# Recent highlights from hermes

## Outline:

**Exploring the nucleon structure via**

- ☆ inclusive
- ☆ semi-inclusive
- ☆ exclusive

**measurements in polarized electron-proton scattering**

Caroline Riedl
DESY

Moriond QCD and High-Energy Interactions
La Thuile (Italy), March 16, 2012

# HERMES mission: Nucleon Structure

I.

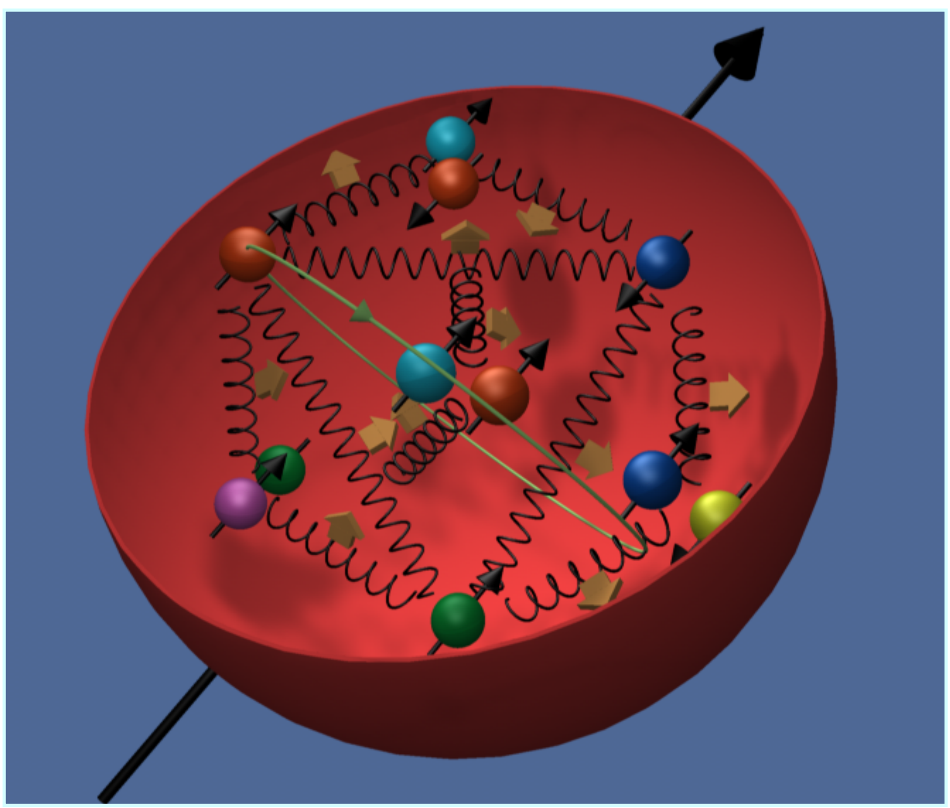
**"Spin Puzzle"**

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

quark spin

quark orbital angular momentum

gluon spin and OAM

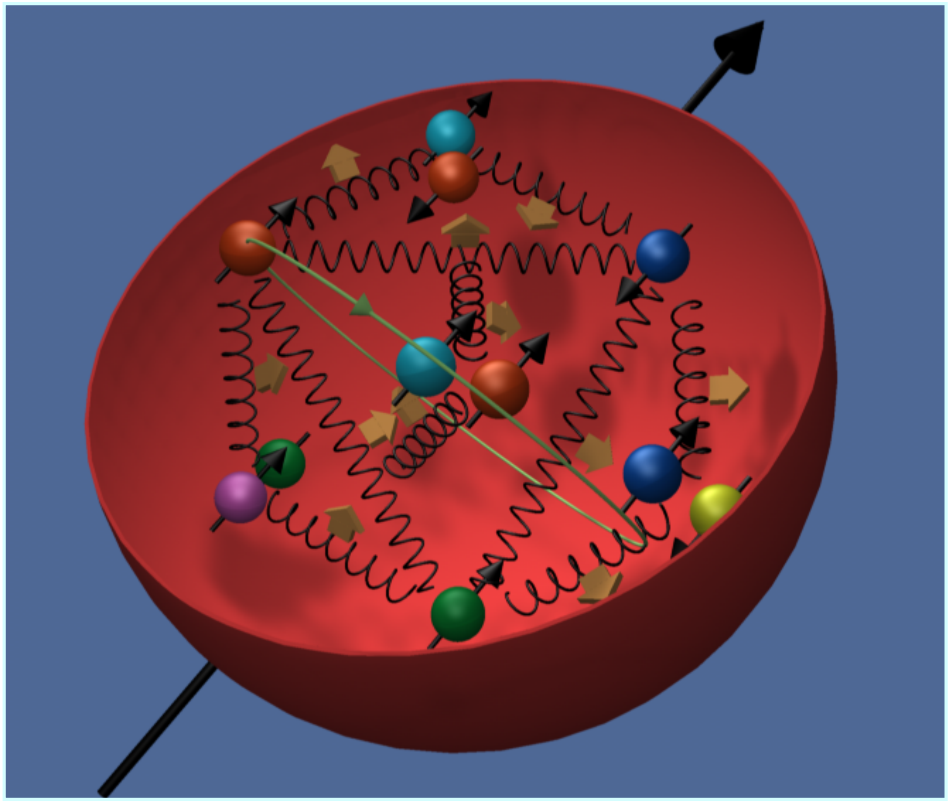


longitudinal momentum
transverse momentum
transverse position

# HERMES mission: Nucleon Structure

1\. "Spin Puzzle"

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



quark spin

quark orbital angular momentum

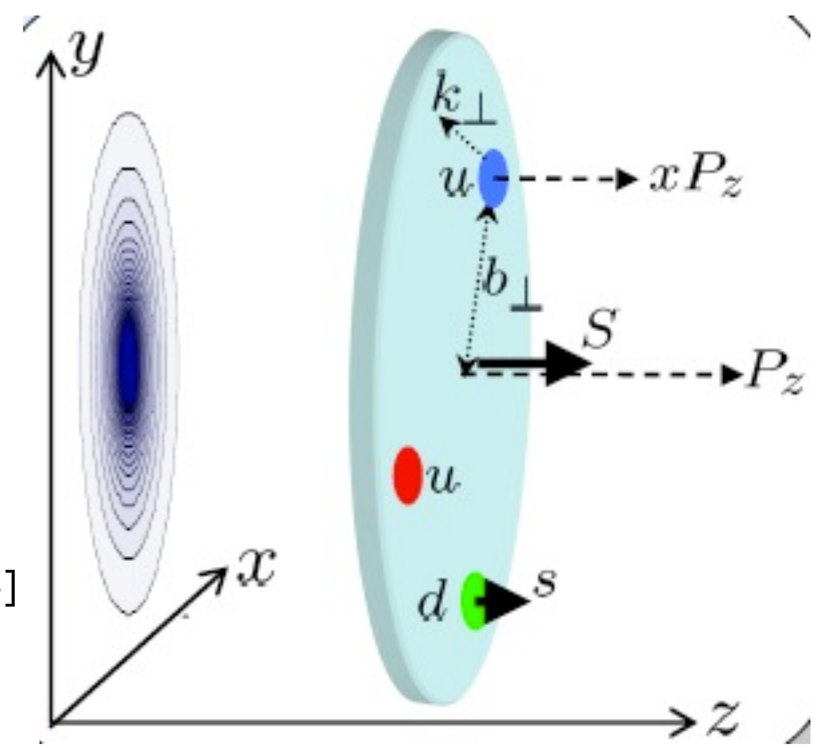
gluon spin and OAM

2\. "Dynamic Hologram"

$W(x, b_\perp, k_\perp)$

probability of finding a quark with certain polarization, position and momentum

longitudinal momentum
transverse momentum
transverse position




Wigner phase-space distributions
[X. Ji, PRL 2003; A. Belitsky, X. Ji, F. Yuan, PRD 2004]

"mother distributions"
[Meissner, Metz, Schlegel, JHEP 0908:056, 2009]

# TMDs and GPDs

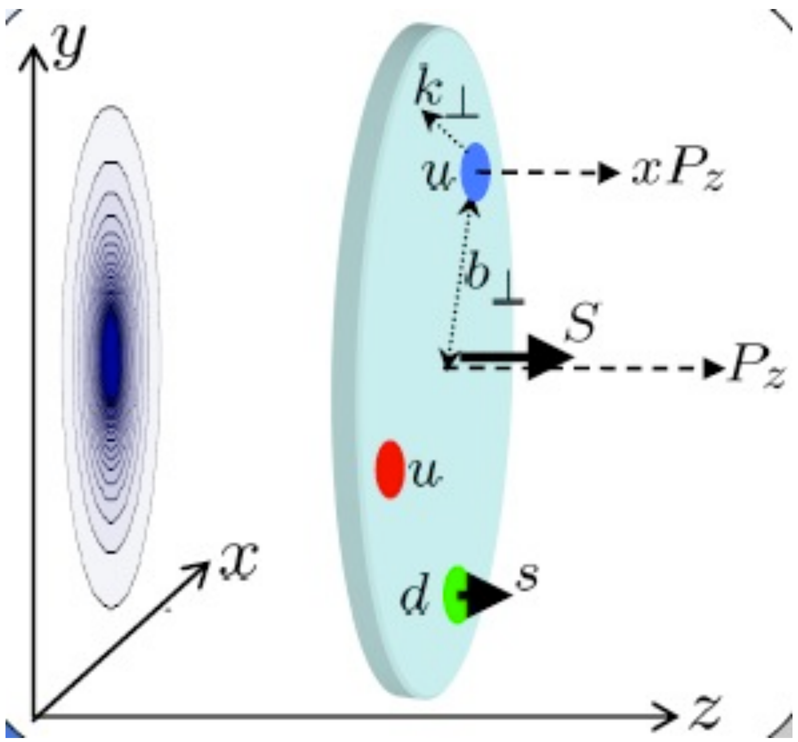
$W(x, b_\perp, k_\perp)$

Correlation between
spin
and
transverse momentum ?

**TMDs:**
Transverse Momentum dependent PDFs

$f(x, k_\perp)$

3D




Correlation between
longitudinal momentum
and
transverse position ?

**GPDs:**
Generalized Parton Distributions

3D

$H(x, b_\perp)$
$\updownarrow$ FT
$H(x, \xi, t)$

"Nucleon Tomo-graphy"

semi-inclusive measurements

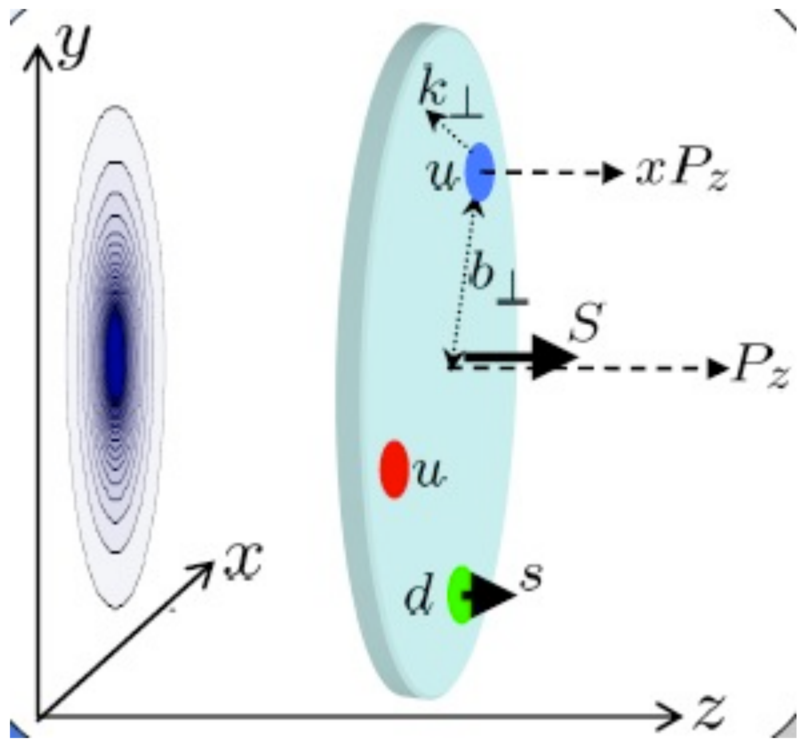
exclusive measurements

# TMDs and GPDs

Correlation between
spin
and
transverse momentum ?

$\longleftarrow$ $\mathbf{W(x,b_\perp,k_\perp)}$ $\longrightarrow$

Correlation between
longitudinal momentum
and
transverse position ?




**TMDs:**
Transverse Momentum dependent PDFs

$\mathbf{f(x,k_\perp)}$ **3D**

$k_\perp$-integration

**GPDs:**
Generalized Parton Distributions

**3D** $\mathbf{H(x,b_\perp)}$
$\updownarrow$ **FT**
$\mathbf{H(x,\xi,t)}$

"Nucleon Tomo-graphy"

$\xi=0,\ t=0$

**PDFs:**
Parton Distribution Functions

$\mathbf{q(x)}$

**1D**

semi-inclusive measurements

inclusive measurements

exclusive measurements

# TMDs and GPDs

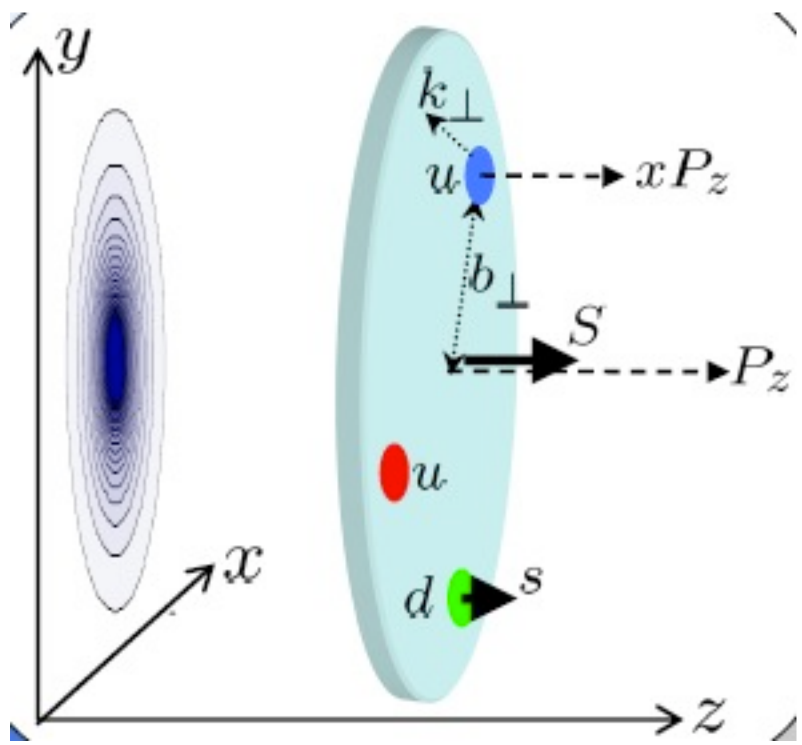
Orbital angular momentum

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

Correlation between **spin** and **transverse momentum** ?

$W(x, b_\perp, k_\perp)$

Correlation between **longitudinal momentum** and **transverse position** ?




**TMDs:**
Transverse Momentum dependent PDFs

$f(x, k_\perp)$

3D

$k_\perp$-integration

**GPDs:**
Generalized Parton Distributions

3D

$H(x, b_\perp)$
↕ FT
$H(x, \xi, t)$

"Nucleon Tomography"

