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SpinFest, Tokai

Spin Structure of the Nucleon studied by HERMES

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1. Introduction

Properties of Particles, Kinematics of Particles

Mass, Charge — Scalar

Momentum p driven by Force — Vector

Energy E

Angular momentum $L = p \times r$ driven by Moment of Force

Spin S — Axial-vector

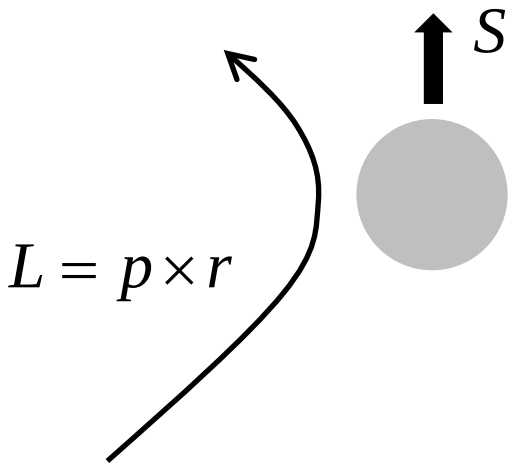
Isospin I — $p \times p'$ Scattering plane

Symmetry based on rotational invariance, SU(2)…

Spin is only a half integer or integer.

Mathematically solid, but sometime difficult to intuitively understand.

Combination or correlation between Spin and Angular Momentum



Single Spin Asymmetry A_N

Spin and Angular Momentum can be added, $S + L$

Cross section can be dependent on the scalar product $(L \cdot S)$

Spin-orbit interaction was a key to nuclear shell mode.

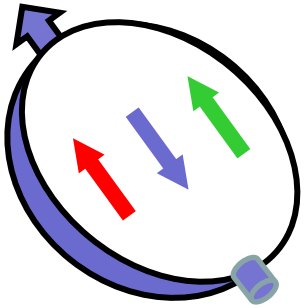
Parity violation $(V \cdot A)$

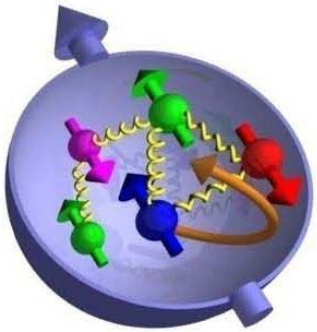
A bound system of a few or many particles with spin

Fast moving system

Spin Structure of the Nucleon

It was discovered that the proton has spin ½ from the measurement of specific heat of hydrogen molecules in 1927.

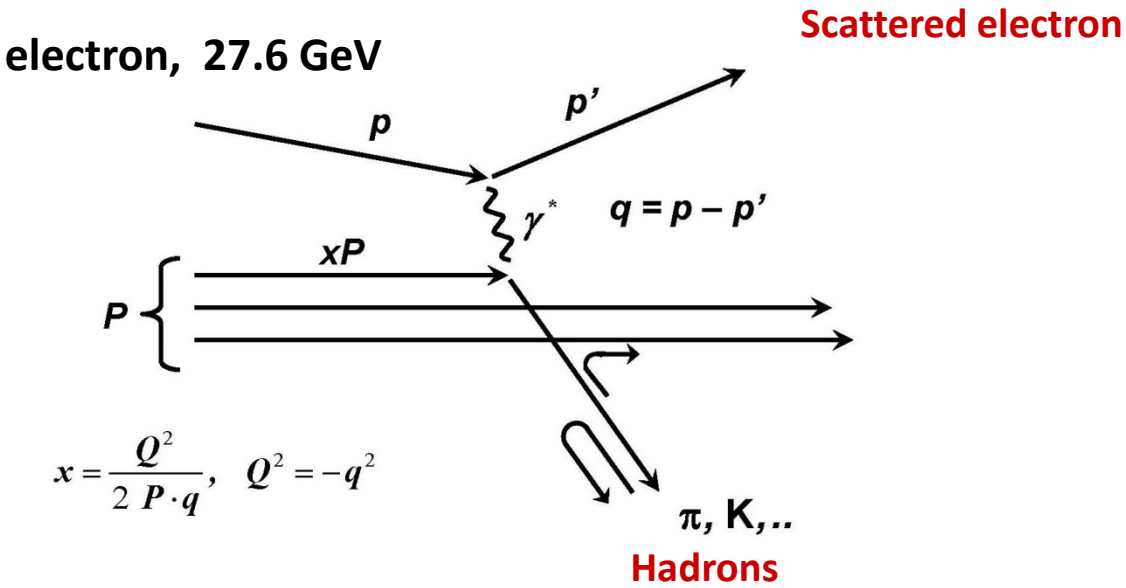




- Longitudinal spin structure of the nucleon, $g_1(x)$ structure function
- Transverse spin structure of the nucleon
- Transverse momentum dependent parton distribution functions

2. HERMES Experiment

Deep inelastic scattering



Typical cuts when electron is detected:

$Q^2 > 1\,\mathrm{GeV}^2,\ W > 3.3\ \mathrm{GeV},$

$0.023 < x < 0.6,\quad 0.2 < y < 0.85$

$z > 0.2,\ x_F > 0.2,\ 1 < P_h < 15\ \mathrm{GeV}$

Bjorken *x* is Lorentz Invariant Quantity $$x = \frac{Q^2}{2P \bullet q}$$

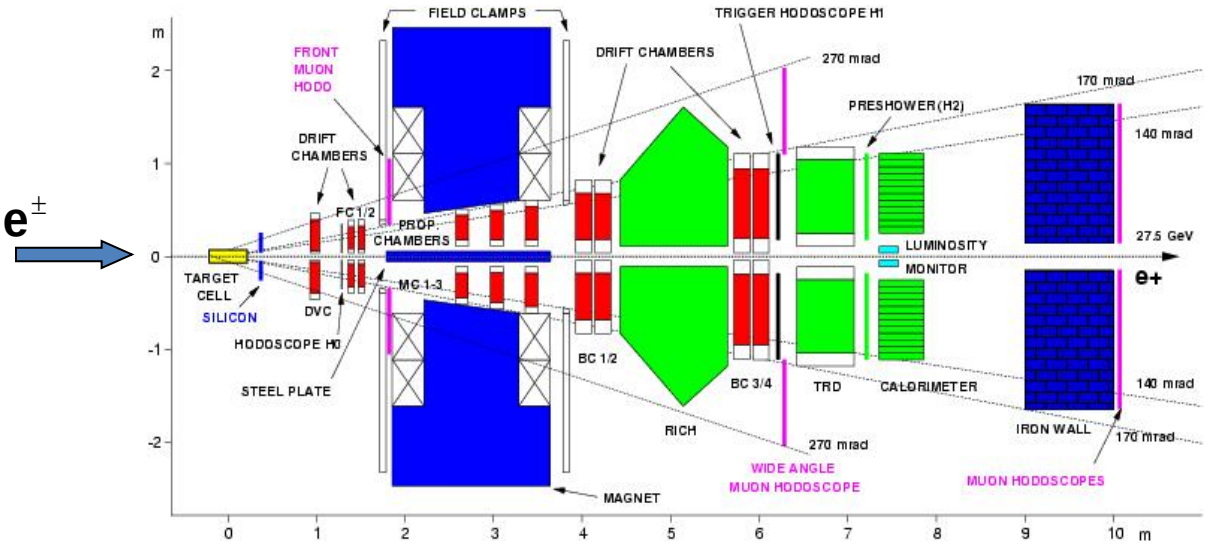
$$x = \frac{Q^2}{2M\nu}$$ in a fixed target experiment, in Lab frame

