Spin Structure Results from HERMES

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on behalf of the hermes collaboration

HELMHOLTZ ASSOCIATION

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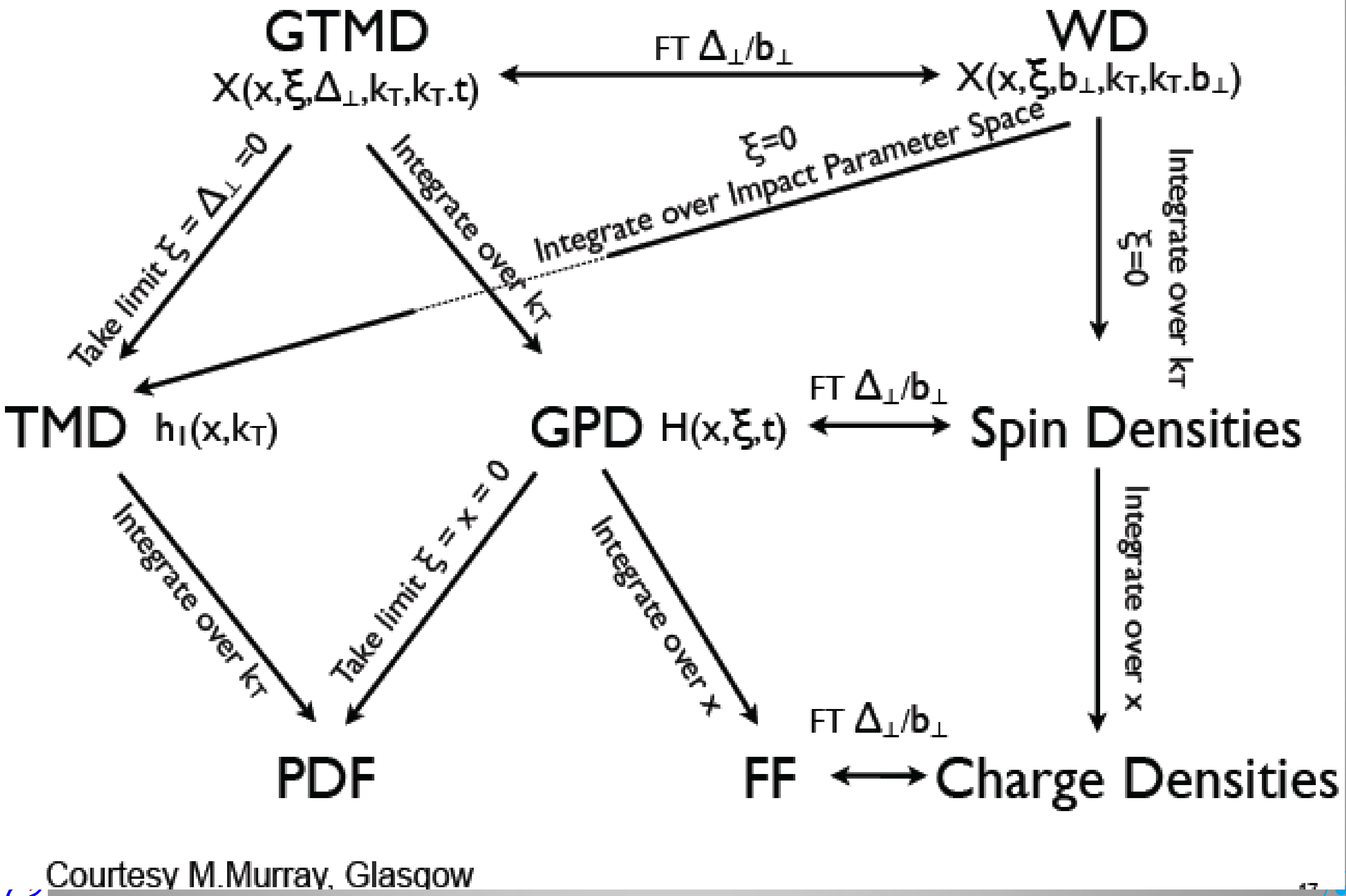
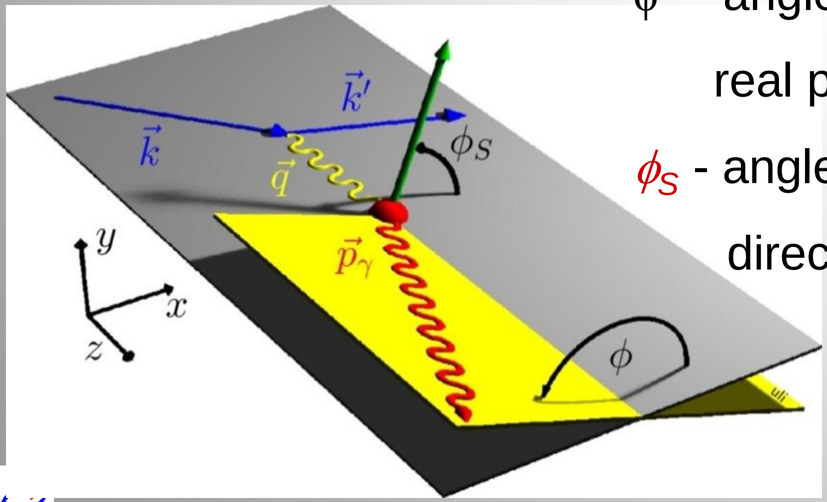
DESY

Contemporary Hierarchy of Partonic Distributions



Unique Experimental Conditions at HERMES

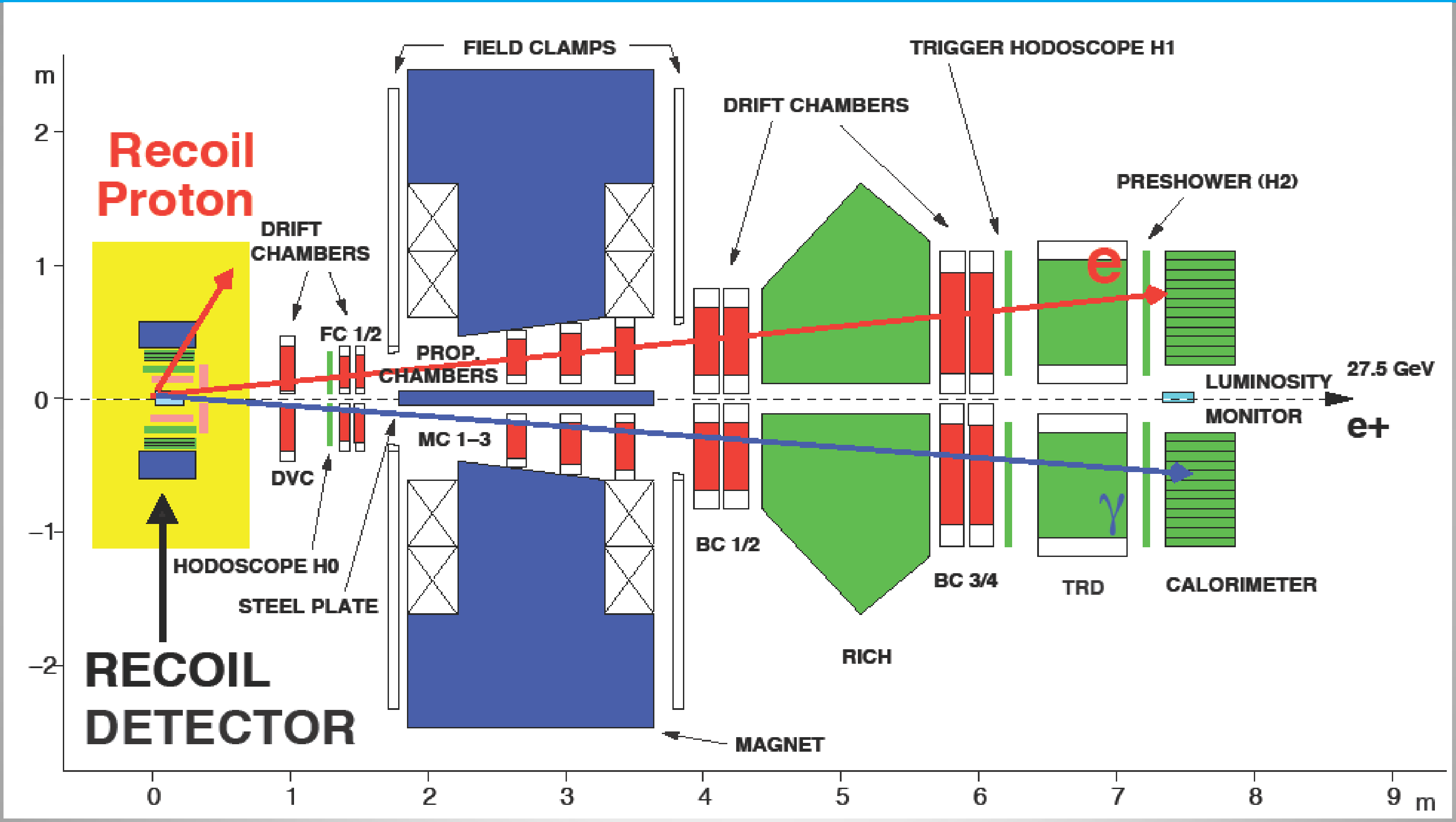
- Running 1996-2007 in 27.5 GeV HERA lepton beam line
- Both beam charges available (positrons, electrons)
- Longitudinal beam polarization (both helicities)
- Various internal gas targets were installed (no dilution)
- Forward spectrometer: tracking and PID (RICH since 1998)
- Recoil detector around target region: 2006-07



ϕ - angle between lepton scattering and real photon (hadron) production planes

ϕ_S - angle between (transverse) target spin direction and lepton scattering plane

