# HERMESによる核子のスピン構造測定結果と他の高エネルギー反応過程へのインパクト

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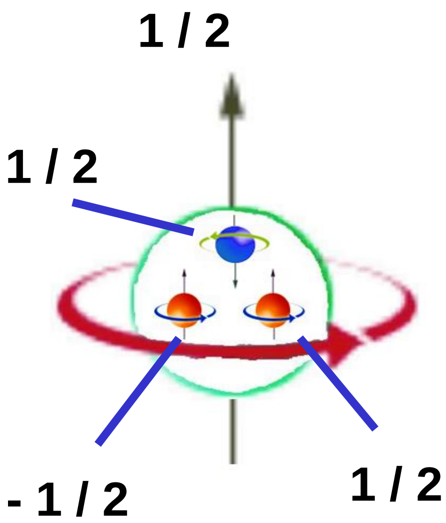
Contents:

- Deep Inelastic Scattering: lepton scattering and pp collision
- Unpolarized and Polarized Gluon Distribution
- Quark Helicity Distribution – Flavor Separation
- Physics with Transverse Targets
- Impact on other high energy reaction processes

# Proton Spin from Viewpoint of Quark Flavors




## SU(6) Quark Wave Functions of Baryons

**Sum of Spins of u u d Quarks = Spin of Proton**

$$\frac{1}{2} + \frac{1}{2} + \left(-\frac{1}{2}\right) = \frac{1}{2}$$

$$\Uparrow + \Uparrow + \Downarrow = \Uparrow$$

$$\frac{1}{2} = \frac{1}{2}\sum_q \left(\underline{\Delta u + \Delta d} + \Delta s\right) + L_q + \Delta G + L_G$$

**HERMES:**

- **Inclusive Deep Inelastic Scattering, $A_1(x)$, $g_1(x)$**

- **Semi-inclusive Deep Inelastic Scattering – Hadron Identification**
  **Flavor Decomposition**

$$\Delta u(x), \Delta d(x), \Delta \bar{u}(x), \Delta \bar{d}(x), \Delta s(x)$$

- **Large $p_t$ hadrons**: $\Delta g(x)$

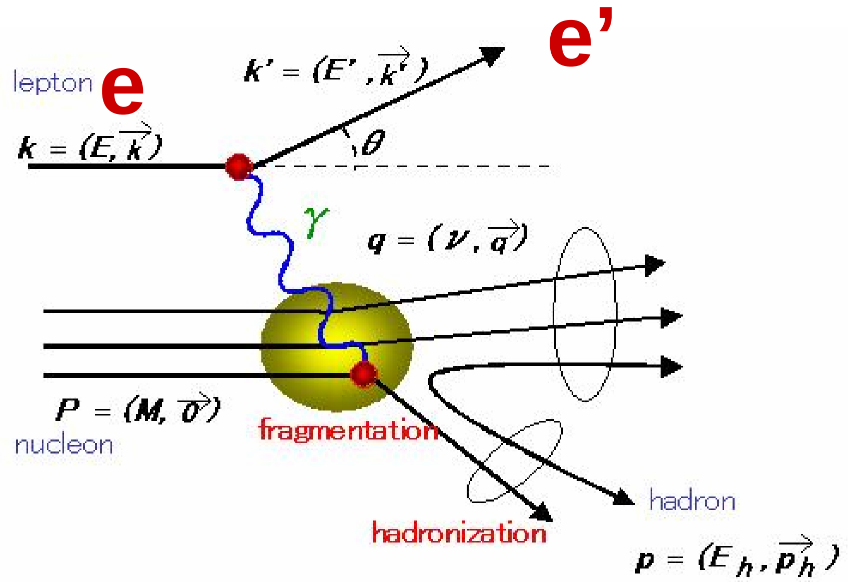
- **Deeply Virtual Compton Scattering and**
  **Exclusive meson productions:**
  **Generalized Parton Distribution → $J_q$**

- **Single spin asymmetry, transversely polarized target:**
  **Sivers effect - *L*q, orbital angular momentum**
  **Collins effect - New structure function**

→ **Impact on RHIC, J-lab, COMPASS, Polarized Drell-Yan, Neutrino Scattering Experiments etc.**

# Electron- Nucleon Deep Inelastic Scattering

**Bjorken $x$** $\quad x_B = \dfrac{-q^2}{2q \bullet P} = \dfrac{Q^2}{2M\nu}$




**Inclusive measurement, e'**

$$\sigma(x_B) \propto F_2(x_B) = x_B \sum_q e_q^2 q(x_B)$$

**Semi-inclusive measurement,**
**e' and $\pi$,K,p,$\bar{\text{p}}$ ...**

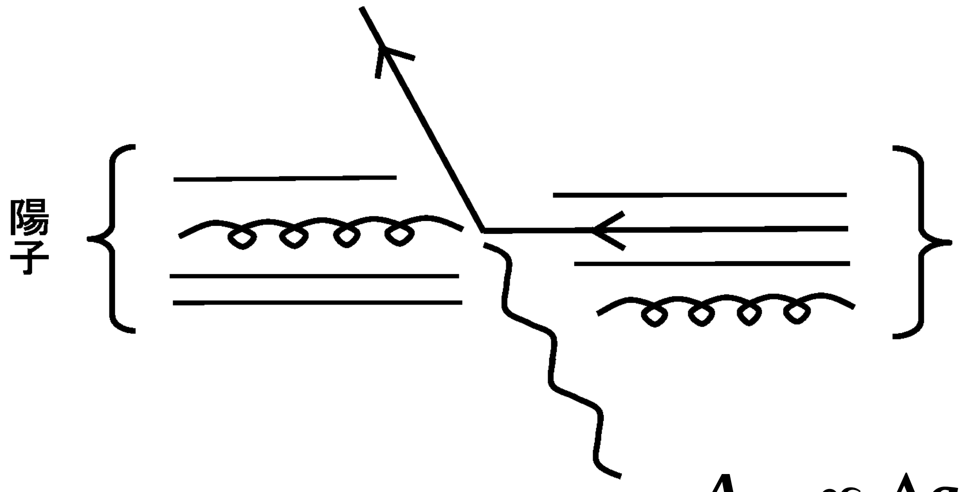
$$\sigma_h(x_B, z) \propto x_B \sum_q e_q^2 \, q(x_B) \, D_q^h(z)$$

