研究会『核子構造研究の新展開2011』
- 2011年1月7日（金）
- KEK　4号館3階セミナー室(345)

レプトン-核子深非弾性散乱実験の発展

主に偏極

As a QCD baby?

山形大理学部
宮地　義之

YAMAGATA UNIVERSITY

手元にあった教科書から

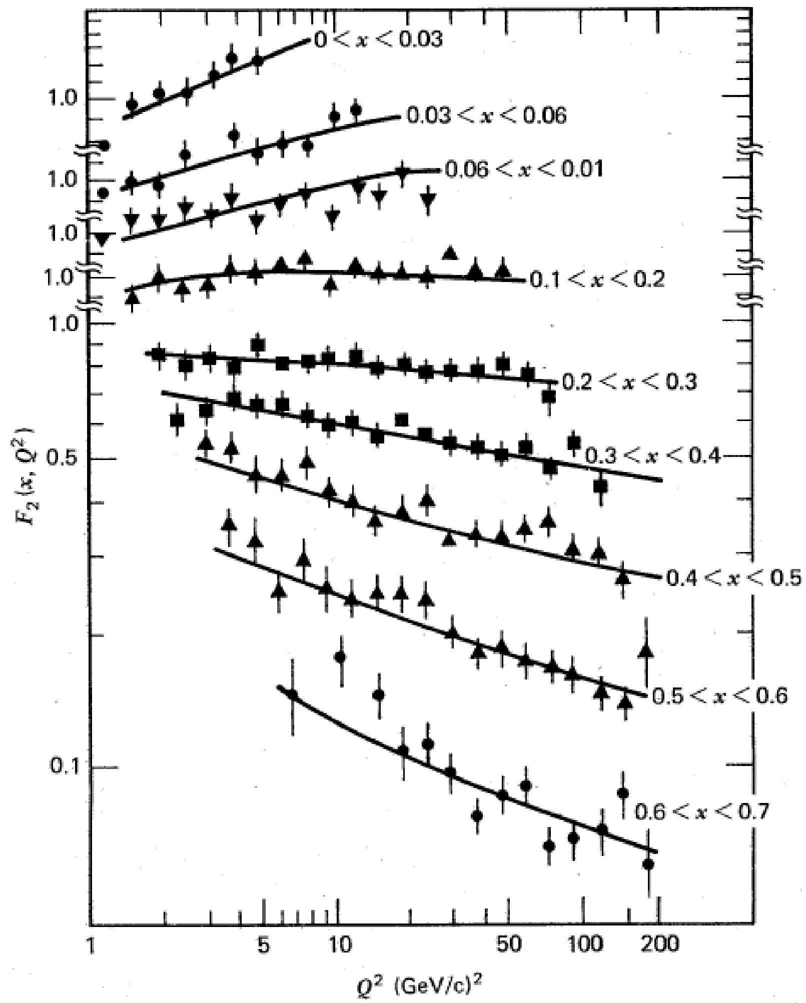


Fig. 10.10 Deviations from scaling. With increasing Q^2, the structure function $F_2(x, Q^2)$ increases at small x and decreases at large x. The data are from the CDHS counter experiment at CERN.

Quark & Leptons, F. Halzen and A. D. Martin (**1984**)

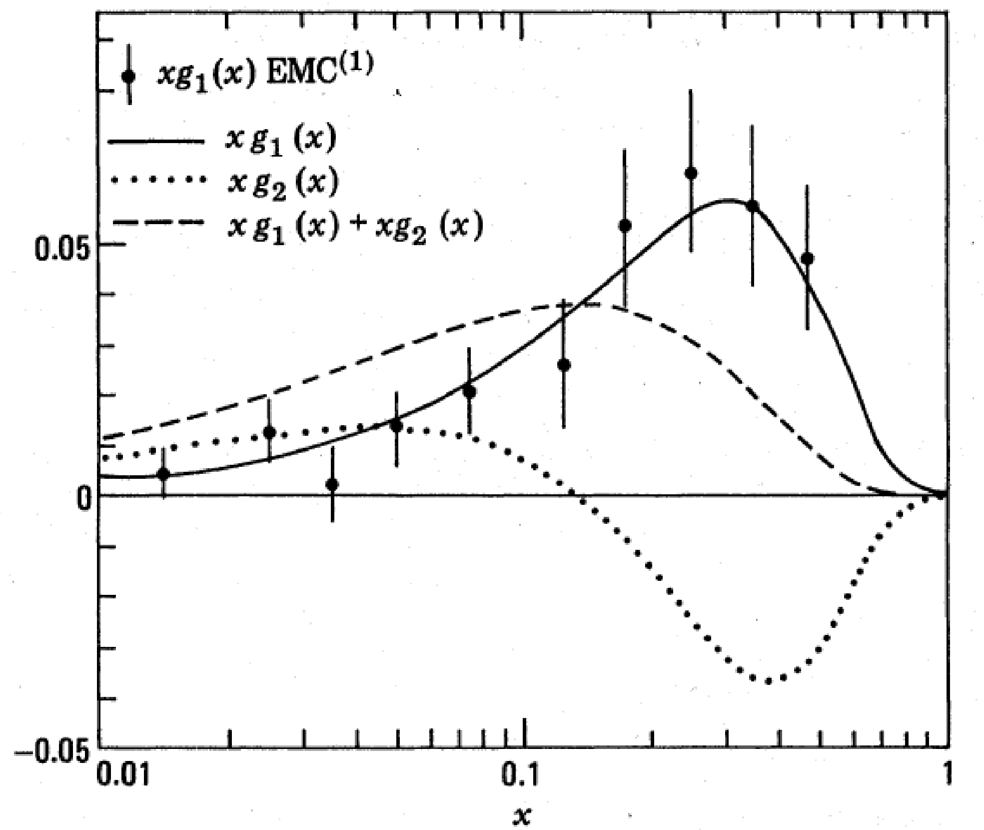


Fig. 3.9 Expectations for $xg_2(x)$, $xg_1(x) + xg_2(x)$ based on taking a parametrisation of the asymmetry $A(x) = g_1(x)/F_1(x)$ together with the measured values of $g_1(x)$.

The structure of the proton, R. G. Roberts (**1990**)

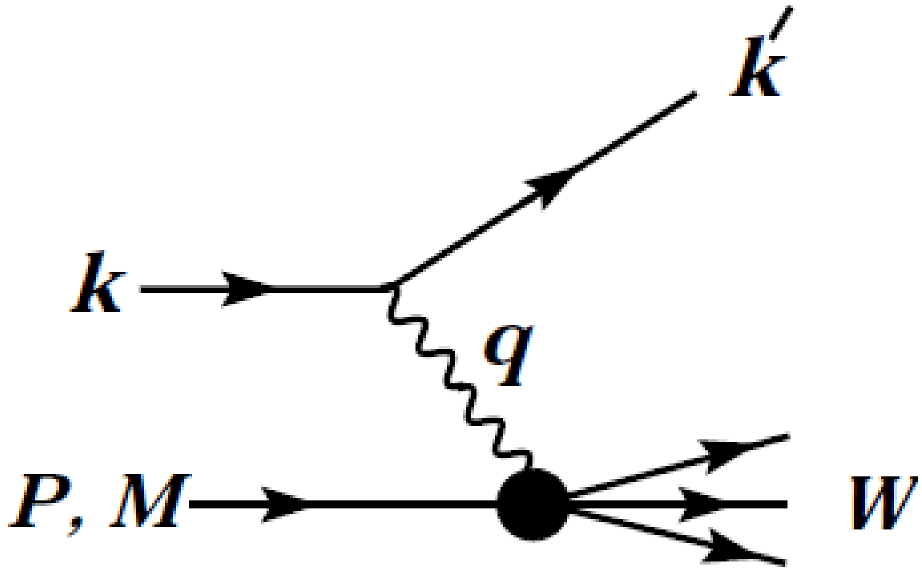
内容

- レプトン - 核子深非弾性散乱
  - 構造関数
  - パートン分布関数
- 非偏極実験
  - 構造関数
  - 海クォークフレーバー非対称性： ゴットフリード和則の破れ
- 偏極実験
  - 構造関数
  - 偏極分布関数
  - 横運動量依存分布関数
  - Hard Exclusive Production
- 今後の課題とまとめ

深非弾性散乱と核子構造関数

非偏極

$$\frac{d^2\sigma^i}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\eta^i\left\{\left(1-y-\frac{x^2y^2M^2}{Q^2}\right)F_2^i + y^2 xF_1^i \mp \left(y-\frac{y^2}{2}\right)xF_3^i\right\},$$



偏極

$$\frac{d^2\Delta\sigma^i}{dxdy} = \frac{8\pi\alpha^2}{xyQ^2}\eta^i\left\{-\lambda_\ell y\left(2-y-2x^2y^2\frac{M^2}{Q^2}\right)xg_1^i + \lambda_\ell 4x^3y^2\frac{M^2}{Q^2}g_2^i\right.$$

$$+\ 2x^2y\frac{M^2}{Q^2}\left(1-y-x^2y^2\frac{M^2}{Q^2}\right)g_3^i$$

$$\left.-\ \left(1+2x^2y\frac{M^2}{Q^2}\right)\left[\left(1-y-x^2y^2\frac{M^2}{Q^2}\right)g_4^i + xy^2g_5^i\right]\right\}$$

ニュートリノ散乱

深非弾性散乱とパートン

$$l + N \rightarrow l' + X$$

At Bjorken limit:

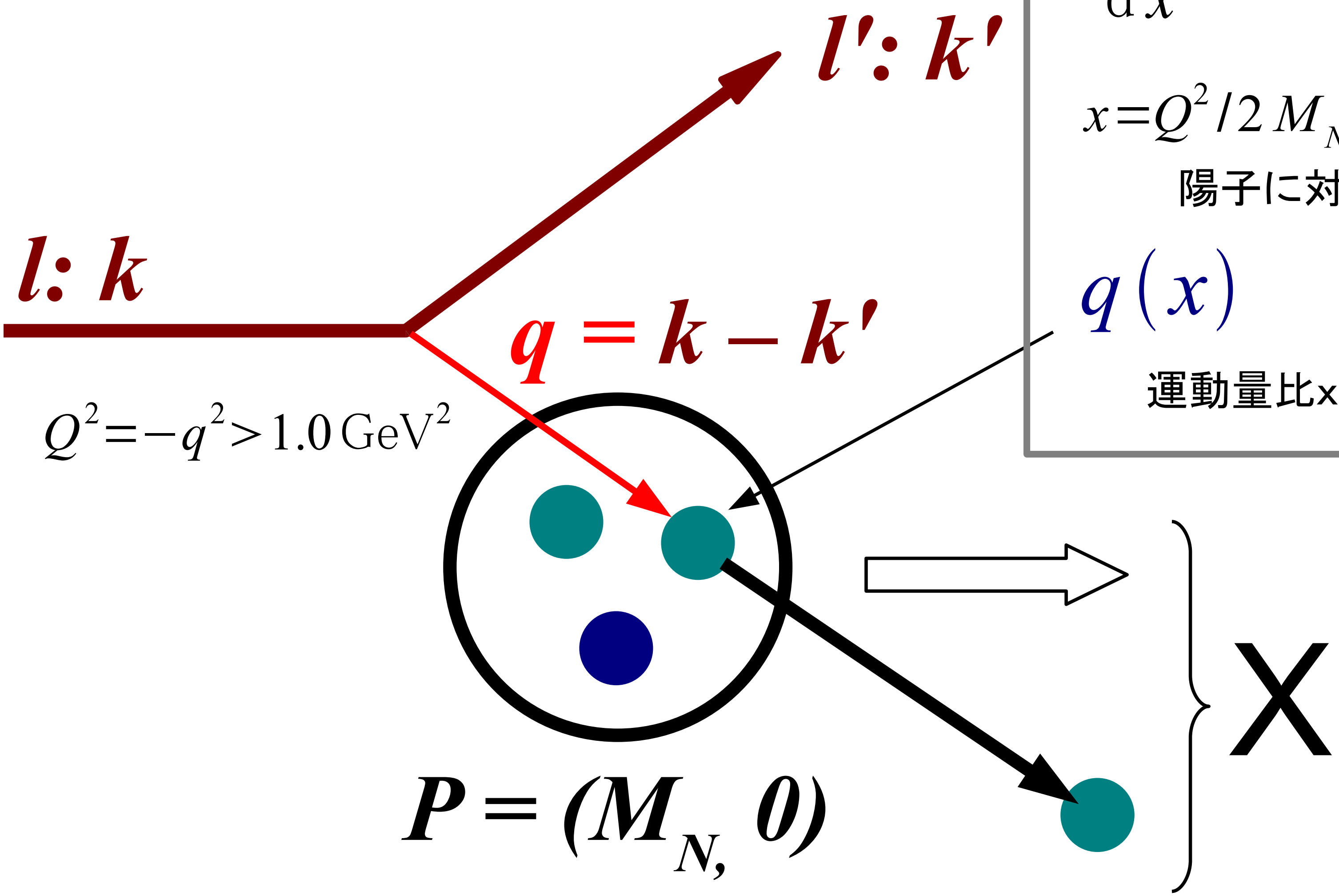
$$\frac{d\sigma}{dx} \propto F_1(x) = \frac{1}{2}\sum_q e_q^2 q(x)$$

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

陽子に対するパートン運動量比

$$q(x)$$

運動量比xをもつパートンの存在確率



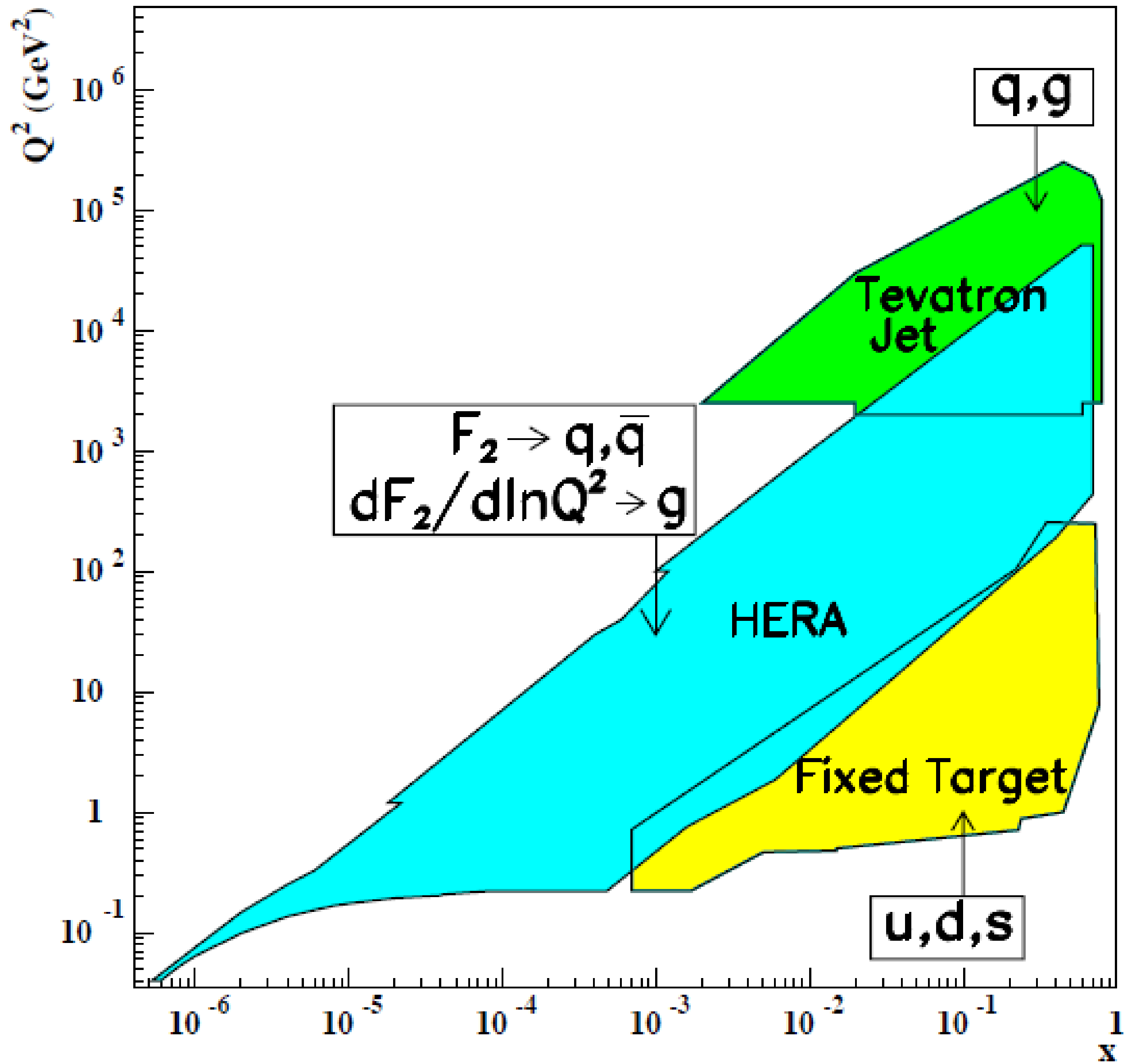
$$Q^2 = -q^2 > 1.0\,\mathrm{GeV}^2$$

$$W^2 = (P+q)^2$$

$$W^2 > 10\,\mathrm{GeV}^2$$

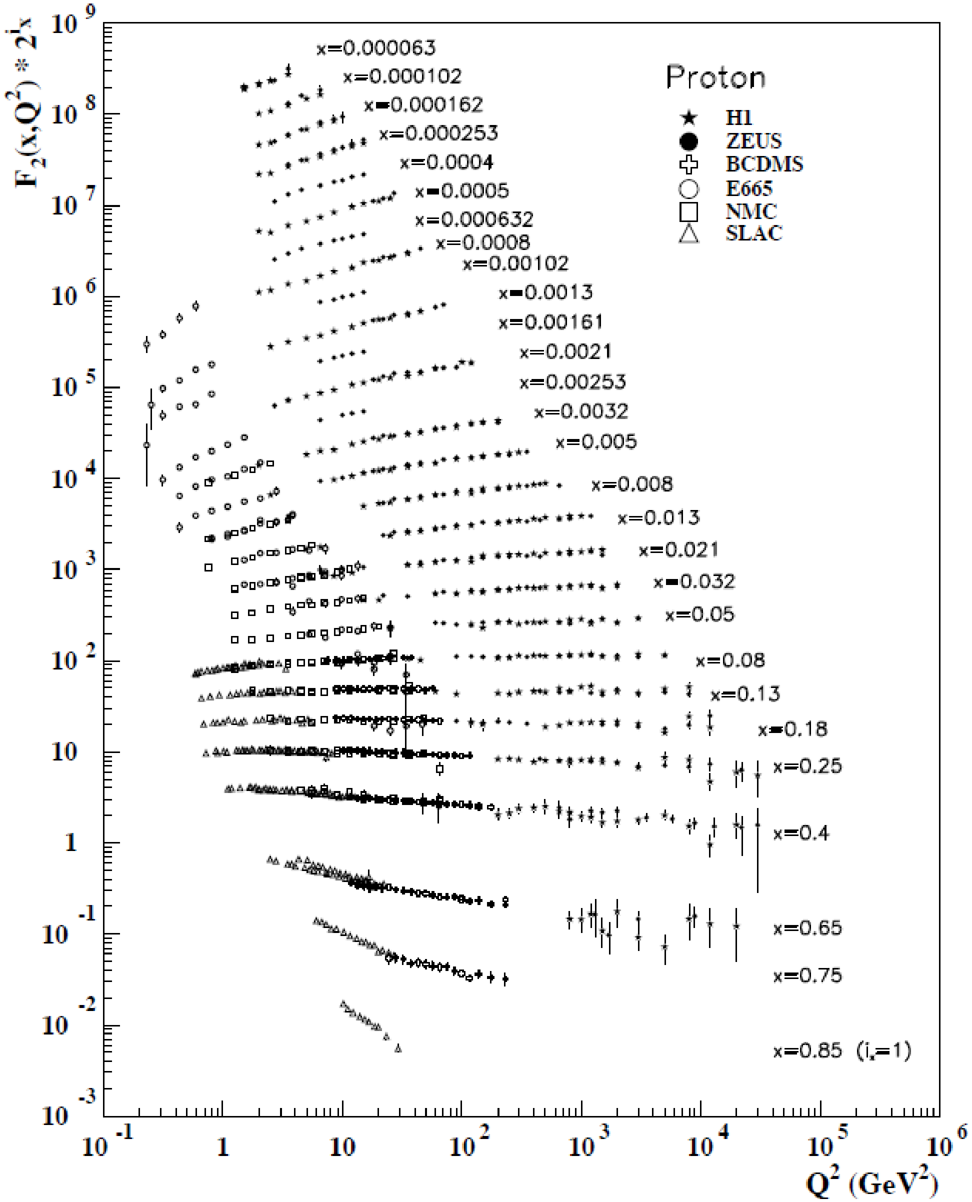
運動学的領域

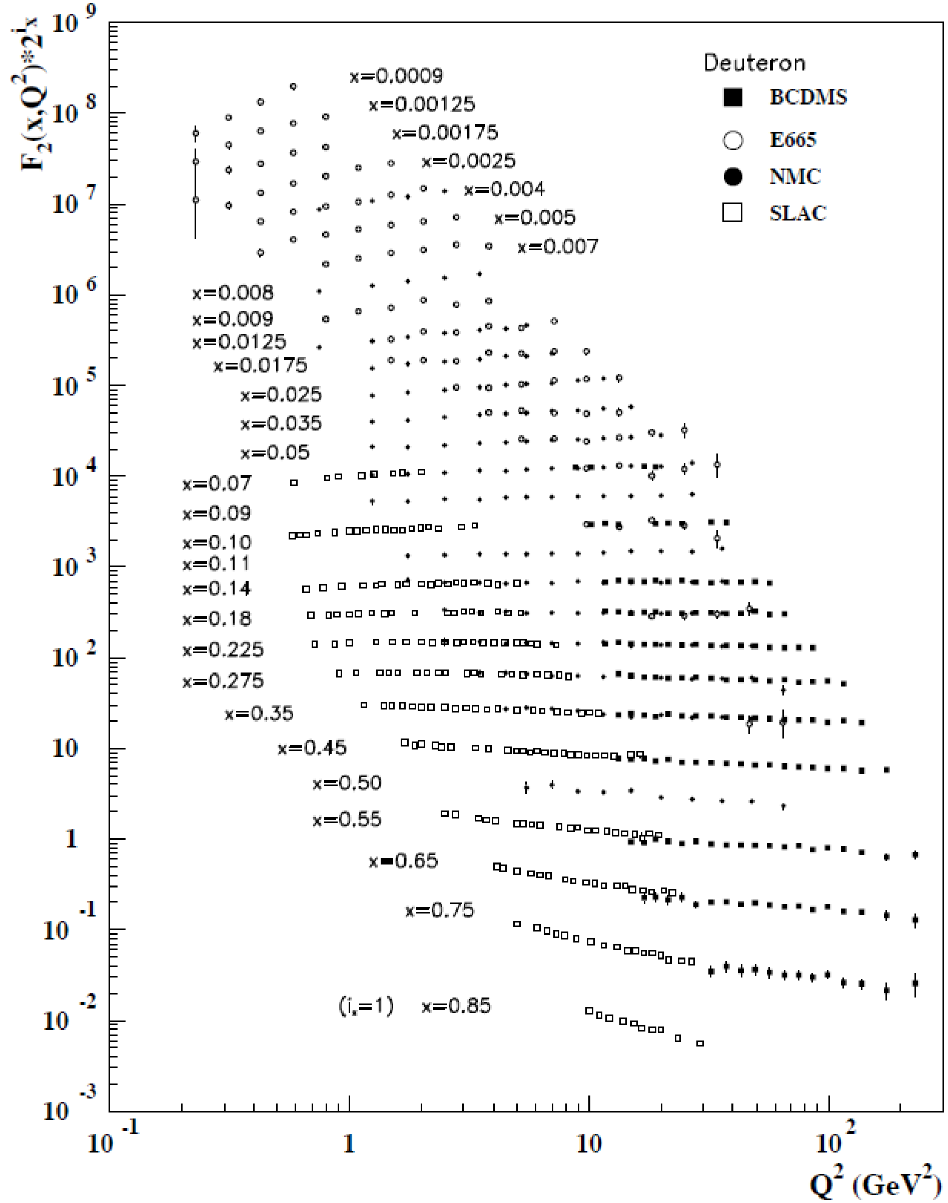
PDG2010 より



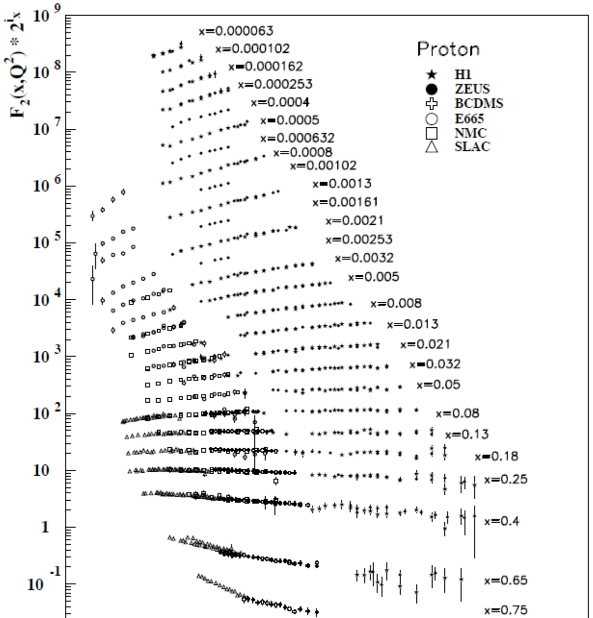
非偏極構造関数

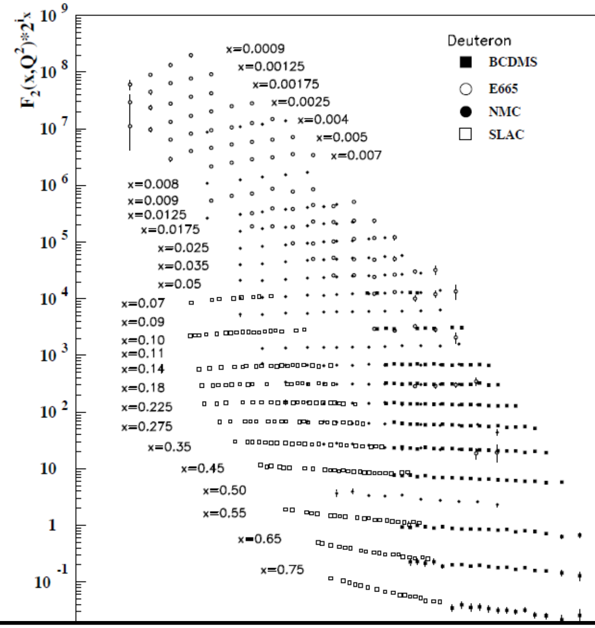
PDG2010 より





非偏極構造関数



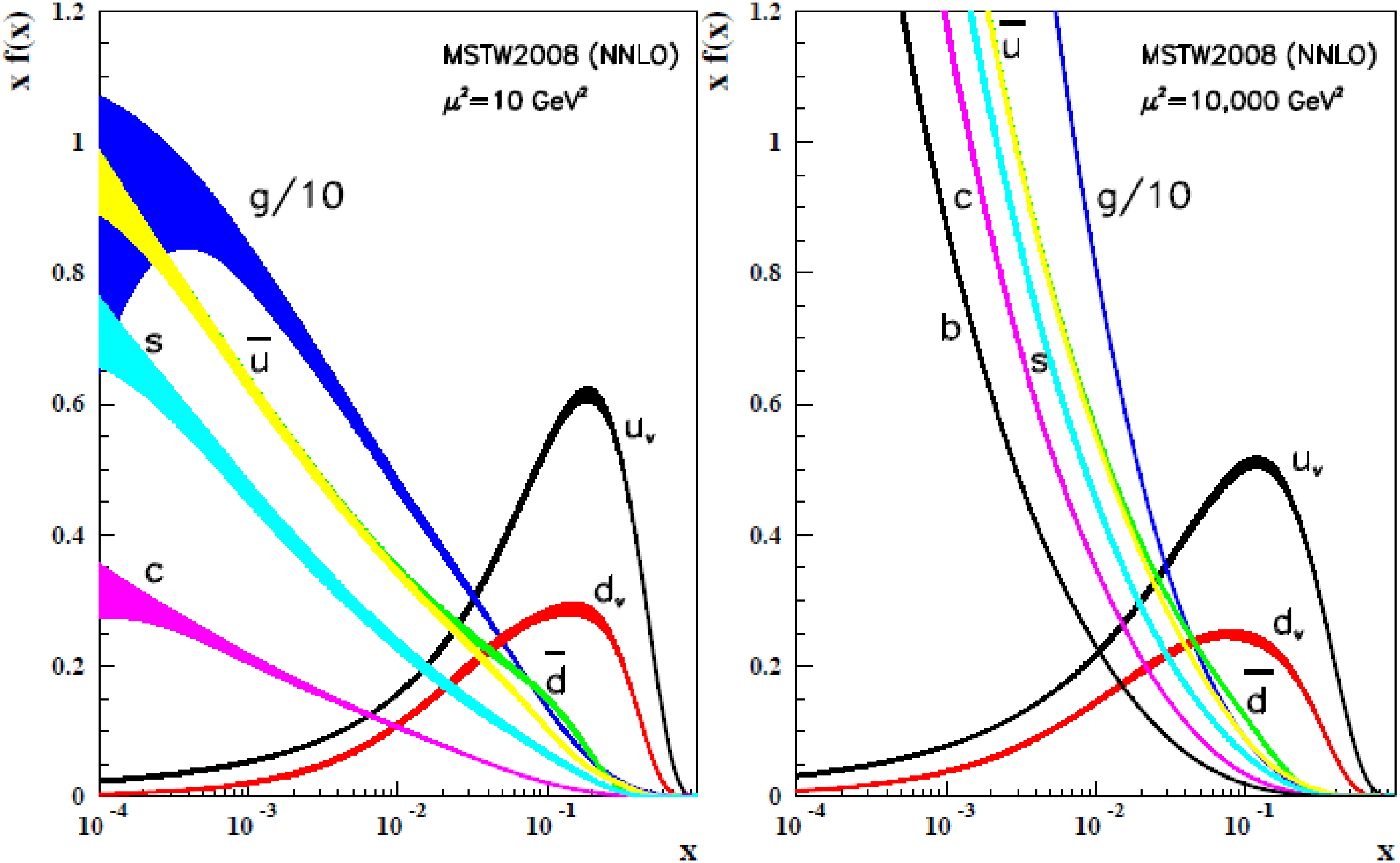


H1	Eur. Phys. J. C21, 33 (2001), Eur. Phys. J. C30, 1 (2003)
ZEUS	Eur. Phys. J. C21, 443 (2001), Phys. Rev. D70, 052001 (2004)
BCDMS	Phys. Lett. B223, 485 (1989), Phys. Lett. B237, 592 (1990)
E665	Phys. Rev. D54, 3006 (1996)
NMC	Nucl. Phys. B483, 3 (1997)
SLAC	Phys. Lett. B282, 475 (1992)

→ 清水志真(CERN)

HERA における陽子構造の研究結果

非偏極パートン分布関数



CT10　Phys. Rev. D82 074024 (2010) 等々

ゴットフリード和則

陽子 (u, u, d) ⟺ 中性子 (d,d,u)

$$\frac{d\sigma^p}{dx} \propto \left(\frac{2}{3}\right)^2 \left(\mathrm{u}^p + \bar{\mathrm{u}}^p\right) + \left(\frac{1}{3}\right)^2 \left(\mathrm{d}^p + \bar{\mathrm{d}}^p\right) + \left(\frac{1}{3}\right)^2 \left(\mathrm{s}^p + \bar{\mathrm{s}}^p\right) + \ldots$$

アイソスピン対称

$(u^p = d^n)$

$$\frac{d\sigma^n}{dx} \propto \left(\frac{2}{3}\right)^2 \left(\mathrm{u}^n + \bar{\mathrm{u}}^n\right) + \left(\frac{1}{3}\right)^2 \left(\mathrm{d}^n + \bar{\mathrm{d}}^n\right) + \left(\frac{1}{3}\right)^2 \left(\mathrm{s}^n + \bar{\mathrm{s}}^n\right) + \ldots$$

$$\frac{d\sigma^n}{dx} \propto \left(\frac{2}{3}\right)^2 \left(\mathrm{d}^p + \bar{\mathrm{d}}^p\right) + \left(\frac{1}{3}\right)^2 \left(\mathrm{u}^p + \bar{\mathrm{u}}^p\right) + \left(\frac{1}{3}\right)^2 \left(\mathrm{s}^p + \bar{\mathrm{s}}^p\right) + \ldots$$

$$\frac{d\sigma^p}{dx} - \frac{d\sigma^n}{dx} \propto \frac{1}{3}\left(\left(\mathrm{u} - \bar{\mathrm{u}}\right) - \left(\mathrm{d} - \bar{\mathrm{d}}\right)\right) - \frac{2}{3}\left(\bar{\mathrm{d}} - \bar{\mathrm{u}}\right)$$

⇓

$$\int \mathrm{u} - \bar{\mathrm{u}}\, dx = 2, \quad \int \mathrm{d} - \bar{\mathrm{d}}\, dx = 1, \quad \bar{\mathrm{u}}(x) = \bar{\mathrm{d}}(x)$$

フレーバー対称な海クォーク

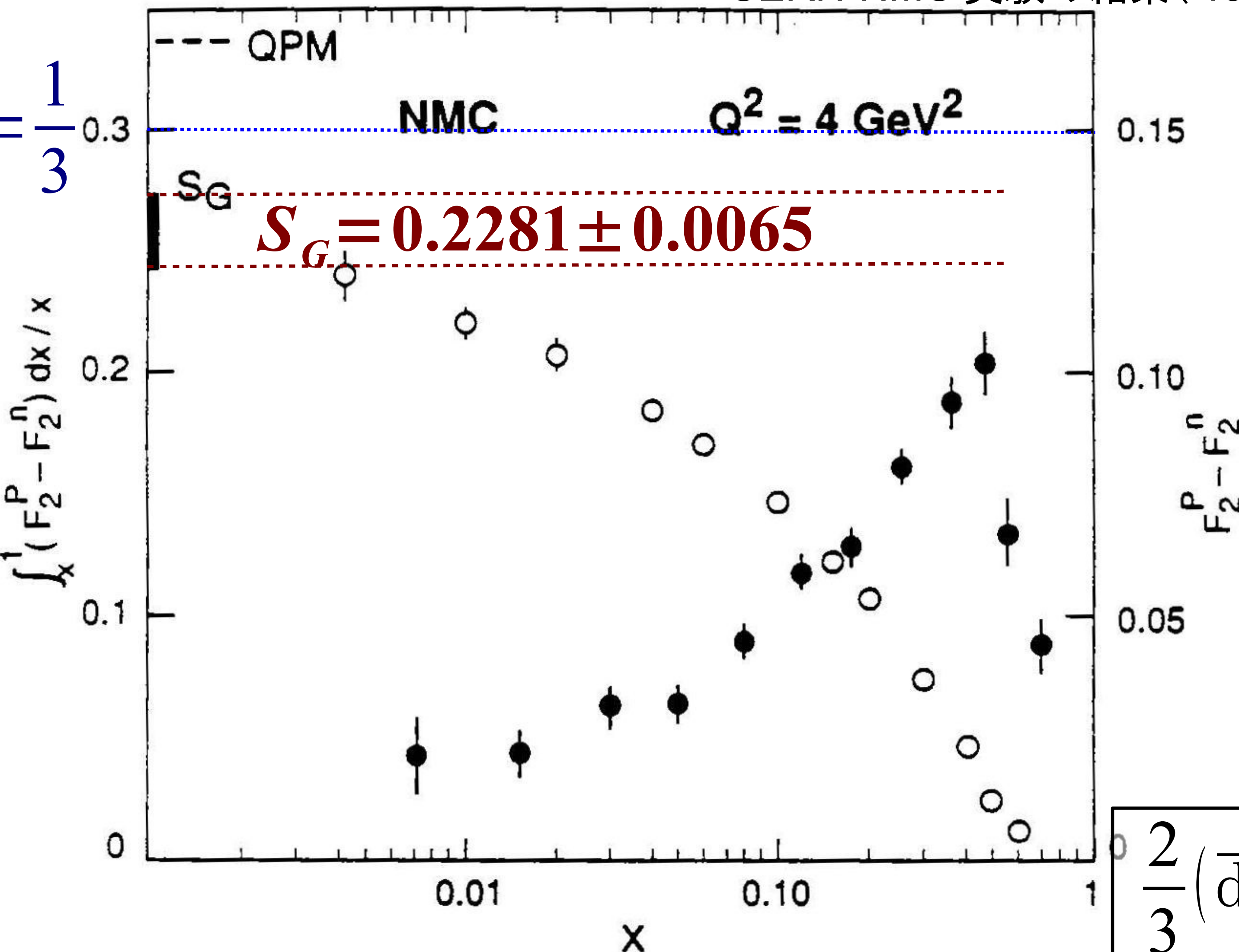
$$\sigma^p - \sigma^n \rightarrow \frac{1}{3}$$

