The Spin Structure of the Nucleon: a phenomenological introduction

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INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
33rd Course: FROM QUARKS AND GLUONS TO HADRONS AND NUCLEI
ERICE–SICILY: 16 – 24 SEPTEMBER 2011

- **the QCD structure**

  Longitudinal

  Transverse

- **the experiments**
- **results on transversity**

  Sivers effects

- **outlook**

Magnetic moments

the nucleon is not a Dirac particle (*point-like* particle)

spin $\frac{1}{2}$ $\mu = \frac{e\hbar}{2mc}$

$\mu_p = +2.79\ \mu_N$ *Frisch and Stern (1933)*

$\mu_n = -1.91\ \mu_N$ **should be 0**

→ per-se indication of internal structure

THE QUARK MODEL

Major Breakthrough

hadron spectoscopy ⇨ **the QUARK MODEL** (1964)

$|p\rangle = |uud\rangle \qquad |n\rangle = |udd\rangle$

SU(6)

magnetic moments:

$$\mu_p = \frac{4}{3}\mu_u - \frac{1}{3}\mu_d \qquad \mu_n = \frac{4}{3}\mu_d - \frac{1}{3}\mu_u$$

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assuming u and d Dirac particles with $m \cong \frac{1}{3} M_N$

$$\mu_u = \frac{q\hbar}{2m_u c} = 2\mu_N \qquad \mu_d = -\mu_N$$

$$\mu_p = 3\mu_N \qquad \mu_n = -2\mu_N$$

$$\frac{\mu_p}{\mu_n} = -\frac{3}{2}$$

similar agreement for all baryons

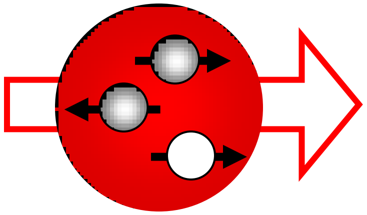
The Constituent Quark Model

in this model the spin of the nucleon
is given by the spin of the quarks

probability of finding a quark in a given state of polarization

$$\overset{\rightrightarrows}{u} = \frac{5}{3} \qquad \overset{\leftrightarrows}{u} = \frac{1}{3} \qquad \Delta u = \overset{\rightrightarrows}{u} - \overset{\leftrightarrows}{u} = \frac{4}{3}$$

$$\overset{\rightrightarrows}{d} = \frac{1}{3} \qquad \overset{\leftrightarrows}{d} = \frac{2}{3} \qquad \Delta d = \overset{\rightrightarrows}{d} - \overset{\leftrightarrows}{d} = -\frac{1}{3}$$



$$\boxed{\Delta\Sigma = \Delta u + \Delta d = 1}$$

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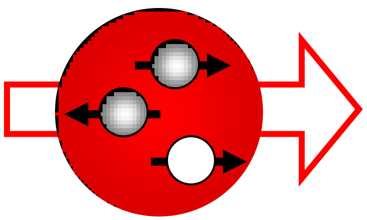


$$\Delta\Sigma = \Delta u + \Delta d = 1$$

the existence of quarks and their properties firmly established in DEEP INELASTIC SCATTERING

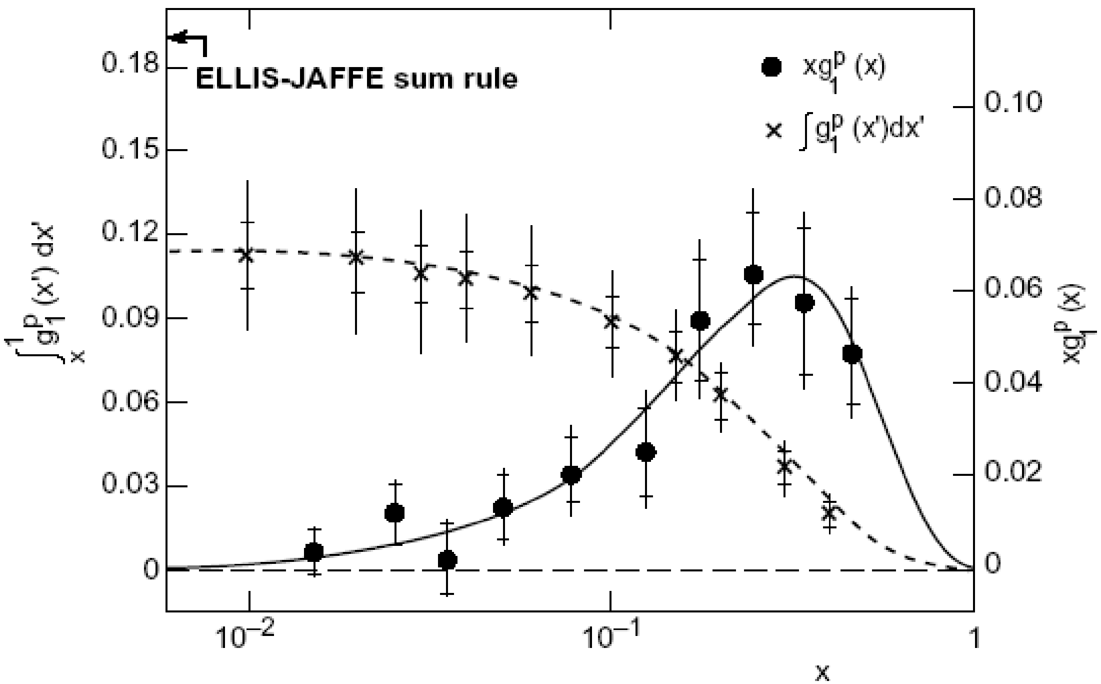
SLAC

Friedmann and Kendell (1969)

Bjorken, Feynman

The Quark Contribution to the Nucleon Spin

EMC **1988**



EMC 1988

$\Gamma_1^p = 0.123 \pm 0.013 \pm 0.019$ $\Delta\Sigma = 0.12 \pm 0.17$

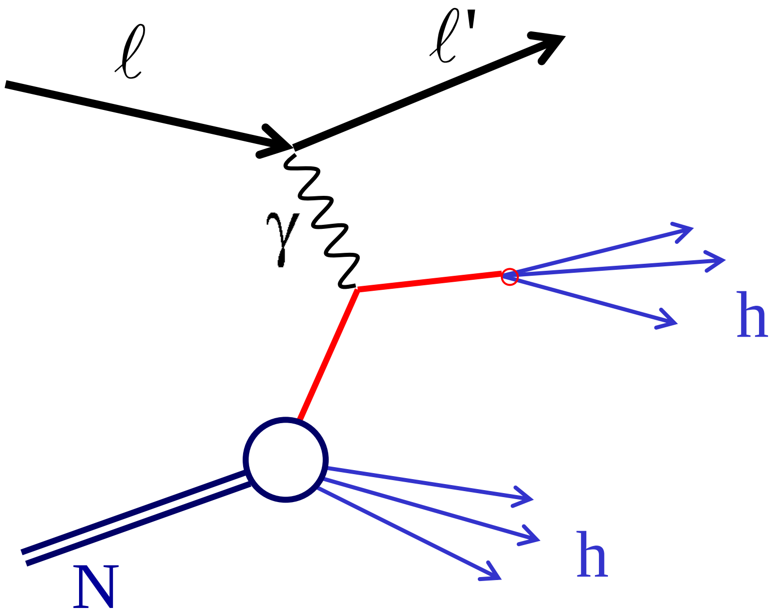
➔ SPIN CRISIS

HOW IS $\Delta\Sigma$ MEASURED?

Deep Inelastic Scattering

key role in the study of the partonic structure of the nucleon

valence quarks
sea quarks
gluons



$$Q^2 = -q^2 > 0$$
$$x = Q^2/2M\nu$$

$$\nu = E - E'$$
$$y = \nu/E$$
$$\gamma = \sqrt{Q^2}/\nu$$

$$Q^2 >> M^2$$
$$W^2 = (P+q)^2 >> M^2$$

Inclusive DIS: only the incident and scattered leptons are measured

Semi-Inclusive DIS: the incident and scattered leptons, and at least one final state hadron are measured

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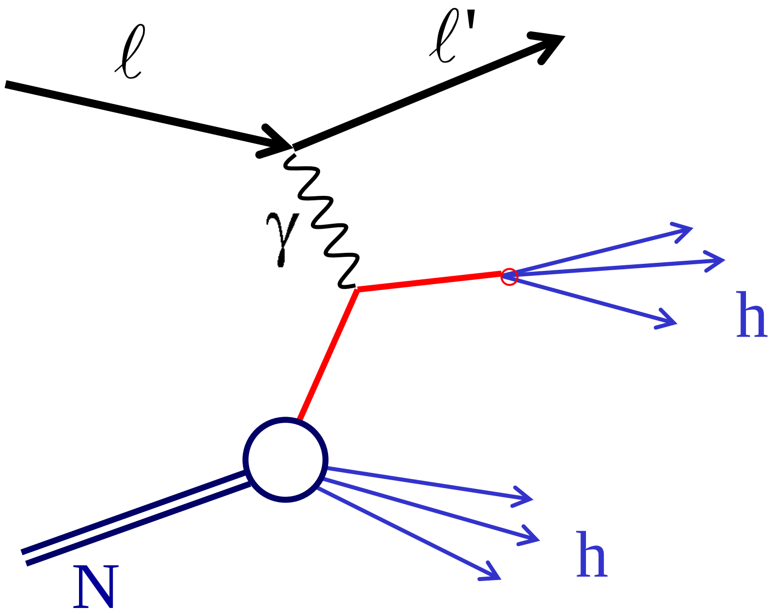

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NB: COMPLEMENTARY APPROACH @ RHIC (will not mention)

Structure Functions and PDFs: q(x)

Inclusive DIS: unpolarised

$$\frac{d\sigma}{dx\,dy} = \frac{e^4}{4\pi^2 Q^2} \cdot \left\{ \frac{y}{2} \cdot F_1 + \frac{1}{2xy} \cdot \left(1 - \frac{y}{2} - \frac{y^2}{4} \cdot \gamma^2 \right) \cdot F_2 \right\}$$

$F_2(x) = 2x \cdot F_1(x)$ Callan-Gross

in the parton model

$$F_1(x) = \frac{1}{2} \sum_q e_q^2 \cdot \left[q(x) + \bar{q}(x) \right]$$

$$q = u, d, s$$

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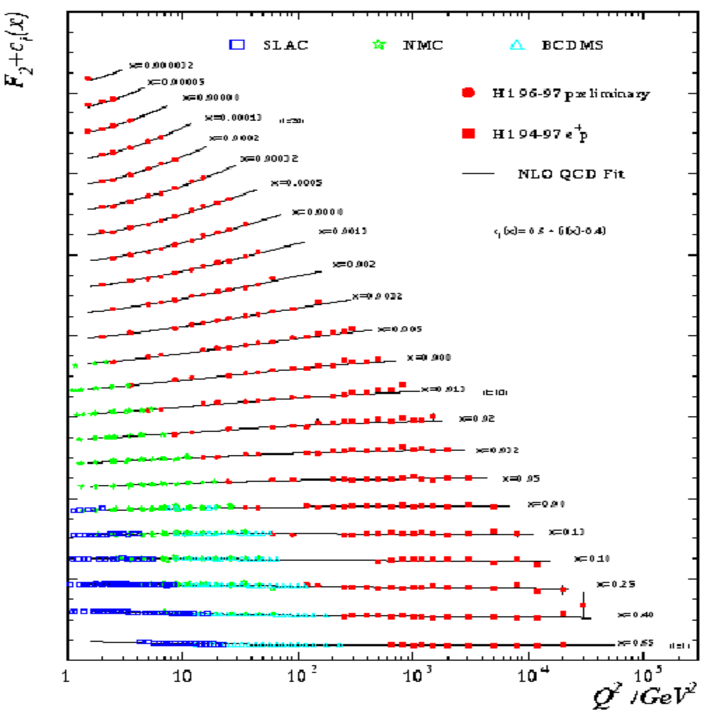
measured at CERN, HERA, SLAC



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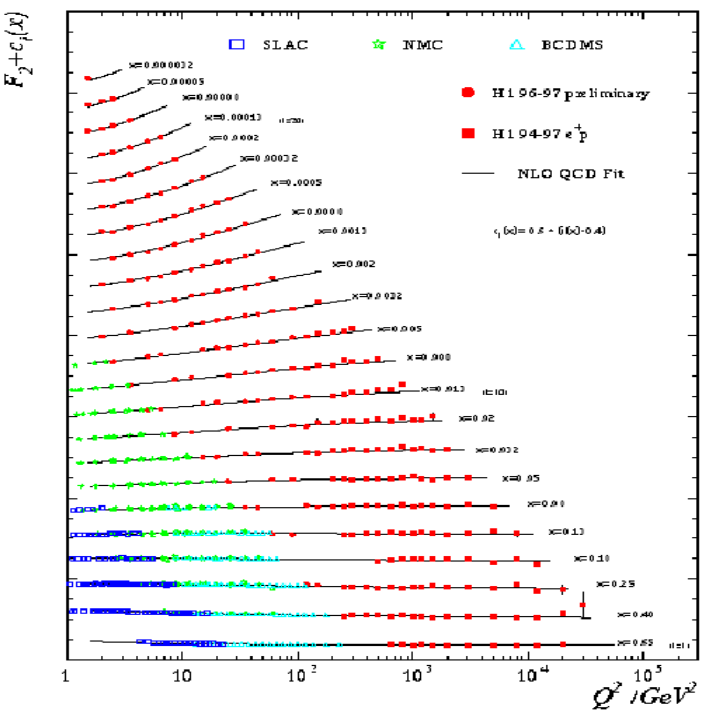

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⇒ **q(x) from global analysis of DIS and hard scattering data (QCD fits)**

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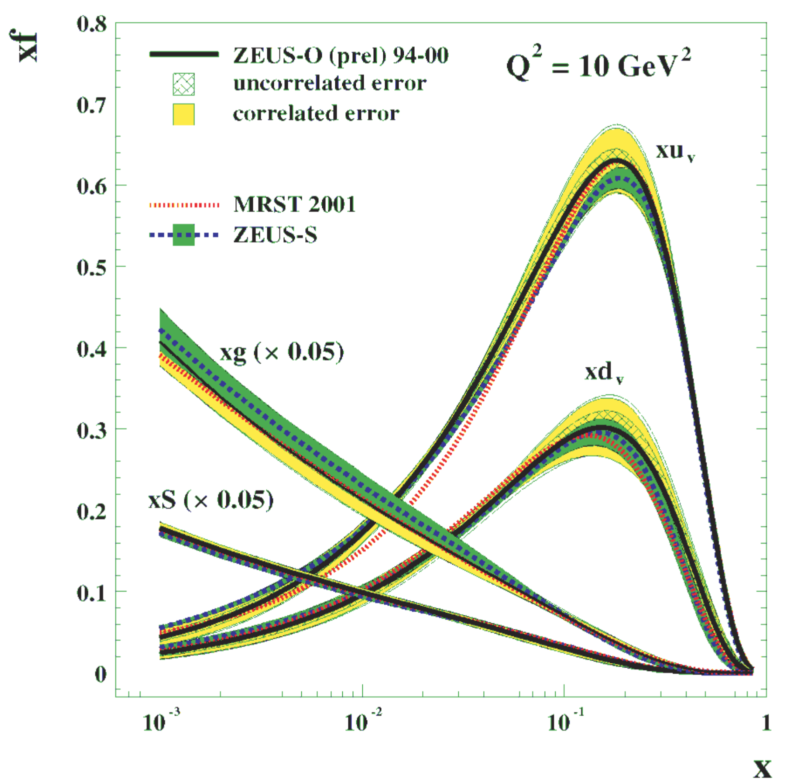

