EXPERIMENTAL STUDY WITH LEPTON SCATTERING

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"Latest results and future programs on the nucleon structure - Toward an understanding of the nucleon spin -"

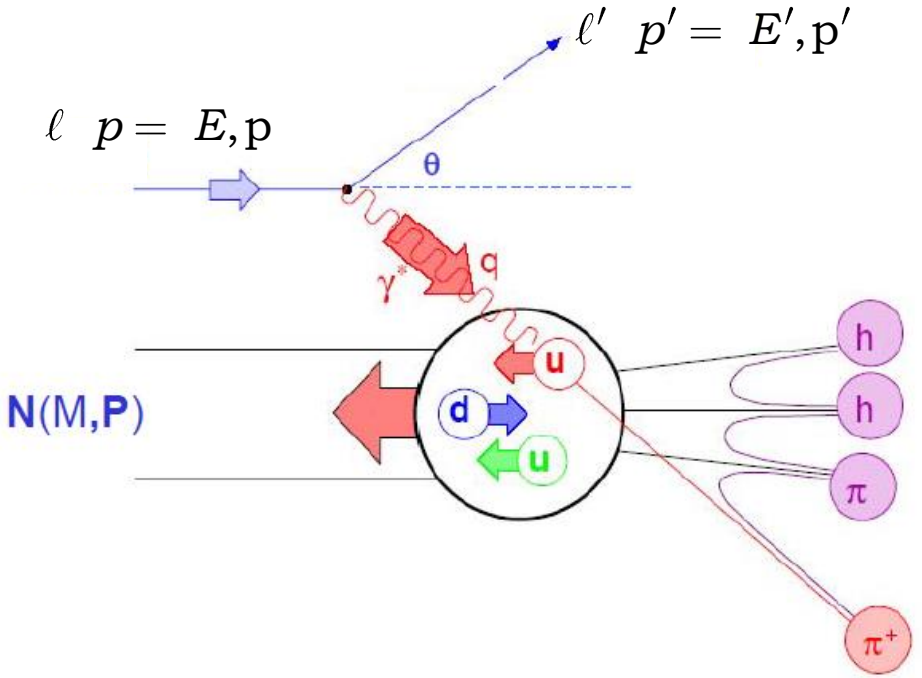
Meeting of the Japan Physical Society, March 27-30, 2014, Hiratsuka, Japan

OUTLINE

- ***Introduction***
  - *DIS, SIDIS & PDF*
  - *The Major Experiments*
- ***Longitudinal Spin Structure***
  - *Polarized Structure Functions*
  - *Helicity Distributions*
  - *Gluon polarization Studies*
- ***Transverse Spin Effects***
  - *Collins & Sivers Asymmetry*
  - *Asymmetry related to BM-PDF*
- ***GPD Studies***
  - *GPD studies by HERMES & Jlab*
  - *Further studies on GPD*
- ***Conclusion***

DIS

Lepton scattering off nucleon



$$Q^2 = -(p - p')^2$$

$$\nu = E - E'$$

Energy of the photon

$$x = Q^2 / 2M\nu \quad (Lab.)$$

$$y = \nu / E$$

momentum fraction of the struck quark in Bjorken limit

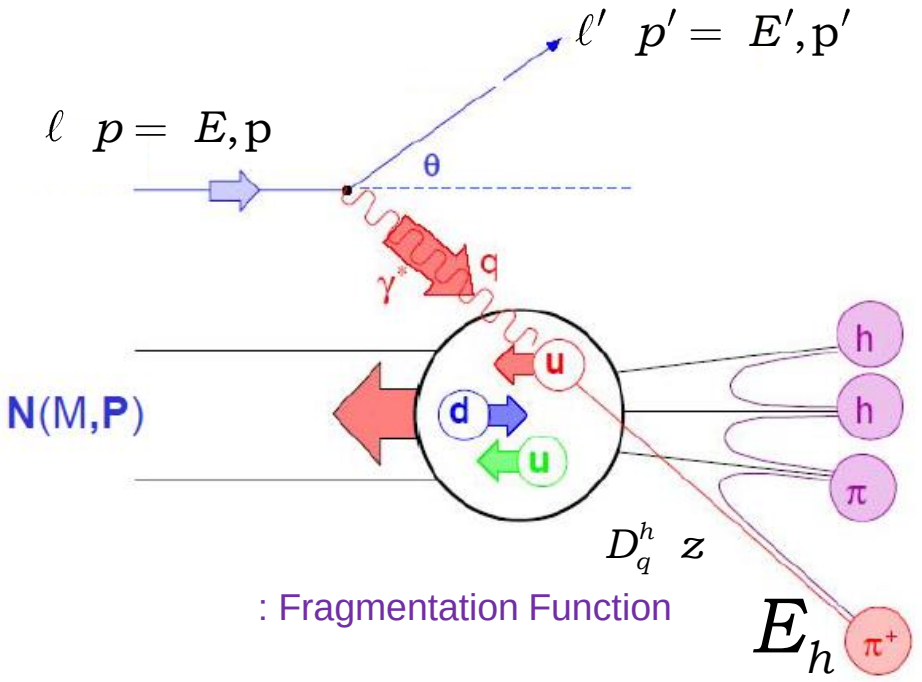
$$Q^2 \to \infty$$

$$\nu \to \infty$$

Inclusive DIS: only the scattered leptons are measured

DIS and SI-DIS

Lepton scattering off nucleon



$$Q^2 = -(p - p')^2$$

$$\nu = E - E'$$ ← Energy of the photon

$$x \overset{Lab.}{=} Q^2/2M\nu$$

$$y = \nu/E$$

momentum fraction of the struck quark in Bjorken limit

$$z = E_h/\nu$$

$$Q^2 \to \infty$$

$$\nu \to \infty$$

Inclusive DIS: only the scattered leptons are measured

Semi-Inclusive DIS: at least one final state hadrons are measured as well as the scattered leptons

PDFs at LO

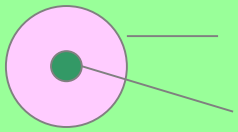
in collinear case, neglecting k_T

Nucleon

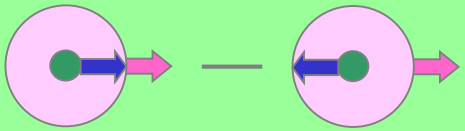
unpol. | long. pol. | trans. pol.

Quark: unpol. | long. pol. | trans. pol.

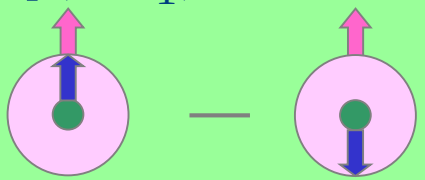
$q(= f_1)$ **number density**



$\Delta q(= g_{1L})$ **helicity**



$\Delta_T q(= h_1)$ **transversity**

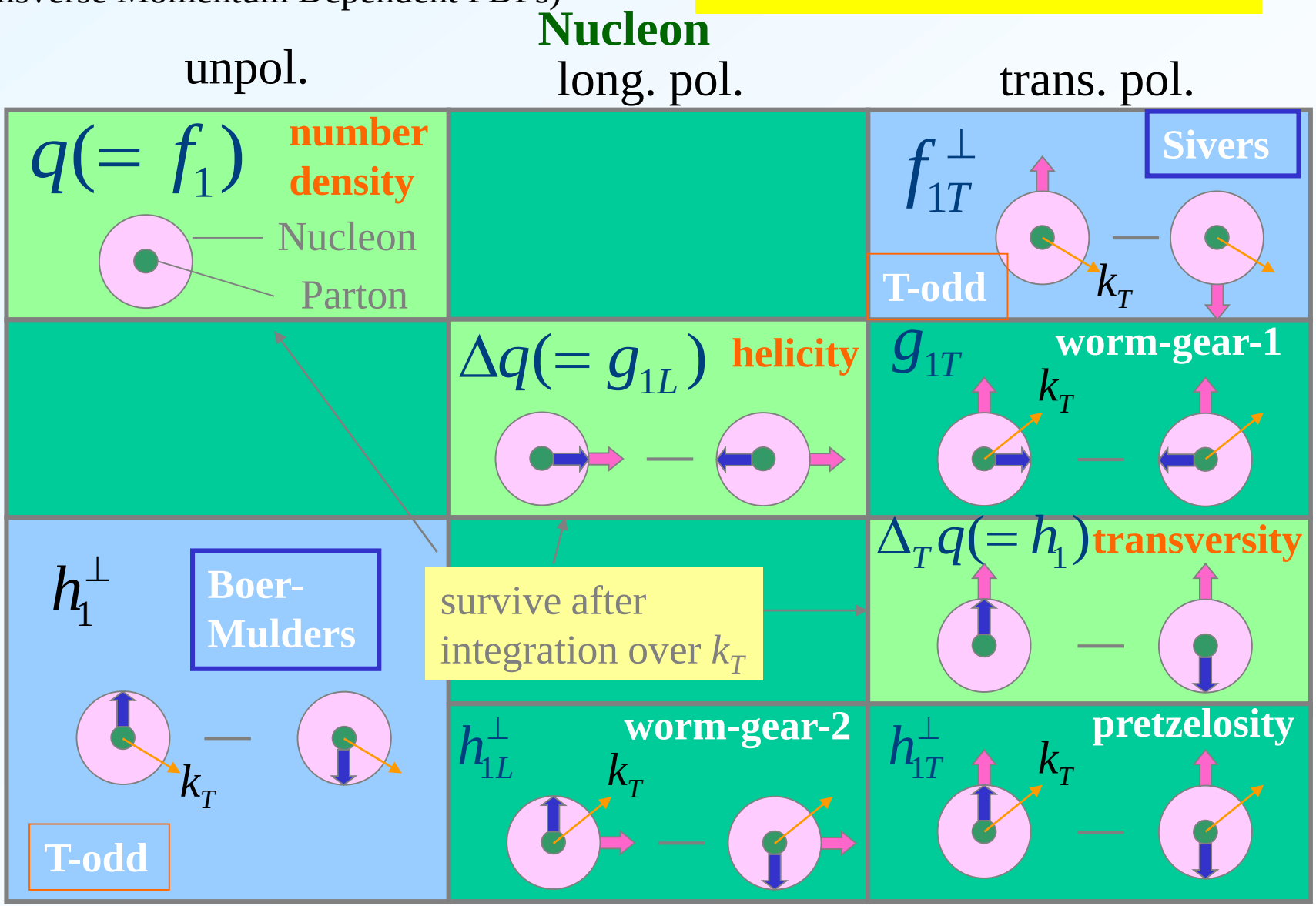


Only three functions to describe the nucleon structure

TMD PDFs

(Transverse Momentum Dependent PDFs)

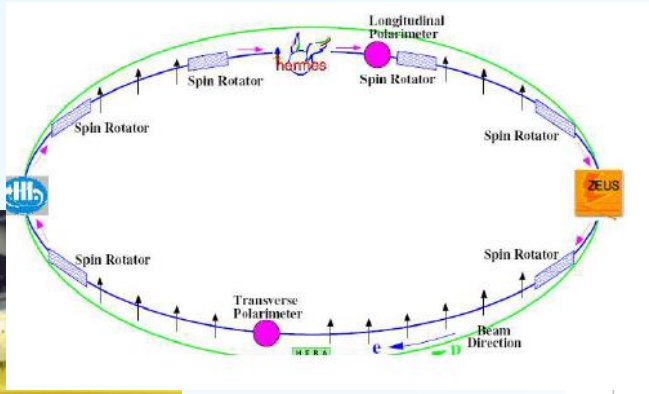
taking account of k_T, additional 5 TMD PDFs are necessary for a full description of uncleon structure at LO

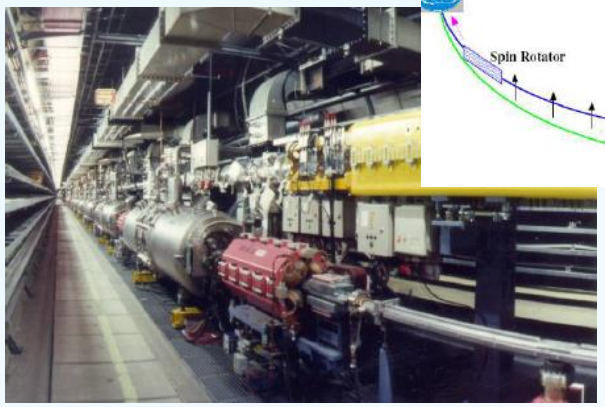


The Major Experiments

HERMES

DIS & SI-DIS experiment





Pol. e^- & e^+

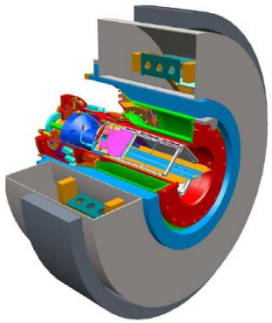
in HERA at 27 GeV

Gaseous internal target

Longit. Polar. 85% H, D, He

Transv. Polar H

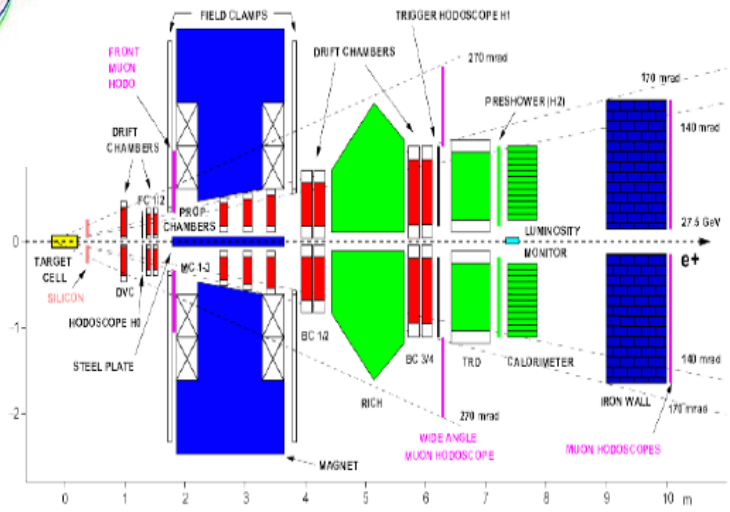
Unpol H, D, Ne, Kr



Detector:

