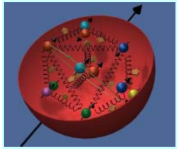
Nucleon Spin:
Experimental Overview

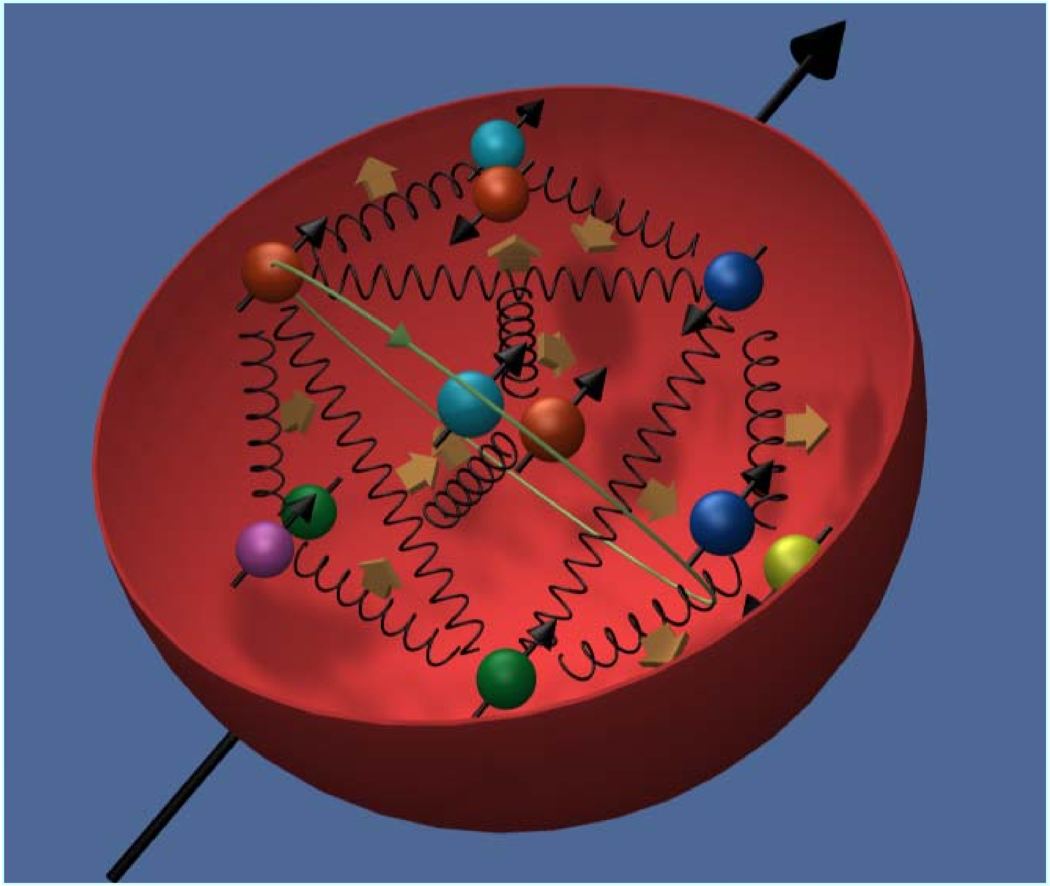
Klaus Rith

University of Erlangen -Nürnberg & DESY

MAMI and Beyond, Schloss Waldthausen, March 30, 2009

Nucleon Spin: QCD picture



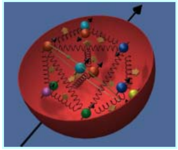


(Quark spins) (Gluon spins)

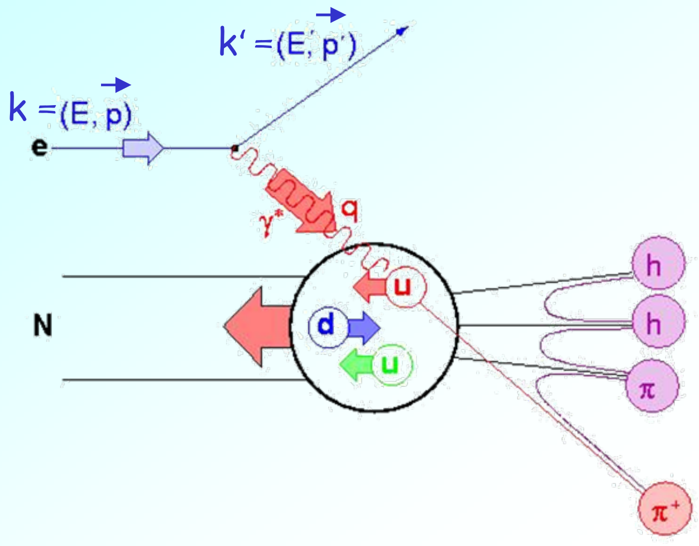
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

(Orbital angular momenta)

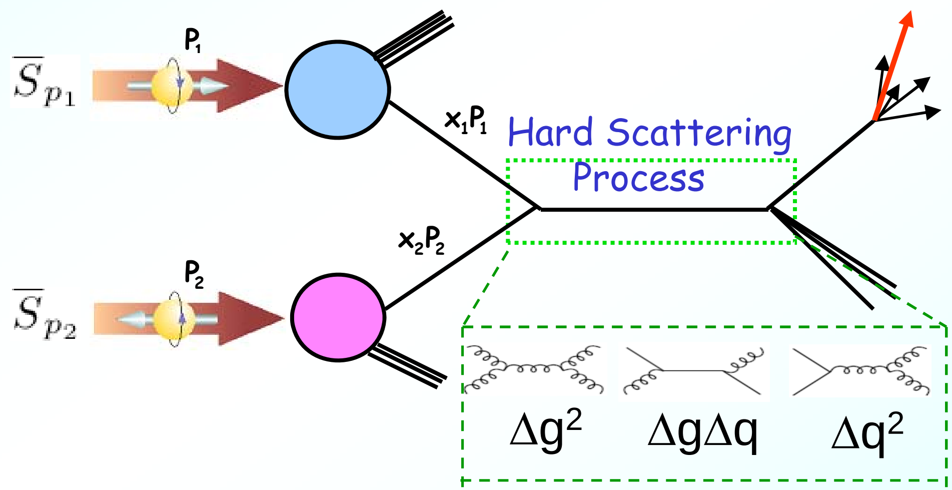
Nucleon Spin - Tools



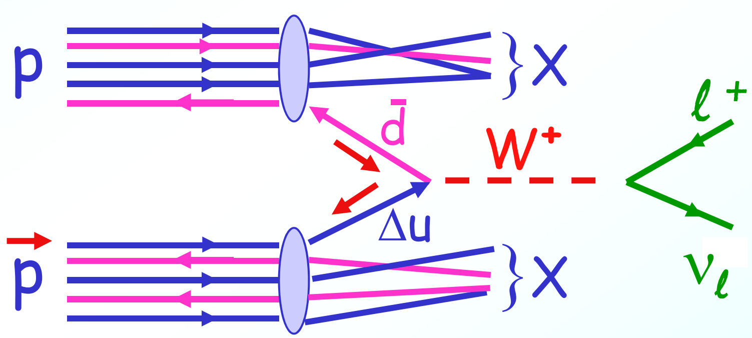
Polarised DIS



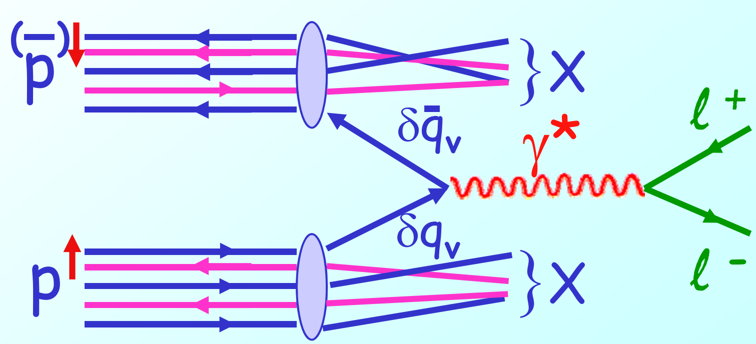
π° or jet production in $\vec{p}\vec{p}$



