HERMES の偏極深非弾性散乱による核子構造の研究

田中 秀和

東京工業大学
基礎物理学専攻

- 核子スピン構造　～スピン危機～
- 深非弾性散乱　（ DIS ）
- HERMES 実験と最近の結果
  - クォーク偏極度
  - クォークの新たな分布関数
    - Sivers & Transversity
- まとめ

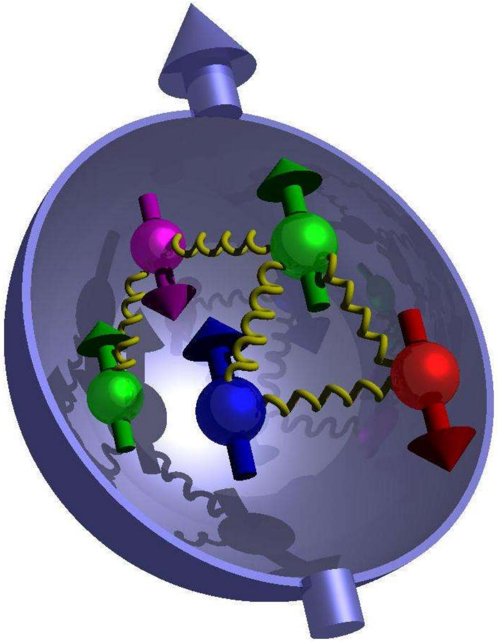
Spin Puzzle

Quark helicity distribution

$$\Delta\Sigma \equiv \Delta u + \Delta d + \Delta\bar{u} + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

Gluon spin distribution

$$\Delta G$$

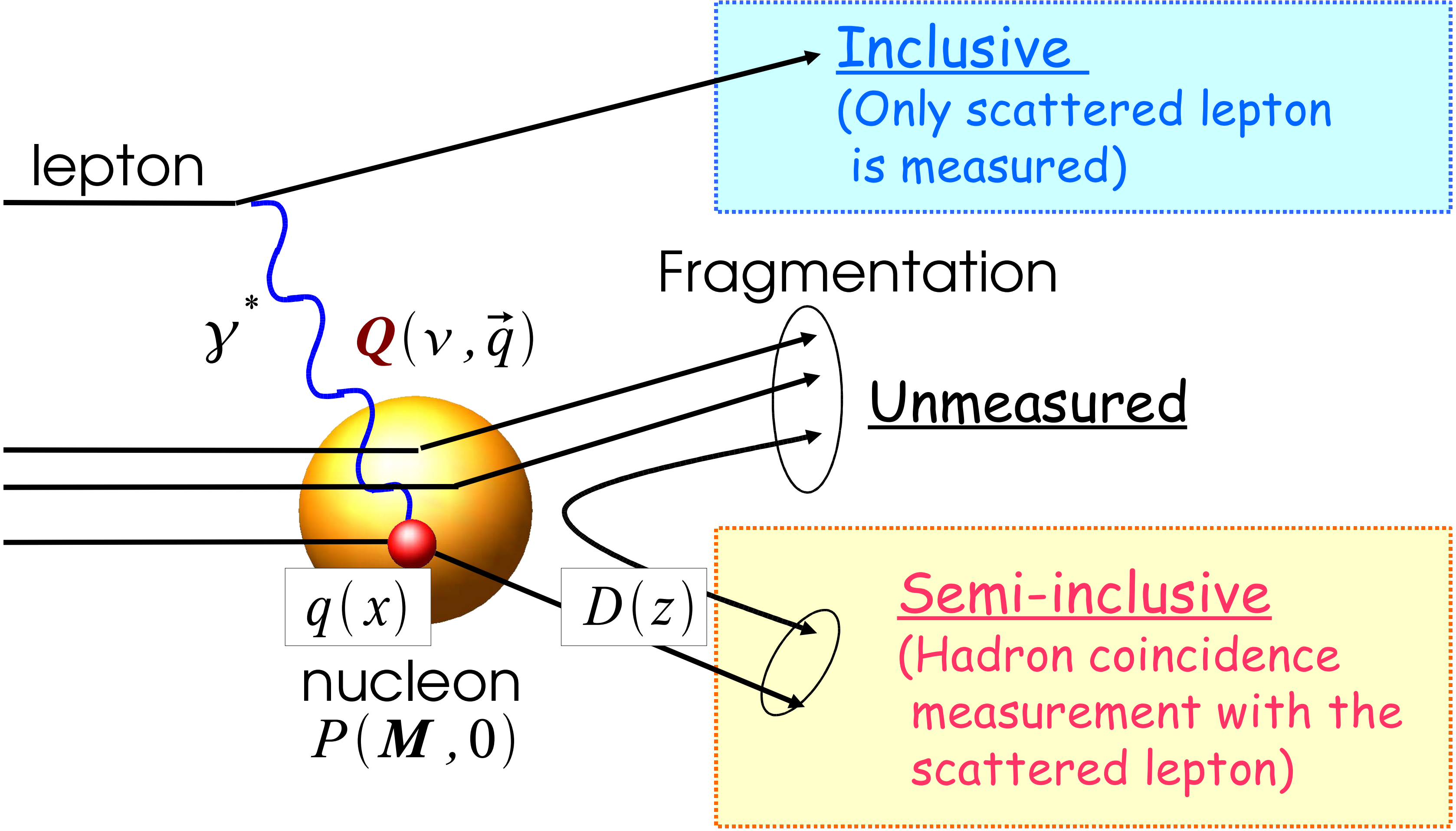


$$\frac{1}{2} = \frac{1}{2}\boxed{\Delta\Sigma} + \boxed{\Delta G} + \boxed{L_q + L_g}$$

Orbital angular momenta of quark and gluon

$$L_q + L_g$$

Deep Inelastic Scattering (DIS)



Inclusive
(Only scattered lepton is measured)

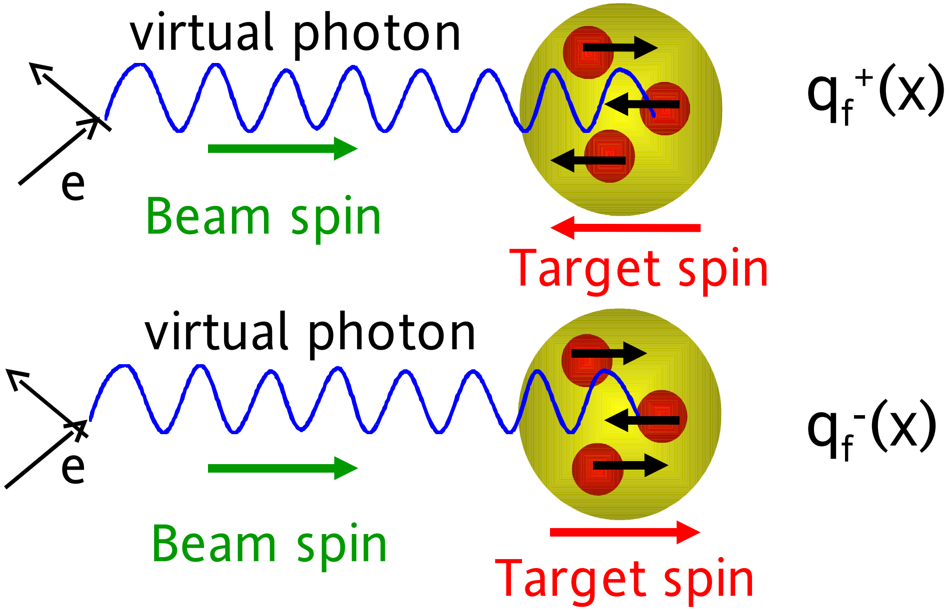
Semi-inclusive
(Hadron coincidence measurement with the scattered lepton)

x : Quark momentum fraction
(Bjorken scaling parameter)

z : Fractional energy of produced hadron

M : Target mass
Q : Virtual photon 4-momentum
ν : Virtual photon energy

Polarized DIS



Polarized Quark Distribution

$\Delta q_f(x) \equiv q_f^+(x) - q_f^-(x)$

Unpolarized Quark Distribution

$q_f(x) \equiv q_f^+(x) + q_f^-(x)$

Inclusive/Simi-inclusive Spin Asymmetry A_1

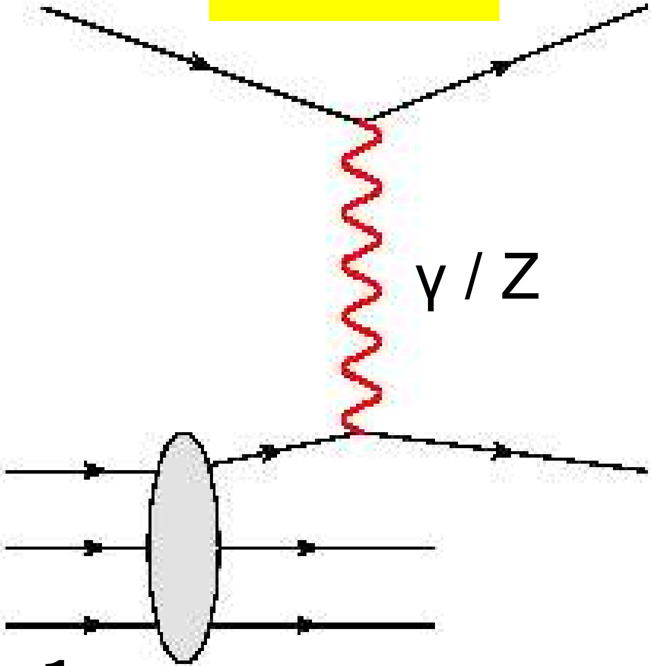
$$A_1^{e/h}(x,Q^2) = \frac{\sigma_{e/h}^{\rightleftarrows} - \sigma_{e/h}^{\rightrightarrows}}{\sigma_{e/h}^{\rightleftarrows} + \sigma_{e/h}^{\rightrightarrows}} \sim \frac{g_1}{F_1}$$

$g_1 \sim \Delta q$: **Polarized structure function**

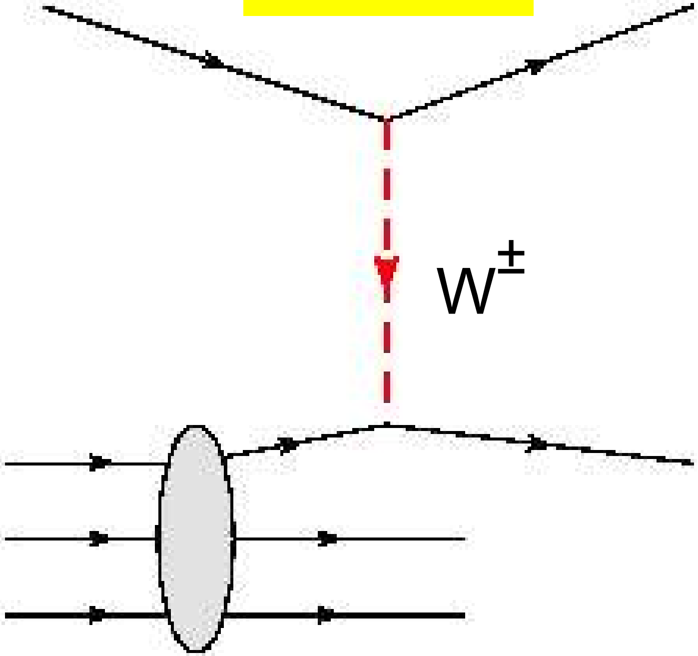
$F_1 \sim q$: Unpolarized structure function

DIS with NC and CC

NC



CC



$$g_1^{\gamma} = \frac{1}{2} x \sum_q e_q^2 (\Delta q + \Delta \bar{q})$$

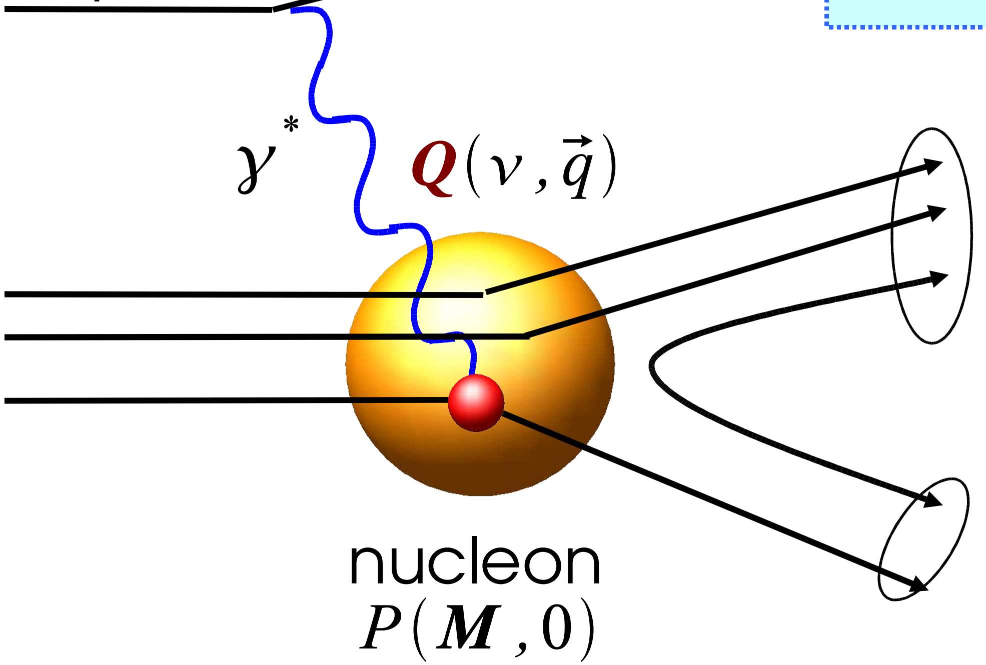
$$g_1^{Z} = \frac{1}{2} \sum_q (g_V^2 + g_A^2)_q (\Delta q + \Delta \bar{q})$$

$$g_1^{W^+} = (\Delta \bar{u} + \Delta d + \Delta s)$$

$$g_1^{W^-} = (\Delta u + \Delta \bar{d} + \Delta \bar{s})$$

NC process : Includes all quark flavors
CC process : Sensitive to sea-quarks

Deep Inelastic Scattering (DIS)