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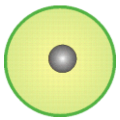
q(x) : number density or **unpolarised distribution**



probability of finding a quark with a fraction x of the longitudinal momentum of the parent nucleon

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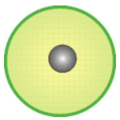

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$\Delta q(x) = q^{\rightrightarrows} - q^{\leftrightarrows}$: longitudinal polarization or **helicity distribution**

in a longitudinally polarised nucleon, probability of finding a quark with a momentum fraction x and spin parallel to that of the parent nucleon

Helicity PDFs

Δq's can be extracted from the DIS cross-section asimmetry Δσ for

parallel → →

and

antiparallel → ←

lepton and nucleon spins

Structure Functions and Helicity PDFs

Inclusive DIS: beam and target longitudinally polarized

$$\frac{d\Delta\sigma}{dx\,dy} = \lambda \cdot \frac{e^4}{4\pi^2 Q^2} \cdot \left[\left(1 - \frac{y}{2} - \frac{y^2}{4} \cdot \gamma^2 \right) \cdot g_1 - \frac{y}{2} \cdot \gamma^2 \cdot g_2 \right]$$

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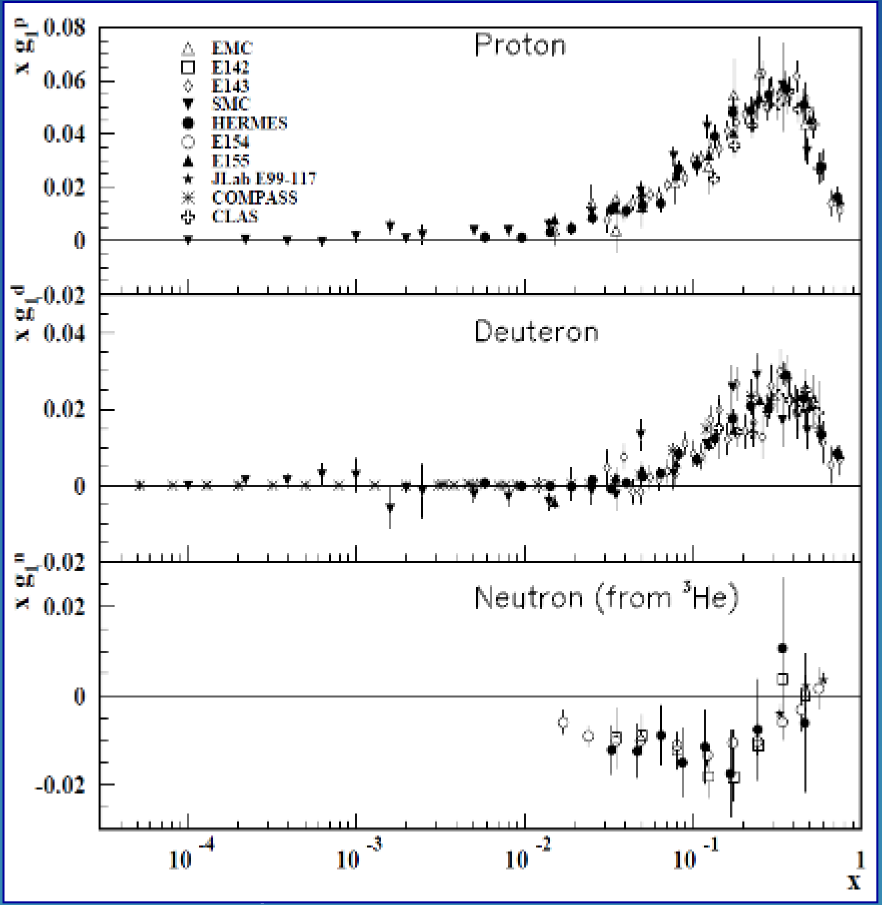
beam/target helicity



g_1 measured at SLAC, EMC, SMC, HERMES, COMPASS

g_2 suppressed by a factor $\gamma^2 \approx 0.01$ at 100 GeV (SMC, SLAC)

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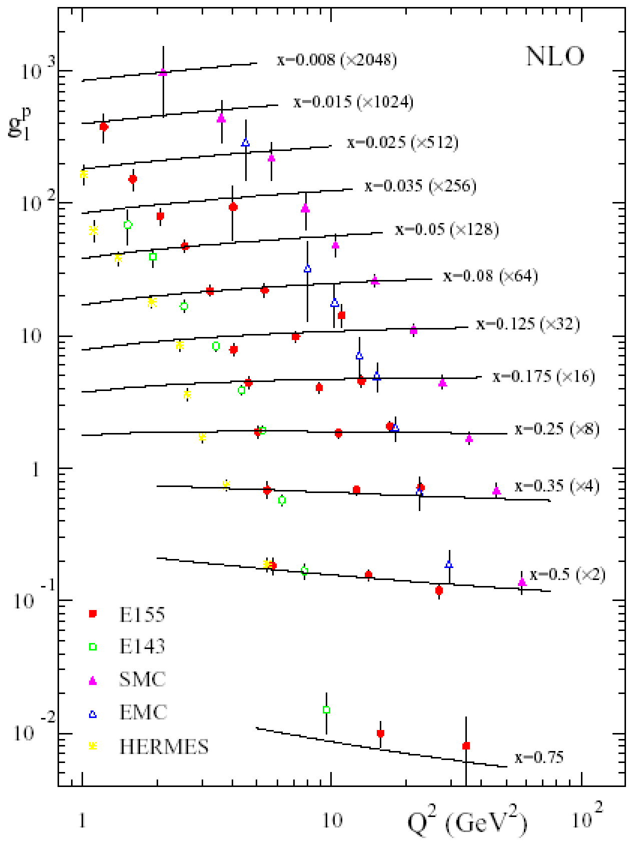

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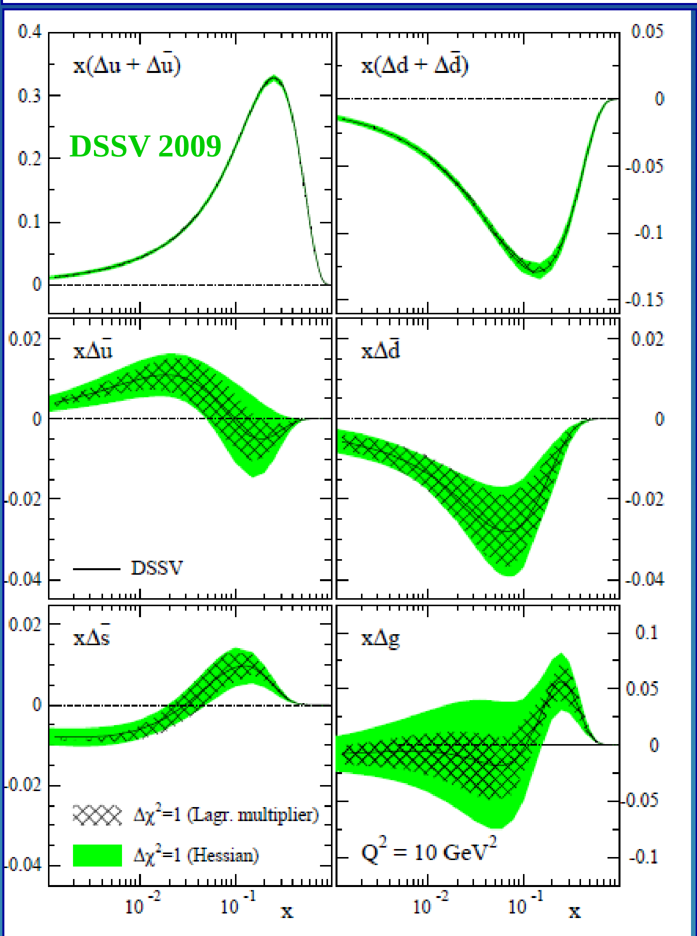

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The Quark Contribution to the Nucleon Spin

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

$$\Delta q = \int_0^1 \Delta q(x) = \int_0^1 \left[q^+(x) - q^-(x) + \bar{q}^+(x) - \bar{q}^-(x) \right] dx$$

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in polarised inclusive DIS one measures

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using complementary information from
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$$\Delta u - \Delta d = F + D = 1.257 \pm 0.003$$

$$\Delta u + \Delta d - 2\,\Delta s = 3F - D = \sqrt{3} \cdot (0.34 \pm 0.02)$$

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Δu, Δd, Δs can also be measured in semi-inclusive DIS

→ *E. Kabuss*

Experiments

a worldwide effort since decades

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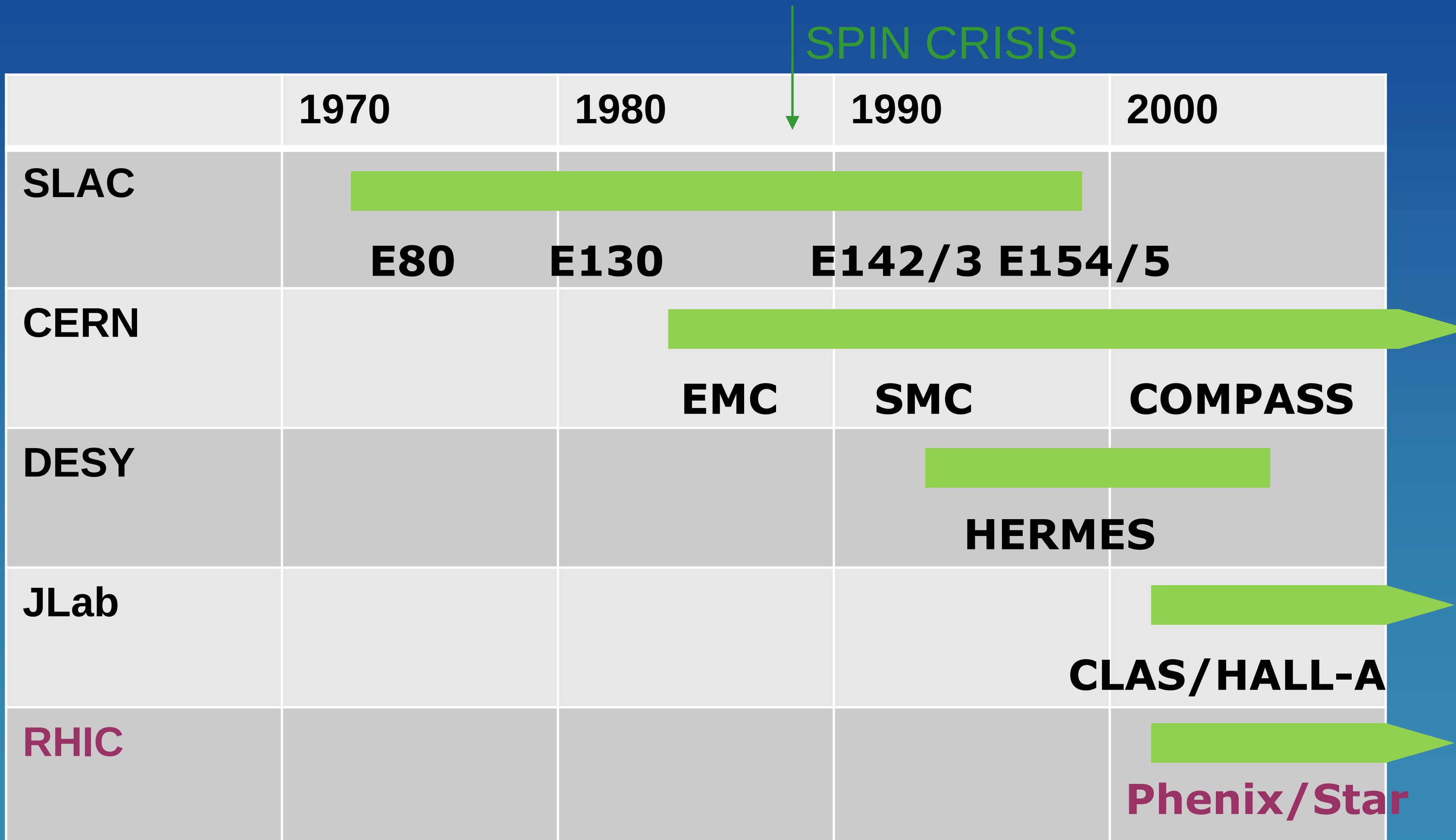


The Players, today

- **HERMES** @ DESY ***pure H and D target***
- **COMPASS** @ CERN ***high energy μ-beam***
- **JLAB** Experiments ***very high luminosity***

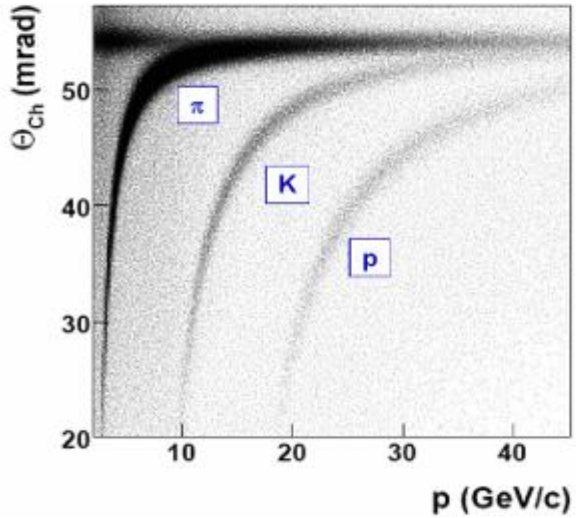
- longitudinally polarised muon beam
- longitudinally or transversely polarised target
- calorimetry
- particle identification

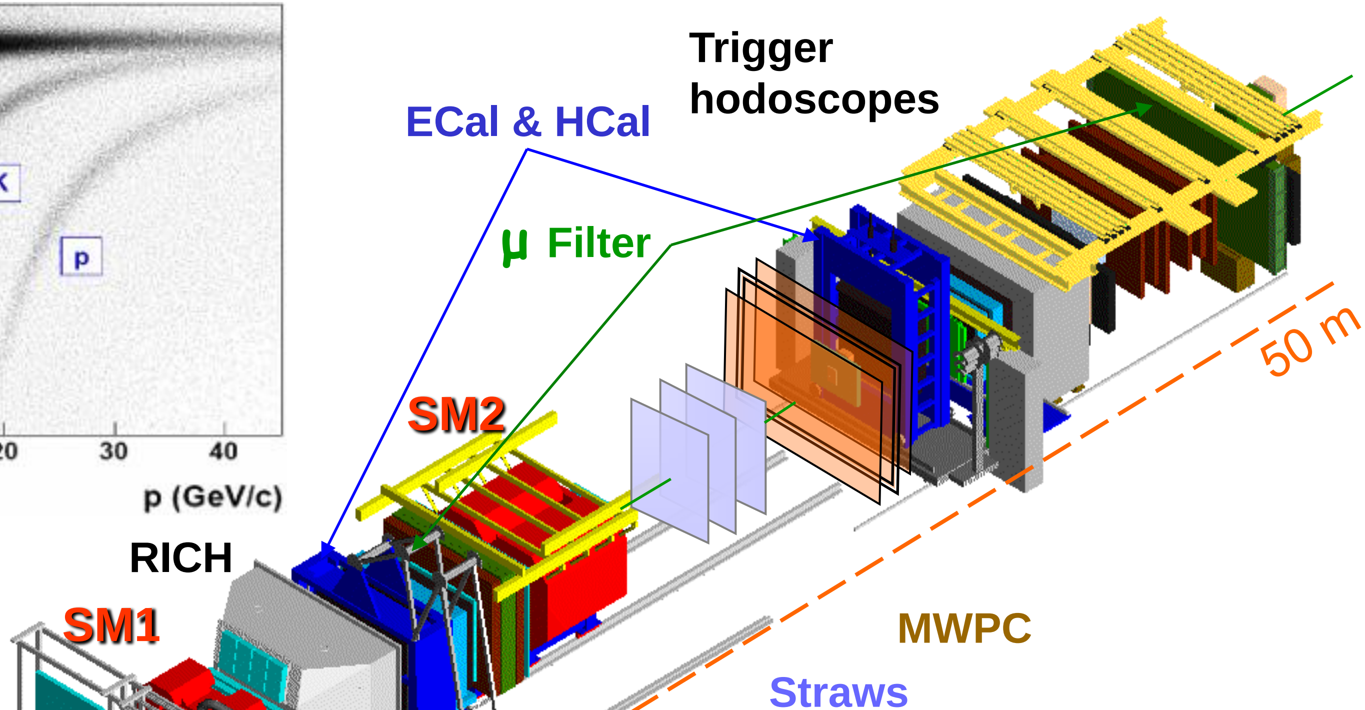
luminosity: ~$5 \cdot 10^{32}$ cm^{-2} s^{-1}