$\Delta p/p \sim 2\%$, $\Delta\theta < 1$ mrad

hadron ID (π, K, p)



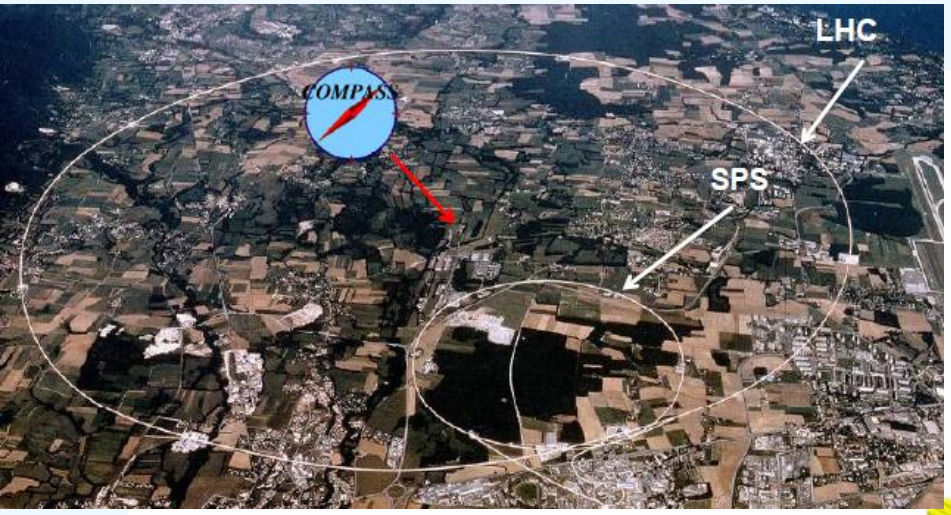
Recoil Proton Detector for DVCS measurements

data taking: 1996-2007

shutdown : 2007

data analysis on going

COMPASS at CERN



data taking: 2002-

running experiment

COMPASS-II in future

Straws
SDC
MWPC
W45

SciFi
Silicon
Micromegas
GEMs

Polarised solid Target

Pol. μ beam

160-200 GeV, pol. 80%

DIS & SI-DIS experiment

two stage spectrometer

- **Large Angle Spectrometer (SM1)**
- **Small Angle Spectrometer (SM2)**

tracking, calorimetry, PID

JLab Experiments

6 GeV polarized electron beam
Pol=85%, 180μA

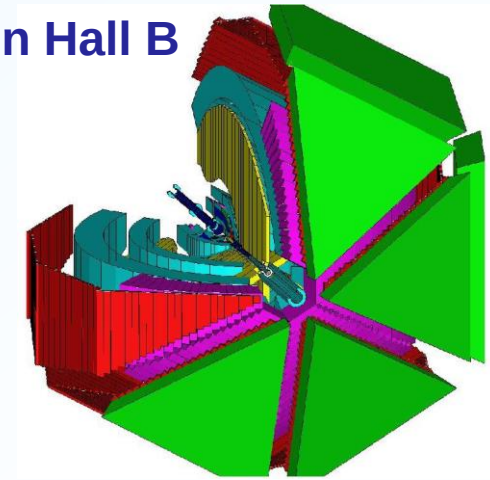
several types of polarized targets
→ various polarization experiments

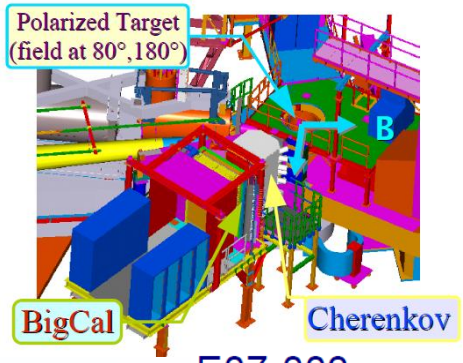
to be upgraded up to 12 GeV by 2014

Hall C

Hall A

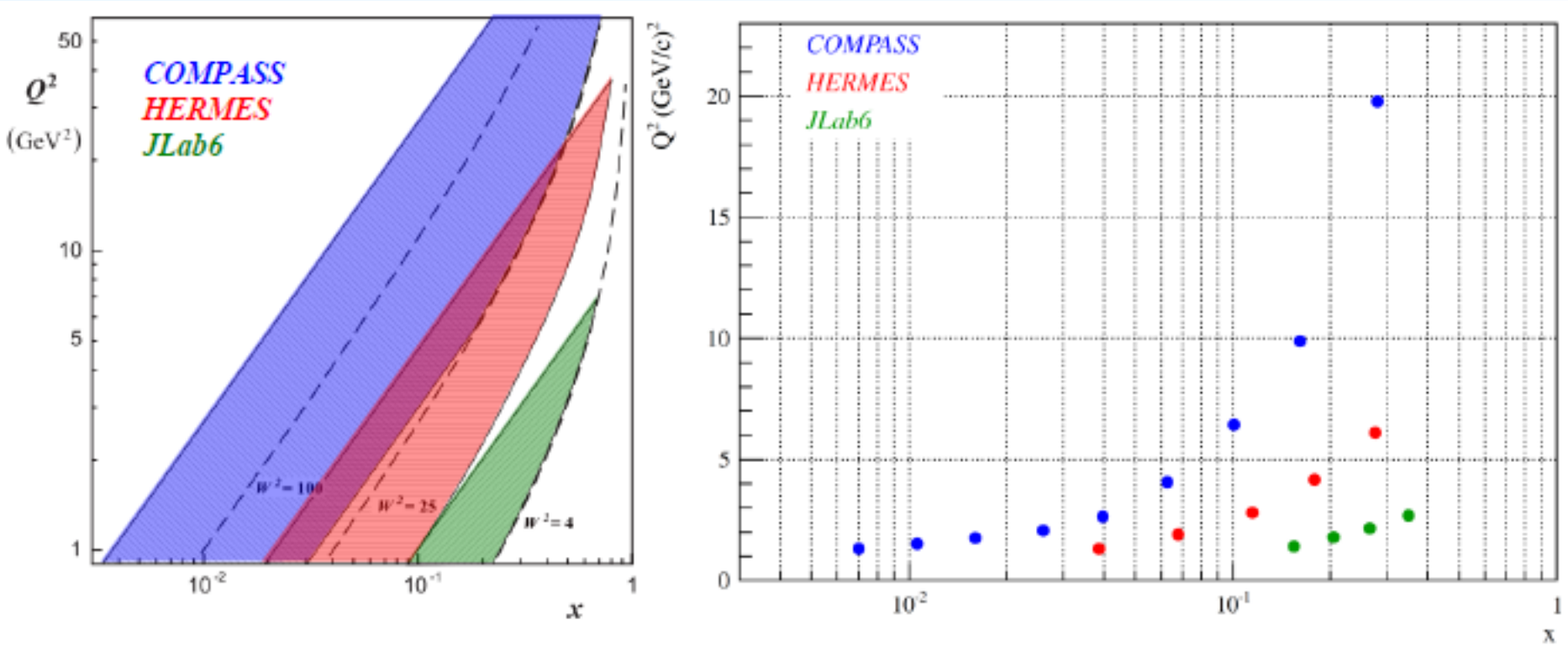
CLAS in Hall B





E07-003

Kinematical Coverage



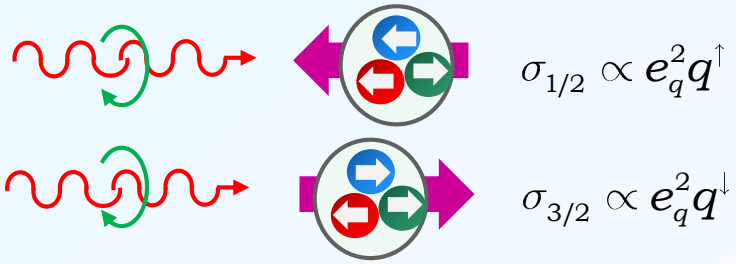
These experiments are complementary

Longitudinal Spin Structure

g_1 from Polarized Inclusive DIS

- **Photon nucleon asymmetry**

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



$$\sigma_{1/2} \propto e_q^2 q^{\uparrow}$$

$$\sigma_{3/2} \propto e_q^2 q^{\downarrow}$$

- **Structure functions with PDF**

$$F_1\ x = \frac{1}{2}\sum\nolimits_q e_q^2\ q\ x + \bar{q}\ x$$

$$g_1\ x = \frac{1}{2}\sum\nolimits_q e_q^2\ \Delta q\ x + \Delta\bar{q}\ x$$

Polarized Structure Function

with

$$q\ x = q^{\uparrow}\ x + q^{\downarrow}\ x$$

$$\Delta q\ x = q^{\uparrow}\ x - q^{\downarrow}\ x$$

- **First moment of g_1**

$$\Gamma_1 = \int_0^1 g_1\ x\ dx = \frac{1}{2}\sum\nolimits_q e_q^2 \underbrace{\int_0^1 dx\ \Delta q\ x + \Delta\bar{q}\ x}_{\Delta q}$$

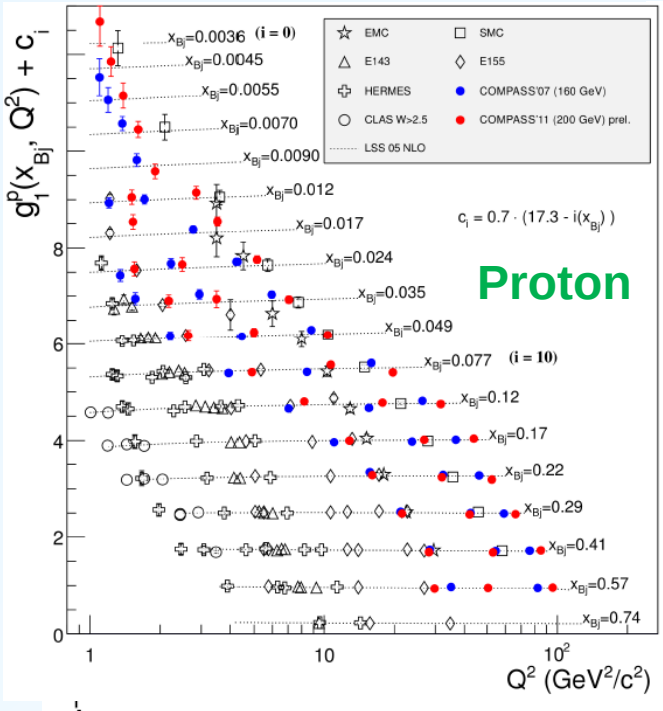
with $\Delta q \equiv \int_0^1 dx \Delta q\ x$

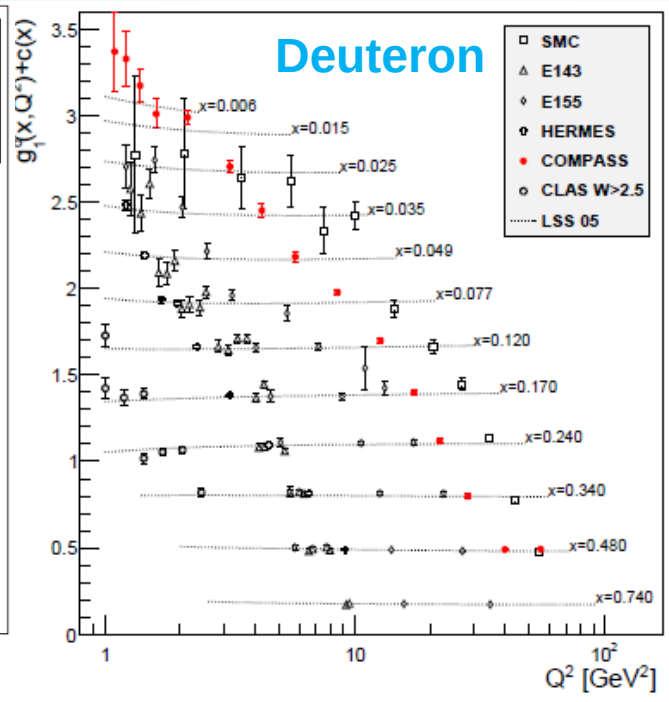
neutron-beta decay
& hyperon decay constants,
Q^2 dependence by pQCD

