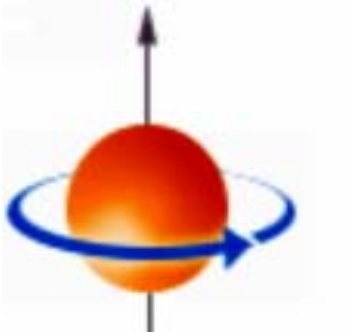

Aug 15, 2003
Lepton-Photon 2003

Measurements with Polarized Hadrons

T.-A. Shibata

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Contents:

Introduction: Spin of Proton

Polarized Deep Inelastic Lepton-Nucleon Scattering

1. Flavor Separation of Quark Helicity Distributions
2. Deeply Virtual Compton Scattering
3. Single-Spin Azimuthal Asymmetries
   in Semi-Inclusive Deep Inelastic Scattering

Polarized Proton-Proton Collisions

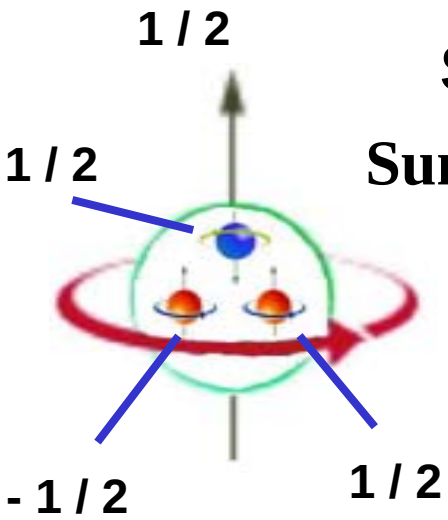
Introduction:

Measurements with Polarized Hadrons

‘Explore spin structure of hadrons and further develop QCD using Spin’

QCD was successful, both in perturbative and non-perturbative regions, but spin of the nucleon still needs to be studied in many aspects to be fully explained with QCD.

Introduction : Spin of Proton

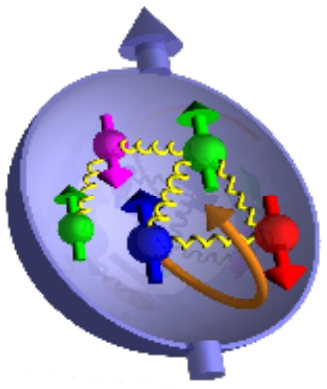


SU(6) Quark Wave Functions of Baryons

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)



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

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

20 – 30 % of Nucleon Spin

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

'Nucleon Spin Problem'

Experimental Methods: Lepton-Hadron Scattering, Hadron-Hadron Collision

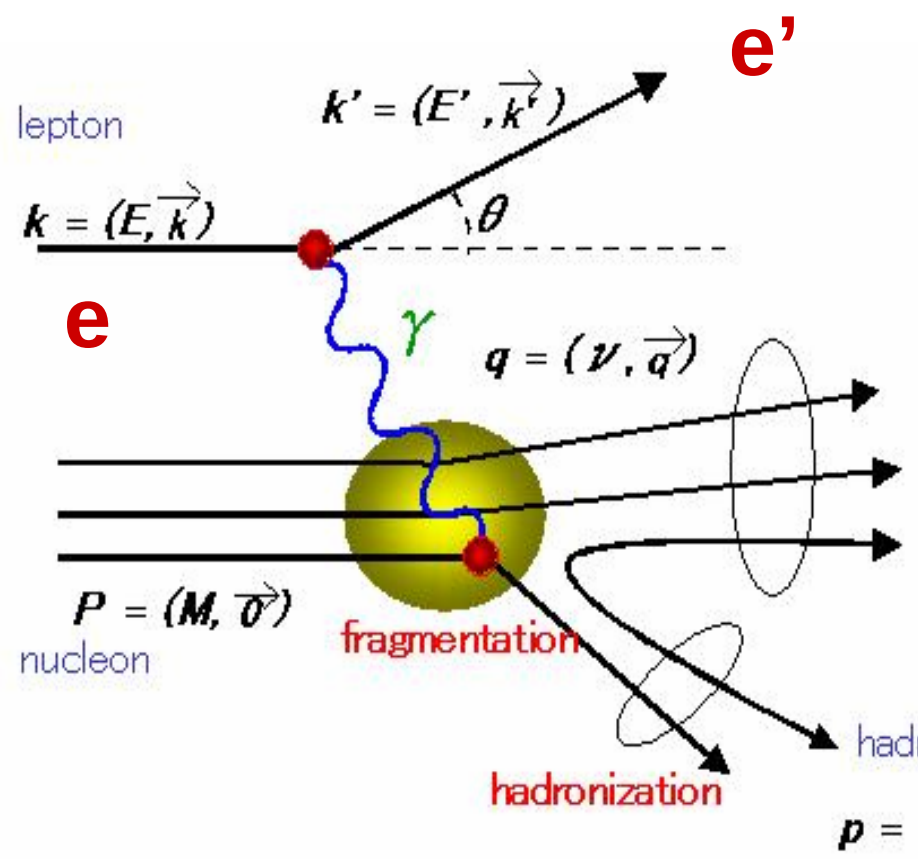
Fixed Target Experiments :

Polarized Targets	+	(Polarized) Beams	
Nucleon (p, n)	+	e^+/e^-	HERMES
		e^-	SLAC, JLab
		μ^+ / μ^-	COMPASS

Collider Experiments :

Polarized Proton - Proton Collisions RHIC

Deep Inelastic Scattering, Semi-inclusive Measurements



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

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

(quark distribution) x
(fragmentation function)

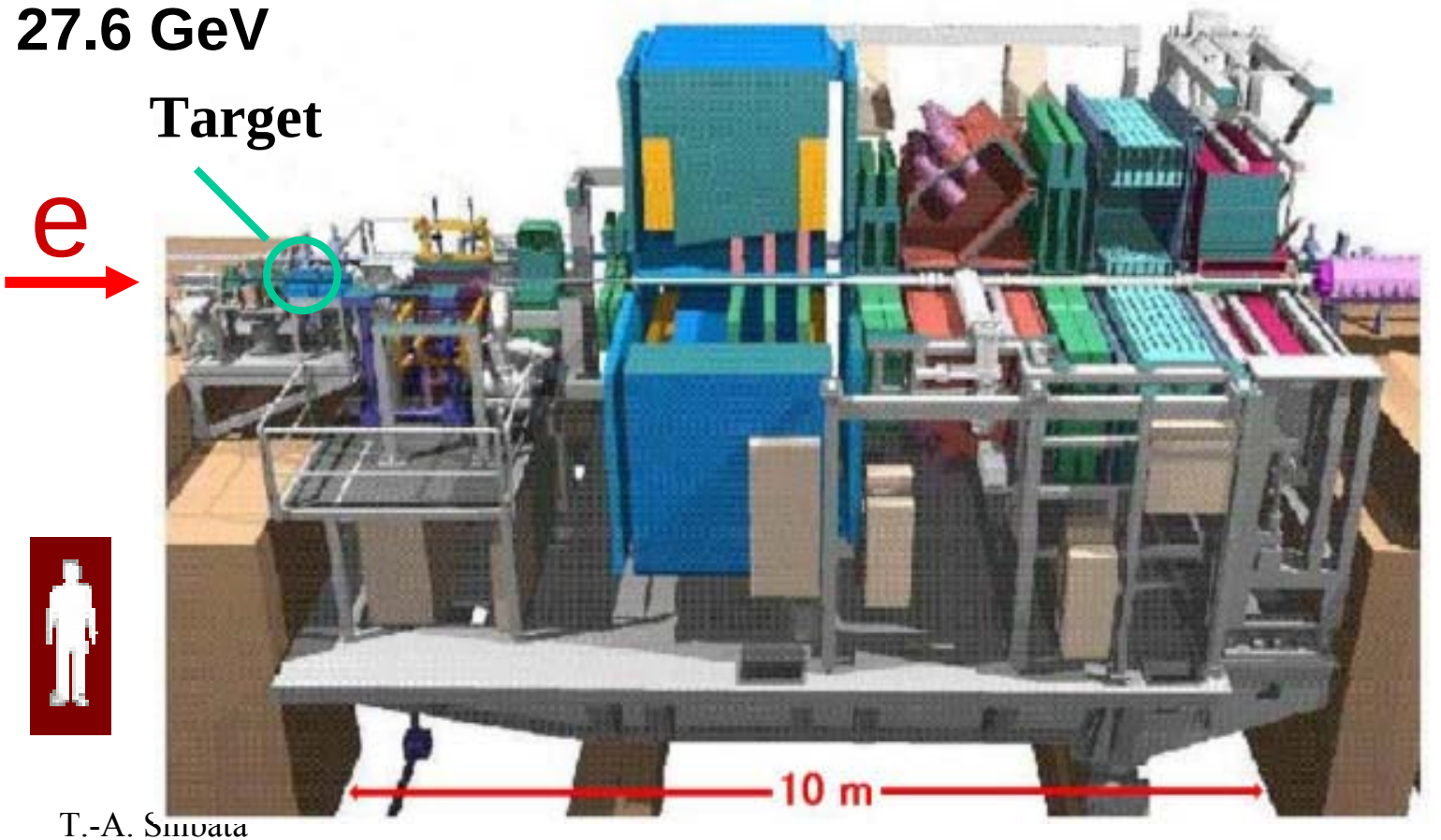
$$z = E_h / \nu$$

Detectors

HERMES @DESY- HERA
1995 --

Polarized Internal gas targets
(^{3}He, H, D)

