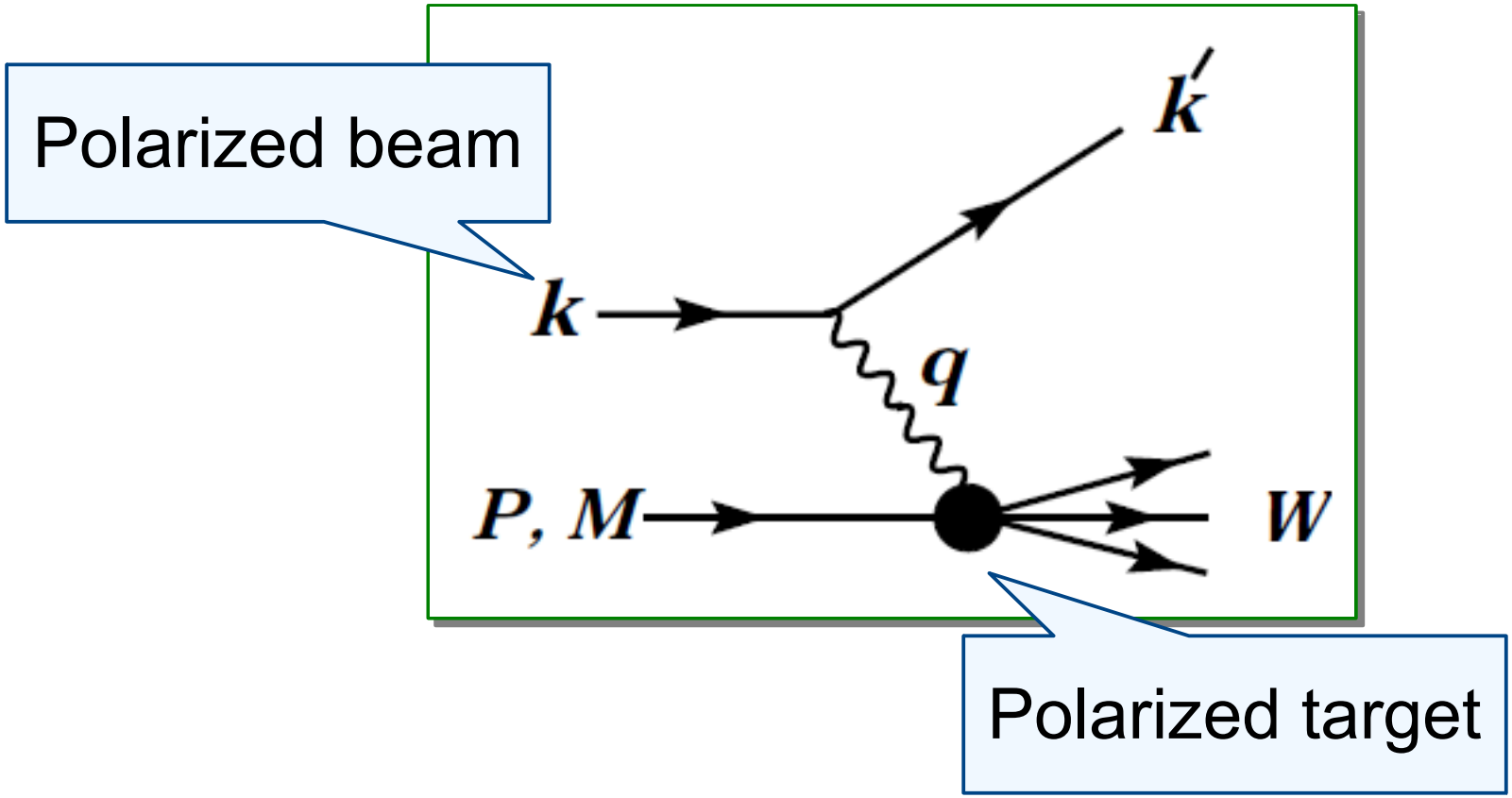
2. Spin structure of the proton in DIS



2. Spin structure of the proton in DIS

- Polarized Deep Inelastic Scattering
- Spin structure of the proton
- Semi-inclusive DIS
  - Flavor tagging
- Spin-Flavor structure of the proton

Polarized DIS:

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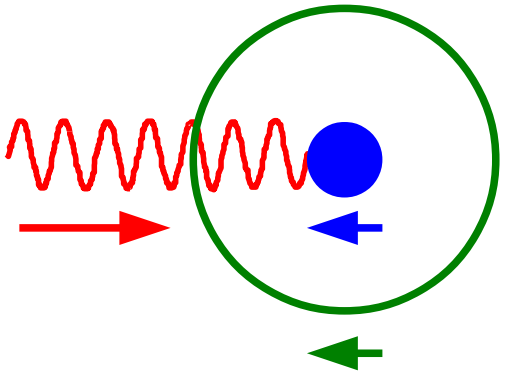
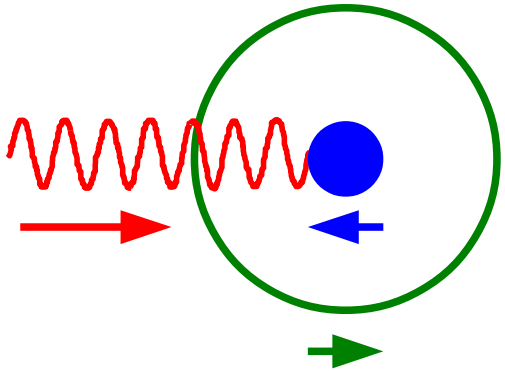
Polarized lepton beam

⇨ Polarized γ^*

⇨ Select quark spin

Polarized nucleon target





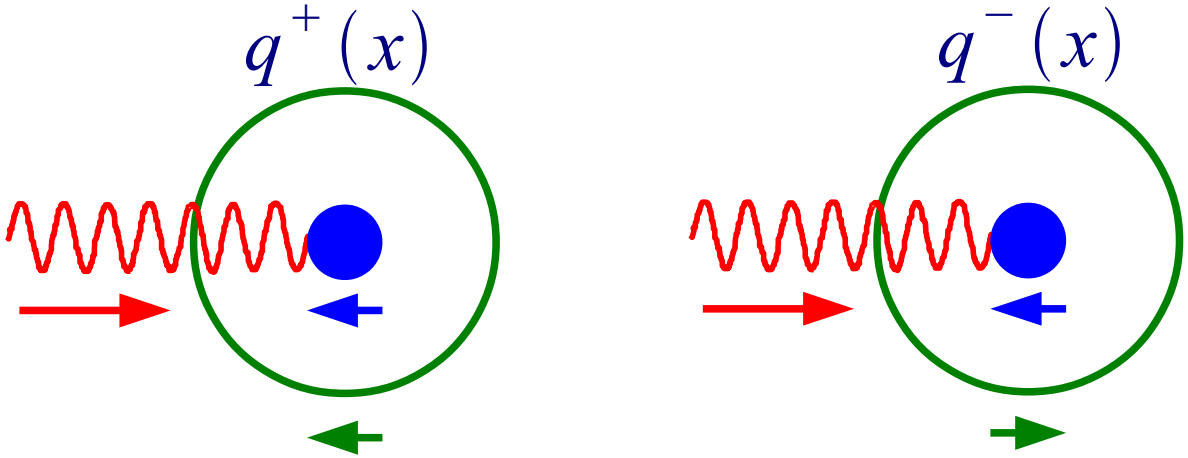
Parallel $q^+(x)$

Anti-parallel $q^-(x)$

Unpol. PDF $q(x)=q^+(x)+q^-(x)$

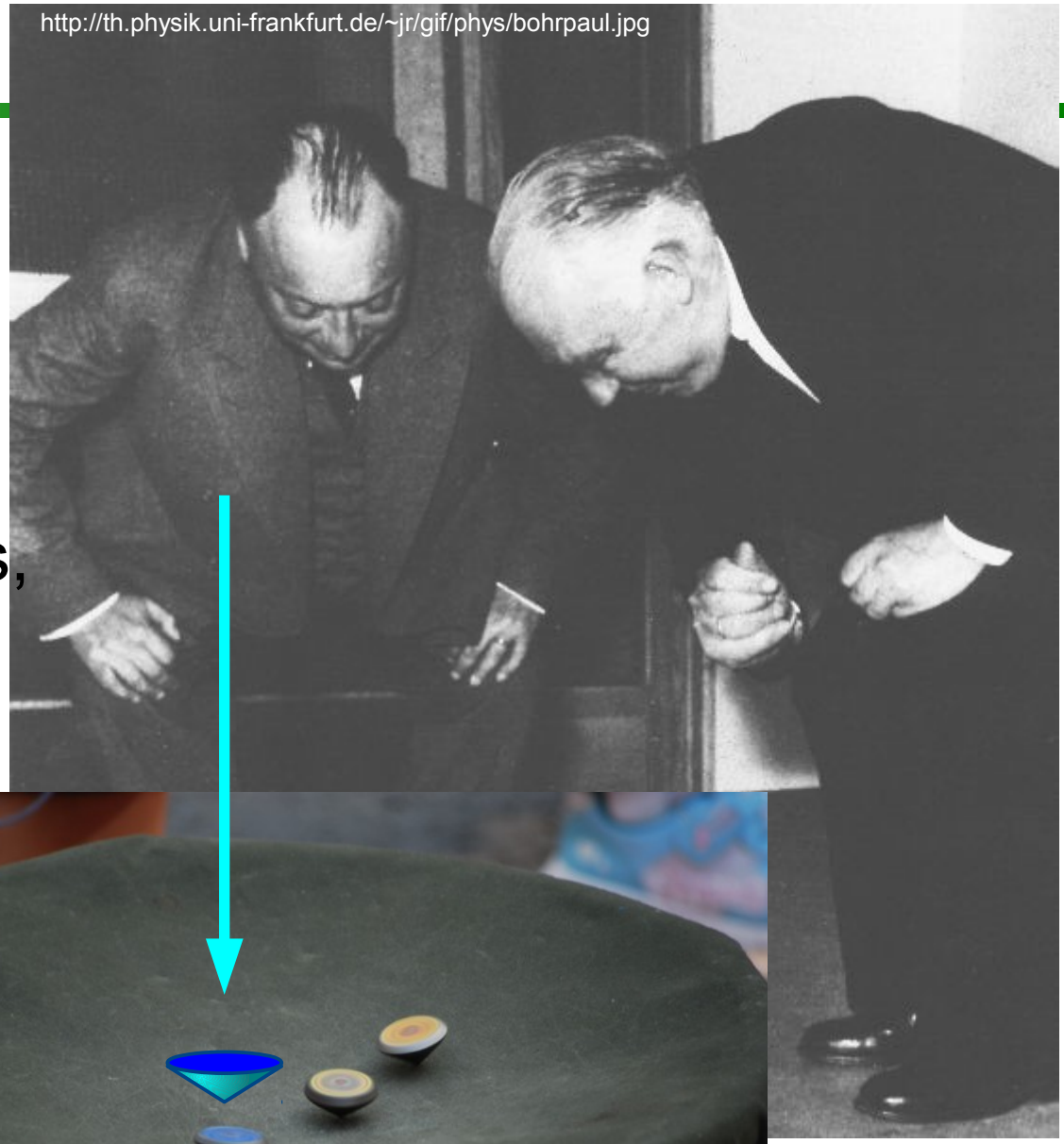
Unpol. Str. Func. $F_1(x)=\frac{1}{2}\sum_q e_q^2 q(x)$

Pol. DIS and Pol. PDF



	Structure function	PDF
Unpol.	$F_1(x)=\frac{1}{2}\sum_q e_q^2 q(x)$	$q(x)=q^+(x)+q^-(x)$
Pol.	$g_1(x)=\frac{1}{2}\sum_q e_q^2 \Delta q(x)$	$\Delta q(x)=q^+(x)-q^-(x)$

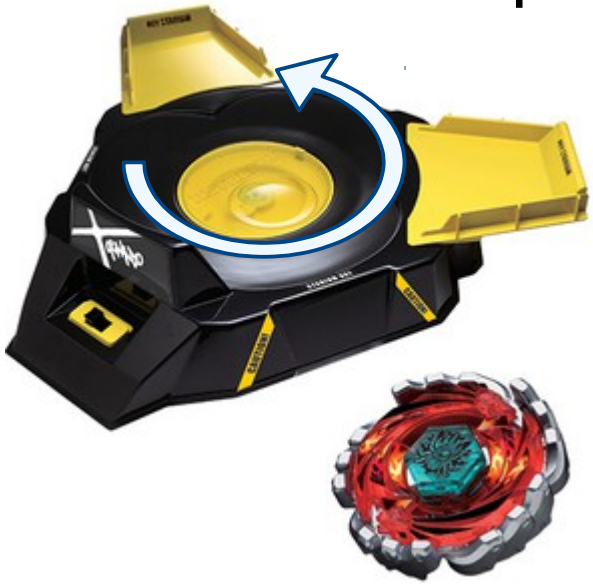
In Japan,
we have a game with tops,
called “be-goma”.



Try to kick the enemy's tops out.

To probe the elements,
let's hit with this top!

Now it becomes possible



CERN-EMC experiment

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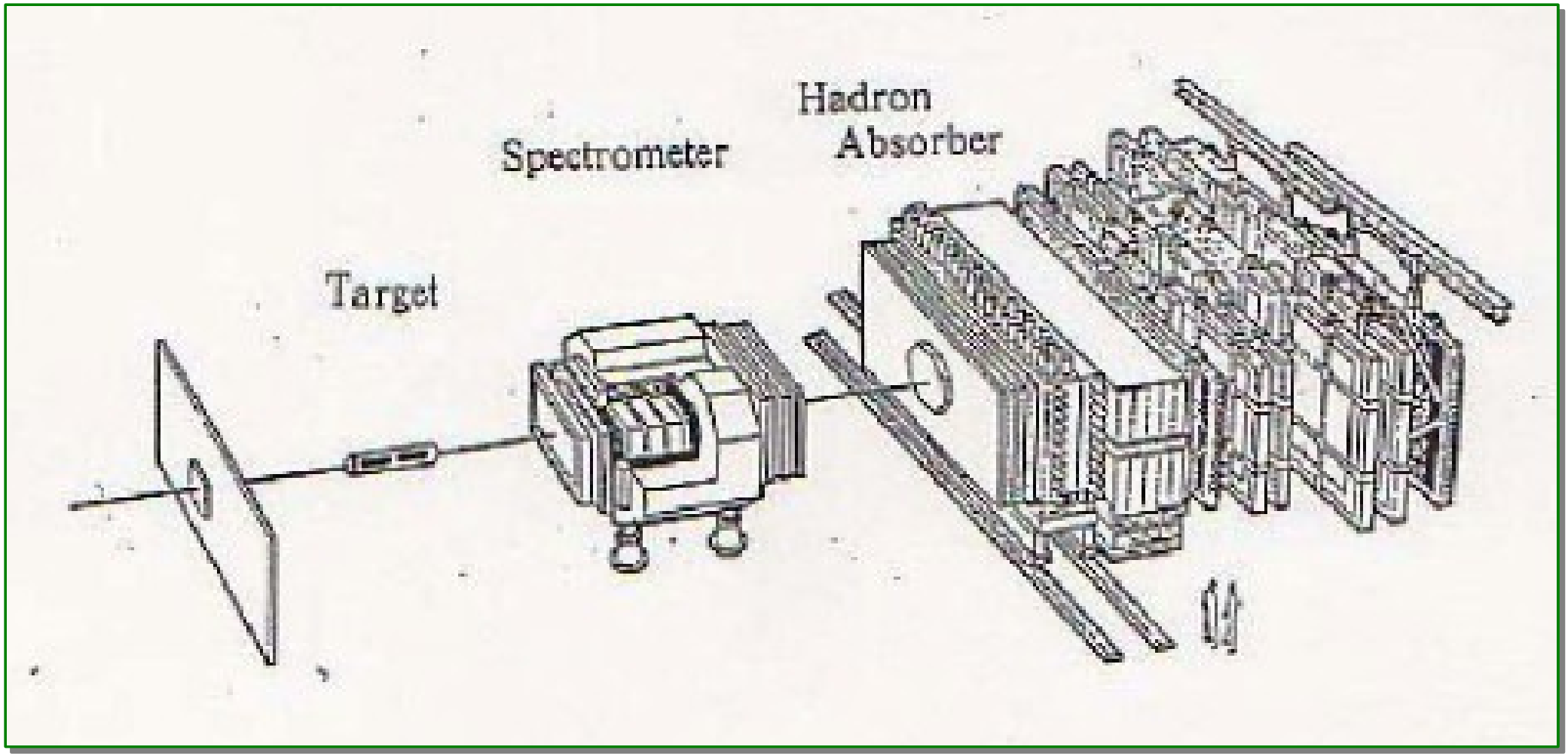

