Spin Physics with HERMES

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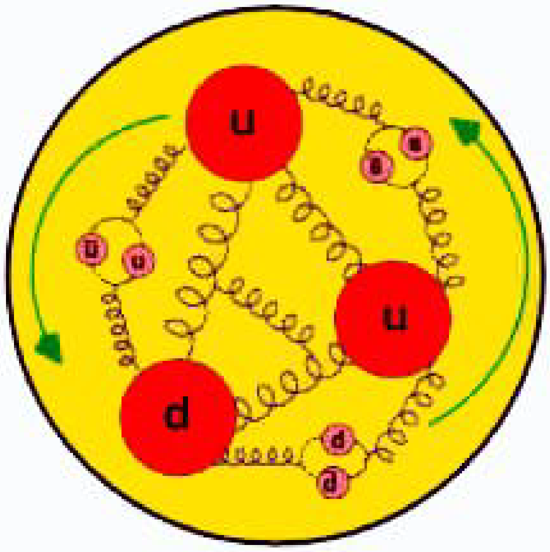
- Introduction to polarized DIS
- The HERMES Experiment
- Double-Spin Asymmetries
  - ▷ inclusive ⇒ Polarized SF g_1
  - ▷ semi-incl $h^{\pm}$ ⇒ Polarized PDF Δq
  - ▷ High p_t $h^{\pm}$ ⇒ Gluon polarization $\Delta G/G$
- Single-Spin Asymmetries
  - ▷ semi-incl $\pi^{\pm}$ ⇒ New polarised SF and FF
- Other physics results
- Summary-outlook

Contributions to the Nucleon Spin

The current view of the proton (and neutron) structure is a complex object made up by moving and interacting quarks (valence and sea) and gluons



One of the current fundamental issue is to understand how the different objects inside the proton contribute to the total spin

$$\frac{1}{2} = \frac{1}{2}\Sigma + \Delta G + \Delta L_{q/g}$$

$\Sigma \rightarrow \Delta u + \Delta d + \Delta s$

$\Delta G \rightarrow$ PGF

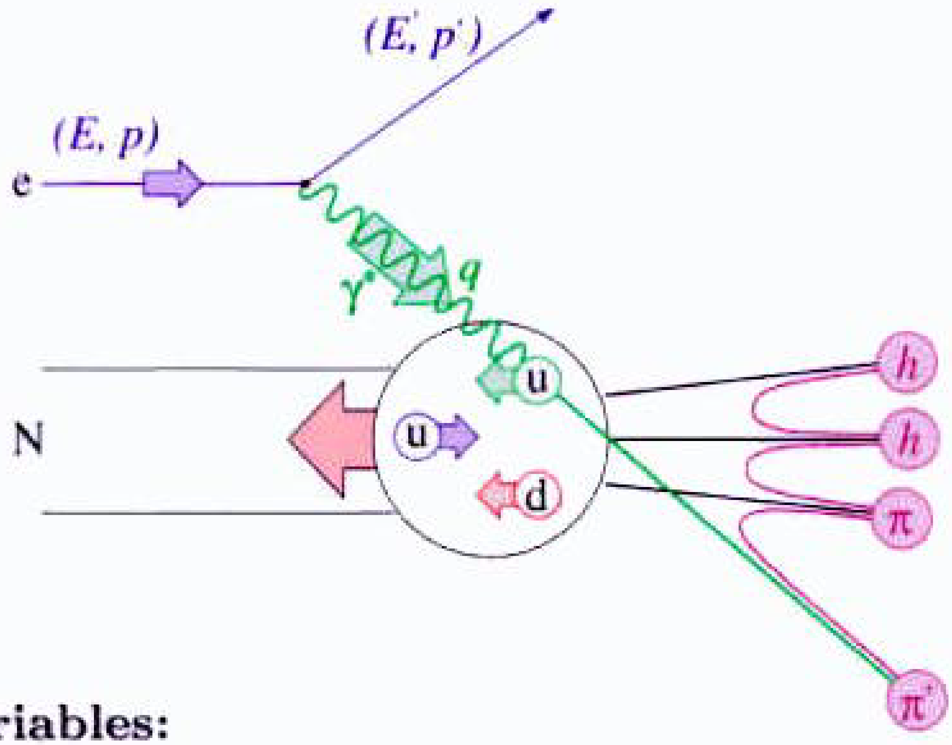
$\Delta L_{q/g} \rightarrow$?

$\Delta u + \Delta d + \Delta s \rightarrow \Delta V$, ΔS

$\Delta V \rightarrow$ inclusive

$\Delta S \rightarrow$ semi-inclusive

Polarized Deep Inelastic Scattering



DIS Variables:

$$
\begin{aligned}
Q^2 &\overset{lab}{=} 4EE'\sin^2(\tfrac{\theta}{2}) \\
\nu &\overset{lab}{=} E - E' \\
x &\overset{lab}{=} \frac{Q^2}{2m\nu} \\
y &\overset{lab}{=} \frac{\nu}{E} = \frac{p\cdot q}{p\cdot k} \\
z &\overset{lab}{=} \frac{E_h}{\nu}
\end{aligned}
$$

- **Inclusive: detect E'**
- **Semi-Inclusive: detect E' and h**

  flavour tagging

Cross Section:

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

$$L^{\mu\nu} = 2\left[k_\mu k'_\nu + k_\nu k'_\mu - (k \cdot k')\, g_{\mu\nu} + Mi\epsilon_{\mu\nu\alpha\beta} S^\alpha (k - k')^\beta\right]$$

Where: $S^\alpha = \frac{1}{2}\overline{u}(k,s)\,\gamma^\alpha\gamma_5 u(k,s)$

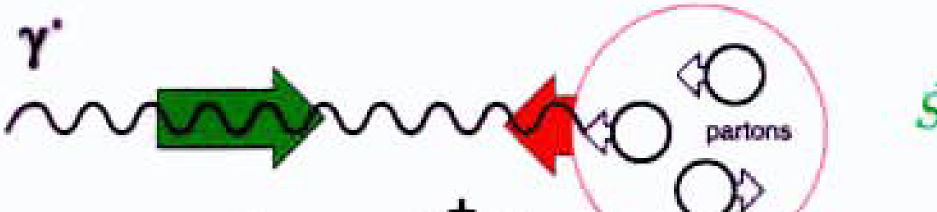
$$\begin{aligned} W_{\mu\nu} \quad = \quad & -g_{\mu\nu} F_1\left(x, Q^2\right) \\ & + \frac{p_\mu p_\nu}{\nu} F_2\left(x, Q^2\right) \\ & + \frac{i}{\nu}\epsilon_{\mu\nu\alpha\beta} q^\lambda S^\sigma g_1\left(x, Q^2\right) \\ & + \frac{i}{\nu^2}\epsilon_{\mu\nu\alpha\beta} q^\lambda \left(p \cdot q S^\sigma - s \cdot q p^\sigma\right) g_2\left(x, Q^2\right) \end{aligned}$$

$F_1, F_2 \Longrightarrow$ **Unpolarized Structure Functions measured averaging over spin**

$g_1, g_2 \Longrightarrow$ **Polarized Structure Functions measured via double spin asymmetries**

Which are the meanings of SF?

Virtual Photon Asymmetry



$\vec{S_\gamma} + \vec{S_N} = 1/2$

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

+: quark spin **parallel** to Nucleon spin

$\vec{S_\gamma} + \vec{S_N} = 3/2$

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

− : quark spin **opposite** to Nucleon spin

Simple interpretation in the Quark Parton Model

$$F_1(x) \quad = \quad \frac{1}{2}\sum_i e_i^2 (q_i^+(x) + q_i^-(x)) \quad = \quad \frac{1}{2}\sum_i e^2 q_i(x)$$

$2xF_1$ measures the quark momentum distribution

$$g_1(x) \quad = \quad \frac{1}{2}\sum_i e_i^2 (q_i^+(x) - q_i^-(x)) \quad = \quad \frac{1}{2}\sum_i e^2 \Delta q_i(x)$$

g_1 measures the quark longitudinal spin distribution

⇒ **flipping spin of target** ⇒ **Quark Spin Distributions:**

What should be measured to extract g_1?

Measurable Asymmetries:

$$A_{\parallel} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} \qquad A_{\perp} = \frac{\sigma^{\uparrow\rightarrow} - \sigma^{\uparrow\leftarrow}}{\sigma^{\uparrow\rightarrow} + \sigma^{\uparrow\leftarrow}}$$

The relation between the asymmetries is:

$A_{\parallel} = D(A_1 + \eta A_2)$ **where** ηA_2 **is small**

$A_{\perp} = d(A_2 + \xi A_1)$

Where: D, η, d, ξ **are Kinematic variables**

$$A_1 = \frac{\sigma_{\frac{1}{2}} - \sigma_{\frac{3}{2}}}{\sigma_{\frac{1}{2}} + \sigma_{\frac{3}{2}}} = \frac{g_1 - \gamma^2 g_2}{F_1}$$

$$A_2 = \frac{\sigma_{TL}}{\sigma_T} = \frac{\gamma(g_1 + g_2)}{F_1} \qquad \gamma = \frac{2Mx}{\sqrt{Q^2}}$$

Neglecting $g_2 \Longrightarrow g_1(x) \approx \frac{F_1(x)}{D} A_{\parallel}$

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \simeq \frac{g_1}{F_1} = \frac{\sum_f e_f^2 \, \Delta q_f(x, Q^2)}{\sum_f e_f^2 \, q_f(x, Q^2)}$$

D,d: virtual photon depolarization factor

R: ratio of long. to trans. photo-absorption

ϵ: transverse pol. of the virtual photon

Sum Rules

No fundamental prediction for $g_1(x)$
(Q^2-evolution from QCD)

Fundamental prediction for the first moments

$$\begin{aligned} \int g_1^p(x) &= \frac{1}{2}\left(\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right) \\ \int g_1^n(x) &= \frac{1}{2}\left(\frac{1}{9}\Delta u + \frac{4}{9}\Delta d + \frac{1}{9}\Delta s\right) \end{aligned}$$

Δu, Δd and Δs polarized quark distribution functions

Bjorken Sum Rule

$$\begin{aligned} \int (g_1^p(x) - g_1^n(x)) &= \frac{1}{2}\left(\frac{1}{3}\Delta u - \frac{1}{3}\Delta d\right) = \frac{1}{6}(\Delta u - \Delta d) \\ \Delta u - \Delta d &= \frac{g_A}{g_V} \qquad \text{(neutron } \beta\text{-decay)} \end{aligned}$$

$$\int (g_1^p(x) - g_1^n(x))dx = \frac{1}{6}\frac{g_A}{g_V} \cdot Corr(QCD)$$

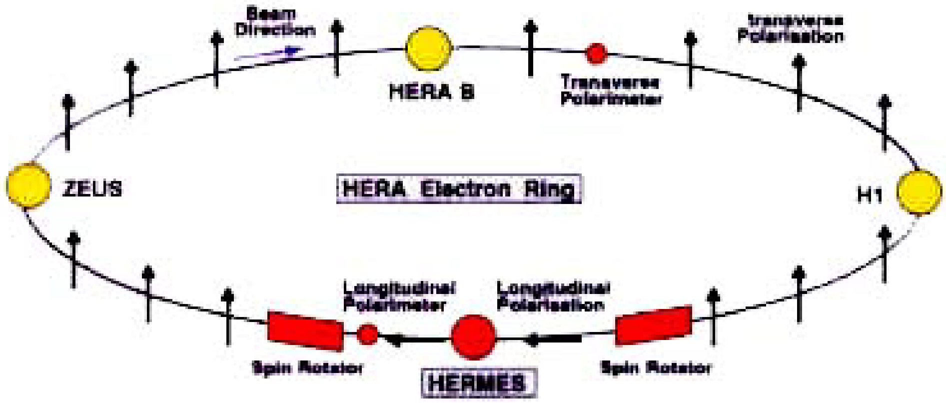
Corrections known to 4th order!