27.6 GeV

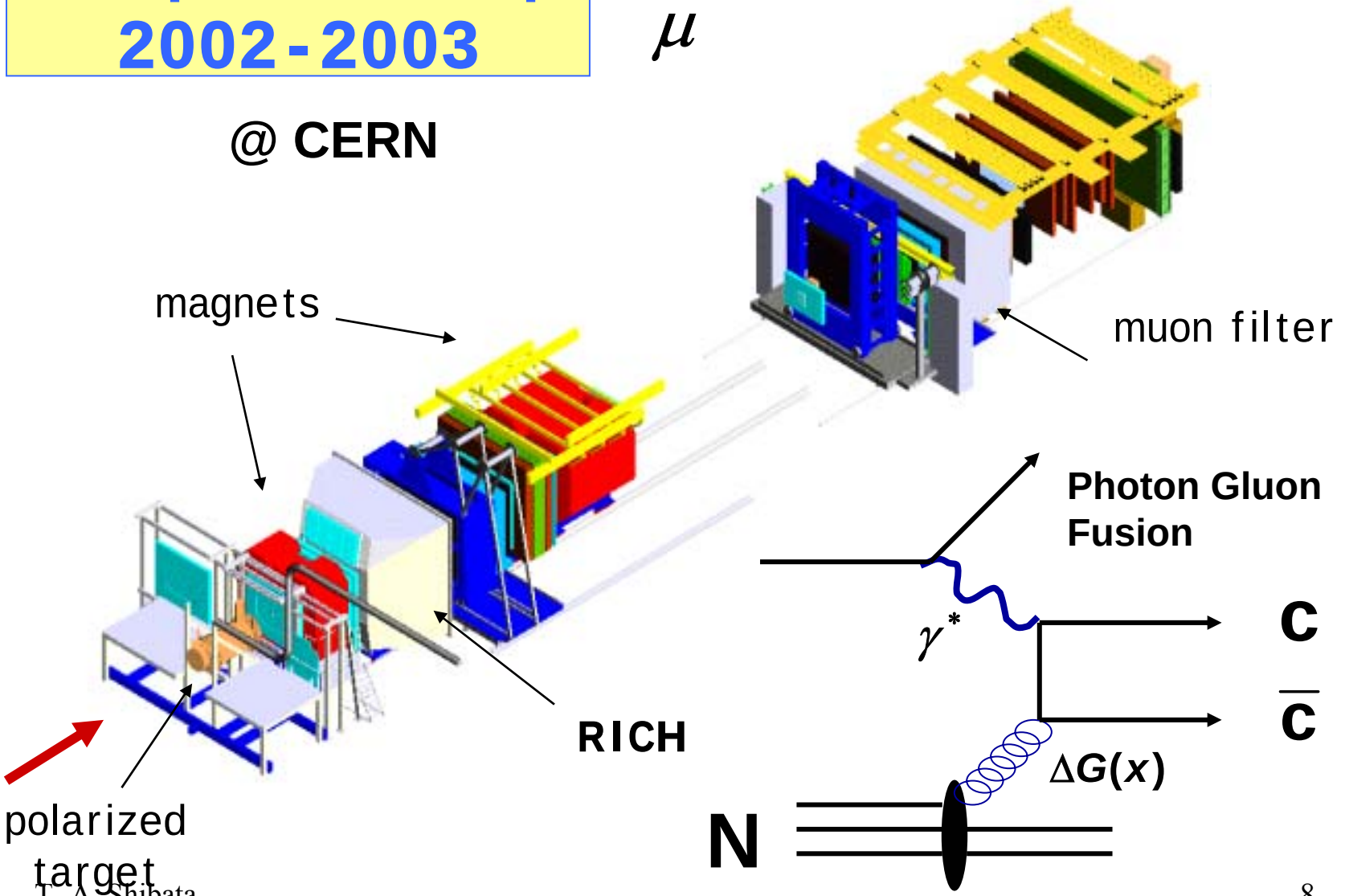


Compass Set-up 2002-2003

@ CERN

160 GeV μ

Gluon Spin Contribution
D's identified in 2002.



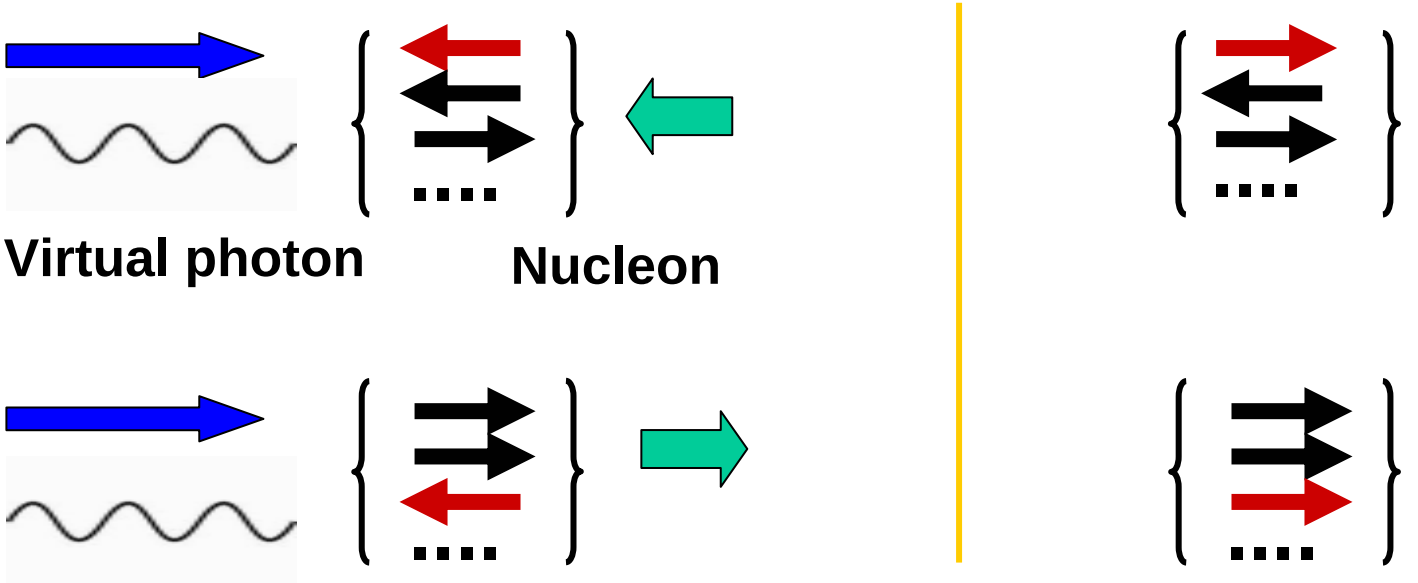
1. Flavor Separation of Quark Helicity Distributions