Inclusive
(Only scattered lepton is measured)

Structure Function

$F_i(x, Q^2)$: Unpolarized

$g_i(x, Q^2)$: Polarized

Parton Distribution

$q(x, Q^2)$: Unpolarized

$\Delta q(x, Q^2)$: Polarized

M : Target mass

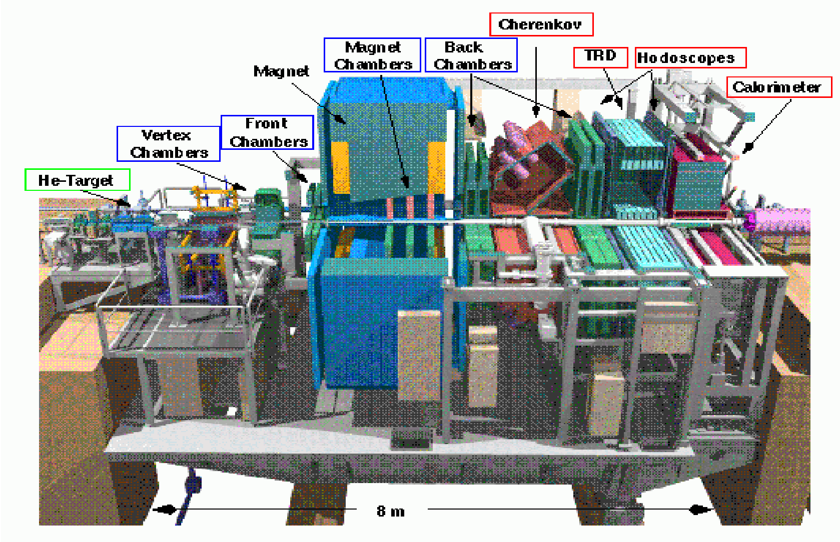
Q : Virtual boson 4-momentum

ν : Virtual boson energy

x : Quark momentum fraction (Bjorken scaling parameter)

$$x = \frac{Q^2}{2M\nu}$$

The HERMES Experiment



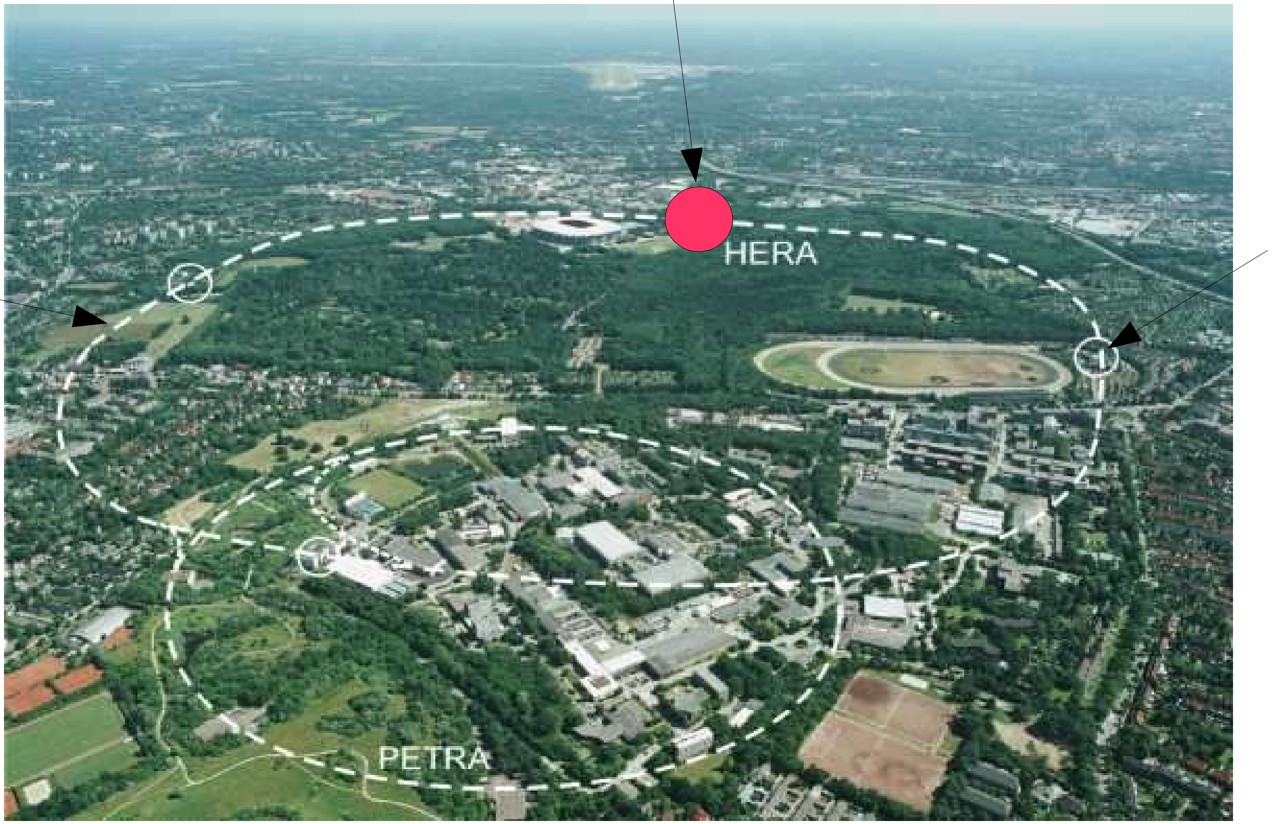
The HERMES experiment have been running since 1995 to investigatie the nucleon spin structure.

- 27.6 GeV longitudinally polarized electron (positron) beam
  polarization: up to ~ 60 %
- Polarized Internal Gas Target
  longitudinally polarized atoms: H, D,^{3}He
  polarization : ~ 90%

The HERMES Experiment

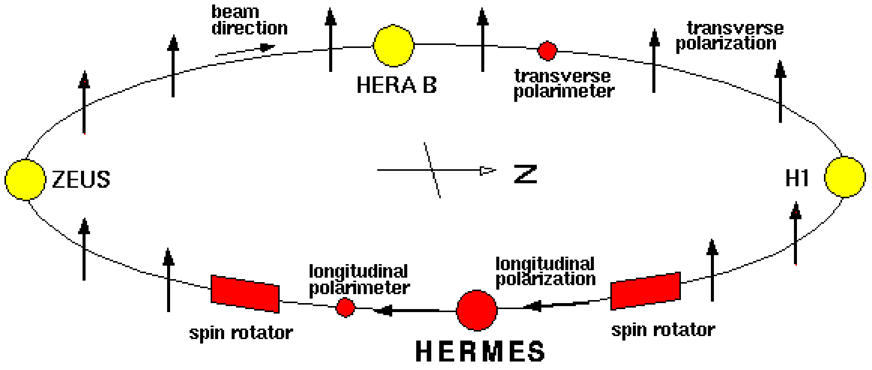
HERMES @ ドイツ・ハンブルグの DESY 研究所

HERA:
e+ : 27.6 GeV
p : 820 GeV

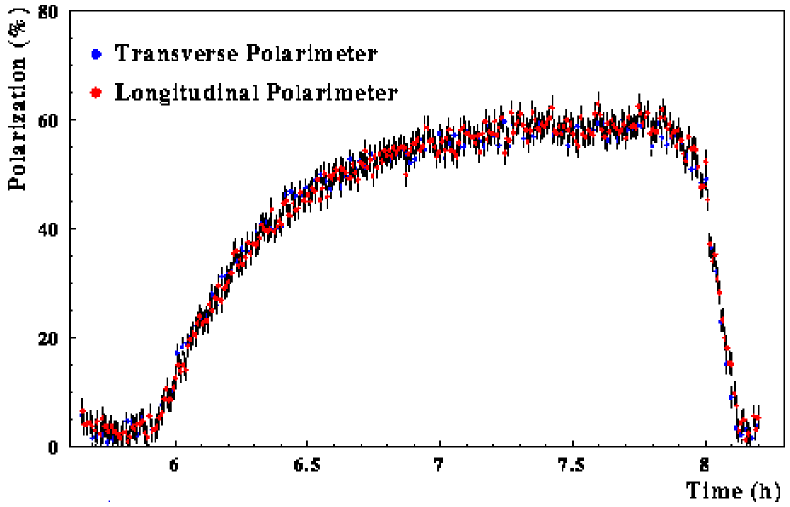


ZEUS

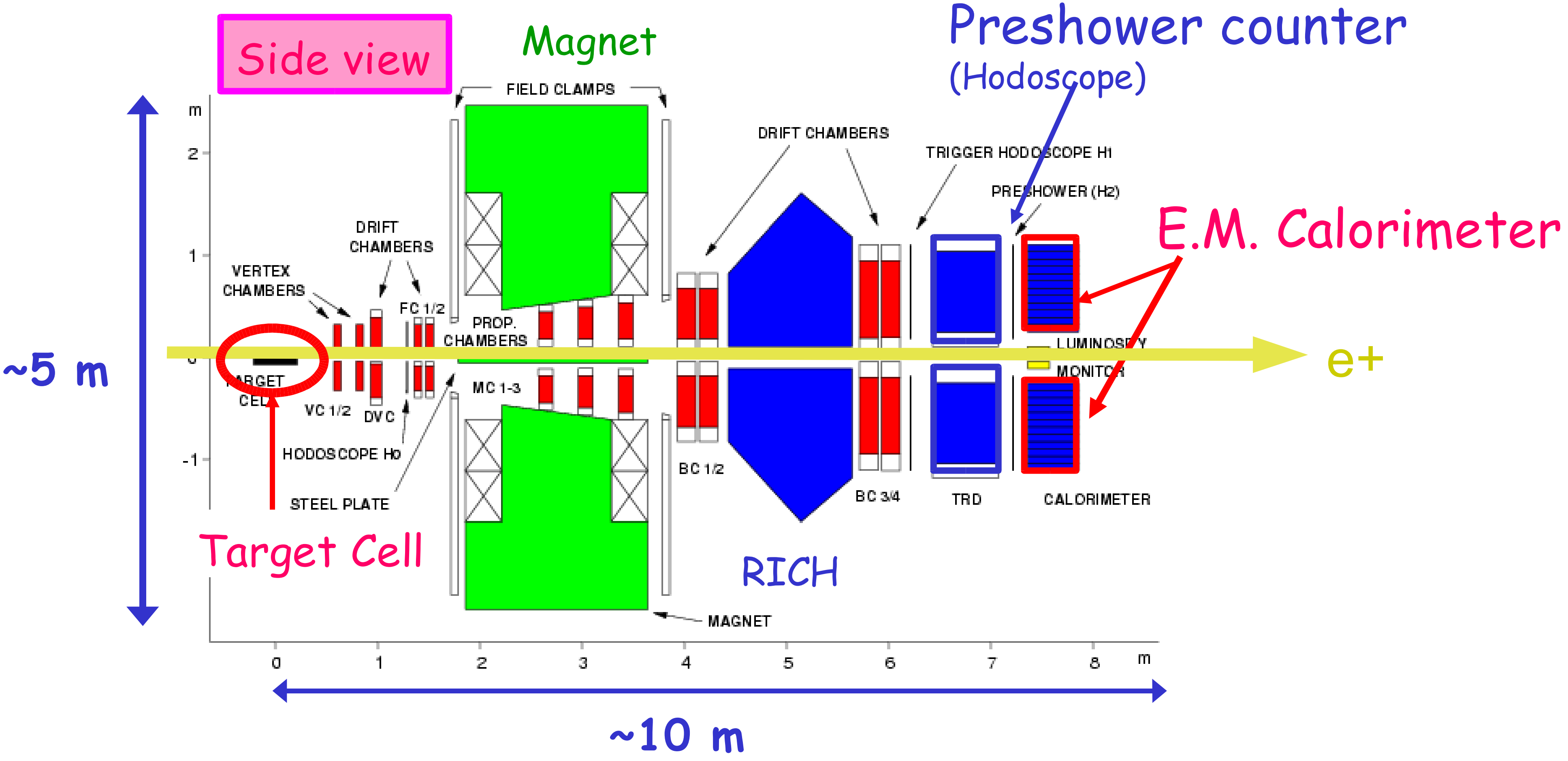
Polarized e+ Beam



- Self-polarization by emission of synchrotron radiation
- Average beam polarization $\langle p_b \rangle$ ~ 55 %

