Study of the spin structure at HERMES

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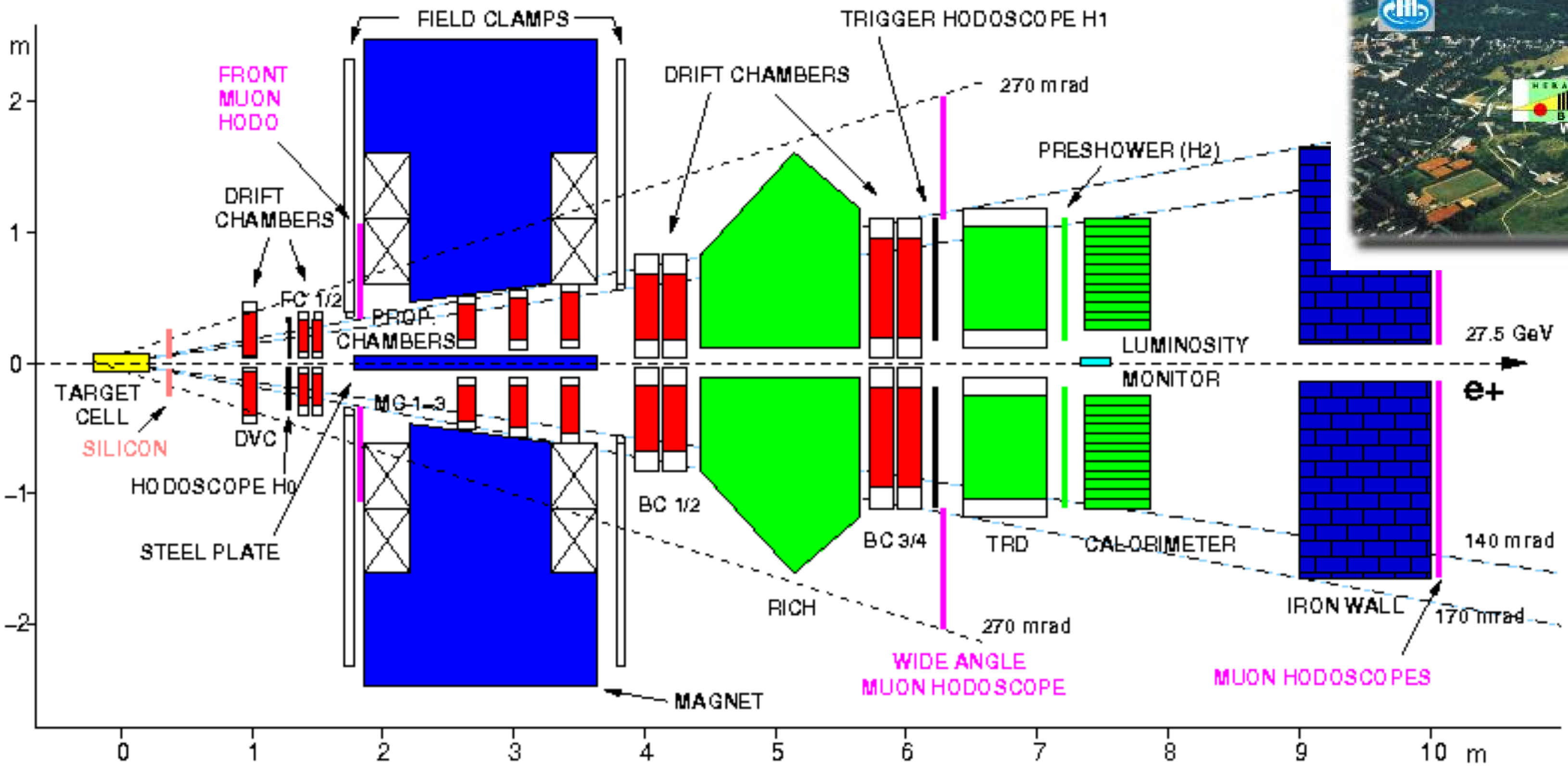
Outline

- The HERMES experiment
- The proton in 3D: generalized parton distributions
- Charge separated single-spin asymmetries
- The proton in 3D: transverse-momentum-dependent parton distributions
- Single-spin asymmetries in semi-inclusive DIS on a transversely polarised target
- Spin-independent non-collinear cross section

The HERMES experiment



data taking from 1995 until 2007

Beam

longitudinally polarised e+ & e-

E=27.6 GeV

Gaseous internal target

transversely polarised H

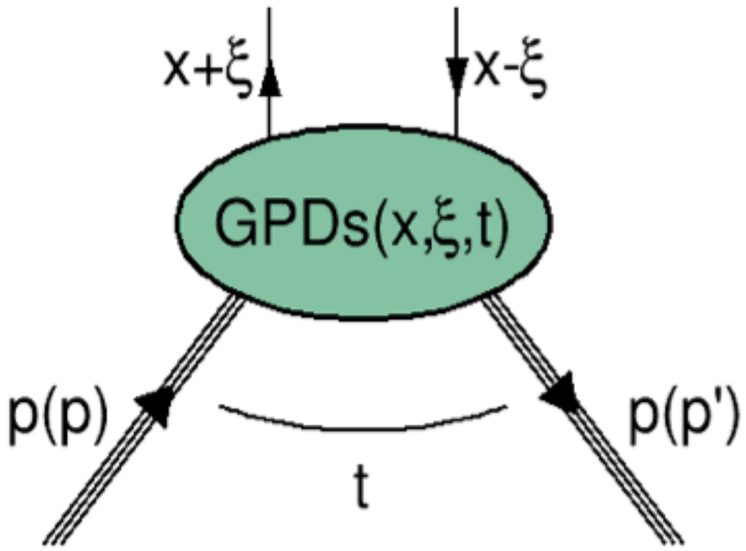
longitudinally polarised H,De,He

unpolarised H,De,He,Ne,Kr,Xe

Particle identification

- lepton-hadron PID: high-efficiency (>98%) & low contamination (<1%)
- hadron PID via RICH 2-15 GeV

Generalized Parton Distributions (GPDs)



x=average longitudinal momentum fraction

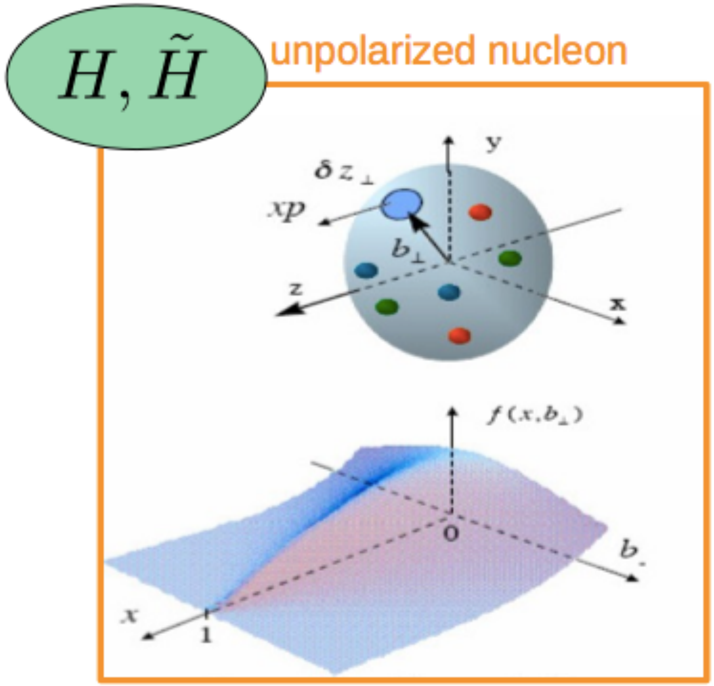
2ξ=average longitudinal momentum transfer

t=squared momentum transfer to nucleon

four quark helicity-conserving GPDs at twist-2

$H^q(x,\xi,t)$	$E^q(x,\xi,t)$	spin independent
$\tilde{H}^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$	spin dependent
proton-helicity non-flip	proton-helicity flip	

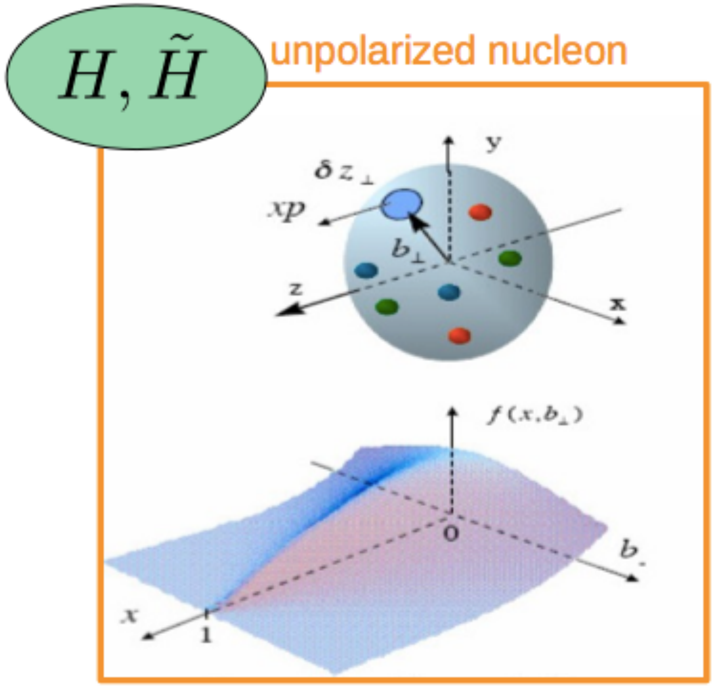
Generalized Parton Distributions (GPDs)

