The Spin Structure of the Nucleon: a phenomenological introduction

Franco Bradamante

Trieste University and INFN

- **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 $\dfrac{1}{2}$ $\qquad \mu = \dfrac{e\hbar}{2mc}$ $\qquad \mu_p = +2.79\ \mu_N$ $\qquad$ *Frisch and Stern (1933)*

$$\mu_n = -1.91\ \mu_N \qquad \textbf{should be 0}$$

$\rightarrow$ **per-se indication of internal structure**

THE QUARK MODEL

                                                                                 F. Bradamante

Major Breakthrough

hadron spectoscopy $\Longrightarrow$ the **QUARK MODEL** (1964)

$$|p\rangle = |uud\rangle \qquad |n\rangle = |udd\rangle \qquad \boxed{\textbf{SU(6)}}$$

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

SU(6)

magnetic moments:

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

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

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

$$\mu_p = 3\mu_N \qquad \mu_n = -2\mu_N \qquad \frac{\mu_p}{\mu_n} = -\frac{3}{2}$$
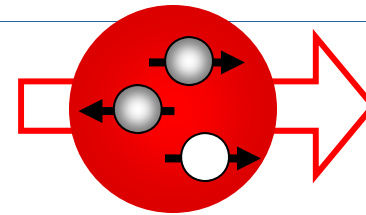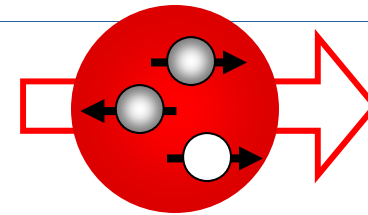
similar agreement for all baryons

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

$$\vec{\underset{\rightarrow}{u}} = \frac{5}{3} \qquad \vec{\underset{\leftarrow}{u}} = \frac{1}{3} \qquad \Delta u = \vec{\underset{\rightarrow}{u}} - \vec{\underset{\leftarrow}{u}} = \frac{4}{3}$$

$$\vec{\underset{\rightarrow}{d}} = \frac{1}{3} \qquad \vec{\underset{\leftarrow}{d}} = \frac{2}{3} \qquad \Delta d = \vec{\underset{\rightarrow}{d}} - \vec{\underset{\leftarrow}{d}} = -\frac{1}{3}$$

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

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

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**
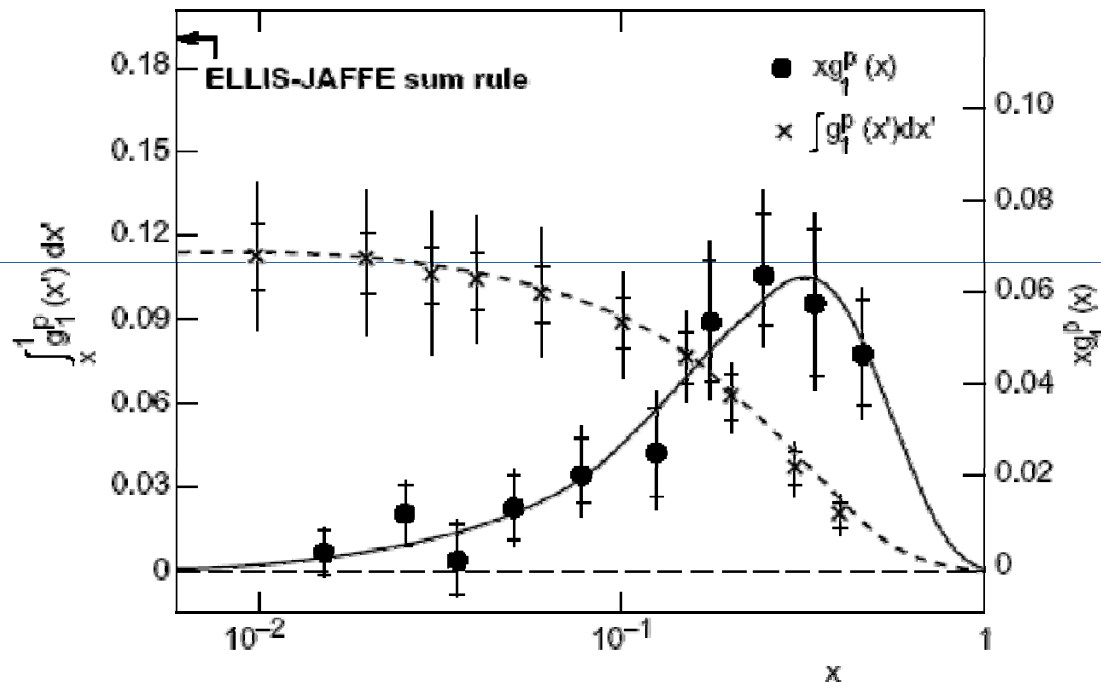
EMC 1988

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

➔ SPIN CRISIS

HOW IS $\Delta\Sigma$ MEASURED?

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Deep Inelastic Scattering

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

valence quarks
sea quarks
gluons

$$Q^2 = -q^2 > 0$$

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

$$\nu = E - E'$$

$$y = \nu/E$$

$$\gamma = \sqrt{Q^2}/\nu$$

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

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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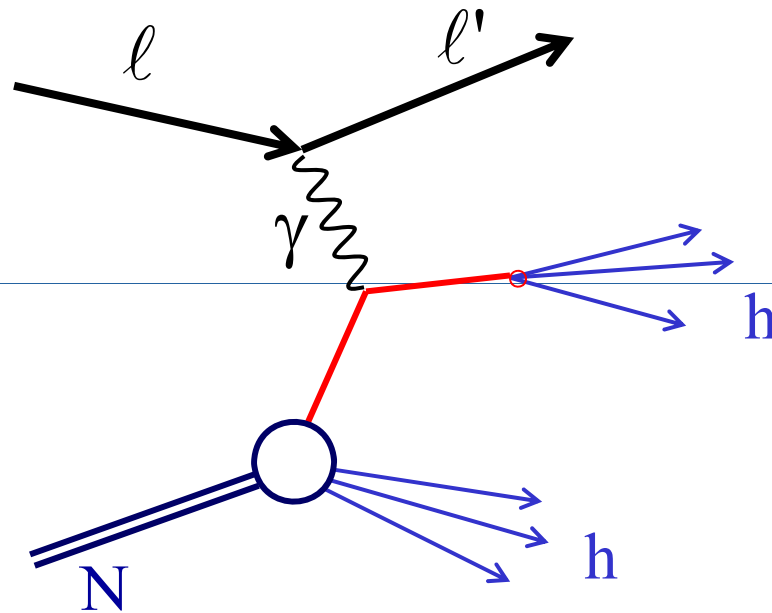
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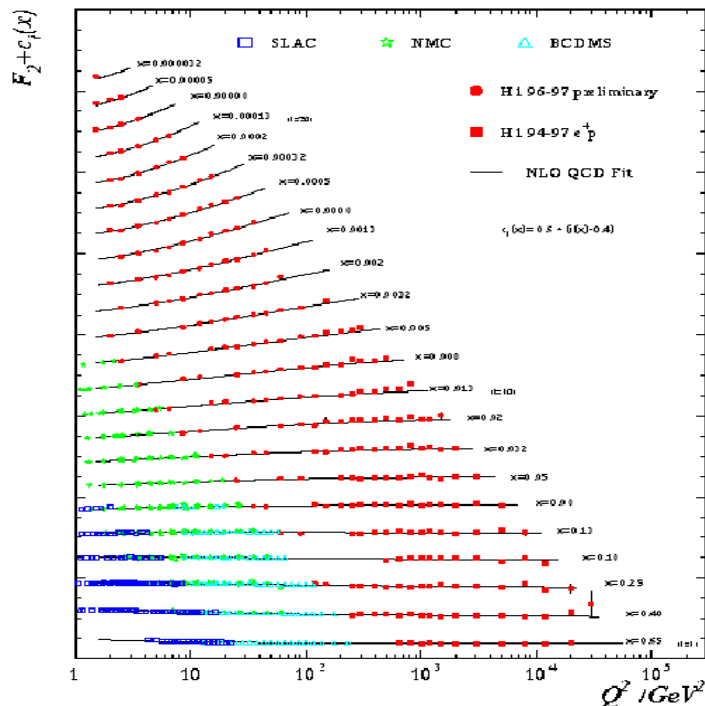
**NB: COMPLEMENTARY APPROACH @ RHIC
(will not mention)**

Structure Functions and PDFs: $q(x)$

Inclusive DIS: unpolarised

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

$$F_2(x) = 2x \cdot F_1(x) \quad \text{Callan-Gross}$$

in the parton model

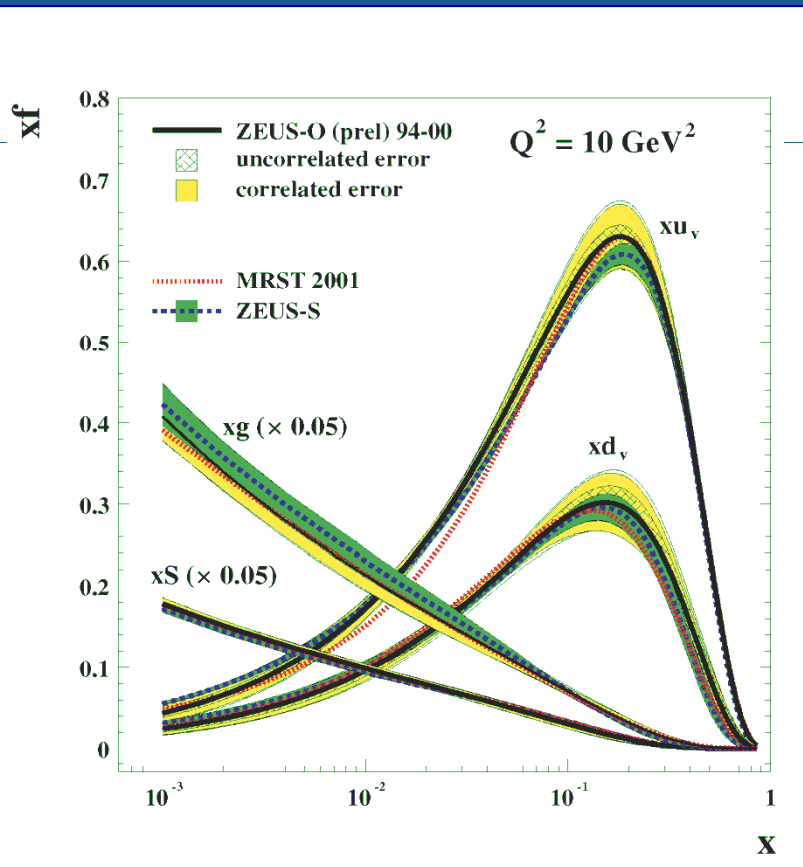$$F_1(x) = \frac{1}{2}\sum_q e_q^2 \cdot \left[q(x) + \overline{q}(x)\right]$$

$$q = u, d, s$$

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measured at CERN, HERA, SLAC

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

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ZEUS-O (prel) 94-00
uncorrelated error
correlated error
$Q^2 = 10$ GeV^2
MRST 2001
ZEUS-S
xu_v
$xg \ (\times 0.05)$
xd_v
$xS \ (\times 0.05)$

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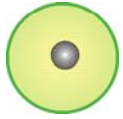
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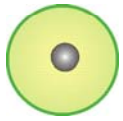
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$\Delta q(x) = q^{\rightrightarrows} - q^{\leftrightarrows}$: longitudinal polarization or helicity distribution

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

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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

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

$$d\sigma = d\overline{\sigma} \pm d\Delta\sigma$$

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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$$d\sigma = d\overline{\sigma} \pm d\Delta\sigma$$

beam/target helicity

DSSV 2009

$x(\Delta u + \Delta\overline{u})$

$x(\Delta d + \Delta\overline{d})$

$x\Delta\overline{u}$

$x\Delta\overline{d}$

— DSSV

$x\Delta\overline{s}$

$x\Delta g$

$\times\times\times\times$ $\Delta\chi^2=1$ (Lagr. multiplier)

$\Delta\chi^2=1$ (Hessian)

$Q^2 = 10 \text{ GeV}^2$

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

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in the parton model

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \cdot \left[\Delta q(x) + \Delta\overline{q}(x)\right]$$

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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

$$g_1(x) = \frac{1}{2} \sum_q e_q^2 \cdot \Delta q(x) \qquad\qquad \Gamma_1 = \int_0^1 g_1(x)\, dx$$

using complementary information from
the **WEAK DECAY CONSTANTS of the BARYONS**

$$\Delta u - \Delta d = F + D = 1.257 \pm 0.003$$

$$\Delta u + \Delta d - 2\,\Delta s = 3F - D = \sqrt{3} \cdot \left[0.34 \pm 0.02 \right]$$

one can get Δu, Δd, Δs and then $\Delta\Sigma$

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one can get Δu, Δd, Δs and then $\Delta\Sigma$

