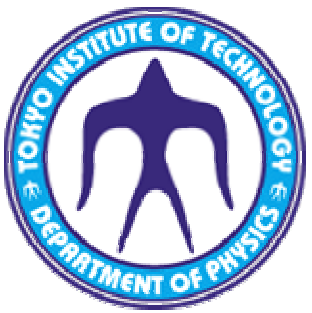
Sept 27, 2004
at Kochi, JPS

$H^q(x,\xi,t)$, $E^q(x,\xi,t)$, ...

一般化されたパートン分布関数：実験の現状

東工大　柴田利明

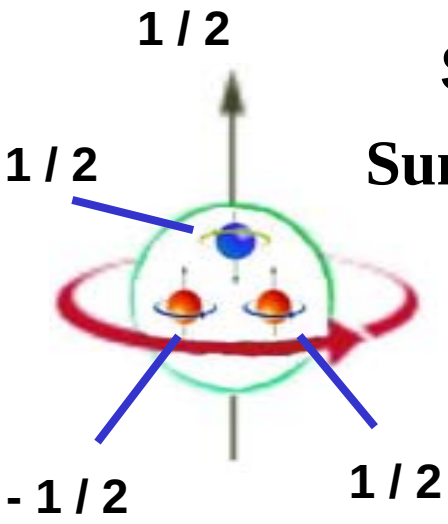


一般化されたパートン分布関数： 実験の現状

目次

1. 陽子のスピン構造、一般化されたパートン分布関数
2. 実験の現状、 Exclusive Process (排他的過程)
3. 電子散乱－Deeply Virtual Compton Scattering
   (深仮想コンプトン散乱)
4. ニュートリノ散乱
5. 展望とまとめ

Introduction : Spin of Proton

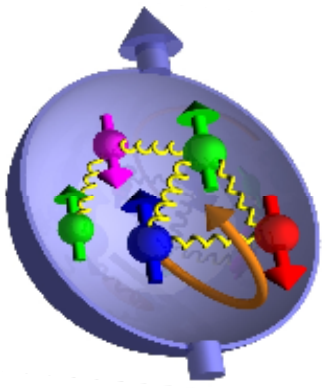


SU(6) Quark Wave Functions of Baryons

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

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

EMC Experiment (1988)



T.-A. Shibata

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

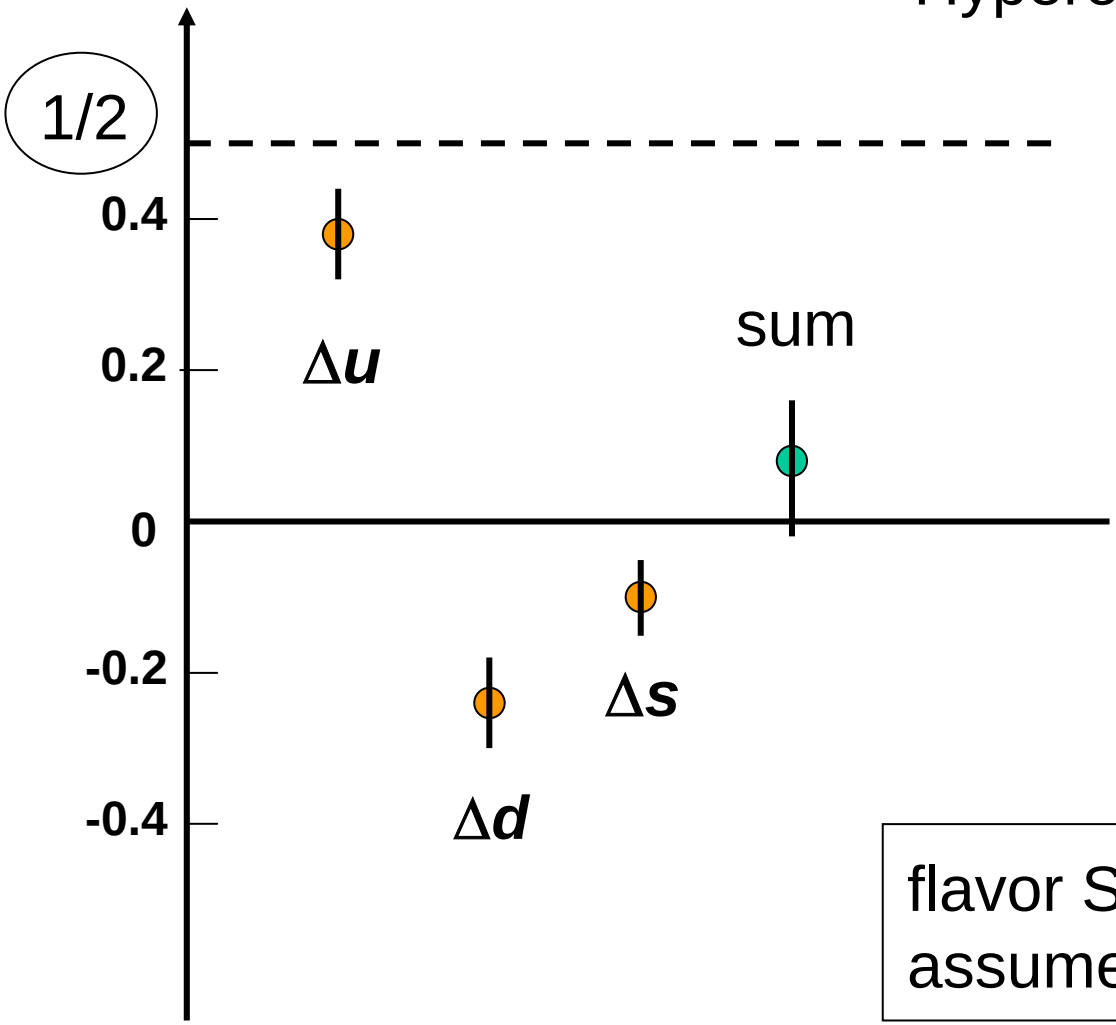
$$(12 \pm 9 \pm 14)\%$$

20 – 30 % of Nucleon Spin

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

'Nucleon Spin Problem'

EMC + Neutron lifetime
Hyperon weak decays



flavor SU(3) symmetry assumed

Experiments on the Proton Spin and related measurements

Fixed Target Experiments:

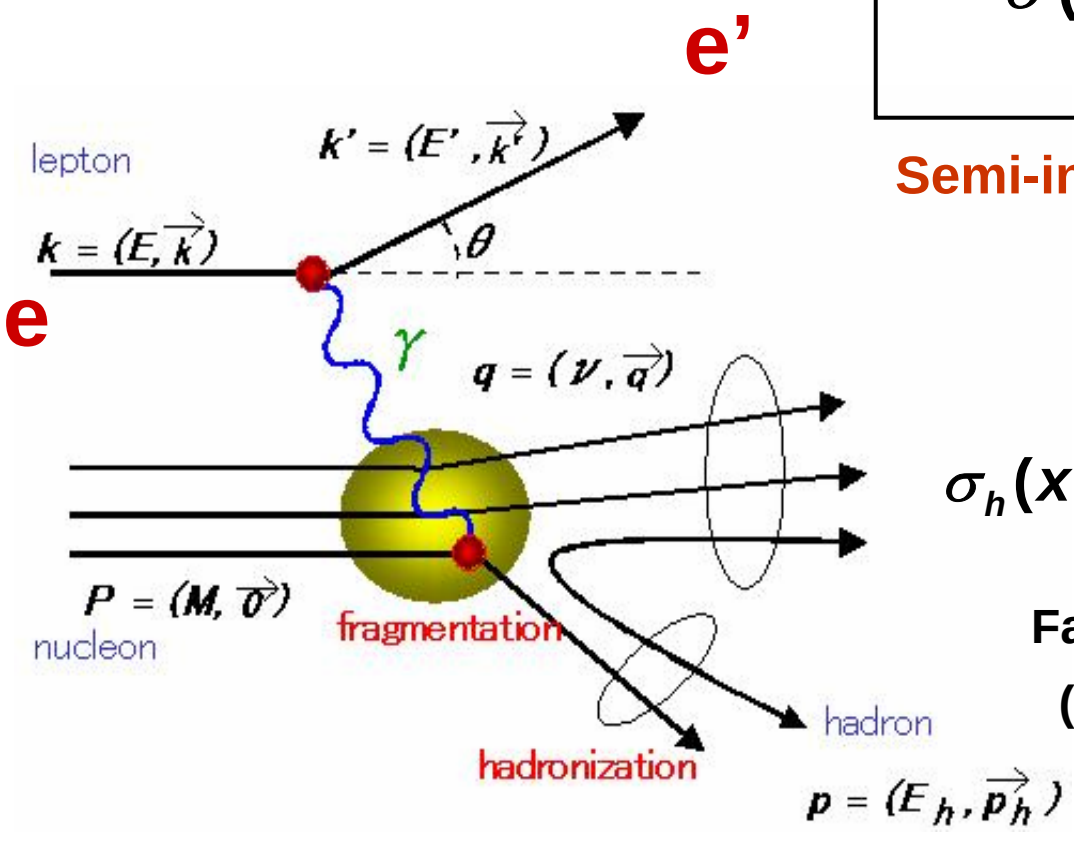
CERN	EMC, SMC, COMPASS	μ 160 GeV	pol p,d	DIS
DESY-HERA	HERMES	e 28 GeV	pol p,d	DIS
SLAC		e 50 GeV	pol 3He, p,d	DIS
JLAb	Hall A	e 6 GeV	pol 3He	DIS
	Hall B	e 6 GeV	pol p,d	Resonance Reg.
	Hall C	e 6 GeV	pol p,d	Resonance Reg.
MIT/Bates	SAMPLE	e 0.2 GeV	p,d	Elastic Scatt. PV
JLAB	G0	e 6 GeV	p,d	Elastic Scatt. PV
JLAB	HAPPEX	e 6 GeV	p,d	Elastic Scatt. PV
Mainz-MAMI		e 0.88 GeV	p,d	Elastic Scatt. PV
BNL	E734	ν 1.3 GeV	p	Elastic Scatt. NC

Collider Experiments:

BNL-RHIC	PHENIX	p+p 200 or 500 GeV	gluon spin, sea quark
	STAR	p+p 200 or 500 GeV	gluon spin, sea quark
KEK B-factory	BELLE	e + e, 8 on 3.5 GeV	fragmentation function

Deep Inelastic Scattering, Semi-inclusive Measurements

$$x = Q^2 / 2M\nu$$



Inclusive measurement, e'

$$\sigma(x) \propto \sum_q e_q^2 q(x)$$

Semi-inclusive measurement,

e' and π,K,p,$\bar{p}$ ...

Flavor tagging

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

Factorization:

(quark distribution) x
(fragmentation function)

$$z = E_h / \nu$$

Theory:

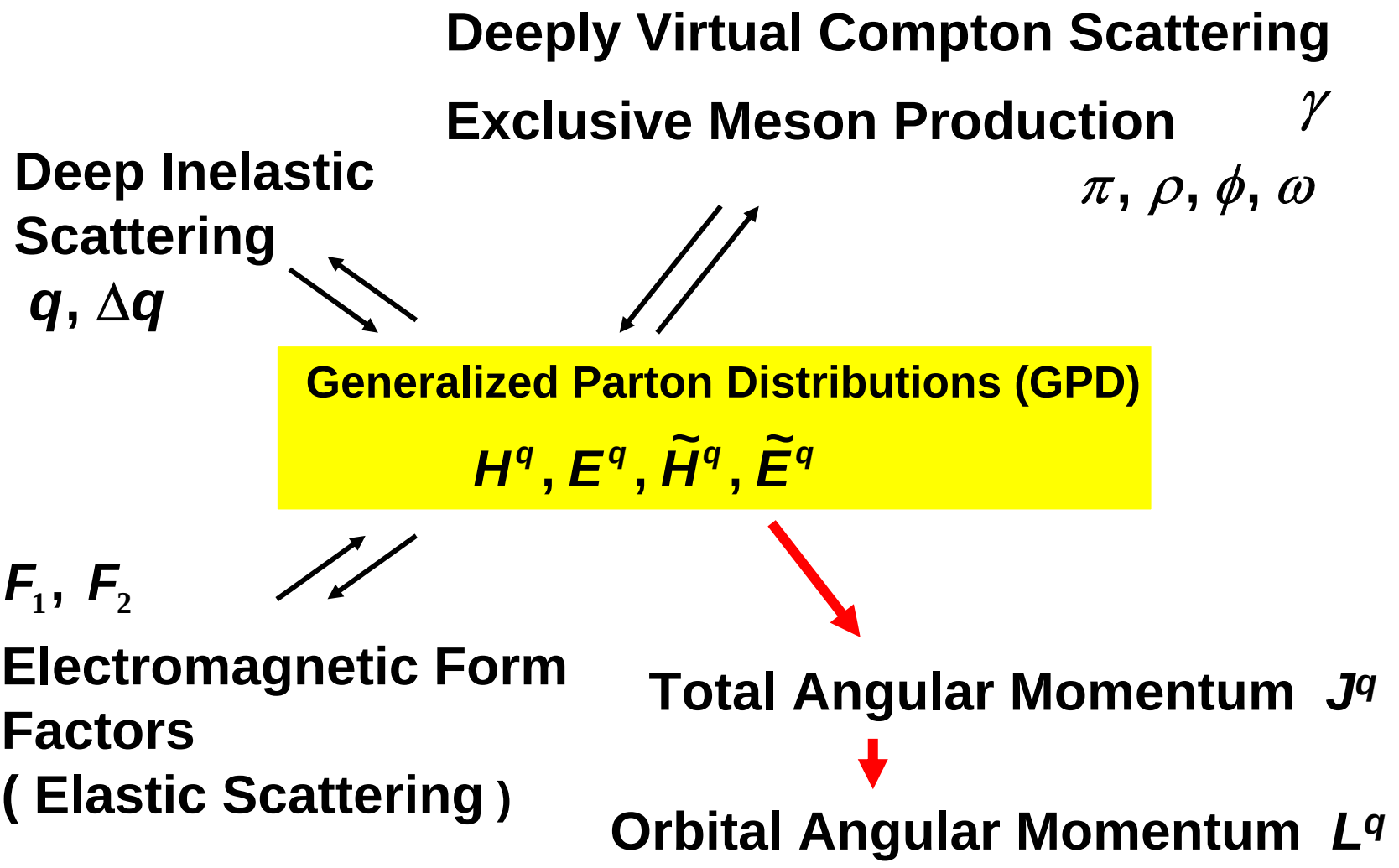
for example,

OFF FORWARD PARTON DISTRIBUTIONS
X. D. Ji,
J. Phys. G24 (1998) 1181-1205 ---- 158

DEEPLY VIRTUAL COMPTON SCATTERING
X. D. Ji,
Phys. Rev. D55 (1997) 7114-7125 ---- 415

…..