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

Quark Spin Contribution

World Data of g_1



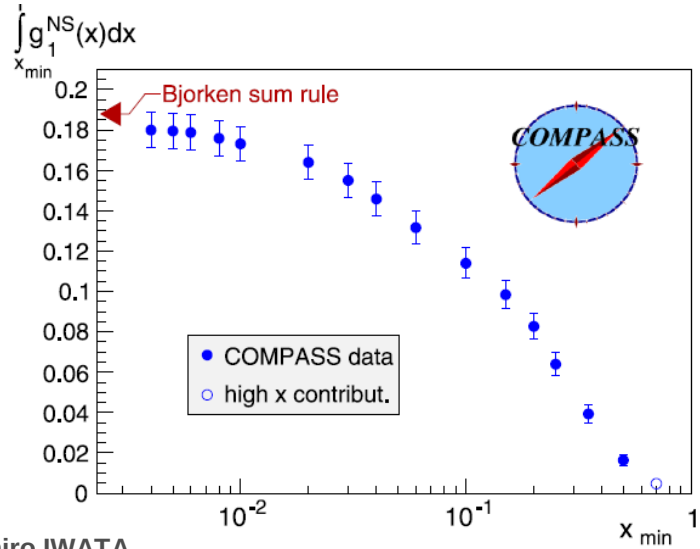


$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.30 \pm 0.01 \pm 0.02 \quad @\ Q^2 = 3\ GeV/c^2$$

$$\Delta s + \Delta\bar{s} = -0.08 \pm 0.01 \pm 0.02 \quad Q^2 \to \infty$$

by COPASS fit for all g_1

arXiv:hep-ex/0609038



Bjorken sum rule

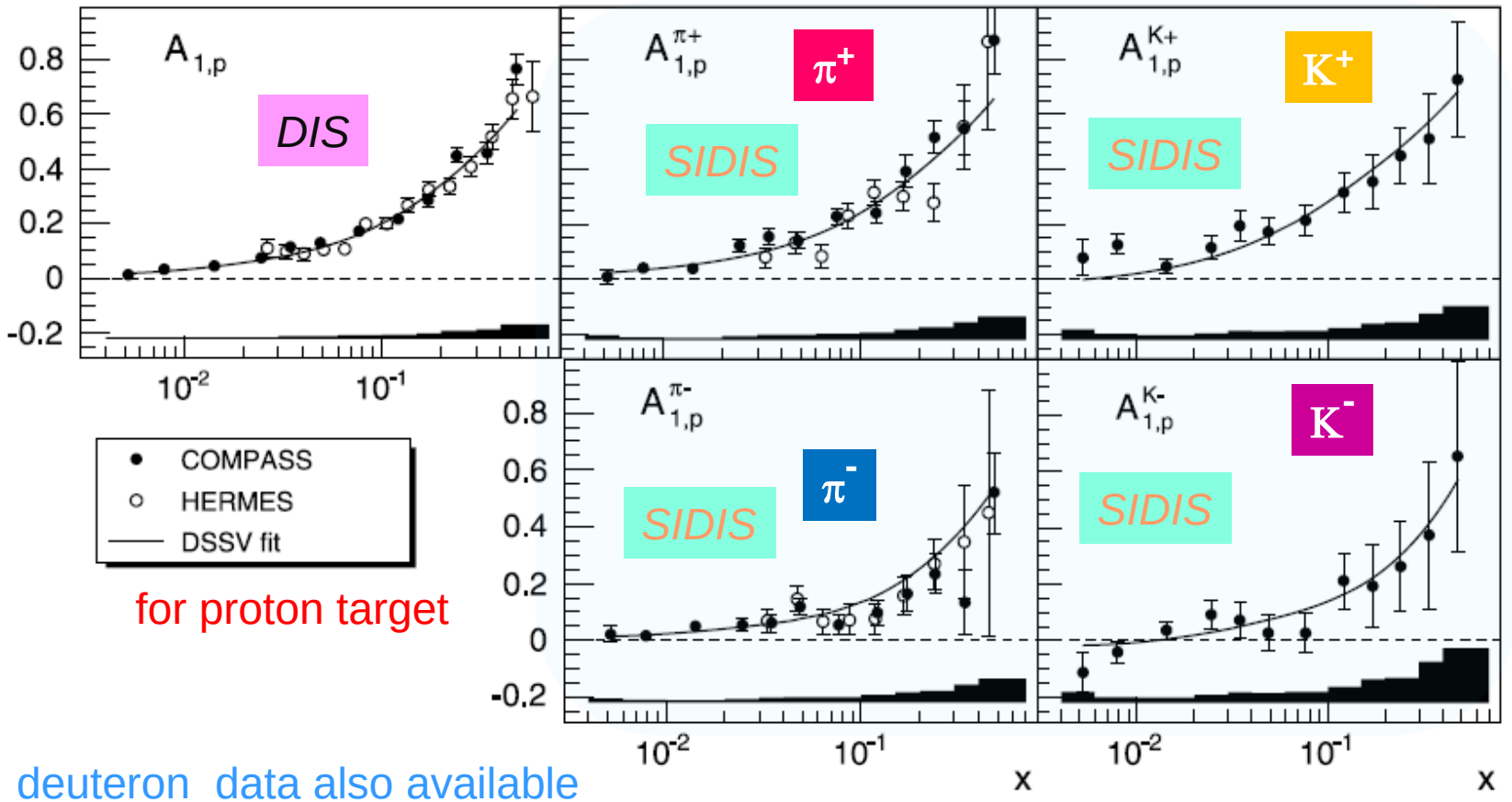
(QCD exact) well satisfied

$$\Gamma_1^{NS}(Q^2) \equiv \Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \frac{1}{6}\left|\frac{g_V}{g_A}\right| C_1^{NS}(Q^2)$$

QCD works well !

COMPASS; Phys.Lett. B 690(2010) 466-472

Semi-Inclusive DIS Asymmetry



for proton target

deuteron data also available

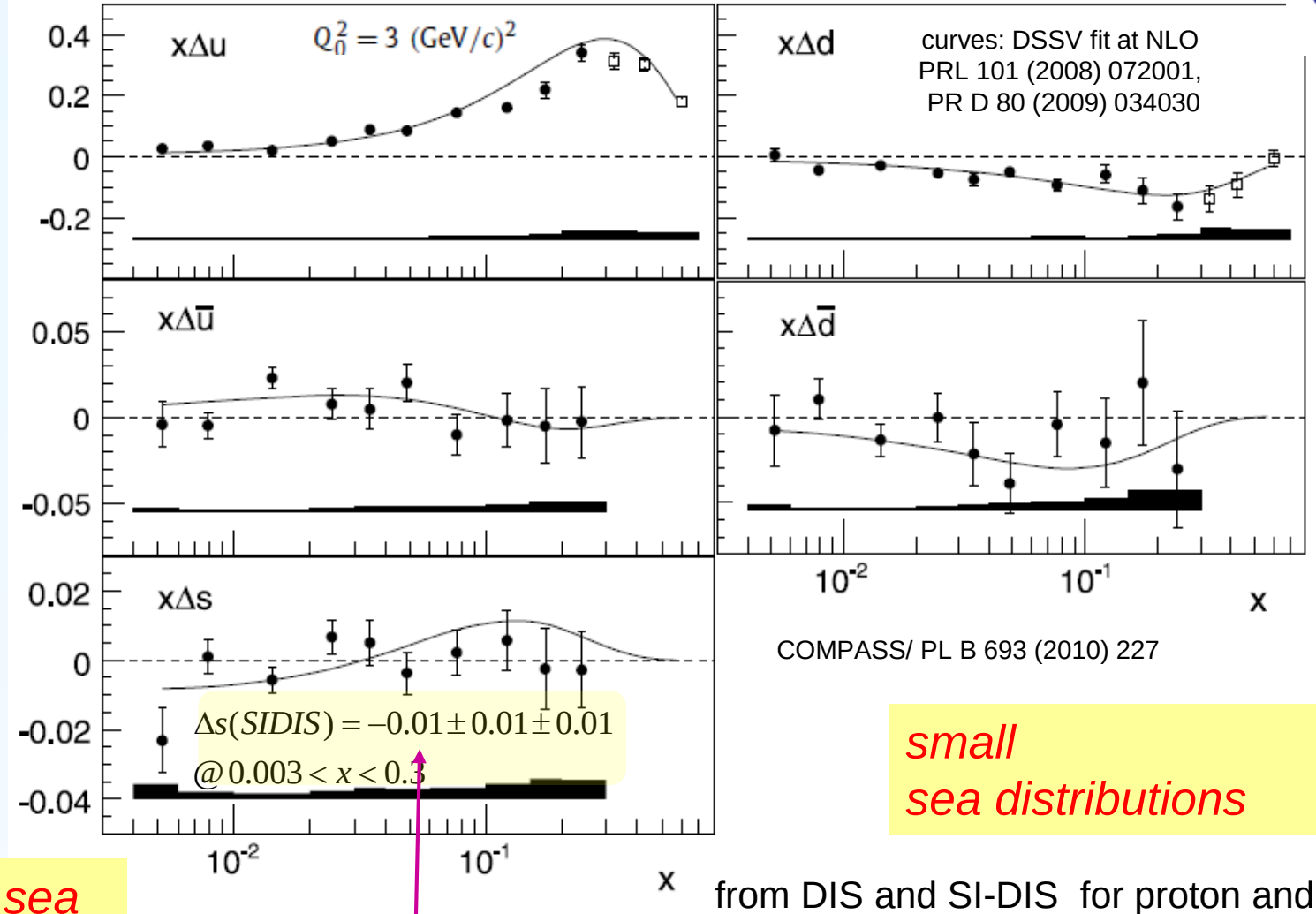
➔ *flavor decomposition*

COMPASS Collaboration / Physics Letters B 693 (2010) 227–235

HERMES Collaboration, A. Airapetian, et al., Phys. Rev. D 71 (2005) 012003.

HERMES Collaboration, A. Airapetian, et al., Phys. Rev. D 75 (2007) 012007.

Flavor Decomposition by COMPASS



COMPASS/ PL B 693 (2010) 227

small sea distributions

strange sea not polarized

from DIS and SI-DIS for proton and deuteron

$2\Delta s(\mathrm{Incl.}) = -0.08 \pm 0.02 \pm 0.02$

LO analysis

DSS fragmentation functions
(Phys. Rev. D75 (2007) 114010)

arXiv:hep-ex/0609038

choice of FF ?

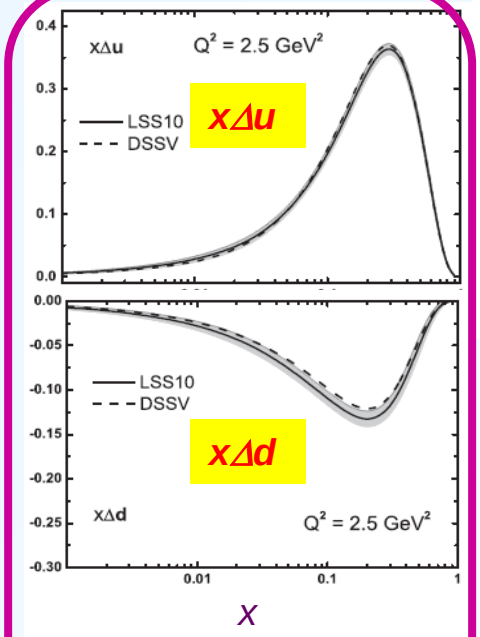
Helicity Distributions from Global Analysis

PHYSICAL REVIEW D 82, 114018 (2010)

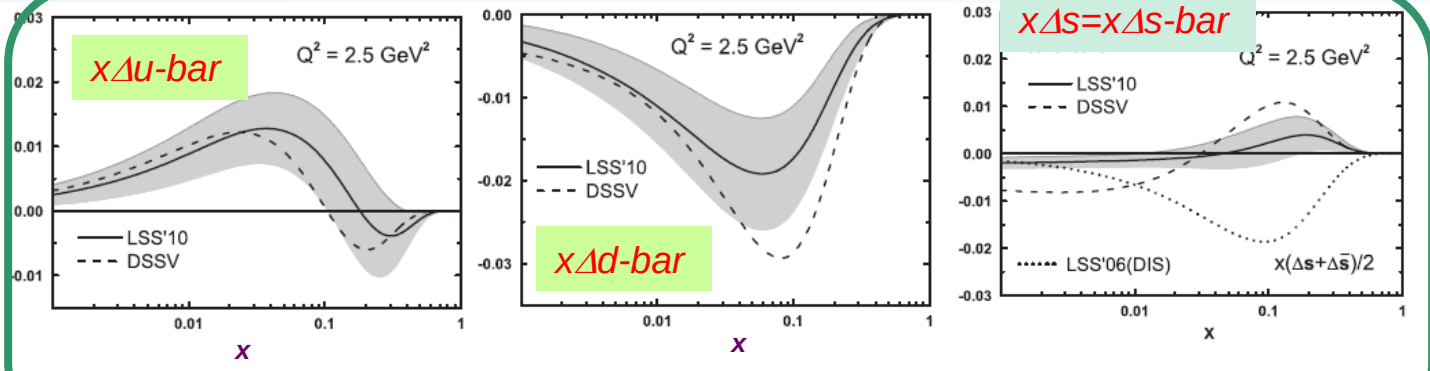
NLO QCD Analysis with DIS and SI-DIS data only, with g_A, F,D constraints

$\overline{\text{MS}}$ scheme.

by LSS



Δu and Δd well determined

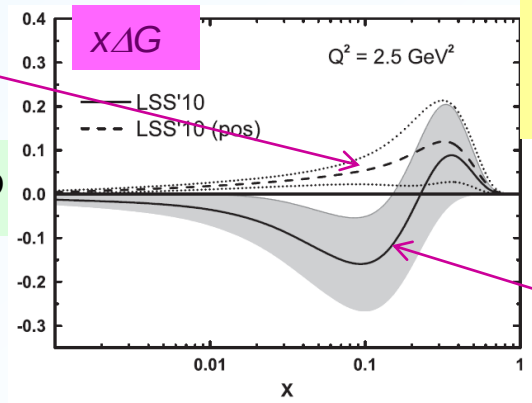


Sea quark distributions small

$$\Delta G\ x \equiv G^{\uparrow}\ x - G^{\downarrow}\ x$$

positive gluon distribution can not be ruled out

$$\int \Delta G dx = 0.316 \pm 0.19$$



gluon distribution shows large uncertainty, even sign not determined

$$\int \Delta G dx = -0.339 \pm 0.458$$

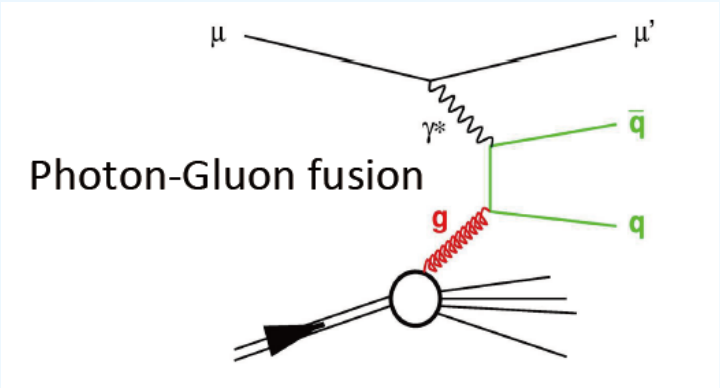
negative gluon distribution (with node)