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

→ *E. Kabuss*

Experiments

a worldwide effort since decades

Experiments

a worldwide effort since decades

SPIN CRISIS

	1970	1980	1990	2000
SLAC				
	E80	E130	E142/3 E154/5	
CERN				
		EMC	SMC	COMPASS
DESY				
			HERMES	
JLab				
				CLAS/HALL-A
RHIC				
				Phenix/Star
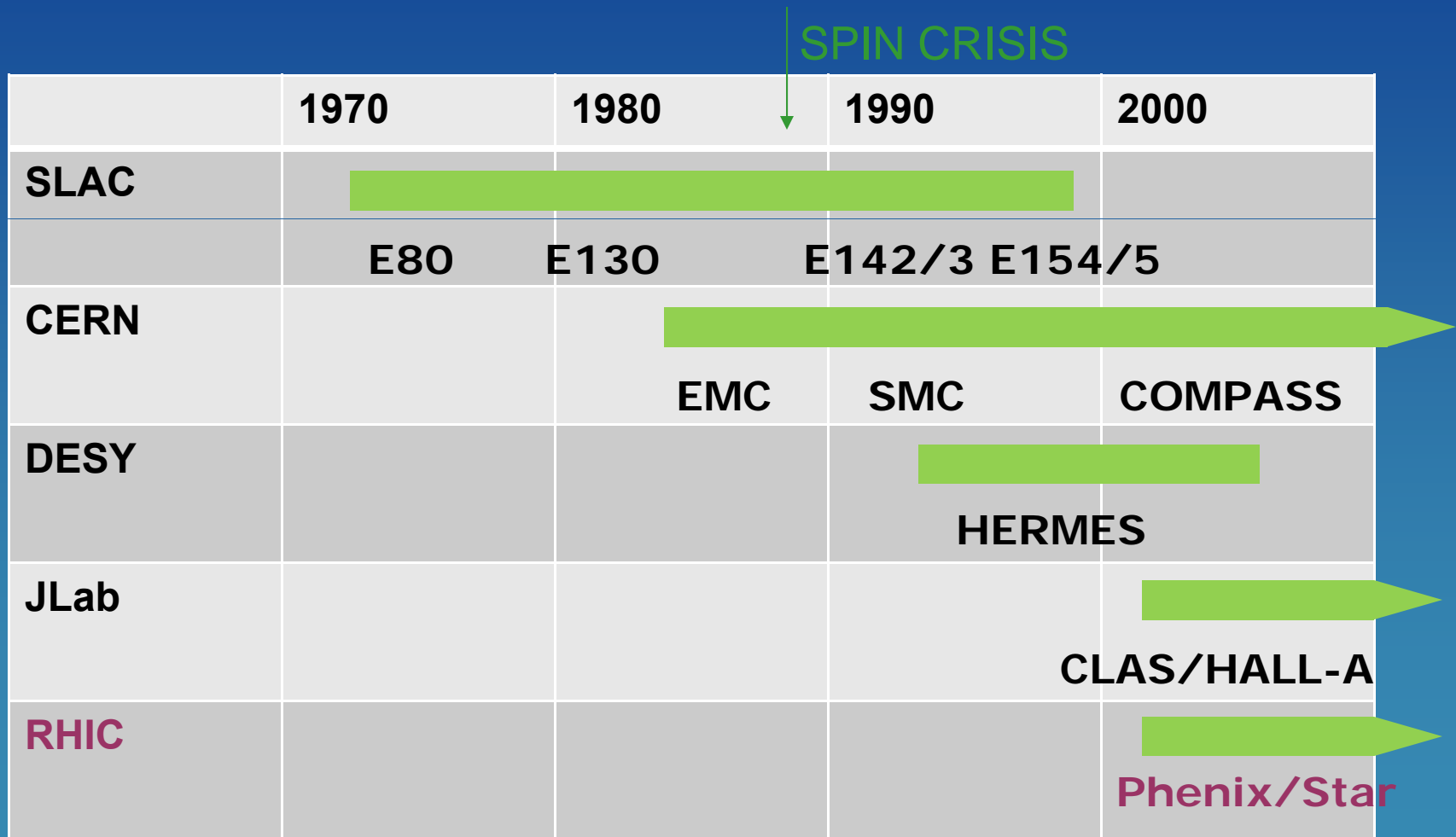
The Players, today

- **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: $\sim 5 \cdot 10^{32}$ cm^{-2} s^{-1}
beam intensity: $2 \cdot 10^8$ μ^+/spill (4.8s/16.2s)
beam momentum: 160 GeV/c

LHC

SPS

COMPASS

N

COMPASS

Θ_Ch (mrad) vs p (GeV/c) plot showing π, K, p bands.

Trigger hodoscopes

ECal & HCal

μ Filter

SM2

RICH

SM1

50 m

MWPC

Straws

⁶LiD Target

160 GeV μ

Micromegas

SciFi   Silicon
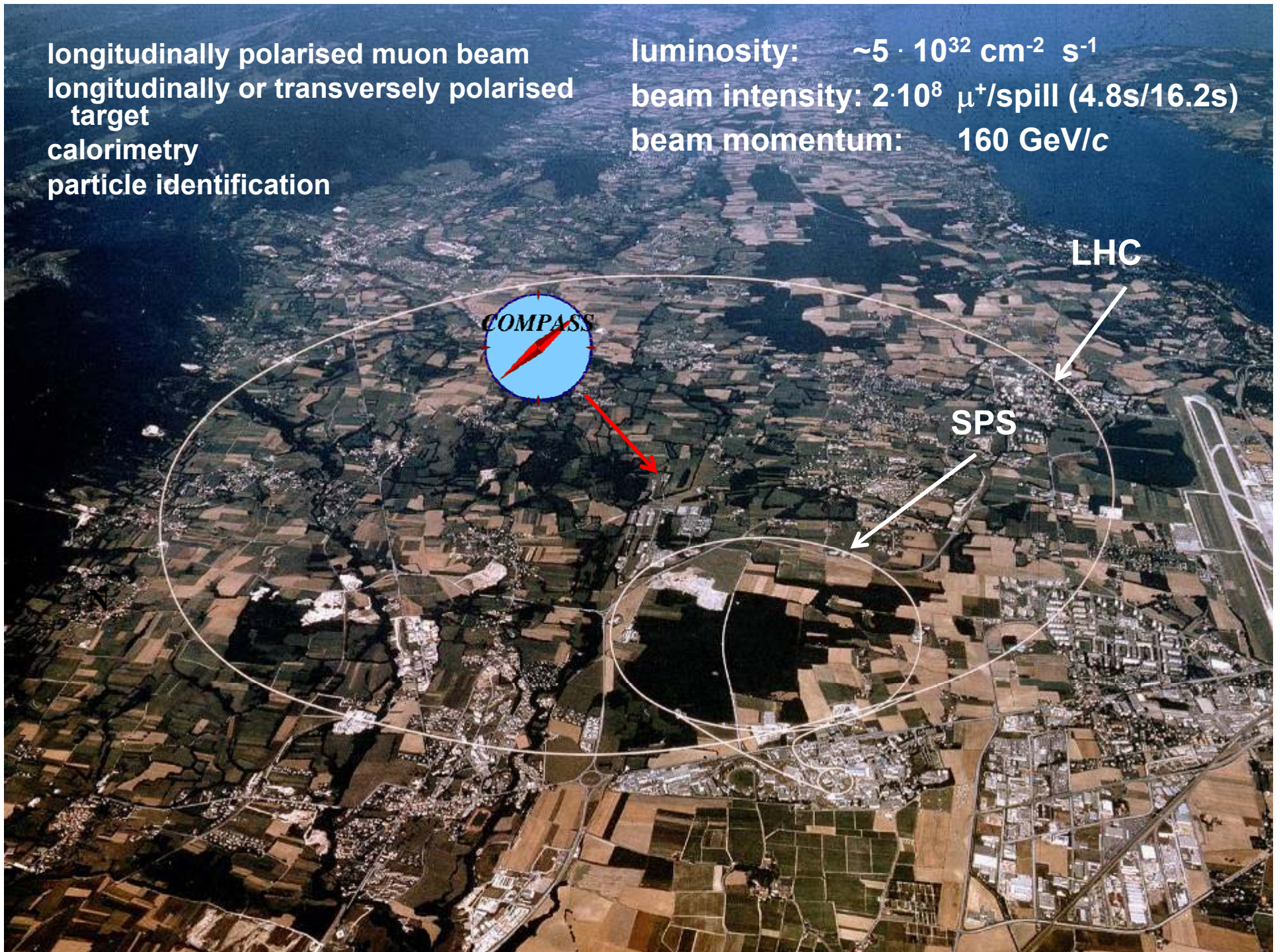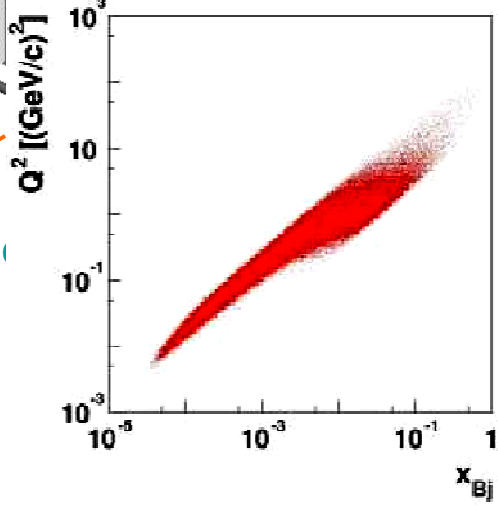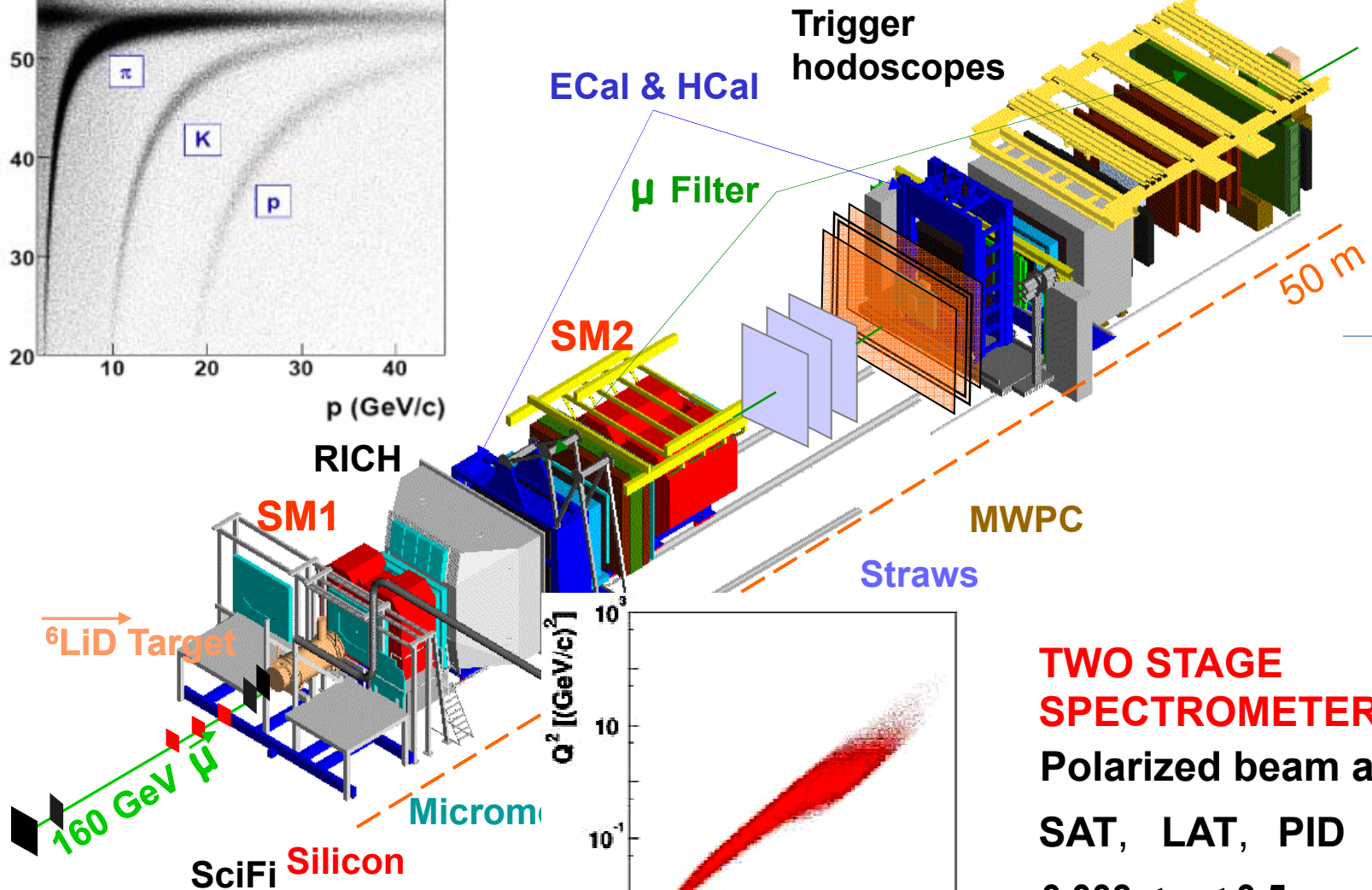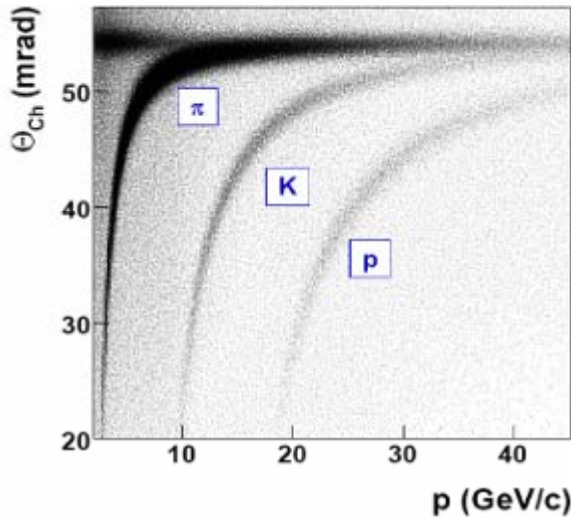
TWO STAGE SPECTROMETER:

Polarized beam and target

SAT, LAT, PID

0.003 < x < 0.5

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

Q^2 [(GeV/c)^2] vs x_{Bj} plot.