hermes

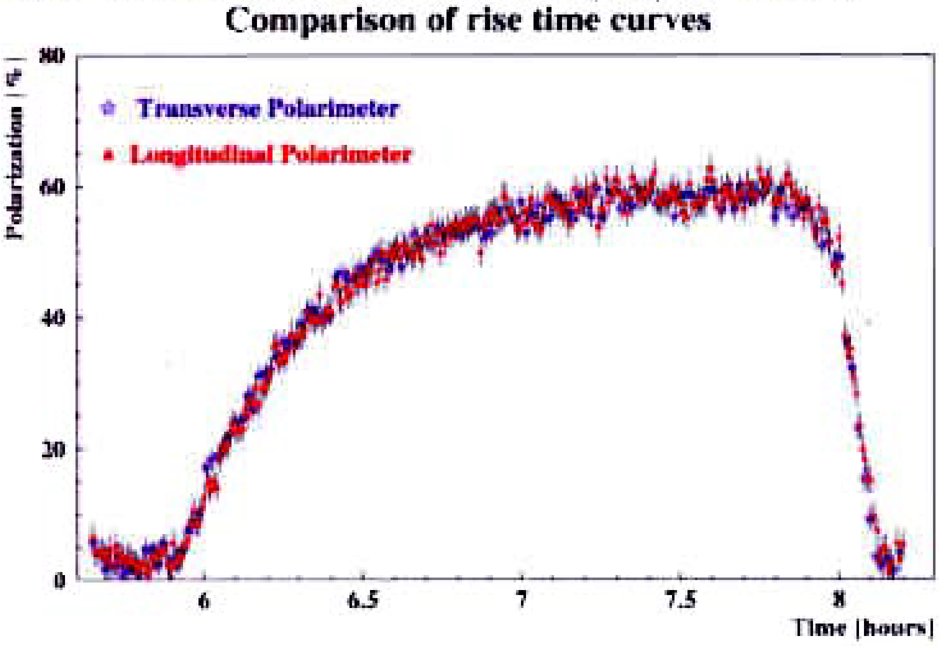
A second generation experiment
designed to study the spin structure
of the nucleon at HERA

Alberta	Freiburg	Munich
Argonne	Gent	N. Mex. St.
Cal Tech	Illinois	NIKHEF
Colorado	JINR, Dubna	Pennsylvania
DESY, Ham.	Kentucky	Rome
DESY, Zeuthen	Liverpool	St. Petersburg
Erlangen	Marburg	Tokyo
Ferrara	MIT	TRIUMF
Florida Int.	Moscow	Wisconsin
Frascati	MPI, Heidelberg	Yerevan

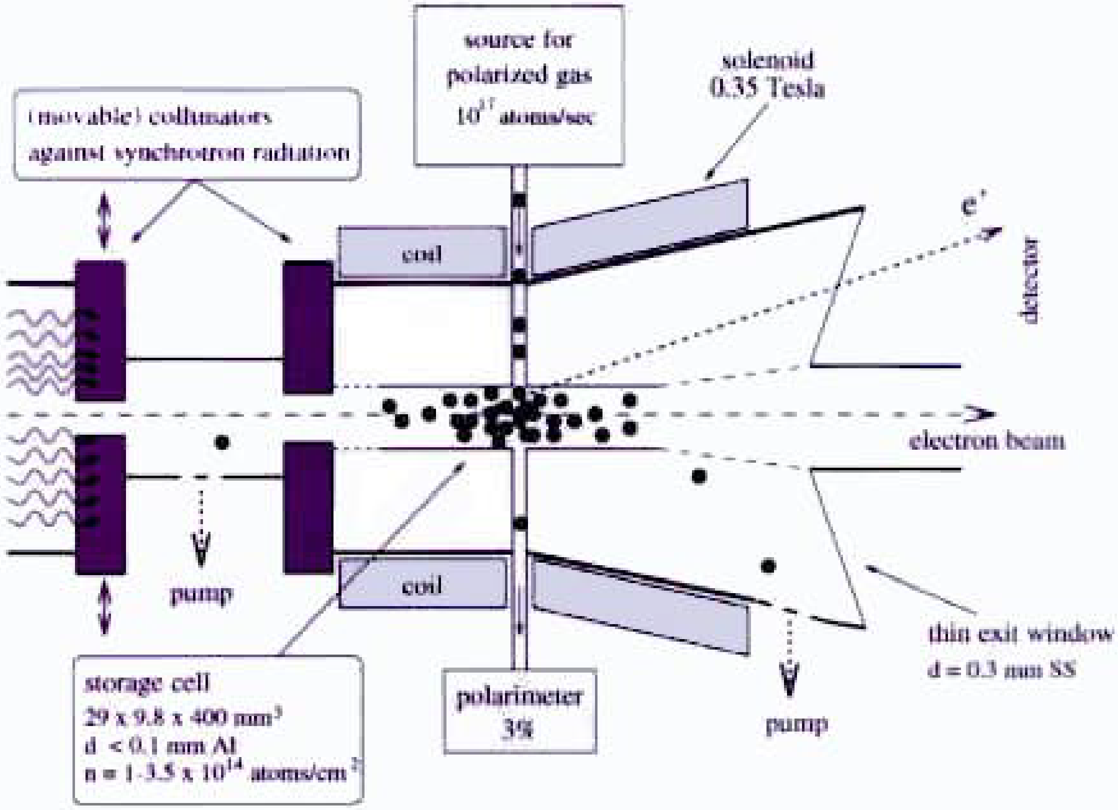
The Polarized Positron Beam at HERA



- 27.5 GeV e^+ (e^-).
- Self-polarization by emission of synchrotron radiation, $P_b(t) = p_b^{max}[1 - exp(t/\tau)]$
- Spin rotators → longitudinal polarization at HERMES IP
- 2 Polarimeters (Compton laser backscattering)
- average beam polarization $\langle P_b \rangle \approx$ 55%

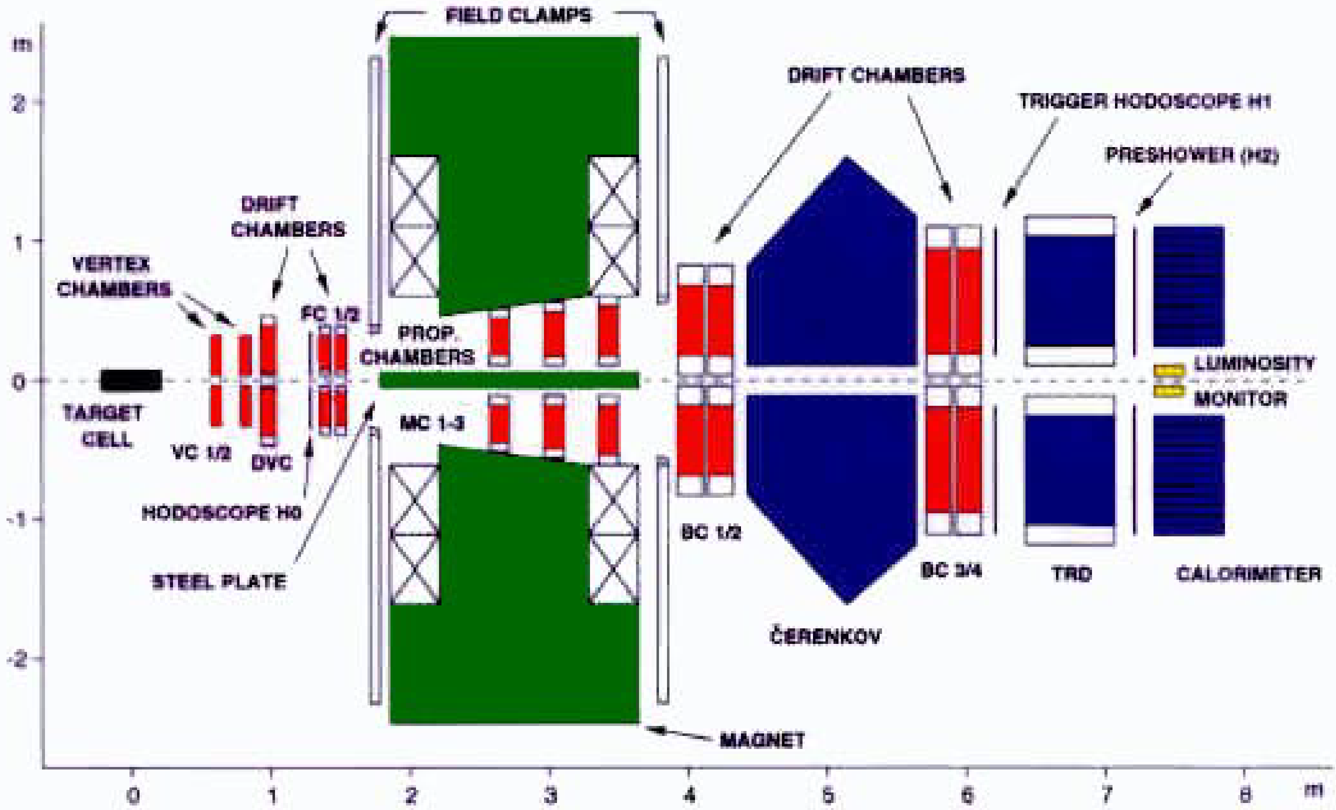


The HERMES Polarized Internal Target



- **Pure (no dilution factor) gas target**
- **laser driven polarised ^{3}He target ($p_T \sim 50\%$) in 95**
- **atomic beam source for polarised H target ($p_T \sim 90\%$) in 96-97**
- **atomic beam source for polarised D target ($p_T \sim 90\%$) in 98-00**
- **transversely polarised H/D target in 01-..**
- **unpolarised high density nuclear target (H, D, ^{3}He, ^{4}He, N, Ne, Kr) in 97-00**

