Spin Physics Overview via HERMES

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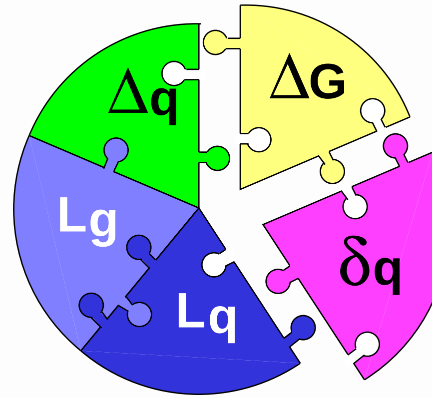
- Motivation
- The HERMES Experiment at HERA
- Polarized Deep Inelastic Scattering
- Inclusive measurements:
  - The structure function g_1
  - Polarized quark distributions from NLO–Fits
  - The structure function b_1^d
- Semi-inclusive measurements:
  - Flavor decomposition of the nucleon spin $\Delta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

Spin of the Nucleon

- Spin decompostion of the nucleon:

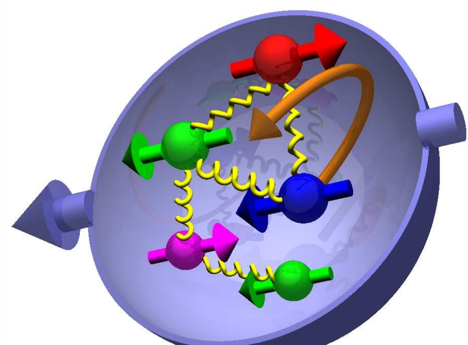


$$S_z = \frac{1}{2}\hbar = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

with

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

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



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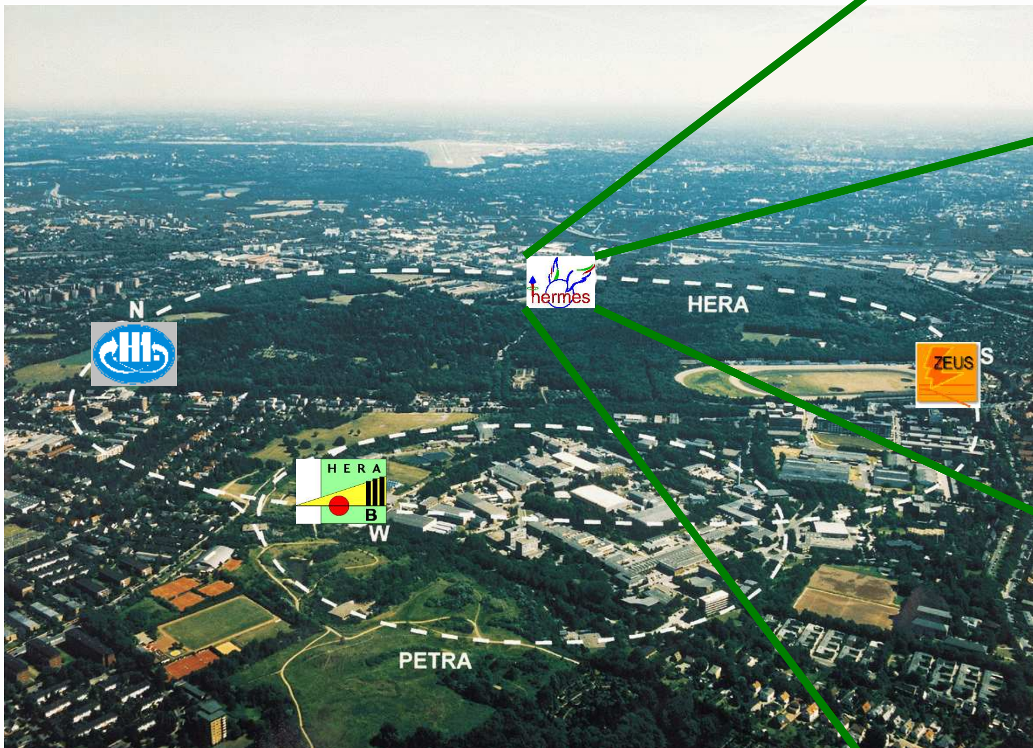
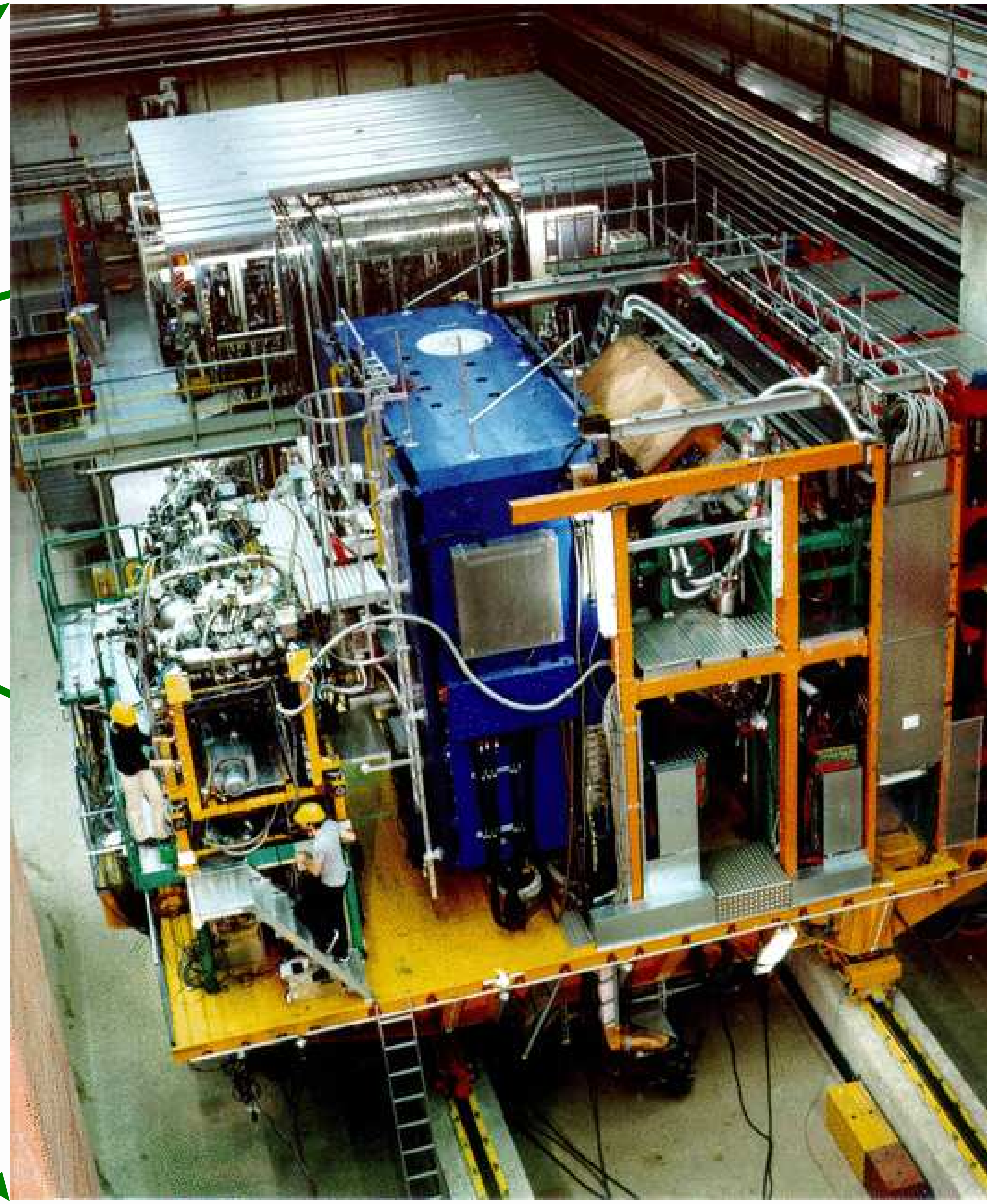
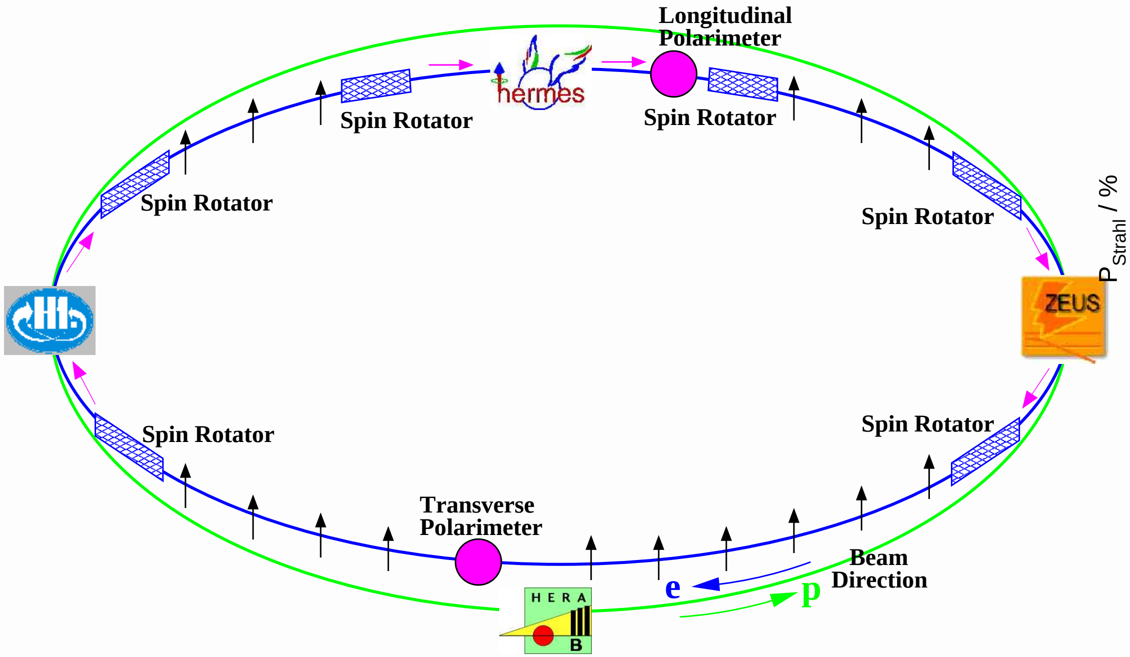
The HERMES Experiment at HERA

