Theoretical and experimental aspects of
the spin-statistics connection and related symmetries

Trieste, Italy - October 21-25, 2008 - Stazione Marittima Conference Center

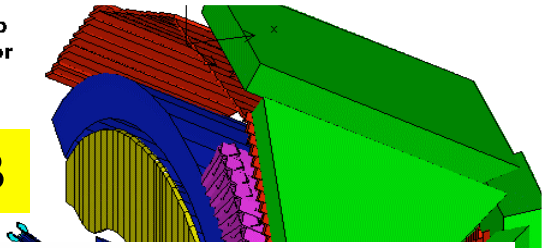
The inner spin structure of the nucleon: a COMPASS perspective

Andrea Bressan

University of Trieste

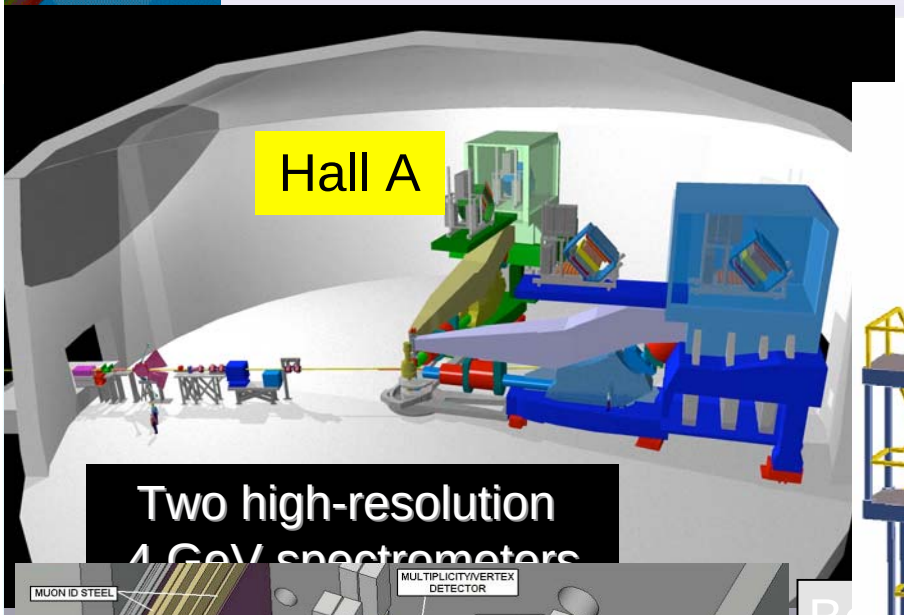
Who are the pla

Jefferson Lab
CLAS Detector



Hall B

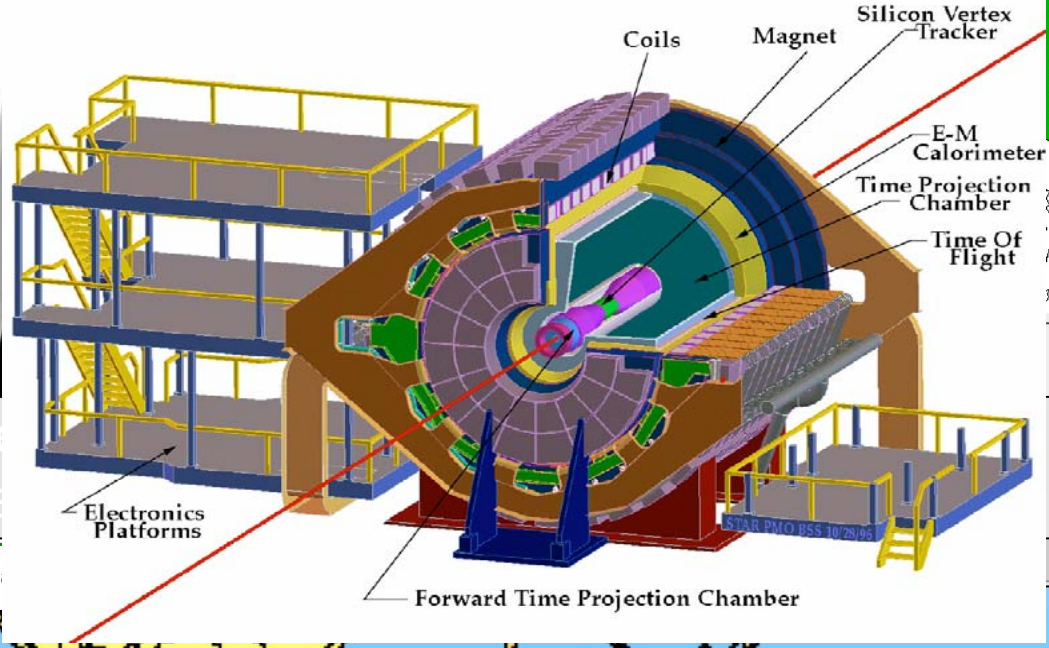
Hall A

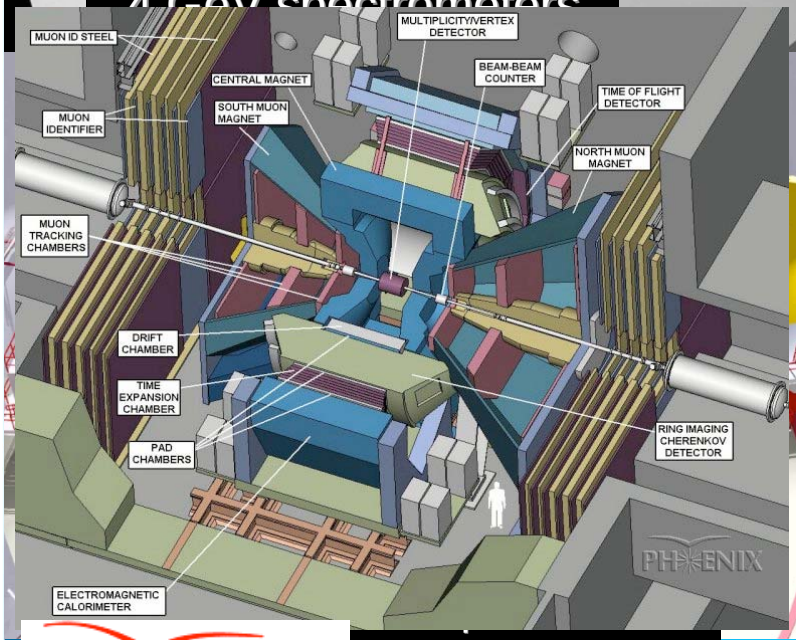


Two high-resolution
4 GeV spectrometers

STAR

STAR Detector





Beams: 250 GeV pp; <60>% polarization
Lumi: 1.2 $10^{31}cm^{-2}s^{-1}$

PHENIX

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

NA58

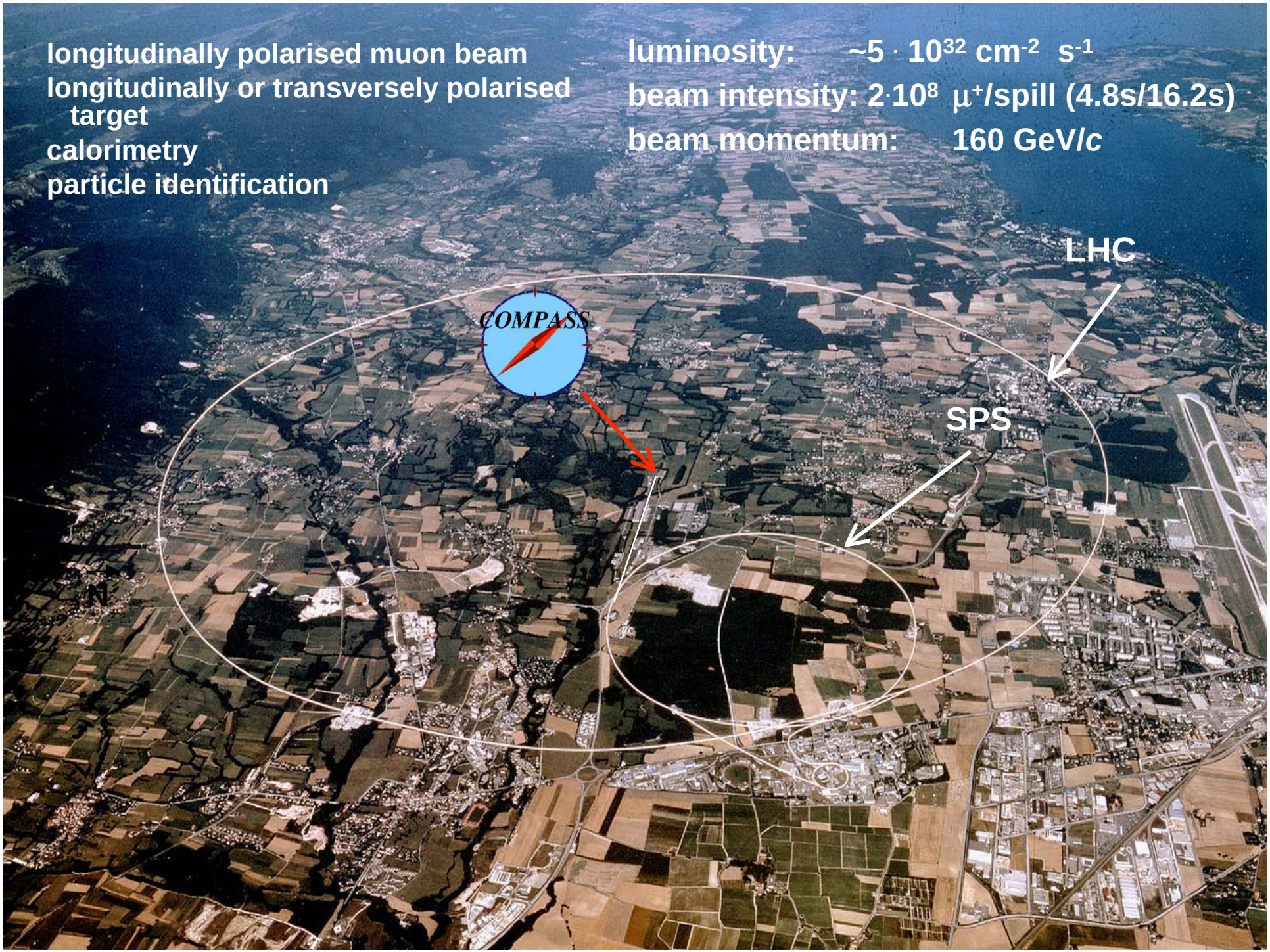
Czech Republic, Finland, France, Germany, India, Israel, Italy, Japan, Poland, Portugal, Russia

Bielefeld, Bochum, Bonn, Burdwan, Calcutta, CERN, Dubna, Erlangen, Freiburg, Heidelberg, Helsinki, Lisbon, Mainz, Miyazaky, Moscow, Munich, Nagoya, Prague, Protvino, Saclay, Tel Aviv, Torino, Trieste, Warsaw

