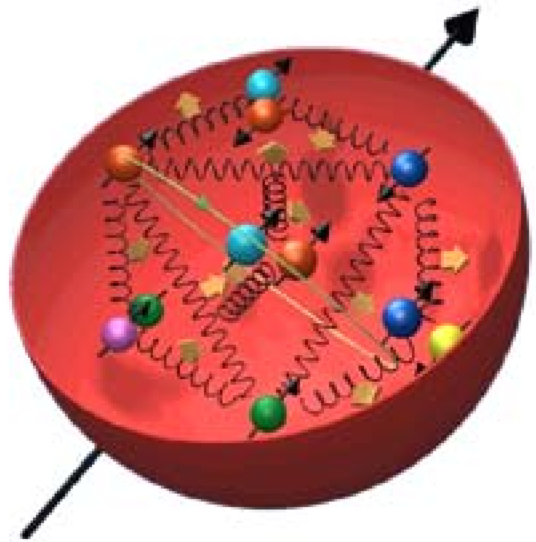
Polarised DIS Experiment

Gerhard Mallot



Plan

- Lecture I
  - introduction
  - kinematics
  - the cross section
  - structure functions & PDFs
  - sum rules
  - the experiments

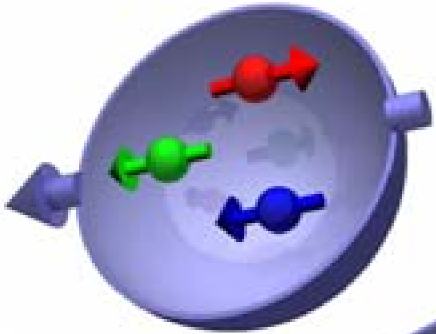
Introduction

- the nucleon is made up from partons
  - valence quarks
  - sea quarks
  - gluons
- quarks and gluons carry about 50 % of longitudinal momentum, respectively.
- What about spin?

Spin Contributions

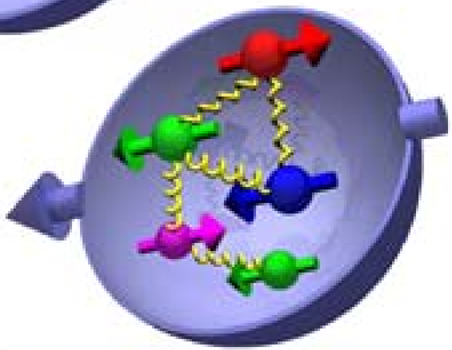
- naive QPM: only valence quarks

$$\Delta q_v$$



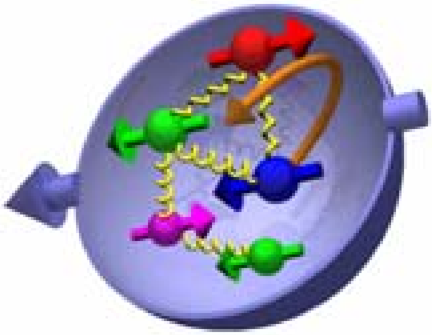
- QCD: sea quarks and gluons

$$\Delta q_s, \ \Delta G$$



- orbital angular momentum:

$$L_q, \ L_g$$



Nucleon Spin

- define: $\Delta q = q^{+} - q^{-}$
- with: q^{+}, q^{-} propabilities to find a quark or antiquark, with spin parallel or antiparallel to the spin of the nucleon,
- then the quarks naively contribute

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

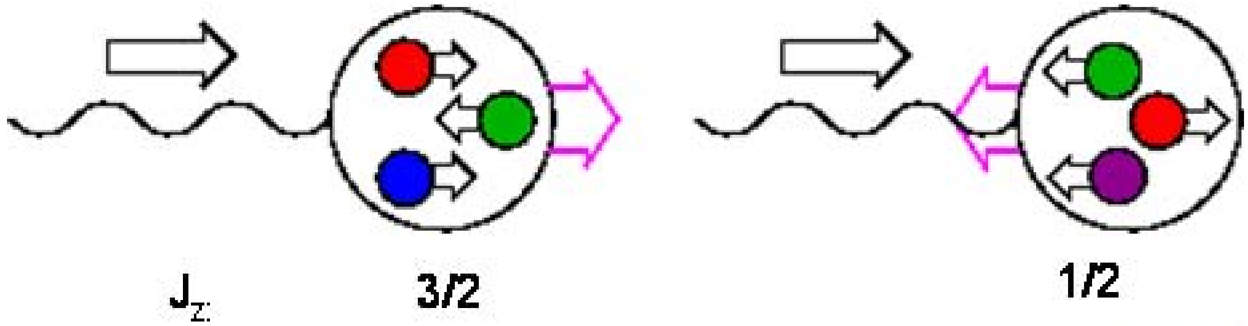
- and

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z \rangle$$

How to measure ΔΣ ?

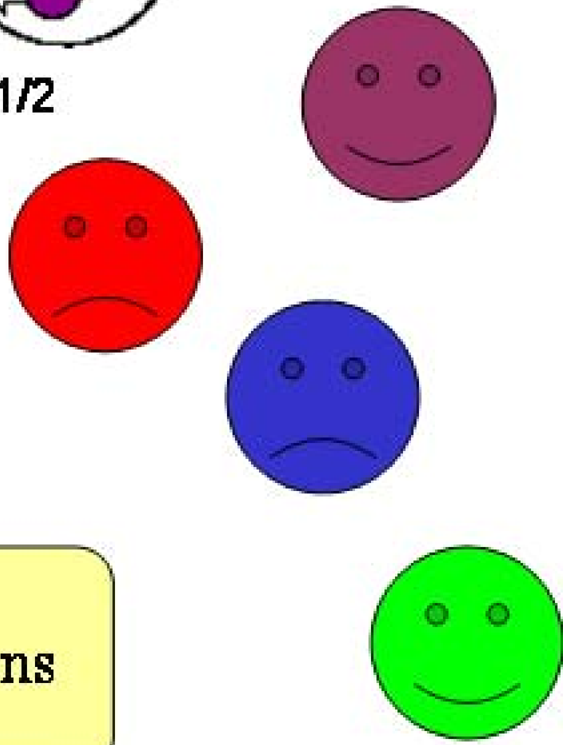
- Photoabsorption:

(flavours ignored)



