# Transversity
# New Results from COMPASS

Christian Schill
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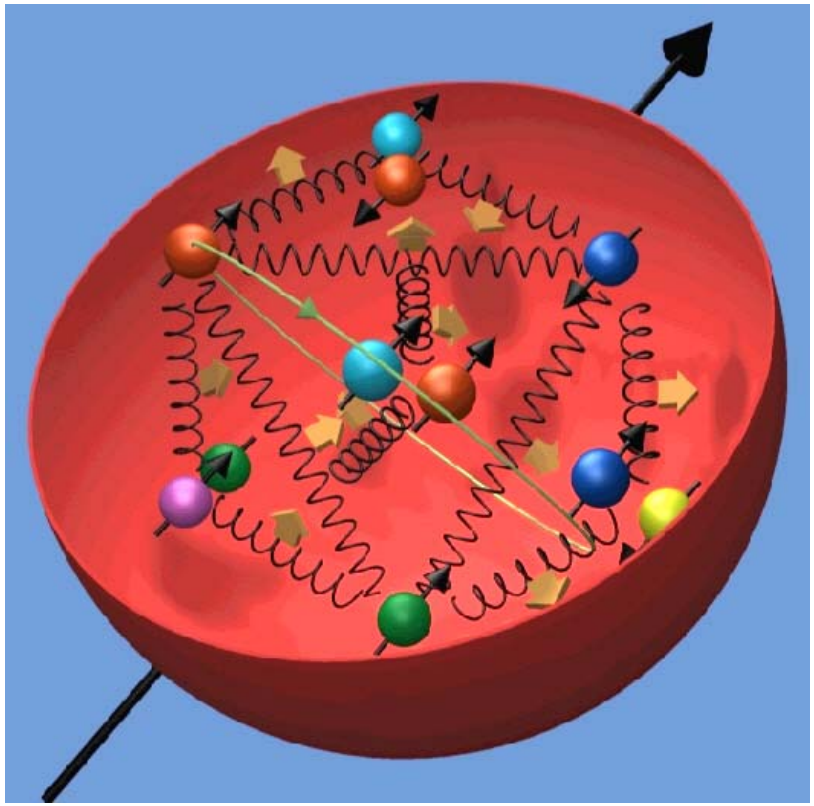
Graduiertenkolleg
Mainz, 7. Nov. 2007

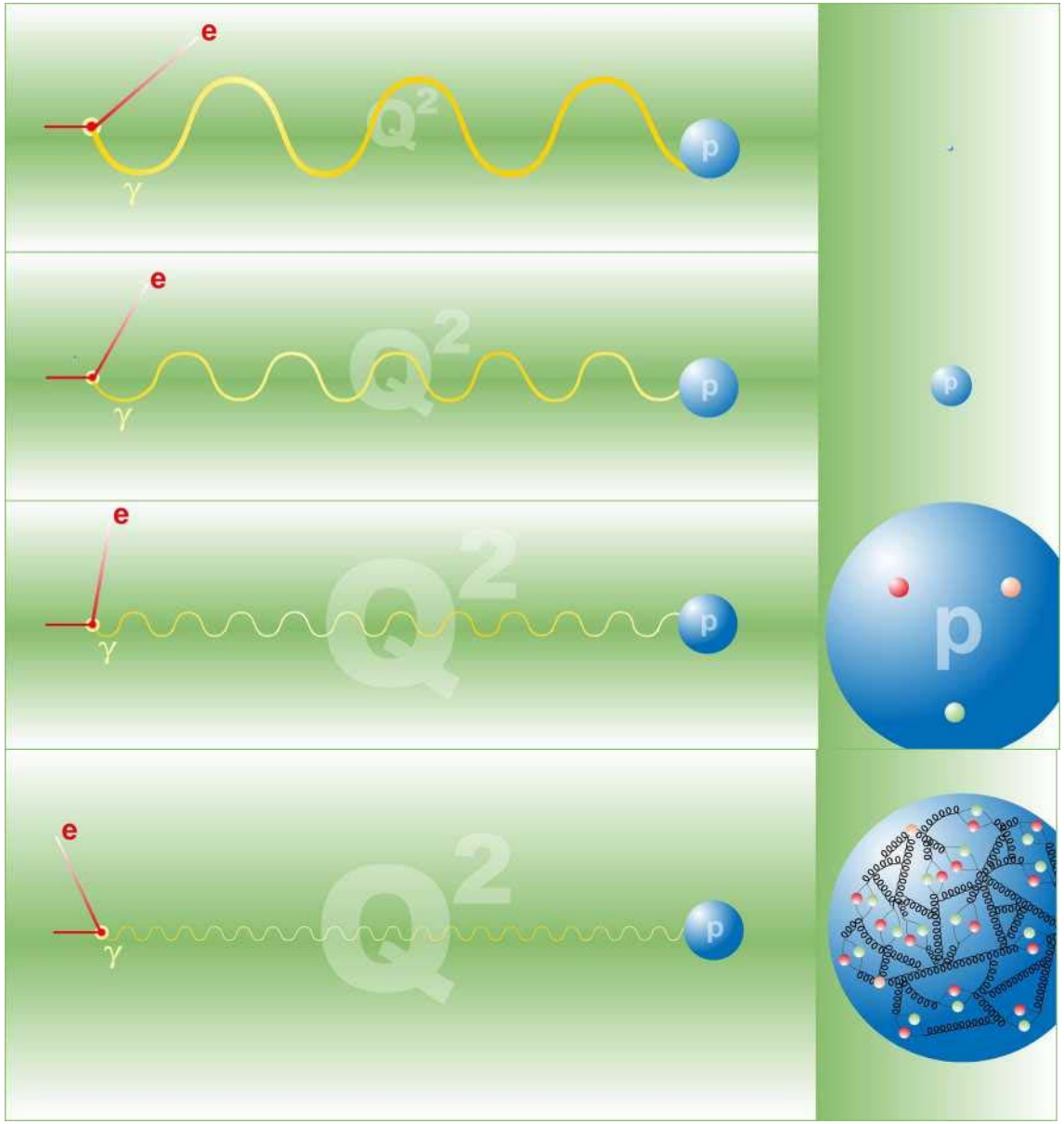


# Contents

- Introduction: Spin Structure of the Nucleon
- The COMPASS experiment
- COMPASS results on asymmetries
  - Transversity distribution function
  - Sivers distribution function
  - Other TMD distribution functions
- Conclusions

# Deep-Inelastic Scattering

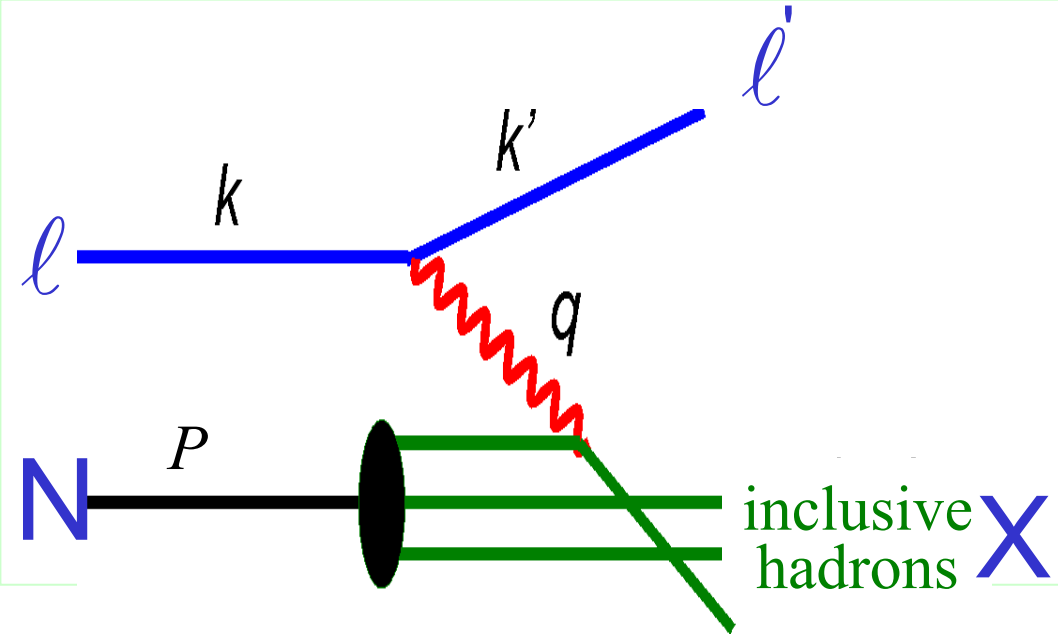
***Q² = negative transferred four-momentum squared***




- *Investigation of the proton structure*
- 1955 Hofstadter: Radius 0,8 fm Nobel Prize 1961
- 1968 Friedman, Kendall, Taylor: Quarks in the proton Nobel Prize 1990
- DESY: highest Q²
  - Quarks and gluons are the elementary constituents

$$\lambda\!\!\!^{-} = \hbar / p \approx 10^{-18}\ \mathrm{m}$$

# Deep-Inelastic Scattering




$$Q^2 = -q^2 = -(k - k')^2$$

$$\nu = E - E'$$

$$x = Q^2 / 2M\nu$$

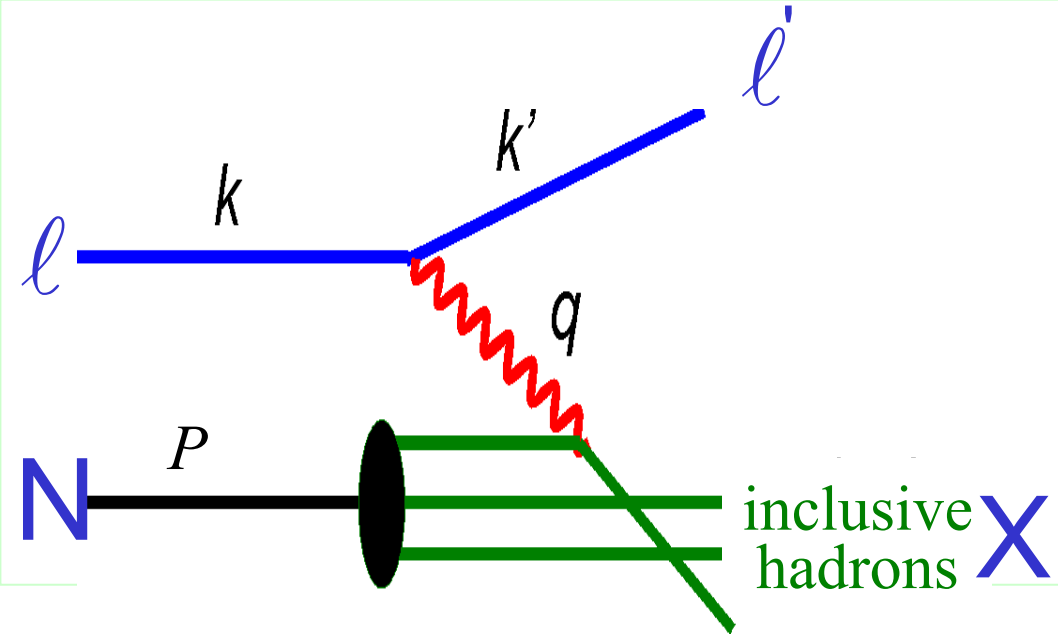
$$y = \nu / E$$

**semi-inclusive scattering:**
**detection of final hadrons**

$$z = E_h / \nu$$

***y = relative energy loss of scattered lepton***
***$Q^2$ = negative four-momentum transfer squared***
***x = Momentum fraction of the proton carried by the quark***

# Cross-Section in Deep-Inelastic Scattering




$Q^2 = -q^2 = -(k - k')^2$

$\nu = E - E'$

$x = Q^2 / 2M\nu$

$y = \nu / E$

$$\frac{d^2\sigma}{dx\, dQ^2} = \frac{4\pi\alpha^2}{Q^4 x}\left[ xy^2 F_1(x,Q^2) + (1-y) F_2(x,Q^2) \right]$$

***y = relative energy loss of scattered lepton***
***Q² = negative four-momentum transfer squared***
***x = Momentum fraction of the proton carried by the quark***

# Structure functions

$$F_1(x) = \tfrac{1}{2}\sum_f e_f^2 q_f(x)$$

partons are point-like particles

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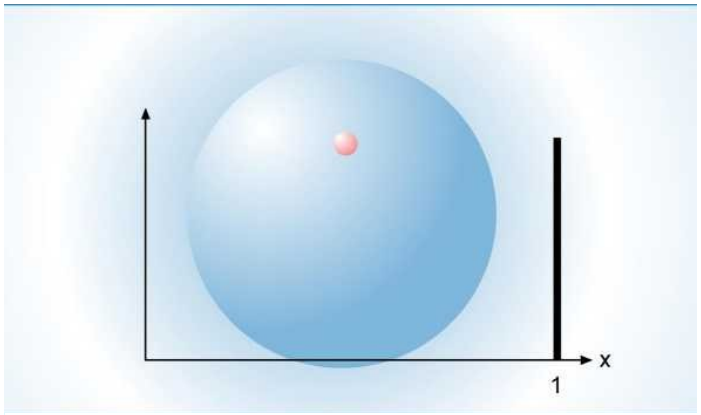


parton carries
all momentum

***x = Fraction of momentum carried by the parton***

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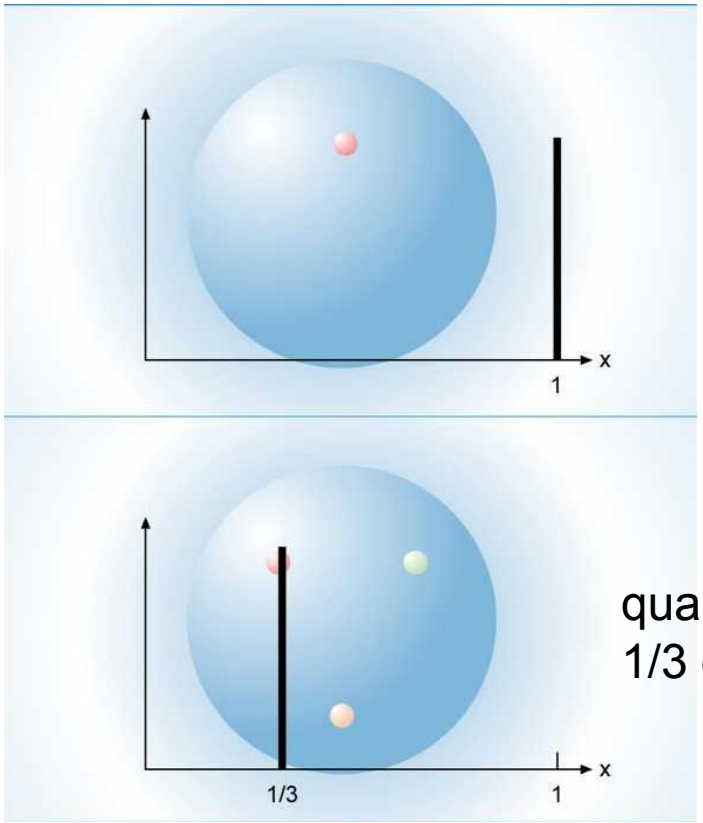


parton carries
all momentum

quark carries
1/3 of momentum

***x = Fraction of momentum carried by the parton***

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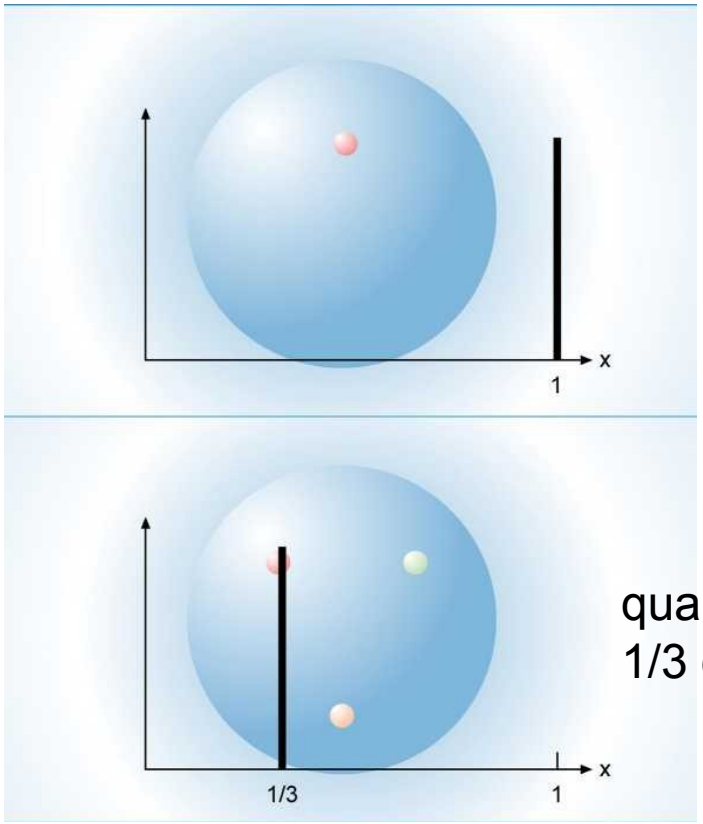


