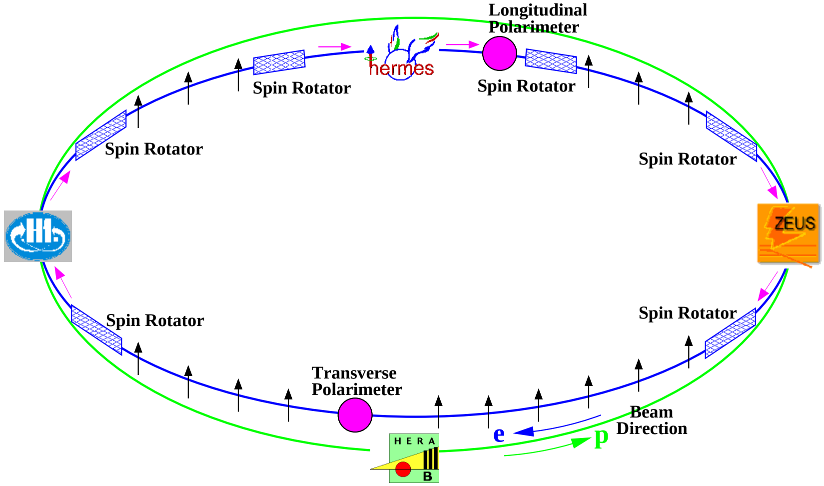
HERMES highlights

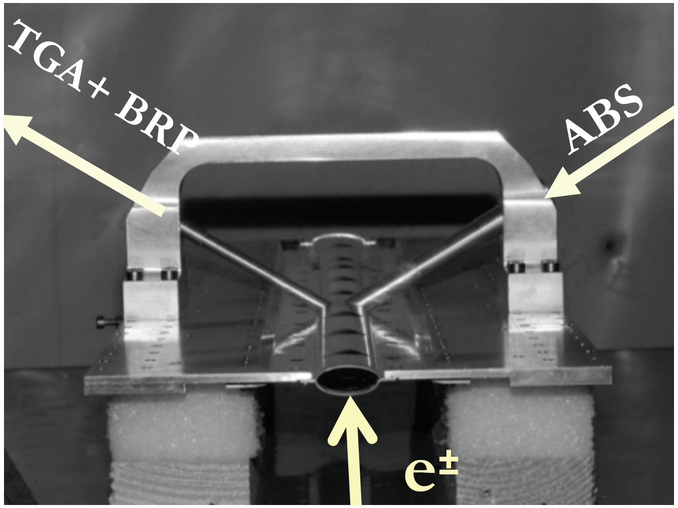
HERA Symposium
Hamburg, Germany, 2010

Ami Rostomyan

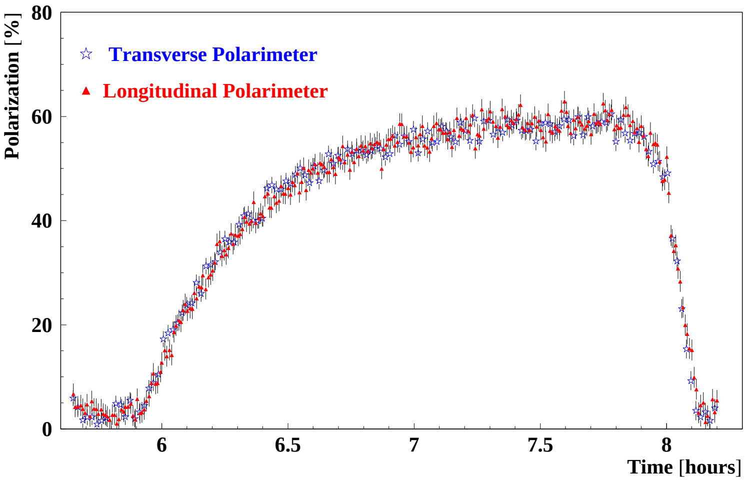
(on behalf of the HERMES collaboration)

HERMES at HERA



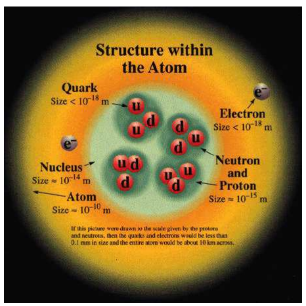


- fixed target experiment
  - longitudinally/transversely polarized or unpolarized internal gas target (H, D, He, N, ... Xe)
- using self-polarizing HERA lepton beam
  - cross section asymmetry in synchrotron radiation emission leads to build-up of transverse polarization (Sokolov-Ternov effect)
- spin-rotators provide longitudinal polarization at HERMES interaction region

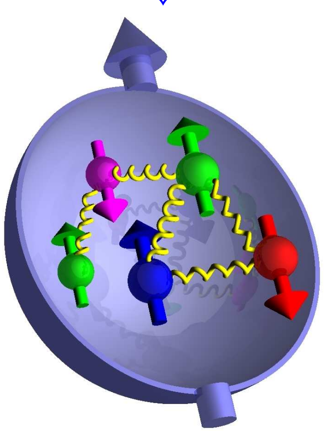


nucleon structure

$\Downarrow$



$\Downarrow$



proton $= uud+$ sea $+$ gluons

charge, momentum, magnetic moment, spin, vector charge, axial charge, tensor charge

- momentum:

$$\int_0^1 x\Big(\sum_i \left(q_i(x) + \bar{q}_i(x)\right) + g(x)\Big) = 1$$

  - quarks only carry $\approx 50\%$
- spin $1/2$:
  - " You think you understand something? Now add spin... " *- Jaffe -*
  - total quark spin contribution only $\approx 30\%$

using the spin in NMR

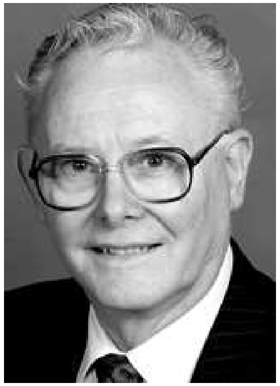
Otto Stern

Nobel Prize, 1943: "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

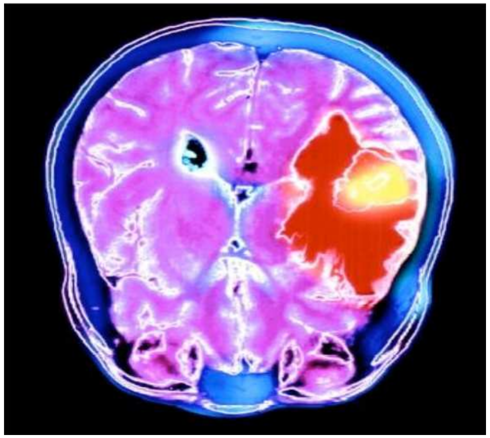
μ_p = 2.5 nuclear magnetons, ± 10% (1933)

Proton spins are used to image the structure and function of the human body using the technique of magnetic resonance imaging.

Paul C. Lauterbur

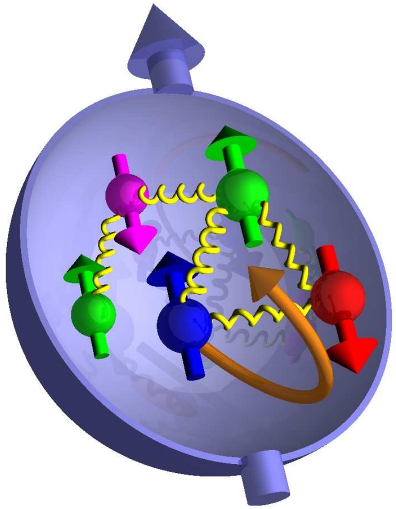


Sir Peter Mansfield



Nobel Prize, 2003: "for their discoveries concerning magnetic resonance imaging"

where does the proton spin come from



Jaffe and Manohar spin sum rule

- longitudinal spin structure

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g$$

- $\Delta\Sigma$ and ΔG can be measured in semi-inclusive deep inelastic ep scattering

Ji sum rule

- longitudinal spin structure

$$S_z = \frac{1}{2} = \underbrace{J^q}_{\frac{1}{2}\Delta\Sigma + \mathcal{L}_z^q} + J^g$$

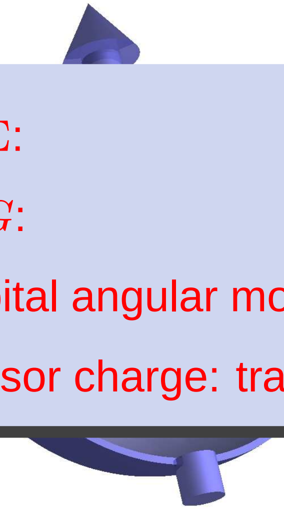
- J^q and J^g accessible through exclusive ep scattering

Bakker, Leader, Trueman sum rule

- transversity sum rule (?)

$$S_T = \frac{1}{2} = \frac{1}{2}\delta\Sigma + L_{S_T}^q + L_{S_T}^g$$

where does the proton spin come from



Jaffe and Manohar spin sum rule

- longitudinal spin structure

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g$$

- $\Delta\Sigma$ and ΔG can be measured in semi-inclusive deep inelastic ep scattering

- $\Delta\Sigma$: *-HERMES Collaboration: Phys. Rev. D 75 012007 (2007) -*
- ΔG: *-HERMES Collaboration: arXiv:1002.3921 (2010)-*
- orbital angular momentum: relations to GPDs and TMDs
- tensor charge: transversity sum rule (?)

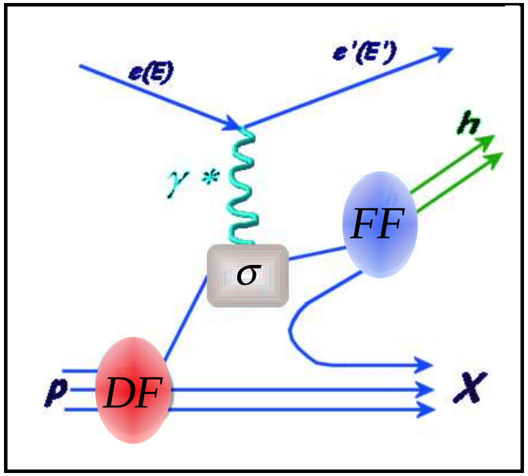
- J^q and J^g accessible through exclusive ep scattering

Bakker, Leader, Trueman sum rule

- transversity sum rule (?)

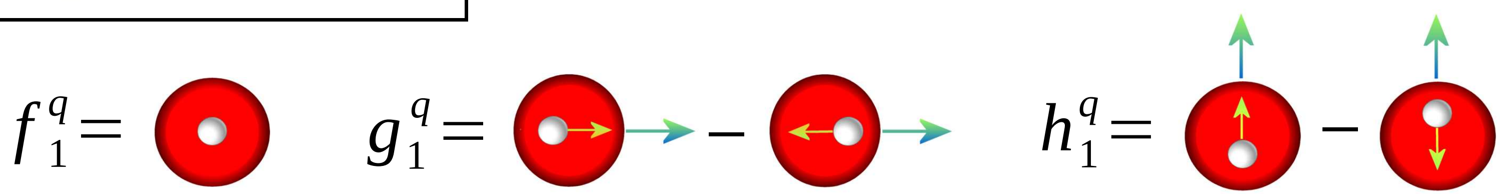
$$S_T = \frac{1}{2} = \frac{1}{2}\delta\Sigma + L_{S_T}^q + L_{S_T}^g$$

quark structure of the nucleon



integrated over transverse momentum

$$\sigma^{ep\to ehX} \propto \sum_q DF(x) \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}(z)$$

