The Abdus Salam
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1942-43

Sixth International Conference on Perspectives in Hadronic Physics

12 - 16 May 2008

Highlights from the COMPASS experiment at CERN.

F. Bradamante
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Italy

HIGHLIGHTS FROM THE COMPASS EXPERIMENT @ CERN

F. Bradamante

University of Trieste and INFN Trieste

on behalf of the COMPASS Collaboration

Sixth International Conference on Perspectives in Hadronic Physics

Trieste, May 16, 2008

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

COMPASS

- **experiment:**

thought of in	April ’94	Trento workshop
	Nov. ‘94	Trieste workshop @ICTP
Lol	March ’95	
encouraged	June ‘95	SPSLC in Cogne
Proposal	March ’96	
recommended	Sept. ’96	
approved by RB	Feb. ‘97	as NA58
Technical run	2000	
Commissioning	2001	

- **since 2002 taking data with**

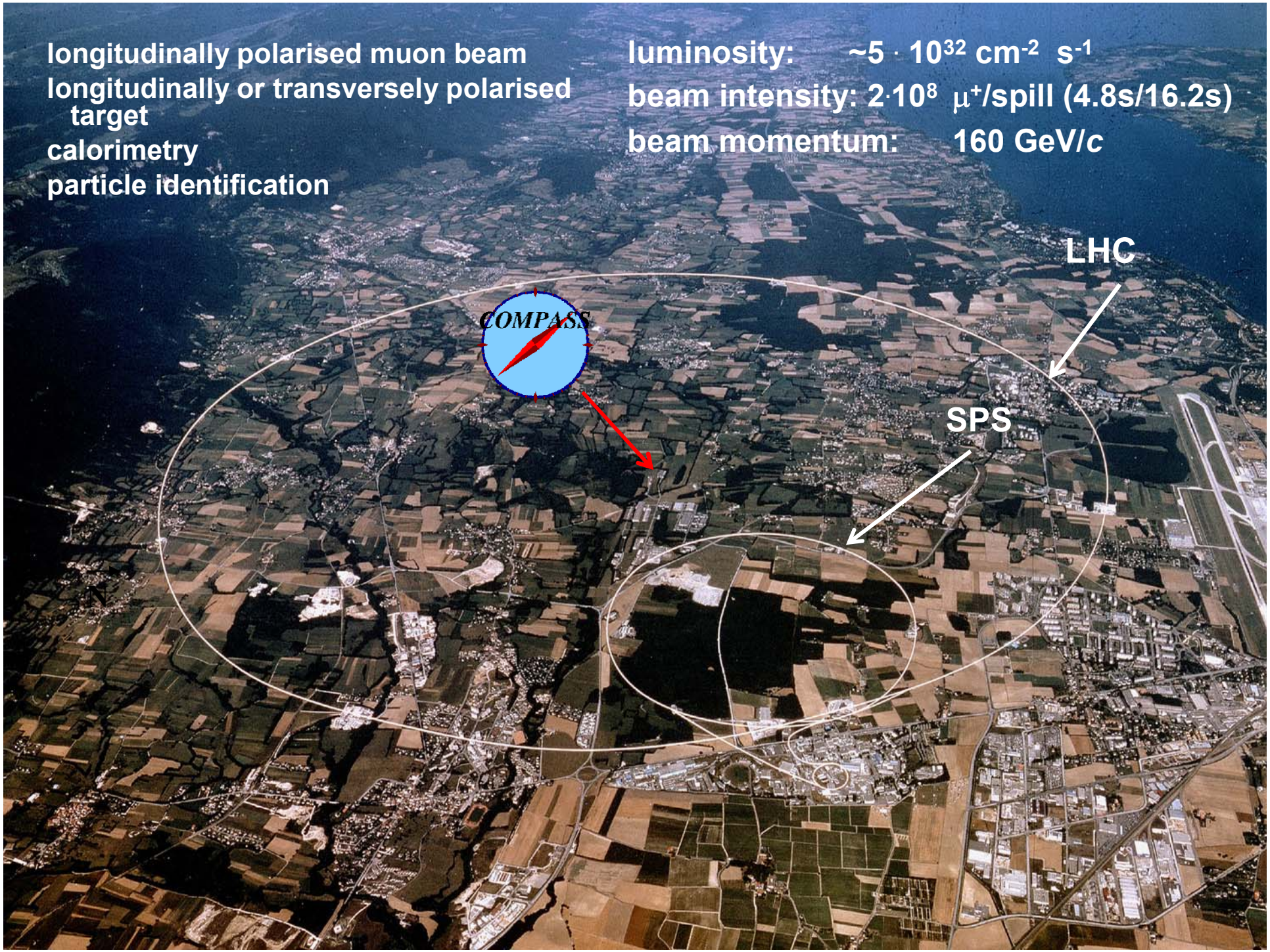
  a new spectrometer with outstanding performances

- **merging of two programmes:** **HMC** (muon beam) **CHEOPS** (hadron beam)

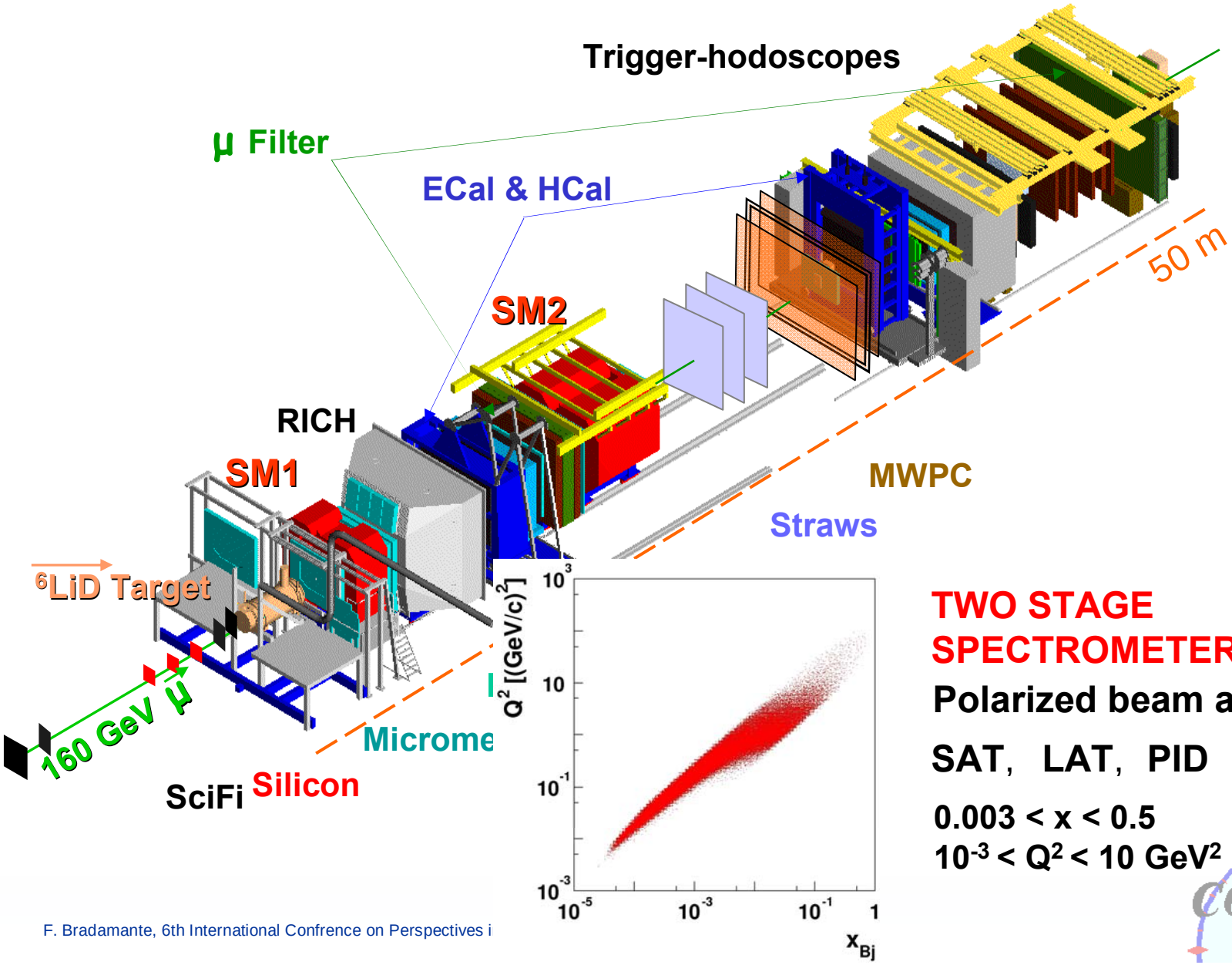
Physics program of COMPASS

- **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**

COMPASS


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:

Polarized beam and target

SAT, LAT, PID

$0.003 < x < 0.5$

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

WHERE ARE WE ?