Q^2=4GeV^2

Fit	$\Delta\bar{s}$	ΔG	$\Delta\Sigma$
LSS10 (pos $x\Delta G$)	-0.063 ± 0.004	0.316 ± 0.190	0.207 ± 0.034
LSS10 (node $x\Delta G$)	-0.055 ± 0.006	-0.339 ± 0.458	0.254 ± 0.042

Direct Measurement of Gluon Polarization

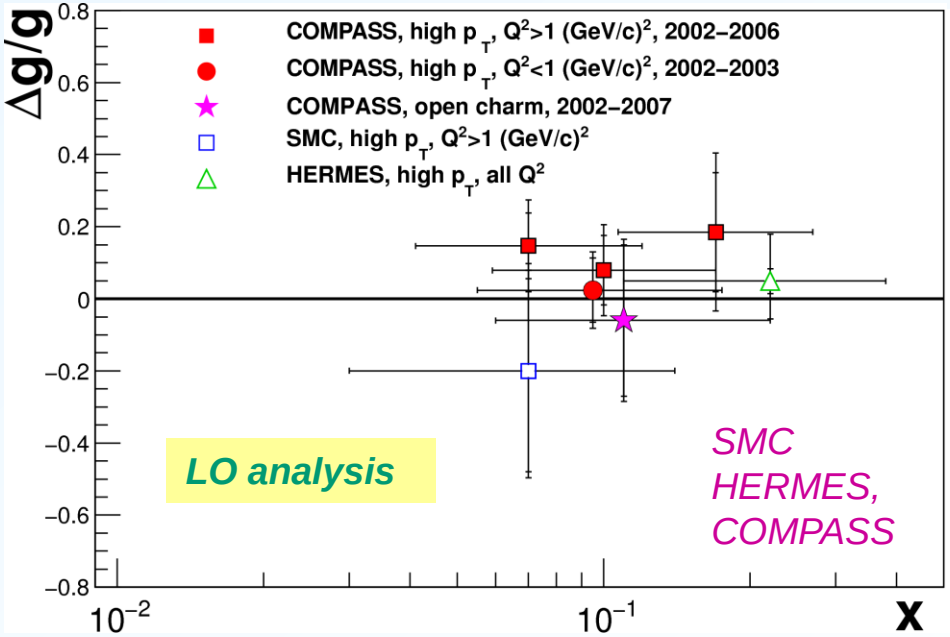
Double Spin Asymmetry for Photon-Gluon fusion

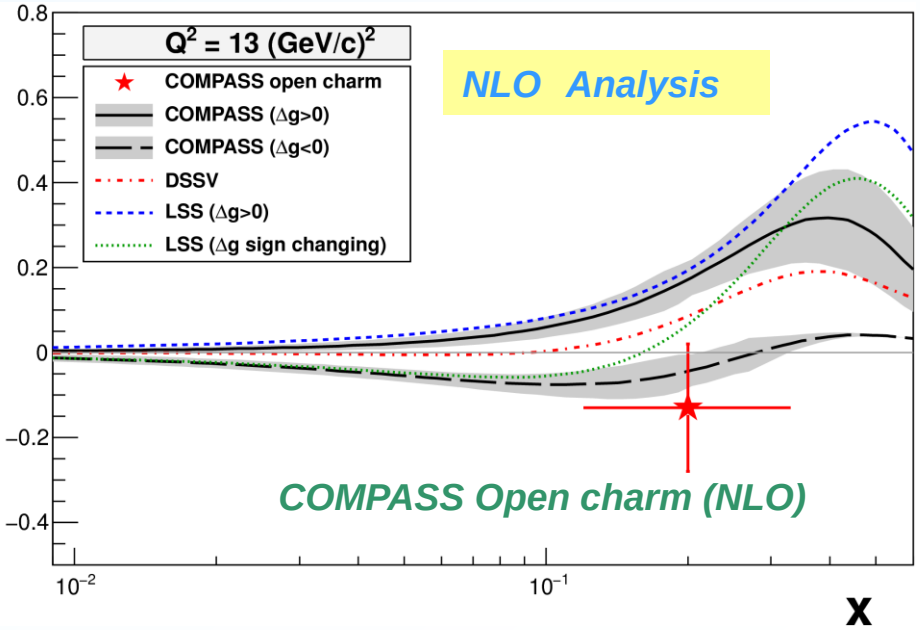


The process is identified by

high Pt hadron pair events
(COMPASS, SMC)
high Pt single hadron events
(HERMES)
open charm events
(COMPASS)

compatible with zero-polarization in this range.





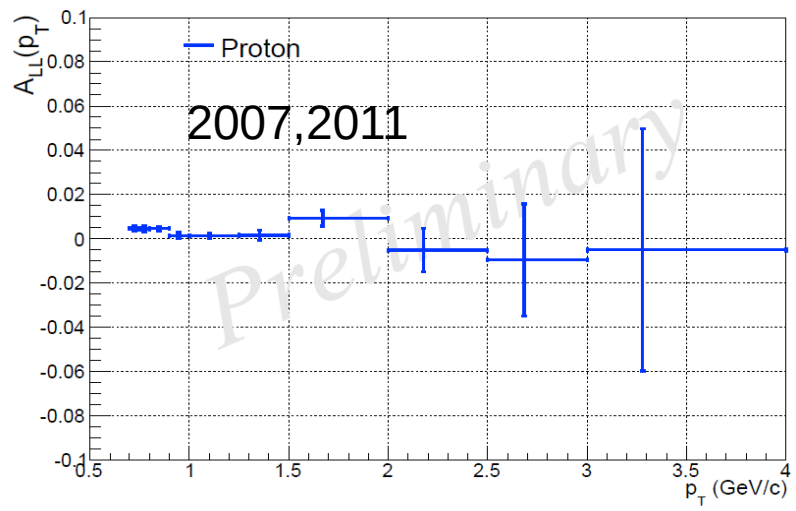
COMPASS, Phys.Rev. D 87 (2013) 052018

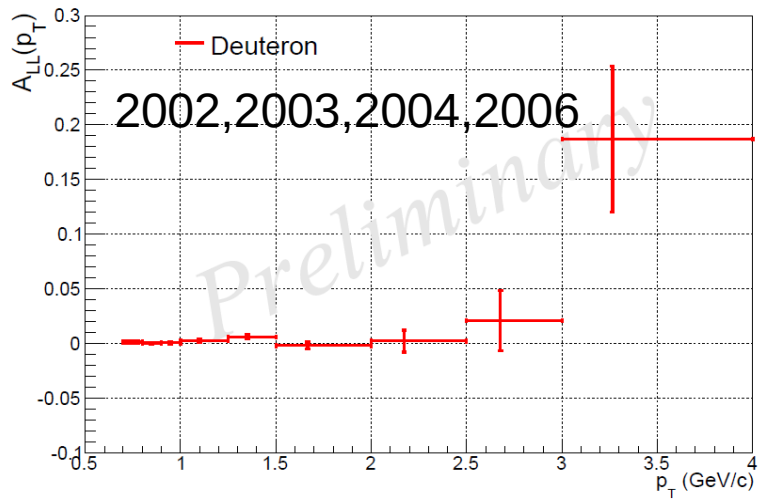
A_{LL} for Inclusive Single High P_T Hadron

Low Q^2 (photo production)
based on the pQCD framework
allowing a NLO extraction of ΔG

VERY NEW !

- $0.1 < y < 0.9$
- $Q^2 < 1$ GeV^2
- $P_T > 0.7$ GeV/c
- $z < 0.8$

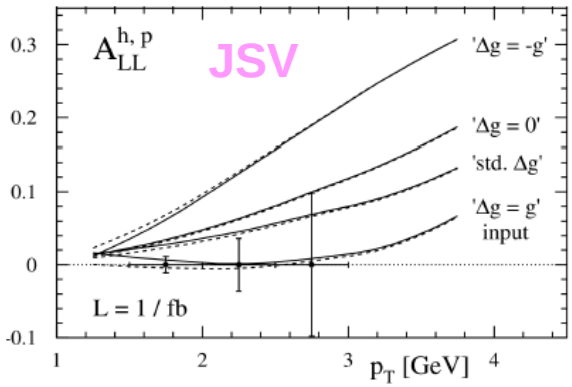


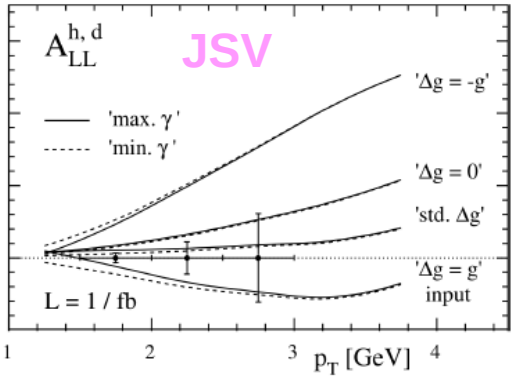


theoretical framework based on

Jäger, B. and Stratmann, M. and Vogelsang, W.,
Eur.Phys.J. **C44**, 533 (2005), hep-ph/0505157.

C. Hendlmeier, A. Schafer, and M. Stratmann,
Eur.Phys.J. **C55**, 597 (2008), arXiv:0803.1940.





Transverse Spin Effects

Angular Modulation in SIDIS & PDFs

SIDIS for transv. pol. target gives angular modulation:

$$d\sigma_{SIDID} \propto \left[1 + \underbrace{a_1 \cdot \sin\phi_C}_{\text{Collins}} + \underbrace{a_2 \cdot \sin\phi_S}_{\text{Sivers}} + \ldots.\right]$$

Transversity, Collins F.F.

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

Sivers PDF

$$A_{Siv} \approx \frac{\sum_q e_q^2 \cdot f_{1T,q}^{\perp} \; D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

Collins angle: **Azim. angle of a hadron wrt struck quark spin**

$\Phi_C = \phi_h - \phi_{S'} \; (= \phi_h + \phi_S - \pi)$

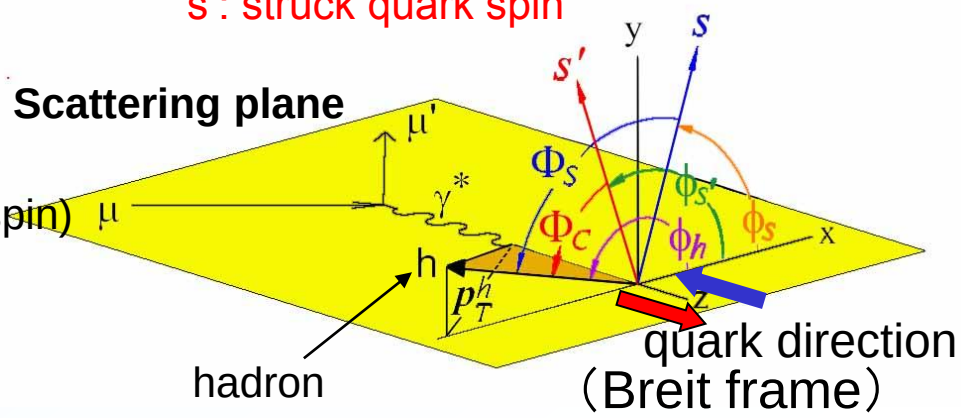
Sivers angle: **Azim. angle of a hadron wrt nucleon spin**

