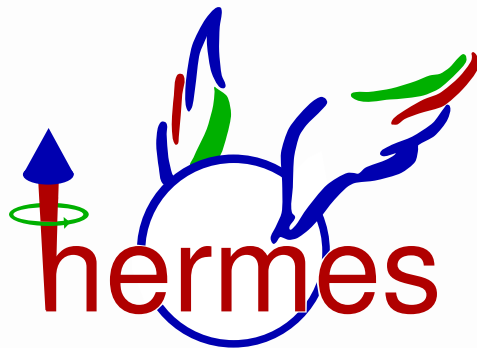


# Spin Physics Overview via HERMES

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(DESY, Hamburg)



HSQCD 2004

St. Petersburg, Repino,

Russia

May 18-22, 2004

- Motivation
- The HERMES Experiment at HERA
- Polarized Deep Inelastic Scattering
- Inclusive measurements:
  - The structure function  $g_1$
  - Polarized quark distributions from NLO-Fits
  - The structure function  $b_1^d$
- Semi-inclusive measurements:
  - Flavor decomposition of the nucleon spin  $\Delta q(x)$
  - Azimuthal asymmetries: a way to *Transversity*
- Exclusive Reactions:
  - DVCS  $\rightarrow$  access to  $L_q$
- Summary

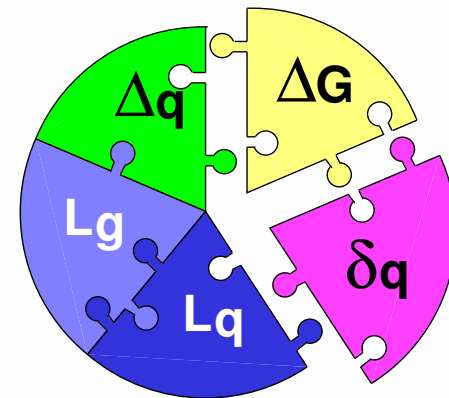
# Spin of the Nucleon

- Spin decomposition of the nucleon:

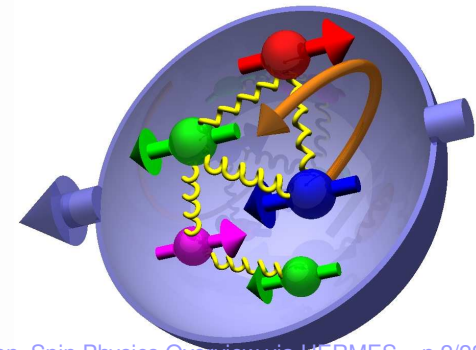
$$S_z = \frac{1}{2}\hbar = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

with

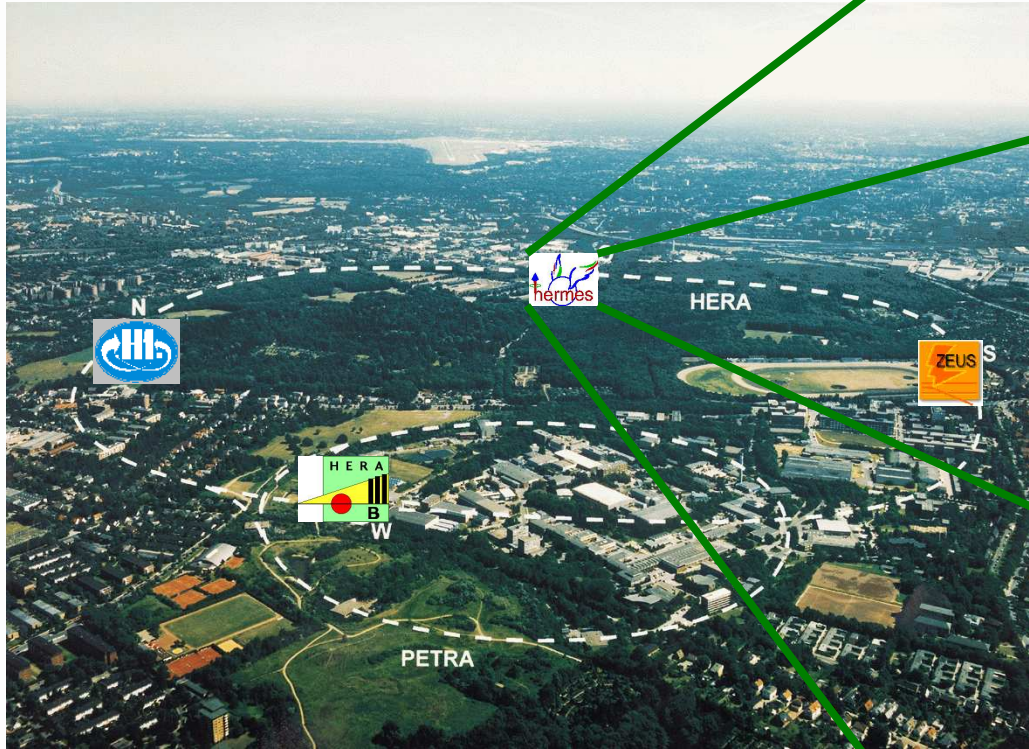
$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} \simeq \begin{cases} 0.14 \dots 0.2 & \text{measured} \\ 0.58 & \text{expected} \end{cases}$$



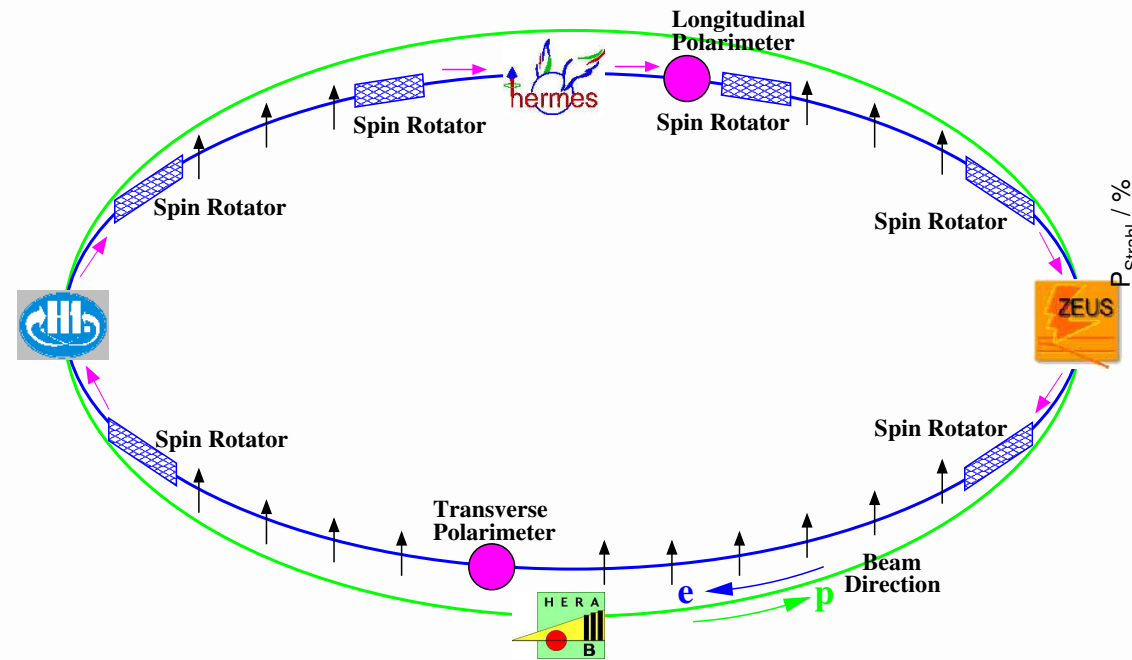
- The  $\Delta q = \Delta u, \Delta\bar{u}, \dots$  are the 1-st moments of polarized quark distributions  $\Delta u(x), \Delta\bar{u}(x), \dots$
- Polarized quark distributions:  $\Delta q(x) = q^+(x) - q^-(x)$
- Polarized gluon distribution:  $\Delta G$
- Orbital angular momenta:  $L_{q,g}$



# The HERMES Experiment at HERA

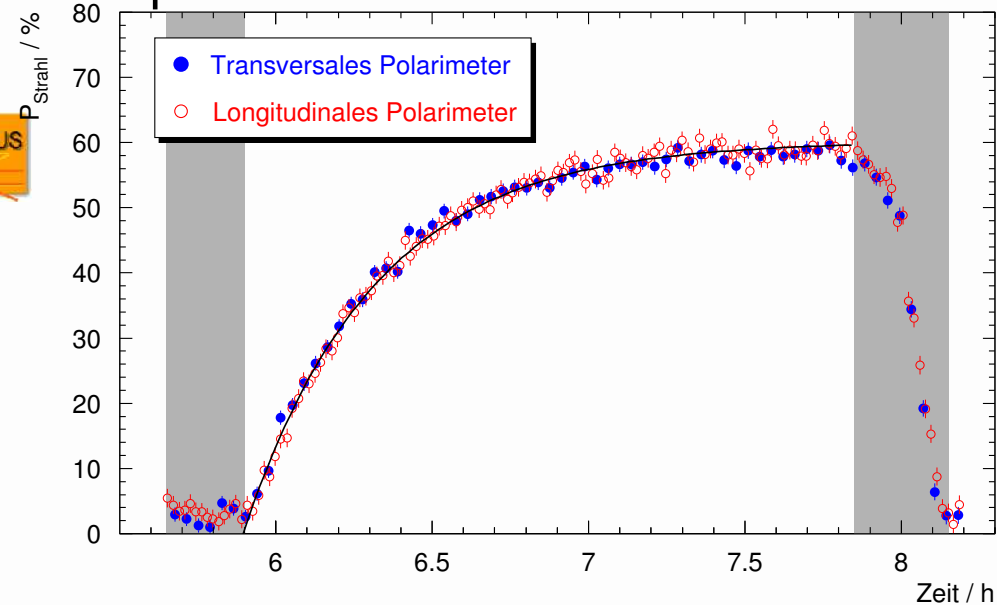


# Polarized $e^\pm$ -beam of HERA



- Transverse selfpolarization due to Synchrotron radiation
- Longitudinal Polarization with spin rotators

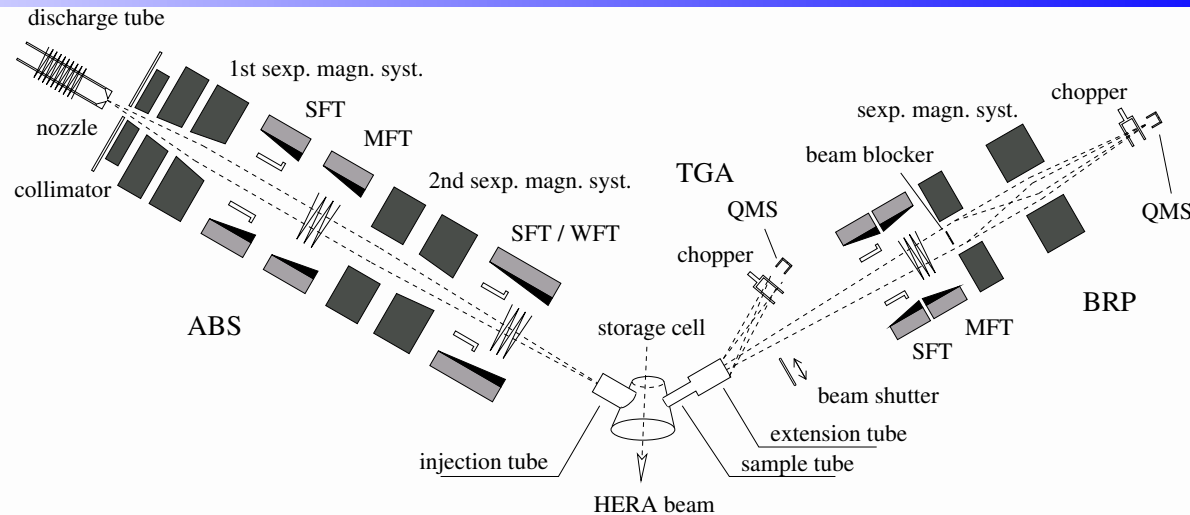
- Measured on-line with two Compton polarimeters



- Average Beam Polarization  
 $\langle P_B \rangle \sim 55\%$ ,  $\delta P_B / P_B = 1.8 \dots 3.4\%$
- Average beam current  $\sim 25$  mA



