Deeply Virtual Compton Scattering

on the Deuteron and Heavier Nuclei at HERMES

Caroline Riedl

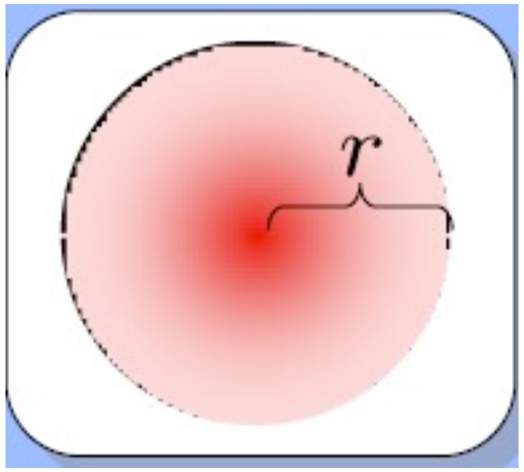
19th International Spin Physics Symposium
Jülich, Germany, October 1, 2010

Outline: DVCS on nuclei

- Theoretical motivation
- HERMES experiment at HERA/DESY
- Azimuthal asymmetries in DVCS and GPDs
- Results on the deuteron and heavier nuclei
- Summary

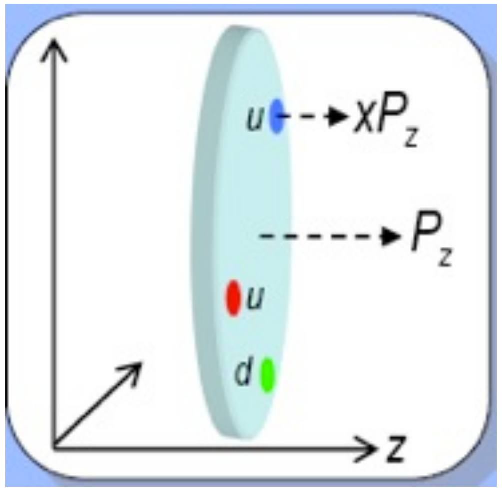
Generalized Parton Distributions

Elastic Form Factors



transverse position
of partons

Parton Distribution
Functions (PDFs)



longitudinal momentum
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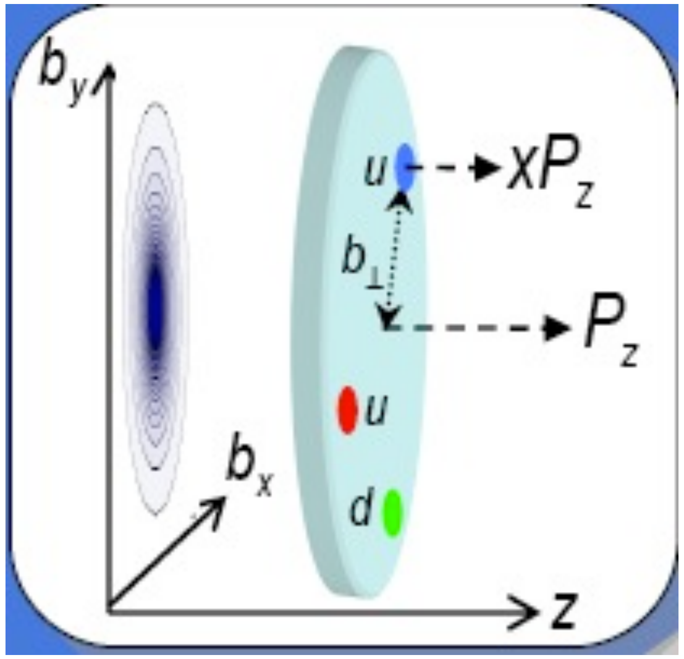
Generalized Parton Distributions



Nucleon Tomography

correlation between longitudinal momentum and transverse position

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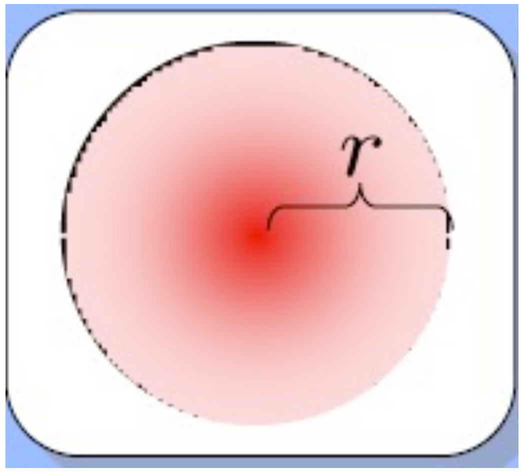

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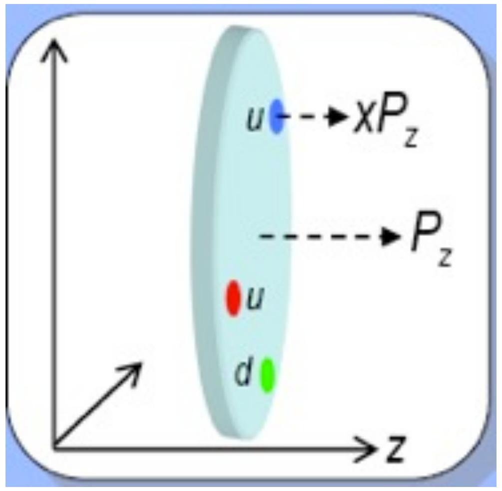
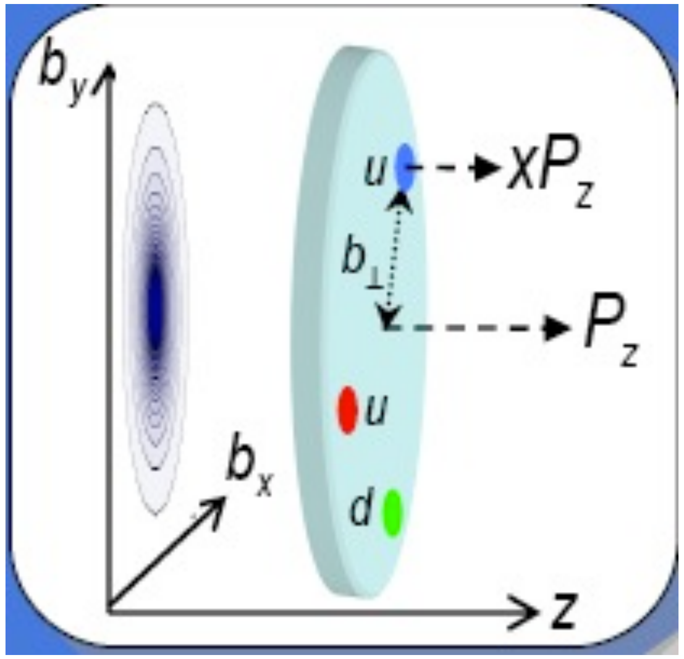


longitudinal momentum of partons

Generalized Parton Distributions

Vector Mesons: see talk by E. Avetisyan



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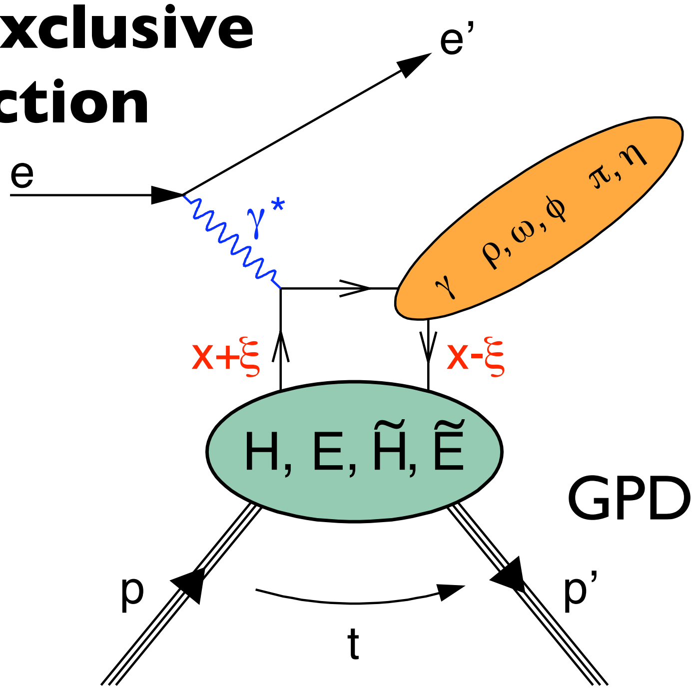
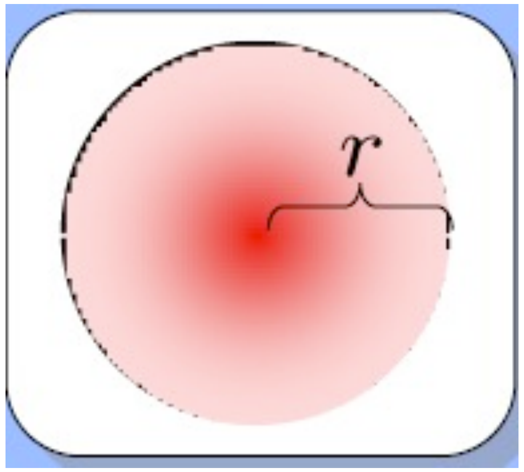
Hard exclusive reaction



GPDs=f(x,ξ,t)

Elastic Form Factors



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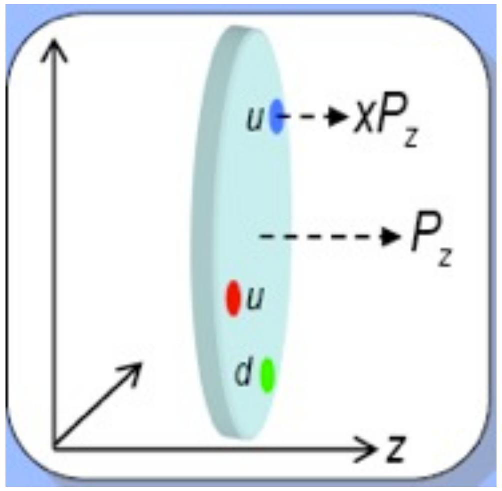

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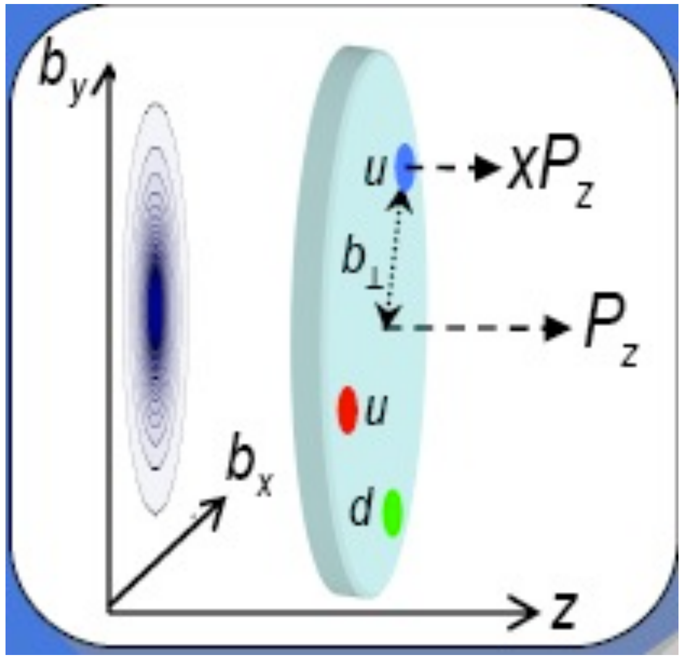

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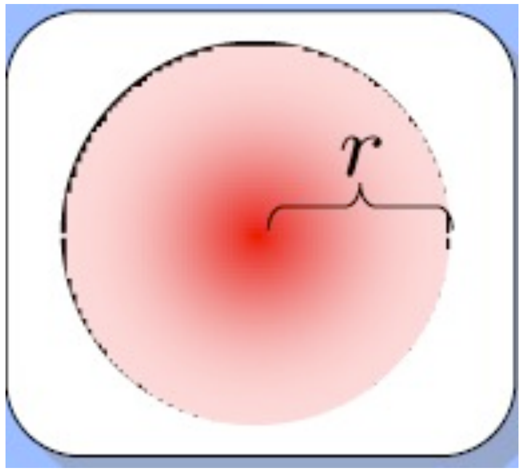

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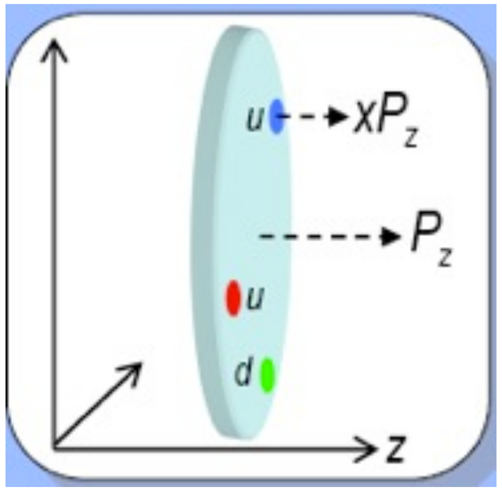

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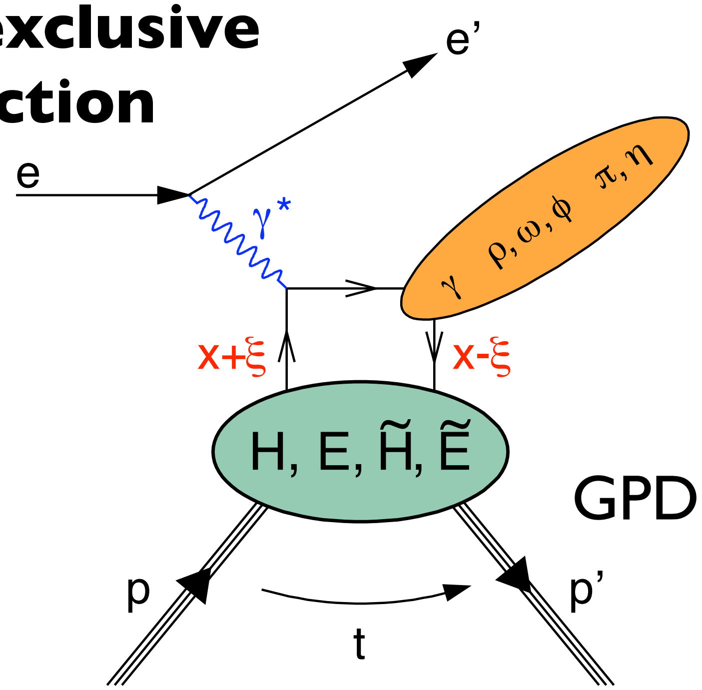

GPDs=f(x,ξ,t)

Ji sum rule for the nucleon

-Ji, PRL 78 (1997) 610-

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

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

Generalized Parton Distributions

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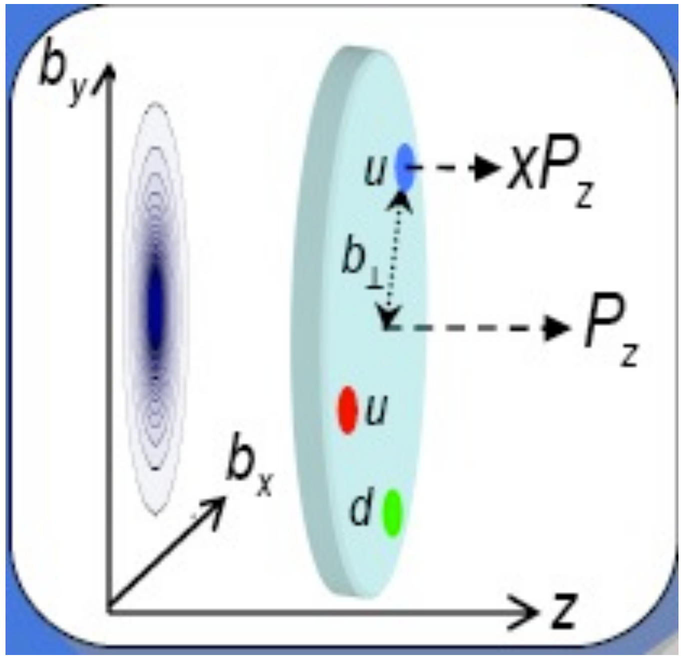

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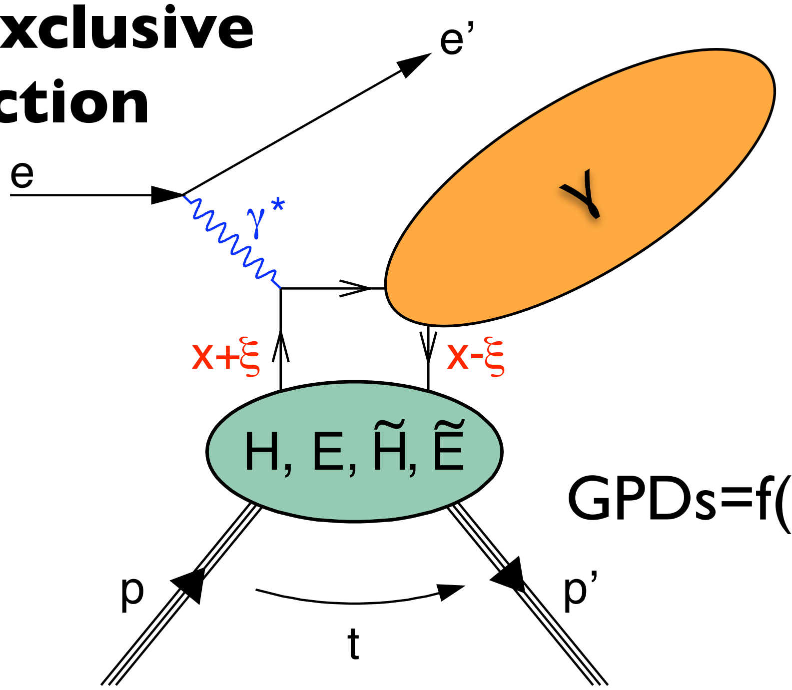

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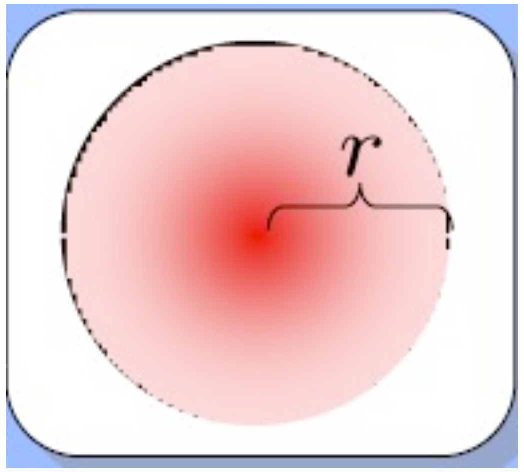

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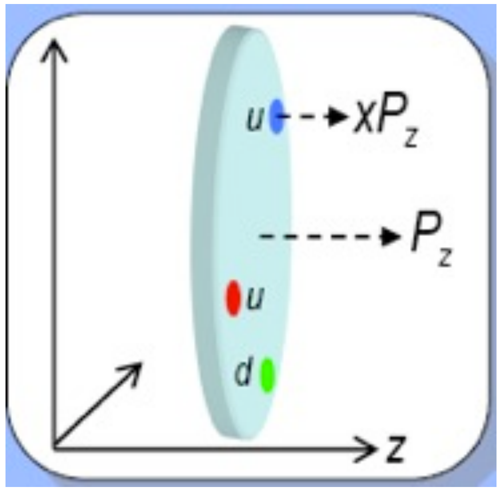

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$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

DVCS on hadrons other than the nucleon

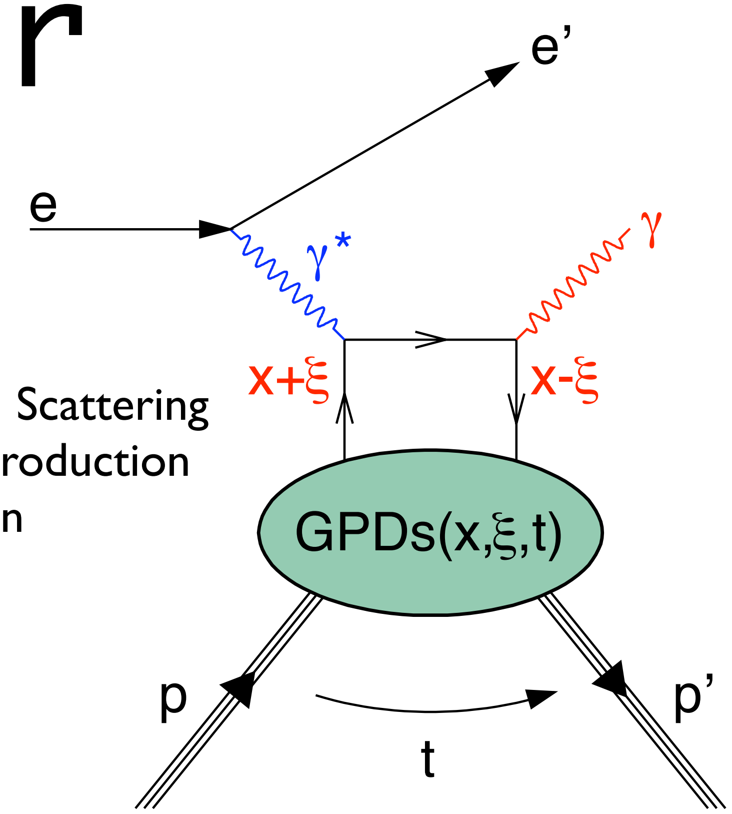
I.

Spin-1/2	flips nucleon helicity	conserves nucleon helicity
does not depend on quark helicity	E	H
depends on quark helicity	$\tilde{E}$	$\tilde{H}$

4 chiral-even quark GPDs at leading twist

(4 more GPDs for chiral-odd case related to transversity)

Deeply Virtual Compton Scattering
= hard exclusive leptoproduction
of a real photon



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$H \rightarrow$ **q(x)**

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

$\tilde{H} \rightarrow$ **Δq(x)**

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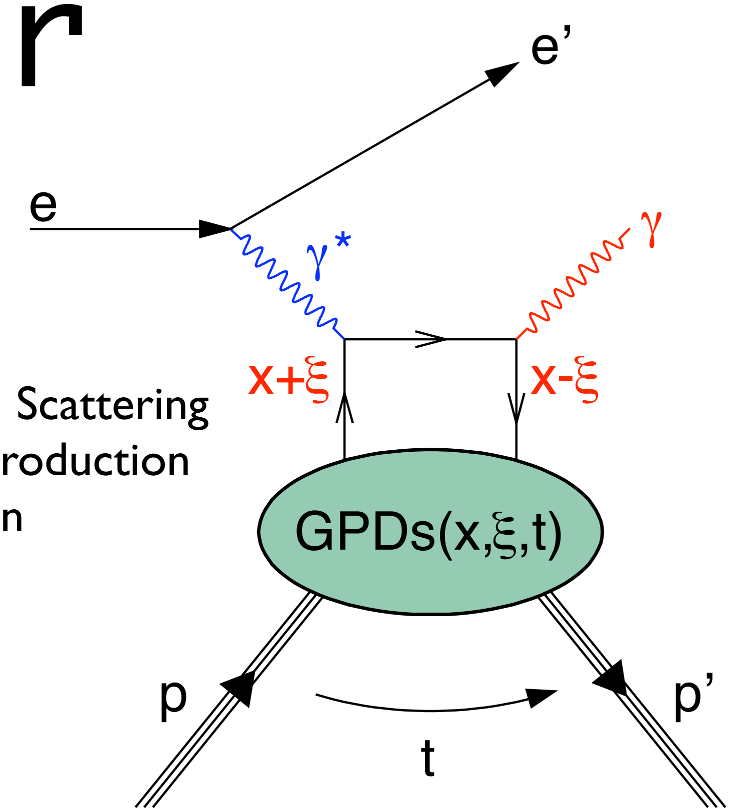

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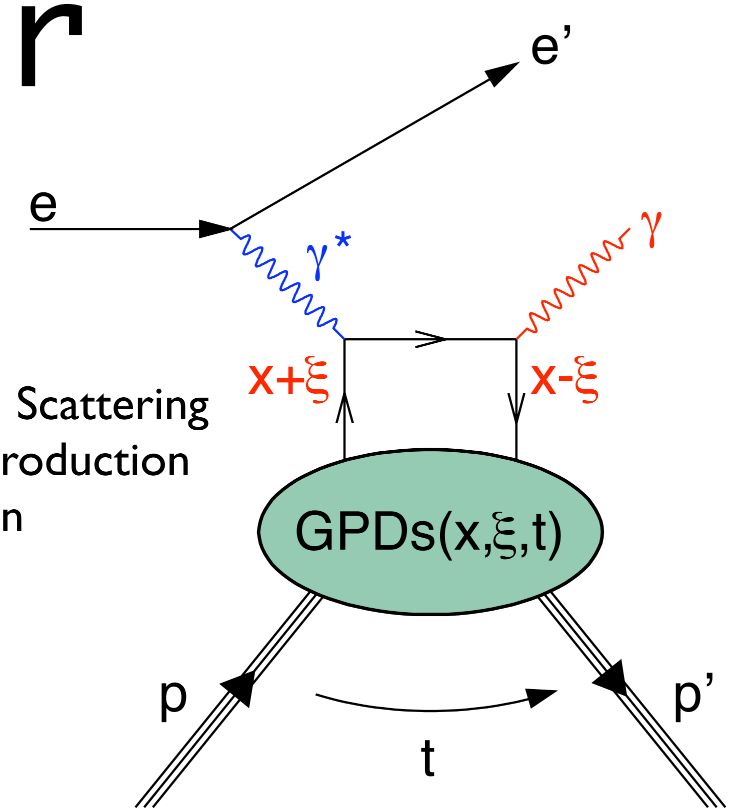

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(4 more GPDs for chiral-odd case
related to transversity)

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

9 chiral-even quark GPDs at leading twist

H_5 → **$b_1(x)$**

tensor structure function

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

DVCS on hadrons other than the nucleon

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Spin-1/2	flips nucleon helicity	conserves nucleon helicity
does not depend on quark helicity	E	H
depends on quark helicity	$\tilde{E}$	$\tilde{H}$

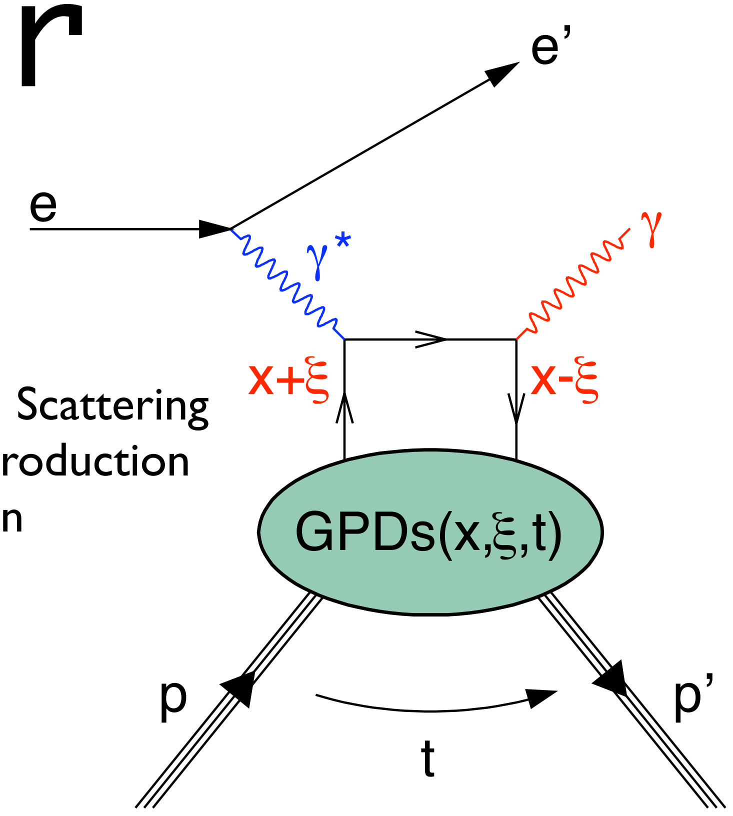
$H \longrightarrow q(x)$

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

$\tilde{H} \longrightarrow \Delta q(x)$

4 chiral-even quark GPDs at leading twist

(4 more GPDs for chiral-odd case related to transversity)



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9 chiral-even quark GPDs at leading twist

$b_1(x)$

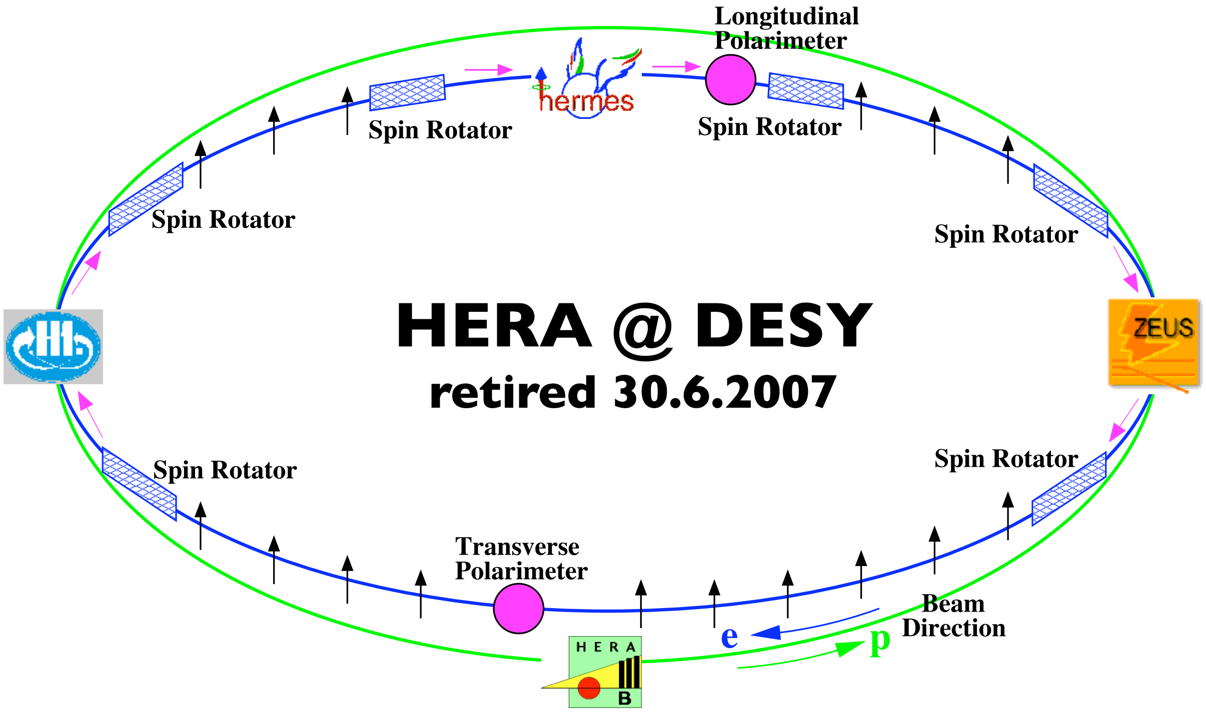
tensor structure function

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

2.