$\Phi_S = \phi_h - \phi_S$

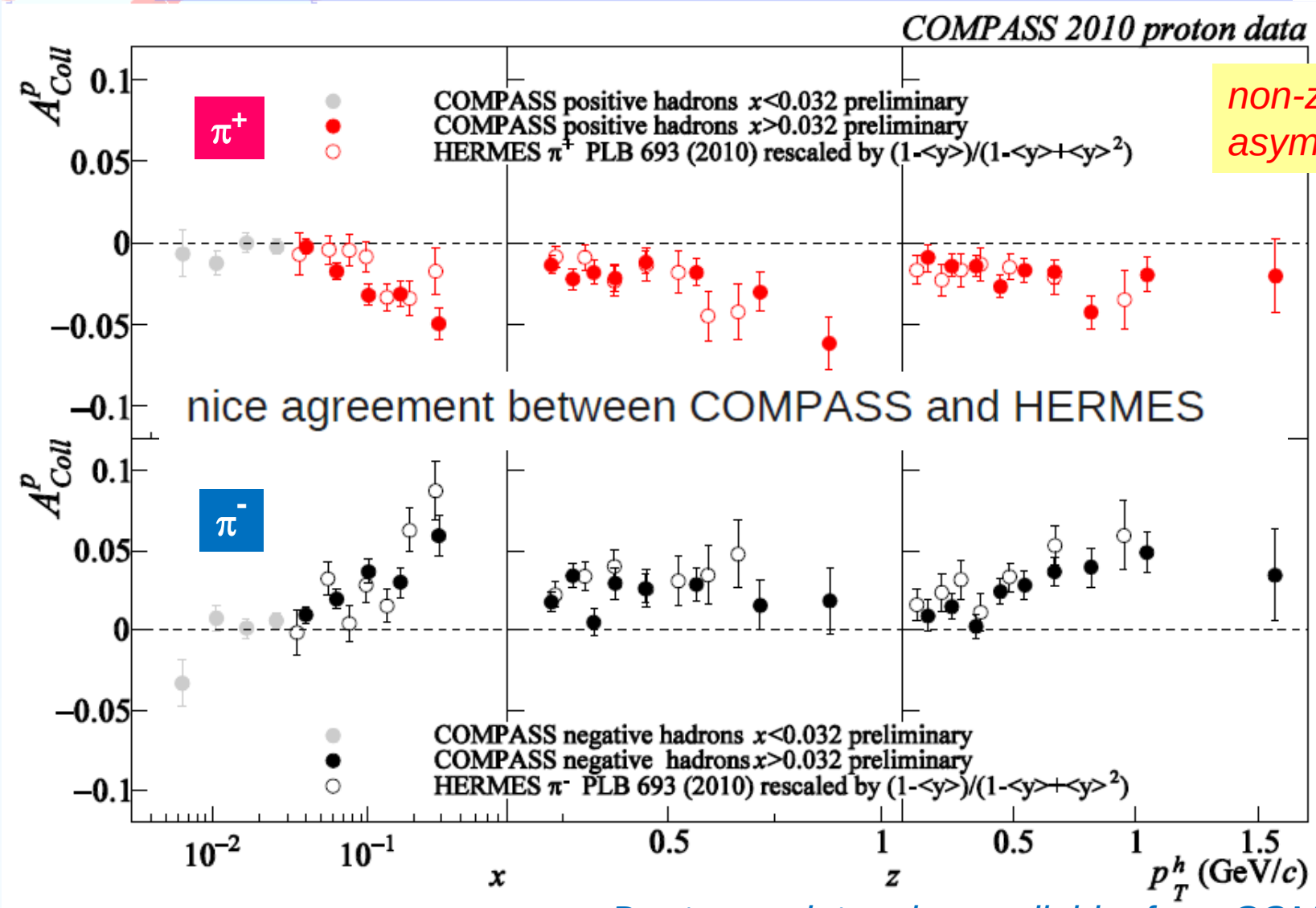
ϕ_S = azim. angle of nucleon spin (initial quark spin)
$\phi_{S'}$ = azim. angle of struck quark spin
$\phi_S = \pi - \phi_{S'}$ (due to helicity conservation)
ϕ_h = azim. angle of leading hadron

s: nucleon spin (initial quark spin)

s': struck quark spin



Collins Asymmetry



non-zero asymmetry

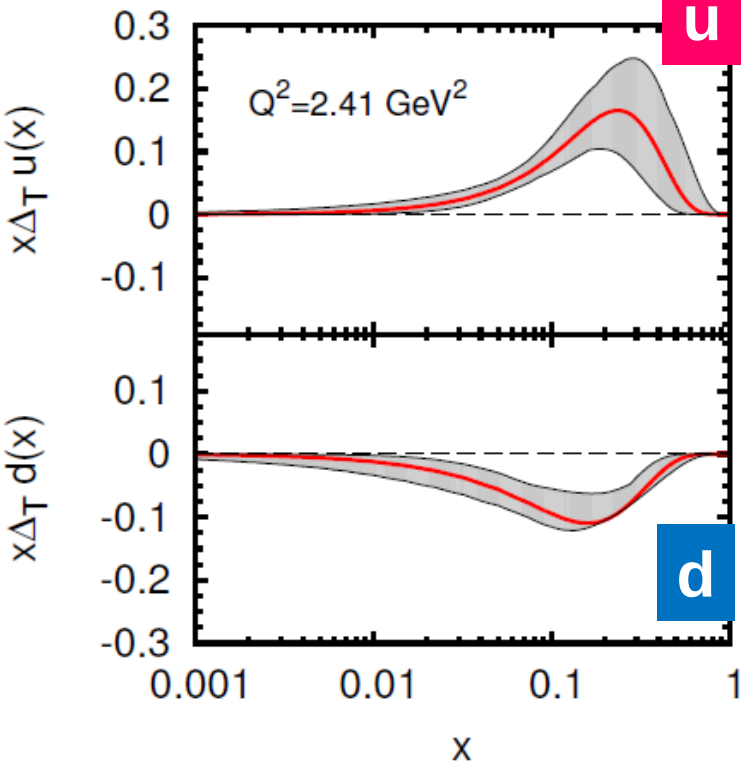
Deuteron data also available from COMPASS

Transversity Global Analysis

M. Anselmino et al., PRD87 (2013) 094019

- fit to $A_{coll}^{p,d}$ from COMPASS, A_{Coll}^{p} from HERMES and BELLE data ($e^+e^- \rightarrow h_1 h_2 X$)

Transversity

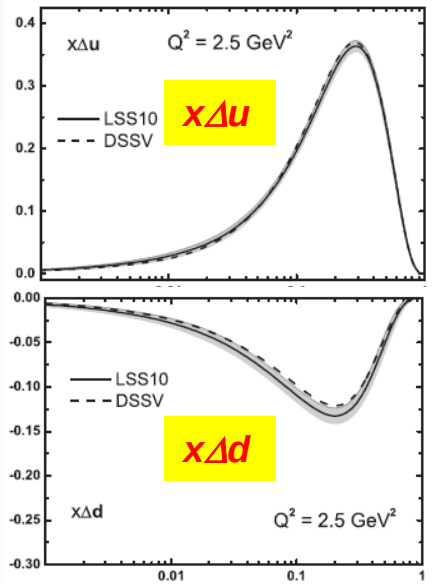


Opposite signs

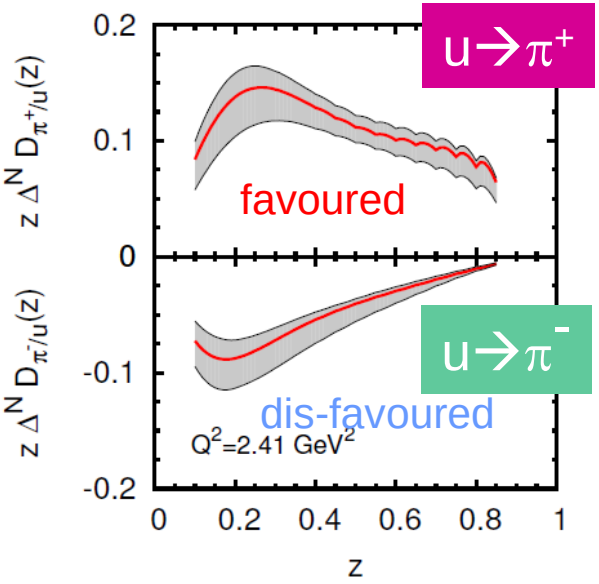
Similar shapes to Helicity PDF

But intensities slightly smaller

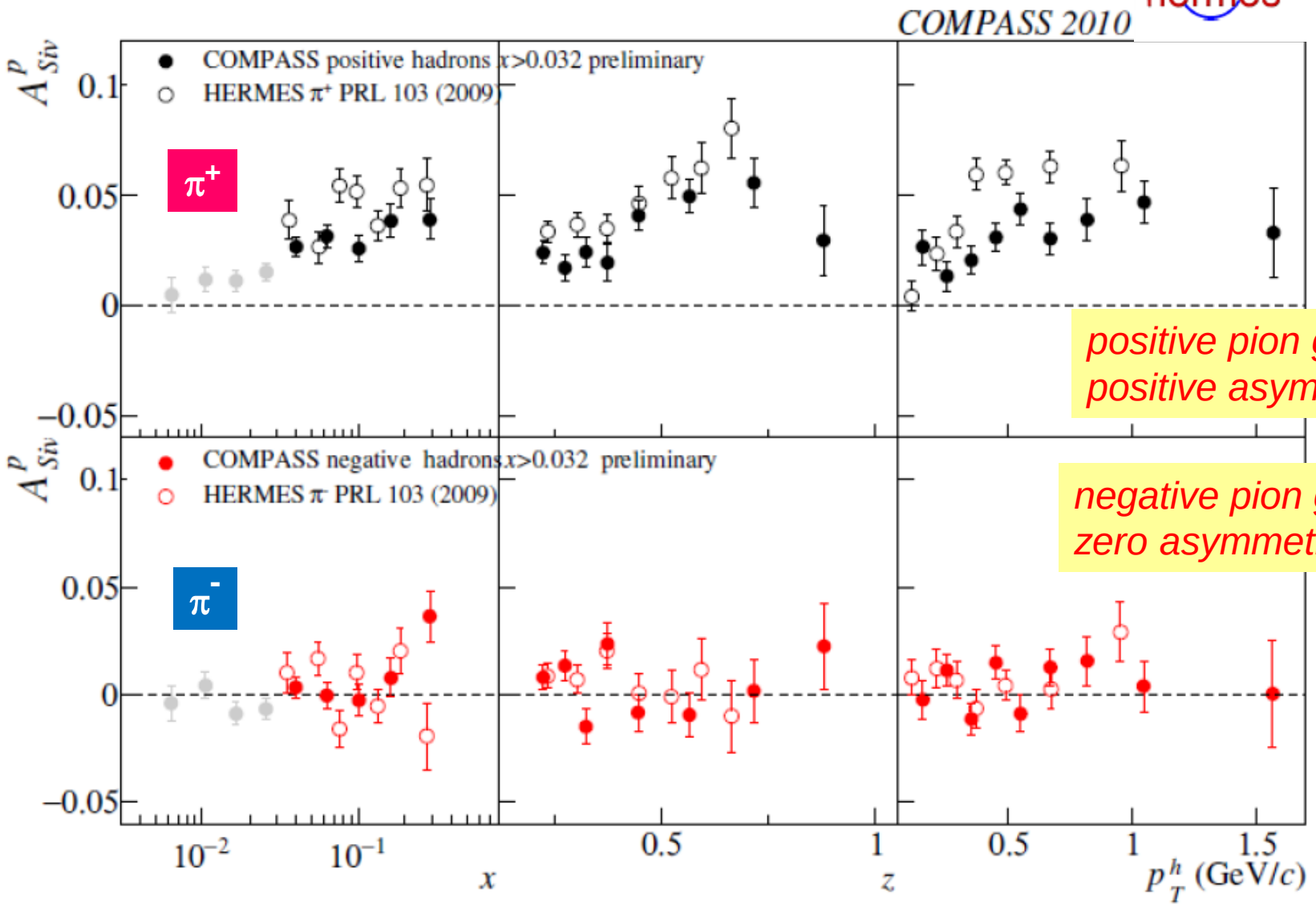
Helicity PDF



Collins F.F.



Sivers Asymmetry



positive pion gives positive asymmetry

negative pion gives zero asymmetry

Deuteron data also available from COMPASS

Sivers PDF Global Analysis

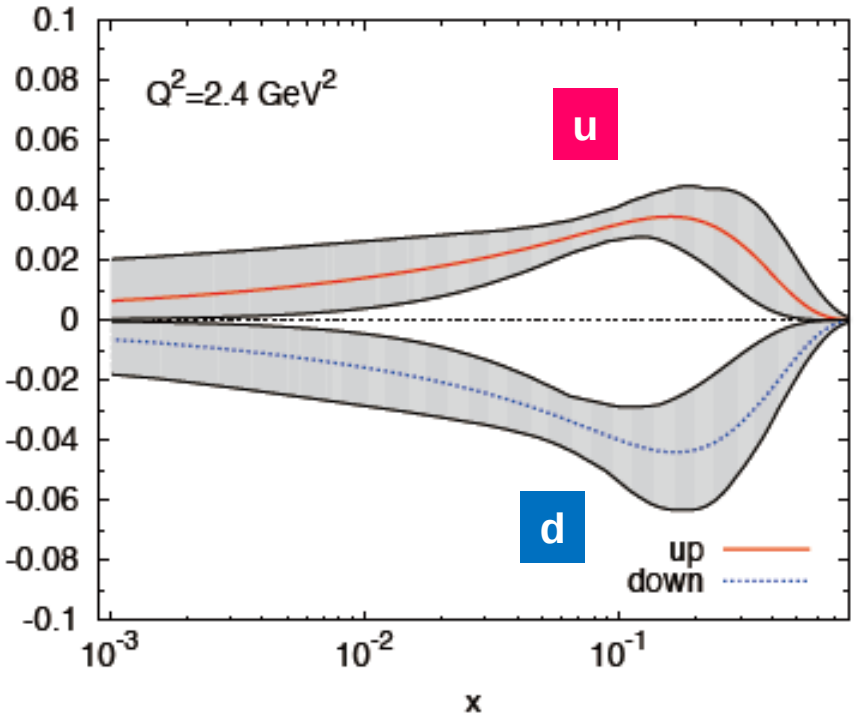
M.Anselmino, QNP2012

fit to $A_{Siv.}^{p,d}$ from COMPASS,
$A_{Siv.}^{p}$ from HERMES

$$\Delta^N f_q^{(1)}(x,Q) = \int d^2\boldsymbol{k}_\perp \frac{k_\perp}{4M_p} \Delta^N \hat{f}_{q/p^\uparrow}(x,k_\perp;Q) = -f_{1T}^{\perp(1)q}(x,Q)$$