- in 2002, 2003, 2004, 2006 and 2007 COMPASS has taken data in the muon program configuration

  160 GeV, polarized μ beam

  2002-2006 ^{6}LiD polarized target (~polarized deuterons)

  2007 NH_3 polarized target (~polarized protons)

  2000 TB ~ $5 \cdot 10^{10}$ events

- pilot run in 2004 for hadron program
- 2008: hadron beam at 190 GeV for diffractive and central production

physics results

1. $\Delta G/G$
2. $\Delta\Sigma$
3. Transversity
4. Cahn asymmetry
5. Pentaquark
6. Exclusive ρ^0
7. Λ physics

1. pion polarizability
2. PWA in diffractive scattering

COMPASS

THE COMPASS MUON PROGRAM

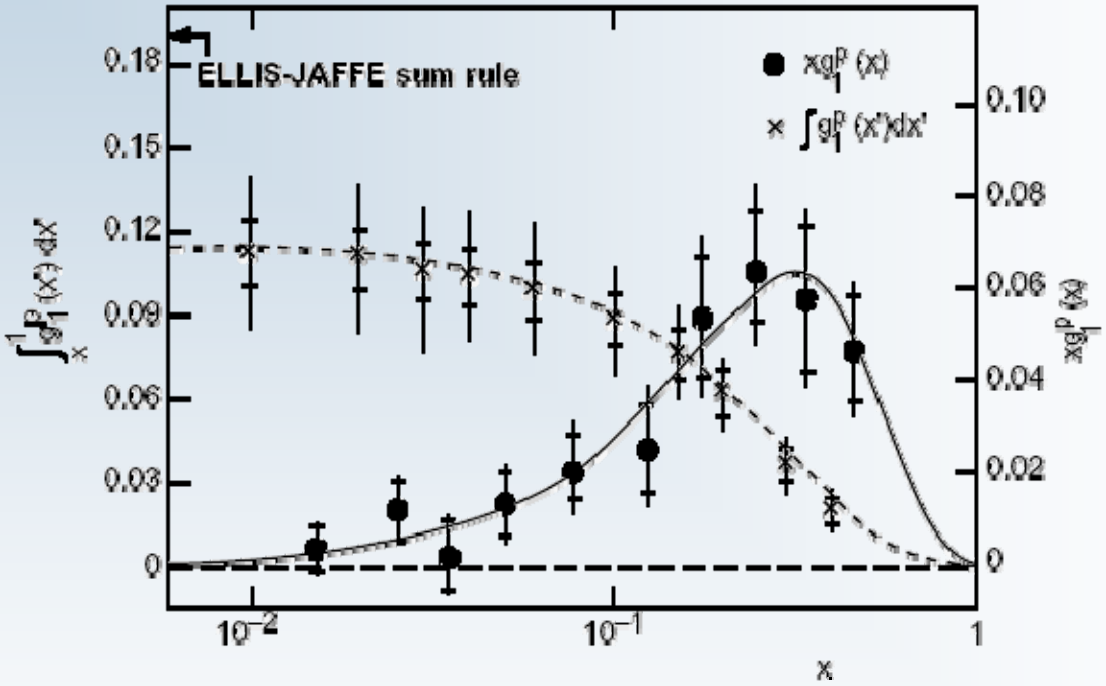
TWO CLASSES OF PHENOMENA:

- LONGITUDINAL SPIN CASE
- TRANSVERSE SPIN CASE

COMPASS

LONGITUDINAL SPIN CASE: the beginning

EMC 1988



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

→ SPIN CRISIS

LONGITUDINAL SPIN CASE

from polarised lepton – polarised nucleon DIS $d\sigma = d\bar{\sigma} \pm d\Delta\sigma$

$$\frac{d\Delta\sigma}{dx\,dy} = \frac{e^4}{4\pi^2 Q^2} \cdot \left\{ \cos\alpha \cdot \left[\left(1 - \frac{y}{2} - \frac{y^2}{4} \cdot \gamma^2 \right) \cdot g_1 - \frac{9}{2} \cdot \gamma^2 \cdot g_2 \right] - \sin\alpha \cdot \cos\varphi \cdot \sqrt{1 - \frac{y}{2} - \frac{y^2}{4} \cdot \gamma^2} \cdot \gamma \cdot \left(\frac{y}{2} \cdot g_1 + g_2 \right) \right\}$$

with $g_1(x) \approx \sum_q e_q^2 \cdot [\Delta q(x) + \Delta\bar{q}(x)]$ and $\Delta q = \overleftarrow{q} - \overrightarrow{q}$

first moments: $\Gamma_1 = \int g_1(x)dx$ $\Delta q = \int \Delta q(x)\,dx$

from Γ_1^p measurement of EMC in 1988 and using complementary information from neutron and hyperon β–decay one obtained

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.12 \pm 0.17$$

at variance with naïve expectation

since $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q,g}$

necessity for measuring Γ_1^n *SMC, SLAC, HERMES*

Δq and $\Delta\bar{q}$ in SIDIS SMC, HERMES, COMPASS

ΔG in SIDIS HERMES, COMPASS

LONGITUDINAL SPIN CASE

physics results

$\Delta G/G$

COMPASS

MEASUREMENTS OF THE GLUON POLARIZATION

FOUR LINES OF ATTACK:

1. Double spin asymmetry of the OPEN CHARM cross-section in high energy μD scattering

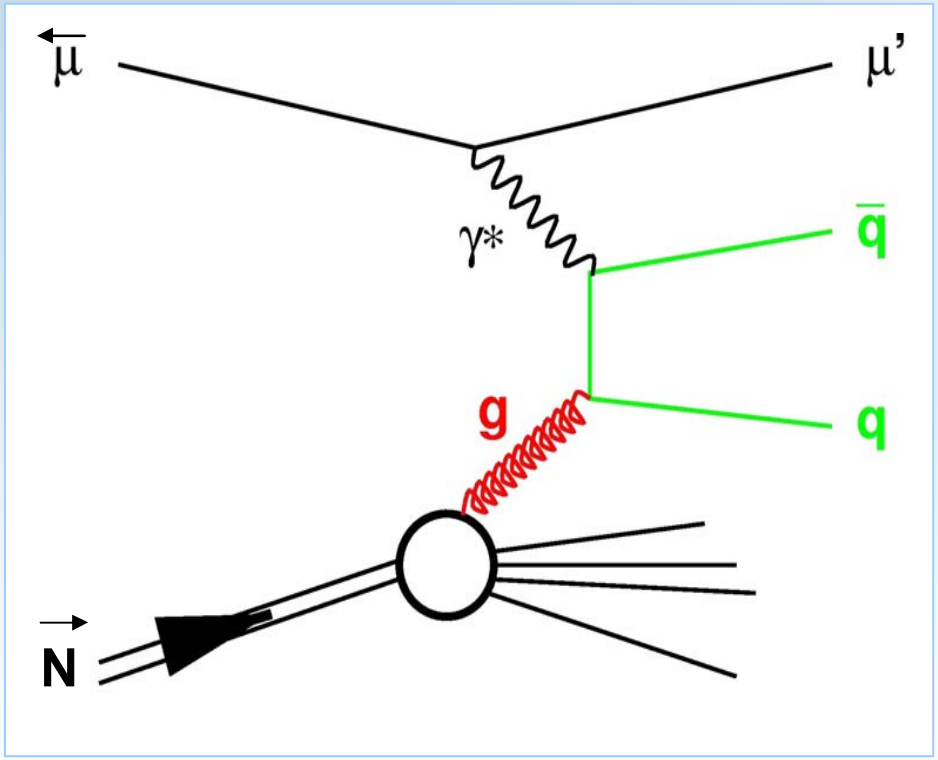
2. Double spin asymmetry of the HIGH-p_t HADRON PAIRS in high energy μD DIS ($Q^2 > 1$ GeV^2)