The HERMES Experiment in 97

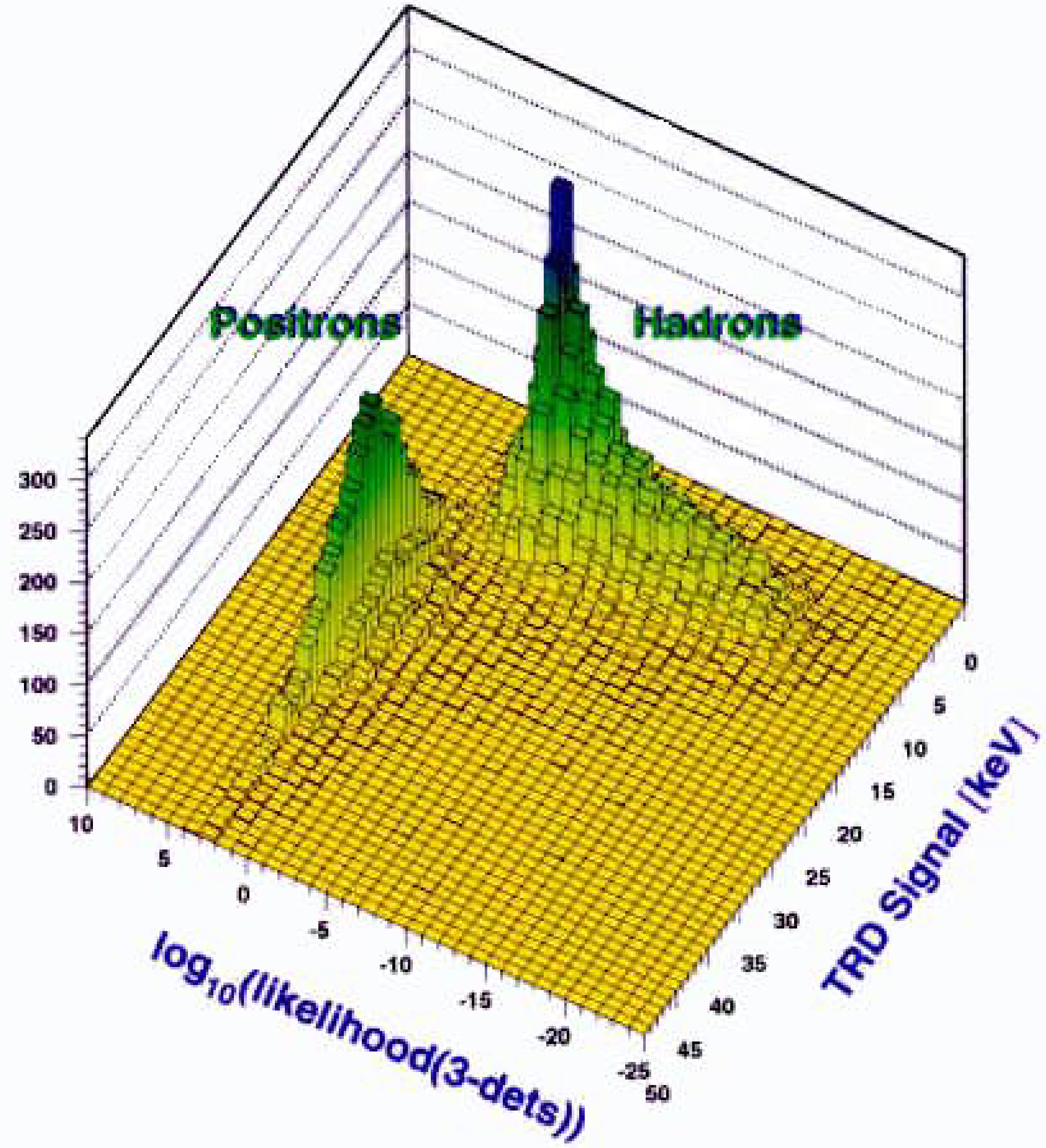


- **Forward dipole spectrometer: 1.5 Tesla m , 40 mrad $< \theta <$ 220 mrad**
- **Charge particle tracking: 57 tracking planes,** $\delta P/P = (0.7 - 1.3)\%$, $\delta\theta < 0.6$ **mrad**
- **Photon detector: 840 lead-glass blocks,** $\delta E/E \sim 5\%/\sqrt{E}$, $\delta\theta \sim 1$ **mrad**
- **Particle identification: Threshold Čerenkov, TRD, Preshower, Calorimeter**

Presented results are related to 95-97 data taking period

Particle Identification

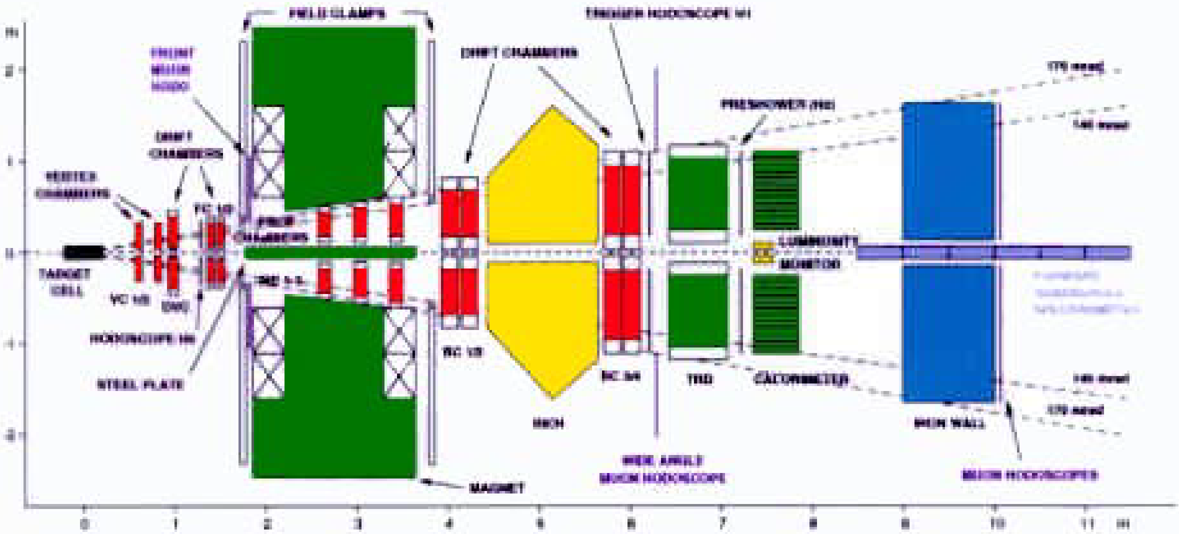
- Lepton hadron separation, from Čerenkov , TRD, Preshower and Calo: e^+ contamination $< 1\%$



- $\pi^{\pm}$ identification: Čerenkov threshold detector

$$4.5GeV < P_{\pi}^{\pm} < 13.5GeV$$

The HERMES Experiment Upgrades



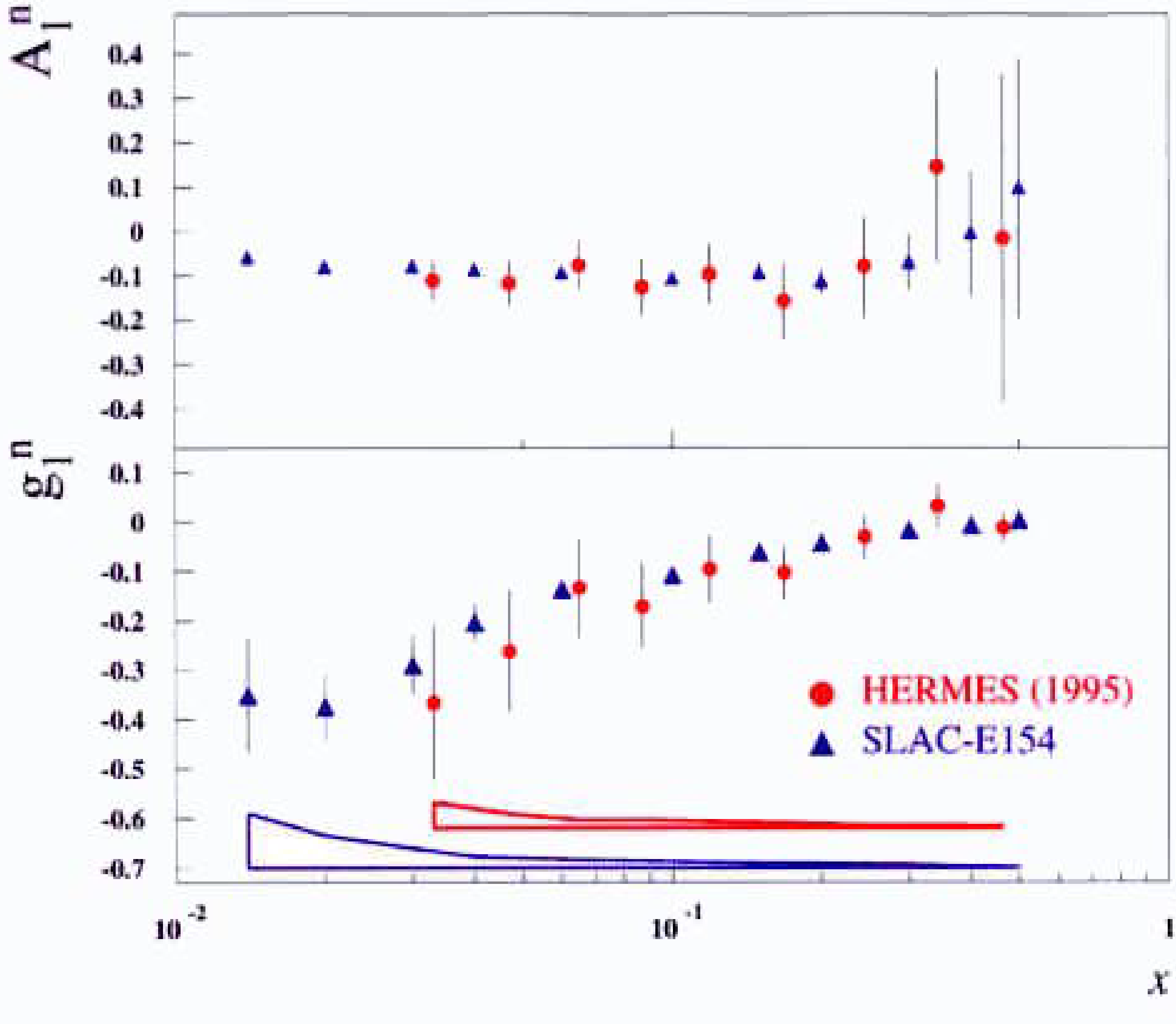
- Double radiator (Aerogel+gas) RICH detector for complete PID in 98
- Muon hodoscope for charm physics in 98
- Forward quadrupole spectrometer for low Q^2 physics in 99
- Large acceptance silicon detector Λ physics in 00
- Silicon recoil detector for exclusive physics in 01

Neutron Spin Structure Function $g_1^n(x)$

Target: $^3\overrightarrow{\mathrm{He}}$, **2 protons paired with spin 0**

$$A_1^{^3\mathrm{He}} \xrightarrow{Nucl.Corr.} A_1^n$$

$$g_1^n \simeq A_1^n \cdot F_1^n = A_1^n \cdot \frac{F_2^n}{2x(1+R)}$$

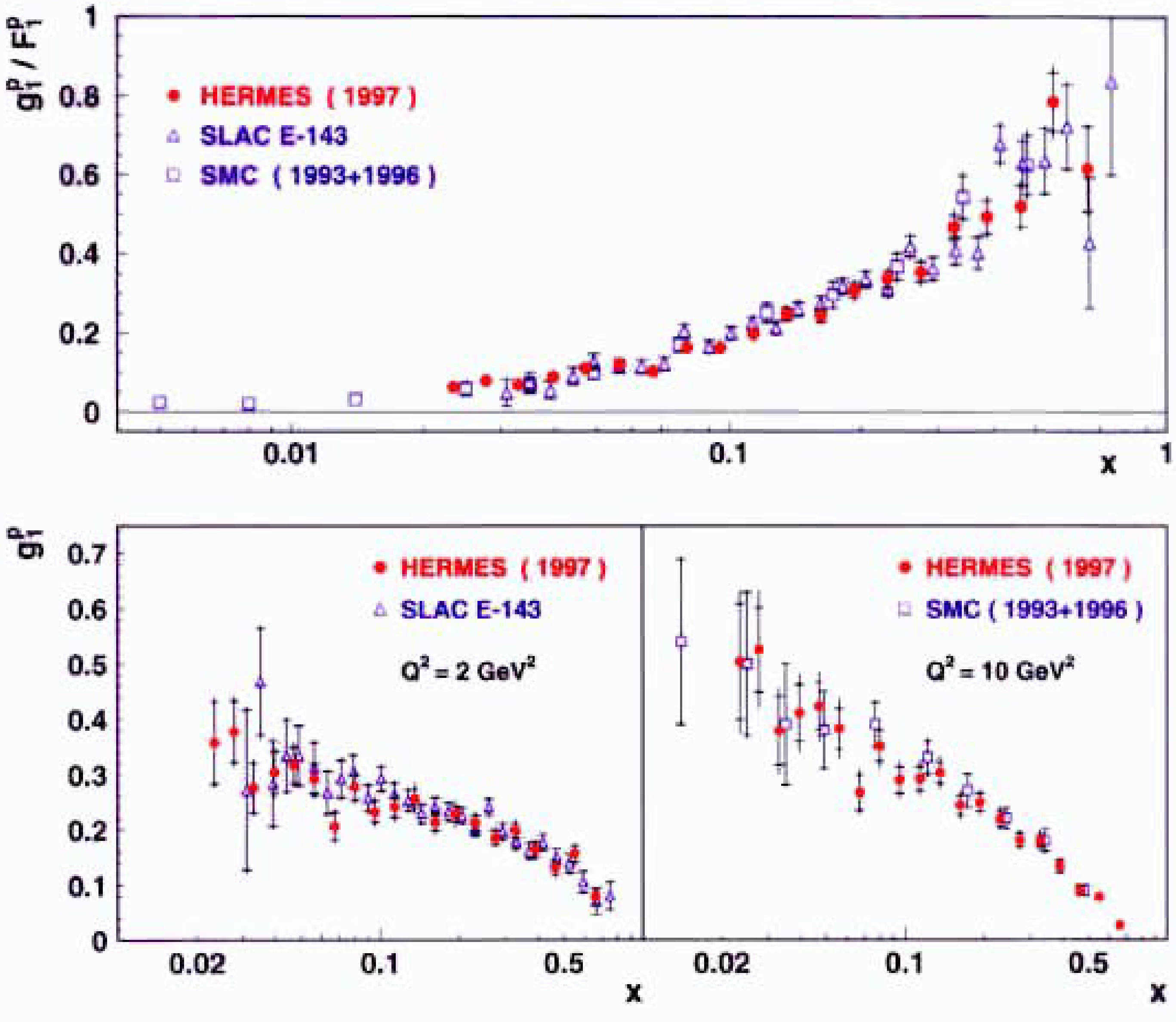


K. Ackerstaff et al., Phys. Lett. B404 (1997) 383-389.

Proton Spin Structure Function $g_1^p(x)$

Target: $\vec{H}$

$$A_1^p \simeq g_1^p / F_1^p \Rightarrow g_1^p \simeq A_1^p \cdot F_1^p = A_1^p \cdot \frac{F_2^p}{2x(1+R)}$$