Spin problem

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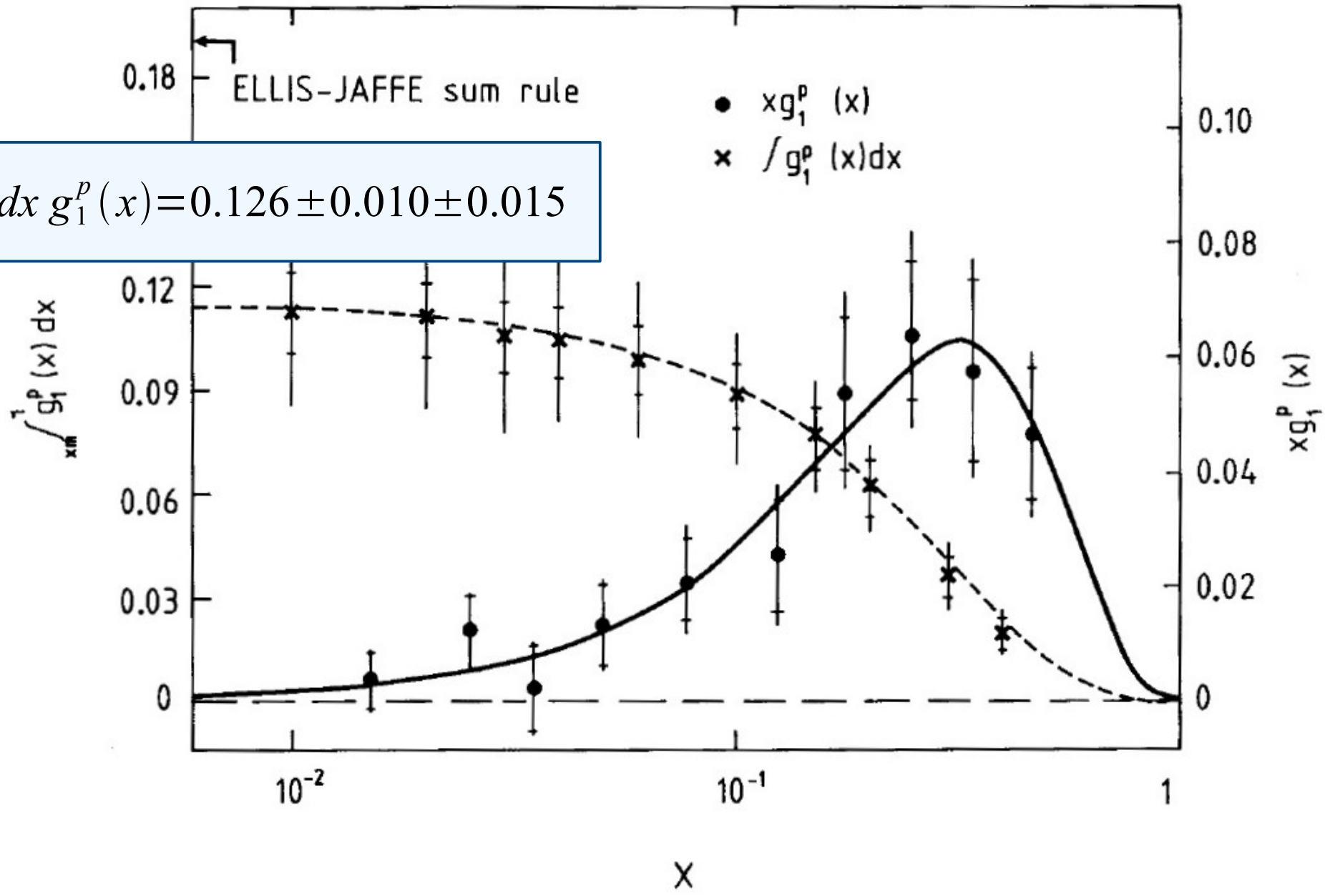
Nucl. Phys. B328 (1989) 1, Phys. Lett. B206 (1988) 364

$$\int_0^1 dx\, g_1^p(x) = 0.126 \pm 0.010 \pm 0.015$$



Spin problem

※ q + q-bar

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

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

$$= \frac{1}{9}a_0 + \frac{1}{12}a_3 + \frac{1}{36}a_8$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = a_0$$

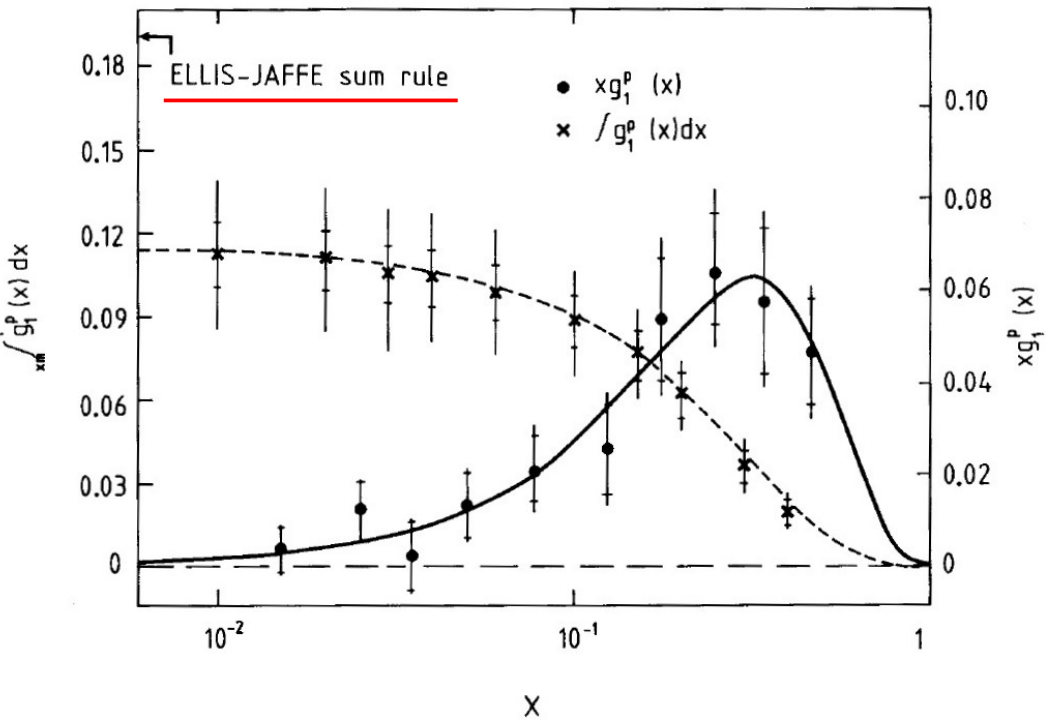
$$\Delta u - \Delta d = a_3$$

$$\Delta u + \Delta d - 2\Delta s = a_8$$

From weak decay:

$=1.26$

$=0.58$



If $\Delta s=0$, $a_0=a_8=0.58$

$$\int_0^1 dx\, g_1^p(x) = 0.186$$

Ellis-Jaffe Sum Rule

$$\int_0^1 dx\, g_1^p(x) = 0.126 \pm 0.010 \pm 0.015$$

Spin problem

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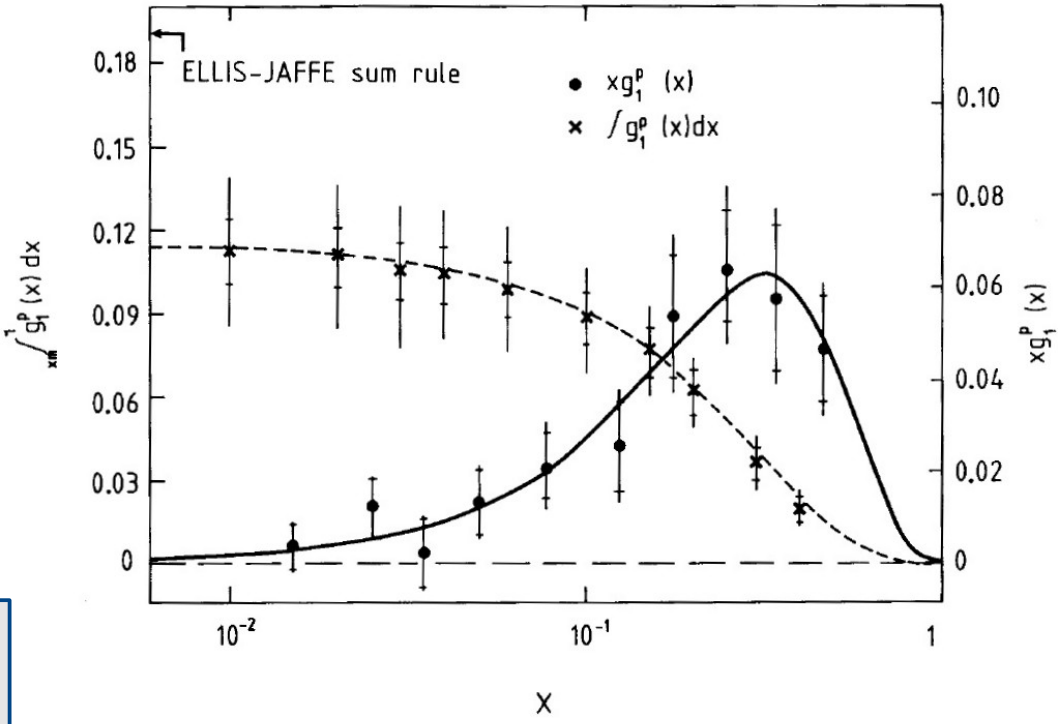
$$\int_0^1 dx\, g_1^p(x) = 0.126 \pm 0.010 \pm 0.015$$

$$= \frac{1}{9}\Delta\Sigma + \frac{1}{12}a_3 + \frac{1}{36}a_8$$

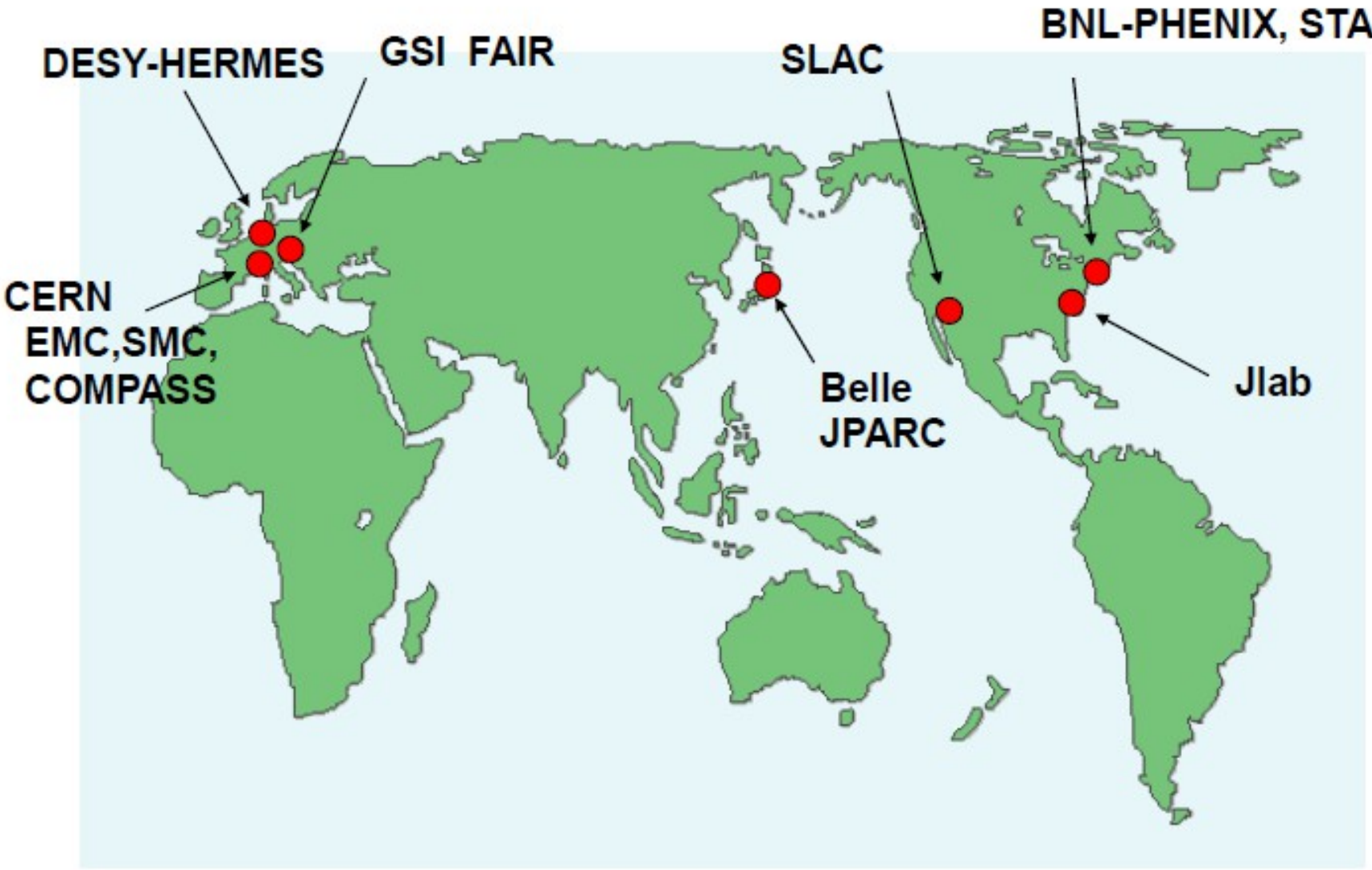
From weak decay:

$a_3 = 1.26$

$a_8 = 0.58$



$$\Delta\Sigma = 0.120 \pm 0.094 \pm 0.138$$



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

Polarized DIS experiment

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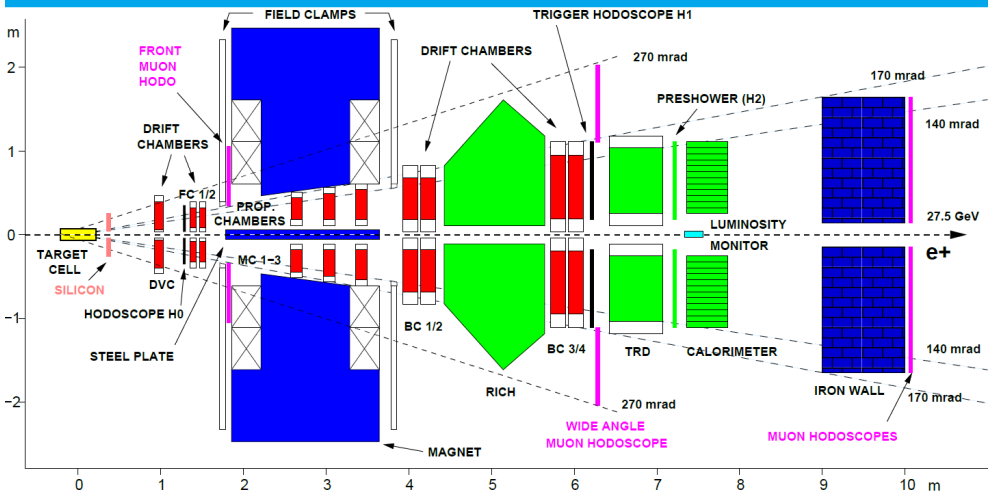
The HERMES spectrometer



Internal gas targets:
- Longitudinally polarized *H, D*
- Transversely polarized *H*
- Unpolarized *H, D, ^{4}He, N, Ne, Kr, Xe*

