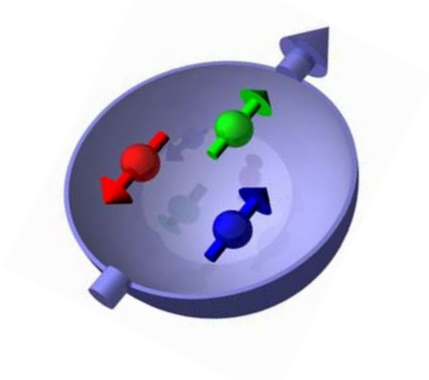


# Nucleon spin structure results
## (from the HERMES experiment)


***Michael Düren***

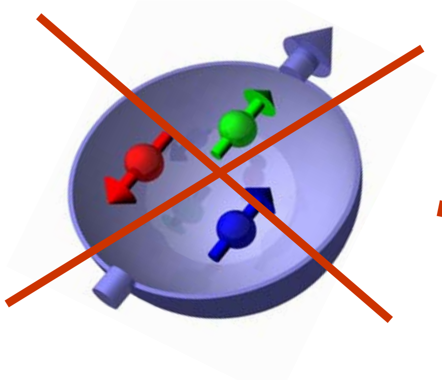
***Universität Gießen***

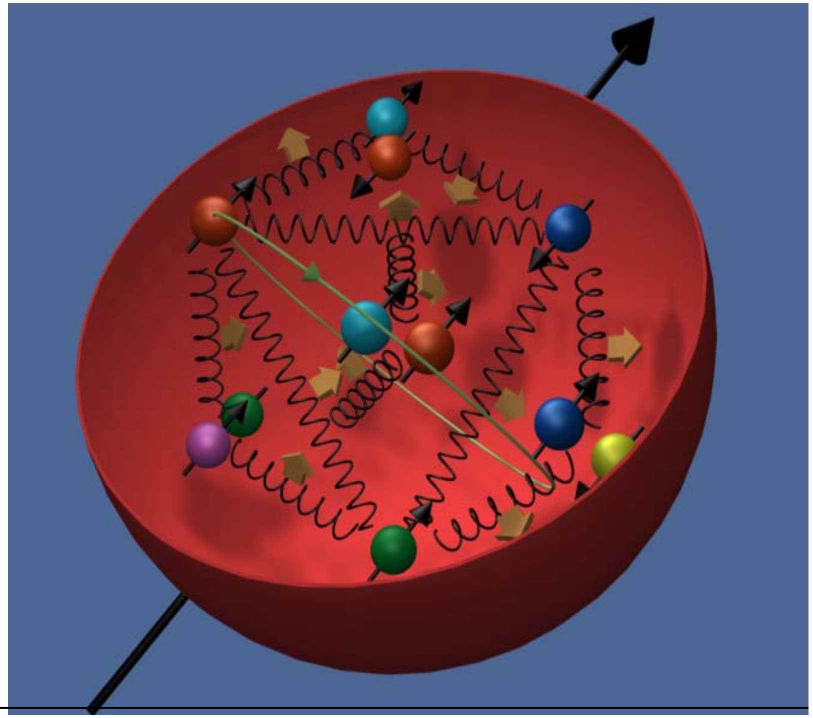


— XII Conference on Hadron Spectroscopy, Frascati, Oct. 10, 2007 —



JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN





**EMC 1988:** Only 12±17% spin of the proton is explained by the spin of the up- and down- quarks

## Helicity sum rule:

$$\underbrace{S_z}_{\substack{\text{proton} \\ \text{spin projection}}} = \frac{1}{2}\underbrace{(\Delta u + \Delta d + \Delta s)}_{\substack{\text{valence and sea} \\ \text{quark spin}}} + \underbrace{\Delta G}_{\substack{\text{gluon} \\ \text{spin}}} + \underbrace{\Delta L_q + \Delta L_g}_{\substack{\text{orbital angular} \\ \text{momentum}}}$$

$$\text{proton spin projection} = ½ \qquad \text{valence and sea quark spin} = \Delta\Sigma$$

$$a_0 \overset{\overline{MS}}{=} \Delta\Sigma = 0.330 \pm 0.011_{\text{(theory)}} \pm 0.025_{\text{(exp)}} \pm 0.028_{\text{(evol)}}$$

**Remember:** 1/3 of the proton spin comes the from quark spin

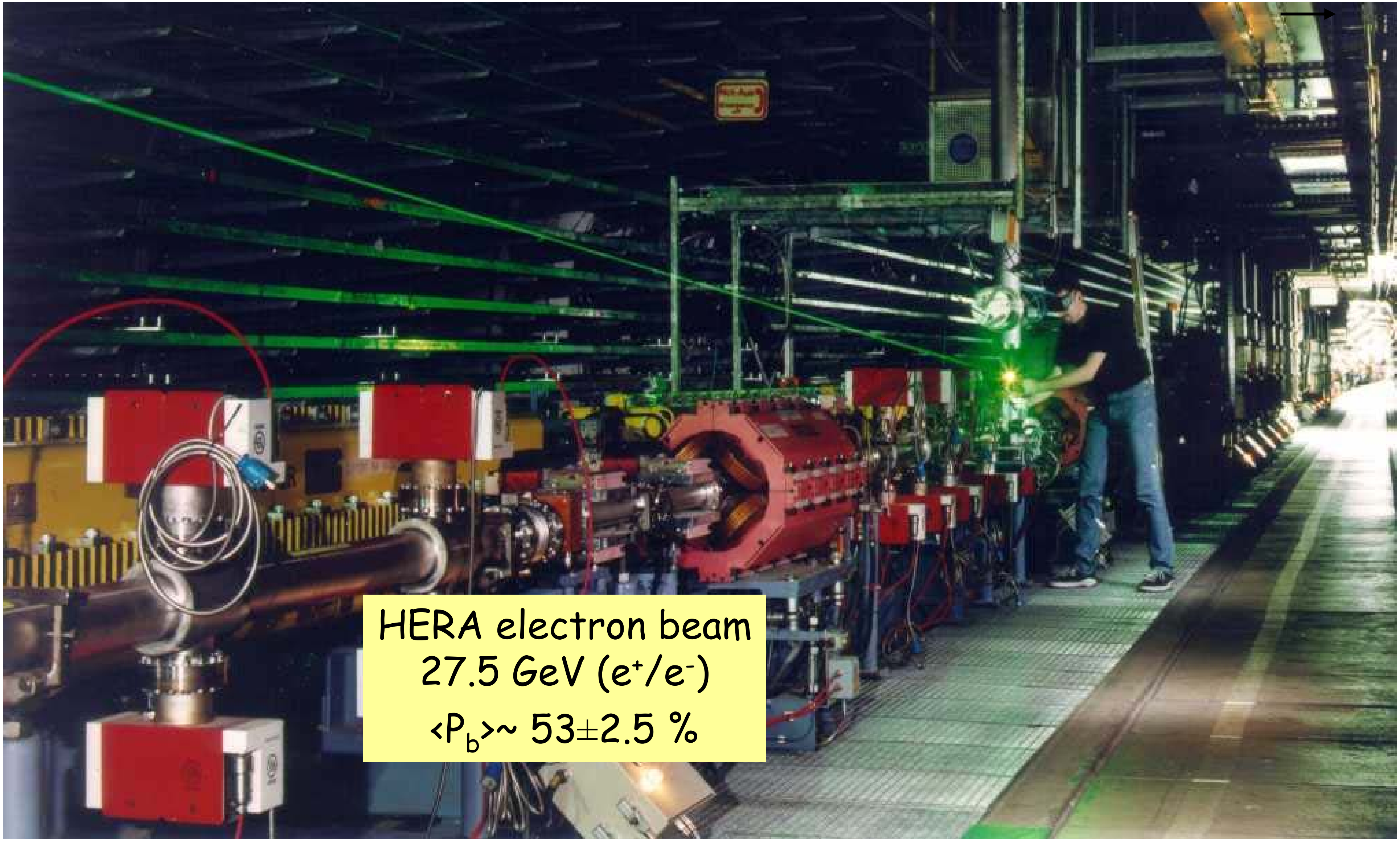
# The Experiment:

hermes

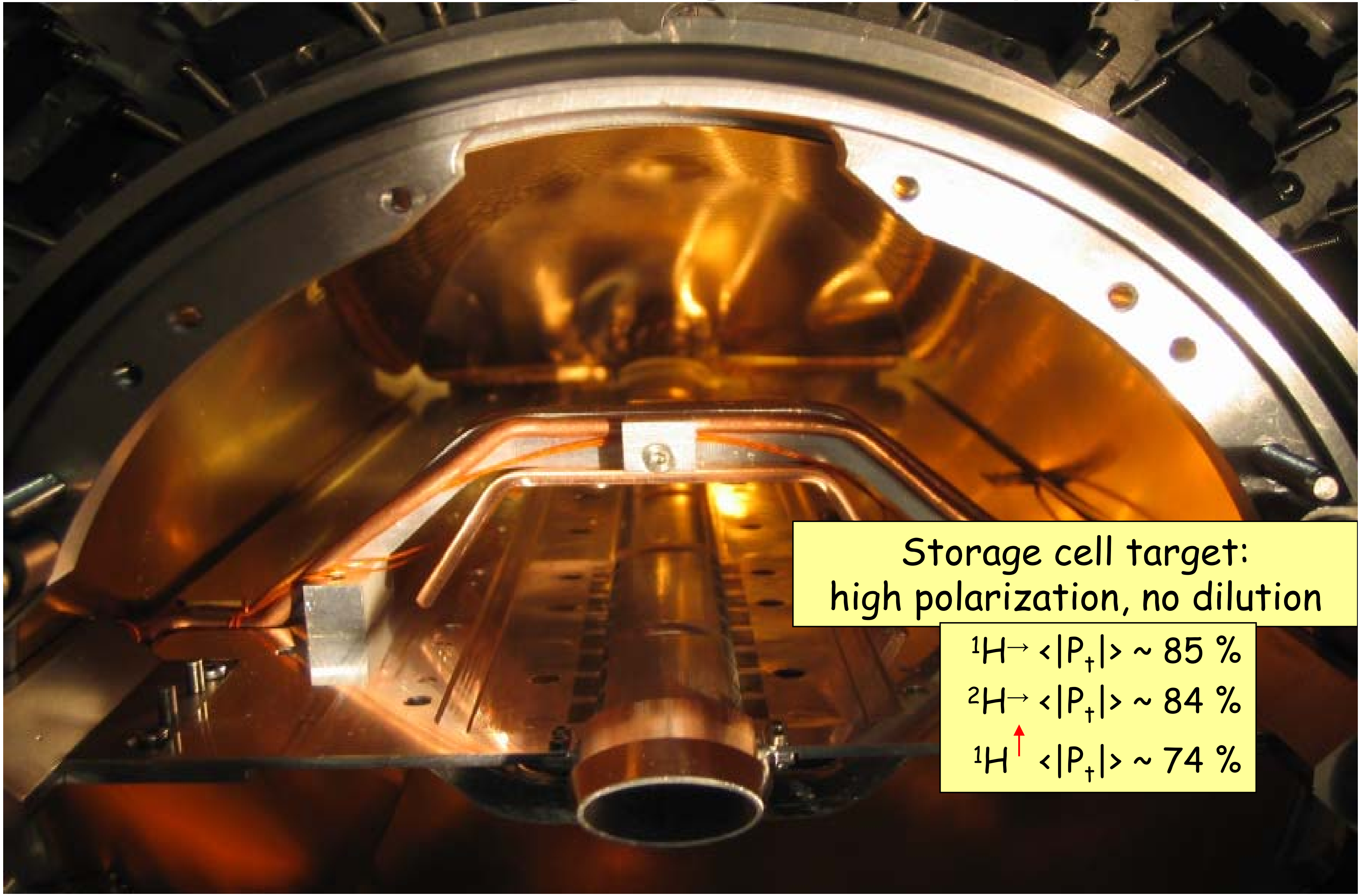
* 1995
† 2007

*) proposed in ~1988 to solve the spin crisis
†) plenty of beautiful data are waiting for being analyzed

# Novel techniques: longitudinally polarized high energy electron/positron beam at HERA for beam-spin and beam-charge asymmetries