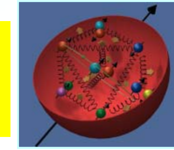
$W^\pm$ -production



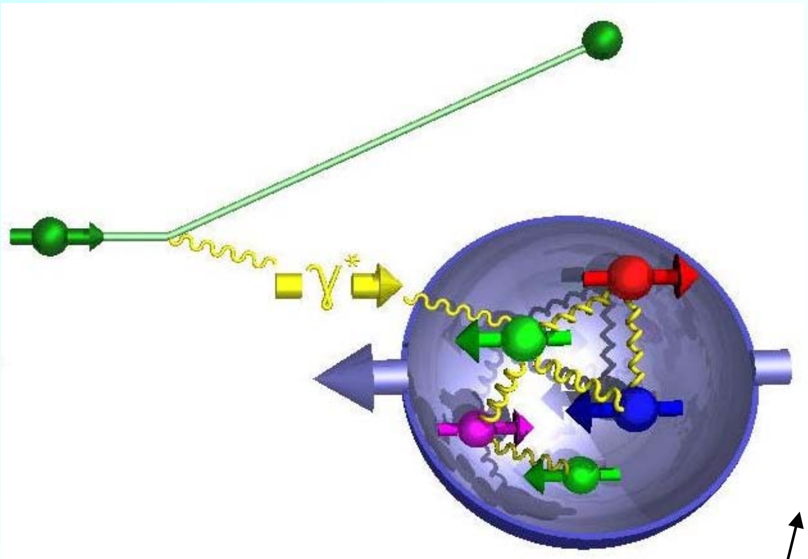
Drell-Yan

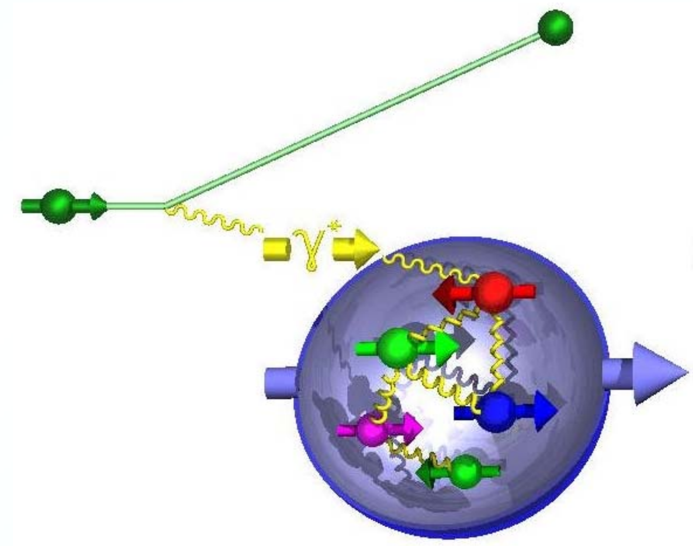


Quark helicity distributions $\Delta q(x)$



More precisely: „helicity weighted momentum distributions“





Proton

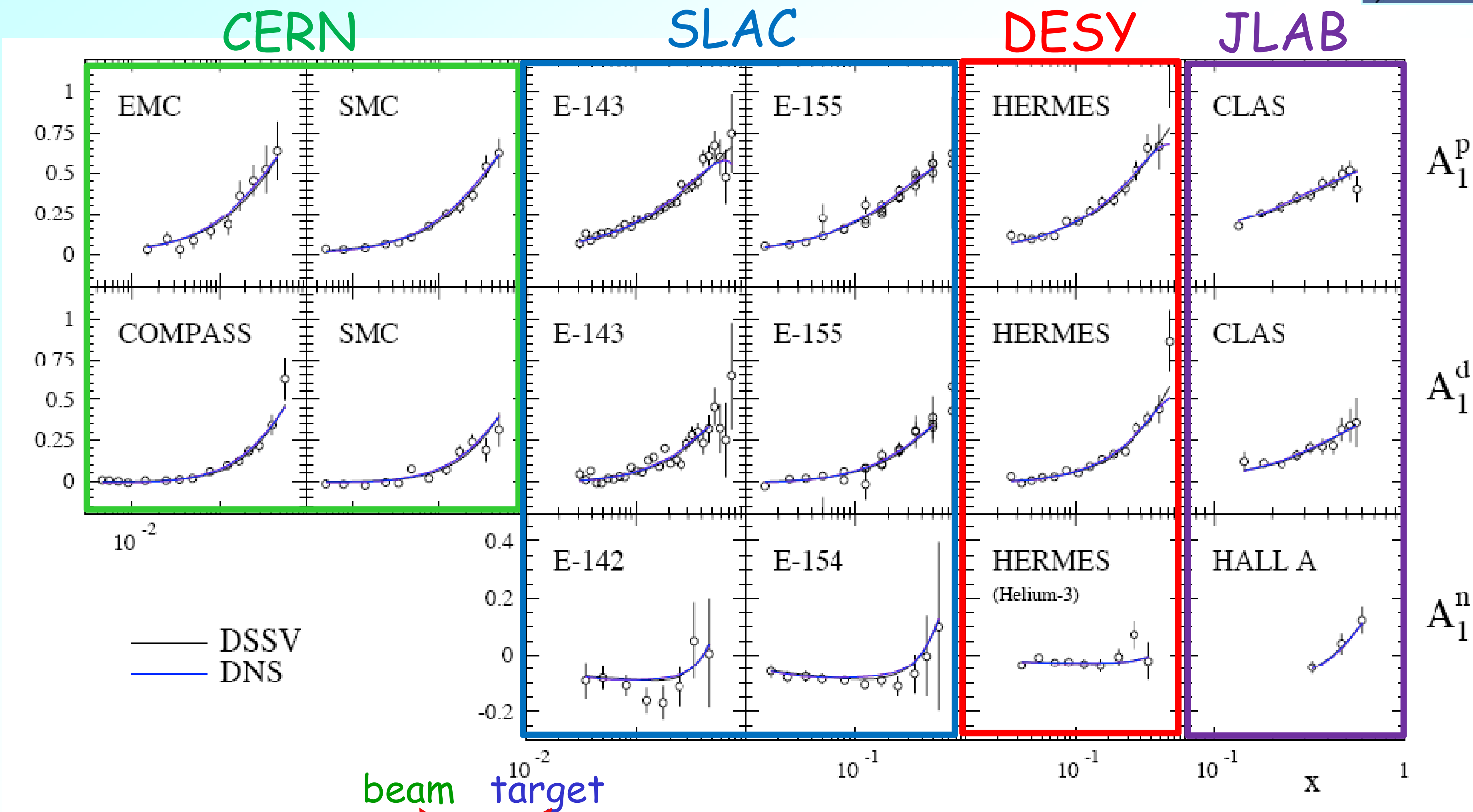
Quark

$q^{+}(x) = q^{\uparrow\uparrow}$

$q^{-}(x) = q^{\downarrow\uparrow}$

$$\Delta q(x) = q^{+}(x) - q^{-}(x)$$

Asymmetries in polarized DIS

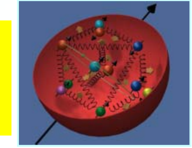


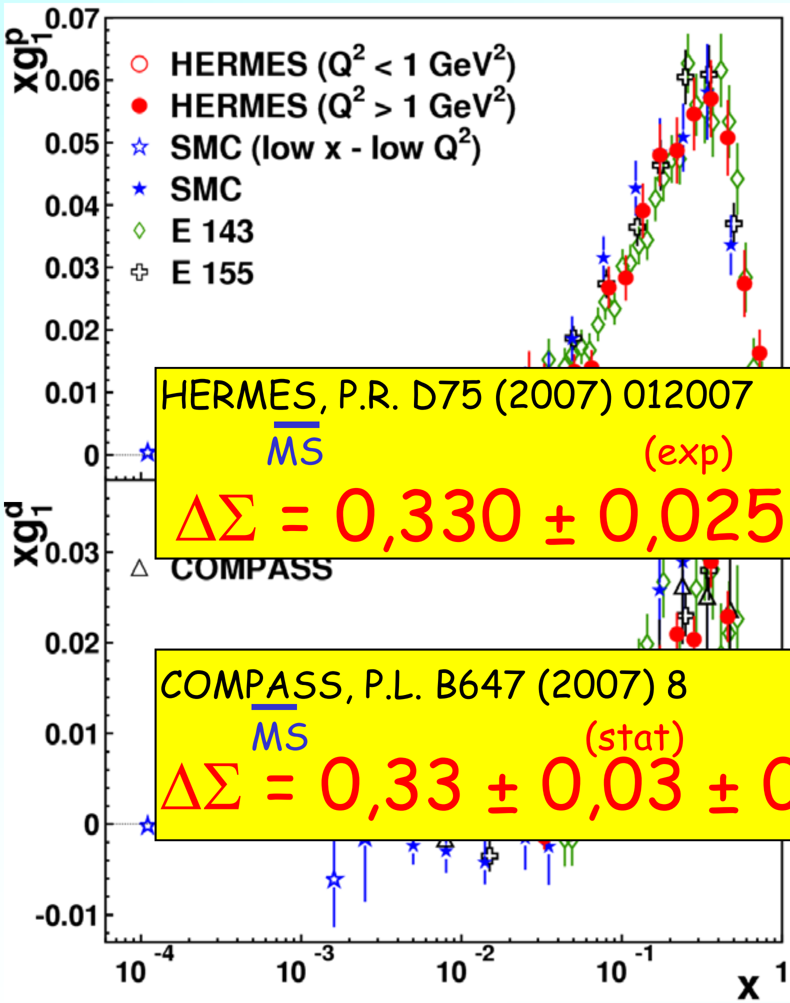
beam target

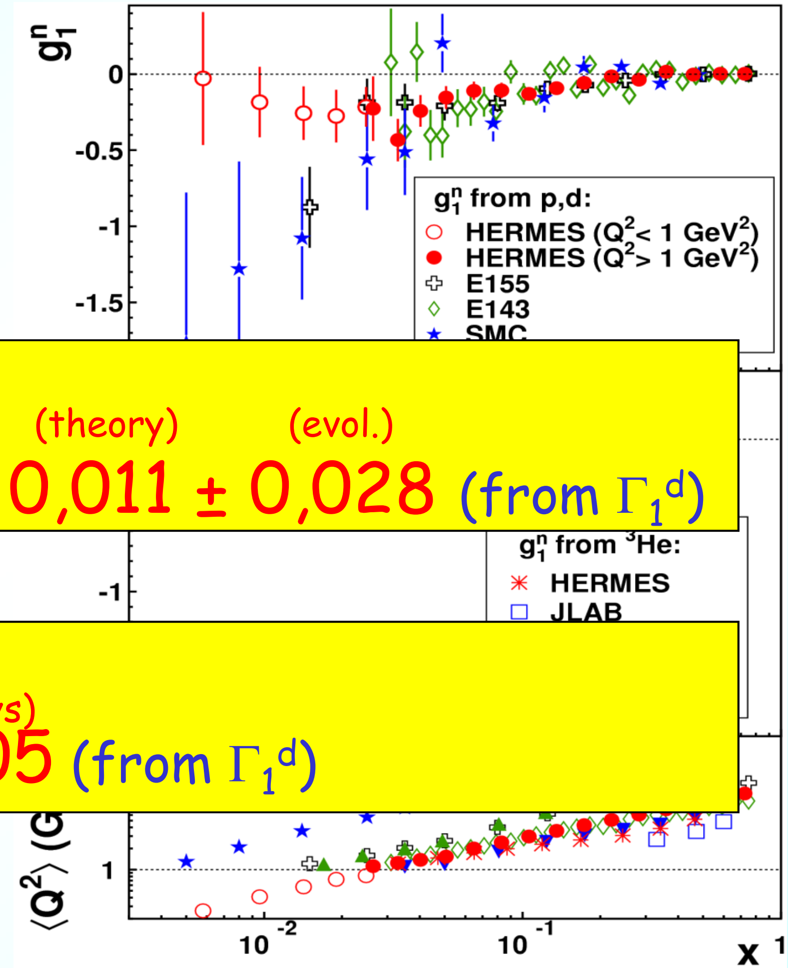
$$A_1(x) \cong \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}} \overset{\text{L.O.}}{\cong} \frac{\sum_q e_q^2 \Delta q(x)}{\sum_q e_q^2 q(x)} = \frac{g_1(x)}{F_1(x)}$$

From W. Vogelsang

$g_1(x)$, $\Delta\Sigma$







HERMES, P.R. D75 (2007) 012007

$\overline{MS}$ (exp) (theory) (evol.)

$\Delta\Sigma = 0,330 \pm 0,025 \pm 0,011 \pm 0,028$ (from Γ_1^d)

COMPASS, P.L. B647 (2007) 8

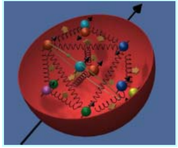
$\overline{MS}$ (stat) (sys)

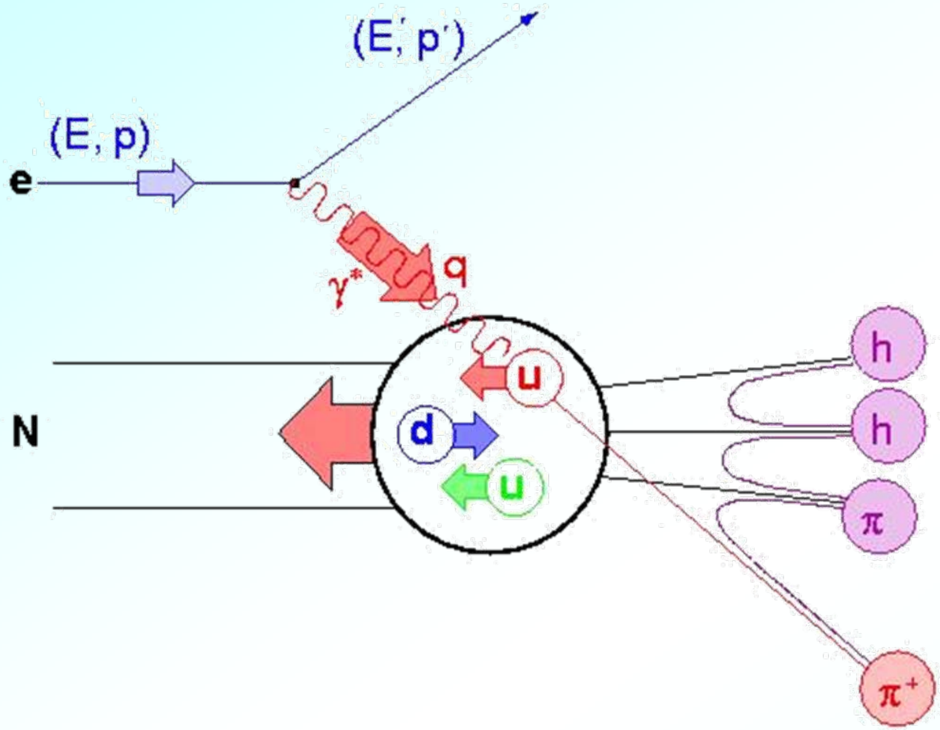
$\Delta\Sigma = 0,33 \pm 0,03 \pm 0,05$ (from Γ_1^d)

EMC, P.L. B206 (1988) 364

$\Delta\Sigma = 0,12 \pm 0,09 \pm 0,14$ (from Γ_1^p)

Quark Distributions from SIDIS





Flavor tagging

Leading hadron originates with large probability from struck quark

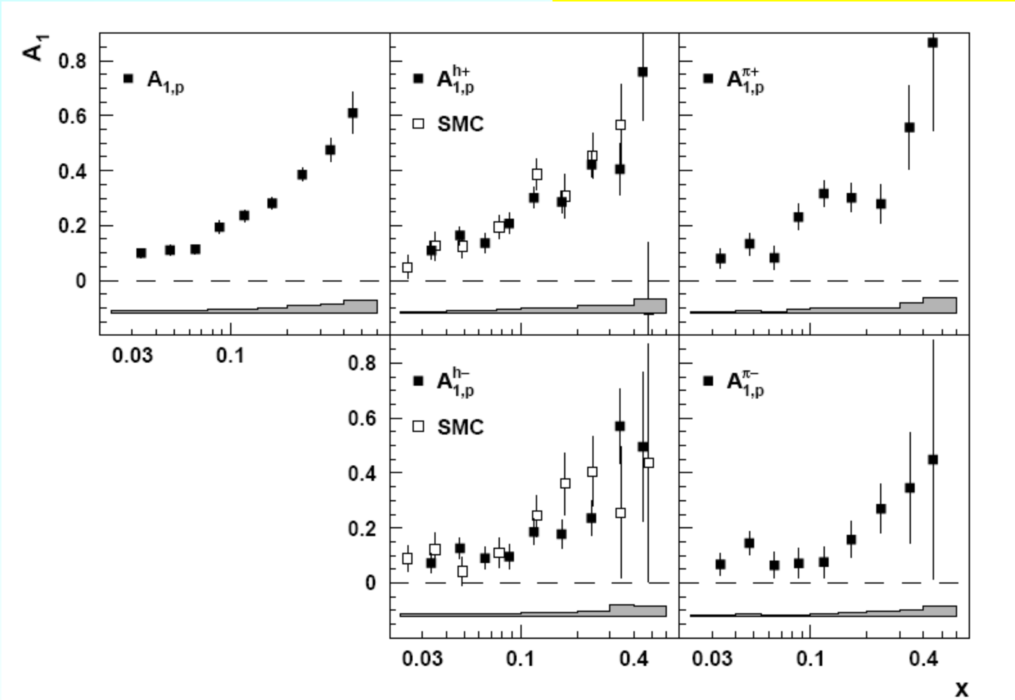
$D_q^h(z)$:= Fragmentation function (FF)

$z = E_h/\nu$

Measure hadron asymmetries

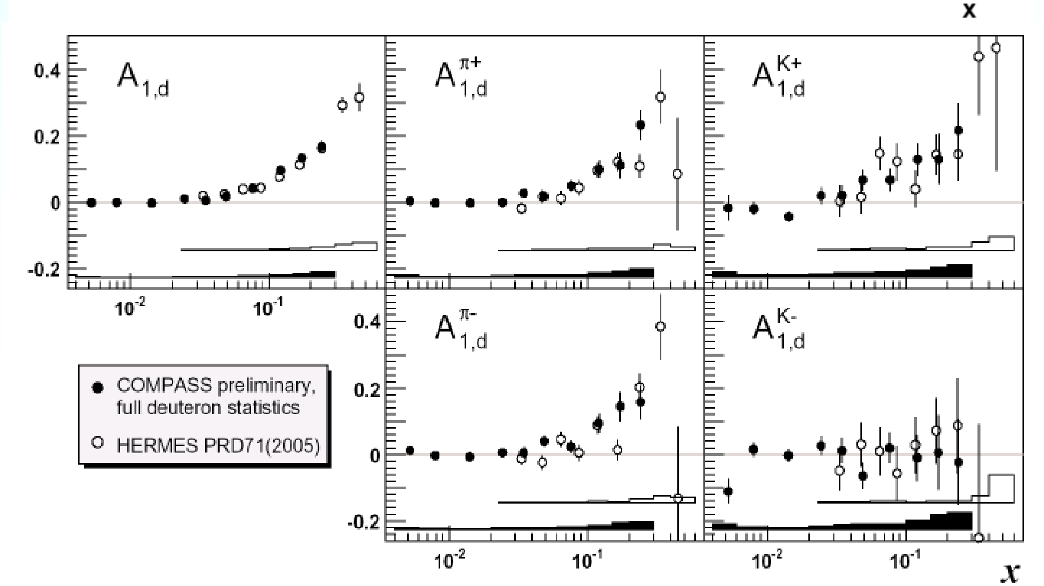
$$A_{LL}(x,z) \cong \frac{\sum_q z_q^2 \Delta q(x)\, D_q^h(z)}{\sum_q z_q^2\, q(x)\, D_q^h(z)}$$

Semi-inclusive Asymmetries



Proton

HERMES & SMC

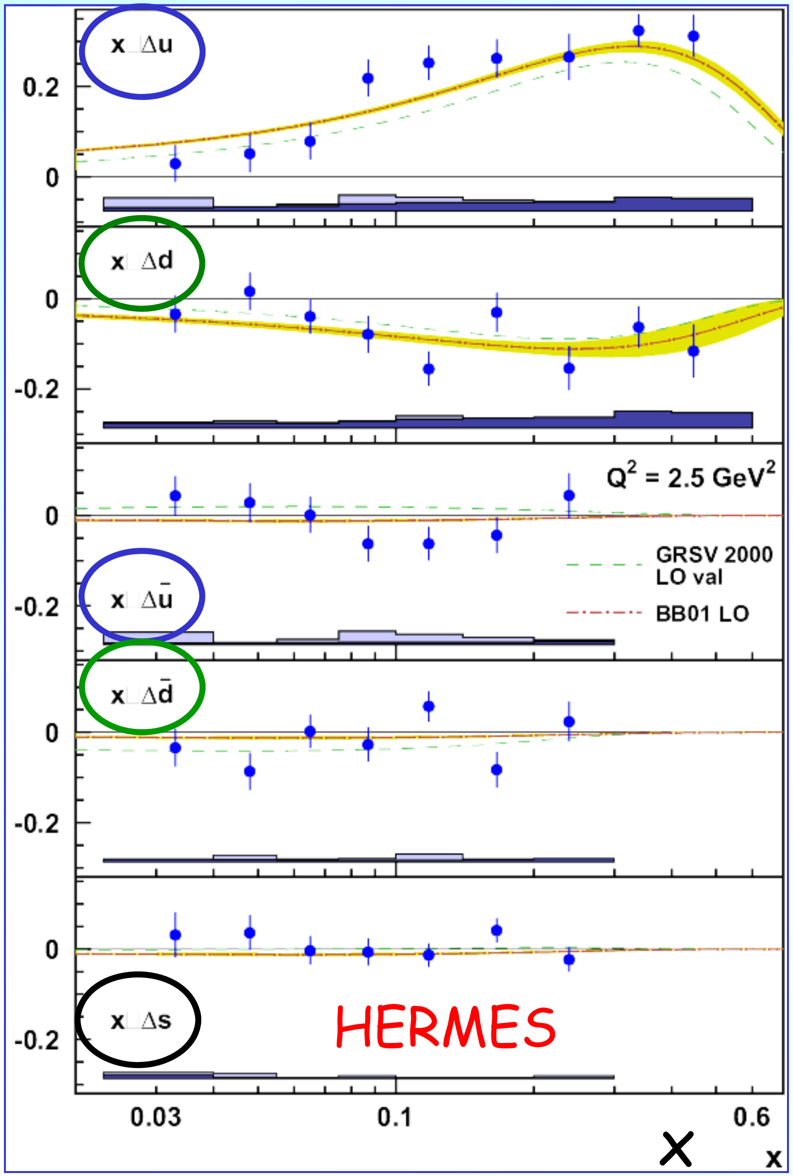


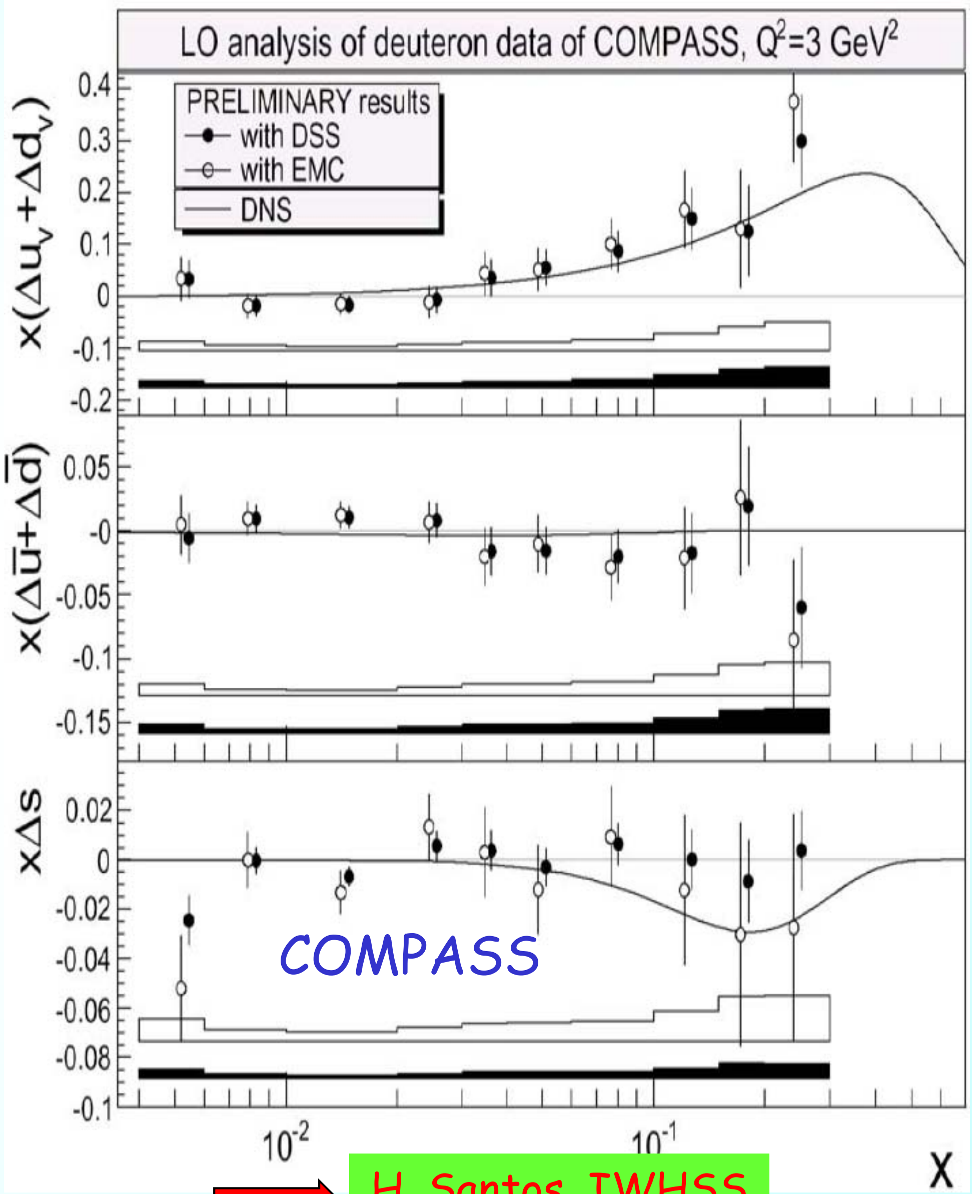
Deuteron

COMPASS & HERMES

Quark Helicity Distributions Δq(x)