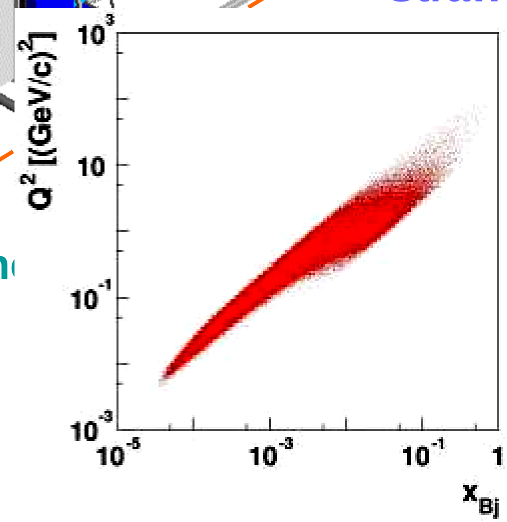
beam intensity: $2 \cdot 10^{8}$ μ^{+}/spill (4.8s/16.2s)

beam momentum: 160 GeV/c

COMPASS







TWO STAGE SPECTROMETER:

Polarized beam and target

SAT, LAT, PID

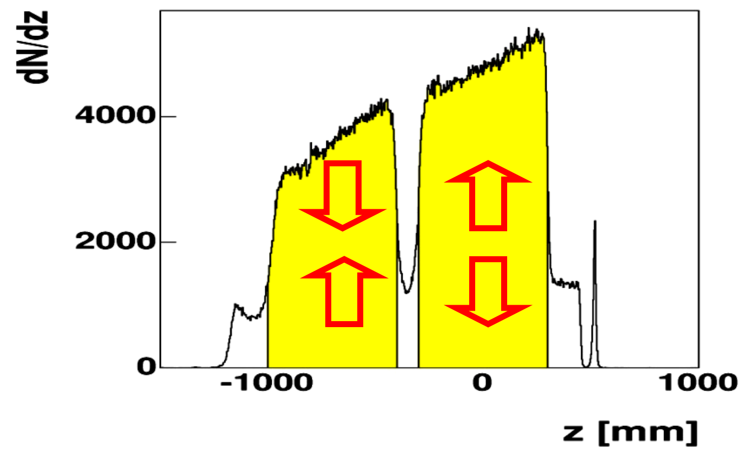
$0.003 < x < 0.5$
$10^{-3} < Q^2 < 10$ GeV^2

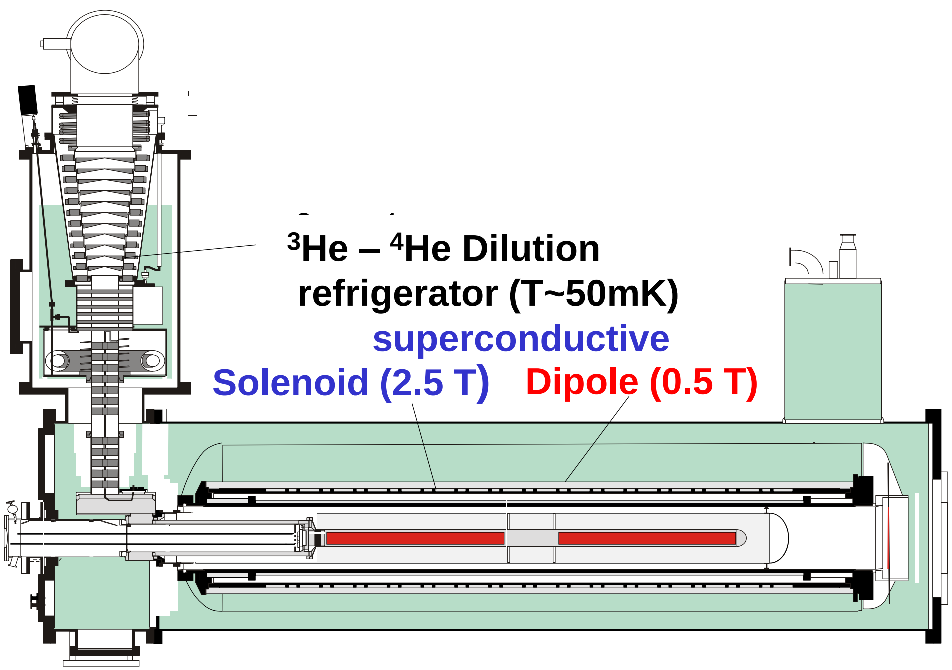
COMPASS the target system

solid state target operated in frozen spin mode

2002-2004: ^{6}LiD (polarised deuteron, L&T)
dilution factor f = 0.38
polarization P_T = 50%

two 60 cm long cells
with opposite polarisation (systematics)





during data taking with transverse polarisation,
polarisation reversal in the cells after ~ 4-5 days

COMPASS the target system

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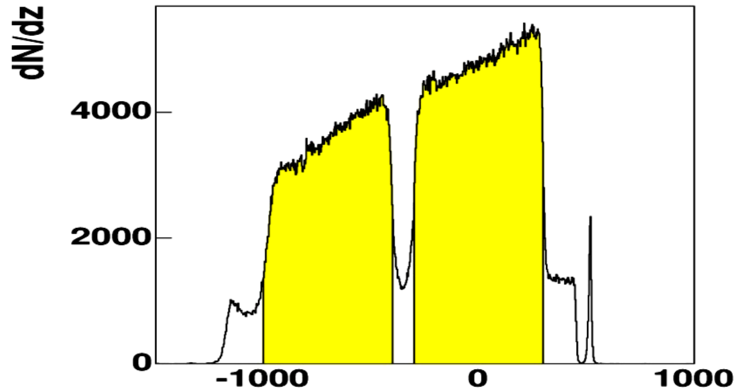
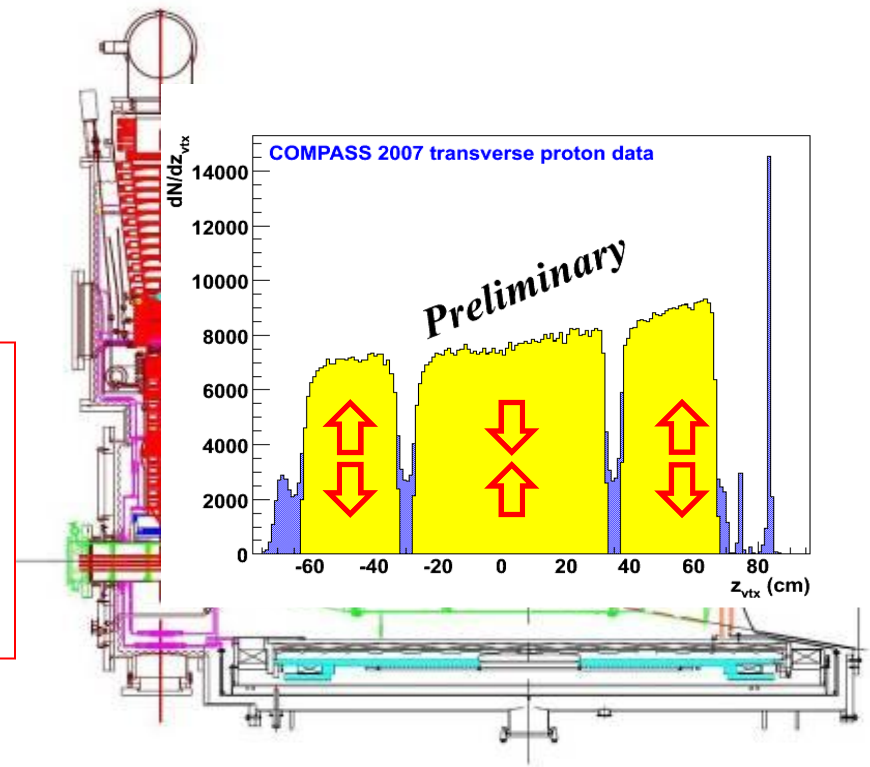


2006:

- **PTM replaced with the large acceptance COMPASS magnet (180 mrad)**
- **2 target cells ➔ 3 target cells**
- **^{6}LiD (L)**

2007: NH_3 (polarised protons, L&T)
dilution factor f = 0.14
polarization P_T = 90%

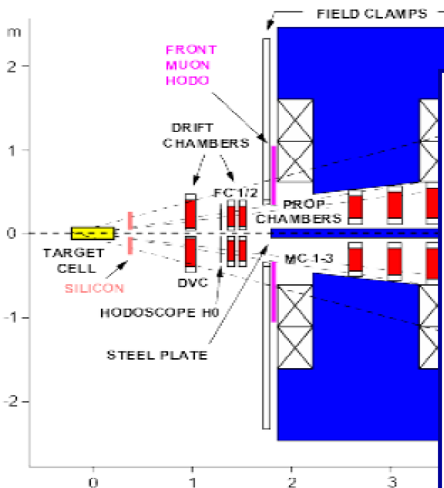
2010: NH_3 (T)
2011: NH_3 (L)



HERMES

27.5 GeV e^+

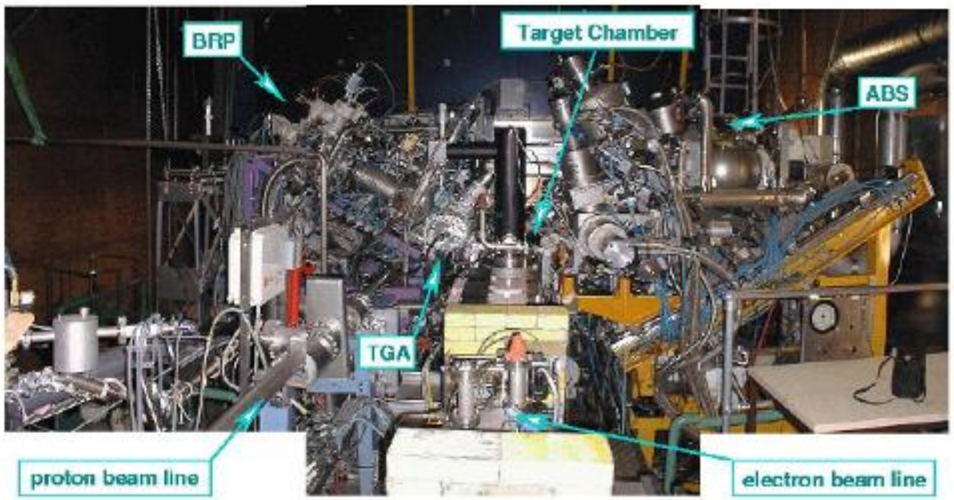
$\sqrt{s}$ = 7 GeV



particle ID: lepton ID v
hadron co
RICH:

the HERMES polarized target

pure hydrogen gas target

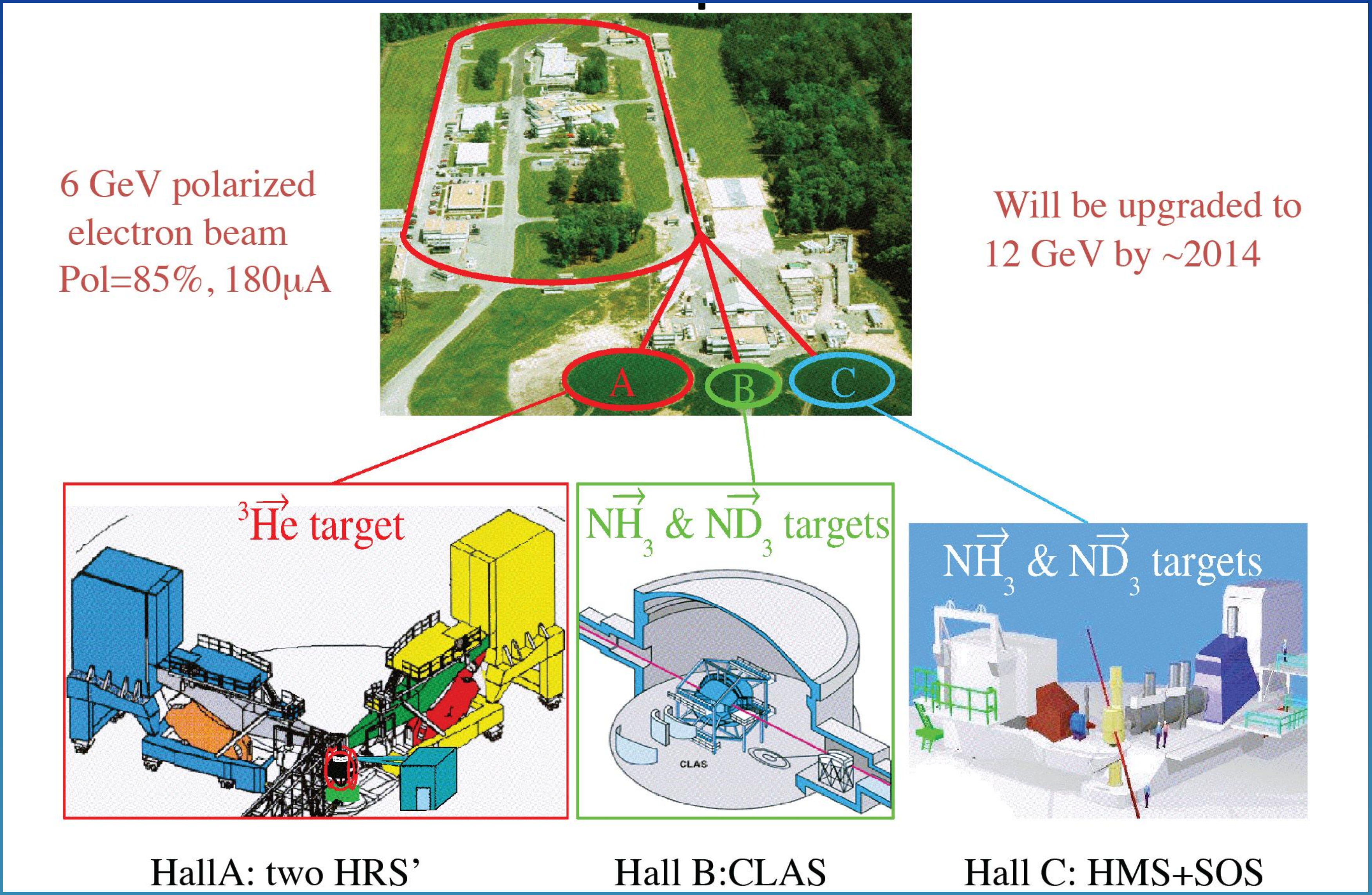


flipped at high frequency (60- 90 s)