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

Double-spin asymmetry

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

Beam and target, both polarized



Virtual photon

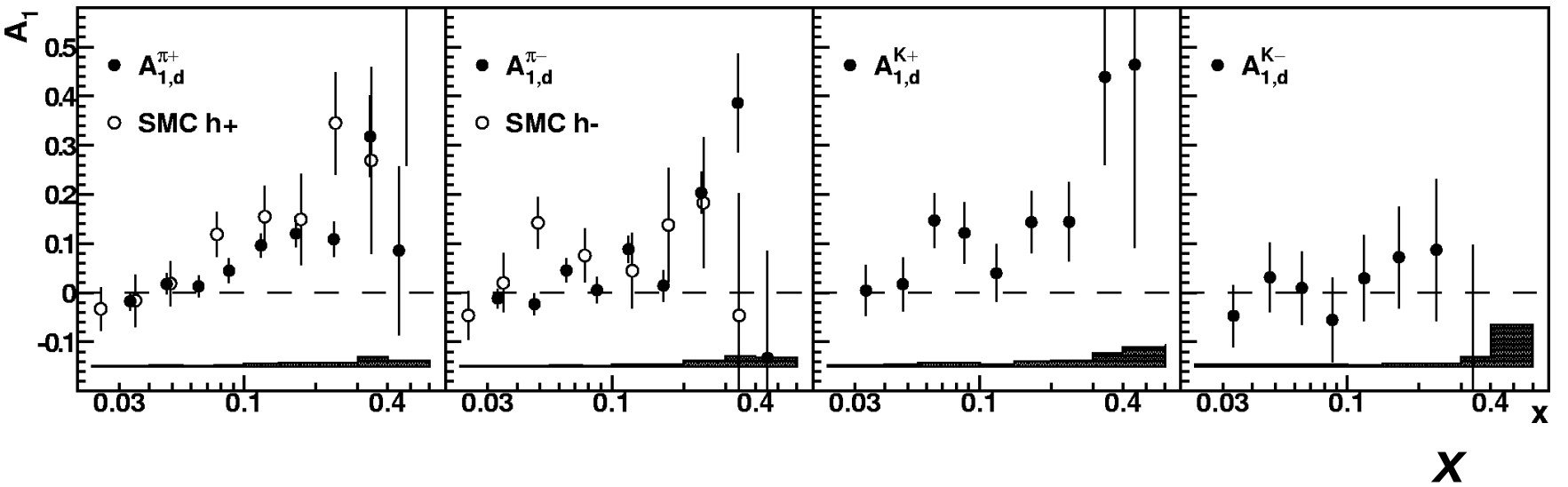
Nucleon

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

Double-spin asymmetries $A^h_1(d)$ from semi-inclusive DIS

Hadron identification for the first time

$A^h_1(x)$ π^+ π^- K^+ K^-



x

$\pi^{\pm}$,K^+ asymmetries similar to inclusive asymmetry, except K^- asymmetry.

HERMES

Quark Helicity Distributions , Flavor Separation

$\vec{e} + \vec{N} \rightarrow e' + m + X$ N = p, d m = $\pi^{\pm}$, $K^{\pm}$

Semi-inclusive DIS cross section

$$\sigma_h(x,z) \propto \sum_q e_q^2 \, q(x) \, D_q^h(z) \qquad z = E_h / \nu$$

Double-spin asymmetry

$$A_1^h(x,z) = \frac{\sigma_h^{\rightleftarrows}(x,z) - \sigma_h^{\rightrightarrows}(x,z)}{\sigma_h^{\rightleftarrows}(x,z) + \sigma_h^{\rightrightarrows}(x,z)} = \frac{\sum_q e_q^2 \Delta q(x) D_q^h(z)}{\sum_q e_q^2 q(x) D_q^h(z)}$$

$q(x) = q^{\rightarrow}(x) + q^{\leftarrow}(x)$ Quark Density Distributions

$\Delta q(x) = q^{\rightarrow}(x) - q^{\leftarrow}(x)$ Quark Helicity Distributions

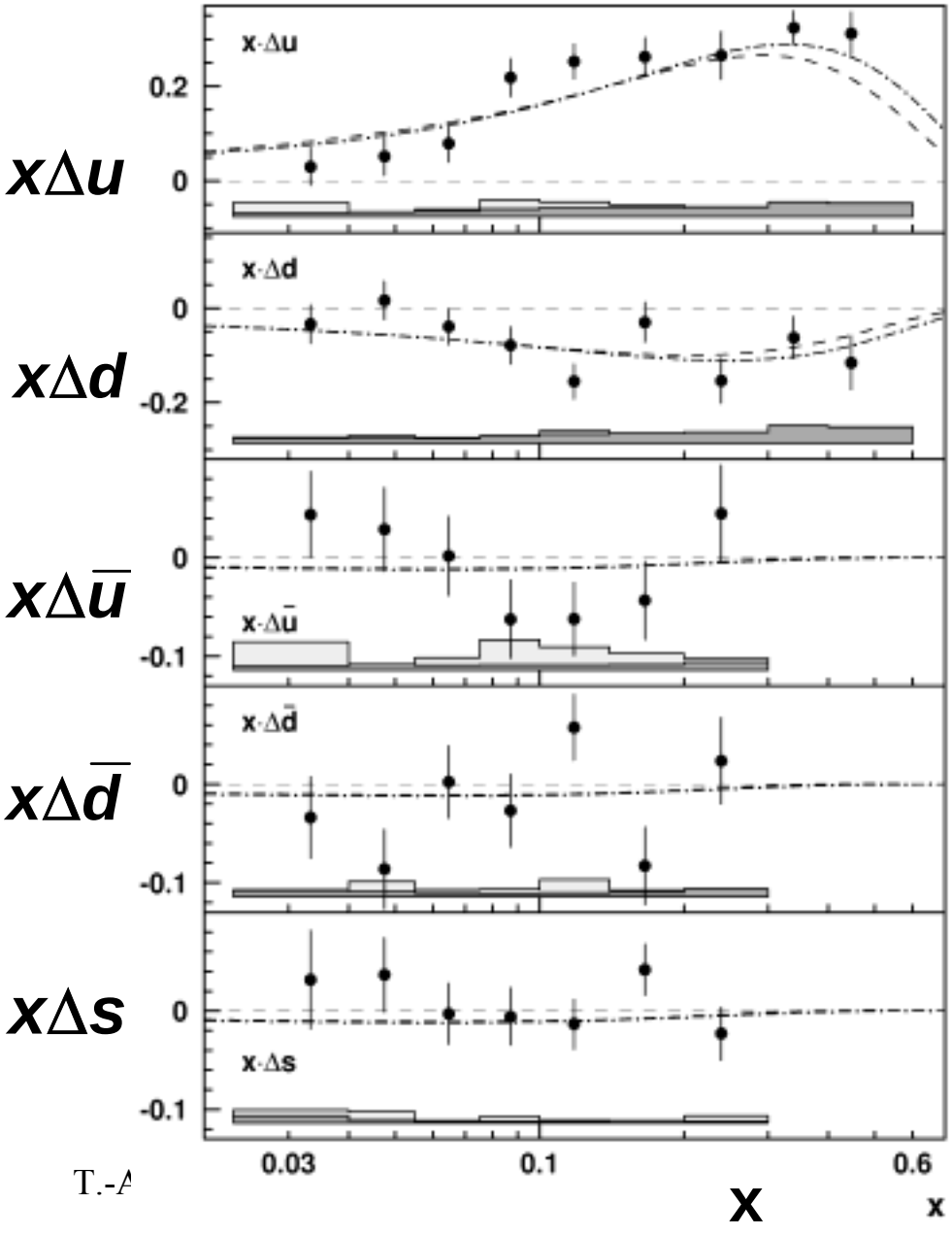
$$\vec{A}_1(x) = P(x) \cdot \vec{Q}(x) \qquad \vec{Q}(x) = \left(\frac{\Delta u}{u}, \frac{\Delta d}{d}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta \bar{d}}{\bar{d}}, \frac{\Delta s}{s}\right)$$

⇧

unpol. PDF and FF from data of unpol. semi-inclusive DIS

$\bar{s}$ unconstrained $\leftarrow K^-(\bar{u}s), K^+(u\bar{s})$

HERMES



Flavor Separation, Quark Helicity Distributions

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

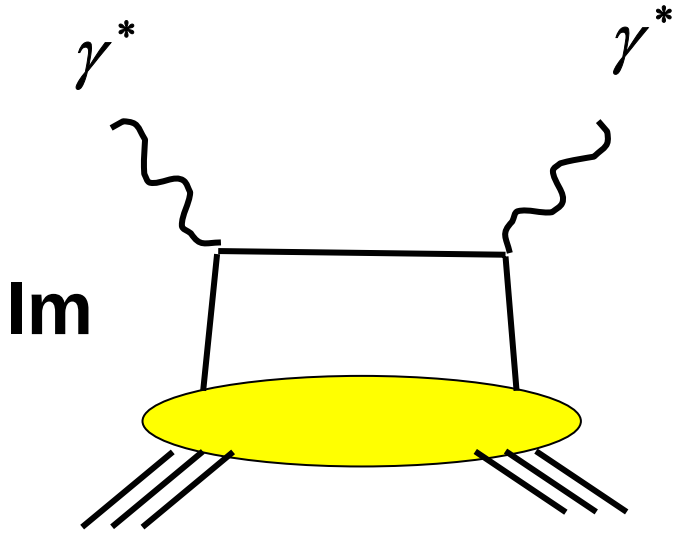
2. Deeply Virtual Compton Scattering

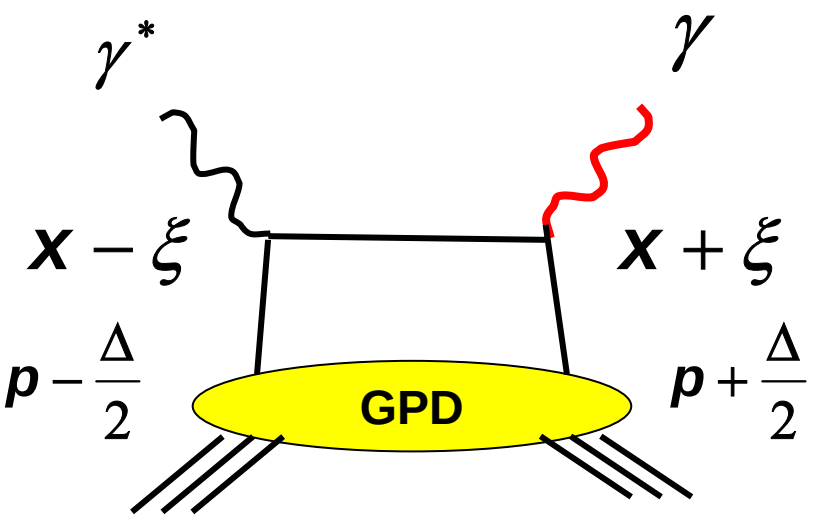
-- Generalized (Off-forward) Parton Distributions