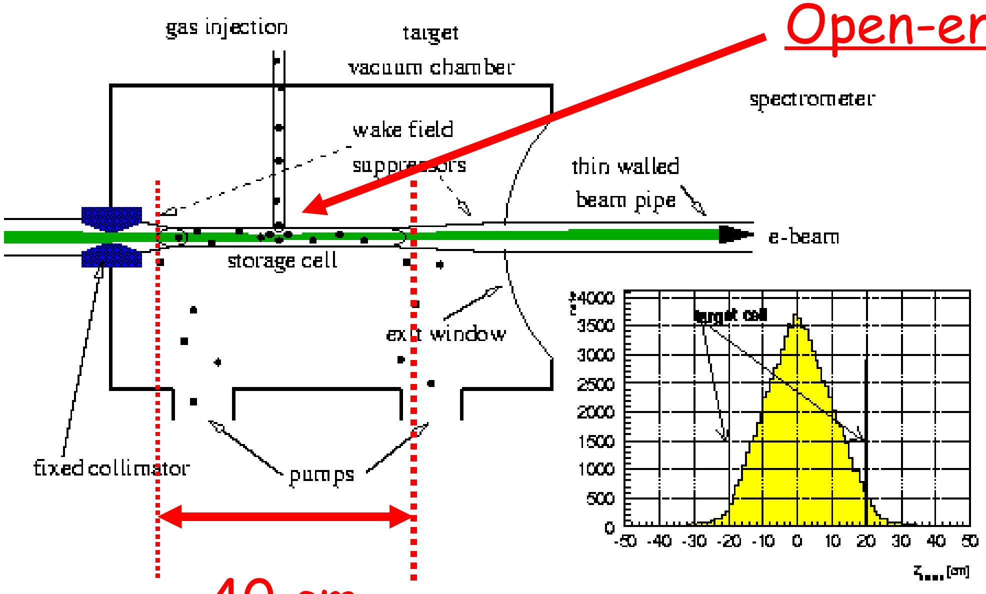


HERMES Spectrometer



Filled in red : Tracking detector , in blue : PID detectors

Internal Gas Target

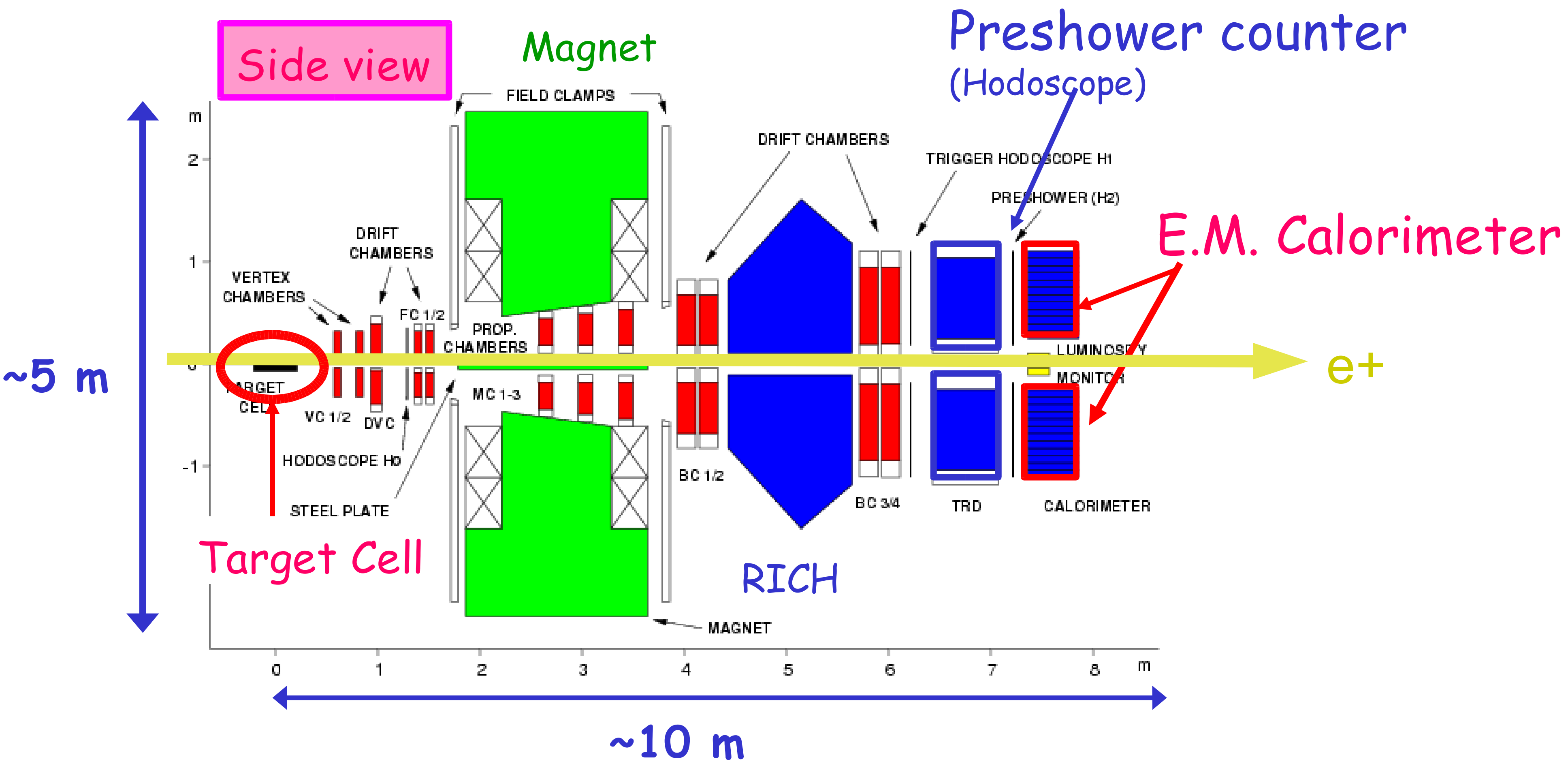


Open-ended storage cell

40 cm

- Atomic Beam Source (Stern-Gerlach separation)
- Undiluted internal targets :
  - H,D,^{3}He longitudinally polarized atoms
- Polarized target polarized H/D (1996 ~ 1999) :
  - P_T~ 90 %,   ρ   ~10^{14} N/cm^2
- Unpolarized gases :
  - H,D,^{3}He,^{14}N,^{83}Kr…, 10^{15} ~ 10^{17} N/cm^2

HERMES Spectrometer

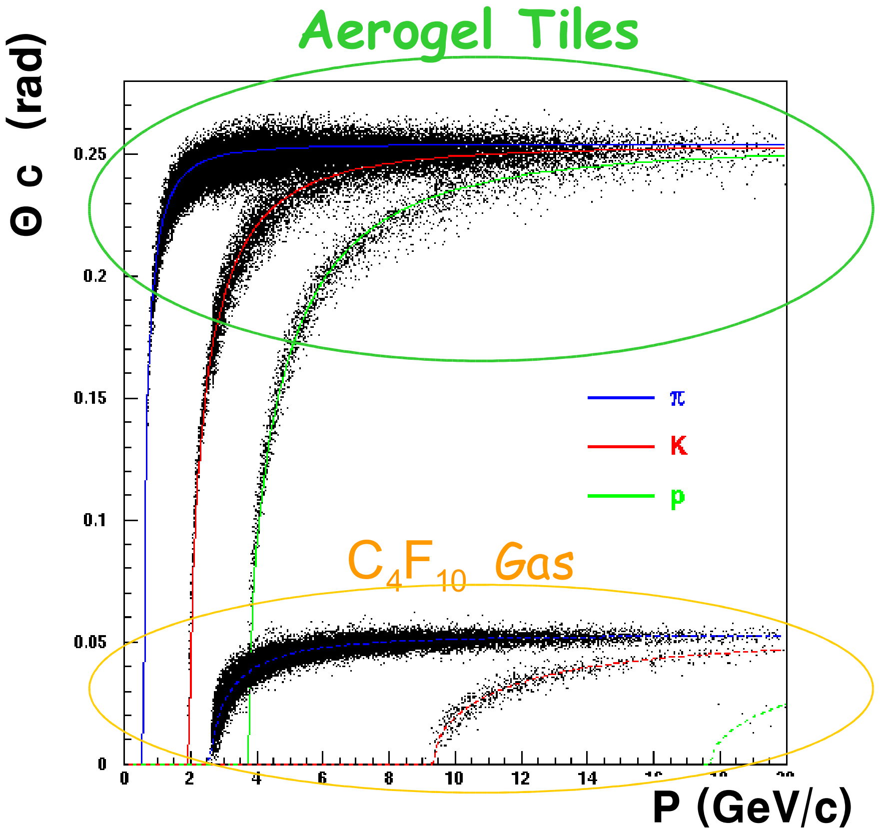


Filled in red : Tracking detector , in blue : PID detectors

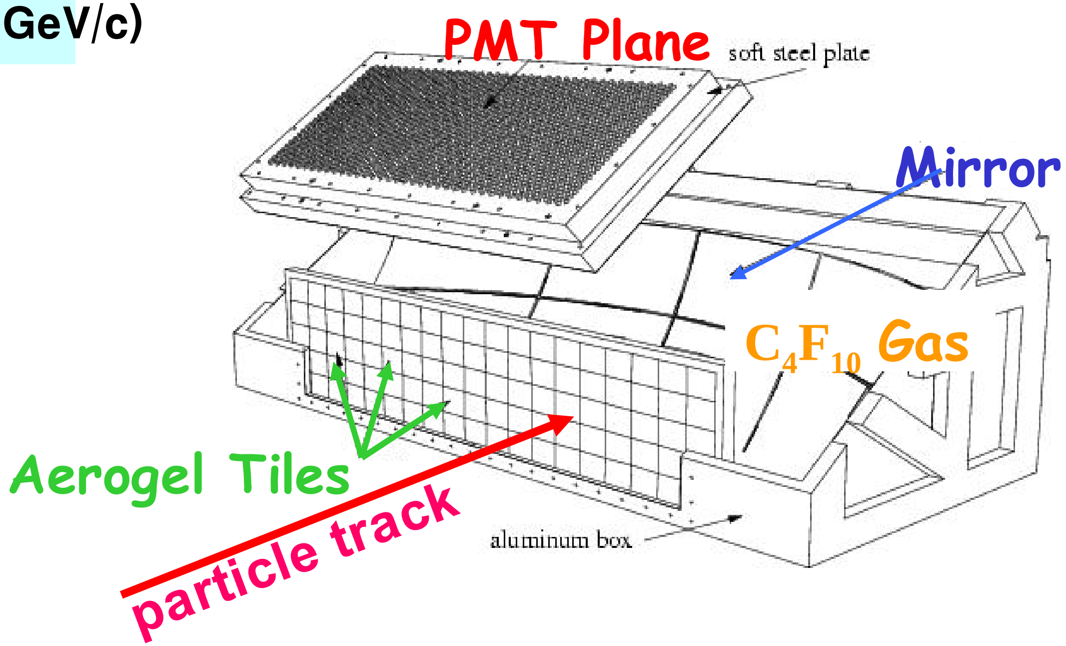
Ring Imaging Cherenkov Detector

1998 ~ 2000 data

Cherencov angle(Θ c) vs Momentum (GeV/c)

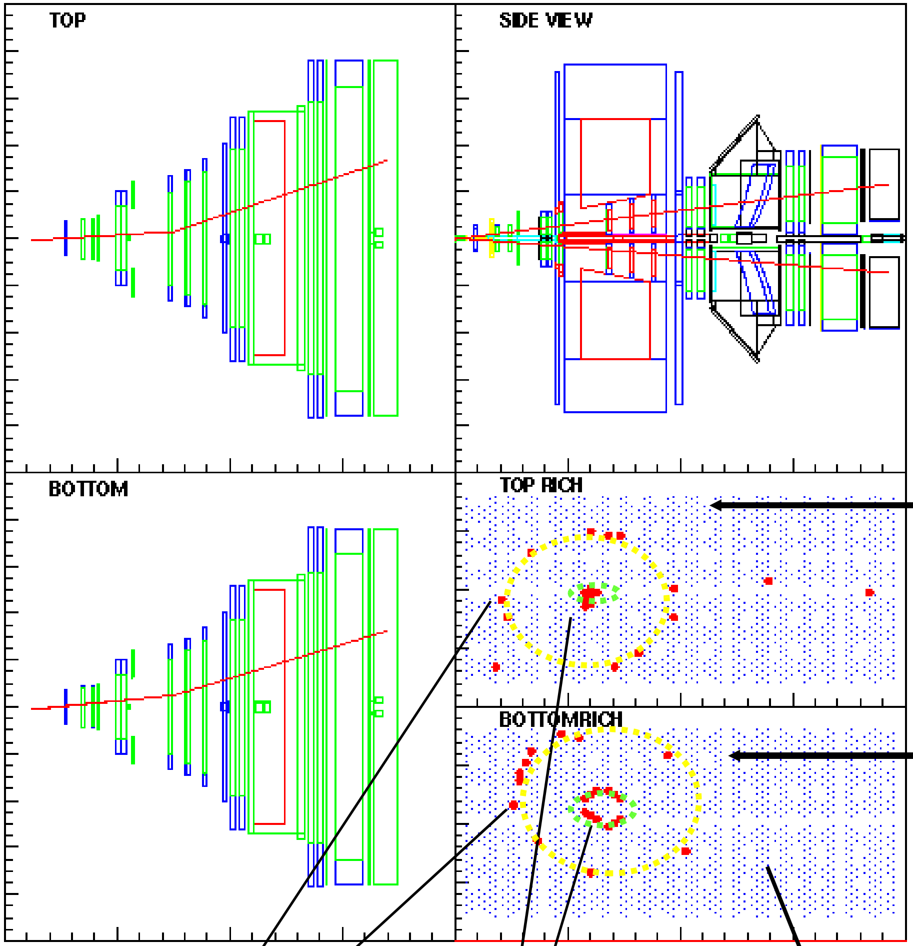


$$\cos\theta_c = \frac{1}{\frac{v}{c}n}$$



- Radiator
  - C_4F_{10} Gas n=1.0014
  - Aerogel Tiles n=1.0303
- PMT
  - 3/4 inch 1934 PMTs
- Momentum region
  - **2 ~ 15 GeV/c**