COMPASS

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)

^{3}He – ^{4}He Dilution
refrigerator (T~50mK)
**superconductive
Solenoid (2.5 T**)   **Dipole (0.5 T)**
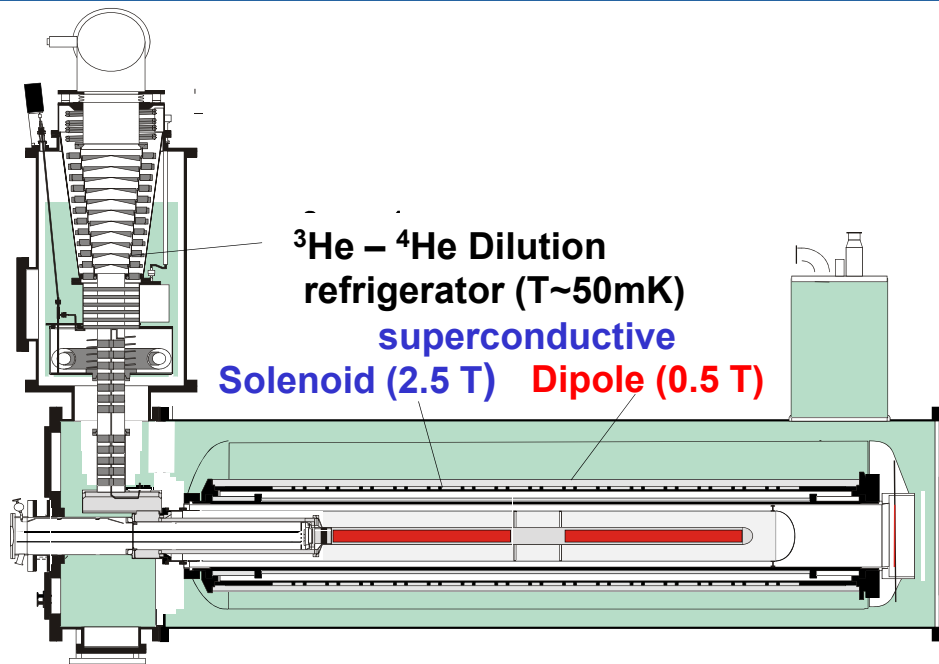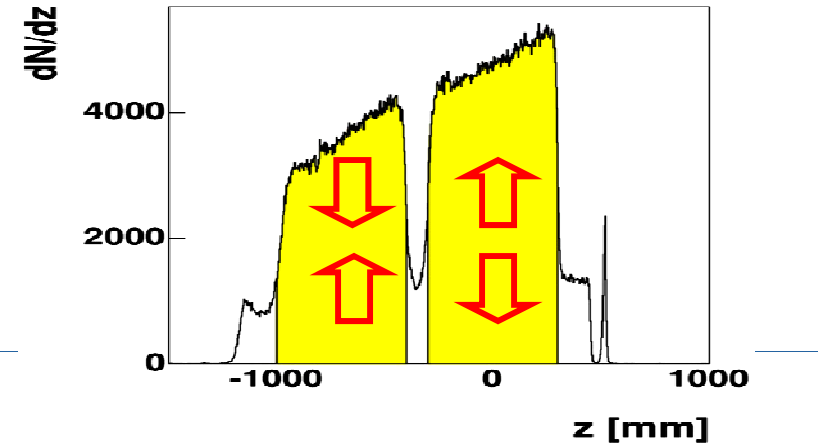
**during data taking with transverse polarisation,
polarisation reversal in the cells after ~ 4-5 days**

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two 60 cm long cells
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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)

COMPASS 2007 transverse proton data

Preliminary
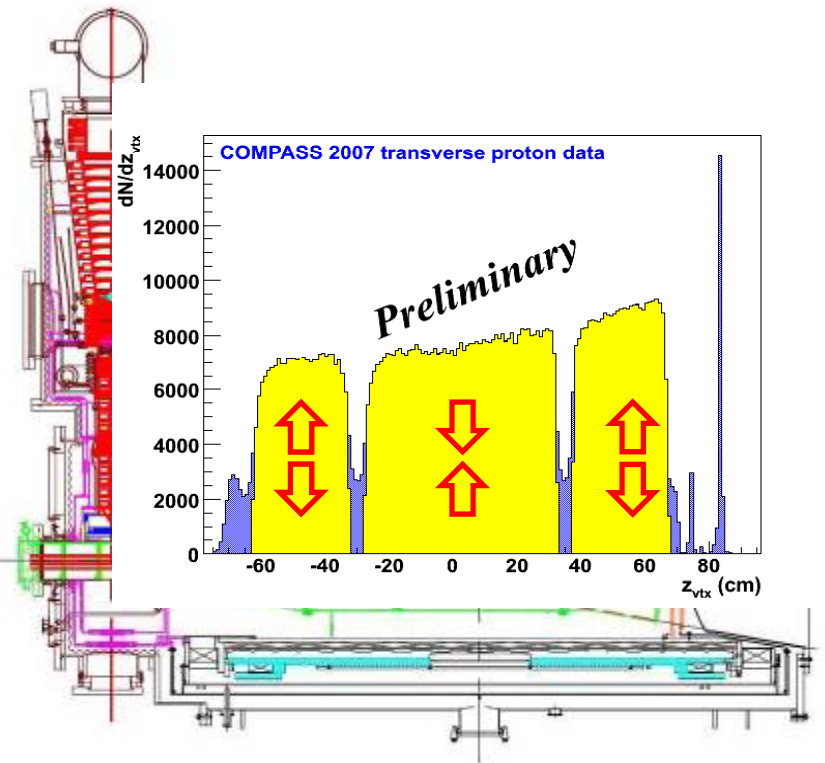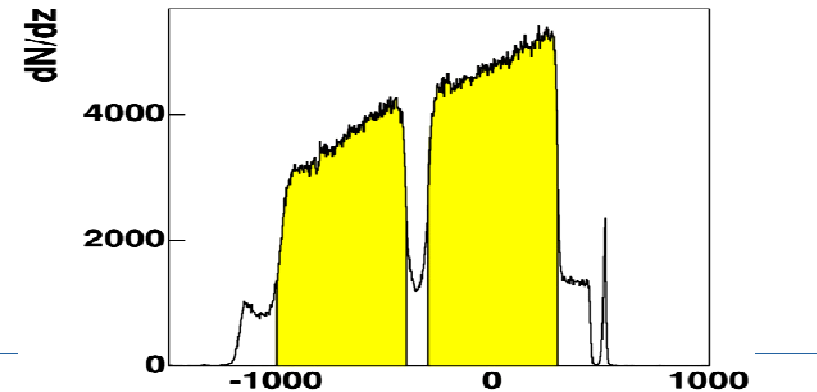
HERMES

27.5 GeV e⁺

$\sqrt{s} = 7$ GeV
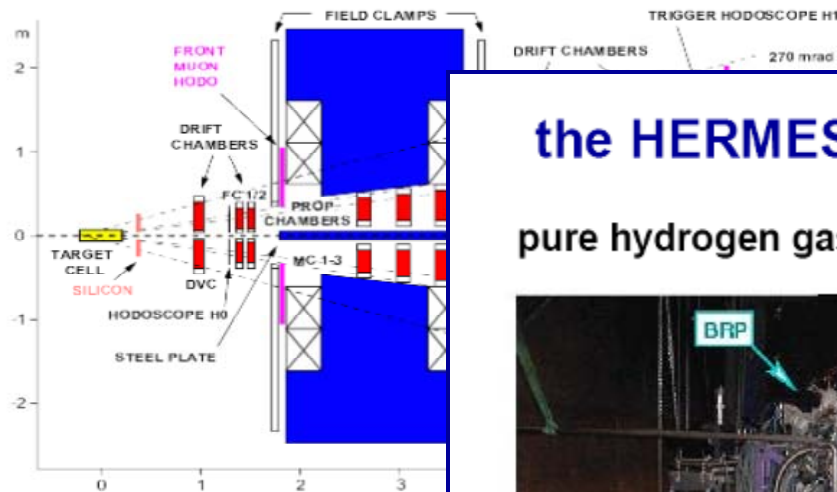
hermes

particle ID: lepton ID w
hadron con
RICH:

the HERMES polarized target

hermes

pure hydrogen gas target
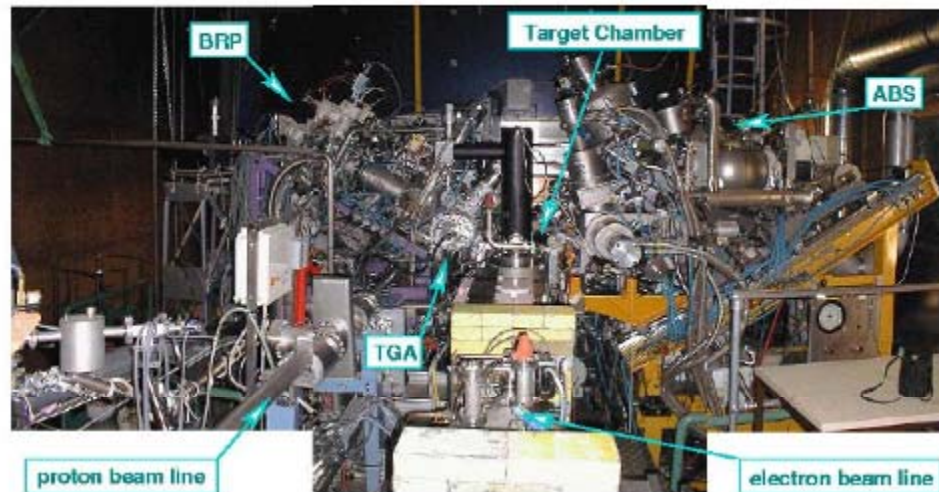
flipped at high frequency (60- 90 s)

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

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

6 GeV polarized electron beam Pol=85%, 180μA
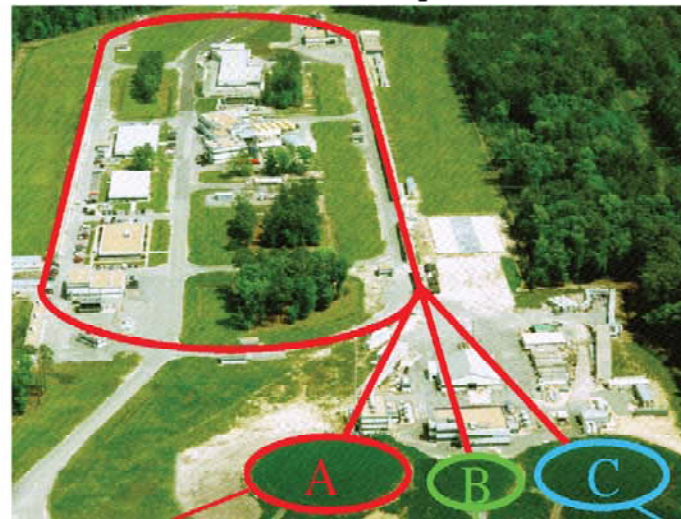
Will be upgraded to 12 GeV by ~2014

