Spin Structure of the Nucleon

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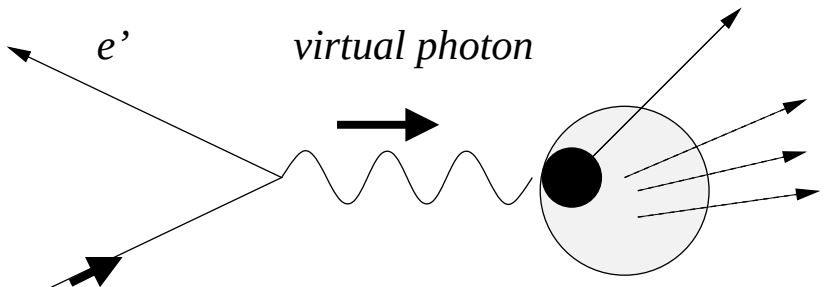
Physics in Collision
Ann Arbor, Michigan, USA
June 23 - 25, 1999

Recent Results in Spin Physics

- Inclusive Spin Structure Studies
- Semi-Inclusive Measurements
- Asymmetry of Pairs of Hadrons at High p_T
- Spin-Azimuthal Asymmetries
- Asymmetry of Diffractive Vector Meson Production

Spin-dependent Deep Inelastic Scattering

In polarized DIS using polarized lepton beams and polarized nuclear targets, one probes the polarization of the partonic constituents of the nucleon.



One measures double spin asymmetries:

$$A_{\parallel} = \frac{N^{\uparrow\downarrow}L^{\uparrow\uparrow} - N^{\uparrow\uparrow}L^{\uparrow\downarrow}}{N^{\uparrow\downarrow}L_P^{\uparrow\uparrow} + N^{\uparrow\uparrow}L_P^{\uparrow\downarrow}}$$

which are interpreted in terms of spin-dependent structure functions:

$$A_1 = \frac{A_{\parallel}}{D(1+\gamma\eta)} \simeq \frac{g_1}{F_1} = \frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$$

$\Delta q(q)$: polarized (unpolarized) quark distribution functions

How do the partonic constitutents of the nucleon produce its total spin of 1/2?

The Experiments

SLAC: E142, E143, E154, E155, E155x

- Polarized e^- beam, E_B = 10 - 50 GeV, $P_B \simeq 80\%$
- Polarized targets: $^{15}NH_3$ (p); ^3He (n); $^{15}ND_3$, ^6LiD (d)
- High luminosity: statistical precision
- E155x in progress: unprecedented precision on the transverse structure function g_2

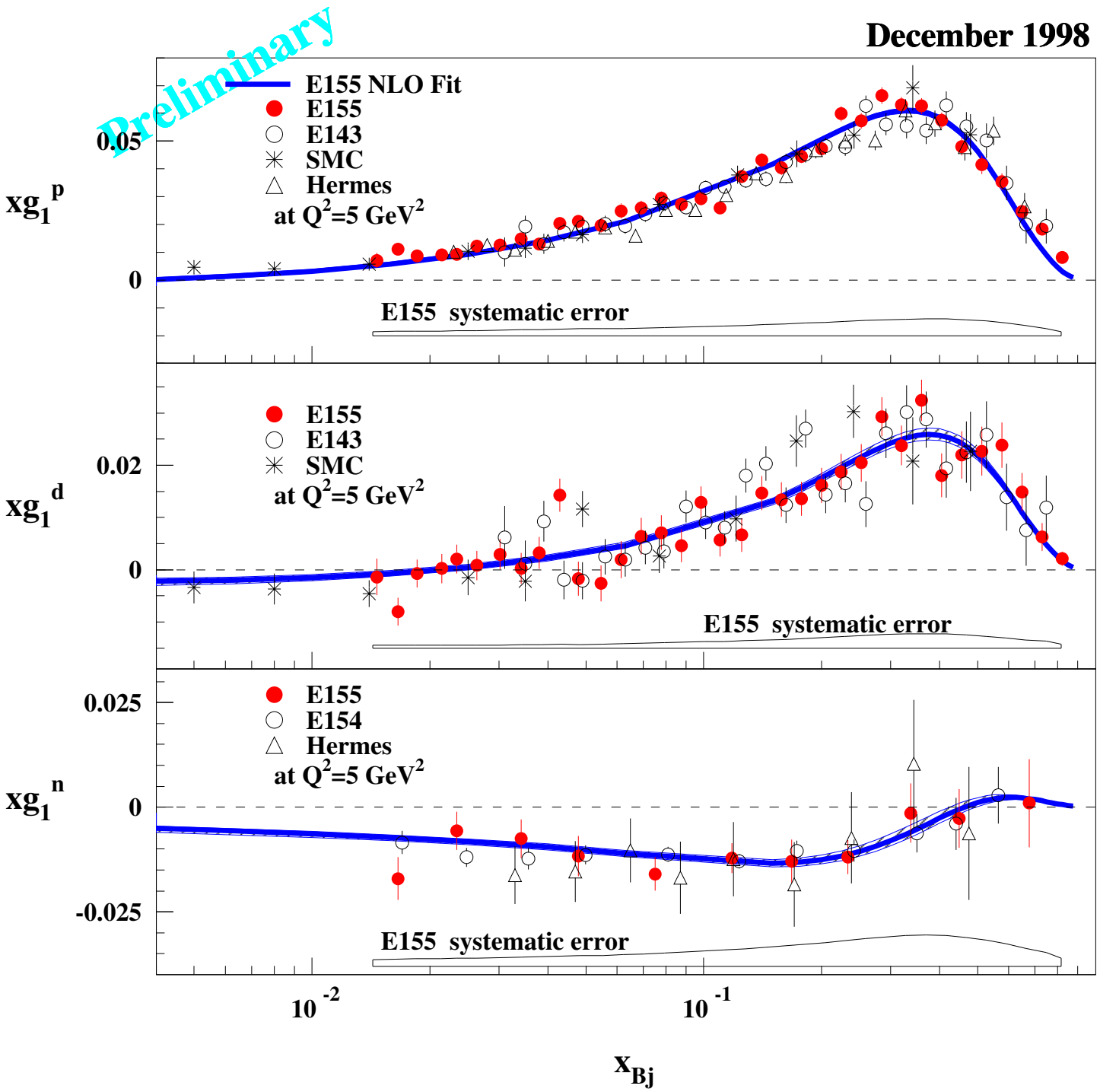
CERN: EMC, SMC

- Polarized μ beam, E_B = 100 - 190 GeV, $P_B \simeq 80\%$
- Polarized targets: C_4H_9OH, NH_3 (p); C_4D_9OD (d)
- High beam energy: able to access low x points
- Open geometry detector: semi-inclusive measurements possible

DESY: HERMES

- Polarized e^+, e^- beam, E_B = 27.5 GeV, $P_B \simeq 57\%$
- Polarized targets: H (p), ^3He (n); D (d)
- Pure internal gas targets: no dilution
- Open geometry detector: high precision semi-inclusive measurements
- Data taking on D target in progress
- 1998 Upgrade: new RICH detector permits full particle identification (π, K, p) across full momentum range

The Inclusive Structure Function g_1



Inclusive Measurements: QCD Fits at NLO

SMC and E143/E155 have performed QCD fits to the x, Q^2 dependence of the measured inclusive structure functions.

$$g_1^{p(n)} = \frac{1}{9}\left(C_{NS} \otimes \left[\pm\frac{3}{4}\Delta q_3 + \frac{1}{4}\Delta q_8\right] + C_S \otimes \Delta\Sigma + 2N_f C_g \otimes \Delta g\right)$$

$$\begin{aligned} \Delta q_3 &= \Delta u - \Delta d, \\ \Delta q_8 &= \Delta u + \Delta d - 2\Delta s, \\ \Delta\Sigma &= \Delta u + \Delta d + \Delta s \end{aligned}$$

Ingredients

- Choose parametrizations of polarized PDFs at some scale Q_i^2
- Constrain non-singlet moments using parameters from hyperon decay (assuming SU(3) flavour symmetry)

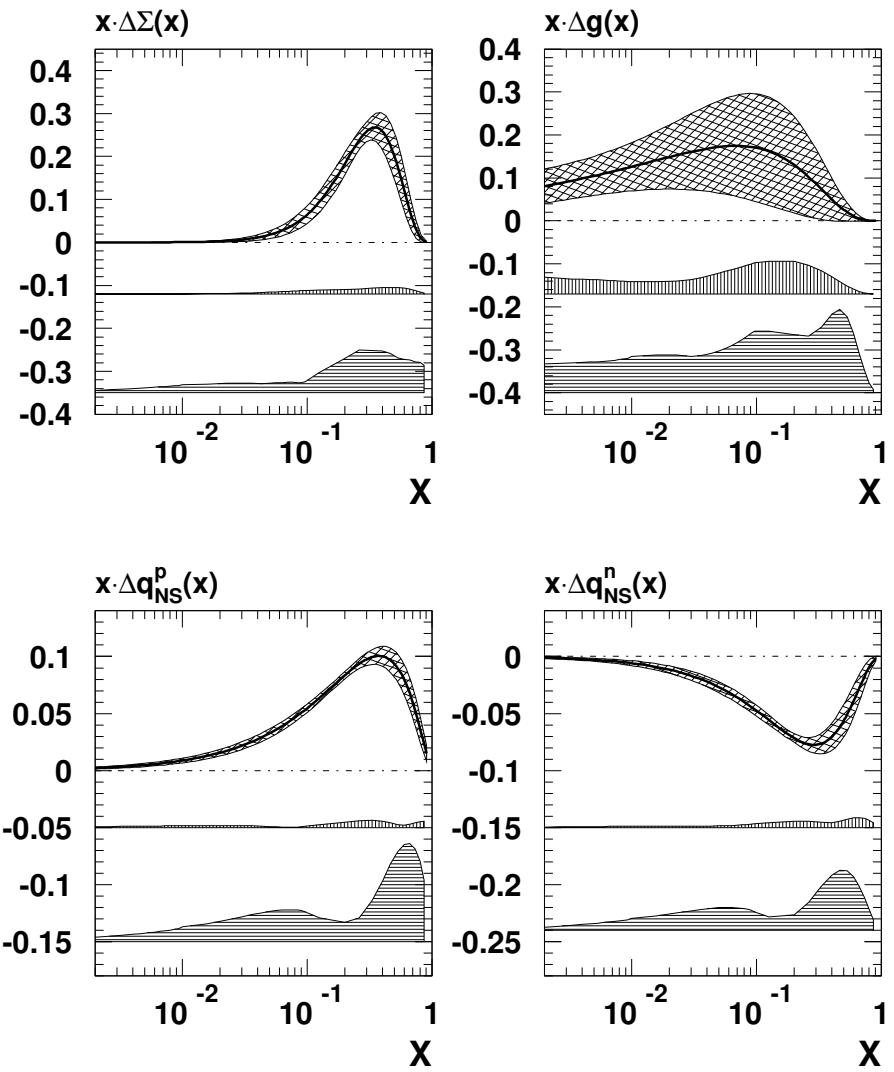
$$\begin{aligned} \Delta q_3 &= F + D = 1.2601 \pm 0.0025 \\ \Delta q_8 &= 3F - D = 0.579 \pm 0.032 \end{aligned}$$

- Choose renormalization & factorization scheme

$$\Delta q_0(Q^2) = \Delta\Sigma_{\overline{\rm MS}}(Q^2) = \Delta\Sigma_{\rm AB} - n_f\frac{\alpha_s(Q^2)}{2\pi}\Delta g(Q^2)$$

- Choose factorization & renormalization scales
- Choose α_s and quark mass thresholds

SMC: NLO QCD Fit



First moments at Q_0^2 = 1 GeV/c^2:

$$\Delta q_0 = 0.23 \pm 0.07 \pm 0.19 \quad \text{(AB scheme)}$$

$$= 0.19 \pm 0.05 \pm 0.04 \quad (\overline{\text{MS}} \text{ scheme})$$

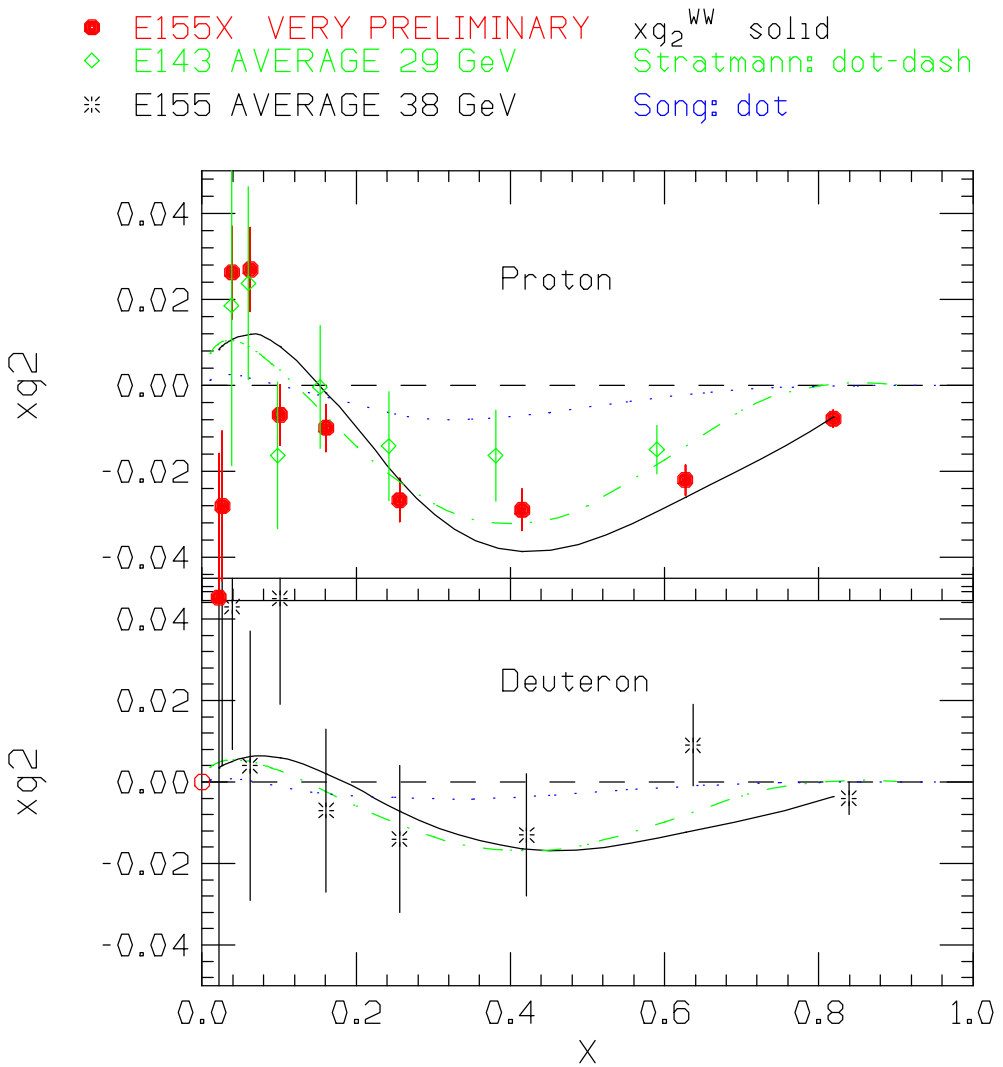
$$\Delta g = 0.99 \; {}^{+1.17}_{-0.31} \; {}^{+0.42}_{-0.22} \; {}^{+1.43}_{-0.45} \quad \text{(AB scheme)}$$

