Highlights from HERMES

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(DESY)

for the hermes collaboration

Overview

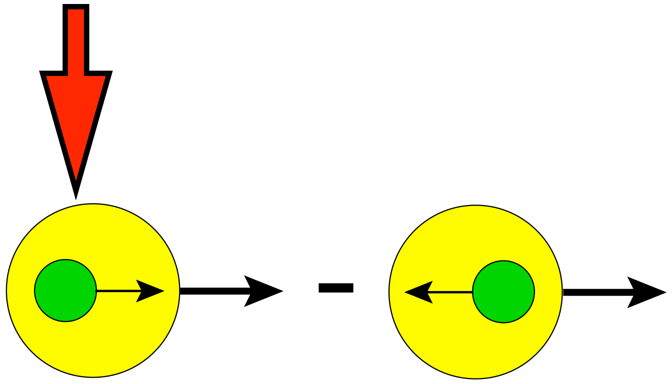
- HERMES @ HERA
- Longitudinal nucleon structure
  - Spin-dependent structure function g_1
  - Strange quark distribution $s(x)$ and $\Delta s(x)$
- Transverse structure of the nucleon
  - Transversity and transverse momentum dependent distribution functions
- 3D picture of the nucleon
  - Accessing Generalized Parton Distributions (GPDs) via Deeply Virtual Compton Scattering (DVCS)

The Quest: Spin Structure of the Proton

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

- $\frac{1}{2}\Delta\Sigma$ ← quark spin
- ΔG ← gluon spin
- $L_q + L_g$ ← orbital angular momentum

$$\Delta\Sigma = \sum_{q=\mathrm{u,d,s}} (\Delta q + \Delta \bar{q})$$



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$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$ quark spin

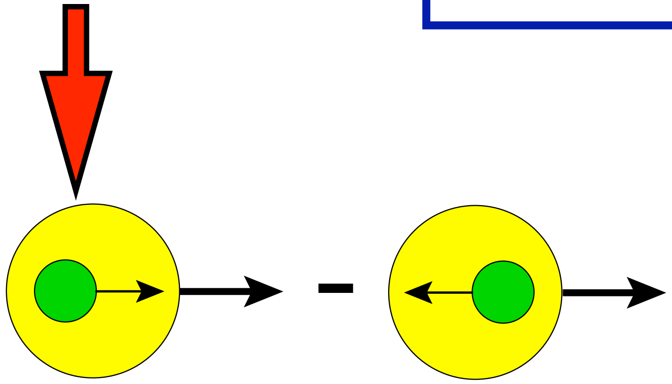
$$+ \Delta G$$ gluon spin

$$+ L_q + L_g$$ orbital angular momentum

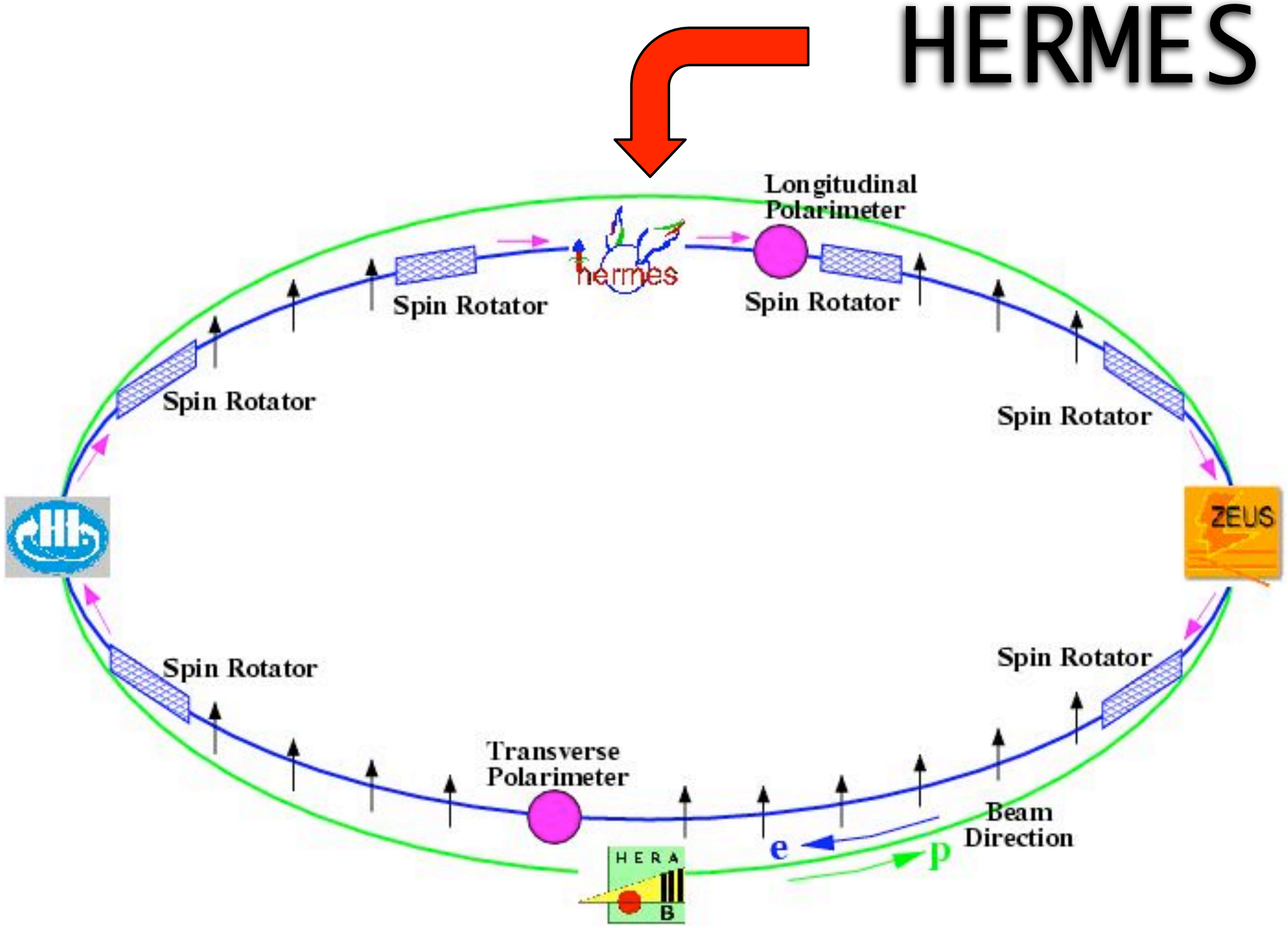
$$\Delta\Sigma = \sum_{q=\mathrm{u,d,s}} (\Delta q + \Delta\bar{q})$$

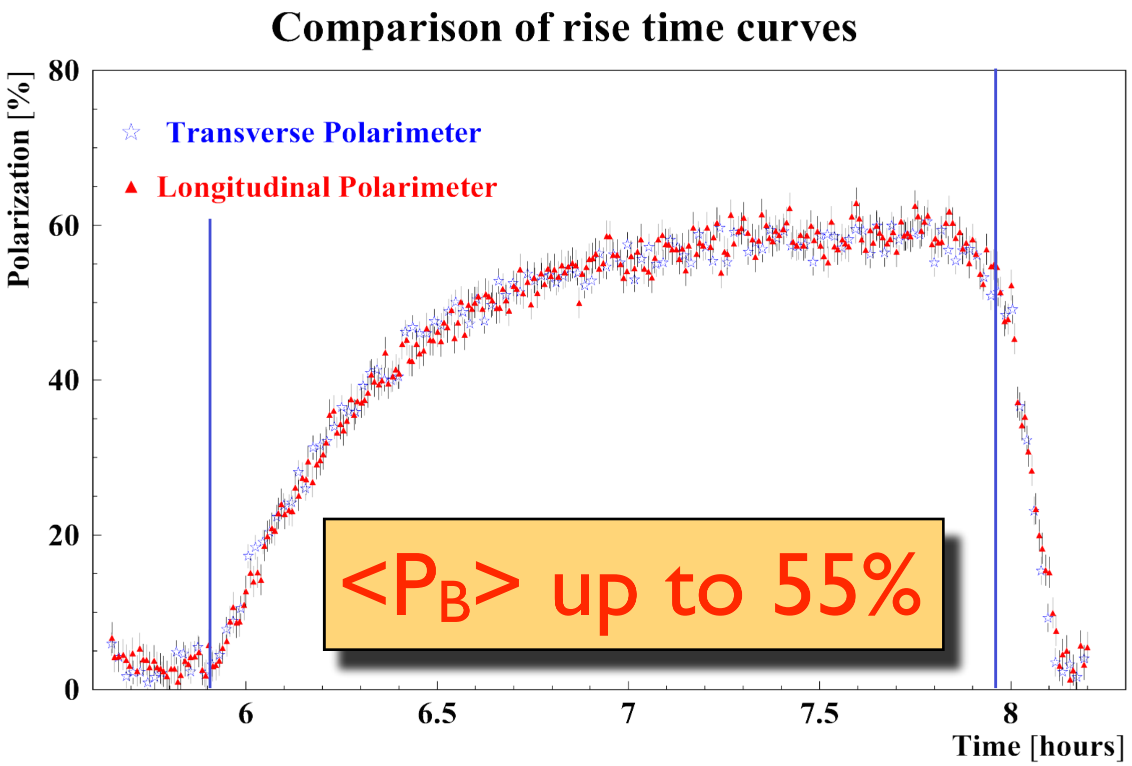
EMC (1988):

$$= 0.120 \pm 0.094(\mathrm{stat}) \pm 0.138(\mathrm{syst})$$



HERMES @ HERA



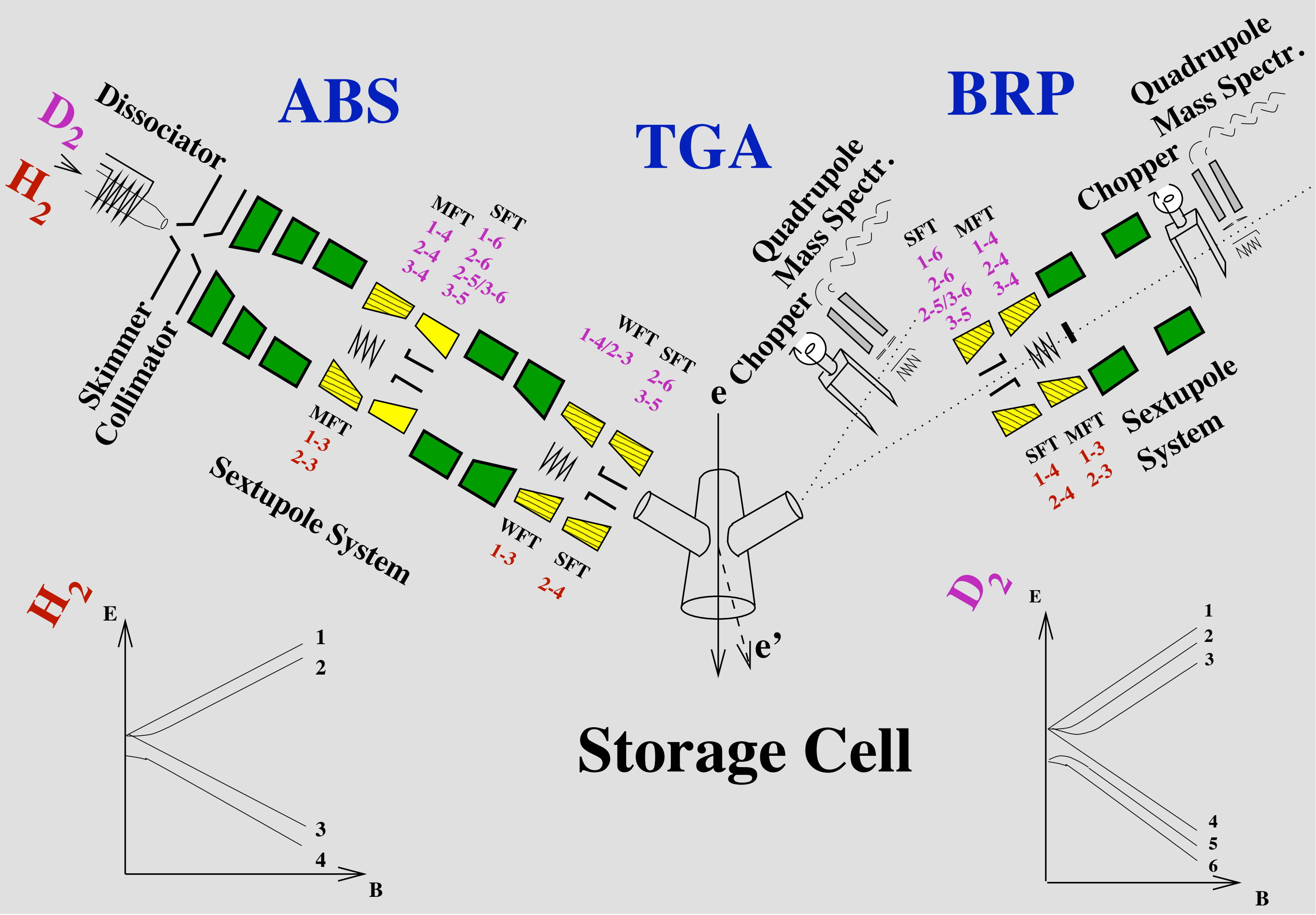


$<P_B>$ up to 55%

- Fixed target experiment
  ➡ only using HERA lepton (e^+/e^-) beam
- HERA lepton beam self-polarizing
  ➡ cross section asymmetry in synchrotron radiation emission leads to build-up of transverse polarization (Sokolov-Ternov effect)
- Spin-rotators ➡ longitudinal polarization at HERMES interaction region
- Beam polarization measured by two independent polarimeters

The HERMES Target

Gaseous target in storage cell aligned with lepton beam

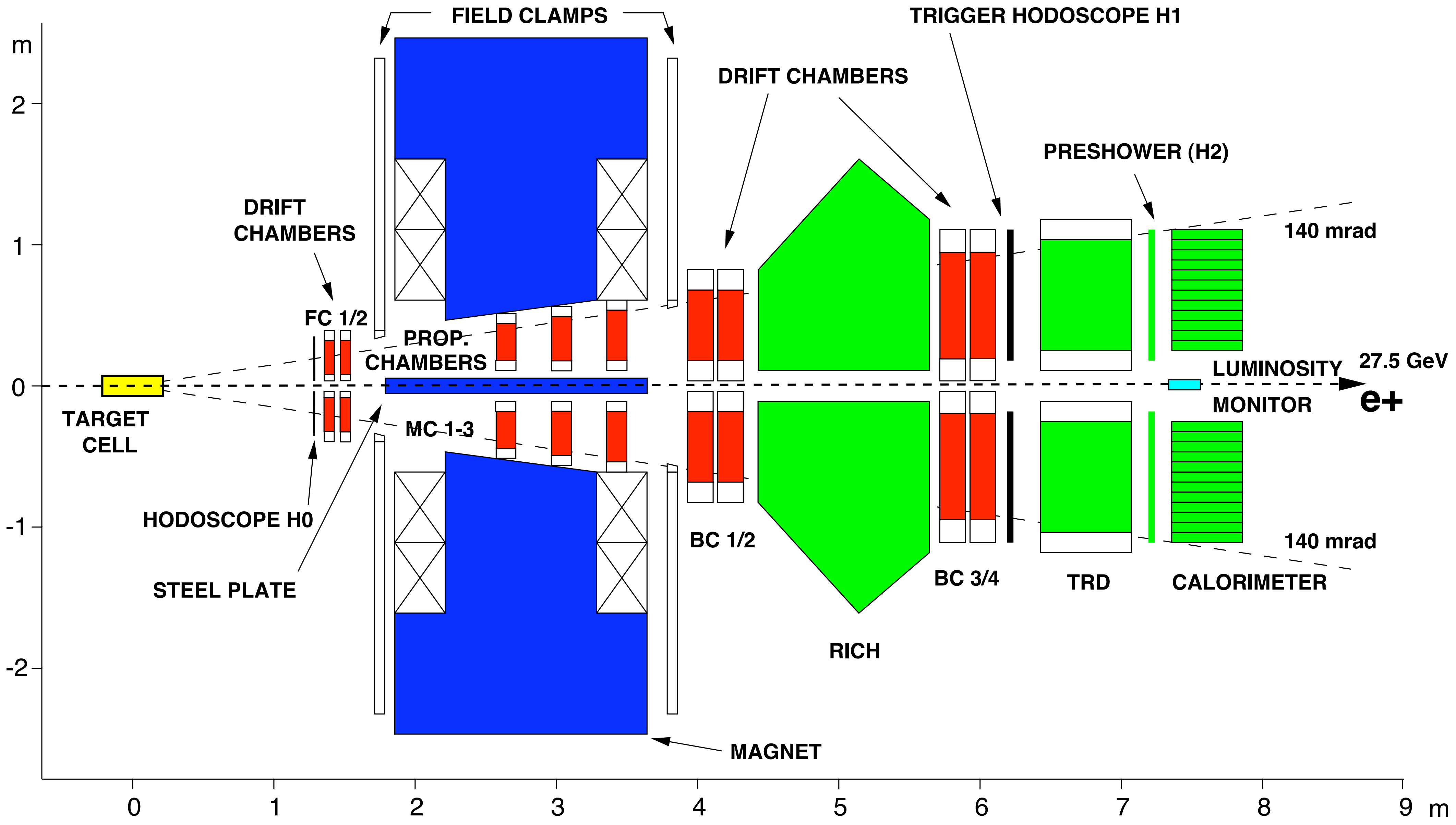


Features:

- Pure target (no dilution)
- Unpolarized targets:
  variety of nuclear targets
  - H, D, He, Ne, Kr, ...
- Polarized targets:
  - Longitudinal pol. (<=2000)
    H, D, He
  - Transverse pol. (2002-2005)
    H
  - Rapid reversal of polarization direction within 0.5s (every 90s)

Polarization:
longitudinal: ~85%
transversal: ~75%

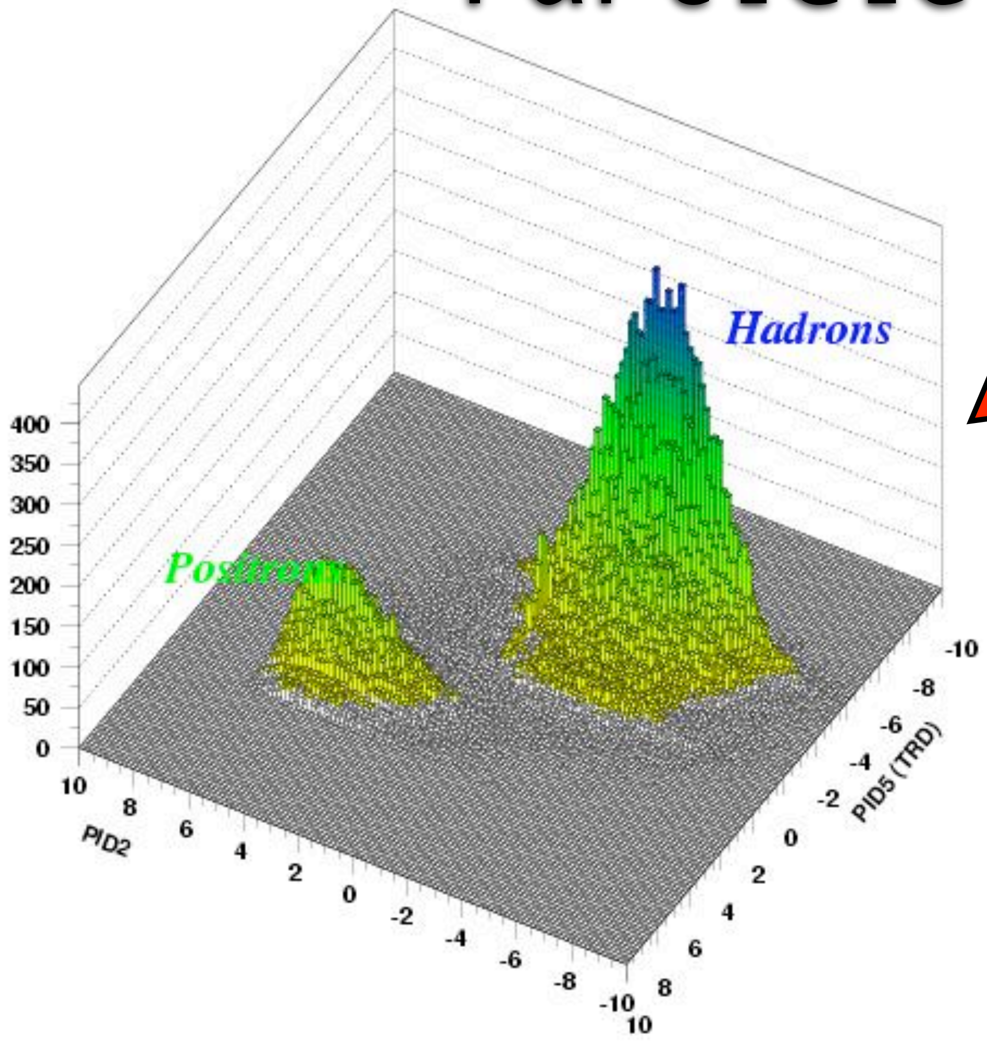
HERMES Spectrometer



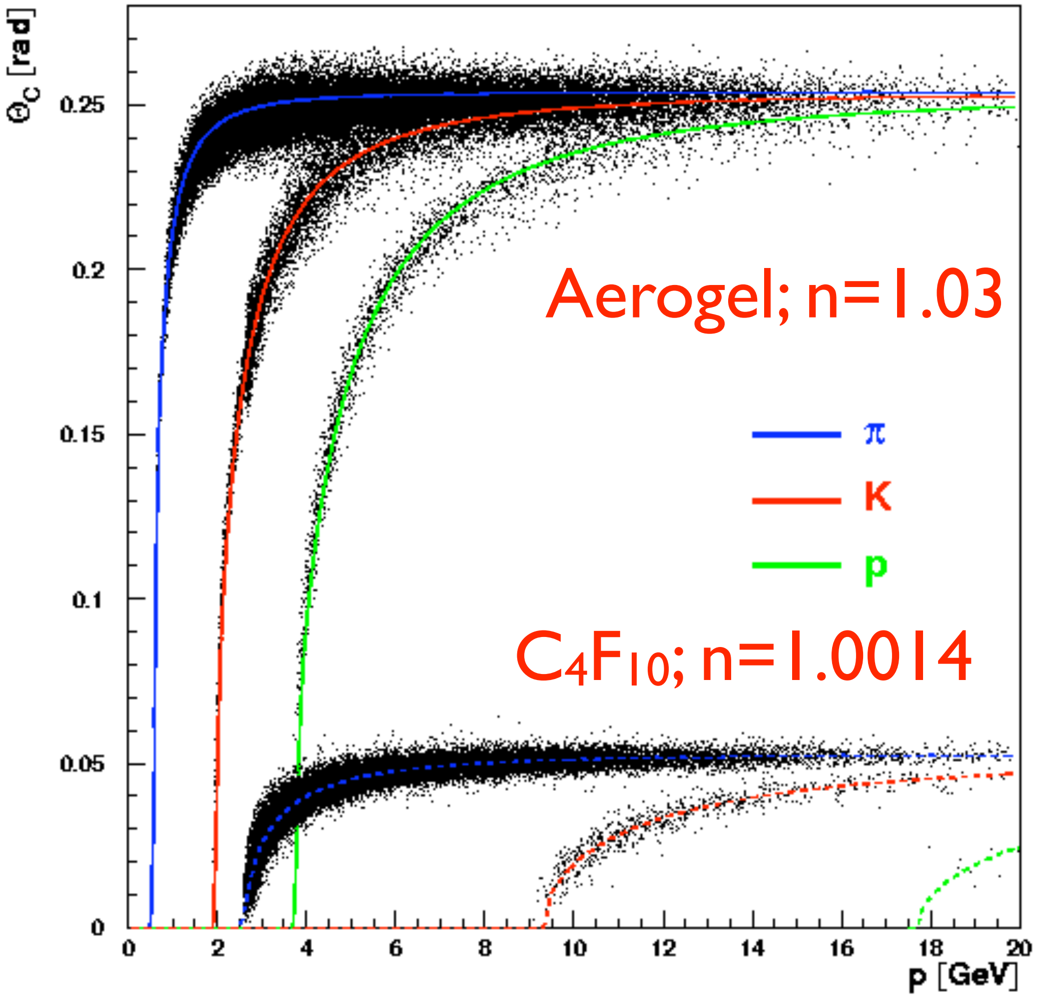
- Forward acceptance spectrometer: 40 mrad ≤ Θ ≤ 220 mrad
- Kinematic coverage: $0.02 \leq x_{Bj} \leq 0.8$ for $Q^2 > 1$ GeV^2 and W > 2 GeV
- Tracking: $\delta P/P = 0.7\% - 2.5\%$, $\delta\Theta \leq 1$ mrad
- PID: TRD, Preshower, Calorimeter, Cherenkov (RICH after 1997)