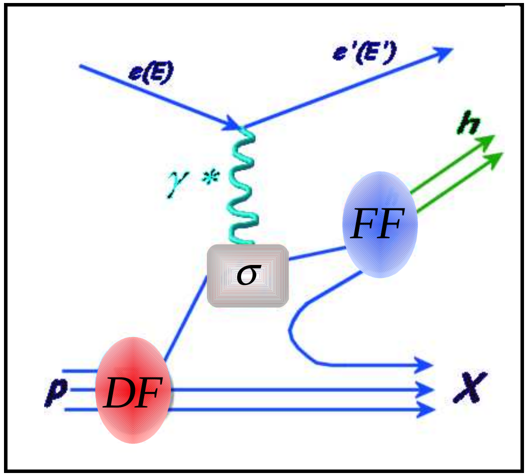


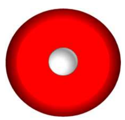
unpolarized quarks and nucleons

longitudinally polarized quarks and nucleons

transversely polarized quarks and nucleons

quark structure of the nucleon



$f_1^q =$  $g_1^q =$

unpolarized quarks and nucleons

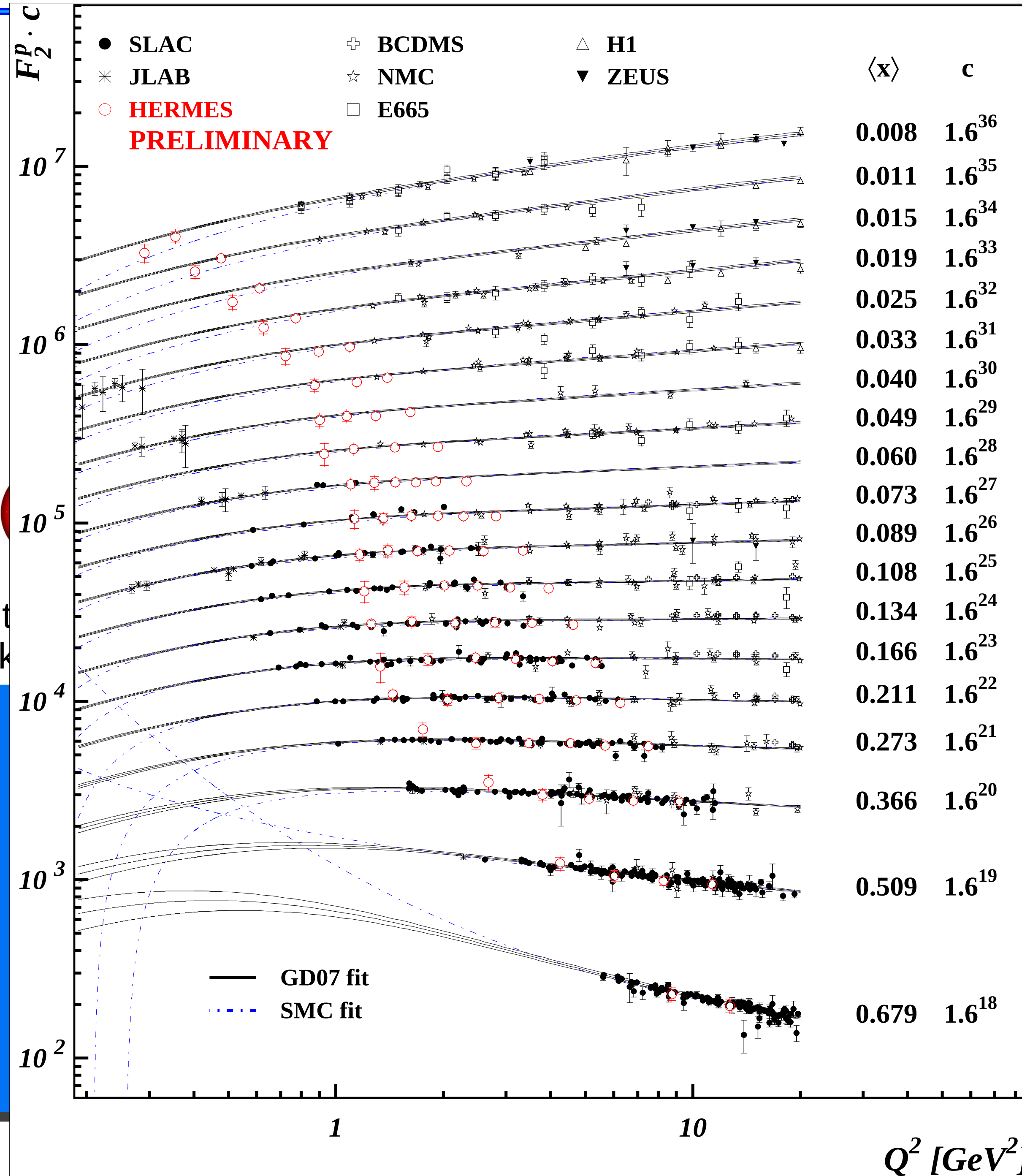
longit
quark

f_1^q: spin averaged (well known)

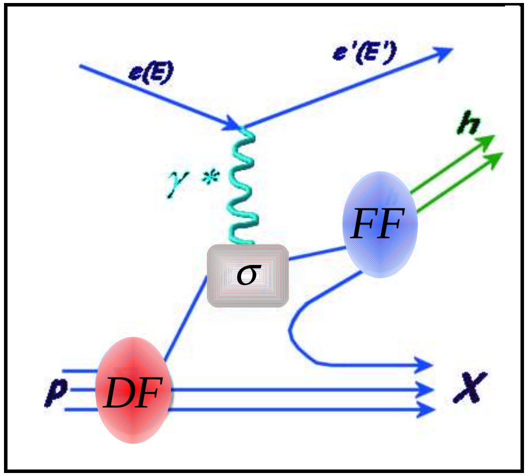
vector charge

$$F_1(x) = \frac{1}{2}\sum_q e_q^2 f_1^q(x)$$

$$F_2(x) = x\sum_q e_q^2 f_1^q(x)$$

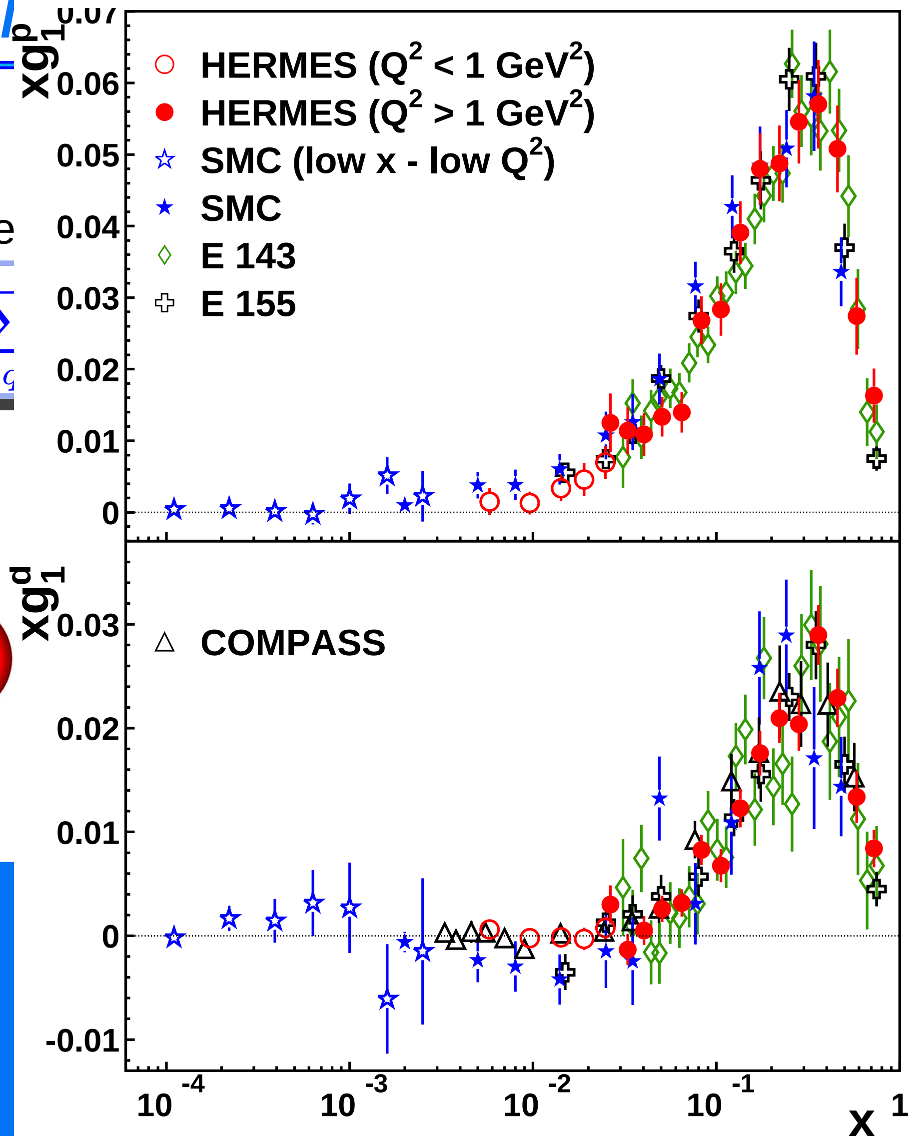


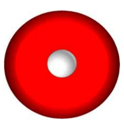
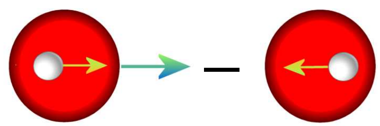
quark structure of the nucl



integrated ove

$$\sigma^{ep\to ehX} \propto \sum_{q}$$



$f_1^q =$  $g_1^q =$ 

unpolarized quarks and nucleons

longitudinally polarized quarks and nucleons

f_1^q: spin averaged (well known)

vector charge

g_1^q: helicity difference (known)

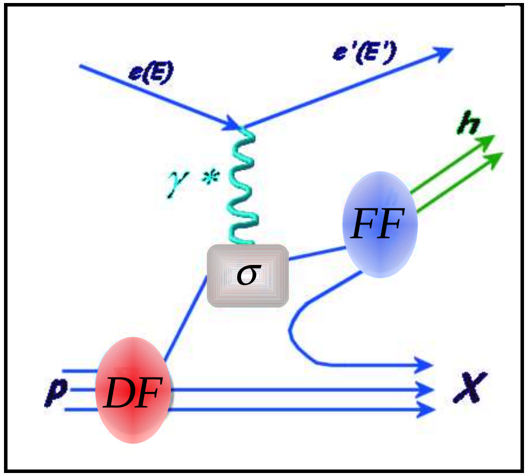
axial charge

$$F_1(x) = \frac{1}{2}\sum_q e_q^2 f_1^q(x)$$

$$F_2(x) = x\sum_q e_q^2 f_1^q(x)$$

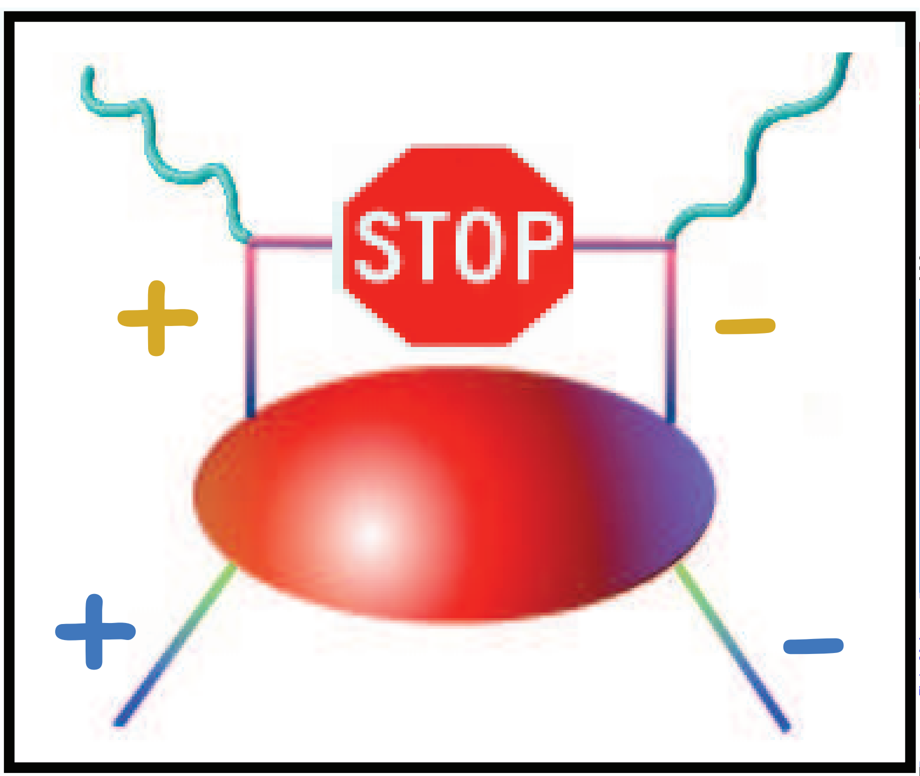
$$g_1(x) = \frac{1}{2}\sum_q e_q^2 g_1^q(x)$$

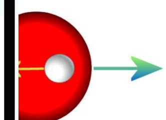
quark structure of the nucleon



integrated over transverse momentum

$$\sigma^{ep\to ehX} \propto \sum_q DF(x) \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}(z)$$





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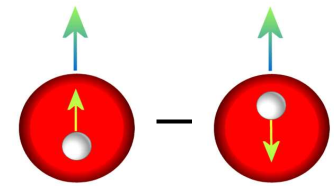
$h_1^q =$ 

transversely polarized
quarks and nucleons

f_1^q:
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vect

$F_1($

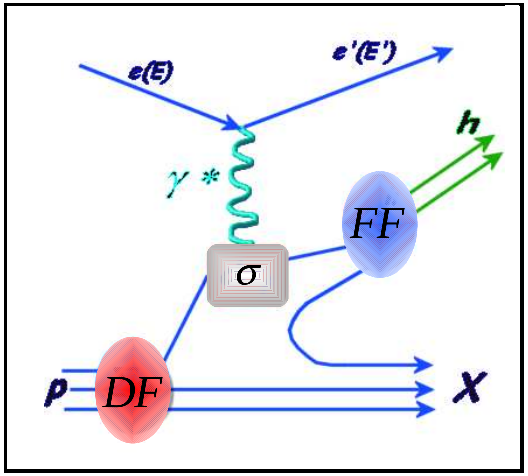
$F_2($

$g_1^q(x)$

h_1^q: transversity
(unmeasured for long time)
tensor charge

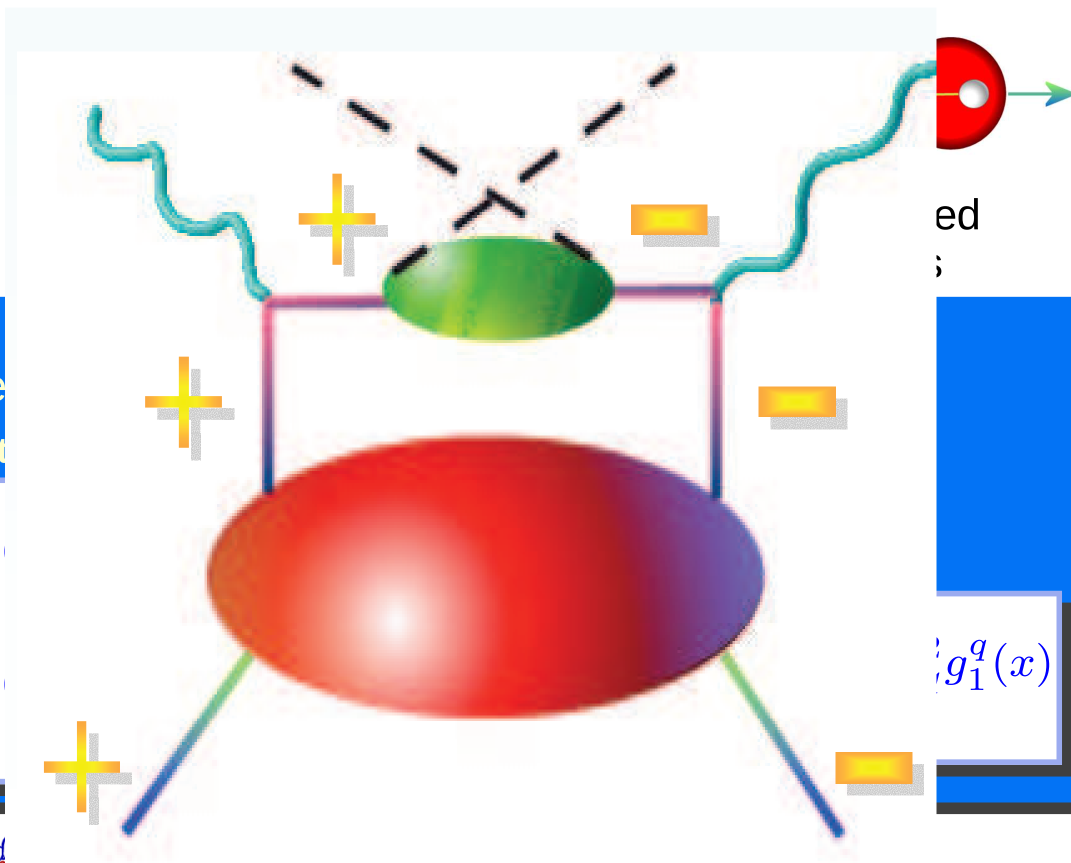
- chiral-odd h_1^q involves quark helicity flip
- need to couple to chiral-odd FF: Collins FF

quark structure of the nucleon



integrated over transverse momentum

$$\sigma^{ep\to ehX} \propto \sum_q h_1^q(x) \otimes \sigma^{eq\to eq} \otimes H_1^{\perp,q\to h}(z)$$