ゴットフリード和則

ゴットフリード和則

CERN-NMC 実験の結果（1990）

$$S_G = \frac{1}{3}$$



$$S_G = 0.2281 \pm 0.0065$$

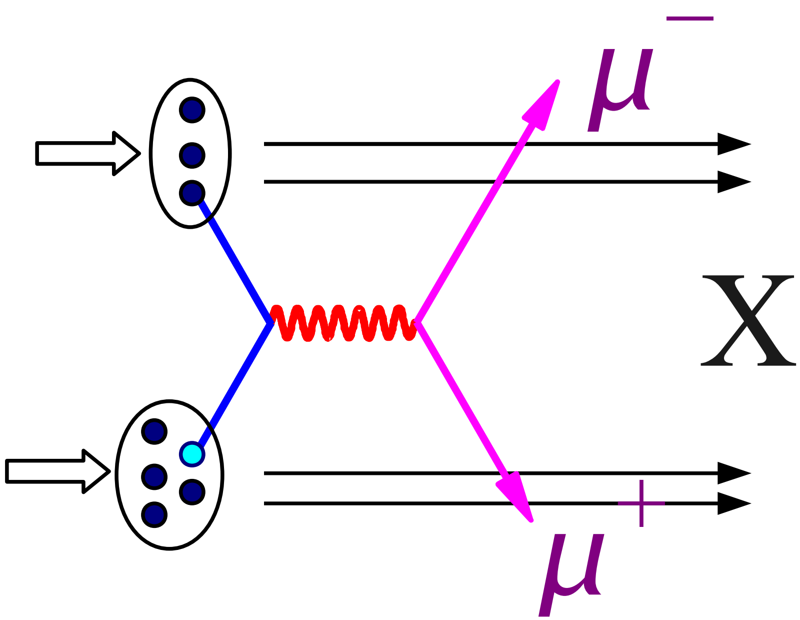
$$\frac{2}{3}\left(\bar{d} - \bar{u}\right) = \frac{1}{3} - \mathbf{0.2281}$$

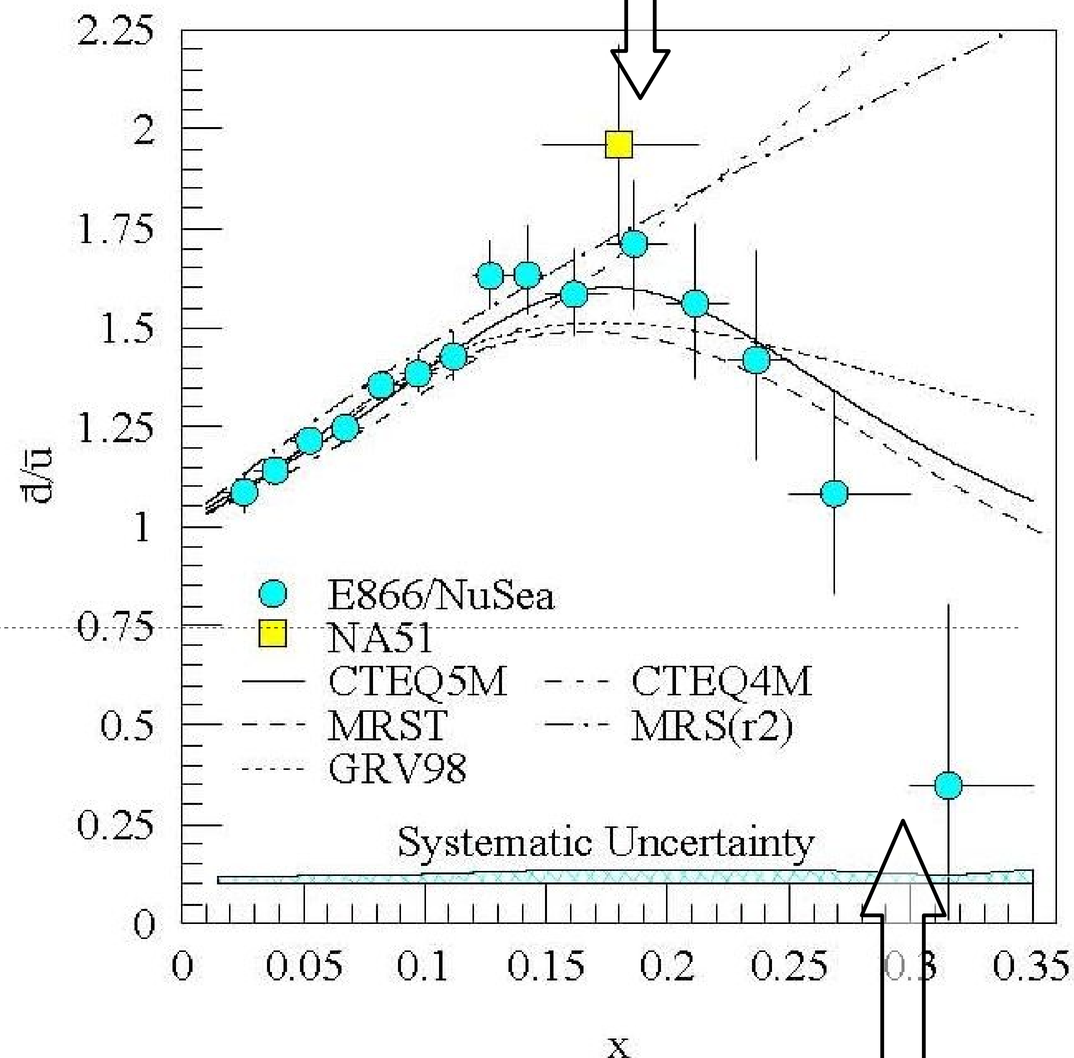
$$\left(\bar{d} - \bar{u}\right) \sim \mathbf{0.11}$$

ドレル・ヤン実験の結果

x~0.2 で
反 d/ 反 u 比 が最大

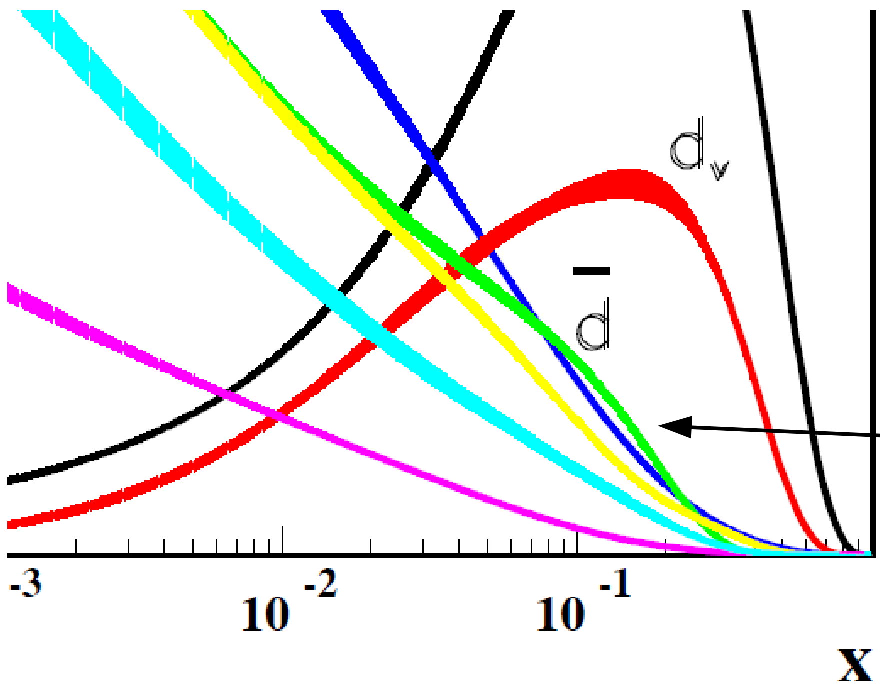
フェルミ研800GeV陽子ビームによる
ドレル・ヤン散乱実験（E867/NuSea）

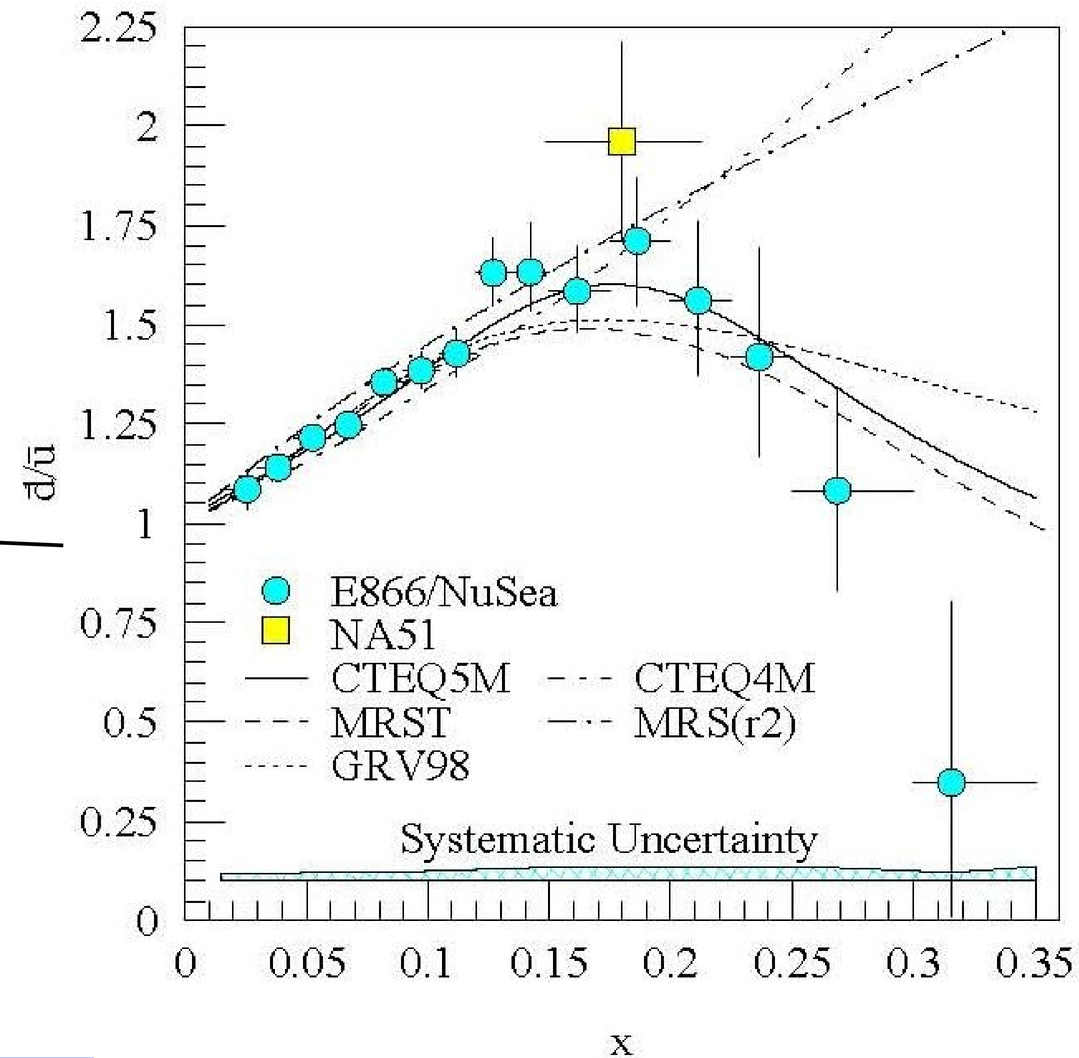




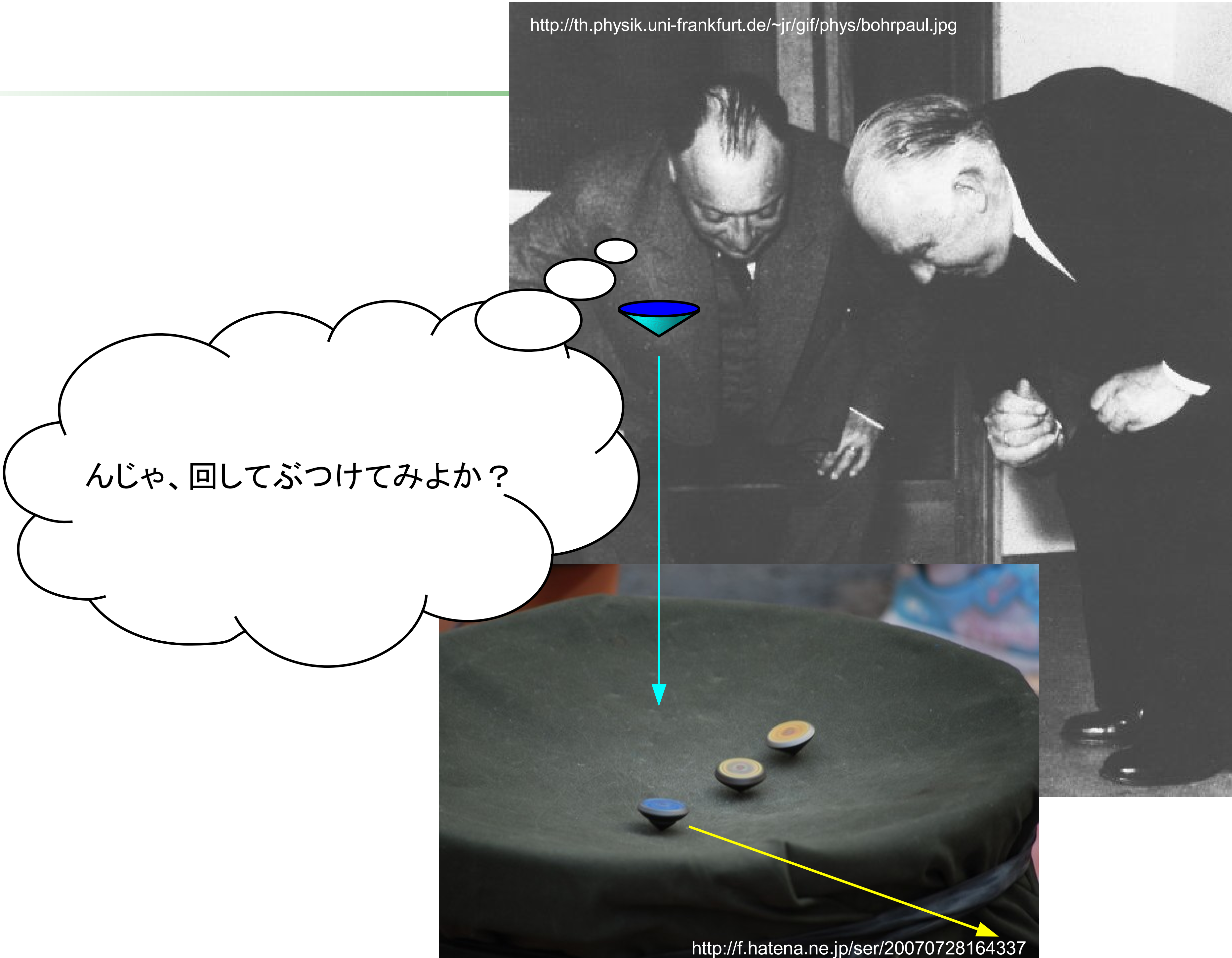
x~0.3 で反 d/ 反 u 比 反転？

PDF 解析への影響

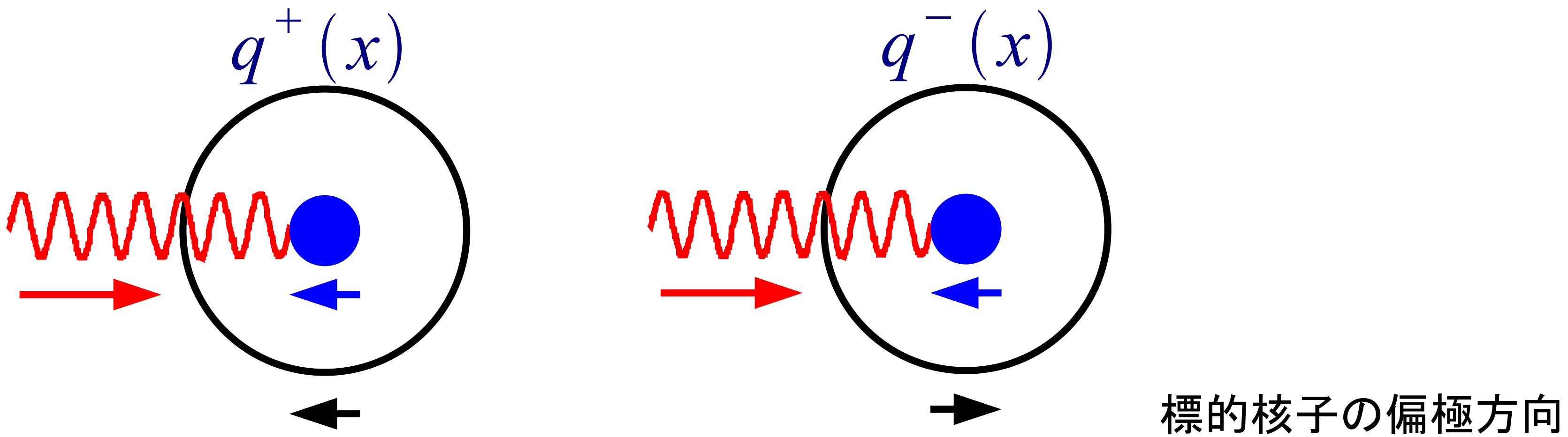




→ Florian Sanftl (Tokyo Tech)
" Drell-Yan experiments: past and future"


http://th.physik.uni-frankfurt.de/~jr/gif/phys/bohrpaul.jpg
んじゃ、回してぶつけてみよか？
http://f.hatena.ne.jp/ser/20070728164337

偏極深非弾性散乱と偏極分布関数

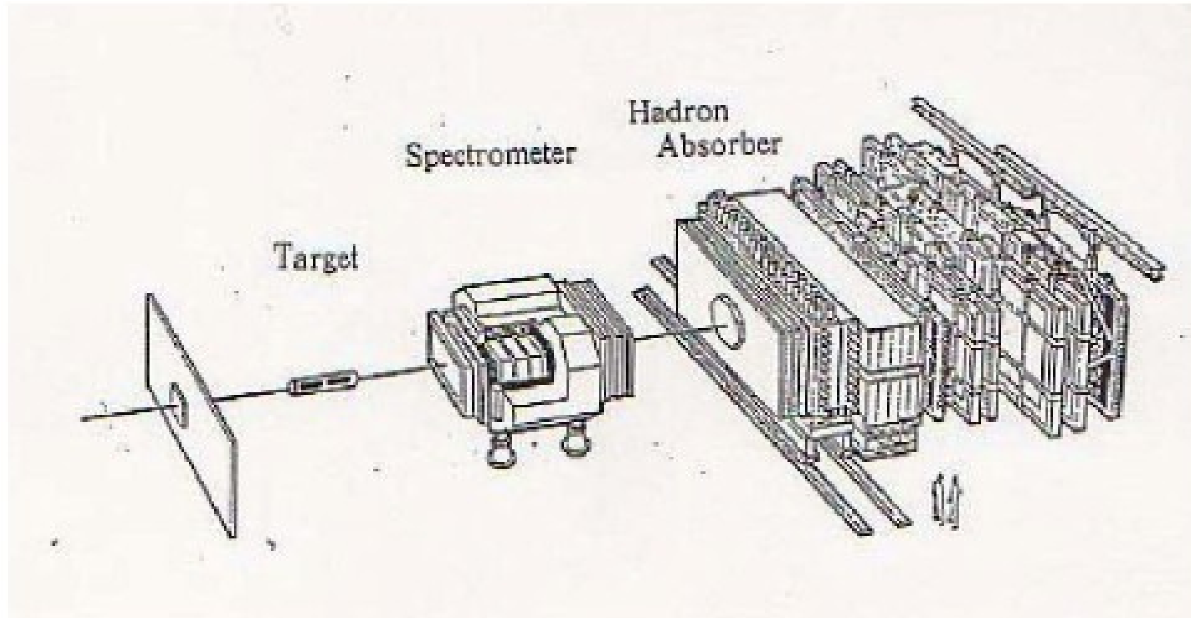


$$F_1(x)=\frac{1}{2}\sum_q e_q^2 q(x) \qquad q(x)=q^+(x)+q^-(x)$$

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

1. Introduction

EMC Experiment
(1988)



Muon – Proton Deep Inelastic Scattering at CERN

E = 100, 120, 200 GeV $\quad P_{\mu} \approx 76\,\%$ $\quad P_{T} \approx 75-80\,\%$ $\quad NH_3$

$$A = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}}$$

陽子スピンの問題：EMC実験

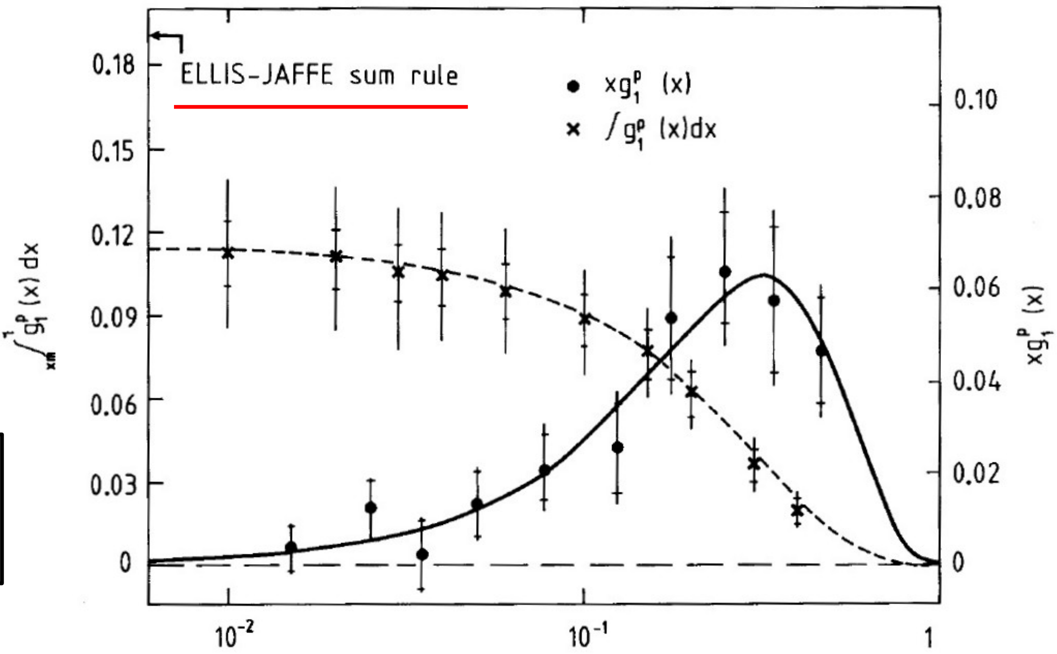
Nucl. Phys. B328 (1989) 1, Phys. Lett. B206 (1988) 364

構造関数の積分値：

$$\int_0^1 dx\, g_1^p(x) = \frac{1}{2}\left(\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right)$$
$$= \frac{1}{9}a_0 + \frac{1}{12}a_3 + \frac{1}{36}a_8$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = a_0$$
$$\Delta u - \Delta d = a_3$$
$$\Delta u + \Delta d - 2\Delta s = a_8$$

From weak decay:
$a_3 = 1.26,\quad a_8 = 0.58$

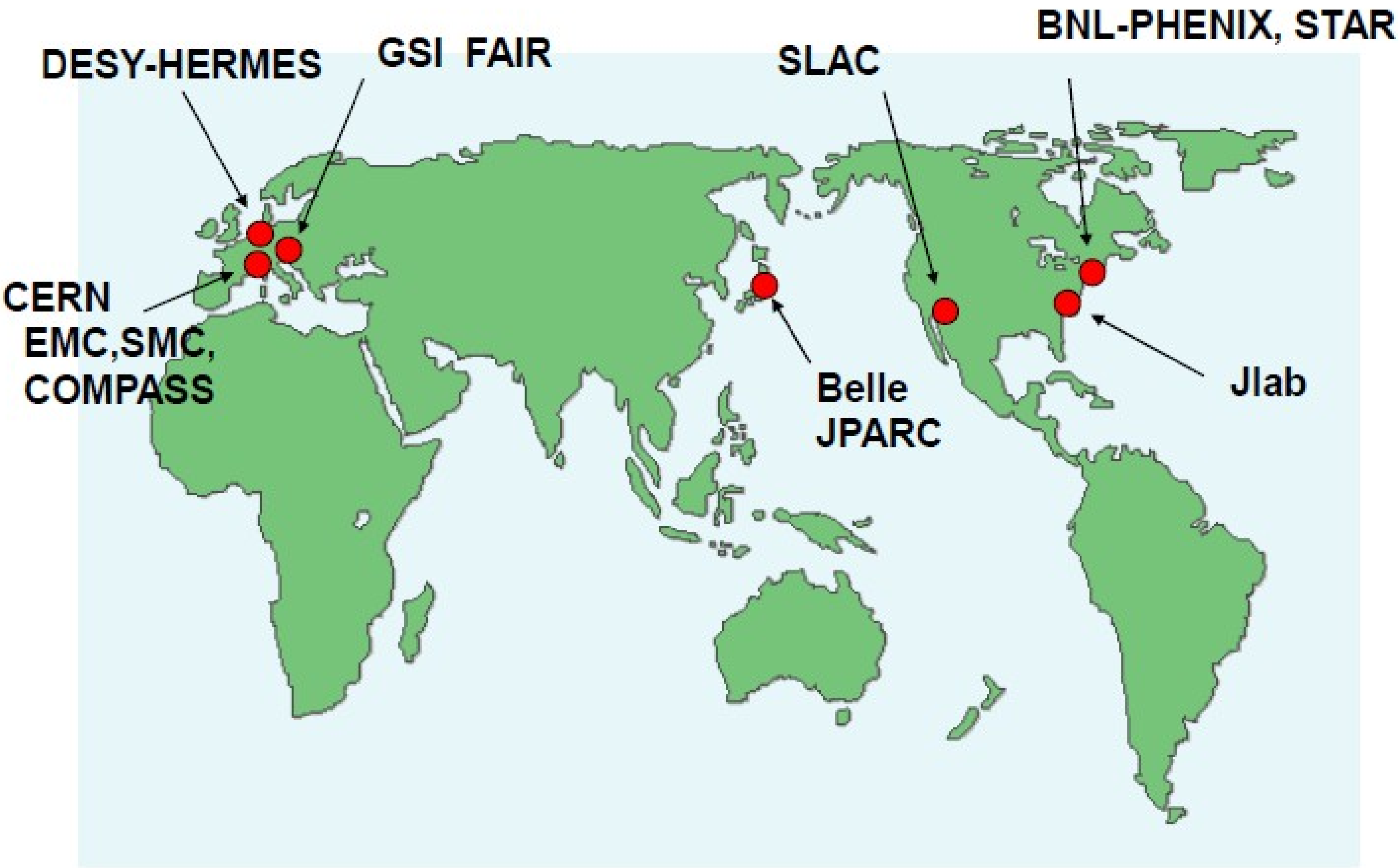


·Δs=0 を仮定すると： $a_0 = a_8 = 0.58$ → $\int_0^1 dx\, g_1^p(x) = 0.186$ Ellis-Jaffe 和則

得られた構造関数の積分値：

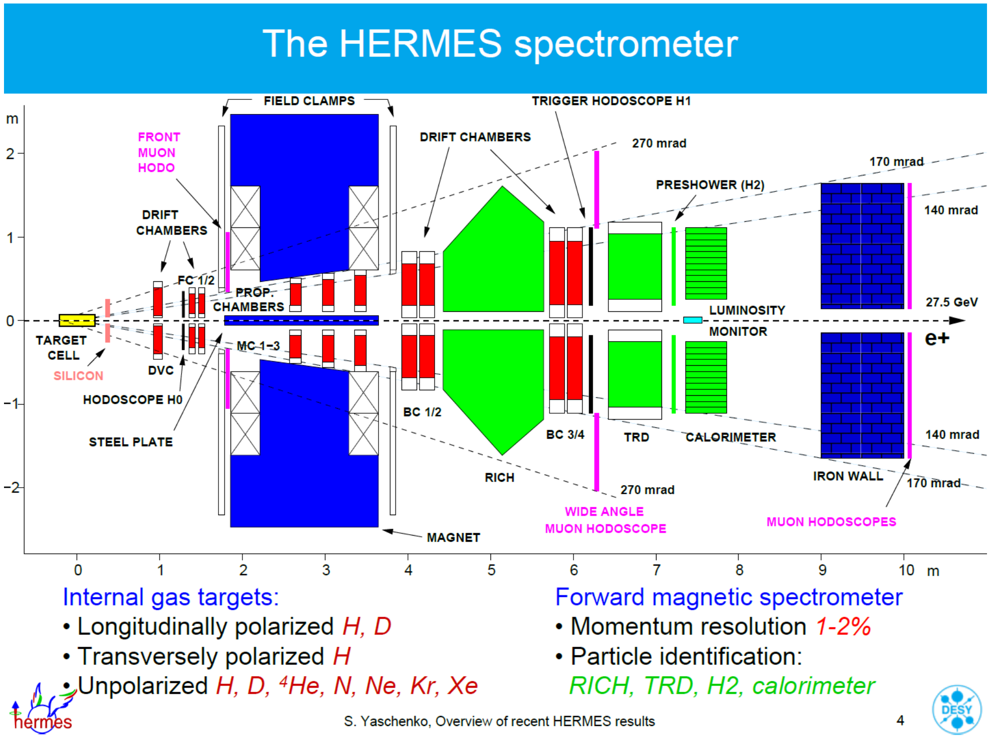
$$\int_0^1 dx\, g_1^p(x) = 0.126 \pm 0.010 \pm 0.015 \longrightarrow \Delta\Sigma = 0.120 \pm 0.094 \pm 0.138$$

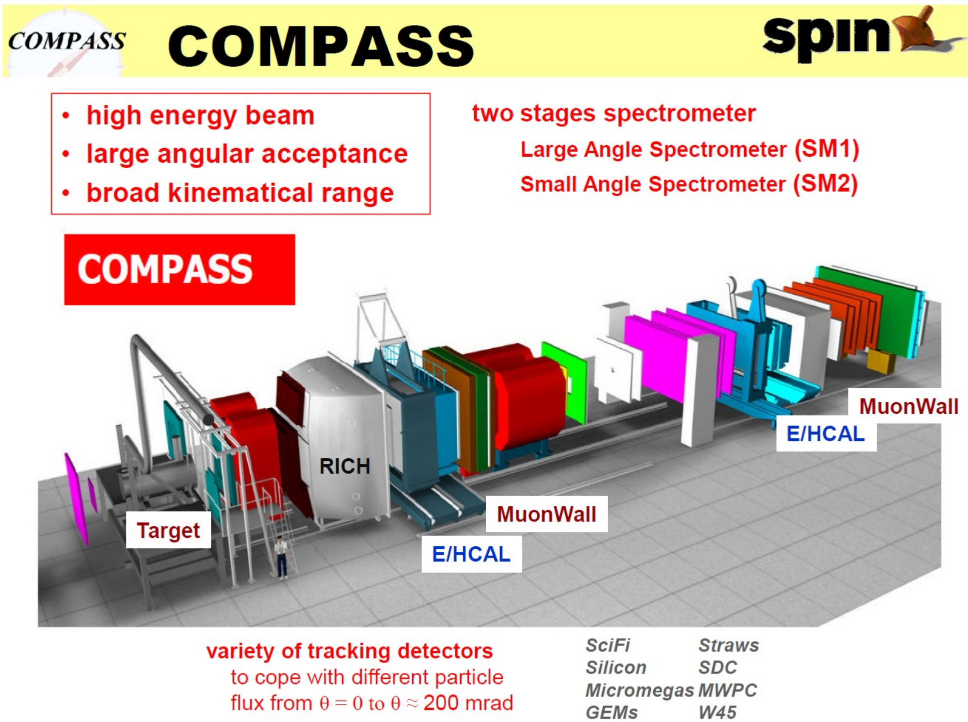
「クォークのスピンを足し合わせても陽子のスピンの2割に満たない」



500 ~ 1000 experimental physicists now,
Strong activities of theoretical physicists

偏極深非弾性散乱実験



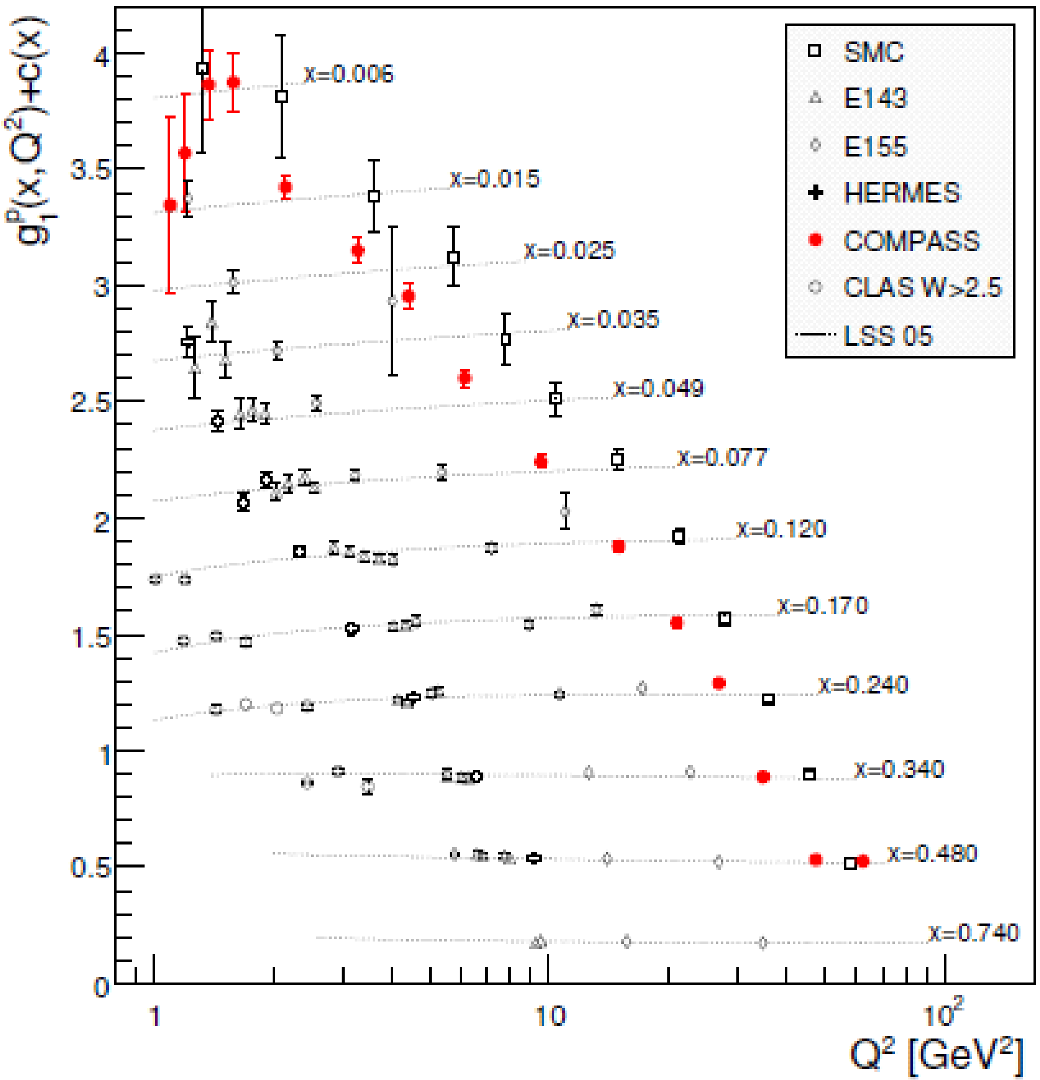


Beam	26.7 GeV	pol. electron/positron
Target	1996-1997	Long. H
	1998-2000	Long. D
	2002-2005	Trans. H
	2006-2007	unpol. H

