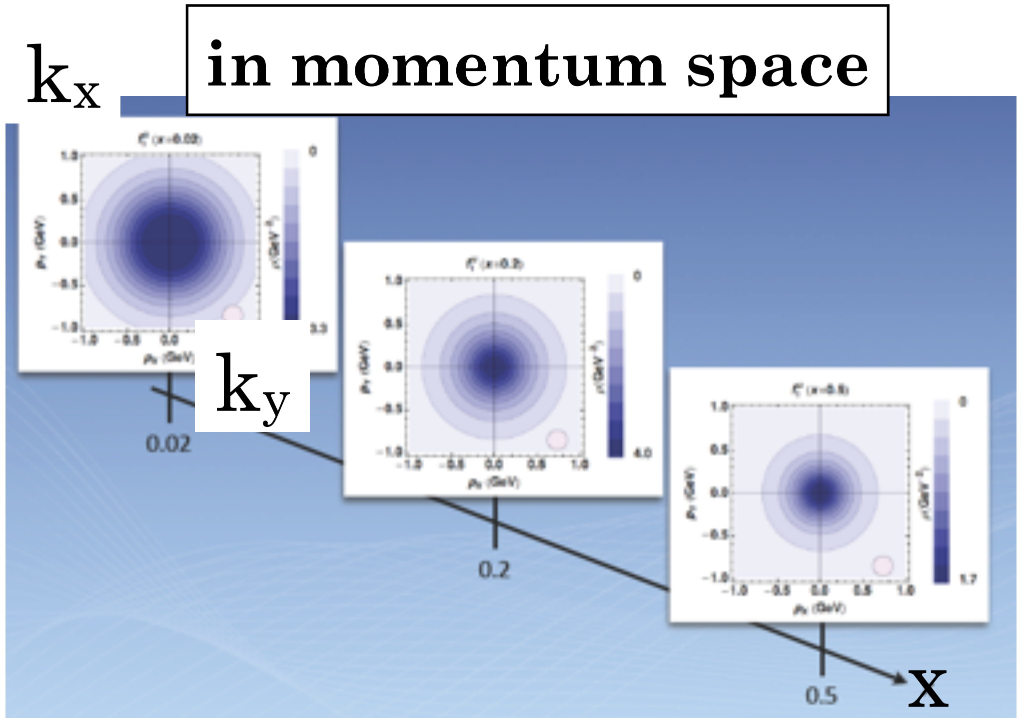
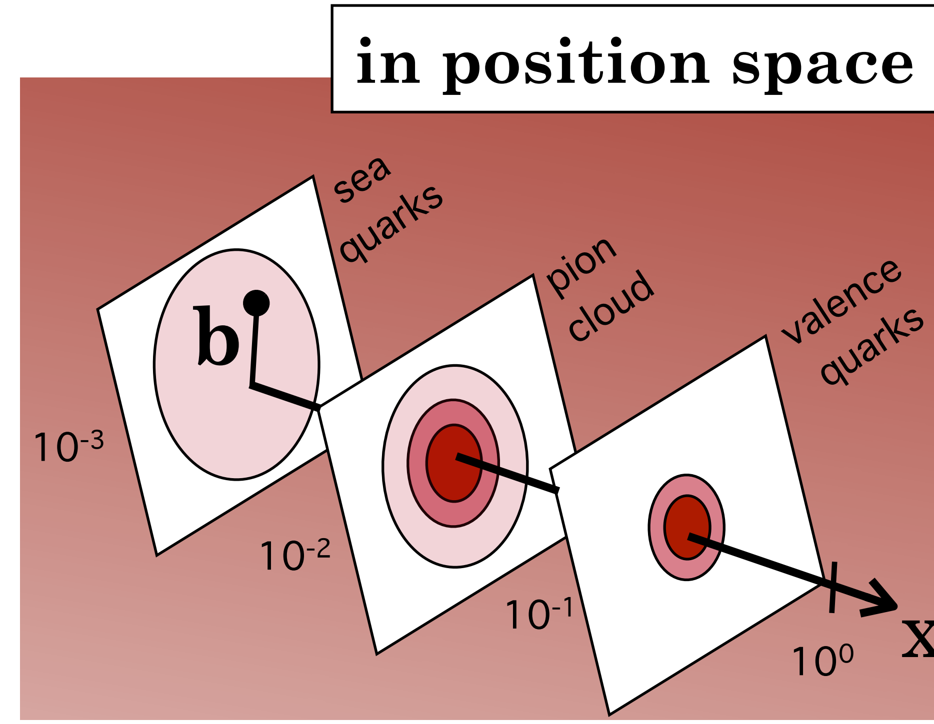
NSF

COMPASS

COMPASS: beyond-2020 workshop
March 20/21, 2016 at CERN

Nucleon Tomography





Correlation between spin and transverse momentum ?

Correlation between longitudinal momentum and transverse position ?

Transverse Momentum dependent PDFs

TMDs
$f(x,k_T)$

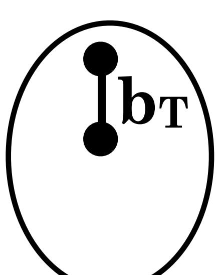
GPDs
$H(x,\xi,t)$

Generalized Parton Distributions

k_T-integration

$\xi=0$, $t=0$

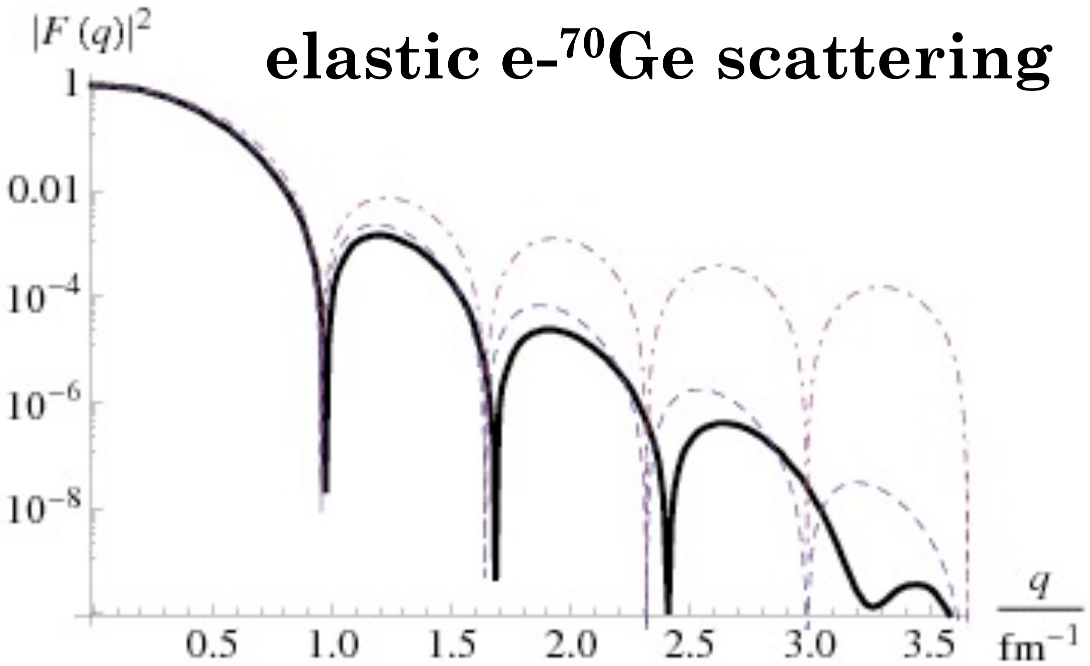
b = impact parameter:
FT(t↔b) ↔
$H(x,\xi,b)$
$\mathbf{k_T \equiv 0}$



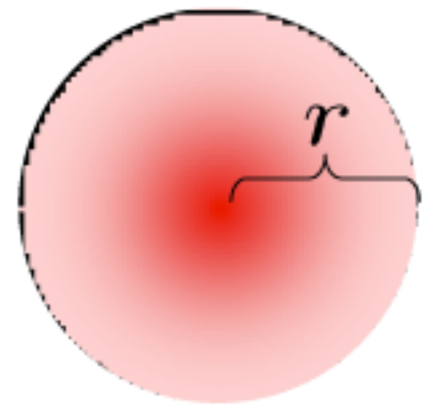
FT(k_T↔b_T) ↔
$f(x,b_T)$
$\mathbf{t \equiv 0}$

(collinear)
PDFs q(x), 1D

Generalized Parton Distributions

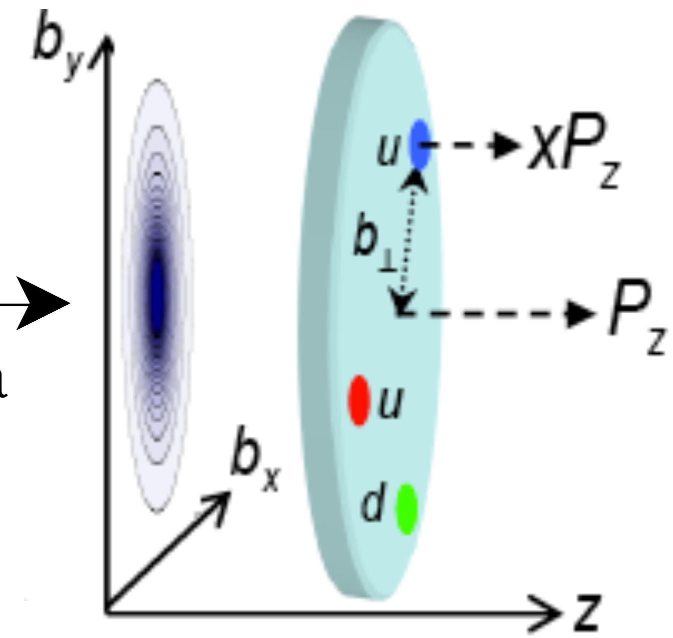


Form Factors



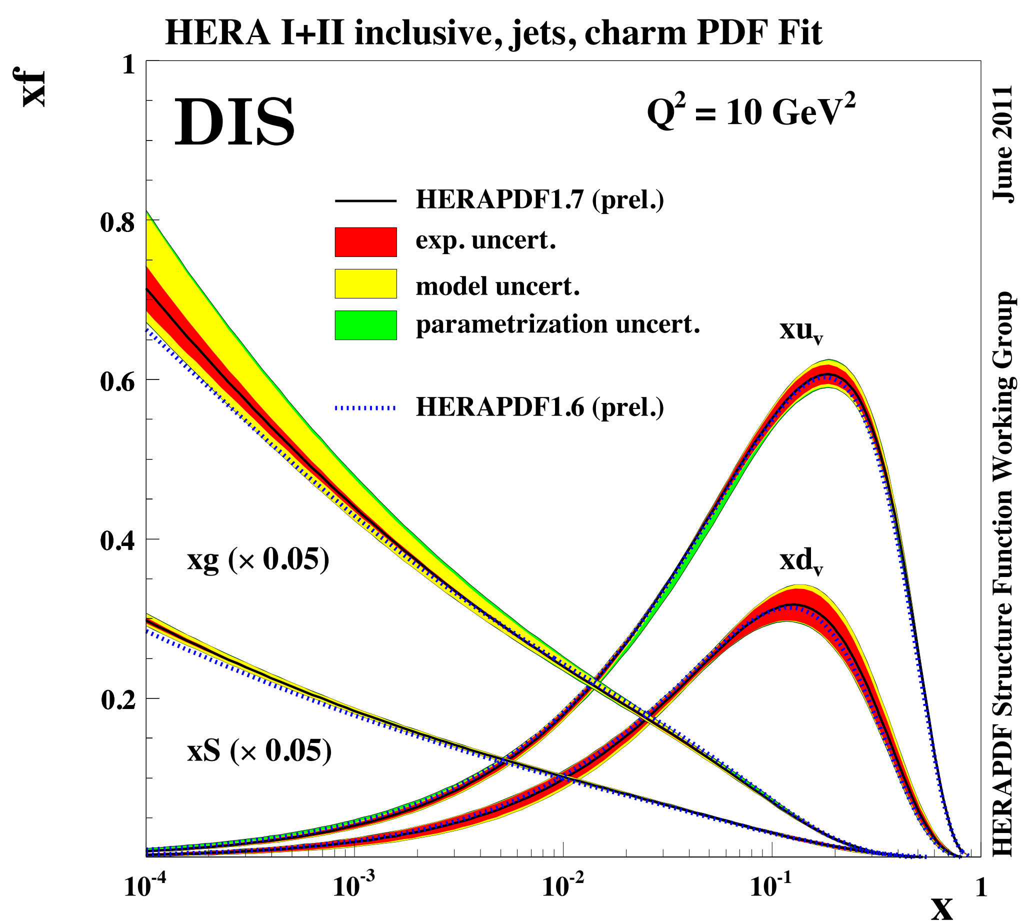
$$\int_{-1}^{+1} \mathrm{d}x\, H^q(x,\xi,t) = F_1^q(t)$$

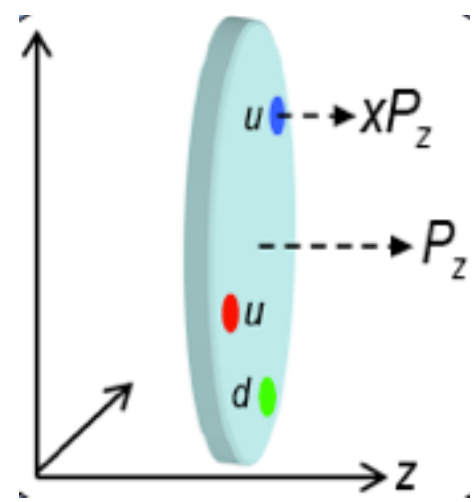
GPDs



transverse parton positions

longitudinal parton momenta



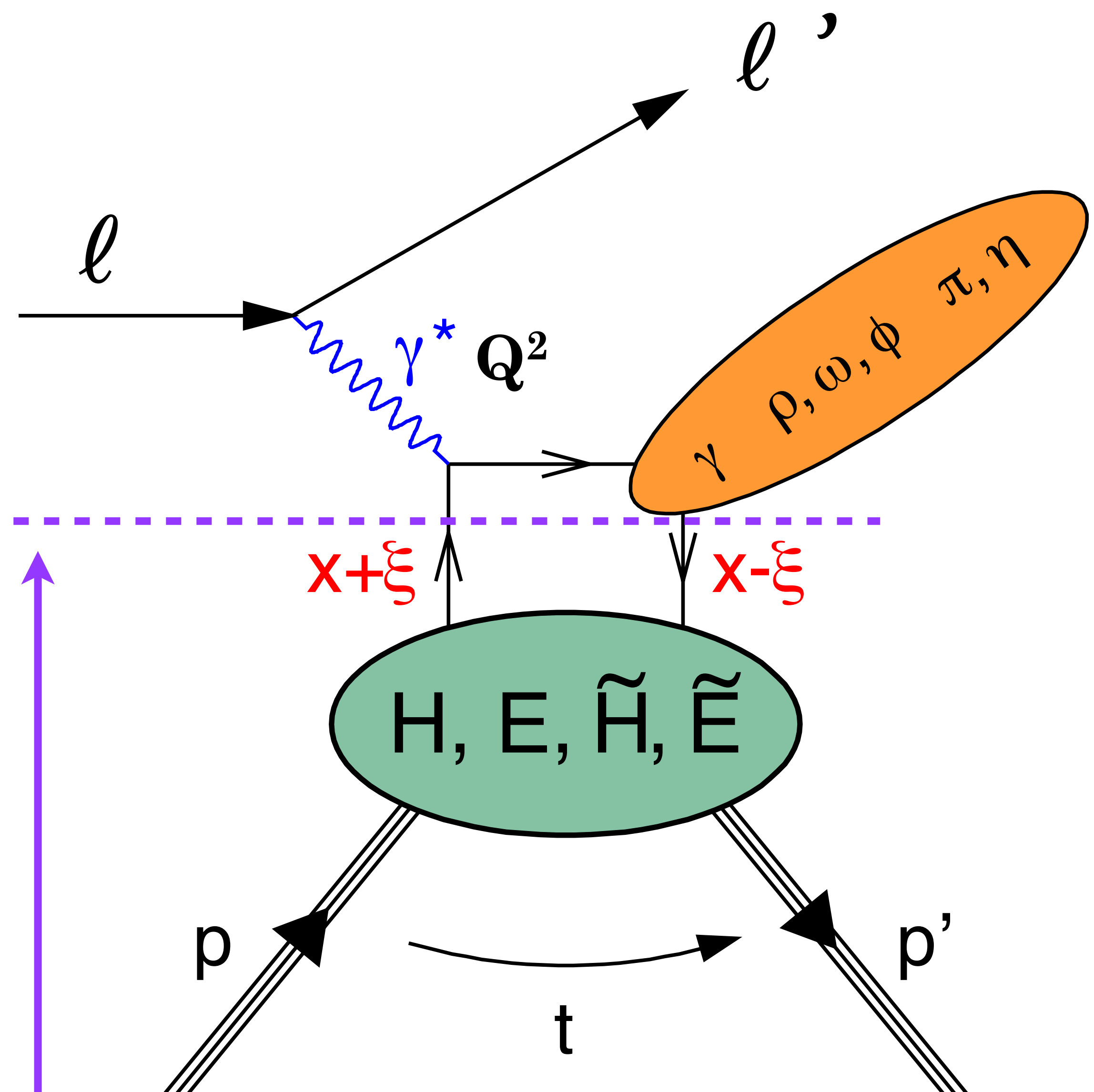


PDFs

$$H^q(x,0,0) = q(x)$$

Illustration: Ph. Hägler

Hard exclusive reactions



Factorization holds if
Q^2 large & t small
(& longitudinal virtual photon)

$\ell p \to \ell p \gamma$ Deeply Virtual Compton Scattering (DVCS)

$\ell p \to \ell p M$ Deeply Virtual Meson Production (DVMP)

- x, ξ: longitudinal momentum fractions of probed quark
  - **skewness $\xi \simeq x_B / (2-x_B)$** in Bjorken limit (Q^2 large & x_B, t fixed)
  - **average mom. x: mute variable**, not accessible in DVCS & DVMP.
- t: squared 4-momentum transfer to target
- Experimentally accessed quantity is **Compton Form Factor (CFF)**

hard scattering kernel ⊗ **GPD**

$$\underset{\textbf{CFF}}{\mathcal{F}(\xi,t)} = \sum_q \int_{-1}^{1} \mathrm{d}x \, C_q^{\mp}(\xi,x) F^q(x,\xi,t)$$

GPDs

	flips nucleon helicity	conserves nucleon helicity
does not depend on quark helicity	E	H → q(x)
depends on quark helicity	$\tilde{E}$	$\tilde{H}$ → $\triangle$q(x)

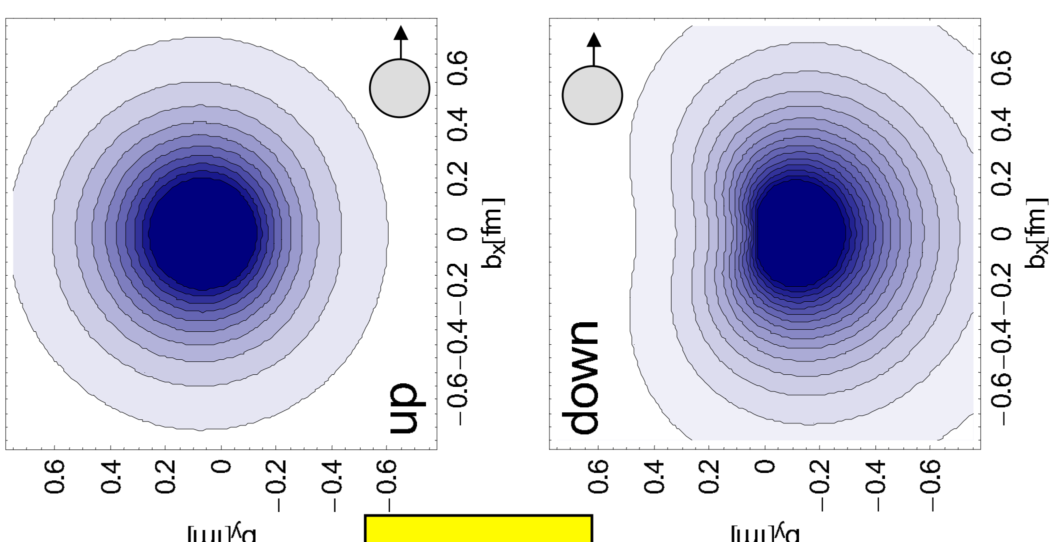
forward limit $\xi \rightarrow 0$, $t \rightarrow 0$

4 chiral-even quark GPDs

@leading twist for a spin-½ target

$J^P=1^-$ vector mesons	$J^P=1^-$ photon (DVCS)
$J^P=0^-$ pseudoscalar mesons	

- **Mesons** allow for **flavor separation**
- **GPD *E*** (and Sivers function)
  - Involve switch of nucleon helicity
  ⇒ sensitive to spin-orbit correlations
  - Closely connected with **orbital angular momentum** of partons



GPD E

The QCDSF/UKQCD collaborations: **Transverse spin structure of the nucleon from lattice QCD simulations,** PRL 98 222001 (2007).

4 chiral-odd quark GPDs

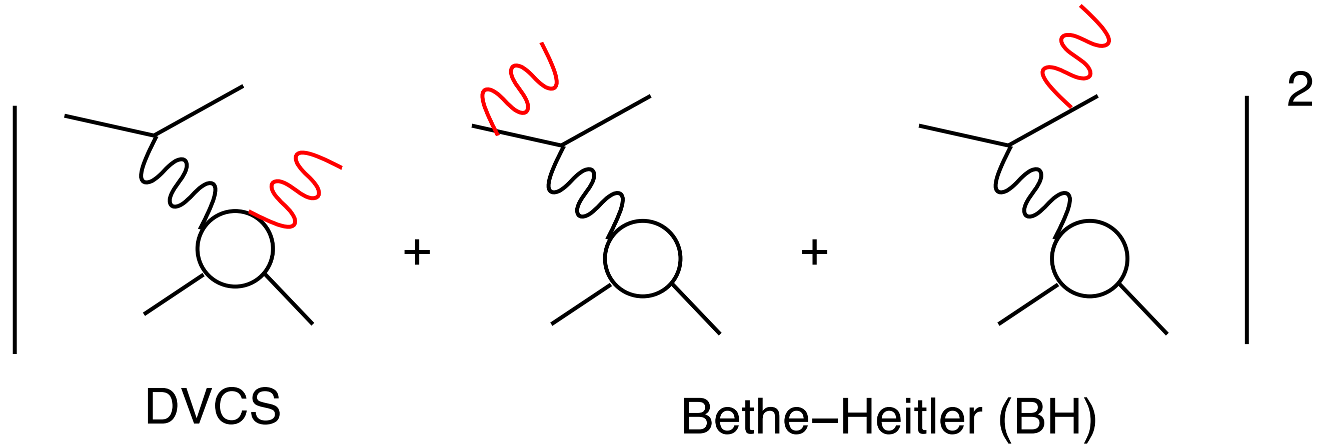
$\tilde{H}_T$ ↔ transversity TMD

$2\tilde{H}_T + E_T$ ↔ Boer-Mulders

$\tilde{E}_T$

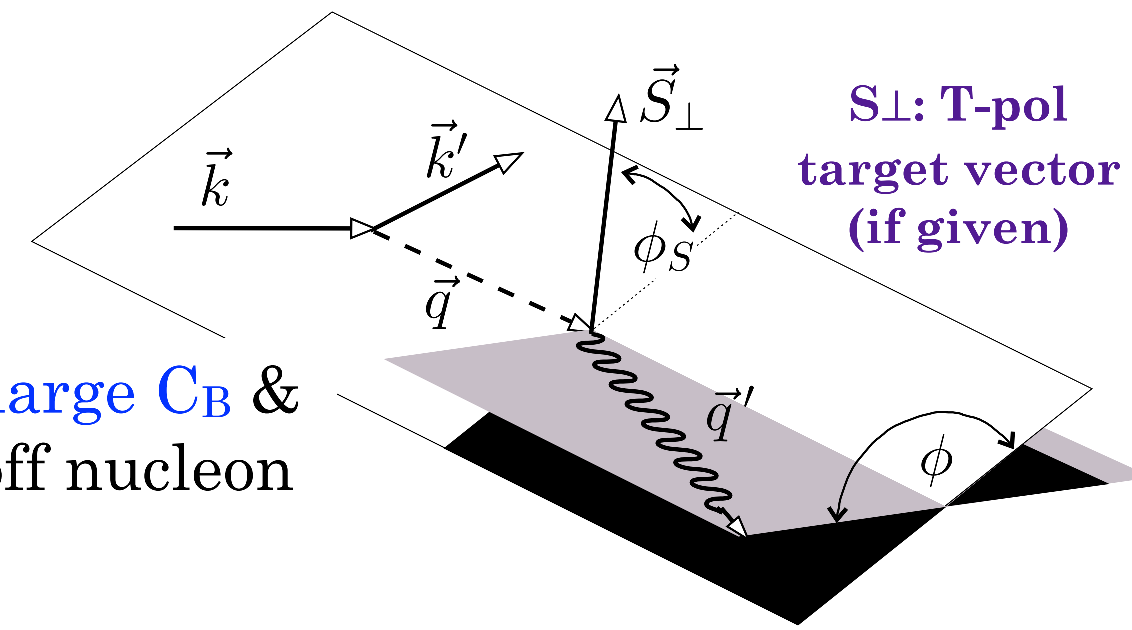
Experimental access to CFFs

DVCS $\sigma_{\gamma^* \gamma N} \sim$



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

Interference term helps to disentangle
Re(τDVCS) and **Im(τDVCS)**



S⊥: T-pol target vector (if given)

E.g.: azimuthal beam-spin asymmetry

$\mathcal{A}_{\rm LU}(\phi)$ — L ↓ Beam, U ↓ Target

Lepton k with charge C_B & polarization P_B off nucleon

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

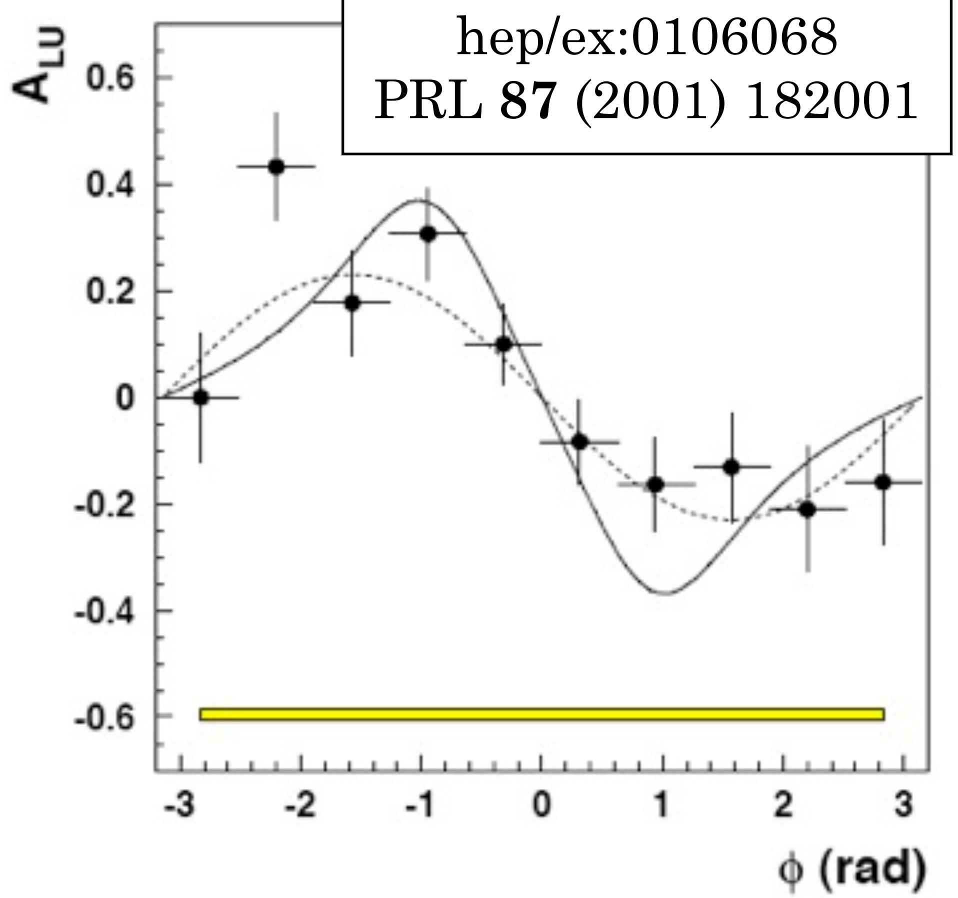
Different experimental configurations (**target polarization**, **beam polarization**, **beam charge**, **and their combinations**) provide access to different (parts of) CFFs.

2001: first observation of azimuthal modulation in DVCS spin asymmetry

HERMES @ DESY

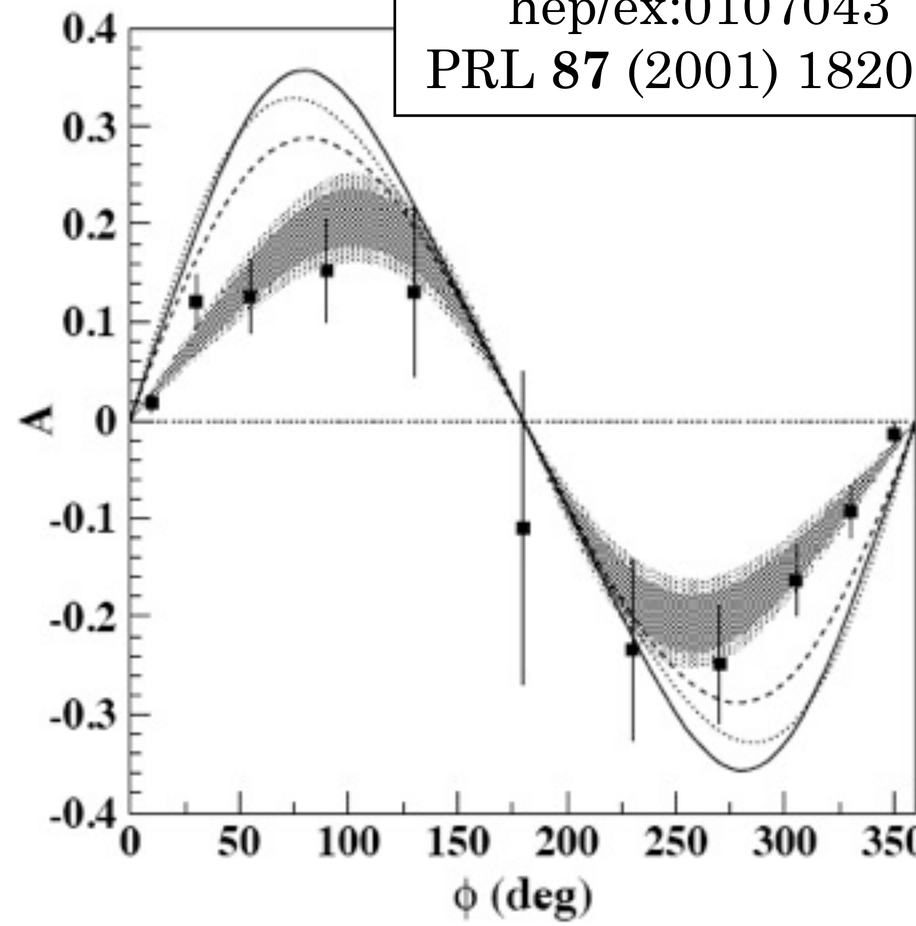
hep/ex:0106068
PRL **87** (2001) 182001

(positrons on proton target)



CLAS @ JLab

hep/ex:0107043
PRL **87** (2001) 182002



(electrons on proton target)

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

Beam-spin asymmetry

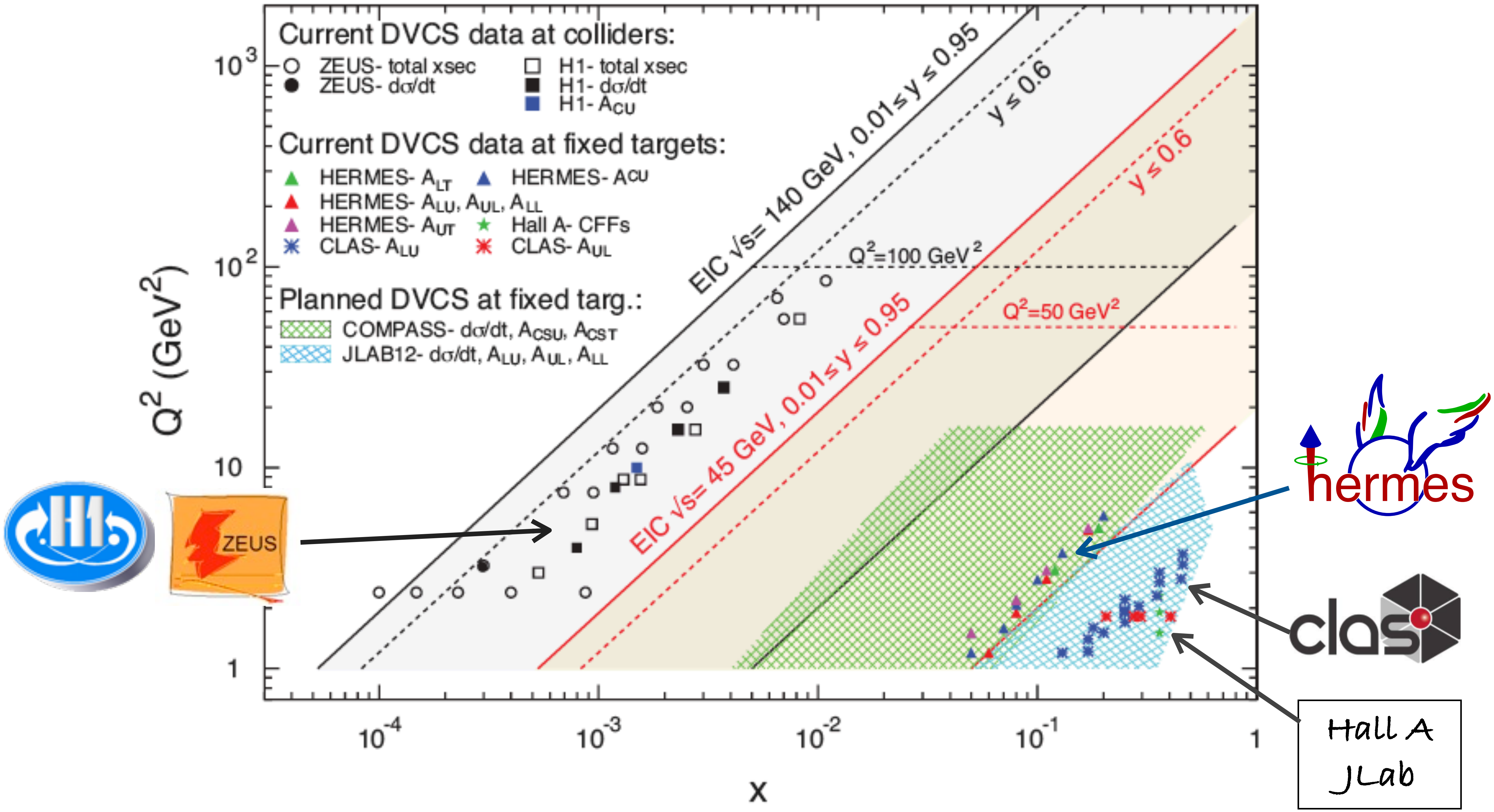
unpolarized target:

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

dominant for the proton

dominant for the neutron

DVCS: kinematic coverage of existing measurements



E.-C. Aschenauer, S. Fazio, K. Kumericki and D. Müller: Deeply Virtual Compton Scattering at a Proposed High-Luminosity Electron-Ion Collider, arXiv:1304.0077 and JHEP **1309** 093 (2013).

DVCS evolution over the years

List might not be exhaustive.

in the pipeline / preliminary

2001
- **H1 @ DESY** cross-section
- **CLAS @ JLab** BSA
- **HERMES @ DESY** BSA (1996/97 data)

2003
- **ZEUS @ DESY** cross-section

2006
- HERMES BCA (1996-2000 data)
- CLAS (eg1b-dvcs) LTSA
- **Hall A @ JLab** E00-110 cross-section (p,n)
- Hall A (E03-106) BSA neutron

2007
- CLAS (e1-dvcs) BSA

2008
- HERMES TTSA

2009
- H1 BCA

2010
- Hall A (2010 data) E07-007 (p) E08-025 (n)
- HERMES Lpol-H, -D; nuclear

2011
- HERMES BSA with recoil and BCA/BSA from complete data set 1996-2007

2012
- COMPASS 2012 data

2013
- HERMES Resonant DVCS (△)

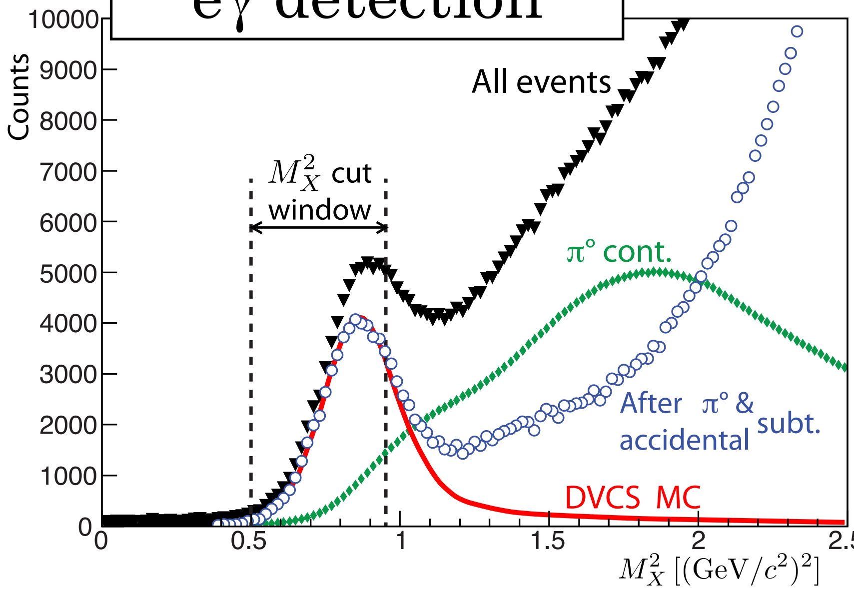
2014
- CLAS eg1-dvcs: LTSA

2015
- Hall A E00-110: final x-section
- CLAS e1-dvcs: x-section

time

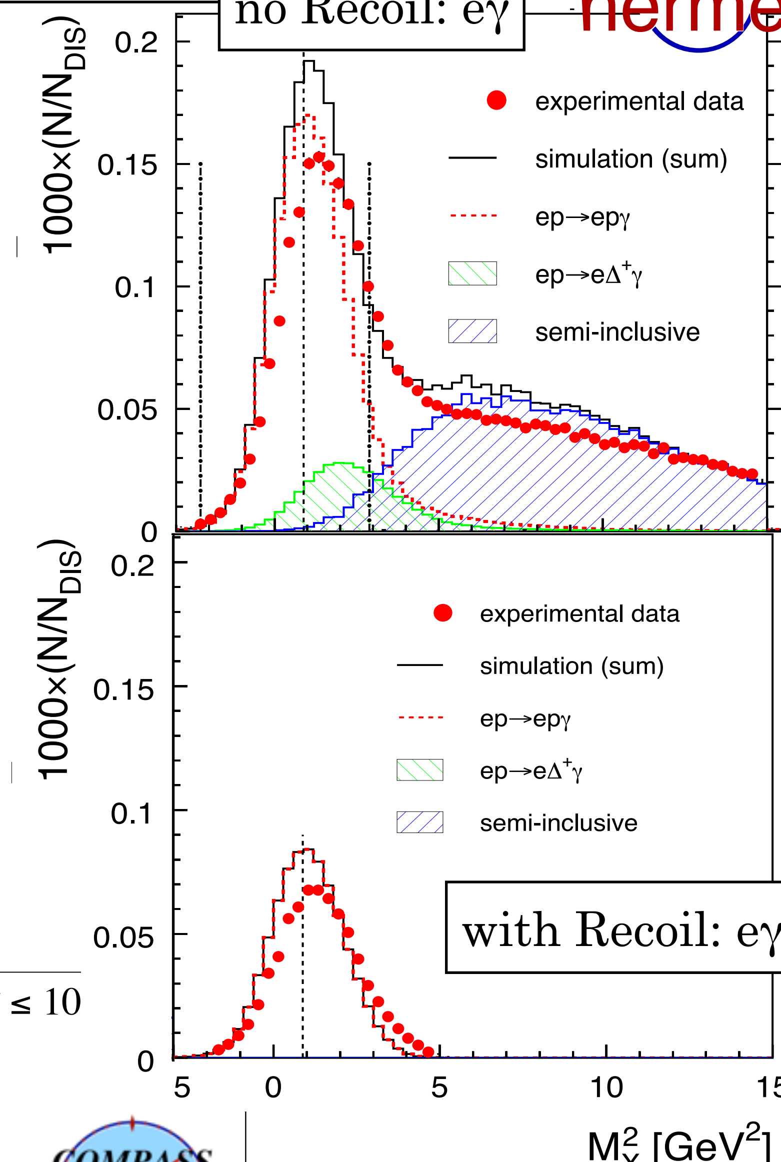
Selection of exclusive data sample

Hall-A DVCS: eγ detection — 6 GeV



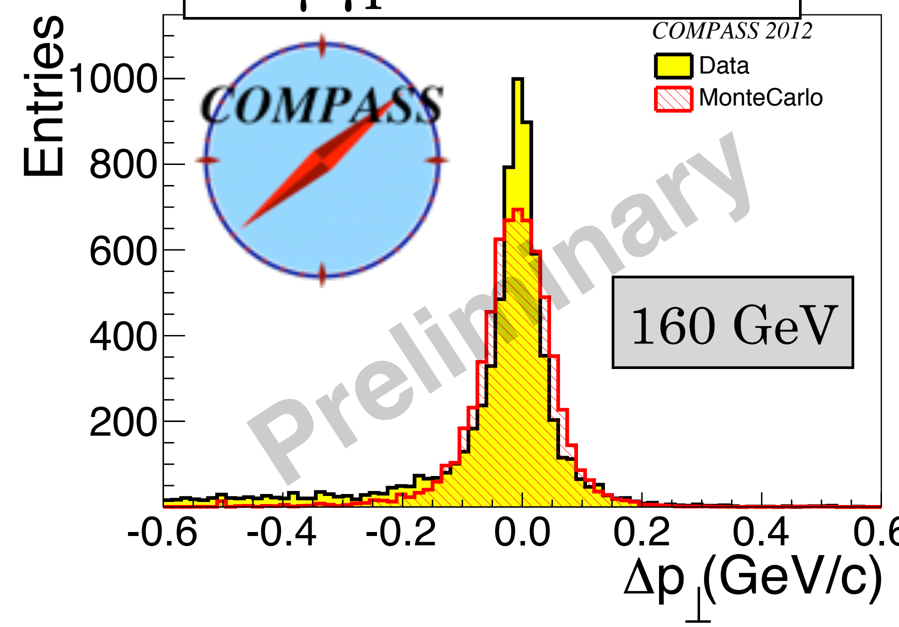
HERMES DVCS: — 27.6 GeV

no Recoil: eγ

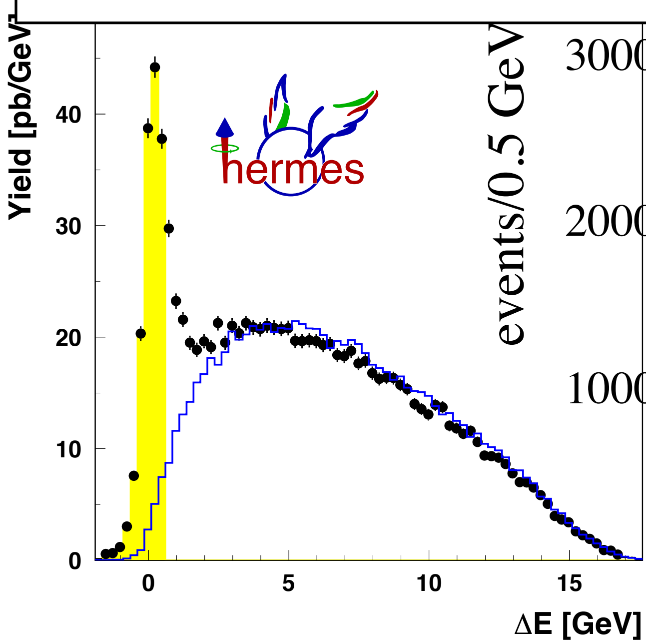


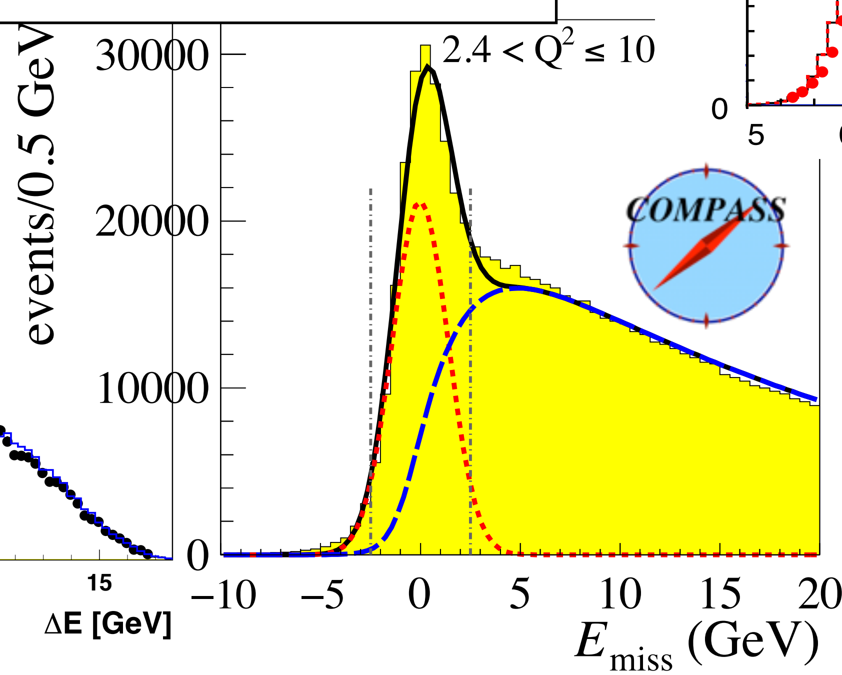
with Recoil: eγp

COMPASS DVCS: μγp detection — 160 GeV



HERMES & COMPASS excl. ϱ: ℓ π-π+ detection





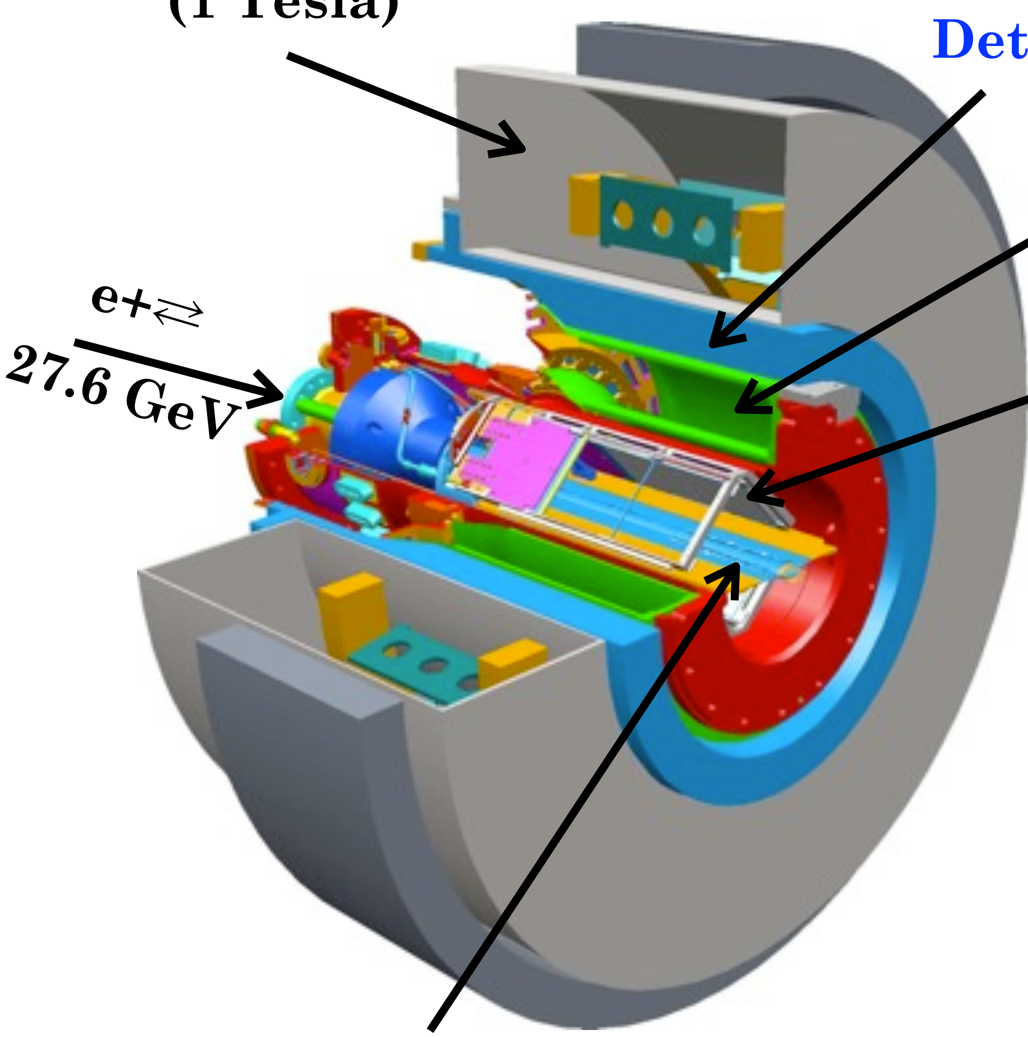
CLAS DVCS:
no Inner Calo: ep or epγ
with Inner Calo: epγ

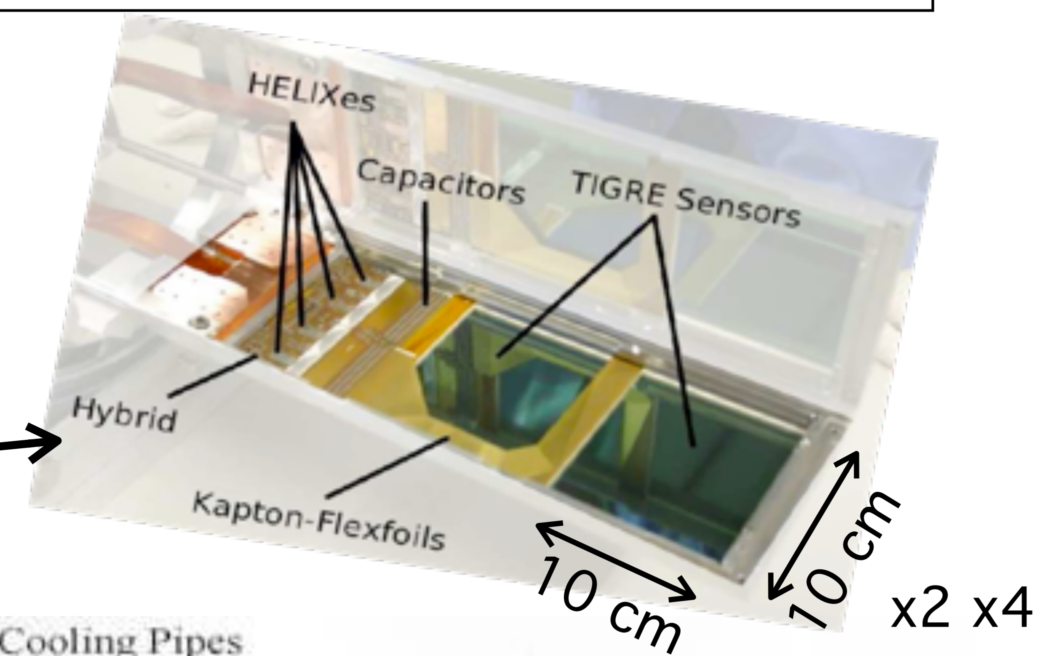
H1/ZEUS DVCS:
eγ + forward veto
ZEUS subsample: epγ

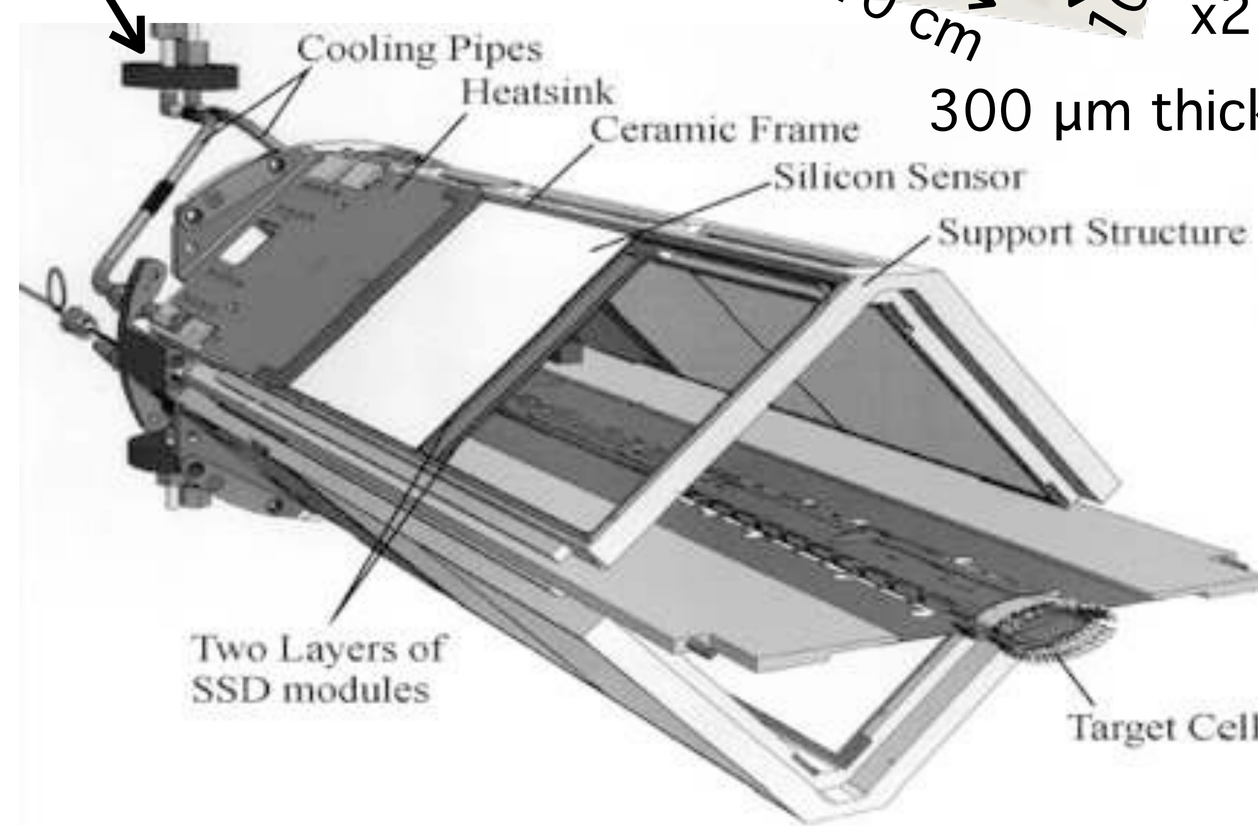
The HERMES recoil detector

JINST 8 (2013) P05012

- $\triangle\phi$=4 mrad, $\triangle\theta$=10 mrad (for p > 500 MeV)
- p_{min}=125 MeV ≡ $-t$=0.016 GeV^2
  (protons that make it at least in 2nd layer of SSD)

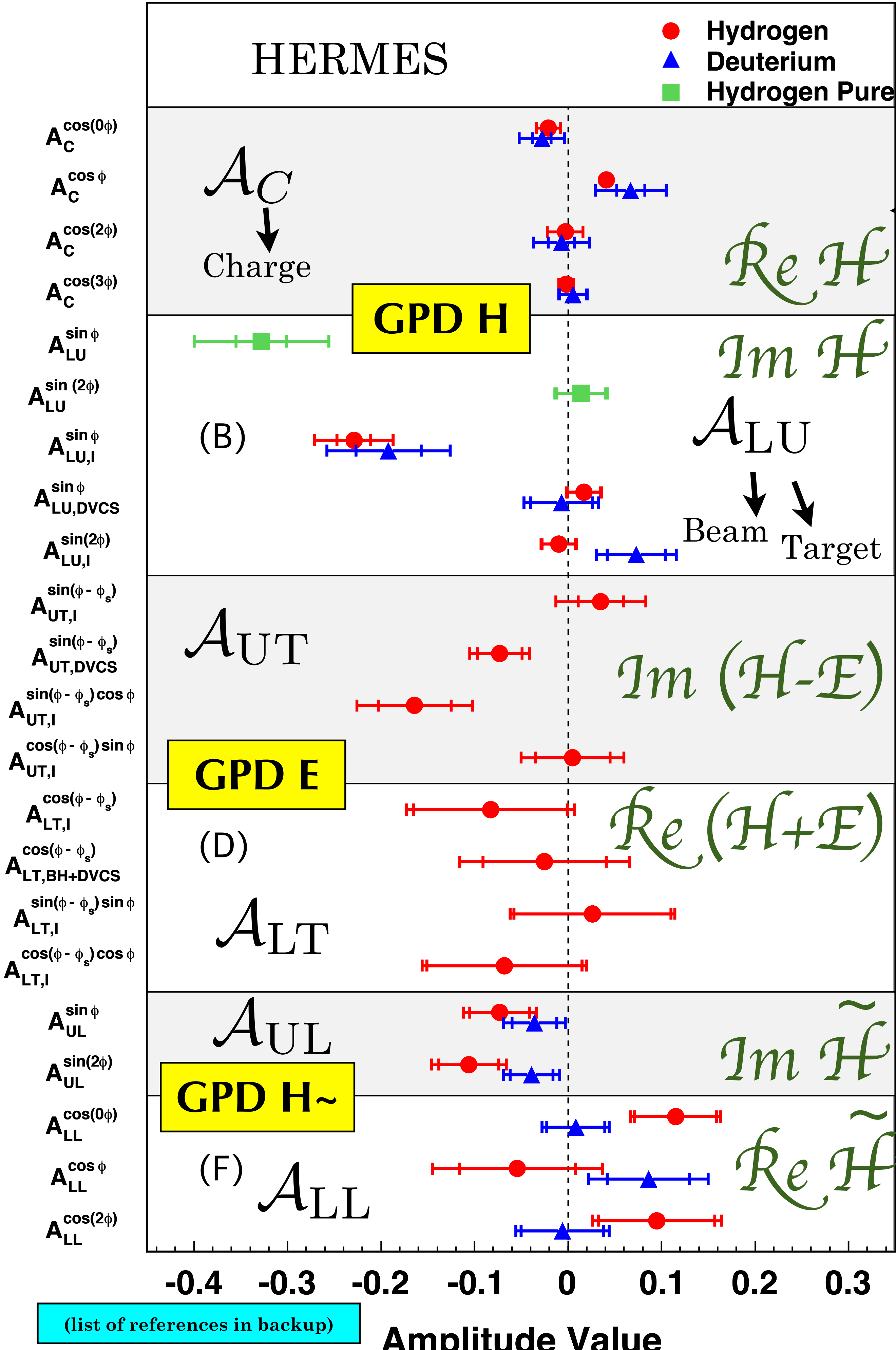






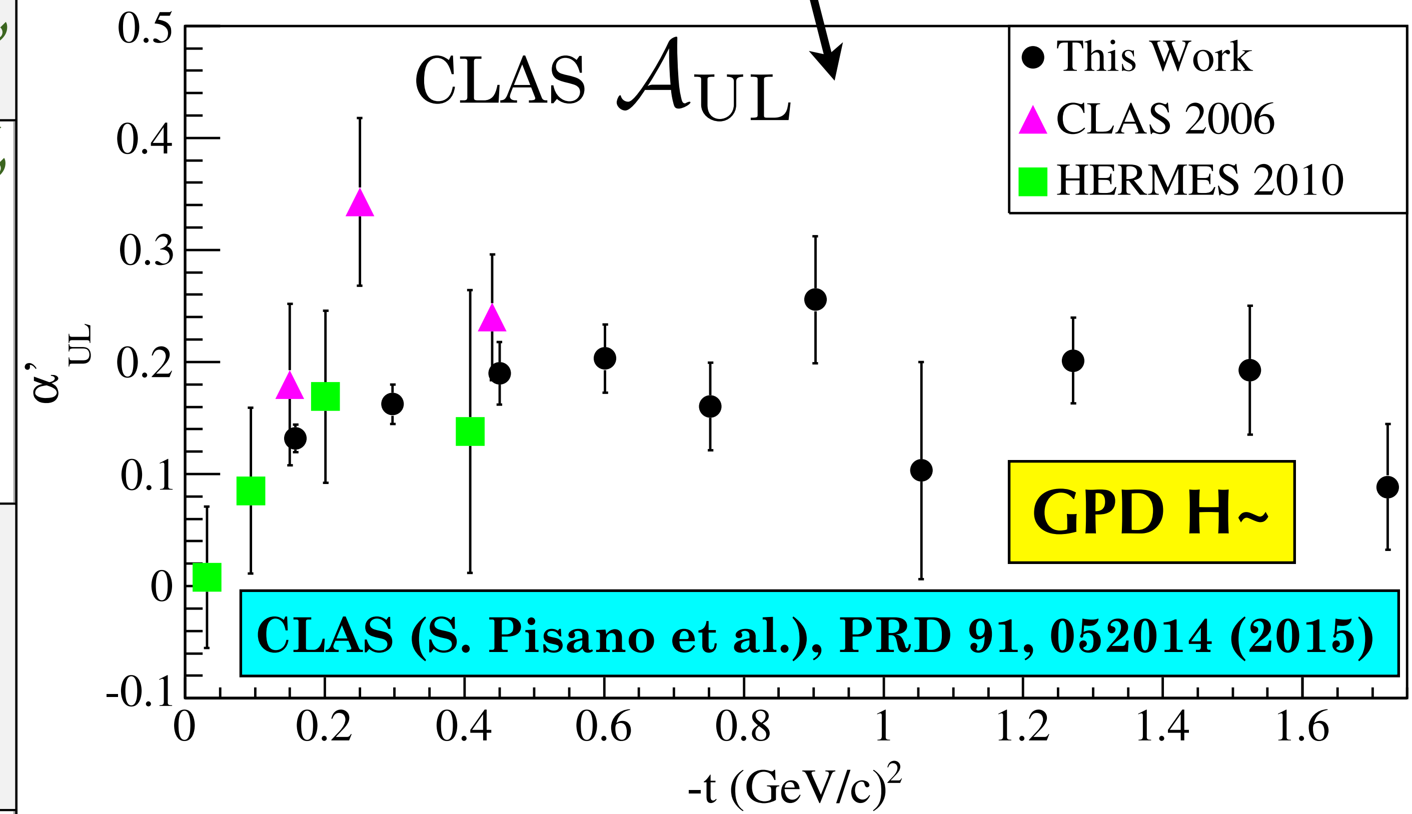
unpolarized proton and
deuteron pure gas targets