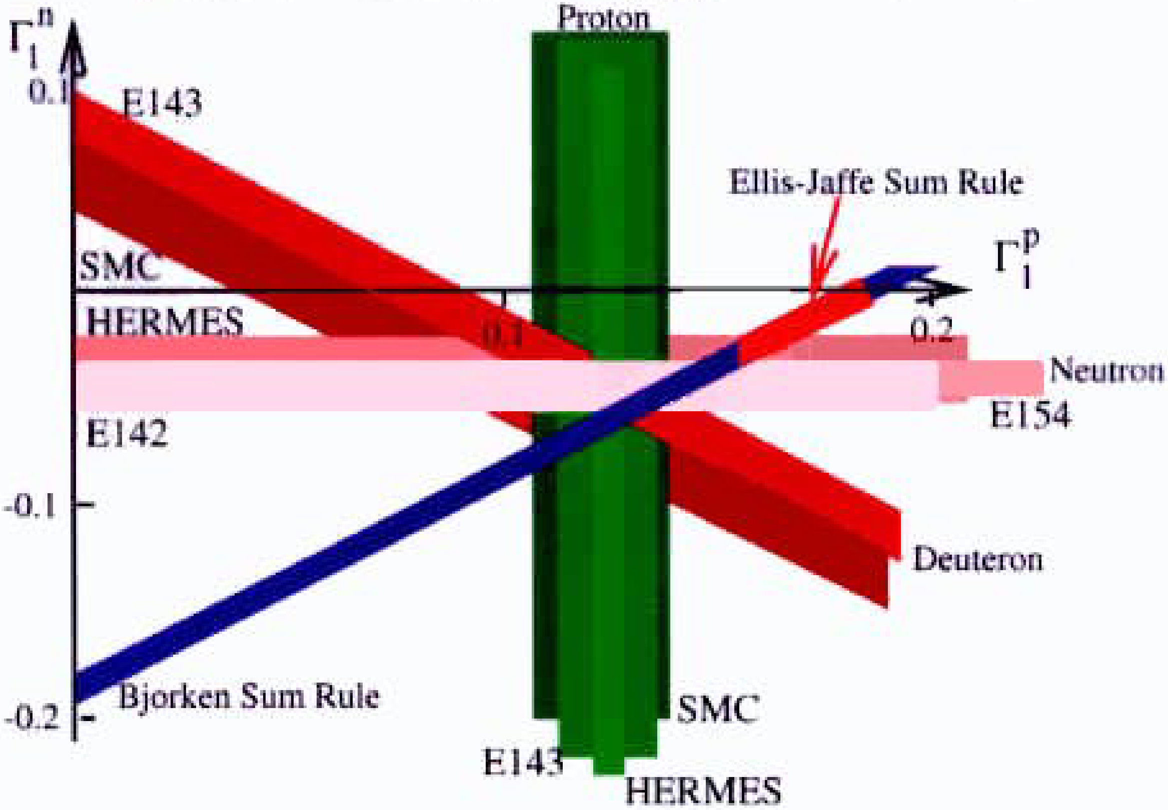


A. Airapetian et al, Phys. Lett. B442 (1998) 484-492.

K. Ackerstaff et al, Phys. Lett. B444 (1998) 531-538.

Bjorken Sum Rule Verification

$$\int (g_1^p(x) - g_1^n(x))dx = \frac{1}{6}\frac{g_A}{g_V} \cdot Corr(QCD)$$



$$\Gamma_1^p = \int_{x=0}^{x=1} g_1^p(x)dx \quad \Gamma_1^n = \int_{x=0}^{x=1} g_1^n(x)dx$$

- **Bjorken Sum Rule OK @ 10% level**
- $\Delta\Sigma \approx 0.2 - 0.4$ **small fraction of the nucleon spin is carried by quarks**
- **New results expected for Deuteron (HERMES) and Proton (E155)**

Semi-inclusive Asymmetries

Flavor - Tagging:
Correlation between struck q_f and detected h.

In LO-QCD:

$$A_1^h(x,Q^2) \simeq \frac{g_1^h(x,Q^2)}{F_1^h(x,Q^2)} = \frac{\int dz \sum_f e_f^2 \Delta q_f(x,Q^2) D_f^h(z,Q^2)}{\int dz \sum_f e_f^2 q_f(x,Q^2) D_f^h(z,Q^2)}$$

- A_1^h Measured semi-inc. asymm.
- Δq_f (q_f) Polarized (unpolarized) quark distributions
- $D_f^h(z)$ fragmentation functions

Unpolarized inputs:

- ▷ $q_f(x,Q^2)$ parameterization
- ▷ $D_f^h(z,Q^2)$ from LUND MC

Assumptions:

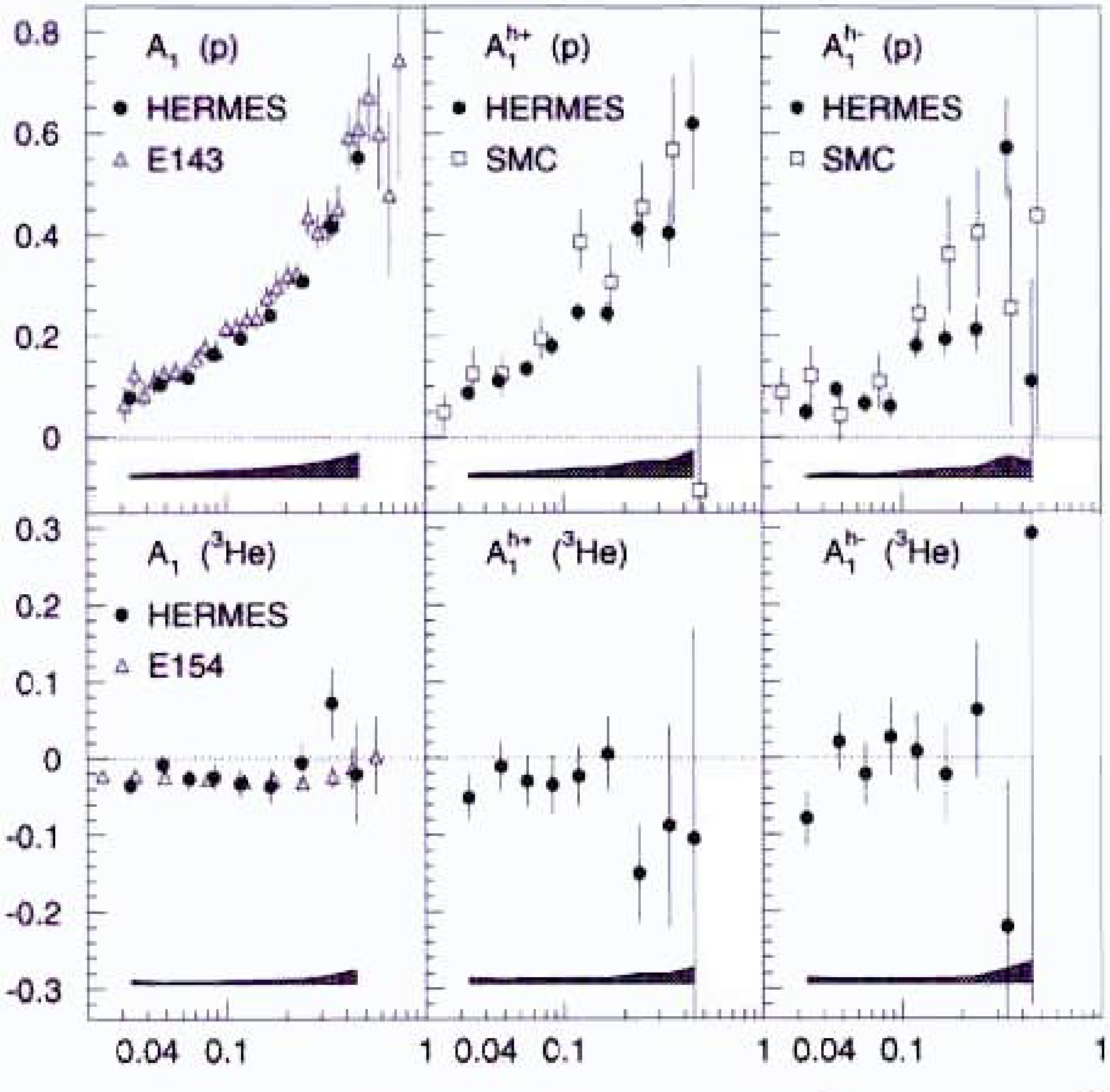
- ▷ Factorization (deep-inelastic scattering, hadronisation)
- ▷ Fragmentation functions spin-independent

Hadron Asymmetries

HERMES Data on $^3\overrightarrow{He}$ (1995) $\overrightarrow{H}$ (1996+1997)

To distinguish between current and target fragments, require:

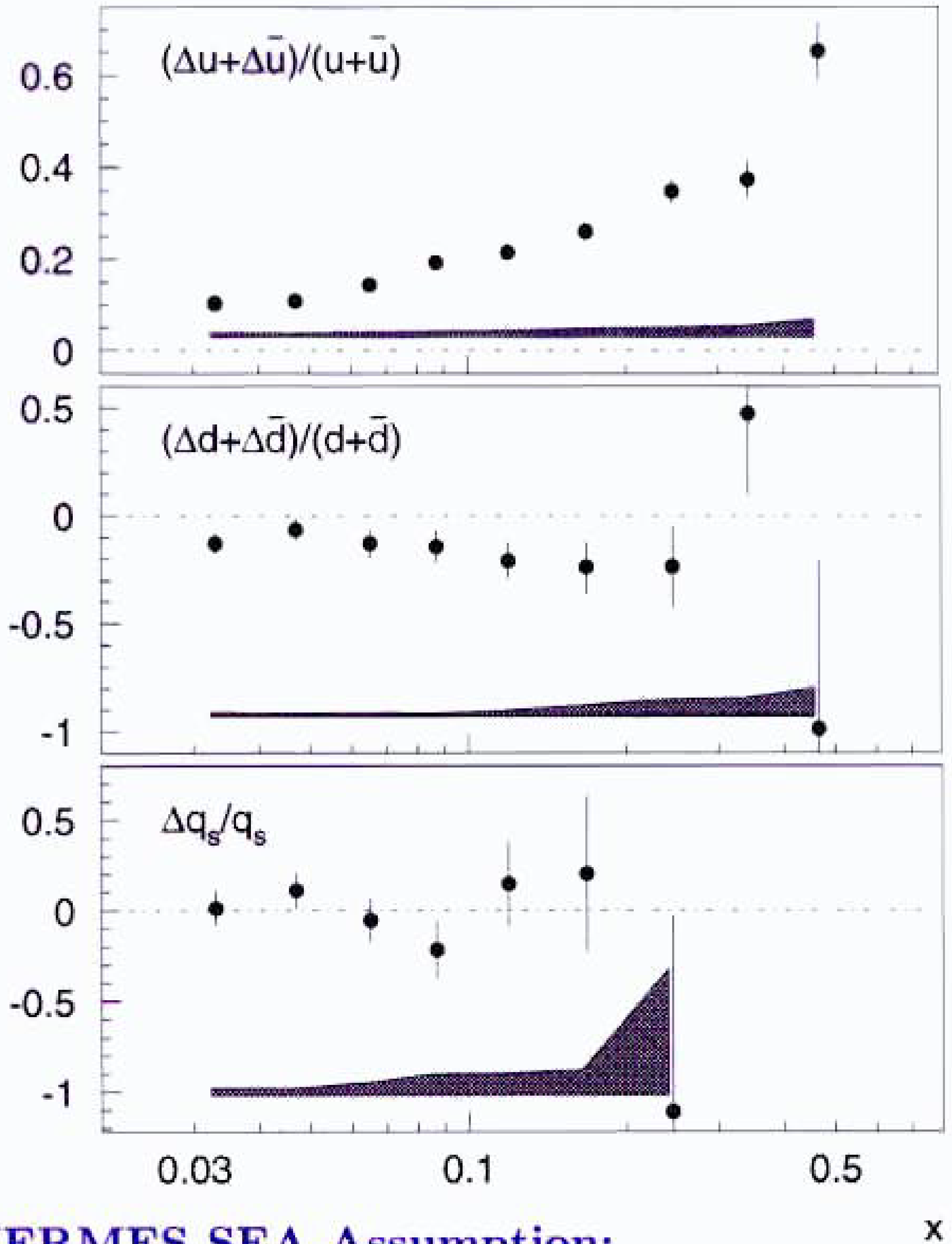
$z = E_h/\nu \geq 0.2$ **and** $x_F \geq 0.1$ **and** $W^2 \geq 10GeV^2$



Syst. err: target/beam polarization, ^3He fluctuation, R.