# The HERMES targets

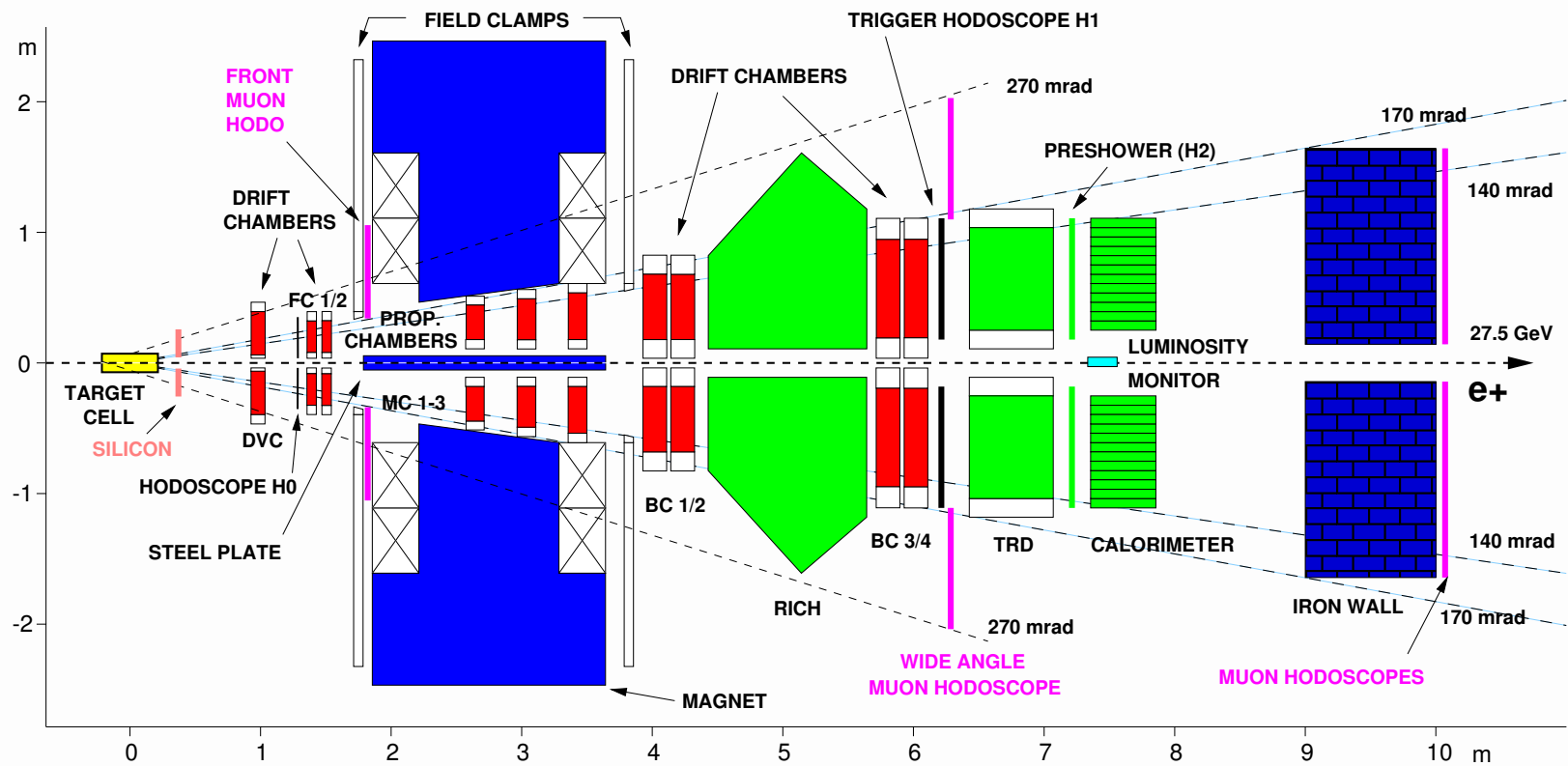


- Until 2000 long. polarized  $\vec{H}^-$  and  $\vec{D}^-$ -Targets
- Average Target Polarization:  
 $\langle P \rangle_{\vec{H}^-} = 0.824 \pm 0.034$ ,  $\langle P \rangle_{\vec{D}^-} = 0.844 \pm 0.037$
- Also: unpol. Targets H, D,  $^4\text{He}$ ,  $^{14}\text{N}$ ,  $^{20}\text{Ne}$ ,  $^{84}\text{Kr}$   
 with  $\sim 10^{16}$  nucleons/cm<sup>2</sup>

- In 2002 transverse polarized  $H^\uparrow$



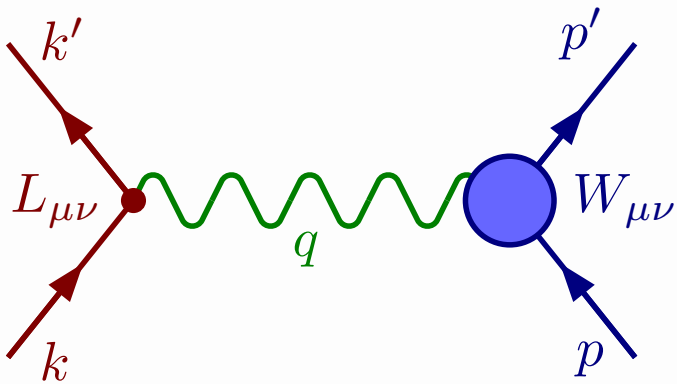
# The HERMES Spectrometer



- Kinematical range:  $0.02 \leq x \leq 0.8$  with  $Q^2 > 1 \text{ GeV}^2$  and  $W > 2 \text{ GeV}$
- Resolution:  $\delta p/p = 1.4 \dots 2.5\%$ ,  $\delta\Theta \lesssim 1 \text{ mrad}$
- Particle Identification: TRD, Preshower, Calorimeter, also:
  - 1997: Threshold gas –Čerenkov counter
  - 1998 →: RICH (dual radiator)



# General Formalism of DIS

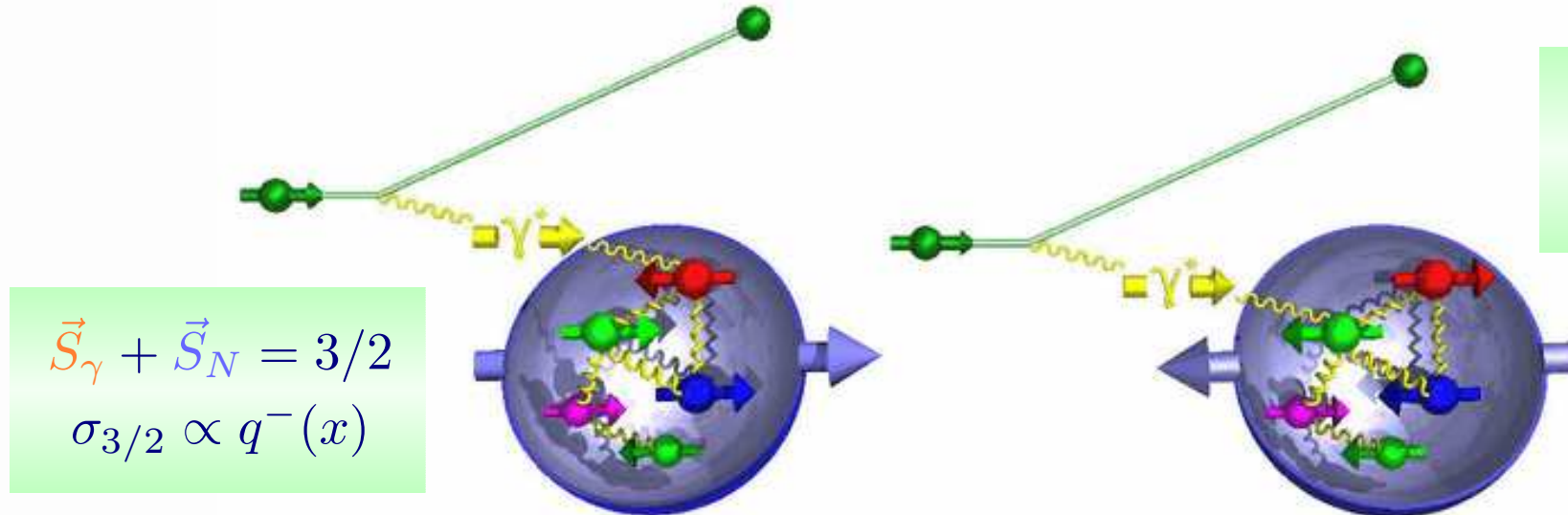


$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{M Q^4} \frac{E}{E'} L_{\mu\nu} W_{\mu\nu}$$

- $L_{\mu\nu}$  leptonic tensor  $\rightarrow$  well under control
- $W_{\mu\nu}$  Hadronic Tensor, parametrized via structure functions:

$$W_{\mu\nu} \sim \left[ \dots F_1(x, Q^2) + \dots F_2(x, Q^2) + \dots g_1(x, Q^2) + \dots g_2(x, Q^2) \right. \\ \left. (\text{for Spin 1}) \dots b_1(x, Q^2) + \dots b_2(x, Q^2) + \dots b_3(x, Q^2) + \dots b_4(x, Q^2) \right]$$

# Polarized DIS and Spin Asymmetries



$$\vec{S}_\gamma + \vec{S}_N = 1/2$$

$$\sigma_{1/2} \propto q^+(x)$$

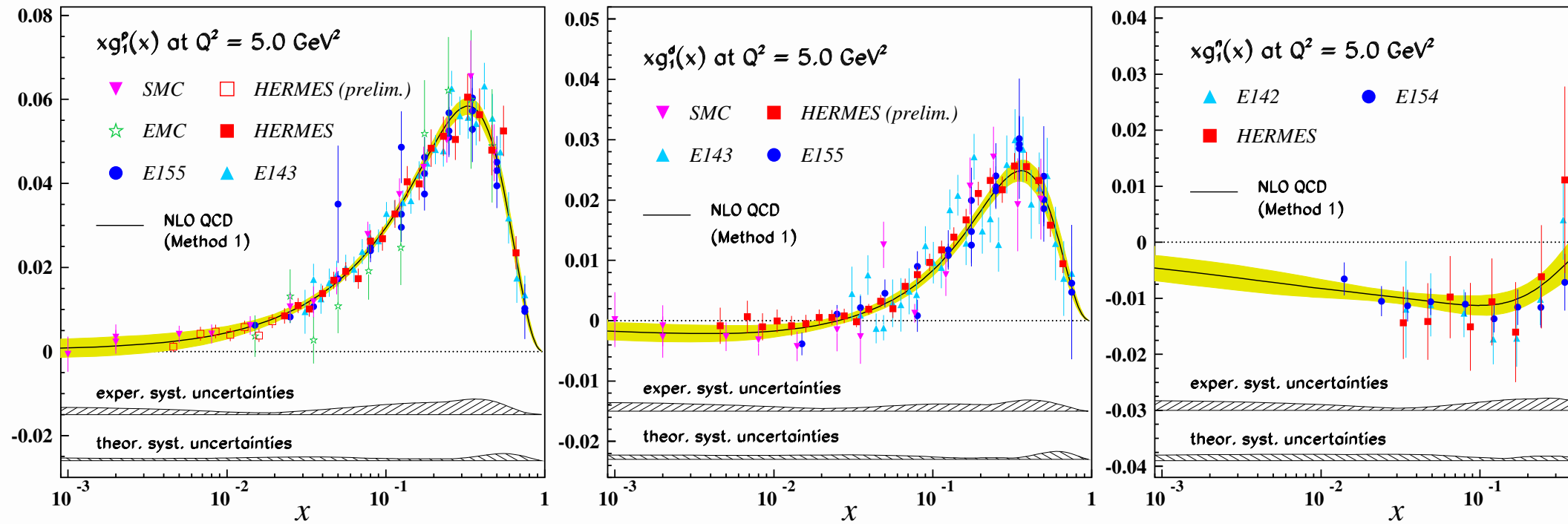
## Photon–Nucleon Asymmetry:

$$A_1(x, Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \simeq \frac{g_1(x, Q^2)}{F_1(x, Q^2)} \stackrel{\text{QPM}}{=} \frac{\sum_q e_q^2 \Delta q(x, Q^2)}{\sum_q e_q^2 q(x, Q^2)}$$

## Measured in the following way:

$$A_1(x, Q^2) = \frac{1}{(1 + \eta\gamma)D} \underbrace{\frac{1}{\langle P_T P_B \rangle} \frac{(N/\mathcal{L})^{\uparrow\downarrow} - (N/\mathcal{L})^{\uparrow\uparrow}}{(N/\mathcal{L})^{\uparrow\downarrow} + (N/\mathcal{L})^{\uparrow\uparrow}}}_{\equiv A_{\parallel}(x, Q^2)}$$

# NLO QCD Fits: Tuning to $g_1$ (exp.)



- Parameterizing  $x \cdot g_1^{p,d,n}(x, Q^2)$  (exp.) as:

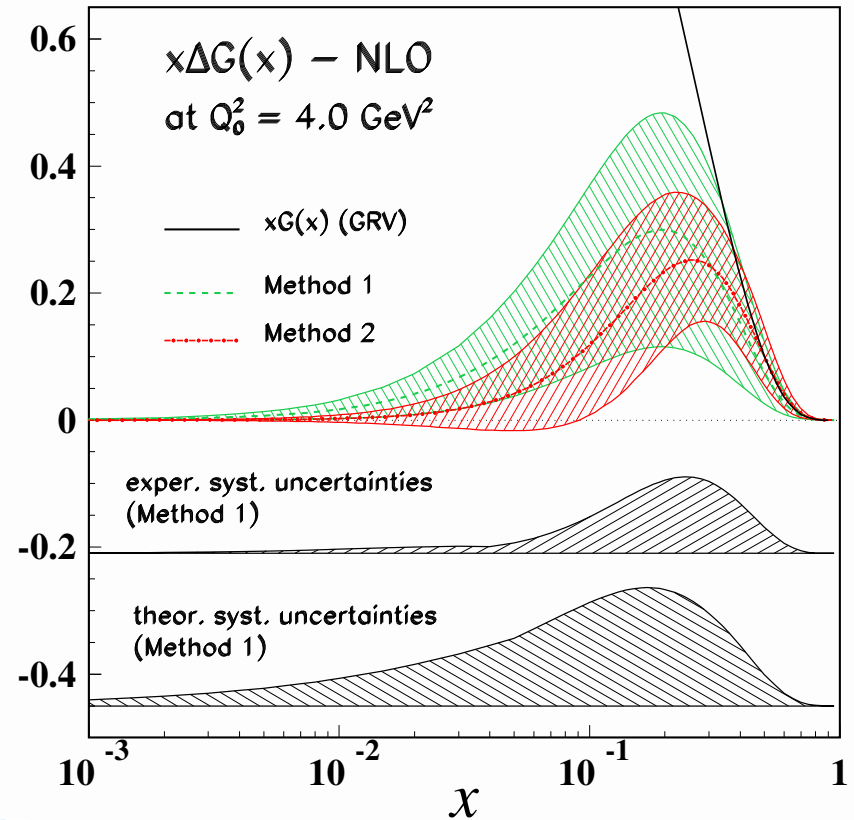
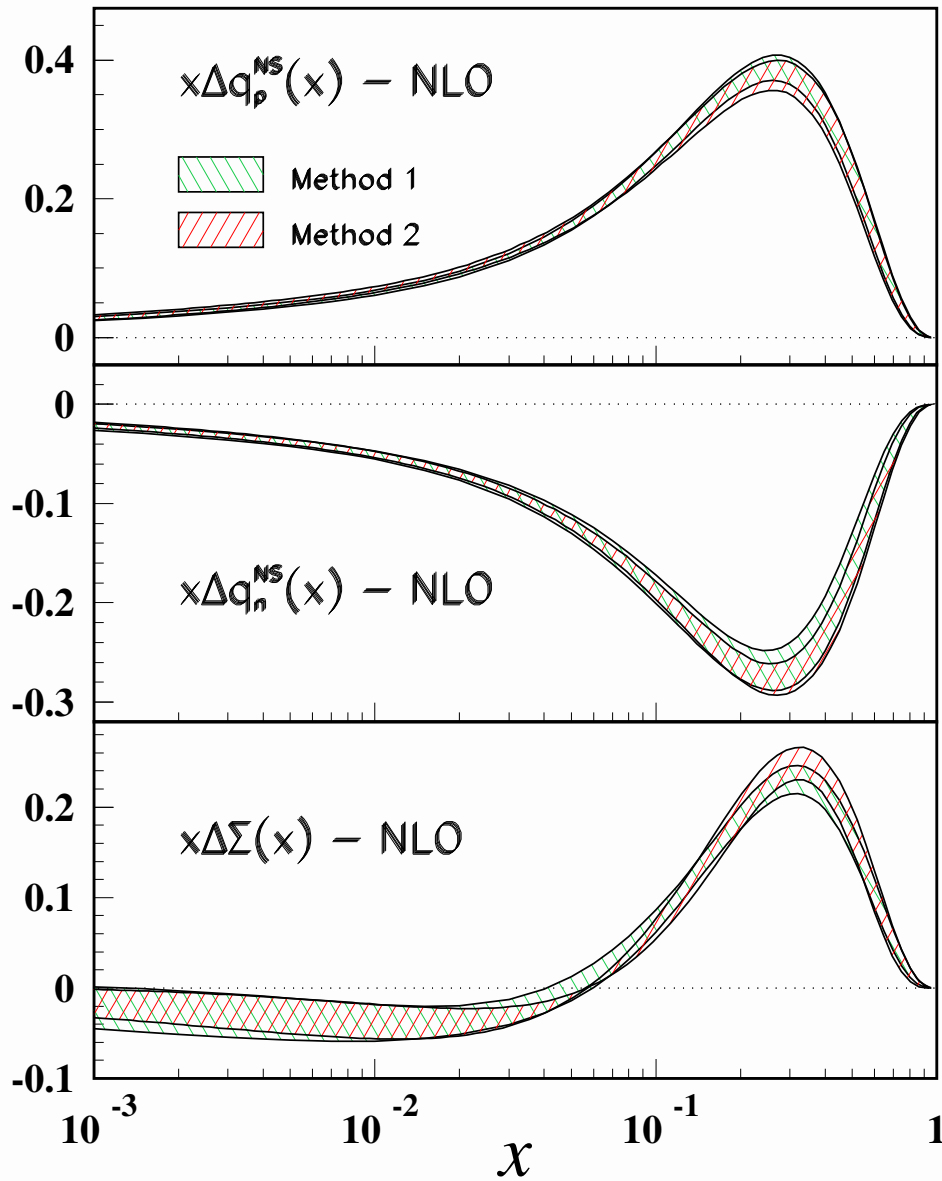
$$x \cdot \Delta f_i(x, Q_0^2) = \eta_i A_i x^{\alpha_i} (1-x)^{\beta_i} (1 + \gamma_i x + \rho_i \sqrt{x})$$

- assuming  $SU(3)_f$ -symmetric see

$$\Delta q_s(x) = \Delta u_s(x) = \Delta \bar{u}(x) = \Delta d_s(x) = \Delta \bar{d}(x) = \Delta s(x) = \Delta \bar{s}(x)$$

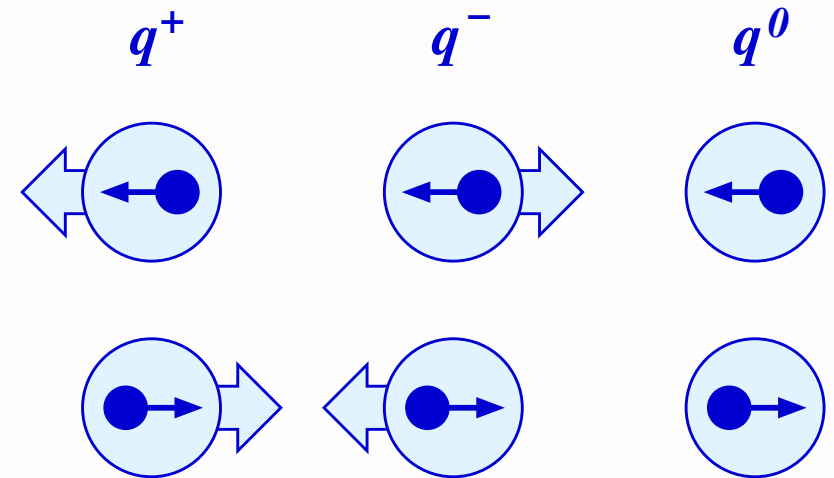
- Two different methods with Mellin moments and finite differences show good agreement

# NLO QCD Fits



- $\Delta q^{NS}(x) \equiv \Delta u(x) + \Delta \bar{u}(x) - [\Delta d(x) + \Delta \bar{d}(x)]$ , as well as  $\Delta\Sigma(x)$  are well constrained
- $\Delta\Sigma = 0.20$  at  $Q_0^2 = 4 \text{ GeV}^2$
- $\Delta G(x)$  with big uncertainty

# Deuteron Structure function $b_1^d(x)$



Proton

$$F_1(x) : \frac{1}{2} \sum_f e_f^2 \left[ q_f^+(x) + q_f^-(x) \right]$$

$$g_1(x) : \frac{1}{2} \sum_f e_f^2 \left[ q_f^+(x) - q_f^-(x) \right]$$

$$b_1(x) :$$

Deuteron

$$\frac{1}{3} \sum_f e_f^2 \left[ q_f^+(x) + q_f^-(x) + \mathbf{q}_f^0(\mathbf{x}) \right]$$

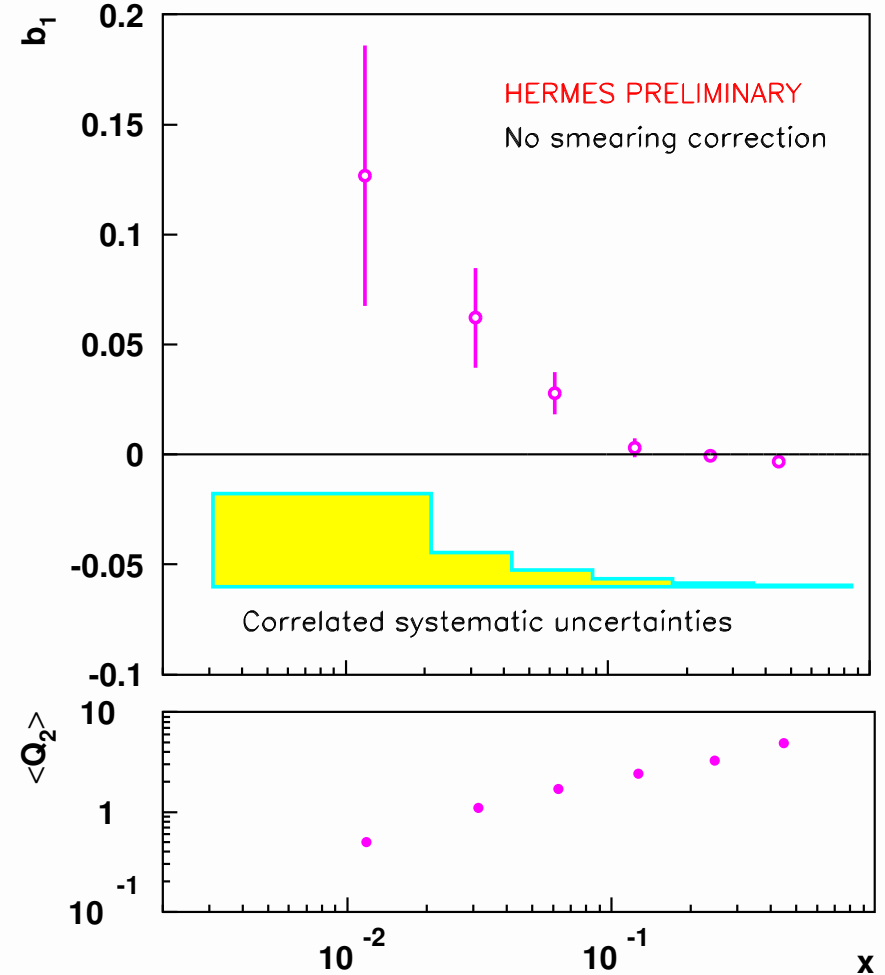
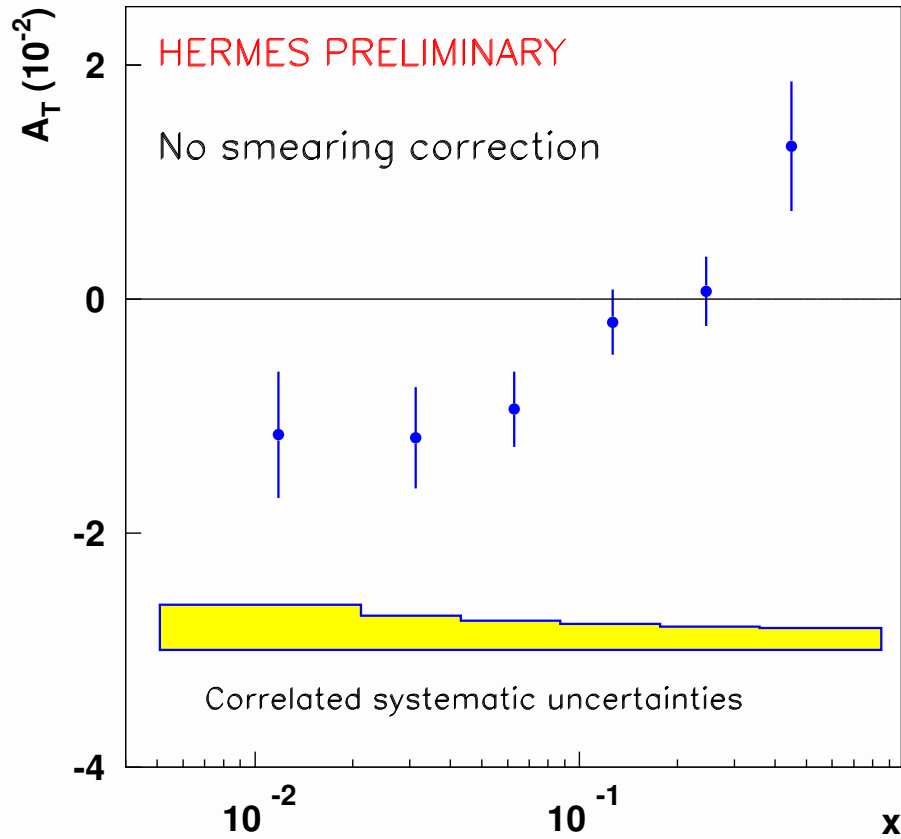
$$\frac{1}{2} \sum_f e_f^2 \left[ q_f^+(x) - q_f^-(x) \right]$$

$$\frac{1}{2} \sum_f e_f^2 \left[ 2 \mathbf{q}_f^0(\mathbf{x}) - \left( q_f^+(x) + q_f^-(x) \right) \right]$$