PRD 71 (2005) 012003



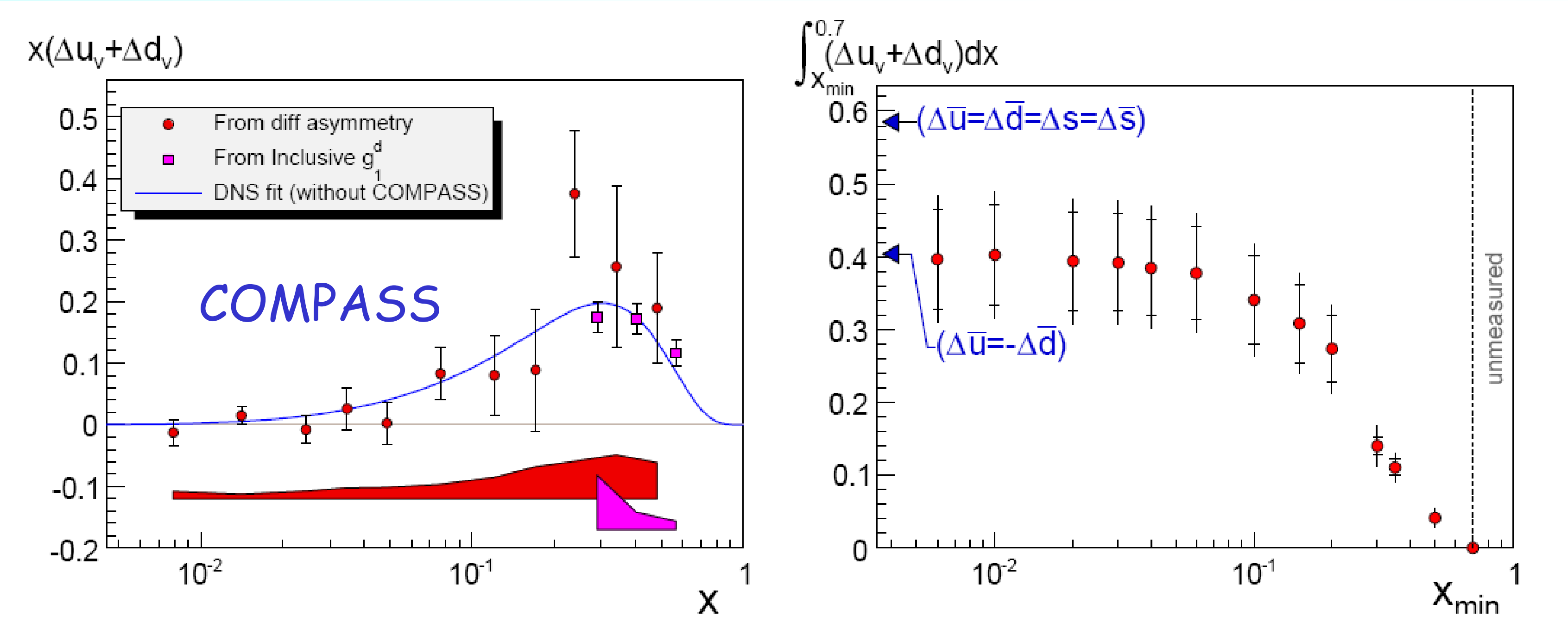


H. Santos, IWHSS

Valence-quark helicity distributions

$$A_d^{\pi^+-\pi^-}(x) \stackrel{L.O.}{=} A_d^{K^+-K^-}(x) \stackrel{L.O.}{=} \frac{\Delta u_v(x)+\Delta d_v(x)}{u_v(x)+d_v(x)}$$

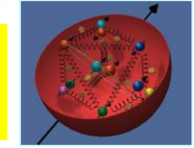
COMPASS, PLB 660 (2008) 458



$$\Delta\bar{u} + \Delta\bar{d} = 3\Gamma_1^N - \tfrac{1}{2}\Gamma_1^v + a_8/12$$

Flavor asymmetric polarized sea ($\Delta\bar{u} = -\Delta\bar{d}$) favoured

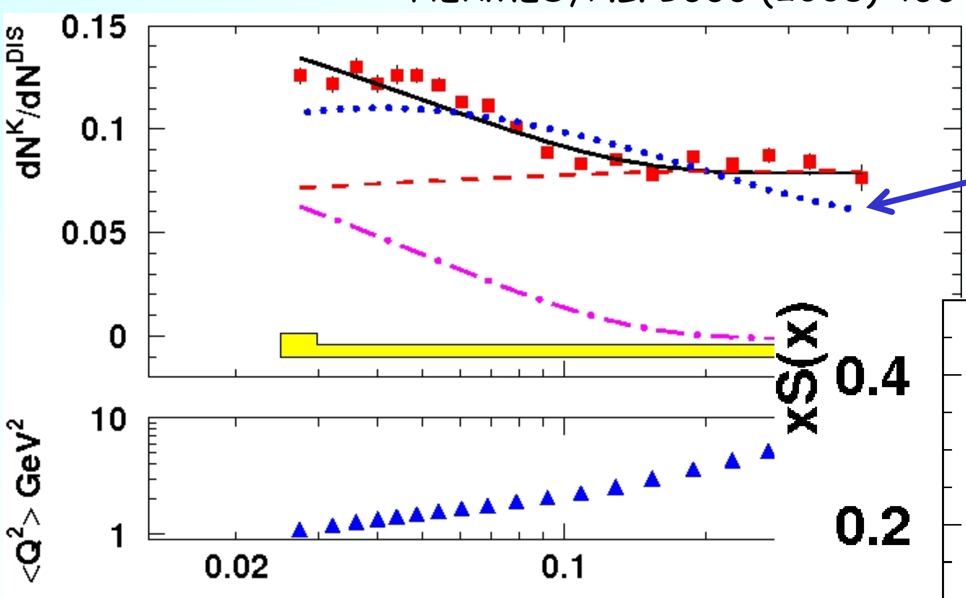
S(x) from $K^{\pm}$ Multiplicities



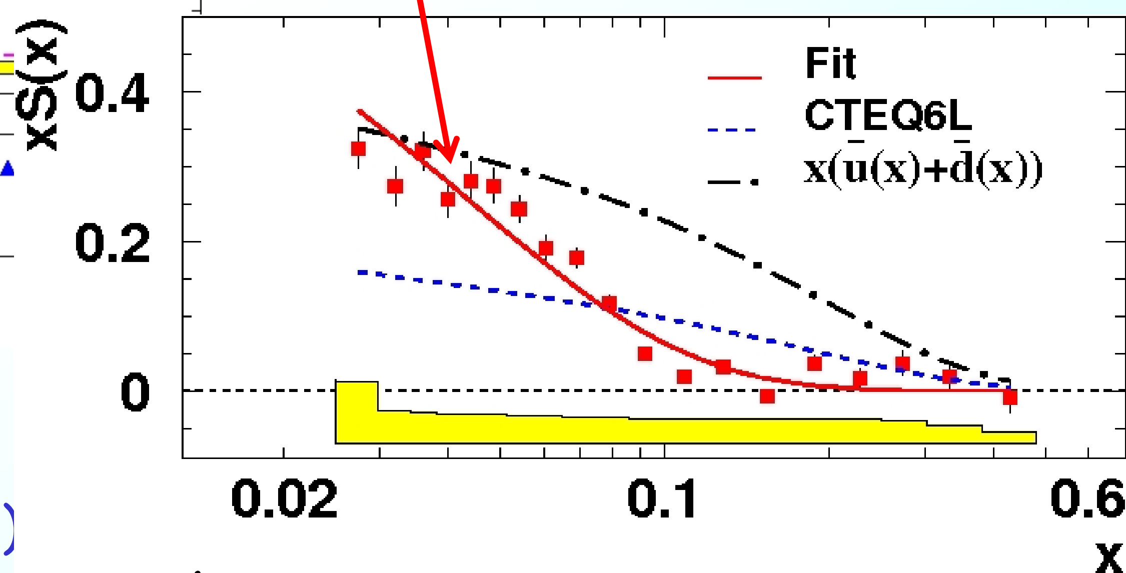
$$\frac{dN^{K\pm}}{dN^{DIS}} = \frac{Q(x)\int D_Q^K(z)dz + S(x)\int D_S^K(z)dz}{5\,Q(x) + 2\,S(x)} \xrightarrow{x>0.3} \frac{\int D_Q^K(z)dz}{5}$$

$$S(x) = s(x) + \bar{s}(x)$$

HERMES, P.L. B666 (2008) 466



- S(x) from CTEQ6L with $\int D_Q^K(z)dz$ & $\int D_S^K(z)dz$ as free parameters (dotted) does not fit the data

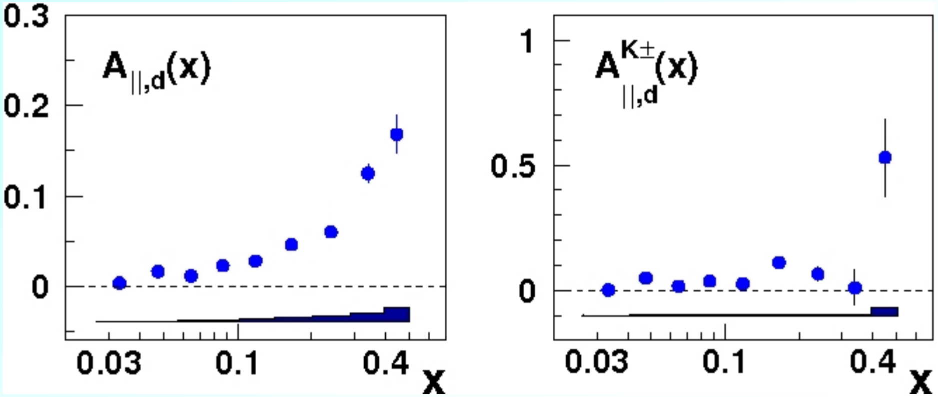


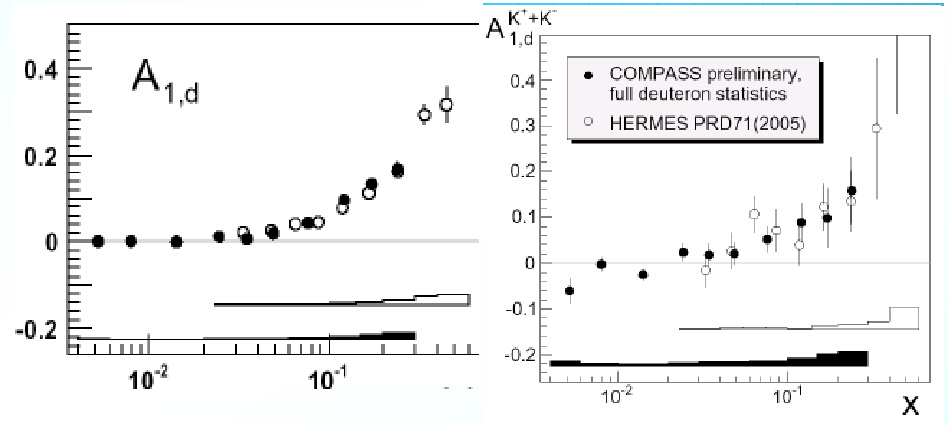
- S(x) much softer than assumed by current PDFs (mainly based on $\overset{(-)}{\nu}N \rightarrow \mu^+\mu^- X$)

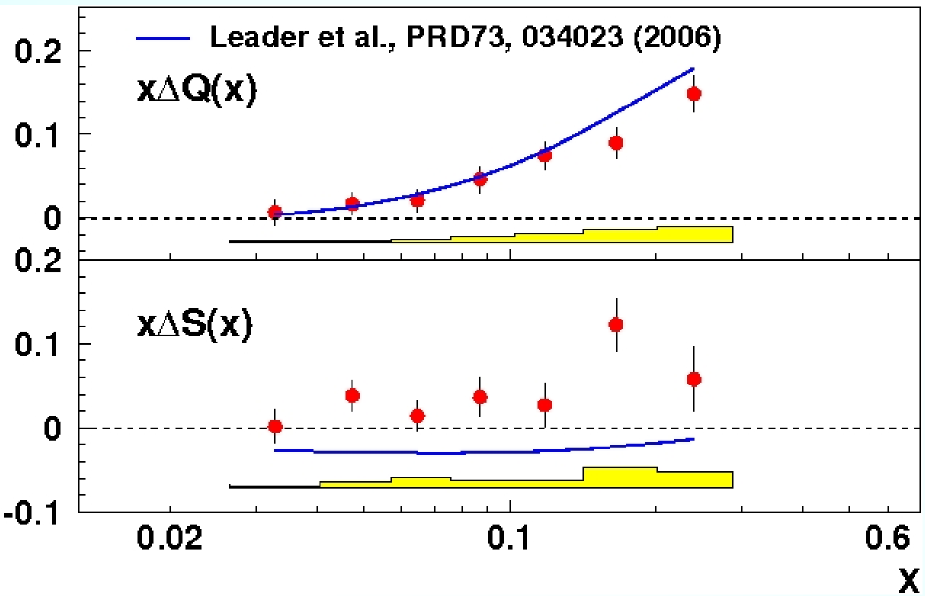
Take $\int D_S^K(z)dz = 1.27 \pm 0.13$ from de Florian et al.

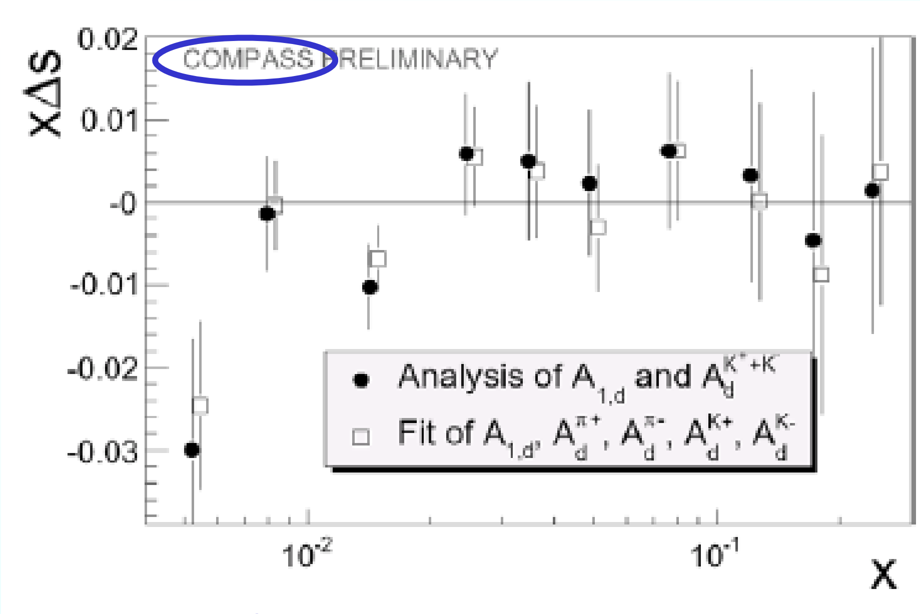
ΔS(x) from (K⁺+K⁻) Asymmetries

HERMES, P.L. B666 (2008) 466



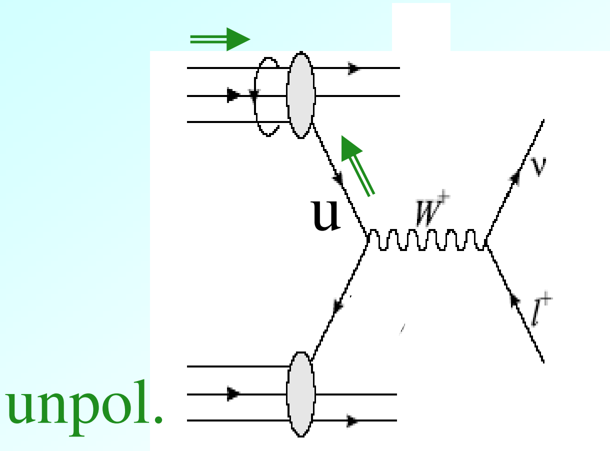






H. Santos, IWHSS

Δq & $\Delta\bar{q}$ at RHIC via $W^{\pm}$ production

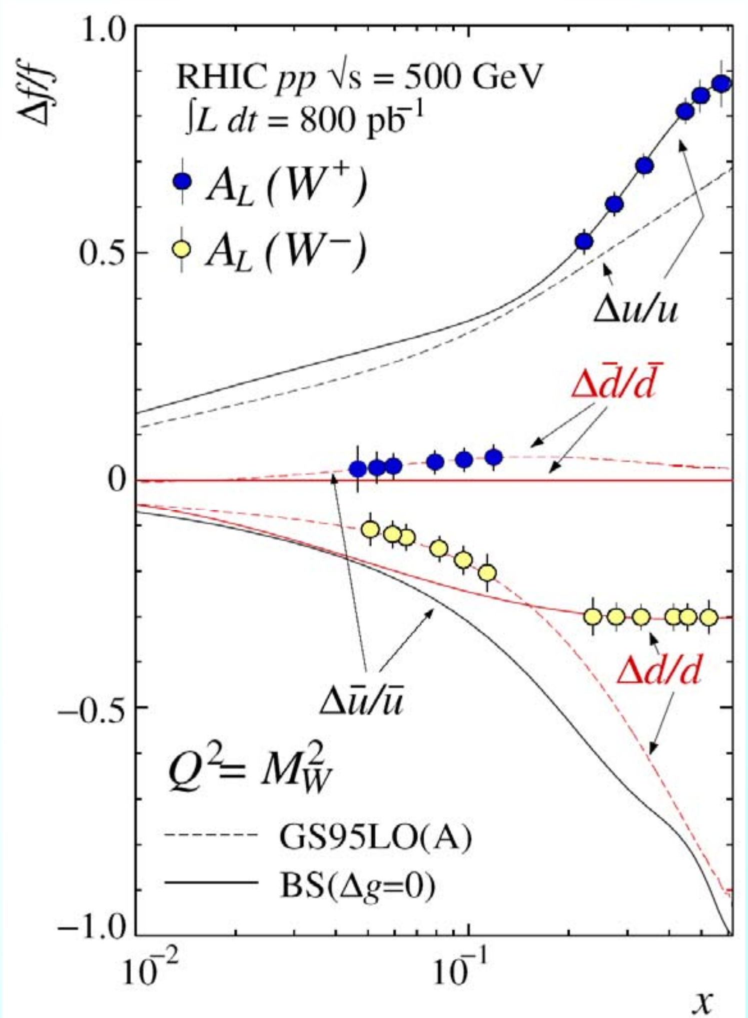


$$\Delta d + \bar{u} \rightarrow W^-$$
$$\Delta\bar{u} + d \rightarrow W^-$$
$$\Delta\bar{d} + u \rightarrow W^+$$
$$\Delta u + \bar{d} \rightarrow W^+$$

$$\mathbf{A_L} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

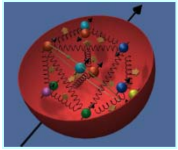
Start: 2 weeks ago

Expectation



A. Deshpande, IWHSS

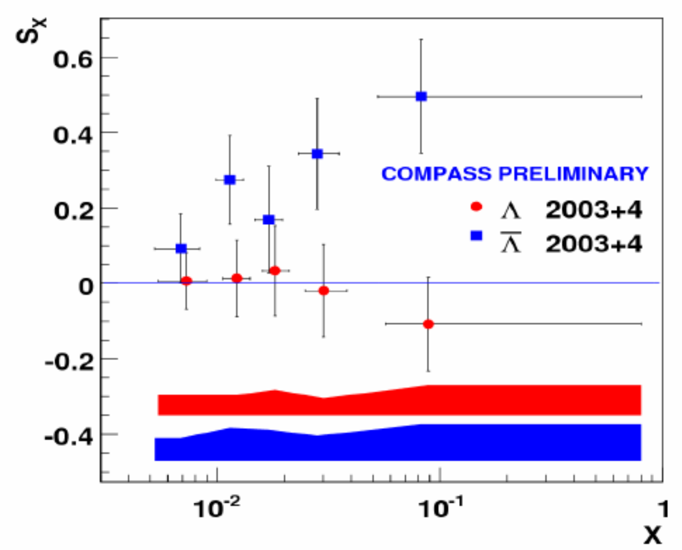
Longitudinal Λ ($\bar{\Lambda}$) Polarization