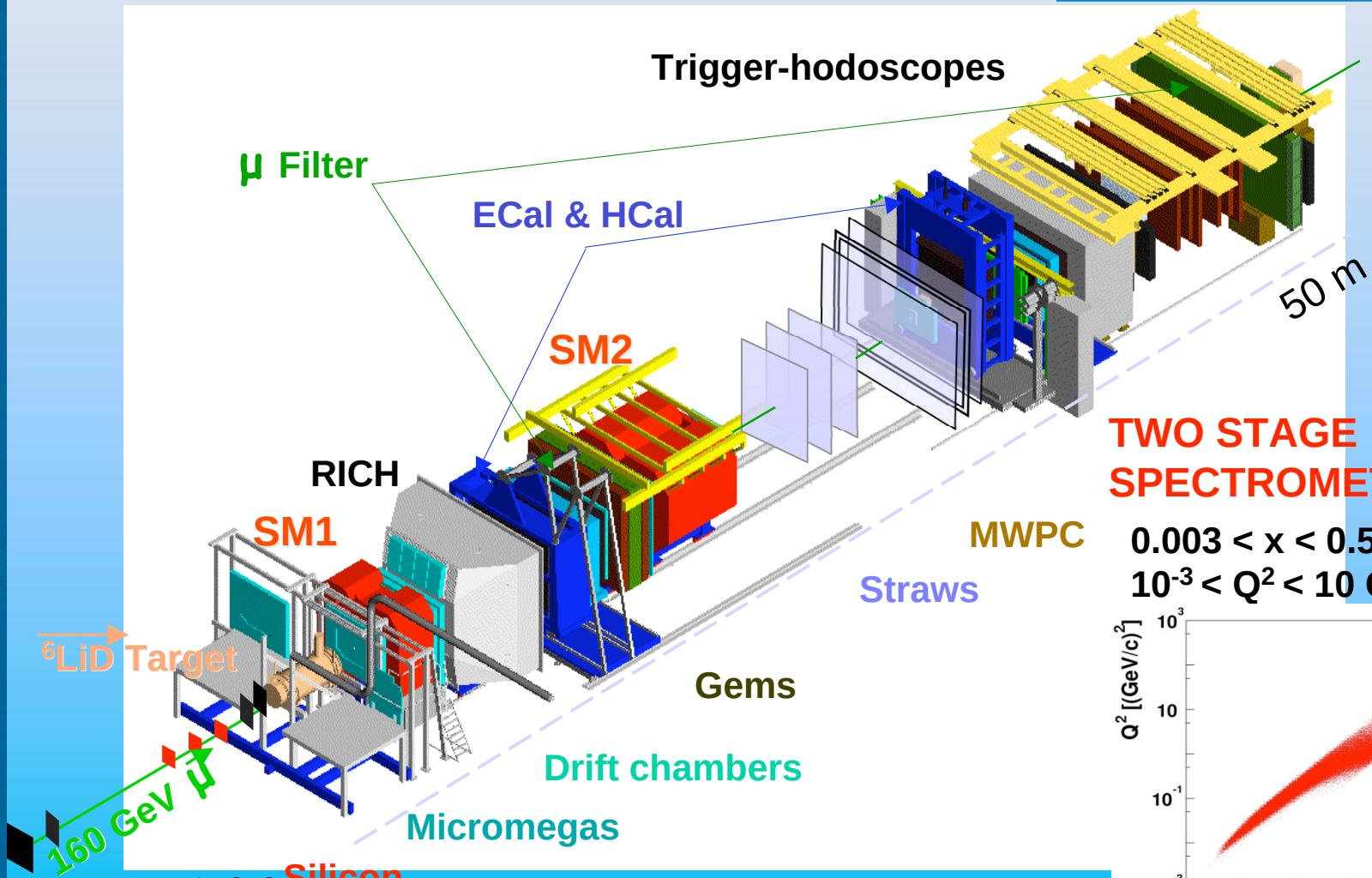
28 Institutes, ~230 physicists

Physics program of COMPASS

- **Experiments with muon beam**
  - **ΔG/G**
  - **g_1**
  - **Transverse spin effects**
  - **Flavor decomposition of spin distribution functions**
  - **Vector meson production**
  - **Spin transfer in Λ-hyperon production**
- **Experiments with hadron beams**
  - **Pion and Kaon polarizabilities**
  - **Diffractive production of exotic states**
  - **Search for glueballs**
  - **Light meson spectroscopy**
  - **Production of double charmed baryons**


longitudinally polarised muon beam
longitudinally or transversely polarised target
calorimetry
particle identification
luminosity: ~5 · 10^32 cm^-2 s^-1
beam intensity: 2·10^8 μ+/spill (4.8s/16.2s)
beam momentum: 160 GeV/c
LHC
COMPASS
SPS
N

The Spectrometer for the Muon Programme



TWO STAGE SPECTROMETER:

$0.003 < x < 0.5$

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

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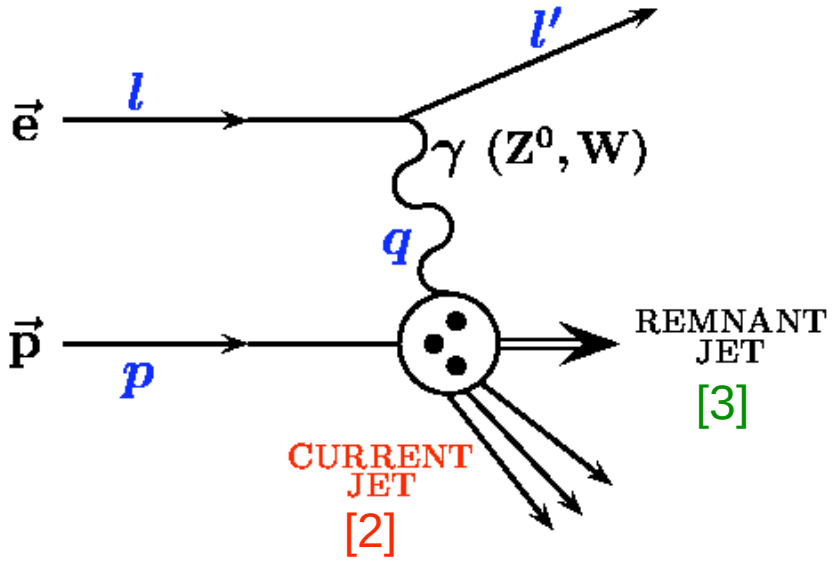
DEEP INELASTIC SCATTERING



$$Q^2 = -q^2 = sxy$$

$$x = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot l}$$

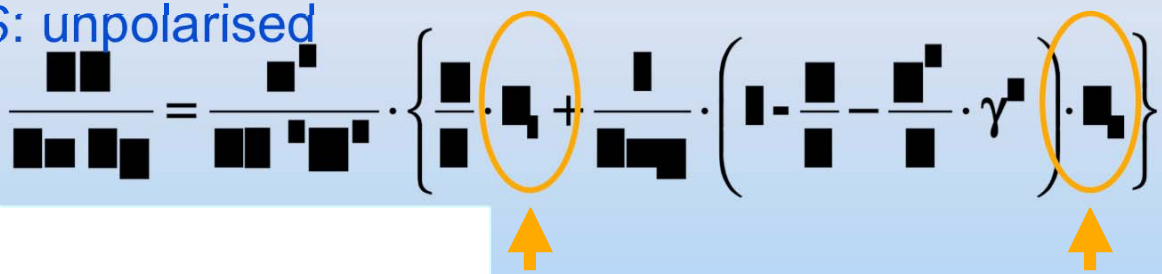
$$s = 4E_e E_p$$

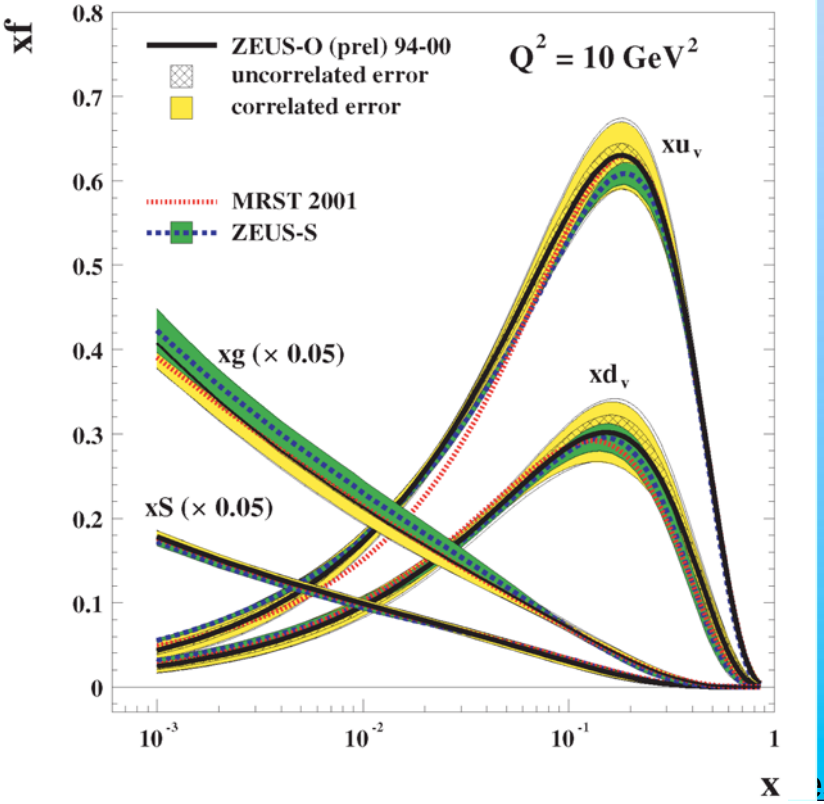
$$W = (q + p)^2$$

- Observe scattered electron/muon [1] → inclusive
- Observe current jet [1]+[2] → semi-inclusive
- Observe remnant jet as well [1]+[2]+[3] → exclusive

PDF AND STRUCTURE FUNCTIONS

Inclusive DIS: unpolarised





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

in the parton model

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

The nucleon structure

three distribution functions

are necessary to describe the structure of the nucleon at LO:

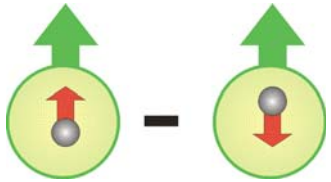
q(x) : number density or unpolarised distribution

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

$\Delta q(x) = q^{\rightrightarrows} - q^{\rightleftarrows}$: 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 transversly polarised nucleon, probability of finding a quark with a momentum fraction x and spin parallel to that of the parent nucleon

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

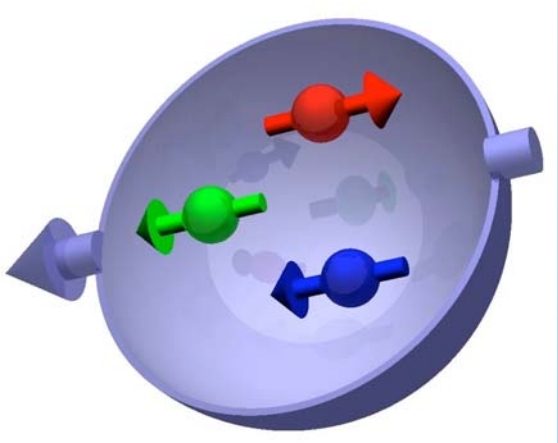
ALL OF EQUAL IMPORTANCE !

TWO CASES

- LONGITUDINAL SPIN
- TRANSVERSE SPIN

WE START FROM LONGITUDINAL →

What we are after?



Naïve parton model

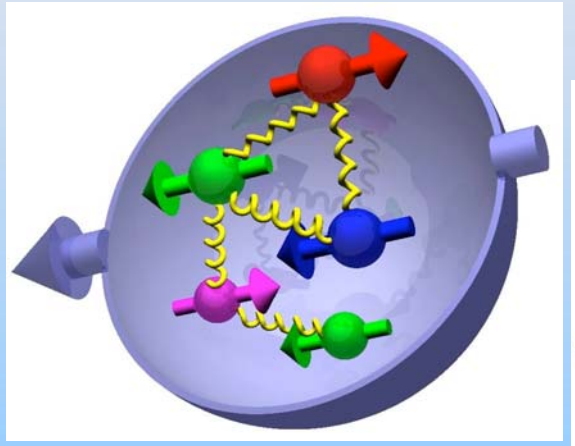
$$\Delta u_v = \frac{4}{3} \quad \Delta d_v = -\frac{1}{3}$$

BUT

1989 EMC measured

$\Sigma = 0.120 \pm 0.094 \pm 0.138$

⟹ Spin Puzzle

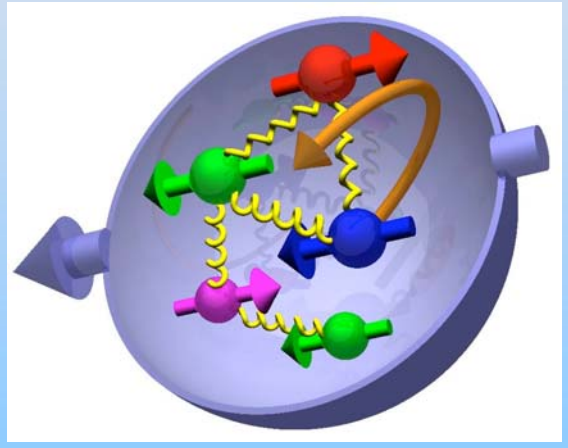


Unpolarised structure fct.