K. Ackerstaff et al., Phys. Lett. B464 (1999) 123-134

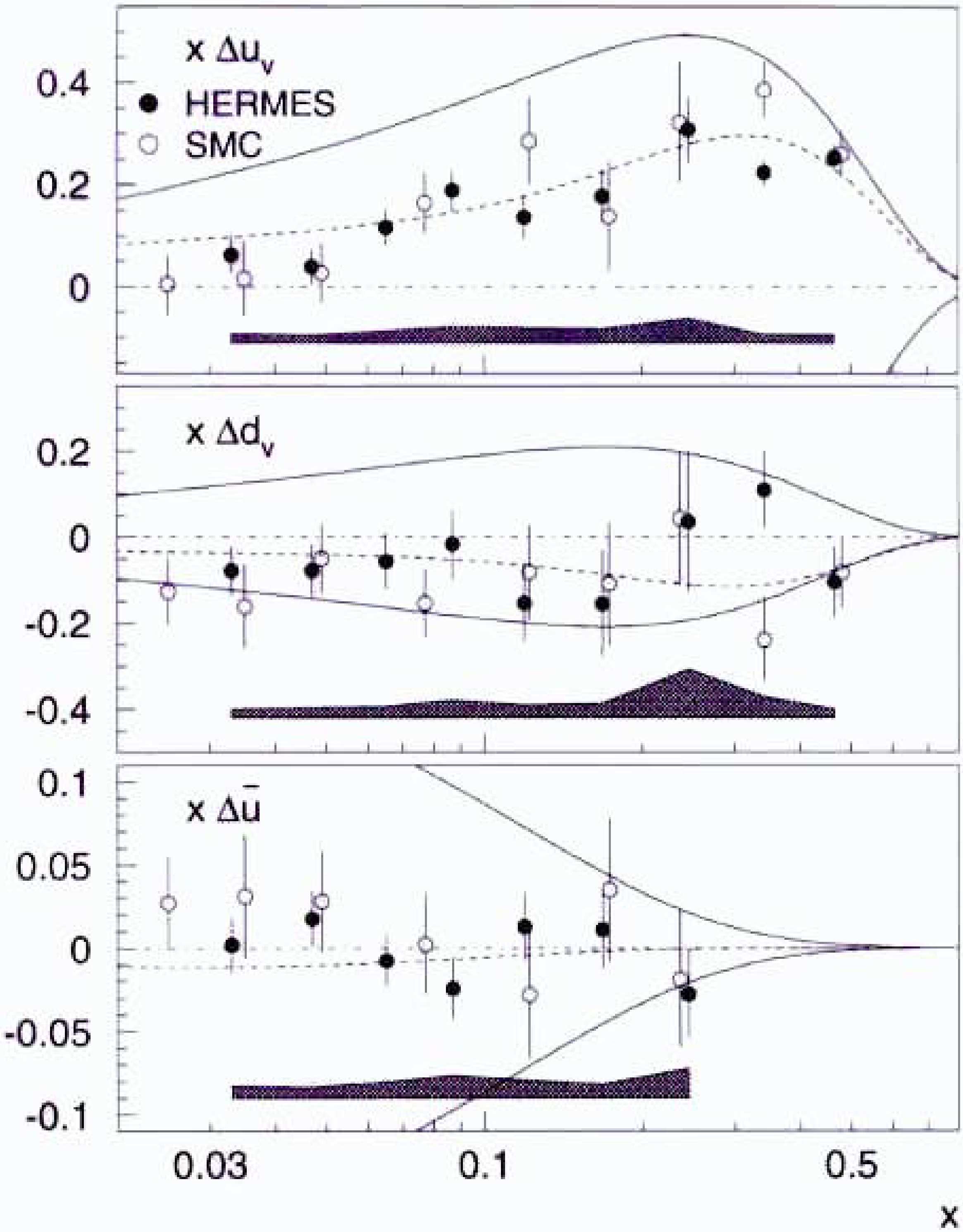
Flavor Decomposition



HERMES SEA Assumption:

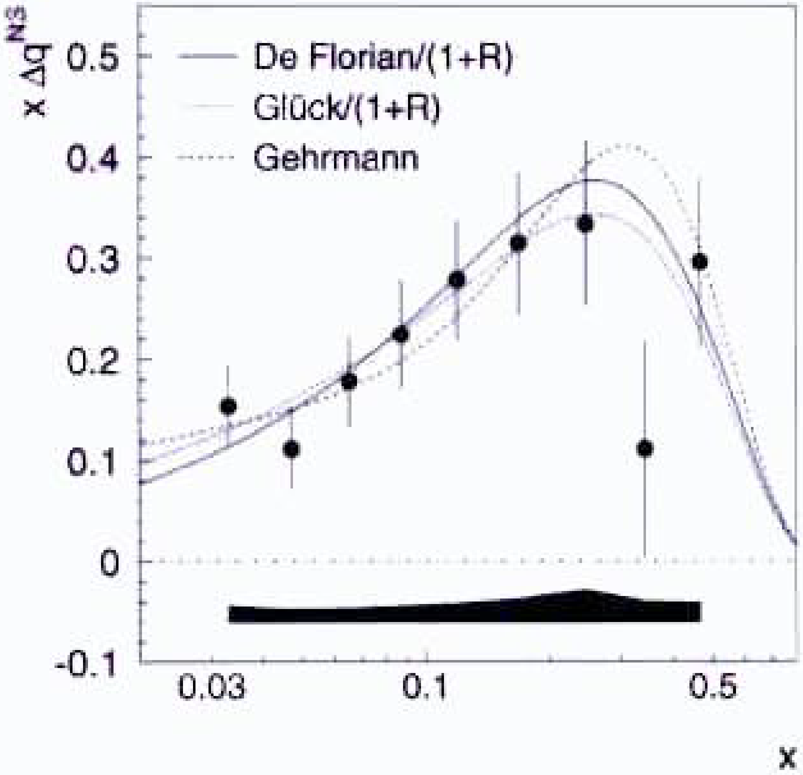
$$\frac{\Delta u_s(x)}{u_s(x)} = \frac{\Delta d_s(x)}{d_s(x)} = \frac{\Delta s(x)}{s(x)} = \frac{\Delta \bar{u}(x)}{\bar{u}(x)} = \frac{\Delta \bar{d}(x)}{\bar{d}(x)} = \frac{\Delta \bar{s}(x)}{\bar{s}(x)}$$

Valence and Sea Quark Distributions



Non-singlet Contribution

$x\Delta q^{NS} = x(\Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d}) \rightarrow$ **Bjorken SR**



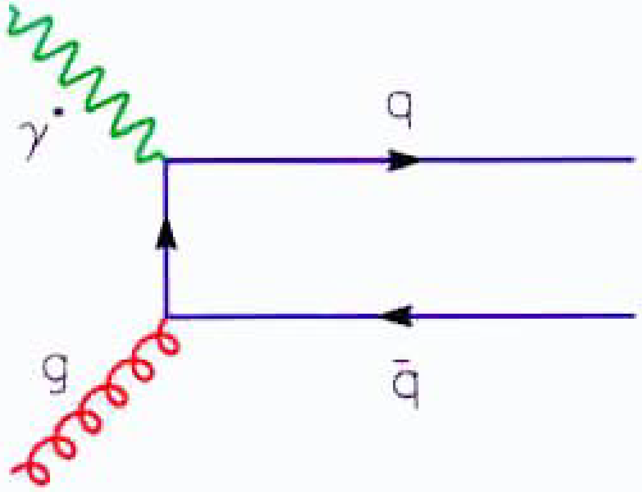
In summary

	Direct measurement total integral	prediction inclus. $SU(3)$
$\Delta u + \Delta\bar{u}$	$0.57 \pm 0.02 \pm 0.03$	0.66 ± 0.03
$\Delta d + \Delta\bar{d}$	$-0.25 \pm 0.06 \pm 0.05$	-0.35 ± 0.03
$\Delta s + \Delta\bar{s}$	$-0.01 \pm 0.03 \pm 0.04$	-0.08 ± 0.02
$\Delta\Sigma$	$0.30 \pm 0.04 \pm 0.07$	0.23 ± 0.04

For a direct measurement of the strange sea contribution : full kaon identification with RICH

Gluon contribution to spin

- Photon gluon fusion process probe $G(x_G)$
- Spin asymmetry in Photon gluon fusion probe $\Delta G/G$

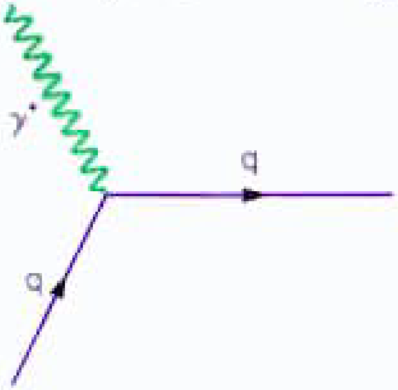


HERMES:
→ Measure asym of high p_T hadron pairs
→ Choose phase space where $(\gamma g \rightarrow q\bar{q})$ dominates
Require:

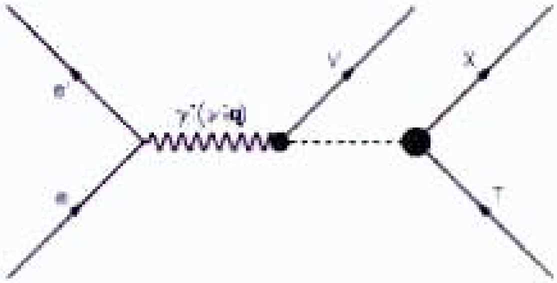
- at least one h^+ and one h^-.
- high momentum ($p_{h^\pm}$ >4.5 GeV) and high p_T (p_T >0.5 GeV).
- $M(2h) > 1.0$ **GeV**, to remove ρ and ϕ resonances.
- do not require scattered e^+ in the spectrometer ⇒ Photoproduction $Q^2 \approx 0$ (maximize cross sect.)