Coss section for inclusive deep inelastic scattering

Deeply Virtual Compton Scattering (DVCS)

-- Exclusive production of a real photon



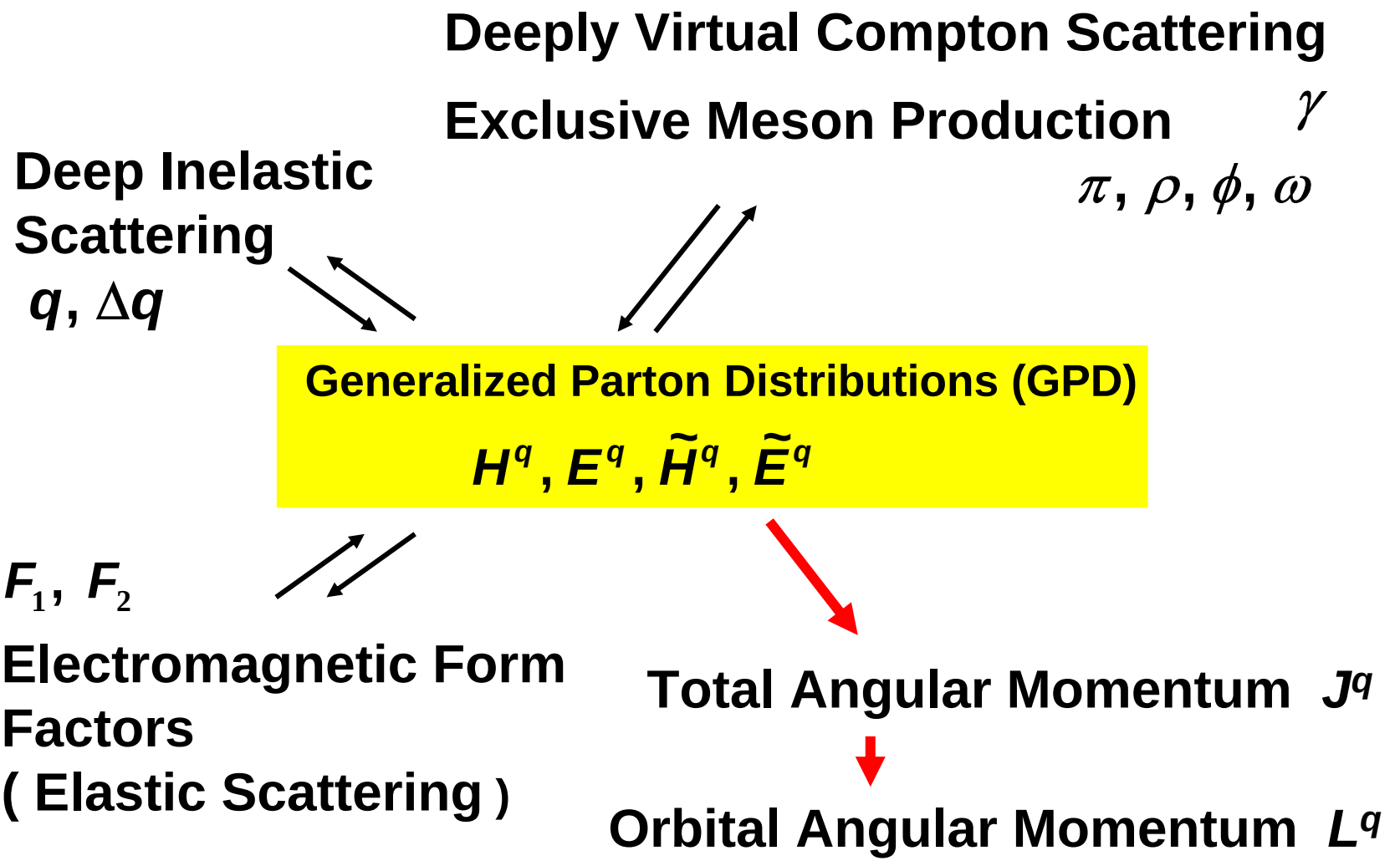


x :Light cone momentum fraction

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

$t = \Delta^2$:Momentum transfer

Generalized (Off-Forward) Parton Distributions



Generalized 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

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

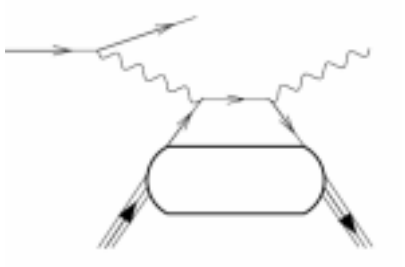
2nd moment

Total angular momentum

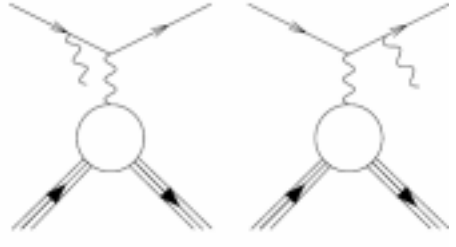
$$J^q = \frac{1}{2}\Delta q + L_z^q$$

Orbital angular momentum

How to measure DVCS



Deeply Virtual Compton Scattering

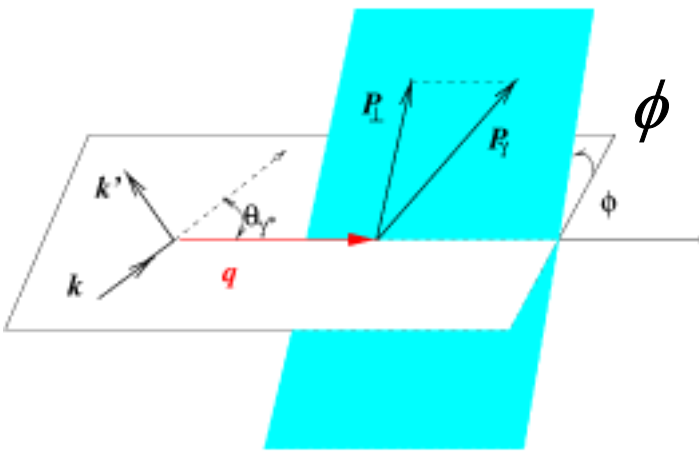


Bethe-Heitler Process, known calculable

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

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

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



Beam-spin asymmetry by HERMES and CLAS

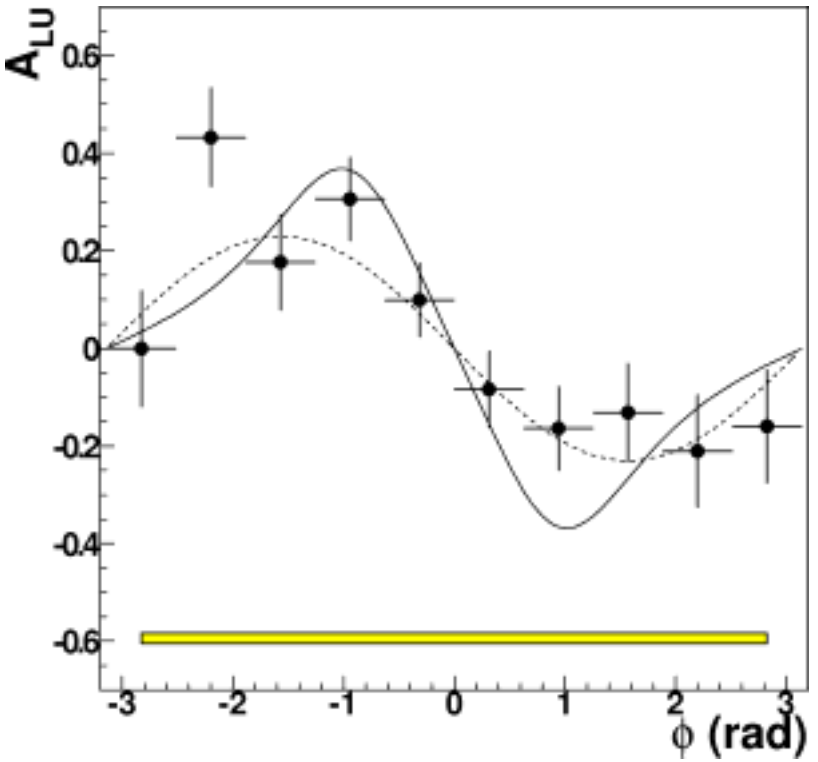
Beam-charge asymmetry by HERMES

-- DVCS-BH Interference, Real and Imaginary

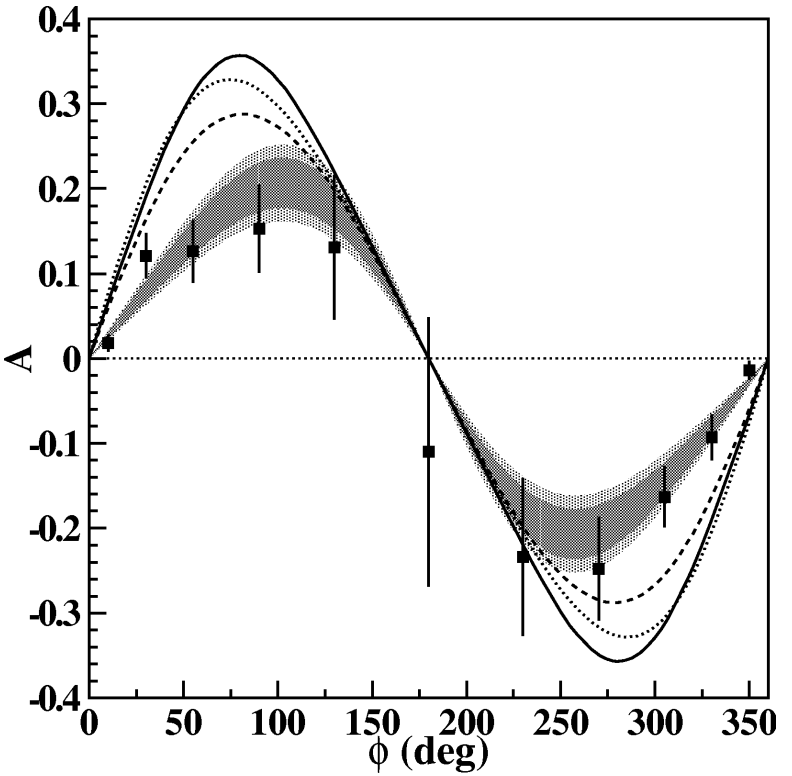
Deeply Virtual Compton Scattering

First observation of beam-spin asymmetry of DVCS

A_{LU} HERMES (2001)



CLAS (2001)