$b_1^d$  measures the difference of quark momentum distribution between tensor and

the sum of vector helicity states

# First measurement of $b_1^d(x)$



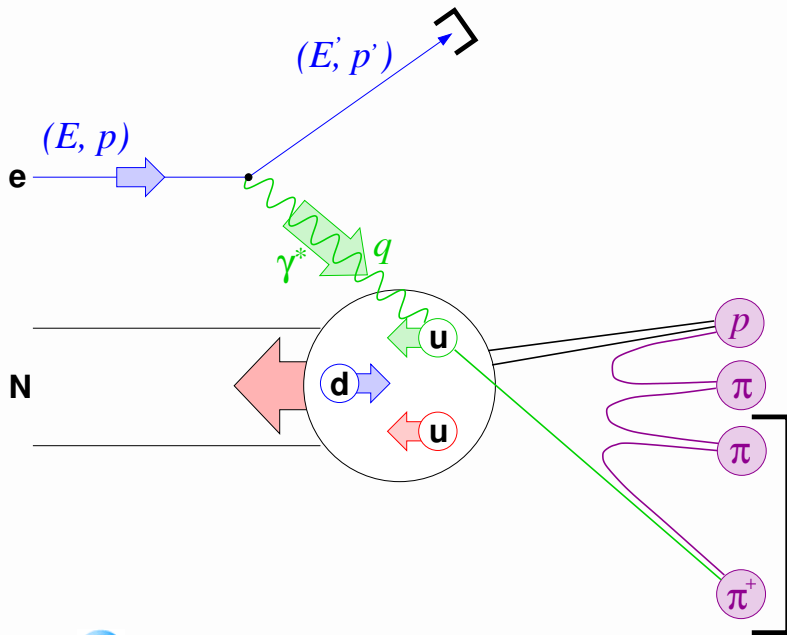
$$A_T = \frac{1}{\langle P_T \rangle} \cdot \frac{\frac{N^+}{\mathcal{L}^+} + \frac{N^-}{\mathcal{L}^-} - 2 \frac{N^0}{\mathcal{L}^0}}{\frac{N^+}{\mathcal{L}^+} + \frac{N^-}{\mathcal{L}^-} + \frac{N^0}{\mathcal{L}^0}}$$

$$b_1^d = -\frac{3}{2} \cdot A_T \cdot F_1^d$$

●  $b_1^d(x) > g_1^d(x)$  ( $x \lesssim 0.05$ )!



# Semi-Inclusive DIS



- In SIDIS  $e + p \rightarrow e' + h + X$  there is a correlation between struck quark  $q$  and detected hadron  $h$

⇒ Separation of the polarized quark distributions is possible:

$$\Delta u, \Delta \bar{u}, \Delta d, \Delta \bar{d}, \Delta s, (\Delta \bar{s})$$

- In LO QCD:

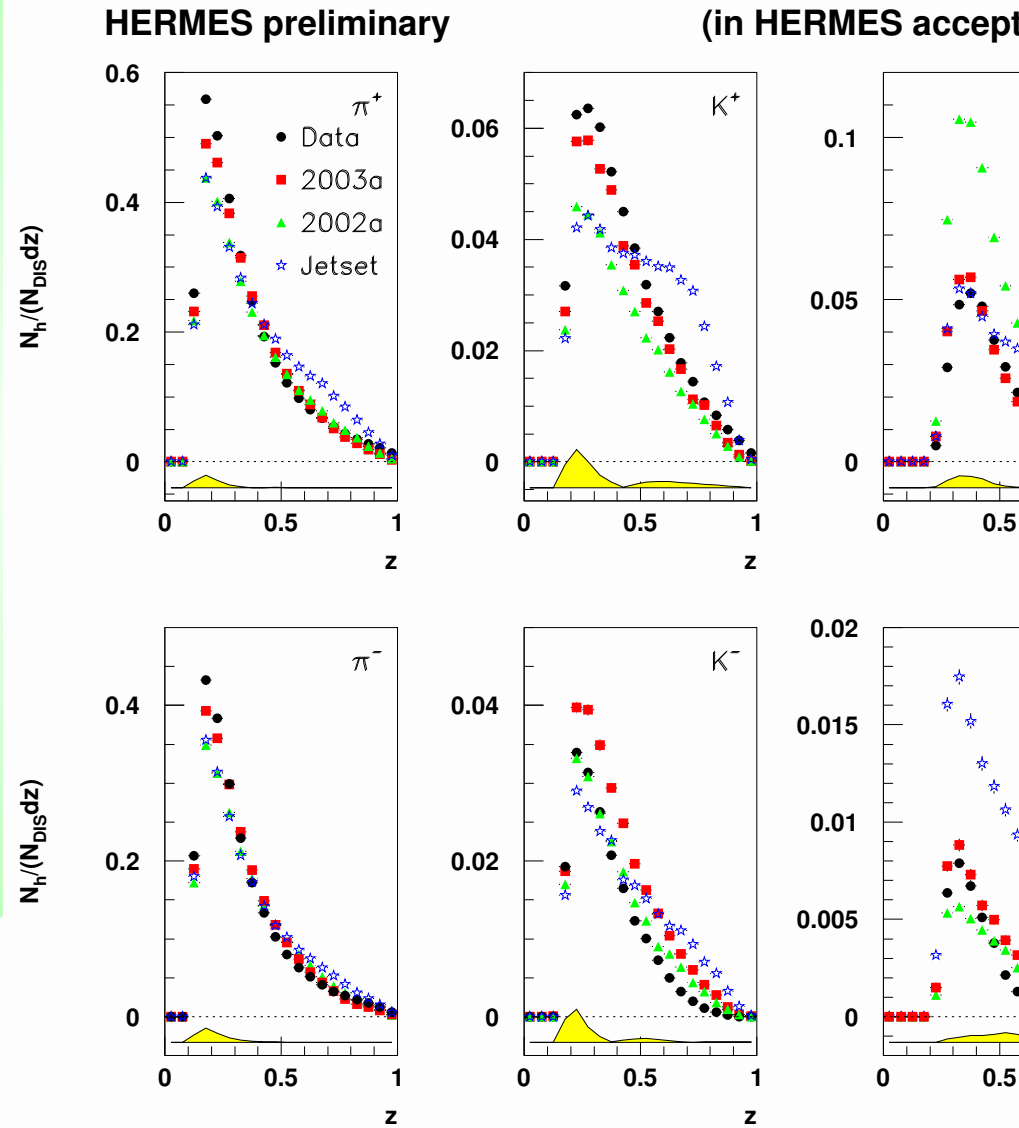
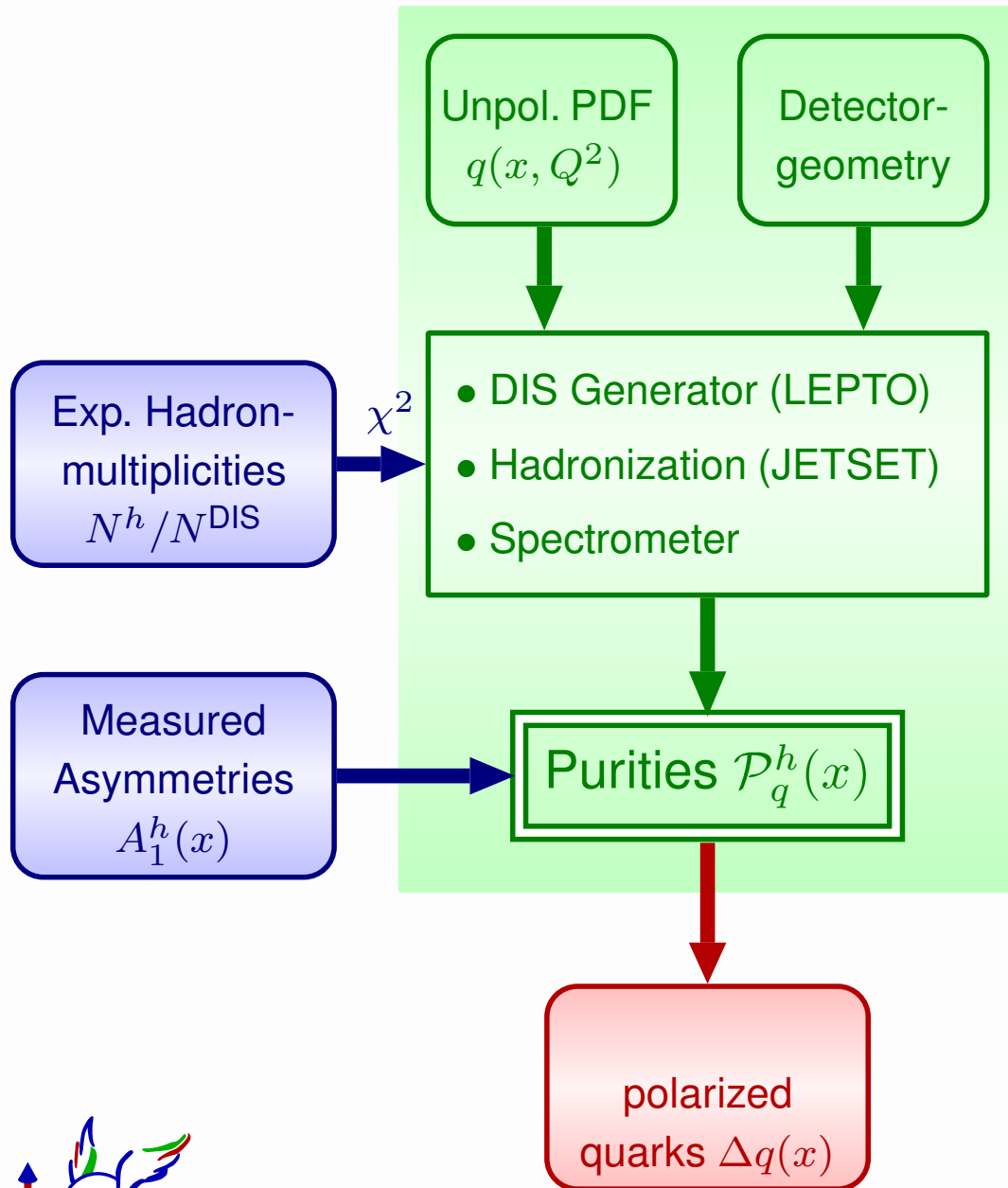
$$A_1^h(x) = \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h} \sim \frac{\sum_q e_q^2 \Delta q(x) \int dz D_q^h(z)}{\sum_q e_q^2 q(x) \int dz D_q^h(z)} = \sum_q \underbrace{\frac{e_q^2 q(x) \int dz D_q^h(z)}{\sum_{q'} e_{q'}^2 q'(x) \int dz D_{q'}^h(z)}}_{\equiv \mathcal{P}_q^h(x,z) \text{ "Purity"}} \cdot \frac{\Delta q(x)}{q(x)}$$