Particle Identification

excellent lepton/hadron separation



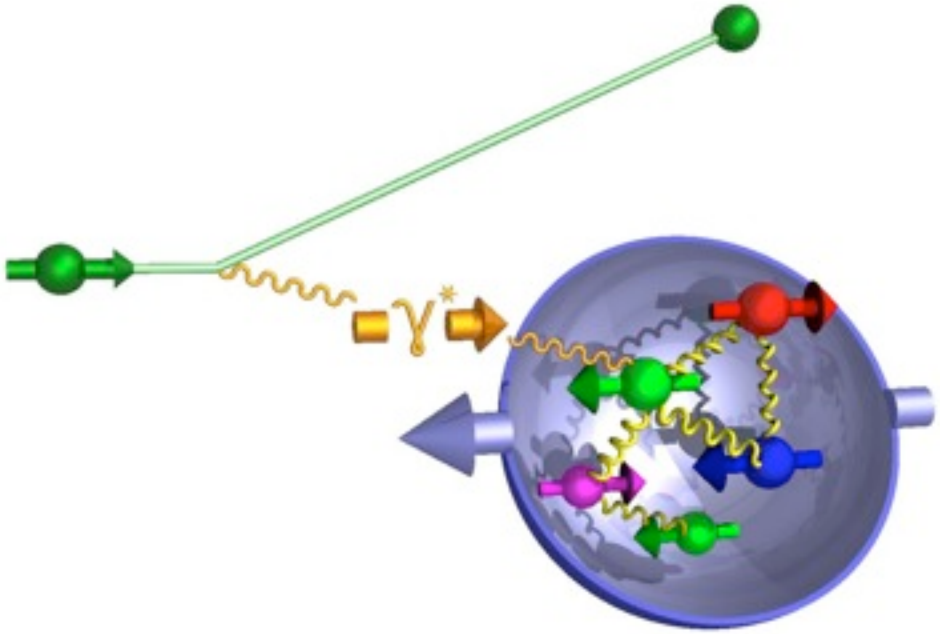
RICH: two radiators allow hadron separation between 2-15 GeV



The spin-dependent structure function g_1

g_1: Inclusive DIS

HERA:
$e^{\pm}$ @ 27.6 GeV
$P_B \sim 53\%$



long. pol. undiluted gas target:
H ($P_z \sim$ 76%, 85%)
D ($P_z \sim$ 84%)

Cross section ➡ structure functions

F_1, F_2	unpol
g_1, g_2	pol
$b_1 \ldots b_4$	pol (spin-1)

$$g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \left[\Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2)\right]$$

in LO QCD

$$\Delta q = q_{\overset{\rightarrow}{\Rightarrow}} - q_{\overset{\rightarrow}{\Leftarrow}}$$

Measured Inclusive Asymmetries

$\boxed{P_{zz} = 0.83 \pm 0.03}$ $\boxed{A_{zz} \sim 0.01}$ $\Rightarrow$ $\frac{b_1^d}{F_1^d} = -\frac{3}{2} A_{zz}$

(measured by HERMES)

$$\sigma = \sigma_{\text{unpol}} \left[1 + P_B P_z A_{\|} + \underbrace{\frac{1}{2} P_{zz} A_{zz}}_{\text{Deuterium}} \right]$$

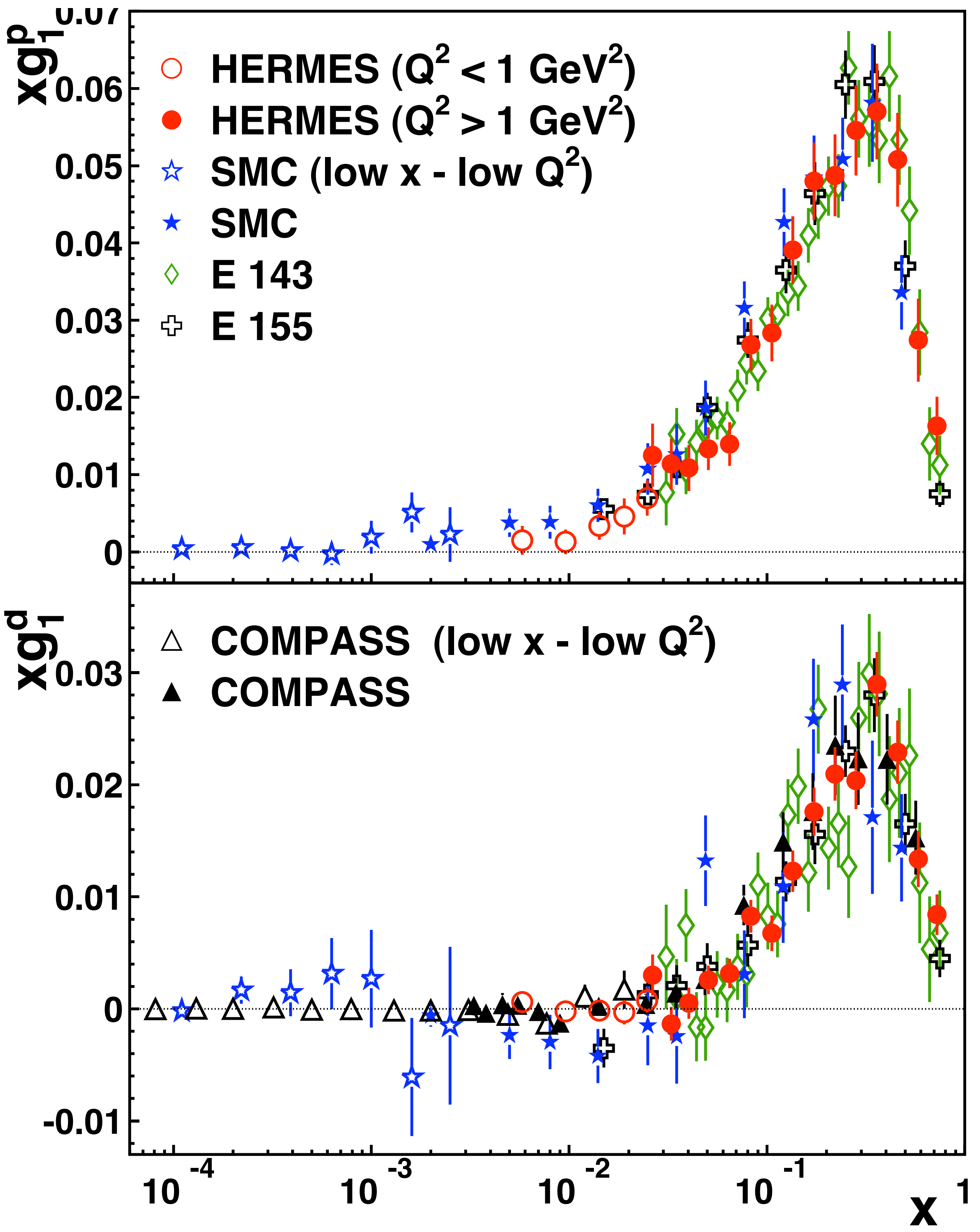
measured DIS cross section

inclusive asymmetry:

$$A_{\|} = \frac{\sigma^{\overleftarrow{\Rightarrow}} - \sigma^{\overrightarrow{\Rightarrow}}}{\sigma^{\overleftarrow{\Rightarrow}} + \sigma^{\overrightarrow{\Rightarrow}}} = \frac{1}{P_B P_z} \cdot \frac{\frac{N^{\overleftarrow{\Rightarrow}}}{L^{\overleftarrow{\Rightarrow}}} - \frac{N^{\overrightarrow{\Rightarrow}}}{L^{\overrightarrow{\Rightarrow}}}}{\frac{N^{\overleftarrow{\Rightarrow}}}{L^{\overleftarrow{\Rightarrow}}} + \frac{N^{\overrightarrow{\Rightarrow}}}{L^{\overrightarrow{\Rightarrow}}}}$$

$$g_1(x, Q^2) = \underbrace{\frac{1}{1 - \frac{y}{2} - \frac{1}{4} y^2 \gamma} \left[\frac{Q^4}{8\pi\alpha^2 y}\right.}_{\text{kinematic factors}} \underbrace{\frac{d^2\sigma_{\text{unpol}}}{dx\, dQ^2}}_{\text{param.}} \underbrace{A_{\|}(x, Q^2)}_{\text{meas.}} + \underbrace{\frac{y}{2} \gamma^2}_{\text{kin. fac.}} \underbrace{\left. g_2(x, Q^2) \right]}_{\text{param.}}$$

g_1 : Results for p and d



- Proton data:
  - Stat. precision comparable to previous data
- Deuteron data:
  - Most precise data in valence x region
- $<Q^2>$ lower compared to SMC/ COMPASS
- HERMES points: stat. and syst. errors added in quadrature
  - Stat. uncertainties are correlated from unfolding of bin-to-bin migrations (shown are the diagonal elements of the cov. matrix)
  - Syst. uncertainties dominated by target and beam polarization

g_1 : Integrals

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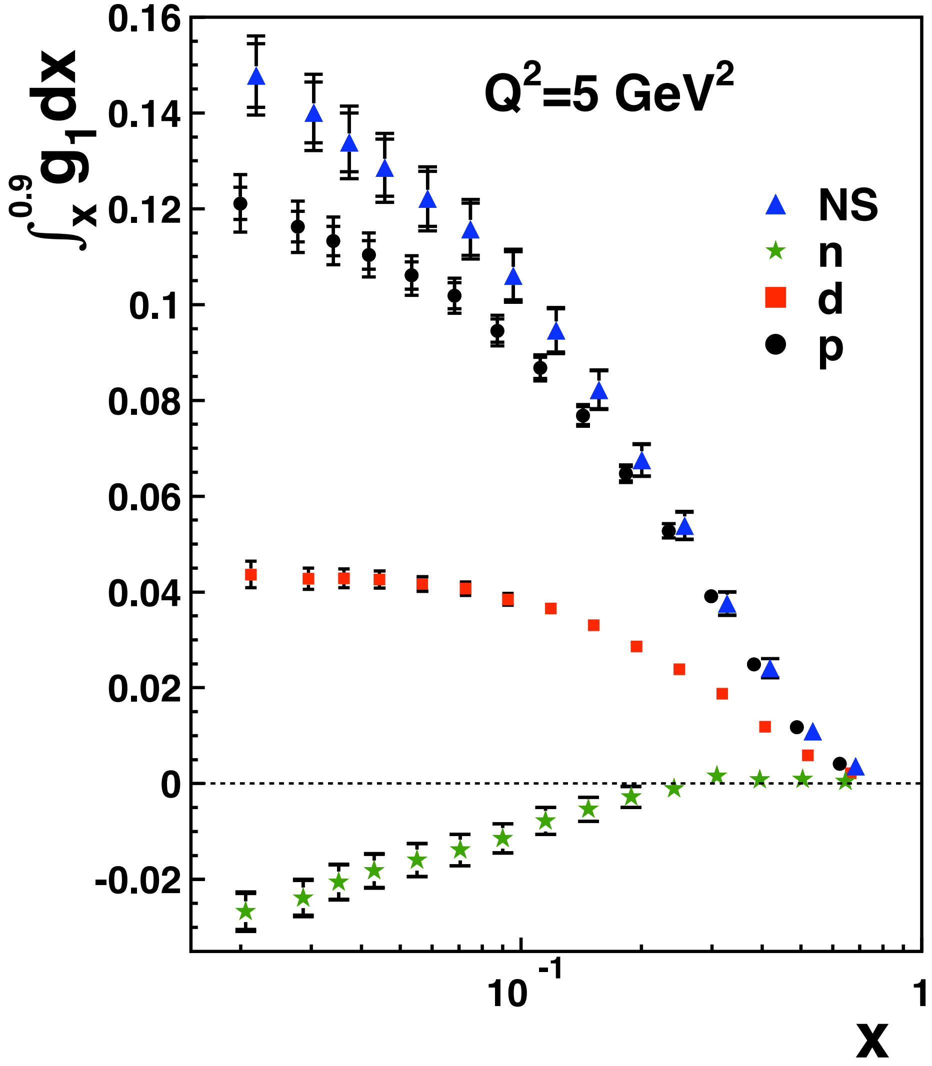

$$\Gamma_1^d = \int dx\, g_1^d$$

Assuming saturation in the deuteron integral:

➠ Use only deuteron data!

$$\Gamma_1^d = \left(1 - \frac{3}{2}\omega_D\right) \frac{1}{36} \left[4 a_0 \Delta C_S^{\overline{MS}} + a_8 \Delta C_{NS}^{\overline{MS}}\right]$$

D-wave contribution to deuteron

$$a_0 \overset{\overline{MS}}{=} \Delta\Sigma$$

in NNLO	central value	uncertainties		
		theor.	exp.	evol.
a_0	0.330	0.011	0.025	0.028
$\Delta u + \Delta\bar{u}$	0.842	0.004	0.008	0.009
$\Delta d + \Delta\bar{d}$	-0.427	0.004	0.008	0.009
$\Delta s + \Delta\bar{s}$	-0.085	0.013	0.008	0.009

$Q^2 = 5\text{GeV}^2$, NNLO in $\overline{\text{MS}}$ scheme

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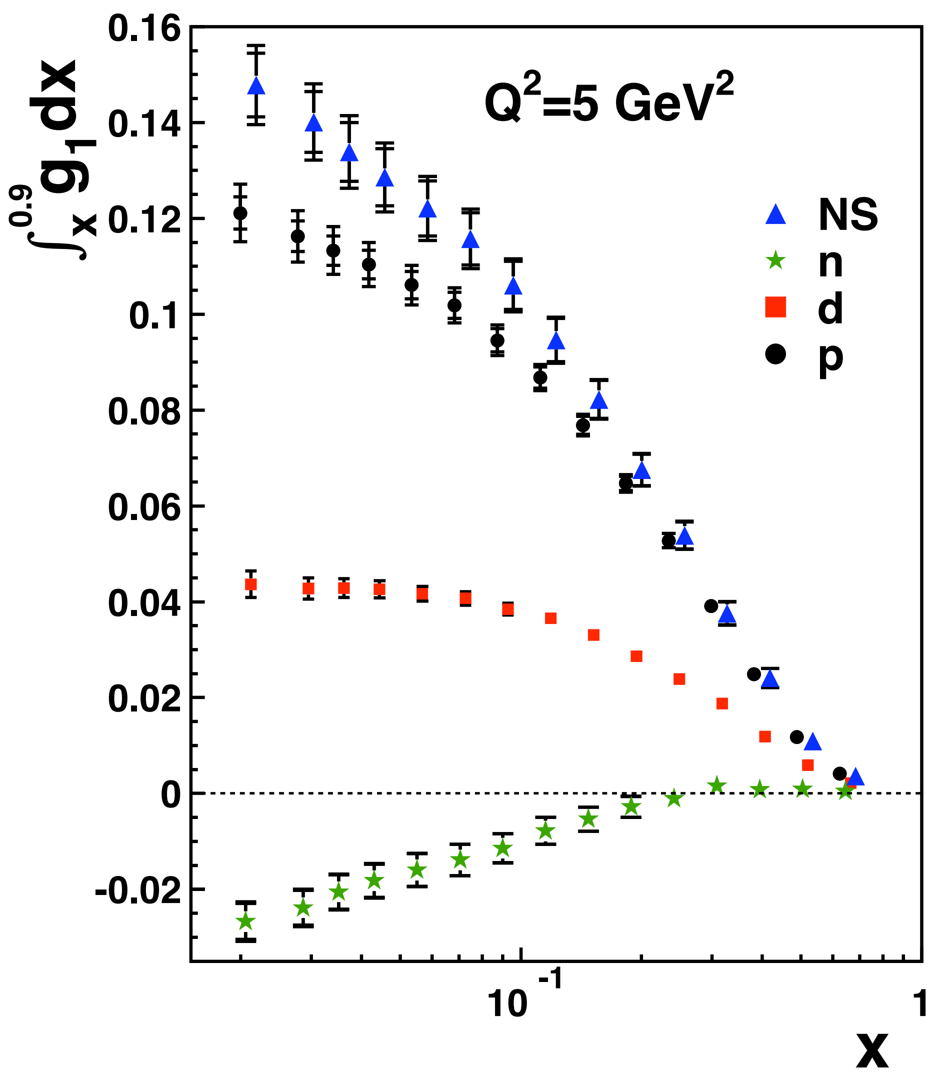

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from hyperon beta decay (a_8=0.586±0.031)

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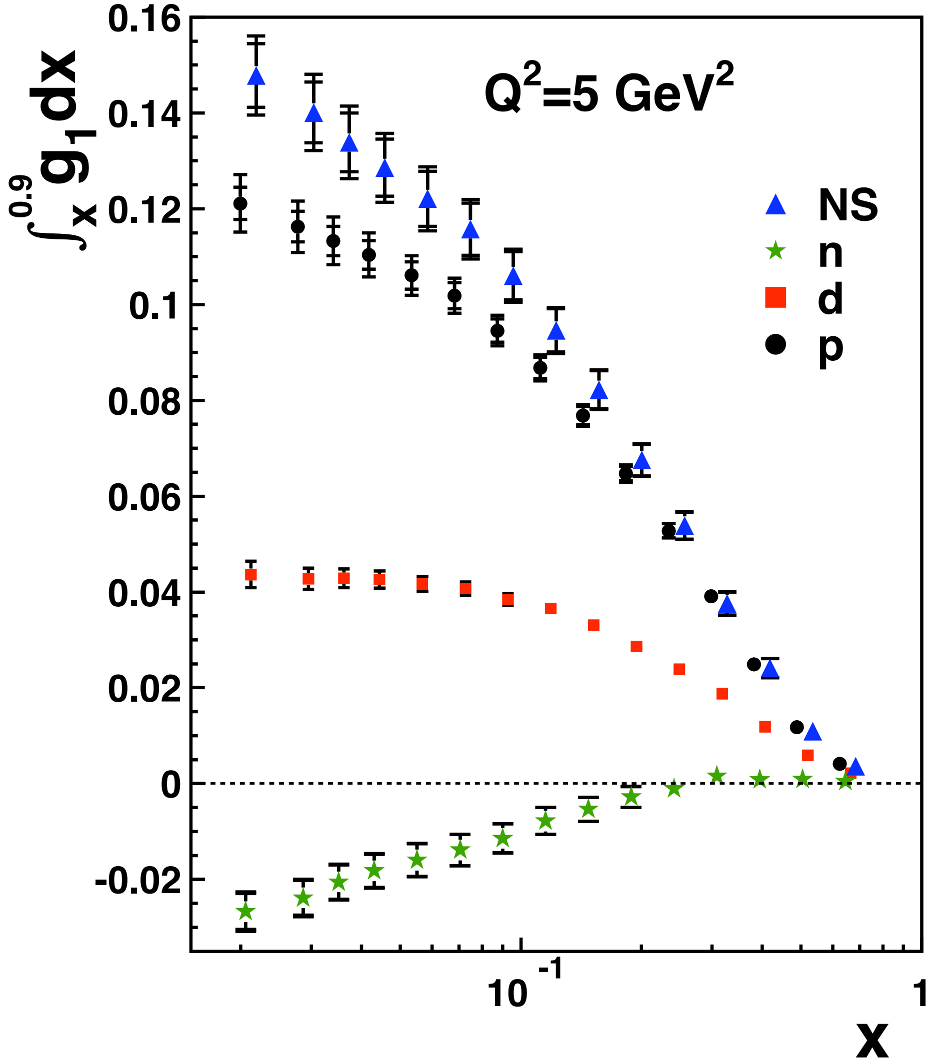

