New Results

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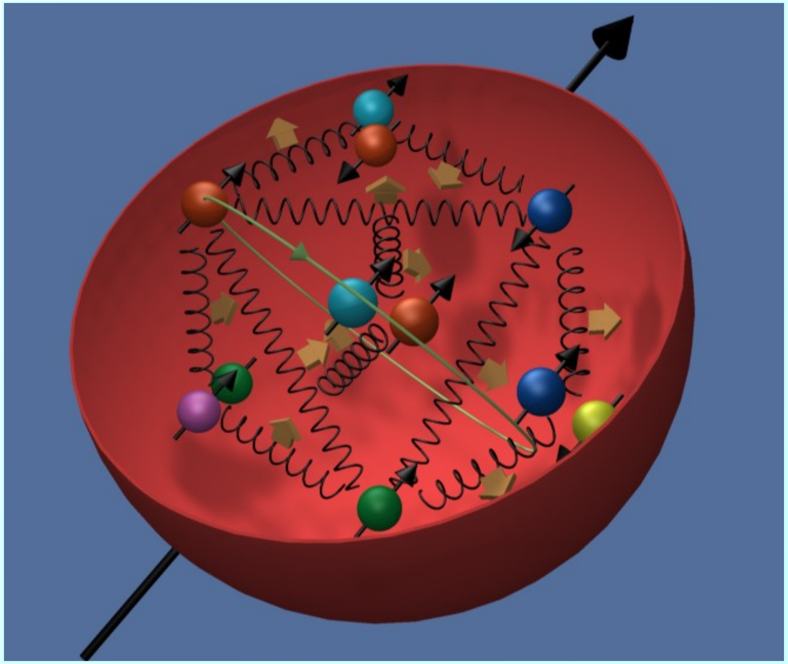
Main HERMES research topics:

- Origin of nucleon spin
- Details of nucleon structure



Quark Properties:

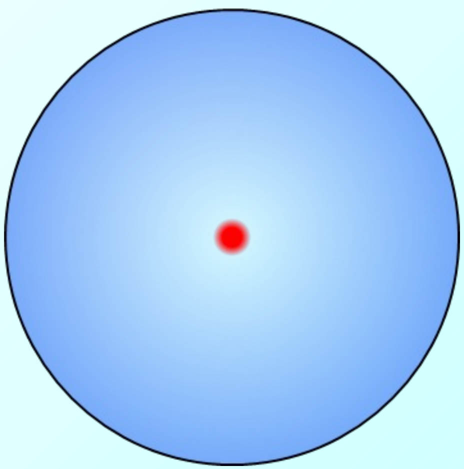
- fractional charge
- spin-1/2
- longitudinal momentum xP
- intrinsic transverse momentum p_T
- spatial position $r_\perp$
- orbital angular momentum L

Atom

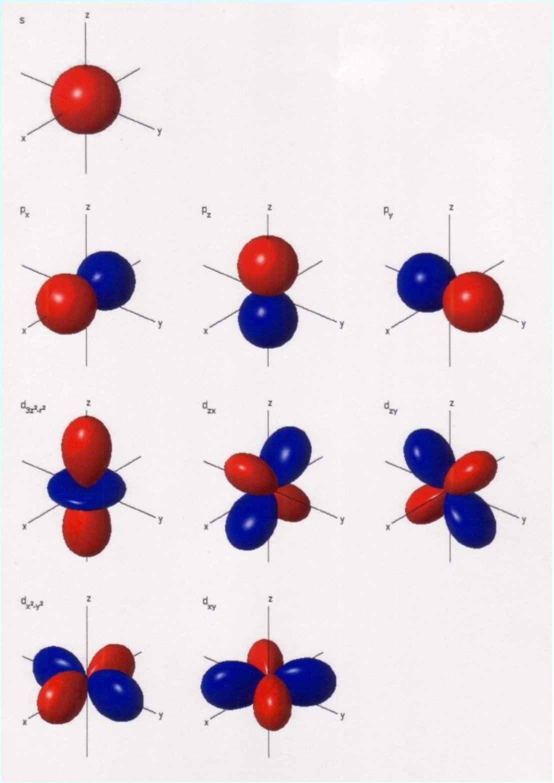
(non-relativistic electrons in Coulomb potential)

Rutherford

Bohr, Schrödinger, ..



Add angular momentum

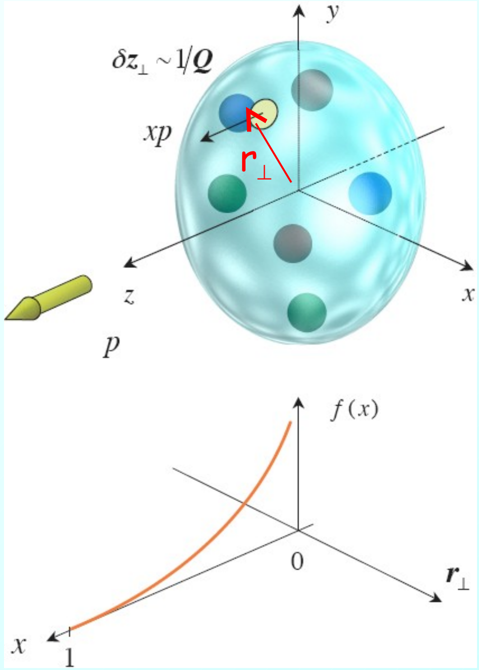


$$\Psi_{n,l,m_l}(r,\theta,\phi)$$

Nucleon

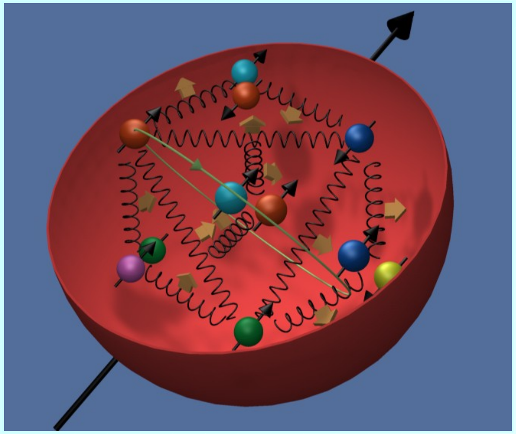
(Relativistic quarks in colour field)

Inclusive DIS



Number density of quarks with longitudinal momentum fraction x

Add angular and transverse momentum



Wigner DF $W(p_T, r_\perp)$

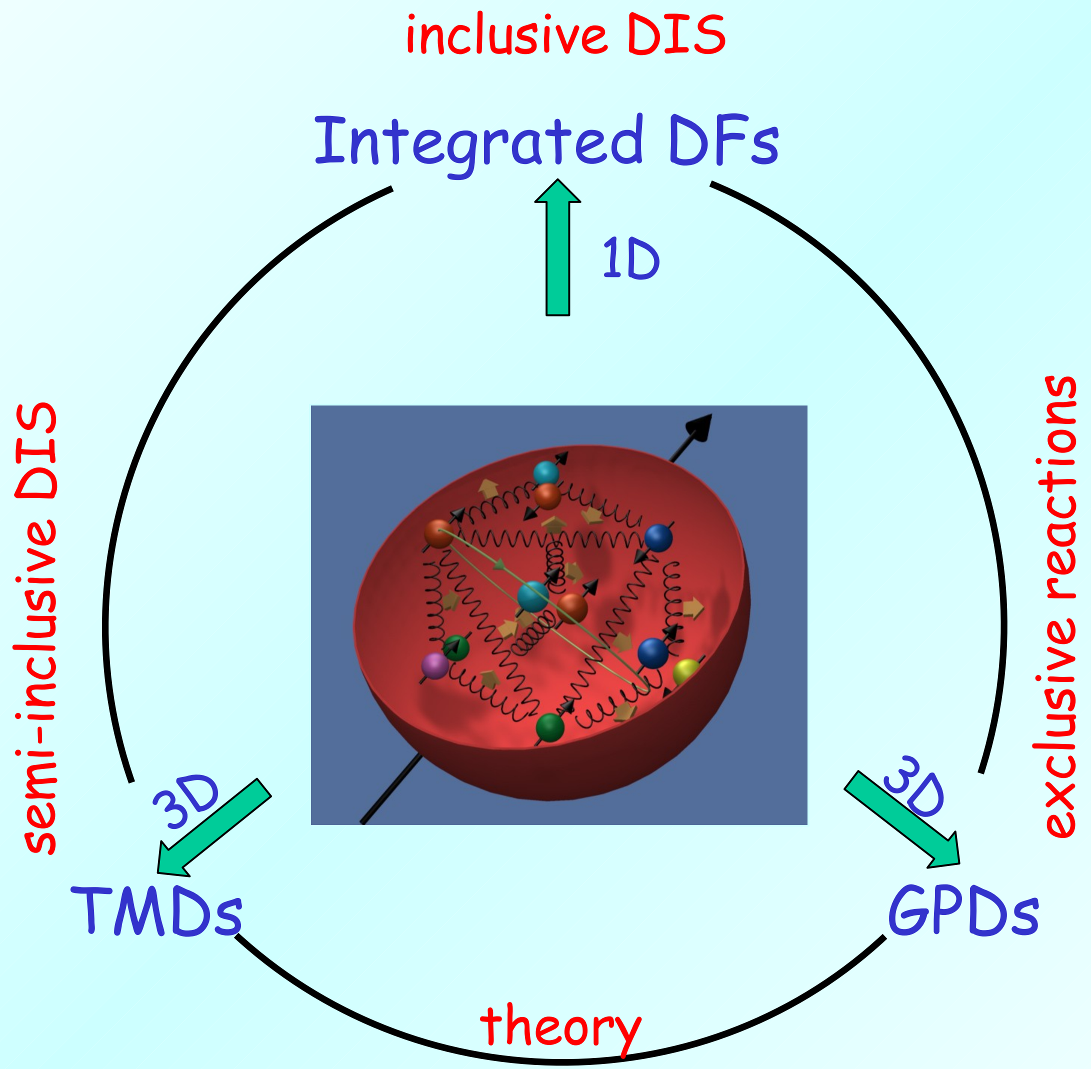
TMDs

(p_T-dependence)

GPDs

($r_\perp$-dependence)

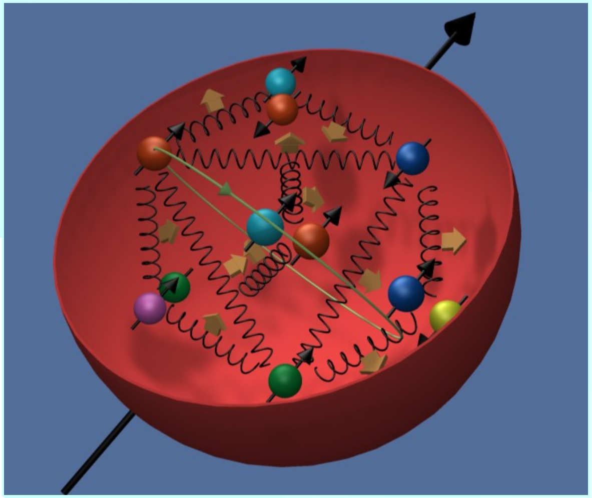
Accessing the nucleon's structure



after G. Schnell

TMDs

Accessible in inclusive DIS



Quark polarisation (columns) / *Nucleon polarisation* (rows)

N/q	U	L	T
U	f_1 Number Density		$h_1^\perp$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^\perp$ Mulders-Kotzinian
T	Sivers	$g_{1T}^\perp$ Worm-gear	h_1 Transversity $h_{1T}^\perp$ Pretzelosity

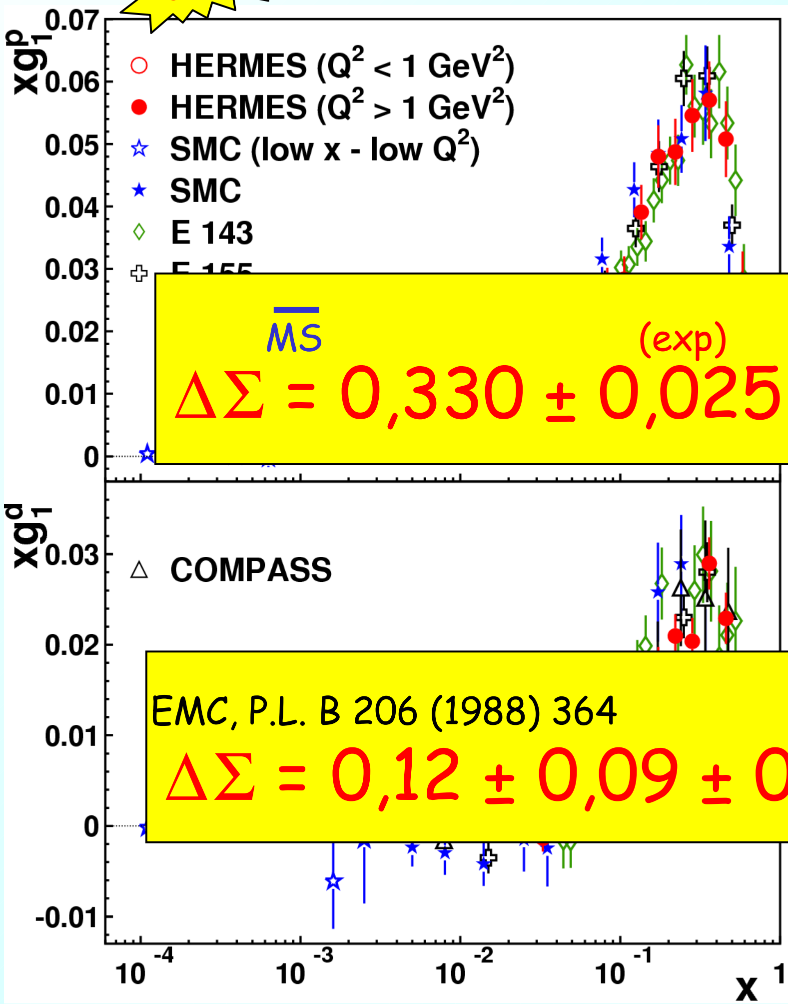
Nucleon structure described by 8 leading-twist (+ many subleading) quark distributions containing information about quark orbital motion and spin-orbit effects

Inclusive Measurements

Longitudinal double-spin asymmetry: g_1, $\Delta\Sigma$

old

P.R. D 75 (2007) 012007



$$g_1(x) = \frac{1}{2} \sum_q e_q^2 \Delta q(x)$$

$\overline{MS}$ (exp) (theory) (evol.)