$^1H \rightarrow$ $<|P_t|>$ ~ 85 ±3.8 %

$^2H \rightarrow$ $<|P_t|>$ ~ 84 ±3.5 % $^1H \uparrow$ $<|P_t|>$ ~ 74 ±4.2 %

JLab experiments



THE QCD STRUCTURE

- LONGITUDINAL
- TRANSVERSE

Parton Distribution Functions

in the collinear case, three distribution functions are necessary to describe the structure of the nucleon at LO:

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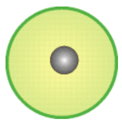
q(x) : number density or **unpolarised distribution**



probability of finding a quark with a fraction x of the longitudinal momentum of the parent nucleon

$\Delta q(x) = q^{\rightrightarrows} - q^{\leftrightarrows}$: longitudinal polarization or **helicity distribution**

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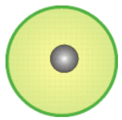

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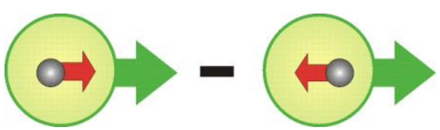
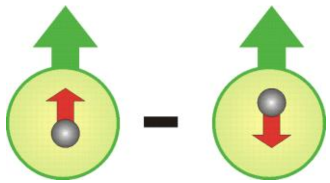


in a longitudinally polarised nucleon, probability of finding a quark with a momentum fraction x and spin parallel to that of the parent nucleon

$\Delta_T q(x) = q^{\uparrow\uparrow} - q^{\downarrow\uparrow}$: transverse polarization or transversity distribution



in a transversely polarised nucleon, probability of finding a quark with a momentum fraction x and polarisation parallel to that of the parent nucleon

q quark or antiquark with a specific flavor [*notation: Barone, Drago, Raftcliffe 2001*]

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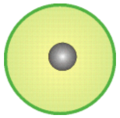

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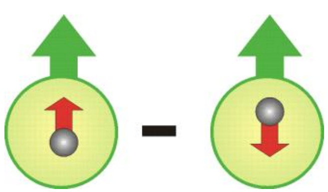
$\Delta_T q(x) = q^{\upuparrows} - q^{\downuparrows}$: transverse polarization or transversity distribution



in a transversely polarised nucleon, probability of finding a quark with a momentum fraction x and polarisation parallel to that of the parent nucleon

q quark or antiquark with a specific flavor [*notation: Barone, Drago, Raftcliffe 2001*]

ALL OF EQUAL IMPORTANCE !

HELICITY vs TRANSVERSITY

HELICITY and TRANSVERSITY

are different

have different properties

are measured in different ways

thus

one has to deal differently the situations when the target spins are

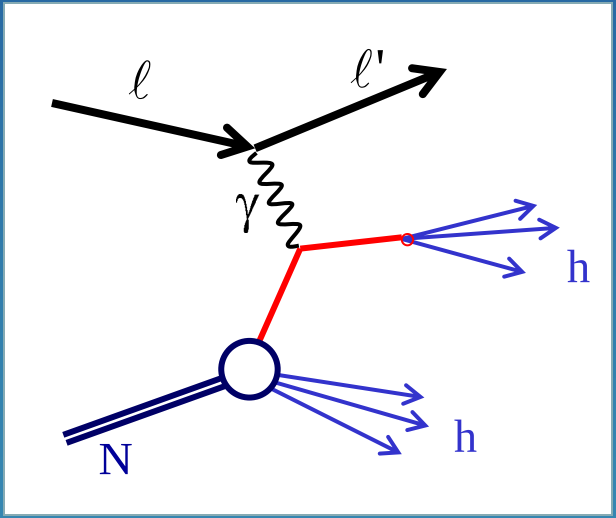
LONGITUDINAL → *E. Kabuss*

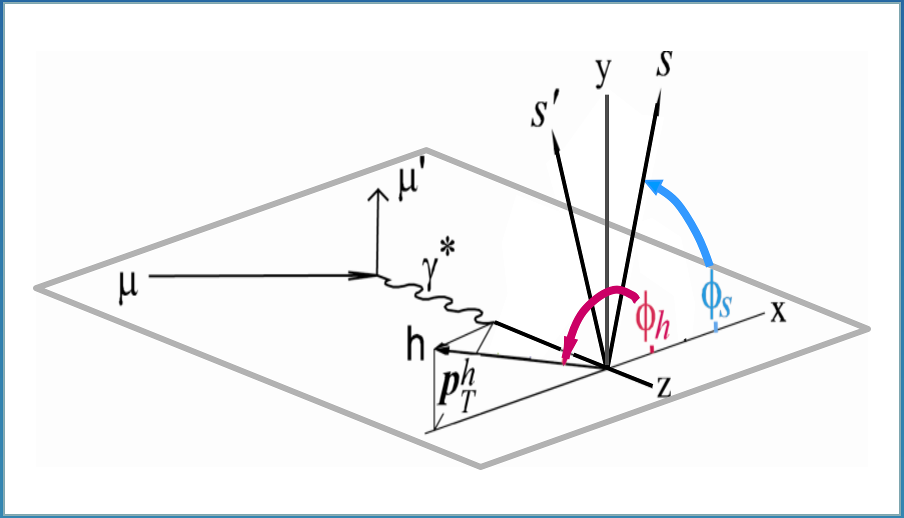
and

TRANSVERSE

TRANSVERSITY PDFs

Transversity can only be accessed in SIDIS from the azimuthal modulation of the final state hadrons with respect to the lepton plane





Puzzles in hadronic reactions

VOLUME 41, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1978

Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

G. L. Kane J. Pumplin W. Repko

The quantum-chromodynamics prediction is that $P=0$ in the scaling limit.

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \frac{\mathbf{m_q}}{\sqrt{\mathbf{s}}}$$

i.e.

$m_q = 3\text{MeV}, \ \sqrt{s} = 20 \text{ GeV} \Rightarrow \mathbf{A_N \approx 10^{-4}}$

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i.e.
$m_q = 3\,\text{MeV}, \ \sqrt{s} = 20\ \text{GeV} \Rightarrow A_N \approx 10^{-4}$

in hadronic reactions like $p^{\uparrow} + p \rightarrow \pi + X$

with a transversely polarized proton,

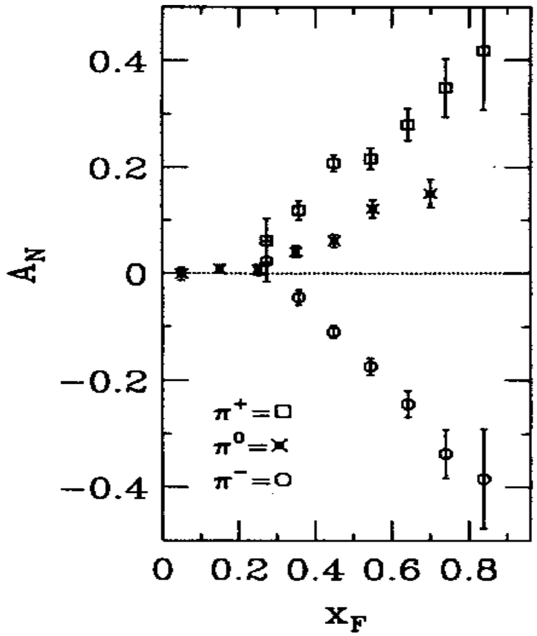
the spin asymmetry in leading twist perturbative QCD is expected to vanish

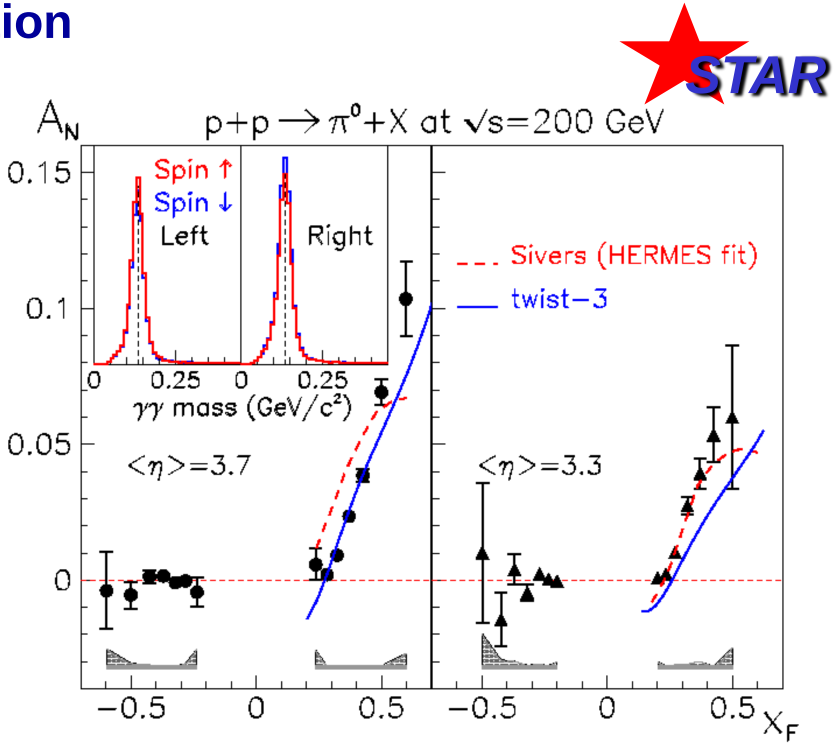
THE DATA STRONGLY CONTRADICT THIS!

Puzzles in hadronic reactions

Since many years intriguing evidence of large transverse spin effects at high energy

- **hyperon polarization**
- **high p_t effects in hadronic interactions**
- **asymmetries in hadron production**





RUN6 PRL 101 (2008) 222001

Puzzles in hadronic reactions

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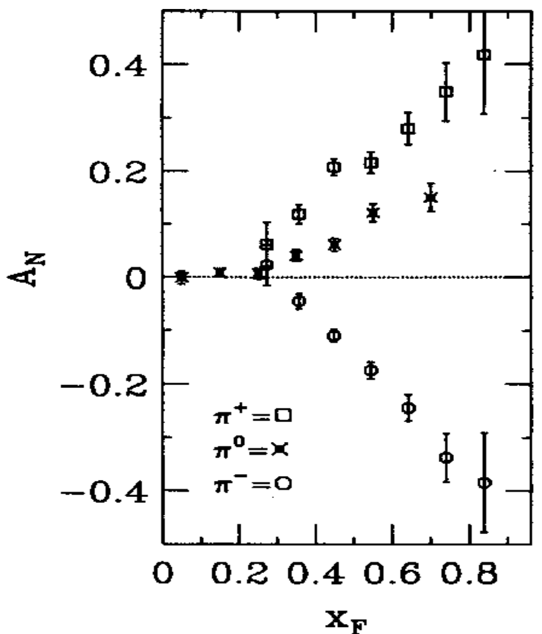

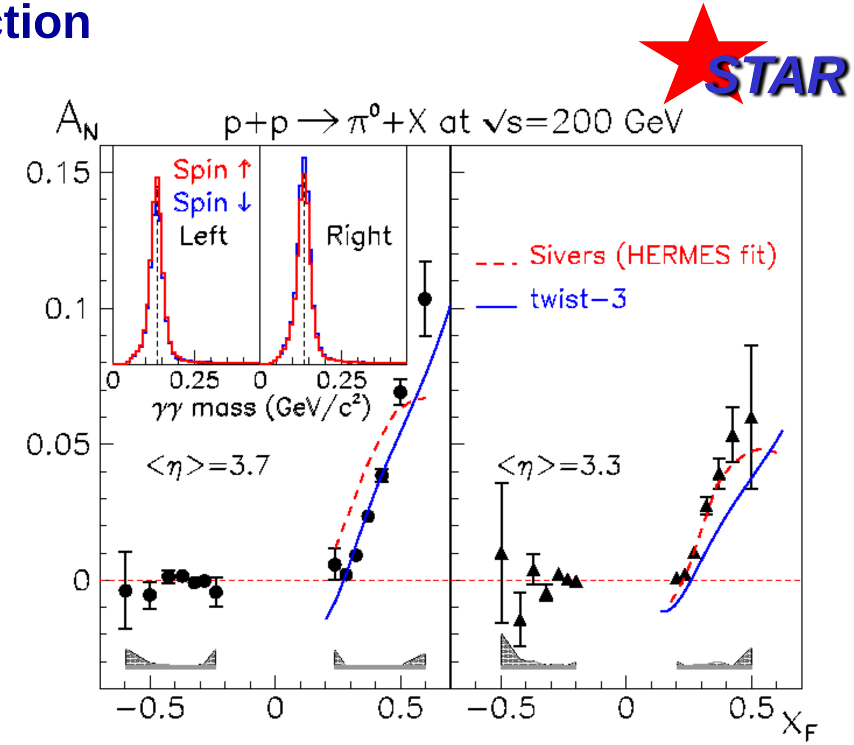

Hope to find solutions at the quark level ($\Delta_T q(x)$ …)

HOW to MEASURE TRANSVERSITY

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$\Delta_T q(x)$ is chiral-odd

→ cannot be measured in inclusive DIS

HOW to MEASURE TRANSVERSITY

$\Delta_T q(x)$ is chiral-odd

→ cannot be measured in inclusive DIS

it can be measured in SIDIS:

the observable is the so- called "Collins asymmetry",
the convolution of $\Delta_T q(x)$ with another chiral-odd quantity,
the "Collins" function, which describes a possible left-right
asimmetry of the hadrons in the hadronization process
of a transversely polarized quark

Collins asymmetry

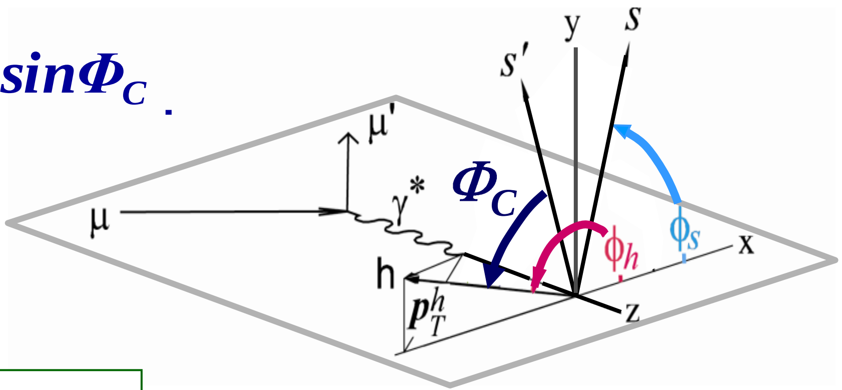
in SIDIS off transversity polarised nucleons

amplitude of the $\sin\Phi_C$ modulation
in the azimuthal distribution
of the final state hadrons

$$\Phi_C = \phi_h + \phi_S - \pi$$

ϕ_h azimuthal angle of the hadron,
ϕ_S azimuhtal angle of the nucleon spin

$$N_h^{\pm}(\Phi_C) = N_h^0 \cdot [1 \pm P_T \cdot D_{NN} \cdot A_{Coll} \cdot \sin\Phi_C] .$$



transversity

"Collins FF"