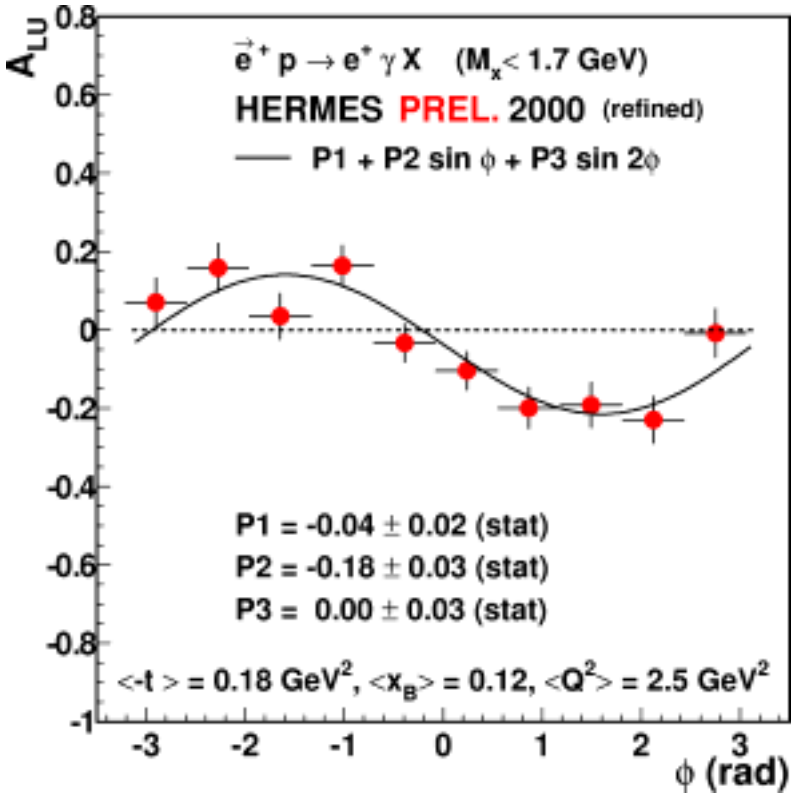


ϕ **~ 30% effect** ϕ

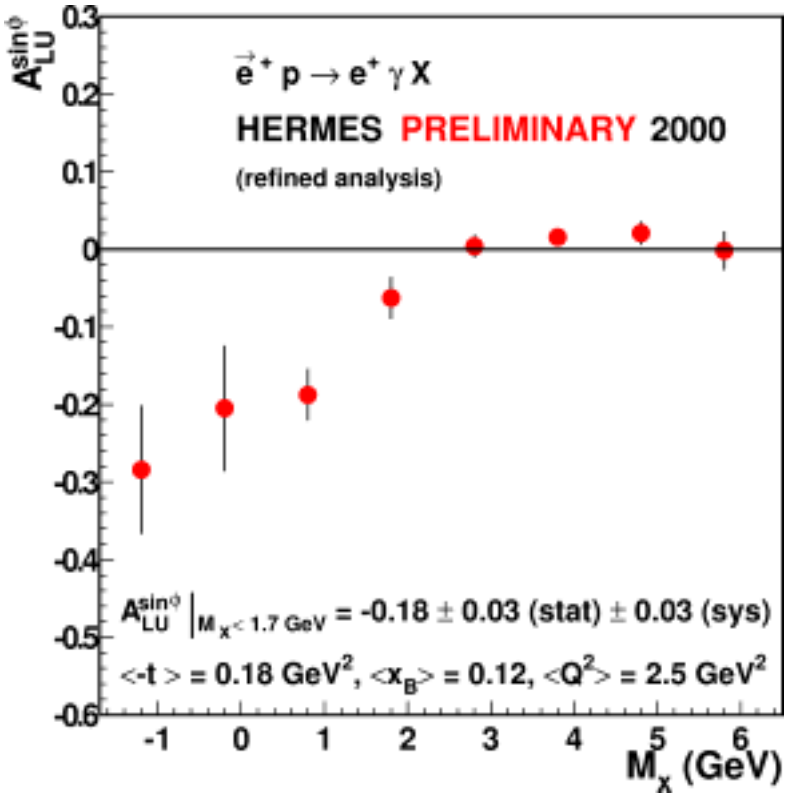
Beam-Spin Asymmetry

$\sin\phi$ Moment

HERMES



ϕ

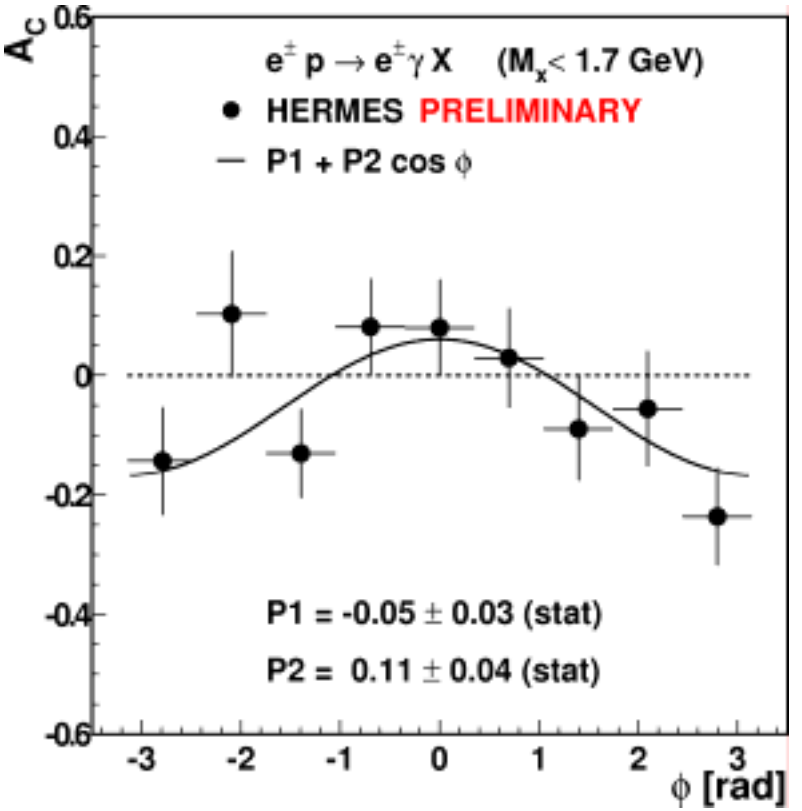


M_X

Missing Mass Resolution 0.8 GeV

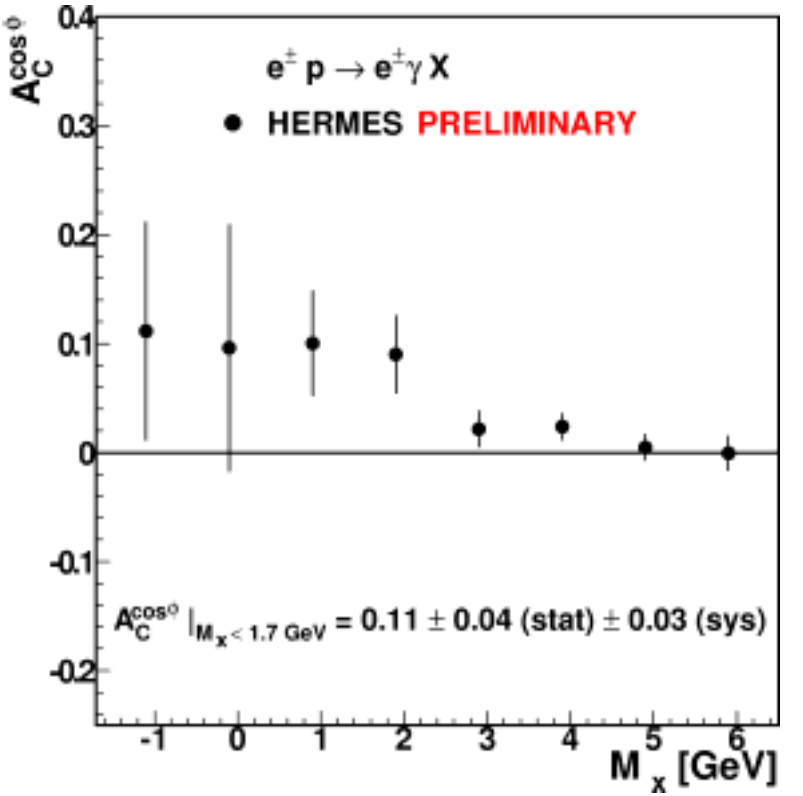
HERMES

Beam-Charge Asymmetry



ϕ

$\cos\phi$ Moment



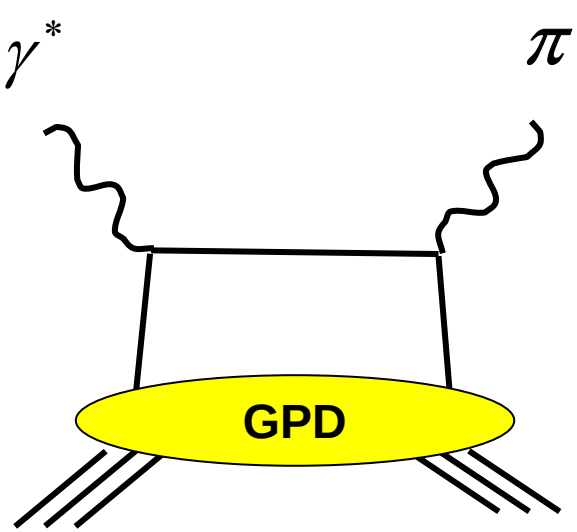
M_X

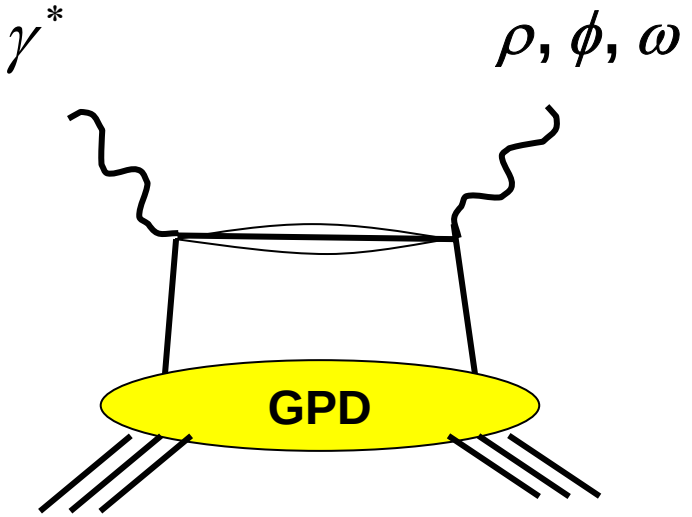
Missing Mass Resolution 0.8 GeV

How to extend