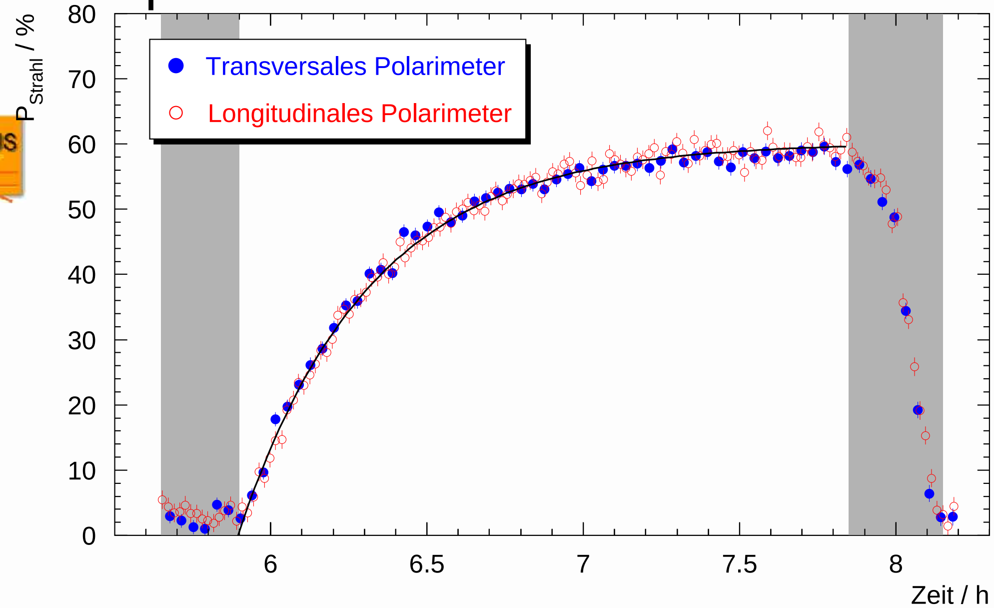




Polarized $e^{\pm}$–beam of HERA



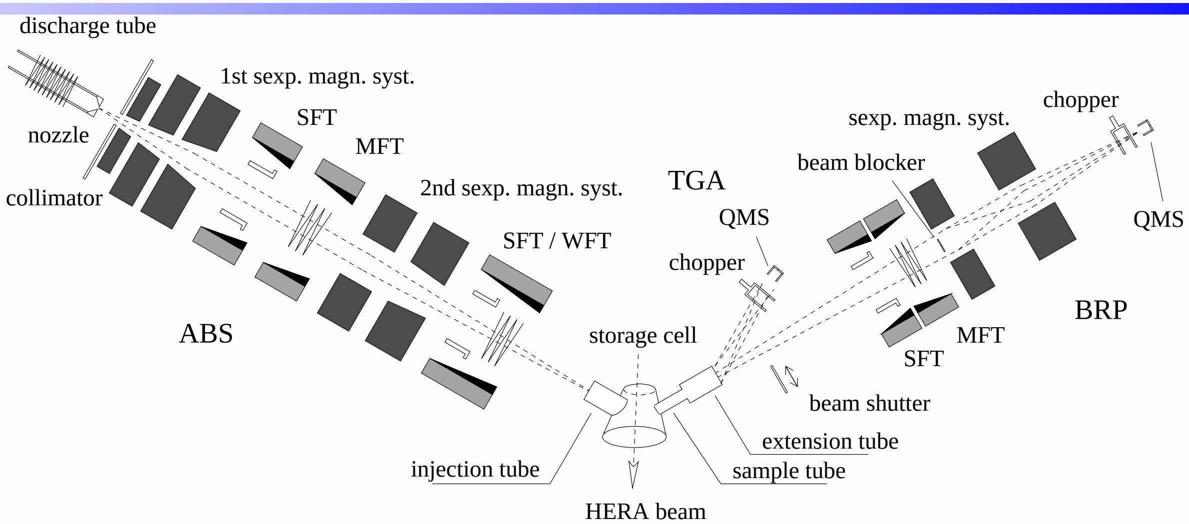
- Measured on-line with two Compton polarimeters



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

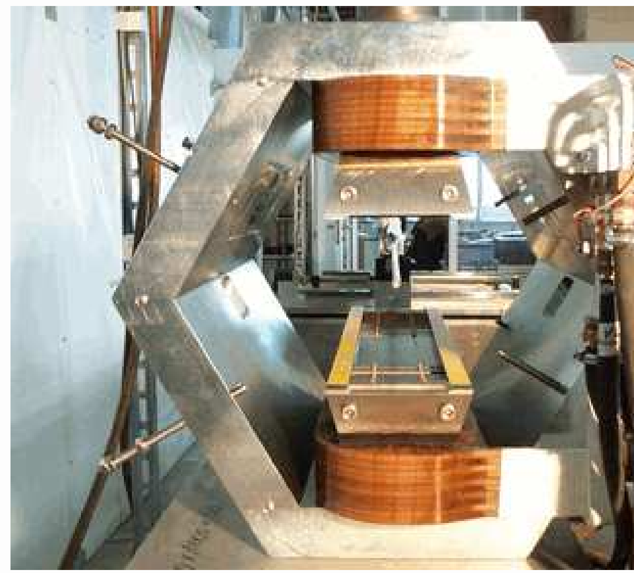
- Average Beam Polarization $\langle P_B \rangle \sim 55\%,\ \delta P_B / P_B = 1.8 \ldots 3.4\%$
- Average beam current $\sim$ 25 mA

The HERMES targets

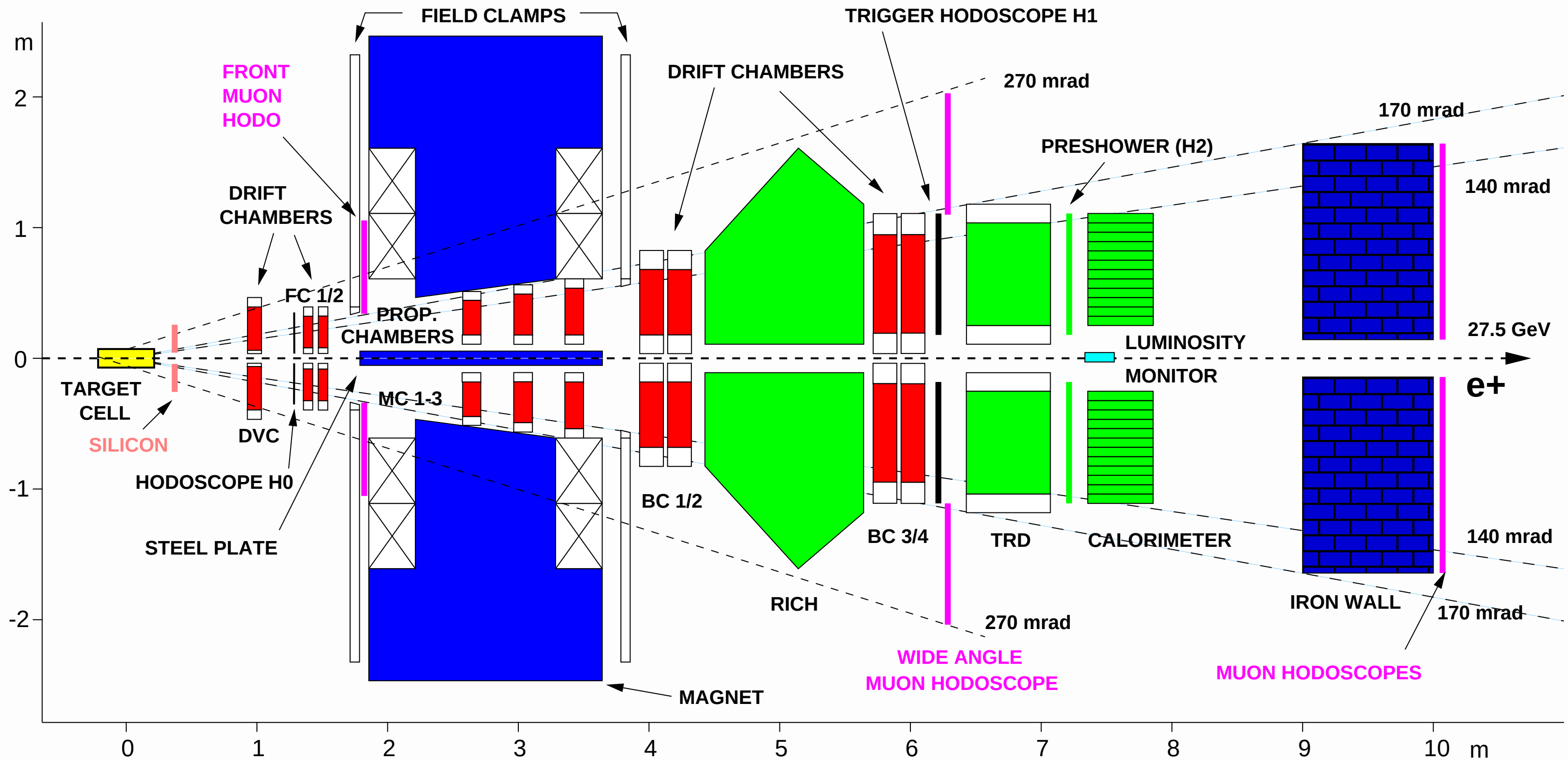


- Until 2000 long. polarized $\vec{\mathrm{H}}$– and $\vec{\mathrm{D}}$–Targets
- Average Target Polarization:
  $\langle P\rangle_{\vec{\mathrm{H}}} = 0.824 \pm 0.034$, $\langle P\rangle_{\vec{\mathrm{D}}} = 0.844 \pm 0.037$
- Also: unpol. Targets H, D, ^{4}He, ^{14}N, ^{20}Ne, ^{84}Kr with $\sim 10^{16}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

- In 2002 **transverse** polarized $\mathrm{H}^{\uparrow}$



The HERMES Spectrometer



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

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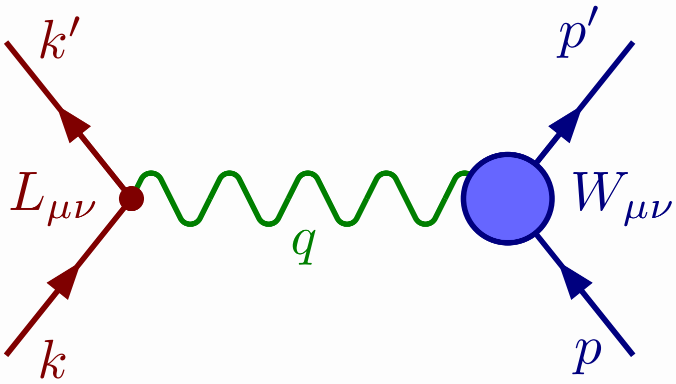
General Formalism of DIS



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

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

$$W_{\mu\nu} \sim \Big[\ldots F_1(x,Q^2) + \ldots F_2(x,Q^2) + \ldots g_1(x,Q^2) + \ldots g_2(x,Q^2)$$

(for Spin 1) $\ldots b_1(x,Q^2) + \ldots b_2(x,Q^2) + \ldots b_3(x,Q^2) + \ldots b_4(x,Q^2)\Big]$

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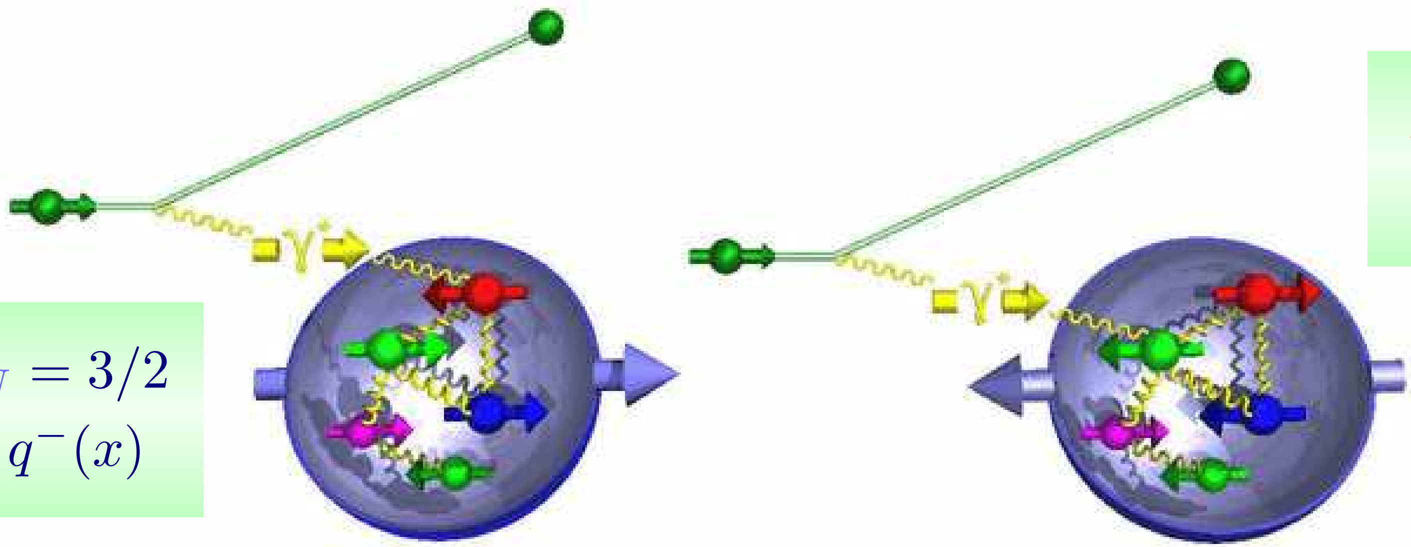
Polarized DIS and Spin Asymmetries