$\xi=0,\ t=0$

**PDFs:**
Parton Distribution Functions

$q(x)$

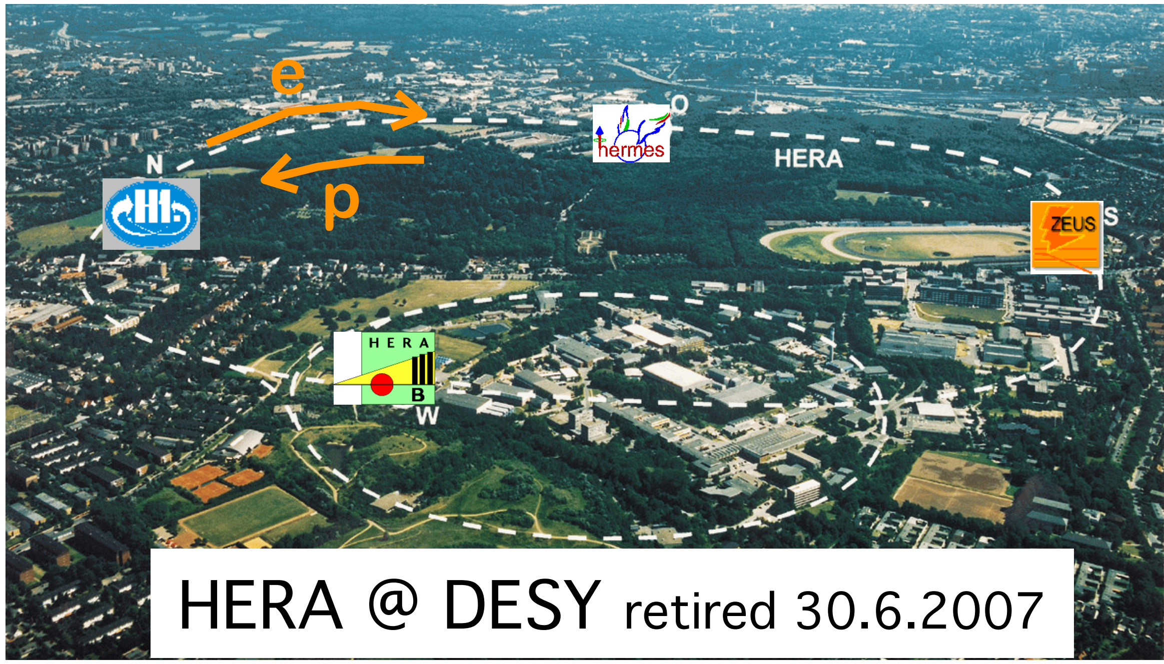
**1D**

semi-inclusive measurements

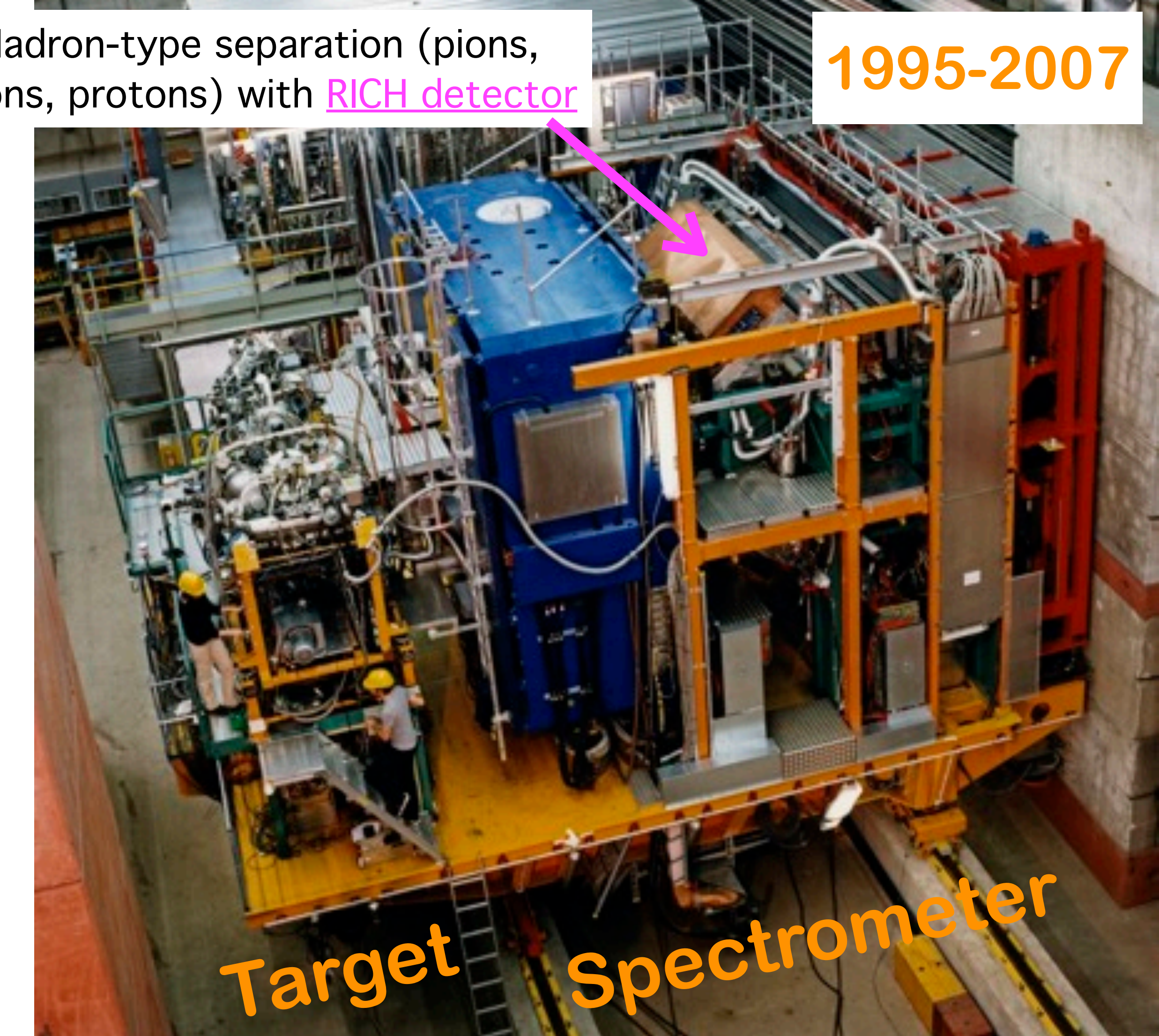
inclusive measurements

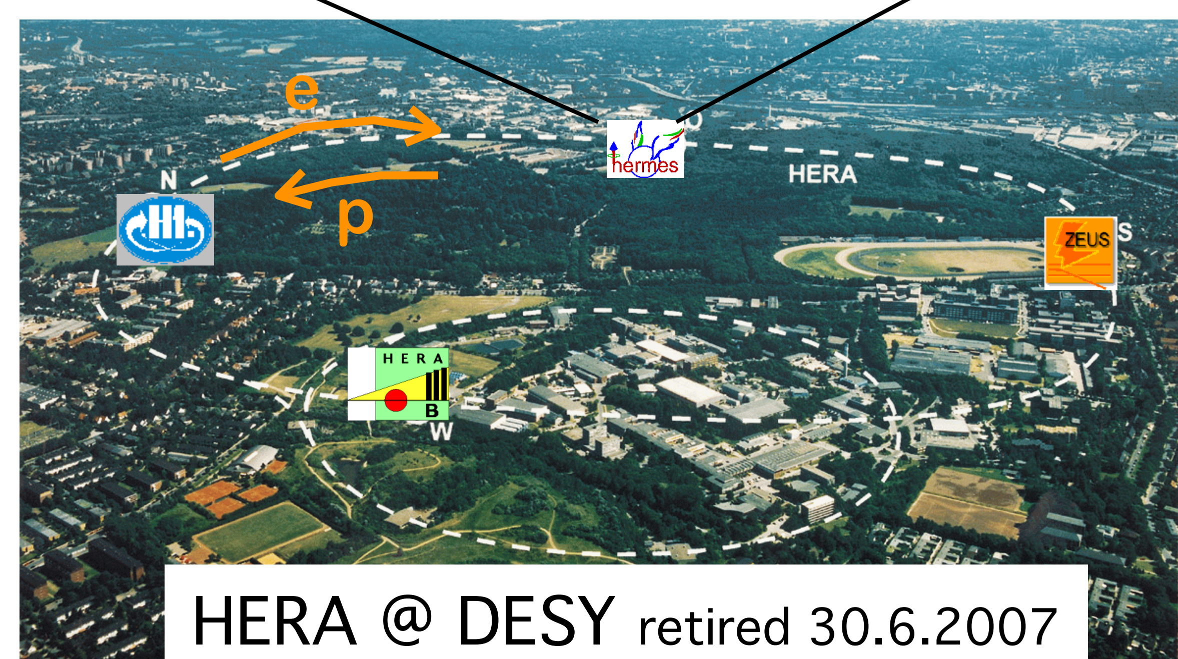
exclusive measurements

# HERMES @ DESY

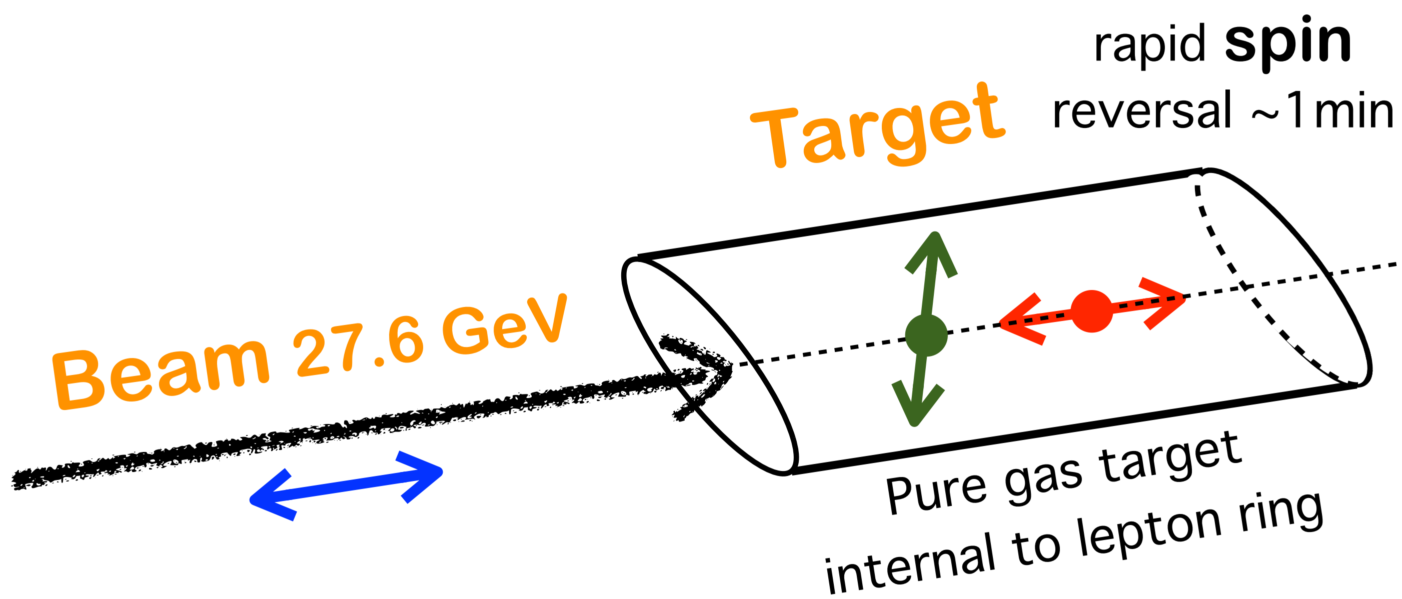


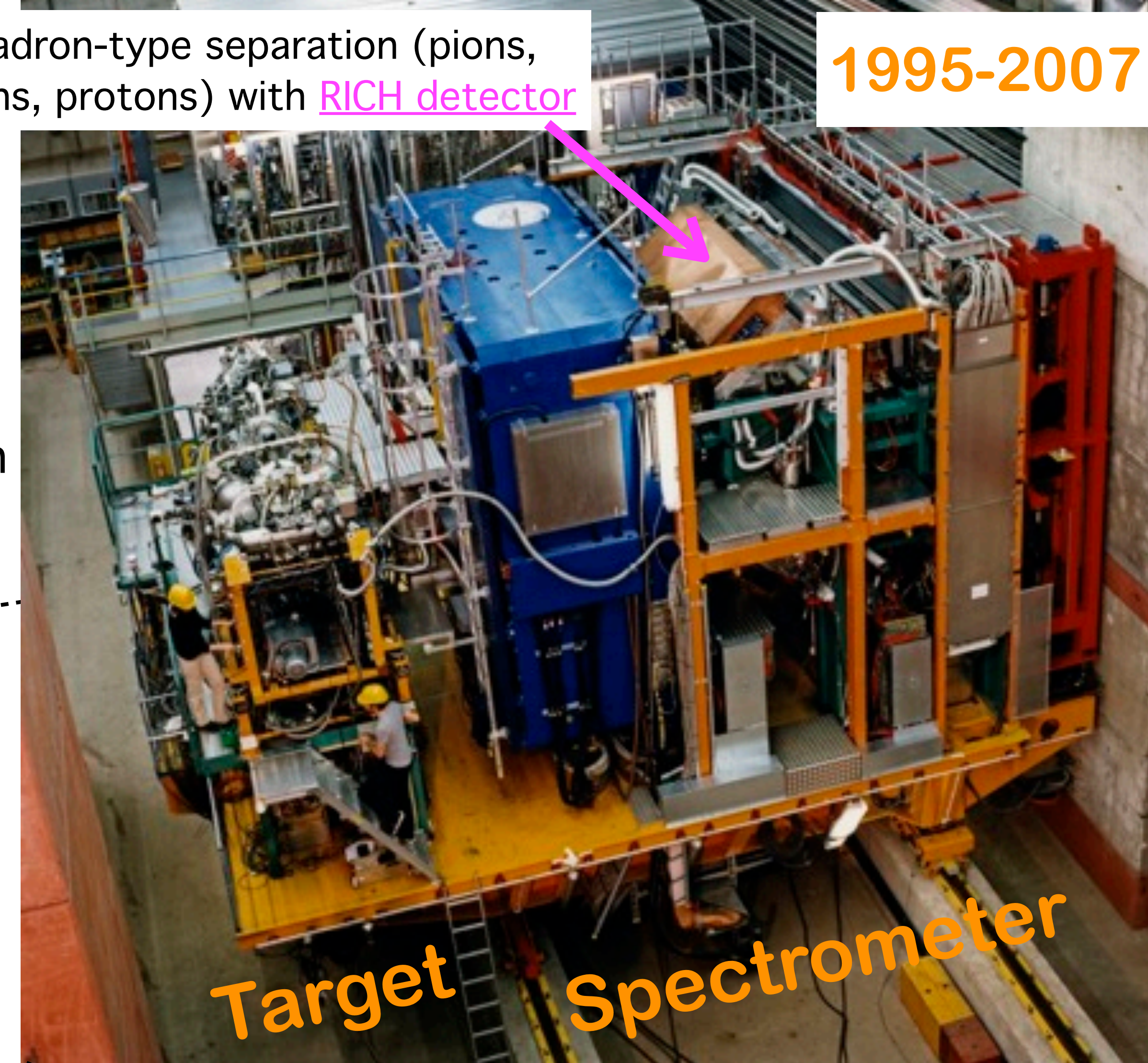
# HERMES @ DESY


Hadron-type separation (pions, kaons, protons) with RICH detector
1995-2007
Target
Spectrometer


e
p
N
hermes
HERA
ZEUS
S
HERA
B
W
HERA @ DESY retired 30.6.2007

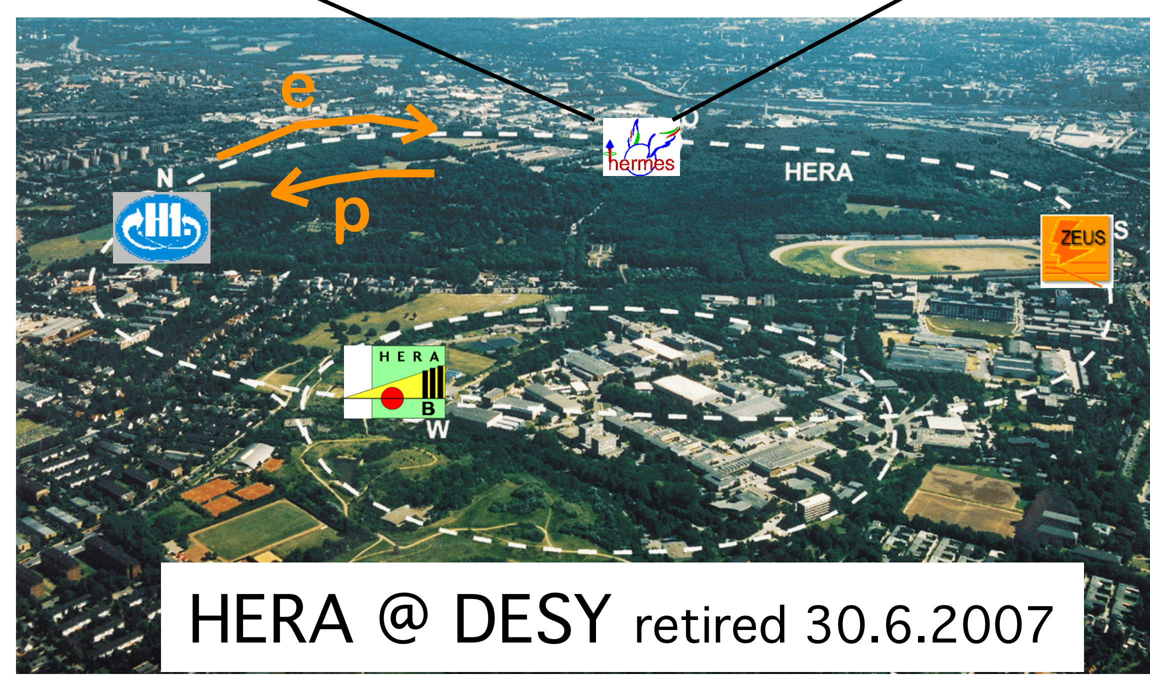
# HERMES @ DESY



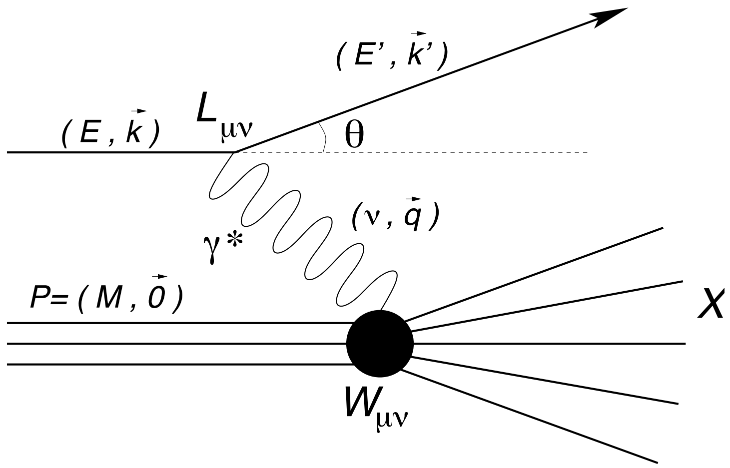




- Longitudinally polarized leptons
- Regular helicity switch (few months)
- Positrons and electrons

- $^1$H with longitudinal (50 /pb) & transverse polarization (150 /pb)
- $^2$H with longitudinal polarization (200 /pb)
- Unpolarized
  $^1$H (1200 /pb), $^2$H (800 /pb)
  He, N, Ne, Kr, Xe (300 /pb)



# Inclusive measurements




leptonic tensor (QED)

hadronic tensor (QCD)

$$\left.\frac{\mathrm{d}^2\sigma}{\mathrm{d}E'\mathrm{d}\Omega}\right|_{1\gamma^*} = \frac{\alpha^2}{2MQ^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$$

$W^{\mu\nu}$ parameterized by 4 structure functions (spin-½):

$$\underbrace{F_1, F_2,}_{\text{spin-independent}} \quad \underbrace{g_1, g_2}_{\text{spin-dependent}}$$

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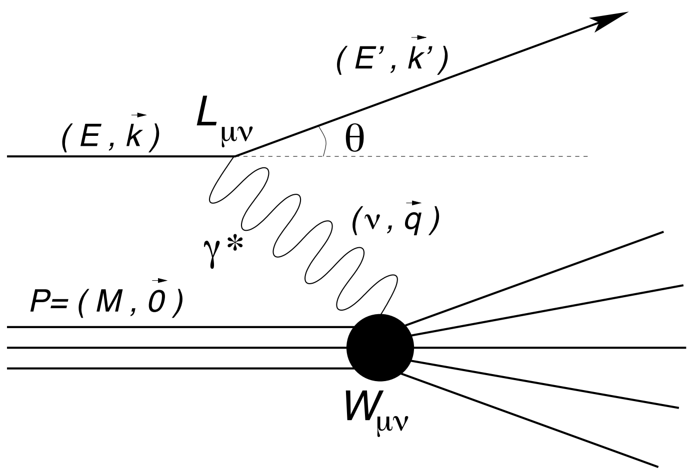


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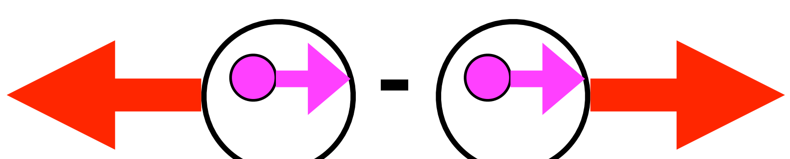