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

Exclusive Meson Productions





Pseudo scalar meson

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

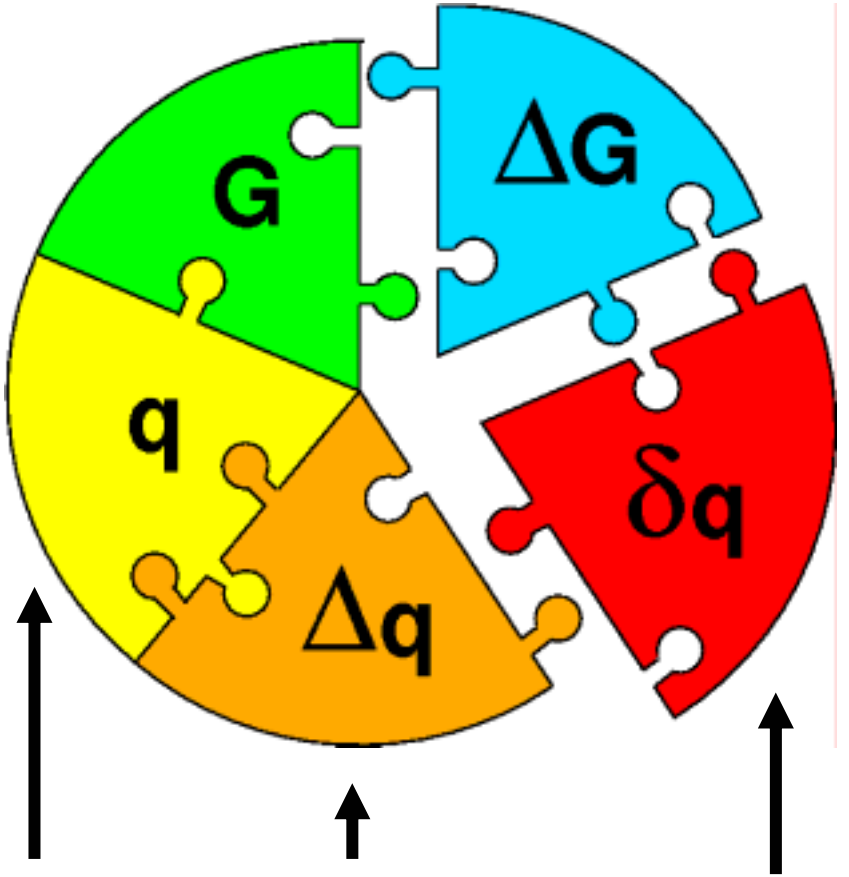
Vector meson

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

HERMES's data

3. Single-Spin Azimuthal Asymmetry in Semi-inclusive Deep Inelastic Scattering

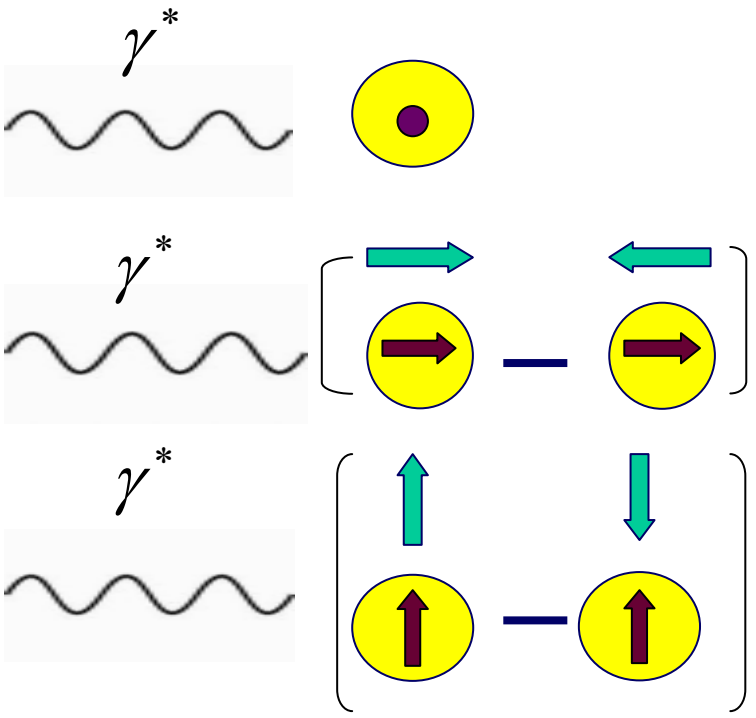
‘Quark Transversity Distributions $\delta q(x)$ ’