First Results from E155x

Asymmetries with **transverse target polarization**

$$A_\perp = \frac{\sigma^{\downarrow\leftarrow} - \sigma^{\uparrow\leftarrow}}{\sigma^{\downarrow\leftarrow} + \sigma^{\uparrow\leftarrow}} = f_k E' \sin\theta \left[g_1(x,Q^2) + \frac{2E}{\nu} g_2(x,Q^2) \right]$$

Results for Q^2-averaged g_2^p



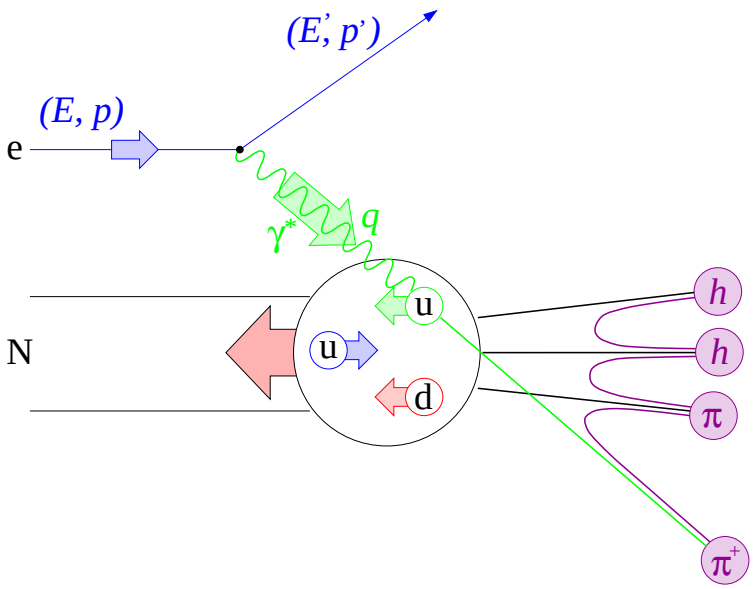
Wandzura-Wilczek relation:

$$g_2^{\mathrm{WW}}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{dy}{y} g_1(x,Q^2)$$

Deviations from this would indicate **higher twist** effects.

Semi-Inclusive DIS

In semi-inclusive DIS a hadron h is detected in coincidence with the scattered lepton



Flavour Tagging

- Select hadrons from the current fragmentation region by minimum cuts on $z = E_h/\nu$ and $x_F = 2p_{||}/W$
- in LO QCD (assuming spin-independence of fragmentation)

$$A_1^h(x,Q^2) = \frac{\int_{z_{\min}}^1 dz \sum_q e_q^2 \, \Delta q(x,Q^2) \cdot D_q^h(z,Q^2)}{\int_{z_{\min}}^1 dz \sum_q e_q^2 \, q(x,Q^2) \cdot D_q^h(z,Q^2)}$$

D_q^h: Fragmentation function

Δq Extraction

- Rewrite photon-nucleon asymmetry

$$A_1^h(x,z) = \sum_q \underbrace{\frac{e_q^2\, q(x) \cdot D_q^h(z)}{\sum_{q'} e_{q'}^2\, q'(x) \cdot D_{q'}^h(z)}}_{P_q^h(x,z)} \cdot \frac{\Delta q(x)}{q(x)}$$

- *Purity* $P_q^h(x,z)$ gives probability that a quark $q(x)$ was struck when a hadron $h(z)$ is detected
- Purities are *spin-independent* quantities
- Define

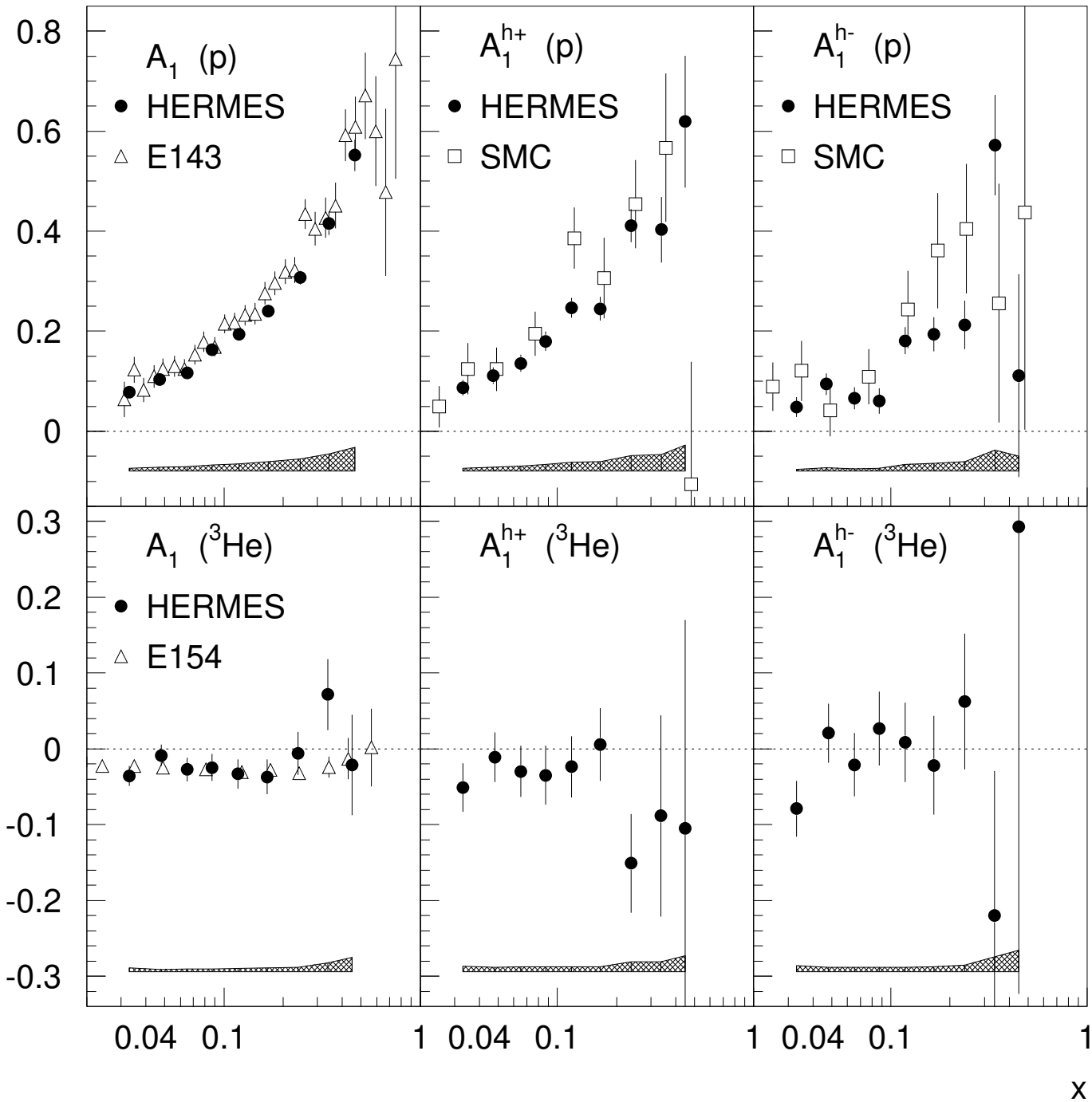
$$\vec{\mathcal{A}} = \begin{pmatrix} A_1^{h_1}(x) \\ \cdots \\ A_1^{h_m}(x) \end{pmatrix} \quad \vec{Q} = \begin{pmatrix} \Delta q_1(x)/q_1(x) \\ \cdots \\ \Delta q_n(x)/q_n(x) \end{pmatrix} \quad \mathcal{P} = \left[P_q^{h_j}(x) \right]_{mn}$$

where $P_q^h(x) = \int_{z_{\min}}^1 P_q^h(x,z)\, dz$

- To extract quark polarizations solve

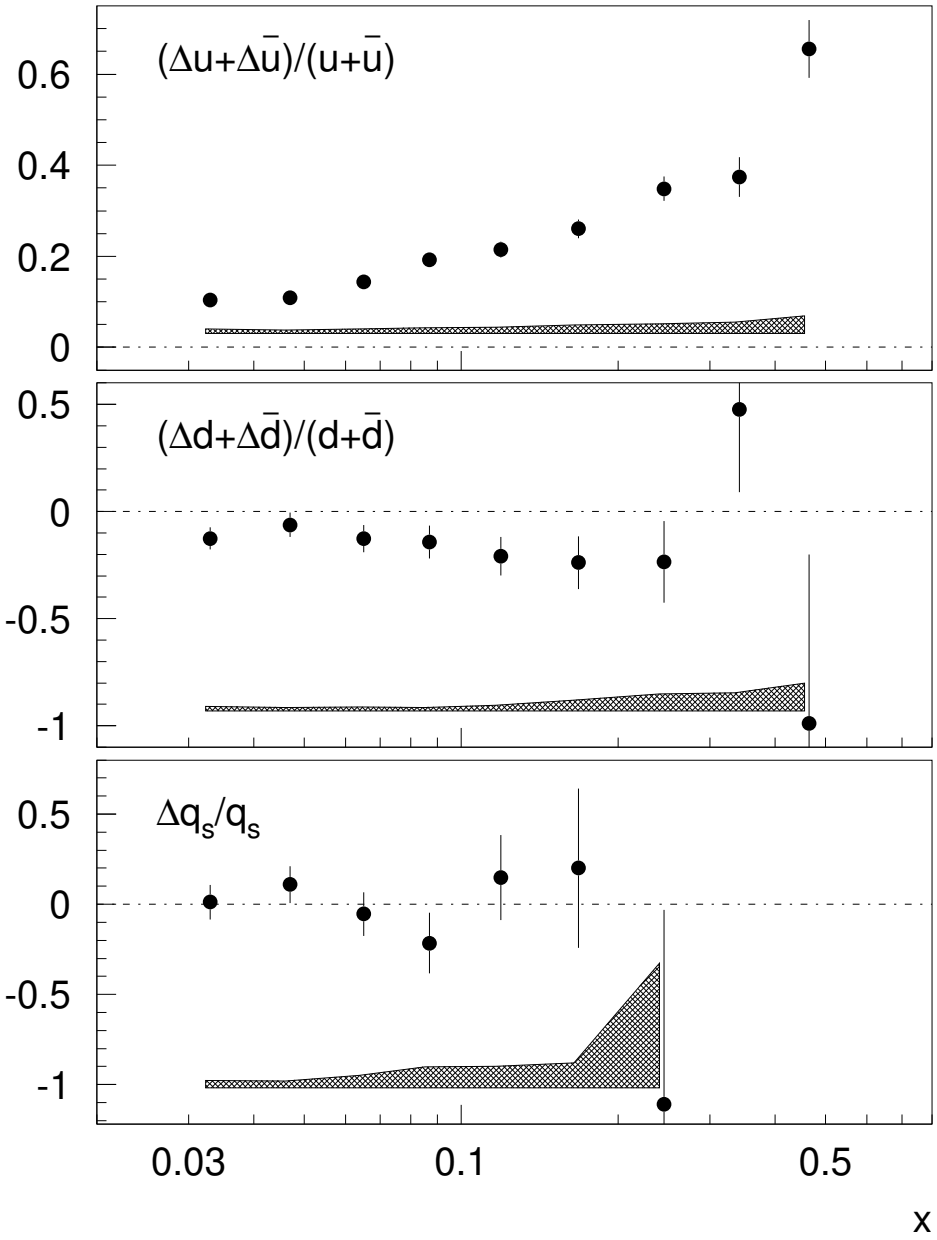
$$\vec{\mathcal{A}} = \mathcal{P}\vec{Q}$$

Semi-Inclusive Asymmetries



Data given at mean Q^2 of each x. Error bars of HERMES (SLAC and SMC) are statistical (total) uncertainties. Bands are HERMES systematic error. Inclusive results compared to SLAC g_1/F_1.

Flavour Decomposition

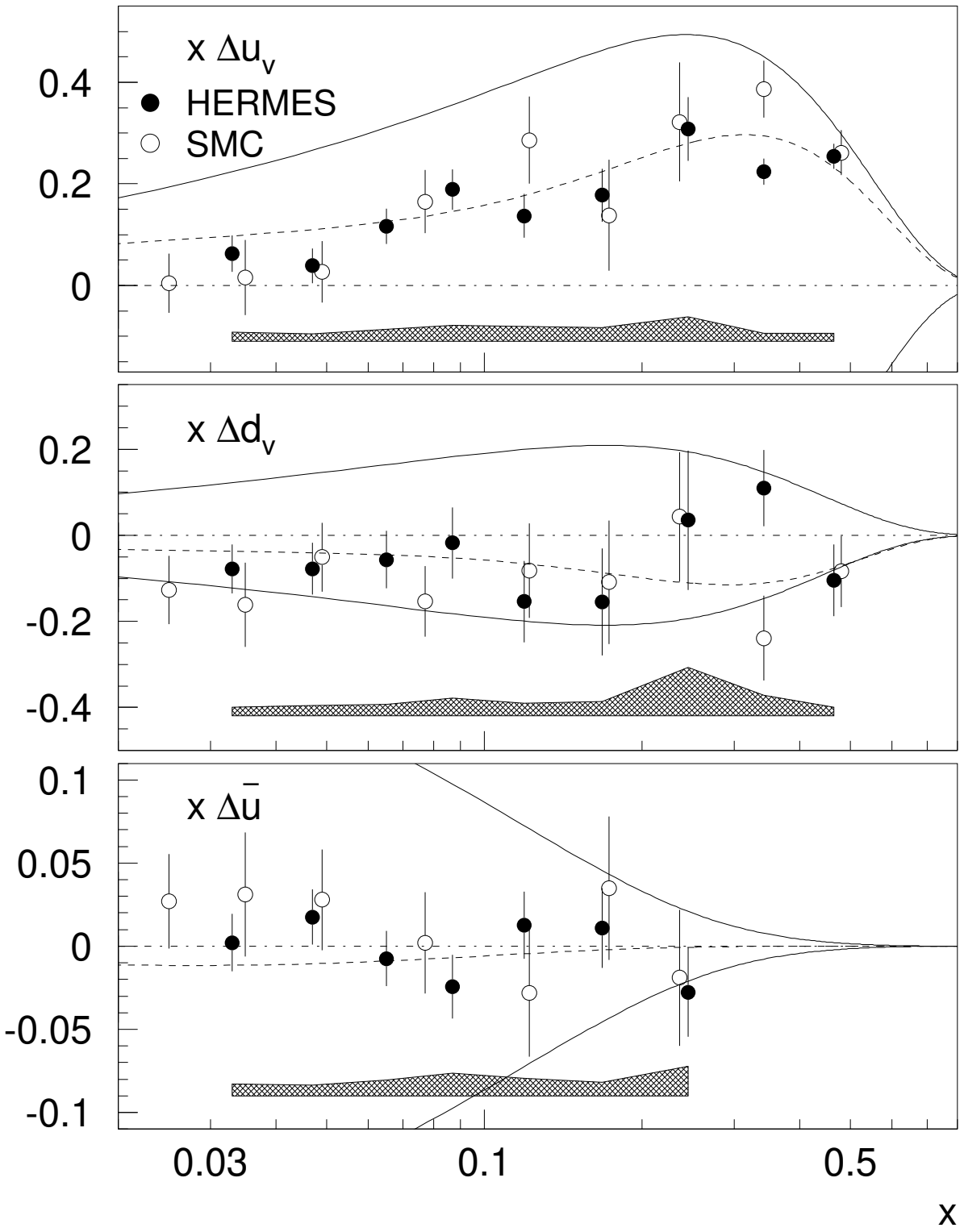


Result insensitive to choice of sea assumption:

$$\frac{\Delta q_s}{q_s} \equiv \frac{\Delta u_s}{u_s} = \frac{\Delta d_s}{d_s} = \frac{\Delta s}{s} = \frac{\Delta \overline{u}}{\overline{u}} = \frac{\Delta \overline{d}}{\overline{d}} = \frac{\Delta \overline{s}}{\overline{s}}$$