$^3\vec{He}$ target

$N\vec{H}_3$ & $N\vec{D}_3$ targets

$N\vec{H}_3$ & $N\vec{D}_3$ targets
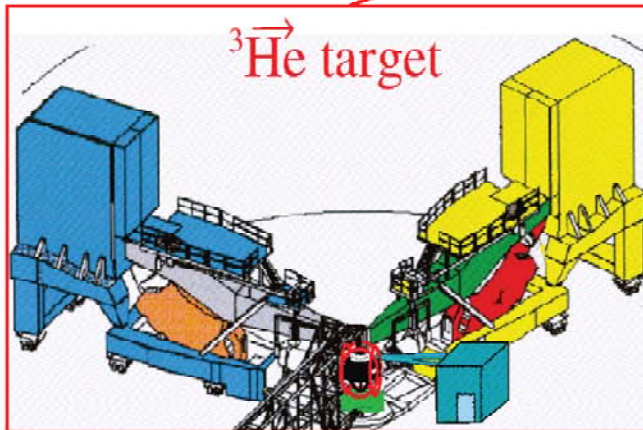
HallA: two HRS'
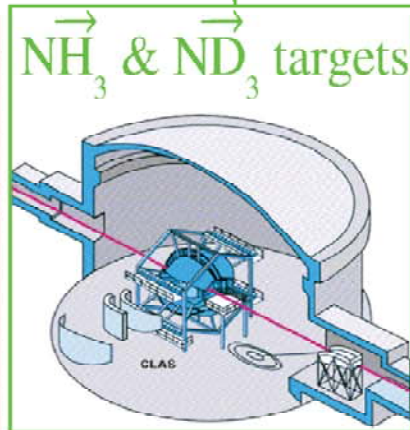
Hall B:CLAS

Hall C: HMS+SOS

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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Parton Distribution Functions

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

$q(x)$: 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

in a longitudinally polarised nucleon, probability of
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$\Delta q(x) = q^{\vec{\Rightarrow}} - q^{\vec{\Leftarrow}}$: 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

$\Delta_T q(x) = q^{\Uparrow\Uparrow} - q^{\Downarrow\Uparrow}$: 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*]

Parton Distribution Functions

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

q(x) : number density or unpolarised distribution

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

$\Delta q(x) = q^{\Rightarrow} - q^{\Leftarrow}$: **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

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

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
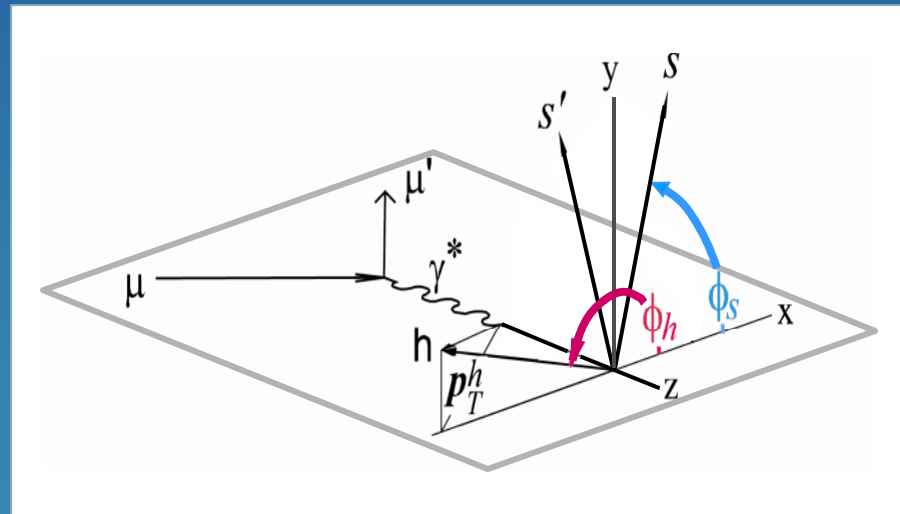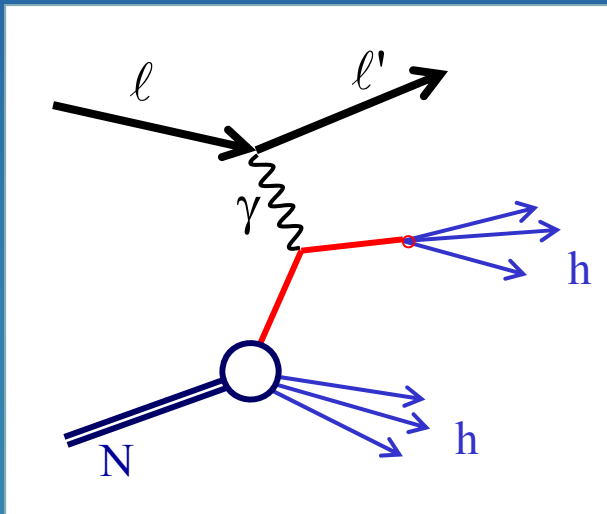
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Puzzles in hadronic reactions

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.

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

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

Puzzles in hadronic reactions

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.

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

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

in hadronic reactions like $p^\uparrow + p \to \pi + X$

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**
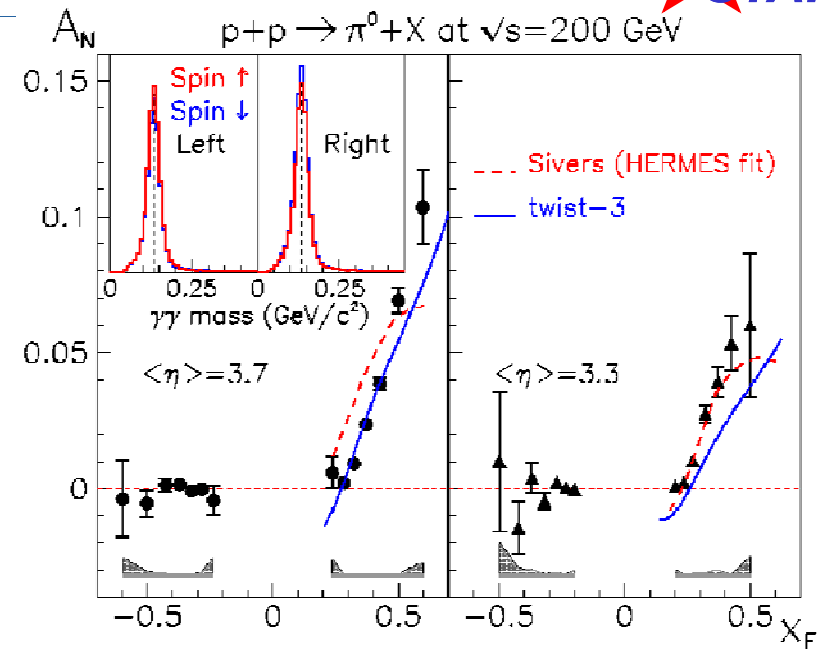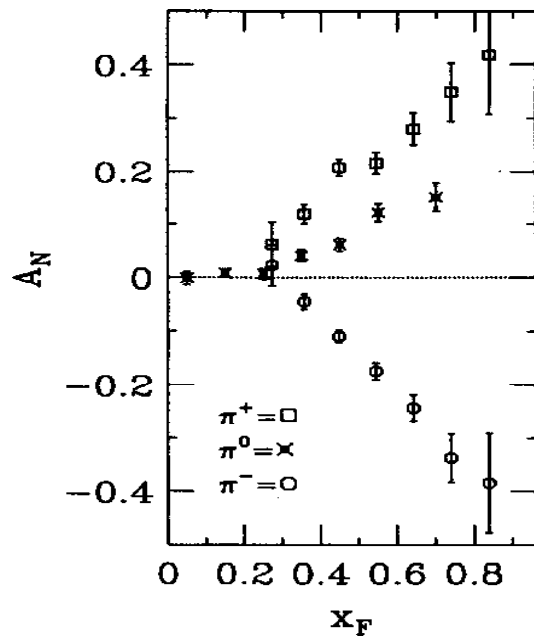
RUN6 PRL 101 (2008) 222001

Puzzles in hadronic reactions

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

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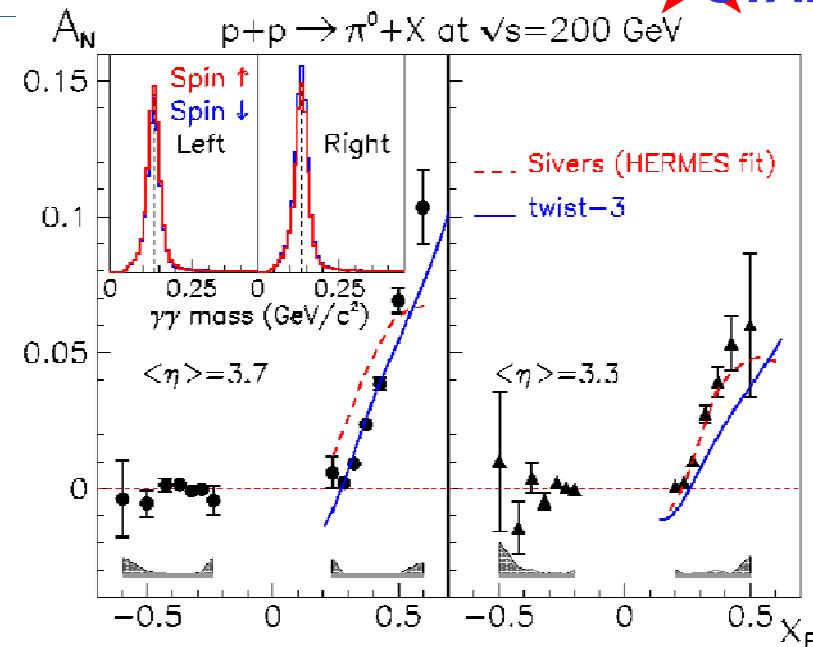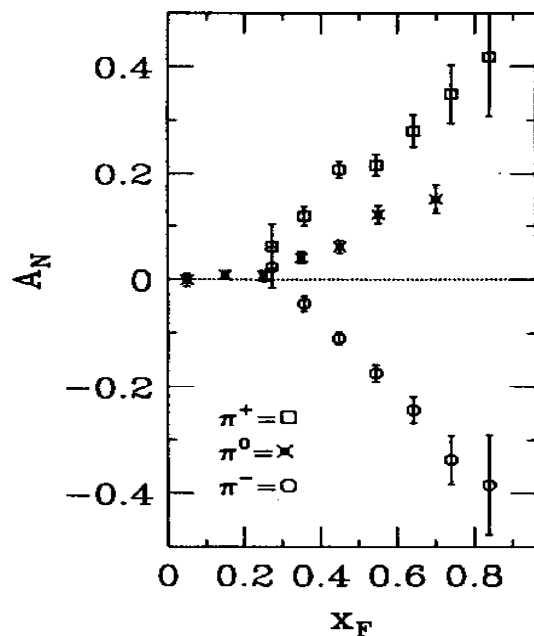
Hope to find solutions at the quark level ($\Delta_T q(x)$ …)

HOW to MEASURE TRANSVERSITY

F. Bradamante

HOW to MEASURE TRANSVERSITY

$\Delta_T q(x)$ 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

$$N_h^{\pm}(\Phi_C) = N_h^0 \cdot \left[1 \pm P_T \cdot D_{NN} \cdot A_{Coll} \cdot \sin\Phi_C \right]$$
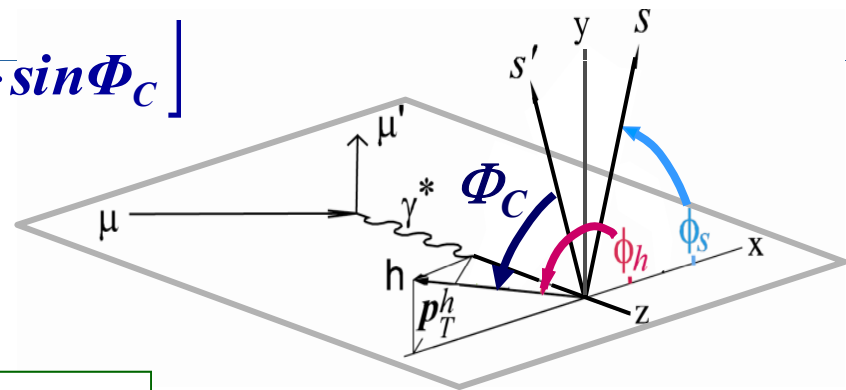
transversity   **"Collins FF"**

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

both unknown !

today the most promising way to access transversity

The conjecture was right !!

F. Bradamante

The conjecture was right !!