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*

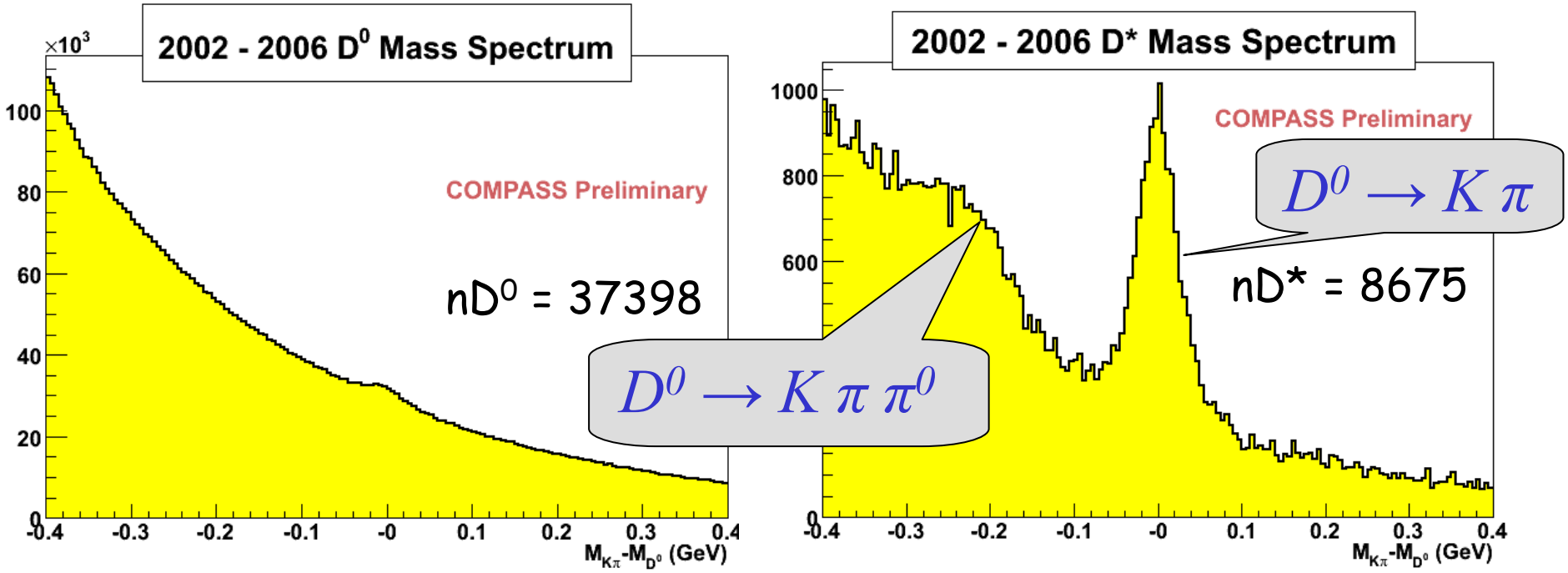
ΔG/G

from Open Charm

COMPASS

D mass spectra

$$D^0 \to K + \pi \qquad D^* \to D^0 + \pi_s \to K + \pi + \pi_s$$



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

COMPASS

$\Delta G/G$

from High-p_t hadron pairs

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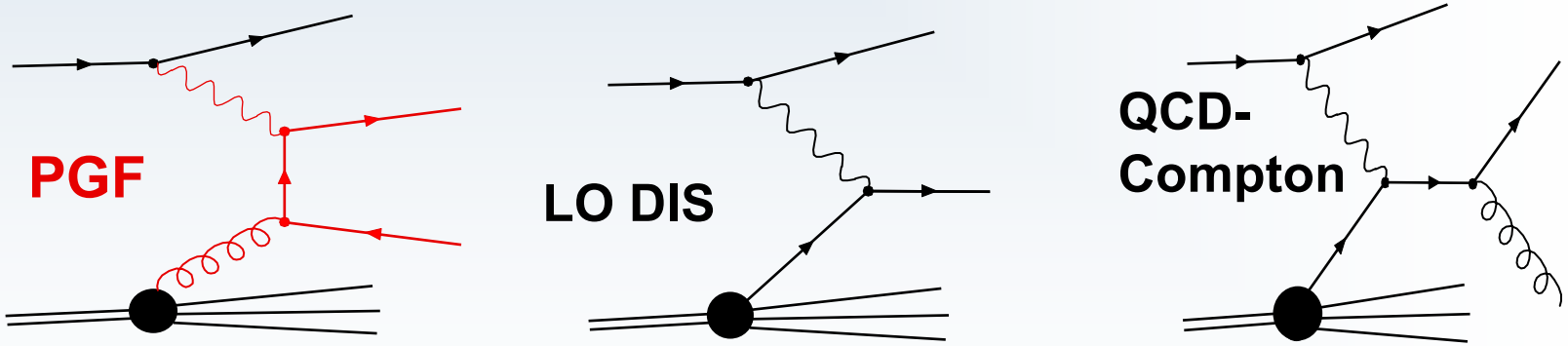
ΔG/G from High-p_t hadrons, $Q^2 > 1$ (GeV/c)^2

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)

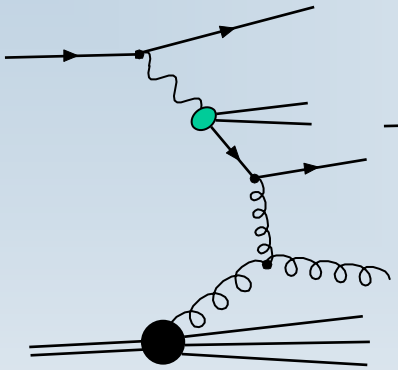
@ $\langle x_g \rangle = 0.082$ (range: 0.055 – 0.123), $\mu^2 \sim 3$ (GeV/c)^2