$\Delta\Sigma \approx ⅓$

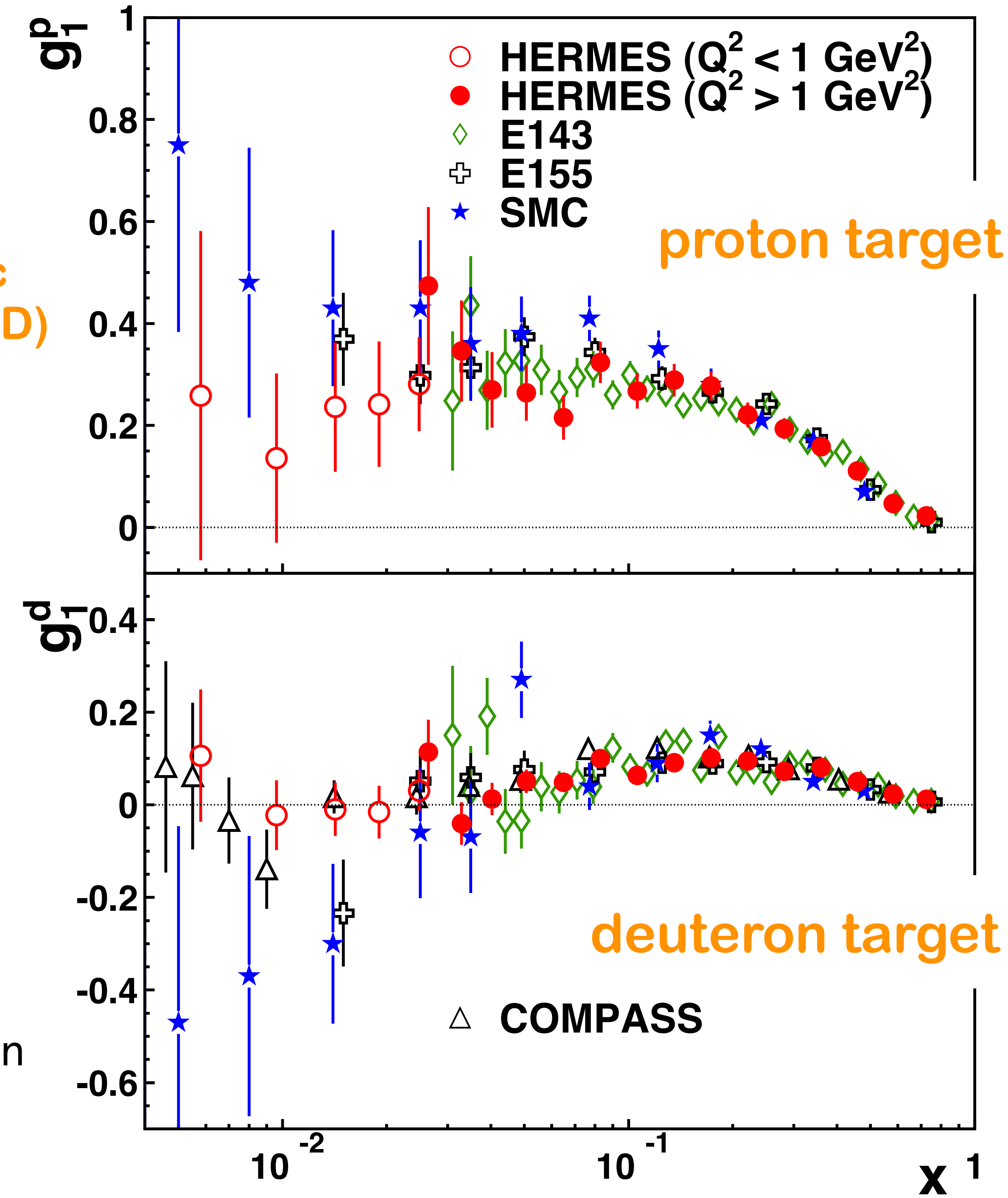
$$g_1 = \frac{1}{2}\sum_q e_q^2 (q^+ - q^-)$$

Probabilistic interpretation in Quark Parton Model (QPM)

## Spin structure function $g_1$

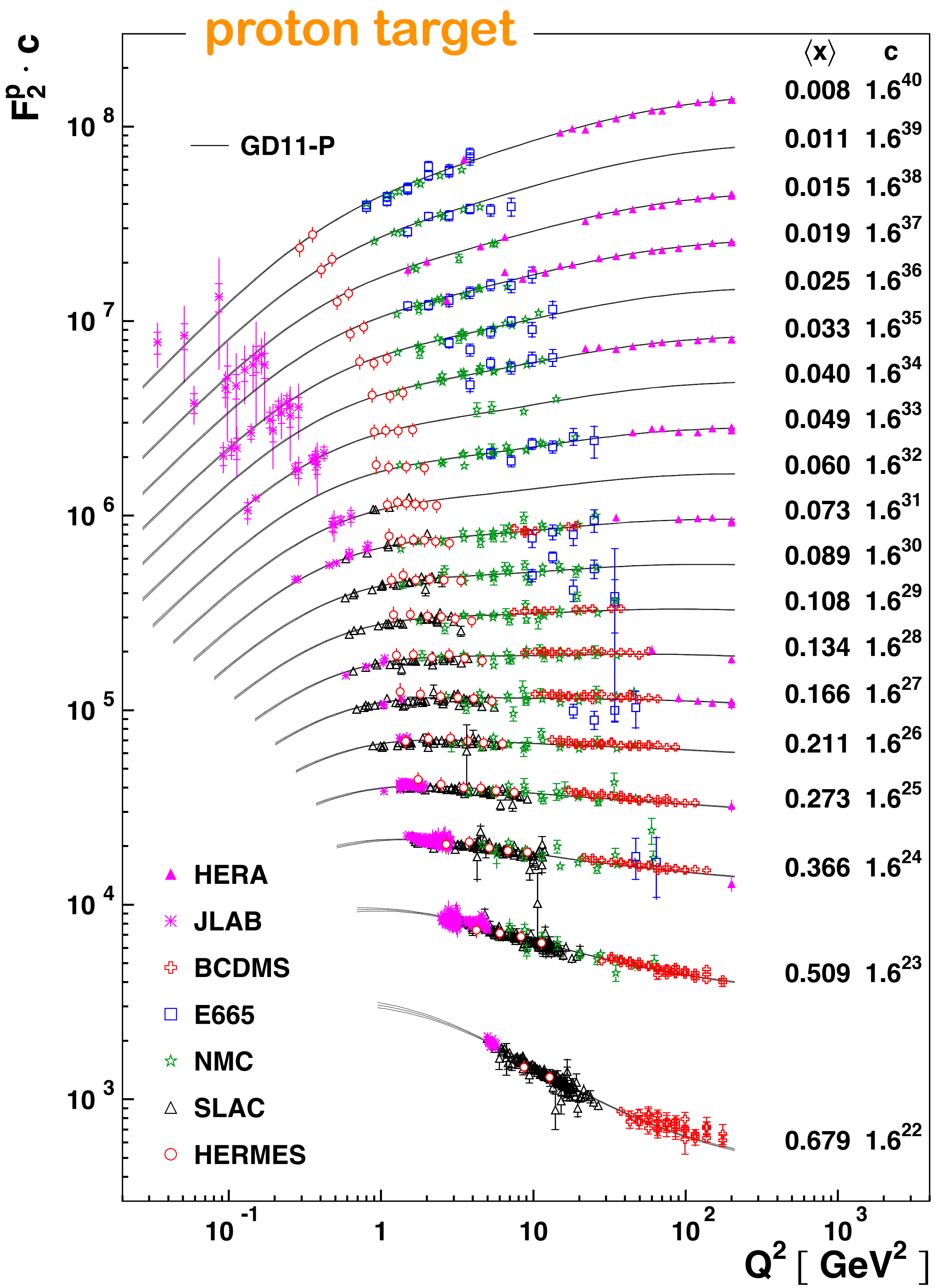
(HERMES final result 2007)

A. Airapetian et al. [HERMES], Phys. Rev. D 75 (2007) 012007

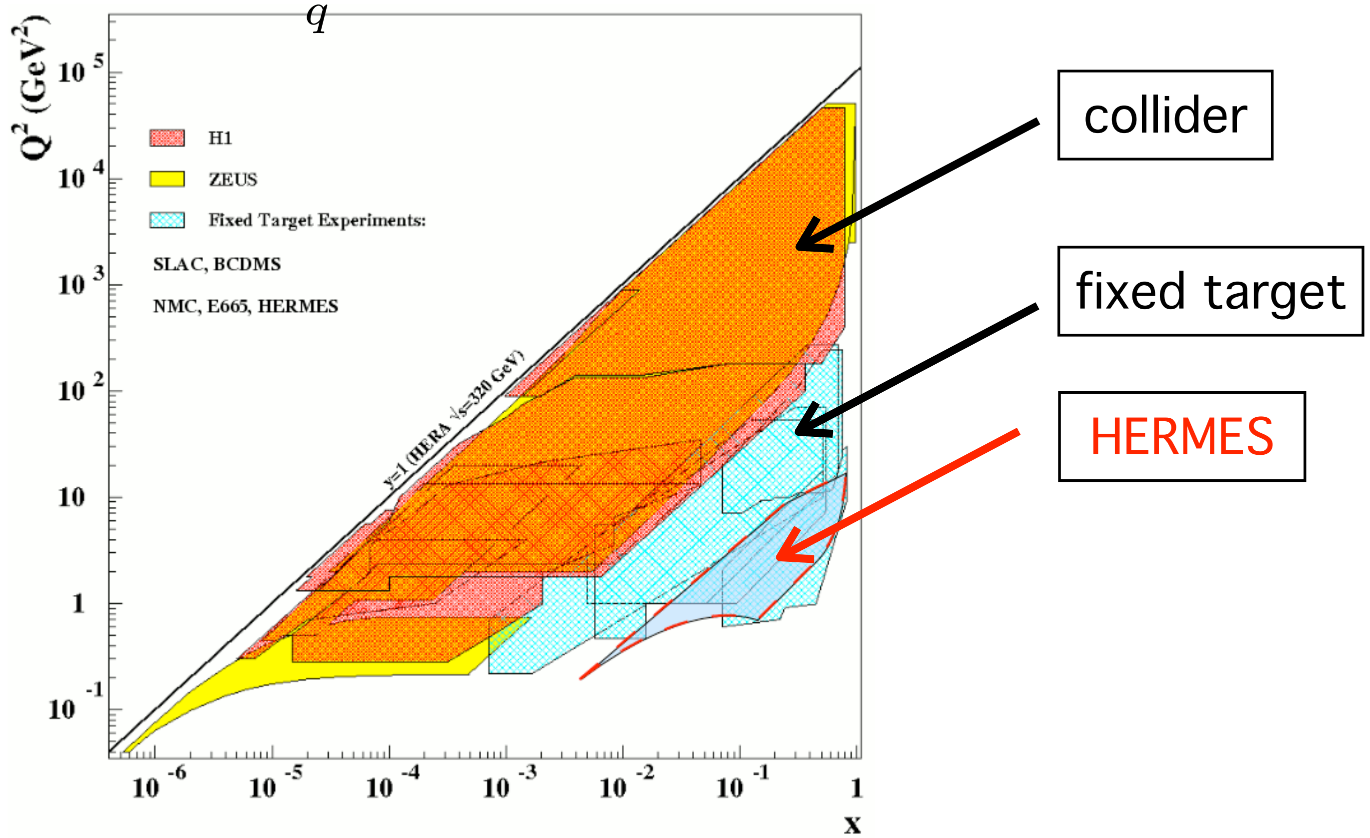


# Structure function $F_2$

A. Airapetian et al. [HERMES], JHEP 05 (2011)




$$F_1 = \frac{1}{2}\sum_q e_q^2(q^+ + q^-) \qquad F_2 = f(F_1, R)$$




- HERMES data complementary to collider data, cover transition region between perturbative and non-perturbative regimes of QCD
- Agreement with world data in overlap region
- New region covered by HERMES
- GD11 global fit
  HERMES rel. normalization ~2%, 0.5% for p/d.

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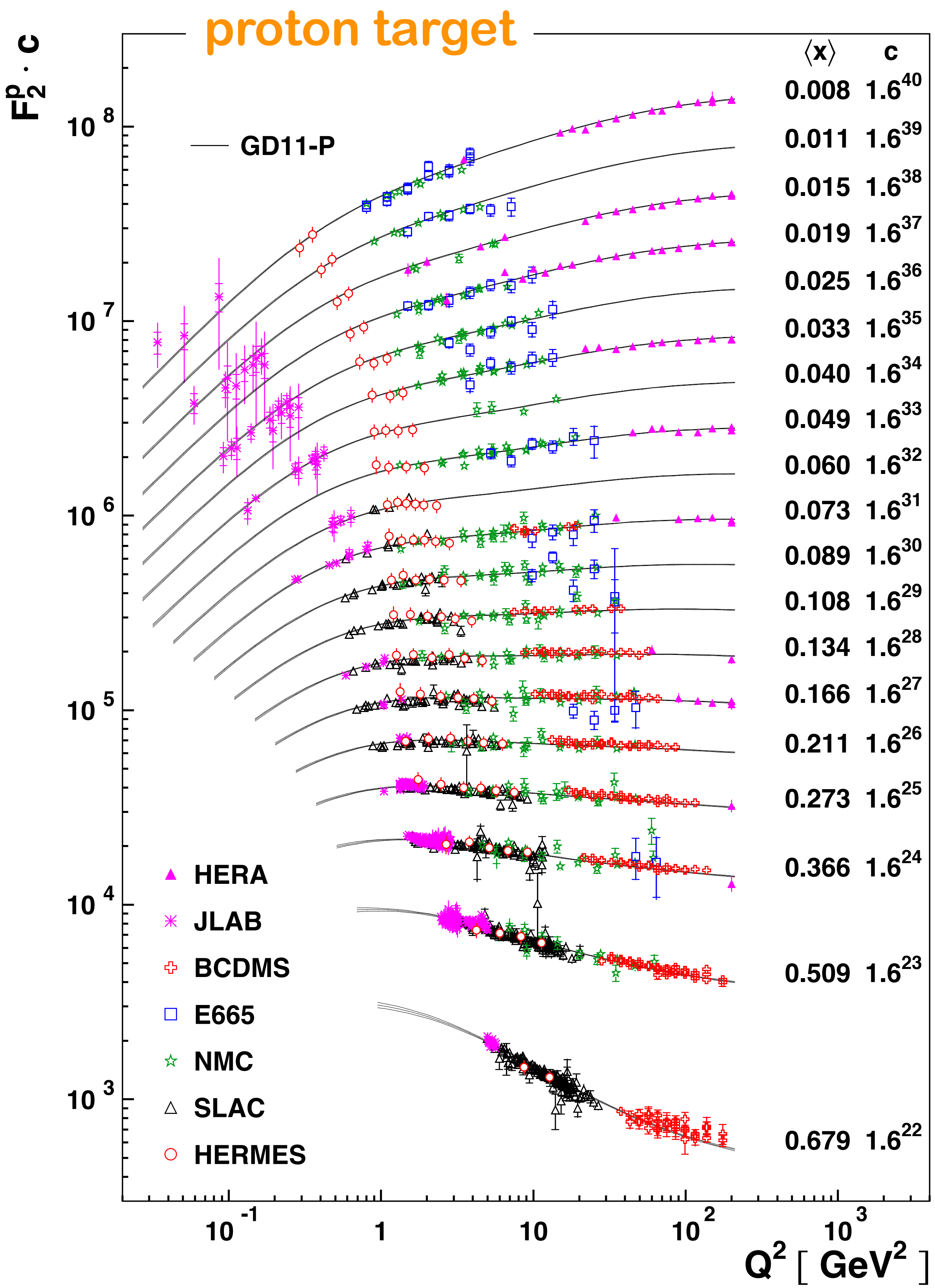
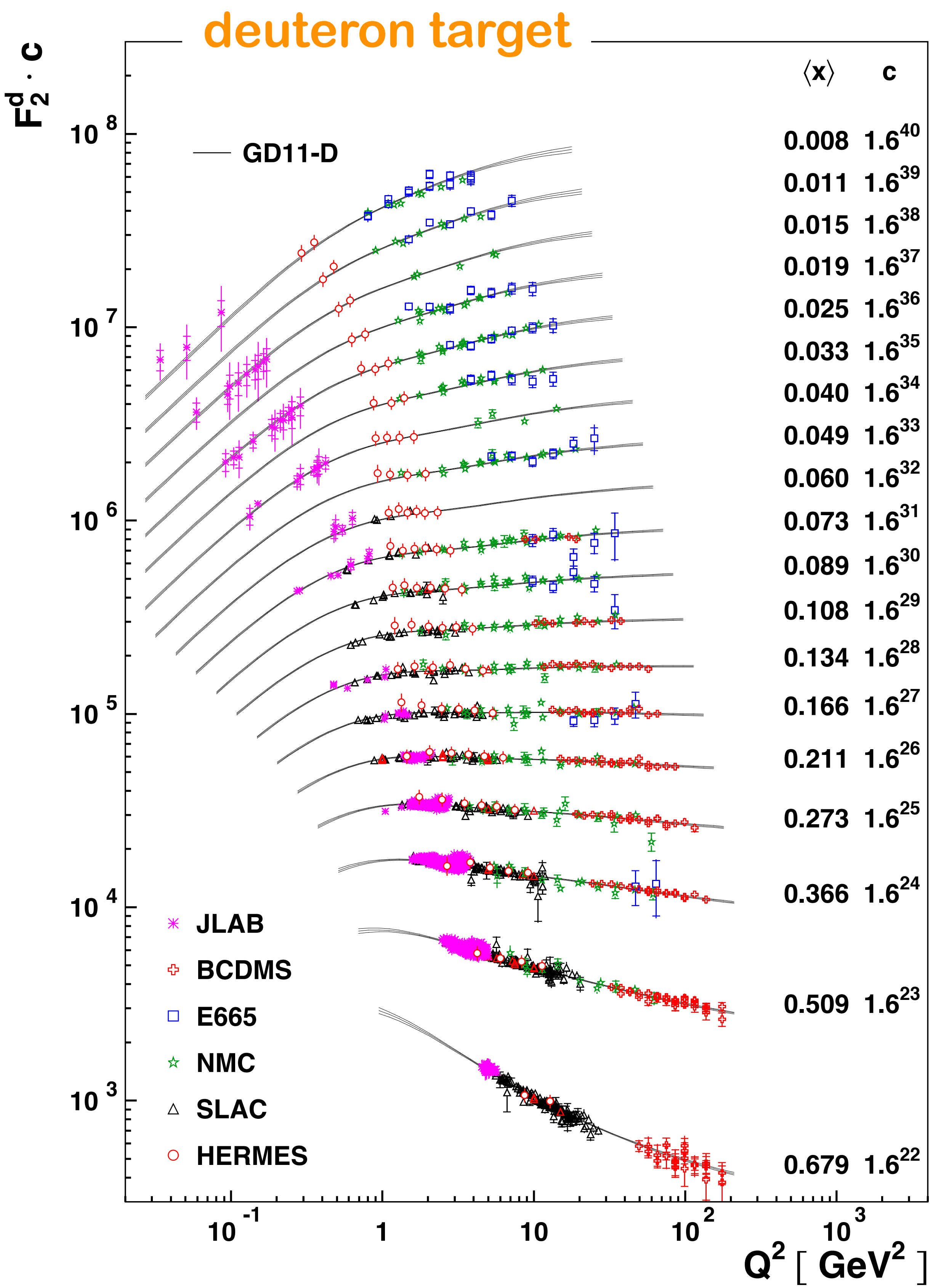
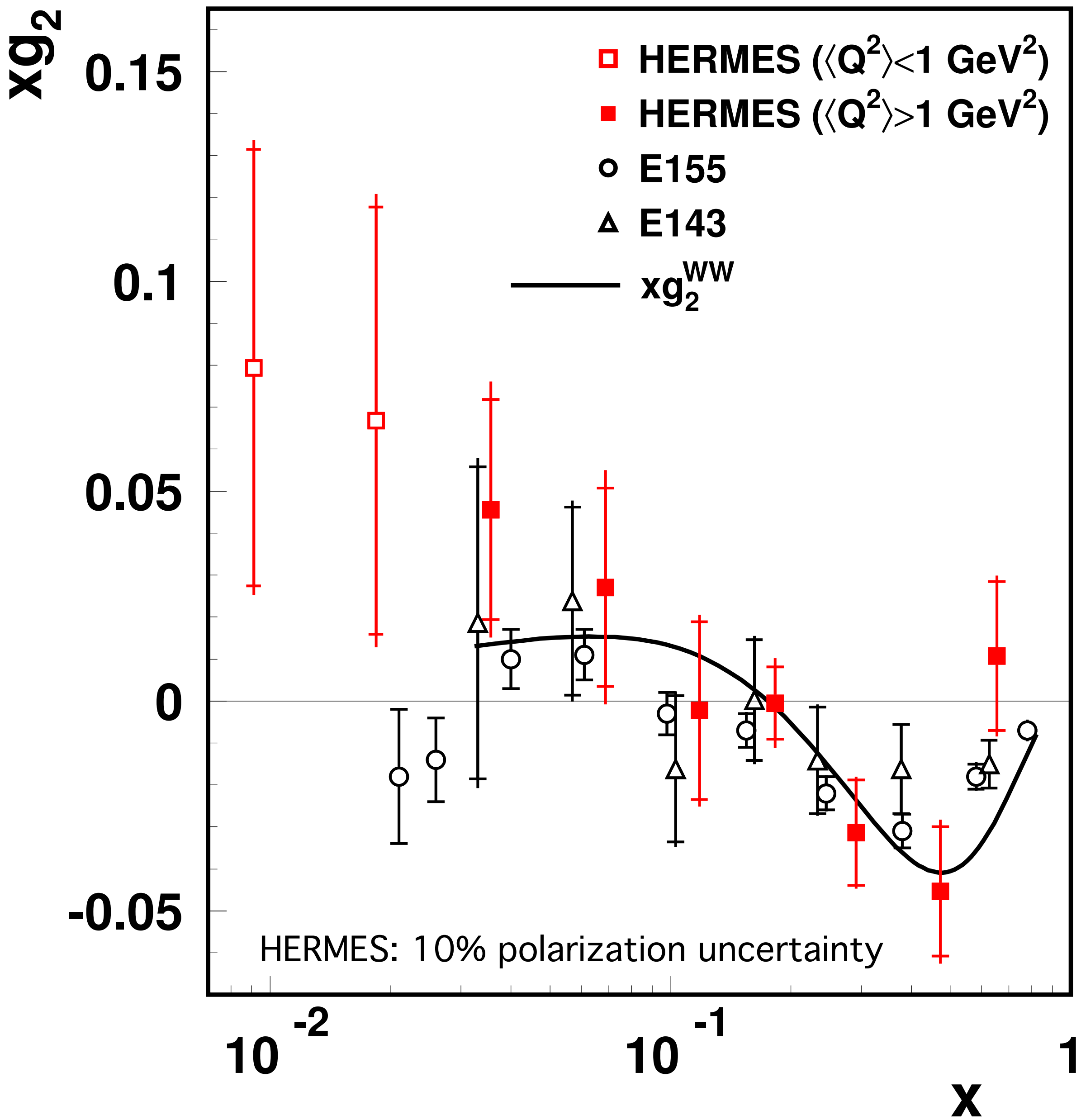
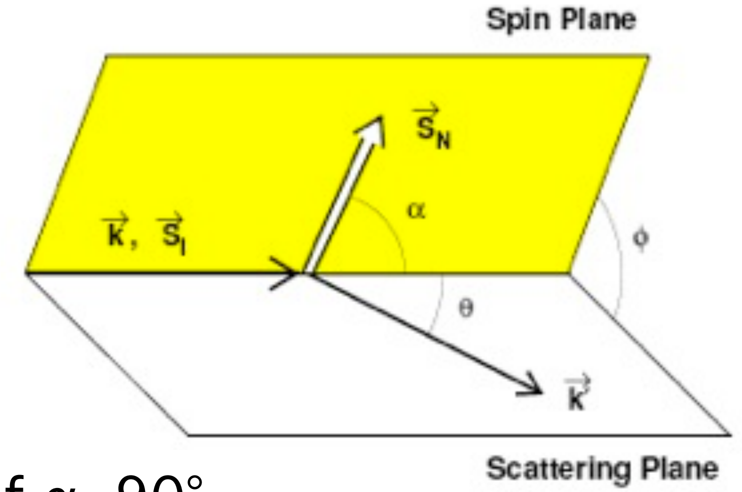