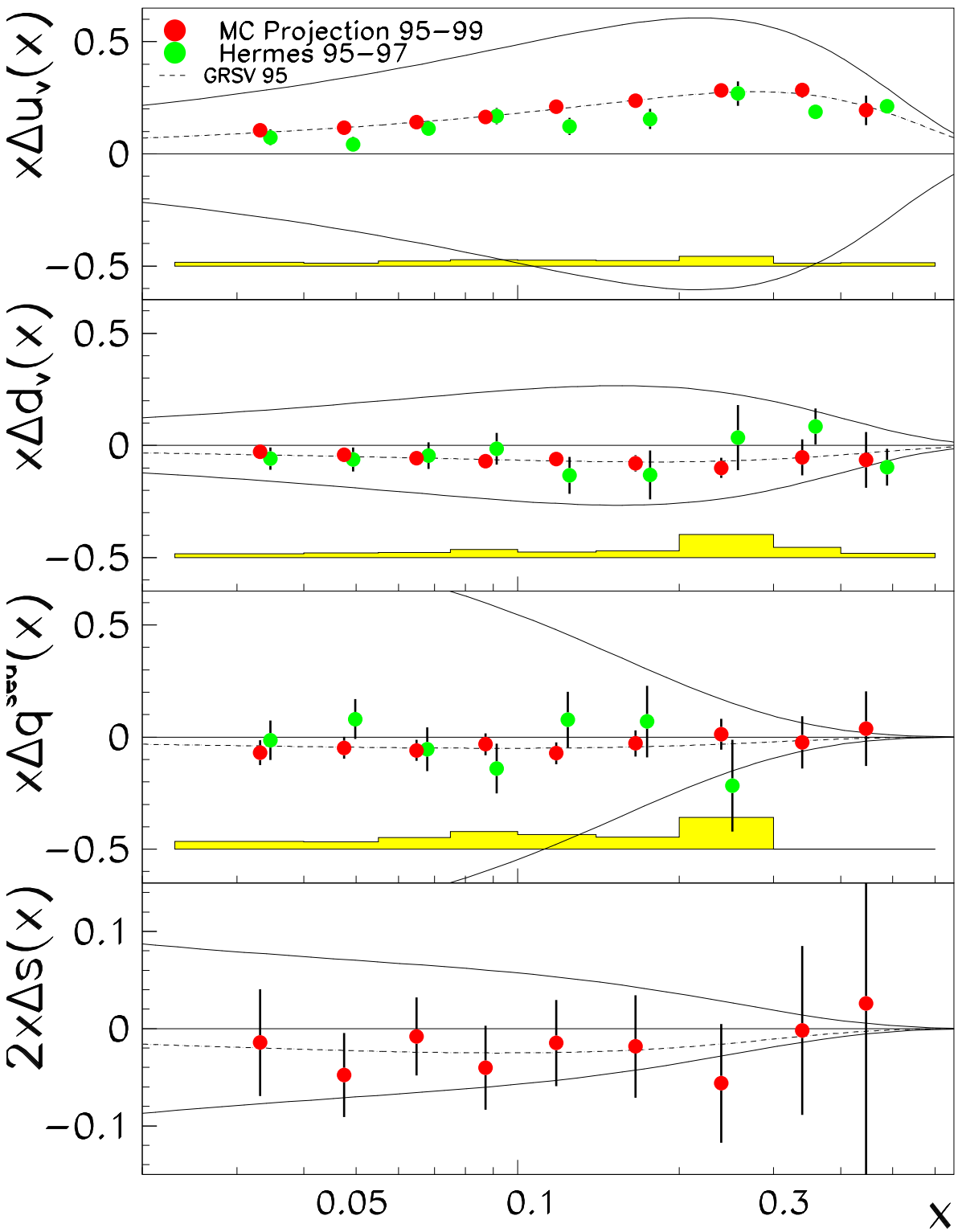
$$\Delta q_s \equiv \Delta u_s = \Delta d_s = \Delta s = \Delta \overline{u} = \Delta \overline{d} = \Delta \overline{s}$$

Valence and Sea Quark Distributions



Polarized valence and sea quark distributions at $Q^2 = 2.5$ GeV/c^2 compared to SMC. Dotted line: *Gehrmann and Stirling* ('Gluon A', LO).
(SMC sea assumption: $\Delta u_s = \Delta d_s = \Delta s = \Delta \overline{u} = \Delta \overline{d} = \Delta \overline{s}$)

Projections



First and Second Moments

HERMES **flavour decomposition** ($Q^2 = 2.5$)

	total integral(extrap.)	prediction		Q^2
$\Delta u + \Delta\bar{u}$	$0.56(+6) \pm 0.04$	0.66 ± 0.03	SU(3)[1]	2.5
$\Delta d + \Delta\bar{d}$	$-0.25(-3) \pm 0.08$	-0.35 ± 0.03	SU(3)[1]	2.5
$\Delta s + \Delta\bar{s}$	$-0.02(\ \ 0) \pm 0.05$	-0.08 ± 0.02	SU(3)[1]	2.5

Low-x extrapolation via Regge parametrization.

HERMES **Singlet** (Δq_0)**, Triplet** (Δq_3)**, Octet** (Δq_8) ($Q^2 = 2.5$)

	total integral(extrap.)	prediction		Q^2
Δq_0	$0.28(+2) \pm 0.10$	0.23 ± 0.04	SU(3)[1]	2.5
Δq_3	$0.83(+11) \pm 0.09$	1.01 ± 0.05	$\lvert g_A/g_V \rvert$	2.5
Δq_8	$0.32(+1) \pm 0.13$	0.46 ± 0.03	$(3F - D)$	2.5

HERMES **valence distributions** ($Q^2 = 2.5$) **vs lattice QCD**

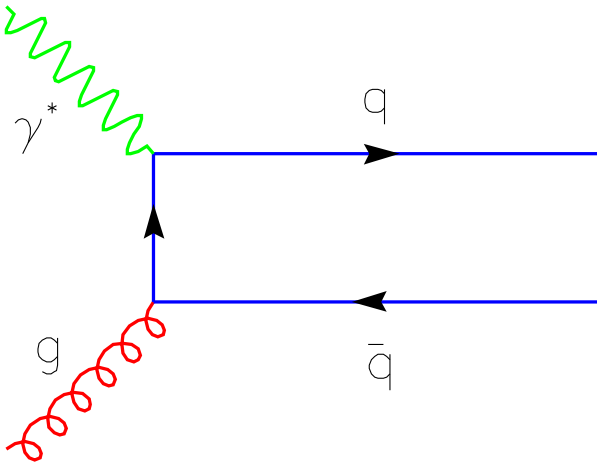
	total integral (extrap.)	prediction	Q^2
Δu_v	$0.57(+5) \pm 0.09$	0.84 ± 0.05[2]	5
Δd_v	$-0.21(-3) \pm 0.16$	-0.25 ± 0.02[2]	5
$x\Delta u_v$	0.124 ± 0.016	0.198 ± 0.008[2]	4
$x\Delta d_v$	-0.022 ± 0.034	-0.048 ± 0.003[2]	4

[1] J. Ellis and M. Karliner, Phys. Lett. B **341** (1995) 397; hep-ph/9601280
[2] M. Göckeler *et al.*, Phys. Lett. B **414** (1997) 81

High p_T Hadron Pairs

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

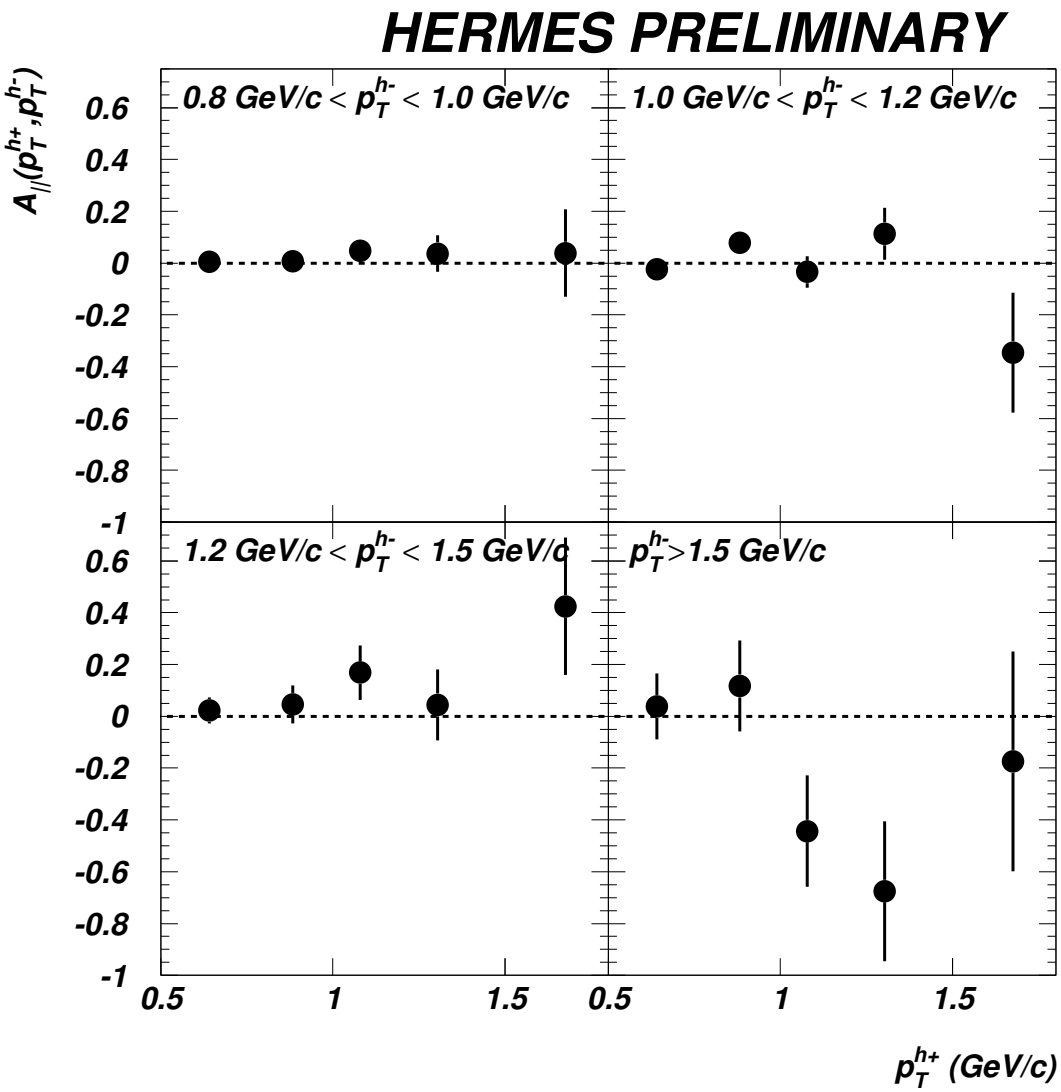
- Isolation of photon gluon fusion process
  $\rightarrow$ sensitivity to **gluon distribution**
- Spin asymmetry in photon gluon fusion
  $\rightarrow$ sensitivity to **gluon polarization** $\Delta G/G$



HERMES: measure asym of pairs of hadrons at high p_T

- require at least **two hadrons of opposite charge**
- require $M(2\pi) > 1.0$ GeV/c^2 to remove ρ and ϕ resonances
- do not require scattered e^+ in spectrometer
  $\Rightarrow$ **photoproduction** ($Q^2 \simeq 0$)

Measured Asymmetry $A_{||}(p_T^{h^+}, p_T^{h^-})$

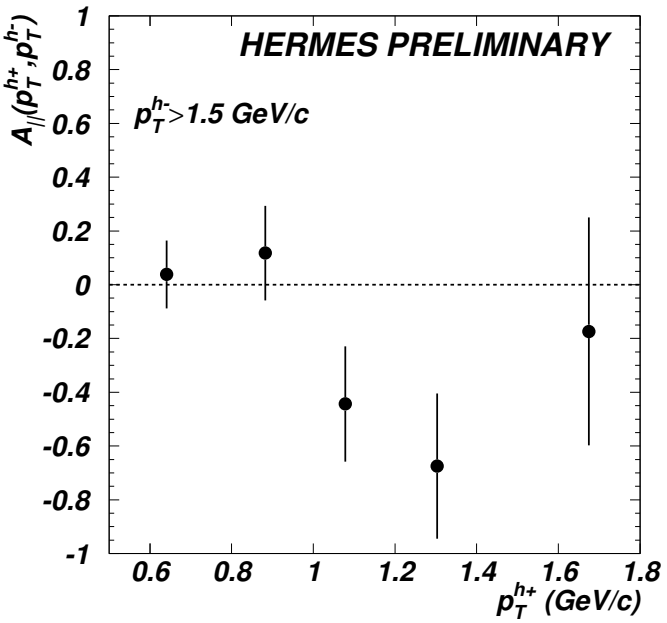


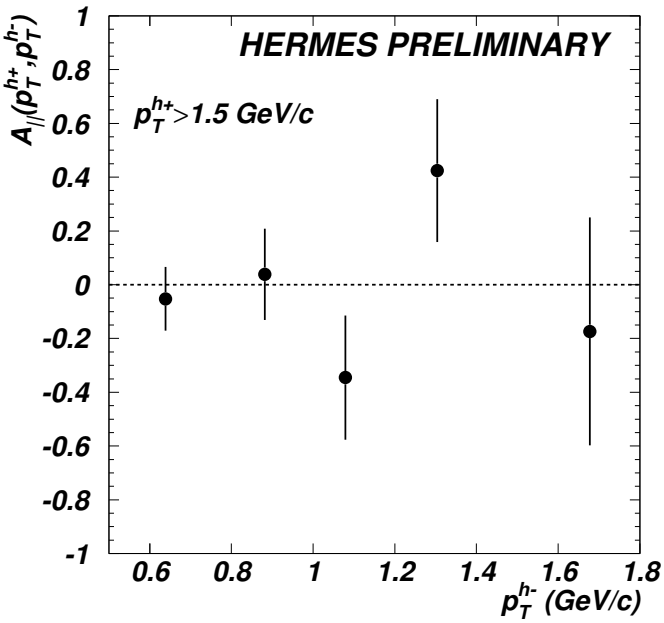
systematic error $\approx$ 8 % of measurement