Gluons are important !

⟹ ΔG

⟹ Sea quarks Δq_s



Full description of J_q and J_g needs

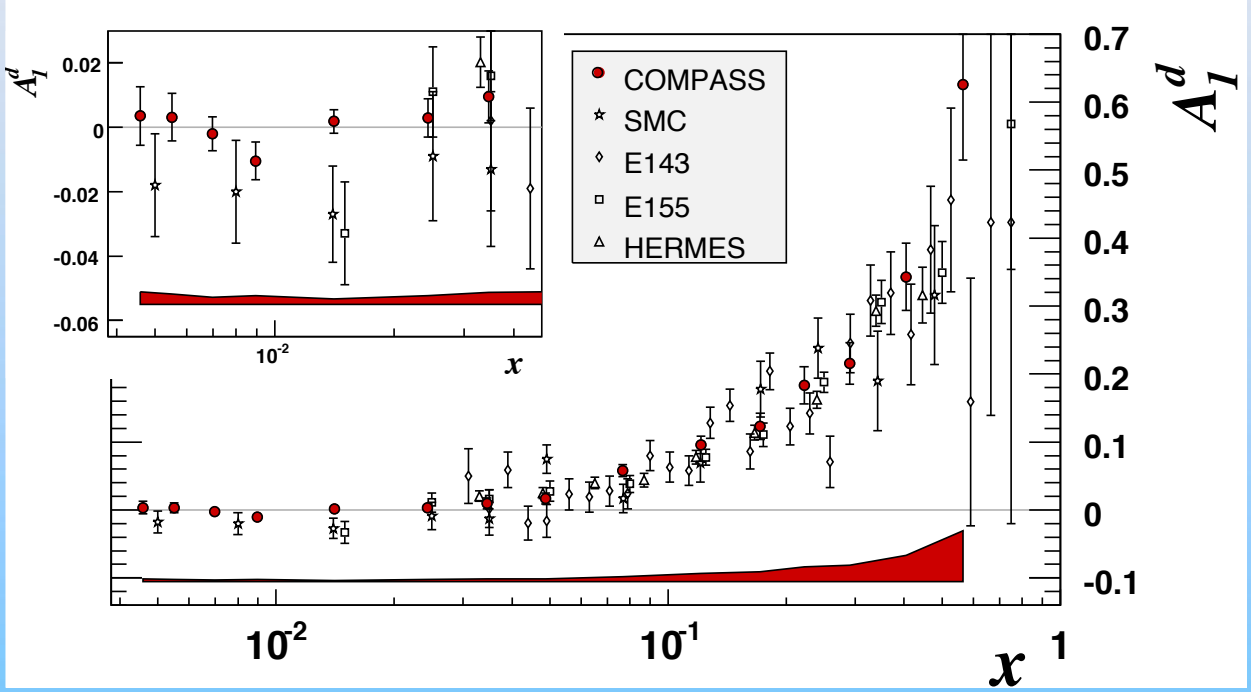
orbital angular momentum

$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v + \Delta u_s + \Delta d_s + \Delta s + \Delta \bar{u} + \Delta \bar{d} + \Delta \bar{s}) + \Delta G + L_g$$

$$\Delta\Sigma$$

A_1^d from COMPASS

Inclusive DIS asymmetry $Q^2>1$ (GeV/c)^2



PLB 647(2007)8

- good agreement with previous experiments
- significantly improved statistics at low x !

LONGITUDINAL SPIN CASE

direct measurement of

ΔG/G:

main objective of the

longitudinal run

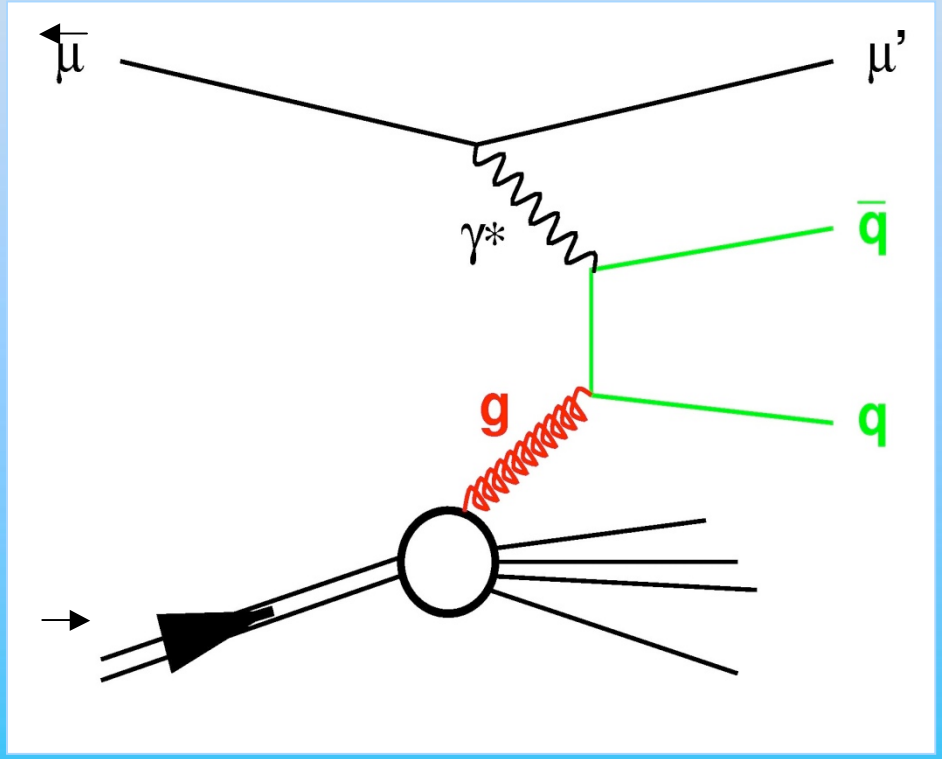
MEASUREMENTS OF THE GLUON POLARIZATION

FOUR LINES OF ATTACK:

1. **Double spin asymmetry of the OPEN CHARM cross-section in high energy μD scattering**
2. **Double spin asymmetry of the HIGH-p_t HADRON PAIRS in high energy μD DIS ($Q^2 > 1$ GeV^2)**
3. **Double spin asymmetry of the high-p_t hadron pairs in high energy μD scattering ($Q^2 < 1$ GeV^2)**
4. **Measurement of g_1 of the deuteron and QCD fit of all the world data**

ΔG/G at COMPASS

Photon Gluon Fusion



q = c cross section difference in charmed meson production

→ *theory well understood*

→ *experiment challenging*

q = u,d,s cross section difference in 2+1 jet production in COMPASS: events with 2 hadrons with high-p_t