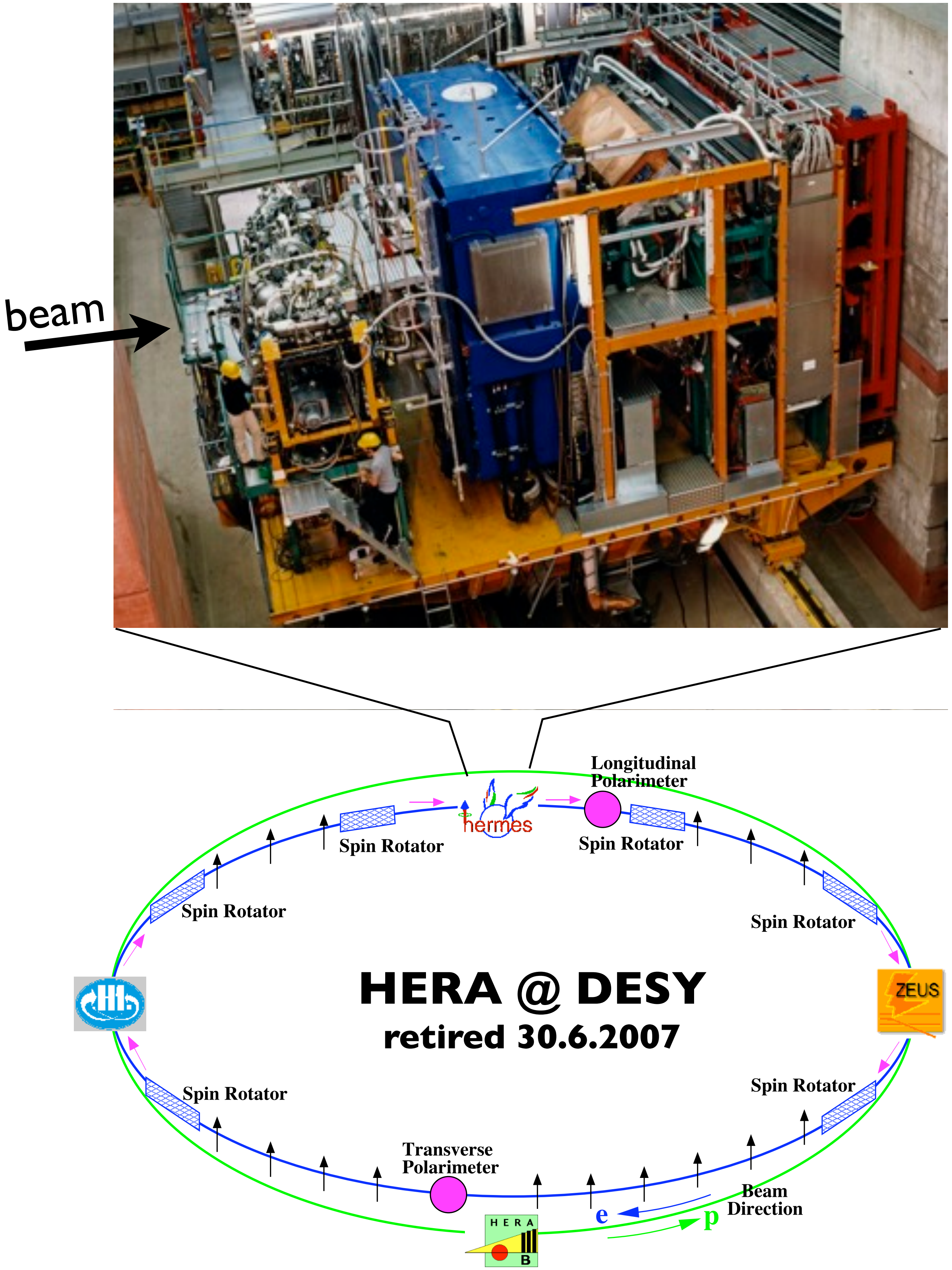
How does the nuclear environment modify the DVCS amplitude?

HERMES at DESY



self-polarized e+ and e- beams
helicity switched every few months

HERMES at DESY



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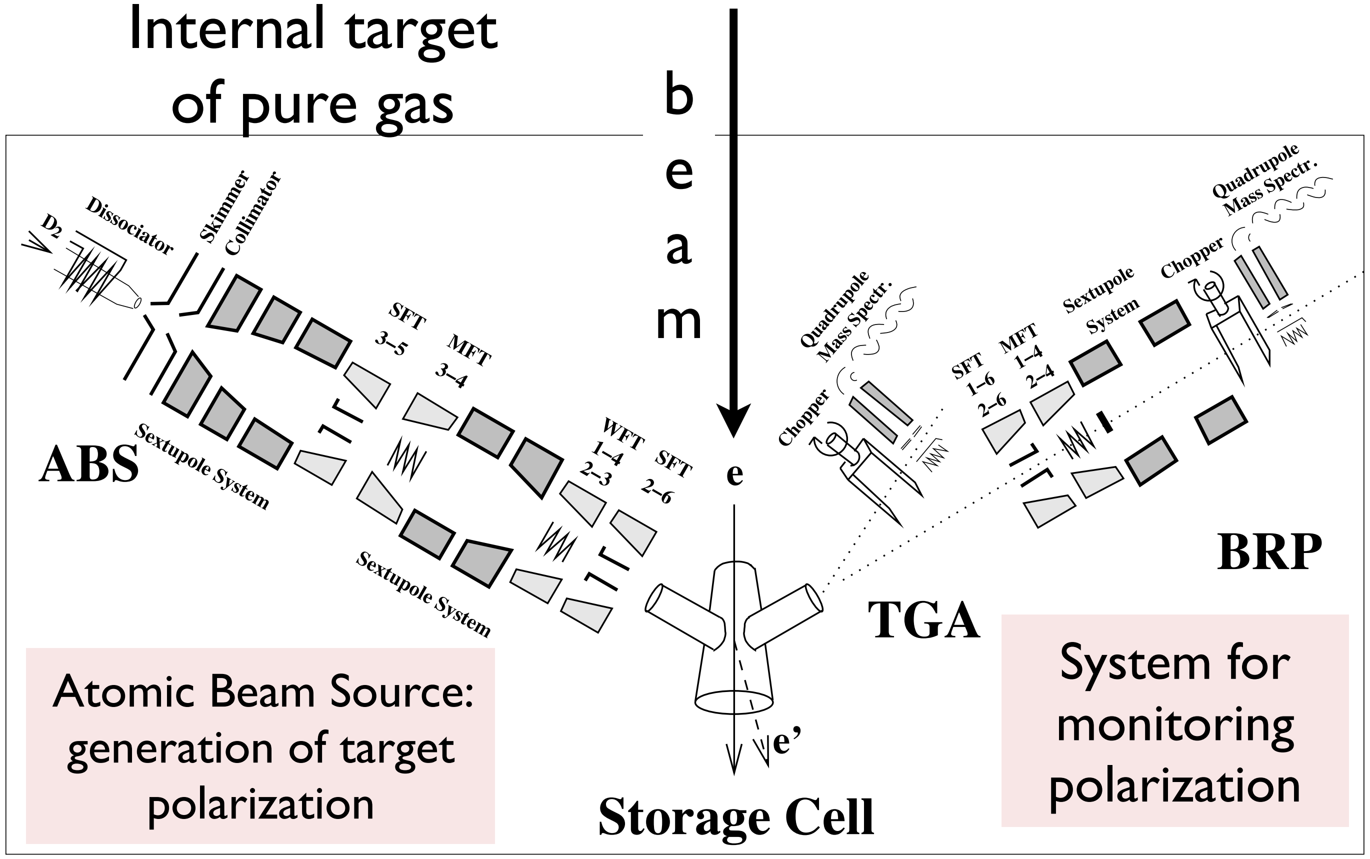
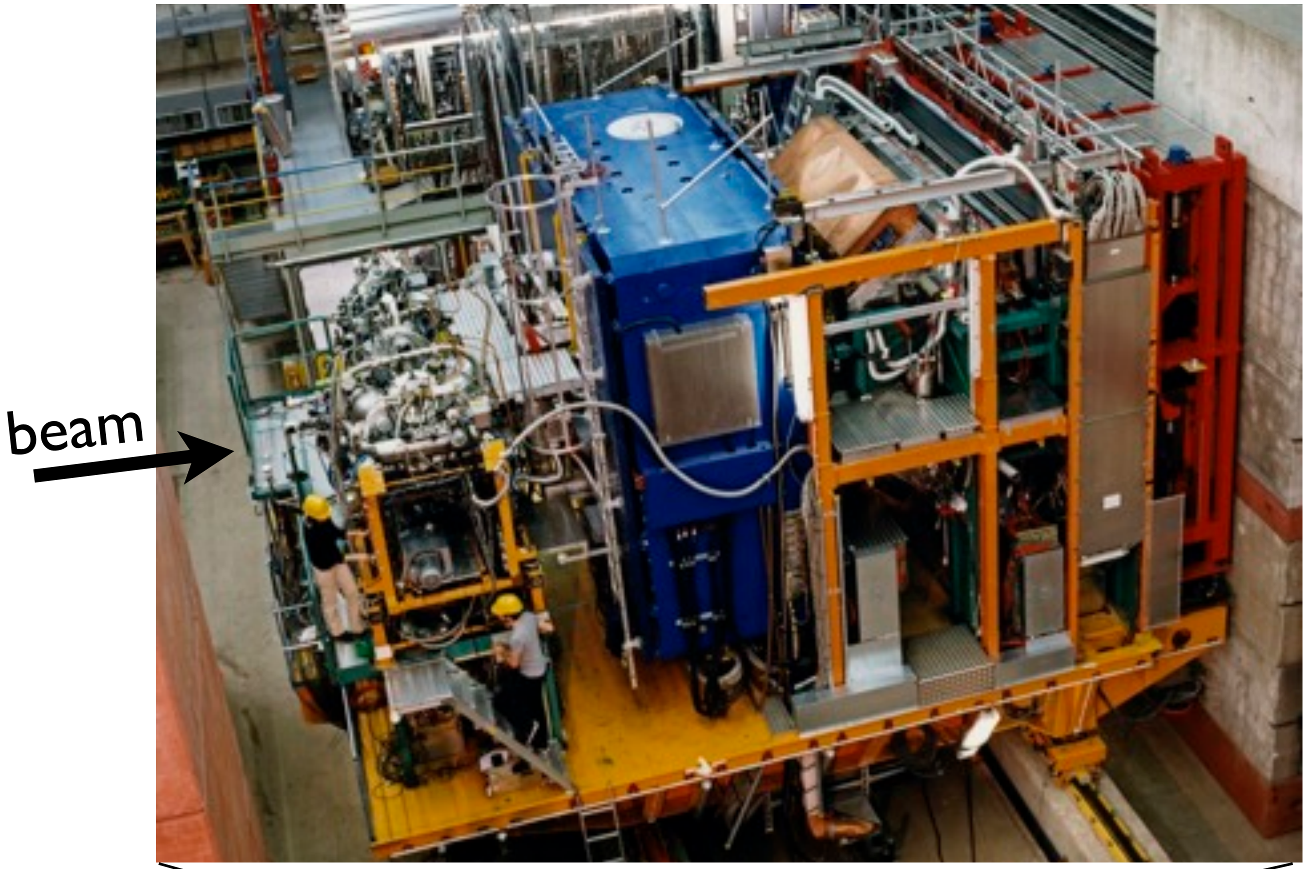
HERMES at DESY

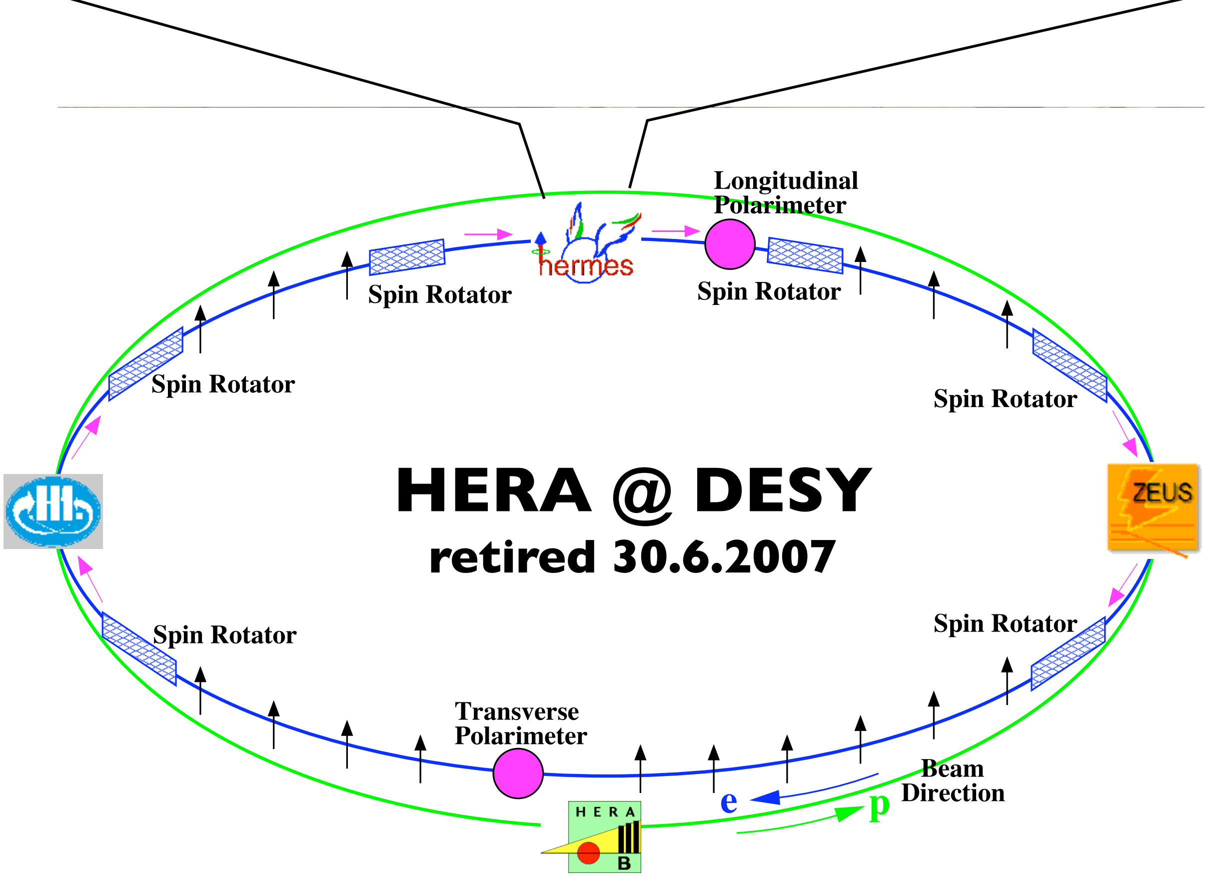
Internal target
of pure gas



Atomic Beam Source:
generation of target
polarization

System for
monitoring
polarization





HERA @ DESY
retired 30.6.2007

self-polarized e+ and e- beams
helicity switched every few months

HERMES at DESY

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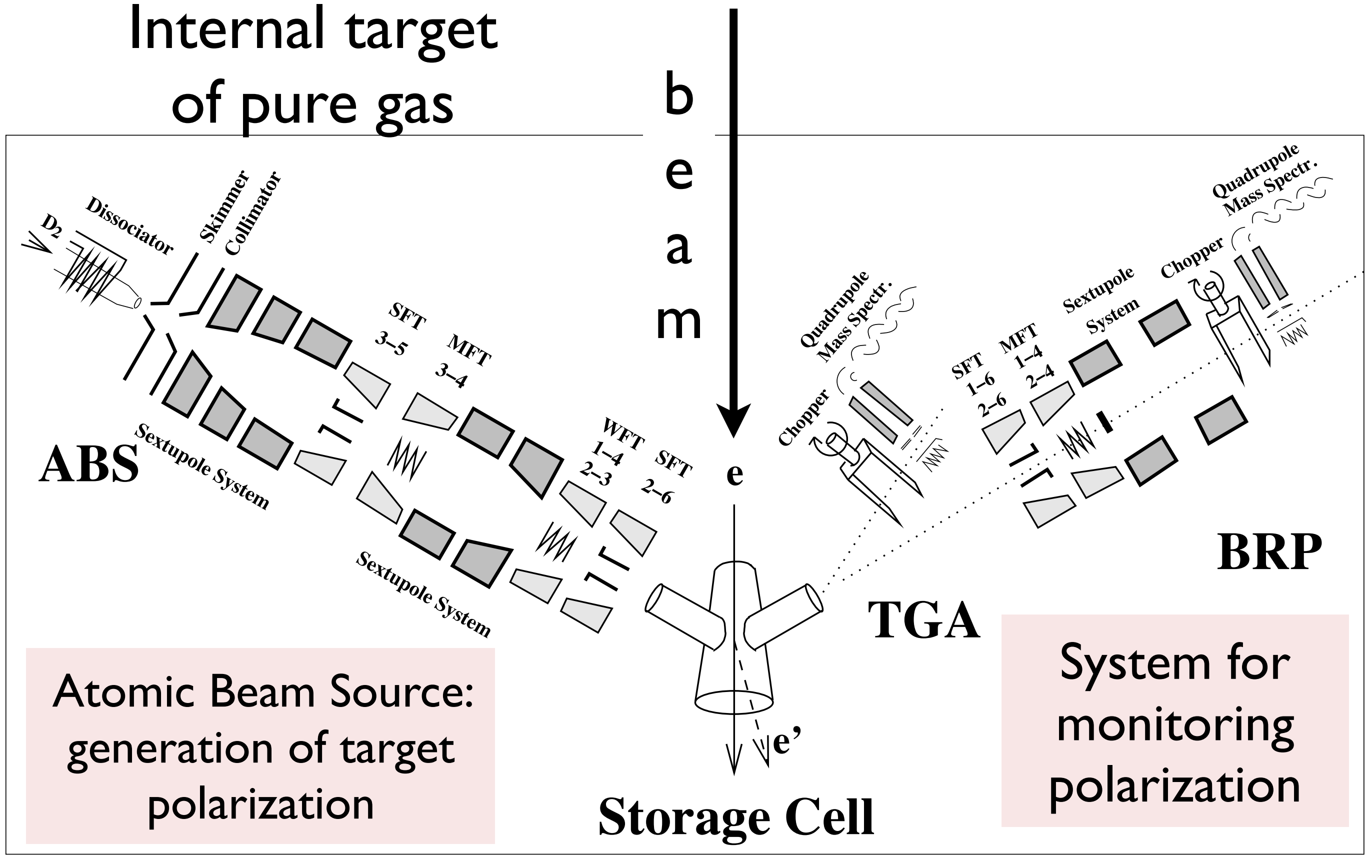
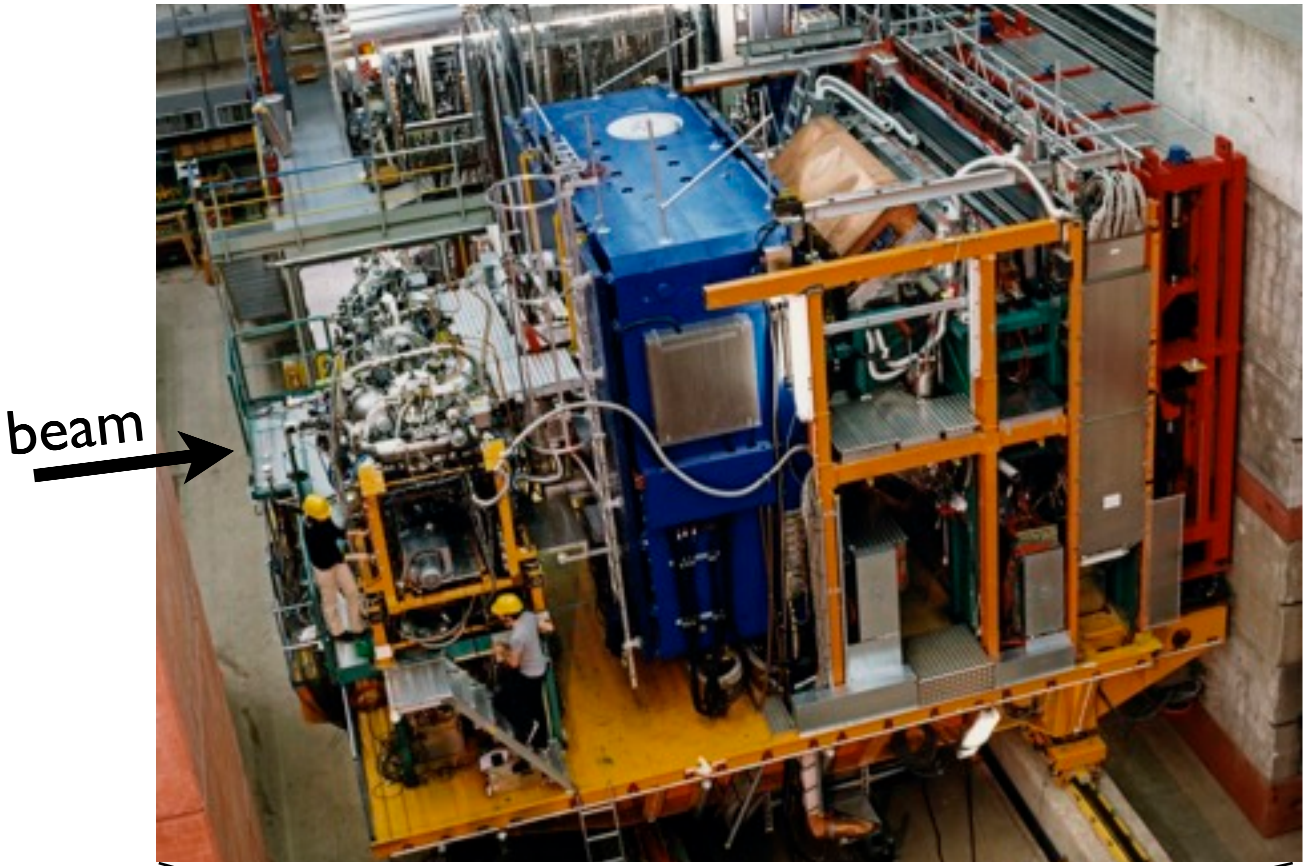
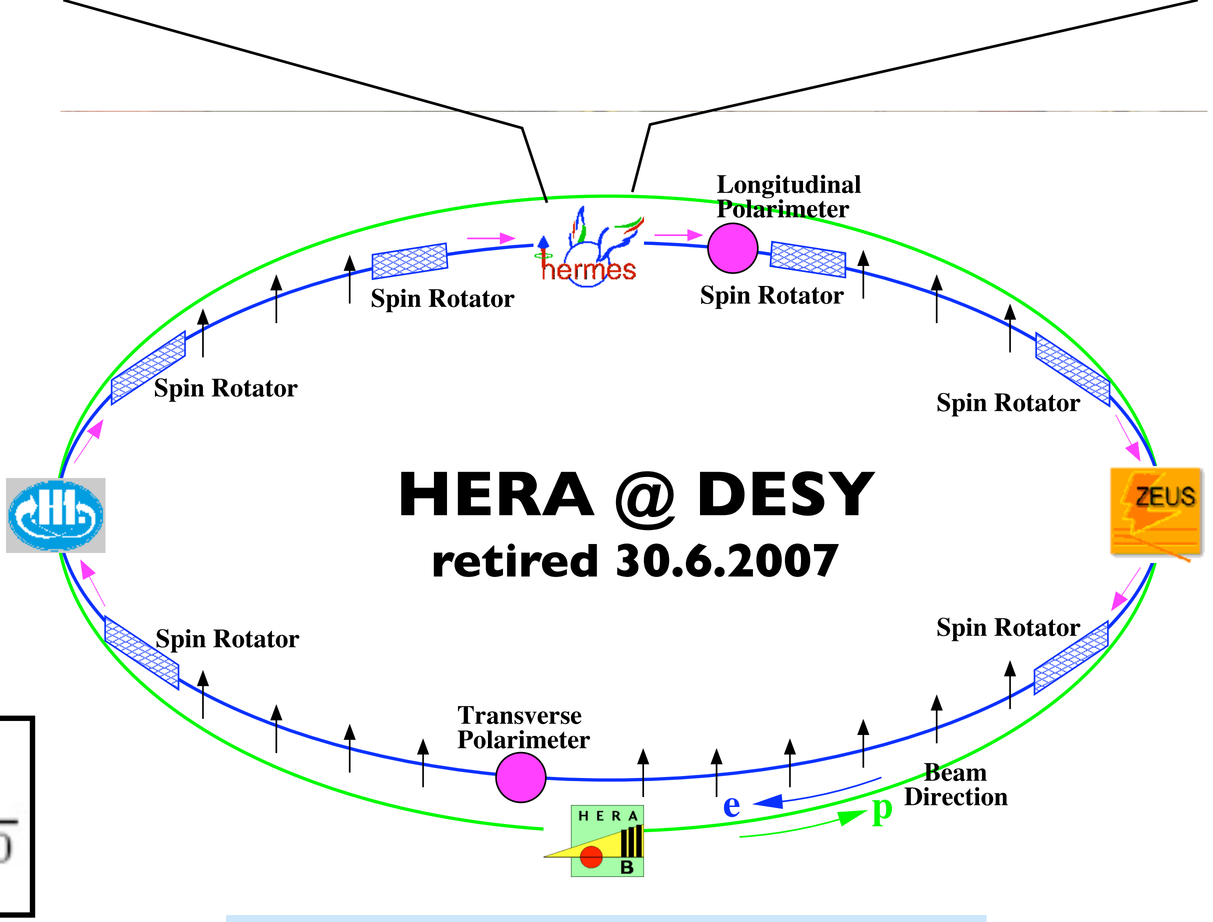


Atomic Beam Source: generation of target polarization

System for monitoring polarization





self-polarized e+ and e- beams
helicity switched every few months

Longitudinally polarized deuterium
(1998-2000)

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

Spin-1 particle
with Λ=-1,0,+1

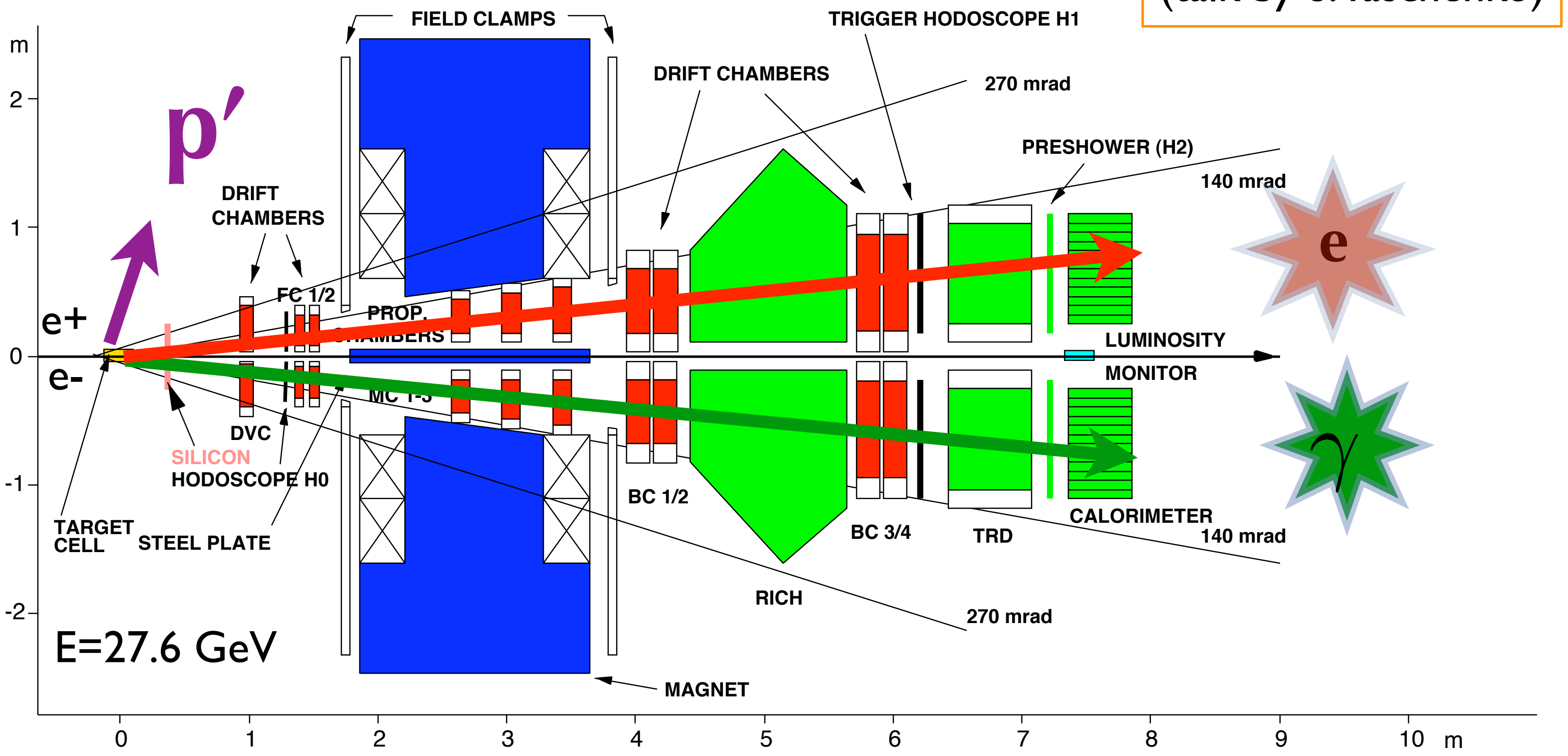
$$P_z = \frac{n^+ - n^-}{n^+ + n^- + n^0}$$

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

DVCS at HERMES 1996-2005

2006/2007: **recoil proton** detected (talk by S. Yaschenko)

Hydrogen target:
400 pb^{-1}
unpolarized Deuterium:
300 pb^{-1}
L-polarized Deuterium:
200 pb^{-1}
`**Heavier Nuclear targets:**
He, N, Ne, Kr, Xe
300pb^{-1}



