July 29, 2013
RIKEN

Deep Inelastic Scattering and Drell-Yan Experiments

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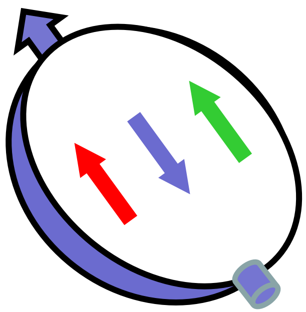
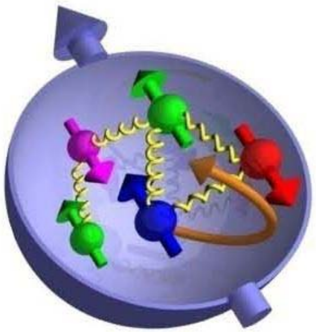
Spin Structure of the Nucleon





Proton spin, 1/2 :
determined by the specific heat of hydrogen molecular (1927)

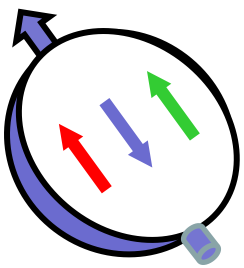
Hydrogen atom, proton spin and electron spin, 21 cm wavelength, astronomy

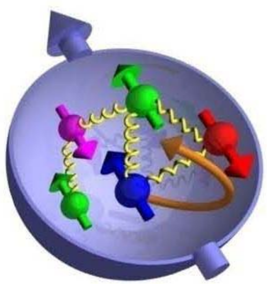
Application, MRI (Magnetic Resonance Imaging) for medical use

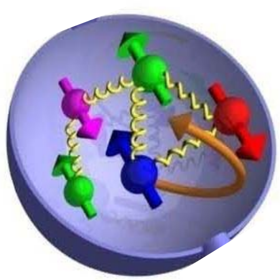
Event by event

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

Spin Structure of the Nucleon







Polarized nucleon

Unpolarized nucleon

Correlation between Quark Spin and its Transverse Momentum in Unpolarized nucleon

Spin-orbit interaction

nth moment

Physics of 1st moment

Integration over *x* from 0 to 1

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

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

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

Analysis of Quark Spin Contribution to the Nucleon Spin

Milestones, HERMES

2001 Deeply Virtual Compton Scattering and Exclusive Hadron Productions — Phys. Rev. Lett. 87 (2001) 182001

2005 Extraction of Collins Asymmetry — Phys. Rev. Lett. 94 (2005) 012002

2007 Quark Spin Contribution to the Nucleon Spin

33 ± 3.9 % — Phys. Rev. D 75 (2007) 012007

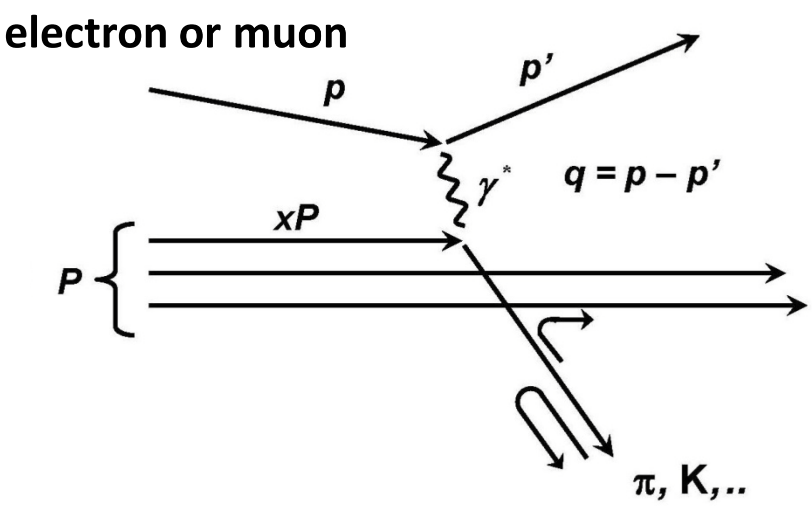
2009 Extraction of Sivers Asymmetry — Phys. Rev. Lett. 103 (2009)152002

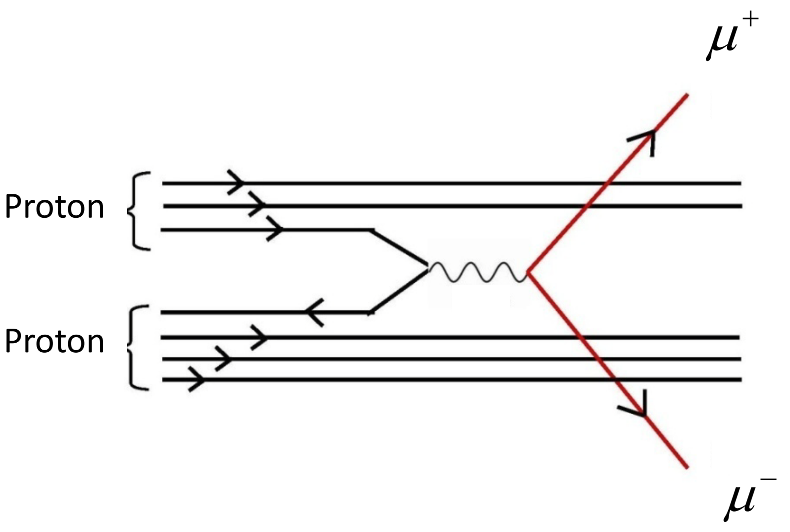
2013 Extraction of Azimuthal Angle Dependence with Unpolarized Targets