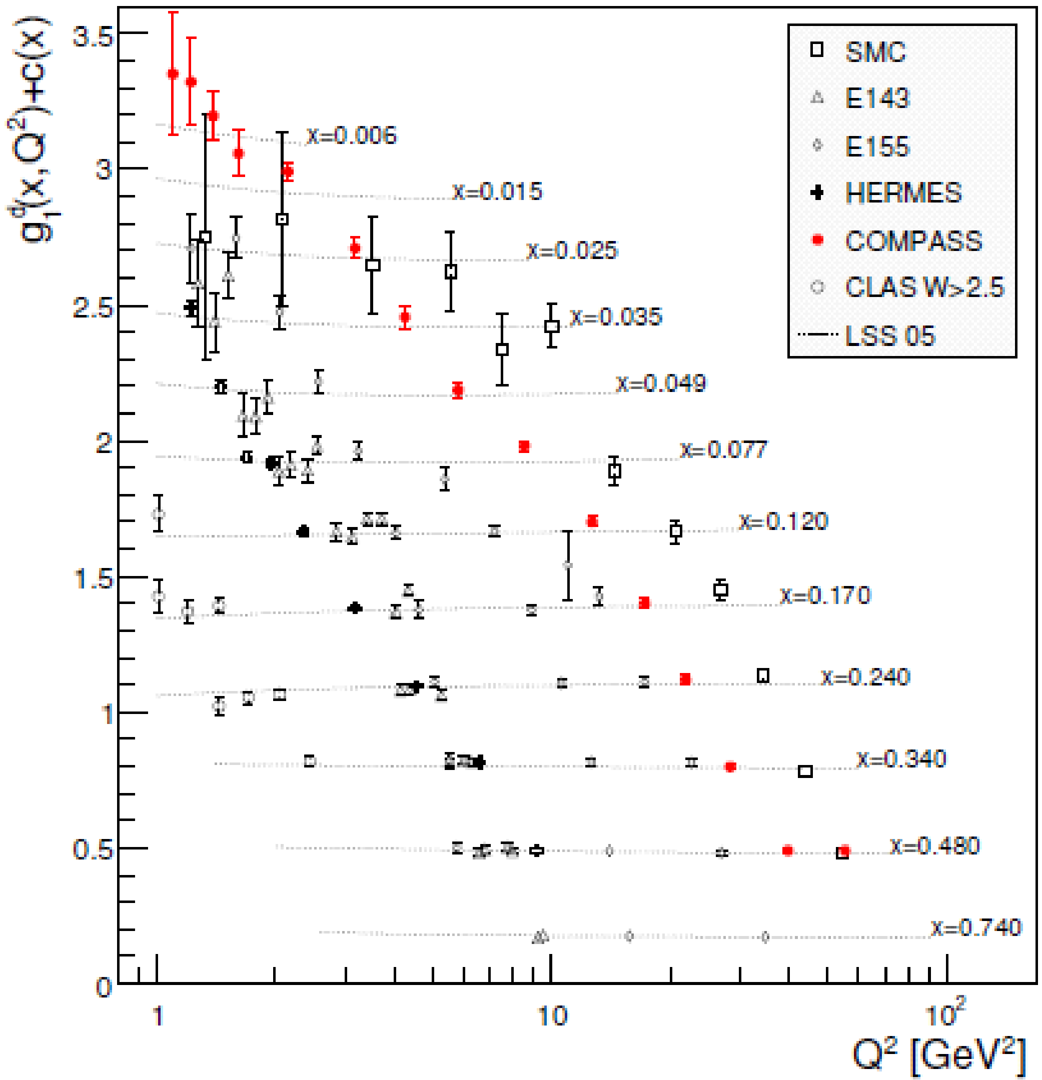
Beam	160 GeV pol. muon	
Target	2002 - 2006	Long. + Trans. ^{6}LiD.
	2007	Long. + Trans. NH_3
	2010	Trans. NH_3
	2011	Long. NH_3

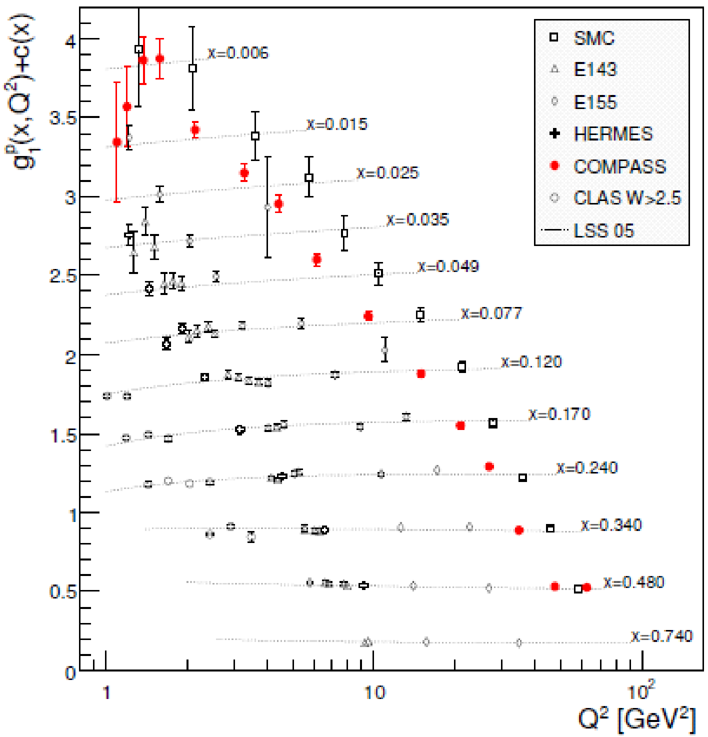
偏極構造関数

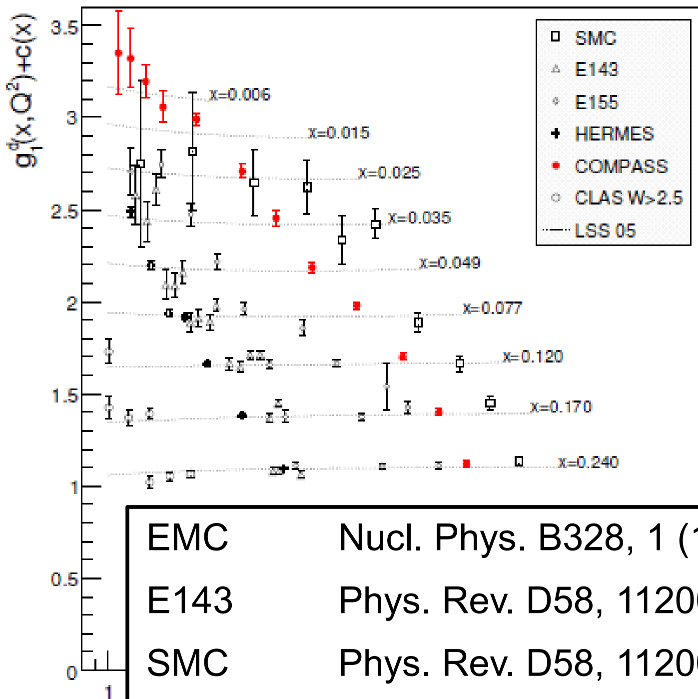
陽子



重陽子







EMC	Nucl. Phys. B328, 1 (1989), Phys. Rev. D54, 6620 (1996)
E143	Phys. Rev. D58, 112003 (1998)
SMC	Phys. Rev. D58, 112001 (1998)
E155	Phys. Lett. B463, 339 (1999), Phys. Lett. B493, 19 (2000)
HERMES	Phys. Rev. D75, 012007 (2007)
COMPASS	Phys. Lett. B690, 466 (2010), Phys. Lett. B647, 8 (2007)
CLAS	Phys. Lett. B641, 11 (2006)

Bjorken 和則

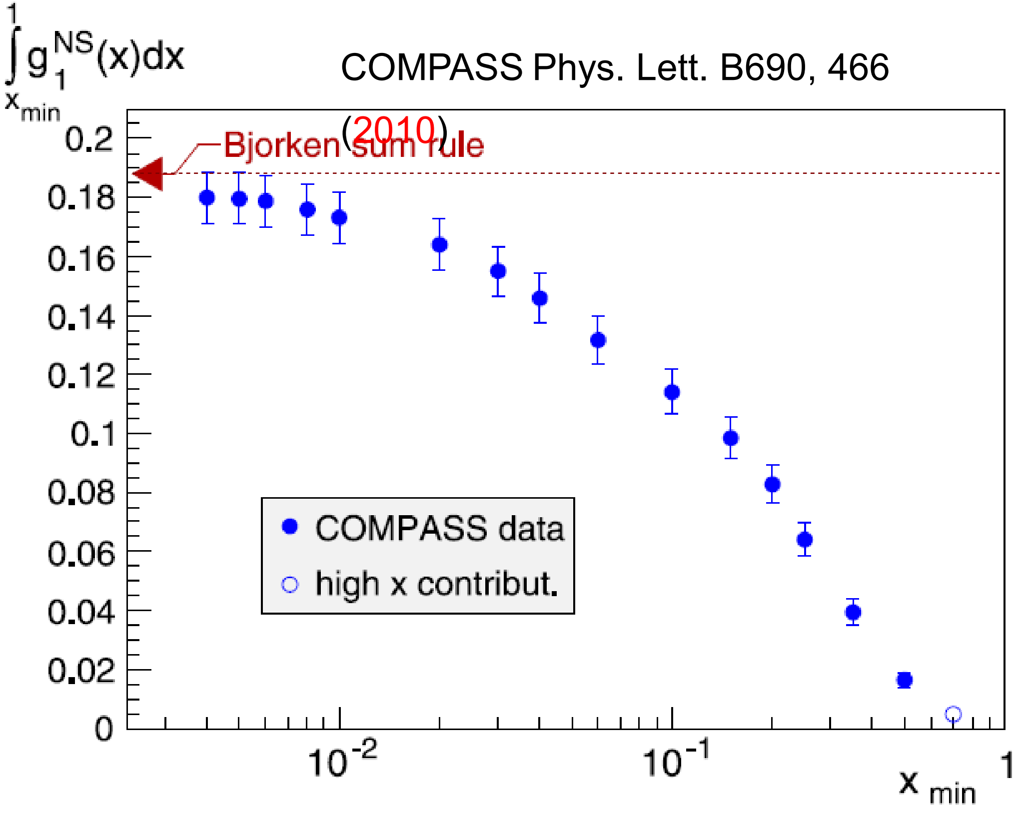
$$g_1^{NS}(x,Q^2) = g_1^p(x,Q^2) - g_1^n(x,Q^2)$$

$$g_1^{NS}(x,Q^2) = \frac{1}{6}\int_x^1 \frac{dx'}{x'} C^{NS}\left(\frac{x}{x'},\alpha_s(Q^2)\right)\Delta q_3(x',Q^2)$$

↓ 1 次モーメント

$$\Gamma_1^{NS}(Q^2) = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$$

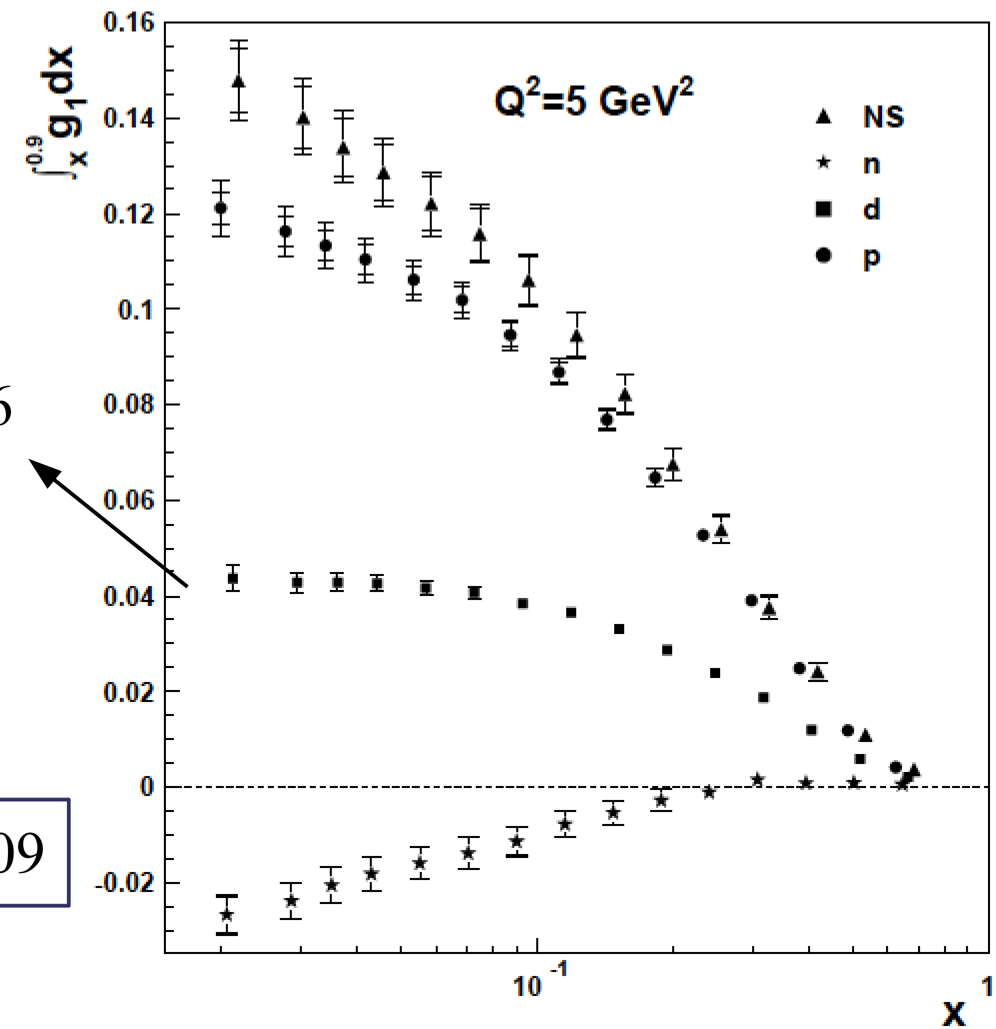
COMPASS Phys. Lett. B690, 466 (2010)



ストレンジクォーク成分

hermes *Phys. Rev. D 75 (2007) 012007*

$$\int_{0.021}^{0.9} g_1^d(x, 5\,\mathrm{GeV}^2)\,dx =$$
$$0.0436 \pm 0.0012 \pm 0.018 \pm 0.0008 \pm 0.0026$$



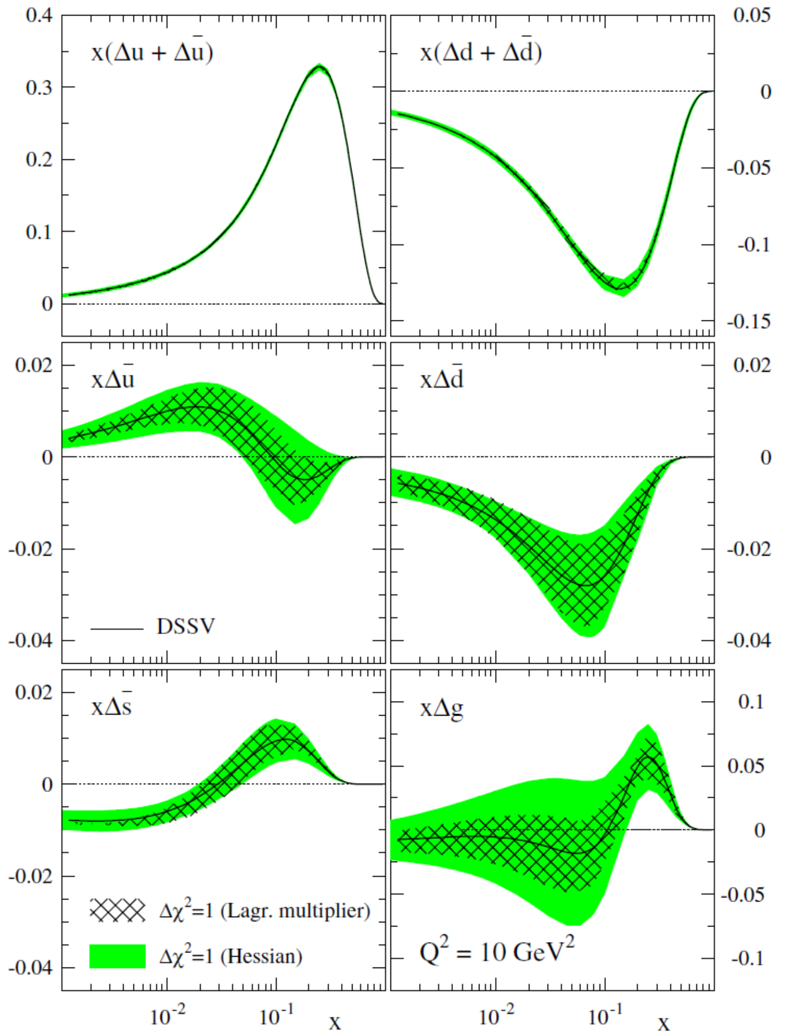
Assumption:

- High x contribution = 0
- Saturation in the lower *x* region
- SU(3) flavor symmetry:

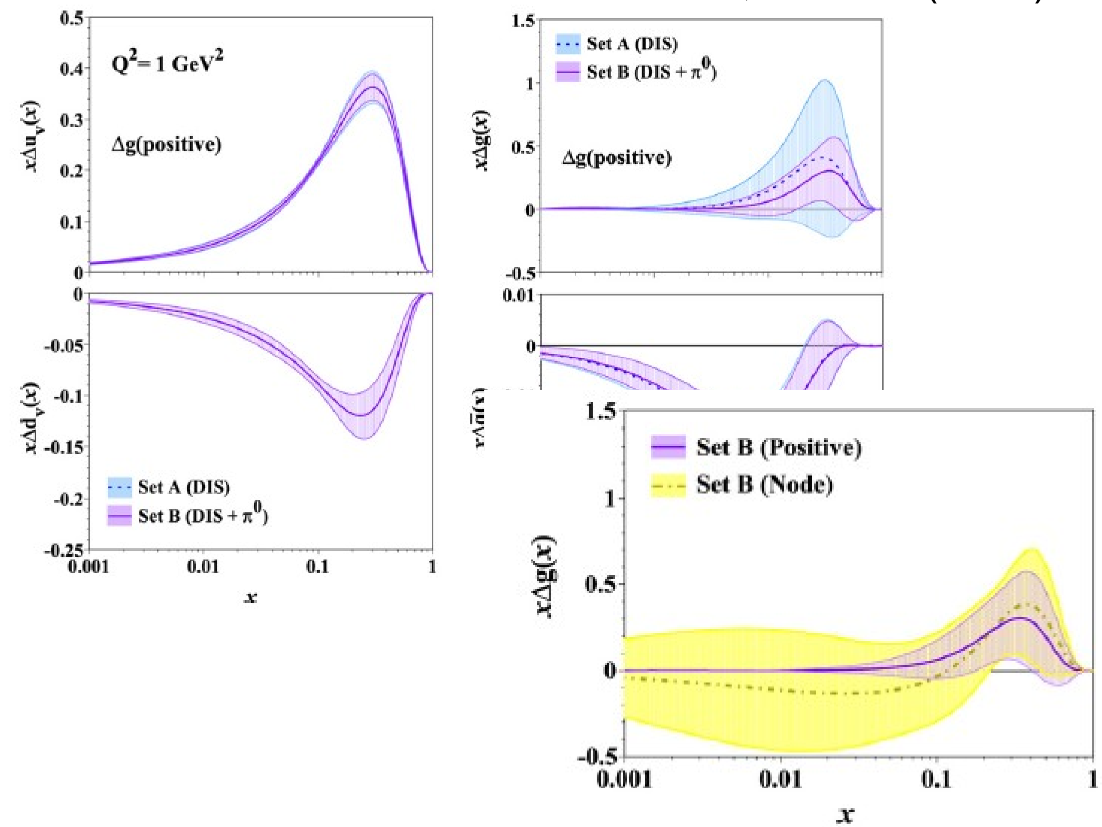
$$\Delta s(5\,\mathrm{GeV}^2) = -0.085 \pm 0.013 \pm 0.008 \pm 0.009$$

偏極パートン分布関数：グローバル解析

DSSV, PRD80(2009)034030



AAC, NPB813(2009)106



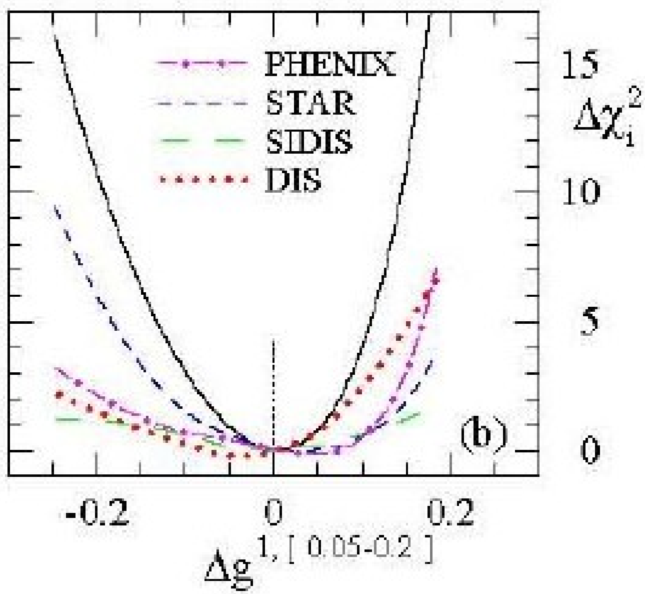
	Lagrange multiplier $\Delta\chi^2 = 1$
$\Delta u + \Delta\bar{u}$	$0.793^{+0.011}_{-0.012}$
$\Delta d + \Delta\bar{d}$	$-0.416^{+0.011}_{-0.009}$
$\Delta\bar{u}$	$0.028^{+0.021}_{-0.020}$
$\Delta\bar{d}$	$-0.089^{+0.029}_{-0.029}$
$\Delta\bar{s}$	$-0.006^{+0.010}_{-0.012}$
$\Delta\Sigma$	$0.366^{+0.015}_{-0.018}$
Δg	$0.013^{+0.106}_{-0.120}$
Δg^{RHIC}	$0.005^{+0.051}_{-0.058}$

Global Analysis and Gluon Spin Contribution

D. de Florian et al. Phys.Rev.Lett.101:072001, 2008. **DSSV08**

Data of deep inelastic lepton scattering and proton-proton collision

$$x\Delta f_j(x,Q_0^2) = N_j x^{\alpha_j}(1-x)^{\beta_j}(1+\gamma_j\sqrt{x}+\eta_j x)$$



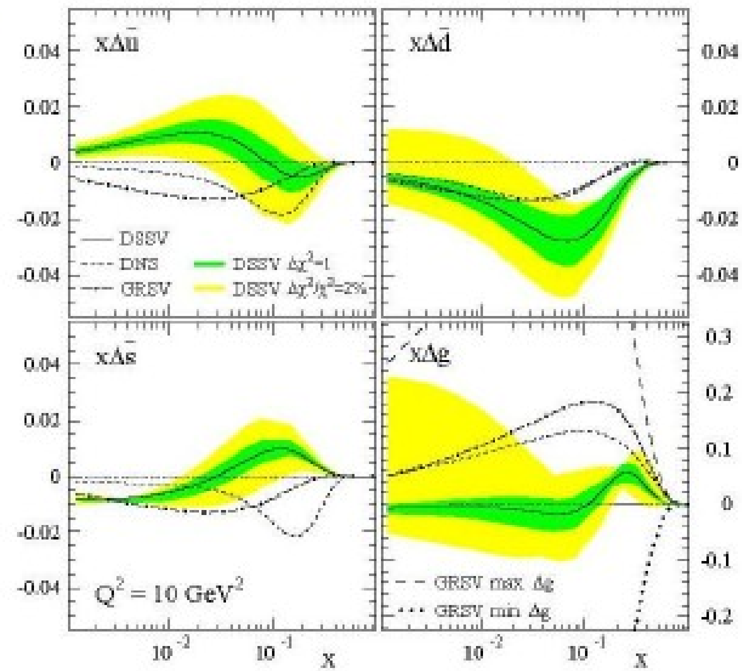


FIG. 2: Our polarized sea and gluon densities compared to previous fits [6, 8]. The shaded bands correspond to alternative fits with $\Delta\chi^2 = 1$ and $\Delta\chi^2/\chi^2 = 2\%$ (see text).

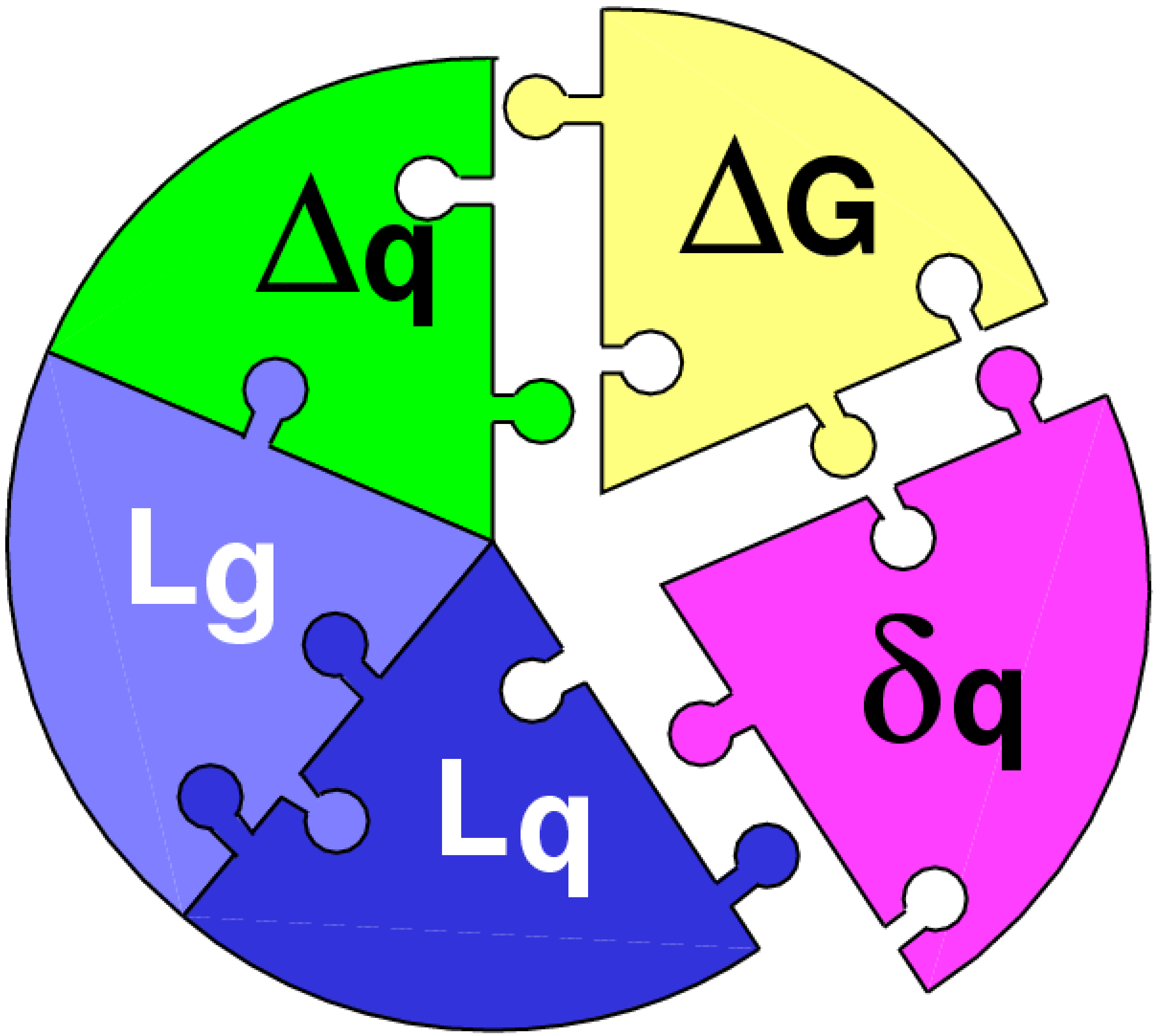
- (Inclusive) DIS data give a constraint on the positive side
- PHENIX data also give a constraint on the positive side
- STAR data give a constraint on the negative side

see also AAC, LSS06,…

Jan 2010, KEK T.-A. Shibata 18

→ 平井正紀（東京理科大学）
偏極パートン分布の現状

スピンパズル



第2世代偏極深非弾性散乱実験

EMC	Nucl. Phys. B328, 1 (1989), Phys. Rev. D54, 6620 (1996)
E143	Phys. Rev. D58, 112003 (1998)
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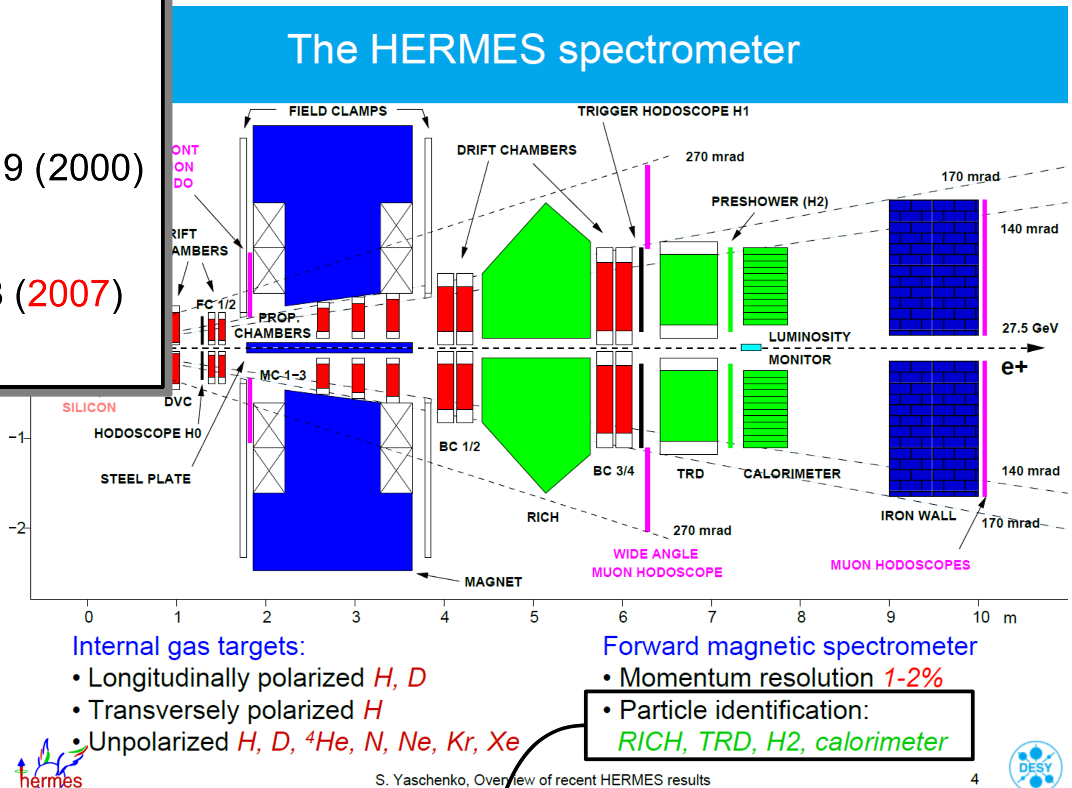
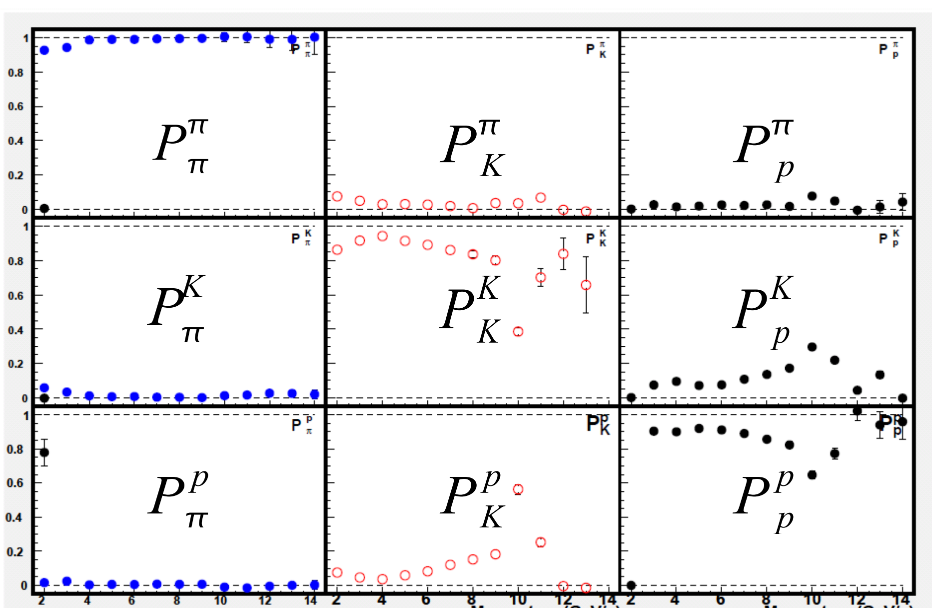




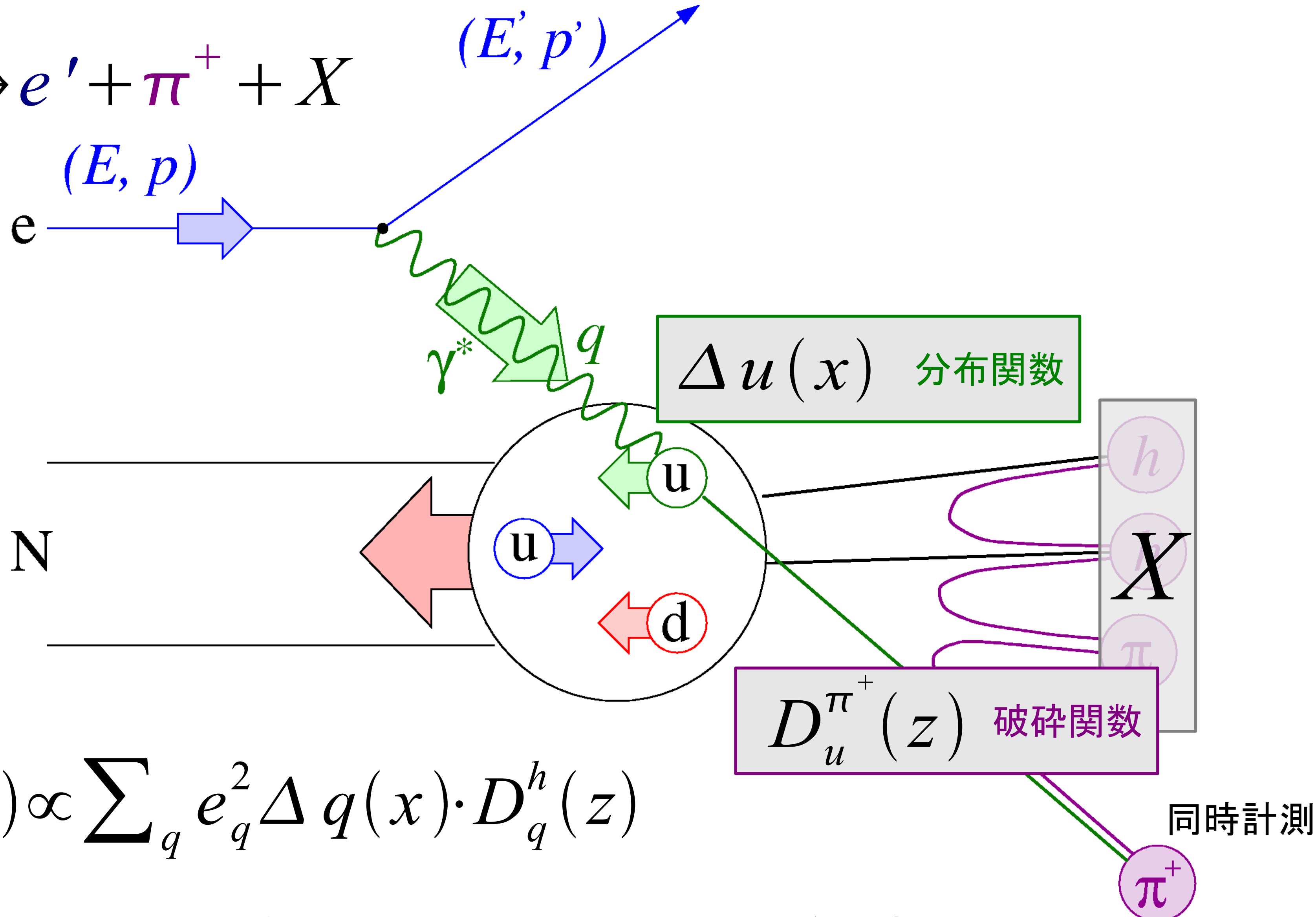
ハドロン同時測定

→　PDFのクォークフレーバー分解

→　ΔG の直接測定

ハドロン同時計測によるフレーバータグ

$$e + N \rightarrow e' + \pi^{+} + X$$

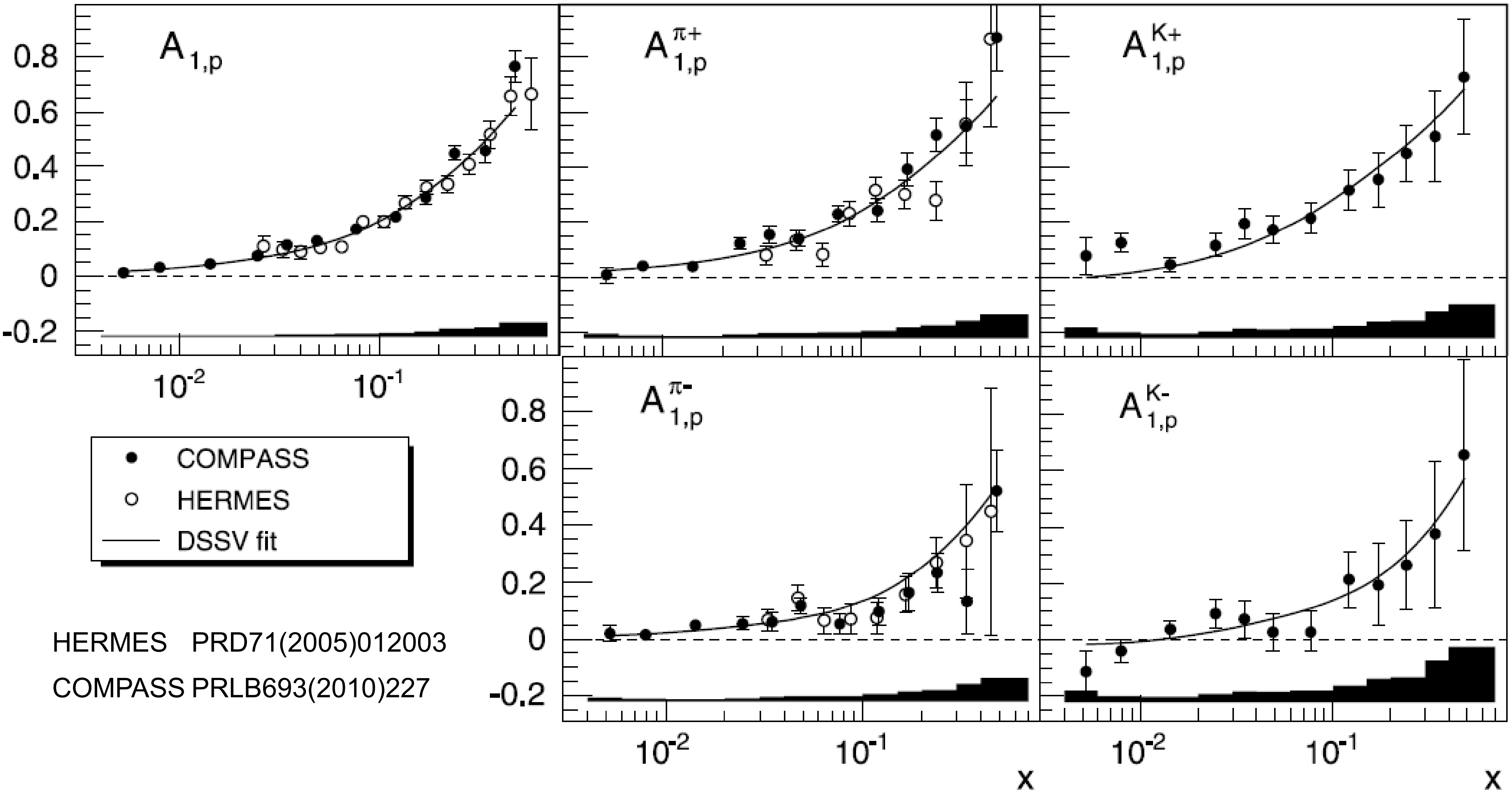


$$\Delta\sigma^{h}(x, z) \propto \sum_{q} e_{q}^{2} \Delta q(x) \cdot D_{q}^{h}(z)$$