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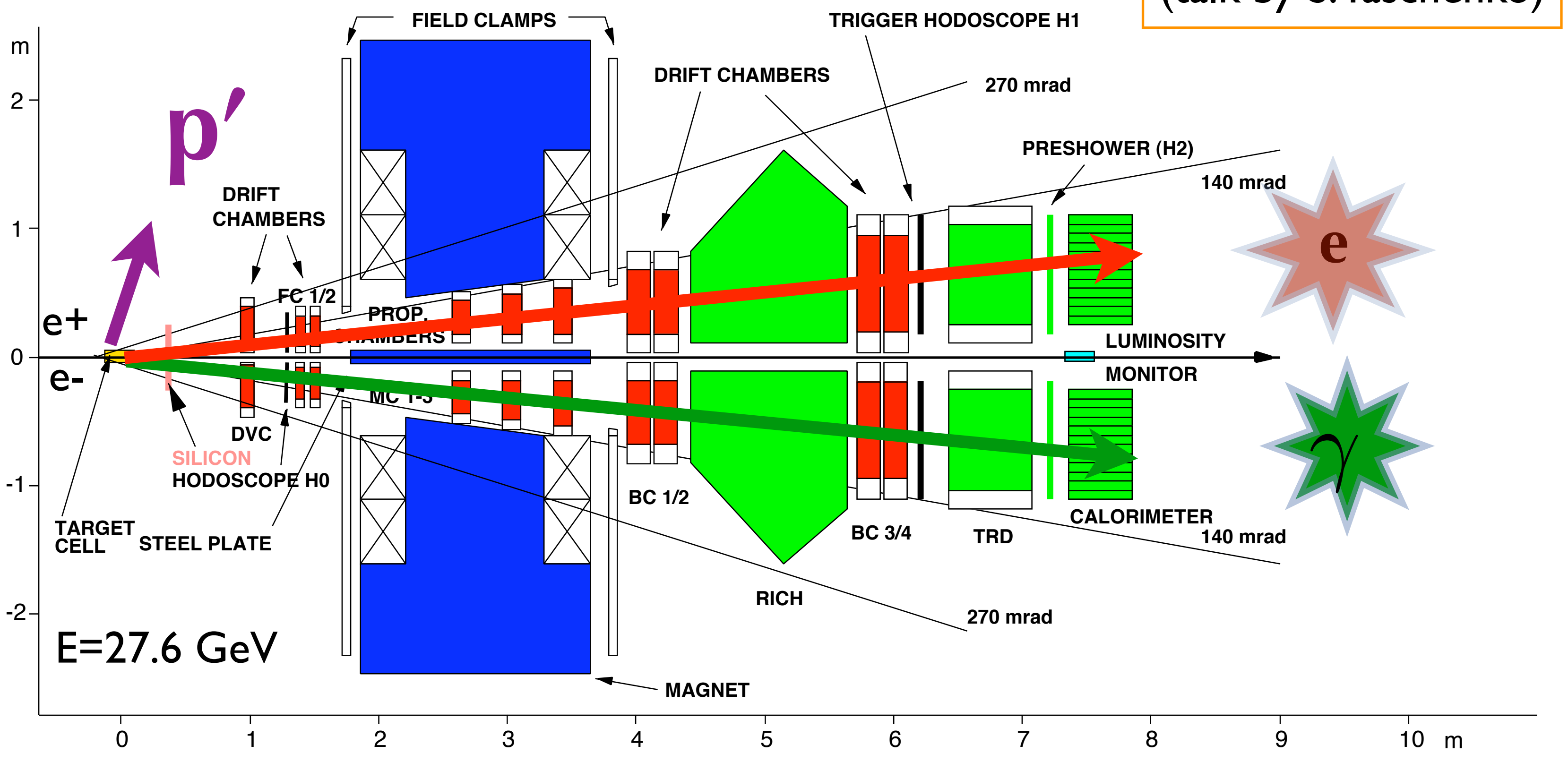
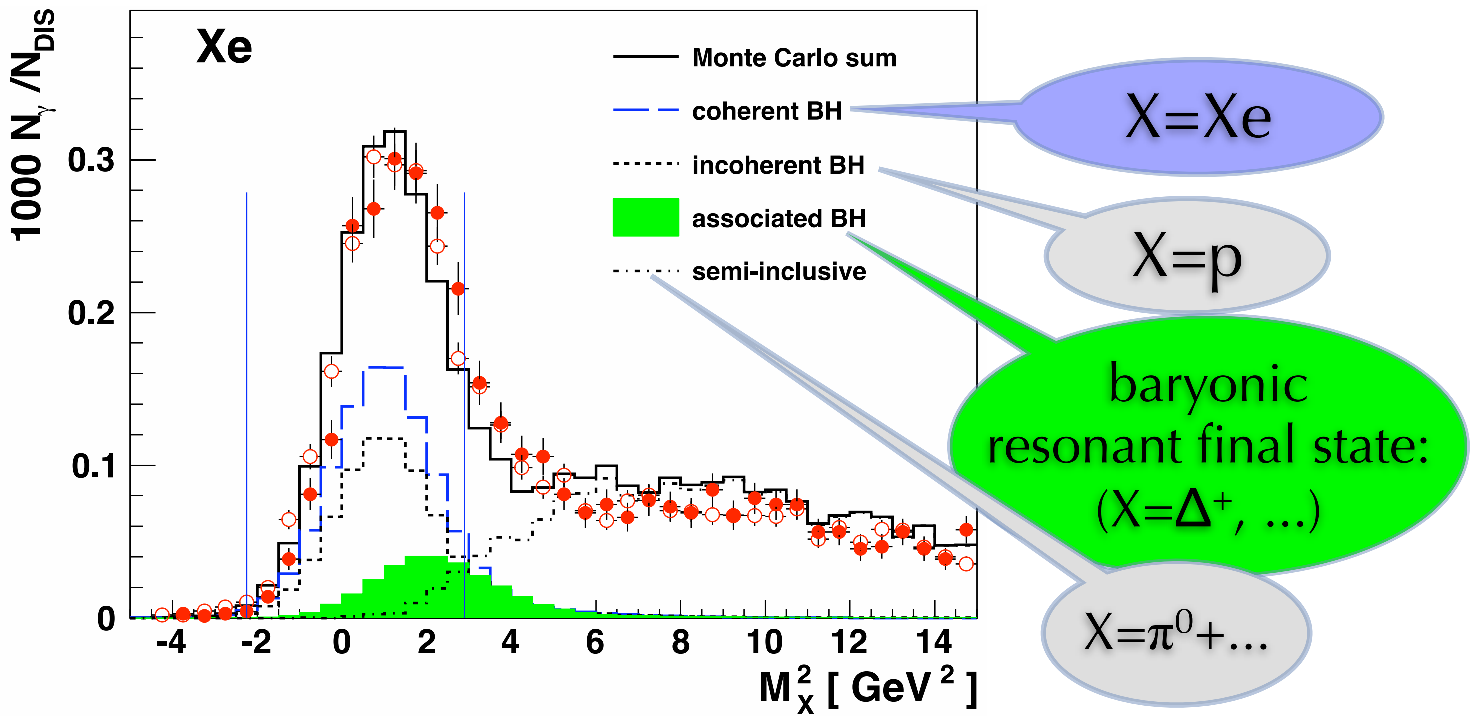
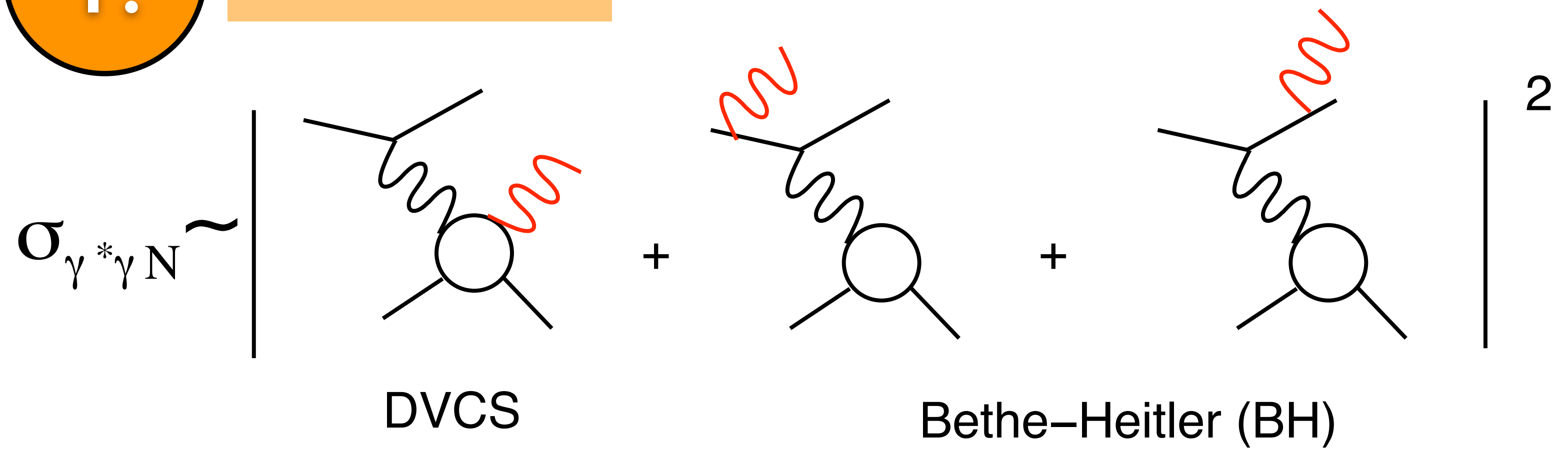


Missing mass technique for **ep→eXγ**
$M_X^2=(p+q-p_\gamma)^2$



Deeply Virtual Compton Scattering

I. Cross-section



Small at HERMES

Exactly calculable in QED given the nucleon elastic form factors F_1 and F_2

$$= |\tau_{DVCS}|^2 + |\tau_{BH}|^2 +$$

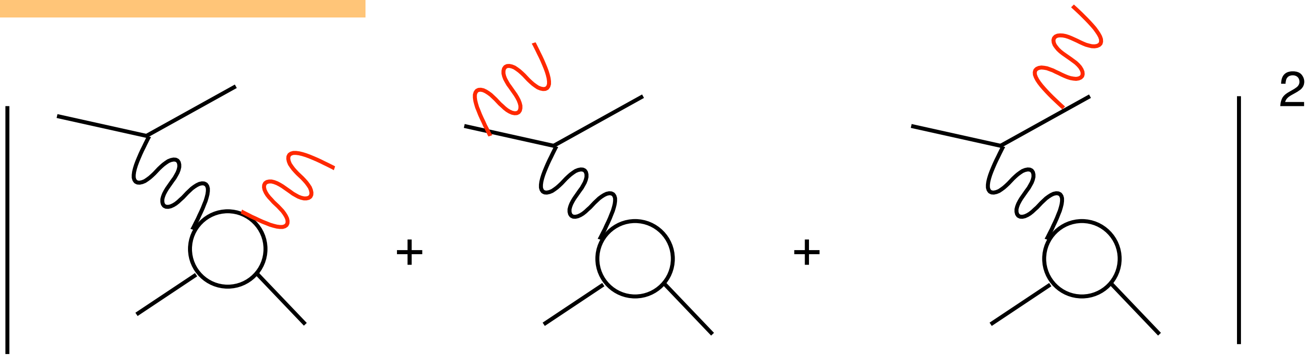
$$(\tau_{DVCS}\tau_{BH}^* + \tau_{DVCS}^*\tau_{BH})$$

DVCS-BH interference term

Deeply Virtual Compton Scattering

1. Cross-section

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



DVCS

Bethe–Heitler (BH)

Small at HERMES

Exactly calculable in QED given the nucleon elastic form factors F_1 and F_2

$$= |\tau_{DVCS}|^2 + |\tau_{BH}|^2 + (\tau_{DVCS}\tau_{BH}^* + \tau_{DVCS}^*\tau_{BH})$$

DVCS-BH interference term

2. Harmonic expansion

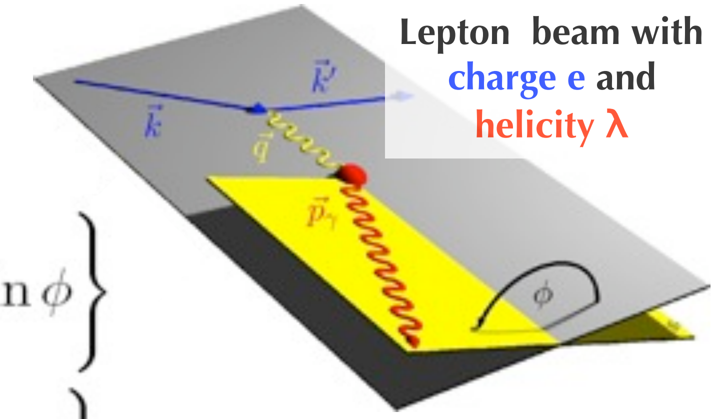
Unpolarized target

Case of polarized target is more complicated!

$$|\tau_{BH}|^2 = \frac{K_{BH}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{2} c_n^{BH} \cos(n\phi) \right\}$$

$$|\tau_{DVCS}|^2 = \frac{1}{Q^2} \left\{ \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + \underline{\lambda}\, s_1^{DVCS} \sin\phi \right\}$$

$$\mathrm{I} = \frac{-\underline{e_\ell}\, K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\mathrm{I}} \cos(n\phi) + \sum_{n=1}^{2} \underline{\lambda}\, s_n^{\mathrm{I}} \sin(n\phi) \right\}$$

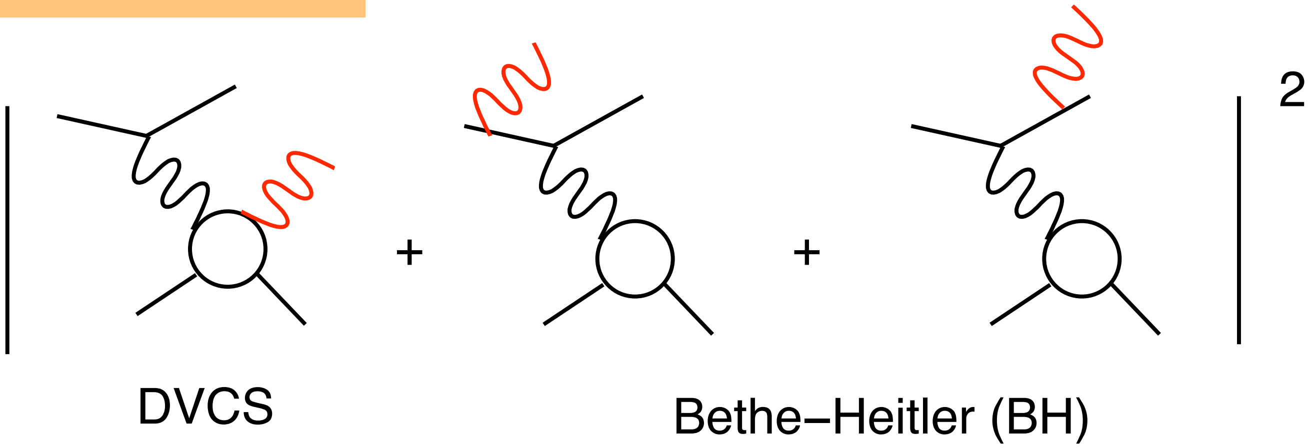


Lepton beam with charge e and helicity λ

Deeply Virtual Compton Scattering

1. Cross-section

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



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DVCS-BH interference term

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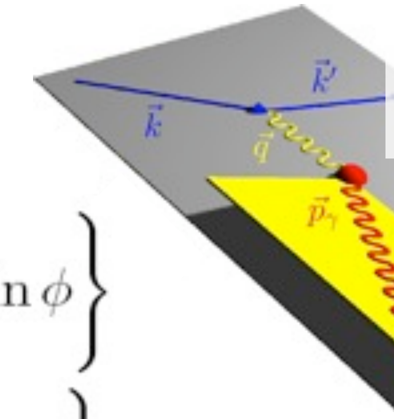

Lepton beam with charge e and helicity λ

3. Express cross-section in terms of azimuthal asymmetries

$$\sigma(\phi; P_\ell, e_\ell) = \sigma_{\mathrm{UU}}(\phi) \times [1 + P_\ell \mathcal{A}_{\mathrm{LU}}^{\mathrm{DVCS}}(\phi) + e_\ell P_\ell \mathcal{A}_{\mathrm{LU}}^{\mathrm{I}}(\phi) + e_\ell \mathcal{A}_{\mathrm{C}}(\phi)]$$

$\mathcal{A}_{\mathrm{LU}}$

Beam Target

Azimuthal Asymmetries and GPDs

$\mathcal{A}_{\mathrm{LU}}$

Beam Target

$$\mathrm{I} = \frac{-e_\ell K_\mathrm{I}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^\mathrm{I} \cos(n\phi) + \sum_{n=1}^{2} \lambda\, s_n^\mathrm{I} \sin(n\phi) \right\}$$

Fourier coefficients = azimuthal asymmetry amplitudes are related to certain linear or bi-linear combinations of CFFs.

Compton Form Factors (CFFs)

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

twist-2 GPD

Azimuthal Asymmetries and GPDs

$\mathcal{A}_{\mathrm{LU}}$

Beam Target

Single-charge beam-helicity asymmetry

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

no separate access to s_1^{I} and s_1^{DVCS}

$$\mathrm{I} = \frac{-e_\ell K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\mathrm{I}} \cos(n\phi) + \sum_{n=1}^{2} \lambda\, s_n^{\mathrm{I}} \sin(n\phi) \right\}$$

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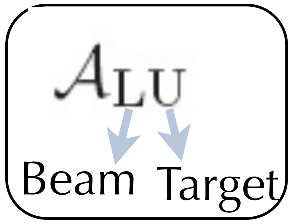

Single-charge beam-helicity asymmetry

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

no separate access
to s_I^I and s_I^{DVCS}

Beam-helicity asymmetries with 2 beam charges

Charge-average
$\mathcal{A}_{LU}$

Charge-difference
$\mathcal{A}_{LU}$

s_I^{DVCS} and s_I^I can be disentangled

$$\mathrm{I} = \frac{-e_\ell K_\mathrm{I}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^\mathrm{I} \cos(n\phi) + \sum_{n=1}^{2} \lambda\, s_n^\mathrm{I} \sin(n\phi) \right\}$$

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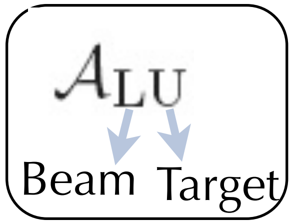


Single-charge beam-helicity asymmetry

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

no separate access
to s_1^{I} and s_1^{DVCS}

Beam-helicity asymmetries with 2 beam charges

Charge-average	**Charge-difference**
$\mathcal{A}_{LU}$	$\mathcal{A}_{LU}$

s_1^{DVCS} and s_1^{I} can be disentangled

Beam-charge asymmetry

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

$$I = \frac{-e_\ell K_{I}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{I} \cos(n\phi) + \sum_{n=1}^{2} \lambda\, s_n^{I} \sin(n\phi) \right\}$$

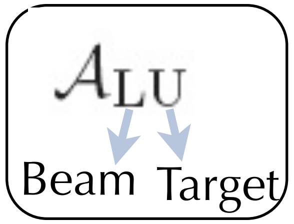
Fourier coefficients = azimuthal asymmetry amplitudes are related to certain linear or bi-linear combinations of CFFs.

Compton Form Factors (CFFs)

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

twist-2 GPD

Azimuthal Asymmetries and GPDs



Single-charge beam-helicity asymmetry

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

no separate access
to s_l^{I} and s_l^{DVCS}

Beam-helicity asymmetries with 2 beam charges

Charge-average
$\mathcal{A}_{\mathrm{LU}}$

Charge-difference
$\mathcal{A}_{\mathrm{LU}}$

s_l^{DVCS} and s_l^{I} can be disentangled

Beam-charge asymmetry

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

$$\mathrm{I} = \frac{-e_\ell K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\mathrm{I}} \cos(n\phi) + \sum_{n=1}^{2} \lambda\, s_n^{\mathrm{I}} \sin(n\phi) \right\}$$

Fourier coefficients = azimuthal asymmetry amplitudes are related to certain linear or bi-linear combinations of CFFs.

Target-spin asymmetry

$$\mathcal{A}_{\mathrm{UL}}(\phi, e_\ell) \equiv \frac{[\sigma^{\leftarrow\Rightarrow}(\phi,e_\ell) + \sigma^{\rightarrow\Rightarrow}(\phi,e_\ell)] - [\sigma^{\leftarrow\Leftarrow}(\phi,e_\ell) + \sigma^{\rightarrow\Leftarrow}(\phi,e_\ell)]}{[\sigma^{\leftarrow\Rightarrow}(\phi,e_\ell) + \sigma^{\rightarrow\Rightarrow}(\phi,e_\ell)] + [\sigma^{\leftarrow\Leftarrow}(\phi,e_\ell) + \sigma^{\rightarrow\Leftarrow}(\phi,e_\ell)]}$$

Compton Form Factors (CFFs)

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

twist-2 GPD

Azimuthal Asymmetries and GPDs

$\mathcal{A}_{\mathrm{LU}}$

Beam Target

Single-charge beam-helicity asymmetry

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

no separate access
to s_1^{I} and s_1^{DVCS}

Beam-helicity asymmetries with 2 beam charges

Charge-average
$\mathcal{A}_{\mathrm{LU}}$

Charge-difference
$\mathcal{A}_{\mathrm{LU}}$

s_1^{DVCS} and s_1^{I} can be disentangled

Beam-charge asymmetry

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

$$\mathrm{I} = \frac{-e_\ell K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\mathrm{I}} \cos(n\phi) + \sum_{n=1}^{2} \lambda\, s_n^{\mathrm{I}} \sin(n\phi) \right\}$$

Fourier coefficients = azimuthal asymmetry amplitudes are related to certain linear or bi-linear combinations of CFFs.

Target-spin asymmetry

$$\mathcal{A}_{\mathrm{UL}}(\phi, e_\ell) \equiv \frac{[\sigma^{\leftarrow\Rightarrow}(\phi, e_\ell) + \sigma^{\rightarrow\Rightarrow}(\phi, e_\ell)] - [\sigma^{\leftarrow\Leftarrow}(\phi, e_\ell) + \sigma^{\rightarrow\Leftarrow}(\phi, e_\ell)]}{[\sigma^{\leftarrow\Rightarrow}(\phi, e_\ell) + \sigma^{\rightarrow\Rightarrow}(\phi, e_\ell)] + [\sigma^{\leftarrow\Leftarrow}(\phi, e_\ell) + \sigma^{\rightarrow\Leftarrow}(\phi, e_\ell)]}$$

Double-spin asymmetry

$$\mathcal{A}_{\mathrm{LL}}(\phi, e_\ell) \equiv \frac{[\sigma^{\rightarrow\Rightarrow}(\phi, e_\ell) + \sigma^{\leftarrow\Leftarrow}(\phi, e_\ell)] - [\sigma^{\leftarrow\Rightarrow}(\phi, e_\ell) + \sigma^{\rightarrow\Leftarrow}(\phi, e_\ell)]}{[\sigma^{\rightarrow\Rightarrow}(\phi, e_\ell) + \sigma^{\leftarrow\Leftarrow}(\phi, e_\ell)] + [\sigma^{\leftarrow\Rightarrow}(\phi, e_\ell) + \sigma^{\rightarrow\Leftarrow}(\phi, e_\ell)]}$$

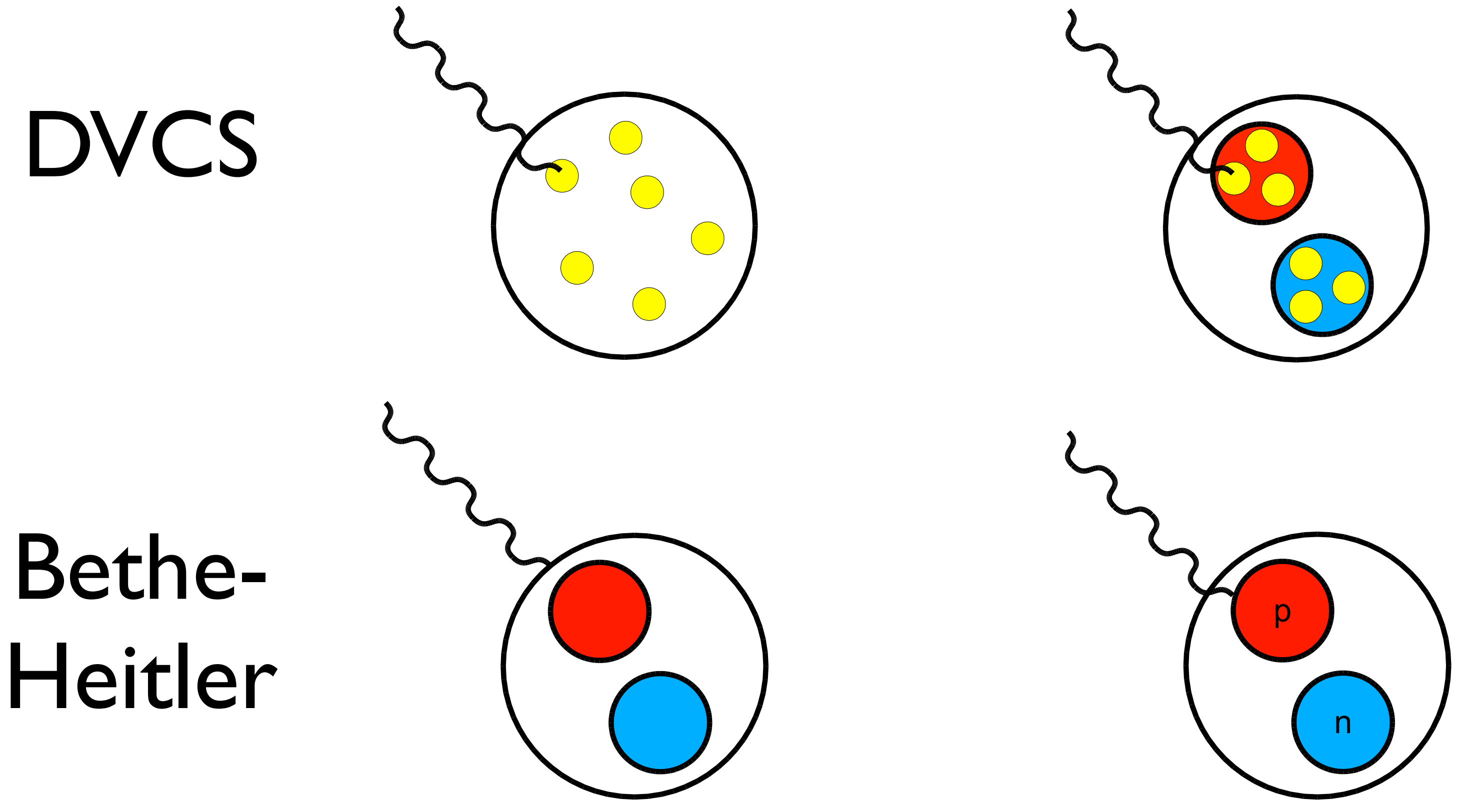
Compton Form Factors (CFFs)

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

twist-2 GPD

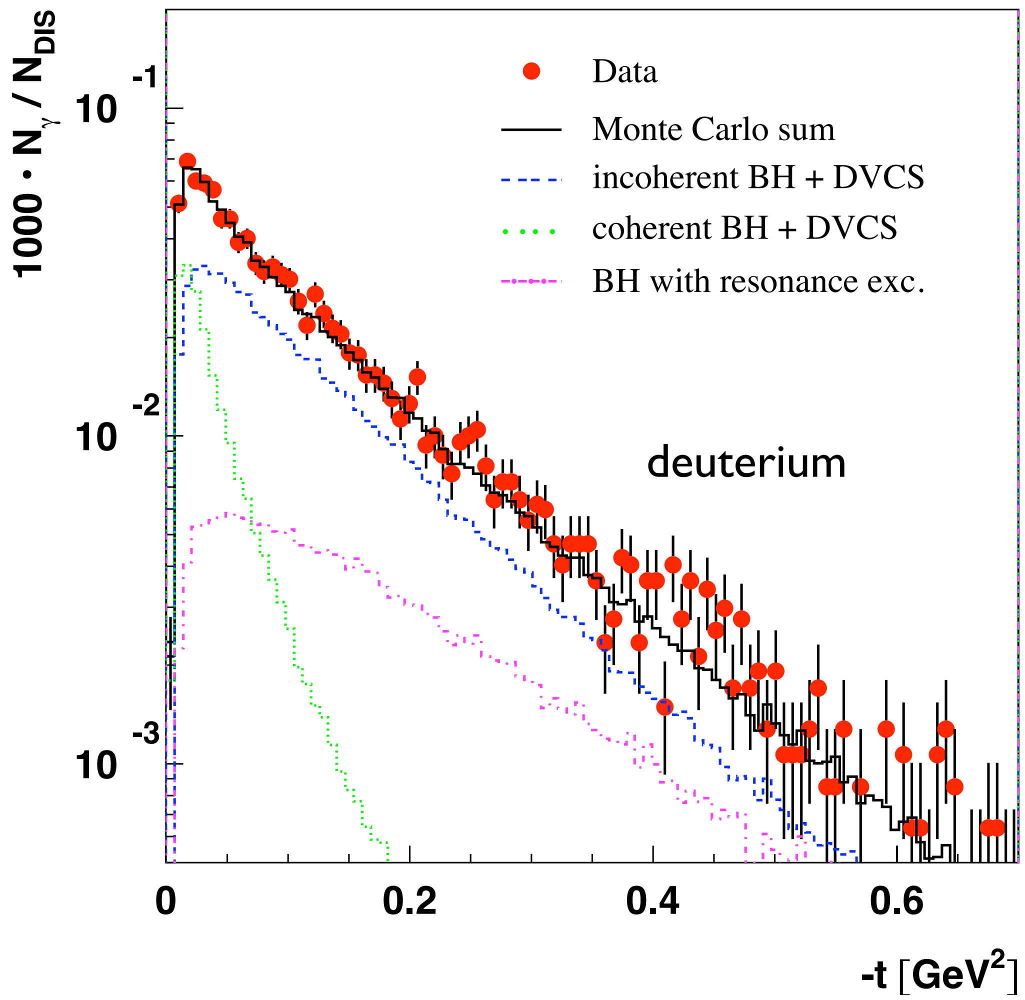
Coherent vs. incoherent

$eA \rightarrow eA\gamma$ $eA \rightarrow e(A-1)N\gamma$



Deuteron: probe spin-1 object

Nucleon: probe spin-1/2 object



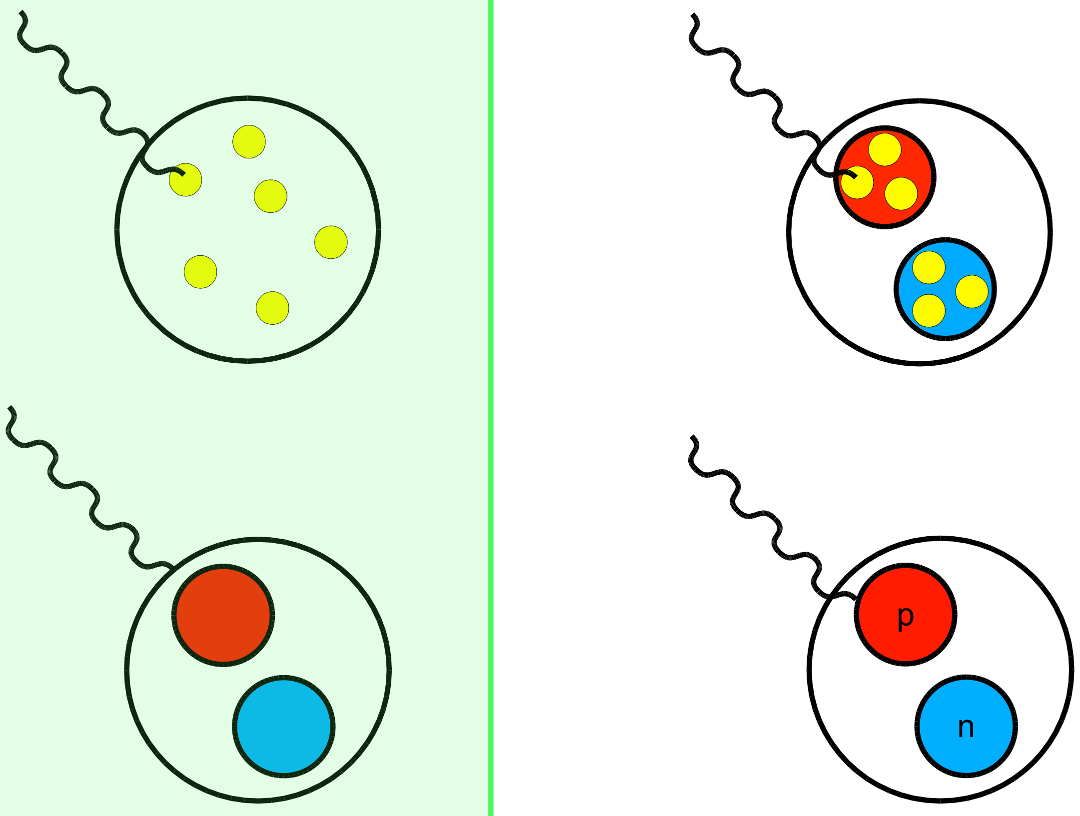
BH (proton) ≫ BH (neutron)
due to elastic electric form factor