$\vec{S}_\gamma + \vec{S}_N = 3/2$

$\sigma_{3/2} \propto q^-(x)$



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

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

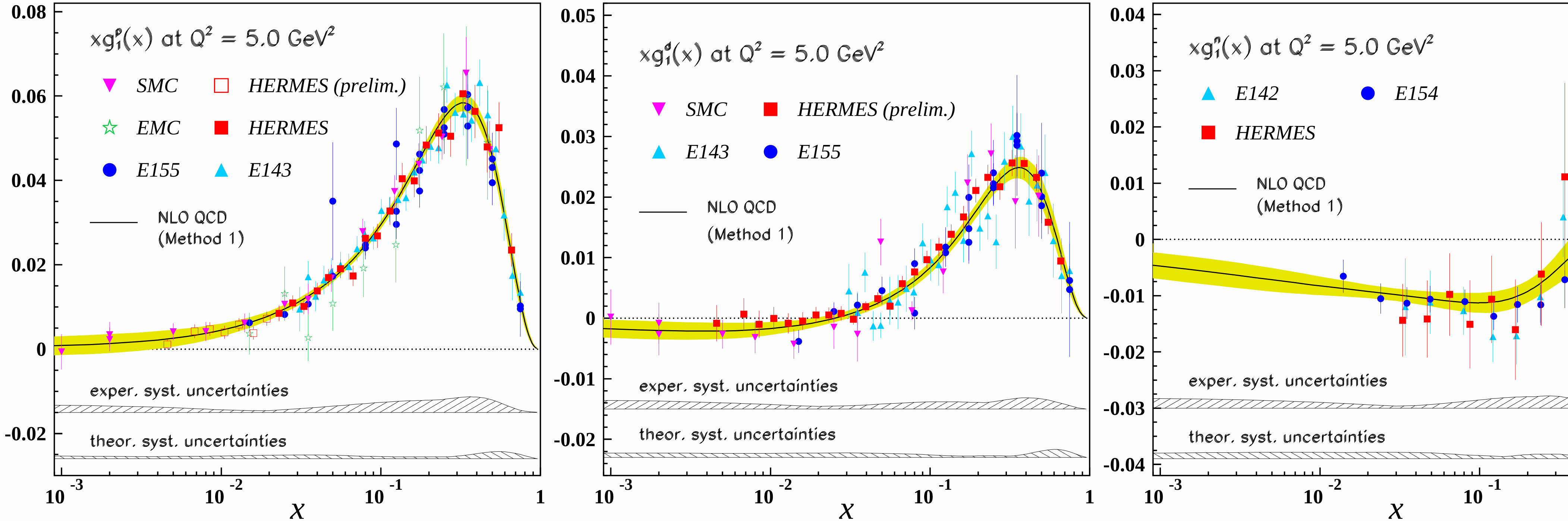
- Photon–Nucleon Asymmetry:

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

- Measured in the following way:

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

NLO QCD Fits: Tuning to g_1 (exp.)



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

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

- 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 differencies show good agreement

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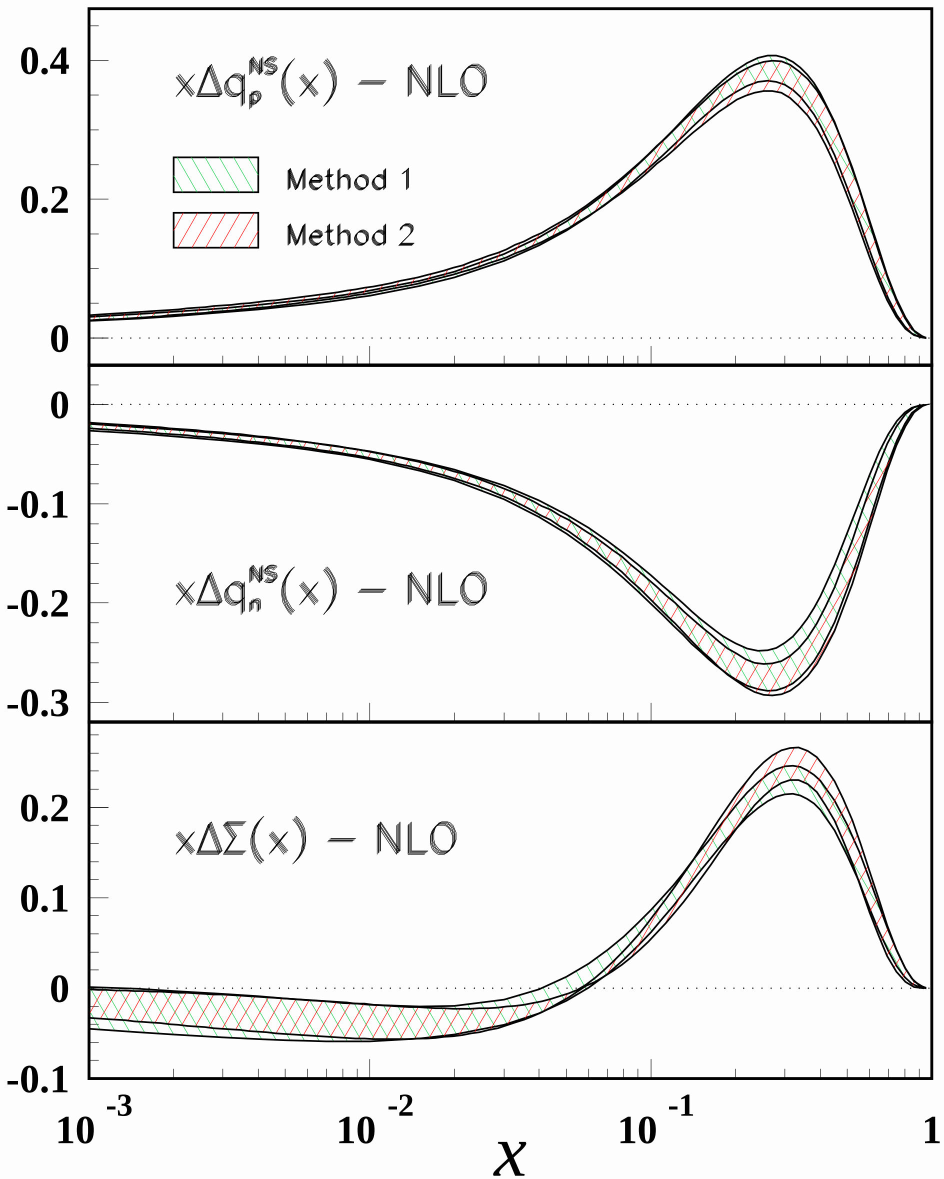
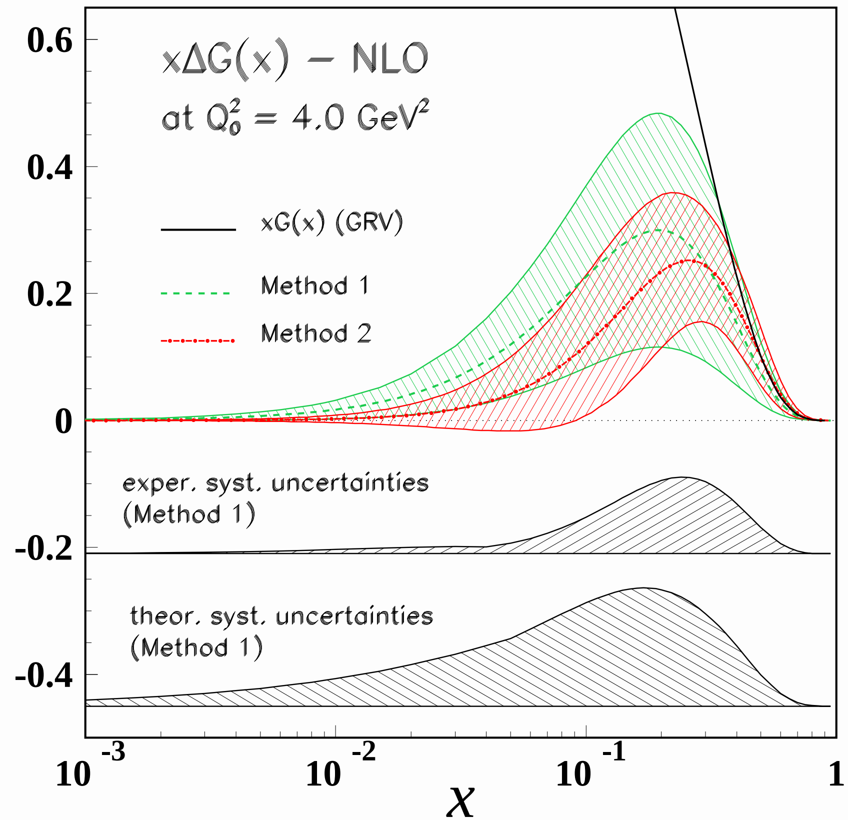
NLO QCD Fits





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

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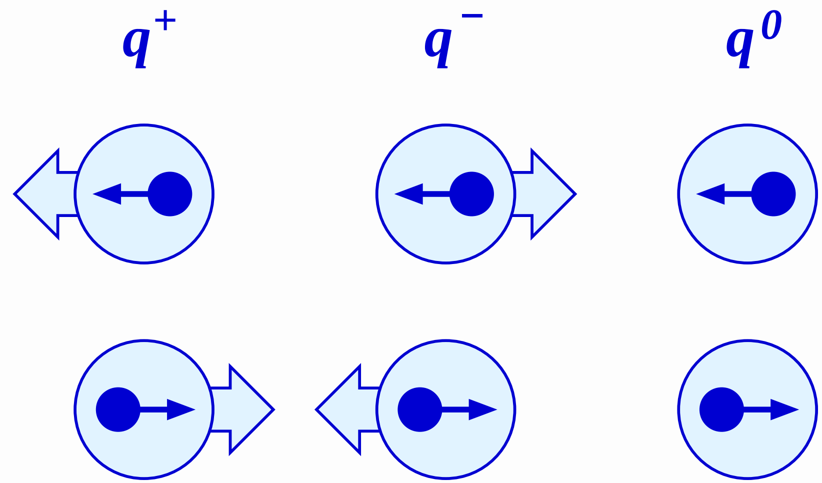
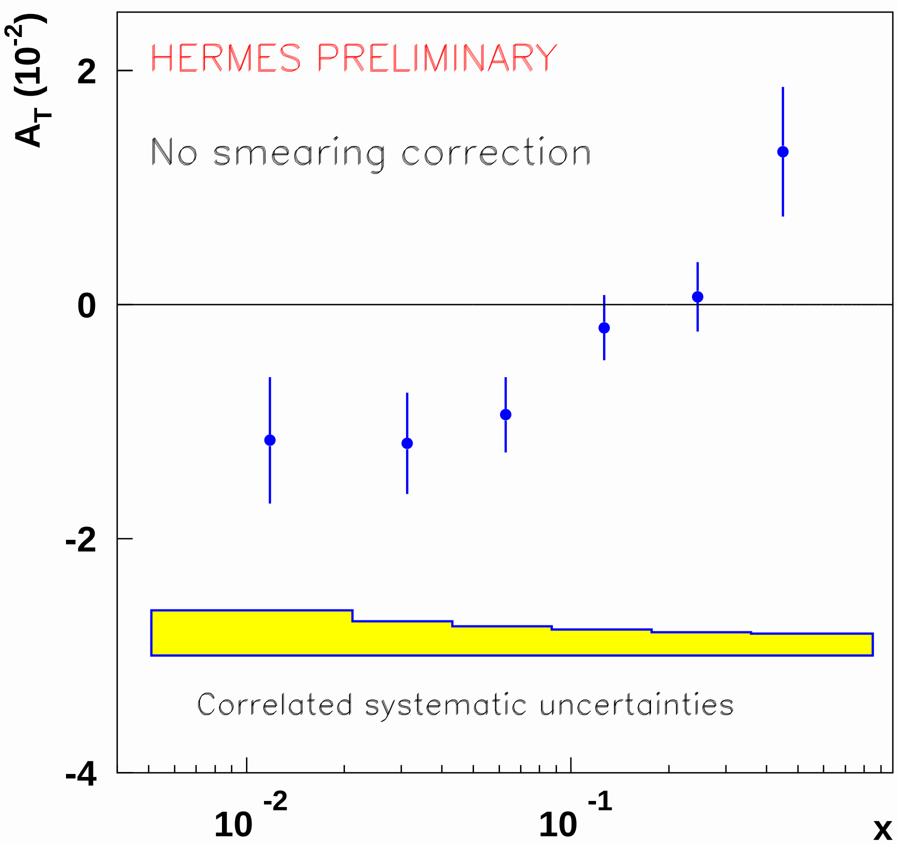
Deuteron Structure function $b_1^d(x)$