# Novel techniques: The longitudinally and transverse polarized internal gas target for double spin asymmetries



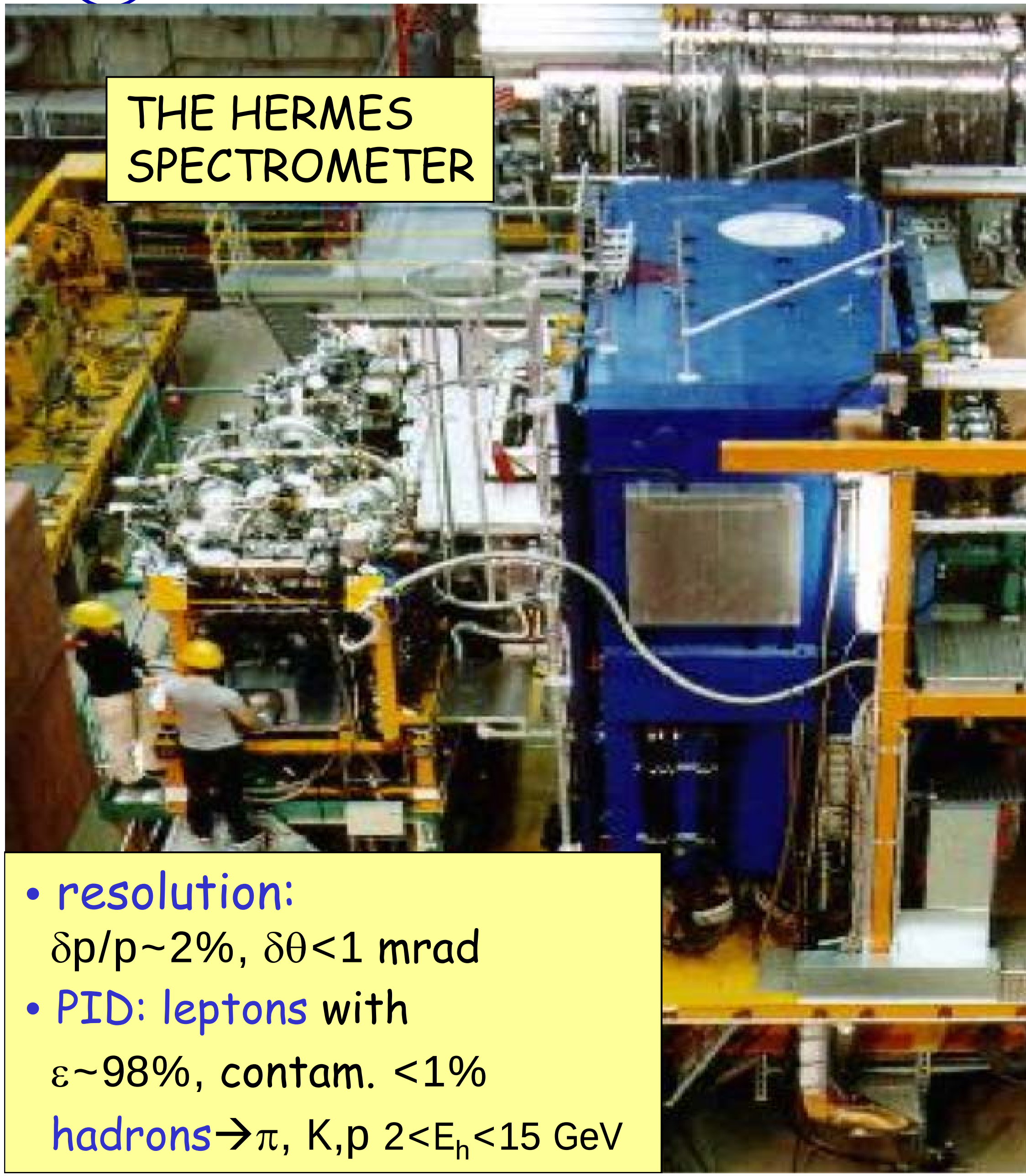
Storage cell target:
high polarization, no dilution

$^{1}H^{\rightarrow}$ $\langle|P_t|\rangle \sim 85\ \%$

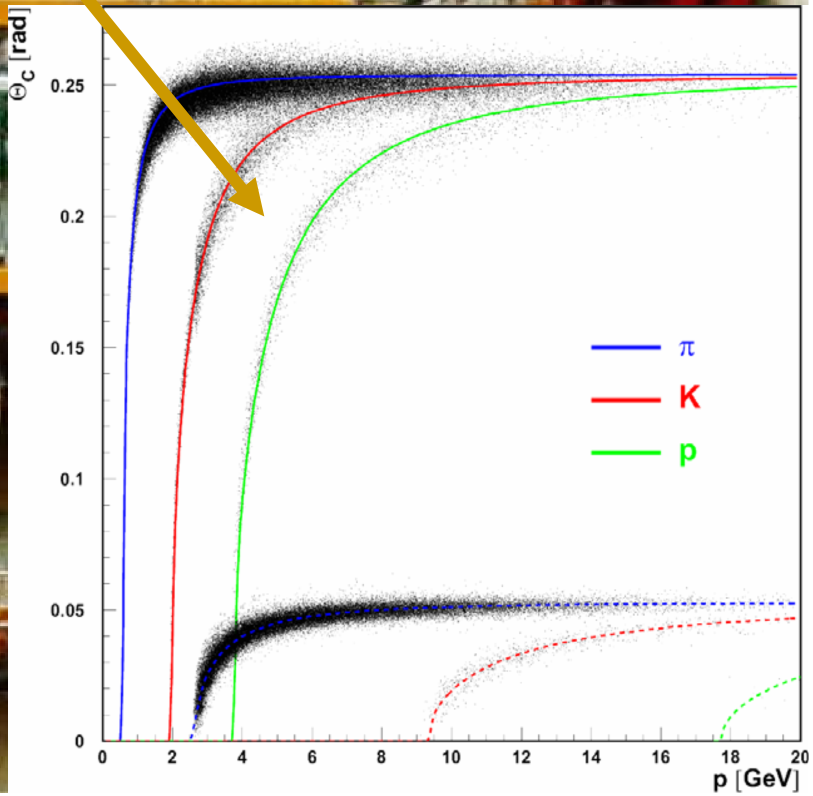
$^{2}H^{\rightarrow}$ $\langle|P_t|\rangle \sim 84\ \%$

$^{1}H^{\uparrow}$ $\langle|P_t|\rangle \sim 74\ \%$

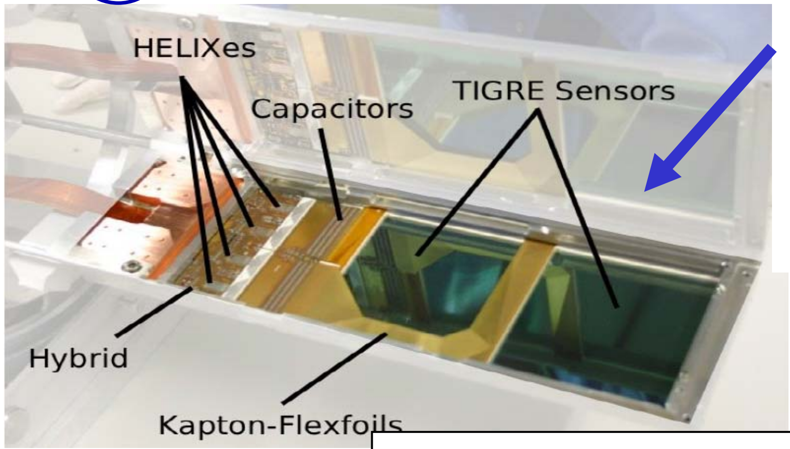
# Novel techniques: Dual radiator RICH for strangeness




- resolution:
  $\delta p/p \sim 2\%$, $\delta\theta < 1$ mrad
- PID: leptons with
  $\varepsilon \sim 98\%$, contam. <1%
  hadrons→π, K,p $2 < E_h < 15$ GeV



# Novel techniques: Recoil detector for exclusive physics

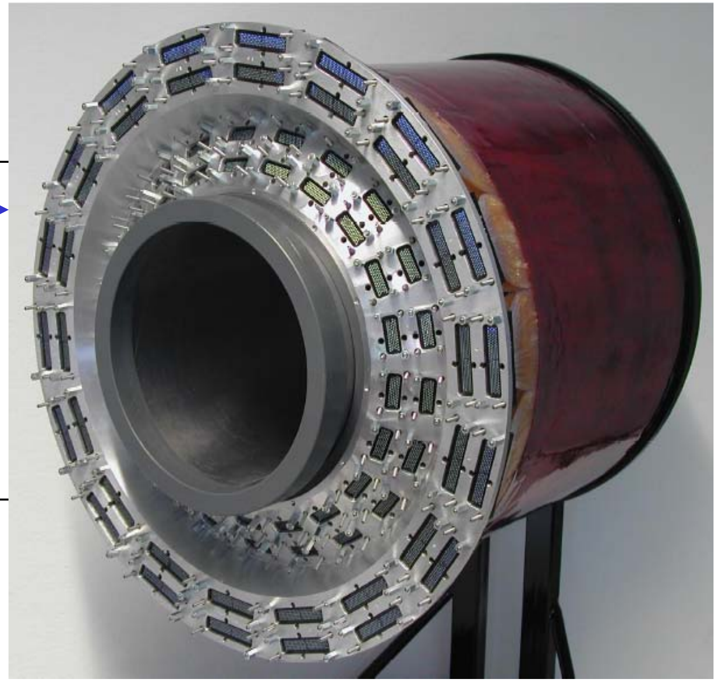


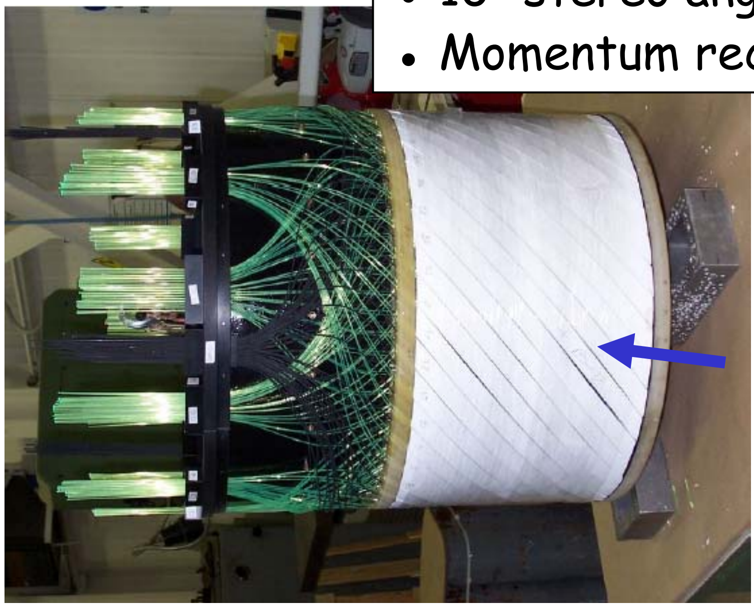

## Silicon Detector

- Inside beam vacuum
- 16 double-sided sensors
- Momentum reconstruction & PID

## Scintillating Fiber Detector

- 2 barrels
- 2x2 parallel and 2x2 stereo layers
- 10° stereo angle
- Momentum reconstruction & PID



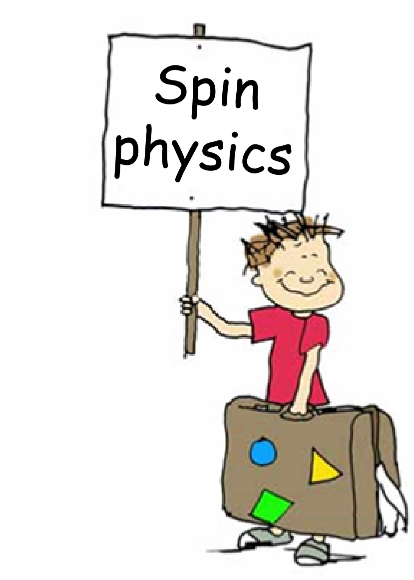


1 Tesla superconducting solenoid

## Photon Detector

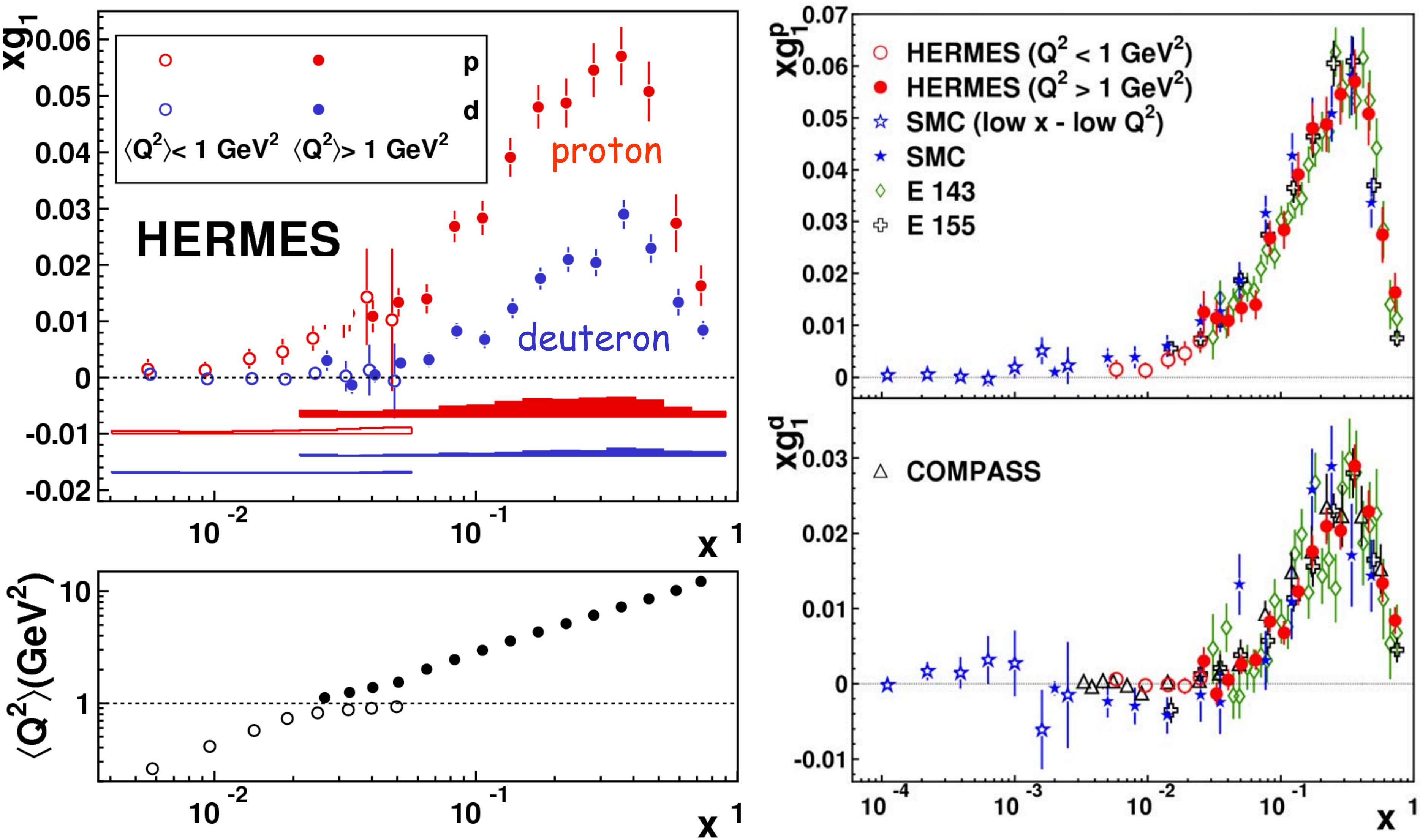
- 3 layers of tungsten/scintillator
- PID for higher momenta
- detects $\Delta^+ \rightarrow p\pi^0$