Bjorken *x* is the momentum fraction of the parton in Breit frame

$$E_{\gamma^*} = 0$$

HERMES Experiment at DESY－HERA

E_e = 27.6 GeV



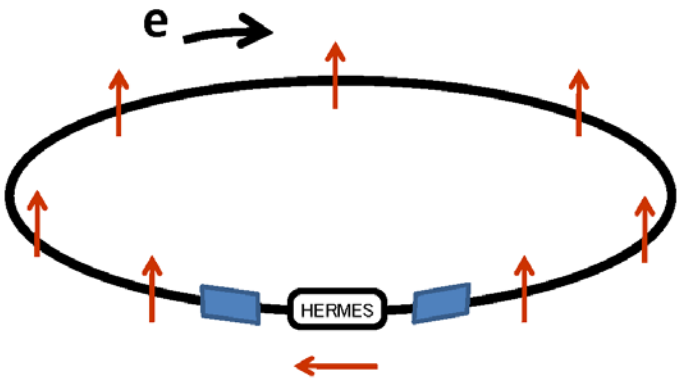
< 170 mrad horizonatally, 40-140 mrad vertically

Transversely polarized <u>proton</u> target $P = 0.713 \pm 0.063$

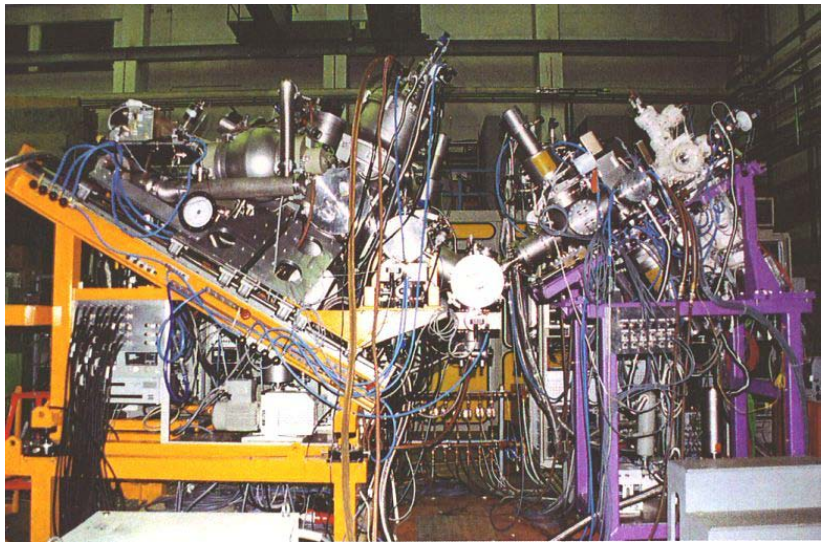
Pion, Kaon, Proton Identification with RICH