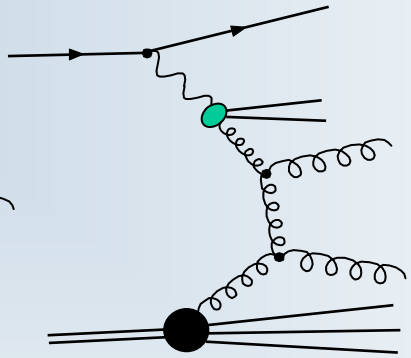
preliminary

COMPASS

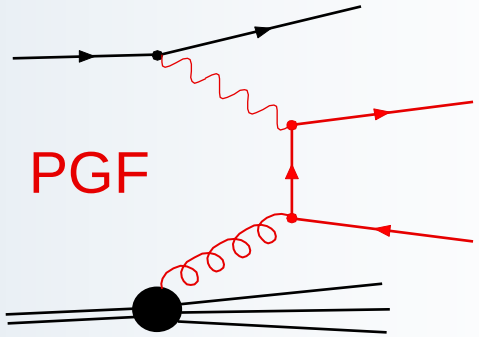
ΔG/G from High-p_t hadrons

low Q^2

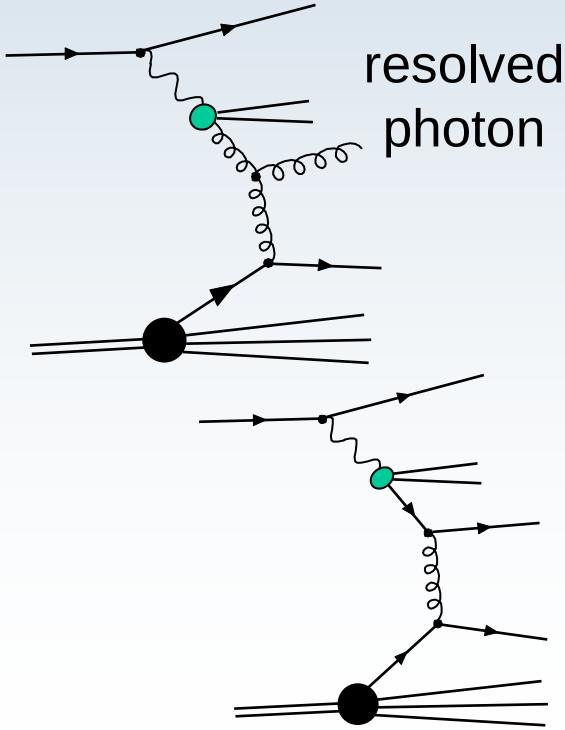




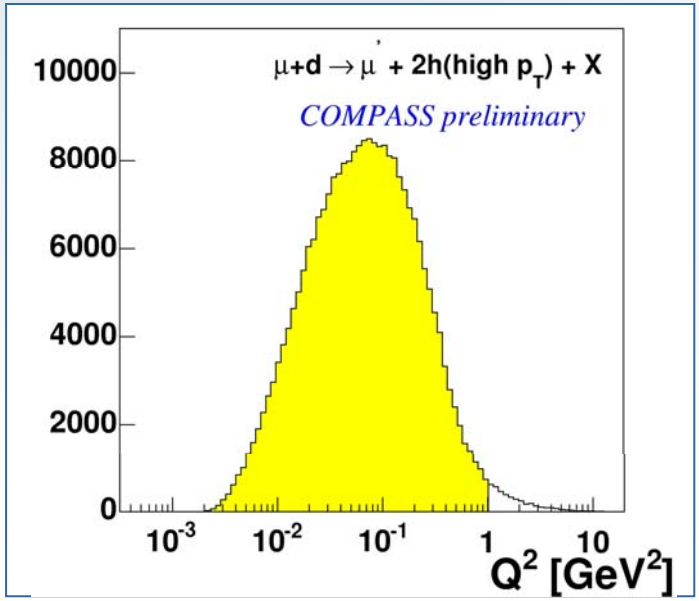
PGF

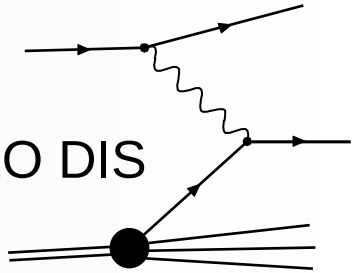


all Q^2

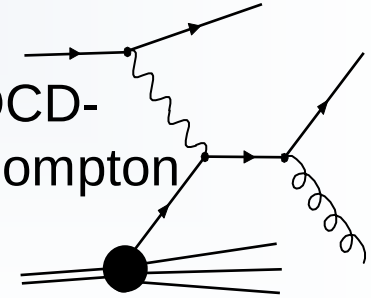


resolved photon





LO DIS



QCD-Compton

COMPASS

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

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

$$\Delta G/G = 0.016 \pm 0.058 \text{ (stat)} \pm 0.055 \text{ (syst)}$$

@ $\langle x_g \rangle = 0.085$, $\mu^2 = 3$ GeV^2

preliminary

COMPASS

Gluon Polarization

COMPASS preliminary results

high-p_T pairs, $Q^2>1GeV^2$: 2002–2004

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

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

high-p_t pairs, $Q^2< 1GeV^2$: 2002–2004

$$\Delta G/G = 0.016 \pm 0.058\,(stat) \pm 0.055\,(syst)$$

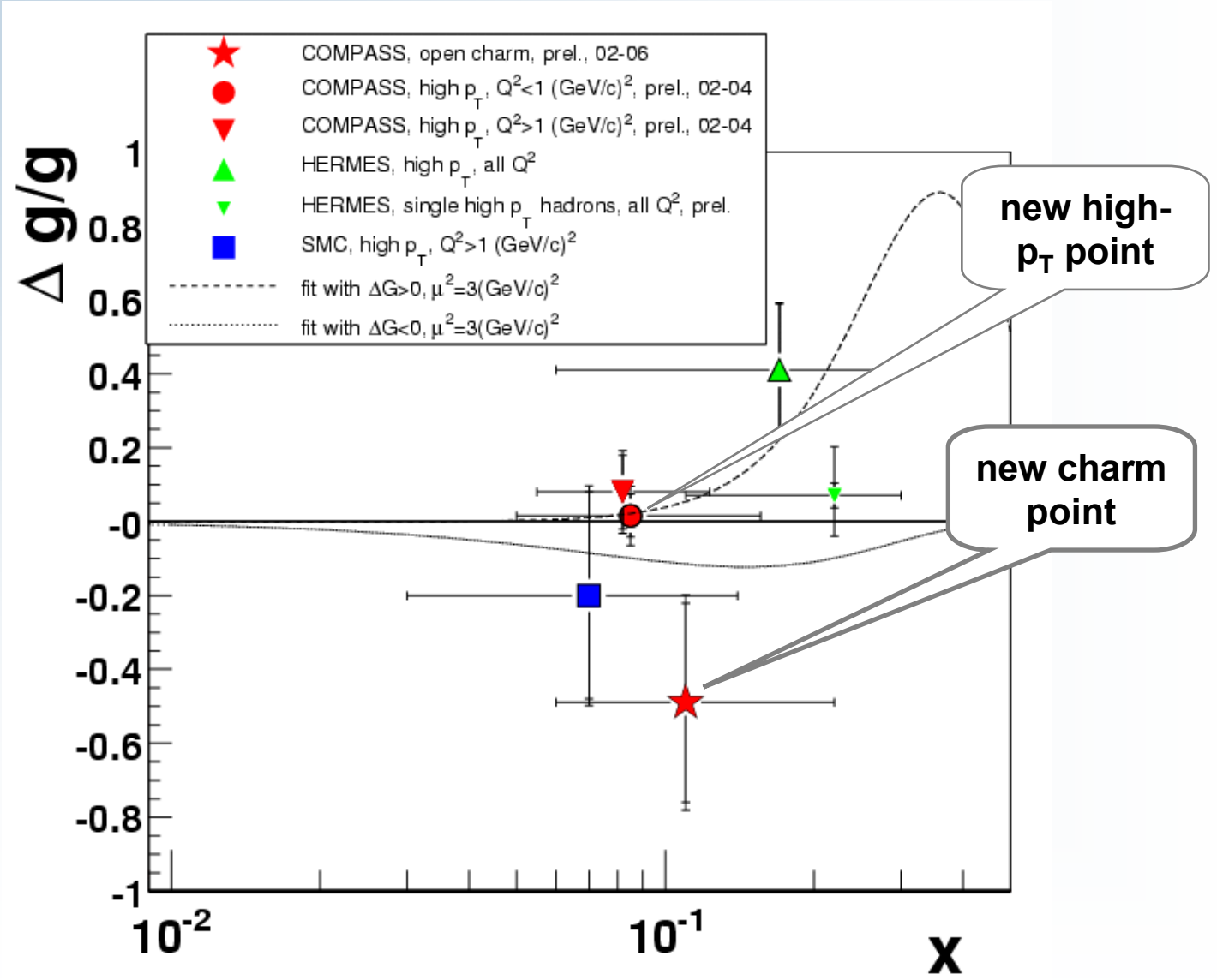
@ $\langle x_g \rangle = 0.085$, $\mu^2 = 3\ GeV^2$

open charm: 2002–2006

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

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

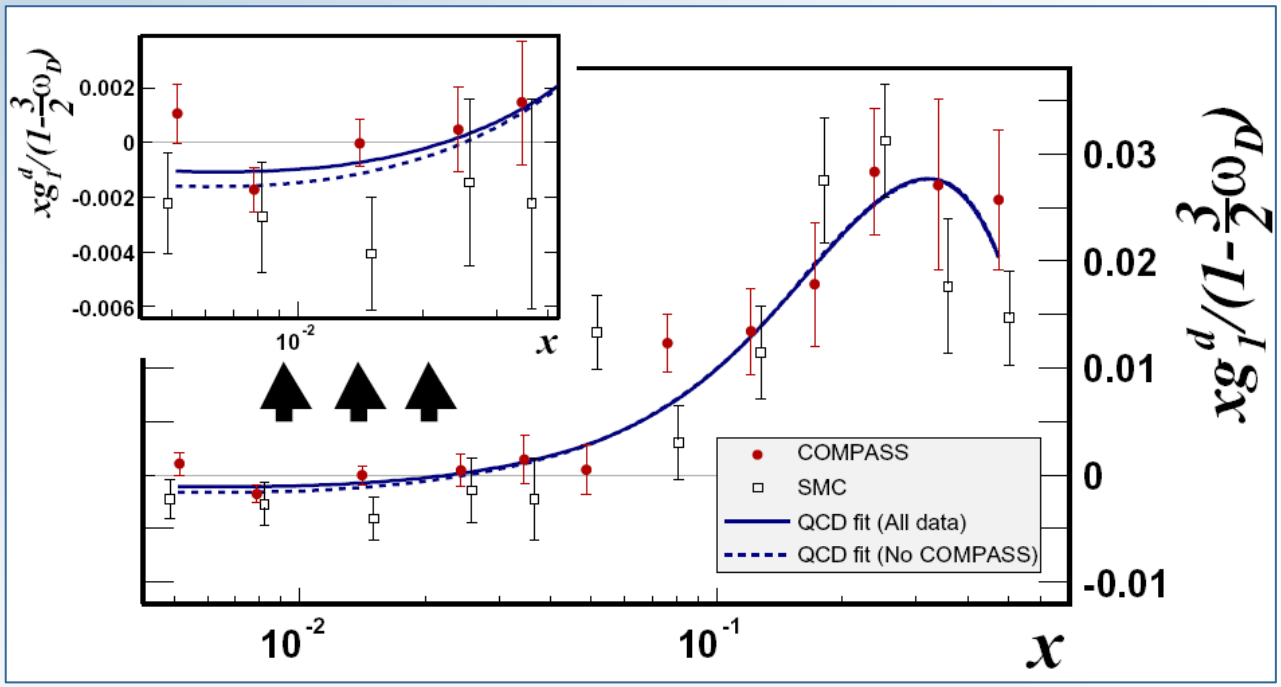
Summary of results



g_1^d

g_1 of the deuteron (2002-2003)

Phys Lett B 612 (2005) 154



- most precise measurement for $0.004 < x < 0.03$
- new NLO QCD fit, precision of a_0 improves factor 2 ($Q^2 = 4$ GeV^2)

$$a_0 = \Delta\Sigma(\overline{MS}) = 0.237^{+0.024}_{-0.029}$$

CONCLUSION from ΔG MEASUREMENTS:

ΔG SMALL

more precise measurements will come soon

COMPASS 2006

RHIC RUN6

....

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q,g}$$

interest in
orbital angular momentum

GPD's

Ji's SUM RULE $J^q(t) = \frac{1}{2}\int dx\, x\,(H^q + E^q)$

more on LONGITUDINAL SPIN CASE

MEASUREMENT OF VALENCE QUARK POLARISATION

COMPASS

valence quark polarisation

hadron asymmetries

Semi-inclusive asymmetries

$$A^{+} = \frac{\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h+}_{\uparrow\uparrow}}{\sigma^{h+}_{\uparrow\downarrow} + \sigma^{h+}_{\uparrow\uparrow}} \qquad A = \frac{\sigma^{h}_{\uparrow\downarrow} - \sigma^{h}_{\uparrow\uparrow}}{\sigma^{h-}_{\uparrow\downarrow} + \sigma^{h-}_{\uparrow\uparrow}}$$

$$A_1^h(x) = \frac{\sum_q e_q^2 (\Delta q(x) D_q^h + \Delta \bar{q}(x) D_{\bar{q}}^h)}{\sum_q e_q^2 (q(x) D_q^h + \bar{q}(x) D_{\bar{q}}^h)}$$

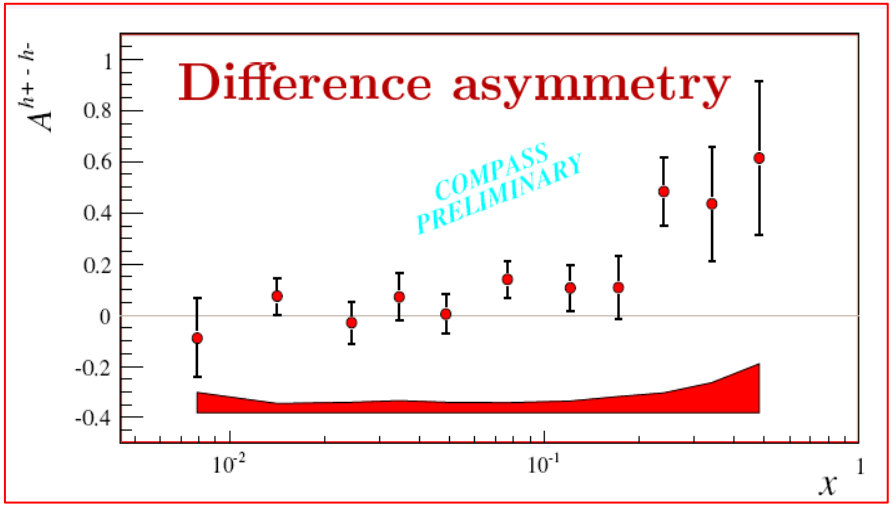
Difference asymmetry

$$A^{+} = \frac{(\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h}_{\uparrow\downarrow}) - (\sigma^{h+}_{\uparrow\uparrow} - \sigma^{h}_{\uparrow\uparrow})}{(\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h}_{\uparrow\downarrow}) + (\sigma^{h+}_{\uparrow\uparrow} - \sigma^{h}_{\uparrow\uparrow})}$$

$$A_d^{\pi^+ - \pi^-}(x) = A_d^{K^+ - K^-}(x) = \frac{\Delta u_v(x) + \Delta d_v(x)}{u_v(x) + d_v(x)}$$