- Solving the system of equations

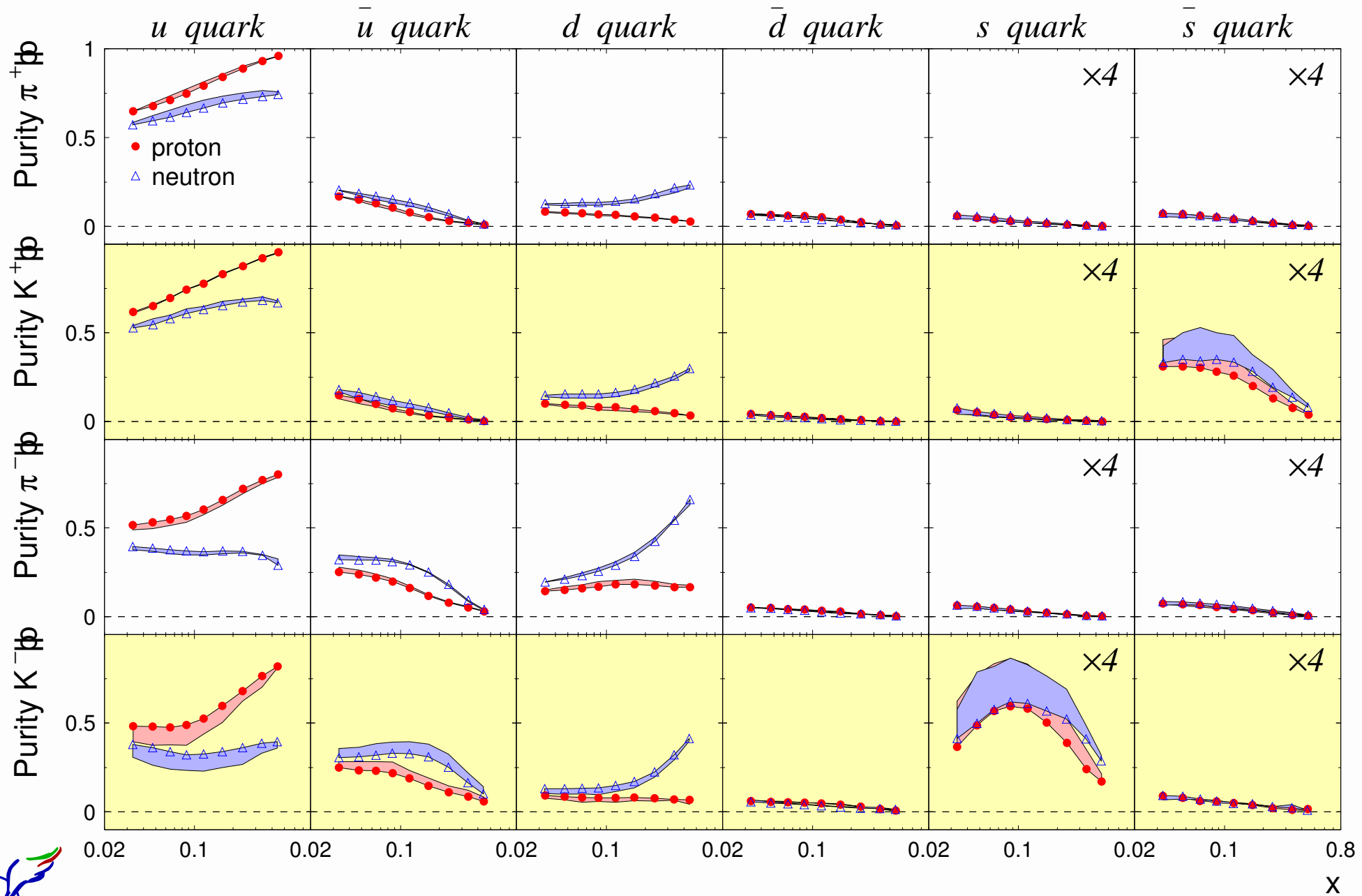
$$\vec{A} = \left( A_{1,p}, A_{1,d}, A_{1,p}^{\pm}, A_{1,d}^{\pm}, A_{1,d}^{K^{\pm}} \right) (x) \text{ und } \vec{Q} = \left( \frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}, \frac{\Delta s}{s}, \frac{\Delta \bar{s}}{\bar{s}} = 0 \right) (x)$$



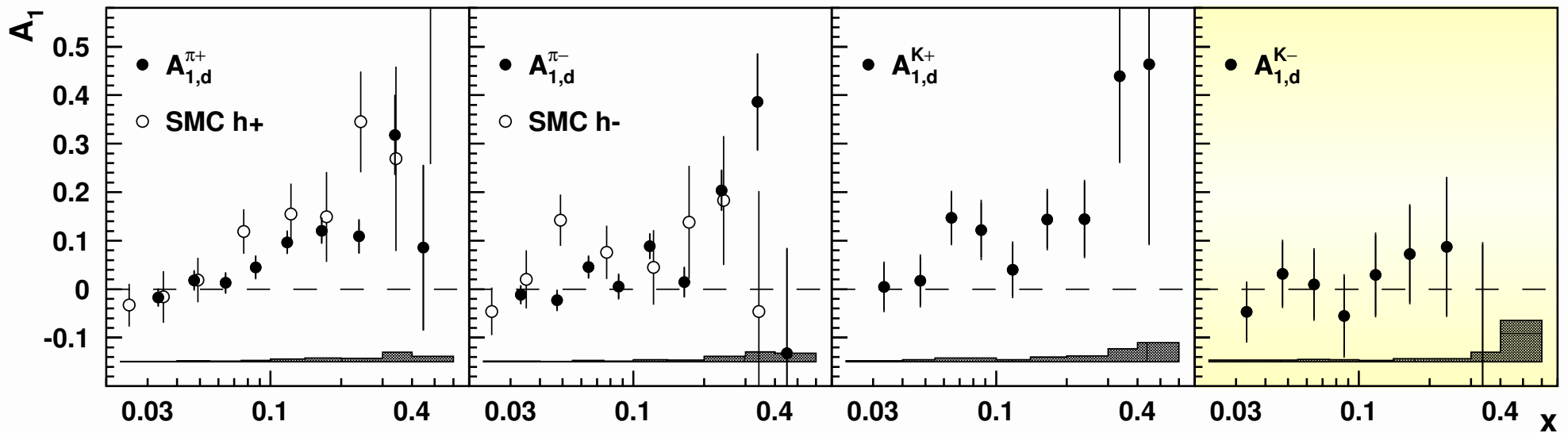
# Monte Carlo Model for Hadronization



# Generated Purities



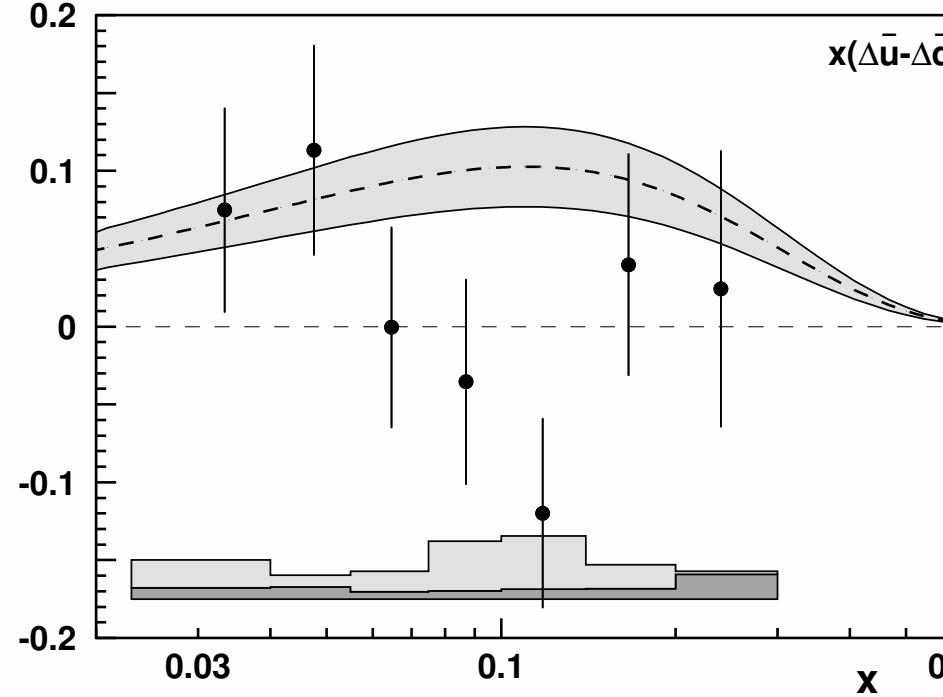
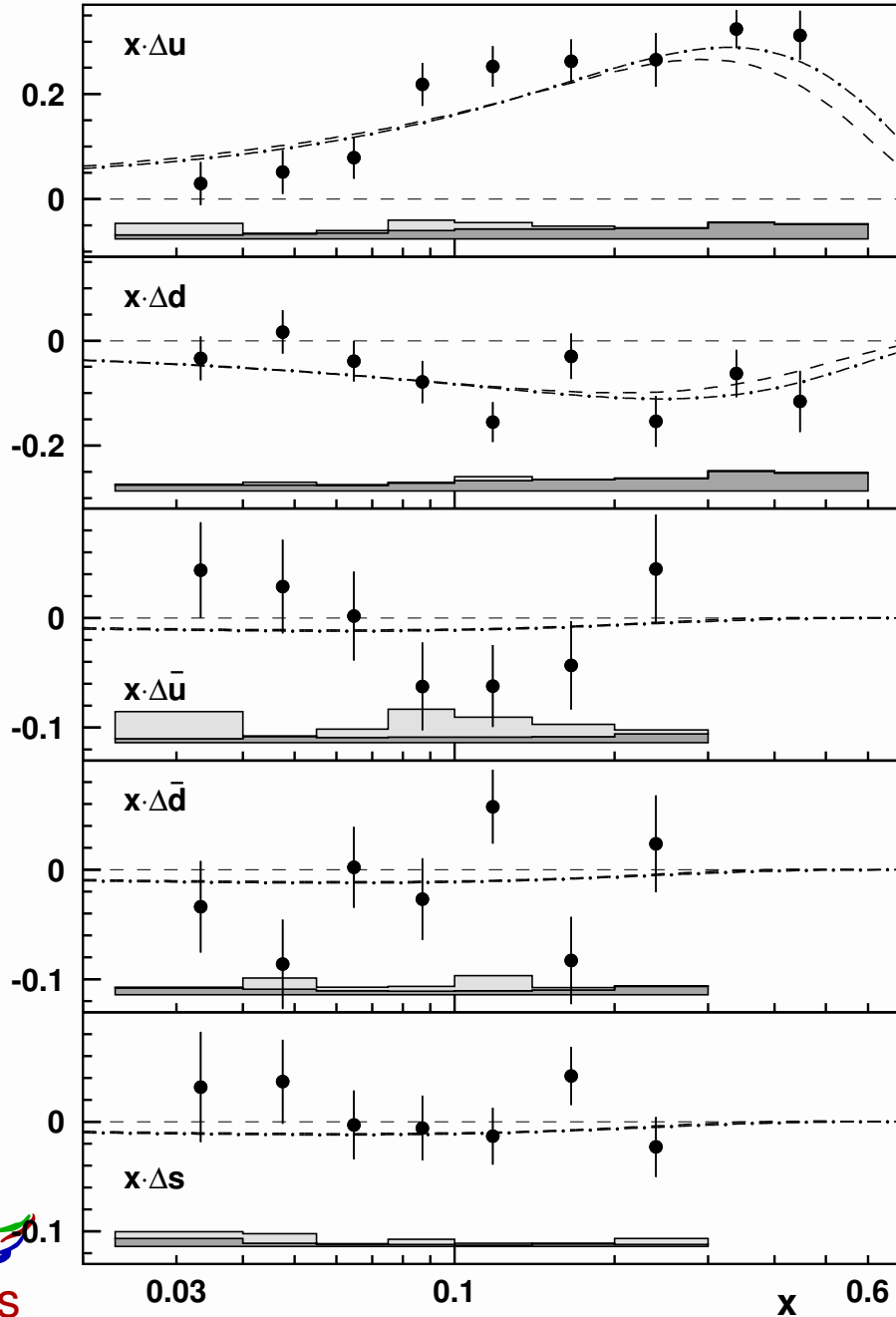
# Pion and Kaon Asymmetries on Deuteron



- Hadrons selected with  $0.2 \leq z = E_h/\nu \leq 0.8$ ,  $x_F \geq 0.1$ ,  $W^2 \geq 10 \text{ GeV}^2$
- $A_1^{K^-}(x) \approx 0$ ,  $\Rightarrow K^- = (\bar{u}s)$   
 $\Rightarrow$  indication for small polarization of sea!
- corrected for radiative effects and kinematical smearing
- systematic errors dominated by beam and target polarization uncertainties

# Polarized Quark Distributions (LO)

[A. Airapetian et al., hep-ex/0307064]



- Results consistent with  $SU(3)_f$  symmetric sea assumption
  - Disagreement with the prediction for  $\Delta \bar{u}(x) - \Delta \bar{d}(x)$  from  $\chi$ QSM
- [B. Dressler et al., Eur. Phys. J. **C14** (2000) 14]

# Transversity

$$f_1^q = \text{[Diagram: A circle with a central blue dot.]}$$

## Unpolarized

Quarks and Nucleons

Vector Charge:

$$\langle PS | \bar{\psi} \gamma^\mu \psi | PS \rangle = \int_0^1 dx q(x) - \bar{q}(x)$$

$q(x)$ : spin averaged  
well known

$$g_1^q = \text{[Diagram: A circle with a central blue dot and a right-pointing arrow.]} - \text{[Diagram: A circle with a central blue dot and a left-pointing arrow.]}$$