DVCS highlights

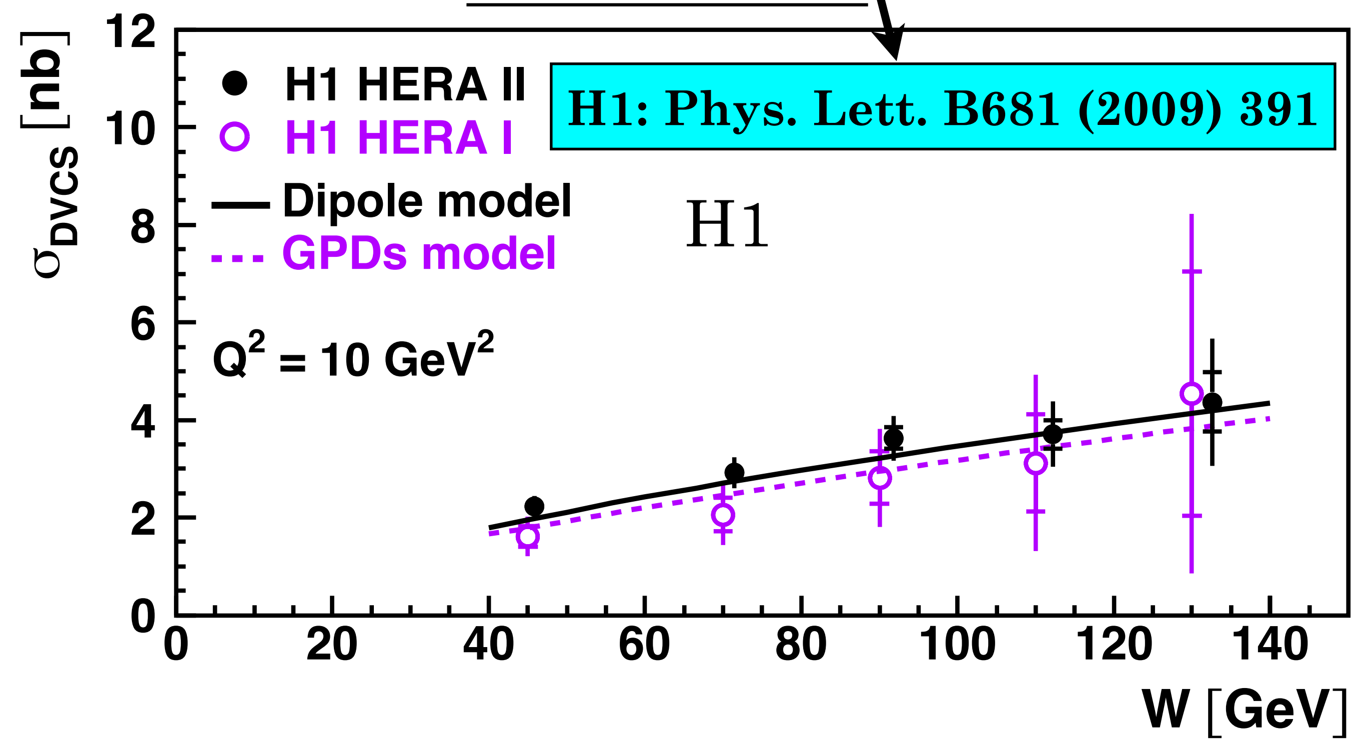


(list of references in backup)

azimuthal asymmetry amplitudes



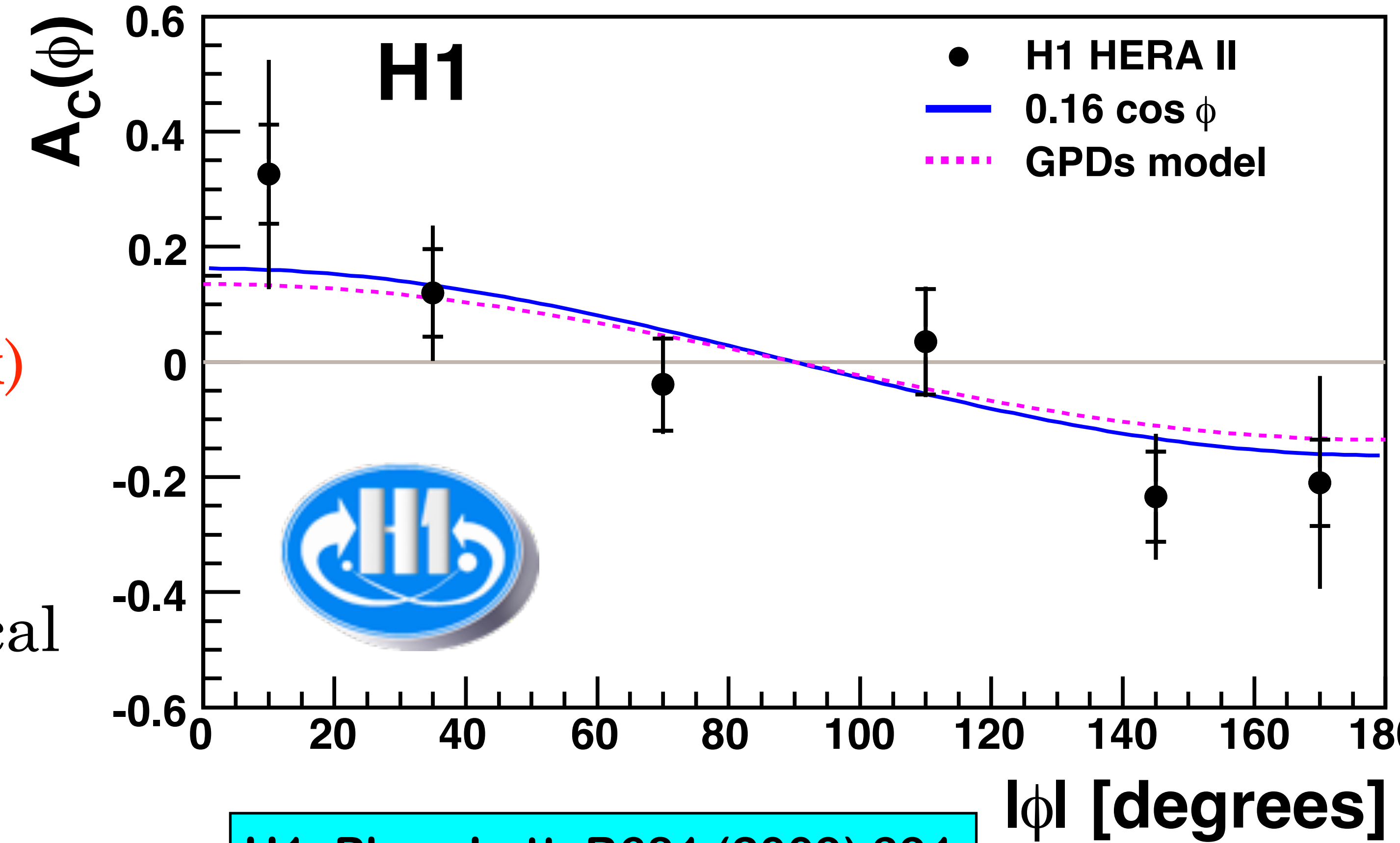
cross sections



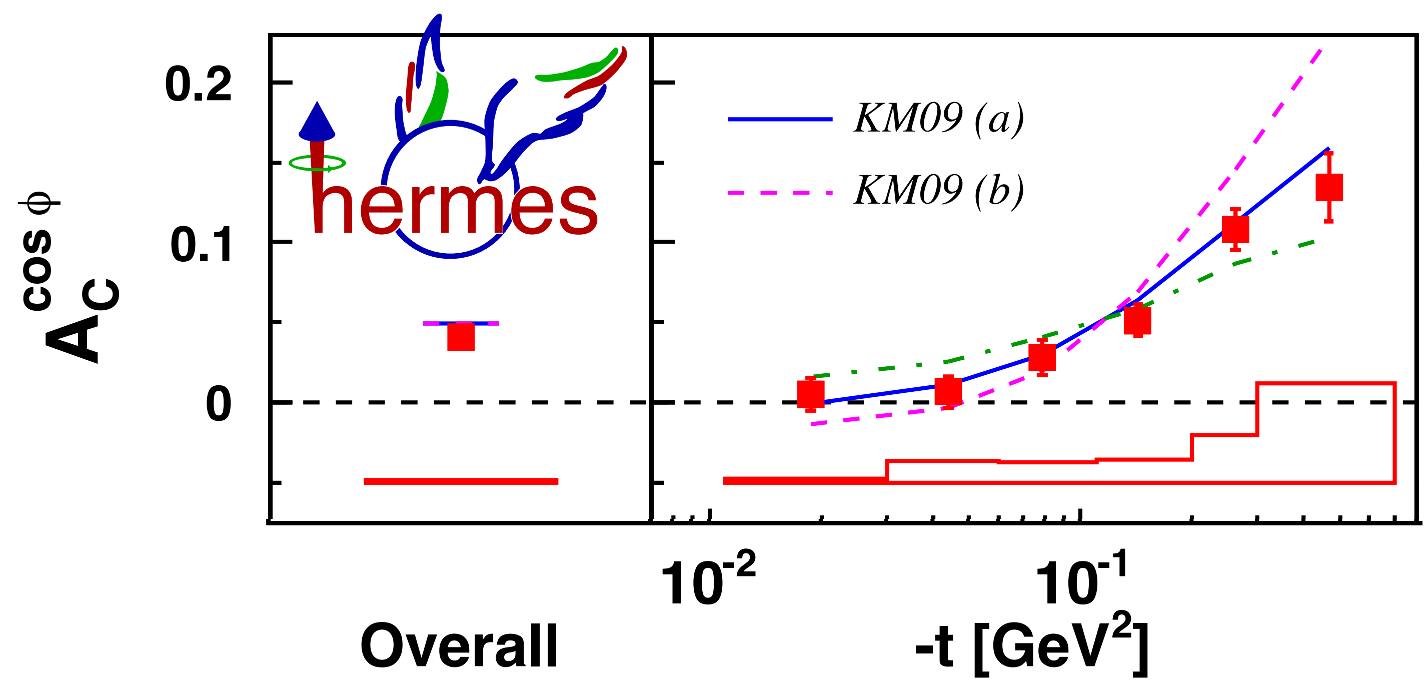
H1 & HERMES: beam-charge asym.

GPD H
Re(τ_{DVCS})

- **Re(τ_{DVCS})** > 0 for HERA (small x)
  Re(τ_{DVCS}) < 0 for HERMES (larger x)
- ϱ = **Re(τ_{DVCS})** / **Im(τ_{DVCS})**
  - ϱ=0.20 ± 0.05(stat) ± 0.08(sys)
  - In good agreement with theoretical calculation (dispersion relation)
- H1@HERA/DESY: first and only measurement at collider
  - low $x_B=10^{-4}...10^{-2}$
  - $6.5 < Q^2 < 80$ GeV^2
  - $30 < W < 140$ GeV
  - $|t|<1$ GeV^2



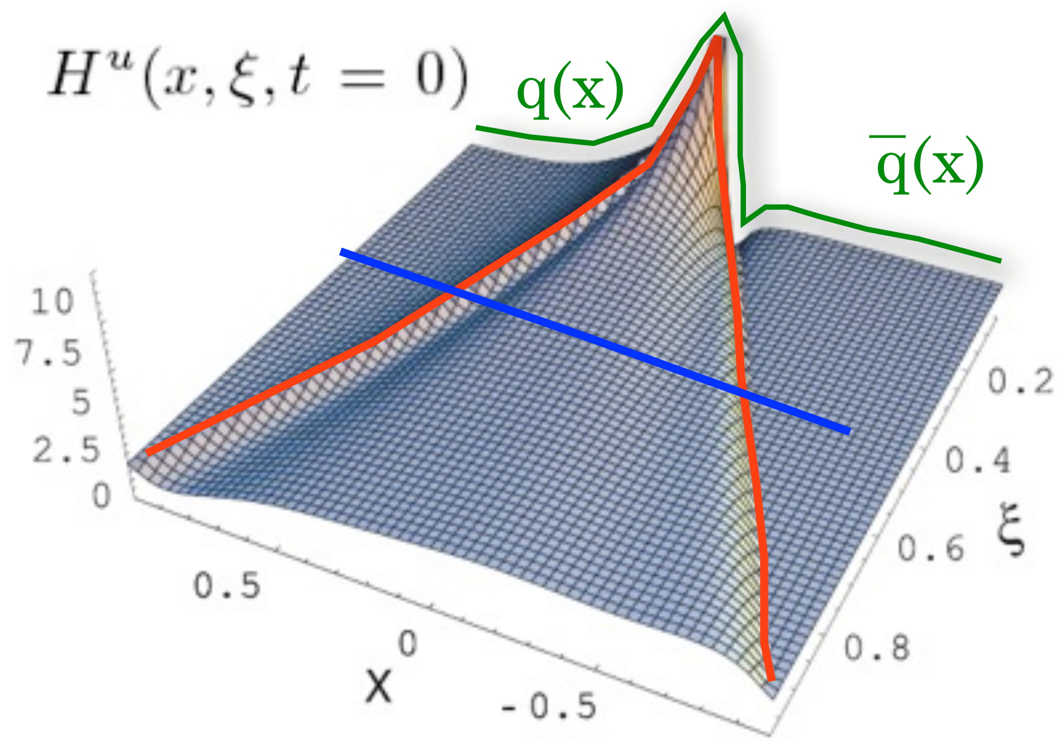
H1: Phys. Lett. B681 (2009) 391



HERMES: JHEP 07 (2012) 032

Global analysis of DVCS data

GPD H



CFF

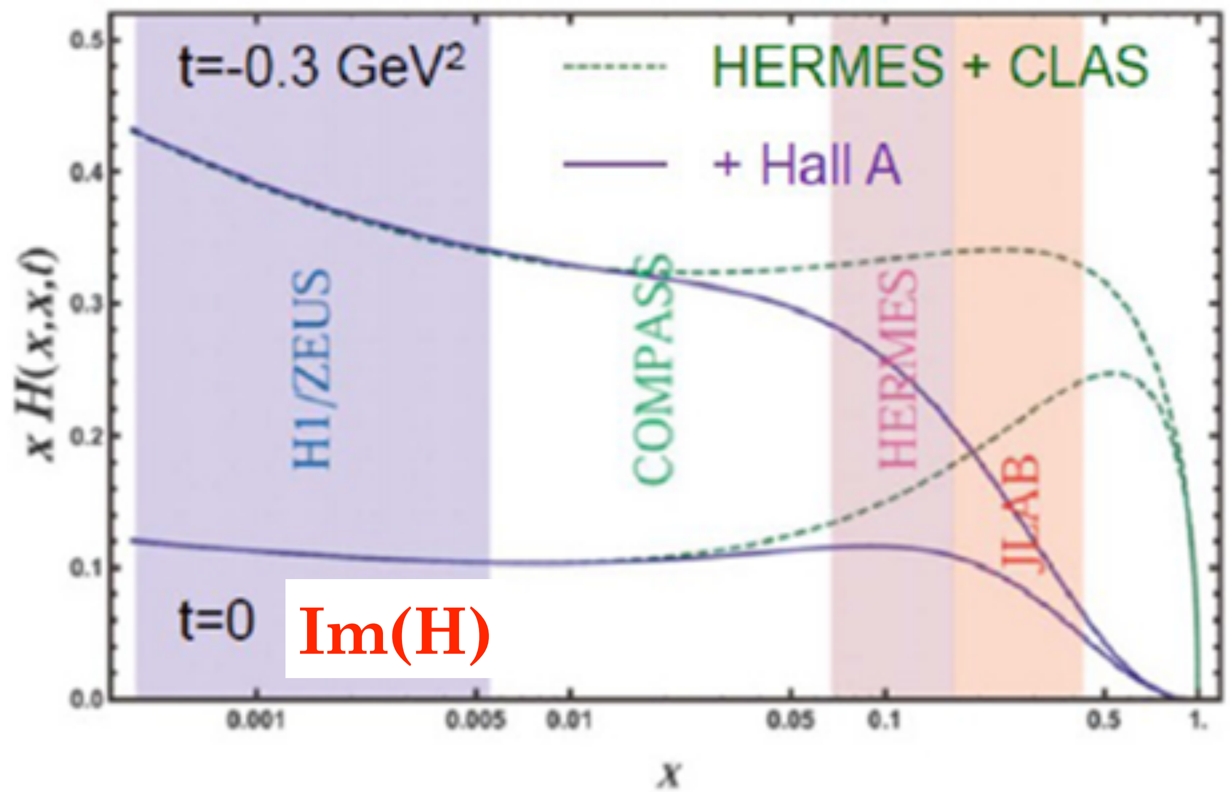
$$\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{+1} \mathrm{d}x\, \frac{H(x,\xi,t)}{x-\xi} - i\pi H(\xi,\xi,t)$$

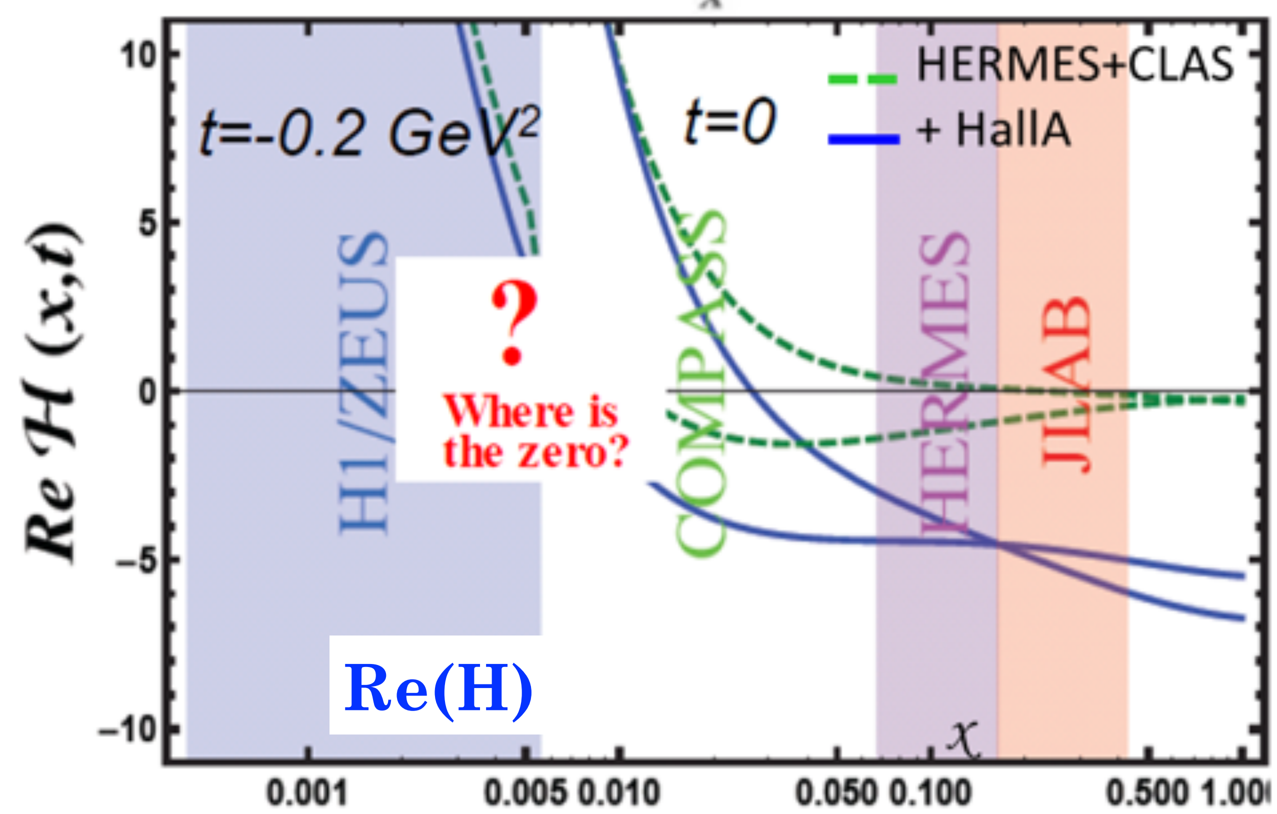
Re(τ$_{DVCS}$)
integral over x

Im(τ$_{DVCS}$)
x=ξ

K. Kumericki and D. Müller (KM)
Nucl. Phys. **B**841 (2010) 1-58

- Global fit to extract GPD H at ξ=x. NNLO
- **HERMES** A$_C$, **CLAS** A$_{LU}$ and **Hall A** x-section.
- Small-x behavior from **HERA collider** data.





lower plot: priv. comm. Mueller & COMPASS

Global analysis of DVCS data

Compton Form Factors

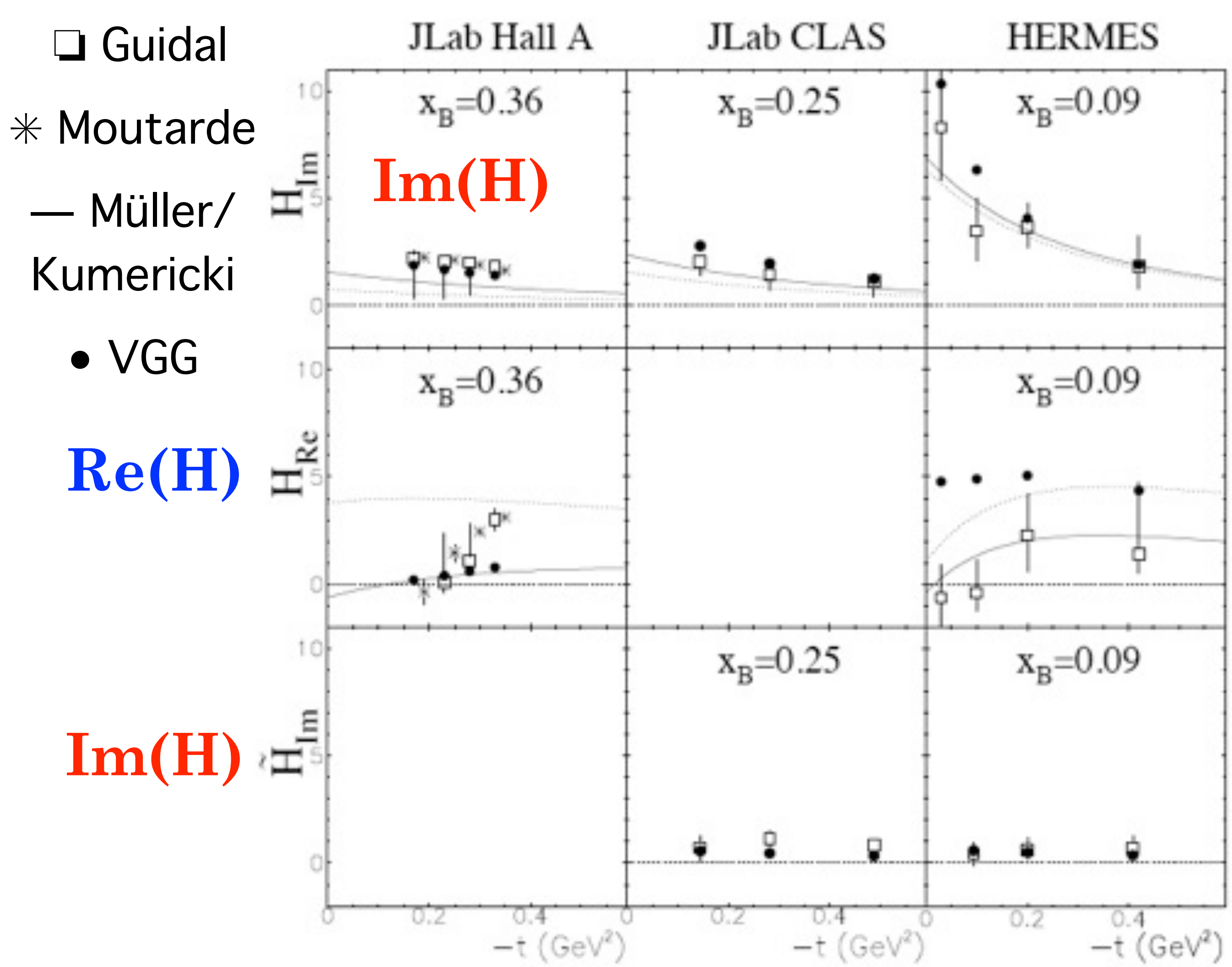
M. Guidal arXiv:1011.4195
Model-independent fit of **Re**(CFF) & **Im**(CFF)
HERMES AC, ALU, AUT, AUL, ALL;
CLAS ALU, AUL; **Hall-A** x-section

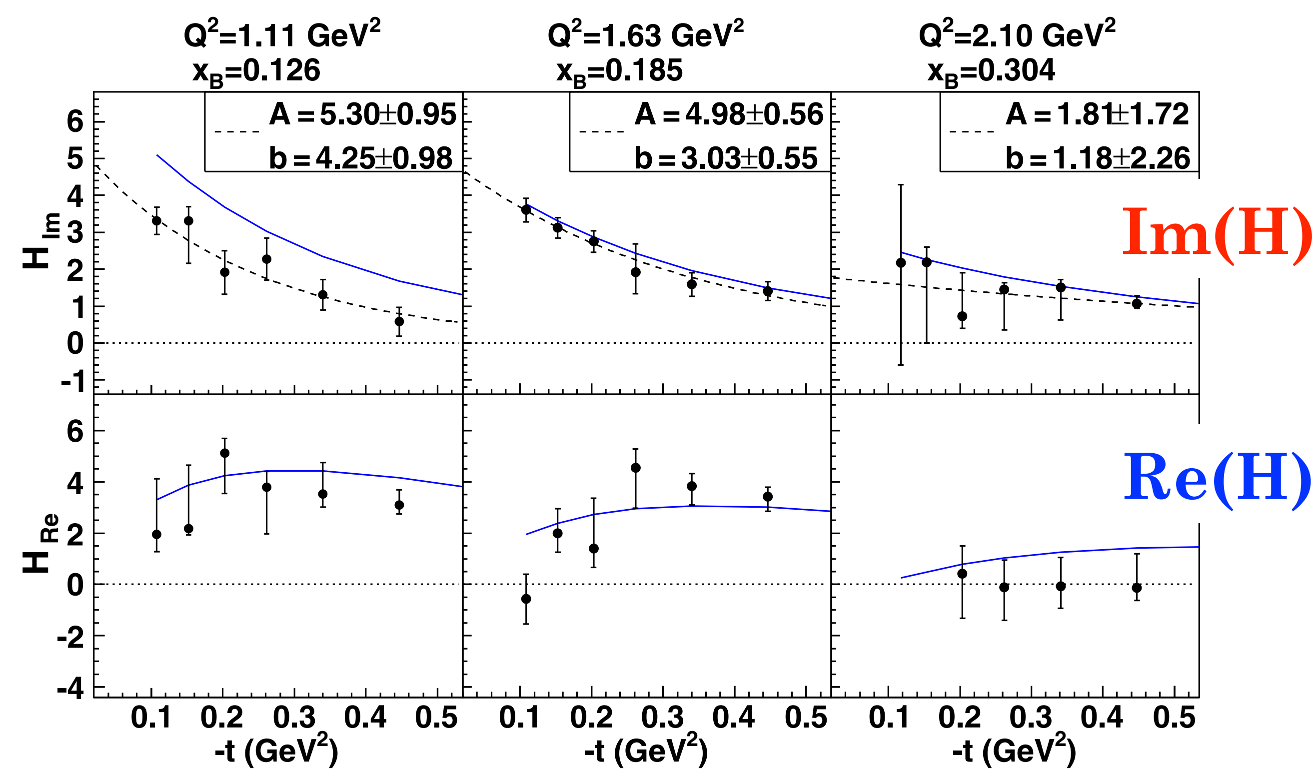
H. Moutarde PRD 79, 094021 (2009)

- Global fit to extract **Re(H)** & **Im(H)**
- **Hall A** x-section & **CLAS** ALU

K. Kumericki, D. Müller, A. Schäfer
arXiv:1106.2808

- Neural-network generated, model-independent parameterizations of CFFs
- Facilitates error propagation from data





even more precise with latest CLAS data →

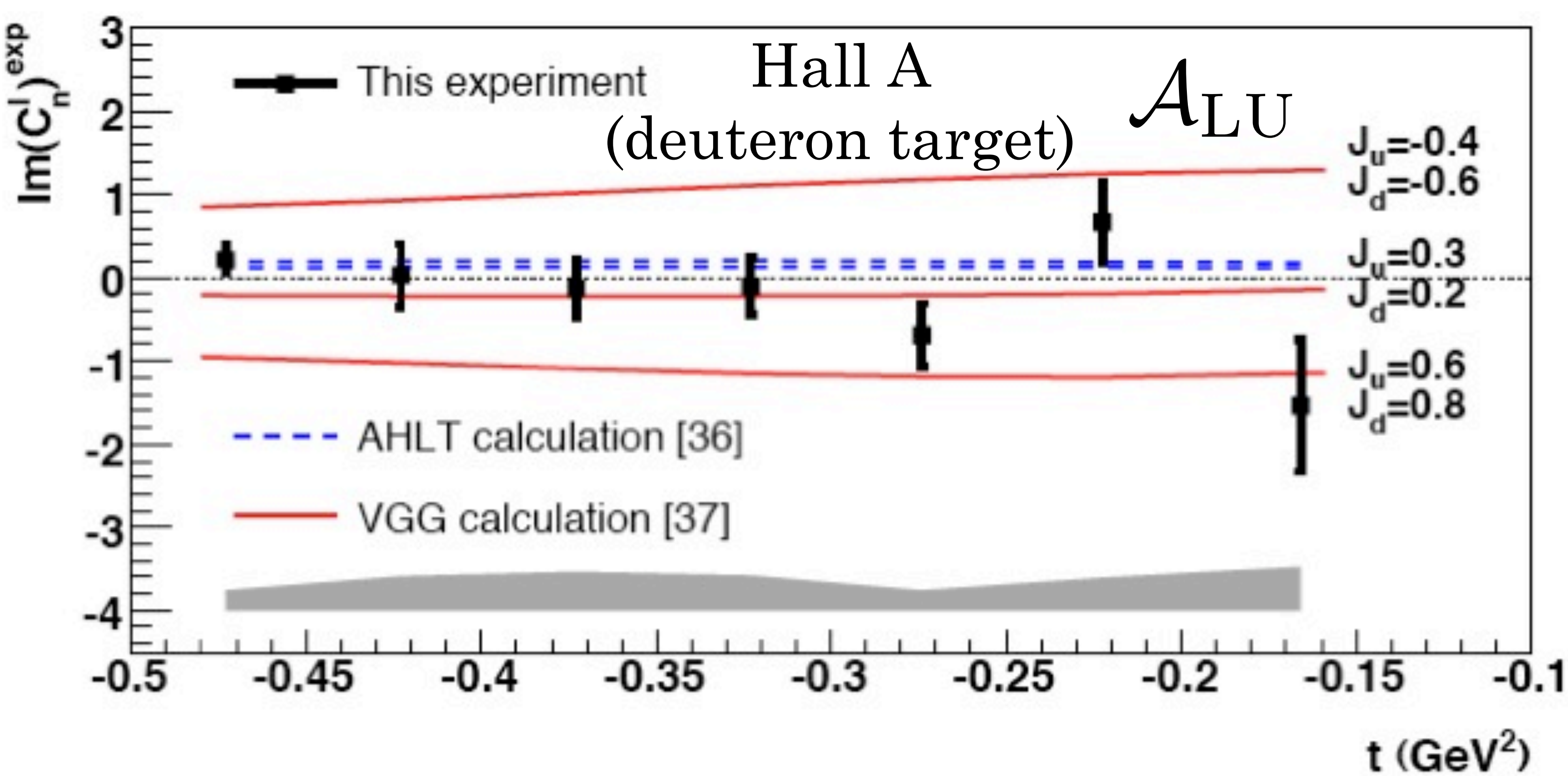
H. S. Jo et al. (CLAS coll.), PRL 115, 212003 (2015)

DVCS to constrain GPD E

GPD E

(A) HERMES: $\mathbf{ep^{\uparrow} \rightarrow ep\gamma}$:
H-E (transversely polarized proton target) $\mathcal{A}_{\mathrm{UT}}$

(B) Hall A: $\mathbf{\vec{e}^{-} n \rightarrow e^{-} n \gamma}$:
E dominant for the neutron (unpolarized deuteron/neutron target) $\mathcal{A}_{\mathrm{LU}}$

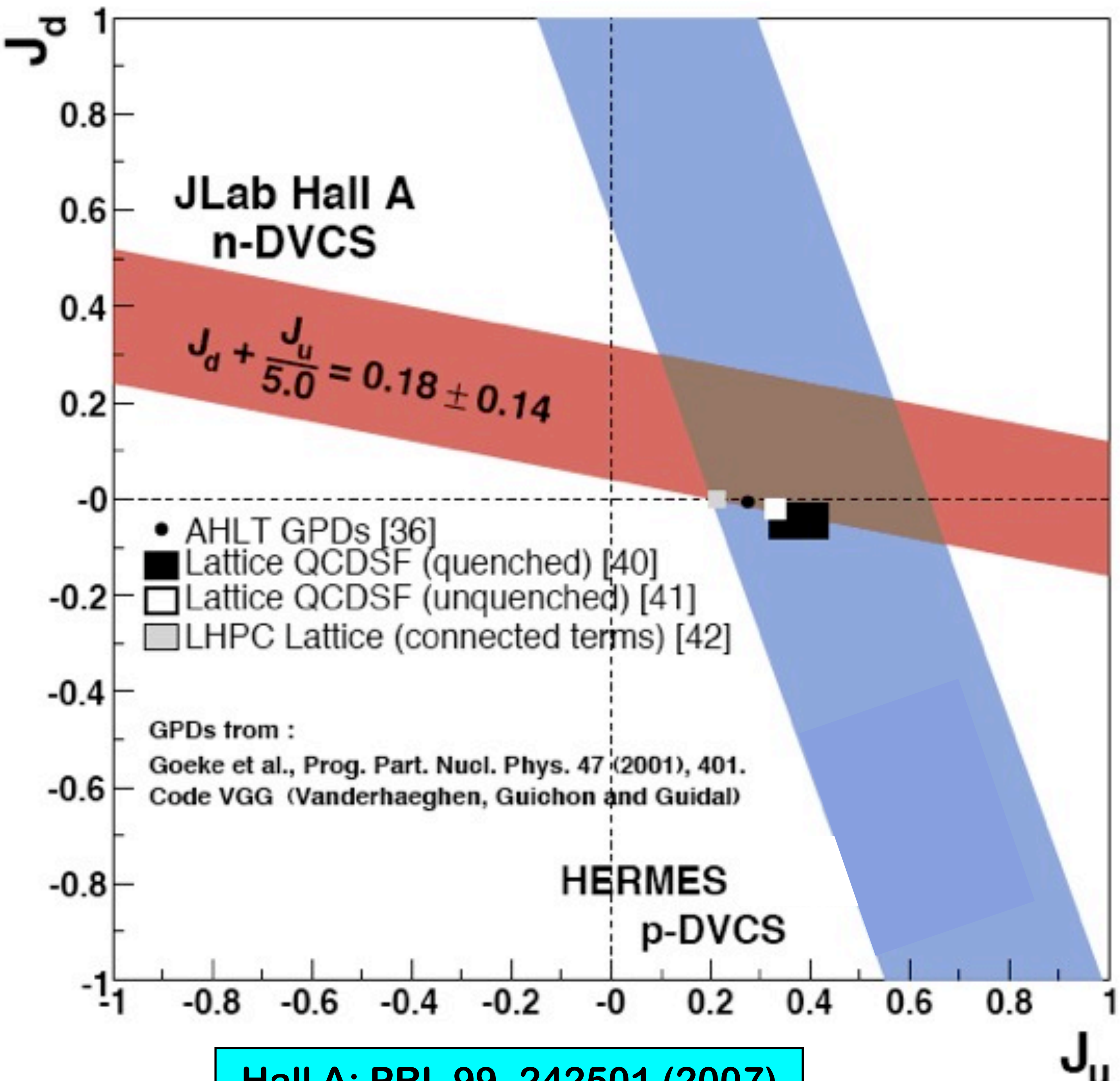


Hall A: PRL 99, 242501 (2007)

GPD E and orbital angular momentum of quarks

GPD E

In principle, measurements sensitive to **GPD E** allow access to the **total angular momentum of quarks, J_q**. Constraint strongly model dependent!



Hall A: PRL 99, 242501 (2007)

Nucleon spin

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + L_q + J_g$$

Ji sum rule for the nucleon:

$$J_q = \frac{1}{2} \lim_{t\to 0} \int_{-1}^{1} dx\, x\, [H^q(x,\xi,t) + E^q(x,\xi,t)]$$

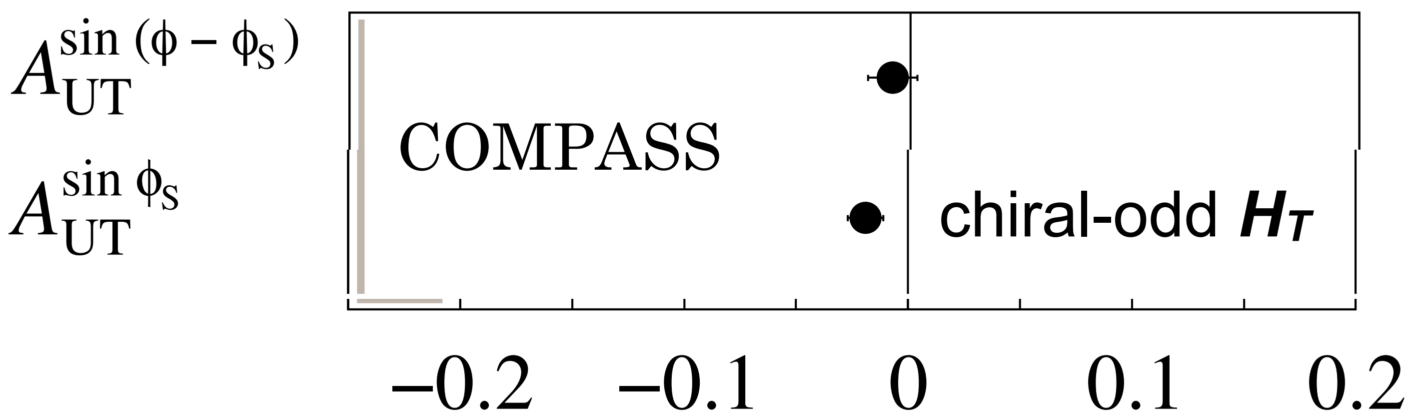
Ji, PRL 78 (1997) 610

Exclusive mesons: target-spin asym.

GPDs E & H_T

$\mu p^{\Uparrow} \to \mu p \rho^0$

COMPASS: PLB B731 (2014) 19



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

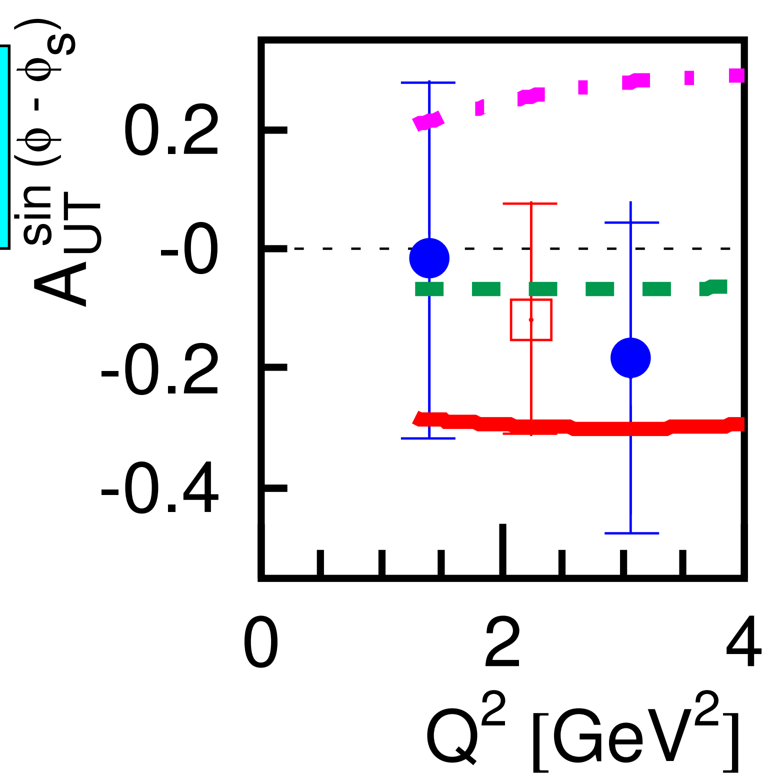
$$A_{UT}^{sin\phi_S} \propto \mathrm{Im}\,(\mathcal{H}_T^* \mathcal{H} - \bar{\mathcal{E}}_T^* \mathcal{E})$$

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

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

Different mesons filter different quark flavors

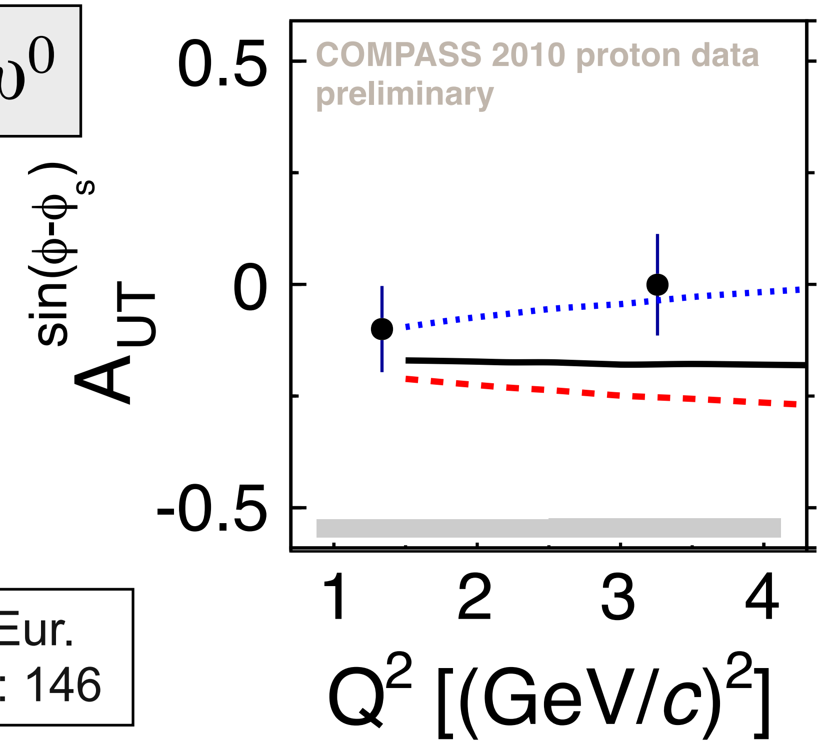
HERMES: EPJ C 75 (2015) 600



$\ell p^{\Uparrow} \to \ell p \omega^0$

Curves are for different πω transition form factors from

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

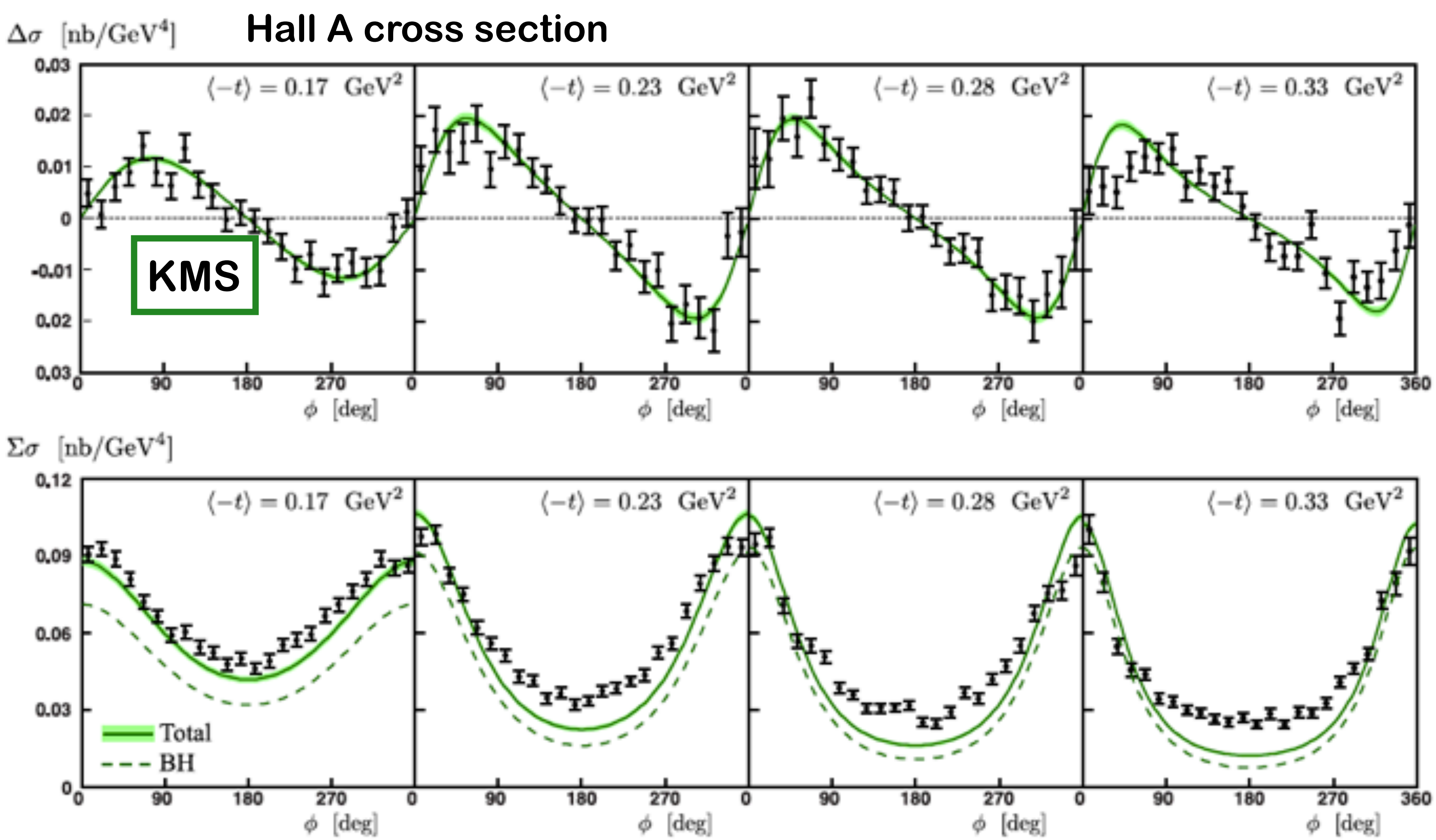


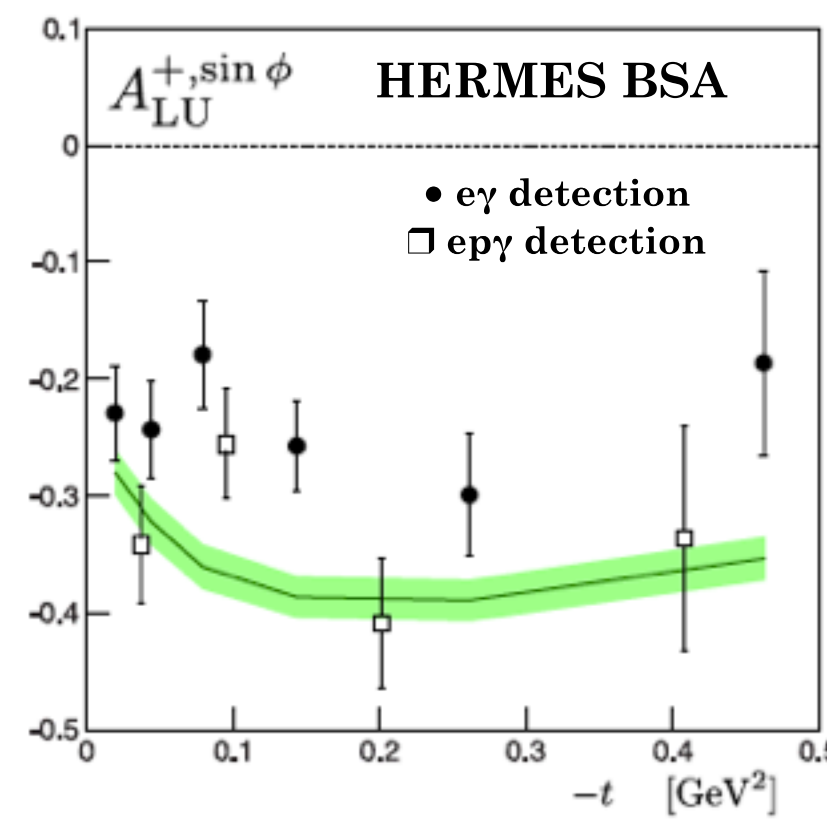
COMPASS ***publication in preparation***

Test of GPD universality

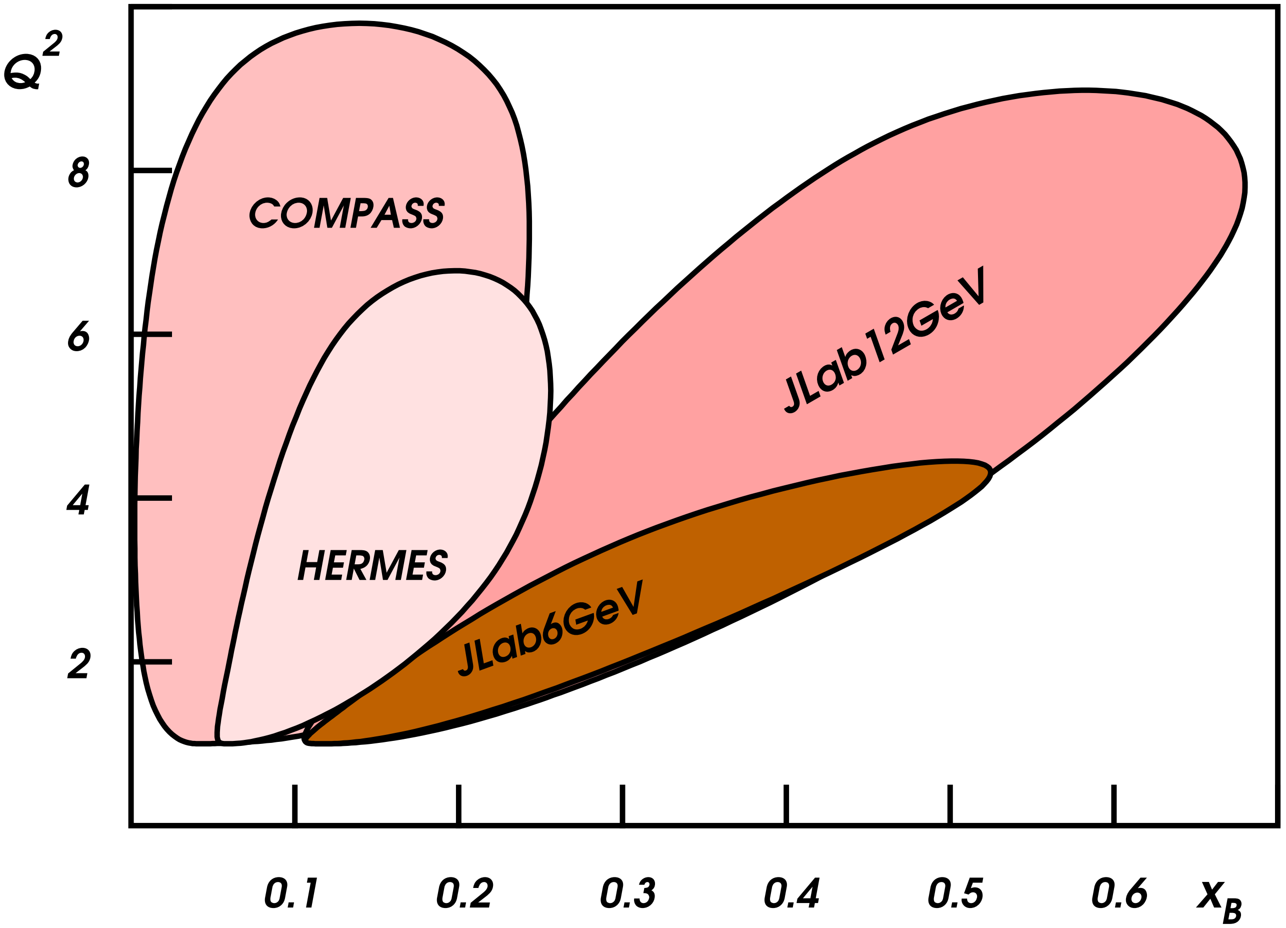
P. Kroll, H. Moutarde and F. Sabatié (KMS): From hard exclusive meson electroproduction to deeply virtual Compton scattering, Eur. Phys. J. C (2013) 73:2278

- Use DVMP data (from H1, ZEUS, E665, COMPASS and HERMES) to constrain GPD parameters (LO, LT): **GK model**
- Compare to DVCS observables - good for HERA and HERMES, fair for JLab