$\Delta\Sigma = 0{,}330 \pm 0{,}025 \pm 0{,}011 \pm 0{,}028$ (from Γ_1^d)

$$\Delta q = \int_0^1 \Delta q(x)$$

EMC, P.L. B 206 (1988) 364

$\Delta\Sigma = 0{,}12 \pm 0{,}09 \pm 0{,}14$ (from Γ_1^p)

$$\Delta\Sigma = \sum_q$$

Furthermore:

new

HERMES, JHEP 08 (2010) 130

$\Delta g/g = 0{,}045 \pm 0{,}034 \pm 0{,}126$ (high-p_T hadrons)

Unpolarised DIS cross section: F_2

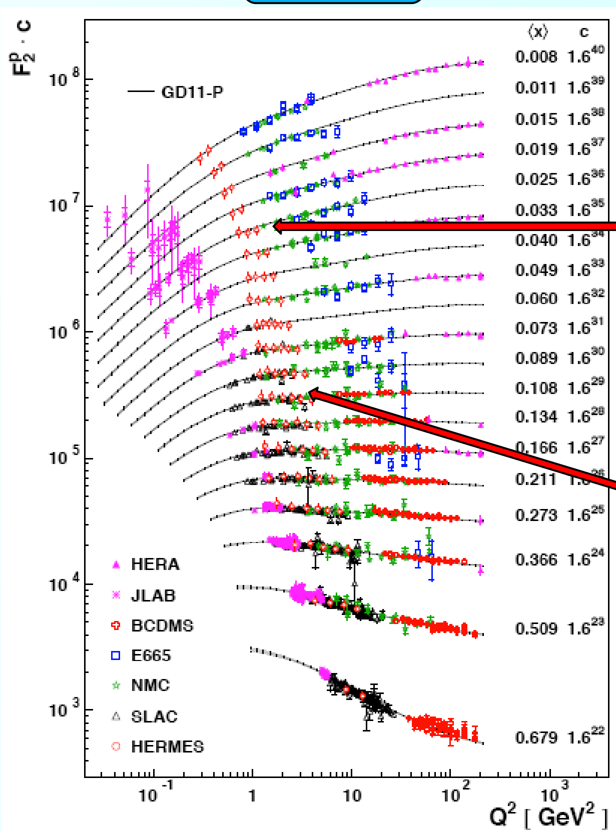
$$\frac{d^2\sigma}{dx\, dQ^2} = \frac{4\pi\alpha_{em}^2}{Q^4}\frac{F_2(x,Q^2)}{x}\left[1 - y - \frac{Q^2}{4E^2} + \frac{y^2 + Q^2/E^2}{2\,(1 + R(x,Q^2))}\right]$$

From global fit: HERMES relative normalisation ~2% for p and d and ~0.5% for the ratio

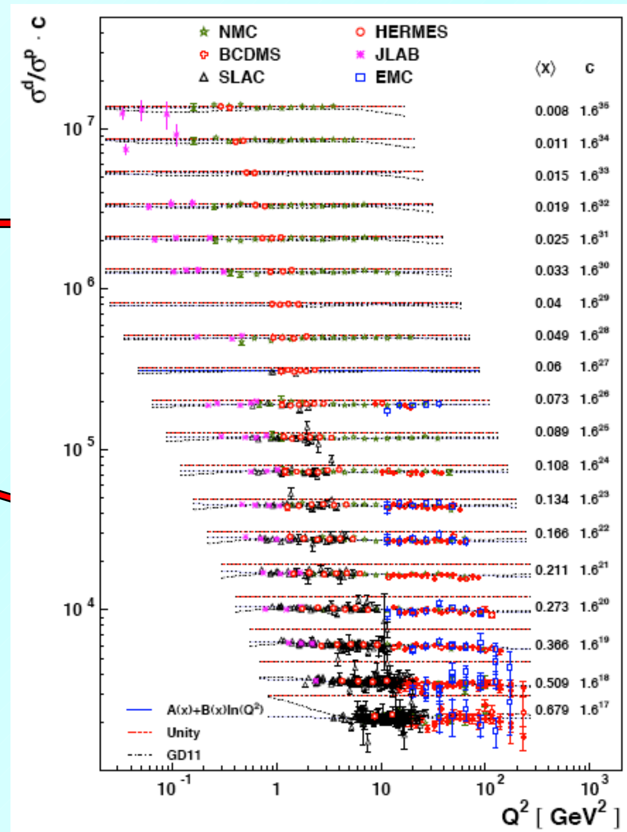
Exploring perturbative to non-perturbative regime in an unmeasured x-Q^2 region
$0.006 < x < 0.9$ $0.1\ GeV^2 < Q^2 < 20\ GeV^2$

new JHEP 05 (2011) 126

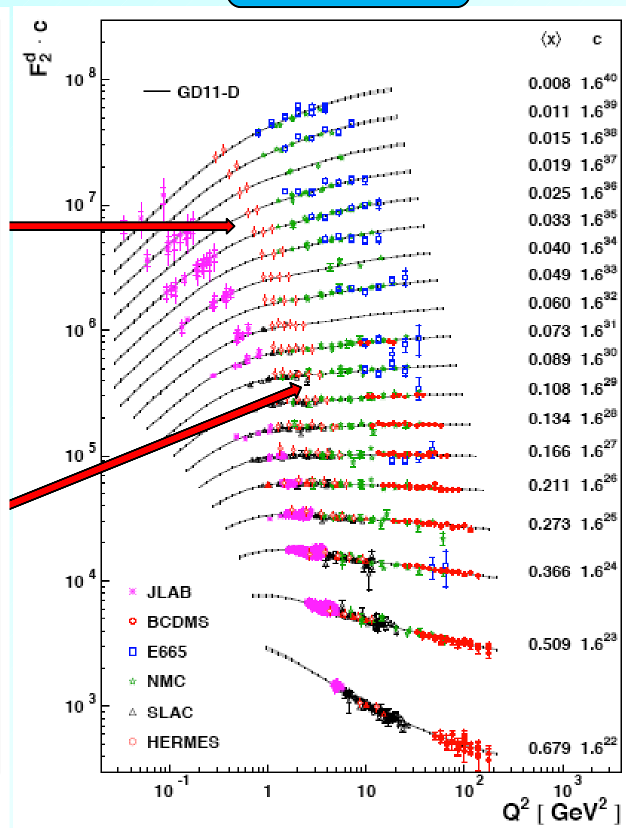
Proton



Ratio σ^d/σ^p (F_2^d/F_2^p)

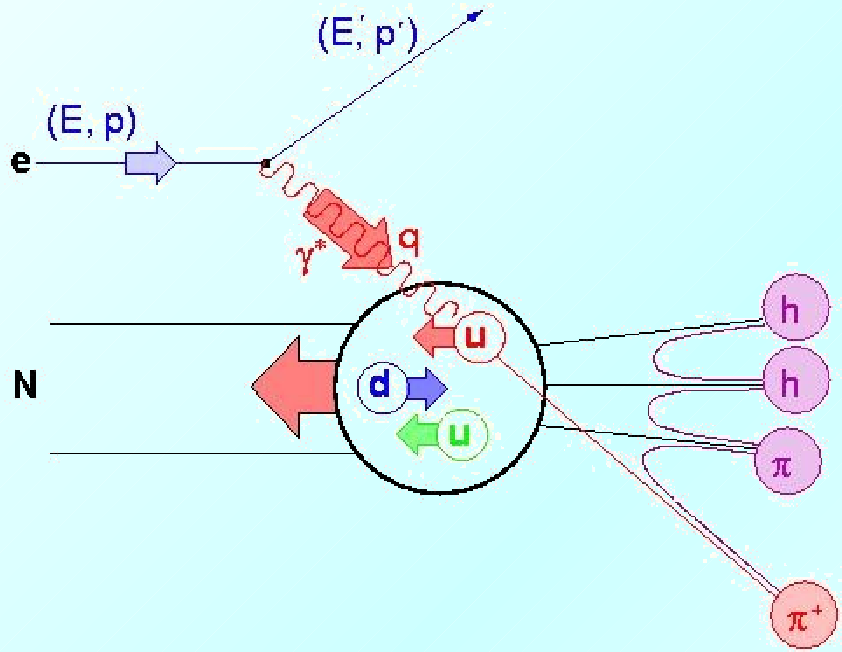


Deuteron



Semi-inclusive Measurements

Semi-inclusive Deep-Inelastic Scattering



$z = E_h/\nu$

Factorisation ⇒ $\sigma^{eN\to ehX} = \sum_q \sigma^{eq\to eq} \otimes DF^{N\to q} \otimes FF^{q\to h}$

DF(x,Q^2): Parton Distribution Function – $q(x,Q^2) \equiv f_1^q(x,Q^2)$, $\Delta q(x,Q^2) \equiv g_1^q(x,Q^2)$, $\delta q(x,Q^2)\ ) \equiv h_1^q(x,Q^2)$, ...

FF(z,Q^2): Fragmentation Function – $D_1^{q\to h}(z,Q^2)$, $H_1^{\perp q\to h}(z,Q^2)$, ...

Charged-hadron multiplicities I

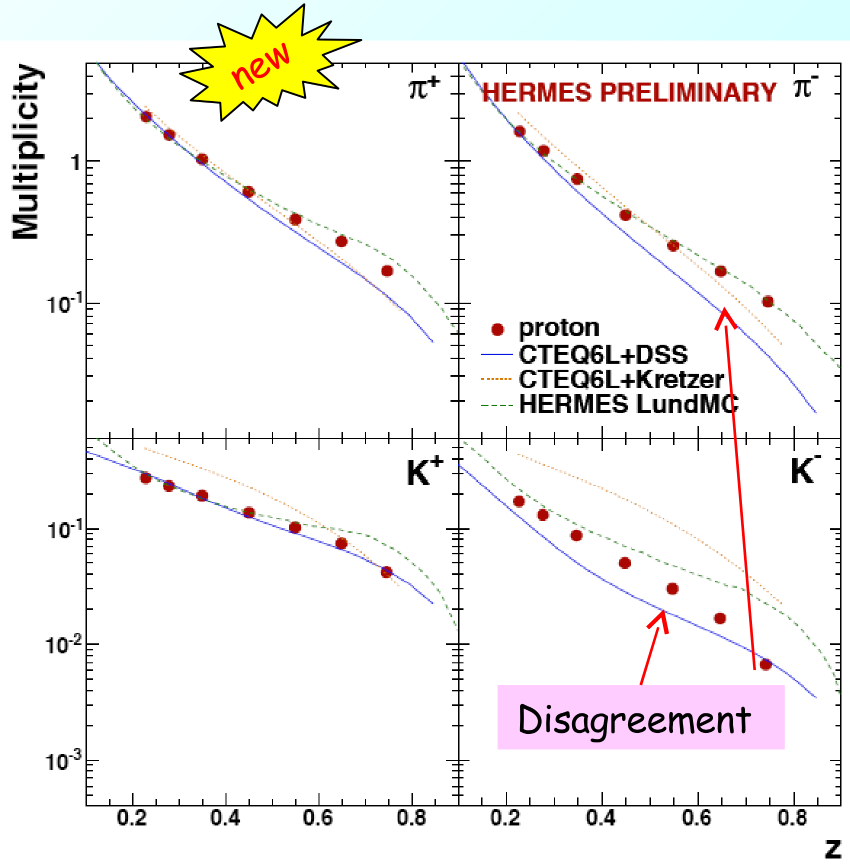
LO interpretation: $\sigma_{UU} \propto f_1^q \otimes D_1^{q\to h}$

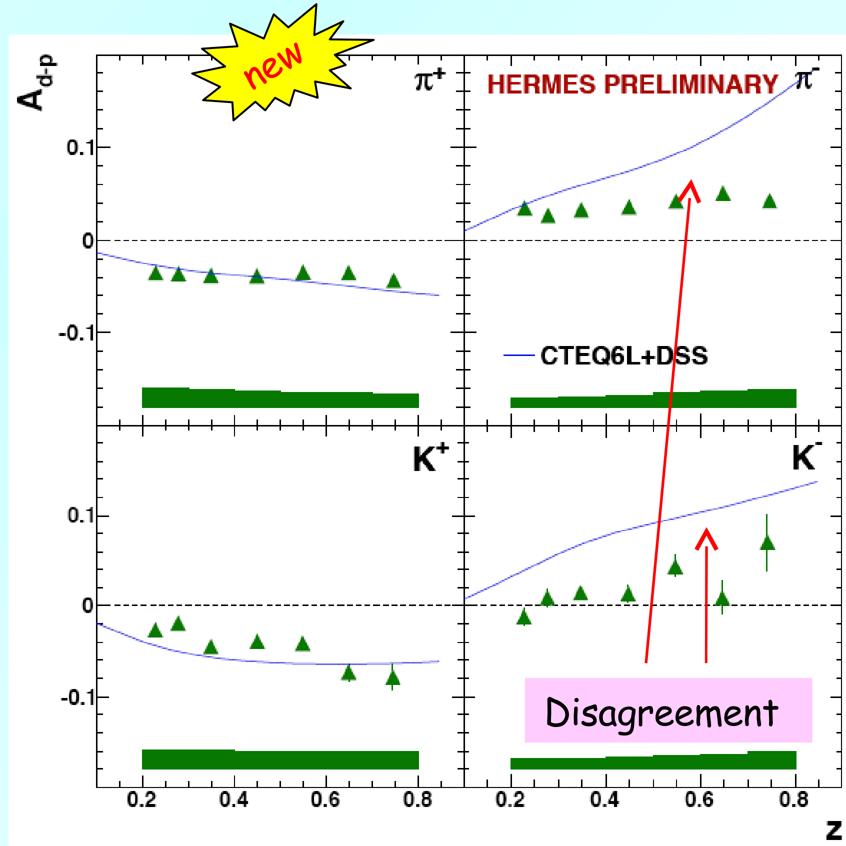
$$M_N^h = \frac{1}{N_N^{DIS}(Q^2)}\frac{dN_N^h(z,Q^2)}{dz} = \frac{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2)}$$

Proton-deuteron asymmetry

$$A_{d-p}^h \equiv \frac{M_d^h - M_p^h}{M_d^h + M_p^h}$$

Reflects different flavor content
Correlated systematics cancel



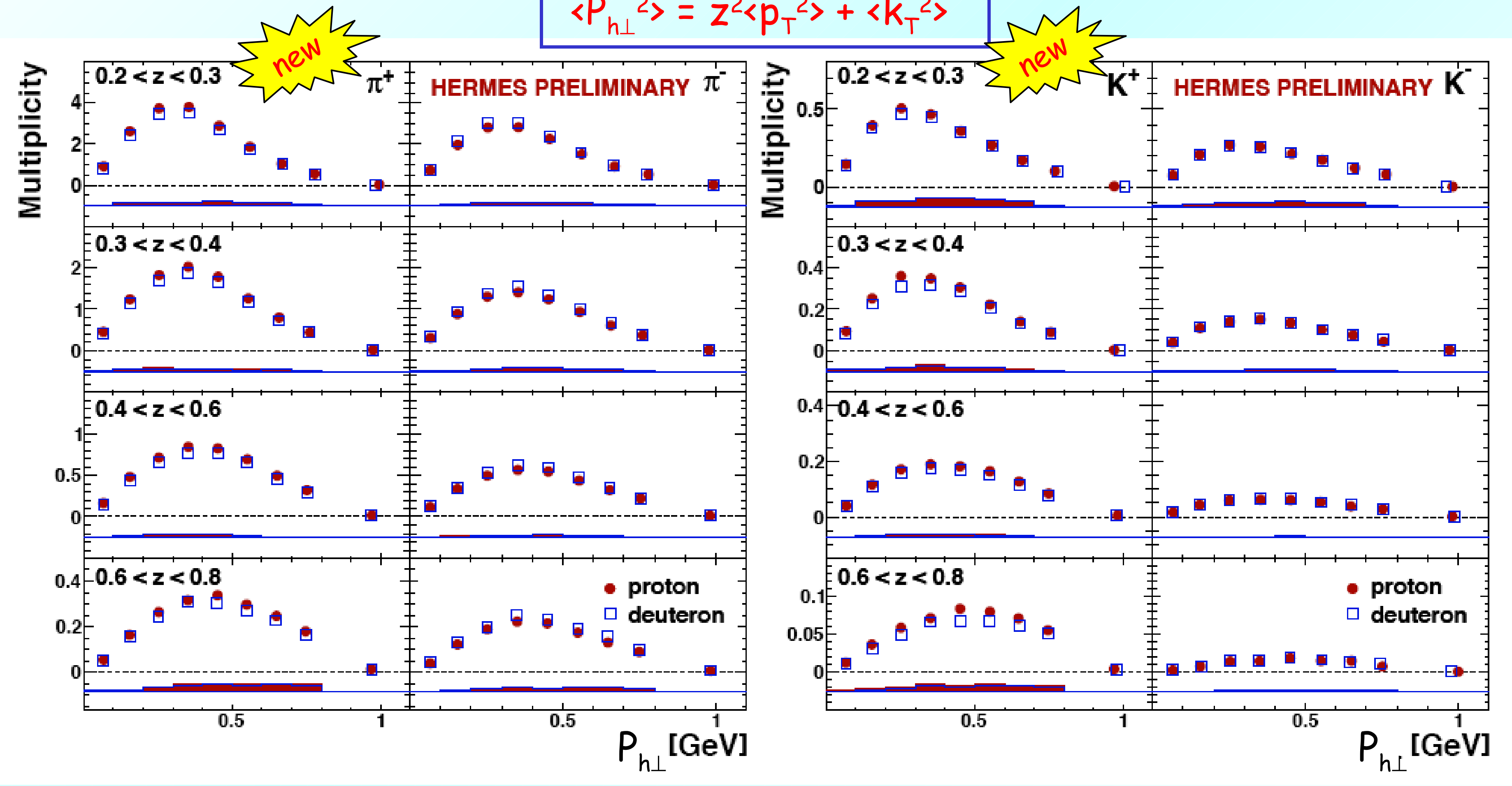


Charged-hadron multiplicities II

- Disentanglement of z and $P_{h\perp}$ dependences
- Access to intrinsic quark p_T and fragmentation k_T