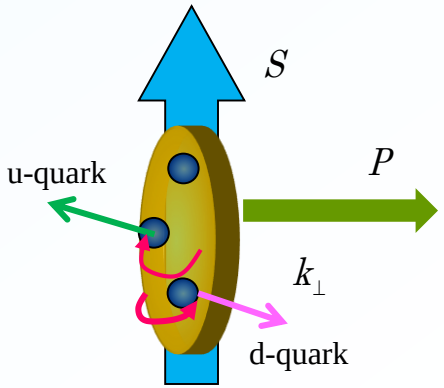
Sivers PDF (k_T^2 integrated)

$$x\,\Delta^N f_q^{(1)}(x,Q)$$



Sivers: distribution of **unpol.** quarks in ⊥ pol. proton

$$f_{q/p^\uparrow}(x,\mathbf{k}_\perp) = f_1^q(x,\mathbf{k}_\perp^2) - f_{1T}^{\perp q}(x,\mathbf{k}_\perp^2)\frac{(\hat{\mathbf{P}}\times\mathbf{k}_\perp)\cdot S}{M}$$



u-quark and d-quark give opposite k_T w.r.t. the proton spin

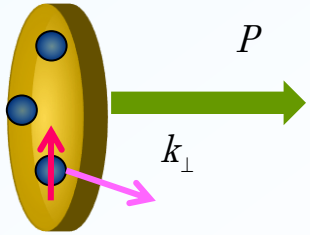
Asymmetry related to Boer-Mulders PDF

Boer-Mulders PDF : transverse spin & transverse momentum of the quark
← access through SIDIS on un-polarized nucleon

$$\frac{\mathrm{d}\sigma}{p_T^h\,\mathrm{d}p_T^h\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}\phi_h} =$$

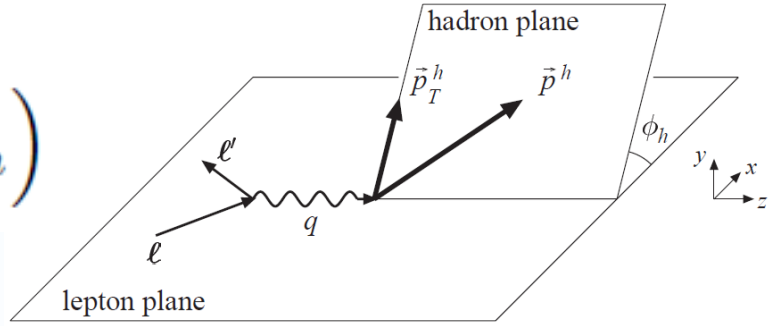
BM x Collins FF +
Cahn effect (kinematical effect from k_T)

$$A^{UU}_{\cos\phi_h} = \frac{1}{Q}\,\mathrm{Cahn} + \frac{1}{Q}\,\mathrm{BM}$$



$$h_1^{\perp\,q}\left(x,k_\perp^2\right) > 0$$

$$\sigma_0\left(1+\epsilon_1 A^{UU}_{\cos\phi_h}\cos\phi_h + \epsilon_2 A^{UU}_{\cos 2\phi_h}\cos 2\phi_h + \lambda\epsilon_3 A^{LU}_{\sin\phi_h}\sin\phi_h\right)$$

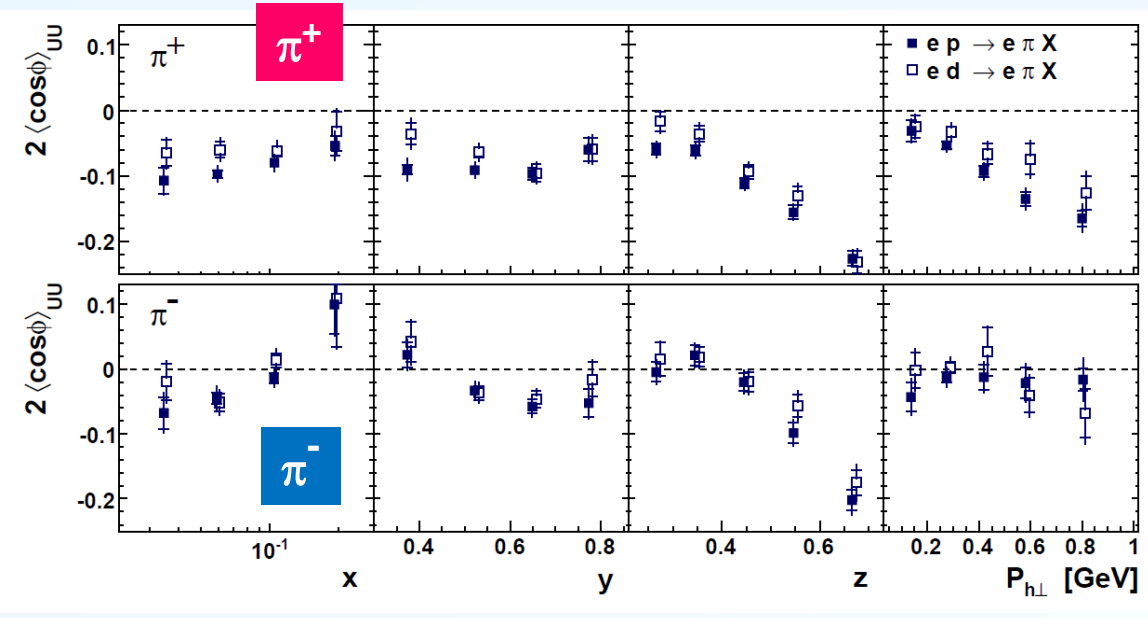


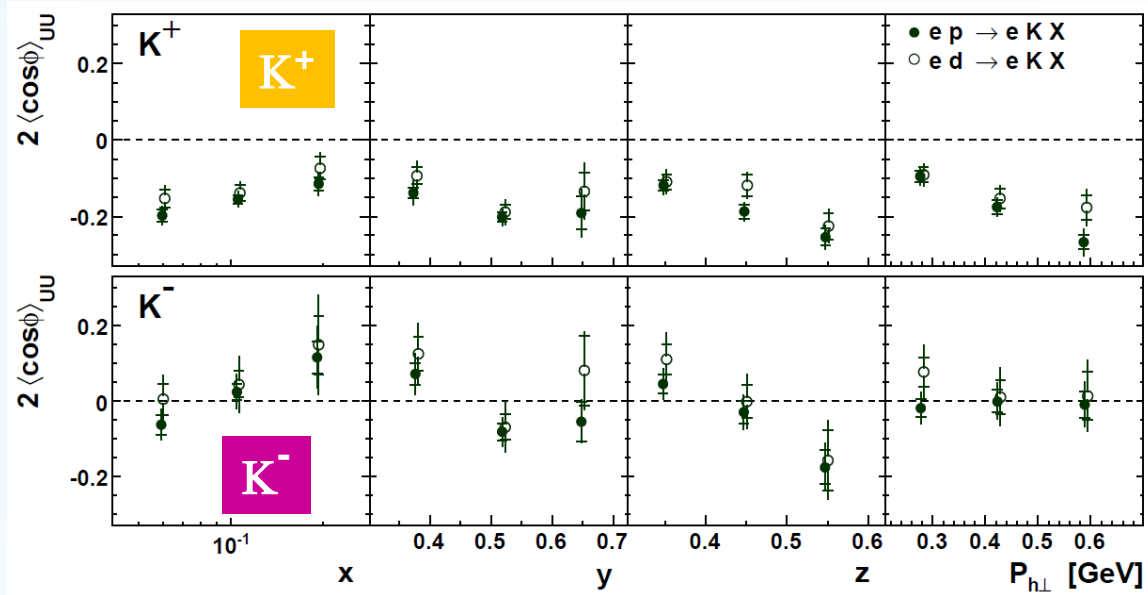
in the $\gamma^* N$ system

BM x Collins FF
+ twist4 Cahn effect

$$A^{UU}_{\cos 2\phi_h} = \mathrm{BM} + \frac{1}{Q^2}\,\mathrm{Cahn}$$

COS ϕ Asymmetry from HERMES





for proton & deuteron targets

π^+/π^- difference
→ may be due to BM effects
(Cahn expected to be flavor blind)

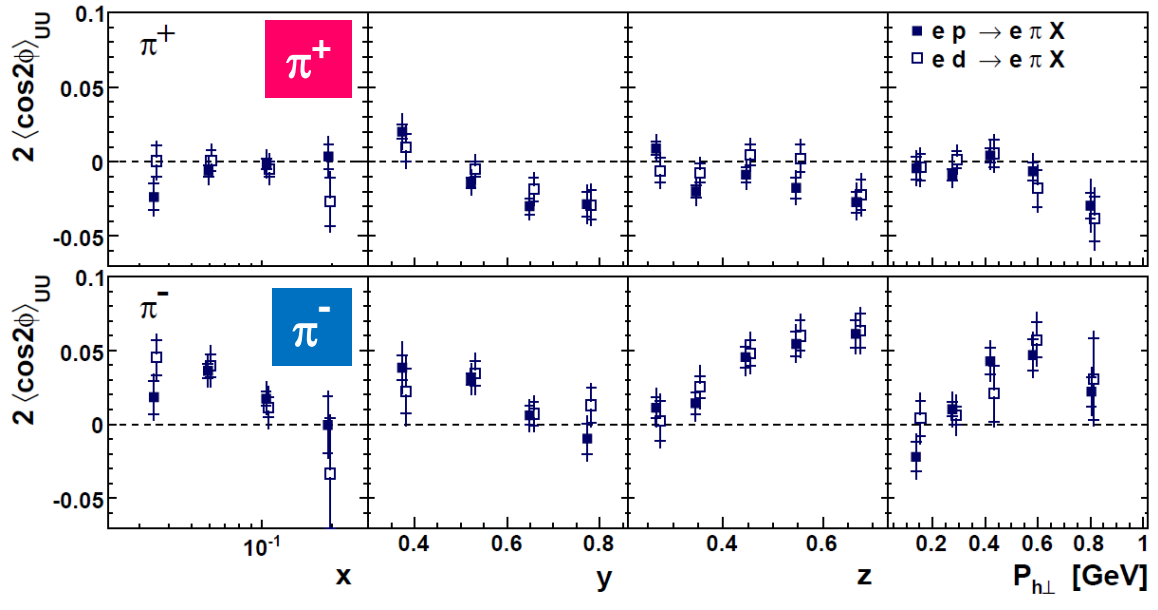
$$A_{UU}^{\cos\phi_h} \propto \frac{M}{Q}\left\{-h_1^{\perp q}\otimes H_{1q}^{\perp q} - f_1^{q}\otimes D_{1q}^{h}\right\}$$

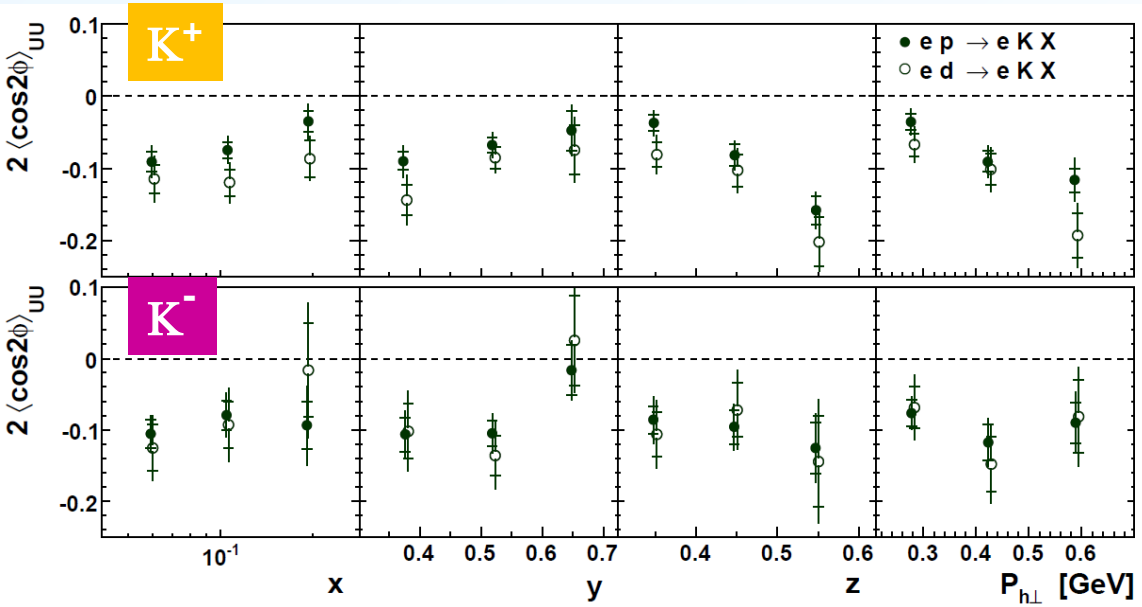
BM Cahn

K^+ :larger than π^+
K^- : compatible with 0

Phys. Rev. D 87, 012010 (2013)

COS 2ϕ Asymmetry from HERMES





for proton & deuteron targets

π^+ : zero or negative
π^- : positive , large signal
→ non-zero BM

$$A_{UU}^{\cos 2\phi_h} \propto -h_1^{\perp q} \otimes H_{1q}^{\perp q} + \left(\frac{M}{Q}\right)^2 f_1^q \otimes D_{1q}^h$$