Generalized (Off-Forward) Parton Distributions



Generalized (Off - Forward) Parton Distributions

$$H^q(x,\xi,t),\ E^q(x,\xi,t),\ \tilde{H}^q(x,\xi,t),\ \tilde{E}^q(x,\xi,t)$$

Forward limit $t \to 0,\ \xi \to 0$

$$H^q(x,0,0) = q(x),\quad \tilde{H}^q(x,0,0) = \Delta q(x)$$

Ordinary Quark Distributions

Sum rules, x – integral, sum over q

$$H^q(x,\xi,t) \to F_1(t),\ E^q(x,\xi,t) \to F_2(t)$$

Dirac and Pauli Nucleon Form Factors

$$\tilde{H}^q(x,\xi,t) \to g_A(t),\ \tilde{E}^q(x,\xi,t) \to h_A(t)$$

Axial-vector and Pseudo-scalar Form Factors

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

2nd moment

Total angular momentum

$$J^q = \frac{1}{2}\Delta q + L_z^q$$

Orbital angular momentum

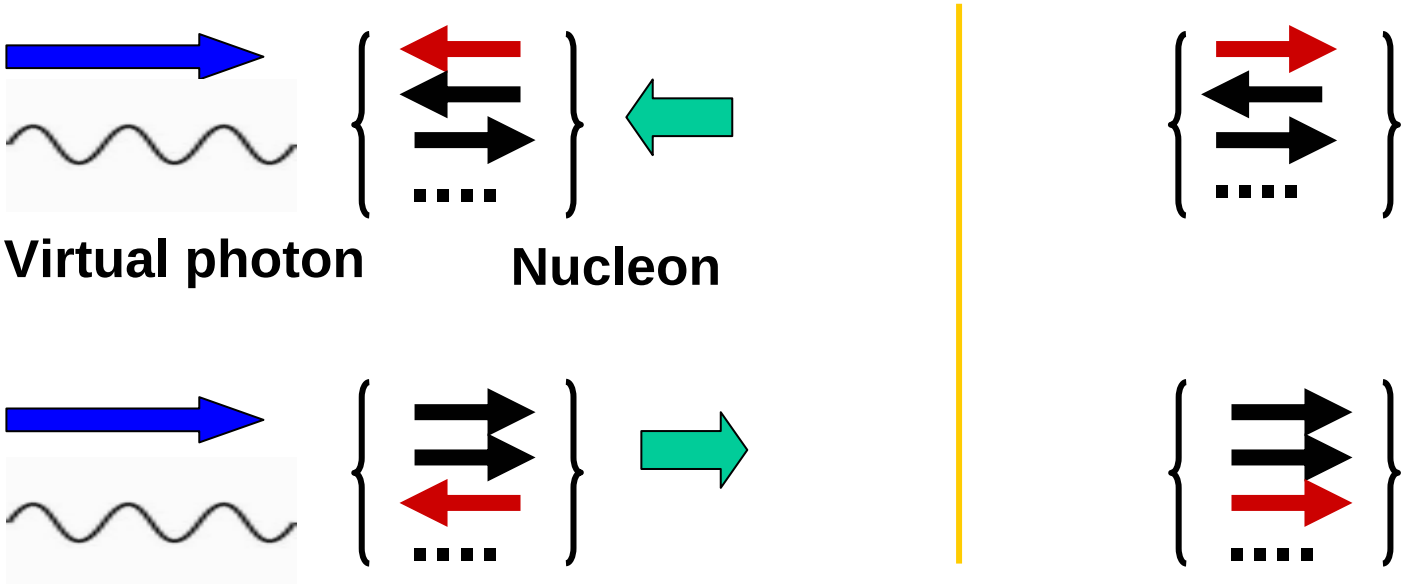
Experimental Methods and Results

Double-spin asymmetry

Polarized e, 1994