COMPASS-II GPD run 2016/17

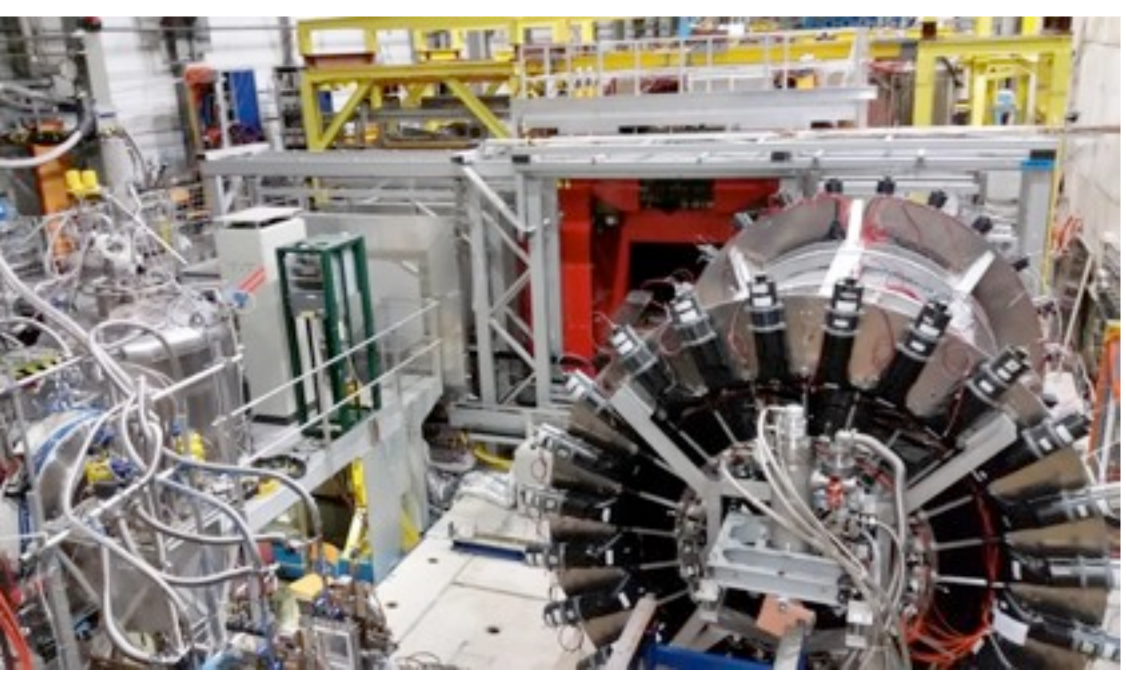


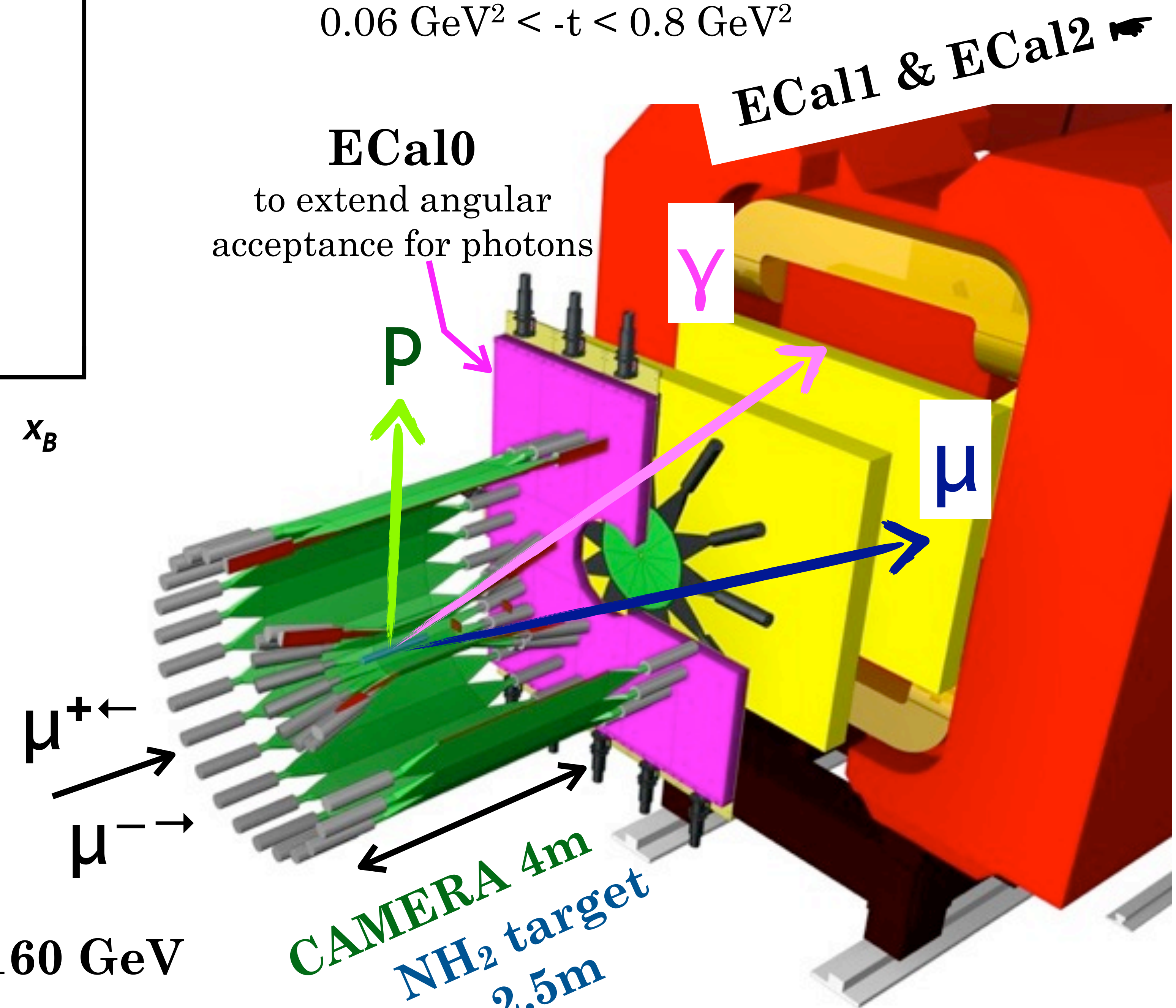
Long recoil detector CAMERA

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 GPDs 2016/2017

GPD H

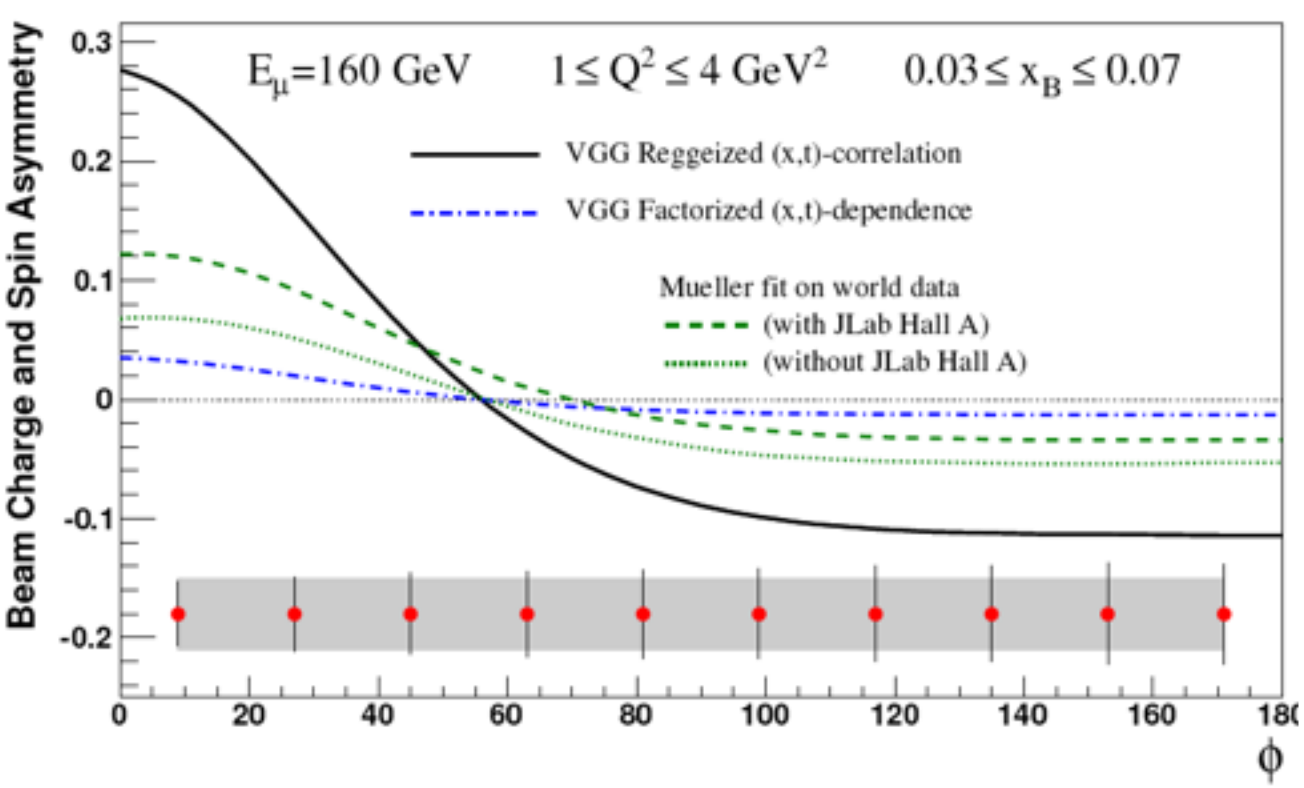
GPD $\boldsymbol{H}$ from DVCS: input for global fits

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

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

+ link to D-term

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

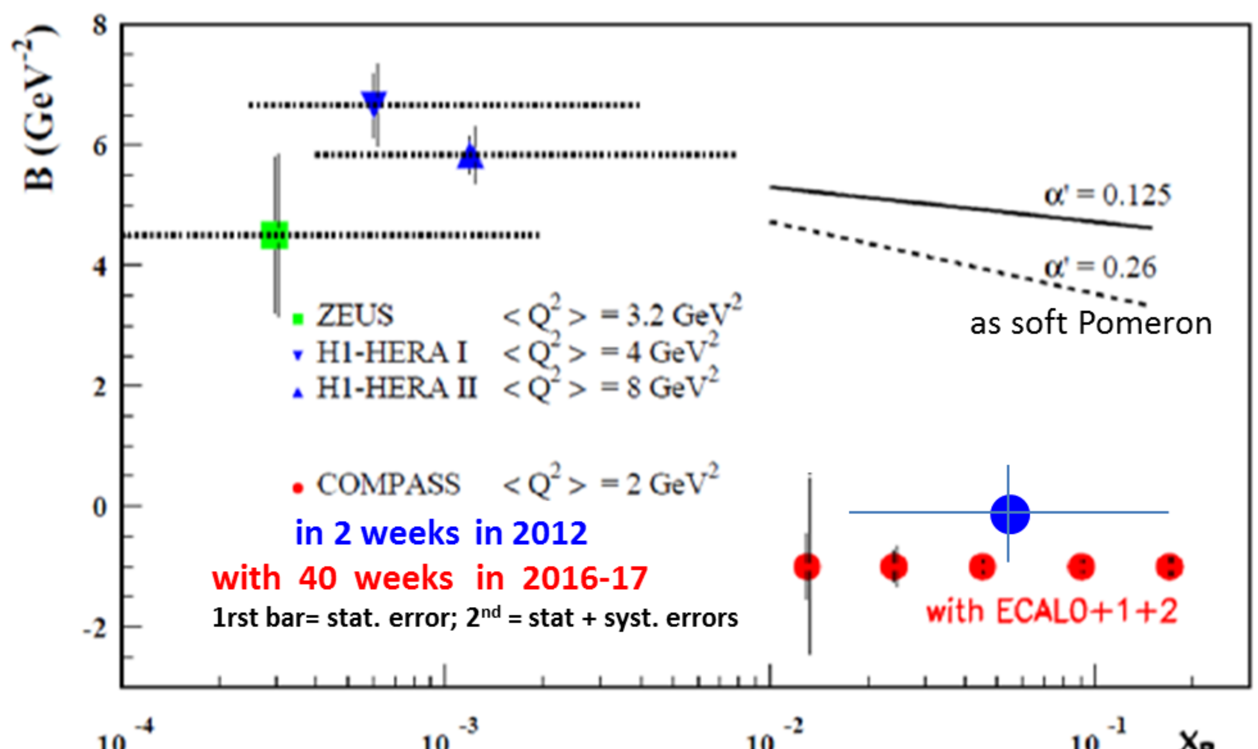


Transverse imaging from DVCS and DVMP

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

t-slope $\boldsymbol{b}$: average impact parameter "transverse size of nucleon"

COMPASS will be important in pinning down the ***transition region*** *between "pomeron" dominance* ***(hard)*** *and "Reggeon"* ***(soft)*** *behavior.*

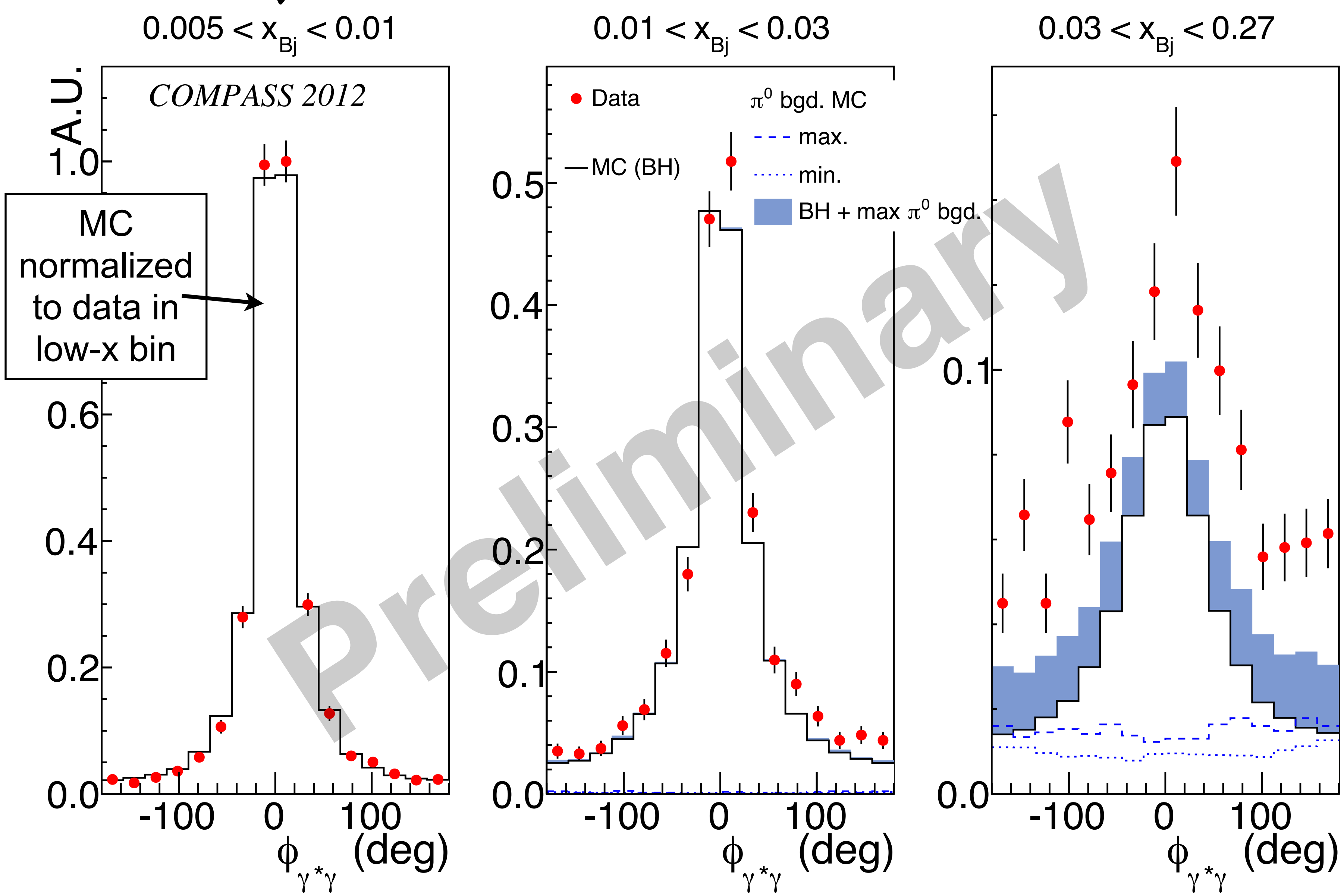


(courtesy Nicole D'Hose)

DVCS vs. BH at COMPASS

2012 DVCS pilot run

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



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) $\Rightarrow$ excess

BH reference yield

DVCS amplitude: Φ-modulations in cross section

Transverse imaging: Φ-integrated cross section

$1\ \mathrm{GeV}^2 < Q^2 < 20\ \mathrm{GeV}^2$

$0.005 < x_{Bj} < 0.27$

$0.06 < |t| < 0.64\ \mathrm{GeV}^2$

From GPDs to spatial densities

Impact-parameter representation:

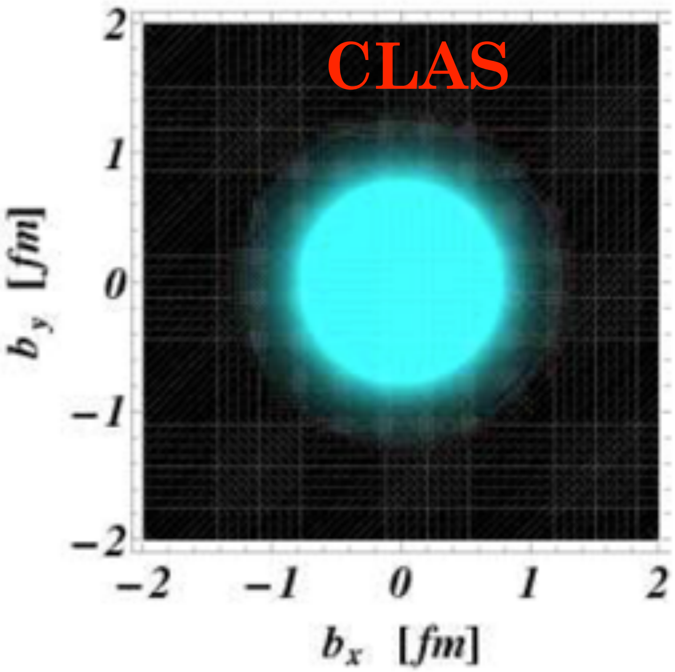
$$q^f(x, \boldsymbol{b}_\perp) = \int \frac{\mathrm{d}^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} H^f(x, 0, -\boldsymbol{\Delta}_\perp^2)$$

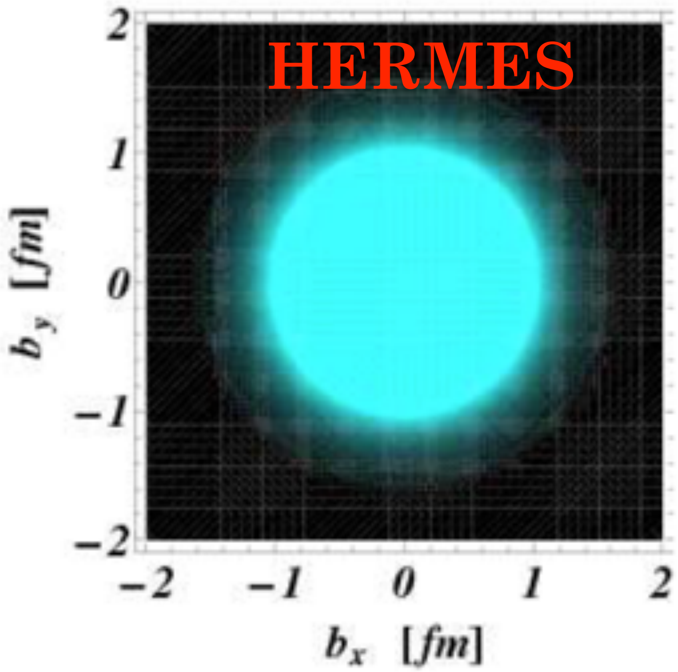
M. Burkardt, Impact Parameter Space Interpretation for Generalized Parton Distributions, Int. J. Mod. Phys. A18 (2003) 173

$$H(x, b_\perp) = \int_0^\infty \frac{d\Delta_\perp}{2\pi} \Delta_\perp \, J_0(b_\perp \Delta_\perp) \, H(x, 0, -\Delta_\perp^2)$$

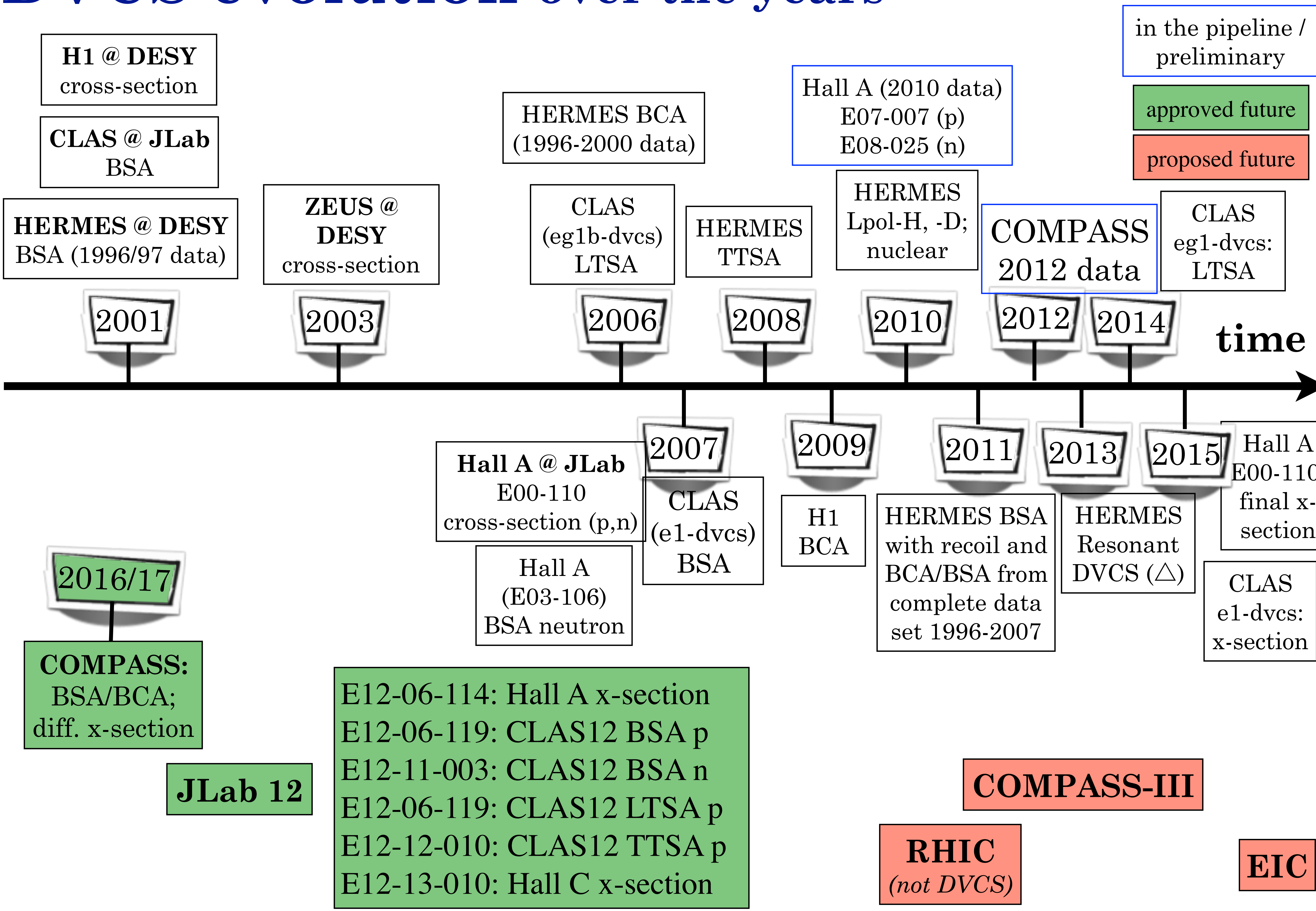
M. Guidal, H. Moutarde, M. Vanderhaeghen: Generalized Parton Distributions in the valence region from Deeply Virtual Compton Scattering, arxiv.org:1303.6600

The first 3D pictures of the proton indicate that when the longitudinal momentum x of the quark decreases, the radius of the proton increases.



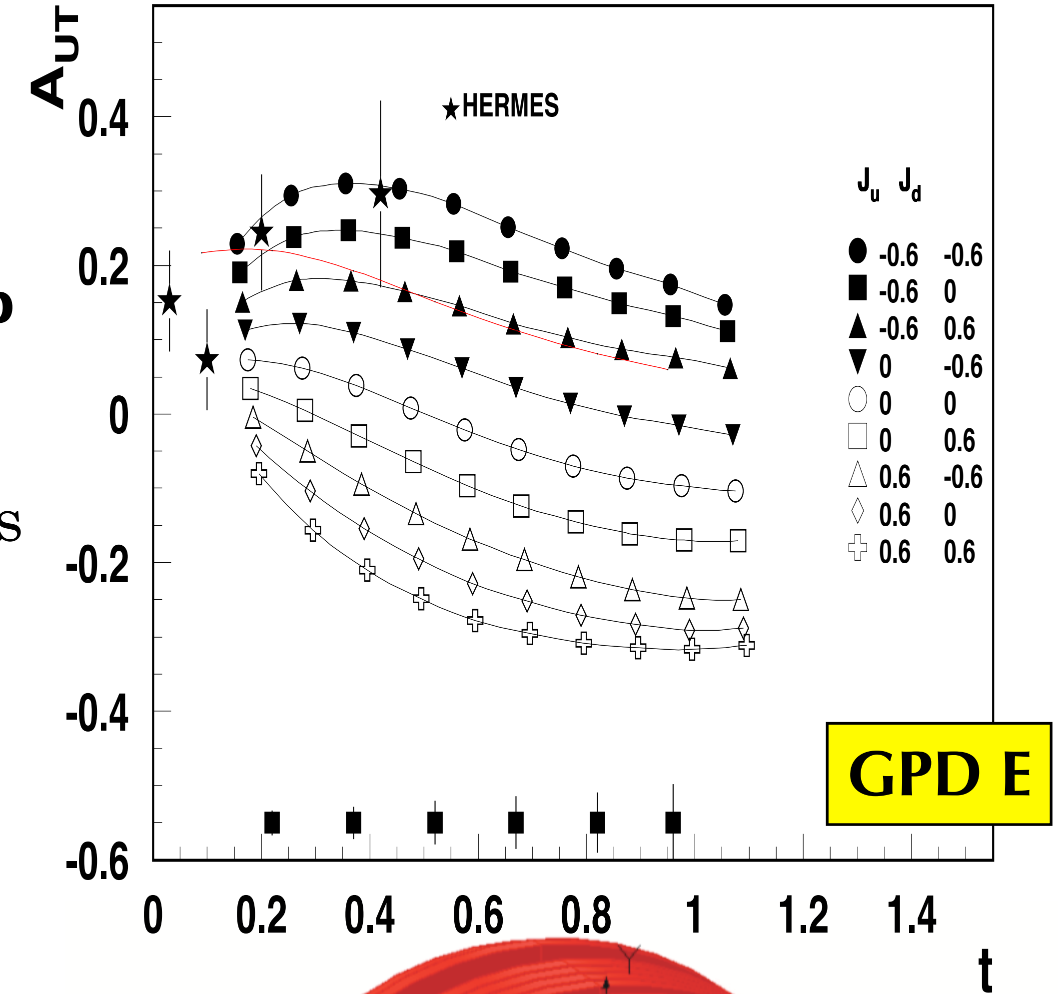


DVCS evolution over the years



JLab-12: DVCS

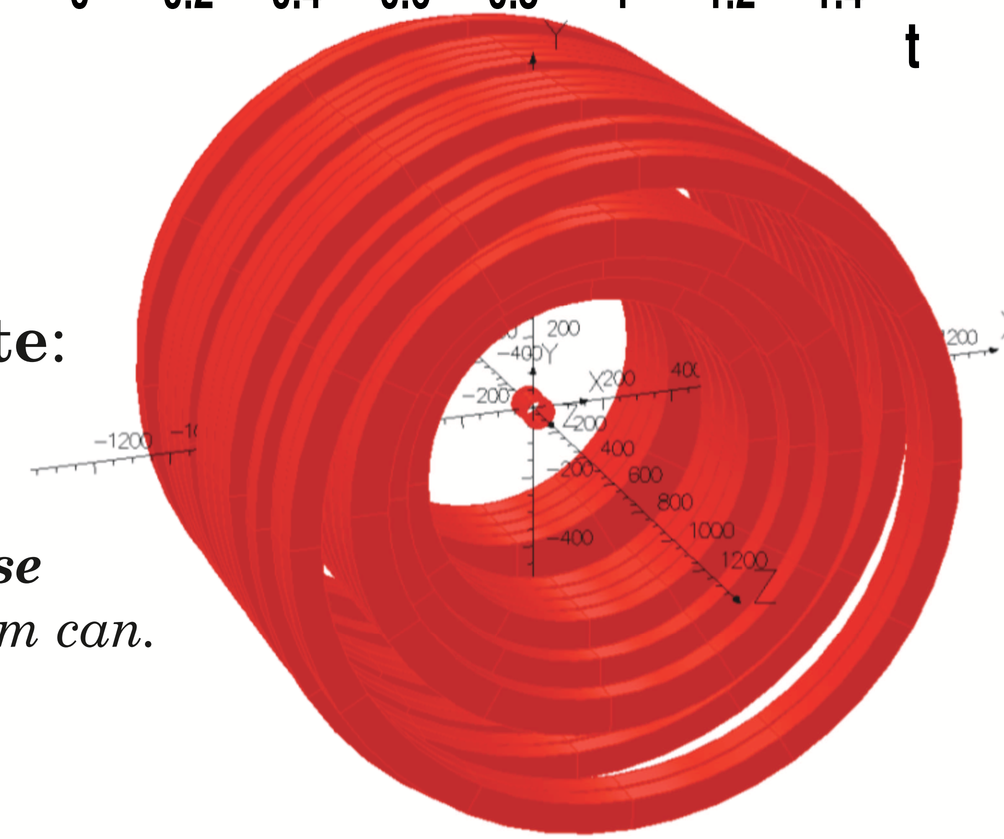
- **High luminosities BUT no kinematic overlap with COMPASS**
- Target- and beam asymmetries, and cross sections
- **Hall A**: precision measurements & focus on specific kinematics.
  Hall B (CLAS 12): wide phase space



E12-12-010: CLAS-12 A_{UT} & A_{LT} from HD ice target (Lumi $5.10^{33}cm^{-2}s^{-1}$, target polarization 60%, 100 days of running)

- **Transversely polarized target in frozen-spin state**: small polarization dilution & low radiation length.

- *Generation of **longitudinal field compensation** and **transverse field** by superconducting coils internal to the HD-Ice liquid helium can.*
- *Almost no impact on the CLAS12 detector configuration.*
- *Allows **detection of recoil protons**.*
- ***Limited resolution** due to additional material budget*



HD-Ice superconducting magnetic system surrounding the target at the center of the CLAS12 recoil detector solenoid

RHIC-spin 2017-2023

The RHIC cold QCD plan for 2017 to 2023: A portal to the EIC. arXiv:1602.03922

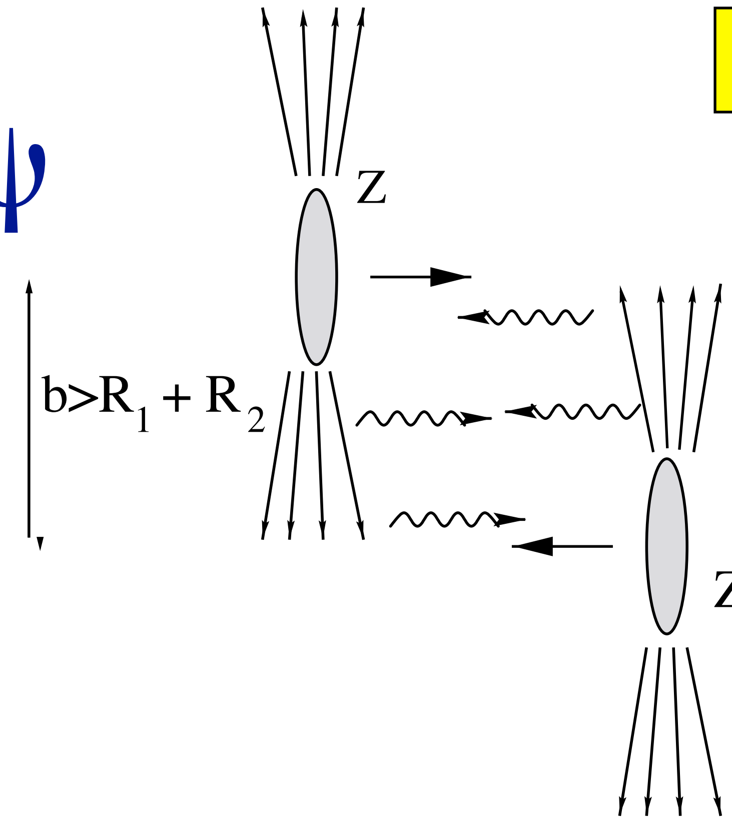
1. **2017:** 12 weeks transversely polarized p+p at $\sqrt{s}$ = 510 GeV
   It is noted that the 2017 data-taking period will be STAR only, due to the transition from PHENIX to sPHENIX
2. **2023:** 8 weeks transversely polarized p+p at $\sqrt{s}$ = 200 GeV
3. **2023:** 8 weeks each of transversely polarized p+Au and p+Al at $\sqrt{s}$ = 200 GeV

Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable
2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3 First look at GPD *Eg*	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/Ψ in UPC

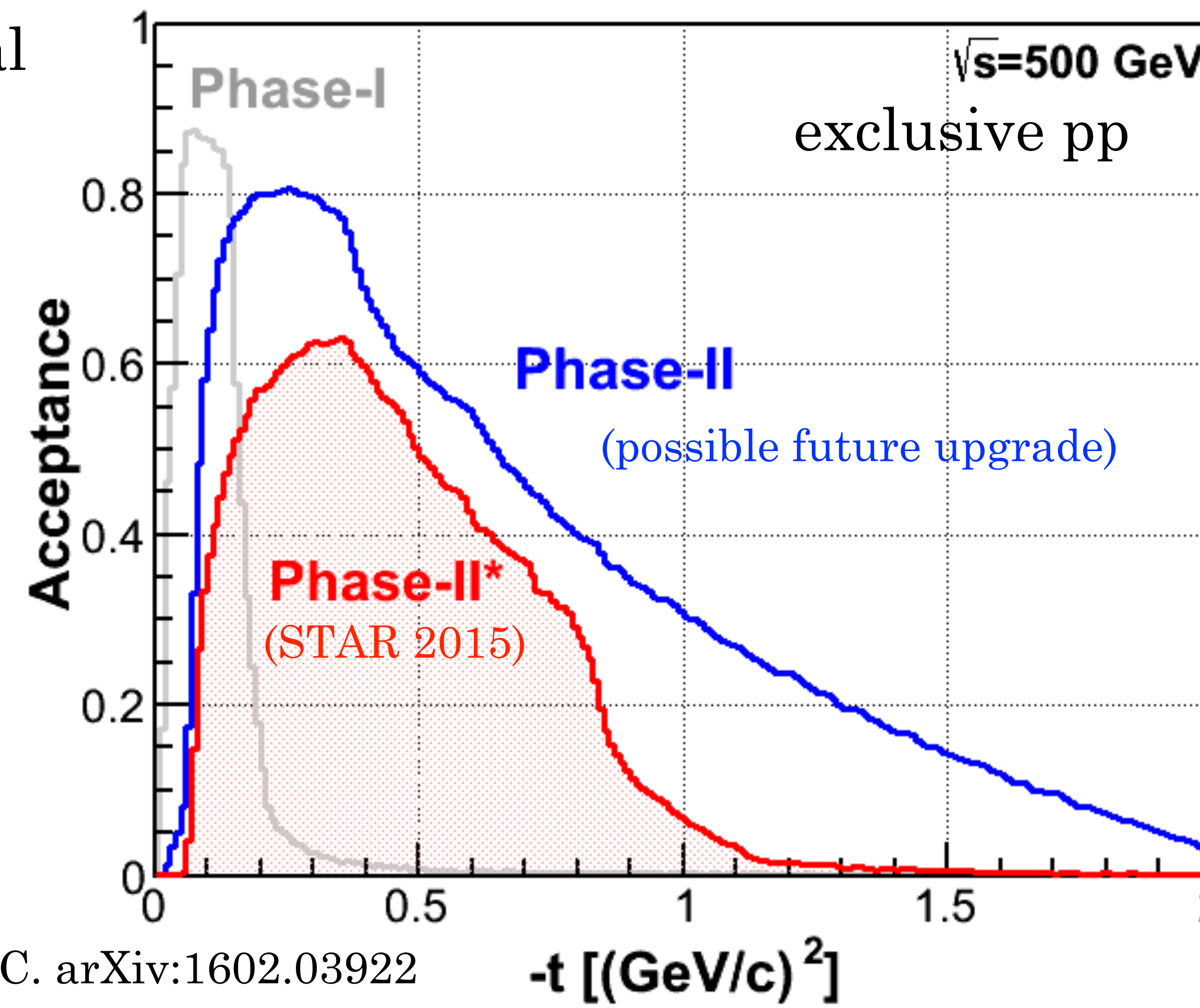
First look at GPD *Eg*

GPD E_g

RHIC 2017: exclusive J/ψ



- A_N of **exclusive J/ψ in ultra-peripheral collisions of protons ($p^{\uparrow}p$)**
- @ fixed $Q^2 = 9 GeV^2$ and $10^{-4} < x < 10^{-1}$
- Non-zero A_N would be first experimental access to **gluon GPD *E***
- Total expected number of *J/ψ's* (400 pb^{-1}) in 2017: ~11k
- Statistical precision can be improved with 2023 data.



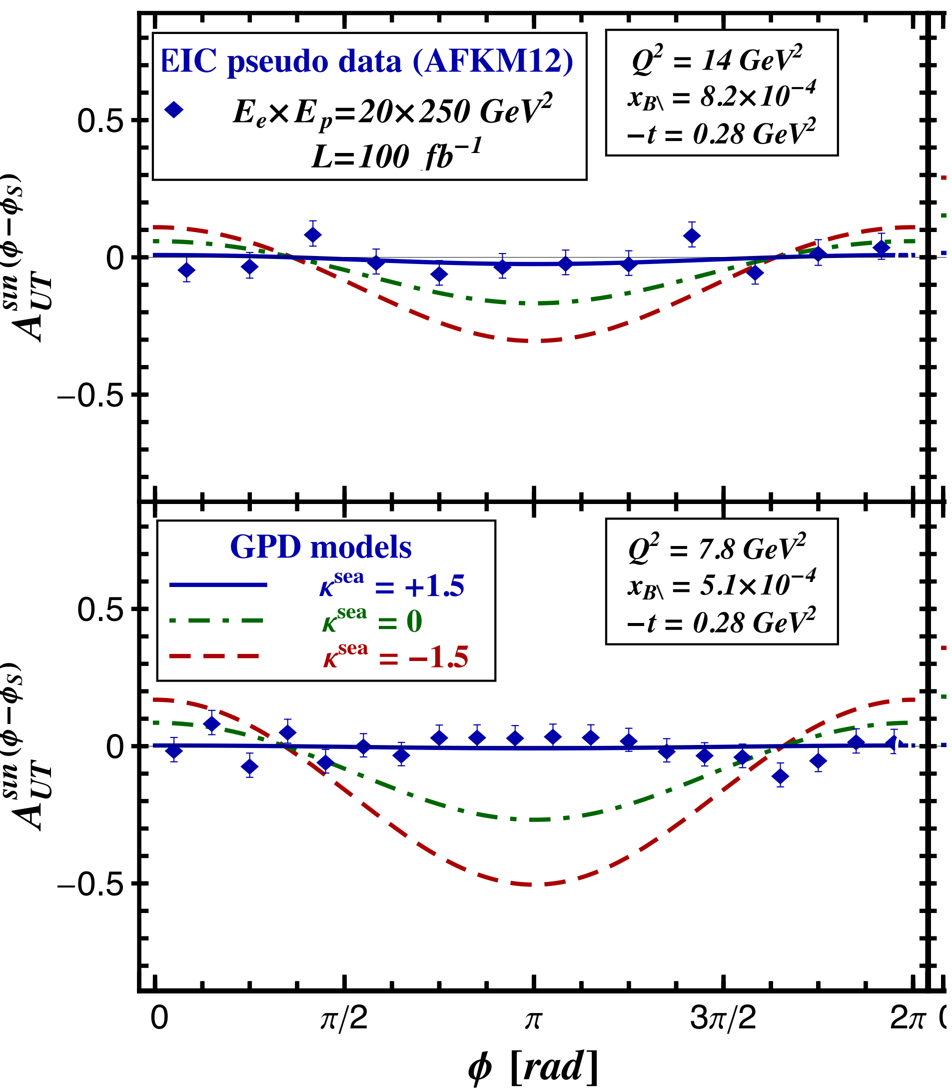
The RHIC cold QCD plan for 2017 to 2023: A portal to the EIC. arXiv:1602.03922

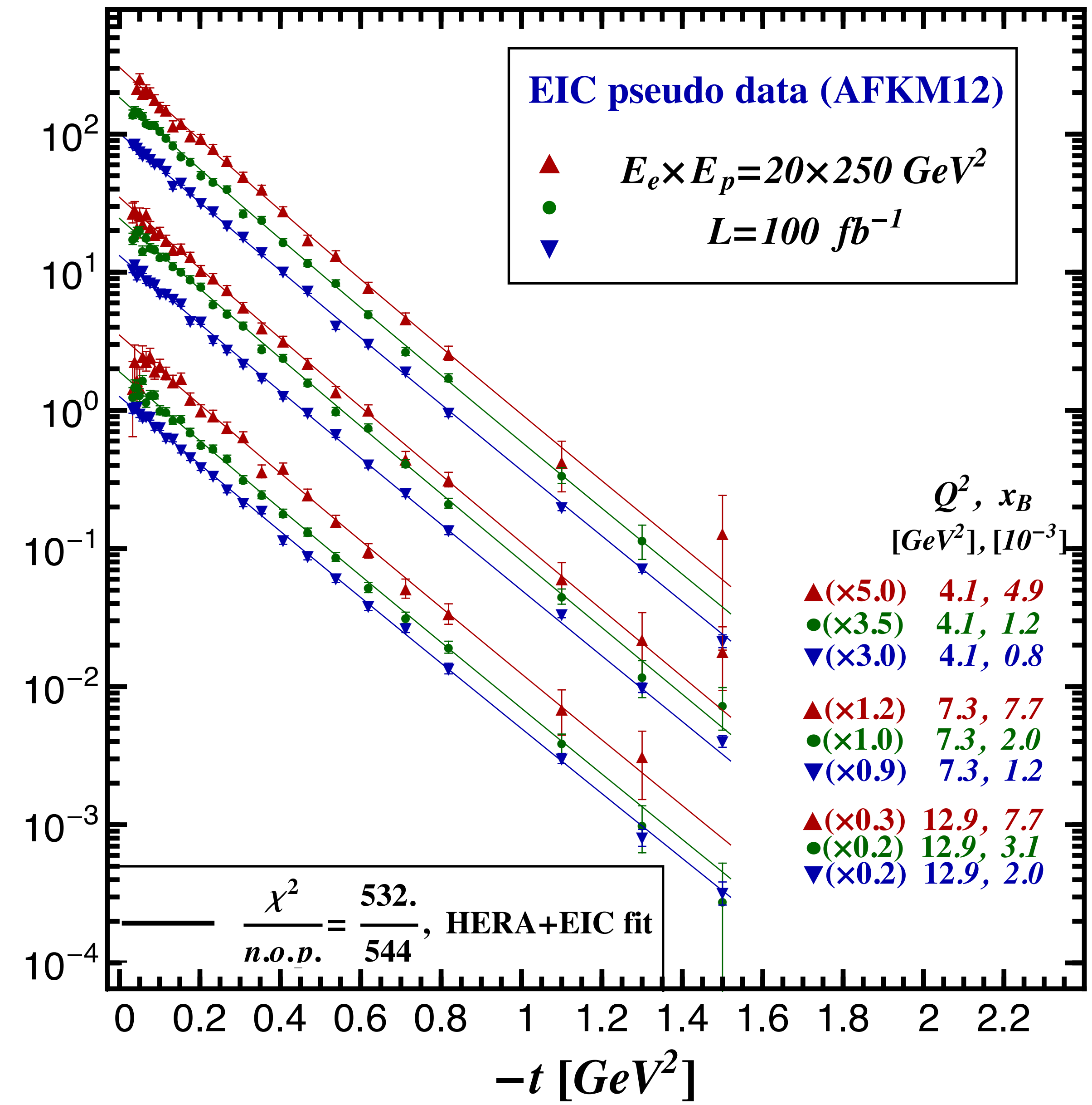
Electron-Ion Collider EIC

GPDs E & H (very) small x_B

Main requirements:
- **Highly polarized** (> 70%) **electron and proton/** light ion beams
- **Ion beams** from deuteron to heaviest nuclei
- Variable center of mass energy (**20 GeV to 150 GeV**)
- **High luminosity** ~ 10^{33-34} $cm^{-2}s^{-1}$.

- Unprecedented opportunity for discovery and precision measurements
- Study of momentum and space-time distribution of gluons and sea quarks in nucleons and nuclei.





E.-C. Aschenauer, S. Fazio, K. Kumericki and D. Müller: Deeply Virtual Compton Scattering at a Proposed High-Luminosity Electron-Ion Collider, arXiv:1304.0077 and JHEP **1309** 093 (2013).

COMPASS-III >2020: "standard ideas"

GPD E
(quark & gluon)

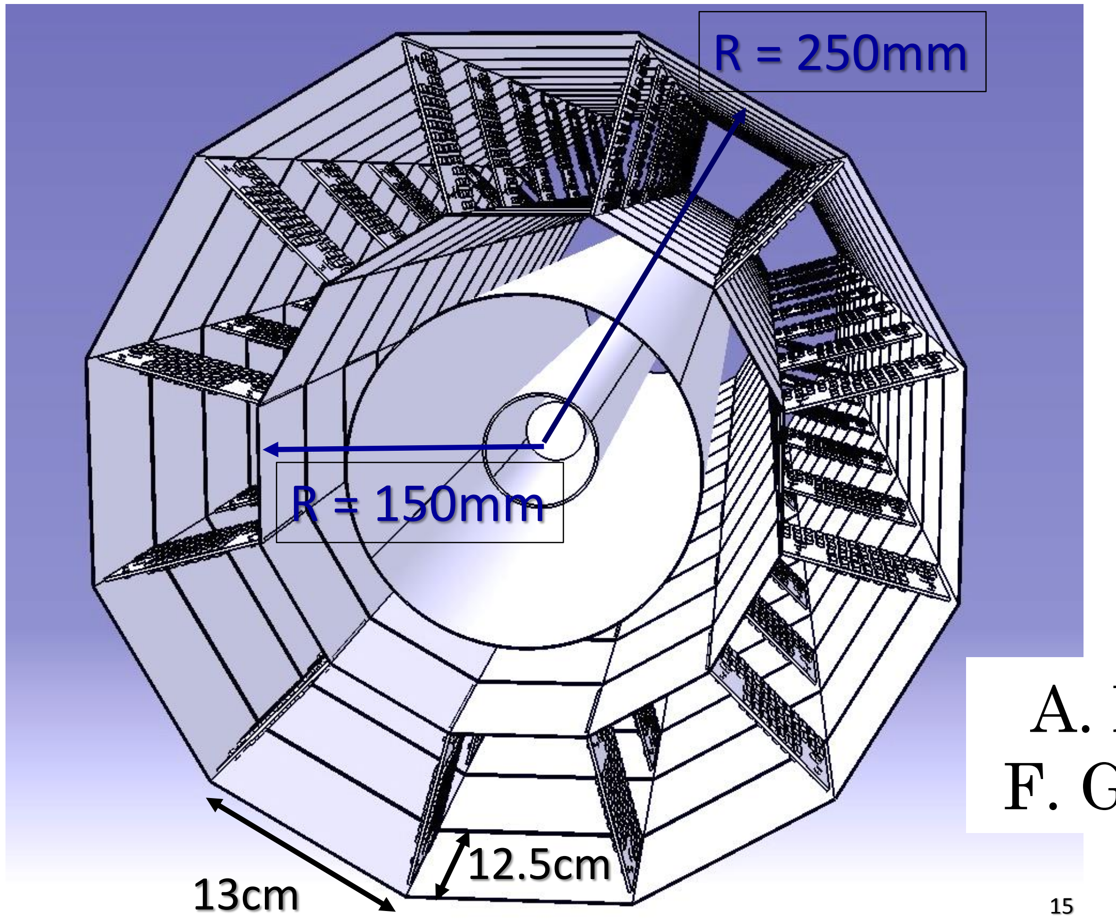
- GPD E from DVCS
- GPD E and **chiral-odd** GPDs from DVMP
  - vector mesons $\boldsymbol{\rho^0}$, $\boldsymbol{\omega}$, $\boldsymbol{\phi}$ (ρ^+ would require neutron recoil detector)
  - pseudoscalar mesons $\boldsymbol{\pi^0}$
- **p↑ target + recoil detector**

Major R&D project: configurations for 2016/17 run are not compatible with a transversely polarized target.

A preliminary sketch of the 2-layers Si station to be inserted in the vacuum space of the COMPASS PT.

Note that full available space for this detector is 100mm(*) < R < 310mm

(*) Radius of present μwave cavity reduced by a factor of 2



A. Magnon, F. Gautheron

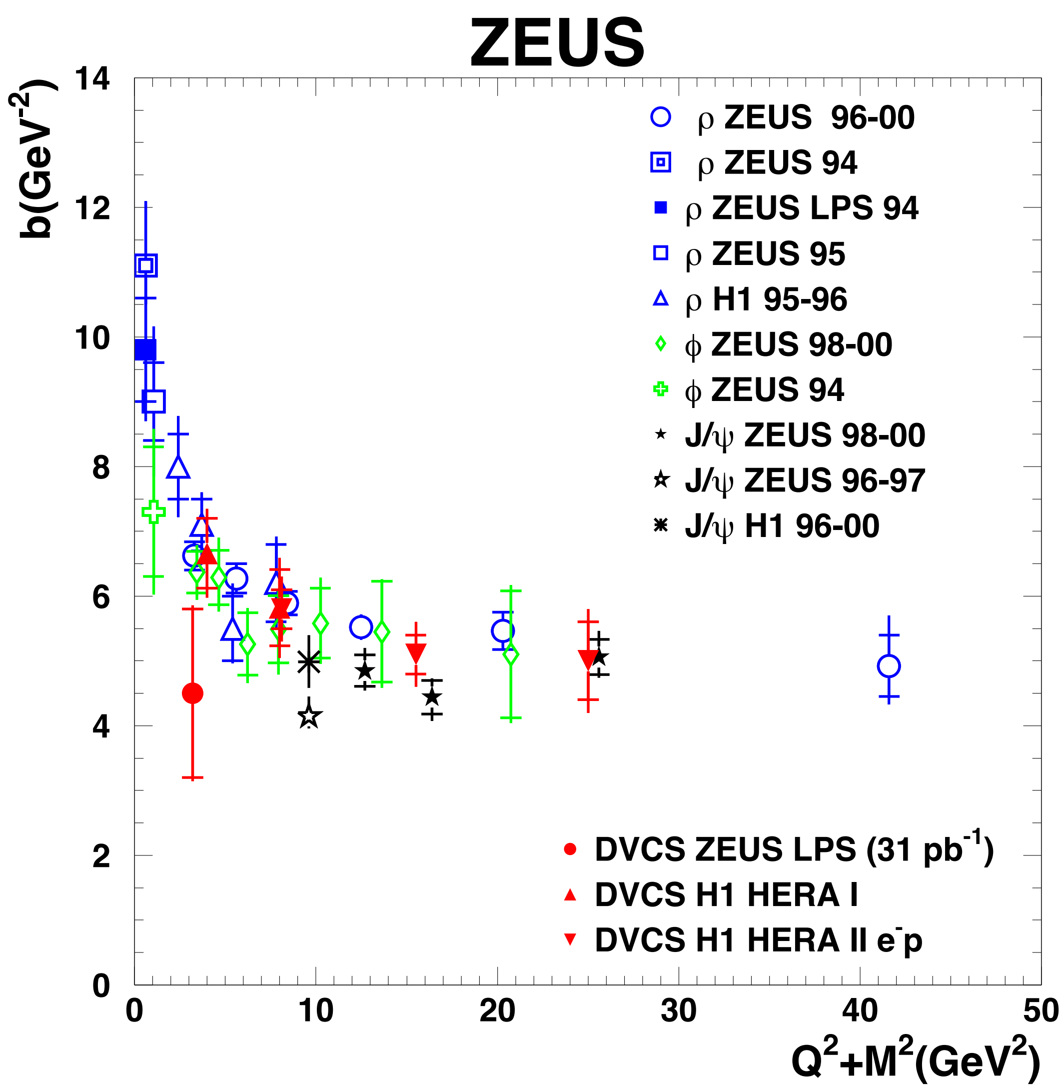
Alternatives to access GPDs at COMPASS in >2020

muon beam

- DVMP with heavier mesons: $\mu p \rightarrow \mu p(V) \rightarrow \mu p(\ell^+ \ell^-)$
  $J/\psi \rightarrow \mu^+\mu^-$ or e^+e^-
  $\phi \rightarrow K^+K^-$ or $\mu^+\mu^-$ (small rate)
- DDVCS: $p\mu \rightarrow p\mu(\gamma^*) \rightarrow p\mu(e^+e^-)$
- Backward meson production
- (DVCS on nuclear targets?)

hadron beam

- GPD E from beam-spin asymmetry on unpolarized deuteron target?
- Exclusive Drell-Yan production
- (PANDA-at-FAIR-like processes?)

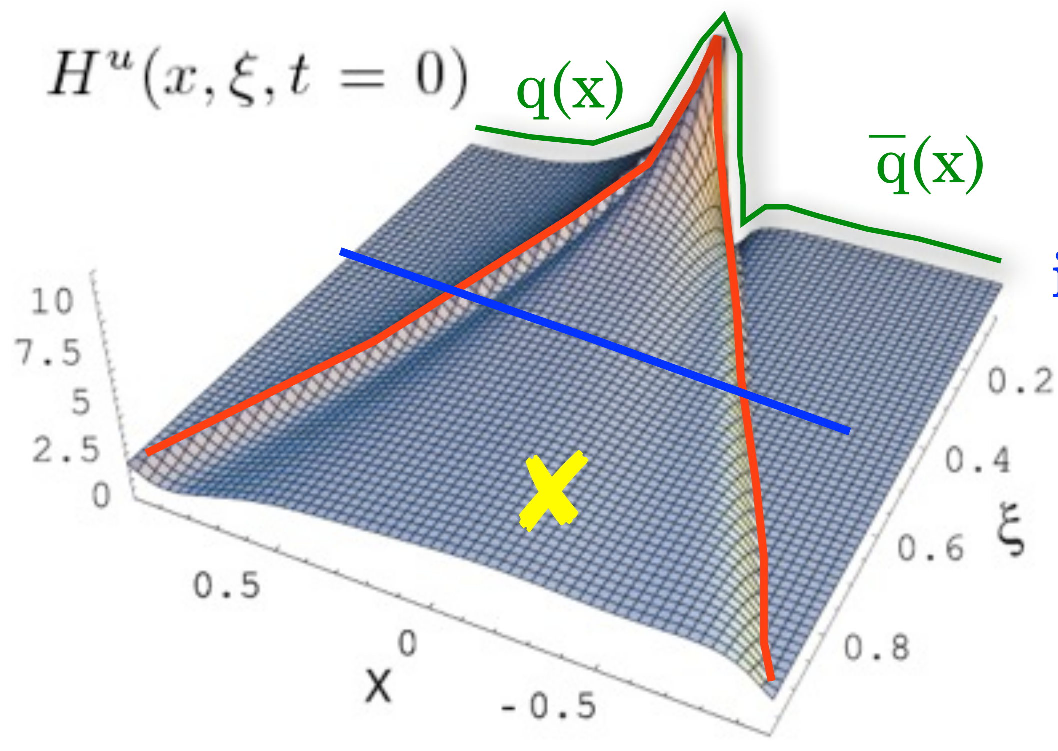


ZEUS arXiv:0812.2517

Detection of di-lepton final state at COMPASS: can gain from **experience of the Drell-Yan group**

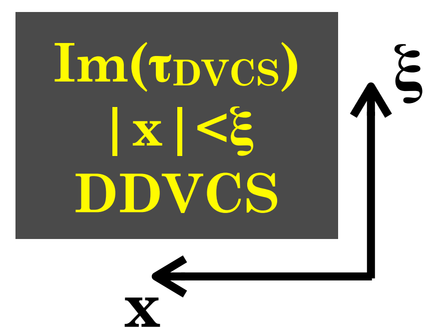
Double DVCS: $p\mu \rightarrow p\mu(\gamma^*) \rightarrow p\mu(e^+e^-)$

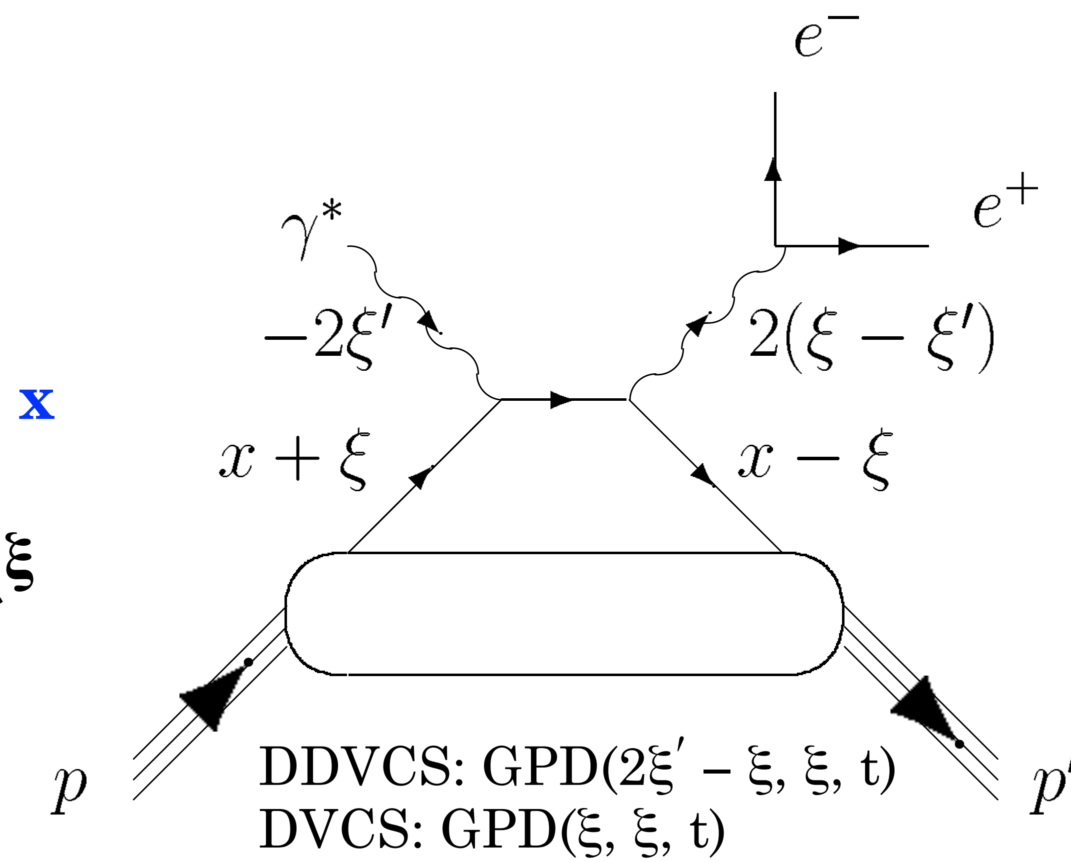
(time-like)



Re(τ_{DVCS})
x=ξ

Im(τ_{DVCS})
integral over x





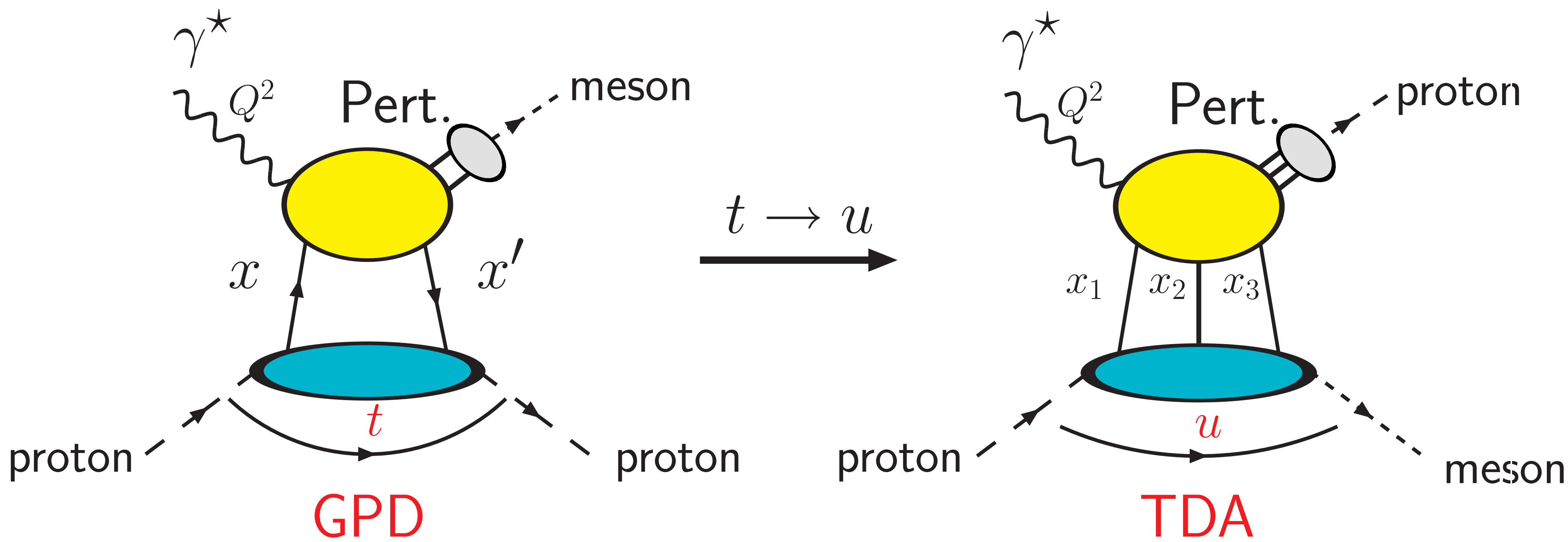
"x is unmuted"

M. Guidal, M. Vanderhaeghen: Double deeply virtual Compton scattering off the nucleon (hep-ph/0208275)

- DDVCS allows for **mapping of GPDs in (x,ξ) space** - *the virtuality of the final photon yields additional lever arm, which allows to vary x and ξ independently*
- Experimentally challenging: needs **high luminosity** & **excellent acceptance**.
- Suppressed wrt DVCS by factor α_{em}; contaminated by resonance background
- Will be hard to measure at COMPASS - but should **in principle be possible**

Backward meson electro-production

(space-like)



TDA = (nucleon-to-meson) **Transition Distribution Amplitude**

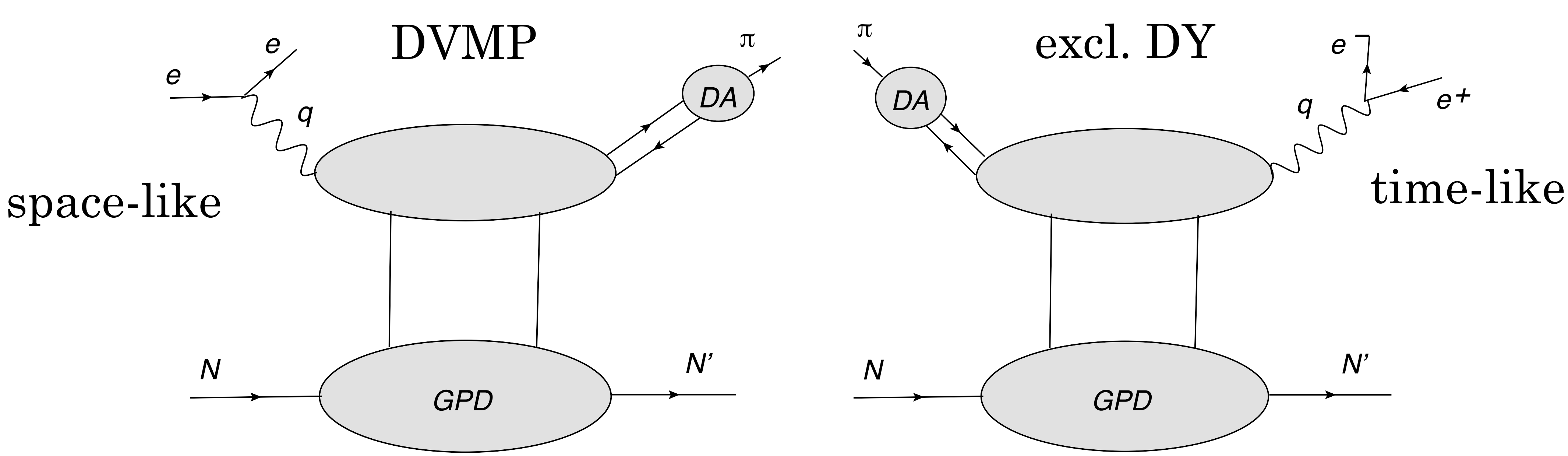
"Building blocks of **collinear factorization** for certain hard exclusive reactions."
"Tool for **spatial imaging of the pion cloud** inside the nucleon."
"Probability of finding a meson in the proton."