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

Deep inelastic scattering

Drell-Yan process



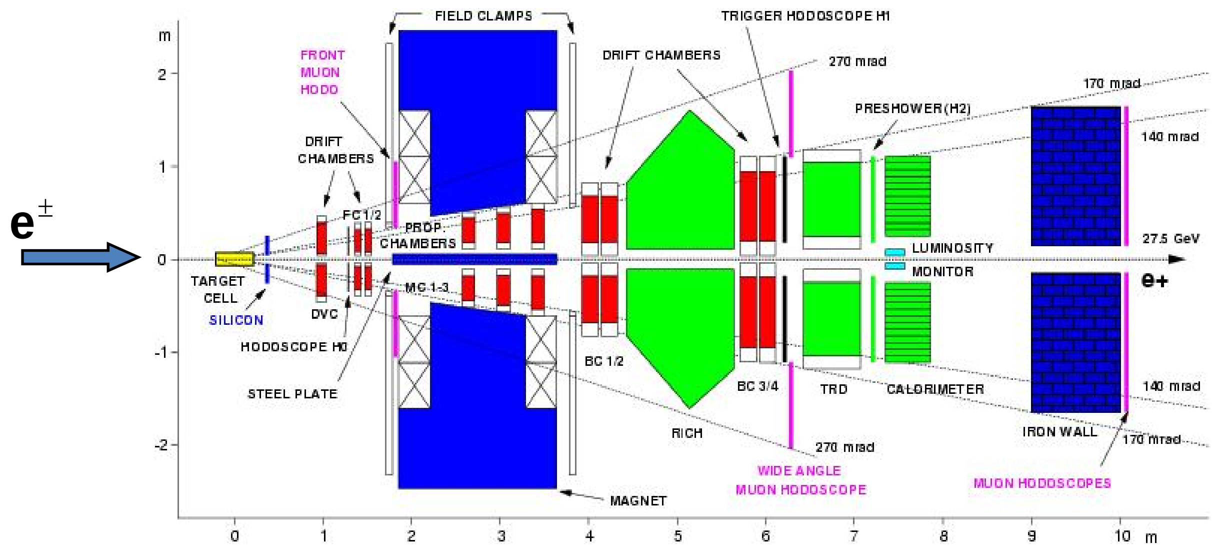


Space-like virtual phton

Time-like virtual photon

HERMES Experiment at DESY－HERA

E_e = 27.6 GeV

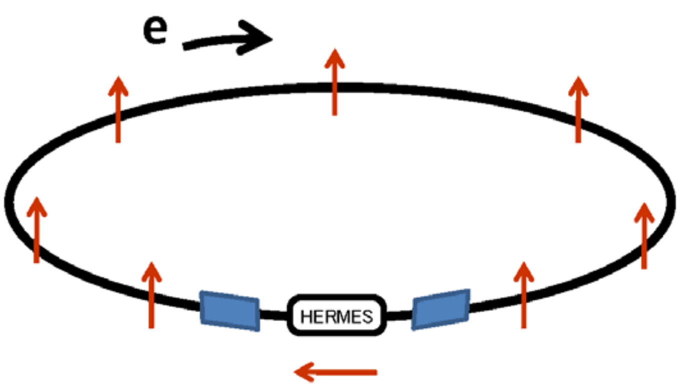


Proton, Deuteron Targets

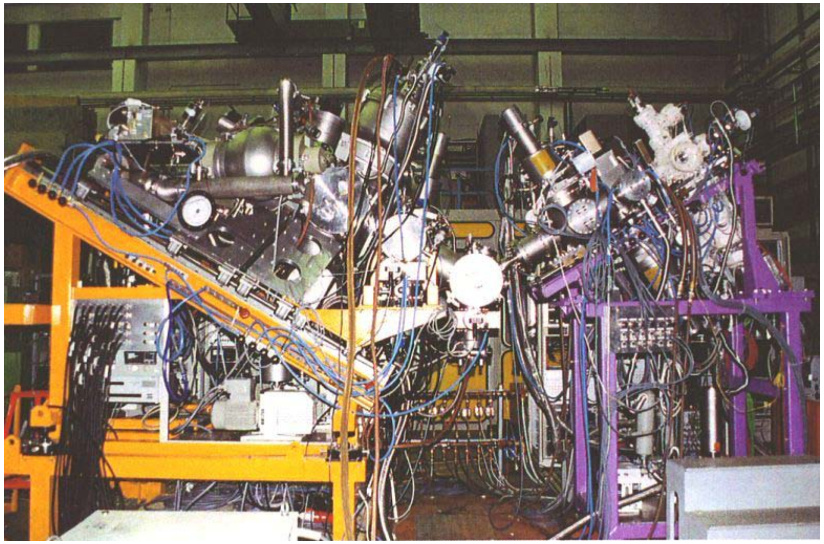
Pion, Kaon Identification with RICH

HERMES Experiment at DESY－HERA

Polarized electron (positron) beam



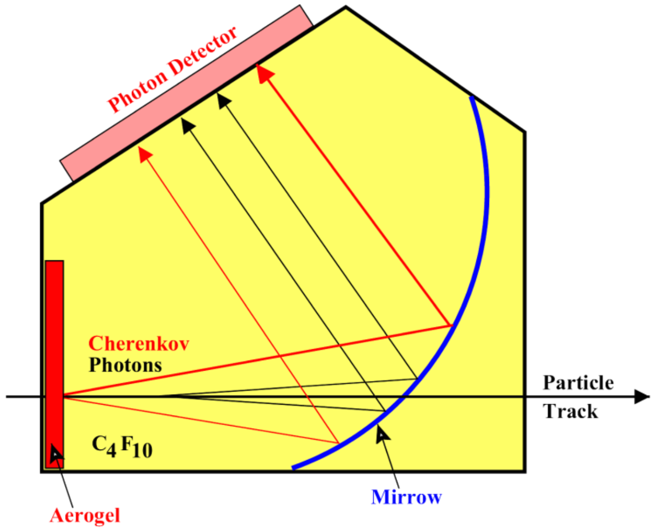
Polarized internal targets

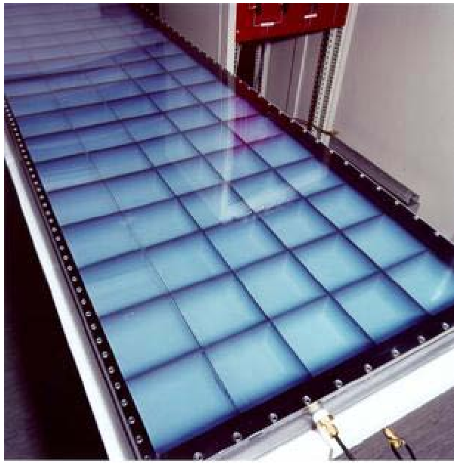


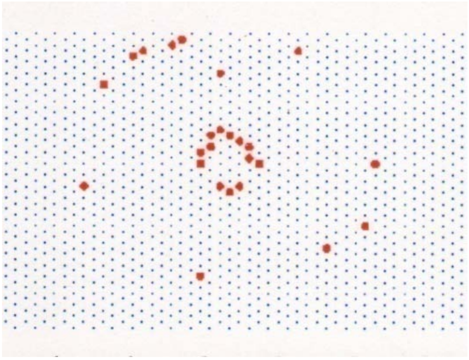