PRL 94 (2005) 012002

proton data

deuteron data

PRL 94(2005)202002
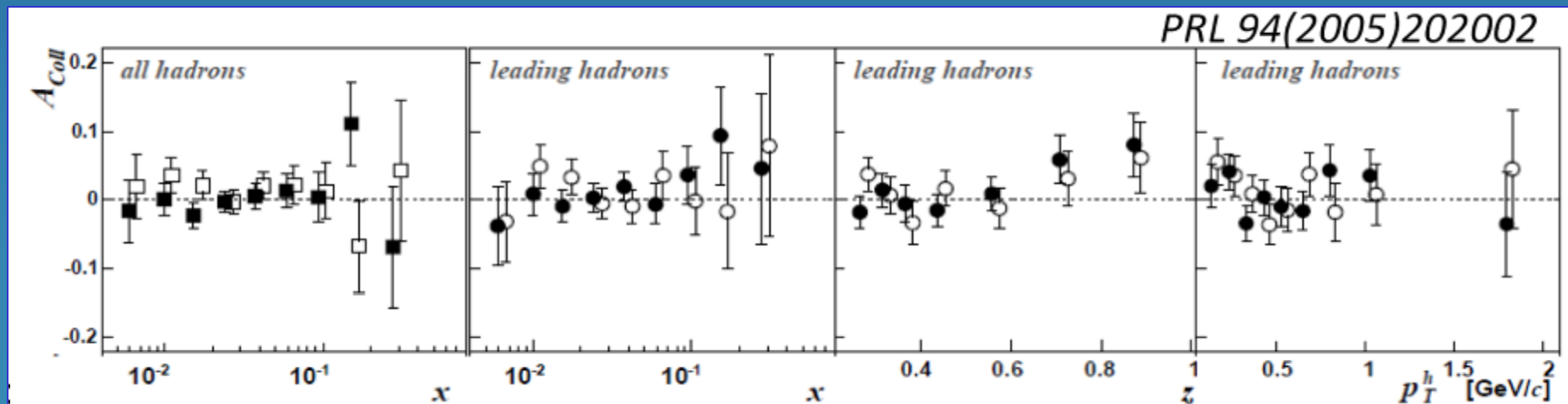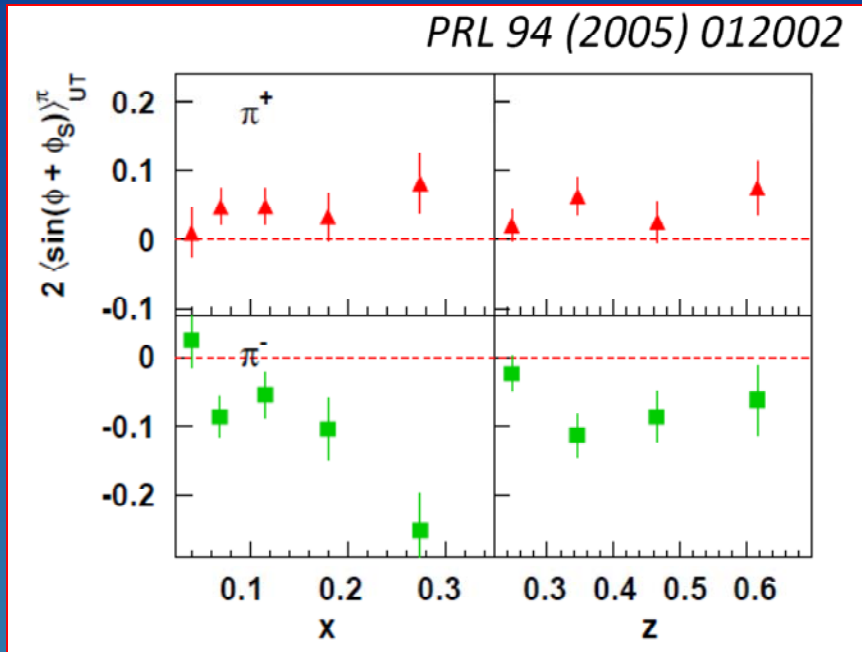
The conjecture was right !!

"Collins FF"

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

gives a LR asymmetry in the hadronisation of transversely polarised quarks

- *products of Collins FFs can be measured in* $\mathbf{e^+ e^- \to \pi^+ \pi^- X}$

- first low statistics results from LEP data

- **2005   first data from BELLE**
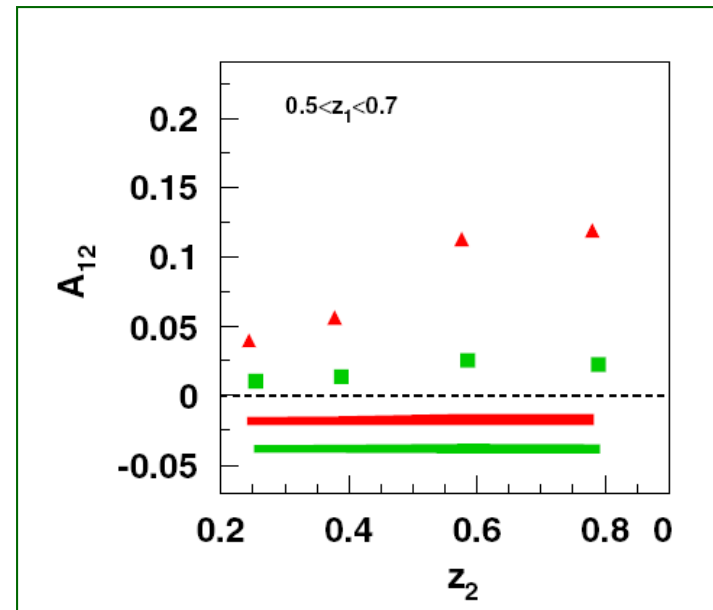
TRANSVERSITY PDFs

Collins asymmetry best fit
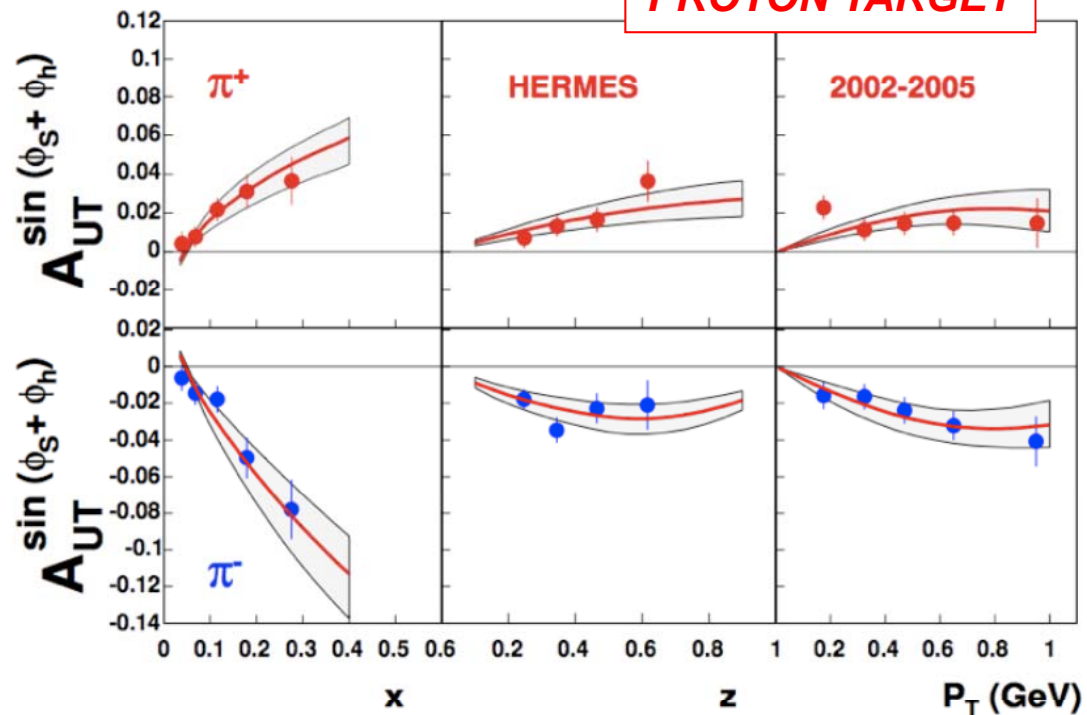
PROTON TARGET

TRANSVERSITY PDFs

Collins asymmetry best fit

PROTON TARGET
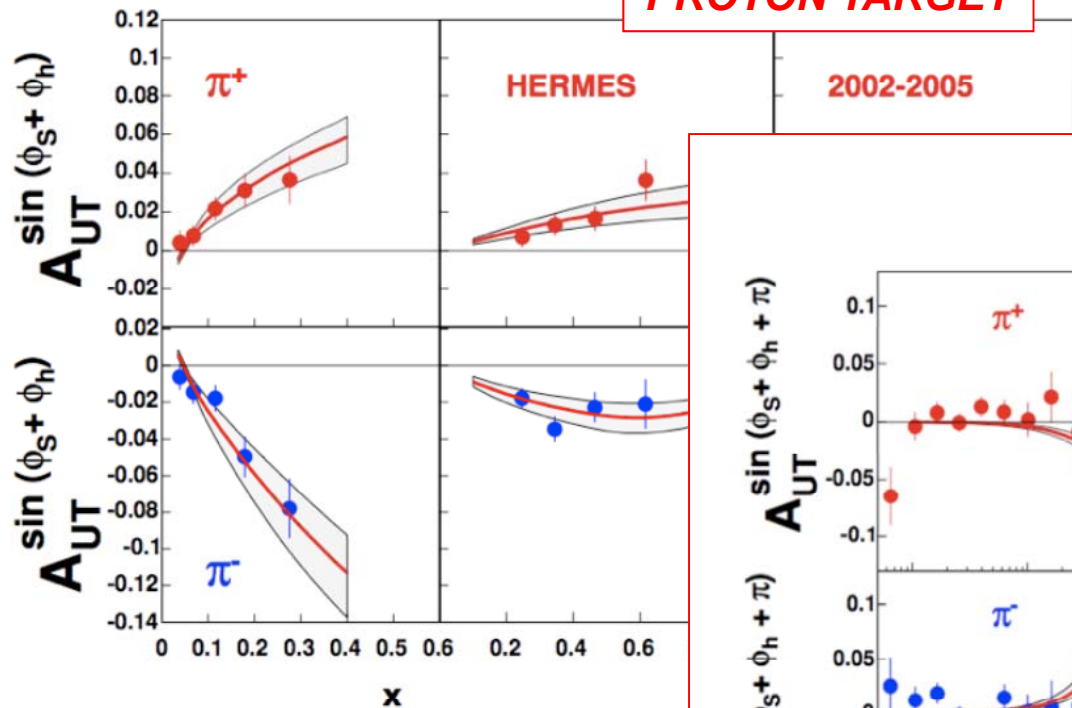
DEUTERON TARGET
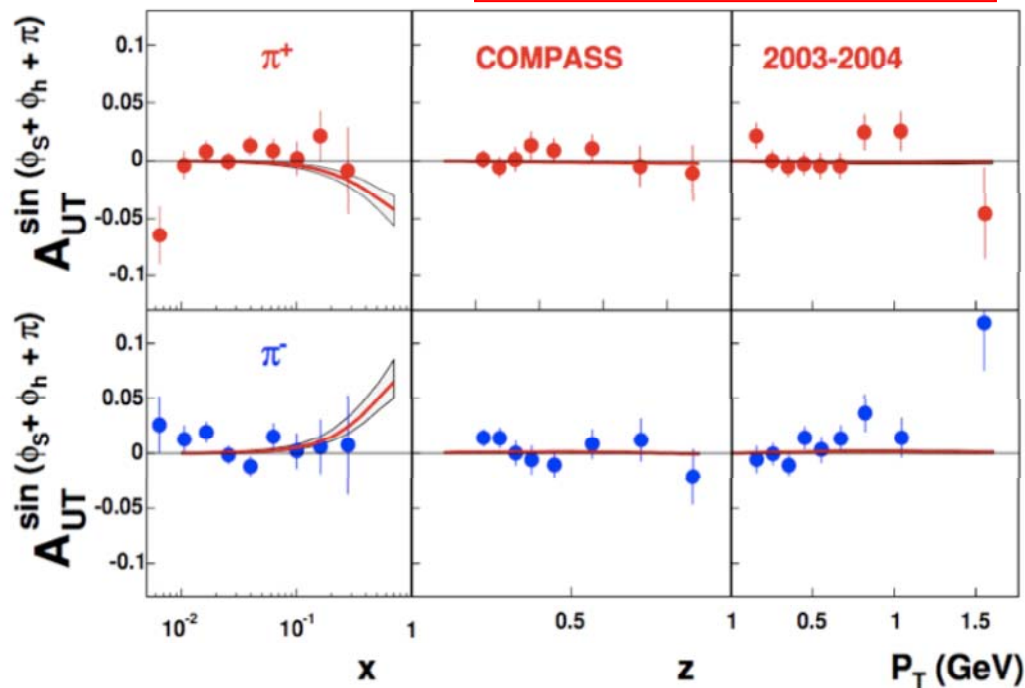
plus BELLE data on $e^+e^- \rightarrow$ hadrons