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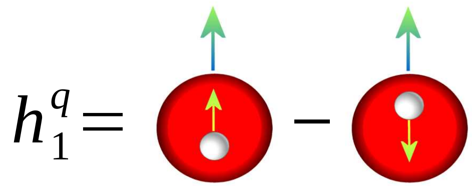

transversely polarized
quarks and nucleons

f_1^q:
(we
vect

F_1
F_2

$g_1^q(x)$

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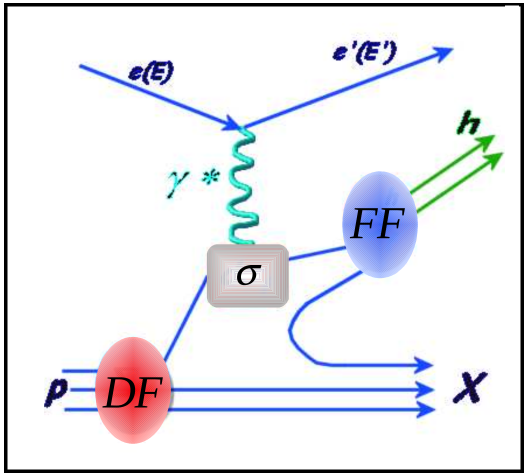
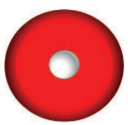
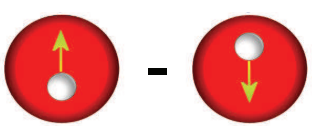


transverse-momentum-dependent (TMD) DF

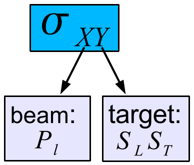
$$\sigma^{ep\rightarrow ehX} \propto \sum_q DF(x,p_T) \otimes \sigma^{eq\rightarrow eq} \otimes FF^{q\rightarrow h}(z,k_T)$$

$D =$ 

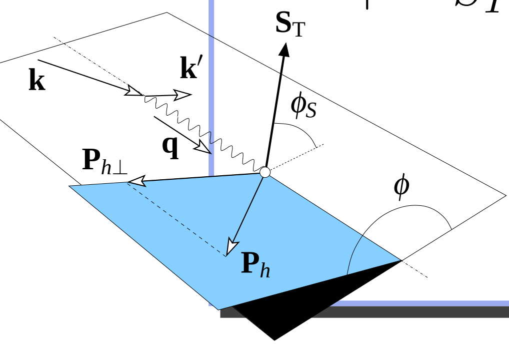
$H_1^{\perp} =$ 

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

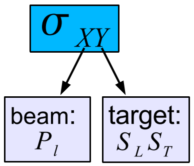
1-hadron production x-section $(ep \rightarrow ehX)$



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

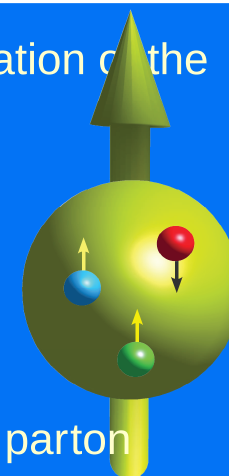


“Collins-effect ”

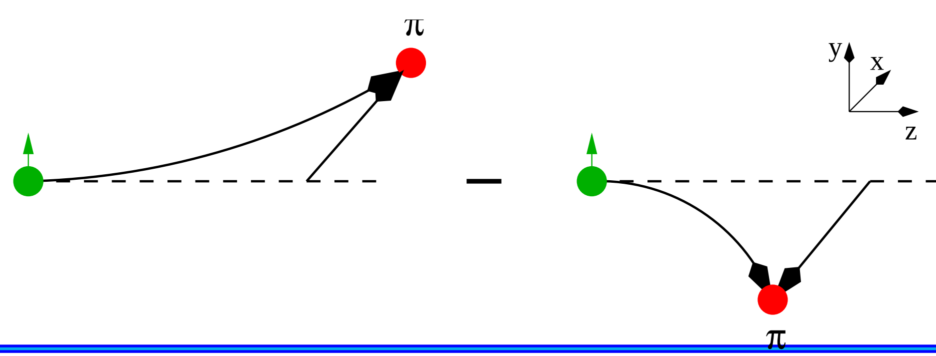


$$
\begin{aligned}
d\sigma \;=\; & d\sigma^0_{UU} + \cos(2\phi)\, d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi)\, d\sigma^2_{UU} \;+\; P_l \frac{1}{Q}\sin(\phi)\, d\sigma^3_{LU} \\
+\; & S_L \Big[\sin(2\phi)\, d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi)\, d\sigma^5_{UL} \;+\; P_l \Big(d\sigma^6_{LL} + \frac{1}{Q}\sin(\phi)\,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

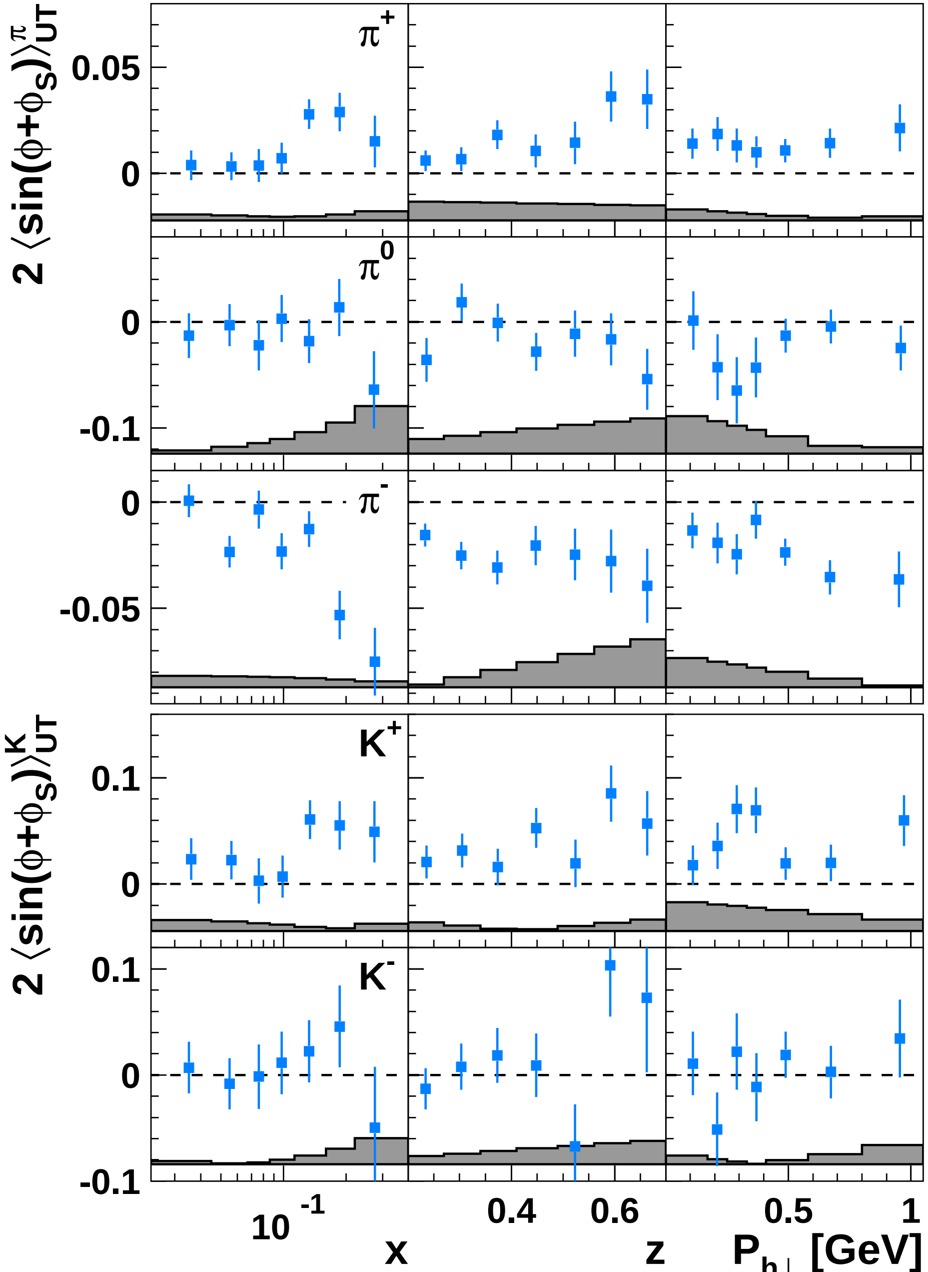
- “Collins-effect ” accounts for the correlation between the transverse polarization of the fragmenting quark and the transverse momentum of the produced unpolarized hadron



- sensitive to quark transverse spin
- generates left-right (azimuthal) asymmetries in the direction of the outgoing parton



Collins amplitudes



$$\mathbf{h_1^q(x) \otimes H_1^{\perp,q}(z)}$$

final results!!!

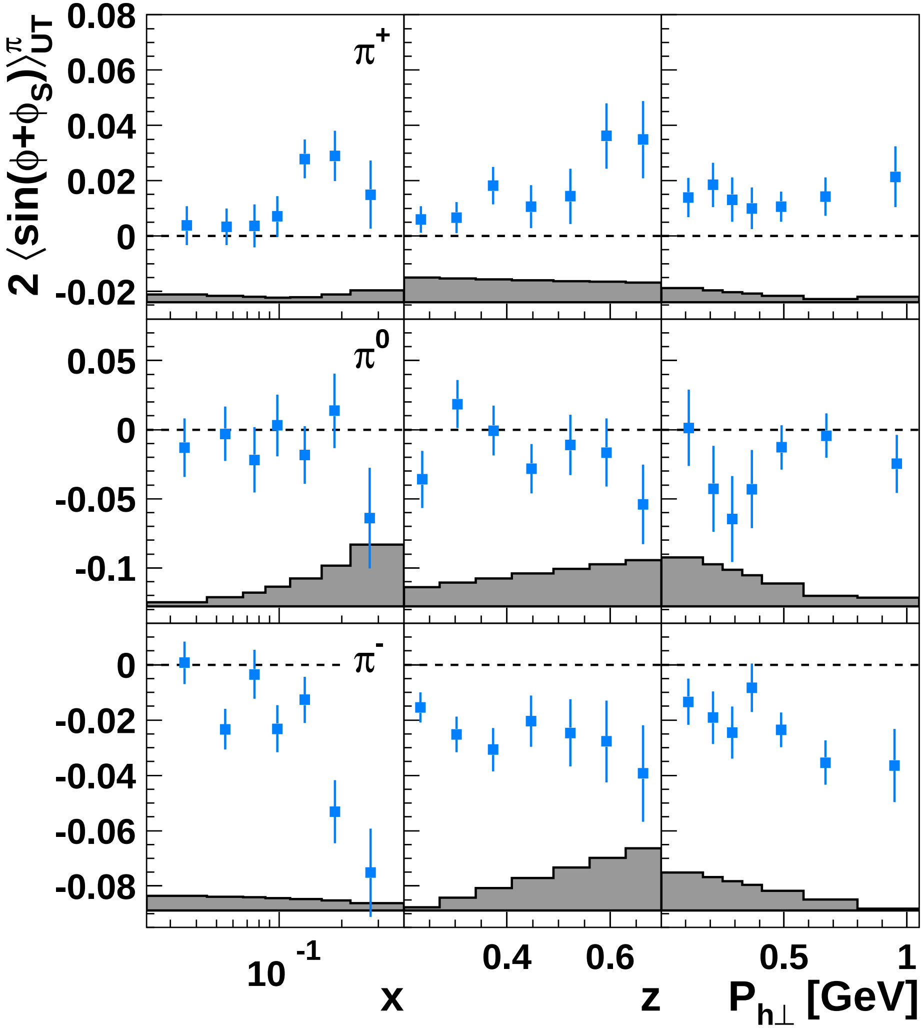
-HERMES Collaboration: arXiv:1006.4221 (2010) -

non-zero Collins effect observed!