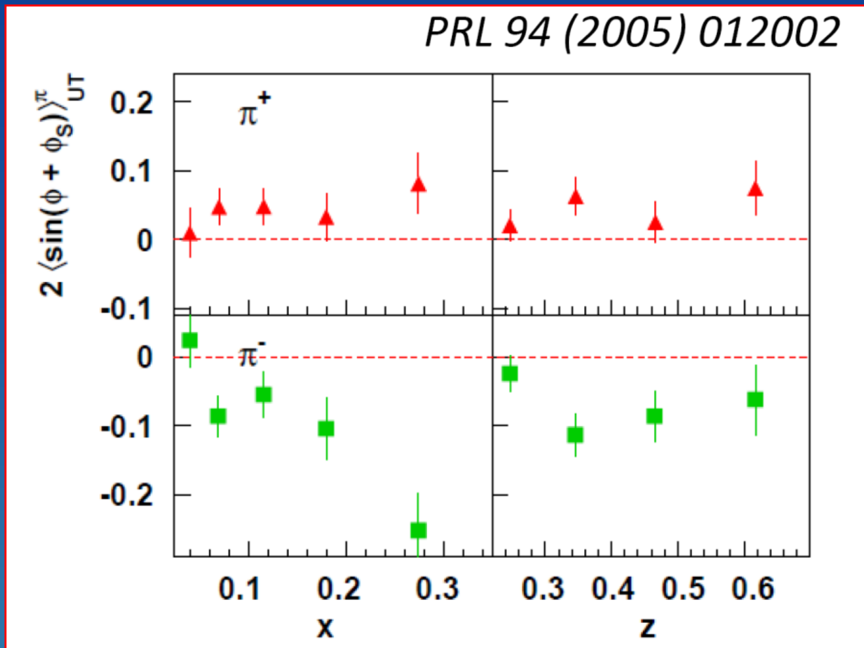
$$A_{Coll} \approx \frac{\sum_q e_q^2 \, \Delta_T q \otimes \Delta_T^0 D_q^h}{\sum_q e_q^2 \, q \otimes D_q^h}$$

both unknown !

today the most promising way to access transversity

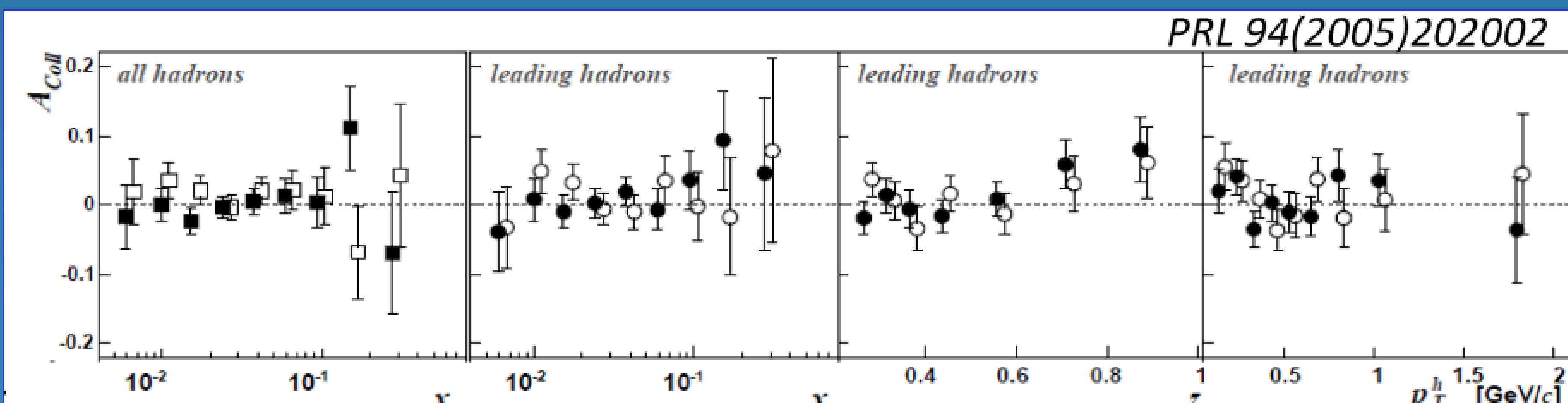
The conjecture was right !!

The conjecture was right !!



proton data

deuteron data



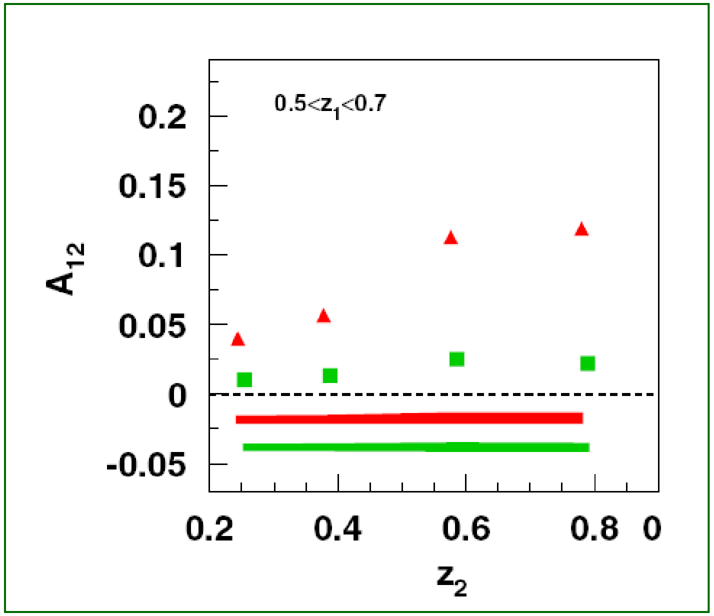
The conjecture was right !!

"Collins FF"

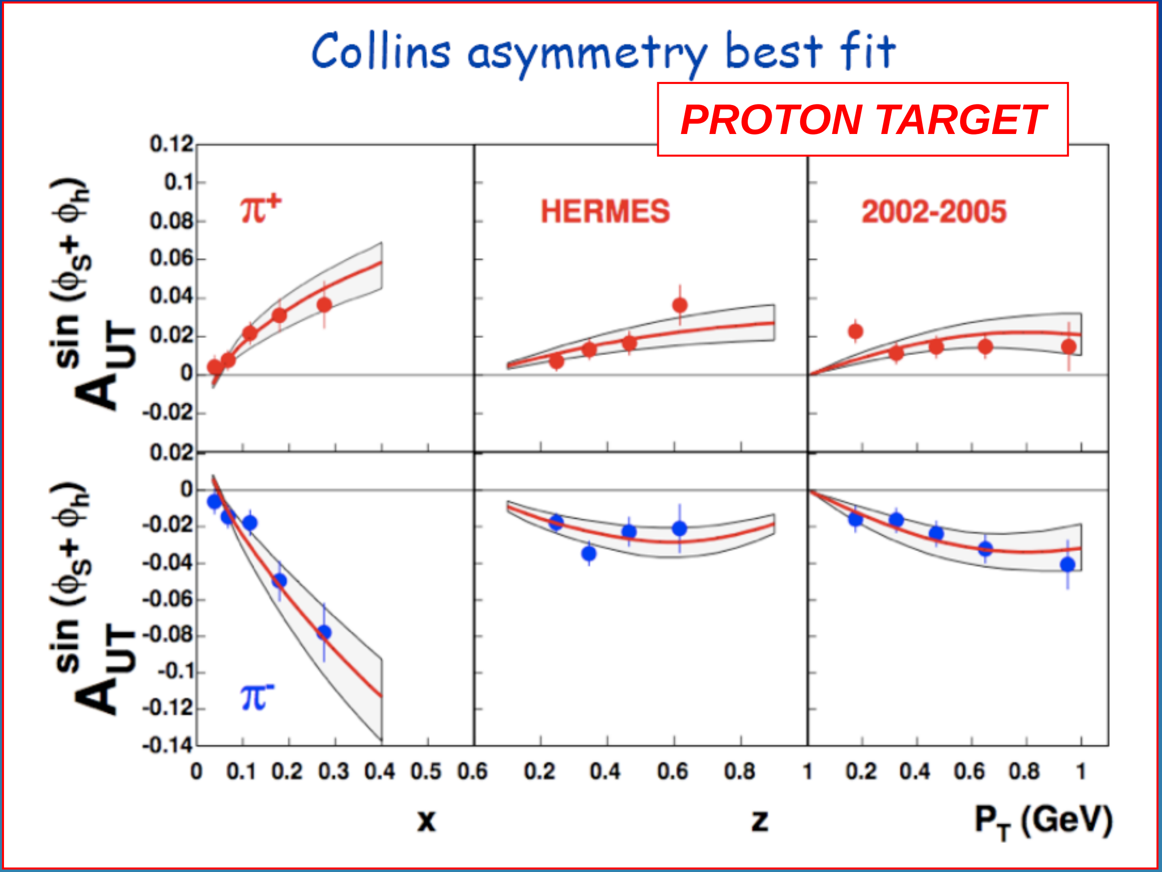
$$A_{Coll} \approx \frac{\sum_q e_q^2\, \Delta_T q \otimes \Delta_T^0 D_q^h}{\sum_q e_q^2\, q \otimes D_q^h}$$

gives a LR asymmetry in the hadronisation of transversely polarised quarks

- ***products of Collins FFs can be measured in*** $e^+e^- \to \pi^+\pi^- X$
- first low statistics results from LEP data
- **2005 first data from BELLE**



TRANSVERSITY PDFs



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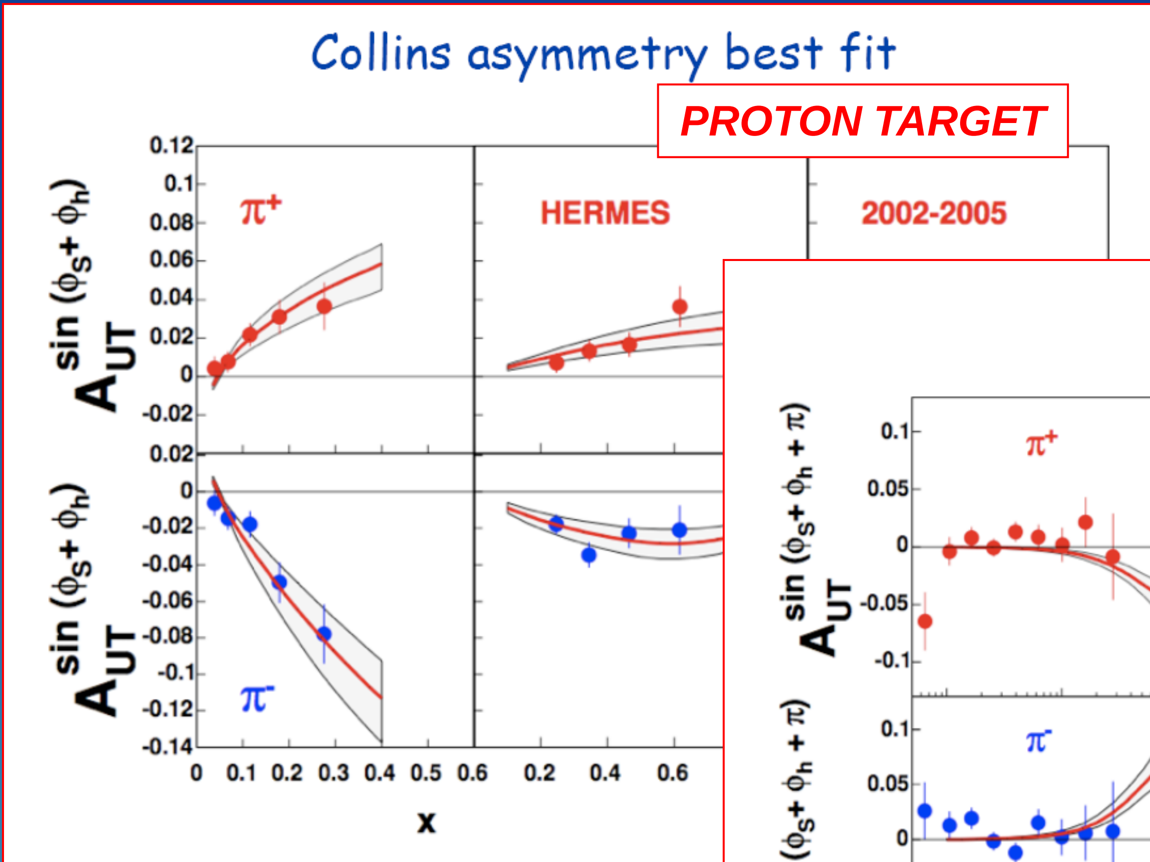
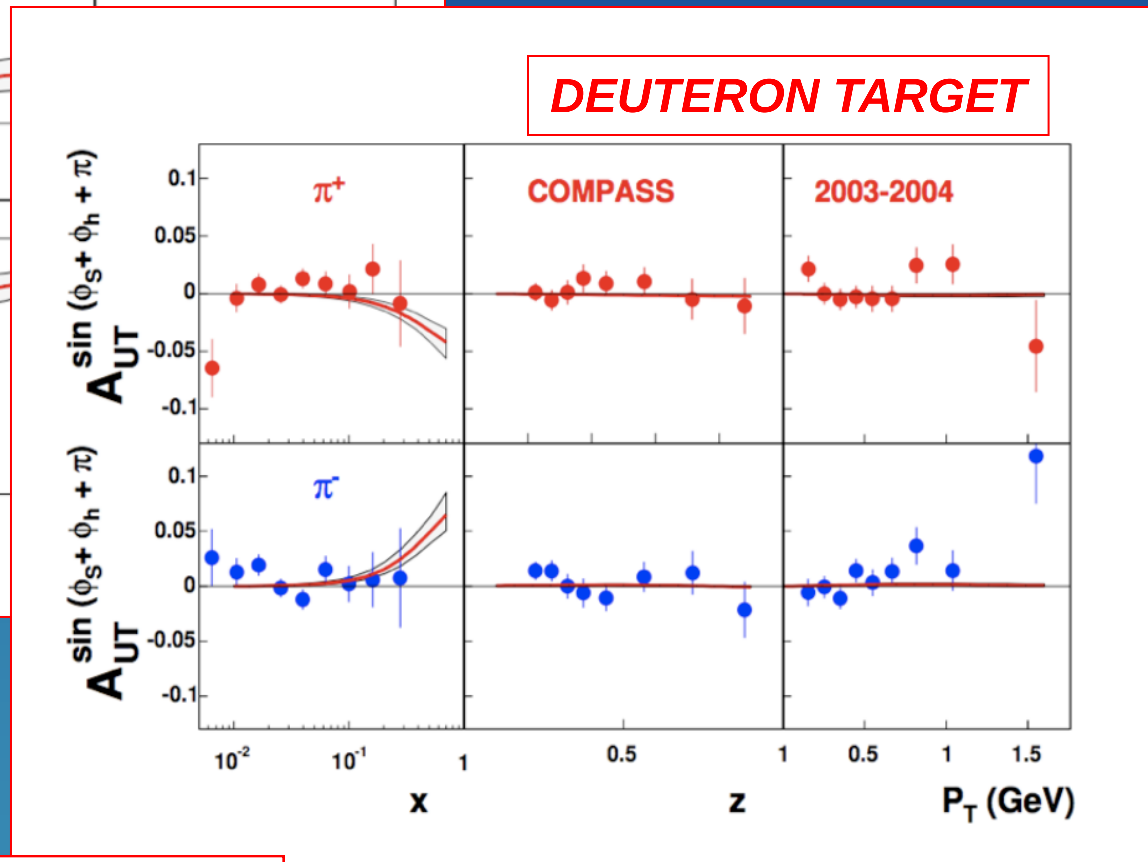
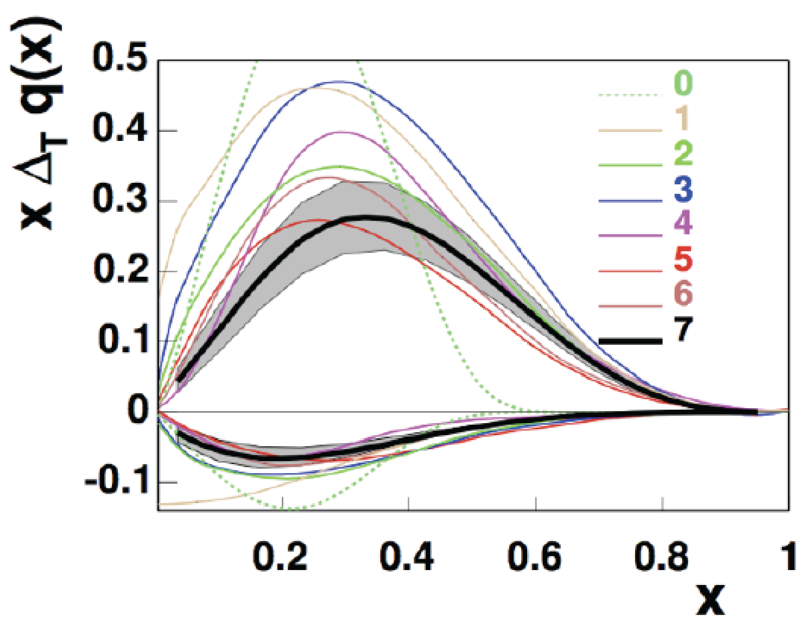