Forward magnetic spectrometer
- Momentum resolution *1-2%*
- Particle identification:
  RICH, TRD, H2, calorimeter

hermes

S. Yaschenko, Overview of recent HERMES results 4

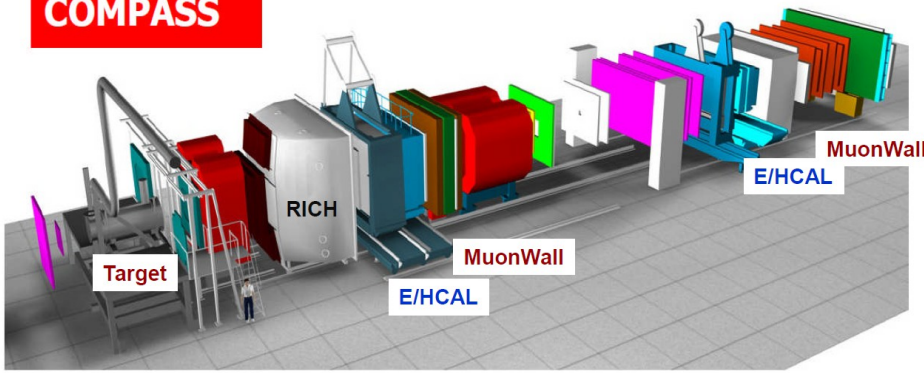
DESY

COMPASS

COMPASS spin

- high energy beam
- large angular acceptance
- broad kinematical range

two stages spectrometer
- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)



variety of tracking detectors
to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad

SciFi	Straws
Silicon	SDC
Micromegas	MWPC
GEMs	W45

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

+ JLab experiments

Polarized structure function

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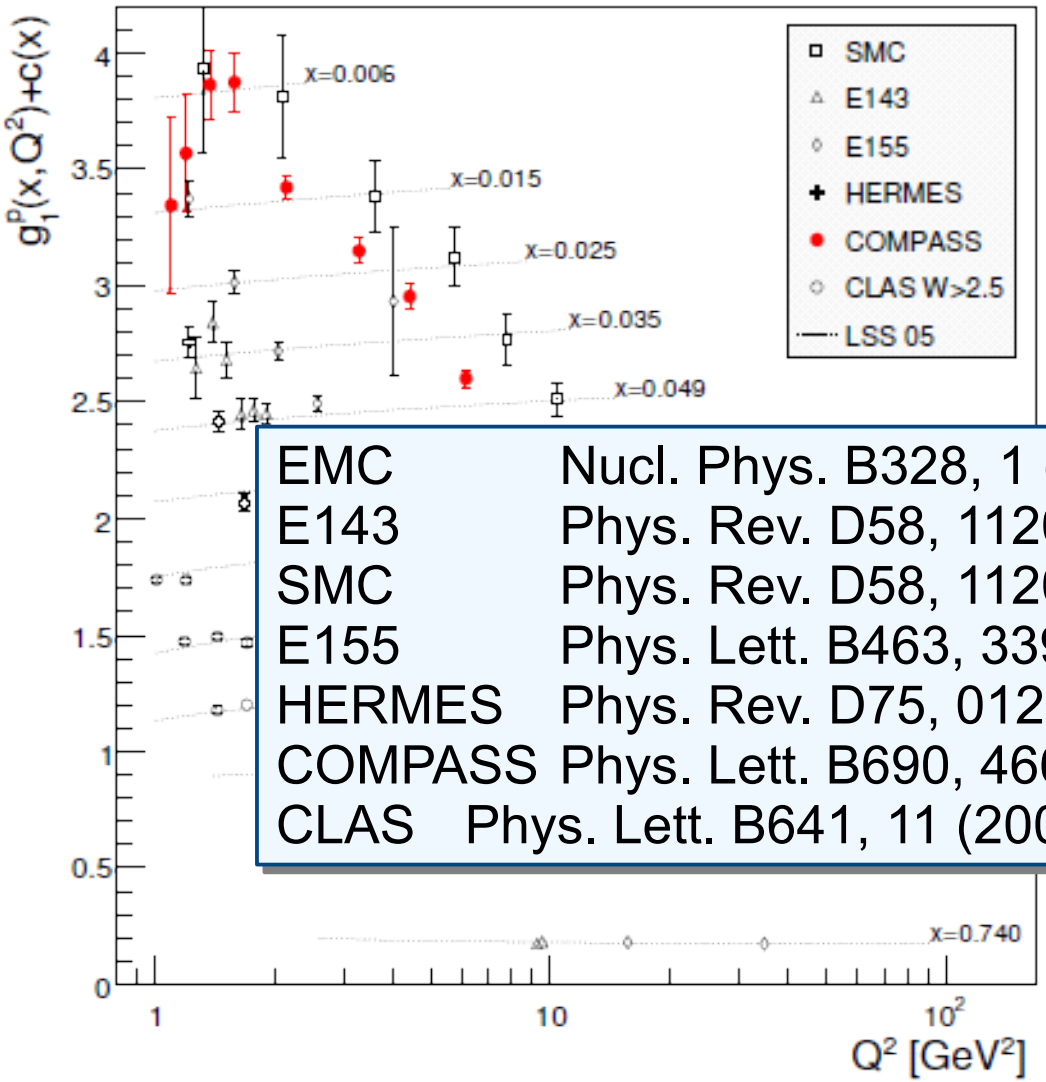
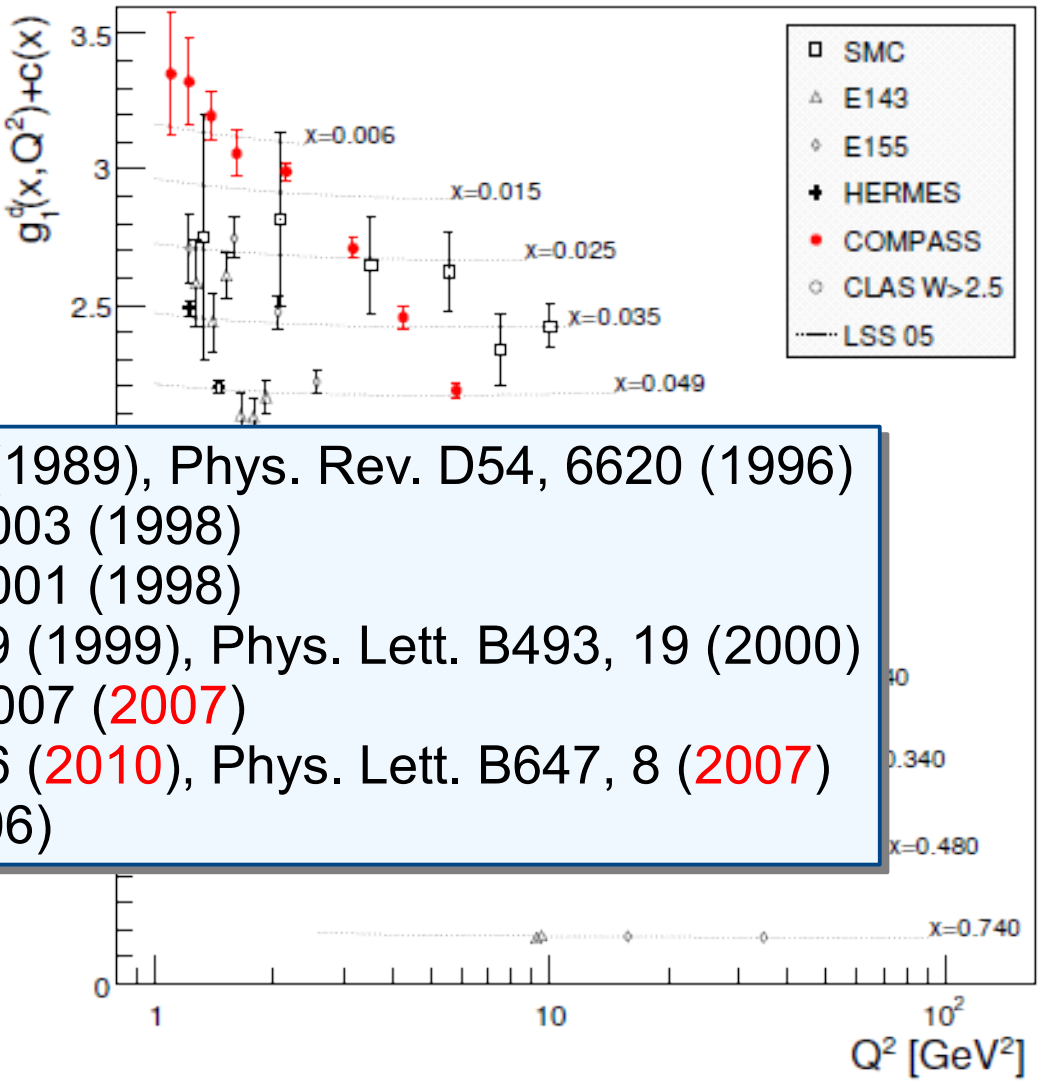
Proton

Deuteron





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)

Polarized structure function

V. Andrieux, DIS2013

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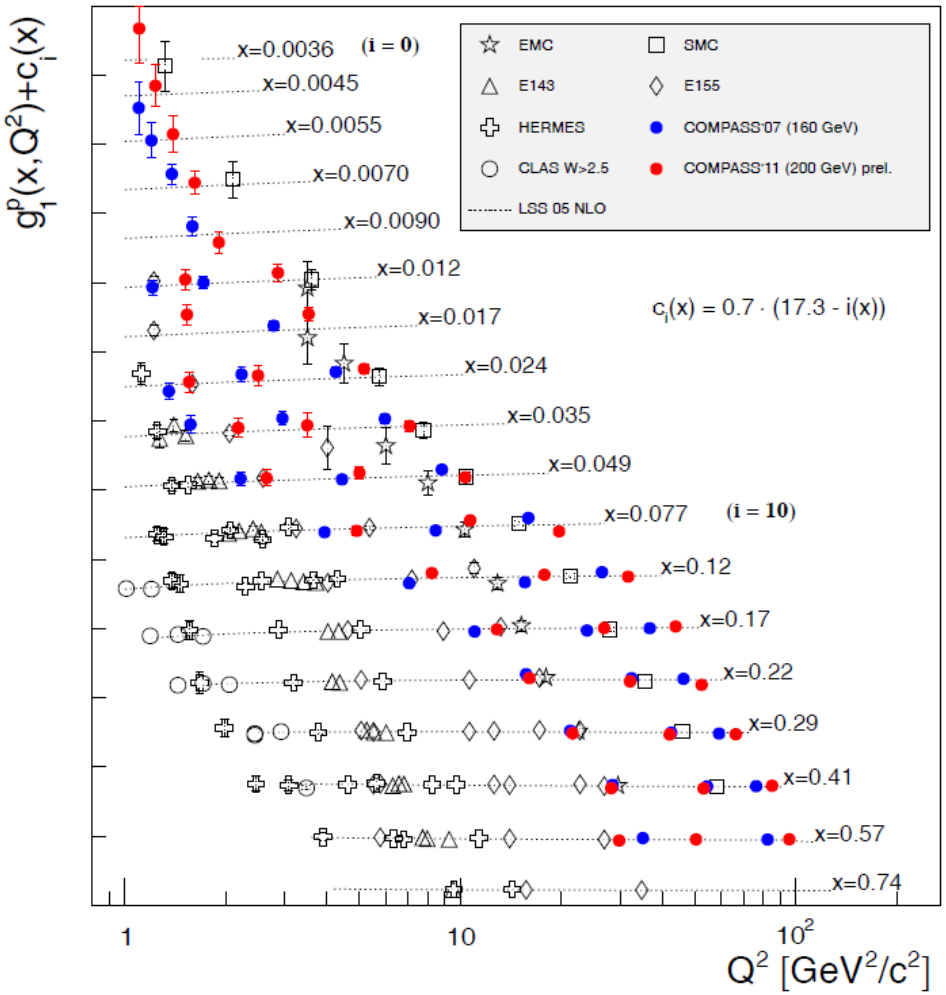
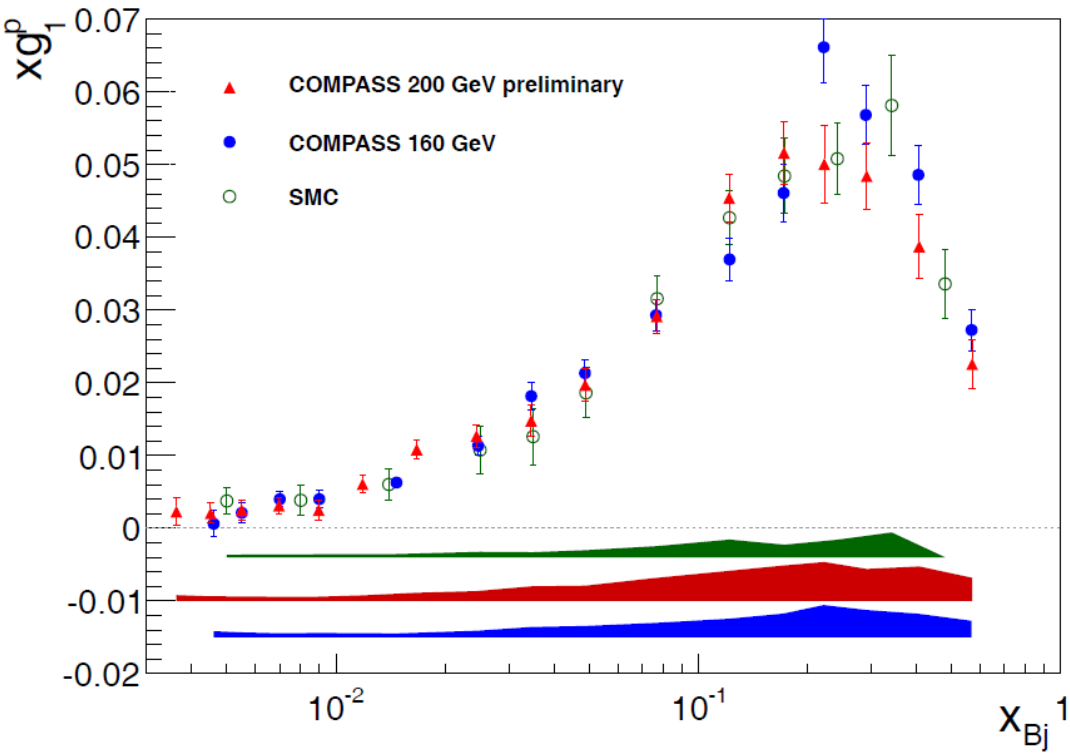
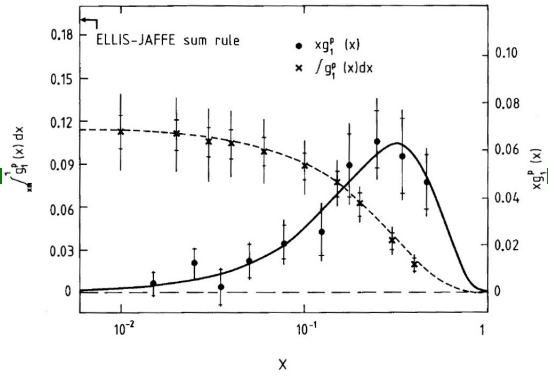
Years	Target	Beam Energy
2002-2006	^{6}LiD	160 GeV
2007	NH_3	160 GeV
2011	NH_3	200 GeV