$\sigma_{UU} \propto f_1^q \otimes D_1^{q \to h}$

$\langle P_{h\perp}^2 \rangle = z^2 \langle p_T^2 \rangle + \langle k_T^2 \rangle$



Double-spin asymmetry A_1^h

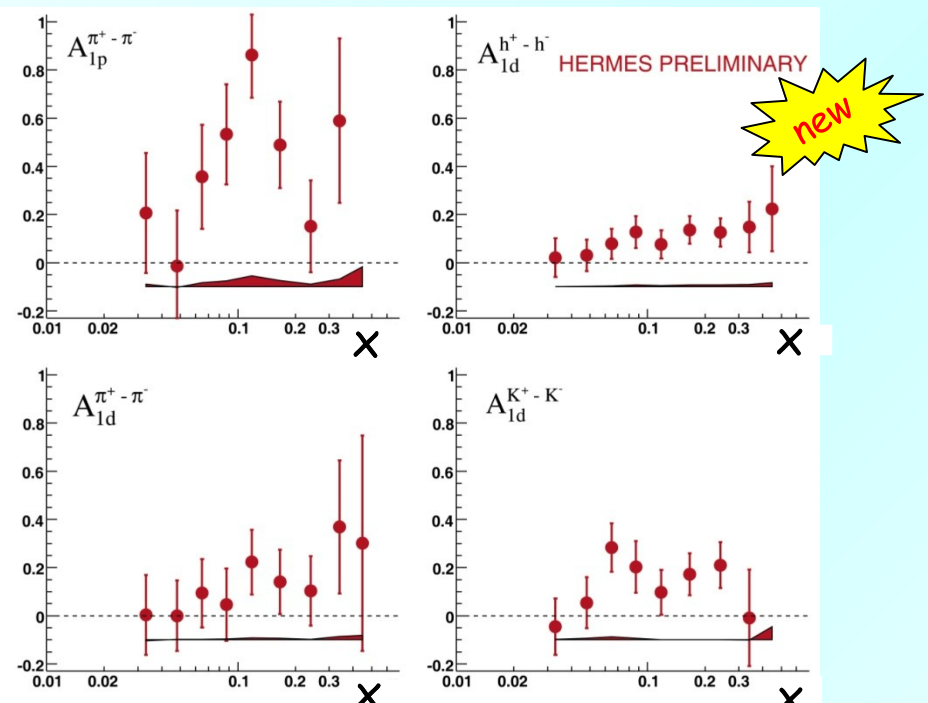
$$\sigma_{LL} \propto g_1^q \otimes D_1^{q\rightarrow h}$$

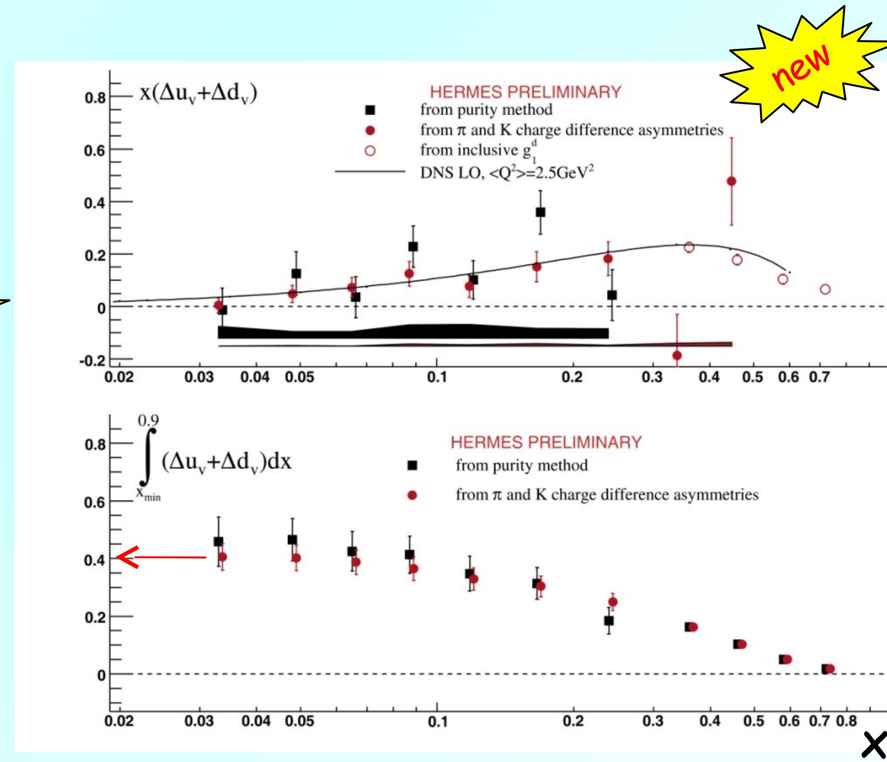
Refined studies extending the work
in Phys. Rev. D 71 (2005) 012003

With charge conjugation
symmetry in fragmentation

$$D_{1,q}^{h+} = D_{1,q}^{h-}$$

$$A_{1d}^{h^+-h^-} = \frac{\Delta u_v +}{\Delta u_v + d_v}(x)$$





Integral over sum of valence distributions
compatible with $\Delta\Sigma$
Sea contribution to nucleon spin small

Leading-twist TMDs

- Nucleon structure described in leading-twist by 8 transverse-momentum dependent quark distributions (TMDs)

- HERMES has access to all of them through specific azimuthal modulations (ϕ , ϕ s) of the cross section thanks to the polarised beam and target

Quark polarisation (columns) / *Nucleon polarisation* (rows)

N/q	U	L	T
U	f_1 Number Density		$h_1^\perp$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^\perp$ Mulders-Kotzinian
T	Sivers	$g_{1T}^\perp$ Worm-gear	h_1 Transversity; $h_{1T}^\perp$ Pretzelosity

Boer-Mulders: $\cos 2\phi$

Mulders-Kotzinian: $\sin 2\phi$

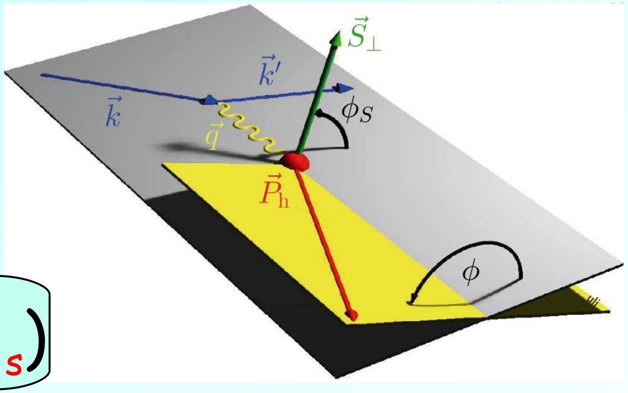
Transversity: $\sin(\phi + \phi_s)$

Pretzelosity: $\sin(3\phi - \phi_s)$

Sivers: $\sin(\phi - \phi_s)$

Worm-gear: $\cos(\phi - \phi_s)$

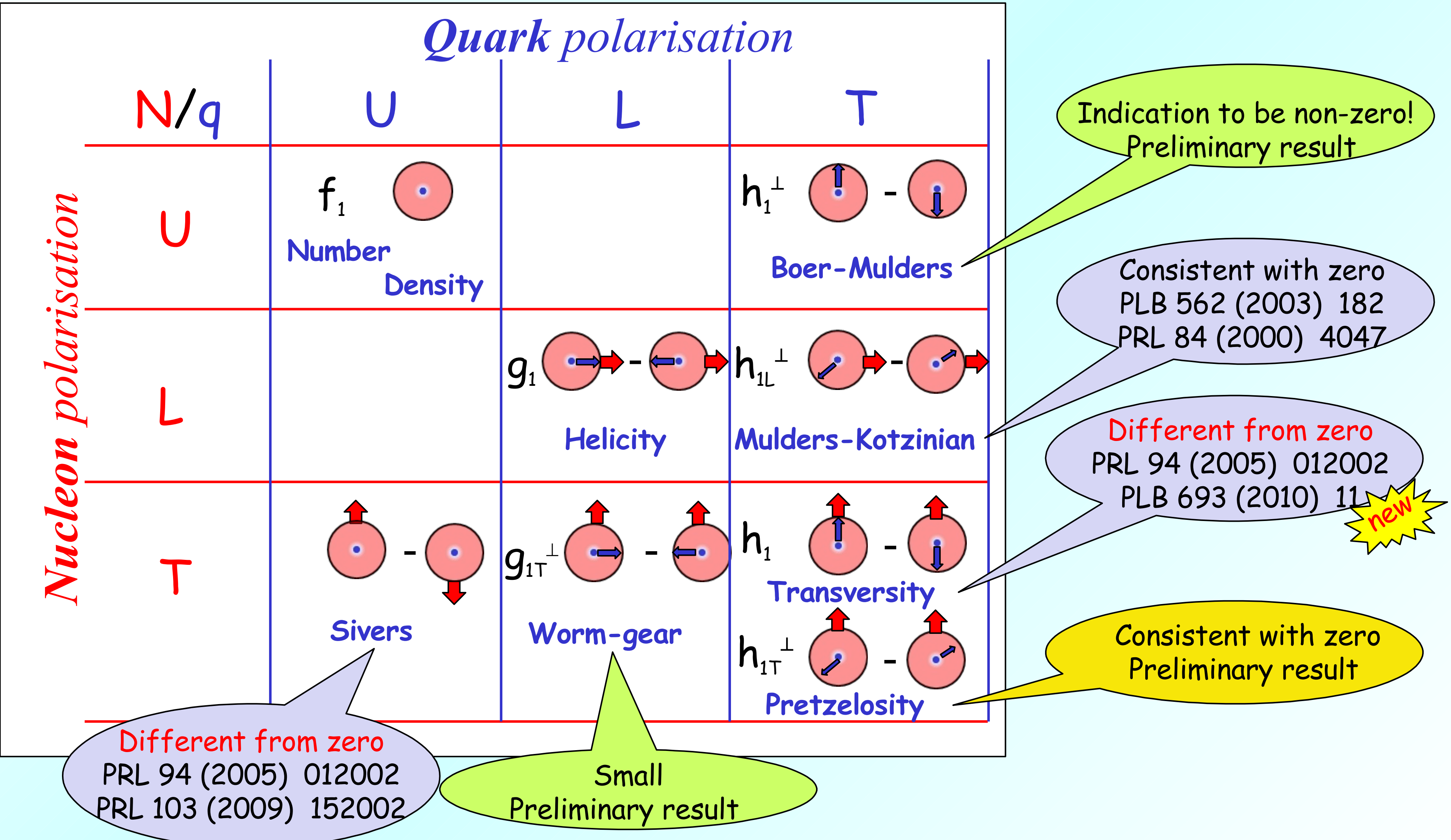
$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi\,d\phi_s\,dP^2_{h\perp}}$$



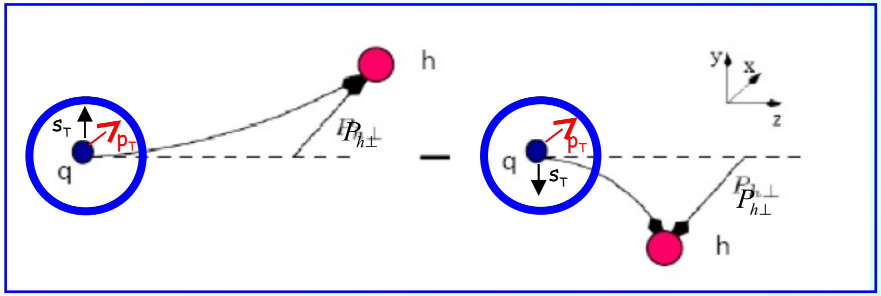
Chiral-odd DFs, need chiral-odd FF: $H_1^{\perp,q\to h}$