plus BELLE data on e^+e^- → *hadrons*

TRANSVERSITY PDFs

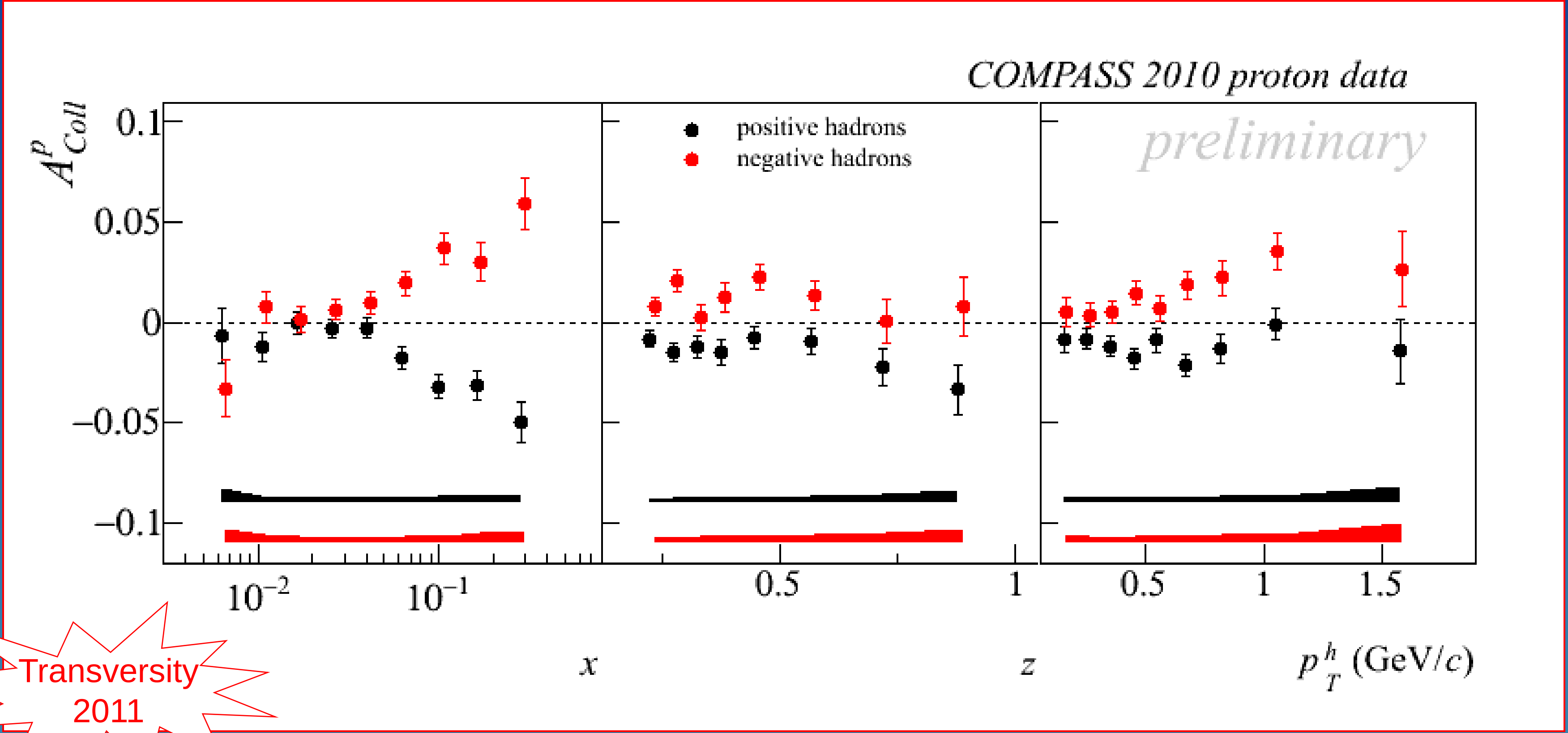
comparison of extracted transversity distributions with models



0. Barone, Calarco, Drago PLB 390 287 (97)
1. Soffer et al. PRD 65 (02)
2. Korotkov et al. EPJC 18 (01)
3. Schweitzer et al. PRD 64 (01)
4. Wakamatsu, PLB B653 (07)
5. Pasquini et al., PRD 72 (05)
6. Cloet, Bentz and Thomas PLB 659 (08)
7. This analysis.

Anselmino et al., PRD75 (2007)

Collins asymmetry

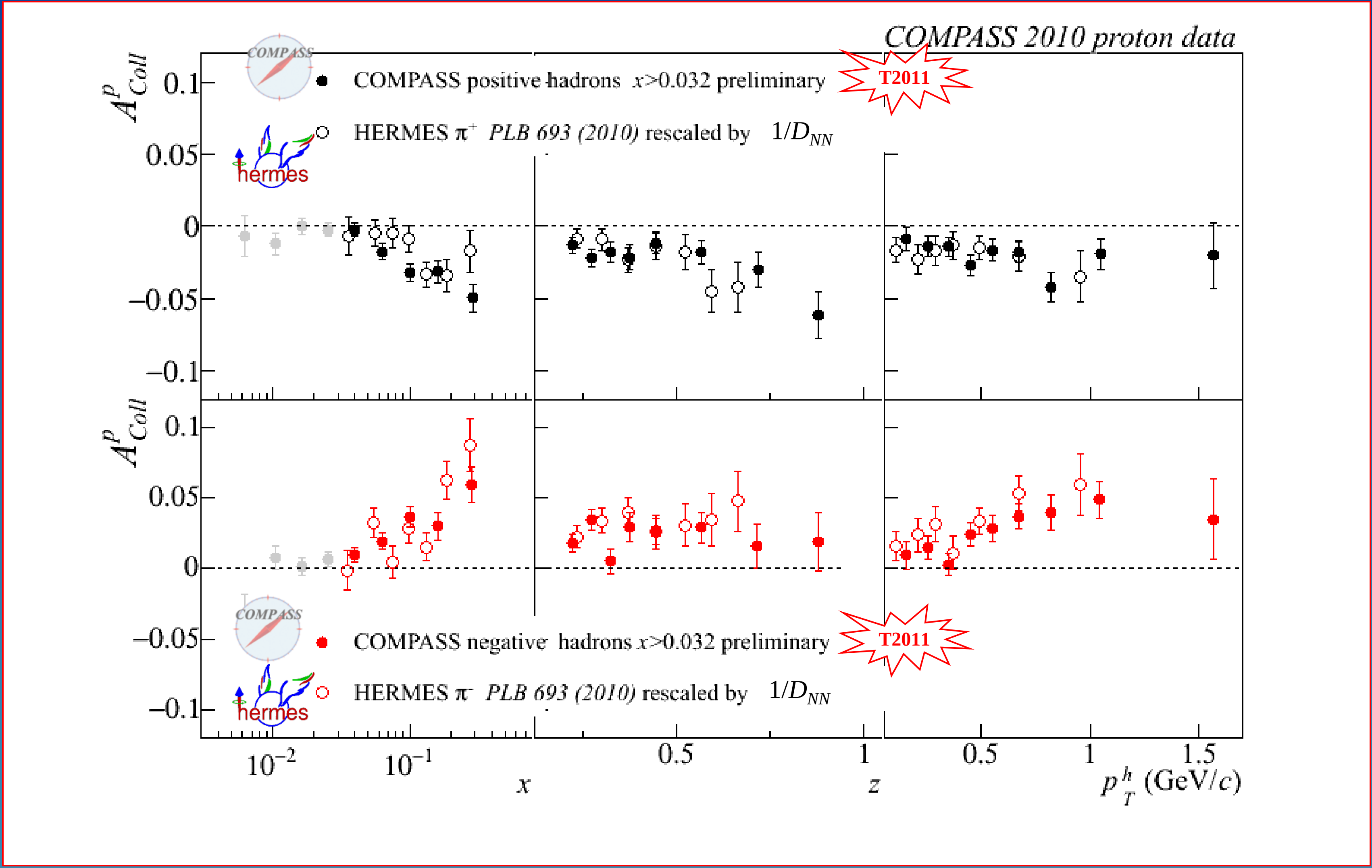


Transversity 2011

nice confirmation of the 2007 results,
with better statistics
$\sigma_{syst} \sim 0.5\ \sigma_{stat}$

Collins asymmetry

x > 0.032 region - comparison with HERMES results



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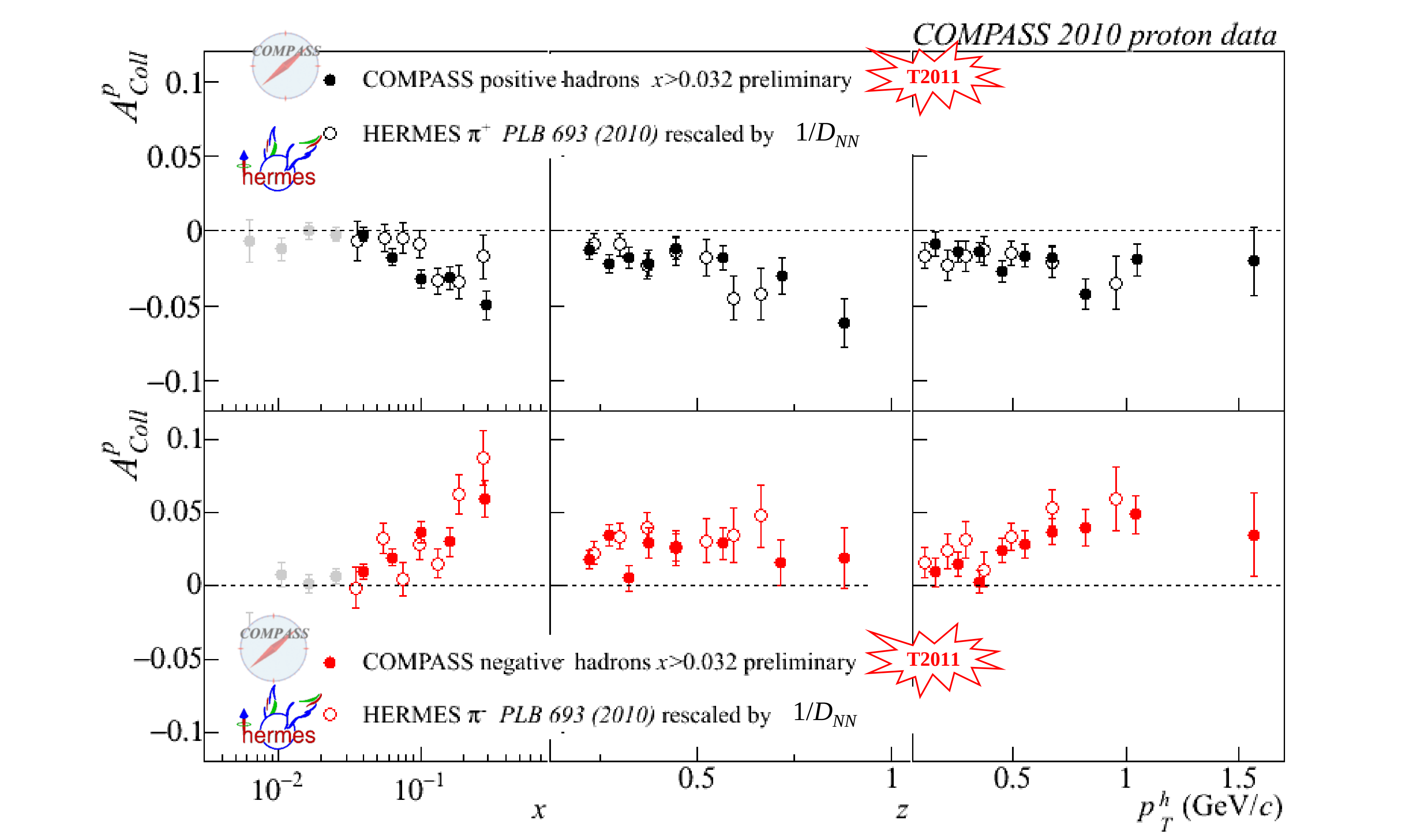

nice agreement in spite of the different Q^2 values
a very important result

The Structure of the Nucleon

new developments

The Structure of the Nucleon

in the collinear case, three distribution functions
are necessary to describe the structure of the nucleon at LO

nucleon polarisation

quark polarisation		U	L	T	
	U	f_1 *number density* q			
	L		g_1 - *helicity* Δq		
	T			h_1 - *transversity*	$\Delta_T q$

The Structure of the Nucleon

taking into account the quark intrinsic transverse momentum k_T,
at leading order 8 PDFs are needed
for a full description of the nucleon structure *"TMDs"*

nucleon polarisation (columns) / **quark** polarisation (rows)

	U	L	T	
U	f_1 *number density* q		$f_{1T}^{\perp}$ *Sivers*	$\Delta_0^T q$
L		g_1 *helicity* Δq	g_{1T}	
T	$h_1^{\perp}$ *Boer Mulders*	$h_{1L}^{\perp}$	h_1 *transversity*; $h_{1T}^{\perp}$	$\Delta_T q$

The Structure of the Nucleon

taking into account the quark intrinsic transverse momentum k_T ,
at leading order 8 PDFs are needed
for a full description of the nucleon structure *"TMDs"*

Sivers function
correlation between the transverse spin of the nucleon and the transverse momentum of the quark
sensitive to orbital angular momentum

T-odd

Boer-Mulders function
correlation between the transverse spin and the transverse momentum of the quark in unpol nucleons

quark polarisation \ **nucleon** polarisation	U	L	T	
U	f_1 *number density* q		$f_{1T}^{\perp}$ *Sivers*	$\Delta_0^T q$
L		g_1 *helicity* Δq	g_{1T}	
T	$h_1^{\perp}$ *Boer Mulders*	$h_{1L}^{\perp}$	h_1 *transversity* $h_{1T}^{\perp}$	$\Delta_T q$

The Structure of the Nucleon

taking into account the quark intrinsic transverse momentum k_T,
at leading order 8 PDFs are needed
for a full description of the nucleon structure *"TMDs"*

SIDIS give access to all of them

nucleon polarisation

	U	L	T	
U	f_1 *number density* q		$f_{1T}^{\perp}$ *Sivers*	$\Delta_0^T q$
L		g_1 *helicity* Δq	g_{1T}	
T	$h_1^{\perp}$ *Boer Mulders*	$h_{1L}^{\perp}$	h_1 *transversity*; $h_{1T}^{\perp}$	$\Delta_T q$

SIDIS

- when taking into account the intrinsic transverse momentum of the quarks several azimuthal modulations are possible in the SIDIS cross-section

- the amplitudes of the modulations are convolutions of the different Transverse Momentum Dependent PDFs e FFs:

  $\sin 2\phi_h$
  $\sin(\phi_h + \phi_S)$ → Transversity PDF x Collins FF
  $\sin(\phi_h - \phi_S)$ → Sivers PDF
  $\sin(3\phi_h - \phi_S)$
  …

- all these amplitudes can be extracted from the SIDIS data

the Sivers function

a long debate

- **1992 introduced by D. Sivers**
- **1993 J. Collins demonstrate that it must vanish**
- **2002 S. Brodsky et al.: it can be ≠ 0 because of FSI**
- **2002 J. Collins: process dependent, change of sign SIDIS ↔ DY**

....

the Sivers function

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....