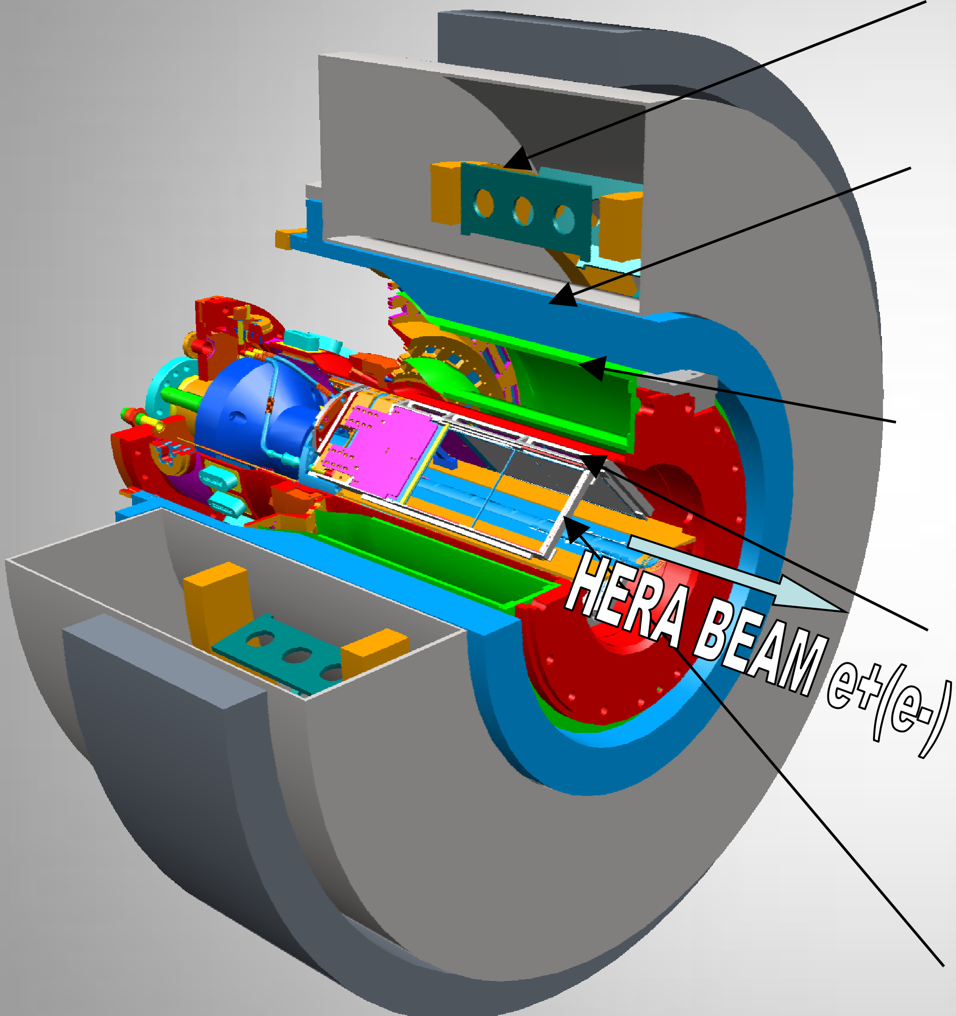
HERMES Spectrometer & Recoil Detector



Internal gas targets:
- Longitudinally polarized *H, D*
- Transversely polarized *H*
- Unpolarized *H, D, ^{4}He, N, Ne, Kr, Xe*

Forward magnetic spectrometer
- Momentum resolution *1-2%*
- Particle identification:
  RICH, TRD, H(odo)2, calorimeter

HERMES Recoil Detector



1 Tesla superconducting solenoid

Photon Detector (PD)

- detect gammas
- p/π PID for momentum > 600 MeV/c

Scintillating Fiber Tracker (SFT)

Momentum reconstruction by bending in magnetic field

Silicon Strip Detector (SSD)

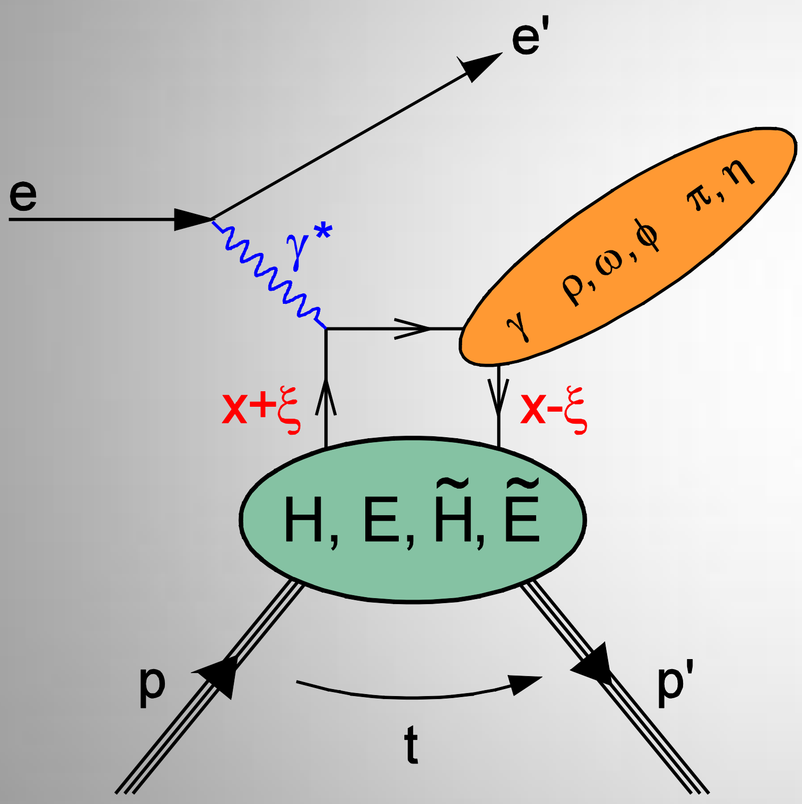
- Inside the HERA vacuum
- 5 cm close to the beam
- Momentum reconstruction by energy deposit for protons and deuterons

Target cell

- Unpolarized hydrogen and deuterium targets

Exclusive Processes: Access to GPDs

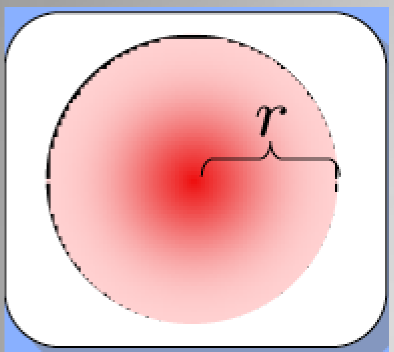
Generalized Parton Distributions (GPDs):



- For spin-1/2 target 4 chiral-even leading-twist quark GPDs: $H, E, \tilde{H}, \tilde{E}$
- $H, \tilde{H}$ conserve nucleon helicity, $E, \tilde{E}$ involve nucleon helicity flip
- Different final states are sensitive to different (combinations of) GPDs:
- DVCS (γ) → $H, E, \tilde{H}, \tilde{E}$
- Vector mesons (ρ, ω, ϕ) → H, E
- Pseudoscalar mesons (π, η) → $\tilde{H}, \tilde{E}$

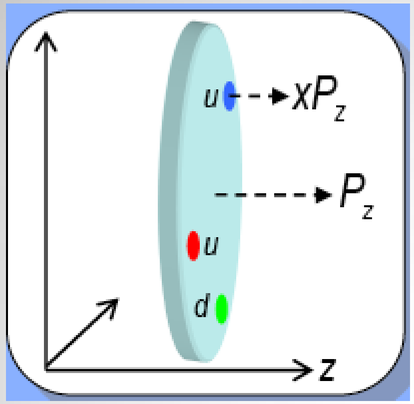
Interpretation of GPDs

Elastic Form Factors

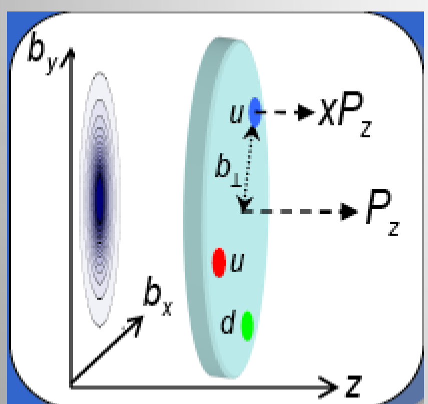


transverse position
of partons

Parton Distribution
Functions (PDFs)



longitudinal momentum
of partons



Correlation between longitudinal
momentum and transverse position

- GPDs include Form Factors and Parton Distribution Functions as moments and forward limits, resp.
- GPDs yield a multidimensional description of nucleon structure (longitudinal momentum vs. transverse position)
  → NUCLEON TOMOGRAPHY
- GPDs offer access to quark total angular momentum through the Ji relation (in principle also for gluons):

$$J_q = \lim_{t \to 0} \int_{-1}^{1} dx\, x \left[H_q(x,\xi,\xi) + E_q(x,\xi,\xi) \right]$$

[X. Ji, Phys. Rev. Lett. 78 (1997) 610]

Principle of Extraction of Asymmetry Amplitudes

- Distribution in expectation value of measured yield (A_{UL} , A_{LL} missing):

$$\langle N(e_l,P_l,S_t,\phi,\phi_S)\rangle \propto$$

$$\sigma_{UU}(\phi)\left[1+e_l A_C + P_l A_{LU}^{DVCS} + e_l P_l A_{LU}^{I} + S_t A_{UT}^{DVCS} + e_l S_t A_{UT}^{I} + P_l S_t A_{LT}^{BH+DVCS} + e_l P_l S_t A_{LT}^{I}\right]$$

- Examples of Fourier expansion of measured (X-section) asymmetries:

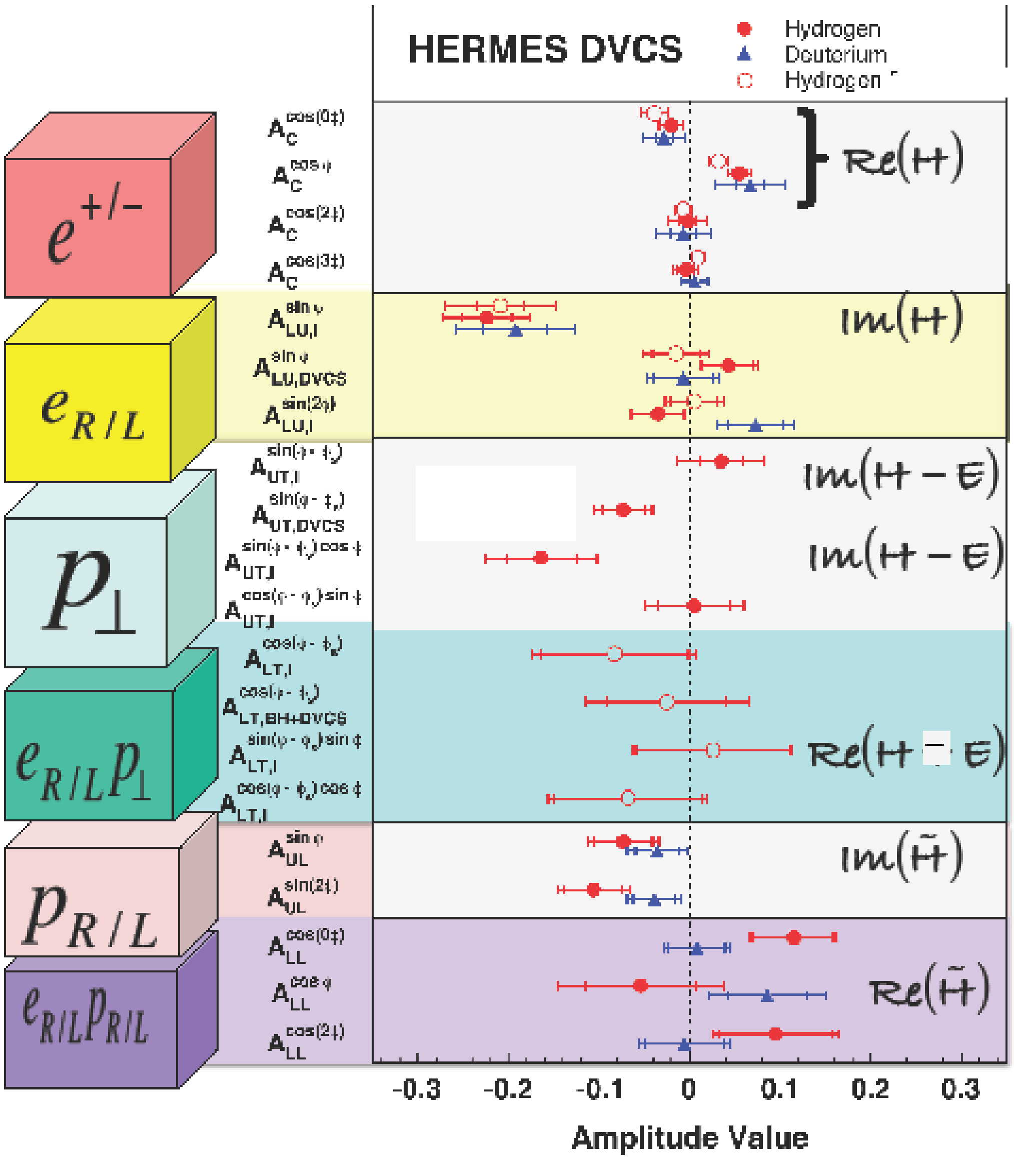
$$A_C \approx \sum_{n=0}^{3} A_C^{\cos(n\phi)} \cos(n\phi) \qquad \left[A_{LU} \approx \sum_{n=1}^{2} A_{LU}^{\sin(n\phi)} \sin(n\phi)\right]$$