Polarized beam and polarized internal gas target

Polarized electron (positron) beam



Polarized internal gas targets



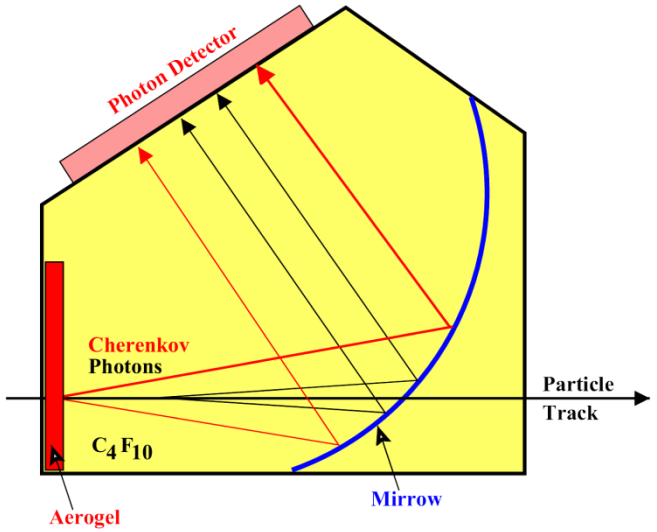
Hadron Identification

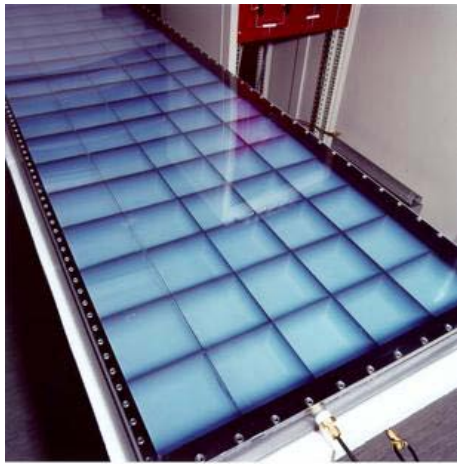
RICH

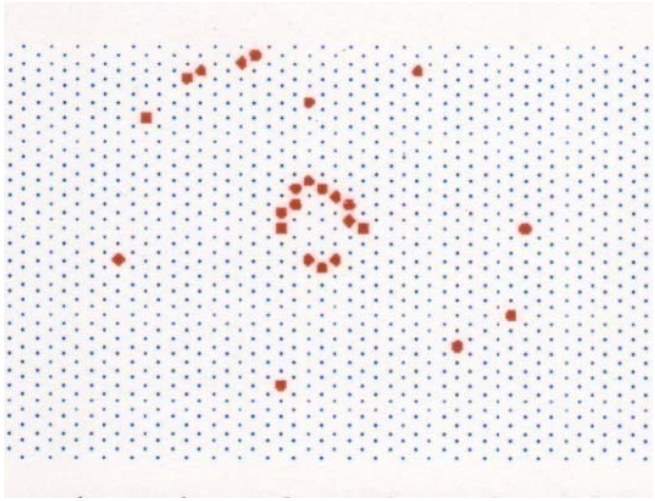
radiators: Aerogel, C_4F_{10}

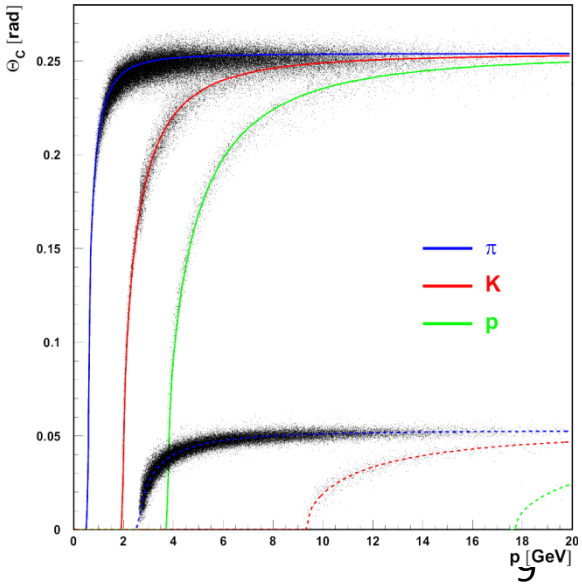
n = 1.03, 1.0014

2 – 15 GeV/c



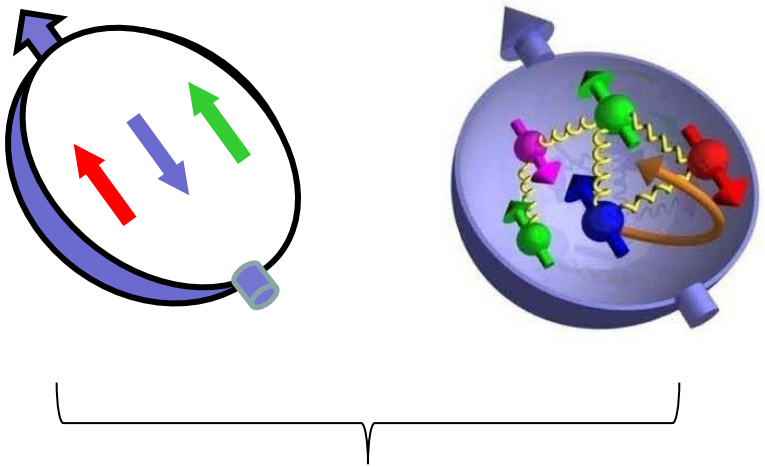






3. Longitudinal Spin Structure of the Nucleon

Spin Structure of the Nucleon



Polarized nucleon

・Longitudinal Spin

1st moment. Integration of $g_1^d(x)$ over x

Physics of 1st moment

Integration over *x* from 0 to 1

nth moment

$$\int_0^1 dx\ x^{n-1} F_1(x,Q^2)$$

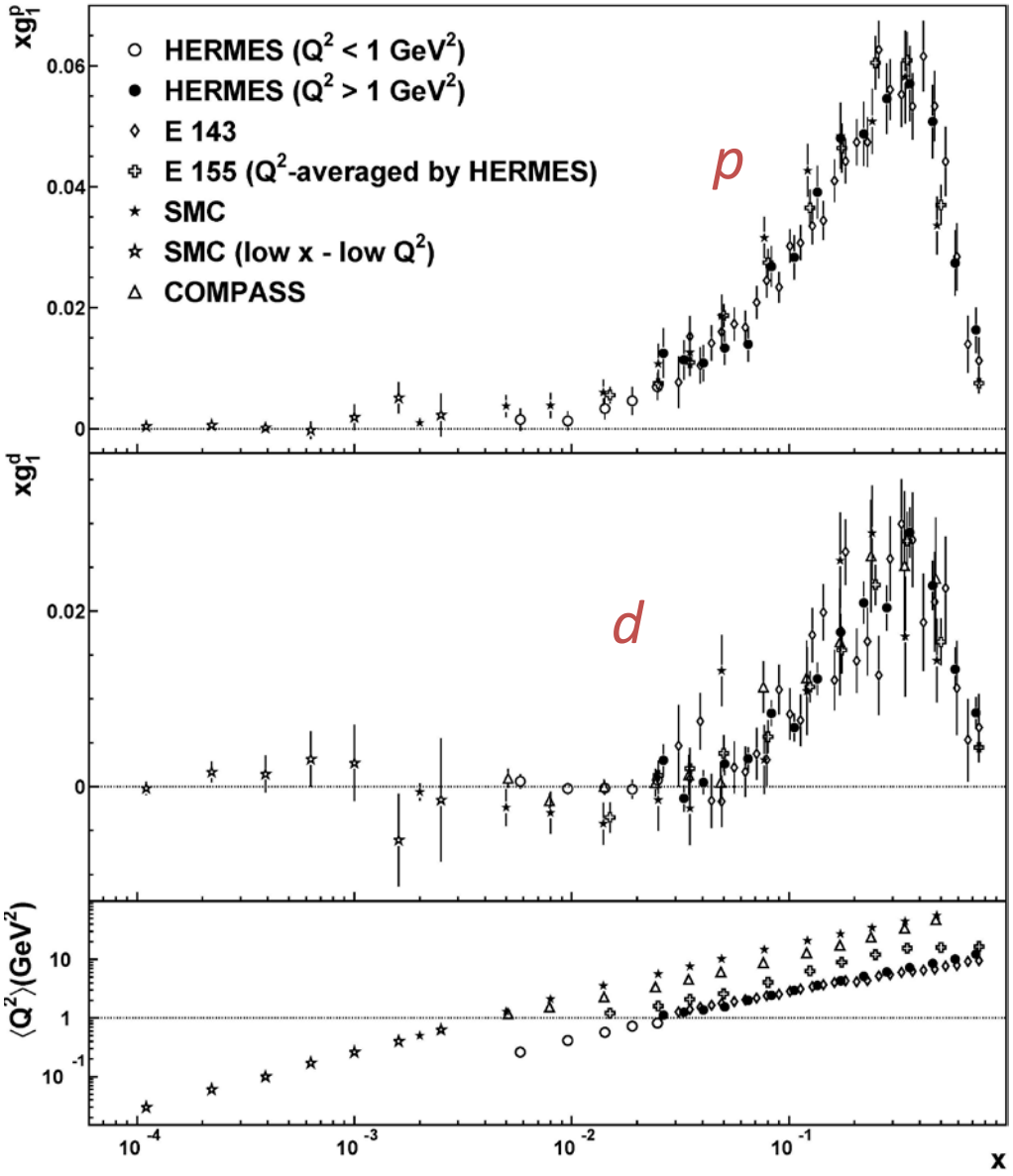
The 1st moment is the quantity we like to determine