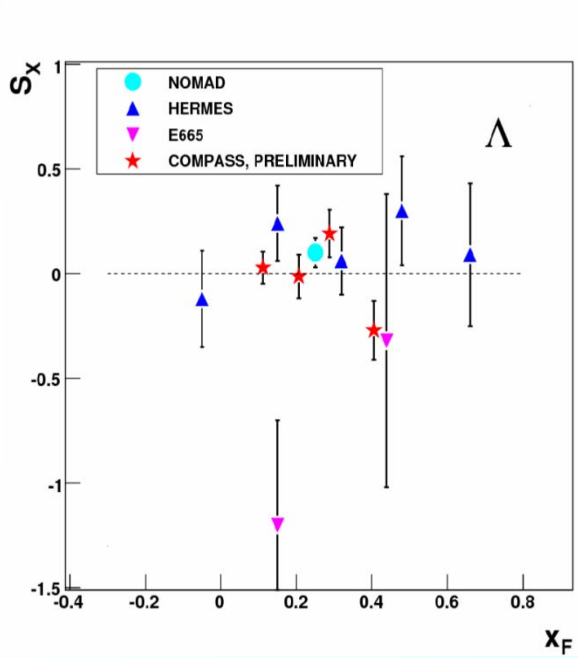


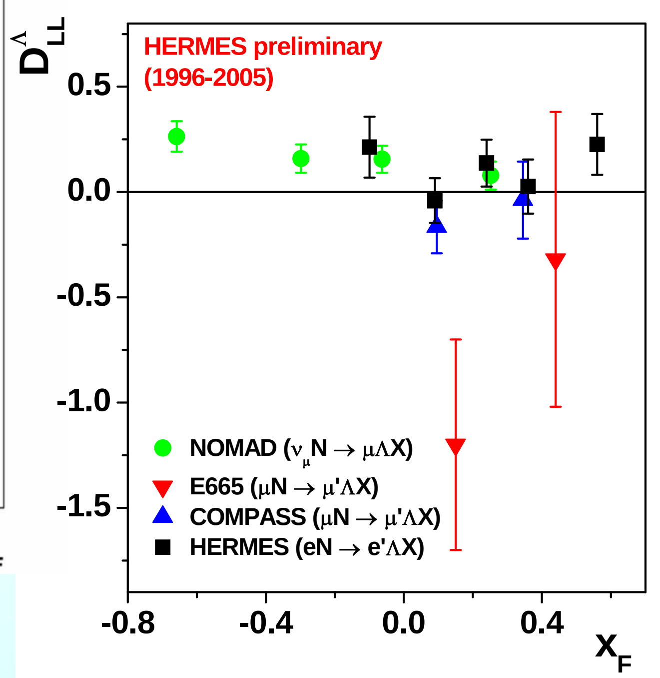
Parity violating decay $\Lambda \rightarrow \pi^- p$: p preferentially emitted along Λ spin

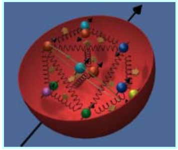
$$\vec{\gamma}^* N \rightarrow \vec{\Lambda} X$$

$$P_x = S_x P_B D(y)$$







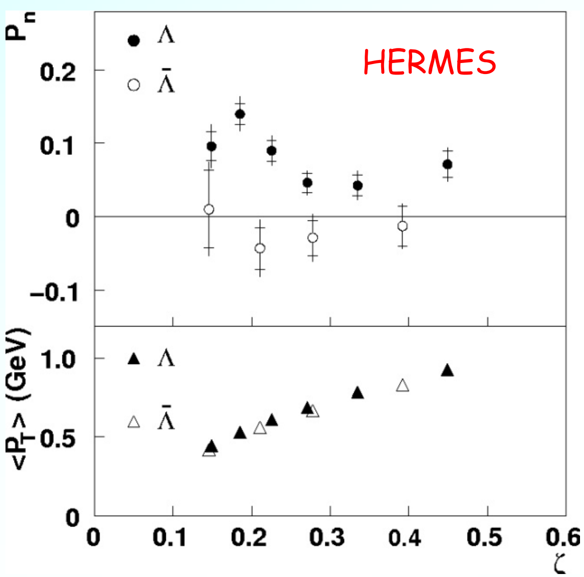


Transverse Λ ($\bar{\Lambda}$) Polarization

Parity violating decay $\Lambda \to \pi^- p$: p preferentially emitted along Λ spin

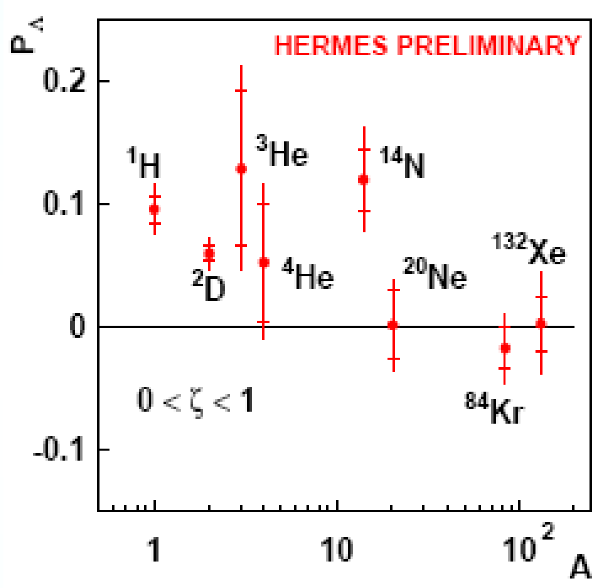
$$\gamma^* N \to \Lambda^{\uparrow} X$$

Phys. Rev. D76 (2007) 092008

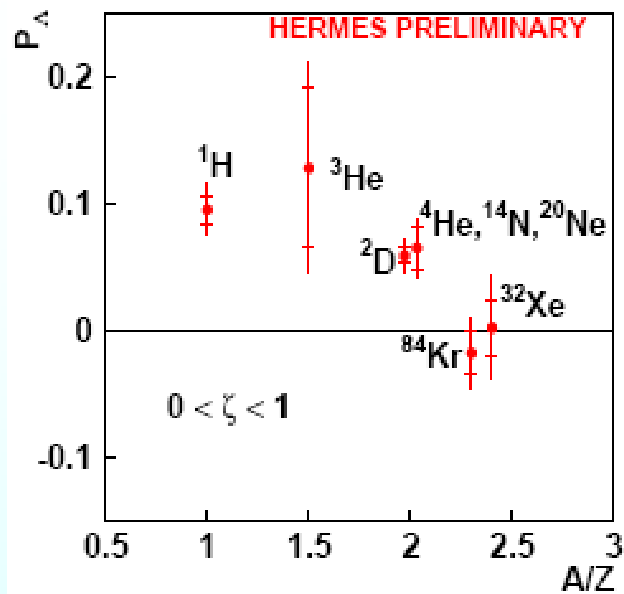


$\zeta = (E_\Lambda + p_{z\Lambda}) / (E_e + p_e)$

Dependence on nuclear mass *A*



0<ζ<1



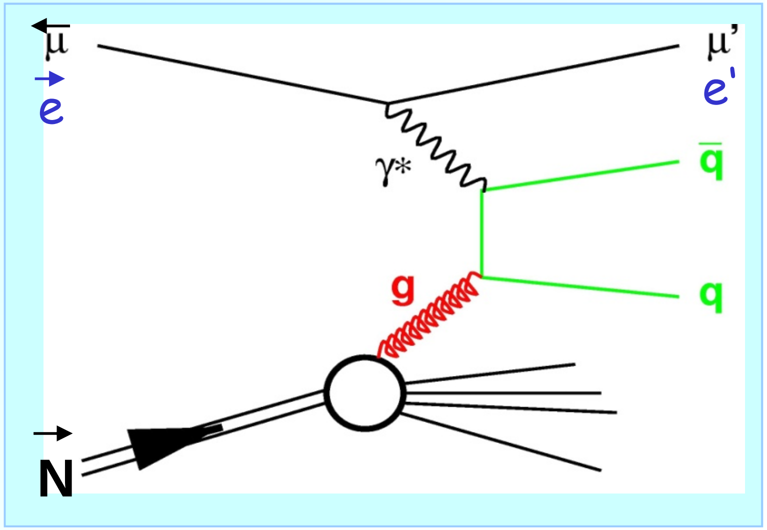
0<ζ<1

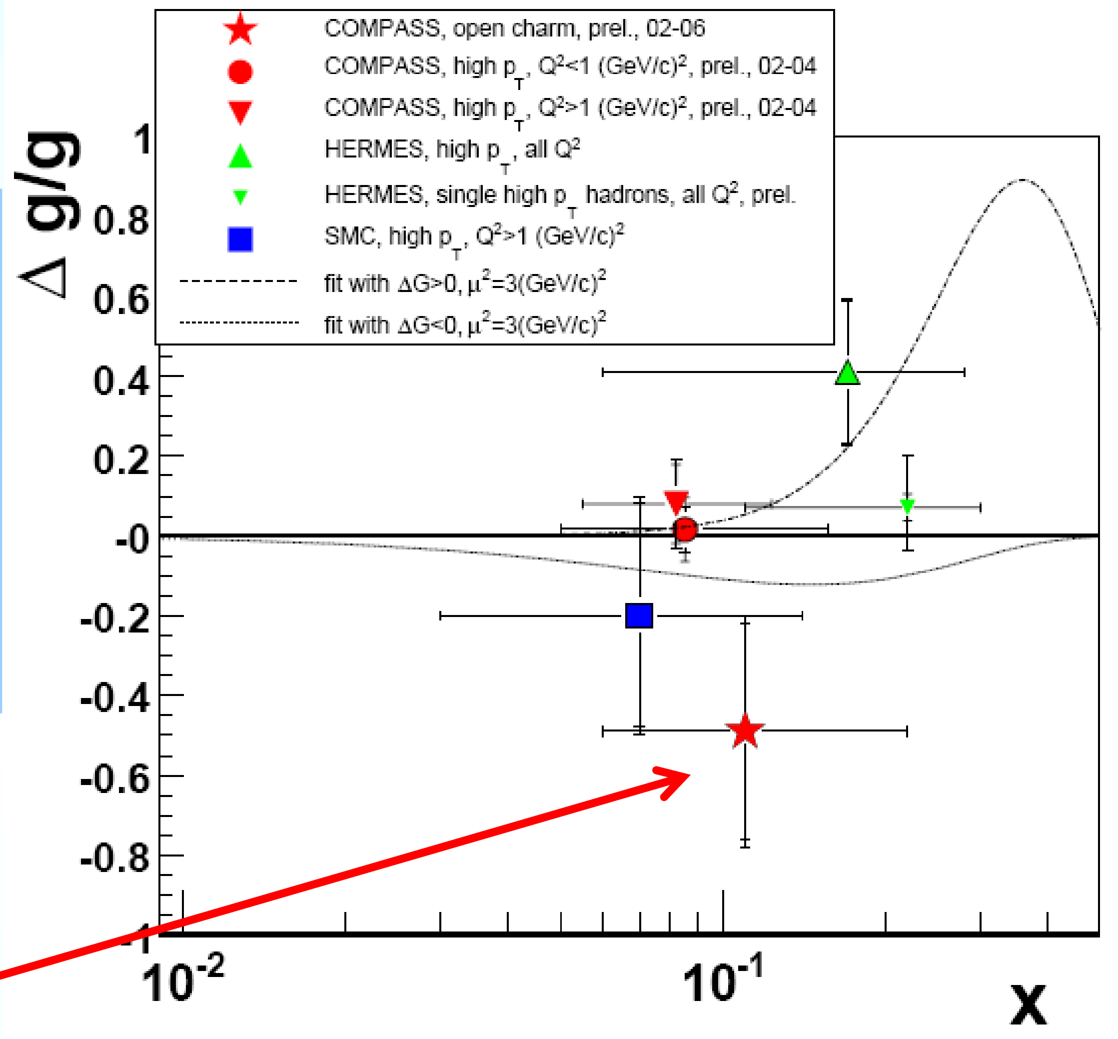
Gluon helicity distribution

$\Delta g(x)$

Gluon helicity distribution

Photon-gluon fusion



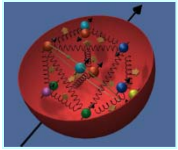


- Hadrons with high pt
- Charm production

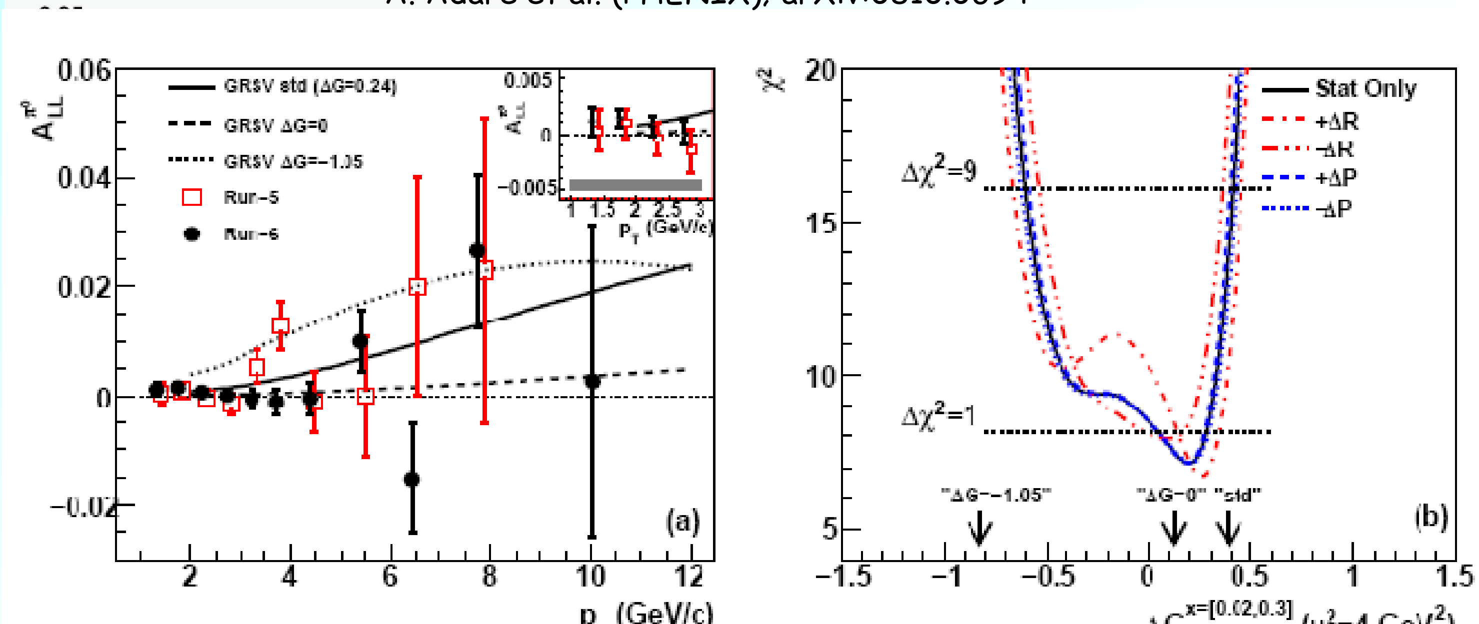
→ M. Stolarski, IWHSS

L.O. analyses

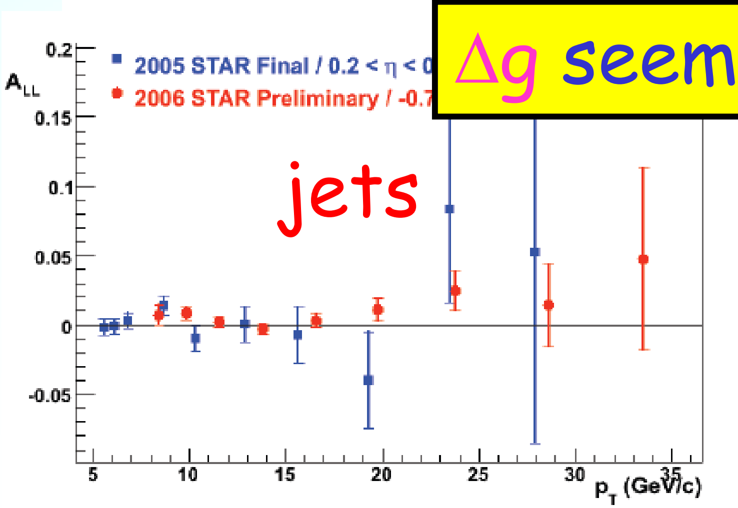
ΔG from $\vec{p}\vec{p} \to \pi^0$ (jet) X