3 leading twist quark distributions

δq : **Last unmeasured leading twist distribution**

Single-Spin Azimuthal Asymmetries in Semi-Inclusive DIS, Transversity



Quark Density Distributions

$q(x)$ Spin averaged, vector charge

Quark Helicity Distributions

$\Delta q(x)$ Helicity difference, axial charge

Quark Transversity Distributions

$\delta q(x)$ Helicity flip, tensor charge

$$|\delta q(x)| \le \frac{1}{2}|q(x)+\Delta q(x)|$$

Soffer bound

$$A^h \approx \sum_q e_q^2 \, \delta q(x) \cdot H_{1,q}^{\perp h}(z)$$

$\delta q(x)$ is Chiral Odd. Not accessible with inclusive DIS

It is accessible with semi-inclusive DIS,

accompanied with a Chiral Odd Fragmentation Function $H_1^{\perp}(z)$

$\delta q(x)$ does not couple with gluon. (Collins FF)

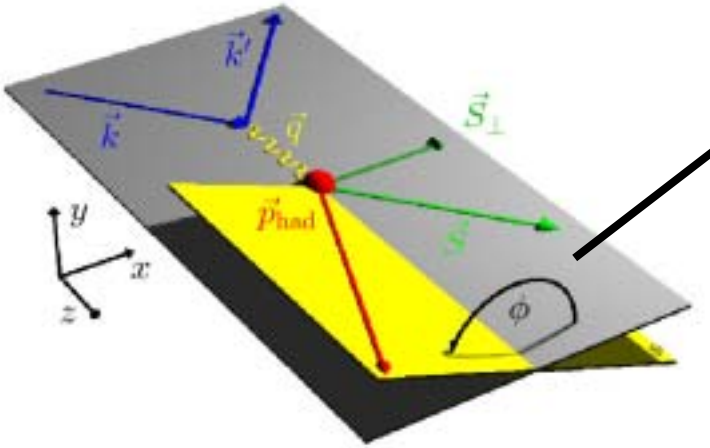
⇨ Q^2 evolution is different from $q(x)$, $\Delta q(x)$

$e + N \rightarrow e' + m + X$

$N\rightarrow$ HERMES, JLab

$N\uparrow$ HERMES, COMPASS, JLab

Longitudinally Polarized Target



Azimuthal Angle ϕ

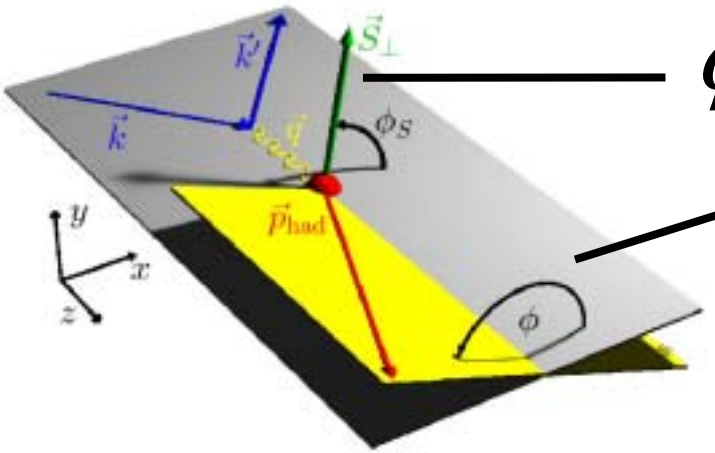
$$S_T \approx \frac{2Mx}{Q}\sqrt{1-y}$$

$$= \langle \sin\theta\gamma \rangle \approx 0.15$$

with respect to γ^*

ϕ dependence

Transversely Polarized Target



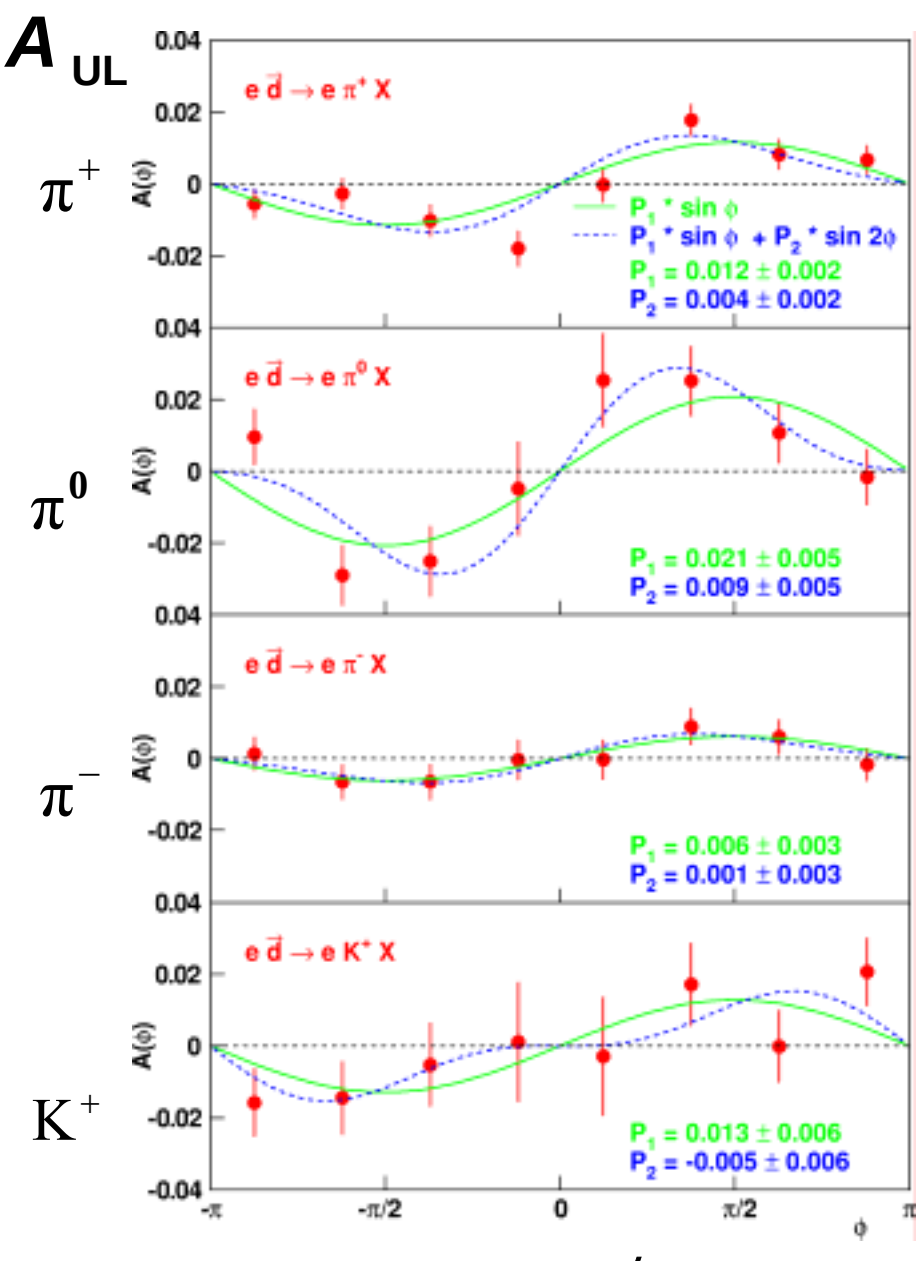
ϕ_S

Azimuthal Angle ϕ

$\phi + \phi_S$ dependence

$\phi - \phi_S$ dependence

Single-Spin Azimuthal Asymmetries in Semi-Inclusive DIS



Longitudinally polarized target ,
Target Spin Asymmetry A_{UL}

$$e + \vec{d} \to e' + m + X$$

$$A_{UL}(\phi) = \frac{1}{|p_L|} \cdot \frac{N^{\rightarrow}(\phi)/L^{\rightarrow} - N^{\leftarrow}(\phi)/L^{\leftarrow}}{N^{\rightarrow}(\phi)/L^{\rightarrow} + N^{\leftarrow}(\phi)/L^{\leftarrow}}$$

——— $P_1 \cdot \sin\phi$

- - - - $P_1 \cdot \sin\phi + P_2 \cdot \sin 2\phi$

→ $A_{UL}^{\sin\phi}$ **positive for π^+, π^0, K^+**
Increases with *x*
nearly zero for π^-

$\sin 2\phi$ **moment ~ 0**

HERMES

$$A_{UL}^{\sin\phi} \sim S_L < \sin\phi >_{UL} - S_T < \sin\phi >_{UT}$$

Origins of $< \sin\phi >$ moment, Longitudinally polarized target

$$\phi_S = 0$$

$$< \sin\phi >_{UL} \sim \frac{1}{Q} \sum_q e_q^2 \, (h_L^q(x) \, H_1^{\perp,q}(z) - \frac{1}{z} h_{1L}^{\perp,q}(x) \, \tilde{H}(z))$$

$$< \sin\phi >_{UT} \sim \sum_q e_q^2 \, \delta q(x) \, H_1^{\perp,q}(z)$$

Collins Effect:

(Quark transversity distribution) x (Chiral odd FF)

$$\sim \sum_q e_q^2 \, f_{1T}^{\perp}(x) \, D_1^q(z)$$

Sivers Effect:

(⟹ *see also polarized pp collisions*)

Transversely polarized target data can distinguish between the two. S_T becomes dominant.