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

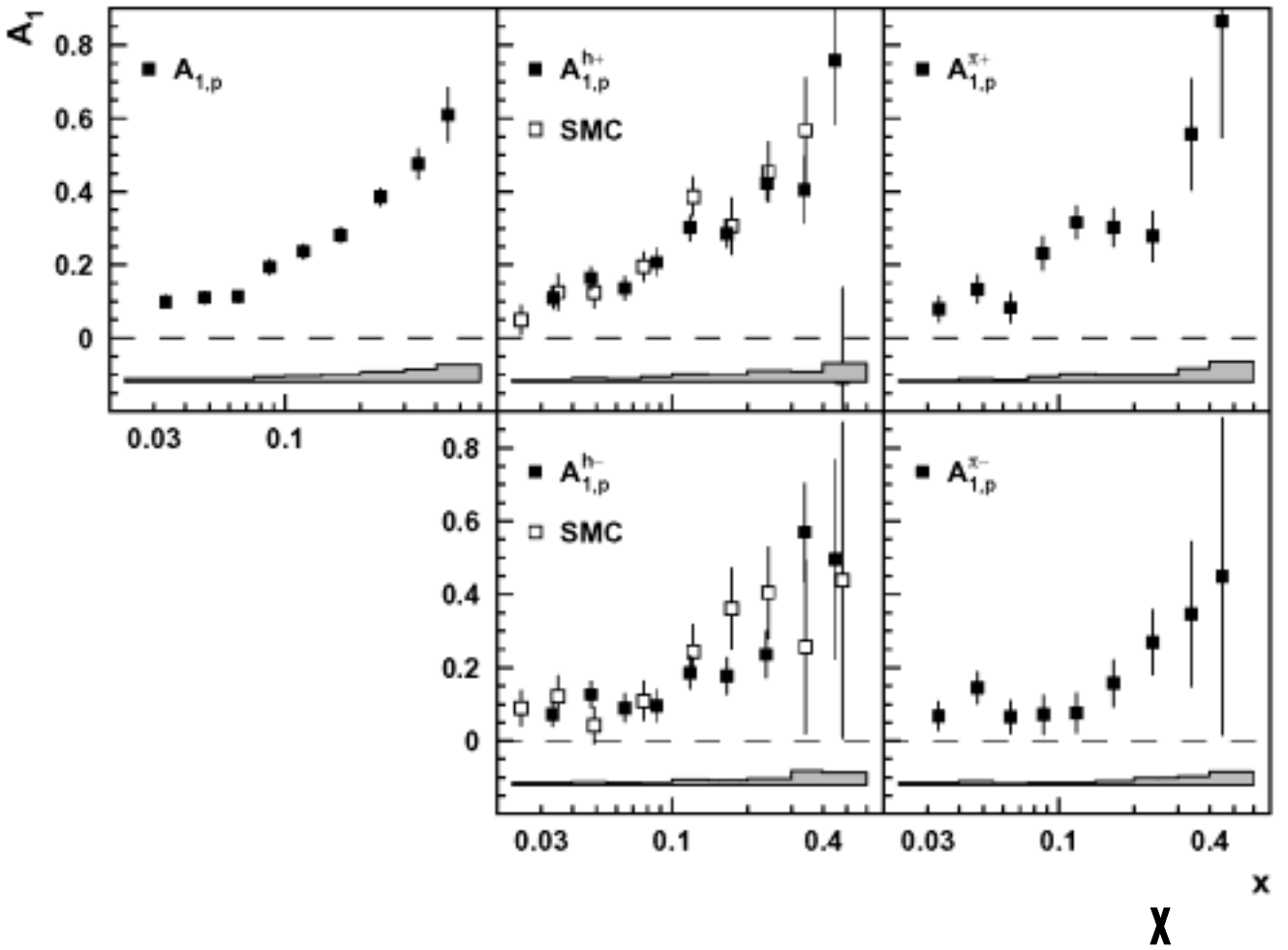
Beam and target, both polarized



$$A_1(x,z) = \frac{\sigma^{\rightarrow}_{\leftarrow}(x) - \sigma^{\rightarrow}_{\rightarrow}(x)}{\sigma^{\rightarrow}_{\leftarrow}(x) + \sigma^{\rightarrow}_{\rightarrow}(x)}$$

HERMES (2004), hep-ex/0407032

A_1



positive

negative

HERMES

Flavor Separation, Quark Helicity Distributions

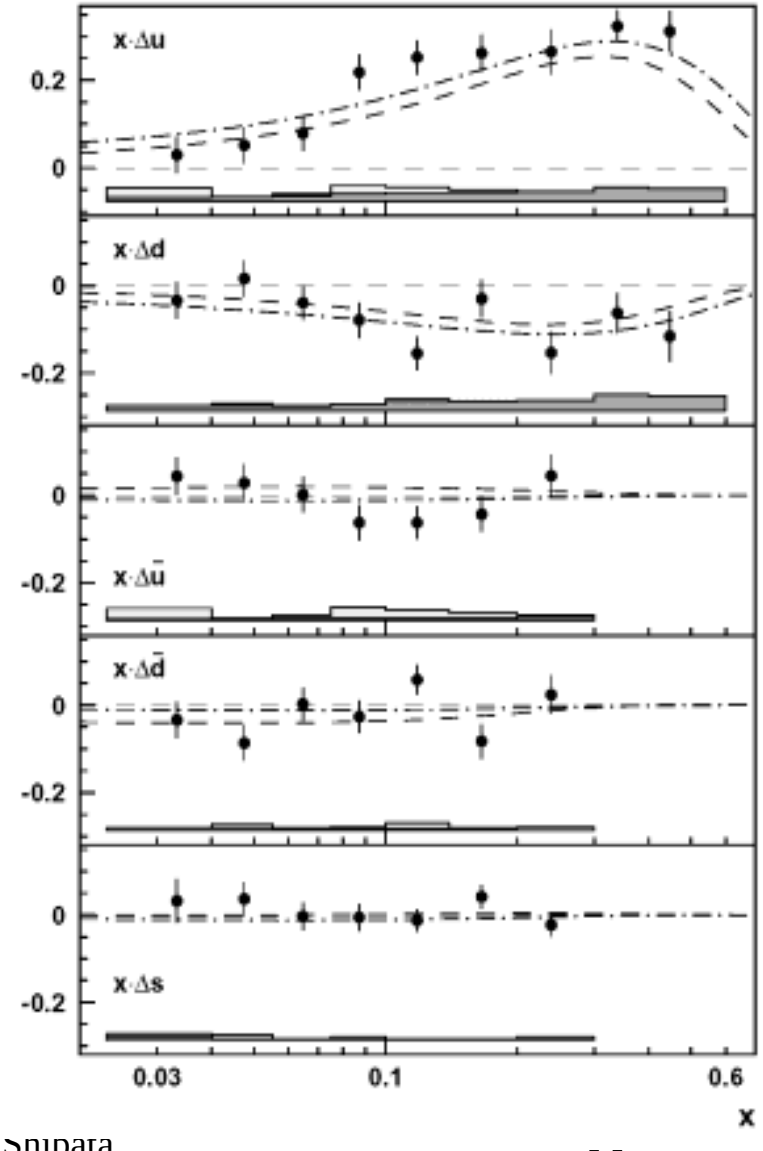
$x\Delta u$

$x\Delta d$

$x\Delta\bar{u}$

$x\Delta\bar{d}$

$x\Delta s$



Result: $\Delta u > 0$

$\Delta d < 0$

$\Delta\bar{q} \approx 0$

- **X bin by bin analysis except for smearing correction.**
- **No functional forms are assumed.**
- **No first moments are assumed.**
- **Helicity conservation not assumed** $\frac{\Delta d}{d} \to 1 \ as \ x \to 1$ **etc.**