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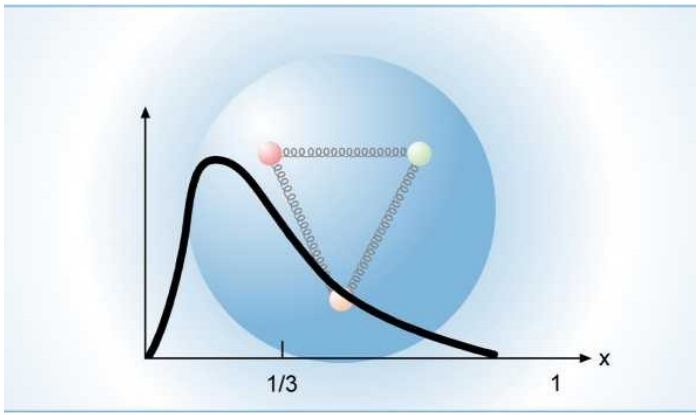


gluons
reduce quark
momentum
contribution

***x = Fraction of momentum carried by the parton***

# Structure functions

$$F_1(x) = \tfrac{1}{2}\sum_f e_f^2 q_f(x)$$

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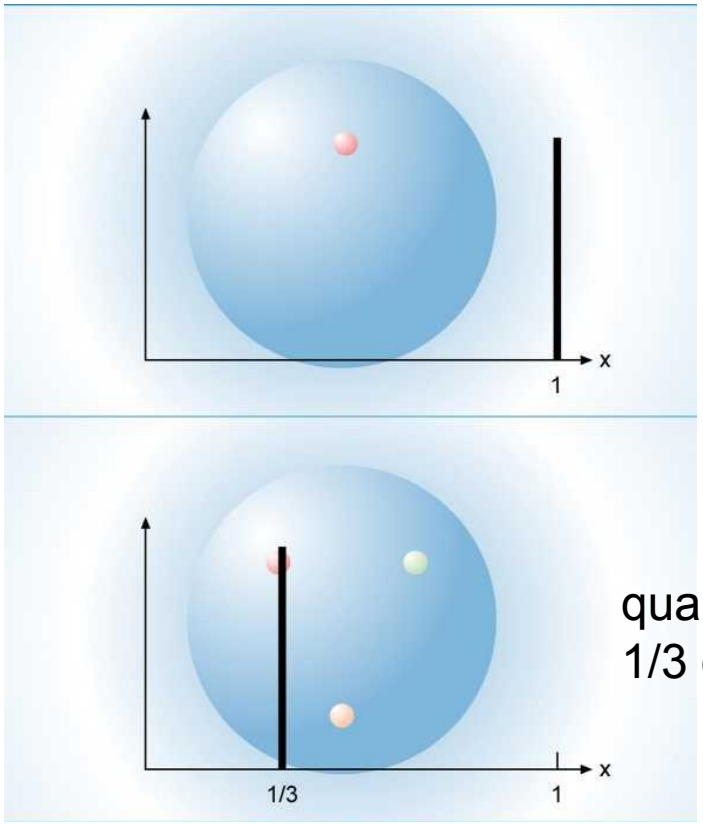


parton carries
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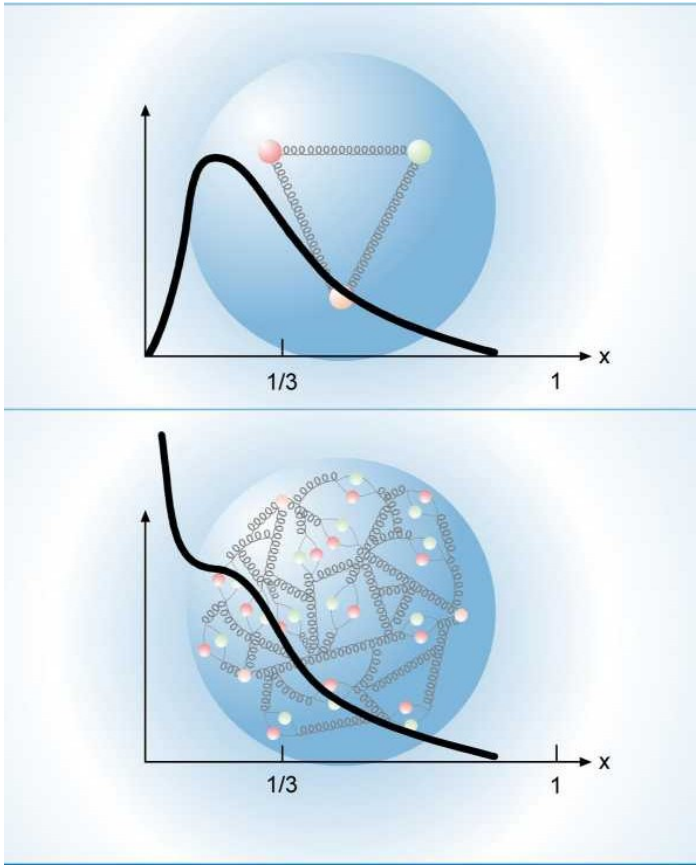
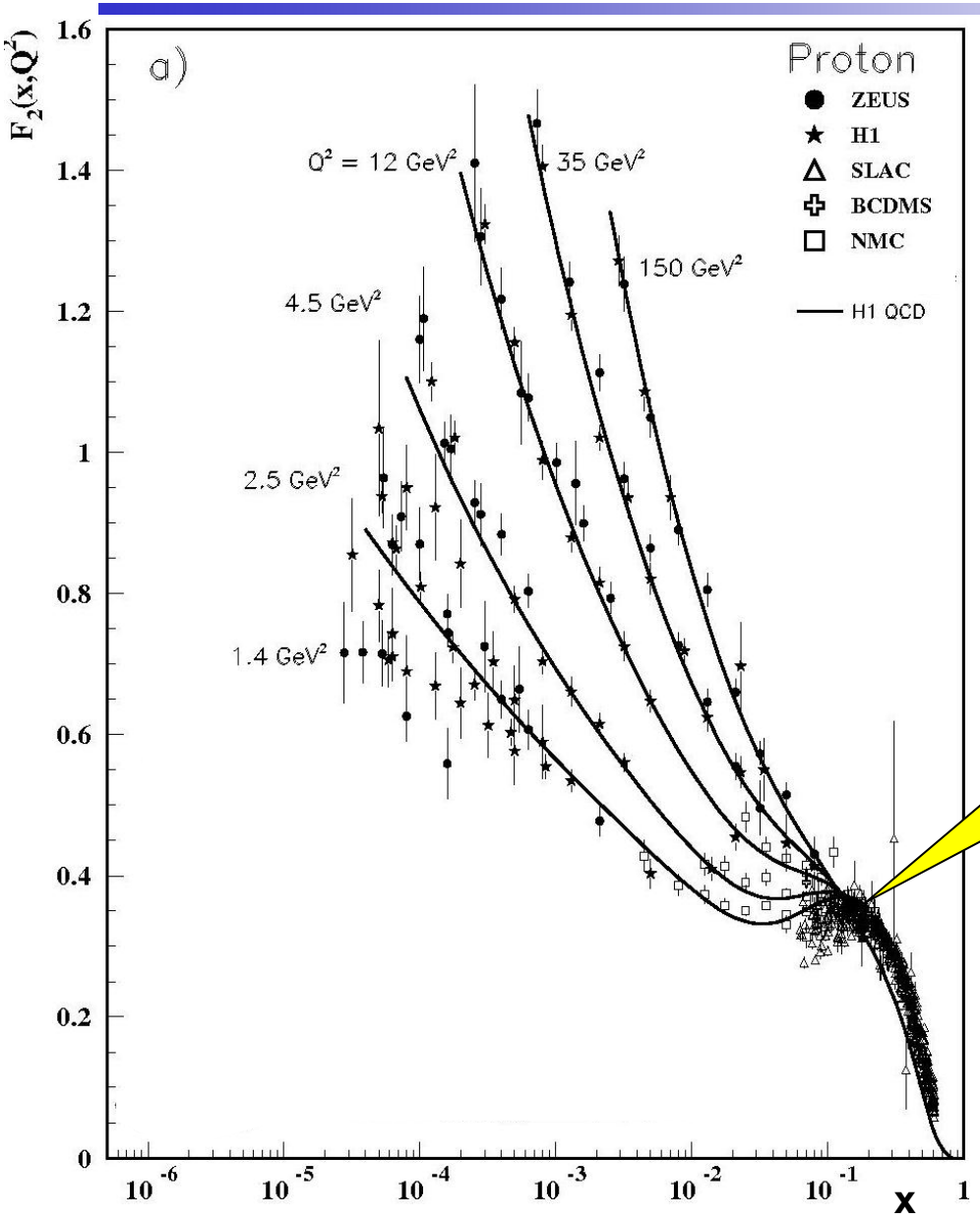



with sea-quarks

***x = Fraction of momentum carried by the parton***

# Structure functions




$$F_2(x,Q^2) = 2x\,F_1(x,Q^2)$$

**scattering on spin ½ particles**

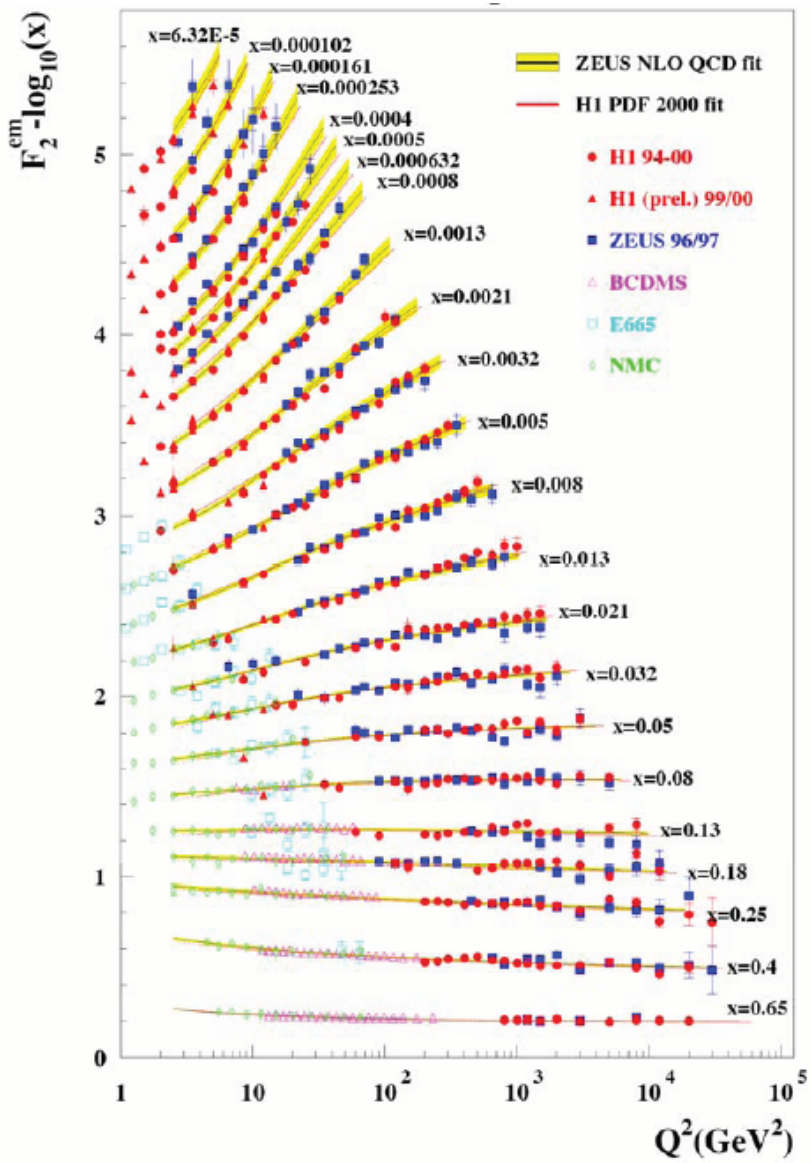
**Scale invariance scattering on point-like objects**

- larger $Q^2$
  - better Resolution
  - more Gluons and see-quarks
- $Q^2$ dependence is described by QCD

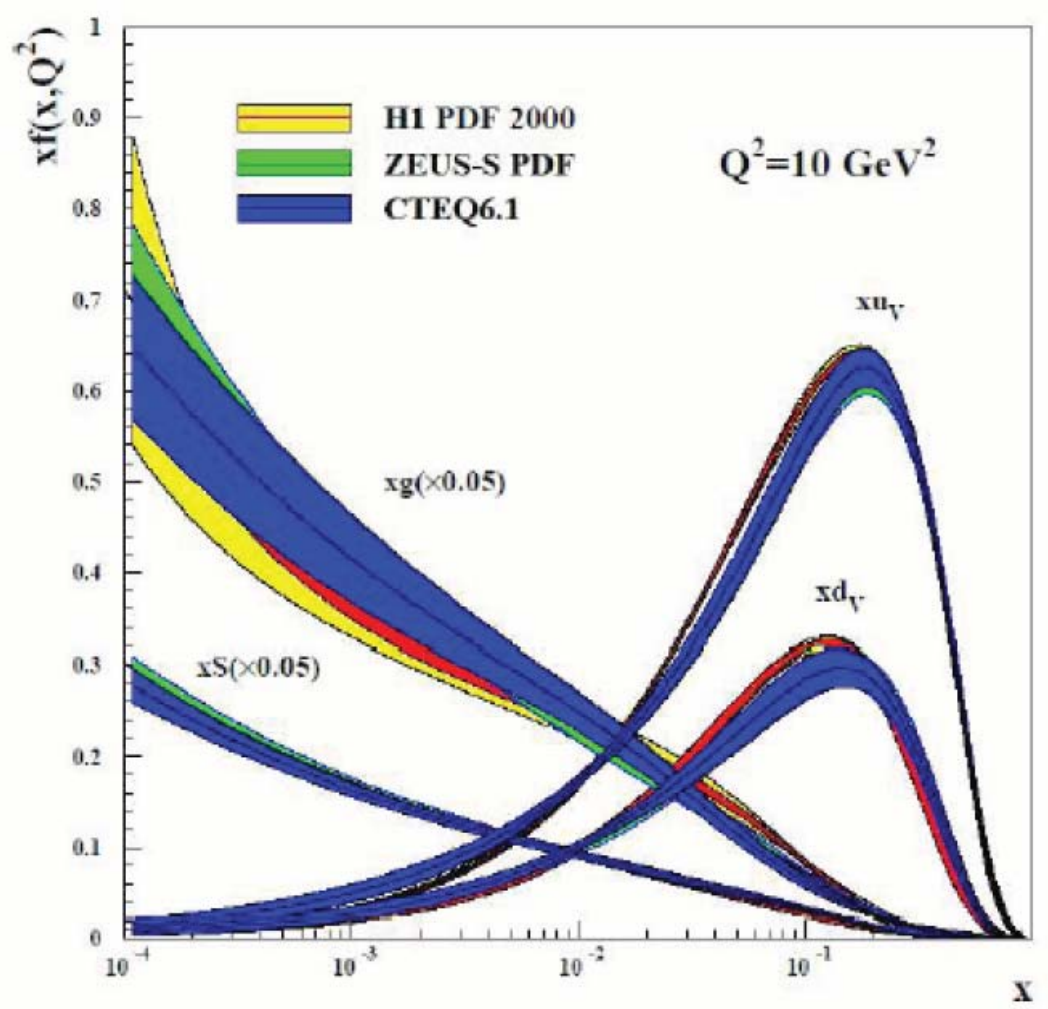
# Parton Distribution Functions

Parton model:

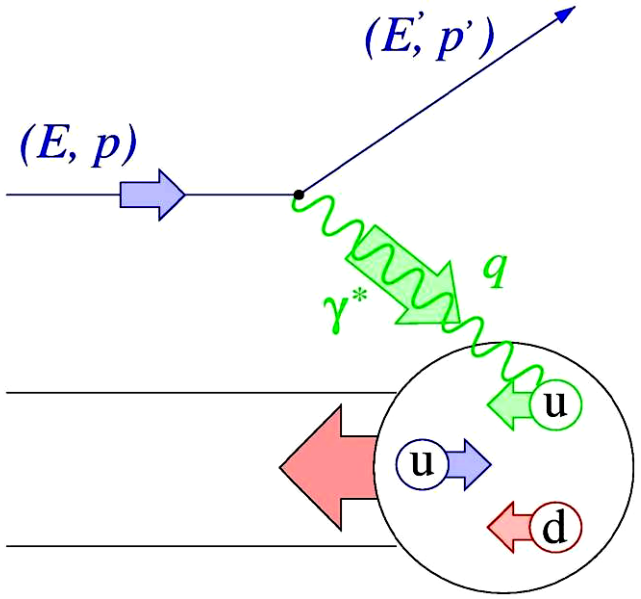
$$F_1^p(x,Q^2) = 1/2 \sum_{i=q,\bar{q}} e_i^2 q(x,Q^2)$$




Parton Distribution Functions:



# Polarized Deep Inelastic Scattering




Experimental Asymmetry:

$$A_1(x) = \frac{\sigma^{1/2} - \sigma^{3/2}}{\sigma^{1/2} + \sigma^{3/2}} \approx \frac{g_1(x)}{F_1(x)}$$

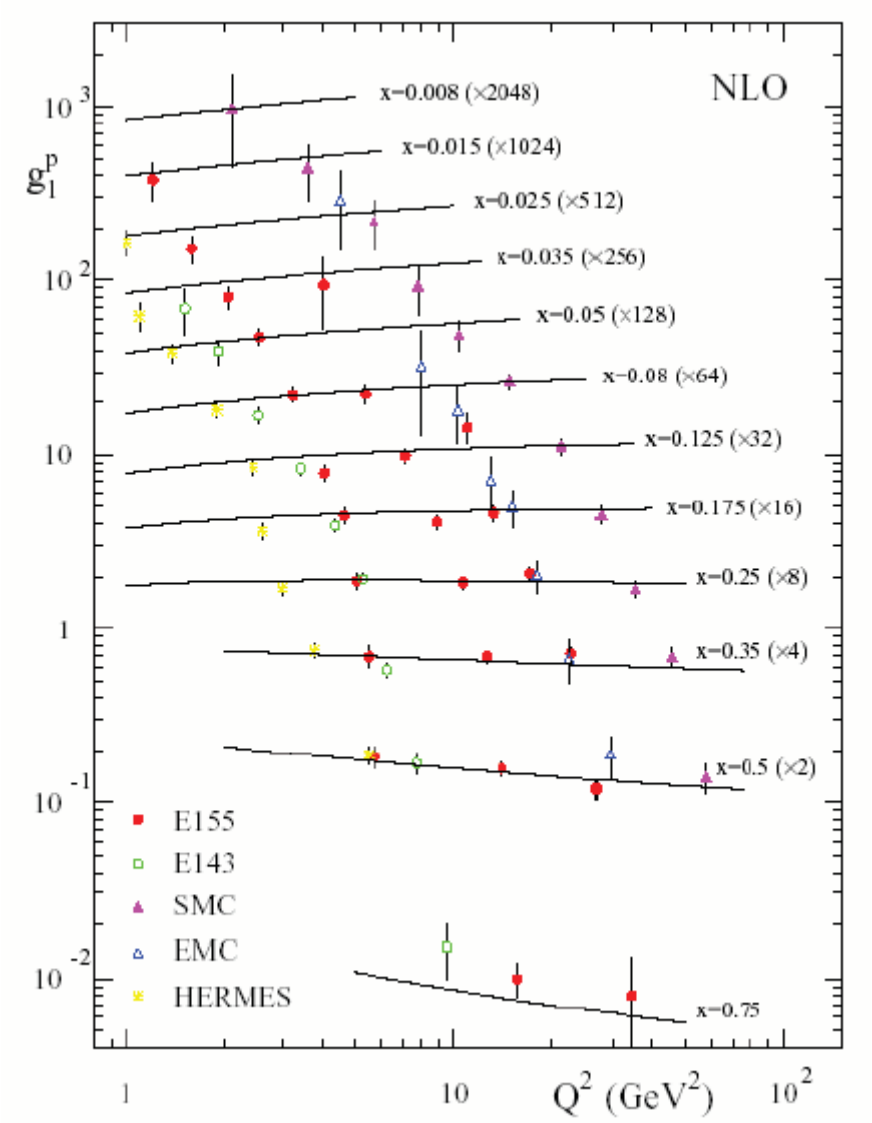
$$g_1(x) = \frac{1}{2} \sum_i e_i^2 \Delta q_i(x)$$

$g_1$: Spin structure function

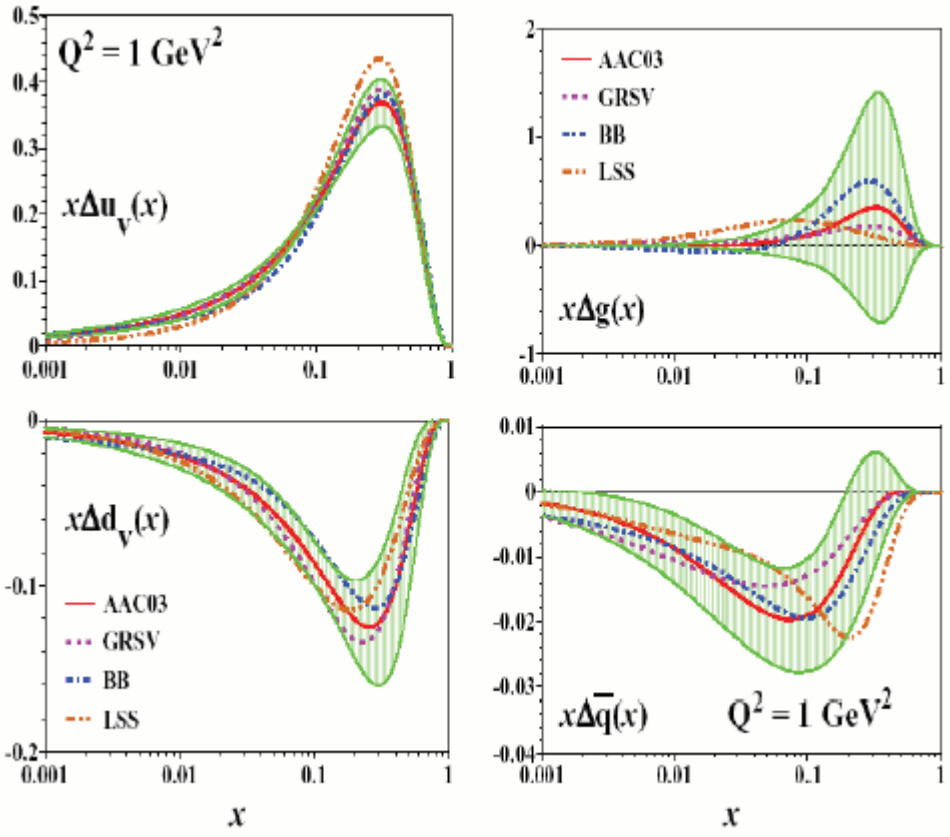
$\Delta q_i$: Polarized parton distribution function