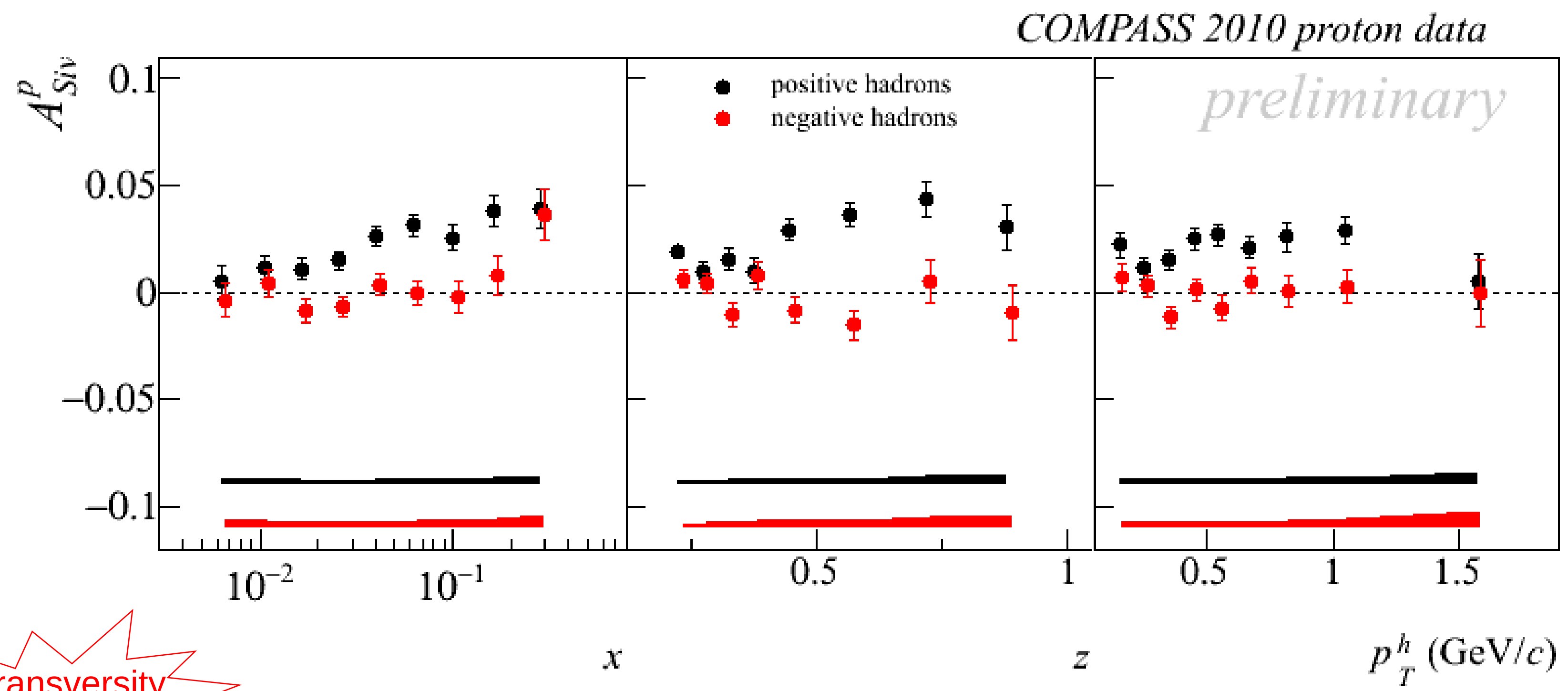
- **2005 first measurements of the Sivers asymmetry in SIDIS**

$$A_{Siv} = \frac{\sum_q e_q^2 \, f_{1T}^{\perp q} \otimes D_1^q}{\sum_q e_q^2 \, f_1 \otimes D_1^q} \qquad \frac{F_{UT}^{\sin(\phi_h - \phi_S)}}{F_{UU}}$$

strong signal seen by HERMES for π^+ on protons

no signal seen by COMPASS for h^+ and h^- on deuterons

Sivers asymmetry

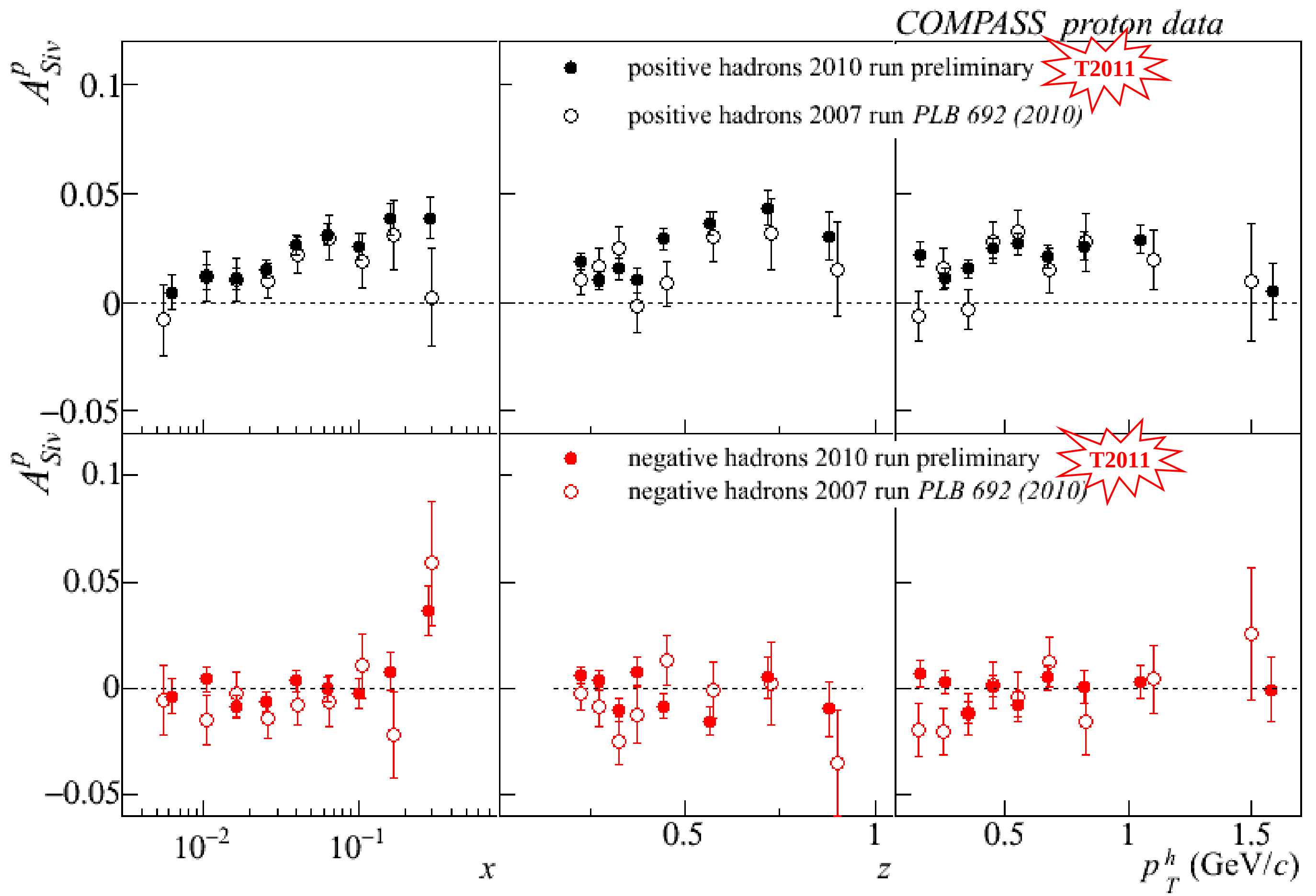


Transversity 2011

again, nice agreement with the 2007 results,
with better statistics
$\sigma_{syst} \sim 0.5\ \sigma_{stat}$ in 2010