Error band – systematic error

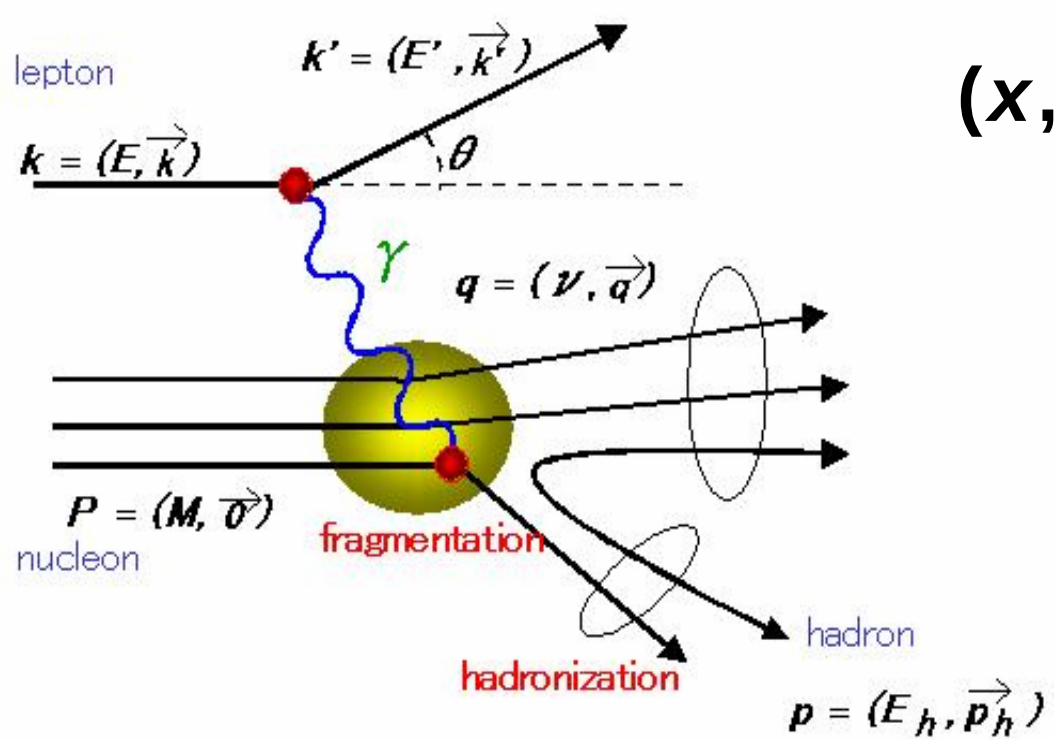
QCD fits to inclusive measurements

Deeply Virtual Compton Scattering

「HERMESによるHard Exclusive 生成過程の測定：一般化されたパートン分布関数による核子構造の研究」
宮地義之、柴田利明、高エネルギーニュース, 22 (2003) 11
http://www-he.scphys.kyoto-u.ac.jp/~nakaya/HEPNews/

Inclusive Measurement:

Total cross section for virtual photon – nucleon reaction

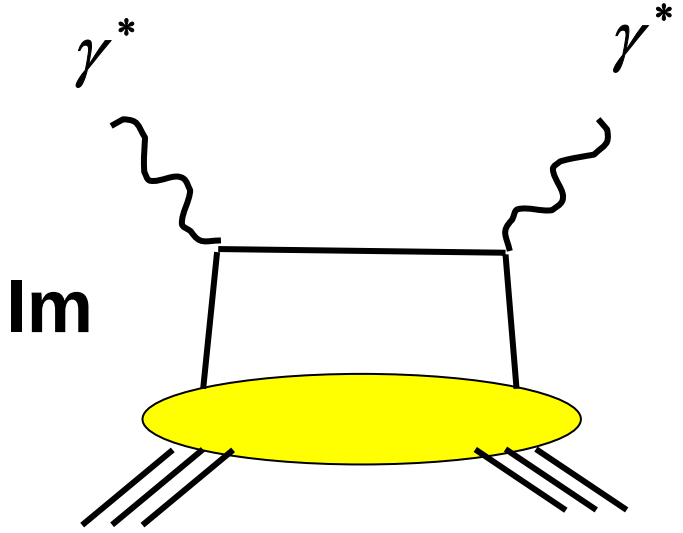


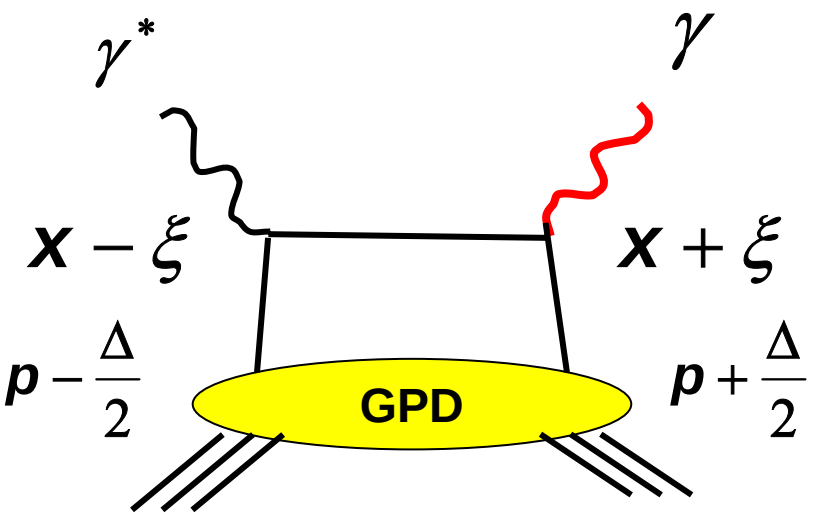
(x, Q^2)

Coss section for inclusive deep inelastic scattering

Deeply Virtual Compton Scattering (DVCS)

-- Exclusive production of a real photon



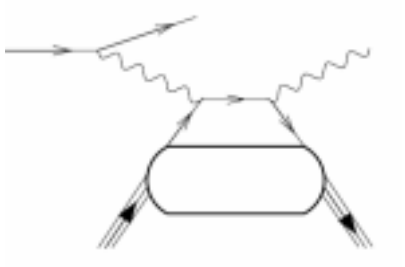


x :Light cone momentum fraction

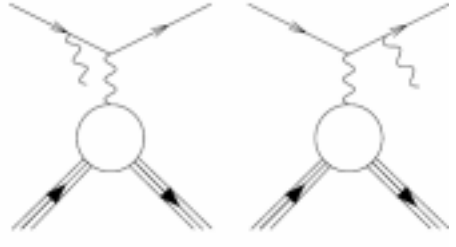
$\xi = \frac{x_{BJ}}{2 - x_{BJ}}$:Exchanged longitudinal momentum fraction

$t = \Delta^2$:Momentum transfer

How to measure DVCS



Deeply Virtual Compton Scattering

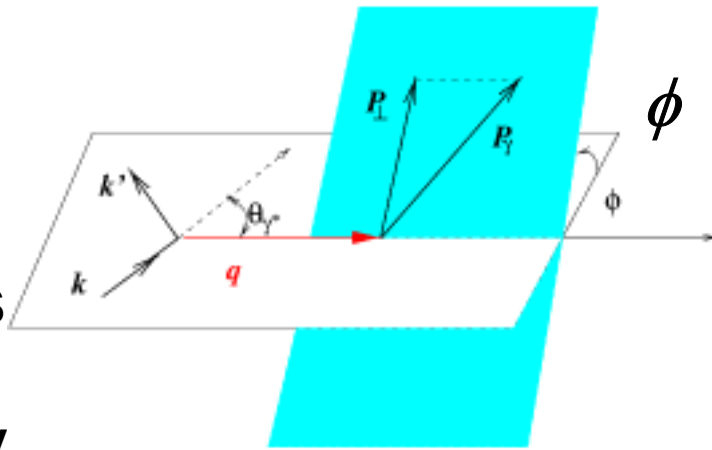


Bethe-Heitler Process, known calculable

$$\frac{d^4\sigma}{d\phi\, dt\, dQ^2 dx} \propto |A_{DVCS} + A_{BH}|^2 = |A_{DVCS}|^2 + |A_{BH}|^2 + I$$

$$\Delta\sigma_{LU} = \sigma(\vec{e}^{\pm} p) - \sigma(\overleftarrow{e}^{\pm} p) \propto \mp \sin\phi \times \mathrm{Im}\, I$$

$$\Delta\sigma_{ch} = \sigma(e^{+} p) - \sigma(e^{-} p) \propto \cos\phi \times \mathrm{Re}\, I$$