# Polarized Parton Distribution Functions

Parton model: $g_1^p(x,Q^2) = 1/2 \sum e_i^2 \Delta q(x,Q^2)$




**Asymmetry Analysis Collaboration,**
**M. Hirai, S. Kumano and N. Saito, PRD (2004)**

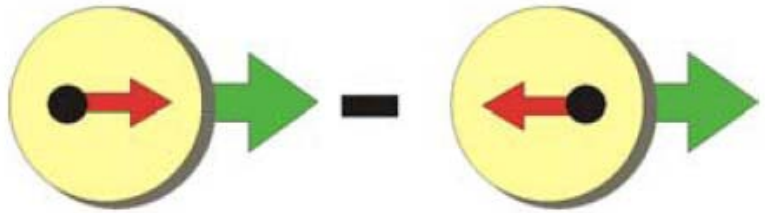


# Transverse Spin Physics

At leading order, the inner structure of the nucleon can be described with three **Parton Distribution Functions:**

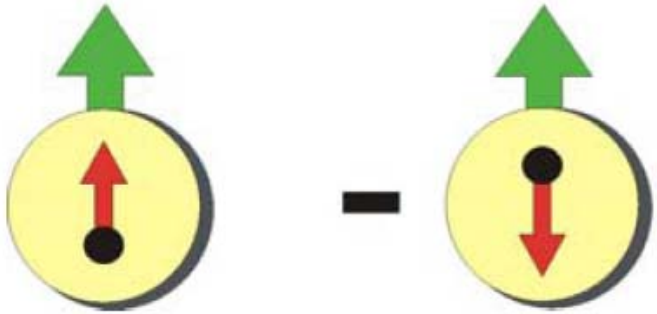
**q(x) Momentum distribution**

**Well known – Unpolarized DIS**



**Δq(x) Helicity distribution**

**known – Polarized DIS**

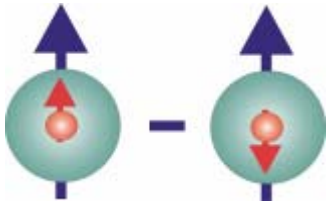


**$\Delta_T$q(x) Transversity distribution**

**Largely unknown**

# Transversity Distribution Function

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



$q=u_v, d_v, q_{sea}$

**quark** with **spin** parallel to the nucleon spin in a transversely polarized nucleon

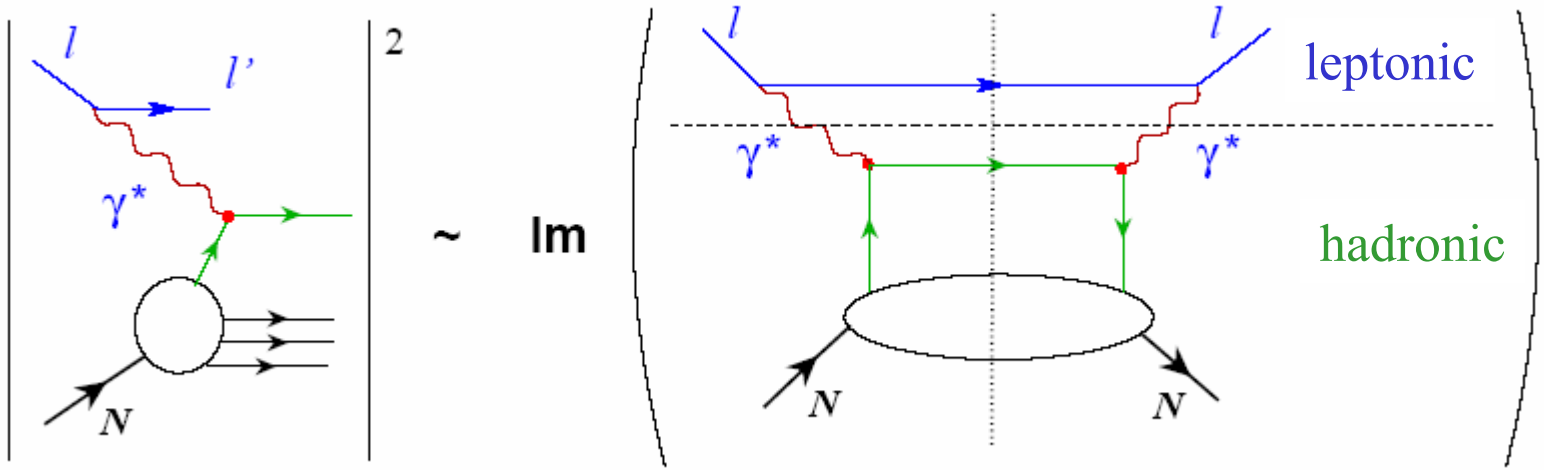
**Properties:**

- **probes the relativistic nature of quark dynamics**
- **positivity (Soffer) bound** $\Delta_T q \leq \frac{1}{2}[q + \Delta q]$
- **sum rule for transverse spin** $\frac{1}{2} = \frac{1}{2}\sum \Delta_T q + L_q + L_g$

*Bakker, Leader, Trueman, PRD 70 (04)*

# How to Measure Transversity?

Optical theorem:




Cross-section of inclusive deep-inelastic scattering:

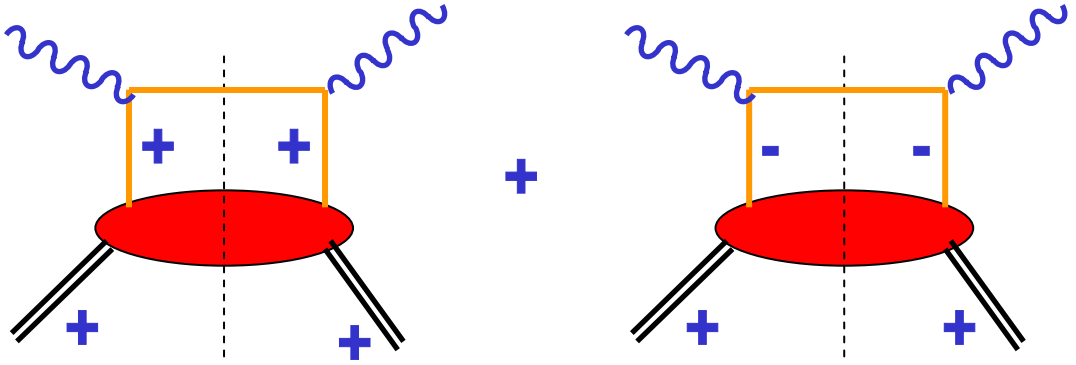
$\gamma^* + N \rightarrow X$

Imaginary part of amplitude of forward Compton scattering:

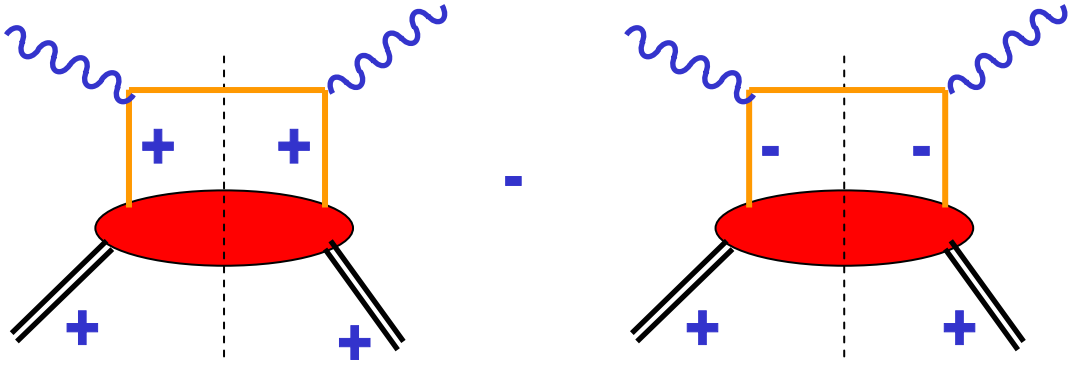
$\gamma^* + N \rightarrow \gamma^* + N$

# Structure Functions in Forward Compton Picture

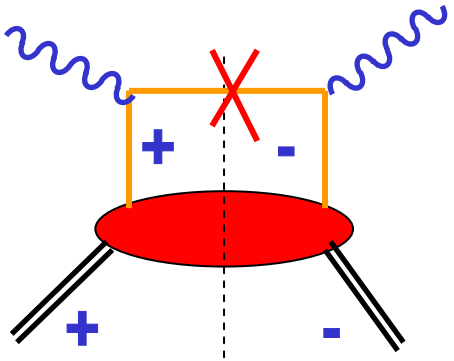
$F_1(x) \sim$




$g_1(x) \sim$



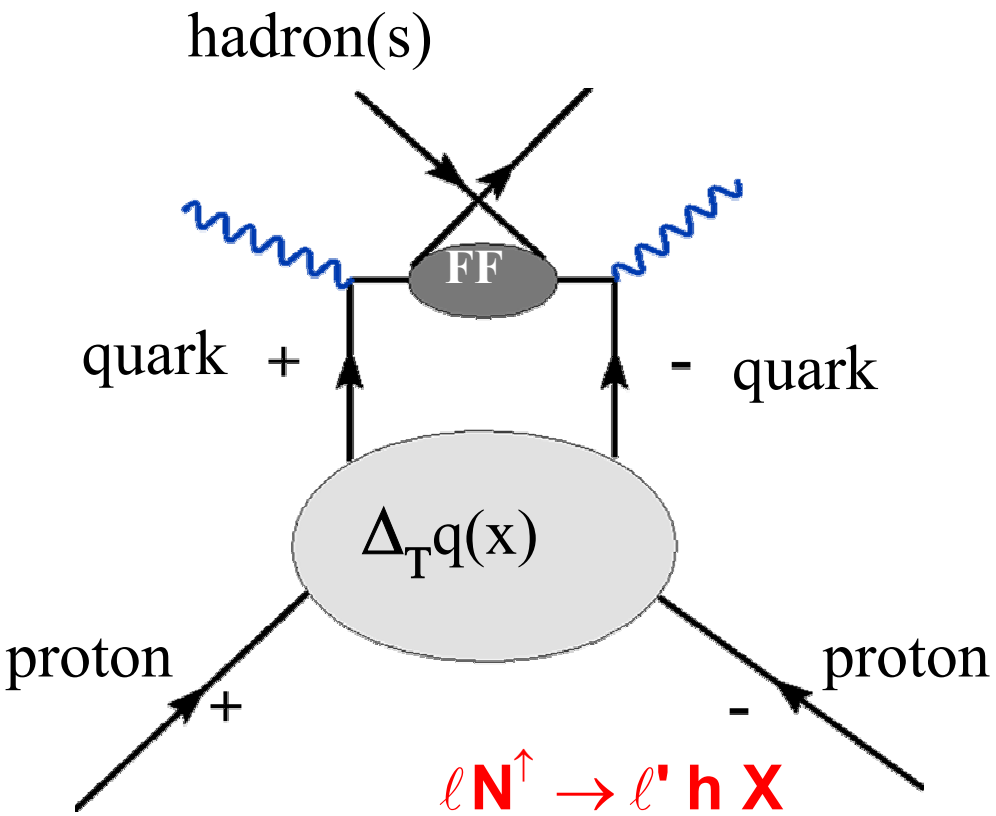

$\Delta_T q(x) \sim$




not possible in inclusive deep-inelastic scattering because of quark helicity flip

# Measuring Transversity

**Only in Semi-inclusive deep-inelastic scattering**




Fragmentation process into hadrons responsible for quark spin flip

**Measured in COMPASS**

# Measuring Transversity

**Can be measured in semi-inclusive deep-inelastic scattering on a transversely polarized target via "quark polarimetry":**

$\ell\, N^{\uparrow} \to \ell'\, h\, X$ — **"Collins" asymmetry**

**"Collins" Fragmentation Function**

$\ell\, N^{\uparrow} \to \ell'\, h\, h\, X$ — **Two-hadron asymmetry**

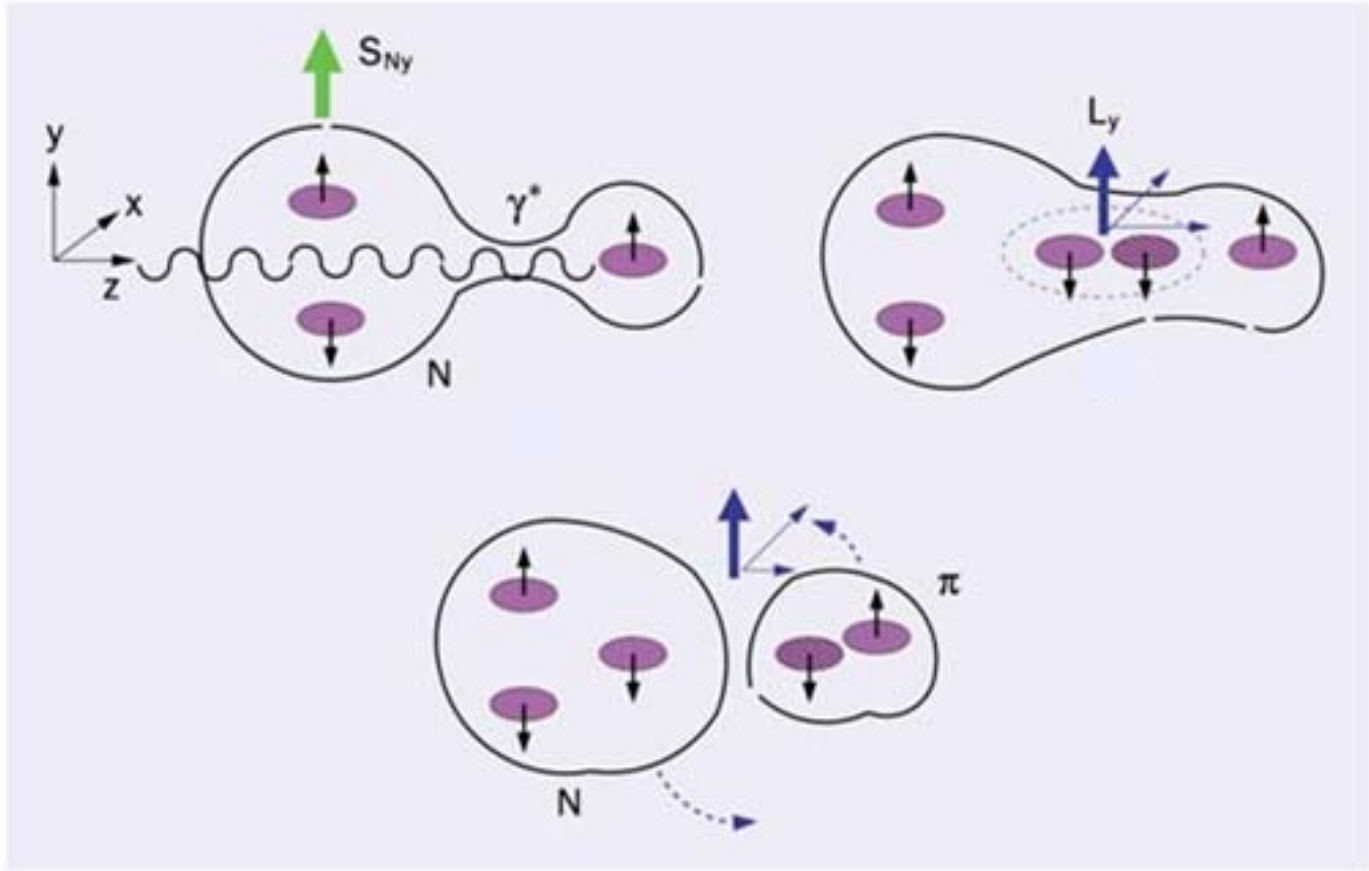
**"Interference" Fragmentation Function**

$\ell\, N^{\uparrow} \to \ell'\, \Lambda\, X$ — **Λ polarization**

**Fragmentation Function of $q^{\uparrow} \to \Lambda$**

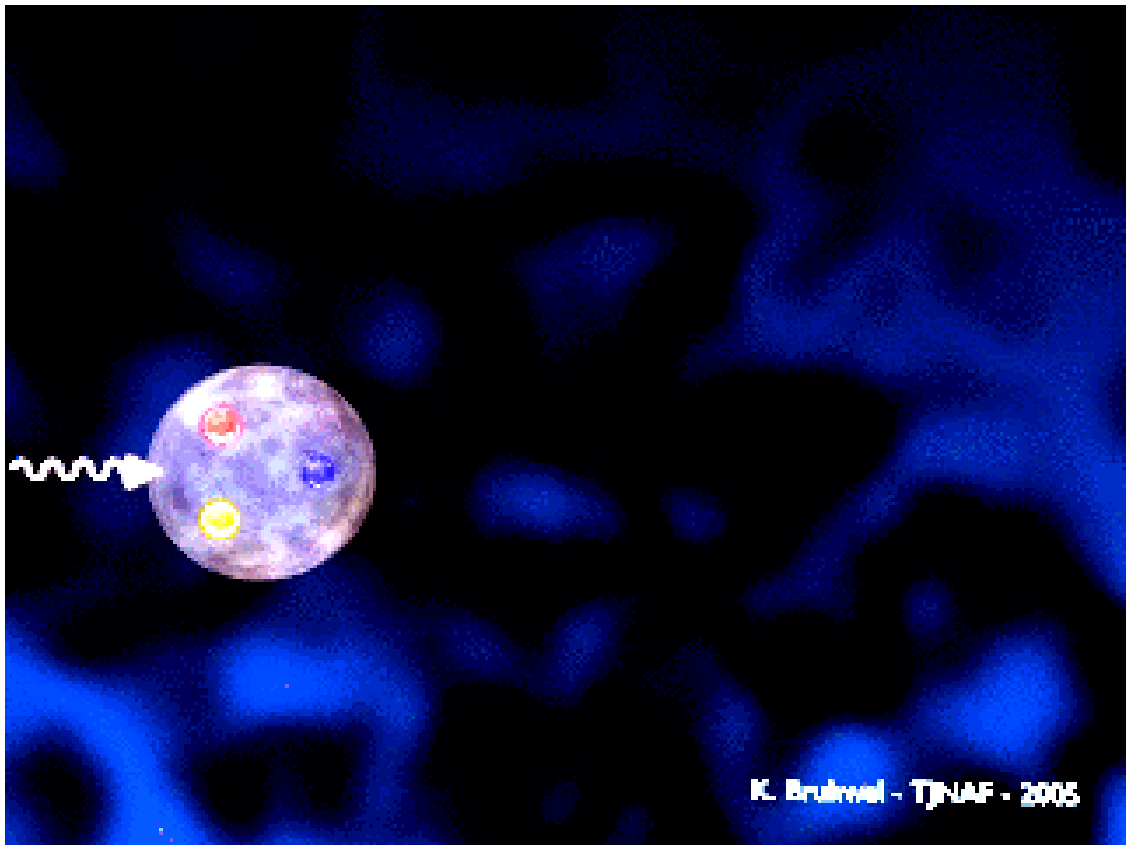
# Collins Fragmentation - Model

http://cerncourier.com/main/article/44/8/19/1




Collins Effect in String Fragmentation
(X. Artru)