Coherent vs. incoherent

$eA \to eA\gamma$ $eA \to e(A-1)N\gamma$

DVCS

Bethe-Heitler



Deuteron: probe spin-1 object

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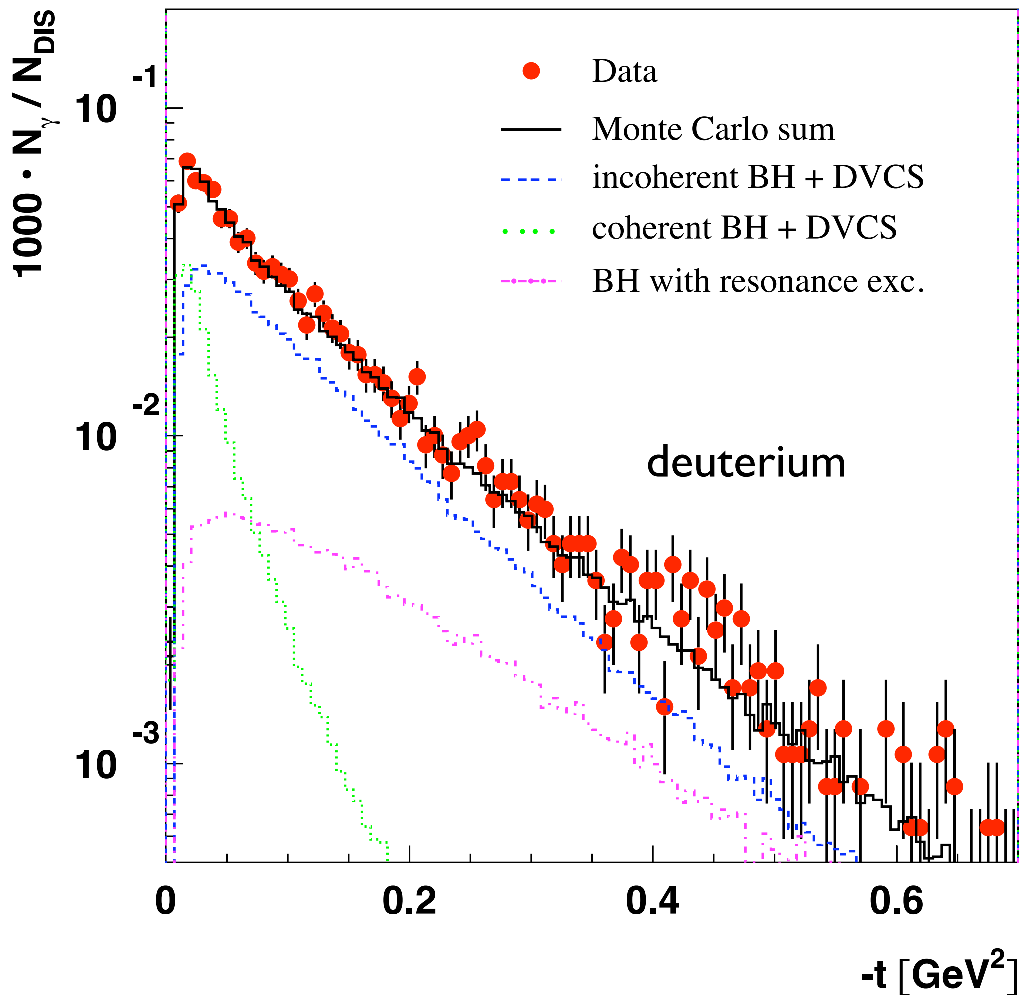

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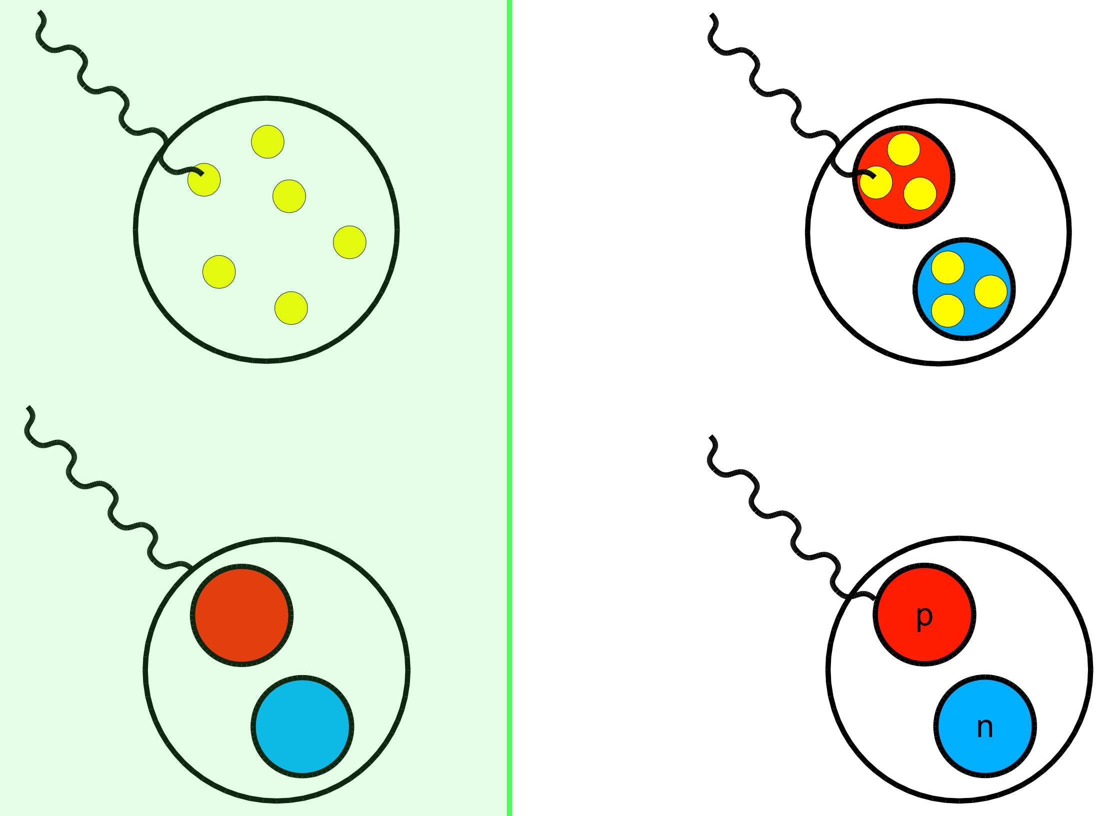
Coherent vs. incoherent

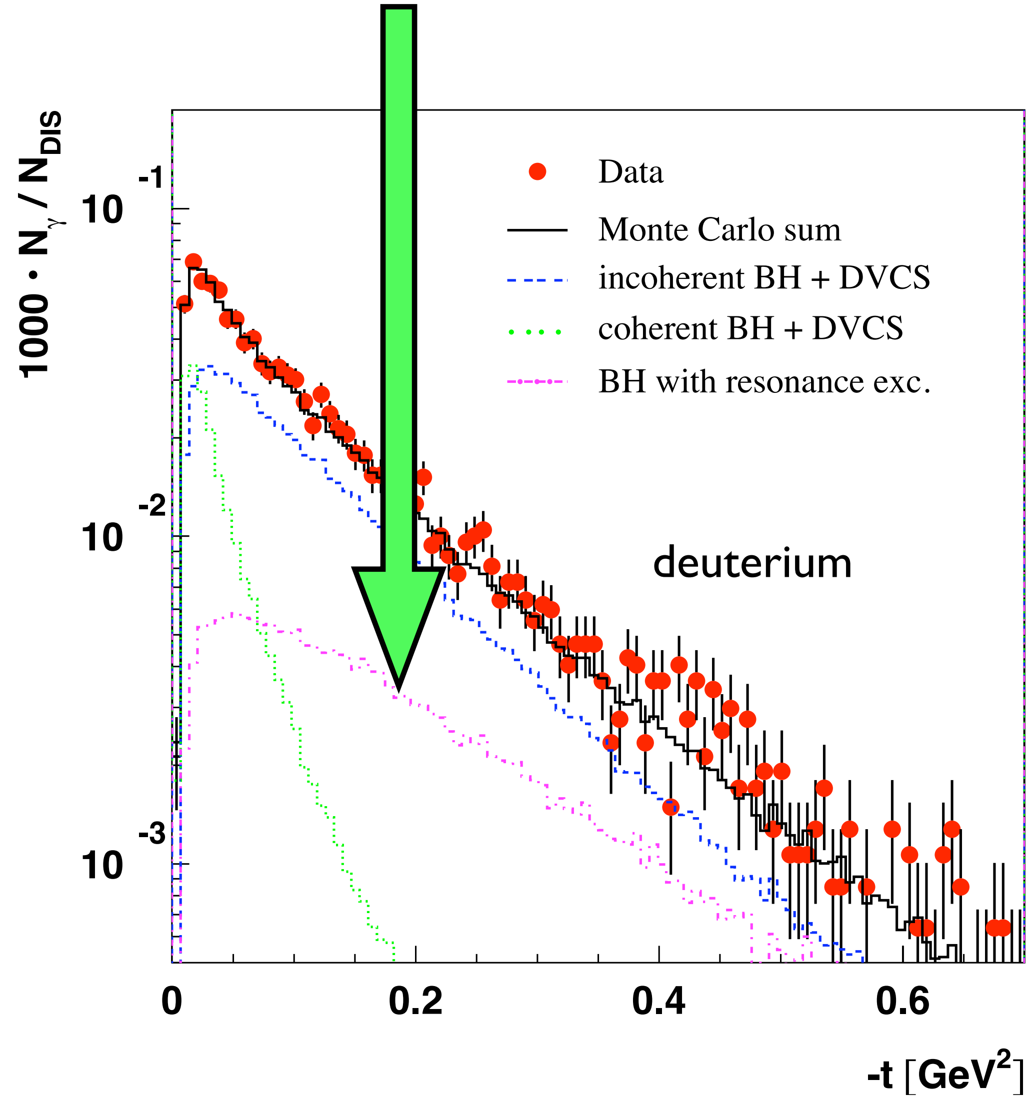
$eA \rightarrow eA\gamma$ $eA \rightarrow e(A-1)N\gamma$



Deuteron: probe spin-1 object

Nucleon: probe spin-1/2 object

Coherent contribution rapidly decreasing with -t



BH (proton) » BH (neutron)
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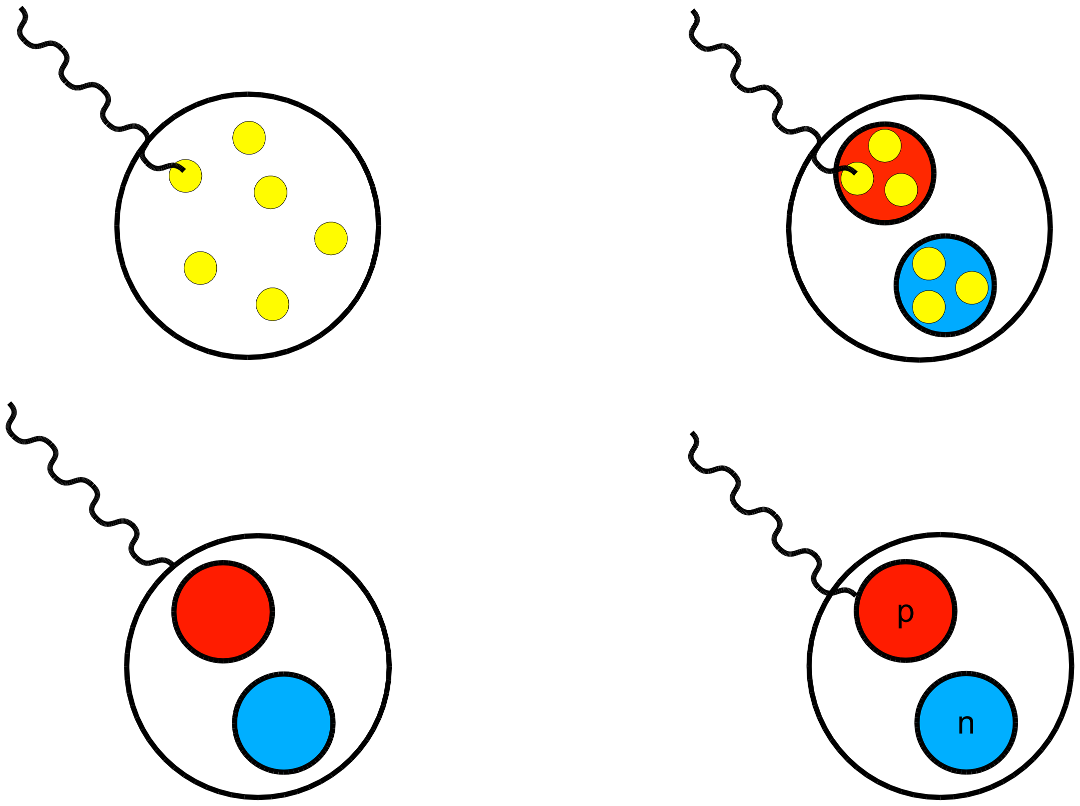
Coherent vs. incoherent

$eA \rightarrow eA\gamma$ $eA \rightarrow e(A-1)N\gamma$



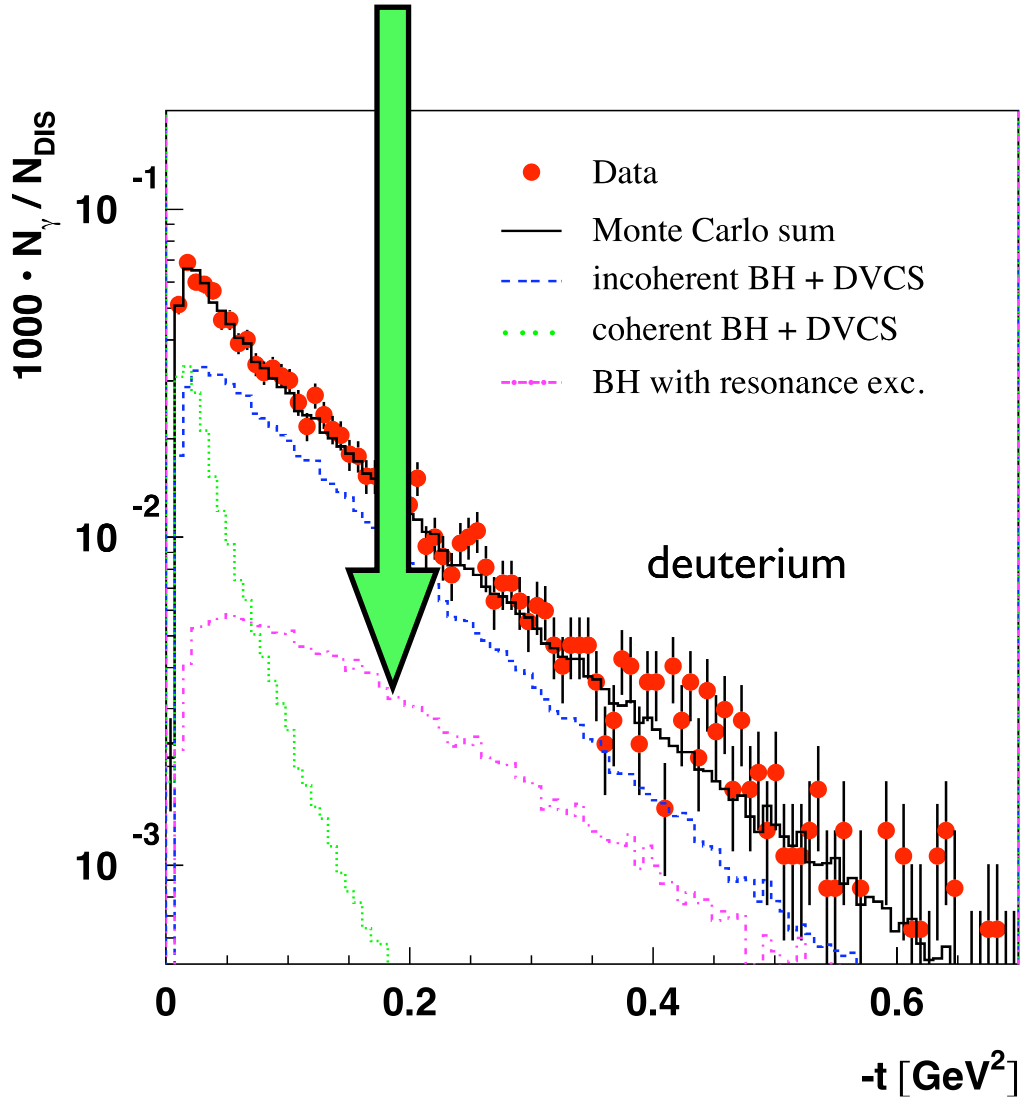
DVCS

Bethe-Heitler

Deuteron: probe spin-1 object

Nucleon: probe spin-1/2 object

Coherent contribution rapidly decreasing with -t



BH (proton) » BH (neutron) due to elastic electric form factor

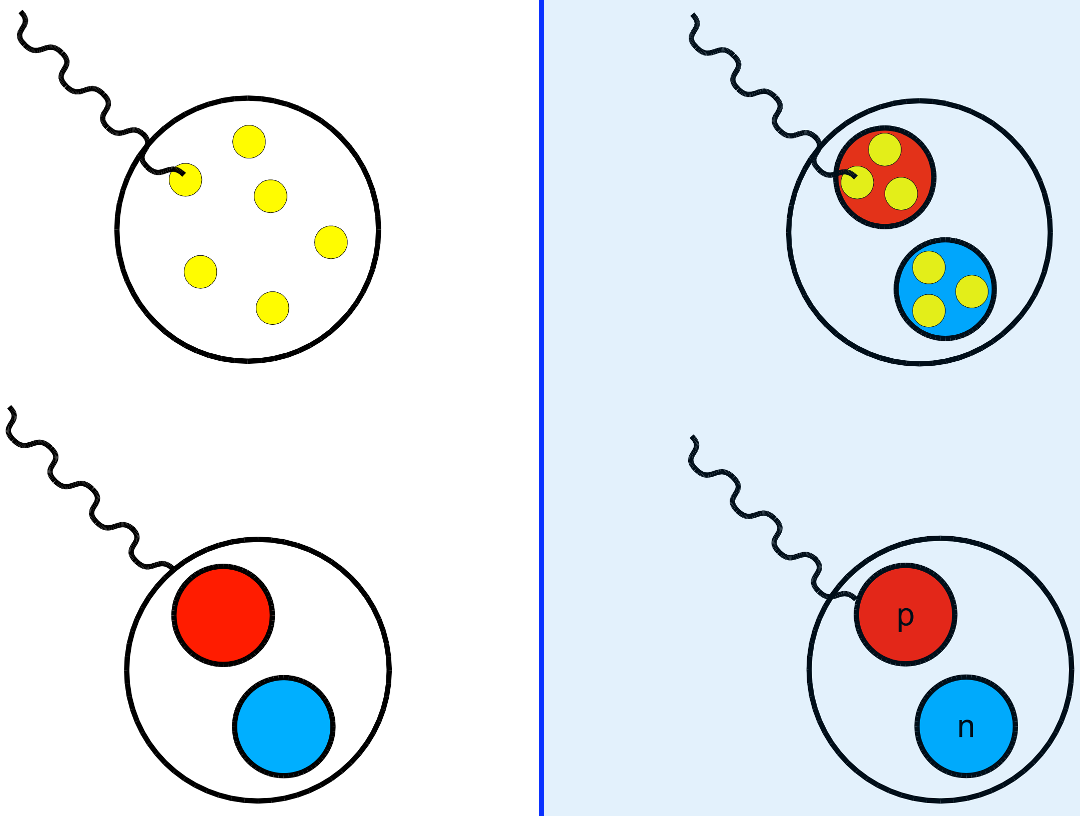
Coherent vs. incoherent

$eA \rightarrow eA\gamma$

$eA \rightarrow e(A-1)N\gamma$

DVCS

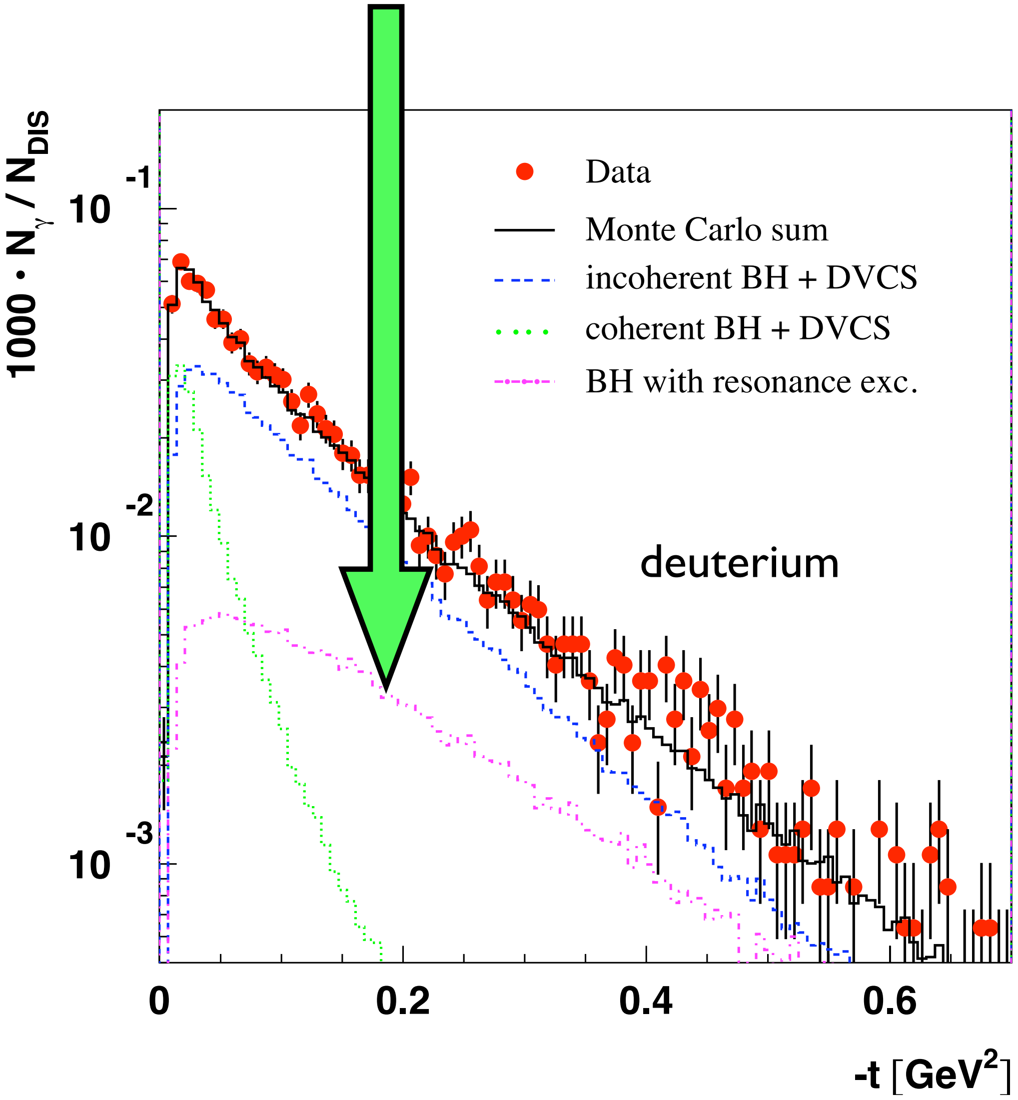
Bethe-Heitler



Deuteron: probe spin-1 object

Nucleon: probe spin-1/2 object

Coherent contribution rapidly decreasing with -t



BH (proton) ≫ BH (neutron)
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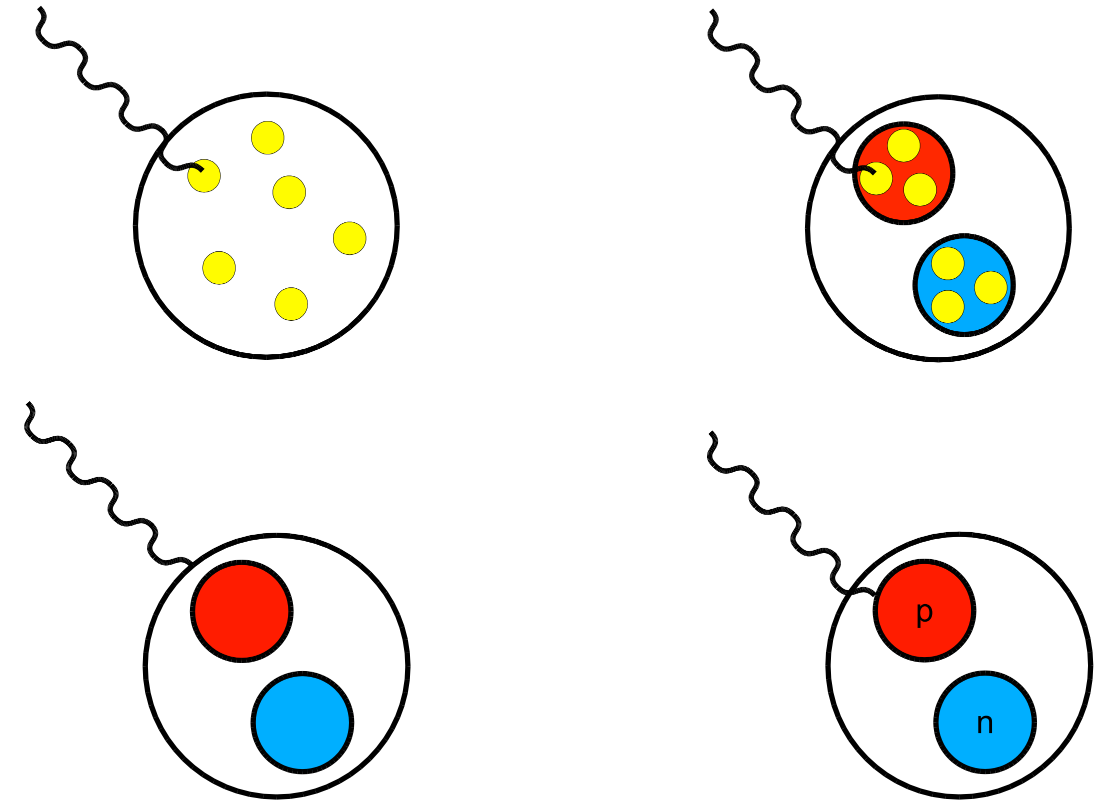
Coherent vs. incoherent