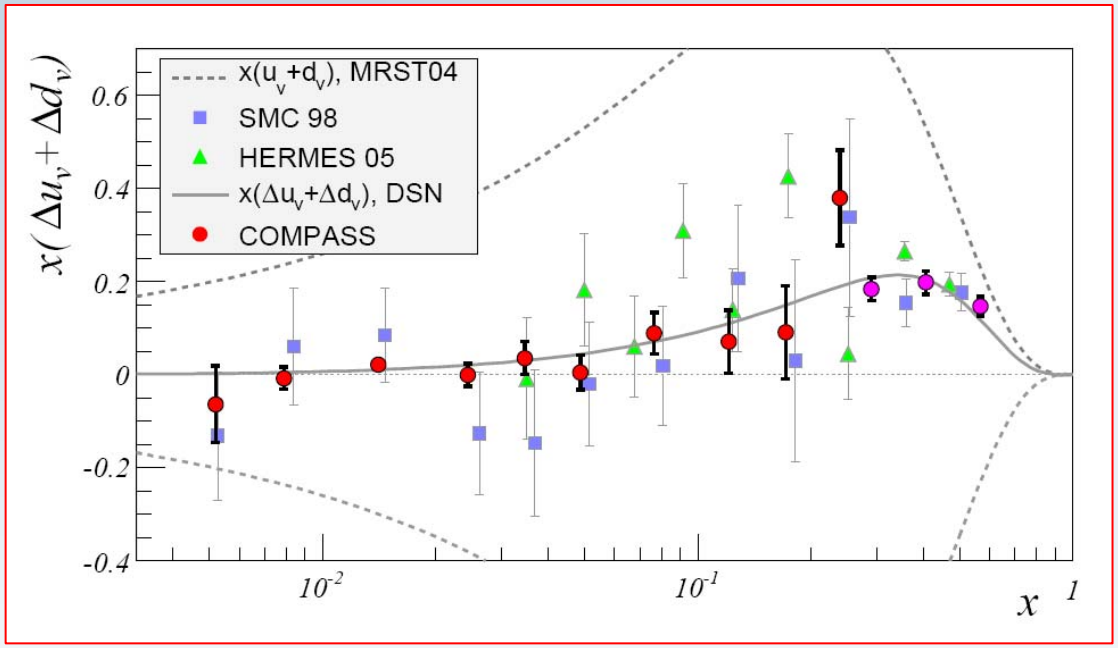
- Fragmentation functions $D_q^h = \int D_q^h(z)dz$ are poorly known
- Difference asymmetry originally was proposed in:

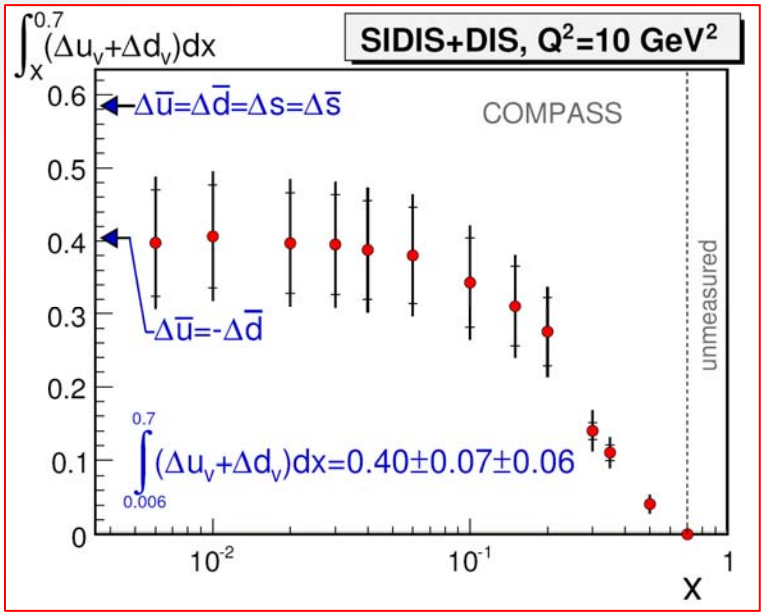
  L.Frankfurt *et al.*, Phys. Lett. B230 (1989) 141
- First was used in SMC: B. Adeva *et al.*, Phys. Lett. B369 (1996) 93.
- Meaningful physics results for the deuteron target in LO QCD even without hadron identification



valence quark polarisation

comparison with other experiments





The Transverse Spin Case

Transverse Spin case

Large effects observed in hadronic interactions

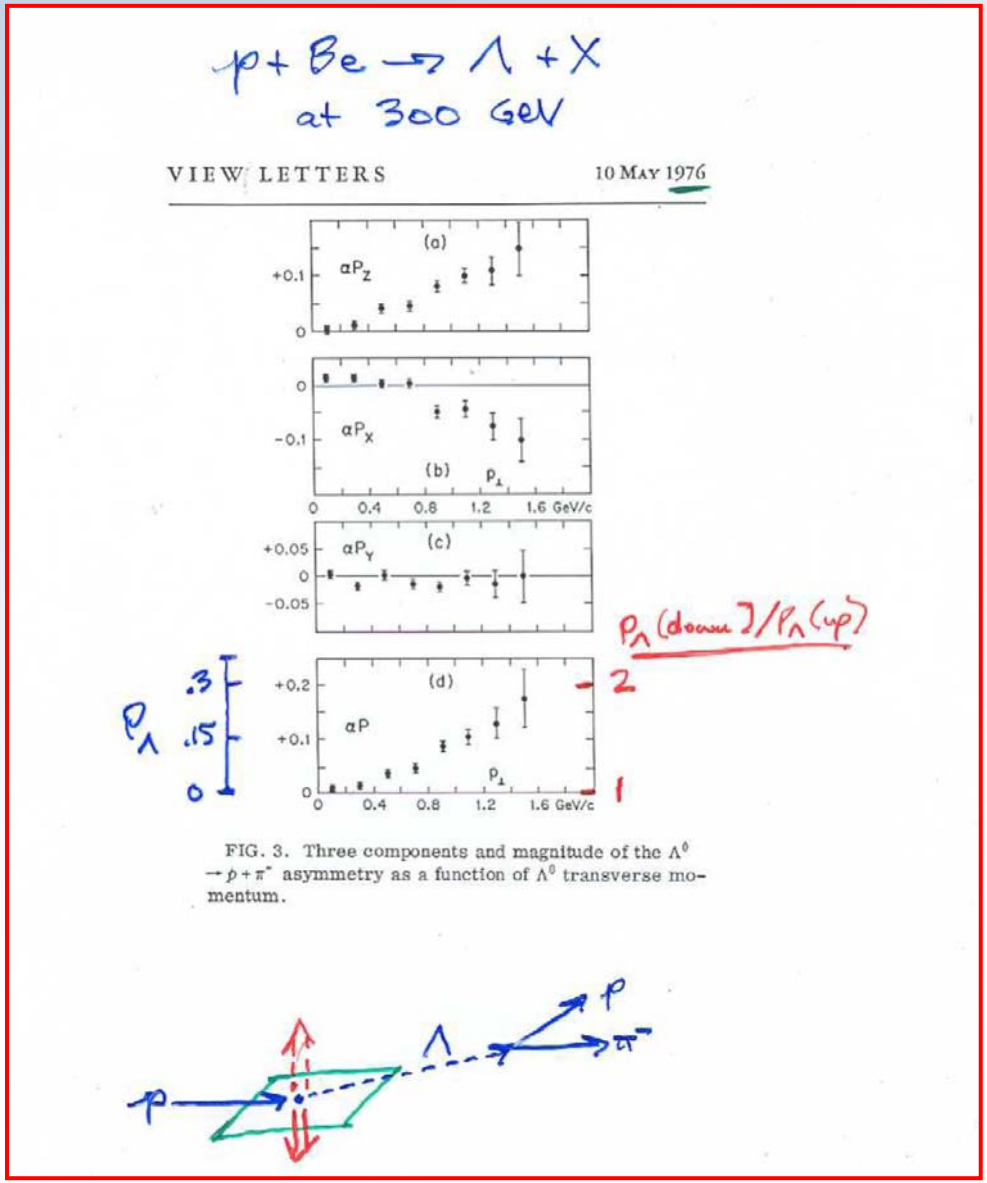


FIG. 3. Three components and magnitude of the $\Lambda^0 \to p + \pi^-$ asymmetry as a function of Λ^0 transverse momentum.