Beam-spin asymmetry by HERMES and CLAS

Beam-charge asymmetry by HERMES

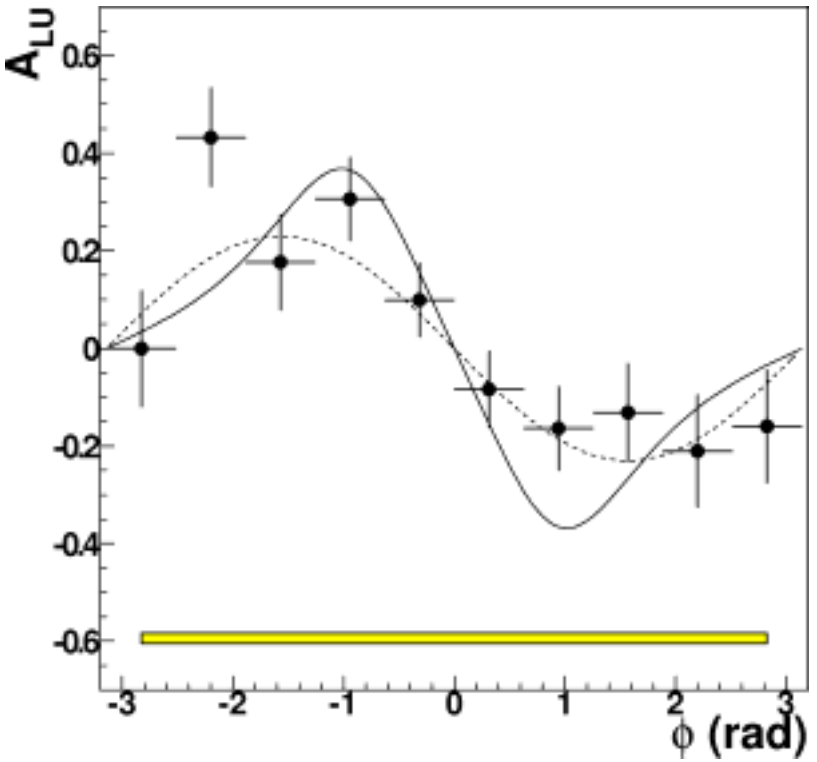
-- DVCS-BH Interference, Real and Imaginary

DVCS Cross Section by ZEUS and H1

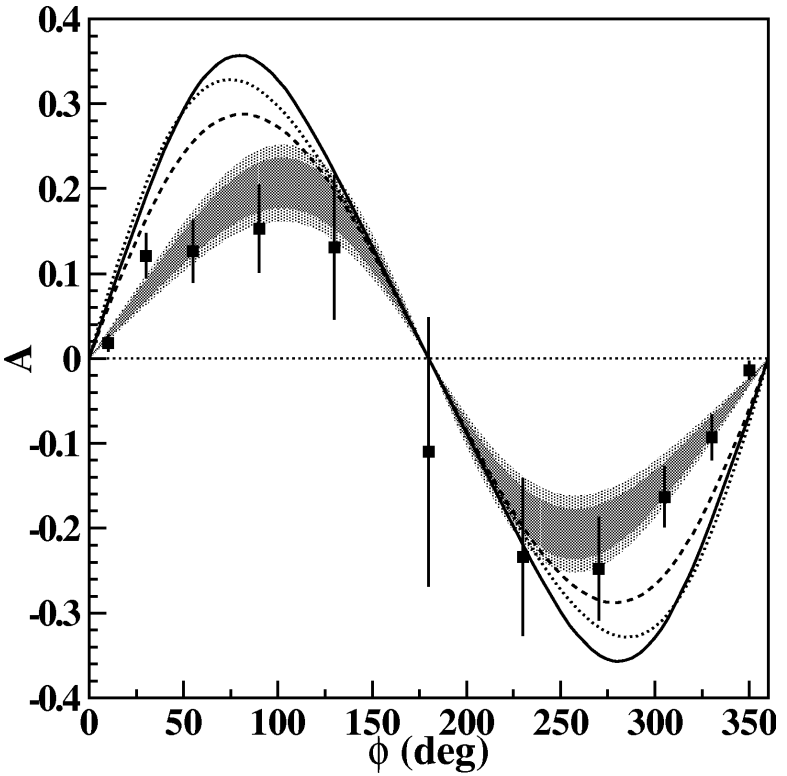
Deeply Virtual Compton Scattering

First observation of beam-spin asymmetry of DVCS

A_{LU} **HERMES (DESY)**



CLAS (JLab)