- Simultaneous extraction of asymmetry amplitudes with Maximum Likelihood Method

- Asymmetry amplitudes provide information about Compton Form Factors (CFFs): convolution of GPDs with hard scattering amplitudes

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

HERMES DVCS results on proton & deuteron targets



Access to GPD H, $\tilde{H}$, E

- JHEP 11 (2009) 083
- Nucl. Phys. B829

sensitive to J_u

- JHEP 06 (2008) 066

- Phys. Lett. B 704 Oct. 5, 2011

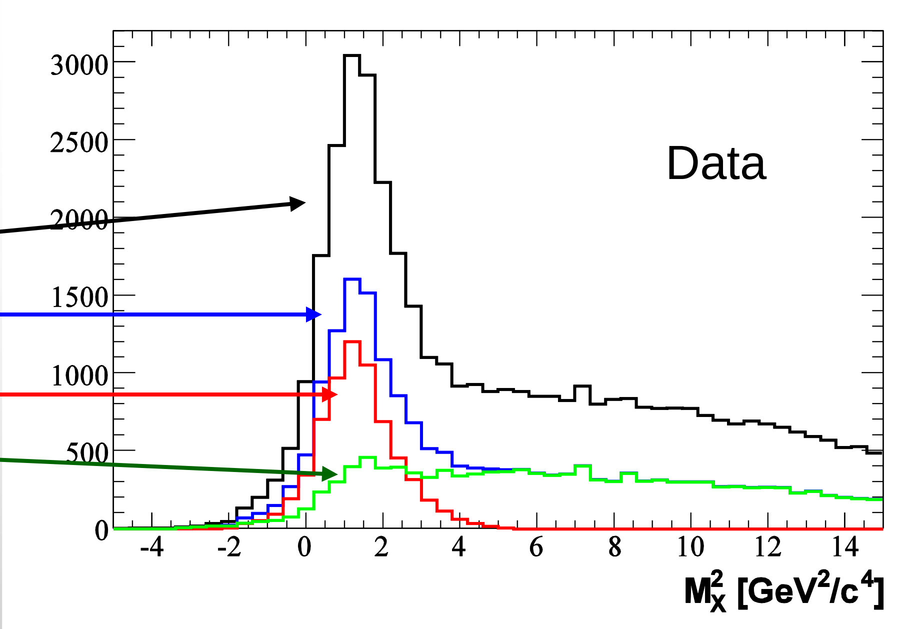
- JHEP 06 (2010) 019
- Nucl. Phys. B 842

15

NEW !! : Exclusivity by Recoil Detector & kinematic event fitting

see poster I. Brodsky

- Kinematic event fitting technique used for DVCS events:
  - All 3 particles in final state detected → 4 constraints from energy-momentum conservation
  - Selection of `pure' BH/DVCS ($ep \rightarrow ep\gamma$) with high efficiency (~84%)
  - Allows to suppress background from associated and semi-inclusive processes to a negligible level (~0.1%)
  - Makes even PID (Particle Identification) unnecessary
- DVCS missing-mass distribution:
  - No requirement for Recoil
  - Positively charged Recoil track
  - Kinematic fit probability > 1%
  - Kinematic fit probability < 1%

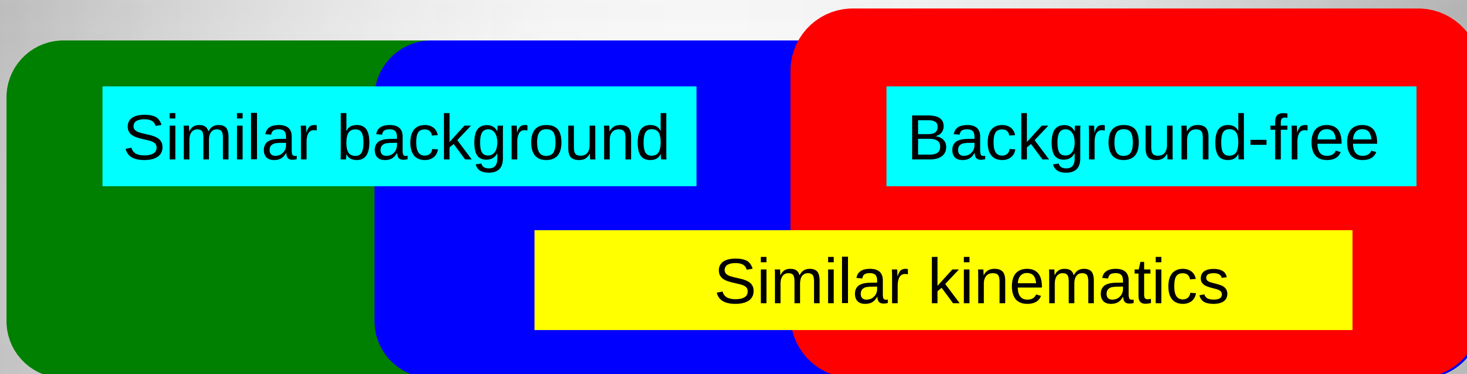


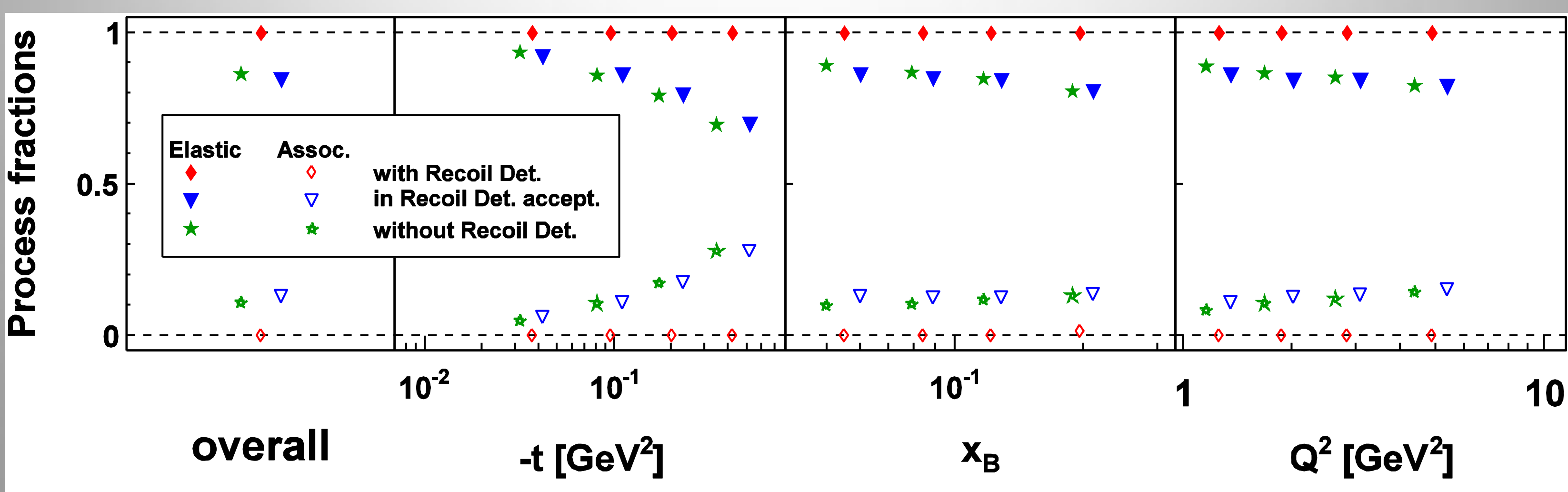
`Traditional' and `Recoil-detector' DVCS samples ($\mathcal{A}_{\mathrm{LU}}$)

Without Recoil Detector (`traditional' or `unresolved')