# Hot topics in spin physics:




- Moments and QCD-fits of PDFs
- Strange sea polarisation; $SU(3)_f$
- Gluon spin
- Transverse spin effects (do not appear in the helicity sum rule)
- Orbital angular momentum of quarks; „3-D views“ of the proton; GPDs

# Polarized structure function $g_1^{p,d}(x)$



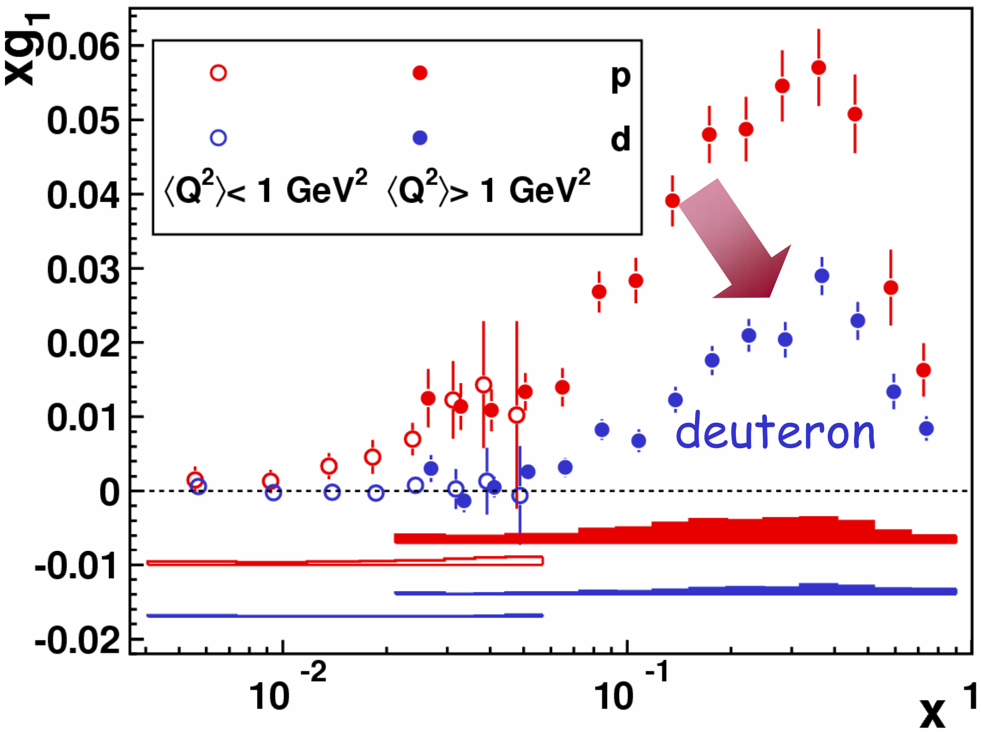

HERMES data set most precise and complete
in valence/sea overlap region

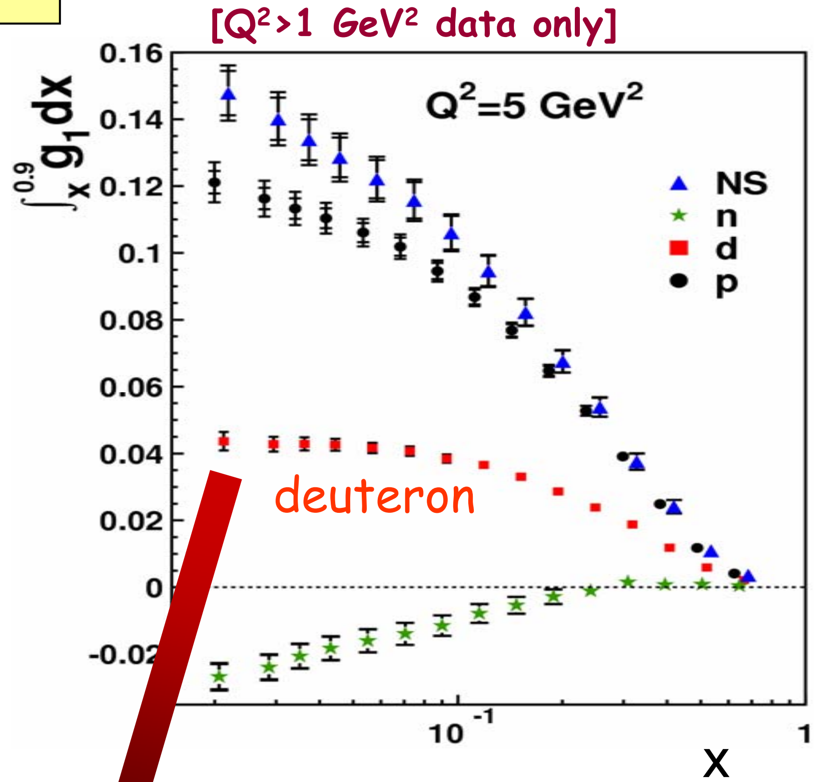


[PRD 75 (2007)]

# First moment $\Gamma_1^d$

Deuteron data alone give $\Delta\Sigma$ !




*$a_8$ from hyperon beta decay*

$$\Delta\Sigma \overset{\overline{MS}}{=} a_0 = \frac{1}{\Delta C_S}\left[\frac{9\Gamma_1^d}{(1-\frac{3}{2}\omega_D)} - \frac{1}{4}a_8\,\Delta C_{NS}\right]$$

*theory* *theory*

$\omega_D = 0.05 \pm 0.05$

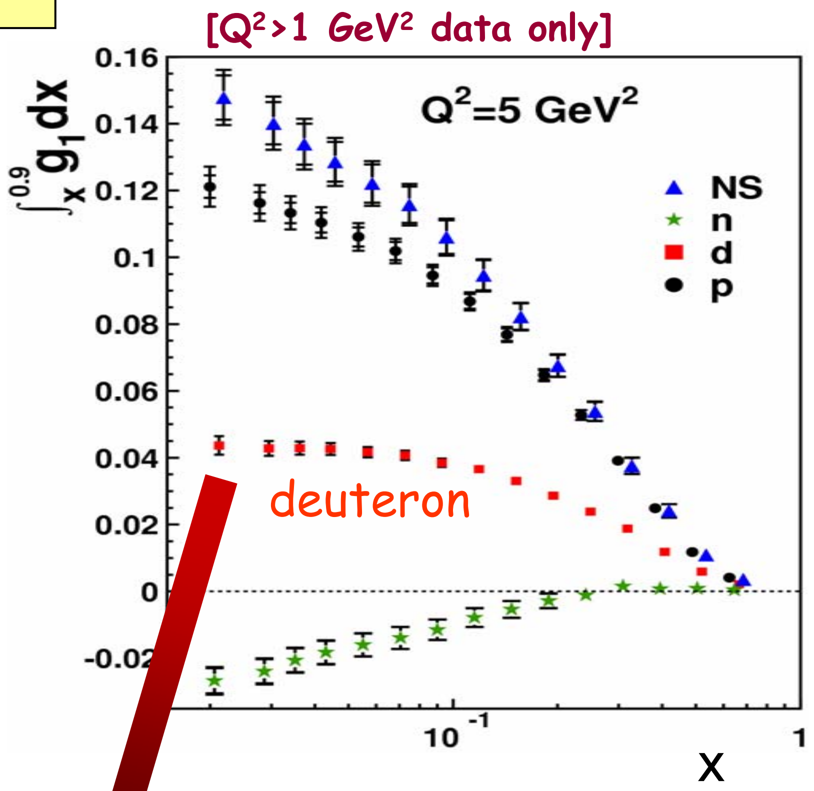
# First moment $\Gamma_1^d$ and $\Delta\Sigma$

Deuteron data alone give $\Delta\Sigma$ !

$a_0 \overset{\overline{MS}}{=} \Delta\Sigma$ (theory) (exp) (evol)

$= 0.330 \pm 0.011 \pm 0.025 \pm 0.028$

Most precise result;
Consistent with other experiments




*$a_8$ from hyperon beta decay*

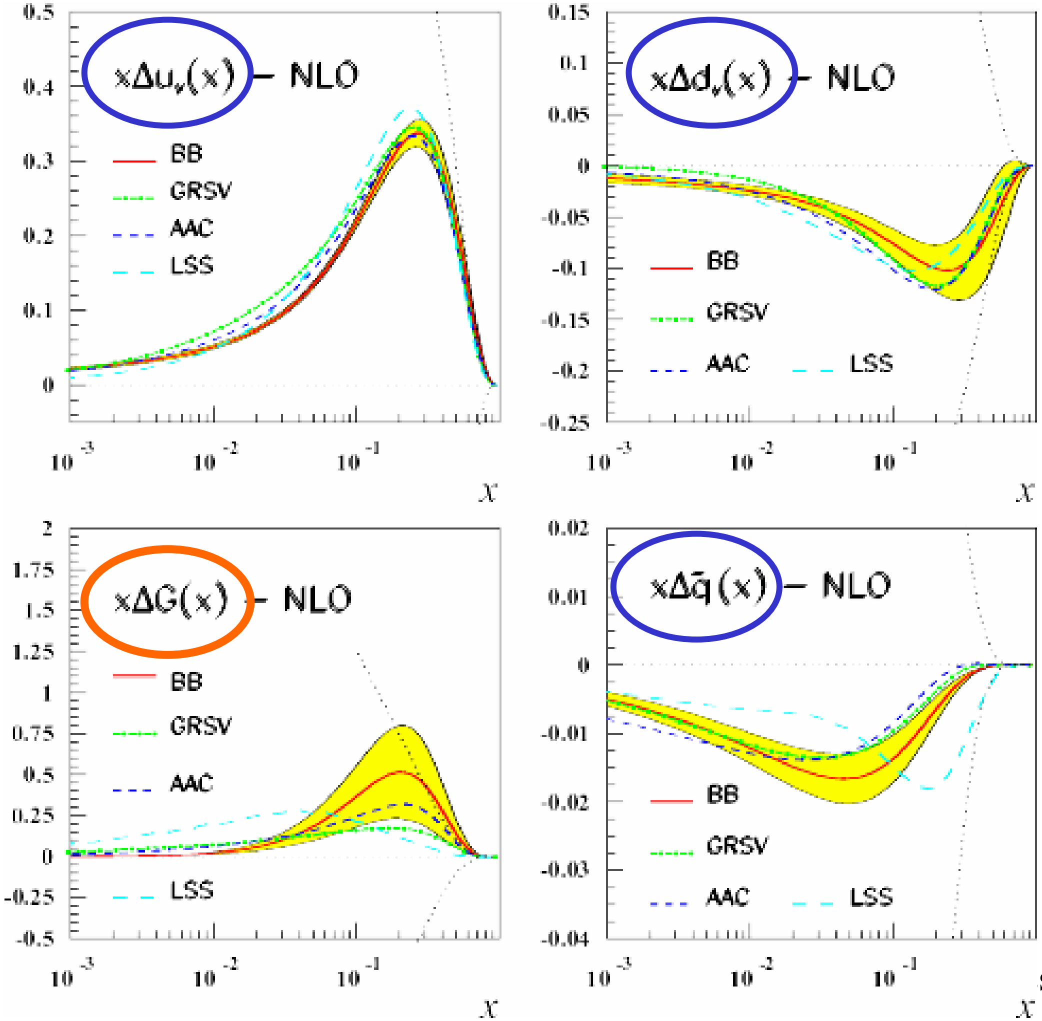
$$\Delta\Sigma \overset{\overline{MS}}{=} a_0 = \frac{1}{\Delta C_S}\left[\frac{9\Gamma_1^d}{(1-\frac{3}{2}\omega_D)} - \frac{1}{4} a_8 \Delta C_{NS}\right]$$