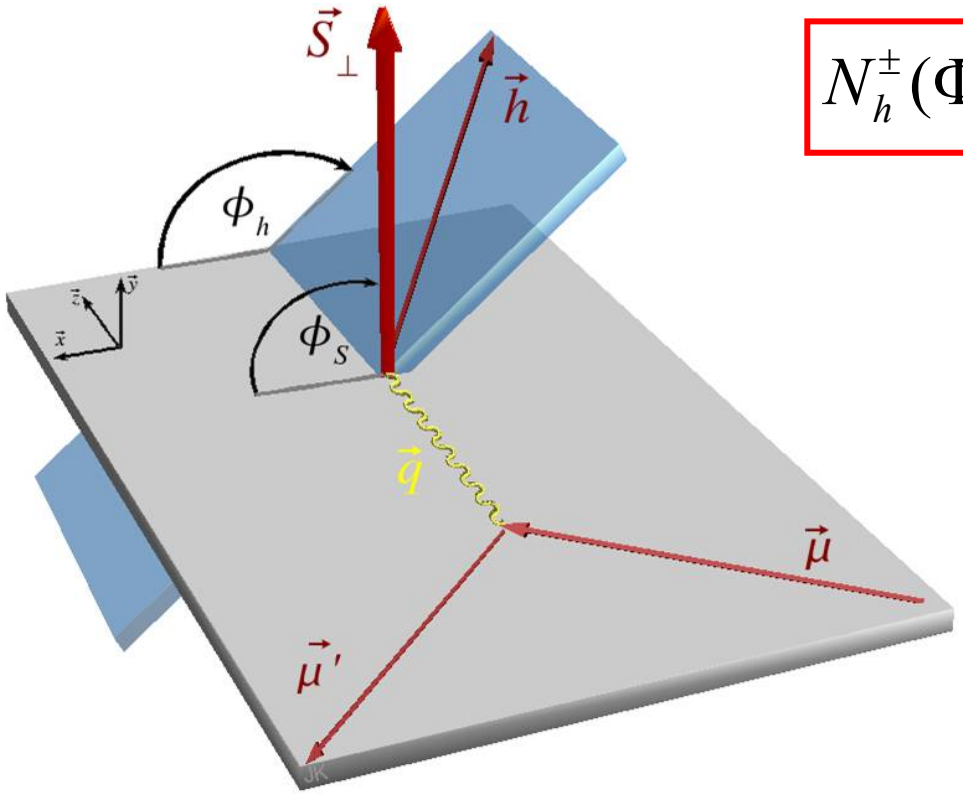
# Collins Fragmentation - Model



# Collins Asymmetry

SIDIS on a transversely polarized target: $l\,N^{\uparrow} \rightarrow l'h\,X$

Fragmentation of a transversely polarized quark into hadrons
→ azimuthal asymmetry:




$$N_h^{\pm}(\Phi_{Coll}) = N_h^0 \cdot \left[1 \pm A_C^h \cdot \sin\Phi_{Coll}\right]$$

The Collins angle $\Phi_{Coll}$ is defined as:

$$\Phi_{Coll} = \phi_h + \phi_S - \pi$$

# Collins Asymmetry

The measured asymmetry $A_{Coll}$ gives access to the transversity distribution times the Collins fragmentation function:

$$A_{Coll} = \frac{A_C^h}{f\ P_T\ D_{nn}} = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h}$$

f: Dilution factor

$D_{nn}$: Depolarization factor

$D_{nn}=2(1-y)/(1+(1-y)^2)$

$P_T$: Target polarization

$\Delta_T q(x)$: Transversity distribution

$\Delta_T^0 D_q^h$: Collins fragmentation function (measured in $e^+e^-$ at BELLE)

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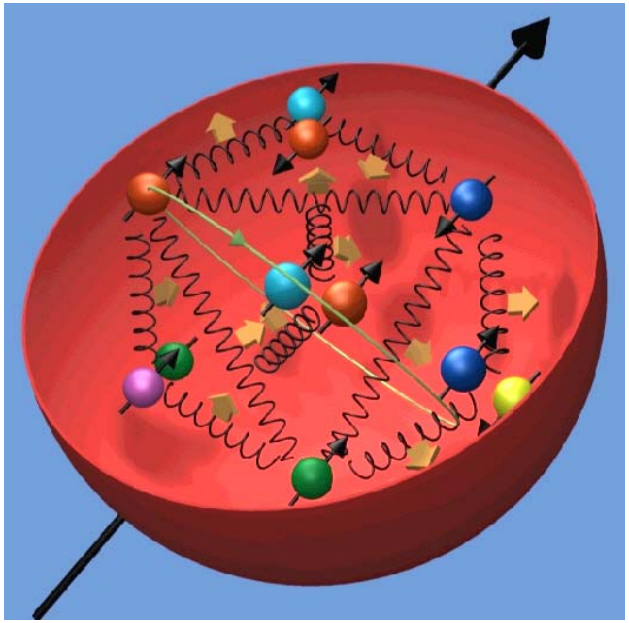
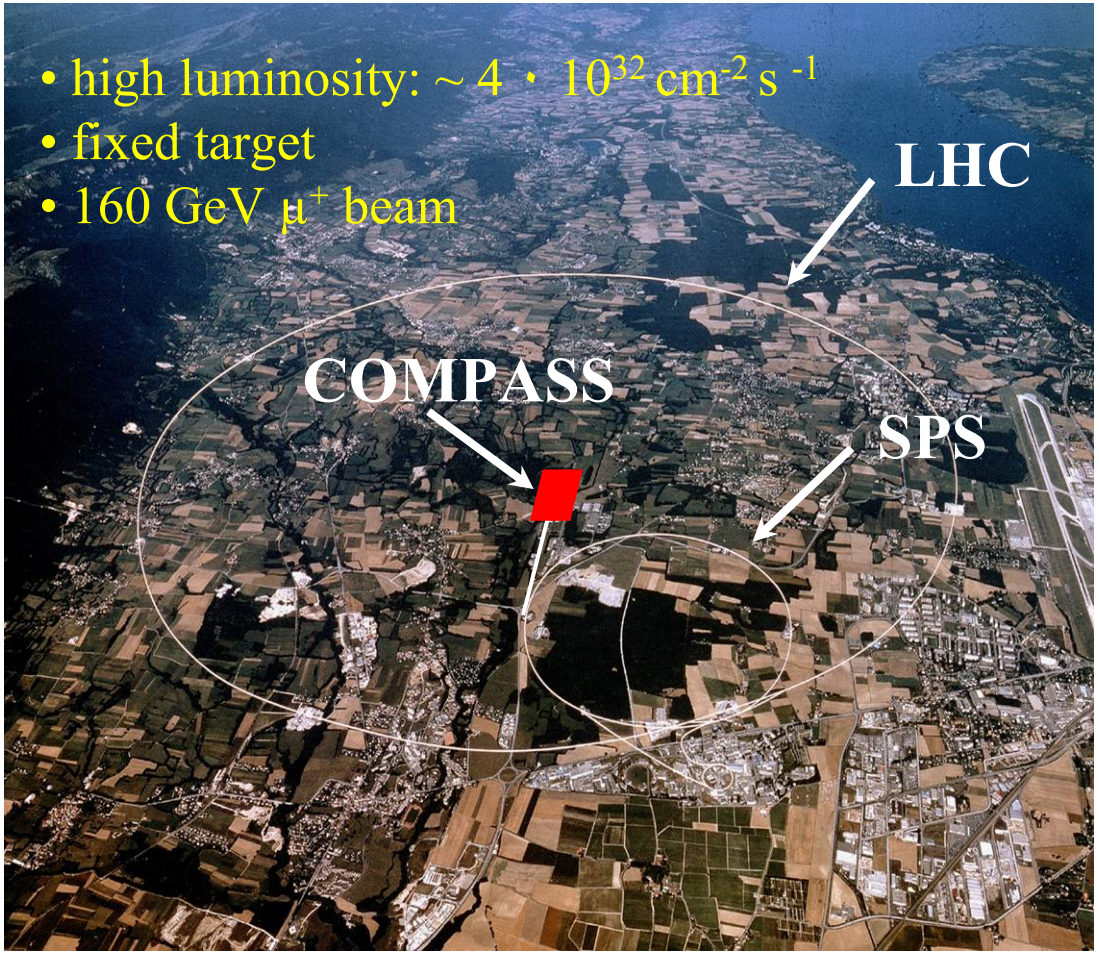
# The COMPASS experiment

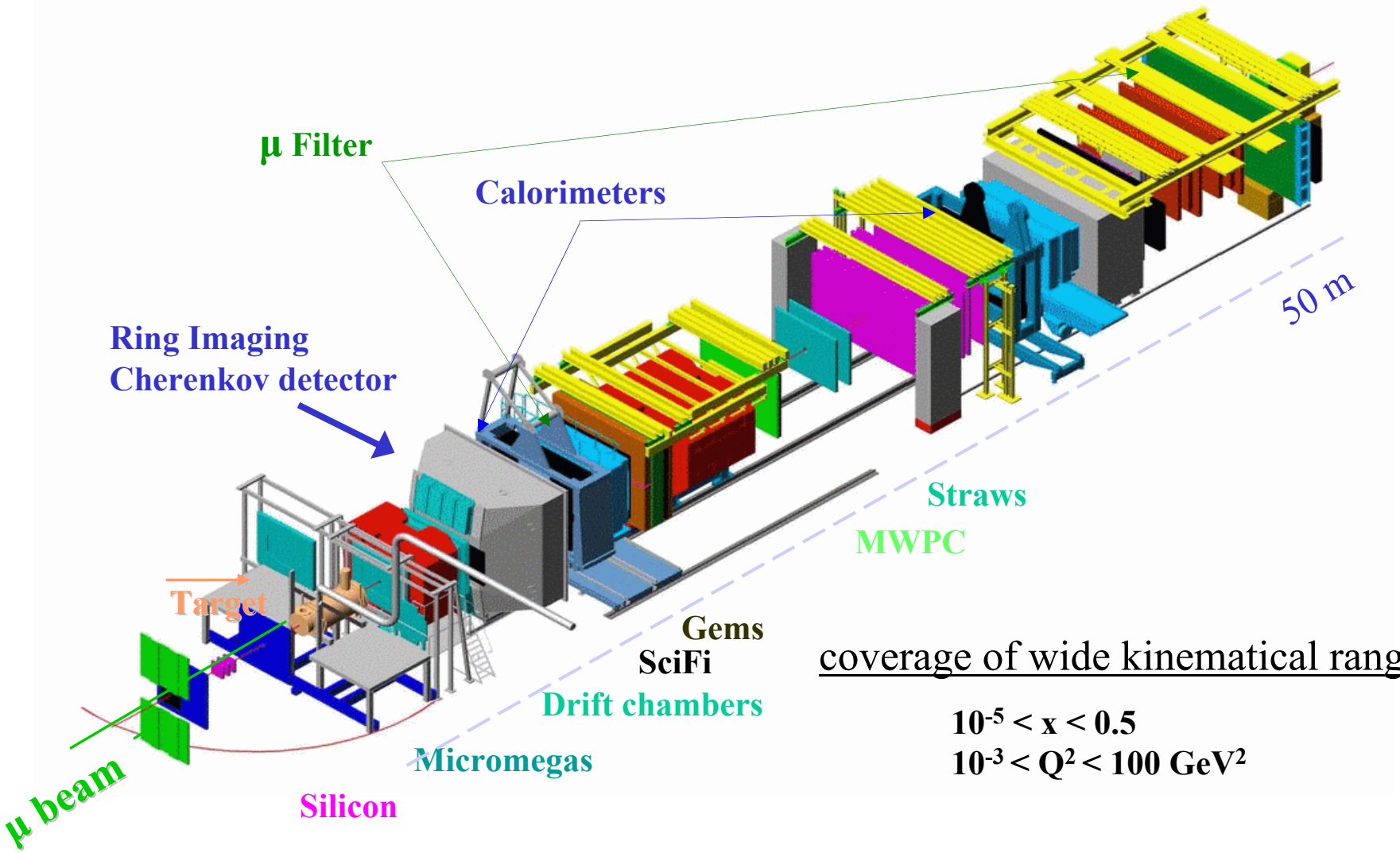
COmmon Muon Proton Apparatus for Structure and Spectroscopy
(270 physicists, 25 institutes, 11 countries)

Investigation of the spin structure of the nucleon:





# The COMPASS spectrometer



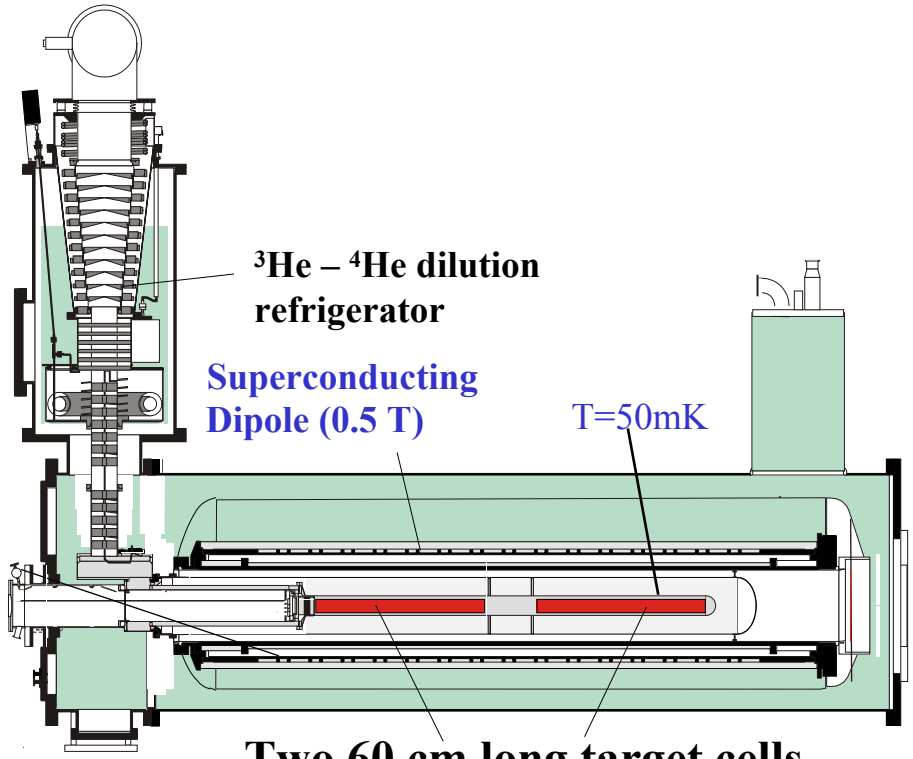

coverage of wide kinematical range:

$10^{-5} < x < 0.5$

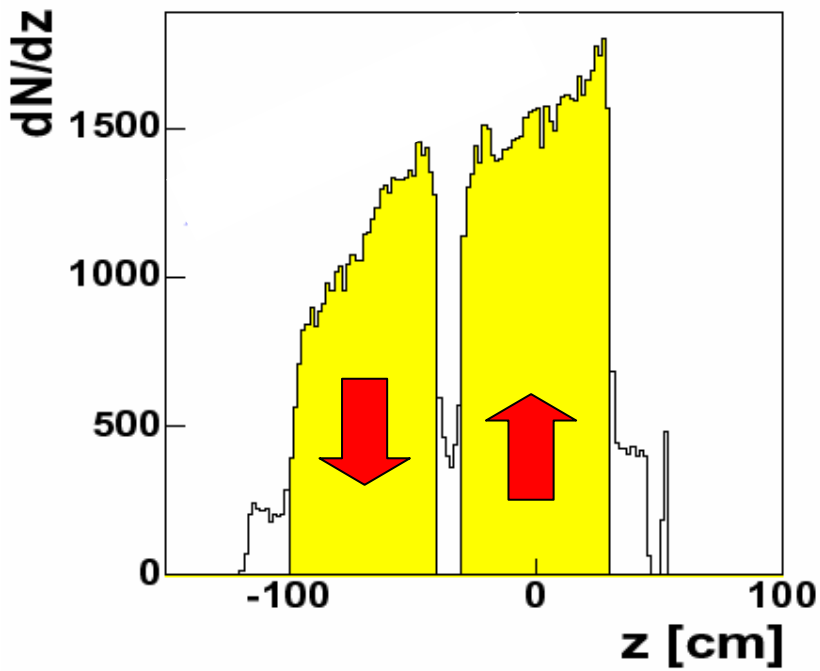
$10^{-3} < Q^2 < 100\ GeV^2$

from Germany: FR, MZ, ER, BN, BO, M, BI

# The polarized $^{6}$LiD-Target




Vertex distribution:




**Polarization** 50 %
**Dilution factor** 0.38

**Transverse target polarization:**
**Reversed once a week**

# Ring Imaging Cherenkov Detector

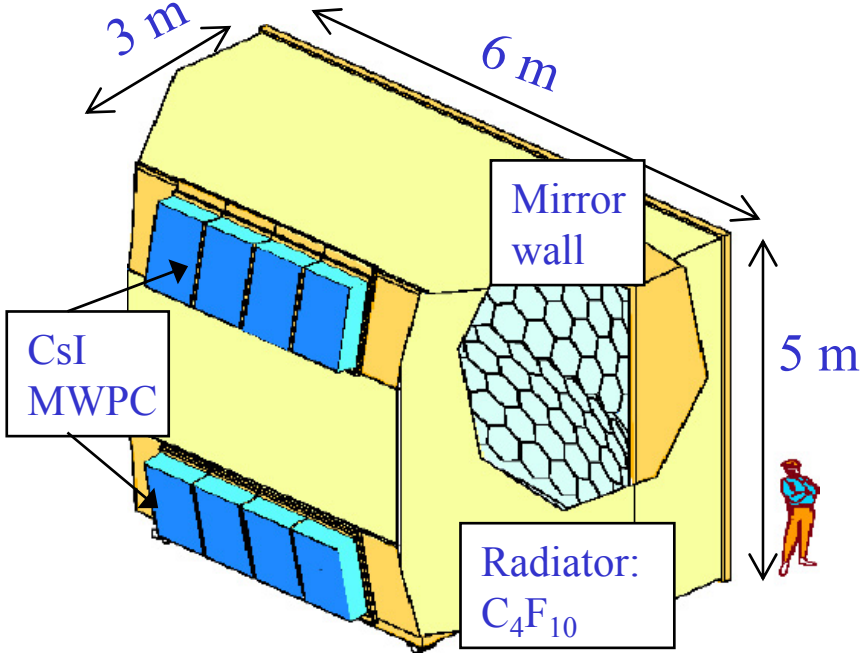
Identification of π, K and protons

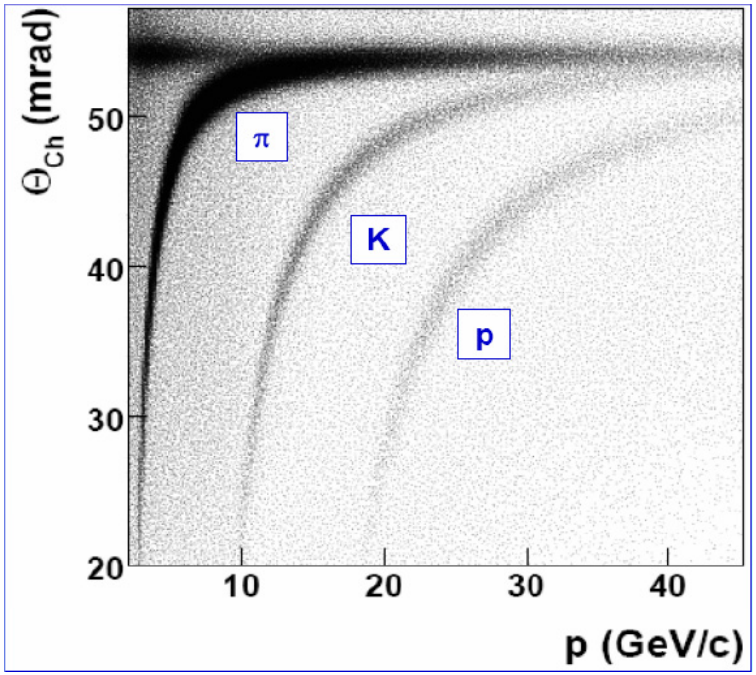
Cherenkov thresholds: π ≈ 3 GeV/c

K ≈ 9 GeV/c

p ≈ 17 GeV/c

2σ π/K separation at 43 GeV/c



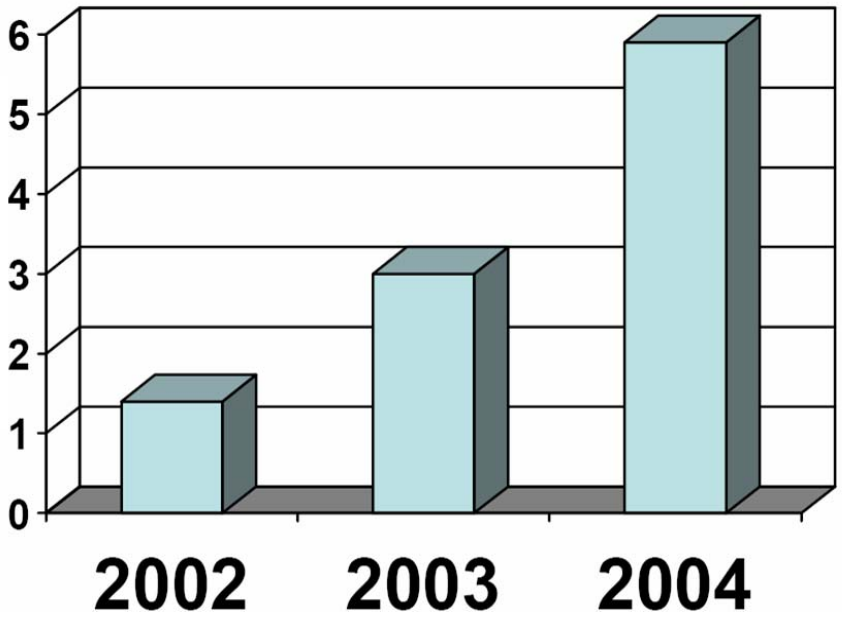
# Transversity Data Sample

**transversely polarized deuteron target**
**~ 20% of the running time**

| | | |
|---|---|---|
| 2002 | 11 days | of data taking |
| 2003 | 9 days | of data taking |
| 2004 | 14 days | of data taking |

trigger (large x, $Q^2$)
+ PID (ECAL, RICH)