Ring Imaging Cherenkov Detector



3.1 GeV pion

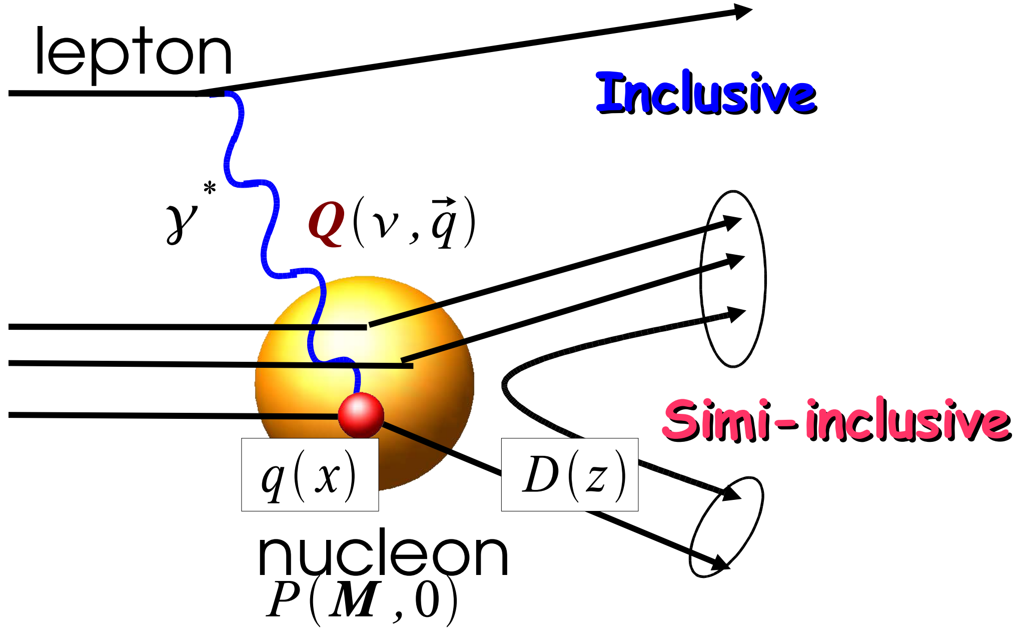
4.5 GeV electron

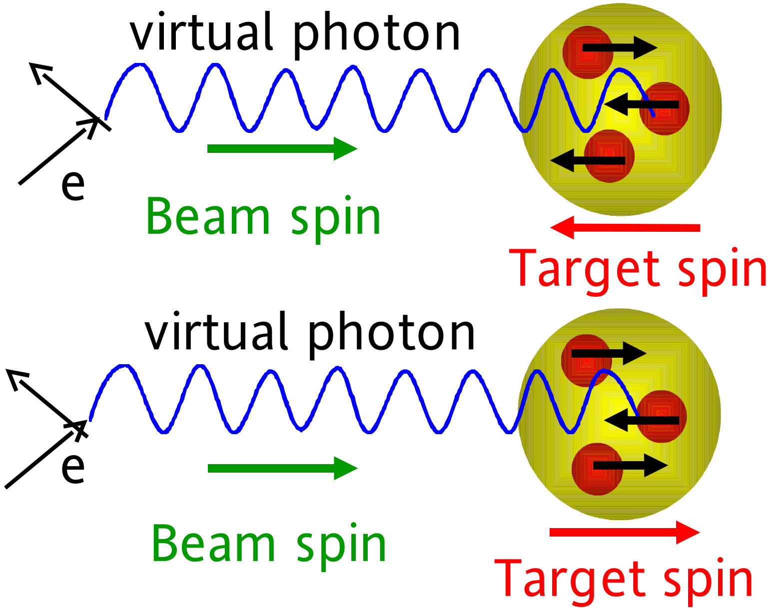
Ring from aerogel

Ring from gas

1934 PMTs

Double Spin Asymmetry A_1





Inclusive/Simi-inclusive Spin Asymmetry A_1

$$A_1^{e/h}(x,Q^2) = \frac{\sigma^{\substack{\rightarrow \\ \leftarrow}}_{e/h} - \sigma^{\substack{\rightarrow \\ \rightarrow}}_{e/h}}{\sigma^{\substack{\rightarrow \\ \leftarrow}}_{e/h} + \sigma^{\substack{\rightarrow \\ \rightarrow}}_{e/h}}$$

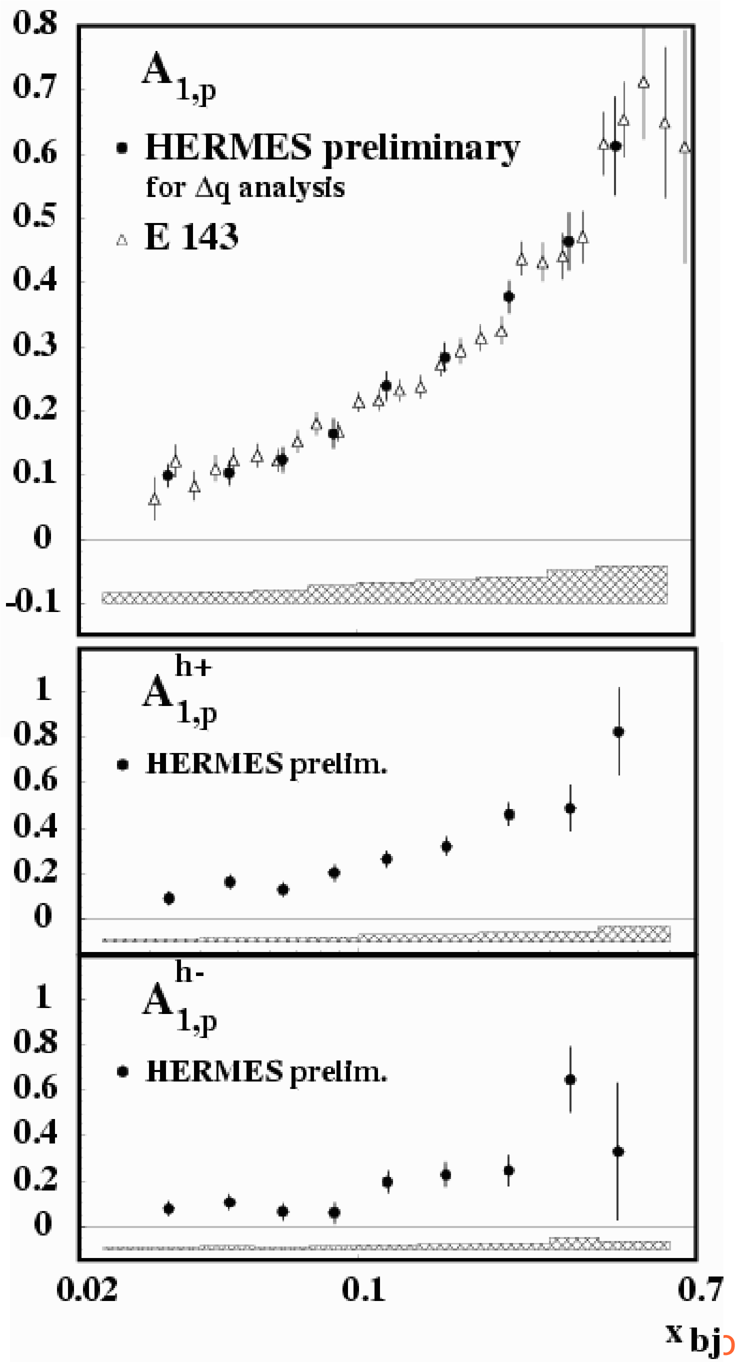
Polarized Quark Distribution

$$\Delta q_f(x) \equiv q_f^+(x) - q_f^-(x)$$

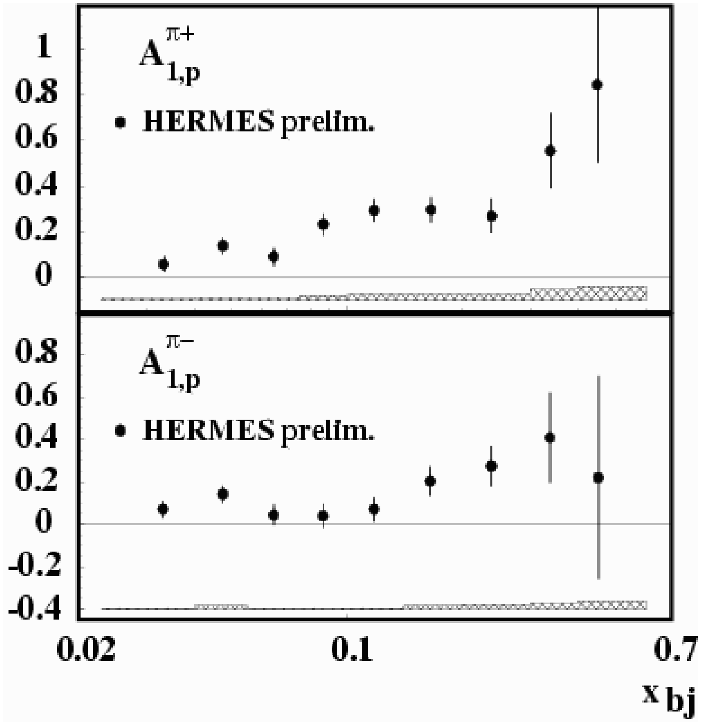
Measured Spin Asymmetry A_1

Inclusive

$h^{+/-}$



$\pi^{+/-}$

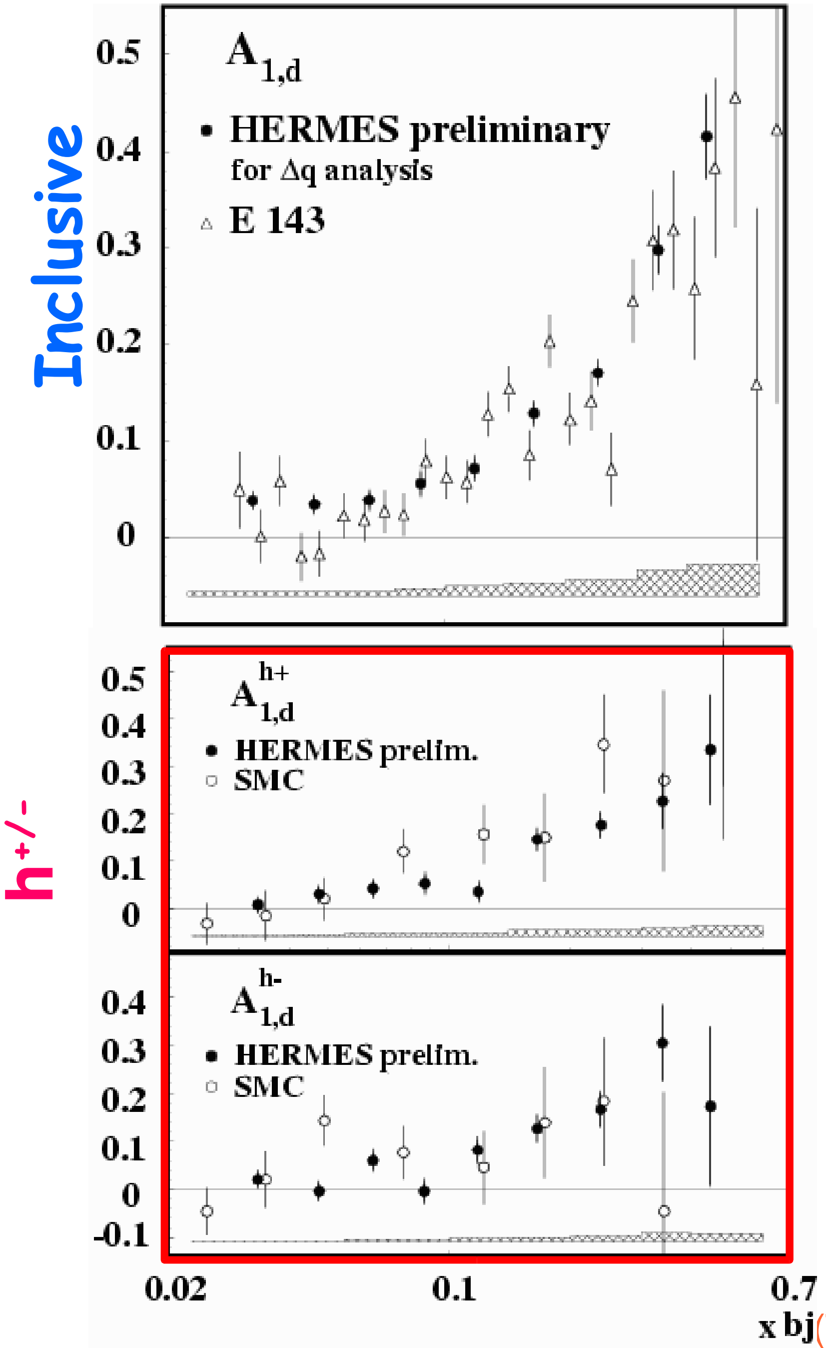


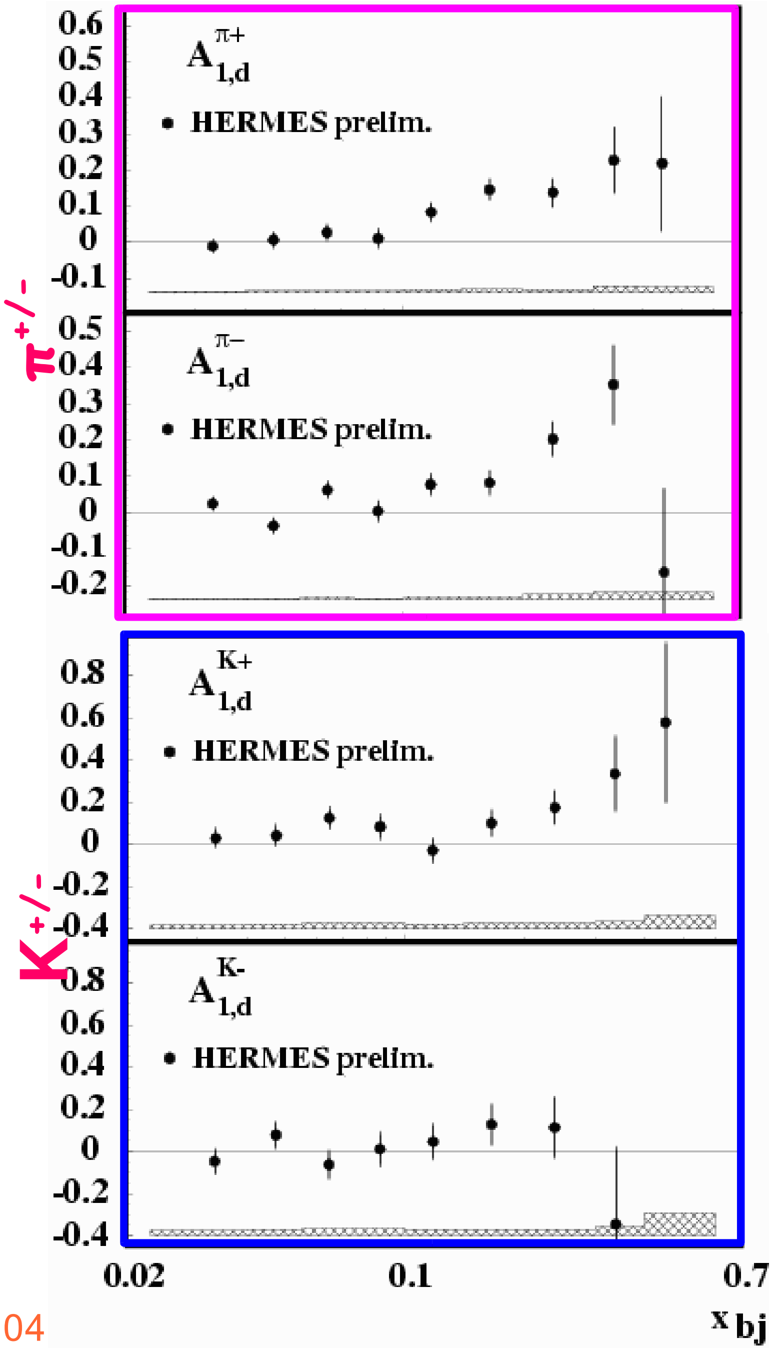
Data :
Proton target (1996 ~ 1997)

Particle Identification :
“Threshold Cherenkov Detector”

$$A_1 = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \sim 0.6 \qquad \sigma^+ : \sigma^- = 4:1$$

Measured Spin Asymmetry A_1





Extracting Quark Polarization

Measured Spin Asymmetry for hadron h in Quark Parton Model (QPM)

$$A_1^h(x) = \frac{d\sigma_h^+ - d\sigma_h^-}{d\sigma_h^+ + d\sigma_h^-} = \sum_q \boxed{P_q^h(x)} \cdot \frac{\Delta q(x)}{q(x)}$$

Purity Matrix Method

Extract the quark polarizations Δq/q(x)

$$A = P \cdot Q$$

$$A = \begin{pmatrix} A_1^{h_1}(x) \\ \vdots \\ A_1^{h_m}(x) \end{pmatrix} \qquad P = \begin{pmatrix} P_{f_1}^{h_1}(x) & \cdots & P_{f_n}^{h_1}(x) \\ \vdots & \ddots & \vdots \\ P_{f_1}^{h_m}(x) & \cdots & P_{f_n}^{h_m}(x) \end{pmatrix} \qquad Q = \begin{pmatrix} \Delta q_1/q_1(x) \\ \vdots \\ \Delta q_n/q_n(x) \end{pmatrix}$$

Measured Asymmetries
(Input)

Purity Matrix

P_q^h : Correlation between hadron "**h**" and quark "**q**".