$eA \rightarrow eA\gamma$ $eA \rightarrow e(A-1)N\gamma$



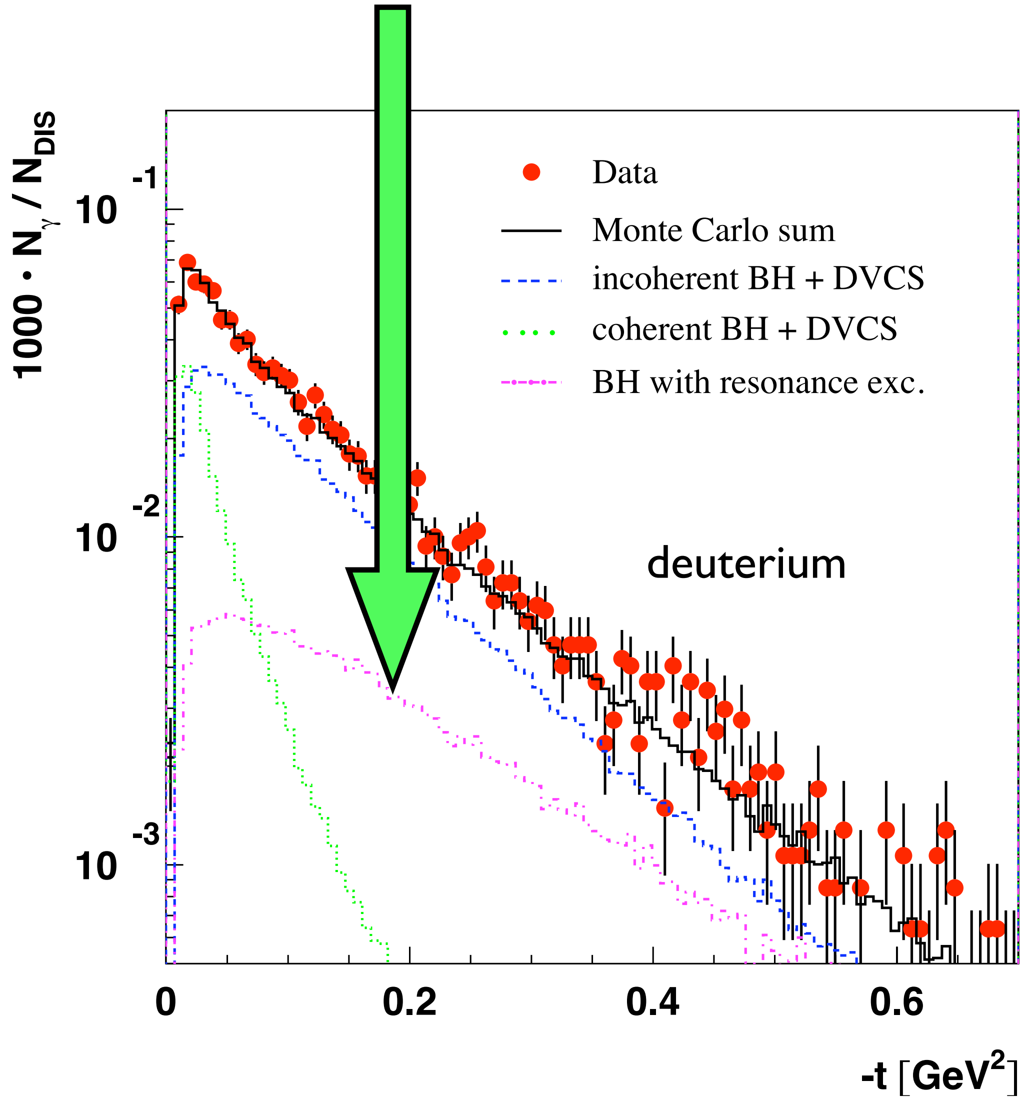
DVCS

Bethe-Heitler

Deuteron: probe
spin-1 object

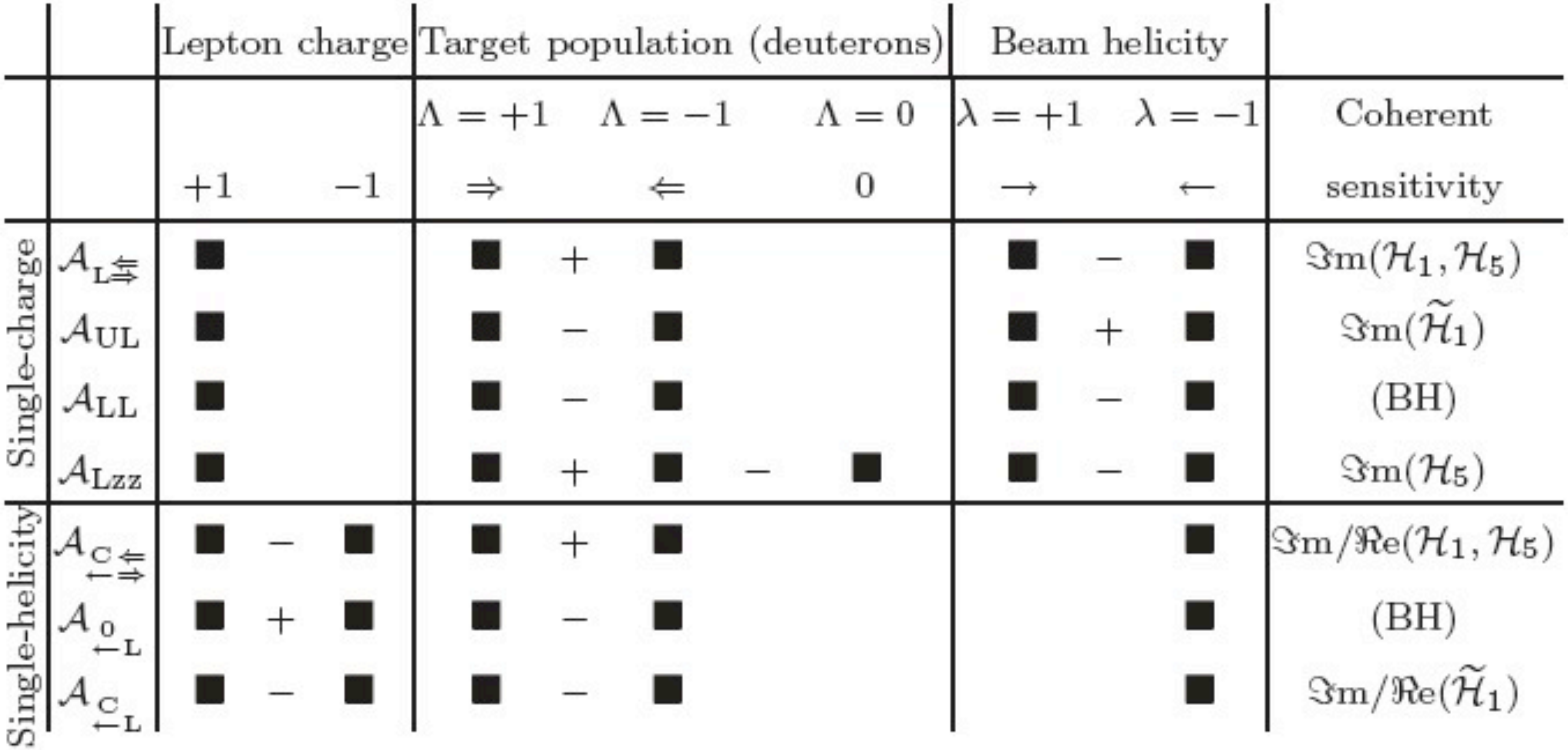
Nucleon: probe
spin-1/2 object

Coherent contribution
rapidly decreasing with -t



BH (proton) ≫ BH (neutron)
due to elastic electric form factor

Asymmetries on polarized deuterons

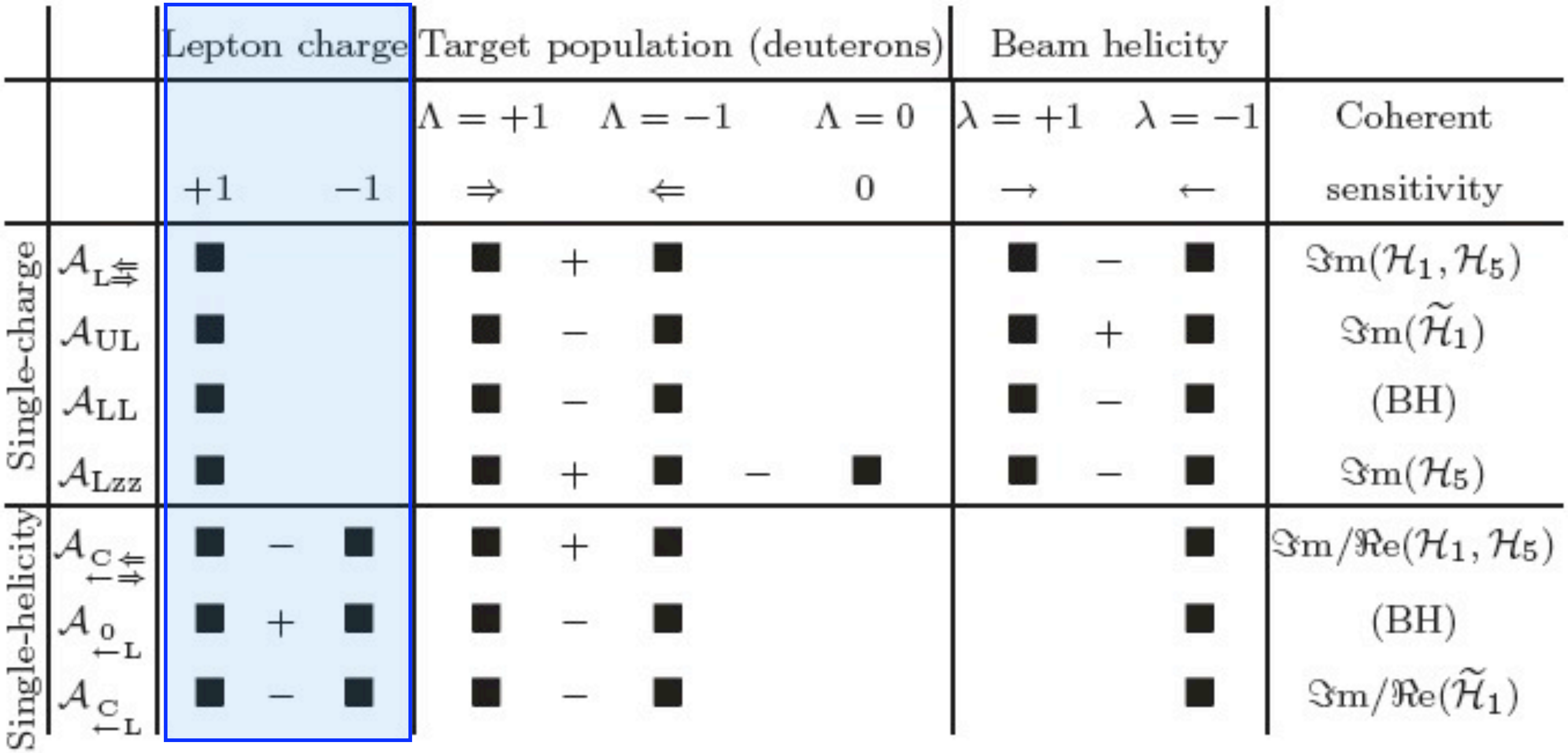


		Lepton charge			Target population (deuterons)					Beam helicity			
					$\Lambda = +1$		$\Lambda = -1$		$\Lambda = 0$	$\lambda = +1$		$\lambda = -1$	Coherent
		$+1$		-1	$\Rightarrow$		$\Leftarrow$		0	$\rightarrow$		$\leftarrow$	sensitivity
Single-charge	$\mathcal{A}_{\mathrm{L}\leftrightarrows}$	■			■	$+$	■			■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\mathrm{UL}}$	■			■	$-$	■			■	$+$	■	$\Im\mathrm{m}(\widetilde{\mathcal{H}}_1)$
	$\mathcal{A}_{\mathrm{LL}}$	■			■	$-$	■			■	$-$	■	(BH)
	$\mathcal{A}_{\mathrm{Lzz}}$	■			■	$+$	■	$-$	■	■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_5)$
Single-helicity	$\mathcal{A}_{\underset{\leftarrow}{\mathrm{C}}\underset{\Rightarrow}{\Leftarrow}}$	■	$-$	■	■	$+$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\underset{\leftarrow}{0}\mathrm{L}}$	■	$+$	■	■	$-$	■					■	(BH)
	$\mathcal{A}_{\underset{\leftarrow}{\mathrm{C}}\mathrm{L}}$	■	$-$	■	■	$-$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\widetilde{\mathcal{H}}_1)$

■ HERMES data set available

Not all combinations of beam-charge and beam-helicity available!

Asymmetries on polarized deuterons

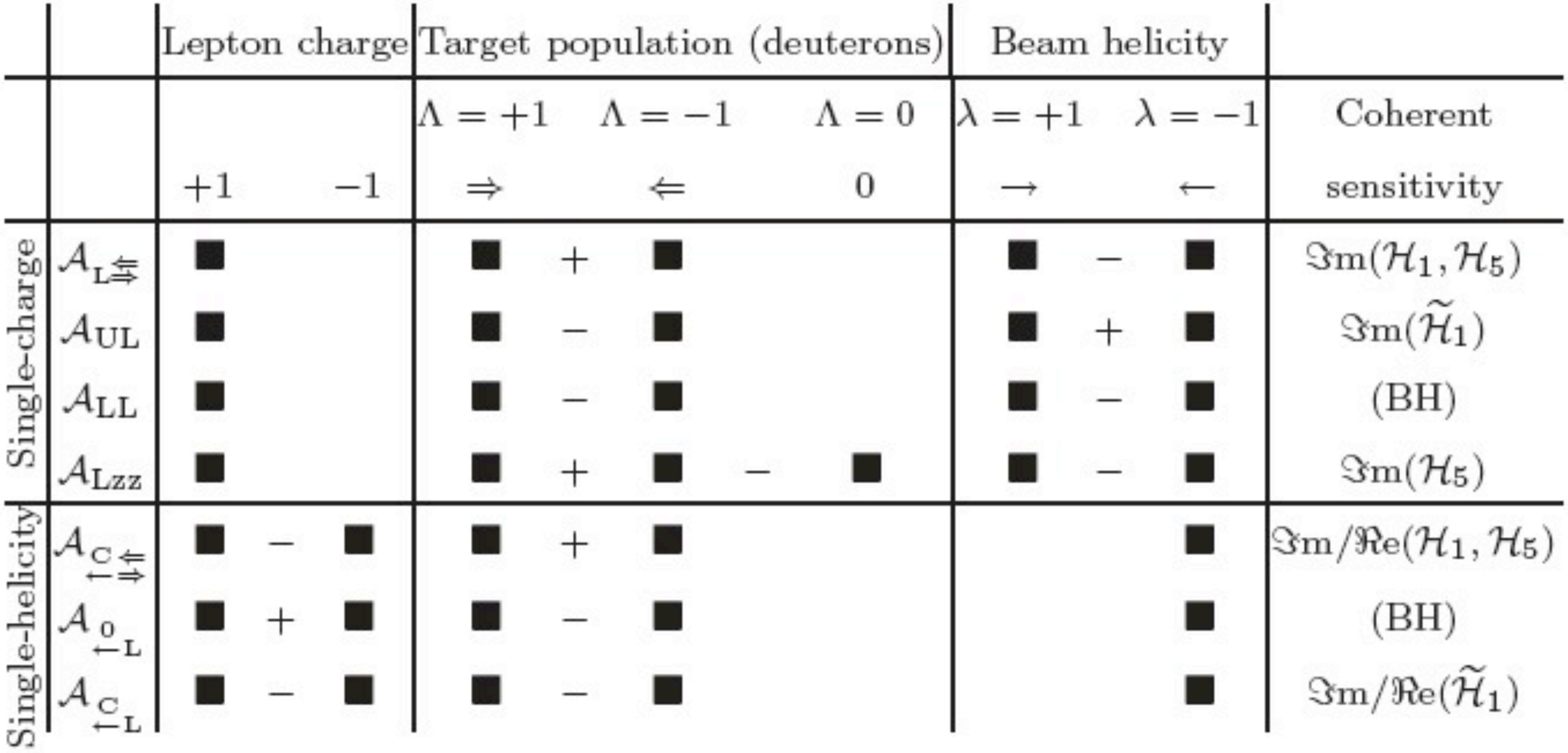


		Lepton charge			Target population (deuterons)					Beam helicity			
					$\Lambda = +1$		$\Lambda = -1$		$\Lambda = 0$	$\lambda = +1$		$\lambda = -1$	Coherent sensitivity
		$+1$		-1	$\Rightarrow$		$\Leftarrow$		0	$\rightarrow$		$\leftarrow$	
Single-charge	$\mathcal{A}_{\mathrm{L}\overset{\Leftarrow}{\Rightarrow}}$	■			■	$+$	■			■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\mathrm{UL}}$	■			■	$-$	■			■	$+$	■	$\Im\mathrm{m}(\widetilde{\mathcal{H}}_1)$
	$\mathcal{A}_{\mathrm{LL}}$	■			■	$-$	■			■	$-$	■	(BH)
	$\mathcal{A}_{\mathrm{Lzz}}$	■			■	$+$	■	$-$	■	■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_5)$
Single-helicity	$\mathcal{A}_{\overset{\mathrm{C}}{\leftarrow}\overset{\Leftarrow}{\Rightarrow}}$	■	$-$	■	■	$+$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\overset{0}{\leftarrow}\mathrm{L}}$	■	$+$	■	■	$-$	■					■	(BH)
	$\mathcal{A}_{\overset{\mathrm{C}}{\leftarrow}\mathrm{L}}$	■	$-$	■	■	$-$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\widetilde{\mathcal{H}}_1)$

■ HERMES data set available

Not all combinations of beam-charge and beam-helicity available!

Asymmetries on polarized deuterons

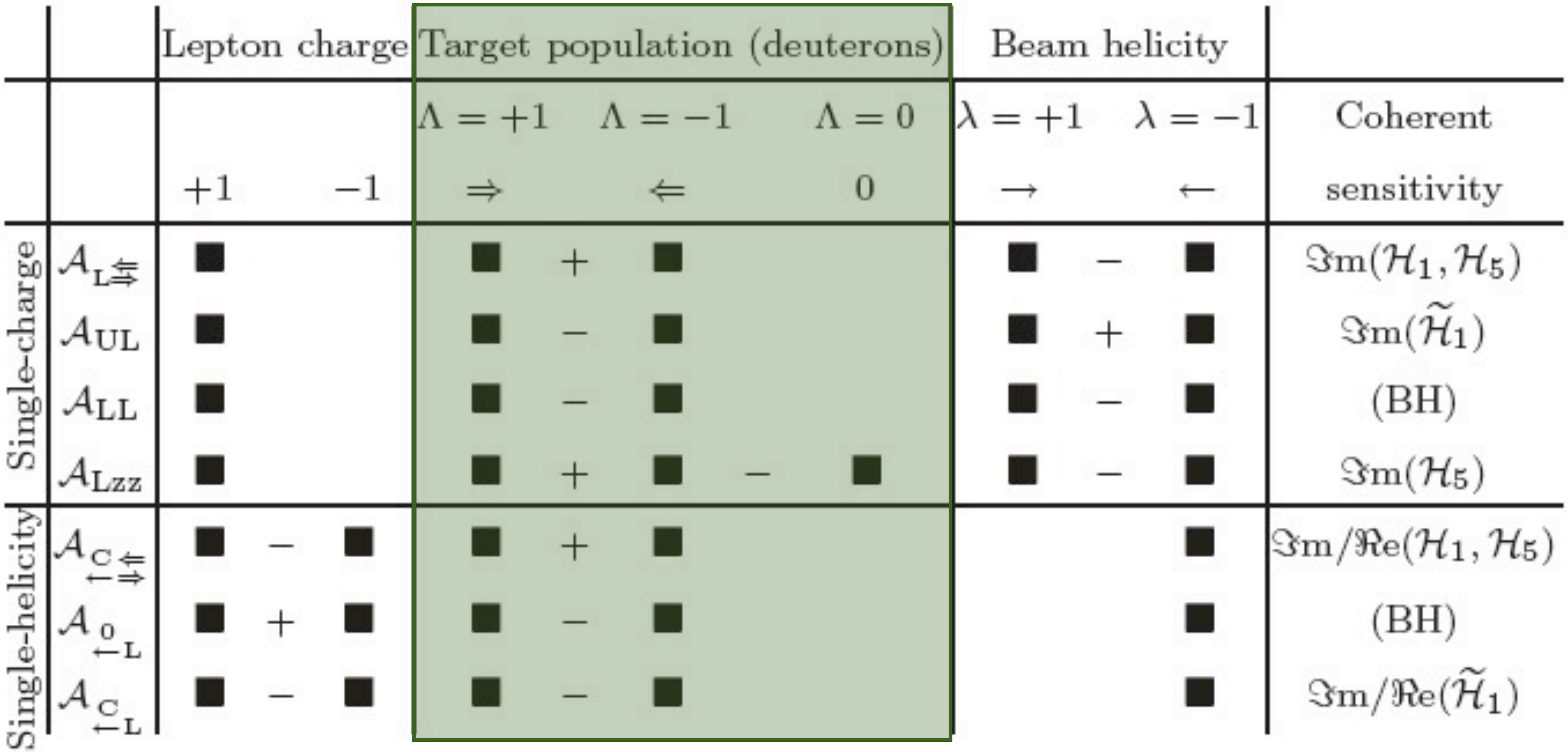


		Lepton charge			Target population (deuterons)					Beam helicity			
					$\Lambda=+1$		$\Lambda=-1$		$\Lambda=0$	$\lambda=+1$		$\lambda=-1$	Coherent
		$+1$		-1	$\Rightarrow$		$\Leftarrow$		0	$\rightarrow$		$\leftarrow$	sensitivity
Single-charge	$\mathcal{A}_{\mathrm{L}\leftrightarrows}$	■			■	$+$	■			■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_1,\mathcal{H}_5)$
	$\mathcal{A}_{\mathrm{UL}}$	■			■	$-$	■			■	$+$	■	$\Im\mathrm{m}(\widetilde{\mathcal{H}}_1)$
	$\mathcal{A}_{\mathrm{LL}}$	■			■	$-$	■			■	$-$	■	(BH)
	$\mathcal{A}_{\mathrm{Lzz}}$	■			■	$+$	■	$-$	■	■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_5)$
Single-helicity	$\mathcal{A}_{\substack{\mathrm{C}\,\Leftarrow\\ \leftarrow\Rightarrow}}$	■	$-$	■	■	$+$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\mathcal{H}_1,\mathcal{H}_5)$
	$\mathcal{A}_{\substack{0\\ \leftarrow\mathrm{L}}}$	■	$+$	■	■	$-$	■					■	(BH)
	$\mathcal{A}_{\substack{\mathrm{C}\\ \leftarrow\mathrm{L}}}$	■	$-$	■	■	$-$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\widetilde{\mathcal{H}}_1)$

■ HERMES data set available

Not all combinations of beam-charge and beam-helicity available!

Asymmetries on polarized deuterons

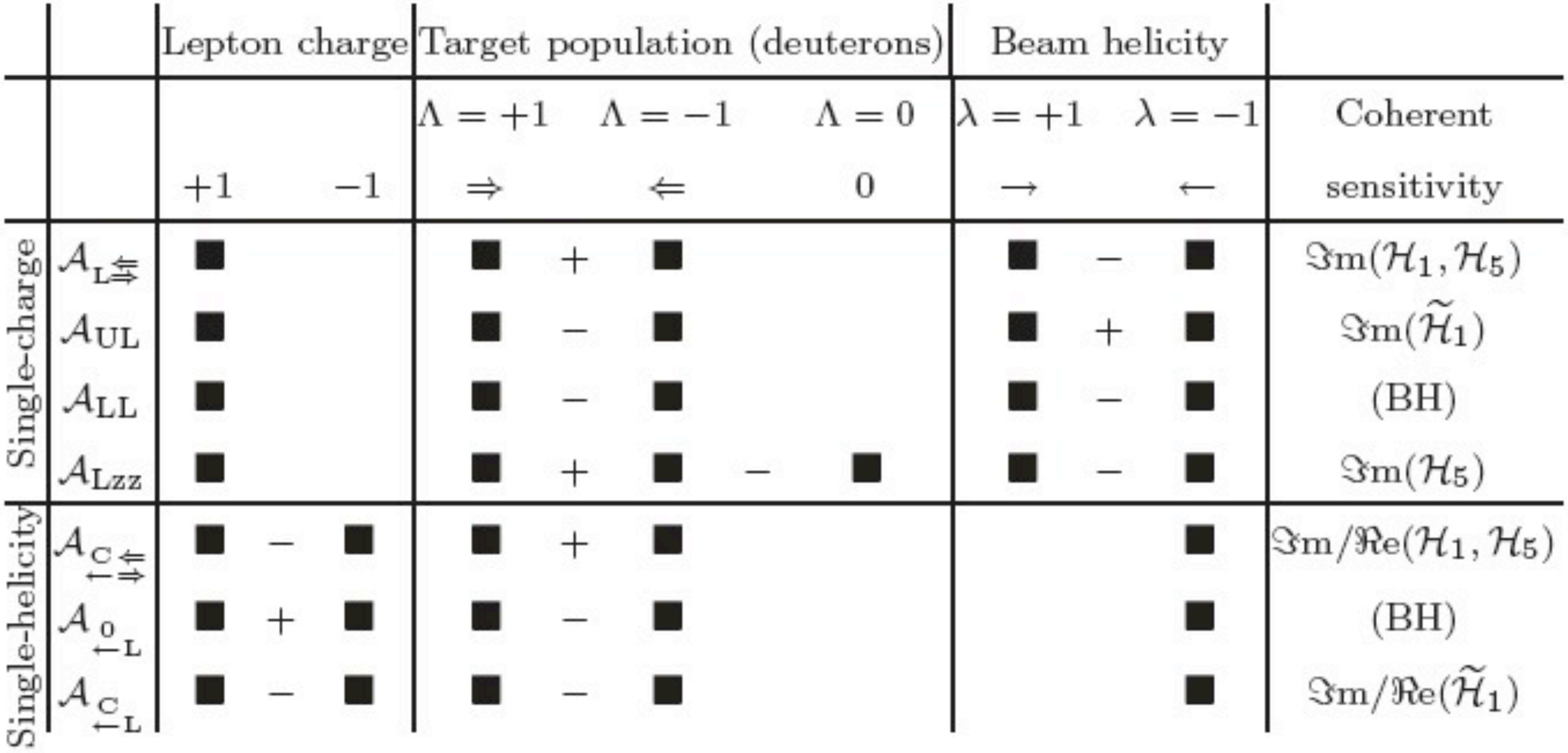


		Lepton charge			Target population (deuterons)					Beam helicity			
					$\Lambda=+1$		$\Lambda=-1$		$\Lambda=0$	$\lambda=+1$		$\lambda=-1$	Coherent
		$+1$		-1	$\Rightarrow$		$\Leftarrow$		0	$\rightarrow$		$\leftarrow$	sensitivity
Single-charge	$\mathcal{A}_{\mathrm{L}\overset{\Leftarrow}{\Rightarrow}}$	■			■	$+$	■			■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_1,\mathcal{H}_5)$
	$\mathcal{A}_{\mathrm{UL}}$	■			■	$-$	■			■	$+$	■	$\Im\mathrm{m}(\widetilde{\mathcal{H}}_1)$
	$\mathcal{A}_{\mathrm{LL}}$	■			■	$-$	■			■	$-$	■	(BH)
	$\mathcal{A}_{\mathrm{Lzz}}$	■			■	$+$	■	$-$	■	■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_5)$
Single-helicity	$\mathcal{A}_{\overset{\mathrm{C}}{\leftarrow}\overset{\Leftarrow}{\Rightarrow}}$	■	$-$	■	■	$+$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\mathcal{H}_1,\mathcal{H}_5)$
	$\mathcal{A}_{\overset{0}{\leftarrow}\mathrm{L}}$	■	$+$	■	■	$-$	■					■	(BH)
	$\mathcal{A}_{\overset{\mathrm{C}}{\leftarrow}\mathrm{L}}$	■	$-$	■	■	$-$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\widetilde{\mathcal{H}}_1)$

■ HERMES data set available

Not all combinations of beam-charge and beam-helicity available!

Asymmetries on polarized deuterons

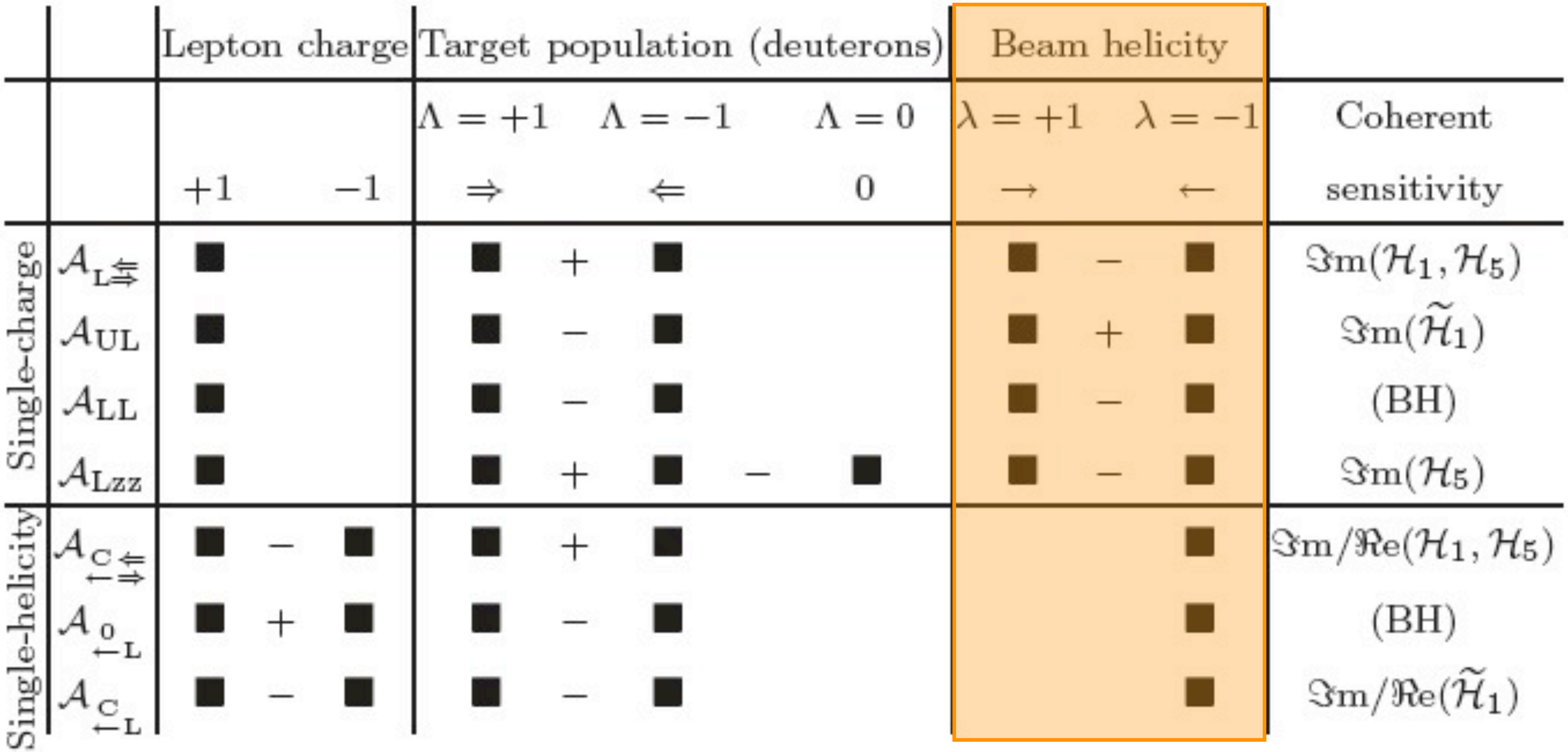


		Lepton charge			Target population (deuterons)					Beam helicity			
					$\Lambda = +1$		$\Lambda = -1$		$\Lambda = 0$	$\lambda = +1$		$\lambda = -1$	Coherent sensitivity
		$+1$		-1	$\Rightarrow$		$\Leftarrow$		0	$\rightarrow$		$\leftarrow$	
Single-charge	$\mathcal{A}_{\mathrm{L}\substack{\Leftarrow\\\Rightarrow}}$	■			■	$+$	■			■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\mathrm{UL}}$	■			■	$-$	■			■	$+$	■	$\Im\mathrm{m}(\widetilde{\mathcal{H}}_1)$
	$\mathcal{A}_{\mathrm{LL}}$	■			■	$-$	■			■	$-$	■	(BH)
	$\mathcal{A}_{\mathrm{Lzz}}$	■			■	$+$	■	$-$	■	■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_5)$
Single-helicity	$\mathcal{A}_{\substack{\mathrm{C}\\\leftarrow}\substack{\Leftarrow\\\Rightarrow}}$	■	$-$	■	■	$+$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\substack{0\\\leftarrow}\mathrm{L}}$	■	$+$	■	■	$-$	■					■	(BH)
	$\mathcal{A}_{\substack{\mathrm{C}\\\leftarrow}\mathrm{L}}$	■	$-$	■	■	$-$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\widetilde{\mathcal{H}}_1)$

■ HERMES data set available

Not all combinations of beam-charge and beam-helicity available!

Asymmetries on polarized deuterons



		Lepton charge			Target population (deuterons)					Beam helicity			
					$\Lambda = +1$		$\Lambda = -1$		$\Lambda = 0$	$\lambda = +1$		$\lambda = -1$	Coherent
		$+1$		-1	$\Rightarrow$		$\Leftarrow$		0	$\rightarrow$		$\leftarrow$	sensitivity
Single-charge	$\mathcal{A}_{\mathrm{L}\underset{\Rightarrow}{\Leftarrow}}$	■			■	$+$	■			■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\mathrm{UL}}$	■			■	$-$	■			■	$+$	■	$\Im\mathrm{m}(\widetilde{\mathcal{H}}_1)$
	$\mathcal{A}_{\mathrm{LL}}$	■			■	$-$	■			■	$-$	■	(BH)
	$\mathcal{A}_{\mathrm{Lzz}}$	■			■	$+$	■	$-$	■	■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_5)$
Single-helicity	$\mathcal{A}_{\underset{\leftarrow}{\mathrm{C}}\underset{\Rightarrow}{\Leftarrow}}$	■	$-$	■	■	$+$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\underset{\leftarrow}{0}\mathrm{L}}$	■	$+$	■	■	$-$	■					■	(BH)
	$\mathcal{A}_{\underset{\leftarrow}{\mathrm{C}}\mathrm{L}}$	■	$-$	■	■	$-$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\widetilde{\mathcal{H}}_1)$

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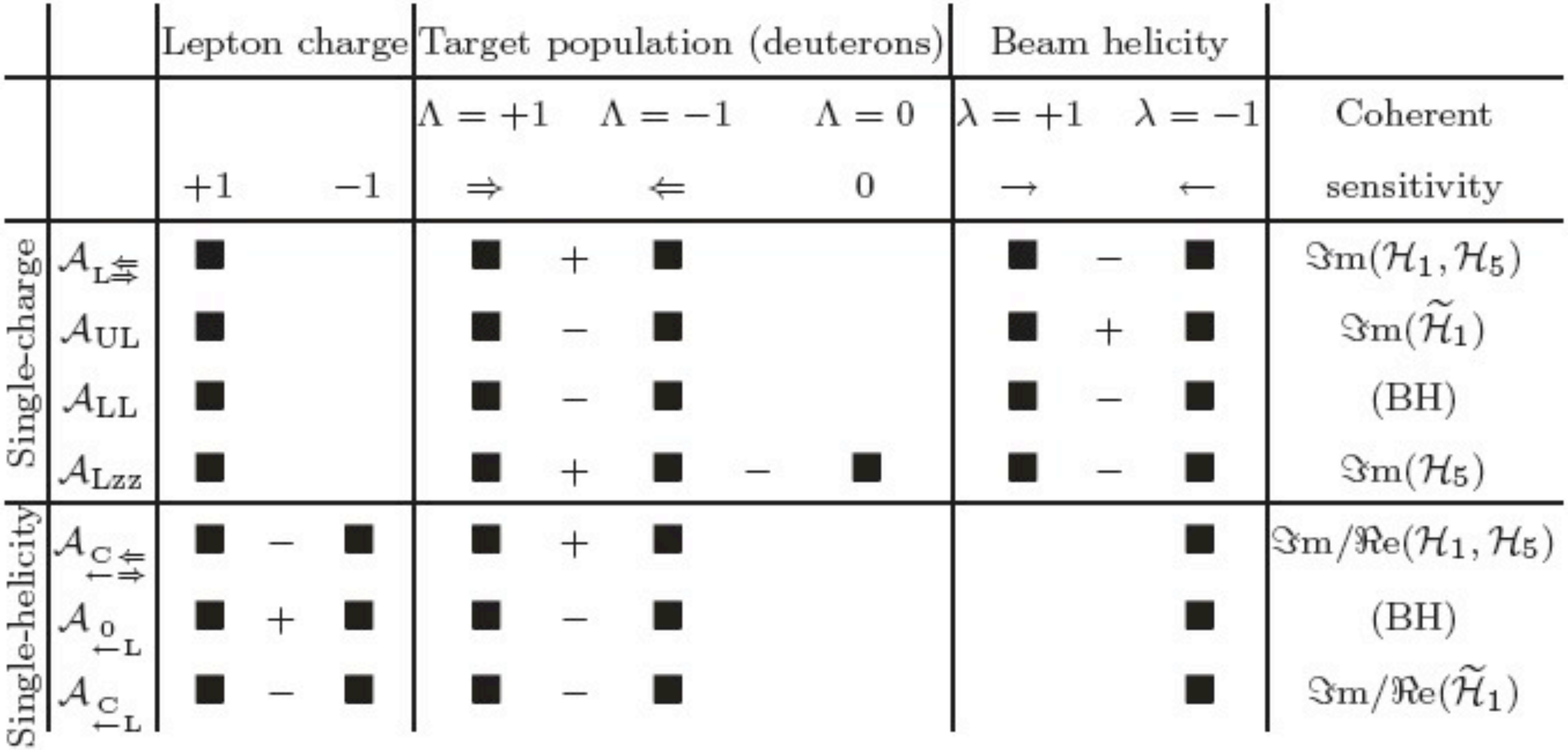
Not all combinations of beam-charge and beam-helicity available!