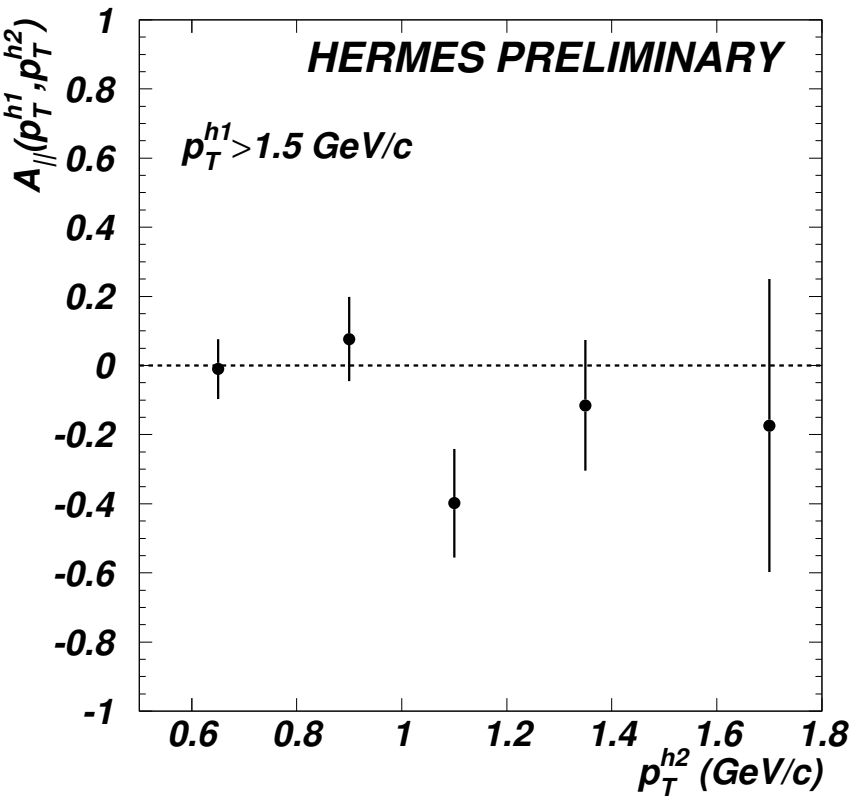
checks that have been performed on the data:

- $e^+ - h^+$ misidentification.
- particle identification cut variation.
- momentum ($\sim z$) cut variation.
- consistent result obtained using identified pions only.

Region of interest



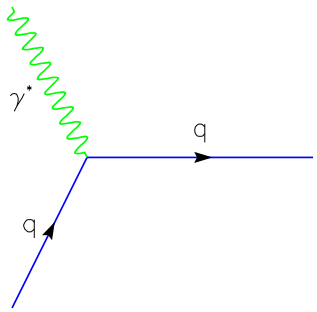




systematic error ≈ 8 % of measurement

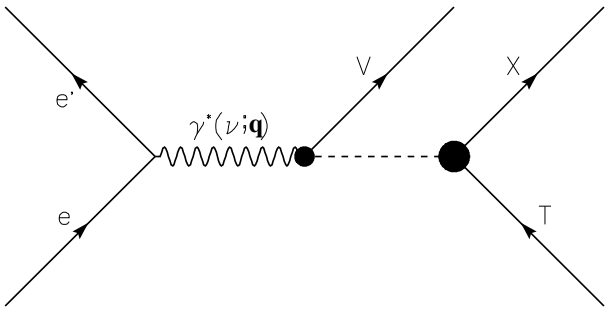
Interpretation

Assume four different processes may contribute:



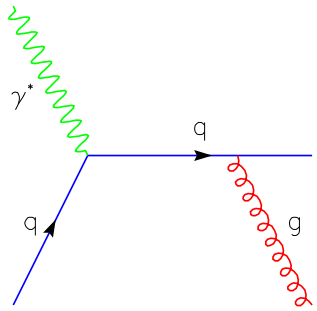
DIS

negligible contribution



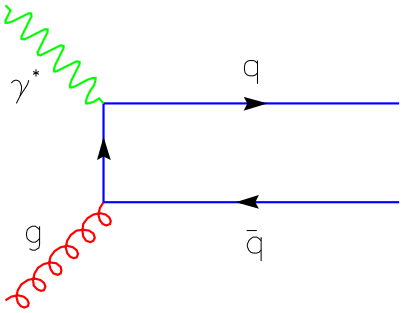
VMD

assume $A_{\mathrm{VMD}} = 0$



QCDC

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



PGF

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

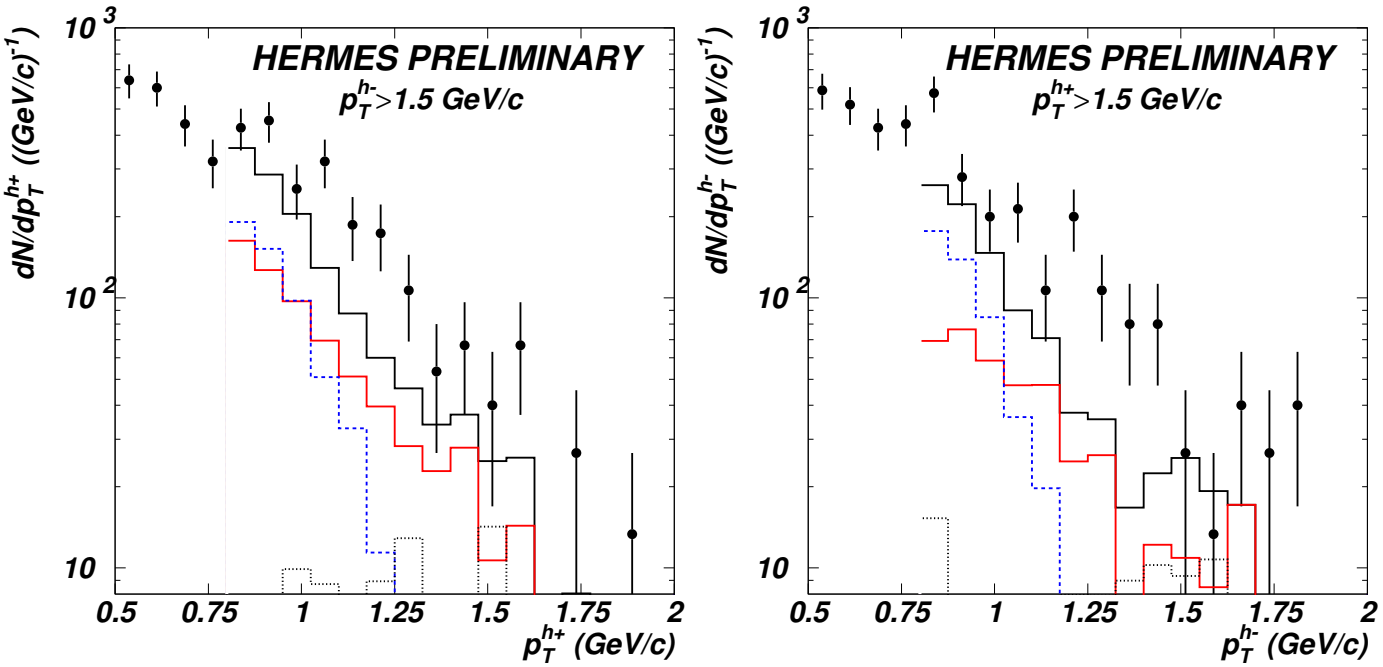
... estimate their relative contributions using PYTHIA

$\rightarrow$ extract $\Delta G/G$

NOTE: Possible contribution from anomalous photon neglected, expected to be small at these energies.

MC-Data Comparisons

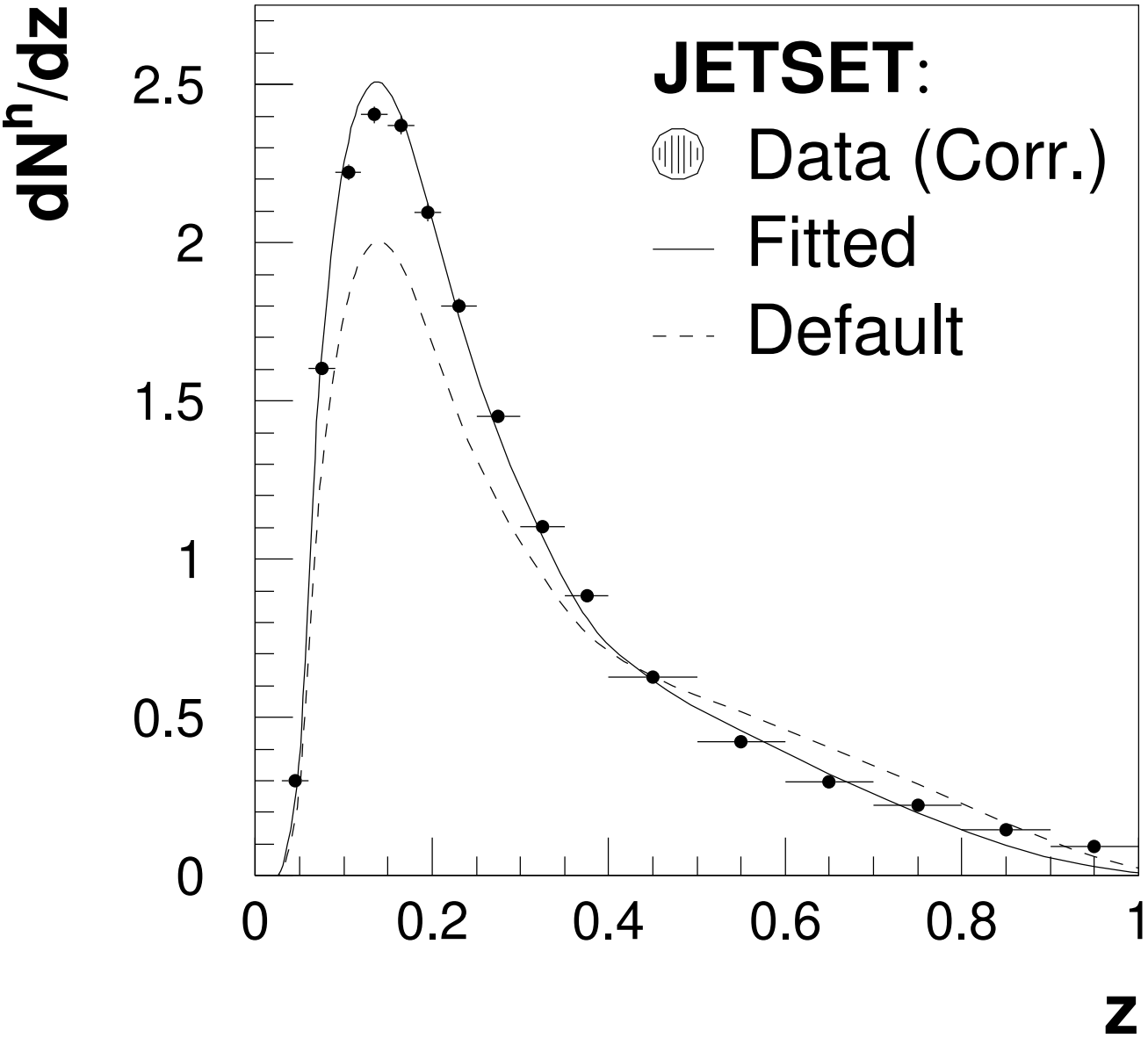
Comparisons of measured yields with predictions of model implemented in PYTHIA.



solid black = total yield
solid red = PGF
dashed blue = QCDC
dotted black = VMD

Data are interpreted in terms of $\Delta G/G$ only in region where PYTHIA model is independent of $\hat{p}_T^{\min}$ cutoff parameter.

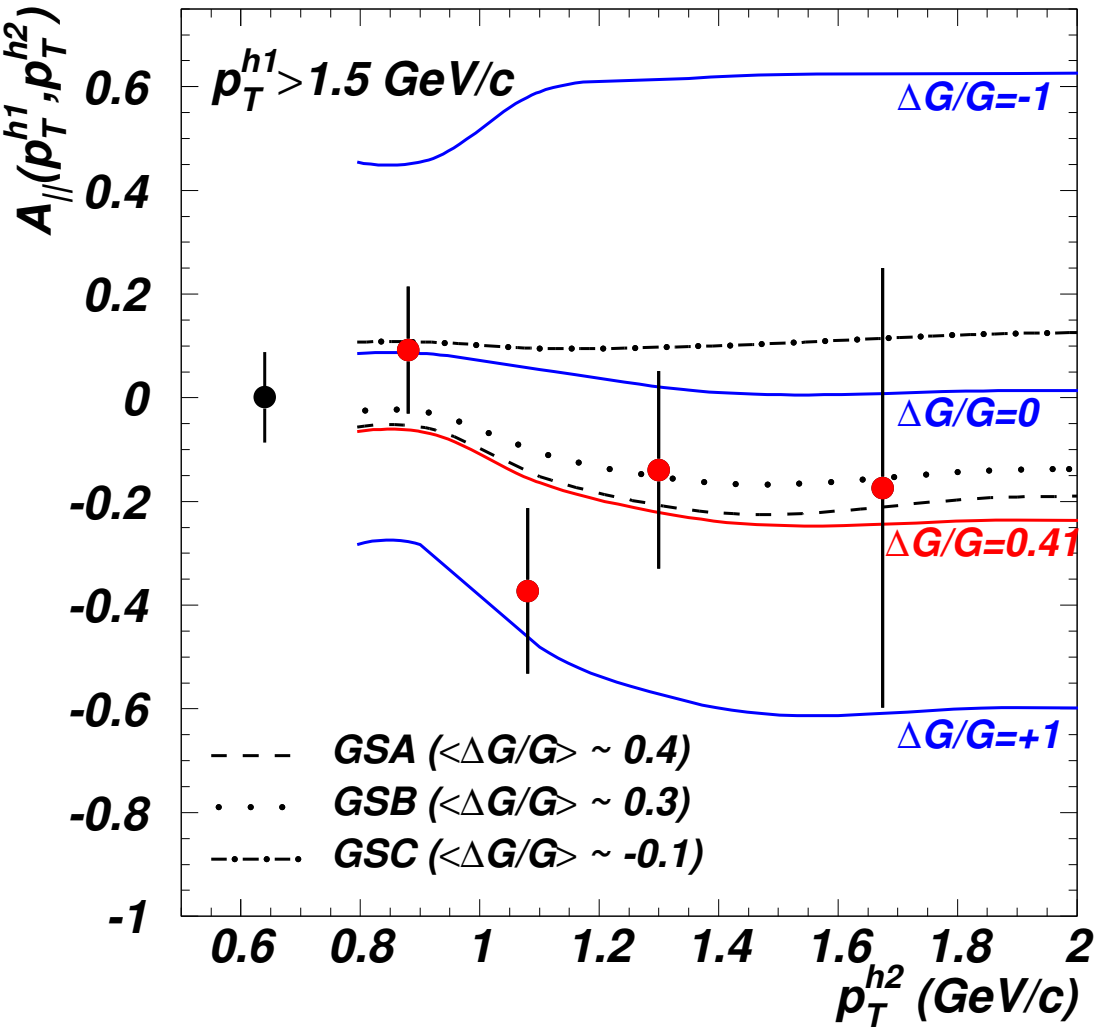
Fragmentation Parameters at hermes



Result Using PYTHIA Model

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

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



Unknown theoretical uncertainty from contribution and spin asymmetry of anomalous photon and NLO QCD corrections. If only a dilution, value of $\Delta G/G$ will increase but significance of deviation from zero will not change.