- both Collins FF and transversity sizeable

Collins amplitudes for pions

$$\mathbf{h_1^q(x) \otimes H_1^{\perp,q}(z)}$$



- positive amplitude for π^+
- compatible with zero amplitude for π^0
- negative amplitude for π^-
- large π^- asymmetry
  - role of disfavored Collins FF:

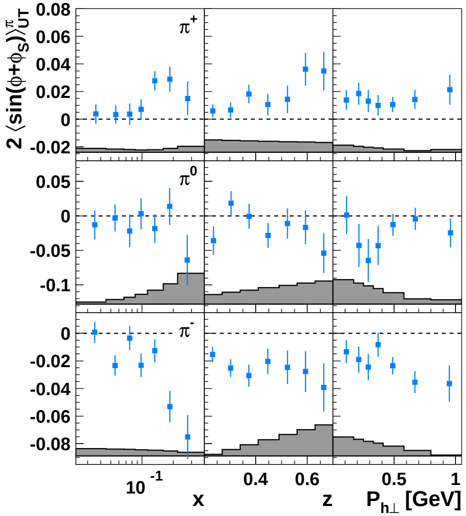
$$H_1^{\perp,disfav} \approx -H_1^{\perp,fav}$$

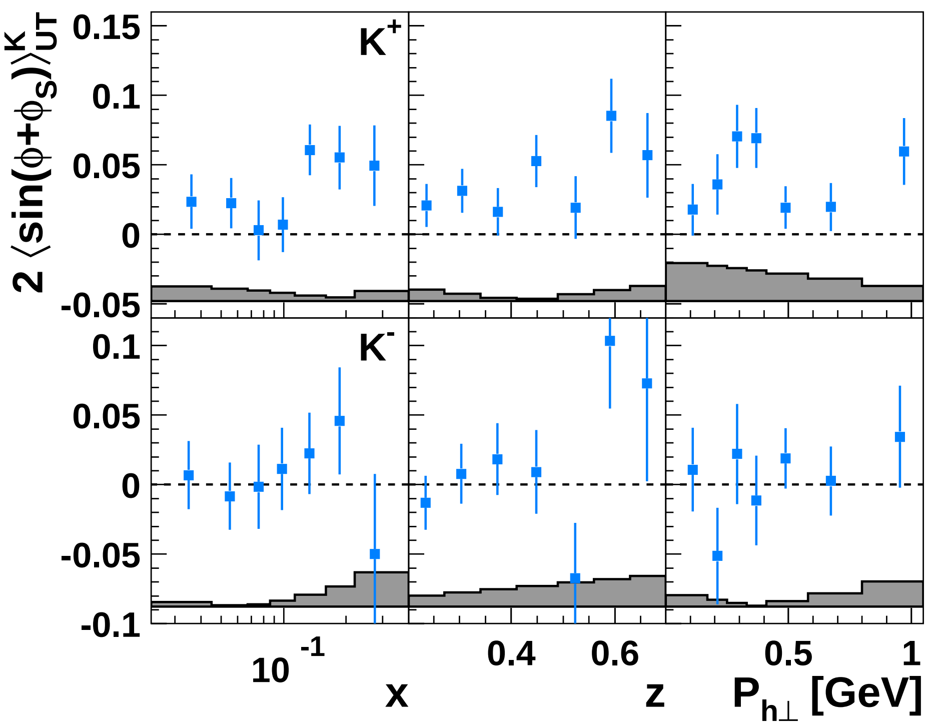
$$u \Rightarrow \pi^+; \qquad d \Rightarrow \pi^-(fav)$$

$$u \Rightarrow \pi^-; \qquad d \Rightarrow \pi^+(disfav)$$

- positive for π^+ and negative for π^-
  - $h_1^u > 0$
  - $h_1^d < 0$

Collins amplitudes for kaons





$$\mathbf{h_1^q(x) \otimes H_1^{\perp,q}(z)}$$

K^+

- K^+ amplitudes are similar to π^+ as expected from u-quark dominance
- K^+ are larger than π^+

K^-

- K^- consistent with zero
- $K^-(\bar{u}s)$ is all-sea object

differences between amplitudes of π and K

- role of sea quarks in conjunction with possibly large FF
- various contributions from decay of semi-inclusively produced vector-mesons
- the k_T dependences of the fragmentation functions

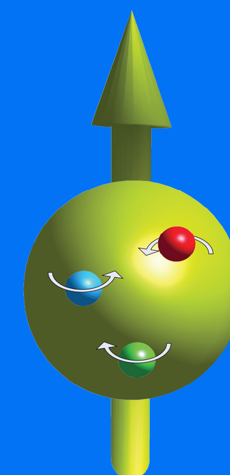
"Sivers-effect "

σ_{XY}

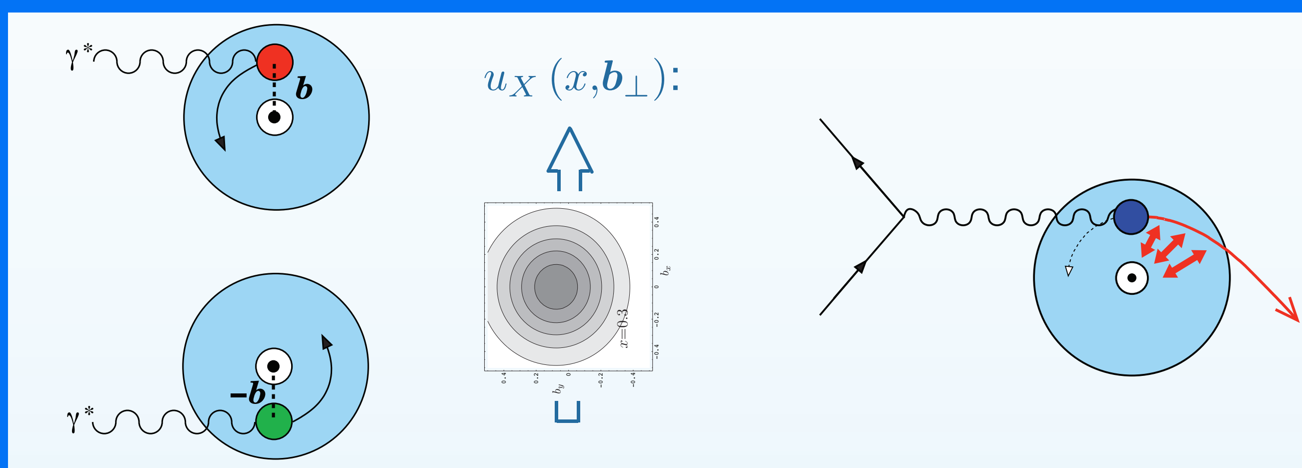
beam: P_l — target: $S_L S_T$

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

- Sivers distribution function $f_{1T}^{\perp q}(x, p_T^2)$ gives the correlation between parton transverse momentum and transverse spin of the nucleon

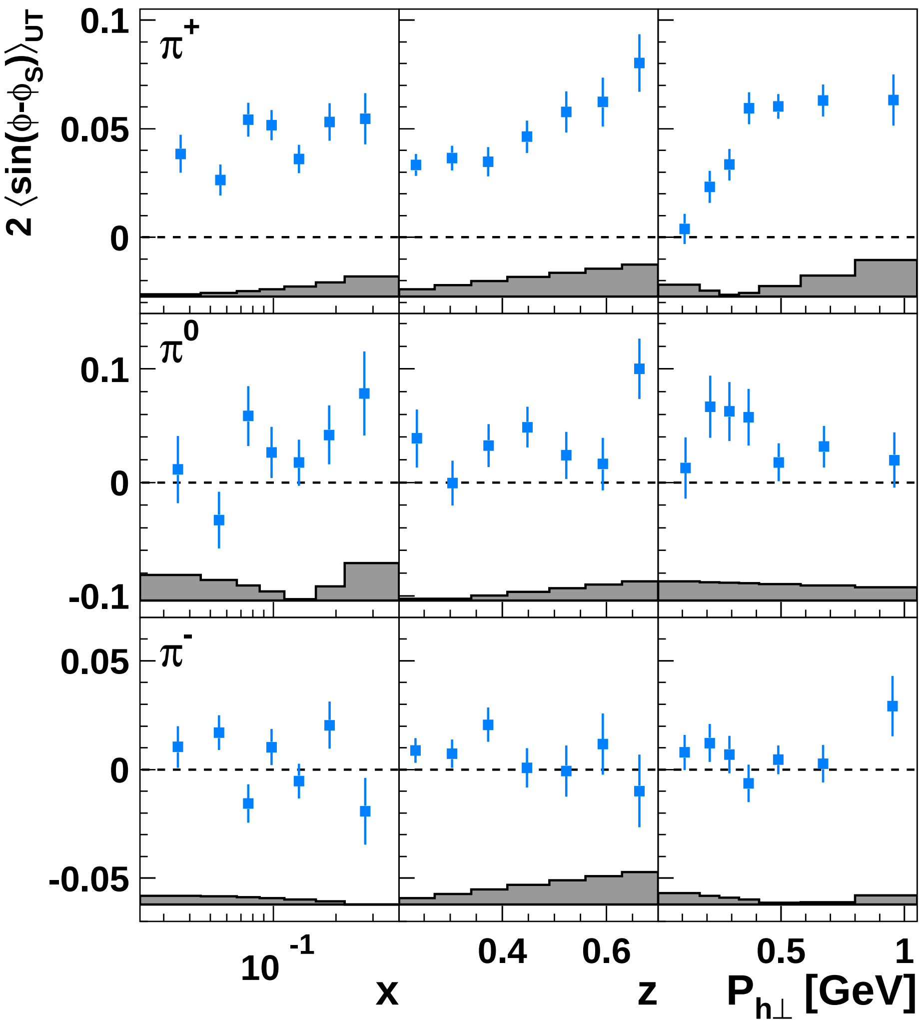


- non-zero Sivers function implies non-zero orbital angular momentum
- generates left-right (azimuthal) asymmetries



Sivers amplitudes for pions

$$2\langle\sin(\phi-\phi_s)\rangle_{UT} = -\frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,p_T^2)\otimes_w D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2)\otimes D_1^q(z,k_T^2)}$$



π^+

- significantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
- dominated by u-quark scattering:
  $\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes_w D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$
- u-quark Sivers $DF < 0$
- non-zero orbital angular momentum

π^0

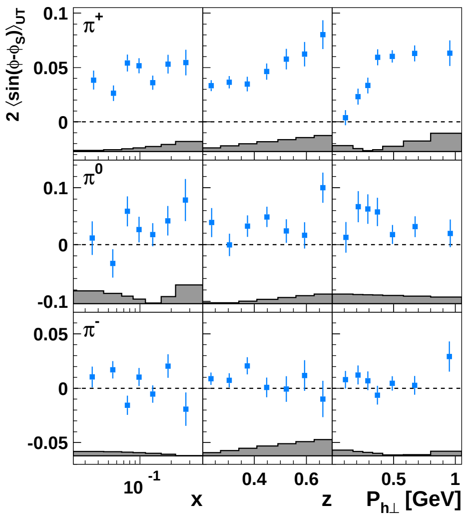
-M.Burkardt (2002)-

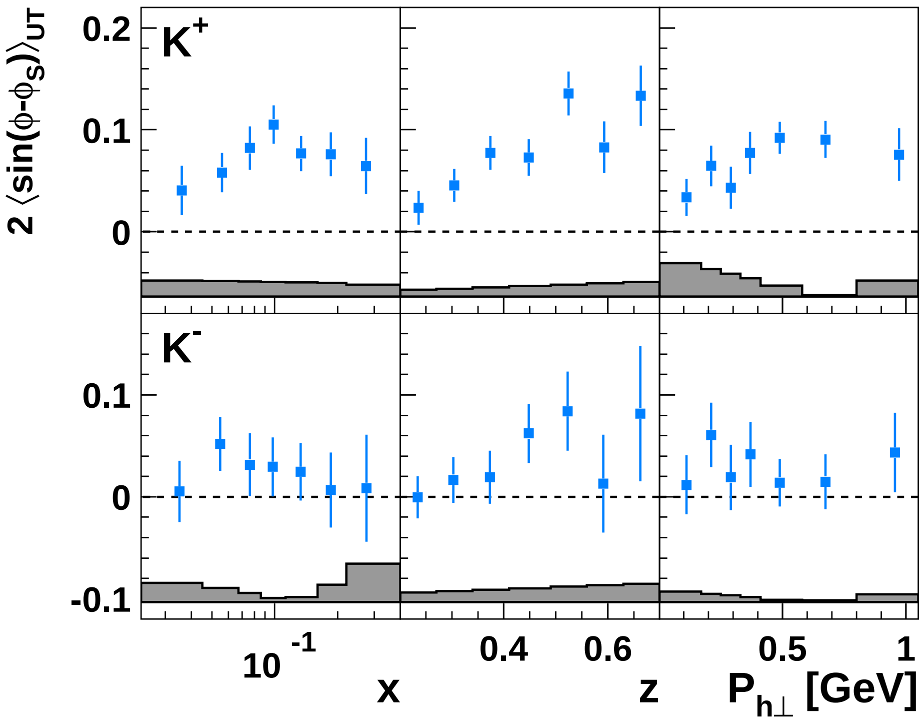
- slightly positive

π^-

- consistent with zero
- u- and d-quark cancellation
- d-quark Sivers $DF > 0$

Sivers amplitudes for kaons





K^+

- significantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
- π^+/K^+ production dominated by scattering off u-quarks:

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

- $\pi^+\equiv|u\bar{d}\rangle$, $K^+\equiv|u\bar{s}\rangle\Rightarrow$ non trivial role of sea quarks

K^-

- slightly positive

"Pretzelosity"