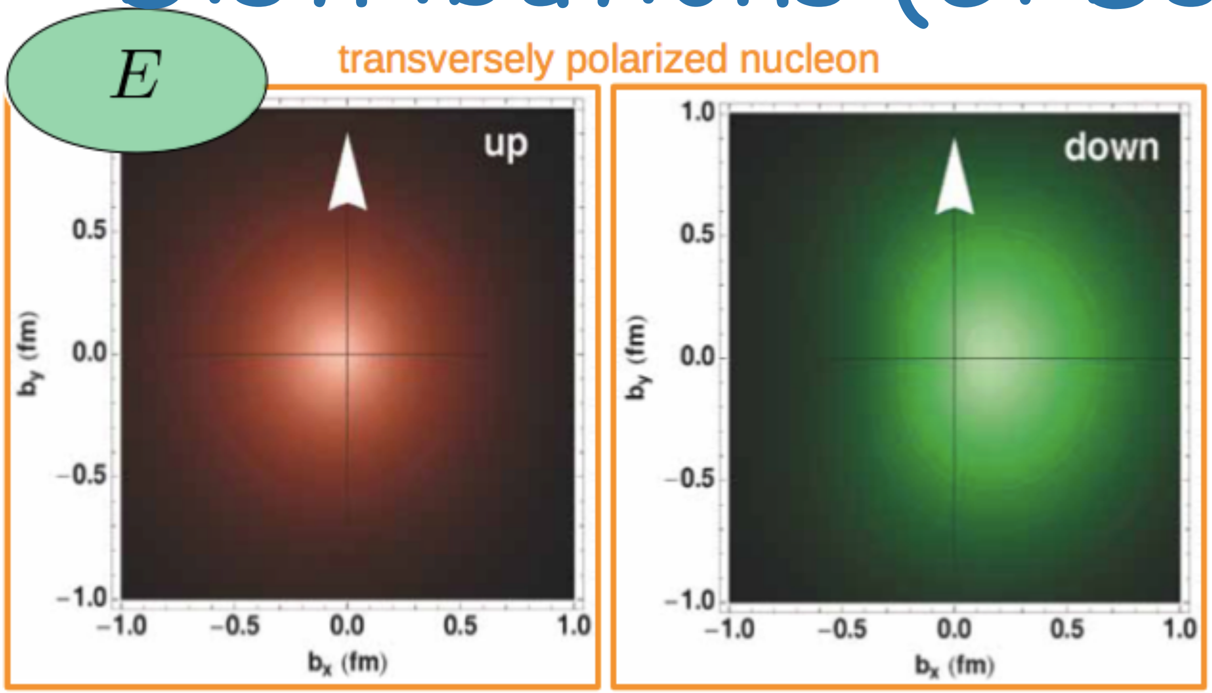


helicity-(in)dependent probability distribution of quarks as a function of their longitudinal fractional momentum and transverse position

M. Burkardt, Phys. Rev. D **62** (2000) 071503

Generalized Parton Distributions (GPDs)





pictures taken from A. Bacchetta and M. Contalbrigo, Il Nuovo Saggiatore **28** (2012) 1-2

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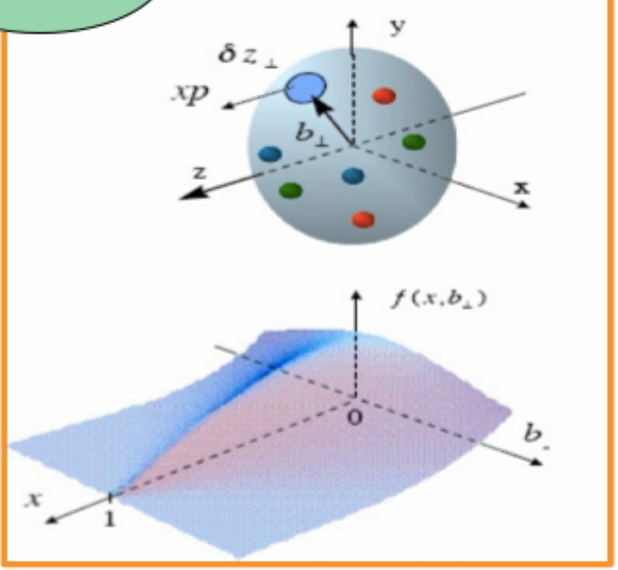
distortion of quark probability distribution compared to unpolarized nucleon

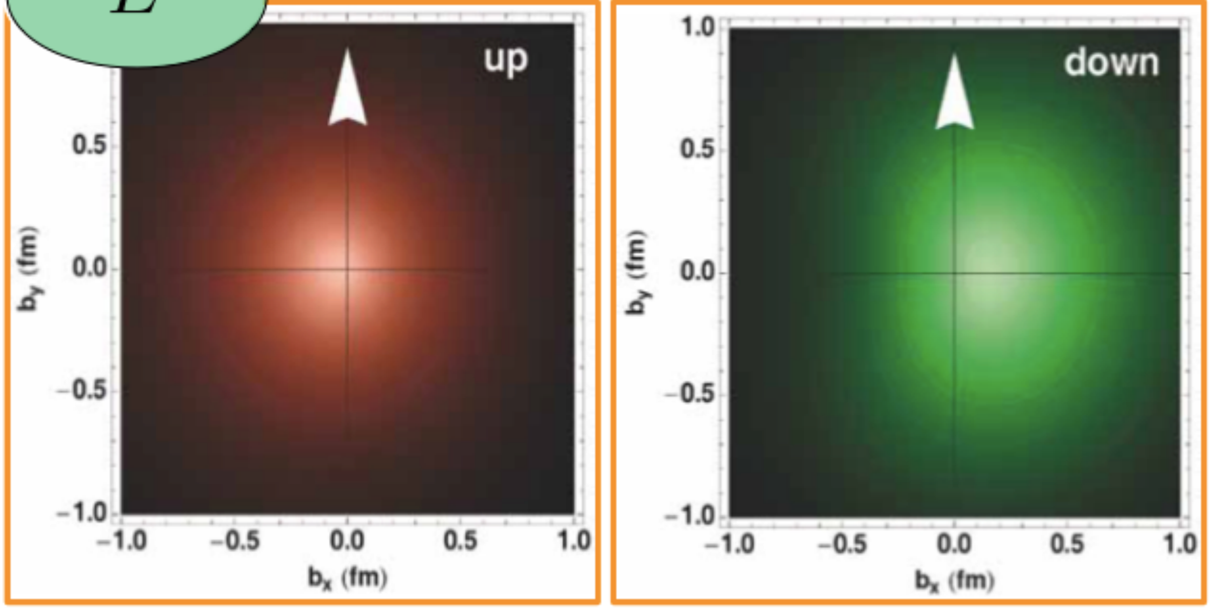
M. Burkardt, Phys. Rev. D **66** (2002) 114005

Generalized Parton Distributions (GPDs)

$H, \tilde{H}$ unpolarized nucleon



E transversely polarized nucleon



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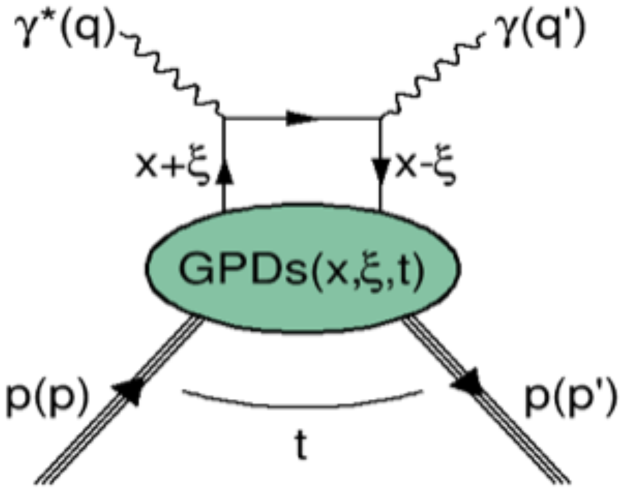
$$J^q = \lim_{t \to 0} \frac{1}{2} \int_{-1}^{1} dx \, x [H^q(x, \xi, t) + E^q(x, \xi, t)]$$ ➡ quark orbital angular momentum

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

Deeply virtual Compton scattering (DVCS)