Leading-twist TMDs

Pioneering measurements by HERMES



Boer-Mulders DF $h_1^{\perp,q}$

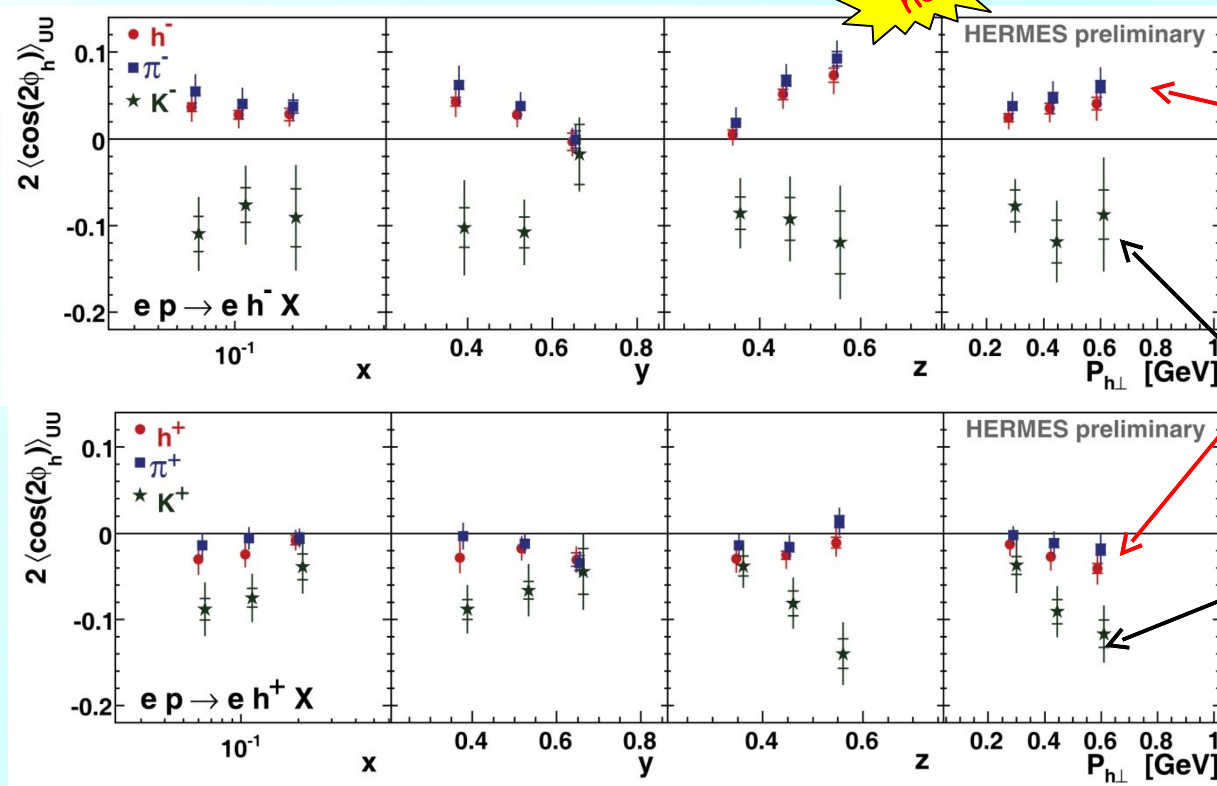


$$\sigma_{UU}^{\cos 2\phi} \propto h_1^{\perp,q} \otimes H_1^{\perp,q \to h}$$

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L	$\perp$	g_1 $\perp$	h_{1L} $\perp$
T	f_{1T}	g_{1T}	h_1 h_{1T}

transversely polarised quarks with p_T in unpolarised nucleon

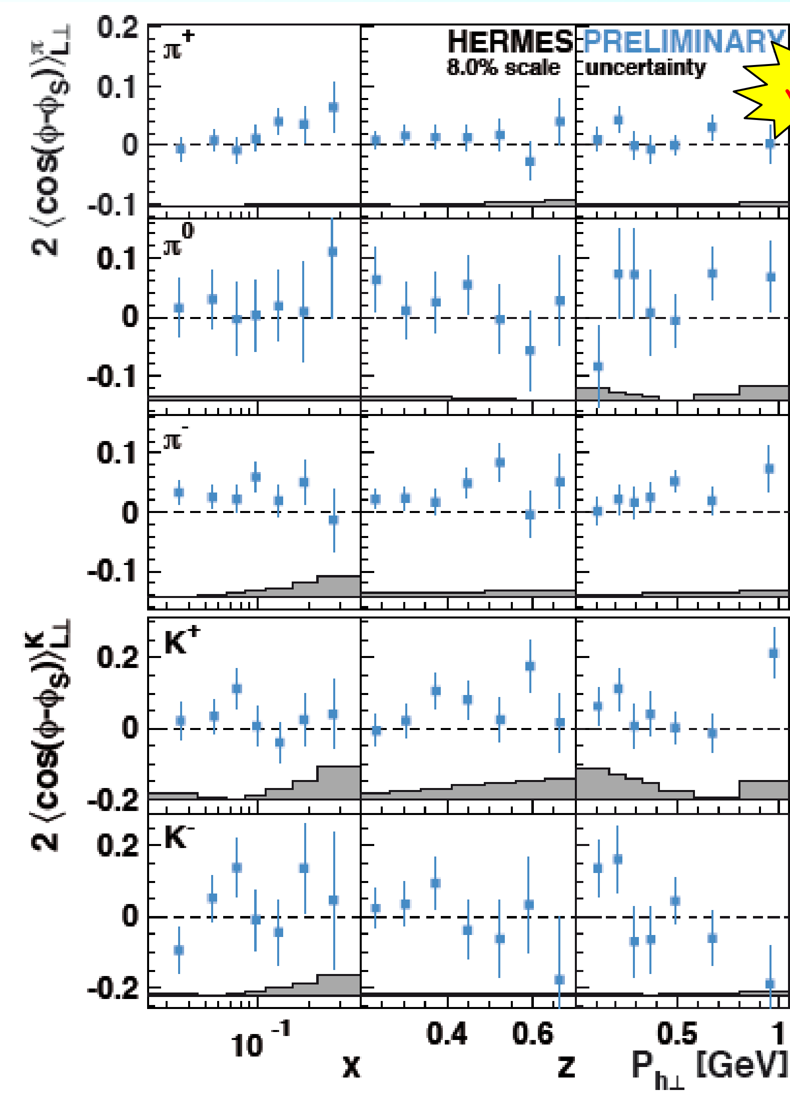
new



- $h_1^{\perp}$ is chiral-odd and naive T-odd (like $f_{1T}^{\perp}$) requires FSI/ISI
- Opposite sign for π+ and π-, larger magnitude for π-
- $h_1^{\perp,u}$ and $h_1^{\perp,d}$ have same sign
- Large signal with same sign for $K^{\pm}$
- sea fragmentation important

Worm-gear DF $g_{1T}^{\perp,q}$

longitudinally polarised quarks in transversely polarised nucleon



new

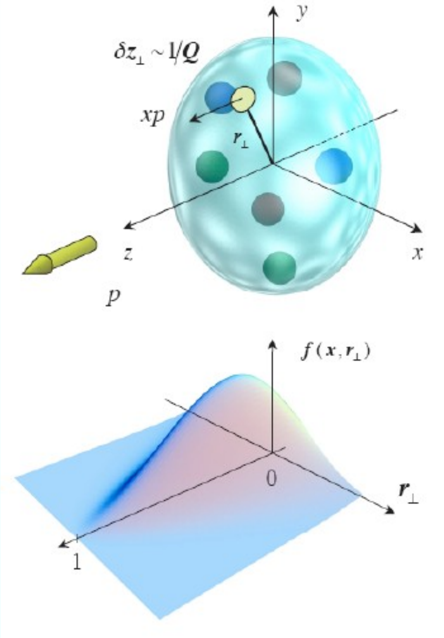
$\sigma_{LT}^{\cos(\phi-\phi_S)} \propto g_{1T}^{\perp,q} \otimes D_1^{q\to h}$

N/q	U	L	T
U	f_1		$h_1^{\perp}$ ⊥
L	⊥	g_1 ⊥	h_{1L} ⊥
T	f_{1T}	g_{1T}	h_1 h_{1T}

- Related to parton orbital motion: requires interference between wave functions with OAM difference by 1 unit
- Slightly non-zero
- $g_{1T}^{\perp,q} = - h_{1L}^{\perp,q}$ (supported by many models)
- $g_{1T}^{\perp,q} \approx x \int_x^1 \frac{dy}{y} g_1^q(y)$ (Wandzura-Wilczek type approximation)

Exclusive Measurements

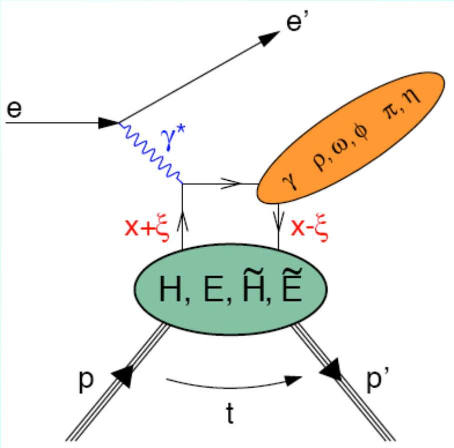
Generalised parton distributions



- Generalisation of Form Factors (moments of GPDs) and PDFs (forward limit)
- Correlated information about longitudinal momentum xp and transverse spatial position $r_\perp$
- Ji relation:

$$J_q = 1/2\Delta\Sigma + L_q = \lim_{t\to 0} \int_{-1}^{1} dx\, x\, [H(x,\zeta,t) + E(x,\zeta,t)]$$

Access: *exclusive processes*



- Final state sensitive to different GPDs
- Spin-½ target: 4 chiral-even leading-twist quark GPDs
- H,H̃ (E,Ẽ) conserve (flip) nucleon helicity
- Vector mesons (ρ, ω, ϕ) H, E
- Pseudoscalar mesons(π, η) H̃, Ẽ
- DVCS (γ) H, E, H̃, Ẽ

Hard exclusive ρ^0-meson production I

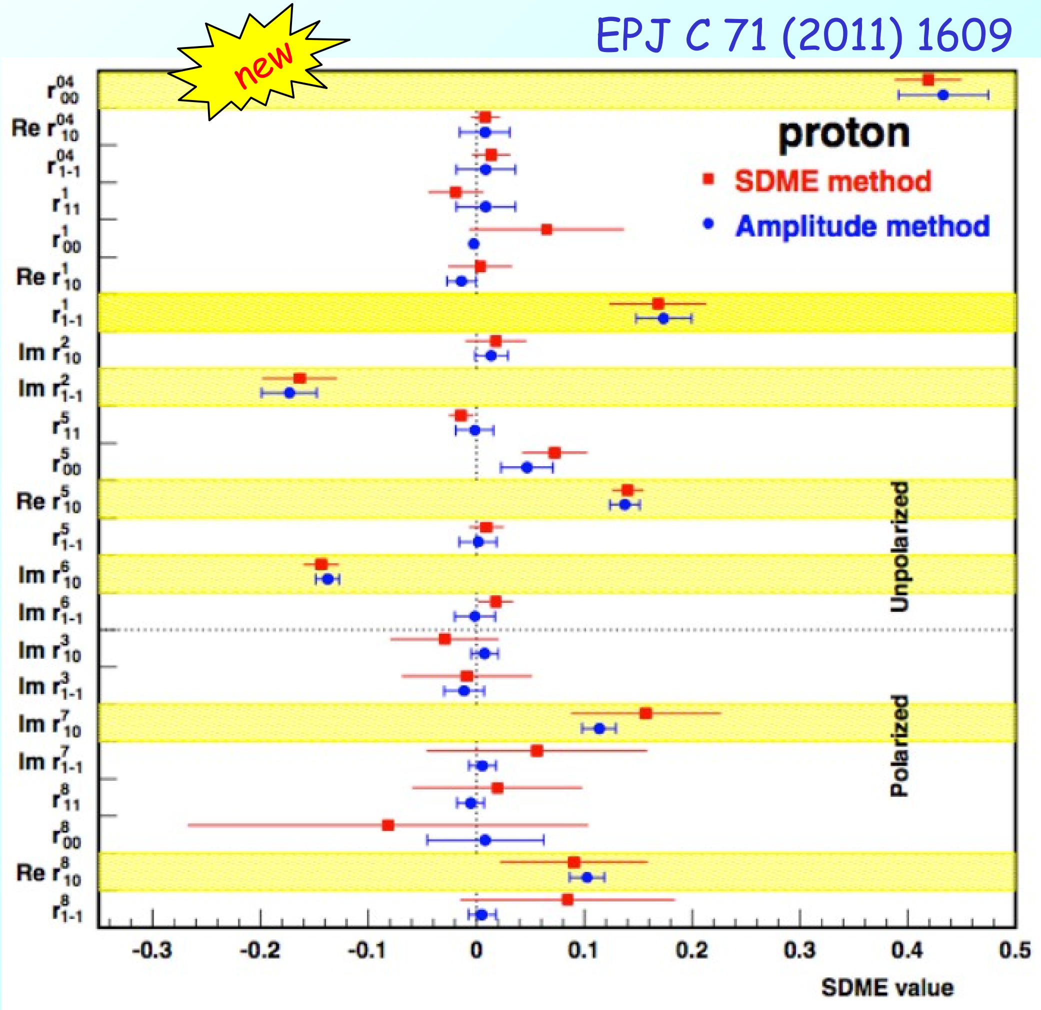
Meson SDMEs
EPJC 62 (2009) 659

Photon SDMEs

$$r^{\eta}_{\lambda_V \mu_V} = \frac{1}{2N} \sum_{\lambda_\gamma \mu_\gamma \lambda'_N \lambda_N} F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \Sigma^{\eta}_{\lambda_\gamma \mu_\gamma} F^{*}_{\mu_V \lambda'_N \mu_\gamma \lambda_N}$$

Helicity amplitudes
$F_{\lambda_V \lambda_\gamma} = T_{\lambda_V \lambda_\gamma} + U_{\lambda_V \lambda_\gamma}$

EPJ C 71 (2011) 1609



- Helicity amplitudes are the fundamental quantities to be compared with theory
- They form a basis for the SDMEs
- Re-derived SDMEs consistent with published ones
- Enhanced sensitivity for polarised SDMEs

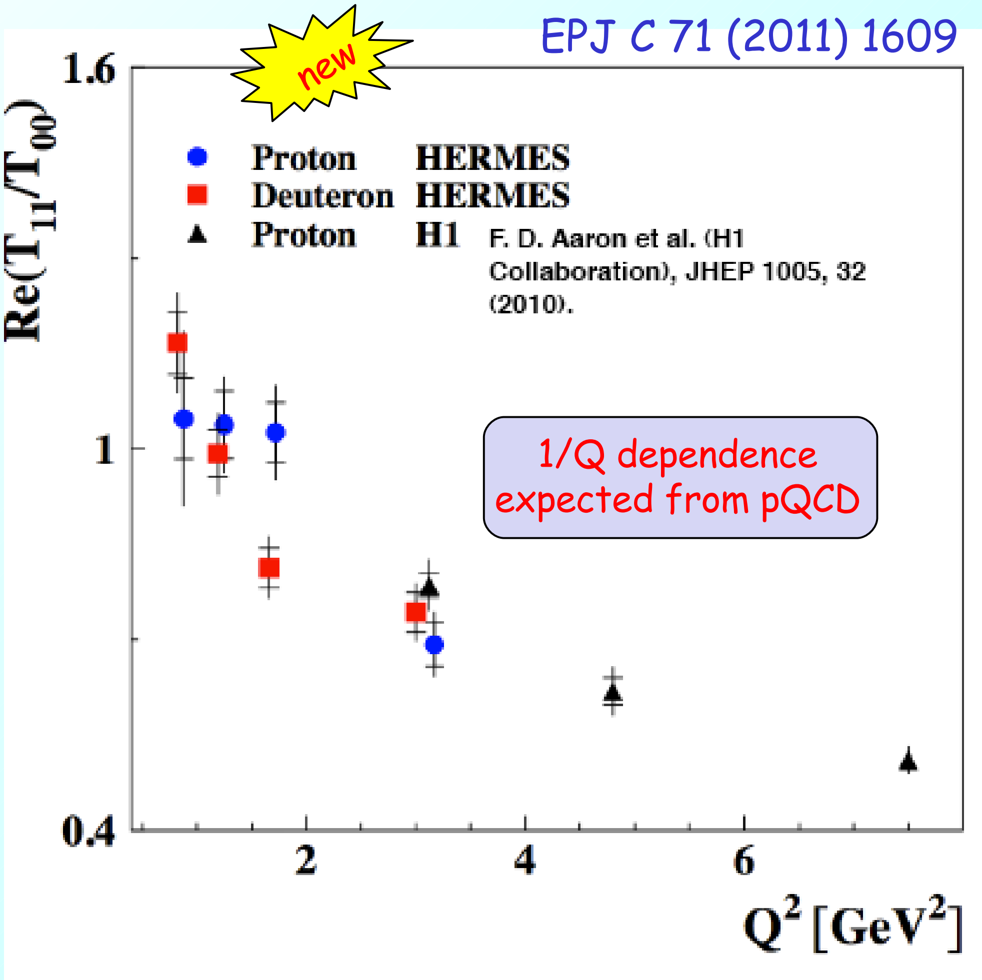
Hard exclusive ρ^0-meson production II

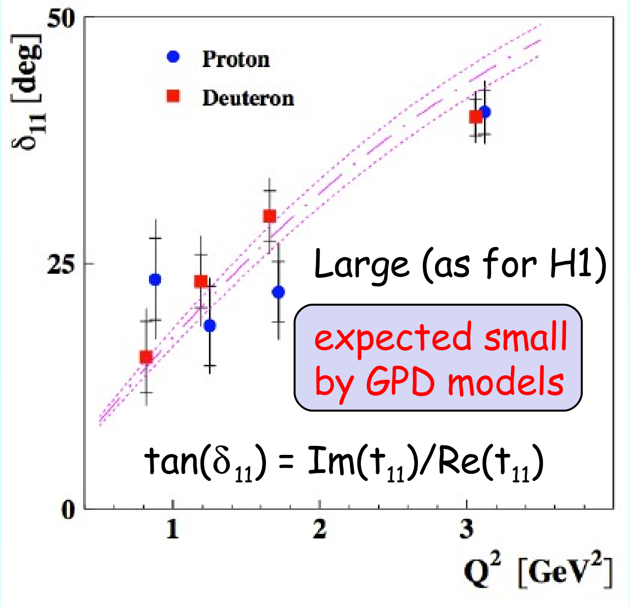
Hierarchy predicted by theory, confirmed by HERMES