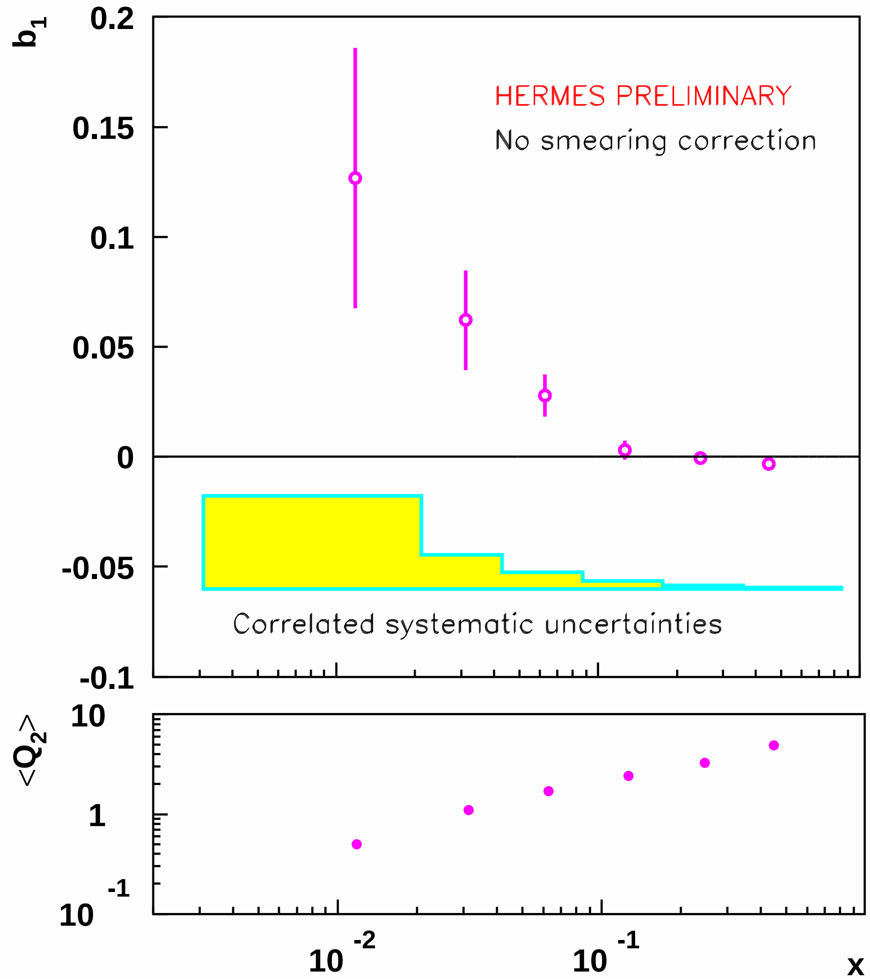


	Proton	Deuteron
$F_1(x)$:	$\frac{1}{2}\sum_f e_f^2\left[q_f^+(x)+q_f^-(x)\right]$	$\frac{1}{3}\sum_f e_f^2\left[q_f^+(x)+q_f^-(x)+\mathbf{q_f^0(x)}\right]$
$g_1(x)$:	$\frac{1}{2}\sum_f e_f^2\left[q_f^+(x)-q_f^-(x)\right]$	$\frac{1}{2}\sum_f e_f^2\left[q_f^+(x)-q_f^-(x)\right]$
$b_1(x)$:		$\frac{1}{2}\sum_f e_f^2\left[2\,\mathbf{q_f^0(x)}-\left(q_f^+(x)+q_f^-(x)\right)\right.$

b_1^d mesures the difference of quark momentum distribution between tensor an the sum of vector helicity states

First measurement of $b_1^d(x)$



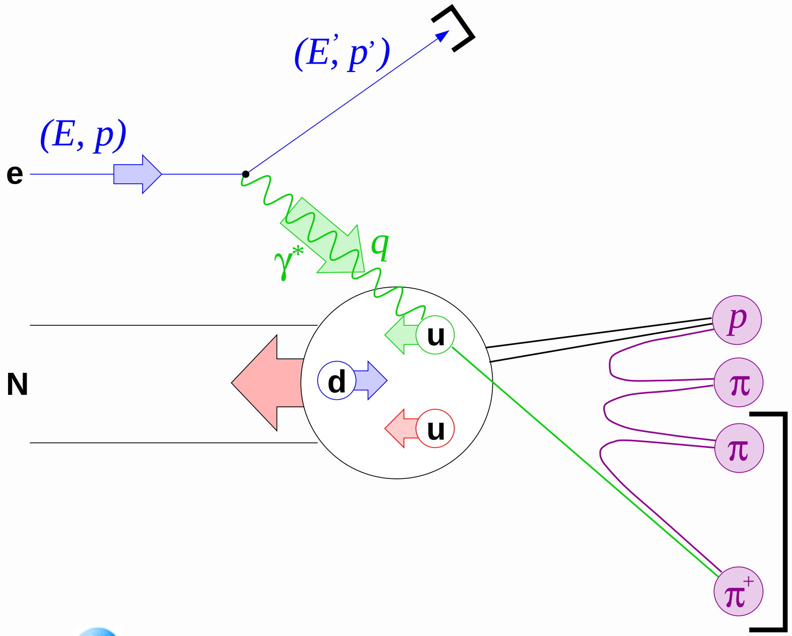


$$A_T = \frac{1}{\langle P_T \rangle} \cdot \frac{\frac{N^+}{\mathcal{L}^+} + \frac{N^-}{\mathcal{L}^-} - 2\,\frac{N^0}{\mathcal{L}^0}}{\frac{N^+}{\mathcal{L}^+} + \frac{N^-}{\mathcal{L}^-} + \frac{N^0}{\mathcal{L}^0}}$$

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

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

Semi–Inclusive DIS



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

$\Rightarrow$ 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:

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

- Solving the system of equations

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

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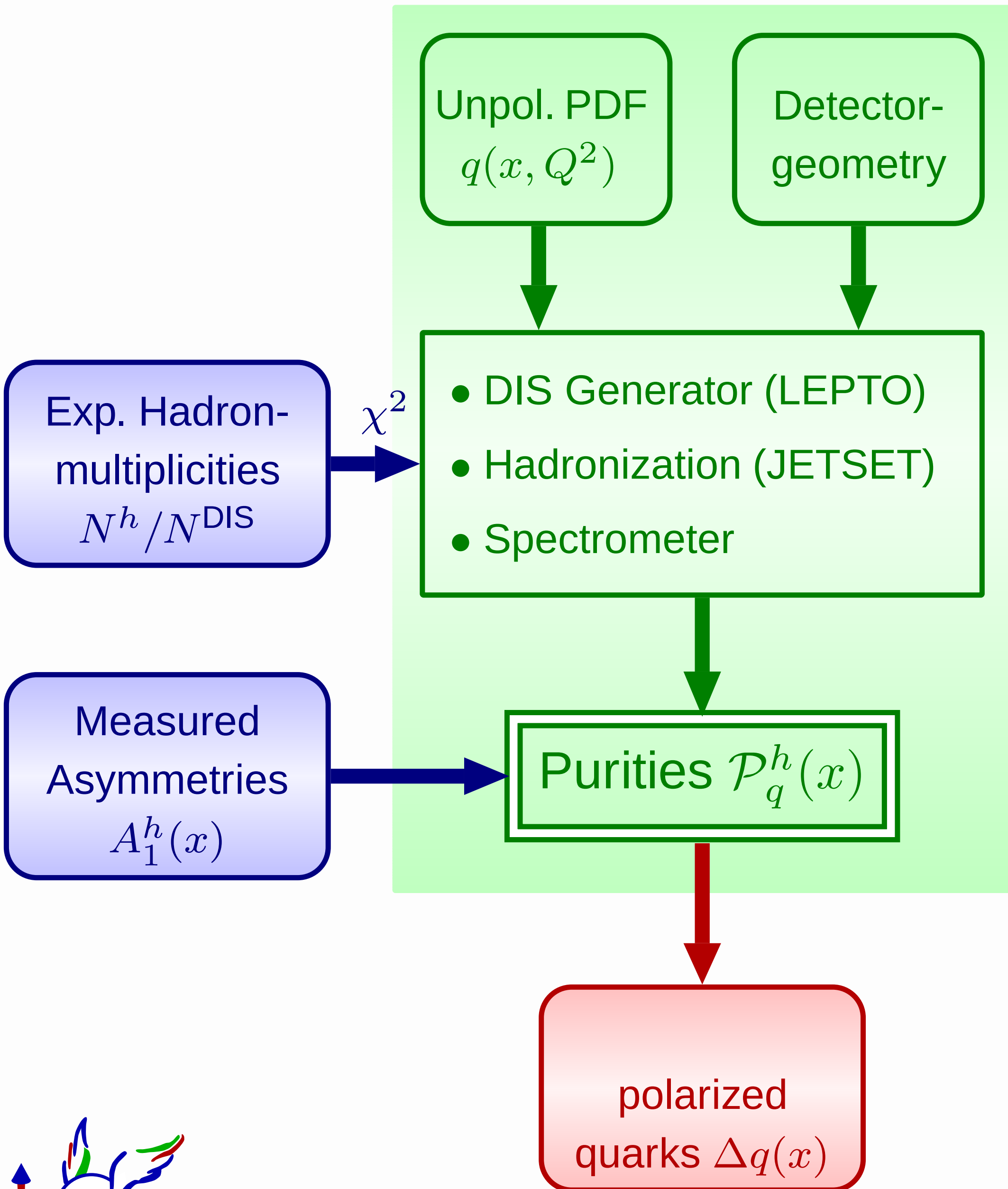
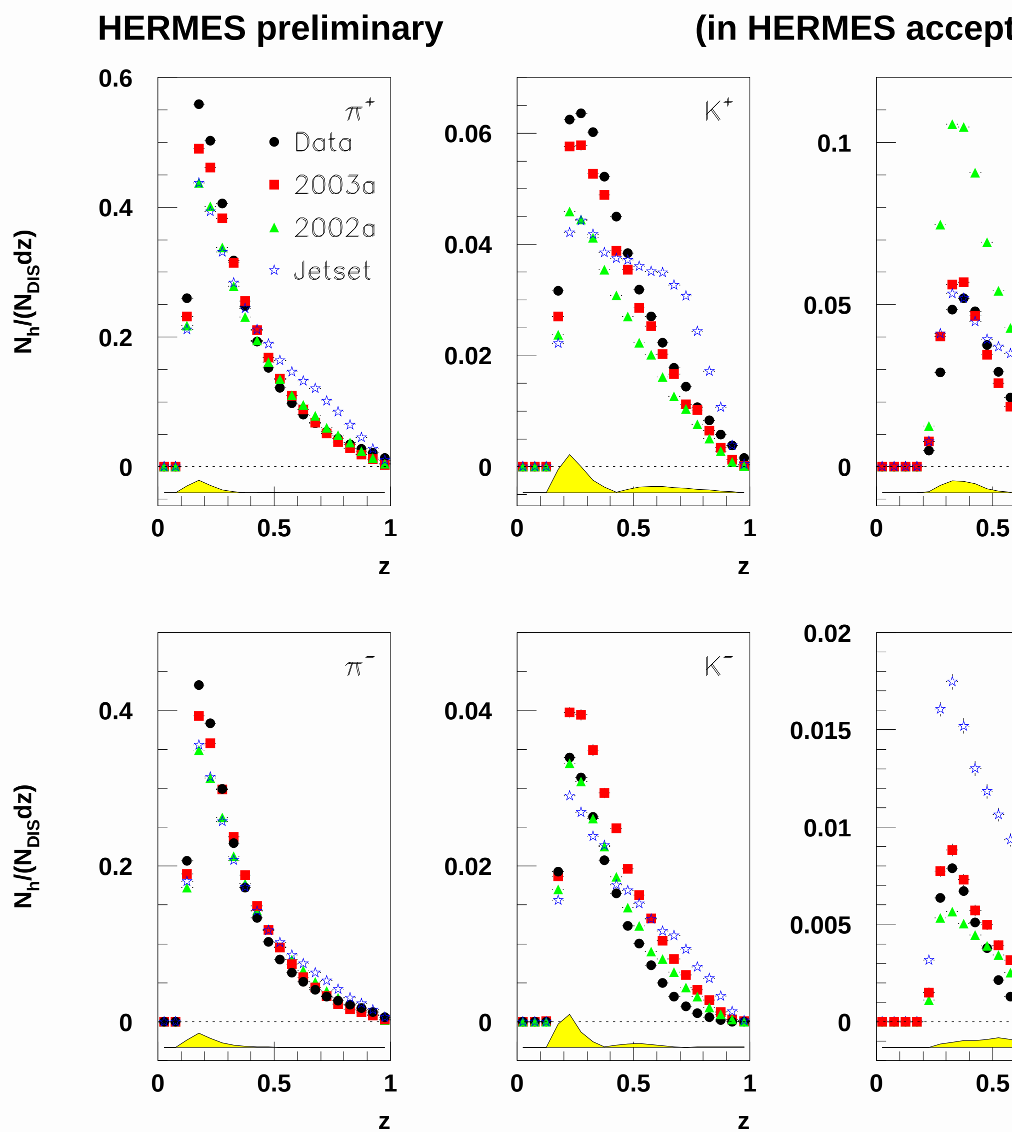
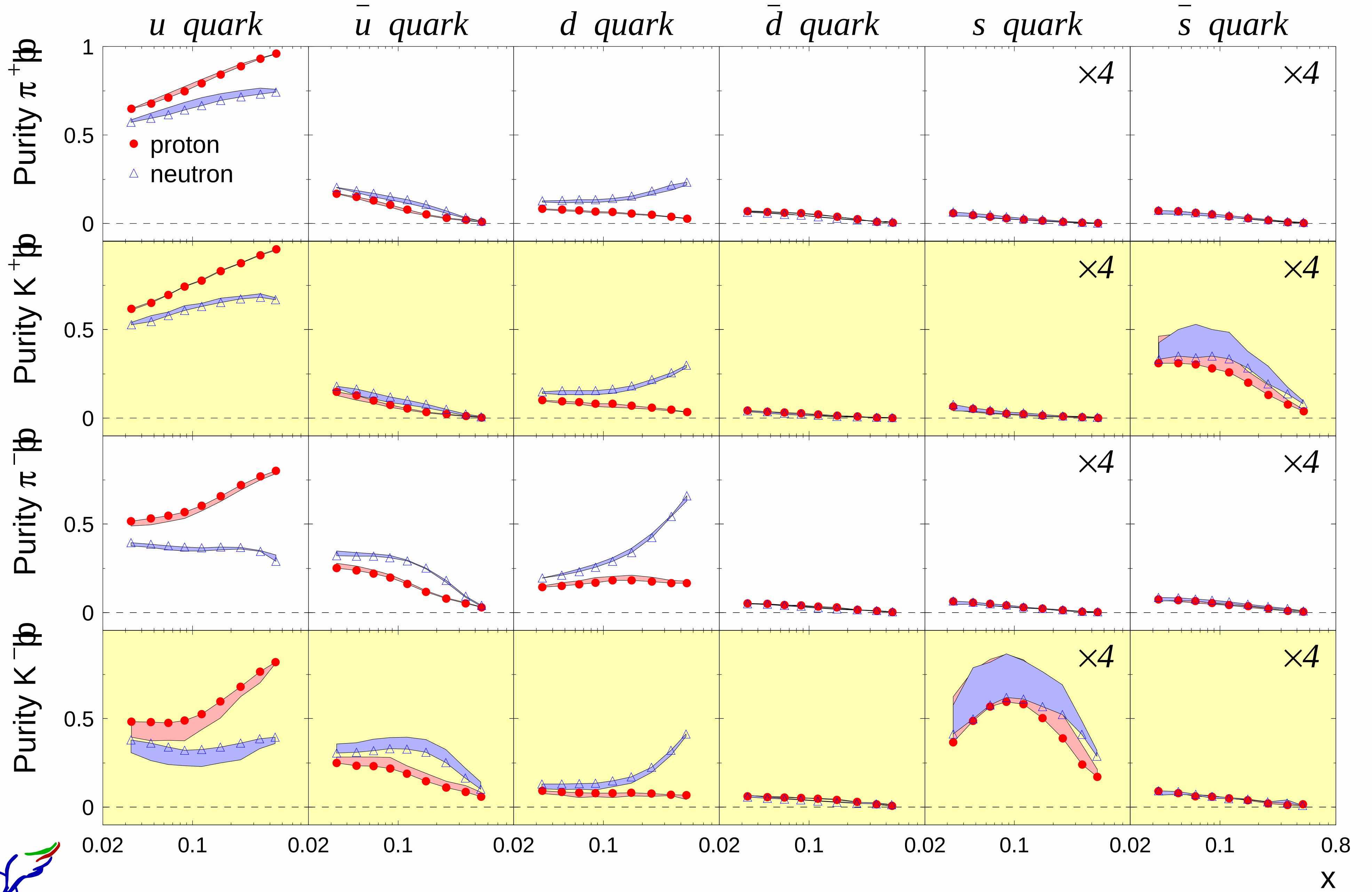
Monte Carlo Model for Hadronization