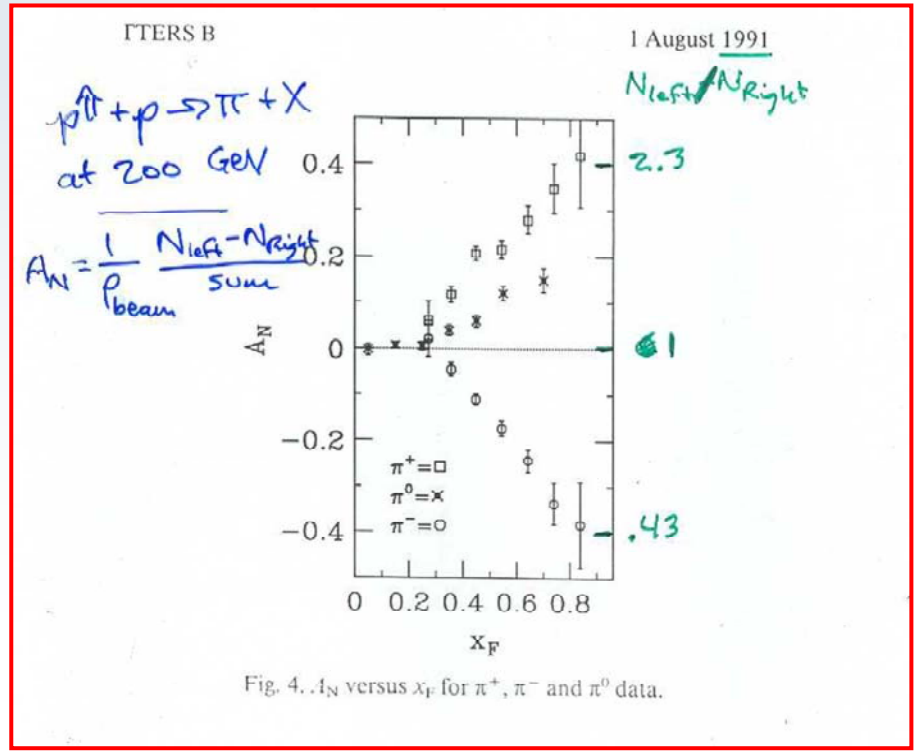


Fig. 4. A_N versus x_F for π^+, π^- and π^0 data.

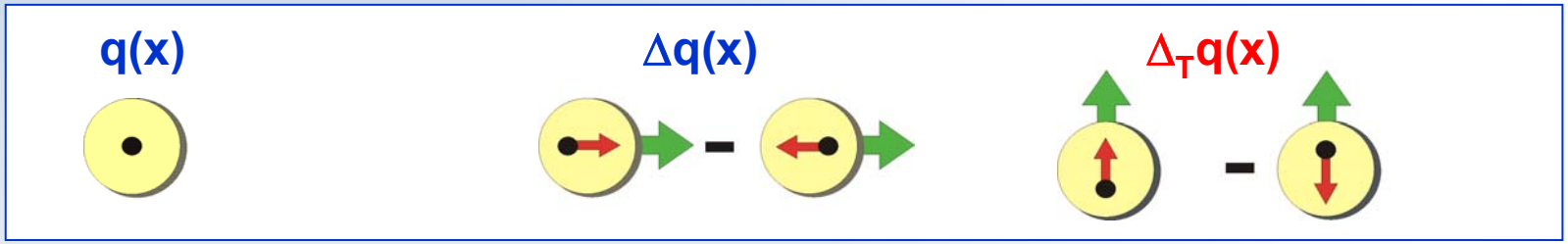
Transverse Spin case

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 $\Delta_T q \otimes \Delta_T \bar{q}$ SIDIS $\Delta_T q \otimes FF$ → Collins function measurable in e+e- → hadrons

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

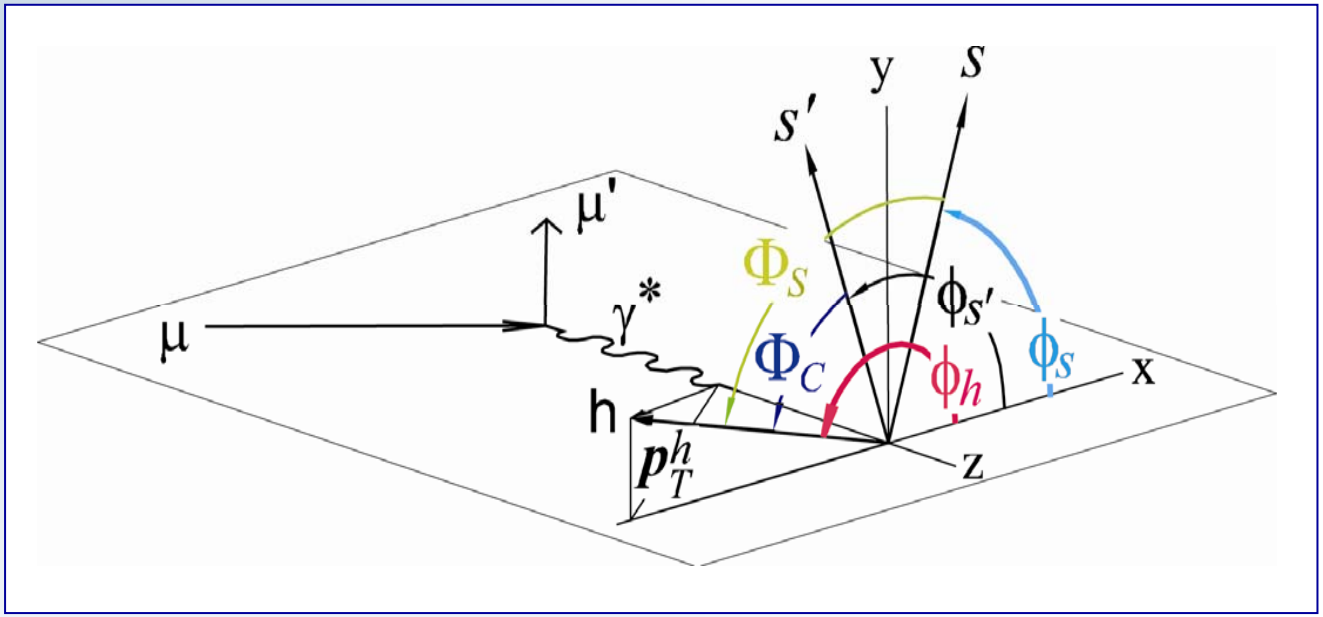
Many Workshops in recent years on *Transverse Momentum, spin, and position distributions of partons in hadrons*

Transversity – single hadron - 1

Collins and Sivers angles

$\Phi_C = \phi_h - \phi_S'$

$\Phi_S = \phi_h - \phi_S$



ϕ_S' , azimuthal angle of spin vector of fragmenting quark ($\phi_S'' = \pi - \phi_S$)

ϕ_h azimuthal angle of hadron momentum

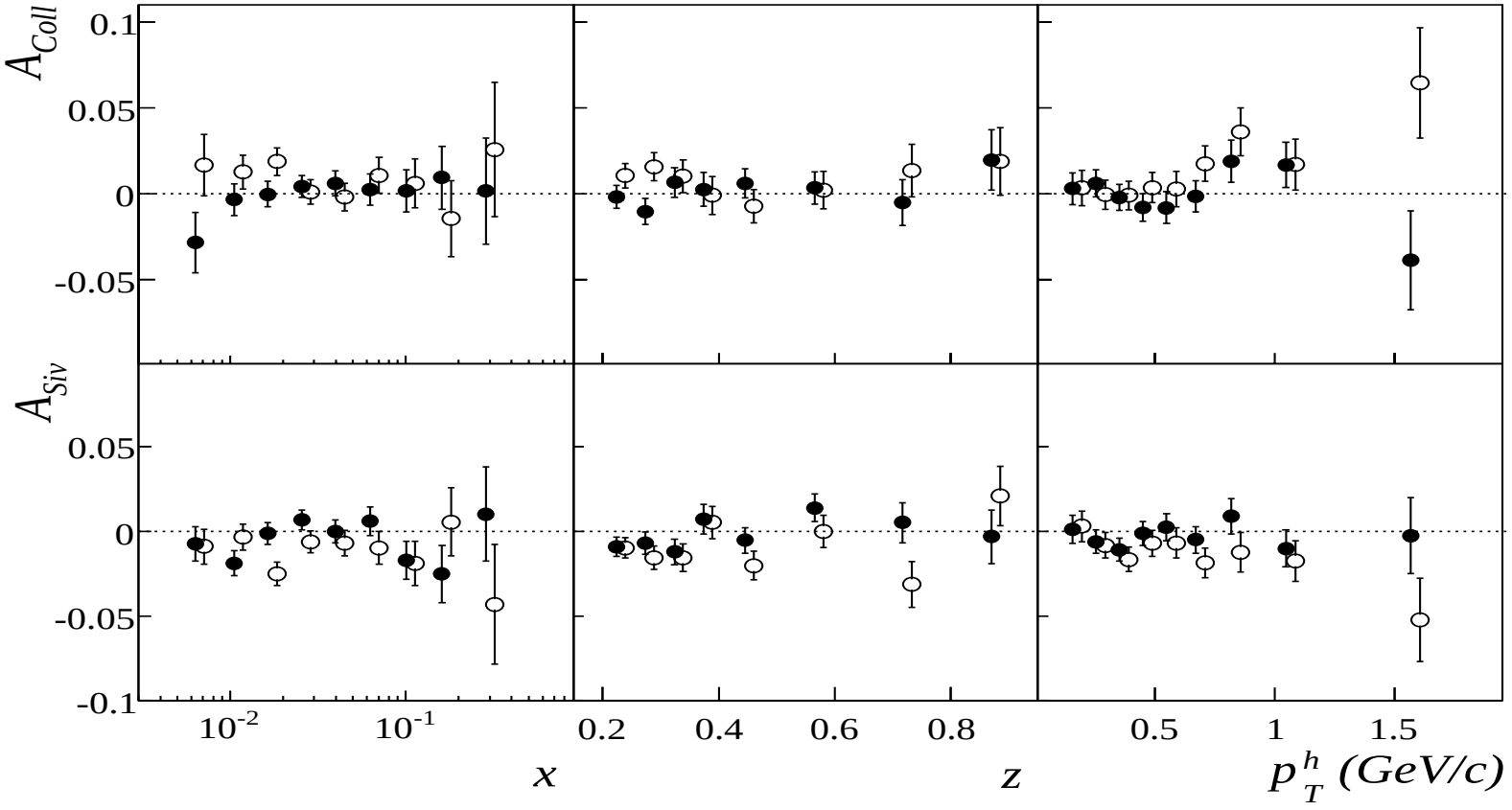
Transversity – single hadron - 2

first measurements of transverse spin asymmetries in DIS of high energy muons on a transversely polarized *deuteron* target

published single hadron asymmetries from 2002-2004 runs

- **Collins:** related to transverse quark distributions
- **Sivers:** related to intrinsic k_T