σ_{XY}

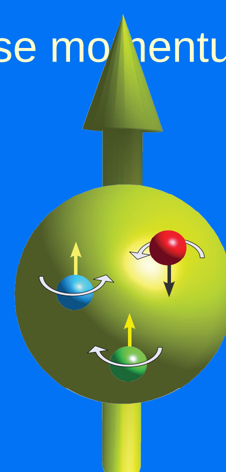
beam: P_l | target: $S_L S_T$

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

- "pretzelosity"DF $h_{1T}^{\perp,q}(x)$ gives a measure of the deviation of the "nucleon shape" from a sphere

$\Rightarrow$

- correlation between parton transverse momentum and parton transverse polarization in a transversely polarized nucleon

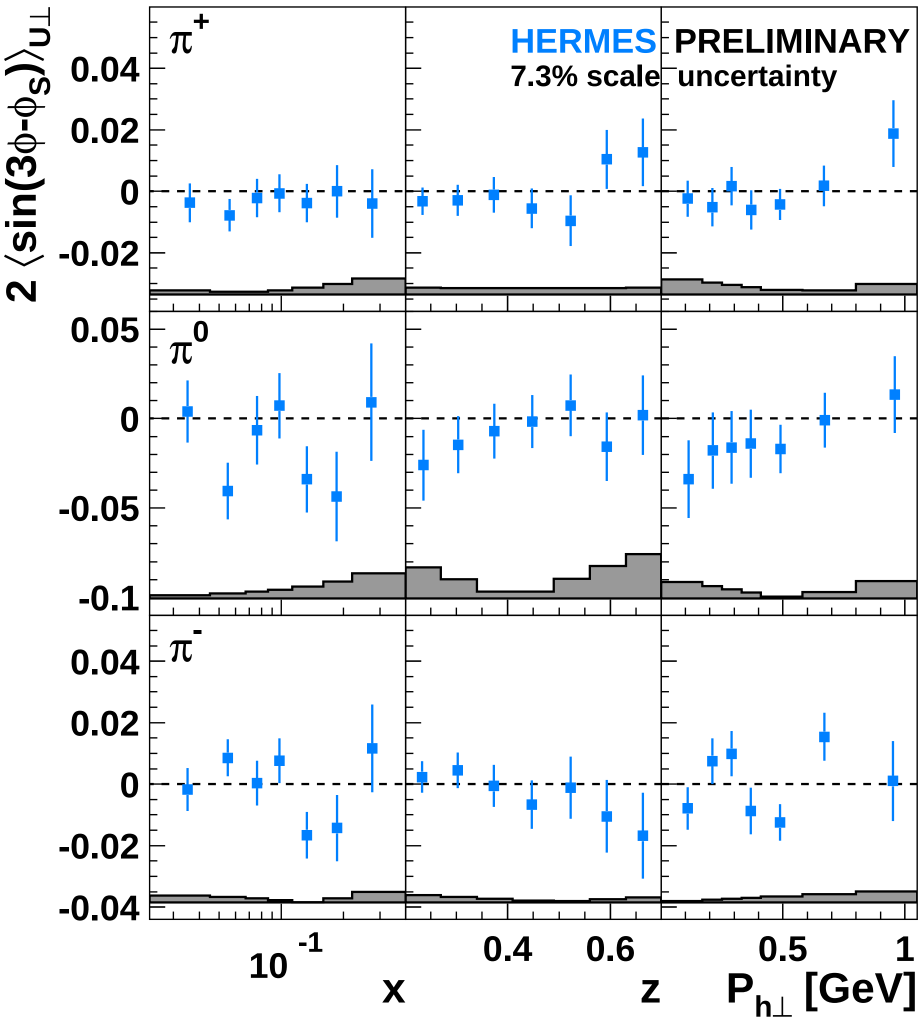


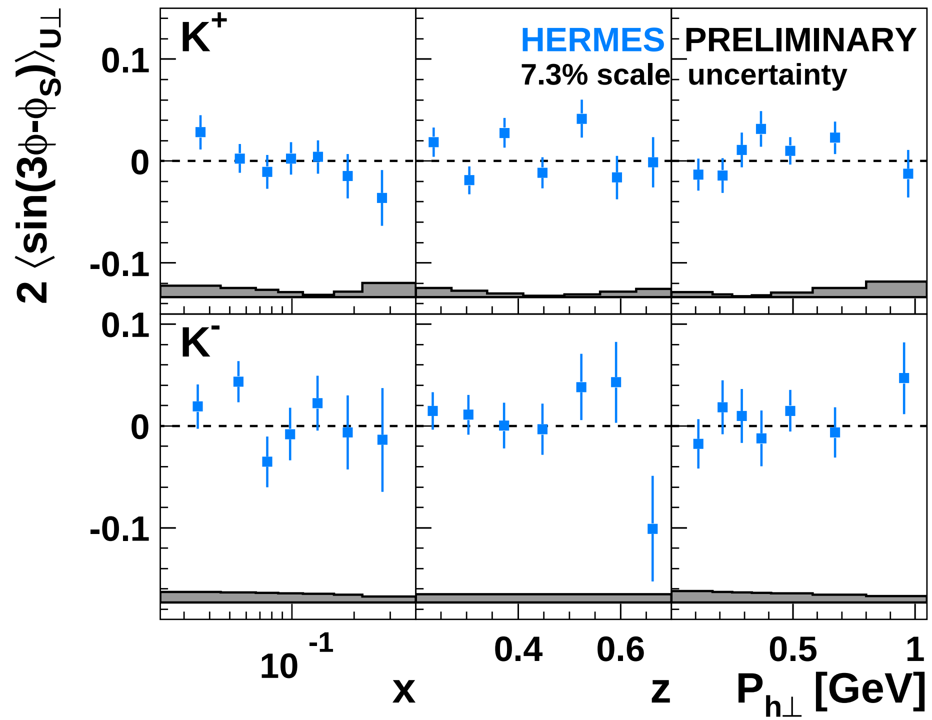
- it is expected to be suppressed w.r.t. f_1^q, g_1^q, h_1^q

hermes

the $\sin(3\phi - \phi_s)$ *Fourier component*

$$\mathbf{h_{1T}^{\perp,q}(x) \otimes H_1^{\perp,q}(z)}$$



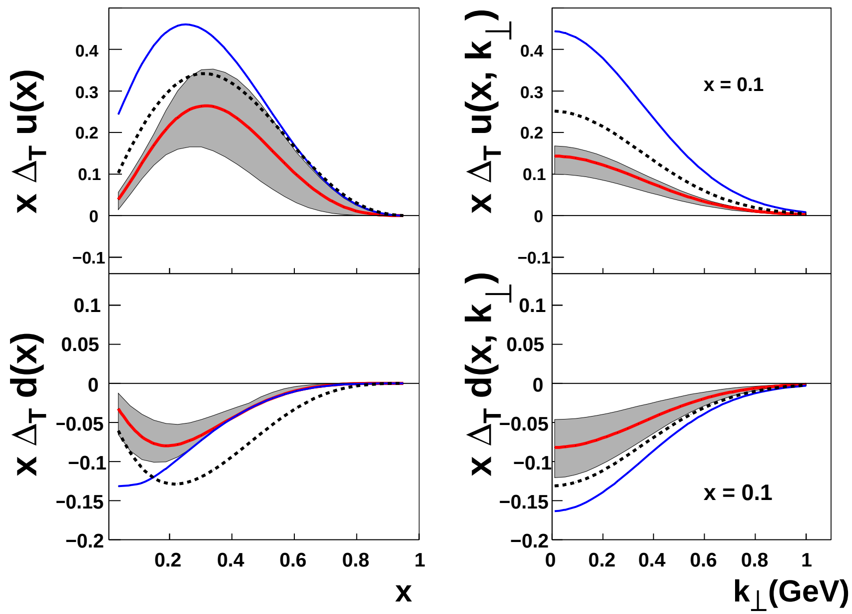


- suppressed by two powers of $P_{h\perp}$ compared to Collins and Sivers amplitudes
- compatible with zero within uncertainties
- $h_{1T}^{\perp,q}(x)$ might be non-zero at higher $P_{h\perp}$

extraction of transversity and Sivers function

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

$lp \to l'hX$ $\quad ld \to l'hX$ $\quad e^+e^- \to h_1h_2X$



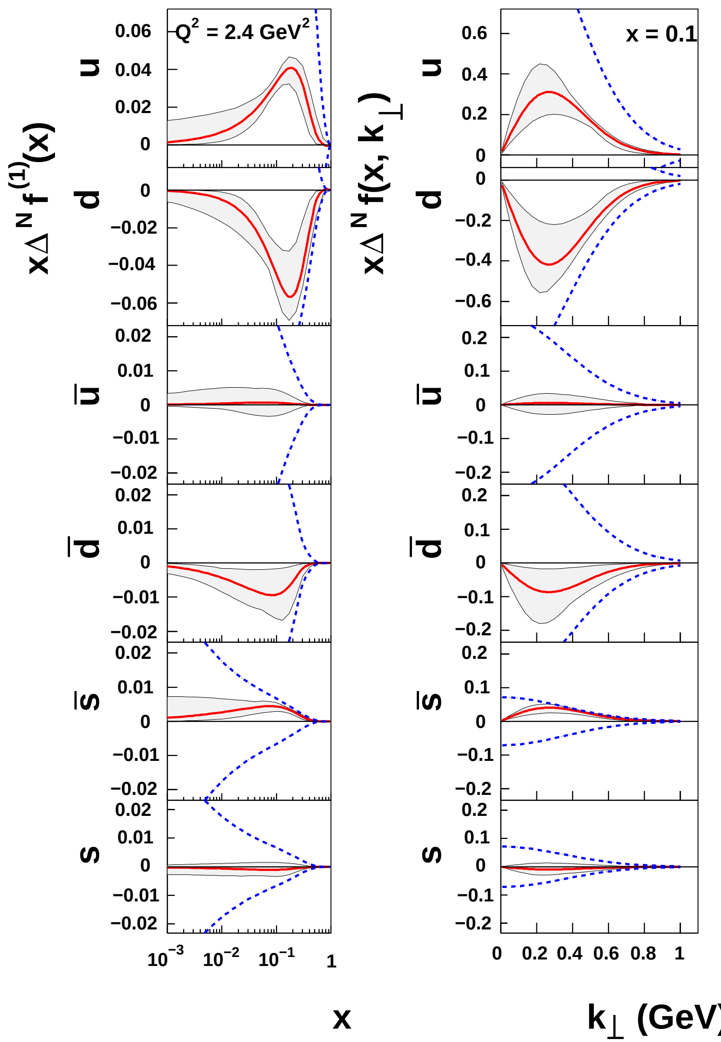
-Anselmino et al. Phys. Rev. D 75 (2007)-

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

Known

$lp \to l'hX$

$ld \to l'hX$

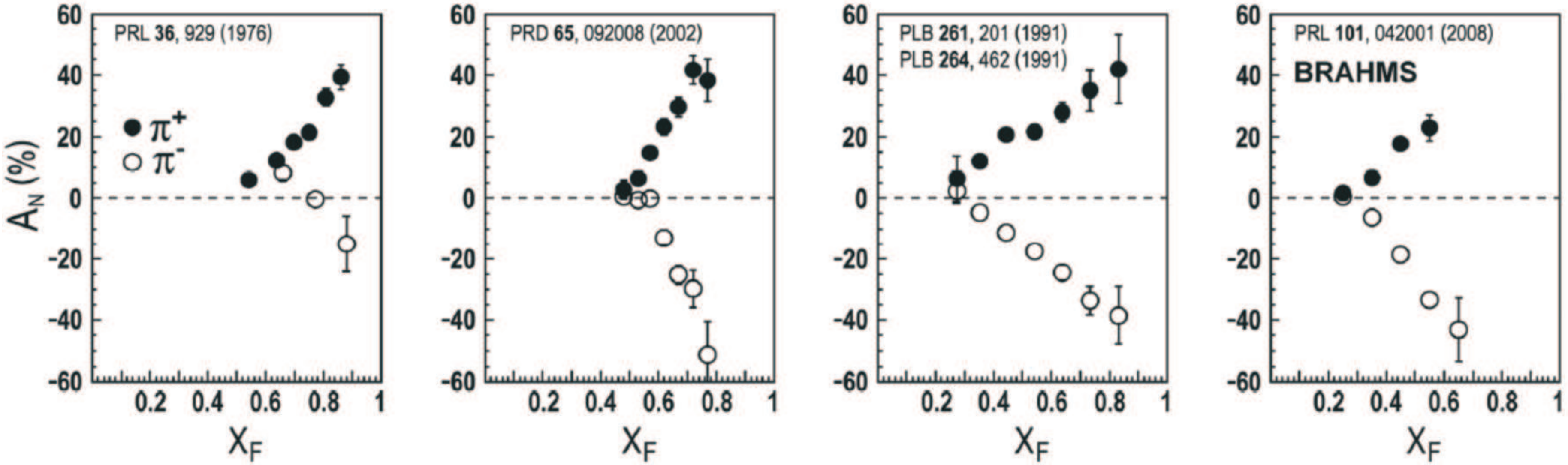


-Anselmino et al. Eur.Phys.J.A39 (2009)-

TSA in inclusive hadron production in $p^{\uparrow}p$

measurements of $A_N = \frac{N_R - N_L}{N_R + N_L}$ in $p^{\uparrow}p \rightarrow \pi X$

ANL (1976)	BNL (2002)	FNAL (1991)	RHIC (2008)
$\sqrt{s} =$ 4.9 GeV	6.6 GeV	19.4 GeV	62.4 GeV



interpretations:

- TMDs (Sivers effect)
- twist-3 qg correlators

suggest:

- increase of A_N with increase of x_F
- decrease of A_N with increase of p_T at fixed x_F
- $A_N \rightarrow 0$ at high p_T