→ *experiment easy*

→ *theory more difficult*

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ΔG/G

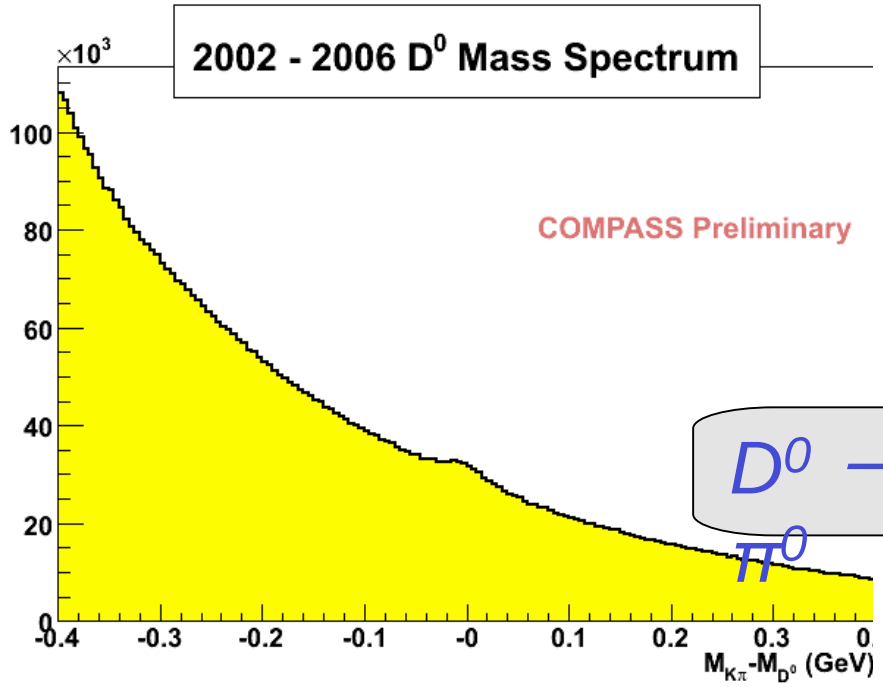
from Open Charm

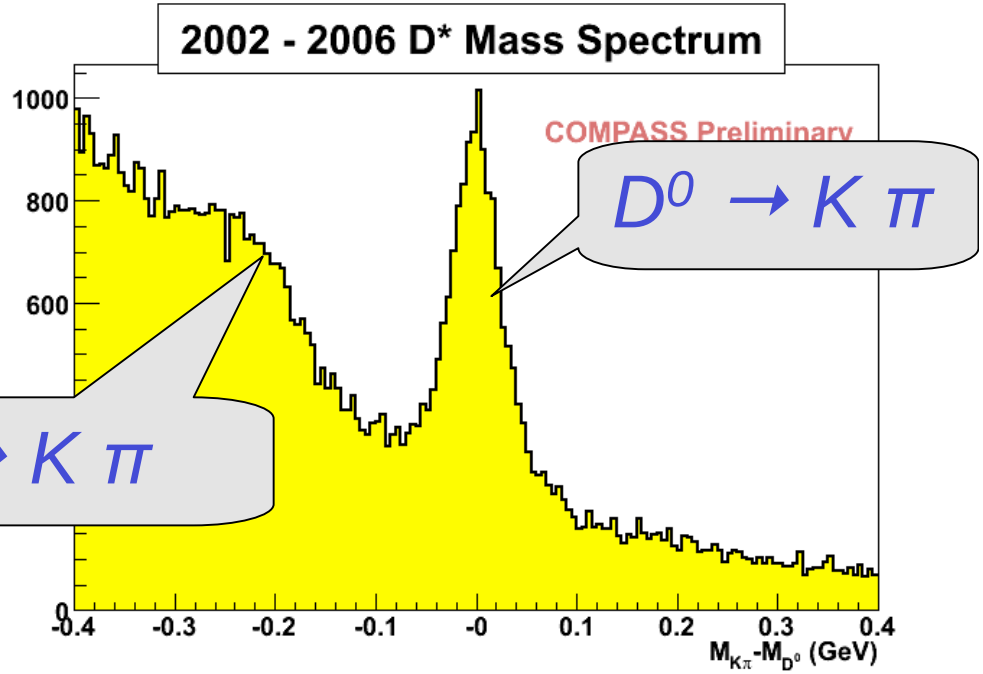
Andrea Bressan

COMPASS

D mass spectra

$$D^0 \to K + \partial \qquad D^* \to D^0 + \partial_s \to K + \partial + \partial_s$$





$D^0 \to K\,\pi\,\pi^0$

ΔG/G from open charm

2002 – 2006 data $D^0 + D^*$

$$\Delta G/G = -0.49 \pm 0.27\ (stat) \pm 0.11\ (syst)$$

@ $\langle x_g \rangle \sim 0.11$, $\langle \mu^2 \rangle \sim 13\ (GeV/c)^2$

preliminary

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ΔG/G

from High-p_t hadron pairs

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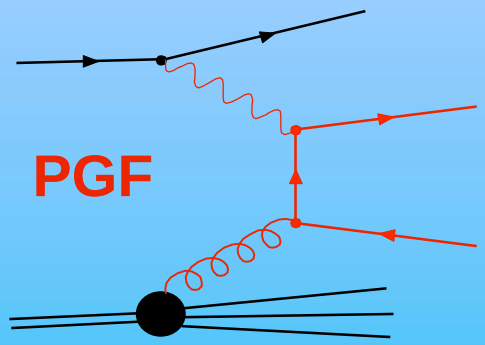
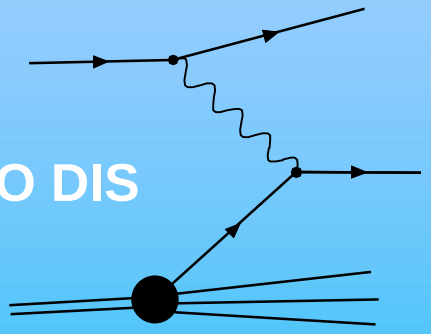
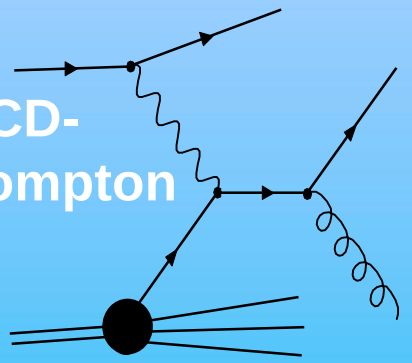
ΔG/G from High-p_t hadrons, $Q^2 > 1$ (GeV/c)^2

PGF and background

$$\frac{A_{LL}}{D} \approx \frac{a_{LL}^{PGF}}{D}\frac{\Delta G}{G}\frac{\sigma^{PGF}}{\sigma^{tot}} + A_1\frac{a_{LL}^{LO}}{D}\frac{\sigma^{LO}}{\sigma^{tot}} + A_1\frac{a_{LL}^{QCD-C}}{D}\frac{\sigma^{QCD-C}}{\sigma^{tot}}$$







$\Delta G/G$ from High-p_t hadrons, $Q^2 > 1$ (GeV/c)^2

2002 – 2004 data: High p_T, $Q^2 > 1$ GeV/c^2

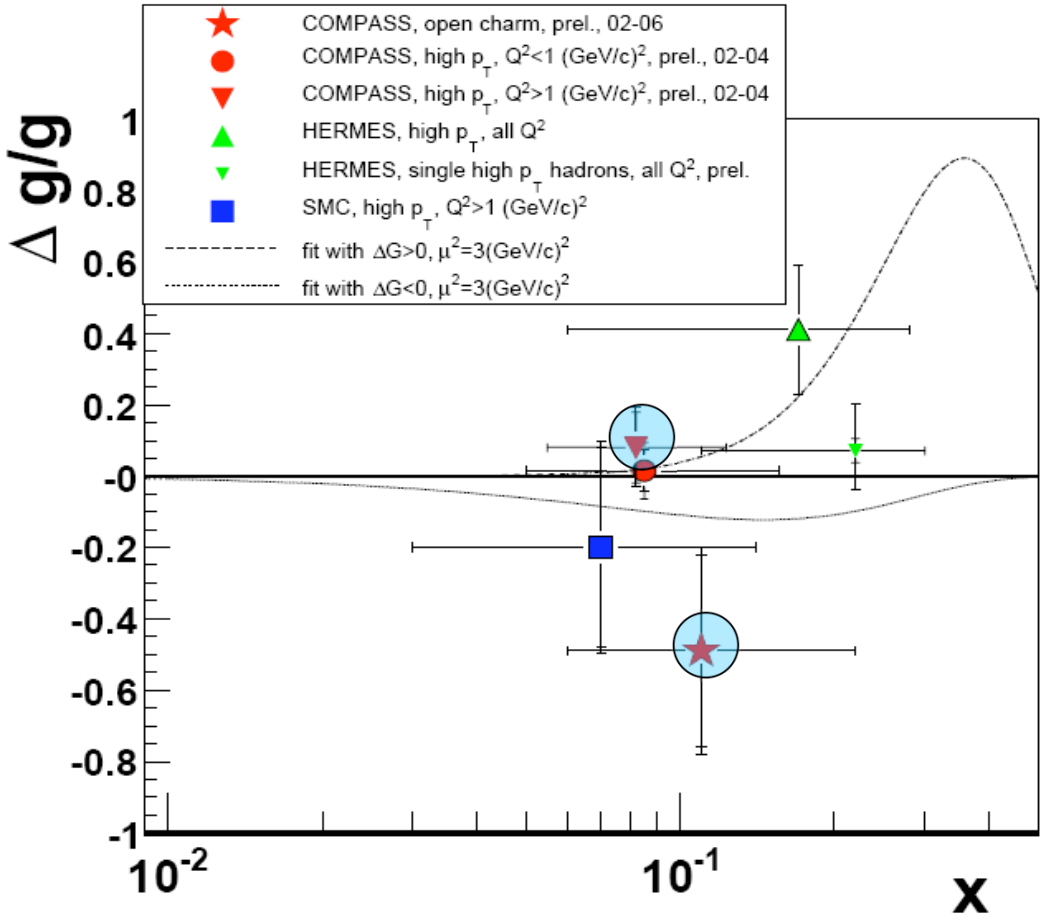
$\Delta G/G = 0.08 \pm 0.10$ (stat) ± 0.05(syst)