Phys Rev Lett 94 (2005) 202002
Nucl Phys B765 (2007) 31



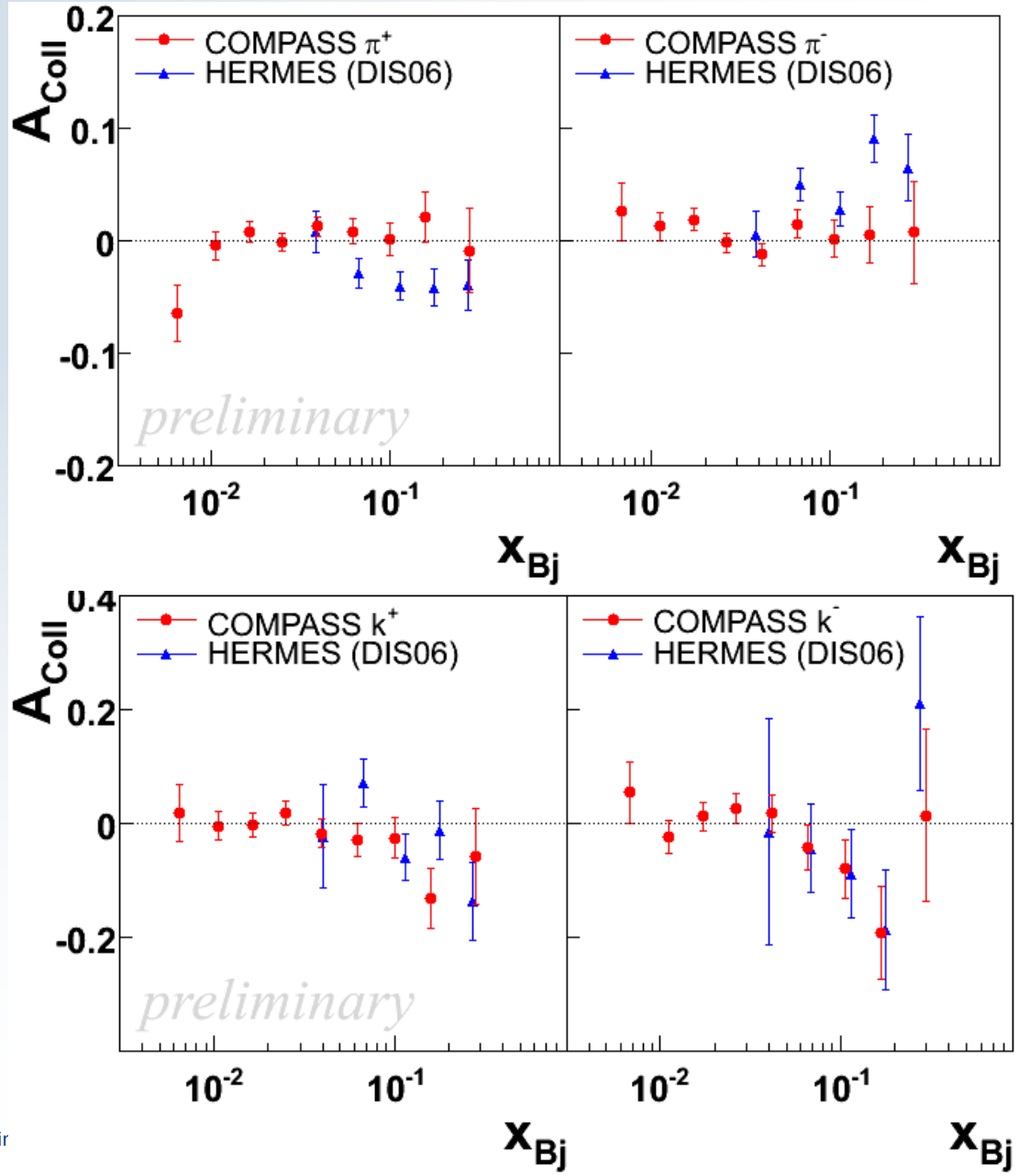
COMPASS

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)

COMPASS
sign convention



Independent Measurement of the Collins FF

measurable in e^+e^- annihilation

- **first attempts to measured it from the correlation between the azimuthal angles of π's from e^+e^- annihilation using LEP data**

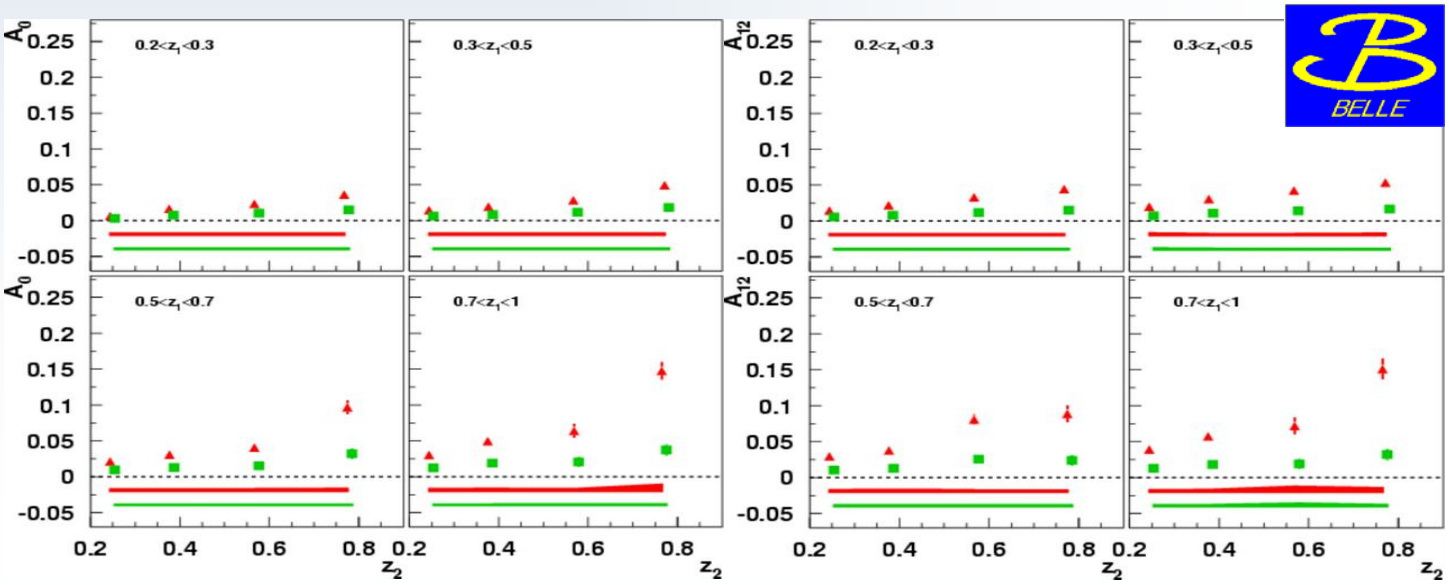
last years: great news from BELLE

the Collins FF is being measured in

e^+e^- annihilation, and it is different from zero!

measurement of the correlation between the azimuthal angles of π's in the near jet and in the far jet from e^+e^- annihilation

- 547 fb^{-1} charm corrected data sample,
- UL and UC double ratios



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:

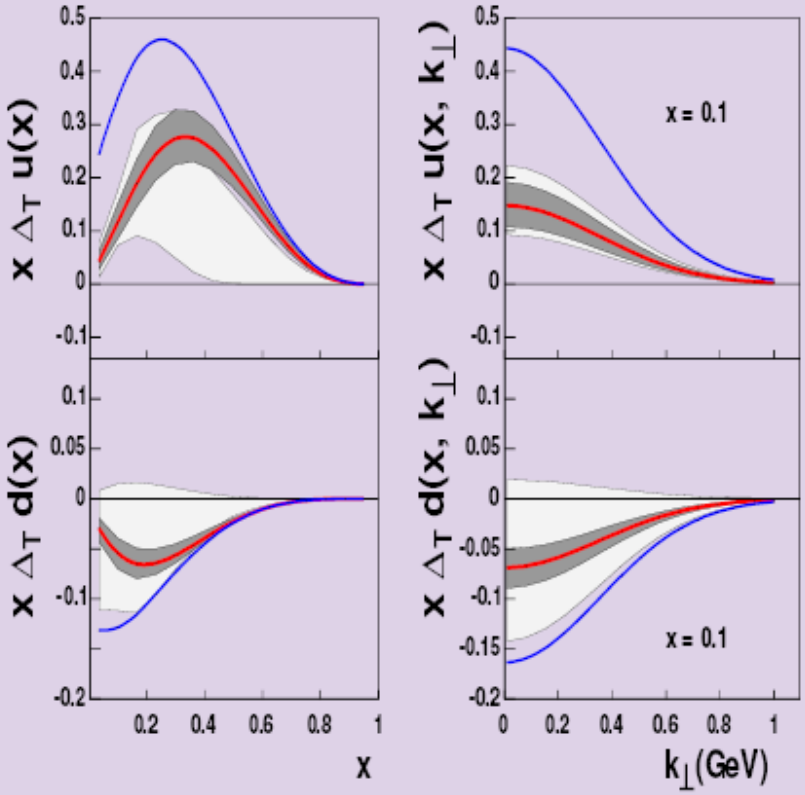
- **Collins mechanism is a real phenomenon**
- **universality of Collins FF**
- **transversity can be measured in SIDIS**

