The Spin Structure of the Nucleon as seen by HERMES

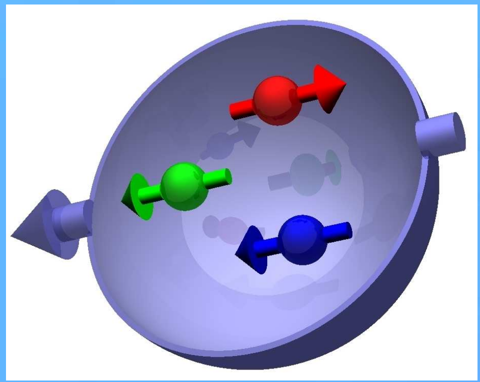
Benedikt Zihlmann
University of Gent

on behalf of the

hermes

collaboration

The Spin Structure of the Nucleon



Naive Parton Model:

$$\Delta u_v + \Delta d_v = 1$$

$$\Longrightarrow \Delta u_v = \frac{4}{3}, \Delta d_v = \frac{-1}{3}$$

BUT

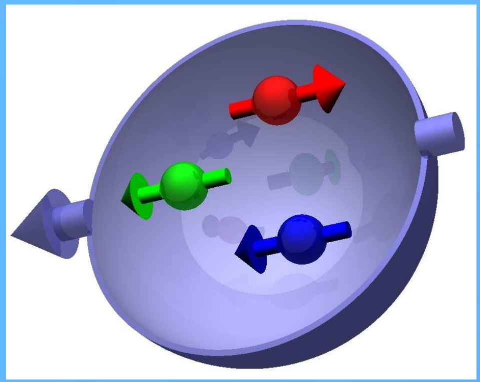
1988 EMC measured:

$\Delta\Sigma$ **= 0.123** $\pm$ **0.013** $\pm$ **0.019**

$\Longrightarrow$ **Spin Puzzle**

$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v)$$

The Spin Structure of the Nucleon



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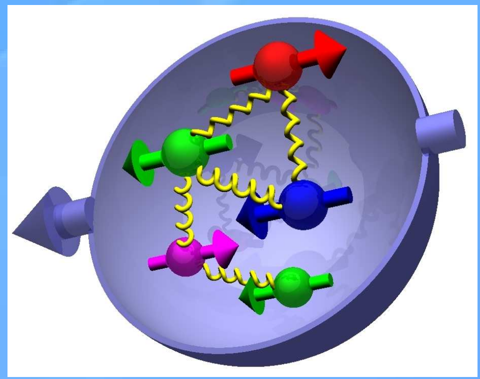

from unpolarized data:

Gluons are important !

$\Longrightarrow$ **sea quarks** $\mathbf{\Delta q_s}$

$\Longrightarrow$ $\mathbf{\Delta G}$

$$\frac{1}{2} = \frac{1}{2}\left(\mathbf{\Delta u_v} + \mathbf{\Delta d_v} + \underbrace{\Delta q_s}_{\mathbf{\Delta u_s, \Delta d_s, \Delta\bar{u}, \Delta\bar{d}, \Delta s, \Delta\bar{s}}}\right) + \mathbf{\Delta G}$$

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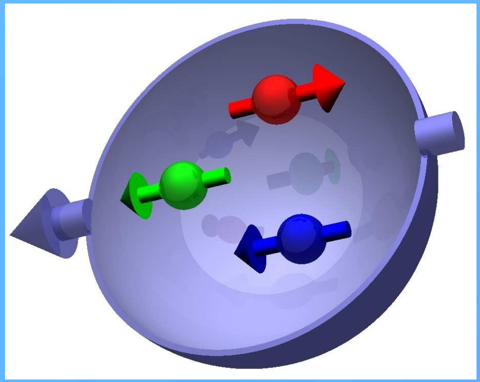

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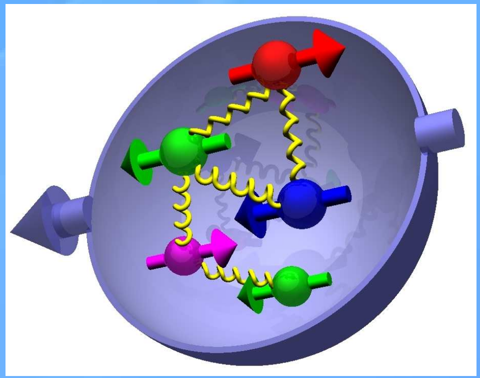

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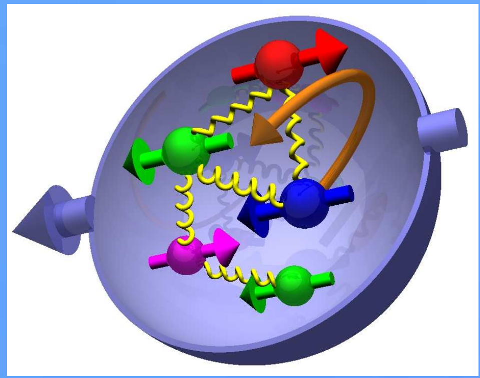


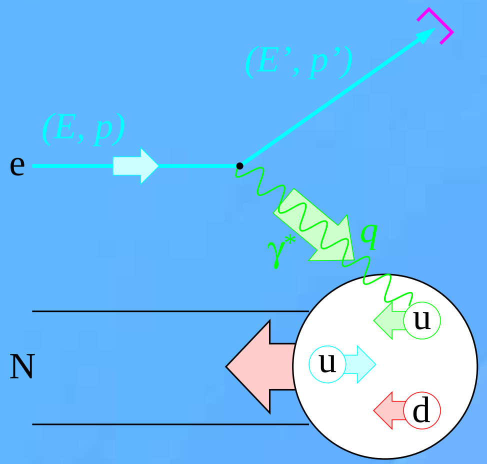
Full description of J$_q$ & J$_g$

needs

orbital angular momentum

$$\frac{1}{2} = \frac{1}{2}\underbrace{(\Delta u_v + \Delta d_v + \Delta q_s)}_{\Delta\Sigma} + L_q + (\Delta G + L_g)$$

Inclusive Scattering:



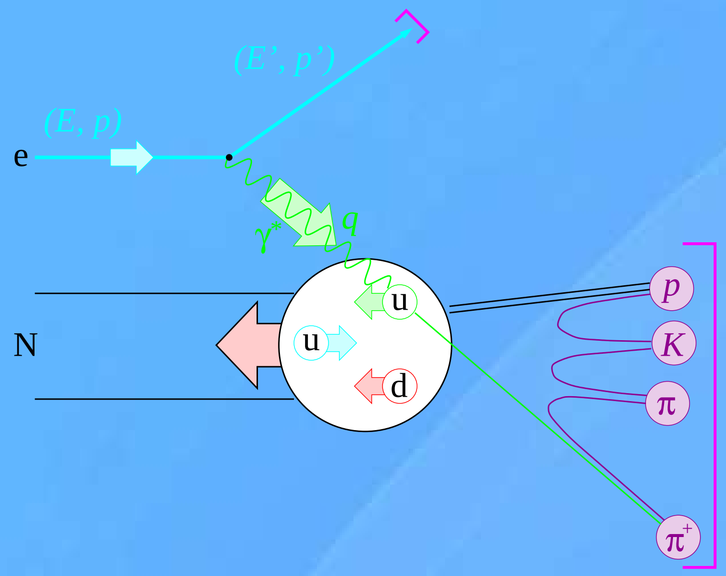
detect scattered lepton

$$\mathbf{Q^2} \overset{lab}{=} \mathbf{4EE'} \sin^{\mathbf{2}}(\frac{\theta}{\mathbf{2}})$$

$$\mathbf{x} \overset{lab}{=} \frac{\mathbf{Q^2}}{\mathbf{2M}\nu} \qquad \mathbf{y} \overset{lab}{=} \frac{\nu}{\mathbf{E}} = \frac{\mathbf{p \cdot q}}{\mathbf{p \cdot k}}$$

Deep Inelastic Scattering

Semi-Inclusive Scattering: detect scattered lepton and produced hadrons



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$$x \stackrel{lab}{=} \frac{Q^2}{2M\nu} \qquad y \stackrel{lab}{=} \frac{\nu}{E} = \frac{p \cdot q}{p \cdot k}$$

$$z \stackrel{lab}{=} \frac{E_h}{\nu}$$

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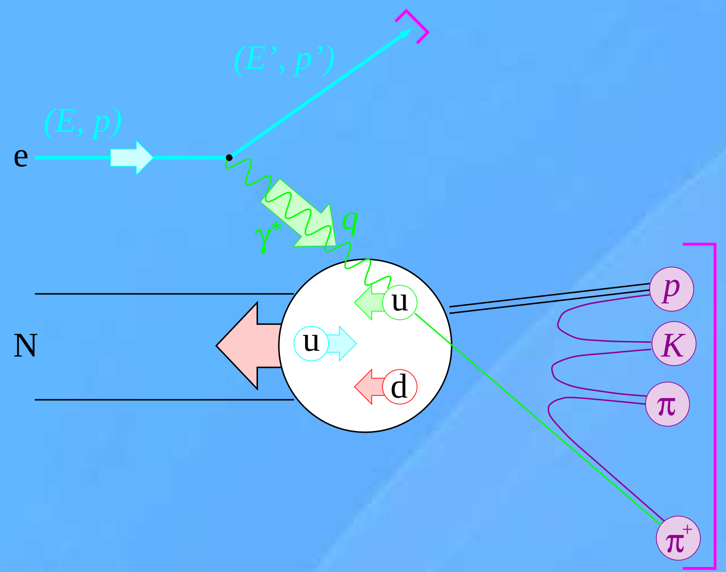

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$$\mathbf{z} \overset{lab}{=} \frac{\mathbf{E_h}}{\nu}$$

Cross Section: $\frac{d^2\sigma}{d\Omega dE^2} = \frac{\alpha^2 E'}{Q^2 E} L_{\mu\nu} W^{\mu\nu}$

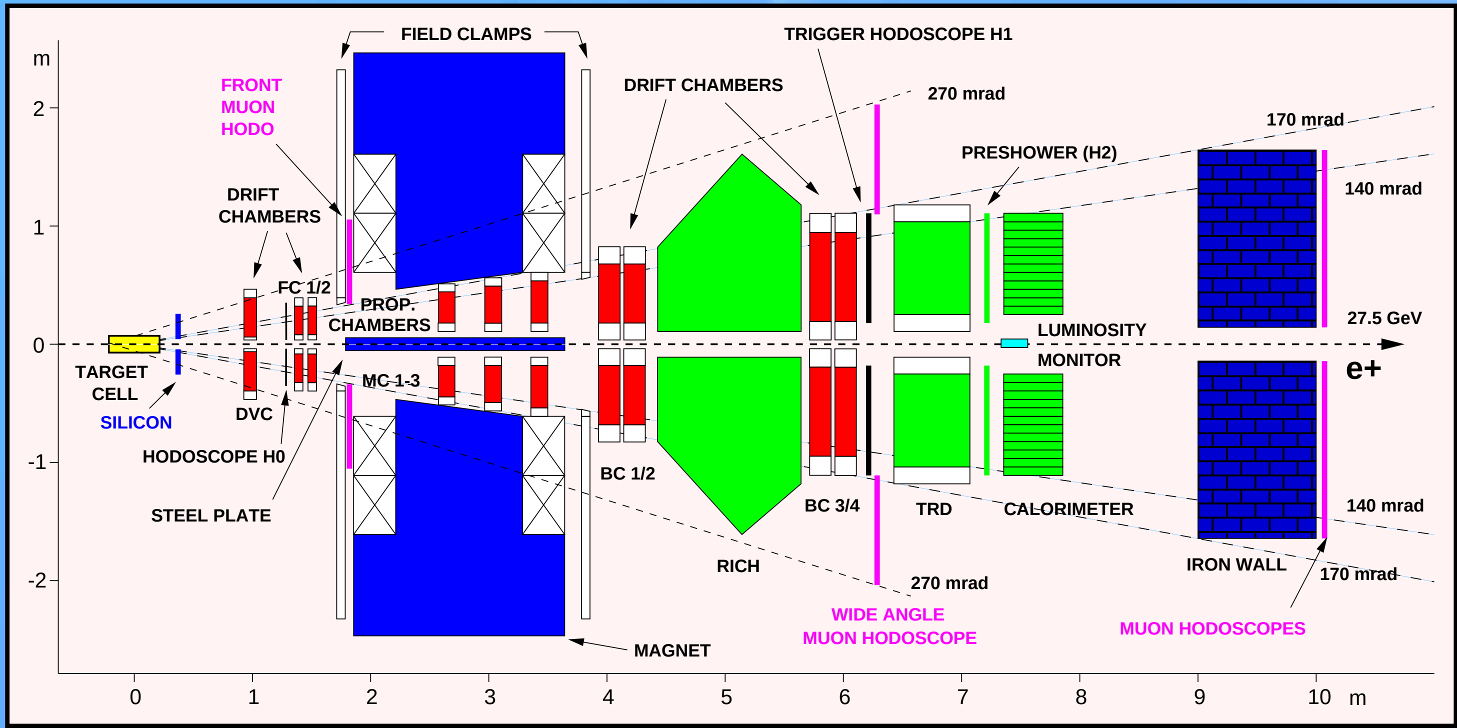
$L_{\mu\nu}$**: purely electromagnetic** $\Longrightarrow$ **calculable**

$W^{\mu\nu} \quad \sim \quad F_1\left(x,Q^2\right)$ **+** $F_2\left(x,Q^2\right)$ **+** $g_1\left(x,Q^2\right) + g_2\left(x,Q^2\right)$