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from hyperon beta decay (a_8=0.586±0.031)

$$a_0 \overset{\overline{MS}}{=} \Delta\Sigma$$

$$\Delta u + \Delta\bar{u} = \frac{1}{6}\left[2a_0 + a_8 + 3a_3\right]$$

$$\Delta d + \Delta\bar{d} = \frac{1}{6}\left[2a_0 + a_8 - 3a_3\right]$$

$$\Delta s + \Delta\bar{s} = \frac{1}{3}\left[\ a_0 - a_8\right]$$

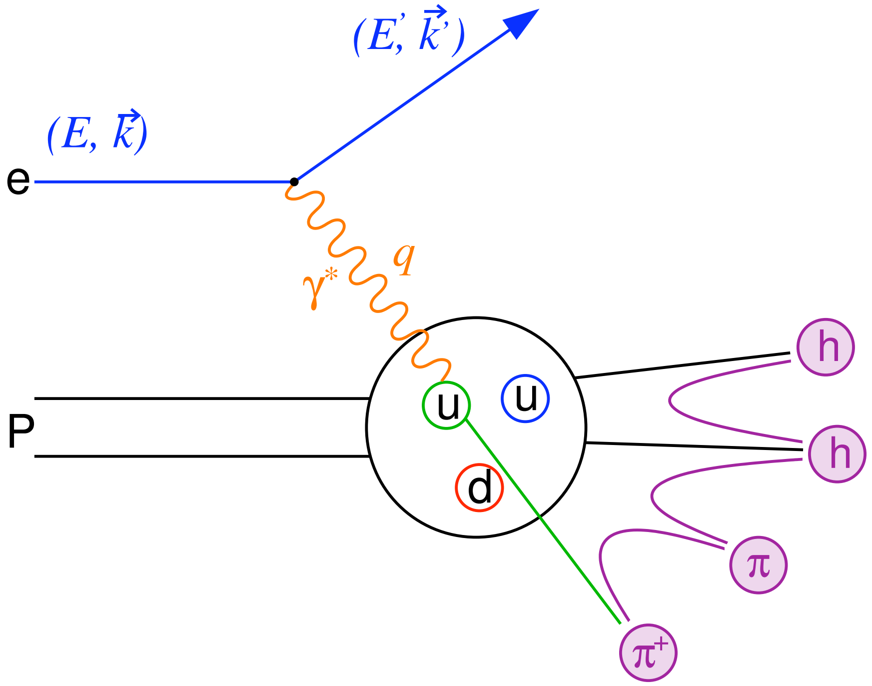
from neutron beta decay (a_3=1.269±0.003)

$Q^2 = 5\text{GeV}^2$, NNLO in $\overline{\text{MS}}$ scheme

Strange quark distributions

Semi-inclusive DIS

e$^{\pm}$ @ 27.6 GeV (HERA)



Targets:
H: <P_{trans}>~74±6%
D: <P_{long}>~84.5 ±3.5%

Cross section contains Distribution Functions and Fragmentation Functions:

$$\sigma^{ep\rightarrow eh} \sim \sum_q \mathrm{DF}^{p\rightarrow q} \otimes \sigma^{eq\rightarrow eq} \otimes \mathrm{FF}^{q\rightarrow h}$$

DF: distribution of quarks in the nucleon
FF: fragmentation of (struck) quark into hadronic final state

Strange PDFs with isoscalar target

Assumptions:
•isospin symmetry between proton and neutron
•charge conjugation invariance in fragmentation

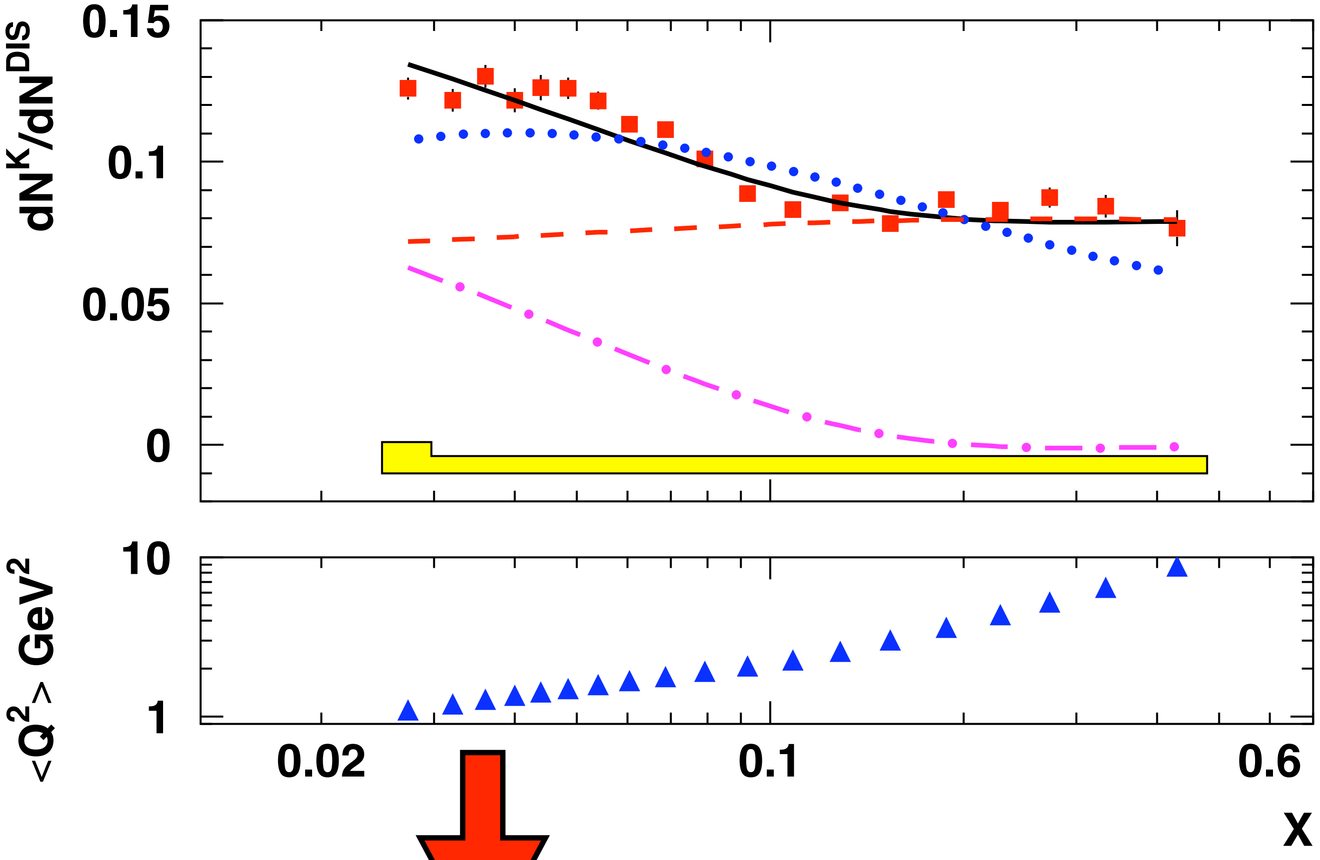
- strange quarks carry no isospin ⇒ S(x)_{Proton} = S(x)_{Neutron}
- deuteron target (isoscalar!):
  fragmentation process in DIS can be described by isospin independent FFs
- Charged kaon multiplicity in LO:

$$\frac{dN^{\mathrm{K}}(x)}{dN^{\mathrm{DIS}}(x)} = \frac{Q(x)\int D_Q^{\mathrm{K}}(z)dz + S(x)\int D_S^{\mathrm{K}}(z)dz}{5Q(x)+2S(x)}$$

$$Q(x) \equiv u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \qquad D_Q^{\mathrm{K}} \equiv 4D_u^{\mathrm{K}}(z) + D_d^{\mathrm{K}}(z)$$

$$S(x) \equiv s(x) + \bar{s}(x) \qquad D_S^{\mathrm{K}}(z) \equiv 2D_s^{\mathrm{K}}(z)$$

Fitting $dN^K(x)/dN^{DIS}(x)$



Assuming S(x)=0 for x>0.15:

$$\int_{0.2}^{0.8} D_Q^K(z)dz = 0.398 \pm 0.010$$

de Florian et al., PRD75, 114010 (2007):

$$\int_{0.2}^{0.8} D_Q^K(z)dz = 0.435 \pm 0.044$$

$$\frac{dN^{\mathrm{K}}(x)}{dN^{\mathrm{DIS}}(x)} = \frac{Q(x)\int D_Q^{\mathrm{K}}(z)dz + \boxed{S(x)\int D_S^{\mathrm{K}}(z)dz}}{5Q(x) + \cancel{2S(x)}}$$

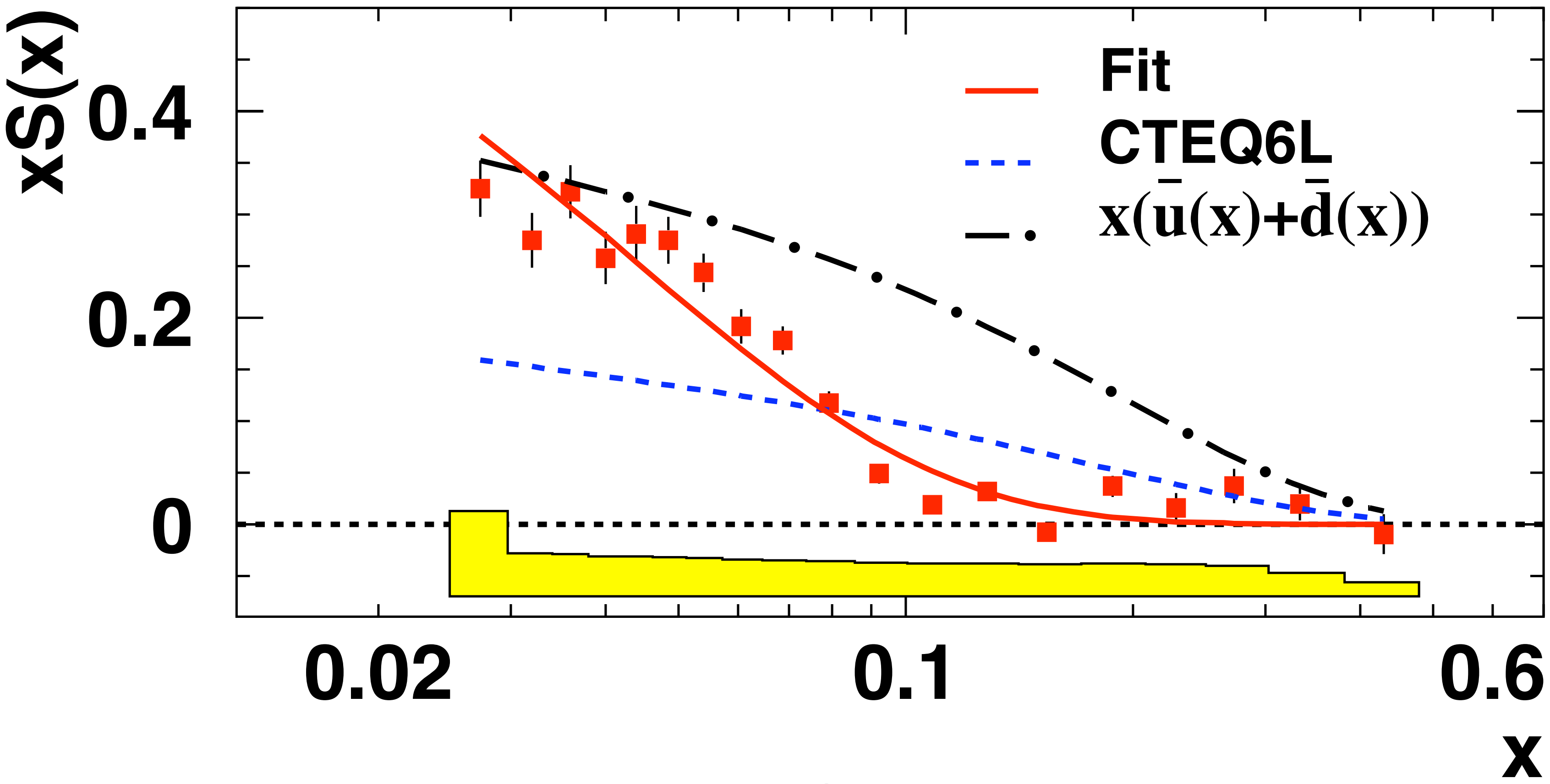
CTEQ6L

S(x) at Q^2=2.5 GeV^2

- xS(x) obtained by evolution of data to Q^2=2.5 GeV^2 using

$$\int_{0.2}^{0.8} D_S^{\mathrm{K}}(z)dz = 1.27 \pm 0.13$$

de Florian et al., PRD75, 114010 (2007)

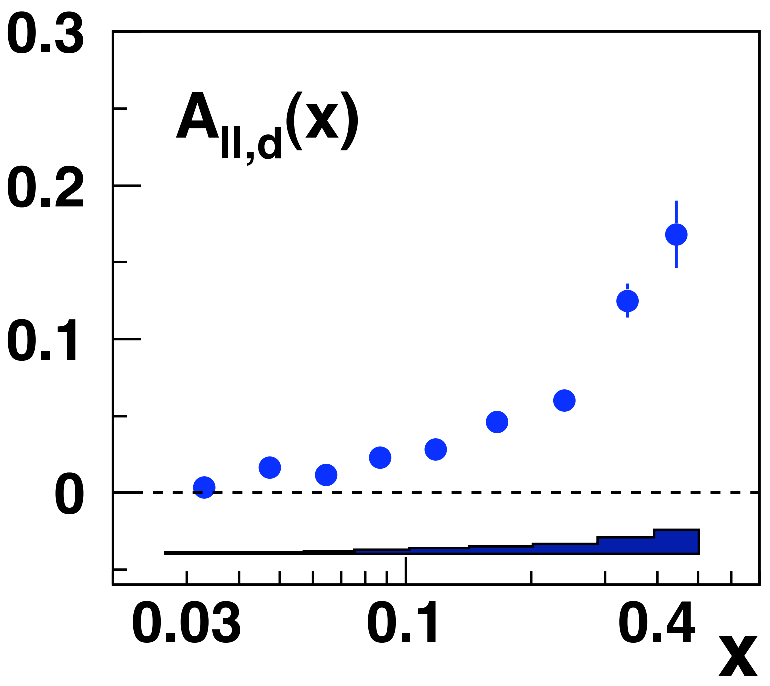


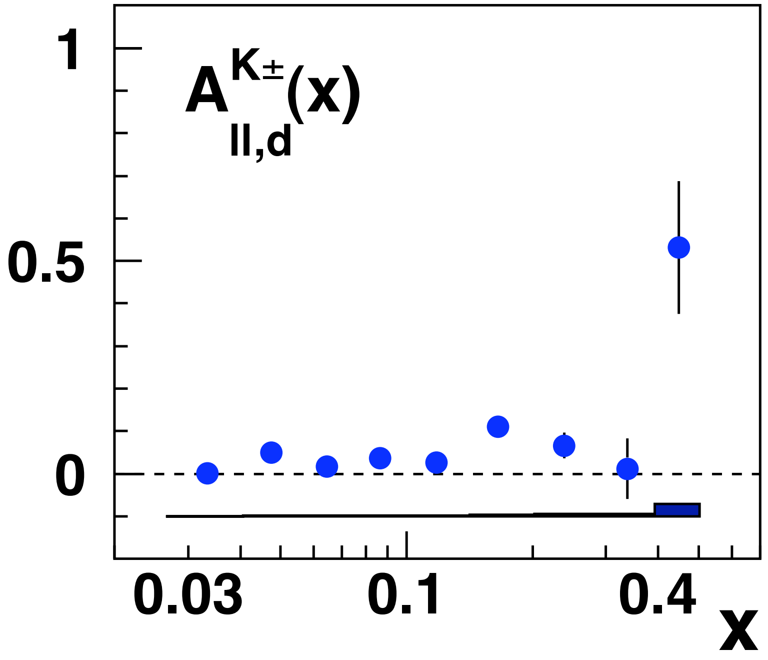
- Shape incompatible with CTEQ6L and with average of the isoscalar non-strange sea

Extraction of ΔQ(x) and ΔS(x)

Double spin asymmetries from long. pol. deuteron target

$$A_{||}^{(h)} = \frac{\sigma^{\overset{\rightarrow}{\Leftarrow},(h)} - \sigma^{\overset{\rightarrow}{\Rightarrow},(h)}}{\sigma^{\overset{\rightarrow}{\Leftarrow},(h)} + \sigma^{\overset{\rightarrow}{\Rightarrow},(h)}}$$





$$A_{||,d}(x)\frac{d^2N^{\mathrm{DIS}}(x)}{dx\,dQ^2} = \mathcal{K}_{LL}(x,Q^2)\,[5\Delta Q(x) + 2\Delta S(x)]$$

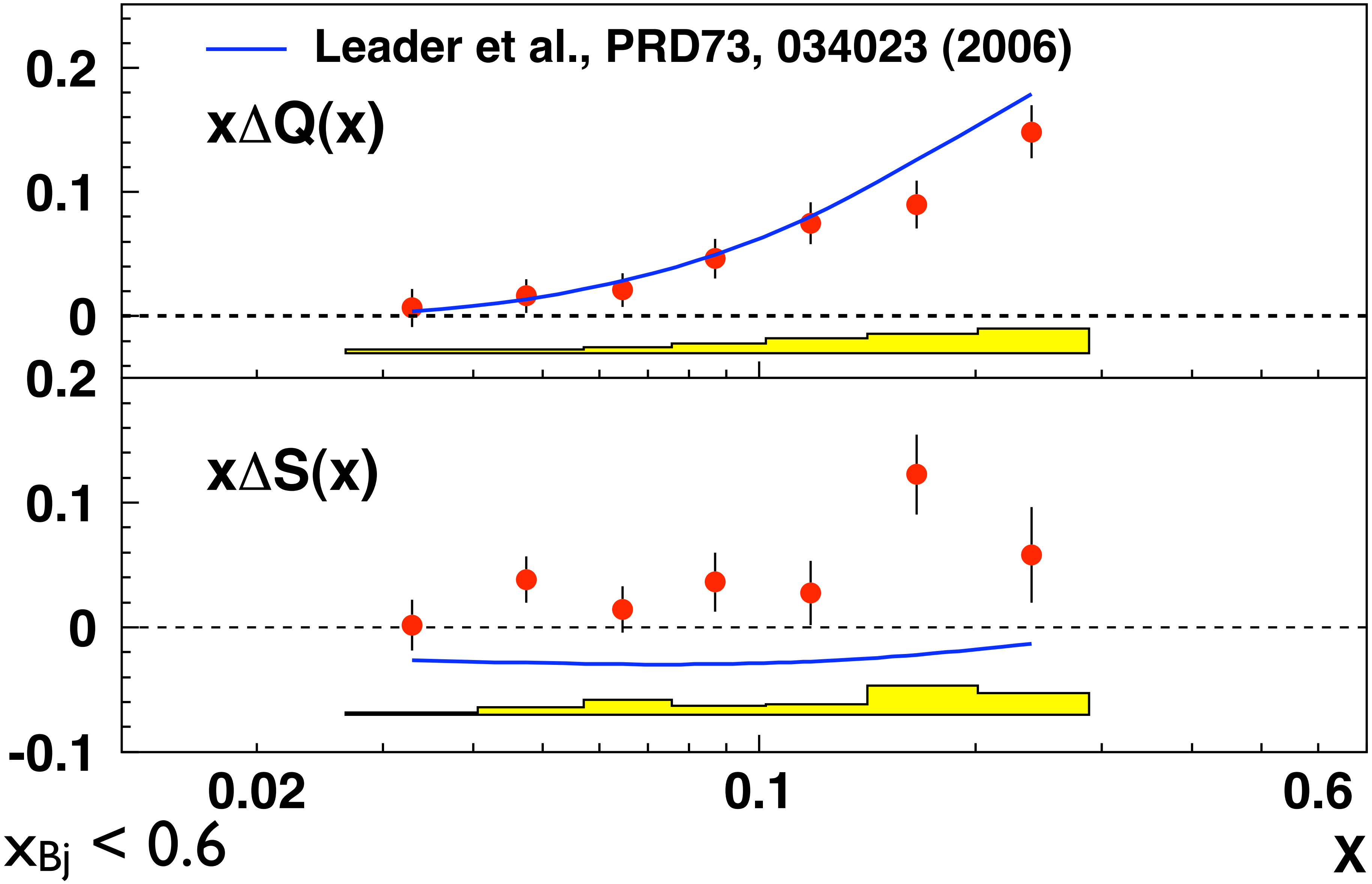
$$A^{\mathrm{K}}_{||,d}(x)\frac{d^2N^{\mathrm{DIS}}(x)}{dx\,dQ^2} = \mathcal{K}_{LL}(x,Q^2)\left[\Delta Q(x)\int D_Q^{\mathrm{K}}(z)dz + \Delta S(x)\int D_S^{\mathrm{K}}(z)dz\right]$$

$$\Delta Q(x) = \Delta u(x) + \Delta\bar{u}(x) + \Delta d(x) + \Delta\bar{d}(x)$$

$$\Delta S(X) = \Delta s(x) + \Delta\bar{s}(x)$$

(from S(X) extraction)

Helicity distributions at Q^2=2.5 GeV^2



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- 0.02 < x_{Bj} < 0.6
- $\Delta q_8 = \Delta Q - 2\Delta S$
- from hyperon decay constants (assuming SU(3) symmetry):

$$a_8 = 0.586 \pm 0.031 \simeq \Delta q_8$$

	Moments in measured range
ΔQ	$0.359 \pm 0.026(\text{stat.}) \pm 0.018(\text{sys.})$
ΔS	$0.037 \pm 0.019(\text{stat.}) \pm 0.027(\text{sys.})$
Δq_8	$0.285 \pm 0.046(\text{stat.}) \pm 0.057(\text{sys.})$