Asymmetries on polarized deuterons



		Lepton charge			Target population (deuterons)					Beam helicity			
					$\Lambda = +1$		$\Lambda = -1$		$\Lambda = 0$	$\lambda = +1$		$\lambda = -1$	Coherent
		$+1$		-1	$\Rightarrow$		$\Leftarrow$		0	$\rightarrow$		$\leftarrow$	sensitivity
Single-charge	$\mathcal{A}_{\mathrm{L}\substack{\Leftarrow\\\Rightarrow}}$	■			■	$+$	■			■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\mathrm{UL}}$	■			■	$-$	■			■	$+$	■	$\Im\mathrm{m}(\widetilde{\mathcal{H}}_1)$
	$\mathcal{A}_{\mathrm{LL}}$	■			■	$-$	■			■	$-$	■	(BH)
	$\mathcal{A}_{\mathrm{Lzz}}$	■			■	$+$	■	$-$	■	■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_5)$
Single-helicity	$\mathcal{A}_{\substack{\mathrm{C}\\\leftarrow}\substack{\Leftarrow\\\Rightarrow}}$	■	$-$	■	■	$+$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\substack{0\\\leftarrow}\mathrm{L}}$	■	$+$	■	■	$-$	■					■	(BH)
	$\mathcal{A}_{\substack{\mathrm{C}\\\leftarrow}\mathrm{L}}$	■	$-$	■	■	$-$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\widetilde{\mathcal{H}}_1)$

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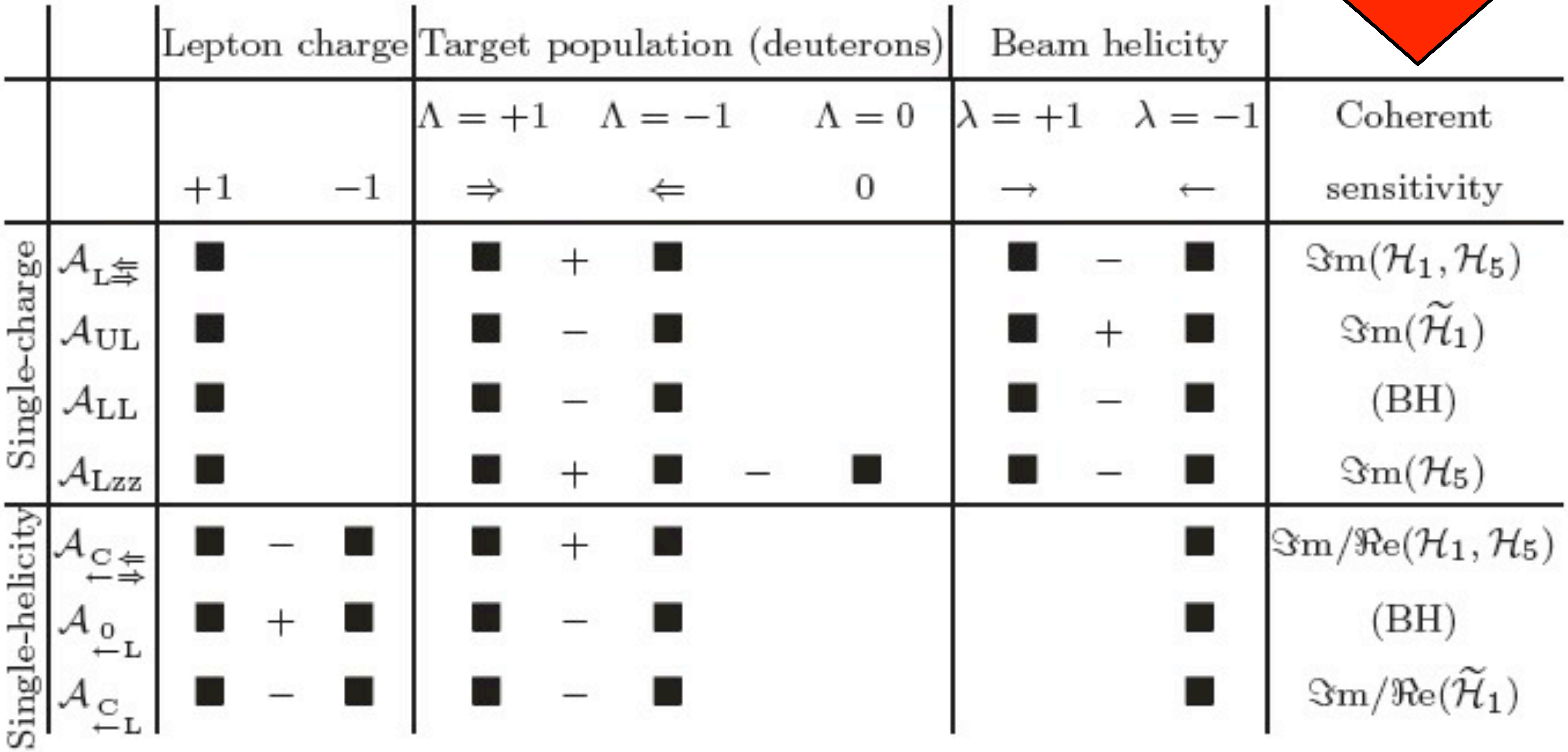
Not all combinations of beam-charge and beam-helicity available!

Asymmetries on polarized deuterons

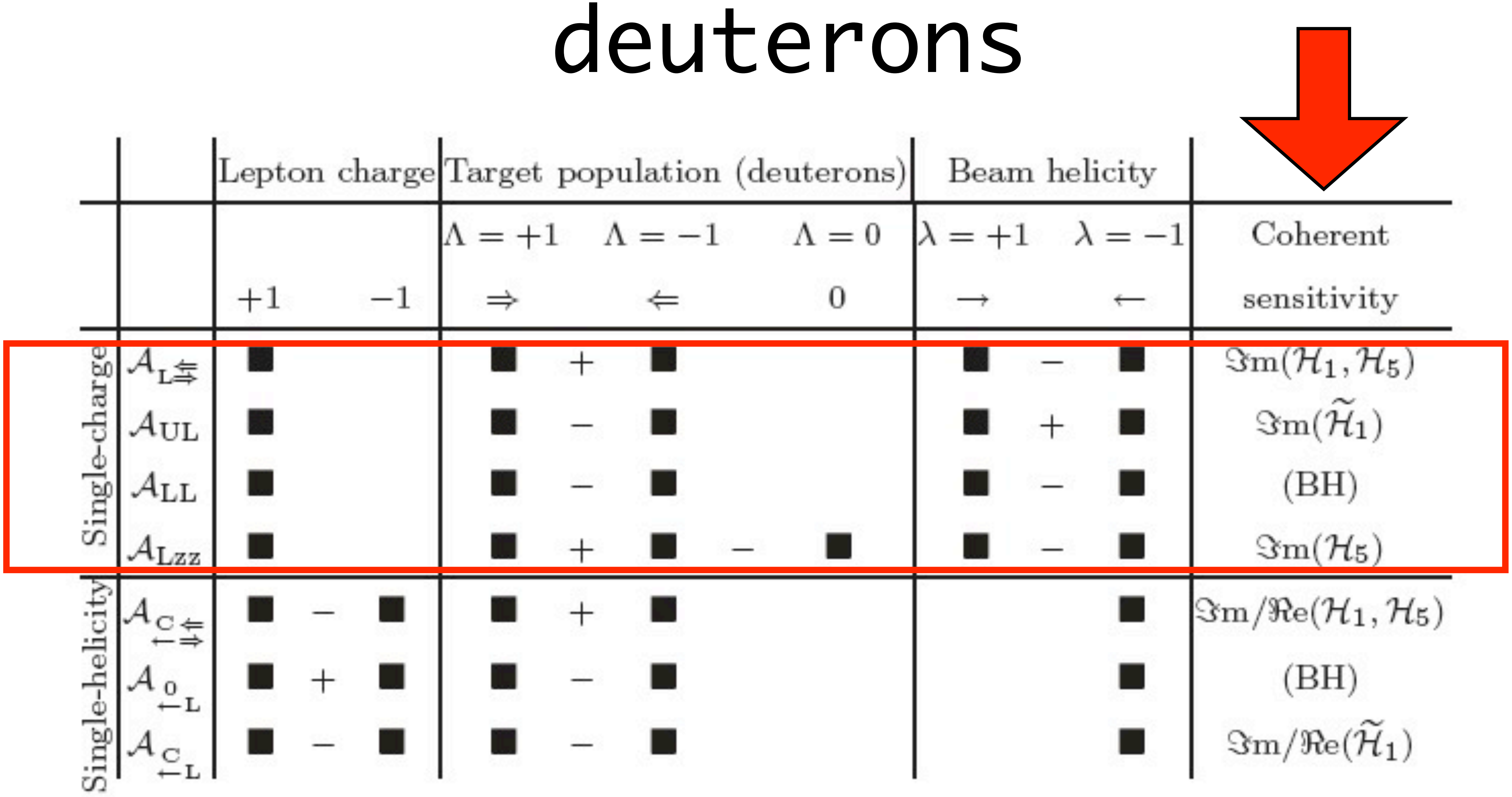


		Lepton charge			Target population (deuterons)					Beam helicity			
					$\Lambda = +1$		$\Lambda = -1$		$\Lambda = 0$	$\lambda = +1$		$\lambda = -1$	Coherent
		$+1$		-1	$\Rightarrow$		$\Leftarrow$		0	$\rightarrow$		$\leftarrow$	sensitivity
Single-charge	$\mathcal{A}_{\mathrm{L}\overset{\Leftarrow}{\Rightarrow}}$	■			■	$+$	■			■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\mathrm{UL}}$	■			■	$-$	■			■	$+$	■	$\Im\mathrm{m}(\widetilde{\mathcal{H}}_1)$
	$\mathcal{A}_{\mathrm{LL}}$	■			■	$-$	■			■	$-$	■	(BH)
	$\mathcal{A}_{\mathrm{Lzz}}$	■			■	$+$	■	$-$	■	■	$-$	■	$\Im\mathrm{m}(\mathcal{H}_5)$
Single-helicity	$\mathcal{A}_{\overset{\mathrm{C}}{\leftrightarrow}\overset{\Leftarrow}{\Rightarrow}}$	■	$-$	■	■	$+$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\overset{0}{\leftarrow}\mathrm{L}}$	■	$+$	■	■	$-$	■					■	(BH)
	$\mathcal{A}_{\overset{\mathrm{C}}{\leftarrow}\mathrm{L}}$	■	$-$	■	■	$-$	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\widetilde{\mathcal{H}}_1)$

■ HERMES data set available

Not all combinations of beam-charge and beam-helicity available!

Asymmetries on polarized deuterons

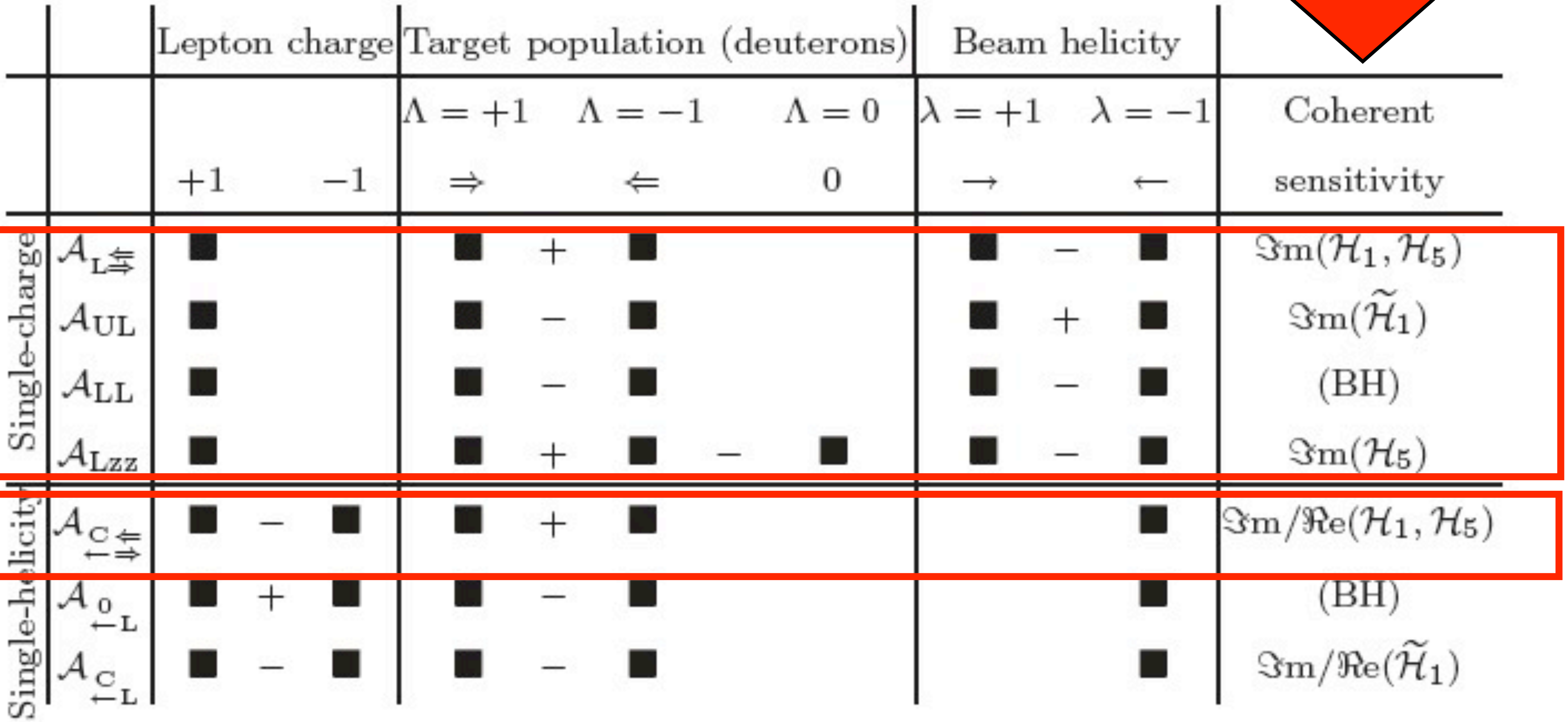


		Lepton charge			Target population (deuterons)					Beam helicity			
					$\Lambda = +1$		$\Lambda = -1$		$\Lambda = 0$	$\lambda = +1$		$\lambda = -1$	Coherent
		$+1$		-1	$\Rightarrow$		$\Leftarrow$		0	$\rightarrow$		$\leftarrow$	sensitivity
Single-charge	$\mathcal{A}_{\mathrm{L}\leftrightarrows}$	■			■	+	■			■	−	■	$\Im\mathrm{m}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\mathrm{UL}}$	■			■	−	■			■	+	■	$\Im\mathrm{m}(\widetilde{\mathcal{H}}_1)$
	$\mathcal{A}_{\mathrm{LL}}$	■			■	−	■			■	−	■	(BH)
	$\mathcal{A}_{\mathrm{Lzz}}$	■			■	+	■	−	■	■	−	■	$\Im\mathrm{m}(\mathcal{H}_5)$
Single-helicity	$\mathcal{A}_{\substack{\mathrm{C}\Leftarrow \\ \leftarrow\Rightarrow}}$	■	−	■	■	+	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\substack{0 \\ \leftarrow\mathrm{L}}}$	■	+	■	■	−	■					■	(BH)
	$\mathcal{A}_{\substack{\mathrm{C} \\ \leftarrow\mathrm{L}}}$	■	−	■	■	−	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\widetilde{\mathcal{H}}_1)$

■ HERMES data set available

Not all combinations of beam-charge and beam-helicity available!

Asymmetries on polarized deuterons



		Lepton charge			Target population (deuterons)					Beam helicity			
					$\Lambda = +1$		$\Lambda = -1$		$\Lambda = 0$	$\lambda = +1$		$\lambda = -1$	Coherent sensitivity
		$+1$		-1	$\Rightarrow$		$\Leftarrow$		0	$\rightarrow$		$\leftarrow$	
Single-charge	$\mathcal{A}_{\mathrm{L}\substack{\Leftarrow\\\Rightarrow}}$	■			■	+	■			■	−	■	$\Im\mathrm{m}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\mathrm{UL}}$	■			■	−	■			■	+	■	$\Im\mathrm{m}(\widetilde{\mathcal{H}}_1)$
	$\mathcal{A}_{\mathrm{LL}}$	■			■	−	■			■	−	■	(BH)
	$\mathcal{A}_{\mathrm{Lzz}}$	■			■	+	■	−	■	■	−	■	$\Im\mathrm{m}(\mathcal{H}_5)$
Single-helicity	$\mathcal{A}_{\overset{\mathrm{C}}{\leftarrow}\substack{\Leftarrow\\\Rightarrow}}$	■	−	■	■	+	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\mathcal{H}_1, \mathcal{H}_5)$
	$\mathcal{A}_{\overset{0}{\leftarrow}\mathrm{L}}$	■	+	■	■	−	■					■	(BH)
	$\mathcal{A}_{\overset{\mathrm{C}}{\leftarrow}\mathrm{L}}$	■	−	■	■	−	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\widetilde{\mathcal{H}}_1)$

■ HERMES data set available

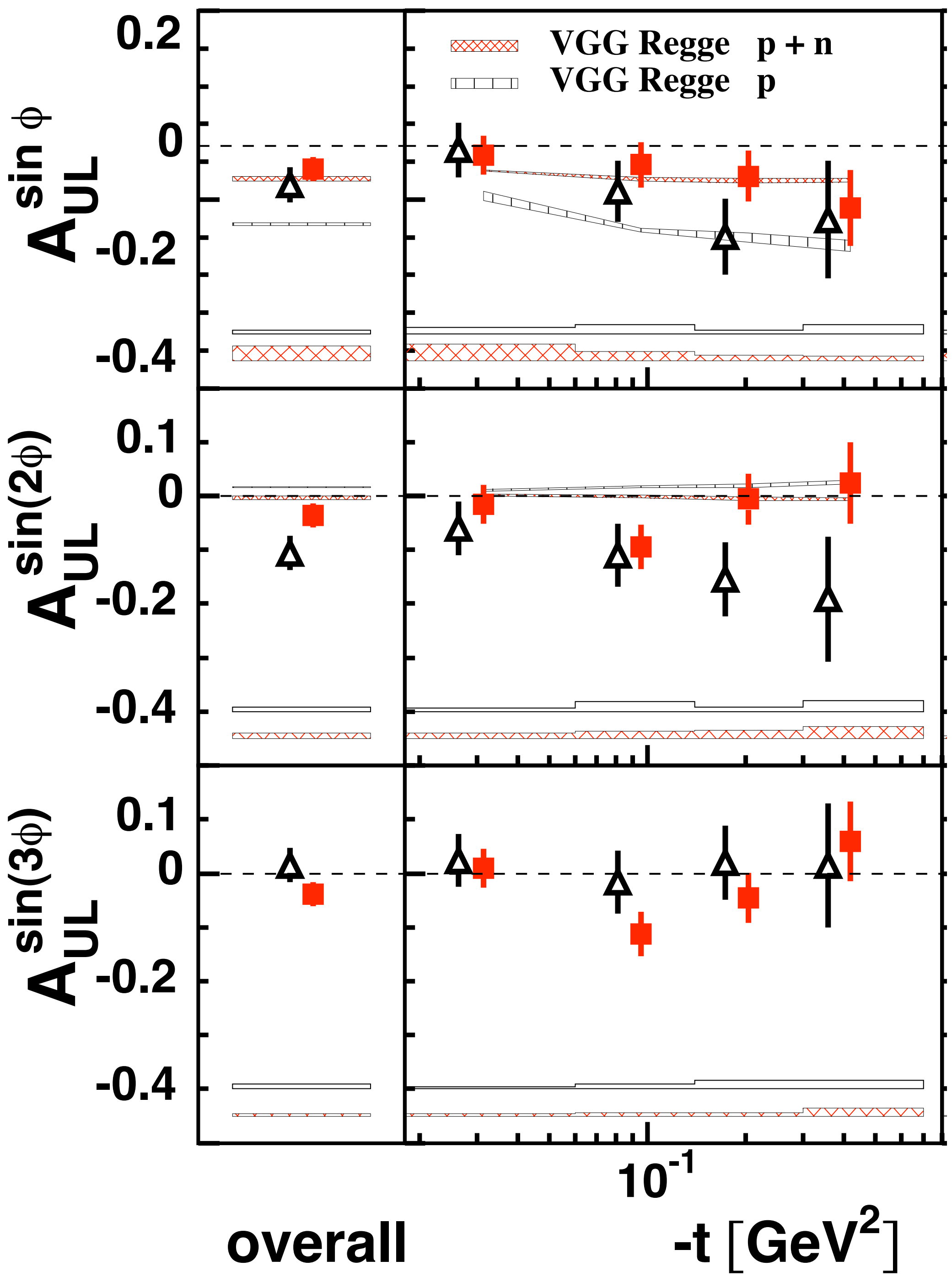
Not all combinations of beam-charge and beam-helicity available!

Target-spin asymmetries on the deuteron (spin-1) in comparison to the proton (spin-1/2)

HERMES $\mathcal{A}_{UL}$ on ^{1}H and ^{2}H

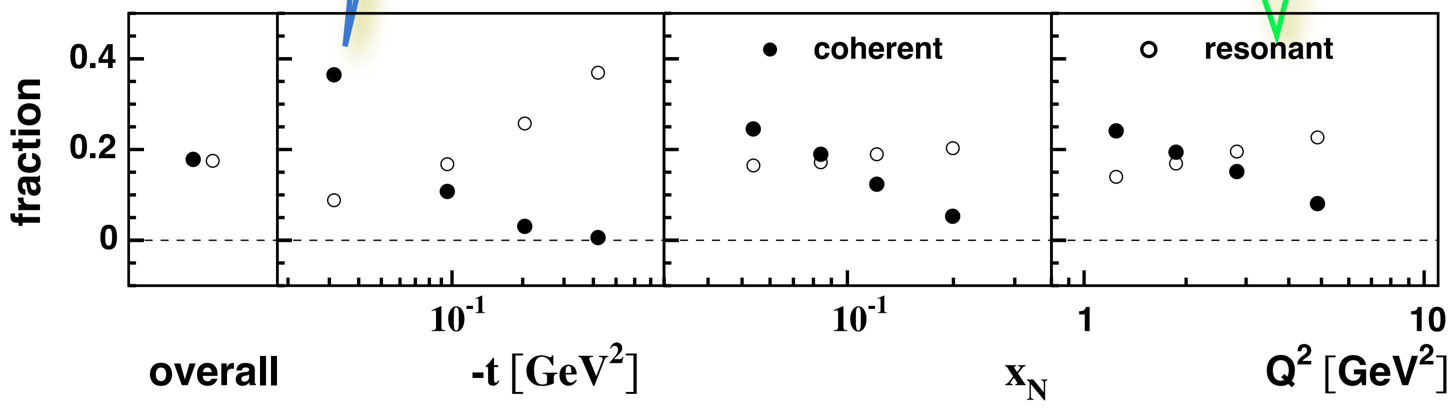
Accepted by Nucl. Phys. B
arXiv:1008.3996 (hep-ex)

Search for coherent signature



Coherent contribution dominates at low values of the squared momentum transfer

Fraction of resonant excitation stays part of the signal



low t
scatter off deuteron
= spin-1 object

higher t
scatter off nucleon
= spin-1/2 object

Im($\tilde{\mathcal{H}}_1$)

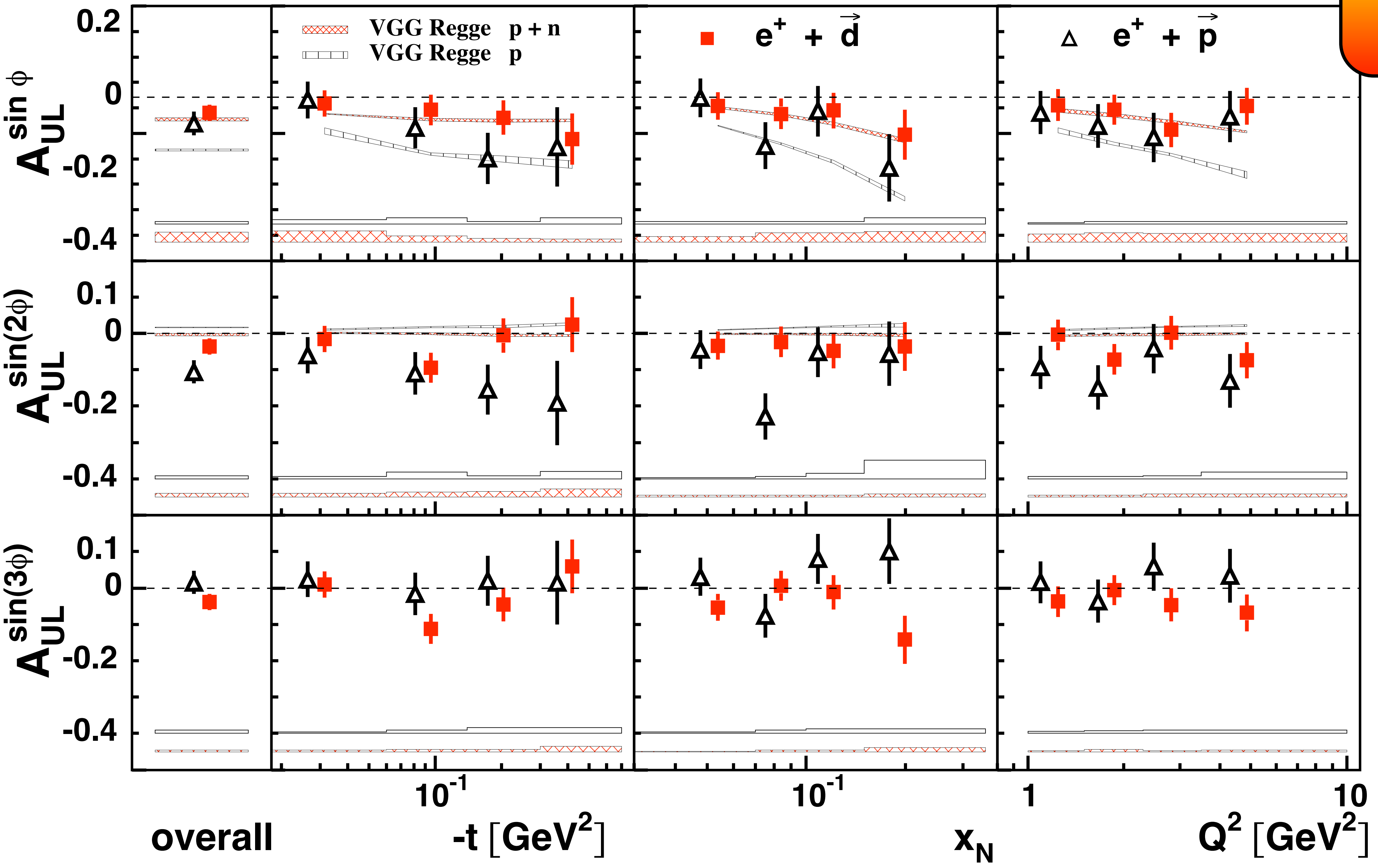
Im($\tilde{\mathcal{H}}$)

HERMES $\mathcal{A}_{UL}$ on ^{1}H and ^{2}H

Accepted by Nucl. Phys. B

arXiv:1008.3996 (hep-ex)

Search for coherent signature



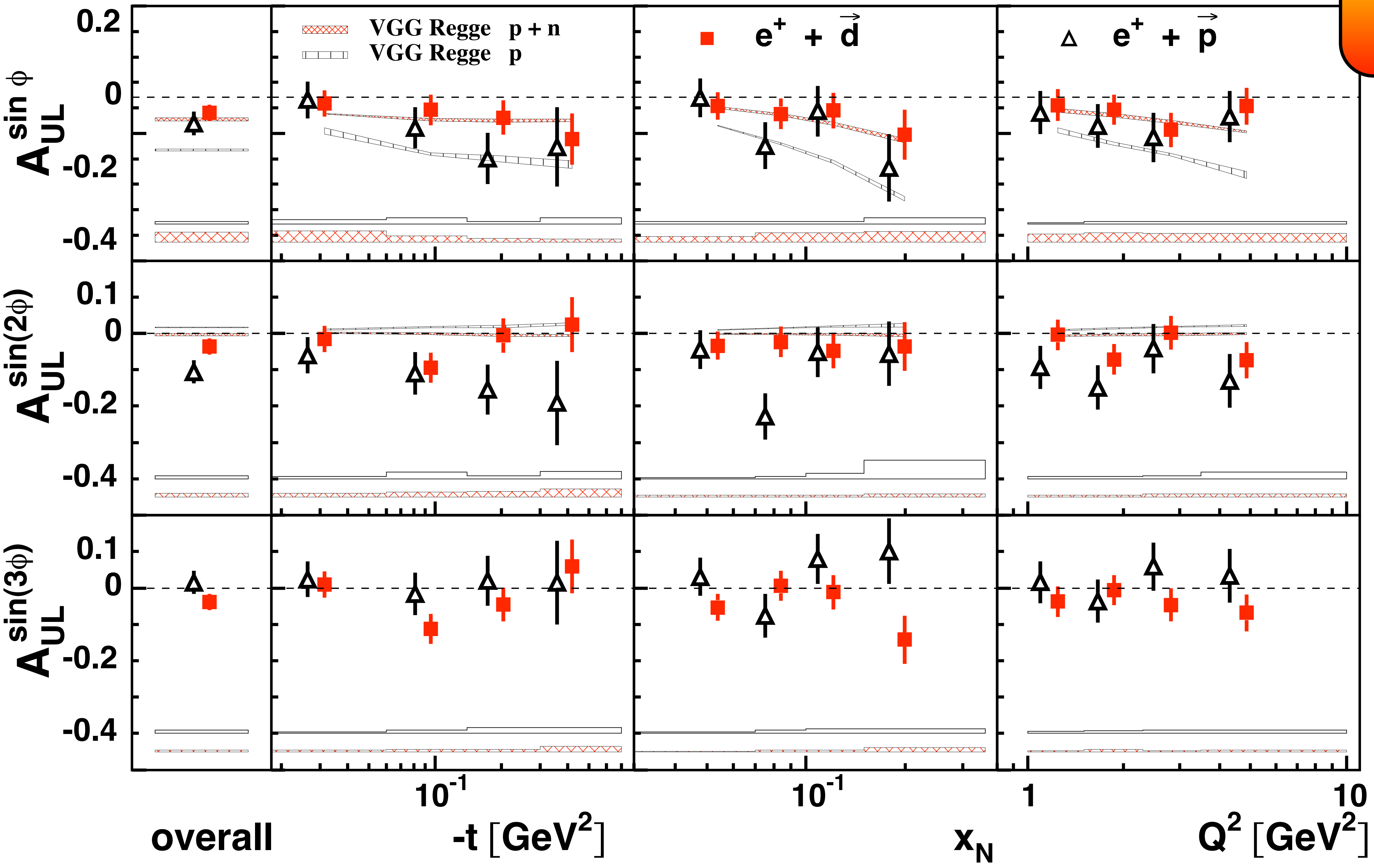
HERMES $\mathcal{A}_{UL}$ on ^{1}H and ^{2}H

in press

Accepted by Nucl. Phys. B

arXiv:1008.3996 (hep-ex)