Hadron Identification

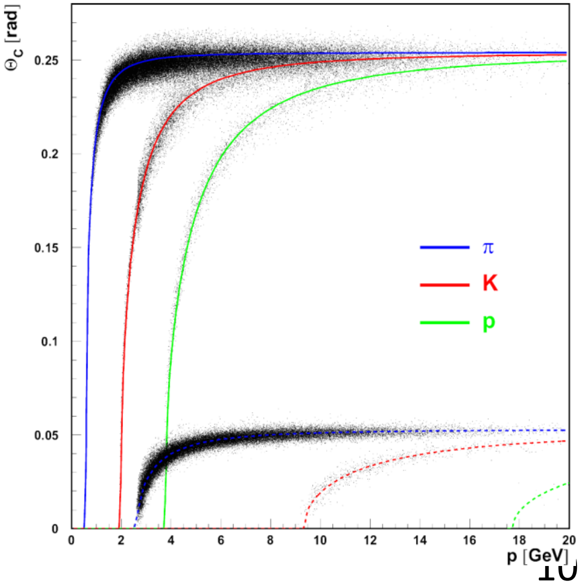
RICH

radiator: Aerogel, C_4F_{10}





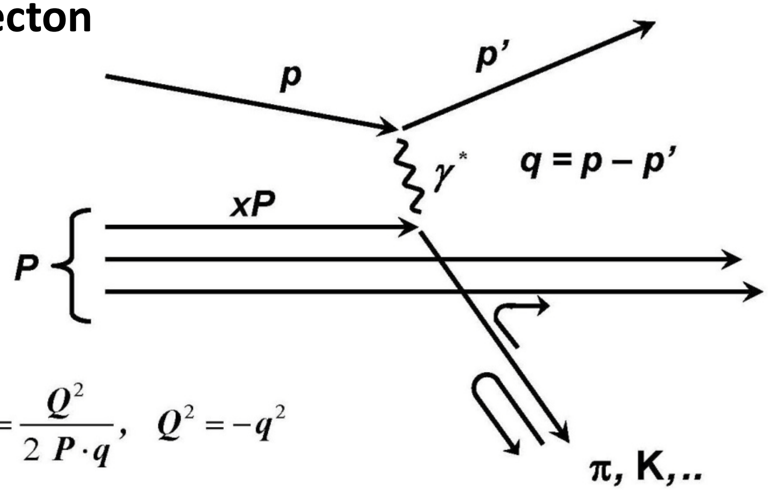




Event by event measurement

Deep inelastic scattering

electon



$$x = \frac{Q^2}{2\,P \cdot q}, \quad Q^2 = -q^2$$

Event by event

Hadron coincidence

$$Q^2 > 1\,\mathrm{GeV}^2,\ \ W > 3.3\ \mathrm{GeV},$$
$$0.023 < x < 0.6, \quad 0.2 < y < 0.85$$
$$z > 0.2,\ \ x_F > 0.2,\ \ 1 < P_h < 15\ \mathrm{GeV}$$

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

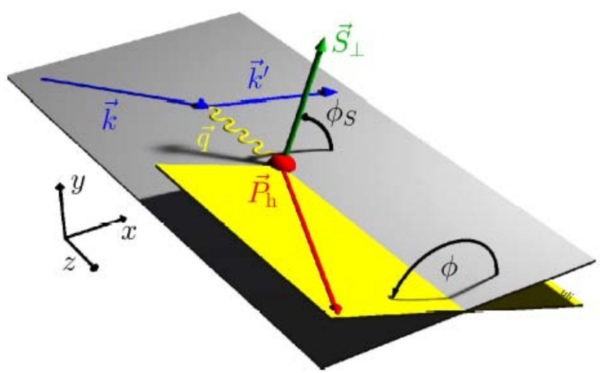
Bjorken *x* is the momentum fraction of the parton in Breit frame