@ $\langle x_g \rangle = 0.082$ (range: 0.055 – 0.123), $\mu^2 \sim 3$ (GeV/c)^2

preliminary

COMPASS ΔG/G

Summary of ΔG/G results



CONCLUSION from ΔG MEASUREMENTS:

ΔG SMALL

more precise measurements will come soon

COMPASS 2006

RHIC RUN6

….

interest in
orbital angular momentum

GPD's

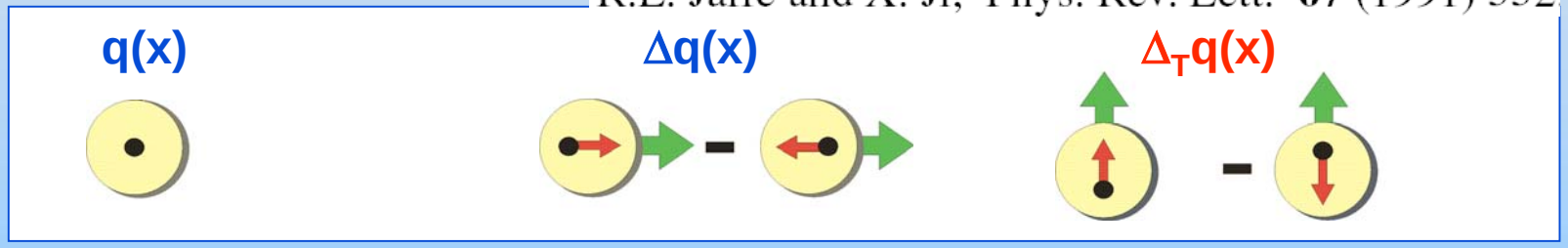
Transverse Spin case

Large effects observed in hadronic interactions

Theoretical developments:

at leading order a third PDF is necessary for a complete description of the structure of the nucleon

R.L. Jaffe and X. Ji, Phys. Rev. Lett. **67** (1991) 552



- $\Delta_T q(x)$ being chiral-odd, it can be measured only in conjunction with another chiral-odd partner:

DY  SIDIS 

Collins function

measurable in e+e- → hadrons

- relevance of transverse momentum dependent (TMD) PDF and FF

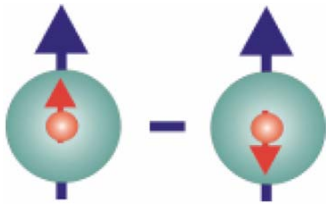
Sivers function

Many Workshops in recent years on *Transverse Momentum, spin, and position distributions of partons in hadrons*

Transversity DF

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

$h_1^q(x)$,
$\delta q(x)$,
$\delta_T q(x)$



$q=u_v$, d_v, q_{sea}
quark with **spin** parallel to the nucleon spin in a transversely polarised nucleon

Properties:

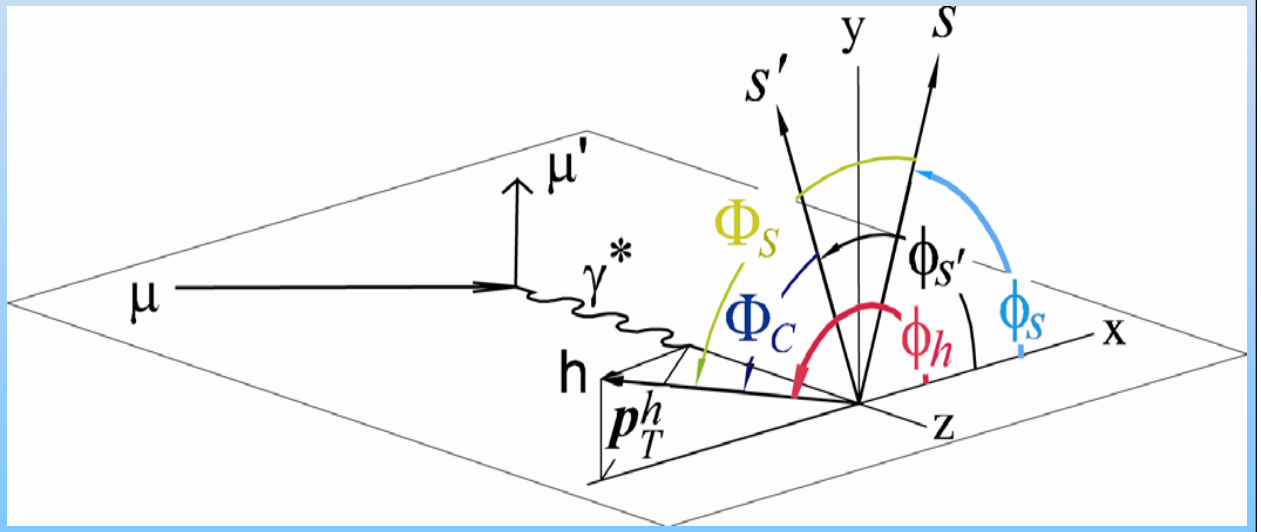
- probes the relativistic nature of quark dynamics
- no contribution from the gluons → simple Q^2 evolution
- Positivity: Soffer bound……. *Soffer, PRL 74 (1995)*
- first moments: tensor charge…….
- sum rule for transverse spin
  in Parton Model framework…… $\frac{1}{2} = \frac{1}{2}\sum \Delta_T q + L_q + L_g$ *Bakker, Leader, Trueman, PRD 70 (04)*
- it is related to GPD's
- is chiral-odd: decouples from inclusive DIS