# Spin structure function $g_2$

A. Airapetian et al. [HERMES], accepted by EPJ C (in press) [arXiv:1112.5584]




- Sensitivity to $g_2$ highest if $\alpha=90°$
- QPM: $g_2 \equiv 0$

  (no transverse degrees of freedom)

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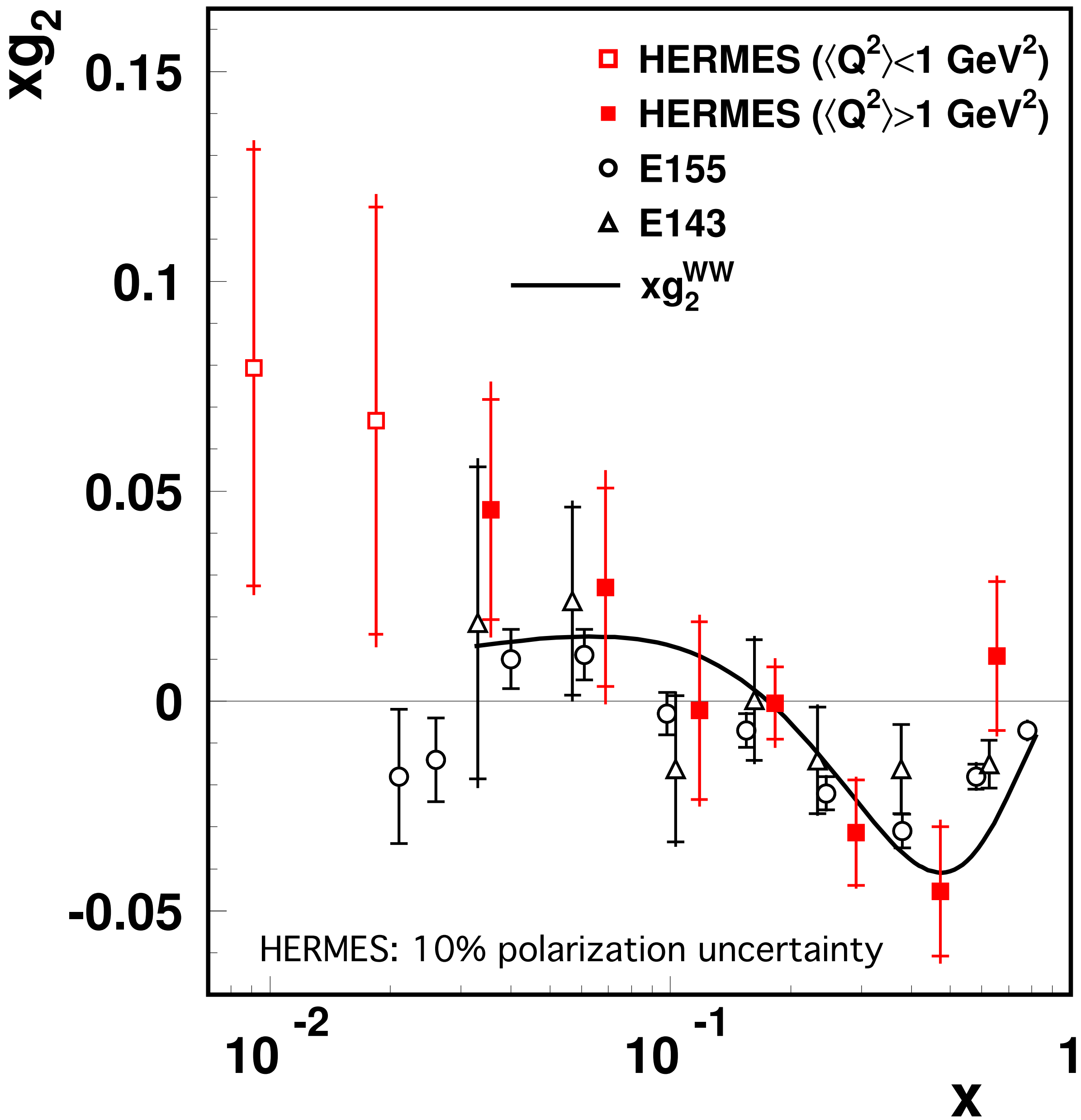


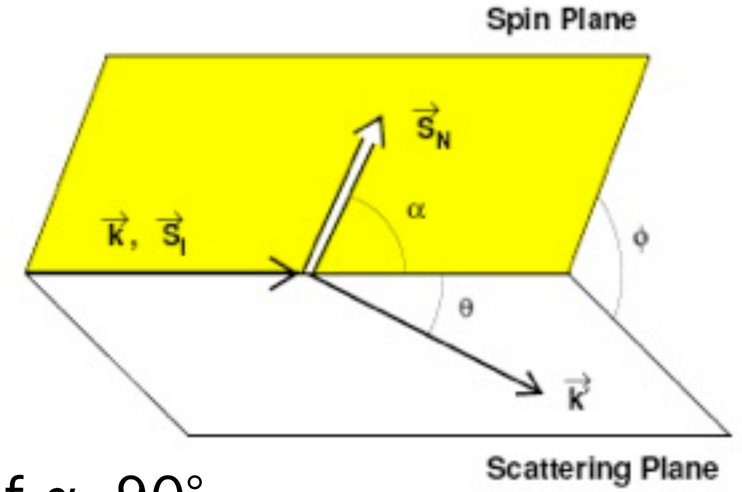


☛ Sensitivity to $g_2$ highest if $\alpha$=90°

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☛ OPE: twist-2 twist-3

$$g_2(x,Q^2) = g_2^{\mathrm{WW}}(x,Q^2) + \bar{g}_2(x,Q^2)$$

$$g_2^{\mathrm{WW}}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2)\frac{\mathrm{d}y}{y}$$

Wandzura-Wilczek relation

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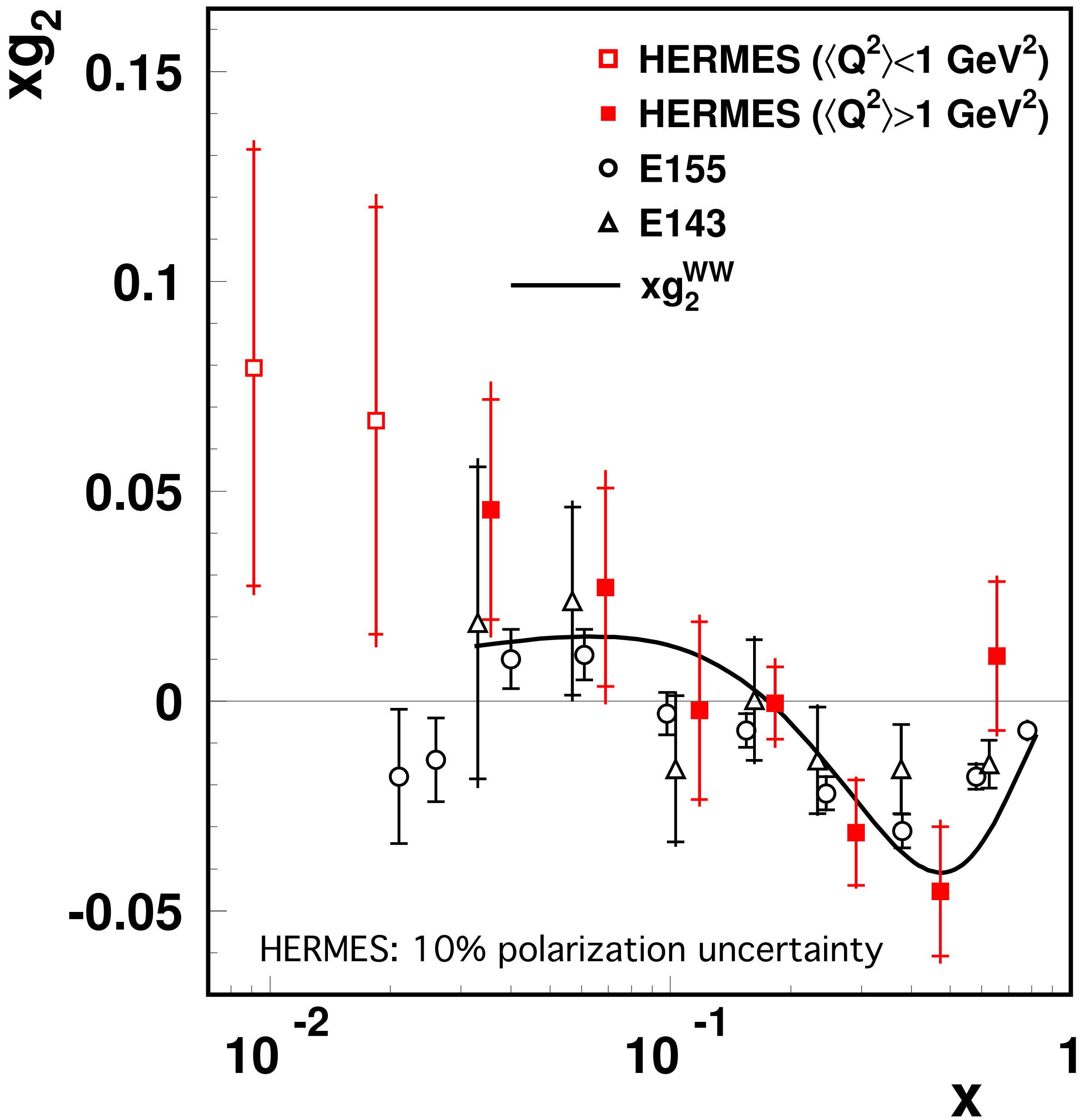


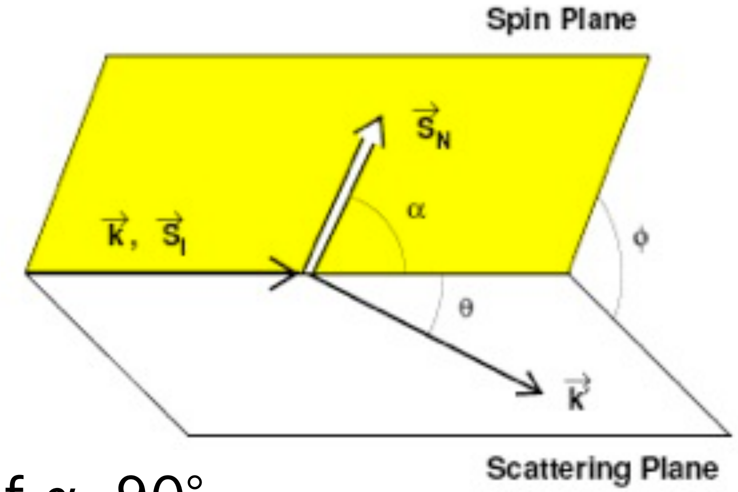


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Wandzura-Wilczek relation

- Test of deviation from WW part:

$$d_2(Q^2) = 3\int_0^1 x^2\,\bar{g}_2(x,Q^2)\,dx$$

**HERMES:**

**$d_2 = 0.0148 \pm 0.0096(\mathrm{stat}) \pm 0.0048(\mathrm{sys})$**

# Spin structure function $g_2$

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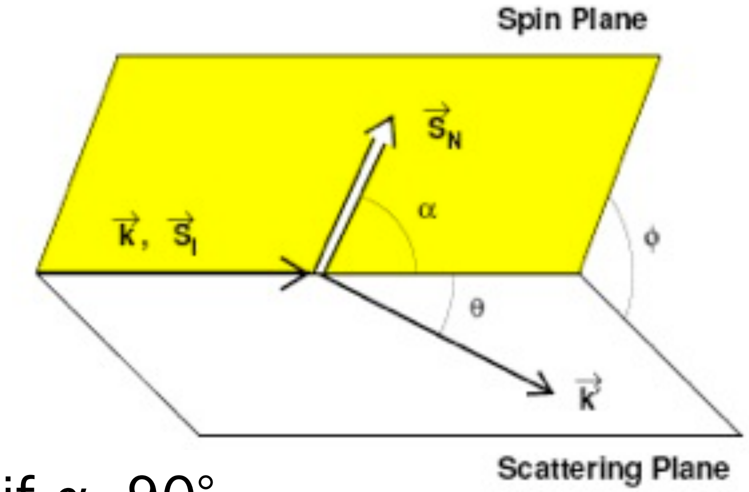


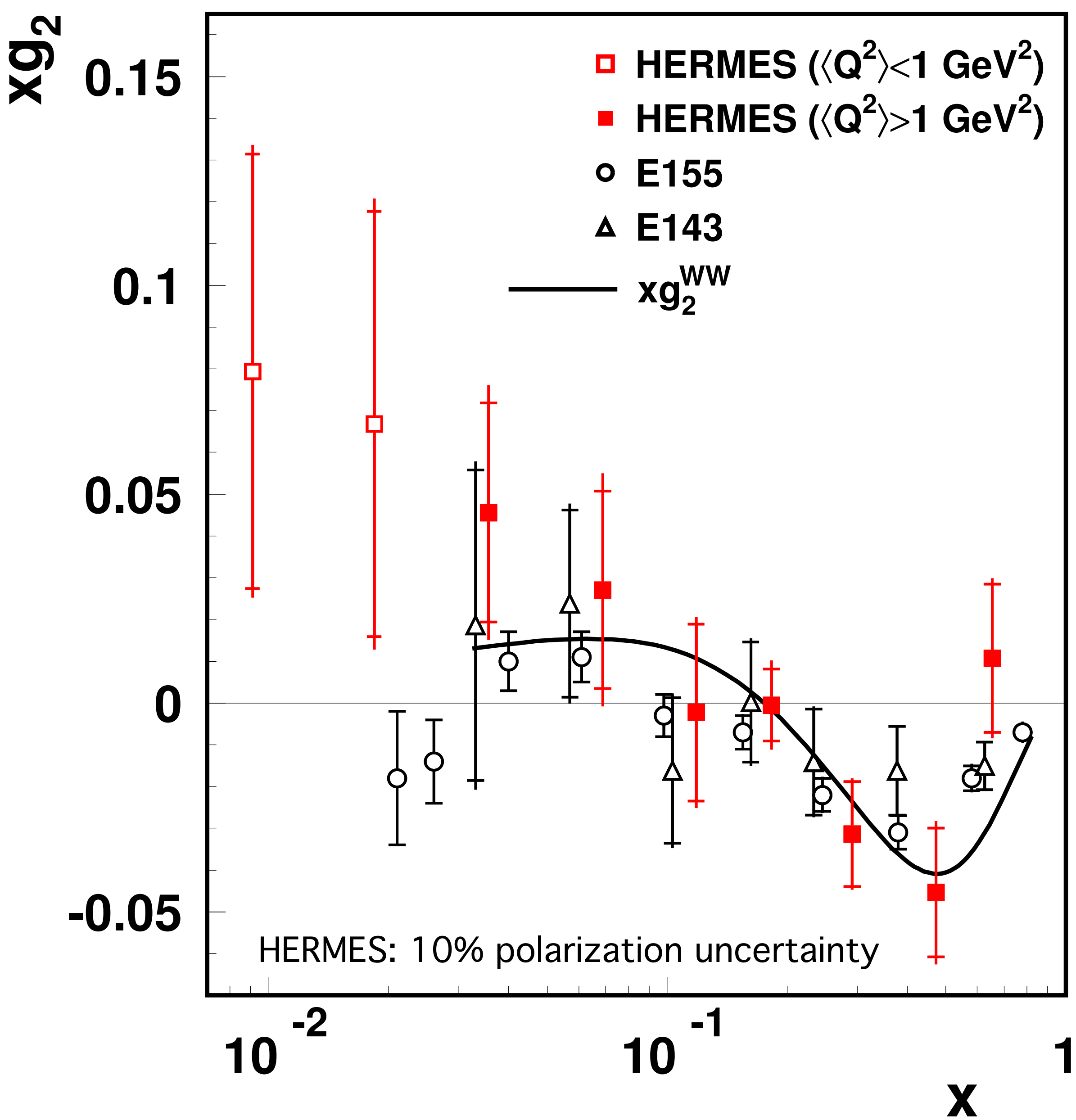


- Sensitivity to $g_2$ highest if $\alpha$=90°
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Wandzura-Wilczek relation