TRANSVERSITY PDFs

comparison of extracted transversity distributions with models
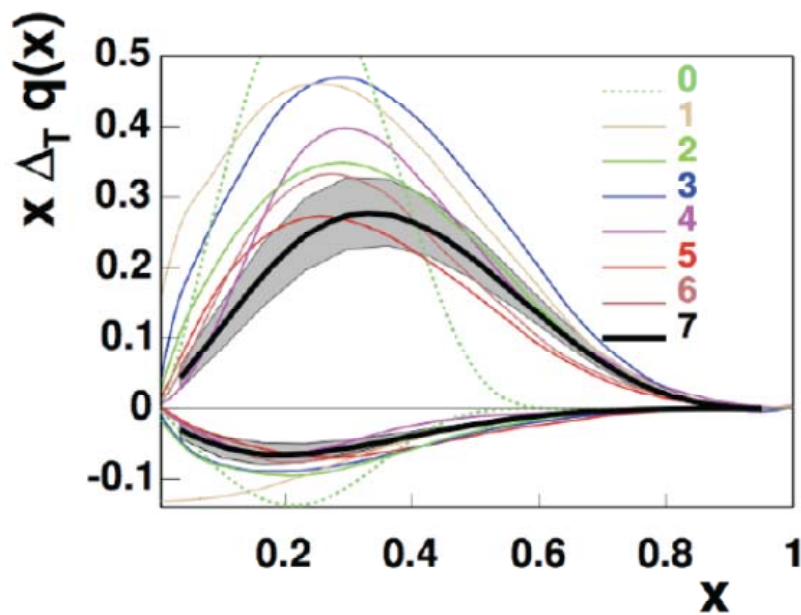
Anselmino et al., PRD75 (2007)

Collins asymmetry

COMPASS 2010 proton data

preliminary

- positive hadrons
- negative hadrons

A^p_{Coll}

x z p^h_T (GeV/c)
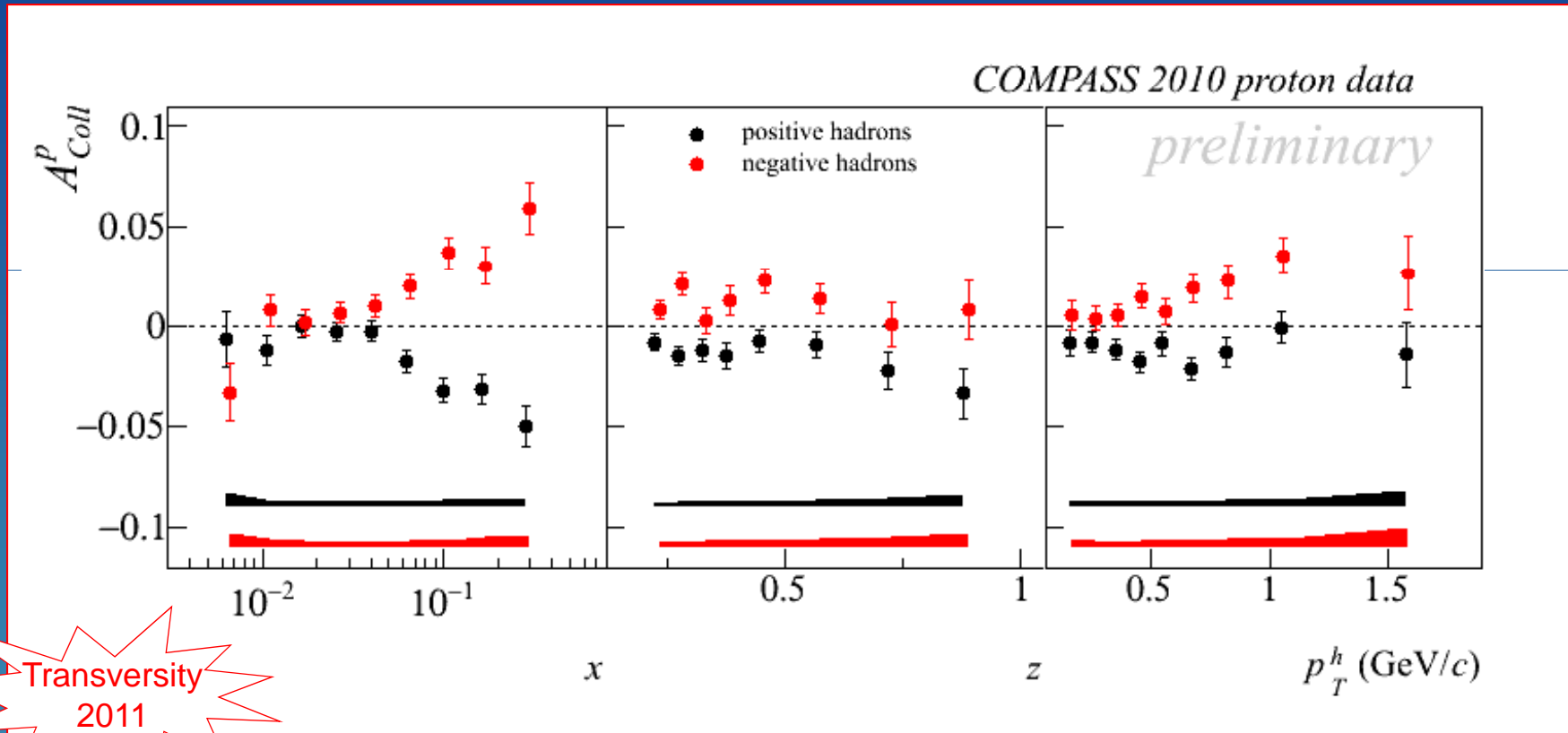
Transversity 2011

**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
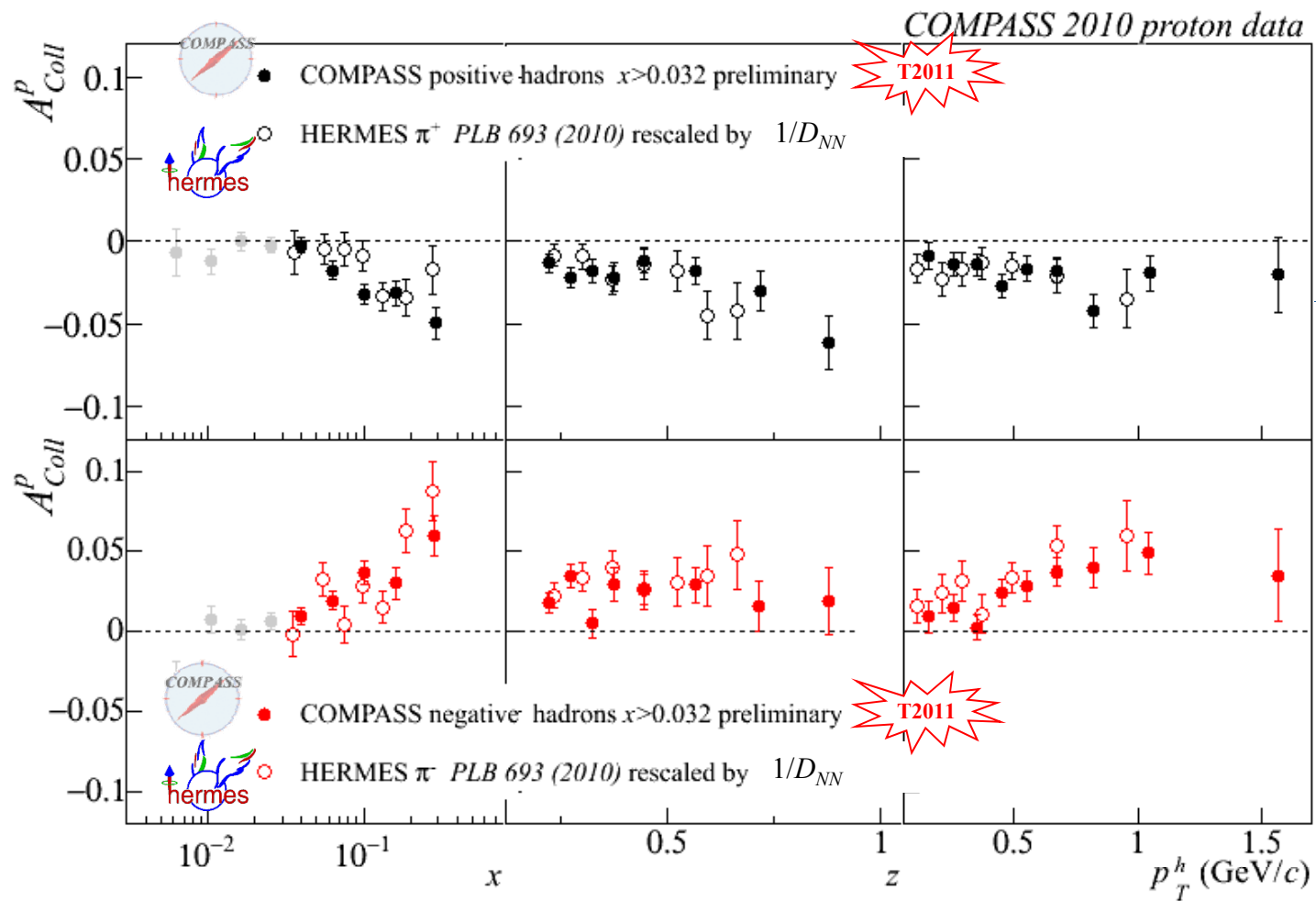
Collins asymmetry

x > 0.032 region   - comparison with HERMES results
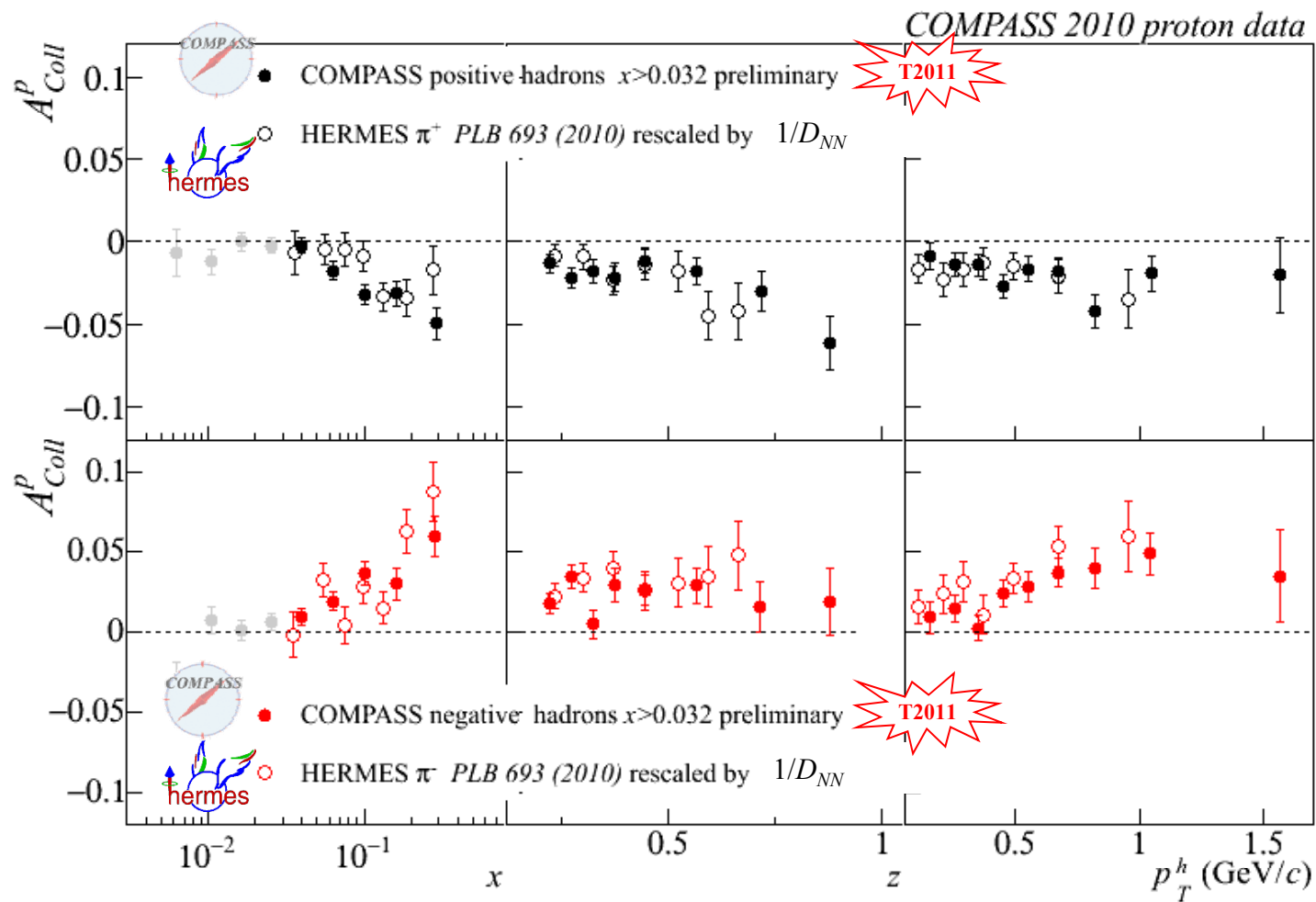
nice agreement in spite of the different Q² values

a very important result

The Structure of the Nucleon

new developments

F. Bradamante

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		
		U	L	T
quark polarisation	U	f_1 number density $\mathbf{q}$		
	L		g_1 helicity $\Delta\mathbf{q}$	
	T			h_1 transversity $\Delta_T\mathbf{q}$

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, quark polarisation table: columns U, L, T; rows U, L, T.