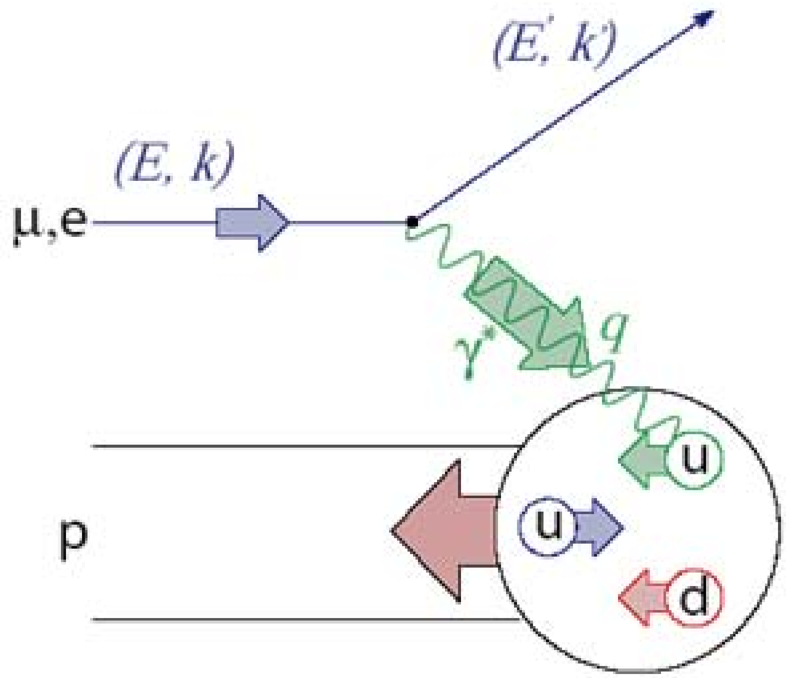
- only quarks with opposite helicity can absorb the polarised photon via spin-flip
- # quarks in direction of nucleon

$$\frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$



need polarised photons & nucleons

Pol. Deep Inelastic Scattering



$$Q^2 = -(k-k')^2 \overset{lab}{=} 4EE'\sin^2\frac{\vartheta}{2}$$

$$P\cdot q \overset{lab}{=} M\nu = M(E-E')$$

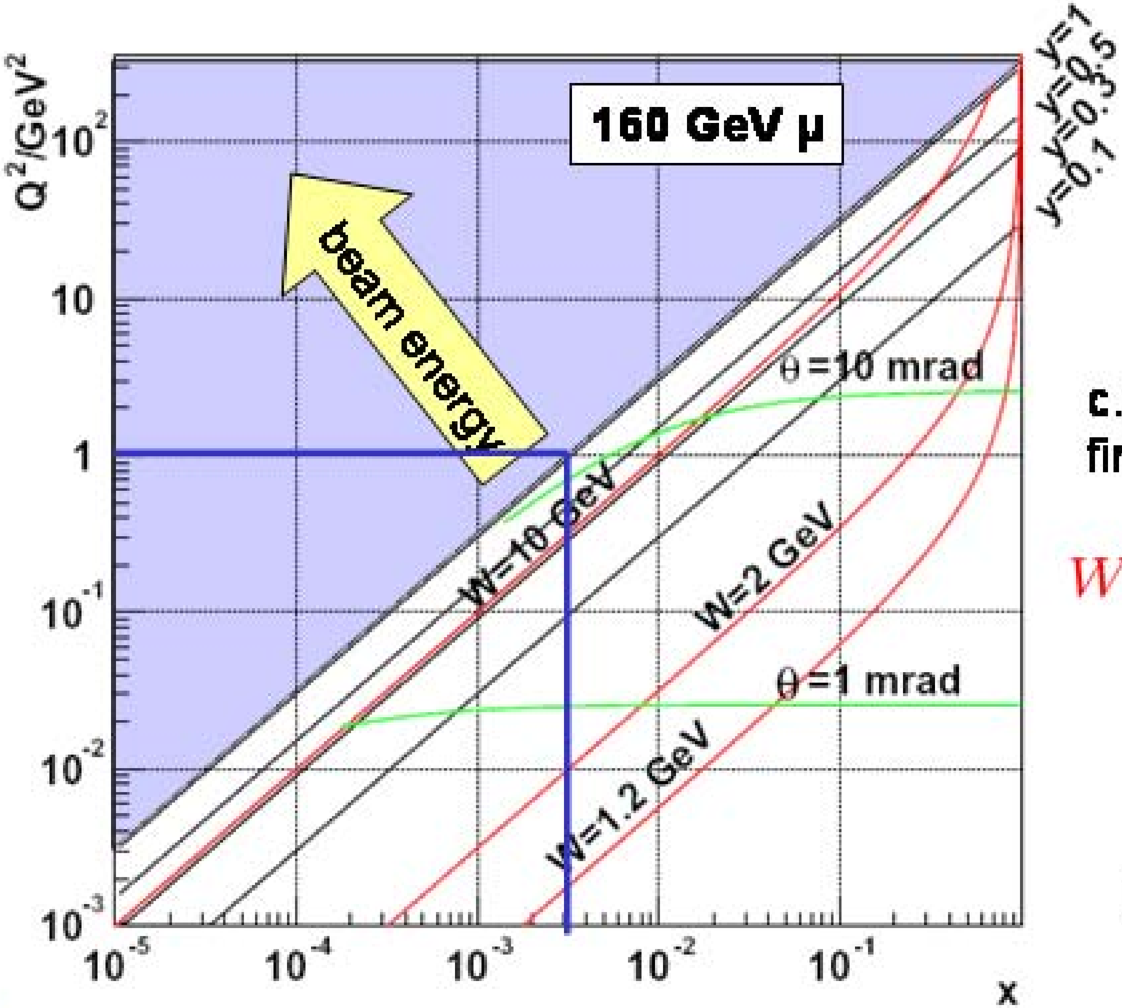
$$P\cdot k \overset{lab}{=} ME$$

Bjorken-x: fraction of longitudinal momentum carried by struck quark in infinite-momentum frame (Breit)

$$x \overset{lab}{=} \frac{Q^2}{2M\nu} = \frac{-q^2}{2P\cdot q}$$

$$y \overset{lab}{=} \frac{\nu}{E} = \frac{P\cdot q}{P\cdot k}$$

Kinematics



$$y = \frac{\nu}{E}$$

$$x_{min} = \frac{Q^2}{2ME}$$

c.m. energy of hadronic final state, W:

$$W^2 = (q+P)^2 = \frac{1-x}{x}Q^2 + M^2$$

DIS: $Q^2, W^2 \to \infty$, x fix

Pol. DIS cross section

lepton spin nucleon

cross section:

$$\frac{d^3\sigma}{dx\,dy\,d\phi} = \frac{\alpha^2}{Q^4}\frac{y}{2} L_{\mu\nu}(k,q,s) W^{\mu\nu}(P,q,S)$$

leptonic tensor $L_{\mu\nu}$: kinematics (QED)

hadronic tensor $W^{\mu\nu}$: nucleon structure

$$W^{\mu\nu} = -\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right) F_1(x,Q^2) + \left(P^\mu - \frac{P\cdot q}{q^2}q^\mu\right)\left(P^\nu - \frac{P\cdot q}{q^2}q^\nu\right)\frac{1}{P\cdot q}F_2(x,Q^2)$$
$$-i\epsilon^{\mu\nu\lambda\sigma}q_\lambda\left(\frac{MS_\sigma}{P\cdot q}\left(g_1(x,Q^2)+g_2(x,Q^2)\right) - \frac{M(S\cdot q)P_\sigma}{P\cdot q}g_2(x,Q^2)\right)$$