- Meson in the recoil detector - target proton in the forward spectrometer
- Described in the literature: **proton-pion TDAs.** $p \to \pi^0 p'$, $p \to \pi^+ \triangle^0$, $p \to \triangle^+ \pi^0$, $p \to \triangle^{++} \pi$.

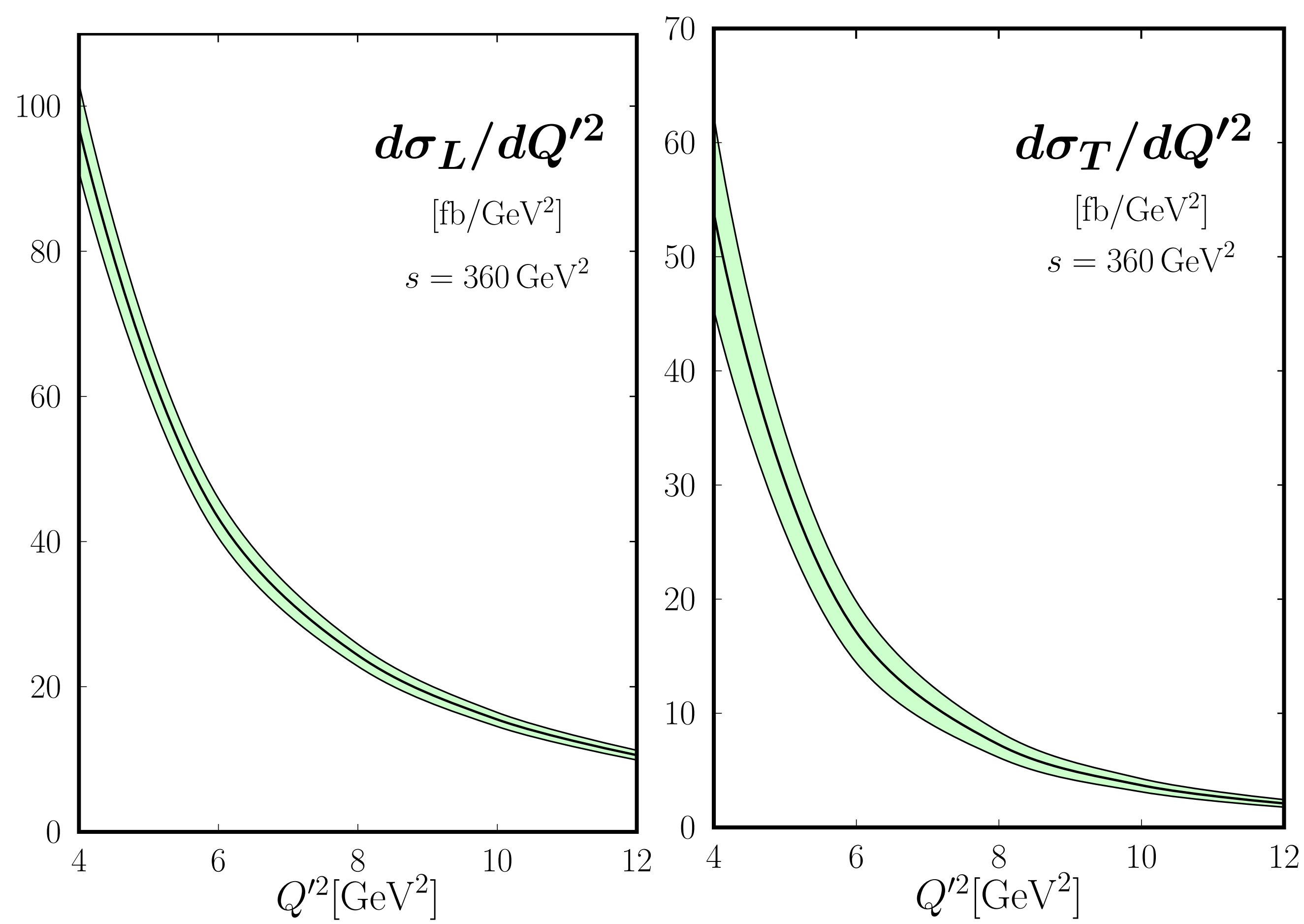
  - **COMPASS** would be able to also look at e.g. **p→J/ψ p TDAs.**
  - Strange cloud in the proton $\ell\, p \to \ell\, \Lambda^0 K^+$ ($\Lambda^0 \to p\pi^-$ in the forward, K slow in the recoil)

J. P. Lansberg, B. Pire, and L. Szymanowski: Hard exclusive electroproduction of a pion in the backward region, PRD 75, 074004 (2007) & priv. comm. with B. Pire 2010/2011 & J.P. Landsberg at ICHEP 2010 & B. Pire, K. Semenov-Tian-Shansky, and L. Szymanowski: Nucleon-to-Pion Transition Distribution Amplitudes, arXiv:1312.7120.

Exclusive Drell-Yan: $\pi^- p \to p \mu^- \mu^+$



Mueller, Pire, Szymanowski, Wagner: On timelike and spacelike hard exclusive reactions, arXiv:1203.4392



Exclusive DY cross section at COMPASS expected to be suppressed by a factor of 1000 compared to JParc.

P. Kroll, priv.comm. Dec. 2015, and S. V. Goloskokov and P. Kroll, PLB 748, 323 (2015), arXiv:1506.04619 [hep-ph]

COMPASS 2008 πp data: feasibility study by Alexey Guskov

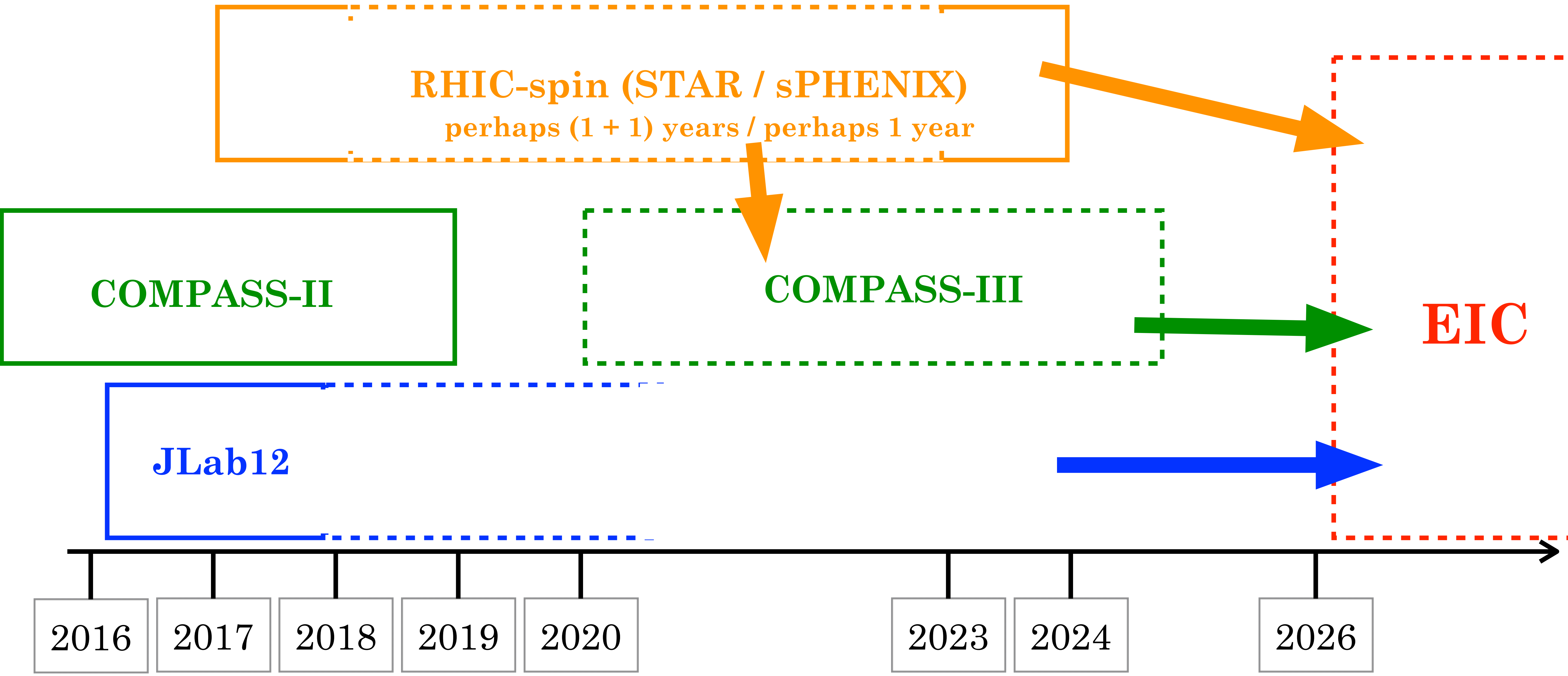
(internal COMPASS talk at AM June 2015)

“upper exclusive limit” for (rather small) data set

more about exclusive DY: see W.-C. Chang’s talk on JParc

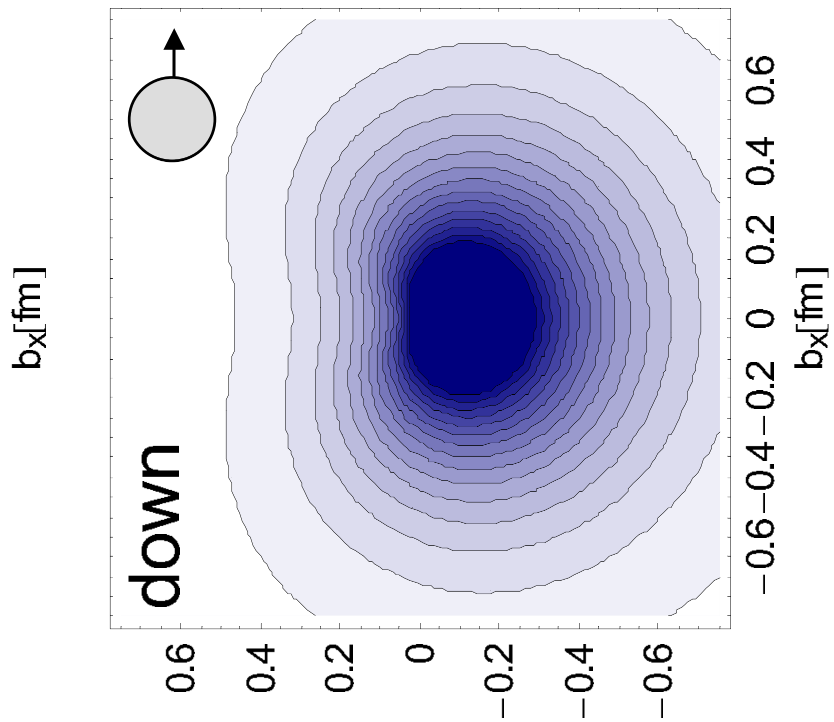
COMPASS-III as physics opportunity for RHIC-spin groups prior to the EIC

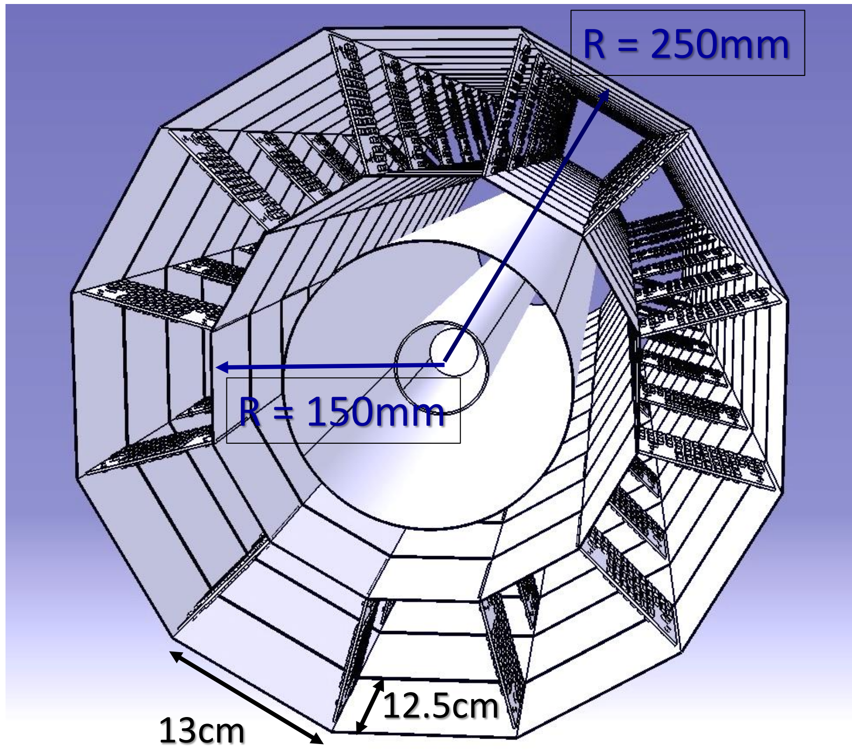
- Preserve knowledge on state-of-the-art techniques
- Prepare next generation of leading physicists to play important roles at the EIC



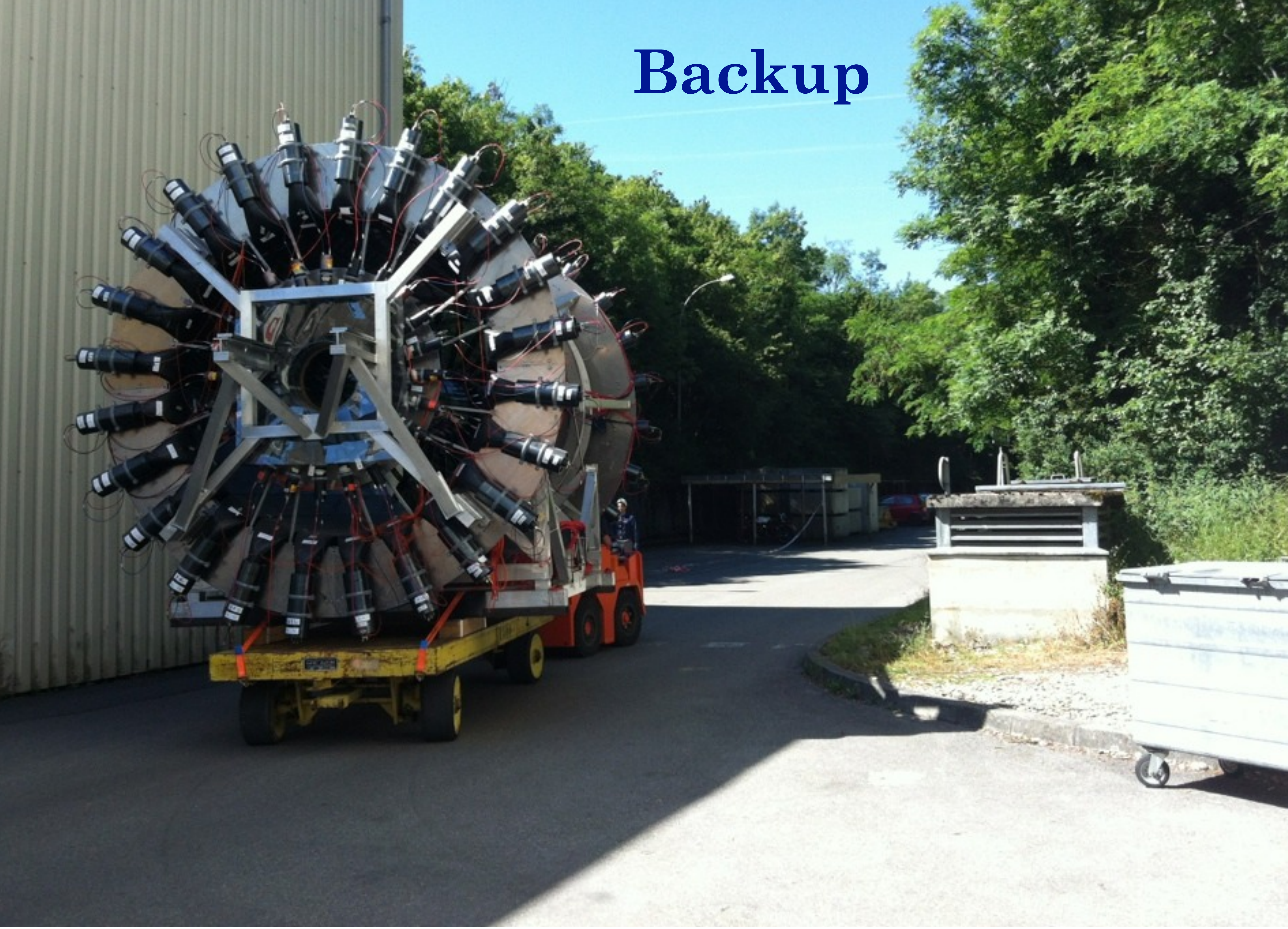
Summary: GPDs@COMPASS >2020

- The strength of COMPASS is the **unique kinematic domain** - but also the availability of **meson beams**!
- **GPD *E*** could be constrained in COMPASS-III, albeit after a major hardware upgrade - the addition of a **recoil detector** to the COMPASS **polarized target**.
- GPD ***H*** is fairly well known - GPD ***E*** not.
- Not necessarily only GDP ***E*** is interesting - there are **other interesting exclusive channels** such as exclusive heavy mesons, double DVCS, backward meson production, exclusive Drell Yan.
- **COMPASS-III could be an opportunity for other spin groups prior to the EIC**!
- … a recoil detector around the target could possibly also be used to measure **tagged structure functions.**





Backup



Transverse imaging of the nucleon

Impact-parameter representation: M. Burkardt, Int. J. Mod. Phys. A18 (2003) 173

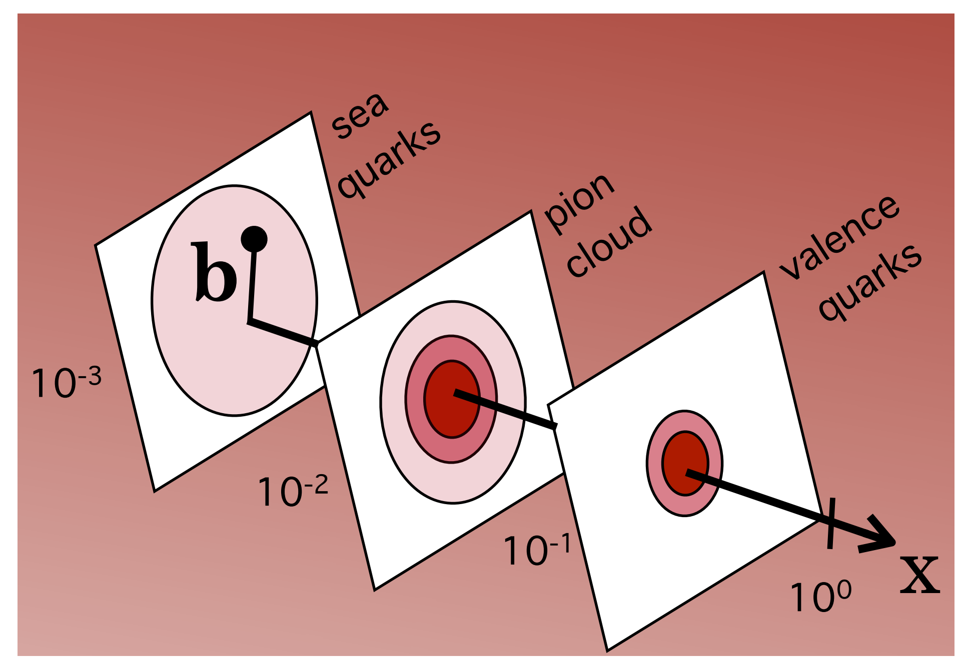
$$q^f(x, \boldsymbol{b}_\perp) = \int \frac{\mathrm{d}^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} \underline{H^f(x, 0, -\boldsymbol{\Delta}_\perp^2)}$$

← GPD(x,ξ=0,b)

Measure differential cross section:

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

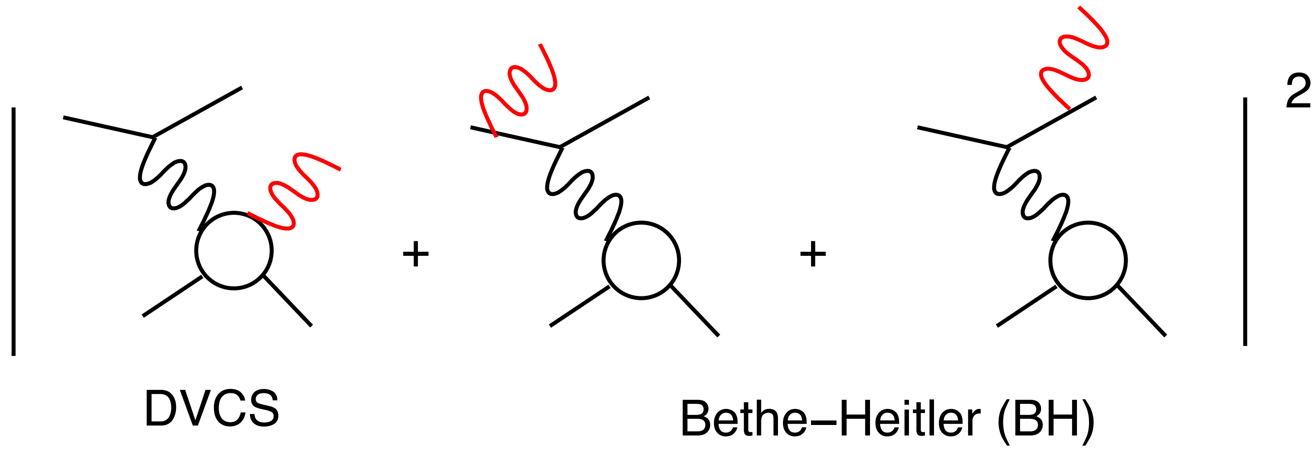
⇒ "Tomographic images" of the nucleon.



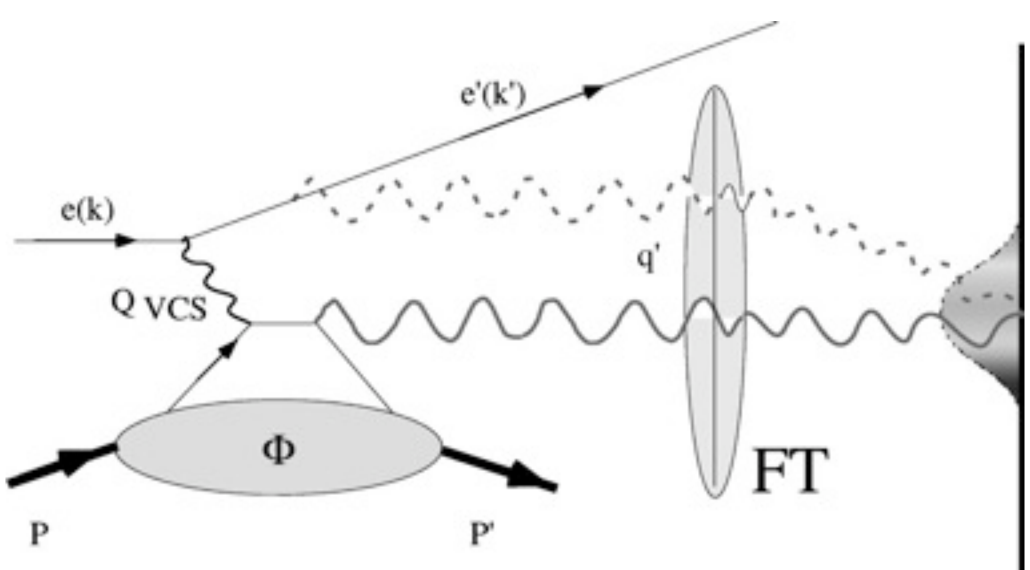
t-slope ***b*** :
Average impact parameter
"transverse size of nucleon"

The γ*N→γN cross section

$\sigma_{\gamma^* \gamma N} \sim$



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

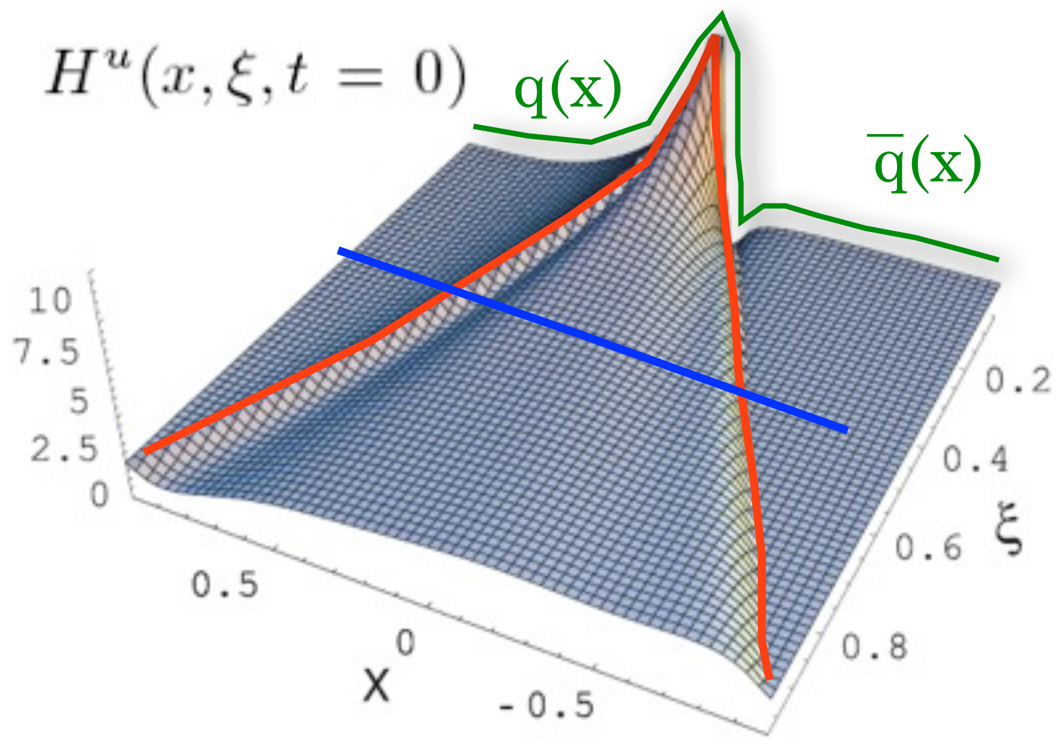


Holographic principle:
- BH reference amplitude magnifies DVCS
- Interference allows to measure magnitude

A **and** phase ϕ of DVCS amplitude $Ae^{i\phi}$
- No “phase problem” as in e.g. x-ray crystallography.

Belitsky, Mueller, hep-ph/0206306

Compton Form Factors



CFF	Re(τDVCS) integral over x	Im(τDVCS) x=ξ

$$\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{+1} \mathrm{d}x\, \frac{H(x,\xi,t)}{x-\xi} - i\pi H(\xi,\xi,t)$$

$$\mathcal{R}e\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{+1} \mathrm{d}x\, \frac{\mathcal{I}m\mathcal{H}(x,t)}{x-\xi} + D(t)$$

Dispersion relation with D-term:
- Shear forces and radial distribution of pressure inside the nucleon
- Description of confinement

M.V. Polyakov, Generalized parton distributions and strong forces inside nucleons and nuclei, arXiv:hep-ph/0210165

Azimuthal asymmetries and GPDs

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

☞ unpolarized target: **Best access**

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

$F_1\mathcal{H}$: dominant for the proton

$F_2\mathcal{E}$: 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**

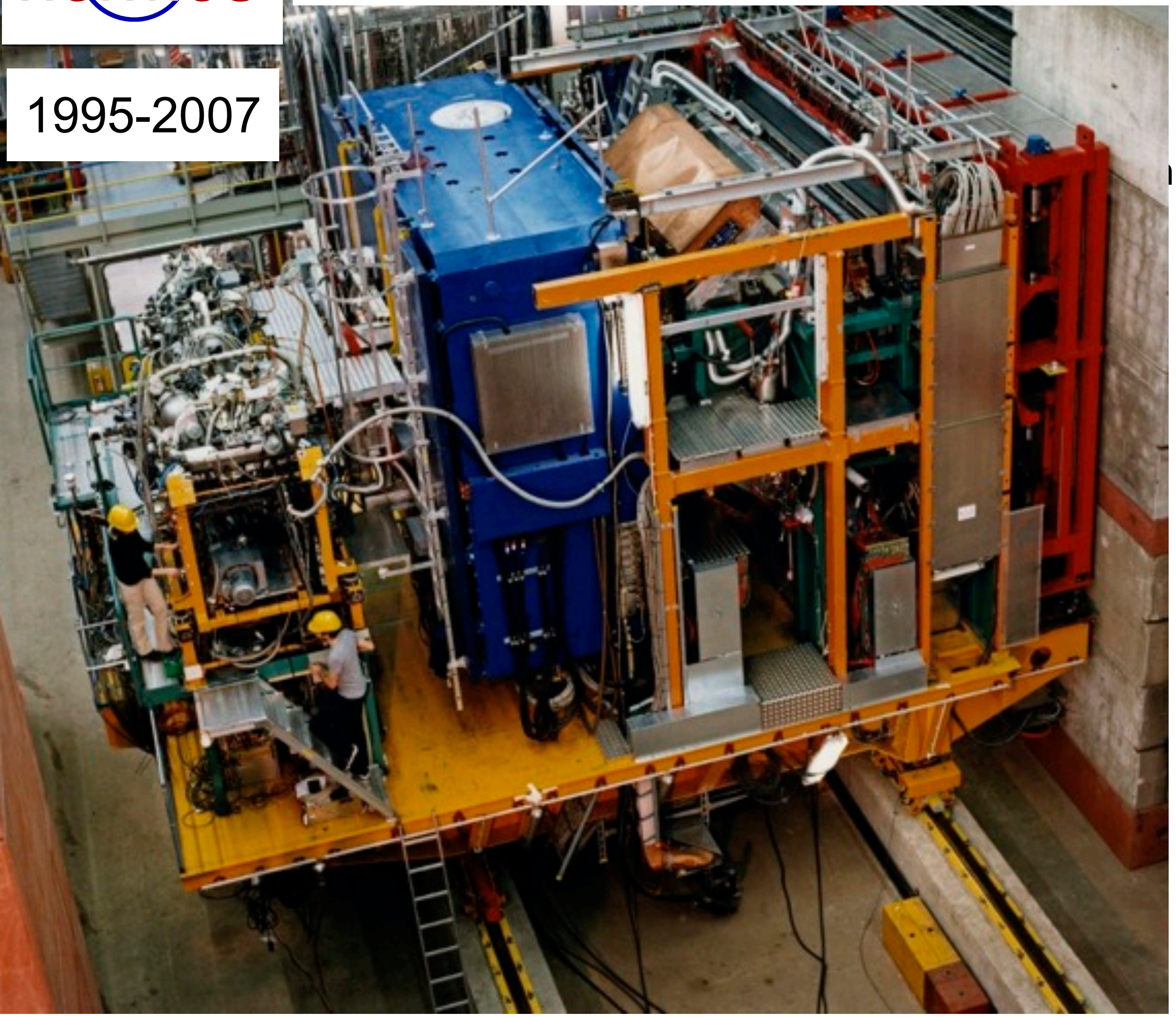
Facilities with results available

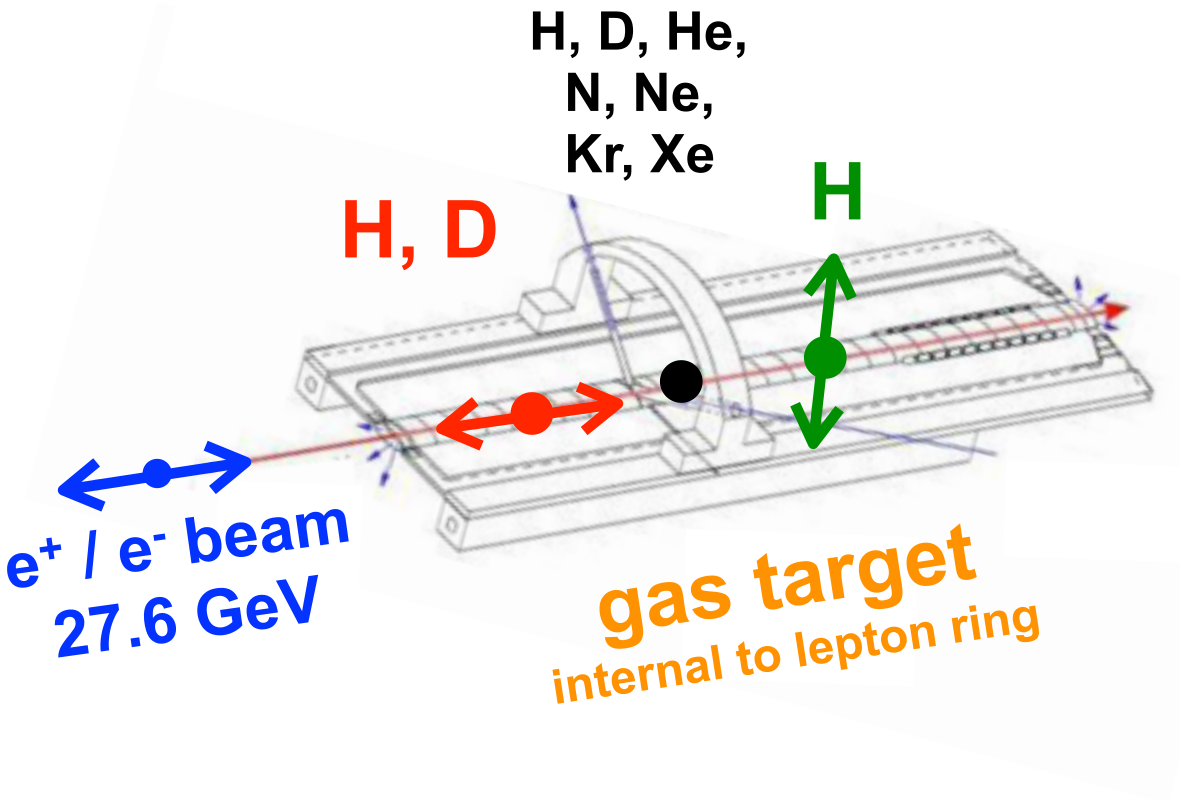
Lab	Beam	Facility	Targets	Detected particles
Jefferson Laboratory	polarized e⁻ beam; electrons: 6 GeV; e-beam on fixed target	Hall A JLab	Targets: • unpolarized p [E00-110] • unpolarized d (→ n) [E03-106]	<u>detected particles:</u> eγ
		clas	Targets: • unpolarized p • longitudinally polarized p • ^{4}He	<u>detected particles:</u> no Inner Calo: ep or epγ with Inner Calo: epγ
HERA	self-polarized electron beam; 2 lepton beam charges: electrons and positrons; electrons: 30 GeV, protons: 920 GeV	hermes	e-beam on fixed pure gas target • unpolarized p, d; He, N, Ne, Kr, Xe • longitudinally polarized p, d • transversely polarized p	<u>detected particles:</u> no Recoil: eγ with Recoil: epγ
		H1, ZEUS	ep-collider (unpolarized protons)	<u>detected particles:</u> eγ + forward veto ZEUS subsamle: epγ

↓ energy

at DESY: exclusive measurements

1995-2007

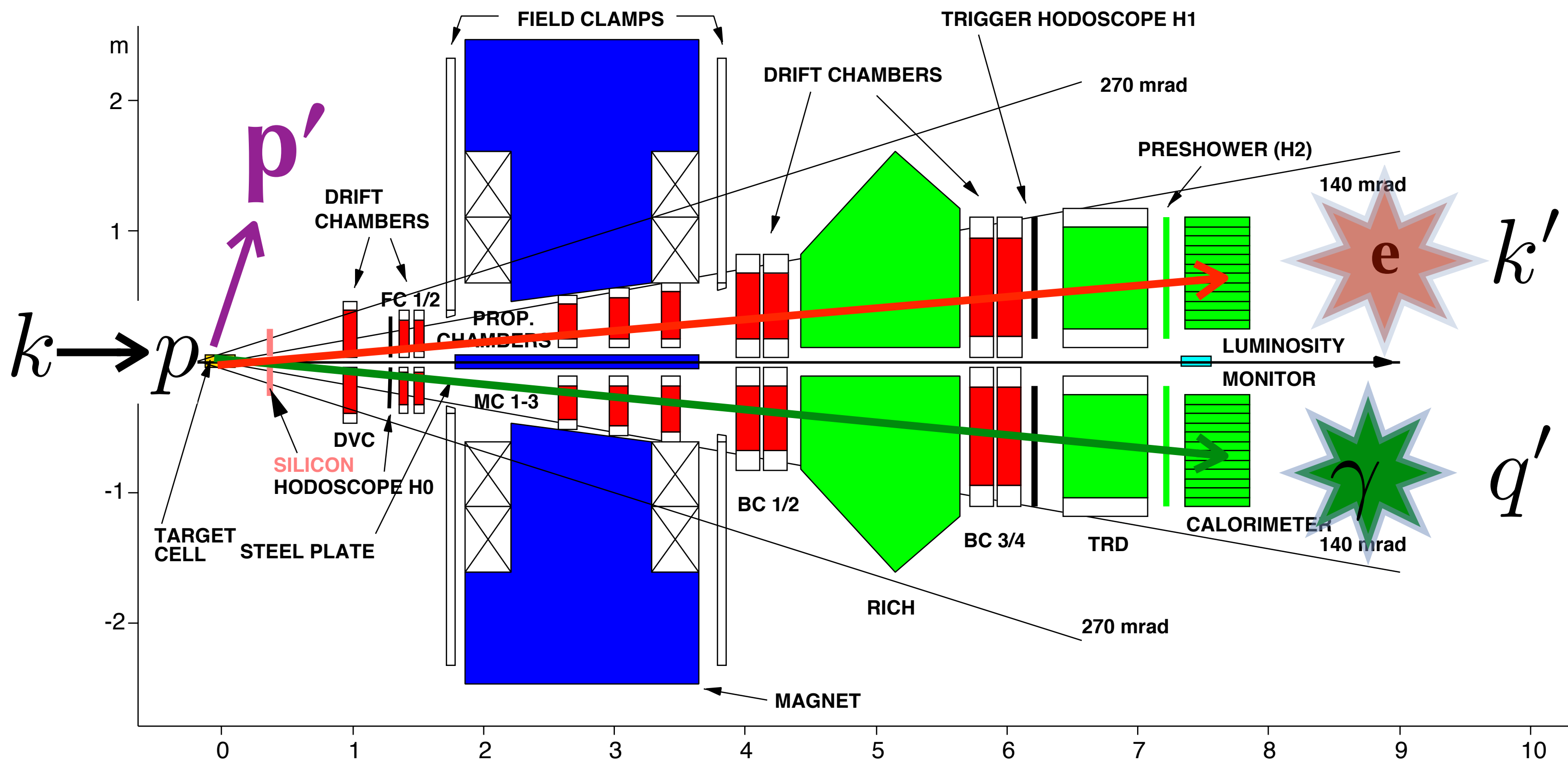


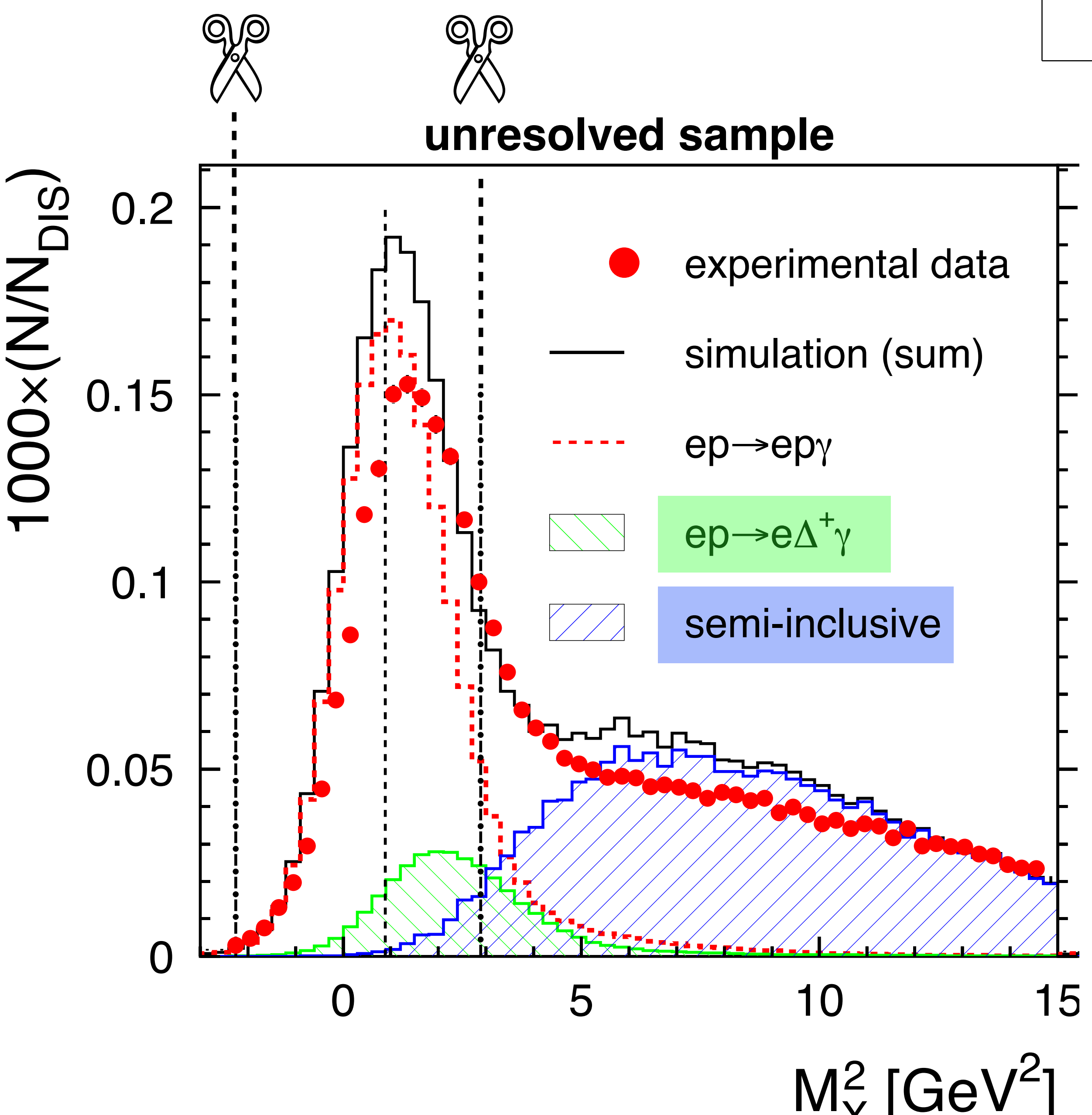


- 1996-2007: **H, D, *He, N, Ne, Kr, Xe***
- 2006/2007: **H, D** with recoil
- 1996/97: **H➔**
- 1999/2000: **D➔**
- 2002-2005: **H⬆**

"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%)

COMPASS

at CERN

since 2002

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

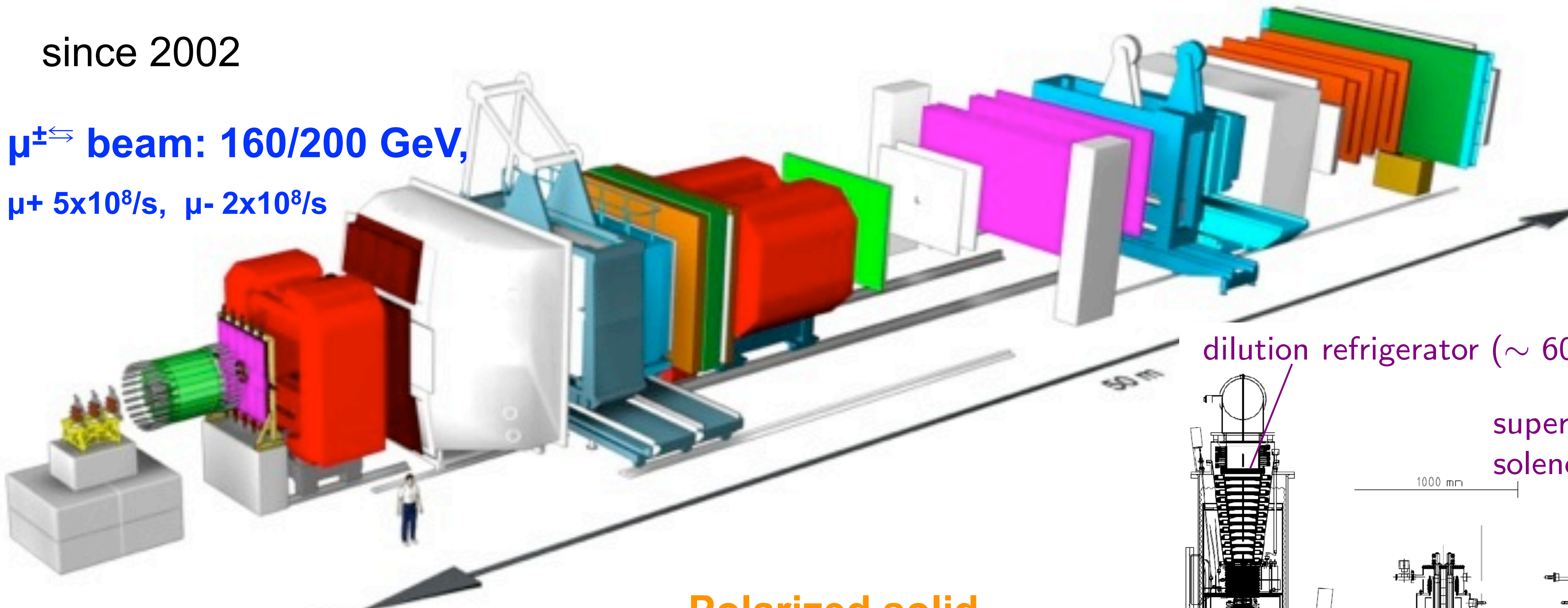
μ+ 5x10^8/s, μ- 2x10^8/s

DVMP:

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

DVCS:

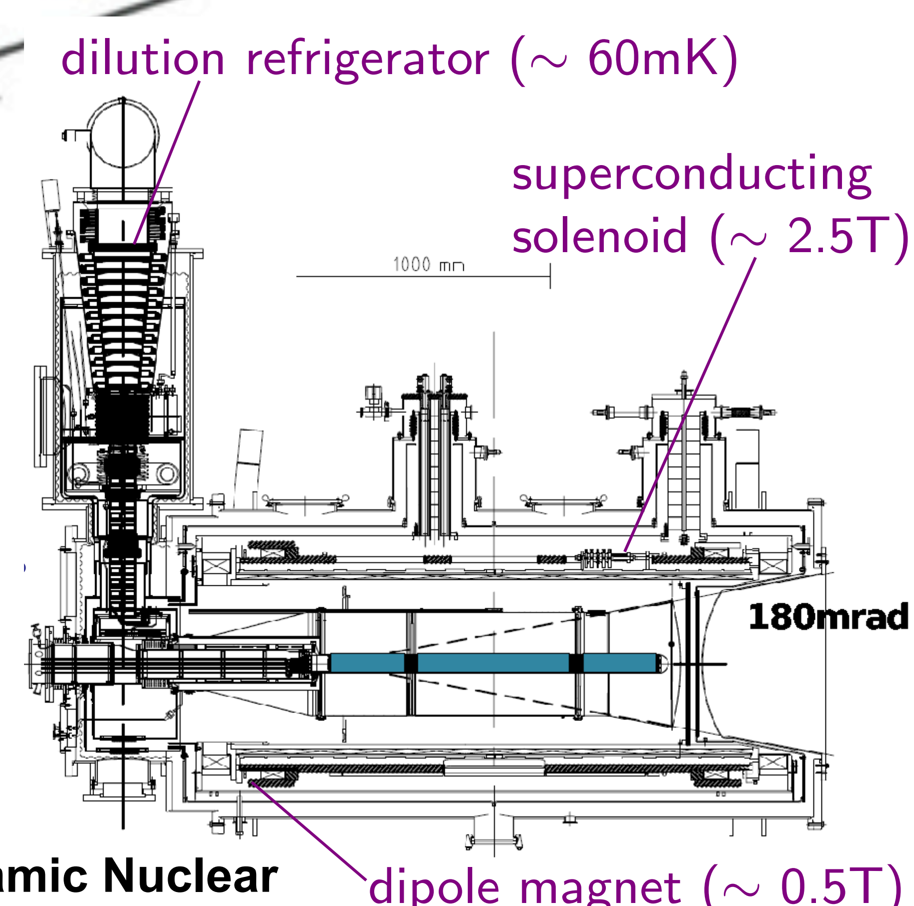
- 2008/09: H with short recoil (test run)
- 2012: H with long recoil (pilot run)
- **2016/17:** H with long recoil



More than 300 tracking planes

18 mrad < θ_μ < 180 mrad

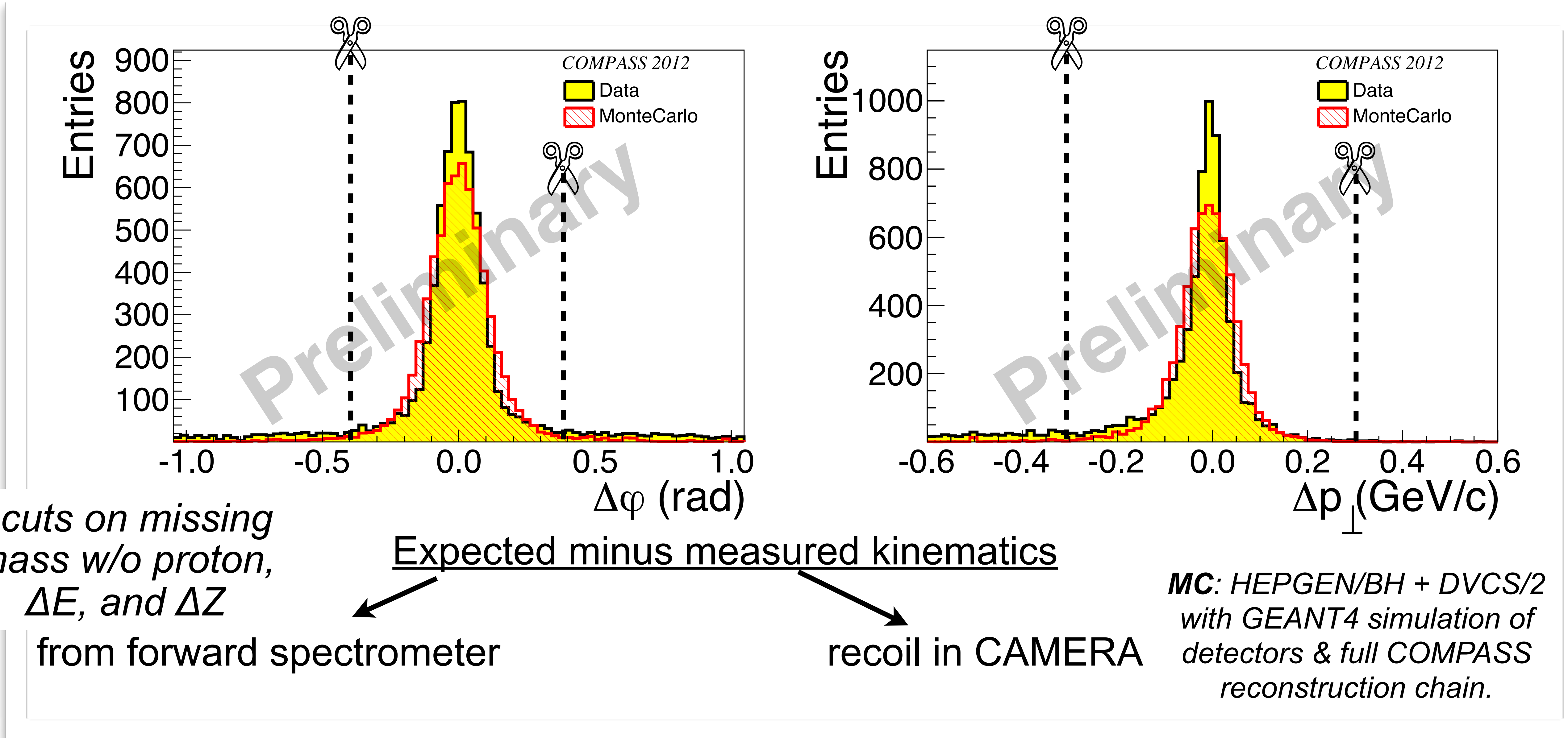
Polarized solid NH_3 & ^6LiD *or* unpolarized liquid NH_2



Dynamic Nuclear Polarization

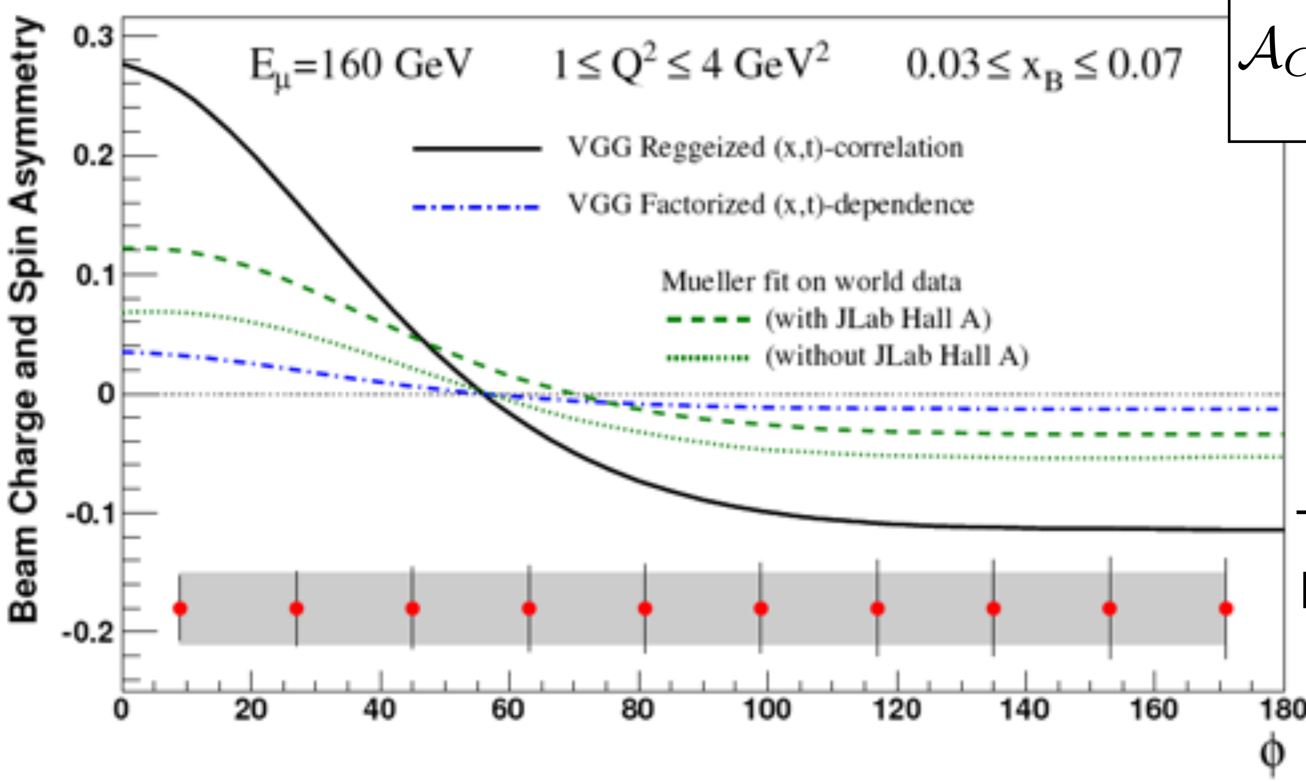
COMPASS DVCS pilot run 2012

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



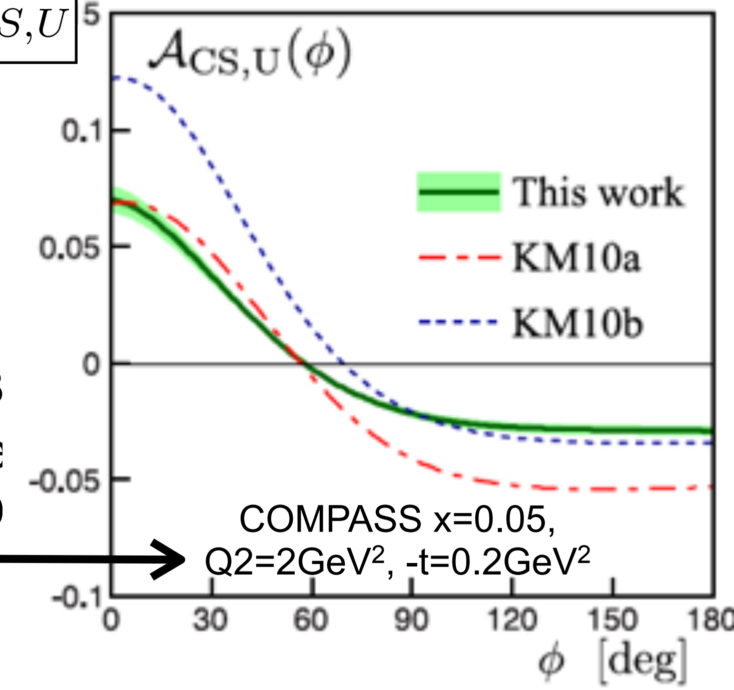
- Visible π^0 background (2 photons reconstructed): measured and corrected for
- Invisible π^0 background (1 photon escapes): estimated by MC. SIDIS: LEPTO; exclusive: HEPGEN/π^0

COMPASS-II proj.: spin & charge asym.