Different possible contributions

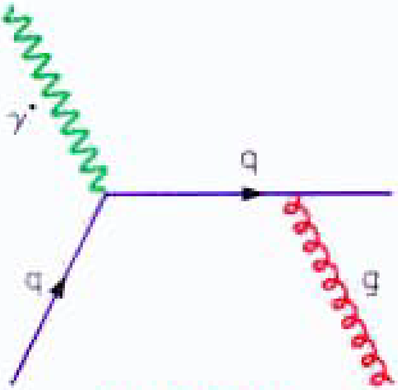
Assume four different processes may contribute (in LO QCD) to the high p_T $h^{\pm}$ pair production:



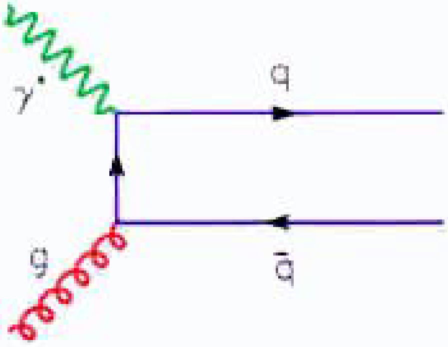
DIS
negligible contribution



VMD
assume $\mathbf{A}_{VMD} = 0$



QCDC
$A_{QCDC} \sim \frac{\Delta q}{q}$



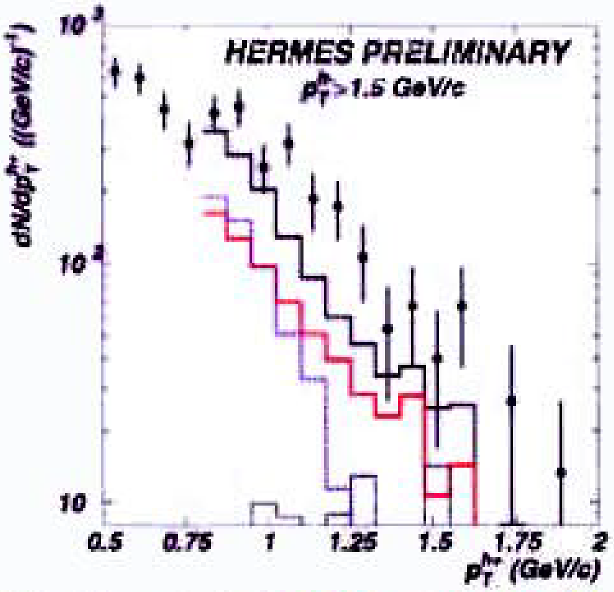
PGF
$A_{PGF} \sim \frac{\Delta G}{G}$

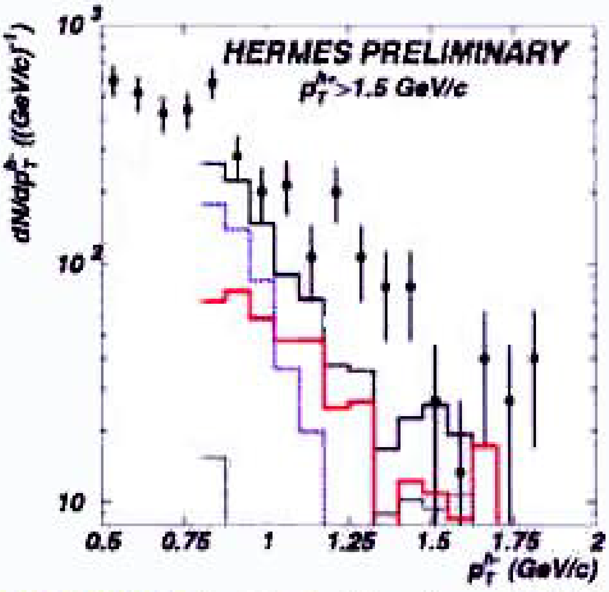
Their spin asymmetries can contribute to the measured asymmetry:

$A_{||} = A_{QCDC} f_{QCDC} + A_{PGF} f_{PGF} + A_{DIS} f_{DIS} + A_{VMD} f_{VMD}$

.. estimate their relative contributions.

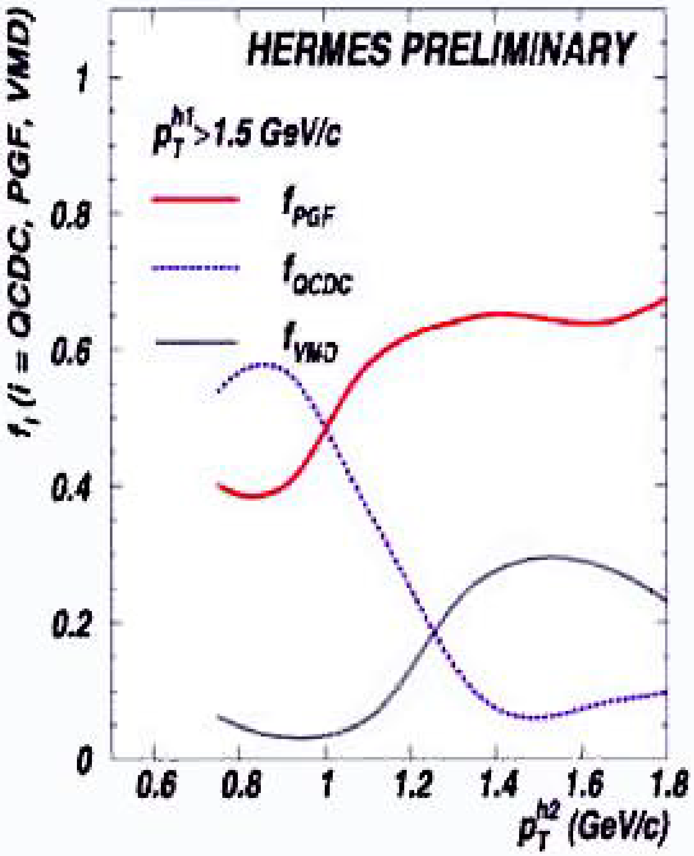
Evaluation of different contributions





black = total, red = PGF, blue = QCDC, dotted black = VMD

Process fractions f_i:
($f_{DIS} \approx 0$ from LEPTO)



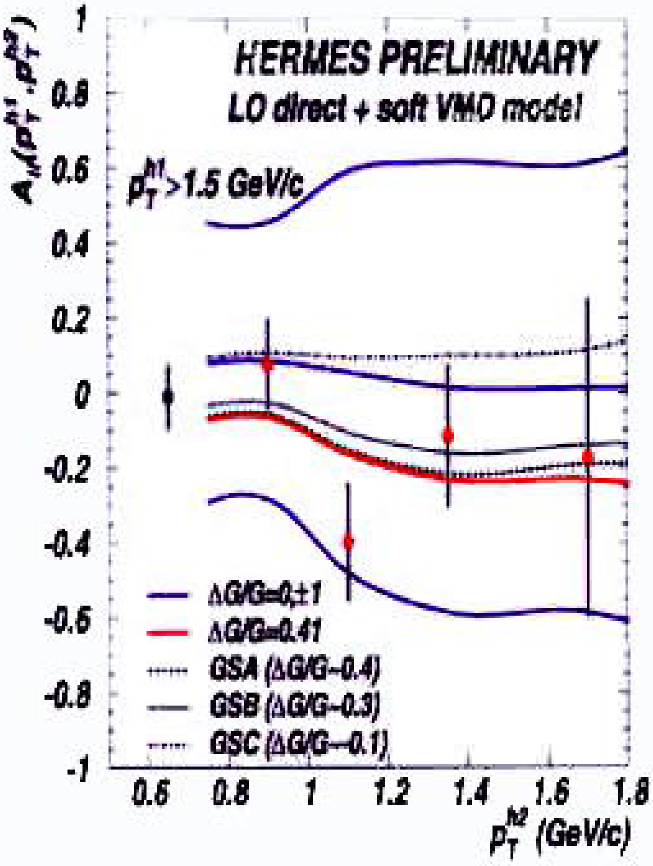
⇒ PGF dominates at large p_T.

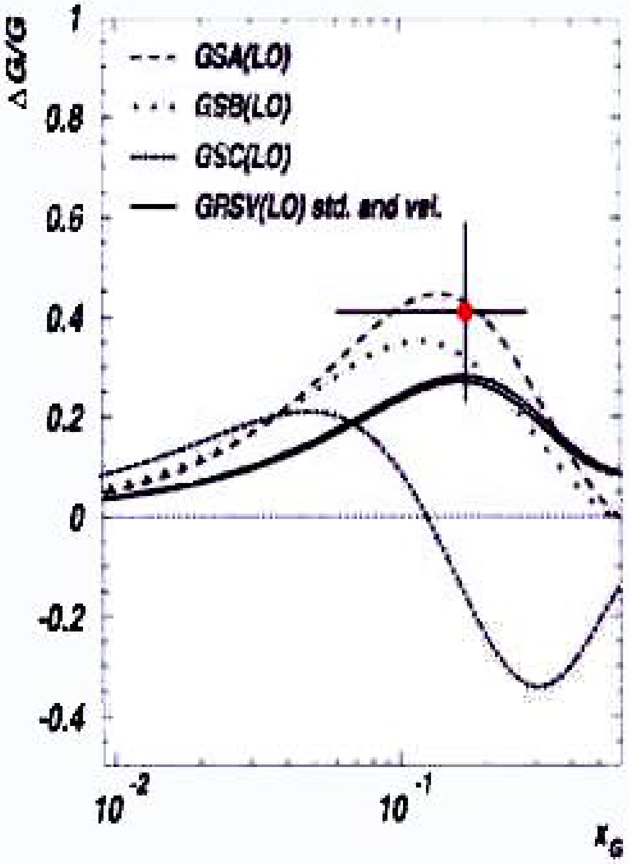
First result for $\Delta G/G$

$$\Delta G/G = +0.41 \pm 0.18\ (\text{stat.}) \pm 0.03\ (\text{exp.syst.})$$

at $\langle x_G \rangle = 0.17$ and $\langle \hat{p}_T^2 \rangle = 2.1\ \text{GeV}^2$

$\Delta G/G$ is positive



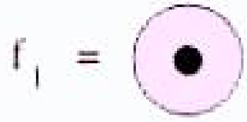


An alternative way to measure $\Delta G/G$ is through charm asymmetry → HERMES charm upgrade

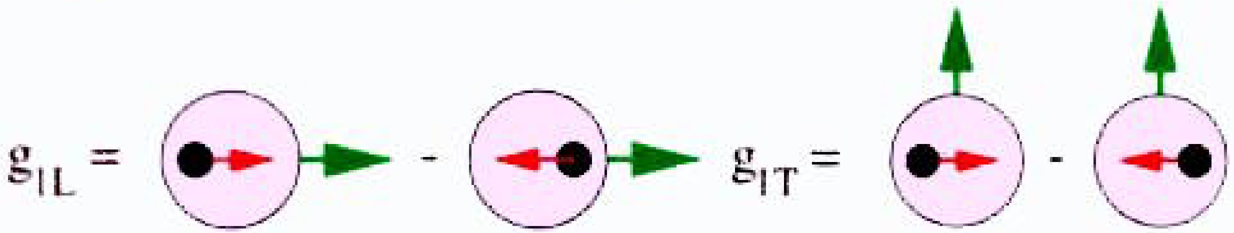
A. Airapetian et al, Phys. Rev. Lett. 84 (2000) 2584

Classification of Distribution Functions

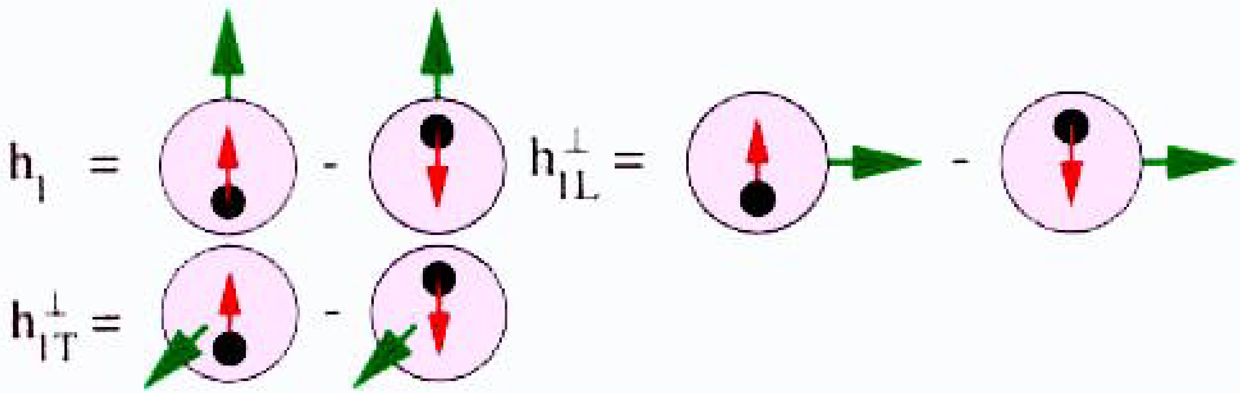
The leading twist description of the nucleon involves 3 types of Distribution Function (+ others at higher level)



Unpolarized quark in unpolarized nucleon.