*theory* *theory*

*$\omega_D = 0.05 \pm 0.05$*

# $\Delta$q and $\Delta$G from inclusive data

$$g_1^{NLO}(x) = g_1^{LO} + \frac{\alpha_s}{2\pi}\frac{1}{2}\sum_q e_q^2 [\Delta q(x,Q^2) \otimes C_q + \Delta G(x,Q^2) \otimes C_g]$$



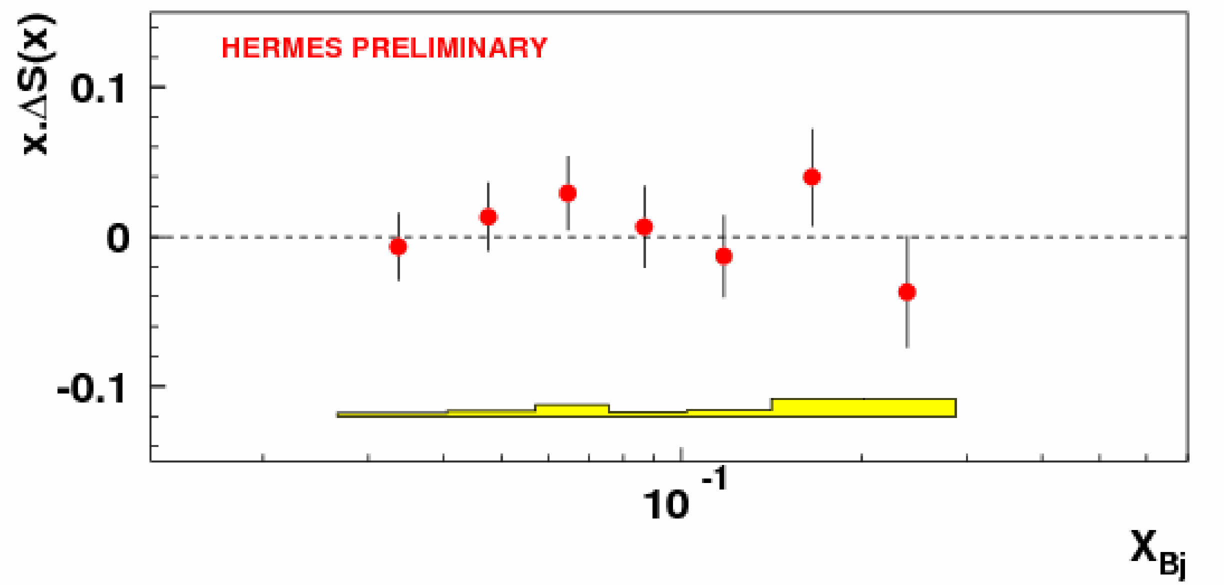

- Valence quarks are well determined: $\Delta u_v > 0$, $\Delta d_v < 0$

- Gluons and sea quarks are weakly constrained by data

SU(3)$_f$ flavor symmetry implicitly assumed!

# Important remark on $SU(3)_f$ and the polarization of strange quarks

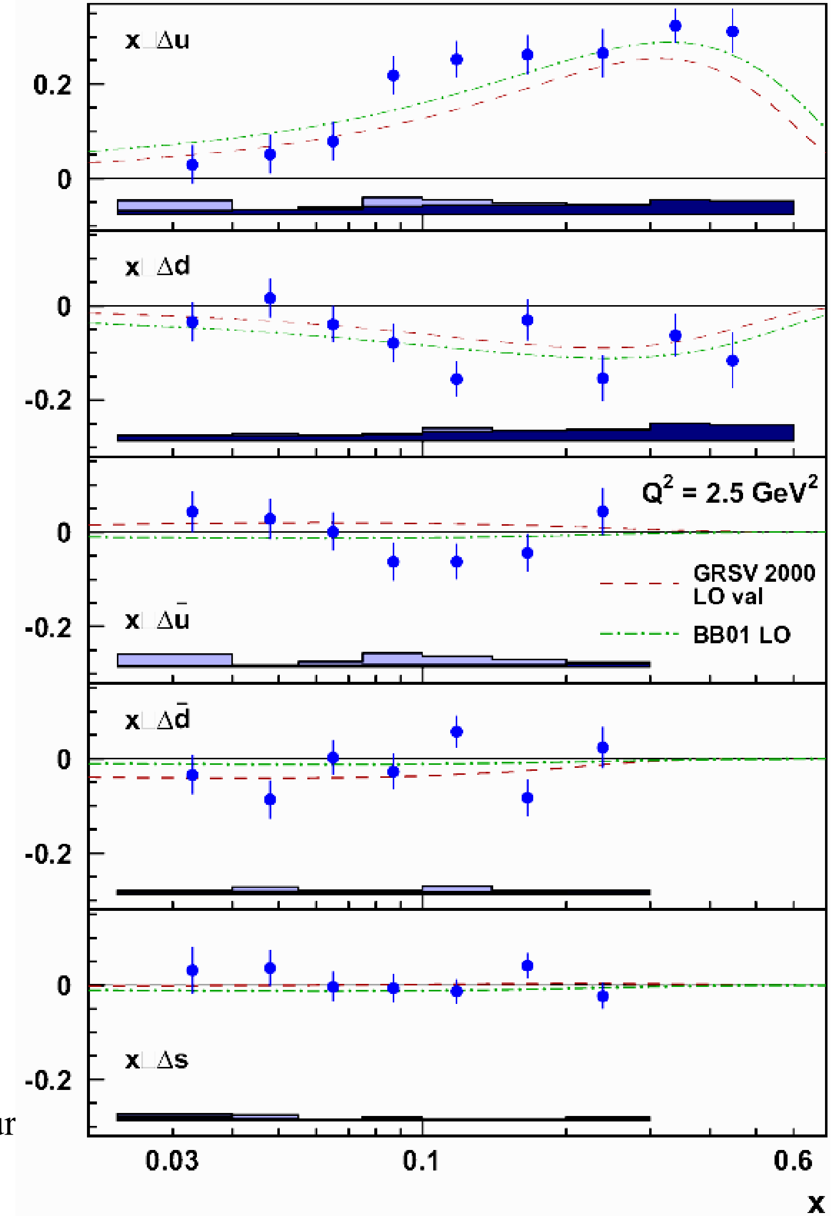
- The violation of the Ellis-Jaffe sum rule means:
  - either the strange quark polarization $\Delta s$ is negative
  - or $SU(3)_f$ flavor symmetry is broken
  - or low-x region different than assumed in parameterizations
- Most analyses assume explicitly or implicitly $SU(3)_f$ flavor symmetry (e.g. in parameterizations of the PDFs)
- Only semi-inclusive data can measure directly $\Delta s$




**Kaon asymmetries on deuterium** allow for the most direct determination of $\Delta s$ ! Final analysis is in progress.

# Flavor separation from semi-inclusive data

HERMES: Only direct 5-flavor separation of polarized PDFs

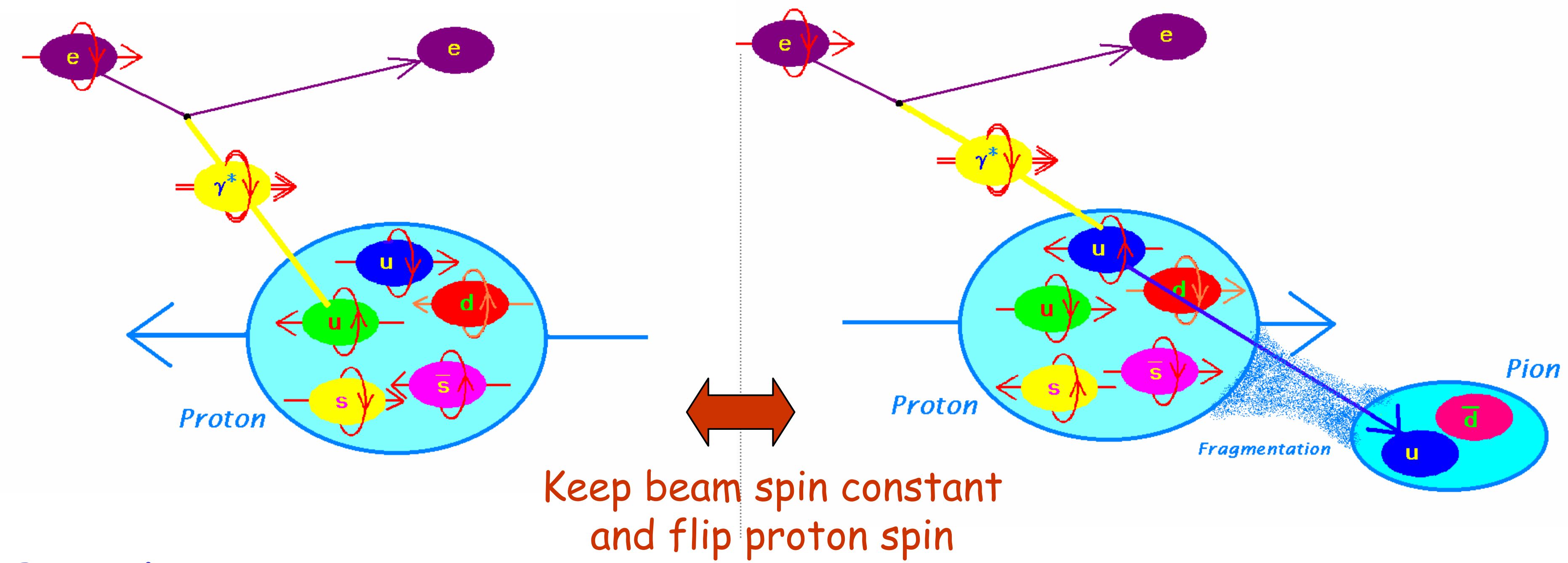



Results (in short):

- Δu(x) is large and positive
- Δd(x) is smaller and negative
- Δs(x) is approx. zero

[PRL92(2004), PRD71(2005)]

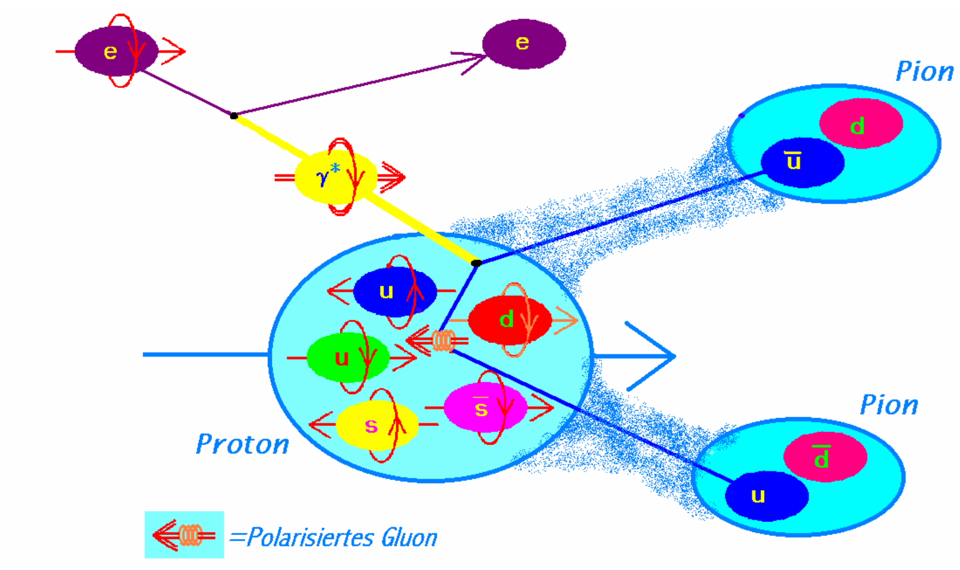
# How does spin flavor separation $\Delta q_f(x)$ work?




**Principles:**

- Helicity conservation in polarized DIS: select specific quark spin orientation
- Hadron tagging: select specific quark flavor
- Matrix inversion brings you back from hadron asymmetries to quark spin flavor distributions $\Delta q_f$ (purity formalism)

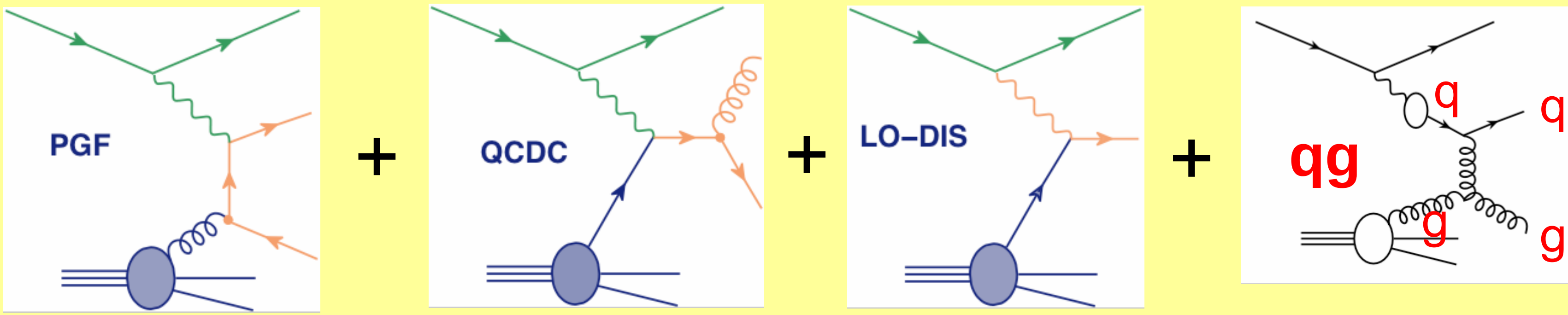
# How does a direct gluon spin extraction work?