**( quark distribution ) x**
**( fragmentation function )**

$$z = E_h / \nu$$

**Fragmentation in $e^+e^-$ annihilation**

# pp collisions




$$A_{LL} \propto \Delta g(x_1)\ \underline{g_1(x_2)}$$

gg, gq… collisions

measured as a function of $\mathbf{p_t}$

$x_{\mathbf{bj}}$, $z$ integrated

two $x_{\mathbf{bj}}$'s involved in each event

# *x resolution*

**Lepton scattering (*l*, *l’ h*)**

**$l'$ detected -- $x$ is determined event by event**

**$l'$ undetected, only *h* is detected -- $x$ is spread and is compared with MC**

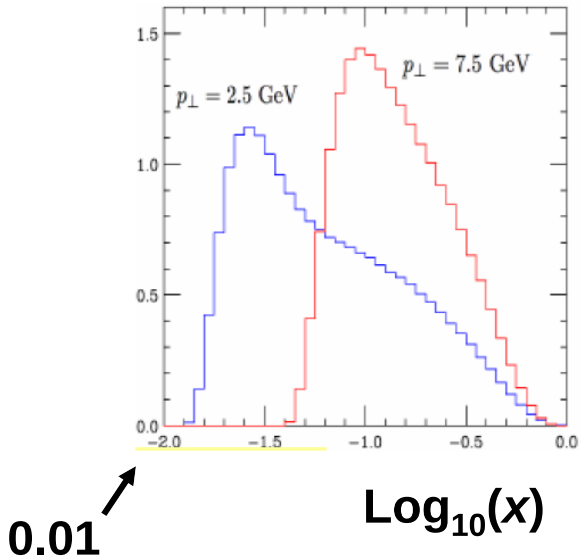
**pp collision**

**jet – jet coincidence -- $x_1$, $x_2$ are determined event by event**

**jet – prompt photon coincidence -- ’ ’**

**inclusive hadron measurement -- $x$ is spread and is compared with MC**

$$\mathrm{pp} \rightarrow \pi^0 X$$




**Unfold, or assume a functional form and compare to the data**

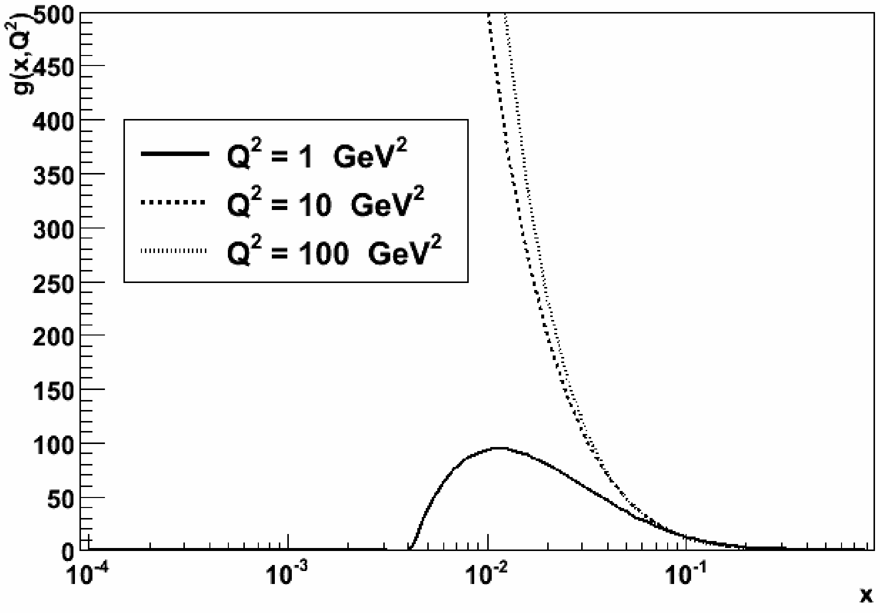
# Gluon Distributions
# - Unpolarized and Polarized

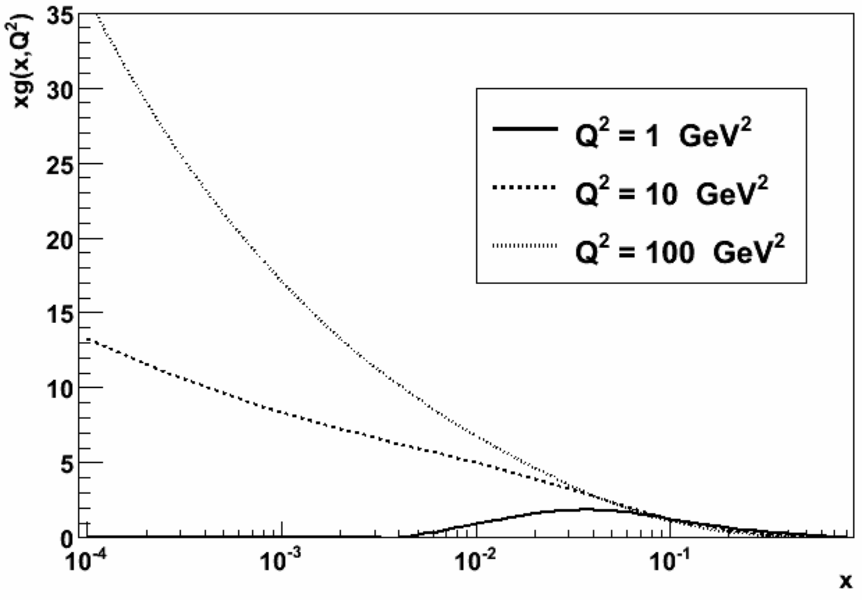
DURHAM HEP Databases, online plot
http://durpdg.dur.ac.uk/hepdata/pdf3.html

S. Kretzer, H.L. Lai, F.I. Olness, W-K. Tung
Phys.Rev. D69 (2004) 114005

CTEQ

$g(x)$ $\qquad\qquad$ $x\,g(x)$

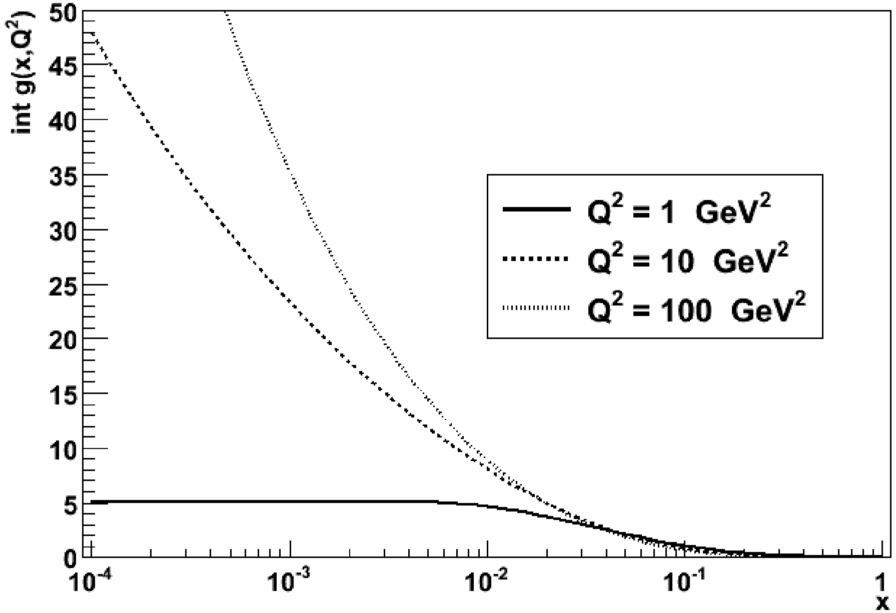


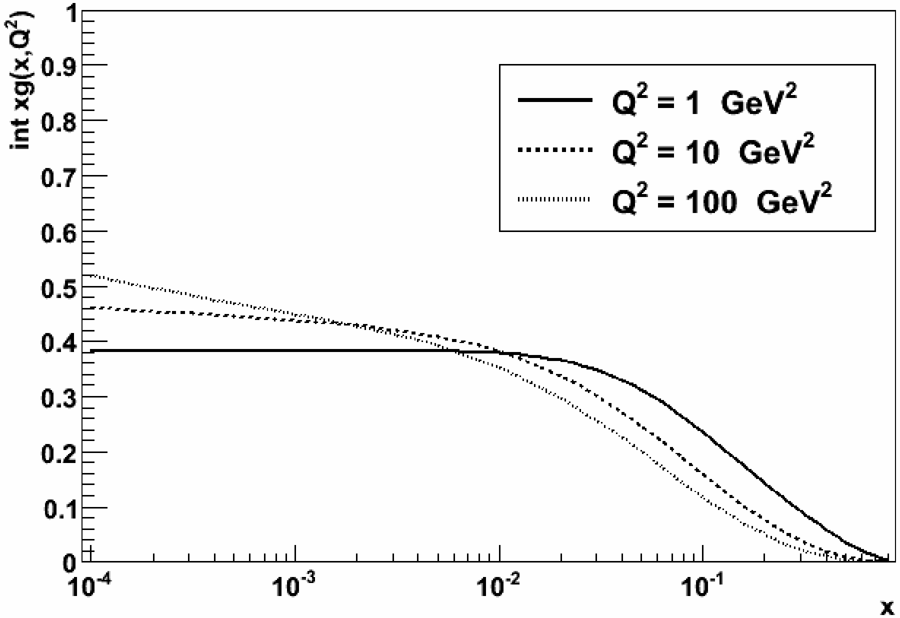




$$\int_{(\log x)=-\infty}^{(\log x)=0} x\,g(x)\;d(\log x) = \int_0^1 x\,g(x)\frac{1}{x}dx = \int_0^1 g(x)\,dx$$

Linear momentum

First moment $\int_x^1 g(x)\,dx$ Second Moment $\int_x^1 x\,g(x)\,dx$




$$|\Delta g(x)| \le g(x)$$

$$|\int_0^1 \Delta g(x)dx| \le \int_0^1 |\Delta g(x)|\,dx \le \int_0^1 g(x)\;dx$$