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

Event by event

Azimuthal Angle dependence

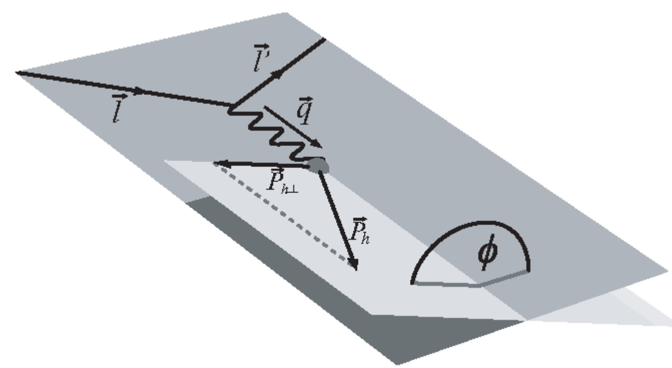
Transversely polarized nucleon



$$\cos(\phi-\phi_s),\quad \cos(\phi+\phi_s)$$

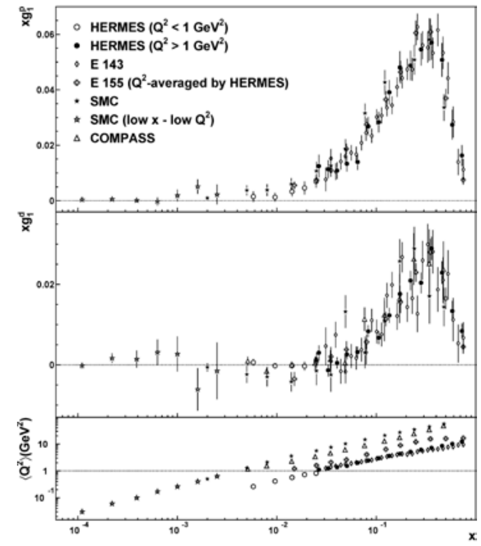
Sivers asymmetry, Collins asymmetry

Unpolarized nucleon



HERMES , 5 dimensional analysis

$$\mathbf{x,\ y,\ z,\ P_{h\perp},}\ \phi$$

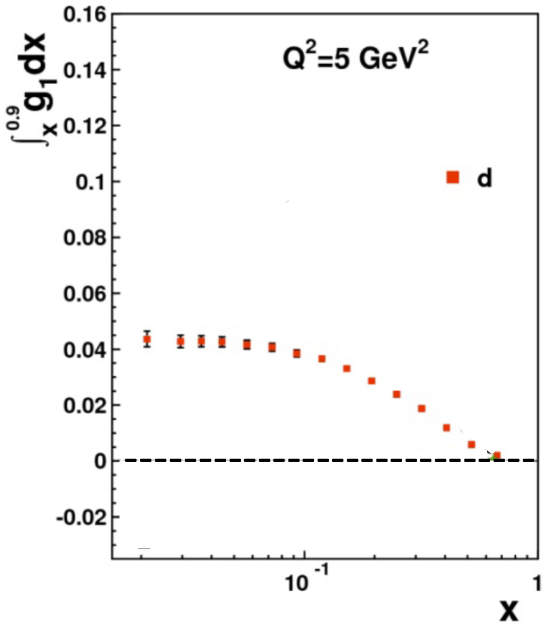


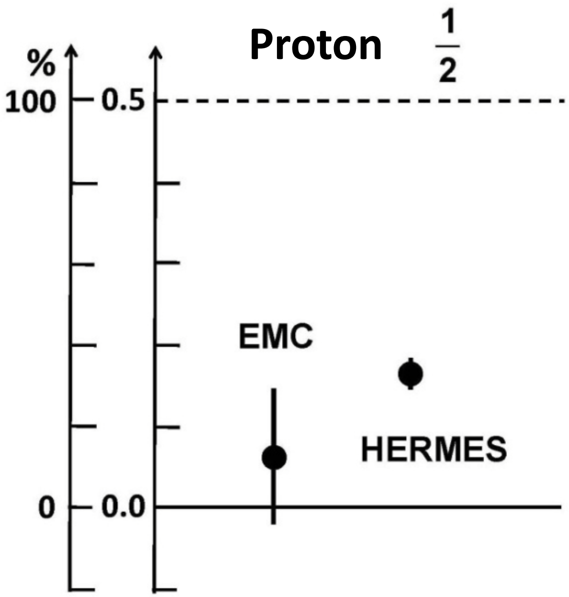
Longitudinal spin structure

- Quark spin contributions to the proton spin

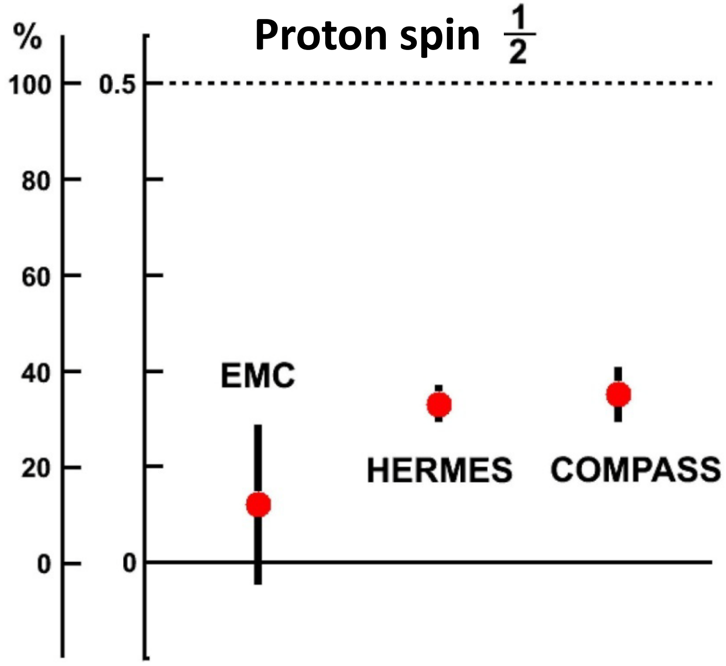
The 1st moment

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



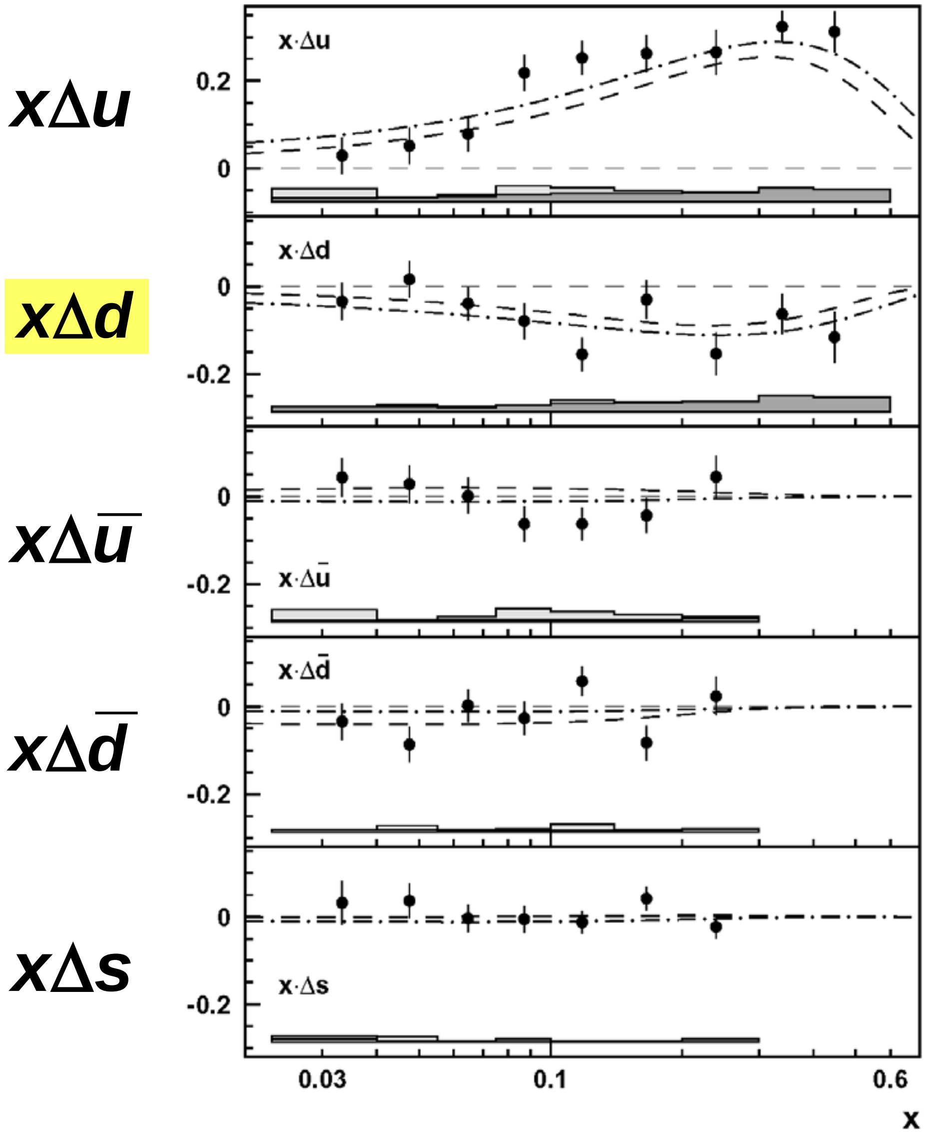


33 ± 3.9 %



33±3.9 %

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
- - - -

Azimutal asymmetry with unpolarized nucleon

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

$$F_{UU}^{\cos 2\phi} \propto -\sum_q\left[h_1^{\perp,q}(x,\underline{p_T^2})\otimes_{\mathcal{W}_1} H_1^{\perp,q}(z,\underline{k_T^2})\right].$$