**reconstructed DIS events ($10^6$)**




10 Mill.
DIS events

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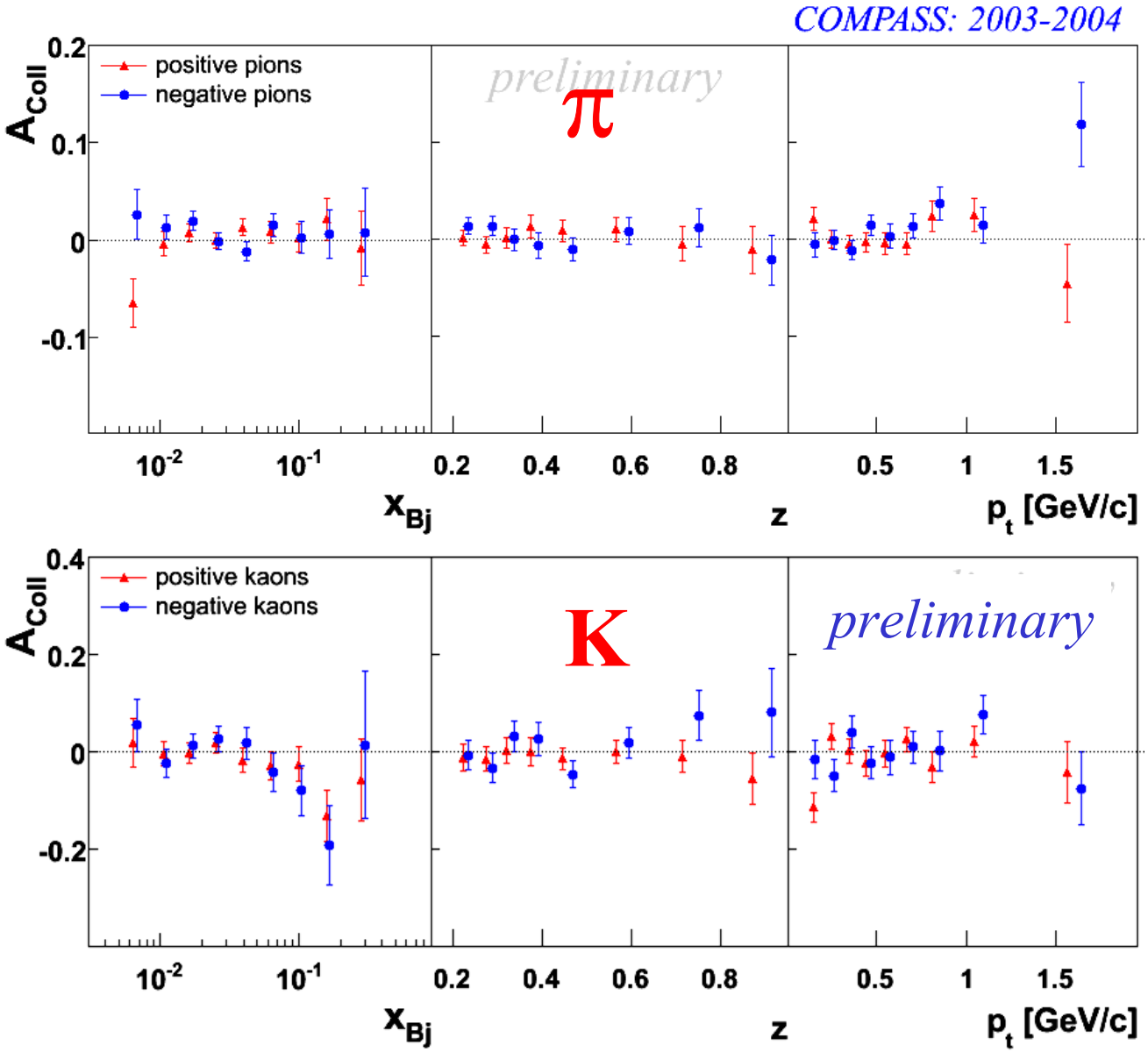
# COMPASS Results: Collins Effect

Deuteron target




only statistical errors shown (systematical errors considerably smaller)

# Interpretation

- Parton model, valence region:

isospin-symmetric deuteron target

$$A_{Coll}^{d,\pi^+}(x) \cong \frac{\Delta_T u_v(x) + \Delta_T d_v(x)}{u_v(x) + d_v(x)} \cdot \frac{4\Delta_T^0 D_1 + \Delta_T^0 D_2}{4D_1 + D_2}$$

$$A_{Coll}^{d,\pi^-}(x) \cong \frac{\Delta_T u_v(x) + \Delta_T d_v(x)}{u_v(x) + d_v(x)} \cdot \frac{\Delta_T^0 D_1 + 4\Delta_T^0 D_2}{D_1 + 4D_2}$$

HERMES (DESY): Proton asymmetries ≠ 0
BELLE (KEK-B): Fragmentation functions ≠ 0

$D_1$: favored FF
$D_2$: disfavored FF

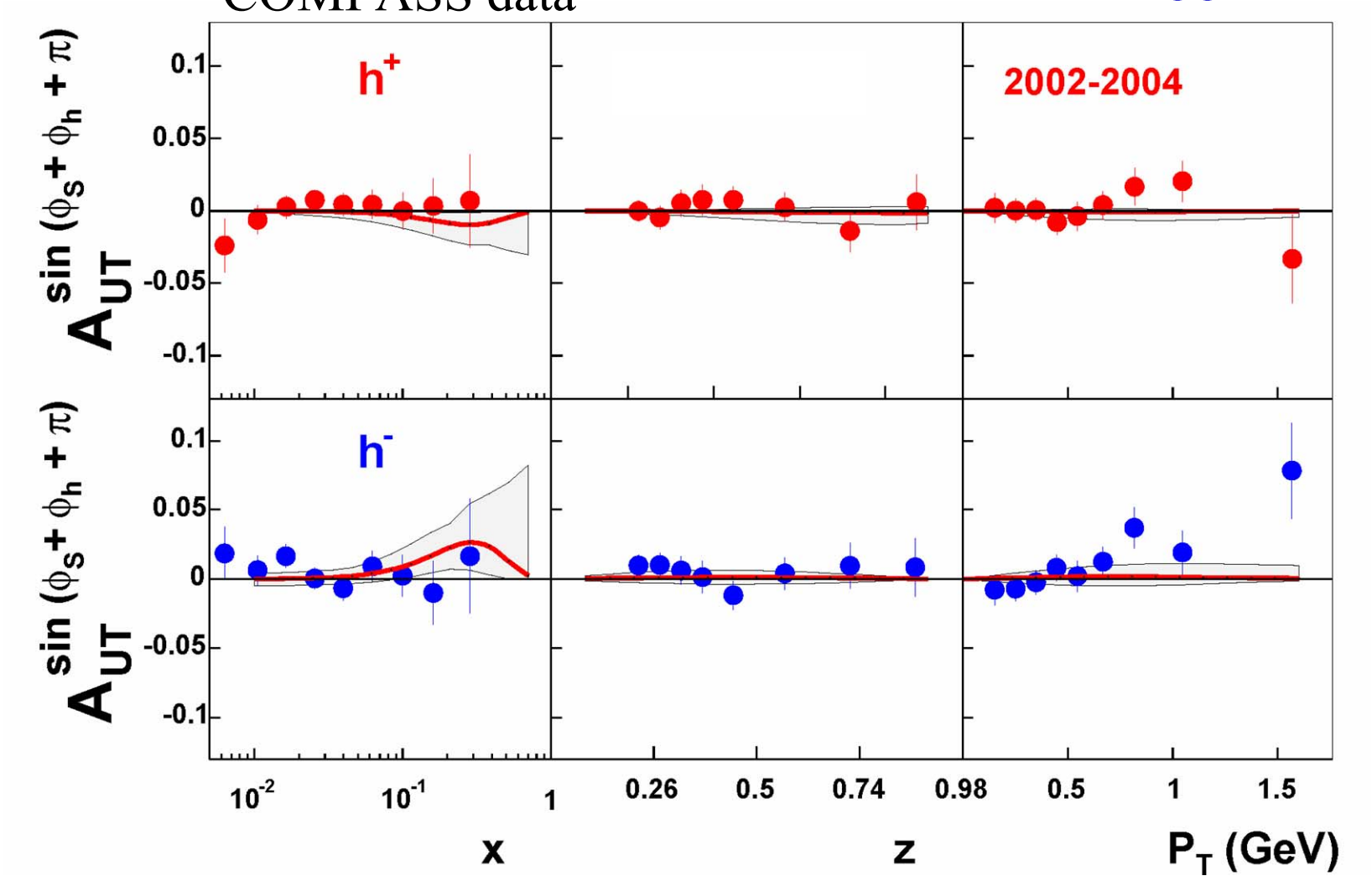
Small asymmetries → cancellation $\Delta_T u(x) \approx -\Delta_T d(x)$

# Collins: Interpretation

**Global fit (COMPASS, HERMES, BELLE):**

COMPASS data

Anselmino et al. hep-ph/0701006



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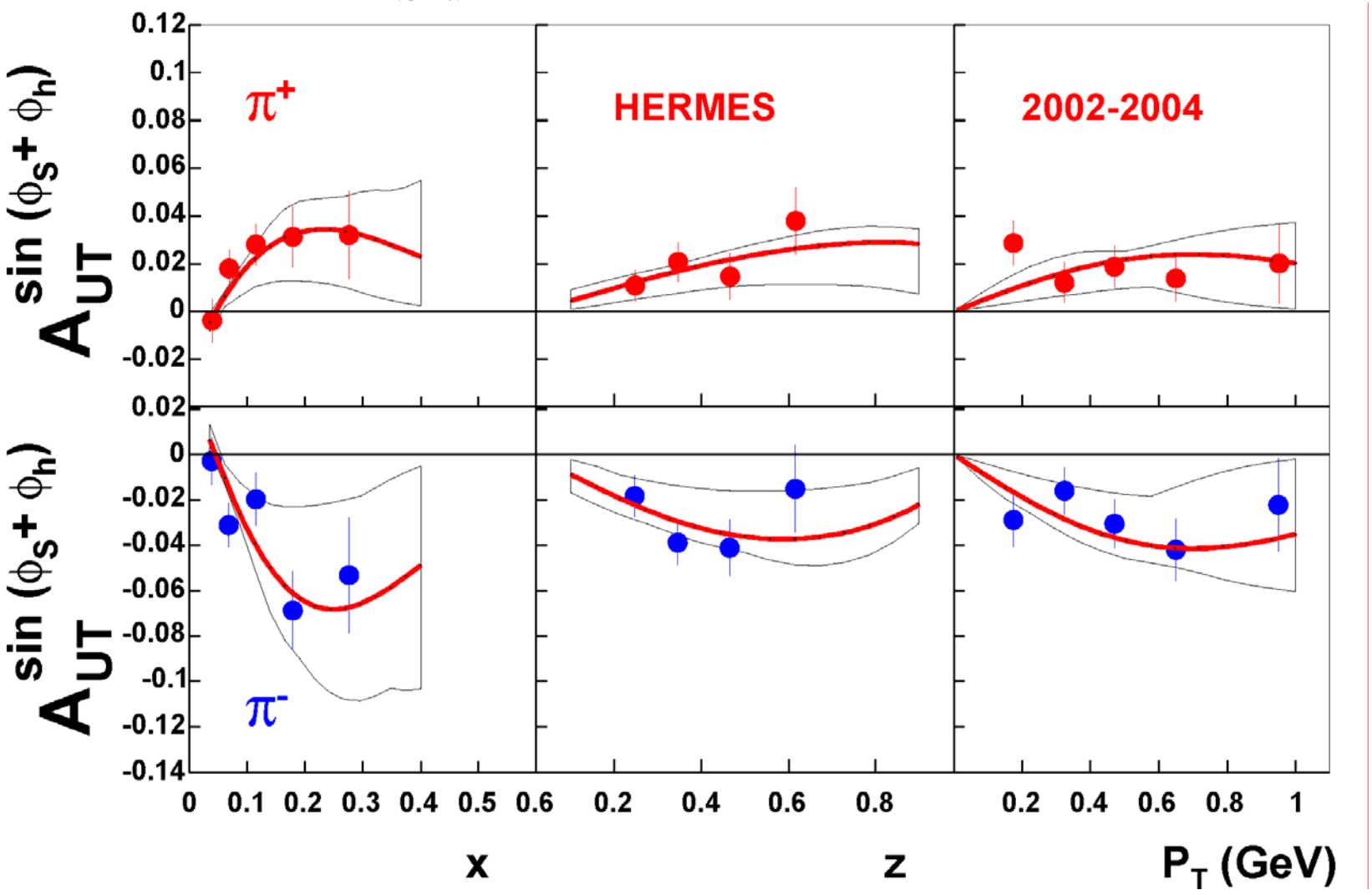

# Collins: Global Fit

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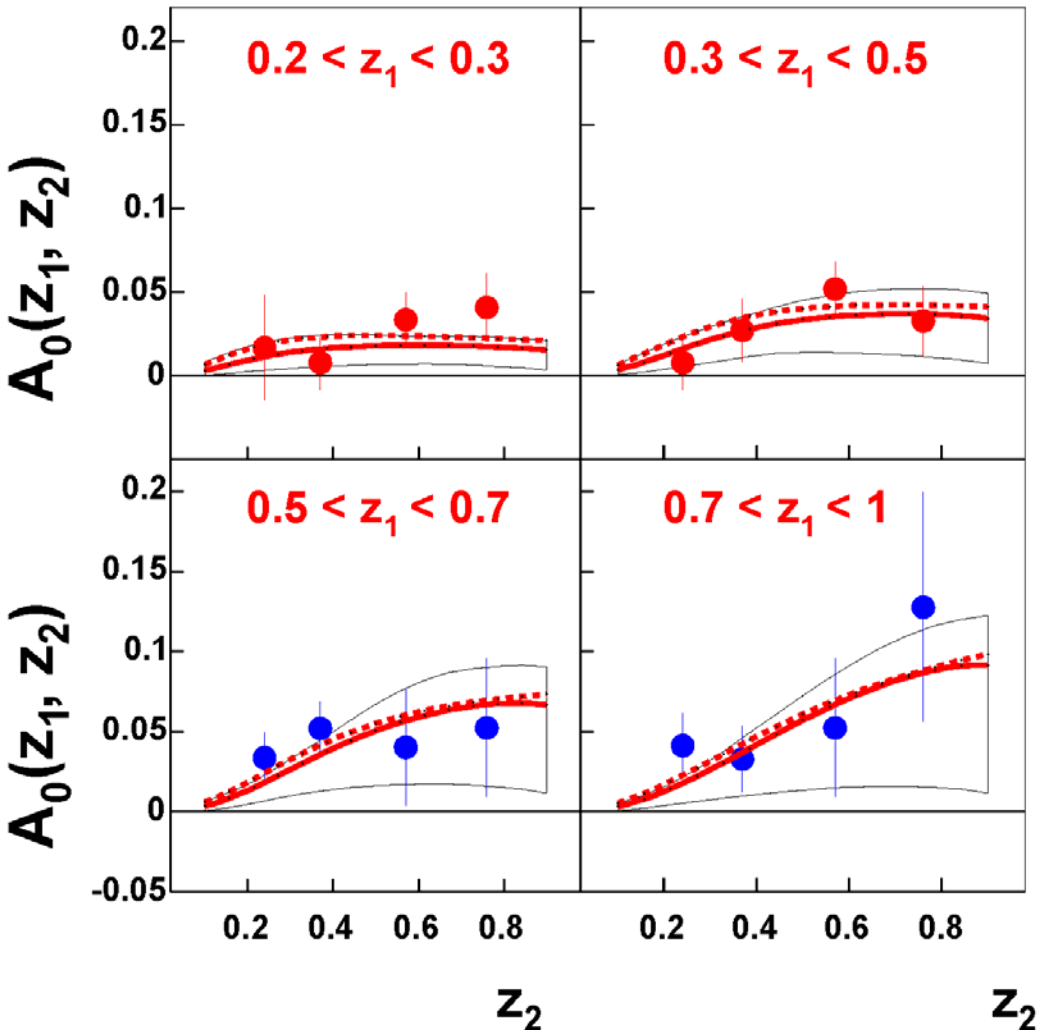
BELLE data