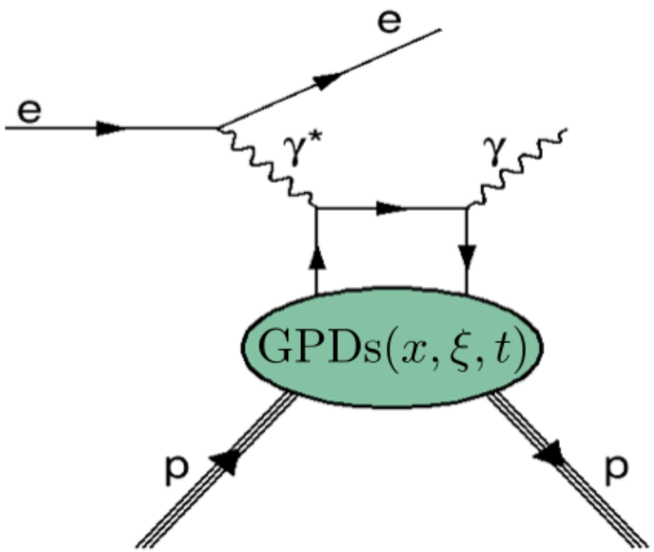


$$Q^2 \equiv -q^2$$

$$x_B \equiv \frac{Q^2}{2pq}$$

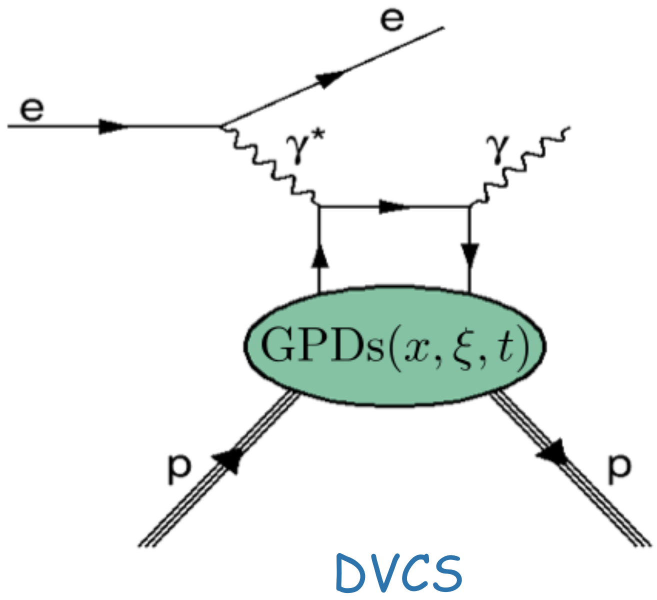
$$\xi \approx \frac{x_B}{2 - x_B}$$

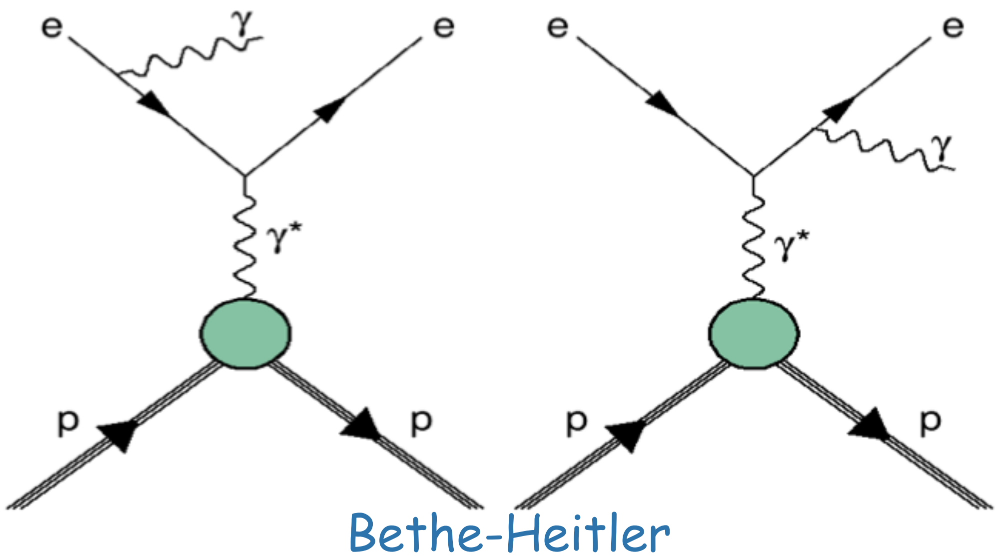
Exclusive lepto-production of real photons



DVCS

Exclusive lepto-production of real photons



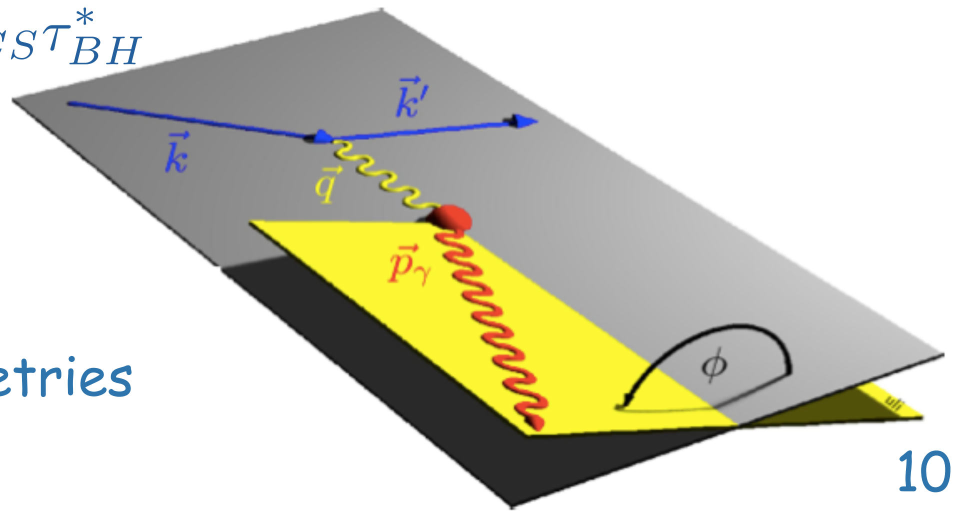


$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{BH}\tau^*_{DVCS} + \tau_{DVCS}\tau^*_{BH}$$

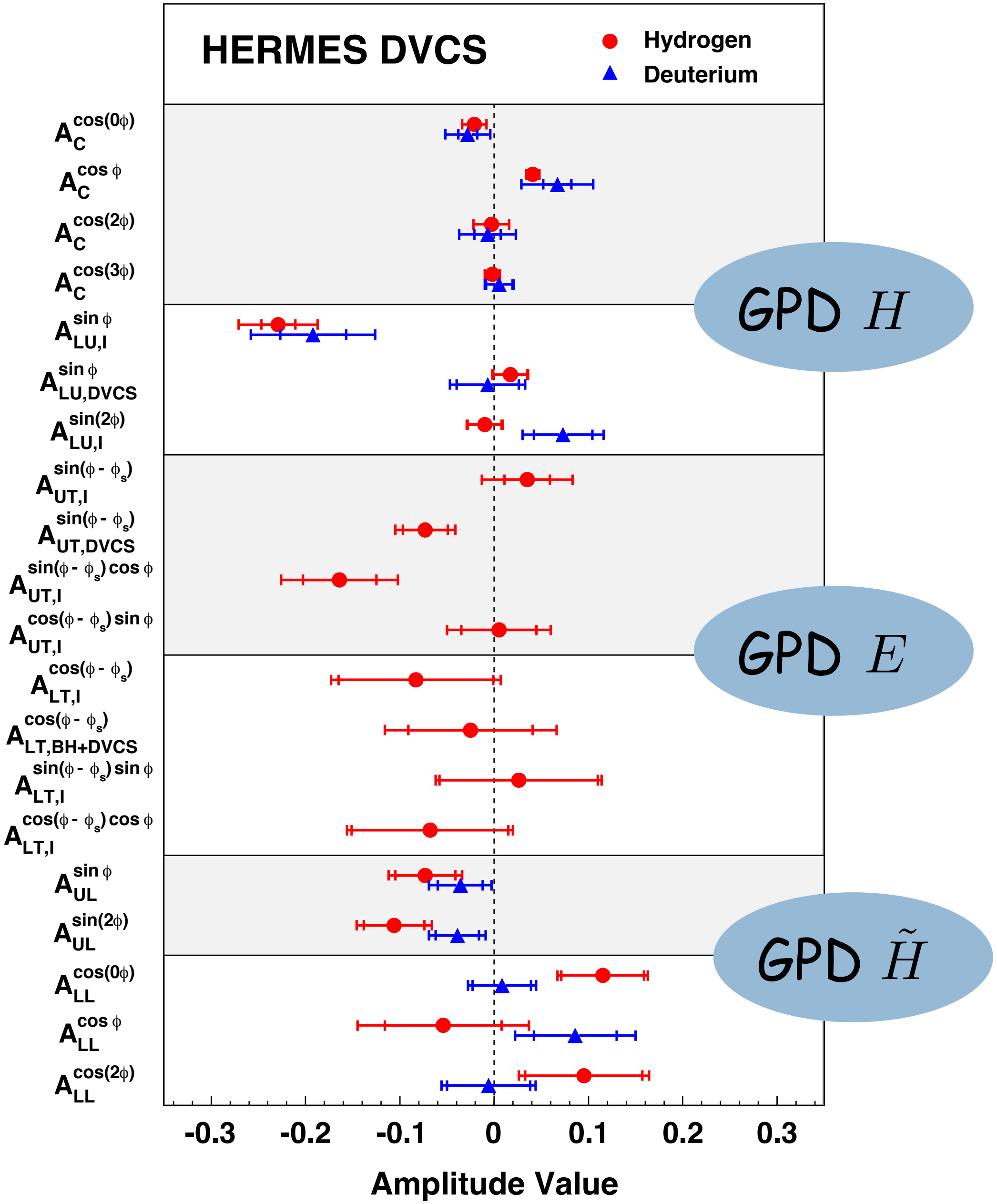
$|\tau_{BH}|$ calculable with knowledge form factors