Boer-Mulders Distribution Function,
Collins Fragmentation Function

Correlation of transverse momentum and transverse spin of quarks

$$F_{UU}^{\cos\phi} \simeq -\frac{M}{Q}\sum_q\left[h_1^{\perp,q}(x,p_T^2)\otimes_{\mathcal{W}_3} H_1^{\perp,q}(z,k_T^2)\right] -\frac{M}{Q}\sum_q\left[f_1^q(x,\underline{p_T^2})\otimes_{\mathcal{W}_4} D_1^q(z,\underline{k_T^2})\right].$$

Cahn Effect

Average transverse momentum of unpolarized quarks

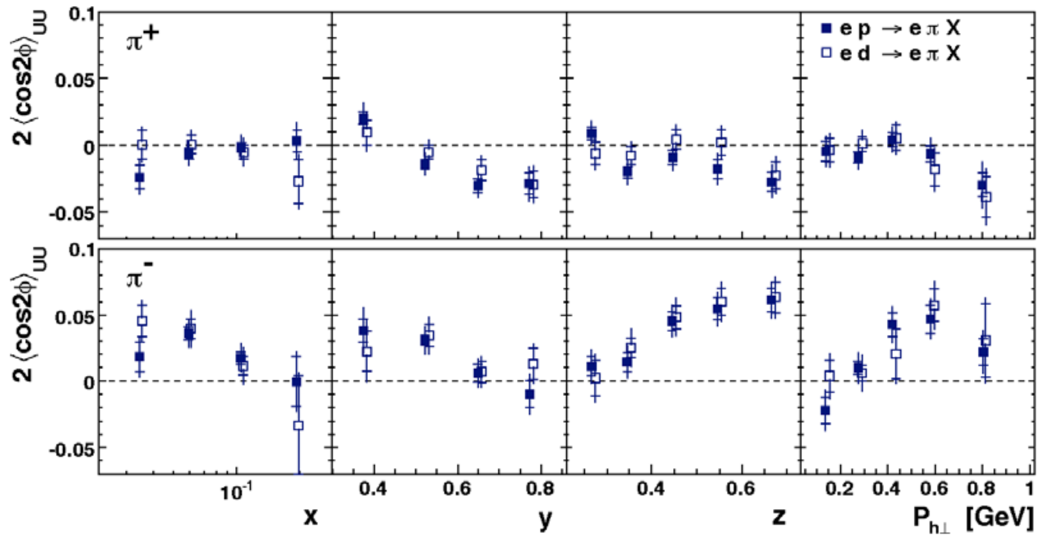
Moment: $$\langle\cos n\phi\rangle_{UU} = \frac{\int_0^{2\pi}\cos n\phi\, d\sigma_{UU}\,\mathrm{d}\phi}{\int_0^{2\pi} d\sigma_{UU}\,\mathrm{d}\phi}$$