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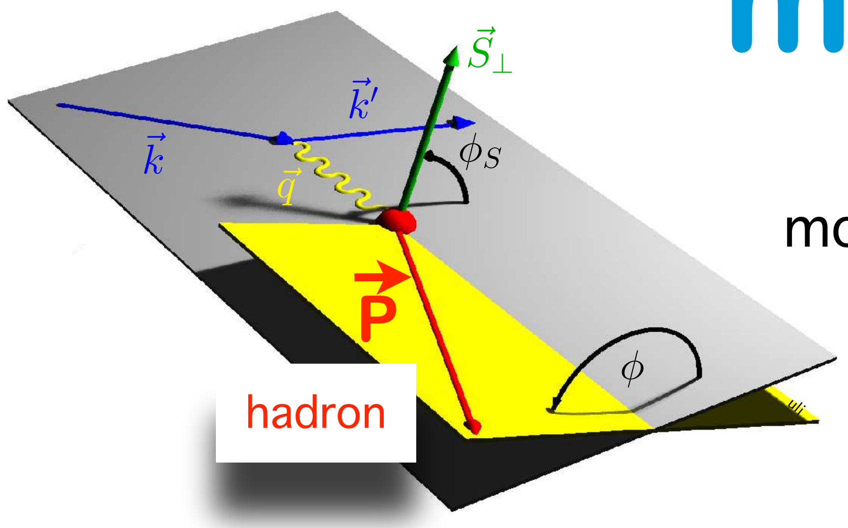
**HERMES:**
**$d_2$ = 0.0148 ± 0.0096(stat) ± 0.0048(sys)**

- Burkhardt-Cottingham sum rule: $$\int_0^1 g_2(x,Q^2)\mathrm{d}x = 0$$

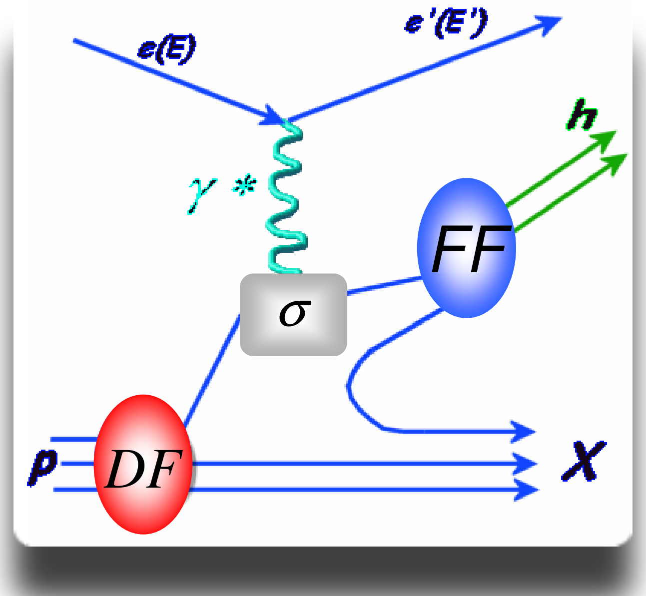
$\equiv$0 in absence of higher-twist effects

**0.006 ± 0.024(stat) ± 0.017(sys)** [0.023 < x < 0.9 @ $Q^2$ = 5 GeV²]

# Semi-inclusive measurements

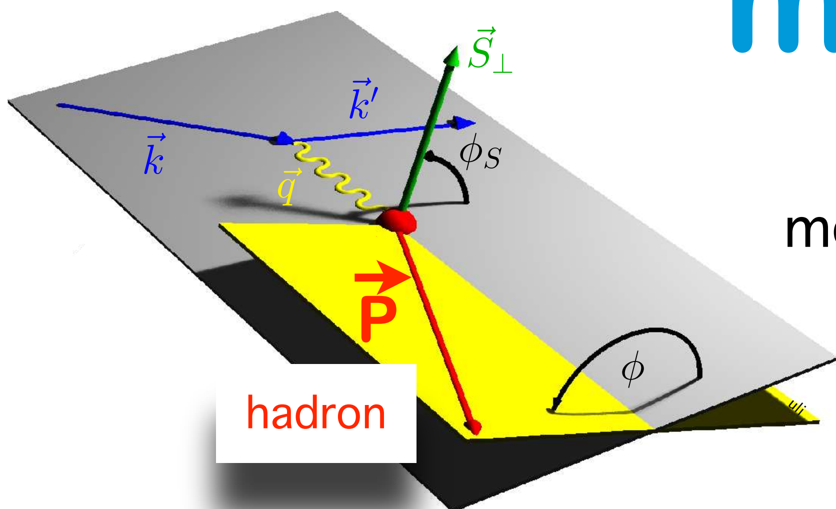



Analysis of harmonic azimuthal modulations ($\Phi$, $\Phi_S$) in the cross section.




$$\boxed{\sigma^{ep\rightarrow ehX} = \Sigma_q \left(DF \otimes \sigma^{eq\rightarrow eq} \otimes FF\right)}$$

# Semi-inclusive measurements

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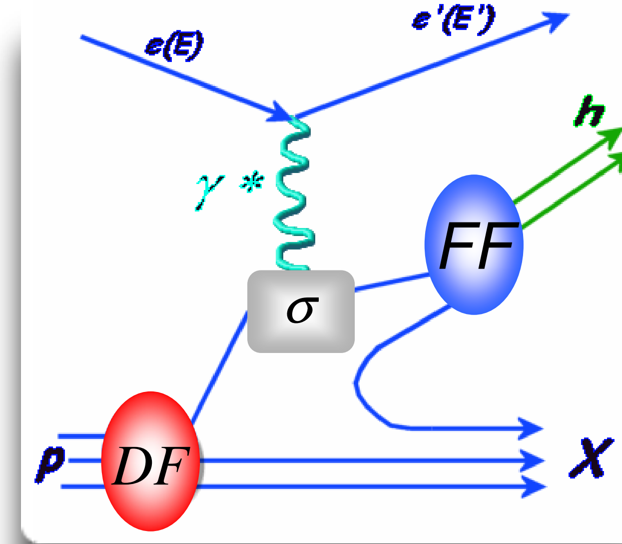



$$\sigma^{ep\to ehX} = \Sigma_q \left(DF \otimes \sigma^{eq\to eq} \otimes FF\right)$$

## Leading -twist TMDs

(transverse-momentum dependent PDFs)

**Quark polarization**

| Nucleon polarization | U | L | T |
|---|---|---|---|
| U | $f_1$ Number Density | | $h_1^\perp$ Boer Mulders |
| L | | $g_1$ Helicity | $h_{1L}^\perp$ Worm-gear |
| T | $f_{1T}^\perp$ Sivers | $g_{1T}^\perp$ Worm-gear | $h_1$ Transversity<br>$h_{1T}^\perp$ Pretzelosity |

Indication to be not-zero ! Preliminary result

Consistent with zero PLB 562 (2003) 182 PRL 84 (2000) 4047

Different from zero ! PRL 94 (2005) 012002 PLB 693 (2010) 11

Consistent with zero Preliminary result

Different from zero ! PRL 94 (2005) 012002 PRL 103 (2009) 152002

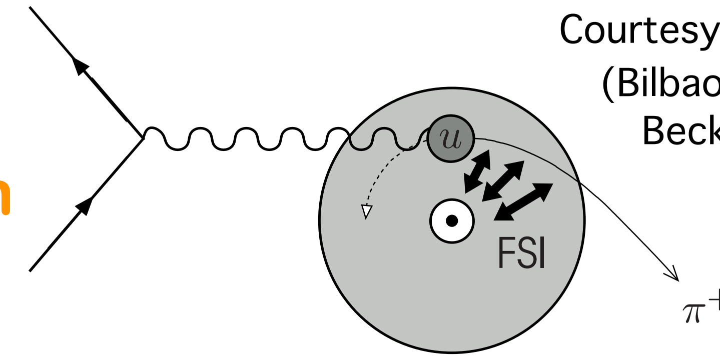
Indication to be non-zero! Preliminary result

**Diagonal elements**
'Survive' integration over transverse momentum $k_T$.
"Collinear analysis"

Courtesy M. Contalbrigo (Ferrara)

# Sivers amplitudes

**Indication of orbital motion**




Courtesy G. Schnell (Bilbao) and U. Beckmann

$L_z^u > 0$

[*M. Burkardt*, Phys. Rev. D66 (2002) 114005]

DF ⊗ FF

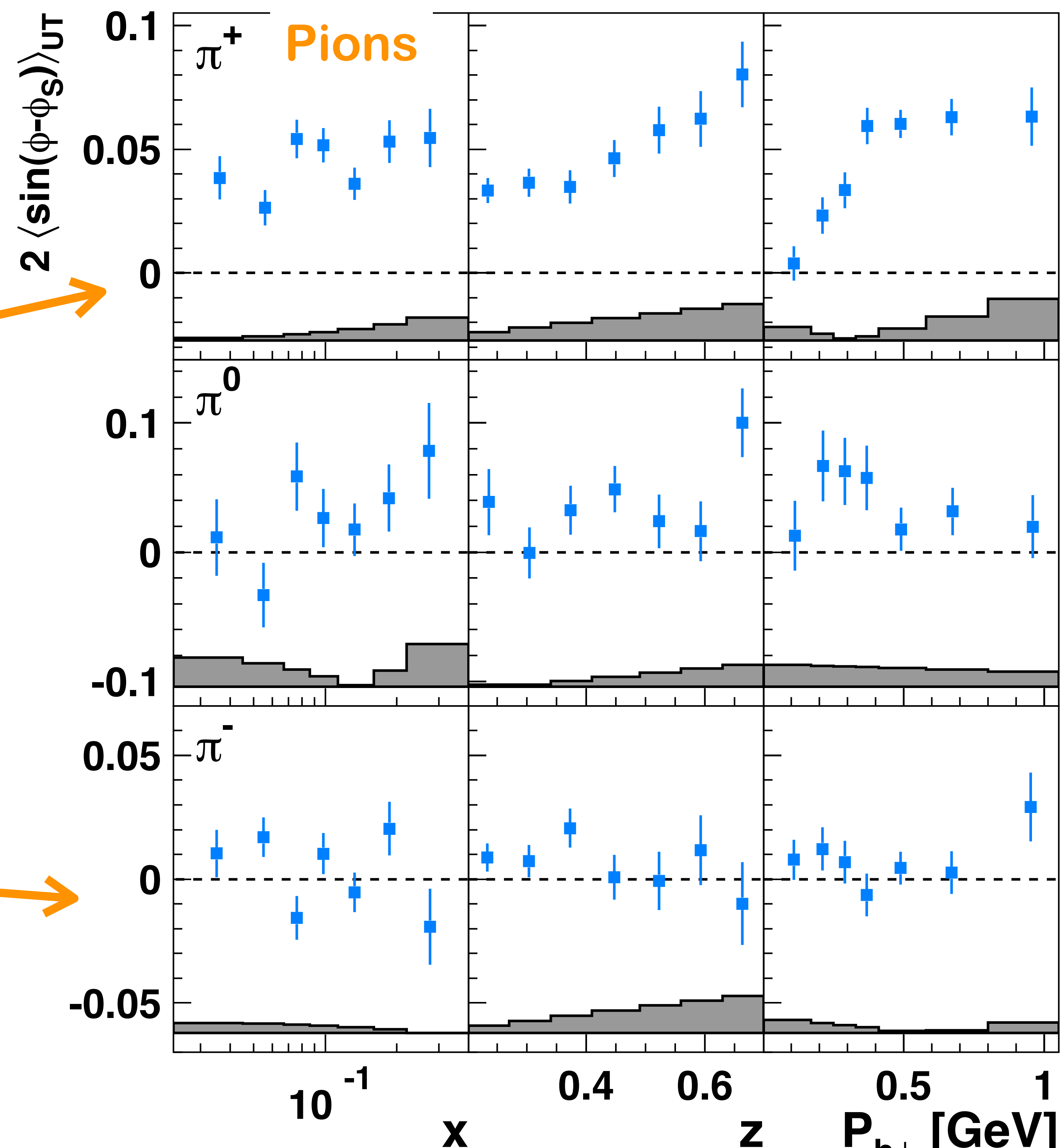
$$2\langle\sin(\phi-\phi_S)\rangle_{UT} = -\frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,p_T^2) \otimes_{\mathcal{W}} D_1^q(z,K_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,K_T^2)}$$

☛ π⁺ dominated by u-quark scattering:

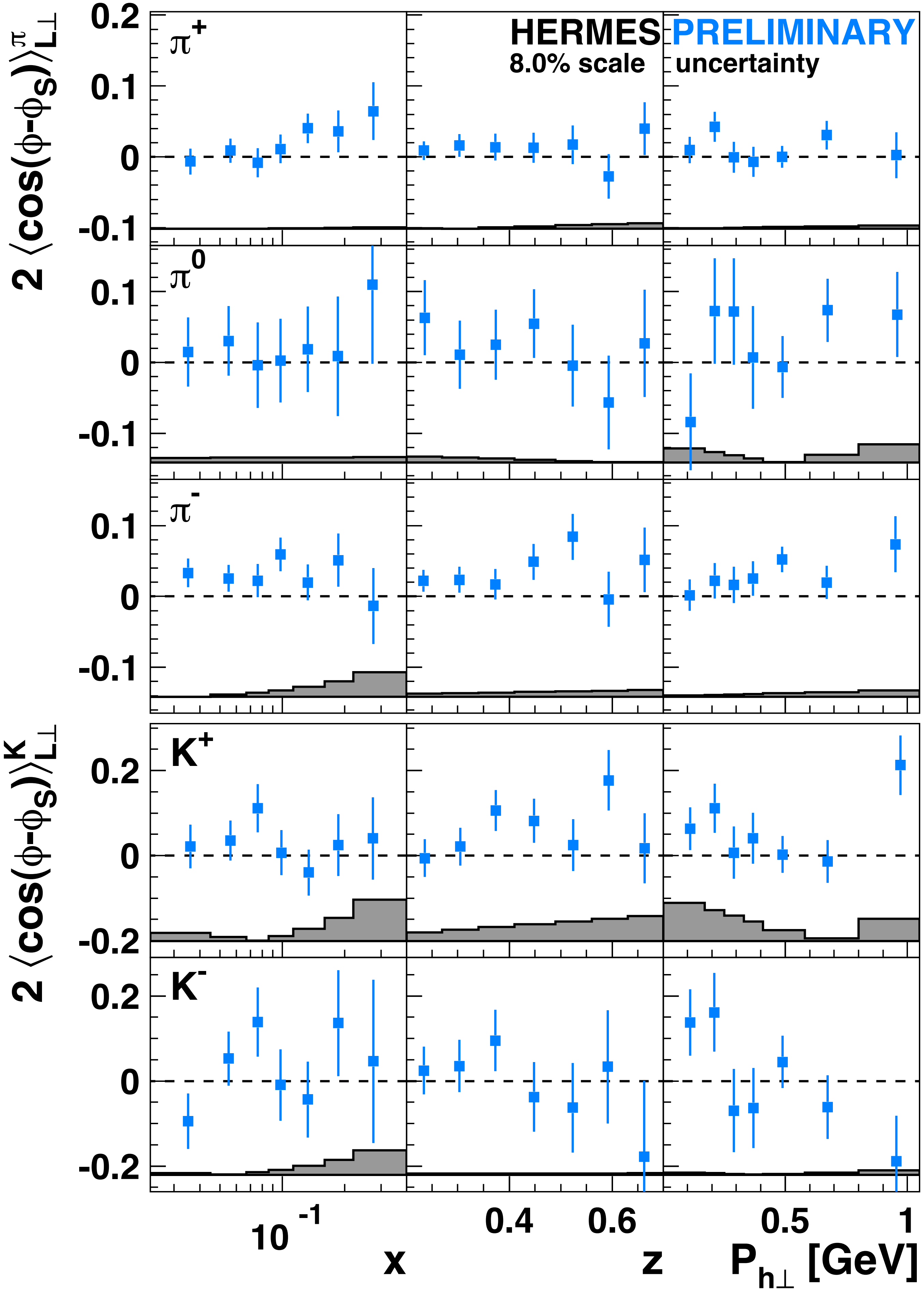
$$\simeq -f_{1T}^{\perp}(x,p_T^2) \otimes D_1^{u\to\pi^+}(z,k_T^2)$$

☛ u-quark Sivers function < 0

☛ d-quark Sivers function > 0
(cancellation for π⁻)



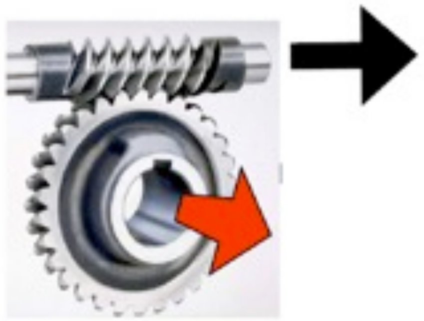

A. Airapetian et al. [HERMES], Phys. Rev. Lett. 103 (2009) 152002




# Worm-gear TMD

DF ⊗ FF

$$\sigma_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \propto g_{1\mathrm{T}}^{\perp} \otimes D_1$$