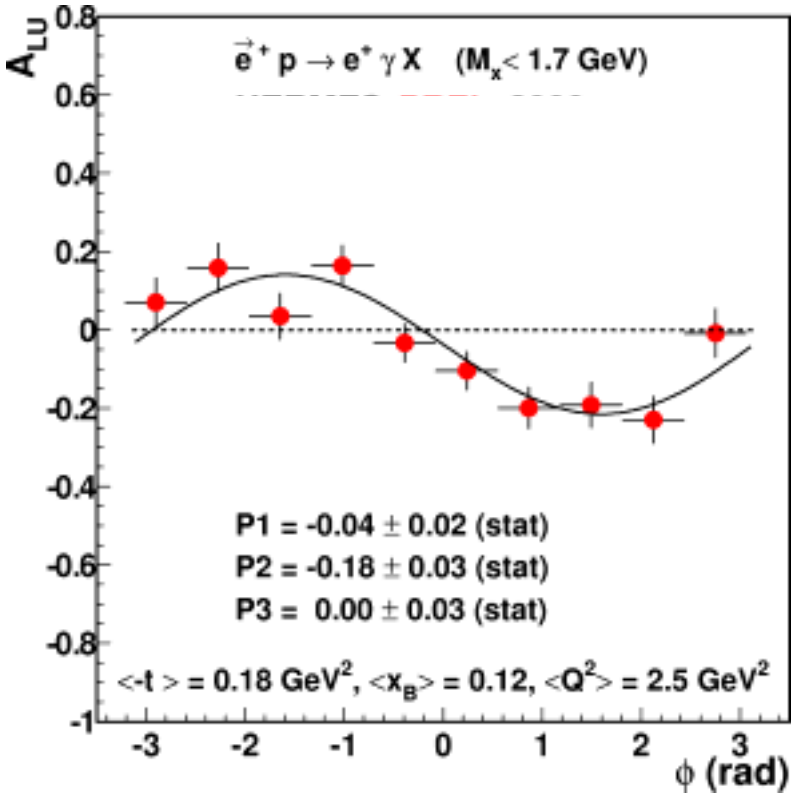


ϕ **~ 30% effect** ϕ

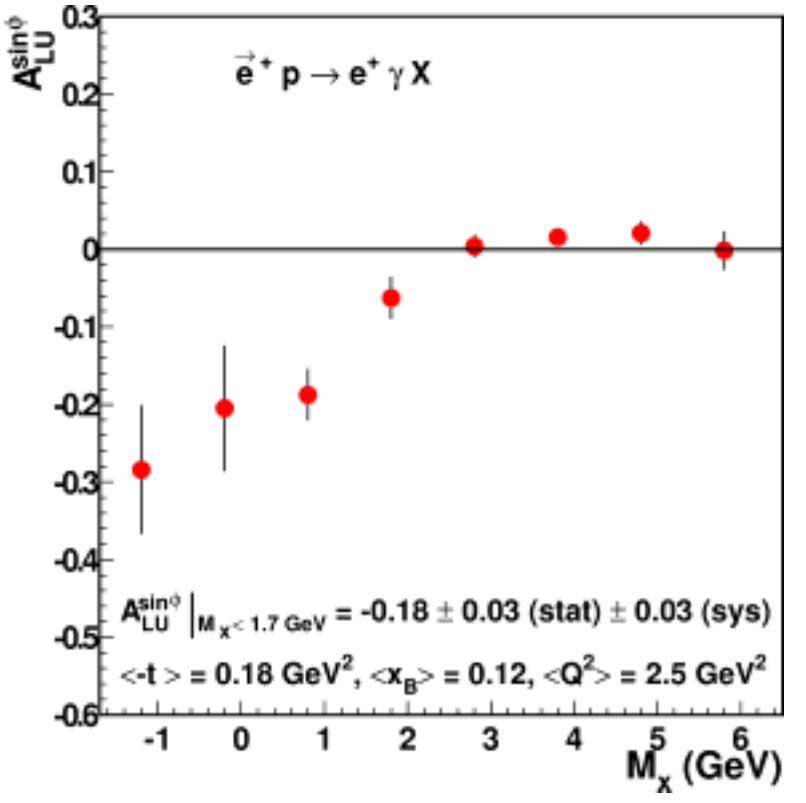
Beam-Spin Asymmetry

$\sin\phi$ Moment

HERMES



ϕ



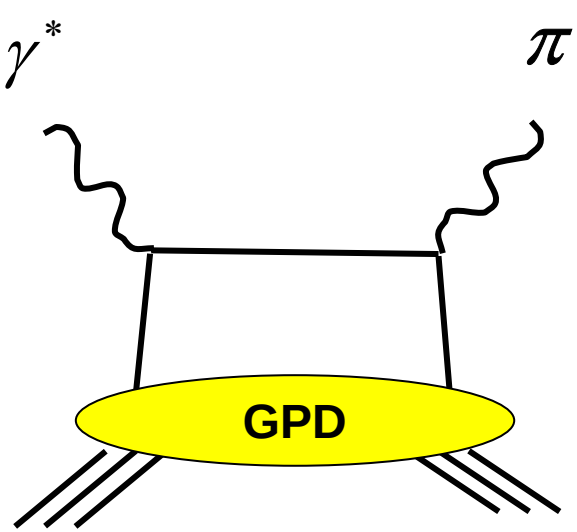
M_X

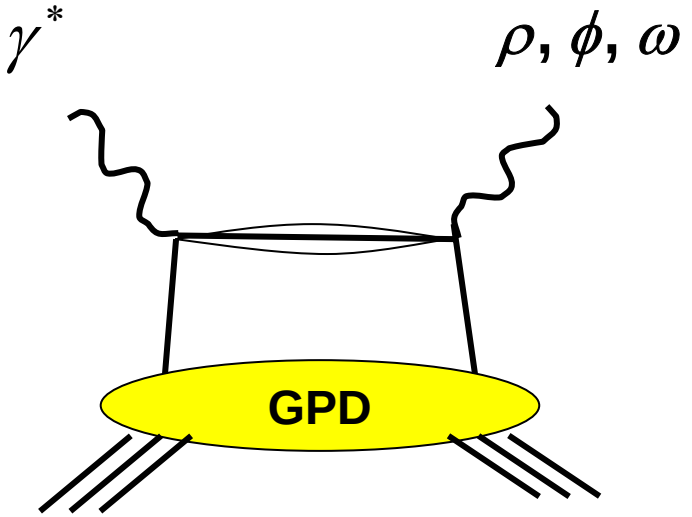
Missing Mass Resolution 0.8 GeV

How to extend

Quantum number of final state → **Select different GPD**

Exclusive Meson Productions





Pseudo scalar meson

$\tilde{H}^q(x,\xi,t),\ \tilde{E}^q(x,\xi,t)$

Vector meson

$H^q(x,\xi,t),\ E^q(x,\xi,t)$

HERMES's data

Neutrino beam experiments

neutrino-proton elastic form factor and Δs

How to measure:

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2}{2\pi}\frac{E_\nu^2}{Q^2}\left[A \pm BW + CW^2 \right], \qquad \begin{array}{l} + \text{ for } \nu, \\ - \text{ for } \bar{\nu} \end{array}$$

$$W = 4(E_\nu / M_p - \tau), \quad \tau = Q^2 / 4M_p^2$$

$$A = \frac{1}{4}\left[G_1^2 (1+\tau) - \left(F_1^2 - \tau F_2^2 \right)(1-\tau) + 4\tau F_1 F_2 \right],$$

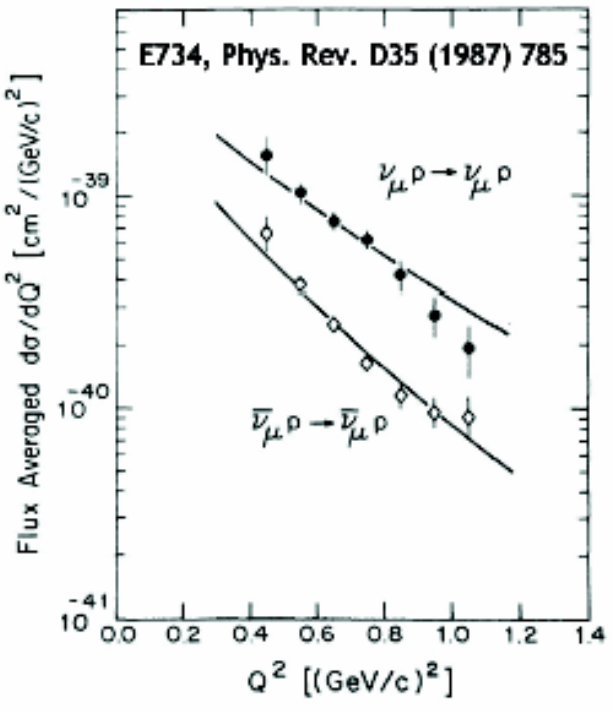
$$B = -\frac{1}{4}\left[G_1 \left(F_1 + \tau F_2 \right) \right], \qquad G_1(Q^2) = \frac{-0.631}{(1+Q^2/M_A^2)^2} + \frac{G_1^s(Q^2)}{2}$$

$$C = \frac{1}{16}\frac{M_p^2}{Q^2}\left[G_1^2 + F_1^2 + \tau F_2^2 \right], \qquad \underline{G_1^s(Q^2 = 0) = \Delta s}$$

Neutrino-nucleon elastic scattering cross section
from viewpoint of strange quark spin Δs in the proton