$|\tau_{BH}| >> |\tau_{DVCS}|$ at HERMES

interference term through azimuthal asymmetries



DVCS at HERMES



beam-charge asymmetry

JHEP **07** (2012) 32
Nucl. Phys. B **829** (2010) 1

beam-helicity asymmetry

JHEP **07** (2012) 32
Nucl. Phys. B **829** (2010) 1

transverse target-spin asymmetry

JHEP **06** (2008) 066

double spin (LT) asymmetry

Phys. Lett. B **704** (2011) 15

longitudinal target-spin asymmetry

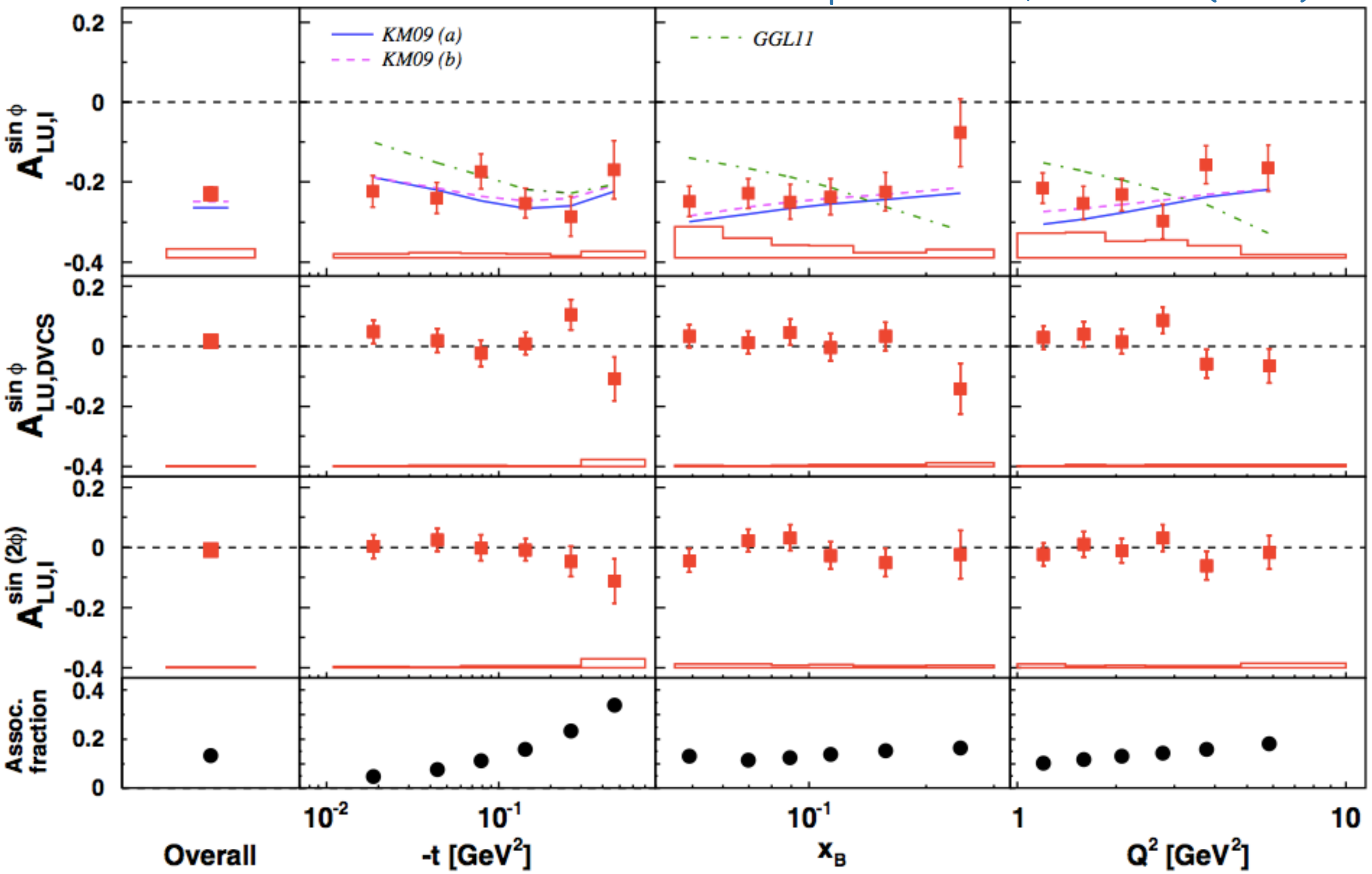
JHEP **06** (2010) 019
Nucl. Phys. B **842** (2011) 265

double spin (LL) asymmetry

JHEP **06** (2010) 019
Nucl. Phys. B **842** (2011) 265

Charge-separated beam-helicity asymmetry

A. Airapetian et al., JHEP **07** (2012) 32



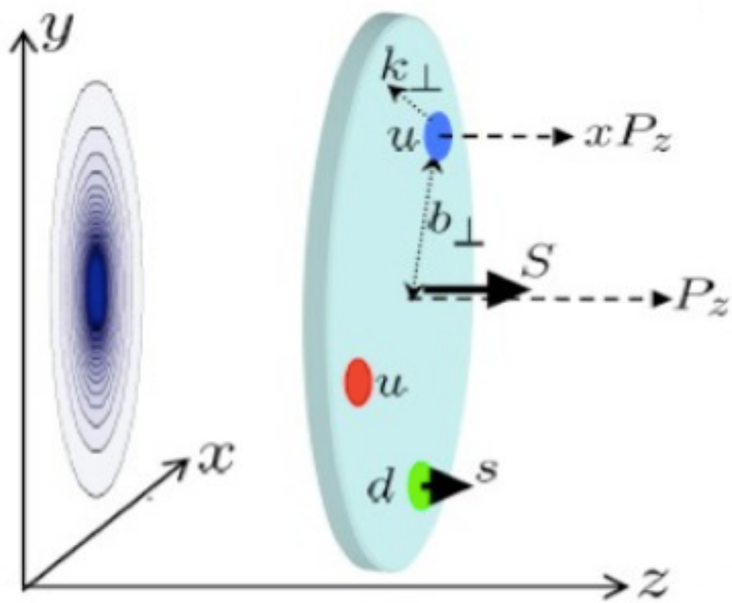
KM09: Nucl. Phys. B **841** (2010) 1:

fit to HERMES, ZEUS, H1 data

Fit to HERMES, ZEUS, H1, Jefferson Lab data

GGL11:

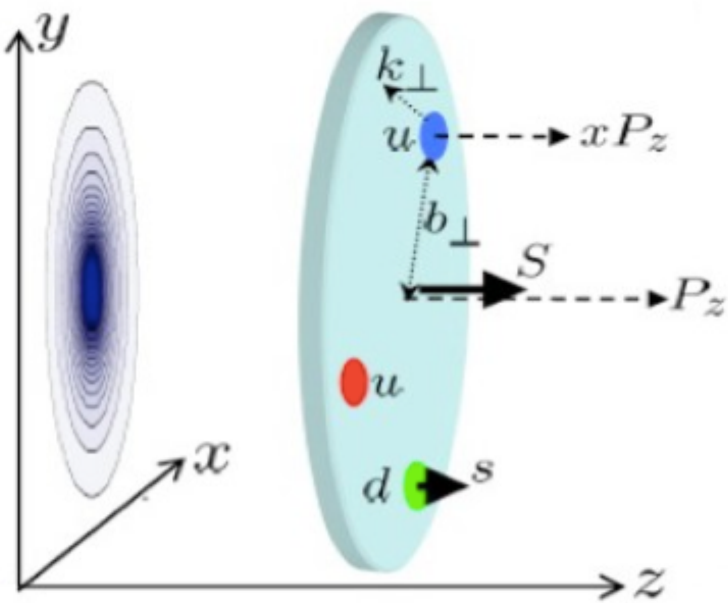
Phys. Rev. D **84** (2011) 034007



$$W(x, \vec{k}_T, \vec{b_\perp})$$

Generalized parton distributions

$$\int d^2\vec{k}_T\, W(x, \vec{k}_T, \vec{b_\perp}) = \text{GPDs}\ (x, \xi, t)$$