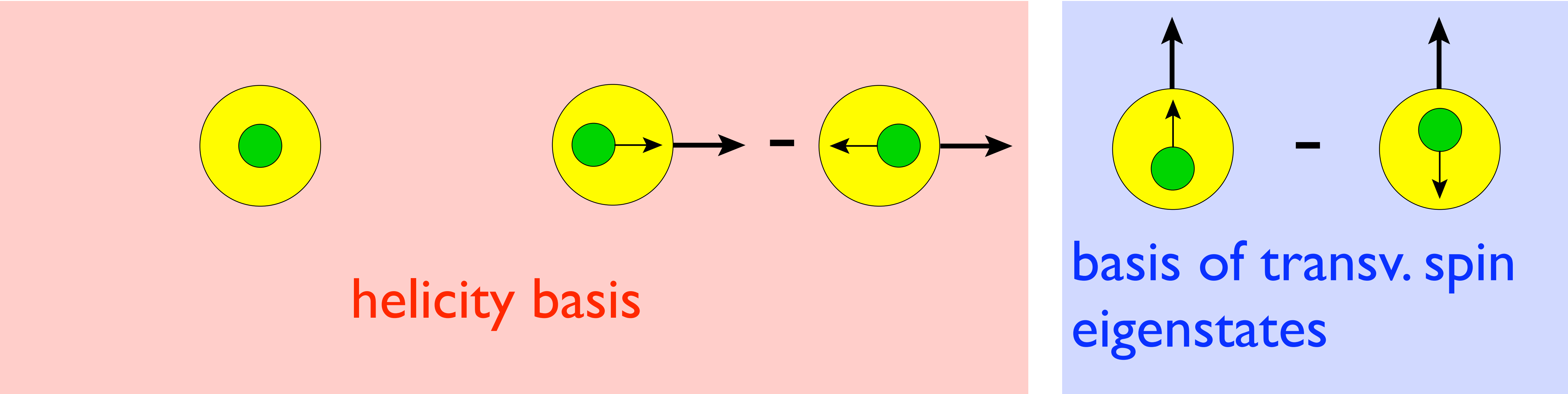
Transverse Structure
of
the Nucleon

Distribution functions (I)

Leading twist:

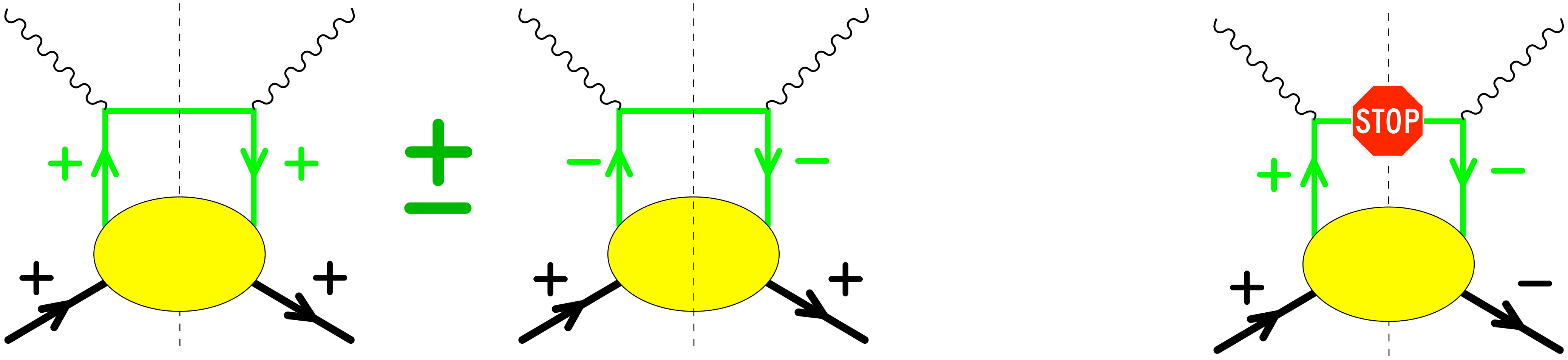
3 DFs survive integration over transverse quark momenta

momentum distribution	**helicity distribution**	**transversity distribution**
$q(x)$	$\Delta q(x)$	$\delta q(x) = h_1^q(x)$



Transversity δq

- δq: helicity-flip of the quark ⇒chiral-odd



$+ \Rightarrow q(x)$ $- \Rightarrow \Delta q(x)$ $\delta q(x)$

Transversity δq

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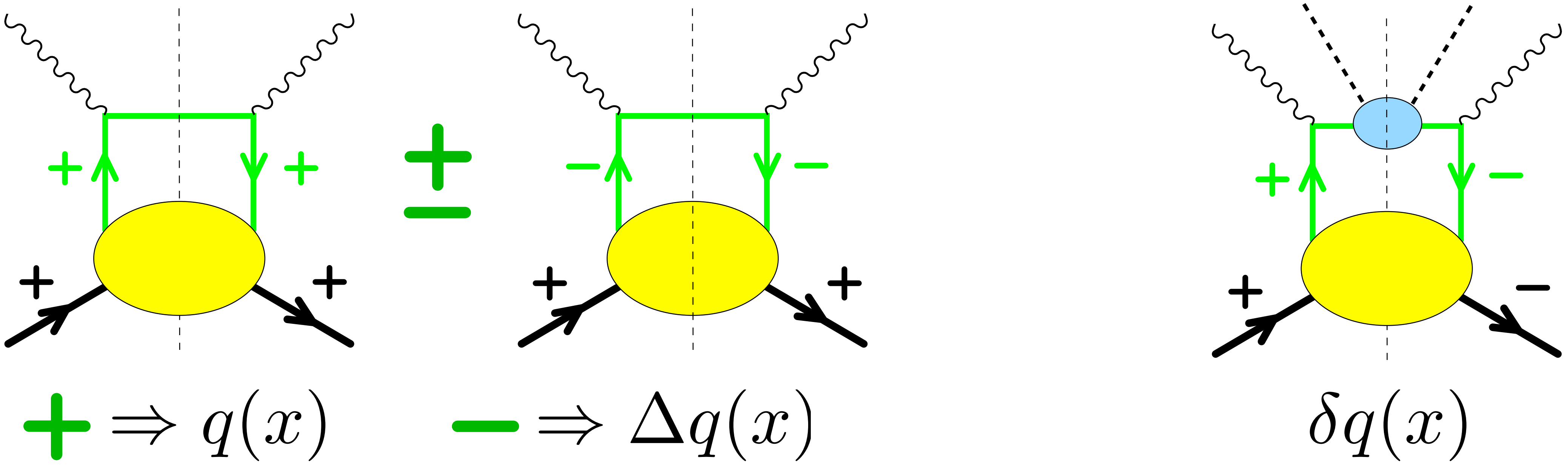
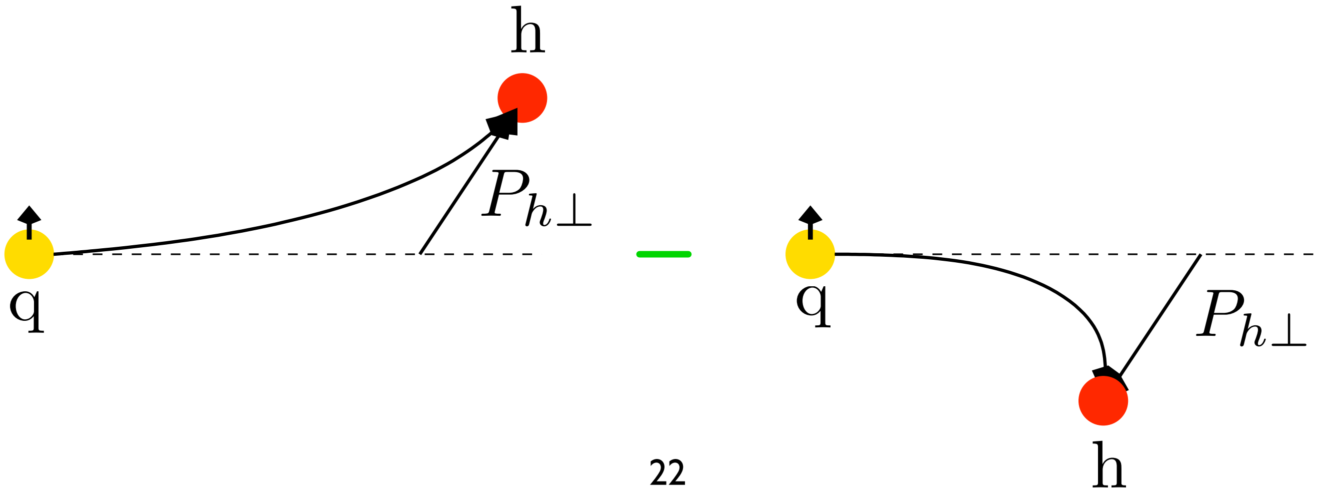


- Collins-FF $H_1^\perp$ describes correlation between transverse polarisation of fragmenting quark and the transverse momentum $P_{h\perp}$ of the produced (unpolarised) hadron



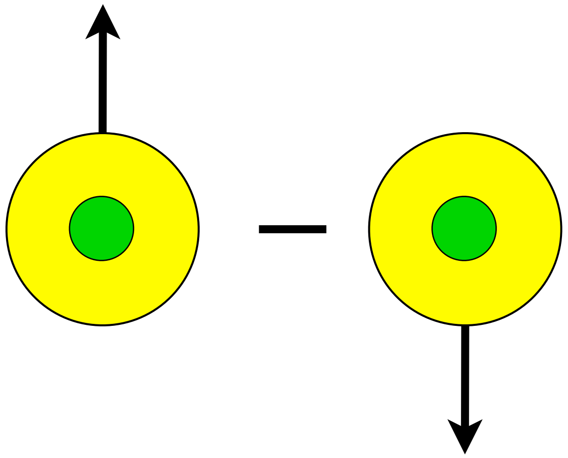
Distribution functions (II)

5 other sets of distribution functions exist which do not survive integration over transverse momentum

→ ‘unintegrated’ or ‘transverse momentum dependent’ distributions (TMDs)

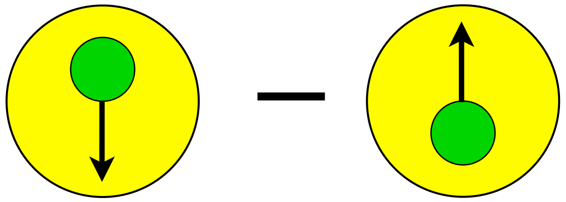
Sivers function:

correlates quark’s transverse momentum with transverse nucleon spin



Boer-Mulders function:

correlates quark’s transverse momentum with transverse quark spin



non-zero Sivers and Boer-Mulders functions require non-vanishing orbital angular momentum in nucleon wave function!

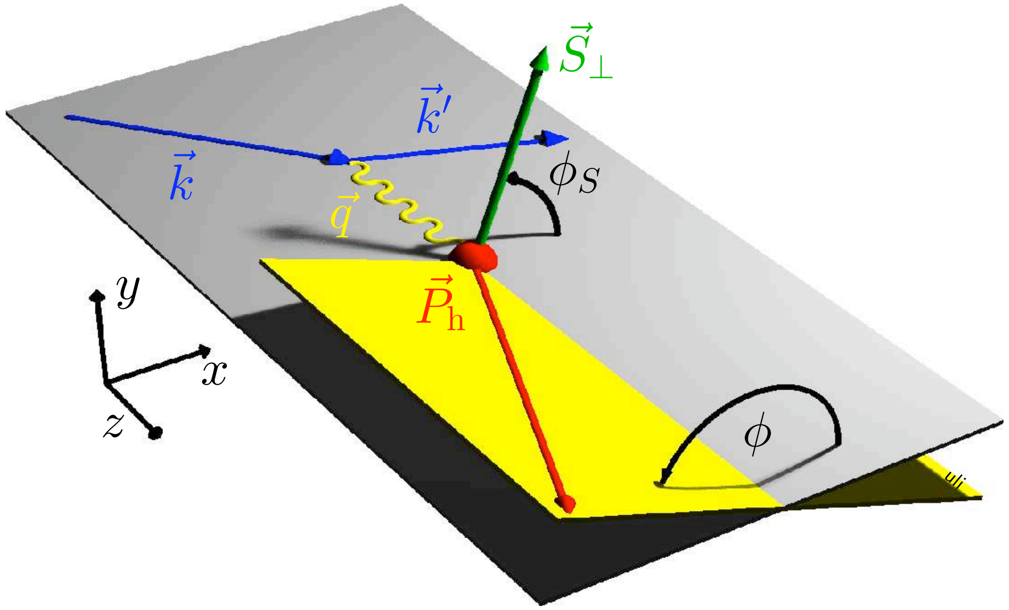
1-Hadron Production (ep→ehX)

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

σ_{XY}

Beam Target

Polarization



1-Hadron Production (ep→ehX)

$$d\sigma = d\sigma^0_{UU} + \boxed{\cos 2\phi\, d\sigma^1_{UU}}$$

Boer-Mulders-DF ⊗ Collins-FF

$$+ \; S_L \left\{ \sin 2\phi\, d\sigma^4_{UL} + \frac{1}{Q} \sin\phi\, d\sigma^5_{UL} + \lambda_e \left[d\sigma^6_{LL} + \frac{1}{Q} \cos\phi\, d\sigma^7_{LL} \right] \right\}$$

$$+ \; S_T \left\{ \boxed{\sin(\phi - \phi_S)\, d\sigma^8_{UT}} + \boxed{\sin(\phi + \phi_S)\, d\sigma^9_{UT}} + \sin(3\phi - \phi_S)\, \sigma^{10}_{UT} \right.$$

$$+ \frac{1}{Q} \left(\sin(2\phi - \phi_S)\, d\sigma^{11}_{UT} + \sin\phi_S\, d\sigma_{UT} \right)$$

$$\left. + \lambda_e \left[\cos(\phi - \phi_S)\, d\sigma_{LT} + \frac{1}{Q} \left(\cos\phi_S\, d\sigma_{LT} + \cos(2\phi - \phi_S)\, d\sigma^{15}_{LT} \right) \right] \right\}$$

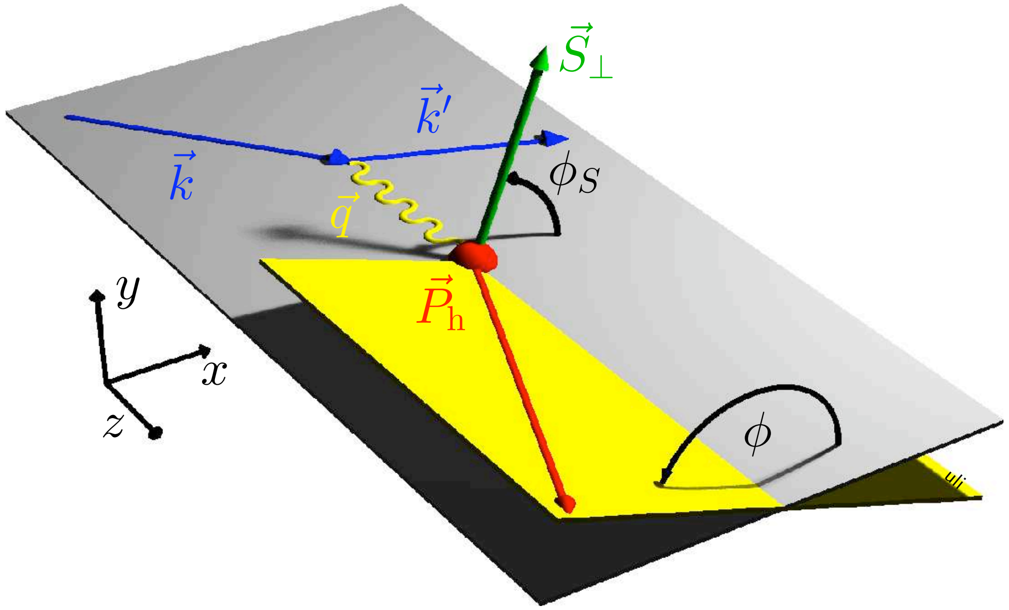
Sivers-DF ⊗ unpol FF

δq-DF ⊗ Collins-FF

σ_{XY}

Beam Target

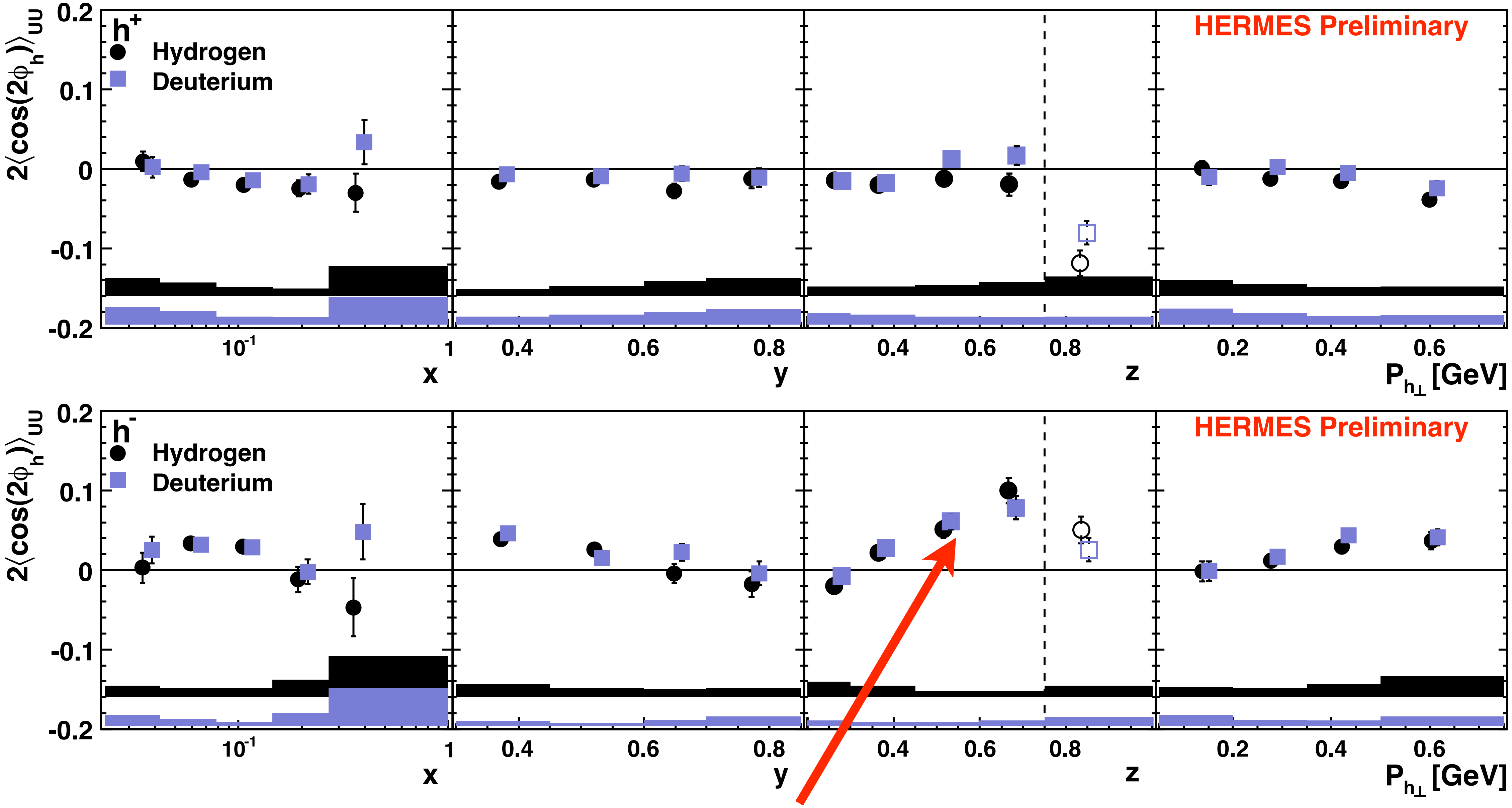
Polarization



Boer-Mulders Amplitudes

Extraction challenging: azimuthal moments also possible due to e.g. acceptance effects

Fully differential analysis, unfolding in 5D (z,y,z,p_{hT},ϕ)



Evidence of transversely polarized quarks in unpolarized nucleons!