E734

$$G_A^s(Q^2 = 0) = \Delta s$$

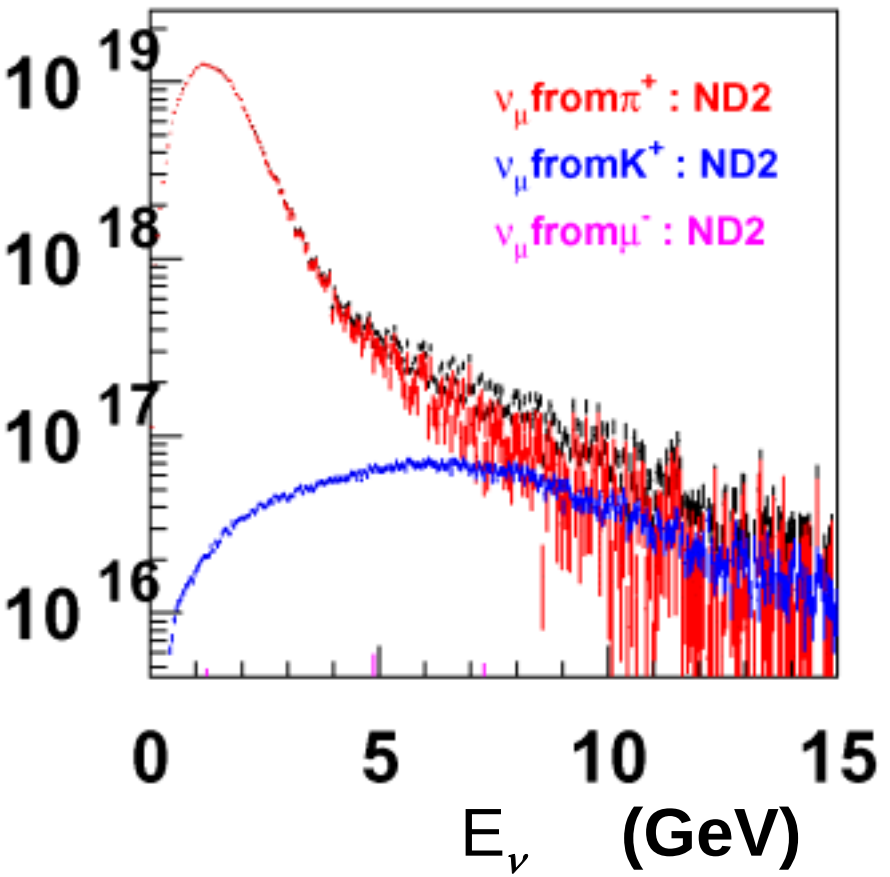


L.A. Ahrens et al., Phys. Rev. D35 (1987) 785,
G.T. Garvey et al., Phys. Rev. C48 (1993) 761

BNL734 experiment with
Neutrino beam from AGS on proton,
ν (mean energy 1.3 GeV) , $\bar{\nu}$ (1.2 GeV)

FINNeSSE at FNAL and BNL,
Experiment at J-PARC (NP04, Aug. 2004)

Neutrino Flux at J-PARC, 50 GeV proton, at 280 m



Summary and Outlook

Many experiments on Spin Structure of the Proton are going on and are planned all over the world.

Genaralized (Off-Forward) Parton Distribution is a 'Grand Unified Theory' of Hadrons

Parton Distribution $q(x)$, Form Factors, and excluive processes can be analysed in the same framework.

Deeply Virtual Compton Scattering, in particular its spin dependence, has been measured.

Form Factors from Neutrino Scattering are important elements.

Exclusive Process of Hadron Reactions (gluon Compton scattering, 2 jet productions in pp collisions) will also contribute.

$\sqrt{s}$ = 200 GeV, L_{int} = 320 pb^{-1}, beam polarization 70% for gluon Compton scattering, $g + q \rightarrow \gamma + q$

$\sqrt{s}$ = 500 GeV, L_{int} = 800 pb^{-1}, beam polarization 70% for W production, $q(x)\ \bar{q}(x) \rightarrow W \rightarrow \mu\bar{\nu}$

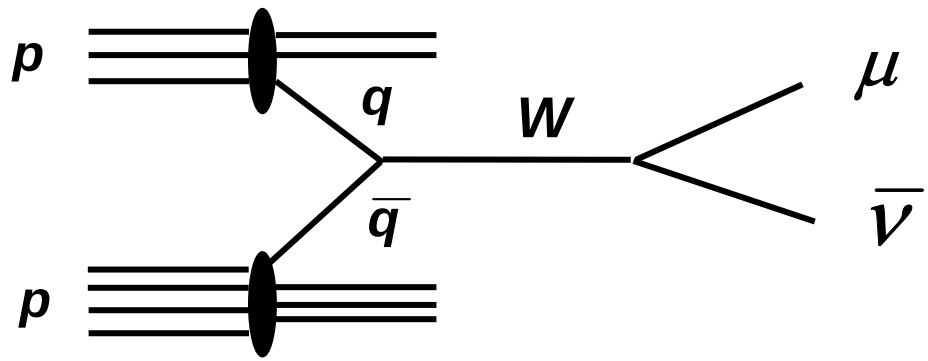
With this universal theoretical framework, the studies of spin structure of the proton will be further developed. Collaborative studies in Japan will be important.

RHIC－SPIN Experiments:

Polarized Proton-Proton Collision

$\sqrt{s}$ = 500 GeV, L_{int} = 800 pb^{-1}, beam polarization 70%

$$q(x)\ \bar{q}(x) \rightarrow W \rightarrow \mu\bar{\nu}$$



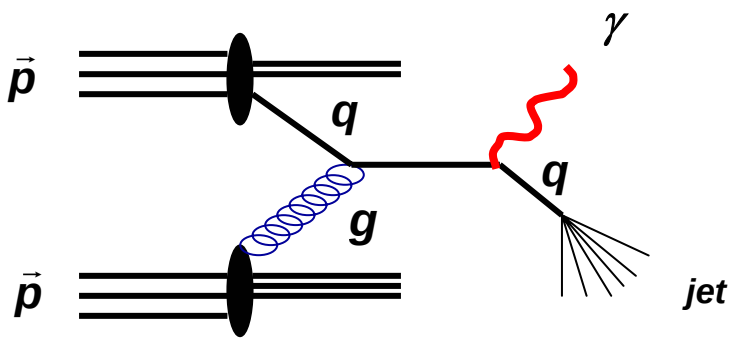
$\Delta\bar{u}(x),\ \Delta\bar{d}(x),\ \Delta u(x),\ \Delta d(x)$ using known $q(x),\ \bar{q}(x)$

$\sqrt{s}$ = 200 GeV, L_{int} = 320 pb^{-1}, beam polarization 70%

direct photon productions

Gluon Compton scattering

$$g + q \rightarrow \gamma + q$$



$$A_{LL} \propto \frac{\Delta G(x_1)}{G(x_1)} \cdot \frac{\Delta q(x_2)}{q(x_2)} \cdot \hat{a}_{LL}$$

2 jet production

Inclusive π^0, $\pi^{\pm}$

$$g + g \rightarrow jet\ (\pi^0) + jet$$

$$g + q$$

$$q + q$$

$$A_{LL} \propto \frac{\Delta G(x_1)}{G(x_1)} \cdot \frac{\Delta G(x_2)}{G(x_2)} \cdot \hat{a}_{LL}$$