P.J. Mulders: Classification of Distribution and Fragmentation Functions

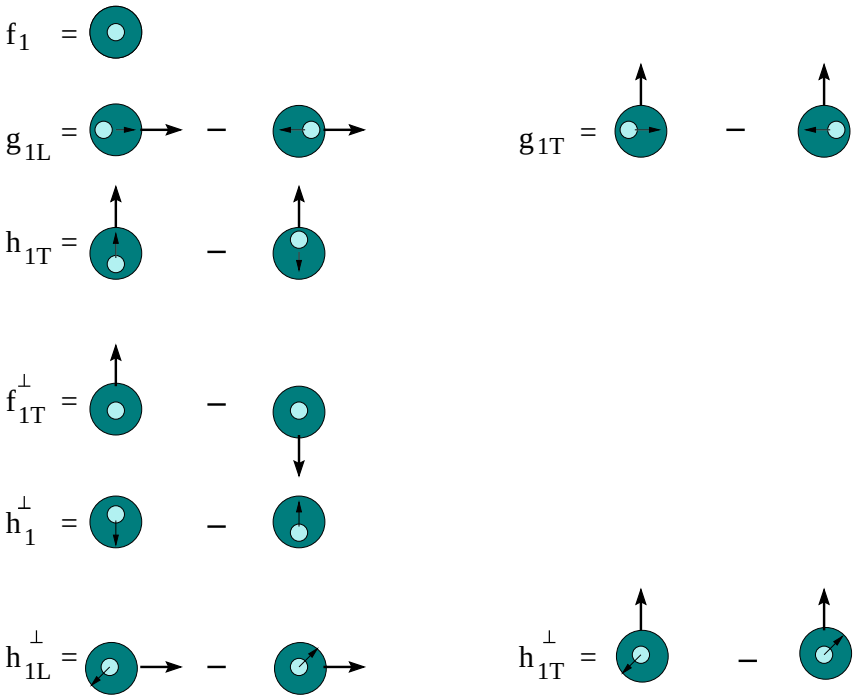
DISTRIBUTIONS (T-even)			
$\Phi^{[\Gamma]}$		chirality even	chirality odd
twist 2	U	f_1	
	L	g_{1L}	$h_{1L}^{\perp}$
	T	g_{1T}	$h_1\ h_{1T}^{\perp}$
twist 3	U	$f^{\perp}$	e
	L	$g_L^{\perp}$	h_L
	T	$g_T\ g_T^{\perp}$	$h_T\ h_T^{\perp}$

DISTRIBUTIONS (T-odd)			
$\Phi^{[\Gamma]}(x, k_T)$		chirality even	chirality odd
twist 2	U	-	$h_1^{\perp}$
	L	-	-
	T	$f_{1T}^{\perp}$	-
twist 3	U	-	h
	L	$f_L^{\perp}$	e_L
	T	f_T	e_T

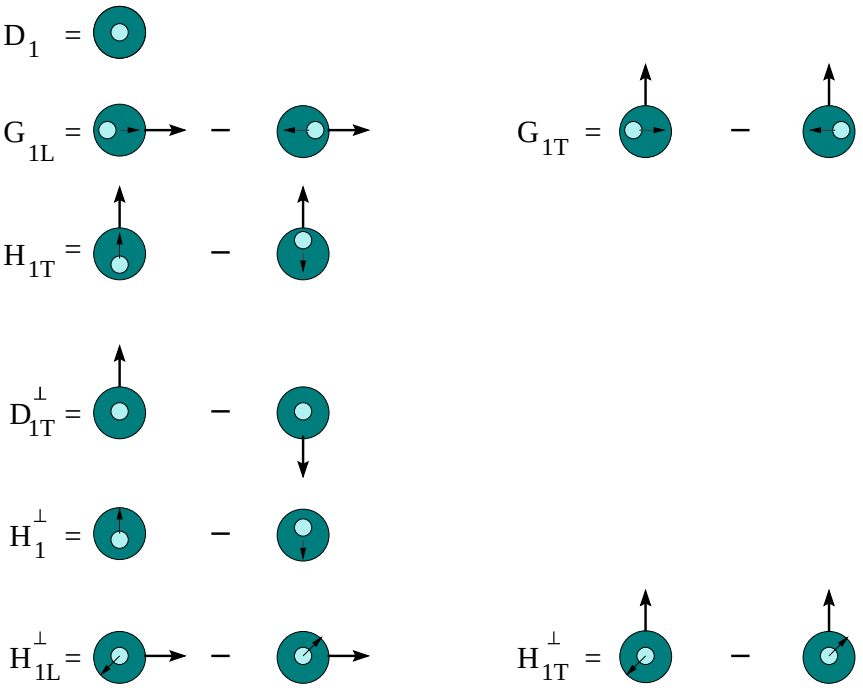
Functions in blue survive after integration over transverse momenta

FRAGMENTATION			
$\Delta^{[\Gamma]}$		chirality even	chirality odd
twist 2	U	D_1	$H_1^{\perp}$
	L	G_{1L}	$H_{1L}^{\perp}$
	T	$G_{1T}\ D_{1T}^{\perp}$	$H_1\ H_{1T}^{\perp}$
twist 3	U	$D^{\perp}$	$E\ H$
	L	$G_L^{\perp}\ D_L^{\perp}\ E_L$	H_L
	T	$G_T\ G_T^{\perp}\ D_T\ E_T$	$H_T\ H_T^{\perp}$

Distribution Functions



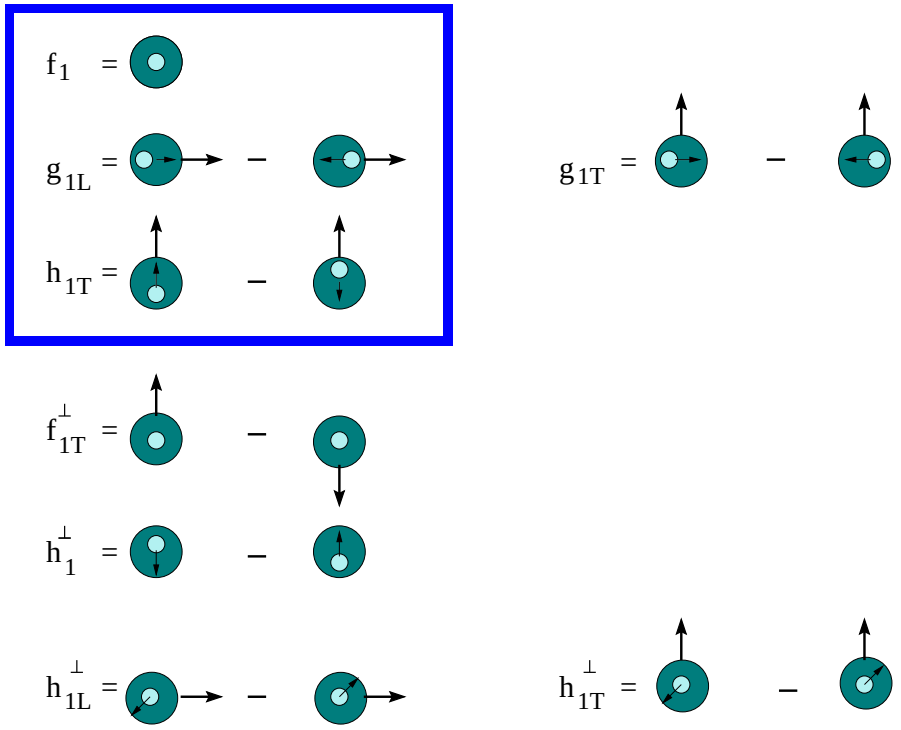
Fragmentation Functions



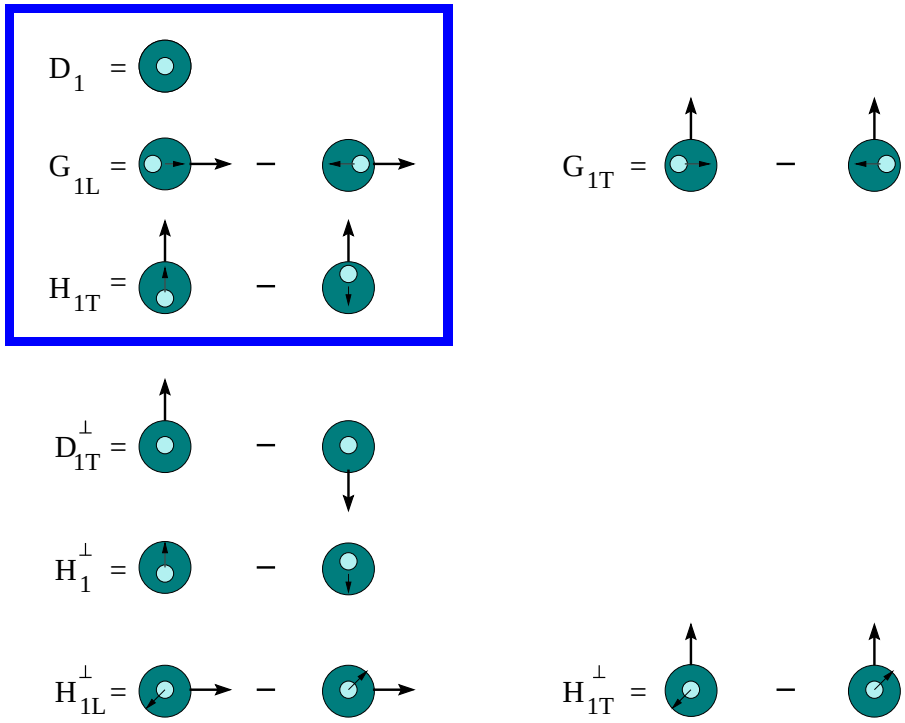
Functions Surviving on Integration over Transverse Momenta

- The others are sensitive to intrisic $< k_t >$ in the nucleon & in the fragmentation process

Distribution Functions



Fragmentation Functions



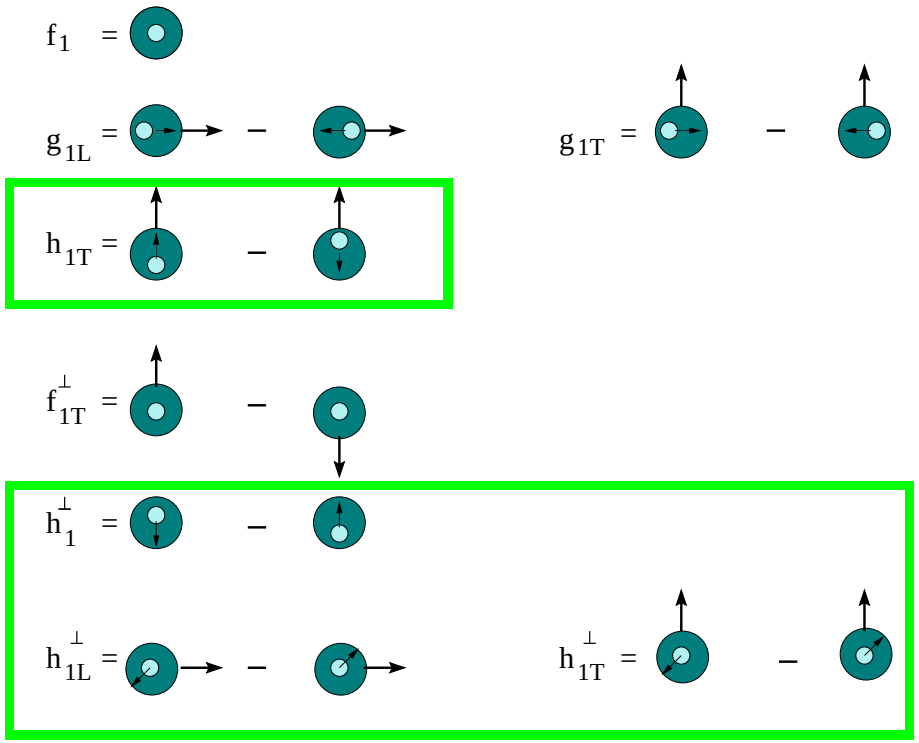
Higher Twist Functions
(no pictures)

- Sensitive to parton-parton correlations
- Have a twist-2 part ... e.g. $h_L(x) = 2x \int_x^1 dy \frac{h_1(y)}{y^2}$