Azimuthal Single-Spin Asymmetries

Measurement of cross-section asymmetries depending on the azimuthal angles Φ and $Φ_S$

$$A_{UT}(\phi,\phi_S,\ldots) = \frac{1}{S_\perp}\frac{\sigma^{\Uparrow}-\sigma^{\Downarrow}}{\sigma^{\Uparrow}+\sigma^{\Downarrow}}$$

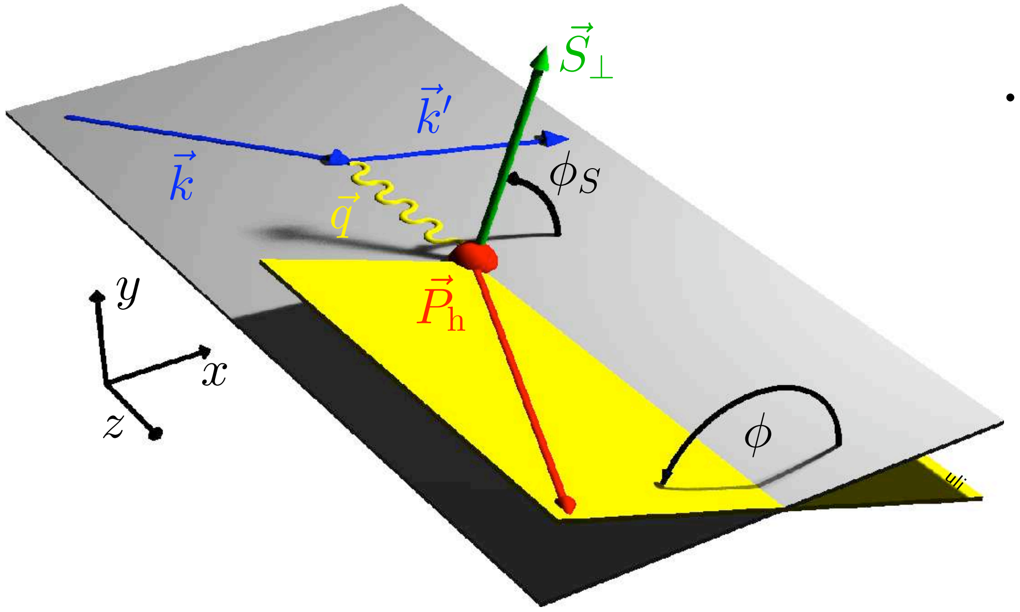
Collins Amplitude

$$\sim \ \ldots \boxed{\sin(\phi+\phi_S)} \frac{\sum_q e_q^2\, \mathcal{I}\left[\ldots \boxed{\delta q(x,\vec{p}_T^{\,2})\cdot H_1^{\perp q}(z,\vec{k}_T^{\,2})}\right]}{\sum_q e_q^2\, q(x)\cdot D_1^q(z)}$$

Sivers Amplitude

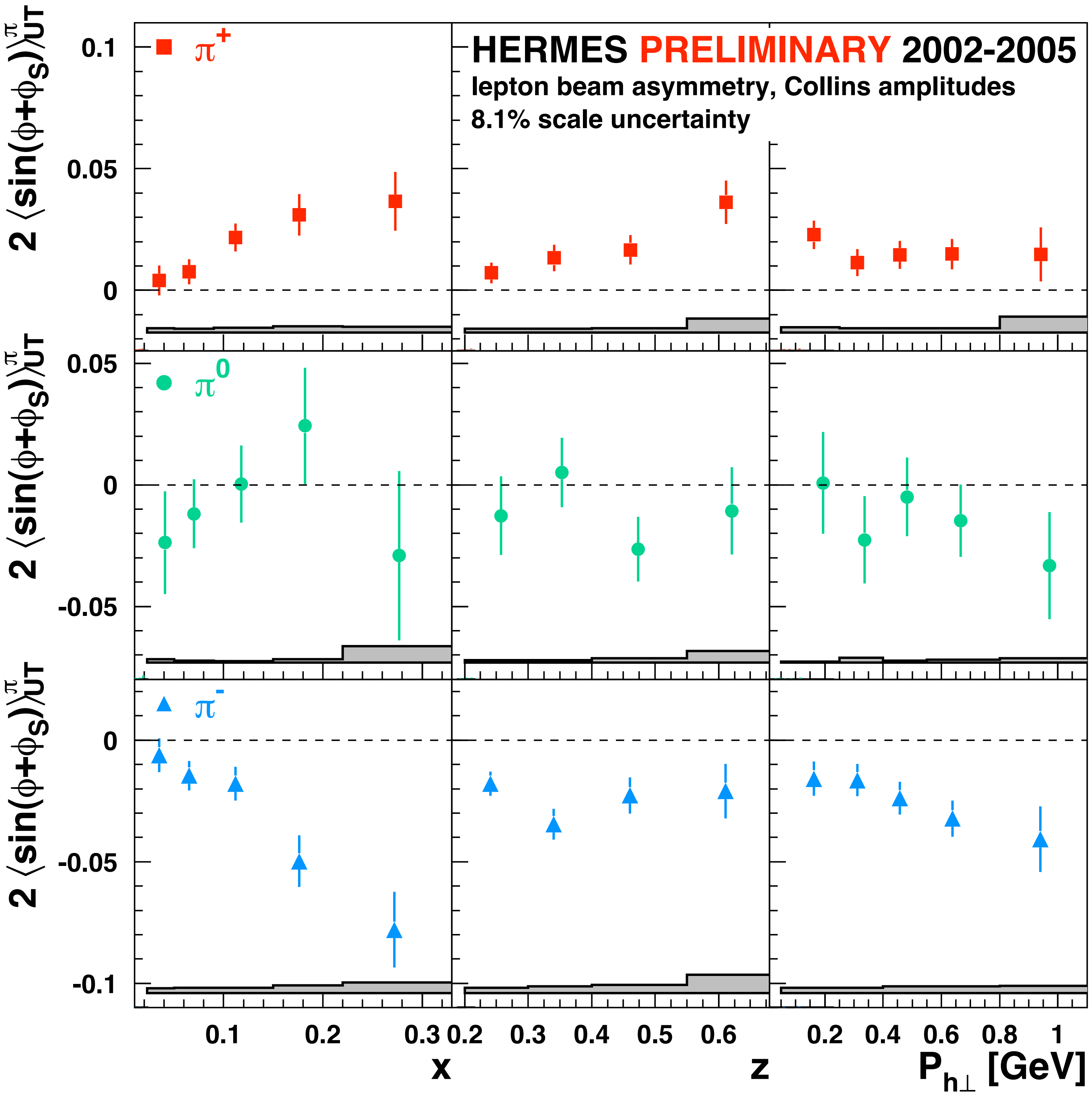
$$+ \ \ldots \boxed{\sin(\phi-\phi_S)} \frac{\sum_q e_q^2\, \mathcal{I}\left[\ldots \boxed{f_{1T}^{\perp q}(x,\vec{p}_T^{\,2})\cdot D_1^q(z,\vec{k}_T^{\,2})}\right]}{\sum_q e_q^2\, q(x)\cdot D_1^q(z)}$$

$$\ldots$$



$\mathcal{I}[\ldots]$ convolution integral over initial (p_T) and final (k_T) quark transverse momenta

Collins Amplitudes for Pions



$$A_C \propto \delta q \otimes H_1^{\perp}$$

- positive amplitudes for π^+
- large negative π^- amplitude

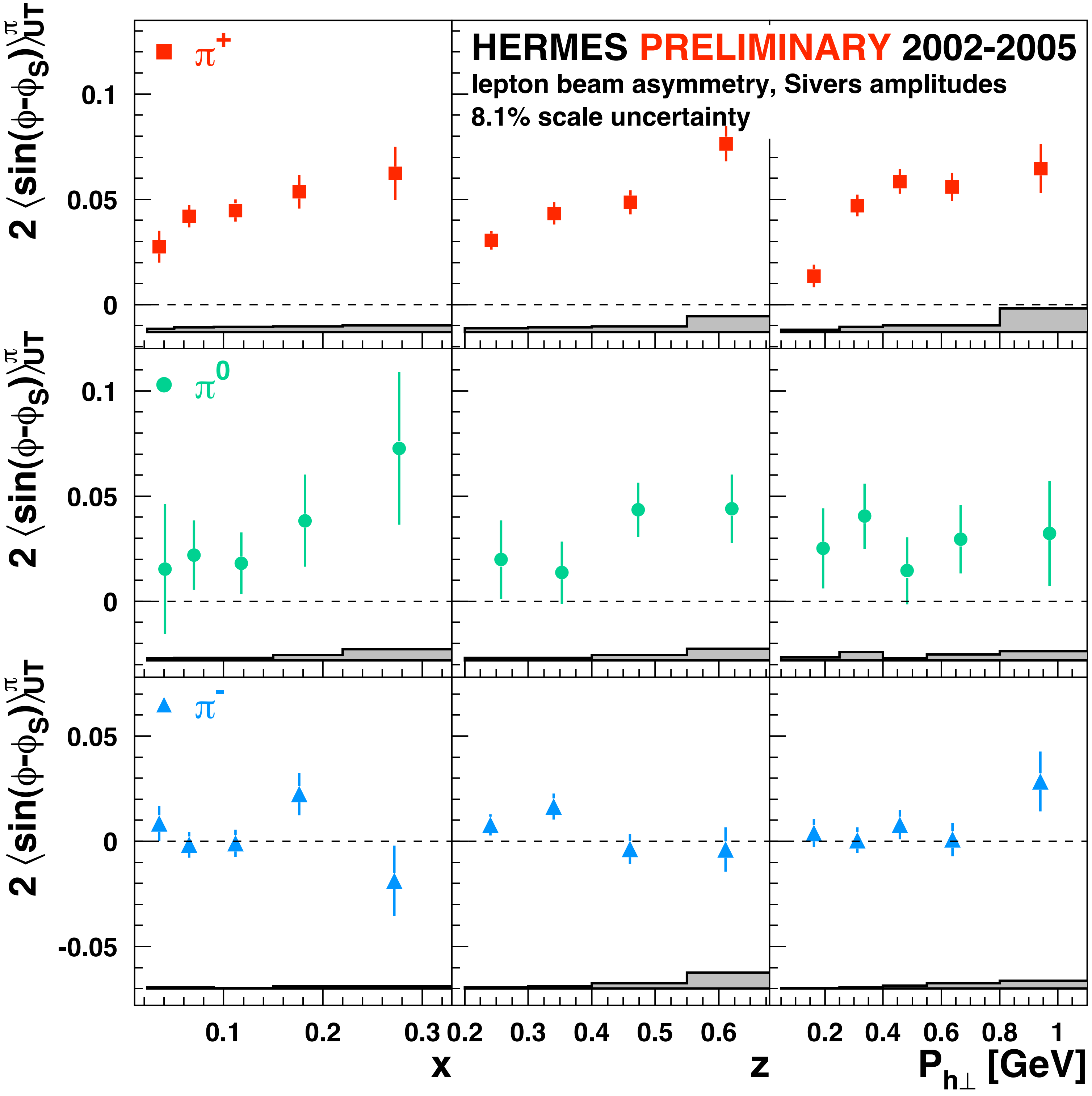
$$u \to \pi^+ \quad \Rightarrow \quad H_1^{\perp,\mathrm{fav}}$$

$$u \to \pi^- \quad \Rightarrow \quad H_1^{\perp,\mathrm{unfav}}$$

$$\Rightarrow \quad H_1^{\perp,\mathrm{fav}} \approx -H_1^{\perp,\mathrm{unfav}}$$

- isospin symmetry in π-fragmentation is fulfilled
- information from another process on Collins FF (BELLE) allows extraction of δq (eg. Anselmino et. al. Phys.Rev.D75:054032,2007)

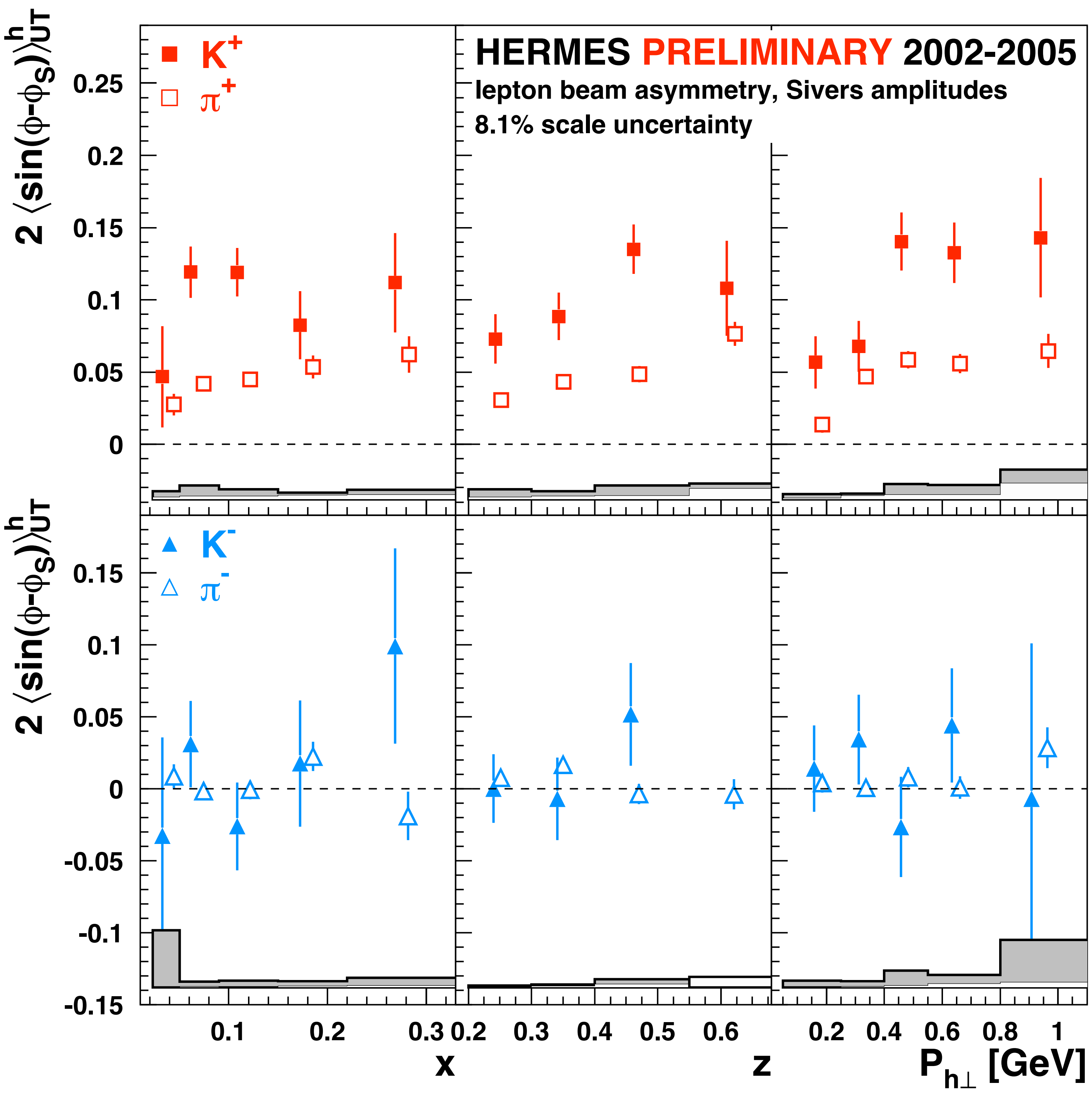
Sivers Amplitudes for Pions



$$A_S \propto f_{1T}^{\perp} \otimes D_1^q$$

- significantly positive for π^+
- implies non-zero orbital angular momentum of quarks
- consistent with zero for π^-
- isospin symmetry of π-mesons fulfilled

Sivers Amplitudes for Kaons



$$A_S \propto f_{1T}^{\perp} \otimes D_1^q$$

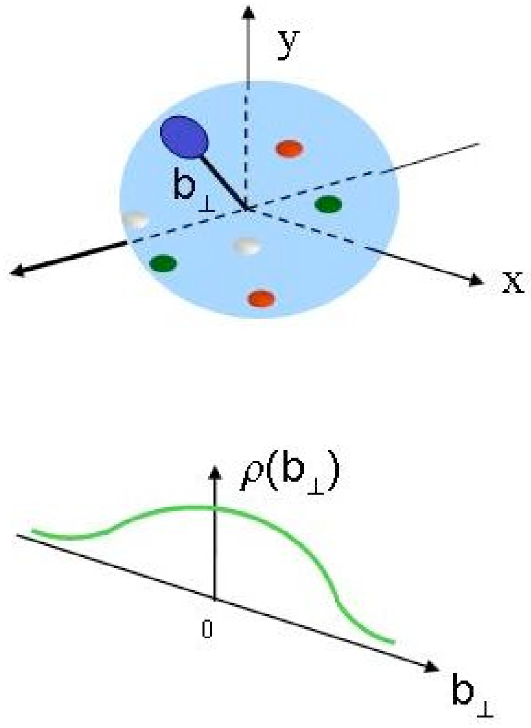
- significantly positive for K$^+$
- implies non-zero orbital angular momentum of quarks
- consistent with zero for K$^-$
- K$^+$ amplitude larger than π$^+$ amplitude

sea quark contribution to Sivers mechanism may be important

$$\pi^+ = |u\bar{d}\rangle \quad K^+ = |u\bar{s}\rangle$$

Accessing Generalized Parton Distribution Functions (GPDs)
via
Deeply Virtual Compton Scattering (DVCS)

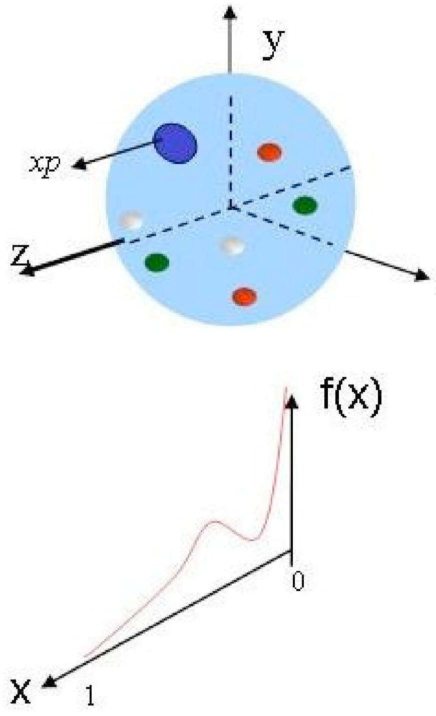
Probing GPDs in Exclusive Reactions



Form factors

Transverse distribution of quarks in space coordinates

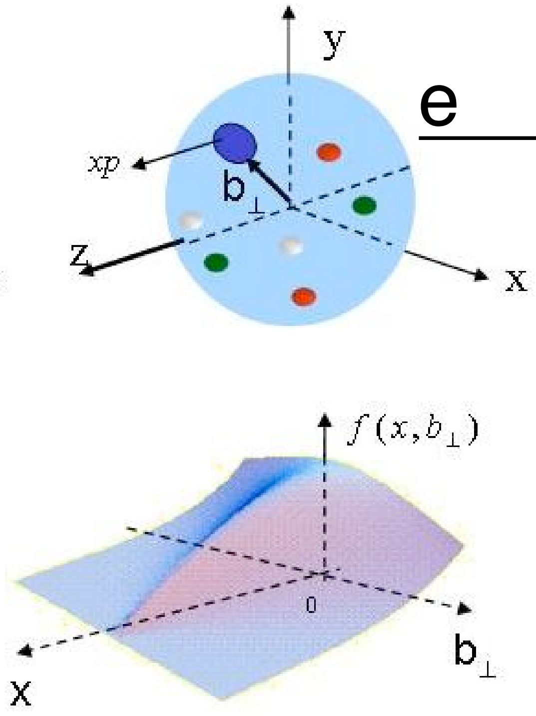
$$\int dx H^q(x,\xi,t) = F_1^q(t)$$
$$\int dx E^q(x,\xi,t) = F_2^q(t)$$



Parton Distribution Functions

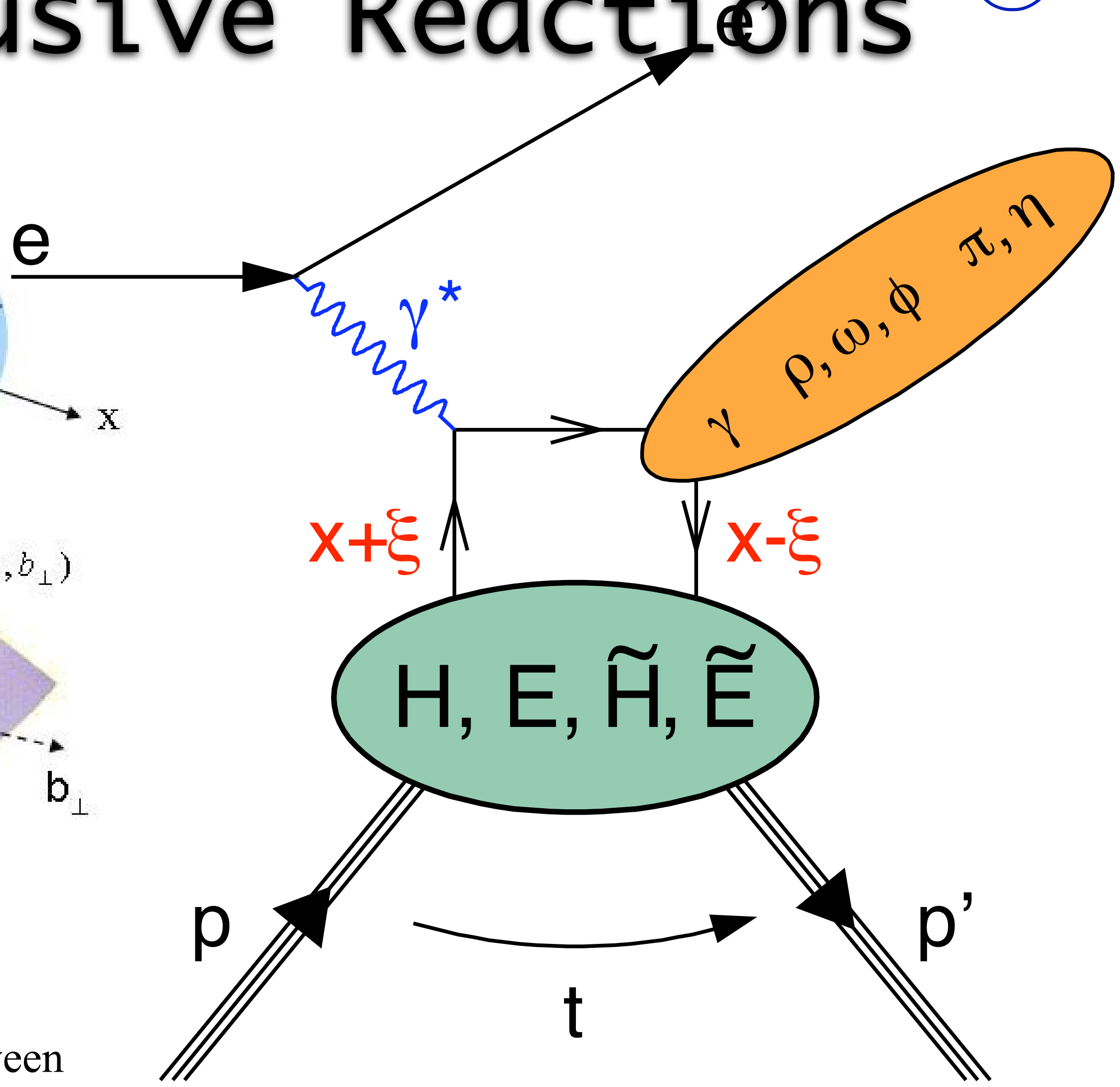
Quark longitudinal momentum fraction distribution in the nucleon

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



GPDs

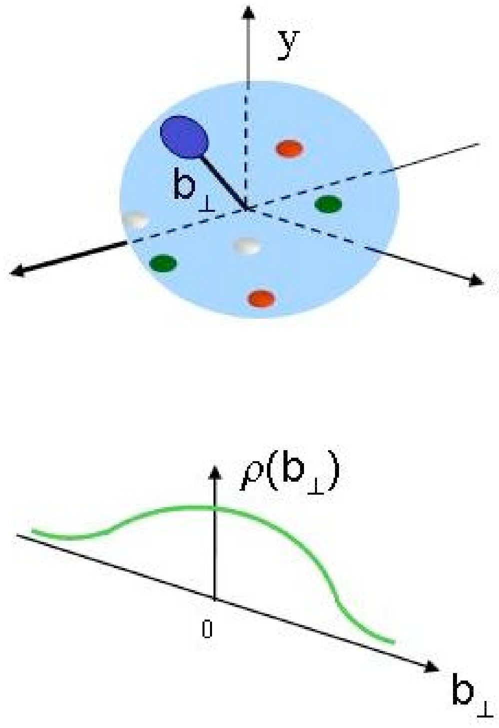
Correlation between transverse position and longitudinal momentum fraction of quark in the nucleon