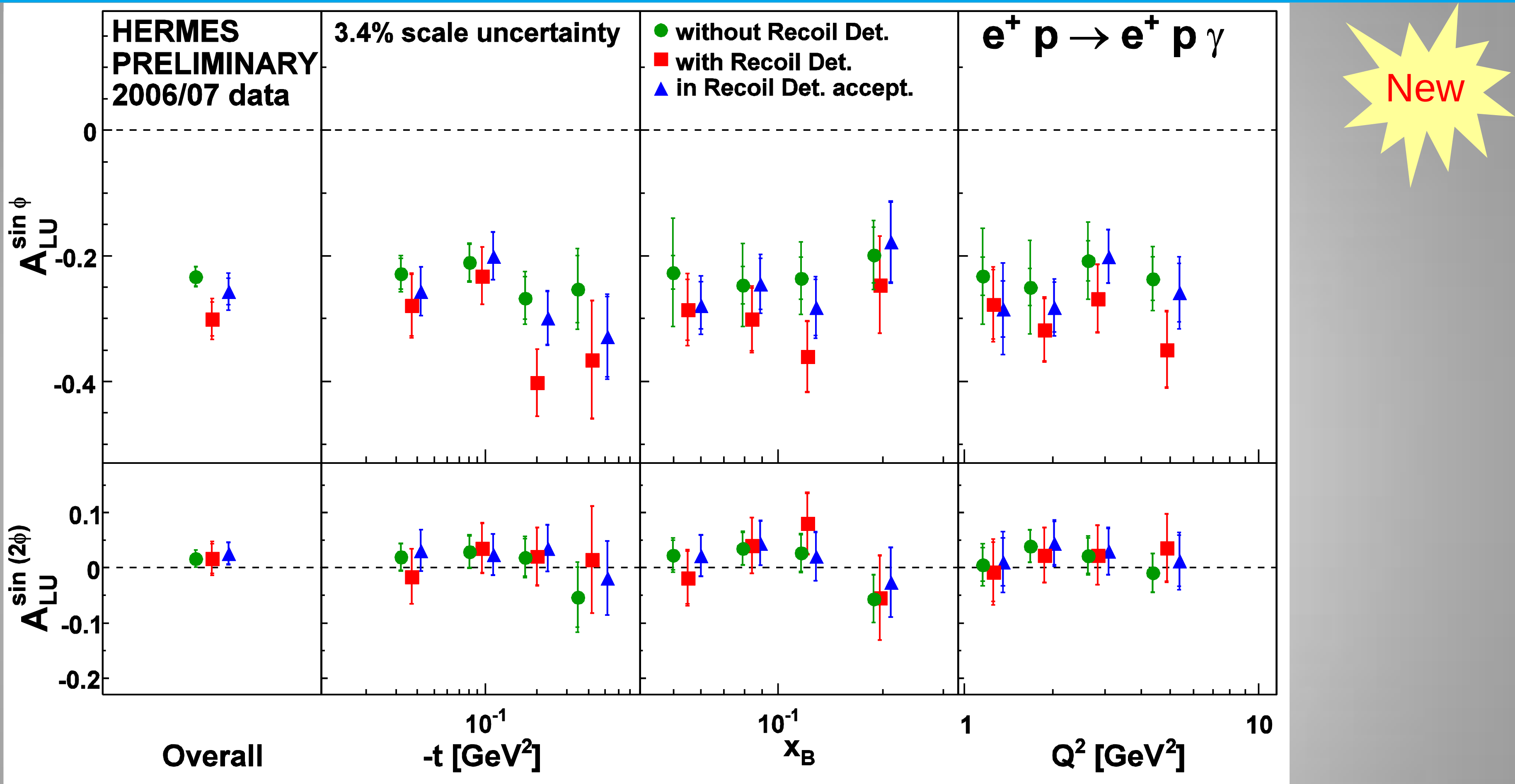
In Recoil Detector acceptance (`unresolved reference')

With Recoil Detector (`pure' sample)





Comparison of traditional & recoil-detector ($\mathcal{A}_{\mathrm{LU}}$) samples



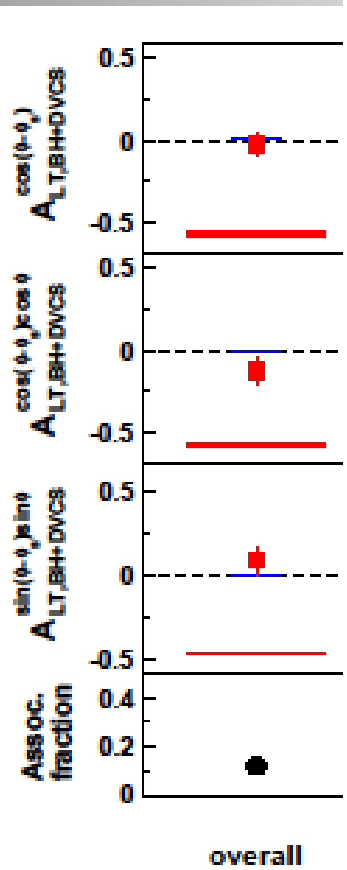
- Indication that the leading amplitude for pure BH/DVCS (background < 0.1%) is slightly larger in magnitude than the one in Recoil Detector acceptance
- Extraction of asymmetry amplitudes for associated processes is a subject of ongoing dedicated analysis

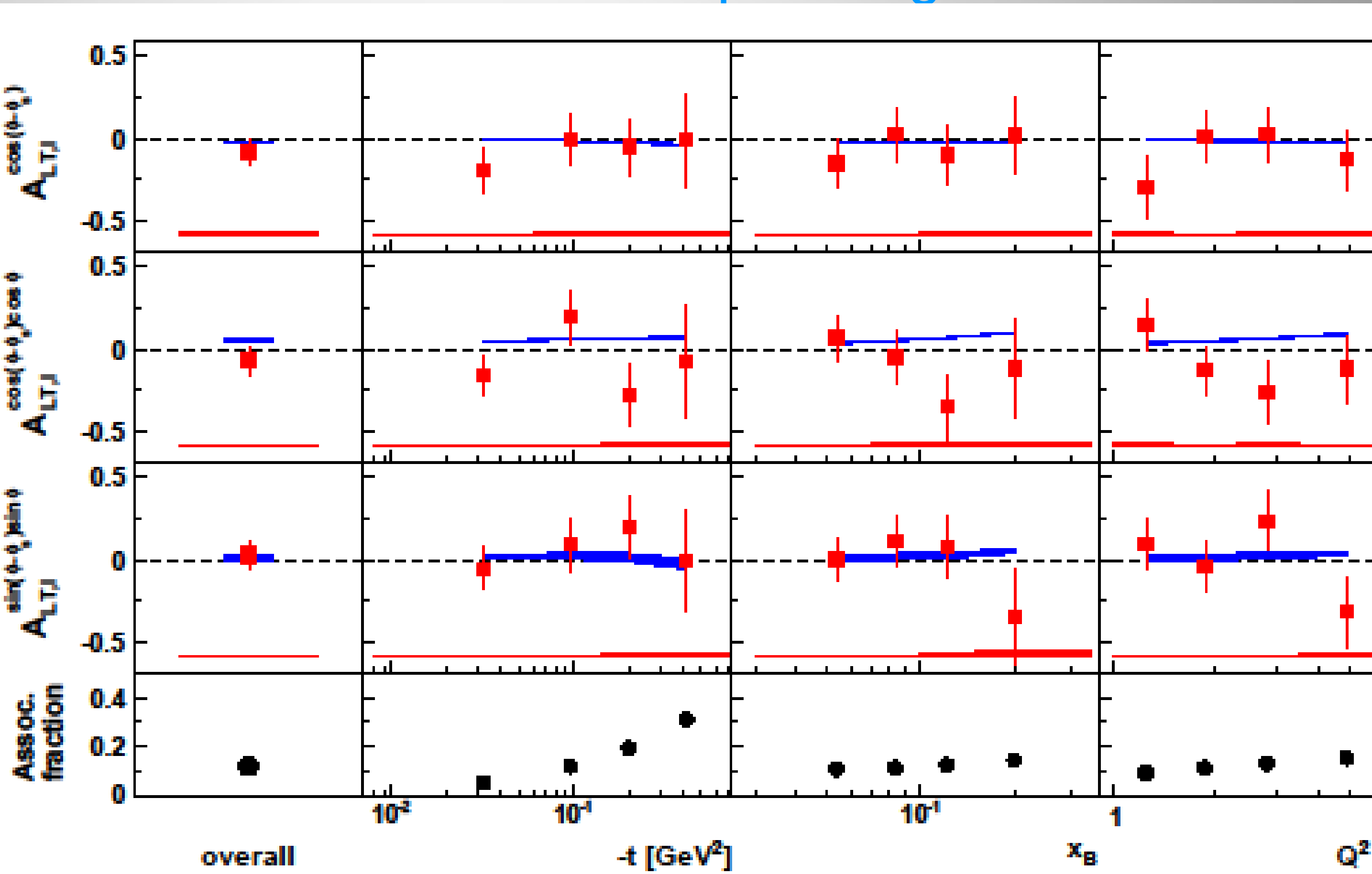
Charge-difference double Spin LT Asymmetry

NEW !!

see poster A. Movsisyan

- Sensitive to Re (H+E)
- All consistent with zero. Still: useful input for global GPD fits!

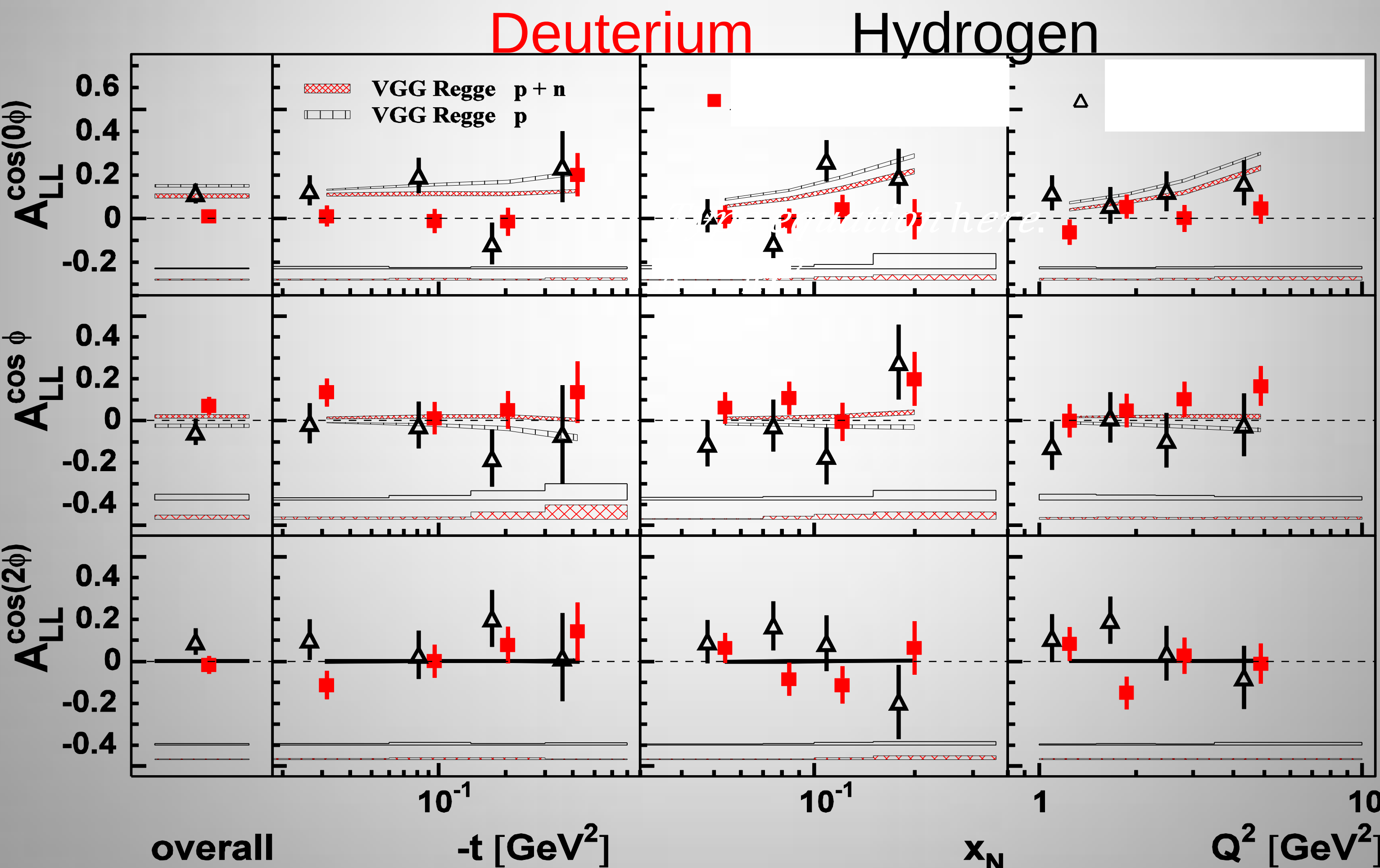




Single-charge double Spin LL Asymmetry

NEW !!