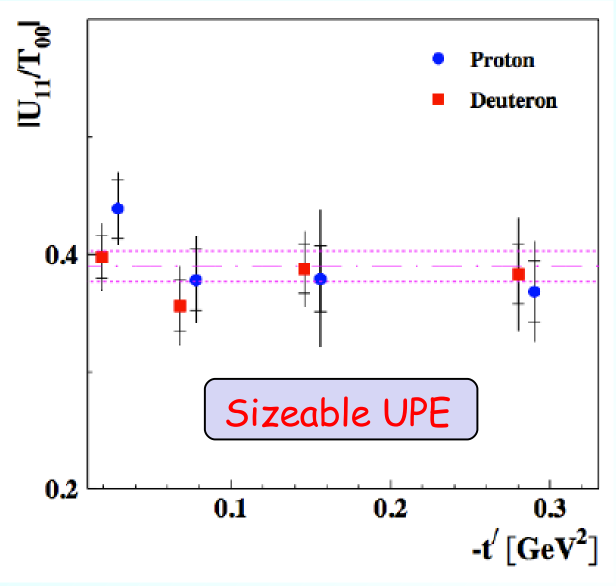
$$|T_{00}|^2 \approx |T_{11}|^2 >> |U_{11}|^2 > |T_{01}|^2 >> |T_{10}|^2 \ldots$$

$\gamma^*_L \to \rho_L$ $\gamma^*_T \to \rho_T$ $\gamma^*_T \to \rho_L$ $\gamma^*_L \to \rho_T$

EPJ C 71 (2011) 1609

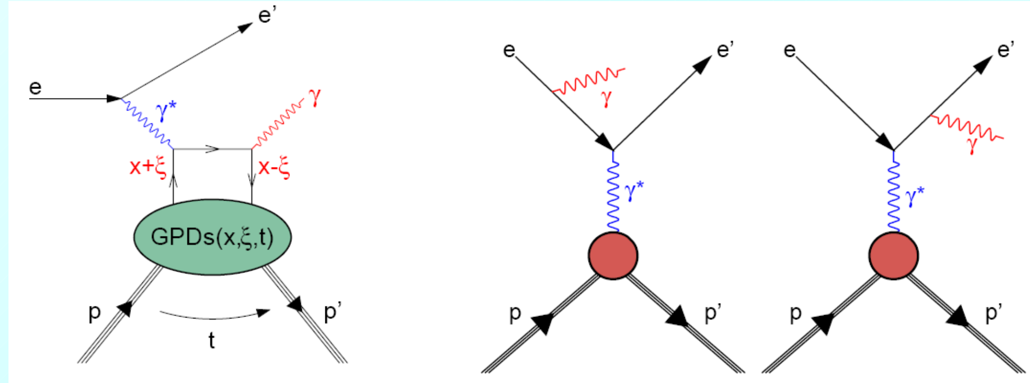






Deeply Virtual Compton Scattering & GPDs

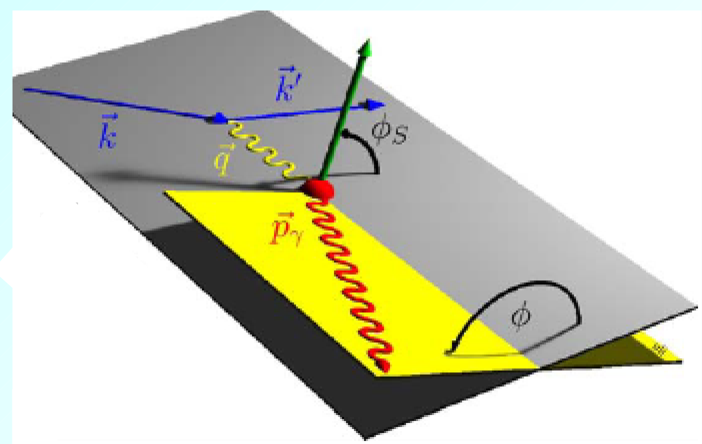
- Theoretically cleanest way to access GPDs
- Interference between DVCS and Bethe-Heitler amplitude
- $|T_{DVCS}| \ll |T_{BH}|$ @ HERMES



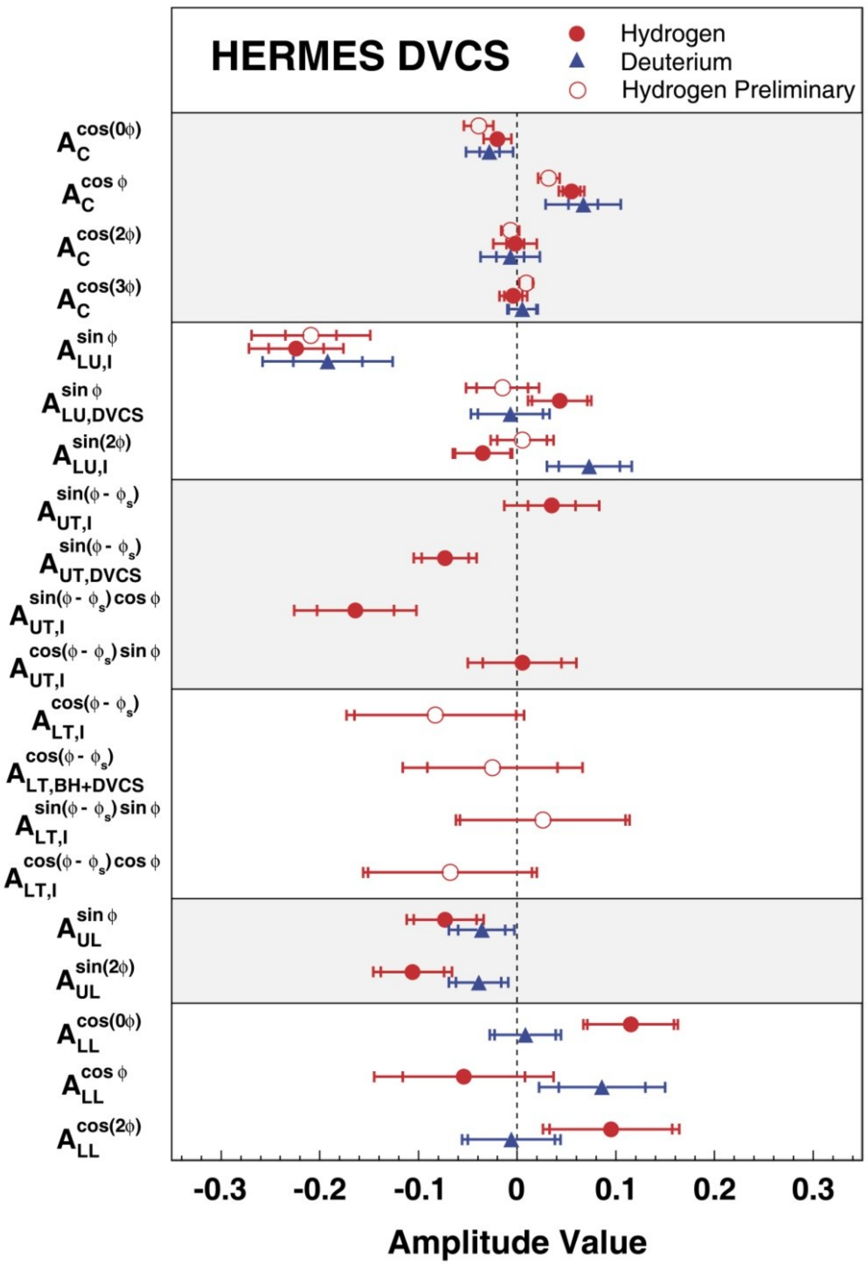
- Access to GPD combinations through azimuthal asymmetries A_{XY} (X: beam, Y: target polarisation)

HERMES: Complete set of asymmetries

- Both beam charges
- Both beam helicities
- Unpolarised H, D and nuclear targets
- Longitudinally polarised H and D targets
- Transversely polarised H target



DVCS asymmetries measured @ HERMES



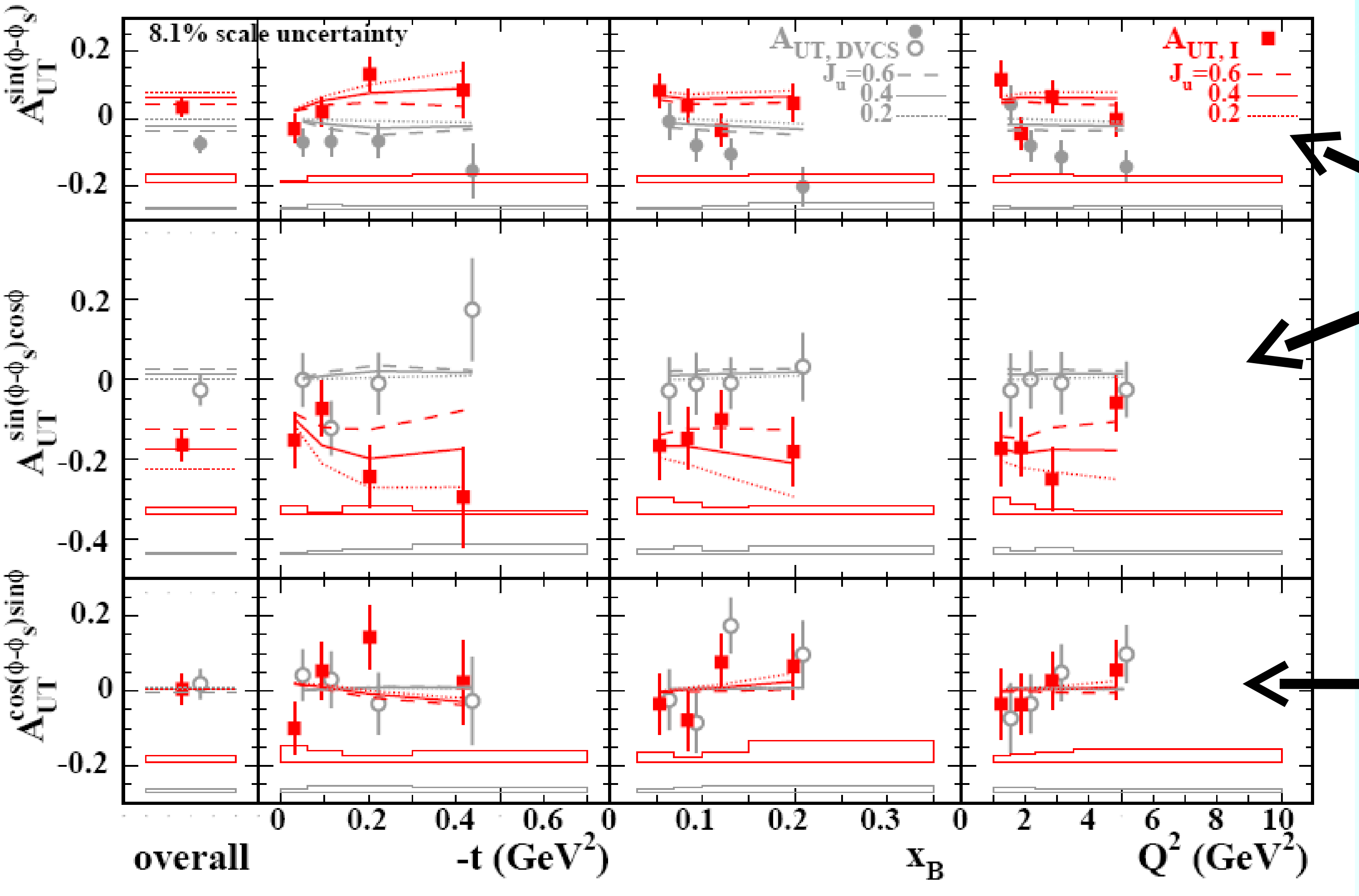
- Beam charge asymmetry
  GPD H
  H: PRL 87 (2001) 182001
  PR D 75 (2007) 011103
  JHEP 11 (2009) 083
  D: Nucl. Phys. B 829 (2010) 1
- Beam helicity asymmetry
  GPD H
- Transverse target-spin asymmetry
  GPD E
  H: JHEP 06 (2008) 066
- Transverse double-spin asymmetry
  GPD E
  H: arXiv:1106.2990 *new*
- Longitudinal target spin asymmetry
  GPD $\tilde{H}$
  H: JHEP 06 (2010) 019
  D: Nucl. Phys. B 842 (2011) 265 *new*
- Longitudinal double spin asymmetry
  GPD $\tilde{H}$

DVCS: transverse target asymmetry A_{UT}

Sensitive to GPD E

JHEP 06 (2008) 066

old



sensitive to J_u:

$\mathrm{Im}(F_2\mathcal{H} - F_1\mathcal{E}) \cdot \sin(\phi - \phi_s)\cos(n\phi)$

NOT sensitive to J_u:

$\mathrm{Im}\left(F_2\widetilde{\mathcal{H}} - (F_1 + \xi F_2)\widetilde{\mathcal{E}}\right) \cdot \cos(\phi - \phi_s)\sin\phi$