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

The Structure of the Nucleon

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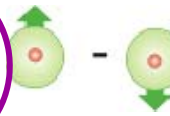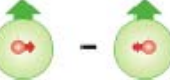
Sivers function
correlation between the transverse spin of the nucleon and the transverse momentum of the quark
sensitive to orbital angular momentum

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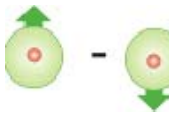
Boer-Mulders function
correlation between the transverse spin and the transverse momentum of the quark in unpol nucleons

nucleon polarisation

quark 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 — $\Delta_T q$ — $h_{1T}^{\perp}$

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:

$$\sin 2\phi_h$$
$$\sin (\phi_h + \phi_S) \qquad \rightarrow \text{ Transversity PDF x Collins FF}$$
$$\sin (\phi_h - \phi_S) \qquad \rightarrow \text{ Sivers PDF}$$
$$\sin (3\phi_h - \phi_S)$$
$$\dots$$

- 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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- **1992   introduced by D. Sivers**
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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

COMPASS 2010 proton data

positive hadrons

negative hadrons

preliminary

Transversity
2011
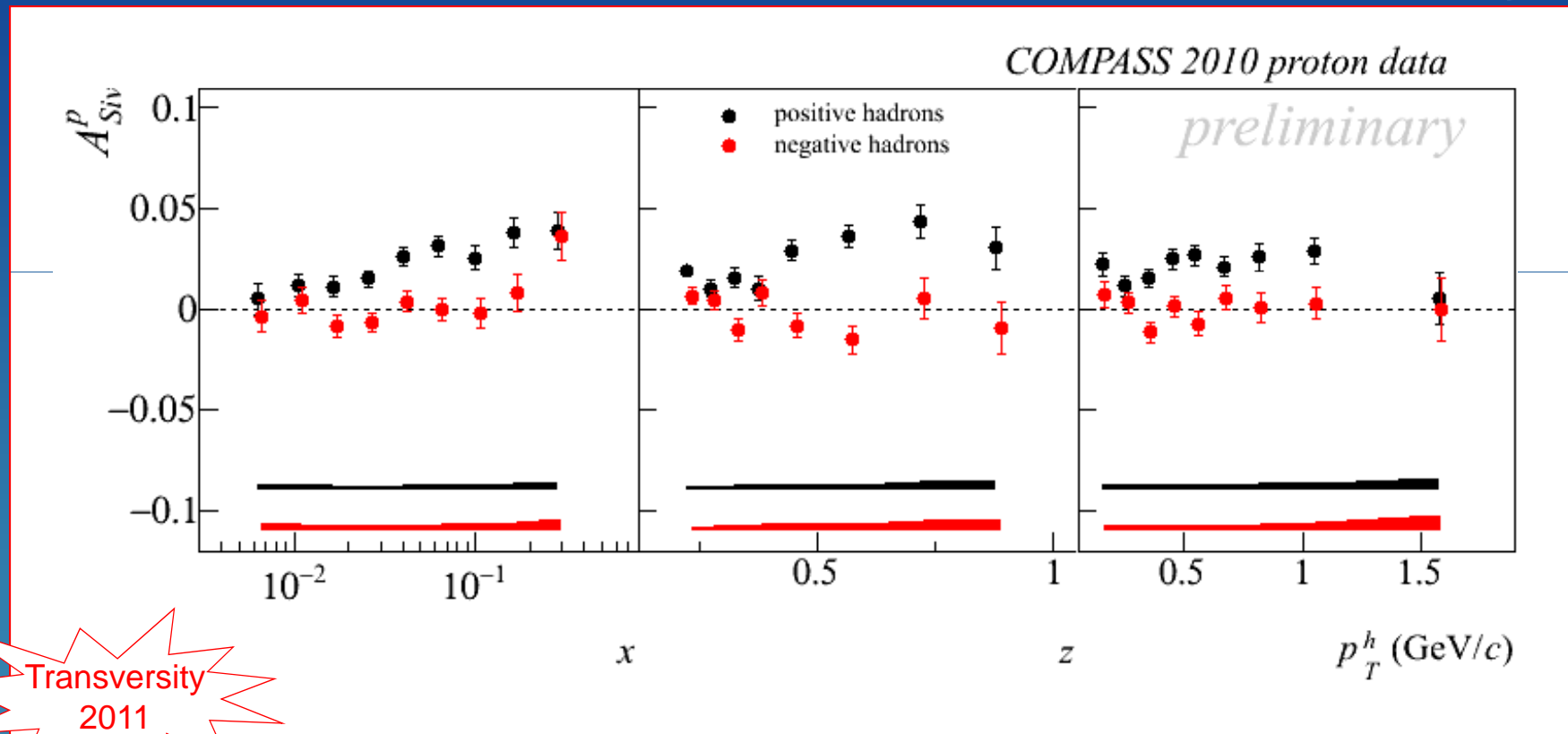
**again, nice agreement with the 2007 results,
with better statistics**