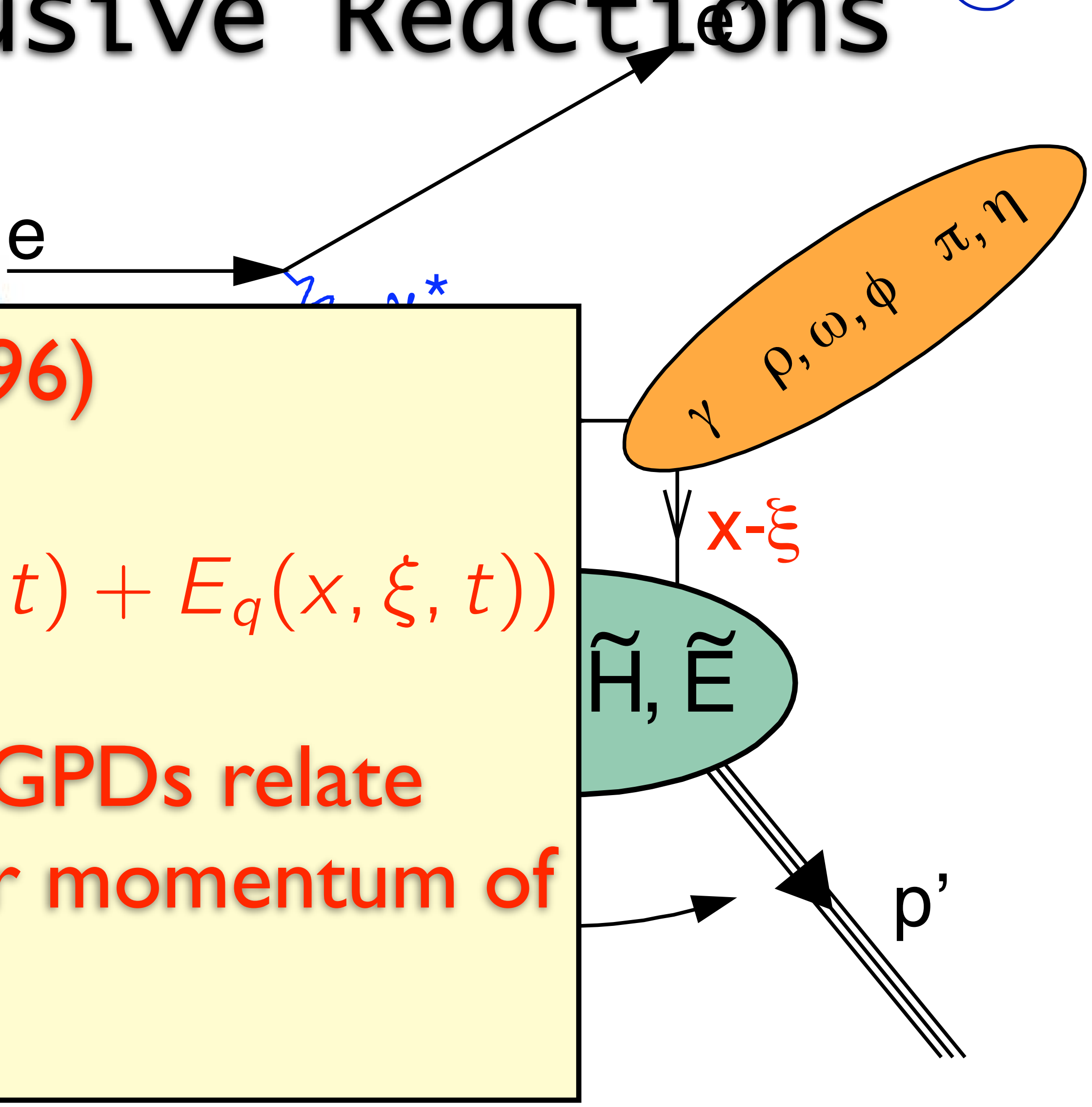


	unpolarized	polarized
no nucleon hel. flip	H	$\widetilde{H}$
nucleon hel. flip	E	$\widetilde{E}$

(+ 4 more chiral-odd functions)

Probing GPDs in Exclusive Reactions





Ji relation (1996)

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

➜Moments of certain GPDs relate directly to the total angular momentum of quarks

Form factors

Transverse distribution of quarks in space coordinates

momentum fraction distribution in the nucleon

longitudinal momentum fraction of quark in the nucleon

$$\int dx H^q(x, \xi, t) = F_1^q(t)$$

$$\int dx E^q(x, \xi, t) = F_2^q(t)$$

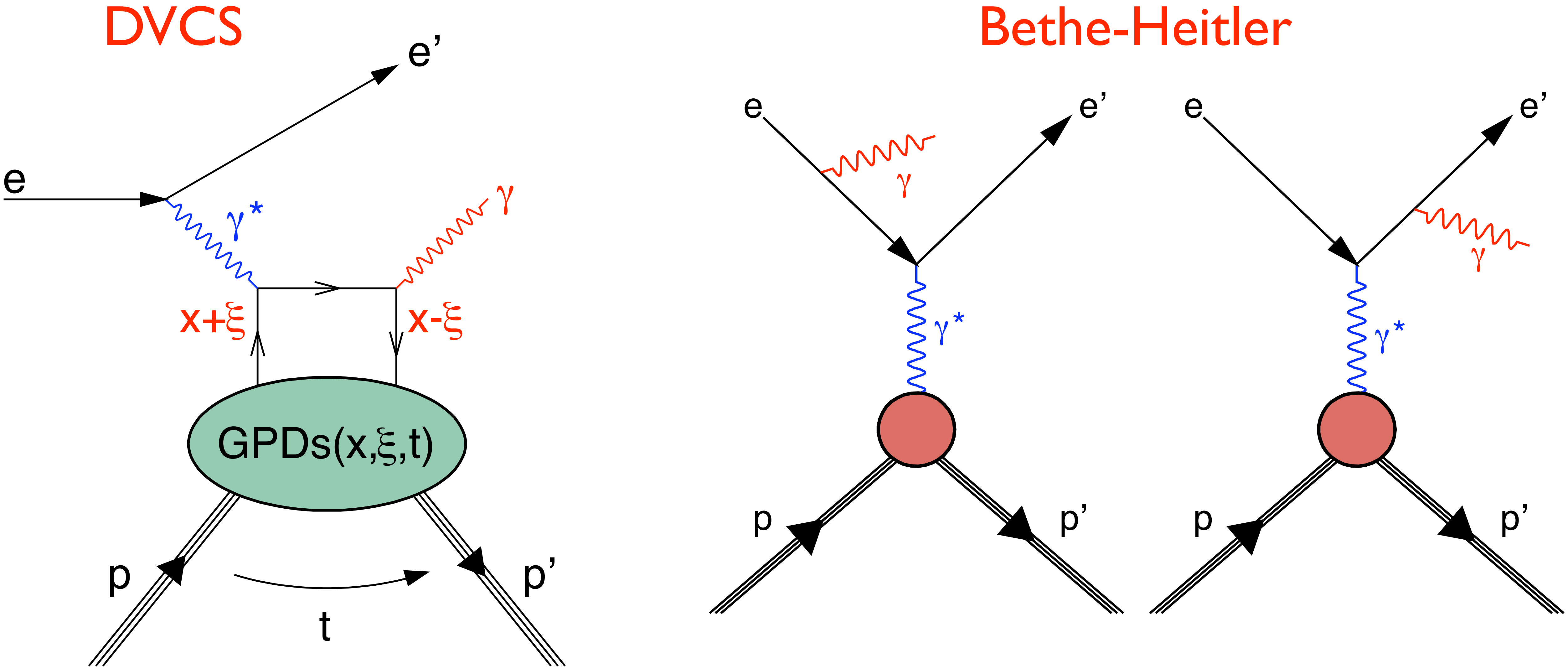
$$H^q(x, \xi = 0, t = 0) = q(x)$$

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

	unpolarized	polarized
no nucleon hel. flip	H	$\widetilde{H}$
nucleon hel. flip	E	$\widetilde{E}$

(+ 4 more chiral-odd functions)

DVCS/Bethe-Heitler Interference

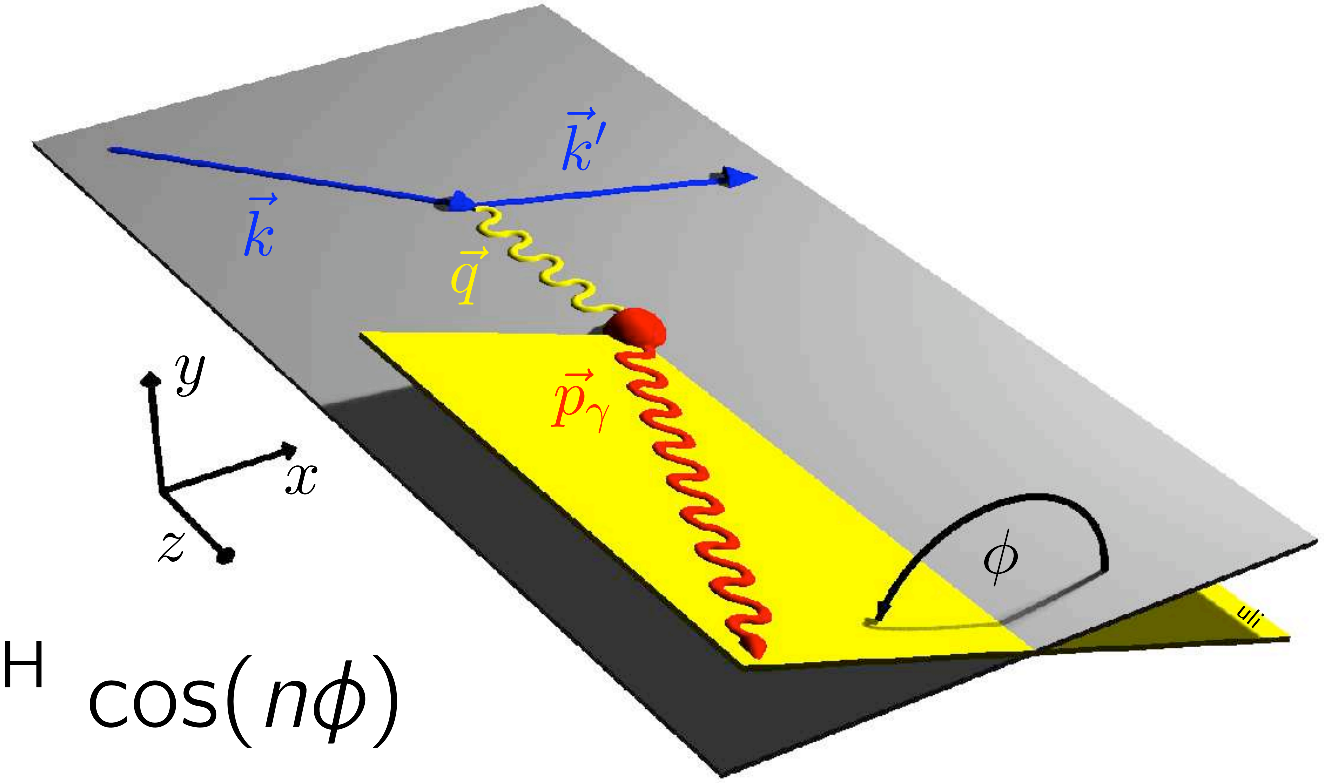


$$\frac{d^4\sigma}{dQ^2\,dx_B\,dt\,d\phi} = \frac{y^2}{32(2\pi))^4\sqrt{1+\frac{4M^2x_B^2}{Q^2}}}\left(|\mathcal{T}_{\mathrm{DVCS}}|^2+|\mathcal{T}_{\mathrm{BH}}|^2+\mathcal{I}\right)$$

Azimuthal Dependences in DVCS

Fourier expansion for Φ:

- beam polarization P_B
- beam charge C_B
- unpolarized target



$$|\mathcal{T}_{\mathrm{BH}}|^2 = \frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi)$$

$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = K_{\mathrm{DVCS}} \left[\sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\mathrm{DVCS}} \sin(n\phi) \right]$$

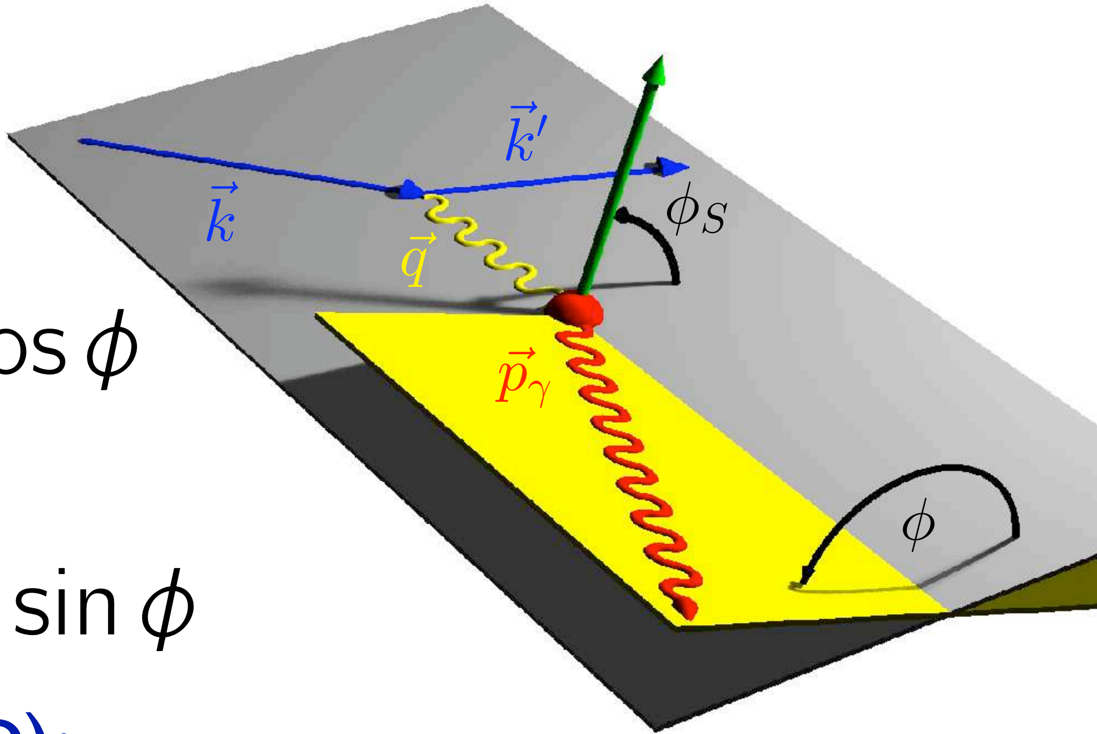
$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Azimuthal Asymmetries in DVCS

Cross section:

$$\sigma(\phi,\phi_S,P_B,C_B,P_T) = \sigma_{\mathrm{UU}}(\phi)\cdot\left[1 + P_B\mathcal{A}_{\mathrm{LU}}^{\mathrm{DVCS}}(\phi) + C_B P_B \mathcal{A}_{\mathrm{LU}}^{\mathcal{I}}(\phi) + C_B\mathcal{A}_{\mathrm{C}}(\phi) + P_T\mathcal{A}_{\mathrm{UT}}^{\mathrm{DVCS}}(\phi,\phi_S) + C_B P_T \mathcal{A}_{\mathrm{UT}}^{\mathcal{I}}(\phi,\phi_S)\right]$$

Azimuthal asymmetries:



- Beam-charge asymmetry $A_C(\Phi)$:

$$d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \propto \mathrm{Re}[F_1\mathcal{H}]\cdot\cos\phi$$

- Beam-helicity asymmetry $A_{LU}{}^{I}(\Phi)$:

$$d\sigma(e^{\rightarrow},\phi) - d\sigma(e^{\leftarrow},\phi) \propto \mathrm{Im}[F_1\mathcal{H}]\cdot\sin\phi$$

- Transverse target-spin asymmetry $A_{UT}{}^{I}(\Phi)$:

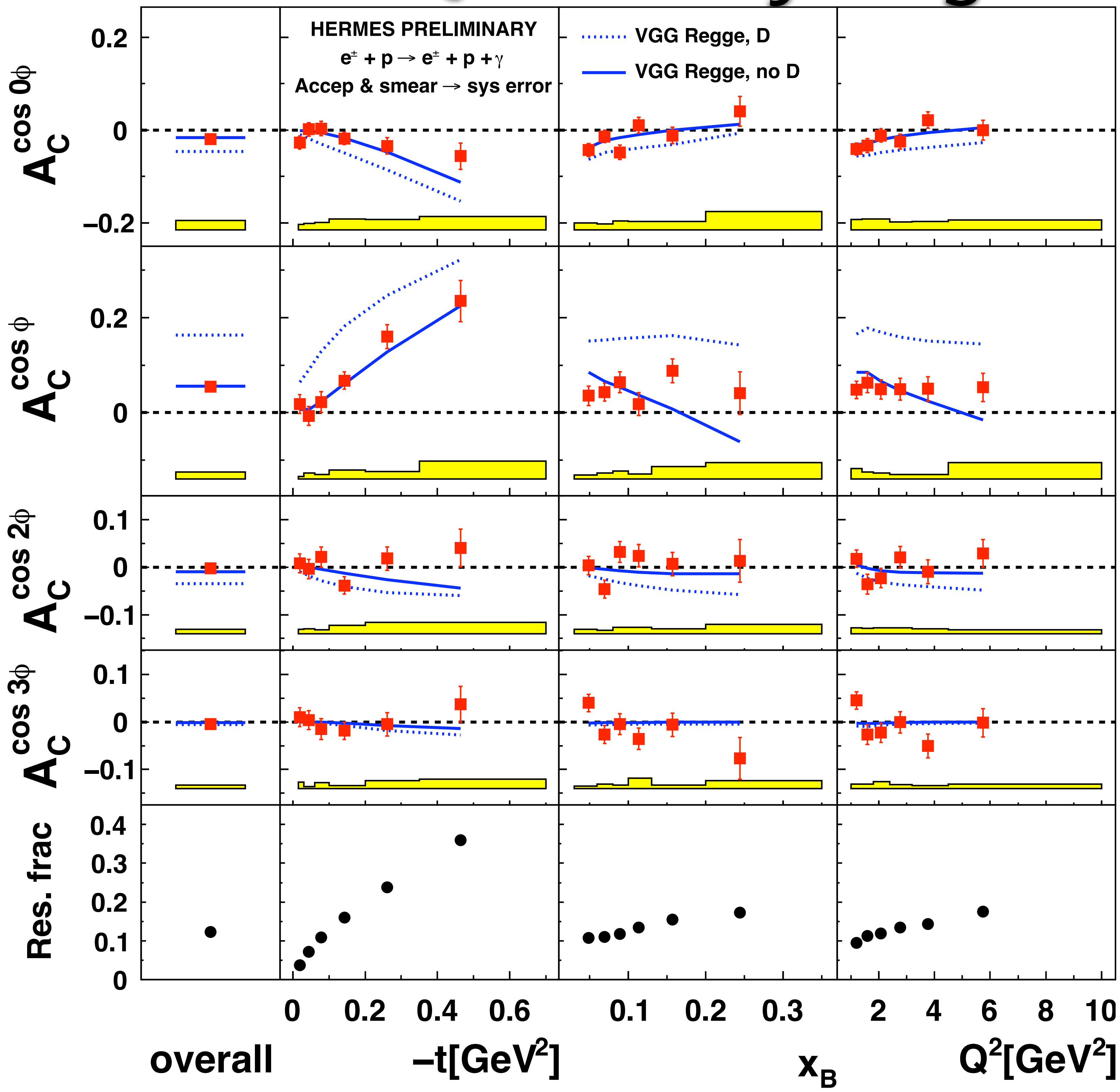
$$d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi) \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}]\cdot\sin(\phi-\phi_S)\cos\phi + \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}]\cdot\cos(\phi-\phi_S)\sin\phi$$

(F_1, F_2 are the Dirac and Pauli form factors)

($\mathcal{H}$,$\mathcal{E}$ ... Compton form factors involving GPDs H, E, ...)