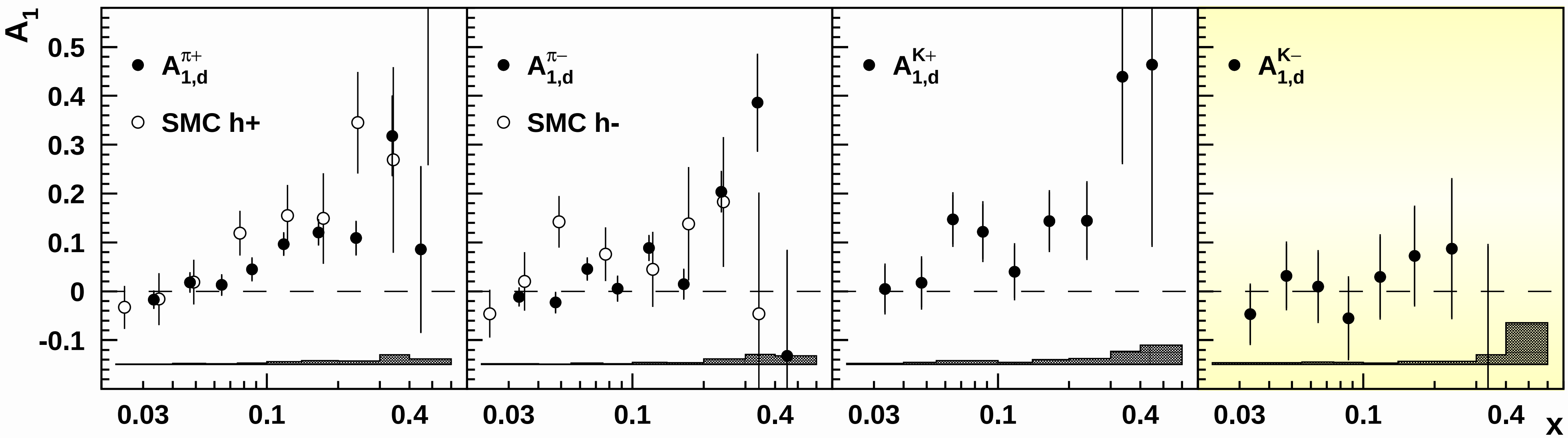




Generated Purities



Pion and Kaon Asymmetries on Deuteron

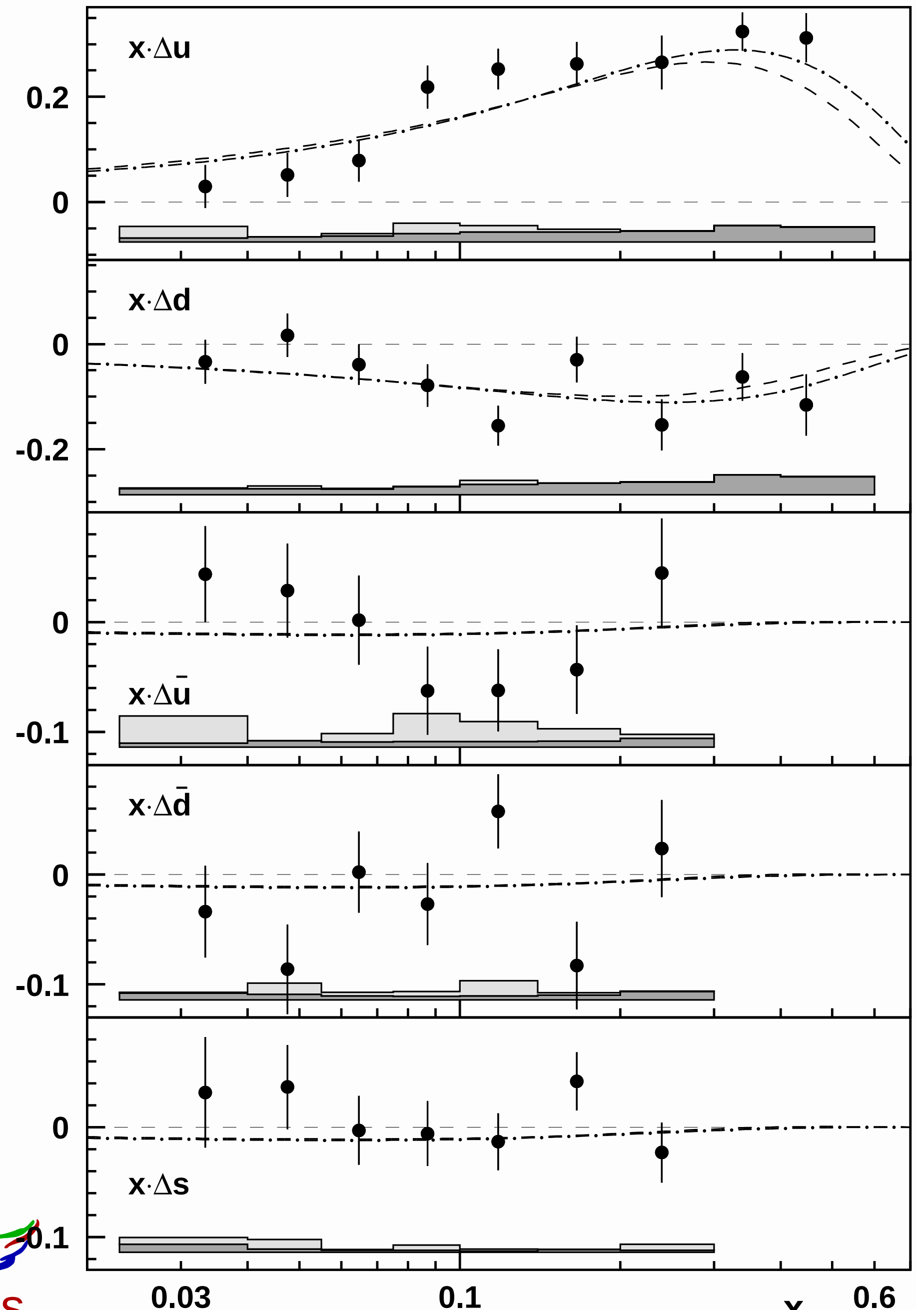


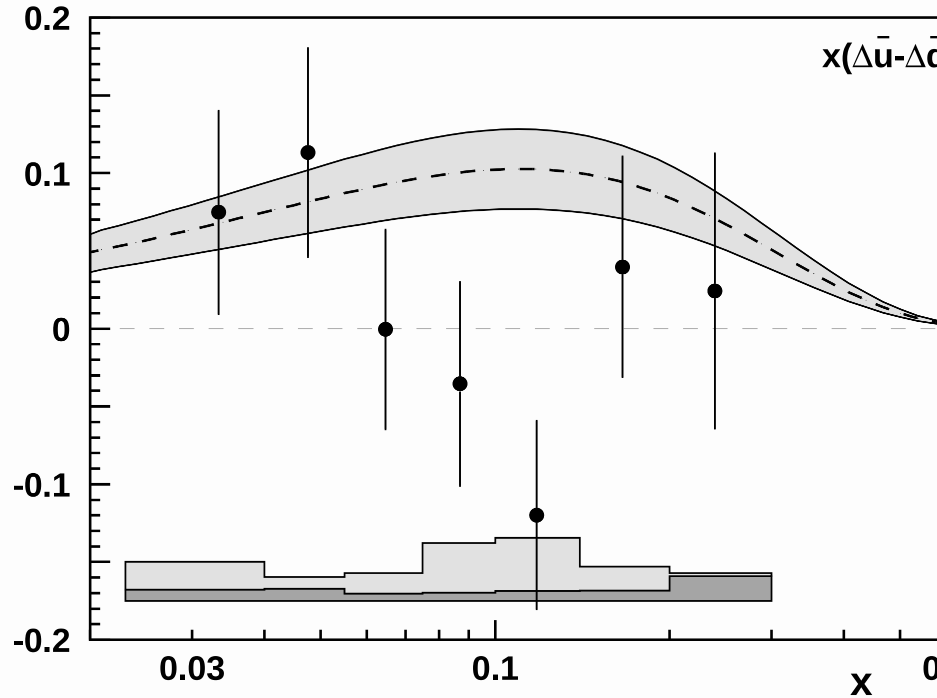
[A. Airapetian et al., hep-ex/0307064]

- Hadrons selected with $0.2 \leq z = E_h/\nu \leq 0.8, \;\; x_F \geq 0.1, \;\; W^2 \geq 10$ 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 erros dominated by beam and target polarization uncertainties

Polarized Quark Distributions (LO)

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

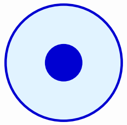




- Results consistent with $SU(3)_f$ symmetric sea assumption
- Disagreement with the prediction for $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ from χQSM

  [B. Dressler et al., Eur. Phys. J. **C14** (2000) 1

Transversity

$f_1^q =$ 

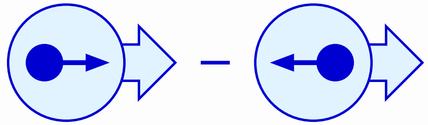
Unpolarized
Quarks and Nucleons

Vector Charge:

$$\langle PS|\bar{\psi}\gamma^{\mu}\psi|PS\rangle =$$

$$\int_0^1 dx\, q(x) - \bar{q}(x)$$

$q(x)$: sping averaged
well known

$g_1^q =$ 

Longitudinally polarized
Quarks and Nucleons

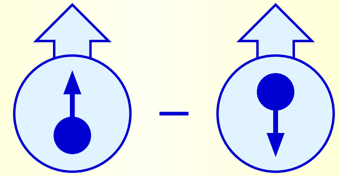
Axial Charge:

$$\langle PS|\bar{\psi}\gamma^{\mu}\gamma_5\psi|PS\rangle =$$

$$\int_0^1 dx\, \Delta q(x) + \Delta\bar{q}(x)$$

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

HERMES: 1995 - 2000

$h_1^q =$ 

Transversly 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

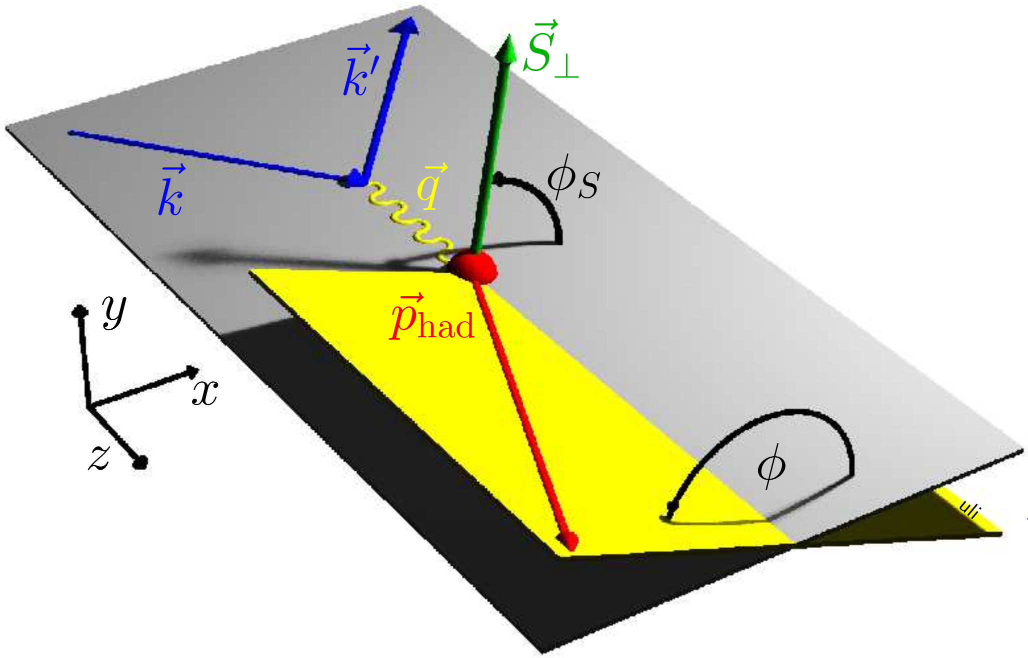
HERMES: 2002. . .

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	Fragmenta[tion] function
Chiral odd	Chiral odd



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

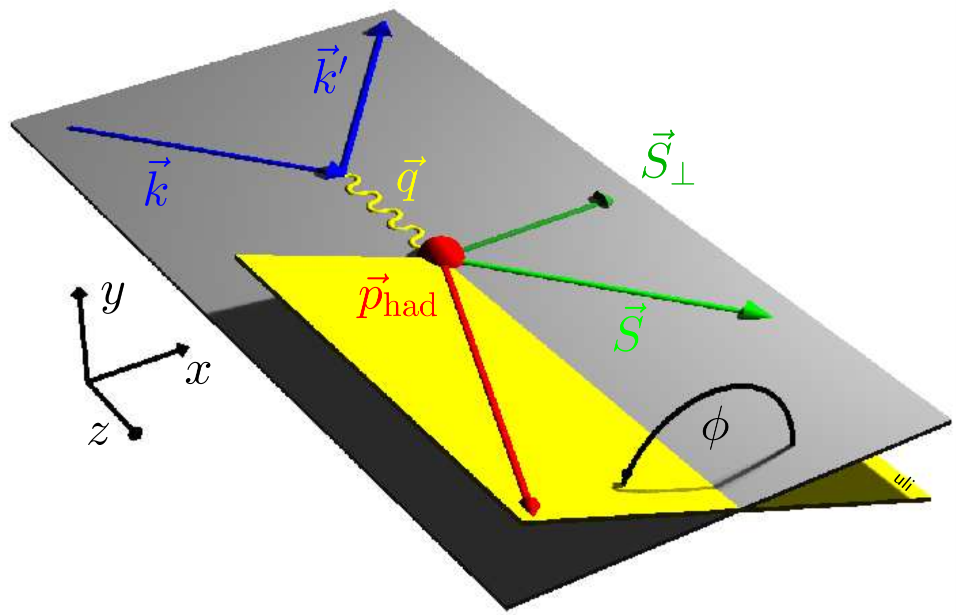
$$A_{UT}^{\sin\Phi} \propto \frac{\sum_{i=1}^{N^+} \sin\Phi - \sum_{i=1}^{N^-} \sin\Phi}{(N^+ + N^-)/2}$$

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

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

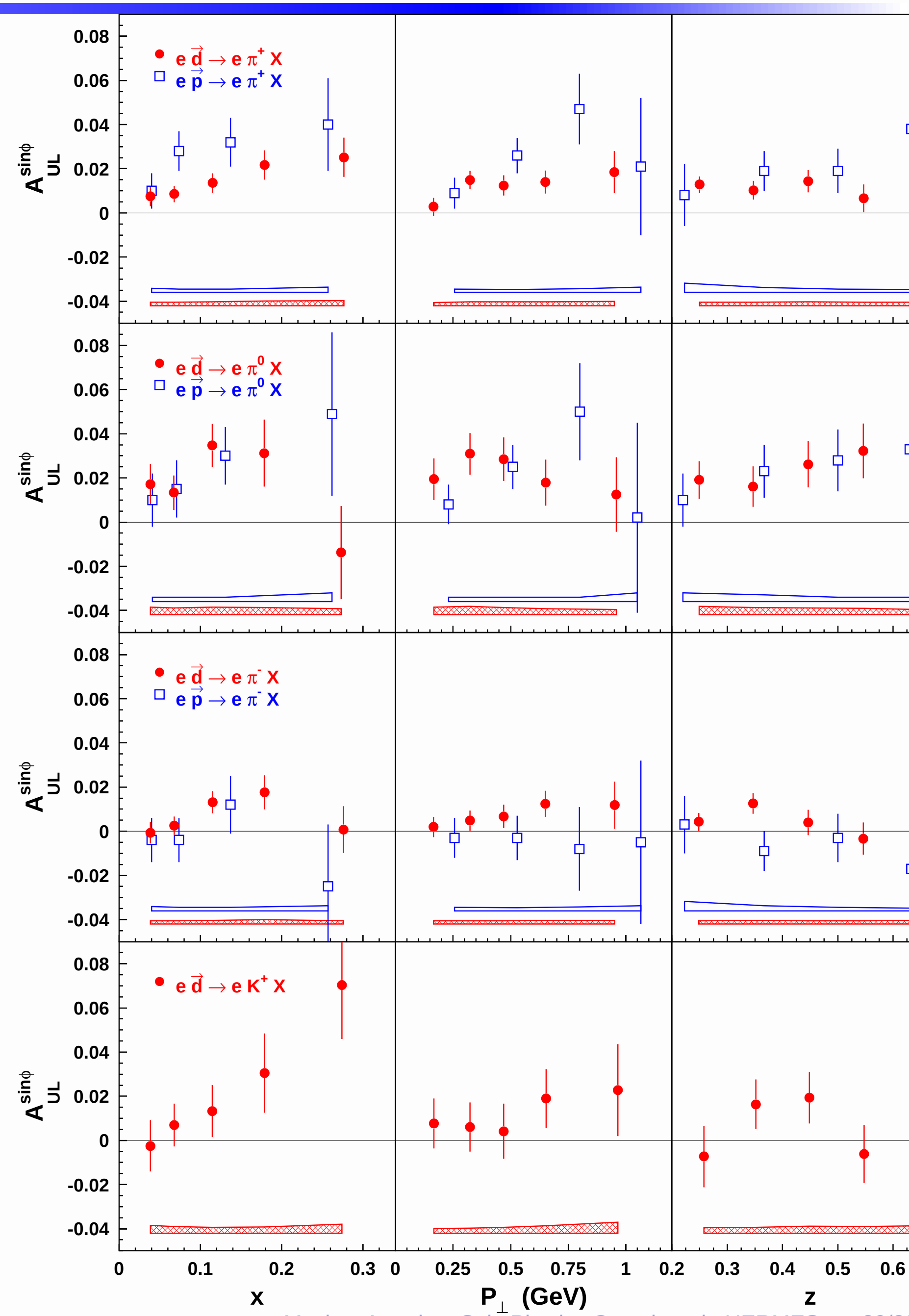
First Hint on Transversity?