Azimuthal modulations: single hadron

Collins and Sivers angles

$\Phi_C = \phi_h - \phi_{S'}$

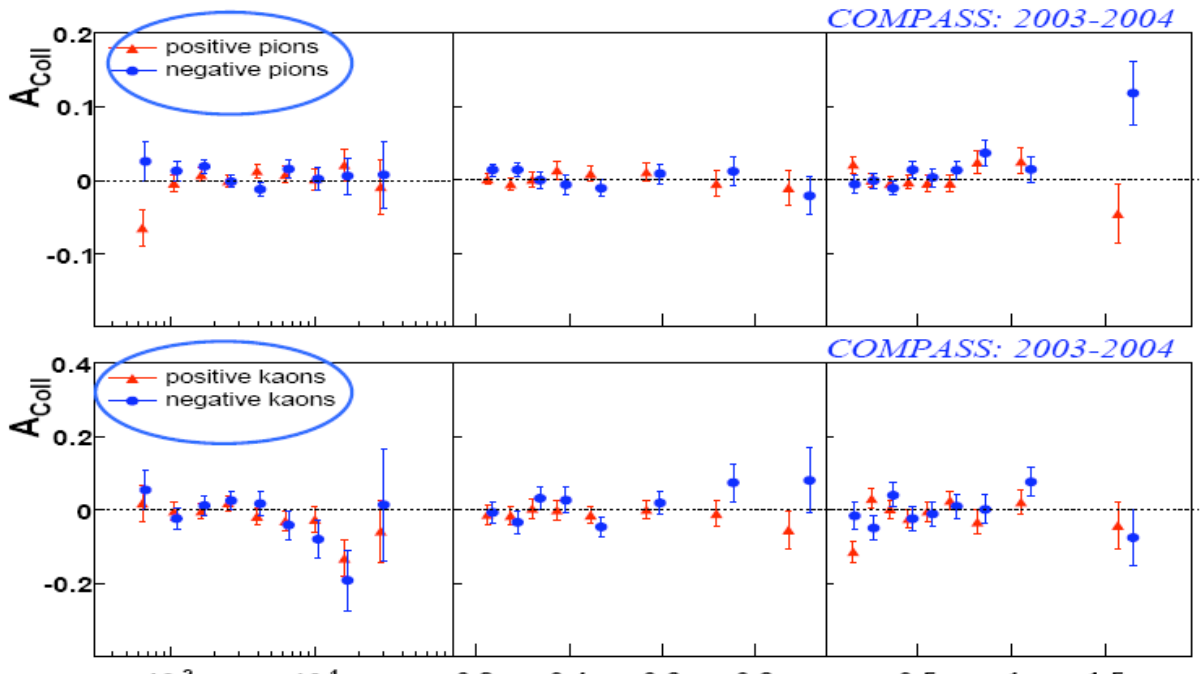
$\Phi_S = \phi_h - \phi_S$

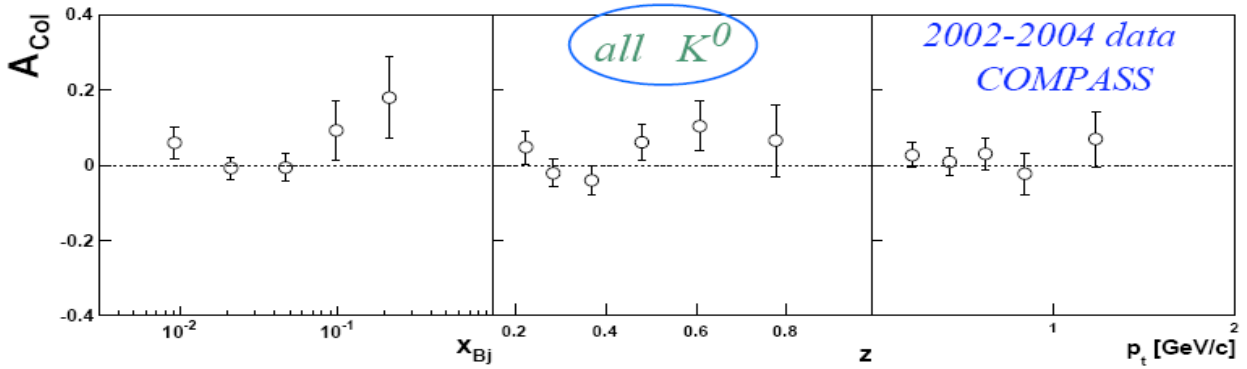


$\phi_{S'}$ azimuthal angle of spin vector of fragmenting quark ($\phi_{S''} = \pi - \phi_S$)

ϕ_h azimuthal angle of hadron momentum

Collins Final on Deteron - COMPASS





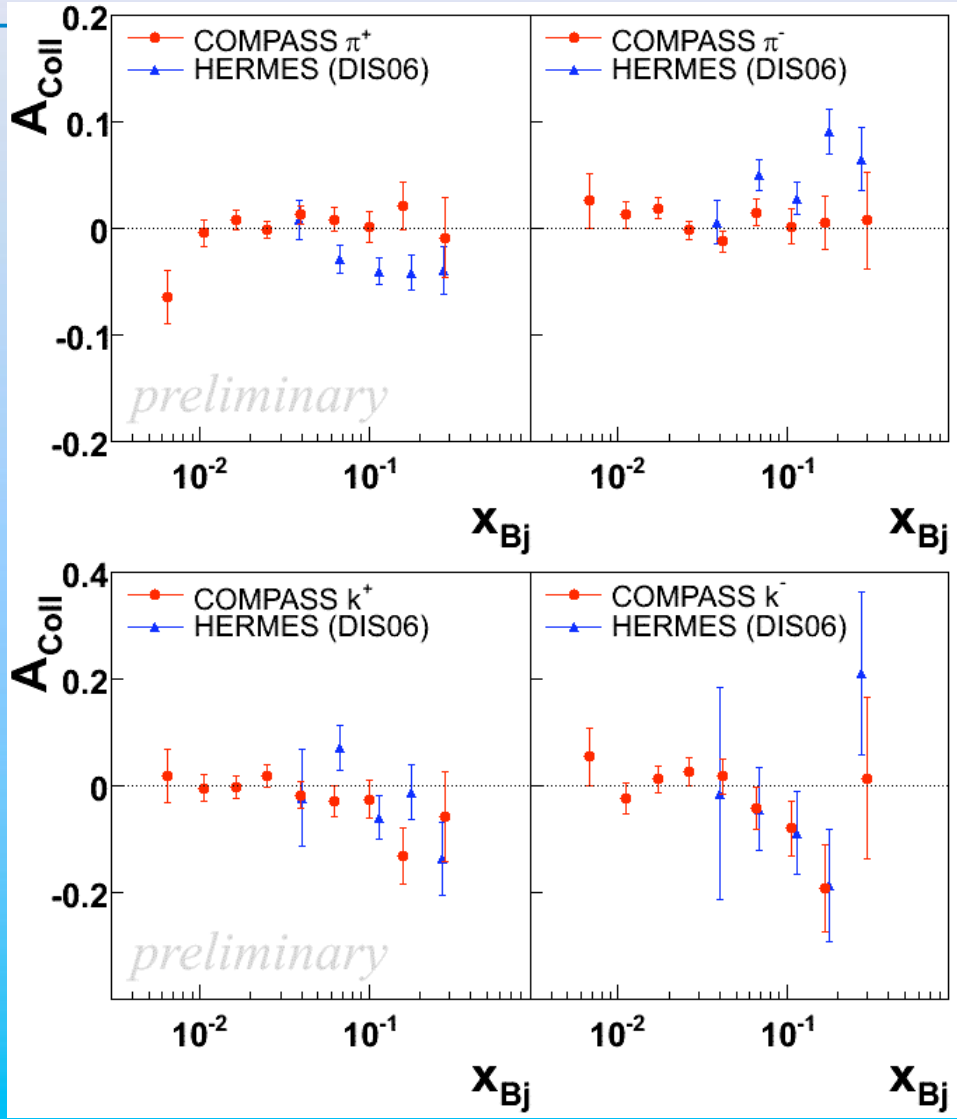
Final Results
all deuteron data
hep-ex/0802.2160
(subm. PLB)

Final Results
all deuteron data
hep-ex/0802.2160
(subm. PLB)

Collins asymmetry for pions and kaons

preliminary
2002-2004 data
proton
(virtual photon asymm)
(lepton beam 2002-05 → DIS07)

final *CERN-PH-EP/2008-002*
hep-ex/0802.2160 (PRL)
2003-2004 data
deuteron
(virtual photon asymm)



Collins asymmetries: SUMMARY

The facts:

- **HERMES has measured on a proton target non-zero Collins asymmetries for π^+ and π^-**
- **COMPASS has measured on a deuteron target Collins asymmetries compatible with zero**
- **BELLE has produced the first results on Collins FF**

Conclusion:

- **Collins mechanism is a real phenomenon**
- **universality of Collins FF**
- **transversity can be measured in SIDIS**

Present picture

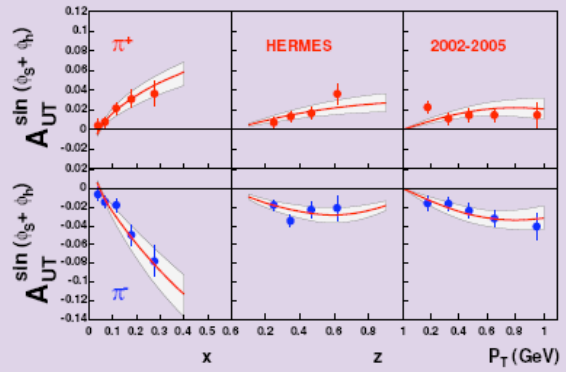
- **Collins:** $\Delta_T u \sim -\Delta_T d$
  $\Delta_T^0 D(\text{fav.}) \sim -\Delta_T^0 D(\text{unfav})$