A_C on a hydrogen target

All data
1996-2005



constant term

$\propto -A_C^{\cos\phi}$

$\propto \mathrm{Re}[F_1\mathcal{H}]$

[higher twist]

[gluon leading twist]

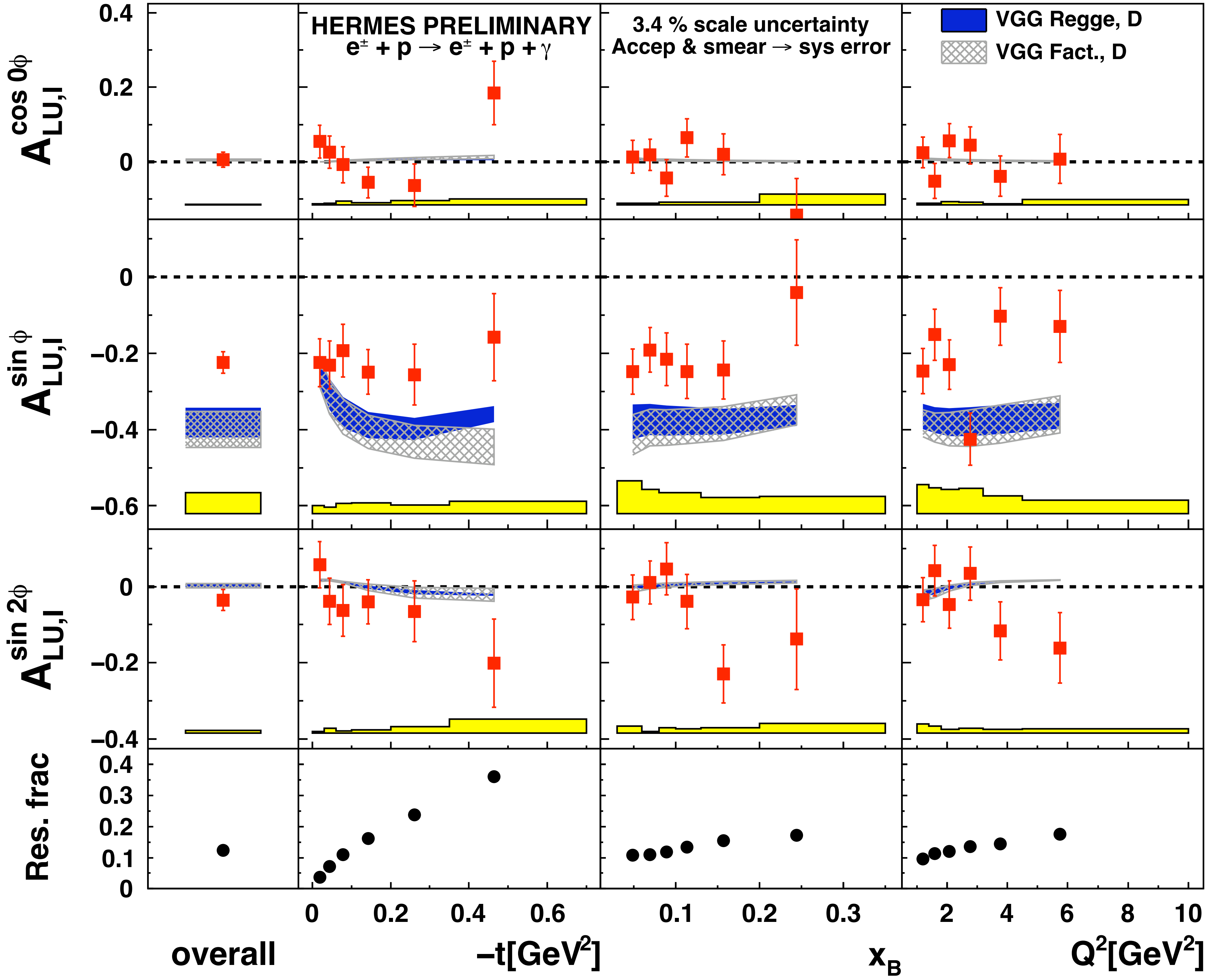
Resonant fraction:

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

GPD model:VGG Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

A_{LU}^{I} on a hydrogen target

All data
1996-2005



$\propto \mathrm{Im}[F_1\mathcal{H}]$

[higher twist]

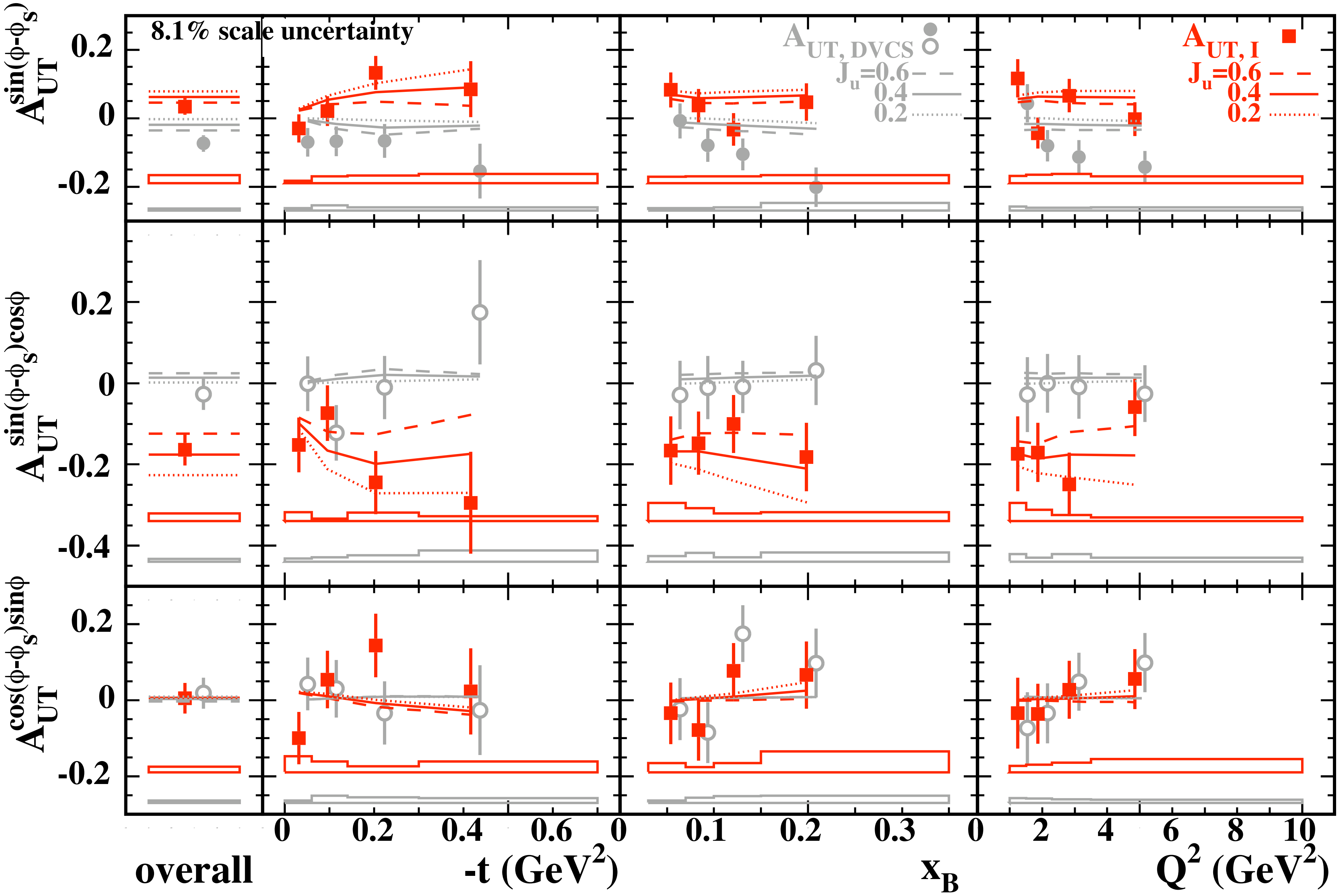
Resonant fraction:

$ep \rightarrow e\Delta^{+}\gamma$

GPD model:VGG Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

A^I_{UT} on a hydrogen target

JHEP06 (2008) 066



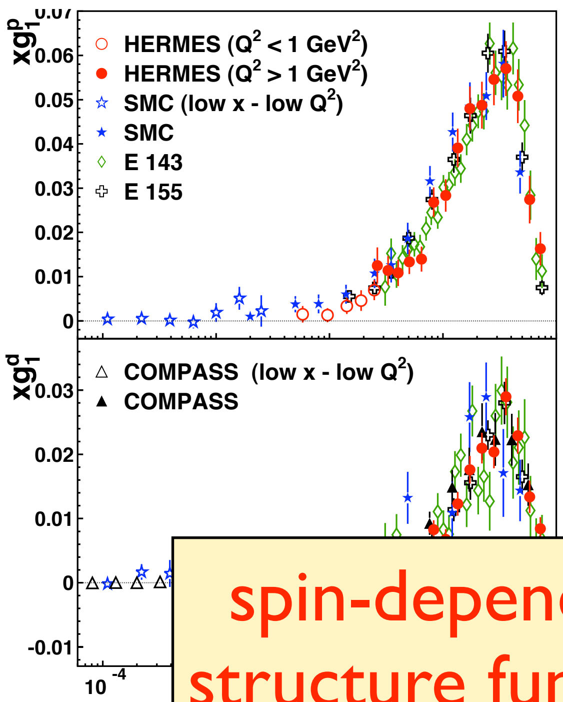
$$\propto -A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$$

- •Substantial magnitude
- •Little kin. dependence

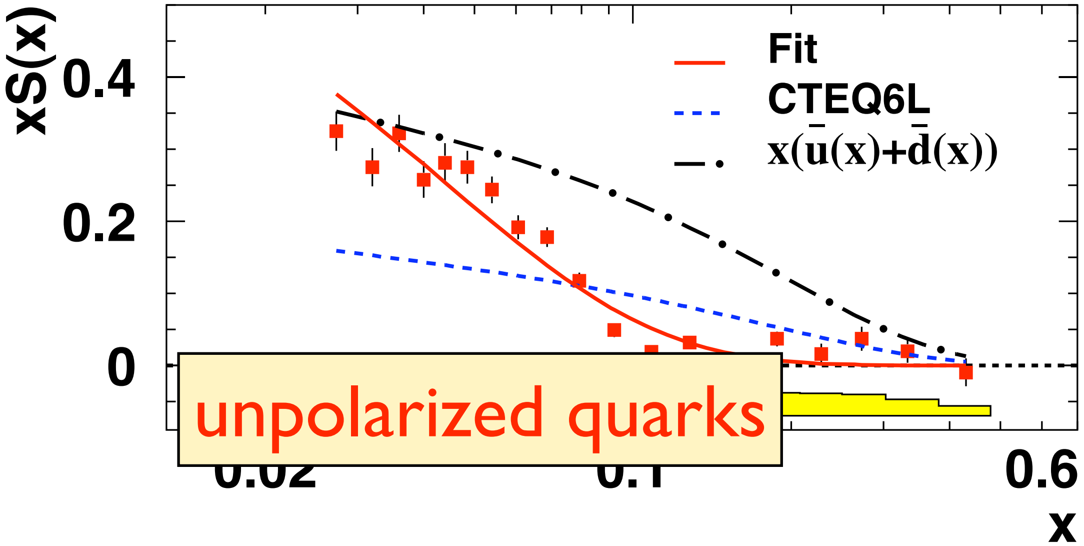
$$\propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}]$$

$$\propto \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}]$$

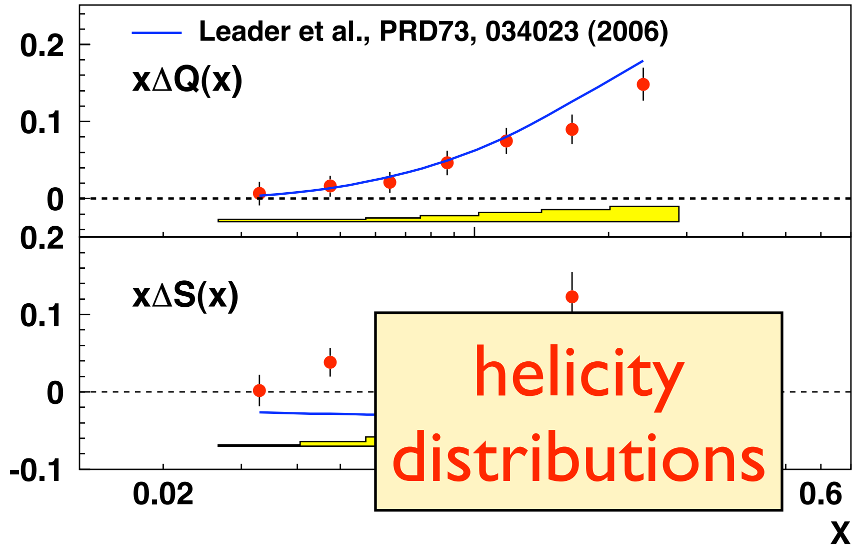
GPD model:VGG Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401