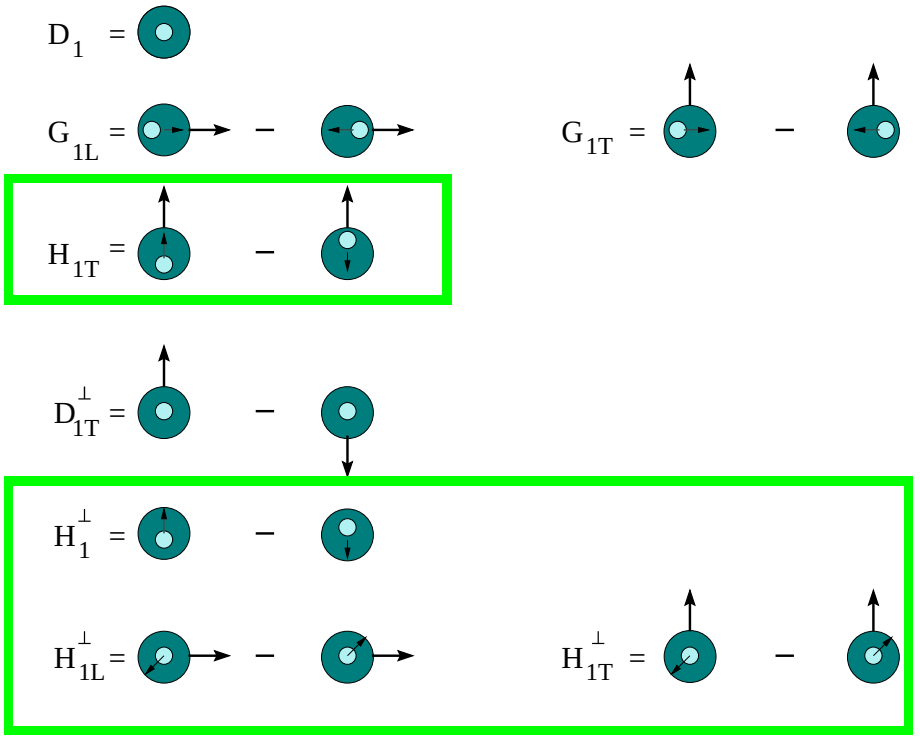
Chiral-Odd Functions

- Involve helicity flip of transverse quark
- Appear in pairs in cross-sections

Distribution Functions



Fragmentation Functions



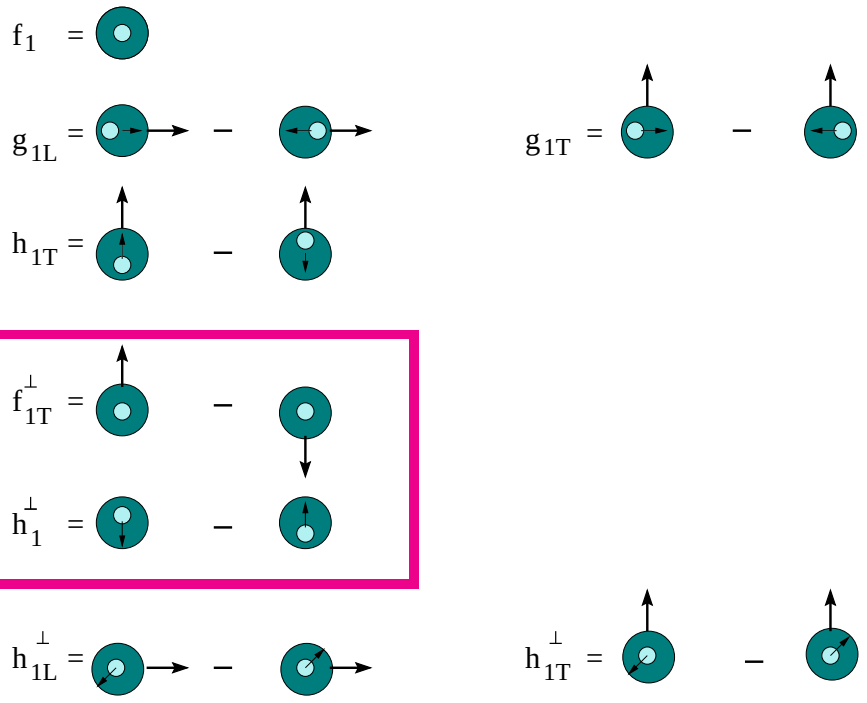
e.g. Transversity $h_1(x)$

- $h_1(x) \sim \delta q(x)$ ... cf. $f_1(x) \sim q(x), g_1(x) \sim \Delta q(x)$
- $\delta q(x) \neq \Delta q(x) \rightarrow$ relativistic / spin-orbit effects

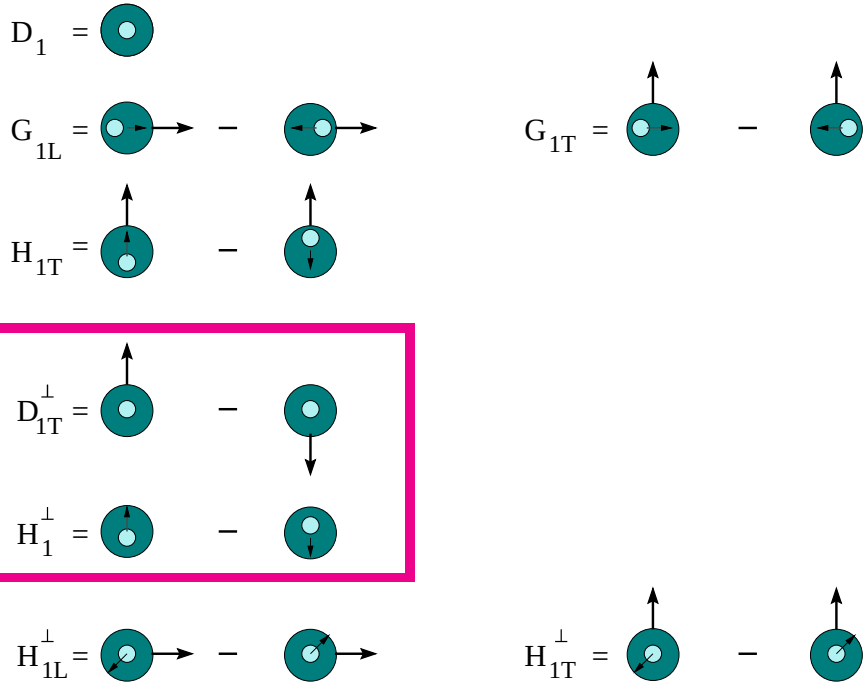
T-Odd Functions

- one T-odd functon required to produce single spin asymmetries in SIDIS
- sensitive to transversely polarized quarks/hadrons given unpolarized hadrons/quarks

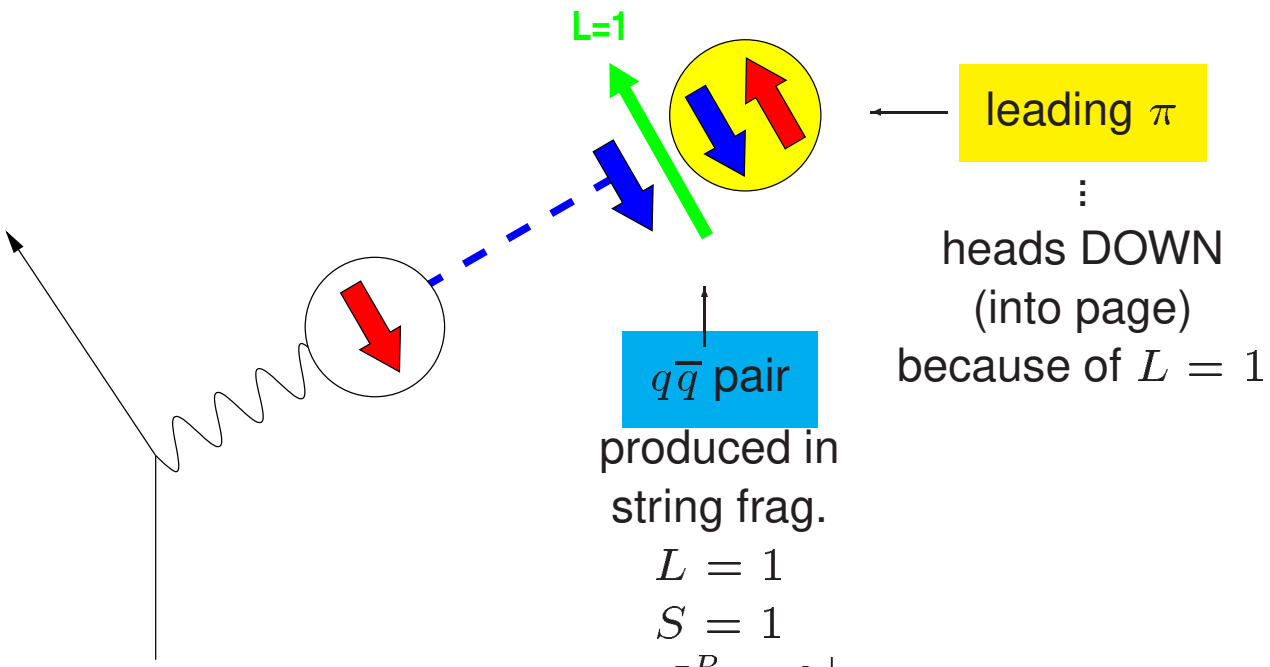
Distribution Functions



Fragmentation Functions



The COLLINS EFFECT in the String Fragmentation Model



Azimuthal angles with respect to lepton scattering plane

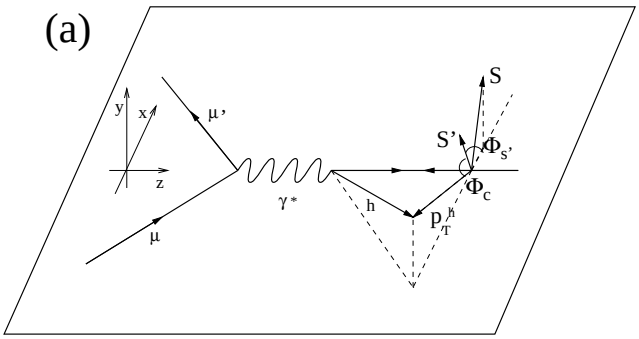
hadron (e.g. π)	$\phi_h^l = -\pi/2$
final q spin S'	$\phi_{S'}^l = 0$
initial q spin S	$\phi_S^l = \pi$

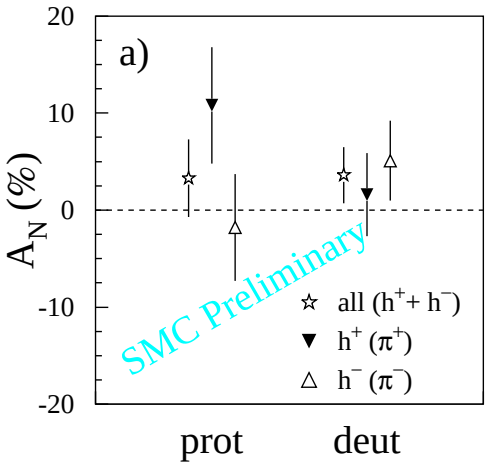
Collins Angle $\phi_c = \phi_h - \phi_{S'} = \phi_h + \phi_s - \pi = -\pi/2$ here

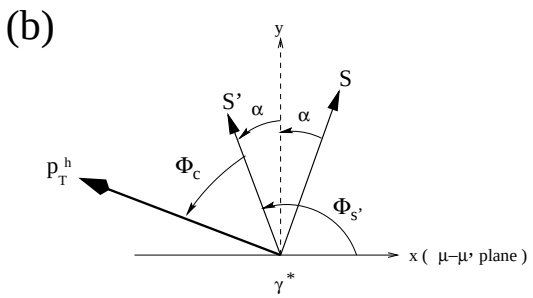
$$\langle \frac{Q_T}{M_h} \sin \phi_c \rangle \sim -h_1(x) \cdot H_1^\perp(z)$$

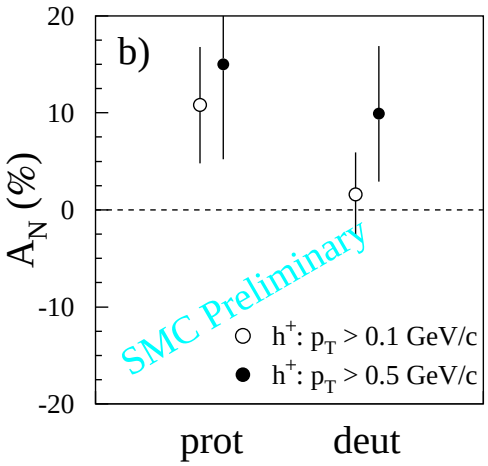
SMC: Azimuthal Asymmetry

$$A_N = \frac{1}{P_T f D_{NN}} \frac{1}{\langle \sin\phi_c \rangle} \frac{N(\phi_c) - N(\phi_c + \pi)}{N(\phi_c) + N(\phi_c + \pi)}$$



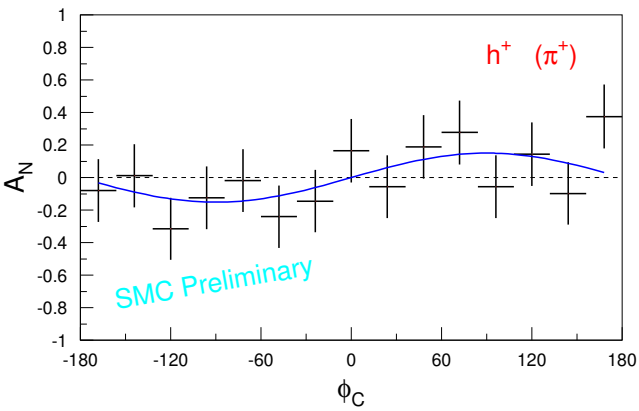


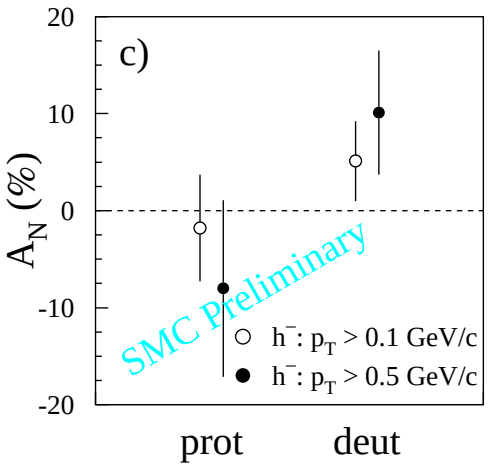




$$d\sigma \sim (1 + A_N \sin\phi_c) d\phi_c$$

Using transversely polarized target

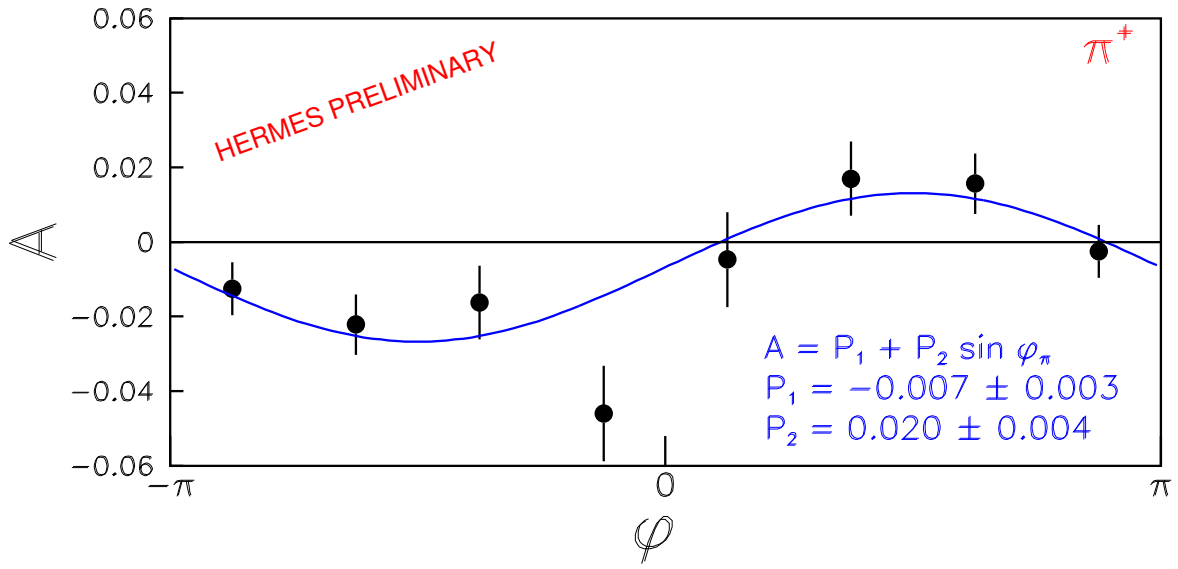


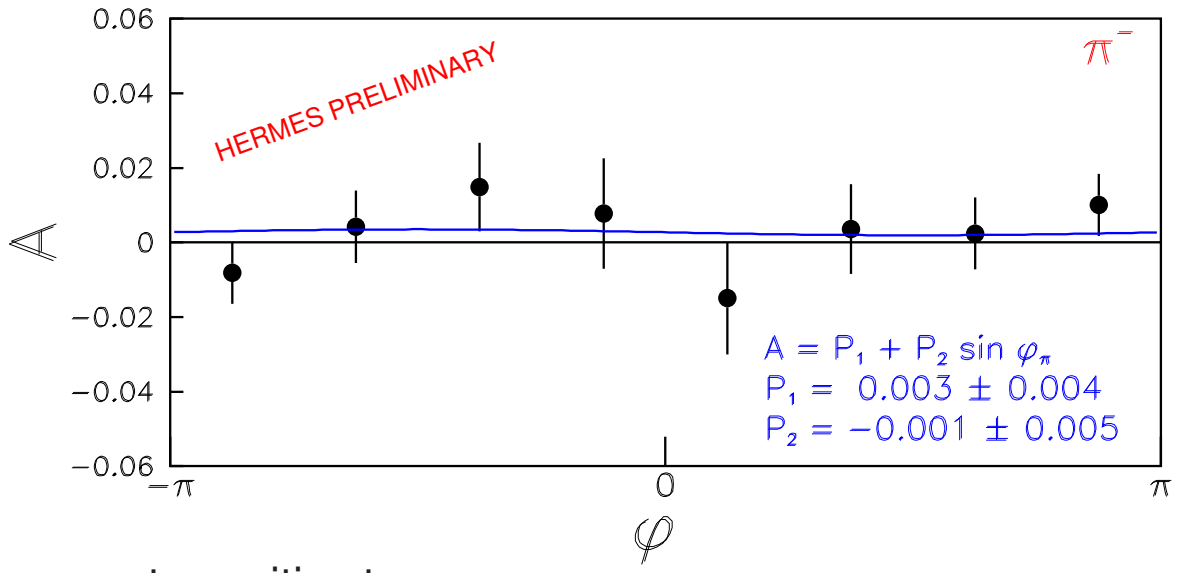


Spin-Azimuthal Asymmetries

Longitudinal target spin asymmetry:

$$A(\phi) = \frac{1}{P}\,\frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$