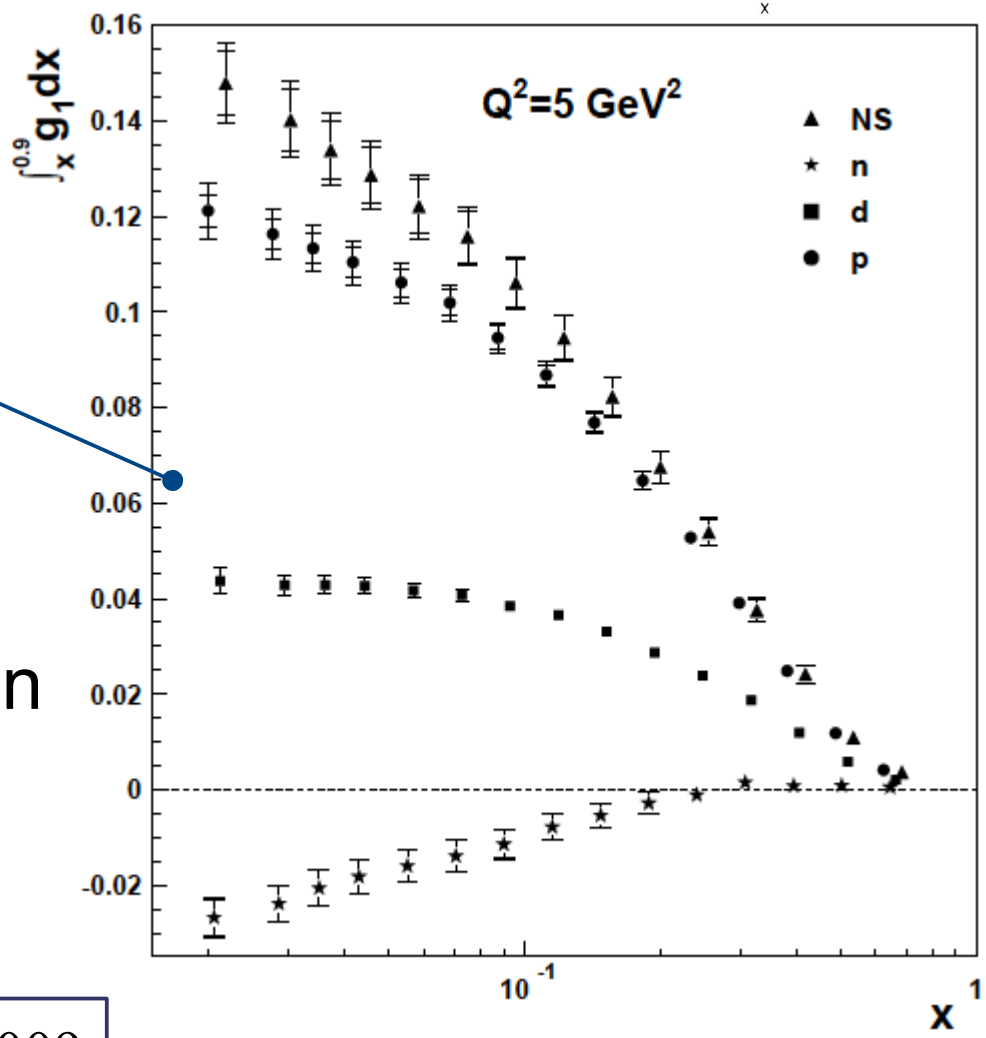


Strange quark: Δs



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:

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

Spin Puzzle

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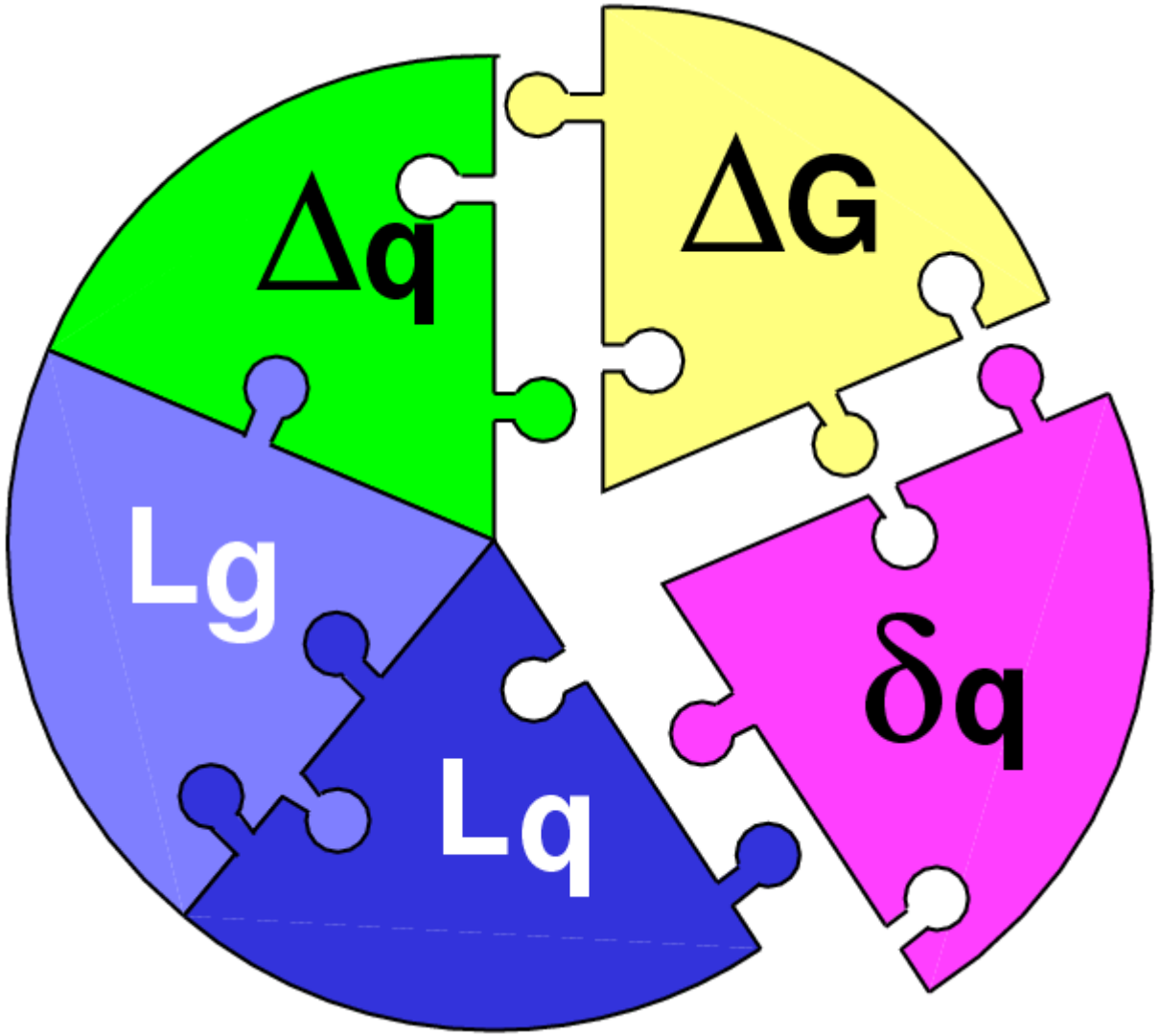
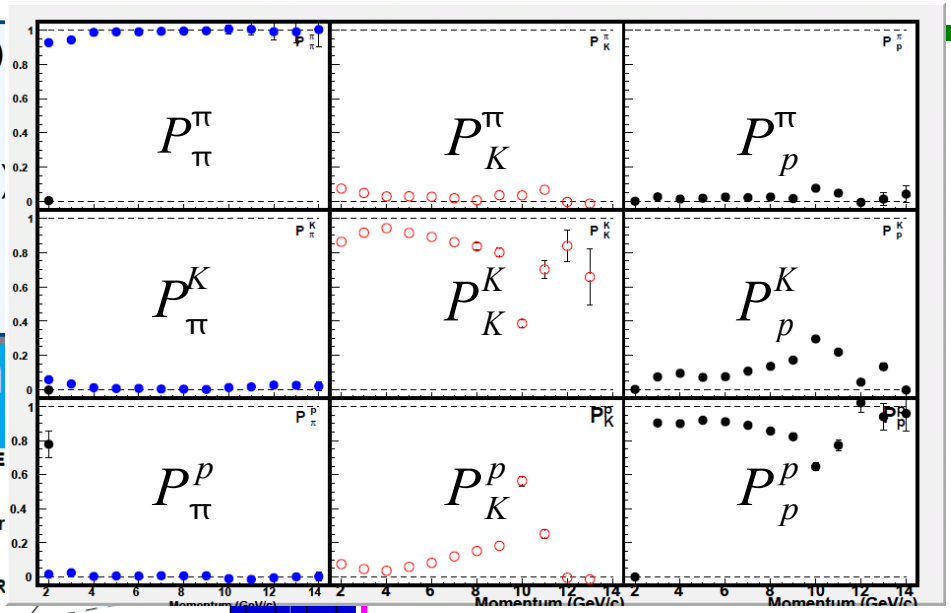
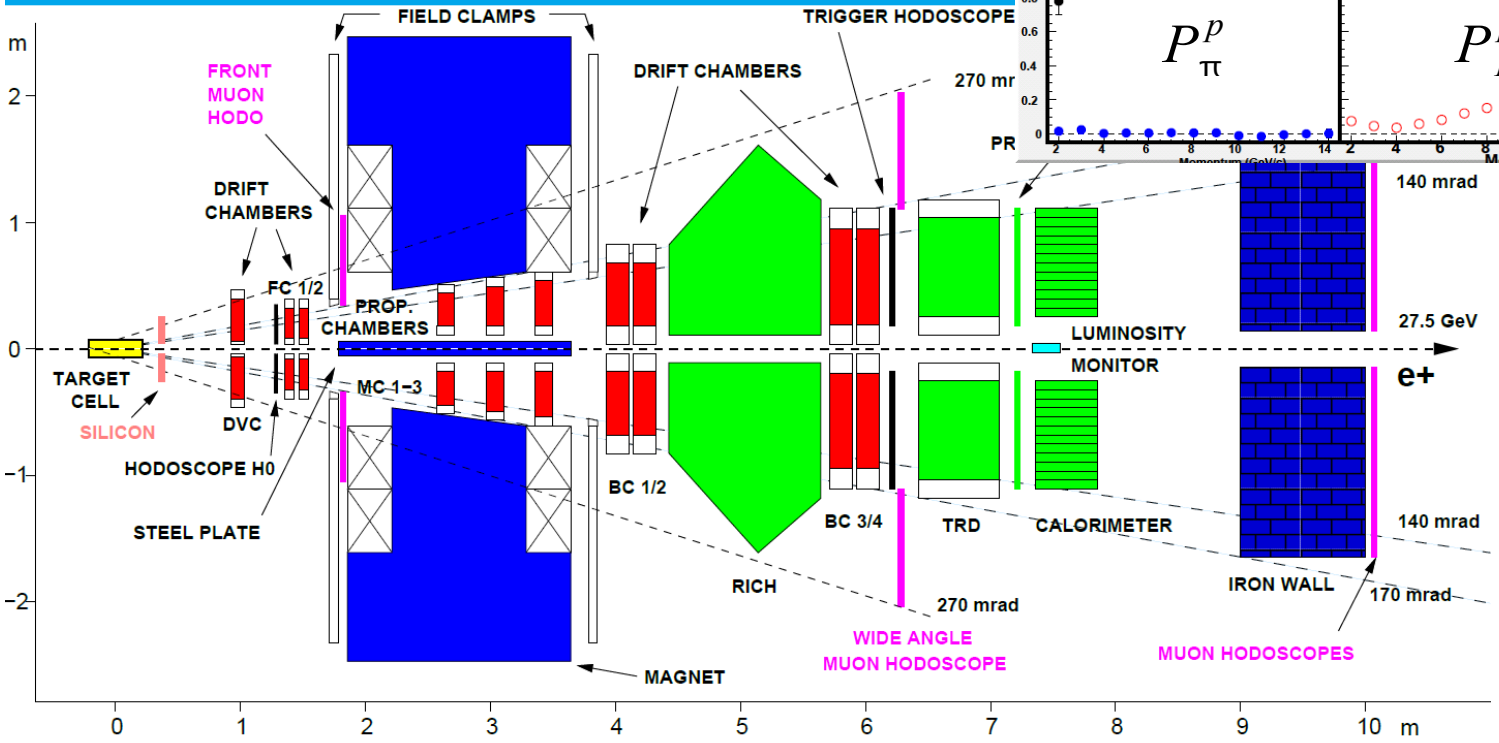


DIS 2nd generation, Semi-Inclusive measurement

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)



The HERMES spectrom

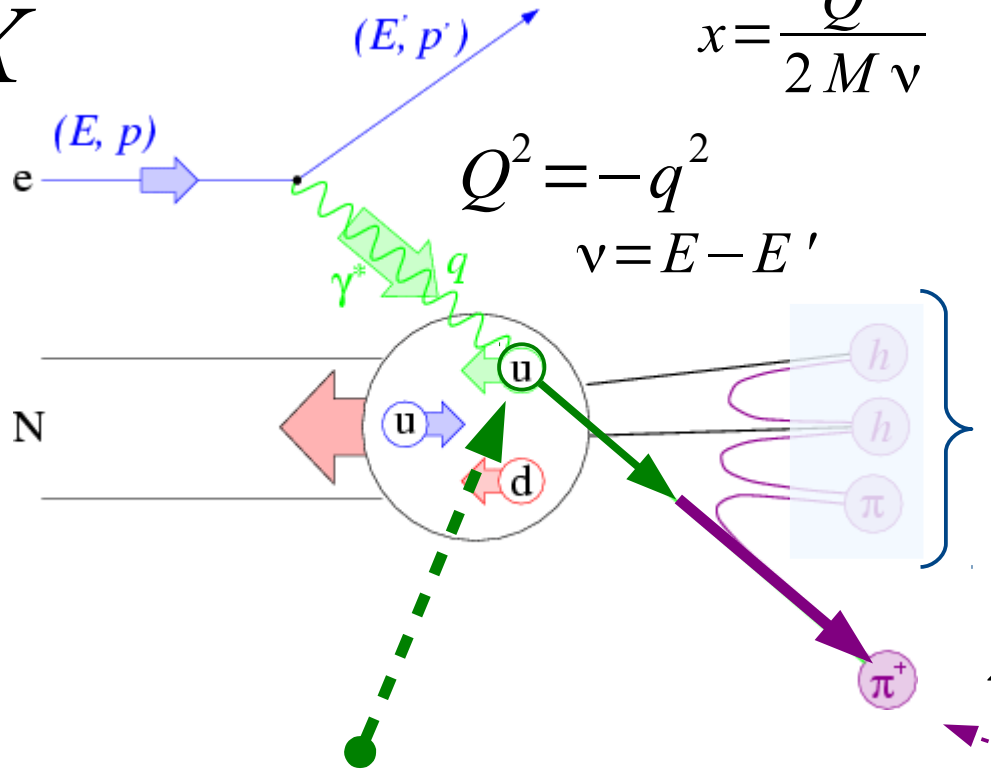


Internal gas targets:
- Longitudinally polarized *H, D*
- Transversely polarized *H*
- Unpolarized *H, D, ^{4}He, N, Ne, Kr, Xe*

Forward magnetic spectrometer
- Momentum resolution *1-2%*
- Particle identification: *RICH, TRD, H2, calorimeter*

Semi-inclusive measurement of DIS

$$e\,N \rightarrow e'\,h\,X$$



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

$$Q^2 = -q^2$$

$$\nu = E - E'$$

$$z = \frac{E_h}{\nu}$$

$$\sigma^{e\,N \rightarrow e'\,h\,X} = \sum_{q} f^{N \rightarrow q} \otimes \hat{\sigma}^{e\,q \rightarrow e'\,q} \otimes D^{q \rightarrow h}$$