Structure Functions & PDF

$F_1,\ F_2$ unpolarised structure functions: momentum distributions

$g_1,\ g_2$ polarised structure functions: spin distributions

QPM: $F_2(x) = 2xF_1$ Calan Gross relation

$g_2 = 0$ twist-3 quark-qluon correlations

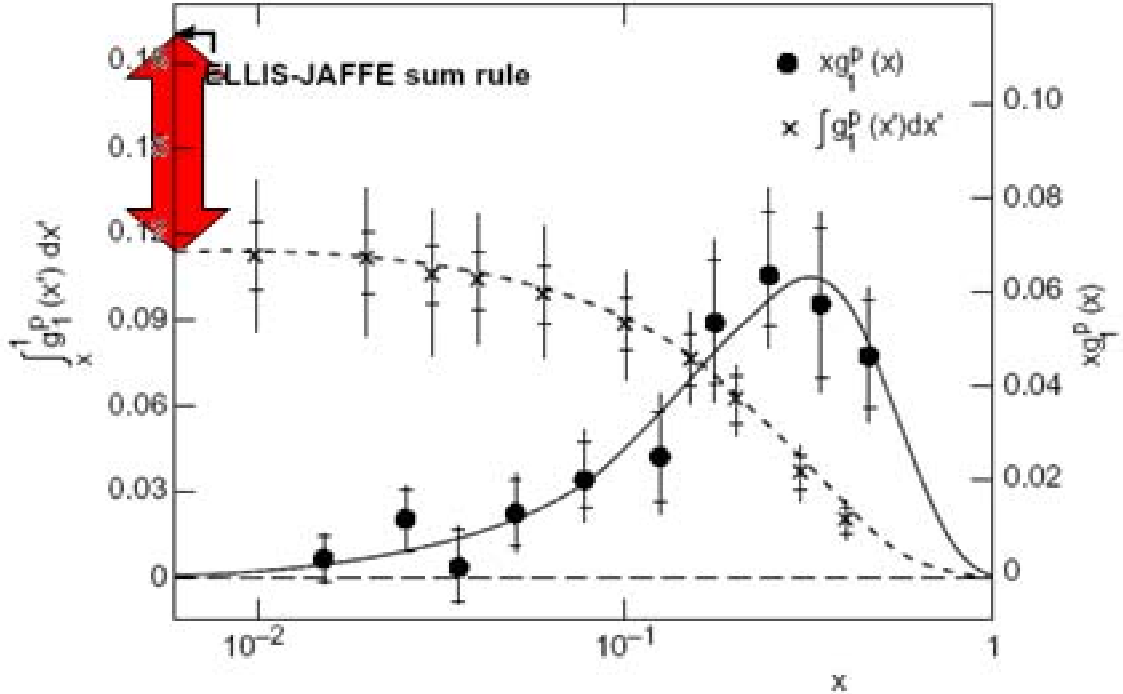
$$F_1(x) = \tfrac{1}{2}\sum_f e_f^2 \left\{q_f^+(x) + q_f^-(x)\right\} = \frac{1}{2}\sum_f e_f^2 q_f(x)$$

$$g_1(x) = \tfrac{1}{2}\sum_f e_f^2 \left\{q_f^+(x) - q_f^-(x)\right\} = \frac{1}{2}\sum_f e_f^2 \Delta q_f(x)$$

The First Moment of g_1

- first moment of g_1

$$\Gamma_1 = \int_0^1 g_1(x)\mathrm{d}x$$



"Spin crisis"
EMC 1987

Sum Rules

- with $\Delta q = \int \Delta q(x) \mathrm{d}x$ we get for the proton

$$\begin{aligned}\Gamma_1^{\mathrm{p}} &= \frac{1}{2}\left\{\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right\} \\ &= \frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{\sqrt{3}a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{a_0}\end{aligned}$$

$$\Gamma_1^{\mathrm{p,n}} = \frac{1}{12}\left(\pm a_3 + \frac{1}{\sqrt{3}} a_8\right) + \frac{1}{9} a_0$$

Neutron decay
$a_3 = g_a$

Hyperon decay
(3F-D)/3

$\Delta\Sigma$

Sum Rules

Bjorken sum rule

PR 148 (1966) 1467

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} g_a$$

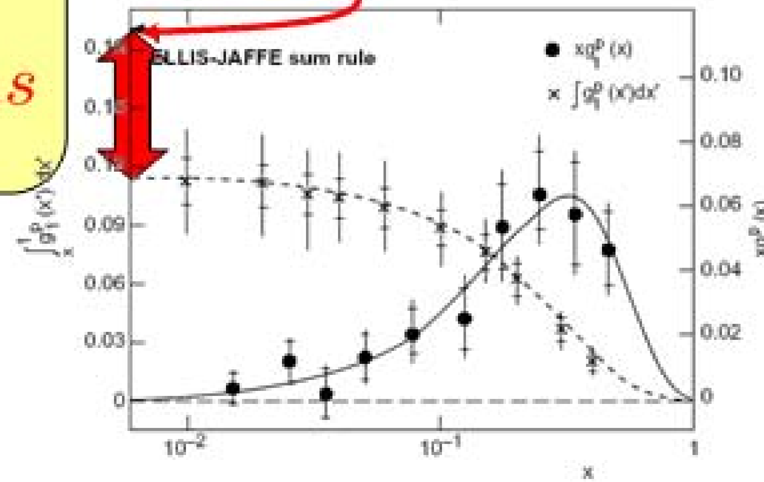
if wrong ⇒ QCD wrong, "worthless equation", needs neutron measurement

Ellis-Jaffe sum rule

PR D9 (1974) 1444

$$\Gamma_1^p = \frac{1}{12} g_a + \frac{5}{36}\sqrt{3} a_8 + \frac{1}{3}\Delta s \Rightarrow \Delta\Sigma \simeq 0.6$$

formulated for $\Delta s=0$, unpolarised strange quarks



Consequences of violation:

$$\Delta s = -0.19 \pm 0.06$$
$$\Delta\Sigma = 0.12 \pm 0.17$$

EMC 1987

Where is the proton spin?