Results

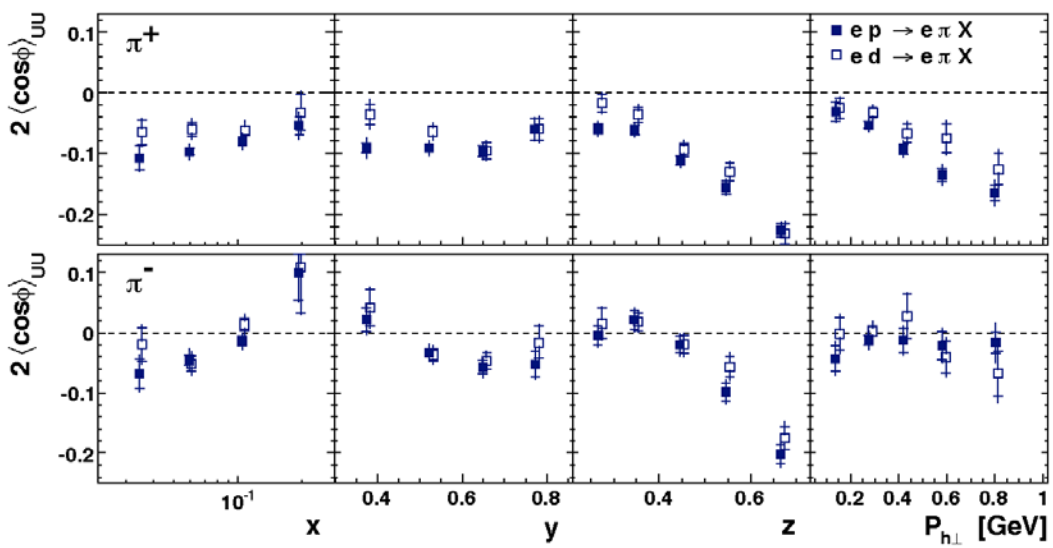
Proton and Deuteron Targets

$\pi^{\pm}$

$\cos 2\phi$



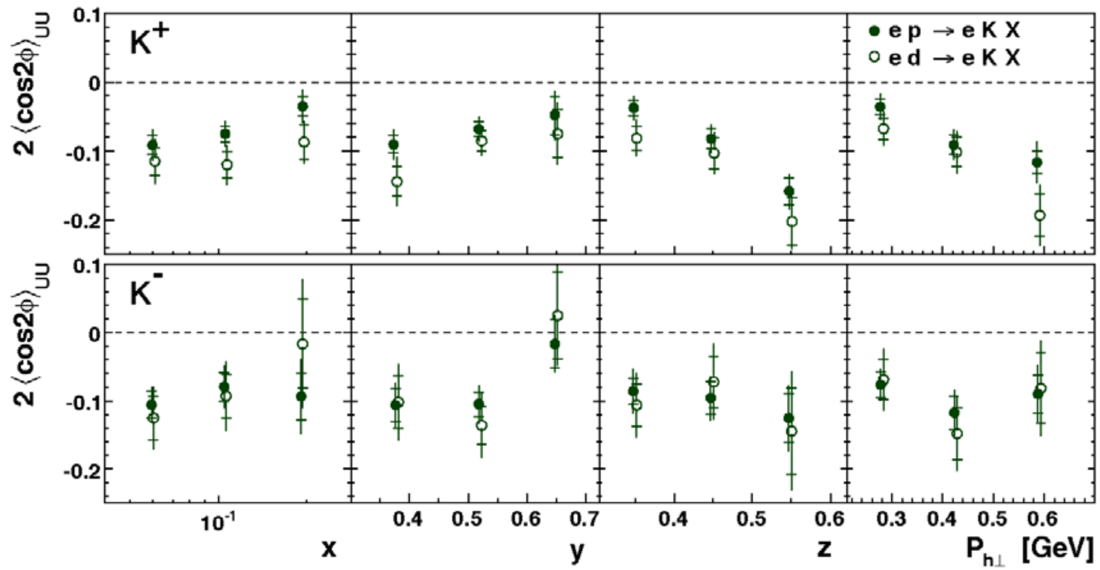
$\cos \phi$



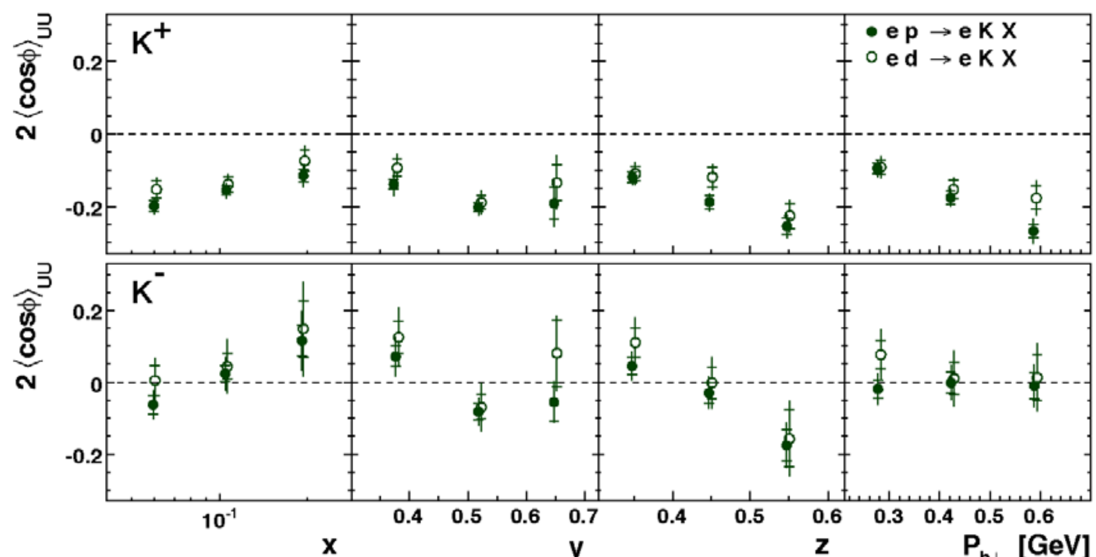
$K^{\pm}$

Proton and Deuteron Targets

$\cos 2\phi$



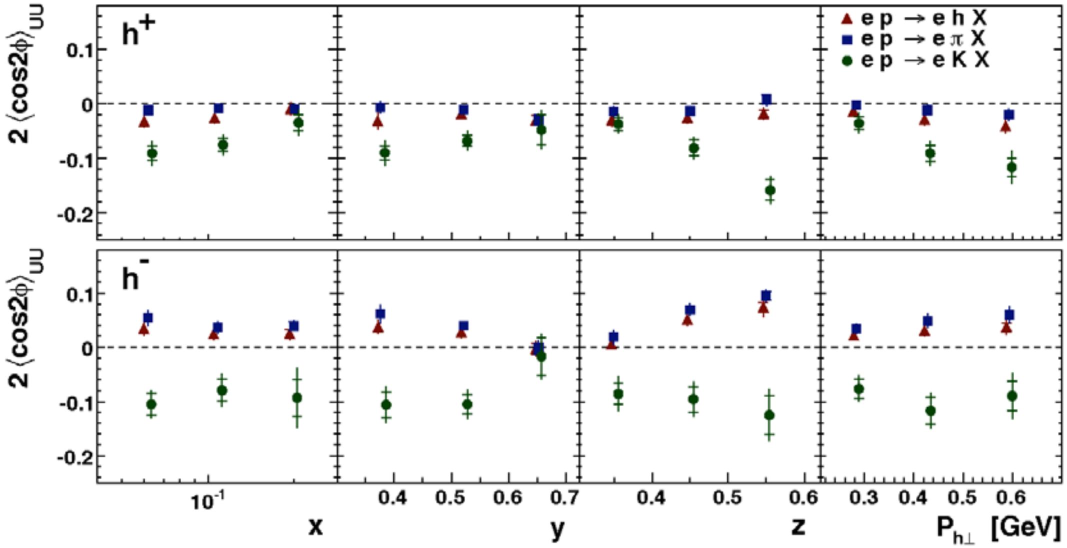
$\cos \phi$



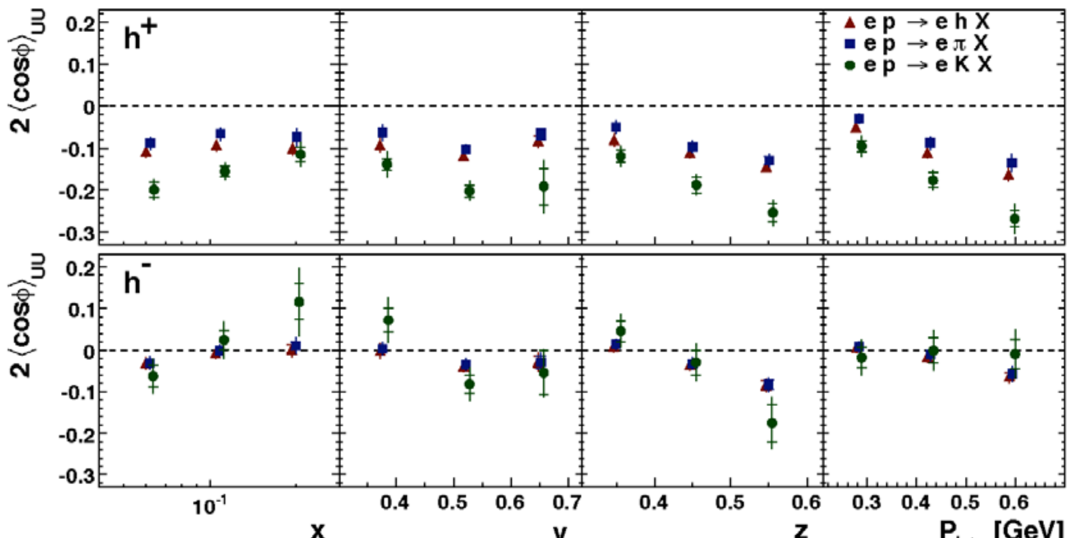
$\pi^{\pm}$ and $K^{\pm}$ comparison