- Model: VGG with variation of J_u, while J_d=0

DVCS transverse double-spin asymmetry A_{LT}

Beam charge

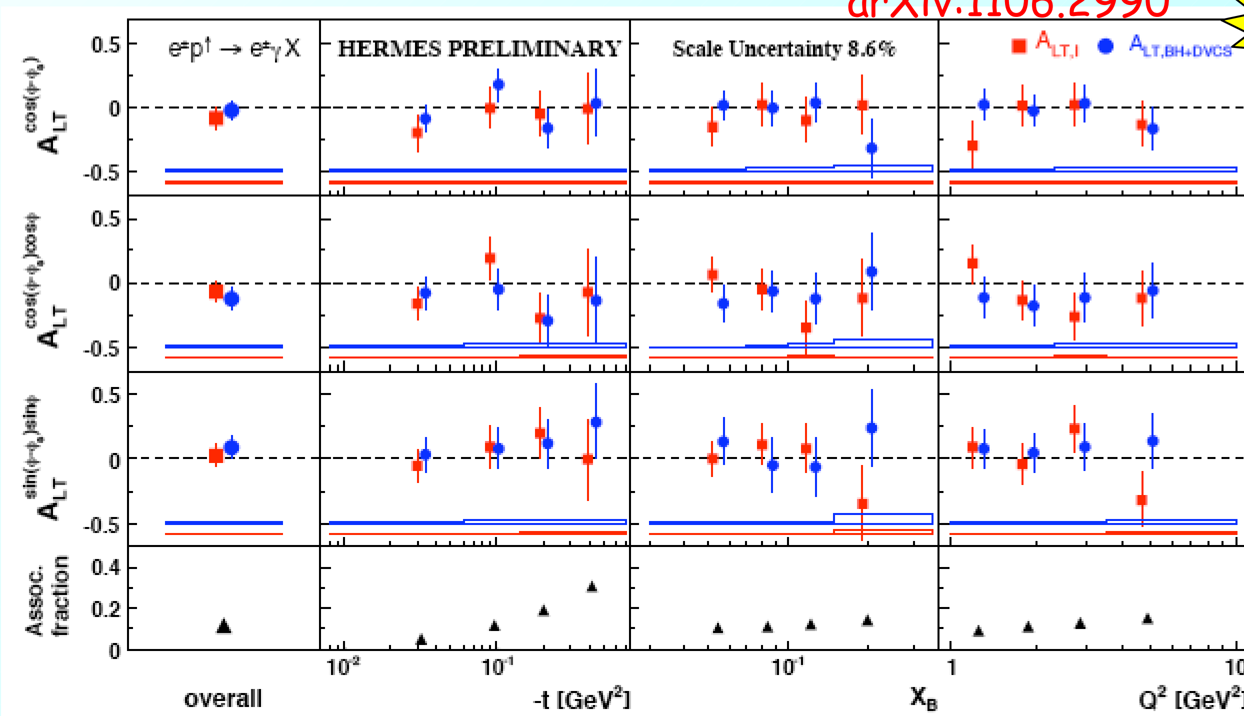
Beam polarisation

Target polarisation

$$\langle \mathcal{N}(e_\ell, P_l, S_t, \phi, \phi_S)\rangle \propto \sigma_{UU}(\phi)[1 + \cdots + P_l S_t \mathcal{A}_{LT}^{BH+DVCS} + e_\ell P_l S_t \mathcal{A}_{LT}^{I}]$$

arXiv:1106.2990

new



$$\propto A_{LT}^{\cos(\phi-\phi_S)\cos(\phi)}$$

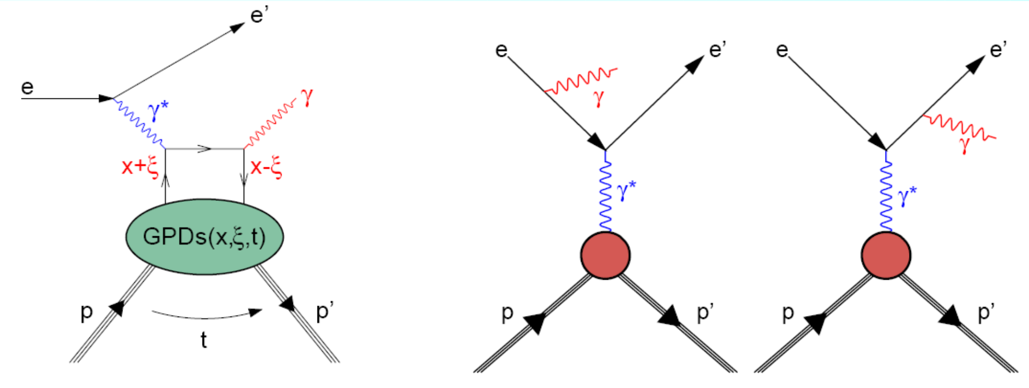
$$\propto \begin{matrix} \mathcal{R}e[F_2\tilde{\mathcal{H}} - (F_1 + \xi F_2)\tilde{\mathcal{E}}] \\ \mathcal{R}e[\mathcal{H}\mathcal{E}^* - \mathcal{E}\mathcal{H}^* - \xi(\tilde{\mathcal{H}}\tilde{\mathcal{E}}^* - \tilde{\mathcal{E}}\tilde{\mathcal{H}}^*)] \end{matrix}$$

$$\propto \begin{matrix} \mathcal{R}e[F_2\mathcal{H} - F_1\mathcal{E}] \\ \mathcal{R}e[-\tilde{\mathcal{H}}\mathcal{E}^* - \tilde{\mathcal{H}}^*\mathcal{E} + \xi(\mathcal{H}\tilde{\mathcal{E}}^* + \tilde{\mathcal{E}}\mathcal{H}^*)] \end{matrix}$$

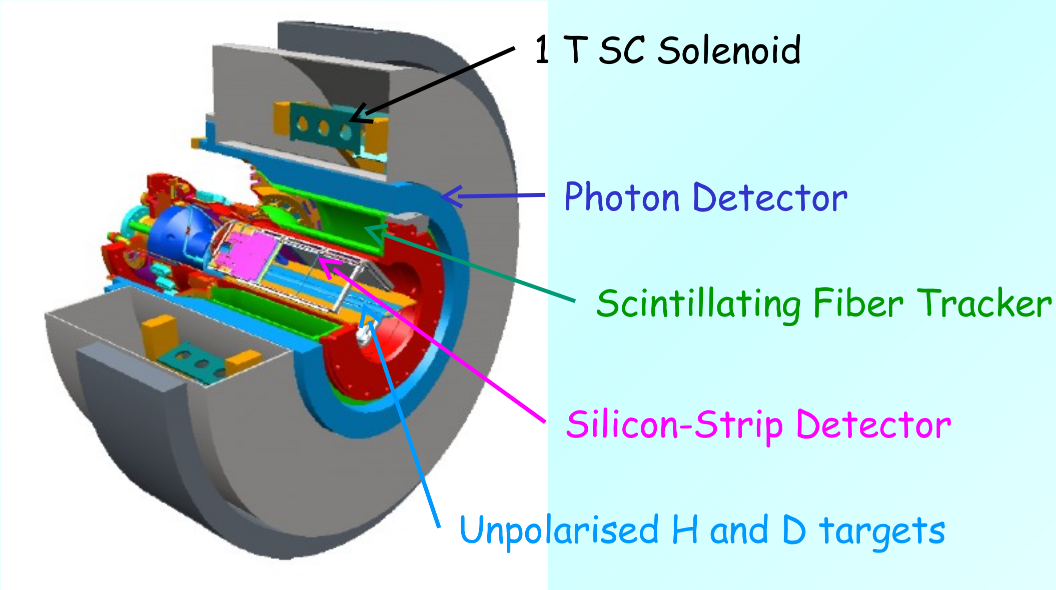
Sensitive to both GPDs entering the Ji sum rule

- Consistent with zero, cancellations between E and H
  Sensitivity to J_u suppressed by kinematic factors

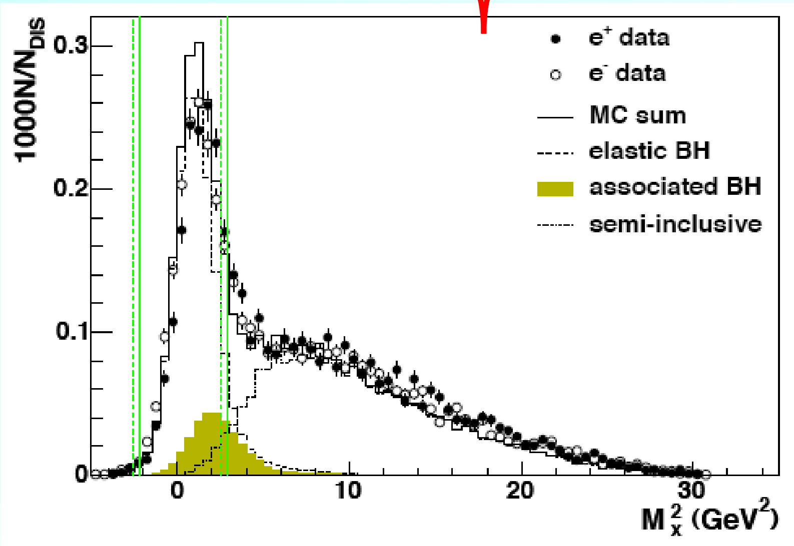
DVCS with Recoil Detector



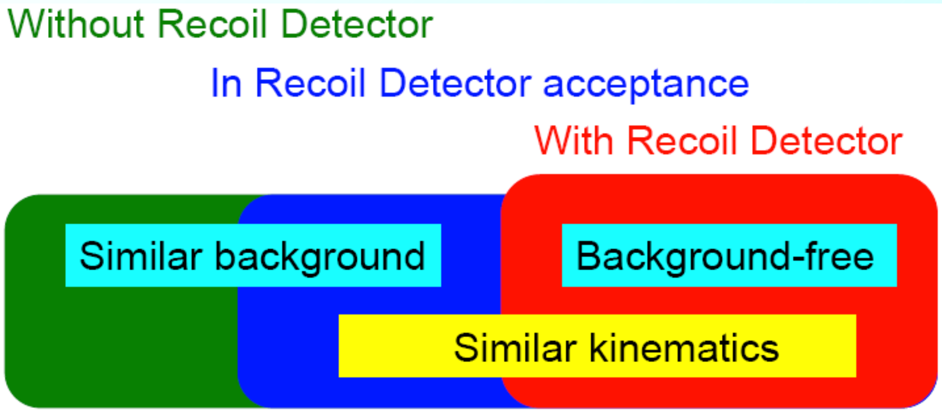
Recoil Detector to tag exclusivity

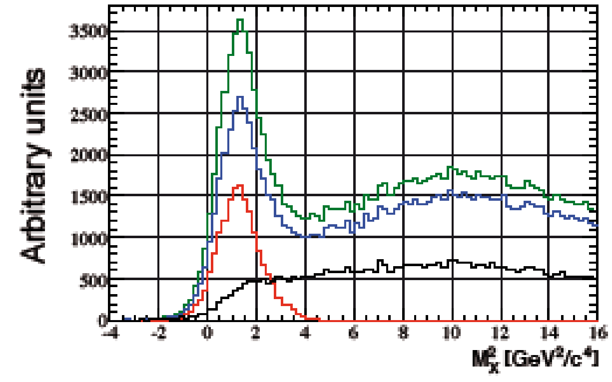


$e\,p \rightarrow e\,\gamma\,p$

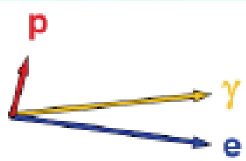


DVCS with Recoil Detector

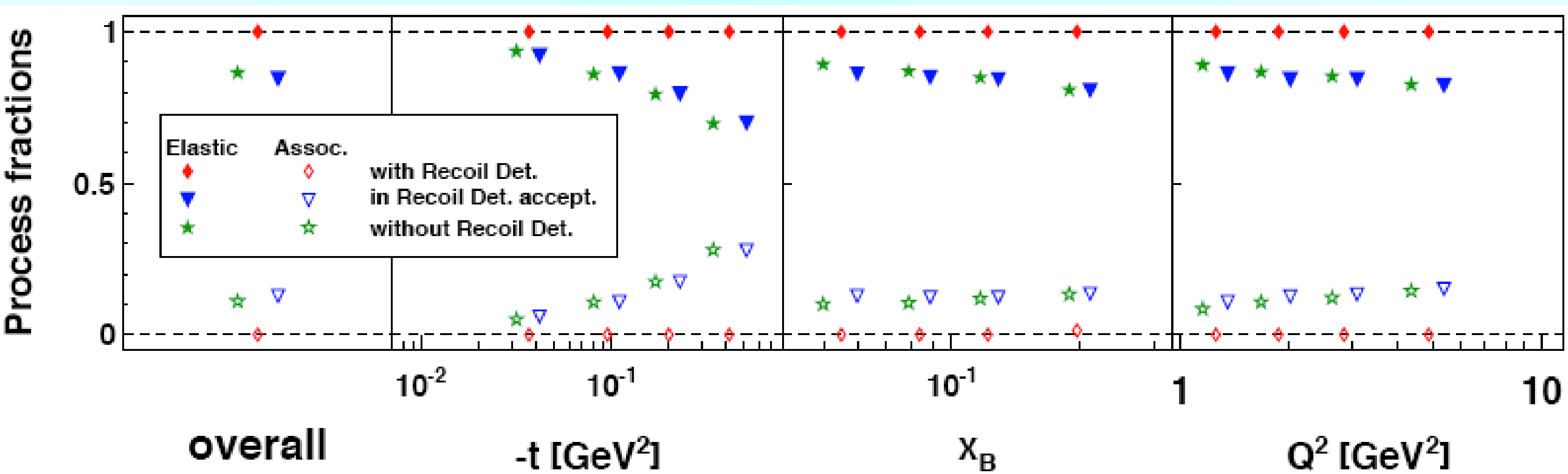




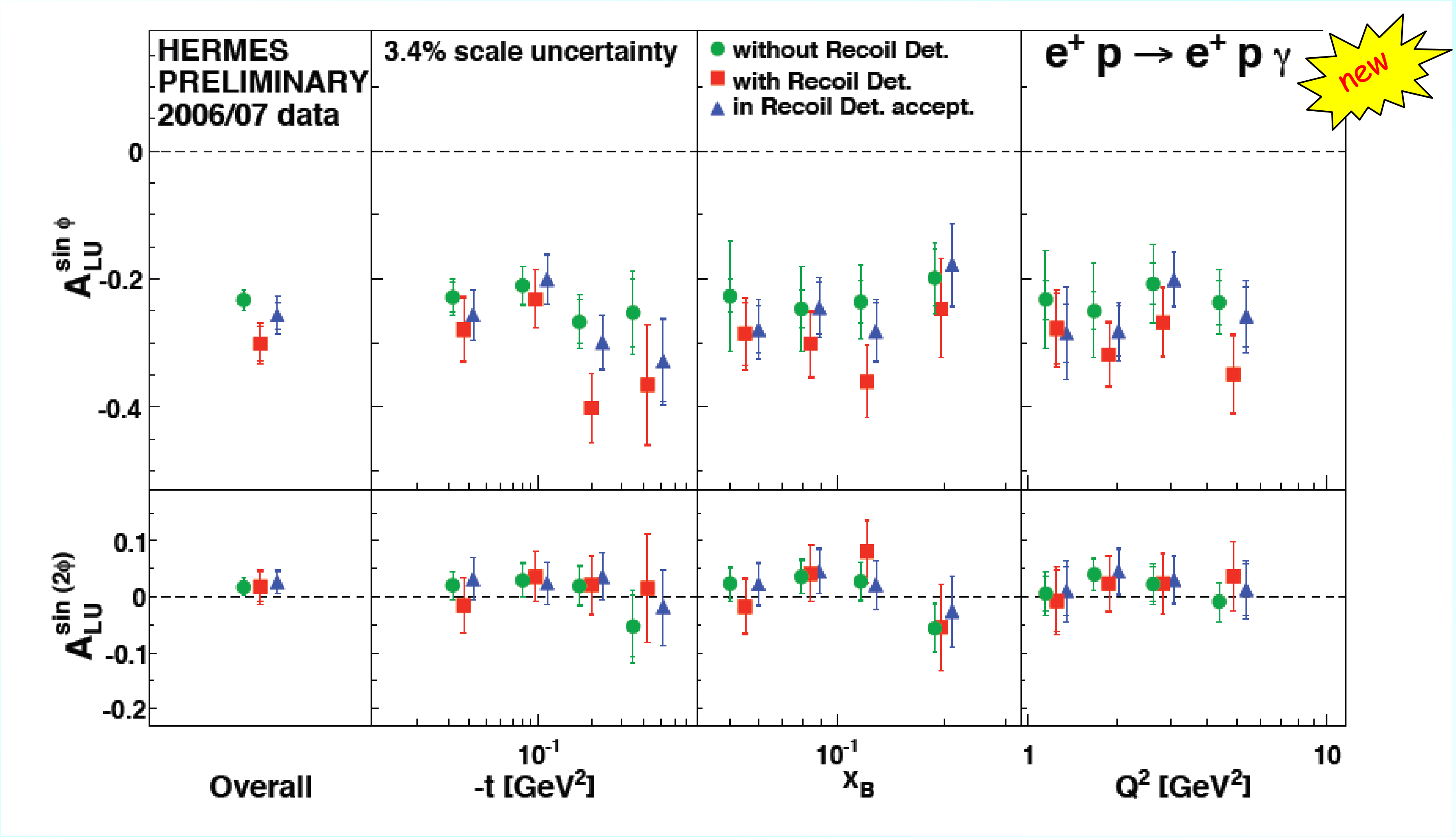
Kinematic event fitting technique: all 3 particles in the final state detected should satisfy 4-constraints on energy-momentum conservation