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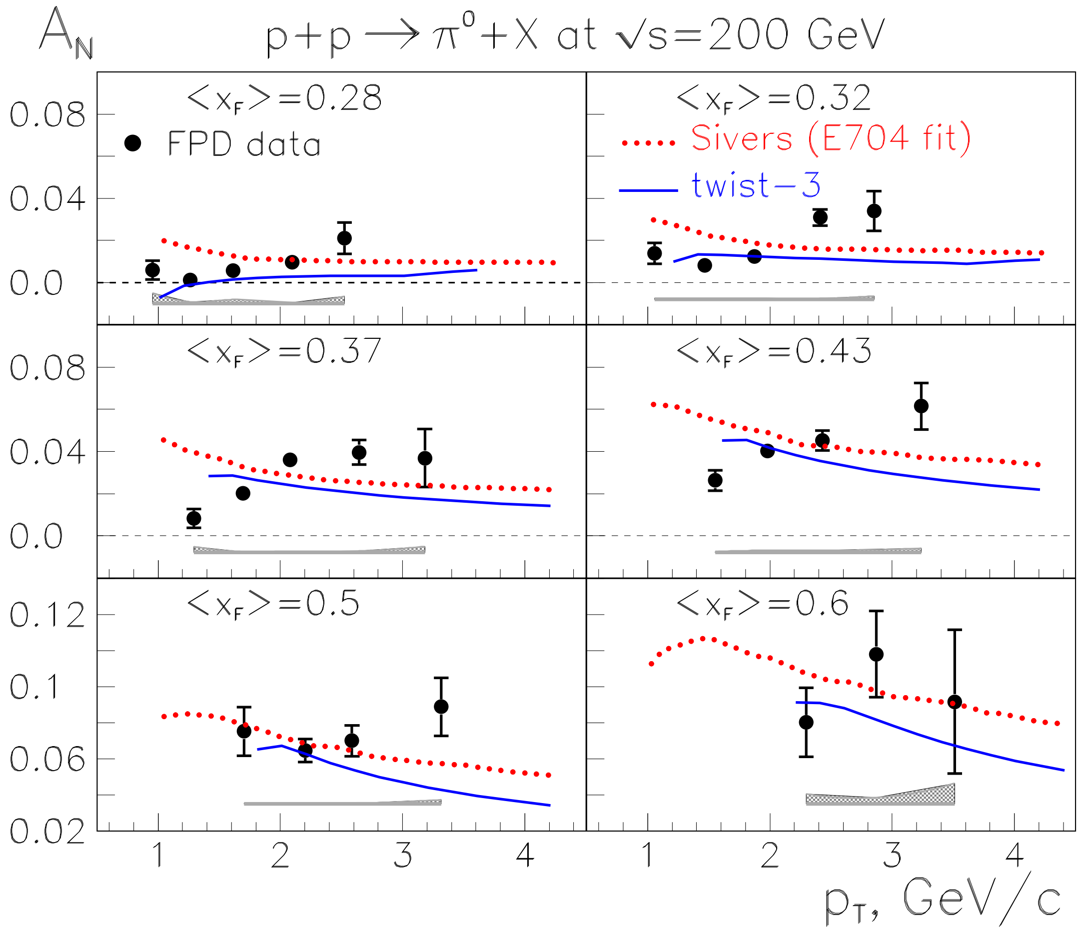
-STAR collab, PRL 101, 222001 (2008) -



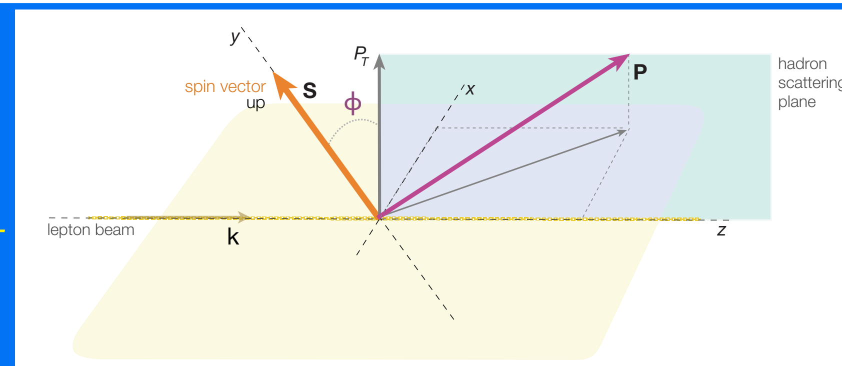
better test of models needed!

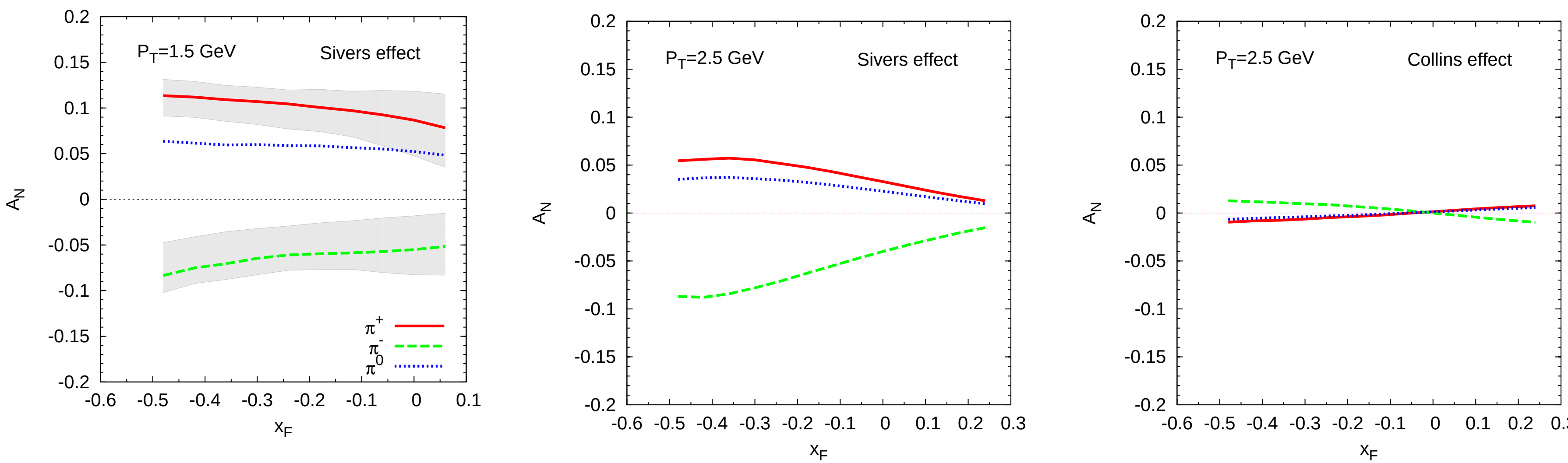
TSA in inclusive hadron production $ep^{\uparrow}$

- up to date: all data coming from pp-scattering
- can be also measured in $ep \rightarrow \pi X$

-Anselmino et al. (2009)-

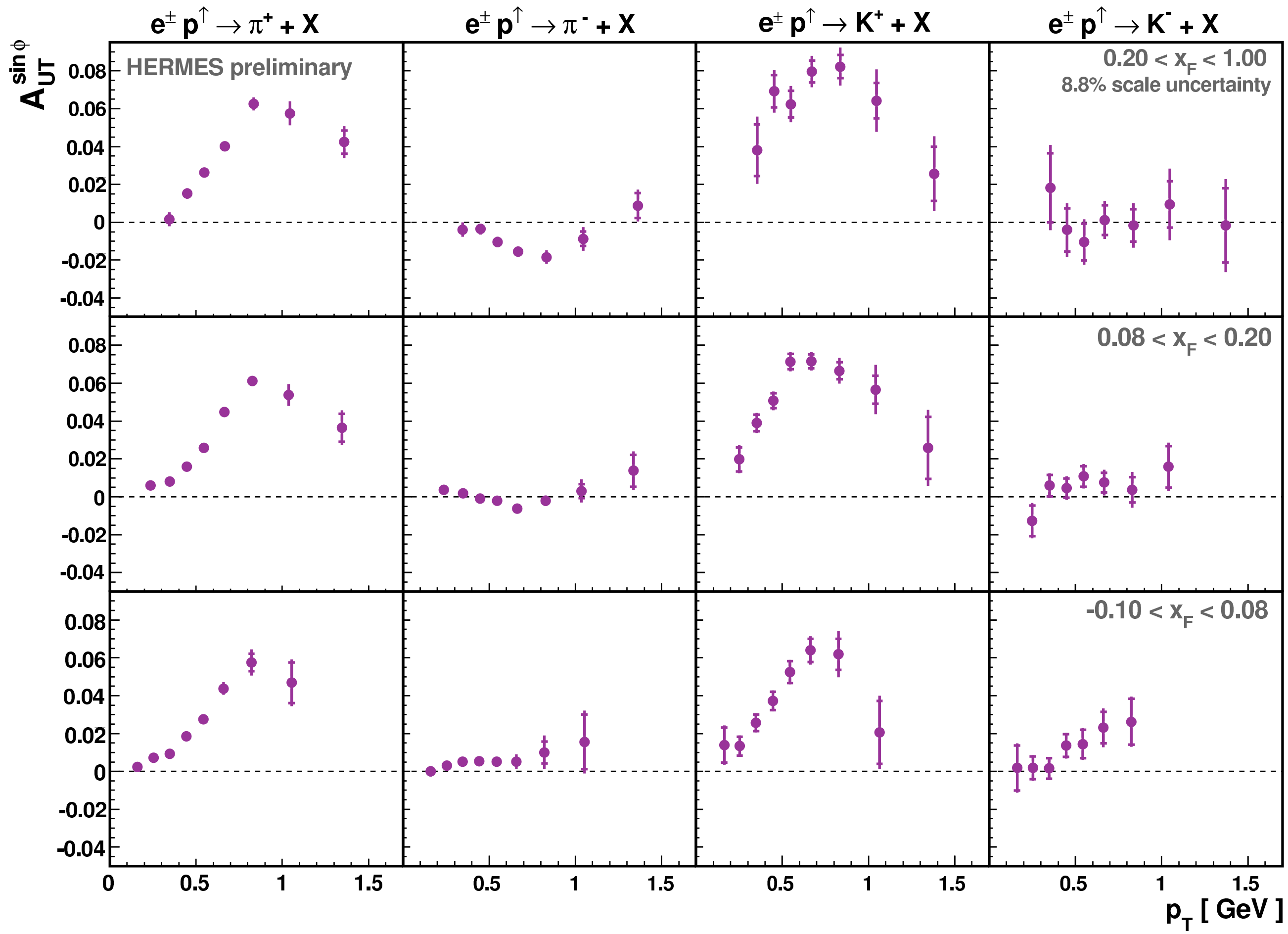
$$A_N = \frac{N_R - N_L}{N_R + N_L} = \frac{2}{\pi} A_{UT}^{\sin\phi}$$





" The measurement of these predicted asymmetries allows a test of the validity of the TMD factorization, largely accepted for SIDIS processes with two scales (small P_T and large Q^2), but still much debated for processes with only one large scale (P_T), like the one we are considering here. A test of TMD factorization in such processes is of great importance for a consistent understanding of the large SSAs measured in the single inclusive production of large P_T hadrons in proton-proton collisions. " *-Anselmino et al. (2009)-*

$A_{UT}^{\sin\phi}$ % p_T & $\mathrm{x_F}$



- π^+ and K^+ asymmetries decrease at high P_T
- sign change for π^-
  - A_N in $p^{\uparrow}p$ is larger than in $ep^{\uparrow}$
  - u-quark dominance in $ep^{\uparrow}$ may explain the smaller size of π^- asymmetry
- positive K^- for $\mathrm{x_F} \approxeq 0$