(for spin 1) $-b1\left(x,Q^2\right) + \frac{1}{6}b2\left(x,Q^2\right) + \frac{1}{2}b3\left(x,Q^2\right) + \frac{1}{2}b4\left(x,Q^2\right)$

F_1,F_2 **/** g_1,g_2 $\Longrightarrow$ **Unpolarized / Polarized Structure Functions**

The HERMES Detector at DESY

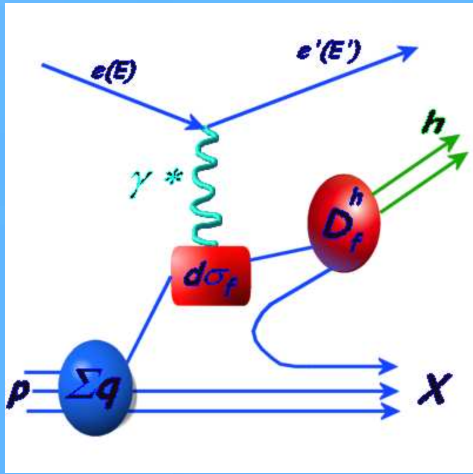


Kinematic Range: **$0.02 \leq x \leq 0.8$, $1\mathrm{GeV}^2 \leq Q^2 \leq 15\mathrm{GeV}^2$ at $W \geq 2\mathrm{GeV}$**
$\Theta_x \leq 175$ mrad, 40 mrad $\leq \Theta_y \leq 140$ mrad

Reconstruction: **δp/p 1.0 - 2.0%, $\delta\Theta \leq 0.6$mrad**

Internal Gas Target: **$\overrightarrow{\mathrm{H}e}$, $\overrightarrow{\mathrm{D}}$, $\overrightarrow{\mathrm{H}}$, $\mathrm{H}^{\uparrow}$ unpol: H_2, D_2, He, N_2, Ne, Ar, Kr, Xe**

Particle ID: **TRD, Preshower, Calorimeter**
$\Rightarrow$ 1997: $\check{C}$erenkov   1998 $\Rightarrow$: RICH



Semi-inclusive DIS

Correlation between detected hadron and struck q_f

$\Longrightarrow$ **'Flavor - Separation'**

Inclusive DIS: $\Delta\Sigma = \sum_i (\Delta q_i(x) + \Delta\bar{q}_i(x))$

Semi-inclusive DIS: $\Delta u, \Delta\bar{u}, \Delta d, \Delta\bar{d}, \Delta s, \Delta\bar{s}$

In LO-QCD:

$$\mathbf{A_1^h(x, Q^2)} = \frac{\sigma^{\mathbf{h}}_{\mathbf{1/2}} - \sigma^{\mathbf{h}}_{\mathbf{3/2}}}{\sigma^{\mathbf{h}}_{\mathbf{1/2}} + \sigma^{\mathbf{h}}_{\mathbf{3/2}}} \sim \frac{\sum_f e_f^2 \Delta q_f(x, Q^2) \int dz D_f^h(z, Q^2)}{\sum_f e_f^2 q_f(x, Q^2) \int dz D_f^h(z, Q^2)}$$

$$\sim \sum_{\mathbf{q}} \underbrace{\frac{e_q^2 q(x) \int dz D_q^h(z)}{\sum_{q'} e_{q'}^2 q'(x) \int dz D_{q'}^h(z)}}_{\mathbf{P_q^h(x, z)}} \frac{\mathbf{\Delta q(x)}}{\mathbf{q(x)}}$$

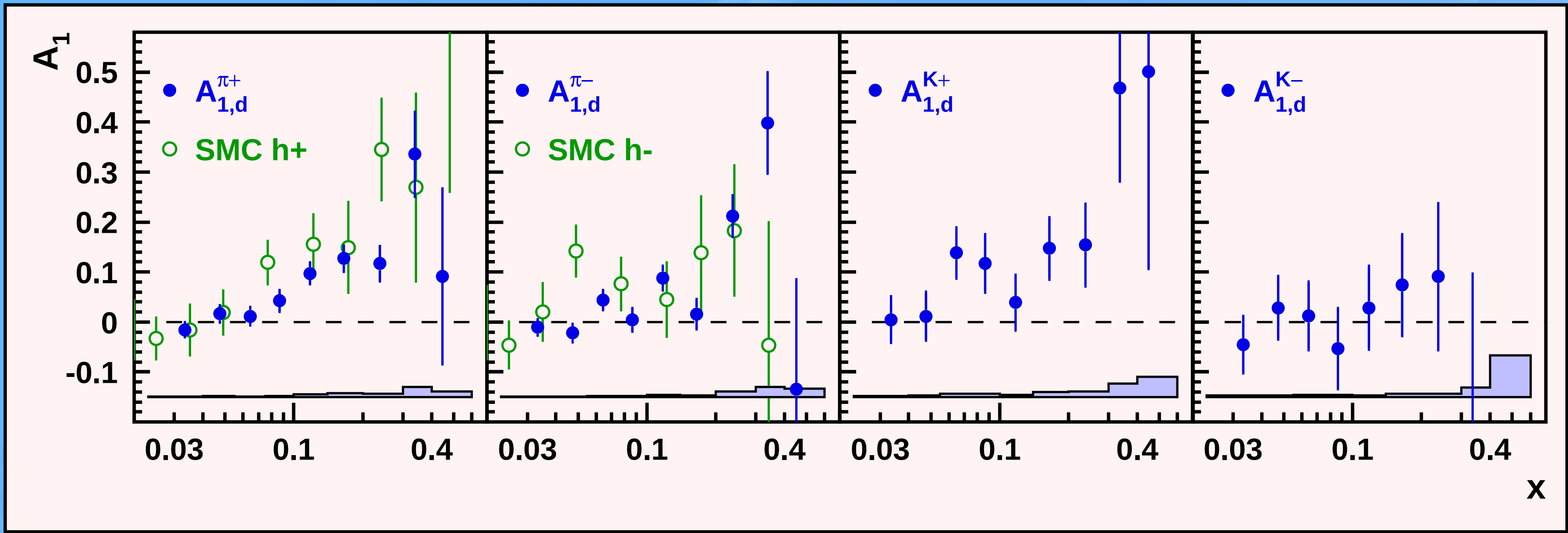
- **Solve linear system for $\vec{Q}$ with**

$$\tilde{\mathbf{A}} = (\mathbf{A_{1,p}(x), A_{1,d}(x), A_{1,p}^{\pi^\pm}(x), A_{1,d}^{\pi^\pm}(x), A_{1,d}^{K^\pm}(x)})$$

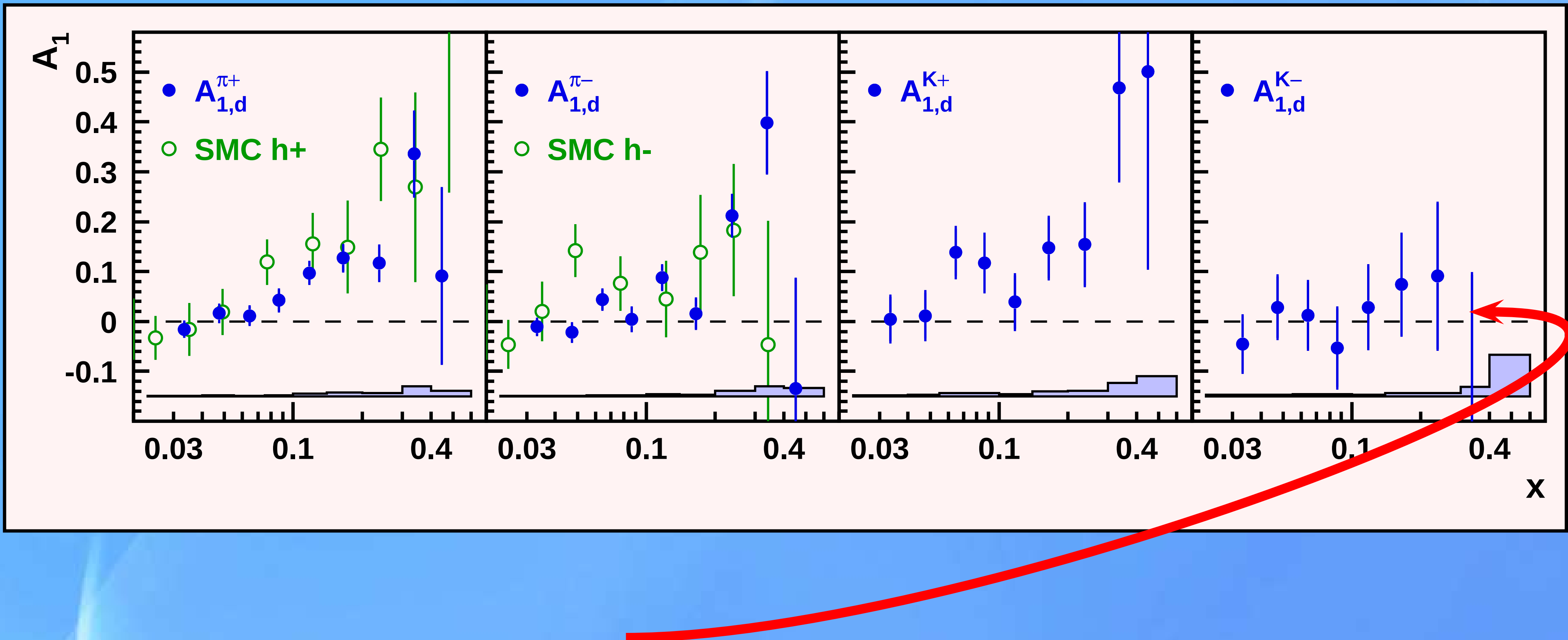
$$\tilde{\mathbf{Q}} = \left(\frac{\mathbf{\Delta u}}{\mathbf{u}}, \frac{\mathbf{\Delta d}}{\mathbf{d}}, \frac{\mathbf{\Delta \bar{u}}}{\mathbf{\bar{u}}}, \frac{\mathbf{\Delta \bar{d}}}{\mathbf{\bar{d}}}, \frac{\mathbf{\Delta s}}{\mathbf{s}}\right)$$