Parton Distribution Function

$$f\left(x, Q^2\right)$$

Fragmentation Function

$$D\left(z, Q^2\right)$$

Example: HERMES experiment

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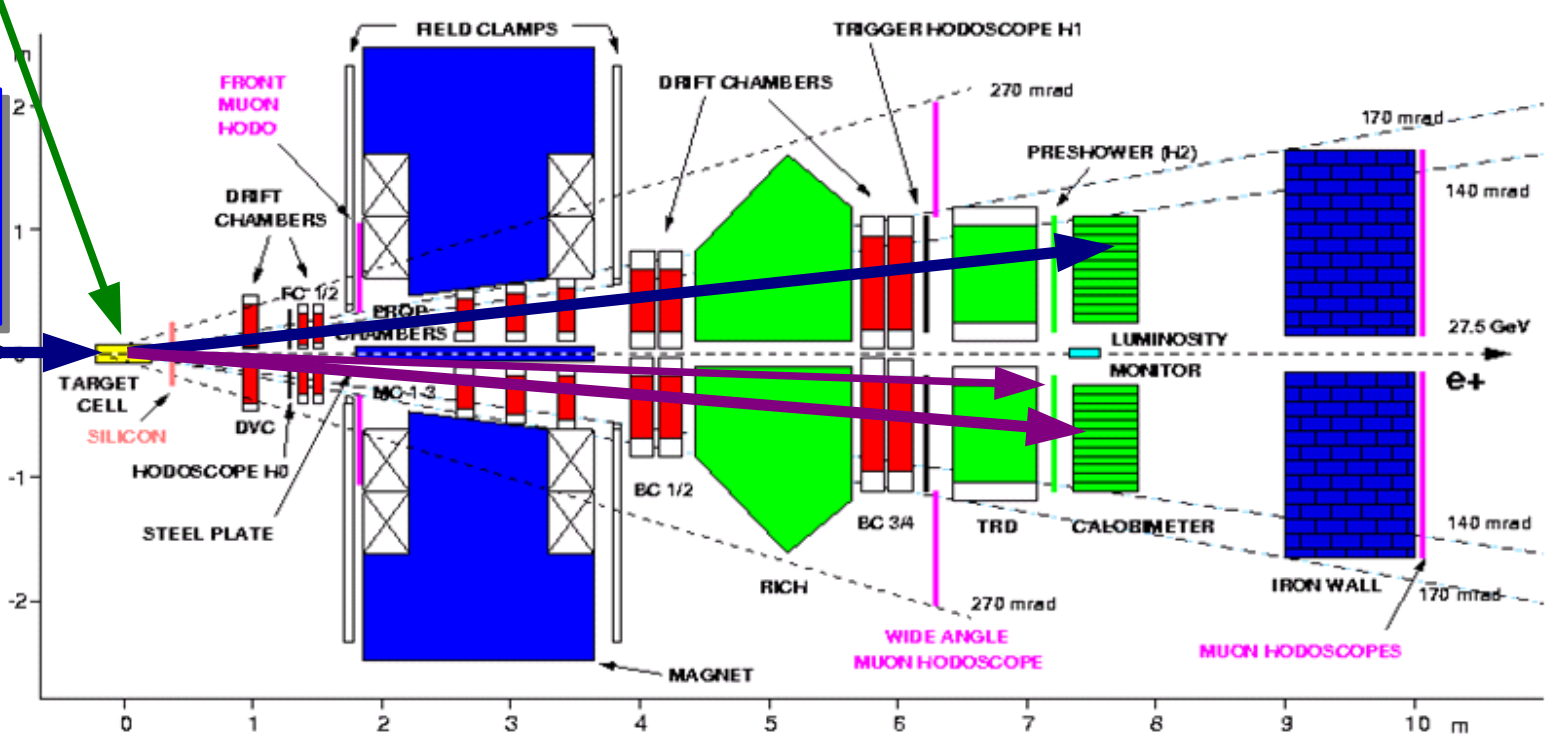
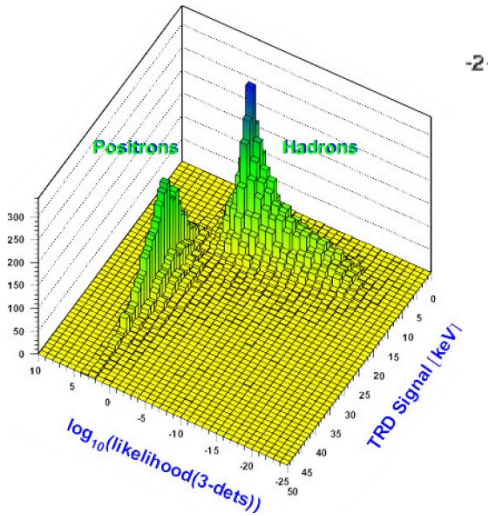
Targets: Unpolarized H, D, nuclei
Longitudinally polarized H, D (P ~ 85 %)
Transversely polarized H (P ~ 75%)

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

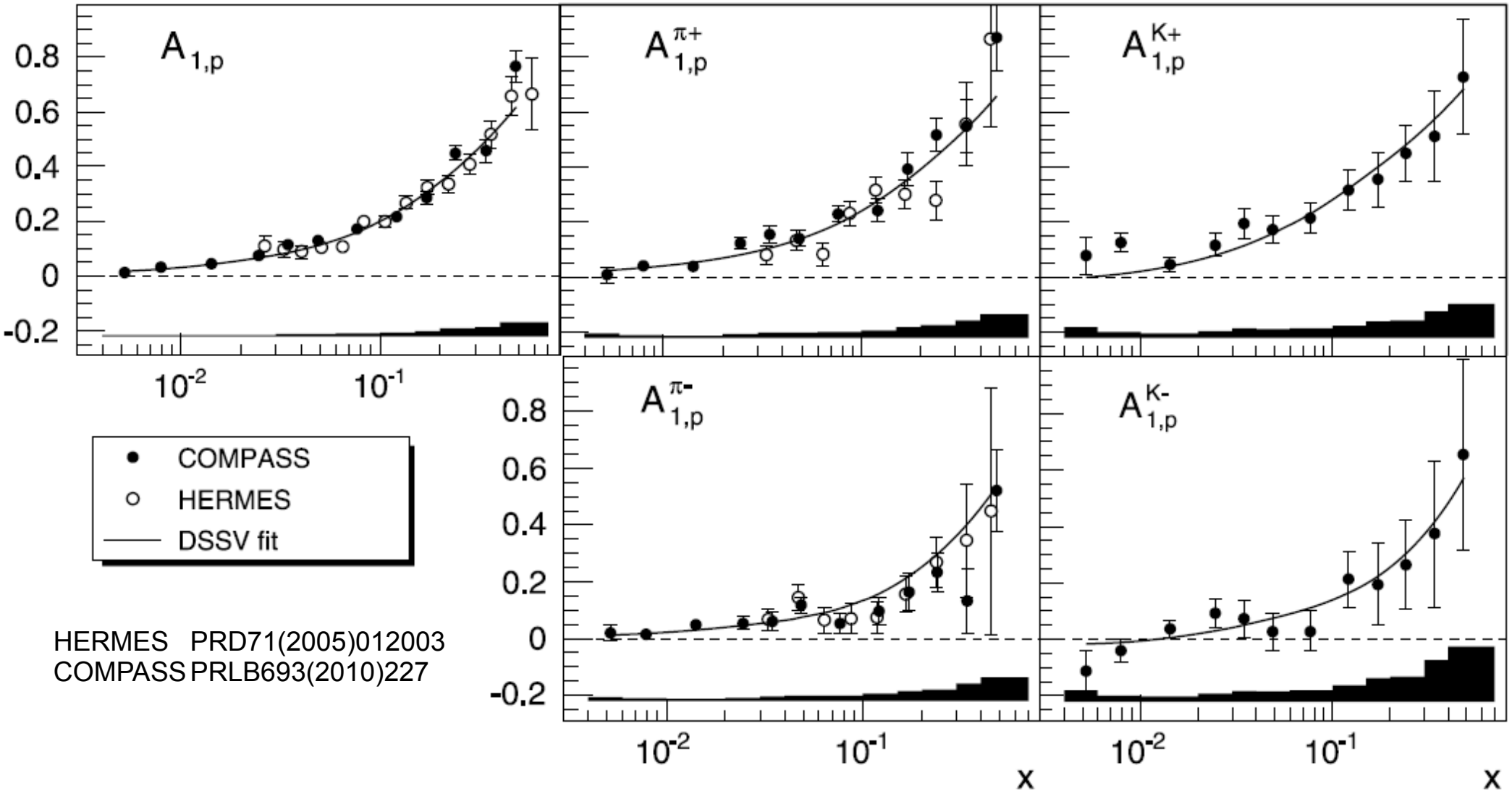
HERA: 27.6 GeV
polarized
electron/positron





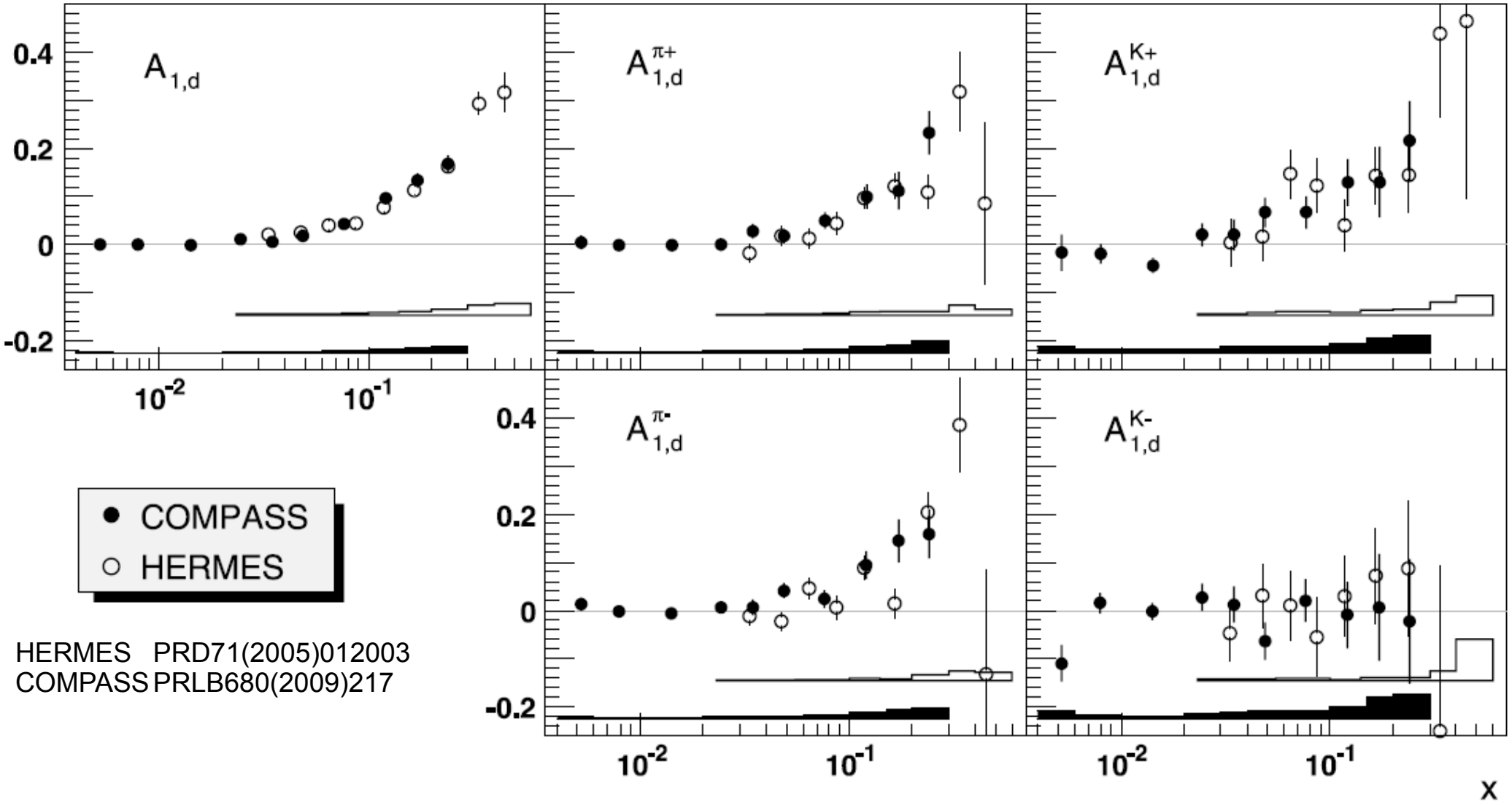
Reconstruction: Δp/p < 2%, Δθ < 0.6 mrad
Lepton selection efficiency: > 99%
with hadron contamination < 1%
Hadron ID with RICH: π, K, p in 2 < p < 15 GeV/c

Double spin asymmetry in SIDIS: proton target



HERMES PRD71(2005)012003
COMPASS PRLB693(2010)227

Double spin asymmetry in SIDIS: proton target



HERMES PRD71(2005)012003
COMPASS PRLB680(2009)217

Quark helicity distributions

PRD71(2005)012003

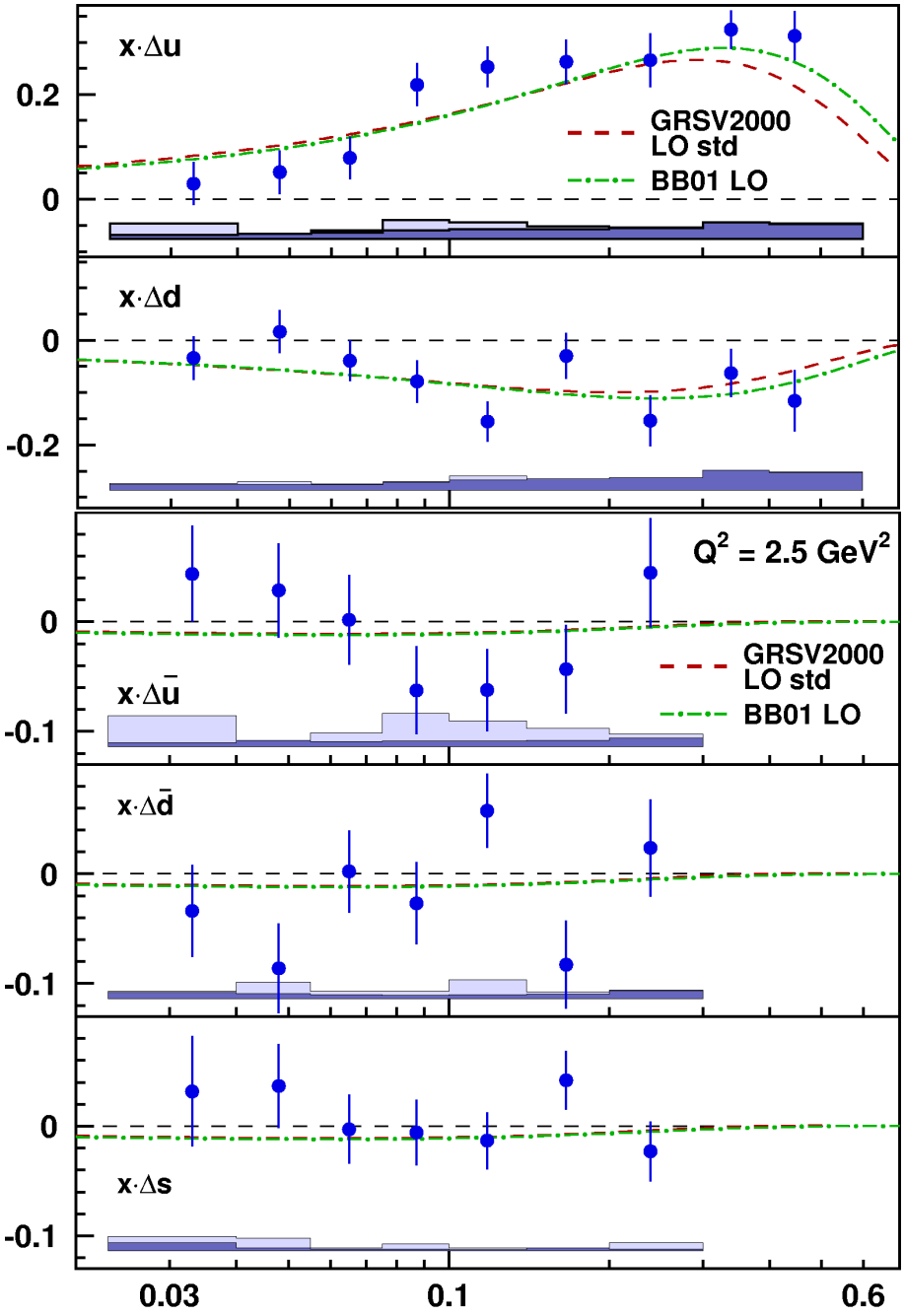


TABLE VIII. First and second moments of various helicity distributions in the measured range at a scale of $Q_0^2 = 2.5\ \mathrm{GeV}^2$.