$$\int_0^1 dx\ F_1(x,Q^2)$$

Example: Violation of Gottfried Sum Rule: NMC

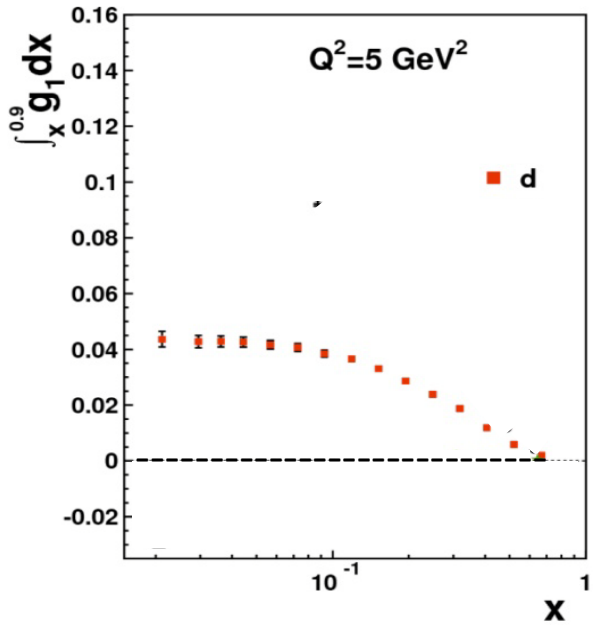
$$\int_0^1 dx\ g_1(x,Q^2), \qquad \int_0^1 dx\ u(x,Q^2), \quad \ldots$$

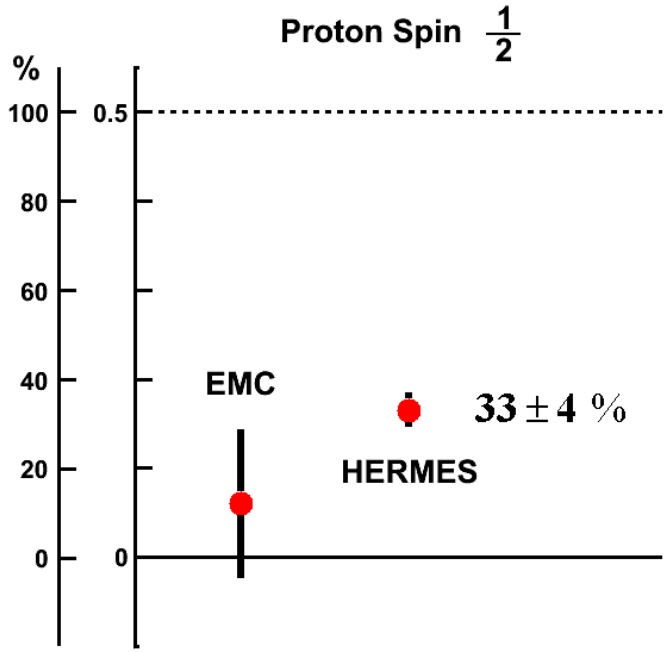
Analysis of Quark Spin Contribution to the Nucleon Spin


xg_1^p
HERMES ($Q^2 < 1$ GeV^2)
HERMES ($Q^2 > 1$ GeV^2)
E 143
E 155 (Q^2-averaged by HERMES)
SMC
SMC (low x - low Q^2)
COMPASS
p
xg_1^d
d
$\langle Q^2 \rangle$(GeV^2)
x

The 1st moment

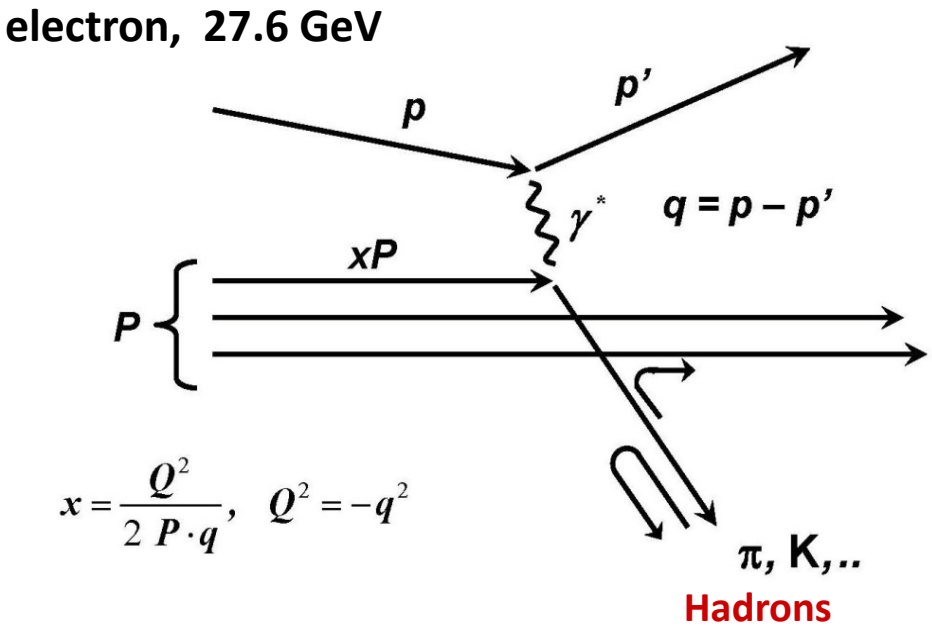
$$\frac{1}{2}\int_0^1 \mathbf{dx}\ (\mathbf{u}^{\uparrow}(\mathbf{x})-\mathbf{u}^{\downarrow}(\mathbf{x}))+(\mathbf{d}^{\uparrow}(\mathbf{x})-\mathbf{d}^{\downarrow}(\mathbf{x}))+(\mathbf{s}^{\uparrow}(\mathbf{x})-\mathbf{s}^{\downarrow}(\mathbf{x})) \;=\; \frac{1}{2}(\Delta\mathbf{u}+\Delta\mathbf{d}+\Delta\mathbf{s})$$