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

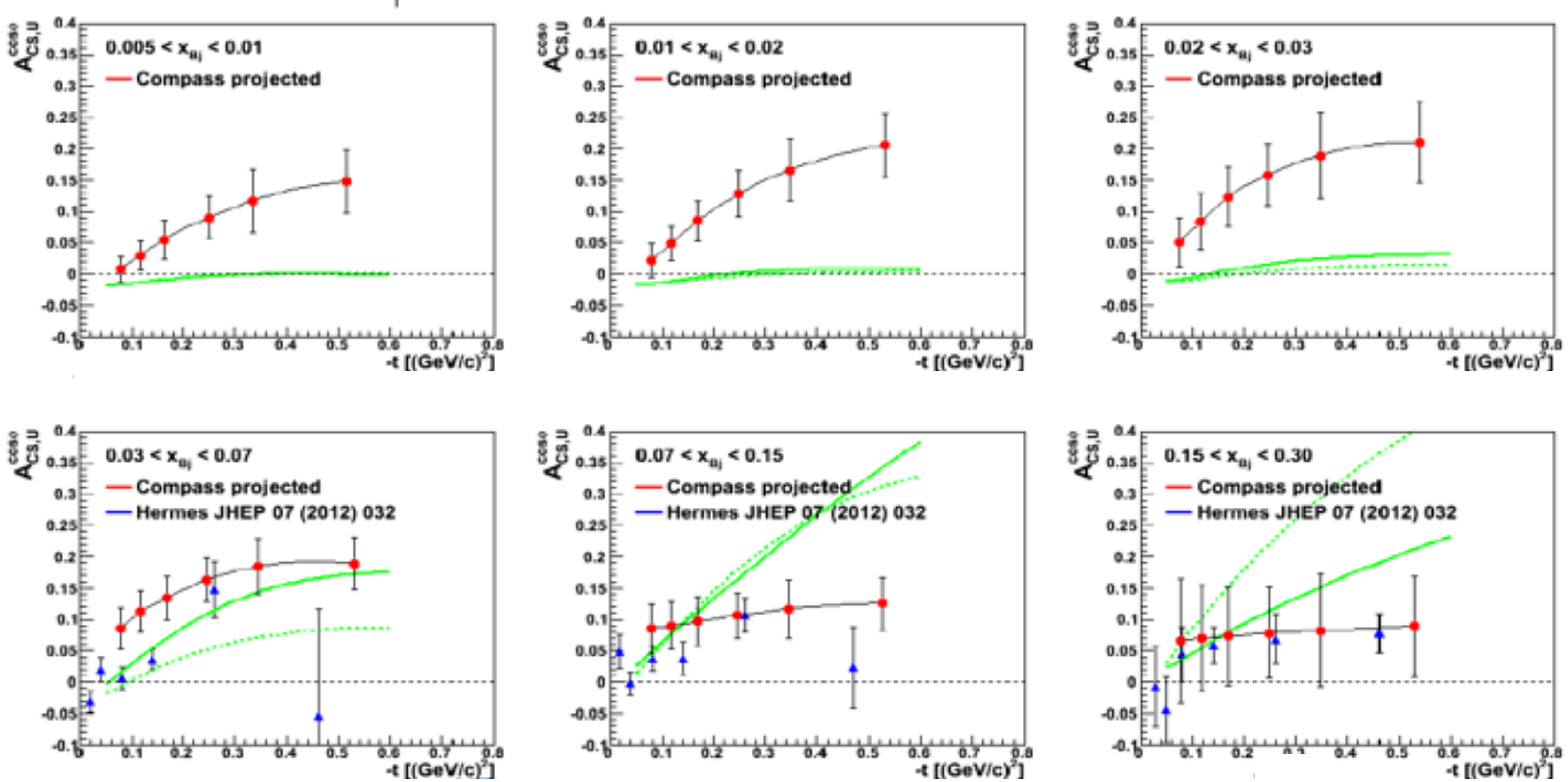
Kroll, Moutarde, Sabatié,
Eur. Phys. J. C (2013) 73:2278
Test of GPD universality: use DVMP data to constrain GPD params



- Projection compared with HERMES beam-charge asymmetry's cosΦ-modulation

- Question: magnitude of cosΦ-modulation in COMPASS data?

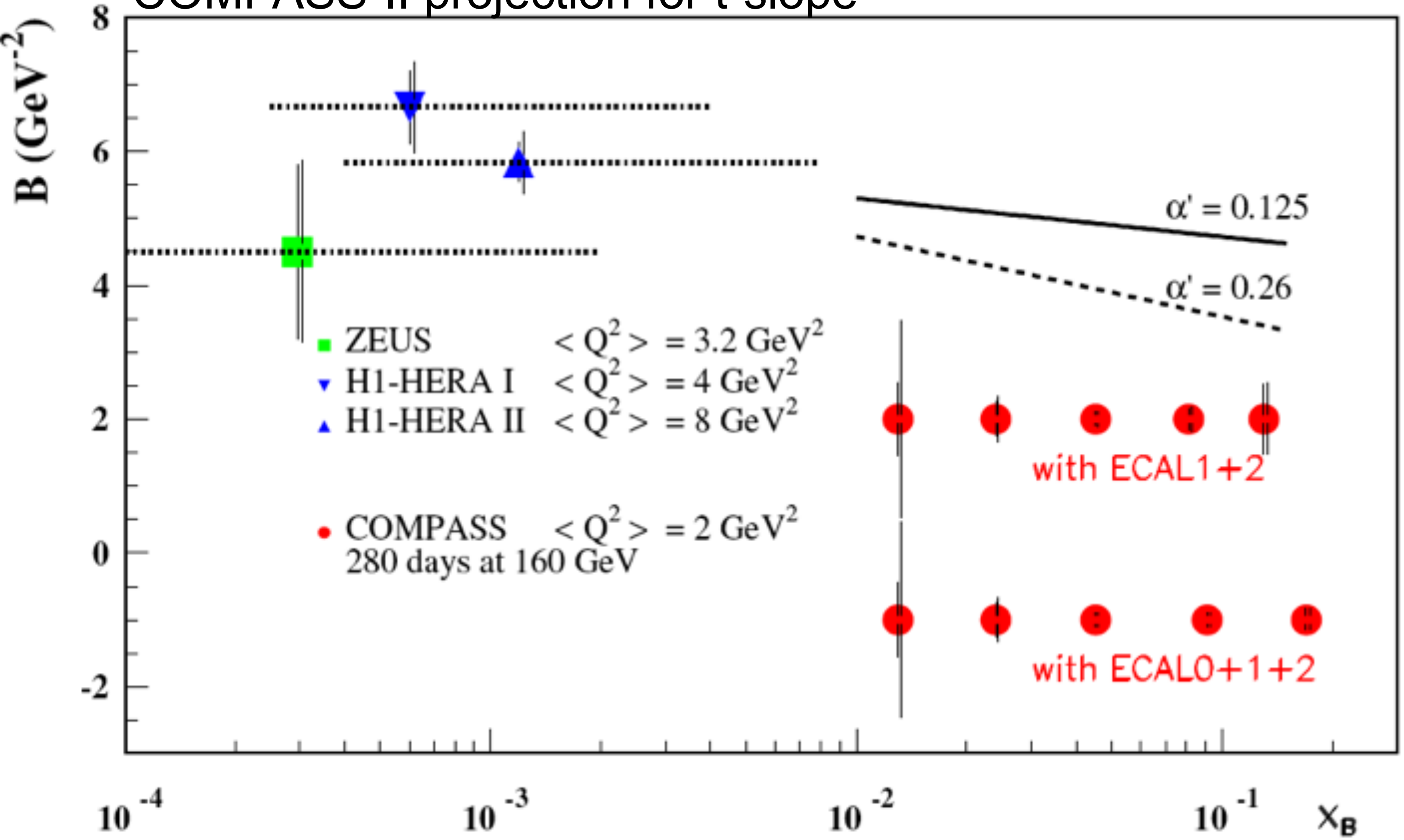
- Changes sign in between H1 and HERMES!



Transverse imaging from DVCS & 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
$b(x_B) = b_0 + 2\alpha' \ln(x_0/x_B)$

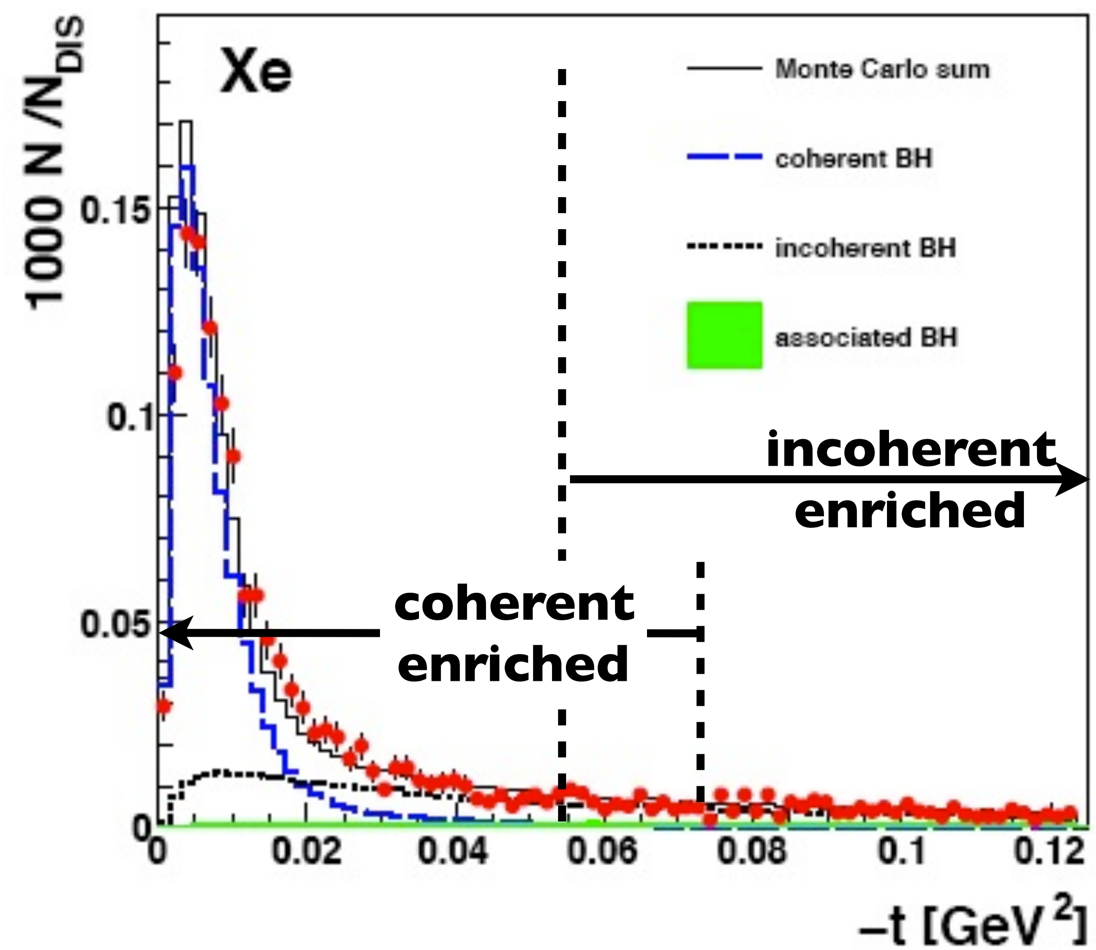
$\alpha' \simeq 0.25$ GeV^{-2}
soft pomeron

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

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

DVCS on hadrons other than the proton

Coherent and tensor signatures; nuclear medium

Nuclear targets

- 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?

Coherent scattering

Deuteron: probe spin-1 object

Nucleon: probe spin-1/2 object

coherent **incoherent**

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

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

☛ **9** chiral-even quark GPDs at LT

☛ H_3, H_5 associated with 5% D-wave component of deuteron wave function

Tensor polarized deuteron

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

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

Spin-1 particle with Λ=-1,0,+1

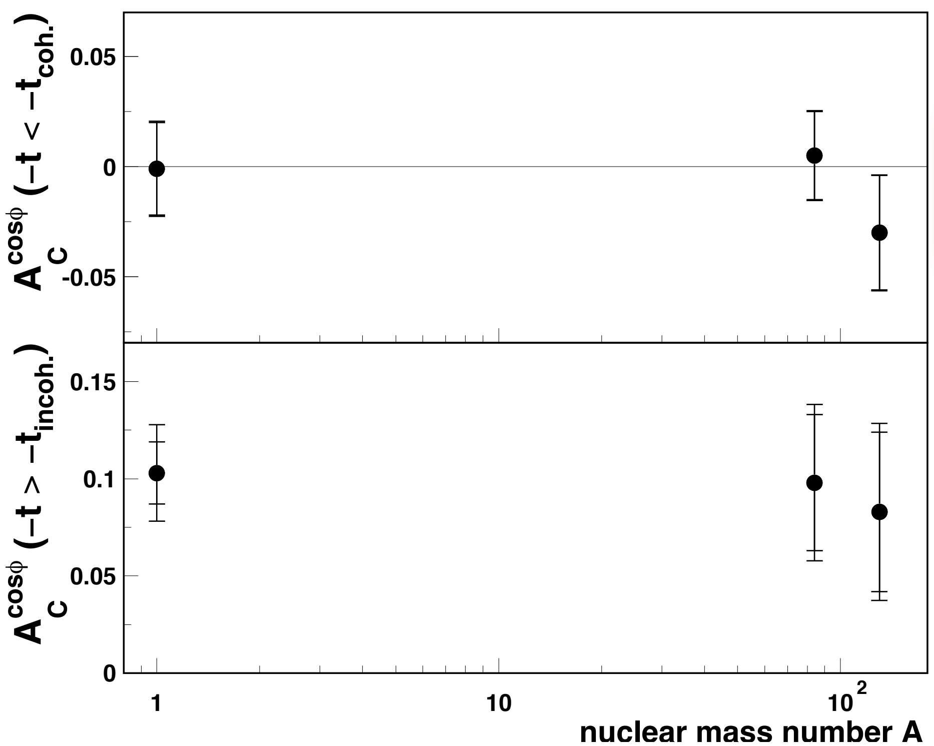
- Vector polarization $P_z \approx 0.85$
- Tensor polarization $P_{zz} \approx 0.83$
- Dedicated data set with with $P_{zz}=-1.656$ && $P_z \approx 0$

HERMES: DVCS nuclear dependence

Nuclear medium

^{1}H, He, N, Ne, Kr, Xe
Heavy gas targets

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

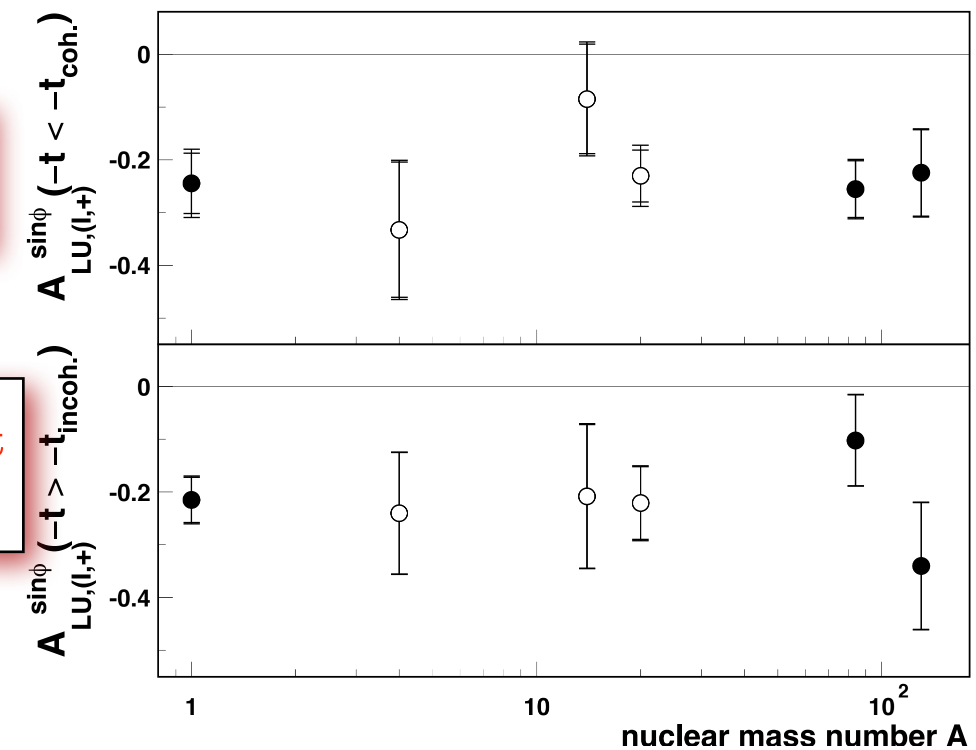


coherent enriched

incoherent enriched

Beam-charge asymmetry

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



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

0.91±0.19
0.93±0.23

Normalization to hydrogen ^{1}H

Beam-helicity asymmetry

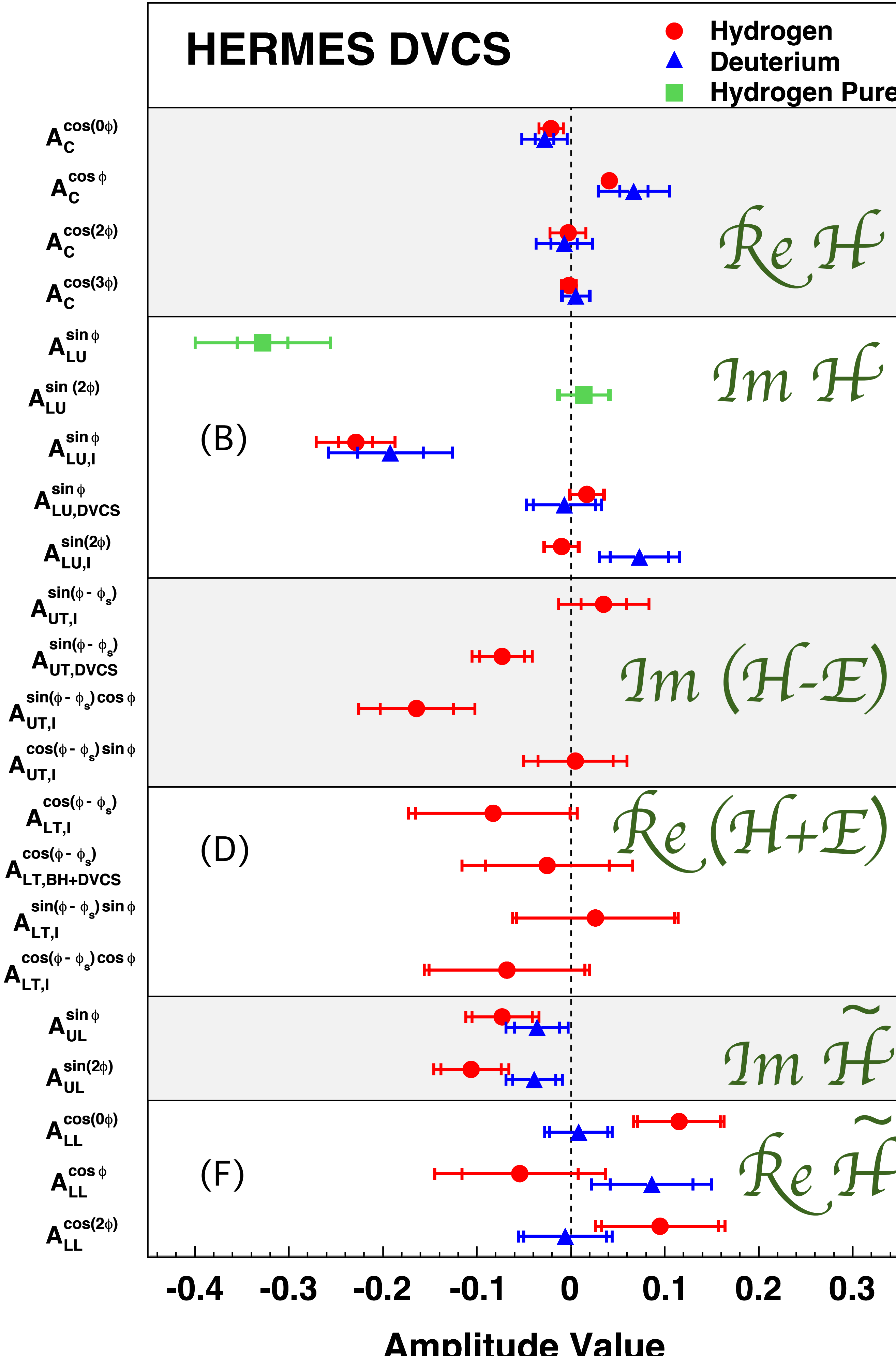
HERMES: Phys. Rev. C 81 (2010) 035202

Coherent and tensor signatures

GPD H_1~ **GPDs H1, H_5**

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

Large experimental uncertainties
- no significant signatures found
in HERMES data



HERMES DVCS

(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]

Variety highly welcome by global fitters

(E) Longitudinal target-spin asymmetry: **GPD H~**

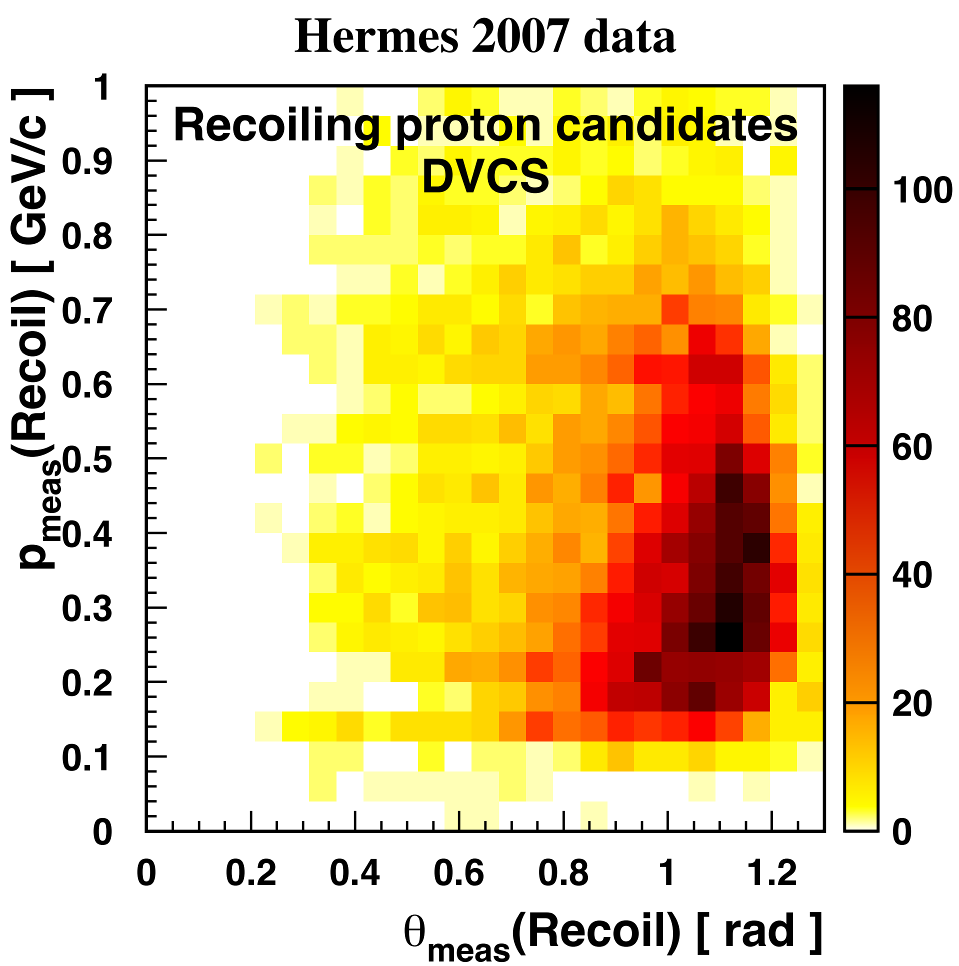
[JHEP 06 (2010) 019 - Nucl. Phys. B 842 (2011) 265-298]

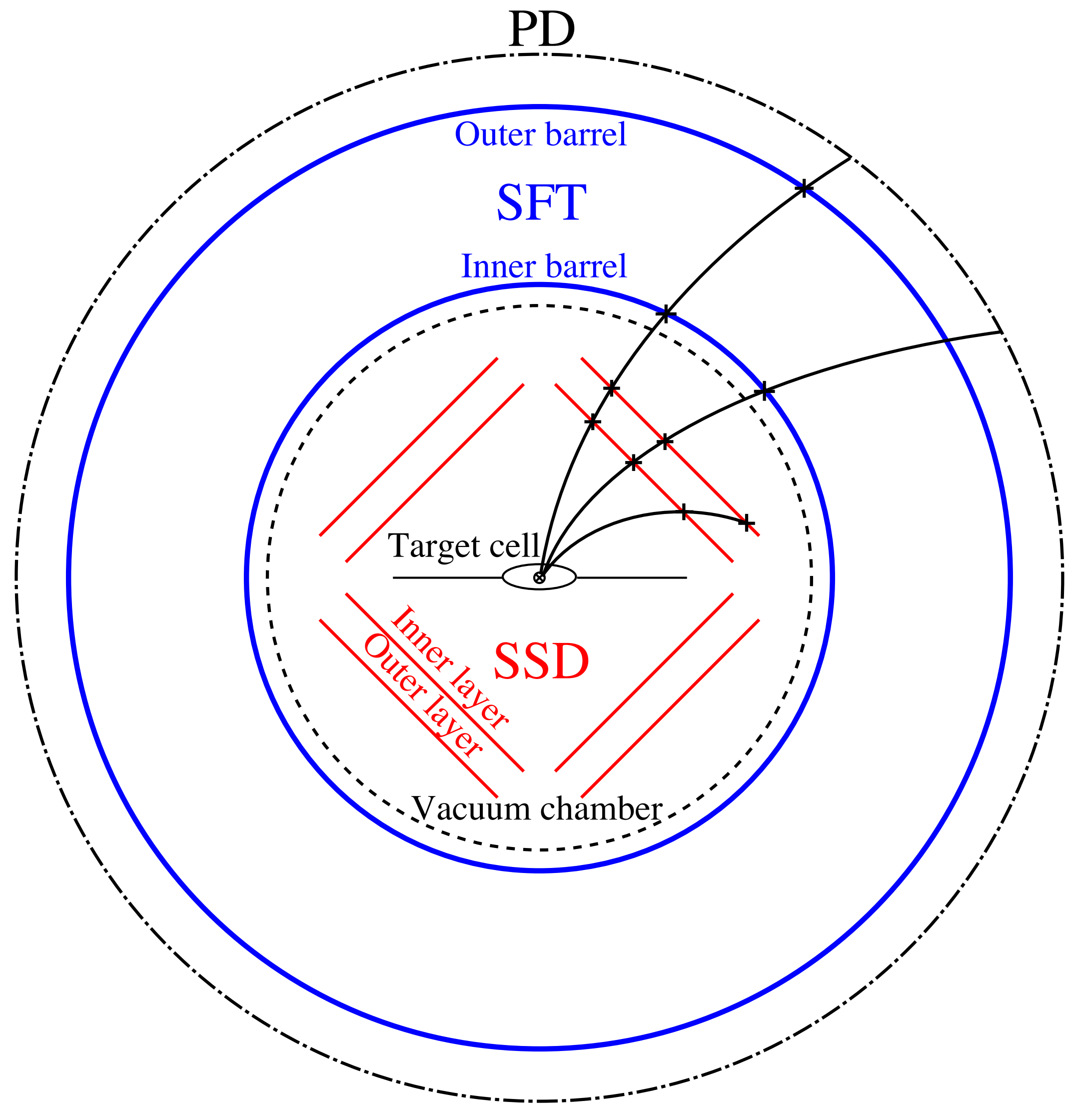
(F) Double-spin (LL) asymmetry: **GPD H~**

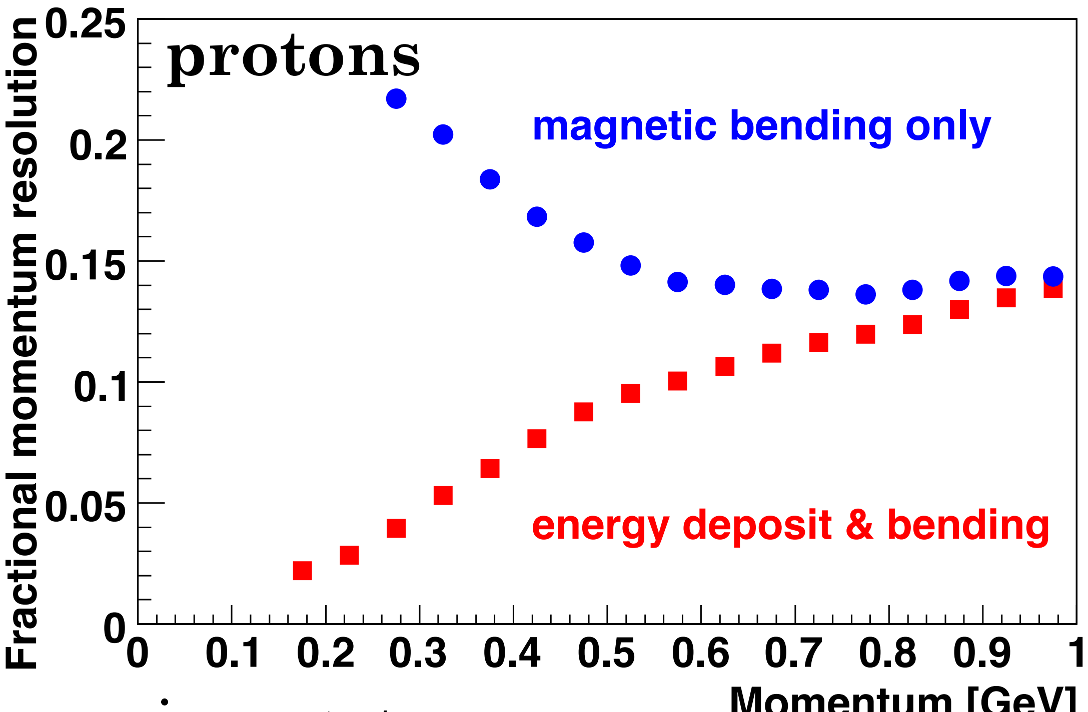
[JHEP 06 (2010) 019 - Nucl. Phys. B 842 (2011) 265-298]

$\langle Q^2\rangle=2.46$ GeV^2, $\langle x_B\rangle=0.10$, $\langle -t\rangle=0.12$ GeV^2

Track reconstruction with HERMES recoil detector



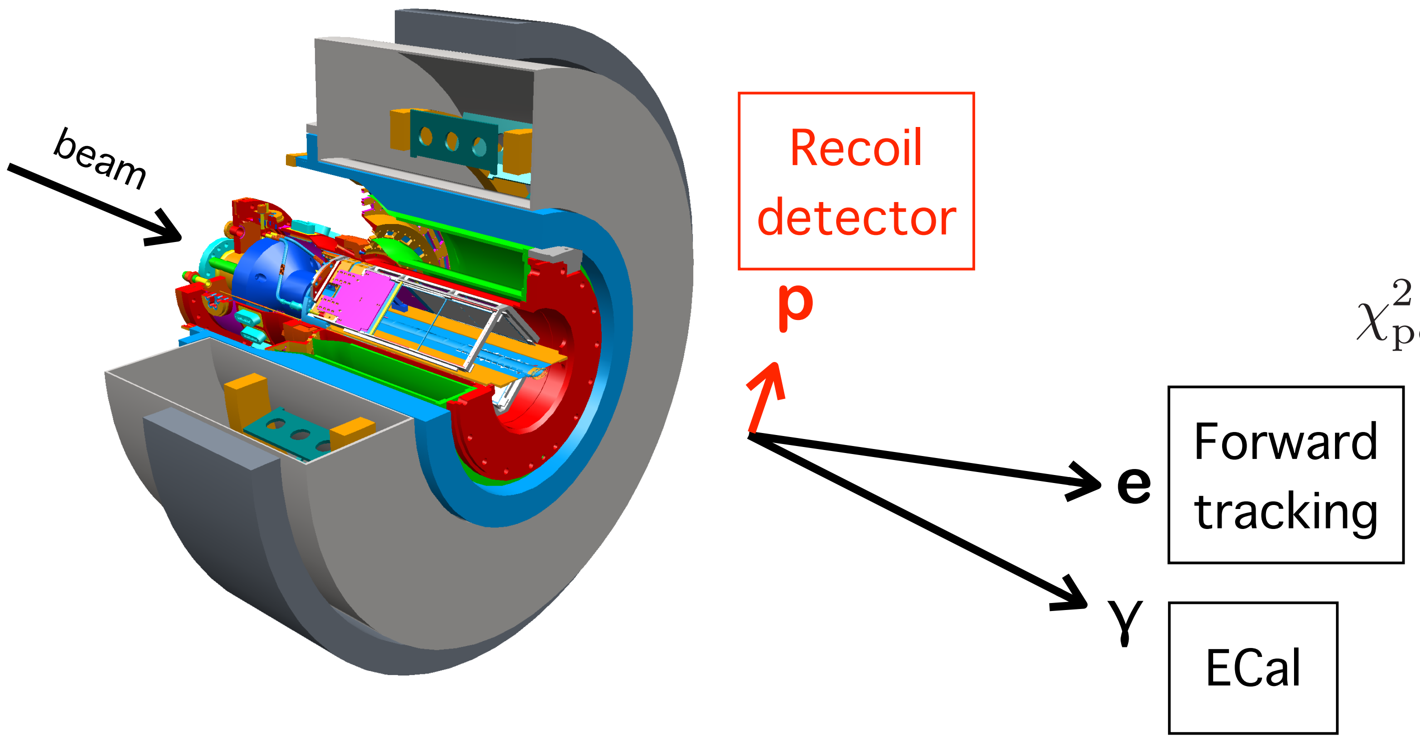




pions: $\Delta p/p = 0.12$

- Azimuthal-angle resolution: 4 mrad
- Polar-angle resolution: 10 mrad (for p > 500 MeV)
- Momentum reconstruction as low as 125 MeV, corresponding to -t=0.016 GeV^2
  (protons that make it at least in 2nd layer of SSD)

HERMES: adding the recoil proton



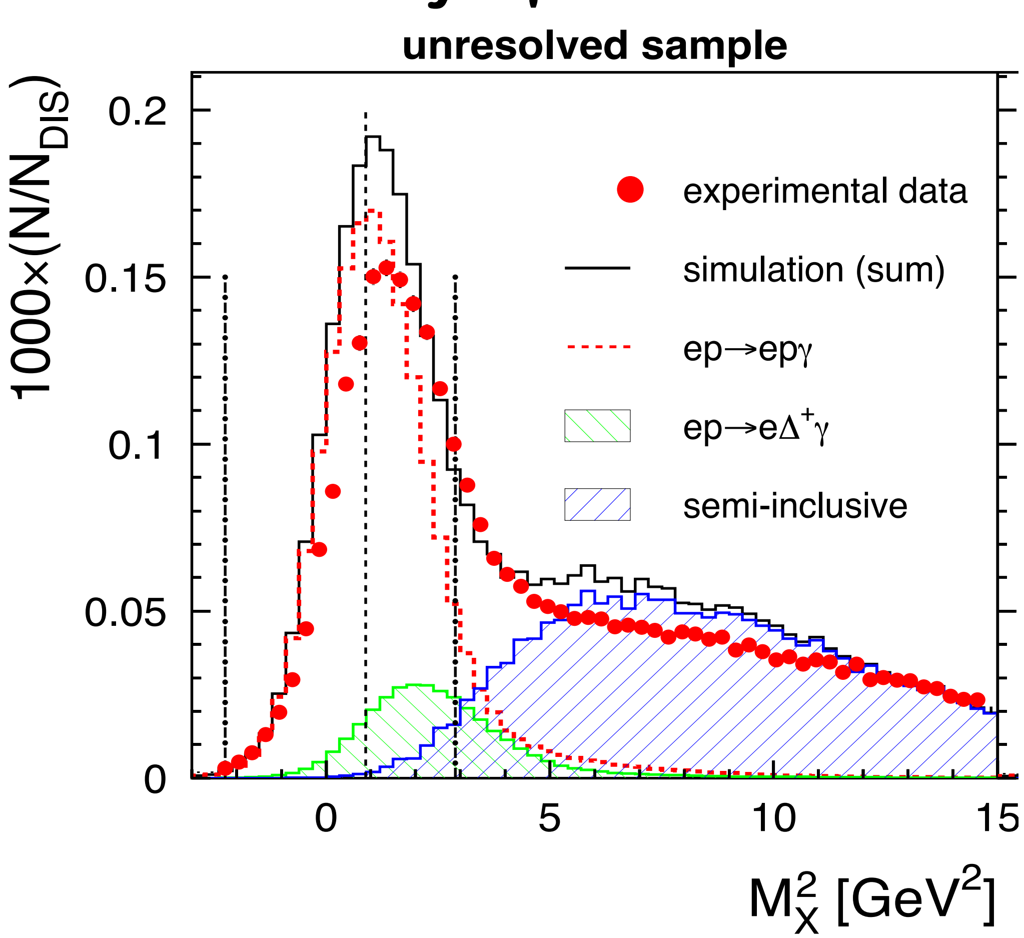
Tag exclusive events via kinematic event fitting:

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

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

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

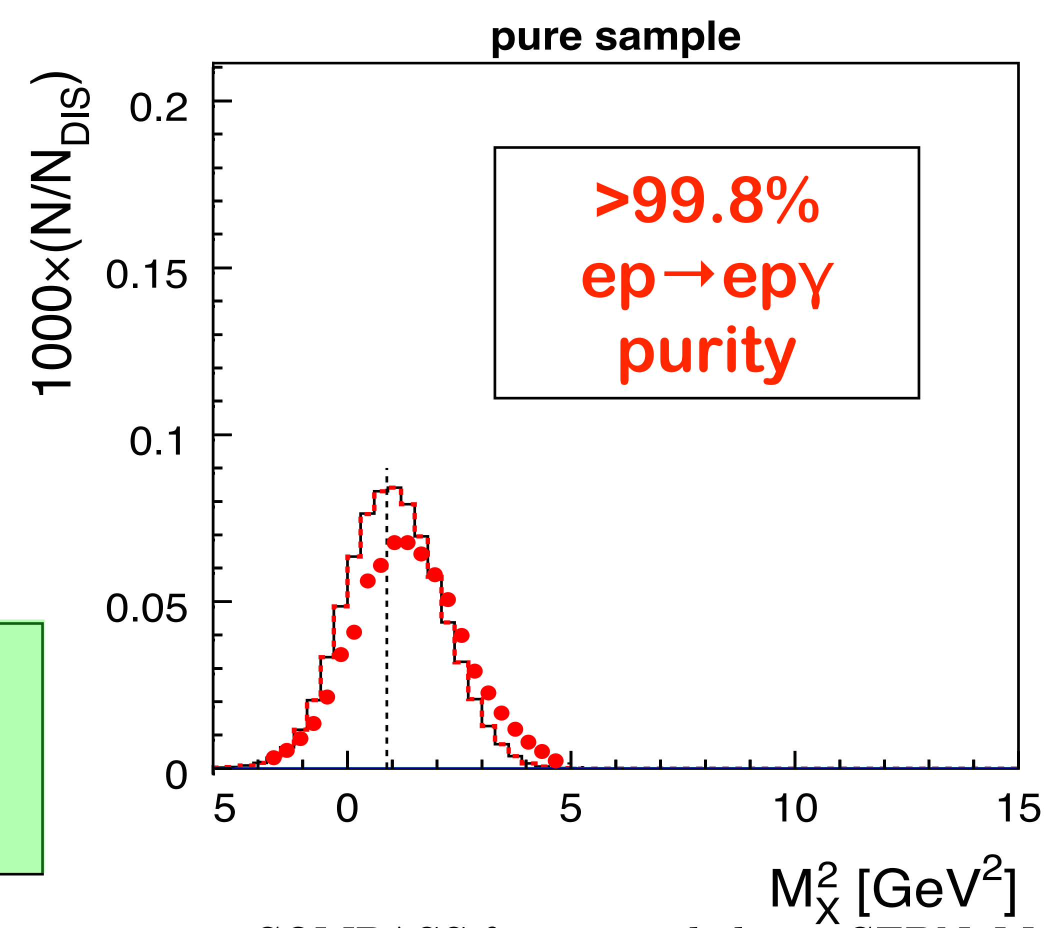
Only eγ detection



unresolved for Δ⁺

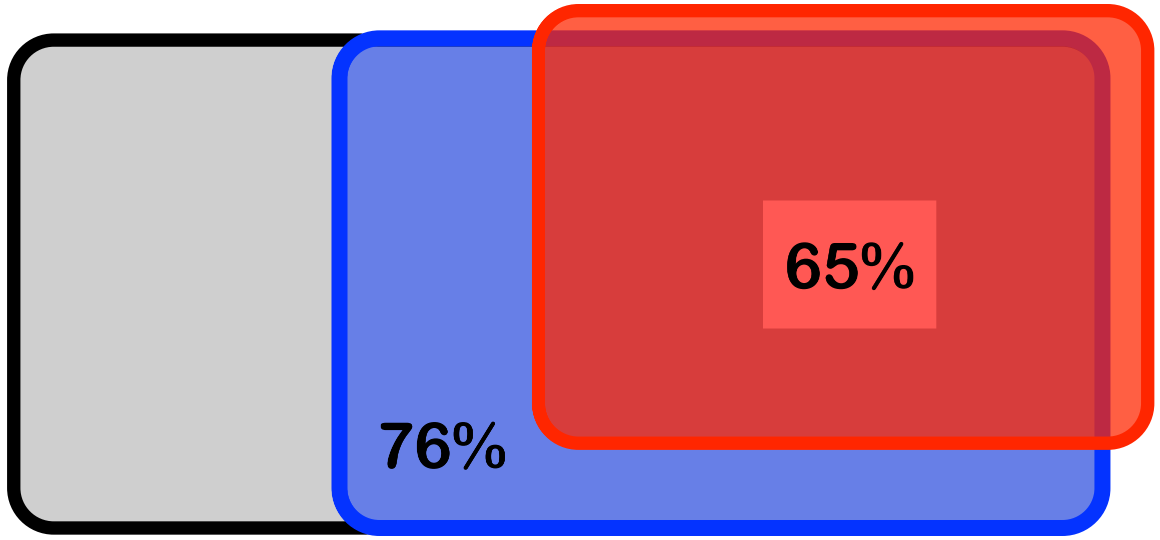
~88% ep→epγ purity

epγ detection



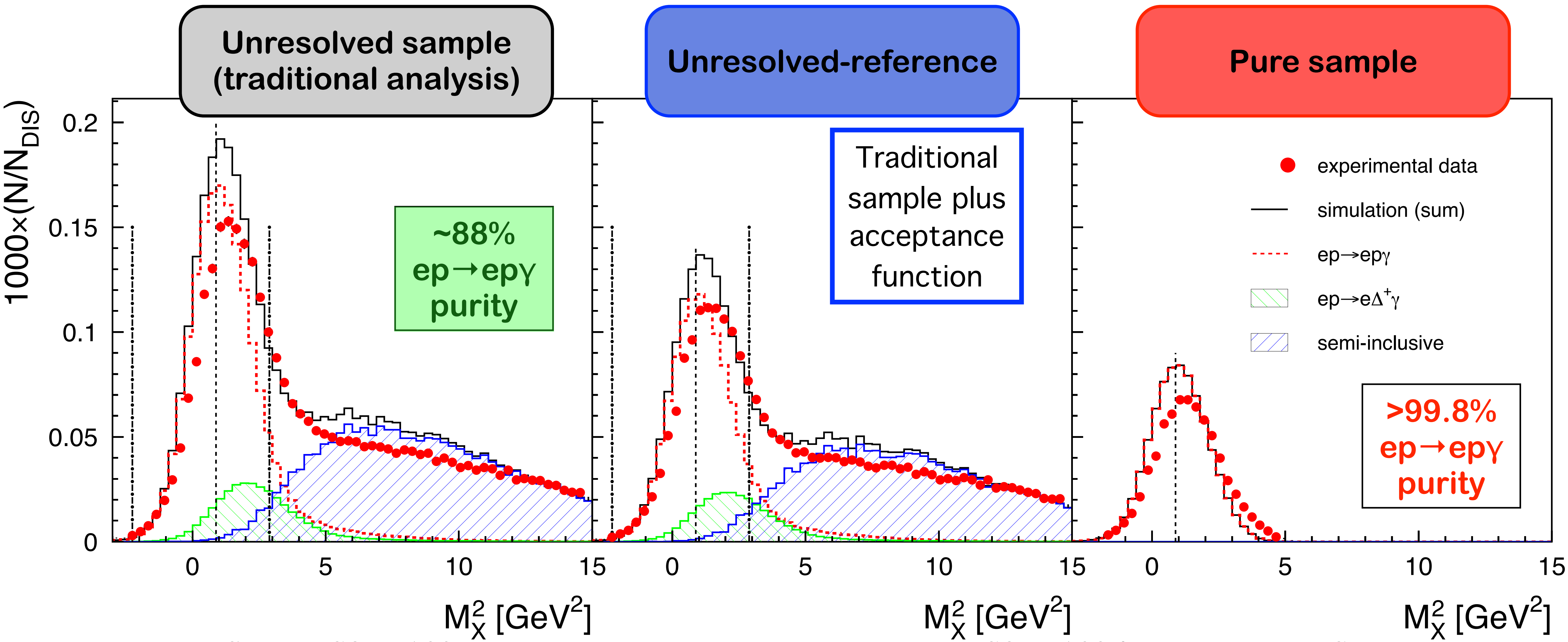
HERMES: unresolved reference sample

Disentangling the effects of recoil-detector acceptance and purification



Loss due to
- lower-mom. threshold
- Φ-gaps of SSD

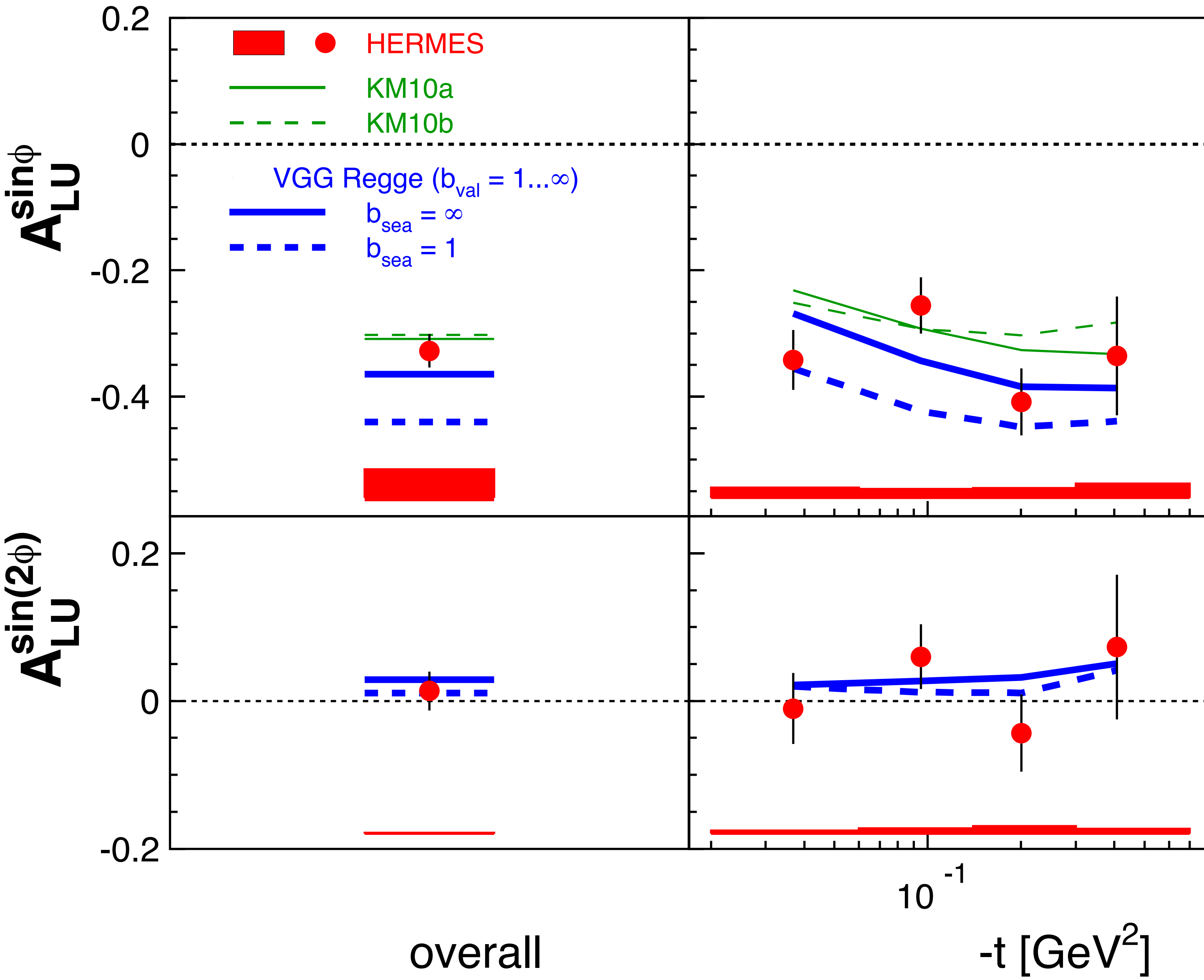
Deficit due to
- removal of background
- inefficiencies of χ^2 cut
- recoil-det. ineffciencies



HERMES (with recoil proton): beam-helicity asymmetry

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

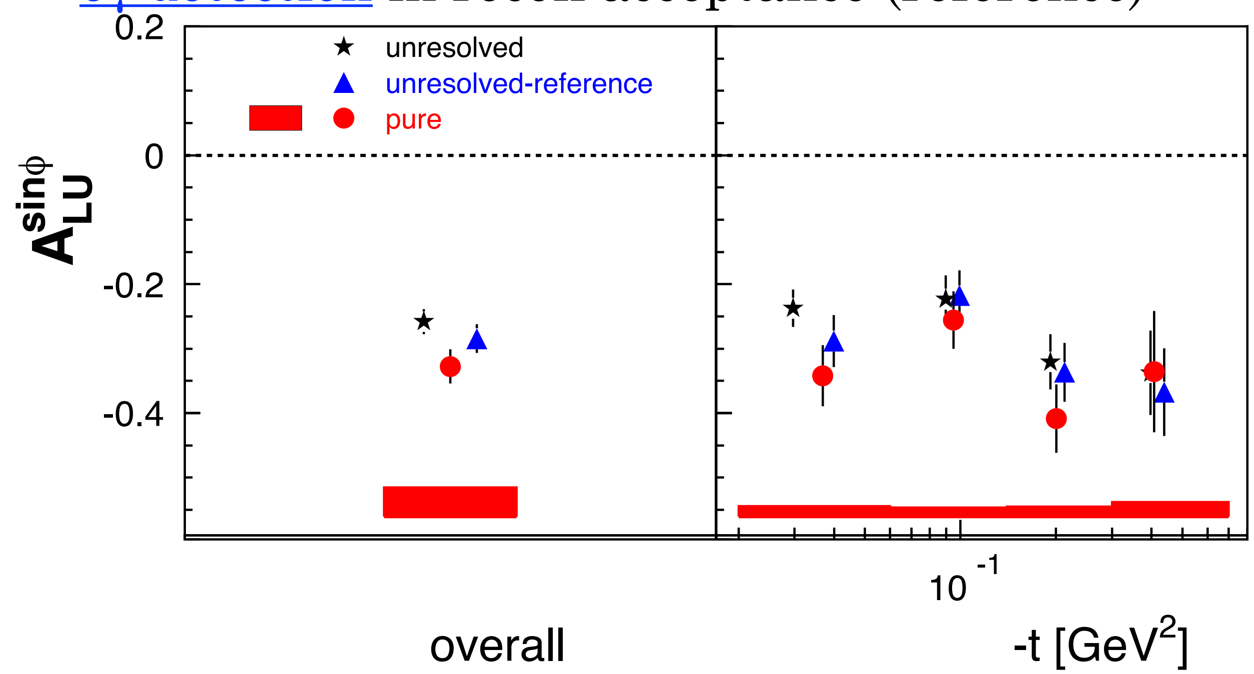
single-beam-charge



● 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)



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

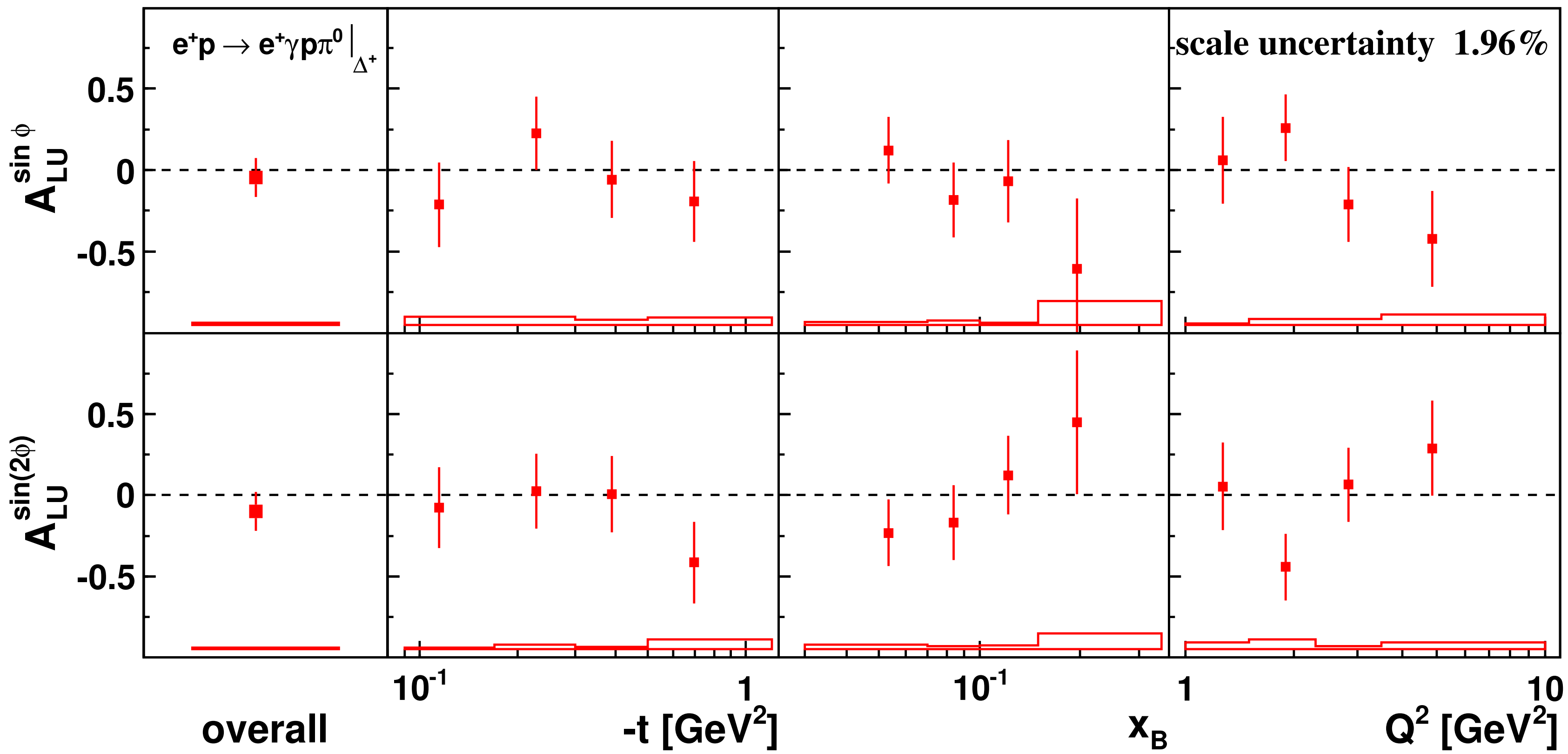
GPD model calculation "VGG Regge"
Phys.Rev. D60 (1999) 094017 and Prog.Nucl.Phys. 47 (2001) 401

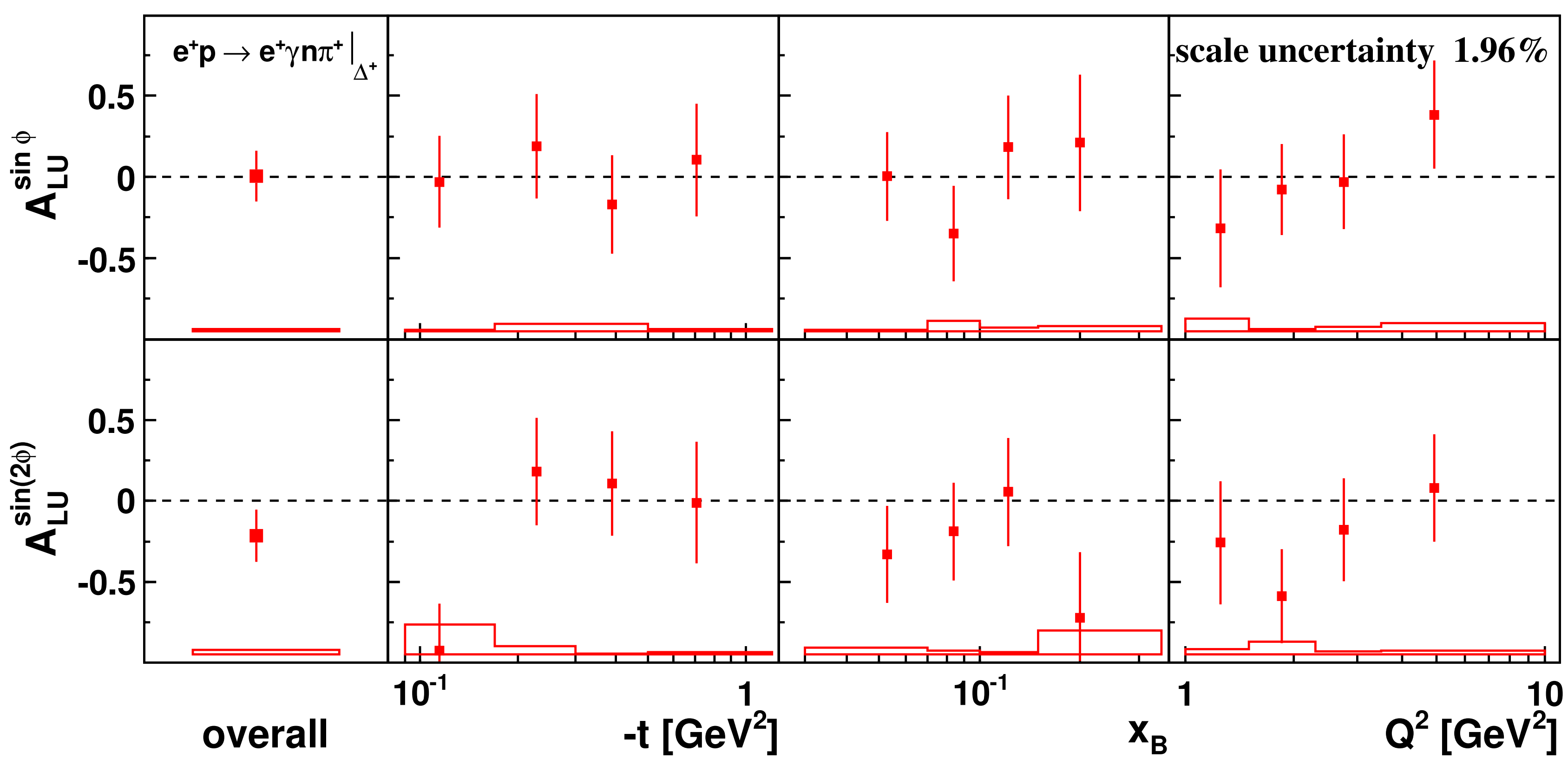
HERMES: JHEP 10 (2012) 042

HERMES: beam-helicity asymmetry

in ep→eγ(πN) 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.