## Longitudinally polarized

Quarks and Nucleons

Axial Charge:

$$\langle PS | \bar{\psi} \gamma^\mu \gamma_5 \psi | PS \rangle = \int_0^1 dx \Delta q(x) + \Delta \bar{q}(x)$$

$\Delta q(x)$ : Helicity difference  
known

$$h_1^q = \text{[Diagram: A circle with a central blue dot, a right-pointing arrow, and an upward-pointing arrow.]} - \text{[Diagram: A circle with a central blue dot, a right-pointing arrow, and a downward-pointing arrow.]}$$

## Transversely polarized

Quarks and Nucleons

Tensor Charge:

$$\langle PS | \bar{\psi} \sigma^{\mu\nu} \gamma_5 \psi | PS \rangle = \int_0^1 dx \delta q(x) - \delta \bar{q}(x)$$

$\delta q(x)$ : Helicity-flip  
**chiral odd!**  
unknown

*HERMES: 1995 - 2000*

*HERMES: 2002...*



# Transverse Spin Asymmetries

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

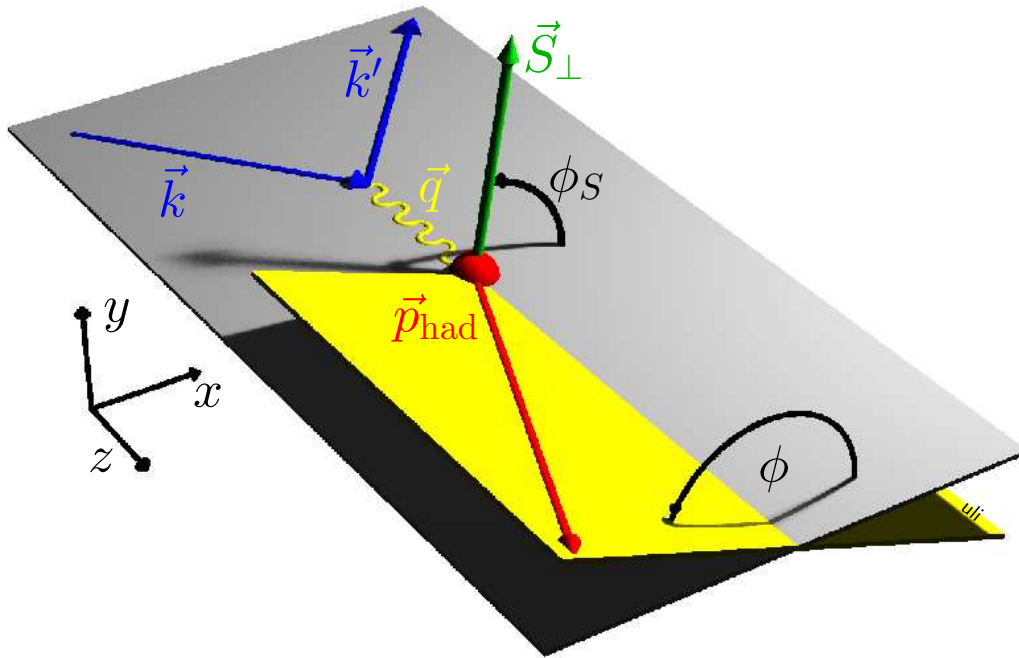
$$\sigma_{ep \rightarrow e\pi X} = \sum_q f^{N \rightarrow q} \otimes \sigma^{eq \rightarrow eq} \otimes D^{q \rightarrow \pi}$$

*Distribution Function*

Chiral odd

*Fragmentation function*

Chiral odd



Collins angle:  $\Phi \equiv \phi + \phi_S$

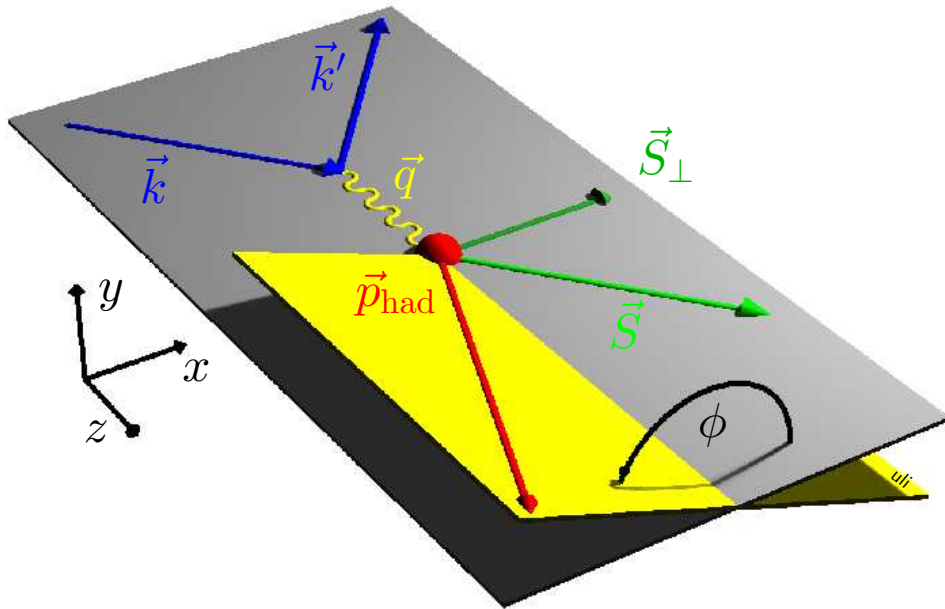
$$A_{UT}^{\sin \Phi} \propto \frac{\sum_{i=1}^{N^+} \sin \Phi - \sum_{i=1}^{N^-} \sin \Phi}{(N^+ + N^-) / 2}$$

$$A_{UT}^{\sin \Phi} \propto \frac{\sum_q e_q^2 \delta q(x) H_1^{\perp, q}(z)}{\sum_q e_q^2 q(x) D_1^q(z)}$$

$H_1^{\perp, q}(z)$ : Collins Fragmentation Function

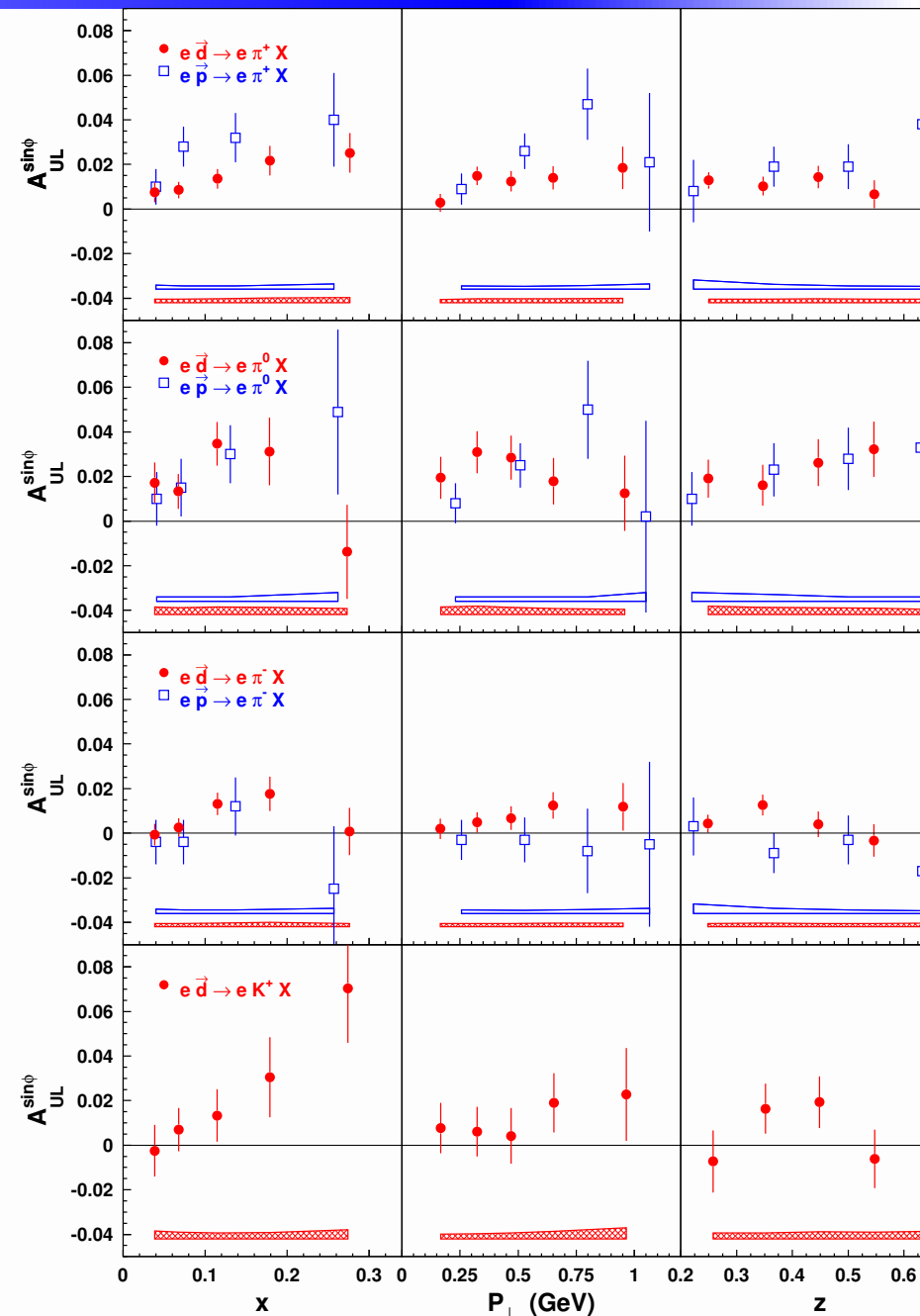
# First Hint on Transversity?

Measurement on **longitudinally** polarized  $\vec{H}^-$  and  $\vec{D}^-$ -targets:



**Transverse** Component  $S_{\perp}$  of target polarization in  $\gamma^* N$ -system:

$$S_{\perp} \propto \sin \Theta_{\gamma} \simeq \frac{2Mx}{Q} \sqrt{1-y} \quad \overset{\text{HERMES}}{\sim} \mathbf{0.15}$$



# Interpretations...

- In principle different explanations for  $\phi$ -Asymmetries on **longitudinally** polarized target:

- **Collins-Effect**  $\rightarrow$   $\chi$ QSM + “DELPHI-motivated assumption”:  $|H_1^\perp / D_1| \simeq 12.5$

[A.V. Efremov et al., Eur. Phys. J. **C24** (2002) 407.]

- **Sivers-Function** [Sivers, Mulders et al.]  $\rightarrow \langle \sin \phi \rangle_{UL} \propto f_{1T}^{\perp(1)} \cdot D_1$

- **Longitudinally polarized target:** **Collins-** and **Sivers-**Effects indistinguishable