$W(x, \vec{k}_T, \vec{b_\perp})$

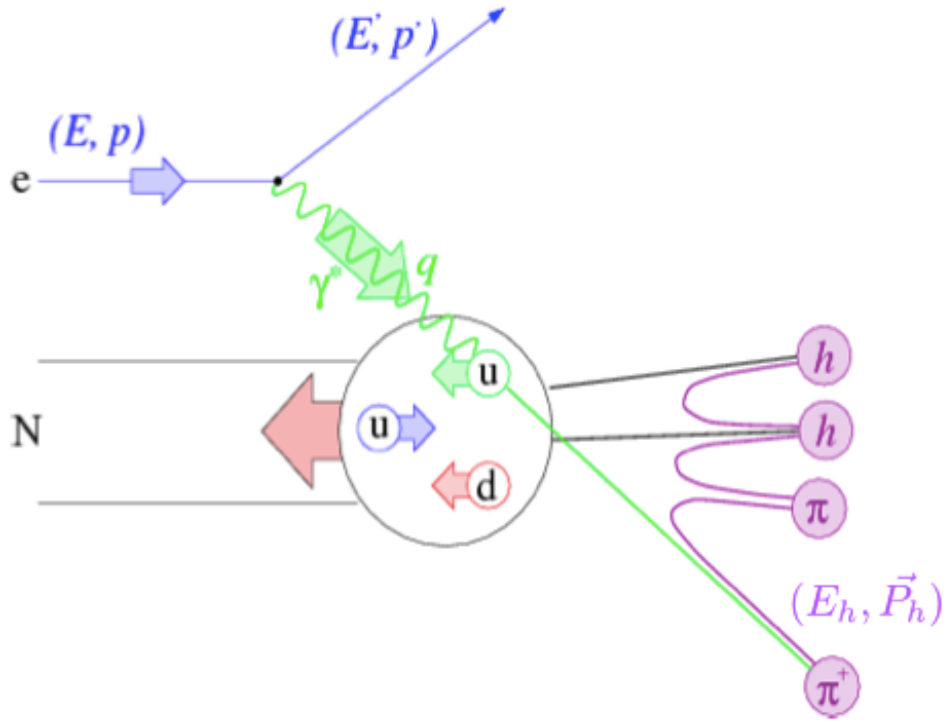
Generalized parton distributions

$$\int d^2\vec{k}_T \, W(x, \vec{k}_T, \vec{b_\perp}) = \text{GPDs } (x, \xi, t)$$

Transverse-momentum-dependent parton distribution functions

$$\int d^2\vec{b_\perp} \, W(x, \vec{k}_T, \vec{b_\perp}) = \text{TMD PDFs } (x, \vec{k}_T)$$

Semi-inclusive deep-inelastic scattering



$$Q^2 = -q^2$$

$$\nu \overset{lab}{=} E - E'$$

$$W^2 = M_N^2 + 2M_N\nu - Q^2$$

$$y \overset{lab}{=} \frac{\nu}{E}$$

$$x_B \overset{lab}{=} \frac{Q^2}{2M_N\nu}$$

$$z \overset{lab}{=} \frac{E_h}{\nu} \qquad P_{h\perp} = \frac{|\vec{q} \times \vec{P}_h|}{|\vec{q}|}$$

$$\sigma^{ep\to eh} = \sum_q DF^{p\to q}(x_B, p_T^2, Q^2) \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}(z, k_T^2, Q^2)$$

Distribution functions (DFs): distribution of quarks in nucleon

Fragmentation functions (FFs): fragmentation of struck quark into final-state hadron

p_T: intrinsic transverse momentum of struck quark

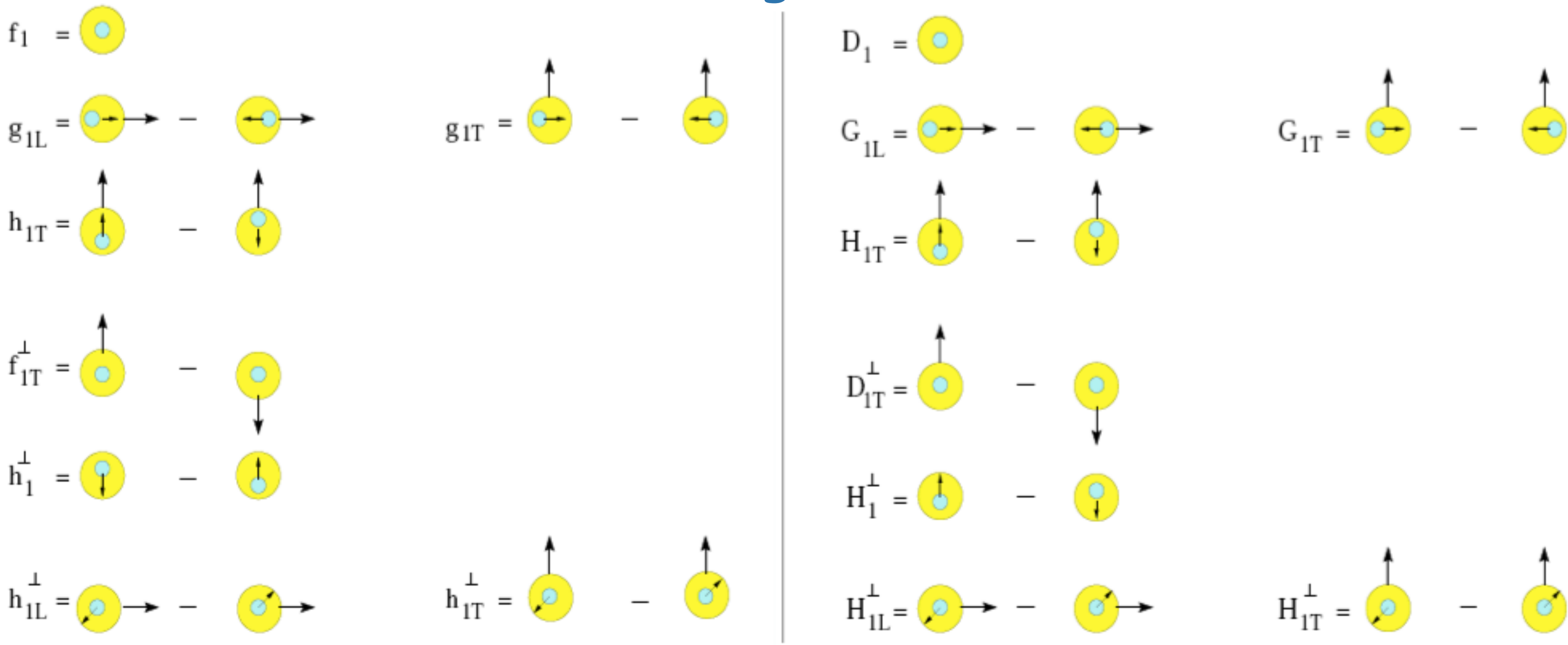
k_T: transverse momentum of struck quark acquired during fragmentation

Transverse-momentum-dependent distributions (TMDs)

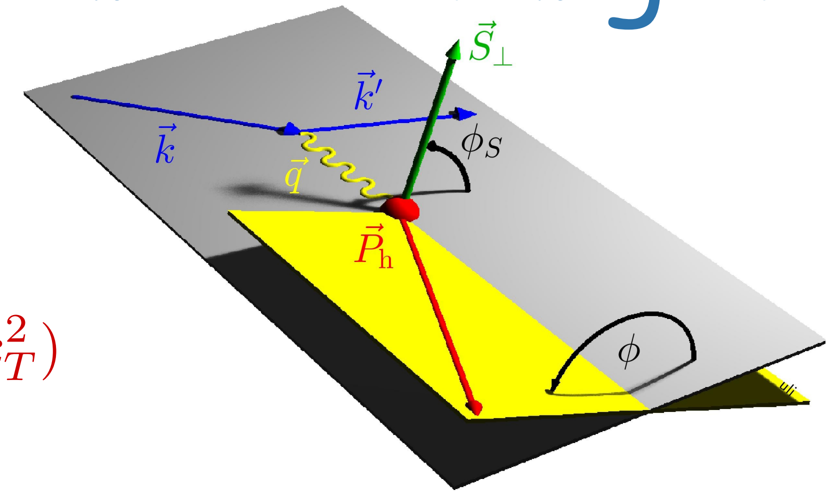
TMD PDFs

TMD FFs

leading twist



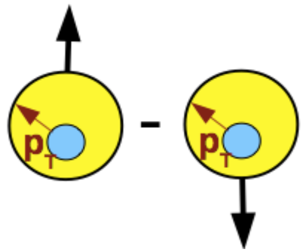
Single-spin asymmetries on a transversely polarised target



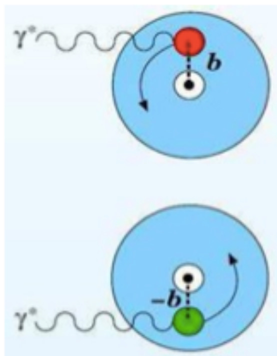
$$A_{UT} = \frac{1}{\langle|S_T|\rangle}\frac{N^\uparrow(\phi,\phi_S) - N^\downarrow(\phi,\phi_S)}{N^\uparrow(\phi,\phi_S) + N^\downarrow(\phi,\phi_S)}$$