Quark spin contributions to the proton spin is 33 ± 4 %

4. Azimuthal Asymmetries with hadron productions

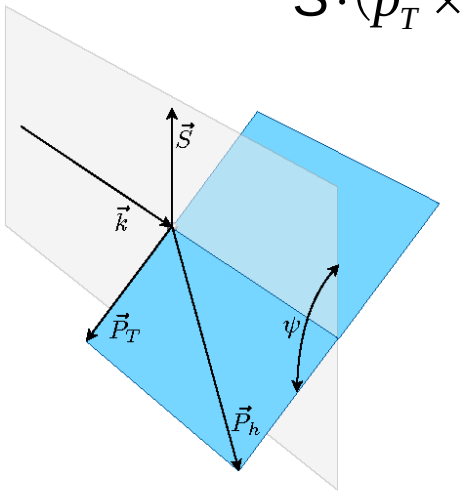


Azimuthal Angle Dependence

$l\,\mathrm{P}^{\uparrow} \rightarrow h\,X$

Hadron <u>inclusive</u> measurements

$\mathrm{S}\cdot(p_T \times \mathrm{k})$



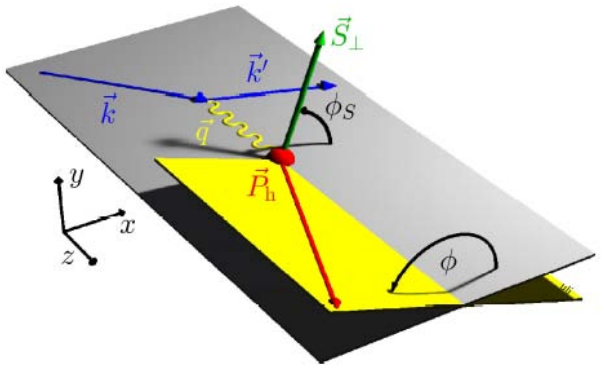
$$d\sigma = d\sigma_{UU}\left[1 + S_T A_{UT}^{\sin\psi}\sin\psi\right]$$

$$A_N \equiv \frac{\int_{\pi}^{2\pi} d\psi\, d\sigma - \int_{0}^{\pi} d\psi\, d\sigma}{\int_{\pi}^{2\pi} d\psi\, d\sigma + \int_{0}^{\pi} d\psi\, d\sigma} = -\frac{2}{\pi} A_{UT}^{\sin\psi}$$

Phys. Lett. B 728 (2014) 183

$l\,\mathrm{P}^{\uparrow} \rightarrow l'\,h\,X$

Electron - hadron coincidence measurements:
semi-inclusive measurements



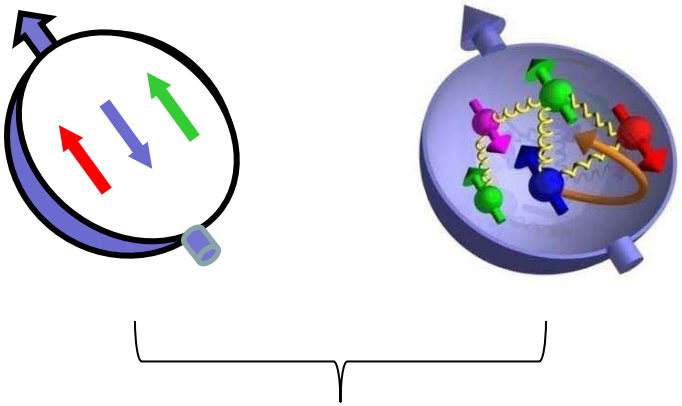
$\phi - \phi_s$, $\phi + \phi_s$

Sivers asymmetry, Collins asymmetry

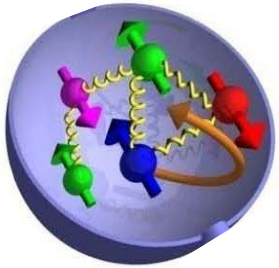
Extraction of Sivers Asymmetry

Phys. Rev. Lett. 103 (2009)152002

Polarized and unpolarized nucleon



Polarized nucleon



Unpolarized nucleon

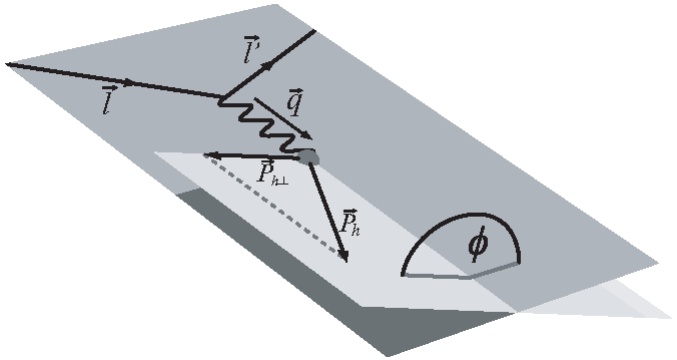
Correlation between Quark Spin and its Transverse Momentum in Unpolarized nucleon

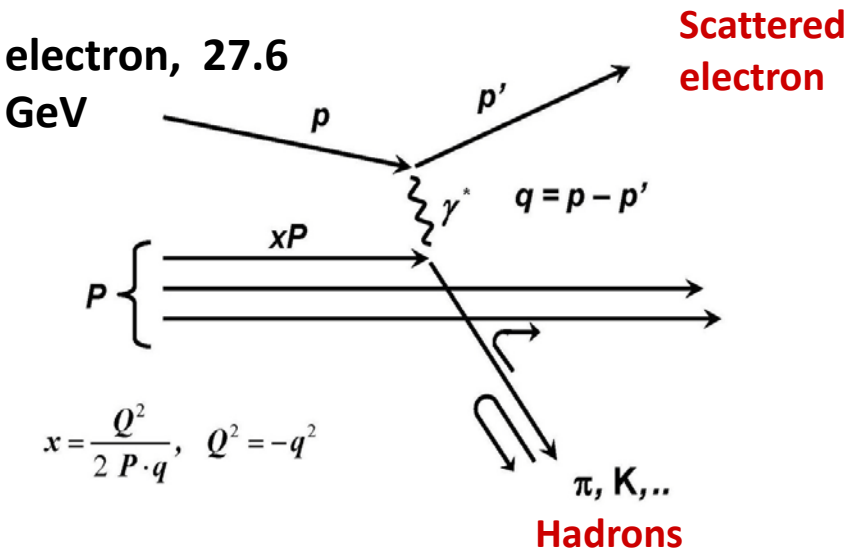
Spin-orbit interaction

Extraction of Azimuthal Angle Dependence with Unpolarized Targets

Azimuthal distributions of charged hadrons, pions, and kaons produced in deep-inelastic scattering off unpolarized protons and deuterons
A. Airapetian et al., HERMES, Phys. Rev. D 87 (2013) 012010