- Sensitive to ($\tilde{H}$), non-zero Hydrogen asymmetry amplitudes
- Useful input for global fits. (Deuterium data are rare!)

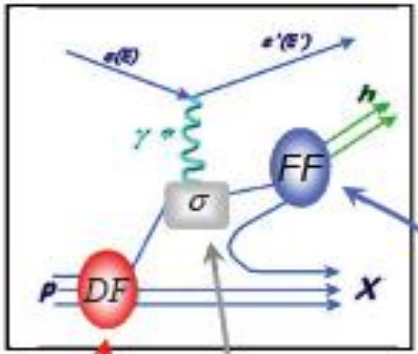


Semi-inclusive deep inelastic scattering

quark polarisation

nucleon polarisation N/q	U	L	T
U	f_1 number density		
L		g_1 helicity	
T			h_1 transversity

Leading Twist PDFs



$$\sigma^{ep\rightarrow ehX} = \sum DF \otimes \sigma^{eq\rightarrow eq} \otimes FF$$

see poster
E. Avetisyan

Leading Twist TMDs

Intrinsic k_T quark distribution

Distribution Functions (DF)

quark polarisation

nucleon polarisation N/q	U	L	T
U	f_1 number density		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$
T	$f_{1T}^\perp$ Sivers	g_{1T}	h_1 transversity $h_{1T}^\perp$

Fragmentation Functions (FF)

N/q	U	L	T
U	D_1 unpolarized		$H_1^\perp$ Collins

Off-diagonal elements are important objects:

Interference between wave functions with different angular momenta: contains infos about parton orbital angular momenta

Testing QCD at the amplitude level

1-hadron production cross section

σ_{XY} → beam: P_l; target: $S_L S_T$

$$
\begin{aligned}
d\sigma \;=\;& d\sigma^0_{UU} + \cos(2\phi)d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi)d\sigma^2_{UU} \;+\; P_l\frac{1}{Q}\sin(\phi)d\sigma^3_{LU} \\
+\;& S_L\left[\sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi)d\sigma^5_{UL} \;+\; P_l\left(d\sigma^6_{LL} + \frac{1}{Q}\cos(\phi)d\sigma^7_{LL}\right)\right] \\
+\;& S_T\left[\sin(\phi-\phi_s)d\sigma^8_{UT} + \sin(\phi+\phi_s)d\sigma^9_{UT} + \sin(3\phi-\phi_s)d\sigma^{10}_{UT} + \frac{1}{Q}\sin(2\phi-\phi_s)d\sigma^{11}_{UT} + \frac{1}{Q}\sin(\phi_s)d\sigma^{12}_{UT}\right. \\
& \left. P_l\left(\cos(\phi-\phi_s)d\sigma^{13}_{LT} + \frac{1}{Q}\cos(\phi_s)d\sigma^{14}_{LT} + \frac{1}{Q}\cos(2\phi-\phi_s)d\sigma^{15}_{LT}\right)\right]
\end{aligned}
$$

- disentangling the contributions:
  - experiments with beam and target polarization states (U, L, T)
  - extract the relevant Fourier amplitudes based on their azimuthal dependences
- if no perfect detection efficieny:

$$
\begin{aligned}
N(\phi,\phi_s) \;=\;& \epsilon(\phi,\phi_s)\;\sigma^0_{UU}\Big\{1 + 2\langle\cos\phi\rangle_{UU}\cos\phi + 2\langle\cos 2\phi\rangle_{UU}\cos 2\phi \\
&+\; S_T\Big(2\langle\sin(\phi-\phi_s)\rangle_{UT}\sin(\phi-\phi_s) + 2\langle\sin(\phi+\phi_s)\rangle_{UT}\sin(\phi+\phi_s) + \\
&\qquad 2\langle\sin(3\phi-\phi_s)\rangle_{UT}\sin(\phi+\phi_s) + \ldots\Big) \\
&+\; S_T P_l\Big(2\langle\cos(\phi-\phi_s)\rangle_{UT}\cos(\phi-\phi_s) + 2\langle\cos\phi_s\rangle_{UT}\cos\phi_s + \\
&\qquad 2\langle\cos(2\phi-\phi_s)\rangle_{UT}\cos(\phi-\phi_s)\Big)\Big\}
\end{aligned}
$$

- fit the cross section asymmetry for opposite spin states

Overview on HERMES activities in SIDIS sector

analysis with higher statistical precision

published

paper coming out soon

published

published

ongoing analysis

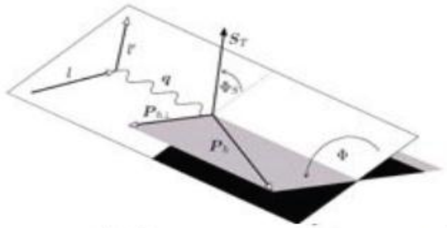
$$
\begin{aligned}
d\sigma &= d\sigma^0_{UU} + \cos(2\phi)d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi)d\sigma^2_{UU} + P_l\,\frac{1}{Q}\sin(\phi)d\sigma^3_{LU} \\
&+ S_L\left[\sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi)d\sigma^5_{UL} + P_l\left(d\sigma^6_{LL} + \frac{1}{Q}\sin(\phi)d\sigma^7_{LL}\right)\right] \\
&+ S_T\left[\sin(\phi-\phi_s)d\sigma^8_{UT} + \sin(\phi+\phi_s)d\sigma^9_{UT} + \sin(3\phi-\phi_s)d\sigma^{10}_{UT} + \frac{1}{Q}\sin(2\phi-\phi_s)d\sigma^{11}_{UT} + \frac{1}{Q}\sin(\phi_s)d\sigma^{12}_{UT}\right. \\
&\left.\quad + P_l\left(\cos(\phi-\phi_s)d\sigma^{13}_{LT} + \frac{1}{Q}\cos(\phi_s)d\sigma^{14}_{LT} + \frac{1}{Q}\cos(2\phi-\phi_s)d\sigma^{15}_{LT}\right)\right]
\end{aligned}
$$

published

published

paper coming out soon

Cahn and Boer-Mulders effect



$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}^2_{h\perp}} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{UU}^{\cos(2\phi)}\Big]$$

$+ \quad \lambda_l$

$+ S_L$

$+ S_L \lambda_l$

$+ S_T$

$+ S_T \lambda_l$

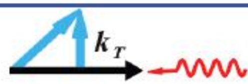
nucleon \ quark	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp + \ldots\right]/Q$$

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[f_1 \otimes D_1 + \ldots\right]/Q^2$$

- **Cahn effect:**

Cahn Effect



kinematical effect due to transv. momentum of partons in the nucleon

- **Boer-Mulders effect: Boer-Mulders TMD**

Boer-Mulders $h_1^\perp$:

correlation of parton transv. momentum and transv. polarization in an unpolarized nucleon

Phi modulations in unpolarized SIDIS pion X-section

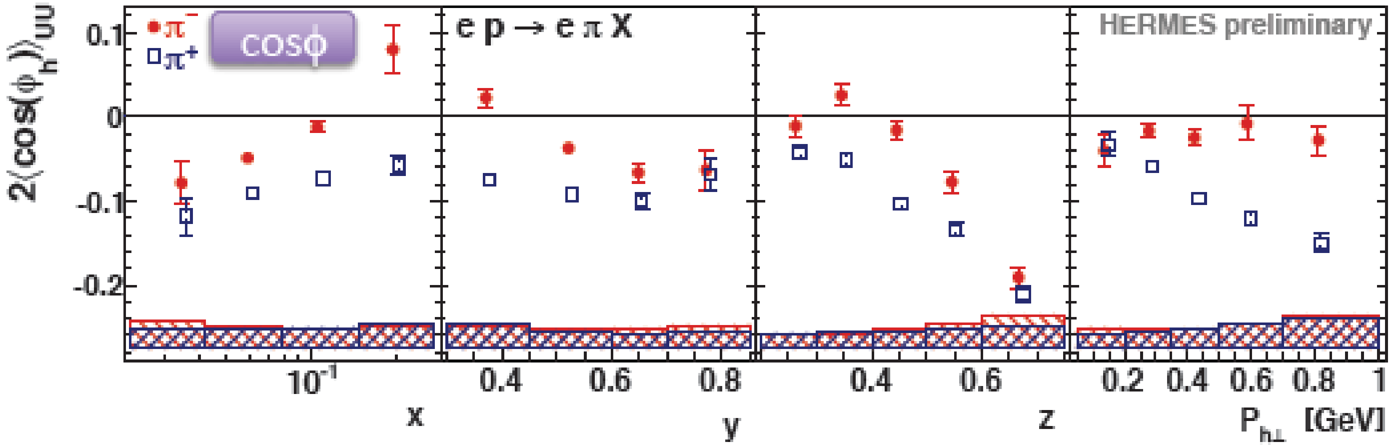
cosϕ large and negative !

$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp + \ldots \right] / Q$$

Increasing with z and P_h

Large difference in hadron charge !