ハドロン同時計測により、散乱されたクォークのフレーバー情報を得る

→　偏極パートン分布関数のクォークフレーバー分解

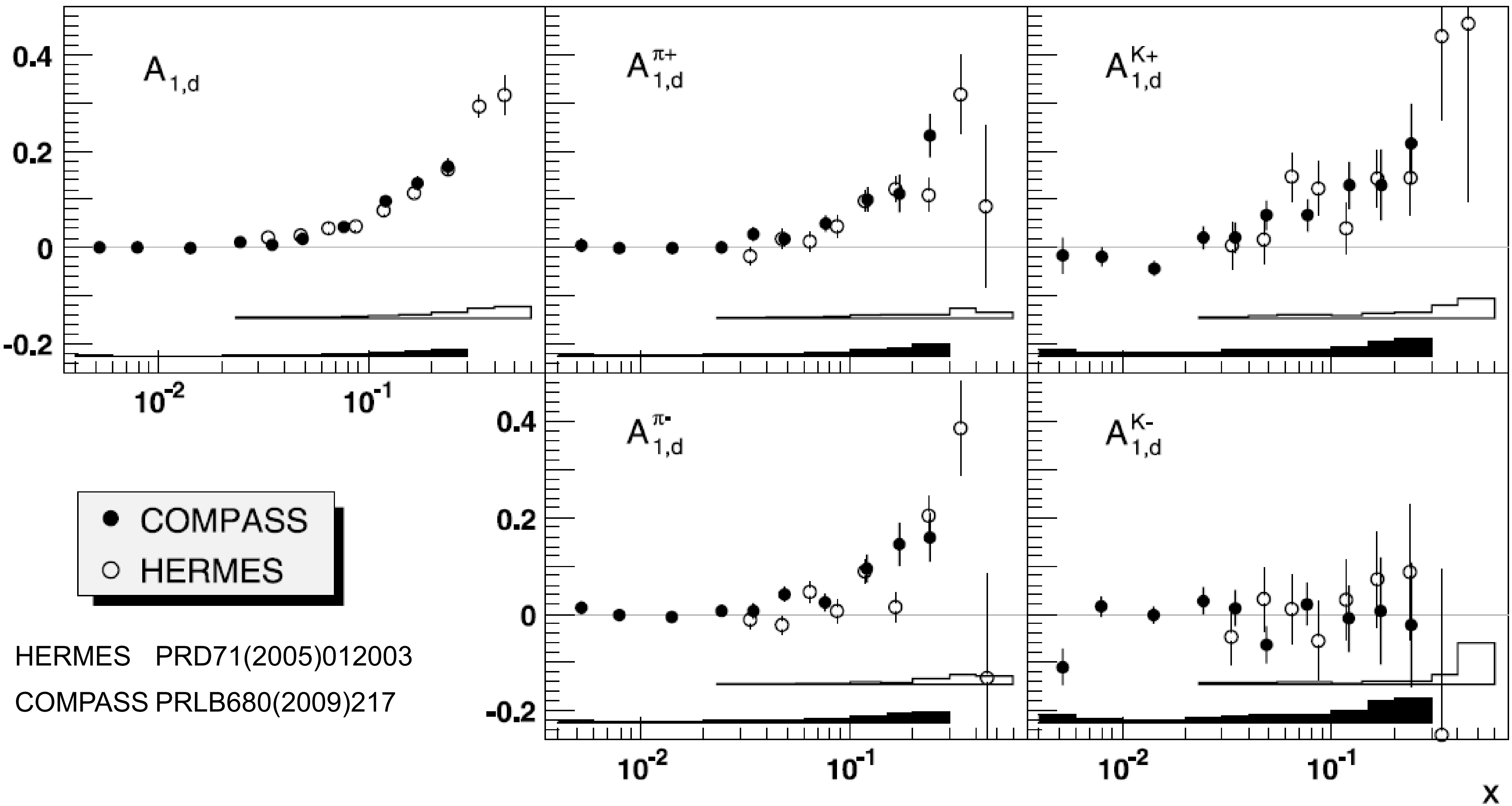
陽子標的による測定



HERMES　PRD71(2005)012003

COMPASS PRLB693(2010)227

重陽子偏極標的による測定



HERMES　PRD71(2005)012003

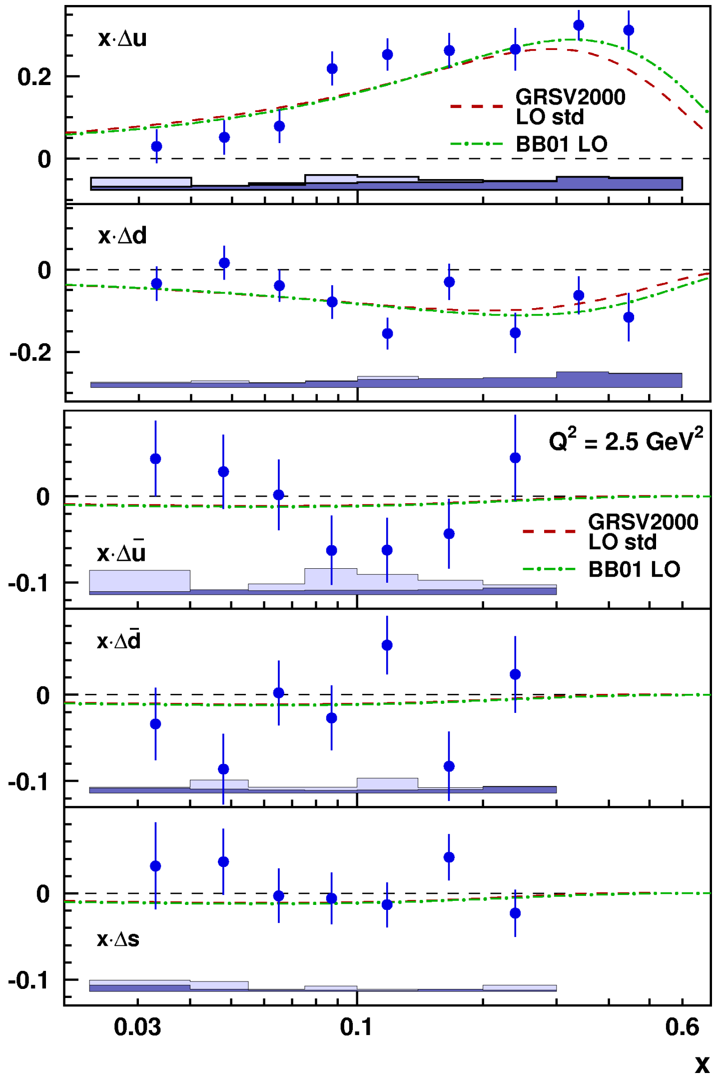
COMPASS PRLB680(2009)217

A_1^h から Δq へ

$$A_1^h(x,z) = \frac{\sum_q e_q^2(\Delta q(x) D_q^h(z) + \Delta\bar{q}(x) D_{\bar{q}}^h(z))}{\sum_q e_q^2(q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z))}$$

HERMES

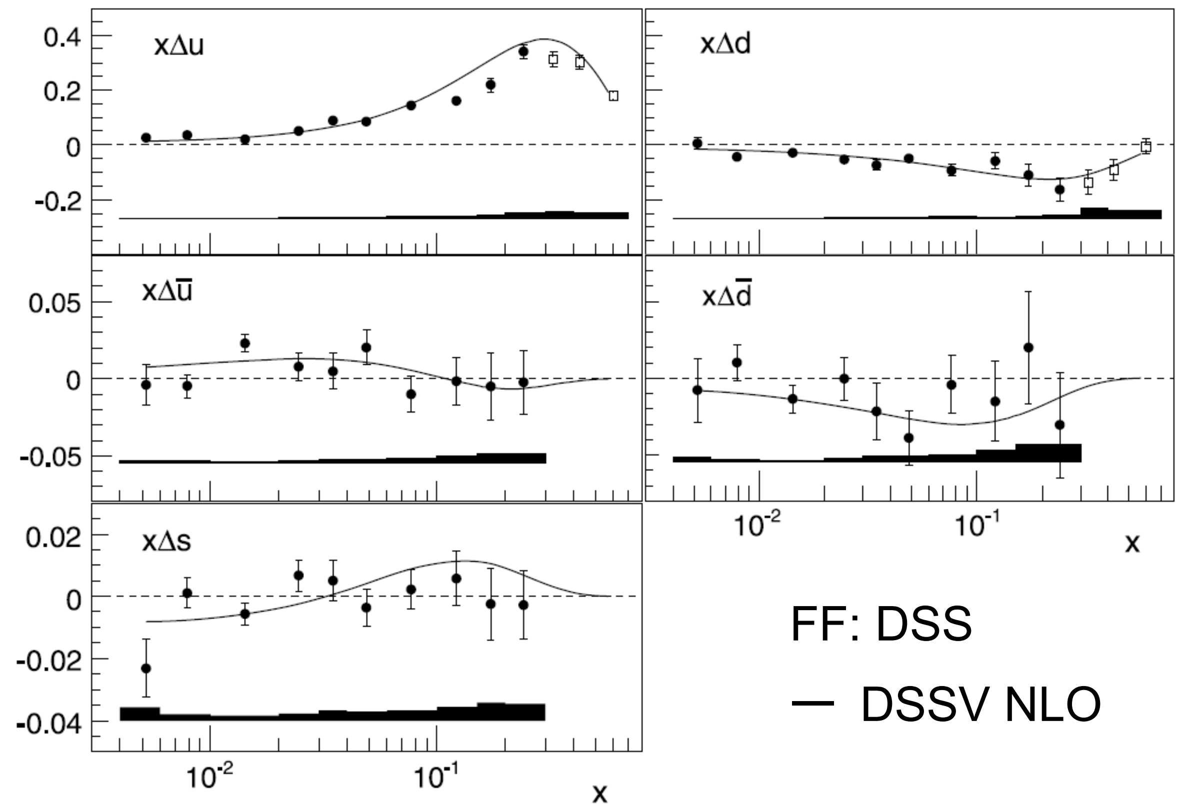
PRD71(2005)012003



FF: MC tuned with HERMES data

COMPASS

PRLB693(2010)227



FF: DSS

— DSSV NLO

1 次モーメント

HERMES

PRD71(2005)012003

TABLE VIII. First and second moments of various helicity distributions in the measured range at a scale of $Q_0^2 = 2.5$ GeV^2.

$0.023 < x < 0.6$	Moments in measured range
Δu	$0.601 \pm 0.039 \pm 0.049$
$\Delta \bar{u}$	$-0.002 \pm 0.036 \pm 0.023$
Δd	$-0.226 \pm 0.039 \pm 0.050$
$\Delta \bar{d}$	$-0.054 \pm 0.033 \pm 0.011$
Δs	$0.028 \pm 0.033 \pm 0.009$
$\Delta u + \Delta \bar{u}$	$0.599 \pm 0.022 \pm 0.065$
$\Delta d + \Delta \bar{d}$	$-0.280 \pm 0.026 \pm 0.057$
Δu_v	$0.603 \pm 0.071 \pm 0.040$
Δd_v	$-0.172 \pm 0.068 \pm 0.045$
$\Delta \bar{u} - \Delta \bar{d}$	$0.048 \pm 0.057 \pm 0.028$
$\Delta \Sigma$	$0.347 \pm 0.024 \pm 0.066$
Δq_3	$0.880 \pm 0.045 \pm 0.107$
Δq_8	$0.262 \pm 0.078 \pm 0.045$
$\Delta^{(2)} u$	$0.142 \pm 0.009 \pm 0.011$
$\Delta^{(2)} \bar{u}$	$-0.001 \pm 0.005 \pm 0.002$
$\Delta^{(2)} d$	$-0.049 \pm 0.010 \pm 0.013$
$\Delta^{(2)} \bar{d}$	$-0.003 \pm 0.004 \pm 0.001$
$\Delta^{(2)} s$	$0.001 \pm 0.003 \pm 0.001$
$\Delta^{(2)} u_v$	$0.144 \pm 0.013 \pm 0.011$
$\Delta^{(2)} d_v$	$-0.047 \pm 0.012 \pm 0.012$

COMPASS

PRLB693(2010)227

Table 4
First moments of the quark helicity distributions at $Q_0^2 = 3$ (GeV/c)^2 truncated to the range of the measurements and derived with the DSS fragmentation functions. The first error is statistical, the second one systematic. The values of the sea quark distributions for $x \geqslant 0.3$ are assumed to be zero.

x range	$0.004 < x < 0.3$	$0.004 < x < 0.7$
Δu	$0.47 \pm 0.02 \pm 0.03$	$0.69 \pm 0.02 \pm 0.03$
Δd	$-0.27 \pm 0.03 \pm 0.02$	$-0.33 \pm 0.04 \pm 0.03$
$\Delta \bar{u}$	$0.02 \pm 0.02 \pm 0.01$	–
$\Delta \bar{d}$	$-0.05 \pm 0.03 \pm 0.02$	–
$\Delta s (\Delta \bar{s})$	$-0.01 \pm 0.01 \pm 0.01$	–
Δu_v	$0.46 \pm 0.03 \pm 0.03$	$0.67 \pm 0.03 \pm 0.03$
Δd_v	$-0.23 \pm 0.05 \pm 0.02$	$-0.28 \pm 0.06 \pm 0.03$
$\Delta \bar{u} - \Delta \bar{d}$	$0.06 \pm 0.04 \pm 0.02$	–
$\Delta \bar{u} + \Delta \bar{d}$	$-0.03 \pm 0.03 \pm 0.01$	–
$\Delta \Sigma$	$0.15 \pm 0.02 \pm 0.02$	$0.31 \pm 0.03 \pm 0.03$

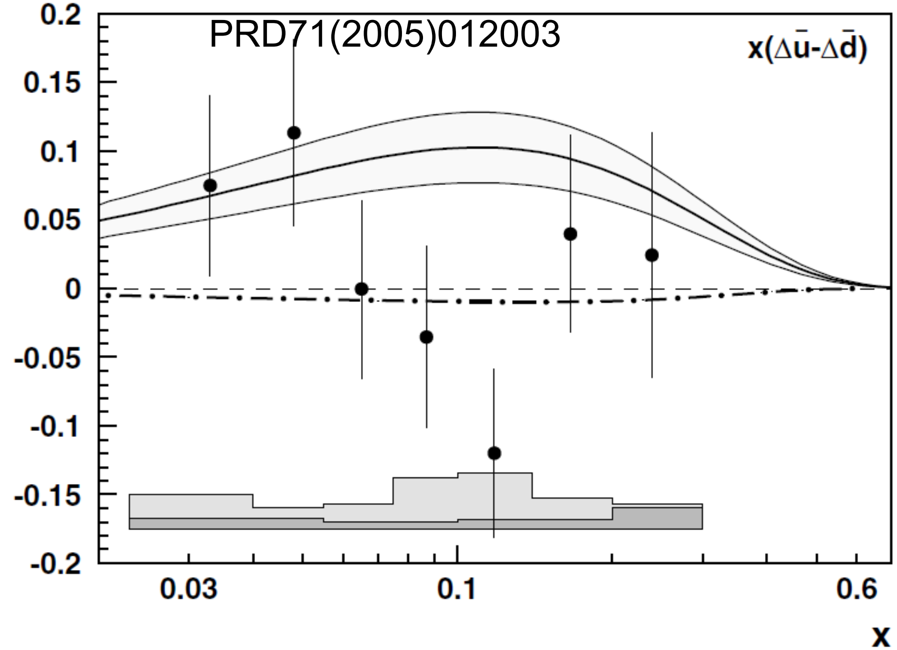
	$0 < x < 1$ (DSSV)
Δu	$0.71 \pm 0.02 \pm 0.03$
Δd	$-0.35 \pm 0.04 \pm 0.03$
$\Delta \bar{u}$	$0.03 \pm 0.02 \pm 0.01$
$\Delta \bar{d}$	$-0.07 \pm 0.03 \pm 0.02$
$\Delta s (\Delta \bar{s})$	$-0.05 \pm 0.01 \pm 0.01$
Δu_v	$0.68 \pm 0.03 \pm 0.03$
Δd_v	$-0.28 \pm 0.06 \pm 0.03$
$\Delta \Sigma$	$0.22 \pm 0.03 \pm 0.03$

フレーバー対称性

$$x\left(\Delta \bar{u} - \Delta \bar{d}\right)$$

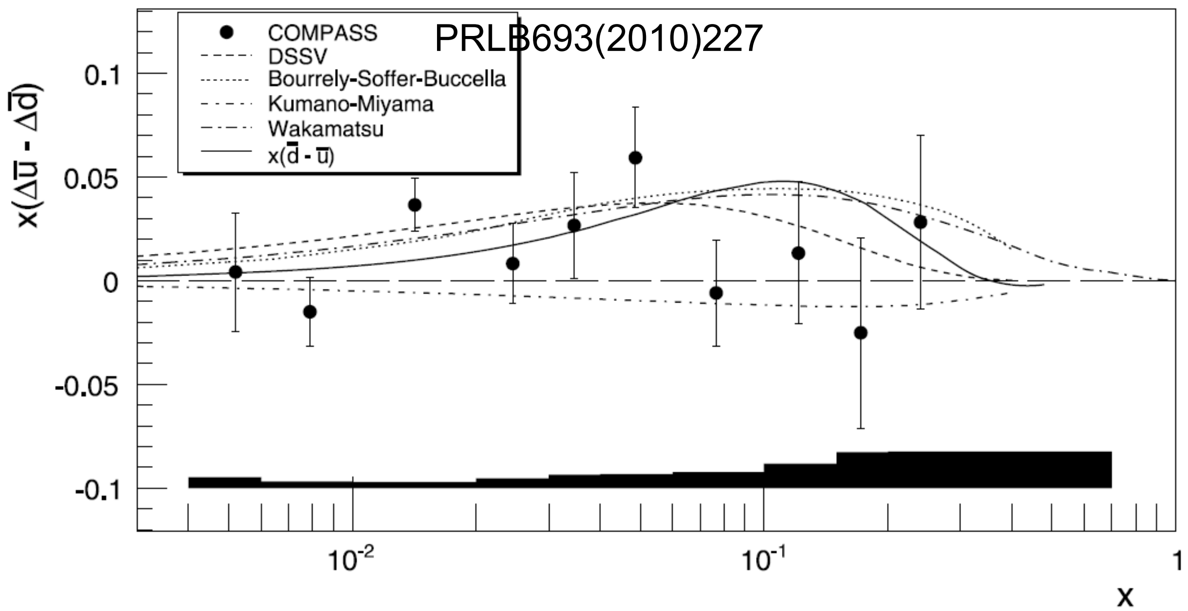
HERMES

PRD71(2005)012003



COMPASS

PRLB693(2010)227

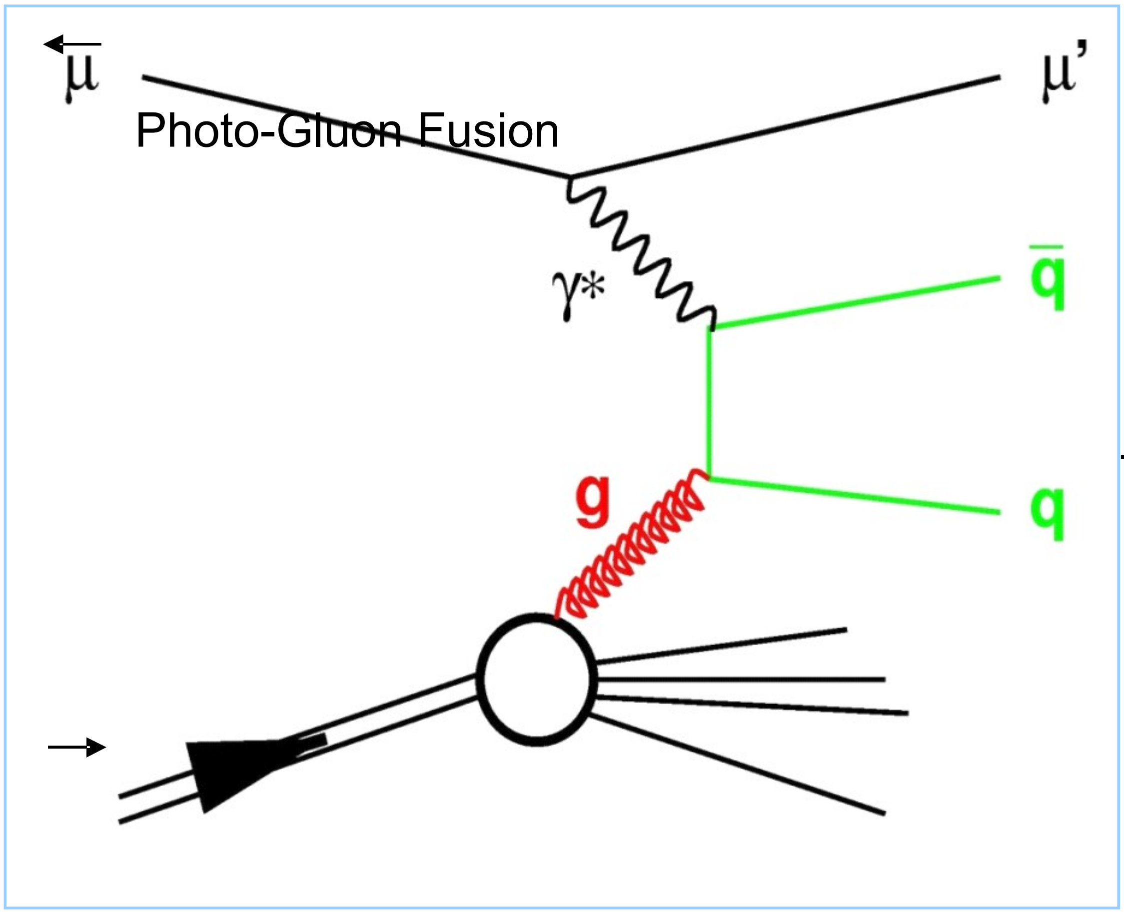


COMPASS $\int_{0.004}^{0.3} (\Delta \bar{u} - \Delta \bar{d})dx = 0.06 \pm 0.04 \pm 0.02$ @ $Q^2 = 3 (GeV/c)^2$

HERMES $\int_{0.023}^{0.6} (\Delta \bar{u} - \Delta \bar{d})dx = 0.048 \pm 0.057 \pm 0.028$ @ $Q^2 = 2.5 (GeV/c)^2$

unp. E866 $\int_{0}^{1} (\bar{u} - \bar{d})dx = -0.118 \pm 0.012$ @ $Q^2 = 54 (GeV/c)^2$

グルーオン



Light quark pair production

→ High Pt hadron (pair)

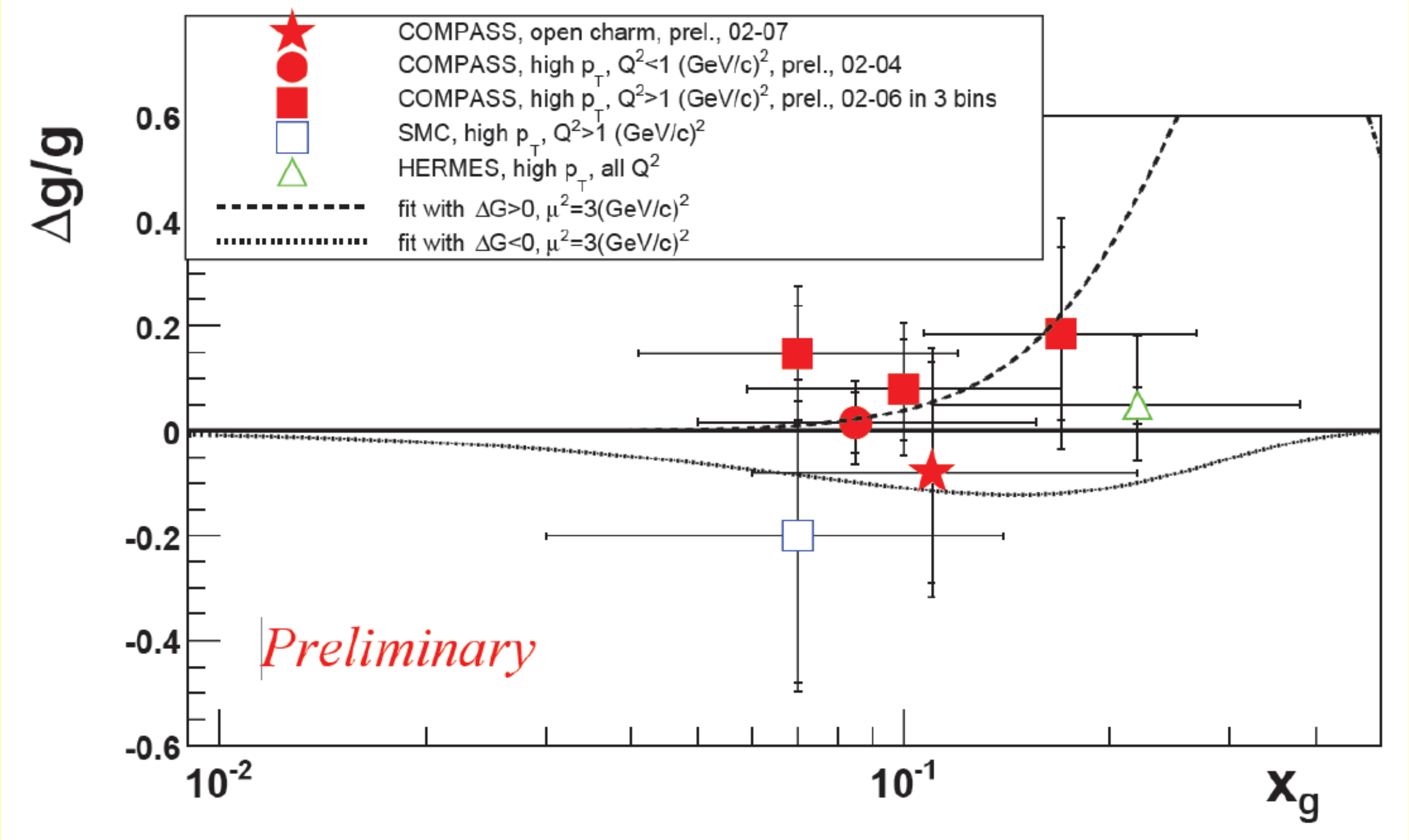
SMC	NPA755(2005)321
HERMES	JHEP08(2010)130
COMPASS	PLB633(2006)25

Heavy quark pair production

→ Open Charm

COMPASS	PLB676(2009)31

Gluon polarization



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Gluon polarization @ LO and NLO

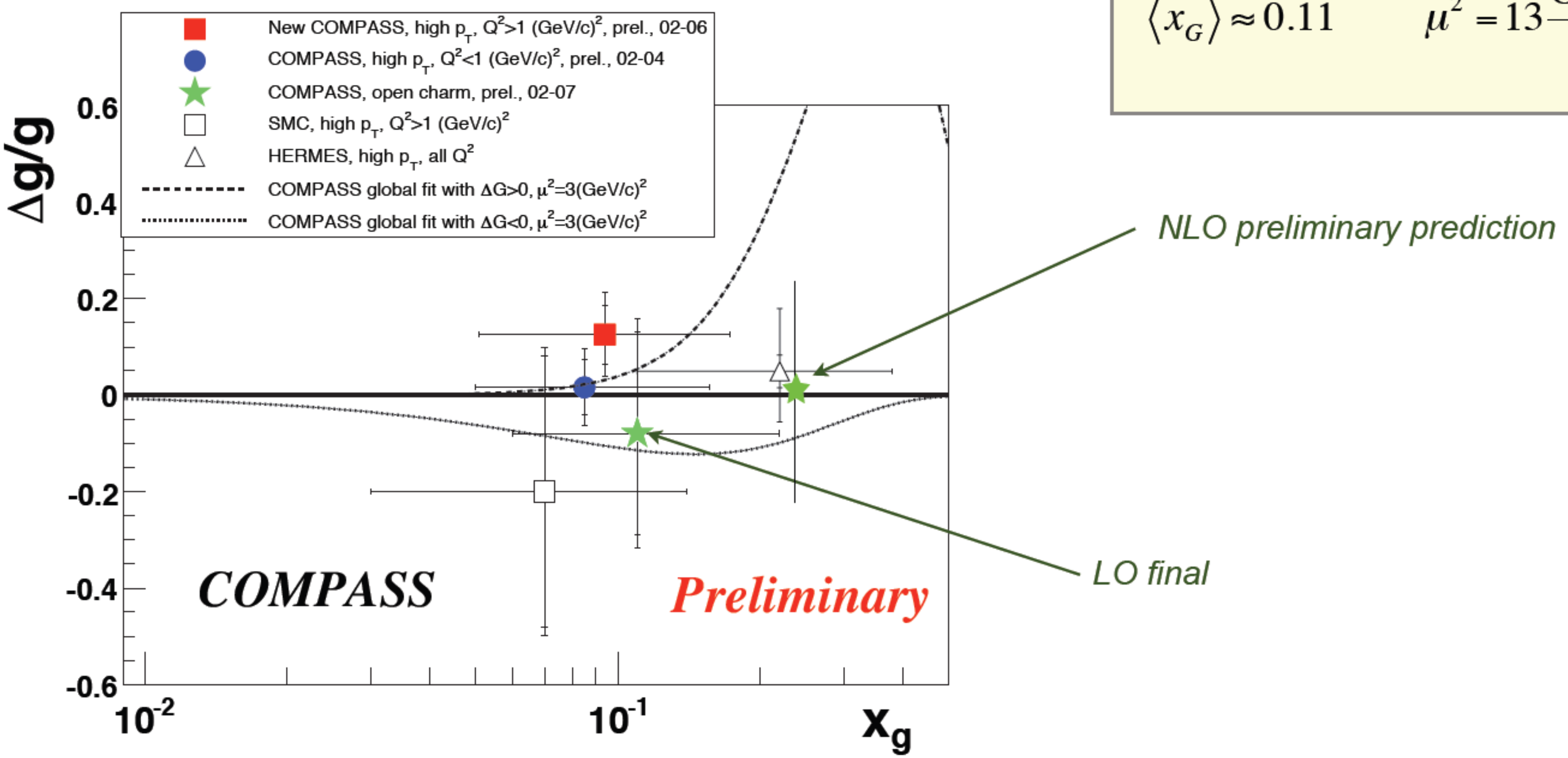
Final gluon polarization from open-charm in LO QCD vs NLO result from published asymmetries set

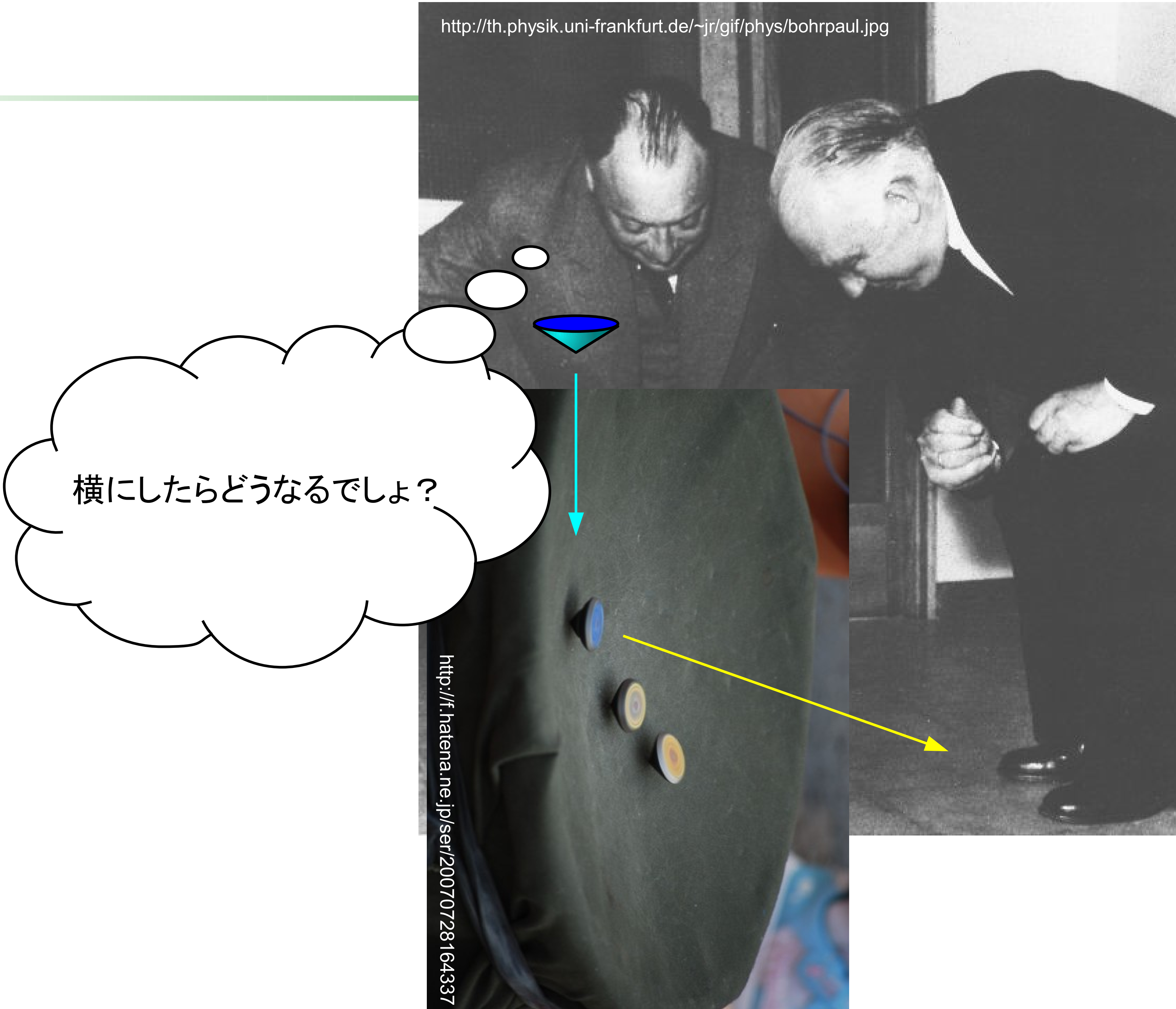
NLO (based on published asymmetries): ΔG/G=+0.008±0.25

test: NLO M-M MC: ΔG/G= +0.005 ±0.22

$$\frac{\Delta G}{G} = -0.08 \pm 0.21 \pm (0.11)$$

$$\langle x_G \rangle \approx 0.11 \qquad \mu^2 = 13 \frac{GeV^2}{c^2}$$




http://th.physik.uni-frankfurt.de/~jr/gif/phys/bohrpaul.jpg
横にしたらどうなるでしょ？
http://f.hatena.ne.jp/ser/20070728164337