To extract TMD DF and FF GLOBAL ANALISYS are necessary

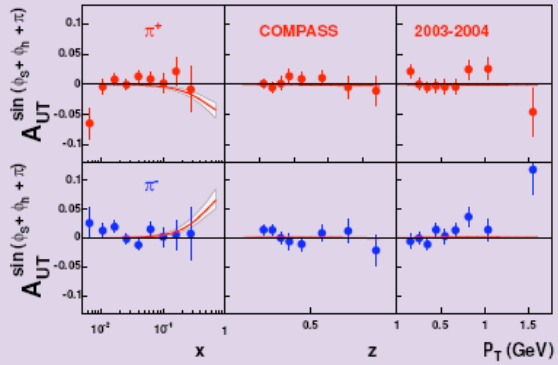
Global Fits

Preliminary results

HERMES $A_{UT}^{\sin(\phi_h+\phi_S)}$

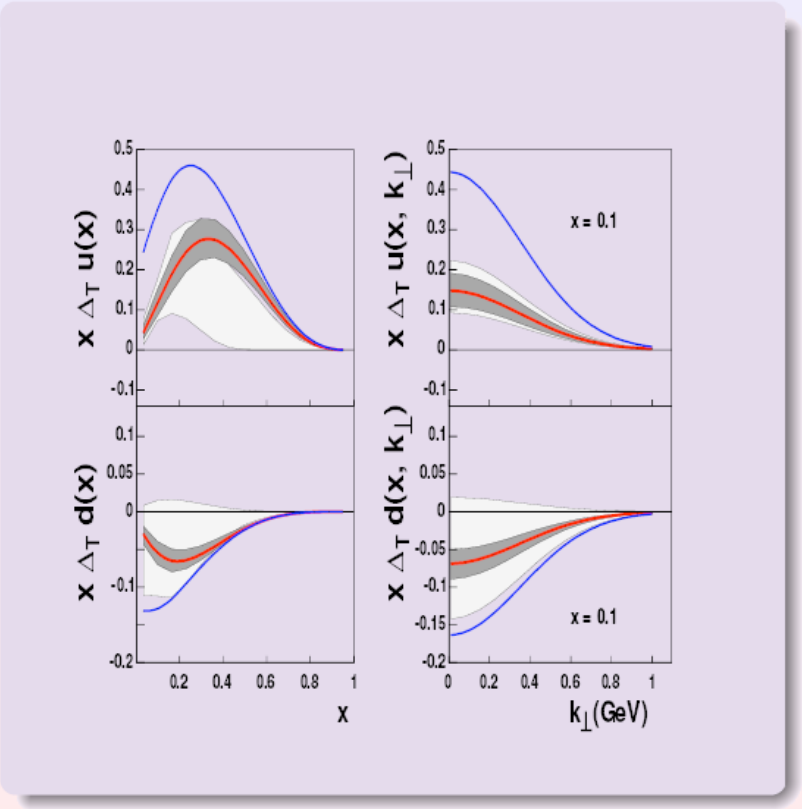


COMPASS $A_{UT}^{\sin(\phi_h+\phi_S+\pi)}$



First Extraction of $\Delta_T q$

Transversity

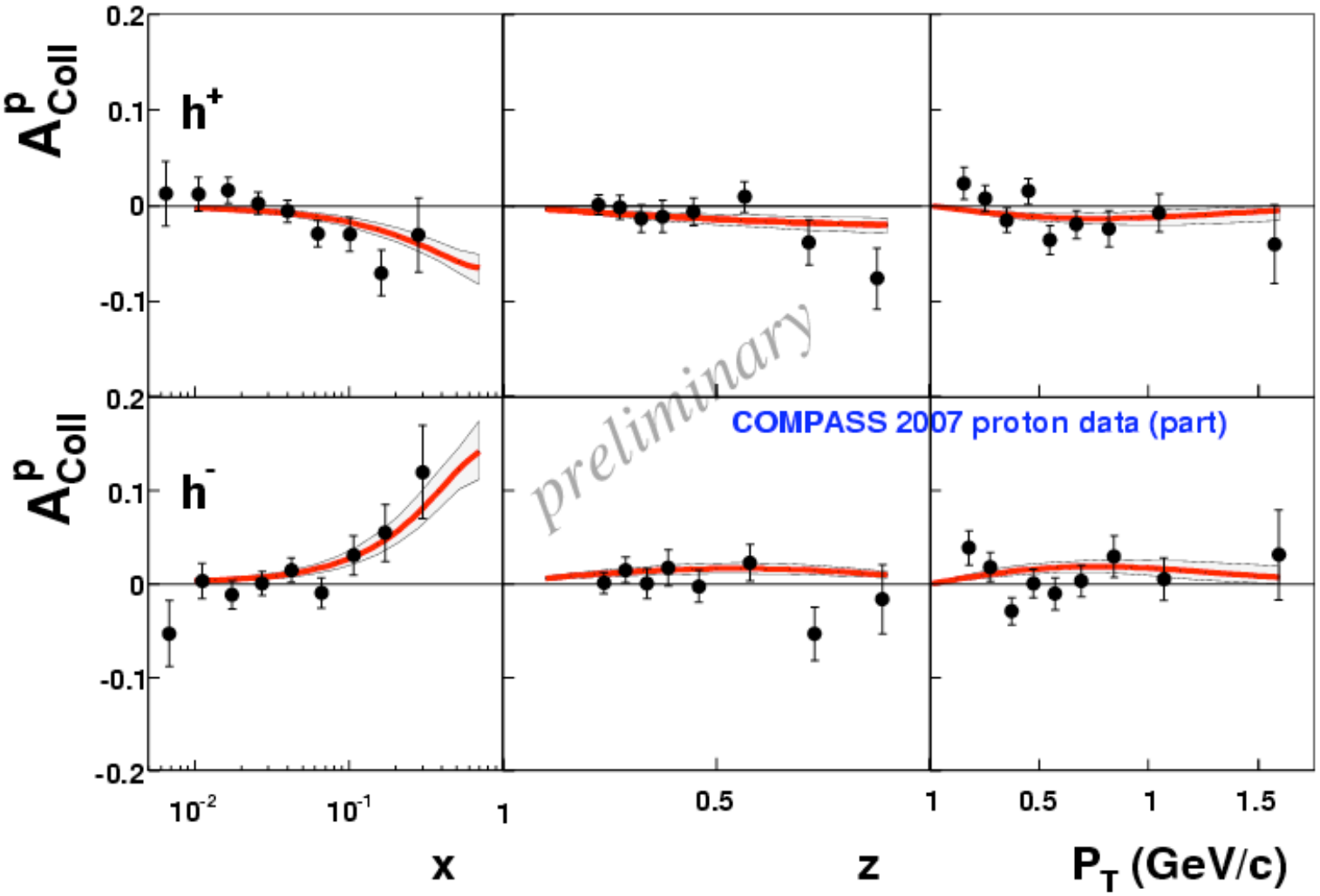


- This is the extraction of transversity from new experimental data.
- Compared to previous extraction PRD75:054032,2007
- $\Delta_T u(x) > 0$ and $\Delta_T d(x) < 0$ The errors are diminished significantly.
- $\Delta_T u(x)$ became larger than that of the previous fit.

HERMES, COMPAS SBELLE

Compass proton data

comparison with M. Anselmino et al. predictions



What else?

When k_T is taken into account…

- **Transverse momentum dependend PDFs and FFs**
  - Transverse momentum dependent (TMD) parton distributions and fragmentation functions are currently under intense investigation both from the experimental and theoretical side
  - The knowledge of correlations of transverse momentum of partons and spin are crucial for the understanding of the spin structure of the nucleon in terms of the quark and gluon degrees of freedom of QCD.

Three parton distributions describing quark's TM and/or TS

Three transverse quantities:

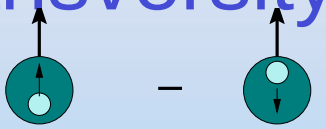
1) Nucleon transverse spin $\vec{S}_\perp^{\,N}$

2) Quark transverse spin $\vec{s}_\perp^{\,q}$

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

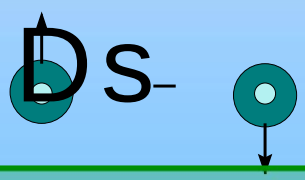
⇒ Three different correlations

1) Transversity

h_{1T} =  –

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

2) Sivers function

$f_{1T}^{\perp}$ =  –

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

3) Boer-Mulders function

$h_1^{\perp}$ =  –

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

COMPASS HAS RESULTS ON SIVERS AND OTHER TMDs but too long…

Thank You