$$\vec{\mathcal{A}} = \mathcal{P}\vec{\mathcal{Q}}$$

Hadron Asymmetries on the Deuteron

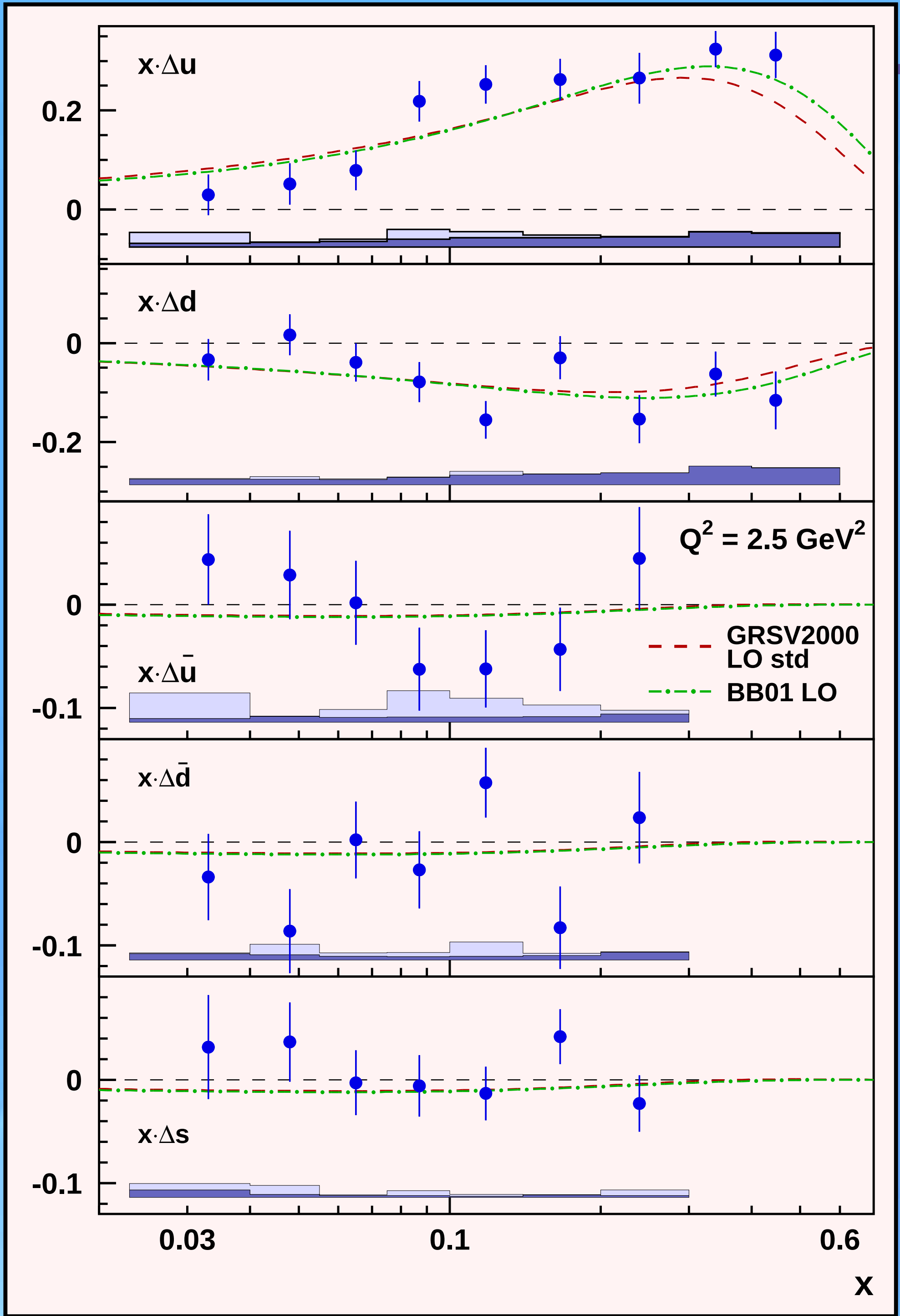


Hadron Asymmetries on the Deuteron



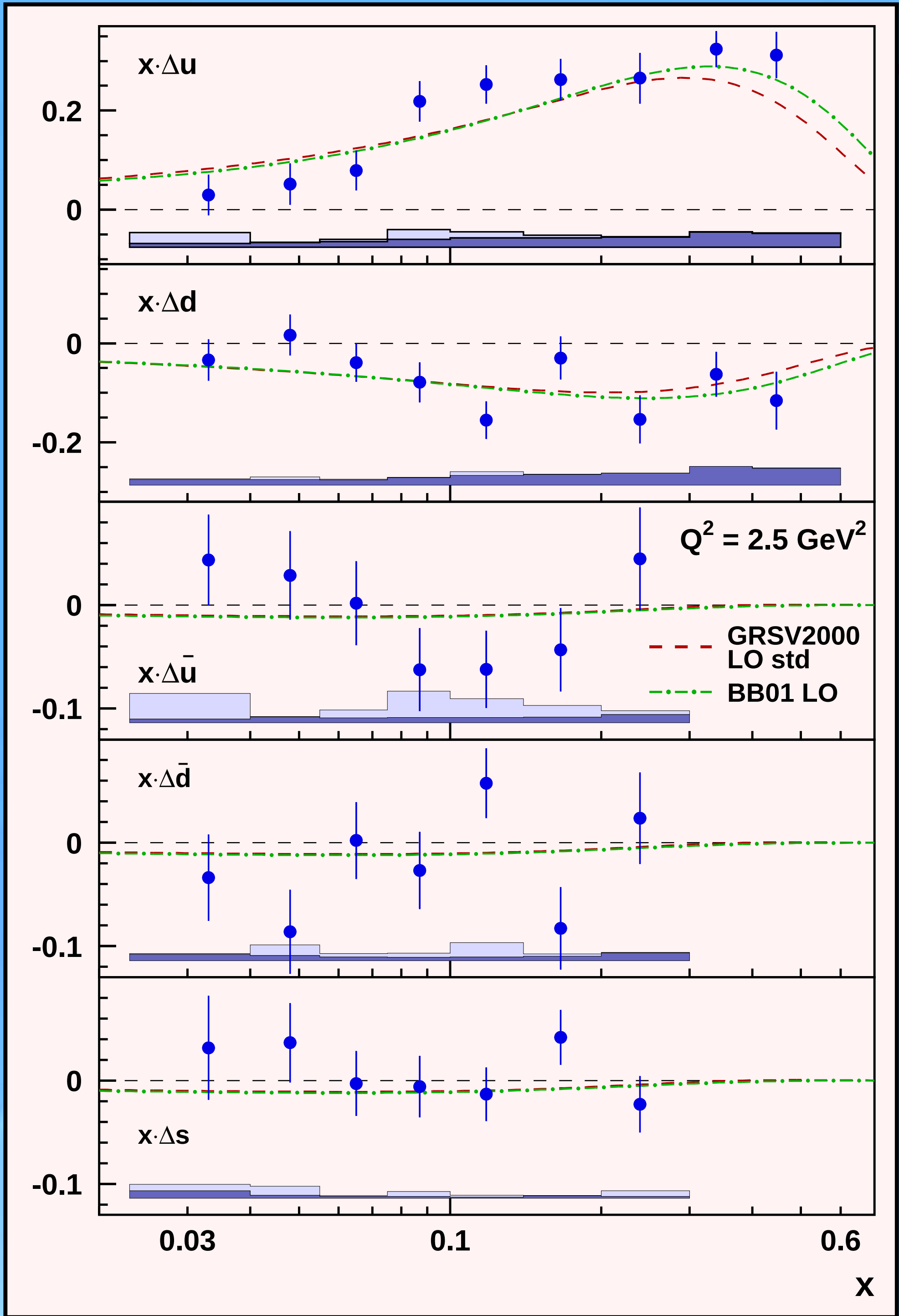
- $A_1^{K^-}(x) \approx 0$ **!!** $\Longrightarrow K^- = (\bar{u}s)$ **is an all–sea object**
- **statistics sufficient for 5-parameter fit** $\tilde{\mathrm{Q}} = (\frac{\Delta \mathrm{u}}{\mathrm{u}}, \frac{\Delta \mathrm{d}}{\mathrm{d}}, \frac{\Delta \bar{\mathrm{u}}}{\bar{\mathrm{u}}}, \frac{\Delta \bar{\mathrm{d}}}{\bar{\mathrm{d}}}, \frac{\Delta \mathrm{s}}{\mathrm{s}})$

Polarized Quark Densities



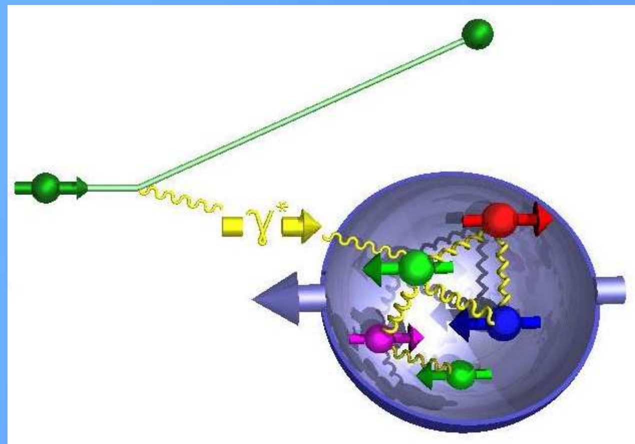
$$\Delta q_f(x) := q_f^+(x) - q_f^-(x)$$

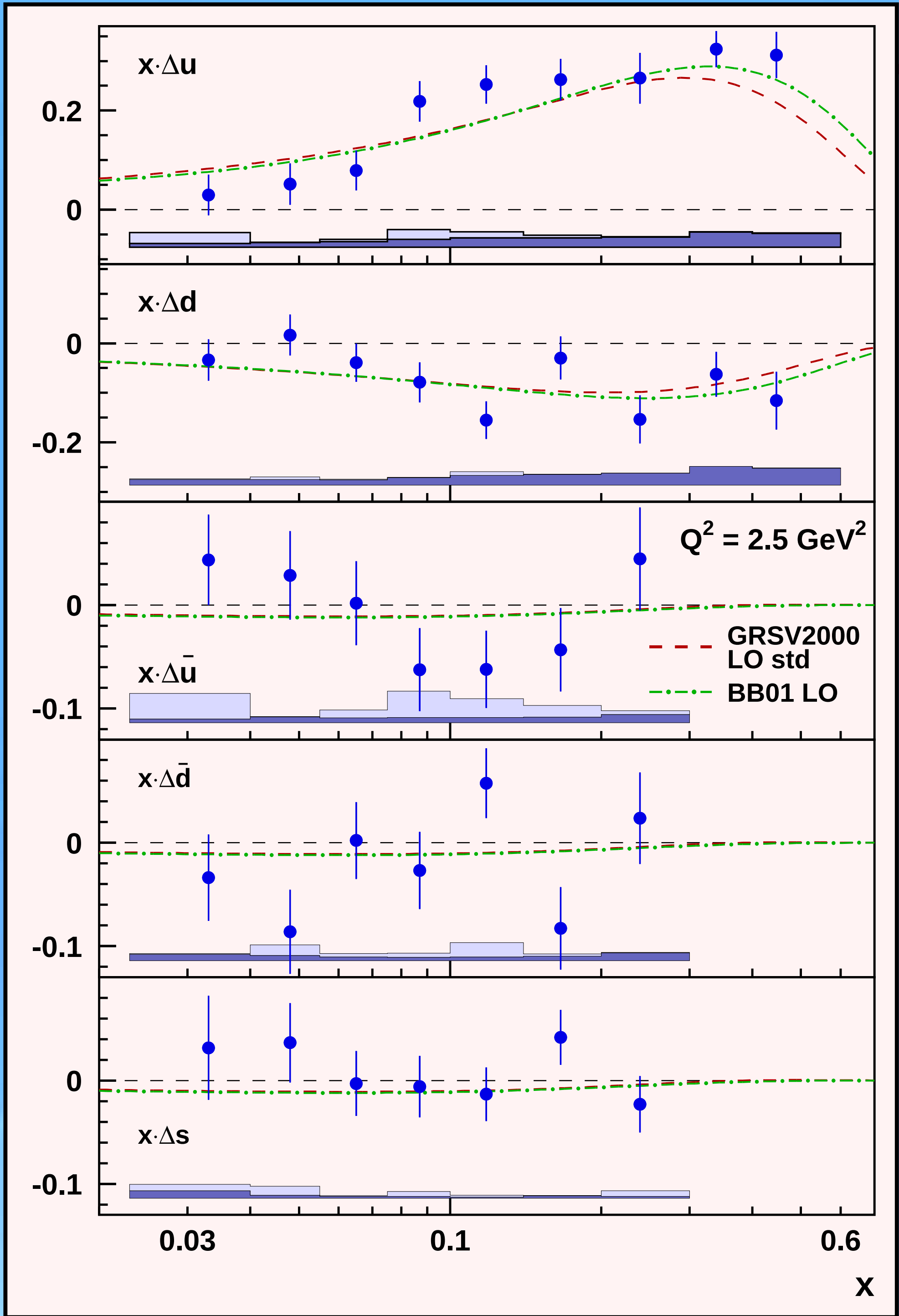
Polarized Quark Densities



$$\mathbf{\Delta q_f(x) := q_f^+(x) - q_f^-(x)}$$

- $\mathbf{\Delta u(x) > 0}$
  $\Longrightarrow$ **polarized parallel to the proton**





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- $\Delta u(x) > 0$
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- $\Delta d(x) < 0$
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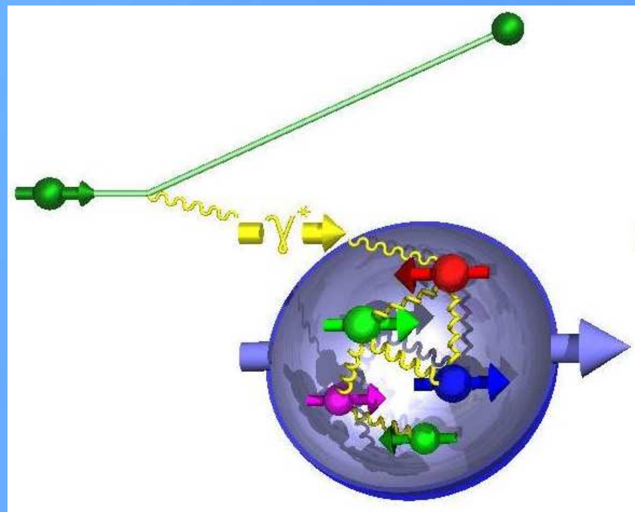

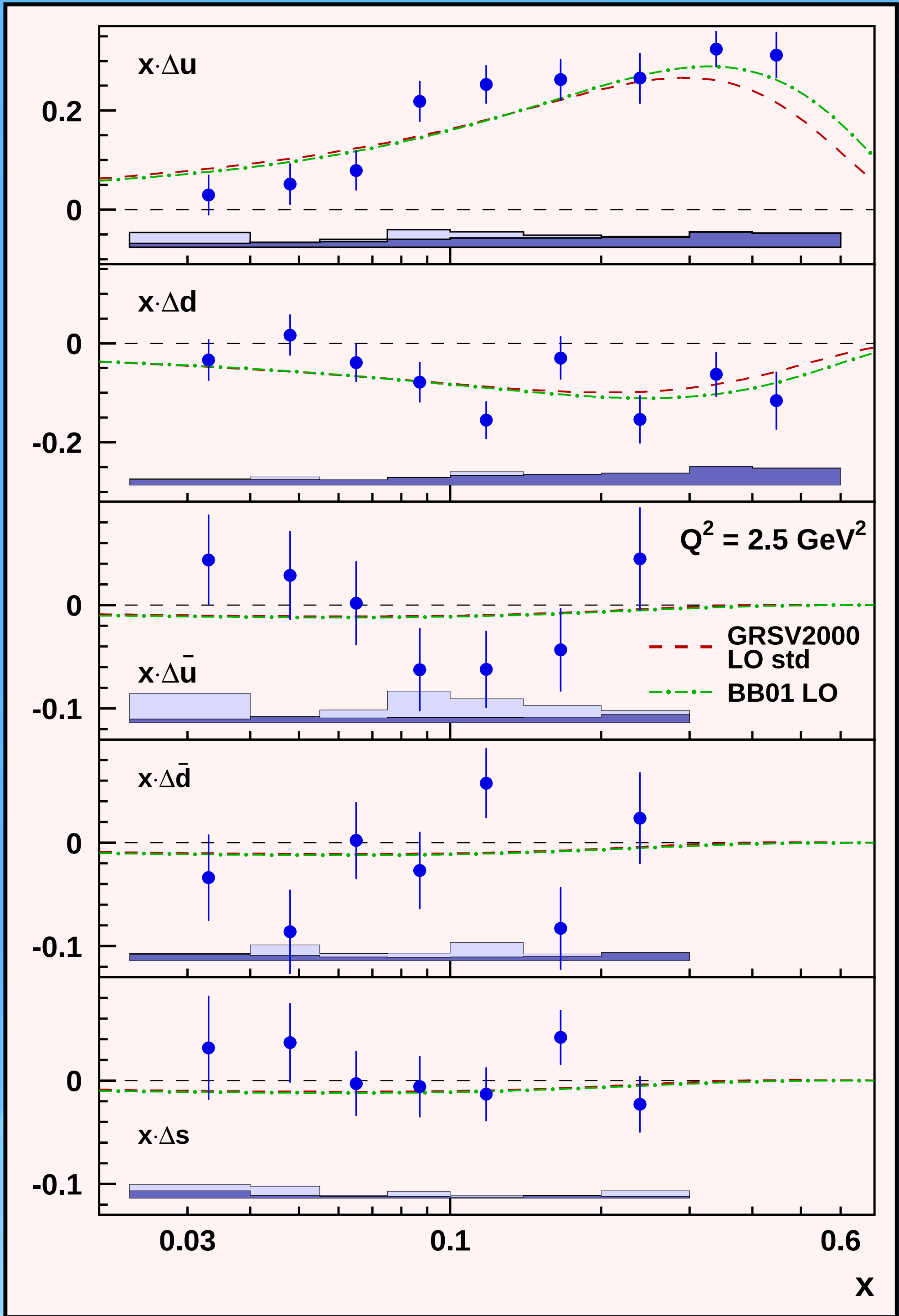

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- $\Delta u(x)$ **and** $\Delta d(x)$
  good agreement with NLO-QCD fit