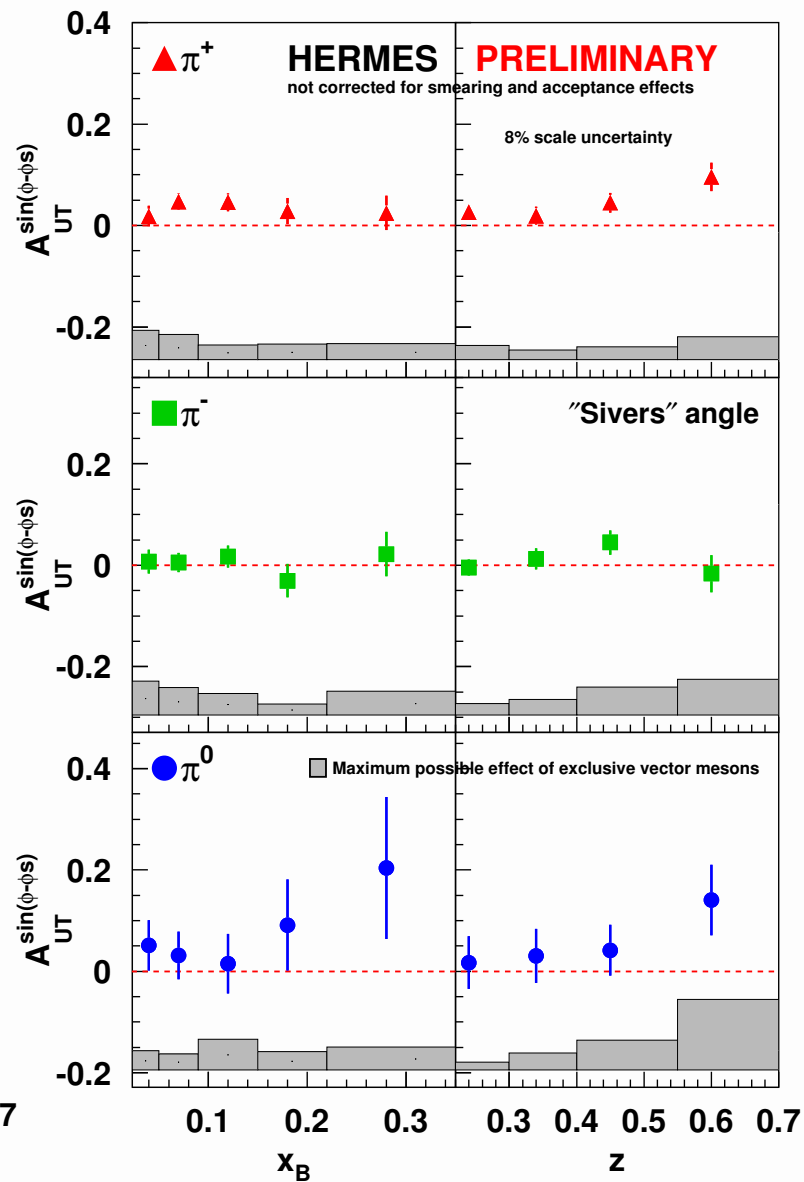
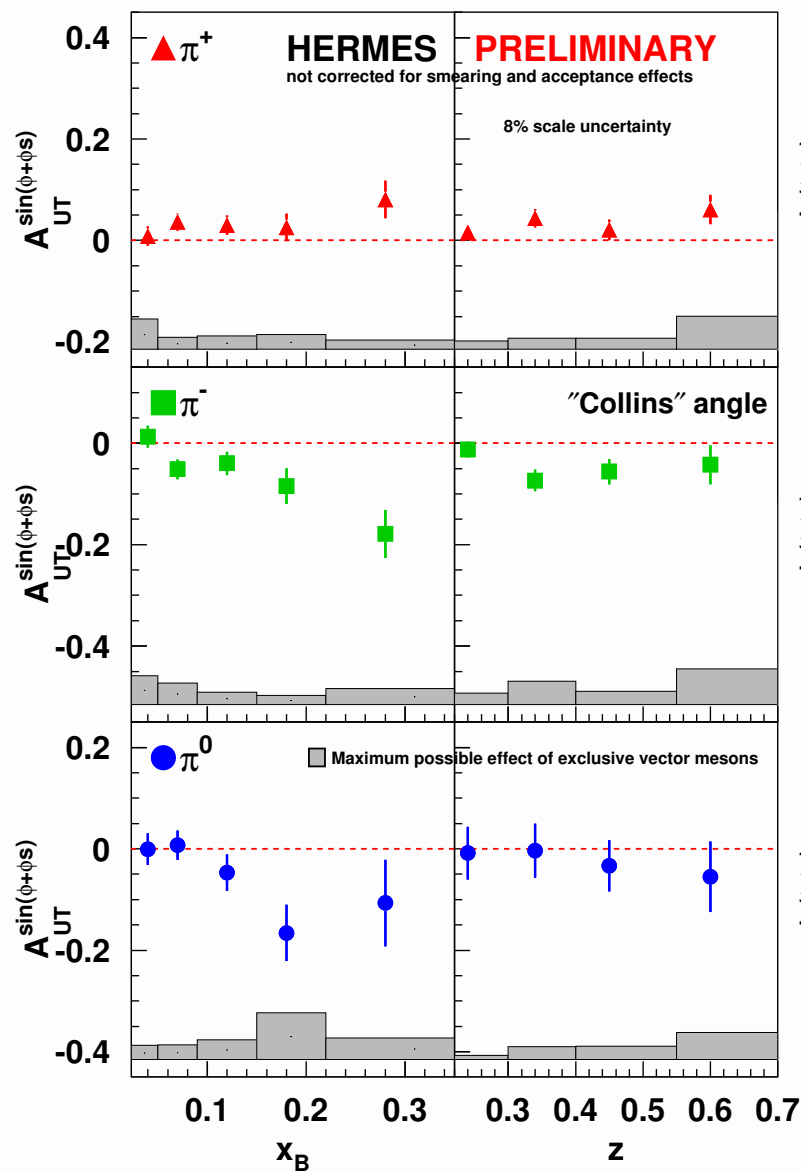
- **Transversely polarized target:**

- **Collins-** and **Sivers-**Effects distinguishable:

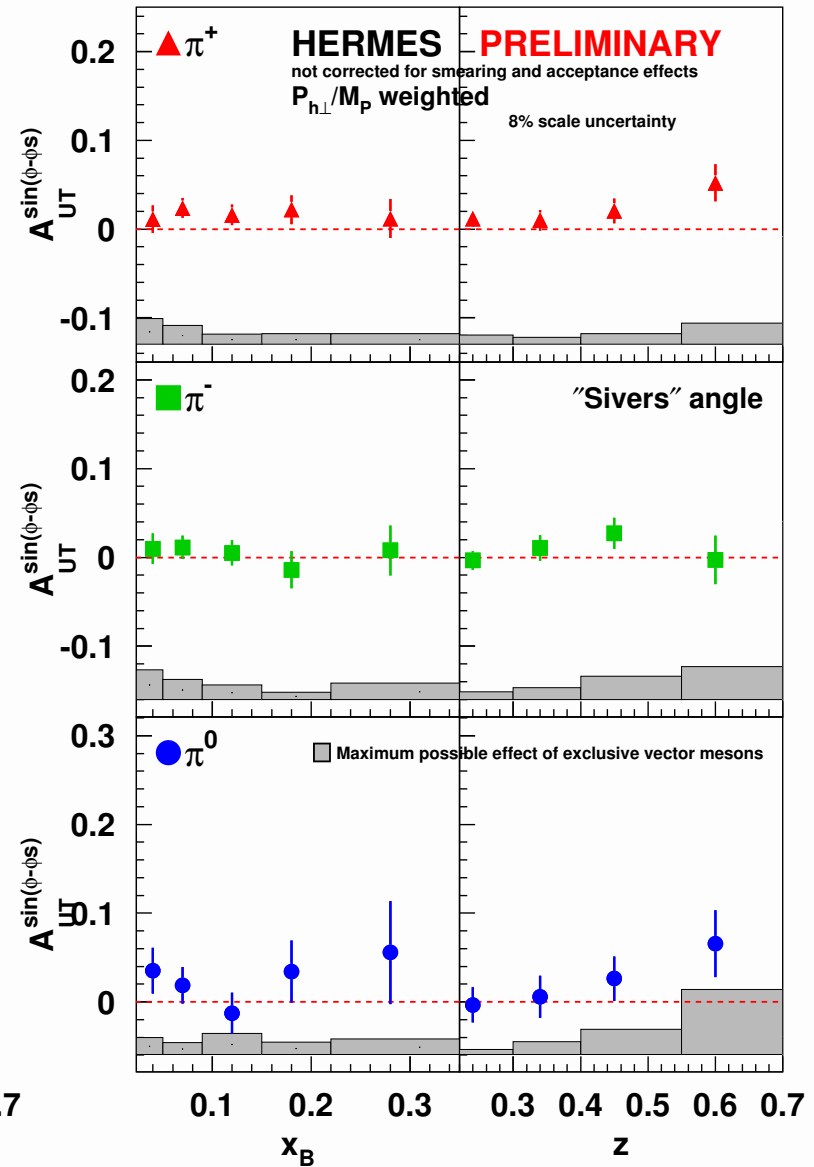
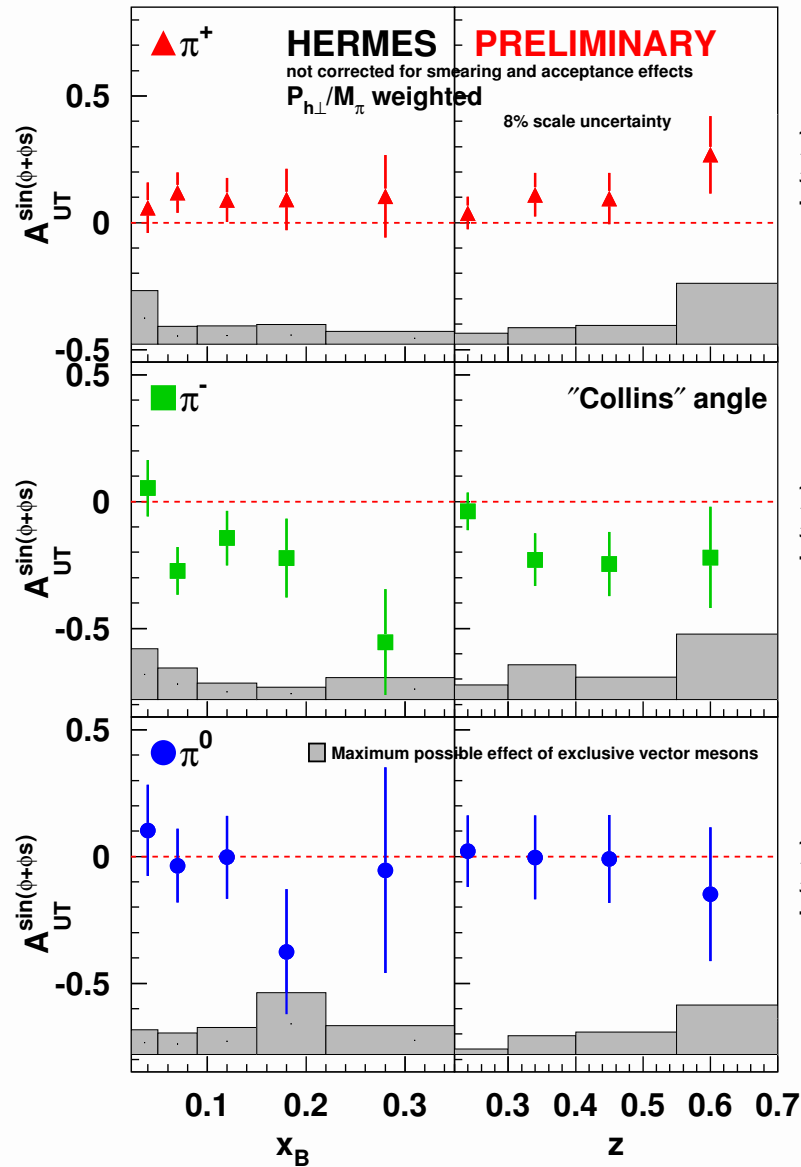
$\langle \sin(\phi_h + \phi_S) \rangle$  Moment  $\longleftrightarrow$   $\langle \sin(\phi_h - \phi_S) \rangle$  Moment

- Large Asymmetries  $\langle \sin \phi \rangle_{UT}$  expected, however ...

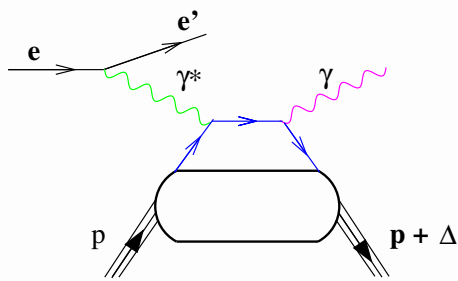
# First Measurement of Transverse Asymmetries



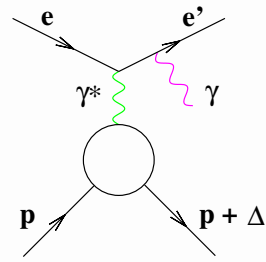
# $P_{h\perp}$ weighted Transverse Asymmetries



# DVCS: $ep \rightarrow e'\gamma p$



DVCS



Bethe-Heitler (BH)

$$d\sigma \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + (\mathcal{T}_{BH}^* \mathcal{T}_{DVCS} + \mathcal{T}_{DVCS}^* \mathcal{T}_{BH})$$

HERMES, CLAS:

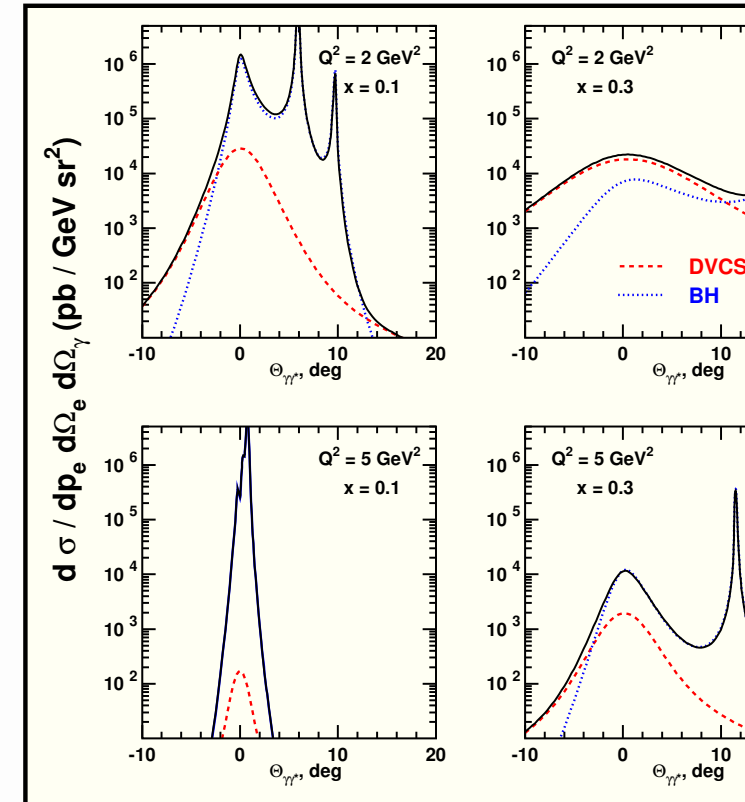
DVCS-BH interference:

⇒ use BH as an amplifier to study DVCS

H1, ZEUS:

measure DVCS cross section directly

HERMES kinematics:  
BH > DVCS



[Korotkov, Nowak, hep-ph/0108077]



# DVCS azimuthal asymmetries

$$d\sigma \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + (\mathcal{T}_{BH}^* \mathcal{T}_{DVCS} + \mathcal{T}_{DVCS}^* \mathcal{T}_{BH})$$

isolate **BH-DVCS interference** term  $\implies$  non-zero azimuthal asymmetries

- imaginary part  $\propto$  beam **helicity** asymmetry:

$$\begin{aligned} d\sigma_{e^+ \leftarrow} - d\sigma_{e^+ \rightarrow} &\propto \text{Im}(\mathcal{T}_{BH} \mathcal{T}_{DVCS}) \\ &\propto \sin \phi \implies H^u(x, \xi, t) \end{aligned}$$

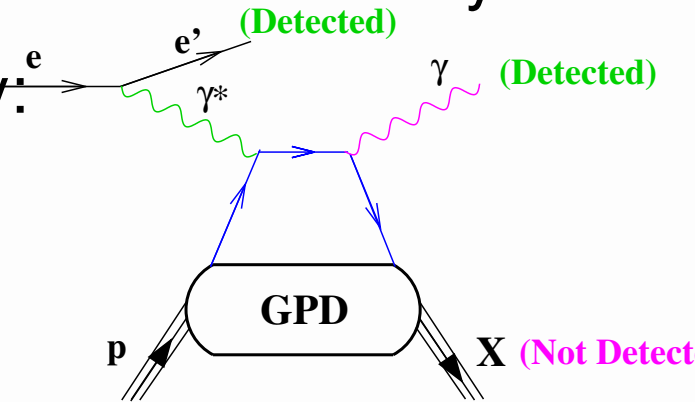
$\implies$  asymmetry measured by **HERMES**

- real part  $\propto$  beam **charge** asymmetry:

$$\begin{aligned} d\sigma_{e^+} - d\sigma_{e^-} &\propto \text{Re}(\mathcal{T}_{BH} \mathcal{T}_{DVCS}) \\ &\propto \cos \phi \implies H^u(x, \xi, t) \end{aligned}$$

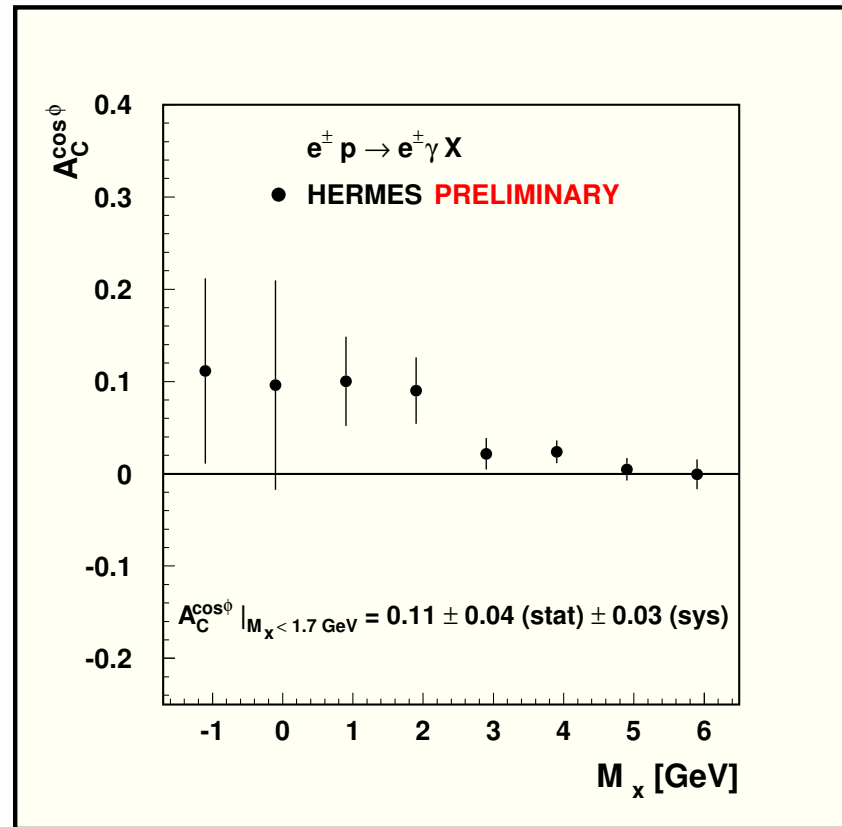
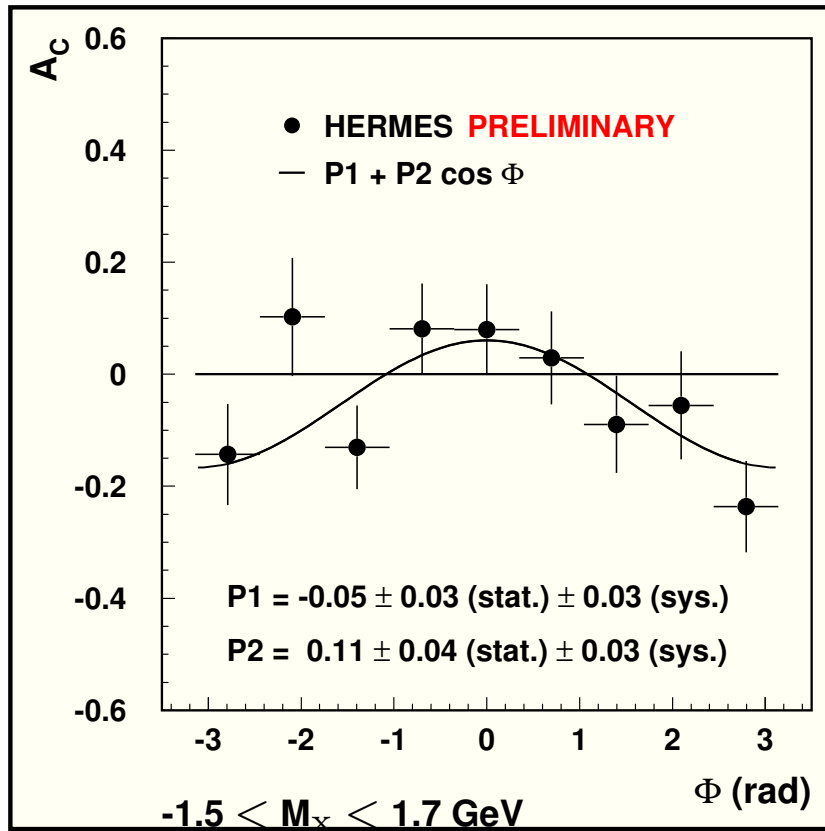
$\implies$  asymmetry measured by **HERMES**  $\implies$  **unique to HERA**

- no polarized target needed



# DVCS beam charge asymmetry (BCA)

●  $d\sigma_{e^+} - d\sigma_{e^-}$  sensitive to  $\text{Re}(\mathcal{T}_{BH}\mathcal{T}_{DVCS}) \implies \cos\phi$



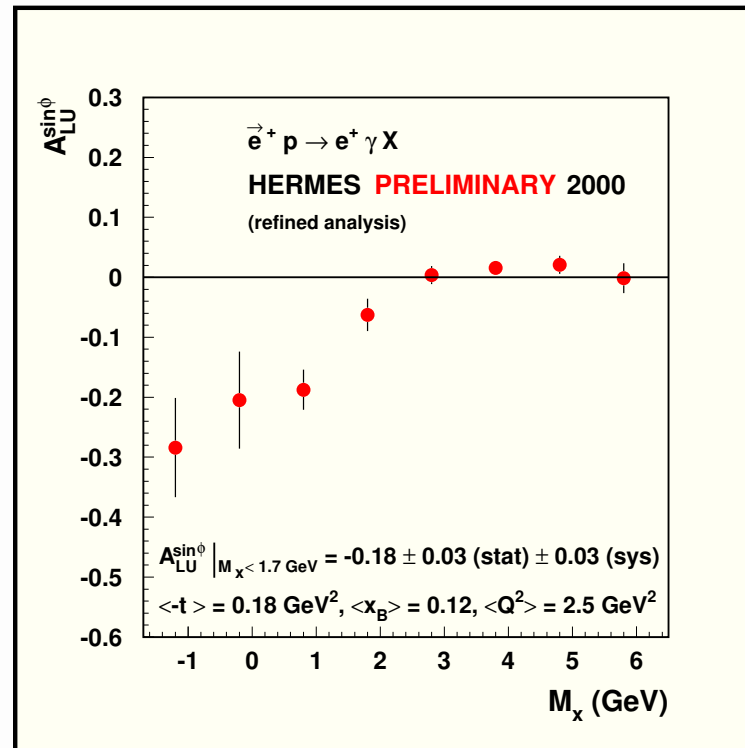
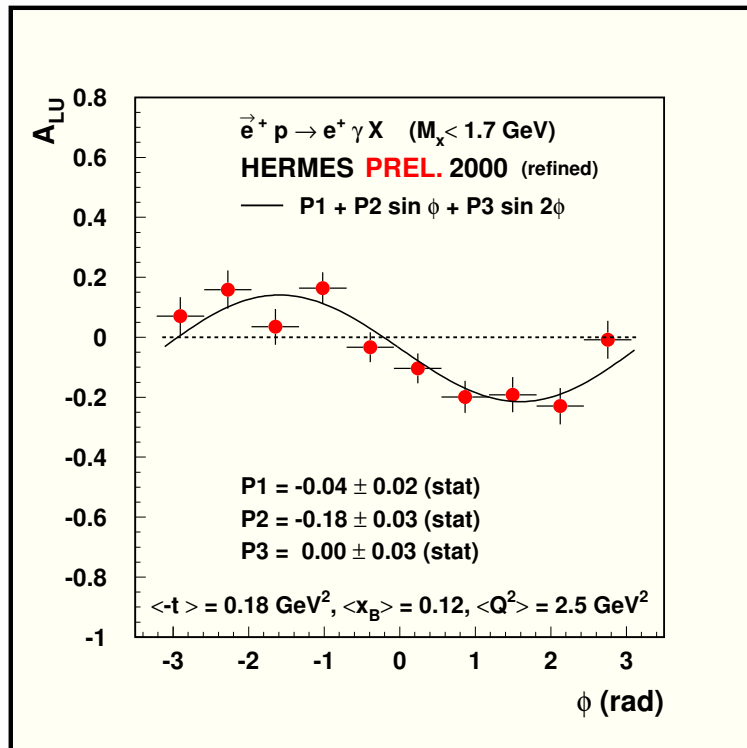
$$A_C(\phi) = \frac{N_{e^+}(\phi) - N_{e^-}(\phi)}{N_{e^+}(\phi) + N_{e^-}(\phi)}$$



● azimuthal asymmetry appears at  $M_x \sim M_p$

# DVCS single beam-spin asymmetry (BSA)

●  $d\sigma_{e^+ \leftarrow} - d\sigma_{e^+ \rightarrow}$  sensitive to  $\text{Im}(\mathcal{T}_{BH} \mathcal{T}_{DVCS}) \implies \sin \phi$



● 96/97 - data set published: [PRL87 (2001), 182001]

● DVCS on polarized proton / deuterium target  $\implies$  access to  $\tilde{H}, \tilde{E}$

● DVCS data on nuclear targets (D, He, Ne, Kr)  
 $\implies$  coherent scattering on nucleus !



# Summary

- Polarized singlet and nonsinglet distributions are well constrained
- Semi-inclusive measurements allow for the first time to extract **polarized quark distributions**
- **Polarized gluon distribution**  $\Delta G$  has very large uncertainty
- For the first time  $b_1$  structure function of the deuteron is measured
- For the first time Collins and Sivers asymmetries are addressed experimentally
- Large amount of data on DVCS is needed to access **orbital angular momentum**
- HERMES experiment will run until summer of 2007
- COMPAS, JLAB and RHIC will contribute to the future efforts on the spin structure of the nucleon