BM Cahn

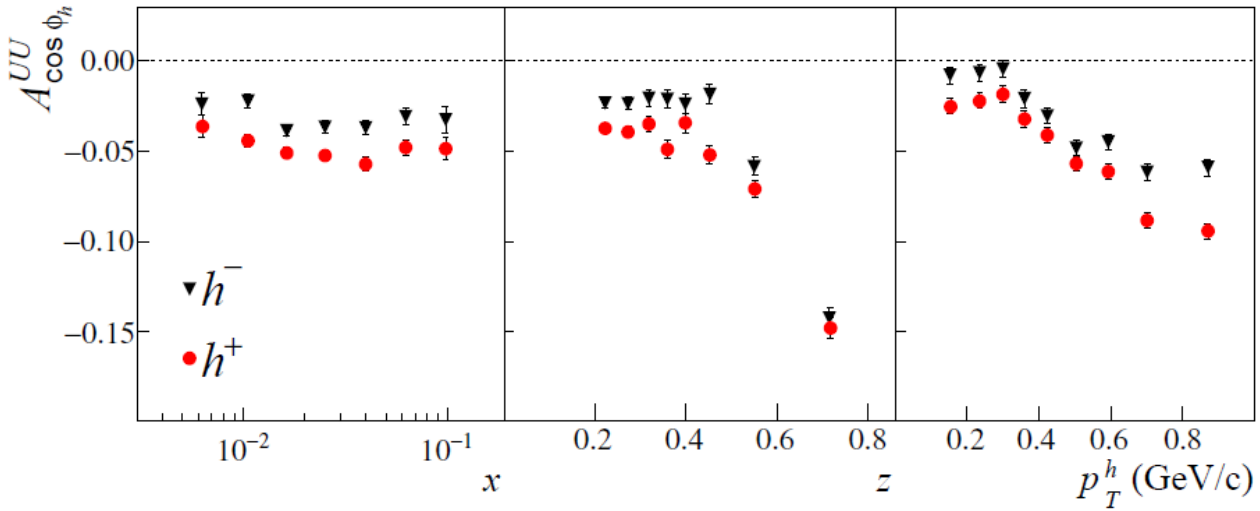
K^+/K^- : larger than π^+/π^-

Phys. Rev. D 87, 012010 (2013)

Asymmetry on deuteron from COMPASS

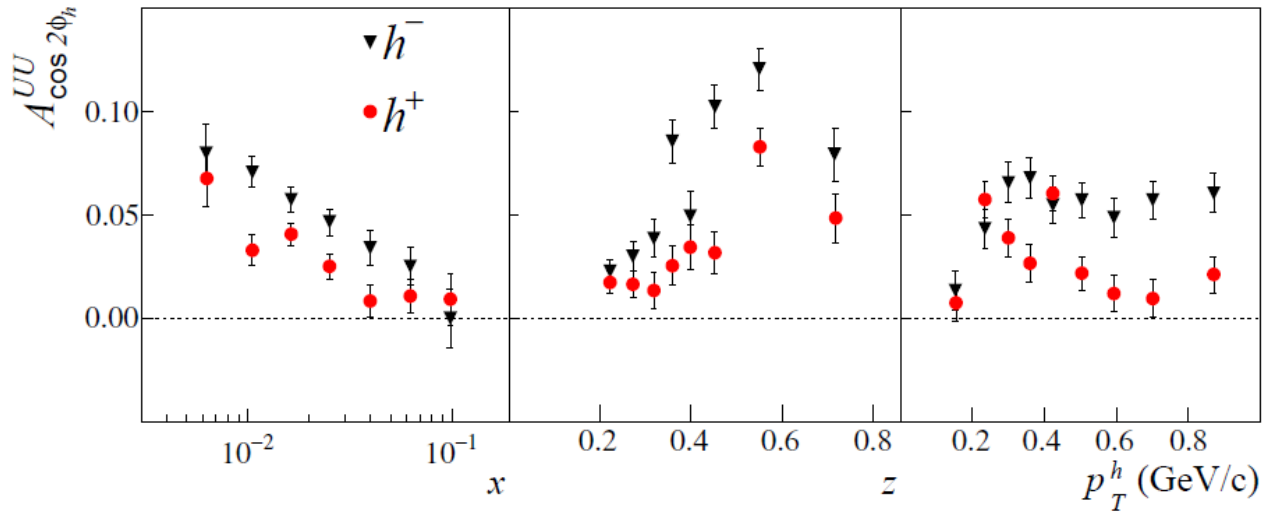
COMPASS 2004 ^{6}LiD

CERN-PH-EP-2014-009



negative for h^+/h^-
strong z dependence

similar trends to HERMES data in overlapping region



positive for h^+/h^-
strong dependence on kinematical variables

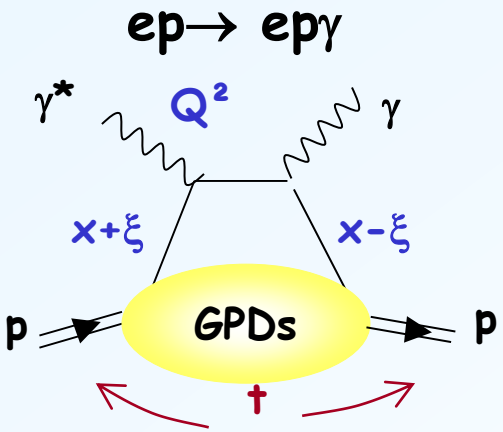
GPD Studies

GPD & DVCS

Generalized Parton Distribution (GPD) ➔ a key concept for nucleon structure

access through Deeply Virtual Compton Scattering (DVCS)

→ In experiments, hard exclusive photon production should be studied



$\Delta = P^* - P \qquad t = -\Delta^2$

GPDs: (in twist-2 level)

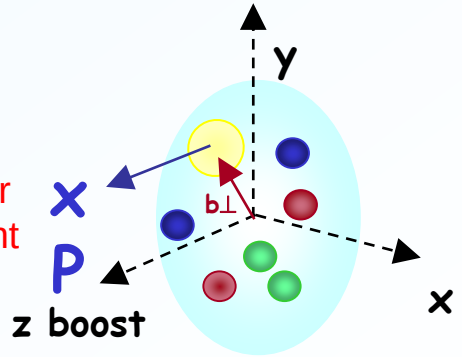
Vector	$H^q(x,\xi,t)$
Tensor	$E^q(x,\xi,t)$
Axial vector	$\tilde{H}^q(x,\xi,t)$
Pseudo scalar	$\tilde{E}^q(x,\xi,t)$

give total angular momentum of quarks

$$\lim_{t\to\infty,\xi\to 0}\frac{1}{2}\int_{-1}^{1} x\left[H^q(x,\xi,t)+E^q(x,\xi,t)\right]dx = J^q$$

[10] X. Ji: J. Phys. G 24 (1998) 1181.

relation to Impact Parameter Dependent PDFs

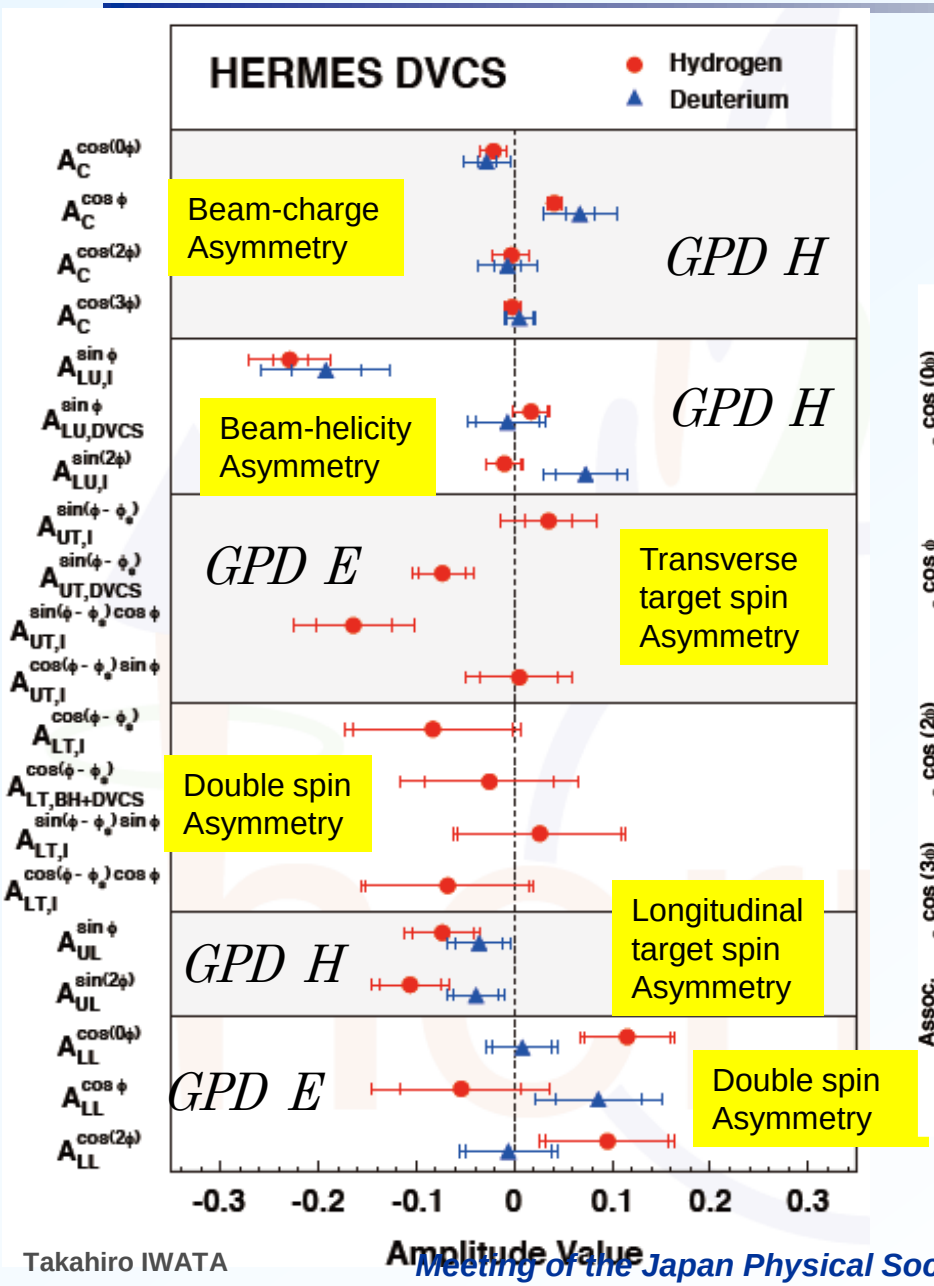


quark distribution as a function of transverse position and longitudinal momentum

BURKARDT M., *Phys. Rev. D*, **66** (2002) 114005.
BURKARDT M., *Int. J. Mod. Phys. A*, **18** (2003) 173.