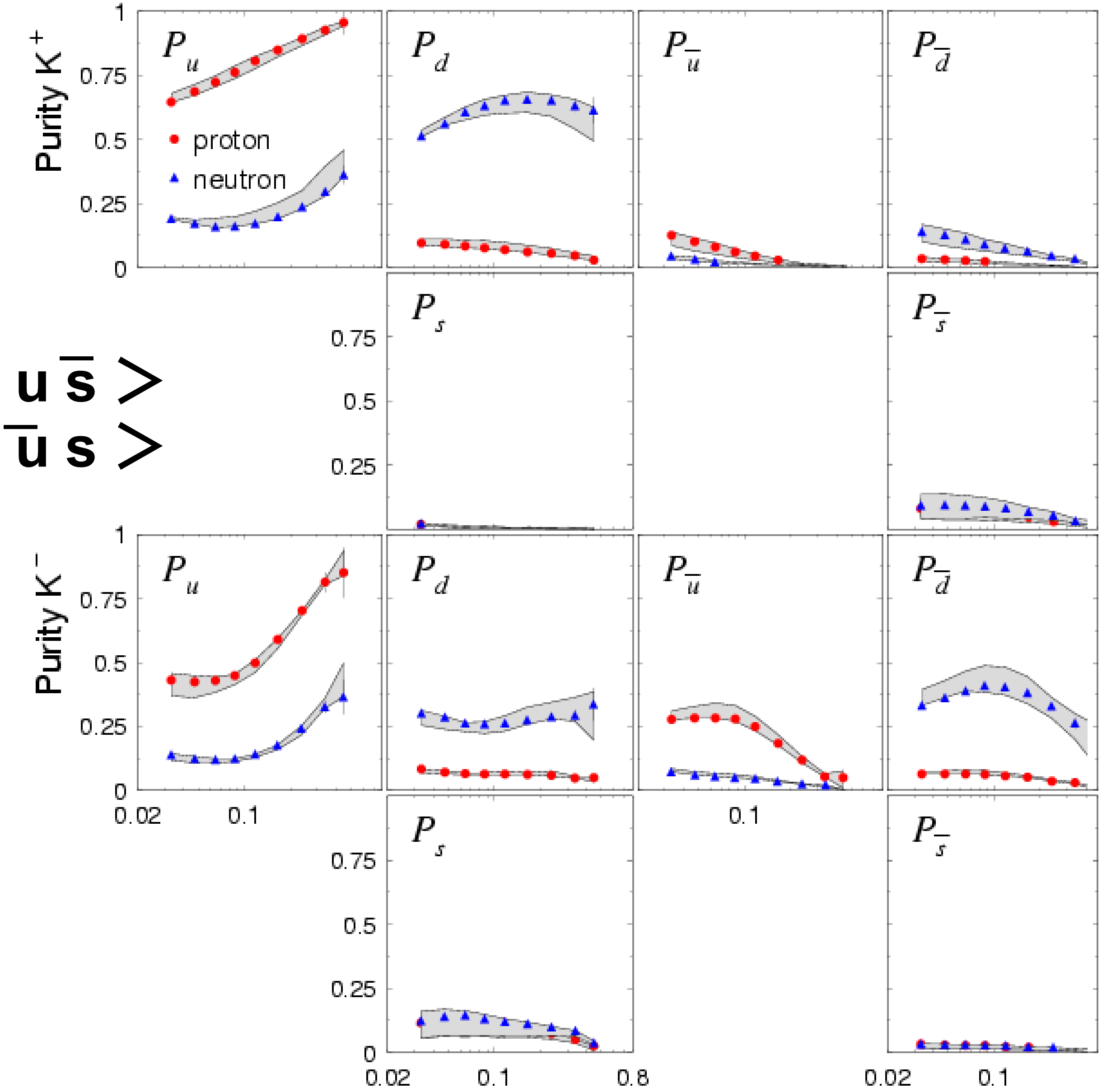
Extracted Quark Polarizations

Δq/q : polarization

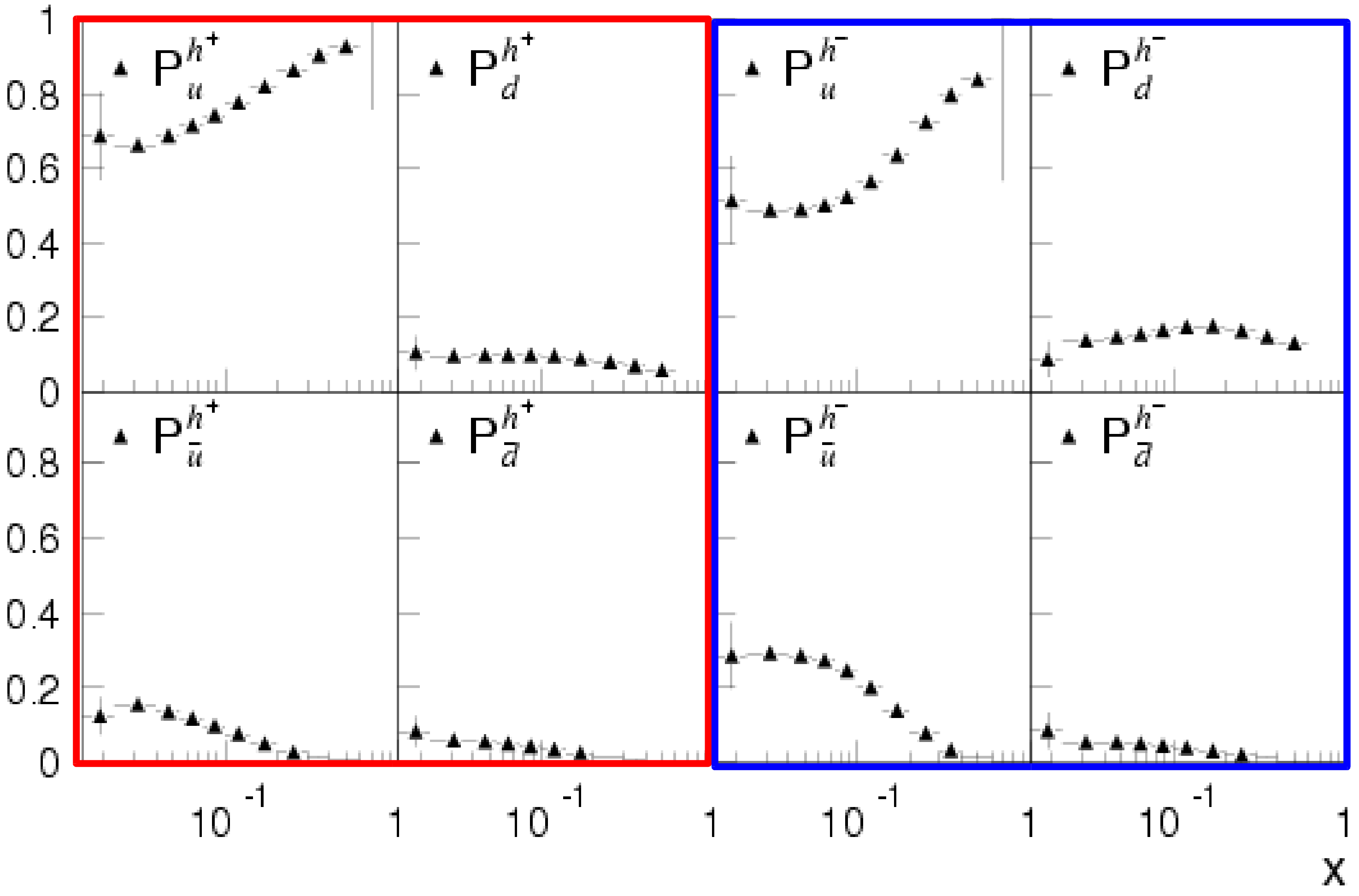
Δq : pol. Distribution

(Output)

Purity Matrix



$$|K^+\rangle = |u\bar{s}\rangle$$
$$|K^-\rangle = |\bar{u}s\rangle$$



$P_u^{h^+}$
$P_d^{h^+}$
$P_u^{h^-}$
$P_d^{h^-}$
$P_{\bar{u}}^{h^+}$
$P_{\bar{d}}^{h^+}$
$P_{\bar{u}}^{h^-}$
$P_{\bar{d}}^{h^-}$
1
0.8
0.6
0.4
0.2
0
10^{-1}
1
x

Extracting Quark Polarization

Measured Spin Asymmetry for hadron h in Quark Parton Model (QPM)

$$A_1^h(x) = \frac{d\sigma_h^+ - d\sigma_h^-}{d\sigma_h^+ + d\sigma_h^-} = \sum_q \boxed{P_q^h(x)} \cdot \frac{\Delta q(x)}{q(x)}$$

Purity Matrix Method

Extract the quark polarizations $\Delta q/q(x)$

$$A = P \cdot Q$$

$$A = \begin{pmatrix} A_1^{h_1}(x) \\ \vdots \\ A_1^{h_m}(x) \end{pmatrix} \qquad P = \begin{pmatrix} P_{f_1}^{h_1}(x) & \cdots & P_{f_n}^{h_1}(x) \\ \vdots & \ddots & \vdots \\ P_{f_1}^{h_m}(x) & \cdots & P_{f_n}^{h_m}(x) \end{pmatrix} \qquad Q = \begin{pmatrix} \Delta q_1/q_1(x) \\ \vdots \\ \Delta q_n/q_n(x) \end{pmatrix}$$

Measured Asymmetries
(Input)

Purity Matrix

P_q^h : Correlation between hadron "**h**" and quark "**q**".

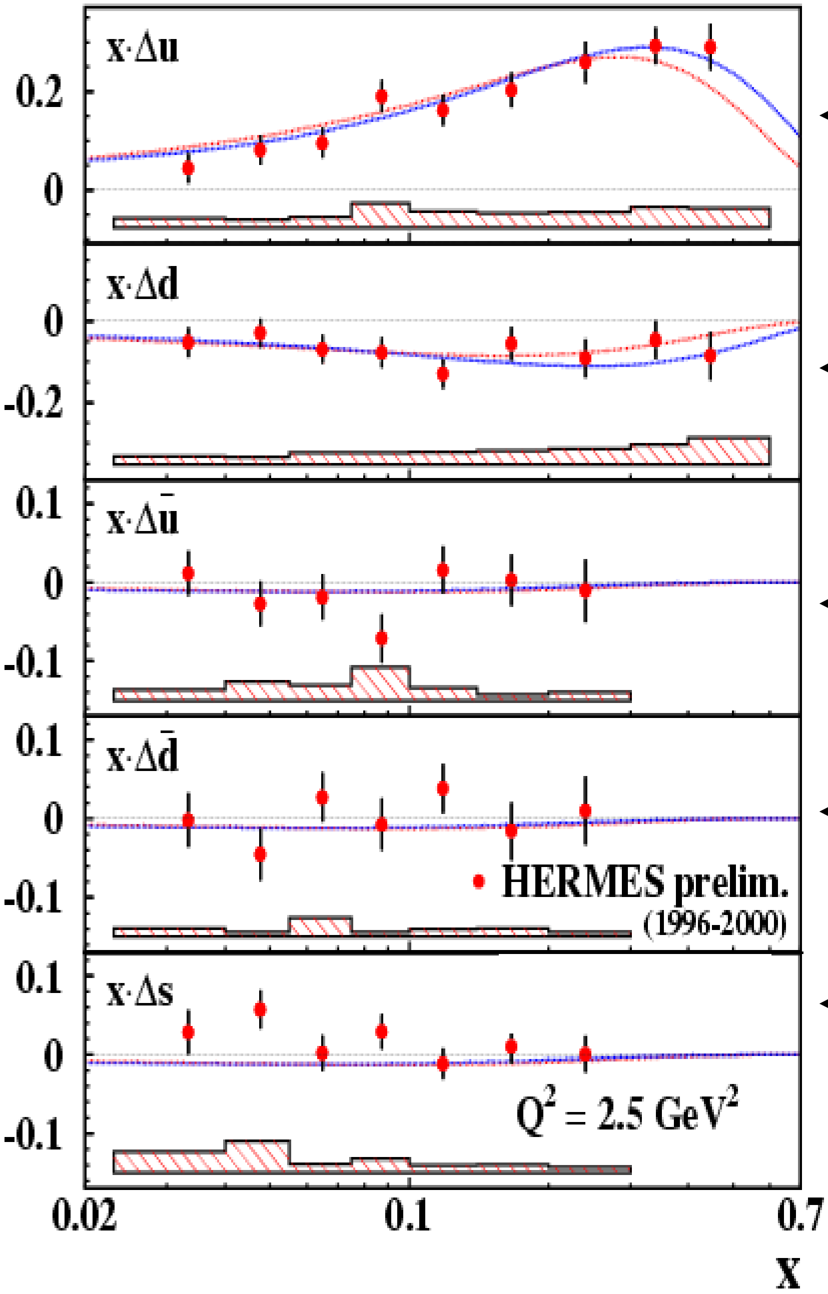
Extracted Quark Polarizations

$\Delta q/q$: polarization

Δq : pol. Distribution

(Output)

Extracted Quark Polarization



Positive contribution to nucleon spin in the measured region.