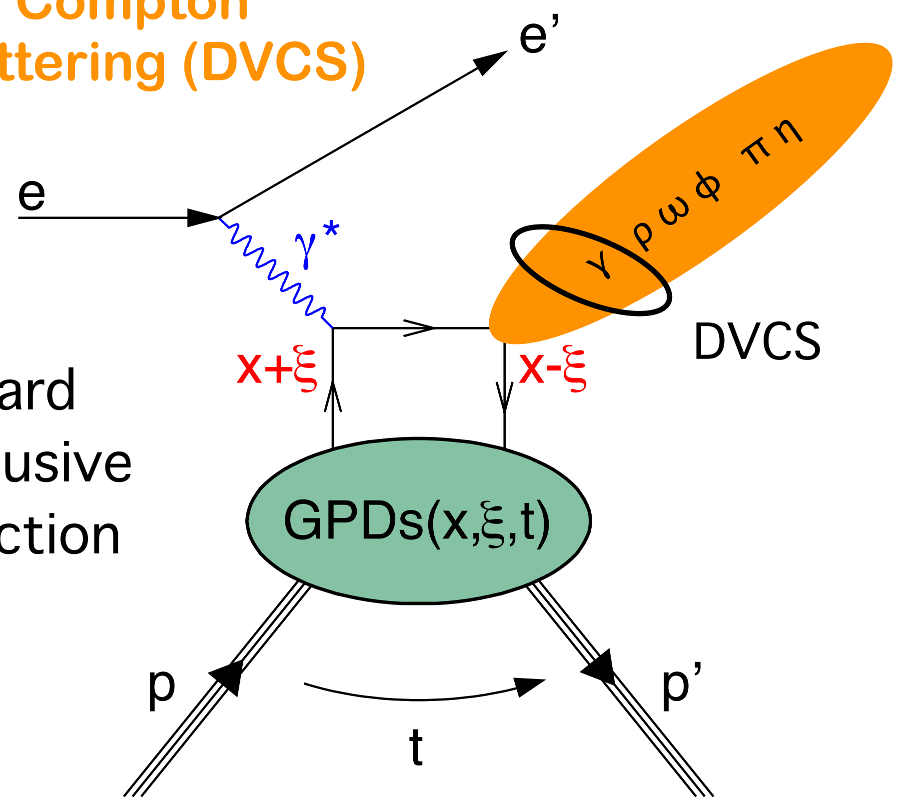
- Longitudinally polarized quarks in transversely polarized nucleon
- Related to parton orbital motion –
  requires interference between wave functions with OAM difference by 1 unit
- Wandzura-Wilczek type approximation:

$$g_{1\mathrm{T}}^{\perp}(x) \approx x \int_0^1 \frac{\mathrm{d}y}{y} g_1(y)$$

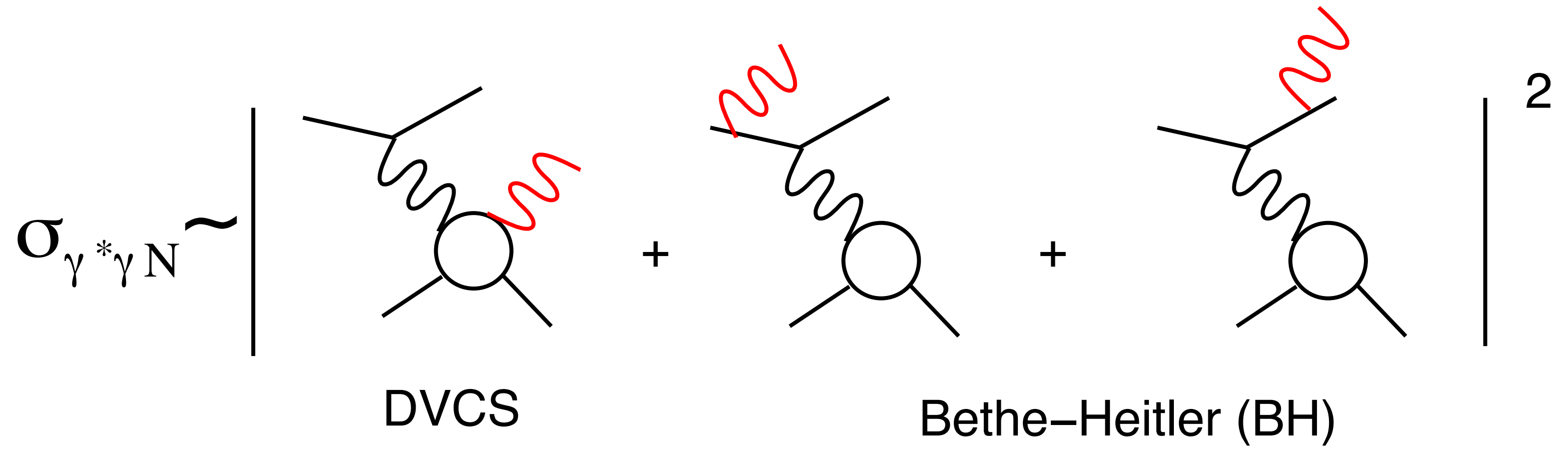
# Exclusive measurements

Deeply Virtual Compton Scattering (DVCS)

Hard exclusive reaction




**Cross section of ep→epγ :**




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

Small at HERMES

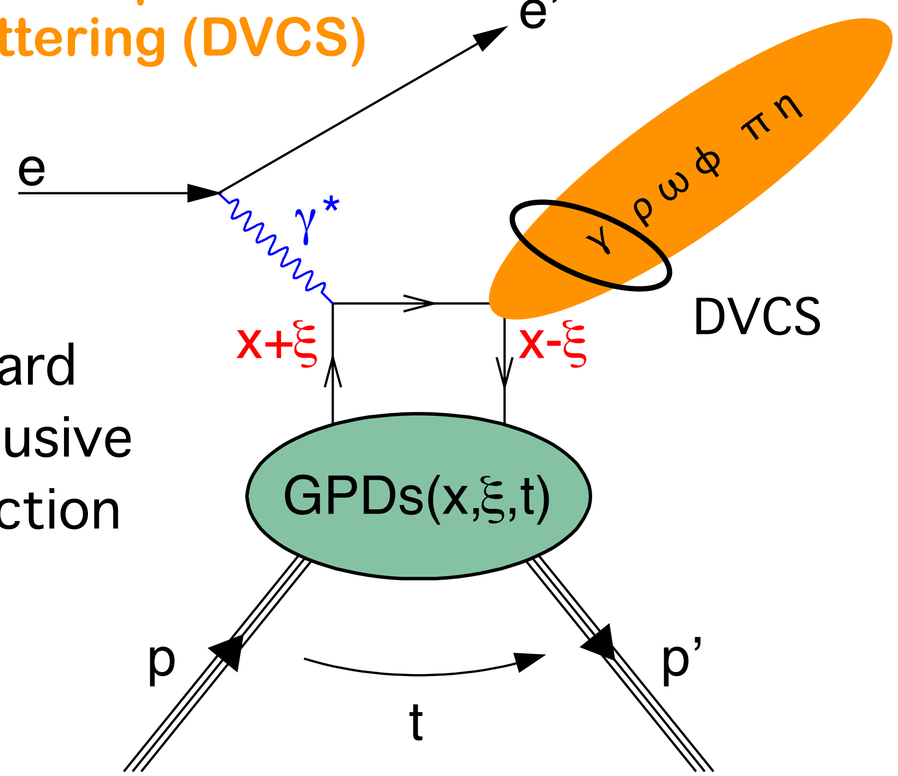
Exactly calculable in QED

**DVCS-BH interference term**

# Exclusive measurements

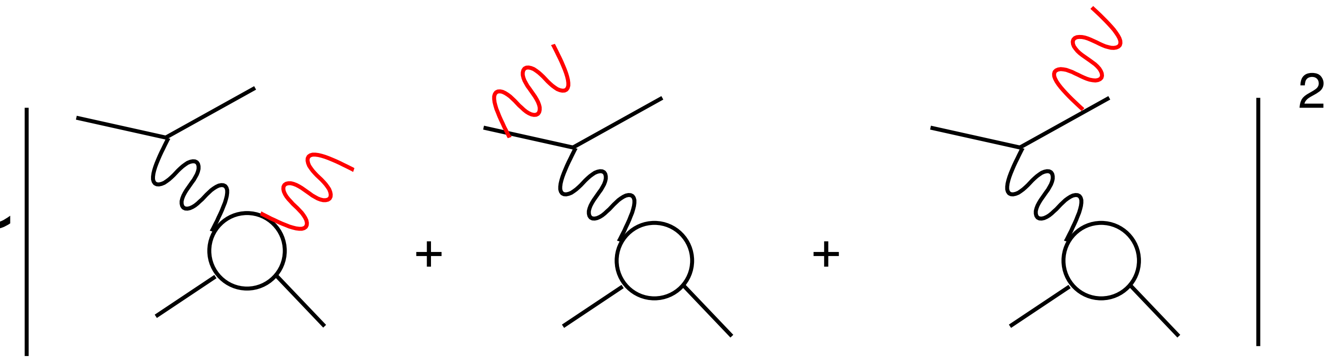
**Deeply Virtual Compton Scattering (DVCS)**

Hard exclusive reaction




## Cross section of ep→epγ :

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




DVCS    Bethe–Heitler (BH)

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

Small at HERMES

Exactly calculable in QED

**DVCS-BH interference term**

4 chiral-even quark GPDs at leading twist

| 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 → q(x)

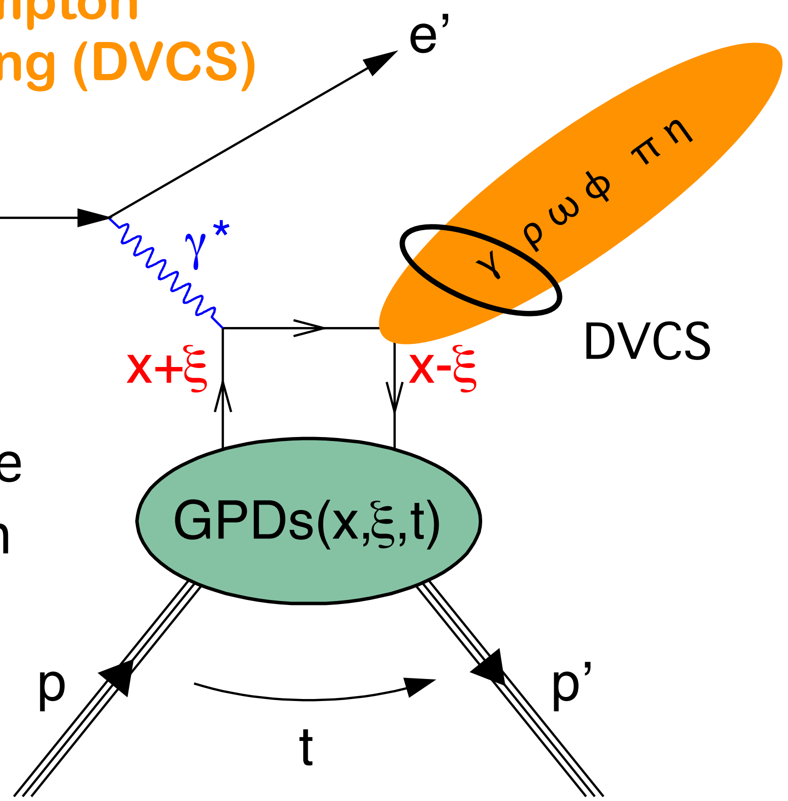
forward limit ξ→0, t→0

$\tilde{H}$ → Δq(x)

# Exclusive measurements

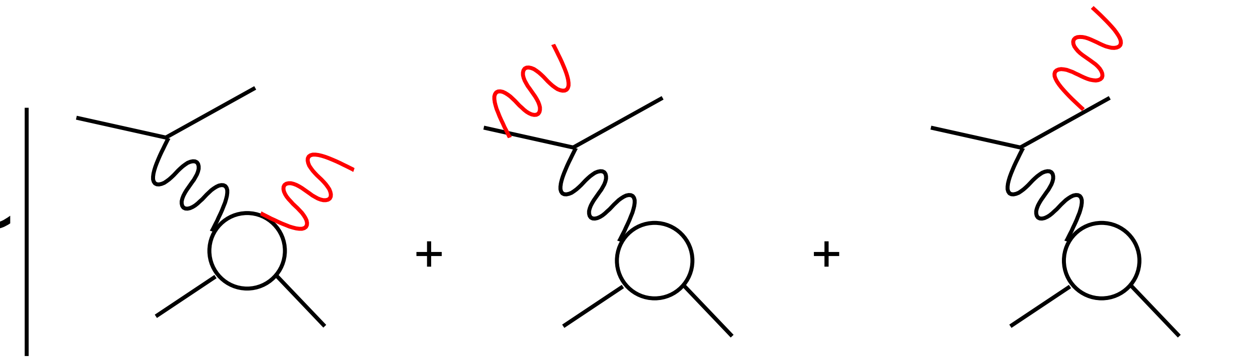
**Deeply Virtual Compton Scattering (DVCS)**

Hard exclusive reaction




**Cross section of ep→epγ :**

$$\sigma_{\gamma^* \gamma N} \sim \left| \quad + \quad + \quad \right|^2$$



DVCS

Bethe–Heitler (BH)

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

Small at HERMES

Exactly calculable in QED

**DVCS-BH interference term**

4 chiral-even quark GPDs at leading twist

| 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 → q(x)

forward limit ξ→0, t→0

$\tilde{H}$ → Δq(x)

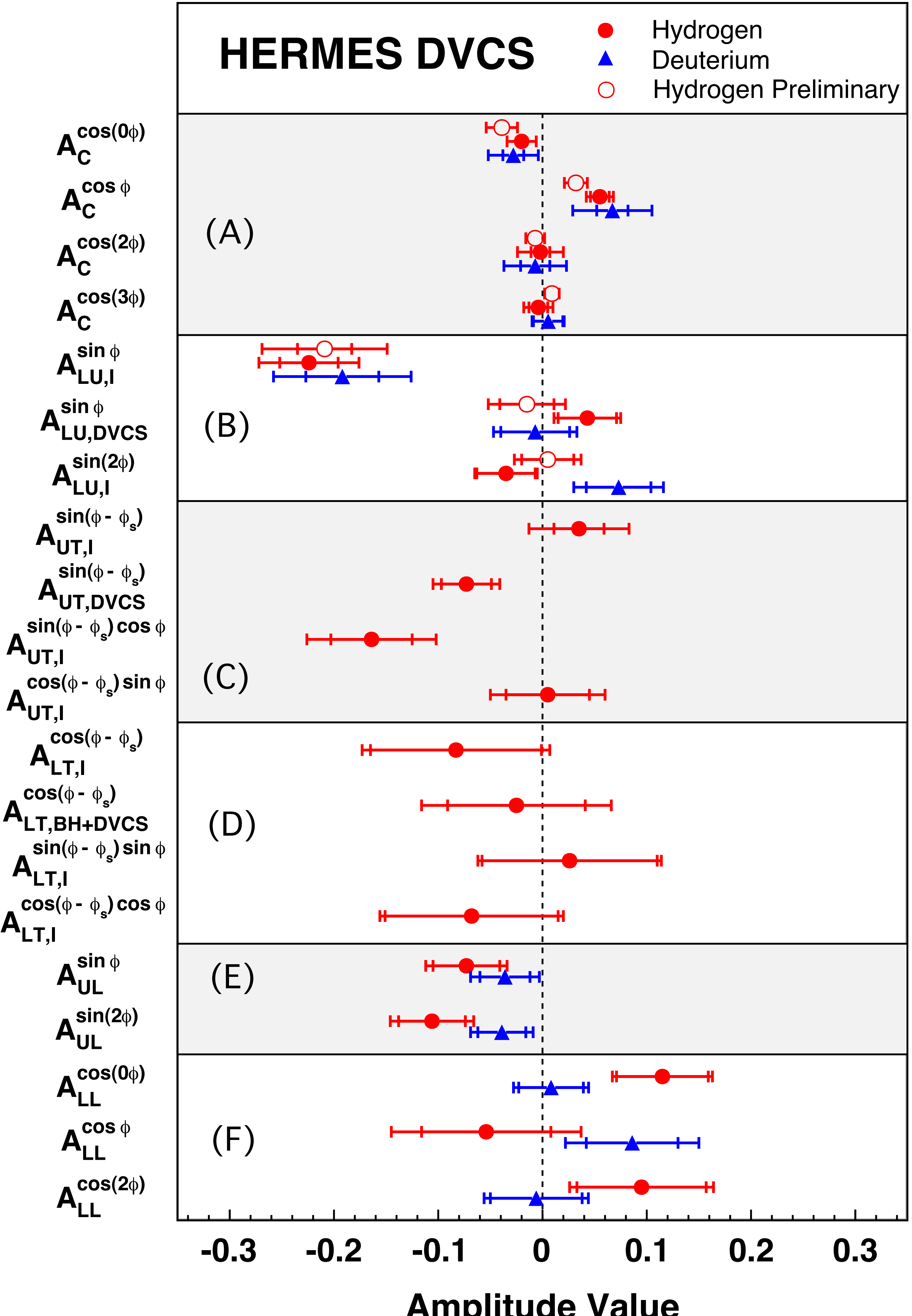
Ji sum rule for the nucleon

-Ji, PRL 78 (1997) 610-

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

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

**Orbital angular momentum**




# DVCS Amplitudes

(A) Beam-charge asymmetry: GPD H

[JHEP 11 (2009) 083 – Nucl. Phys. B 829 (2010) 1–27]

**Unique & complete set**

(B) Beam-helicity asymmetry: GPD H

[JHEP 11 (2009) 083 – Nucl. Phys. B 829 (2010) 1–27]

(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~

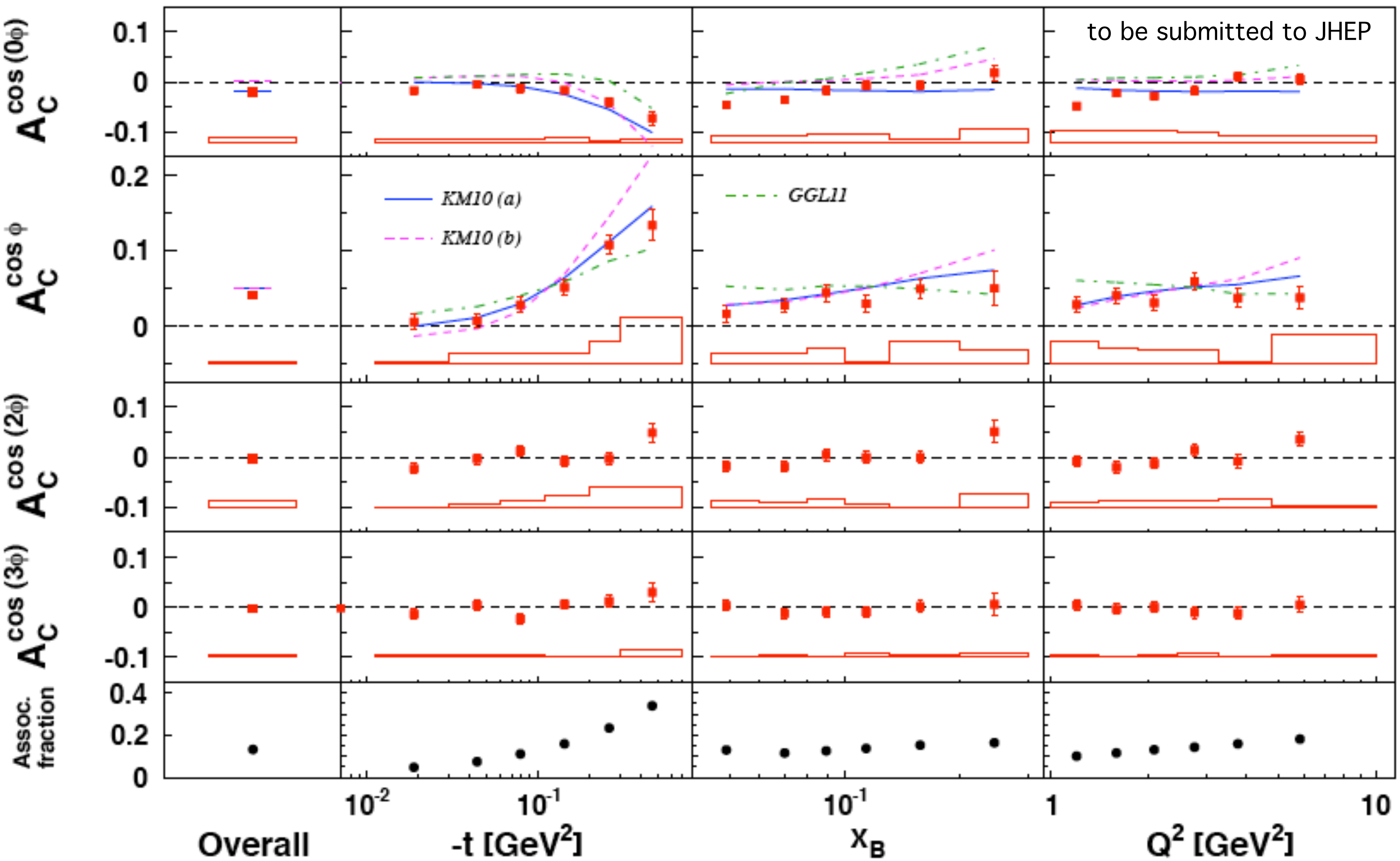
[JHEP 06 (2010) 019 - Nucl. Phys. B 842 (2011) 265–298]

# Beam-charge asymmetry amplitudes in DVCS

☆ All 1996–2007 HERMES proton data

☆ Detection of e and γ

arXiv:1103.xxxx




☆ 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 [arXiv:0904.0458]