**Principle:**

- Large $p_T$ hadron pairs come from photon gluon fusion processes
- They carry information of the gluon spin

However, other sub-processes make life hard:

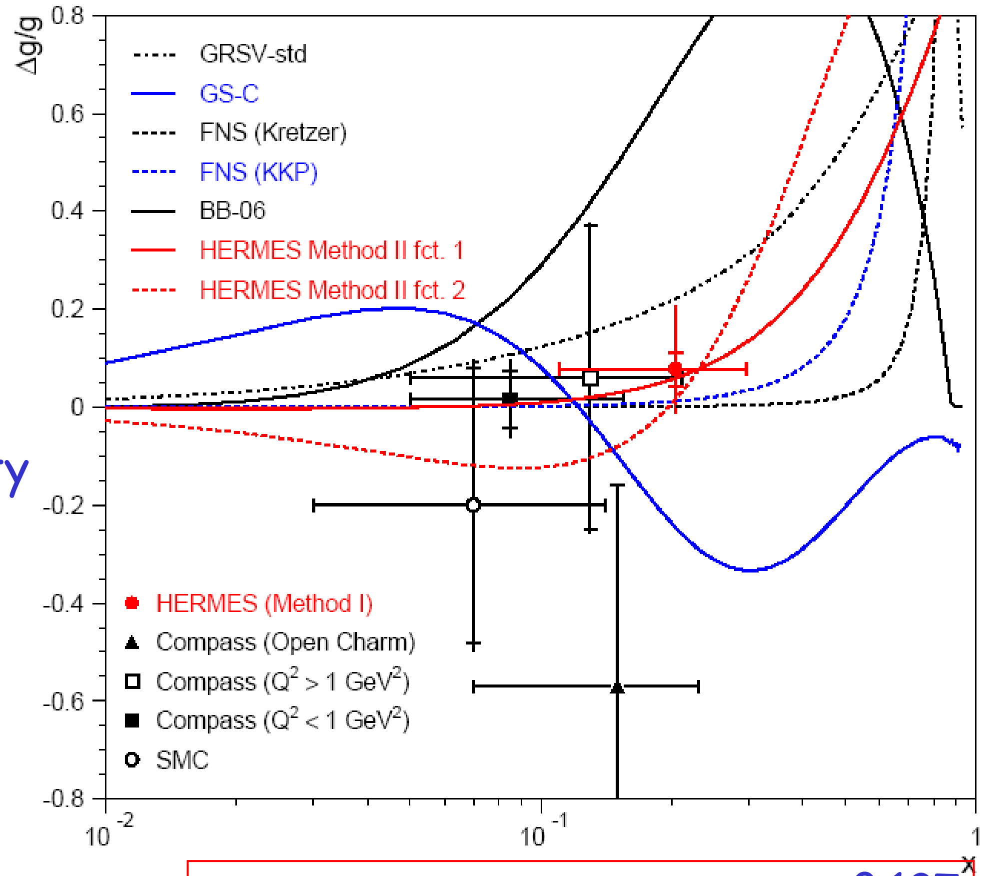


# Measurement of gluon polarisation

HERMES: first measurement of gluon polarisation
[PRL 84 (2000)] **TOPCITE 50+**

Further analysis going on:
- Measurement of high $p_T$ pairs
- Separation of the subprocesses
- Two different methods

- Significant reduction of $\Delta g$ uncertainty
- Still sign ambiguity at low x

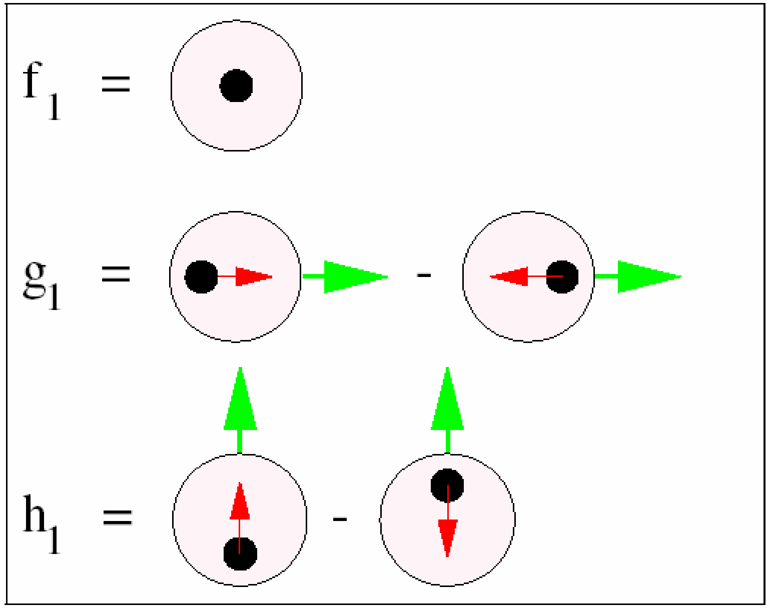



$\Delta g/g = 0.071 \pm 0.034 \pm 0.010 \, ^{+0.127}_{-0.105}$

For more details see talk by Riccardo FABBRI

# Transverse spin effects

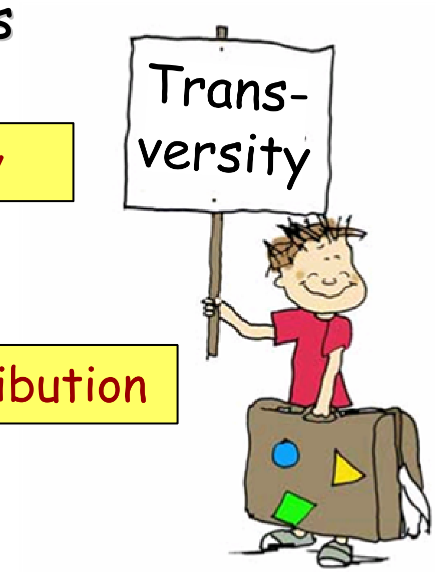
There are ~~two~~ three leading-twist structure functions




$\sim \bar{\psi}\gamma^{\mu}\psi$ Quark density

$\sim \bar{\psi}\gamma^{\mu}\gamma_5\psi$ Helicity distribution

$\sim \bar{\psi}\sigma^{\mu\nu}\gamma_5\psi$ Transversity



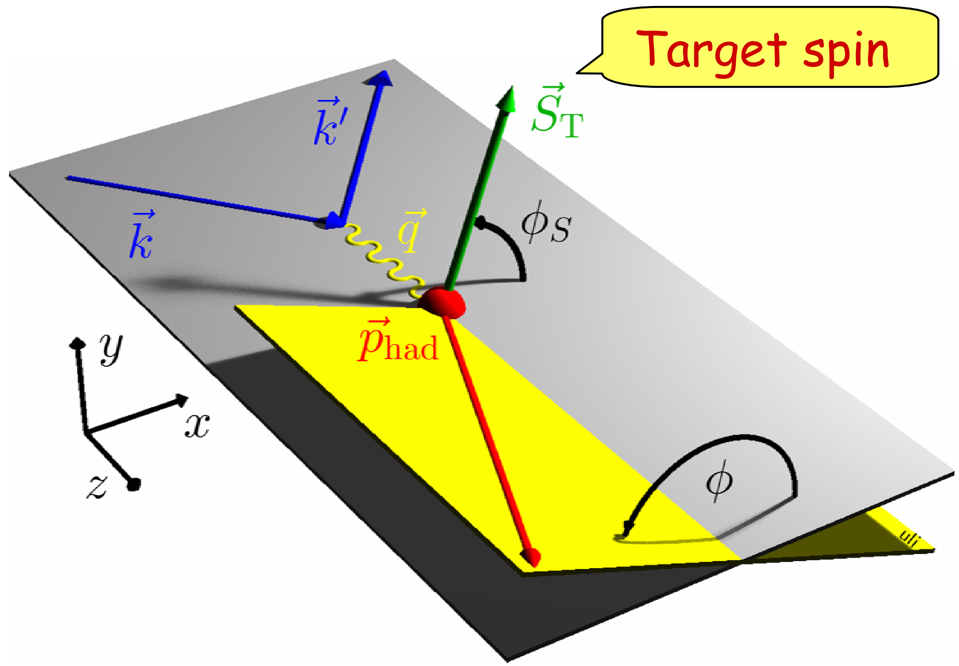

**Interesting properties of transversity:**

- **QCD-evolution independent of gluon distribution** (to be tested by experiment)
- 1st moment of $\delta$**q** is **tensor charge** (pure valence object); value predicted by lattice QCD

✷ Transversity is chiral odd (i.e.does not contribute to inclusive DIS cross section!)

# Transverse spin distribution of quarks

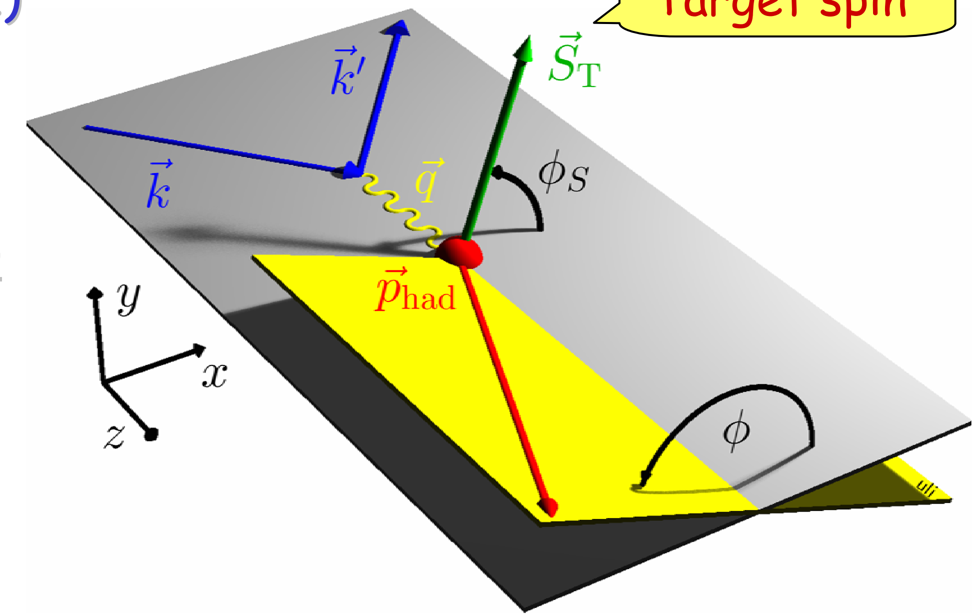
- The azimuthal angular distributions of hadrons from a transversely polarized target show two effects:
  - Collins asymmetry in $\sin(\phi+\phi_s)$
  - Sivers asymmetry in $\sin(\phi-\phi_s)$



# Transverse spin distribution of quarks

- The azimuthal angular distributions of hadrons from a transversely polarized target show two effects:
  - Collins asymmetry in $\sin(\phi+\phi_s)$
    Product of the chiral-odd transversity distribution $h_1(x)$ and the chiral-odd fragmentation function $H_1^{\perp}(z)$
    → related to the transverse spin distribution of quarks
  - Sivers asymmetry in $\sin(\phi-\phi_s)$