Negative contribution.

Sea quark contribution almost zero.

$$\Delta\Sigma \sim 0.2-0.3$$

$$\left(\Delta\Sigma \equiv \Delta u + \Delta d + \Delta\bar{u} + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

ここまでをまとめると ...

- HERMES 実験では縦偏極 e+ ビームと縦偏極標的を使って偏極核子内でのクォーク偏極度を測定した。
その結果、

  - u-quark は核子の偏極方向に平行
  - d-quark は " 反平行
  - sea-quark は偏極していない (核子ないで平均すると)

- クォークスピンの核子スピンへの寄与は Sea-quark を考慮したとしても 20-30 % 程度にしかならない。

- 核子内には まだ unknown な「構造」が存在している .....
何か手掛かりはあるか ？

Spin Puzzle

Quark helicity distribution

$$\Delta\Sigma \equiv \Delta u + \Delta d + \Delta\bar{u} + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

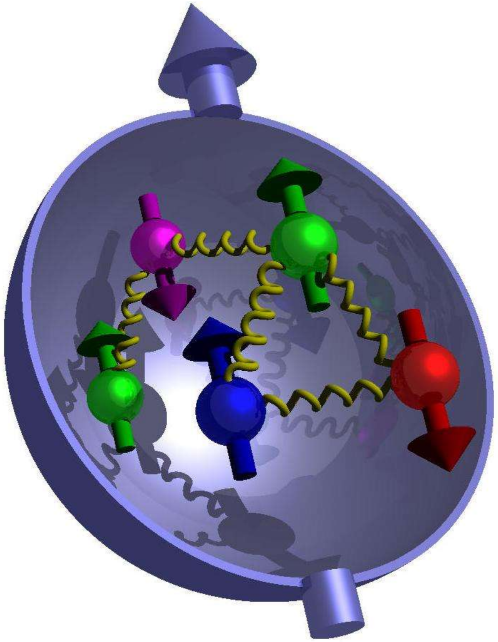
$$(\Delta\Sigma \sim 0.2 - 0.3)$$

Known

Gluon spin distribution

$$\Delta G$$

now in measuring



$$\frac{1}{2} = \frac{1}{2}\boxed{\Delta\Sigma} + \boxed{\Delta G} + \boxed{L_q + L_g}$$

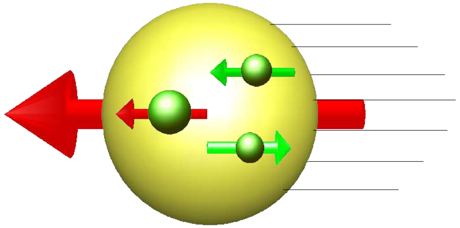
Orbital angular momenta of quark and gluon

$$L_q + L_g$$

Unknown ....

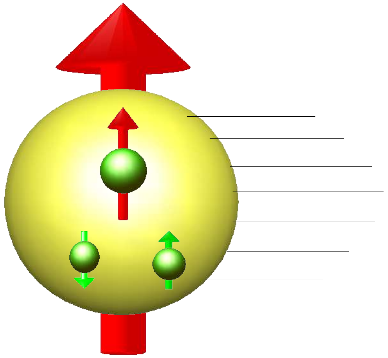
Other Spin-related PDFs

Δq



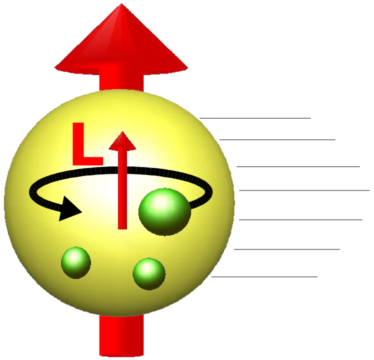
Helicity distribution

δq



Transversity

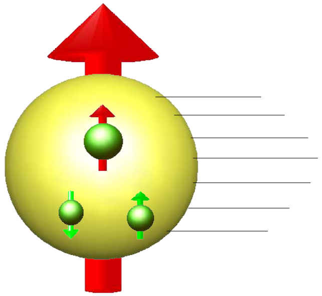
$f_{1T}^{\perp}$



Sivers function

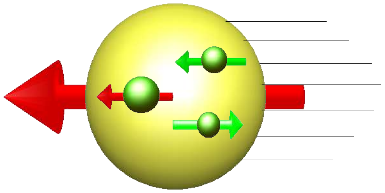
What's Transversity ?

Transversity δq describes transverse quark polarization in the transversely polarized nucleon.

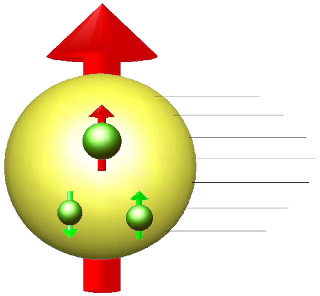


δq

Δq



$\overset{??}{=}$



δq

quark polarization
in the long. pol.
nucleon

quark polarization
in the trans. pol.
nucleon

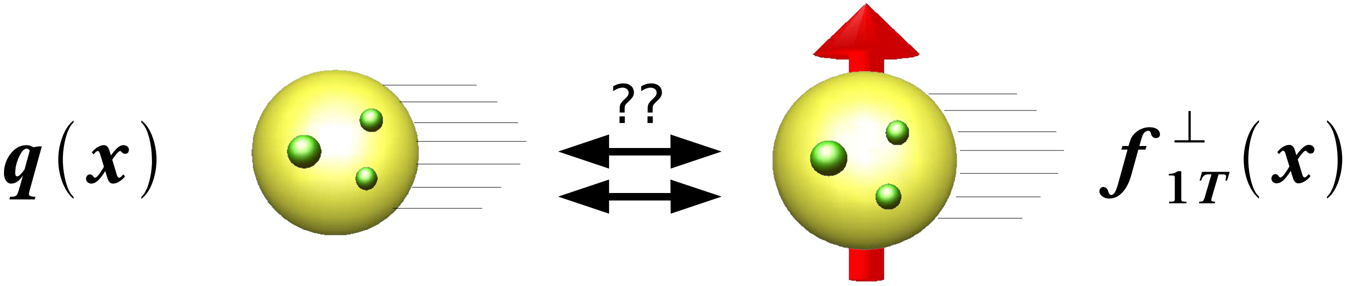
$$\Delta q - \delta q = ??$$

Non-realtivestic limit ; $\Delta q - \delta q = 0$

What's Sivers Function ?

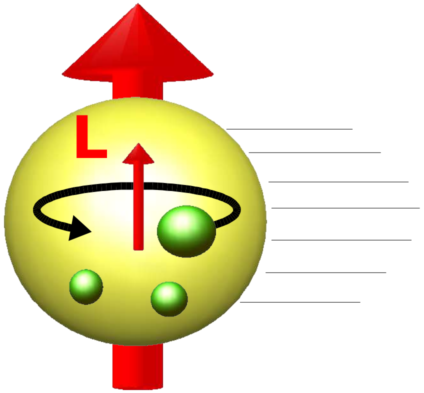
Other quark distribution is "Sivers function" $f_{1T}^{\perp}$.

The Sivers function describes unpolarized quark in the transversely polarized nucleon.



quark momentum distribution in unpol. nucleon

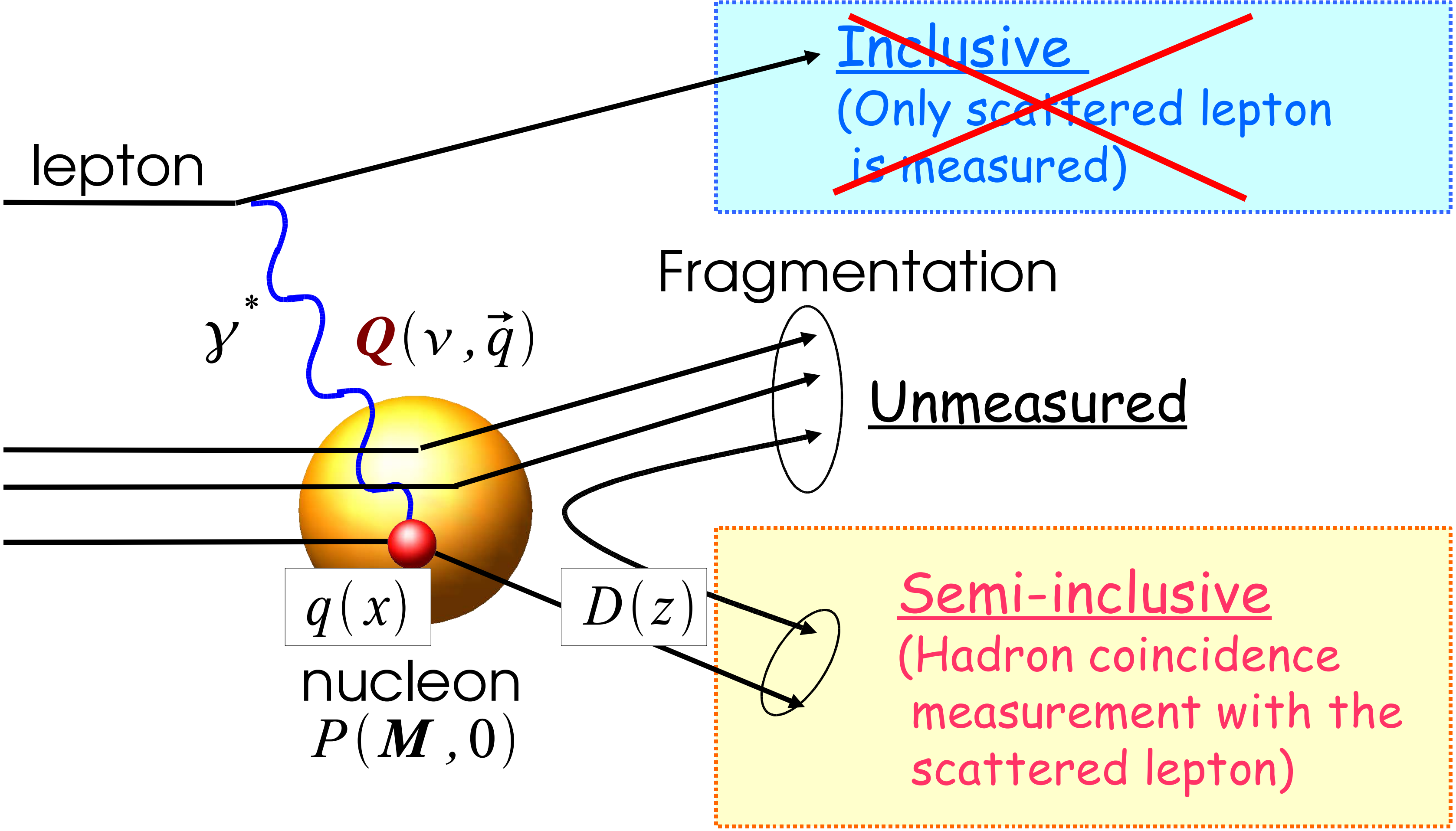
quark momentum distribution in trans. pol. nucleon



$f_{1T}^{\perp}(x)$

The Sivers function is related to quark orbital angular momentum.

How do we measure them ?