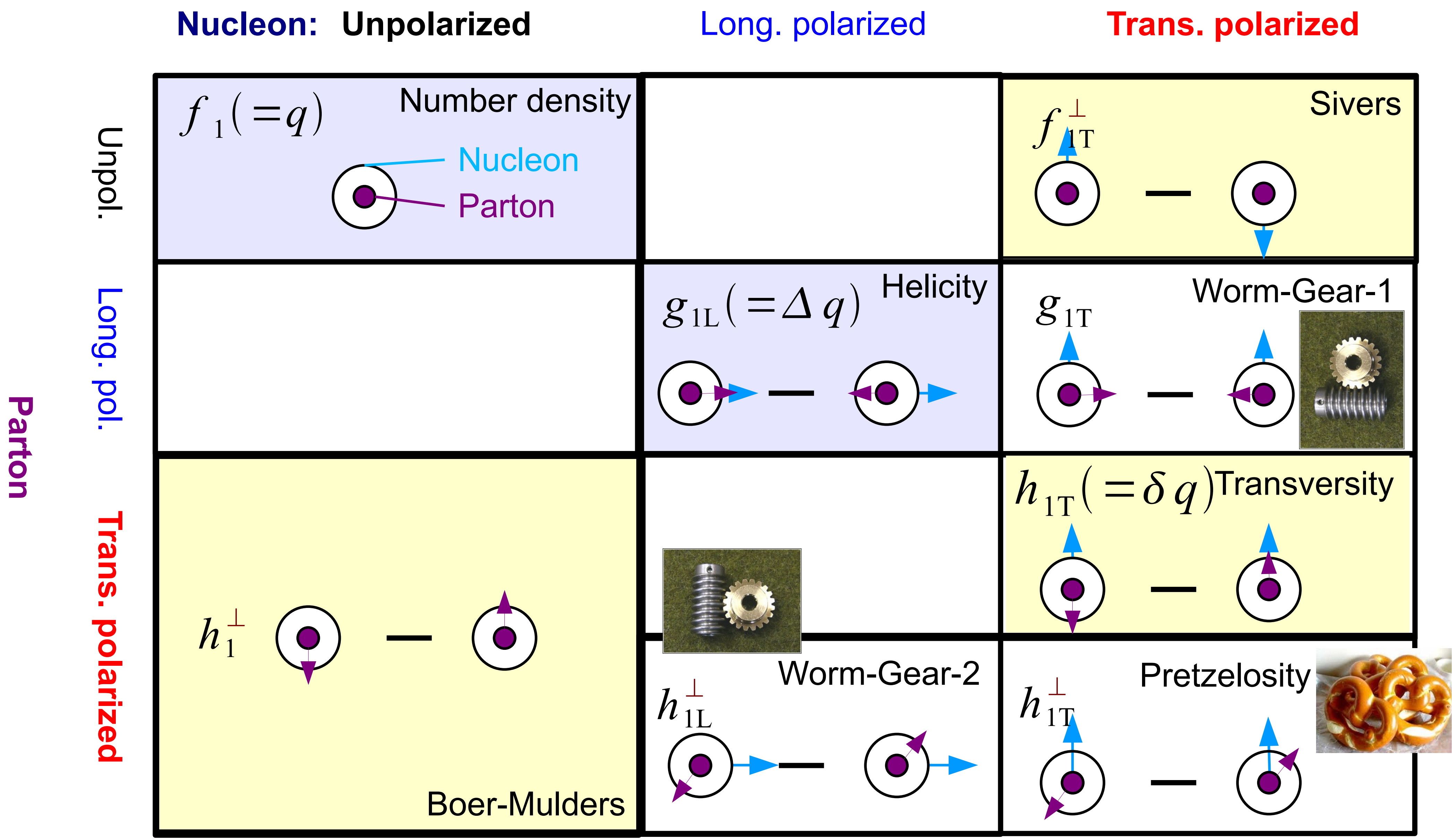
パートン分布関数

Nucleon: Unpolarized | Long. polarized

Parton \ Nucleon	Unpolarized	Long. polarized	
Unpol.	$f_1 (=q)$ Number density Nucleon Parton		
Long. pol.		$g_{1L} (= \Delta q)$ Helicity	

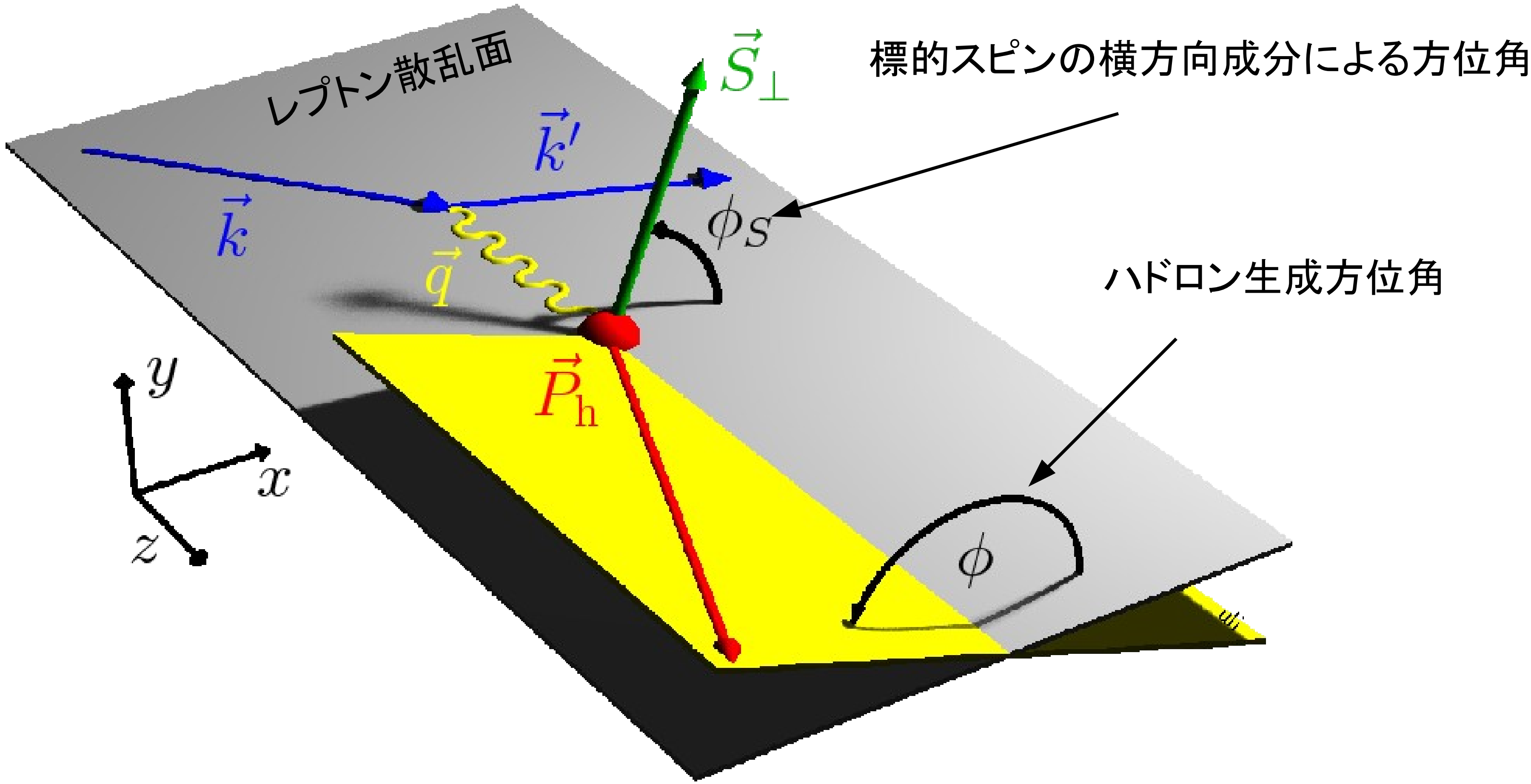
Nucleon spin Parton spin

Transverse Momentum Dependent PDF



深非弾性散乱： ハドロン生成方位角

$\mathbf{l} + \mathbf{N} \rightarrow \mathbf{l}' + \mathbf{h} + \mathrm{X}$



断面積と方位角依存性

$$\frac{d\sigma^{\ell(S_\ell)p(S)\to\ell' hX}}{dx_B\, dQ^2\, dz_h\, d^2\boldsymbol{p}_\perp\, d\phi_S} =$$

$$\frac{4e^2}{y^2}\left\{\frac{1+(1-y)^2}{2}F_{UU} + (2-y)\sqrt{1-y}\cos\phi_h F_{UU}^{\cos\phi_h} + (1-y)\cos 2\phi_h F_{UU}^{\cos 2\phi_h}\right.$$

$$+\ S_L\left[(1-y)\sin 2\phi_h F_{UL}^{\sin 2\phi_h} + (2-y)\sqrt{1-y}\sin\phi_h F_{UL}^{\sin\phi_h}\right]$$

$$+\ S_L P_z^l\left[\frac{1-(1-y)^2}{2}F_{LL} + y\sqrt{1-y}\cos\phi_h F_{LL}^{\cos\phi_h}\right]$$

$$+\ S_T\left[\frac{1+(1-y)^2}{2}\sin(\phi_h-\phi_S)F_{UT}^{\sin(\phi_h-\phi_S)}\right.$$

$$+(1-y)\left(\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}\right)$$

$$\left.+(2-y)\sqrt{1-y}\left(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\right)\right]$$

$$+\ S_T P_z^l\left[\frac{1-(1-y)^2}{2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}\right.$$

$$\left.\left.+y\sqrt{1-y}\left(\cos\phi_S F_{LT}^{\cos\phi_S} + \cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\right)\right]\right\}$$

The F structure functions contain all the TMD's

Unpolarized proton and lepton

Longitudinally polarized proton, polarized lepton

Transversely polarized proton, unpolarized lepton

Transversely polarized proton, polarized lepton

方位角依存性とTMD

$$F_{UU} \sim \sum_a e_a^2 \, f_1^a \otimes D_1^a$$

Density

$$F_{LT}^{\cos(\phi-\phi_S)} \sim \sum_a e_a^2 \, g_{1T}^{\perp a} \otimes D_1^a$$

$$F_{LL} \sim \sum_a e_a^2 \, g_{1L}^a \otimes D_1^a$$

Helicity

$$F_{UT}^{\sin(\phi-\phi_S)} \sim \sum_a e_a^2 \, f_{1T}^{\perp a} \otimes D_1^a$$

Sivers

chiral-even TMDs

$$F_{UU}^{\cos(2\phi)} \sim \sum_a e_a^2 \, h_1^{\perp a} \otimes H_1^{\perp a}$$

Boer-Mulders

$$F_{UT}^{\sin(\phi+\phi_S)} \sim \sum_a e_a^2 \, h_{1T}^a \otimes H_1^{\perp a}$$

Transversity

$$F_{UL}^{\sin(2\phi)} \sim \sum_a e_a^2 \, h_{1L}^{\perp a} \otimes H_1^{\perp a}$$

$$F_{UT}^{\sin(3\phi-\phi_S)} \sim \sum_a e_a^2 \, h_{1T}^{\perp a} \otimes H_1^{\perp a}$$

chiral-odd TMDs

$$\frac{1}{Q} \cos\phi \, F_{UU}^{\cos\phi} \sim f_1^q \otimes D_1^q \otimes \mathrm{d}\hat{\sigma} + \left(h_1^{q\perp} \otimes H_1^{q\perp} \otimes \mathrm{d}\Delta\hat{\sigma} \right)$$

Cahn kinematical effects

関連する講演

→　小池裕司（新潟大学）
スピン構造関数研究の最近の発展：シングルスピン非対称を中心として

→　若松正志（大阪大学）
一般化パートン分布関数と横運動量依存分布関数

→　後藤雄二（理化学研究所）
偏極ドレル・ヤン実験による核子構造の多次元的理解へ向けて

TMD in Semi-Inclusive DIS

$$d\sigma \propto$$

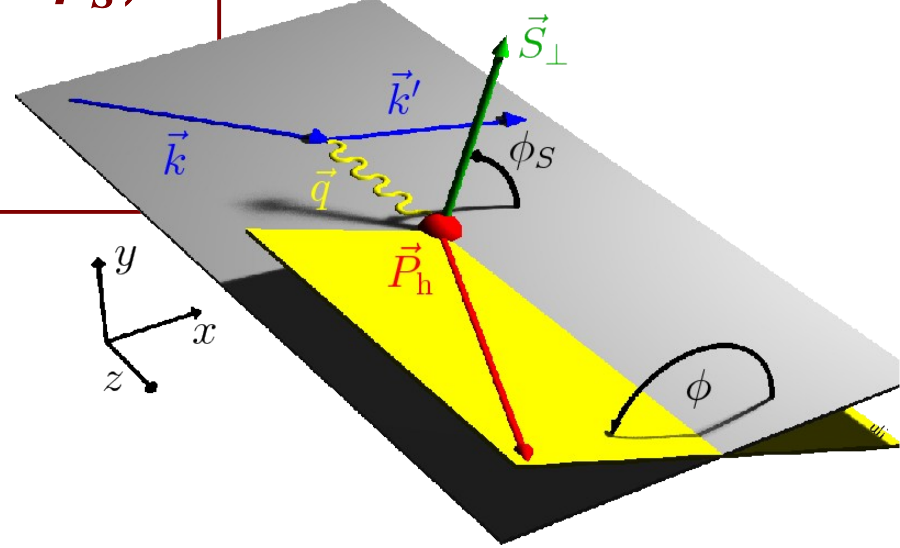
$$F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\, F_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h$$

$$+ |S_T| \Big[\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)} \Big) \sin(\phi_h-\phi_S)$$

$$+ \varepsilon F_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S)$$

$$+ \cdots \Big]$$

$$F = F(x, y, z, P_{h_\perp})$$



Boer-Mulders

$$F_{UU}^{\cos 2\phi_h} = 2\langle \cos 2\phi_h \rangle_{UU} \propto -C[h_1^\perp \cdot D]$$

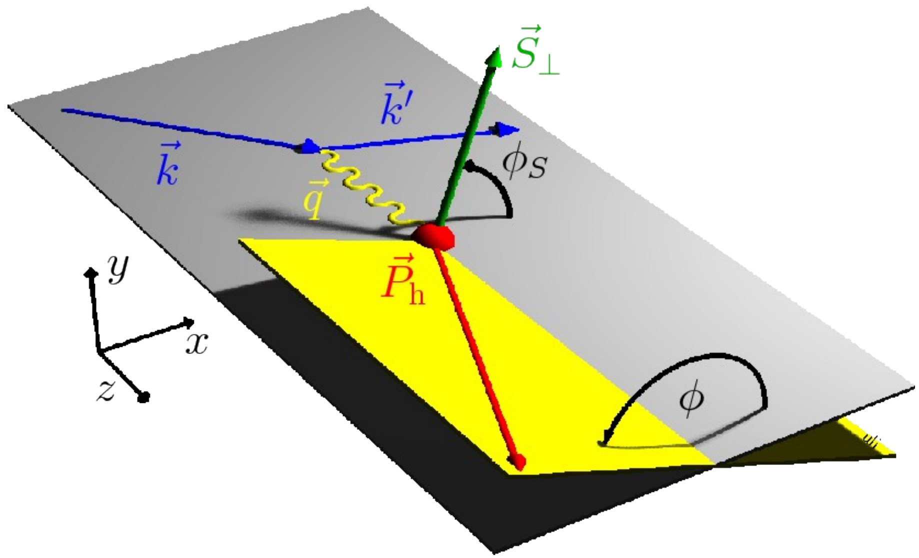
Sivers

$$F_{UT}^{\sin(\phi_h-\phi_S)} = 2\langle \sin(\phi_h-\phi_S) \rangle_{UT} \propto -C[f_{1T}^\perp \cdot D]$$

Transversity + Collins FF

$$F_{UT}^{\sin(\phi_h+\phi_S)} = 2\langle \sin(\phi_h+\phi_S) \rangle_{UT} \propto C[h_{1T} \cdot H_1^\perp]$$

ターゲットシングルスピン非対称度



$$A_{UT}(\phi_h,\phi_S)=\frac{1}{\langle|S_\perp|\rangle}\frac{N^{\uparrow}(\phi_h,\phi_S)-N^{\downarrow}(\phi_h,\phi_S)}{N^{\uparrow}(\phi_h,\phi_S)+N^{\downarrow}(\phi_h,\phi_S)}$$

↓

Sivers, Collins, ... amplitudes

	Target	Sivers	Collins
HERMES	p	PRL103(2009)152002	PLB693(2010)11
COMPASS	p	PLB692(2010)240	
	d	PLB673(2009)127	

測定

HERMES | COMPASS

Boer-Mulders $\langle \cos 2\phi \rangle_{UU}$

HERMES: (p) h, π, K; (d) h, π, K

$\langle \sin 2\phi \rangle_{UL}$

HERMES: (d) π, K
PLB562(2003)182

Sivers $\langle \sin(\phi - \phi_S) \rangle_{UT}$

HERMES: (p) π, K
PRL103(2009)152002

Transversity $\langle \sin(\phi + \phi_S) \rangle_{UT}$

HERMES: (p) π, K
PLB693(2010)11

COMPASS (Sivers and Transversity):
(p) h
PLB692(2010)240
(d) pi, K
PLB673(2009)127

$\langle \sin(3\phi - \phi_S) \rangle_{UT}$

HERMES: (p) π, K

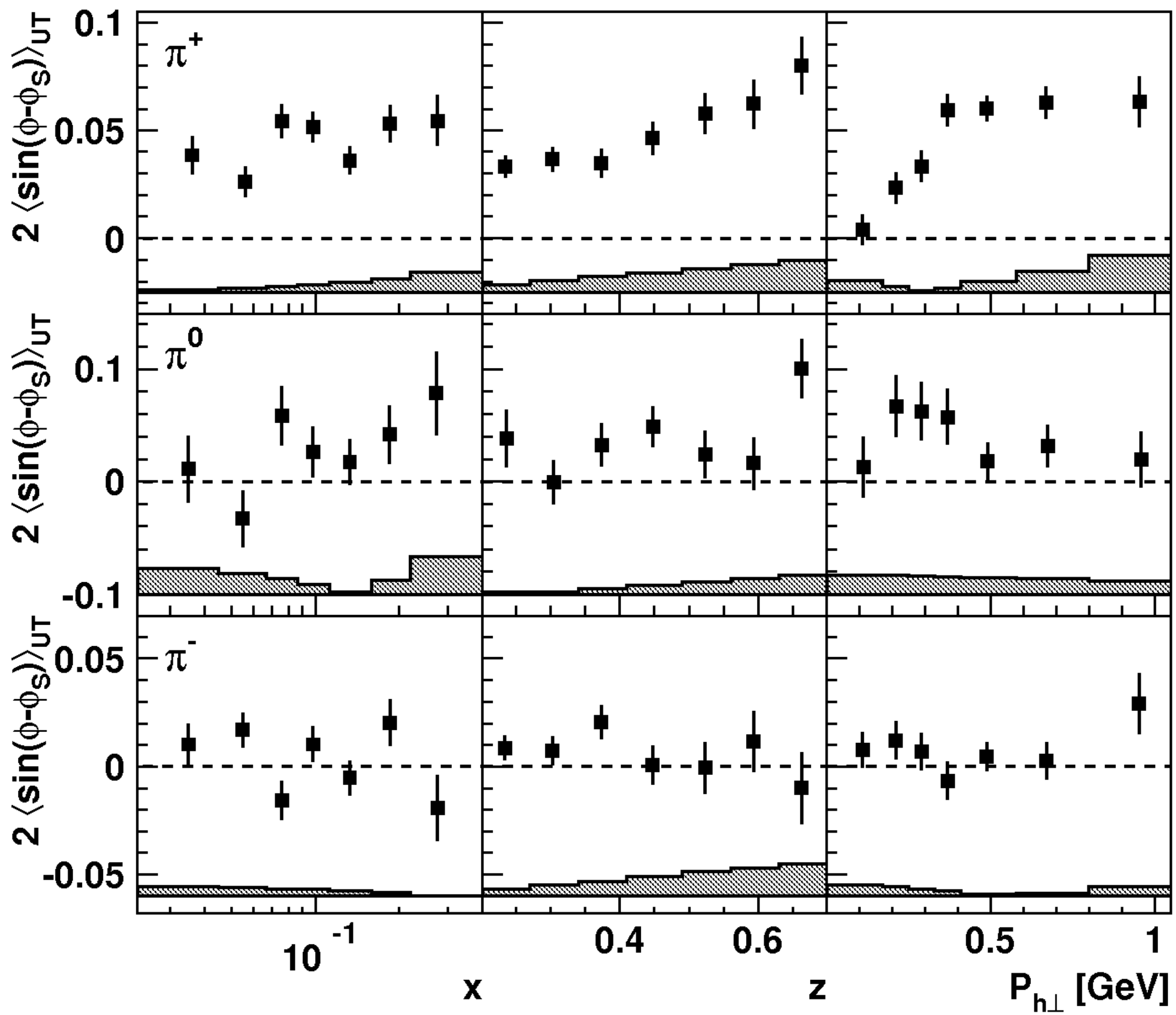
$\langle \cos(\phi - \phi_S) \rangle_{LT}$

Sivers asymmetries (pion)

HERMES PRL103(2009)152002

Sivers

$$F_{UT}^{\sin(\phi_h-\phi_S)} = 2\langle \sin(\phi_h-\phi_S)\rangle_{UT} \propto -C[f_{1T}^{\perp}\cdot D]$$

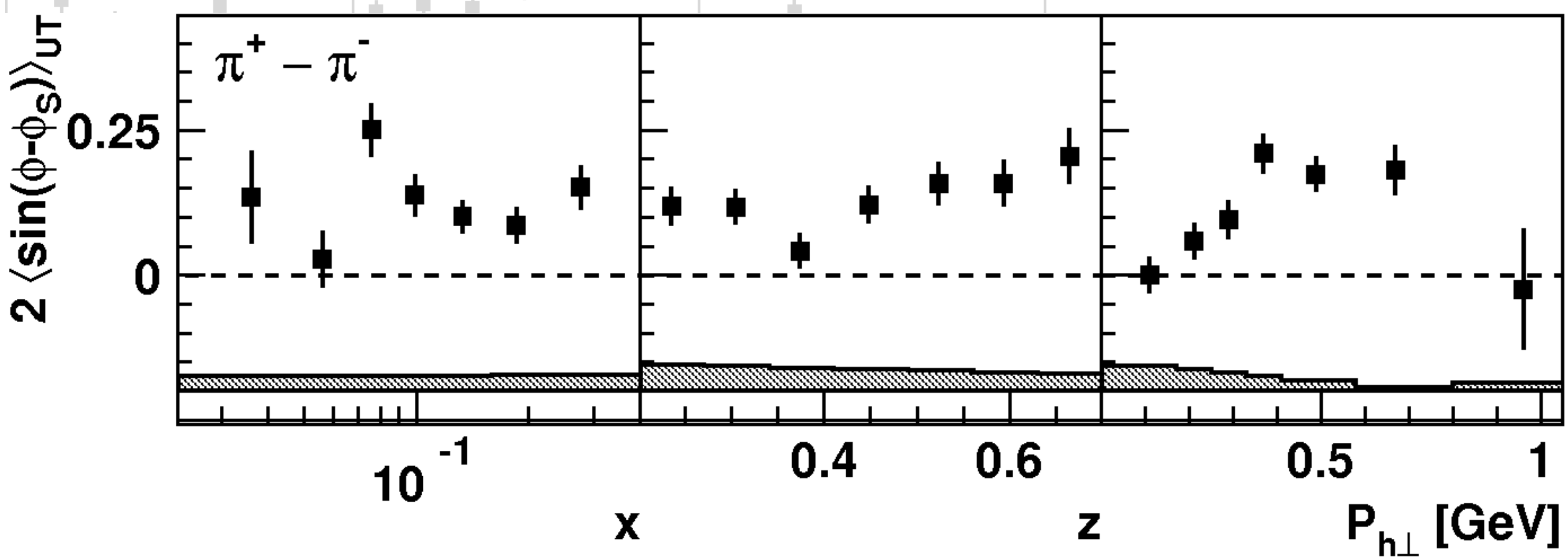


Sivers asymmetries (difference)

HERMES PRL103(2009)152002

Sivers

$$F_{UT}^{\sin(\phi_h-\phi_S)} = 2\langle \sin(\phi_h-\phi_S)\rangle_{UT} \propto -C[f_{1T}^{\perp}\cdot D]$$



→ Valence quark contribution: u_v, d_v

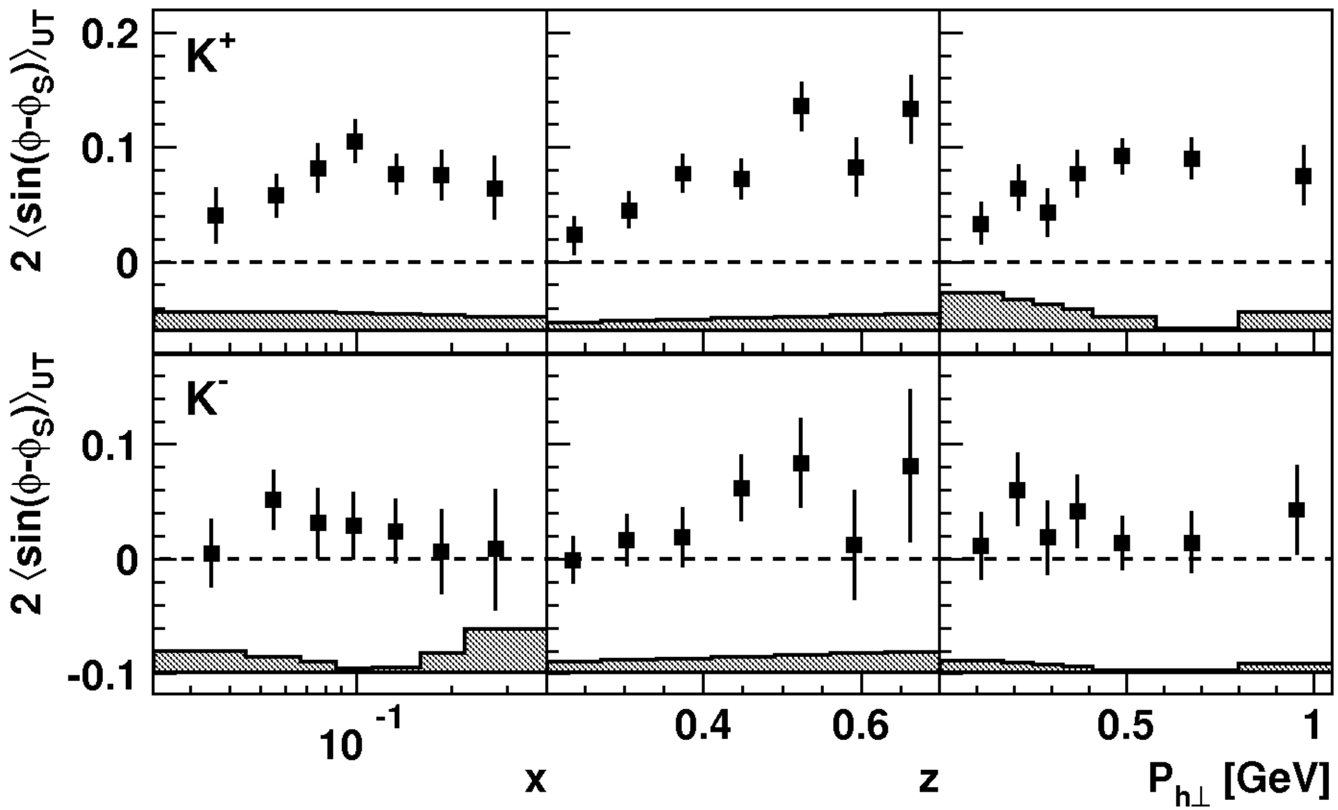
$$\propto f_{1T}^{\perp,d_v} - 4 f_{1T}^{\perp,u_v}$$

Sivers asymmetry (Kaon)

HERMES PRL103(2009)152002

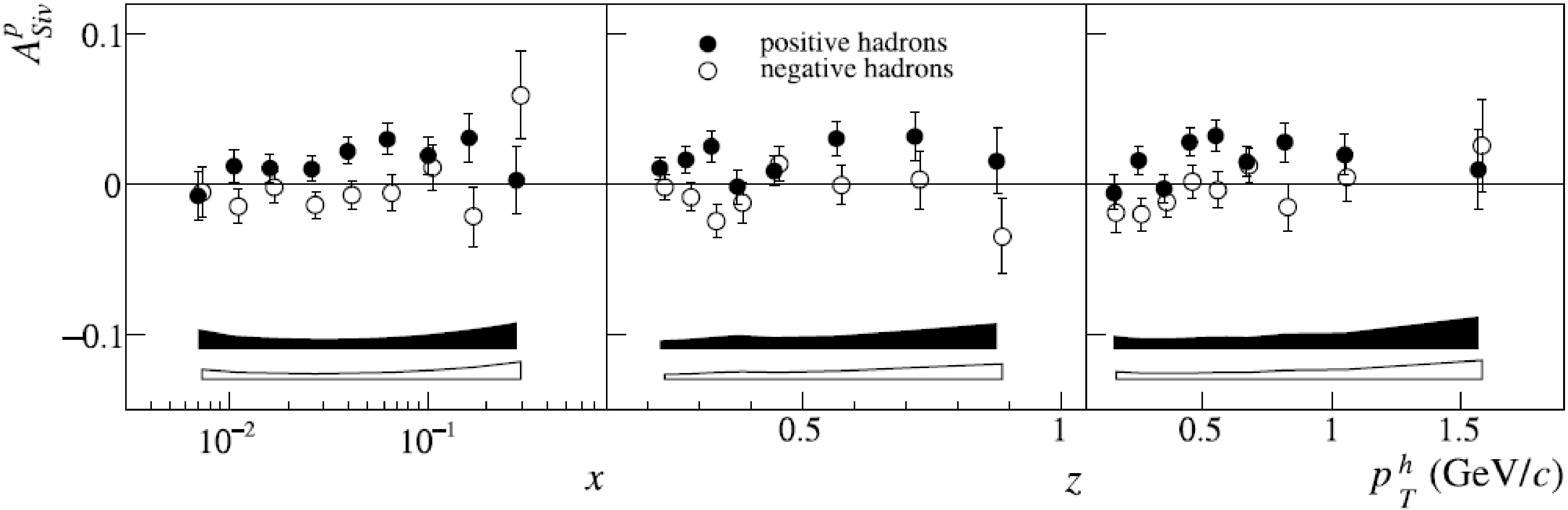
Sivers

$$F_{UT}^{\sin(\phi_h-\phi_S)} = 2\langle \sin(\phi_h-\phi_S)\rangle_{UT} \propto -C[f_{1T}^{\perp} \cdot D]$$



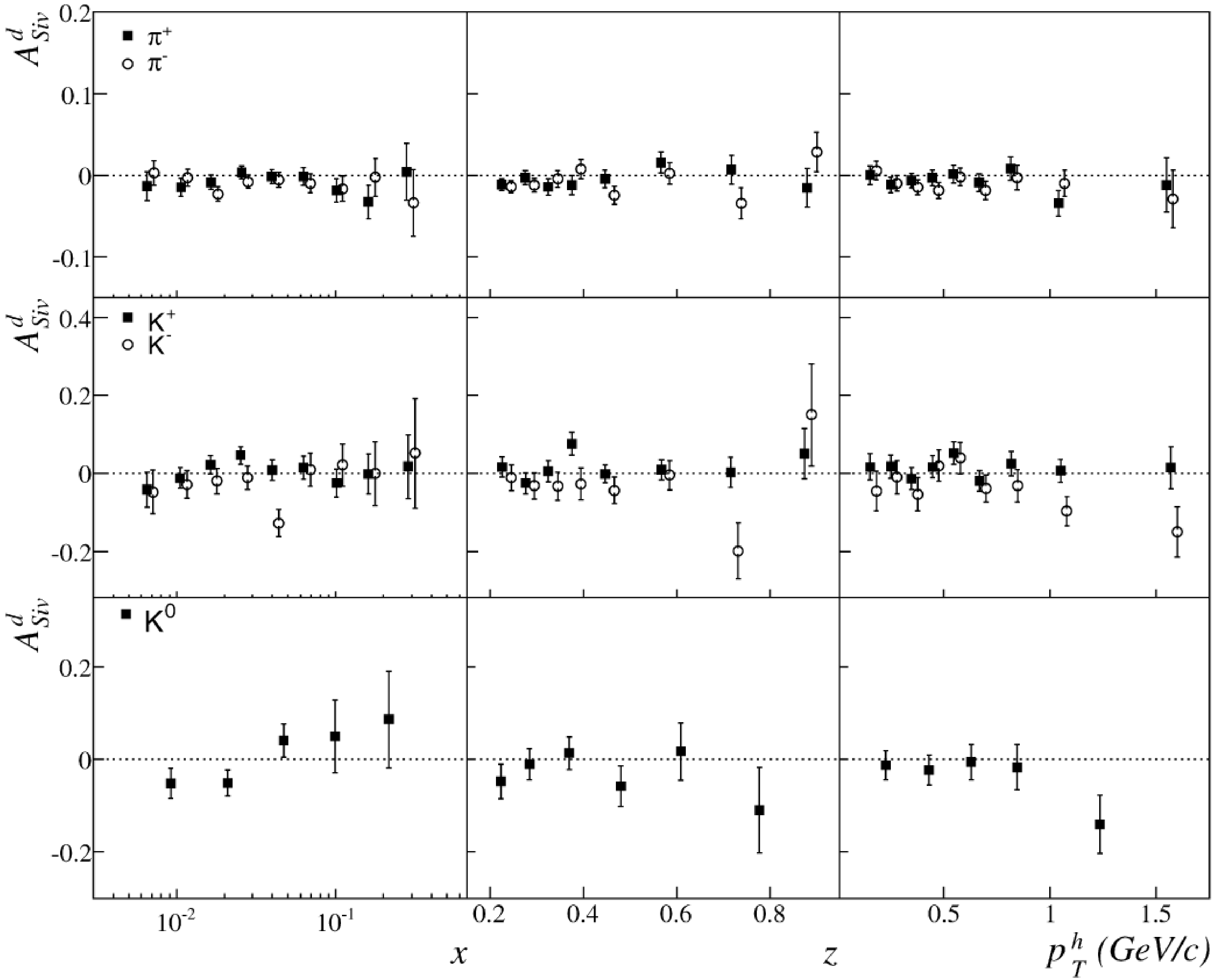
Sivers Asymmetry

COMPASS PLB692(2010)240



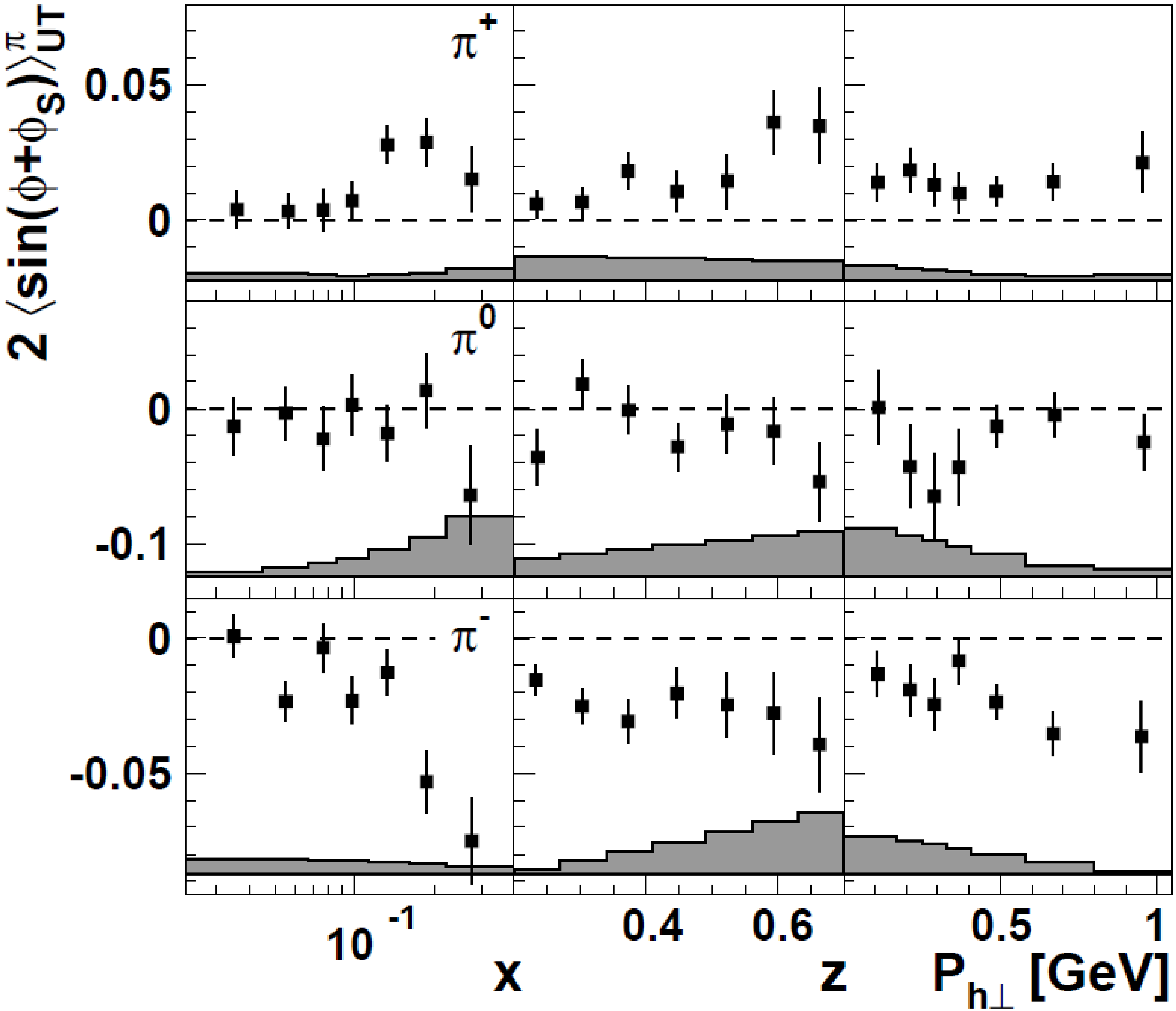
Sivers Asymmetry (deuteron)