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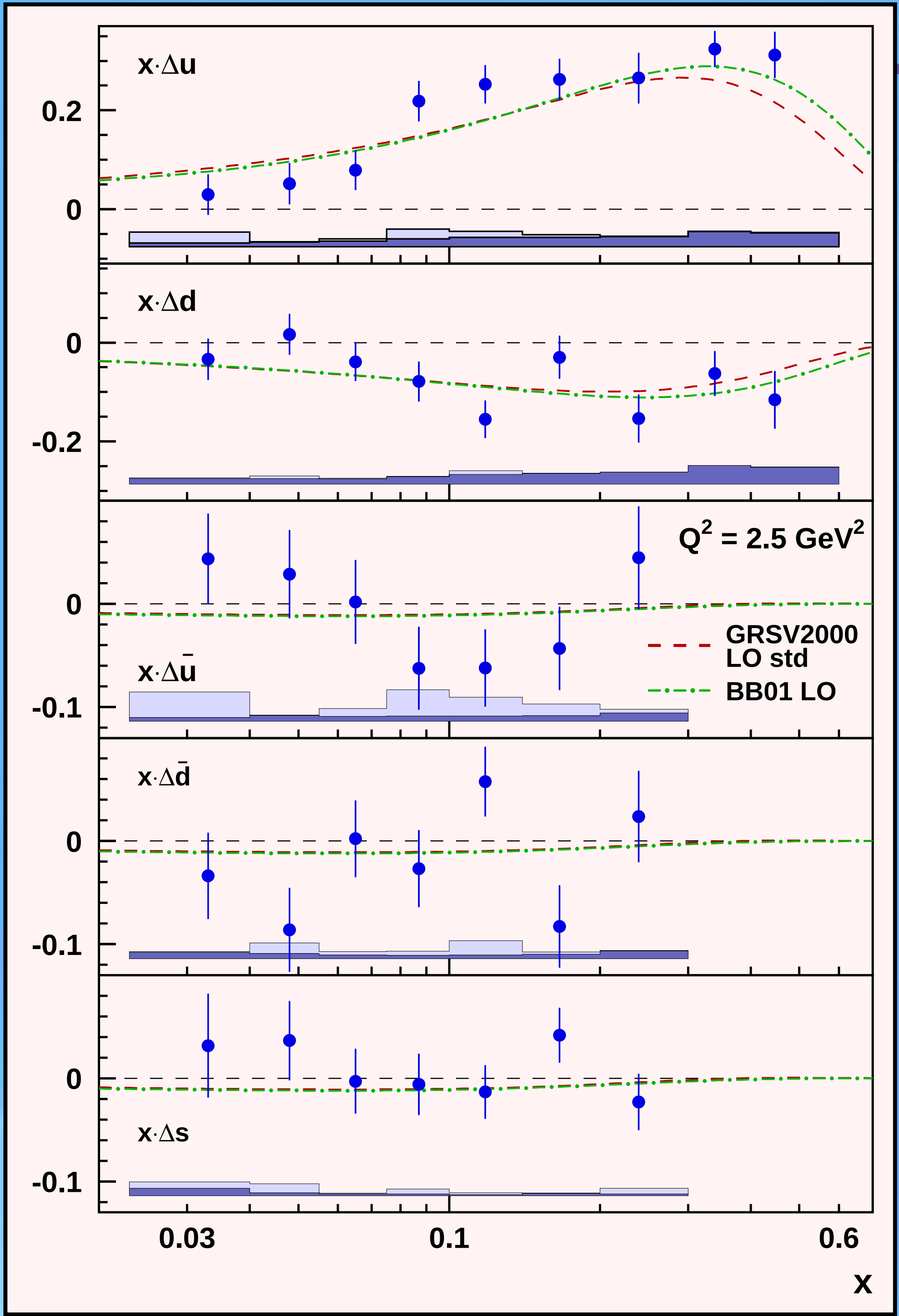

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- $\Delta \bar{u}(x), \Delta \bar{d}(x) \sim 0$

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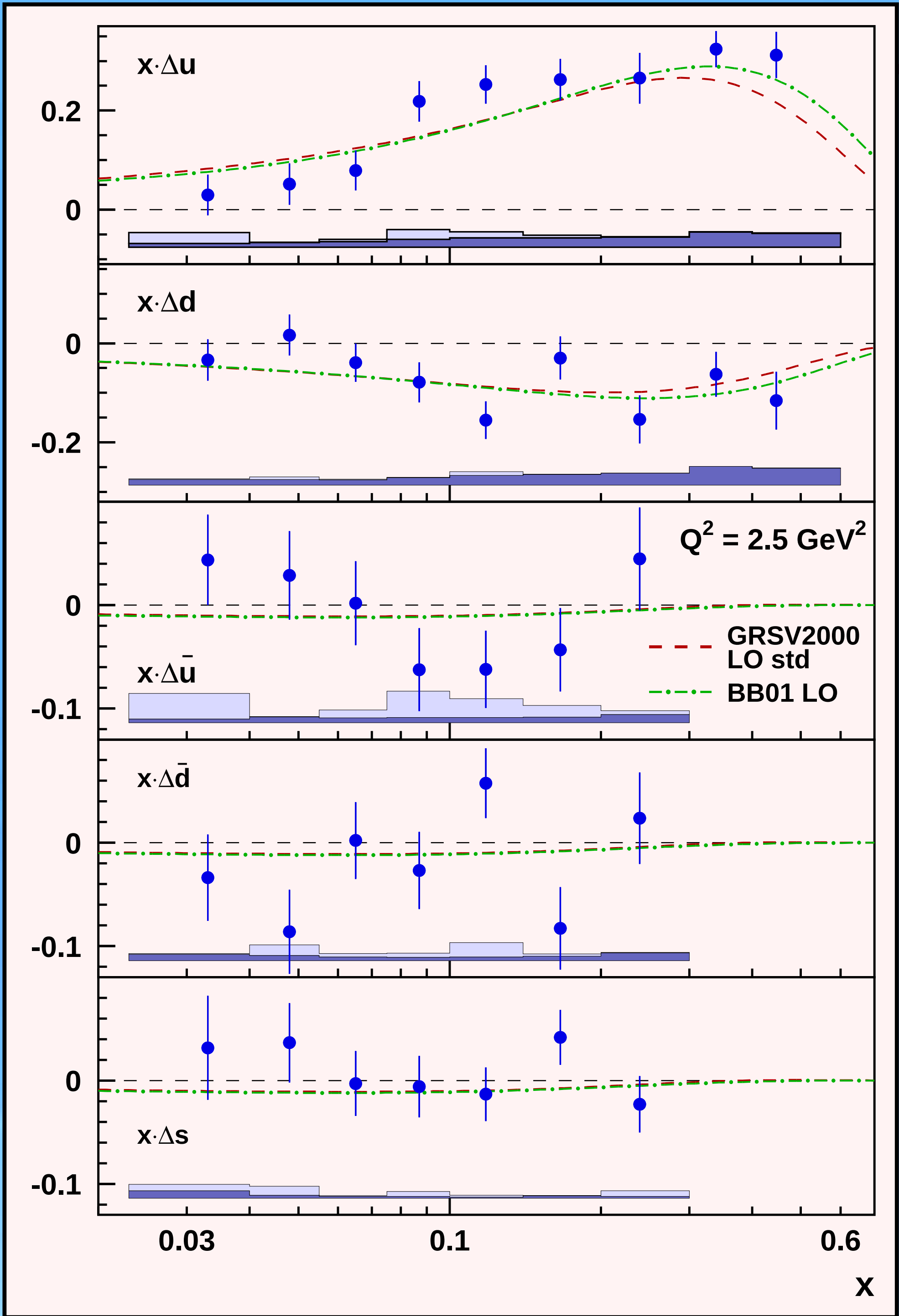

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- $\mathbf{\Delta u(x) > 0}$
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- $\mathbf{\Delta d(x) < 0}$
  $\Longrightarrow$ **polarized anti-parallel to the proton**
- $\mathbf{\Delta u(x)}$ **and** $\mathbf{\Delta d(x)}$
  good agreement with NLO-QCD fit
- $\mathbf{\Delta \bar{u}(x), \Delta \bar{d}(x)} \sim 0$
- **No indication for** $\mathbf{\Delta} s(x) < 0$

Access to Transversity

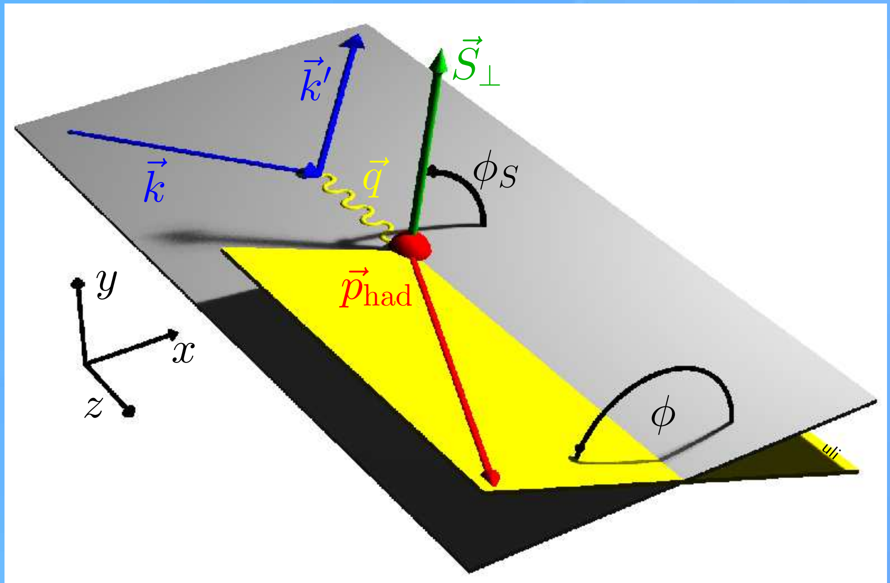
Single spin azimuthal asymmetries on a transverse polarized Target

$$ep^{\uparrow} \longrightarrow e'\pi X$$

$$\sigma^{ep\to e\pi X} = \sum_q f^{N\to q} \otimes \sigma^{eq\to eq} \otimes D^{q\to\pi}$$

Distribution-function h_1

Fragmentat.-function $H_1^{\perp}$ **(Collins)**

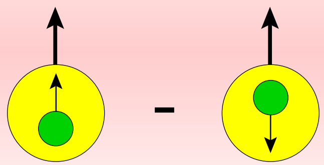


$$A^h_{UT}(\phi,\phi_s) = \frac{1}{|S_T|}\frac{N_h^{\uparrow}(\phi,\phi_s) - N_h^{\downarrow}(\phi,\phi_s)}{N_h^{\uparrow}(\phi,\phi_s) + N_h^{\downarrow}(\phi,\phi_s)}$$

$$A^{Collins}_{UT} \propto \frac{\sum_q e_q^2\, \delta q(x)\, H_1^{\perp,q}(z)}{\sum_q e_q^2\, q(x)\, D_1^q(z)}$$

Transversely Polarized Target

Transversity $h_1(x)$

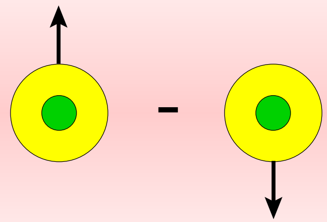


T-even

χ-odd

combined with χ-odd
fragmentation function $H_1^\perp(z)$
(Collins function)

Sivers function $f_{1T}^\perp(x)$



“naïve T-odd”