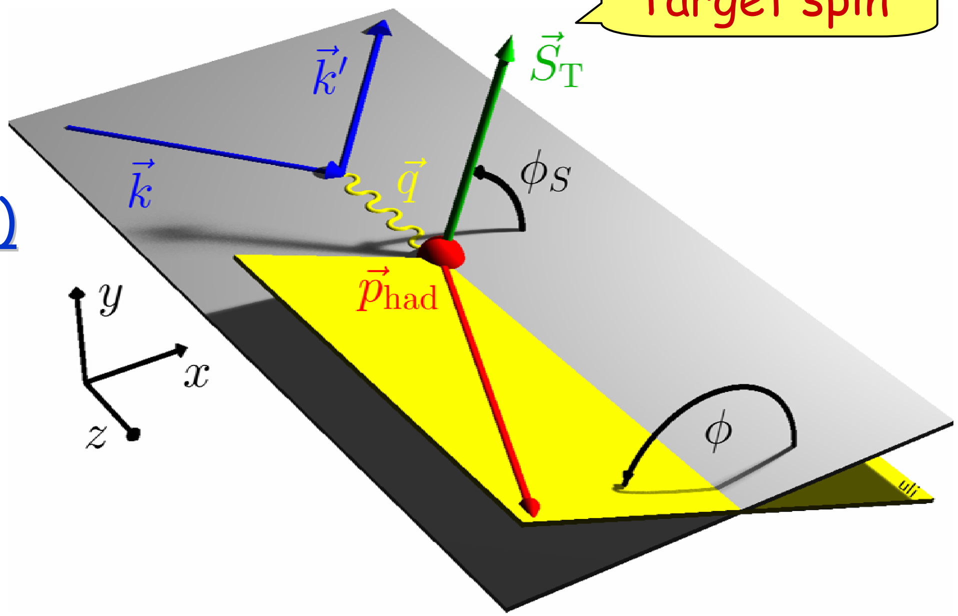
First results from Belle



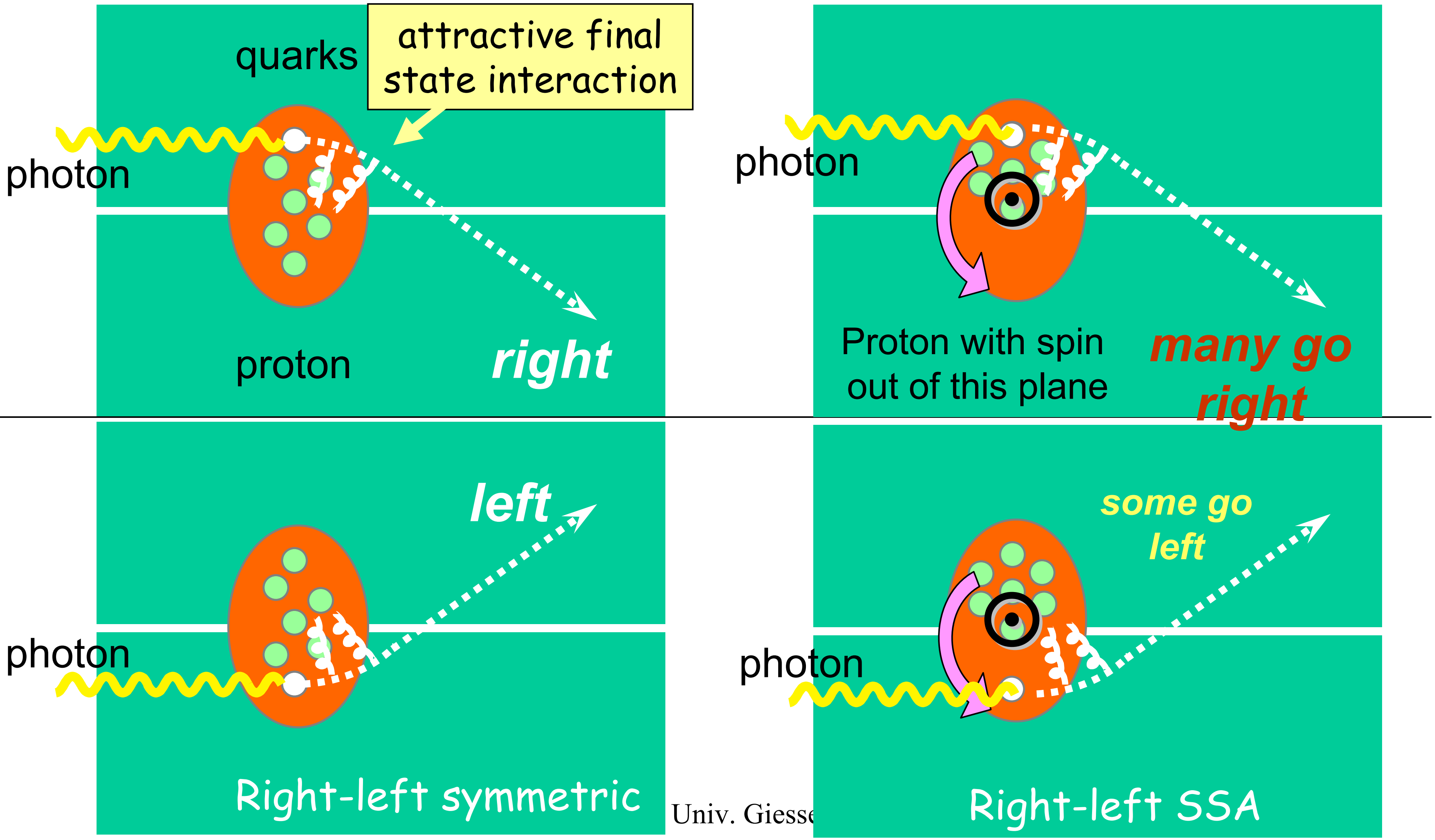
# Transverse spin distribution of quarks

- The azimuthal angular distributions of hadrons from a transversely polarized target show two effects:
  - Collins asymmetry in $\sin(\phi+\phi_S)$
    Product of the chiral-odd transversity distribution $h_1(x)$ and the chiral-odd fragmentation function $H_1^{\perp}(z)$
    → related to the transverse spin distribution of quarks
  - Sivers-Asymmetrie in $\sin(\phi-\phi_S)$
    Product of the T-odd distribution function $f_{1T}^{\perp}(x)$ and the ordinary fragmentation function $D_1(z)$
    → related to the orbital angular momentum of quarks

First results from Belle



# Sivers function is related to orbital angular momentum of quarks

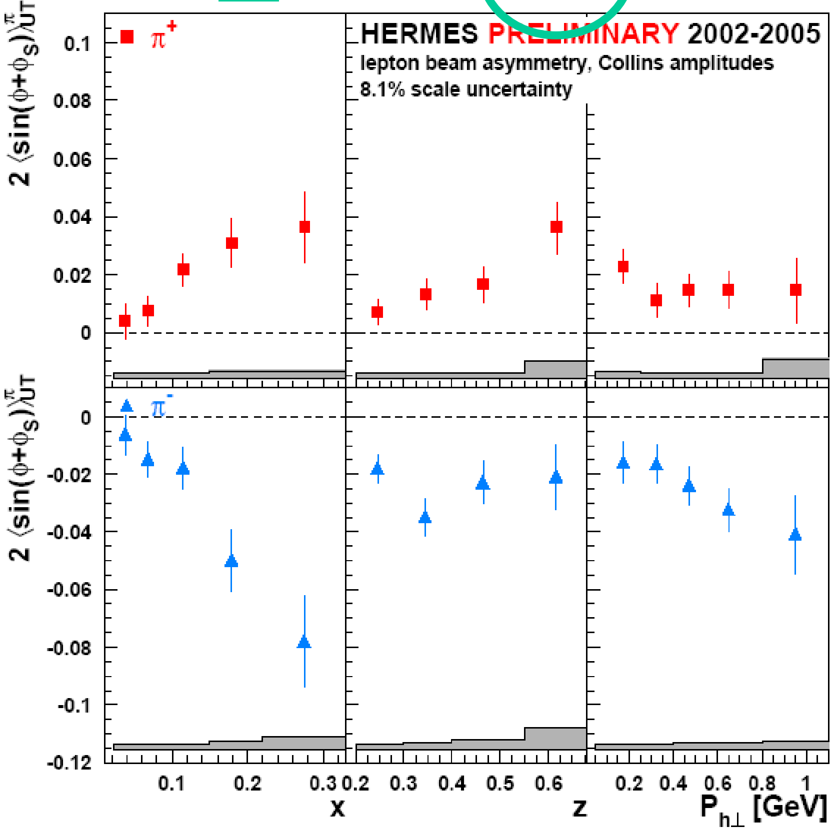



(M. Burkardt)

# SSA for pions [PRL94(2005)]

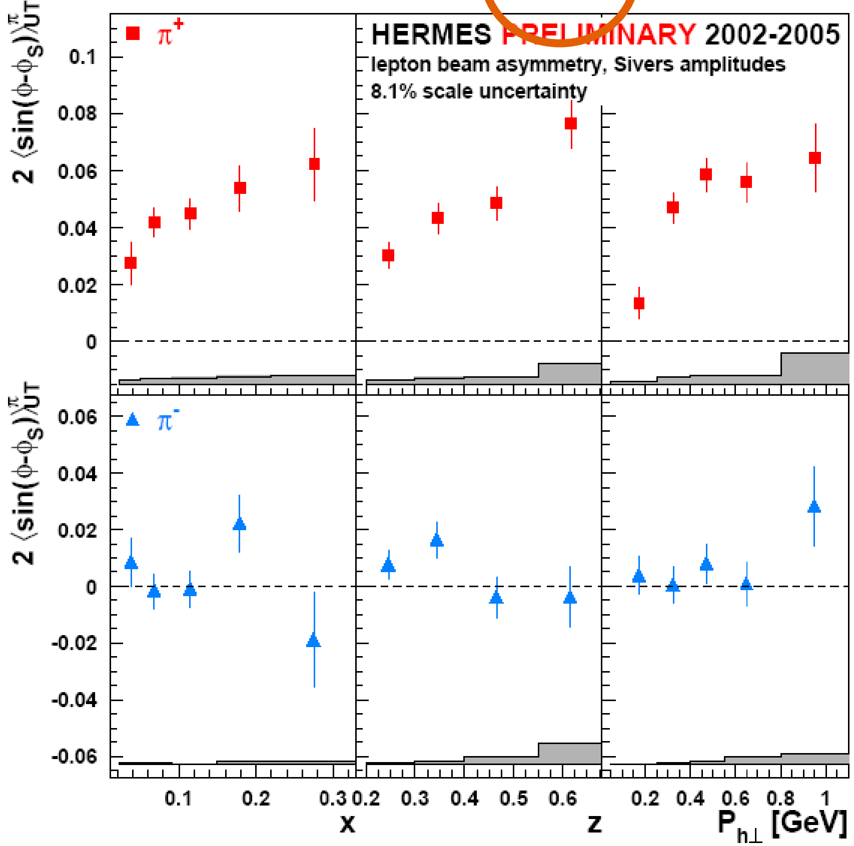
**Collins**

$$A_{coll}(\phi+\phi_S) \propto \delta q(x) H_1^{\perp}(z)$$




**Sivers**

$$A_{siv}(\phi-\phi_S) \propto f_{1T}^{\perp}(x) D_1(z)$$




- Significant non zero asymmetries
  - $A_{\pi+}>0$, $A_{\pi-}<0$
- Evidence of $H^{\perp}_{1,disf} \approx -H^{\perp}_{1,fav}$

en, Univ.

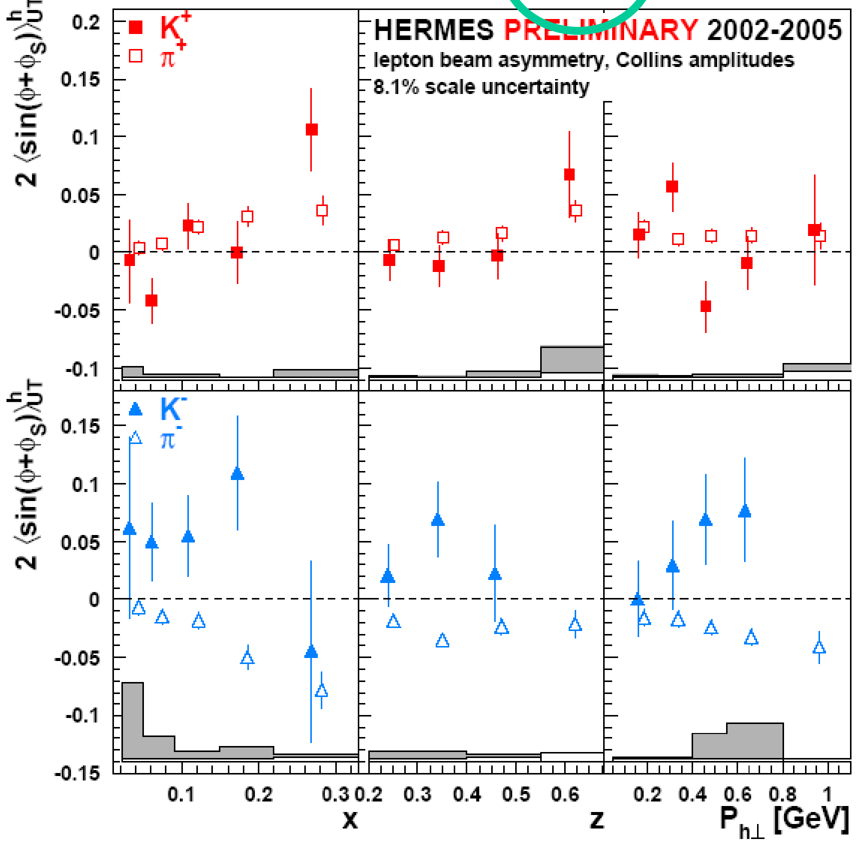
First measurement of naïve T-odd distr. fkt. in DIS