Measurement on **longitudinally** polarized $\vec{\mathrm{H}}$– and $\vec{\mathrm{D}}$–targets:



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

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



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Interpretations. . .

- In principle different explanations for ϕ–Asymmetries on **longitudinally** polarized target:
  - Collins–Effect $\rightarrow$ χQSM + “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.] $\rightarrow$ $\langle \sin\phi \rangle_{\mathrm{UL}} \propto f_{1T}^{\perp(1)} \cdot D_1$
- **Longitudinally polarized target:** Collins– and Sivers–Effects indistinguishable
- **Transversly 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 $\langle \sin\phi \rangle_{\mathrm{UT}}$ expected, however ...

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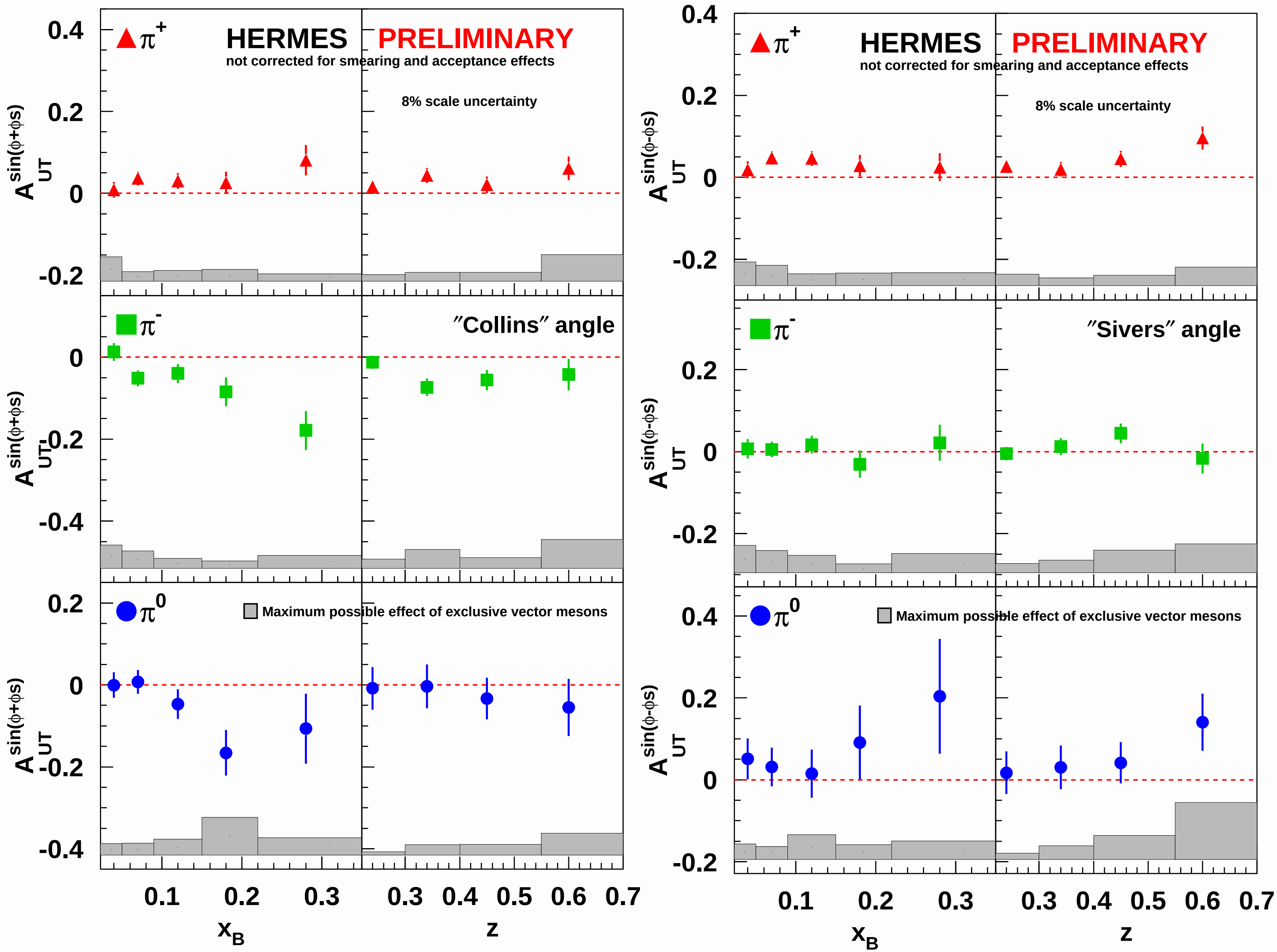
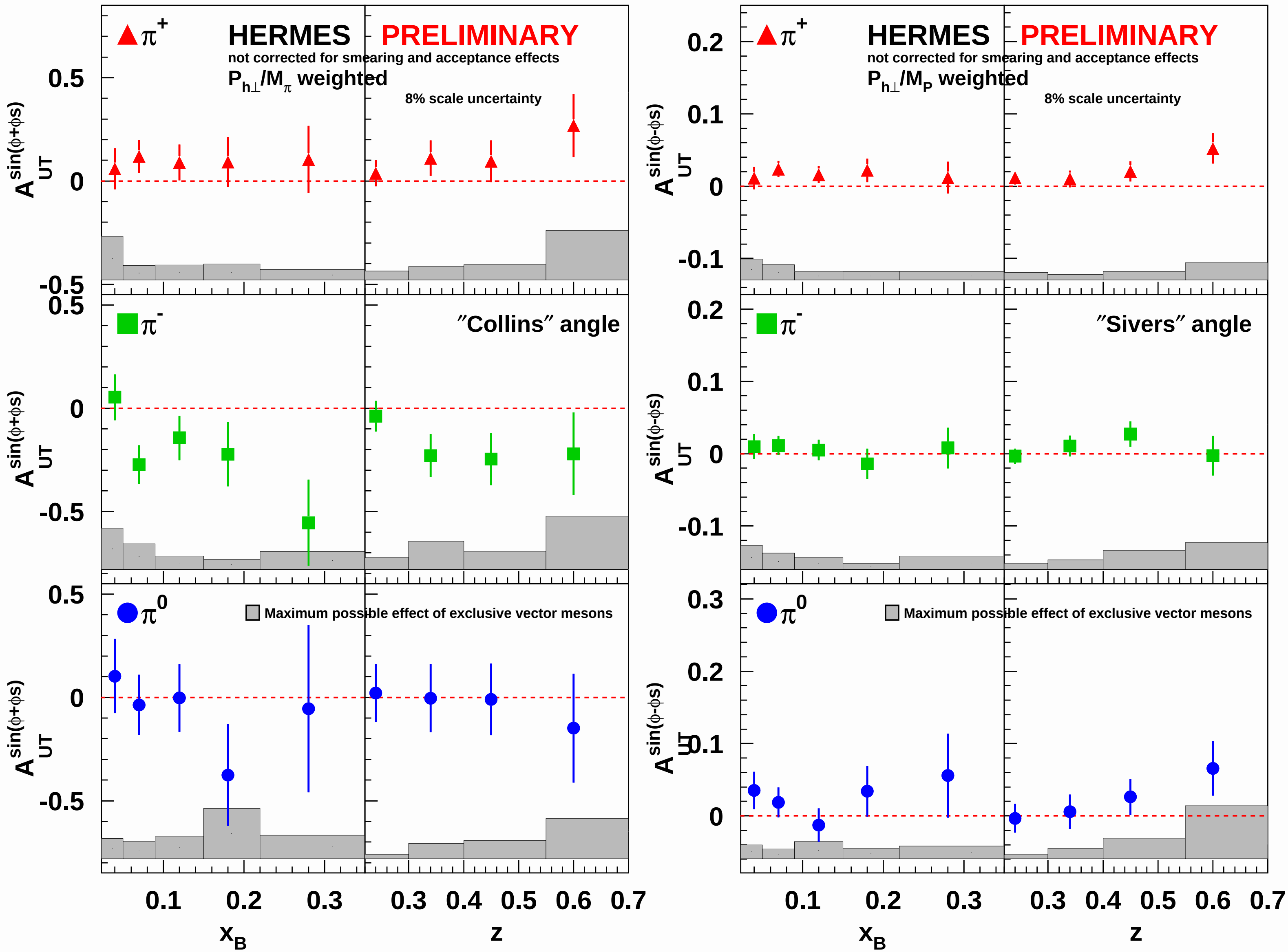
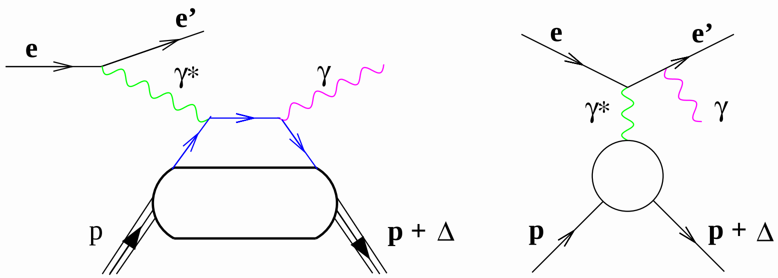
First Measurement of Transverse Asymmetries



$P_{h\perp}$ weighted Transverse Asymmetries



DVCS: $ep \to e'\gamma p$



DVCS Bethe-Heitler (BH)

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

HERMES, CLAS:

DVCS-BH interference:

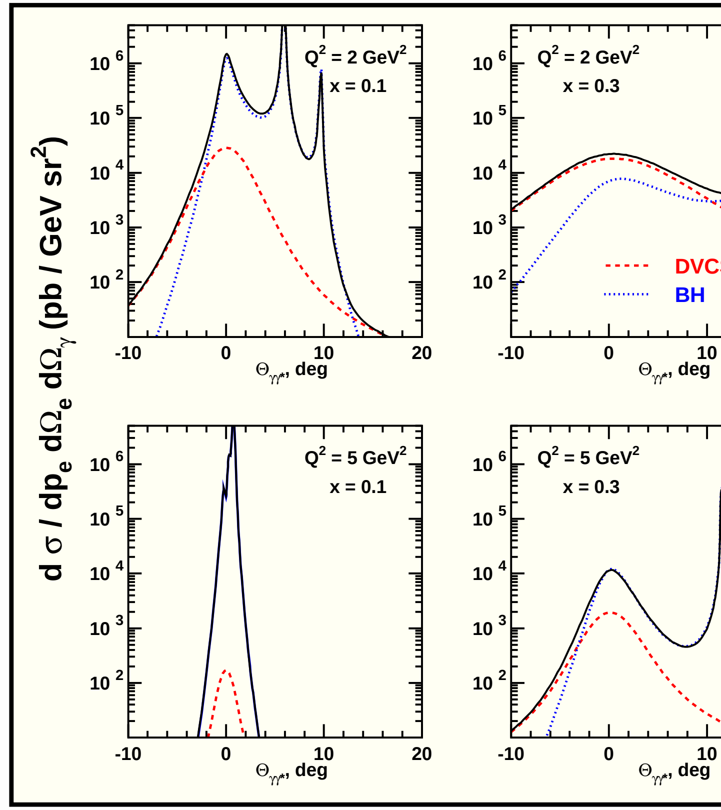
$\Longrightarrow$ use BH as an amplifi er to study DVCS