~~Inclusive~~
~~(Only scattered lepton is measured)~~

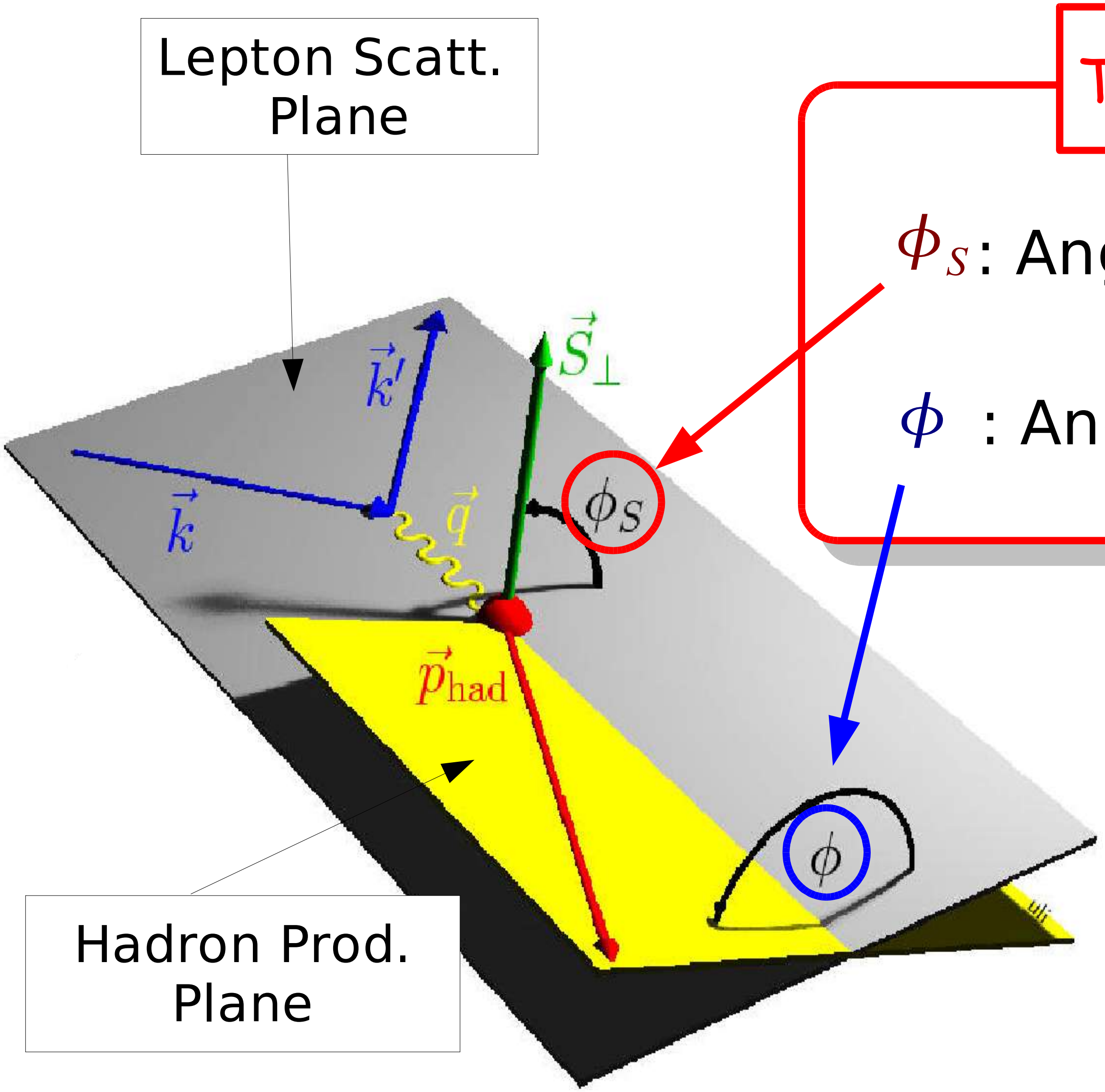
Semi-inclusive
(Hadron coincidence measurement with the scattered lepton)

x : Quark momentum fraction
(Bjorken scaling parameter)

z : Fractional energy of produced hadron

M : Target mass
Q : Virtual photon 4-momentum
ν : Virtual photon energy

Transversely Polarized DIS



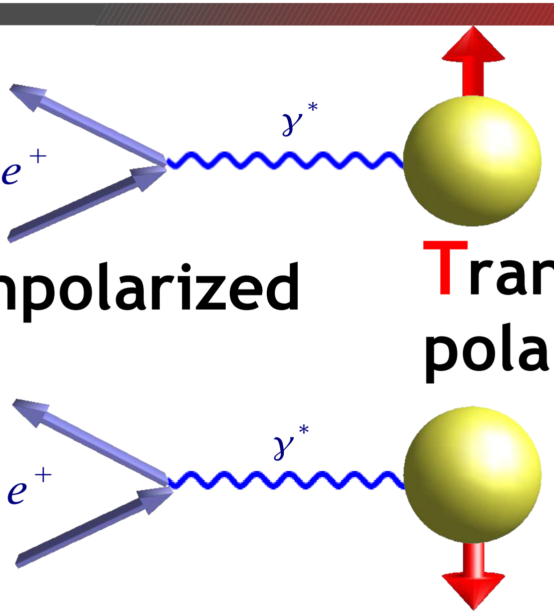
Two Azimuthal angles

ϕ_S: Angle between $\vec{S}_\perp$ and L.P.

ϕ : Angle between L.P. and H.P.

$\vec{k}, \vec{k}'$: Lepton momentum
$\vec{q}$: Virtual photon momentum
$\vec{p}_{had}$: Hadron momentum

Single Target-Spin Asymmetry (SSA)



$d\sigma^{\uparrow}$

Unpolarized **Transversely polarized**

$d\sigma^{\downarrow}$

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$d\sigma^{\uparrow,\downarrow}$ π production cross-section

$$A_{UT} \equiv \boxed{A_{UT}^{Collins}} \sin(\phi + \phi_S) + \boxed{A_{UT}^{Sivers}} \sin(\phi - \phi_S)$$

Collins asymmetry

$$A_{UT}^{Collins} \propto \boxed{\delta q(x)}\, H_1^{\perp}(z)$$

Transversity

Sivers asymmetry

$$A_{UT}^{Sivers} \propto \boxed{f_{1T}^{\perp}(x)}\, D_1(z)$$

Sivers function

Contents of the SSA

$$A_{UT} \equiv A_{UT}^{Collins} \sin(\phi + \phi_S) + A_{UT}^{Sivers} \sin(\phi - \phi_S)$$

Collins Asymmetry

$$A_{UT}^{Collins} \propto \delta q(x) \; H_1^{\perp}(z)$$

Transversity
(Polarized PDF)

&

Collins FF
(Polarized FF)

Sivers Asymmetry

$$A_{UT}^{Sivers} \propto f_{1T}^{\perp}(x) \; D_1(z)$$

Sivers function
(Unpolarized PDF)

↓

Orbital angular momenta

1. Collins Asymmetry

$$A_{UT} = \boxed{A_{UT}^{Collins}} \sin\left(\underline{\phi + \phi_S}\right) + A_{UT}^{Sivers} \sin\left(\phi - \phi_S\right)$$

Collins Asymmetry

$$A_{UT} \equiv \boxed{A_{UT}^{Collins}} \sin\left(\phi+\phi_S\right) + A_{UT}^{Sivers} \sin\left(\phi-\phi_S\right)$$

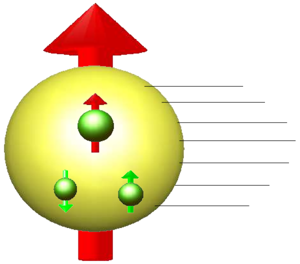
Collins asymmetry

$$A_{UT}^{Collins} \propto \delta q(x) \quad H_1^{\perp}(z)$$

Transversity
(Polarized PDF) δq

h_1 describes transverse quark polarization in the transversely polarized nucleon.

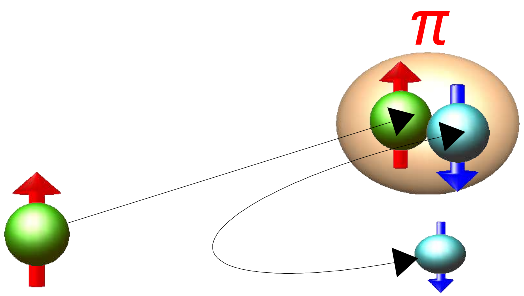
δq



Provides information about relativistic nature of the nucleon.

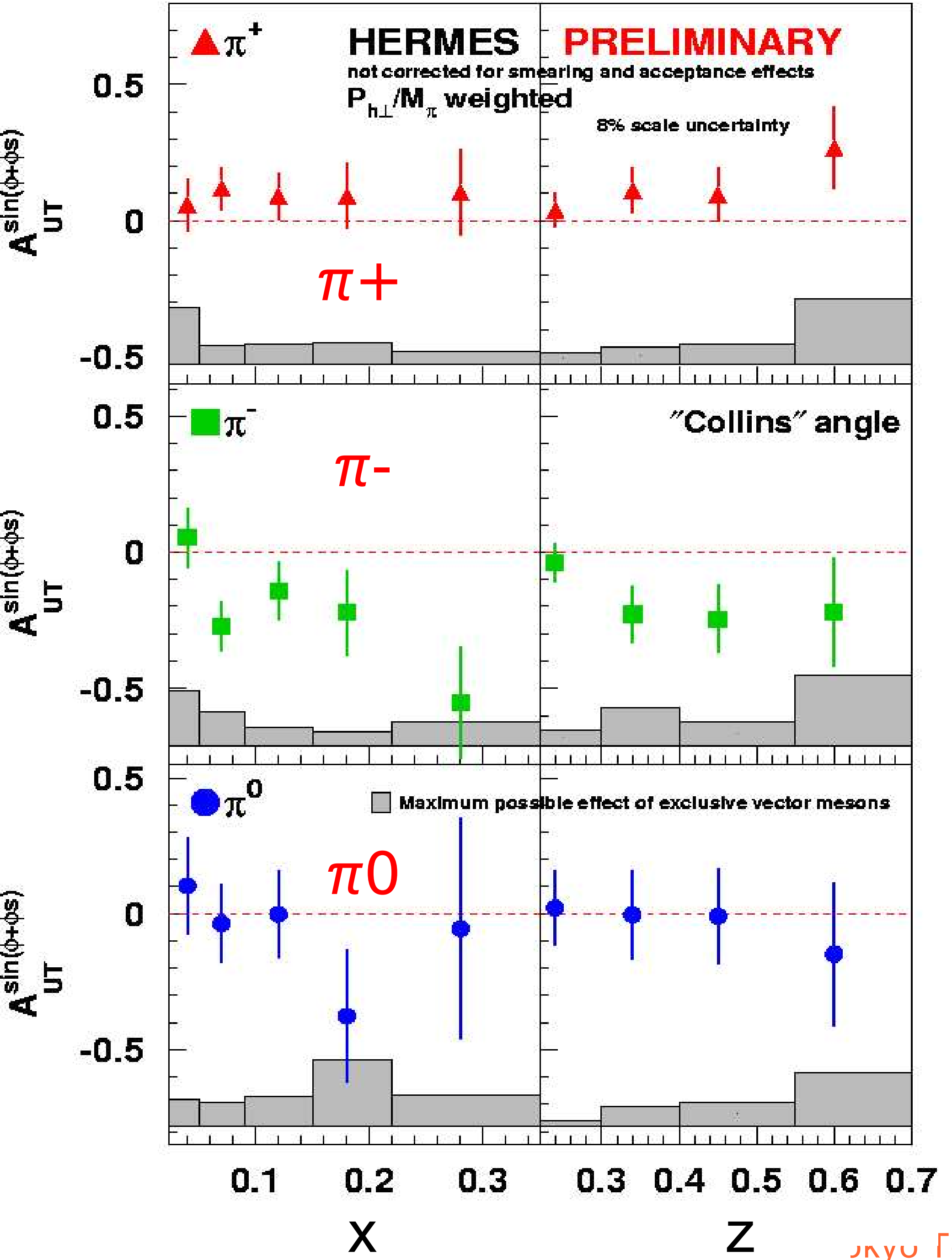
$H_1^{\perp}$ Collins FF
(Polarized FF)

$H_1^{\perp}$ describes fragmentation of pol. quark into unpol hadron.



Collins effects generates single-spin azimuthal asymmetry.

Measured Collins Asymmetries



$$A_{UT}^{Collins} \propto \delta q(x)\ H_1^{\perp}(z)$$

Averaged Asymmetries

(0.023 < x < 0.4, 0.2 < z < 0.7)

$$\langle A_{UT}^{Collins}(\pi^+)\rangle > 0$$

$$\langle A_{UT}^{Collins}(\pi^-)\rangle < 0$$

$$\langle A_{UT}^{Collins}(\pi^0)\rangle \sim 0$$

Interpretation of Collins Results

Collins asymmetries have two unknown components.

well-known unpol. quantities

$$A_{UT}^{Collins} \approx \frac{\sum_q e_q^2 \boxed{\delta q^q(x)} \boxed{H_1^{\perp}(z)}}{\sum_q e_q^2 \boxed{q(x) \;\; D(z)}}$$

- Define favored (ex. u→π+) and disfavored (ex. u→π-) FF

$$H^{fav} \equiv H_1^{u\to\pi^+} = H_1^{d\to\pi^-} = \ldots \qquad H^{dis} \equiv H_1^{u\to\pi^-} = H_1^{d\to\pi^+} = \ldots$$

- π+, π- and π0 asymmetries;

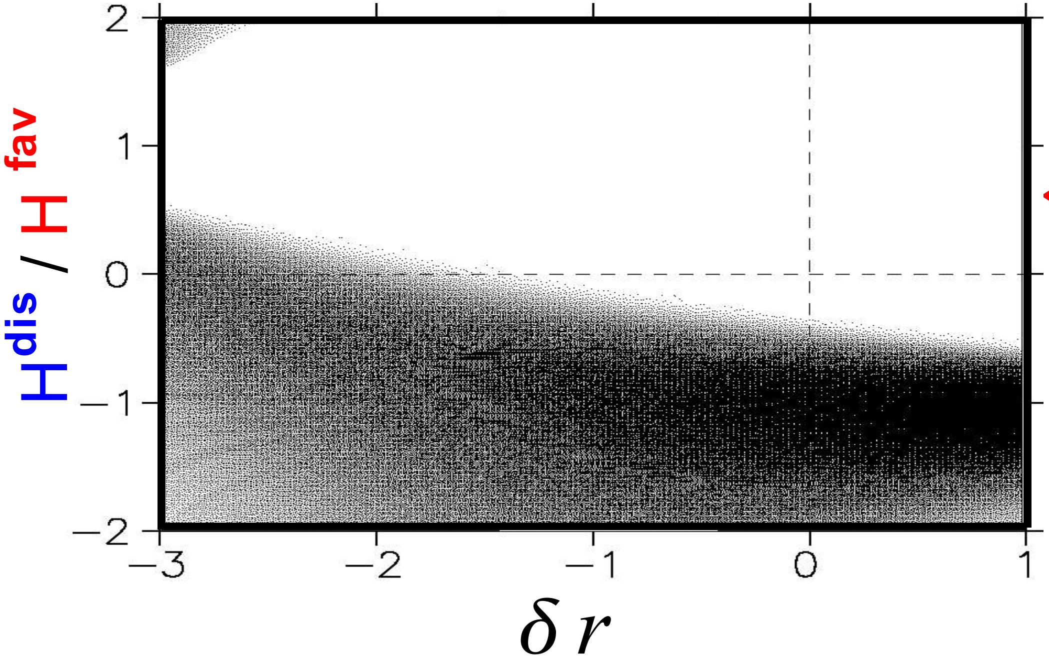
$$A^{\pi^+} = \frac{(4\delta u + \delta\bar{d})\boldsymbol{H}^{\boldsymbol{fav}} + (\delta d + 4\delta\bar{u})\boldsymbol{H}^{\boldsymbol{dis}}}{(4u + \bar{d})D^{fav} + (4\bar{u} + d)D^{dis}},$$

$$A^{\pi^-} = \frac{(4\delta u + \delta\bar{d})\boldsymbol{H}^{\boldsymbol{dis}} + (\delta d + 4\delta\bar{u})\boldsymbol{H}^{\boldsymbol{fav}}}{(d + 4\bar{u})D^{dis} + (4u + \bar{d})D^{fav}}, \qquad A^{\pi^0} = \frac{\cdots\cdot}{\cdots\cdot}$$