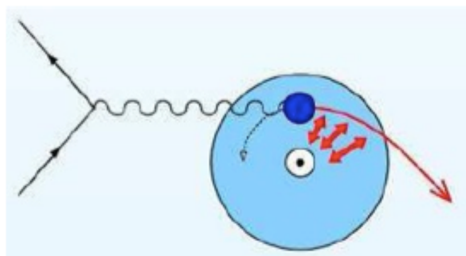
$$\propto \sin(\phi - \phi_S)\sum_q e_q \frac{\vec{p}_T.\hat{P}_{h\perp}}{M_h} f_{1T}^{\perp,q}(x_B, p_T^2) \otimes D_1^q(z, k_T^2)$$

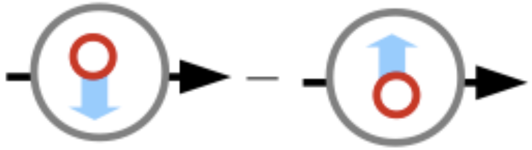
Sivers distribution function $f_{1T}^{\perp,q}(x_B, p_T^2, Q^2)$



- requires non-zero quark orbital angular momentum
- naïve-T-odd
- FSI left-right (azimuthal) asymmetry in direction of outgoing hadron



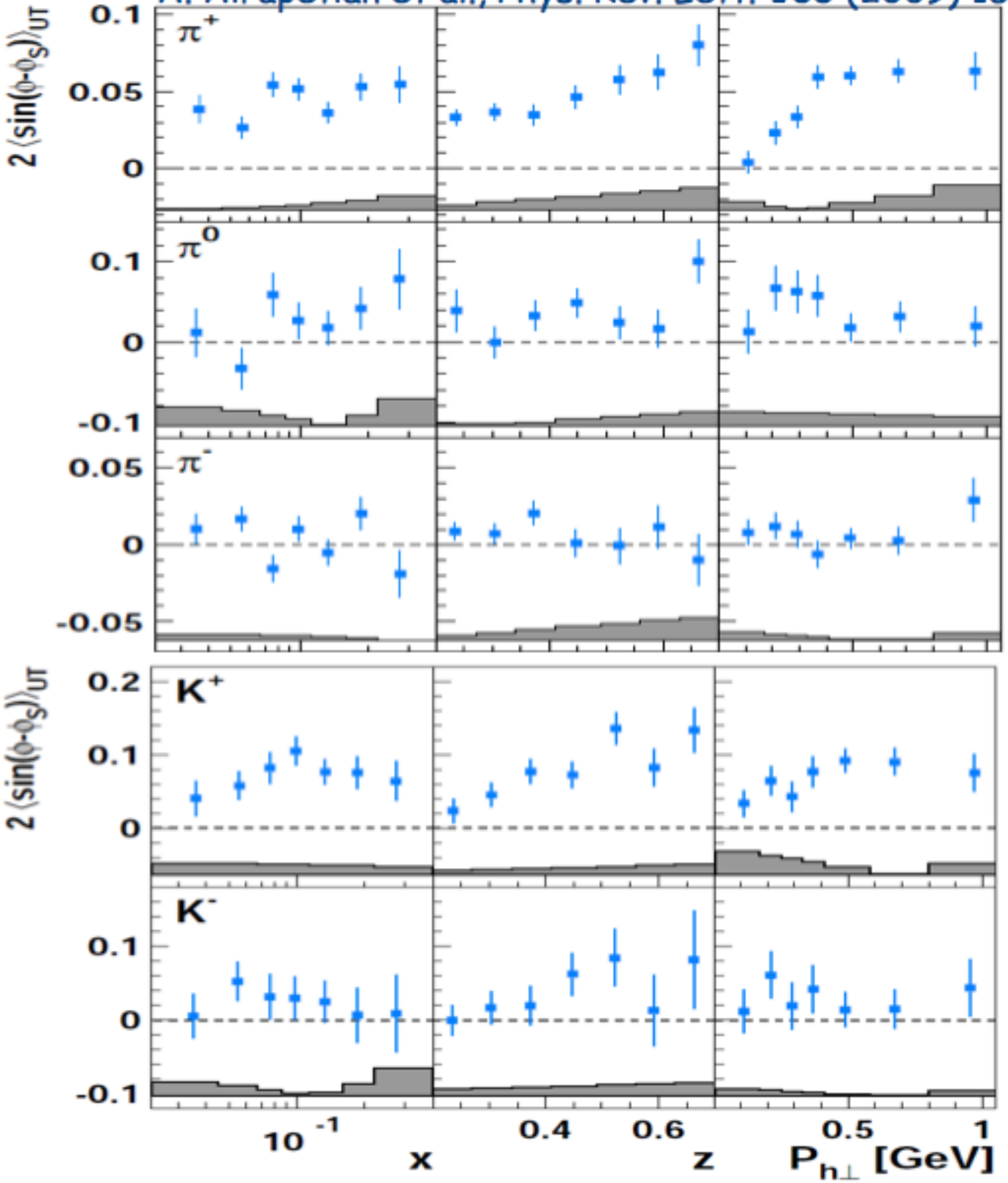




Sivers amplitude

$$F_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$$

A. Airapetian et al., Phys. Rev. Lett. **103** (2009) 152002



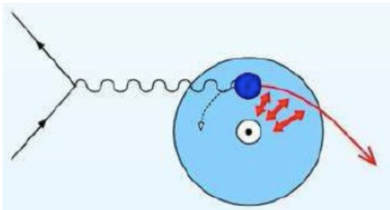
- π^+ significantly positive

  ⟶ orbital angular momentum

- u-quark dominance for π^+ amplitude

$$\approx -\frac{f_{1T}^{\perp,u}(x,k_T^2)\otimes D_1^{u\to\pi^+}(z,p_T^2)}{f_1^u(x,k_T^2)\otimes D_1^{u\to\pi^+}(z,p_T^2)}$$

⟶ $f_{1T}^{\perp,u}(x,k_T^2) < 0$



- π^-: u- and d-quark cancelation

⟶ $f_{1T}^{\perp,d}(x,k_T^2) > 0$

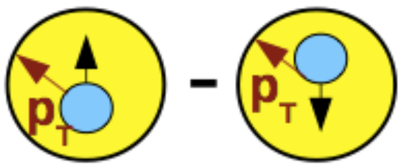
Non-collinear spin-independent semi-inclusive DIS cross section

$$\frac{d\sigma}{dx_B\,dy\,dz\,dP^2_{h\perp}\,d\phi_h} = \frac{\alpha^2}{x_B y Q^2}(1+\frac{\gamma^2}{2x_B})(A(y)F_{UU,T} + B(y)F_{UU,L}$$

$$+C(y)\cos\phi_h F^{\cos\phi_h}_{UU} + B(y)\cos 2\phi_h F^{\cos 2\phi_h}_{UU})$$

$$F^{\cos 2\phi_h}_{UU} = -\frac{2(\hat{P}_{h\perp}.\vec{p}_T)(\hat{P}_{h\perp}.\vec{k}_T) - \vec{p}_T.\vec{k}_T}{M_h M} h_1^\perp \otimes H_1^\perp$$