$$\boldsymbol{\Delta g(x) = N\; x^{\alpha}\,(1-x)^{\beta}\; g(x)}$$

$\Delta g(x) \;\propto\; x^{\alpha} g(x)$ at $x \to 0$

$\Delta g(x)$

Lepton scattering

hadron pair production

charm-anticharm production

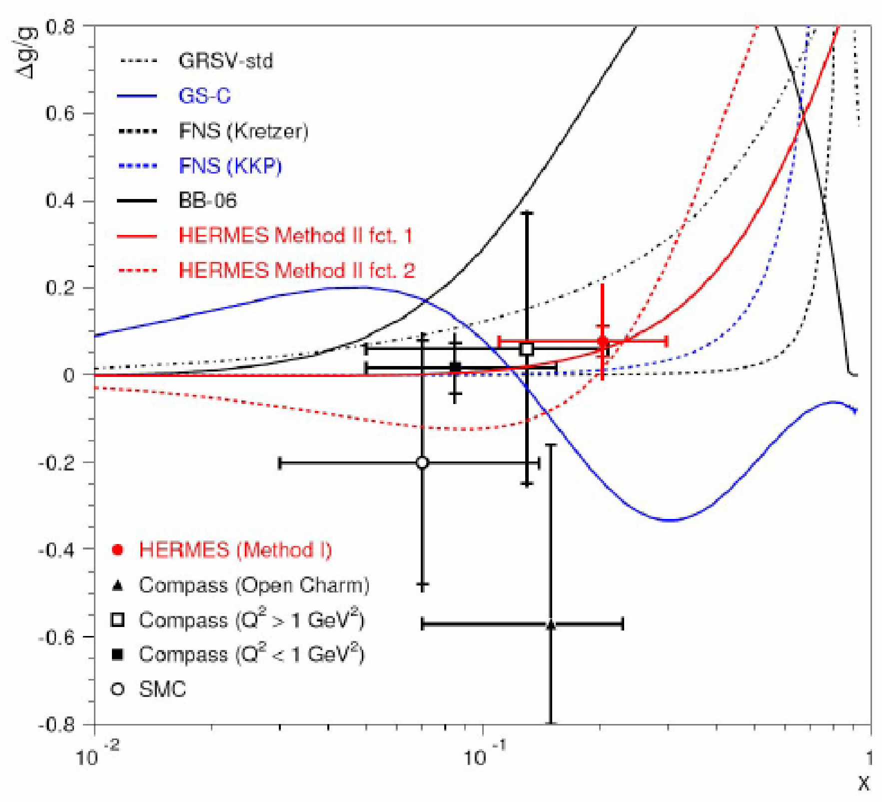
pp collisions

$\pi^0$ production

prompt photon production (gq $\rightarrow$ q$\gamma$)

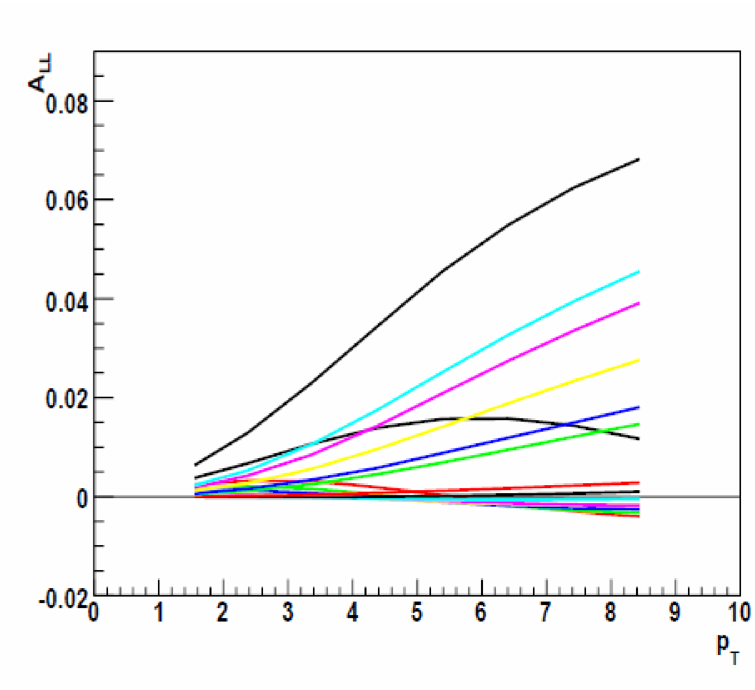
…

## $\Delta g(x)/g(x)$ from lepton scattering



$$\mathrm{pp} \rightarrow \pi^0 X$$

# pp collision




GRSV

$$\Delta g(x) = N\, x^{\alpha} (1-x)^{\beta}\, g(x)$$

$$\Delta q(x) = N'\, x^{\alpha'} (1-x)^{\beta'}\, q(x)$$

...

**12 parameters**

$\chi^2$ **increase by 1** $\leftrightarrow$ **one** $\sigma$

**PHENIX's error evaluation**
**different from AAC's approach**

## Helicity Distributions of Partons in the Nucleon

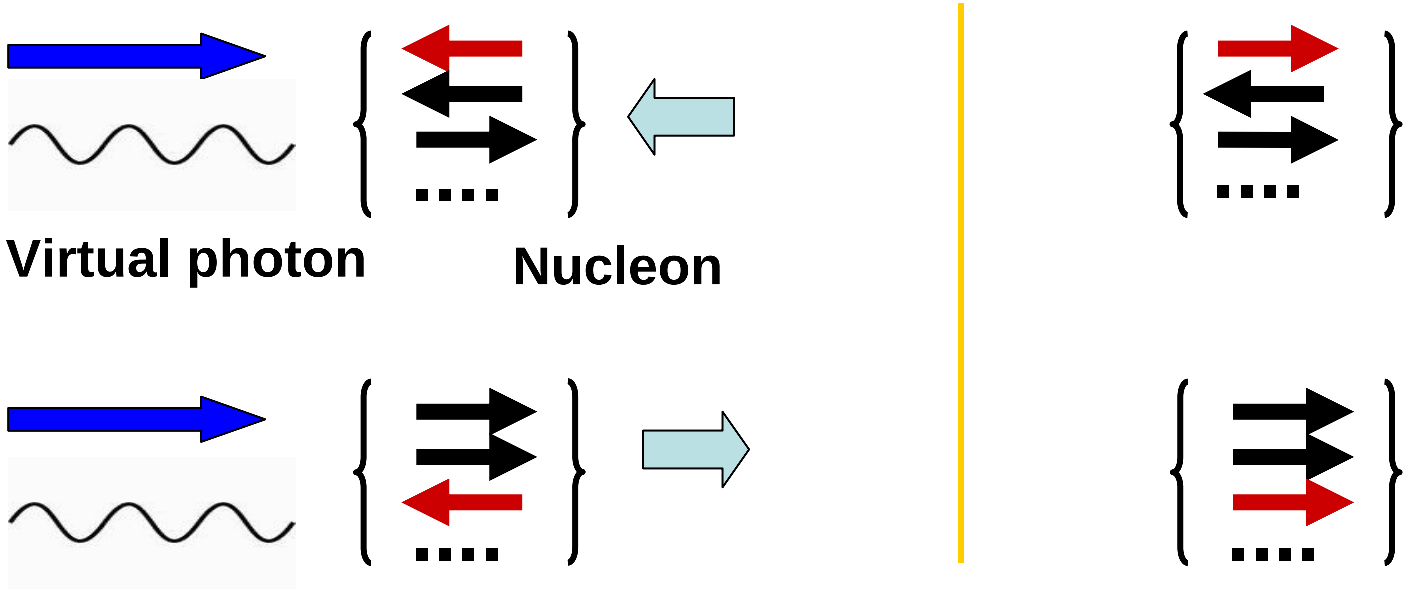
Contents:

- $\boldsymbol{A}_1$ and $\boldsymbol{g}_1$ Measurement
- Semi-inclusive Measurement of Hadrons with a precise PID
- Flavor Separation of Quark Helicity Distributions

## Double-spin asymmetry

$$\vec{e} + \vec{N} \rightarrow e' + X$$

**Beam and target, both polarized**




$$A_1(x,z) = \frac{\sigma_{\rightleftarrows}(x) - \sigma_{\rightrightarrows}(x)}{\sigma_{\rightleftarrows}(x) + \sigma_{\rightrightarrows}(x)}$$

# Proton Spin Problem

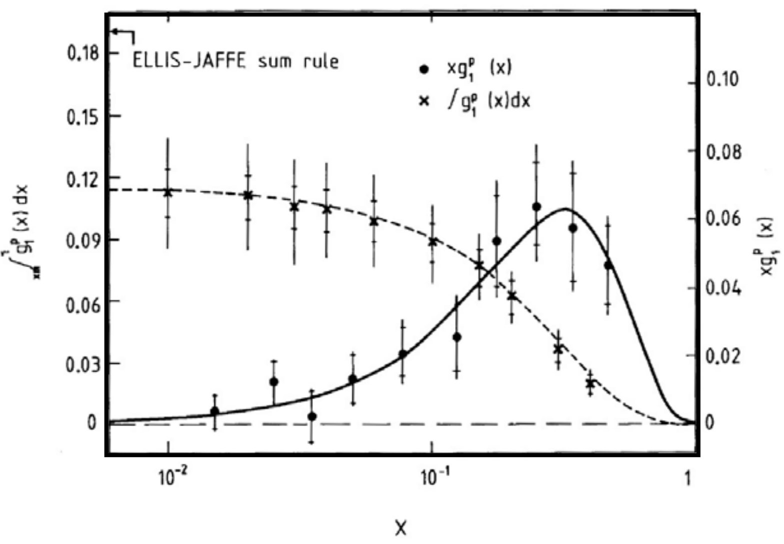
**EMC Experiment (1988)**

**EMC's Flavor Decomposition with First Moments**

$$\int_0^1 g_1^{p}(x_B)\, dx$$

$$\frac{1}{2}(\Delta u + \Delta d + \Delta s) = 0.06 \pm 0.047 \pm 0.068 \;\le\; \frac{1}{2}$$

$$(12 \pm 9 \pm 14)\%$$




**0.01 < $x_B$ < 0.6**

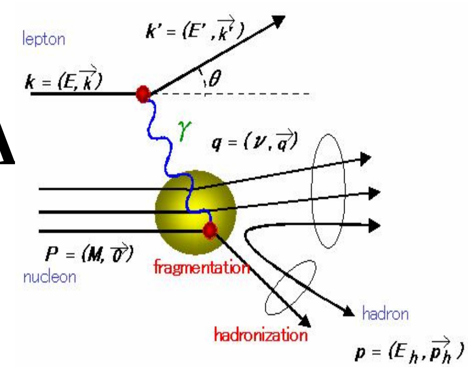
**'Quark spin contribution to the proton spin is small': Nucleon Spin Problem**