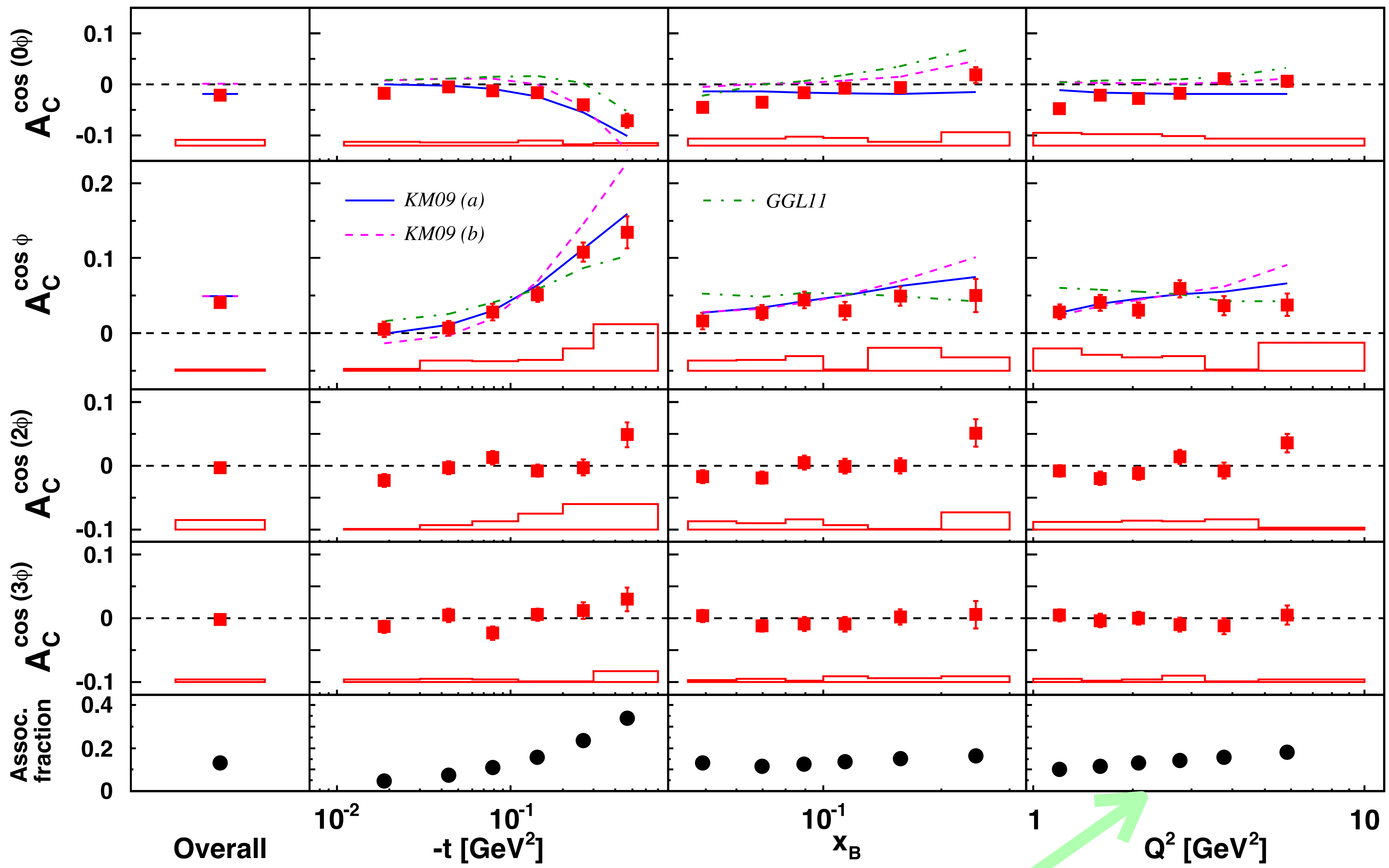
☛ Only existing model prediction for sinφ amplitude: $\pi^0 p$: -0.15, $\pi^+ n$: -0.10

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

HERMES: JHEP01 (2014) 077

HERMES: beam-charge asymmetry

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

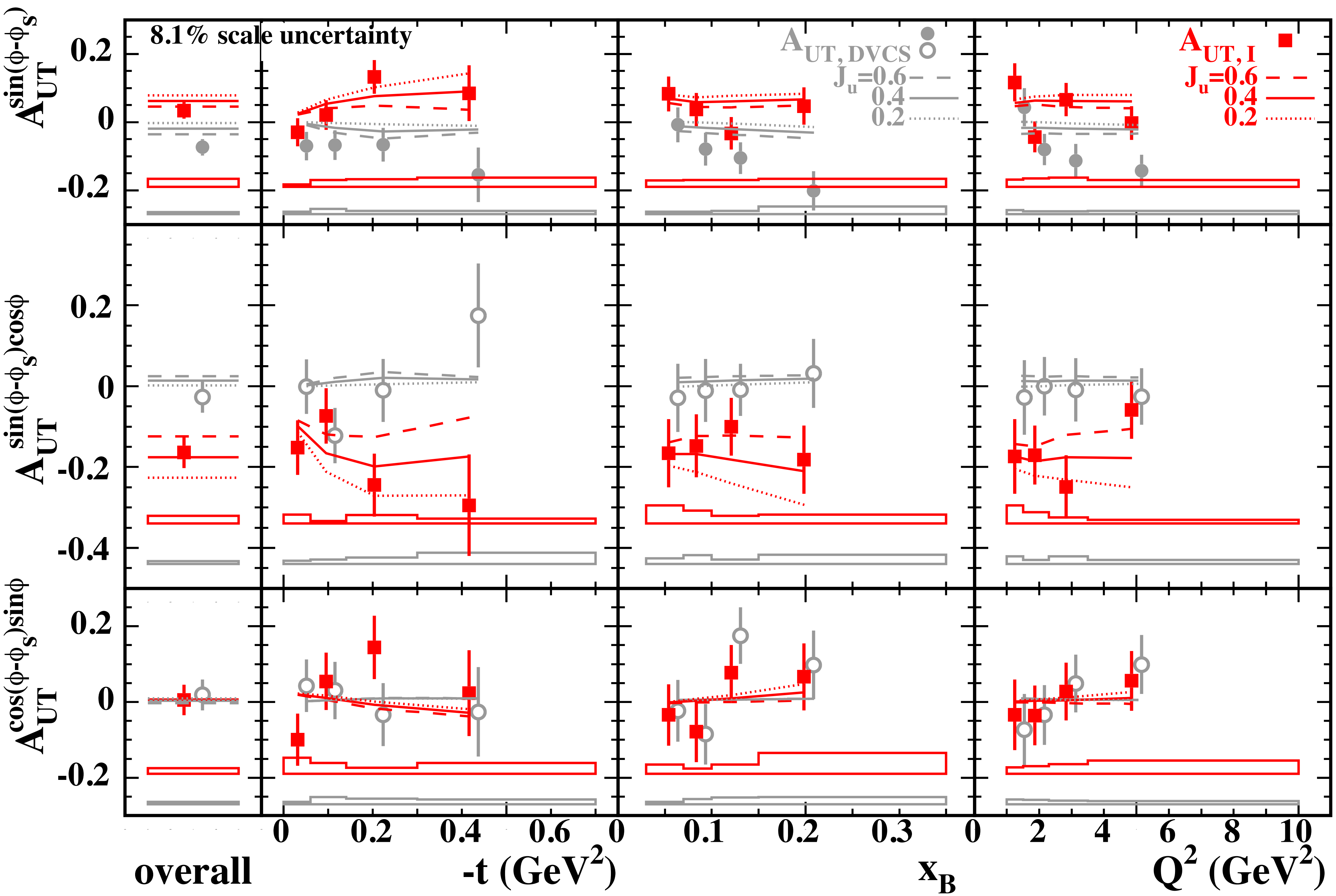
All 1996–2007 proton data.
No recoil-proton detection

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

HERMES: JHEP 07 (2012) 032

HERMES: transverse target-spin asym.

GPD E



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

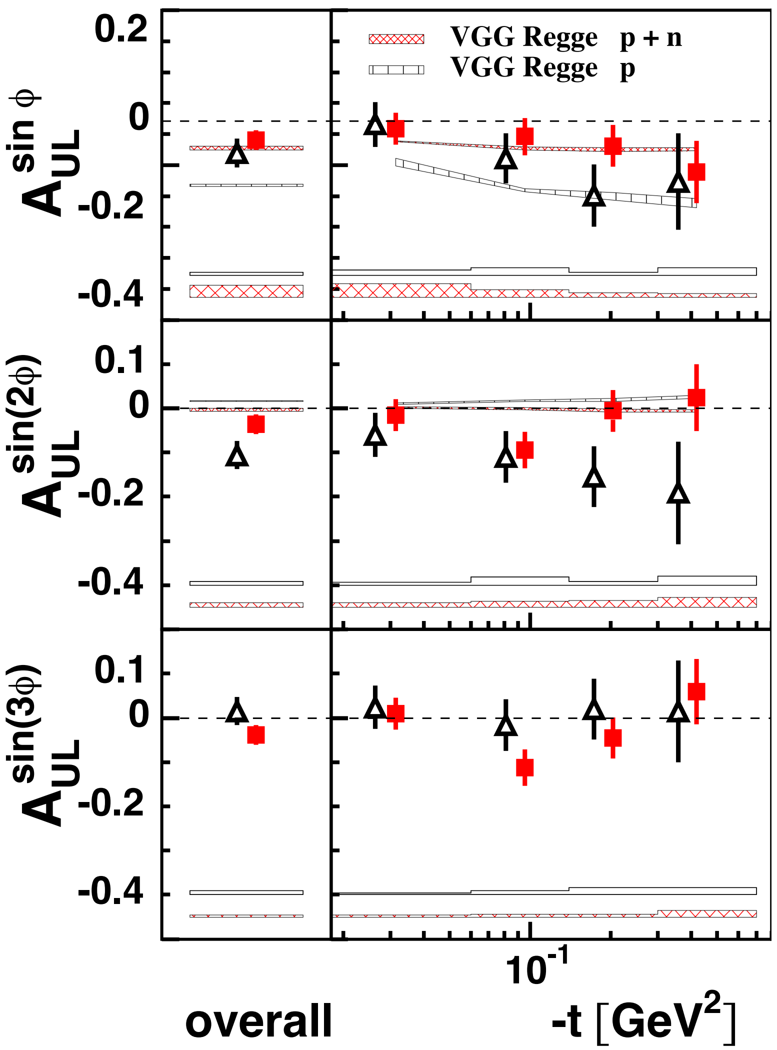
HERMES: JHEP 06 (2008) 066

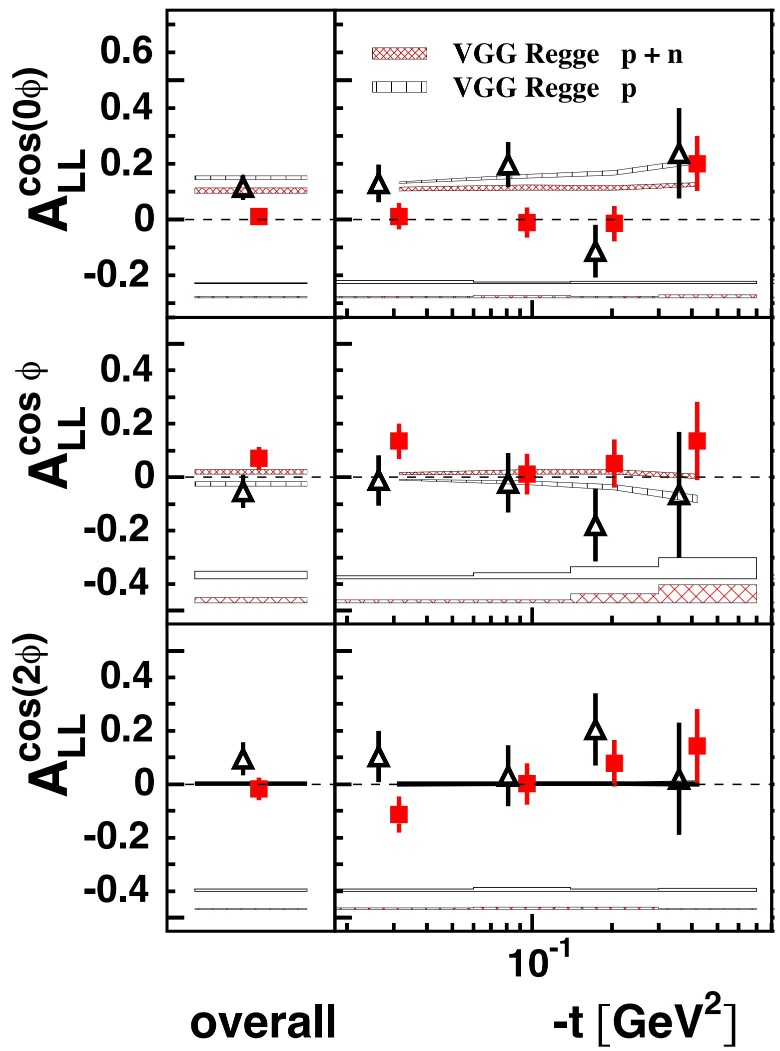
GPD $\tilde{H}_1$

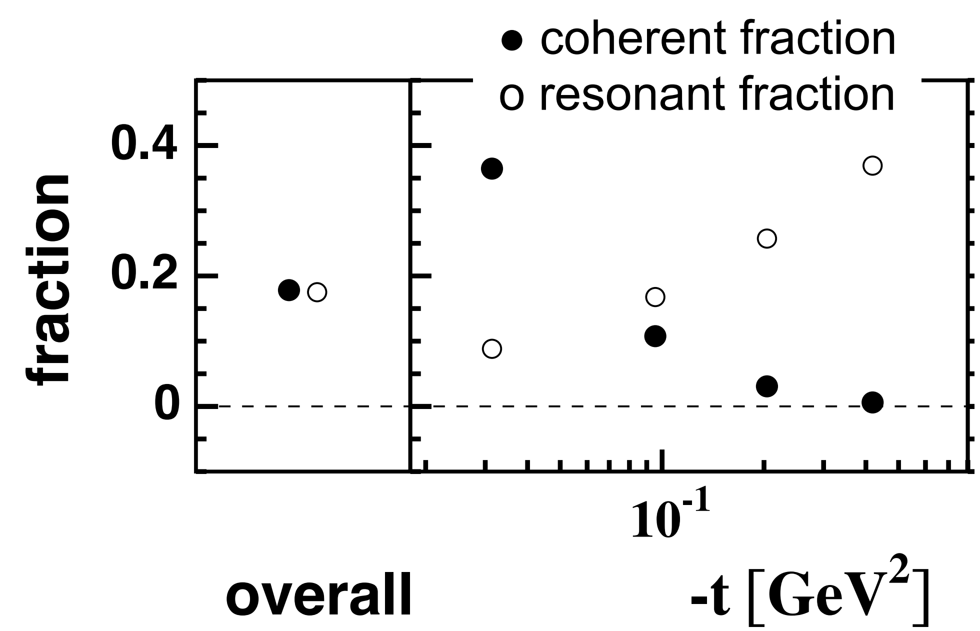
Target-Spin Asymmetry on p and d

Search for coherent signature

1998–2000 longitudinally polarized deuteron data







□ **Proton:**

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

■ **Deuteron:**

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

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

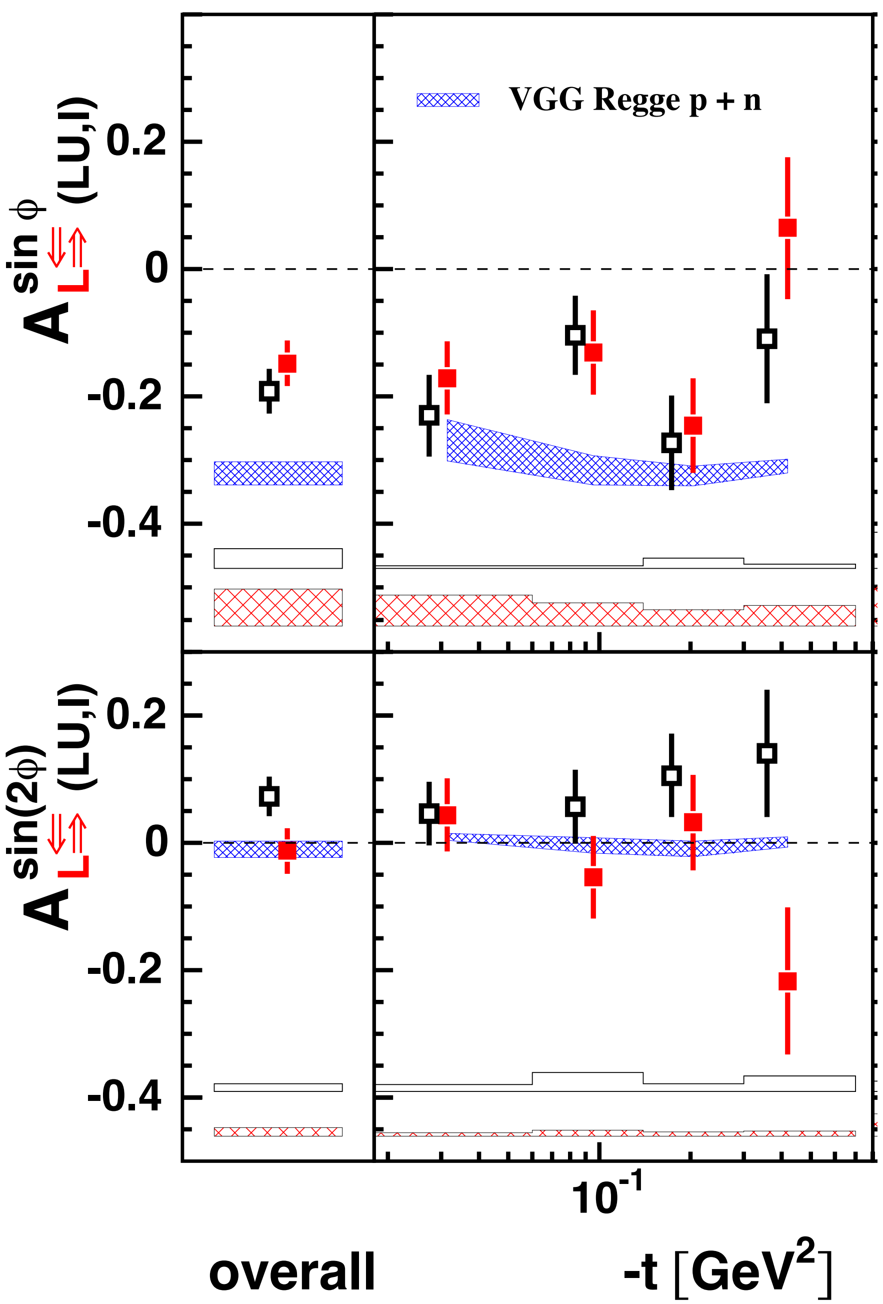
Nucl. Phys. B 842 (2011) 265-298

GPDs H1, H_5

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

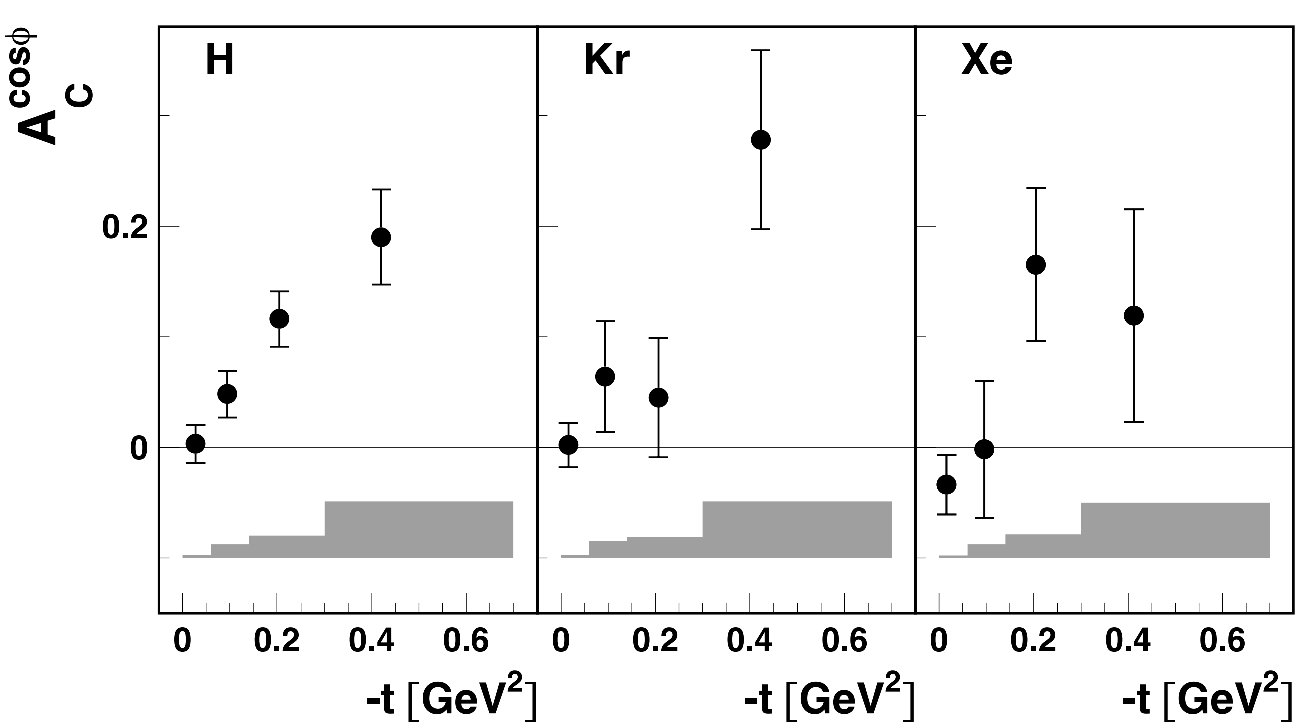
(-t<0.06 GeV², 40% coherent)

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

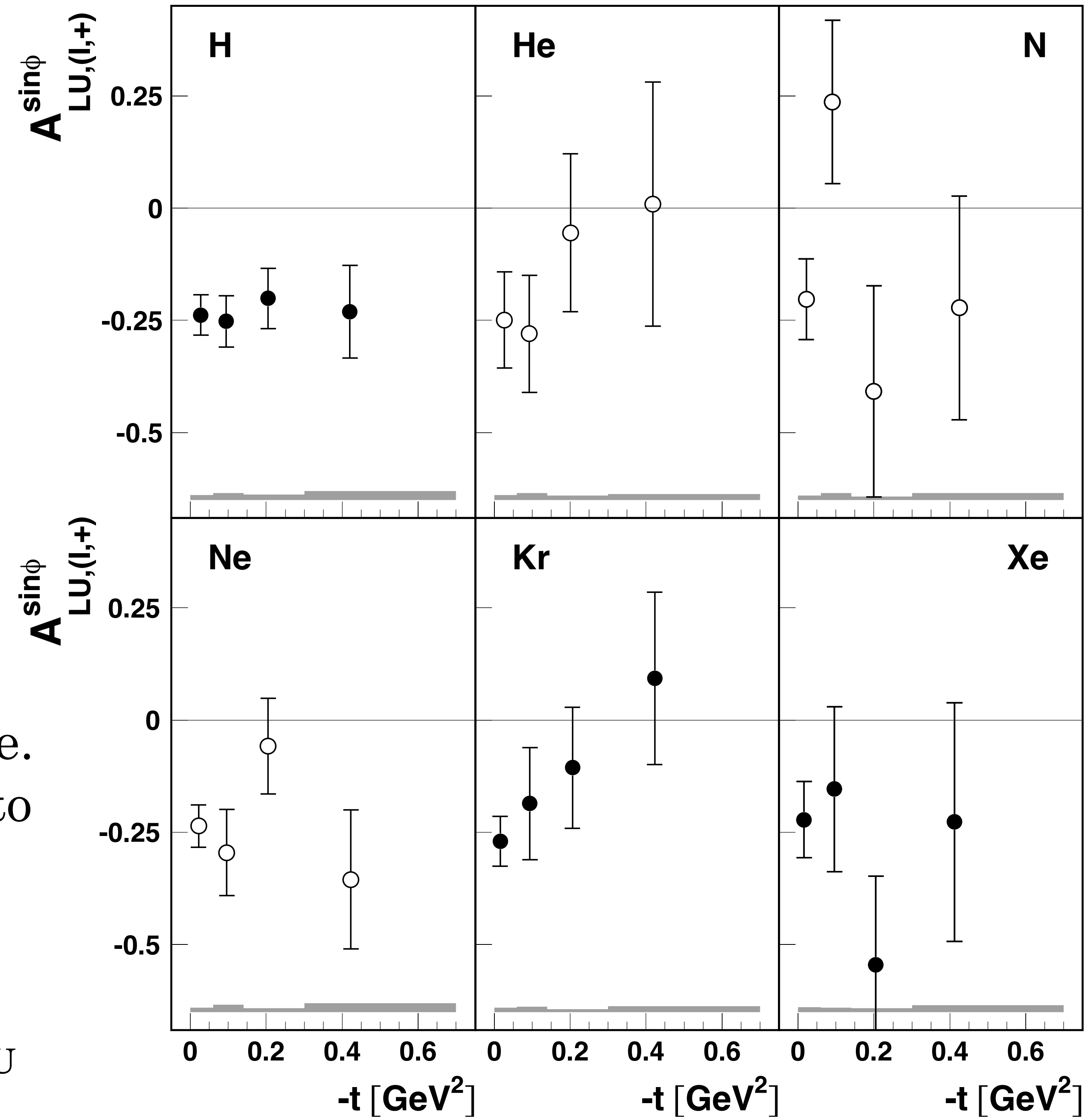
HERMES DVCS asymmetries on nuclei

1996–2005 nuclear data

Beam-charge asymmetry



Beam-helicity asymmetry



Phys. Rev. C 81 (2010) 035202

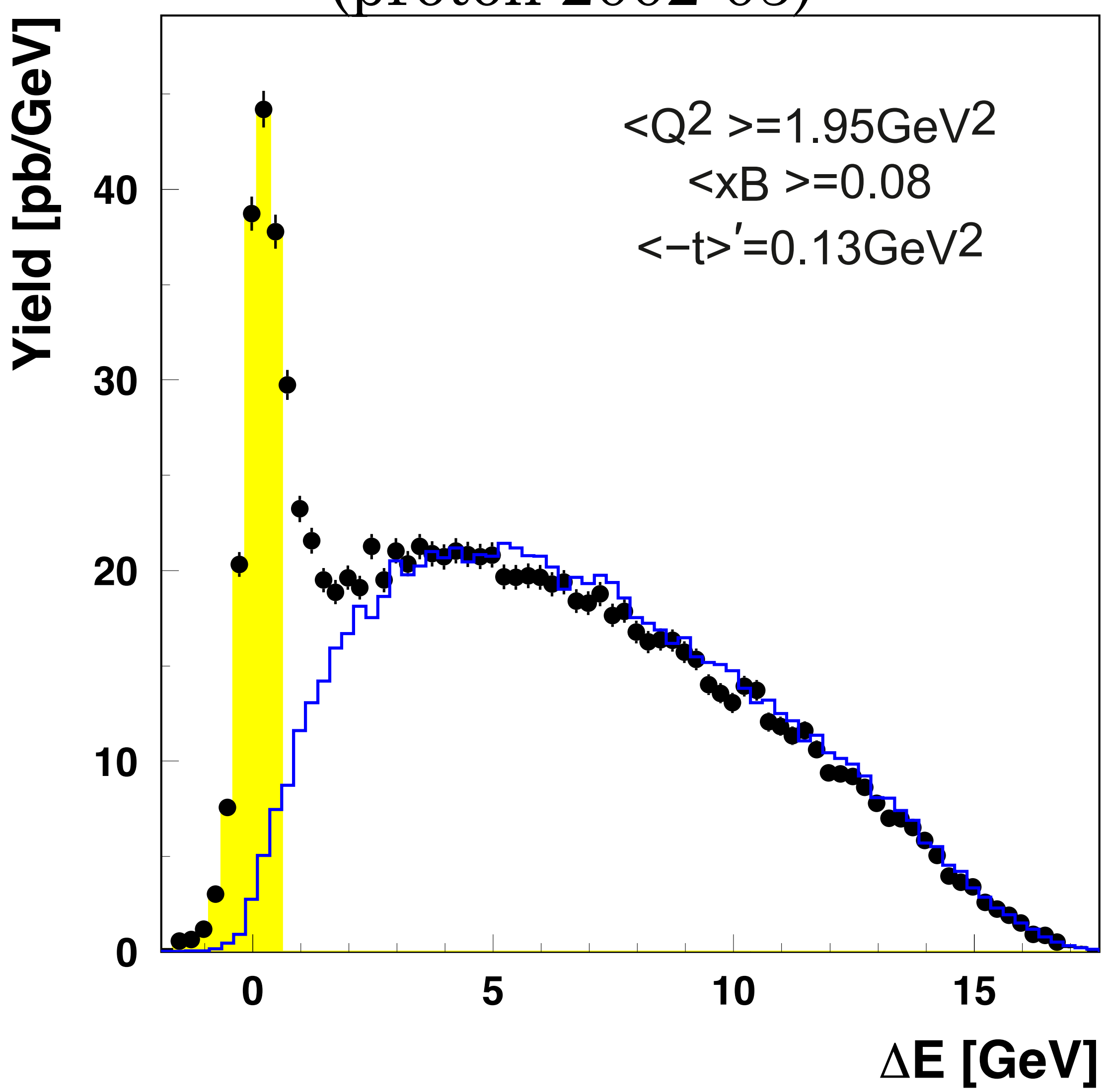
● Targets with 2 beam charges available. A_C and charge-difference A_{LU} sensitive to DVCS-BH interference term

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

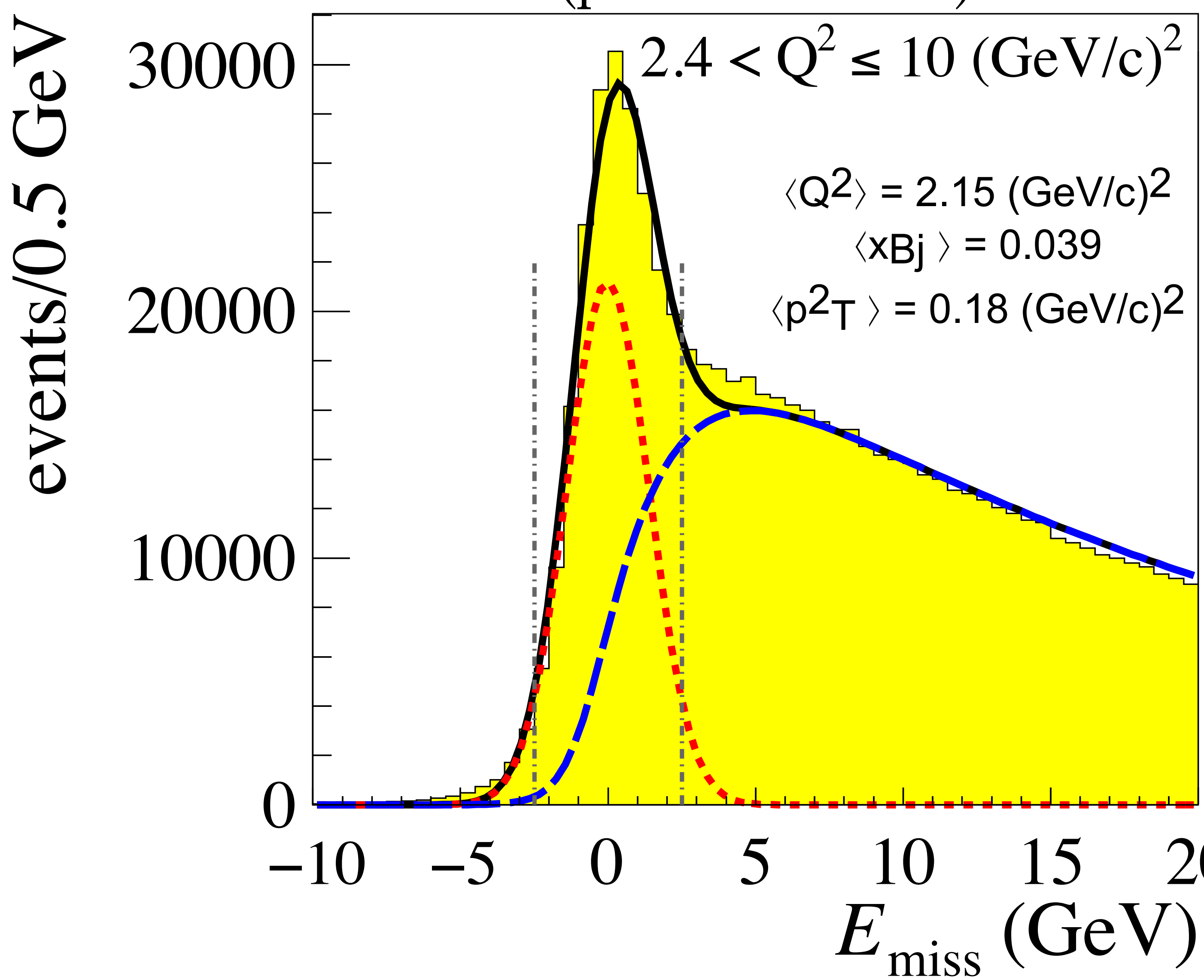
Selection of exclusive meson sample lp→lpM

- 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)

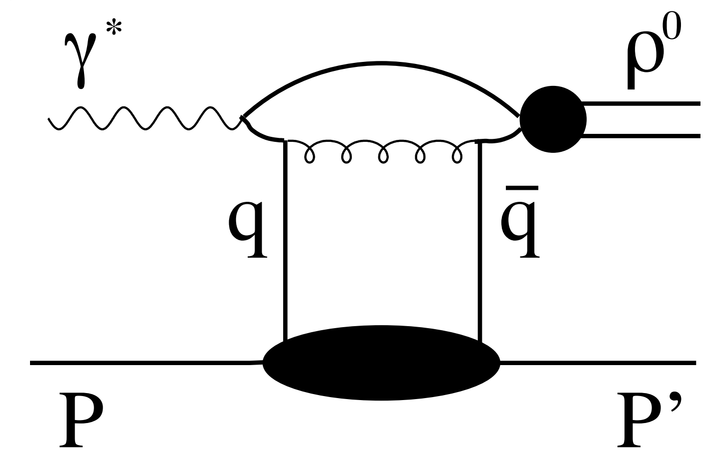


COMPASS exclusive ϱ^0
(proton 2007/10)



lp→lpV: Exclusive vector mesons

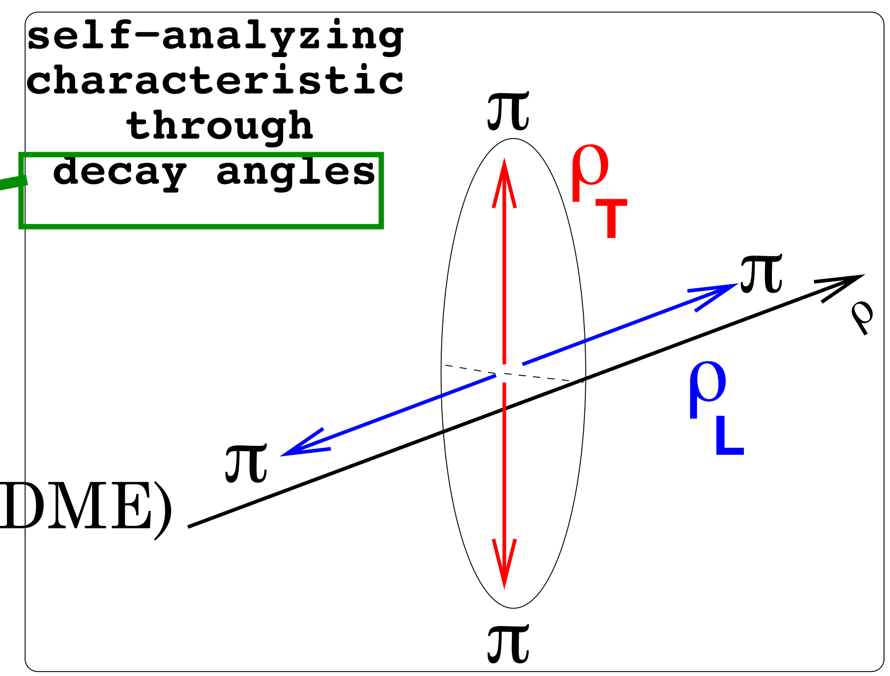
- pQCD at sufficiently large Q^2 and W: 1. $\gamma^*\rightarrow$(qqbar) 2. (qqbar) scatters off nucleon 3. formation of observed vector meson.



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

- Cross section for exclusive leptoproduction of vector mesons:

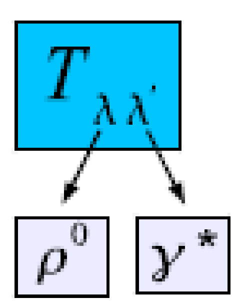
$$\frac{d\sigma}{dx_B\, dQ^2\, dt}\, W(x_B, Q^2, t, \phi, \phi_S, \varphi, \vartheta)$$



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

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

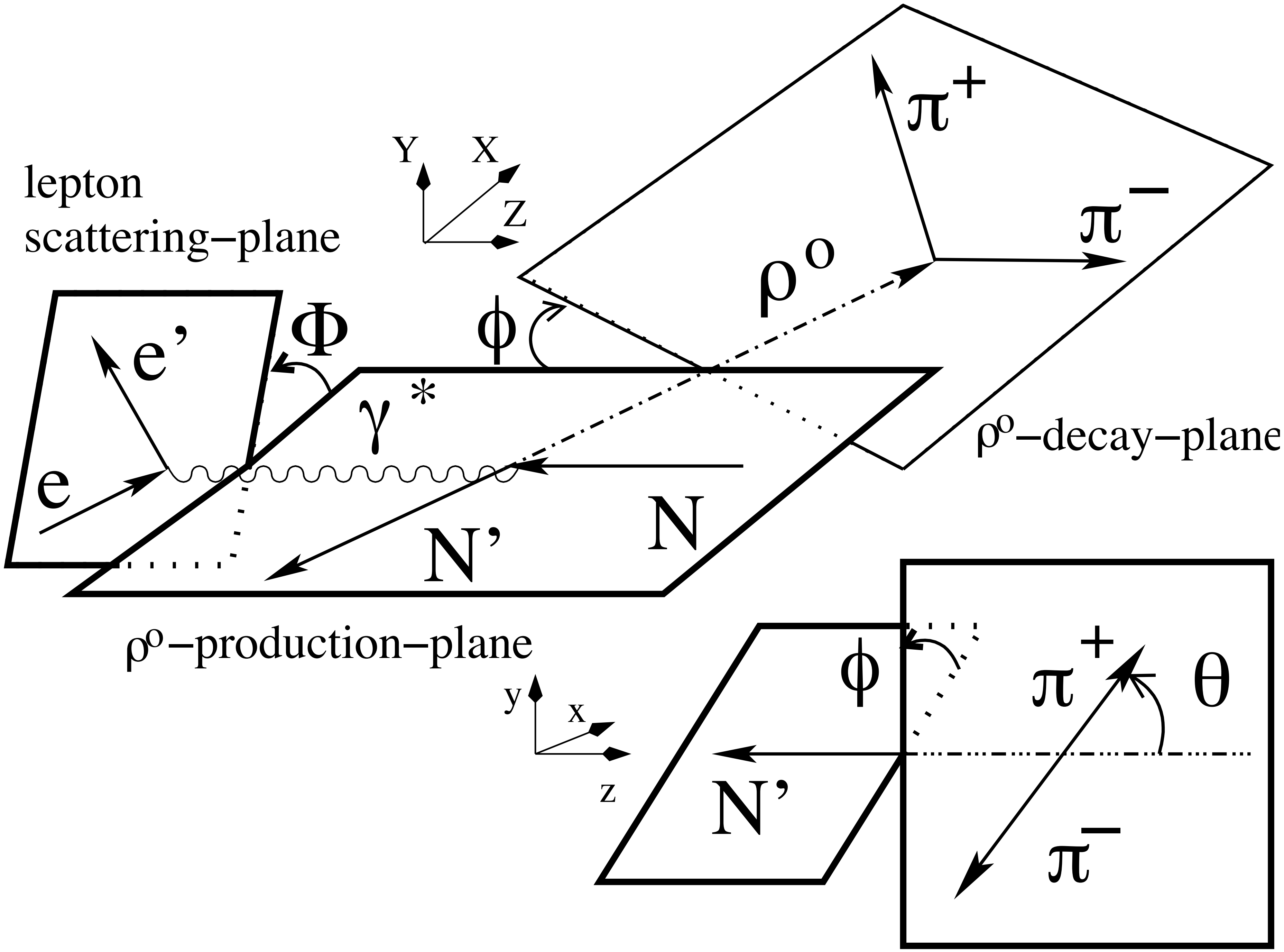
- Hierarchy of helicity amplitudes:
  $|T_{00}| \sim |T_{11}| \gg |T_{01}| > |T_{10}| >=$



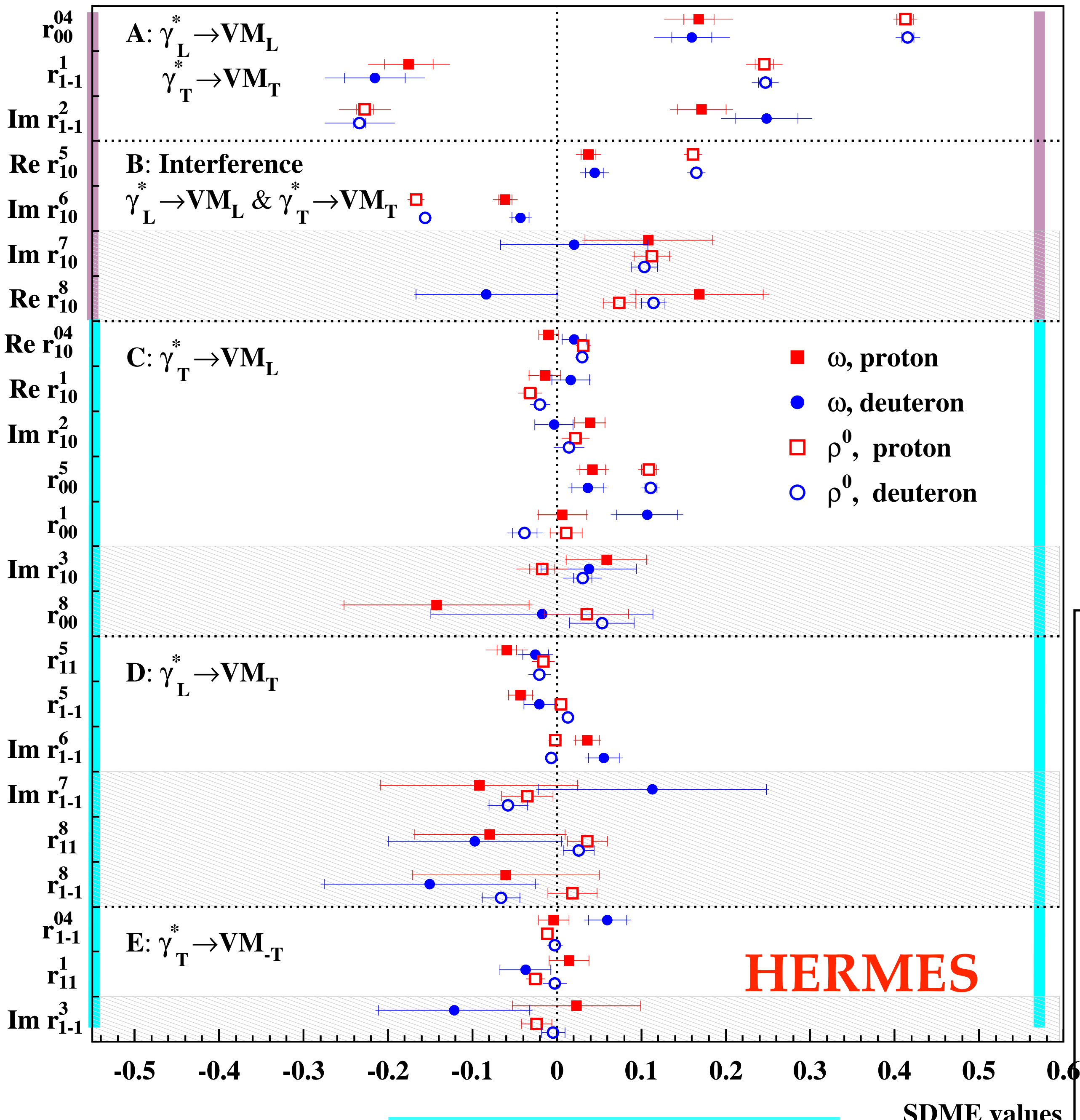
- s-channel helicity conservation (SCHC)
  T→T, L→L

- s-channel helicity violation

Vector meson production and decay



HERMES: Rho, Phi, and Omega SDME



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

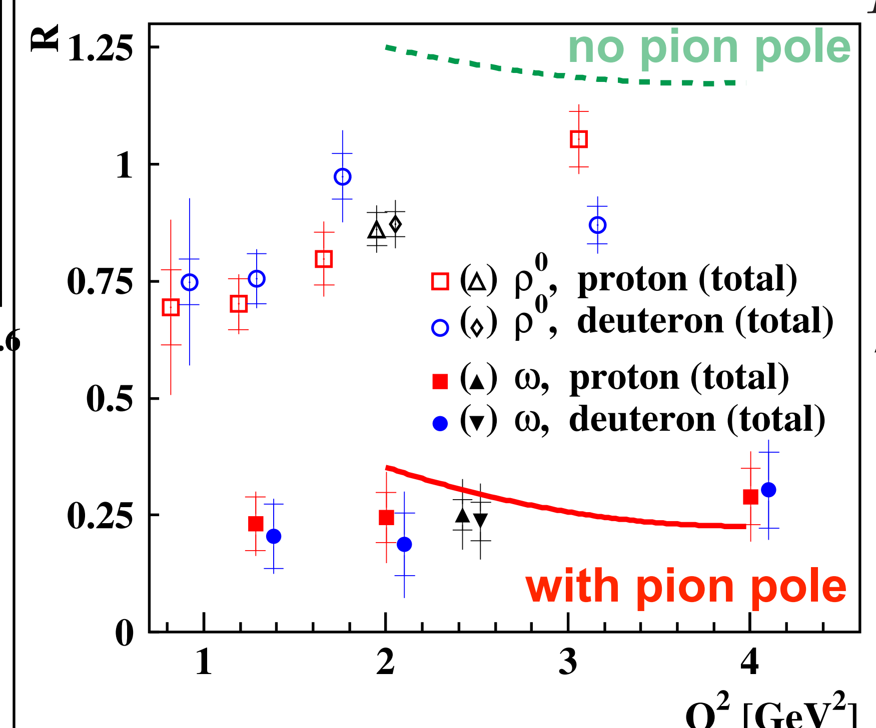
- **Φ** *(preliminary analysis)*
  - Hierarchy of amplitudes ✔
  - Helicity-conserving amplitudes 10-20% larger than for ρ^0

- **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

- Cross section ratio of longitudinal to transverse vector mesons

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



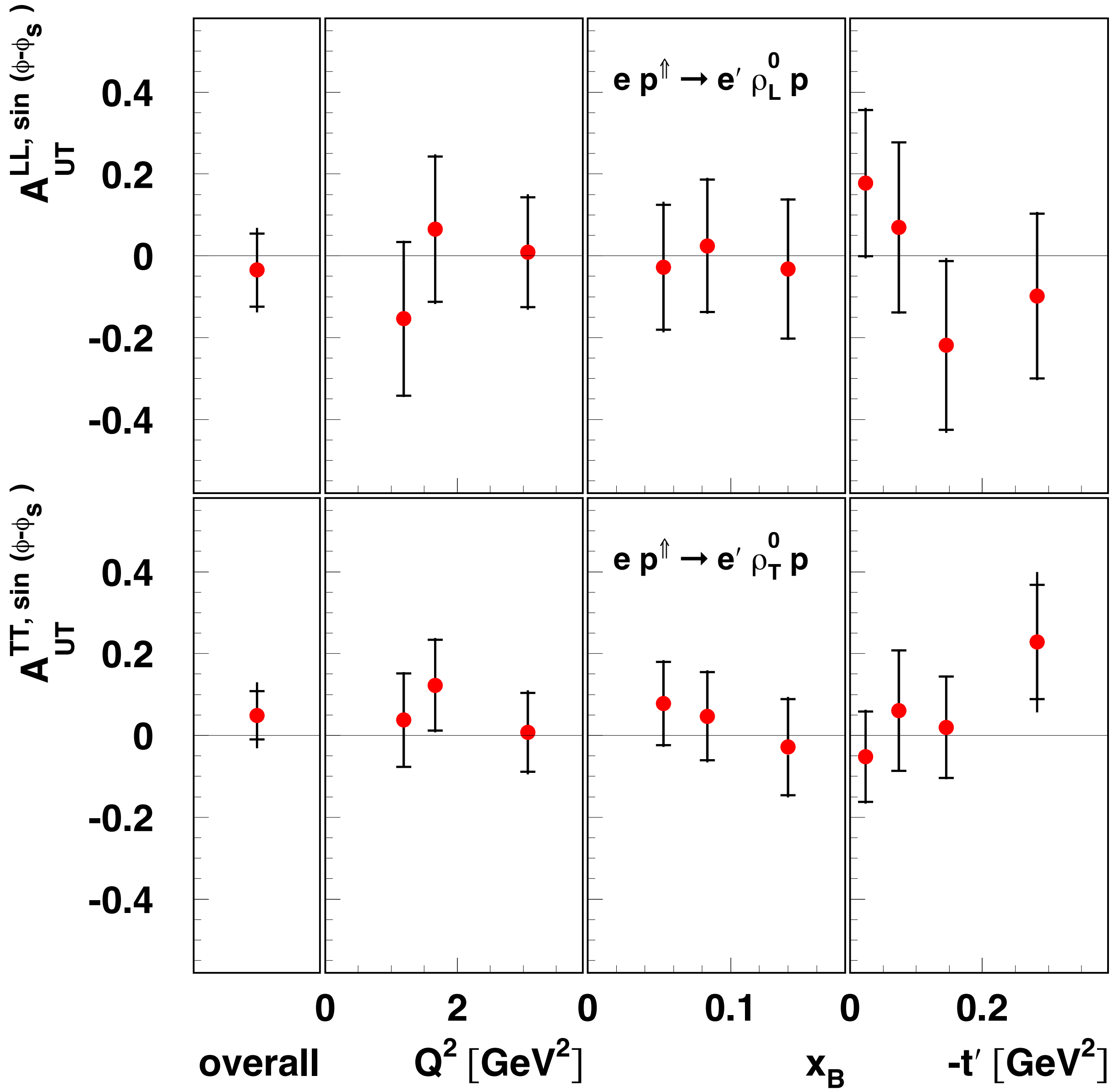
Goloskokov, Kroll, Eur. Phys. J. A (2014) 50: 146

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

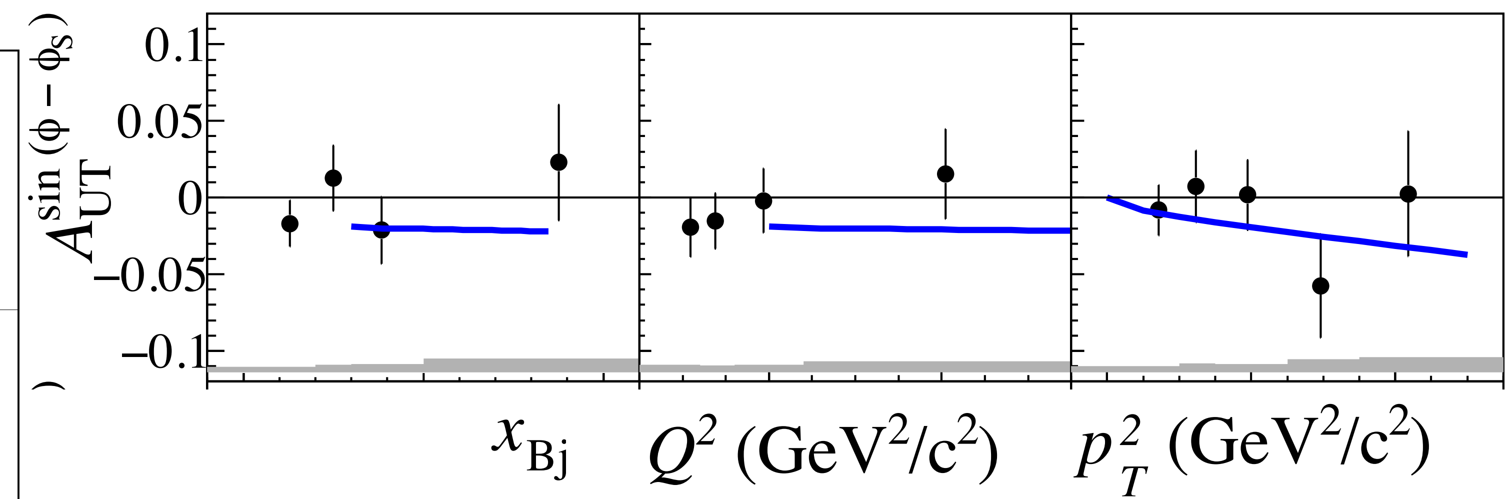
Importance of pion pole for ω production.

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

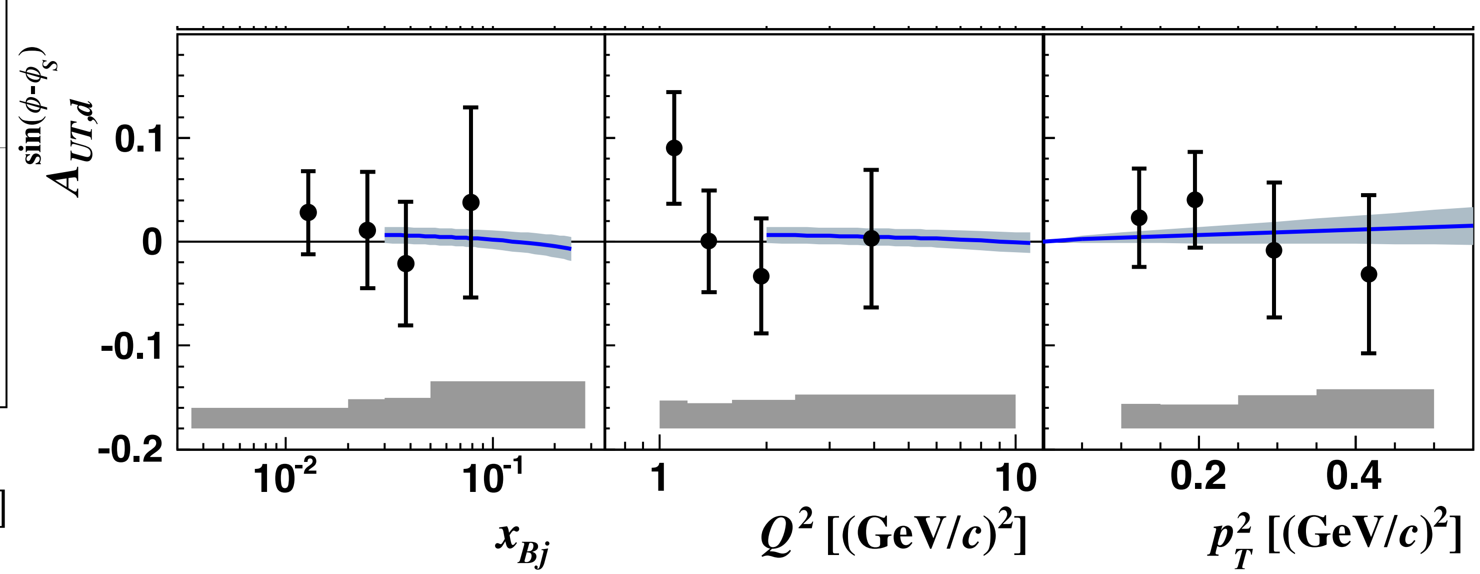
HERMES proton *Phys. Lett. B679 (2009) 100-105*



COMPASS proton *PLB B731 (2014) 19*



COMPASS deuteron *NPB 865 (2012) 1*



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

Transverse asymmetry for excl. ρ^0 & ω

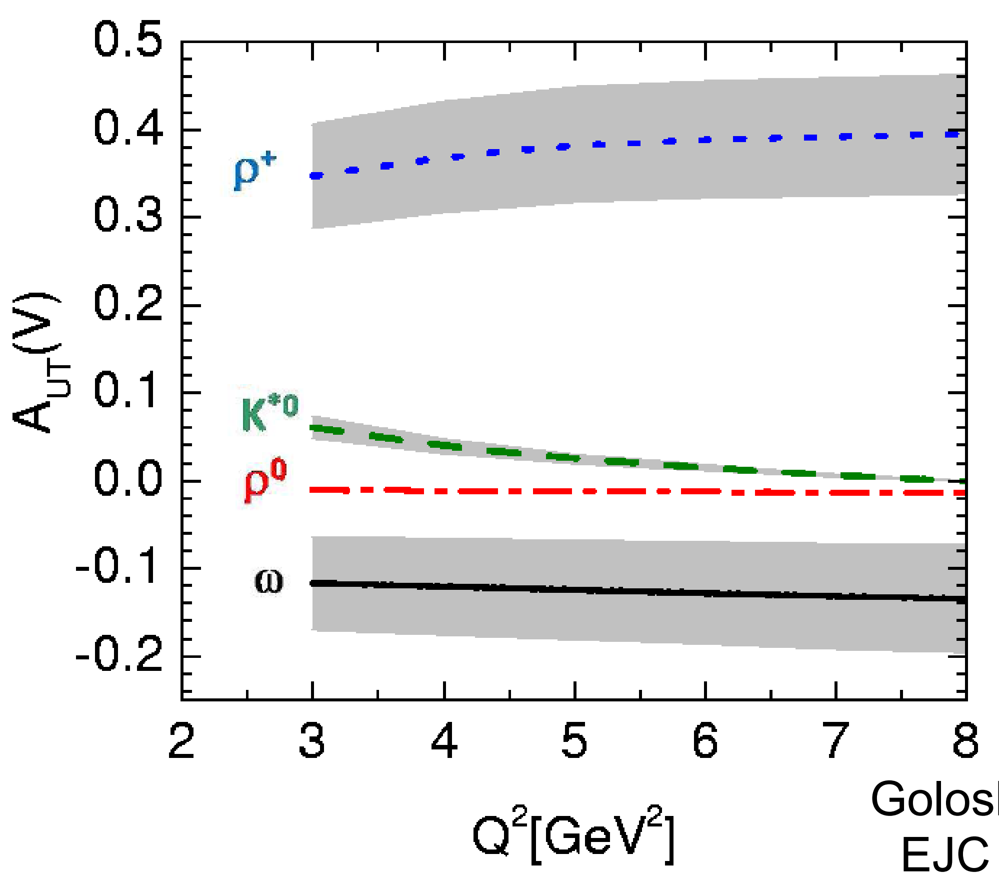
$A_{UT}^{sin(\phi-\phi_S)} \propto \mathrm{Im}\left(\mathcal{E}^\star \mathcal{H}\right)$ GPD ***E*** linked to quark orbital angular momentum.

$A_{\mathrm{UT}}^{\sin\phi_S}$ sensitive to **chiral-odd GPD *H_T*** (analogous to transversity TMD).