$$\pi^+ : A_{UT}^{\sin\varphi} > 0 \Rightarrow L_q \neq 0$$

# SSA for pions and kaons

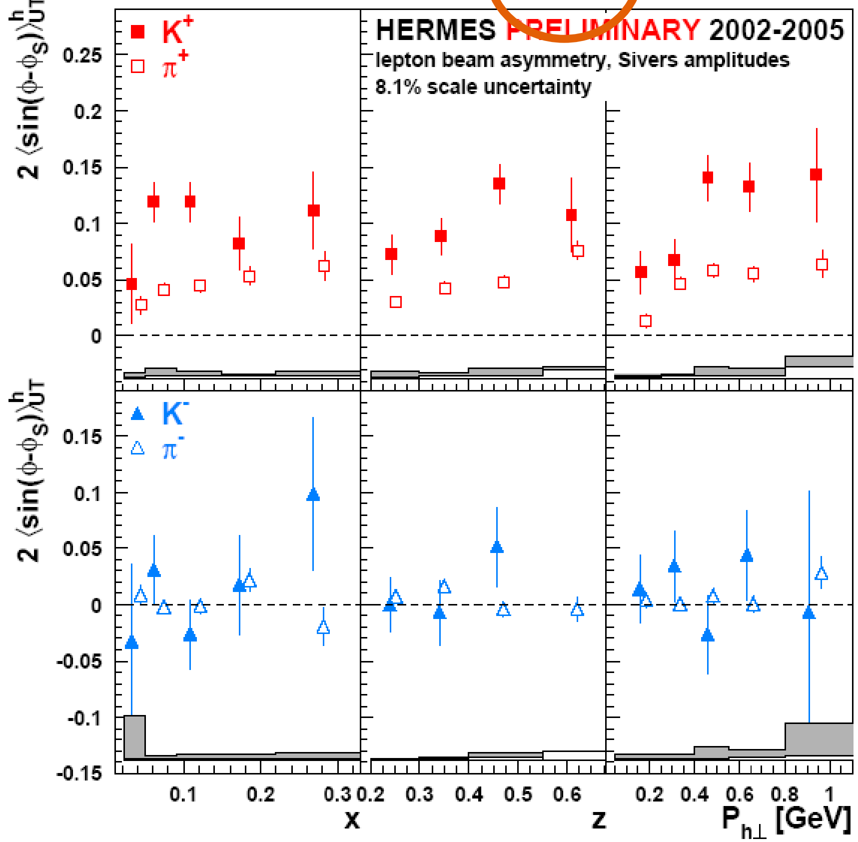
**Collins**

$$A_{coll}(\phi+\phi_S) \propto \delta q(x) H_1^{\perp}(z)$$




**Sivers**

$$A_{siv}(\phi-\phi_S) \propto f_{1T}^{\perp}(x) D_1(z)$$




For more details see talk by Luciano PAPPALARDO

$A_{siv}(K^+) > A_{siv}(\pi^+)$

Sea quarks may provide important contribution to Sivers function

# General Parton Distributions

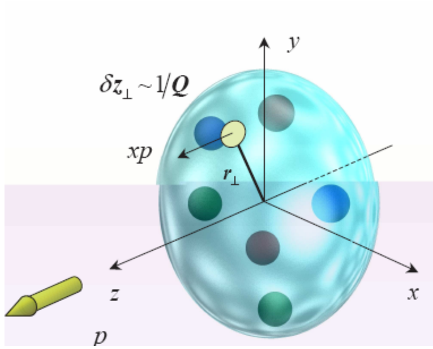
Quantum phase-space „tomography“ of the nucleon

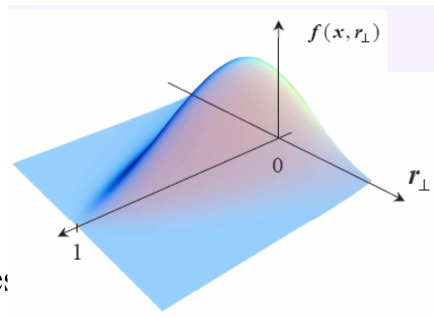

- Wigner introduced the first phase-space distribution in quantum mechanics (1932)

The Wigner function contains the *most complete (one-body) info* about a quantum system.

- A Wigner operator can be defined that describes quarks in the nucleon; The reduced Wigner distribution is related to GPDs

GPDs contain a *more complete info than* form factors or parton distributions



# Quarks in quantum mechanical phase-space

- Elastic form factors $\rightarrow$ charge distribution (space coordinates)
- Parton distributions $\rightarrow$ momentum distribution of quark (momentum space)
- Generalized parton distributions (GPDs) are reduced Wigner functions $\rightarrow$ correlation in phase-space $\rightarrow$ e.g. the orbital momentum of quarks:

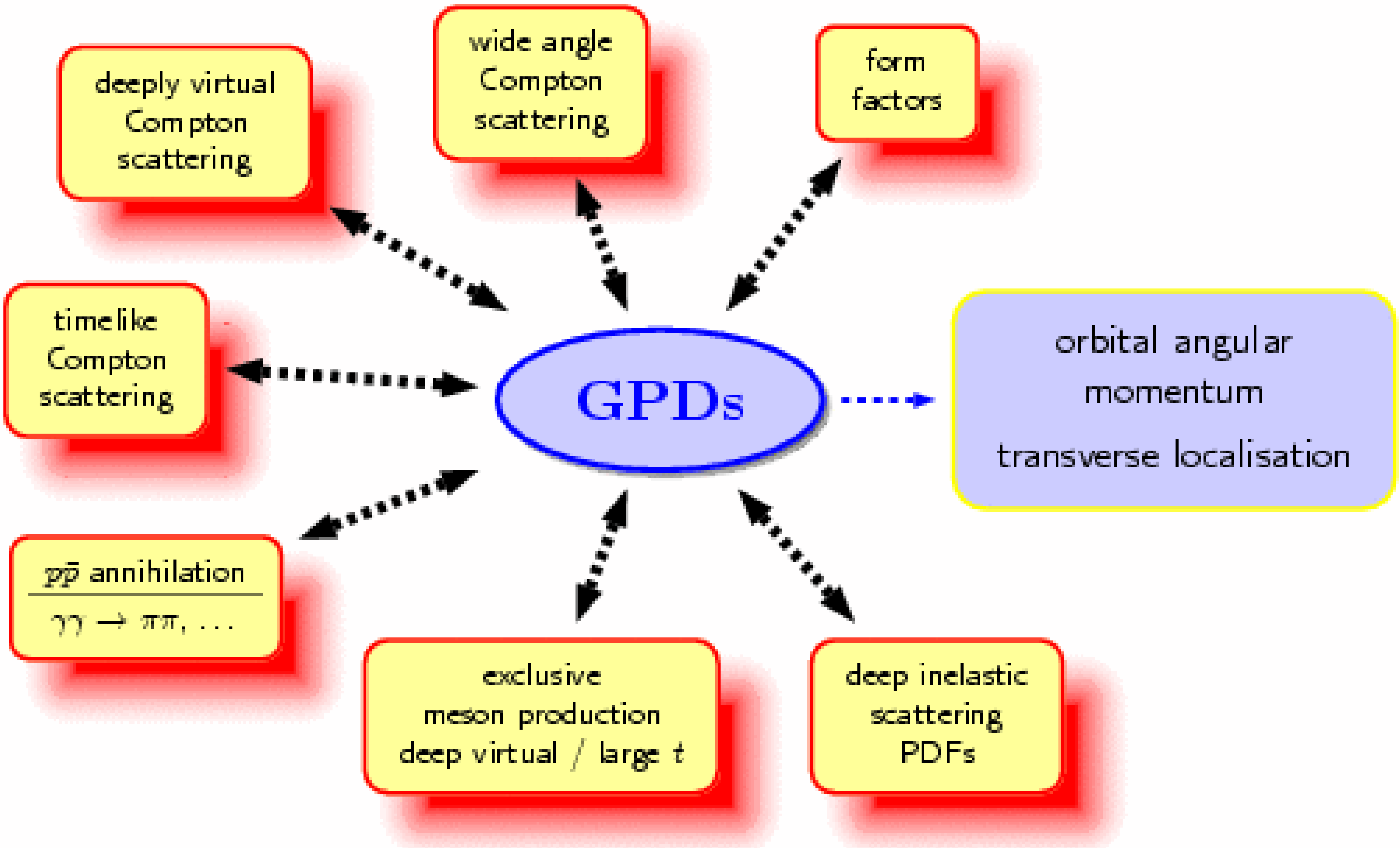
$$L = r \times p$$

- Angular momentum of quarks can be extracted from GPDs:

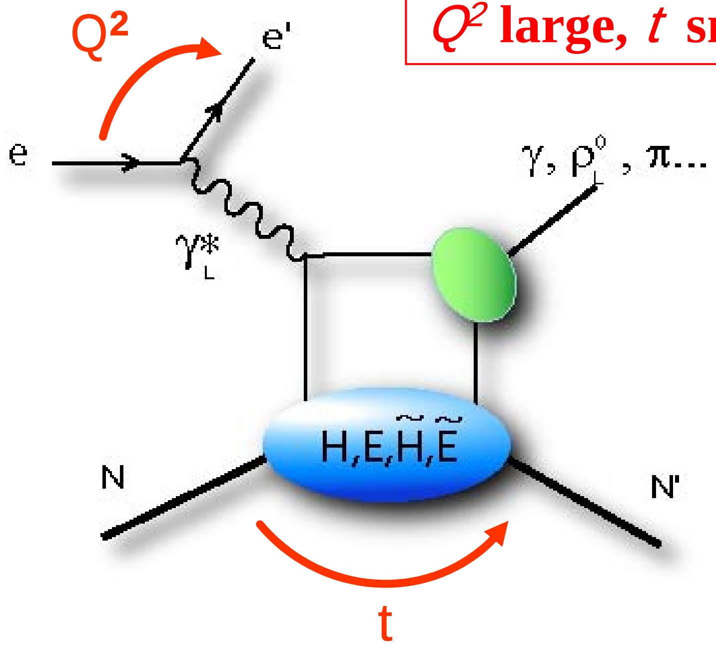
Ji sum rule:

$$J_q = \tfrac{1}{2}\int_{-1}^{1} x dx \left[H_q(x,\xi,0) + E_q(x,\xi,0)\right]$$

- GPDs provide a unified theoretical framework for many experimental processes


deeply virtual
Compton
scattering
wide angle
Compton
scattering
form
factors
timelike
Compton
scattering
GPDs
orbital angular
momentum
transverse localisation
$p\bar{p}$ annihilation
$\gamma\gamma \rightarrow \pi\pi$, ...
exclusive
meson production
deep virtual / large $t$
deep inelastic
scattering
PDFs

# Exclusive processes: The handbag diagram




**$Q^2$ large, $t$ small**

- high $Q^2$ ← hard regime
- high luminosity ← $\sigma \sim 1/Q^4$, $1/Q^6$
- high resolution ← exclusivity

⟶ Quantum number of final state selects different GPDs:

Vector mesons (ρ, ω, φ): H E

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

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

→ polarization provides new observables sensitive to different (combinations of) GPDs