H1, ZEUS:

measure DVCS cross section directly

HERMES kinematics:

BH > DVCS

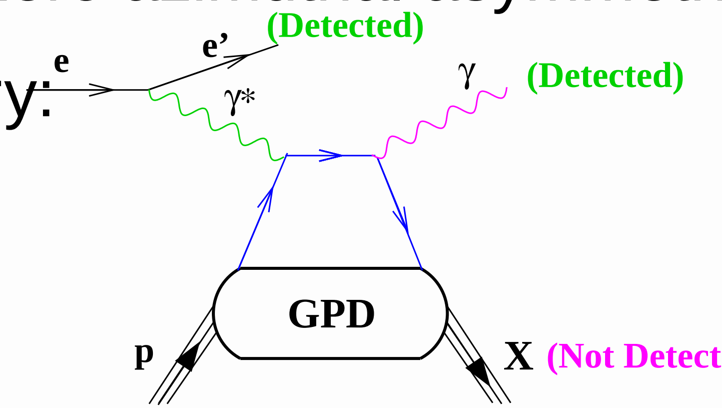


[Korotkov, Nowak, hep-ph/0108077]

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 $\Longrightarrow$ non-zero azimuthal asymmetri



- imaginary part $\propto$ beam helicity asymmetry:

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

$\Rightarrow$ asymmetry measured by HERMES

- real part $\propto$ beam charge asymmetry:

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

$\Rightarrow$ asymmetry measured by HERMES $\Rightarrow$ unique to HERA

- no polarized target needed

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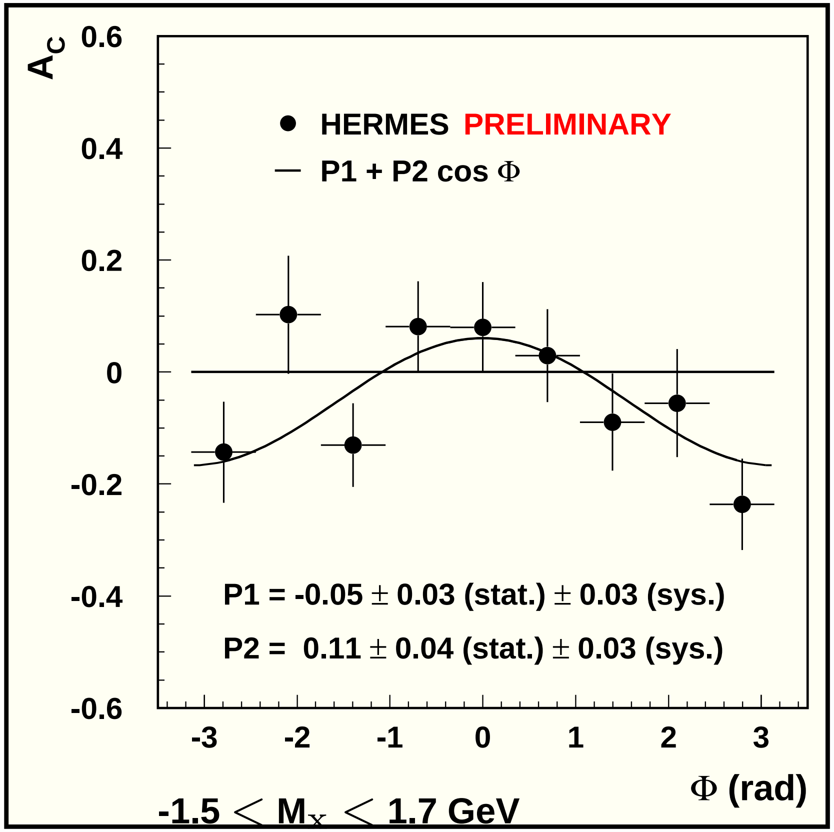
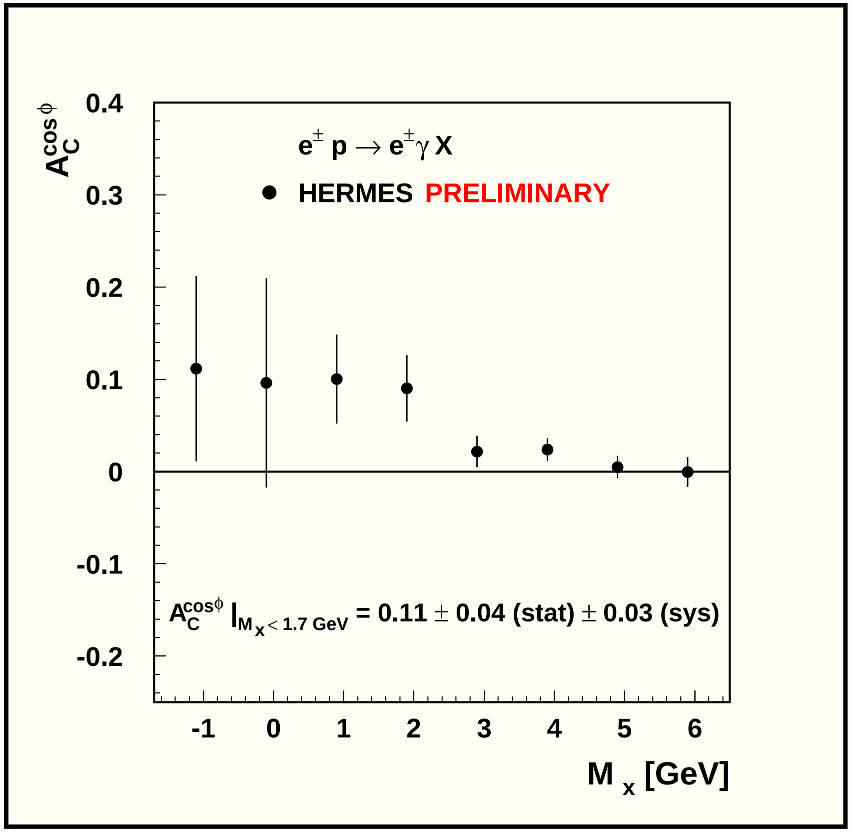
DVCS beam charge asymmetry (BCA)

- $d\sigma_{e^+} - d\sigma_{e^-}$ sensitive to $\mathrm{Re}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS}) \Longrightarrow \cos\phi$





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

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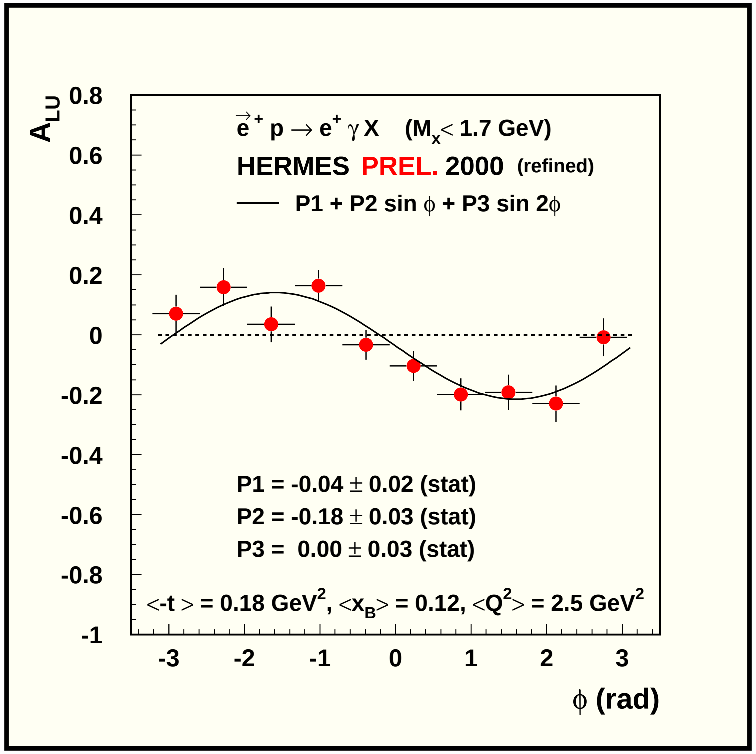
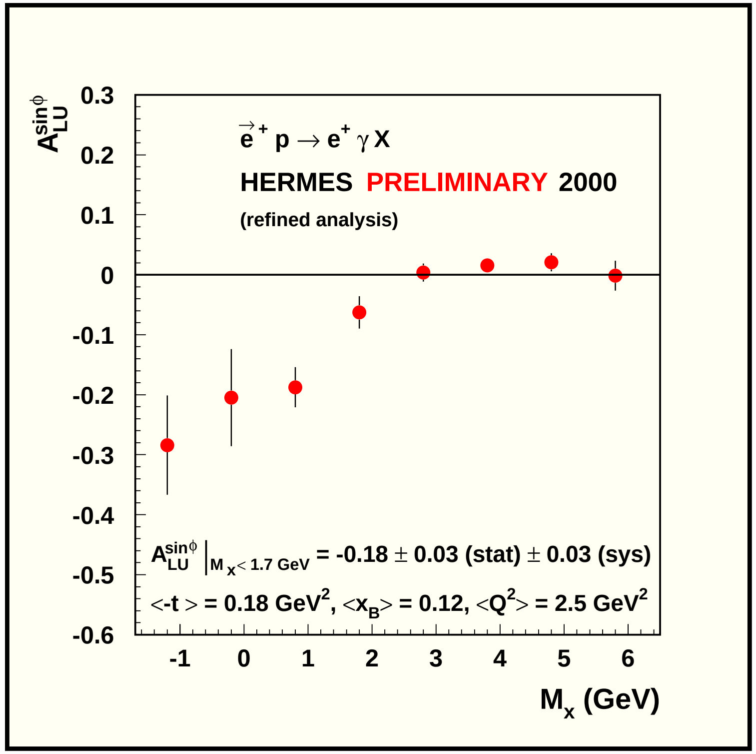
- azimuthal asymmetry appears at $M_x \sim M_p$

DVCS single beam-spin asymmetry (BSA)

- $d\sigma_{\overleftarrow{e}^+} - d\sigma_{\overrightarrow{e}^+}$ sensitive to $\mathrm{Im}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS}) \Longrightarrow \sin\phi$





- 96/97 - data set published: [PRL87 (2001), 182001]
- DVCS on polarized proton / deuterium target $\Longrightarrow$ access to $\tilde{\mathrm{H}}, \tilde{\mathrm{E}}$
- DVCS data on nuclear targets (D, He, Ne, Kr)
  $\Longrightarrow$ coherent scattering on nucleus !

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Summary

- Polarized $\underline{singlet}$ and $\underline{nonsinglet}$ distributions are well constrained
- Semi-inclusive measurements allow for the first time to extract polarized quark distributions
- Polarized gluon distribution ΔG has very large uncertainty
- For the first time $b1$ structure function of the deuteron is measured
- For the first time $\underline{Collins}$ and $\underline{Sivers}$ asymmetries are addressed experimentally
- Large amount of data on $\underline{DVCS}$ 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

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