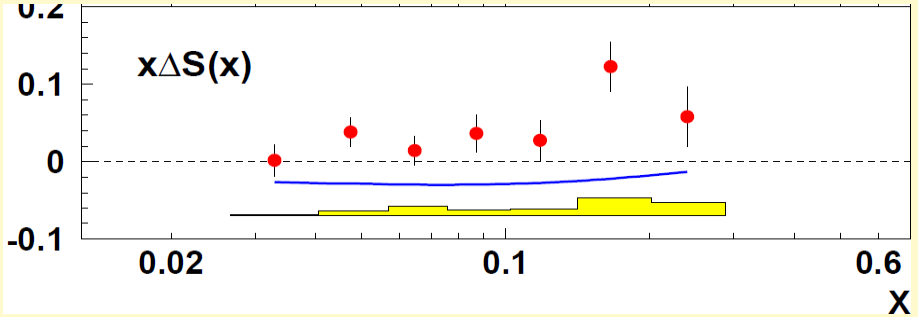
$0.023 < x < 0.6$	Moments in measured range
Δu	$0.601 \pm 0.039 \pm 0.049$
$\Delta \bar{u}$	$-0.002 \pm 0.036 \pm 0.023$
Δd	$-0.226 \pm 0.039 \pm 0.050$
$\Delta \bar{d}$	$-0.054 \pm 0.033 \pm 0.011$
Δs	$0.028 \pm 0.033 \pm 0.009$
$\Delta\Sigma$	$0.347 \pm 0.024 \pm 0.066$
Δq_3	$0.880 \pm 0.045 \pm 0.107$
Δq_8	$0.262 \pm 0.078 \pm 0.045$

Inclusive measurements PRD75(2007)012007

$$\Delta s + \Delta \bar{s} = -0.085 \pm 0.013 \pm 0.008 \pm 0.009$$

$$\Delta \Sigma = 0.330 \pm 0.025 \pm 0.011 \pm 0.028$$

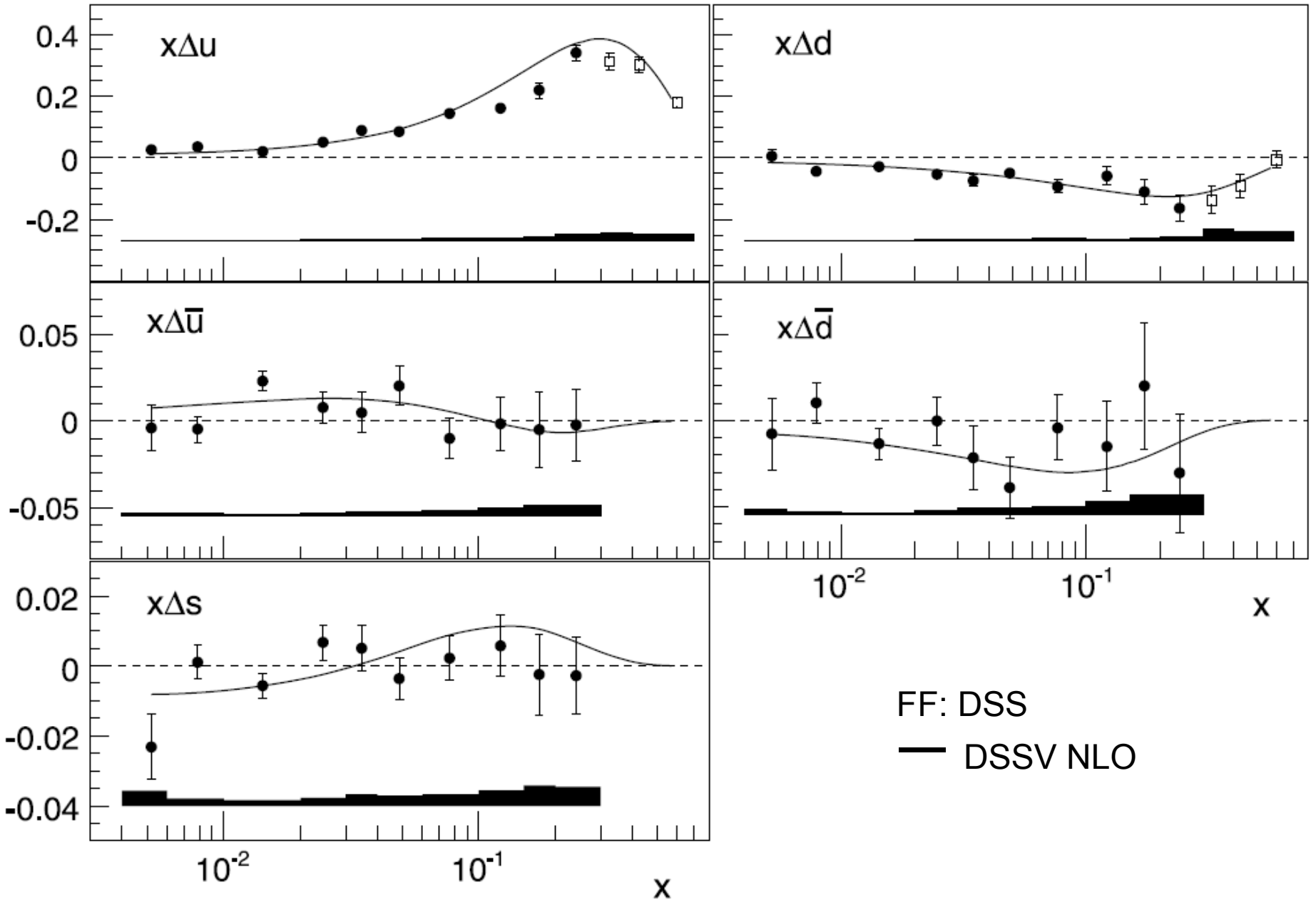
From charged kaon asymmetry PLB666(2008)446



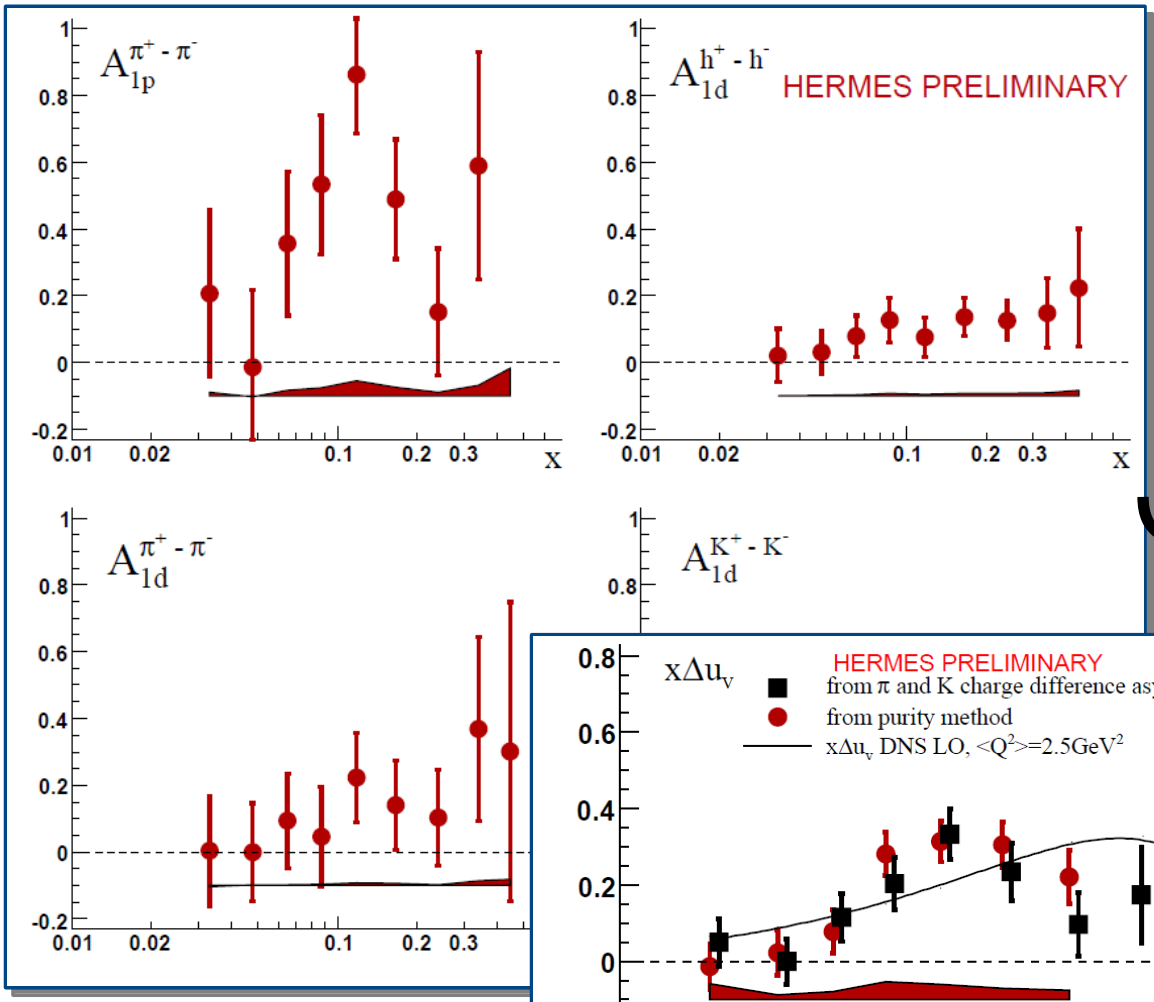
$$\Delta s + \Delta \bar{s} = 0.037 \pm 0.019 \pm 0.027$$

Quark helicity distributions

COMPASS PRLB693(2010)227

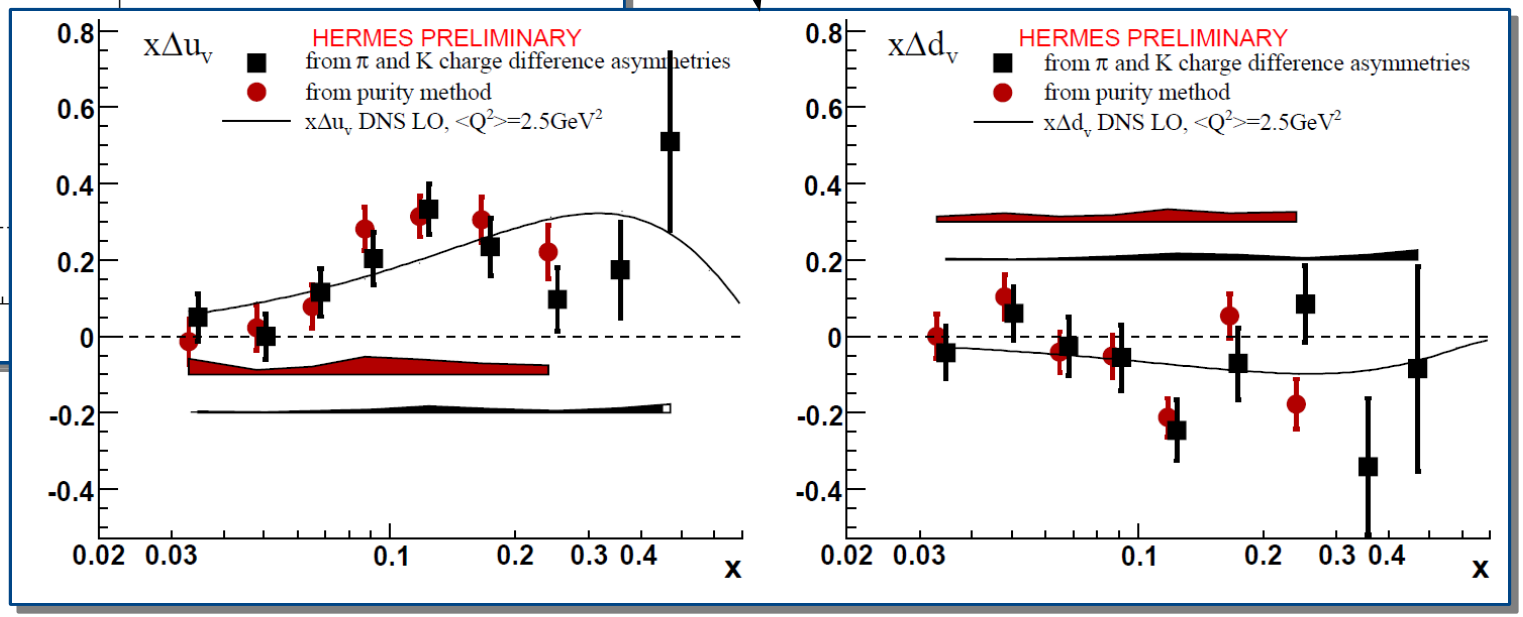


Difference asym. & valence quark



$$A_{1p}^{\pi^+ - \pi^-} = \frac{\Delta 4u_v - \Delta d_v}{4u_v - d_v}$$

$$A_{1d}^{\pi^+ - \pi^-} = \frac{\Delta u_v - \Delta d_v}{u_v - d_v}$$



フレーバー対称性

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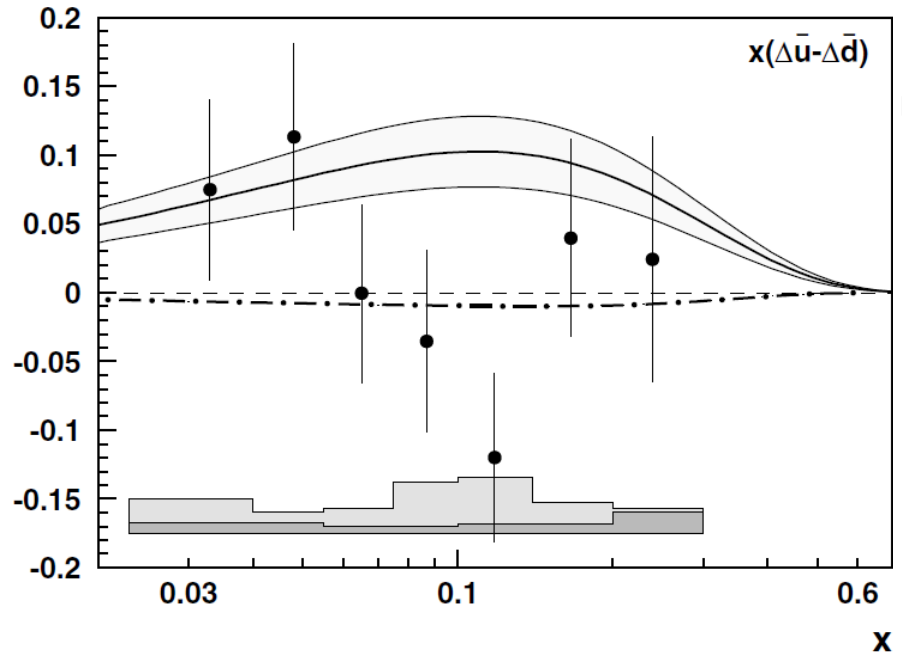
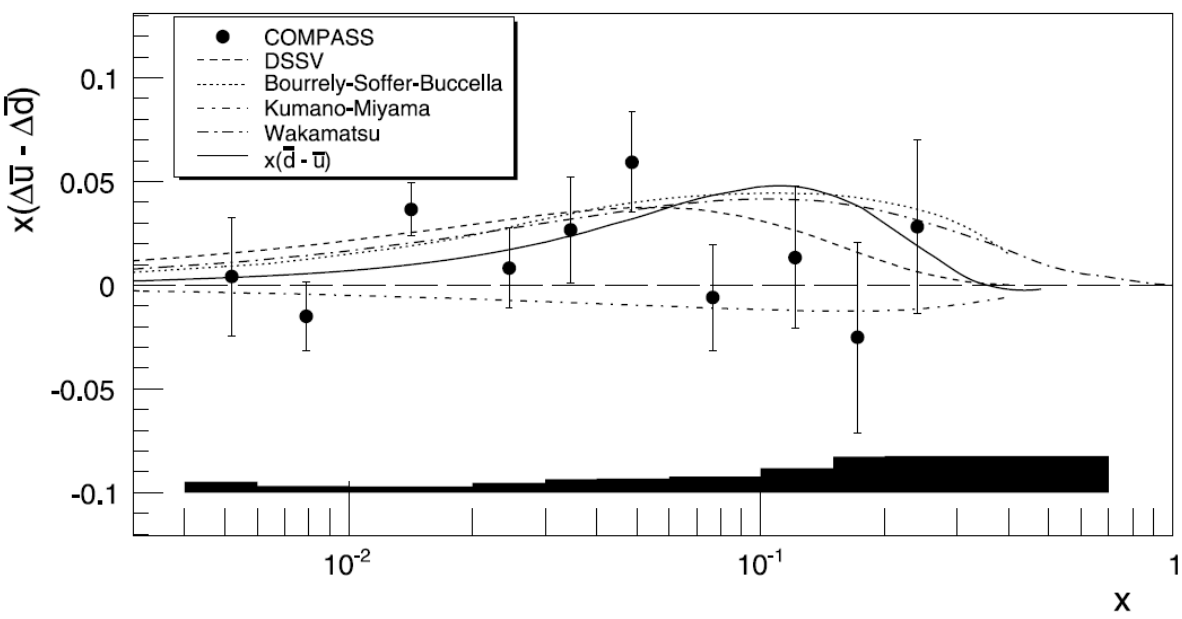
$$x\left(\Delta\bar{u}-\Delta\bar{d}\right)$$