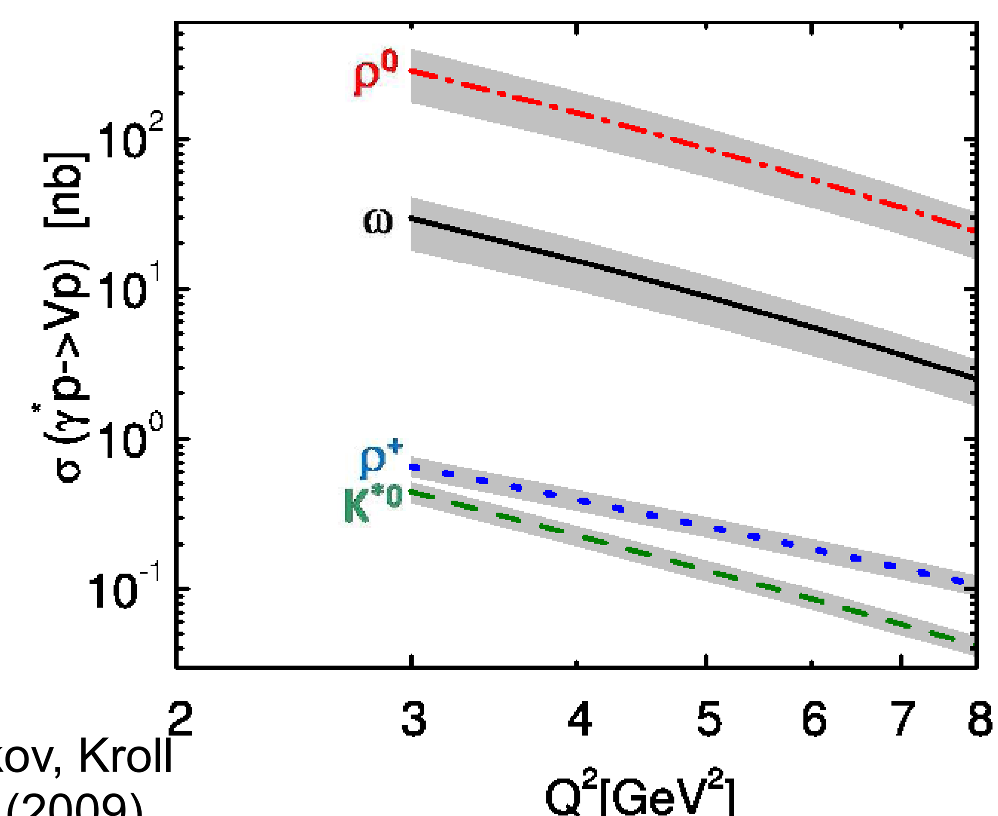
$$
\begin{aligned}
E^{\rho^0} &= 1/\sqrt{2}(2/3E^u + 1/3E^d + 3/8E^g) \\
E^{\omega} &= 1/\sqrt{2}(2/3E^u - 1/3E^d + 3/8E^g)
\end{aligned}
$$

Different mesons filter different quark flavors

Cancellation effects expected for ρ production.

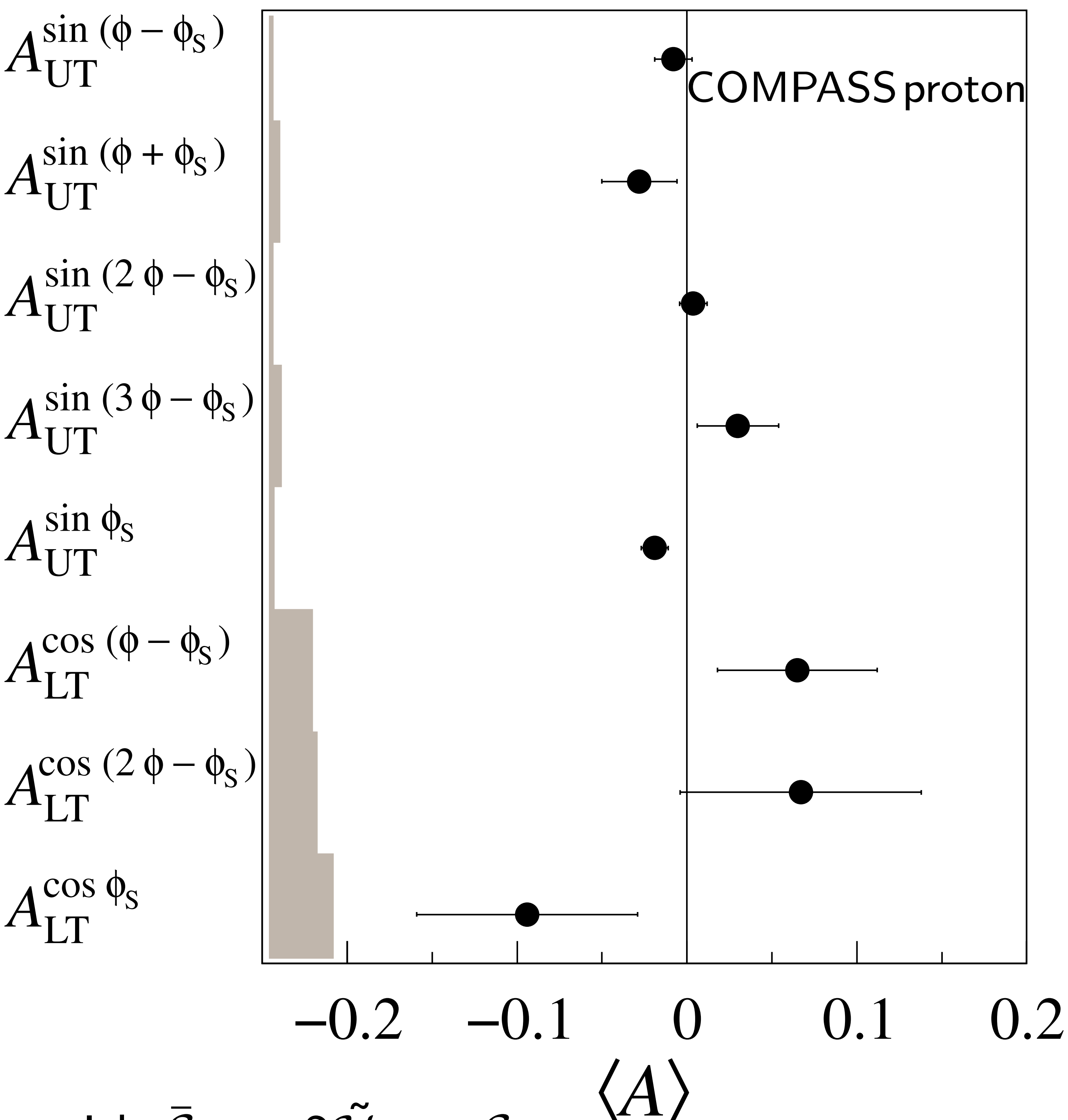


Goloskokov, Kroll
EJC 59 (2009)



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

GPDs E & H_T



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

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

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

0

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

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

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

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

- Evidence for existence of H_T

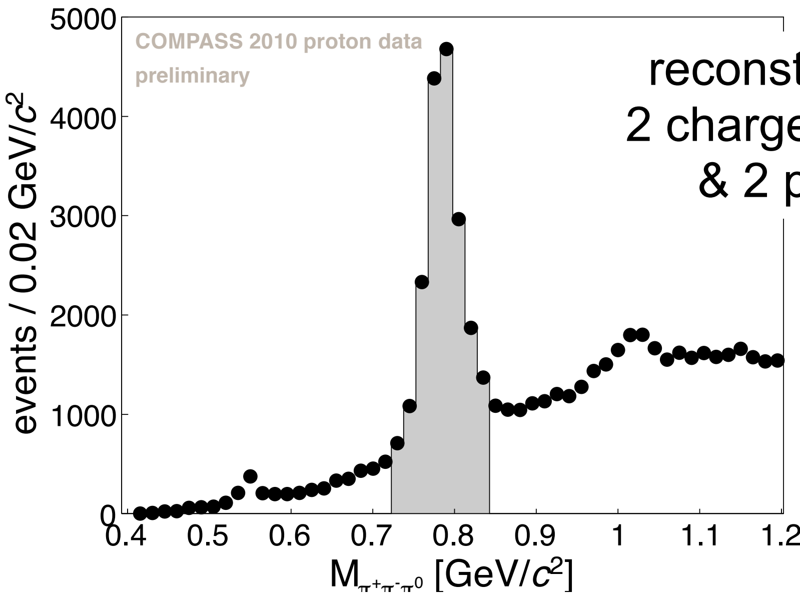
$A^{\sin \phi S}$ = –0.019 ± 0.008(stat.) ± 0.003(syst.)

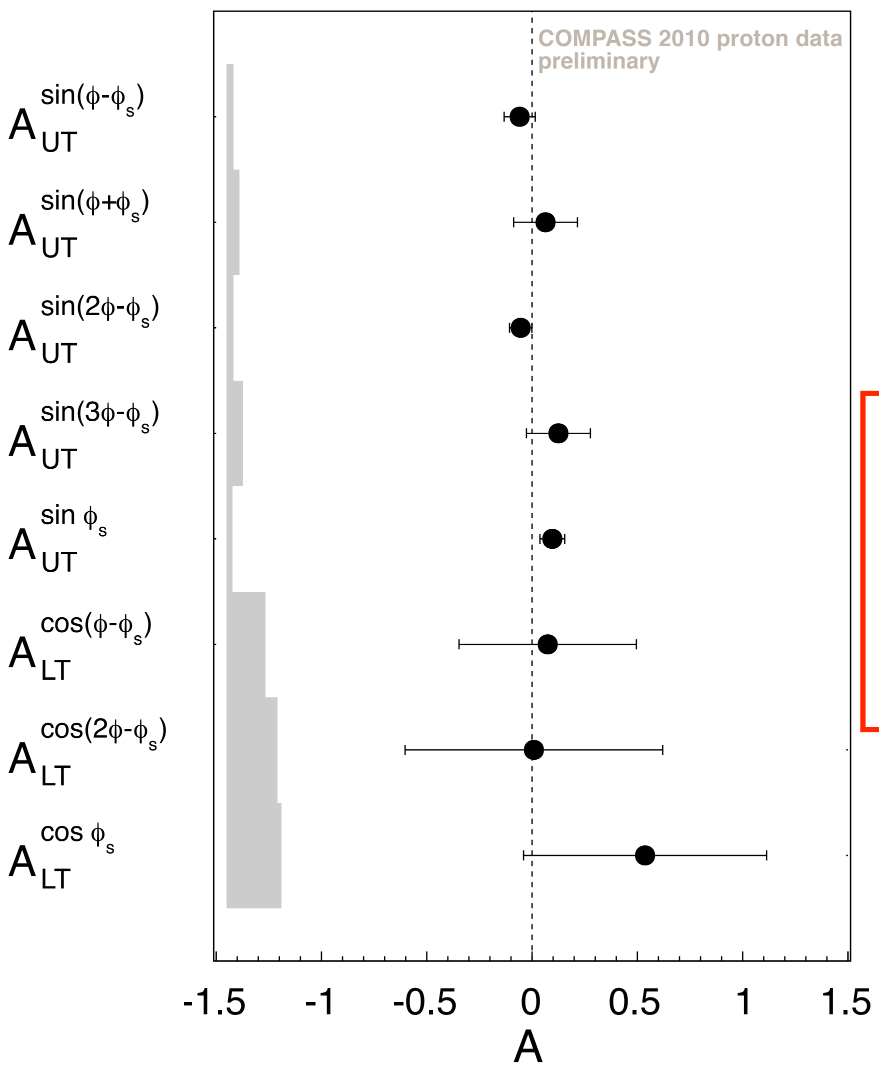
with $\bar{\mathcal{E}}_T = 2\tilde{\mathcal{H}}_T + \mathcal{E}_T$

Slide courtesy Katharina Schmidt (University of Freiburg)

All amplitudes consistent with GK 2014

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



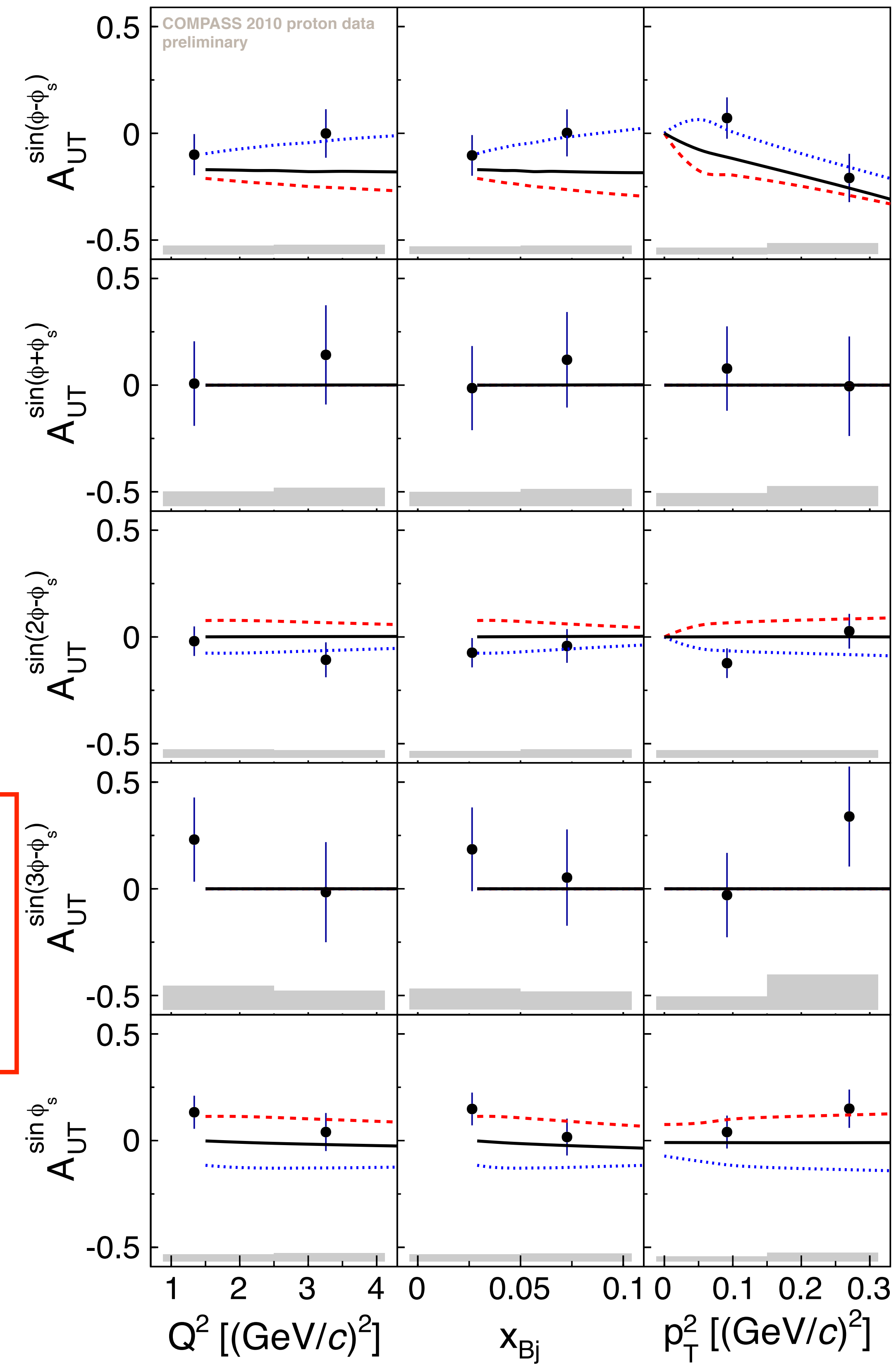


GK 2014

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

COMPASS: results do not allow unambiguous determination of $\pi\omega$ transition form factor.

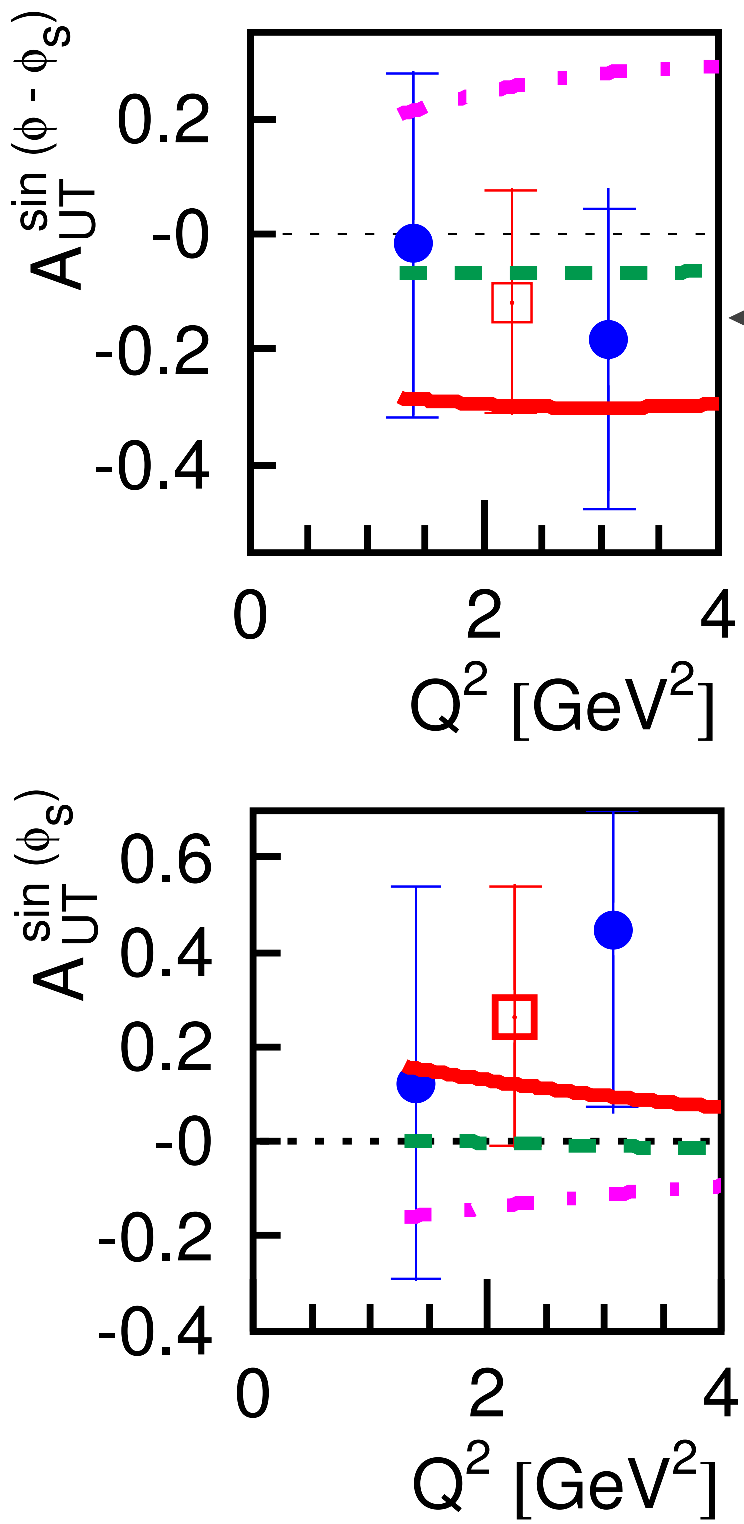
COMPASS proton *publication in preparation*

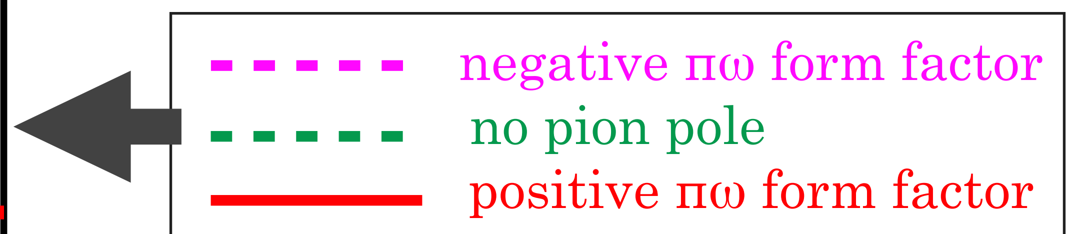


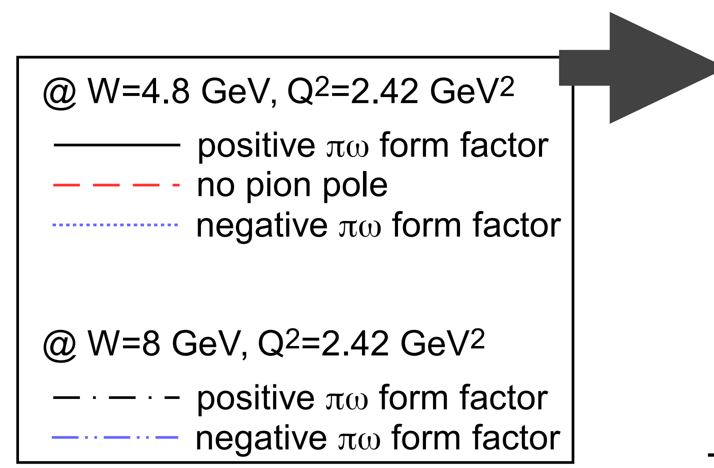
HERMES: asymmetry in $ep^{\Uparrow} \rightarrow ep\omega$

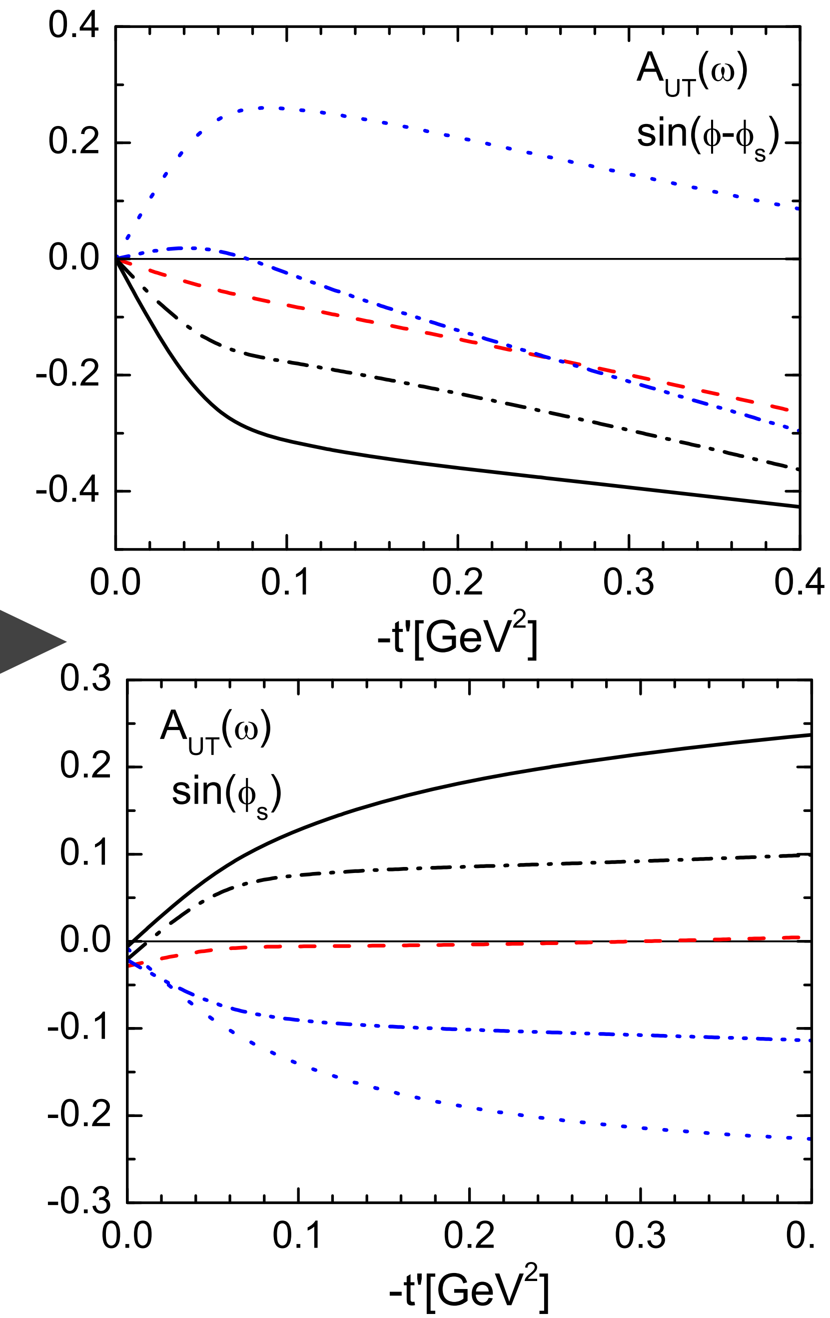
HERMES: EPJ C 75 (2015) 600

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







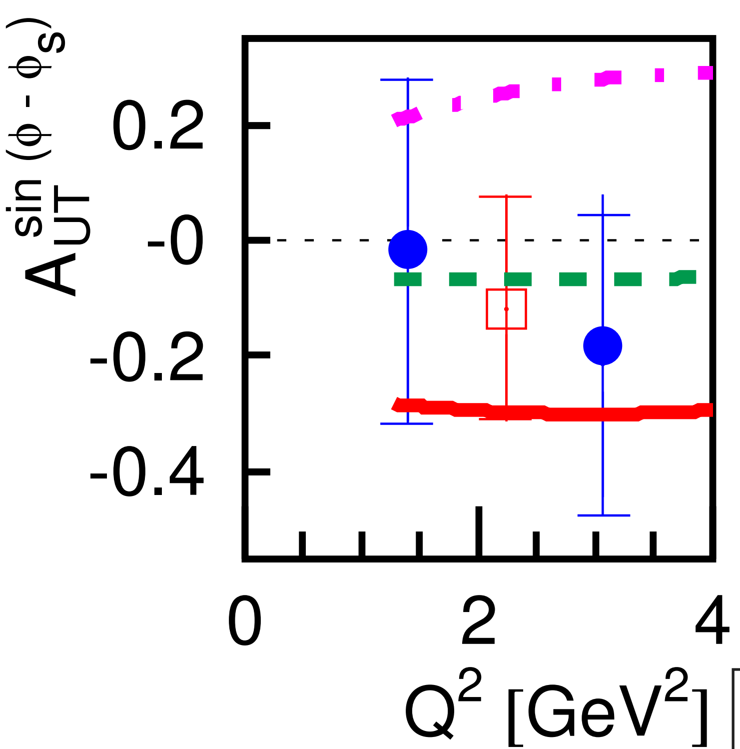


HERMES: too large experimental uncertainties to constrain sign of πω transition form factor.

Asymmetry in $lp^{\Uparrow} \rightarrow lp\omega$

GPDs E & H_T

HERMES: EPJ C 75 (2015) 600



Results do not allow unambiguous determination of πω transition form factor.

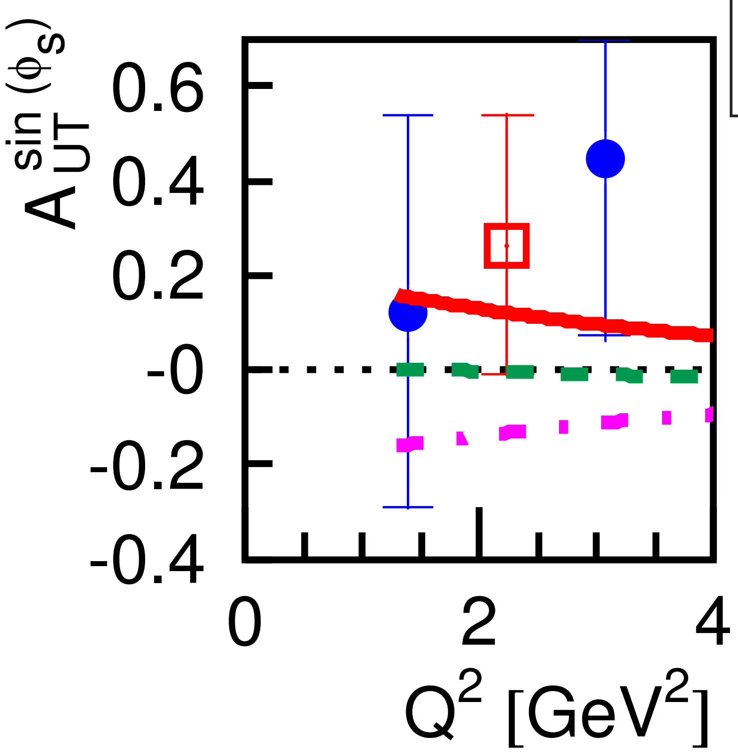
(HERMES legend)

- negative πω form factor
- no pion pole
- positive πω form factor

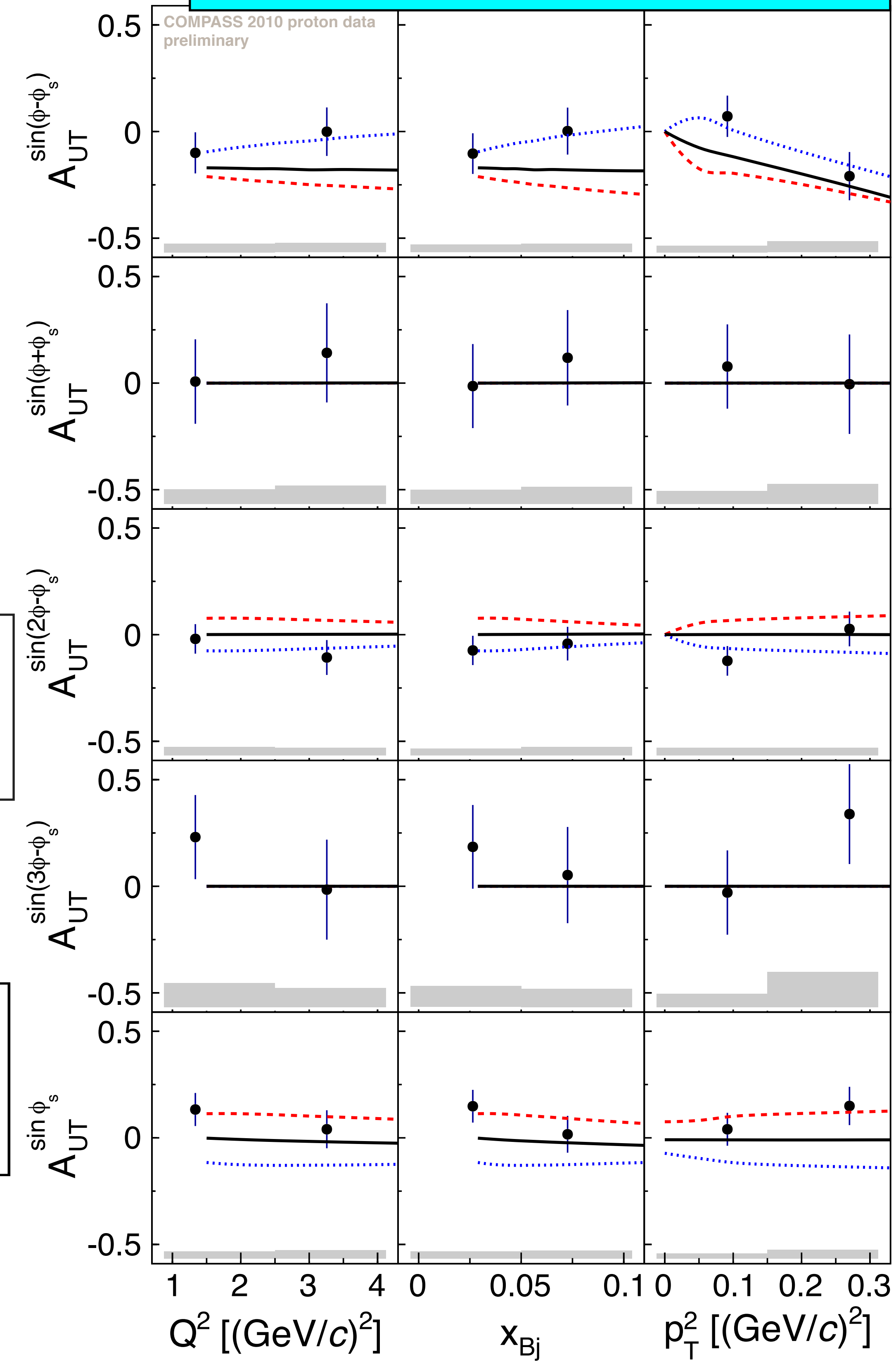
Goloskokov, Kroll, Eur. Phys. J. A (2014) 50: 146

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

(COMPASS legend)

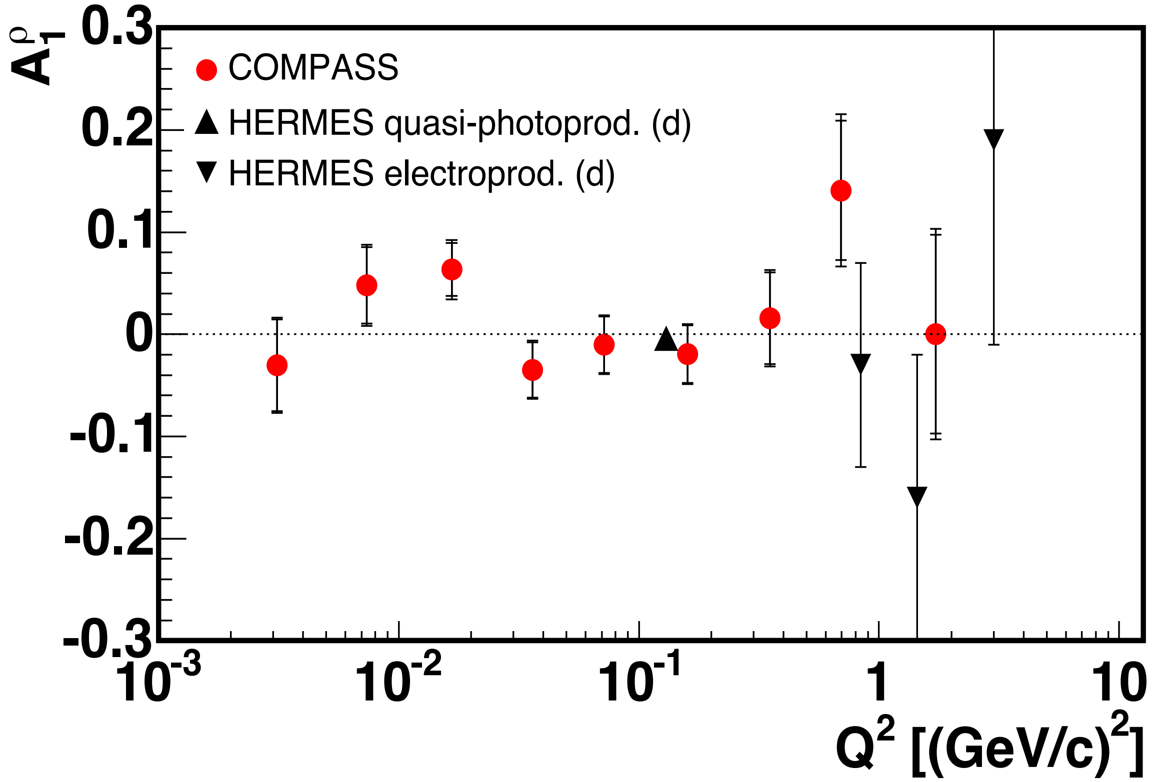


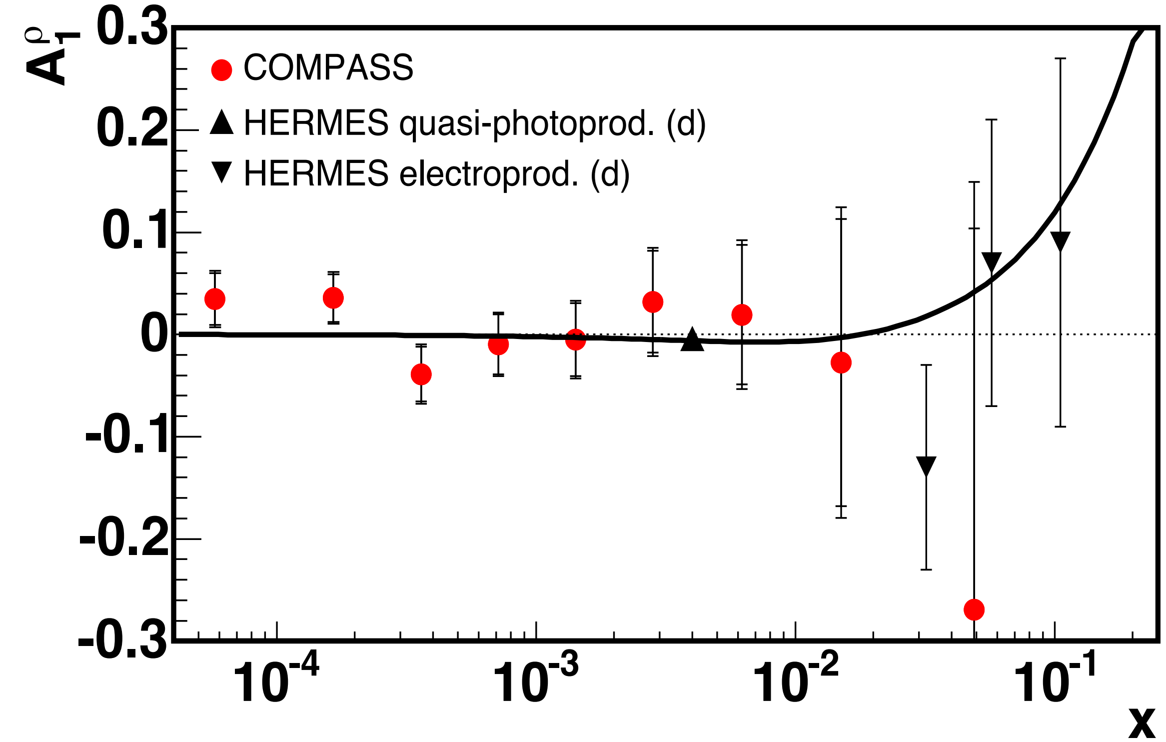
COMPASS ***publication in preparation***



COMPASS: double-spin asymmetry in diffractive $\vec{\mu}\vec{N} \to \mu N \rho^0$

COMPASS: EPJ C52 (2007) 255





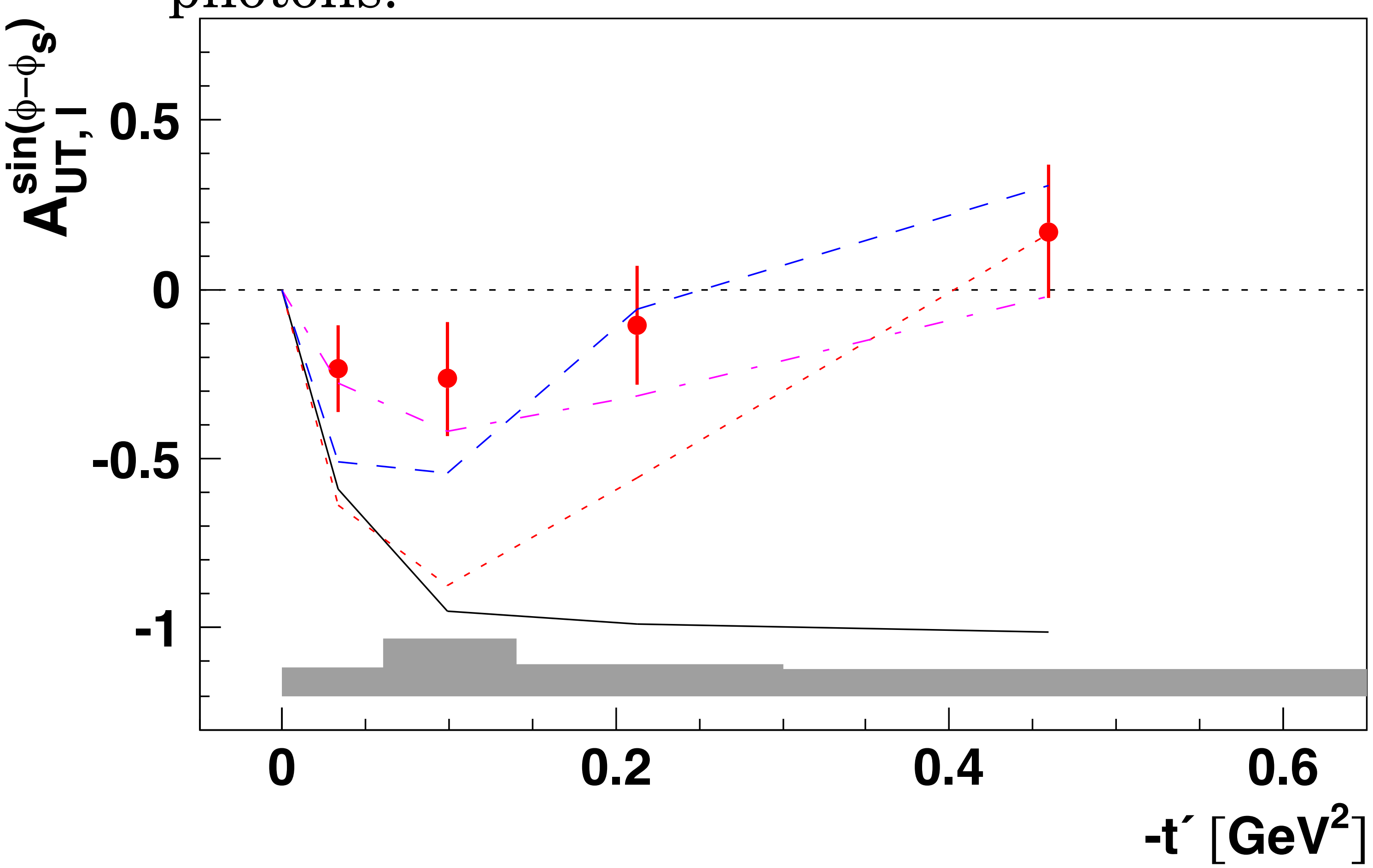
Compatible with zero ⇒ indication that role of unnatural parity exchanges (π- or A1-Reggeon exchange) is small in measured kinematical domain.

Exclusive π+ on transversely polarized protons

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

- Consistent with zero. A vanishing Fourier amplitude in this model implies the dominance (due to the pion pole) of E~ over H~ at low –t′. Excludes a pure pion-pole contribution to E~.

- sinΦS 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.

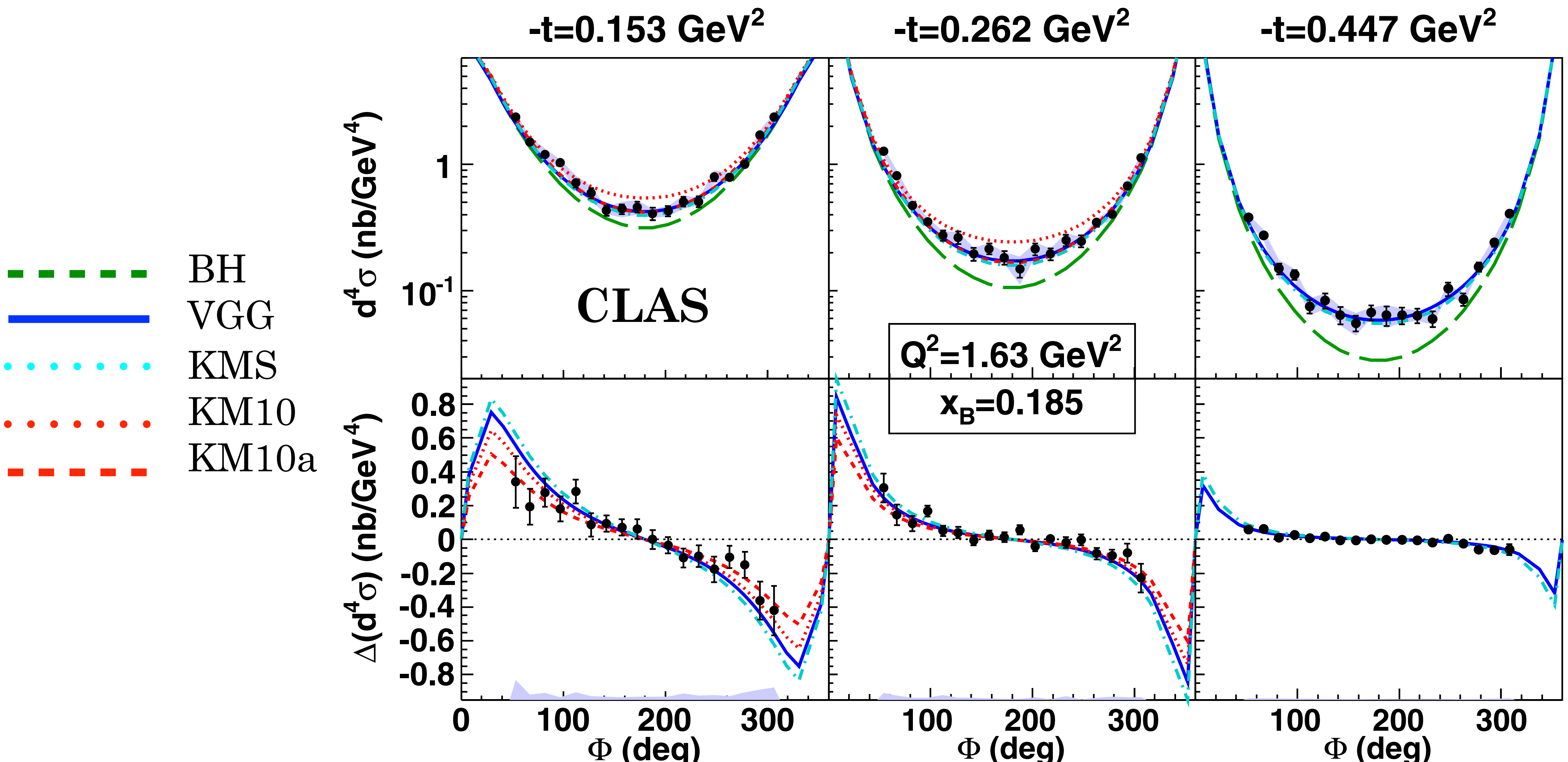
solid, dashed and dotted: Ch. Bechler and D. Müller, arXiv:0906.2571 [hep-ph]

HERMES, Phys. Lett. B 682 (2010) 345-350

Jefferson lab cross section

in the valence region

GPD H
x-section

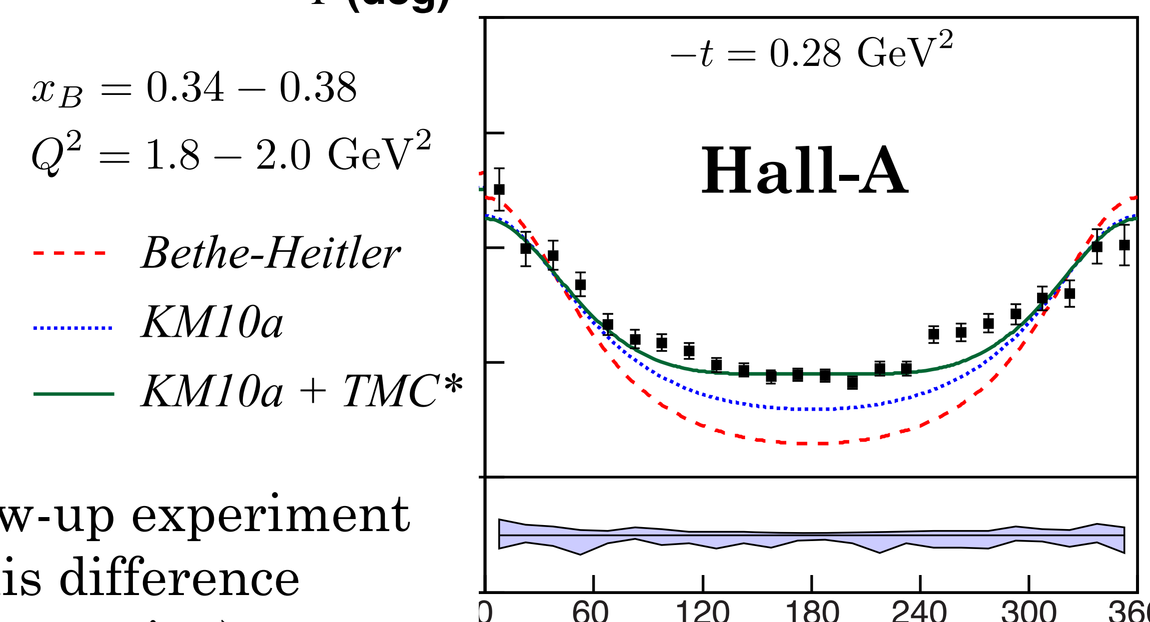


$\mathrm{d}\sigma^{\rightarrow} + \mathrm{d}\sigma^{\leftarrow}$

$\mathrm{d}\sigma^{\rightarrow} - \mathrm{d}\sigma^{\leftarrow}$

H. S. Jo et al. (CLAS coll.), PRL 115, 212003 (2015)

- Deviation from pure BH, attributed to $DVCS^2$ or BH-DVCS. Larger @Hall-A.
- No Q2 dependence, compatible with the **dominance of the leading-twist diagram** in this region of moderate Q^2 and x_B.

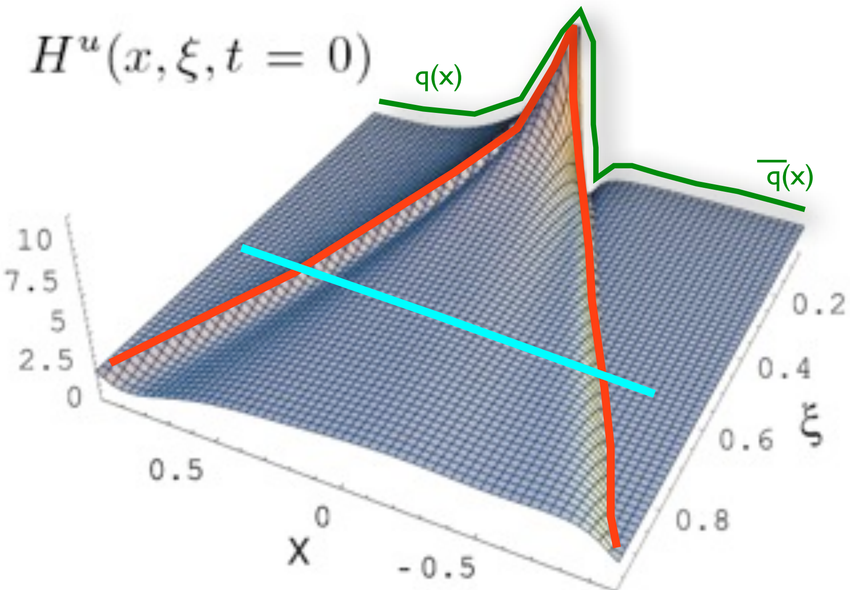


Hall A: Phys.Rev. C 92, 055202 (2015)

Hall A: PRL 97, 262002 (2006)

Hall-A-E07-007: follow-up experiment to investigate this difference (Rosenbluth separation)

Hall A (E00-110): cross section in the valence quark region



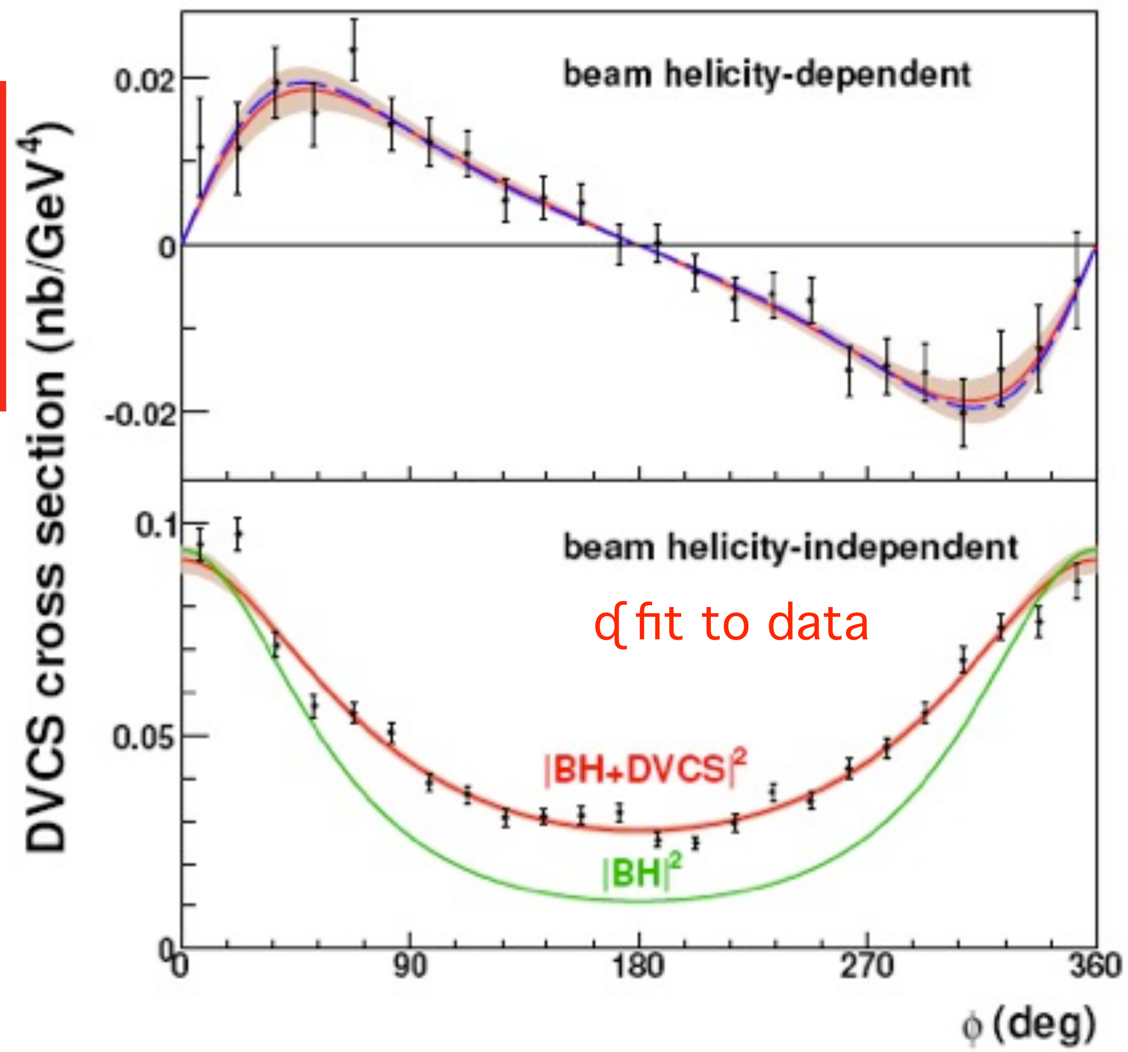
Goeke, Polyakov, Vanderhaeghen, hep-ph/0106012

Δσ
helicity-dependent
➥ Im(τ_{DVCS})
GPDs @ x=ξ

Σσ
helicity-independent
➥Re(τ_{DVCS})
integral of GPDs over x

Differential cross section vs. azimuthal angle

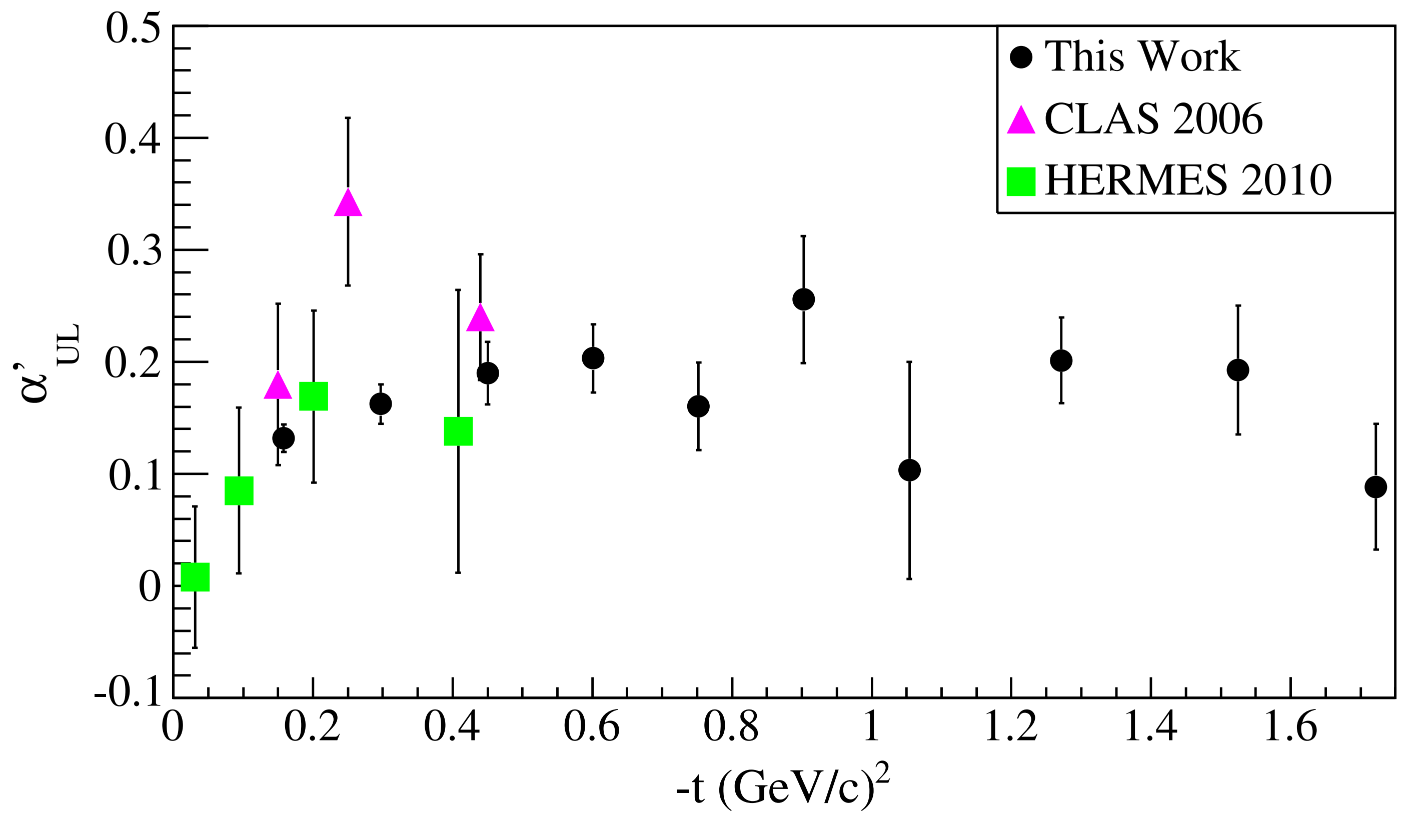
Bin: $\langle x_B \rangle=0.36$, $\langle Q^2 \rangle=2.3$ GeV^2, $\langle t \rangle=-0.28$ GeV^2

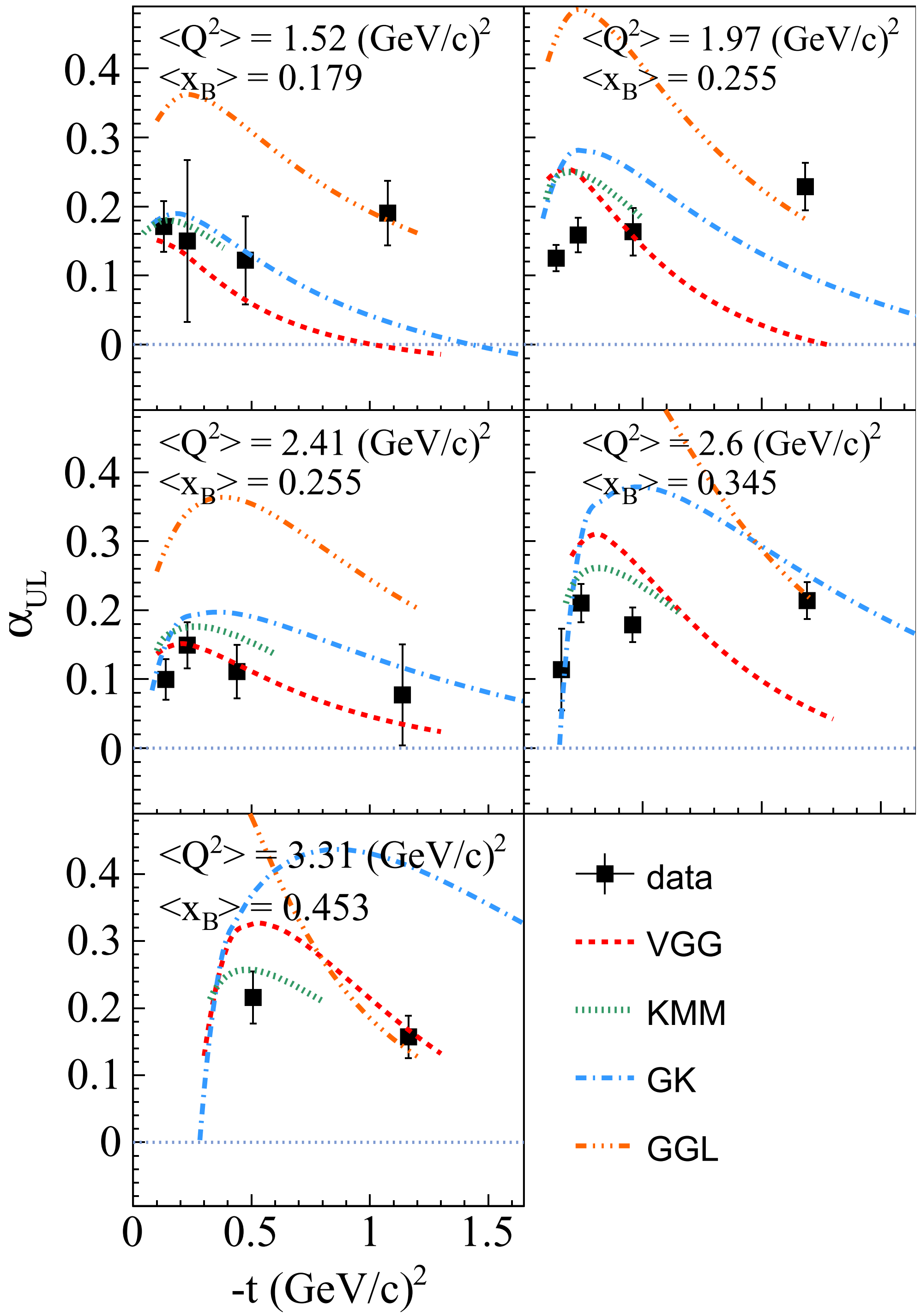


- Twist-2 (“handbag”) dominance
  ☛ GPDs accessible at moderate Q^2.
- No Q^2 dependence of Im(I) over 1.5, 1.9 and 2.3 GeV^2
  ☛ Indication of perturbative QCD scaling behavior.