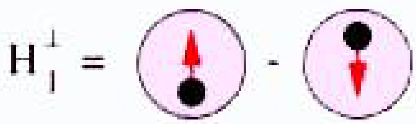


Longitudinall quark in longitudinal and transverse nucleon.



Transverse quark in longitudinal and transverse nucleon.

h_1 is chiral odd $\rightarrow$ observed only in combination with an other chiral odd structure $\rightarrow$ (Collins) Fragm. Function in SIDIS



Single Spin Azimuthal Asymmetries

- Double Spin Asymmetries:

  Polarized Beam and Target.

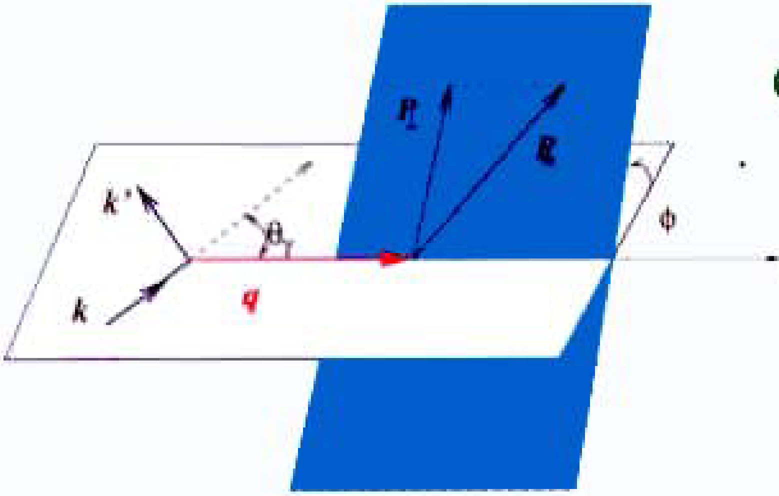
  $g_1^n \; g_1^p \; \Delta q \; \cdots$

  Longitudinal quark polarization densities.

- Single Spin Asymmetry (SSA):

  Polarized Beam or Target.

  Transverse quark polarization densities.



Chiral odd, T-even DF

⇓

Chiral-odd T-odd FF

⇓

SSA

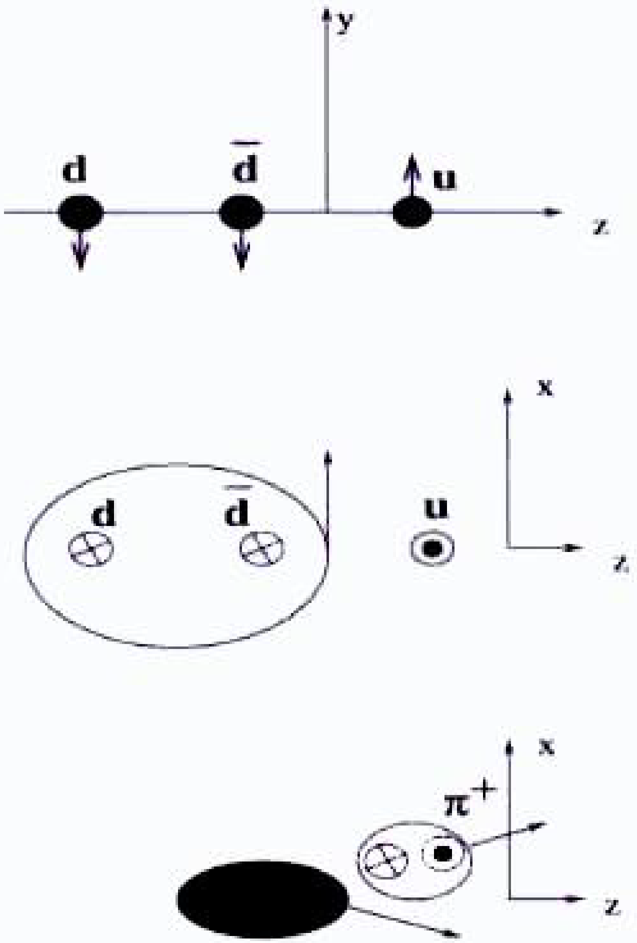
Naive parton models, non interacting collinear parton
Parity, Angular momentum, Helicity Cons. ⇒ SSA = 0

SSA originates from multi-parton correlation and intrisic quark transverse momentum k_T.

COLLINS FF

transverse quark polarimeter

Simple interpretation (Semi classical string model)



Correlation between the spin of the valence quark and the transverse momentum of the outgoing $\bar{q}$ (pion).

COLLINS FF:

Contributions to $\sin\phi$

$$\mathcal{A}_{UL}^{\sin\phi} = \frac{\frac{L^+}{L_P^+}\int_0^{2\pi}\sin\phi\,\mathrm{d}N_+ - \frac{L^-}{L_P^-}\int_0^{2\pi}\sin\phi\,\mathrm{d}N_-}{\frac{1}{2}[\int_0^{2\pi}\mathrm{d}N_+ + \int_0^{2\pi}\mathrm{d}N_-]}$$

- Chirality structure of DF $\otimes$ FF : even
- Time reversal structure of DF $\otimes$ FF : odd

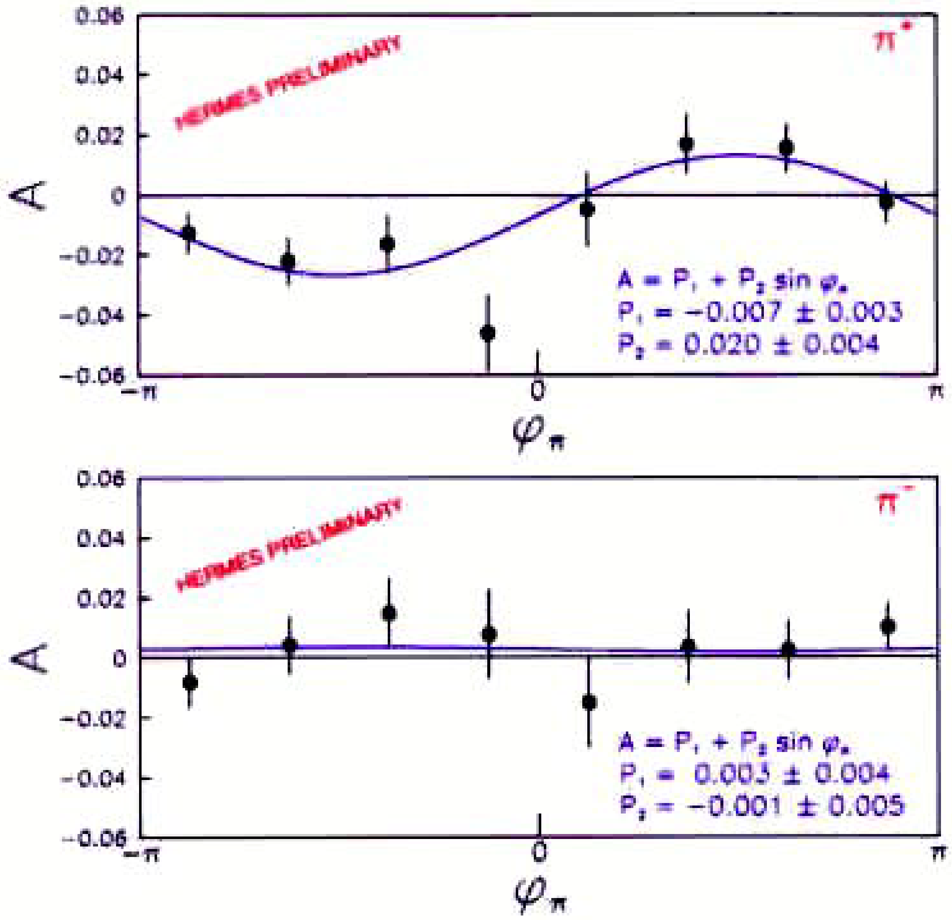
		T-even DF		T-odd FF	
		chirality		chirality	
		even	odd	even	odd
twist 2	U	$\mathbf{f}_1$			$H_1^\perp$
	L	$\mathbf{g}_{1L}$	$h_{1L}^\perp$		
	T	g_{1T}	$\mathbf{h}_1$ $h_{1T}^\perp$	$D_{1T}^\perp$	
twist 3	U	$f^\perp$	$\mathbf{e}$		$\mathbf{H}$
	L	$g_L^\perp$	$\mathbf{h}_L$	$D_L^\perp$	E_L
	T	$\mathbf{g}_T$ $g_T^\perp$	h_T $h_T^\perp$	$\mathbf{D_T}$	E_T

$$\langle \sin\phi \rangle_{UL} \propto S_L \sum_{a,\bar{a}} e_a^2 x h_L^a(x) H_1^{\perp a}(z) + S_T \sum_{a,\bar{a}} e_a^2 x h_1^a(x) H_1^{\perp a}(z)$$

HERMES, Longitudinally polarized target:
$S_T << S_L$

Cross section Asymmetry

Asymmetry in the cross section $A(\phi) = \frac{1}{P_H} \frac{N^+ - N^-}{N^+ + N^-}$.



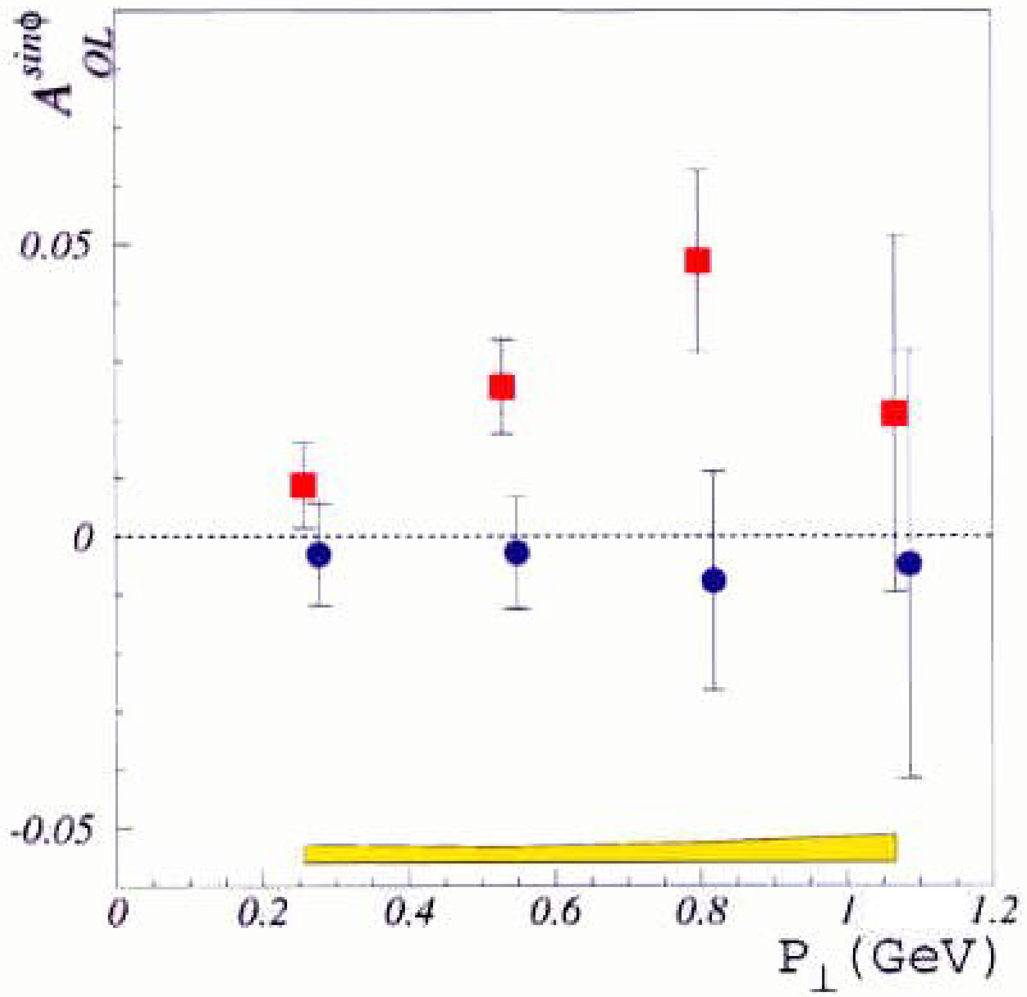
$$\pi^+ \quad \mathcal{A}_{UL}^{sin\phi} = 0.022 \pm 0.005(stat) \pm 0.003(syst)$$

$$\pi^- \quad \mathcal{A}_{UL}^{sin\phi} = -0.005 \pm 0.008(stat) \pm 0.004(syst)$$

$$\pi^+ \quad \mathcal{A}_{UL}^{sin\phi} \propto \frac{4}{9} h_L^u \mathbf{H_1^{\perp u \to \pi^+}} + \frac{1}{9} h_L^d H_1^{\perp d \to \pi^+}$$

$$\pi^- \quad \mathcal{A}_{UL}^{sin\phi} \propto \frac{4}{9} h_L^u H_1^{\perp u \to \pi^-} + \frac{1}{9} h_L^d \mathbf{H_1^{\perp d \to \pi^-}}$$