HERMES PRD71(2005)012003



COMPASS PRLB693(2010)227



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

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

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

Δq, ΔG from the global analysis

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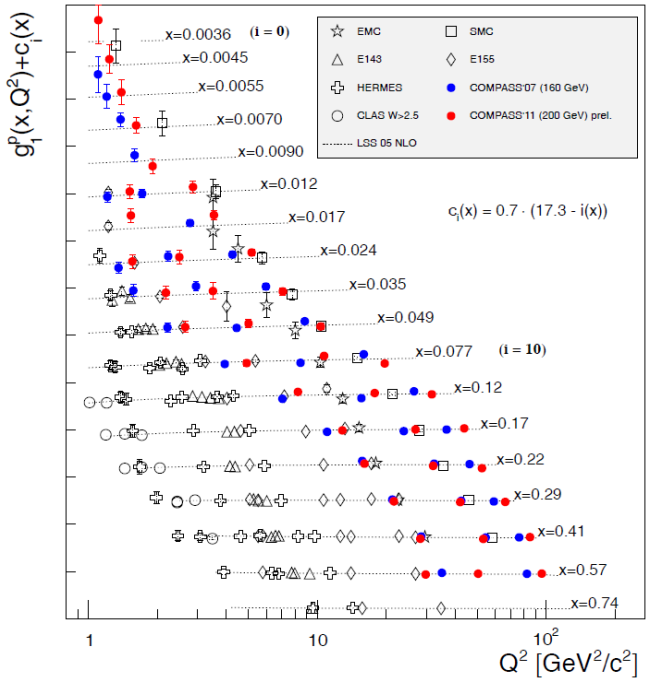
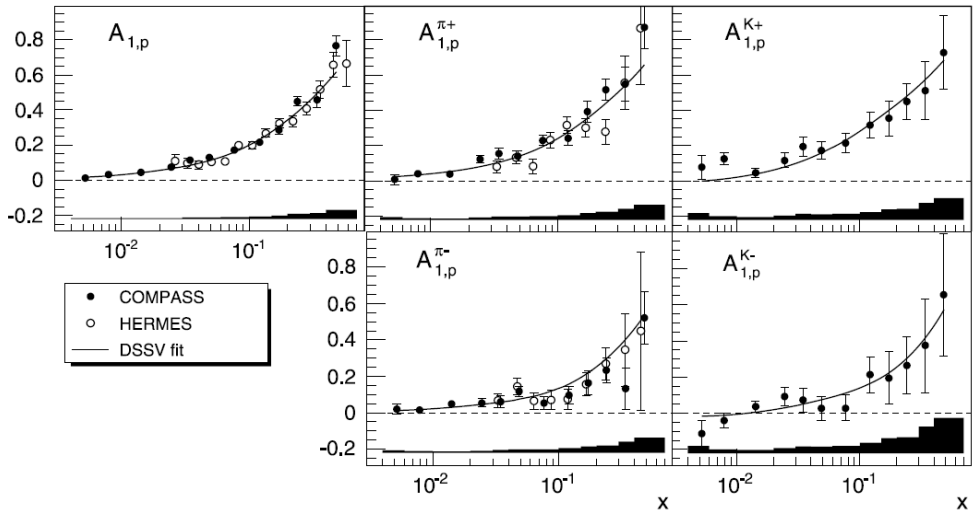




Fragmentation **F**unction

$D(z, Q^2)$ i.e., DSS

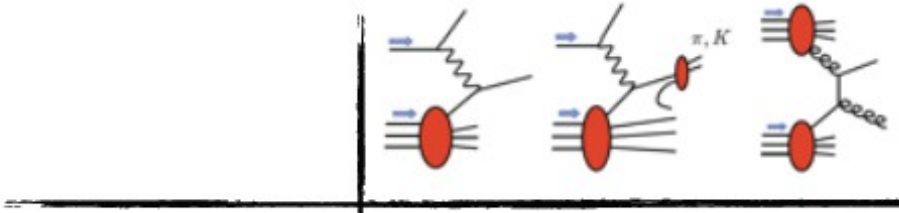
\+ QCD Evolution (pQCD parts)

$$\Delta q(x), \Delta G(x)$$

Target difference
Hadron difference

From scaling violation

overview of recent helicity PDF fits @ NLO



	uncertainties	last update
NNPDF Ball, Forte, Guffanti, Nocera, Rodolfi, Rojo	100 replicas stat. approach	1303.7236 Nocera (Tue)
DSSV de Florian, Sassot, MS, Vogelsang	L.M. $\Delta\chi^2 = 8$ (1) (Hessian $\Delta\chi^2 = 1$)	0904.3821 [DSSV+/++: 1112.0904 1304.0079]
LSS Leader, Sidorov, Stamenov	Hessian $\Delta\chi^2 = 1$	1010.0574
BB Blumlein, Bottcher	Hessian $\Delta\chi^2 = 1$	1010.3113
⋮	⋮	⋮
GRSV Gluck, Reya, MS, Vogelsang		1st NLO analysis 9508347

Δq, ΔG from the global analysis

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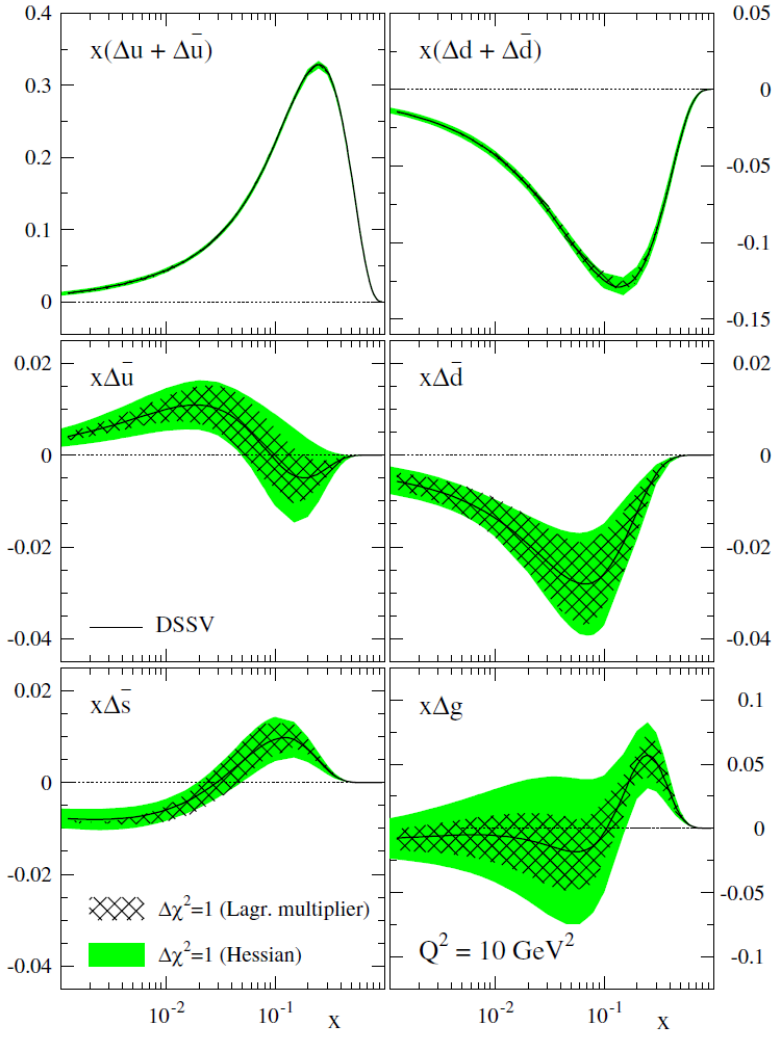
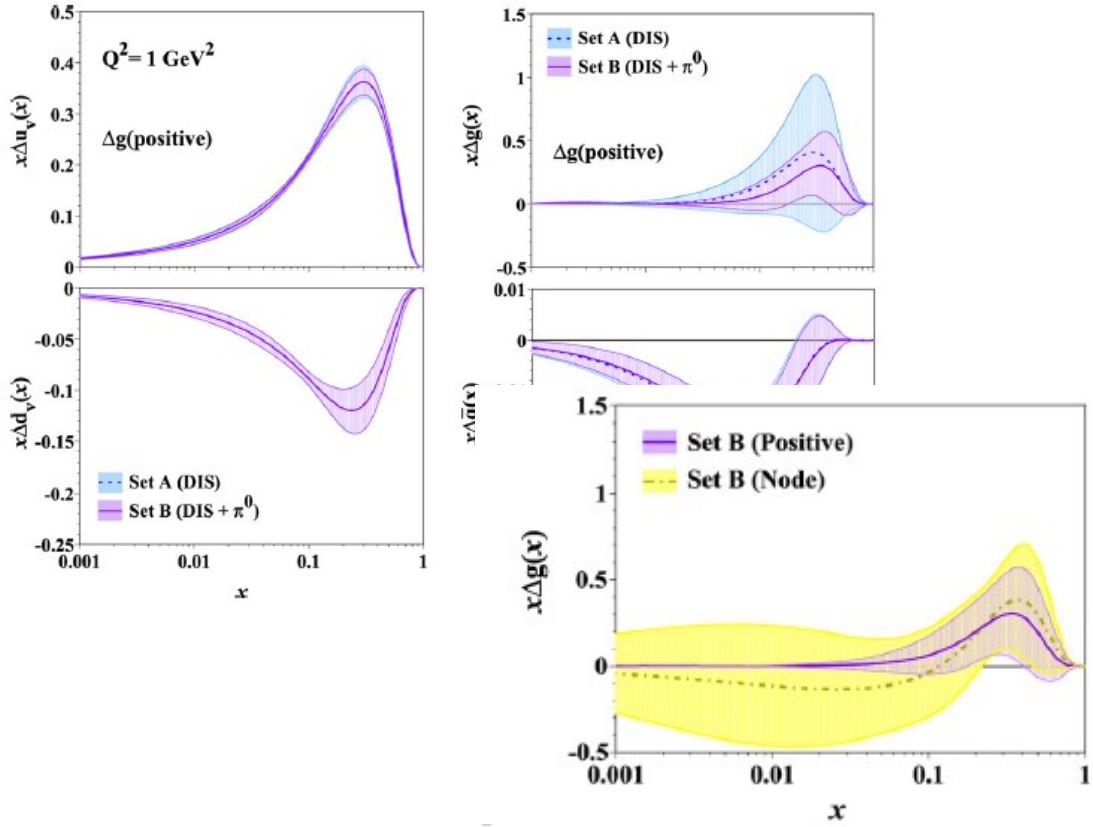
DSSV, PRD80(2009)034030



AAC, NPB813(2009)106

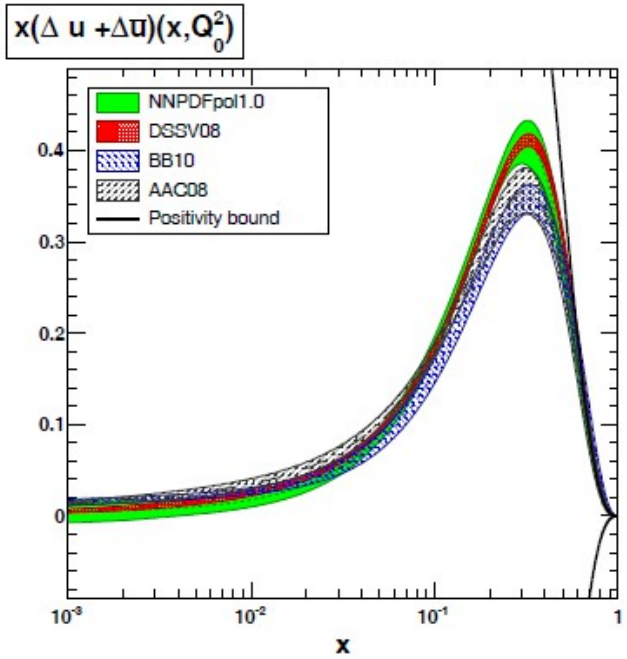


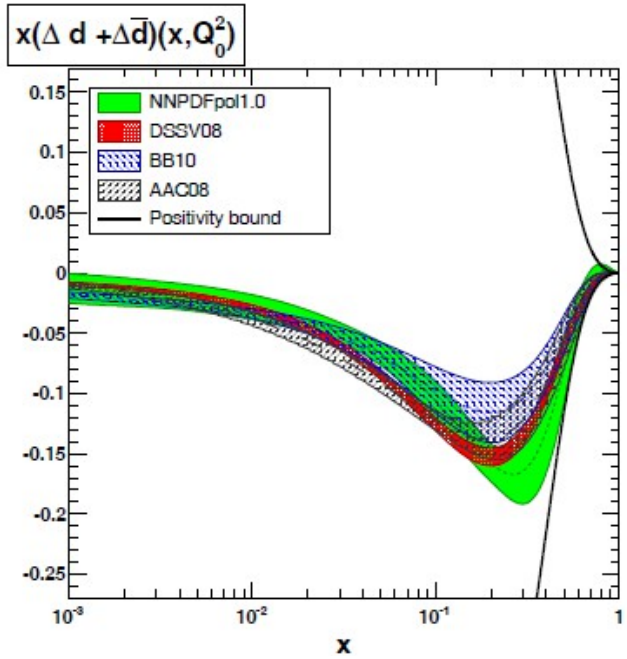
	Lagrange multiplier $\Delta\chi^2 = 1$
$\Delta u + \Delta\bar{u}$	$0.793^{+0.011}_{-0.012}$
$\Delta d + \Delta\bar{d}$	$-0.416^{+0.011}_{-0.009}$
$\Delta\bar{u}$	$0.028^{+0.021}_{-0.020}$
$\Delta\bar{d}$	$-0.089^{+0.029}_{-0.029}$
$\Delta\bar{s}$	$-0.006^{+0.010}_{-0.012}$
$\Delta\Sigma$	$0.366^{+0.015}_{-0.018}$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

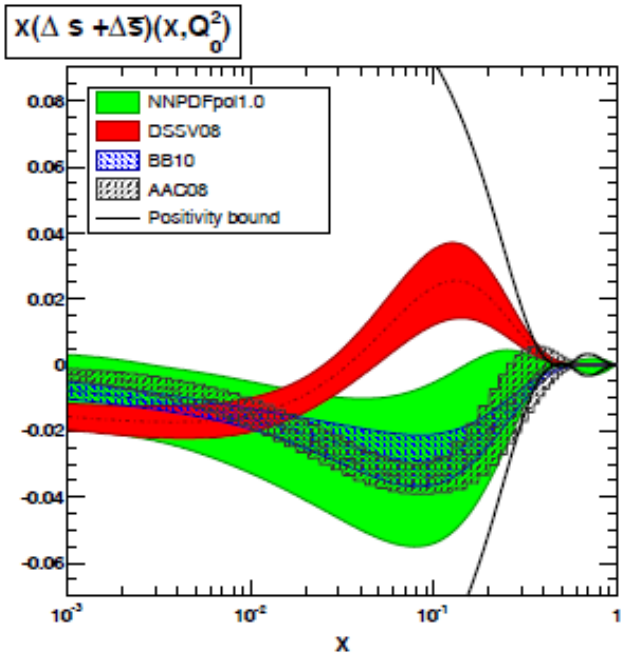
Δq, ΔG from the global analysis

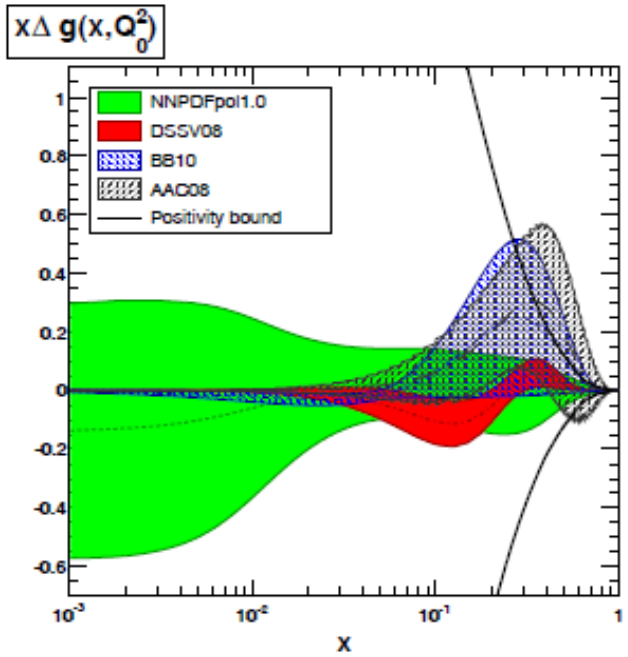
E. R. Nocera, DIS2013

YAMAGATA UNIVERSITY









DSSV08

[arXiv:0904.3821]