➔ *3D picture*

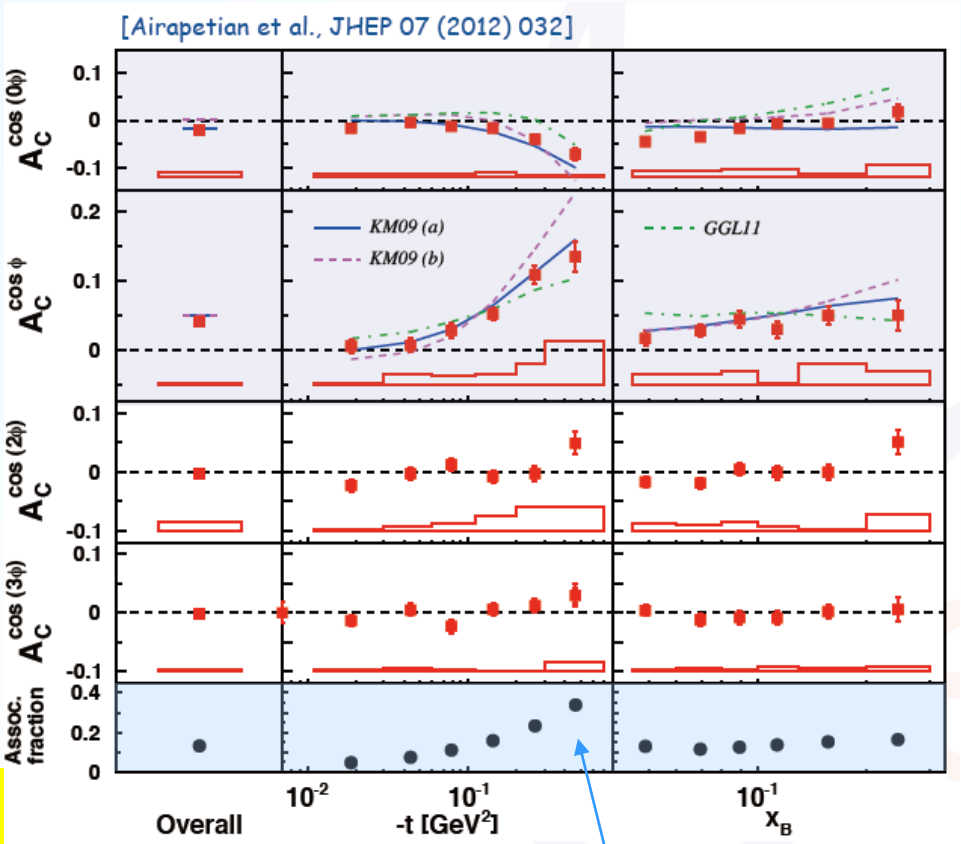
DVCS Data Accumulated by HERMES



Pioneering work by HERMES

Hard Exclusive Photon Production identified with missing mass technique

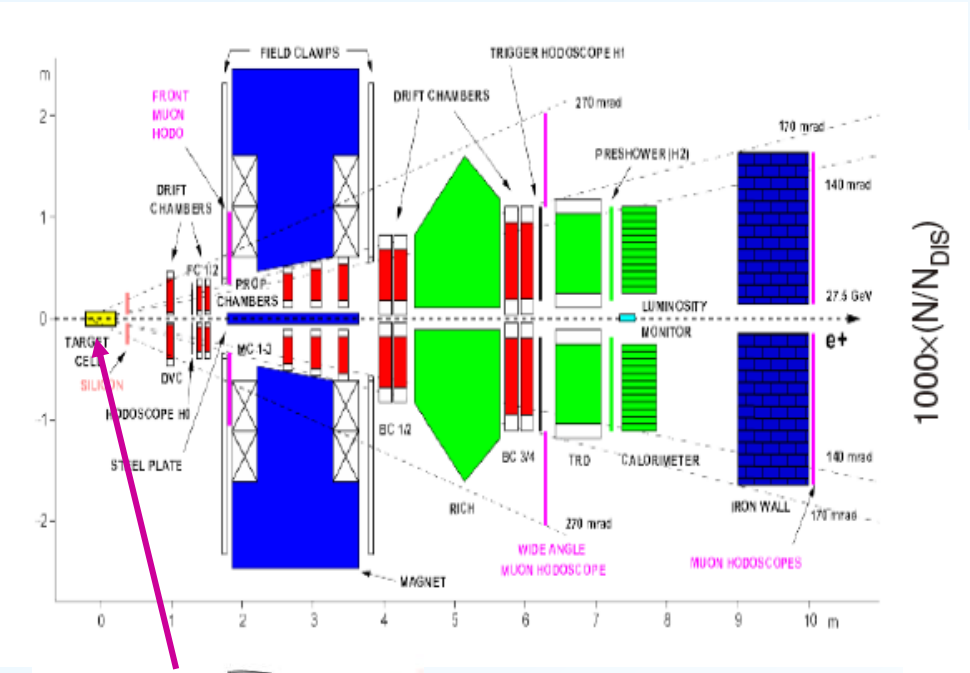
Beam-charge Asymmetry

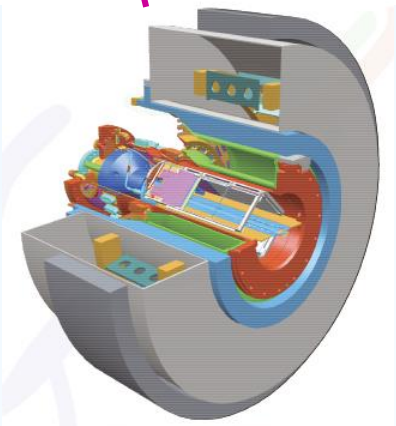


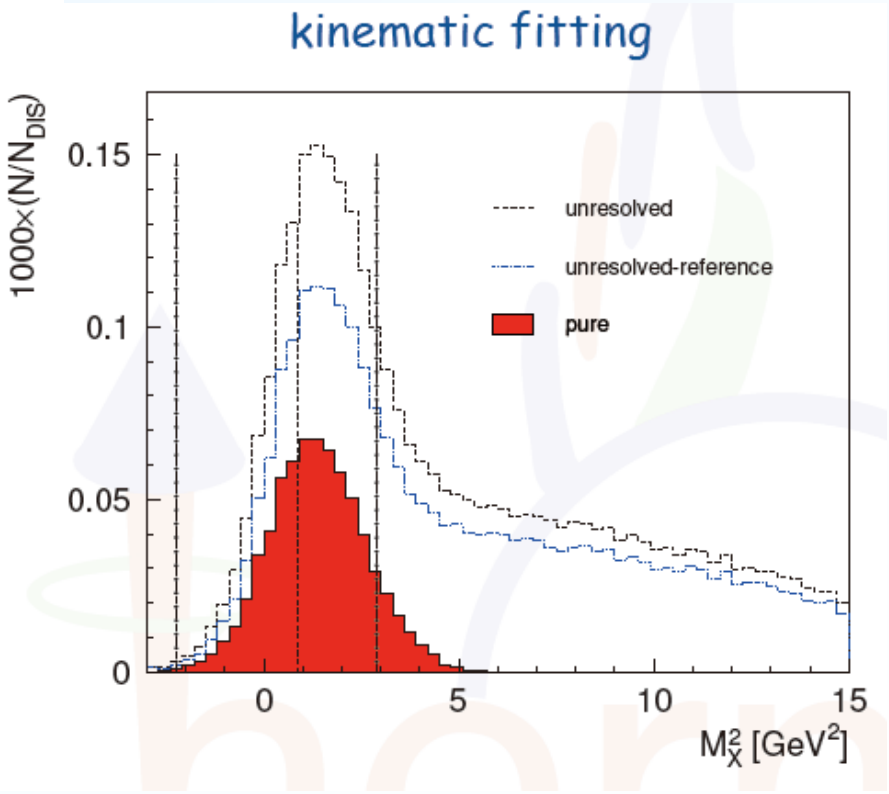
Resonant fraction :ep→eΔ⁺γ

Courtesy: G.Shnell, DVCS 2014

The Recoil Detector at HERMES



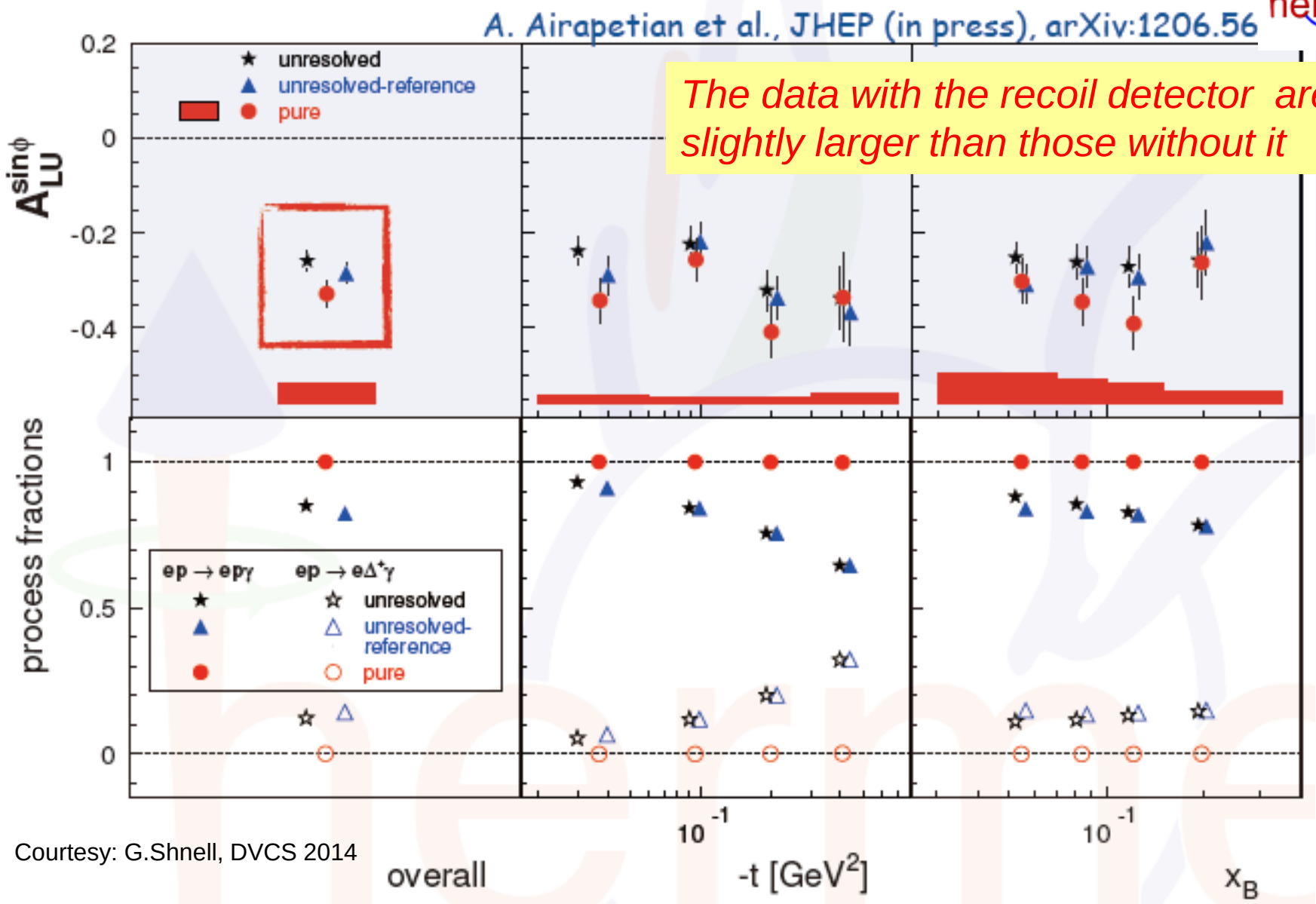




Courtesy: G.Shnell, DVCS 2014

∗ Selection of pure BH/DVCS(ep→epγ) with high efficiency
∗ Allows to suppress background to a negligible level (<0.2%)

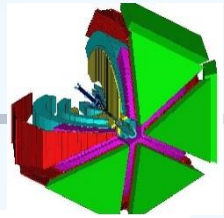
Data with Recoil Detector at HERMES



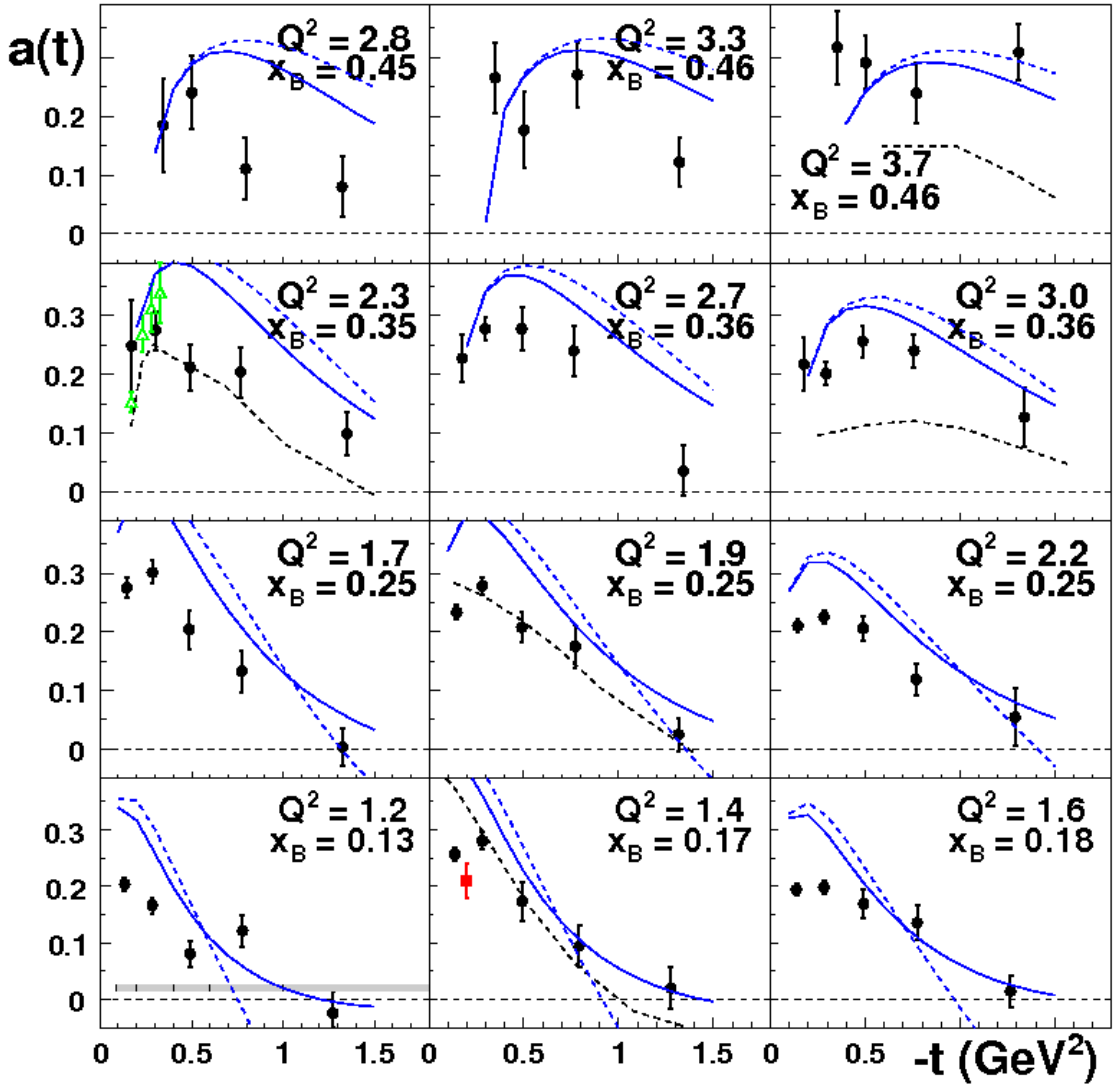
The data with the recoil detector are slightly larger than those without it

Courtesy: G.Shnell, DVCS 2014

GPD Studies in JLab



Beam-Spin asymmetries by CLAS



F.-X. Girod et al., Phys. Rev. Lett. **100**, 162002 (2008).

Jlab experiments are playing an important role to study GPD

Precise data in valence region

Hall A:
high accuracy,
limited kinematics,

Hall B:
wide kinematic range,
limited accuracy

Ee=5.766 GeV

Further Studies on GPD

Dedicated GPD programs at Jlab-12 GeV

- **Hall A: E12-06-114** fixed x, several Q^2 , several beam energies, t-dependence, Im H, Re H
- **Hall B: E12-06-119** large kinematic coverage with CLAS beam energy at 11GeV, high statistics, BSA, TSA
- **Hall B: E12-11-003** CLAS with new recoil neutron detector, BSA, flavour separation of GPD-H

GPD program in COMPASS-II

polarized μ^+ & μ^- , hydrogen target

new recoil proton detector, new 2.5m hydrogen target, new ECAL0

Beam Charge Spin Sum, Beam Charge Spin Difference

simultaneously HEMP, SIDIS on proton(FF, TMDs)

data taking: 2016,17 (after the run for pol. DY)

Conclusions

- Significant progress in the study with lepton scattering was achieved
- Δu and Δd are well determined
- Polarized sea distributions are small
- Gluon polarization is compatible with 0 in the measured range
- Transversity and Sivers PDF have been extracted
- The asymmetry on un-polarized nucleon gives a hint of BM PDF
- Wealth of GPD data were accumulated by HERMES and Jlab-experiments
- Exciting GPD programs at COMPASS-II and JLab-12GeV are planned