GPDs are 'hybrid' objects

form factors

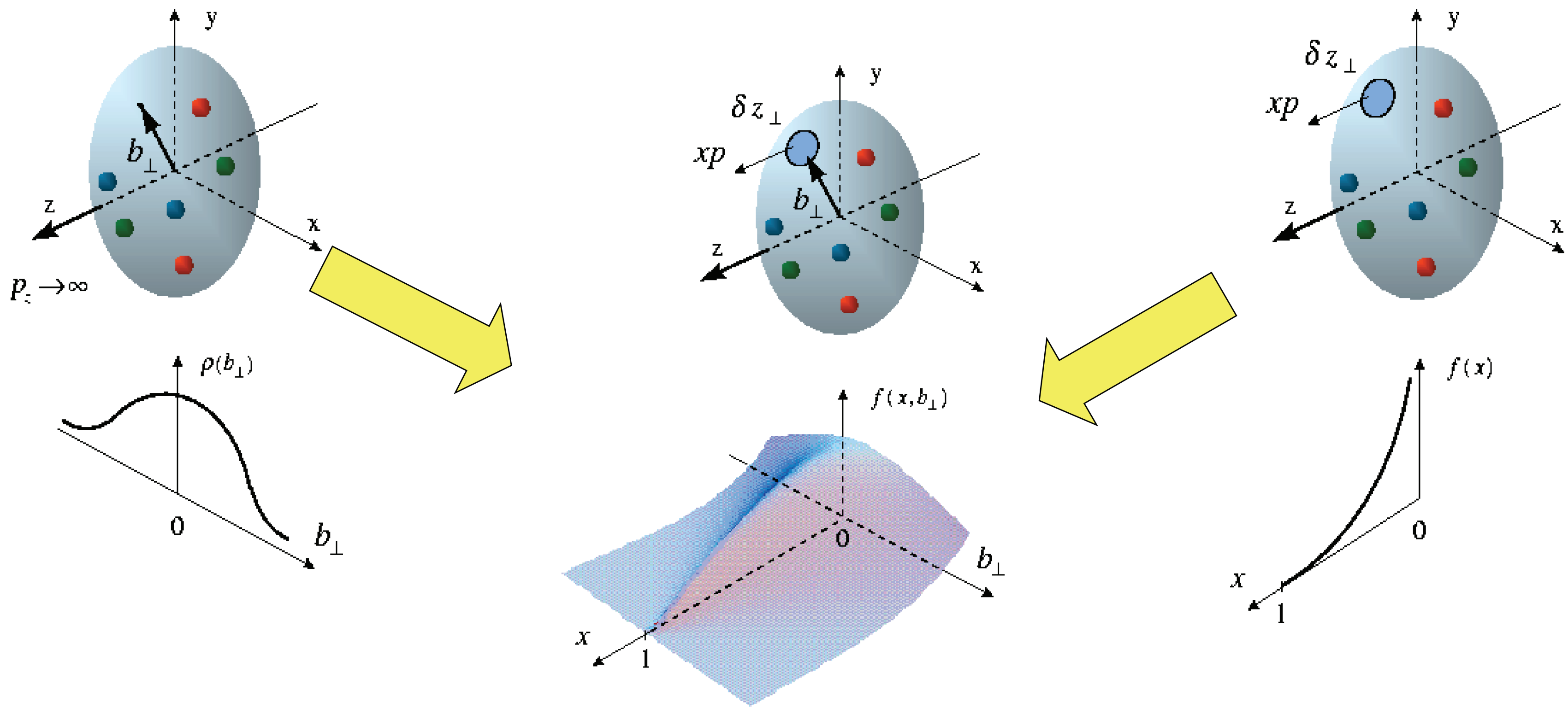
$ep \to e'p'$

GPDs

$ep \to e'Xp'$

parton density

$ep \to e'X$



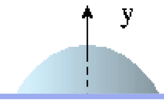
parton's transverse localization $b_\perp$

parton's transverse localization $b_\perp$ for a given longitudinal momentum fraction x

parton's longitudinal momentum distribution $q(x)$ at resolution scale $1/Q^2$

GPDs are ’hybrid’ objects

form factors	GPDs	parton density
$ep \to e'p'$	$ep \to e'Xp'$	$ep \to e'X$



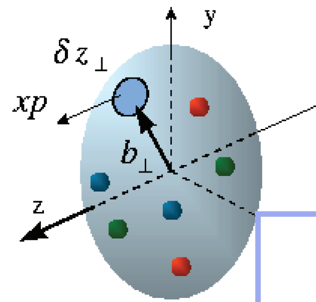
$$\int_{-1}^{1} dx H^q(x,\xi,t,\mu^2) = F_1^q(t)$$

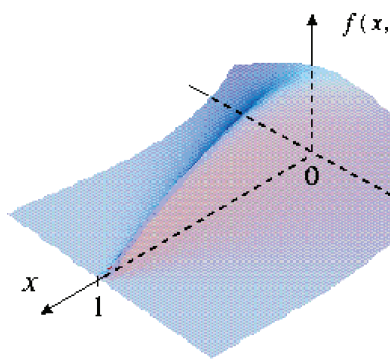
$$\int_{-1}^{1} dx E^q(x,\xi,t,\mu^2) = F_2^q(t)$$

$$\int_{-1}^{1} dx \widetilde{H}^q(x,\xi,t,\mu^2) = G_A^q(t)$$

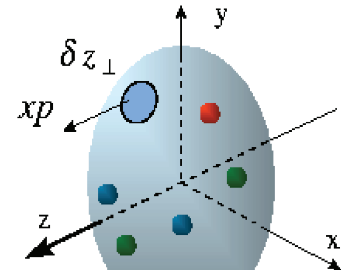
$$\int_{-1}^{1} dx \widetilde{E}^q(x,\xi,t,\mu^2) = G_P^q(t)$$

ization $b_\perp$





n’s transverse localiza- $_\perp$ for a given longitudi- nal momentum fraction x



$$H^q(x,0,0) = q(x)$$

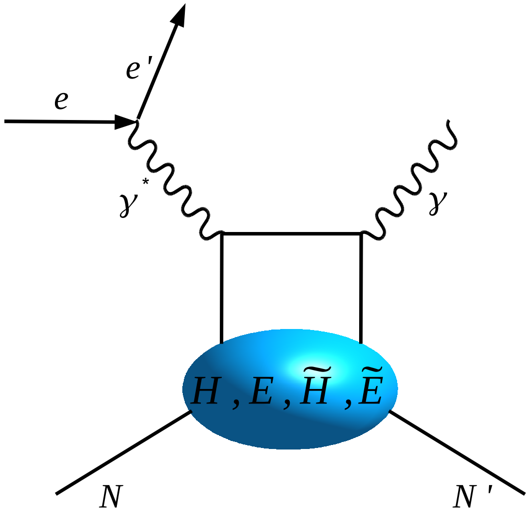
$$H^g(x,0,0) = xg(x)$$

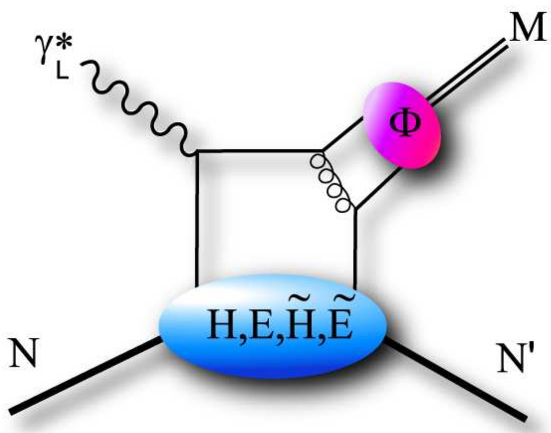
$$\widetilde{H}^q(x,0,0) = \Delta q(x)$$

$$\widetilde{H}^g(x,0,0) = x\Delta g(x)$$

parton’s longitudinal momentum distribution $q(x)$ at resolution scale $1/Q^2$

Exclusive reactions, GPDs





$$S_z = \frac{1}{2} = \underbrace{J^q}_{\frac{1}{2}\Delta\Sigma + L_z^q} + J^g$$

second x-moment of GPDs

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

$$J^g = \frac{1}{2} \lim_{t \to 0} \int_{0}^{1} dx \left[H^g(x,\xi,t) + E^g(x,\xi,t) \right]$$

x, ξ longitudinal momentum fractions

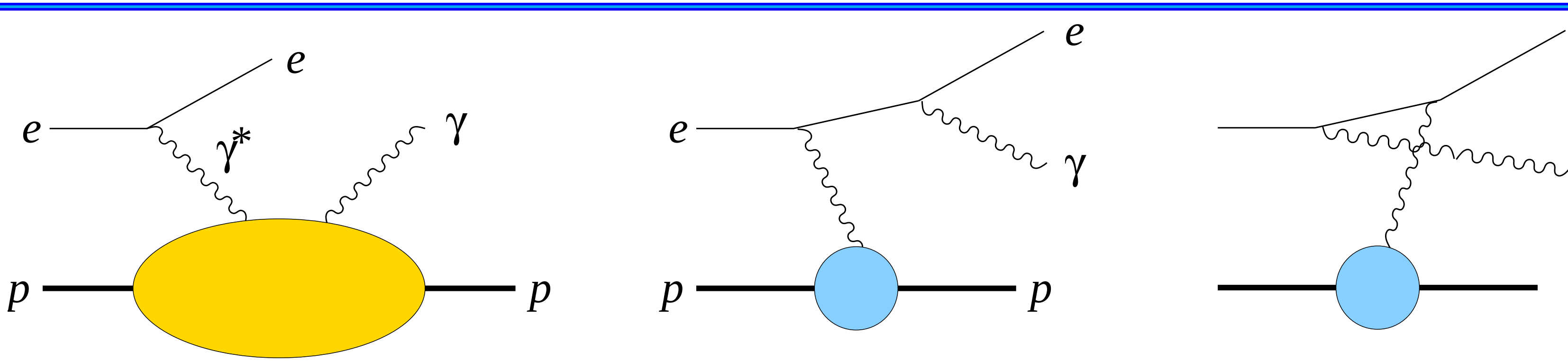
t squared four-momentum transfer

- an experimental evaluation is complicated
- get convolutions of GPDs ($F : H, E, \widetilde{H}, \widetilde{E}$) and hard scattering functions

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

- the only presently known way

deeply virtual compton scattering (DVCS)



same initial and final states in DVCS and Bethe-Heitler ⇒ Interference!

$$\sigma_{ep} \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}}_{\mathcal{I}}$$

σ_{XY}

beam: P_l | target: $S_L S_T$

$$\begin{aligned}
d\sigma \sim d\sigma^{BH}_{UU} &+ e_\ell d\sigma^{I}_{UU} + d\sigma^{DVCS}_{UU} \\
&+ e_\ell P_\ell d\sigma^{I}_{LU} + P_\ell d\sigma^{DVCS}_{LU} \\
&+ e_\ell S_L d\sigma^{I}_{UL} + S_L d\sigma^{DVCS}_{UL} \\
&+ e_\ell S_T d\sigma^{I}_{UT} + S_T d\sigma^{DVCS}_{UT} \\
+P_\ell S_L d\sigma^{BH}_{LL} &+ e_\ell P_\ell S_L d\sigma^{I}_{LL} + P_\ell S_L d\sigma^{DVCS}_{LL} \\
+P_\ell S_T d\sigma^{BH}_{LT} &+ e_\ell P_\ell S_T d\sigma^{I}_{LT} + P_\ell S_T d\sigma^{DVCS}_{LT}
\end{aligned}$$

Bethe-Heitler contribution:
- calculated in QED

DVCS contribution:
- HERMES: $|\mathcal{T}_{DVCS}|^2 << |\mathcal{T}_{BH}|^2$

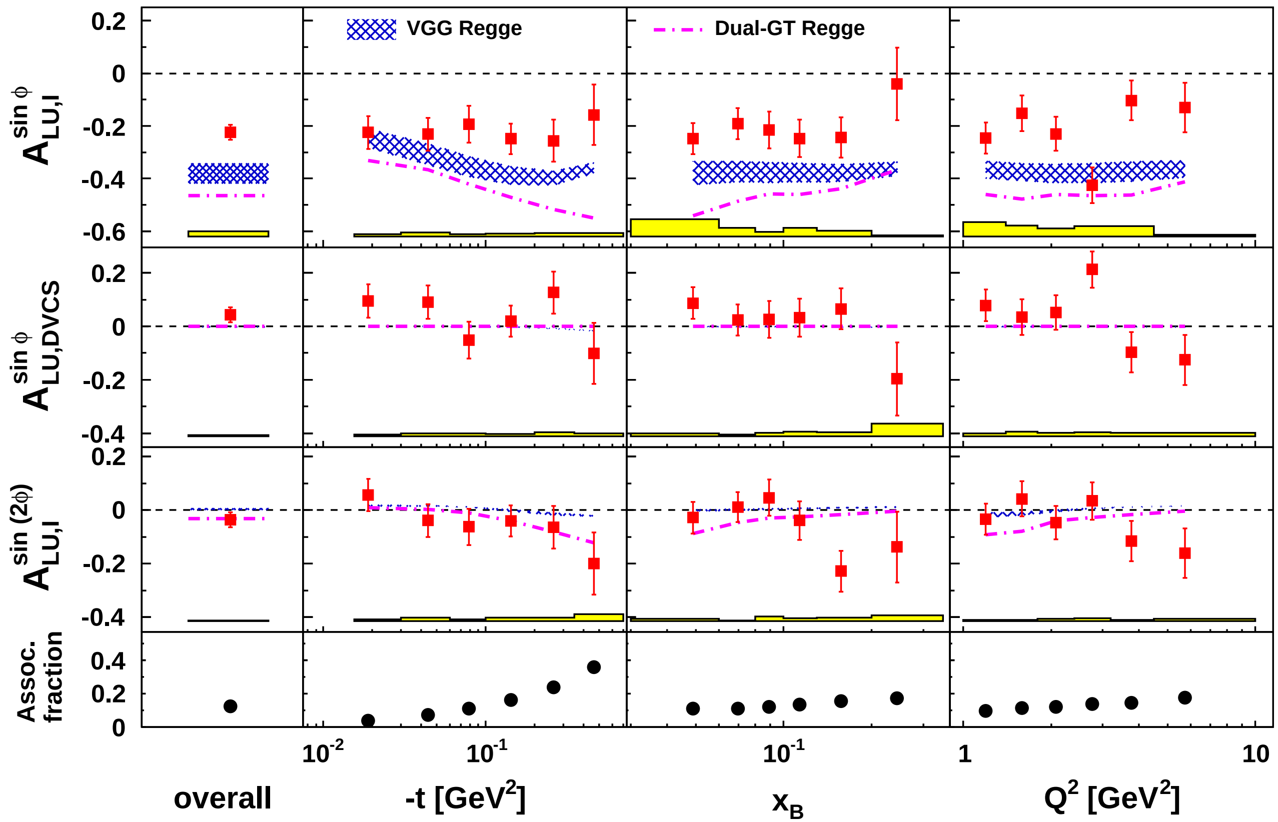
interference term:
- depend on a linear combination of Compton form factors
- access to GPD combinations through azimuthal asymmetries

beam helicity asymmetry

$$\mathcal{A}_{LU}^{I}(\phi) = \sum_{n=1}^{2} A_{LU,\mathrm{I}}^{\sin(n\phi)} \sin(n\phi)$$

$$A_{LU,\mathrm{DVCS}}^{\sin\phi} \propto s_1^{\mathrm{DVCS}} \sin\phi$$

-HERMES Collaboration: arXiv:0909.3587 (2009)-



$A_{LU,\mathrm{I}}^{\sin\phi}$

- twist-2: $\propto F_1 \mathrm{Im}\mathcal{H}$
- large overall value
- no kin. dependencies