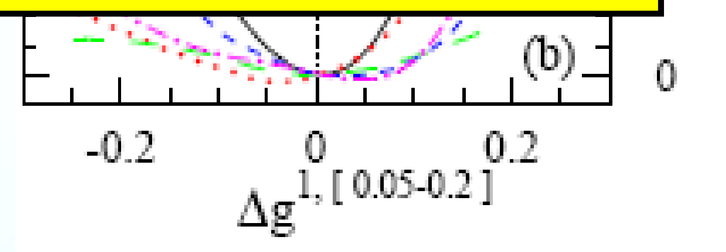
A. Adare et al. (PHENIX); arXiv:0810.0694



Δg seems to be rather small !!



jets

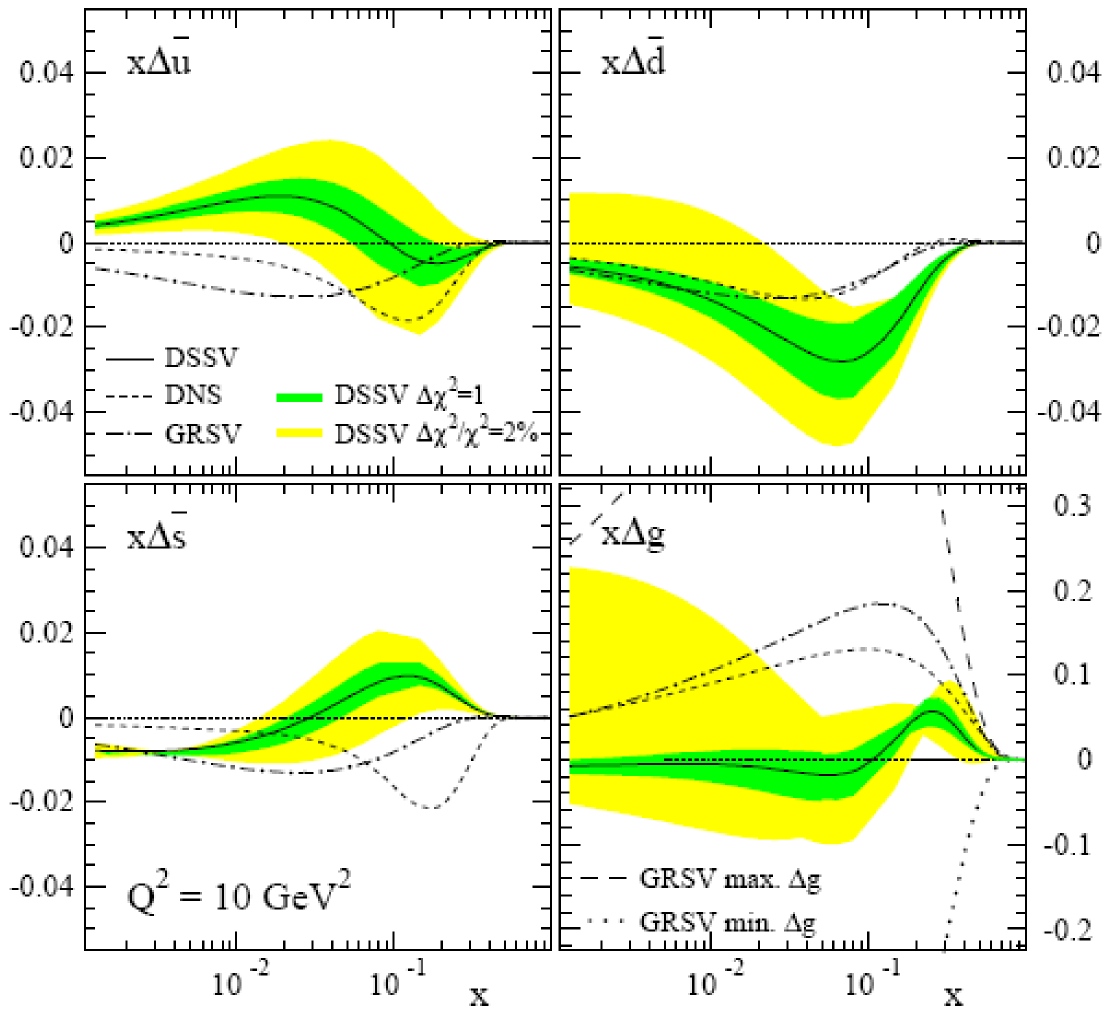


NLO analysis of world data
(without data from previous slide)

A. Deshpande, IWHSS

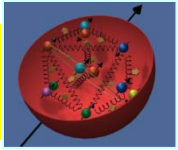
Fits to $\Delta g(x)$ and $\Delta\bar{q}(x)$

De Florian et al.: P.R.L. 101 (2008) 072001



$\Delta g = -0.1 \pm 0.1$

Spin budget



- <u>Origin of nucleon spin still unclear:</u>

  Where do the remaining ~65% come from?
  X. Ji: ‚Dark Spin'

- Is there a substantial contribution of Δg and/or $\Delta\bar{q}$ at very low x?

  ➡ EIC, ENC ?

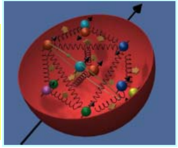
- What is the contribution of orbital angular momenta

  L ???

Quark orbital angular momentum

L_q

Transverse Momentum Dependent DFs



Quark distribution functions

		quark		
		U	L	T
nucleon	U	f_1		$h_1^{\perp}$
	L		g_1	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$

Boer-Mulders DF

Transversity DF

Pretzelosity DF

Sivers DF

Fragmentation functions (FF)

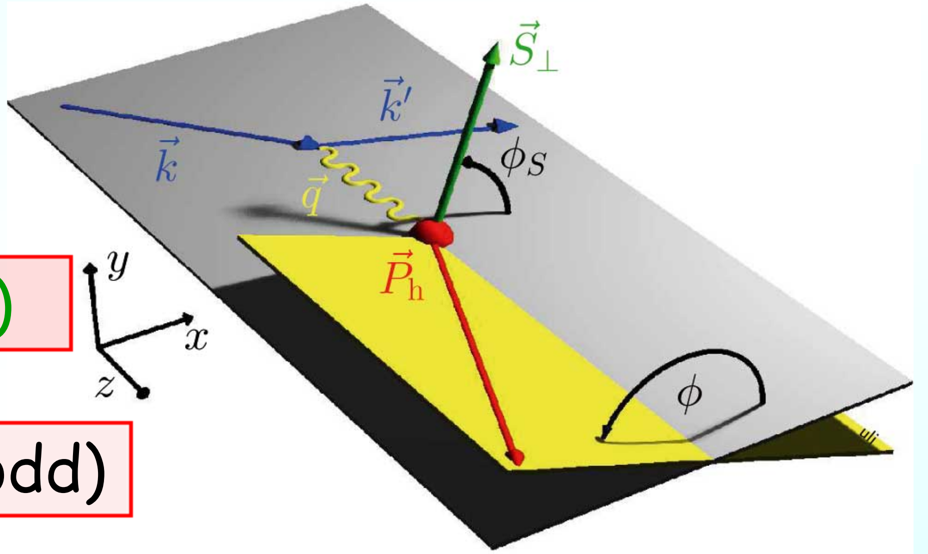
$D_1 \equiv D_q^h$ = ‚normal' FF,

$H_1^{\perp}$ = spin-dependent Collins FF

M. Anselmino

Transverse Azimuthal Angular Asymmetries

Amplitude has 2 components:



Transversity DF (χ-odd)

$2\langle\sin(\phi + \phi_S)\rangle^h_{UT} \sim h_1^q(x) \otimes H_1^{\perp q}(z)$

Collins FF (χ-odd)

U: unpol. e±-beam

T: transv. pol. Target

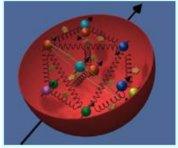
$z = E_h/\nu$

Unpolarised FF

$2\langle\sin(\phi - \phi_S)\rangle^h_{UT} \sim f_{1T}^{\perp q}(x) \otimes D_1^q(z)$

Sivers DF (T-odd)

(Requires FSI and non-vanishing orbital angular momenta L_q of quarks)



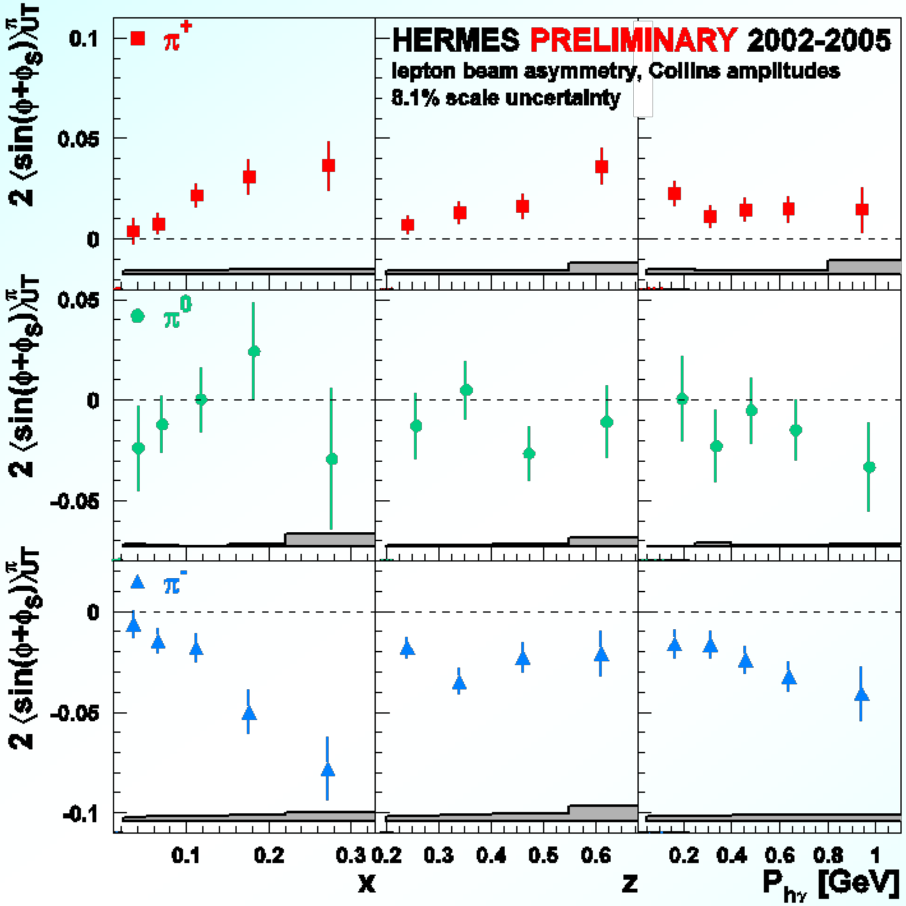
Collins Amplitudes

Transversity DF

$$2\langle\sin(\phi + \phi_S)\rangle^h_{UT} \sim h_1^q(x) \otimes H_1^{\perp q}(z)$$

Collins FF

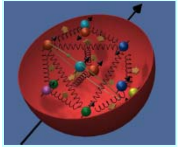
N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$



- First measurement of non-zero Collins effect
- Both Collins fragmentation function and transversity distribution function are sizeable
- Surprisingly large π^- asymmetry
- Possible source: large contribution (with opposite sign) from unfavored fragmentation, i.e. $u \rightarrow \pi^-$

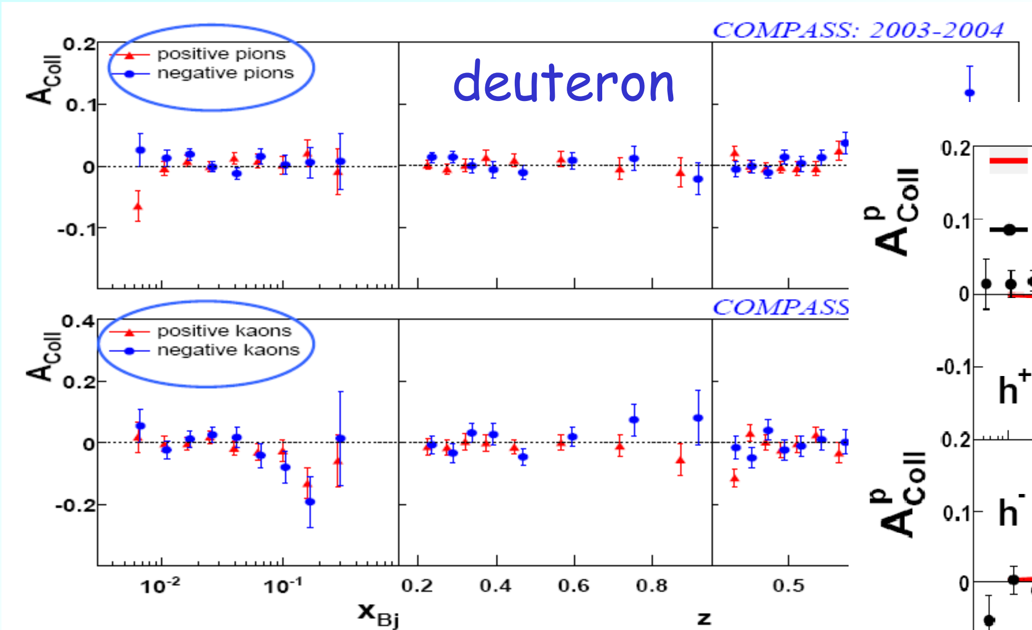
$$H_1^{\perp}{}_{,disf} \approx - H_1^{\perp}{}_{,fav}$$

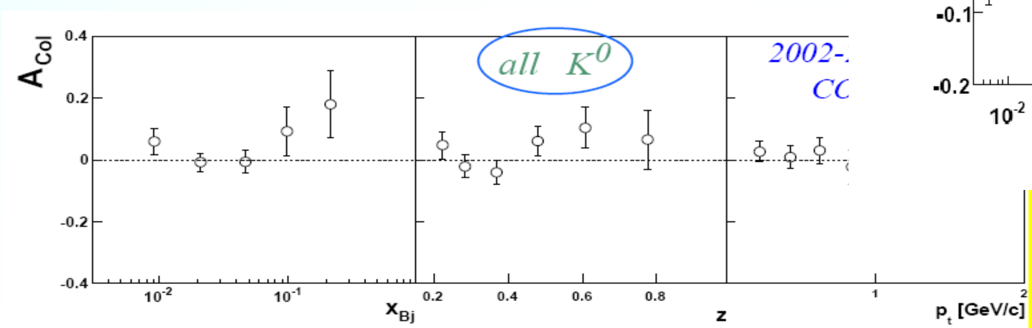
Collins amplitudes (d +p)