Search for coherent signature



HERMES $\mathcal{A}_{LL}$ on ^{1}H and ^{2}H

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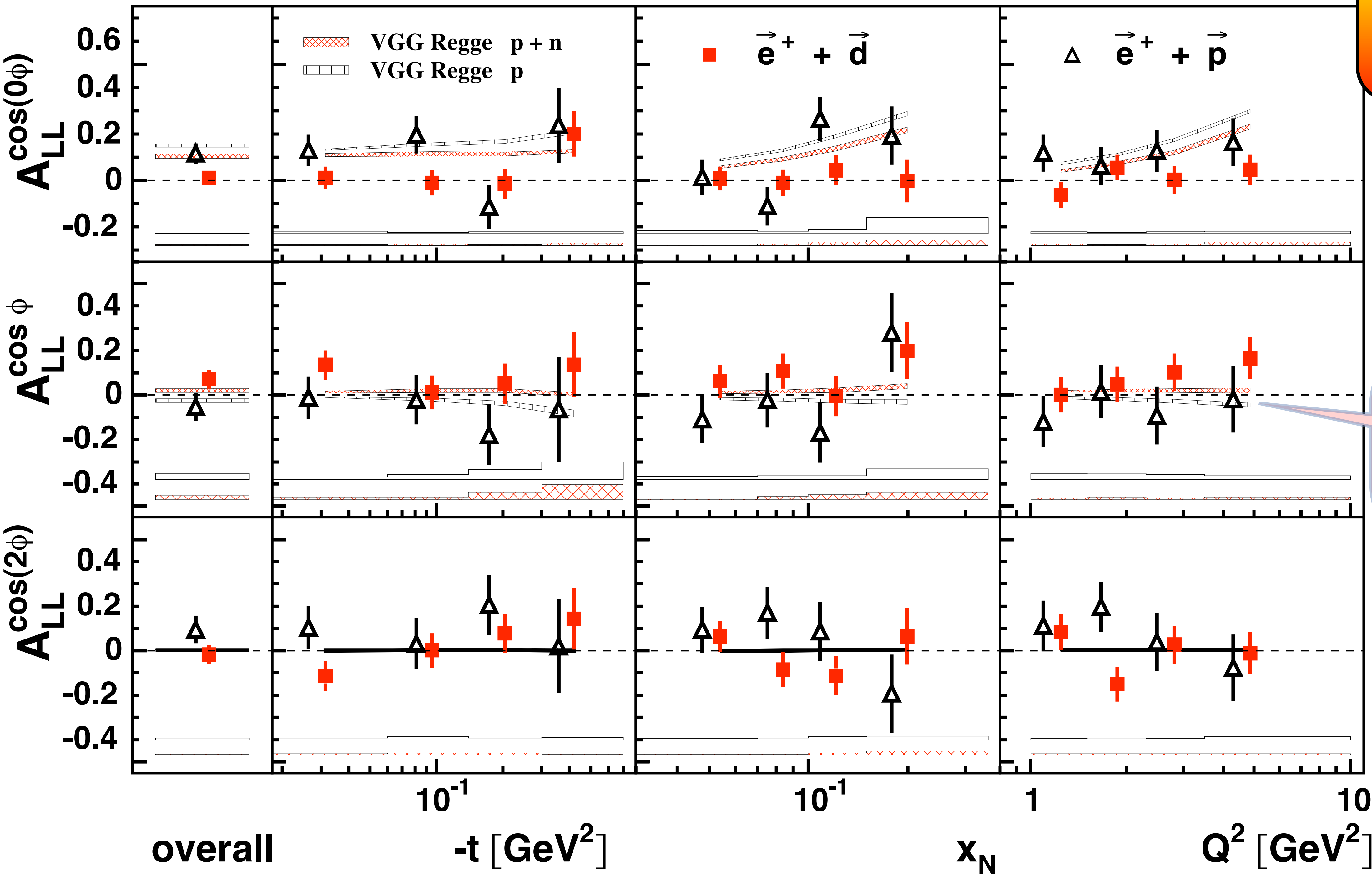
arXiv:1008.3996 (hep-ex)

Search for coherent signature



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

@low t, scatter off deuteron = spin1 object: Re($\widetilde{\mathcal{H}}_1$)

@higher t, scatter off nucleon = spin1/2 object: Re($\widetilde{\mathcal{H}}$)

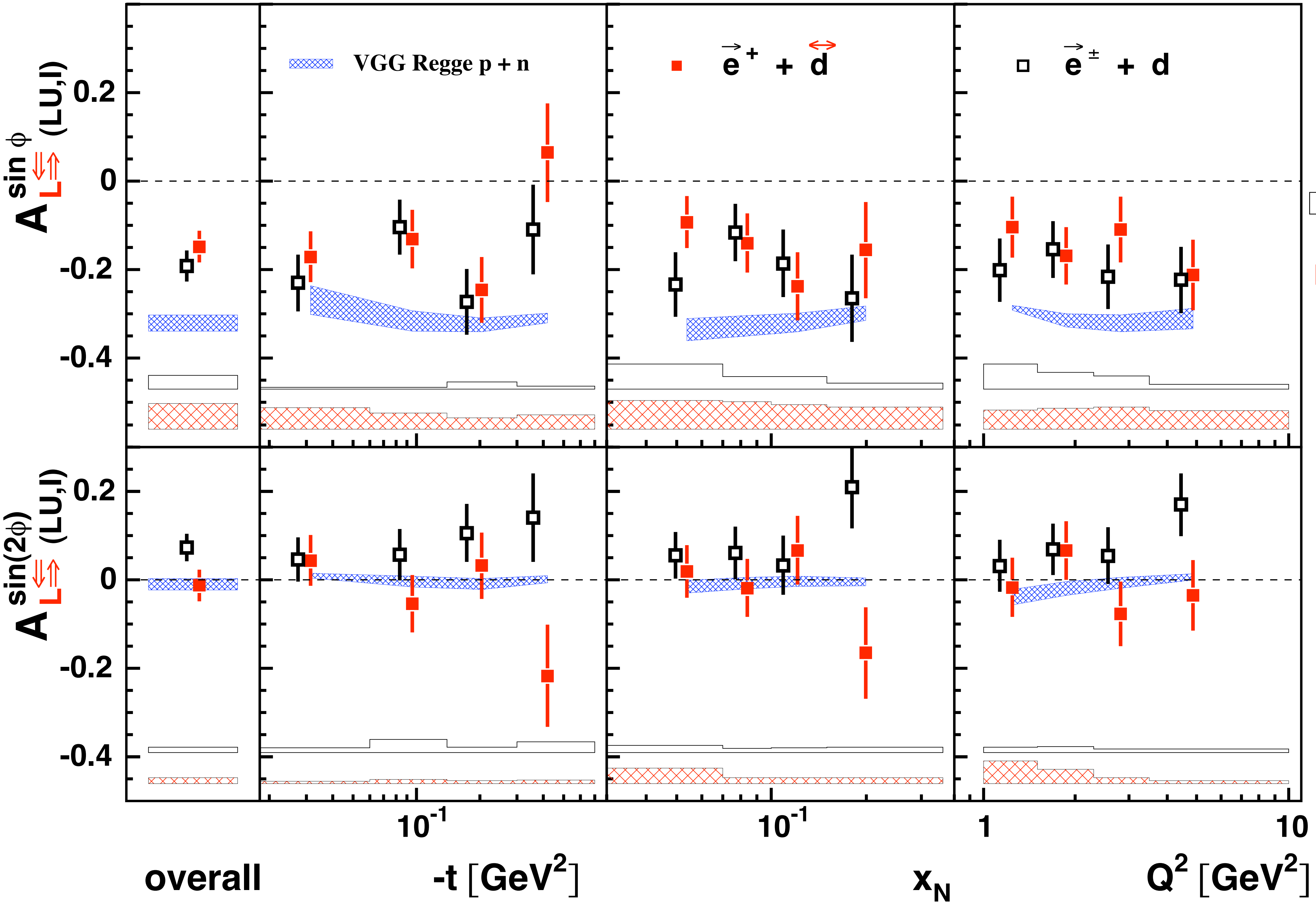
Beam-helicity and beam-charge asymmetries on tensor-polarized deuterons with P_{zz}=0.827 in comparision to unpolarized deuterons

HERMES $\mathcal{A}_{LU}$ on (un)polarized ^{2}H

Accepted by Nucl. Phys. B

arXiv:1008.3996 (hep-ex)

Search for tensor signature



☐ $\mathcal{Re}\ \mathcal{H}_1$

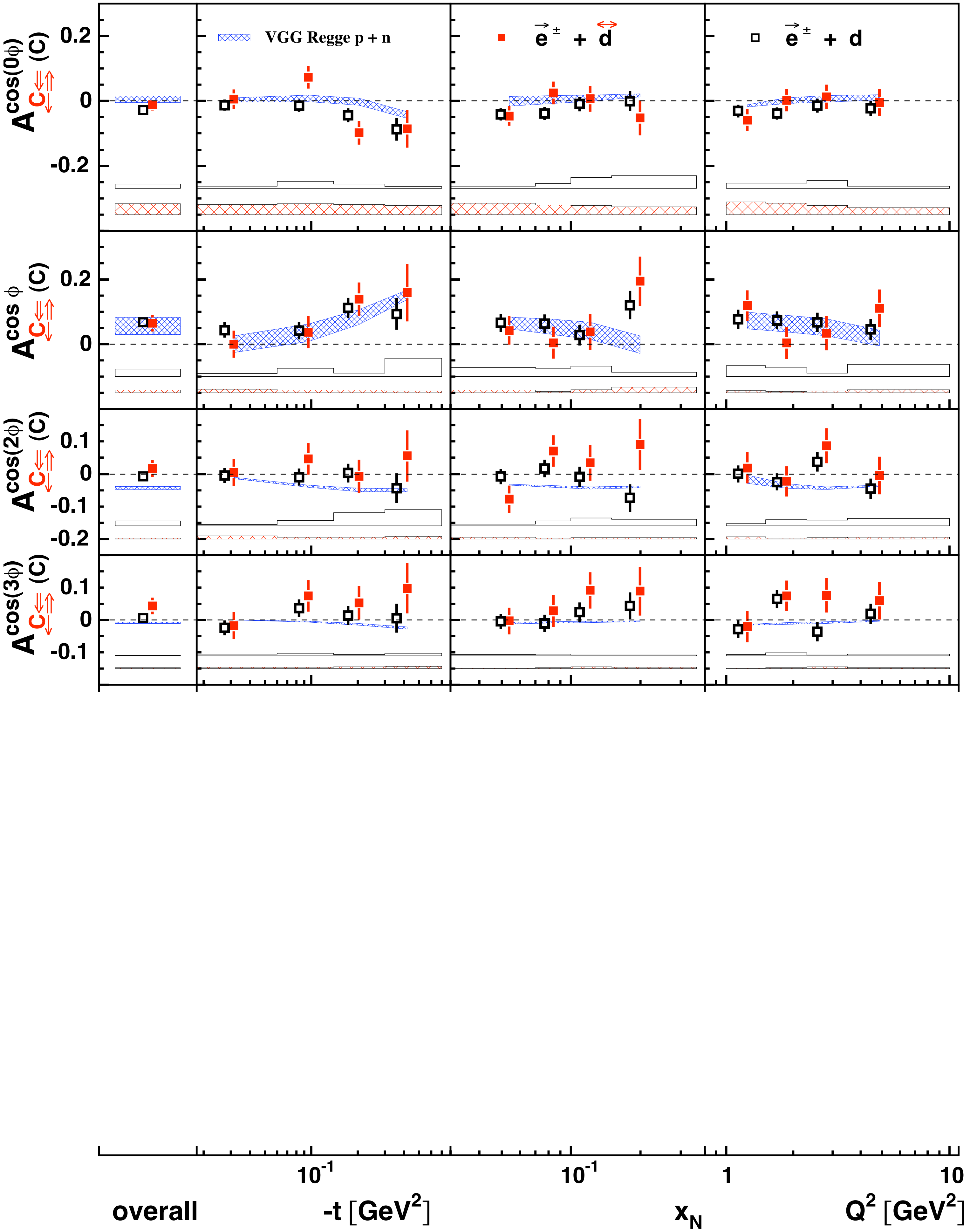
■ $\mathcal{Re}\ (\mathcal{H}_1 - \frac{1}{3}\mathcal{H}_5)$

for coherent scattering

$\mathcal{H}_5$

tensor structure function in the forward limit

HERMES $\mathcal{A}_C$ on (un)polarized ^{2}H



Search for tensor signature

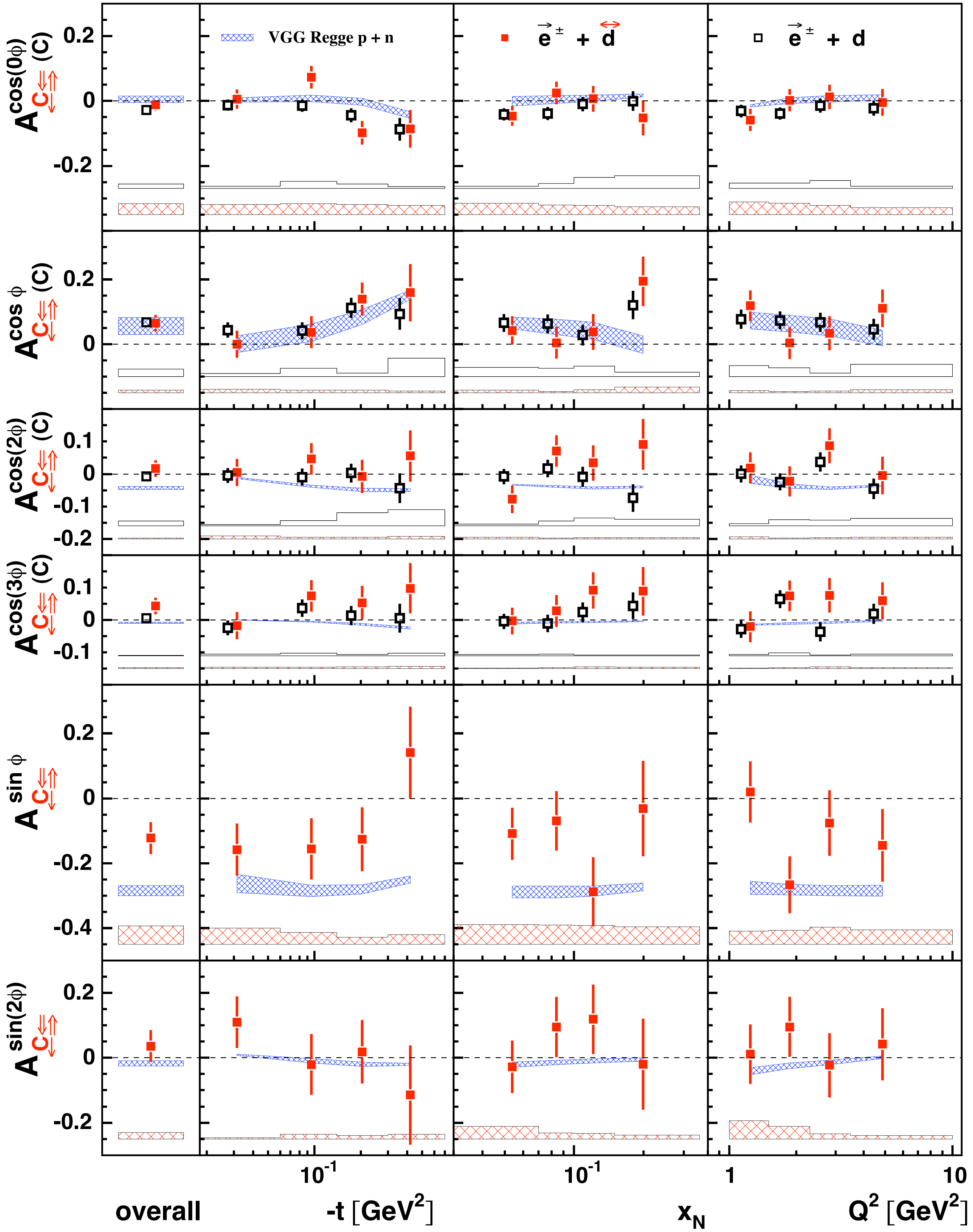
□ $\mathcal{R}e\ \mathcal{H}_1$

■ $\mathcal{R}e\ (\mathcal{H}_1 - \frac{1}{3}\mathcal{H}_5)$

for coherent scattering

Accepted by Nucl. Phys. B

arXiv:1008.3996 (hep-ex)



HERMES $\mathcal{A}_C$ on (un)polarized ^{2}H

Search for tensor signature

☐ $\mathcal{R}e\ \mathcal{H}_1$

■ $\mathcal{R}e\ (\mathcal{H}_1 - ⅓\mathcal{H}_5)$

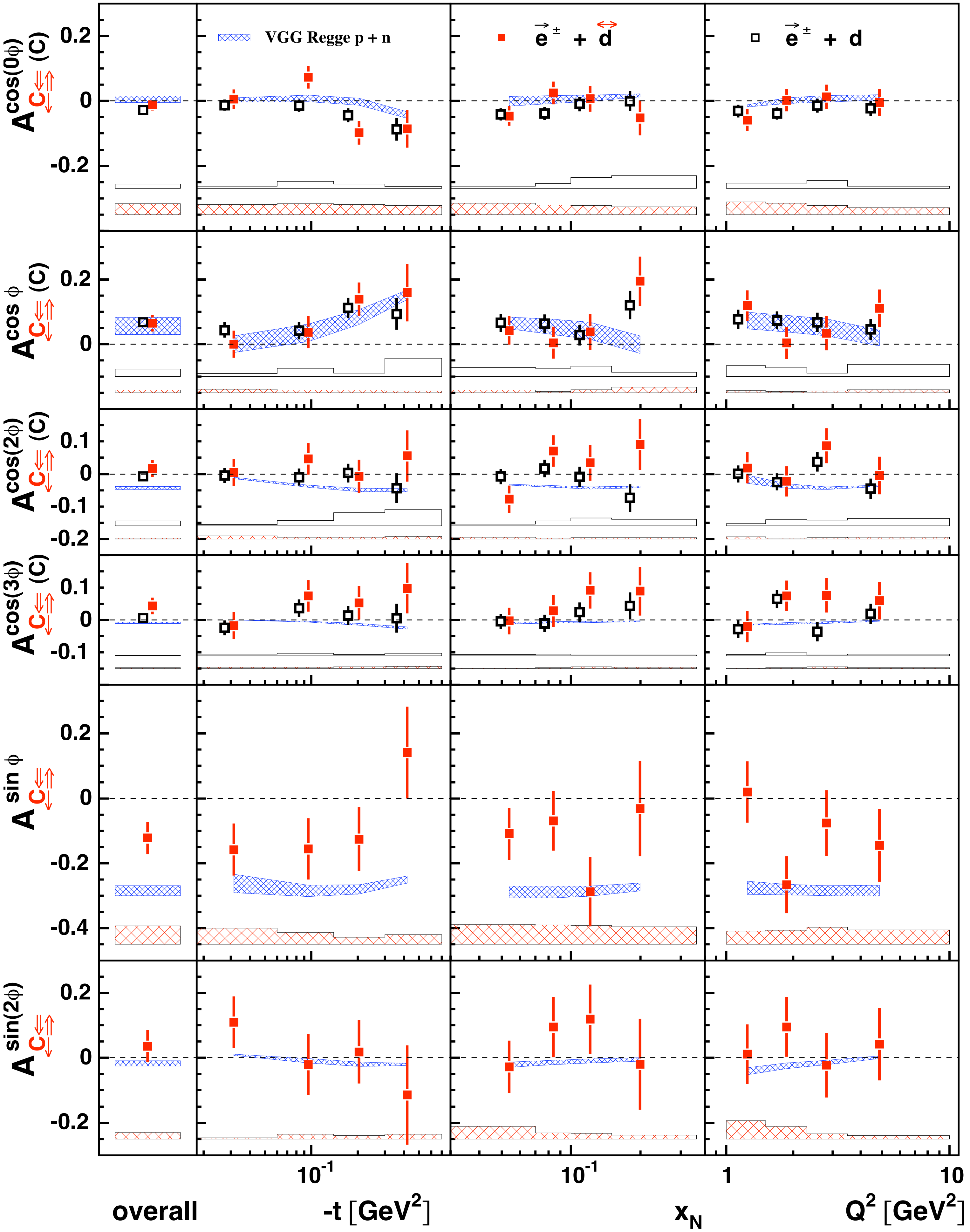
for coherent scattering

■ $\mathcal{I}m\ (\mathcal{H}_1 - ⅓\mathcal{H}_5)$

Accepted by Nucl. Phys. B

arXiv:1008.3996 (hep-ex)

HERMES $\mathcal{A}_C$ on (un)polarized ^{2}H



Search for tensor signature

- ☐ $\mathcal{R}e\ \mathcal{H}_1$
- ■ $\mathcal{R}e\ (\mathcal{H}_1$-⅓$\mathcal{H}_5)$

for coherent scattering

- ■ $\mathcal{I}m\ (\mathcal{H}_1$-⅓$\mathcal{H}_5)$

DVCS $\mathcal{A}_{LZZ}$ sinϕ amplitude:

0.074 ± 0.196 ± 0.022

(-t<0.06 GeV², 40% coherent)

Accepted by Nucl. Phys. B

arXiv:1008.3996 (hep-ex)

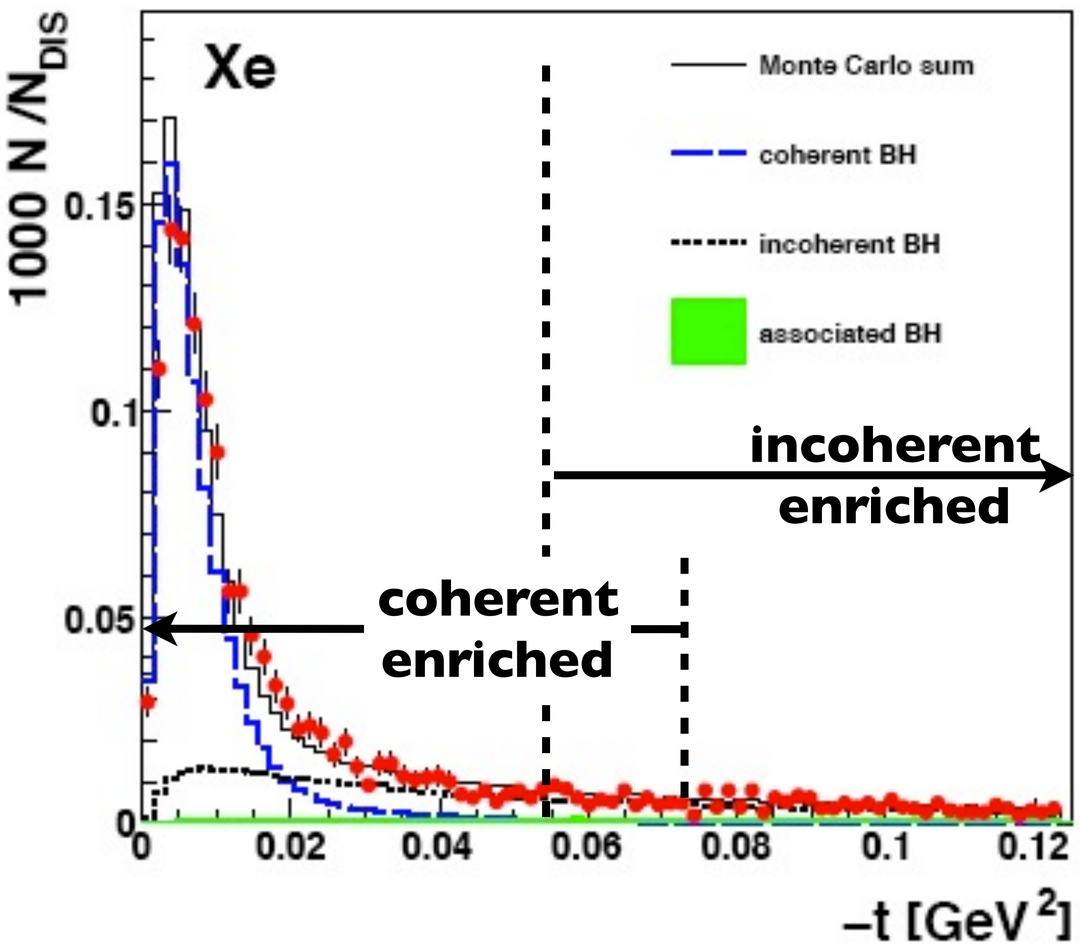
Beam-spin and beam-charge asymmetries on heavier nuclei

Nuclear data sets

HERMES
Phys. Rev. C 81 (2010) 035202
arXiv:0911.0091

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

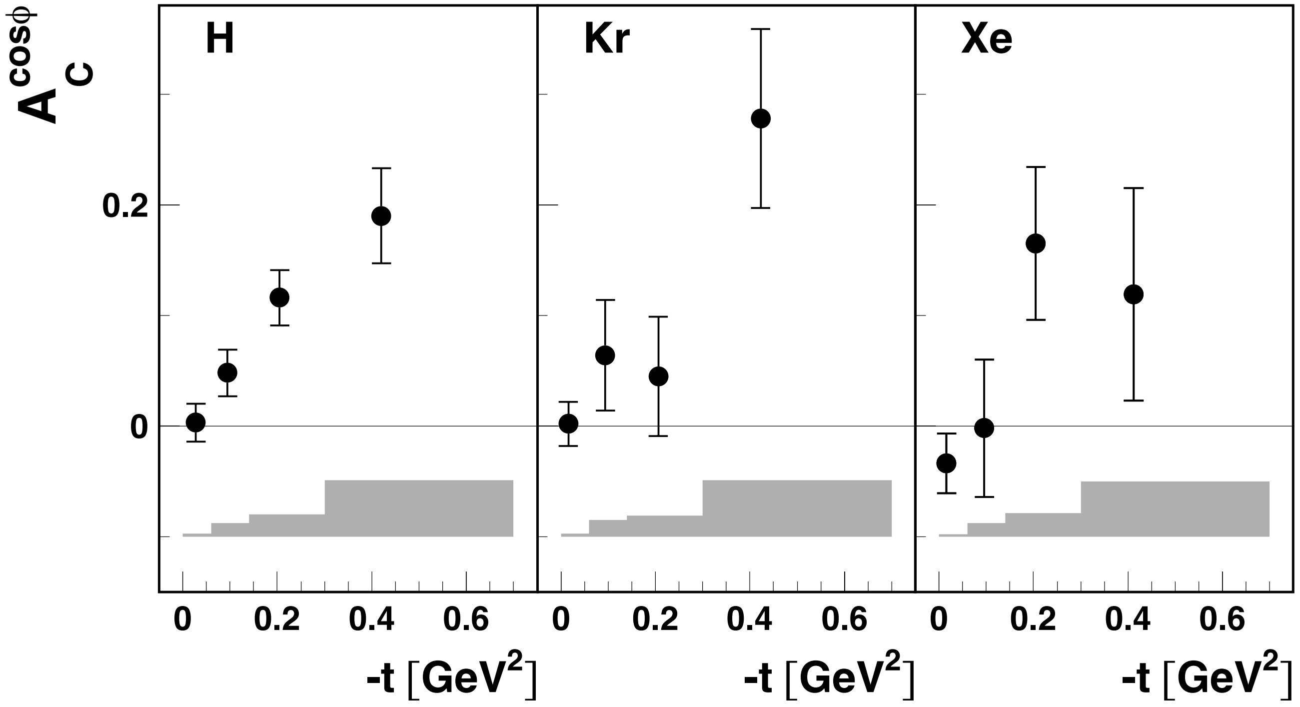
Heavy target data taken at the end of each HERA fill ("high density runs")



- 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 asymmetries on Nuclei

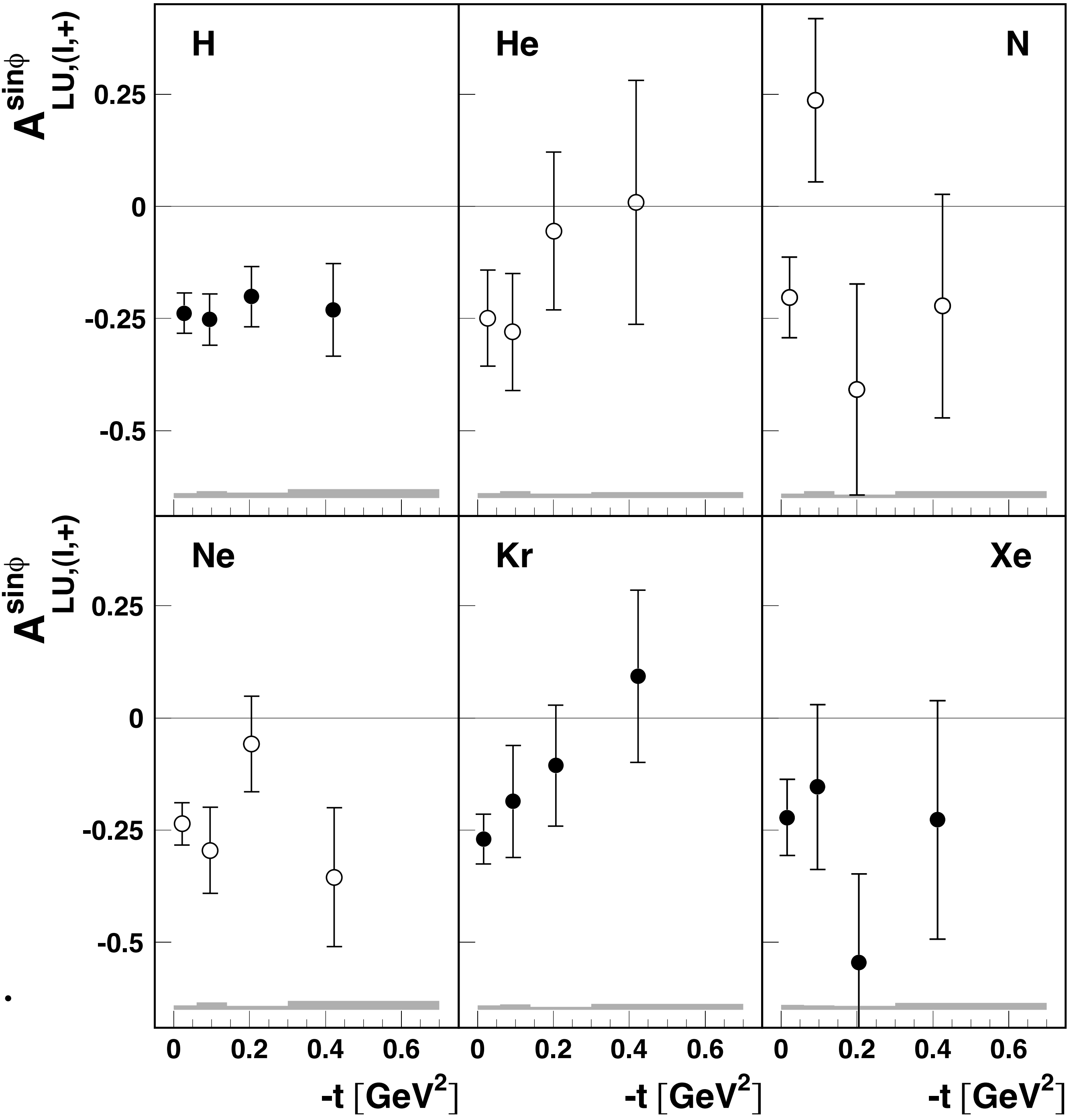
Leading amplitude of
beam-charge asymmetry



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

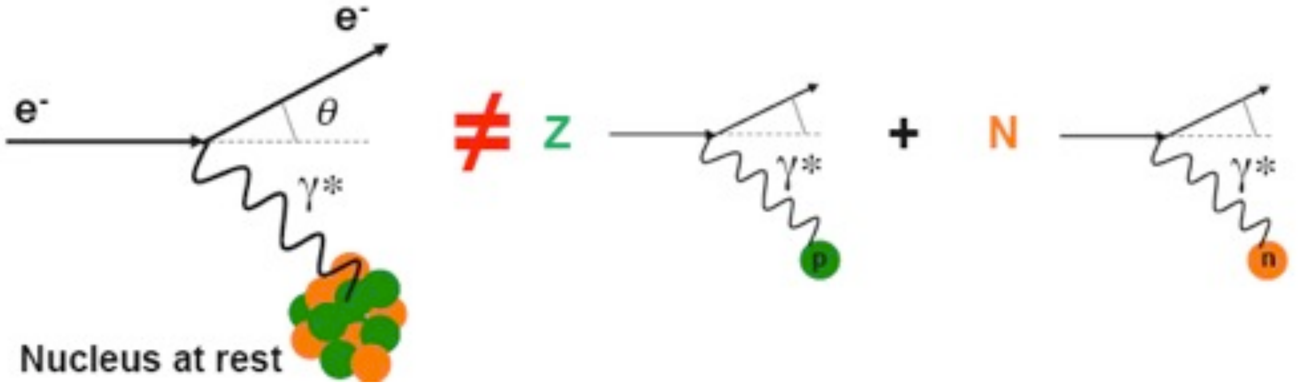
○ Targets with only one beam charge available.
No A_C and single-charge A_{LU}
with entangled s_1 coefficients

Leading amplitude of
beam-helicity asymmetry



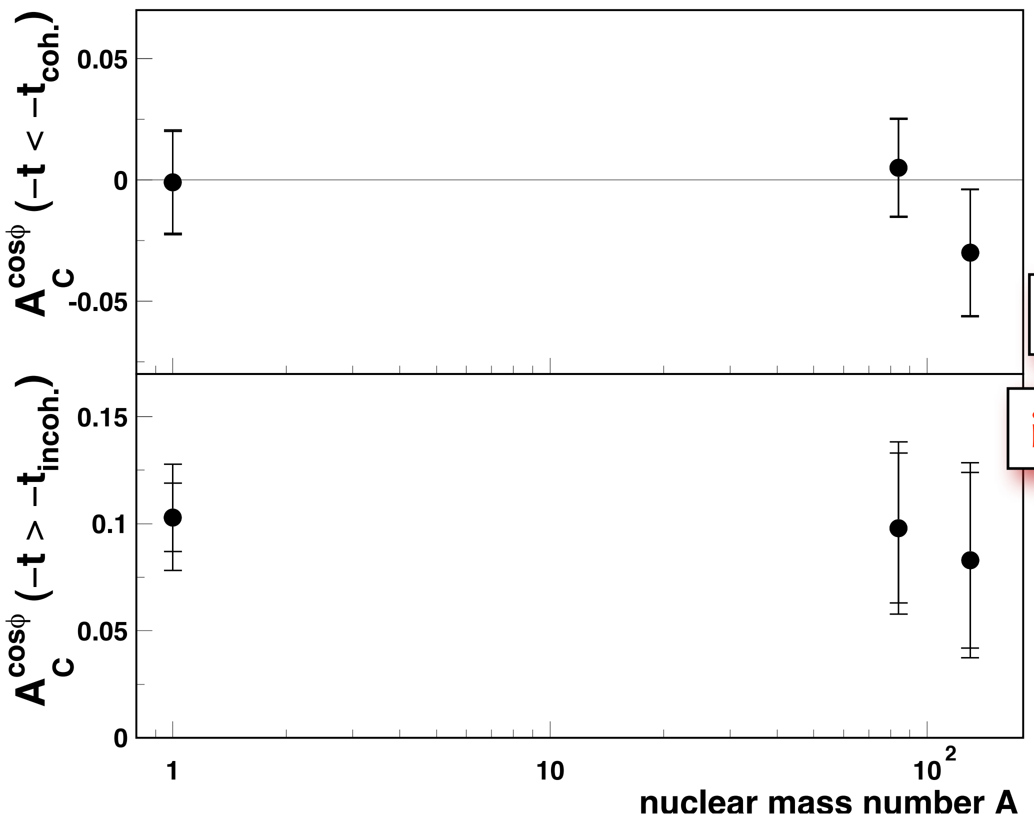
A-dependence of DVCS asymmetries

- 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 if τ_{DVCS} with A?