COMPASS PLB673(2009)127



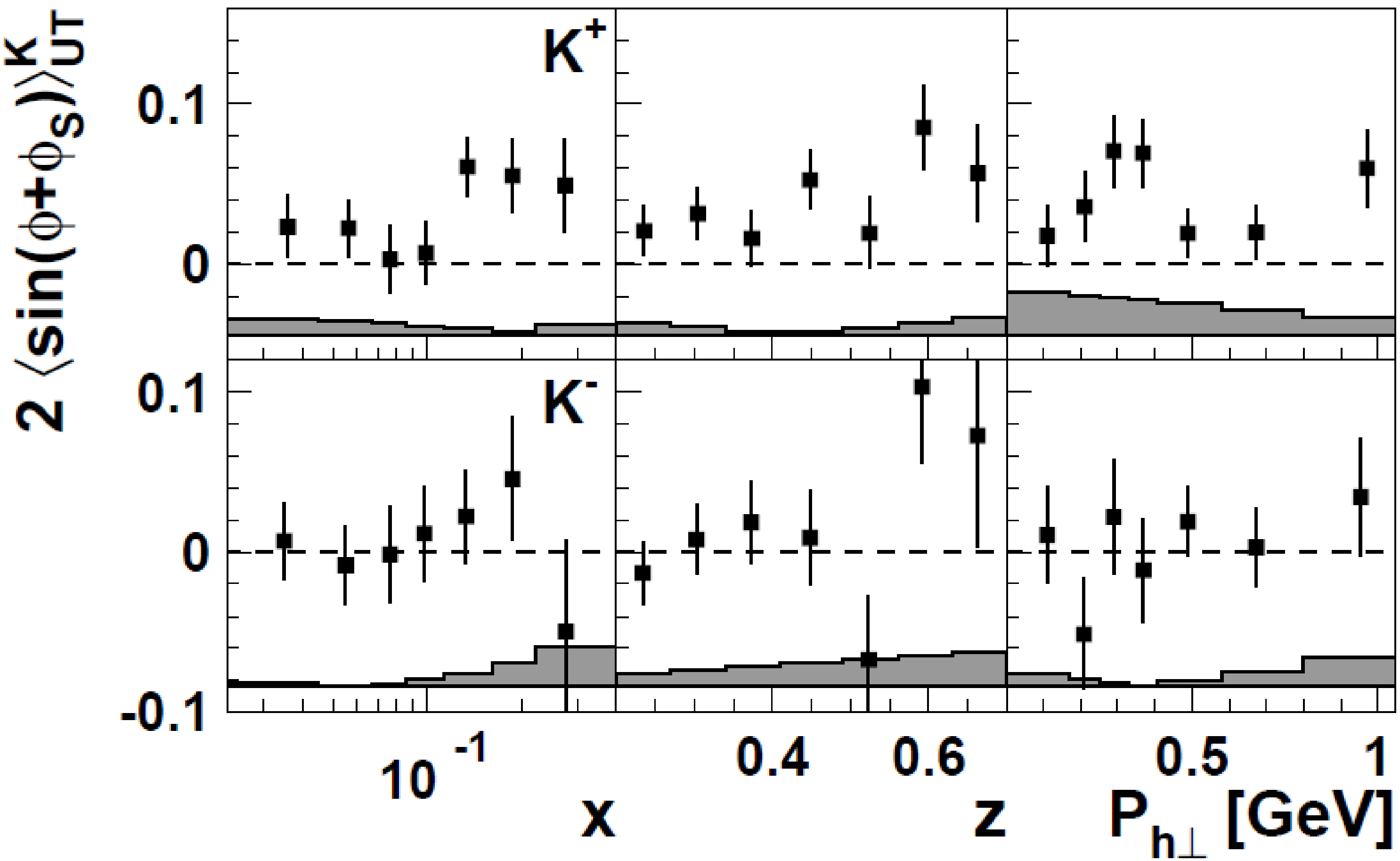
Collins Asymmetry

HERMES PLB693(2010)11



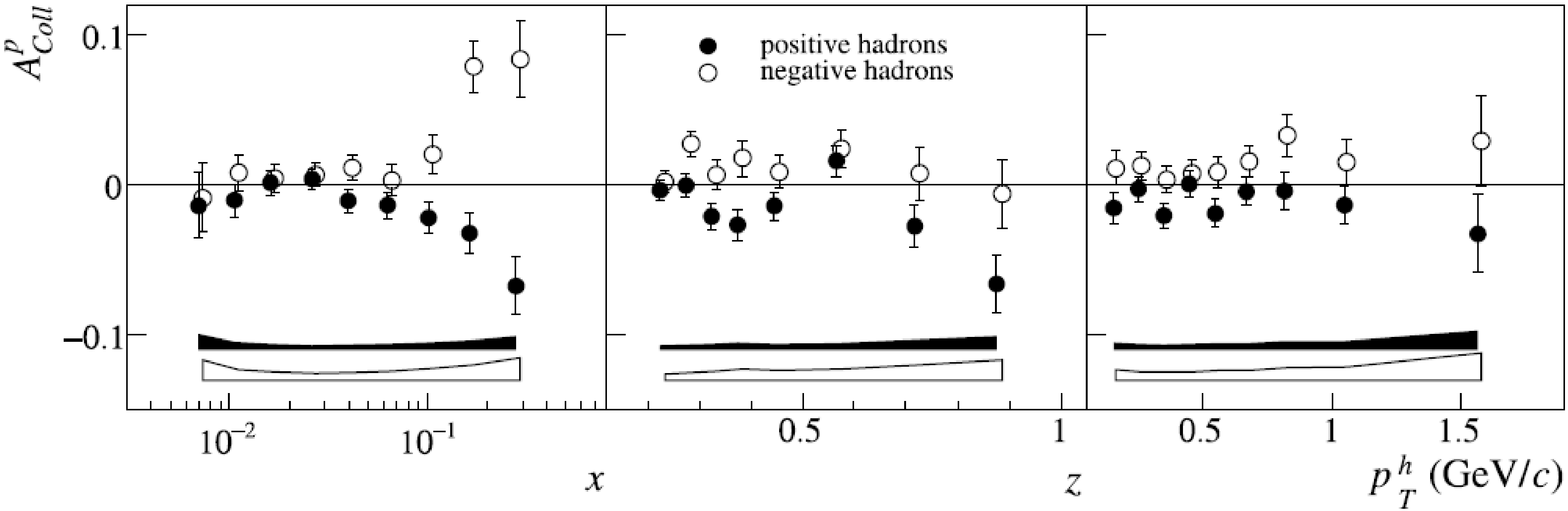
Collins Asymmetry (kaon)

HERMES PLB693(2010)11



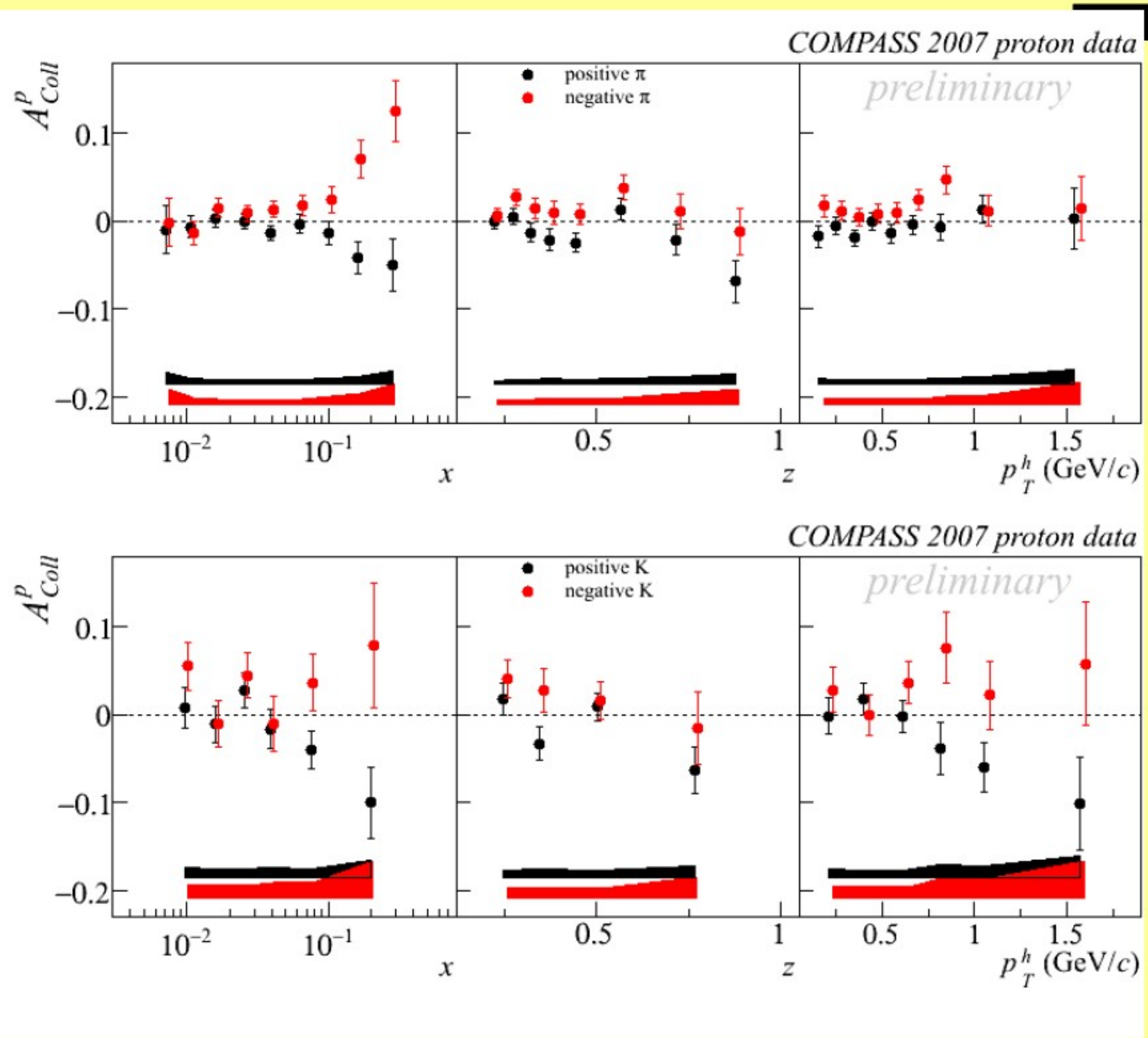
Collins Asymmetry

COMPASS PLB692(2010)240



Collins asymmetry ID

COMPASS



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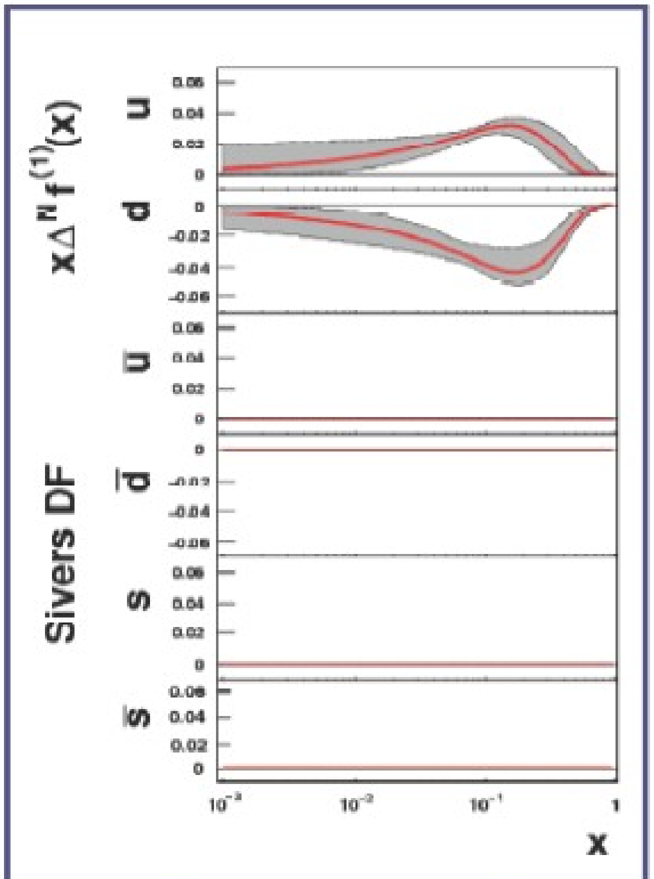
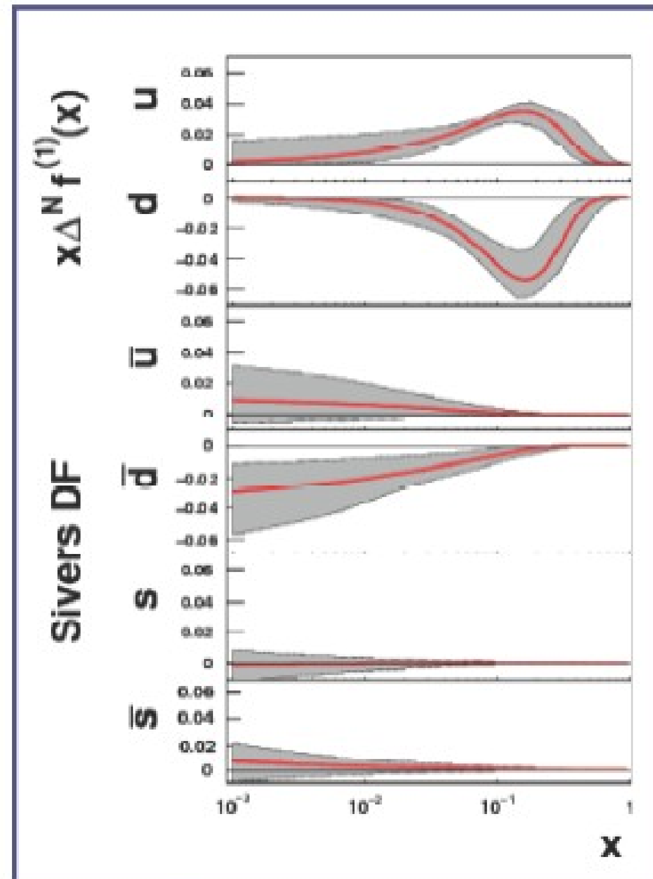
Extruction of Sivers Function

Sivers Function
New fit



Valence only

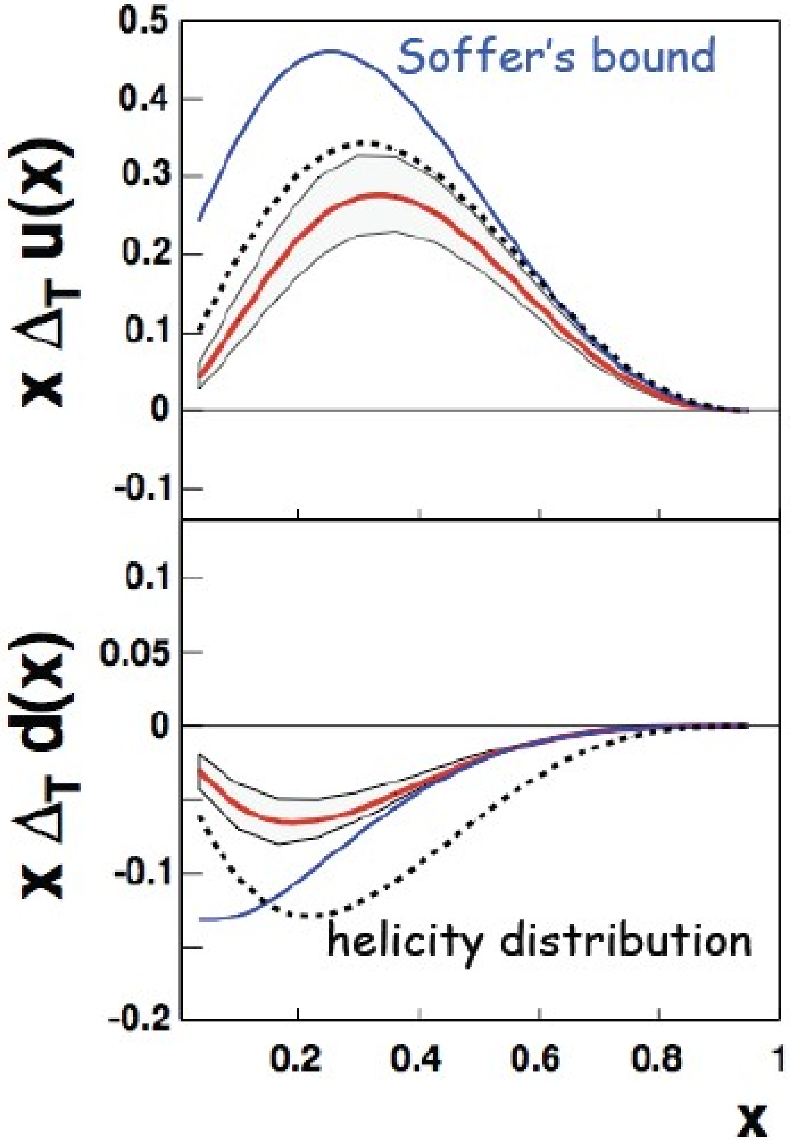


Valence + sea

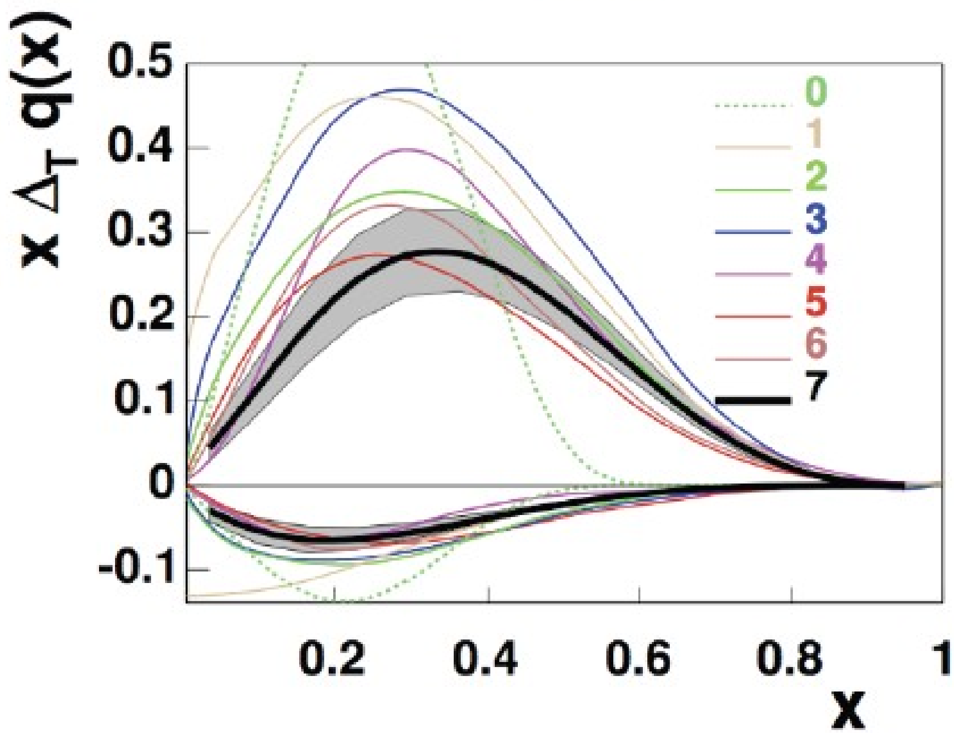
M. Boglione 30

Extraction of Transversity

SPIN2010, M. Anselmino



extracted transversity and comparison with models

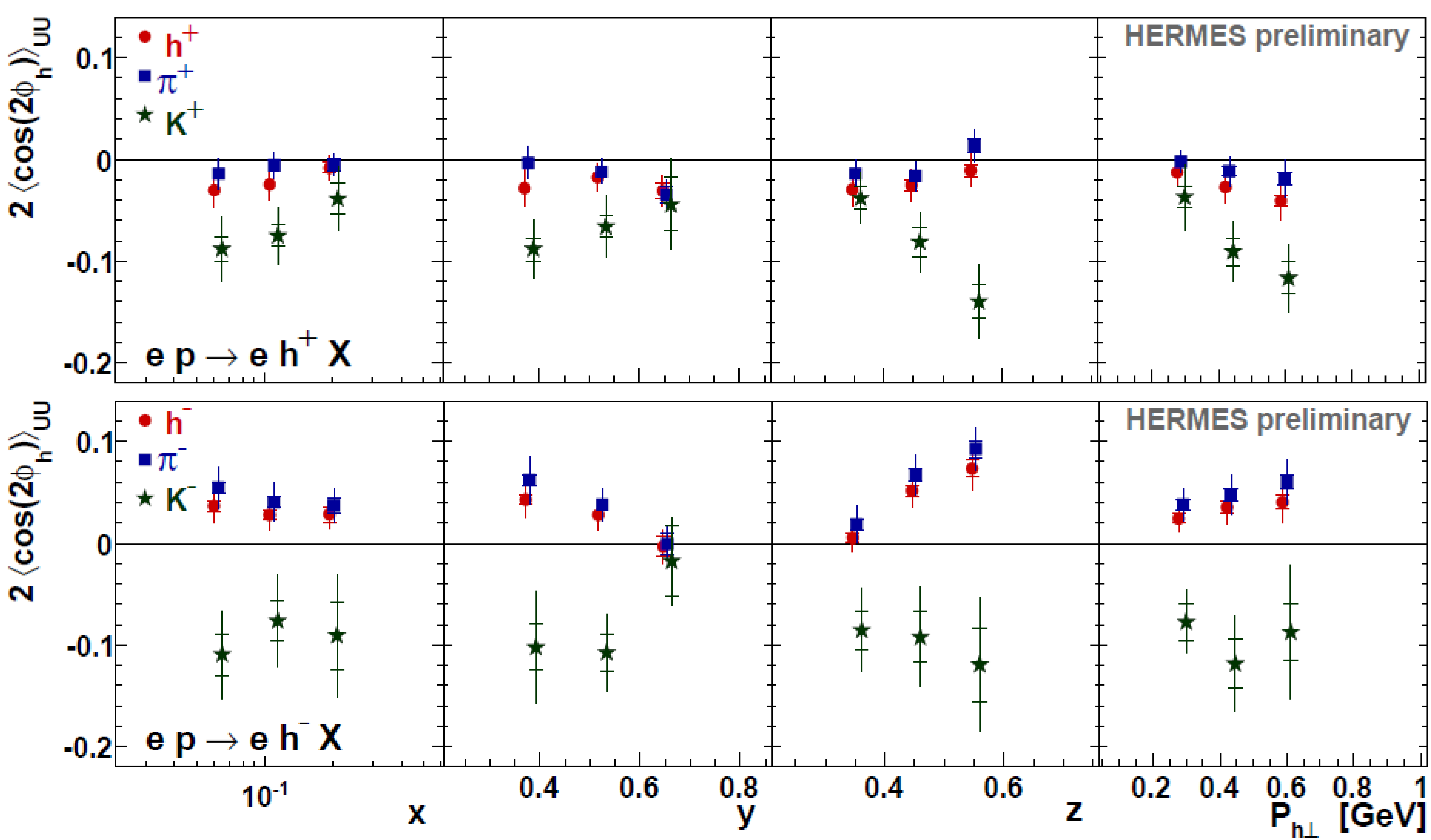


M.A., M. Boglione, U. D'Alesio, A. Kotzinian, S. Melis, F. Murgia, A. Prokudin, C. Türk

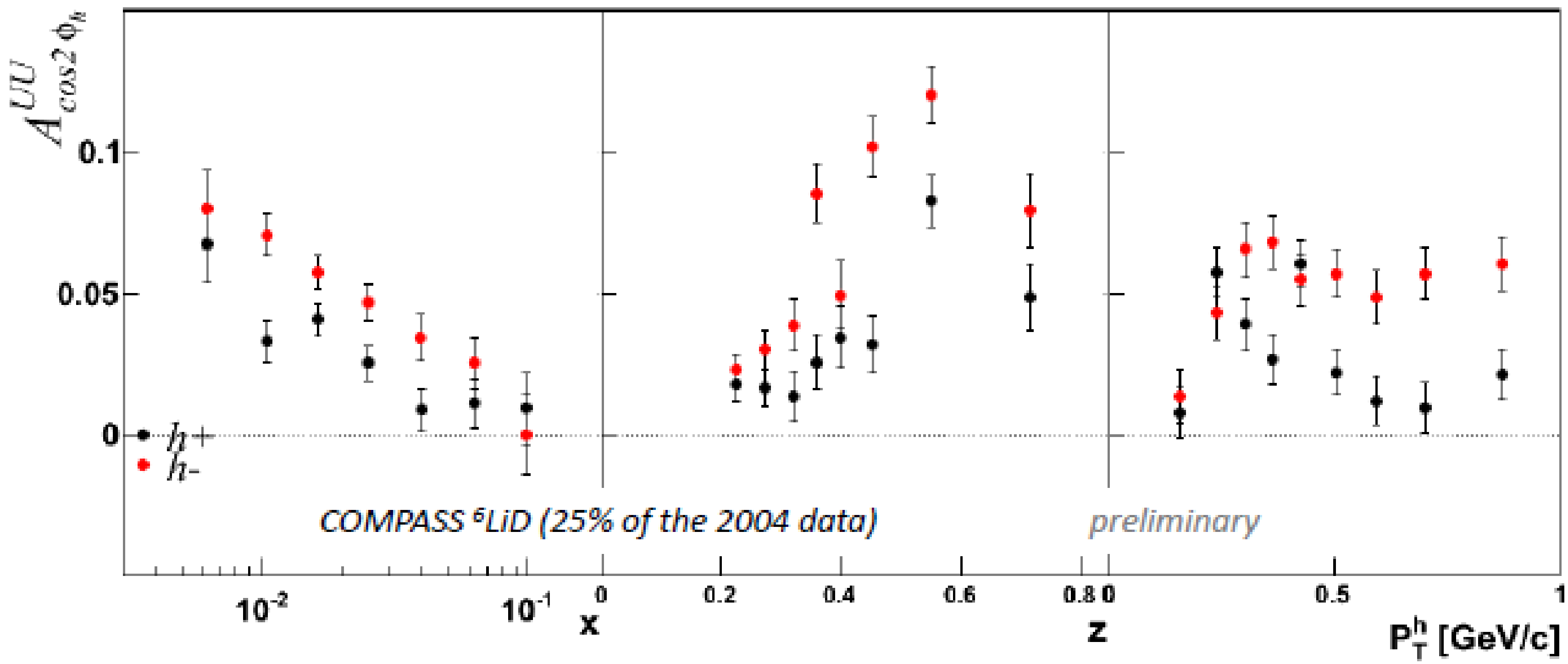
Boer-Mulders amplitude

Boer-Mulders

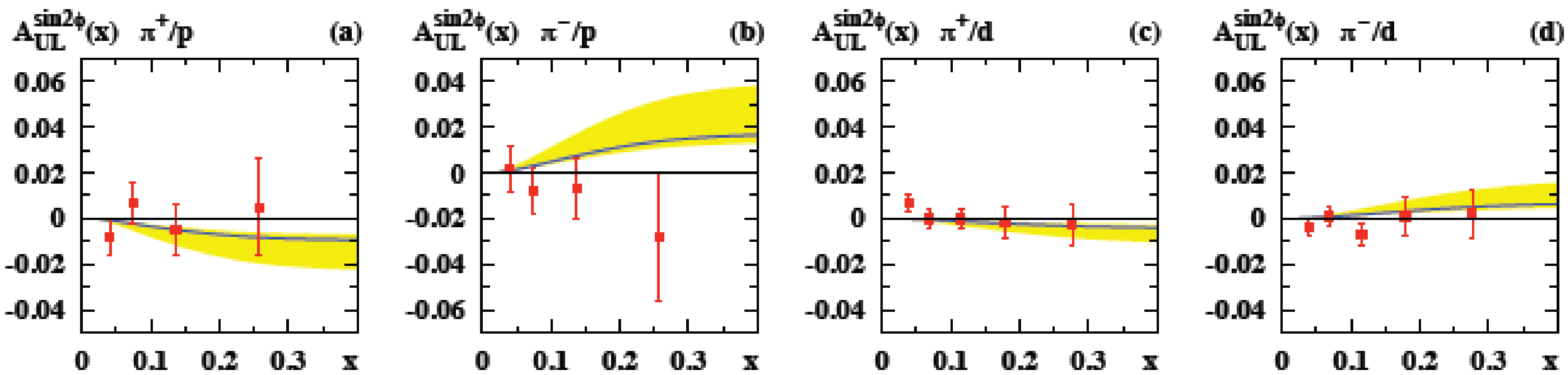
$$F_{UU}^{\cos 2\phi_h} = 2\langle \cos 2\phi_h \rangle_{UU} \propto -C[h_1^{\perp} \cdot D]$$



Boer-Mulders amplitude

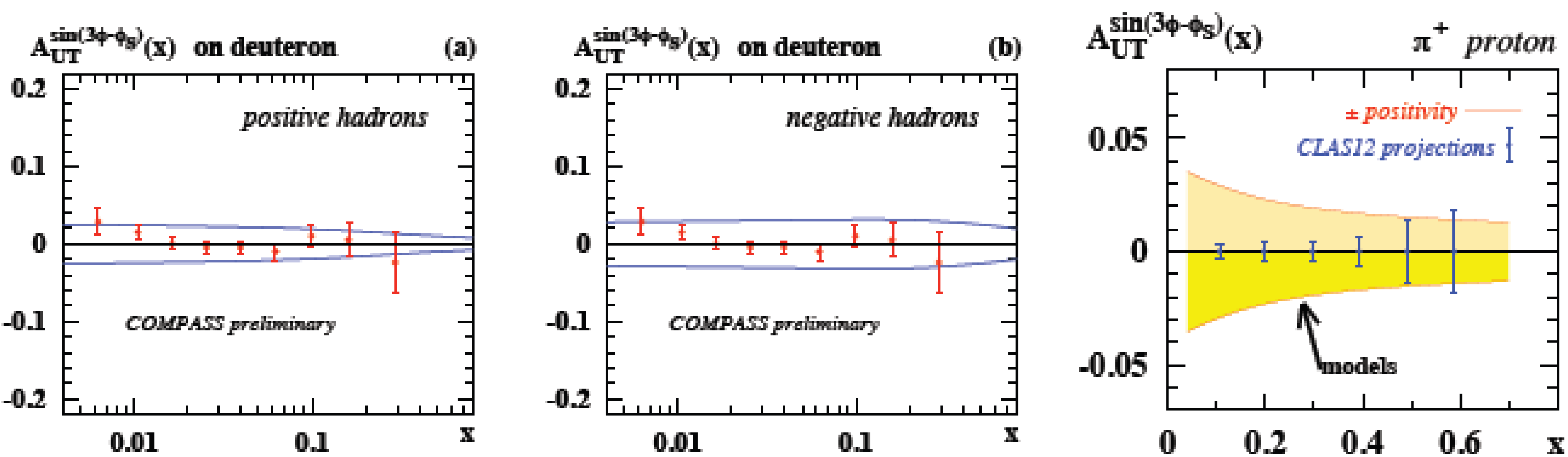


HERMES data, PRL 84 (2000) 4047; PL B562 (2003) 182



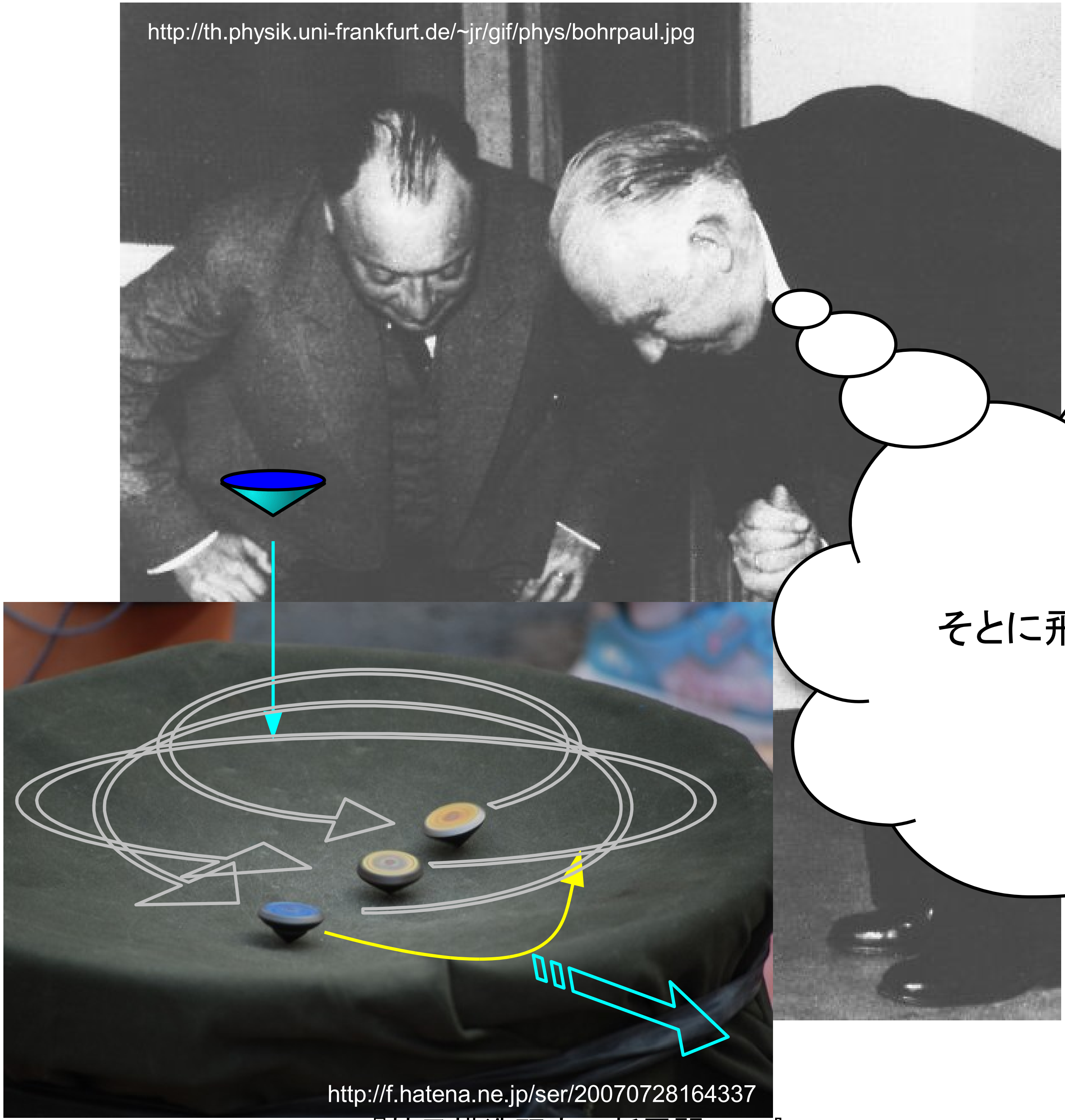
$$F_{UL}^{\sin(2\phi)} \sim \sum_a e_a^2 \, h_{1L}^{\perp a} \otimes H_1^{\perp a}$$

COMPASS data, arXiv:0705.2402



$$F_{UT}^{\sin(3\phi-\phi_S)} \sim \sum_a e_a^2 \, h_{1T}^{\perp a} \otimes H_1^{\perp a}$$

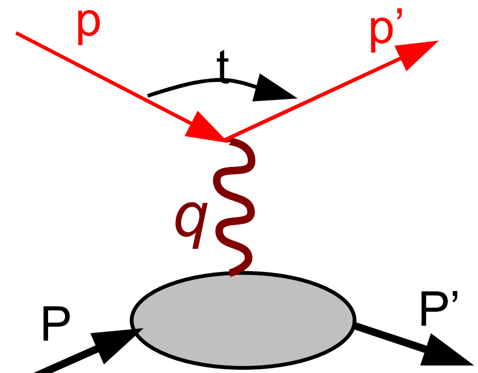
SPIN2010, M. Anselmino



そとに飛ばさんようにしたら？

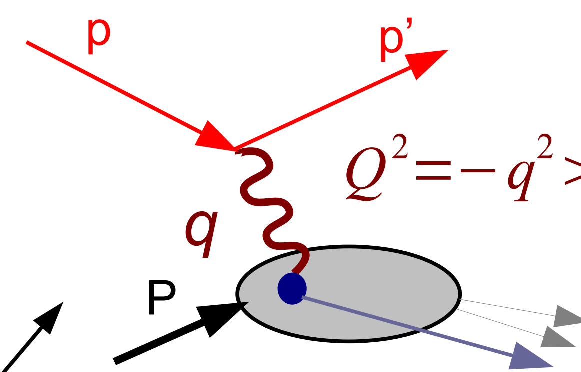
Generalized Parton Distribution
in hard exclusive production

Elastic scattering



Form Factor: F(t), G(t)