**SMC, SLAC, … 20 – 30 % of Nucleon Spin**

$$\frac{1}{2} = \frac{1}{2}(\Delta u + \Delta d + \Delta s) + L_q + S_g + L_g$$

# Main Features of HERMES：
# HERa MEasurement of Spin

1995 –2007 at DESY




- **Polarized Electron (Positron) Beam of HERA**
  **E = 27.6 GeV, P ≈ 60%**

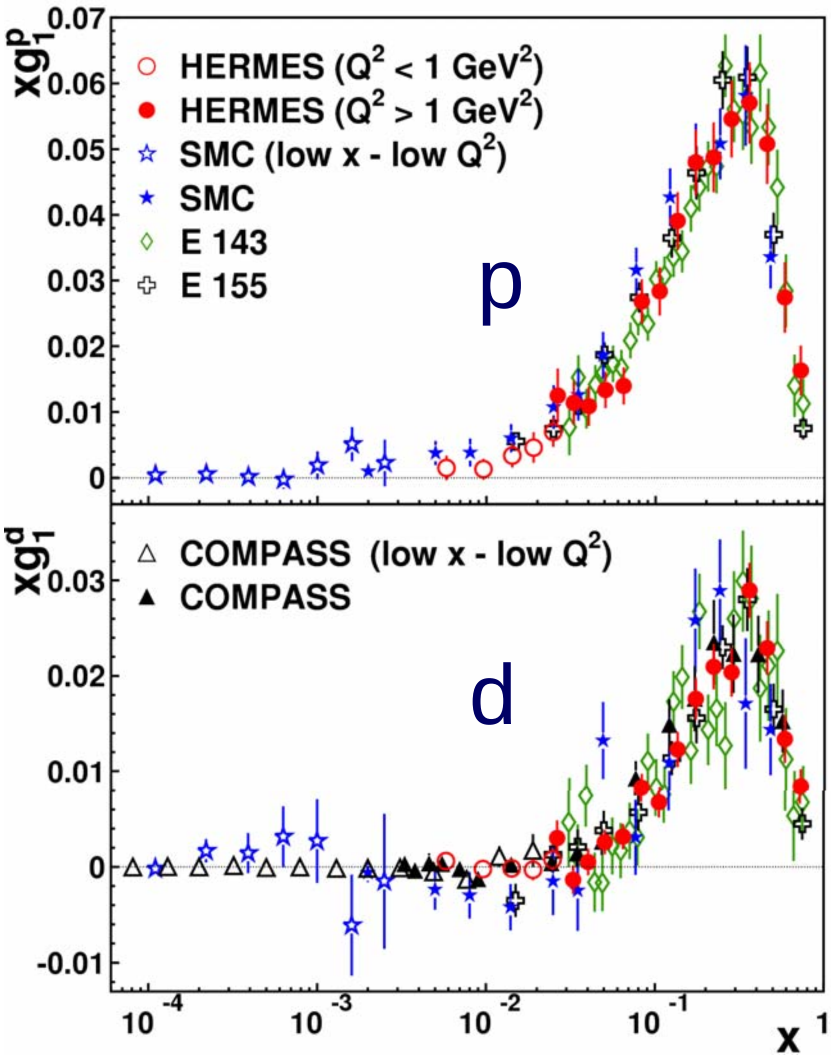
- **Internal Gas Targets**
  **Longitudinally polarized $^3$He, D, H** $\quad$ ***P*(H) 85%**
  **Transversely polarized H**
  **Unpolarized High Density Targets ($H_2$, $D_2$, He, $N_2$, Ne, Ar, Kr, Xe)**

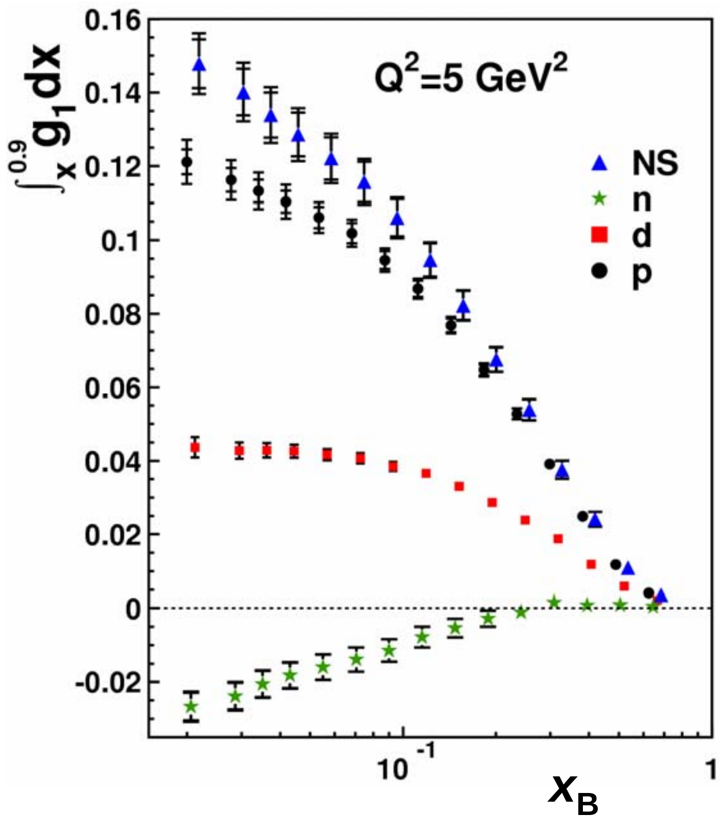
- **Semi-inclusive Measurement, Hadron Detection with a good PID of $\pi$, K, p**
  **Ring Imaging Cherenkov Counter （RICH)**

## Flavor Separation of Quark Helicity Distributions at HERMES

$$\Delta u(x),\ \Delta d(x),\ \Delta \bar{u}(x),\ \Delta \bar{d}(x),\ \Delta s(x)$$

# $g_1(x_B)$ from HERMES and other experiments




| | central value | uncertainties theor. | exp. | evol. |
|---|---|---|---|---|
| $a_0$ | 0.330 | 0.011 | 0.025 | 0.028 |
| $\Delta u + \Delta \bar{u}$ | 0.842 | 0.004 | 0.008 | 0.009 |
| $\Delta d + \Delta \bar{d}$ | -0.427 | 0.004 | 0.008 | 0.009 |
| $\Delta s + \Delta \bar{s}$ | -0.085 | 0.013 | 0.008 | 0.009 |

**Quark spin contributions to the nucleon spin, 33%**

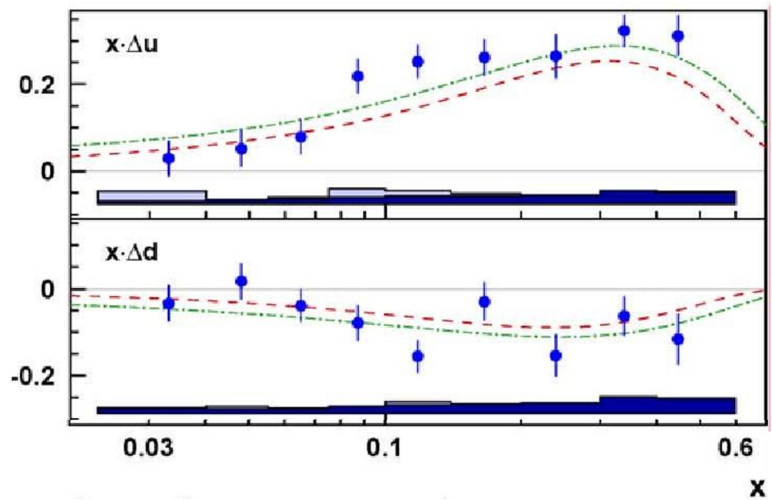
**Semi-inclusive measurement:** $e + \mathrm{N} \rightarrow e' + \pi^{+} + X, \quad \text{etc.}$ ($\mathrm{K}^{+}$)