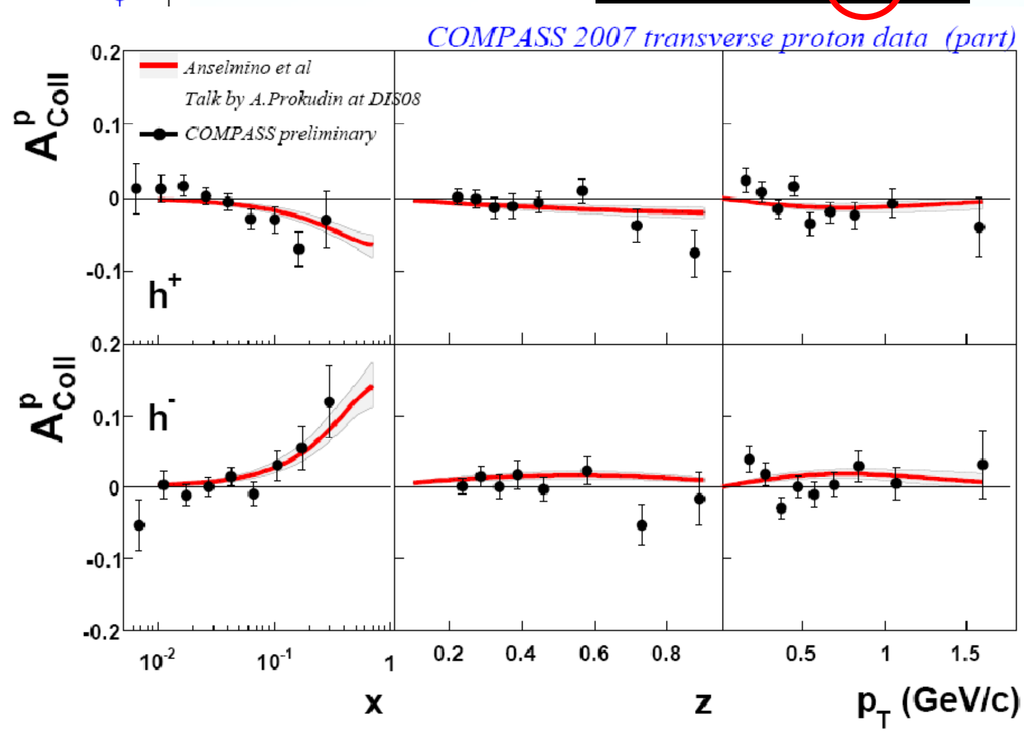


N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

COMPASS, Phys. Lett. B673 (2009) 127







Compatible with zero
cancellation of δu & δd

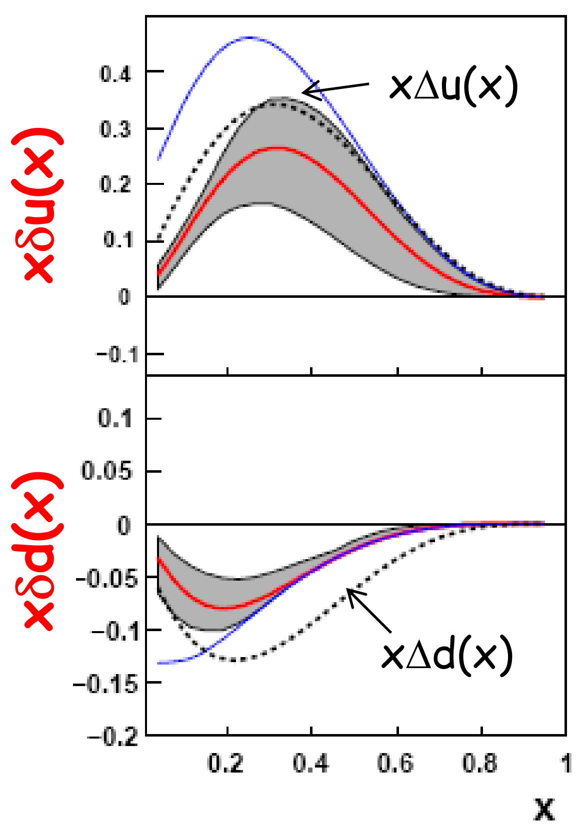
Different from zero,
Compatible with HERMES

→ F. Bradamante, IWHSS

Extraction of Transversity

Fit to HERMES ($ep^{\uparrow} \to ehX$), COMPASS ($\mu d^{\uparrow} \to \mu hX$), BELLE ($e^+e^- \to h^+h^-X$) data

M. Anselmino et al., arXiv-0812.4366

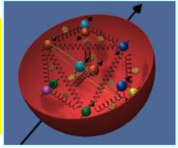


$\delta q(x) \equiv \Delta q(x)$ at low Q^2??

M. Anselmino

hermes

Sivers Amplitudes (p)

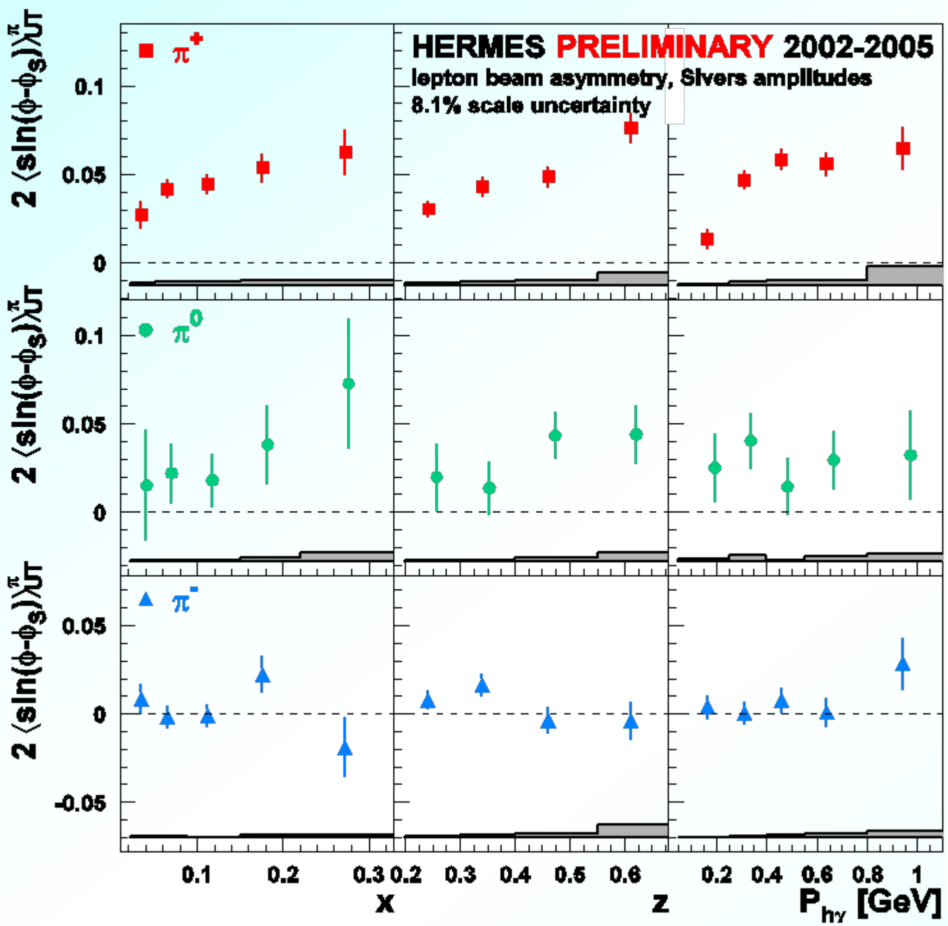


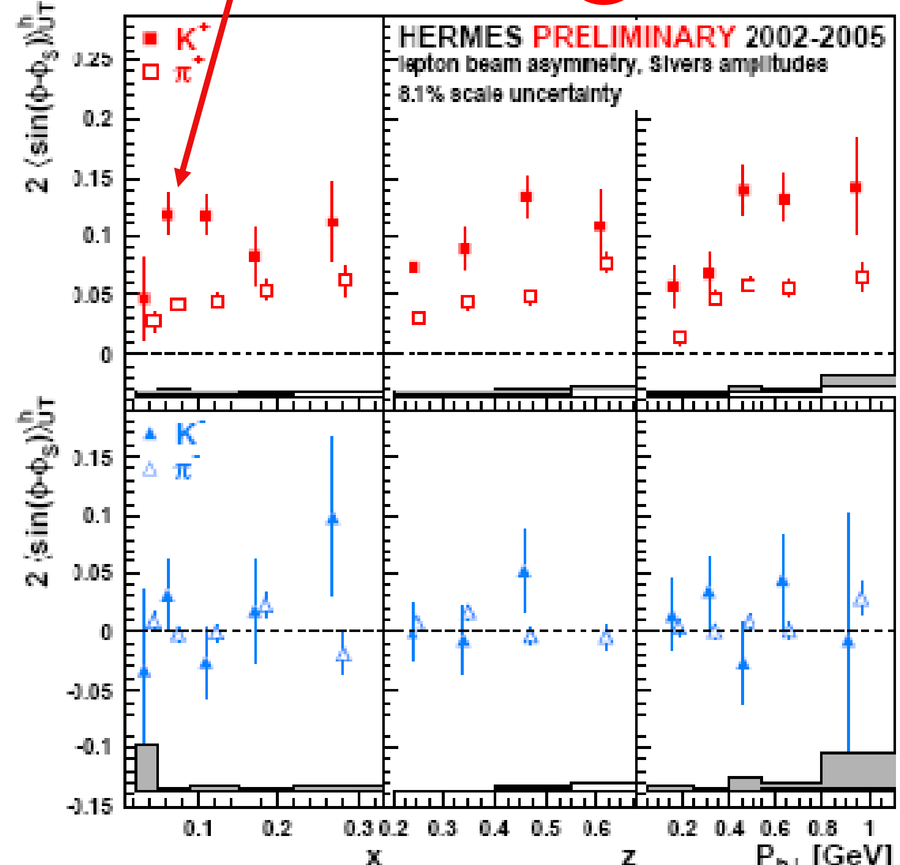
Sivers DF

$$2\langle \sin(\phi - \phi_S)\rangle^h_{UT} \sim f_{1T}^{\perp q}(x) \otimes D_1^q(z)$$

N/q	U	L	T
U	f_1		$h_{1T}^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

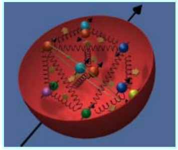
large!





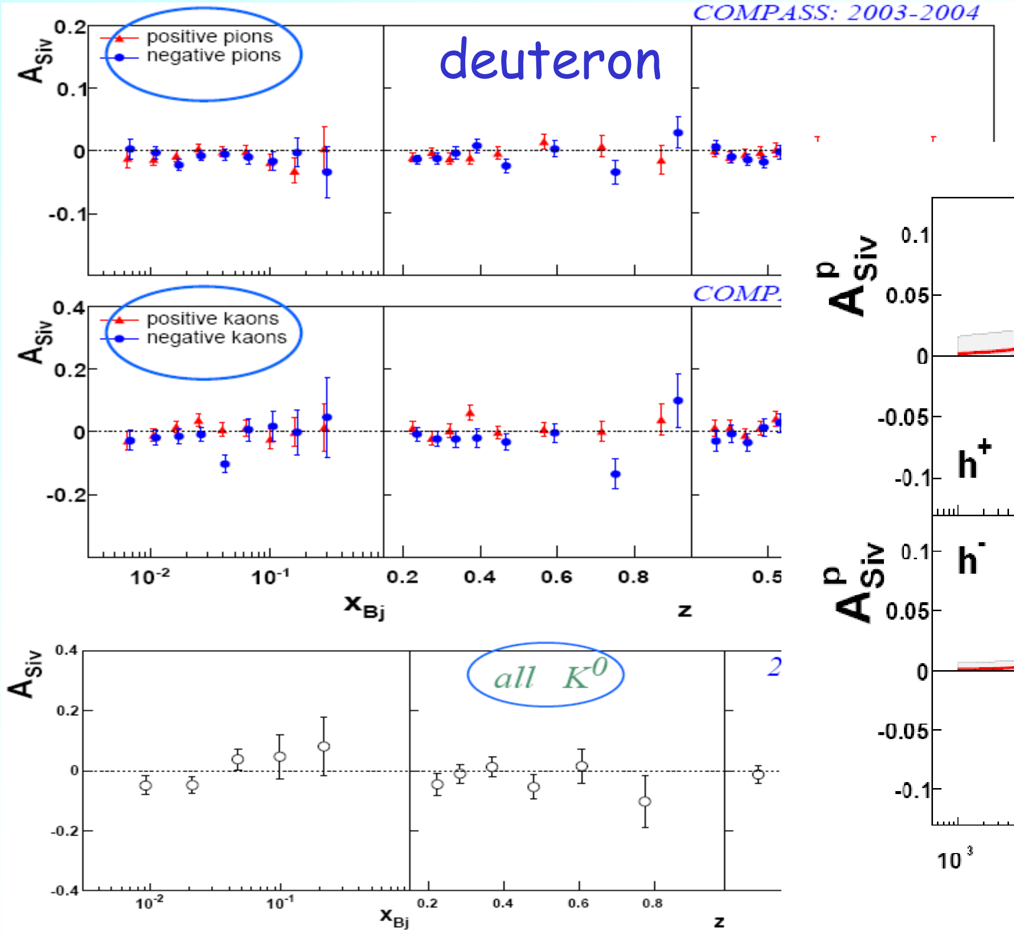
Final result: K^+ enhancement will be smaller, Q^2 dependent?

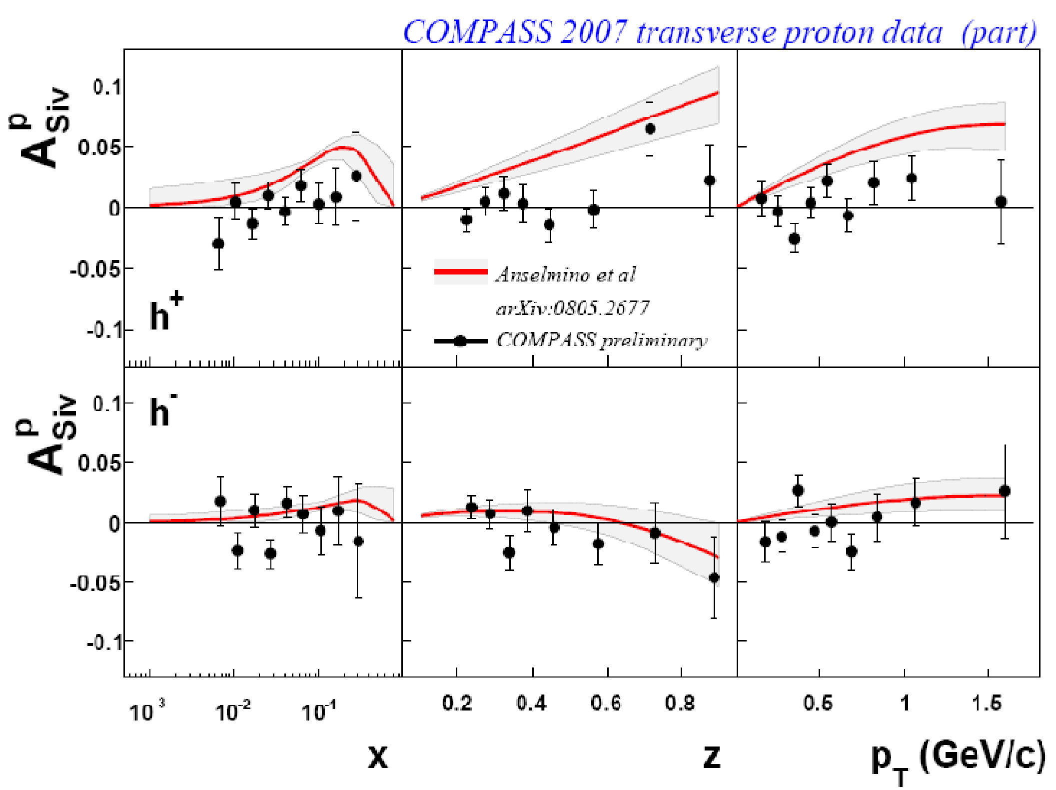
Sivers ampl. (d +p)