Larger in magnitude for $\pi+$



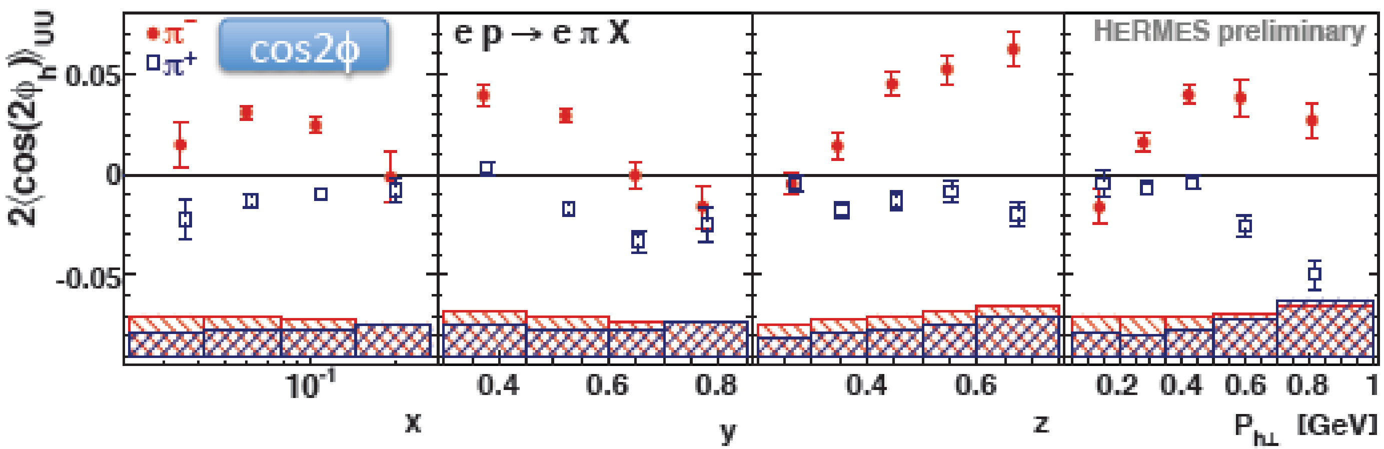
cos2ϕ non-zero !

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$

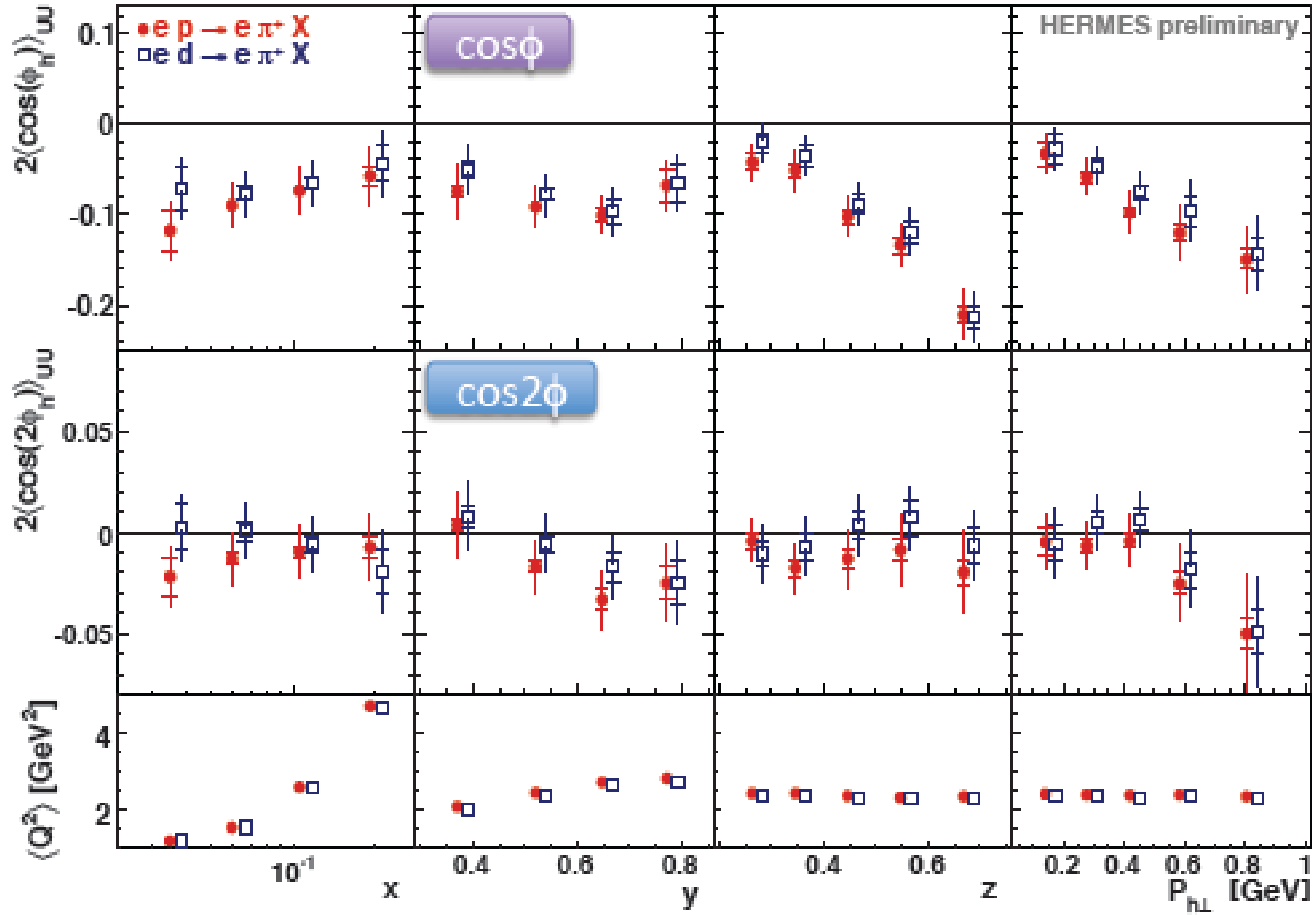
Difference in hadron charge !

Positive for π-

Negative for π+

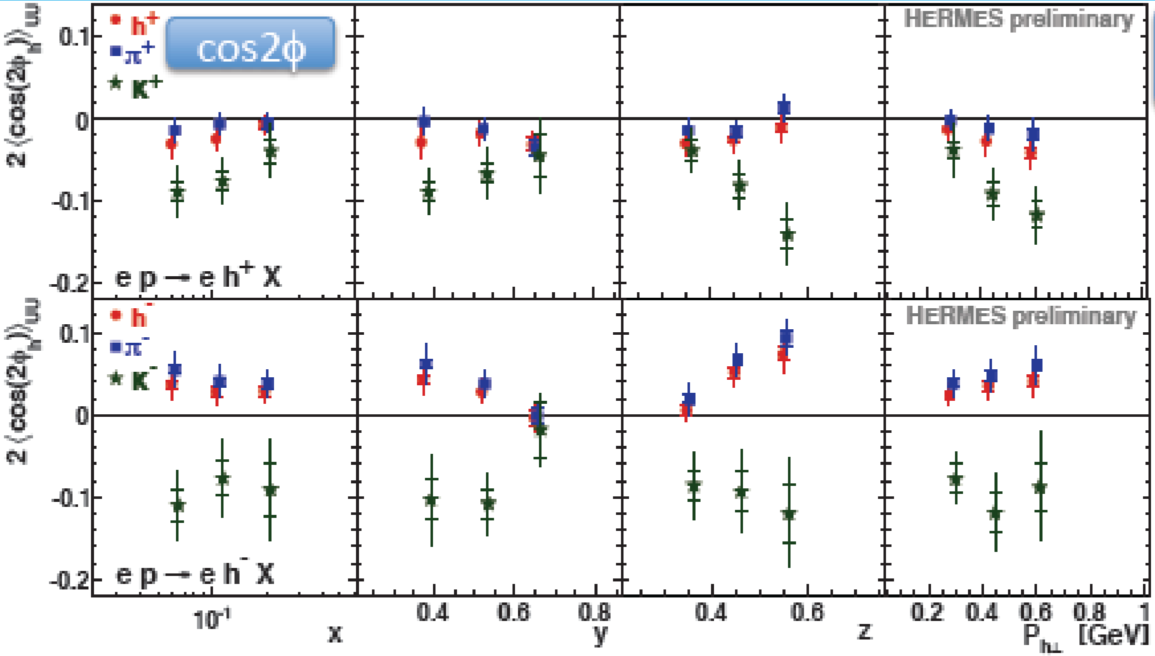


Proton vs. deuteron data: u- vs d-quark Boer-Mulders fct



Quark d vs u contribution ?
DATA support Boer-Mulders of same sign for u and d

Boer-Mulders: kaons vs pions



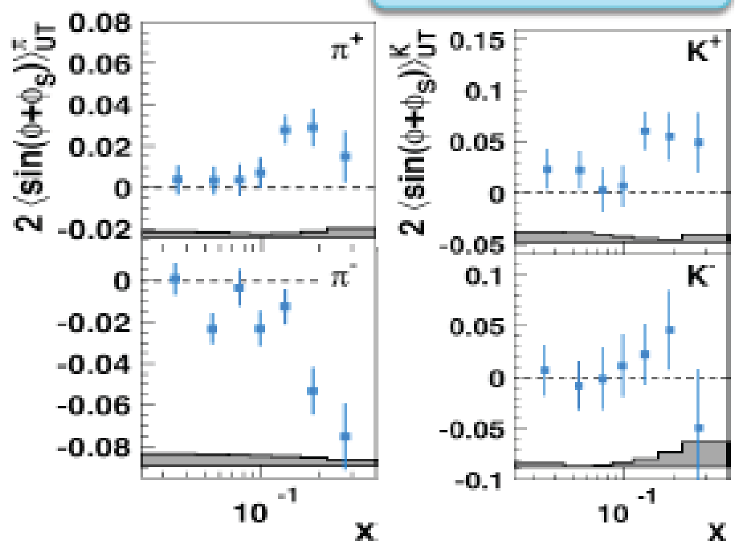
$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$

NEW !!

Striking difference versus pions !

Phys. Lett. B 693 (2010) 11-16

$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 H_1^\perp$$



The kaon puzzle

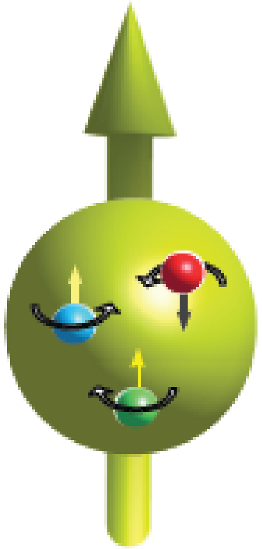
Already found in A_{UT}: Collins+Transversity

Role of the sea in
distribution and fragmentation functions

`Pretzelosity' DF from transversely polarized proton

$$
\begin{aligned}
d\sigma &= d\sigma^0_{UU} + \cos(2\phi) d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi) d\sigma^2_{UU} + P_l \frac{1}{Q}\sin(\phi) d\sigma^3_{LU} \\
&+ S_L \left[\sin(2\phi) d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi) d\sigma^5_{UL} + P_l \left(d\sigma^6_{LL} + \frac{1}{Q}\cos(\phi) d\sigma^7_{LL} \right)\right] \\
&+ S_T \left[\sin(\phi - \phi_s) d\sigma^8_{UT} + \sin(\phi + \phi_s) d\sigma^9_{UT} + \sin(3\phi - \phi_s) d\sigma^{10}_{UT} + \frac{1}{Q}\sin(2\phi - \phi_s) d\sigma^{11}_{UT} + \frac{1}{Q}\sin(\phi_s) d\sigma^{12}_{UT} \right. \\
&\left. P_l \left(\cos(\phi - \phi_s) d\sigma^{13}_{LT} + \frac{1}{Q}\cos(\phi_s) d\sigma^{14}_{LT} + \frac{1}{Q}\cos(2\phi - \phi_s) d\sigma^{15}_{LT} \right)\right]
\end{aligned}
$$