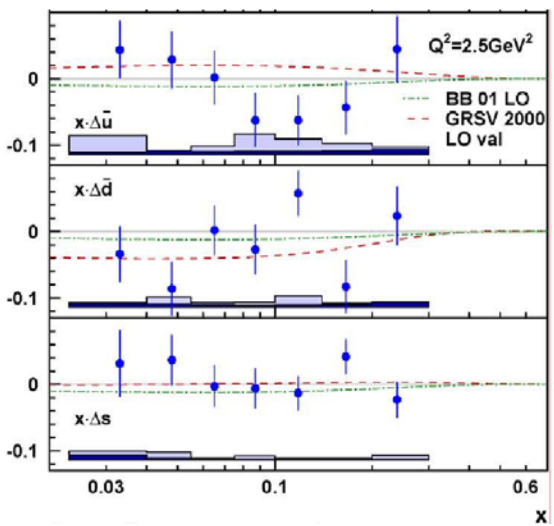
**RICH**

$$\begin{pmatrix} A^{\pi^+} \\ A^{\pi^-} \\ A^{\mathrm{K}^+} \\ A^{\mathrm{K}^-} \\ .. \end{pmatrix} = \begin{pmatrix} u \rightarrow \pi^{+}, & \\ \ldots & \\ & \\ & \end{pmatrix} \begin{pmatrix} \Delta u \\ \Delta d \\ \Delta s \\ \Delta \bar{u} \\ \Delta \bar{d} \\ .. \end{pmatrix}$$

$\Delta u$

$\Delta d$




$\Delta \bar{u}$

$\Delta \bar{d}$

$\Delta s$

**Result:**

$$\Delta u\,(x_{\mathrm{B}}) > 0$$
$$\Delta d\,(x_{\mathrm{B}}) < 0$$
$$\Delta \bar{q}\,(x_{\mathrm{B}}) \approx 0$$

- x bin by bin analysis
- First moment from neutron lifetime or hyperon decay, not used
- No functional forms as a function of x are assumed
- Helicity conservation not assumed ($\Delta q \rightarrow 1$ when $x_{\mathrm{B}} \rightarrow 1$)

## Conclusions of this part

- HERMES is a Deep Inelastic Scattering Experiment at HERA-DESY with 27.6 GeV Electron (Positron) Beam and Polarized Internal Gas Targets

- $\pi$, $K$, $p$ Identification with RICH

- $A_1(x)$, $g_1(x)$, and $A_1^h(x)$ are measured

- Flavor Separation of Quark Helicity Distribution $\Delta q(x)$ from Semi-Inclusive Measurement with $\pi$, $K$ Identification for the First Time, an Independent Extraction from data of DIS

- Positive $u$, negative $d$ Distributions, Sea Quarks nearly zero

## Further new approaches – Access to total angular momentum of quark $J_q$

$$\frac{1}{2} = \underbrace{\frac{1}{2}(\Delta u + \Delta d + \Delta s) + L_q}_{J_q} + \underbrace{S_g + L_g}_{J_g}$$

**Ji's sum rule** PRL 78 (1997) 610

$$J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx\, x[H_q(x,\xi,t) + E_q(x,\xi,t)],$$

$$J_g = \ldots$$

**Generalized Parton Distributions (GPD)**

↑

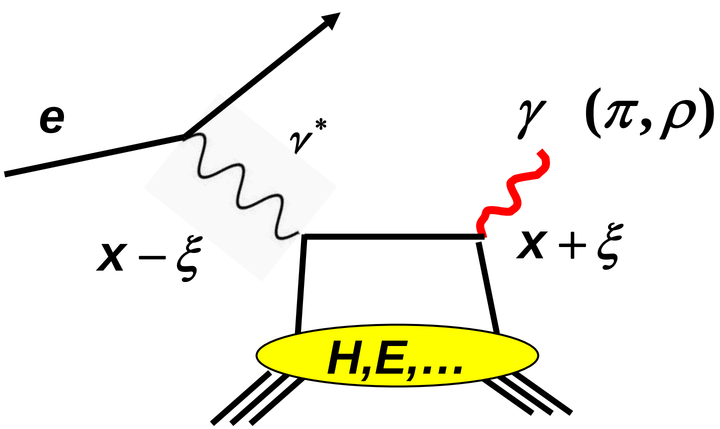
**Structure Functions**

↑

**Form Factors**

**How to measure**

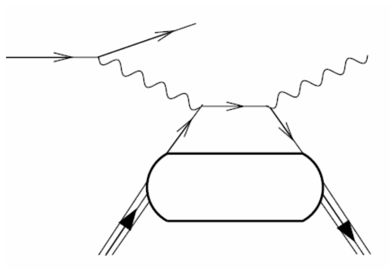
| |
|---|
| **Deeply Virtual Compton Scattering (DVCS)**<br>**and exclusive meson productions** |

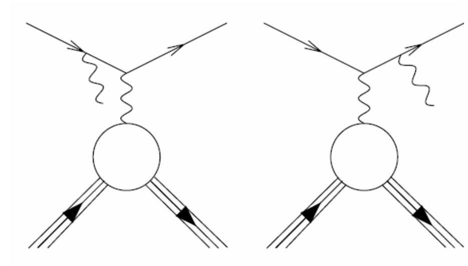



Cross section of DVCS is measured at H1 and ZEUS

Interference with Bethe-Heitler is measured at HERMES

## Interference between

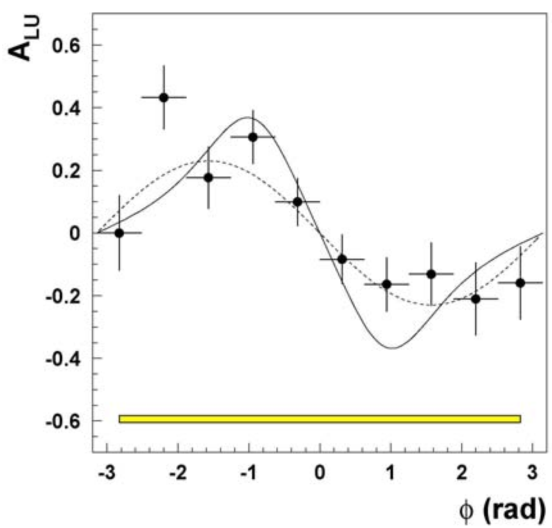


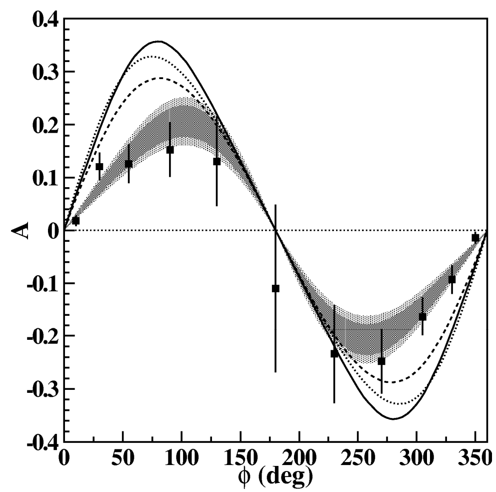


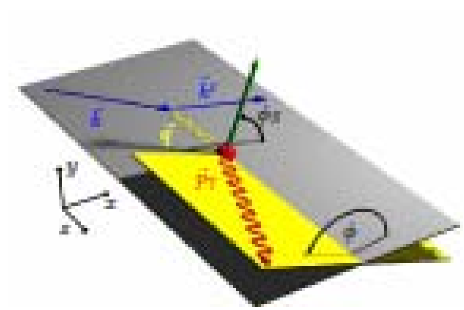
**Deeply Virtual Compton Scattering** **Bethe-Heitler**