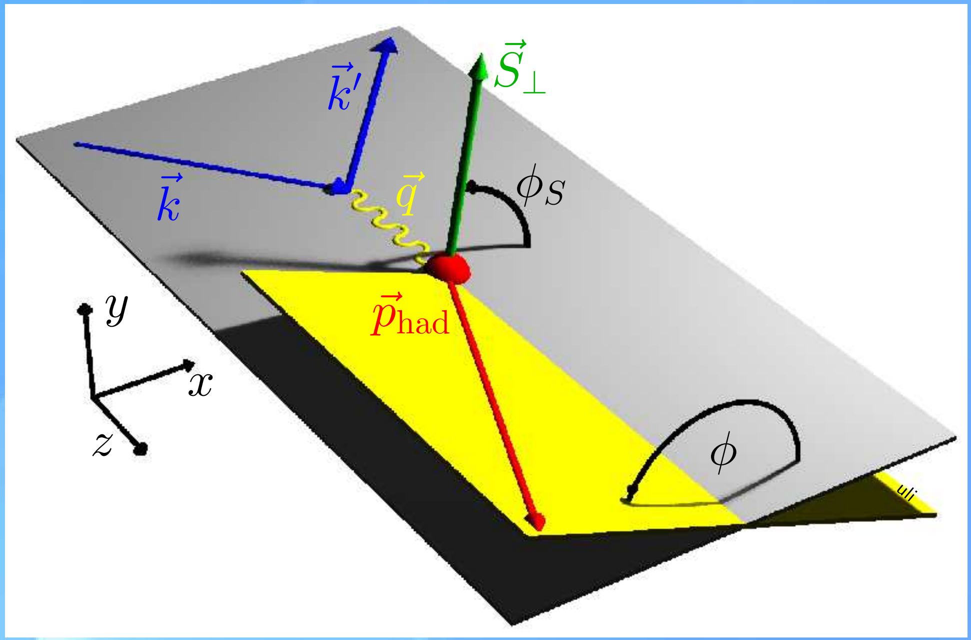
χ-even

$\neq 0$ indicates
non-vanishing orbital angular
momentum of quarks

Azimuthal Asymmetries

Measurement of cross section asymmetries depending on the azimuthal angles ϕ and ϕ_S

$$\mathbf{A}(\phi, \phi_\mathbf{S}) = \frac{\mathbf{1}}{\mathbf{S}_\perp} \frac{\mathbf{N}^\uparrow(\phi, \phi_\mathbf{S}) - \mathbf{N}^\downarrow(\phi, \phi_\mathbf{S})}{\mathbf{N}^\uparrow(\phi, \phi_\mathbf{S}) + \mathbf{N}^\downarrow(\phi, \phi_\mathbf{S})}$$



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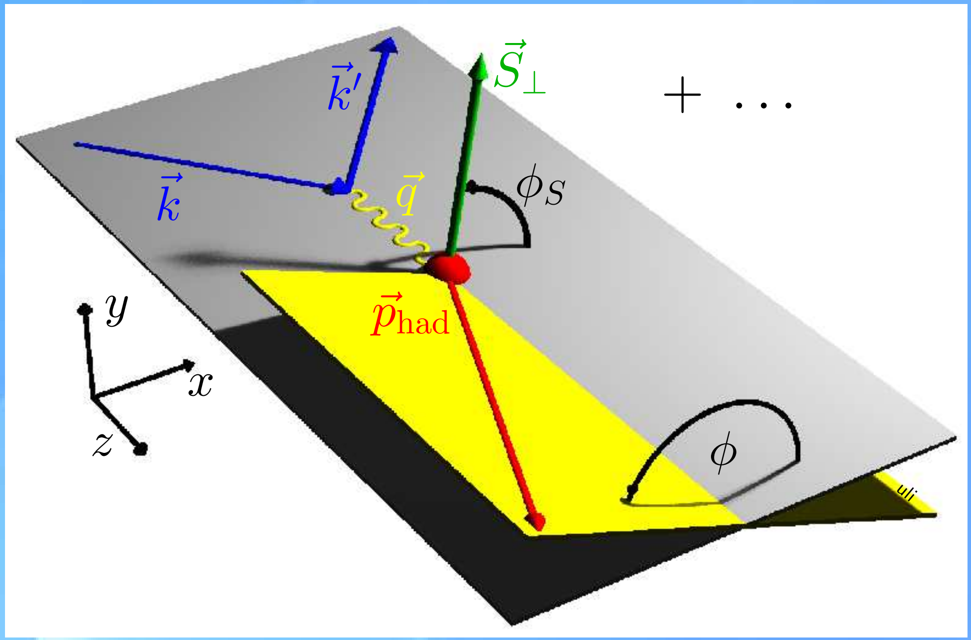
$$\sim \ldots\sin(\phi+\phi_\mathbf{S})\sum_\mathbf{q}\mathbf{e_q^2}\cdot\mathcal{I}\left[\ldots\ \mathbf{h_1^q}(\mathbf{x},\vec{\mathbf{p}}_\mathbf{T}^\mathbf{2})\cdot\mathbf{H_1^{\perp q}}(\mathbf{z},\vec{\mathbf{k}}_\mathbf{T}^\mathbf{2})\right]$$

$$+\ \ldots\sin(\phi-\phi_\mathbf{S})\sum_\mathbf{q}\mathbf{e_q^2}\cdot\mathcal{I}\left[\ldots\ \mathbf{f_{1T}^{\perp q}}(\mathbf{x},\vec{\mathbf{p}}_\mathbf{T}^\mathbf{2})\cdot\mathbf{D_1^q}(\mathbf{z},\vec{\mathbf{k}}_\mathbf{T}^\mathbf{2})\right]$$

$$+\ \ldots$$



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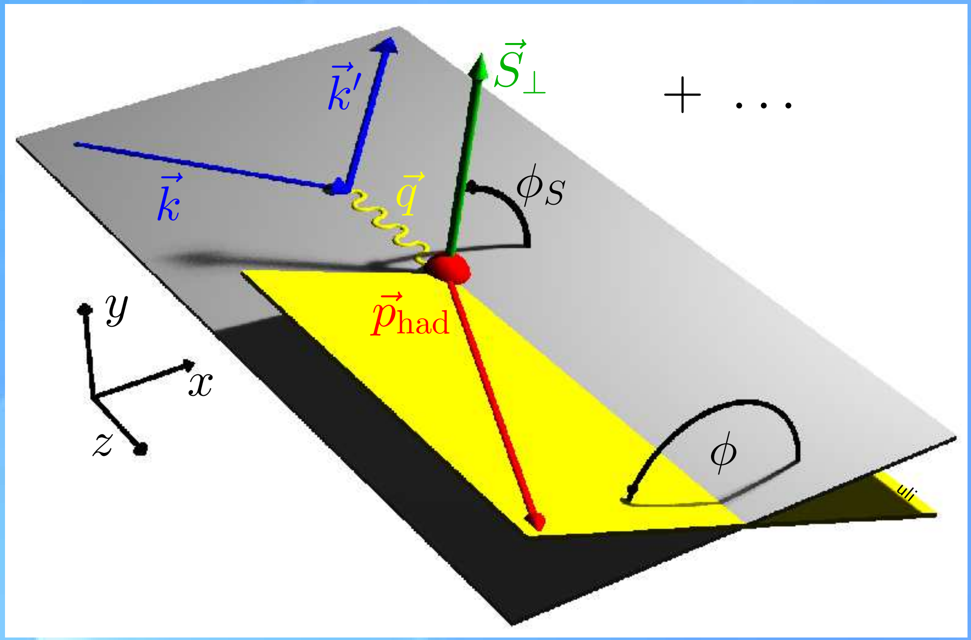
$$\sim \ \ldots\sin(\phi+\phi_\mathbf{S})\sum_\mathbf{q}\mathbf{e}_\mathbf{q}^\mathbf{2}\cdot\mathcal{I}\left[\ldots\ \mathbf{h}_\mathbf{1}^\mathbf{q}(\mathbf{x},\vec{\mathbf{p}}_\mathbf{T}^\mathbf{2})\cdot\mathbf{H}_\mathbf{1}^{\perp\mathbf{q}}(\mathbf{z},\vec{\mathbf{k}}_\mathbf{T}^\mathbf{2})\right]$$

$$+ \ \ldots\sin(\phi-\phi_\mathbf{S})\sum_\mathbf{q}\mathbf{e}_\mathbf{q}^\mathbf{2}\cdot\mathcal{I}\left[\ldots\ \mathbf{f}_\mathbf{1T}^{\perp\mathbf{q}}(\mathbf{x},\vec{\mathbf{p}}_\mathbf{T}^\mathbf{2})\cdot\mathbf{D}_\mathbf{1}^\mathbf{q}(\mathbf{z},\vec{\mathbf{k}}_\mathbf{T}^\mathbf{2})\right]$$

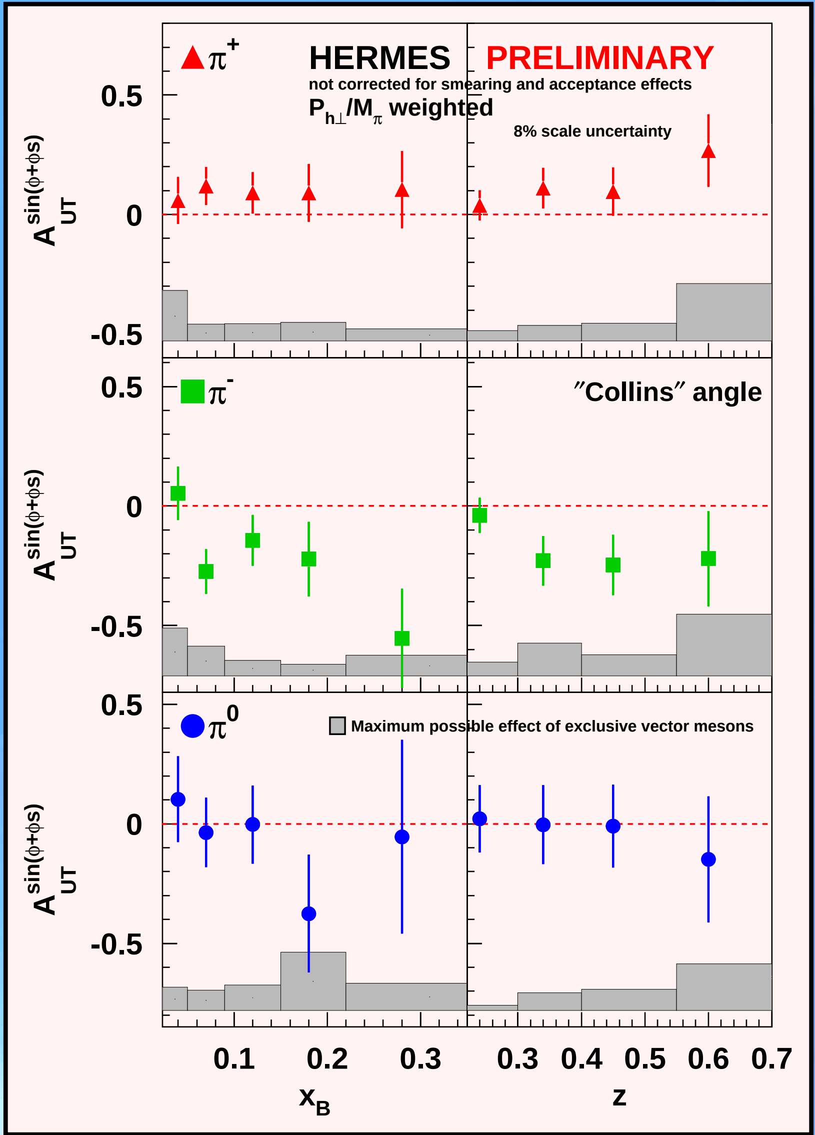
$$+ \ \ldots$$

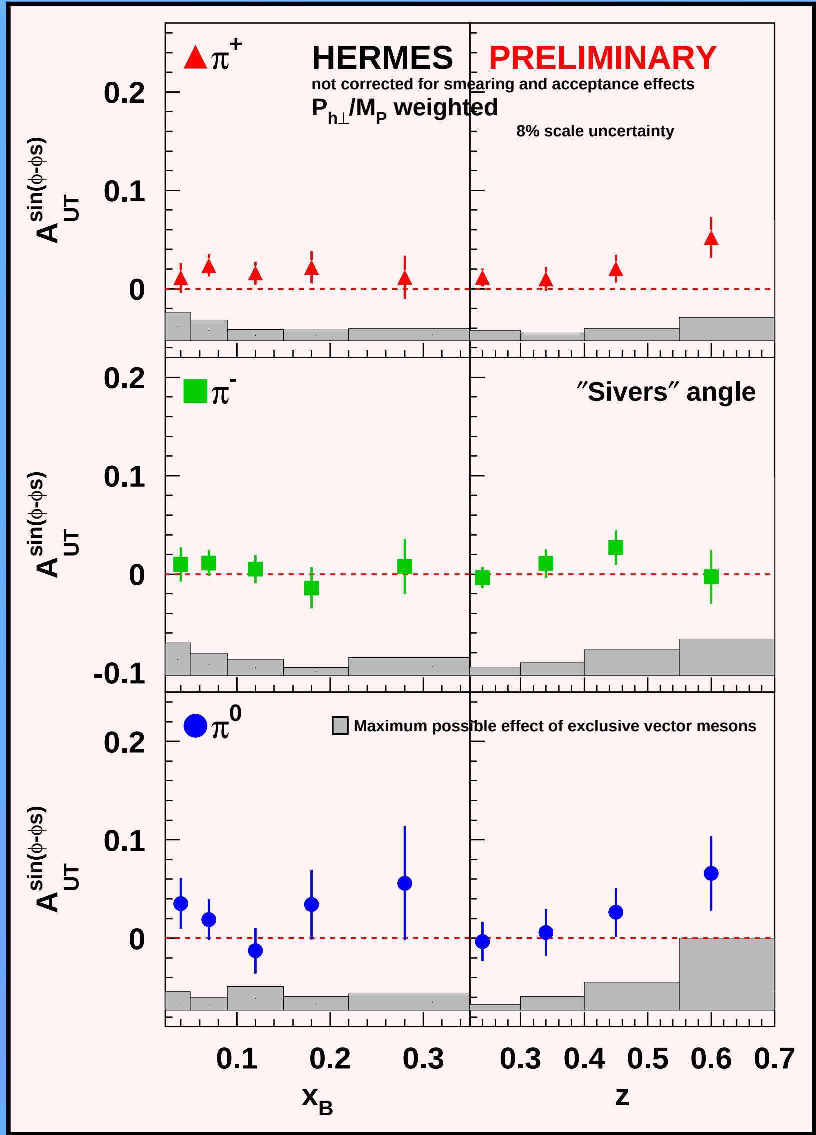


$\mathcal{I}[\ldots]$: **convolution integral over initial ($\vec{\mathbf{p}}_\mathbf{T}$) and final ($\vec{\mathbf{k}}_\mathbf{T}$) quark transverse momenta**