Boer-Mulders DF $h_1^\perp$



- chiral odd
- naïve-T-odd

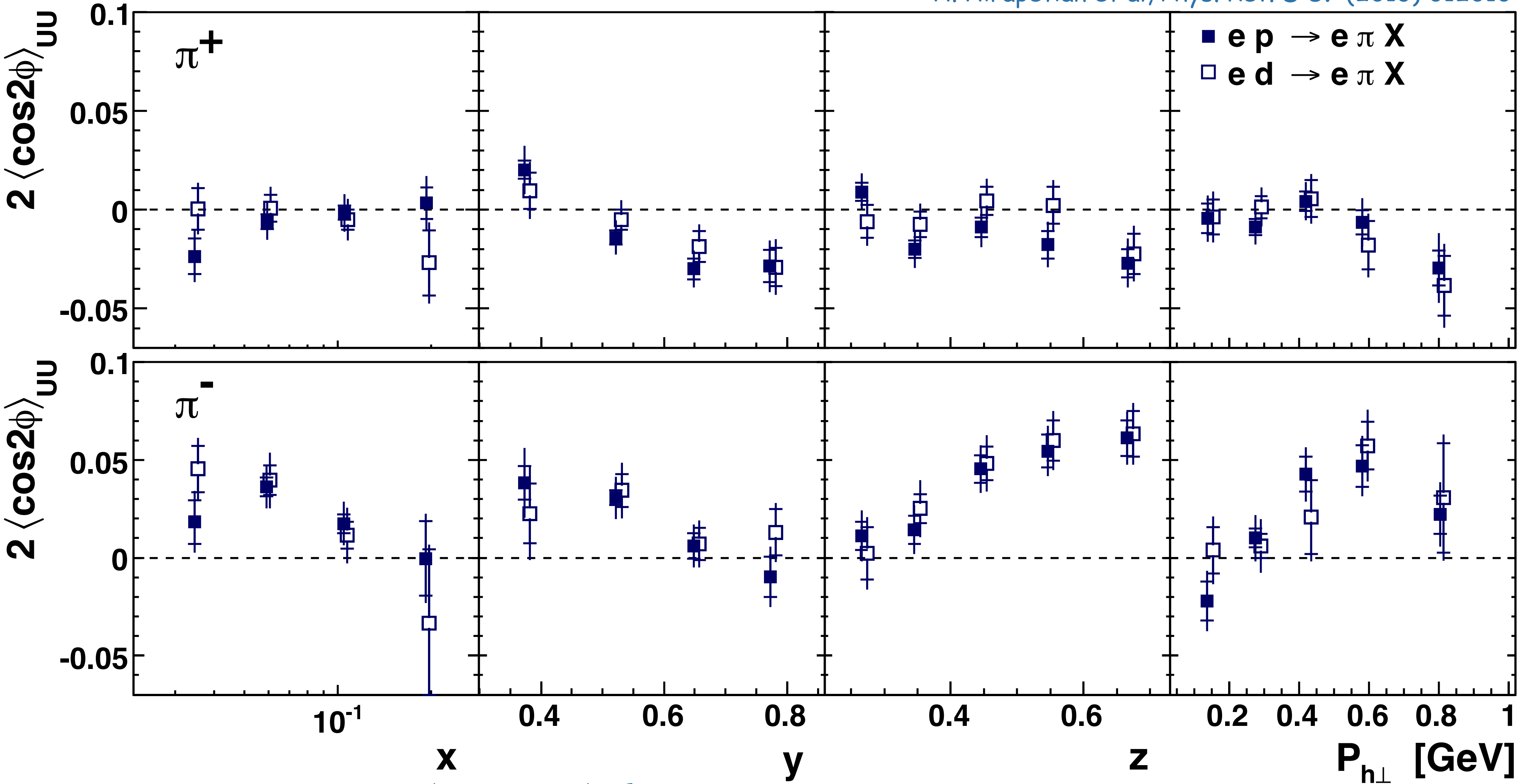
↔

Collins FF $H_1^\perp$

- chiral odd
- naïve-T-odd

Results for pions

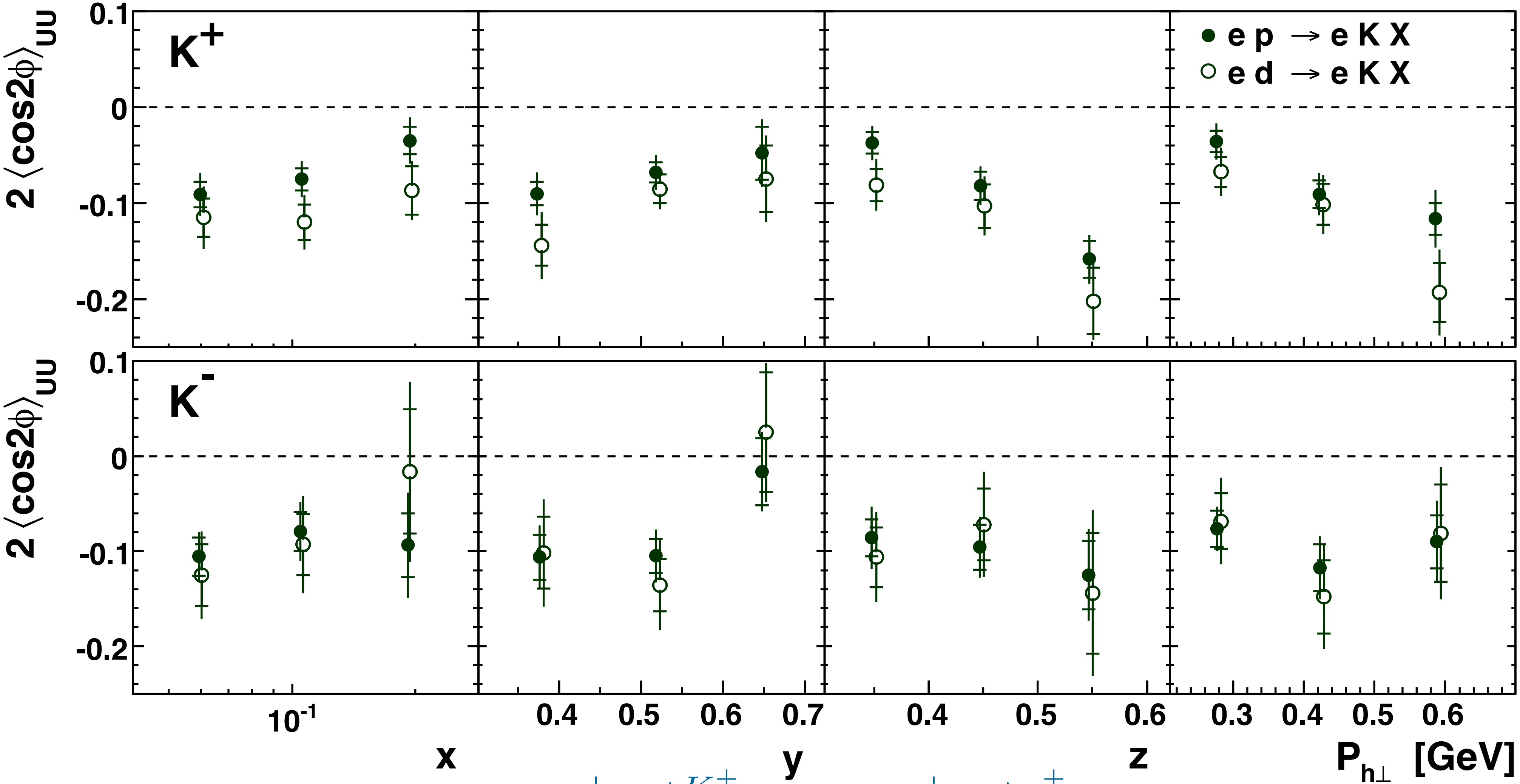
A. Airapetian et al, Phys. Rev. D **87** (2013) 012010



- H-D comparison: $h_1^{\perp,u} \approx h_1^{\perp,d}$
- $\pi^- > 0 \leftrightarrow \pi^+ \leq 0 :\ H_1^{\perp,fav} \approx H_1^{\perp,unfav}$

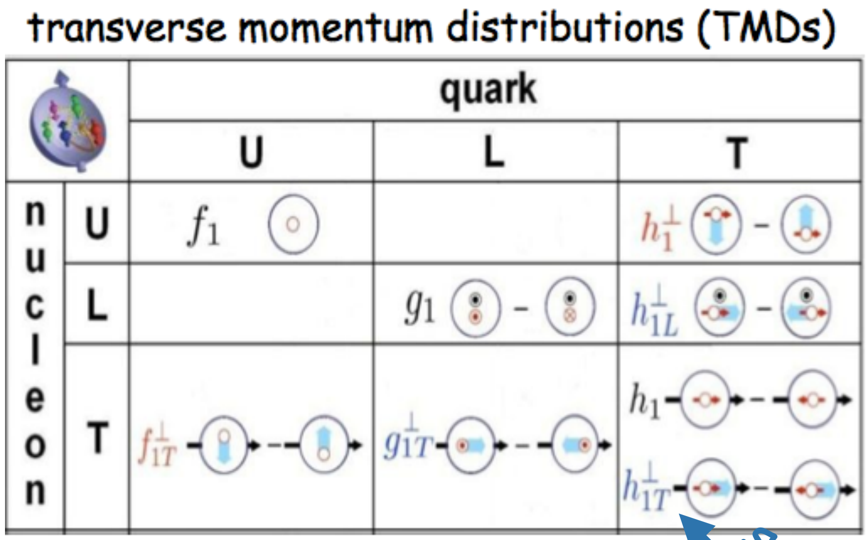
Results for kaons

A. Airapetian et al, Phys. Rev. D **87** (2013) 012010



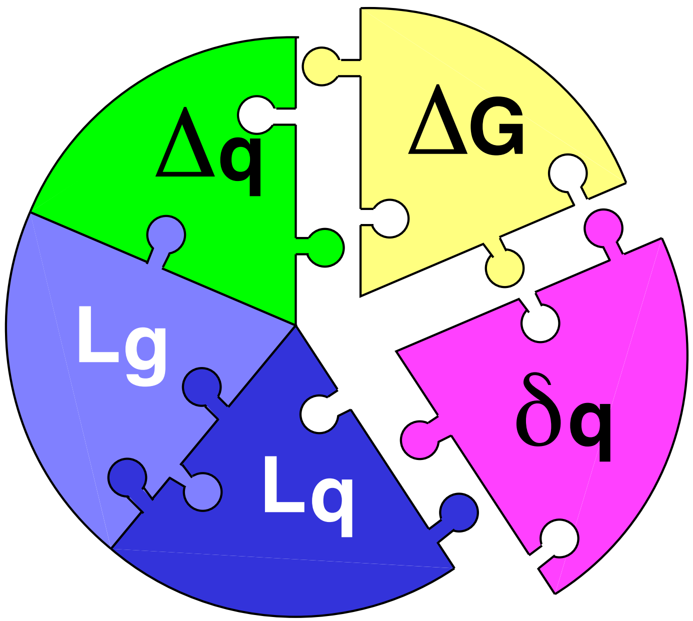
- $K^+<0$: Artru model: sign $H_1^{\perp,u\to K^+}$ = sign $H_1^{\perp,u\to\pi^+}$
- $K^+ \simeq K^-$: u dominance $\xrightarrow{?}$ $H_1^{\perp,u\to K^+} = H_1^{\perp,u\to K^-}$; role of sea quarks?