DIS+SIDIS+pp (π^0/jet)

BB10

[arXiv:1005.3113]

DIS only

AAC08

[arXiv:0808.0413]

DIS+pp (π^0)

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[arXiv:1005.3113]

DIS only

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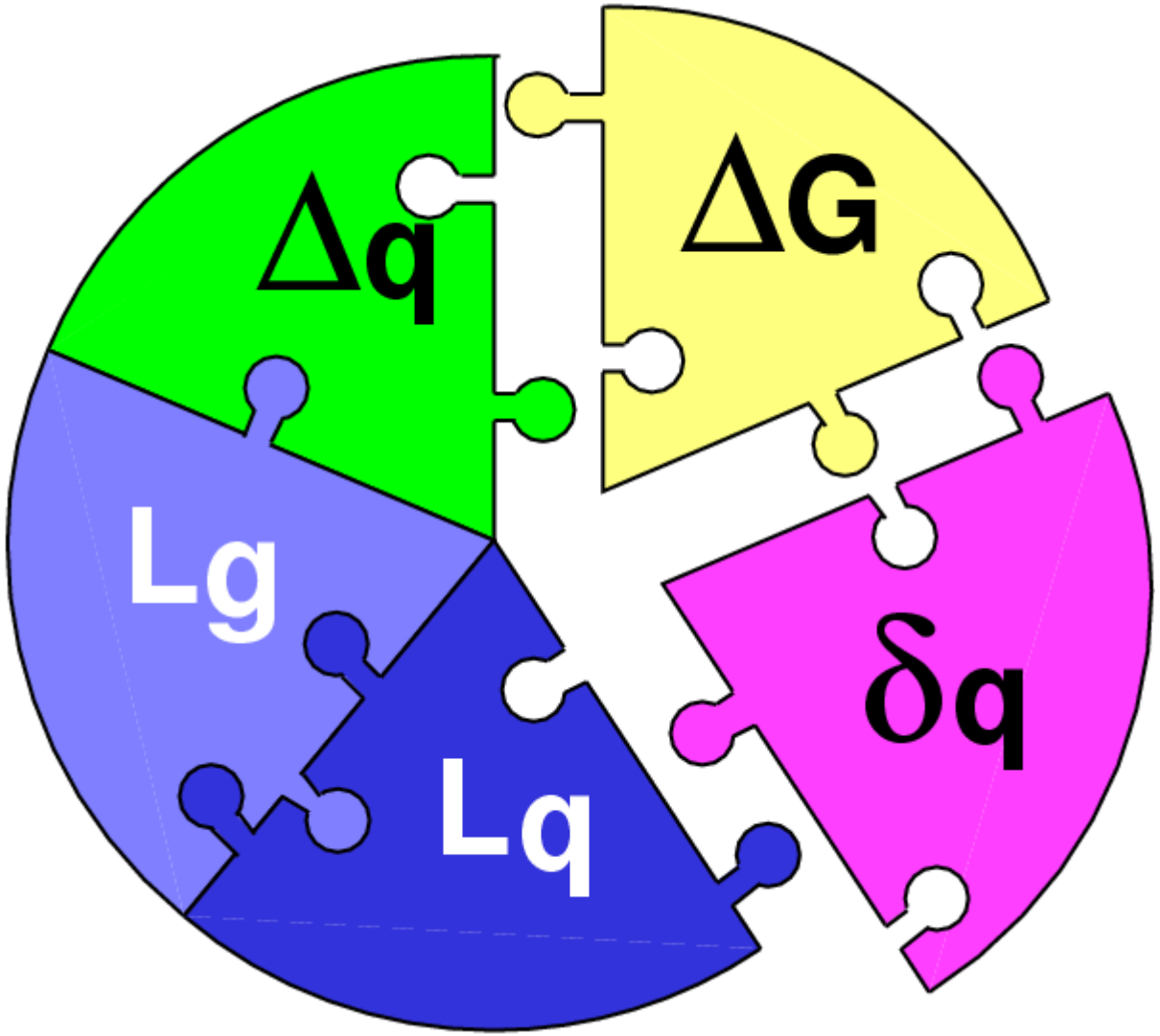
DIS+pp (π^0)


Δq
ΔG
Lg
δq
Lq

Direct determination on ΔG in SIDIS

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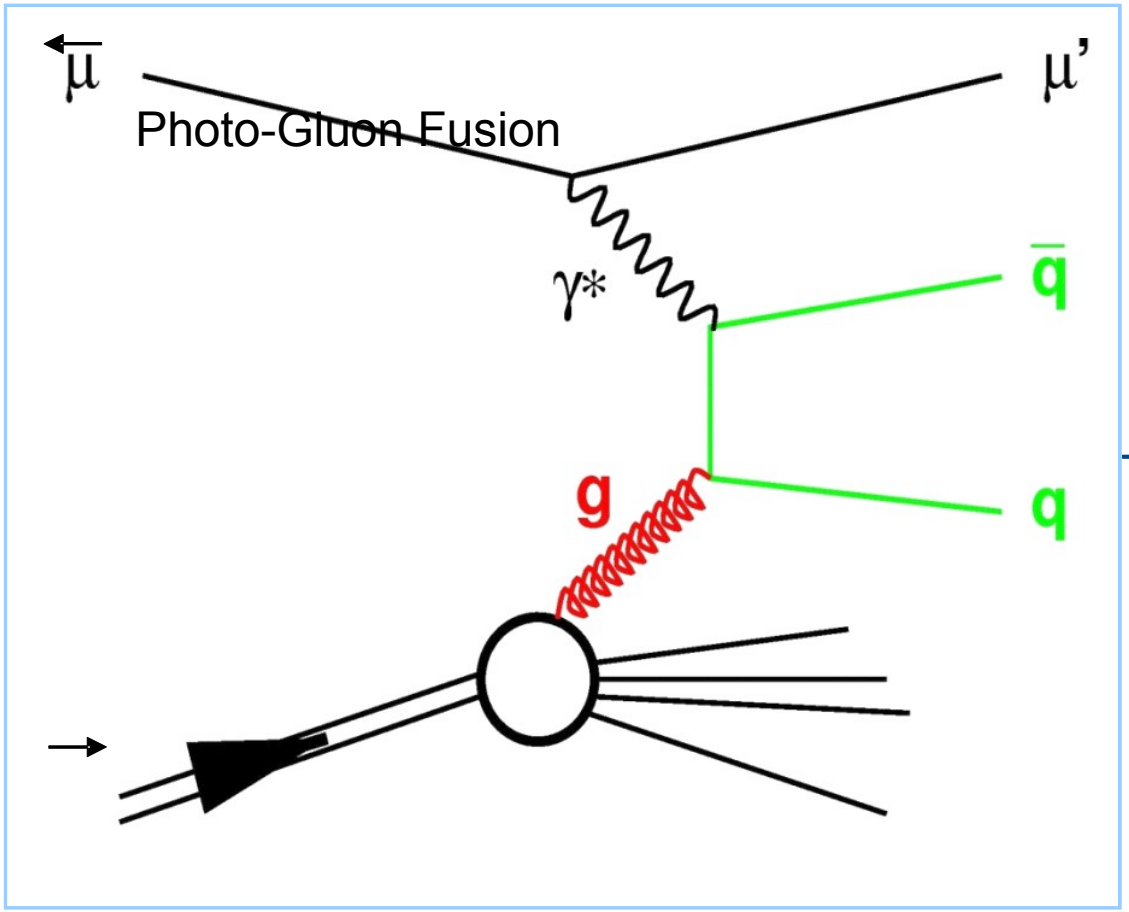
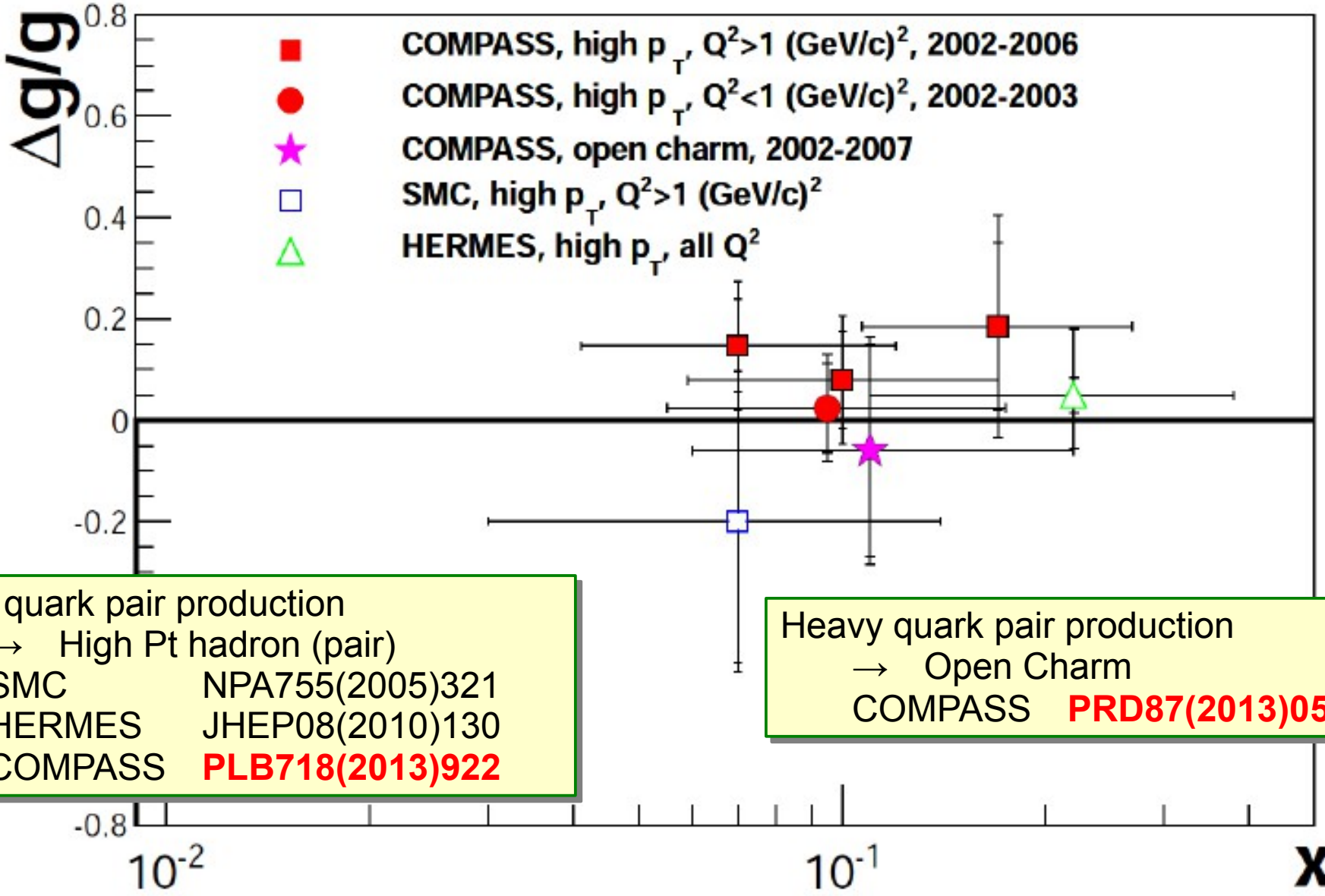


Light quark pair production
→ High Pt hadron (pair)
SMC NPA755(2005)321
HERMES JHEP08(2010)130
COMPASS **PLB718(2013)922**

Heavy quark pair production
→ Open Charm
COMPASS **PRD87(2013)052018**



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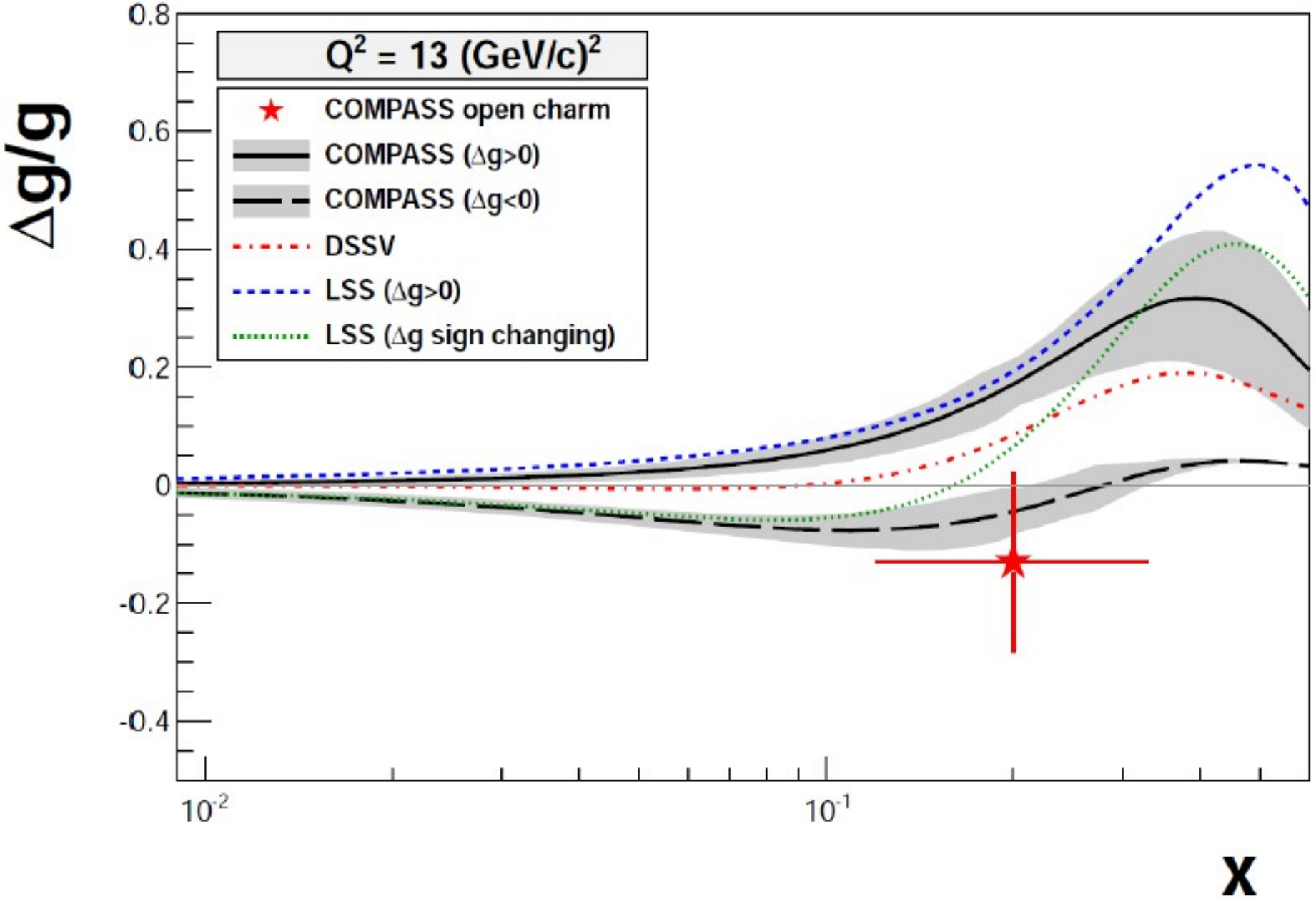
Q^2 = 13 (GeV/c)^2
COMPASS open charm
COMPASS (Δg>0)
COMPASS (Δg<0)
DSSV
LSS (Δg>0)
LSS (Δg sign changing)
Δg/g
0.8
0.6
0.4
0.2
0
-0.2
-0.4
10^{-2}
10^{-1}
X