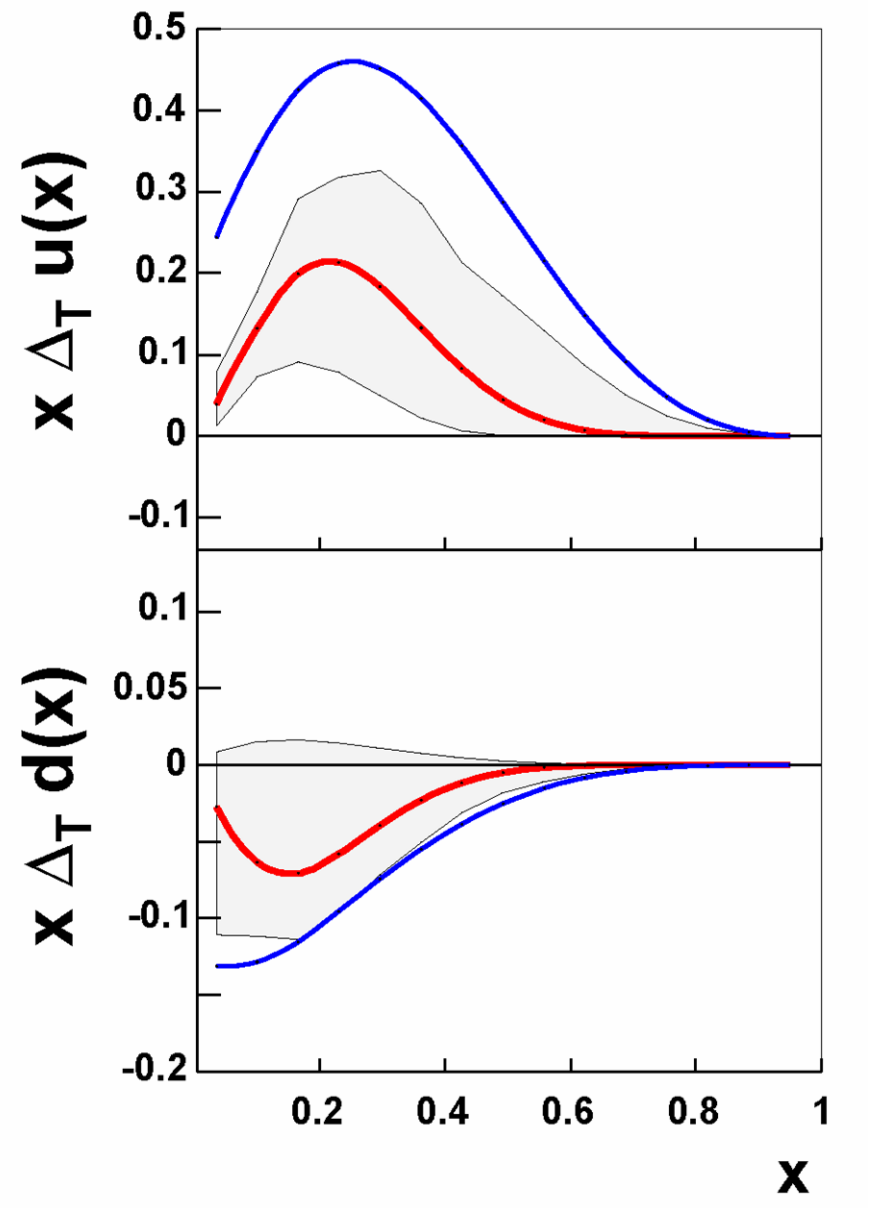
Anselmino et al. hep-ph/0701006



# Results for Transversity

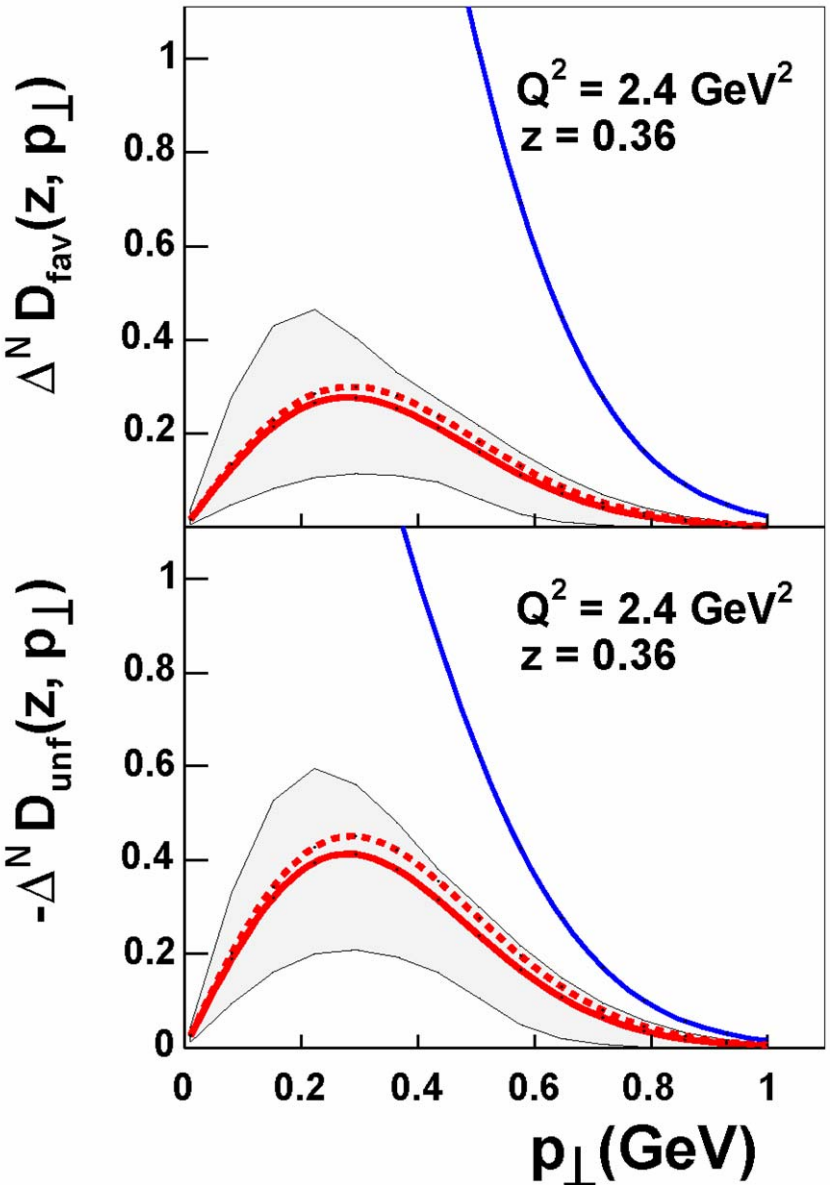
global fit

Soffer bound




Anselmino et al.
hep-ph/0701006

# Collins Fragmentation Function




Favored and unfavored FF with opposite sign

Anselmino et al. hep-ph/0701006

# Measuring Transversity

**Can be measured in semi-inclusive deep-inelastic scattering on a transversely polarized target via "quark polarimetry":**

$\ell\, N^{\uparrow} \to \ell'\, h\, X$ — **"Collins" asymmetry**

**"Collins" Fragmentation Function**

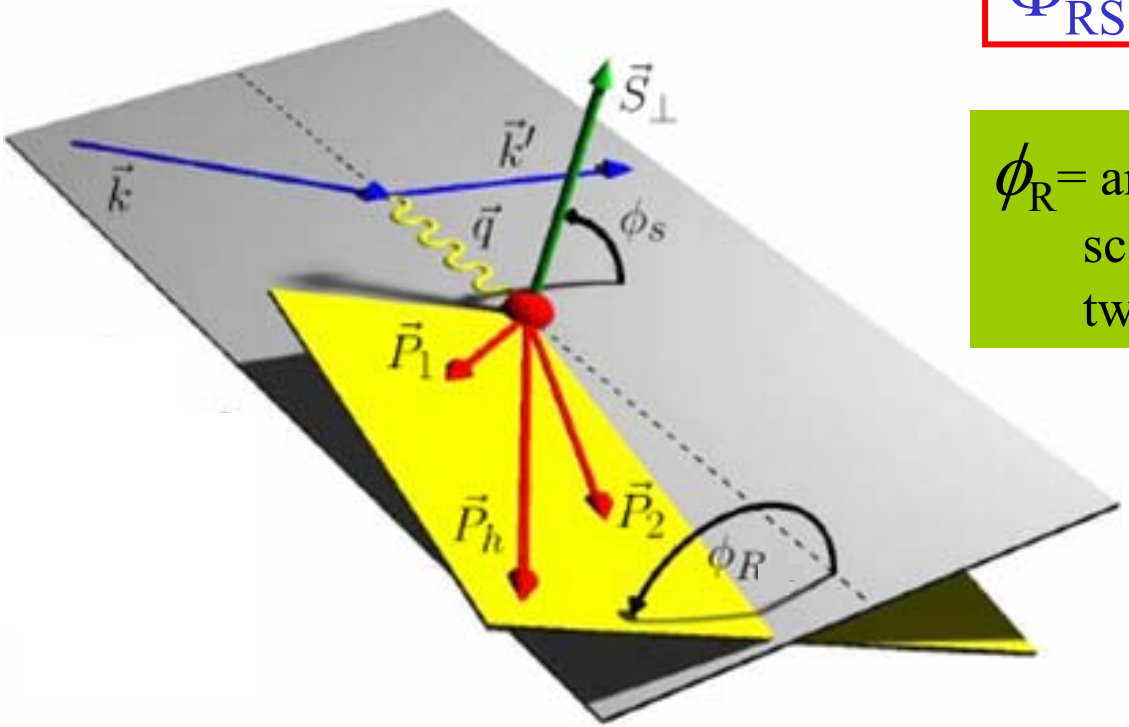
$\ell\, N^{\uparrow} \to \ell'\, h\, h\, X$ — **Two-hadron asymmetry**

**"Interference" Fragmentation Function**

$\ell\, N^{\uparrow} \to \ell'\, \Lambda\, X$ — **Λ polarization**

**Fragmentation Function of $q^{\uparrow} \to \Lambda$**

# Transversity in Hadron-Pair Production




Collins-Angle replaced by:

$$\Phi_{RS} = \phi_R + \phi_S - \pi$$

$\phi_R$= angle between lepton scattering plane and two-hadron plane

(A. Bacchetta, M. Radici, hep-ph/0407345)

(X. Artru, hep-ph/0207309)

# Azimuthal Asymmetry for Hadron-Pair Production

Target single spin asymmetry $A_{RS}(x,z,M_h^2)$: $z=z_1+z_2$

$$A_{RS}(x,z,M_h^2) = \frac{1}{fP_T D} \cdot \frac{\sum_q e_q^2 \, \Delta_T q(x) \, H_q^{\sphericalangle h}(z,M_h^2)}{\sum_q e_q^2 \; q(x) \; D_q^h(z,M_h^2)}$$

(X. Artru, hep-ph/0207309)

$H_q^{\sphericalangle h}(z,M_h^2)$: Two-hadron interference fragmentation function

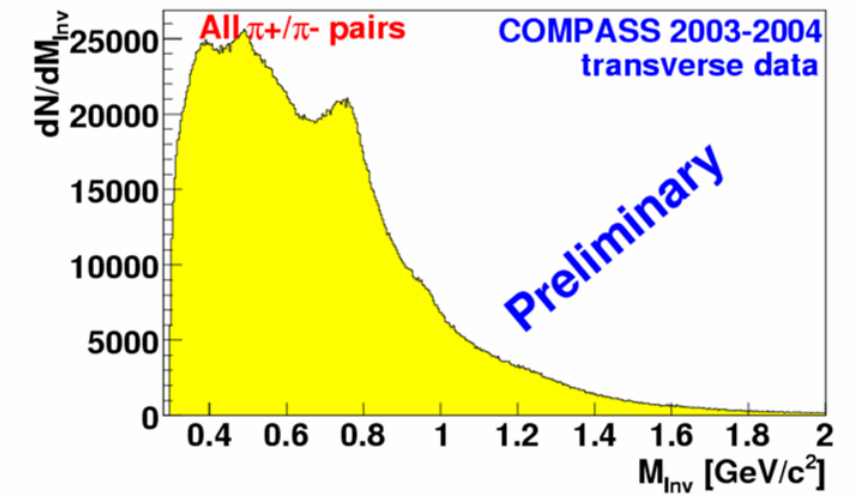
$D_q^h$, $H_q^{\sphericalangle h}$ ↓

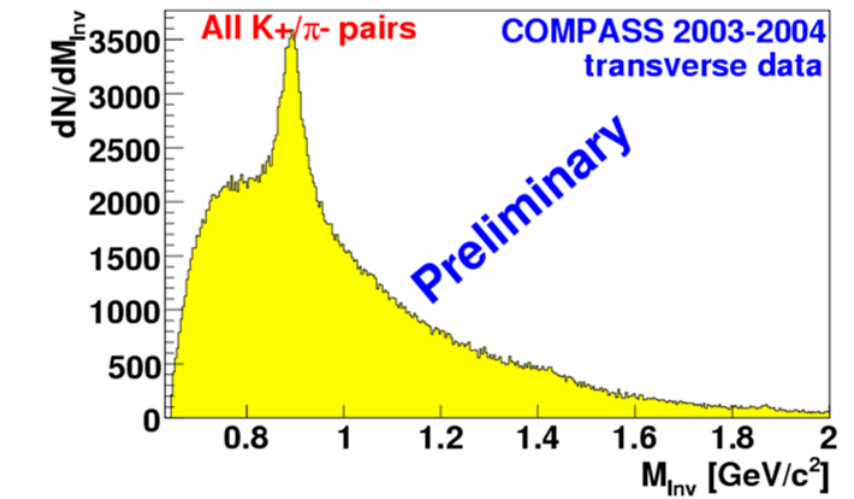
presently unknown
can be measured
in $e^+e^-$ (BELLE)

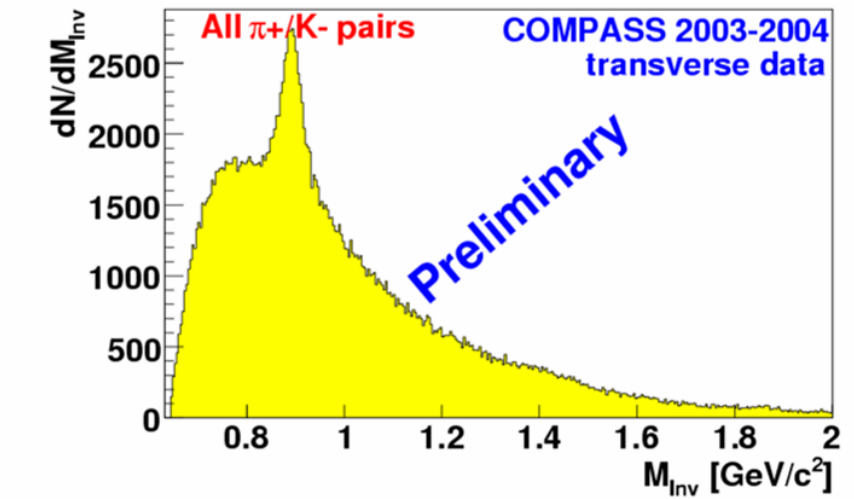
expected to depend on the hadron
pair invariant mass