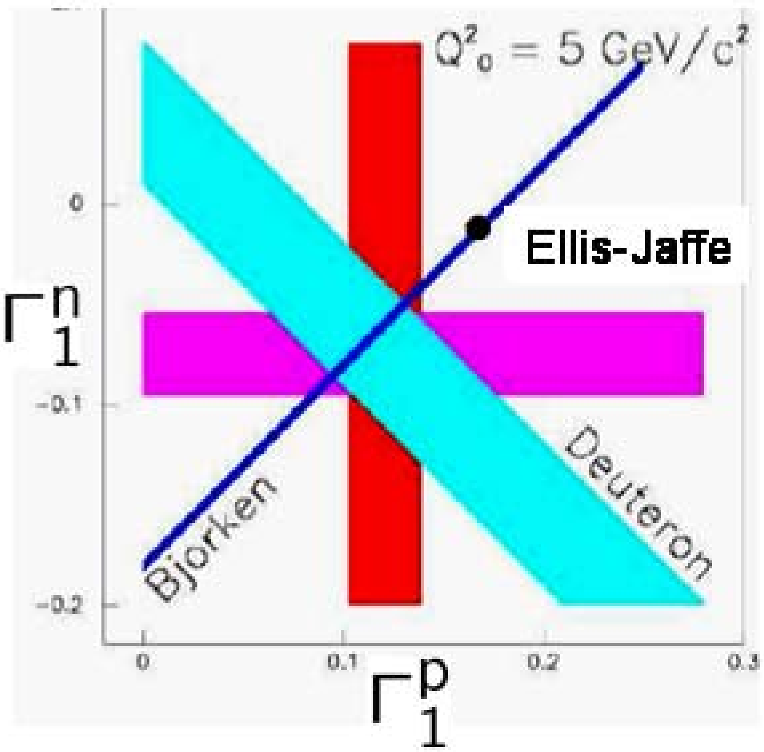
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z \rangle$$

small

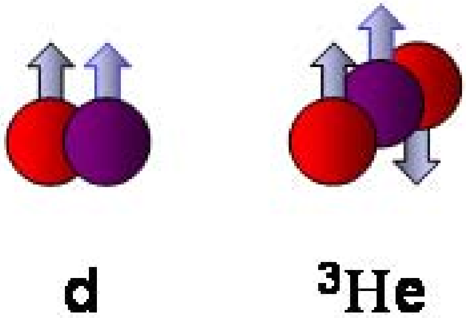
unknown
next challenge

$(\text{unknown})^2$

Bjorken Sum Rule



- Need proton AND neutron data
- neutron targets: deuteron, ^3He



Bjorken Sum Rule verified to about 10 %

Spin Experiments are puzzling

Wolfgang Pauli and Niels Bohr, 1955

wondering about a tippe top toy

Cross Section Asymmetries

unpolarised:

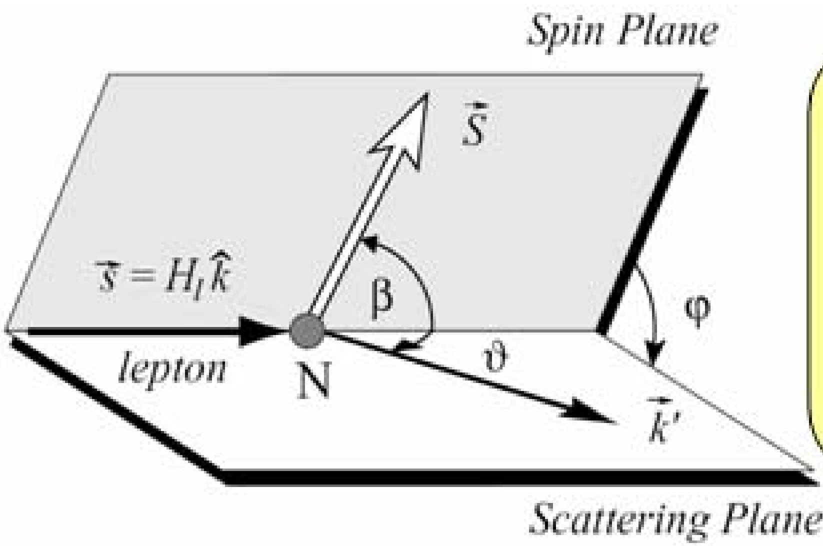
$$\frac{d^3\overline{\sigma}}{dx\,dy\,d\varphi} = \frac{4\alpha^2}{Q^2}\left\{\frac{y}{2}F_1 + \frac{1}{2xy}\left(1-y-\frac{y^2\gamma^2}{4}\right)F_2\right\}$$

longitudinally polarised nucleon: β=0,π

$$\frac{d^3\Delta_{\parallel}\sigma}{dx\,dy\,d\varphi} = \frac{4\alpha^2}{Q^2}\left\{\left(1-\frac{y}{2}-\frac{y^2\gamma^2}{4}\right)g_1 - \frac{y}{2}\gamma^2 g_2\right\}$$

transversely polarised nucleon: β=±π/2

$$\frac{d^3\Delta_{\perp}\sigma}{dx\,dy\,d\varphi} = \frac{4\alpha^2}{Q^2}\left\{\gamma\sqrt{1-y-\frac{y^2\gamma^2}{4}}\left(\frac{y}{2}g_1 + g_2\right)\right\}$$



Measure asymmetries:

$$A_{\parallel}(x,Q^2;E) = \frac{\Delta_{\parallel}\sigma}{\overline{\sigma}} = \frac{\sigma^{\leftrightarrows} - \sigma^{\rightrightarrows}}{\sigma^{\leftrightarrows} + \sigma^{\rightrightarrows}},$$

$$A_{\perp}(x,Q^2;E) = \frac{\Delta_{\perp}\sigma}{\overline{\sigma}} = \frac{\mathcal{H}_\ell}{\cos\varphi}\cdot\frac{\sigma(\varphi)-\sigma(\pi\pm\varphi)}{\sigma(\varphi)+\sigma(\pi\pm\varphi)}$$

Experimental Essentials

- up to now only fixed-target pol. DIS experiments
- need polarised targets and beams
- need detection of scattered lepton, energy, direction, identification
- need to know energy and direction of incoming lepton
  - detection or given by machine

gets grid of normalisation, measurable asymmetries sometimes very small

- need excellent control of fake asymmetries, e.g. time variations of detector efficiencies

Experiment Essentials

- **Beams & targets:**

	target	beam pol	$x_{min}(1\ \mathrm{GeV}^2)$
▪ SLAC 48 GeV,	solid/gas	e, pol. source	0.01
▪ DESY 28 GeV,	gas internal	e, Sokolov-Ternov	0.02
▪ CERN 200 GeV,	solid	μ, pion decay	0.0025

- **fake asymmetries:**
  - rapid variation of beam polarisation (SLAC)
  - rapid variation of target polarisation (HERMES)
  - simultaneous measurement of two oppositely polarised targets in same beam (CERN)