COMPASS, Phys. Lett. B673 (2009) 127

N/q	U	L	T
U	f_1		$h_{1T}^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$



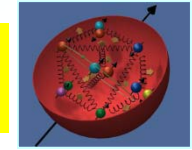


Compatible with zero

Still compatible with zero

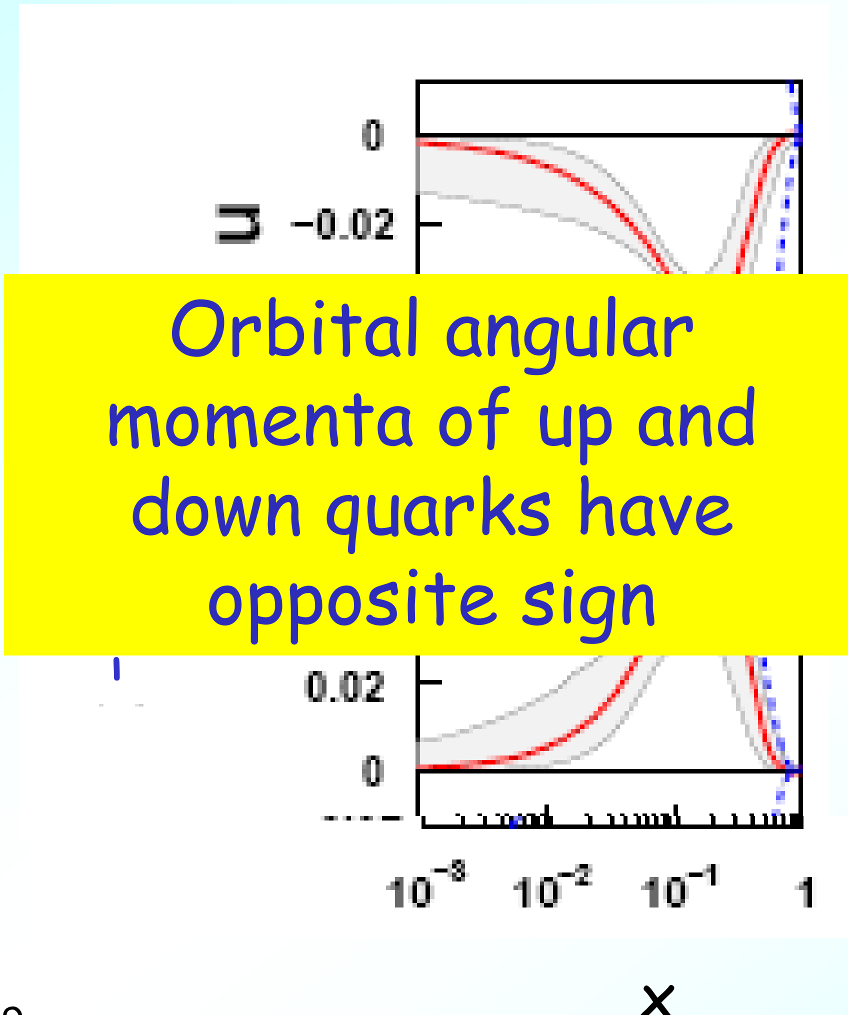
F. Bradamante, IWHSS

Sivers distribution



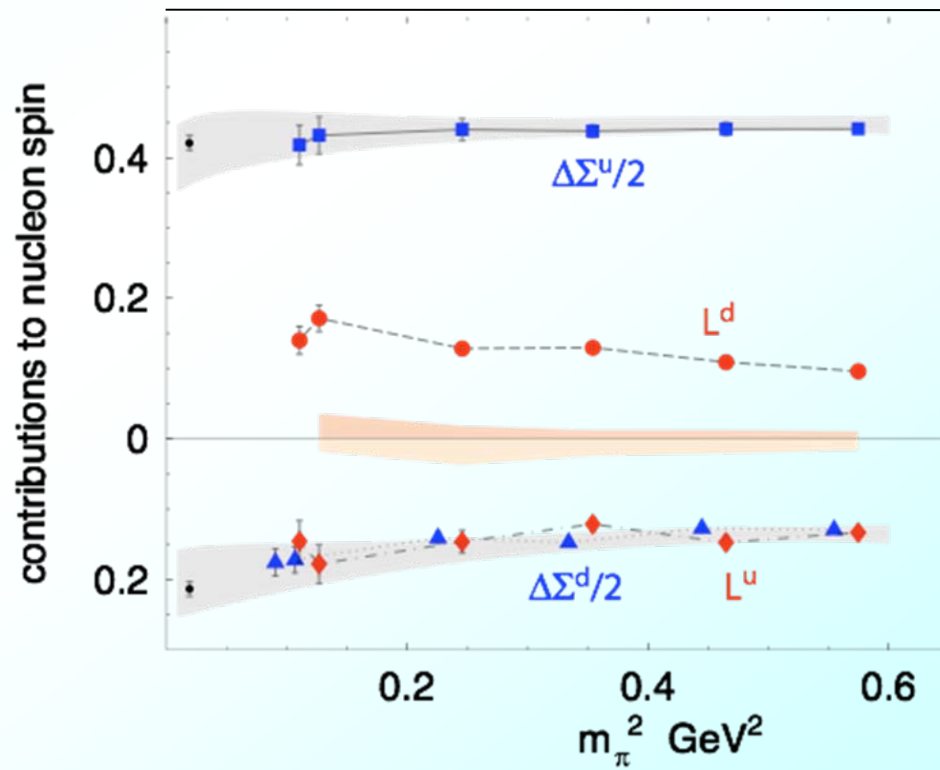
Fit to HERMES (ep↑ -> ehX) and COMPASS (μd↑ -> μhX) data

M. Anselmino et al., Phys. Rev. D79 (2009) 054010



Orbital angular momenta of up and down quarks have opposite sign

Lattice



$L_d \approx -L_u \approx 0.2$

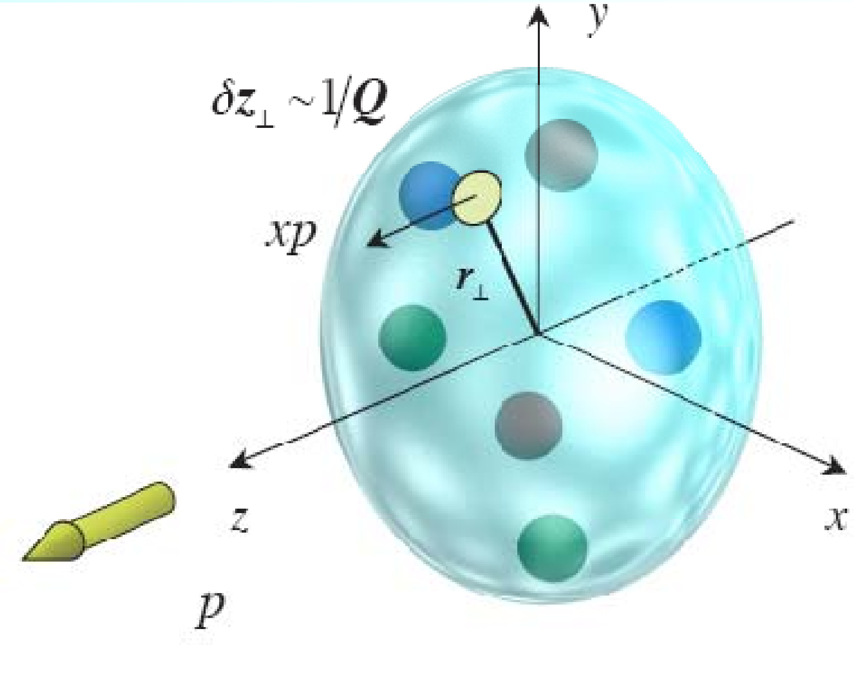
$L_d + \Delta d/2 \approx 0$!??

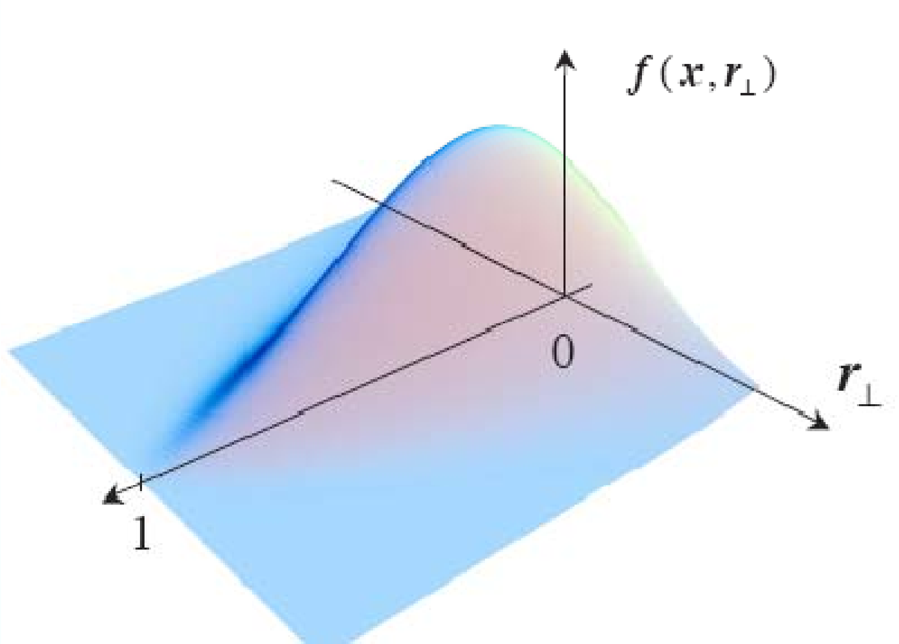
sign ??

Determination of L_q - GPDs

Tool: Generalised Parton Distributions (GPDs)

Generalised description of nucleon structure in 2+1 dim

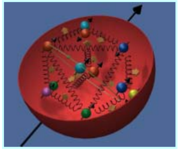




Number density of quarks with longitudinal momentum fraction x at radial position $r_\perp$

→ M. Polyakov

Determination of L_q

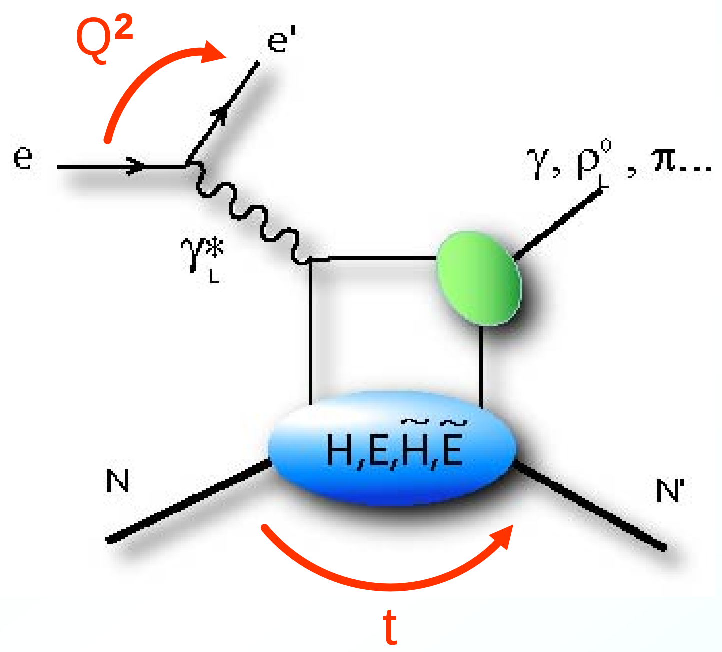


Ji relation:

$$J_q = 1/2\Delta\Sigma + L_q = \lim_{t \to 0} \int_{-1}^{1} dx\, x\, [H(x,\zeta,t) + E(x,\zeta,t)]$$

$H(x,\zeta,t)$, $E(x,\zeta,t)$: Generalised Parton Distributions (GPDs)

Access: *exclusive processes*

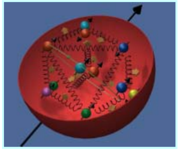


Final state sensitive to different GPDs

Vector mesons (ρ, ω, ϕ) H, E

Pseudoscalar mesons(π,η) $\tilde{H}$, $\tilde{E}$

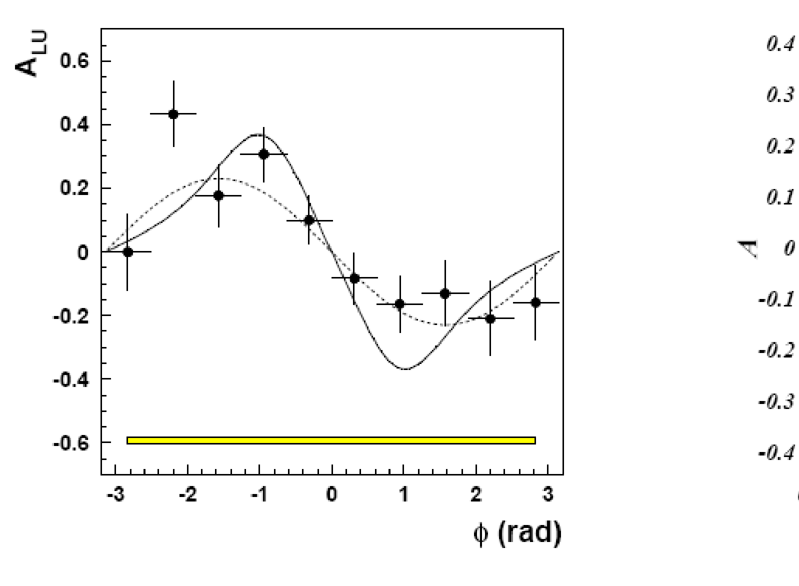
DVCS (γ) H, E, $\tilde{H}$, $\tilde{E}$



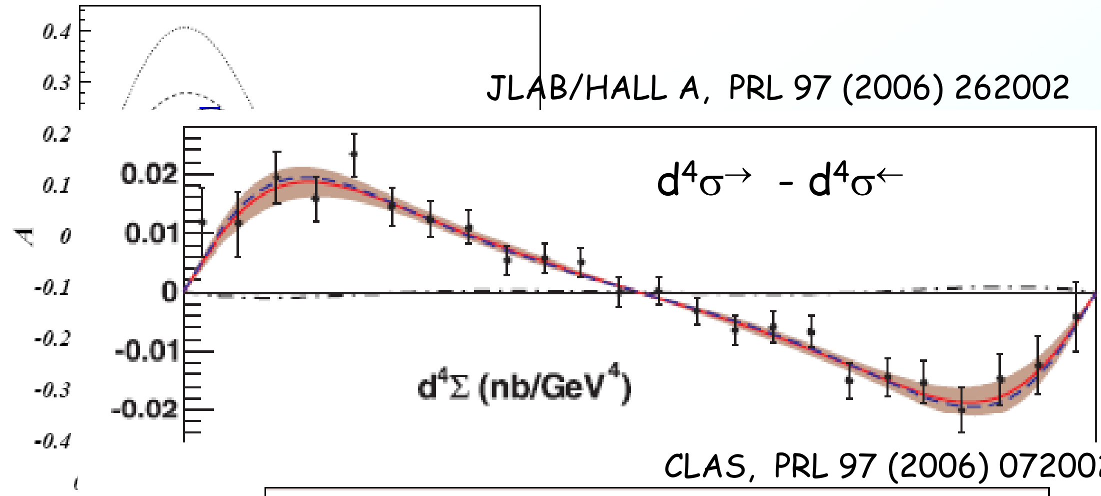
Azimuthal asymmetries

DVCS: Beam-spin asymmetry

HERMES, PRL 87 (2001) 182001

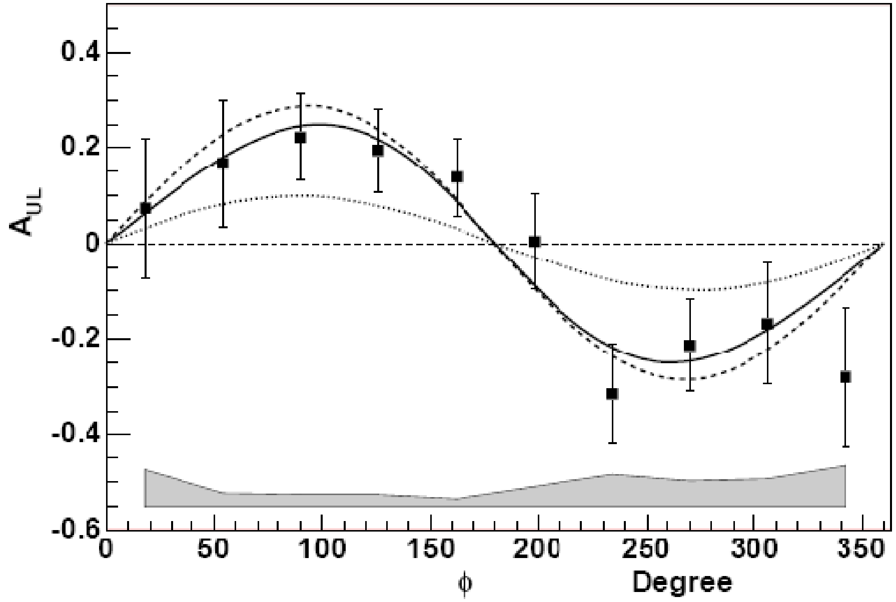


CLAS, PRL 87 (2001) 182002



JLAB/HALL A, PRL 97 (2006) 262002

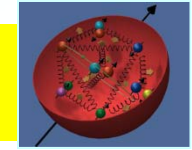
CLAS, PRL 97 (2006) 072002



DVCS: Longitudinal target-spin asymmetry

→ M. Guidal

Determination of L_q - GPDs



DVCS: Beam Charge asymmetry

Pioneer measurements

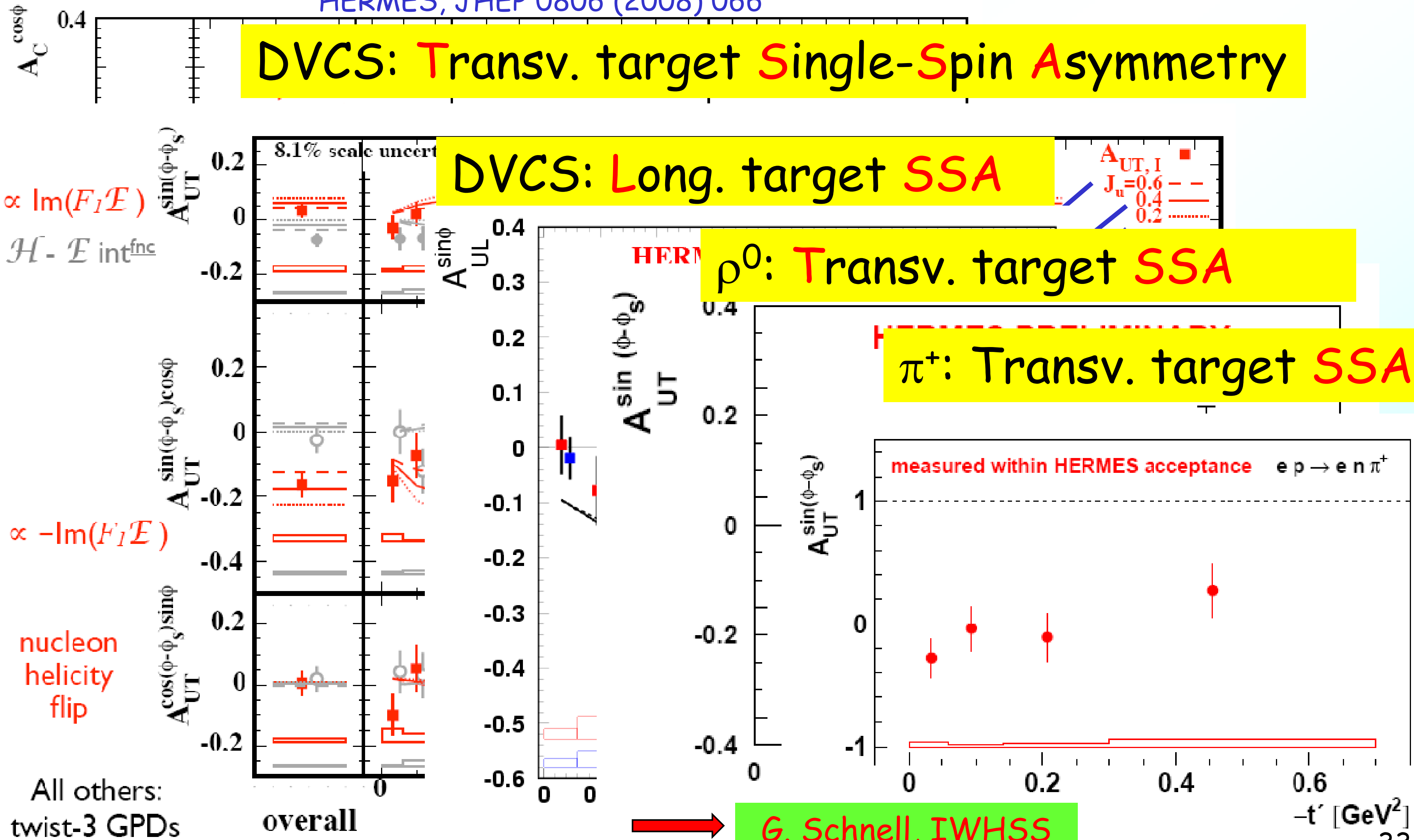
HERMES, JHEP 0806 (2008) 066

DVCS: Transv. target Single-Spin Asymmetry

DVCS: Long. target SSA

ρ^0: Transv. target SSA

π^+: Transv. target SSA



$\propto$ Im($F_1 \mathcal{E}$)