Proton Target

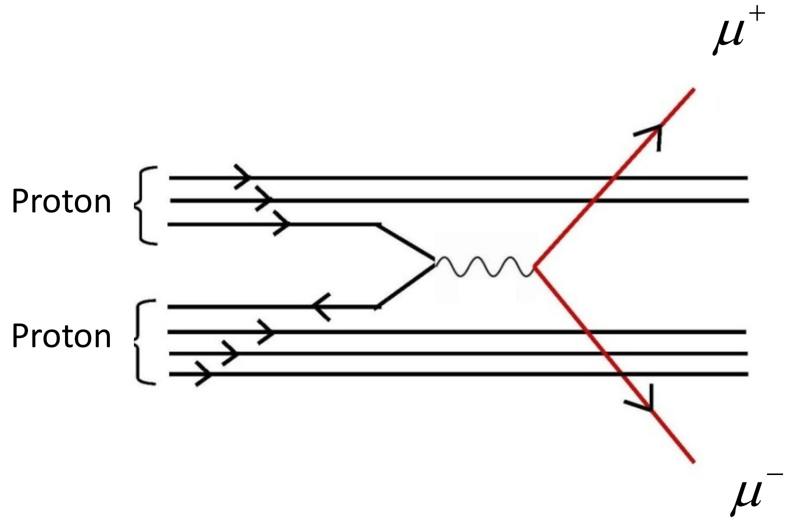
cos 2ϕ



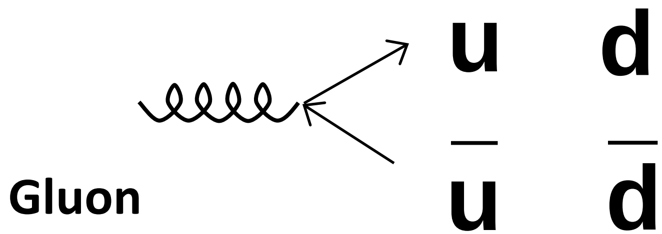
cos ϕ

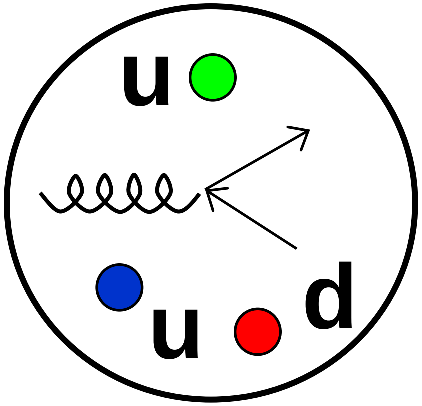


Drell-Yan process



Flavor asymmetry of anti-quarks in the proton





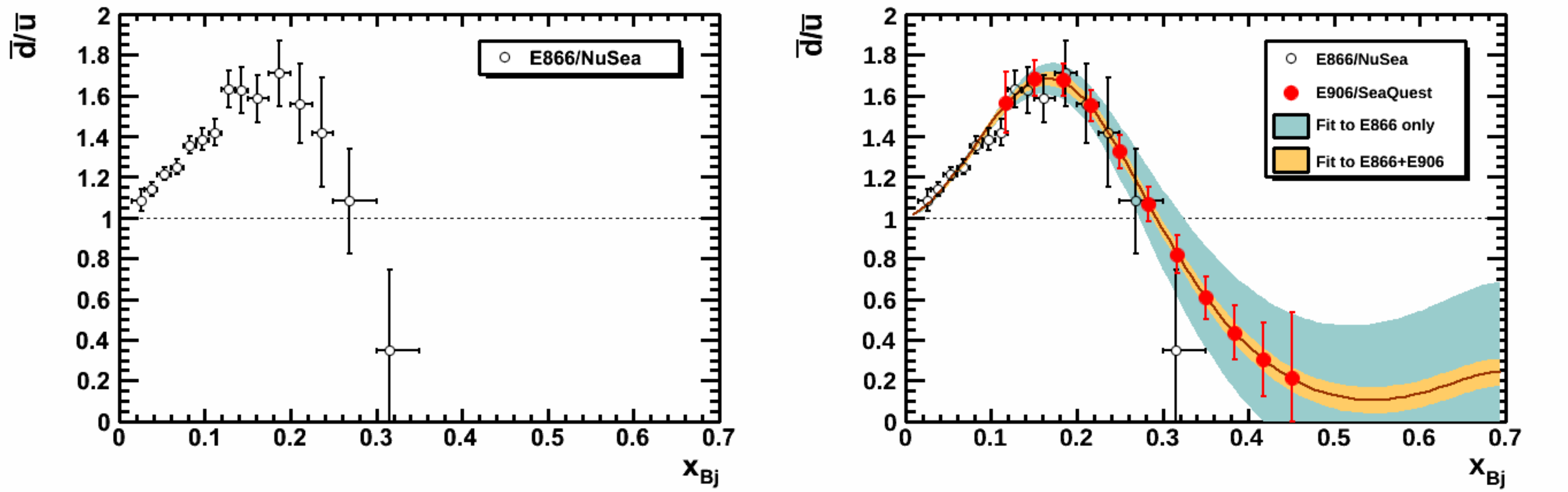
Proton

- 1991 NMC at CERN Deep inelastic muon scattering $\bar{d} > \bar{u}$
- **Drell-Yan at SeaQuest**