Measurable asymmetries

$$A_{meas} = P_t P_b f\, A$$

P_b, P_t beam and target polarisations,

f target dilution factor = polarisable N/total N

note: linear in error: f=1/2 => requires 4 times statistics

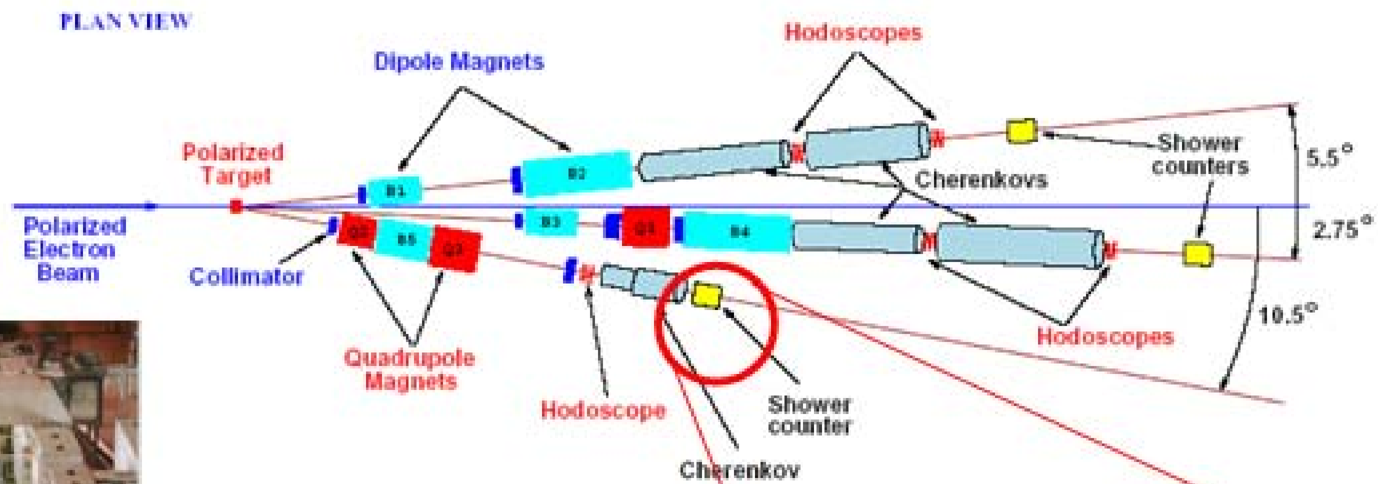
$$g_1 \simeq \frac{A_{\|}}{D} F_1 \simeq \frac{A_{\|}}{D} \frac{F_2}{2x}$$

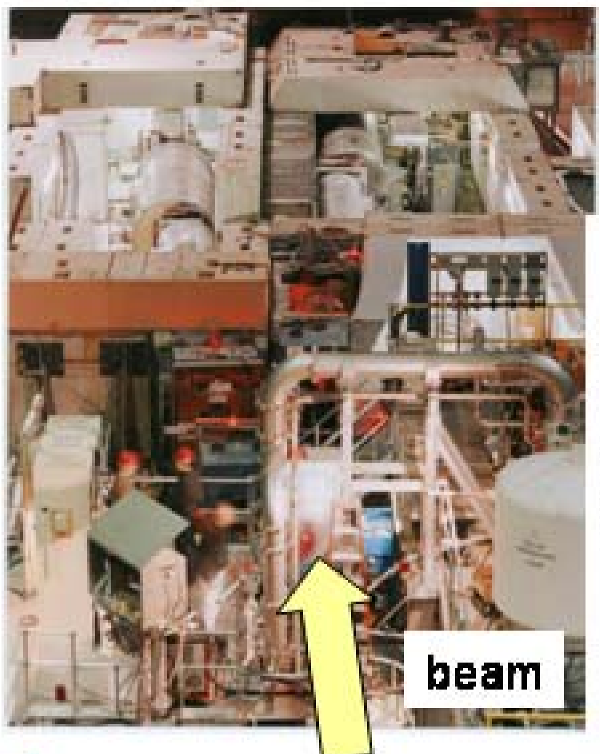
huge rise of ***$F_2/2x$*** at small ***x***

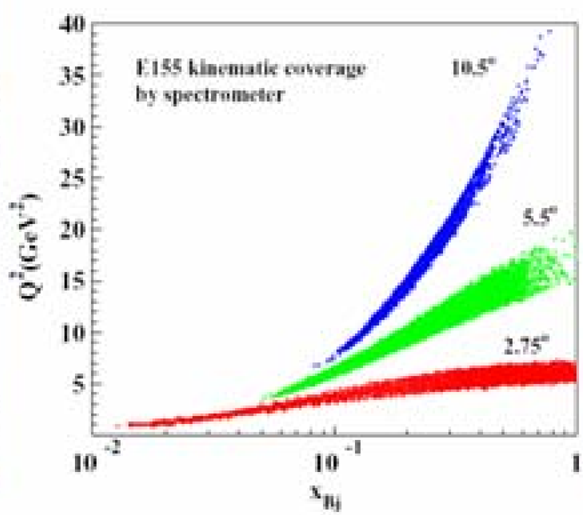
D depolarisation factor, kinematics, polarisation transfer from polarised lepton to photon, ***$D \approx y$***