DVCS Nuclear Mass Dependence

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

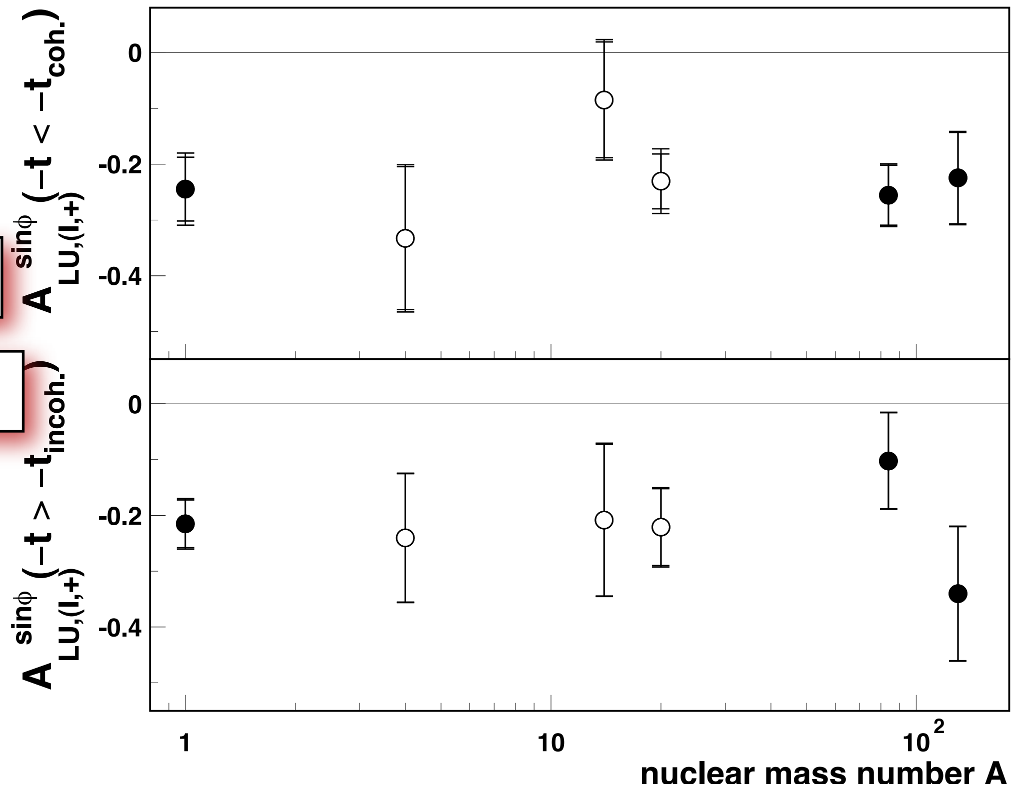


Beam-charge asymmetry

coherent enriched

incoherent enriched

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



Beam-helicity asymmetry

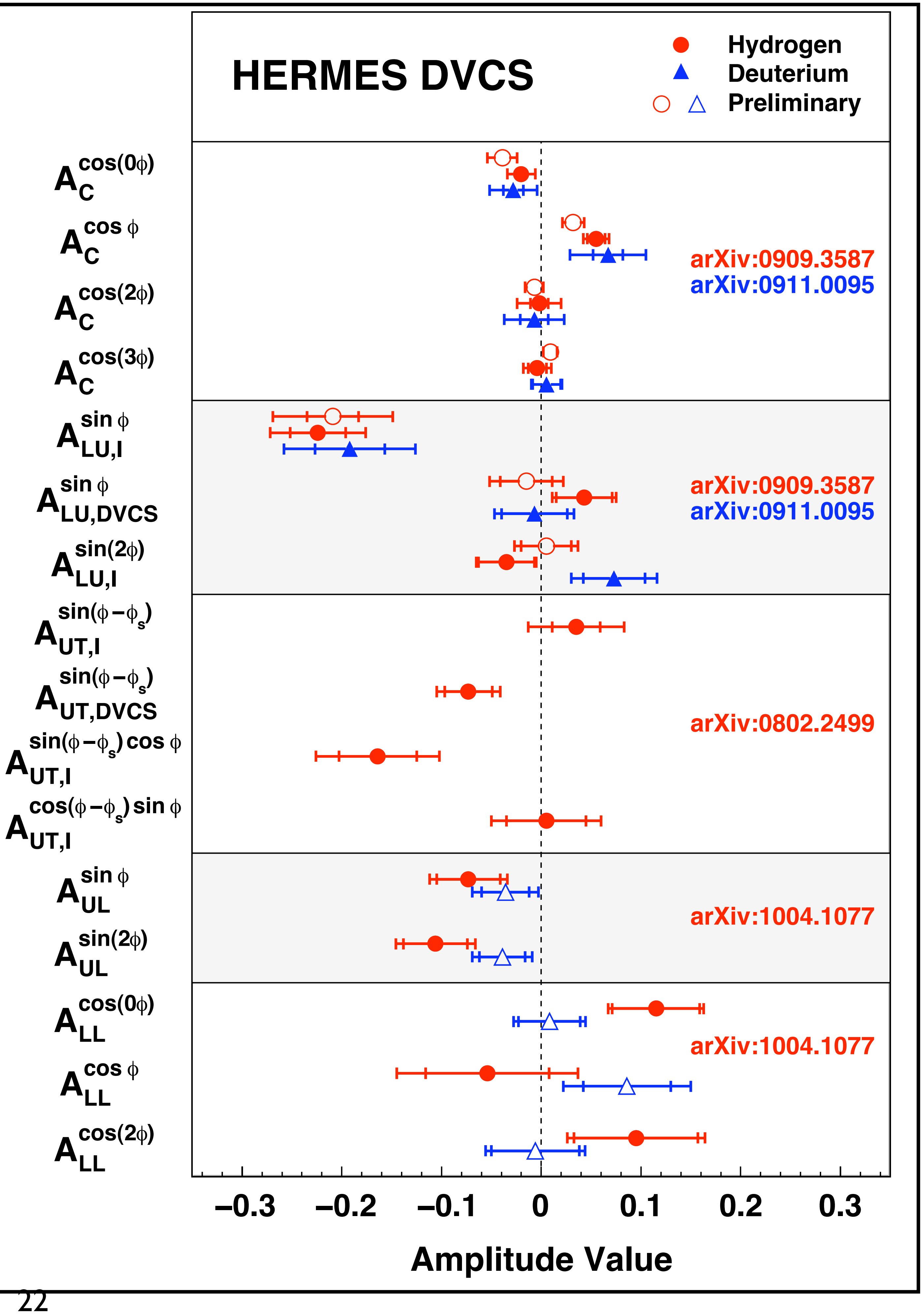
HERMES
Phys. Rev. C 81 (2010) 035202
arXiv:0911.0091

Normalization to hydrogen ^1H ⇒

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

coherent enriched: 0.91±0.19

incoherent enriched: 0.93±0.23



HERMES results for spin-1/2 GPDs

See talk by M. Düren

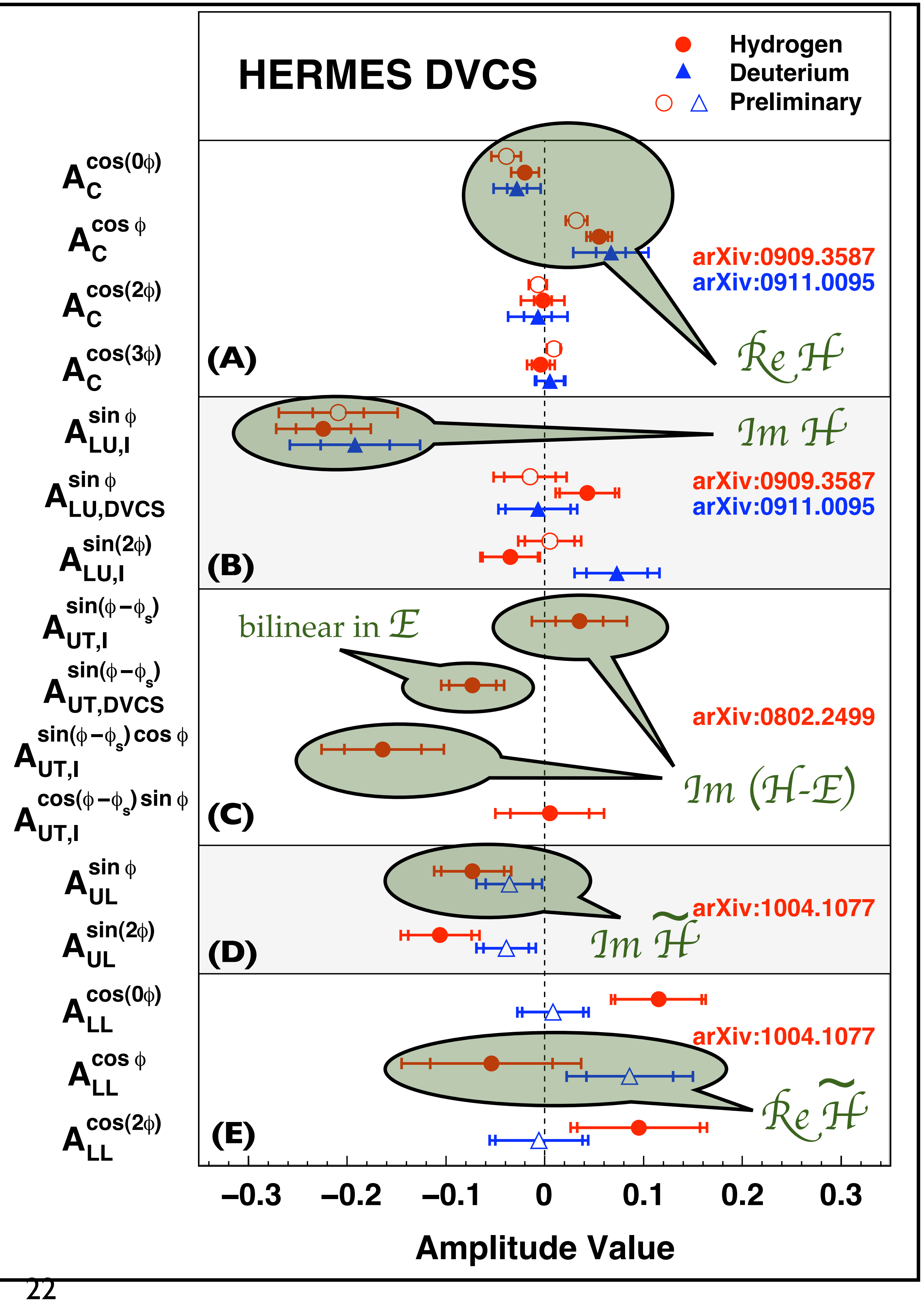
(A) Beam charge asymmetry:
GPD H

(B) Beam helicity asymmetry:
GPD H

(C) Transverse target spin asymmetry:
GPD E from proton target

(D) Longitudinal target spin asymmetry:
GPD $\tilde{H}$

(E) Double-spin asymmetry:
GPD $\tilde{H}$



HERMES results for spin-1/2 GPDs

See talk by M. Düren

(A) Beam charge asymmetry:
GPD H

(B) Beam helicity asymmetry:
GPD H

(C) Transverse target spin asymmetry:
GPD E from proton target

(D) Longitudinal target spin asymmetry:
GPD $\tilde{H}$

(E) Double-spin asymmetry:
GPD $\tilde{H}$

Summary: DVCS on nuclear targets at HERMES

- HERMES has analyzed its rich set of DVCS data on nuclear targets (Deuterium, Helium, Neon, Nitrogen, Krypton, Xenon):
  ➤beam-helicity, beam-charge, target-spin and double-spin asymmetries.
  Final results. **Unique data set!**

- These measurements allow for the search for
  - the coherent signature expected for a deuteron target at low t.
  - the tensor signature expected for tensor-polarized deuterons.

    No obvious signatures revealed within the experimental uncertainties.

- No A-dependence of the DVCS asymmetries was found within the experimental uncertainties.

- Measure these observables with greater precision at an EIC

Backup slides

Systematics and corrections

- Results corrected for background from decays of neutral mesons (semi-inclusive: 4.6%, exclusive: <0.7%)

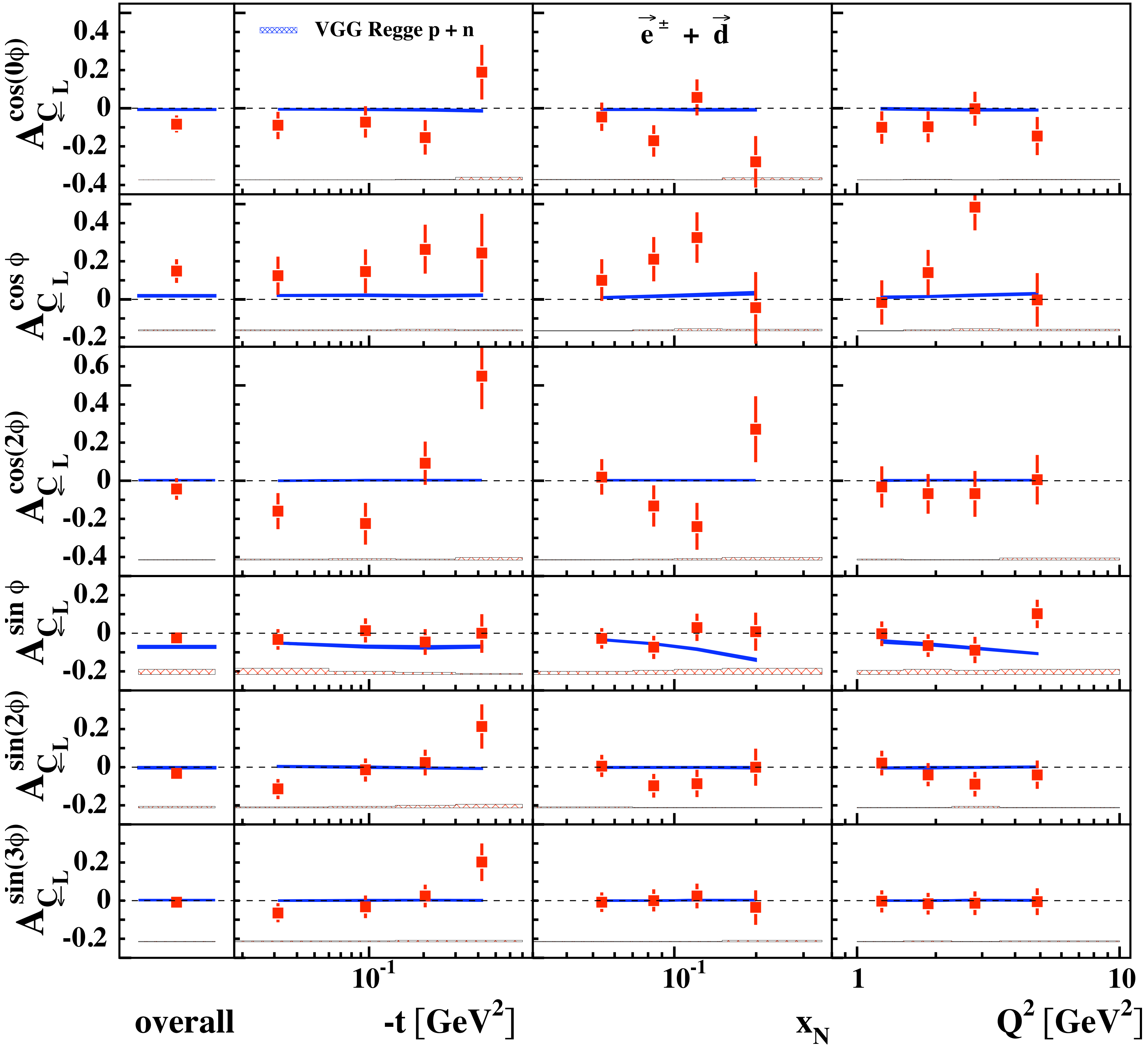
- Dominant contribution to systematics: limited spectrometer acceptance and finite bin widths.

  - Combined contribution from acceptance, finite bin width, detector misalignment and kinematic smearing determined from MC simulation.

- Scale uncertainties due to polarization measurement:

  - deuterium target polarization: 4.0%

  - beam polarization, unpolarized deuterium: 2.4%, polarized deuterium: 1.9%



HERMES $\mathcal{A}_{CL}$

(single helicity)

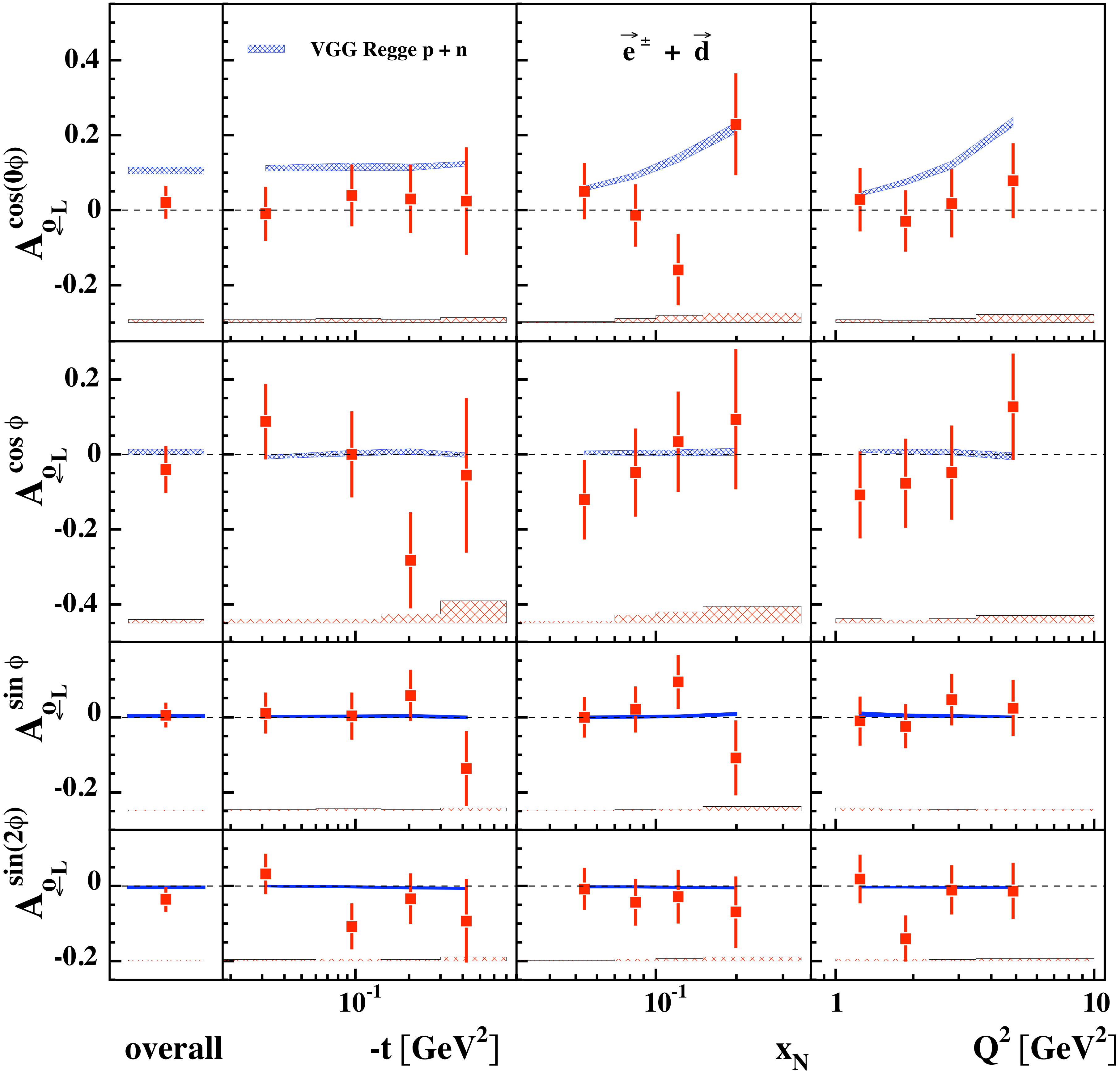
on polarized

^{2}H

Re/Im($\tilde{\mathcal{H}}_1$)

Accepted by
Nucl. Phys. B
arXiv:1008.3996 (hep-ex)

HERMES $\mathcal{A}_{UL}$ (single helicity) on polarized ^{2}H



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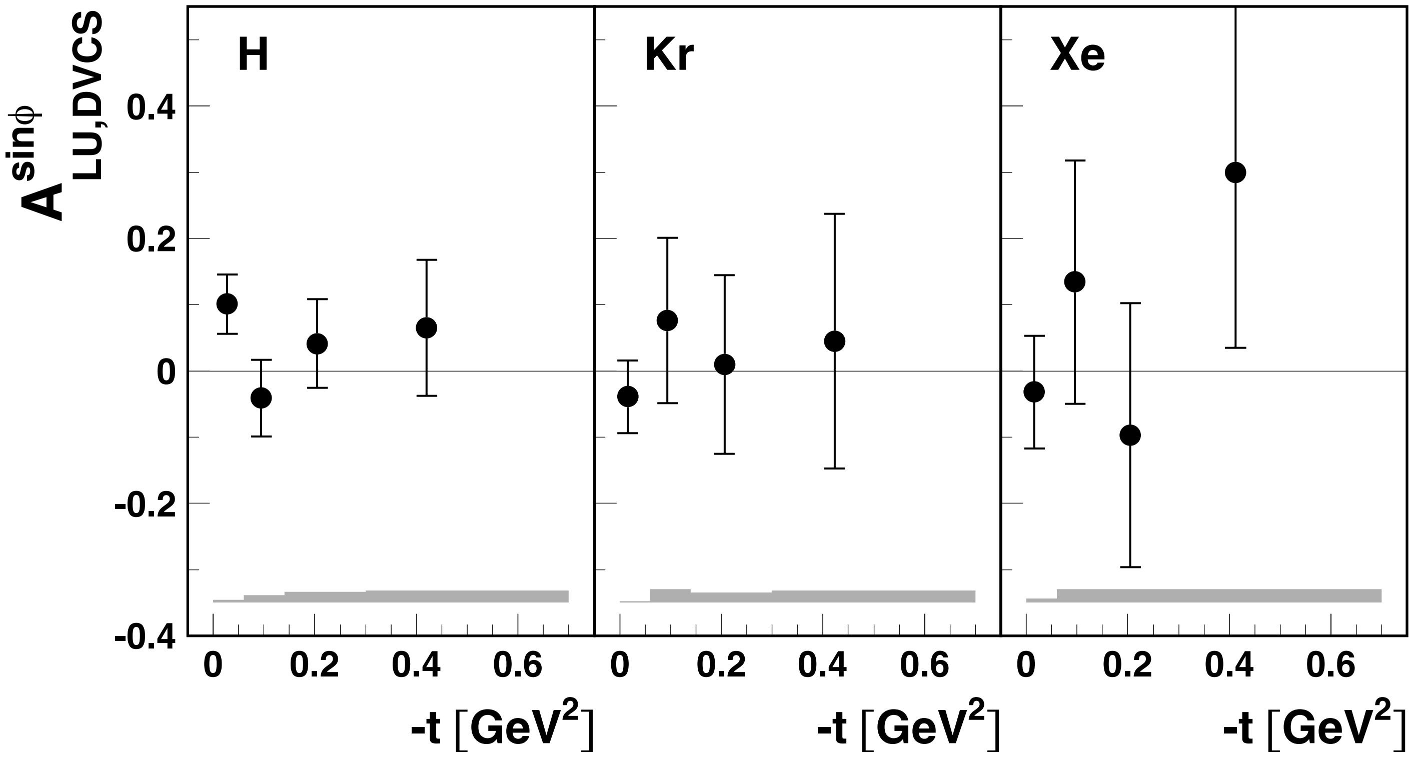
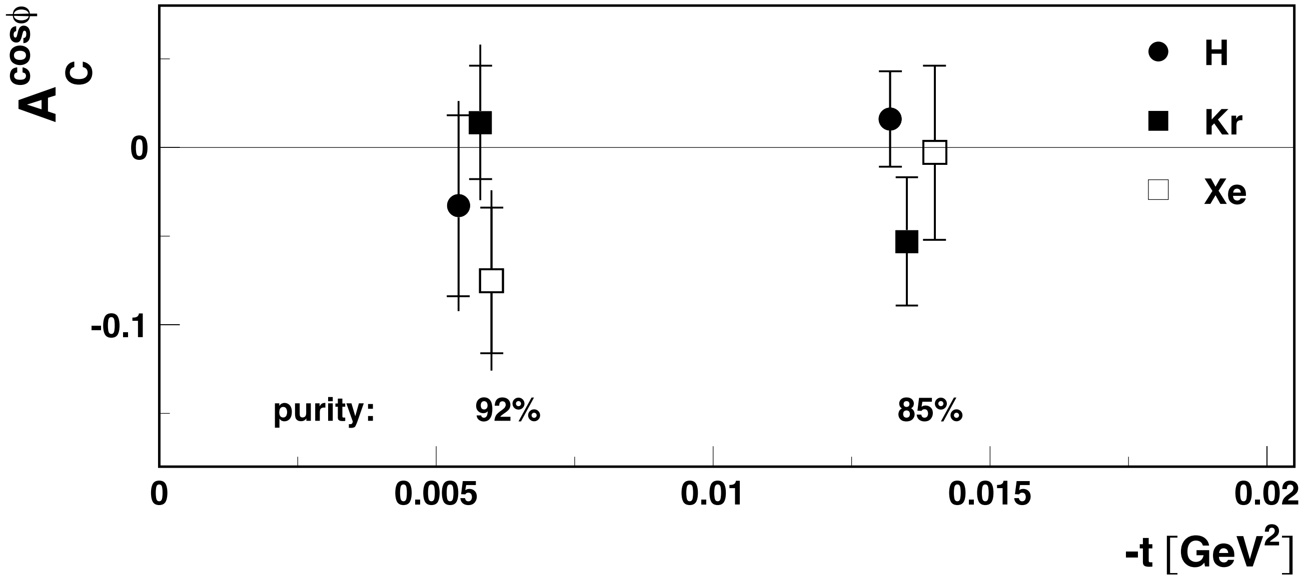
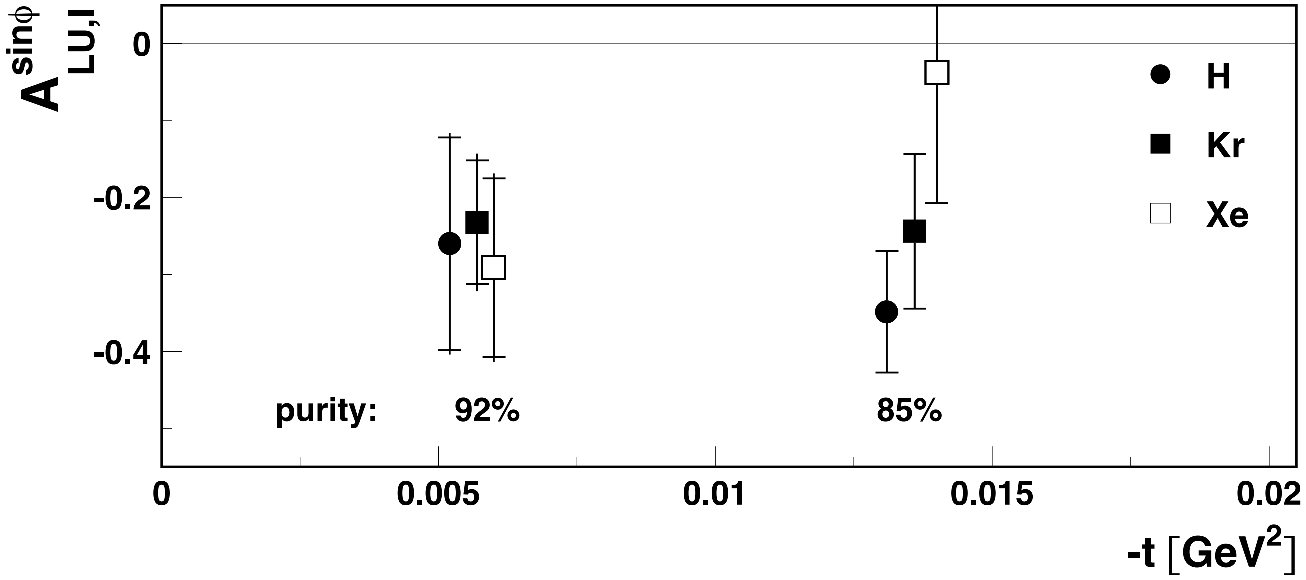
arXiv:1008.3996 (hep-ex)

Nuclear DVCS backup



$\mathcal{A}_{LU}$ amplitude sensitive to squared DVCS-term for nuclear targets with 2 beam charges





2 coherent-enriched t-bins