Azimuthal Angle ϕ





HERMES can perform 5 dimensional analysis

x, y (6bin), z, $P_{h\perp}$ (7bin), ϕ (12bin)

Typical cuts when electron is detected:

$Q^2 > 1\,GeV^2$, $W > 3.3$ GeV,

$0.023 < x < 0.6$, $0.2 < y < 0.85$

$z > 0.2$, $x_F > 0.2$, $1 < P_h < 15$ GeV

$$d\sigma_{UU} \equiv \frac{\mathrm{d}^5\sigma_{UU}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = 2\pi\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\{F_{UU,T}+\epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\,F_{UU}^{\cos\phi}\cos\phi + \epsilon F_{UU}^{\cos 2\phi}\cos 2\phi\}.$$

$$F_{UU}^{\cos 2\phi} \propto -\sum_q [h_1^{\perp,q}(x, p_T^2) \otimes w_1\, H_1^{\perp,q}(z, k_T^2)]$$

Boer-Mulders Distribution Function,
Collins Fragmentation Function

Correlation between transverse spin and
transverse motion of quarks in unpolarized nucleon

$$F_{UU}^{\cos\phi} \propto -\frac{M}{Q}\sum_q [h_1^{\perp,q}(x, p_T^2) \otimes w_3\, H_1^{\perp,q}(z, k_T^2)]$$