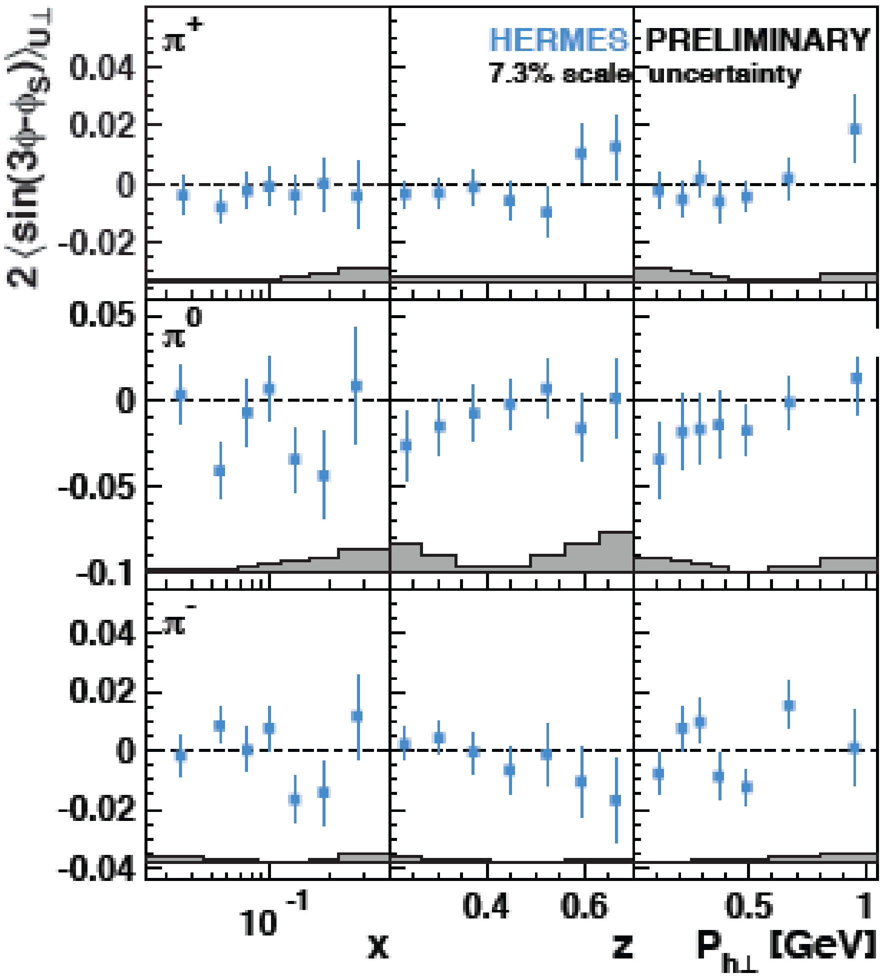
- "pretzelosity" DF $h_{1T}^{\perp,q}(x, p_T^2)$ gives a measure of the deviation of the nucleon shape from a sphere
- correlation between parton transverse momentum and parton transverse polarization in a transversely polarized nucleon
- it is expected to be suppressed at small and large x w.r.t. f_1^q, g_1^q, h_1^q

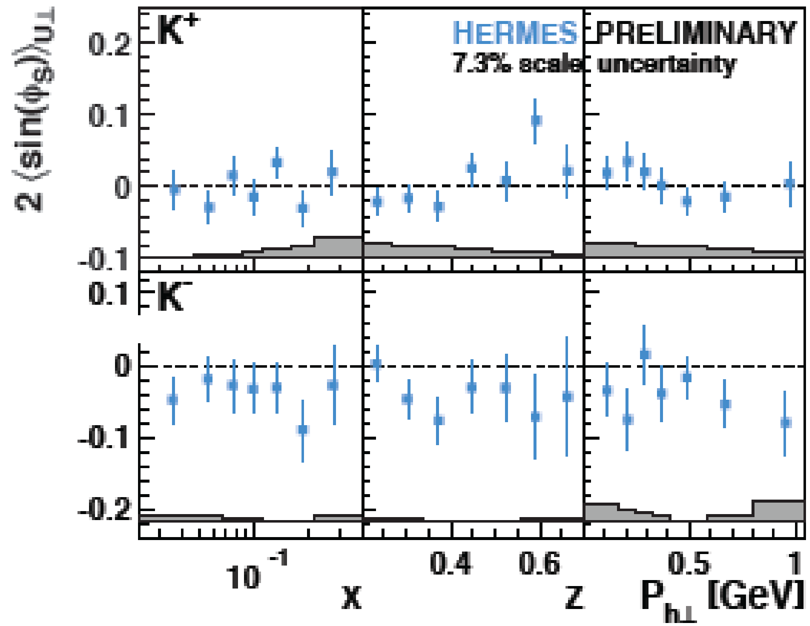


- envolve quark and nucleon helicity flips; is related to chiral-odd GPD $h_{1T}^{(0)\perp,q}(x, p_T^2) = \frac{3}{(1-x)^2}\widetilde{H}_T^q(x,0,0)$
- gives the measure of 'relativistic effects' in the nucleon: $\frac{p_T^2}{2M^2} h_{1T}^{\perp q}(x, p_T^2) = g_1^q(x, p_T^2) - h_1^q(x, p_T^2)$

NEW !! :Result on pretzelosity

$$2\langle\sin(3\phi-\phi_s)\rangle_{UT} \propto \frac{\sum_q e_q^2\, x\, h_{1T}^{\perp(1),q}(x) \otimes_w H_1^{\perp(1/2)\,q}(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$





- suppressed by two powers of $P_{h\perp}$ compared to Collins and Sivers amplitudes
- compatible with zero within uncertainties
- pretzelosity might be non-zero at higher $P_{h\perp}$

`Worm-gear' DFs from transversely polarized proton

$$
\begin{aligned}
d\sigma \;=\;& d\sigma^0_{UU} + \cos(2\phi)d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi)d\sigma^2_{UU} \;+\; P_l\frac{1}{Q}\sin(\phi)d\sigma^3_{LU} \\
+\;& S_L\Big[\sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi)d\sigma^5_{UL} \;+\; P_l\Big(d\sigma^6_{LL} + \frac{1}{Q}\cos(\phi)d\sigma^7_{LL}\Big)\Big] \\
+\;& S_T\Big[\sin(\phi-\phi_s)d\sigma^8_{UT} + \sin(\phi+\phi_s)d\sigma^9_{UT} + \sin(3\phi-\phi_s)d\sigma^{10}_{UT} + \frac{1}{Q}\sin(2\phi-\phi_s)d\sigma^{11}_{UT} + \frac{1}{Q}\sin(\phi_s)d\sigma^{12}_{UT} \\
& P_l\Big(\cos(\phi-\phi_s)d\sigma^{13}_{LT} + \frac{1}{Q}\cos(\phi_s)d\sigma^{14}_{LT} + \frac{1}{Q}\cos(2\phi-\phi_s)d\sigma^{15}_{LT}\Big)\Big]
\end{aligned}
$$

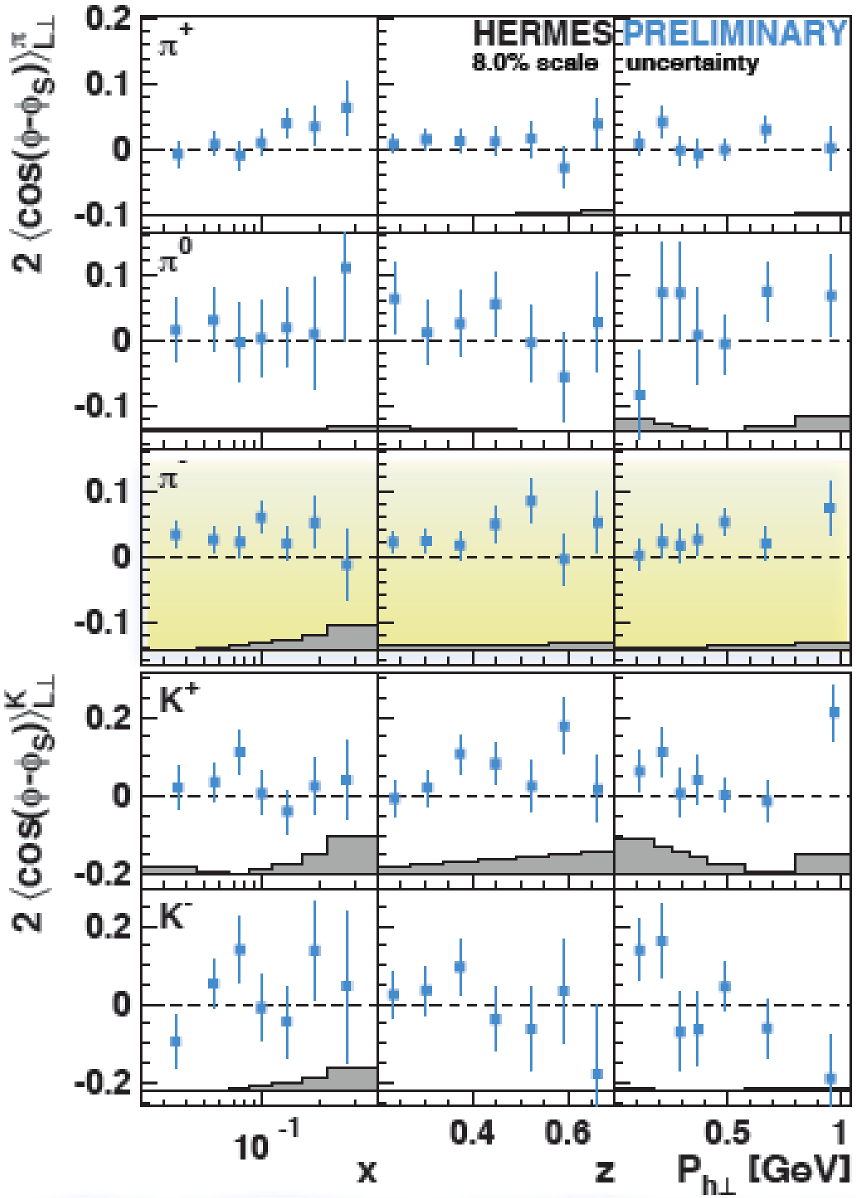
- worm-gear DF $g^q_{1T}(x,p_T^2)$ and $h^{\perp,q}_{1L}(x,p_T^2)$ describes the probability to find a longitudinal/transverse polarized quark in a transversely/longitudinally polarized nucleon
- on a transversely target $h^{\perp,q}_{1L}(x,p_T^2)$ accessible in the measurements through $\sin(2\phi+\phi_s)$ Fourier component
- gives correlation between parton transverse momentum and parton longitudinal / transverse polarization in a longitudinal / transversely polarized nucleon
- model dependent relations:

$$g^{\perp,q}_{1T}(x,p_T^2) \;\approx\; x\int_x^1 \frac{1}{y}\, g^q_1(y,p_T^2)dy$$

$$h^{\perp,q}_{1L}(x,p_T^2) = -g^{\perp,q}_{1T}(x,p_T^2) \qquad h^{\perp,q}_{1L}(x,p_T^2) \;\approx\; -x\int_x^1 \frac{1}{y}\, h^q_1(y,p_T^2)dy$$

NEW !!