Even big ***g_1*** at small ***x*** means small asymmetries

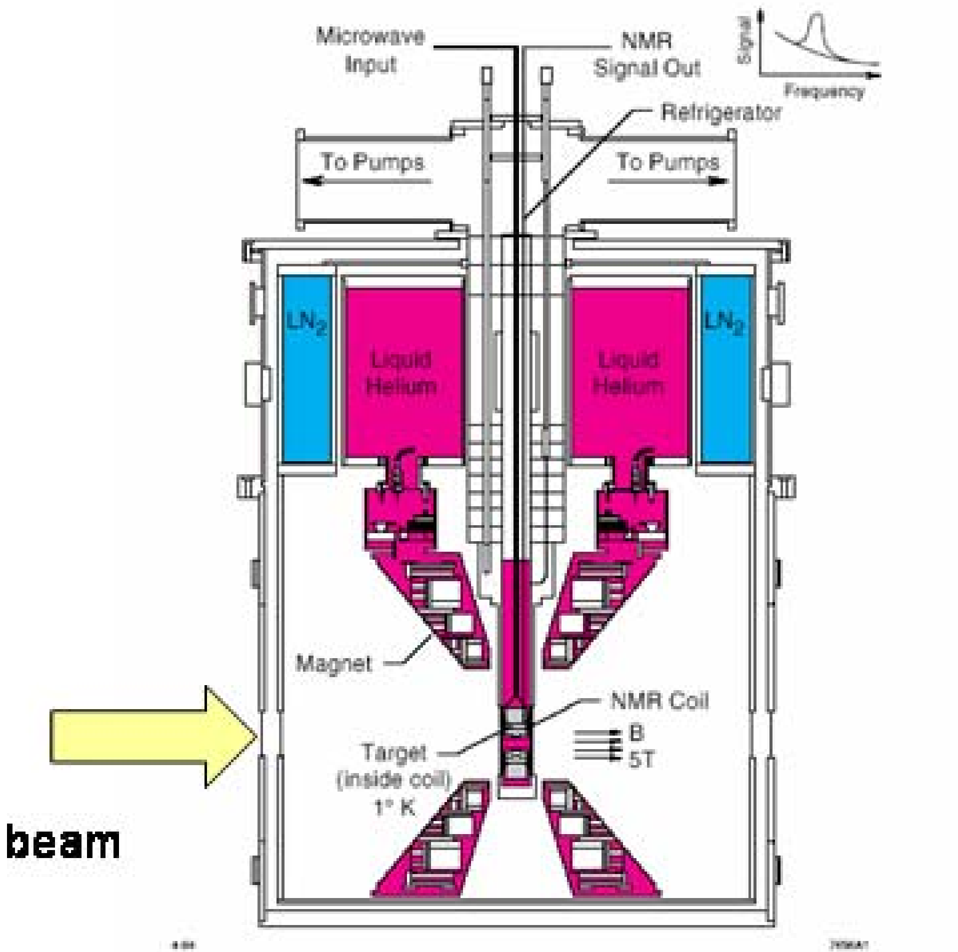
SLAC E155 Spectrometer







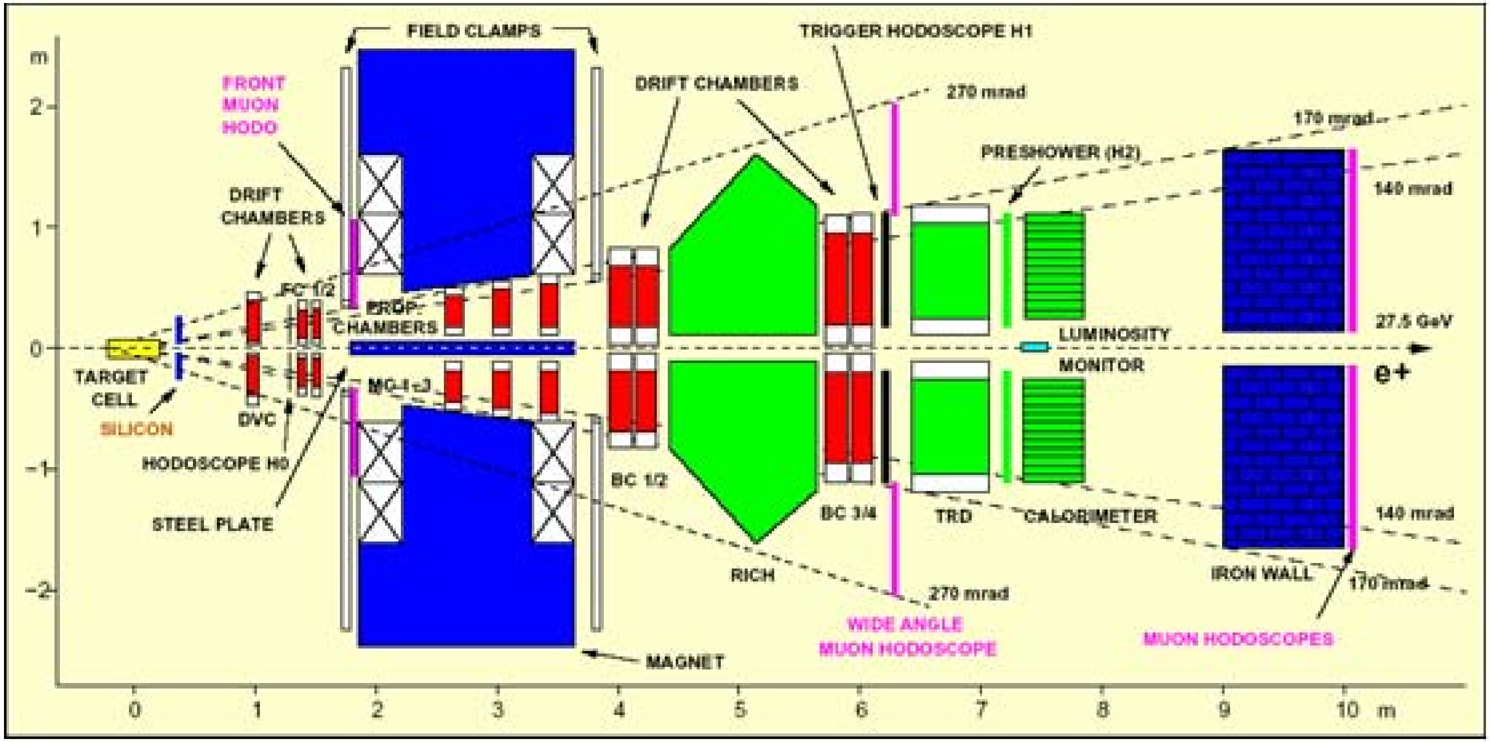
E155 Target



cryogenic target
^{6}LiD, NH_3

1K evaporator fridge
5 T magnetic field

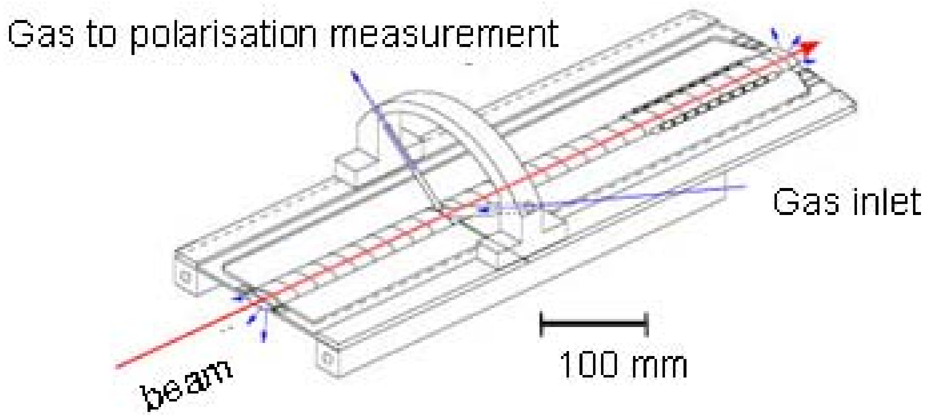
HERMES

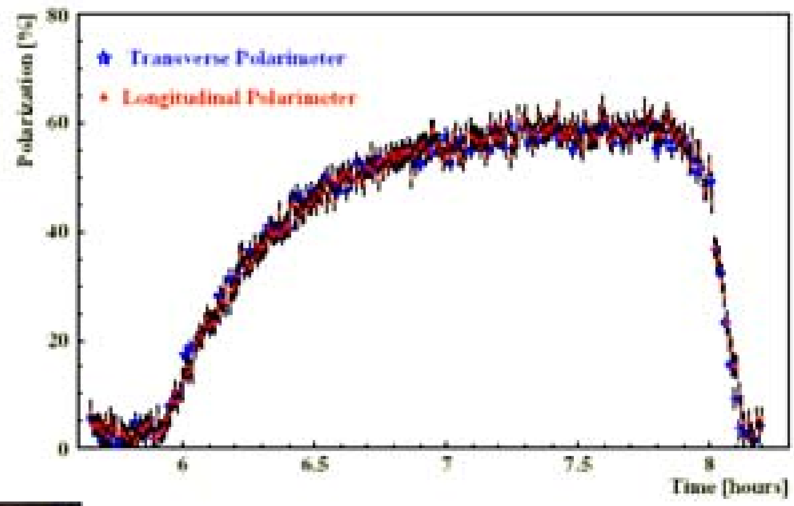


FIELD CLAMPS
TRIGGER HODOSCOPE H1
FRONT MUON HODO
DRIFT CHAMBERS
270 mrad
170 mrad
PRESHOWER (H2)
140 mrad
DRIFT CHAMBERS
FC 1/2
PROP. CHAMBERS
LUMINOSITY MONITOR
27.5 GeV
e+
TARGET CELL
SILICON
DVC
MC 1-3
HODOSCOPE H0
STEEL PLATE
BC 1/2
BC 3/4
TRD
CALORIMETER
140 mrad
RICH
IRON WALL
170 mrad
270 mrad
WIDE ANGLE MUON HODOSCOPE
MUON HODOSCOPES
MAGNET
m
0
1
2
3
4
5
6
7
8
9
10