Interpretation of Collins Results

$$\frac{A^{\pi^-}}{A^{\pi^+}} \equiv \frac{4\tilde{H} + \delta r}{4\tilde{D} + r} \qquad \frac{A^{\pi^0}}{A^{\pi^+}} \equiv \frac{(4+\delta r)(1+\tilde{H})}{(4+r)(1+\tilde{D})}$$

Solution space populated according to statistical error



Likelihood distribution in solution space of

$$\tilde{H} \equiv \frac{H^{dis}}{H^{fav}}$$

$$\delta r \equiv \frac{\delta d + 4\,\delta\bar{u}}{\delta u + (1/4)\delta\bar{d}}$$

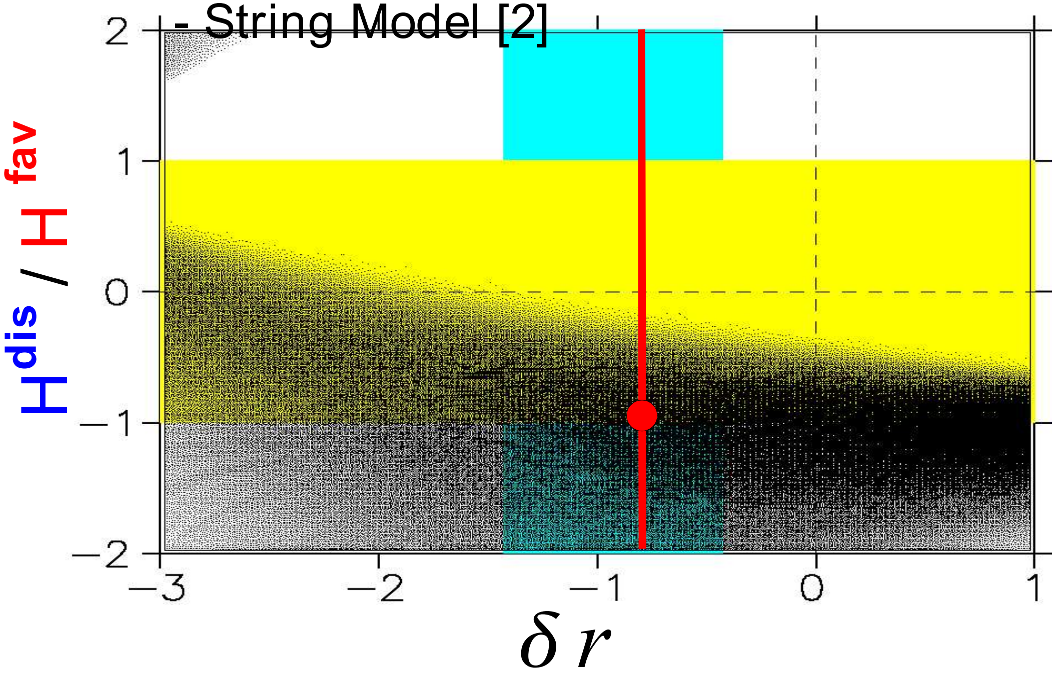
Well-known objects

$$\tilde{D} \equiv \frac{D^{dis}}{D^{fav}} \qquad r \equiv \frac{d + 4\,\bar{u}}{u + (1/4)\bar{d}}$$

Interpretation of Collins Results

$$\frac{A^{\pi^-}}{A^{\pi^+}} \equiv \frac{4\tilde{H} + \delta r}{4\tilde{D} + r} \qquad \frac{A^{\pi^0}}{A^{\pi^+}} \equiv \frac{(4 + \delta r)(1 + \tilde{H})}{(4 + r)(1 + \tilde{D})}$$

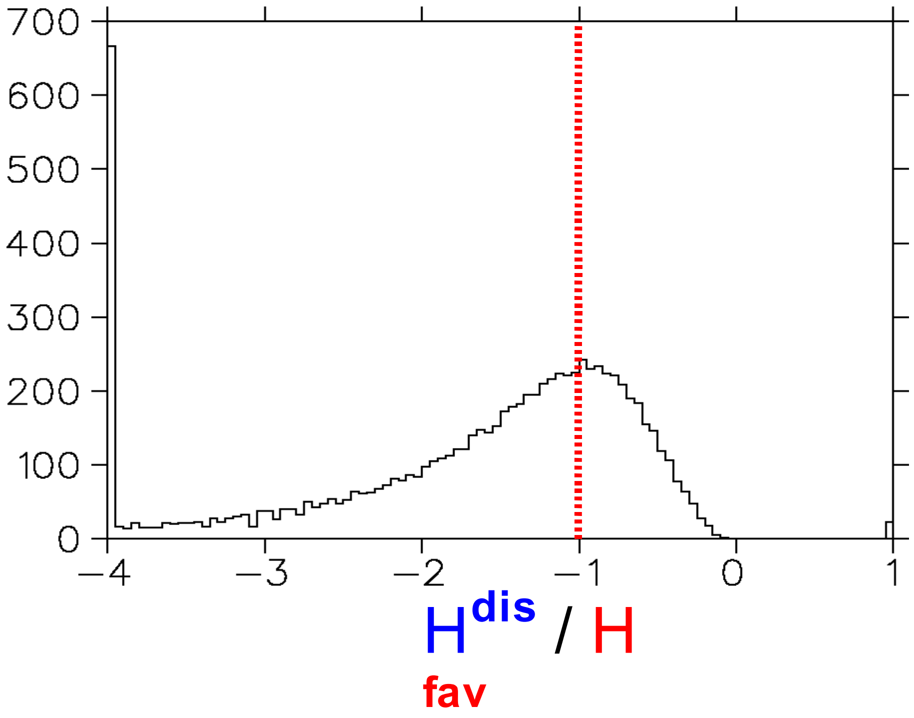
- Chiral Quark Soliton Model (CQSM) [1]
- String Model [2]



[1] M. Wakamatsu et al., Phys. Rev. D60, 034020
[2] X. Artru, hep-ph/9310323

H^{dis} / H^{fav} solution at CQSM value

δr = - 0.93 (Q^2=2.5 GeV^2)



Collins FF has opposite sign for favored and disfavored

(neglecting VM contamination)

2. Sivers Asymmetry

$$A_{UT} = A_{UT}^{Collins} \sin(\phi + \phi_S) + \boxed{A_{UT}^{Sivers}} \sin(\underline{\phi - \phi_S})$$

Sivers Asymmetry

$$A_{UT} \equiv A_{UT}^{Collins}\sin(\phi+\phi_S) + \boxed{A_{UT}^{Sivers}}\sin(\phi-\phi_S)$$

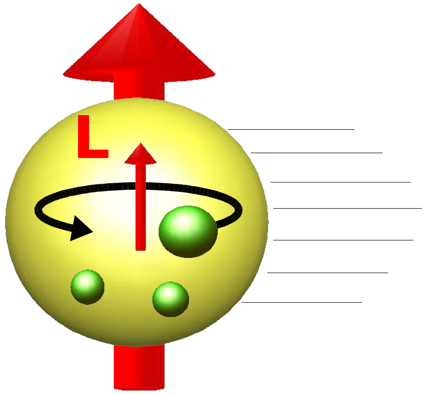
Sivers asymmetry

$$A_{UT}^{Sivers} \propto f_{1T}^{\perp}(x)\, D_1(z)$$

Sivers function

Unpol. FF

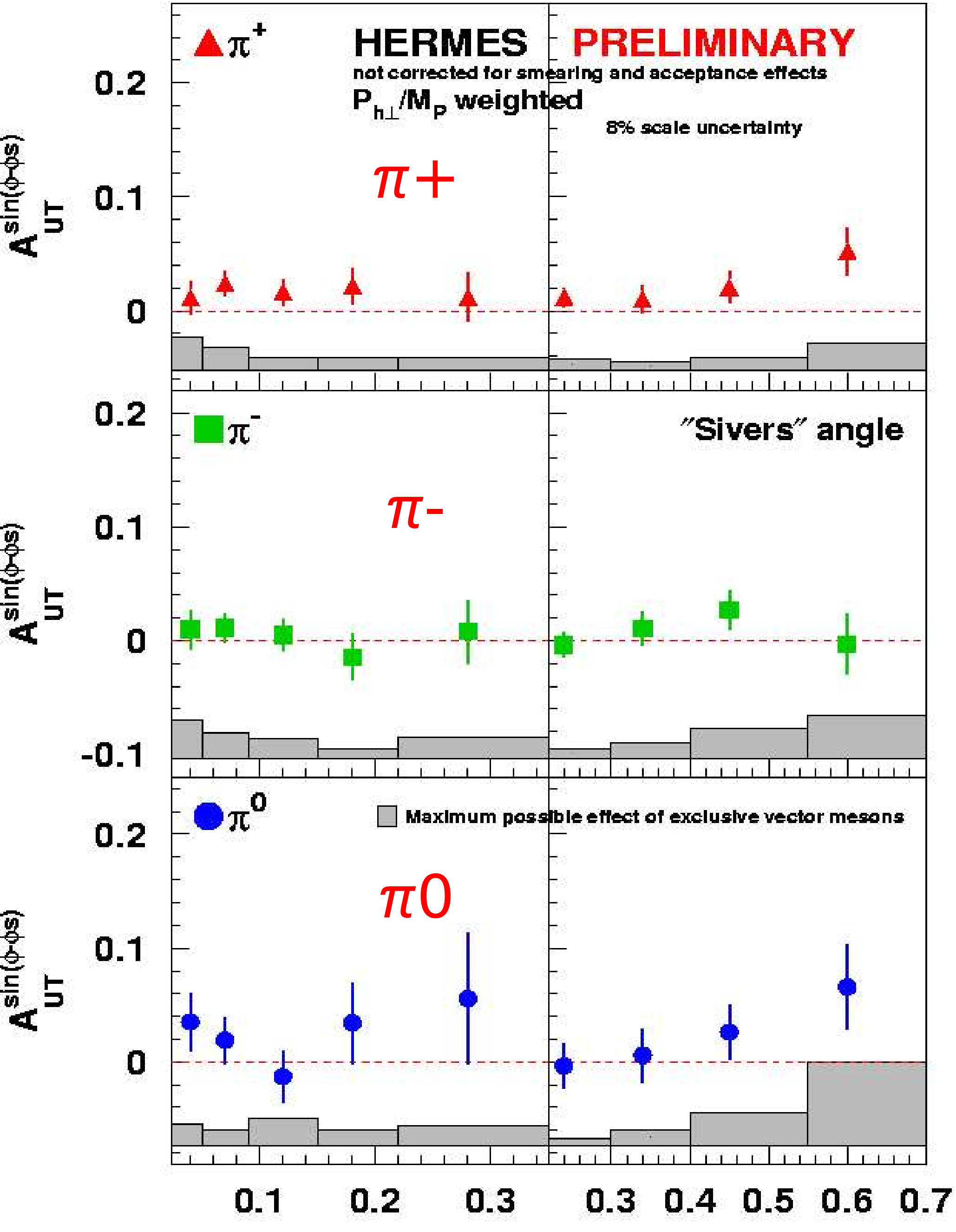
The Sivers function describes unpolarized quark in the transversely polarized nucleon.



$$f_{1T}^{\perp}(x)$$

Non-zero Sivers function requires quark orbital angular momentum.

Measured Sivers Asymmetries



$$A_{UT}^{Sivers} \propto f_{1T}^{\perp}(x)\ D_1(z)$$

Averaged Asymmetries

(0.023 < x < 0.4, 0.2 < z < 0.7)

$$\langle A_{UT}^{Sivers}(\pi^{+}) \rangle > 0$$

3σ away from zero.

$$\langle A_{UT}^{Sivers}(\pi^{-}) \rangle \sim 0$$

$$\langle A_{UT}^{Sivers}(\pi^{0}) \rangle \sim 0$$

Interpretation Sivers Results

$$A_{UT}^{Sivers} \approx \frac{\sum_q e_q^2 \boxed{f_{1T}^{\perp}(x)} \boxed{D(z)}}{\sum_q e_q^2 \boxed{q(x) \quad D(z)}}$$

Only one unknown

well-known
unpol. objects

Combine $\pi+$ and $\pi-$ asymmetries

$$C_1 A^{\pi^+} + C_2 A^{\pi^-} = f_{1T}^{\perp u} + (1/4) f_{1T}^{\perp \bar{d}}$$

$$C_3 A^{\pi^+} + C_4 A^{\pi^-} = f_{1T}^{\perp d} + 4 f_{1T}^{\perp \bar{u}}$$

Experimental results indicate;

$$f_{1T}^{\perp}(u) + \frac{1}{4} f_{1T}^{\perp}(\bar{d}) > 0$$

$$f_{1T}^{\perp}(d) + 4 f_{1T}^{\perp}(\bar{u}) < 0$$

- Non-zero Sivers function.
- Sivers function of u-quark has positive sign.
- Quark angular momentum could contribute to the nucleon spin.

Conclusion

- Single-spin asymmetry have been measured using 27.6 GeV positron beam and transversely polarized hydrogen target at the HERMES experiment.

- Collins asymmetry;

$$\langle A_{UT}^{Collins}(\pi^{+})\rangle > 0$$

$$\langle A_{UT}^{Collins}(\pi^{-})\rangle < 0$$

  - Favored and disfavored Collis FF have opposite sign.

- Sivers asymmetry;

$$\langle A_{UT}^{Sivers}(\pi^{+})\rangle > 0$$

  - First observation of non-zero Sivers effect.
  - Sivers function for u-quark is positive.

- More data are coming soon (about factor 4 by end of 2004).