☆ GGL11

Model calculation

G. Goldstein, J. Hernandez and S. Liuti, Phys. Rev. D 84 034007 (2011) [arxiv:1012.3776]

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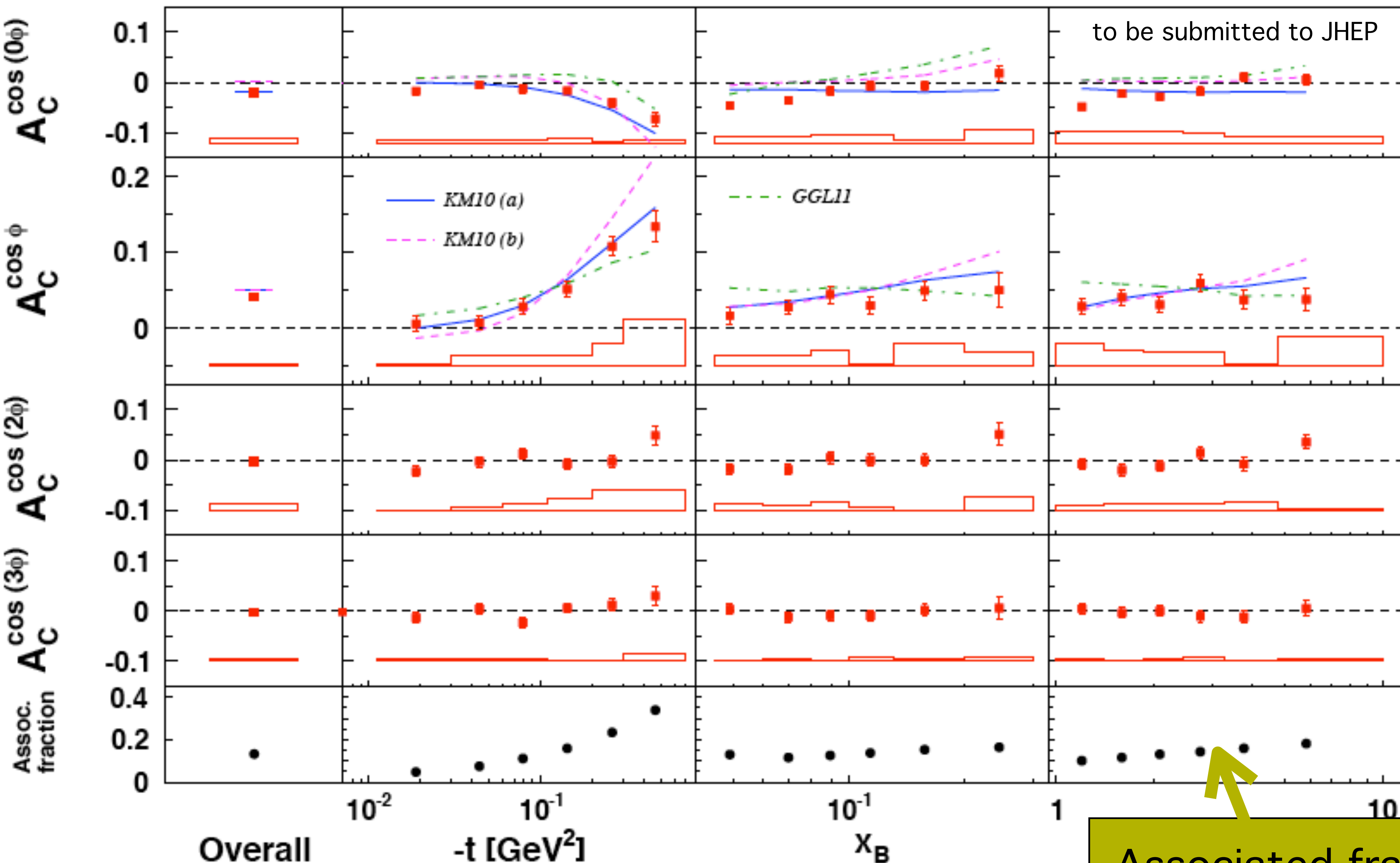


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Associated fraction $ep \to e\Delta^+\gamma$

(from MC simulation)

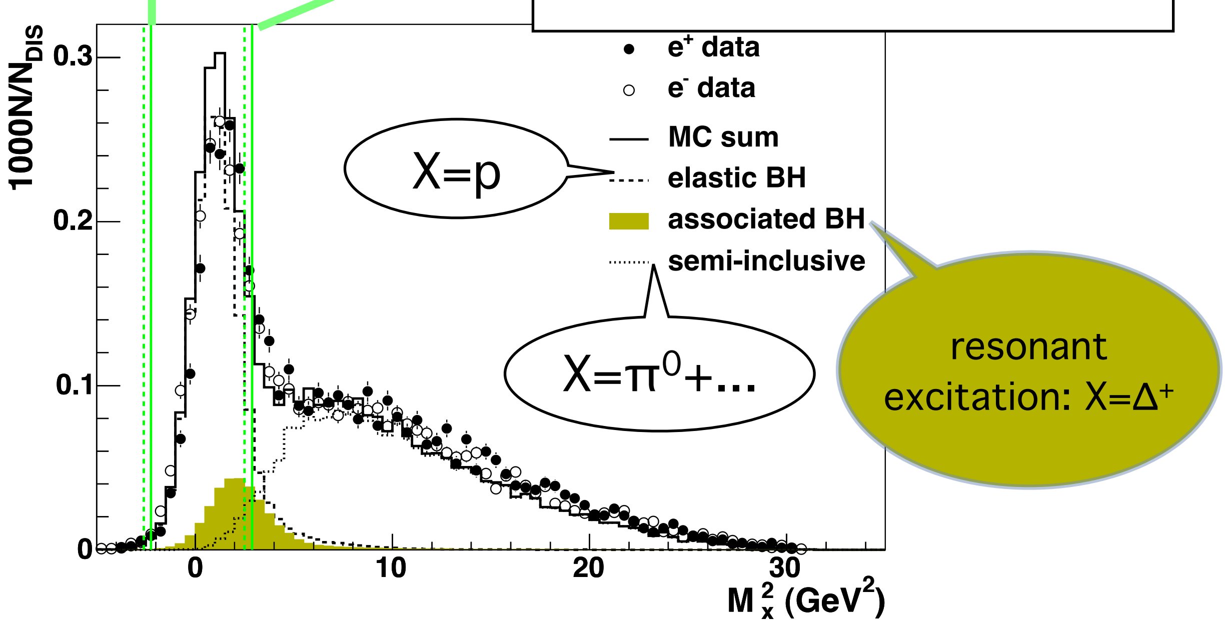
# DVCS event samples

## Only eγ detection

**“Unresolved”** for associated production.

Exclusive sample selected by **missing-mass** technique

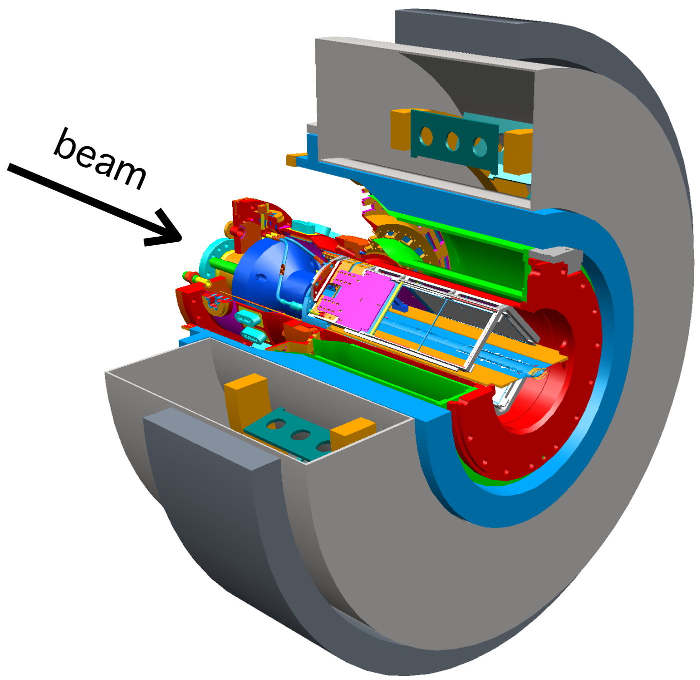
$$M_X^2 = (p_e + p_{p_0} - p_{e'} - p_\gamma)^2$$




~87% ep→epγ purity

Improvement by Recoil detector

# DVCS event samples




Recoil detector

p

e

Forward tracking

γ

ECal

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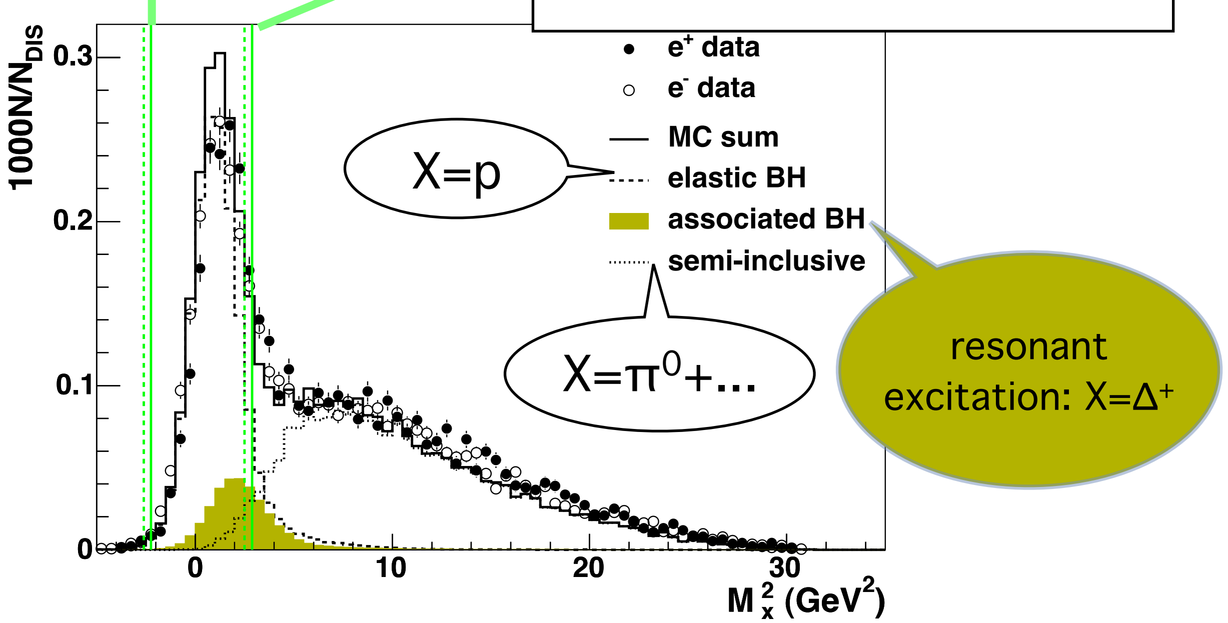


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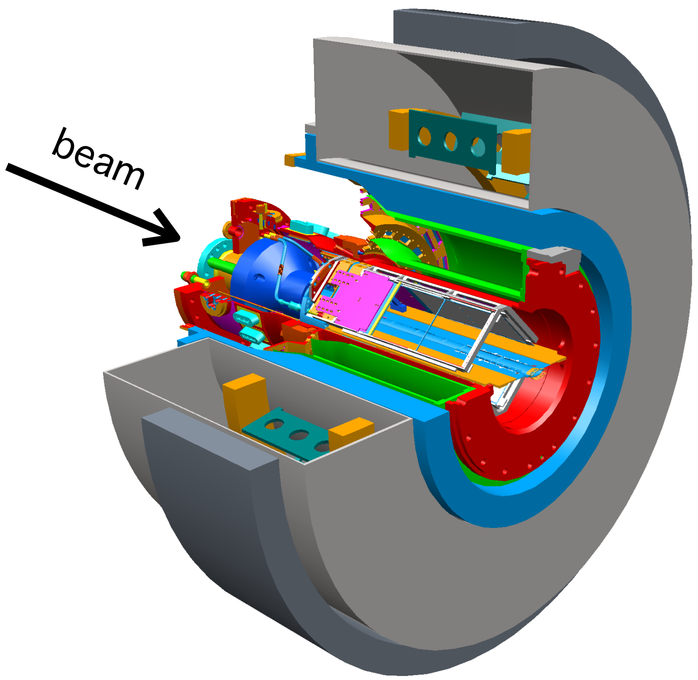



Recoil detector

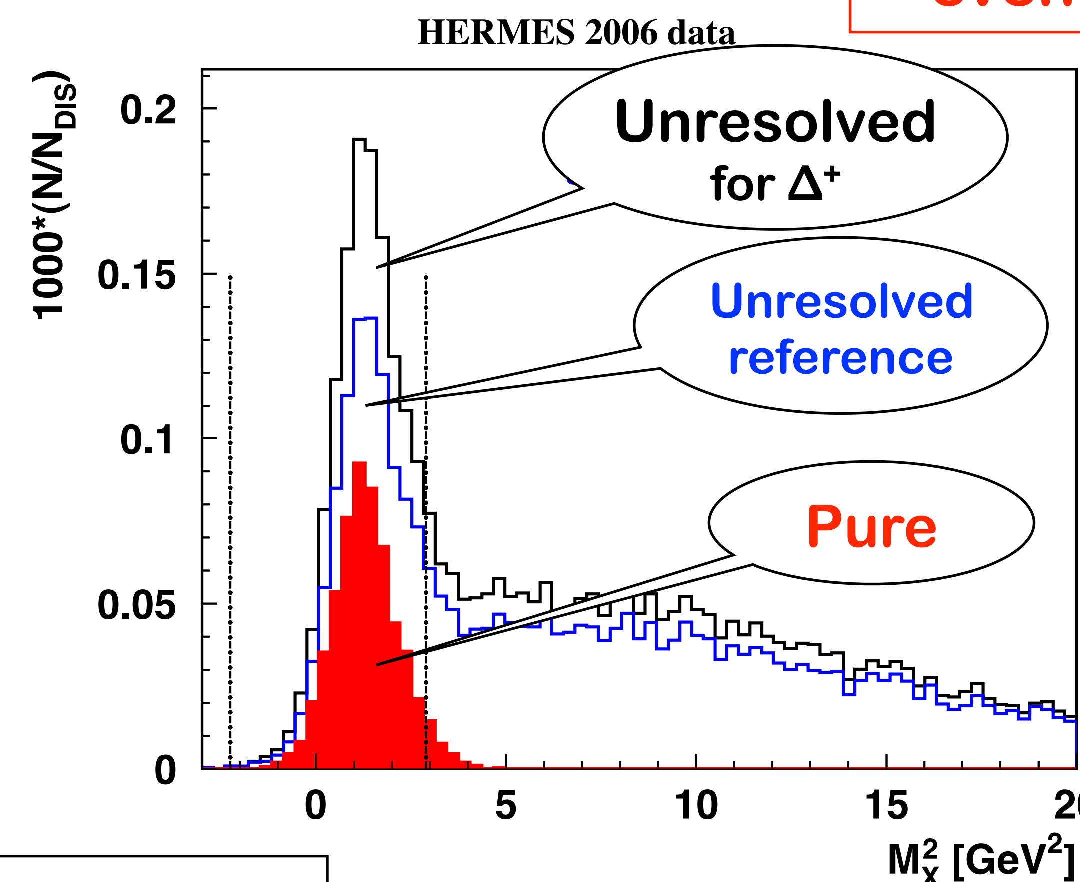
p

e — Forward tracking

γ — ECal

## epγ detection

Kinematic event fit

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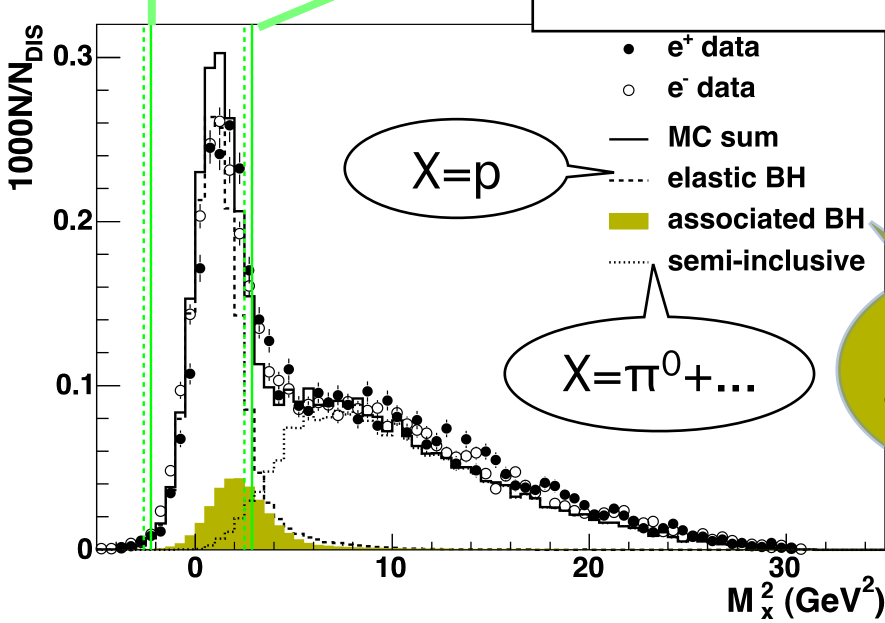