$$-\frac{M}{Q}[\, f_1^q(x, p_T^2) \otimes w_4\, D_1^q(z, k_T^2)]$$

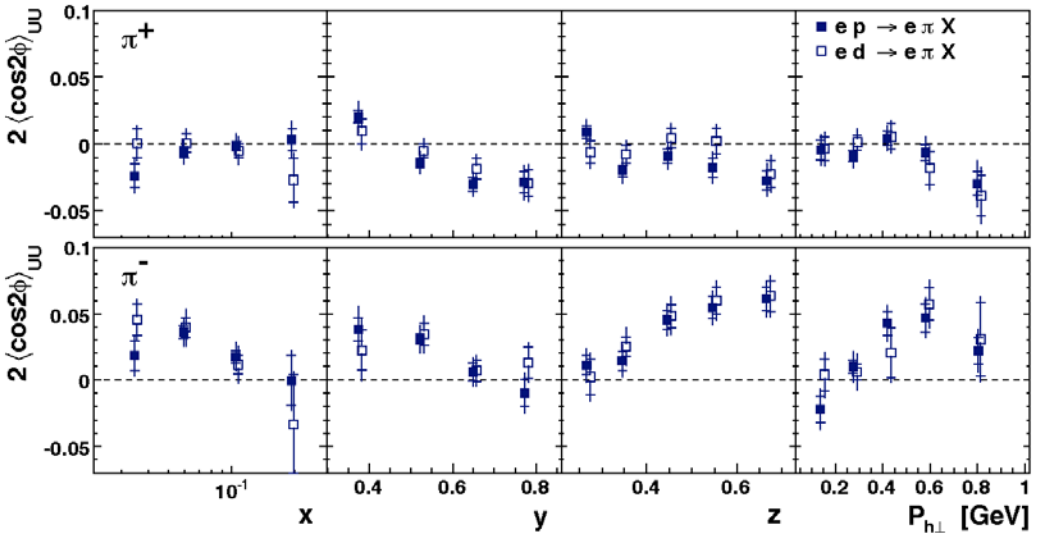
Cahn Effect

Average transverse momentum of
unpolarized quarks in unpolarized
nucleon

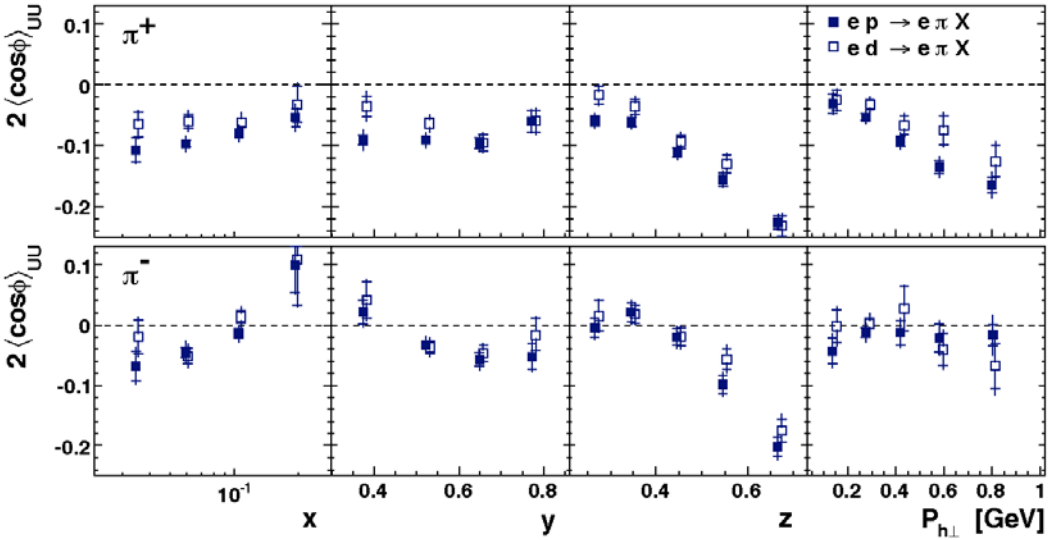
Proton and Deuteron Targets

$\pi^{\pm}$

$\cos 2\phi$



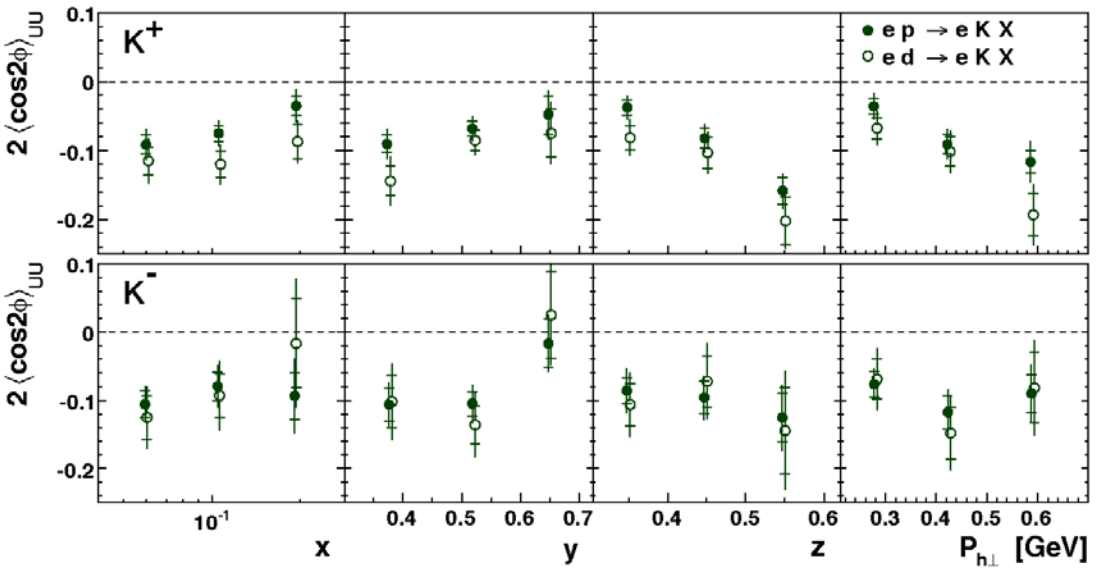
$\cos \phi$



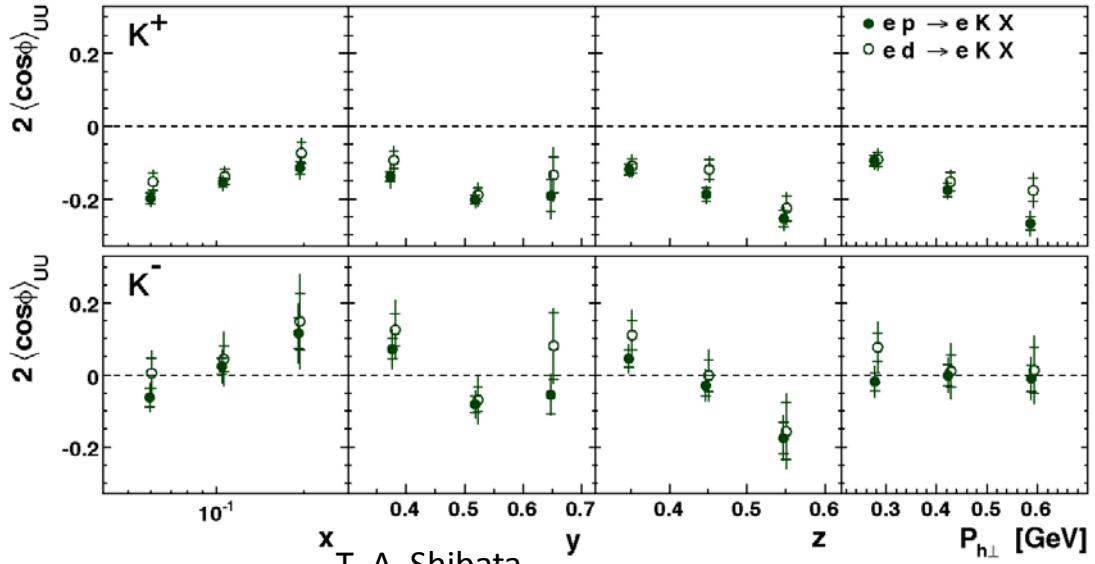
$K^{\pm}$

Proton and Deuteron Targets

cos 2ϕ



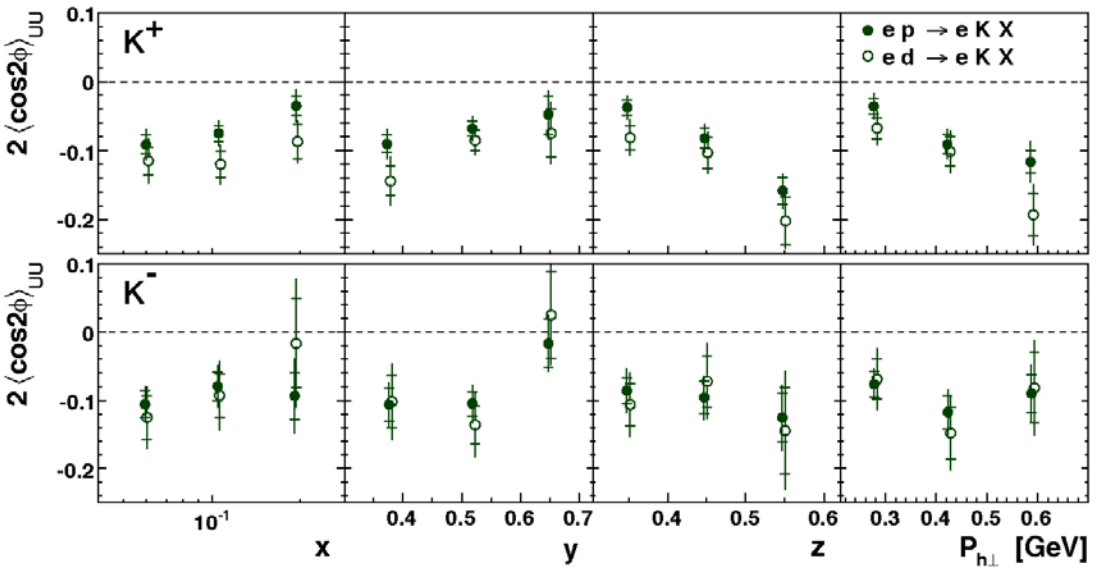
cos ϕ



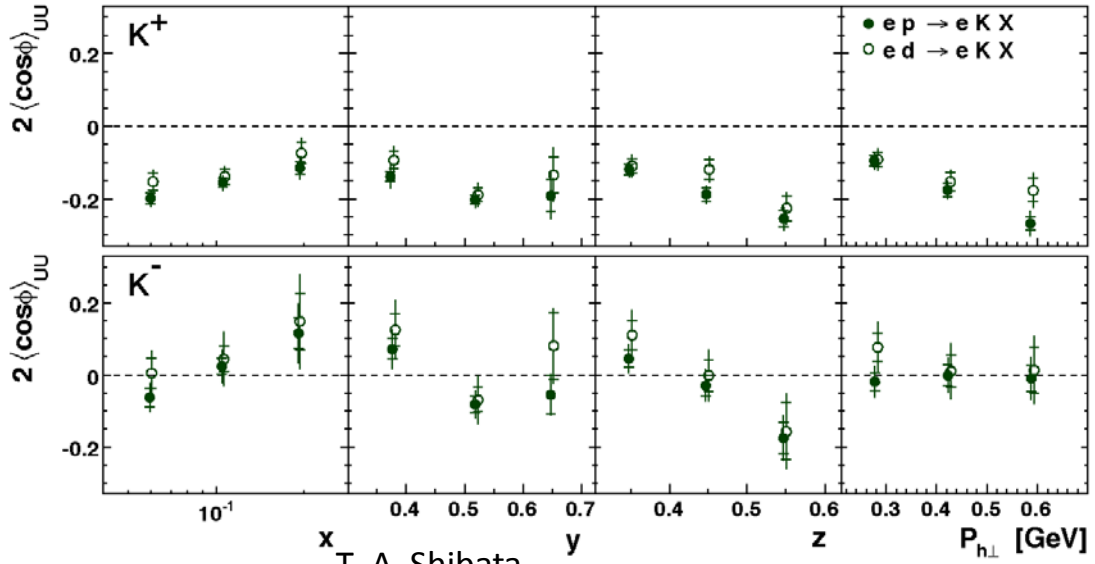
$K^{\pm}$

Proton and Deuteron Targets

cos 2ϕ



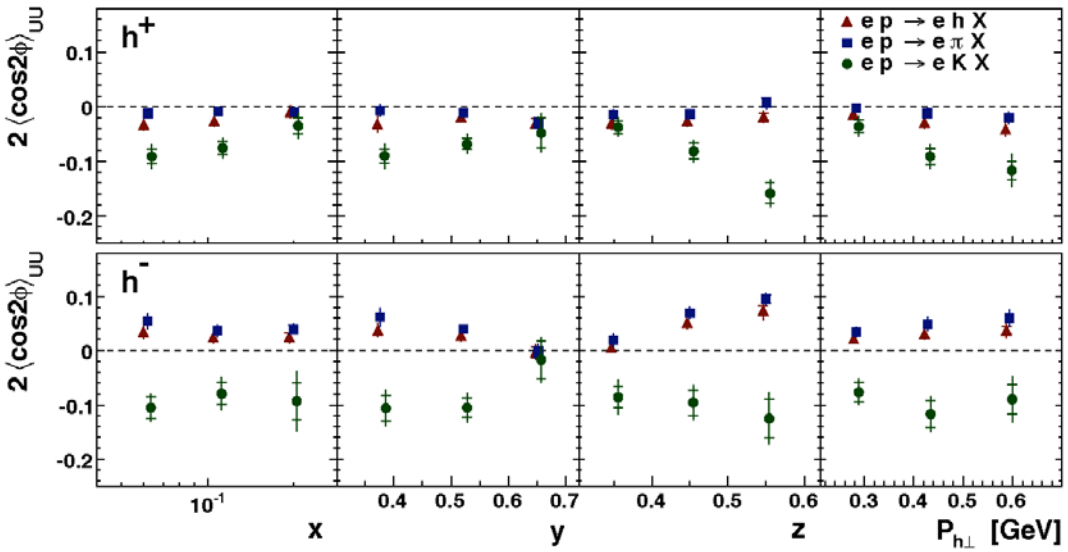
cos ϕ



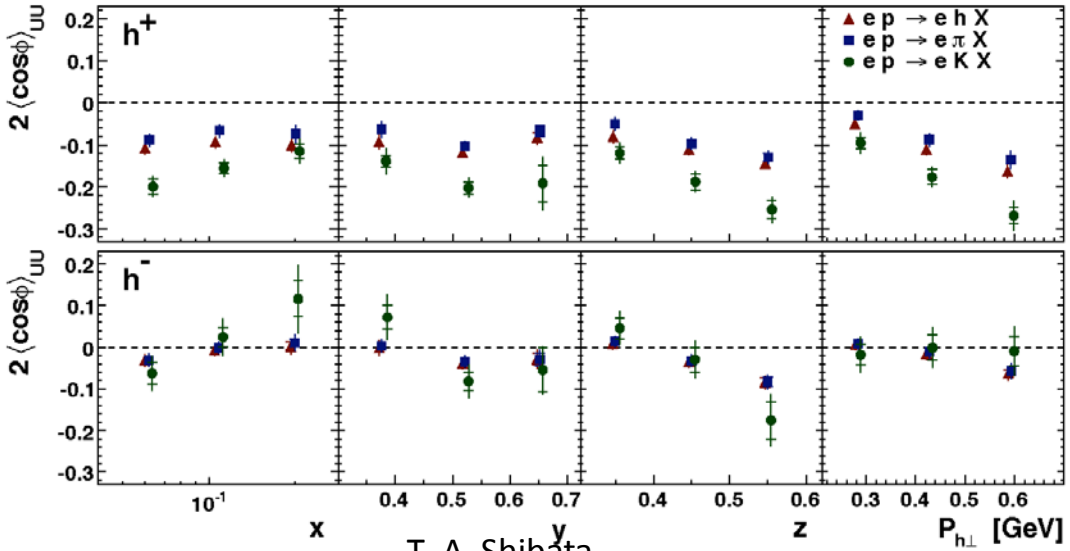
$\pi^{\pm}$, $K^{\pm}$ comparison

Proton Target

$\cos 2\phi$



$\cos \phi$



-- Other program of HERMES is deep virtual Compton scattering and exclusive meson production for Generalized Parton Distributions(GPD)

Recent publications by HERMES

Transverse polarization of Lambda hyperons from quasireal photoproduction on nuclei
A. Airapetian et al, Phys. Rev. D 90 (2014) 072007

Spin density matrix elements in exclusive omega electroproduction on ^{1}H and ^{2}H targets at 27.6 GeV beam energy
A. Airapetian et al, Eur. Phys. J. C 74 (2014) 3110

Reevaluation of the parton distribution of strange quarks in the nucleon
A. Airapetian et al, Phys. Rev. D 89 (2014) 097101

Beam-helicity asymmetry in associated electroproduction of real photons ep → epγπN in the Δ-resonance region *A. Airapetian et al, JHEP01(2014)077*

5. Summary

-- HERMES is a deep inelastic scattering experiment with gas targets internal to the DESY-HERA electron/positron beam

-- Electron/positron beam energy is 27.6 GeV. HERMES spectrometer has wide acceptance and a RICH for hadron identification

-- Longitudinal spin structure of the proton
Quark contributions to the proton spin, 33+-4%.

-- Transverse spin structure and transverse momentum dependent structure functions are also studied.

Azimuthal asymmetry with hadron productions.

Transversely polarized target or unpolarized target is used.

-- Data on Boer-Mulders effect and Cahn effect are obtained in 4 dimension..

-- Other program of HERMES is deeply virtual Compton scattering and exclusive meson production for GPD studies.

-- Further analyses are in progress.