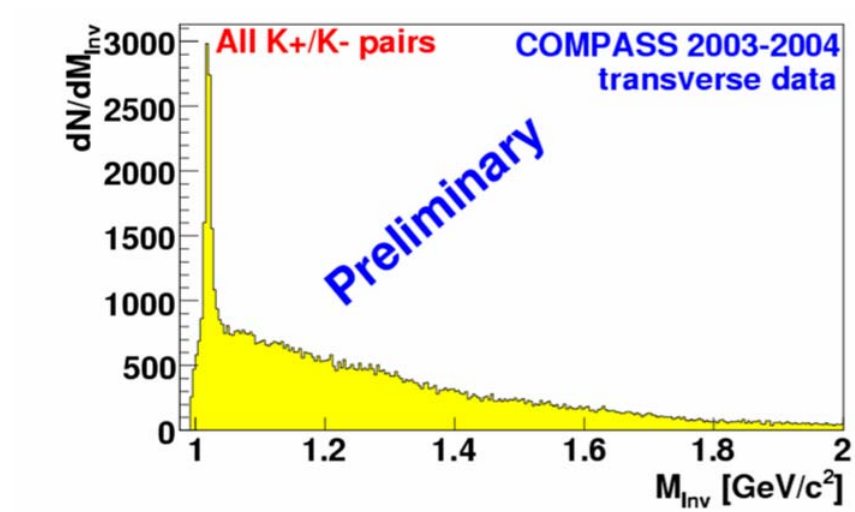
# Hadron Pairs Invariant Mass Spectra

**all hadron pairs: 5.3 M**

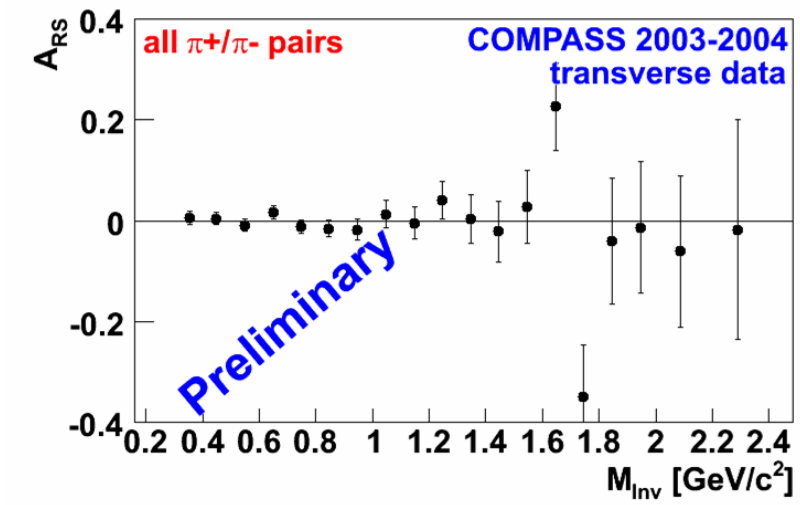


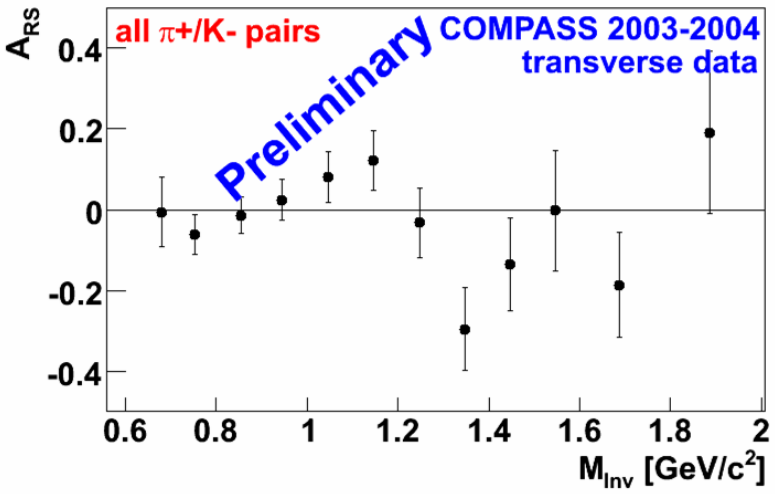



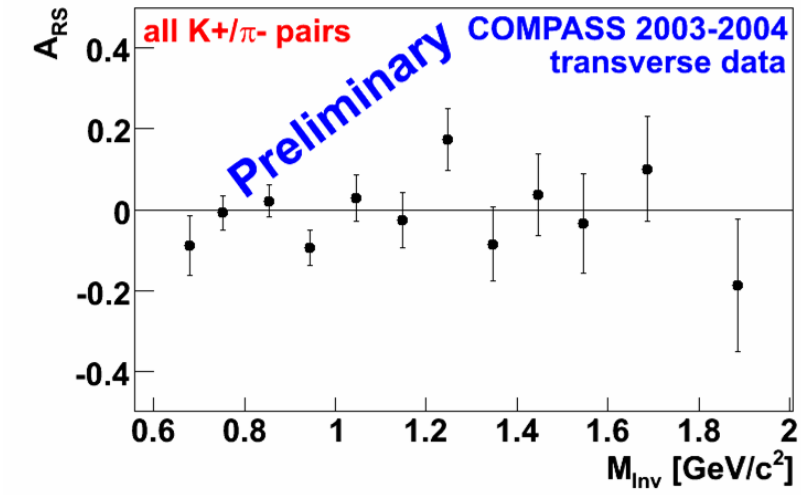



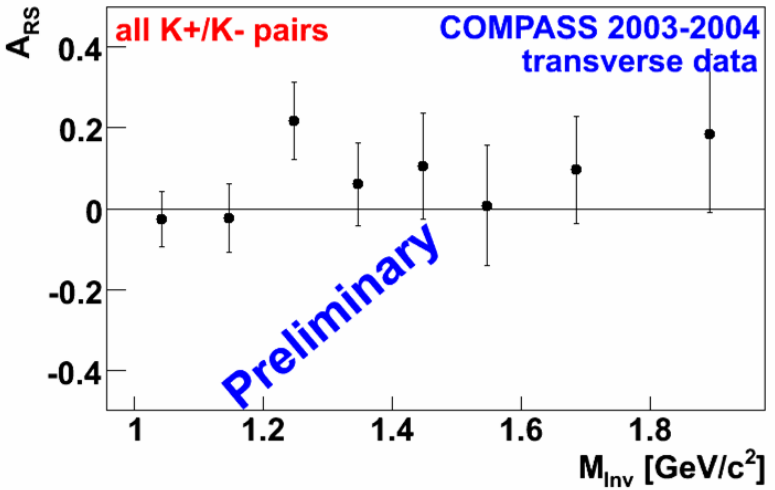



# COMPASS Results for Hadron Pairs



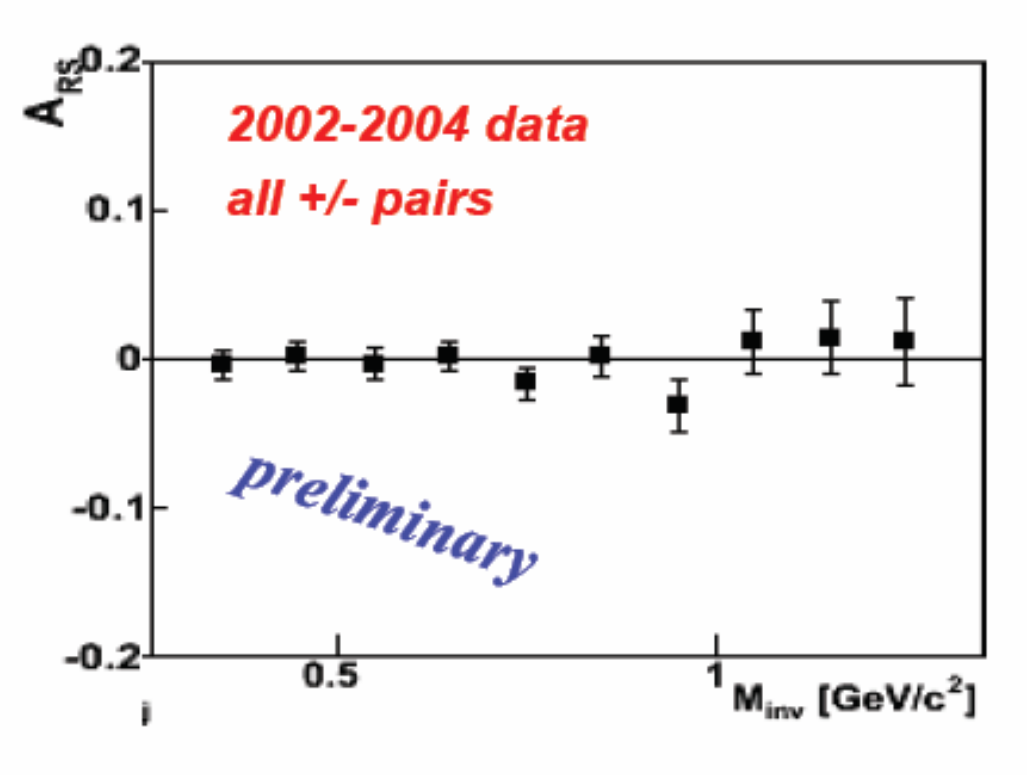




systematic uncertainty considerably smaller than statistical error

# COMPASS Result for All Hadron Pairs




deuteron target

# Interpretation

Two-hadron Asymmetry:

$$A_{RS} = \frac{1}{f\, P_T\, D} \cdot \frac{\sum_q e_q^2 \Delta_T q(x) H_q^{\sphericalangle h}}{\sum_q e_q^2 q(x) D_q^h}$$

On a deuteron target:

$$A^{d,\pi^+}(x) \cong \frac{\Delta_T u_v(x) + \Delta_T d_v(x)}{u_v(x) + d_v(x)} \cdot \frac{4H_1^{\sphericalangle h} + H_2^{\sphericalangle h}}{4D_1 + D_2}$$

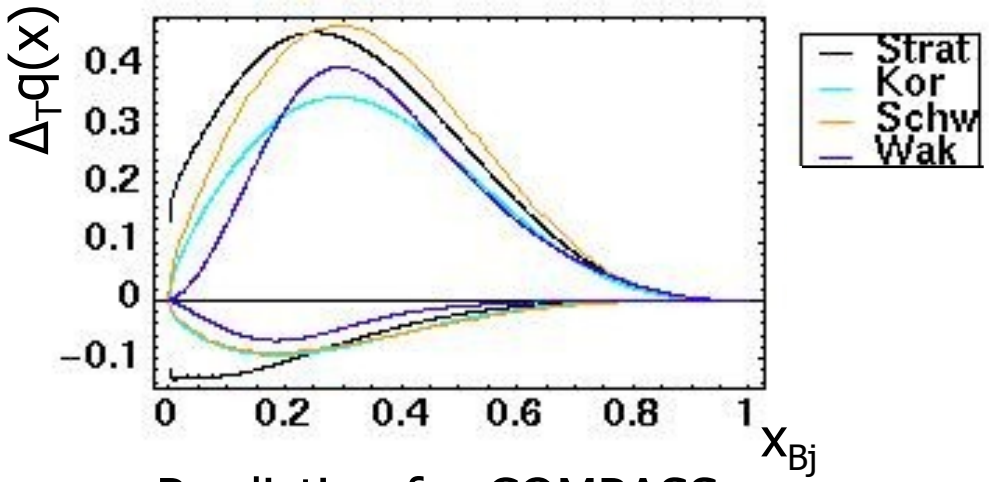
Independent measurement from Collins asymmetry with different fragmentation functions.

Data suggest as well: $\Delta_T u_v(x) = -\Delta_T d_v(x)$

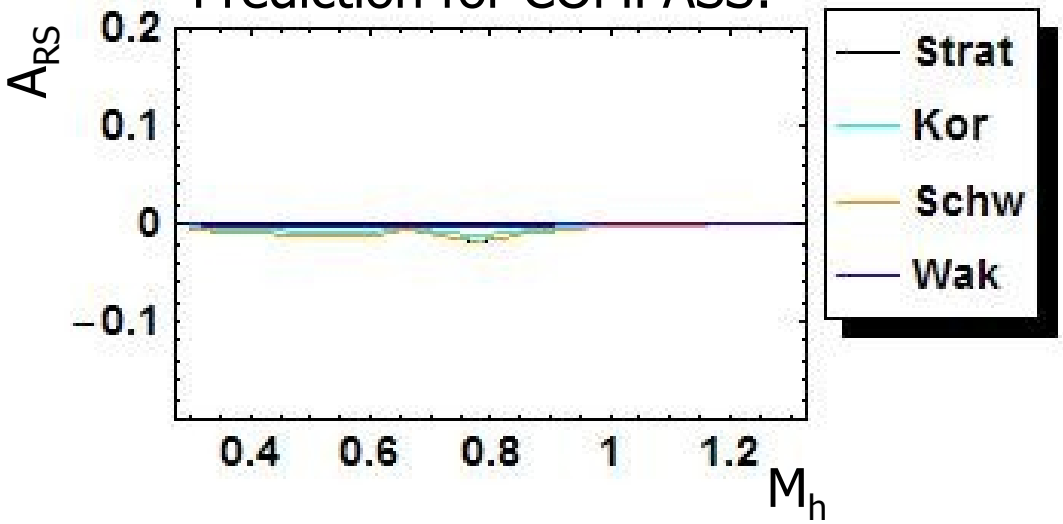
# Model Calculations

Model calculations for COMPASS kinematics (M. Radici, QCDN 06, hep-ph/0608037):

Model for transversity:




Prediction for COMPASS:



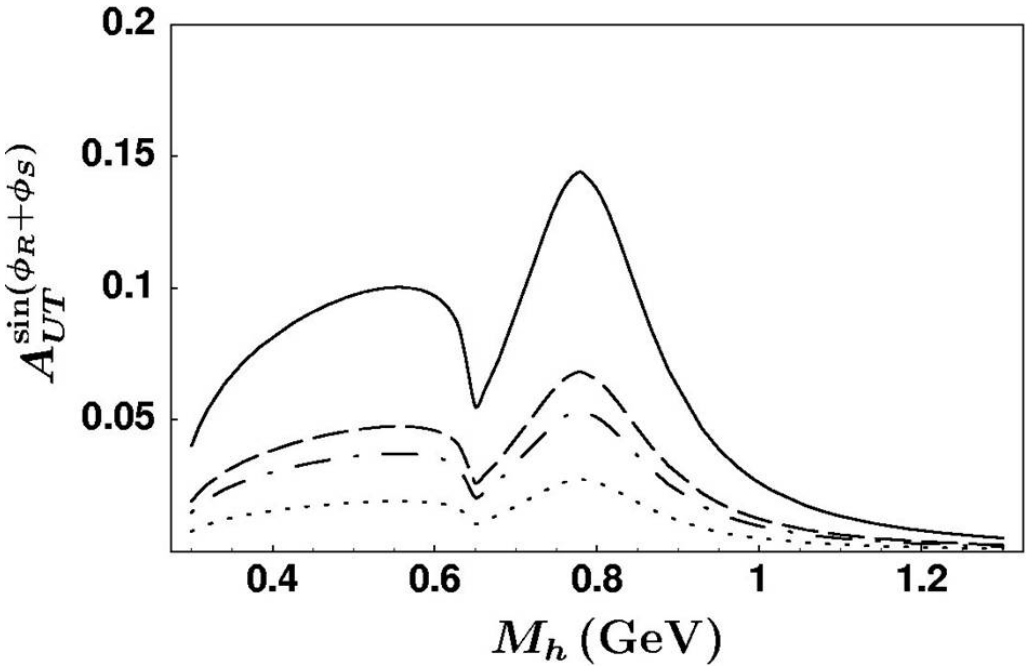

- Soffer, Stratmann, Vogelsang, P.R. D65 (02) 114024
- Korotkov, Nowak, Oganessian, E.P.J. C18 (01) 639
- Schweitzer et al., P.R. D64 (01) 034013
- Wakamatsu P.L. B509 (01) 59

➔ small asymmetries on the deuteron

# Model Predictions for a Proton Target

COMPASS kinematics

Proton Target




A.Bacchetta, M.Radici
PRD74(2006)114007
Model for Di-Hadron
Fragmentation Function

new data on a proton target have been already taken this year!

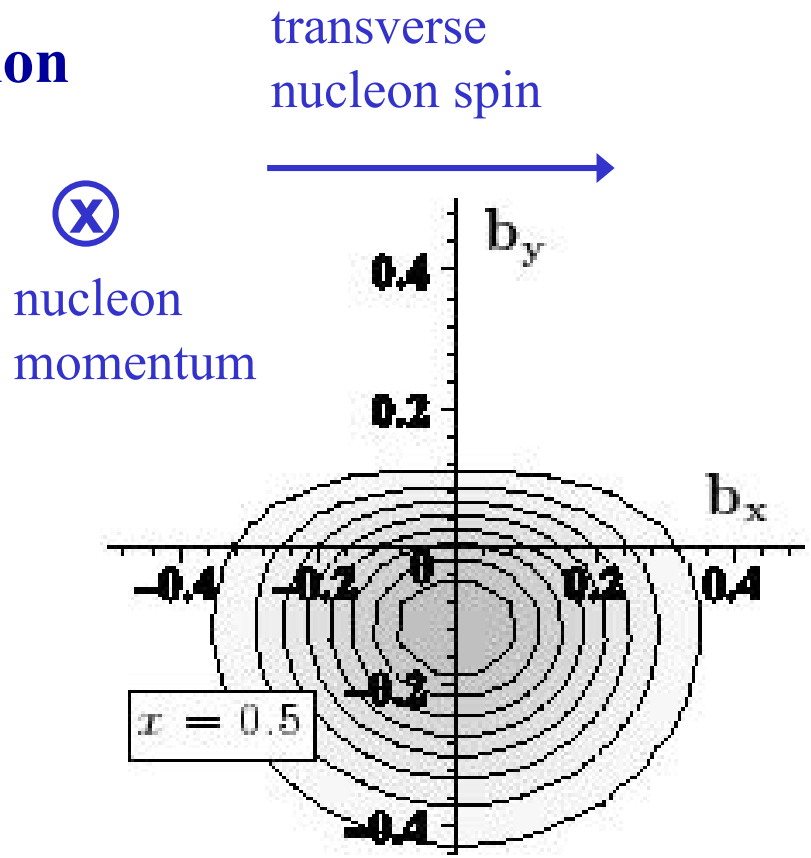
# Contents

- Transverse spin physics
- The COMPASS experiment
- COMPASS results on asymmetries
  - Transversity distribution function
  - Sivers distribution function
  - Other TMD distribution functions
- Conclusions

# The Sivers Distribution Function $\Delta_0^T q$

**most famous transverse momentum dependent parton distribution function**

**describes an intrinsic asymmetry in the parton transverse momentum distribution induced by the nucleon spin**




quark density

- **it is related to the parton orbital angular momentum in a transversely polarized nucleon**

M. Burkardt, PRD, **66,** 114005(2002)

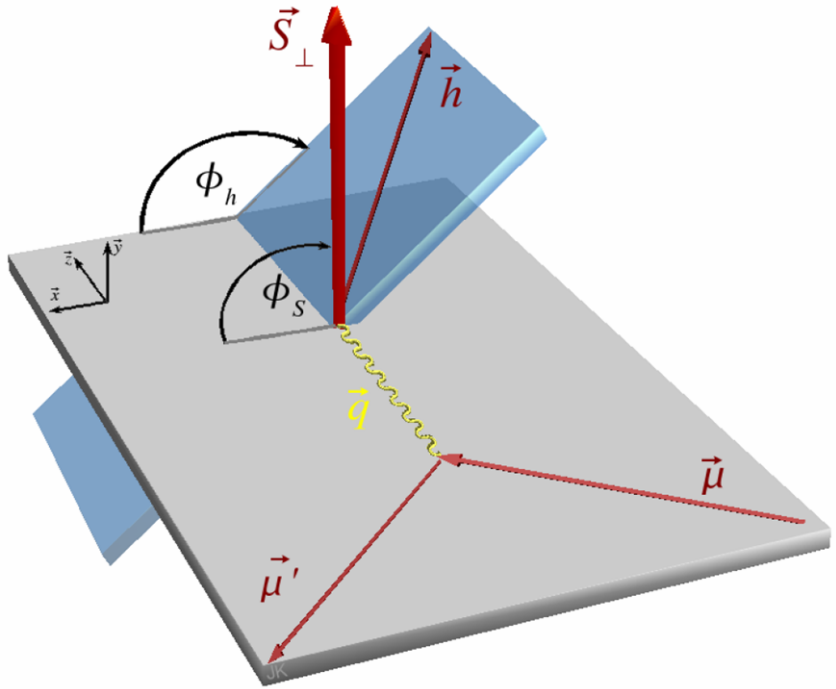
# Measurement of Sivers Asymmetry

$\Delta_0^T q$

**The "Sivers angle" is**

$$\Phi_S = \phi_h - \phi_S$$

Independent from Collins angle, possible to measure both effects in the same data

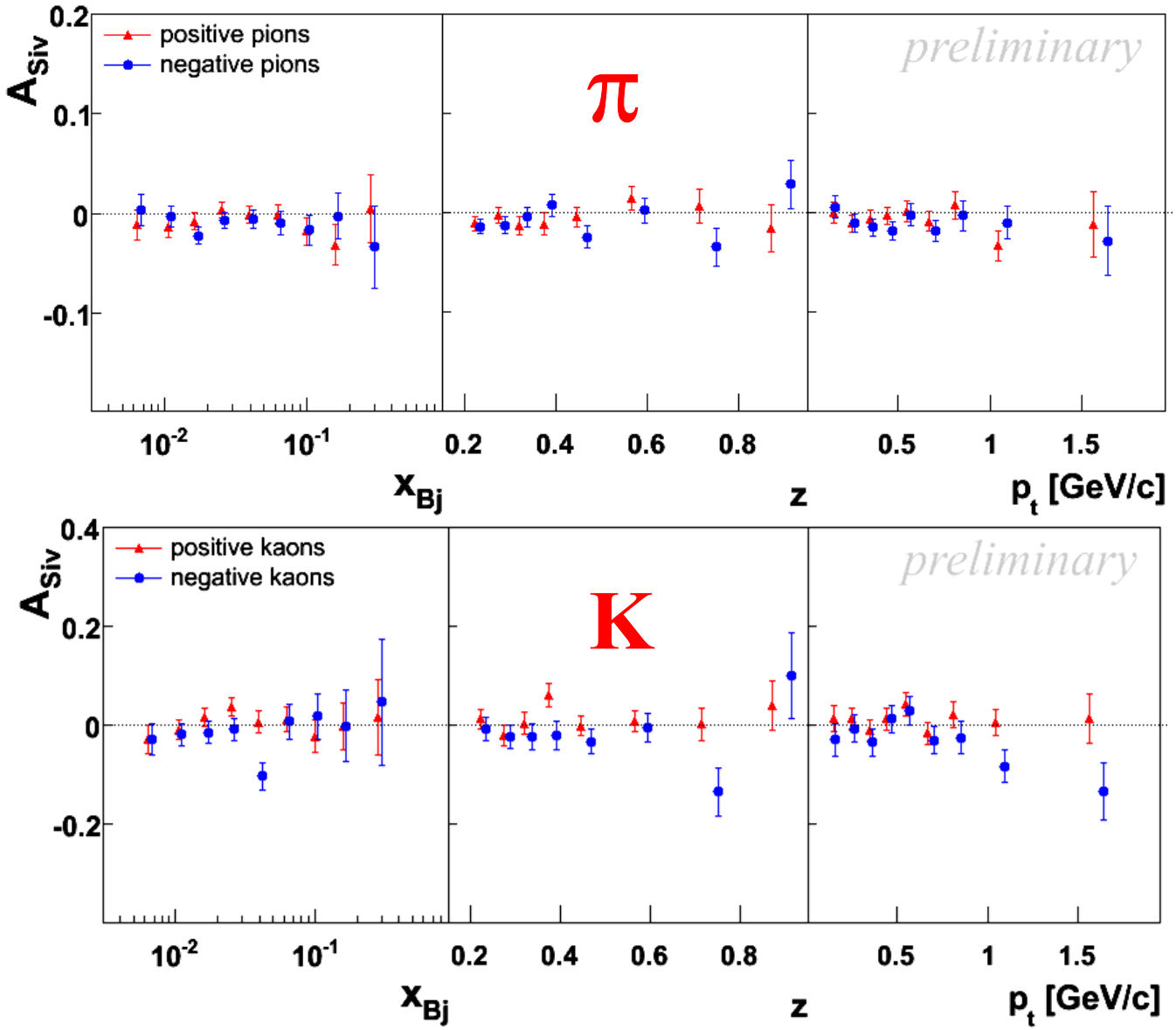



$$N_h^{\pm}(\Phi_S) = N_h^0 \cdot \left[1 \pm P_T \cdot A_{Siv} \cdot \sin\Phi_S\right]$$

$$A_{Siv} \approx \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

$\phi_{h,,s}$ azimuthal angles of the hadron, transverse spin of the initial quark