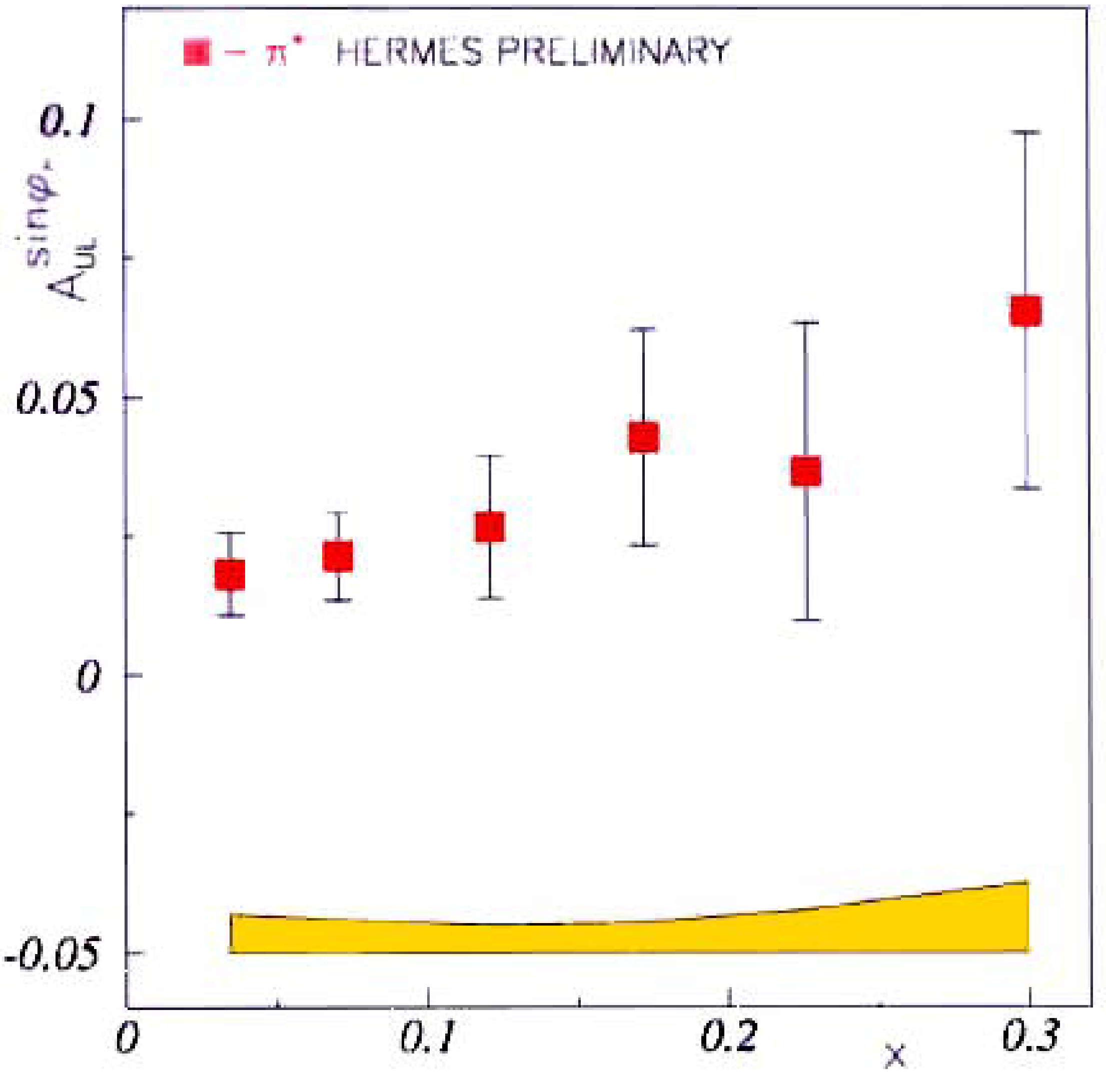
SSA $\mathcal{A}_{UL}$: $P_\perp$ dependence



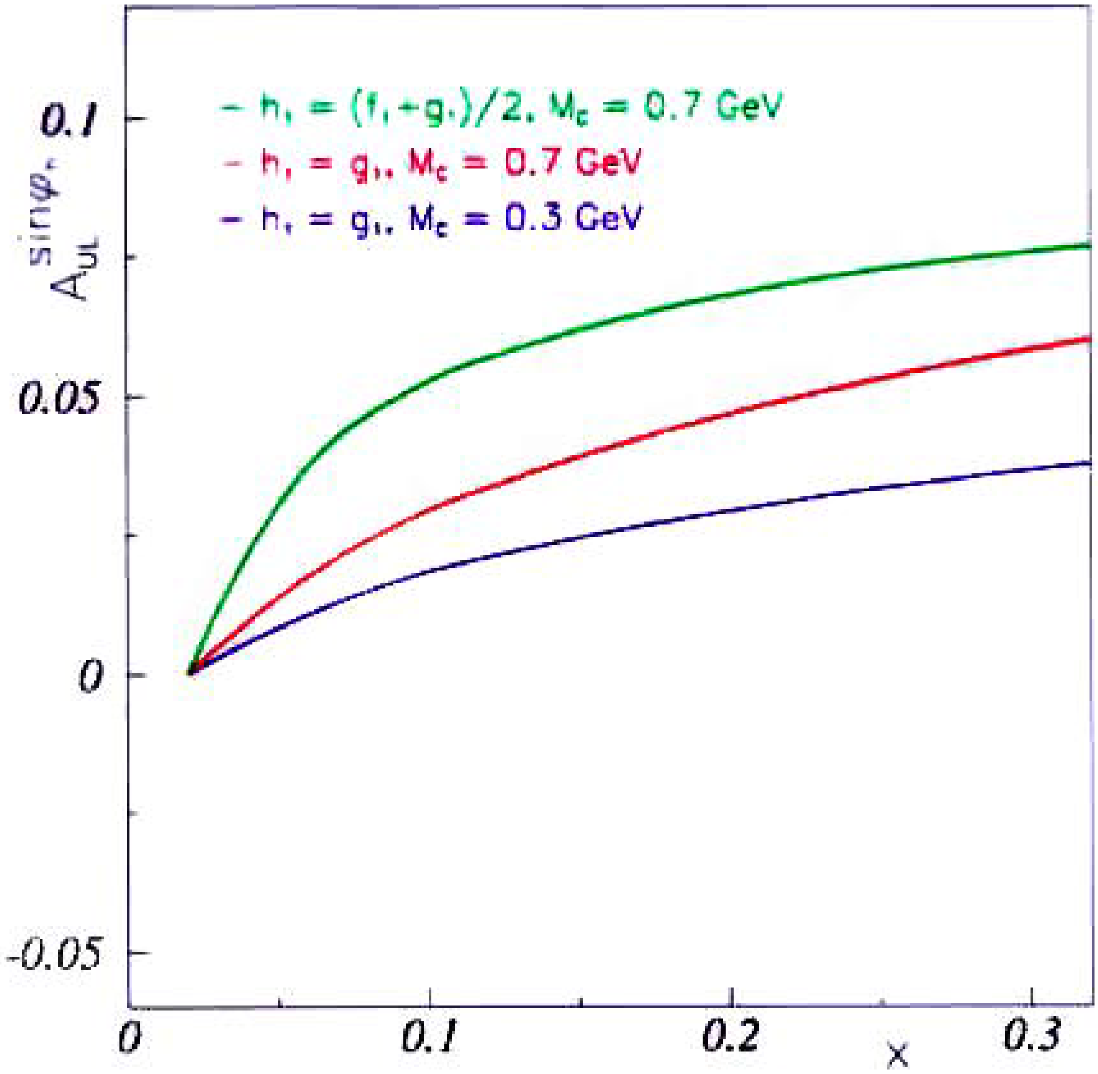
Dominant role of intrinsic k_T when $P_T \leq$ hadronic mass scale ~ 1 GeV.

A. Airapetian et al, Phys. Rev. Lett. 84 (2000) 4047

SSA $\mathcal{A}_{UL}$, x dependence: π^+



SSA $\mathcal{A}_{UL}$, x dependence: π^+



Dominant role of valence quarks

→ First evidence of transversity in a longitudinal target

→ Accurate measurement of h_1 (transversity) with the transversely polarised target in 01

Other HERMES results not presented

Polarized Physics Program

- Longitudinal Spin Transfer to Λ
- Spin asymmetries in diffractive Vector Meson Production

Unpolarized Physics Program

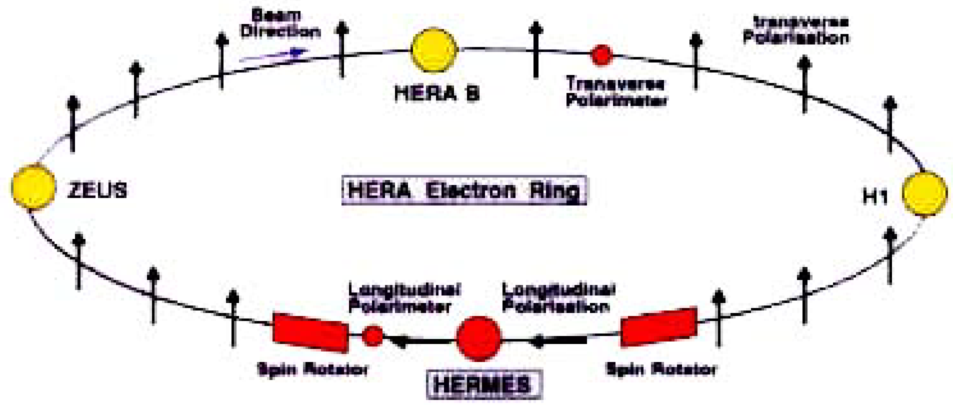
- sea flavor asymmetry $\bar{u}/\bar{d}$
- exclusive meson production and Skewed Parton Distribution
- Fragmentation Functions for light quarks $\longrightarrow \pi, K, P, \Lambda$
- longitudinal and transverse polarization of Λ

Nuclear Physics Program

- Diffractive Vector Meson Production (coherence length effect).
- $\sigma^{N/He/Kr}/\sigma^{D} \longrightarrow$ HERMES effect on σ_L/σ_T
- Measurement of the hadron formation times in the fragmentation process

→ http://hermes.desy.de/notes/

The Polarized Positron Beam at HERA



- 27.5 GeV e^+ (e^-).
- Self-polarization by emission of synchrotron radiation, $P_b(t) = p_b^{max}[1 - exp(t/\tau)]$
- Spin rotators → longitudinal polarization at HERMES IP
- 2 Polarimeters (Compton laser backscattering)
- average beam polarization $\langle P_b \rangle \approx 55\%$