**HERMES** **CLAS at JLab**

$A_{LU}$



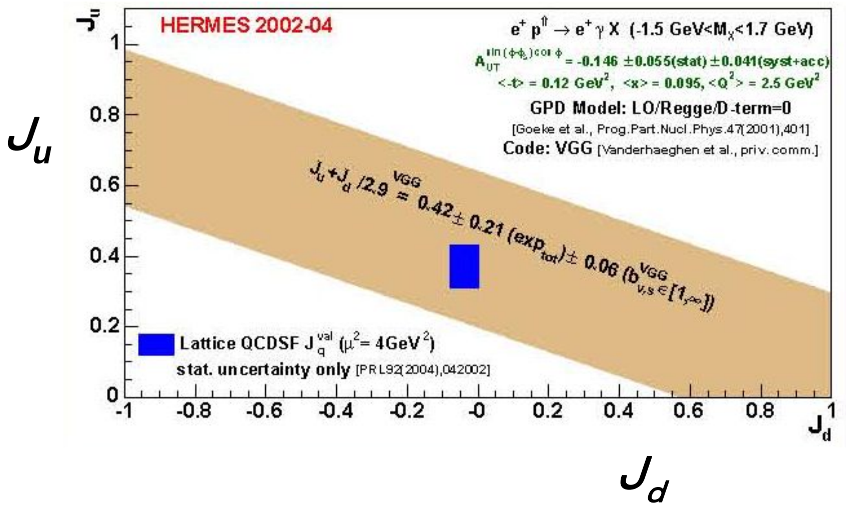
$\phi$ $\phi$

**Beam Spin Asymmetry: $A_{LU}$**

**Beam Charge Asymmetry: $A_c$**

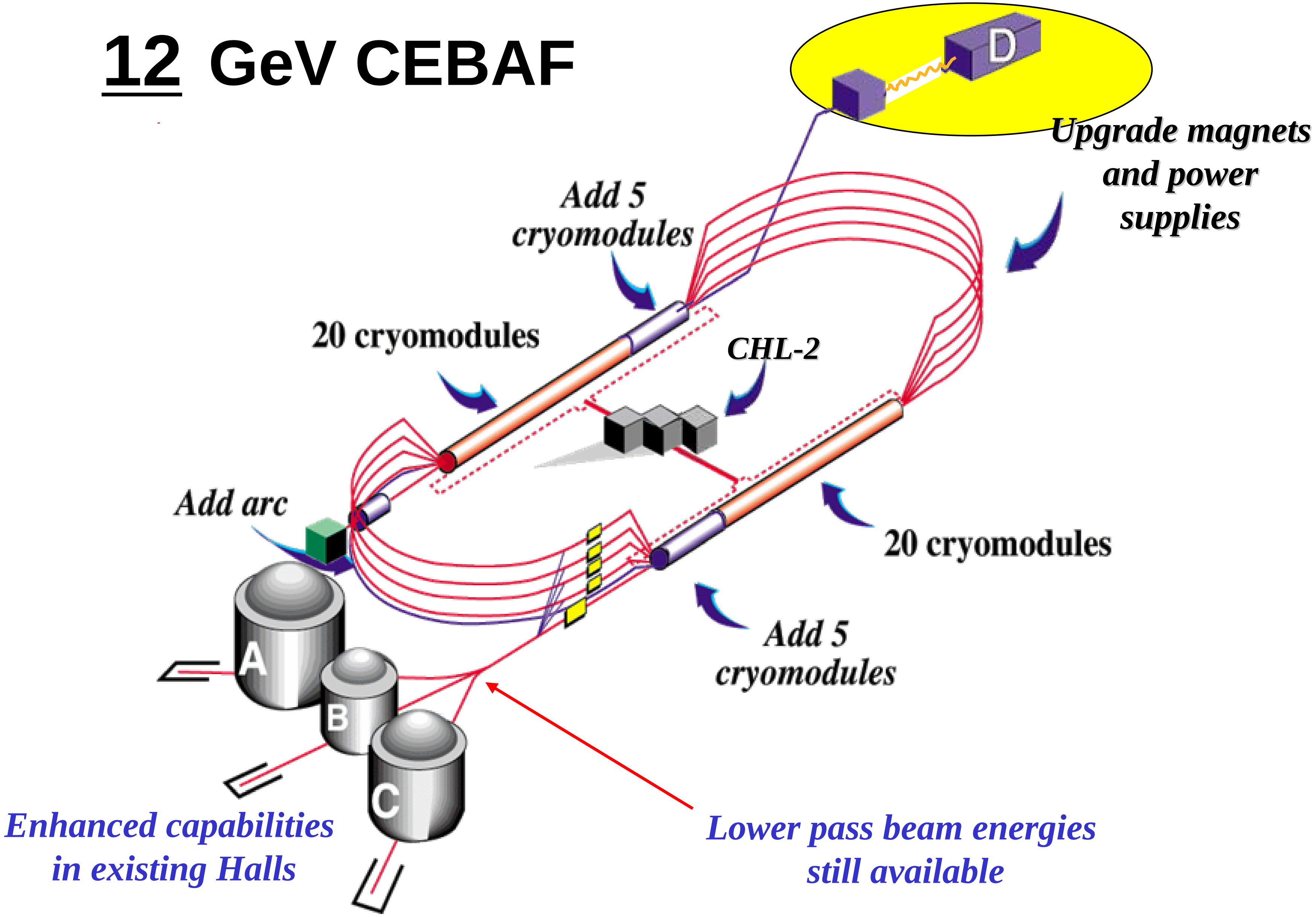
**Longitudinal Target Spin Asymmetry: $A_{UL}$**

**Transverse Target Spin Asymmetry: $A_{UT}$**




**Exclusive meson productions also give access to GPD.**

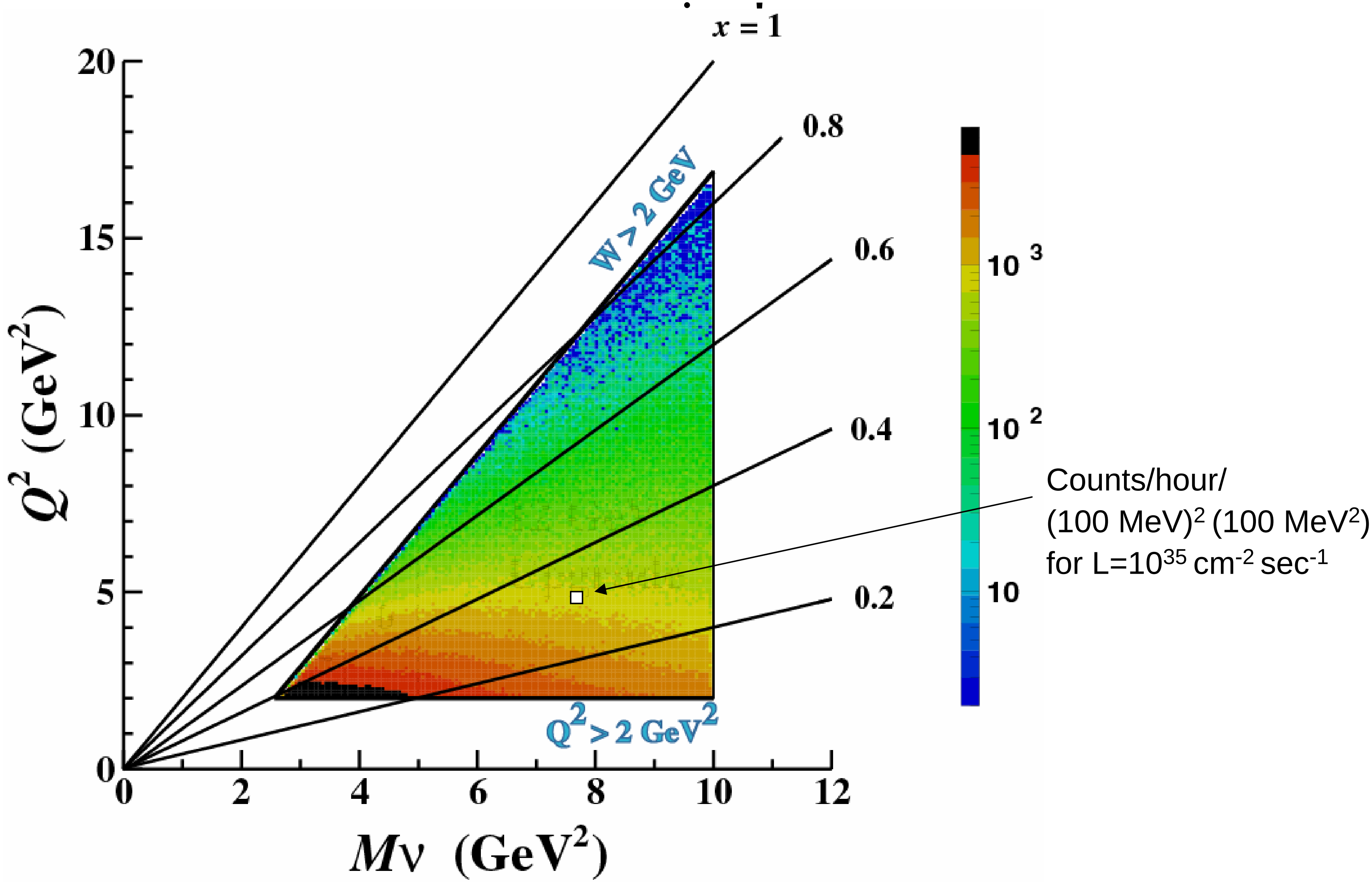
# 12 GeV CEBAF



D
Upgrade magnets
and power
supplies
Add 5
cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5
cryomodules
A
B
C
Enhanced capabilities
in existing Halls
Lower pass beam energies
still available