Deep Inelastic Scattering



$Q^2 = -q^2 > 1\ \mathrm{GeV}^2$

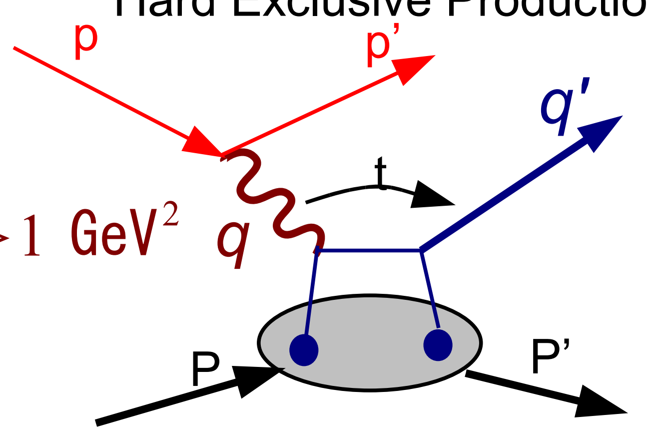
Parton distribution: **q(x), Δq(x)**

$\int_{-1}^{1} dx$

Forward limit

Hard Exclusive Production:

$Q^2 > 1\ \mathrm{GeV}^2$



$$e + N \rightarrow e' + N' + \{\gamma,\ \rho,\ \pi, ...\}$$

Generalized Parton Distribution:

$$\boldsymbol{H},\ \boldsymbol{E},\ \tilde{\boldsymbol{H}},\ \tilde{\boldsymbol{E}}$$

$$J_q = \frac{1}{2}\int_{-1}^{1} dx\, x\left[H^q(x,\xi,t\rightarrow 0) + E^q(x,\xi,t\rightarrow 0)\right]$$

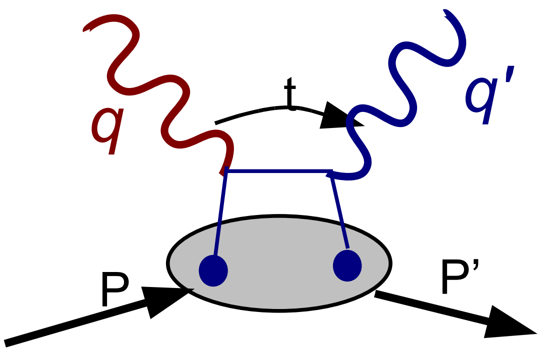
Hard Exclusive Production and GPD

Deeply Virtual Compton Scattering:

$$e+N \rightarrow e'+N'+\gamma$$

Involved GPDs: $H\,,\ E\,,\ \tilde{H}\,,\ \tilde{E}$

clean reaction



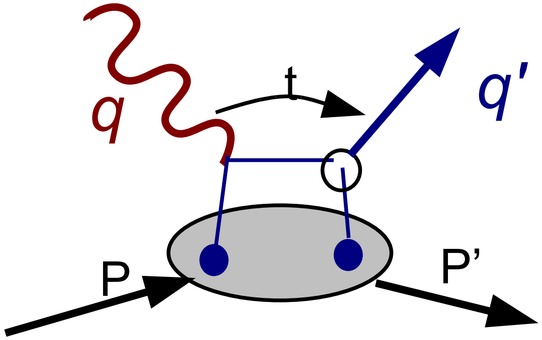
Hard exclusive meson production:

$$e+N \rightarrow e'+N'+\{\rho,\ \pi,\ldots\}$$

vector meson: $H\,,\ E$

pseudo-scalar meson: $\tilde{H}\,,\ \tilde{E}$

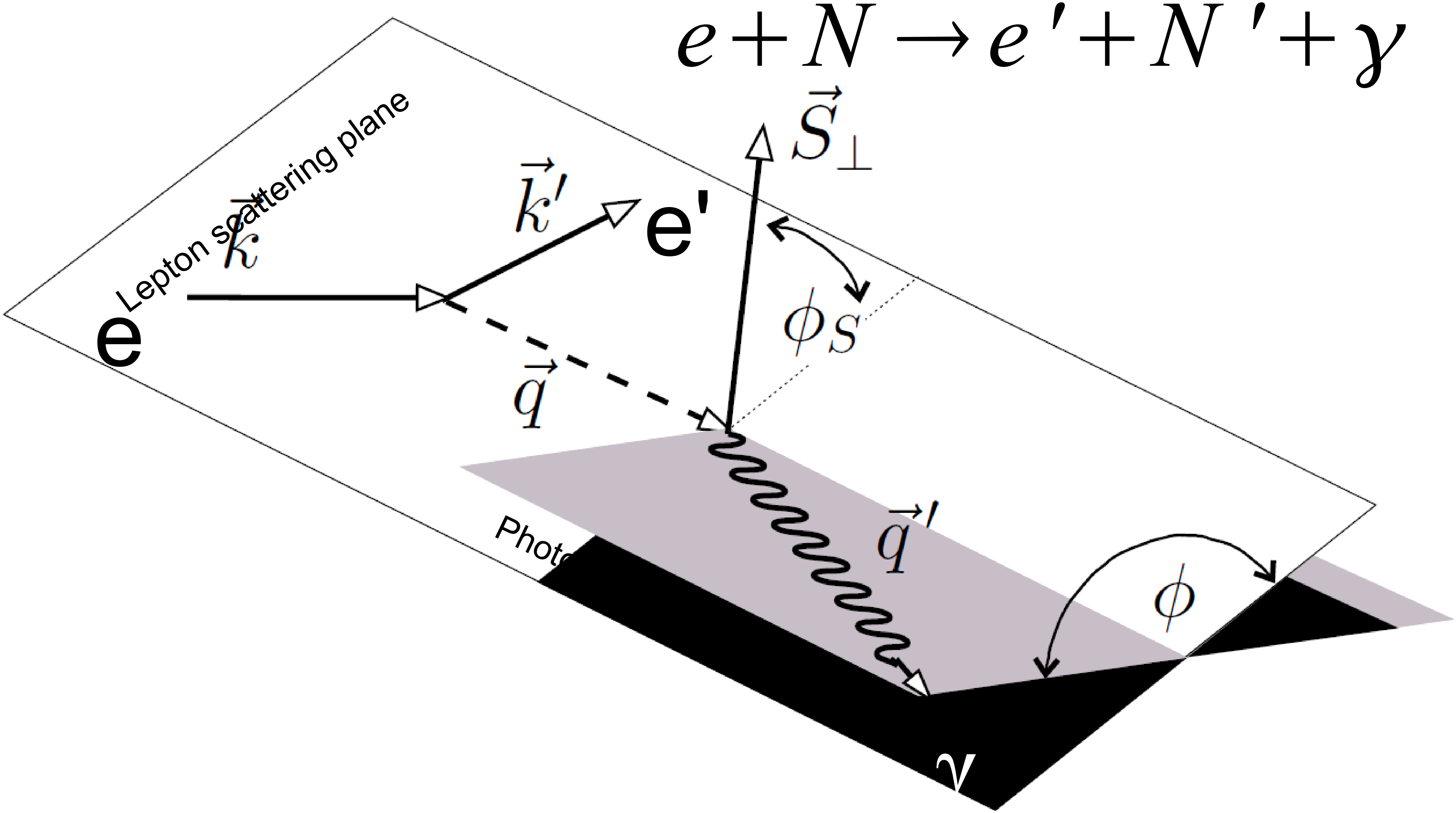
Meson amplitude involved



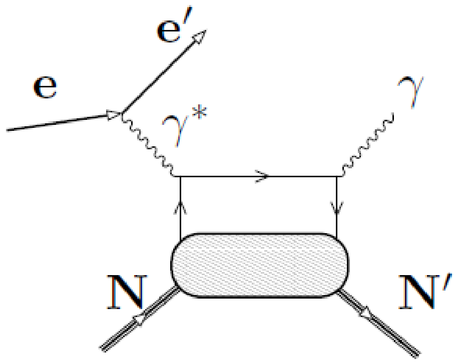
(given in the next talk by A. Rostomyan)

Azimuthal angles in DVCS

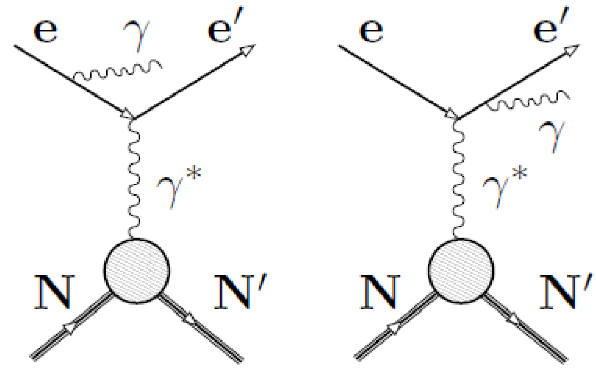
$$e + N \rightarrow e' + N' + \gamma$$



DVCS cross section

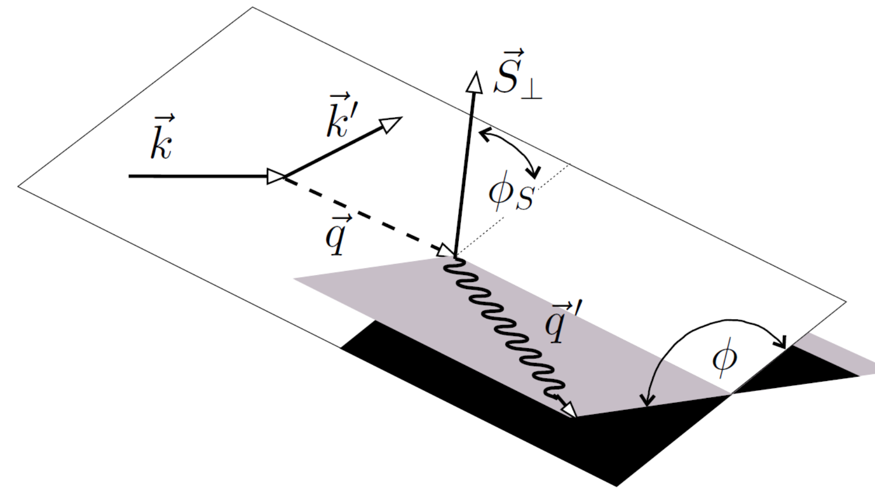


DVCS



Bethe-Heitler (BH)

$\sigma_{\rm DVCS} \ll \sigma_{\rm BH}$ @HERMES



$$|\mathrm{T}|^2 = |\mathrm{T}_{\rm DVCS}|^2 + |\mathrm{T}_{\rm BH}|^2 + \mathrm{T}_{\rm DVCS}\mathrm{T}^*_{\rm BH} + \mathrm{T}^*_{\rm DVCS}\mathrm{T}_{\rm BH}$$

$$\mathcal{I} = \mathcal{T}_{\rm DVCS}\mathcal{T}^*_{\rm BH} + \mathcal{T}^*_{\rm DVCS}\mathcal{T}_{\rm BH}$$

$$|\mathcal{T}_{\rm BH}|^2 = \frac{e^6}{x_{\rm B}^2 y^2 (1+\epsilon^2)^2 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\rm BH} + \sum_{n=1}^{2} c_n^{\rm BH} \cos(n\phi) + s_1^{\rm BH} \sin(\phi) \right\}$$

$$|\mathcal{T}_{\rm DVCS}|^2 = \frac{e^6}{y^2 Q^2} \left\{ c_0^{\rm DVCS} + \sum_{n=1}^{2} \left[c_n^{\rm DVCS} \cos(n\phi) + s_n^{\rm DVCS} \sin(n\phi) \right] \right\}$$

$$\mathcal{I} = \frac{\pm e^6}{x_{\rm B} y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi) \right] \right\}$$

A.V. Belitsky, D. M¨uller and A. Kirchner, NPB 629 (2002) 323

$\phi \to \pi - \phi$

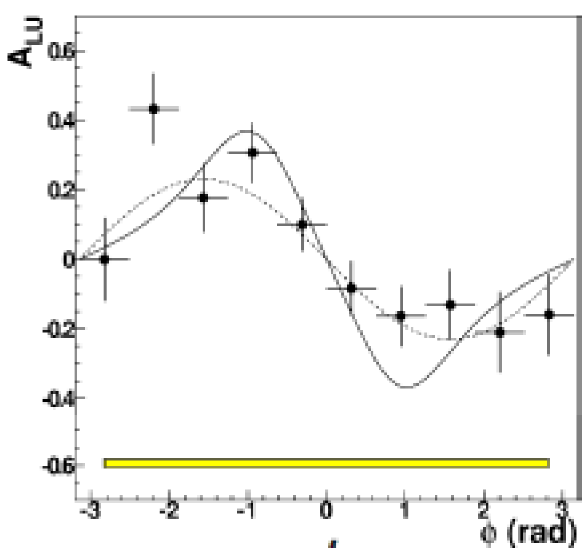
Deeply Virtual Compton Scattering

First observation of beam-spin asymmetry of DVCS (2001)

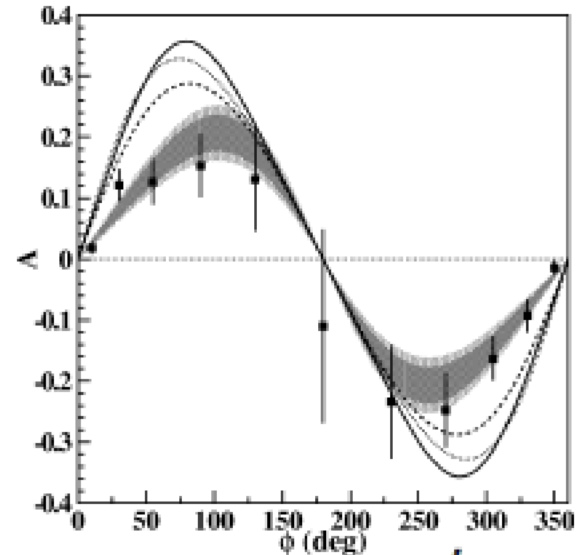
A_{LU}

HERMES (DESY)

CLAS (JLab)



ϕ



ϕ

~ 30% effect

DVCS @ HERMES

Year	Beam		Targets			Detector
	Charge	Helicity	Pol.	Unpol.		
1996	+	+	H(l)	H, D,	^{3}He	
1997	+	+, -	H(l)	H, D,	N	
1998	-	+, -	D(l)	H, D,	Kr	
1999	+	+, -	D(l)	D,	N, Kr	
2000	+	+, -	D(l)	H, D,	^{4}He, Ne, Kr	
2002	+	-	**H(t)**	H, D,	Kr	
2003	+	+	**H(t)**	H,	Kr	
2004	+	+, -	**H(t)**	H, D,	Kr, Xe	
2005	-	+, -	**H(t)**	H, D,	Xe	
2006	-, +	+, -		H, D		Recoil
2007	+	+, -		H, D		Recoil

* combined analysis with BCA

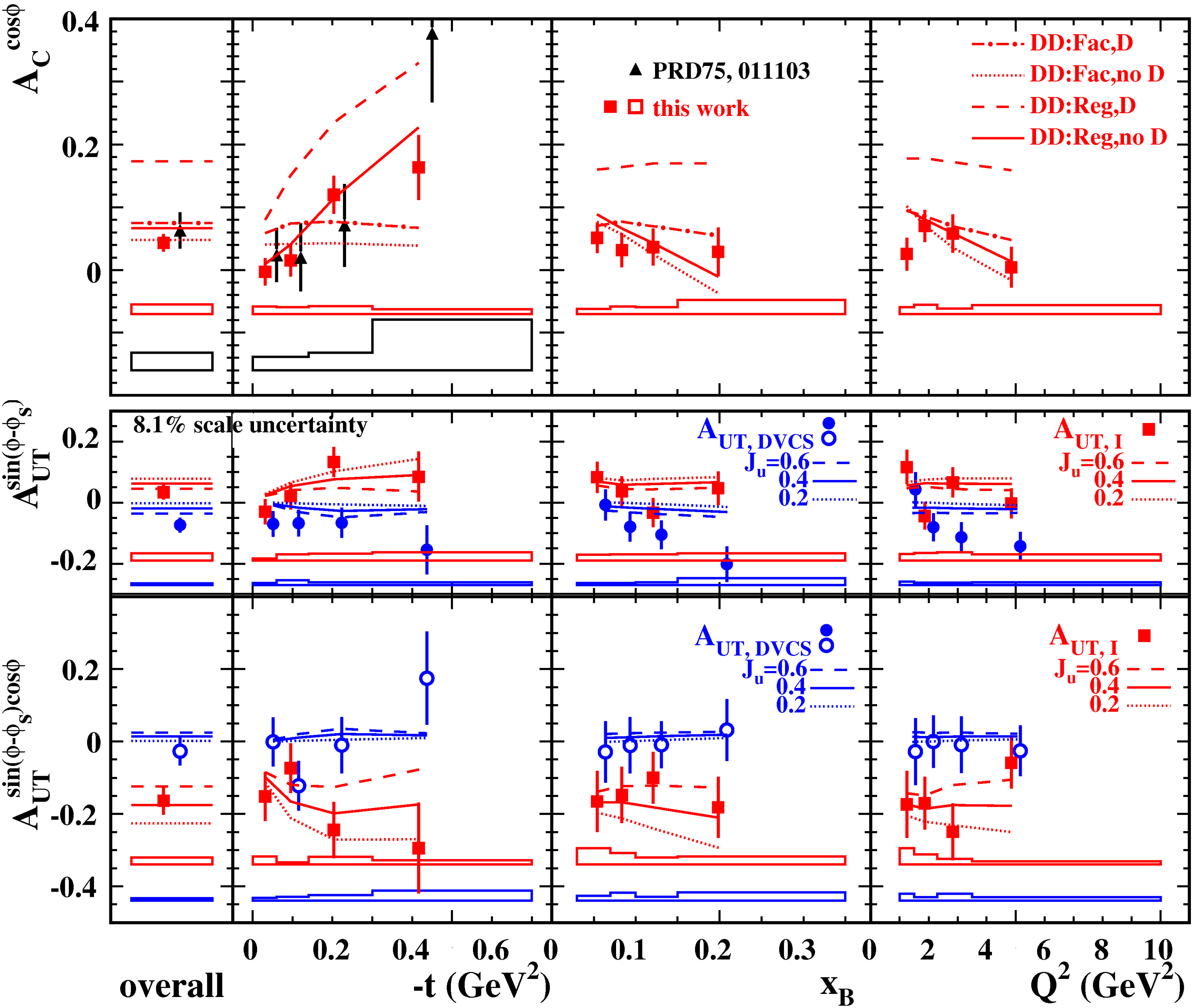
DVCS @ HERMES

- Beam spin, charge asymmetry	H	PRL87 (2001) 182001
	H	JHEP 11 (2009) 083
	D	NPB829 (2010) 1-27
- Beam charge asymmetry	H	PRD75 (2007) 011103
- Longitudinal target spin asymmetry	H	JHEP06 (2010) 019
	D	NPB842 (2011) 265-298
- Transverse target spin asymmetry	H	JHEP 06 (2008) 066
- DVCS on nucleus targets		PRC81 (2010) 035202

without Recoil Detector

Extracted amplitudes:

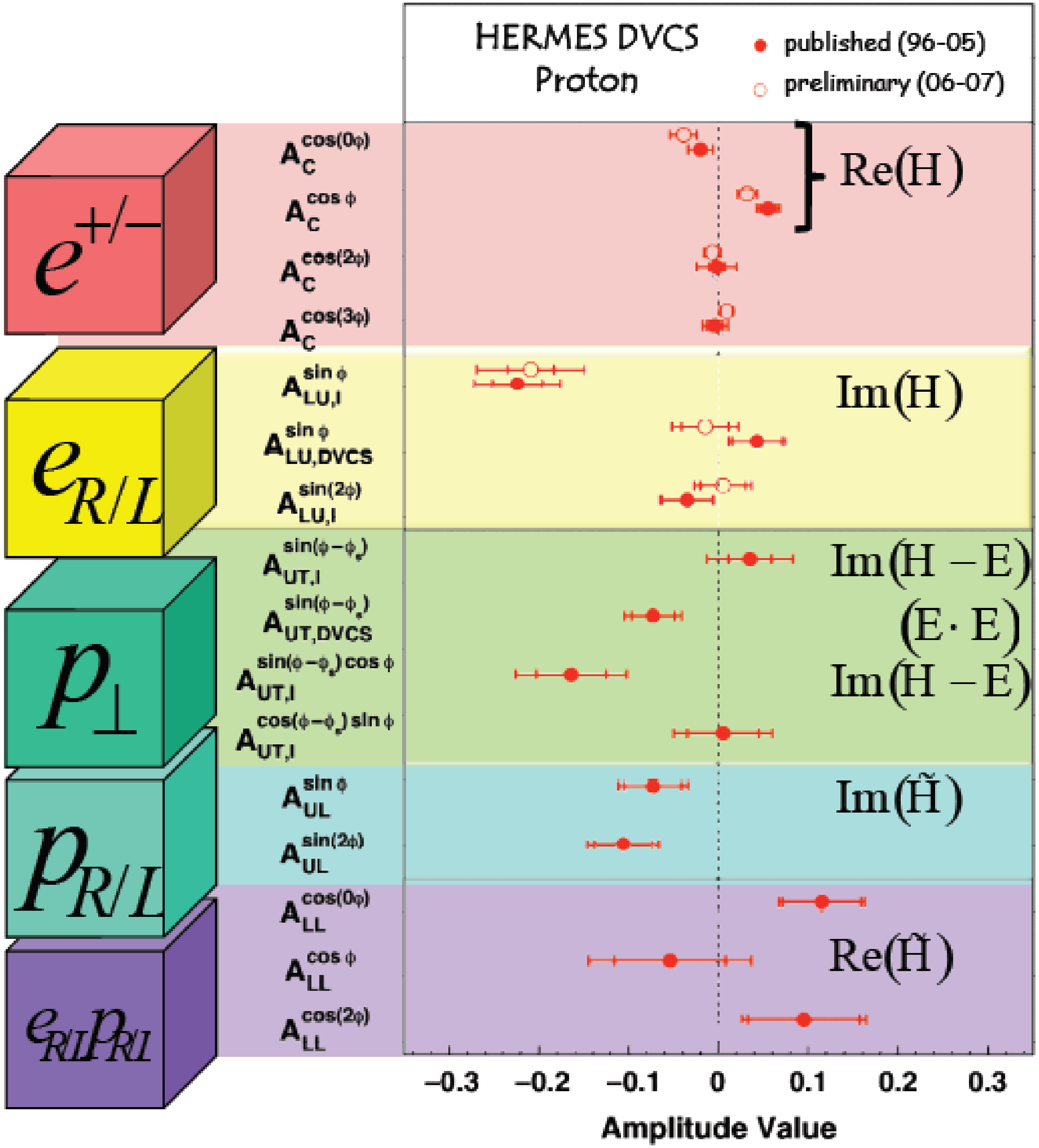
HERMES Collaboration, JHEP06 (2008) 066



$$A_C^{\cos\phi} \propto \Re[F\mathcal{H}]$$

$$A_{UT,\,DVCS}^{\sin(\phi-\phi_s)} \propto \Im[\mathcal{H}\mathcal{E}^* - \mathcal{E}\mathcal{H}^* + \xi\tilde{\mathcal{E}}\tilde{\mathcal{H}}^* - \tilde{\mathcal{H}}\xi\tilde{\mathcal{E}}^*]$$

$$A_{UT,\,I}^{\sin(\phi-\phi_s)} \propto -A_{UT,\,I}^{\sin(\phi-\phi_s)\cos\phi} \propto \Im[F_1\mathcal{E} - F_2\mathcal{H}]$$



Access to GPD H, H̃, E

JHEP 11 (2009) 083

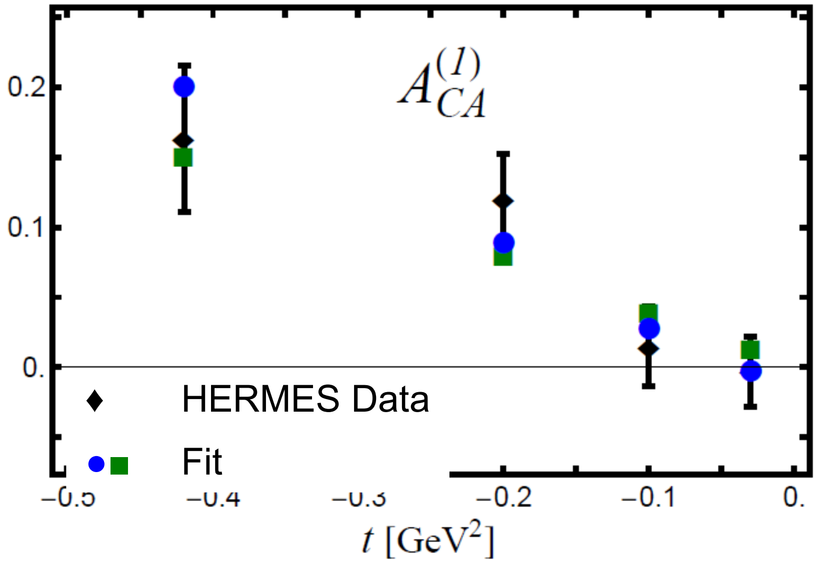
JHEP 06 (2008) 066

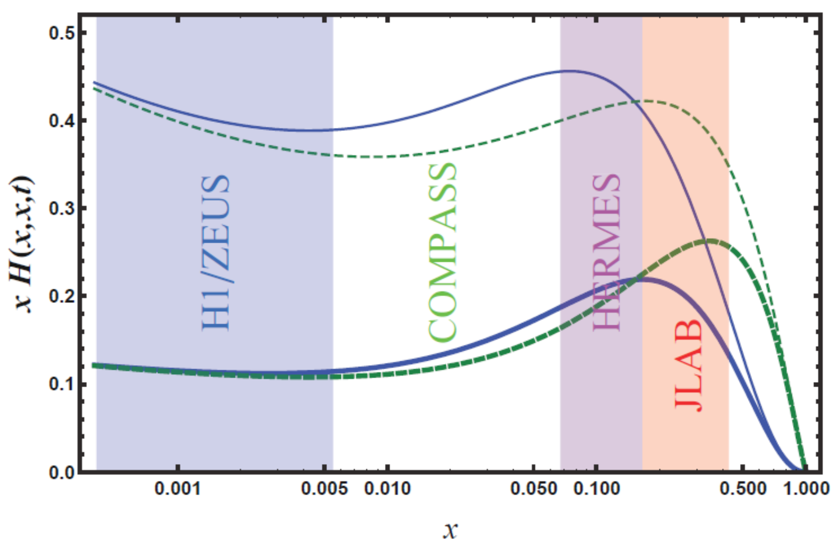
JHEP 06 (2010) 019

SPIN2010, M. Dueren

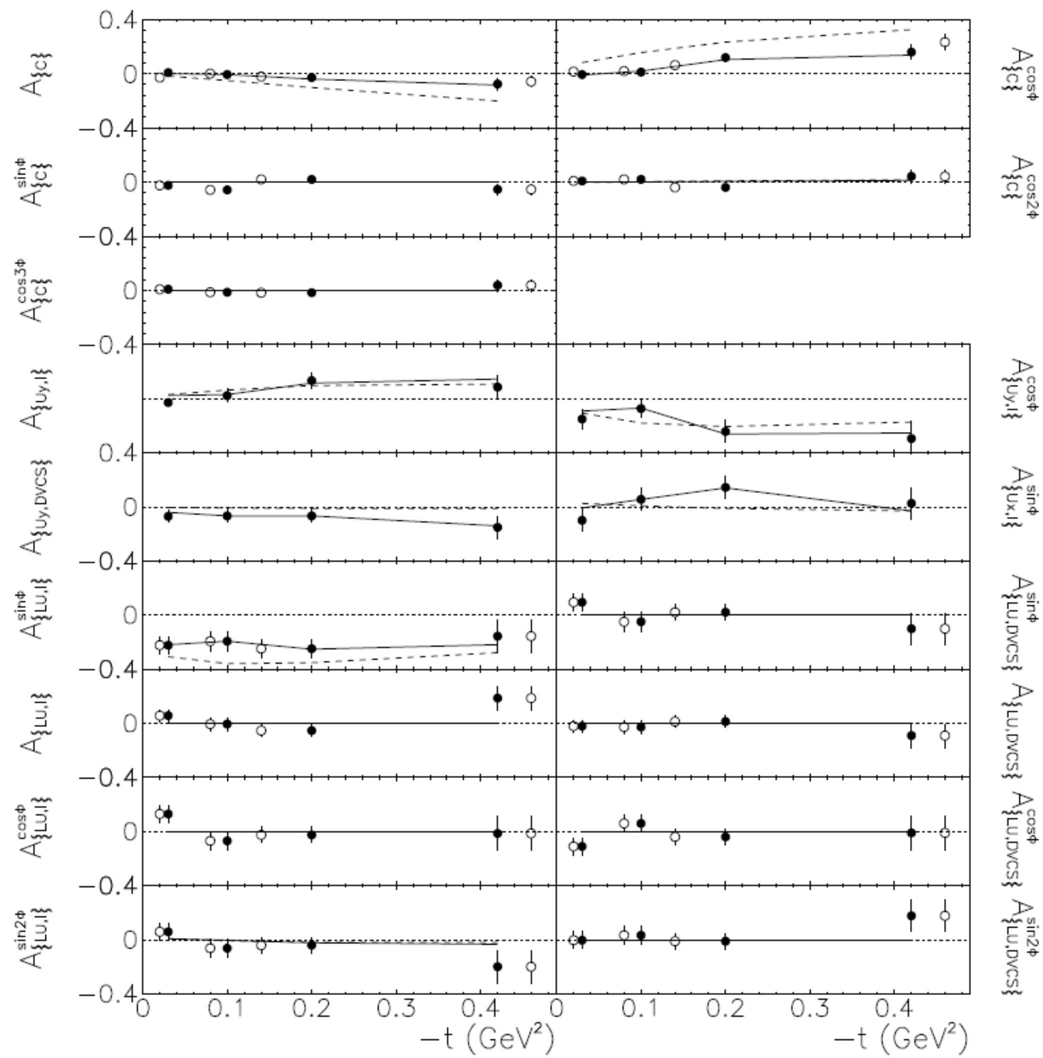
Fit to the HERMES data

K. Kumericki and D. Muller, arXiv:0904.0458

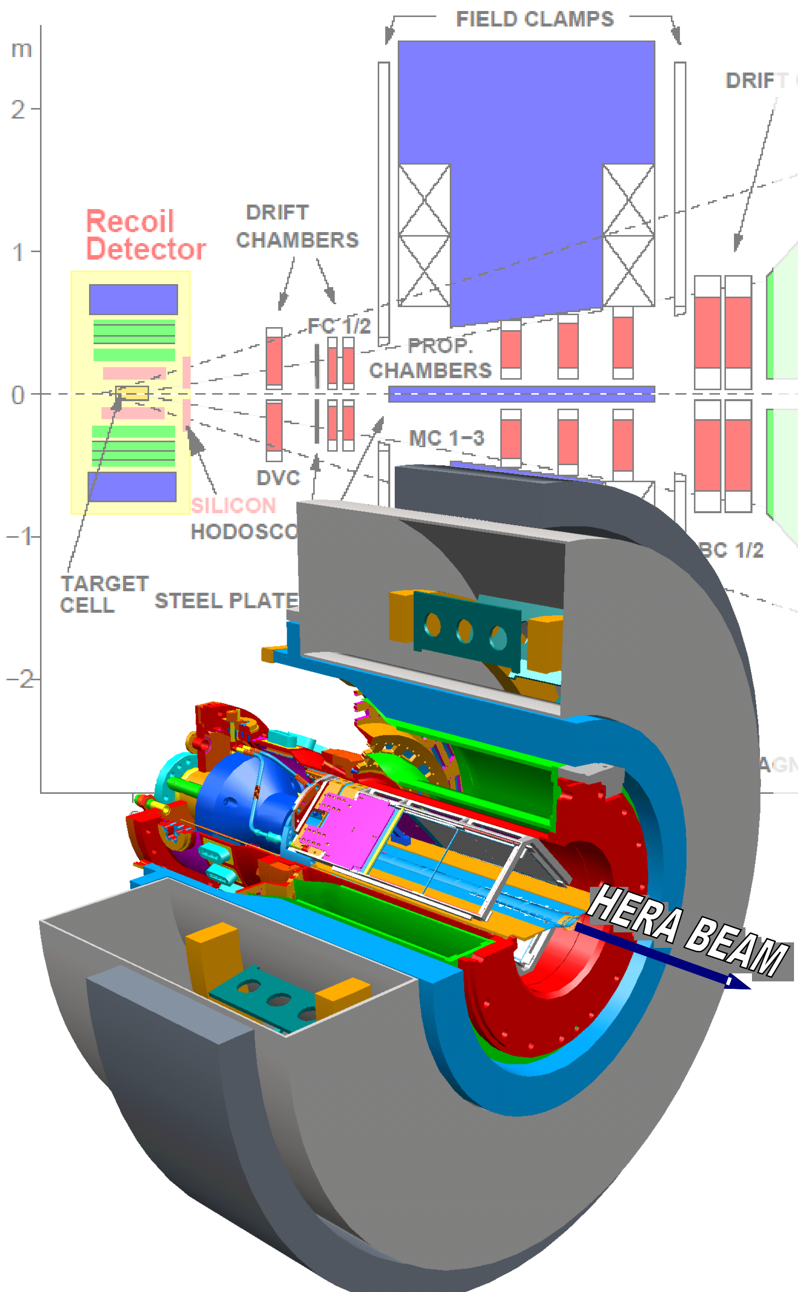




M. Guidal and H. Moutarde, arXiv:0905.1220

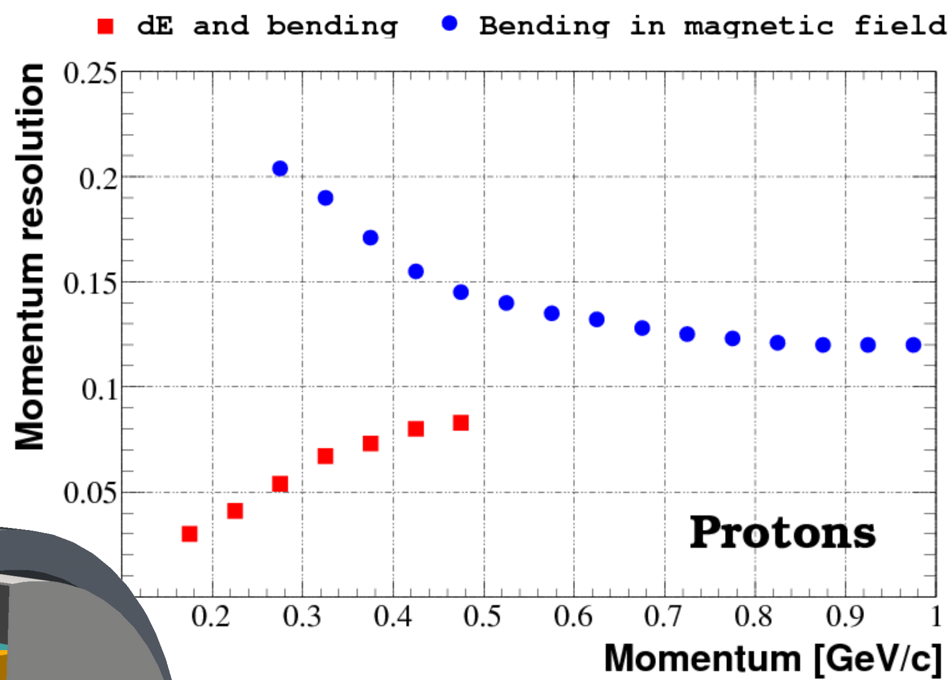


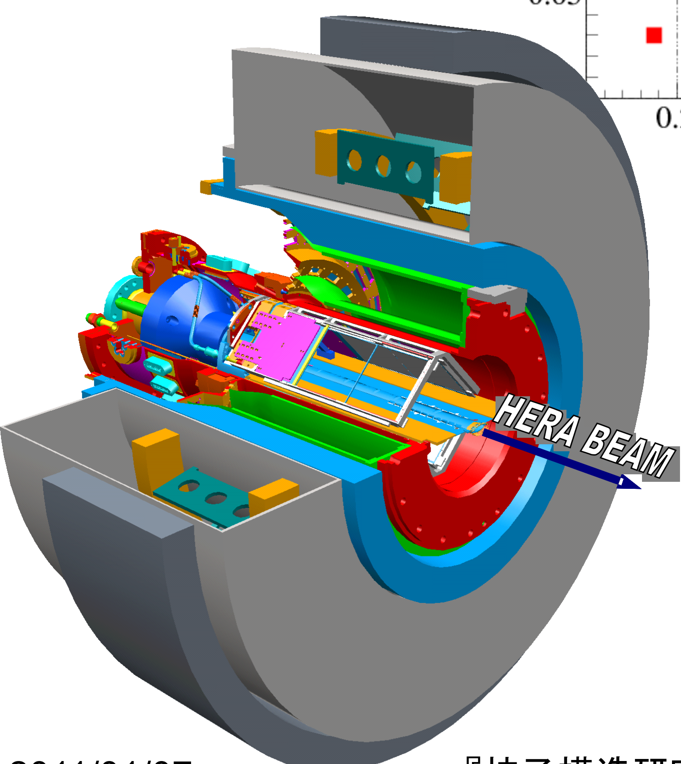
HERMES Recoil Detector:

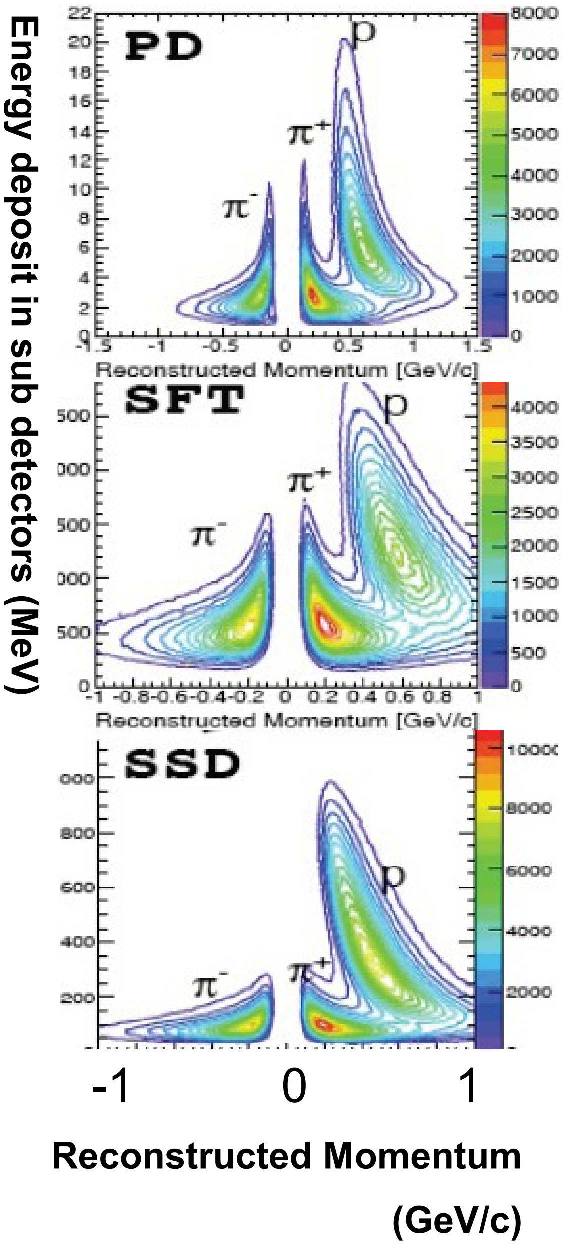


- Sub-detectors in 1 T Solenoid Magnet
  - Photon Detector (**PD**)
    - 3 Tungsten/Scintillator layers, π^0, π/p
  - Scintillation Fiber Tracker (**SFT**)
    - 2 x (2 Parallel and 2 Stereo layers), momentum reconstruction and π/p
  - Silicon Strip Detector (**SSD**)
    - 2 layers of 16 double sided sensor, momentum reconstruction and π/p
- Unpol. H&D targets: 2006 - 2007

HERMES Recoil Detector





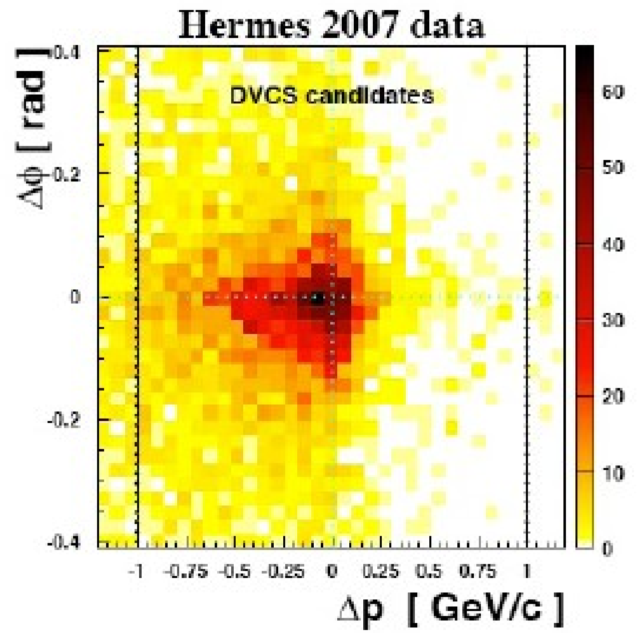


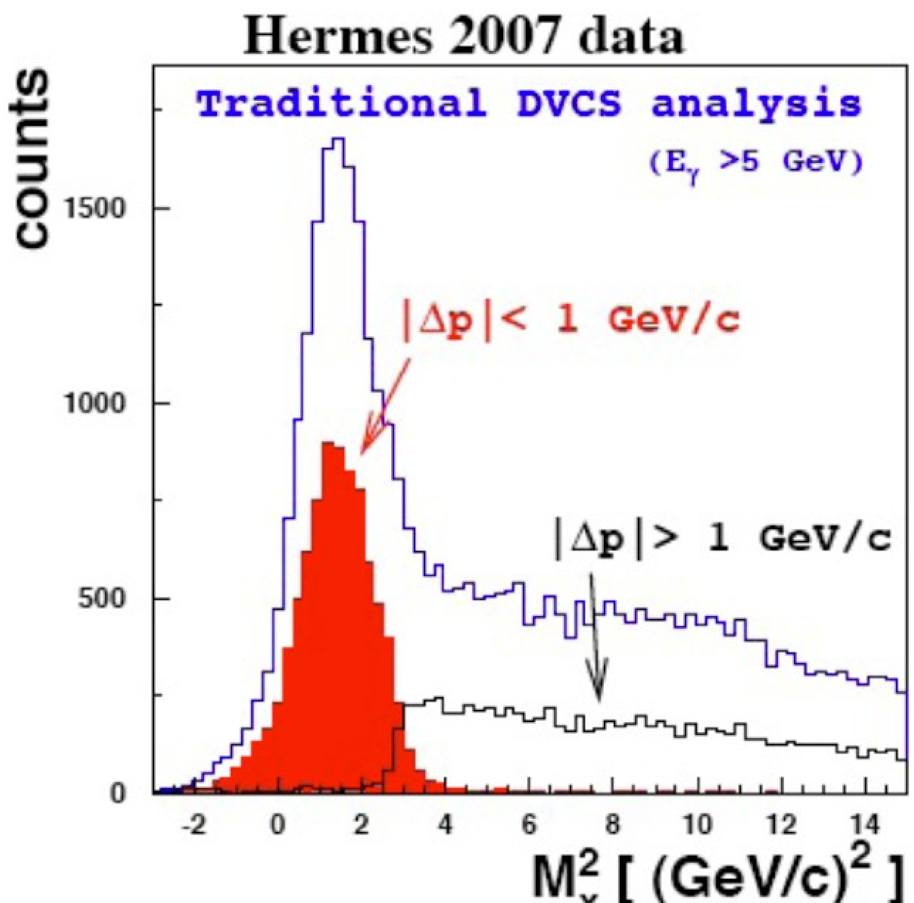
Recoil in DVCS analys

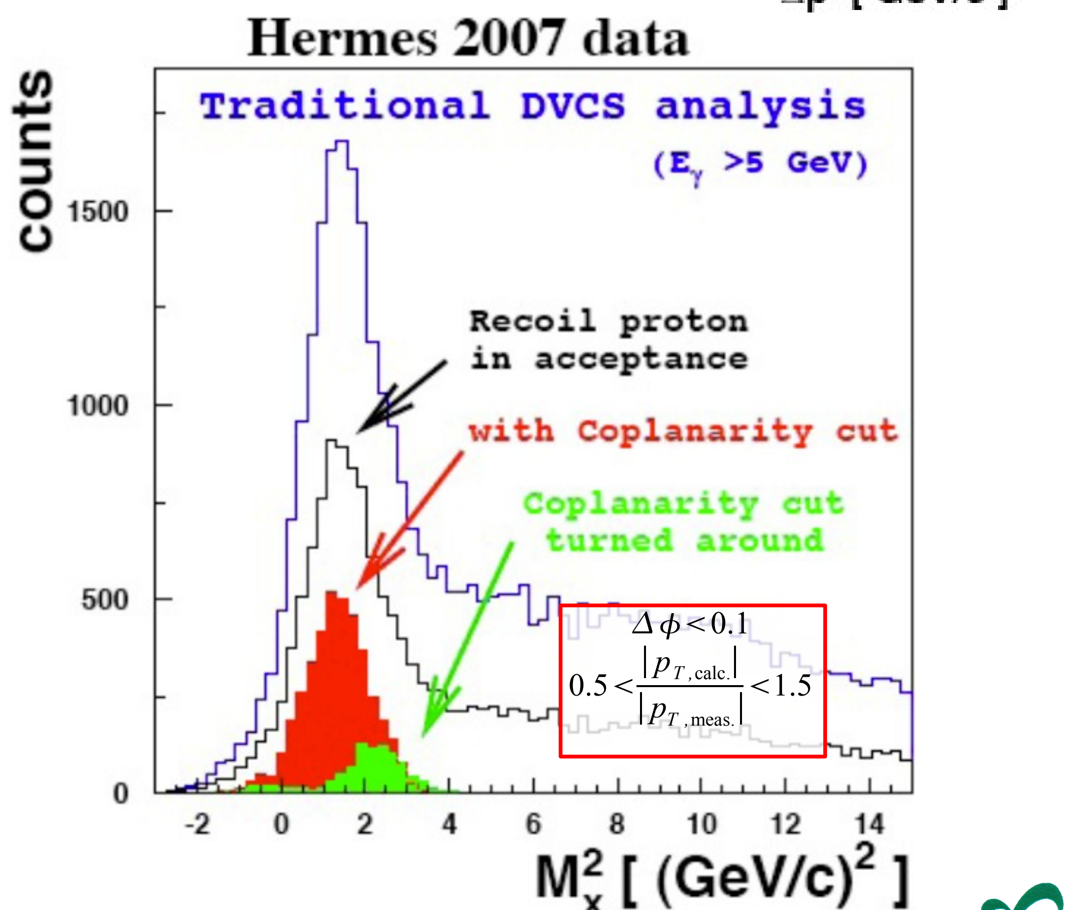
$$e + p \rightarrow p' + e' + \gamma$$

$$\Delta p = p_{\text{meas.}} - p_{\text{calc.}}$$

$$\Delta \phi = \phi_{\text{meas.}} - \phi_{\text{calc.}}$$



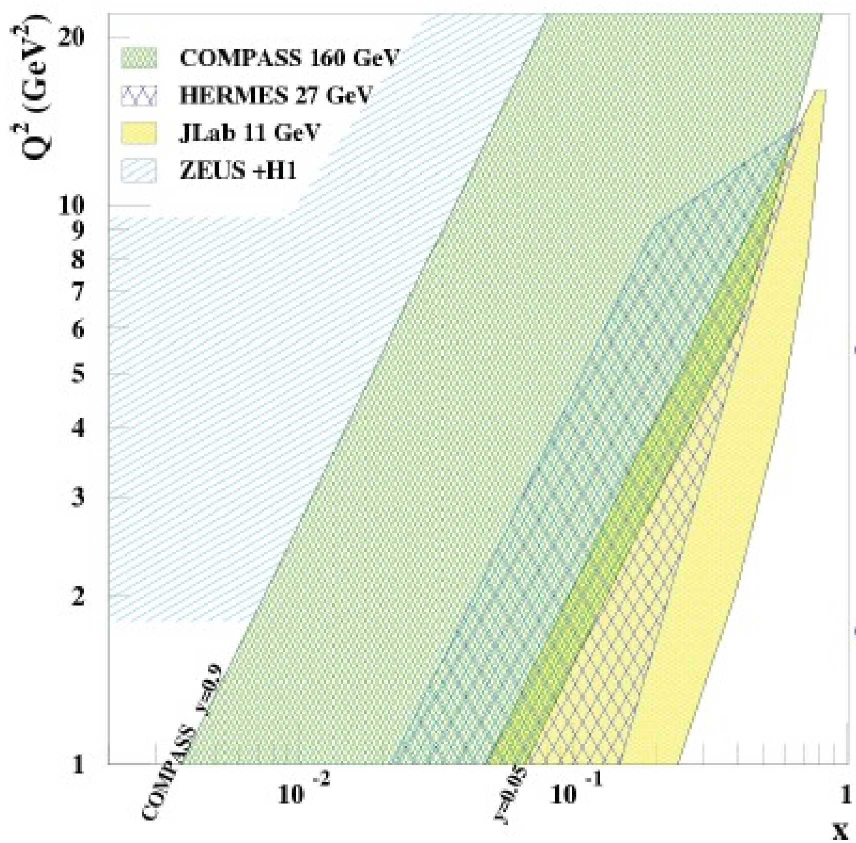




DVCS@COMPASS

2013-2014 COMPASS-II DVCS

What Makes COMPASS Unique?



CERN high energy muon beam

- 100 - 190 GeV
- 80% polarization
- μ^+ and μ^- beams with opposite polarization

- Uncovered region between ZEUS+H1 and HERMES+Jlab before new colliders may be available

- low x_B: pure BH (useful for normalization)

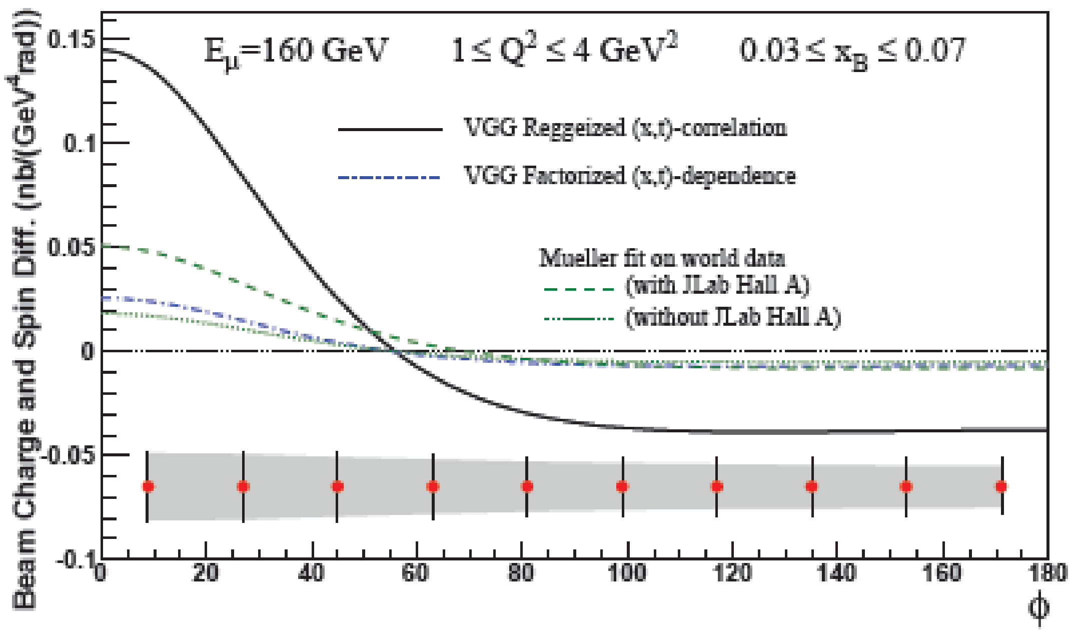
high x_B: DVCS predominance

SPIN2010, A. Ferrero

Angular Dependence of $d\sigma$

$$d\sigma_{\mu p \to \mu p \gamma} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVCS}_{pol} + e_\mu \mathrm{Re}(I) + e_\mu P_\mu \mathrm{Im}(I)$$

Combine μ^+ and μ^- data with opposite beam polarizations



$$\mathcal{D}_{CS,U} \equiv d\sigma^{\mu^{+\downarrow}} - d\sigma^{\mu^{-\uparrow}} \propto c_0^{Int} + c_1^{Int}\cos(\phi)$$

$$c^{Int}_{0,1} \propto \mathrm{Re}(F_1 \mathcal{H})$$

Red points: COMPASS Projected

- 2 years of data
- eff = 10%
- lumi = $1222 pb^{-1}$

$\mathrm{Re}\mathcal{H}(\xi, t) = P \int dx\, H(x, \xi, t)/(x - \xi)$ → **Exp. constrain to GPD H!**

Syst. error: 3% charge-dependent effect between μ^+ and μ^-

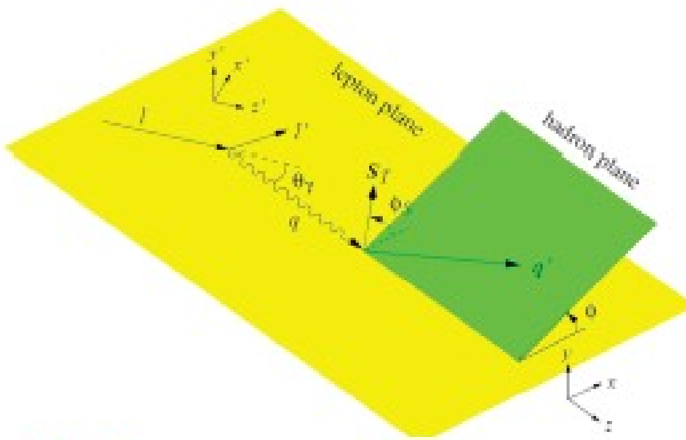
DVMP with Transversely Pol. Target

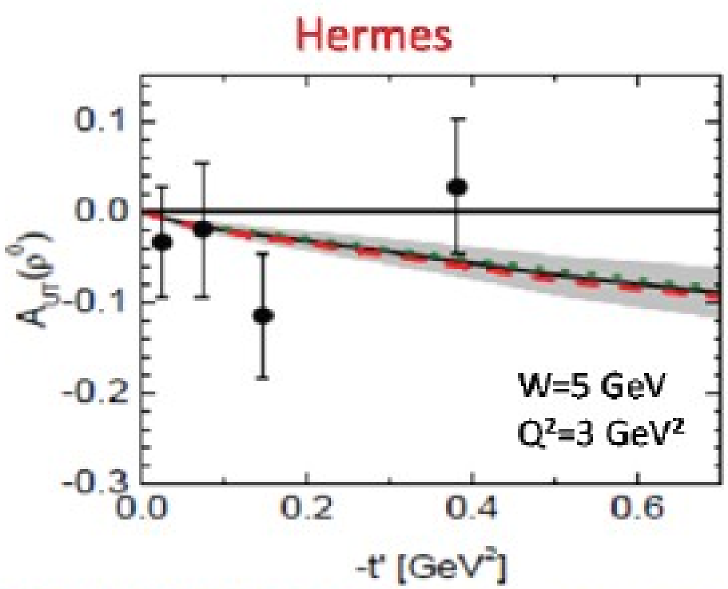
- **Cross-section measurement:**

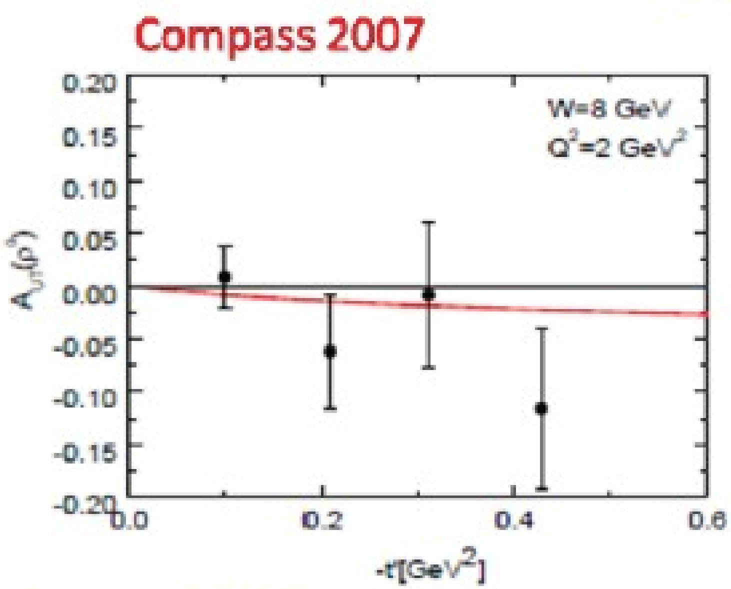
  Vector meson production $(\rho,\ \omega,\ \phi) \rightarrow \mathbf{H},\ \mathbf{E}$
  Pseudo-scalar production $(\pi,\ \eta,\ \ldots) \rightarrow \tilde{\mathbf{H}},\ \tilde{\mathbf{E}}$

- **Tranverse target spin asymmetry $A_{UT}^{\sin(\phi-\phi_S)}$**

$$A_{UT}(\rho^0) \propto \sqrt{|-t'|}\mathrm{Im}(\mathcal{E} * \mathcal{H})/|\mathcal{H}|^2$$







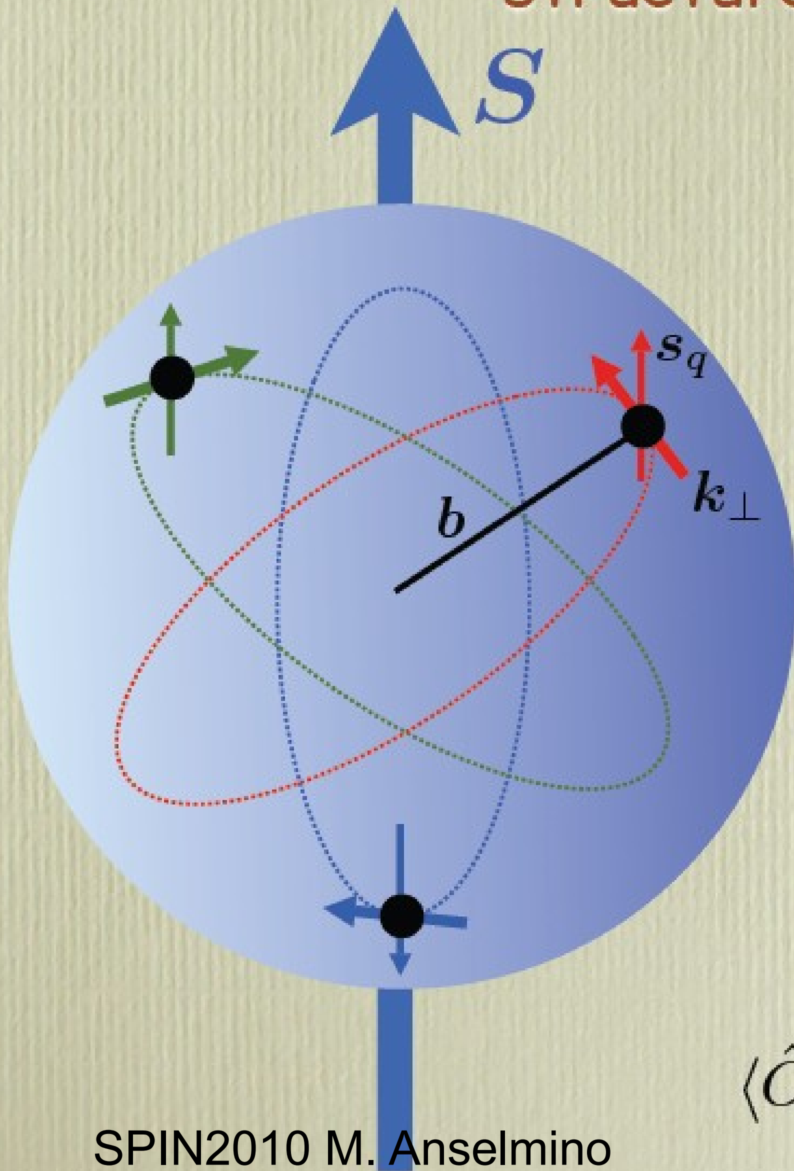
COMPASS data: transversely polarized proton target

SPIN2010, A. Ferrero

なーんとなく見えてきたけど、
もうちょっとはっきりみえんかなぁ？

強くあてる？
たくさんあてる？
飛ばされたものをよーくみる？
自独楽かえる？

mission: exploring the 3-dimensional phase-space structure of the nucleon



intrinsic motion
spin-$k_\perp$ correlations?
orbiting quarks?

Ideally: obtain a quantum phase-space distribution (like the Wigner function)

in 1-dimensional QM:

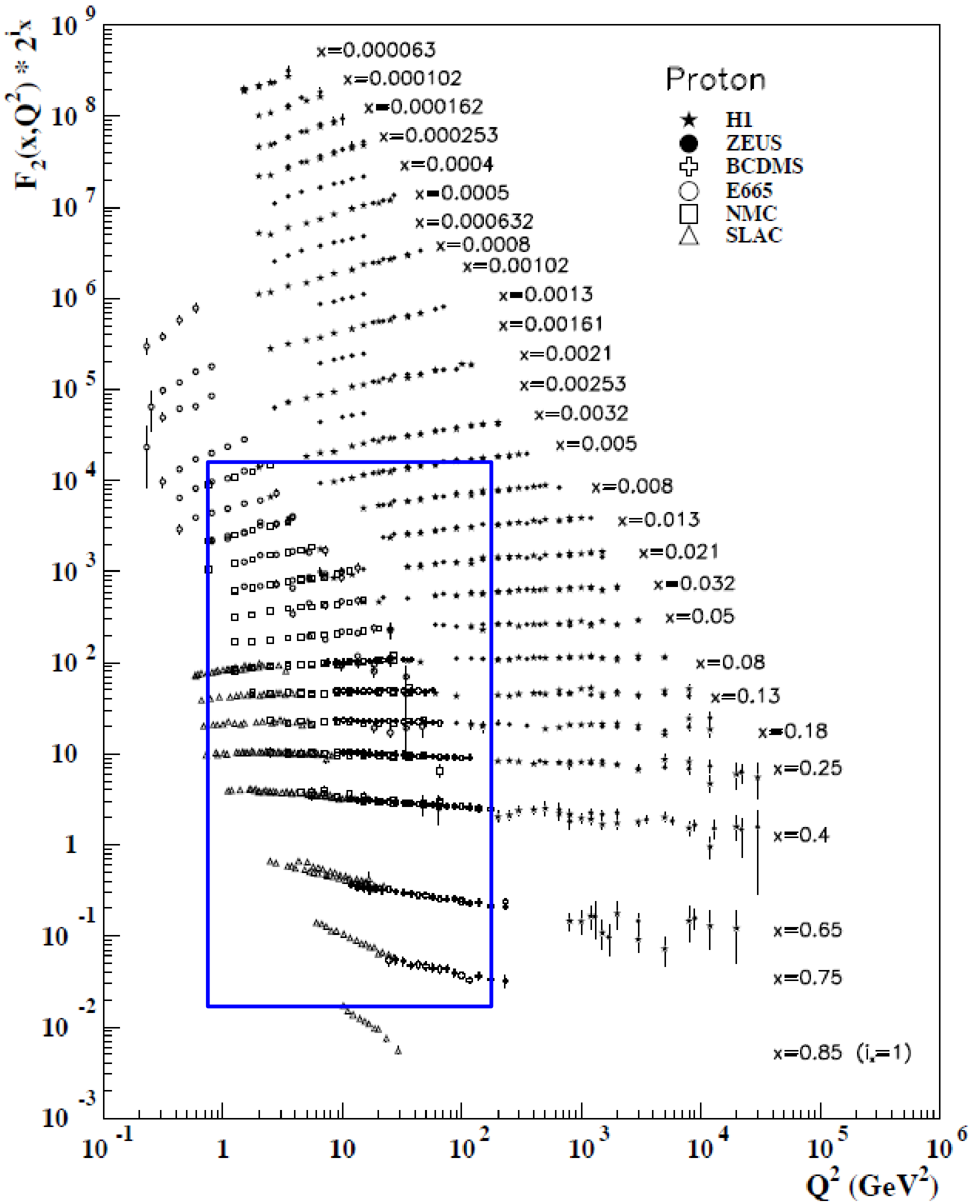
$$\int dp\, W(x,p) = |\psi(x)|^2$$

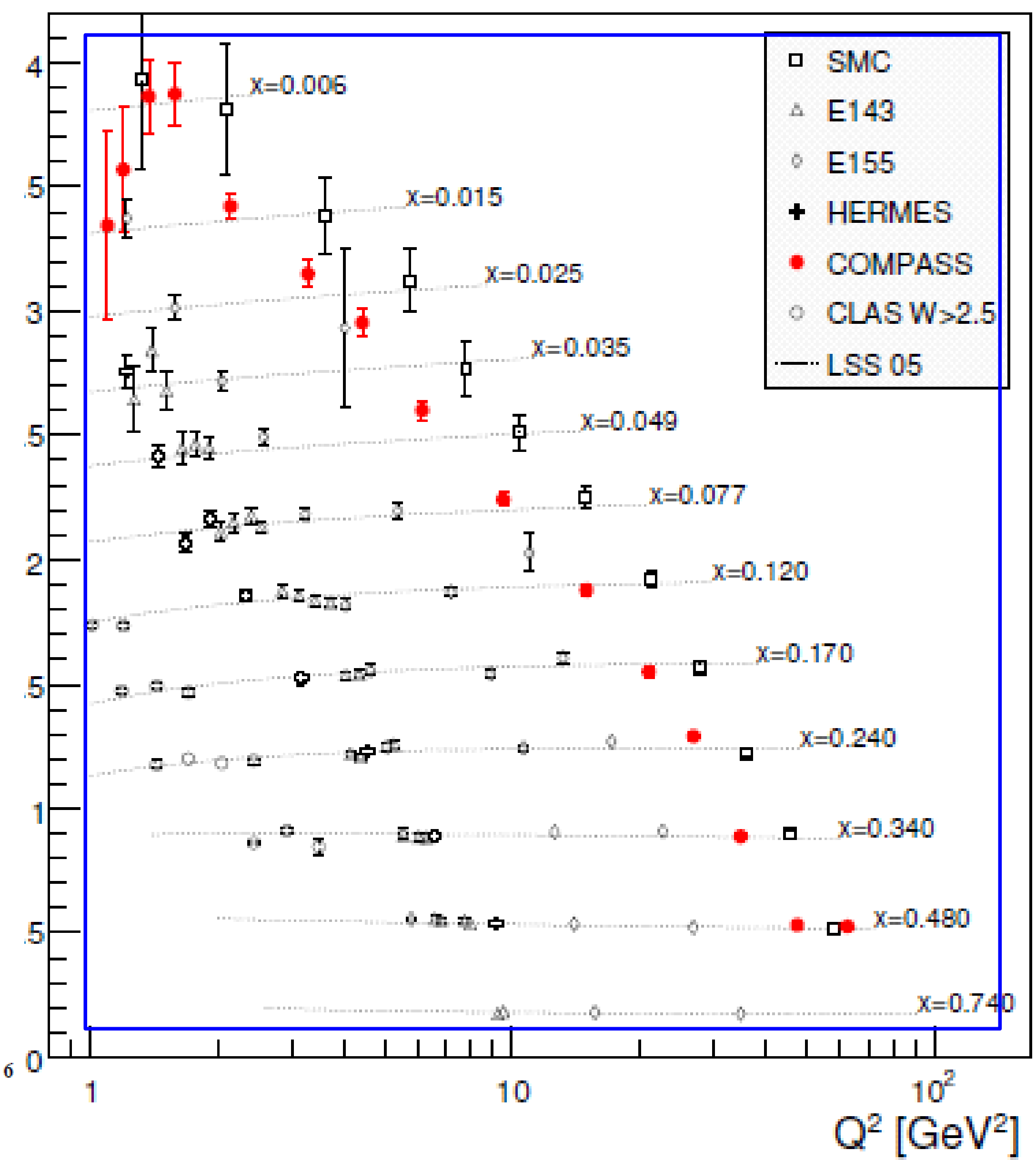
$$\int dx\, W(x,p) = |\phi(p)|^2$$

$$\langle \hat{O}(x,p) \rangle = \int dx\, dp\, W(x,p)\, O(x,p)$$

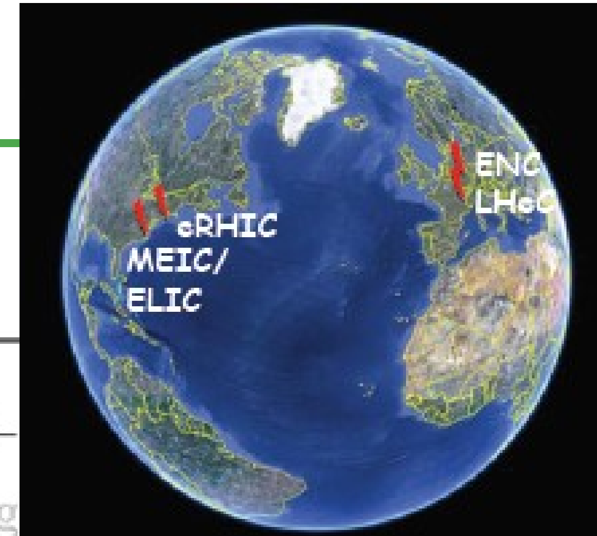
SPIN2010 M. Anselmino

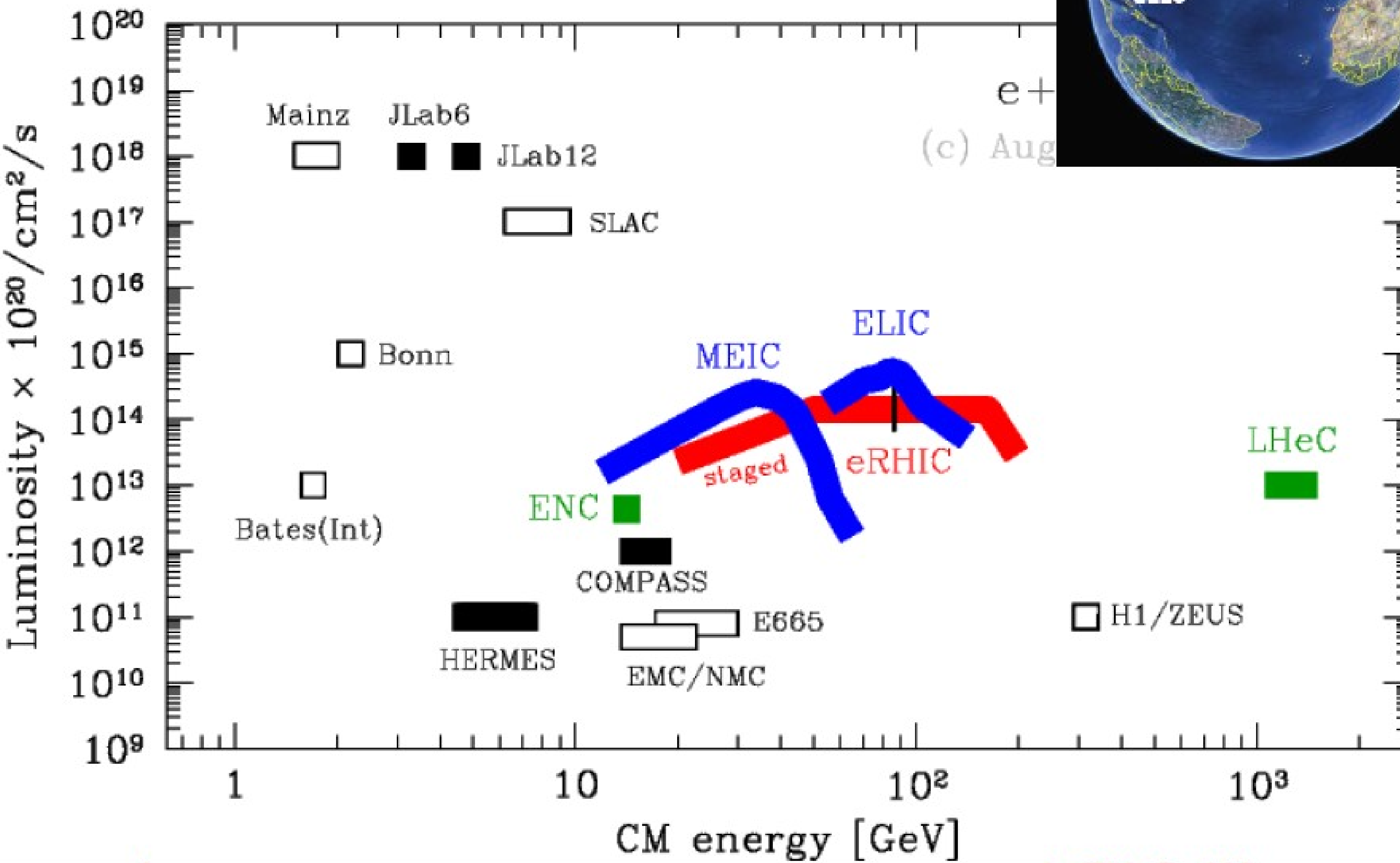
非偏極との比較： 運動学的領域





LHeC, EIC, ENC, ...


ENC
LHeC
eRHIC
MEIC/
ELIC


Luminosity × 10²⁰/cm²/s
CM energy [GeV]
e+
(c) Aug
Mainz
JLab6
JLab12
SLAC
Bonn
Bates(Int)
ENC
COMPASS
HERMES
E665
EMC/NMC
MEIC
ELIC
staged
eRHIC
LHeC
H1/ZEUS

まとめ

- 核子構造
  - パートン: 数密度 → スピン → 3次元構造
  - パートン分布関数
    - → 横運動量依存パートン分布関数 TMD
    - → 一般化されたパートン分布関数 GPD
- レプトン深非弾性散乱実験:「運動学的に明確な実験」
  - 固定標的 → 衝突実験
  - 偏極 → 非偏極 → ダブルスピン非対称度 → SSA
  - 包括測定 → ハドロン同時測定 → Exclusive 生成
  - 散乱角依存性 → 方位角依存性
- 陽子スピンの問題: 陽子の(スピン)内部構造
  - より複雑に、でも光明はみえかけている?
  - → 偏極 ep 衝突実験