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

Transversity



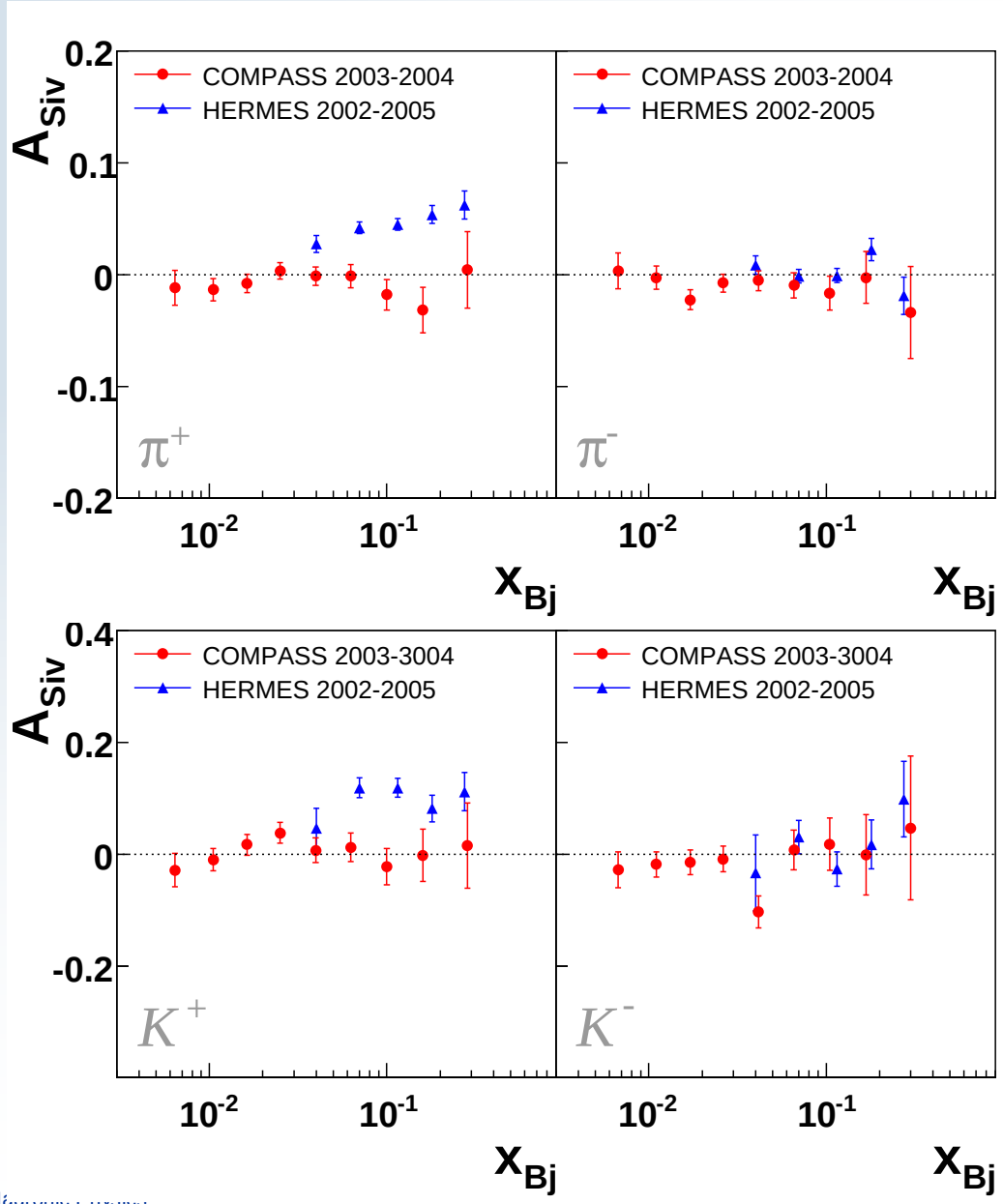
HERMES, COMPASS, BELLE

- 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.

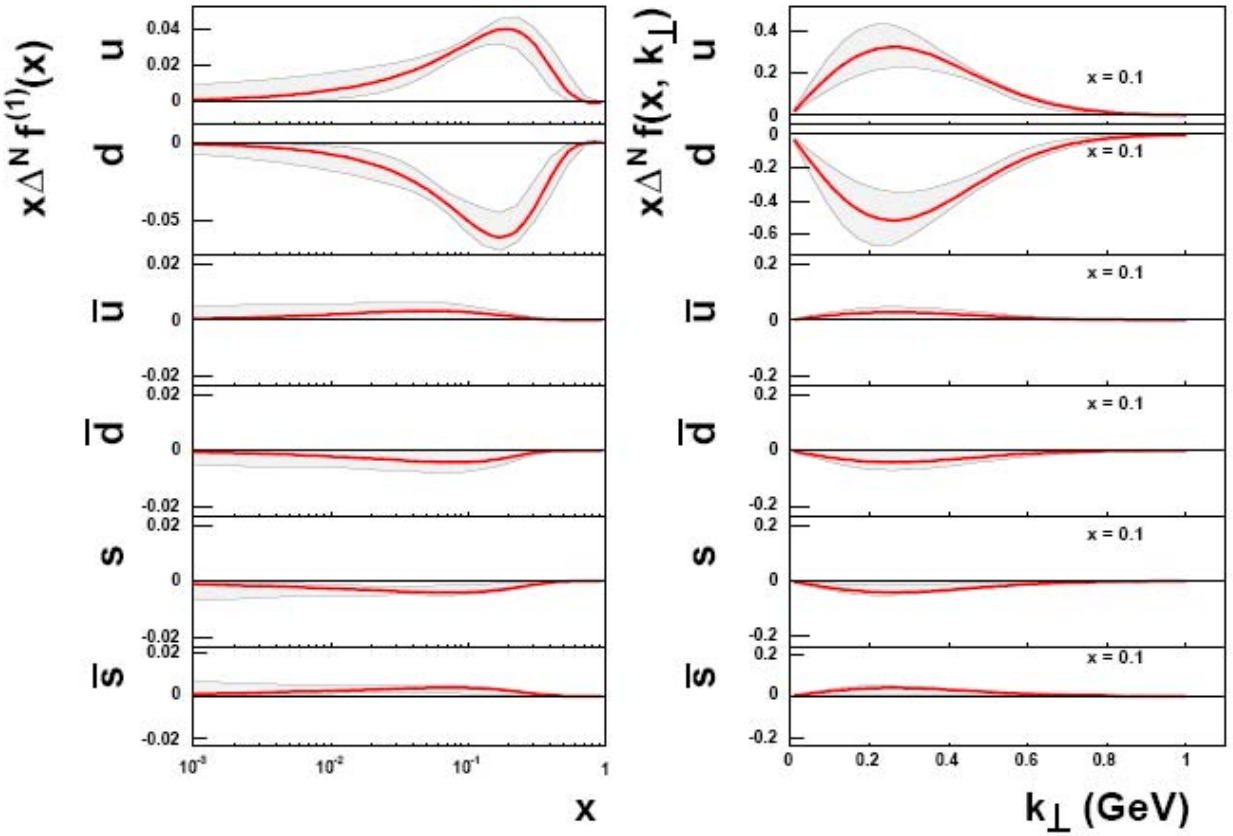
Sivers asymmetry for pions and kaons

preliminary
2002-2005 data
proton
(*DIS07*)

CERN-PH-EP/2008-002
hep-ex/0802.2160 (PRL)
2003-2004 data
deuteron



First moment of the Sivers functions



$$\diamond\ \Delta^N f_q^{(1)}(x) \equiv \int d^2\boldsymbol{k}_\perp \frac{k_\perp}{4m_p} \Delta^N f_{q/p^\uparrow}(x, k_\perp) = -f_{1T}^{\perp(1)q}(x)$$

Sivers asymmetry

the measured asymmetry on deuteron compatible with zero has been interpreted as

Evidence for the Absence of
Gluon Orbital Angular Momentum in the Nucleon

S.J. Brodsky and S. Gardner, PLB643 (2006) 22

The approximate cancellation of the SSA measured on a deuterium target suggests that the gluon mechanism, and thus the orbital angular momentums carried by gluons in the nucleon, is small.

SUMMARY AND OUTLOOK

- **a technically challenging new experiment is IN OPERATION SINCE 2002**

  "LHC" technologies *detectors*
  read-out
  data handling

- **a privileged situation at CERN**

- **MANY PHYSICS RESULTS have been produced**
  MANY MORE IN THE PIPE-LINE

- **COMPASS is foreseen to run up to the end of the present mid-term plan of CERN (2010)**

  BIG DISCOVERY POTENTIAL

- **with some upgrade COMPASS might be an interesting option even in the second decade of this century**