$A_{LU,\mathrm{DVCS}}^{\sin\phi}$, $A_{LU,\mathrm{I}}^{\sin 2\phi}$

- twist-3
- overall value compatible with 0
- no kin. dependencies

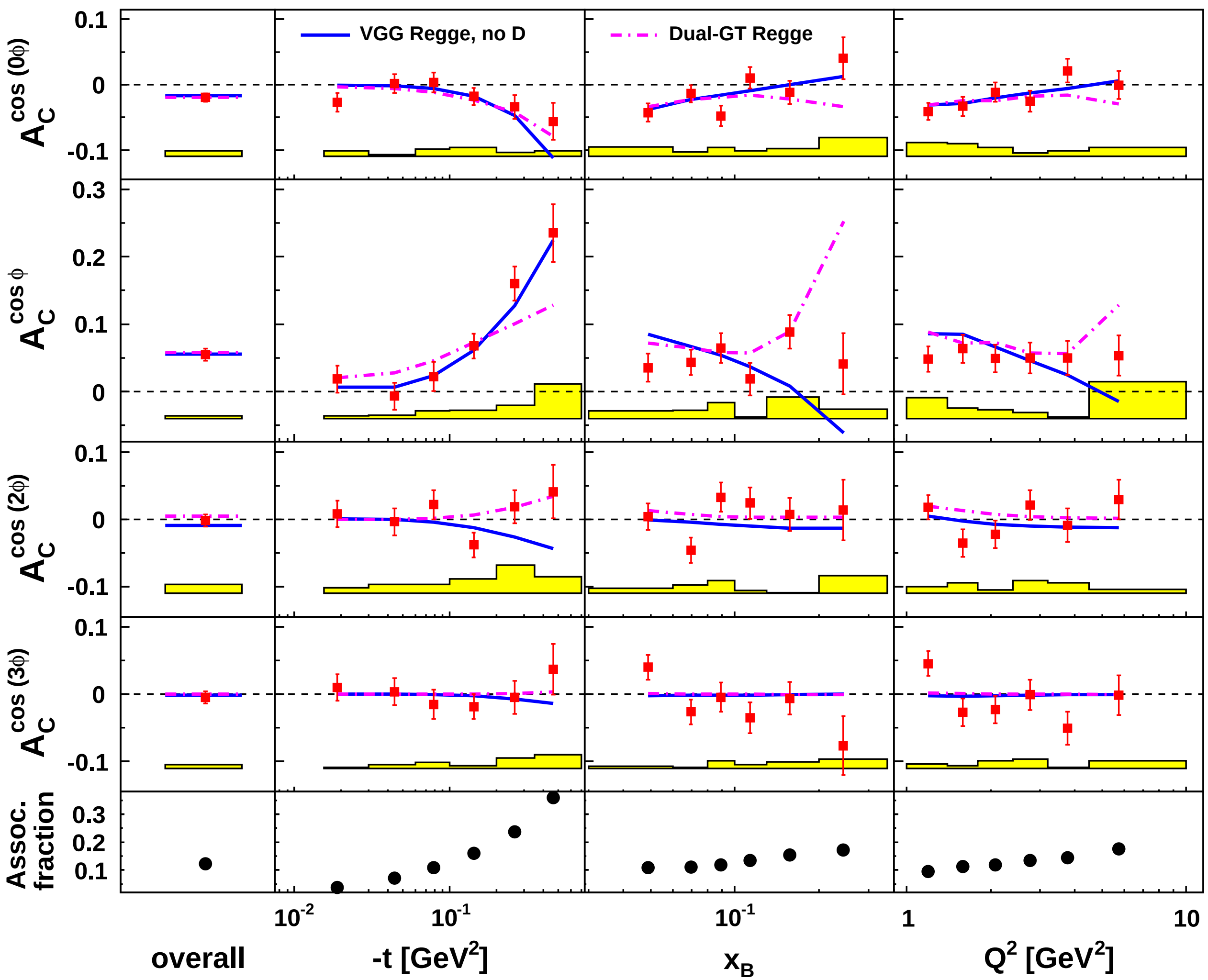
model predictions:

- overshoot the magnitude of $A_{LU,\mathrm{I}}^{\sin\phi}$ by a factor of 2

beam charge asymmetry

$$\mathcal{A}_C(\phi) = \sum_{n=0}^{3} A_C^{\cos(n\phi)} \cos(n\phi)$$

-HERMES Collaboration: arXiv:0909.3587 (2009)-



twist-2 GPDs: $A_C^{\cos\phi}$, $A_C^{\cos 0\phi}$

- strong t-dependence
- no x_B, Q^2 dependencies

$$A_C^{\cos\phi} \propto F_1 \mathrm{Re}\mathcal{H}$$

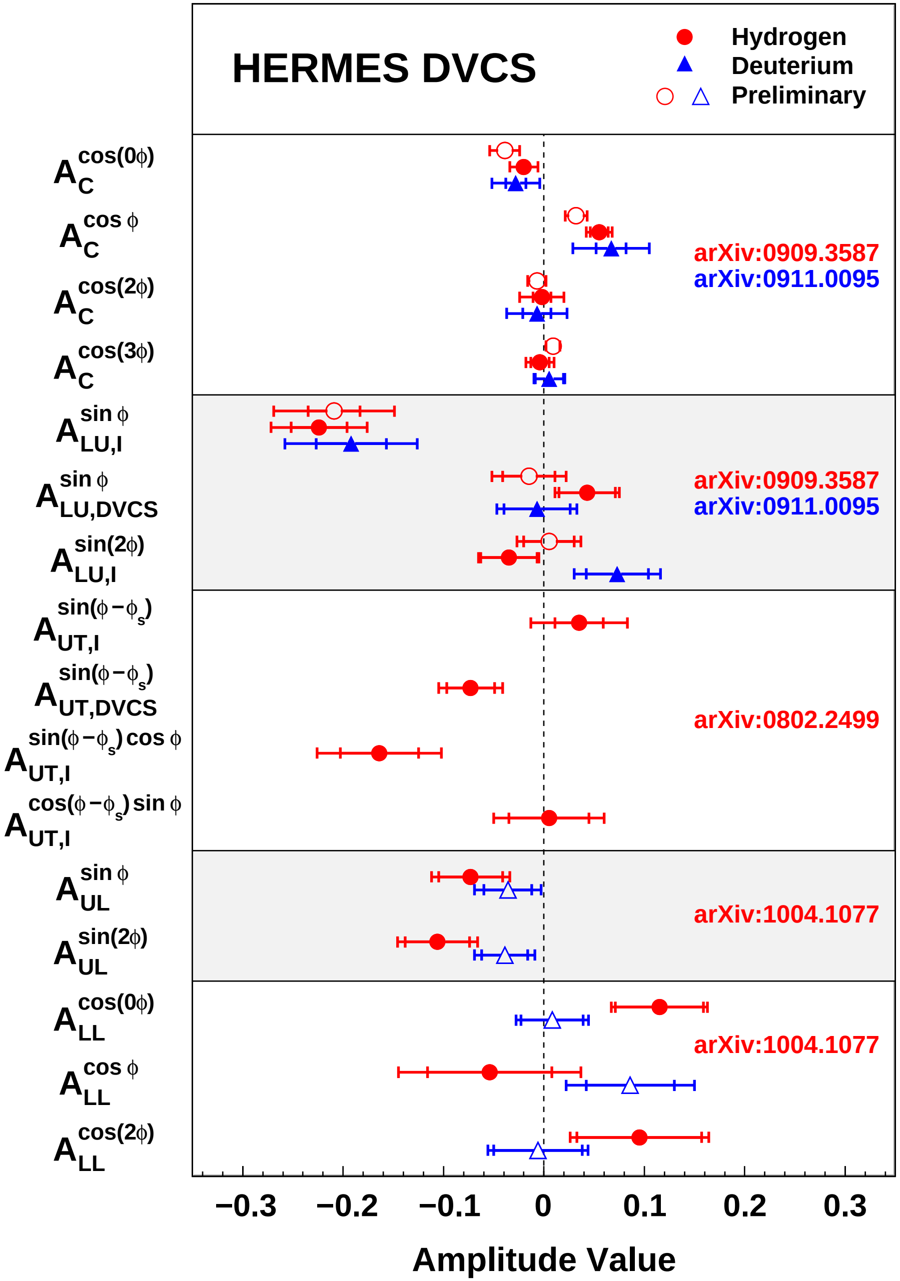
$$A_C^{\cos 0\phi} \propto -\frac{t}{Q} A_C^{\cos\phi}$$

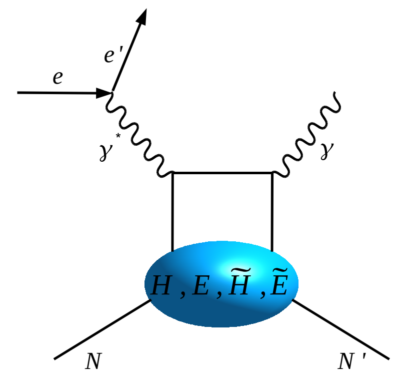
$A_C^{\cos(2\phi)} \approx 0$: twist-3 GPDs
$A_C^{\cos(3\phi)} \approx 0$: gluon helicity-flip GPDs

theoretical predictions:

- does not describe the beam-helicity data, but in good agreement with this data

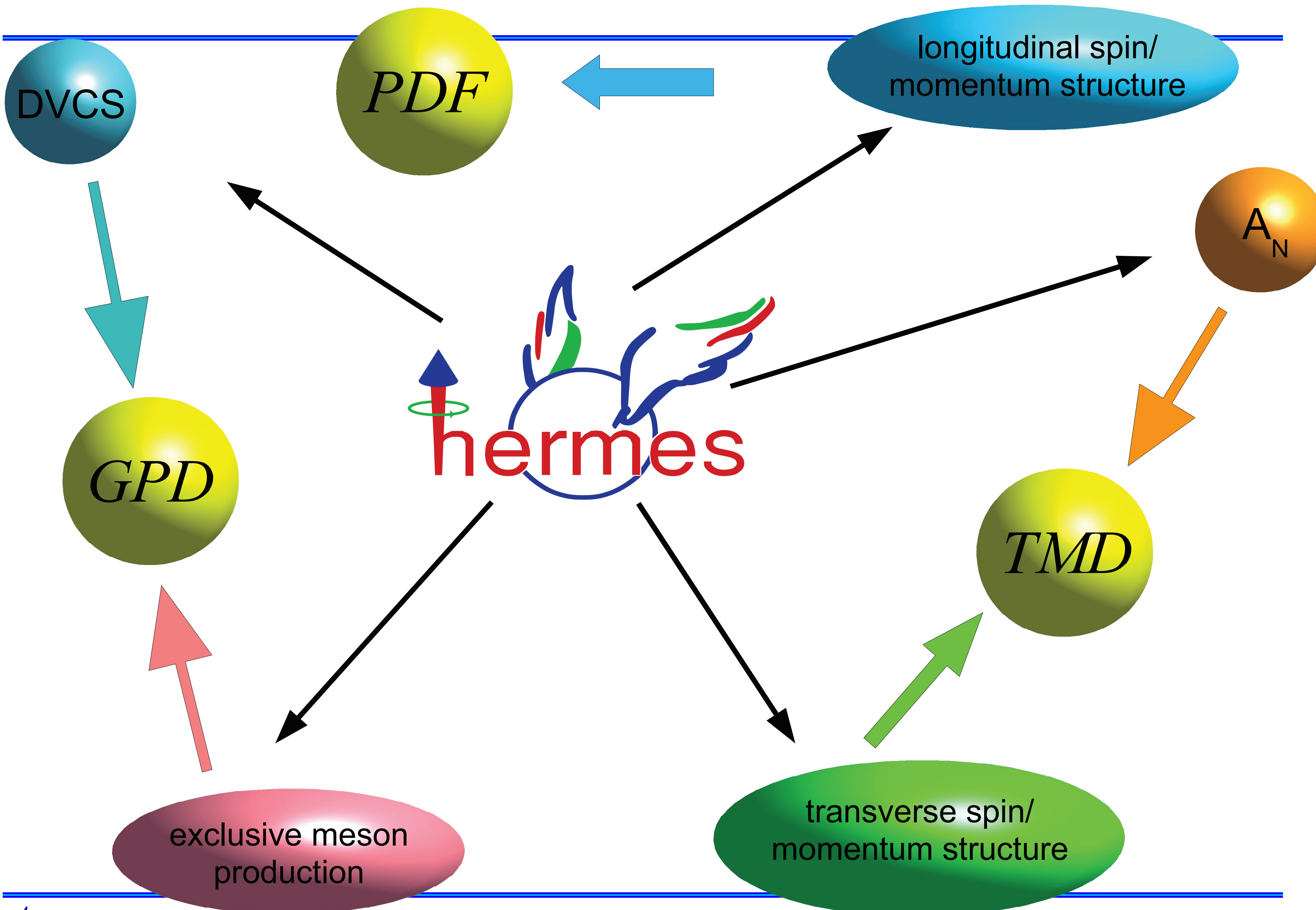
GPDs, DVCS and HERMES





- beam-charge asymmetry:
  - $\mathrm{Re}\mathcal{H}$
- beam-helicity asymmetry:
  - $\mathrm{Im}\mathcal{H}$
- transverse target-spin asymmetry:
  - $\mathrm{Im}(\mathcal{H}\,\mathcal{E})$
- longitudinal target-spin asymmetry:
  - $\mathrm{Im}\widetilde{\mathcal{H}}$
- double-spin asymmetry:
  - $\mathrm{Re}\widetilde{\mathcal{H}}$

towards global fits!


DVCS
PDF
longitudinal spin/ momentum structure
A_N
GPD
hermes
TMD
exclusive meson production
transverse spin/ momentum structure

outlook