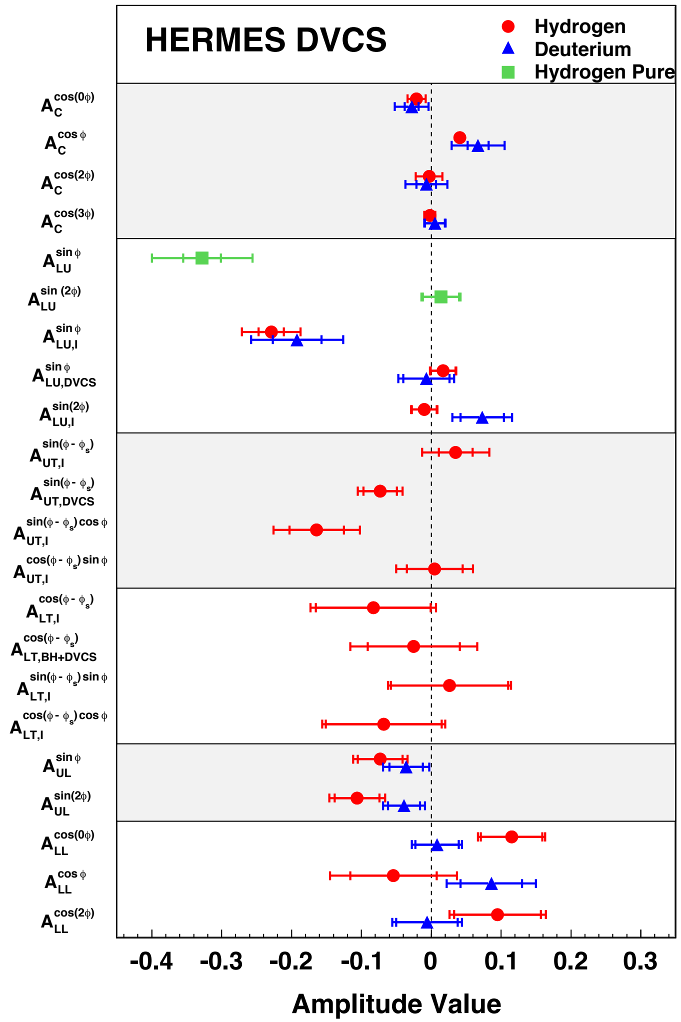
Summary



semi-inclusive

exclusive





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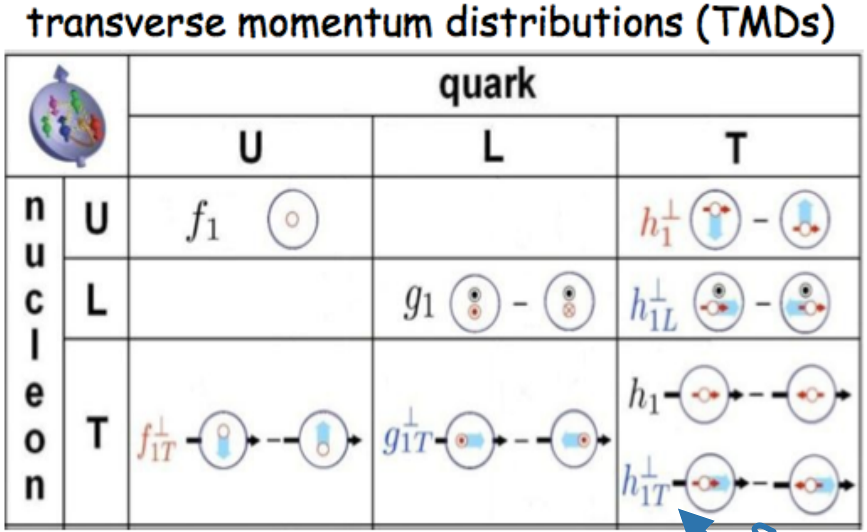

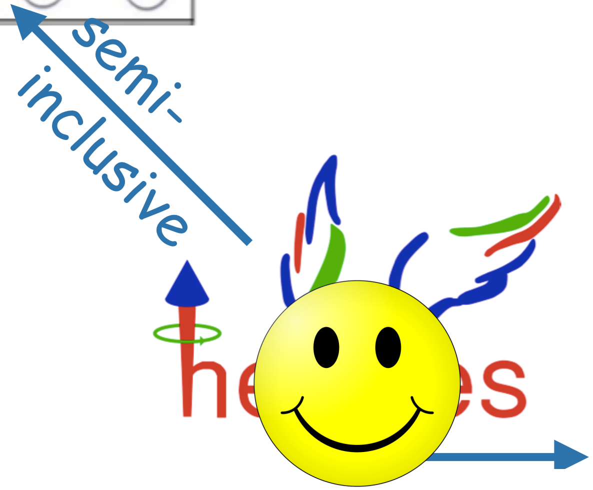

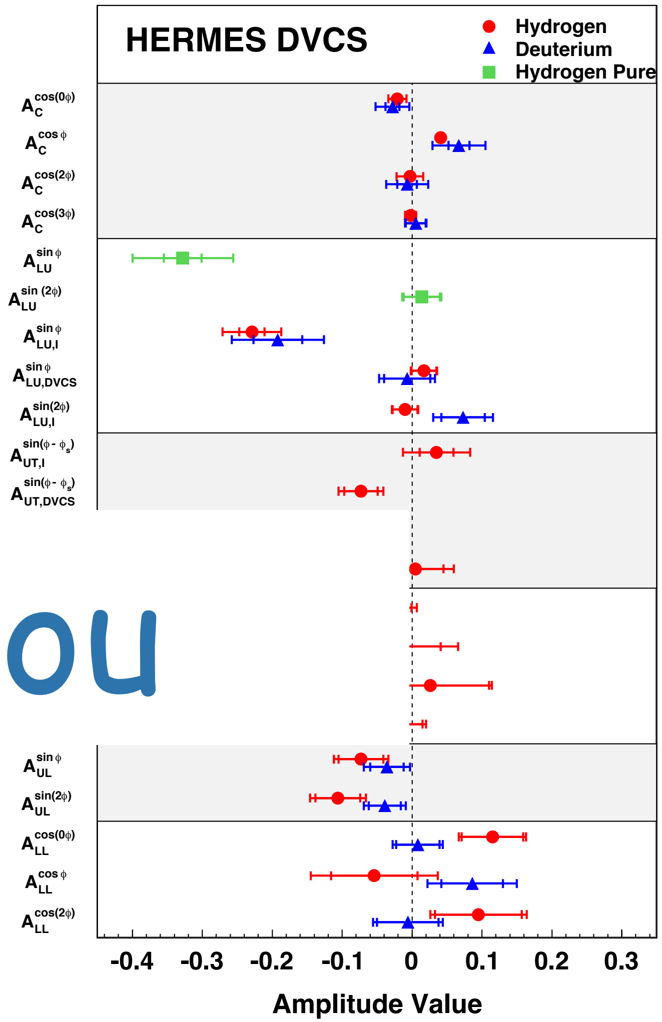

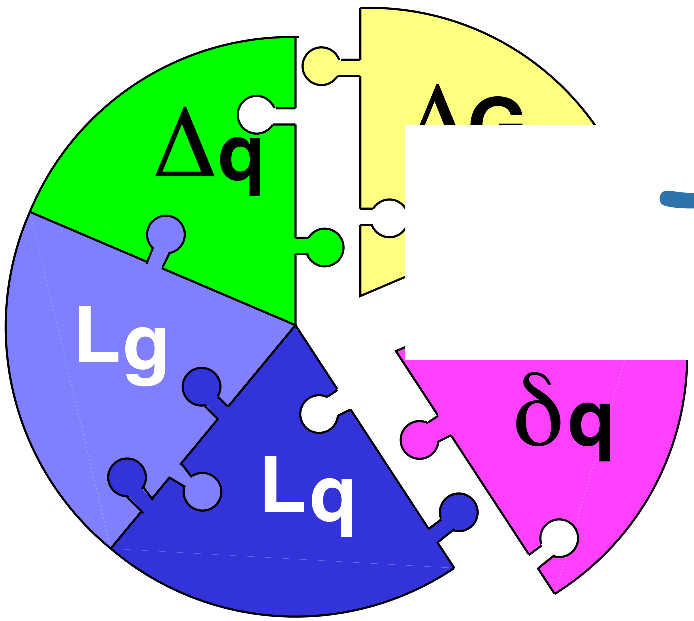

Thank you