Worm-gear DF from long.pol. beam/transv.pol.target



the cos(φ - φ$_S$) amplitudes

$$2\langle\cos(\phi-\phi_s)\rangle_{LT} \propto \frac{\mathcal{C}\left[-\frac{\hat{\mathbf{P}}_{h\perp}\cdot\mathbf{p}_T}{M_h}\, g_{1T}^{\perp,q}(x,p_T^2)D_1^q(z,k_T^2)\right]}{\mathcal{C}\left[f_1^q(x,p_T^2)D_1^q(z,k_T^2)\right]}$$

- uncertainties are larger than in single-spin asymmetries scaled by the beam polarization value

π^+
- slightly positive

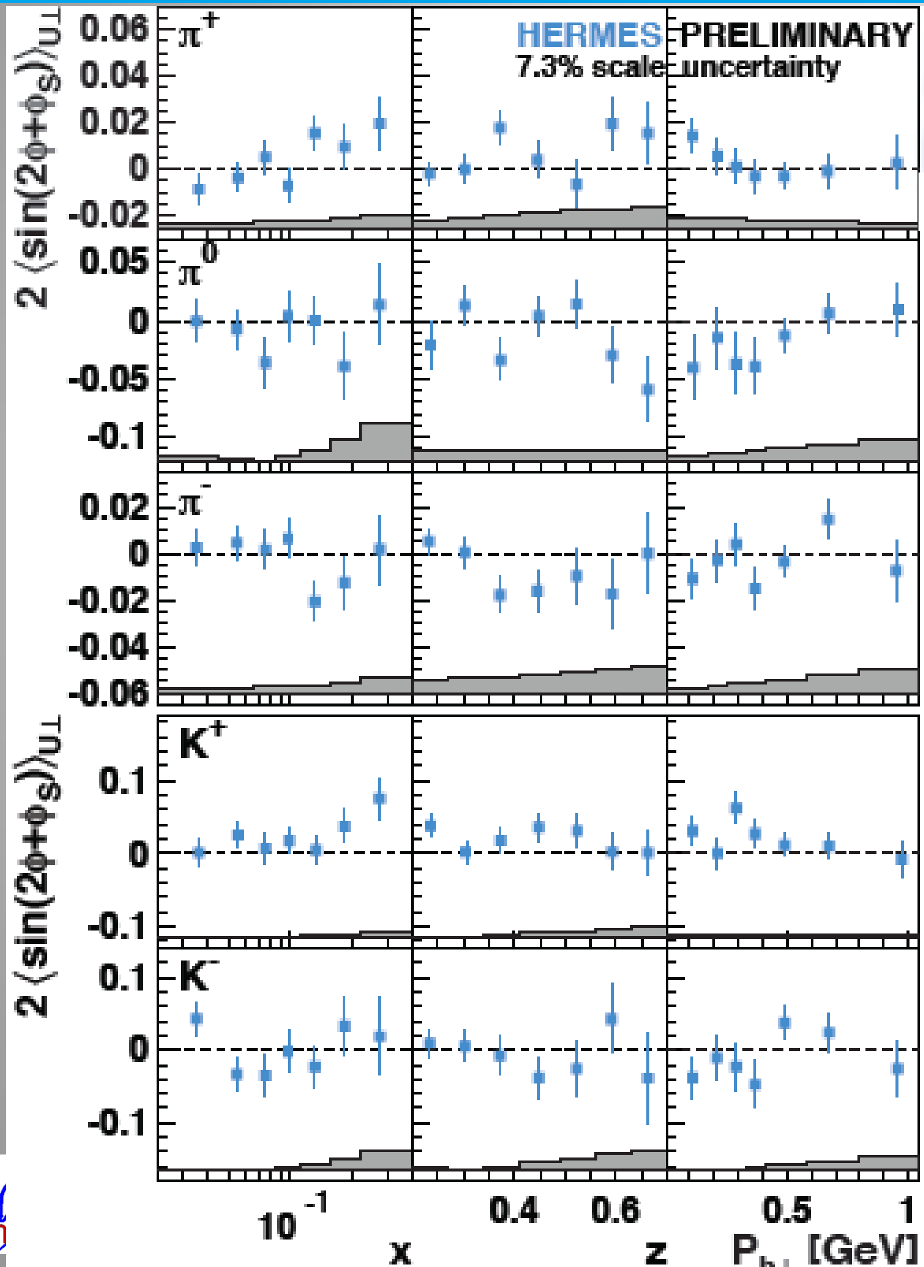
π^0
- compatible with zero

π^-
- positive
  - evidence for non-zero worm-gear distribution

K^+
- slightly positive

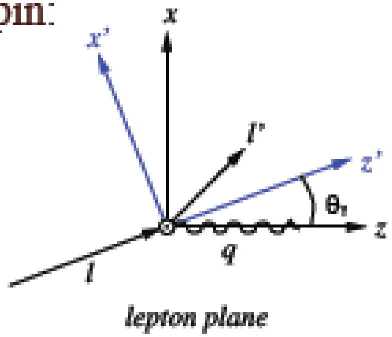
K^-
- compatible with zero

NEW !! :Subleading-twist amplitudes for pions & kaons



the subleading-twist $\sin(2\phi+\phi_s)$ amplitudes

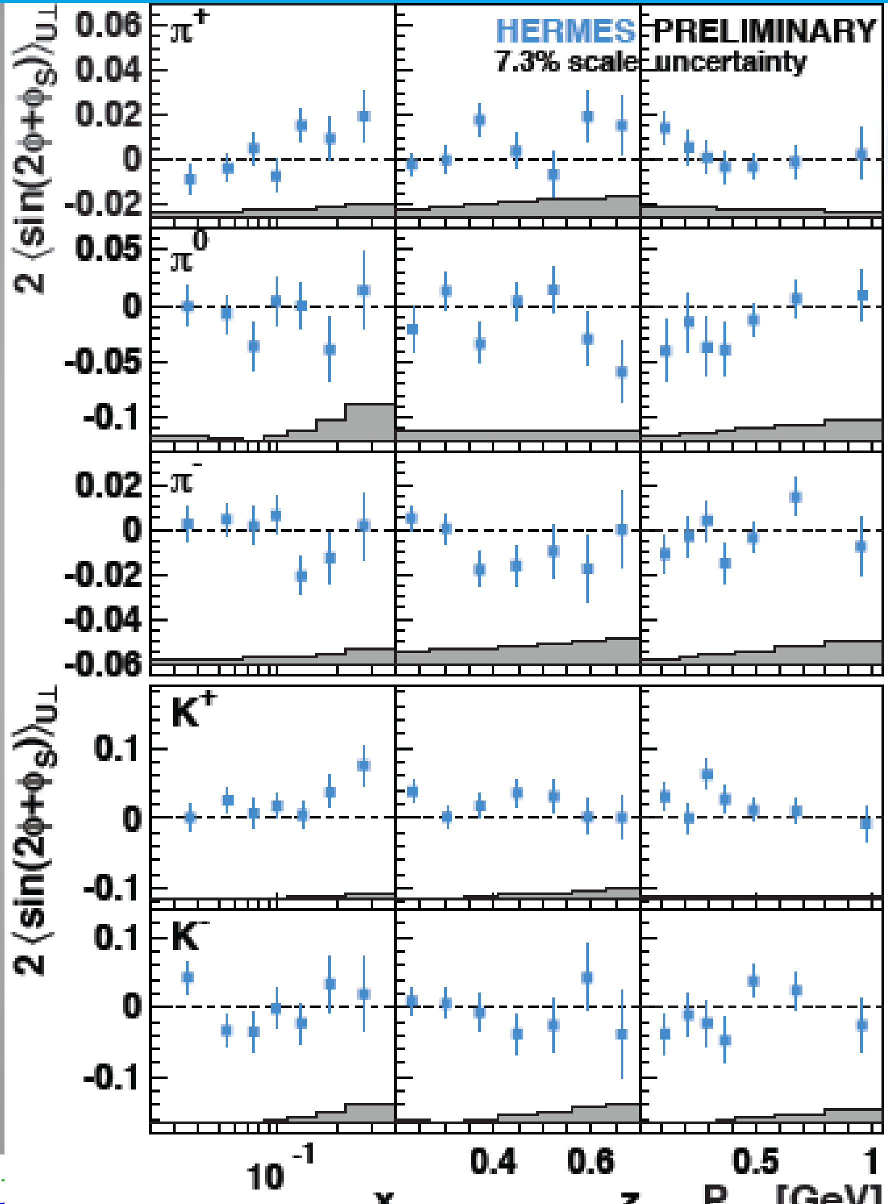
- arises solely from longitudinal component of the target spin:



$$P_T A_{U\perp}(\phi,\phi_s) = S_T A_{UT}(\phi,\phi_s) + S_L A_{UL}$$

- longitudinal component of the target spin <15\%
- expected to scale as $\sin\theta_{\gamma^*}\langle\sin(2\phi)_{UL}\rangle$
- related to worm-gear DF $h_{1L}^{\perp,q}$
- sin(2ϕ+ϕ$_s$) amplitude is suppressed by one powers of $P_{h\perp}$ compared to Collins and Sivers amplitudes
- compatible with zero within uncertainties except maybe K+

NEW !! :Subleading-twist amplitudes for pions & kaons



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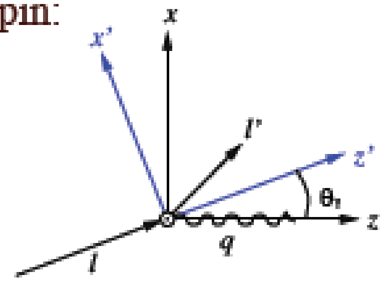

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Conclusions and Outlook

- HERMES has been pioneering the experimental study of the spin structure of the nucleon towards GPDs and TMDs
- HERMES will stay unique (for a while) offering exclusive and semi-inclusive data taken with both beam charges and undiluted Hydrogen and Deuterium targets
- HERMES has been publishing an almost full spectrum of asymmetries in DVCS and intends to publish more on exclusive meson production (Rho, Phi, Omega, Eta, Pi0)
- HERMES intends to soon have published results on a wide variety of (flavor-separated) SIDIS asymmetries

Spin results not addressed in this talk: Exclusive VM production **(see poster B. Marianski)**

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