$< \sin(\phi + \phi_s) >_{UT}$ **moment: Collins Effect**

$< \sin(\phi - \phi_s) >_{UT}$ **moment: Sivers Effect**

HERMES (2002--) focused on it. 700K D.I.S. events recorded.

Further data taking 2003-- . COMPASS data at higher Q^2, JLab Q^2 evolution of $\delta q(x, Q^2)$

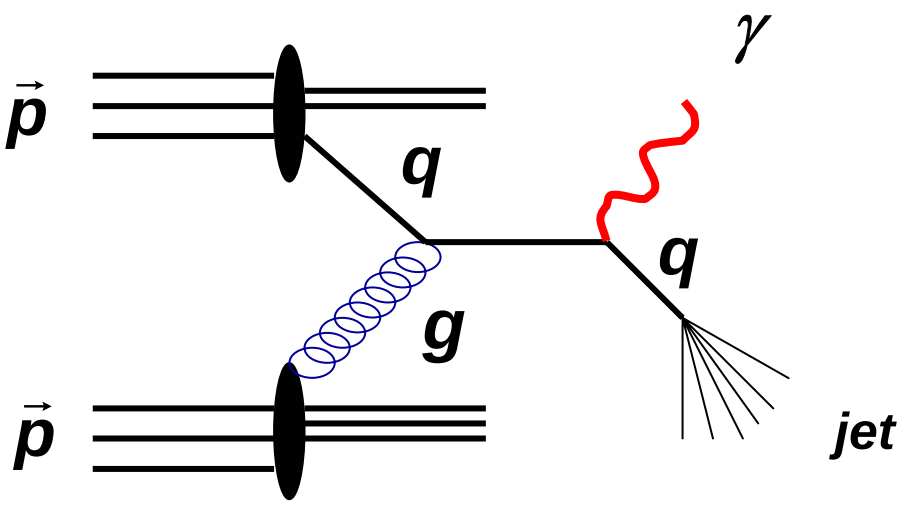
Polarized Proton-Proton Collisions

Polarized Parton-Parton Collision

Gluon spin contribution to the nucleon spin

Gluon Compton scattering

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



2 jet production

Inclusive π^0 measurement

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

$$g + q$$

$$q + q$$

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

Polarized pp Collisions at RHIC

100 GeV + 100 GeV

2001/2002 **P = ~0.2, Int L ~ 0.3 pb^{-1}, transverse**

- May 2003 **P = ~0.3, Int L ~ 0.8 pb^{-1}, transverse + longitudinal**

Physics Goal **P = 0.7, Int L = 320 pb^{-1} , at 100 + 100 GeV**

800 pb^{-1} , at 250 + 250 GeV

PHENIX and STAR collected data of inclusive π^0 production

Single-Spin Asymmetry, Transversely Polarized Beam

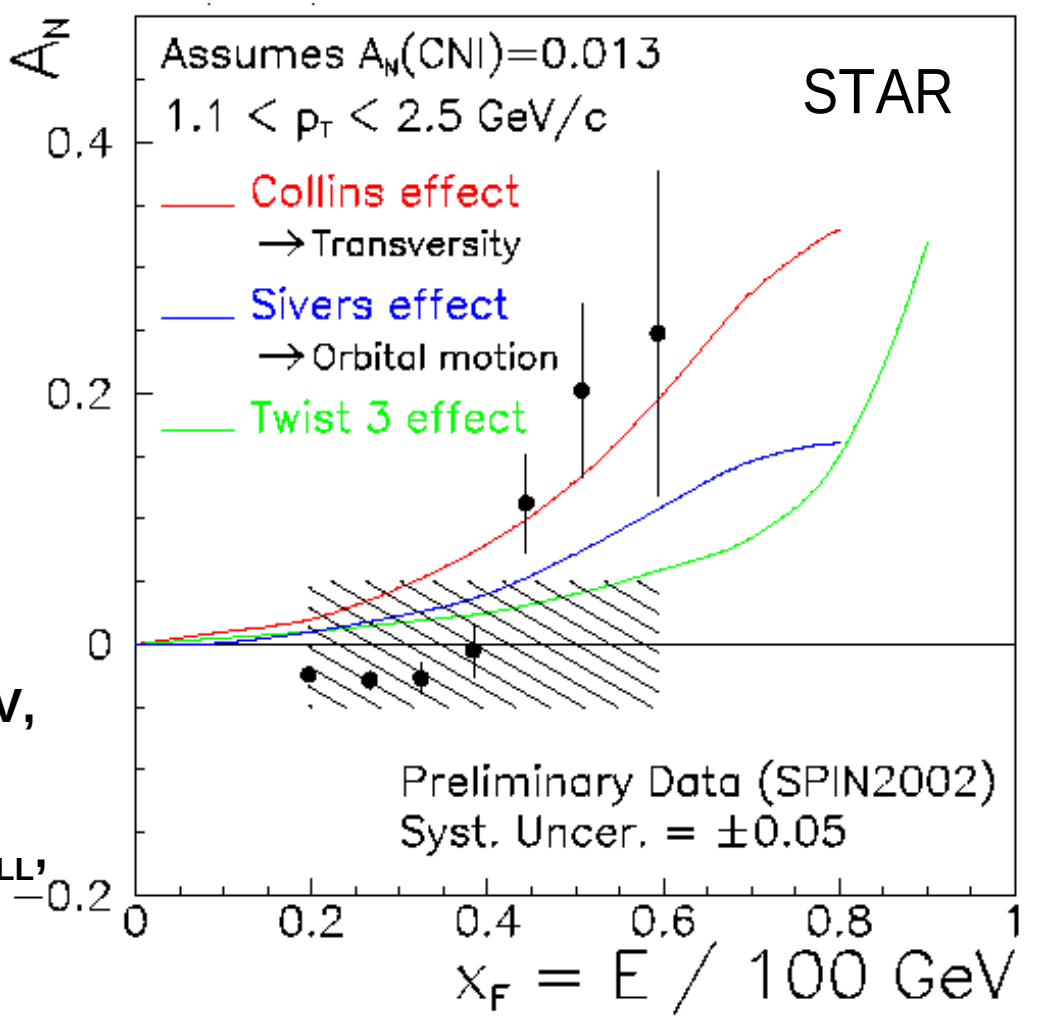
$$p_\uparrow + p \rightarrow \pi^0 + X\,,$$

$$\sqrt{s} = 200\ \mathrm{GeV}$$

Forward π^0, small p_T

Similar to the earlier Fermilab data at √s=20 GeV, p_T = 0.5-2.0 GeV/c

Double spin asymmetry, A_{LL}, at large p_T will become available soon



Conclusions 1

- To understand hadrons in terms of QCD, Spin Structure of the Nucleon is an important subject.
- Many experiments are currently running with $e, \mu, \gamma, p \ldots$ beams at different labs in the world.
- Flavor separation of quark helicity distributions Δq has been made.
- Deeply Virtual Compton Scattering provides access to Generalized Parton Distributions.
- Single-spin azimuthal asymmetries in semi-inclusive DIS have been observed. Quark Transversity Distributions δq is a new subject which is being investigated. Results from transversely polarized targets will become available soon.

Conclusions 2

- Polarized proton-proton collider has now longitudinally as well as transversely polarized beams. Single-spin asymmetries in π^0 productions at small angles from transversely polarized beam have been obtained. The asymmetries at large p_T are being analyzed.

- Spin physics with the nucleon is a rapidly expanding field. Many new ideas of measurements are being proposed. High precision data as well as new surprises are expected.