Hall A: Phys. Rev. Lett. 97, 262002 (2006)

CLAS (eg1-dvcs): DVCS longitudinal target spin asymmetry





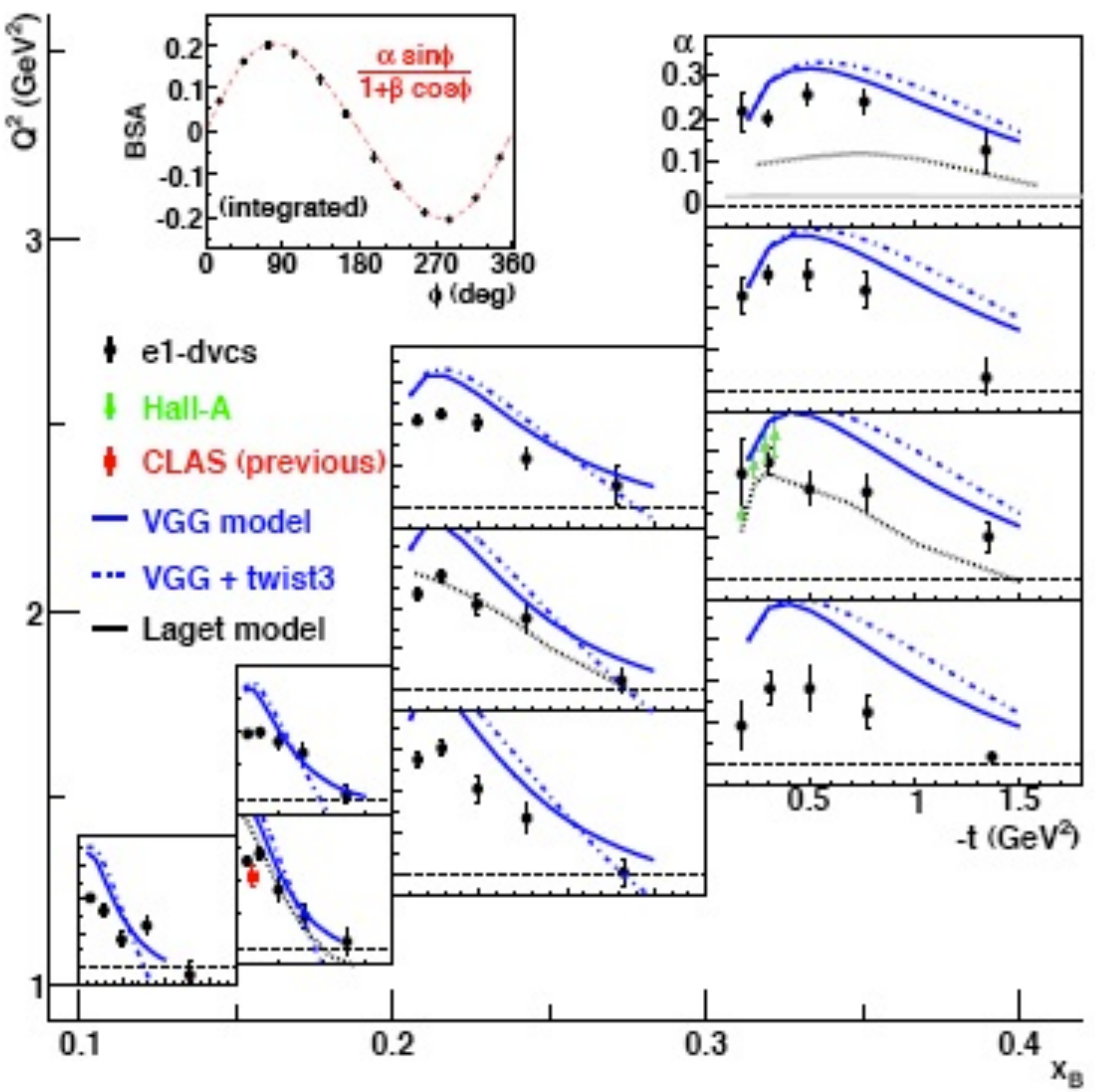
CLAS (E. Seder et al.), PRL 114, 032001 (2015)
CLAS (S. Pisano et al.), PRD 91, 052014 (2015)

HERMES: JHEP 06 (2010) 019

CLAS (e1-dvcs): beam-helicity asymmetry

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

CLAS: $\langle Q^2 \rangle = 1.82\ GeV^2$, $\langle x_B \rangle = 0.28$, $\langle -t \rangle = 0.31\ GeV^2$



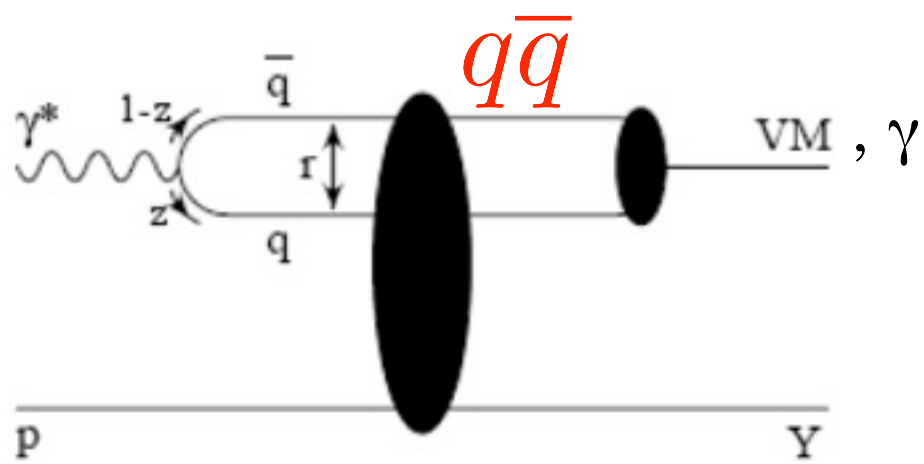
- Data taken with inner electromagnetic calorimeter for the detection of the BH/DVCS photon
- VGG Model overshoots data.

GPD model calculation
"VGG" (Vanderhaeghen, Guidal, Guichon):
Phys. Rev. D60 (1999) 094017 and
Prog. Nucl. Phys. 47 (2001) 401

CLAS: PRL 100 (2008) 162002

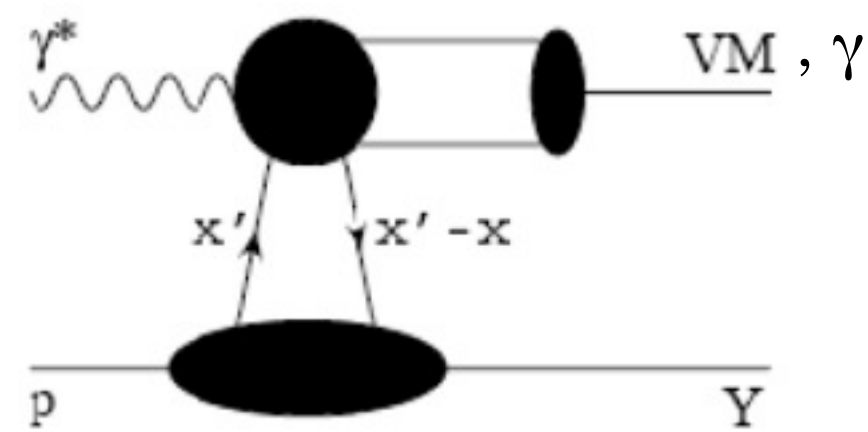
Hard exclusive reactions

High energy factorization



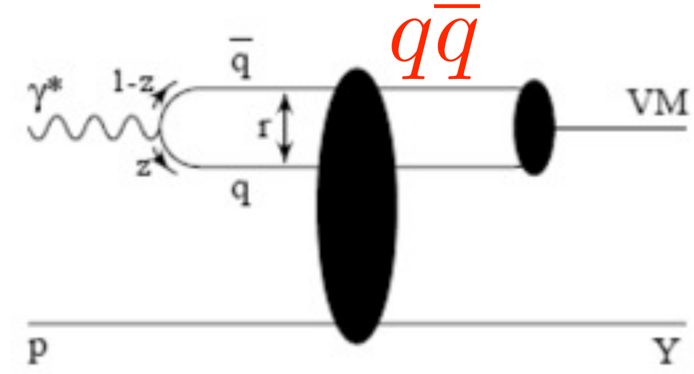
- Universal dipole interactions
- Low x ↔ large W
- Scale: $Q^2 + m_V^2$

Collinear factorization

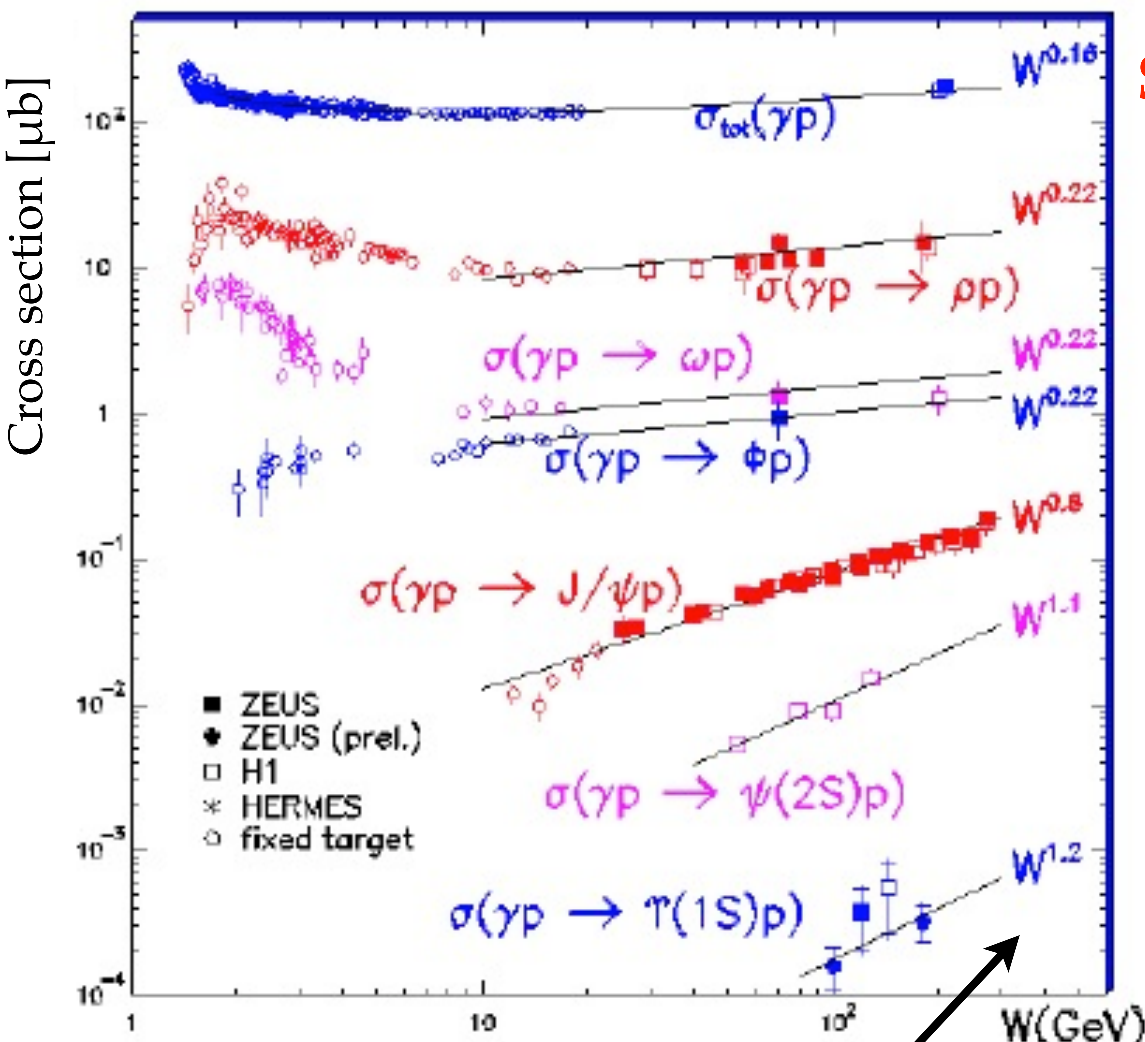


- Parameterization of non-perturbative nucleonic structure
- Information on parton-parton correlations
- VM: proven only for $\sigma_{Longitudinal}$

Photoproduction ep→epV: kinematic landscape



$\sigma(W) \propto W^{\delta}$



A. Levy, arXiv:0907.2178

$d\sigma/dt \propto [xg(x,Q^2)]^2$

$q\bar{q}$ size

M_V, ⟨W⟩

HERA sees interplay between soft and hard

ϱ, ω, ϕ δ=0.2 b=10 GeV^{-2} **SOFT** Regge, soft pomeron exchange

J/Ψ, ϒ δ≥0.8 b=4-5 GeV^{-2} **HARD** pQCD, 2-gluon exchange

(extraction of **effective Pomeron trajectory**)

$d\sigma/dt \propto \exp(-b\|t\|)$	$d\sigma/dt \propto \|t\|^{-n}$
small	large

1 GeV² → **t**

HERA (H1 and ZEUS): cross section in the sea/glue region

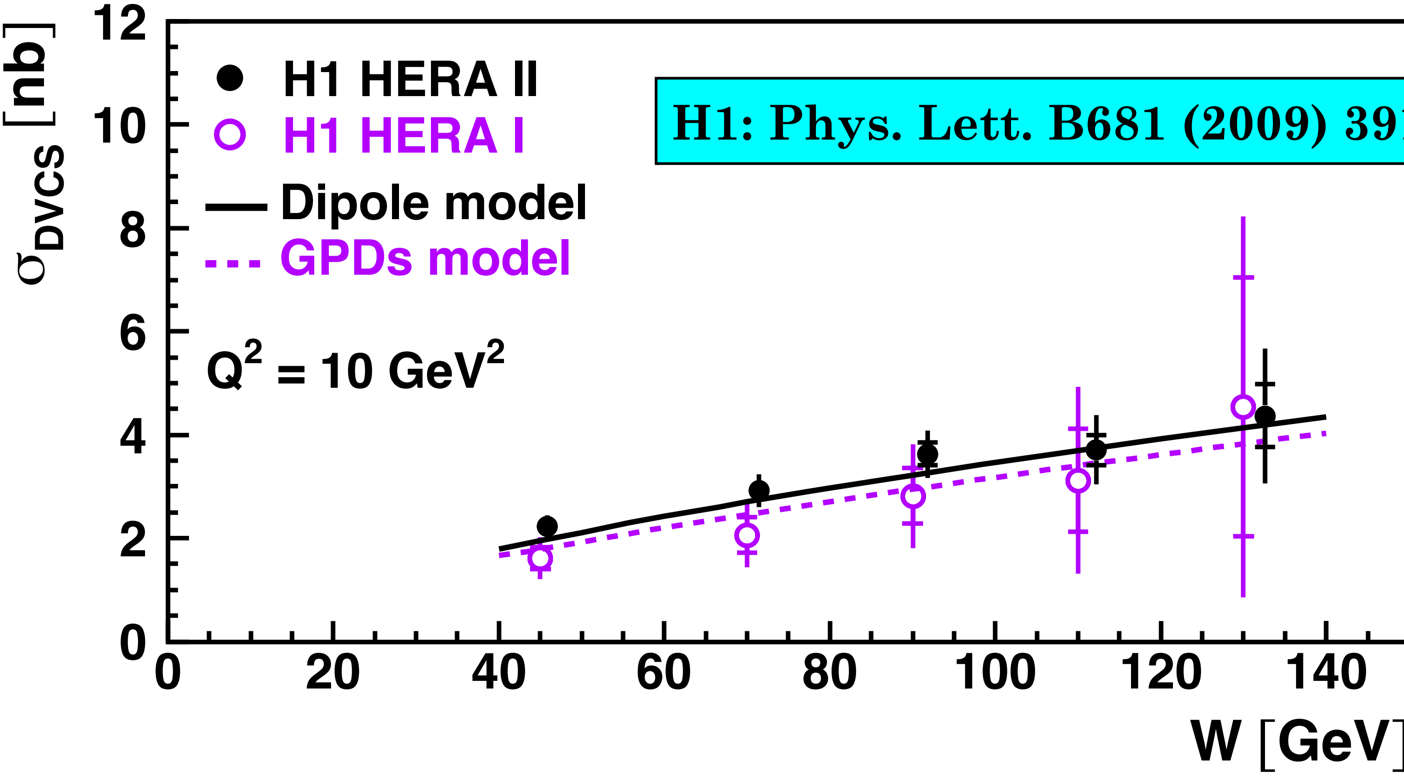
GPD H
x-section & t-slope

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

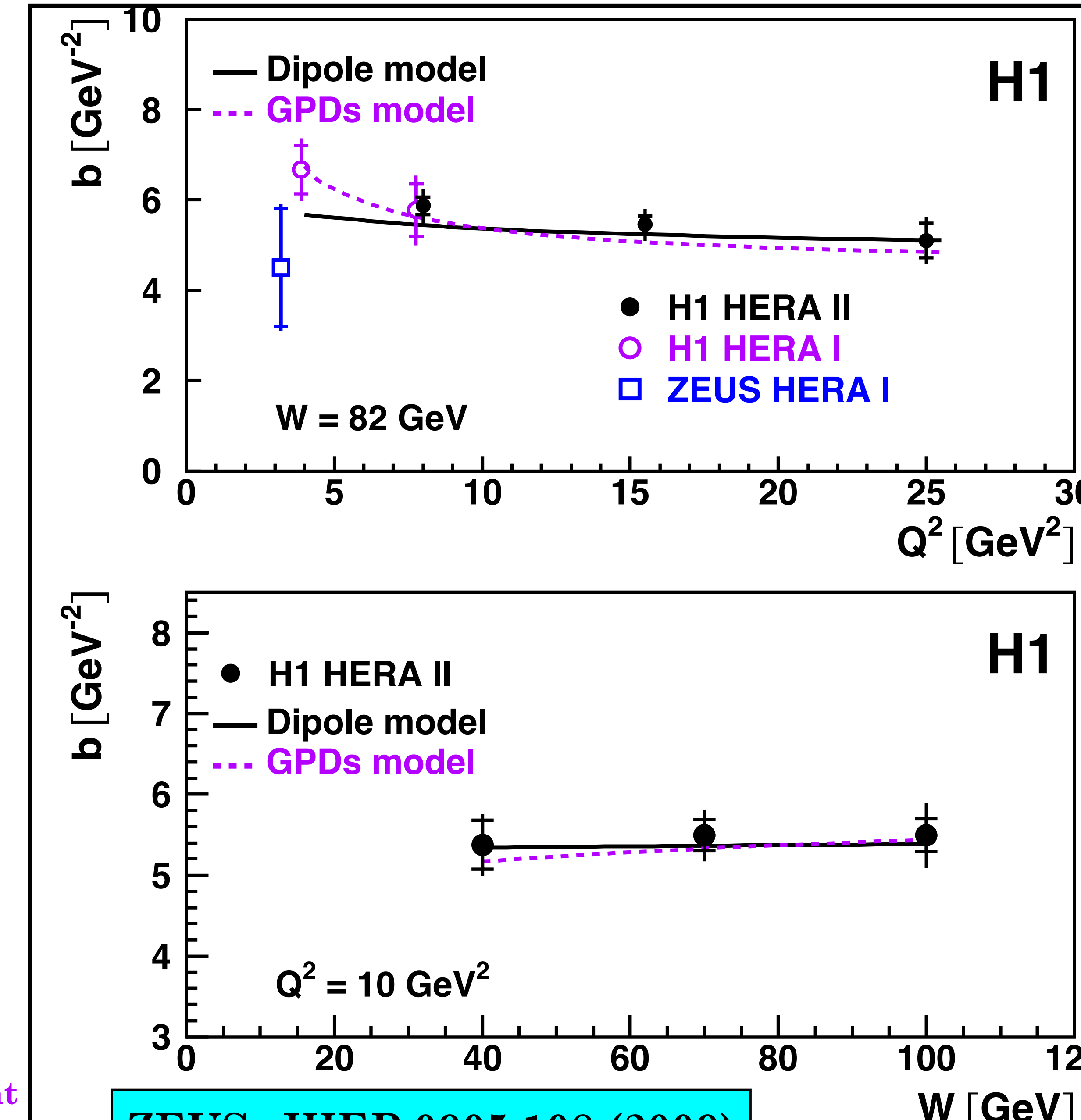
t-slope: average impact parameter

Description of transverse extension of partons in the proton
$\sqrt{\langle r_T^2 \rangle} = (0.65 \pm 0.02)$ fm @ $x_B = 10^{-3}$

Steep W-dependence: $\sigma(W) \propto W^{\delta}$ with $\delta \approx 0.7$
DVCS is hard process, gluons resolved.



H1: Phys. Lett. B681 (2009) 391

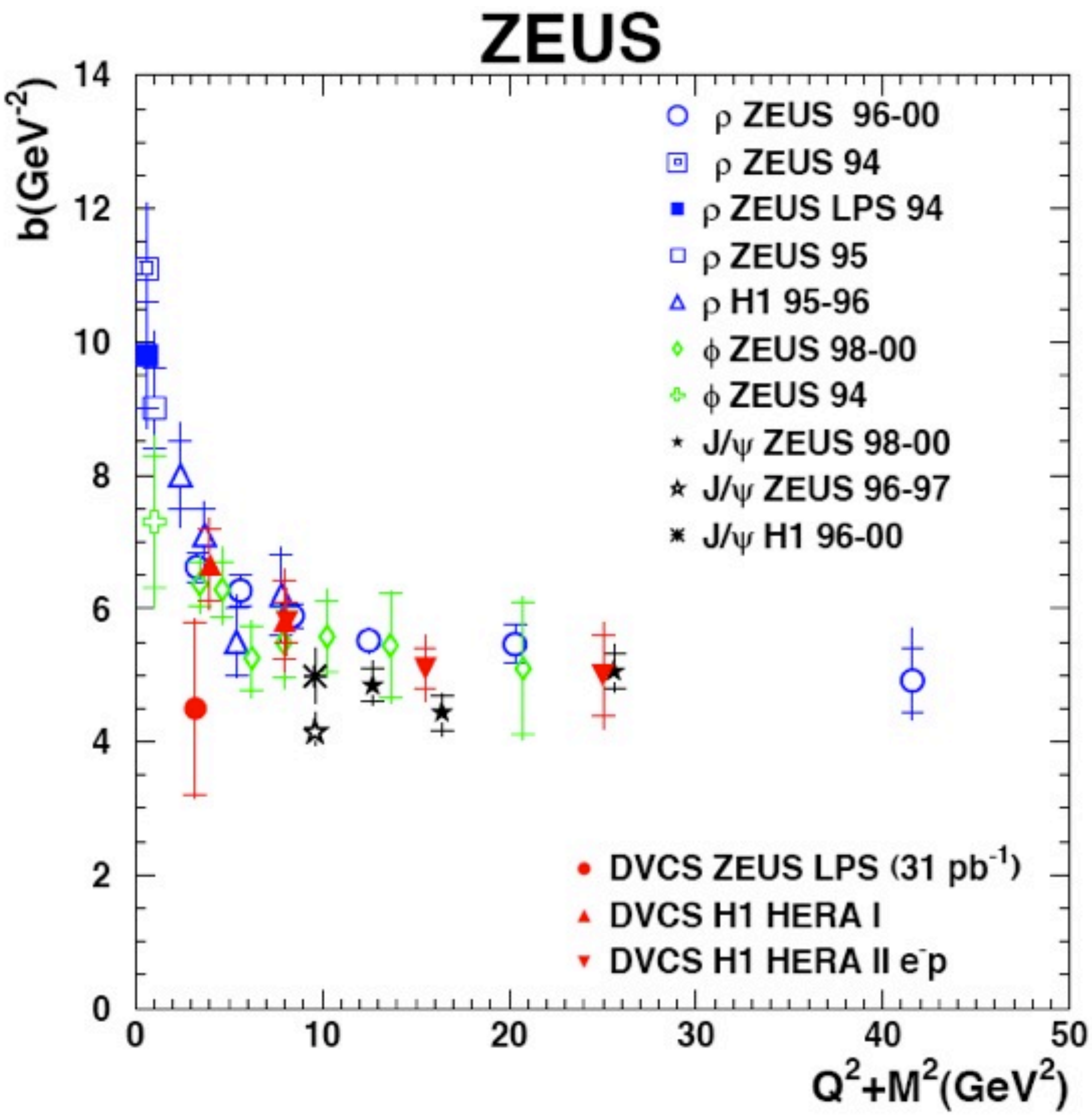


ZEUS: JHEP 0905:108 (2009)

GPD model: K. Kumericki, D. Müller, fit to previous HERA measurement

Dipole model: C. Marquet, R. Peschanski, G. Soyez, hep-ph/0702171

HERA: t-slopes



ZEUS arXiv:0812.2517

- Slope from differential cross section in exclusive vector-meson production

$$\frac{d\sigma}{dt} = e^{-b|t|}$$

- b measures transverse size of VM $\oplus$ nucleon
- VM shrinks with increasing photon virtuality
- Universal value of b $\approx$ 5 GeV^{-2} at large scale

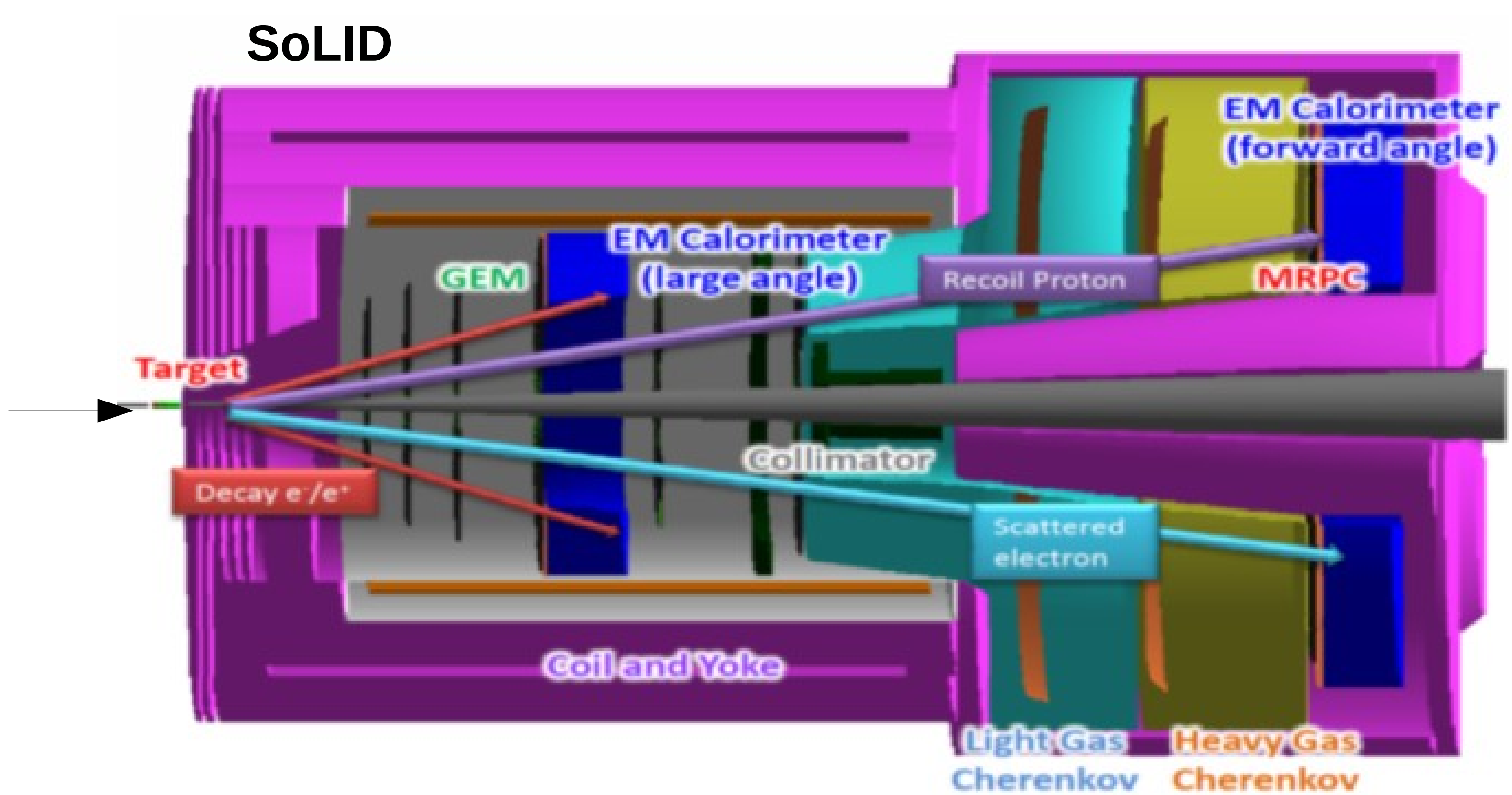
TCS & DDVCS @ JLab12

The results from the TCS studies with tagged real photons and quasi-real photons can be used as a basis for the development of a program at 12 GeV Jefferson Lab. The […] **CLAS12** detector […] will be ideal for **TCS measurements** with **quasi-real photons with circular polarization**. […] With the addition of a low-Q2 tagger, it could also be possible to study the reaction with incoming photons having linear polarization and a small, but finite virtuality (**double DVCS**). […] It would […] be of great interest to compare with a hermetic detector such as the **GlueX** detector constructed in Hall D at 12 GeV Jefferson Lab. This natural extension of the TCS measurements in Hall B would also provide access to **linearly polarized tagged real photons**.

JLab12 PR12-12-001 proposal: *In addition to discriminating between GPD models and constraining fits of CFFs, a measurement of* ***TCS*** *may also offer a unique possibility to address the issue of the* ***so-called D-term****. Technically, the D-term is defined as the contribution to the GPD H that provides the highest power of ξ in Mellin moments of this GPD. The D-term of the GPD E has the same magnitude but opposite sign. The D-term contribution to GPDs has support only in the region $x \in [-\eta, \eta]$, which makes it elusive and inaccessible in the forward limit. This unambiguously indicates that the D-term cannot be interpreted in terms of the usual parton densities. Instead, the D-term describes the emission of a $q\bar{q}$ pair by the nucleon, revealing the complex nature of the nucleon as a many-body system.*

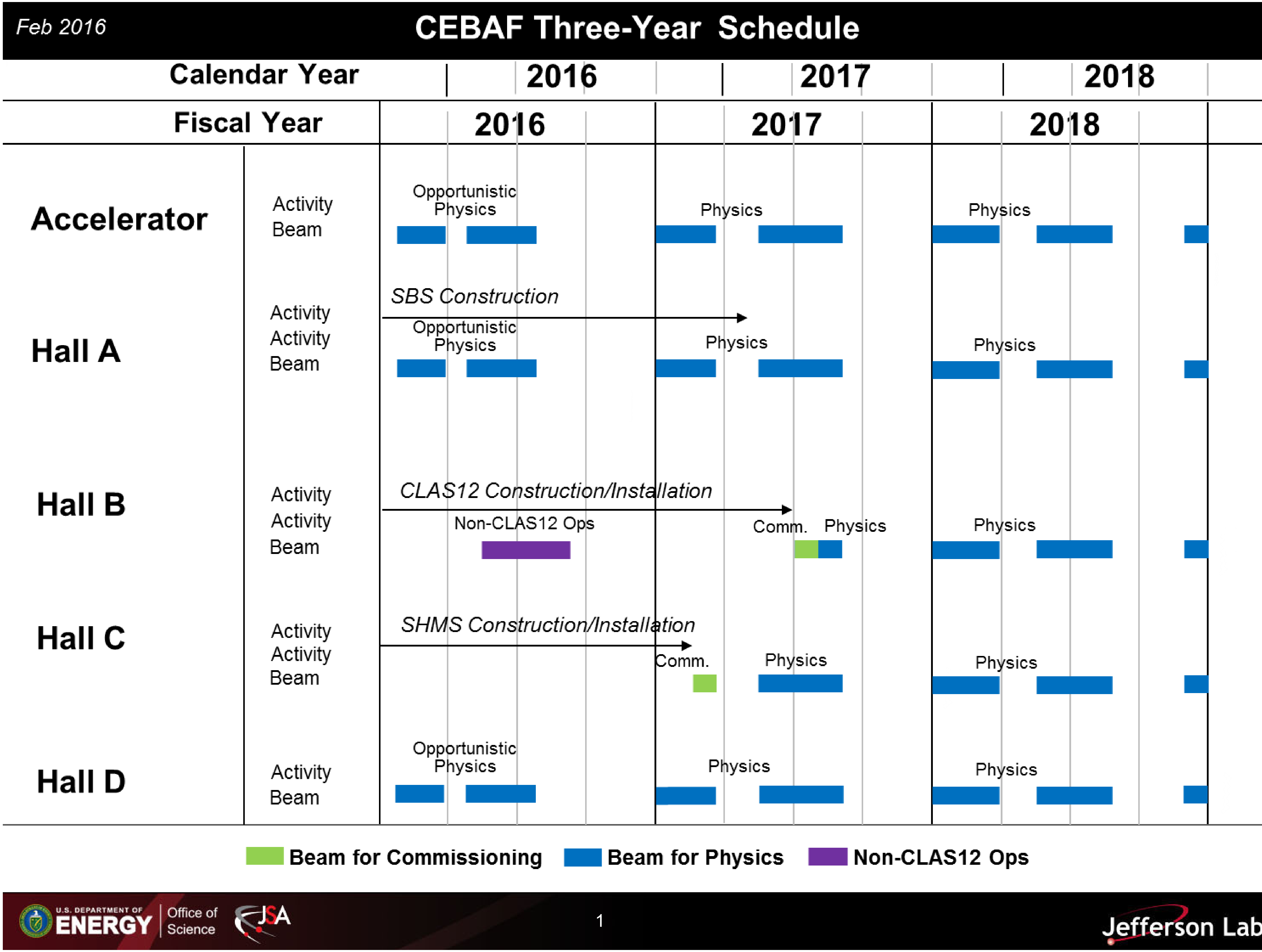
DDVCS @ JLab12

LOI12-15-005 (May 2015): *This letter proposes to investigate the DDVCS process $ep \to ep\gamma*$ at 11 GeV incident beam energy in the di-muon channel ($ep\gamma* \to ep\mu+\mu-$) with the SoLID spectrometer supplemented with muon detectors. The experiment would develop according to a parasitic step followed by a dedicated running period. [...] The dedicated run would involve a strong luminosity increase together with a specific detector configuration to take advantage of the full potential of DDVCS for GPDs phenomenology at 11 GeV.*

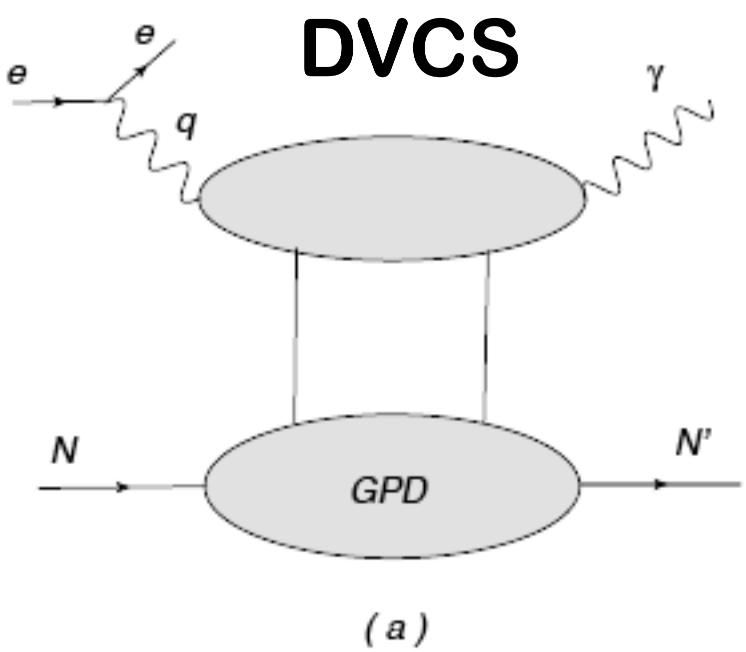


+ CLEO
muons chamber

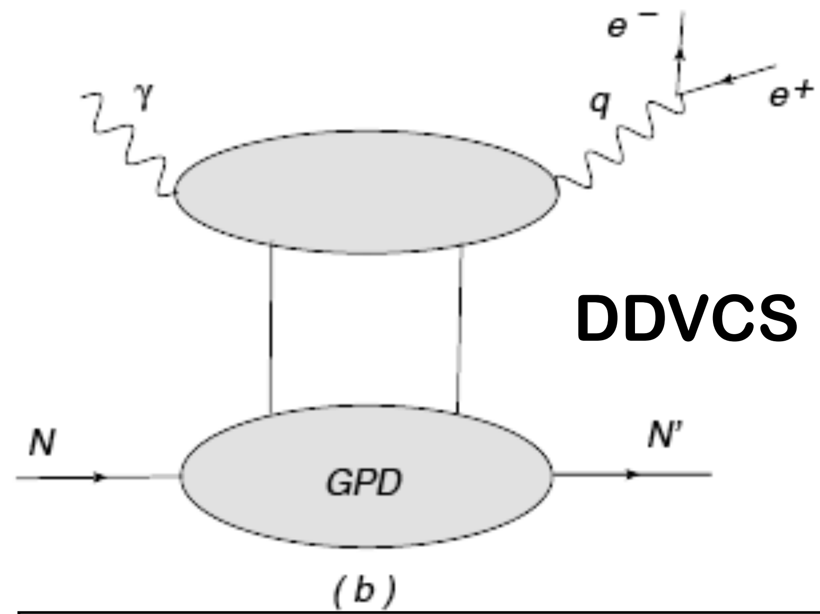
Marie Boër, IPN Orsay, France V. Experimental perspectives. August 18, 2015 36


Feb 2016
CEBAF Three-Year Schedule
Calendar Year
2016
2017
2018
Fiscal Year
2016
2017
2018
Accelerator
Activity
Beam
Opportunistic Physics
Physics
Physics
Hall A
Activity
Activity
Beam
SBS Construction
Opportunistic Physics
Physics
Physics
Hall B
Activity
Activity
Beam
CLAS12 Construction/Installation
Non-CLAS12 Ops
Comm.
Physics
Physics
Hall C
Activity
Activity
Beam
SHMS Construction/Installation
Comm.
Physics
Physics
Hall D
Activity
Beam
Opportunistic Physics
Physics
Physics
Beam for Commissioning
Beam for Physics
Non-CLAS12 Ops
U.S. DEPARTMENT OF ENERGY
Office of Science
JSA
1
Jefferson Lab

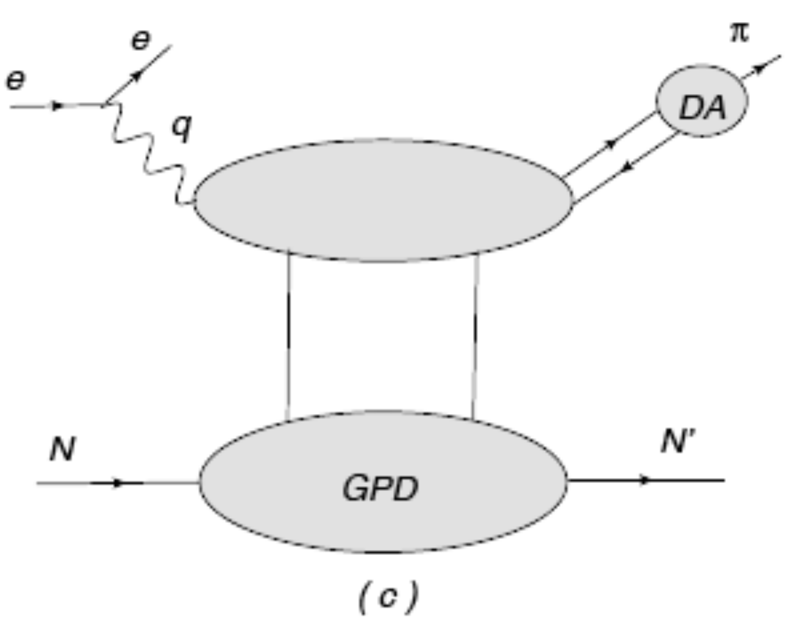
Time-like and space-like hard exclusive reactions



(a)



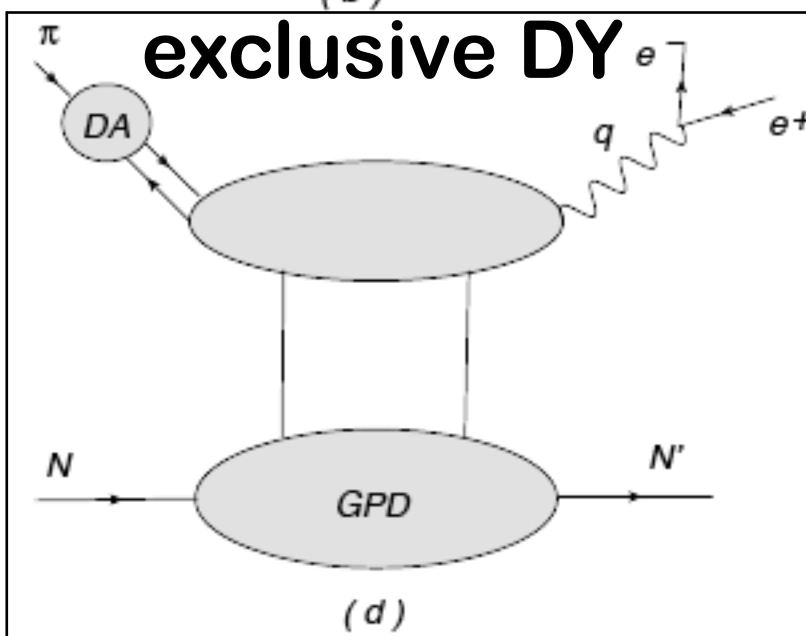
(b)



(c)

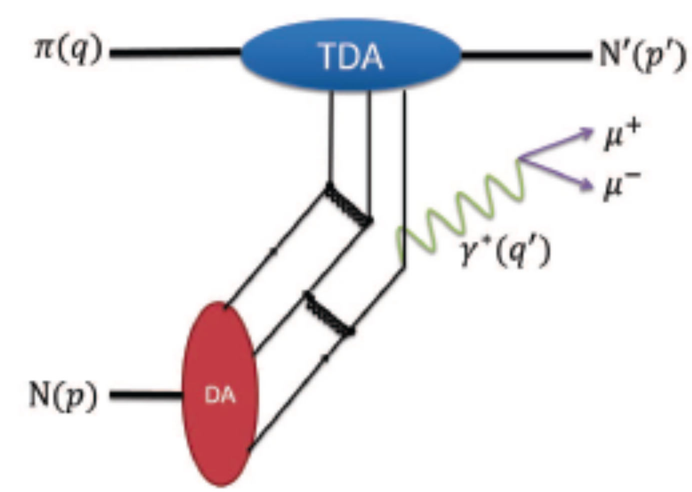
hard exclusive pion production (DVMP)

space-like



(d)

Preferred @lower beam energy to enhance exclusive cross section



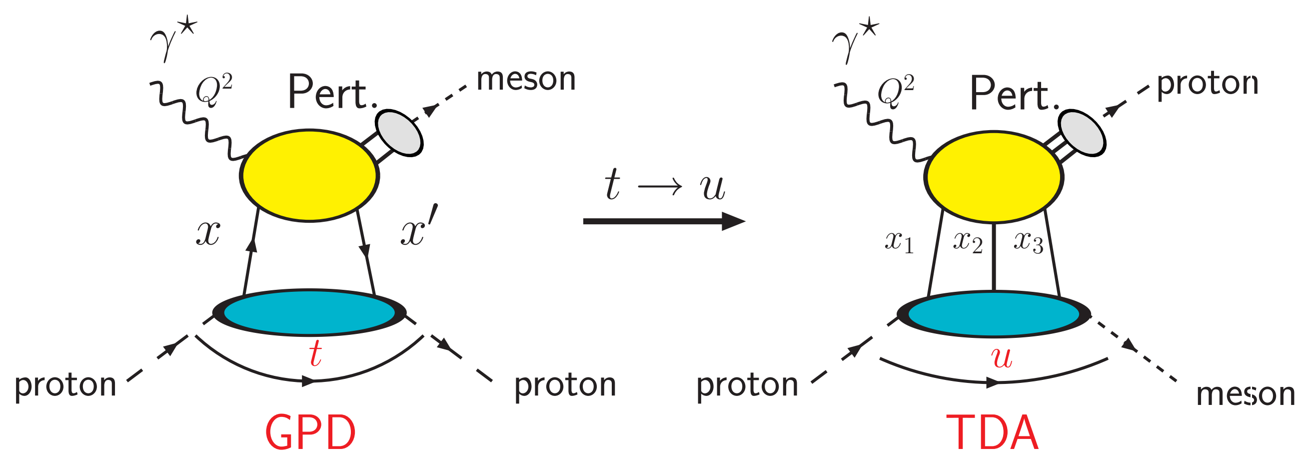
@larger momentum transfer to the target: involves TDA

time-like

Mueller, Pire, Szymanowski, Wagner: On timelike and spacelike hard exclusive reactions, arXiv:1203.4392

Hard limit for backward exclusive processes

➡ Let us analyse the hard electroproduction of a meson



but **backward !**

↕

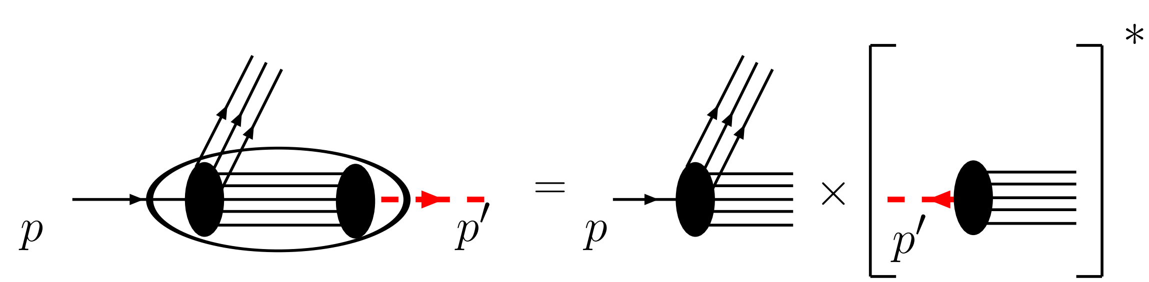
meson nearly at rest in the target rest frame

➡ The kinematics imposes the exchange of 3 quarks in the u channel

➡ Factorisation in the generalised Bjorken limit: $Q^2 \to \infty$, u, x fixed

B. Pire, L. Szymanowski, PLB 622:83,2005.

➡ The object factorised from the hard part is a Transition Distribution Amplitude (TDA)



➡ Interpretation at the amplitude level in the ERBL region (for $x_i > 0$)

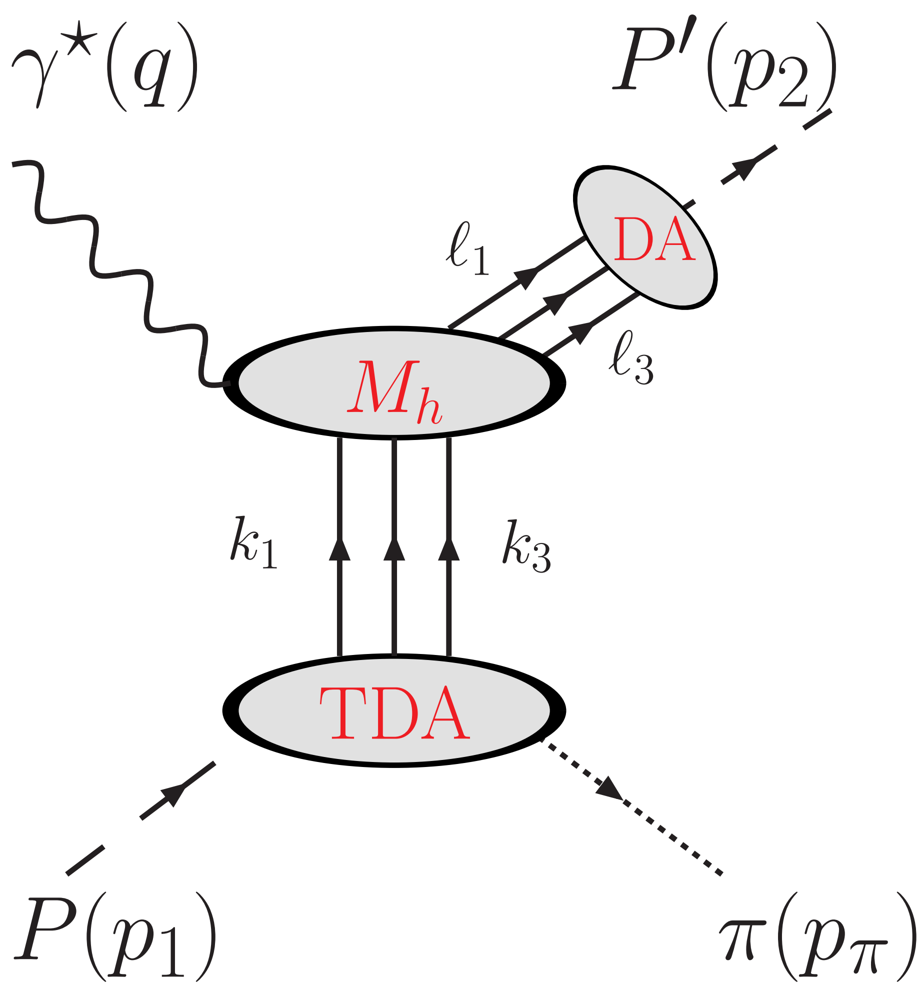
Amplitude of probability to find a meson within the proton !

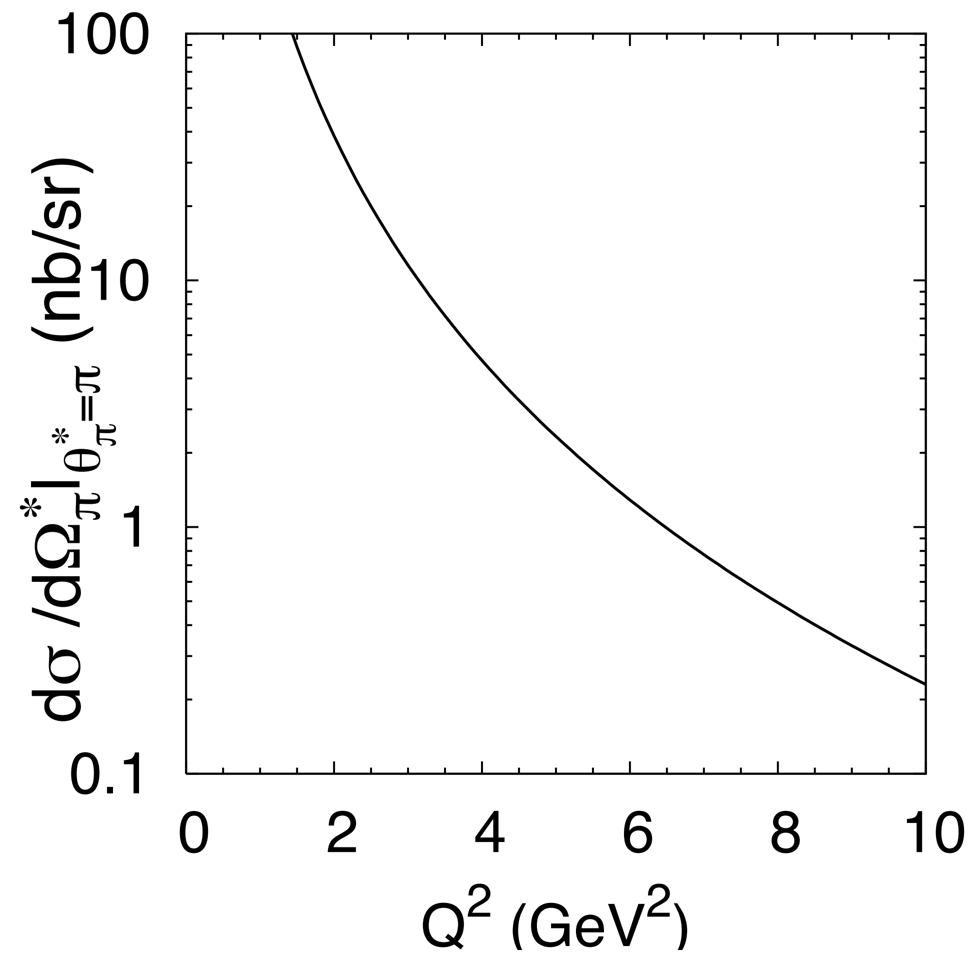
J.P. Landsberg at ICHEP 2010

Backward Electroproduction of a pion: III

JPL, B. Pire, L. Szymanowski,PRD 75:074004,2007

At $\xi = 0.8$ and using CZ Distribution Amplitudes, one gets:





NOTE: the result with asymptotic DAs is not zero !

J.P. Landsberg at ICHEP 2010

Backward Electroproduction of a pion: IV

JPL, B. Pire, L. Szymanowski,PRD 75:074004,2007

- Model-independent predictions
  - Scaling law for the amplitude:

$$\mathcal{M}(Q^2) \propto \frac{\alpha_s^2(Q^2)}{Q^4}$$

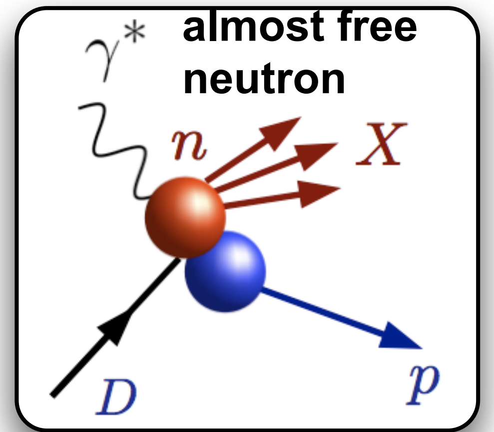
  - Approximate Q^2-independence of the ratios

$$\frac{\mathcal{M}(\gamma^\star p \to p\pi)}{\mathcal{M}(\gamma^\star p \to p\gamma)}, \frac{\mathcal{M}(\gamma^\star p \to p\pi)}{\mathcal{M}(\gamma^\star p \to p\rho)} \text{ and } \frac{\frac{d\sigma(p\bar{p}\to\ell^+\ell^-\pi^0)}{dQ^2}}{\frac{d\sigma(p\bar{p}\to\ell^+\ell^-)}{dQ^2}} \text{(see later)}$$

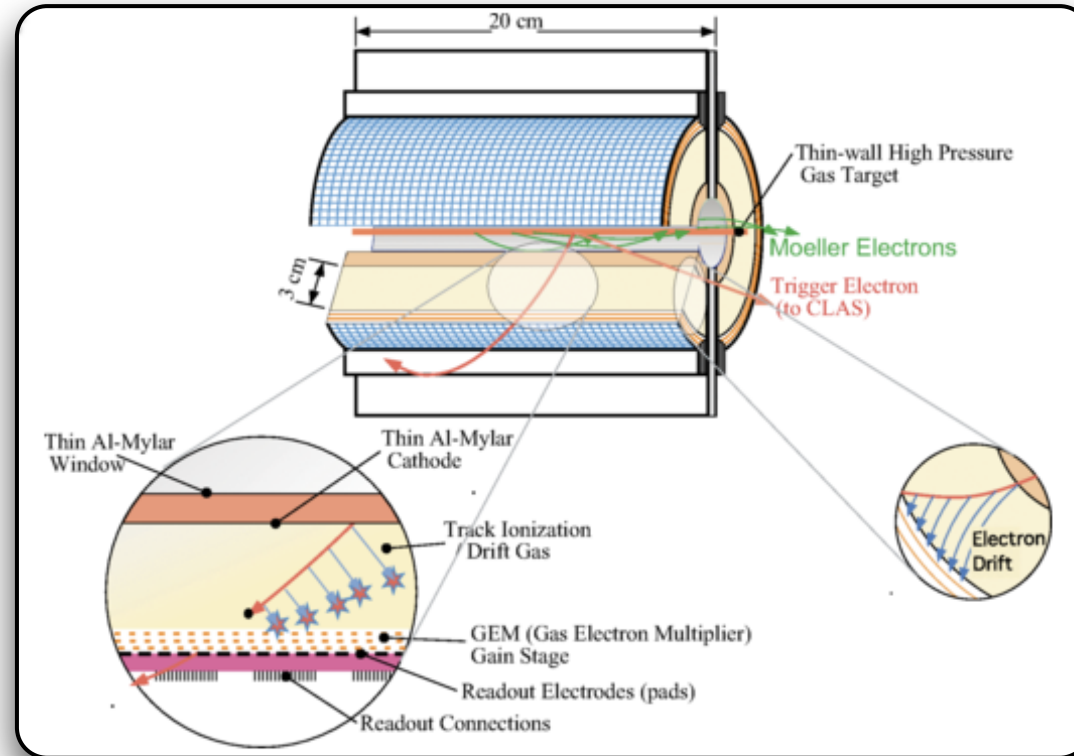
  - Dominance of $\gamma_T^\star p \to p\pi, \ldots$

J.P. Landsberg at ICHEP 2010

Spectator tagging is now an established technique



Deuteron **Spectator proton (backward going slow proton)**



Almost-free neutron structure function studied with spectator tagging, technique successfully used by BoNuS

PRL 108, 142001 (2012); PRC 89, 045206 (2014)

Mississippi State U. D. Dutta FIU, February 2016 13 /33