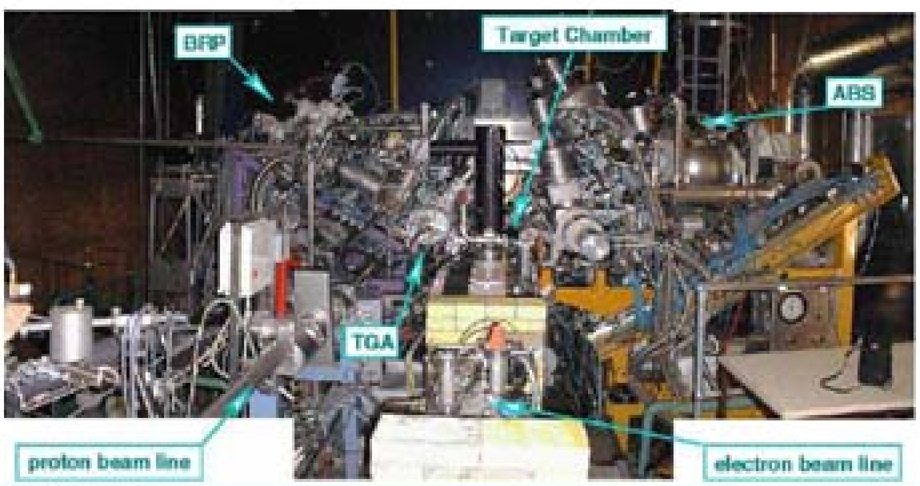
HERMES

Target cell

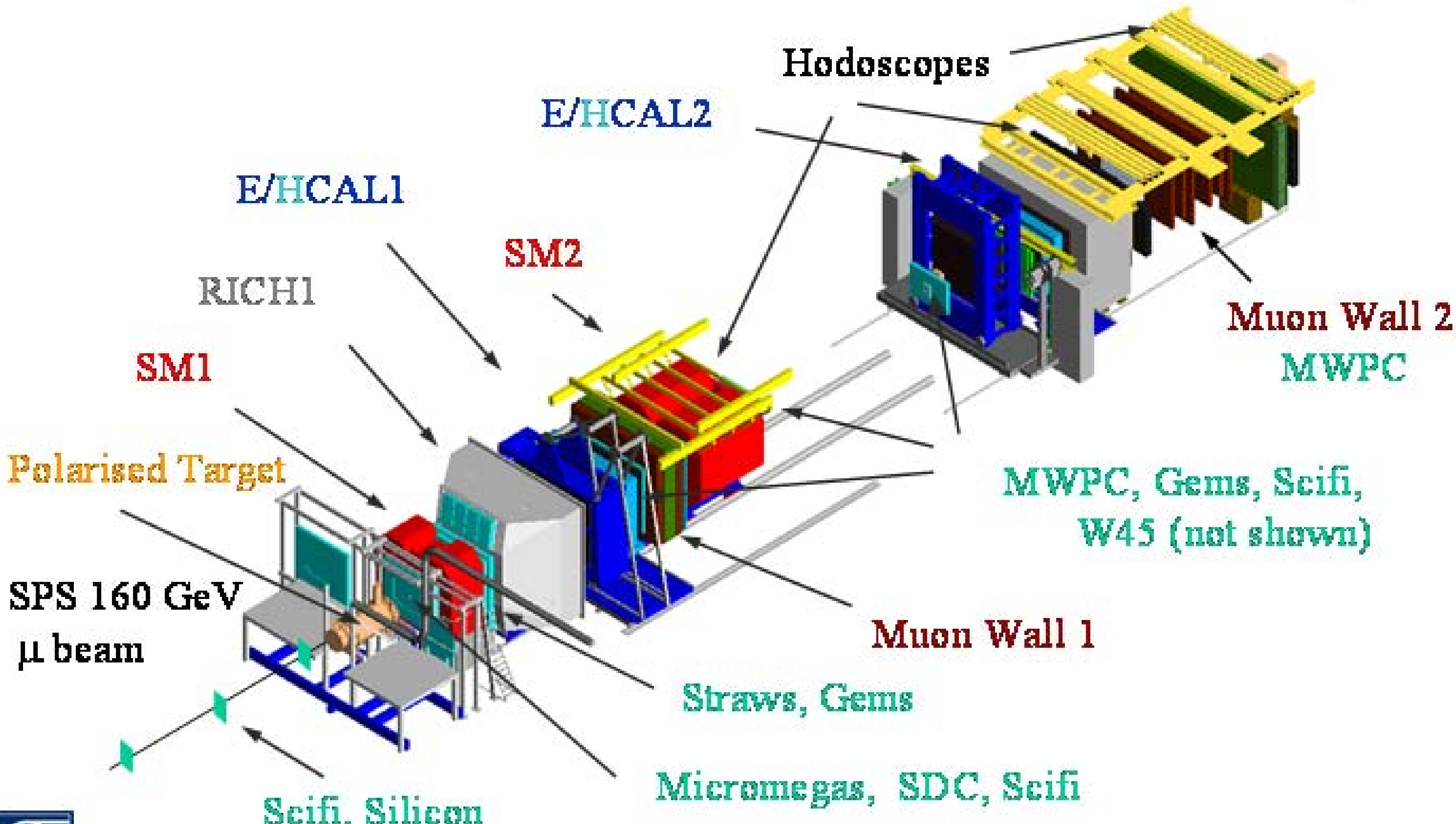




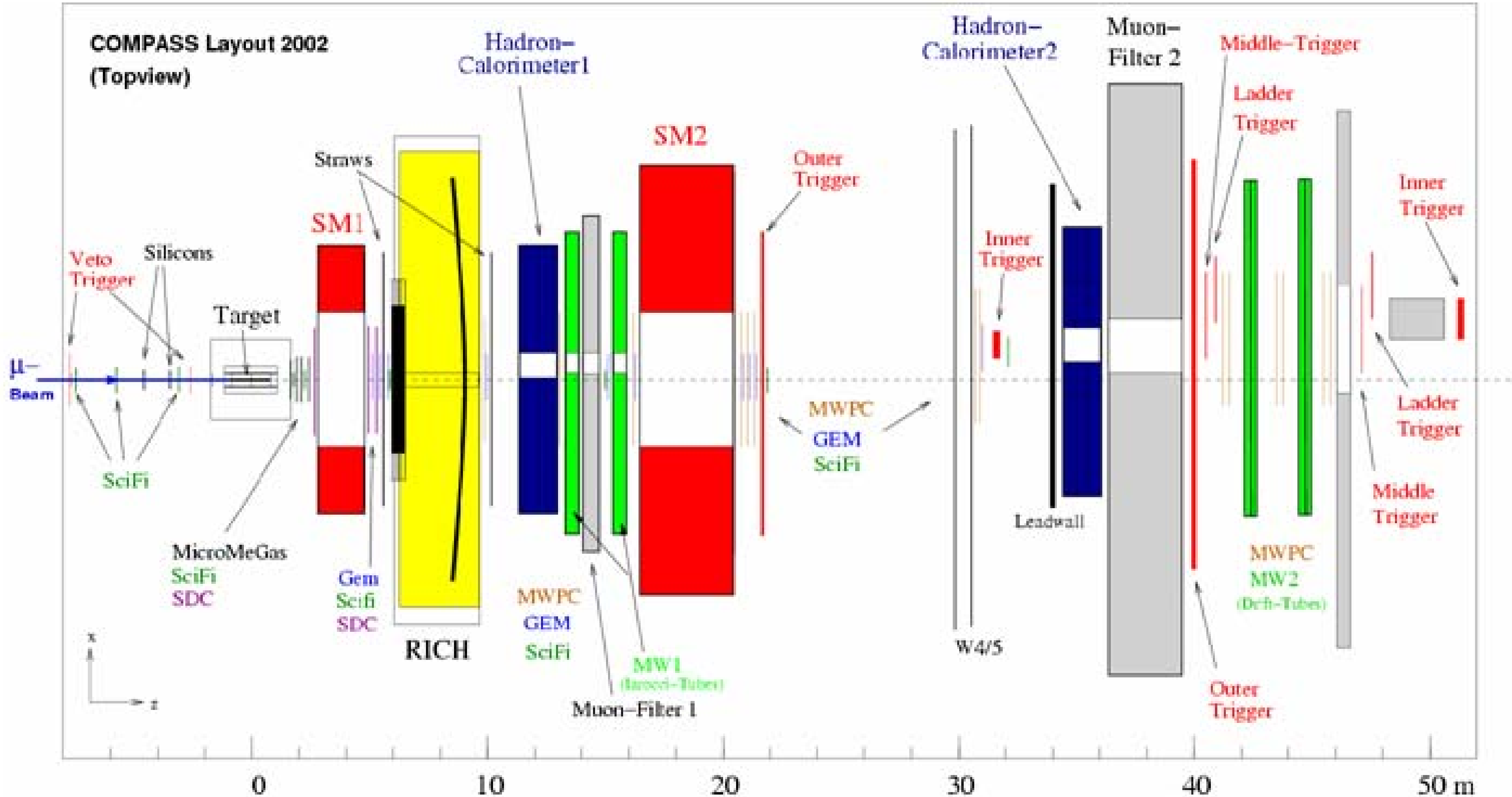
beam polarisation built-up



The COMPASS Spectrometer