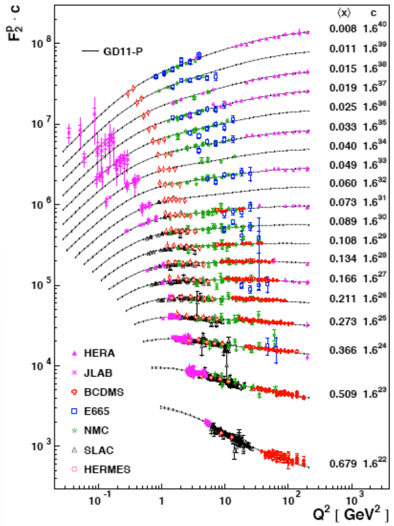
- No requirement for Recoil
- Charged recoil track in acceptance
- Kinematic fit probability > 1 %
- Kinematic fit probability < 1 %



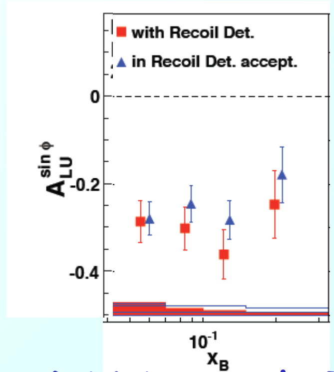
Pure elastic DVCS



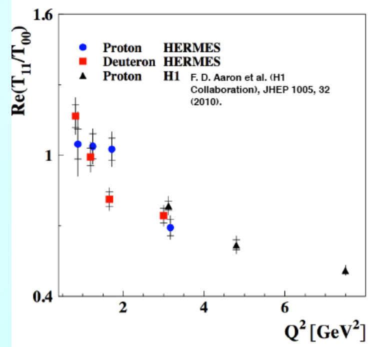
- Indication that leading amplitude for pure elastic process is slightly larger than for unresolved signal (elastic + associated)



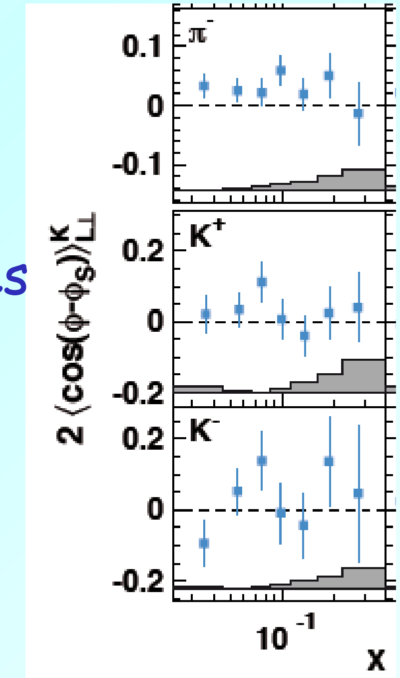
F_2



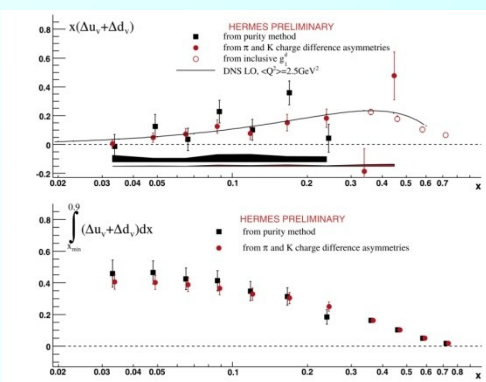
DVCS with RD



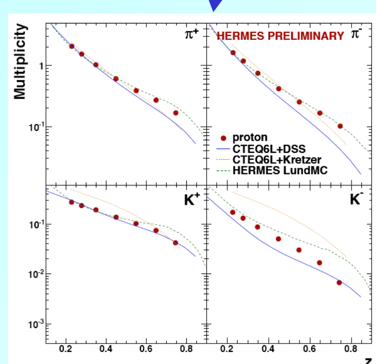
ρ Helicity amplitudes



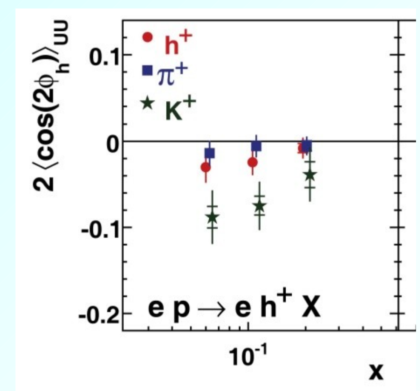
Worm-gear DF



$x(\Delta u_v + \Delta d_v)$



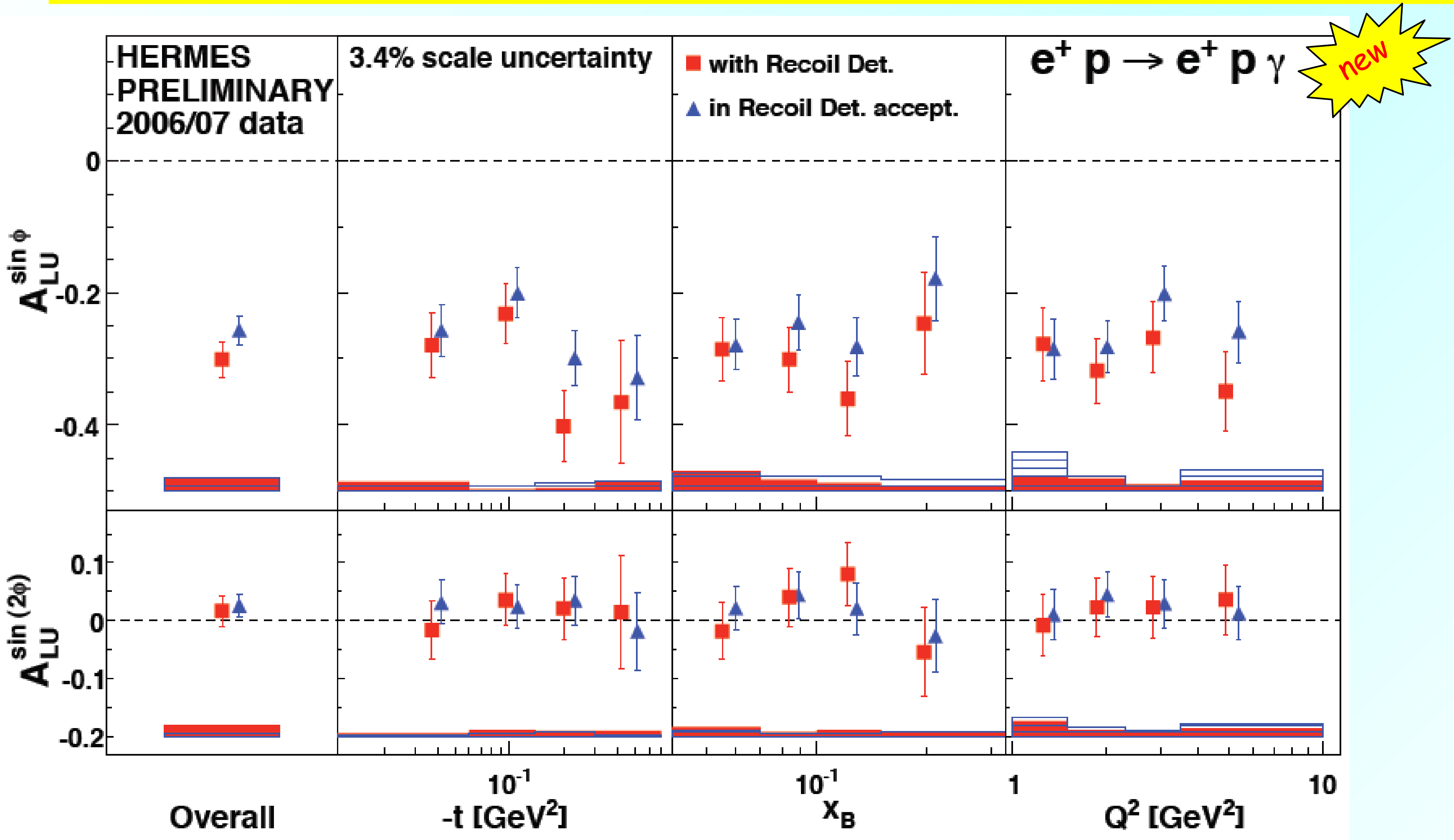
Hadron Multiplicities



Boer-Mulders DF

Backups

Pure elastic DVCS



- Indication that leading amplitude for pure elastic process is slightly larger than for unresolved signal (elastic + associated)

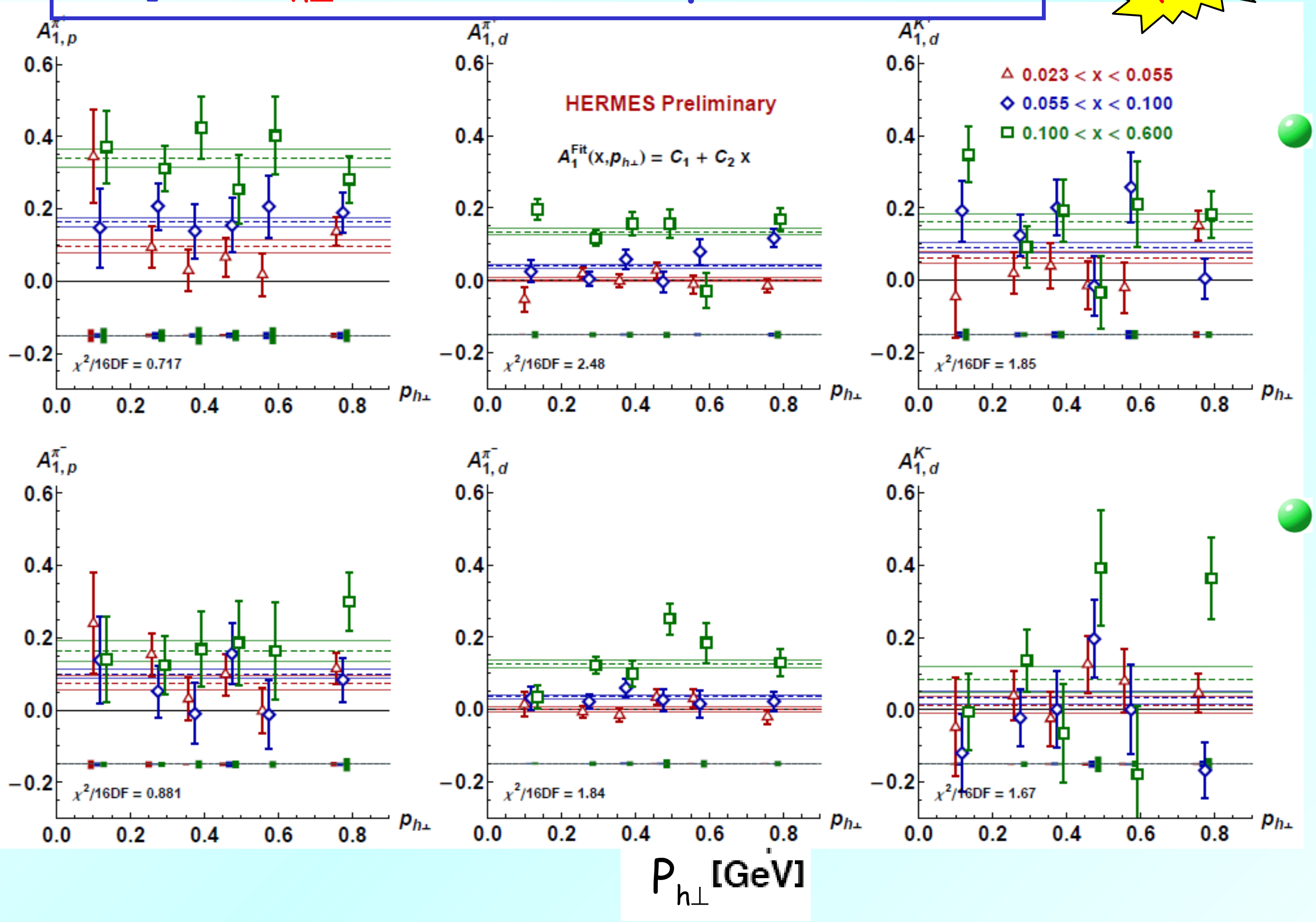
Double-spin asymmetry A_1^h

$\sigma_{LL} \propto g_1^q \otimes D_1^{q \to h}$

Refined studies extending the work in Phys. Rev. D 71 (2005) 012003

$A_1^h(x, P_{h\perp})$ 2D - dependencies

new



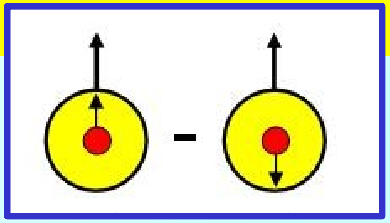
- Sensitive to differences in transverse momentum dependence of g_1 and f_1
- No significant $P_{h\perp}$ dependence observed