$$\frac{\sigma^{DY}(pd)}{\sigma^{DY}(pp)} \rightarrow \frac{\bar{d}}{\bar{u}}$$

Simulation of projected error of SeaQuest

E866

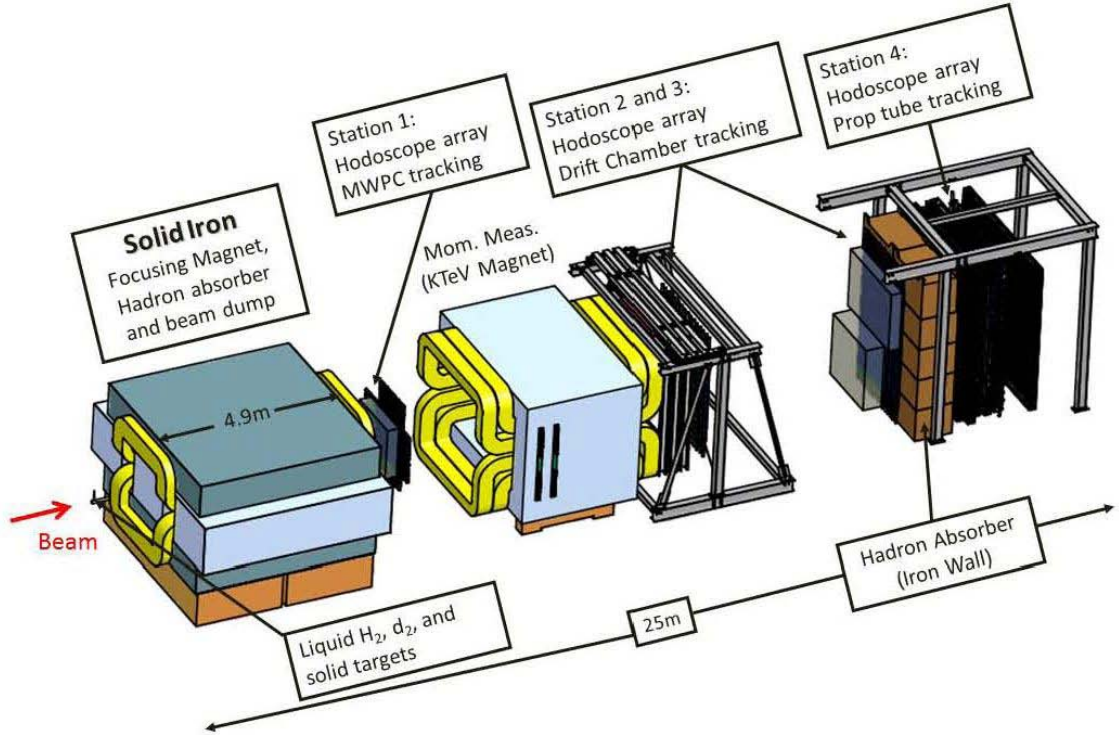


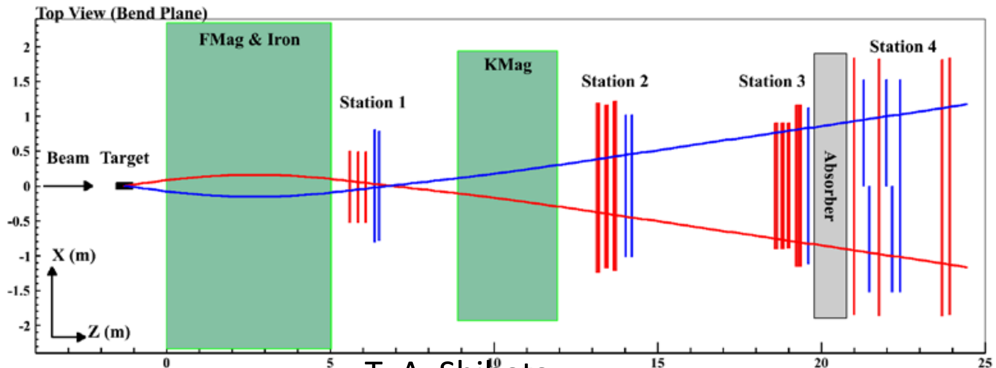
Bjorken x

$$p = |p> + |n\pi^+> \qquad u\bar{d}$$

SeaQest at FNAL

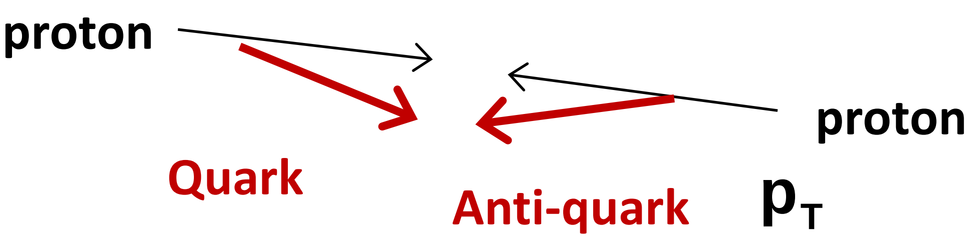
120 GeV proton, Beamtime 2013-





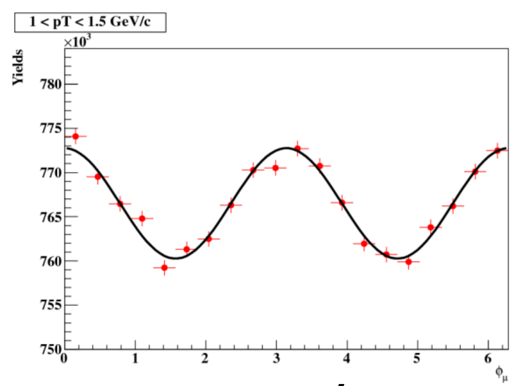
Study of

Correlation of quark and anti-quark spin and orbital angular momentum



Boer-Mulders function

Simulation of ϕ distribution of μ^+



ϕ

Summary

-- Physics of the 1st moment. Integration over *x*.
Event by event determination of $x,\ Q^2,\ \phi, ...$
is important

-- Longitudinal polarized DIS → quark spin contributions to the proton spin, **33 ± 3.9 %**

-- Transverse spin and transverse motion of quarks are also key elements to understand the structure of the nucleon.
Sivers asymmetry and Collins asymmetry have been measured.

-- Azimuthal asymmetry with unpolarized nucleons has been found.
→ Boer-Mulders function and Cahn effect

-- Drell-Yan Process is another important process in which complete kinematics can be determined event by event.