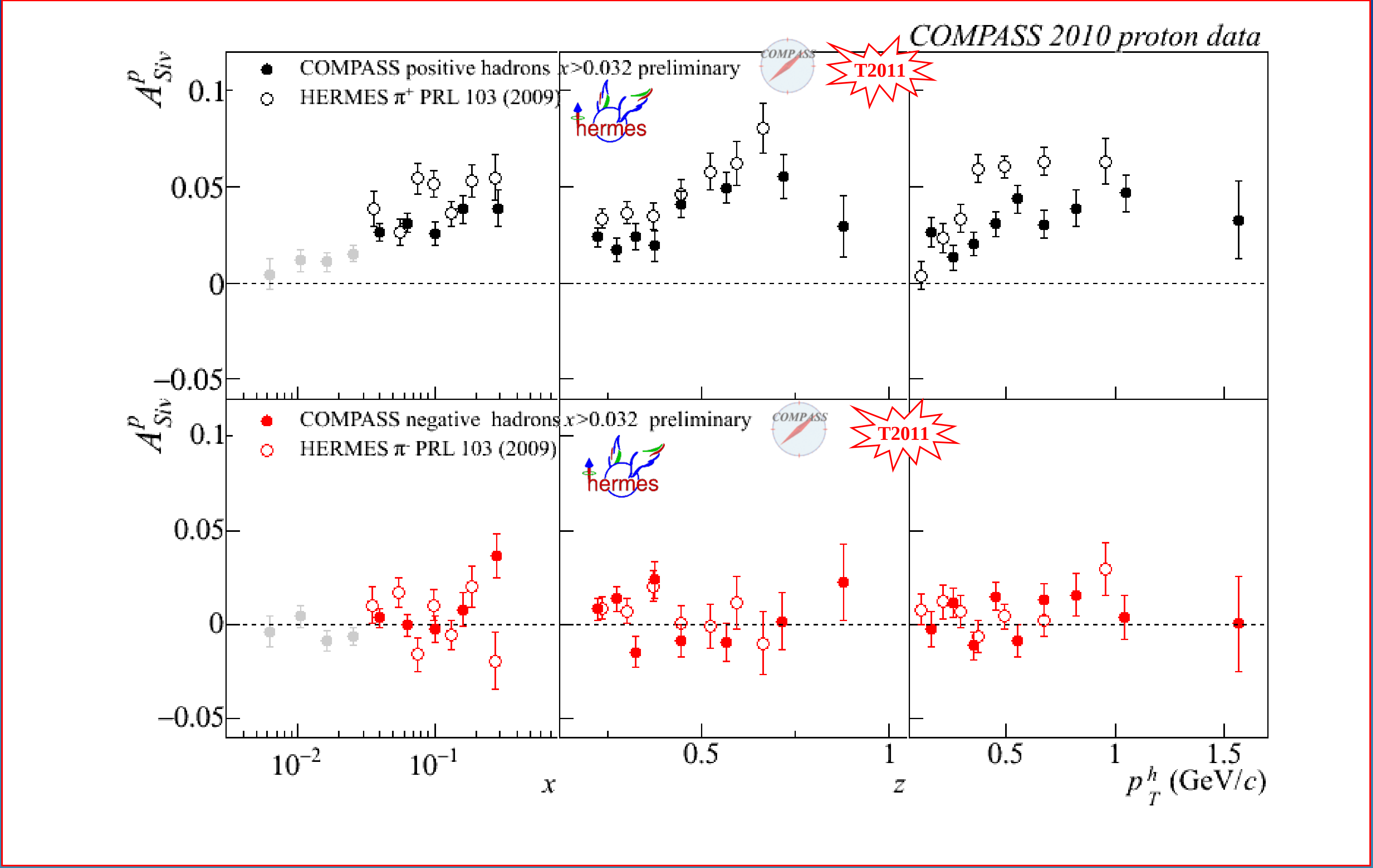
Sivers asymmetry

results from 2010 data vs results from 2007data



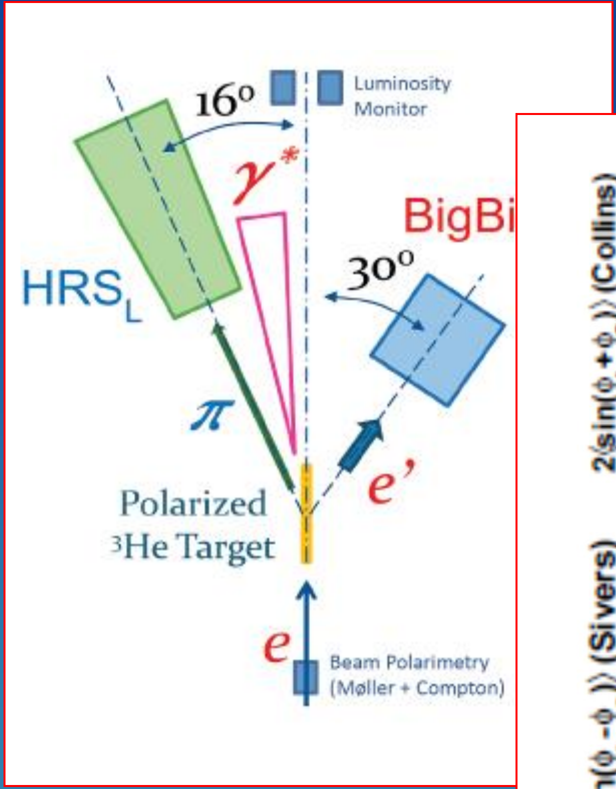
Sivers asymmetry

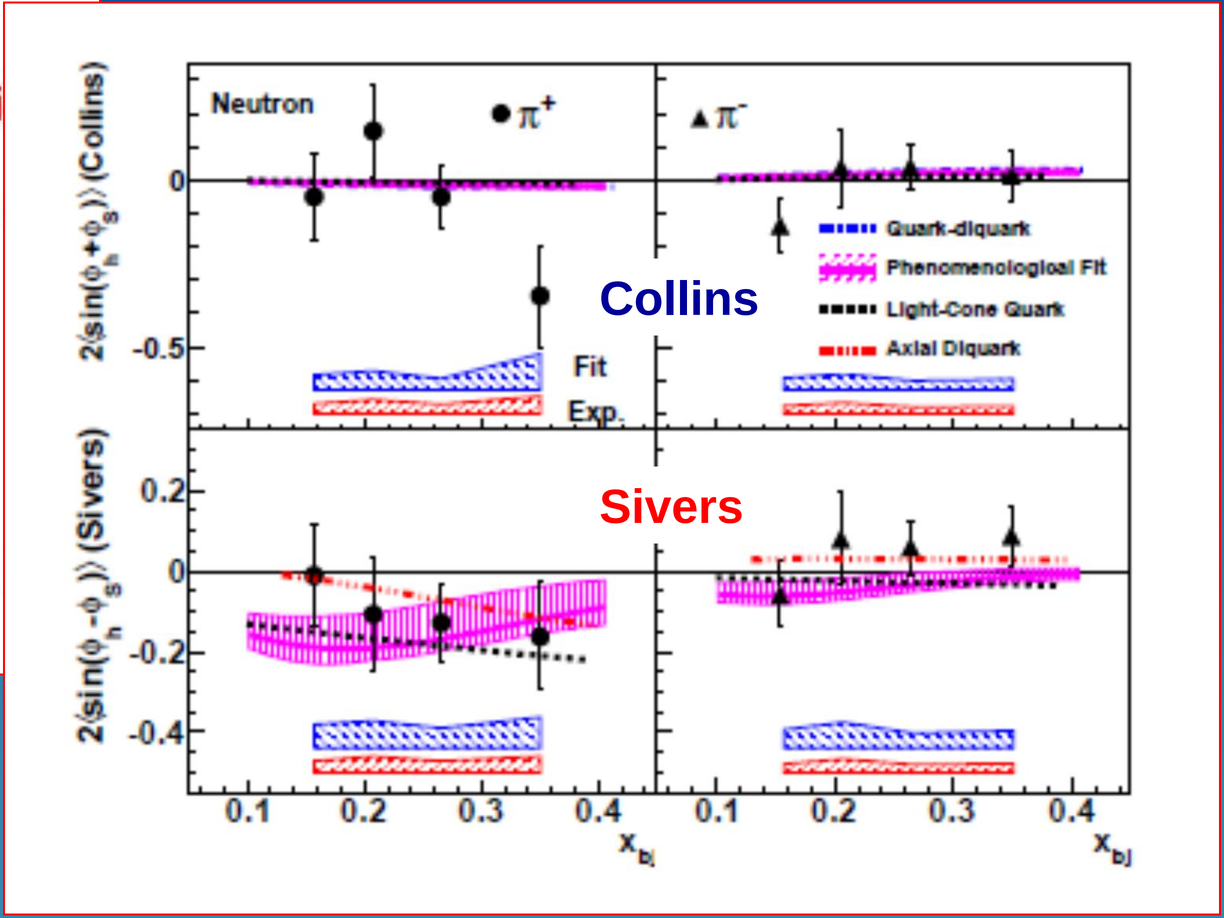
x > 0.032 region 2010 COMPASS data vs HERMES results



Sivers asymmetry

JLab - neutron





CONCLUSIONS
on transverse spin and transverse momentum phenomena

- **TRANSVERSITY is being measured**

- **NEW Properties of matter have been unveiled**

  Collins effect   Sivers effect

  OTHER correlations are still possible (Boer-Mulders)

- **more precise measurements are needed to compare with calculations (pQCD and Lattice)**

  COMPASS   JLab   *RHIC   GSI*

  and in the long run

  AN ELECTRON-NUCLEON COLLIDER

NEAR FUTURE

COMPASS

- further results from
  2010: SIDIS off transversely polarized p target (160 GeV)
  2011: SIDIS off longitudinally polarized p target (160 GeV)

HERMES

- further results on SIDIS and DVCS (28 GeV)

JLab

- SIDIS and DVCS (6 GeV)
- upgrade to 12 GeV

FUTURE

COMPASS II proposal

submitted to CERN in July 2010

approved for 3 years of running

→ *E. Rocco*

DVCS & DVMP

Transverse Imaging

Beam Charge & Spin asymmetry

GPD H (later GPD E)

μ p SIDIS

s(x), Kaon FF

Boer Mulders PDFs and k_T

Drell-Yan π p↑

Sivers and Boer Mulders PDFs

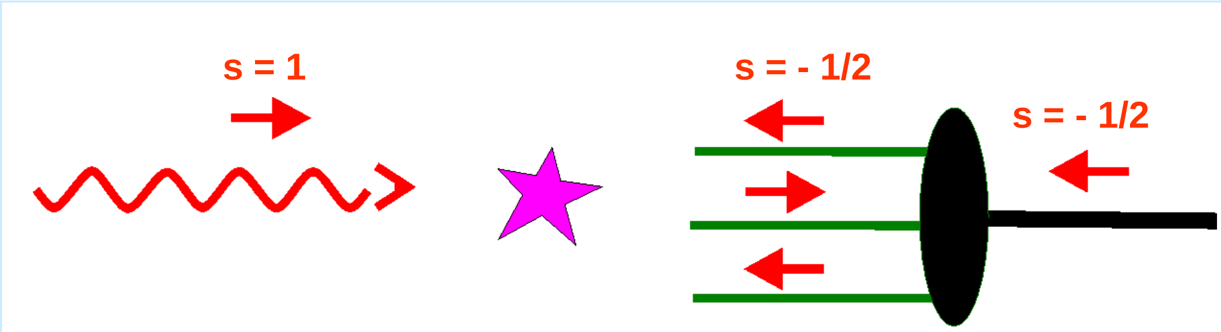
Test of universality

Primakoff

Chiral Perturbation Theory

SPARE SLIDES

g_1 and F_1 in Quark Parton Model



$$\sigma_{3/2} \sim e_q^2 \cdot q^- \qquad \sigma_{1/2} \sim e_q^2 \cdot q^+$$

$$2F_1(x) = \sigma_{1/2} + \sigma_{3/2} \sim \sum_q e_q^2 \cdot \left[q^+(x) + q^-(x)\right]$$

$$2g_1(x) = \sigma_{1/2} - \sigma_{3/2} \sim \sum_q e_q^2 \cdot \left[q^+(x) - q^-(x)\right]$$

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

definitions:

$$\Delta u = \int_0^1 \left[u^+(x) - u^-(x) + \bar{u}^+(x) - \bar{u}^-(x)\right] dx \equiv \int_0^1 \Delta u(x)\, dx$$

$$\Delta d = \int_0^1 \left[d^+(x) - d^-(x) + \bar{d}^+(x) - \bar{d}^-(x)\right] dx$$

$$\Delta s = \int_0^1 \left[s^+(x) - s^-(x) + \bar{s}^+(x) - \bar{s}^-(x)\right] dx$$

Measurement of g_1 in inclusive DIS

$$A = \frac{\frac{d^2\sigma^{\rightleftarrows}}{d\Omega dE'} - \frac{d^2\sigma^{\rightrightarrows}}{d\Omega dE'}}{\frac{d^2\sigma^{\rightleftarrows}}{d\Omega dE'} + \frac{d^2\sigma^{\rightrightarrows}}{d\Omega dE'}}$$

$$\Delta = \frac{N^{\rightleftarrows} - N^{\rightrightarrows}}{N^{\rightleftarrows} + N^{\rightrightarrows}} = P_\mu \cdot P_p \cdot f \cdot A$$

~0.2

0.15

target ~0.8

beam ~0.8

$$A = D \cdot (A_1 + \eta A_2) \cong D \cdot A_1$$

D, η kinematical quantities

A_1 and A_2 are the asymmetries in γ^*p (n) scattering

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \quad A_2 = \frac{2\sigma_{TL}}{\sigma_{1/2} + \sigma_{3/2}}$$

$$g_1 = \frac{A_1(x) \cdot F_2(x)}{2x \cdot (1 + R(x))} \qquad R = \frac{\sigma_L}{\sigma_T}$$

$$\approx A_1(x) \cdot F_1(x)$$

TRANSVERSITY

$\Delta_T q(x)$, $h_1^q(x)$, $\delta q(x)$, $\delta_T q(x)$, $q = u_v, d_v, q_{sea}$

recently much interest !

properties:

- **$\Delta_T q(x) \neq \Delta q(x)$**
- **probes the relativistic nature of quark dynamics**
- **no contribution from the gluons → simple Q^2 evolution**
- **positivity (Soffer) bound** $$2|\Delta_T q| \leq q + \Delta q$$
- **first moments: tensor charge** $$\Delta_T q \equiv \int dx\, \Delta_T q(x)$$
- **sum rule for transverse spin in Parton Model framework** $$\frac{1}{2} = \frac{1}{2}\sum \Delta_T q + L_q + L_g$$ *Bakker, Leader, Trueman, PRD 70 (04)*
- **it is related to GPD's**
- **is chiral-odd: decouples from inclusive DIS**

Transversity and TMD PDFs

Three parton distributions describing quark's transverse momentum and/or transverse spin

Three transverse quantities:

1) Nucleon transverse spin

$\vec{S}_\perp^N$

2) Quark transverse spin

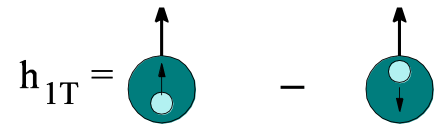
$\vec{s}_\perp^q$

3) Qaurk transverse momentum

$\vec{k}_\perp^q$

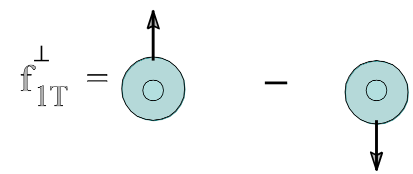
$\Rightarrow$ Three different correlations

1) Transversity



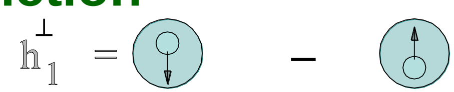
Correlation between $\vec{s}_\perp^q$ and $\vec{S}_\perp^N$

2) Sivers function



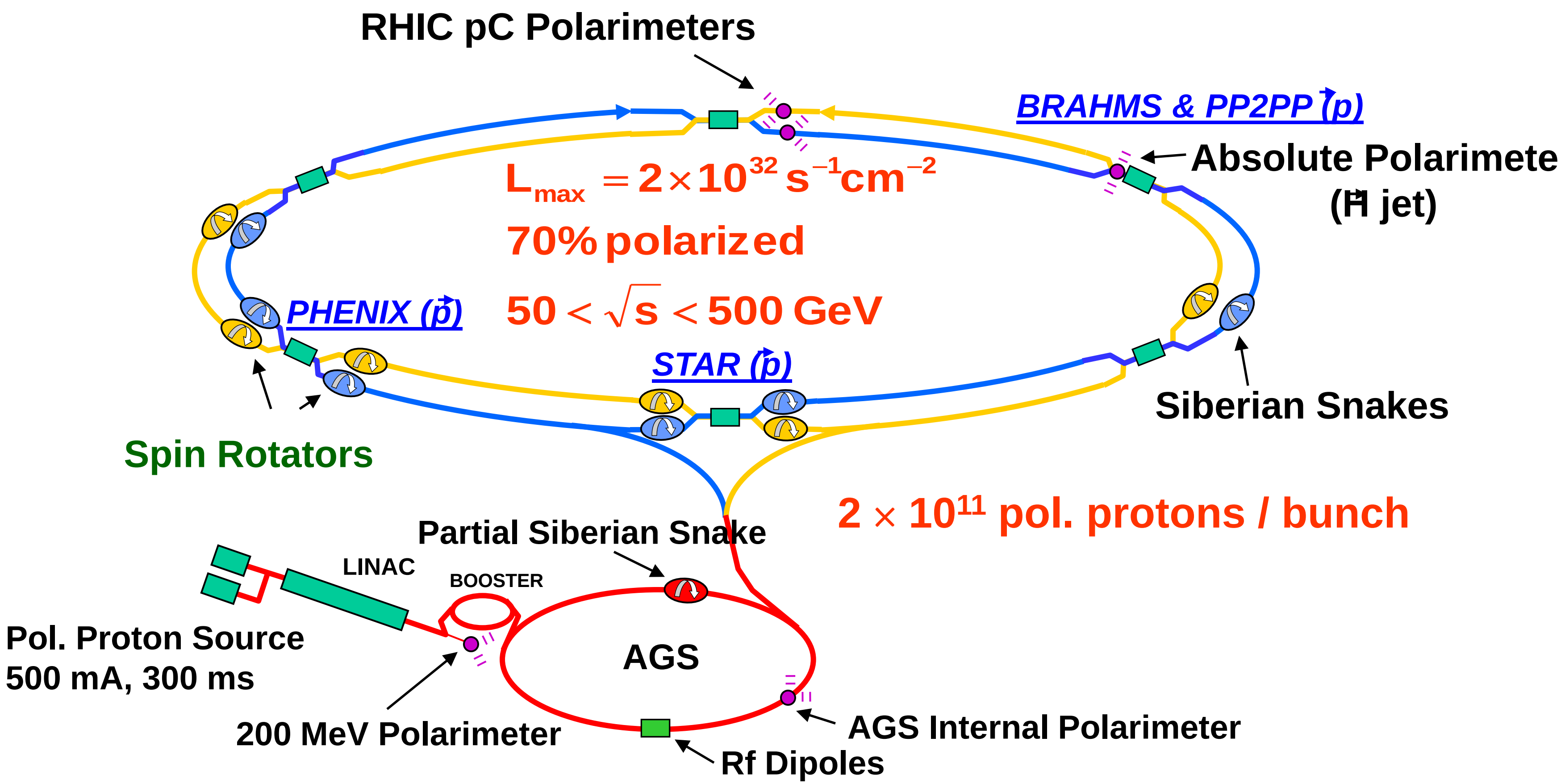
Correlation between $\vec{S}_\perp^N$ and $\vec{k}_\perp^q$

3) Boer-Mulders function



Correlation between $\vec{s}_\perp^q$ and $\vec{k}_\perp^q$

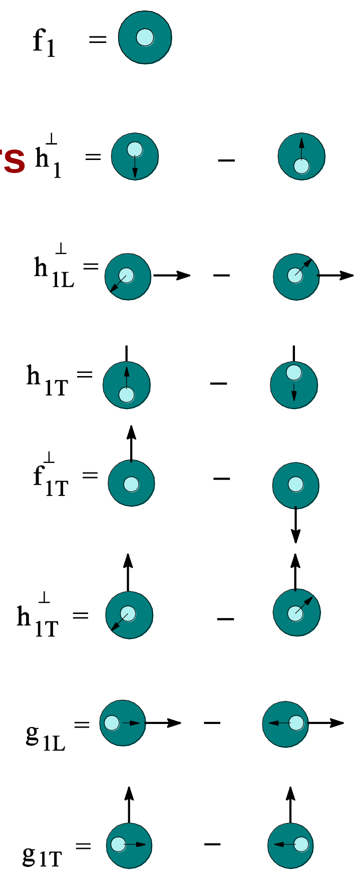
Relativistic Heavy Ion Collider



RHIC accelerates heavy ions to 100 GeV/A and polarized protons to 250 GeV

TMD PDFs and SIDIS cross-section

$$d^6\sigma = \frac{4\pi\alpha^2 s x}{Q^4}\times$$



Unpolarized

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$

Boer-Mulders

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Transversity

$$+|S_T|(1-y)\frac{P_{h\perp}}{z M_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Sivers

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{z M_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized target

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{z M_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

Polarizied beam and target

S_L and S_T: L/T target polarizations; λ_e: beam L polarization