# COMPASS: Sivers Asymmetries




only statistical errors shown (systematical errors considerably smaller)

# Interpretation

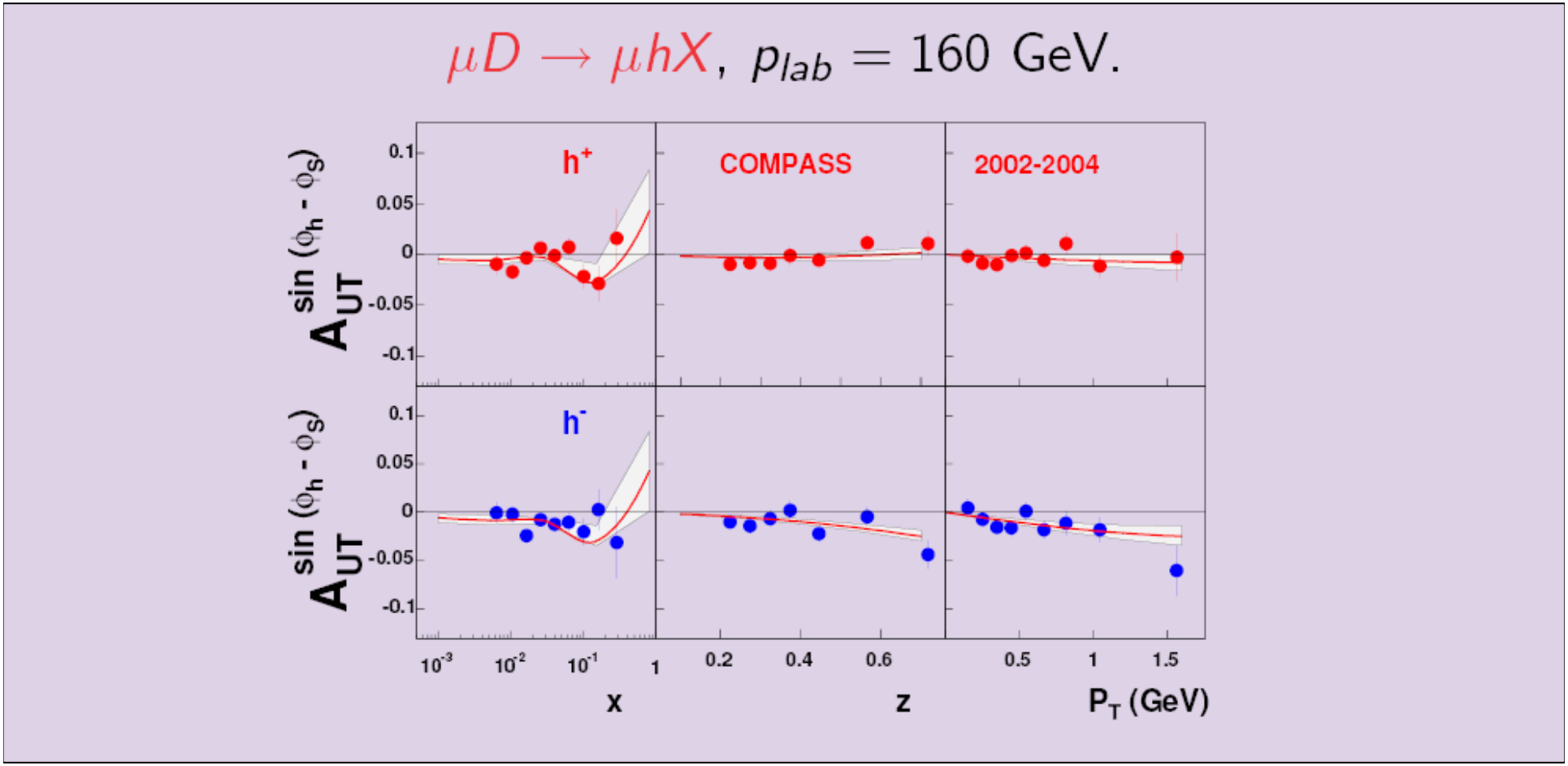
- Parton model, valence region:

$$A_{Siv}^{d,\pi^+}(x) \approx A_{Siv}^{d,\pi^-}(x) \approx \frac{\Delta_0^T u_v(x) + \Delta_0^T d_v(x)}{u_v(x) + d_v(x)}$$

Small asymmetries suggest $\Delta_0{}^T d_v(x) \cong -\Delta_0{}^T u_v(x)$

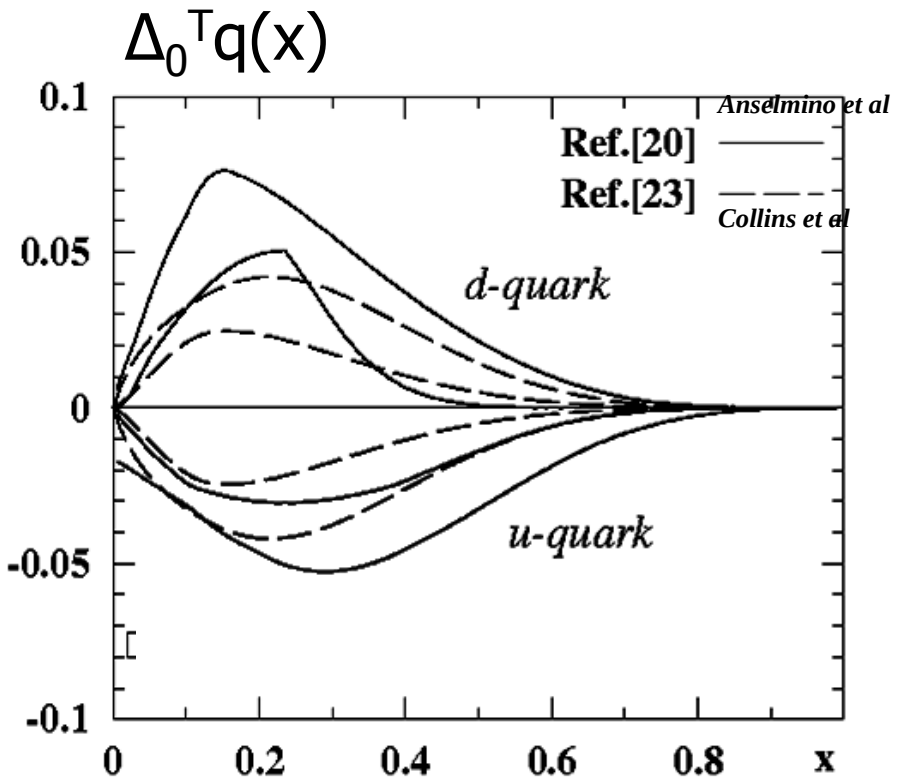
# Global Fit: Sivers Asymmetry

**M. Anselmino *et.al*** hep-ph/0511017



# Global Analysis: Sivers function

- Extraction of the Sivers function from COMPASS & HERMES:




Anselmino et al. hep-ph/0511017

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# Beyond Collins and Sivers Mechanism

SIDIS cross-section in one-photon exchange approximation:
8 transverse target spin dependent azimuthal modulations

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{ \cdots$$

Sivers

$$+ |\boldsymbol{S}_\perp| \Big[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \right)$$

Collins

$$+ \varepsilon \sin(\phi_h + \phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+ \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Big]$$

6 further modulations

$$+ |\boldsymbol{S}_\perp|\lambda_e \Big[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_S\, F_{LT}^{\cos\phi_S}$$

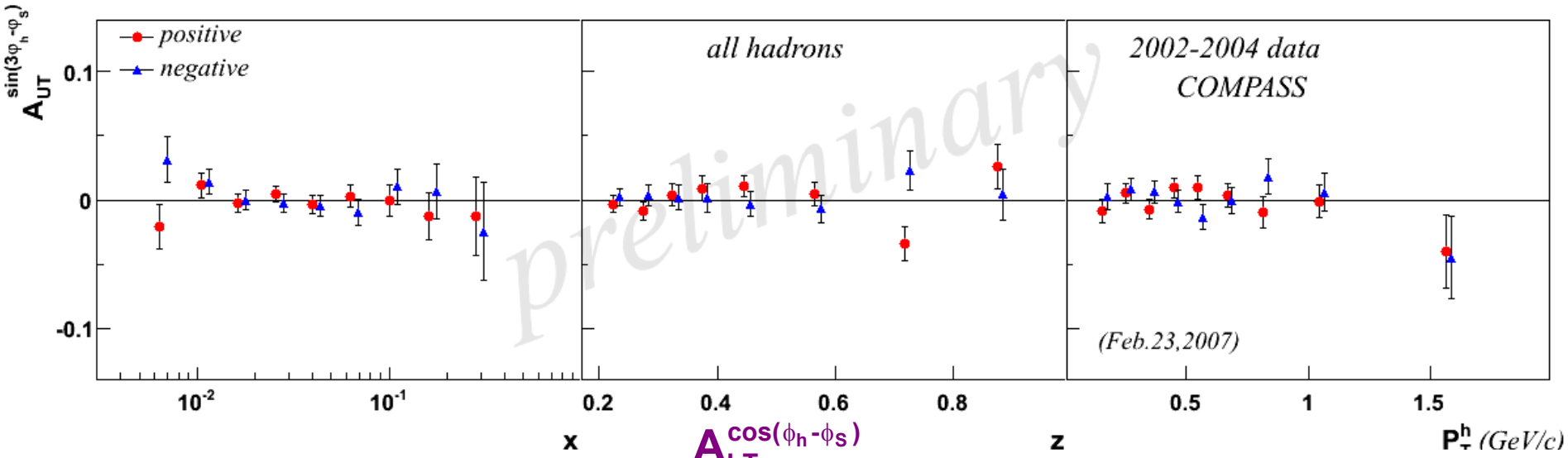
$$+ \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)} \Big] \Big\},$$

ε-photon flux

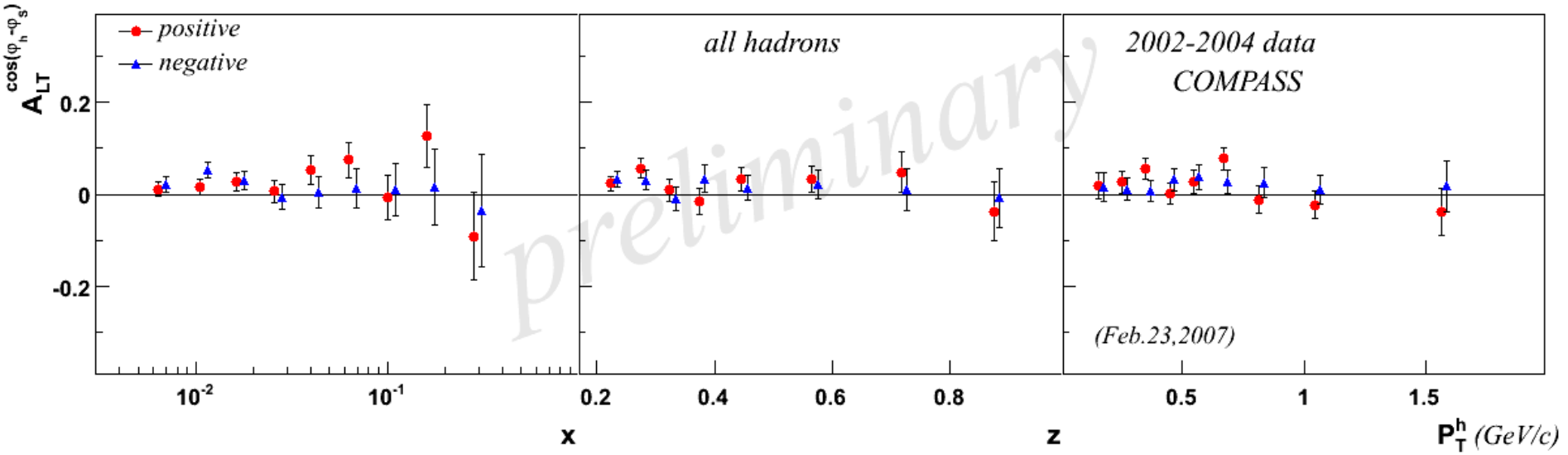
M. Diehl, S. Sapeta,
Eur.Phys.J **C41** (2005) 515-533
hep-ph/0503023

# Results beyond Collins and Sivers

$A_{UT}^{\sin(3\phi_h - \phi_S)}$




$A_{LT}^{\cos(\phi_h - \phi_S)}$




all transverse target spin asymmetries on the deuteron ≈ 0

# Conclusions

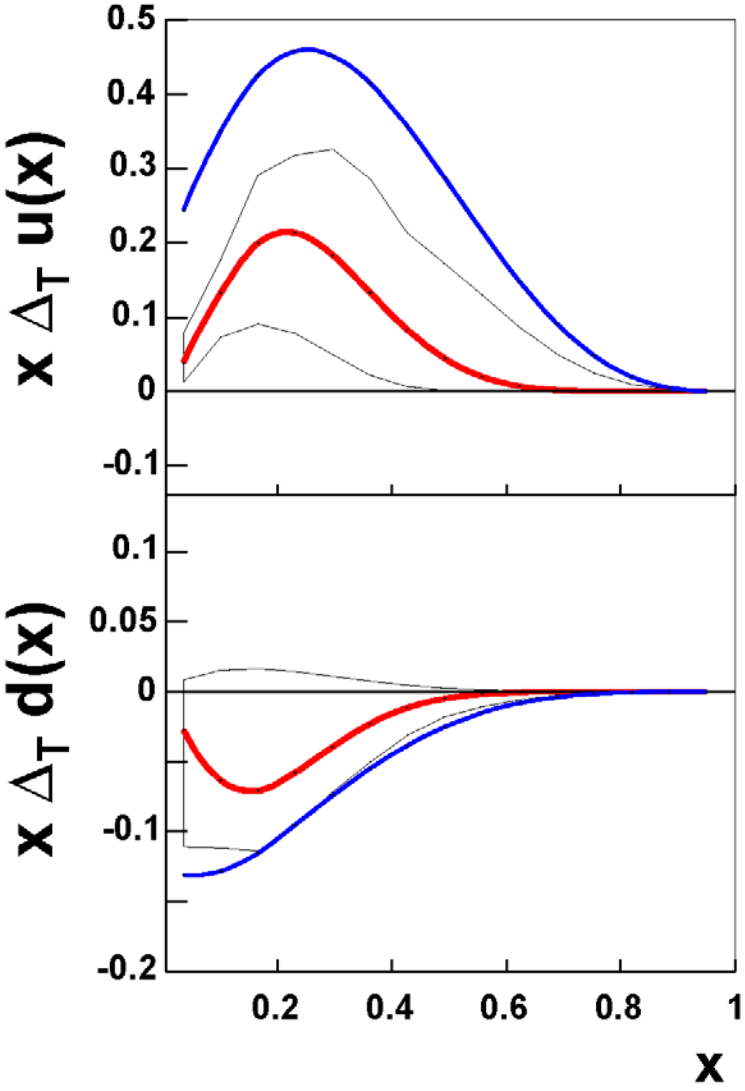
- Compass results for Collins effect and Sivers effect on the deuteron

- Together with the Collins Fragmentation Function (BELLE) and data on the proton (HERMES+COMPASS 2007):

TRANSVERSITY CAN BE MEASURED

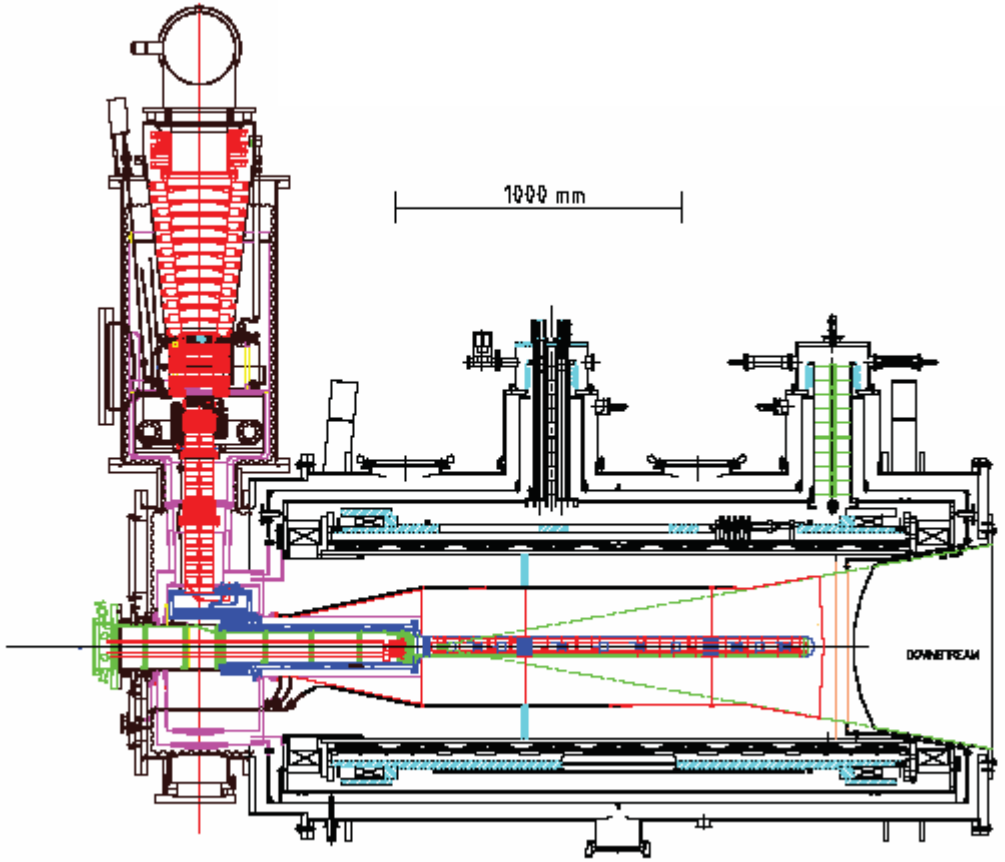
First global analyses being done

# Conclusions



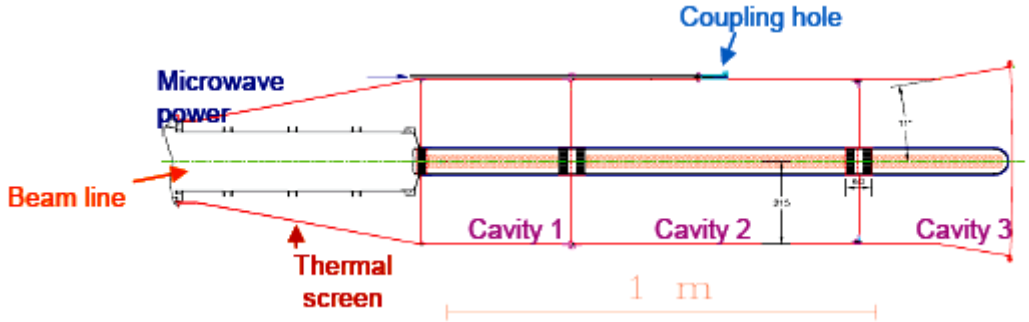

- $\Delta_T u(x) > 0$ and $\Delta_T d(x) < 0$
- Both $\Delta_T u(x)$ and $\Delta_T d(x)$ do not saturate Soffer bound
- 2007 COMPASS data on a proton target will allow us to determine $\Delta_T u(x)$ and $\Delta_T d(x)$ with greater precision!

# COMPASS 2007 Proton Transversity Run




**2007: $NH_3$**
**dilution factor f = 0.14**
**polarization $P_T$ = 90%**

**2 ➔ 3 cells**




Data taking just finished,
waiting for the first results…

# Thank you!