# Deeply Virtual Compton Scattering (DVCS)

$\overleftrightarrow{e} p \rightarrow e' p' \gamma$

*Beam Spin Asymmetry*

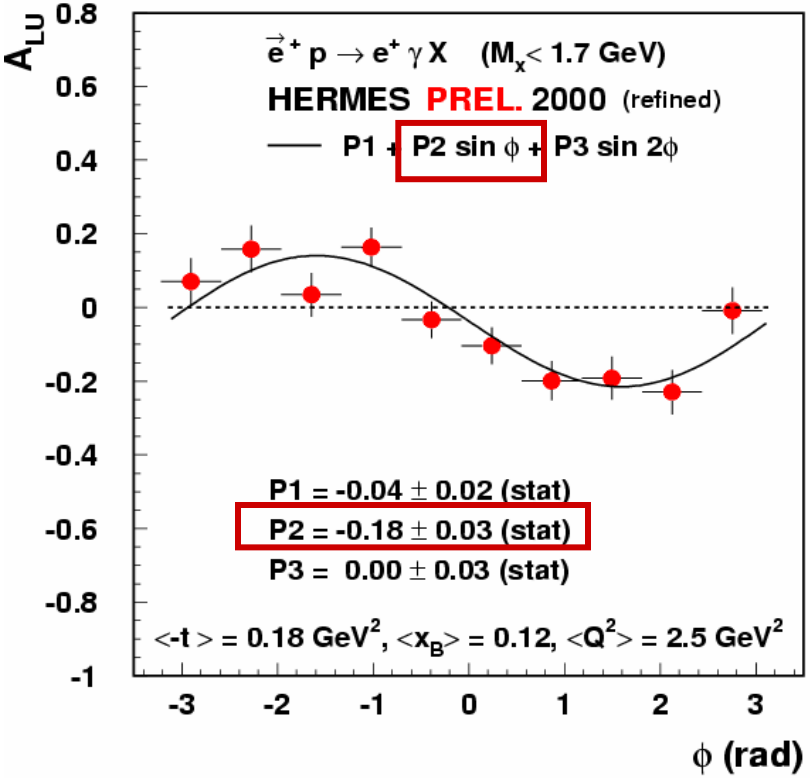
$\sigma \propto \sin\phi \times \ldots$

only at HERA $e^{+/-} p \rightarrow e' p' \gamma$

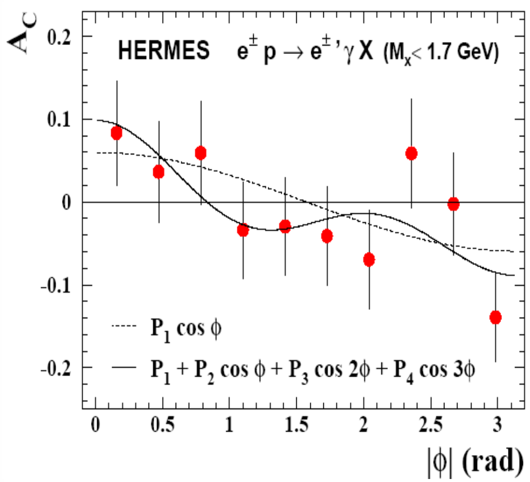
*Beam Charge Asymmetry*

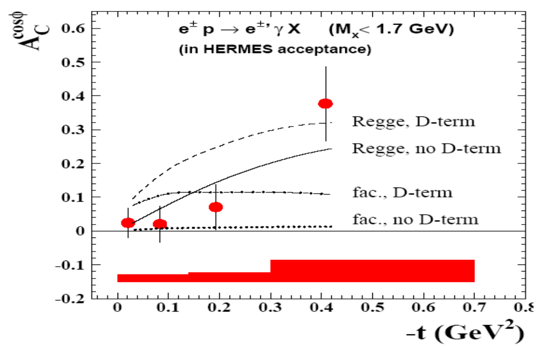
$\sigma \propto \cos\phi \times \ldots$

[PRL87(2001)] **+100 top cite**

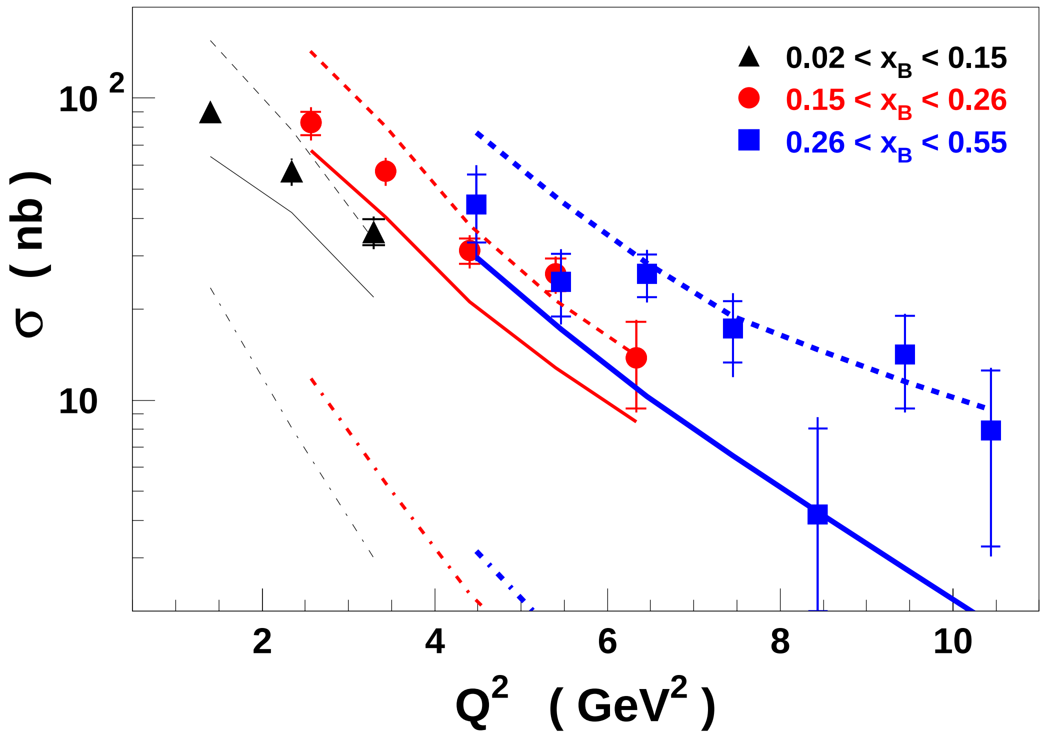



[PRD 75 (2007)]



# Hard exclusive meson production
# e p → e' n $\pi^+$




[hep-ex/0405078,

arXiv 07070222 PLB submitted]

## GPDs predictions:

- Vanderhaeghen, Guichon & Guidal [PRD 60 (1999)]
(LO and LO+ power corrections)

## Model calculation:

- Regge formalism, Laget [PRD 70 (2004)]

- LO predictions + *power correction* to *space like pion form factor* in agreement with magnitude of data
- Regge formalism for long. and transv. part of the cross section provides good description of dependence of data



→ Information on *pion form factor* at high $Q^2$ and on polarised GPDs

# Quark total angular momentum

$A_{UT}$ most sensitive observable to access $J_q$ via GPDs

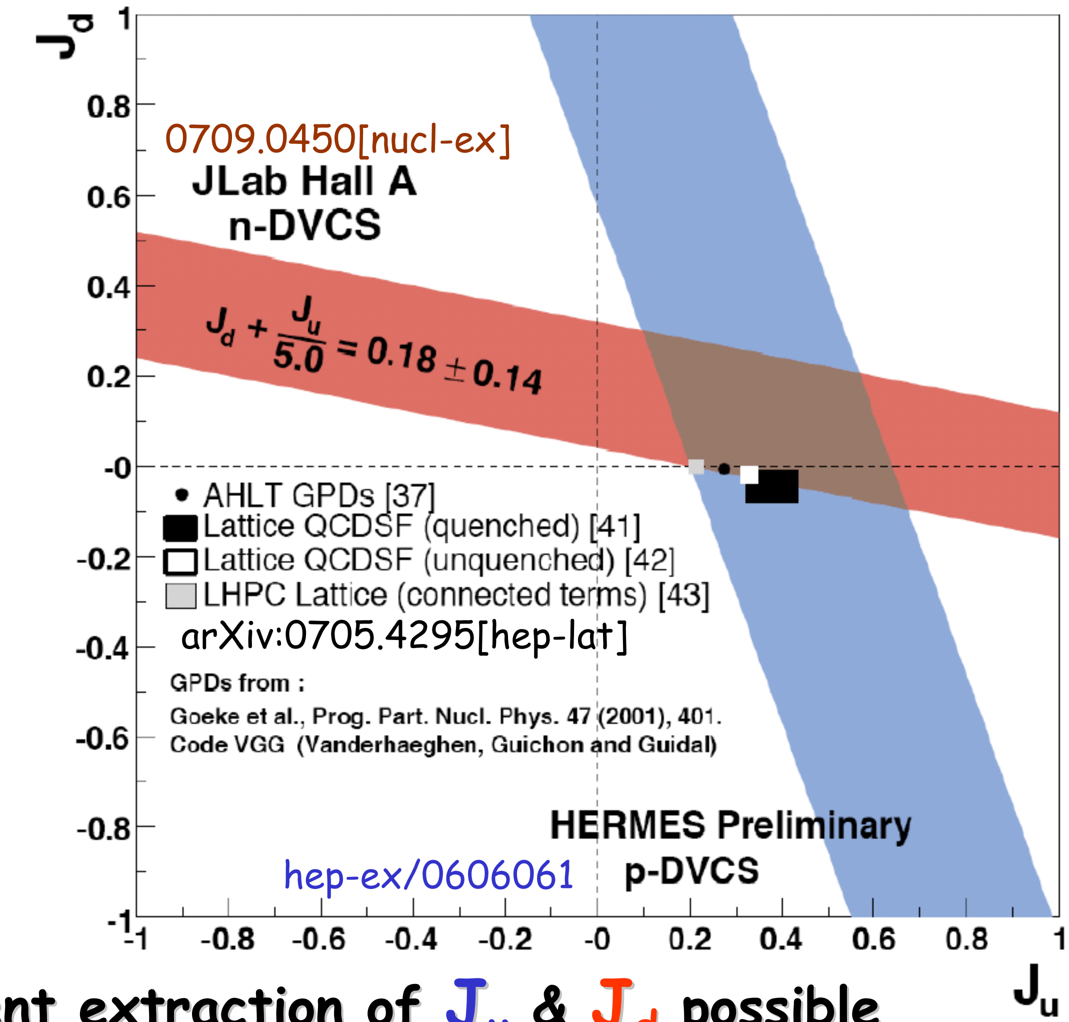
<u>HERMES data 2002-04:</u>

- U: unpolarized beam
- T: transv. pol. Target
- ~50% of total stat.

$$\propto \mathrm{Im}[F_2 H - F_1 E]$$

GPD model by:

[Goeke et al. (2001)]
[Ellinghaus et al. (2005)]

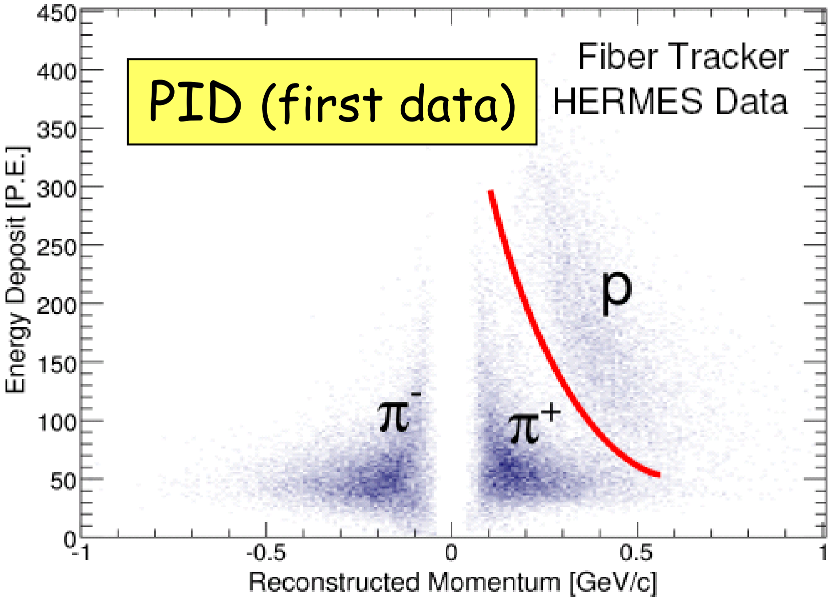



➡ **first model dependent extraction of $J_u$ & $J_d$ possible**
**VGG-Code: GPD-model: LO/Regge/D-term=0**

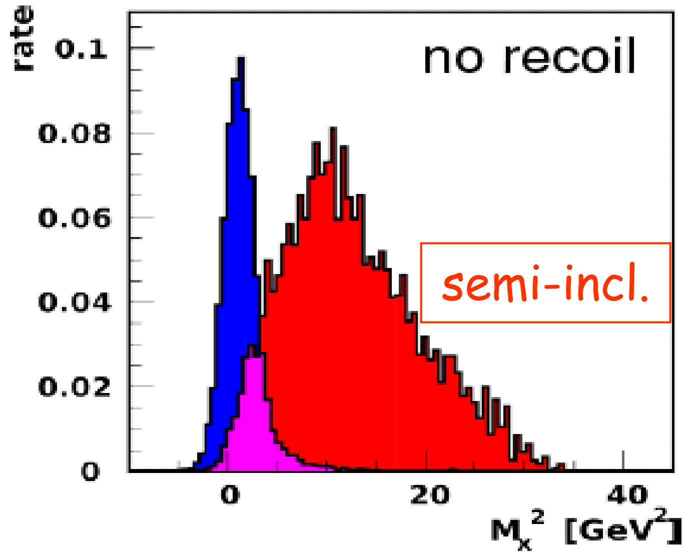
# The HERMES recoil detector (2006-07)

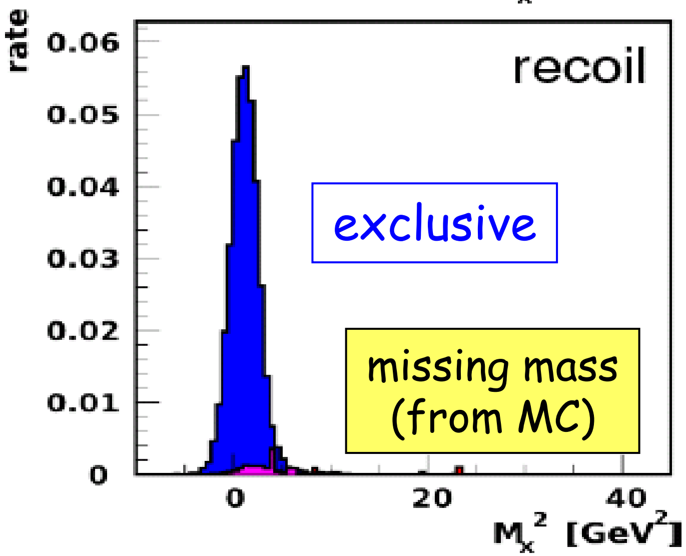
- Installed Dec 05, commissioned and successfully operated
- Dedicated to exclusive processes:
  - Recoil proton detection
  - High luminosity:

2006: 7 M DIS events e-
20 M DIS events e+
2007: 20 M DIS events e+




v. Giessen




For more details see talk by Tibor KERI

# Conclusions

- 1/3 of the proton spin comes from quark spin
- Direct measurements of the strange quark sea could not verify a negative strange polarization. This indicates a $SU(3)_f$ flavor symmetry breaking or large contributions from low x.
- Analysis of gluon spin from inclusive DIS is difficult and ongoing
- Transversity and Sivers functions are non-zero. Sivers asymmetry for kaon data indicates an orbital angular momentum contribution from sea quarks.
- DVCS beam charge and beam spin asymmetries have been measured. First data of orbital angular momentum (OAM) fits to GPD functions indicate non-zero OAM of up-quarks
- HERMES has the potential of further discoveries in spin physics with the new abundant recoil data!