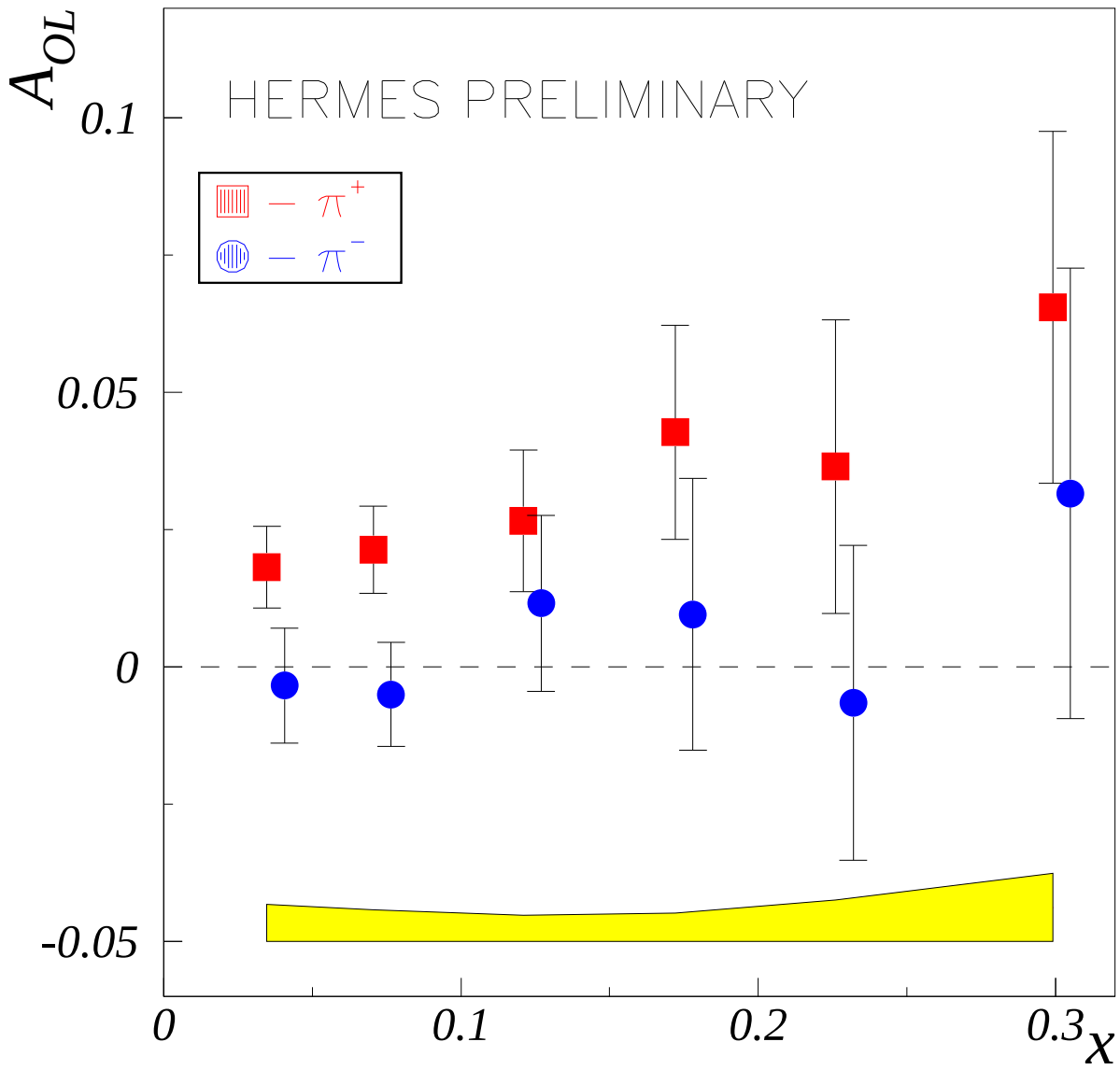


Sin ϕ moment sensitive to:

- $h_L(x)$ = twist 3, chiral odd distribution function, related to h_1, $h_{1L}^{\perp}$
- $H_1^{\perp}(z)$ = T-odd, chiral odd "Collins" fragmentation function

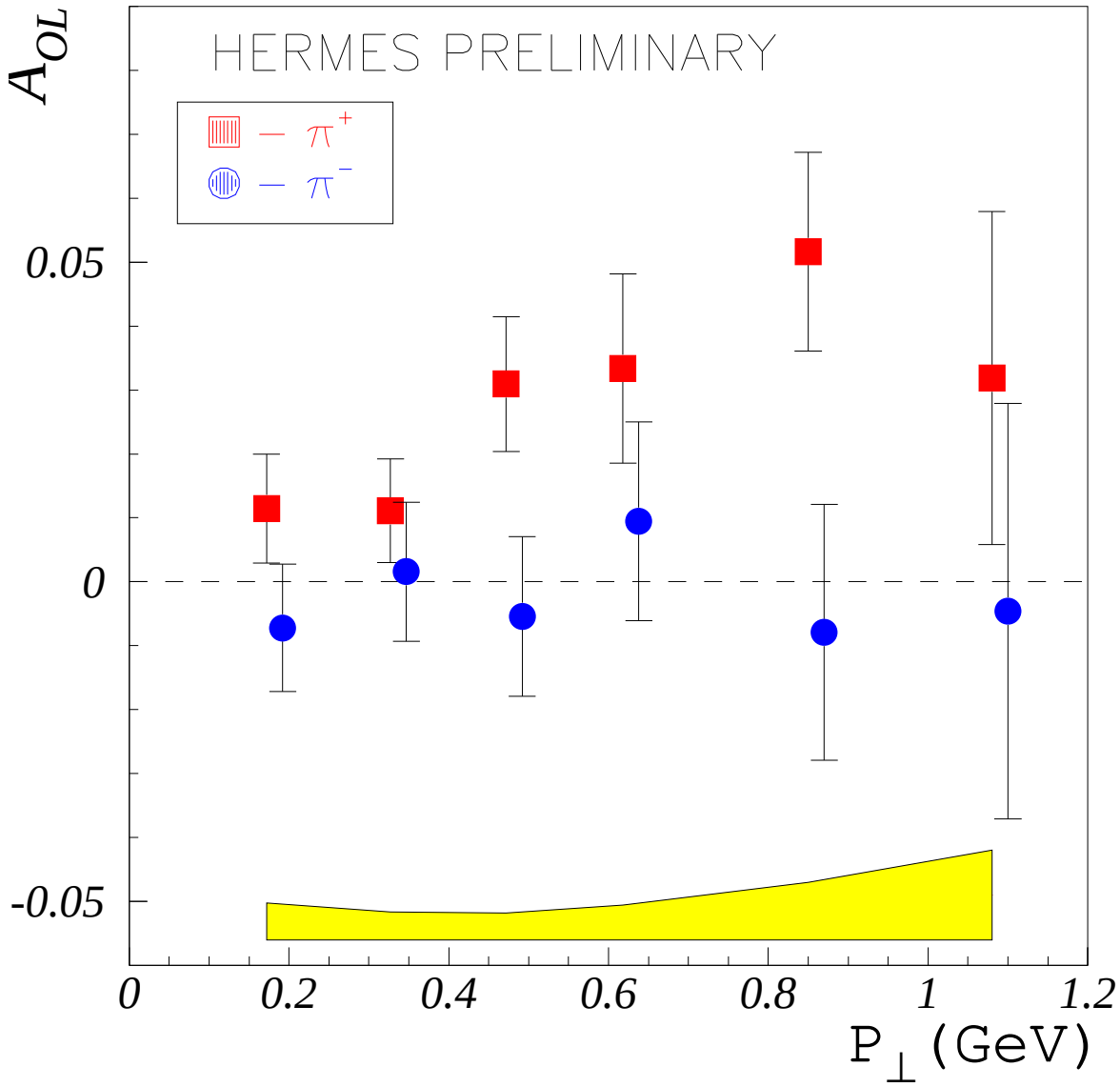
A_{OL}: x dependence

$A_{OL} = \langle \sin\phi \rangle$ moment of longitudinal target asymmetry



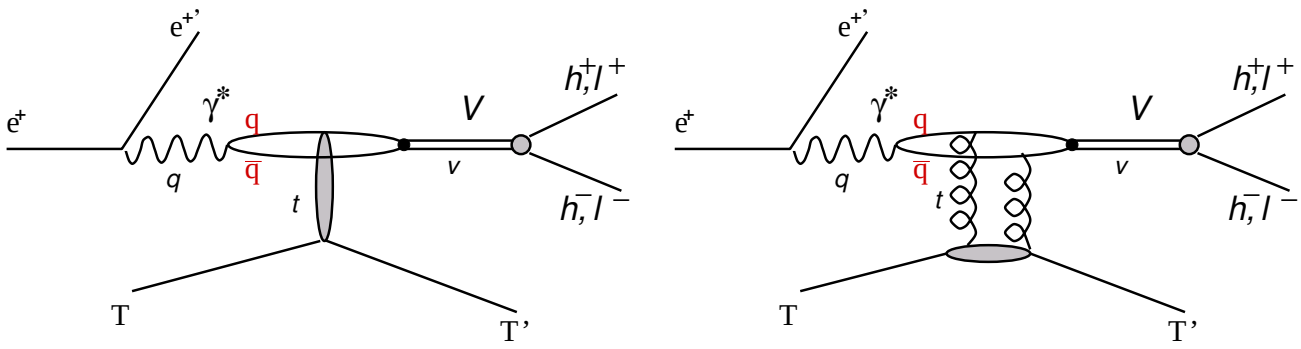
Band on bottom of plot represents systematic uncertainty.

A_{OL}: $P_\perp$ dependence



Band on bottom of plot represents systematic uncertainty.

Diffractive Vector Meson Production



Channels reconstructed at HERMES

$\rho^0 \to \pi^+\pi^-$ $\qquad$ $\phi \to K^+K^-$

$J/\psi \to e^+e^-$ $\qquad$ $J/\psi \to \mu^+\mu^-$

Kinematics

ρ, ϕ: e' detected

$\Rightarrow$ complete event kinematics reconstructed

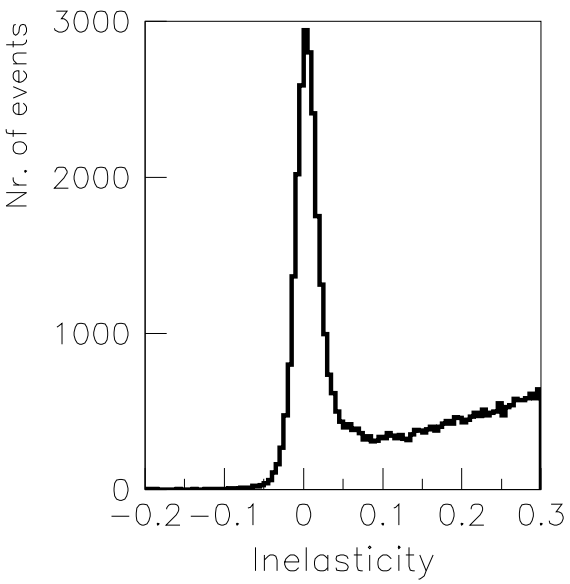
J/ψ: e' not detected

$\Rightarrow$ $Q^2 \sim 0$, kinematics not fully known

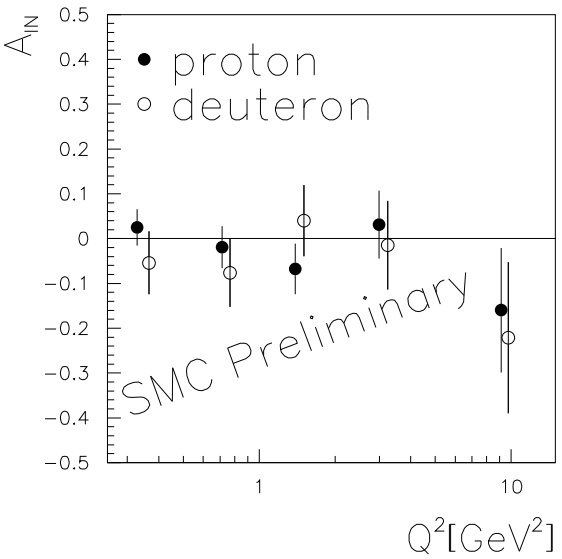
	Exclusive
4-momentum transfer to target $t = (q - \nu)^2$	$-t < \mathcal{O}$ (1 GeV^2)
minimum t $t_0 = t(V\|\|\gamma^*)$	$t_0 \sim 0$
transverse component of t $t' = t - t_0 \sim p_T^2$	$t' \sim t$
energy transfer to the target $\Delta E = \frac{(M_X^2 - M_T^2)}{2M_T}$	$\Delta E = 0$