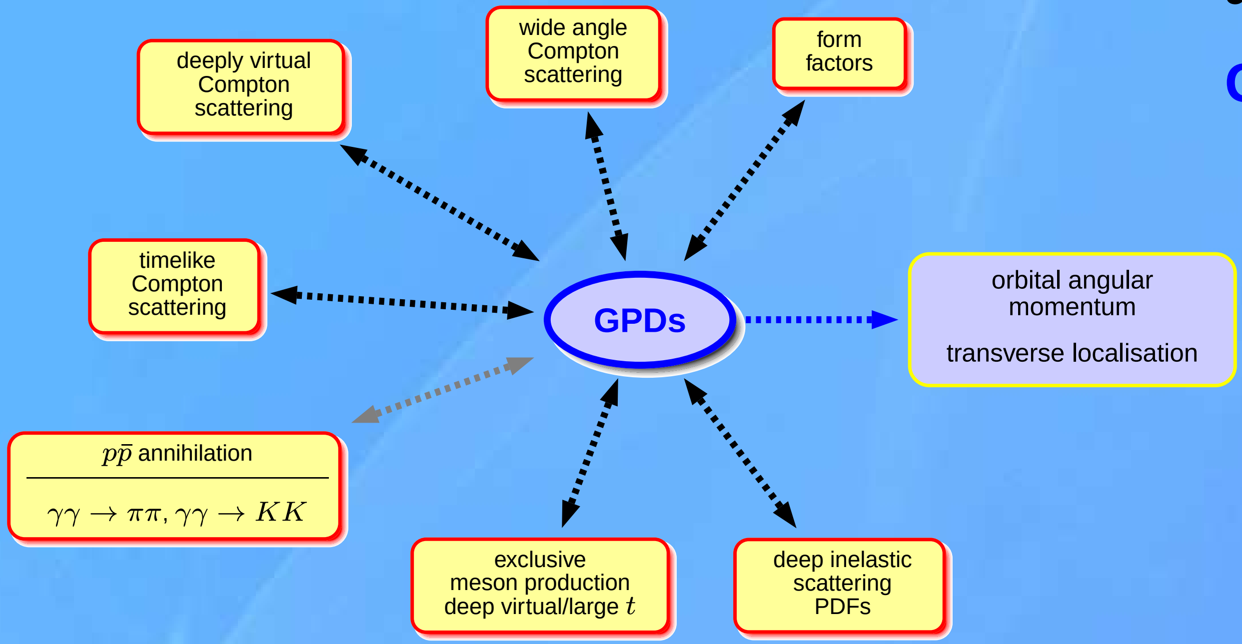
$P_{h\perp}$ Weighted Asymmetries

$$A^{\sin(\phi+\phi_S)} \sim h_1(x) \cdot H_1^{\perp(1)}(z) \qquad A^{\sin(\phi-\phi_S)} \sim f_{1T}^{\perp(1)}(x) \cdot D_1(z)$$





The Hermes Quest for $\mathrm{L_q}$



Study of hard exclusive processes leads to a new class of PDFs

Generalised Parton Distributions

$H^q, E^q, \tilde{H}^q, \tilde{E}^q$

$\Rightarrow$ possible access to orbital angular momentum

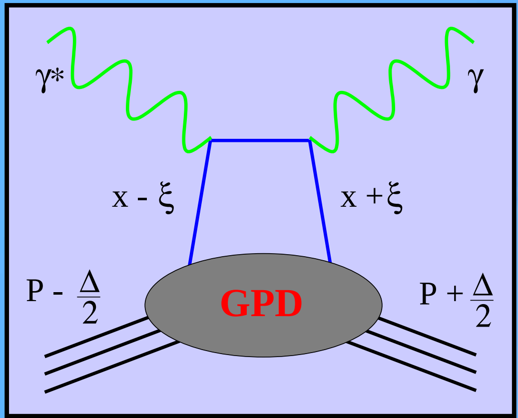
$$J_q = \frac{1}{2}\left(\int_{-1}^{1} x\mathrm{d}x (H^q + E^q)\right)_{t\to 0}$$
$$J_q = \frac{1}{2}\Delta\Sigma + L_q$$

exclusive: all products of a reaction are detected

$\Longrightarrow$ missing energy ($\Delta\mathrm{E}$) and missing Mass ($\mathrm{M_x}$) = 0

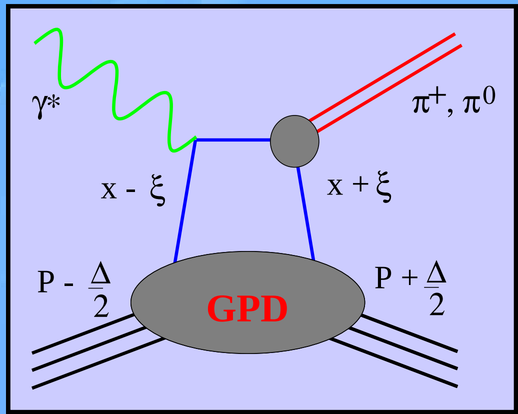
GPDs Introduction

quantum numbers of final state $\Rightarrow$ select different GPDs



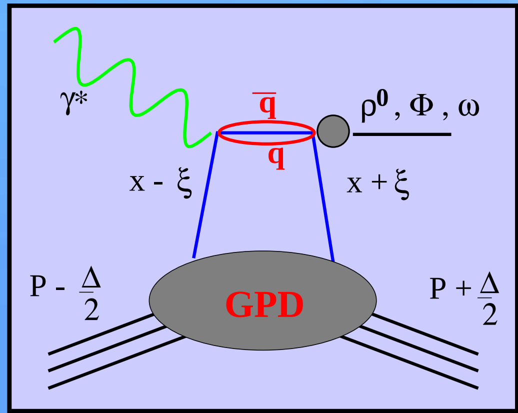
DVCS:

$H^q, E^q, \tilde{H}^q, \tilde{E}^q$



pseudo-scalar mesons

$\tilde{H}^q, \tilde{E}^q$



vector mesons

H^q, E^q

What does GPDs characterize?

unpolarized	polarized	
$H^q(x,\xi,t)$	$\tilde{H}^q(x,\xi,t)$	**conserve nucleon helicity**
		$H^q(x,0,0) = q$ **,** $\tilde{H}^q(x,0,0) = \Delta q$
$E^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$	**flip nucleon helicity**
		not accessible in DIS

How to Measure GPDs ?

meson production $\rightarrow \sigma_{\mathrm{L}}$

@ Hermes kinematics:

	vector mesons		pseudoscalar mesons	
	σ_{L}	A_{UT} **(nominator)**	σ_{L}	A_{UT} **(nominator)**
H	$(1-\xi^2)$	$\sqrt{1-\xi^2}$		
$\tilde{H}$			$(1-\xi^2)$	$\sqrt{1-\xi^2}\cdot\xi$
E	$(\xi^2+\frac{t}{4M^2})$	$\sqrt{1-\xi^2}$		
$\tilde{E}$			$\xi^2\frac{t}{4m^2}$	$\sqrt{1-\xi^2}\cdot\xi$

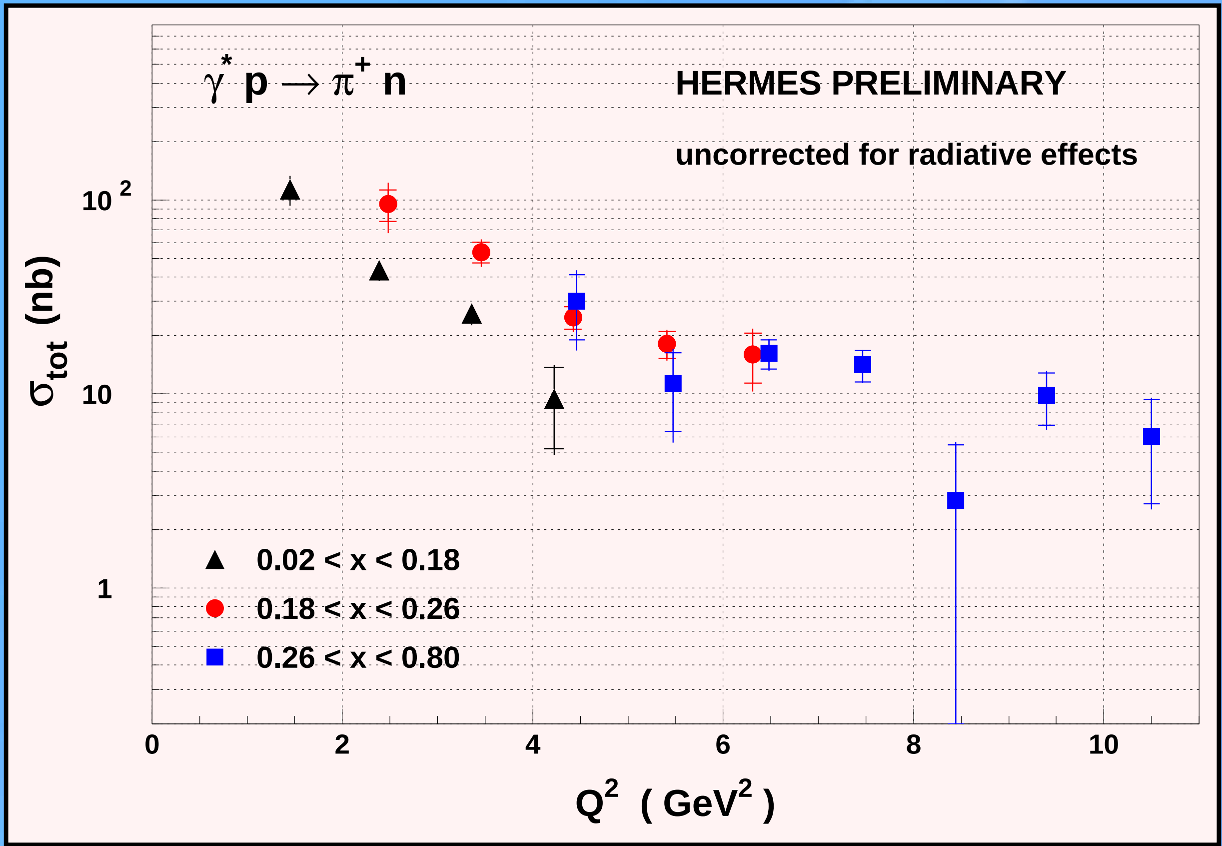
$$\xi \approx \frac{x_{\mathrm{B}}}{2-x_{\mathrm{B}}}$$

$$\xi \approx 0.01 - 0.3$$

$$\xi_{|x=0.1} \approx 0.05$$

$$\frac{t}{4M^2} \approx 0.02 - 0.1$$

Exclusive π^+ result



- **complete new data**
- **cross section in 3 x-bins**
- **sensitivity to $\tilde{E}$ at higher x**
- **absolute normalization of GPDs**

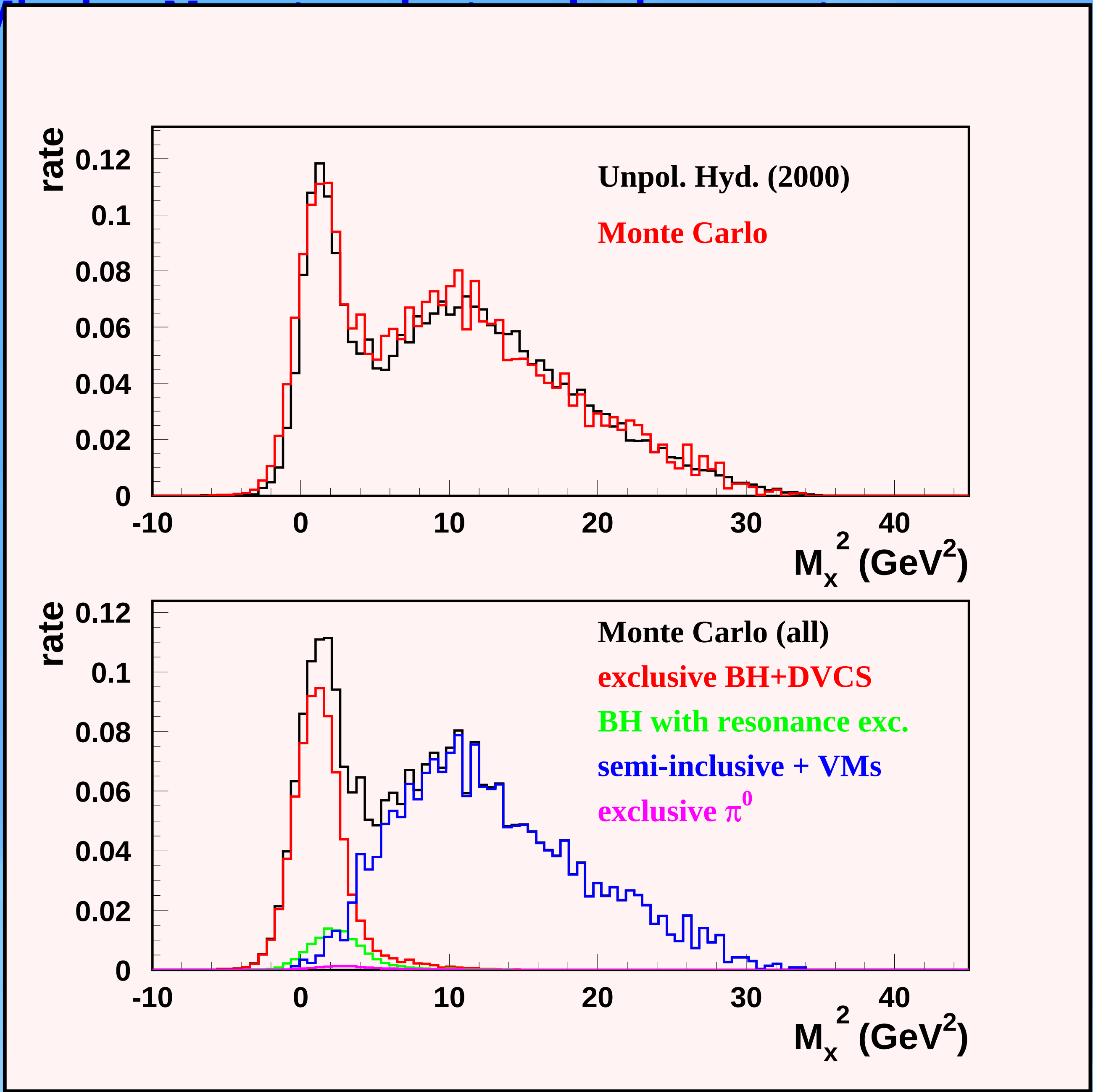
How to Measure GPDs ?