resonant excitation: X=Δ⁺

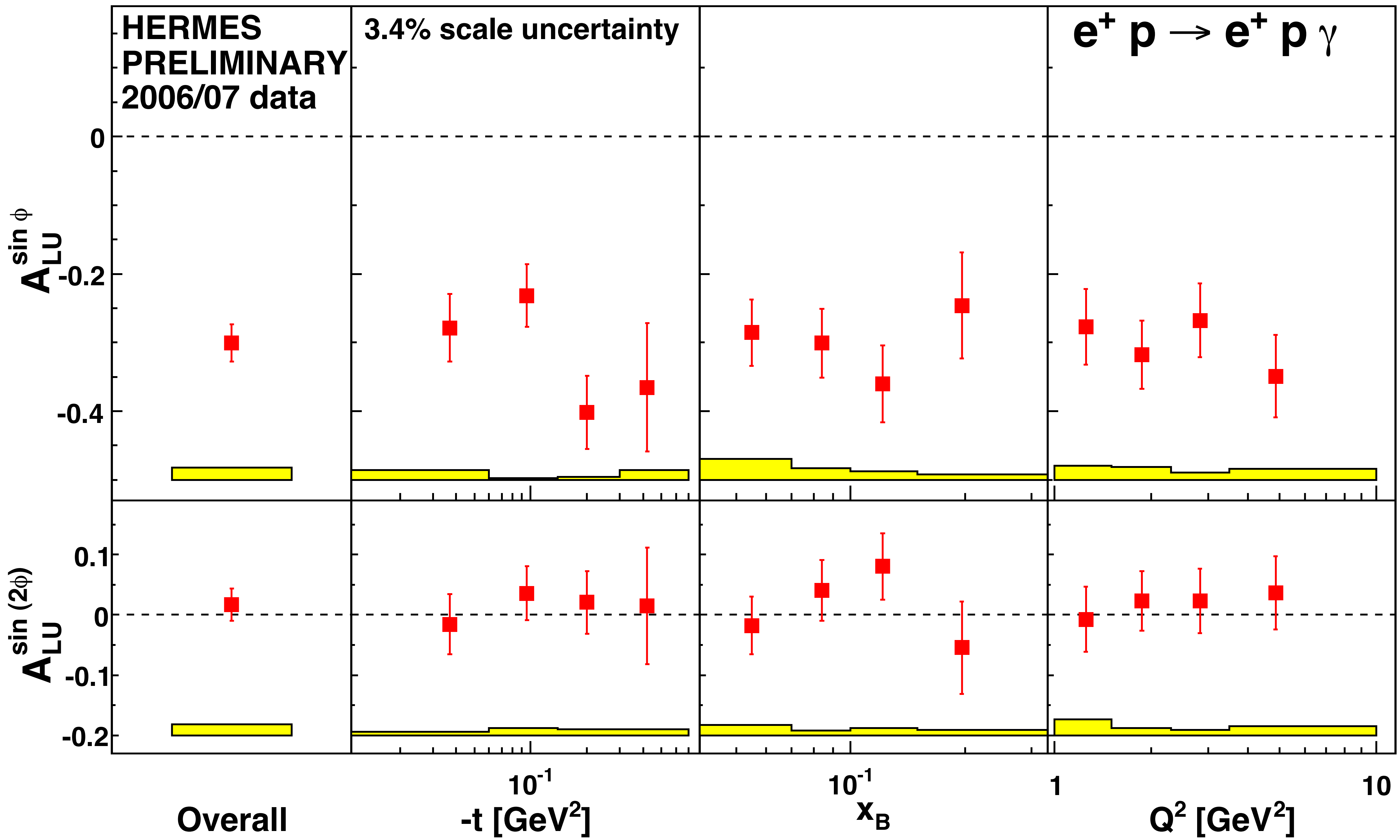
~87% ep→epγ purity

>99.9% ep→epγ purity

"Hypothetical" proton required in recoil-detector acceptance

# Beam-helicity asymmetry amplitudes in DVCS

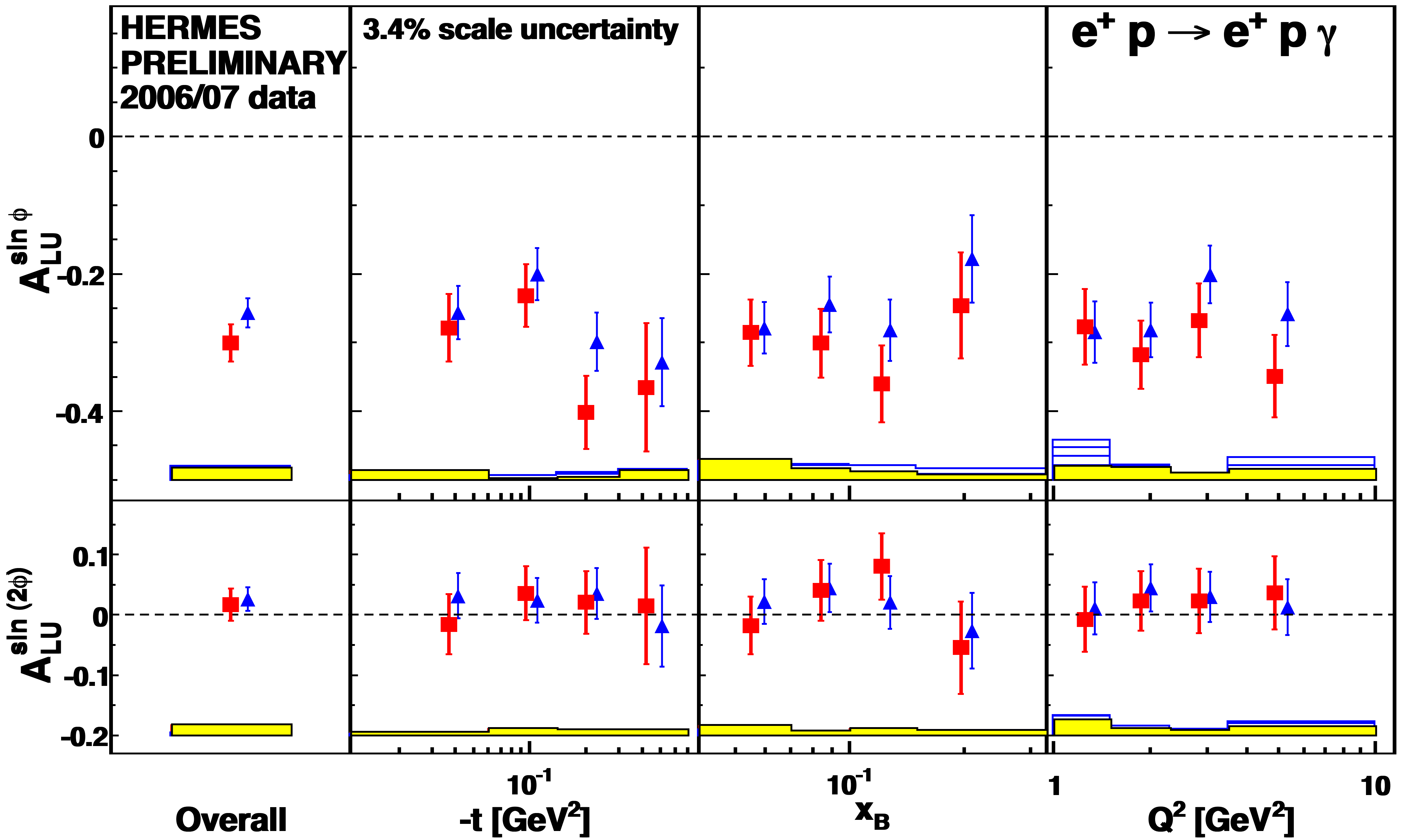
- **Pure** (with recoil proton detection)



# Beam-helicity asymmetry amplitudes in DVCS

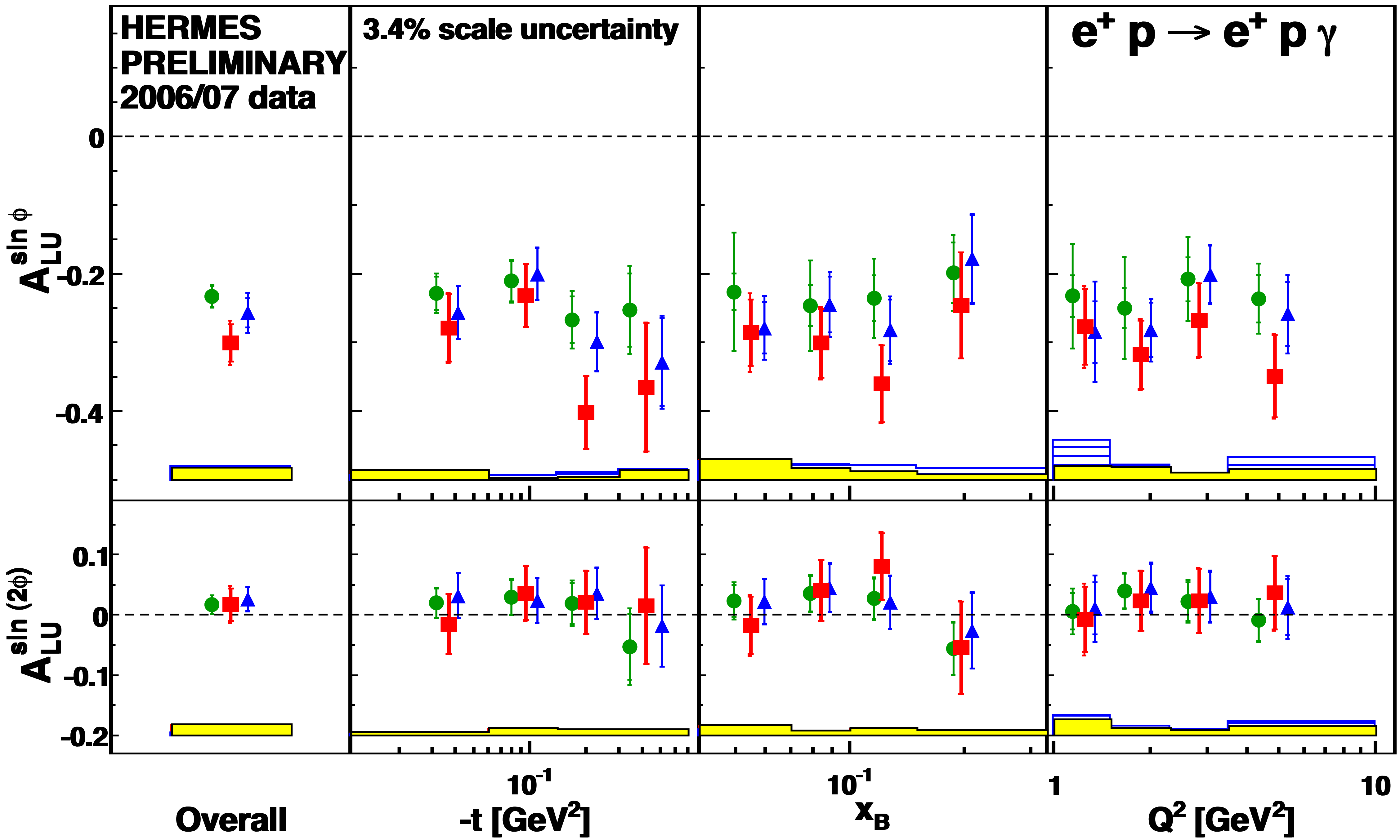
■ Pure (with recoil proton detection)

▲ Unresolved reference (in recoil acceptance)



# Beam-helicity asymmetry amplitudes in DVCS

■ Pure (with recoil proton detection)
▲ Unresolved reference (in recoil acceptance)
● Unresolved



# Summary

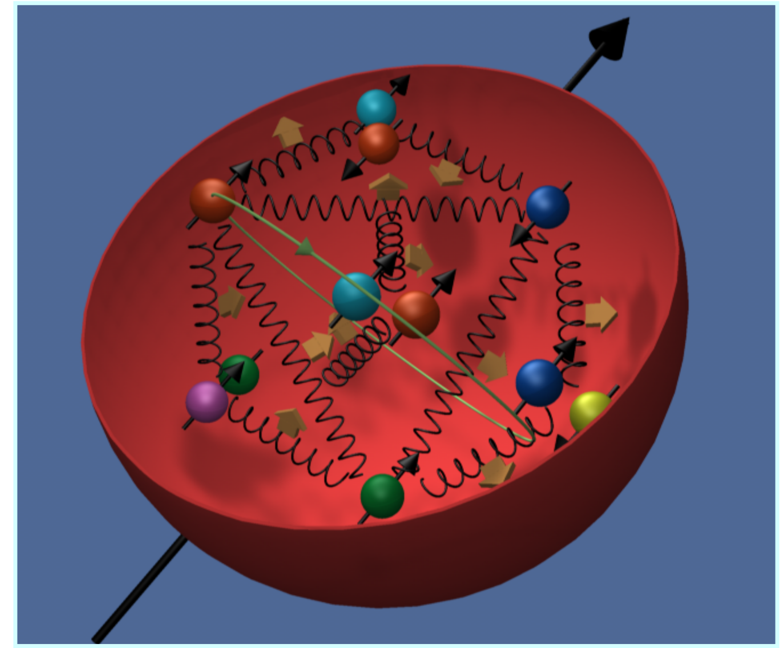
hermes

"Spin puzzle"

Orbital angular momentum

Quark Spin

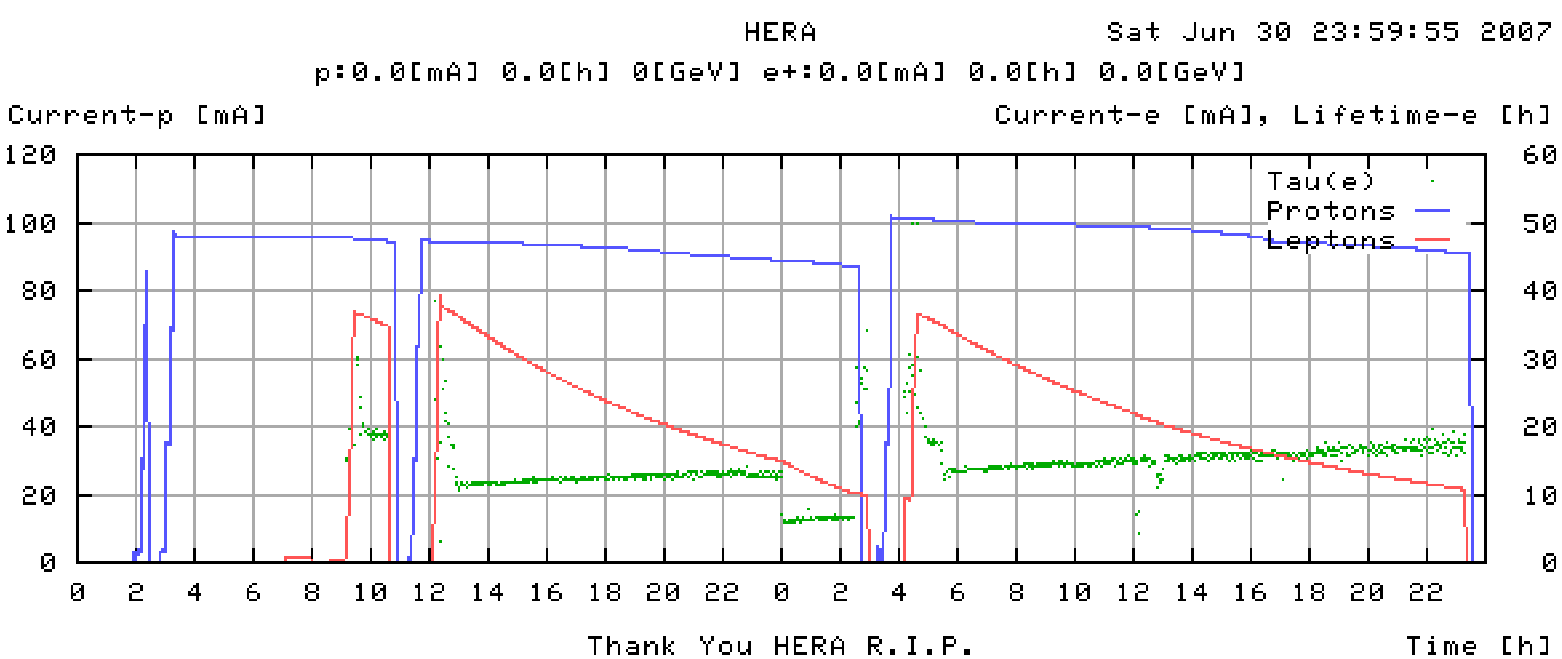
Generalized Parton Distributions



Transverse-momentum dependent PDFs

"Dynamic nucleon hologram"

Almost 5 years after the dump of the last HERA beams... (June 30, 2007)




**Many pioneering measurements**

A lot of exciting topics could not be addressed in this talk!

Click here for more:

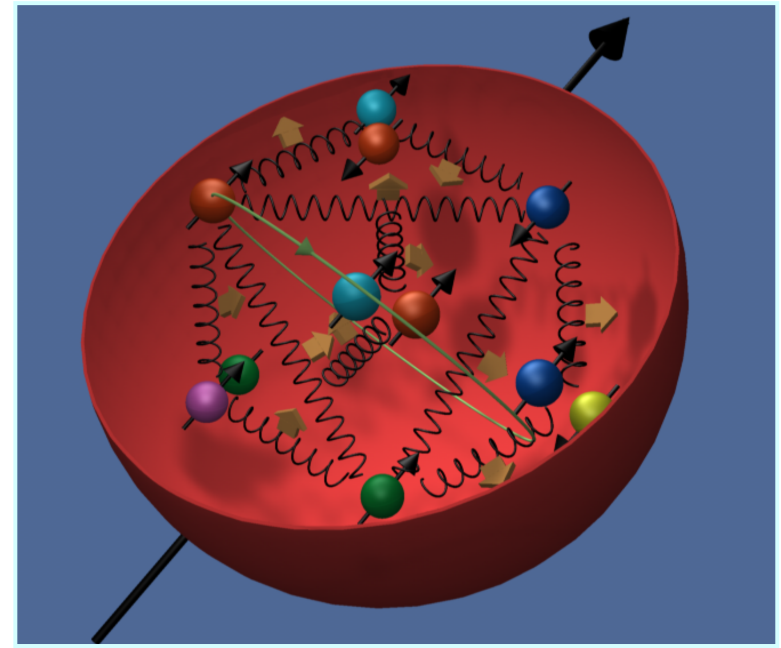
http://www-hermes.desy.de/notes/pub/publications.html

# Summary

“Spin puzzle”

Orbital angular momentum

Quark Spin



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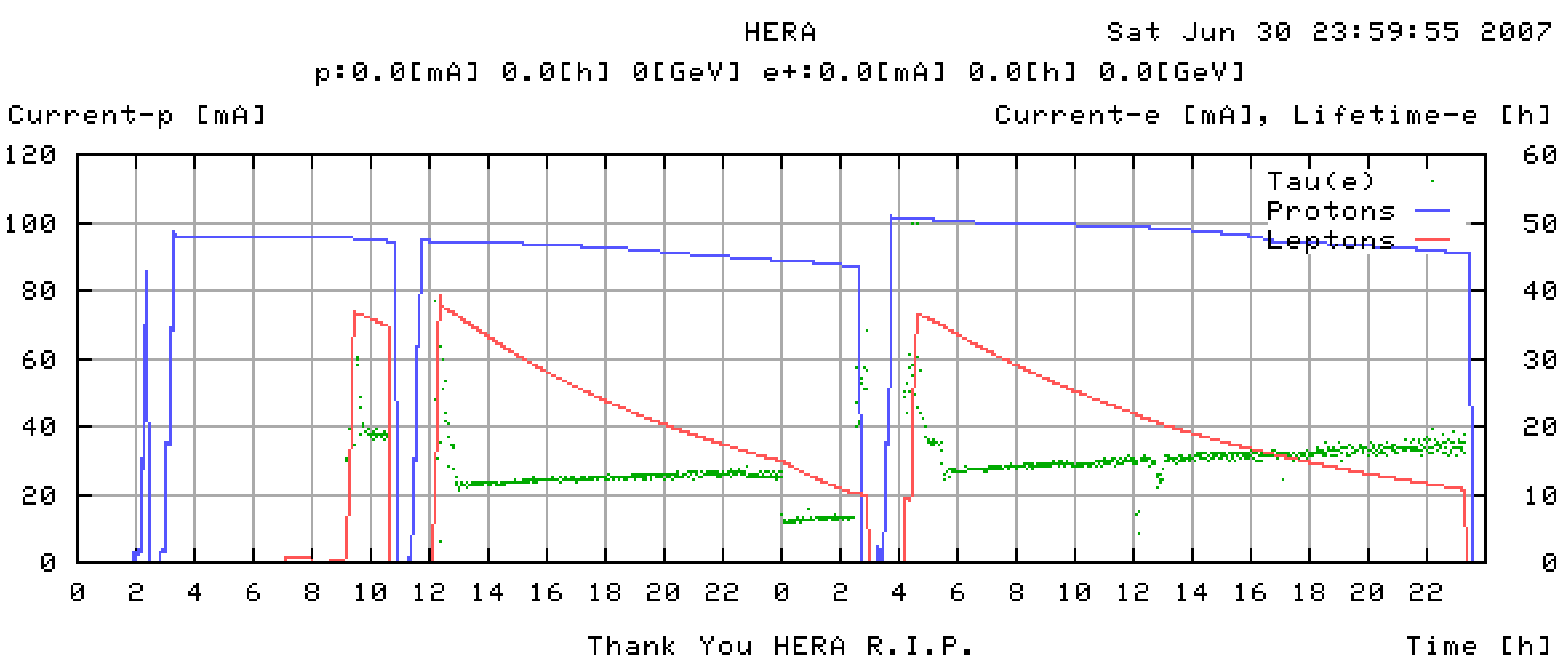


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