# Access to the DIS Regime @ 12 GeV

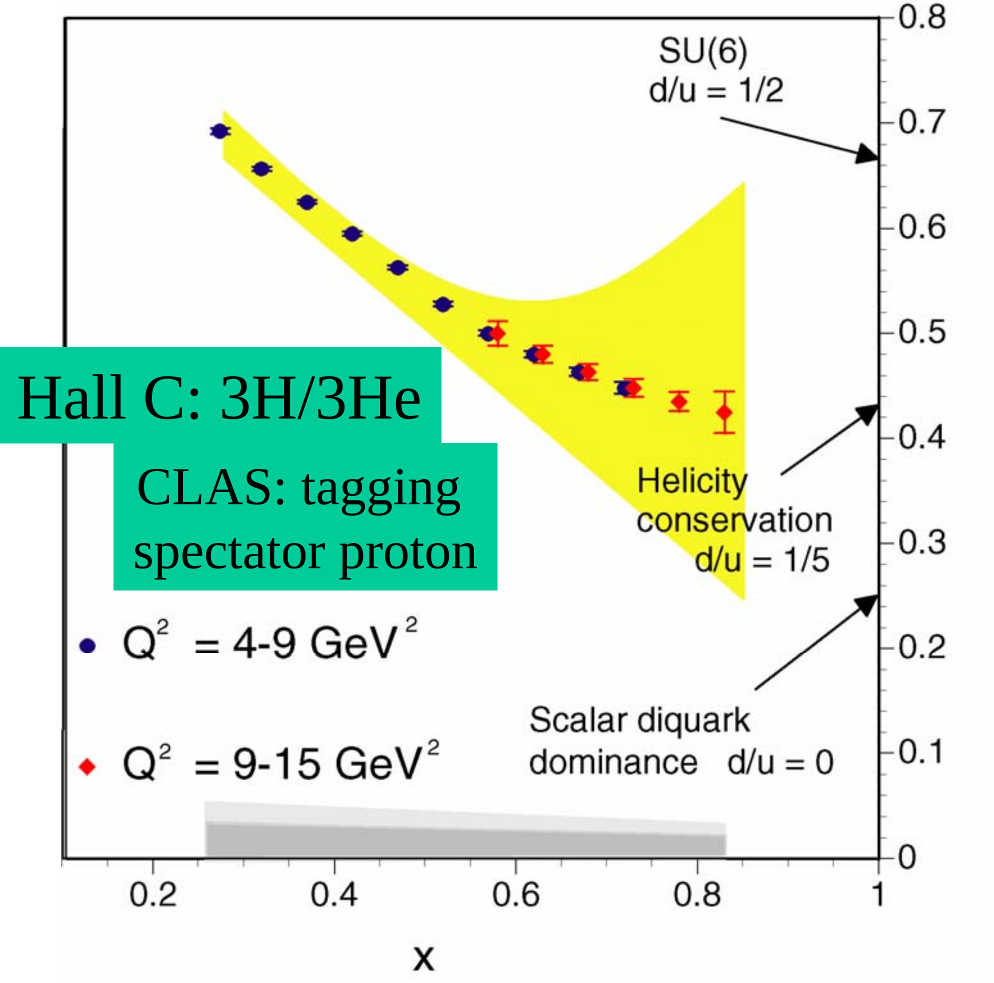
## with enough luminosity to reach the high-$Q^2$, high-x



# Extending DIS to High x

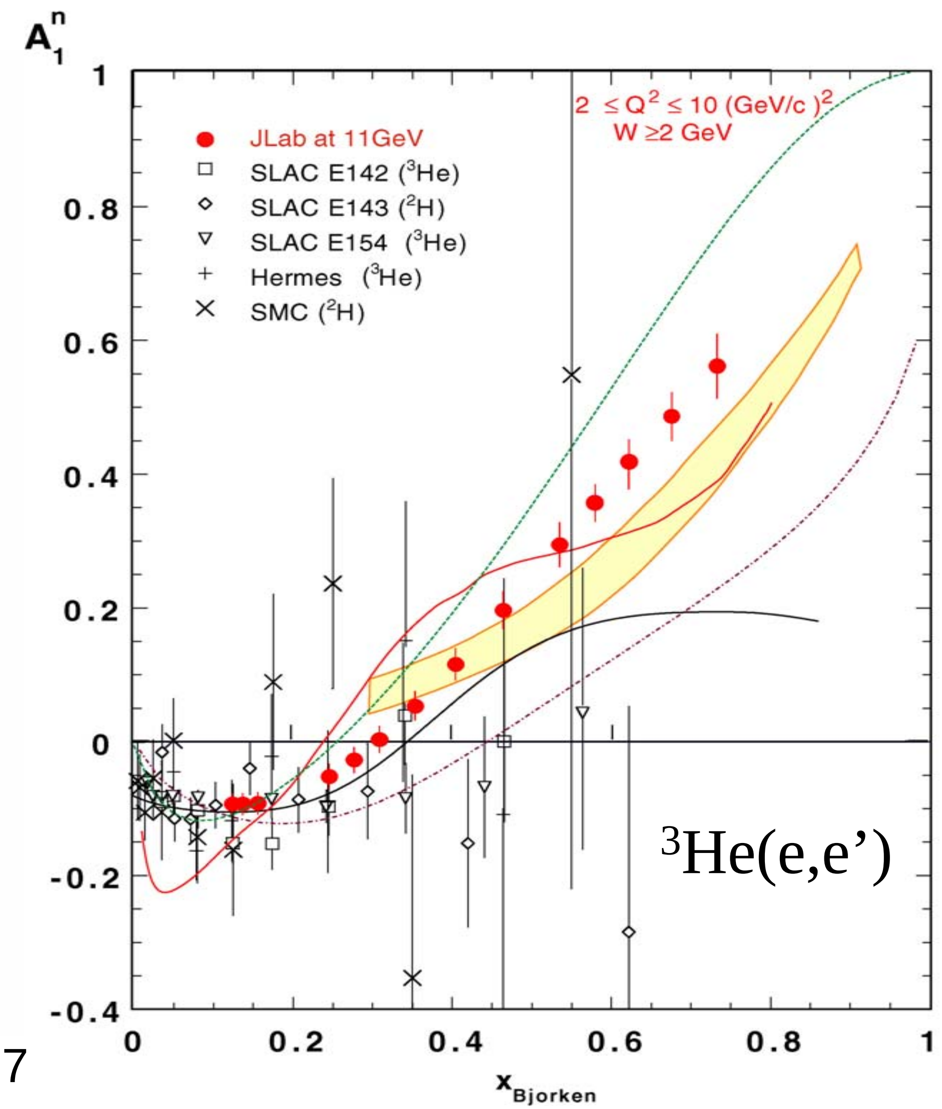
< Projection >

## The Neutron to Proton Structure Function Ratio




## The Neutron Asymmetry $A_1$

(similar precision for p and d)




A. Brull, Pacific-Spin07

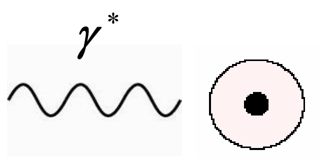
# Single Spin Asymmetry with a Transversely Polarized Hydrogen Target at HERMES

- Separation of Collins Effect and Sivers Effect

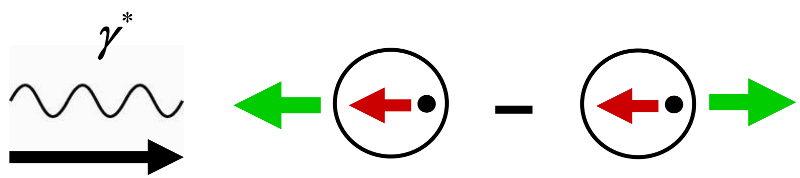
Fourier Amplitude $\langle \sin(\phi + \phi_S) \rangle_{UT}$ is expected

from the Transversity $h_1(x_B)$

$h_1(x_B)$ is coupled with fragmentation function
which is measured in fragmentation at $e^+e^-$ collider
Belle at KEK.