	DVCS A_{C}, A_{LU}	A_{UL}	A_{UT} (twist-2 amplitudes of the interference terms only)
H	F_1	$\xi(F_1+F_2)$	$\xi^2 F_1 + \frac{t}{4M^2}(1-\xi^2)F_2$
$\tilde{H}$	$\xi(F_1+F_2)$	F_1	$\xi^2(F_1+F_2)$
E	$\frac{t}{4M^2}F_2$	$\frac{\xi^2}{1+\xi}(F_1+F_2)$	$\xi^2 F_1 + \frac{t}{4M^2}(F_1+\xi^2 F_2)$
$\tilde{E}$		$\frac{\xi^2}{1+\xi}F_1 + \xi\frac{t}{4M^2}F_2$	$\xi^2\frac{t}{4M^2}(F_1+F_2)$

F_1 and F_2 ...Dirac and Pauli form factor

$\Rightarrow$ to access E transverse target polarisation is essential

DVCS - Exclusive Scattering



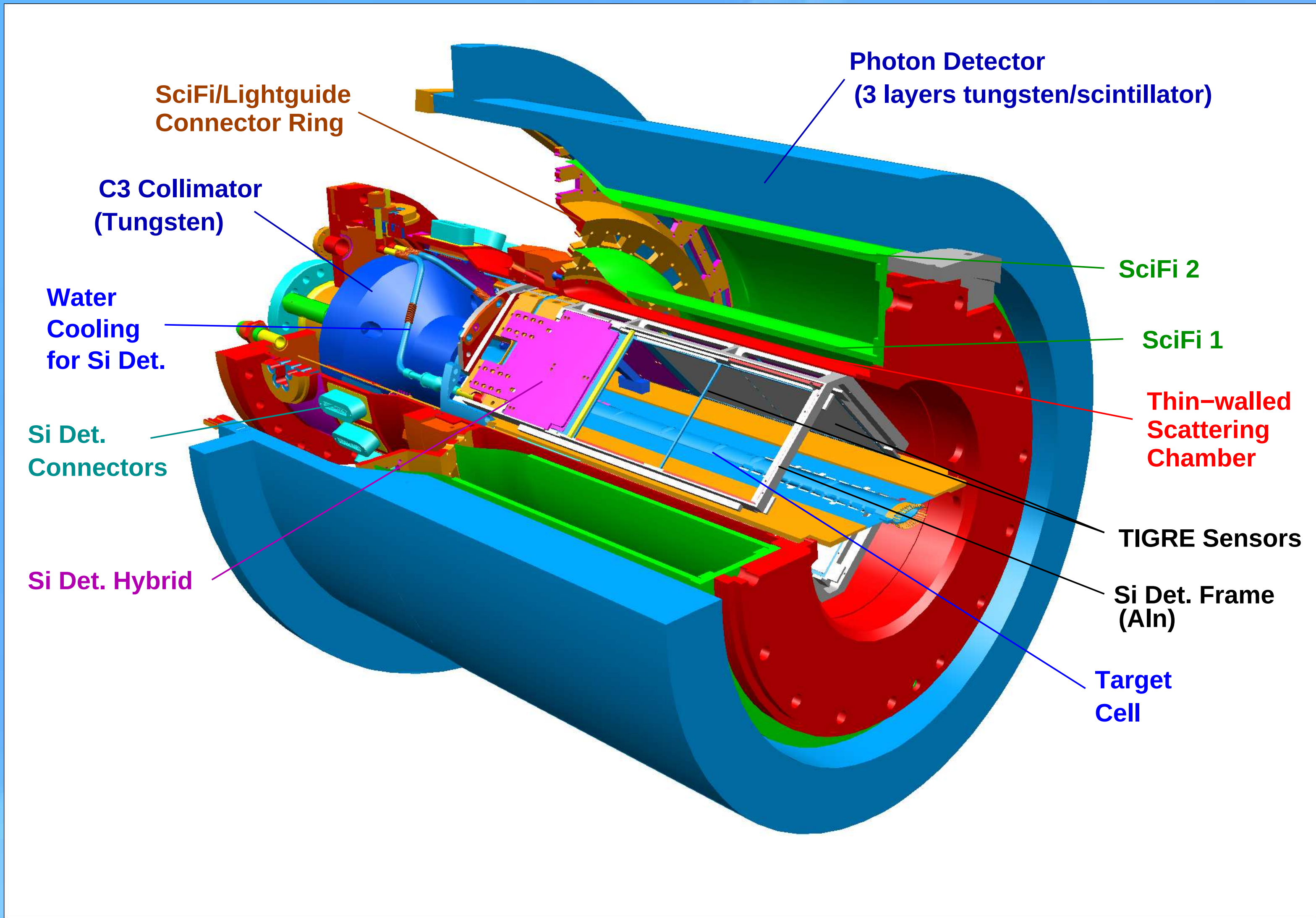
Background from

- **Resonances**
- **SIDIS**

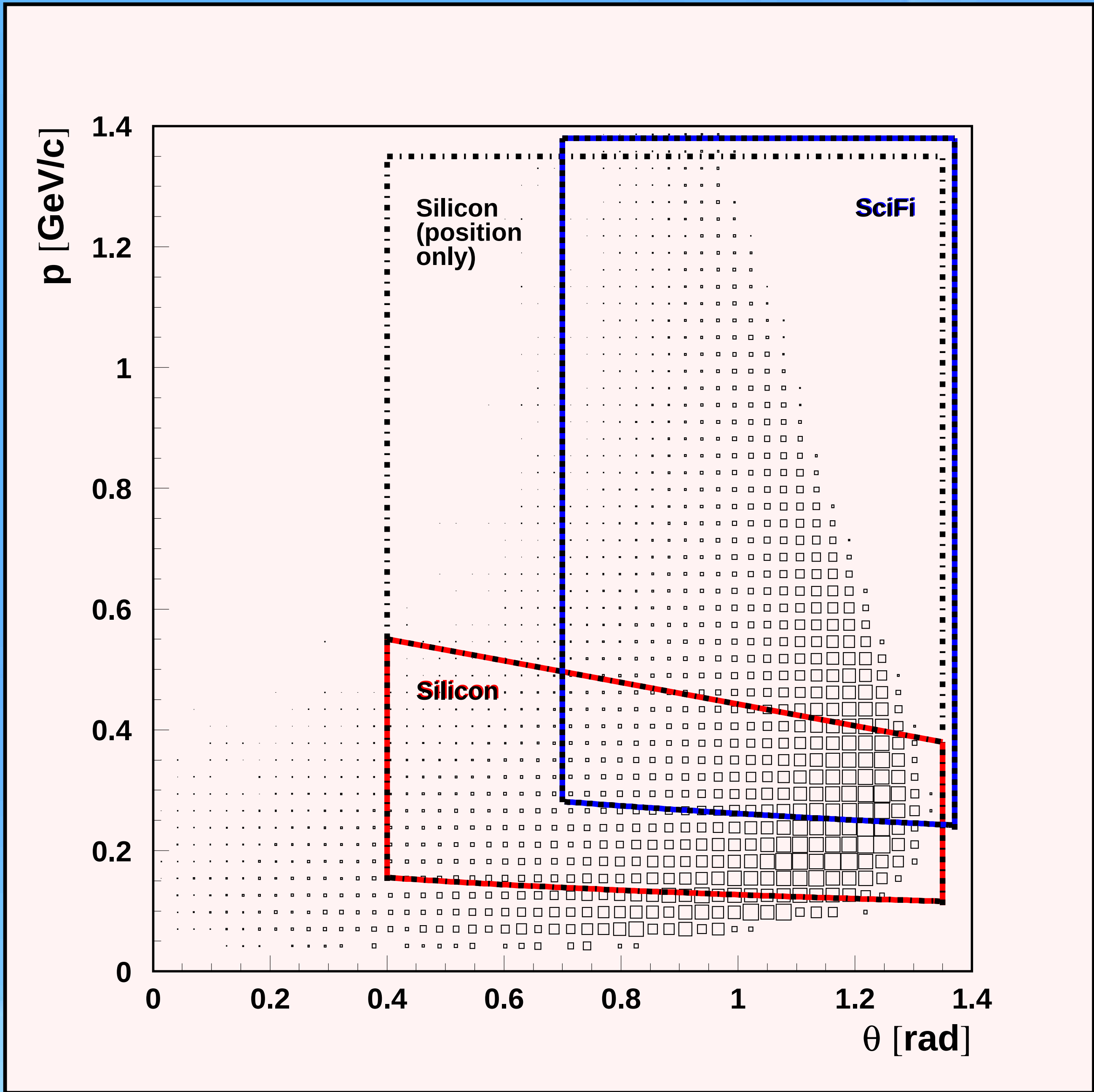
$\Rightarrow$ **tag recoil Nucleon**

Recoil Detector

Measure the recoiling target nucleon



Recoil Detector

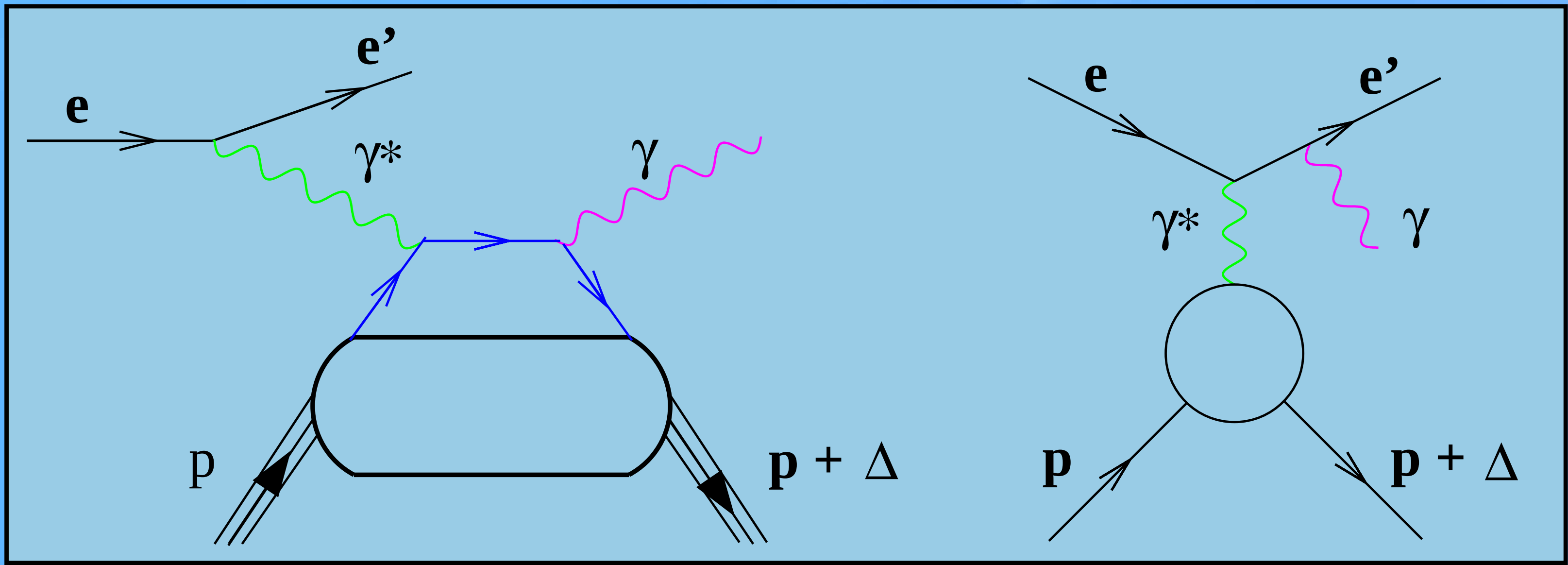


- **135 to 1400 MeV/c momentum coverage**
- **low p cut off due to E-loss in target cell**
- **76% acceptance in ϕ**
- **π-p separation via dE/dx**
- **Installation summer 2005**
- **DVCS with with e- and e+ beams**