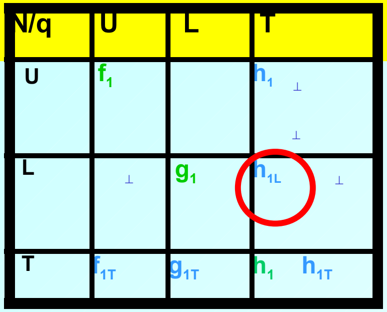
Transversity, Collins Amplitudes

Transversity DF

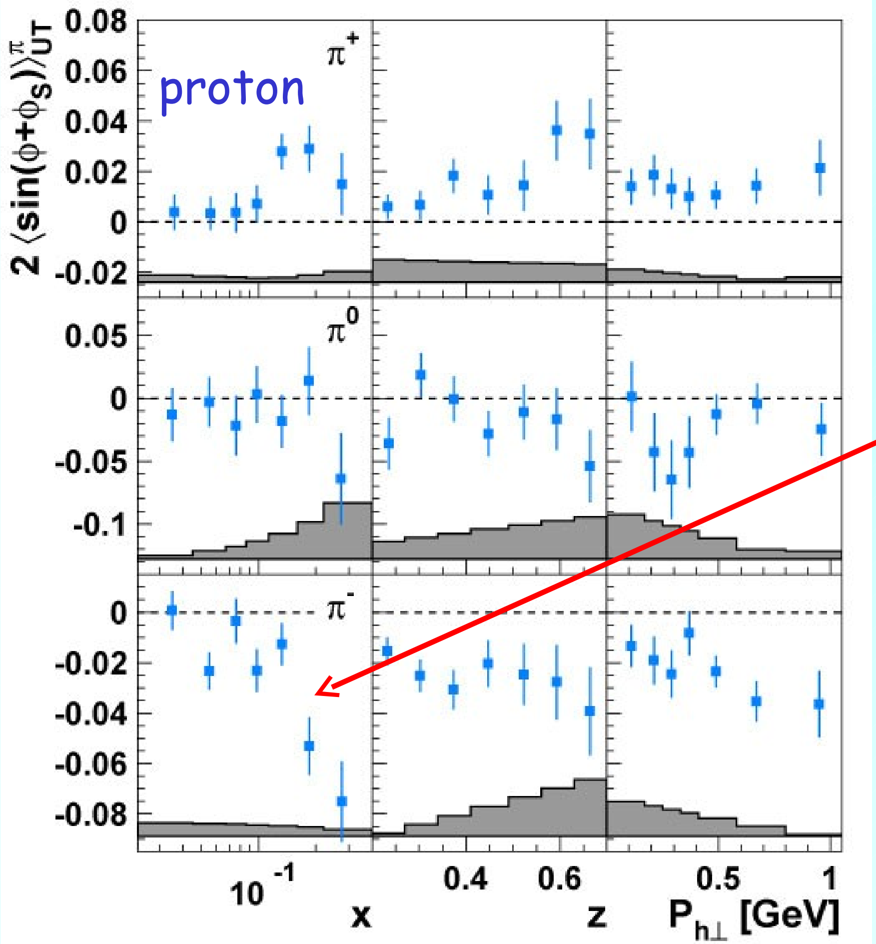
$2\langle\sin(\phi+\phi_S)\rangle^h_{UT} \propto h_1^q(x) \otimes H_1^{\perp q}(z)$

Collins FF





arXiv:1006.4221



- Both Collins fragmentation function and transversity distribution function are sizeable
- Surprisingly large π^- asymmetry
- Possible source: large contribution (with opposite sign) from unfavored fragmentation,

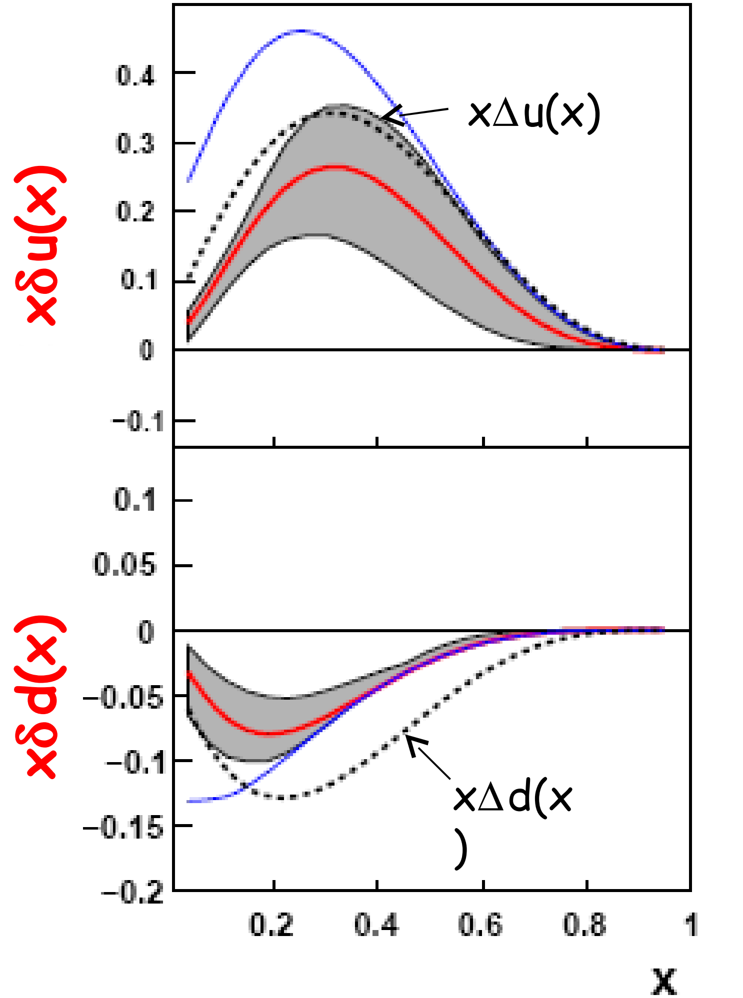
$H_1^{\perp}{}_{,disf} \approx -H_1^{\perp}{}_{,fav}$

Extraction of Transversity

Fit to HERMES (ep↑->ehX), COMPASS (μd↑->μhX),

BELLE (e^+e^- ->h^+h^-X) data

M. Anselmino et al., Nucl. Phys. Proc. Suppl. 191 (2009) 98

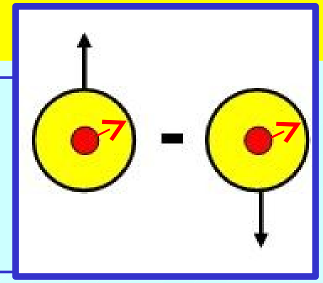


Sivers Amplitudes for Pions

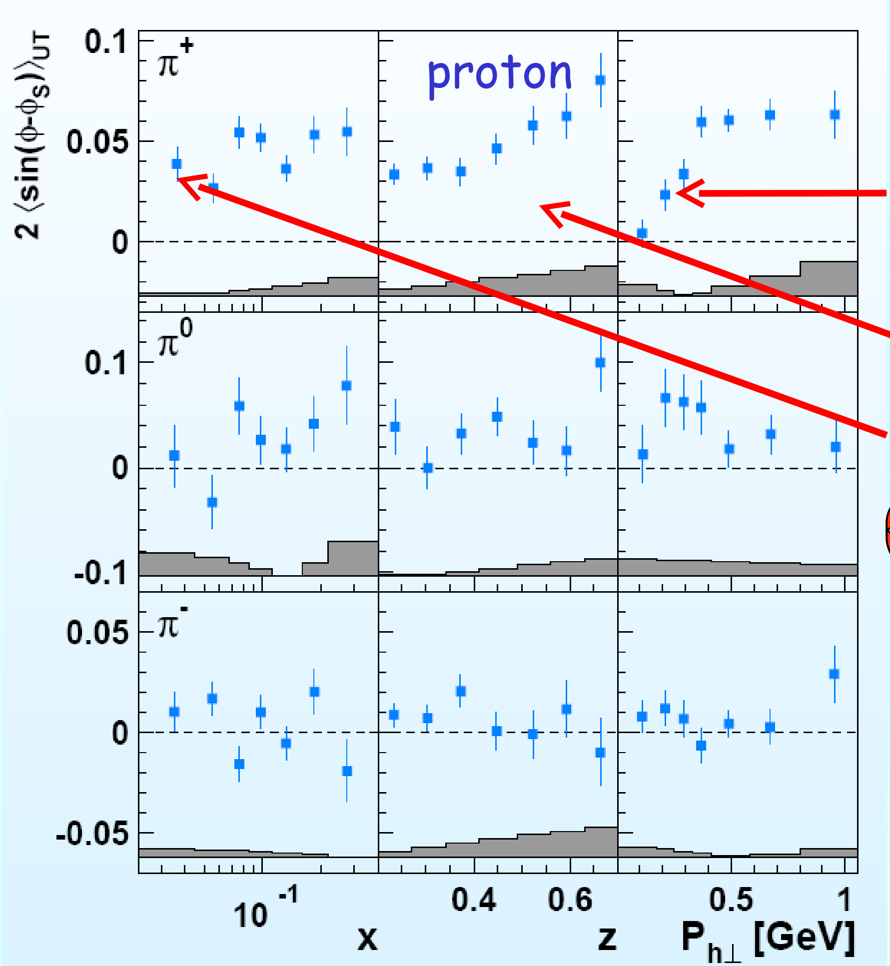
Sivers DF

$2\langle\sin(\phi - \phi_S)\rangle^h_{UT} \propto f_{1T}^{\perp,q}(x) \otimes D_1^q(z)$

PRL 103 (2009) 152002



N/q	U	L	T
U	f_1		$h_1^{\perp}$
L	$\perp$	g_1	$h_{1L}^{\perp}$
T	f_{1T}	g_{1T}	h_1 h_{1T}

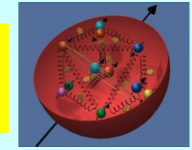


- First observation of non-zero Sivers DF in DIS
- Rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
- Clear rise with z
- Non-zero at low x

Experimental evidence for orbital angular momentum L_q of quarks

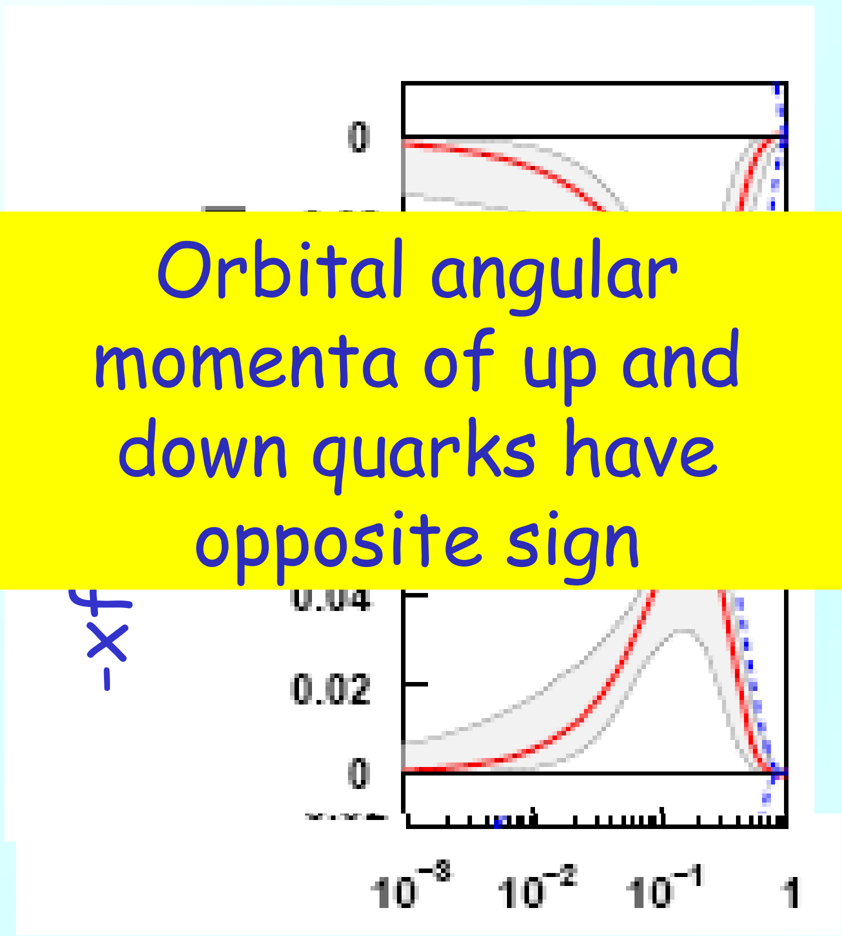
But: Quantitative contribution of L_q to nucleon spin still unclear

Sivers distribution



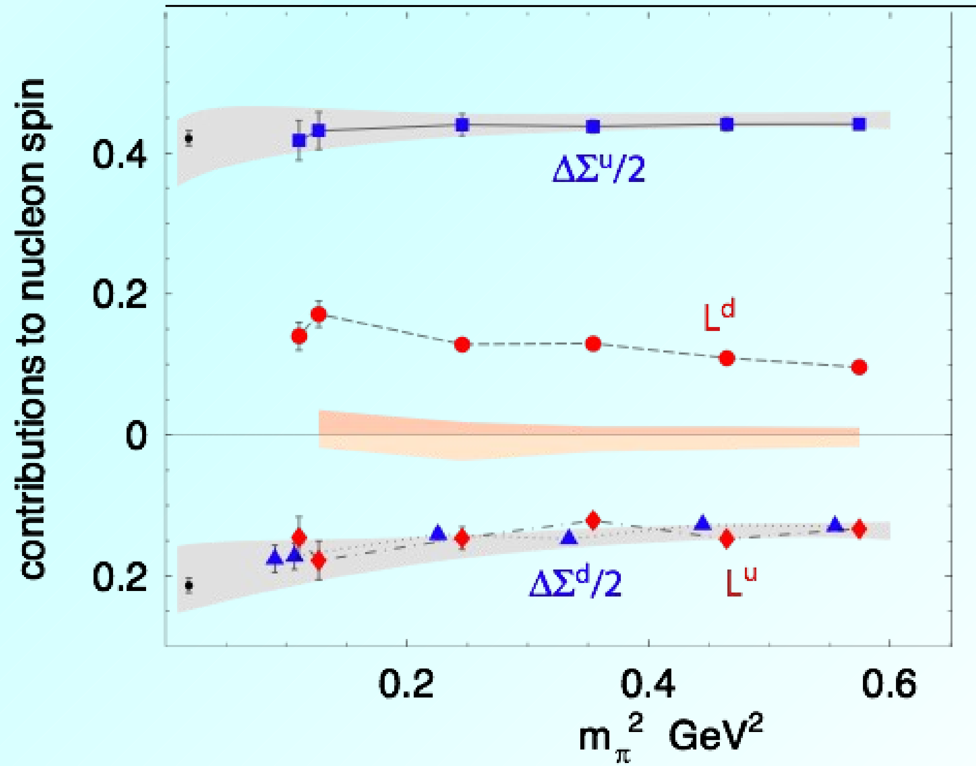
Fit to HERMES ($ep^{\uparrow} \to ehX$) and COMPASS ($\mu d^{\uparrow} \to \mu hX$) data

M. Anselmino et al., Phys. Rev. D79 (2009) 054010



Orbital angular momenta of up and down quarks have opposite sign

Lattice



$L_d \approx -L_u \approx 0.2$

$L_d + \Delta d/2 \approx 0$!??