$\sigma_{syst} \sim 0.5\ \sigma_{stat}$ in 2010

Sivers asymmetry

results from 2010 data vs results from 2007data

Sivers asymmetry
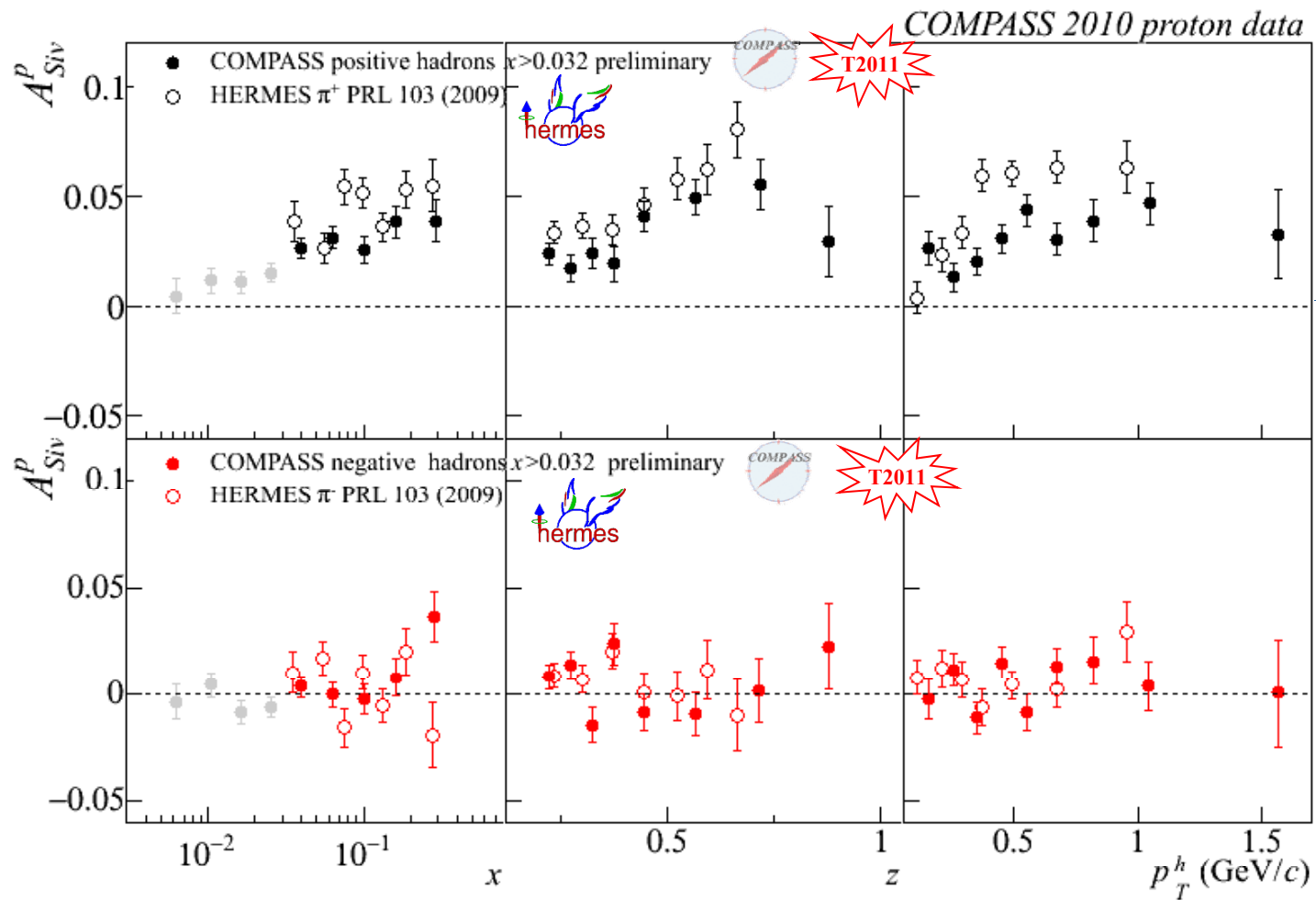
Sivers asymmetry

JLab - neutron
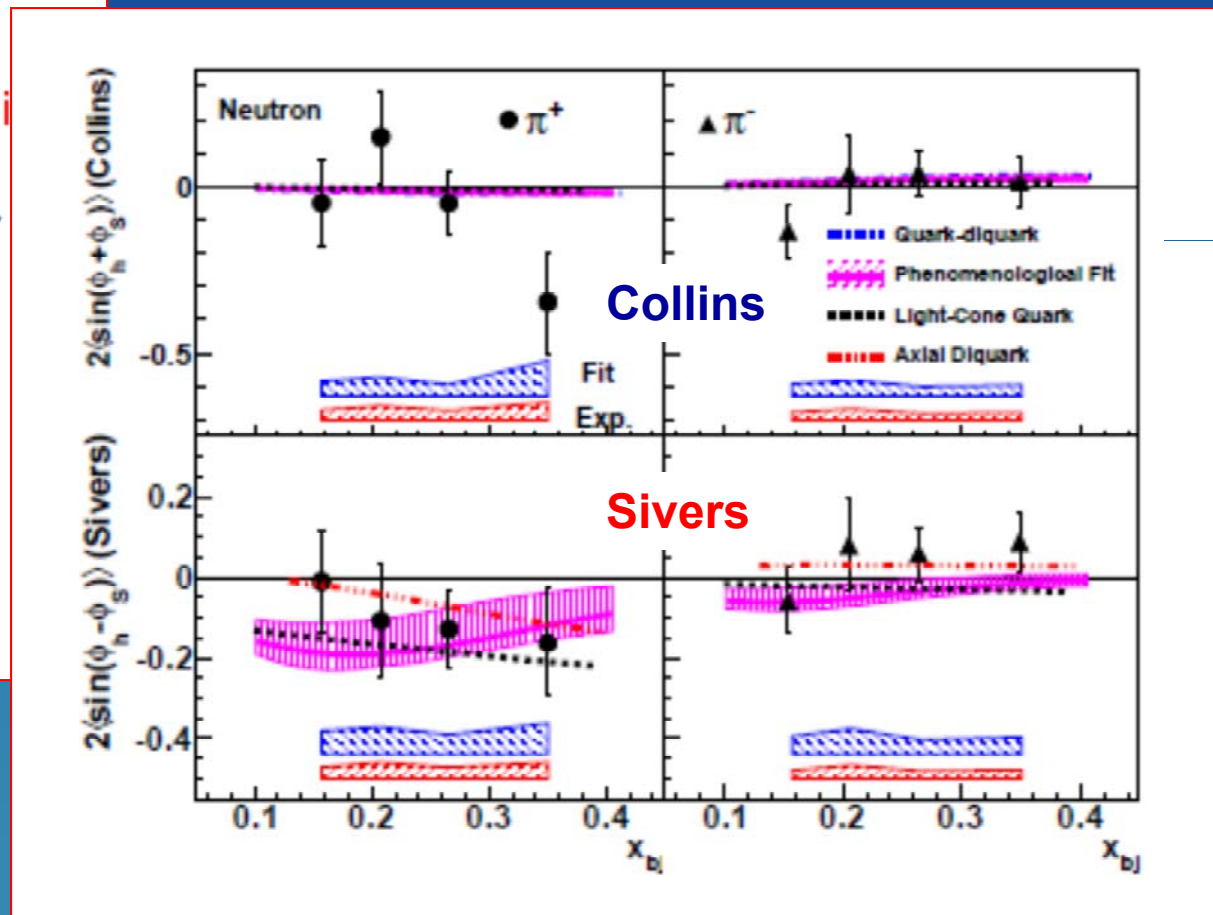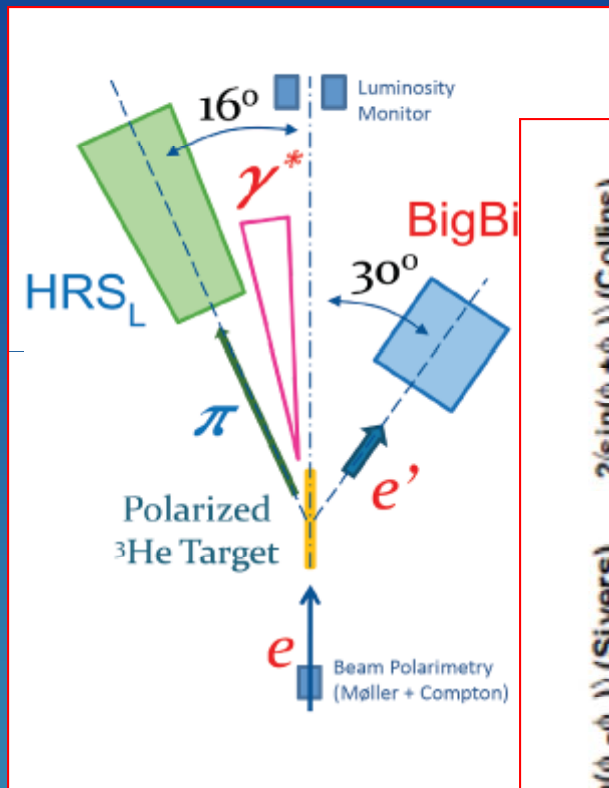
CONCLUSIONS
on transverse spin and
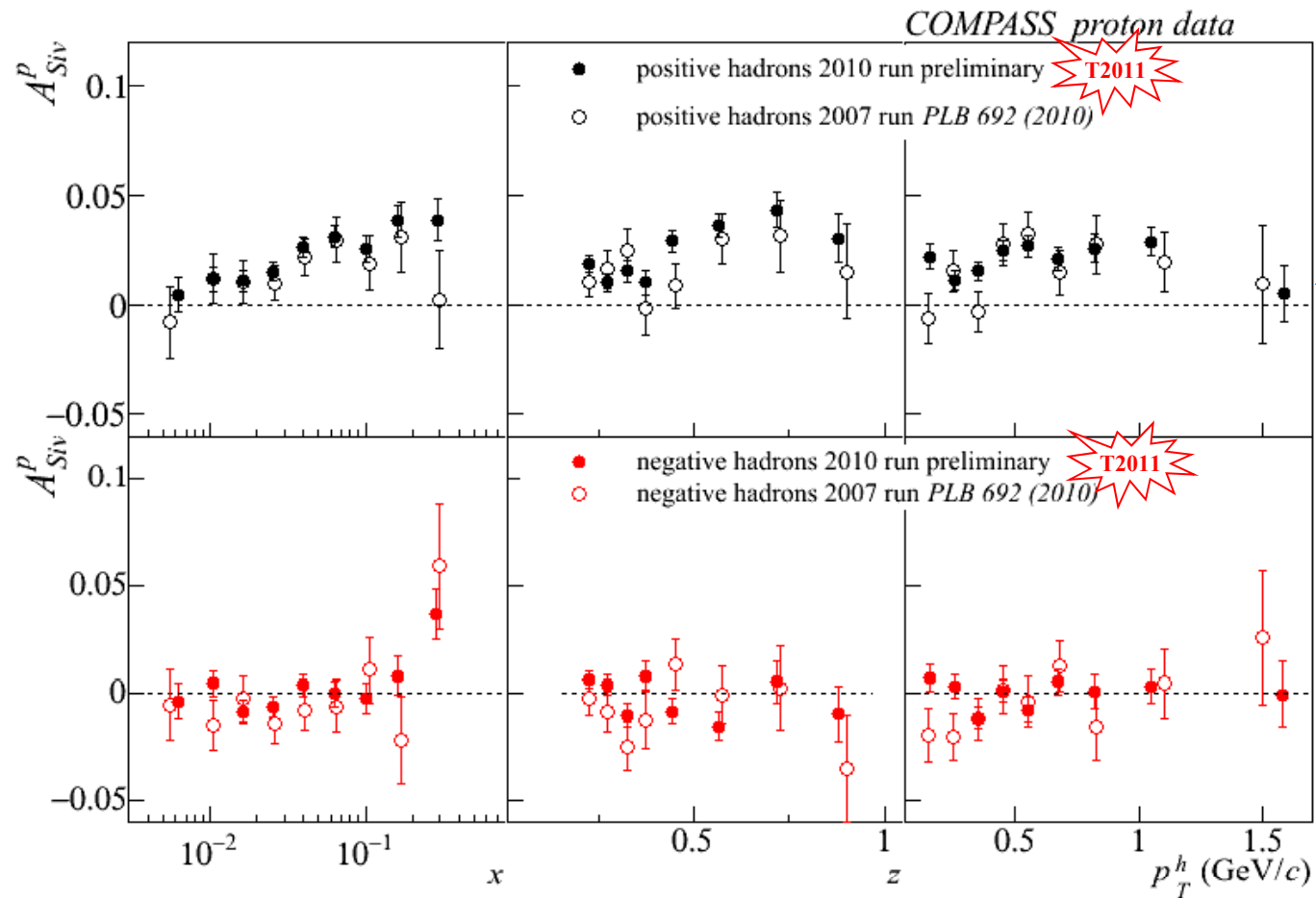## transverse momentum phenomena

- **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)

$\mu\,p$ SIDIS
s(x), Kaon FF
Boer Mulders PDFs and k_T

Drell-Yan $\pi\,p\uparrow$
Sivers and Boer Mulders PDFs
Test of universality

Primakoff
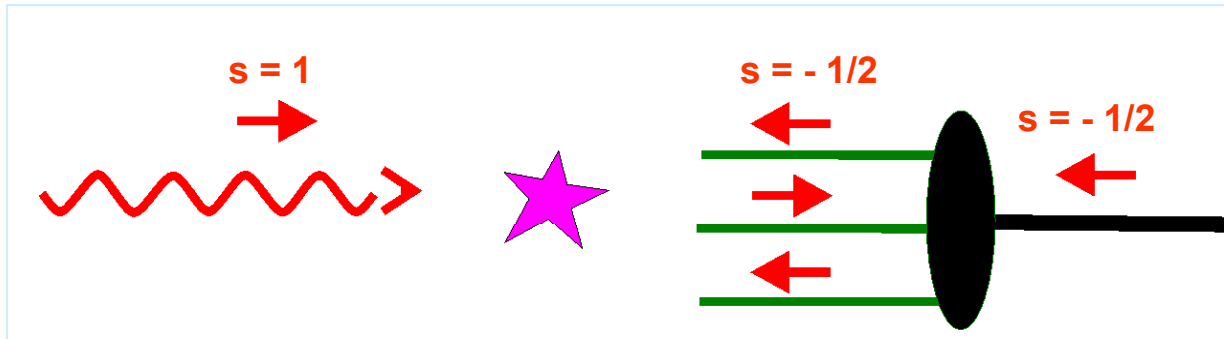Chiral Perturbation Theory

SPARE SLIDES

g$_1$ and F$_1$ in Quark Parton Model

s = 1

s = - 1/2

s = - 1/2

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

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

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

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

definitions:

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

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

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

F. Bradamante

Measurement of g_1 in inclusive DIS

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

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

~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 $\gamma^* p$ (n) scattering

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

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

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

Erice, 17 September 2011

F. Bradamante

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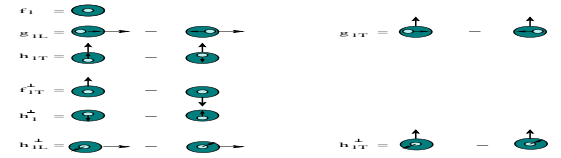
$$\vec{S}_\perp^N$$

2) Quark transverse spin

$$\vec{s}_\perp^q$$
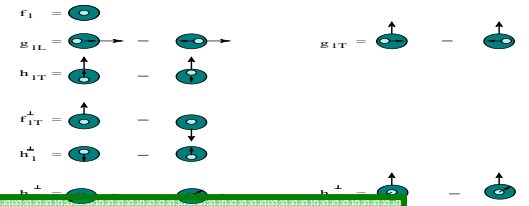
3) Qaurk transverse momentum

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

$\Rightarrow$ Three different correlations
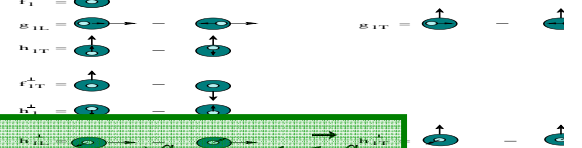
1) Transversity

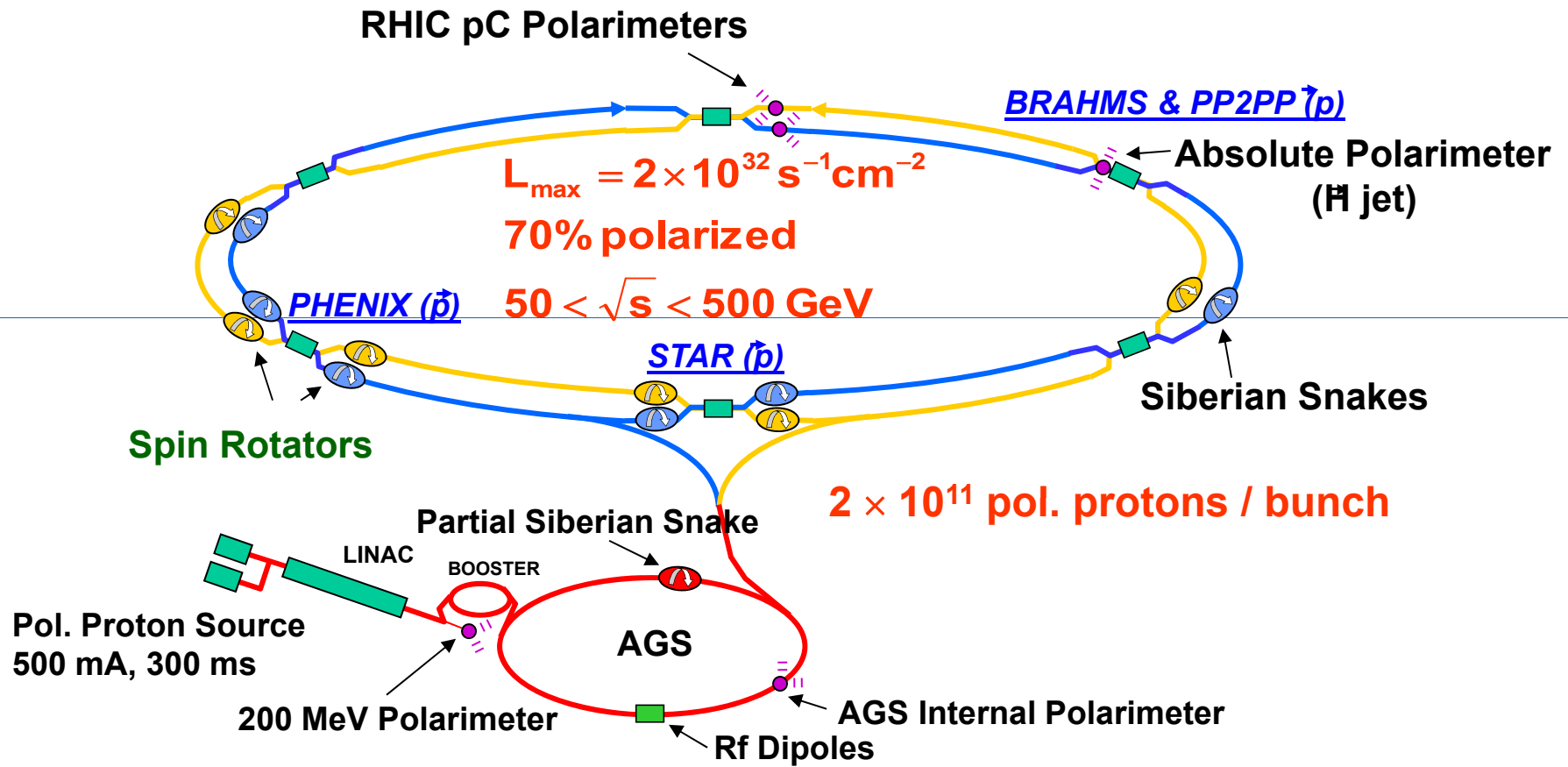Correlation between $\vec{s}_\perp^q$ and $\vec{S}_\perp^N$

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

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

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

Unpolarized

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

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

Polarized target

Sivers

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

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

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

Polarizied beam and target

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

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