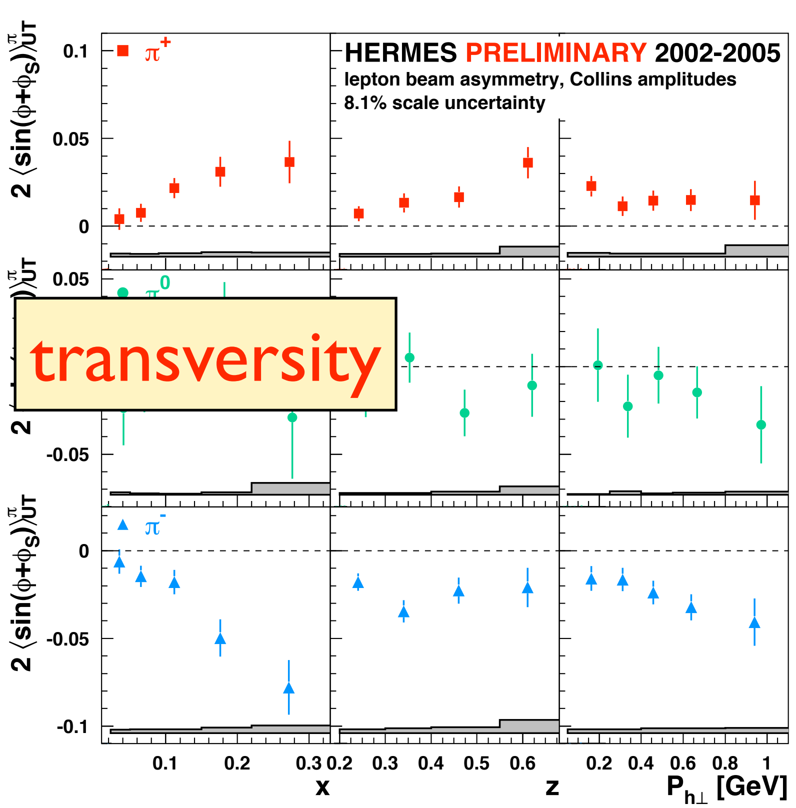
spin-dependent structure function



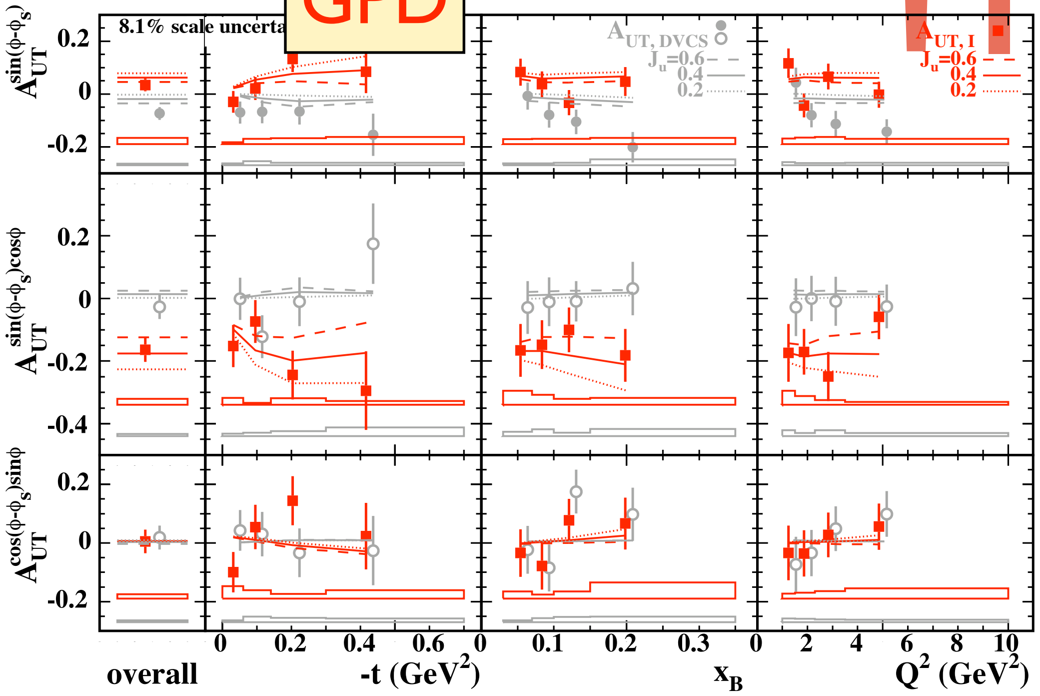
unpolarized quarks



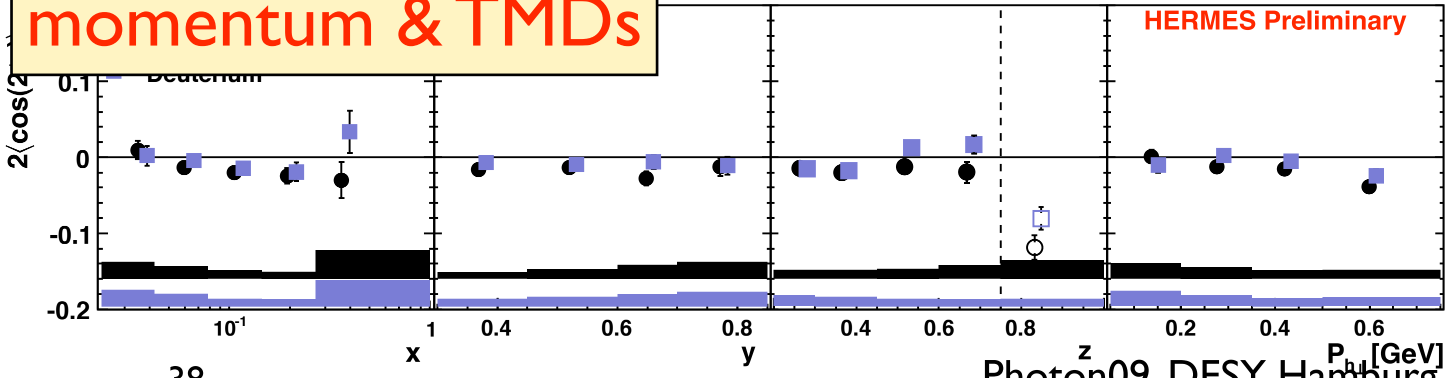
helicity distributions



transversity



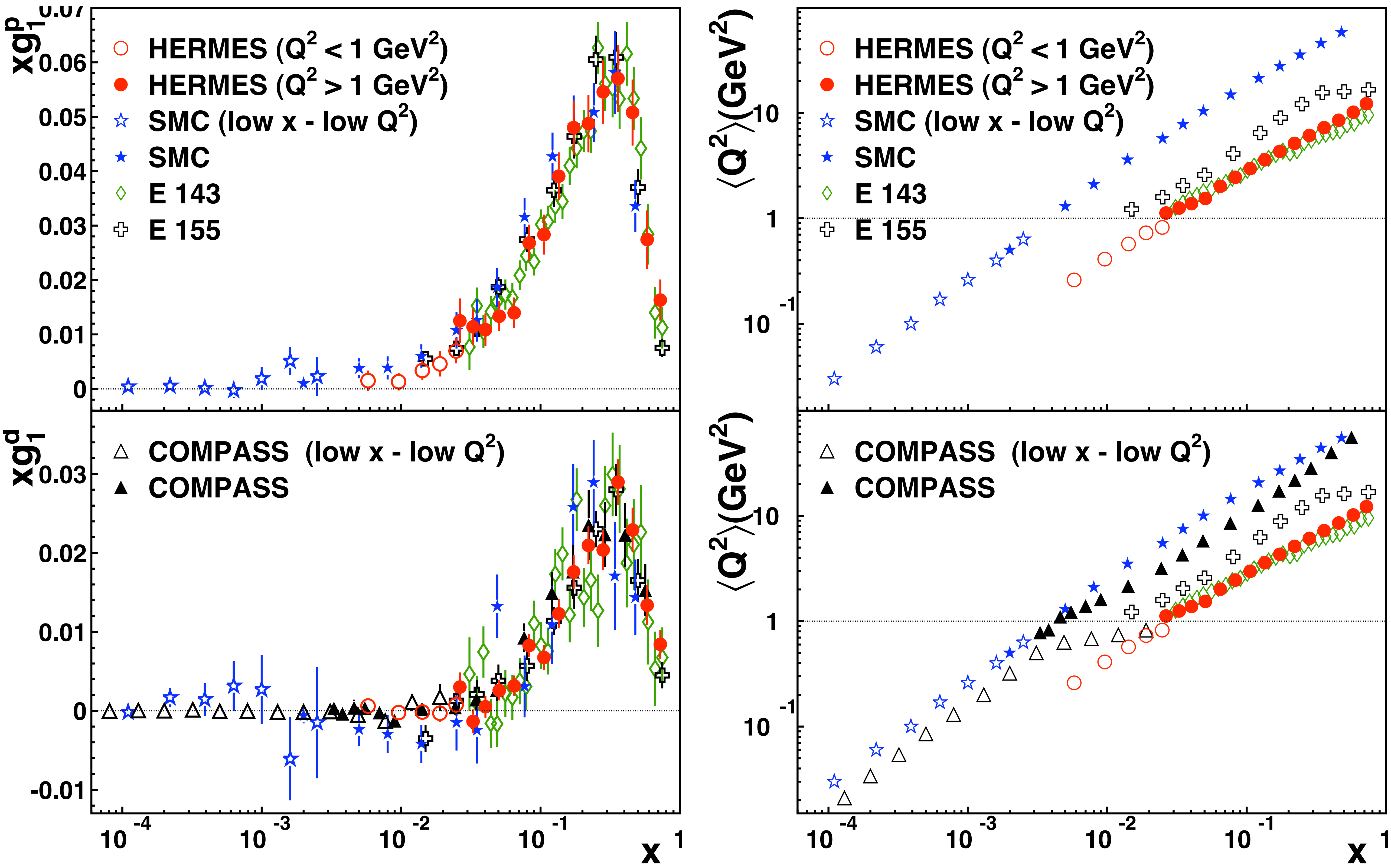
GPD



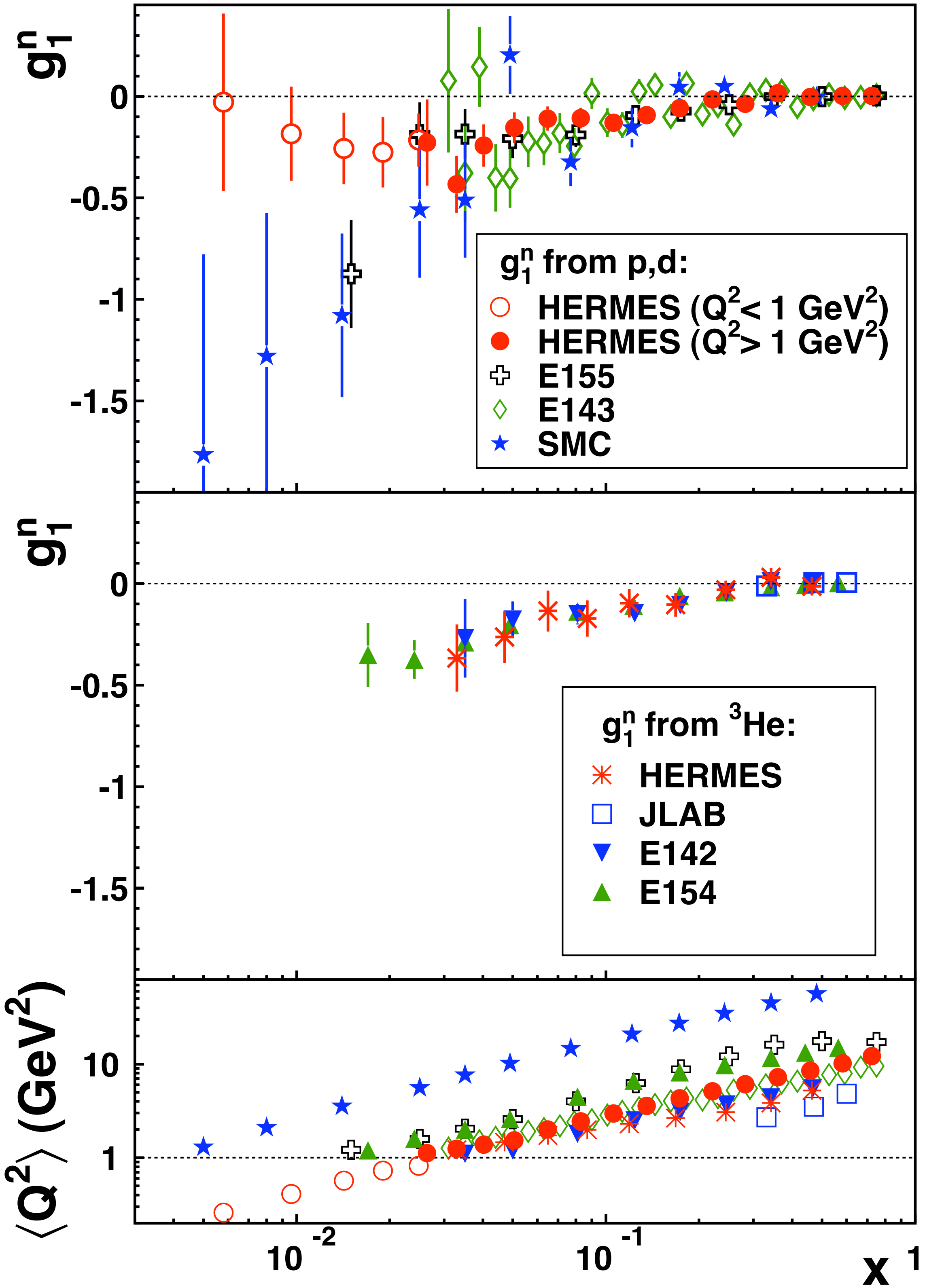
orbital angular momentum & TMDs

Backup

g_1 : Results for p and d



g_1 : Neutron results



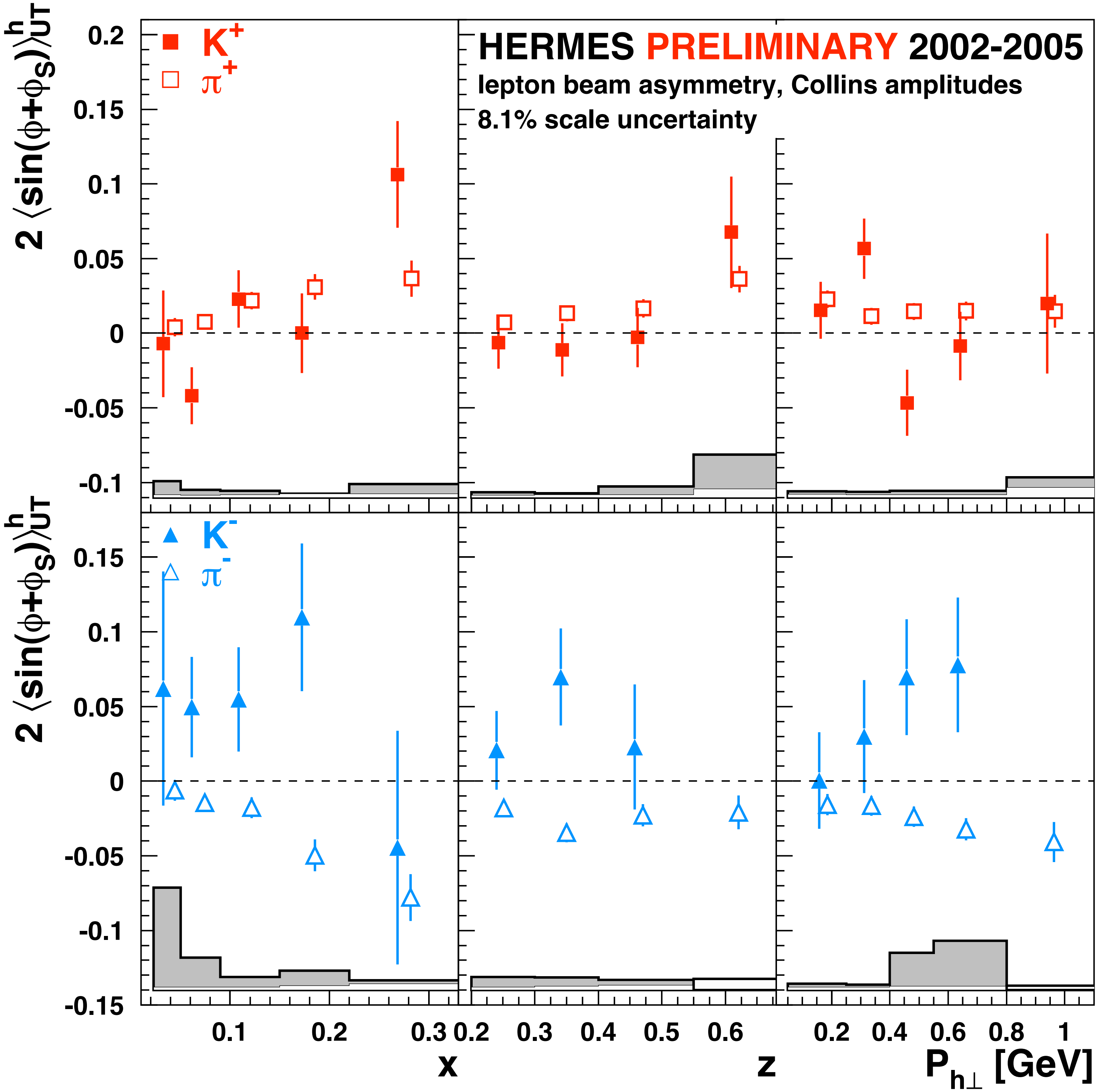
$$g_1^n = \frac{2}{1 - \frac{3}{2}\omega_D} \cdot g_1^d - g_1^p$$

$$\omega_D = 0.05 \pm 0.01$$

- g_1^n negative everywhere except at very high x
- Low-Q^2 data tends to zero at low x
  - Contrary to SMC data at higher Q^2

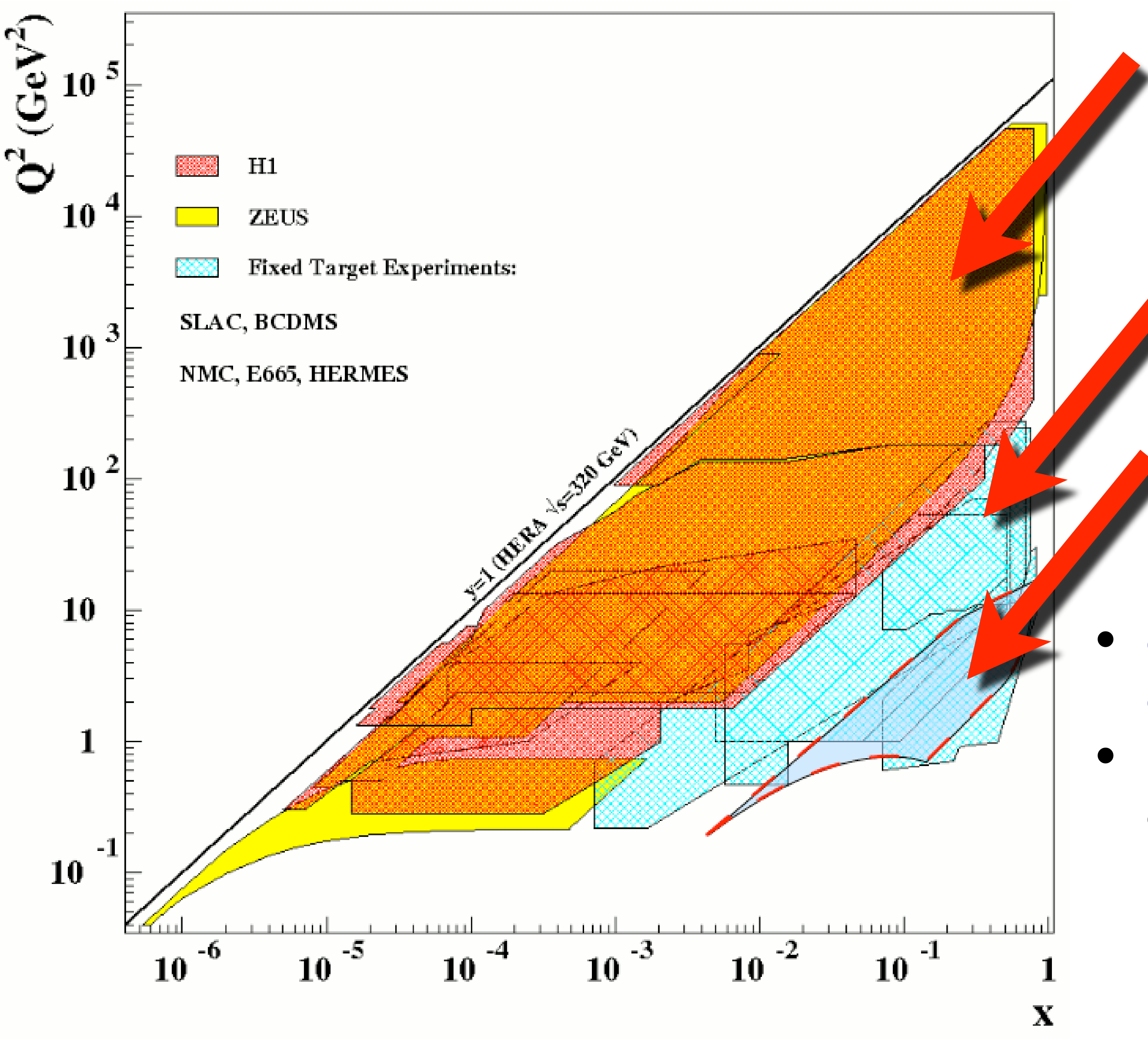
Collins Amplitudes for Kaons

$$A_C \propto \delta q \otimes H_1^{\perp}$$



- no significant non-zero Collins amplitudes for both K^+ and K^-
- Collins amplitudes for K^+ are within statistical accuracy consistent with π^+
- Collins fragmentation function for kaons unknown
- Sea quark transversity expected to be small

Why measuring inclusive DIS cross sections at HERMES?



Collider experiments

Fixed target experiments

HERMES

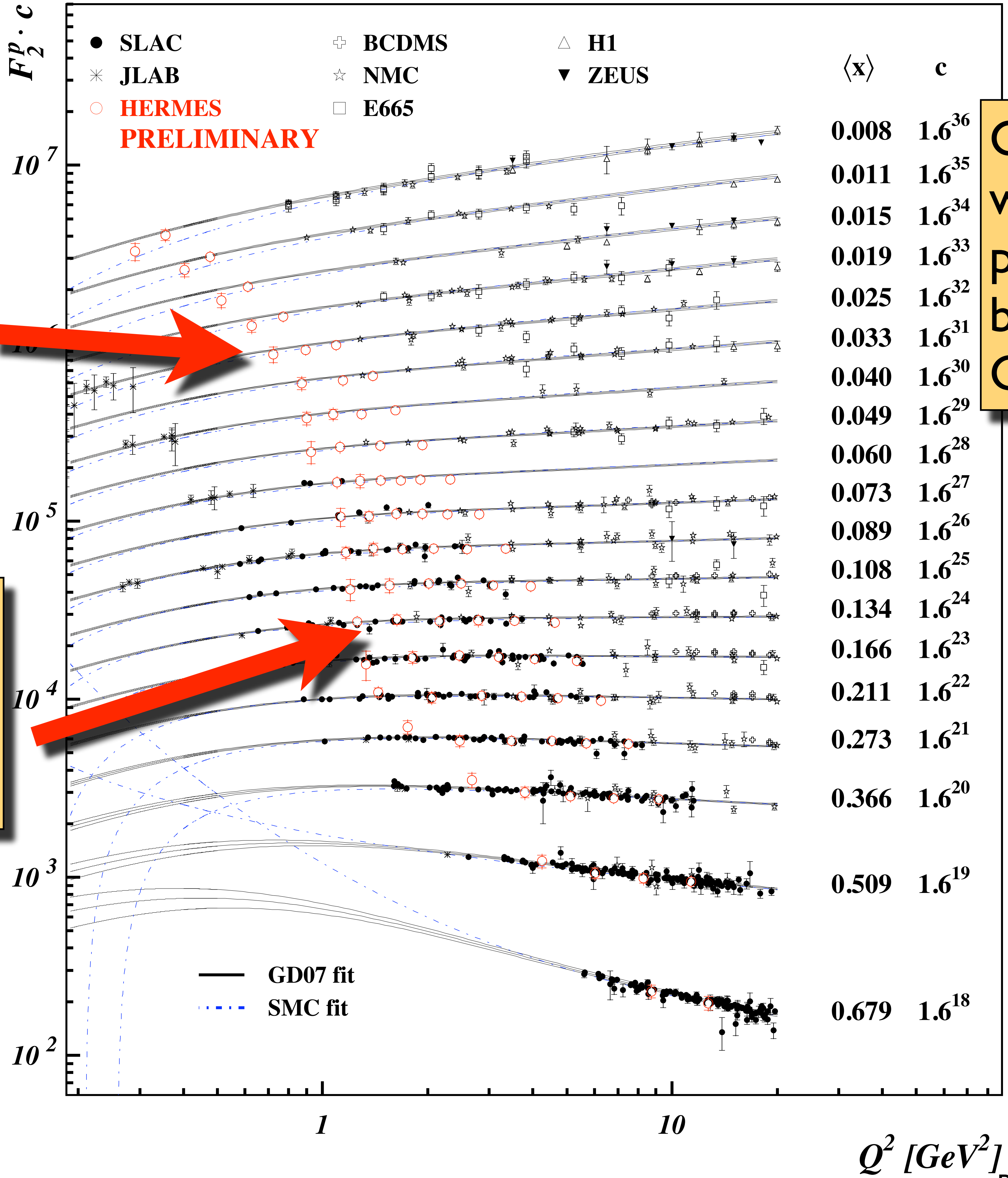
- complementary kinematic coverage compared to colliders
- higher statistics compared to other fixed target experiments:
  - HERMES: 58 million DIS (P+D)
  - NMC: 9 million DIS (P+D)

F_2^P

Proton

New region covered by HERMES

Agreement with world data in the overlap region



Comparison with parameterization by SMC and GD07

GD07: hep-ph0708.3196

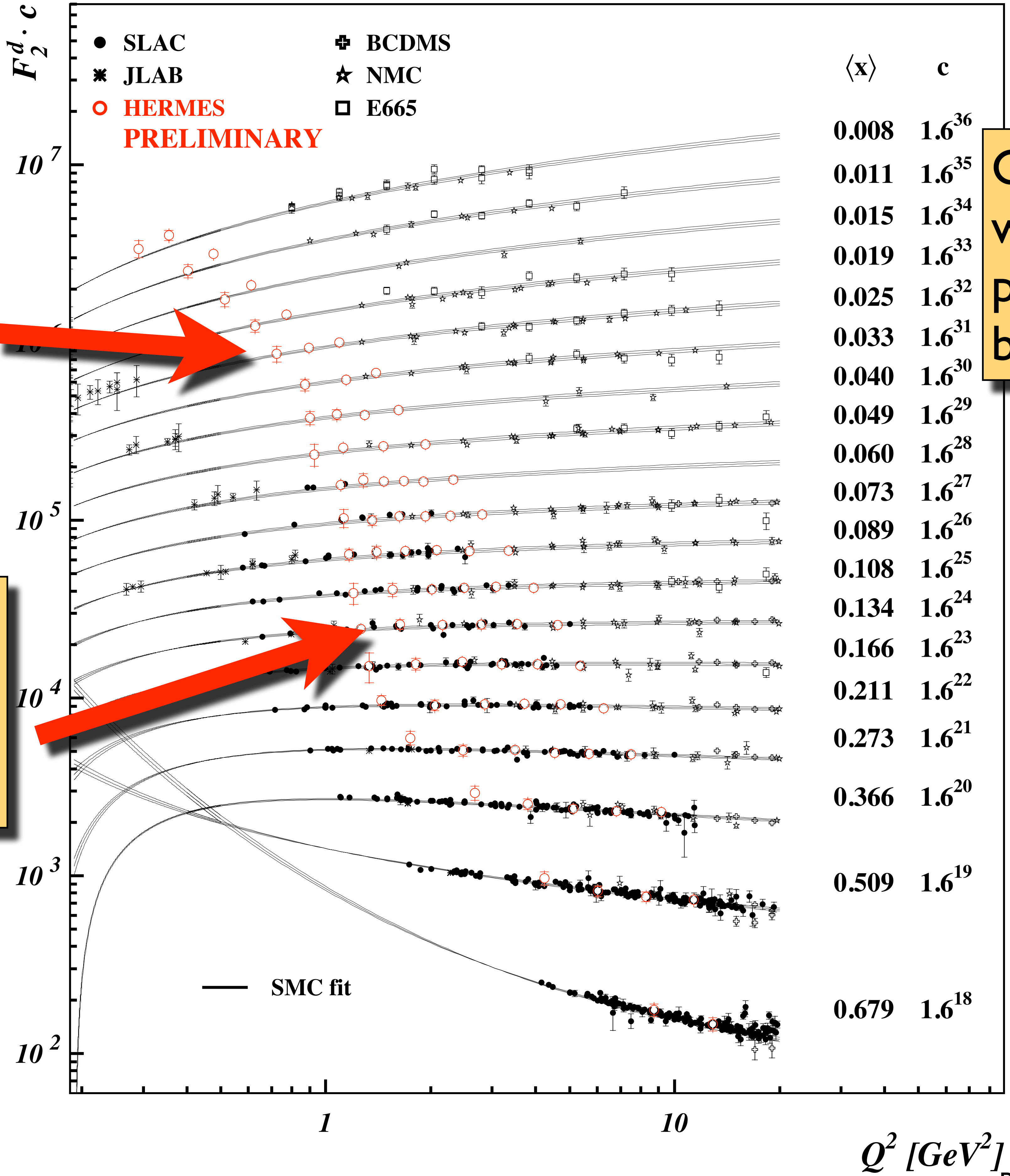
SMC: Phys. Rev. D, Vol. 58, 112001

F_2^D

Deuteron

New region covered by HERMES

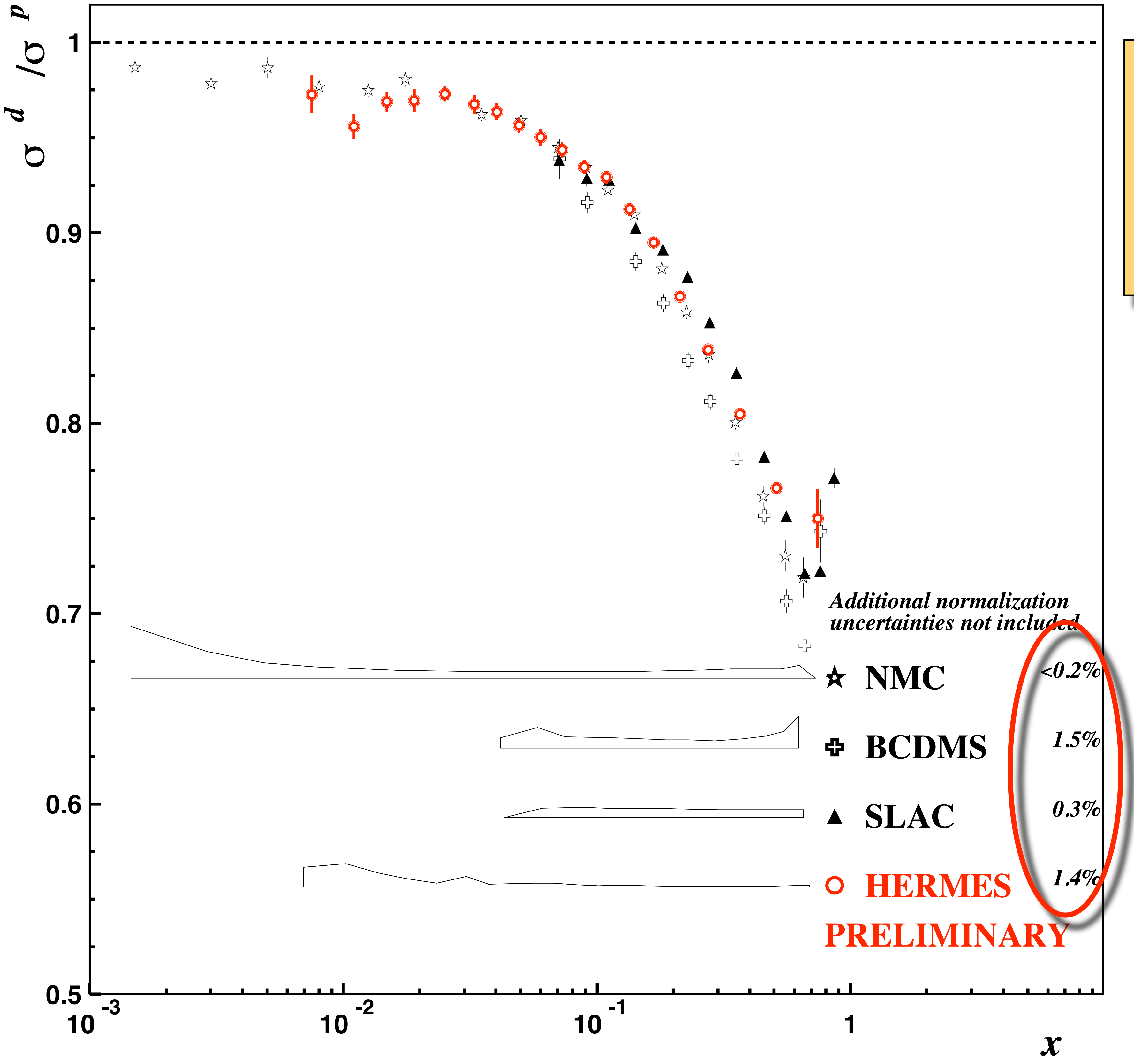
Agreement with world data in the overlap region



Comparison with parameterization by SMC

SMC: Phys. Rev. D, Vol. 58, 112001

World data on σ^d/σ^p



Many systematic errors common to proton and deuteron cross sections cancel in ratio

Normalization uncertainties