Concluding

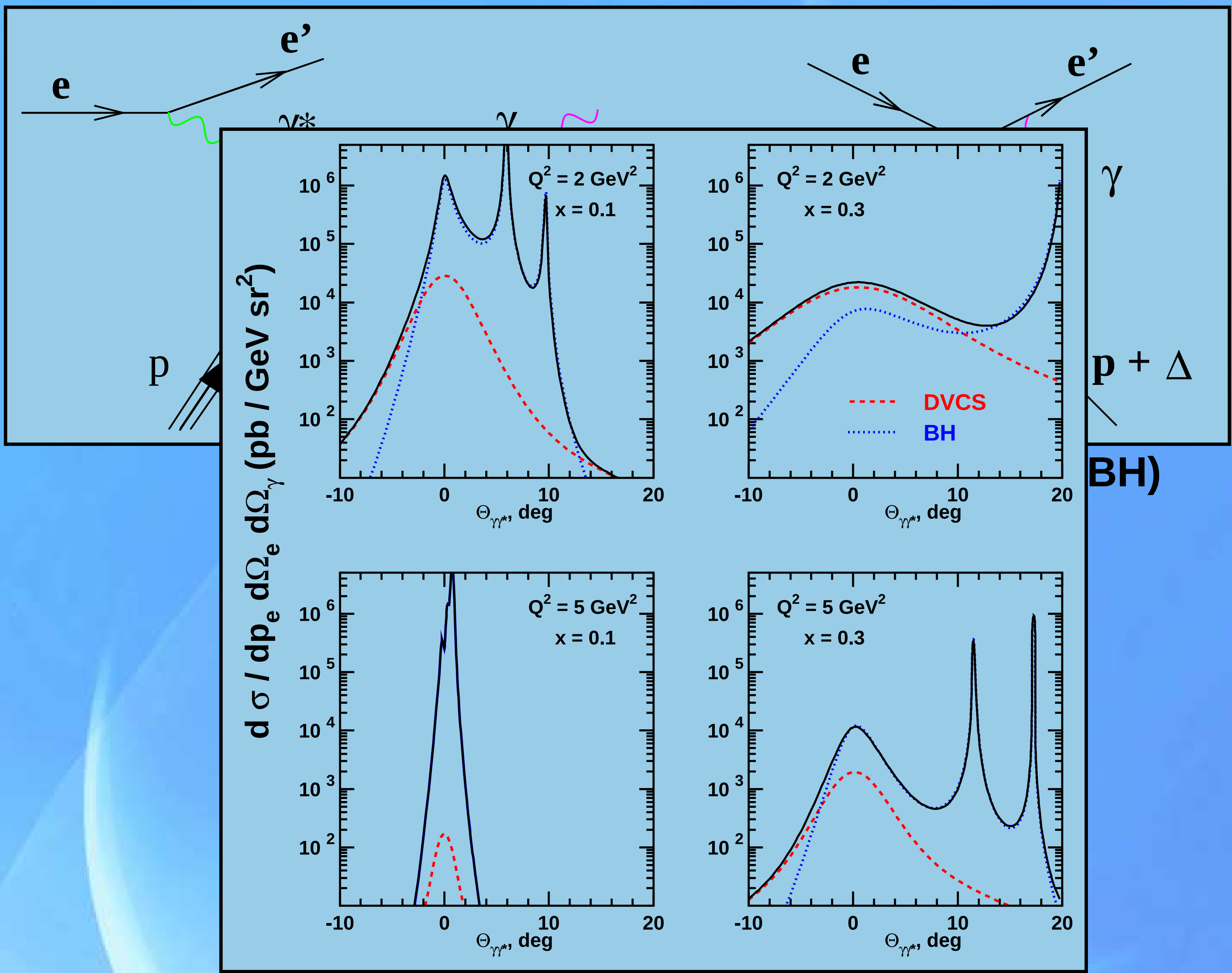
- **PID essential for flavor decomposition**
- **Transverse polarized hydrogen data suggest Collins and Sivers**
- **GPDs give access to orbital angular momentum of quarks**
- **transverse pol. target needed to access E**
- **exclusive π production access to $\tilde{H}, \tilde{E}$**
- **DVCS access to H**
- **install the Recoil Detector in sumer 2005**
- **focus on DVCS with e- and e+ beam**

DVCS $\gamma^* p \to \gamma p$

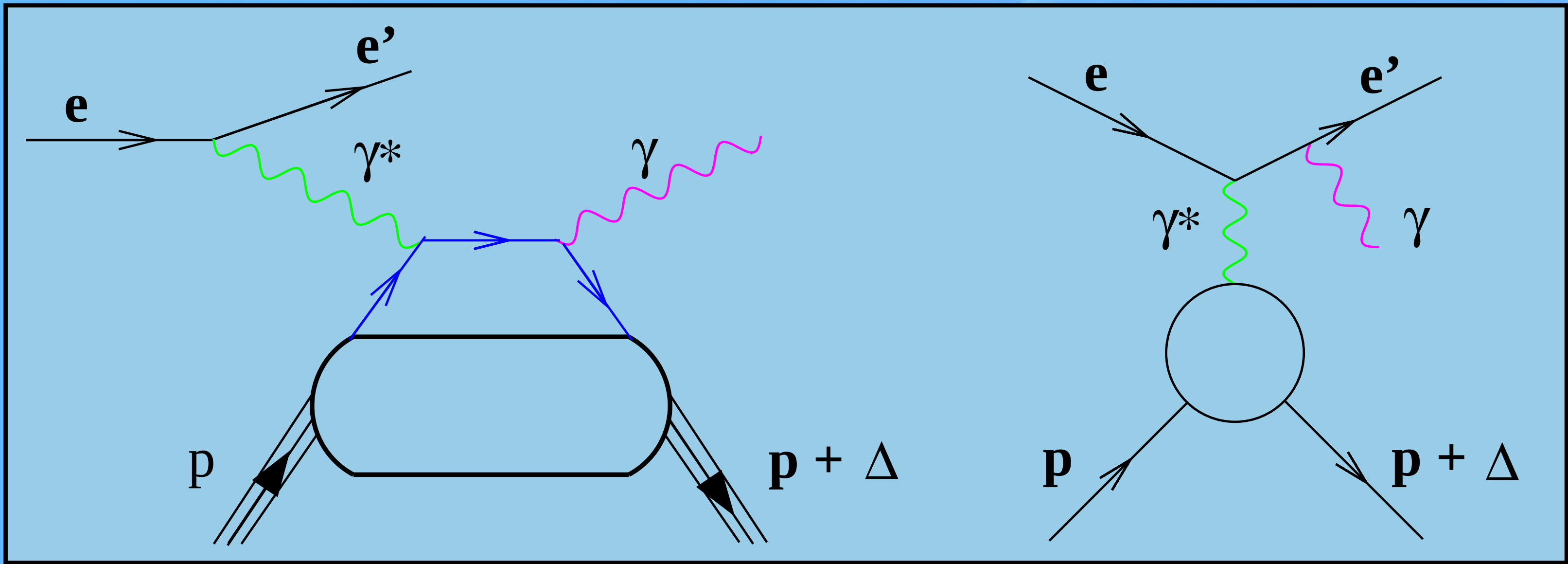


DVCS **Bethe-Heitler (BH)**

DVCS $\gamma^* p \to \gamma p$



DVCS $\gamma^* p \to \gamma p$



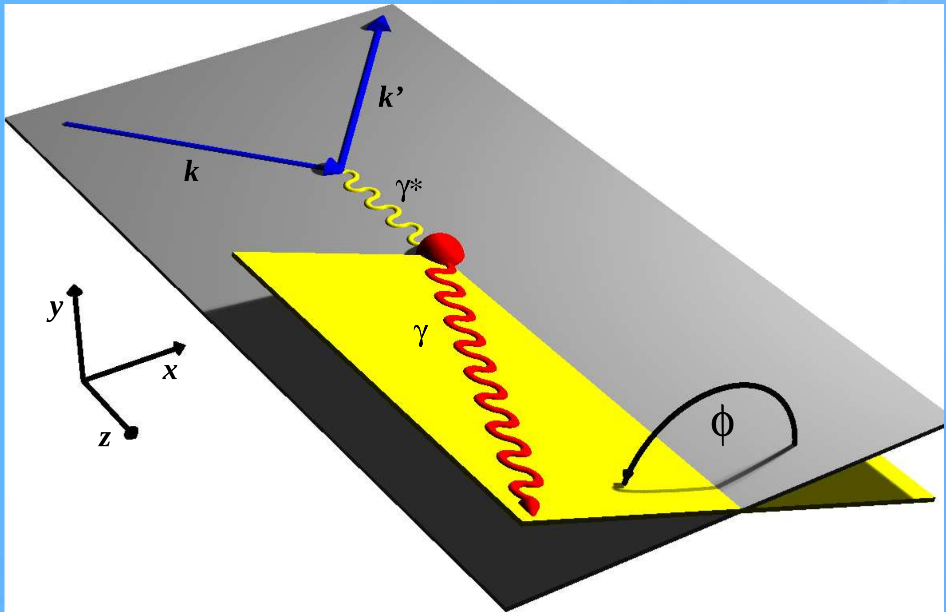
DVCS   **Bethe-Heitler (BH)**

$$
\begin{aligned}
d\sigma \quad \propto \quad & |\mathcal{T}_{BH} + \mathcal{T}_{DVCS}|^2 = \\
& |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 \\
& + (\mathcal{T}^*_{BH}\mathcal{T}_{DVCS} + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH})
\end{aligned}
$$

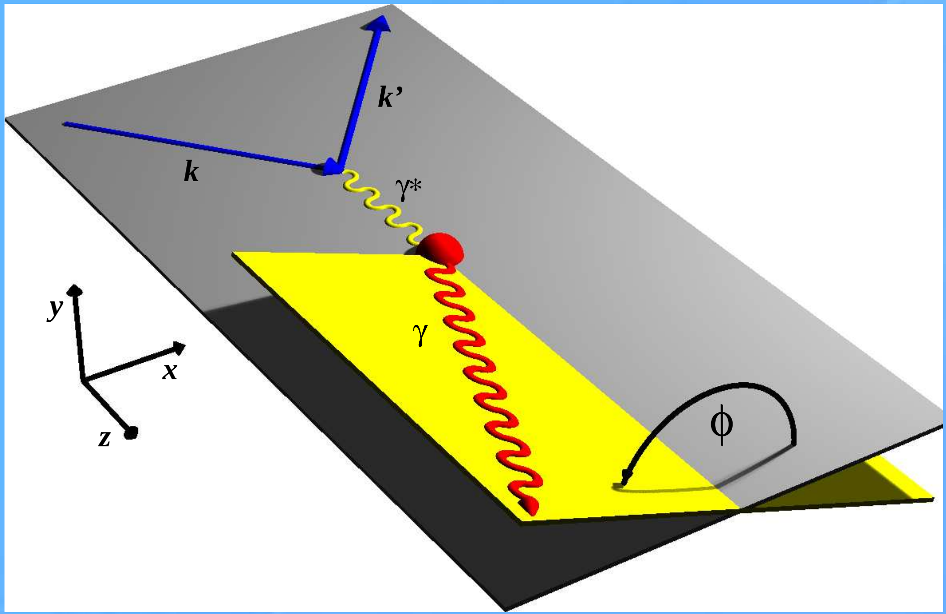
$\Rightarrow$ **Interference term a tool to study DVCS**

exploit azimuthal cross section asymmetries

DVCS Azimuthal Asymmetries



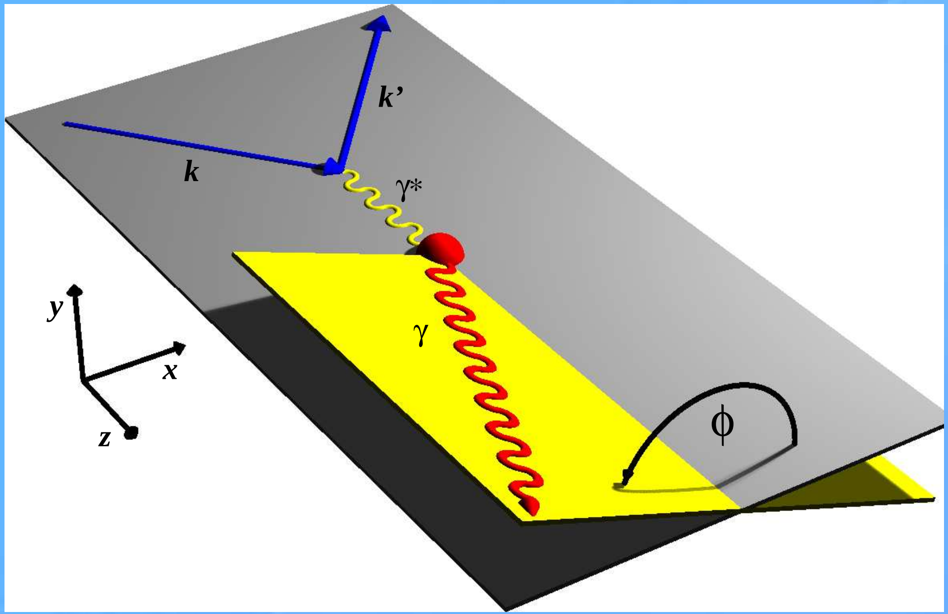
DVCS Azimuthal Asymmetries



Beam Helicity Asymmetry $\propto$
Imaginary Part

$$d\sigma_{\overrightarrow{e}^+} - d\sigma_{\overleftarrow{e}^+} \quad \propto \quad \mathrm{Im}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS})$$
$$\propto \quad \sin\phi \Longrightarrow H^q(x,\xi,t)$$

DVCS Azimuthal Asymmetries



Beam Helicity Asymmetry $\propto$
Imaginary Part

$$d\sigma_{\overrightarrow{e}^+} - d\sigma_{\overleftarrow{e}^+} \propto \mathrm{Im}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS})$$
$$\propto \sin\phi \Longrightarrow H^q(x,\xi,t)$$

Beam Charge Asymmetry $\propto$
Imaginary Part

$$d\sigma_{e^+} - d\sigma_{e^-} \propto \mathrm{Re}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS})$$
$$\propto \cos\phi \Longrightarrow H^q(x,\xi,t)$$

e^+ and e^- beams unique to HERA