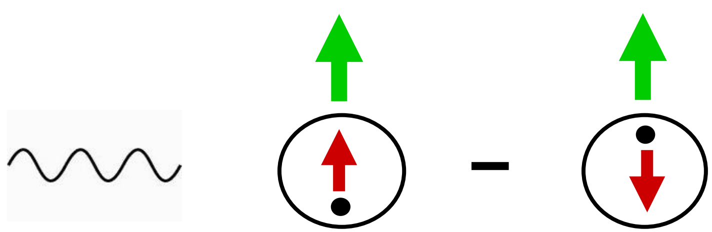
1. 


$$F_2(x_B) = x_B \sum_q e_q^2 q(x_B)$$

2. 


$$g_1(x_B) = 2\sum_q e_q^2 \Delta q(x_B)$$

helicity

3. 

$$\underline{h_1(x_B)} \propto \sum_q e_q^2 \delta q(x_B)$$

transversity

## Why Are Quark Transversity Distributions $\delta q(x)$ Interesting?

$\delta q(x) \neq \Delta q(x) \Rightarrow$ **proves Quark's Relativistic Nature in the Nucleon**

**Because of Lack of Transversity of Gluon, $Q^2$ Evolution Should Be Different From That of $q(x)$ and $\Delta q(x)$.**

**Collins Effect: Chiral Odd. So Far Never Measured**

$$h_1(x, p_T^2)\, H_1^{\perp}(z, k_T^2)$$

$p_T$ **initial quark transverse momentum**
$k_T$ **final quark transverse momentum**

---

**Sivers Effect: could be related to orbital motion of quarks**

$$f_{1T}^{\perp}(x, p_T^2)\, D_1(z, k_T^2)$$

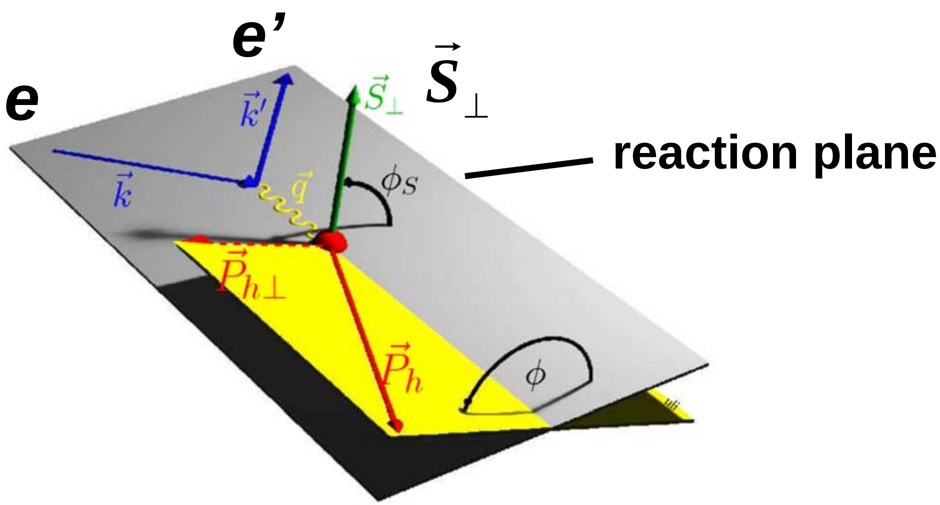
---

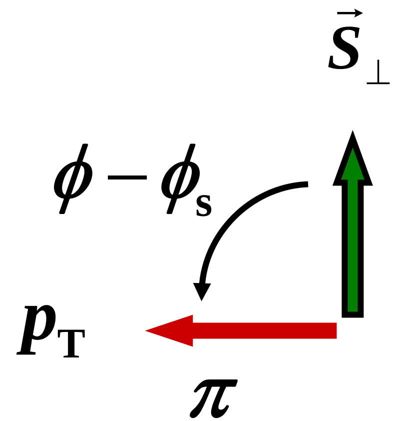
**The separation of the two effects was carried out for the first time.**

## Access to <u>orbital angular momentum of *quarks*</u>: $L_q$ Sivers mechanism

$$\frac{1}{2} = \frac{1}{2}(\Delta u + \Delta d + \Delta s) + L_q + S_g + L_g$$

**Two azimuthal angles** $\phi_s$ , $\phi$
**in semi-inclusive measurement of** $\pi, \mathrm{K}$ **with a transversely polarized target**



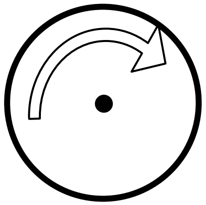




**Target polarization**
**P = 0.78 ± 0.04**

**Fourier Amplitude**

$$< \sin(\phi - \phi_S) >_{UT}$$

**expected**



# Azimuthal Single Spin Asymmetry

## Asymmetry around the virtual photon direction

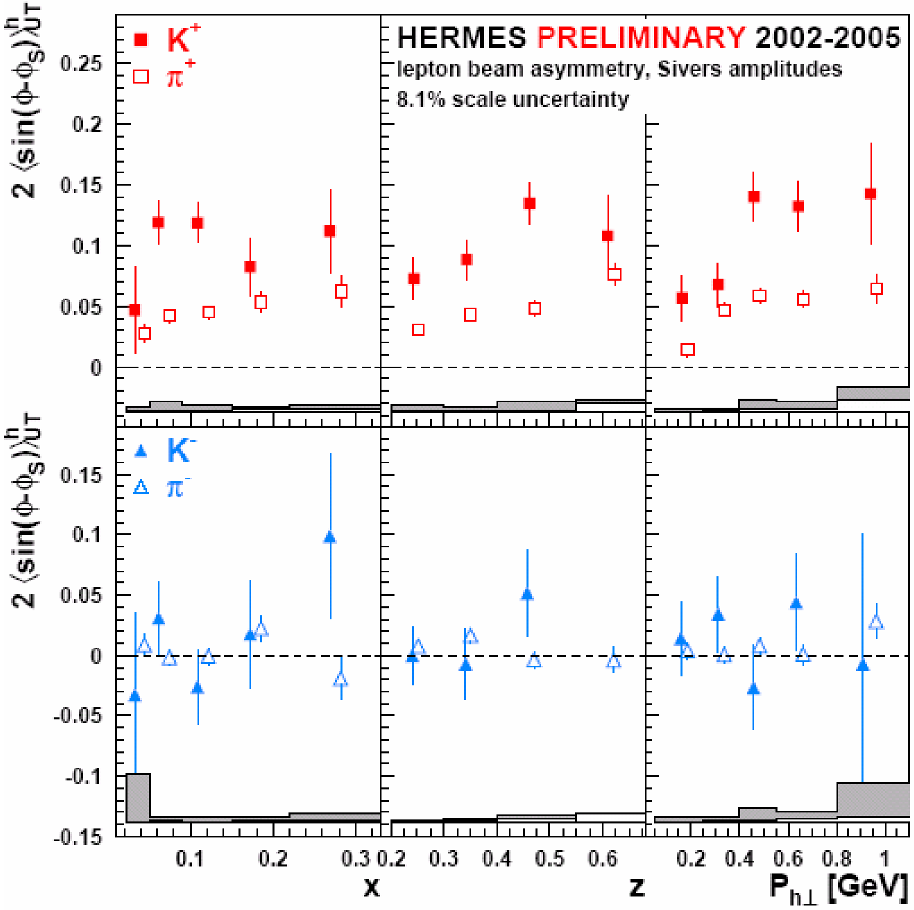
Fit in 2-dimension $(\phi, \phi_s)$ in each x bin

$$A_{UT}(\phi,\phi_s) = 2 < \sin(\phi+\phi_s) >^1_{UT} \sin(\phi+\phi_s)$$ Collins

$$+ 2 < \sin(\phi-\phi_s) >^1_{UT} \sin(\phi-\phi_s)$$ Sivers

Fourier Component

# Sivers Amplitudes for $\pi, \mathrm{K}$




**non-zero orbital angular momentum**

$\pi^+$, $K^+$ amplitudes significantly positive

$\pi^-$, $K^-$ amplitudes consistent with 0

# Conclusions of this part

- The separation of Collins effect and Sivers effect was carried out for the first time.

- Non-zero asymmetry is observed for Collins asymmetry. Positive $\pi^+$ asymmetry, negative $\pi^-$ asymmetry are compatible with helicity distribution $\Delta q(x)$. But the amplitude of $\pi^-$ asymmetry is large.

- $\pi^+$ asymmetry is positive, and $\pi^-$ asymmetry is nearly 0 for Sivers asymmetry.

# Spin Structure of The Nucleon and Related Topics

$Q^2 > 0$, **Lepton Scattering:**

**HERMES at DESY-HERA**
**COMPASS at CERN**
**JLab (CEBAF) → 12 GeV**
**SLAC**

$Q^2 = 0$, **Real Photon: (GDH Integral)**

**Mainz, Bonn, JLab,**
**SPring8, LEGS at BNL**

**Hadron Reaction :** RHIC SPIN
J-PARC, GSI

$e^+e^-$ **Collider: Belle**

Over 500 experimental physicists

## Summary

**Gluon distribution, Unpolarized and polarized**
**Several approaches with lepton scattering and pp collisions**

**Quark helicity distributions, quark flavor separation**

**Physics with transversely polarized proton**
**Collins effect**
**Sivers effect - Orbital angular momentum**

**Generarized Parton Distributions -- $J_q$**

**Fragmentation processes – Fragmentation functions**

**Impact on programs of COMPASS, J-lab, RHIC, polarized Drell-Yan, Neutrino Scattering Experiments etc.**