$\mathcal{H}$ - $\mathcal{E}$ int^{fnc}

$\propto$ −Im($F_1 \mathcal{E}$)

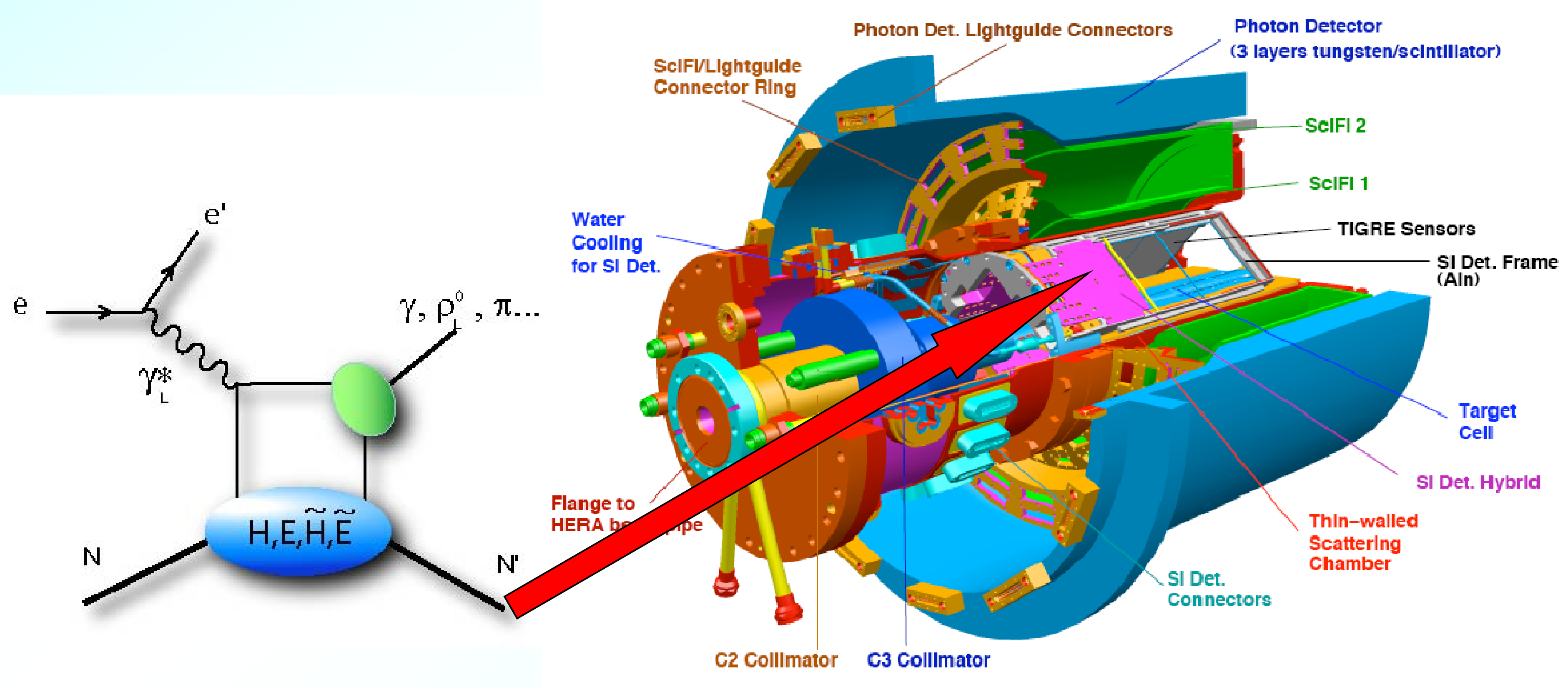
nucleon helicity flip

All others: twist-3 GPDs

G. Schnell, IWHSS

Exclusive Processes with Recoil Detector

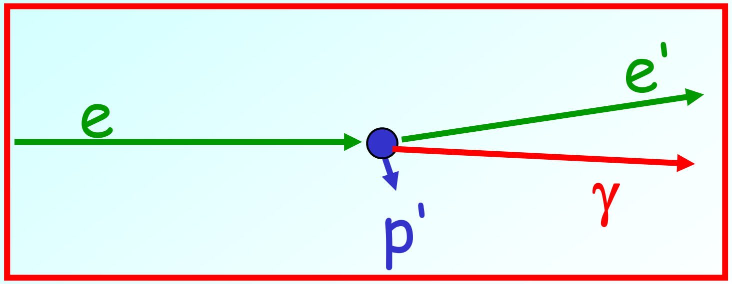
Main purpose: reduce background, identify events from resonance production and determine their asymmetries

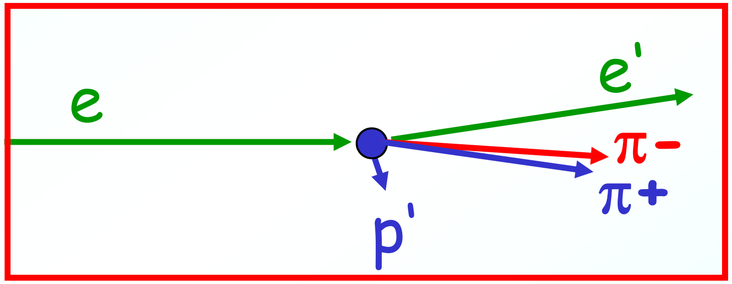


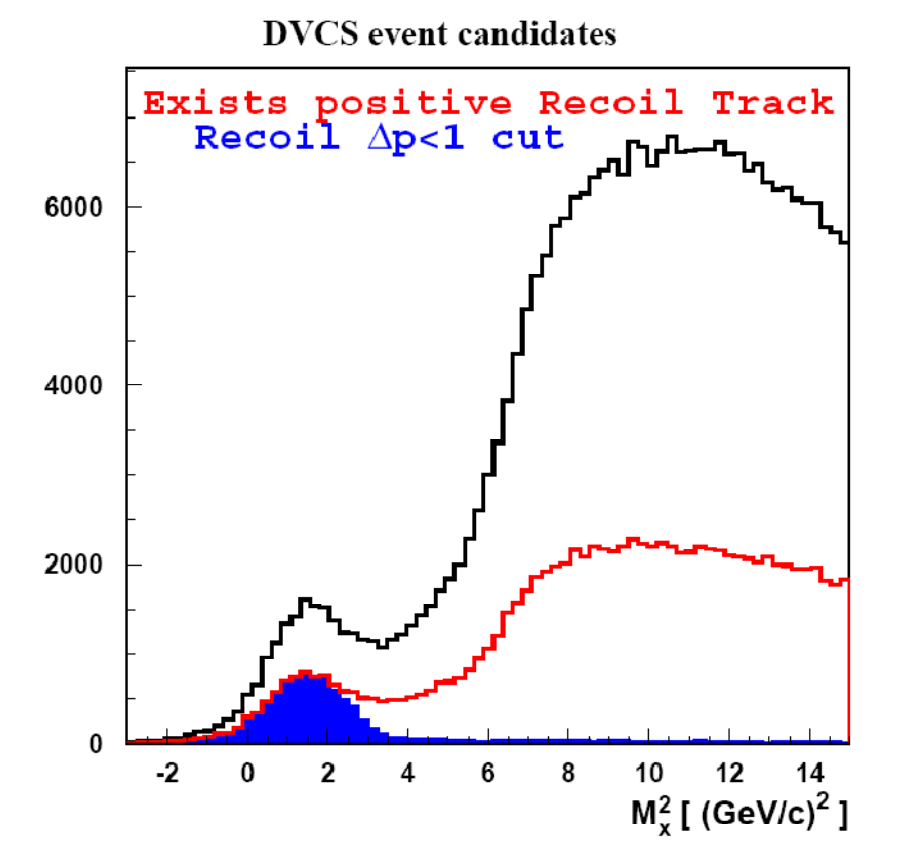
Event Selection with Recoil Detector

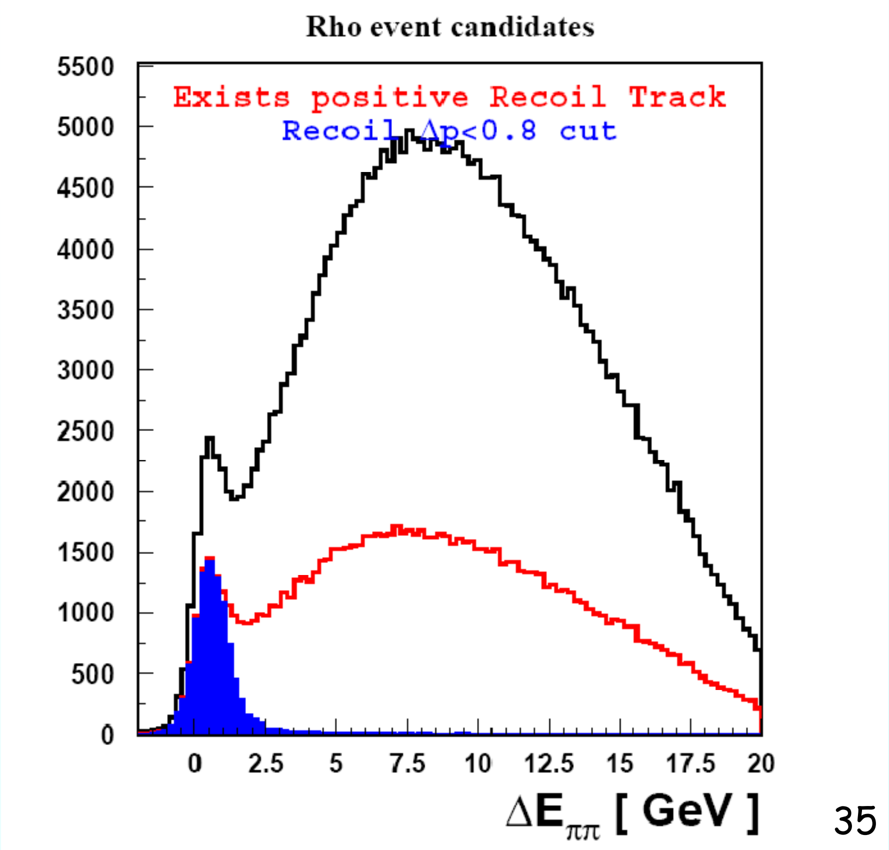
$e\,p \rightarrow e'\,\gamma\,X^+$

$e\,p \rightarrow e'\,\rho\,X^+$

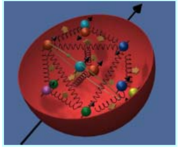






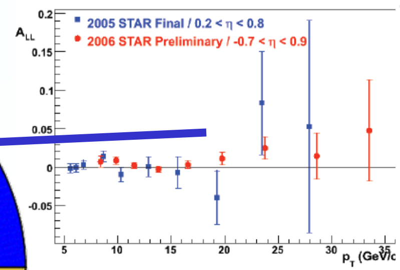


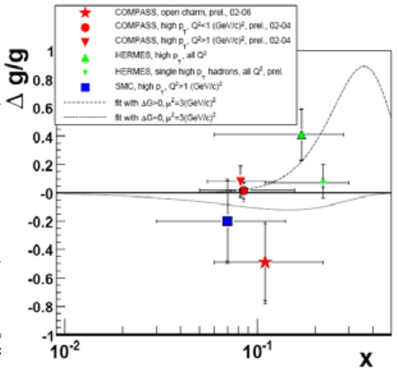
Nucleon Spin Structure



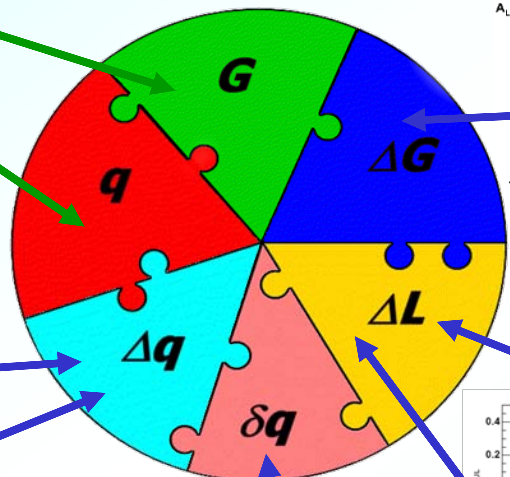
Unpolarised DIS
SLAC, BCDMS, NMC, HERA…

$\rightarrow \Delta g/g$: small ?

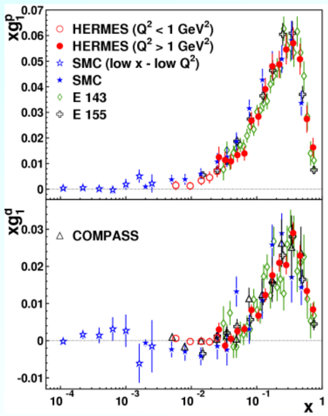


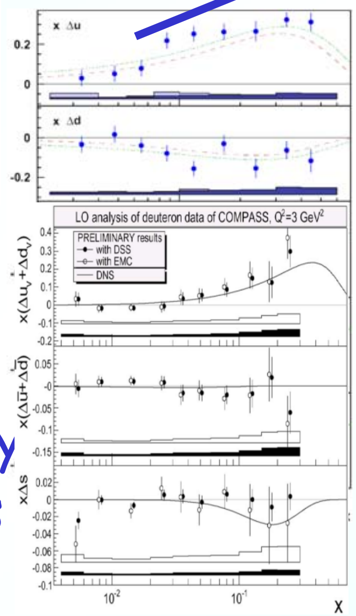


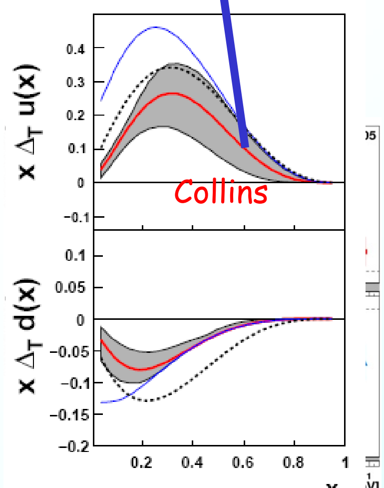
$\rightarrow \Delta\Sigma$
$\cong 0.33 \pm 0.03(\text{exp})$

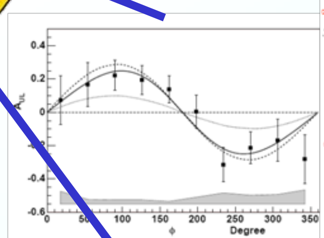


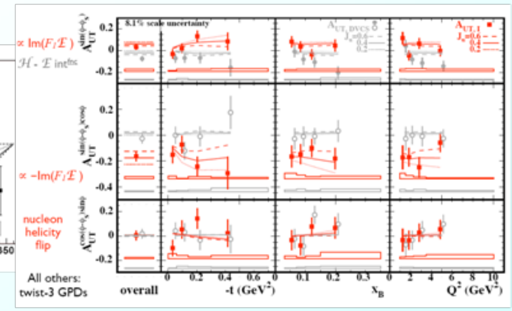
$\rightarrow$ Signals for GPDs $\rightarrow J_u + J_d$

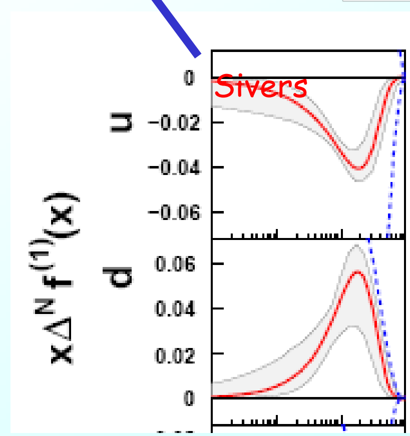










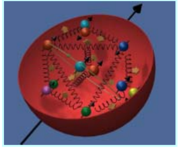


$\rightarrow$individual quark helicity distributions

$\rightarrow \delta q(x) \neq 0$

$\rightarrow L_q \neq 0$

Summary



Spin experiments have provided a wealth of detailed information about the nucleon spin structure

We know much more about the nucleon spin than 20 years ago, but its origin still remains to be somewhat mysterious