SMC: A_1 in Exclusive ρ^0 Production

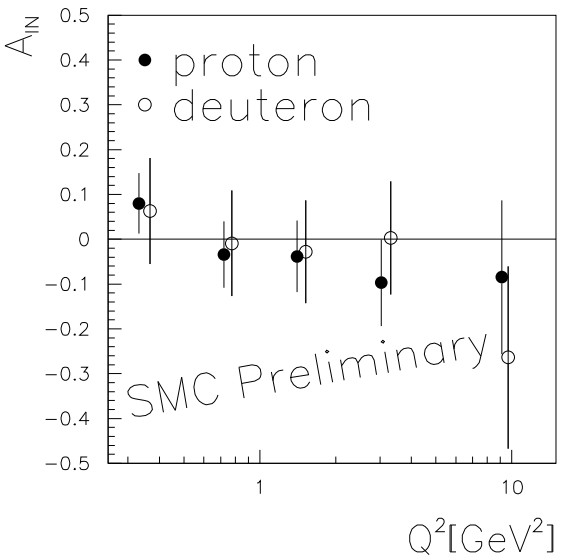
Exclusive Peak



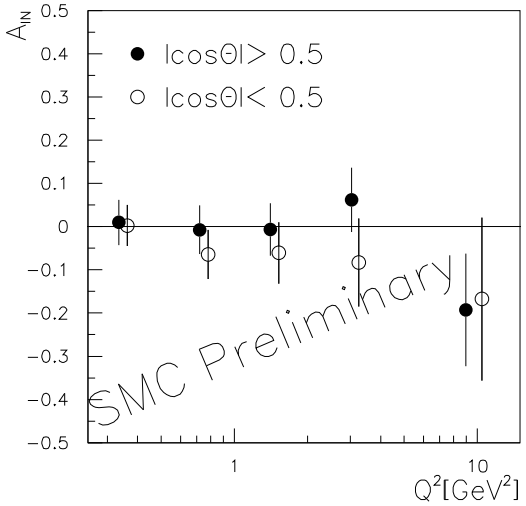
A_1^ρ vs Q^2, $\langle W \rangle \simeq 15$ GeV



requiring $p_T^2 > 0.09$ GeV/c^2

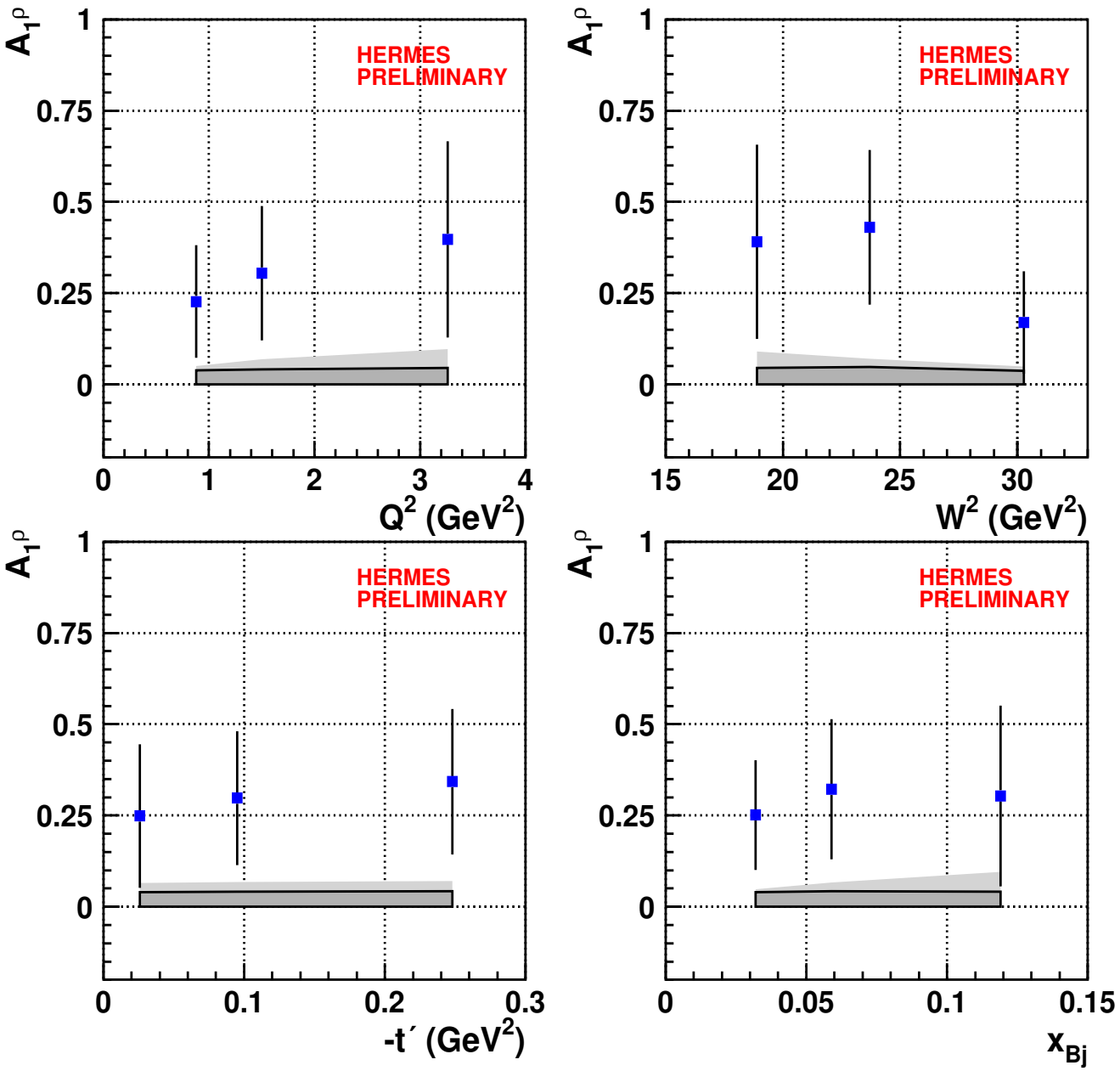


two bins in decay angle



Error bars are statistical only.

Photon Absorption Asymmetry



Maximum possible contribution of unknown A_2^ρ added in quadrature to experimental systematic uncertainty

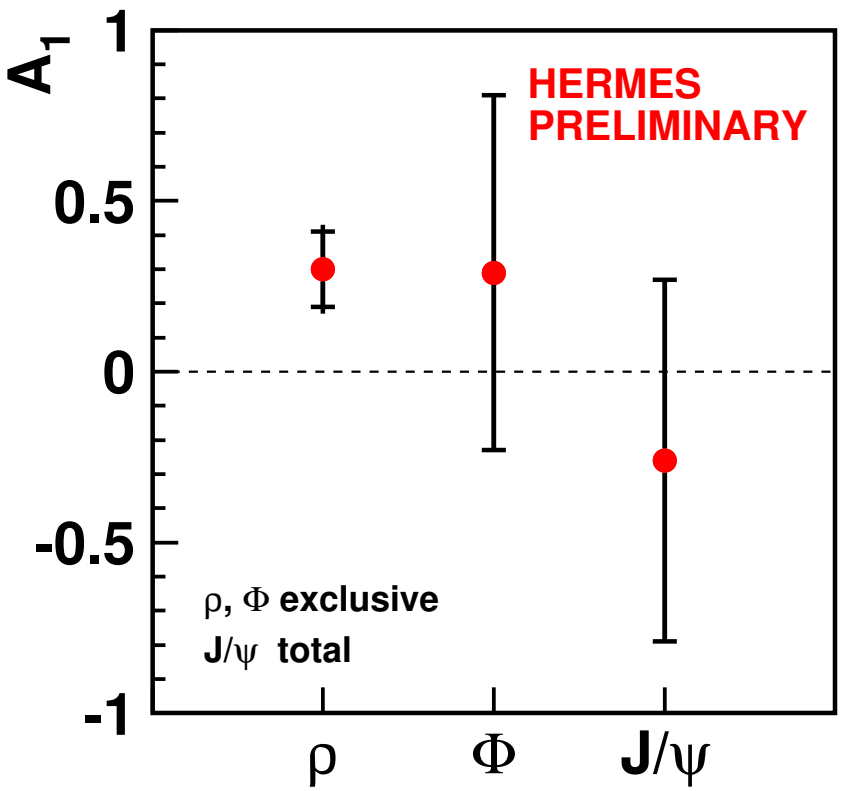
$\Rightarrow$ light gray error band

Assume $A_2^\rho = \pm\min(\sqrt{R}, 1) \Rightarrow \delta_{\rm syst}(A_1^\rho) \leq \eta A_2^\rho$

(Theorists claim that this is probably an overestimate).

Summary

Comparison of Vector Meson Asymmetries



- Clear positive asymmetry for diffractive ρ's

$$A_1^{\rho} = 0.30 \pm 0.11(\text{stat}) \pm 0.04(\text{sys}) \pm 0.05(\text{theor})$$

$\Rightarrow$ Evidence of non-trivial spin structure in this reaction

- A_1^{ϕ} and $A_1^{J/\psi}$ consistent with zero within stat. errors

  For J/ψ scattered positron is not detected $\Rightarrow$ kinematics not fully known, possible inelastic contribution

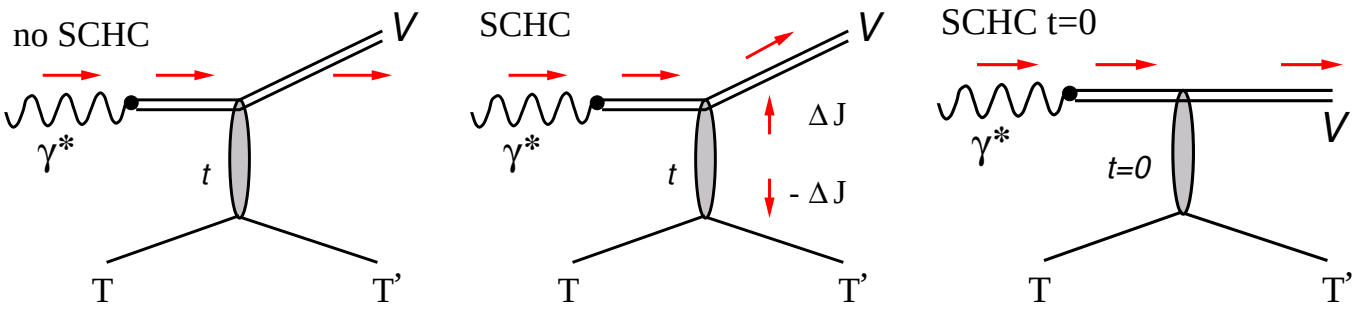
Possible Physics Interpretations

Diffractive VM production related to ΔG?

... already at the low mass of the ρ?
(M. Ryskin, hep-ph/9706505)

Spin density matrix elements

measured via angular distributions in VM production
$\rightarrow$ extraction of $R = \sigma_L/\sigma_T$ assuming SCHC.
Does a non-zero asymmetry at small t imply a violation of SCHC?

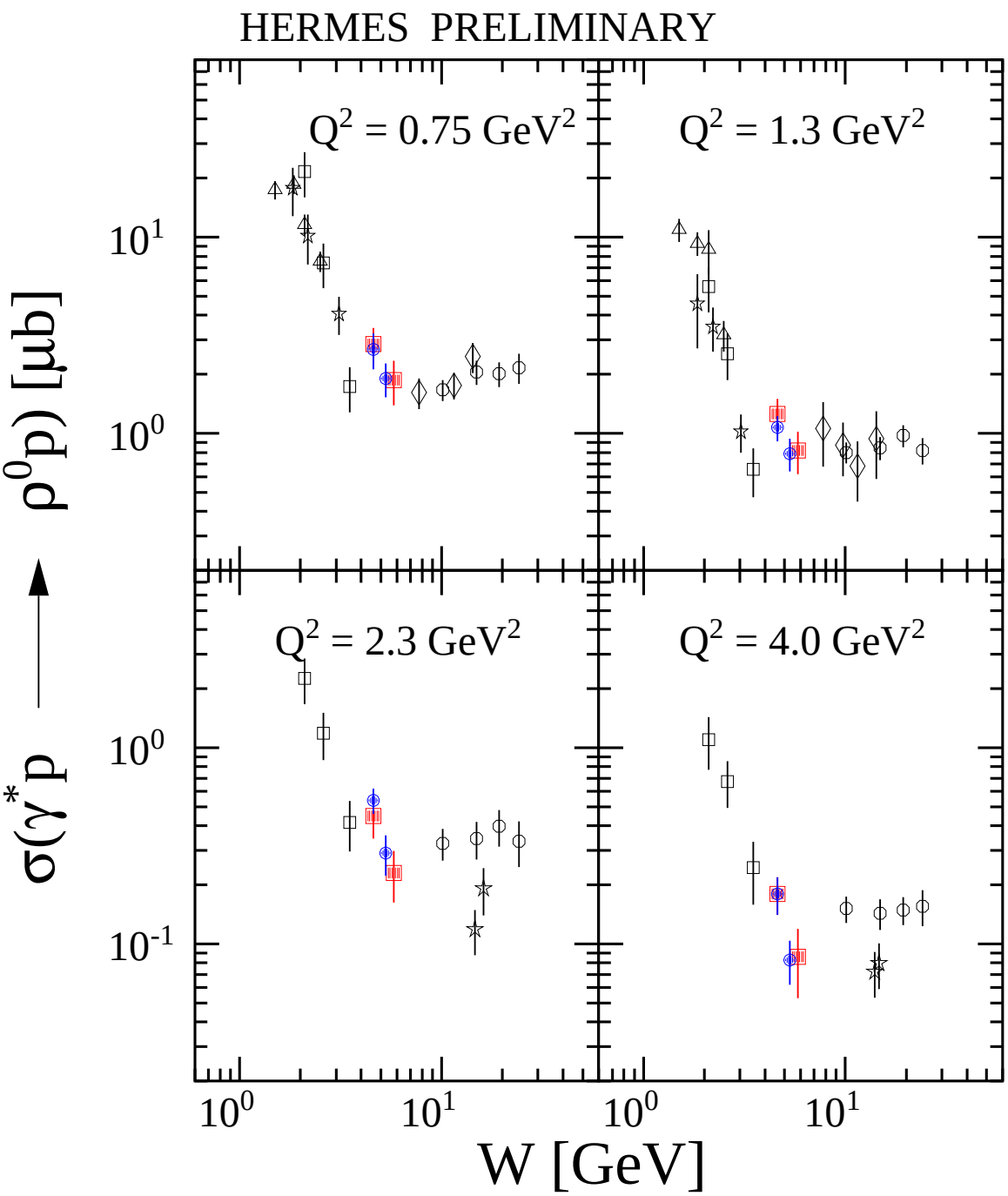


Off-forward parton distributions

Asymmetry in diffractive pair production of charged mesons and exclusive ρ production may give access to OFPD's? (A. Schaefer et al. hep-ph/9901283)

A significant non-zero asymmetry in diffractive ρ production is an unexpected and exciting result, which is presently without theoretical explanation.

ρ^0 Photoproduction Cross Section



The Future

HERMES

- 1998-2000 data set on D being collected
- 1998/99 upgrades:
  - RICH = full $\pi/K/p$ separation
  - Charm Upgrade = wide angle μ detection + far-forward lepton detection
  - Silicon Upgrade = enhanced acceptance for Λ
- Will continue running after 2000/01 Lumi Upgrade at HERA
  $\rightarrow$ transverse target program under study

COMPASS

- Upgrade of SMC experiment: higher luminosity + improved PID
- Measure ΔG via charm production and high p_T hadrons
- Long range: transverse target measurements

RHIC SPIN

- Access to ΔG from polarized proton-proton scattering