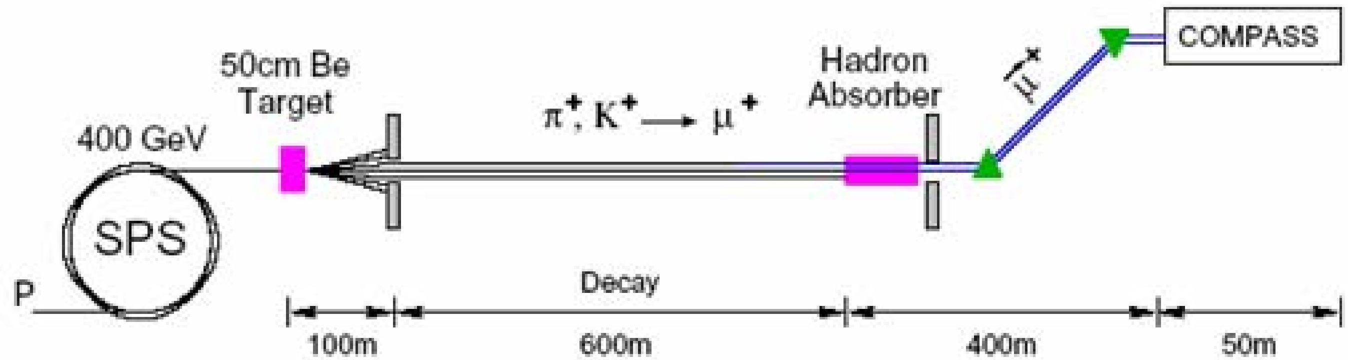


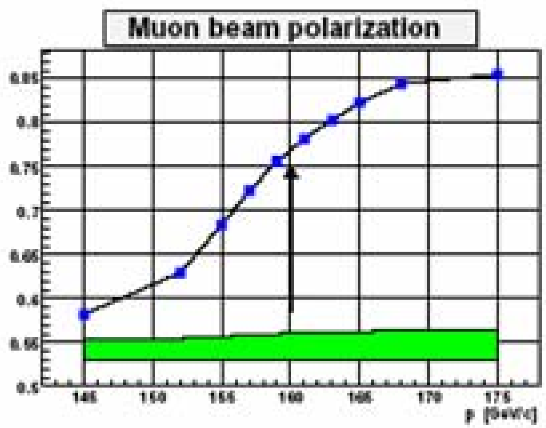
Spectrometer 2002

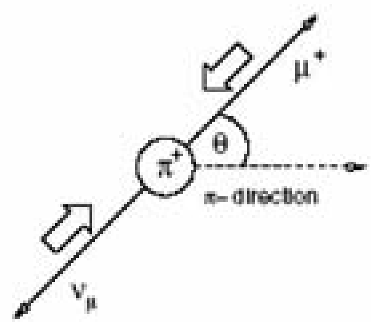


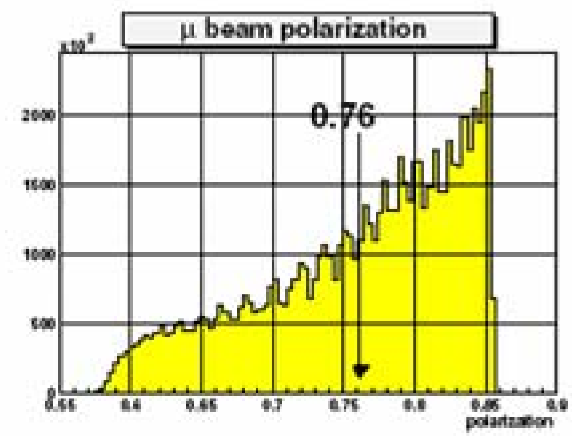
G. Mallot/CERN

The CERN Muon Beam



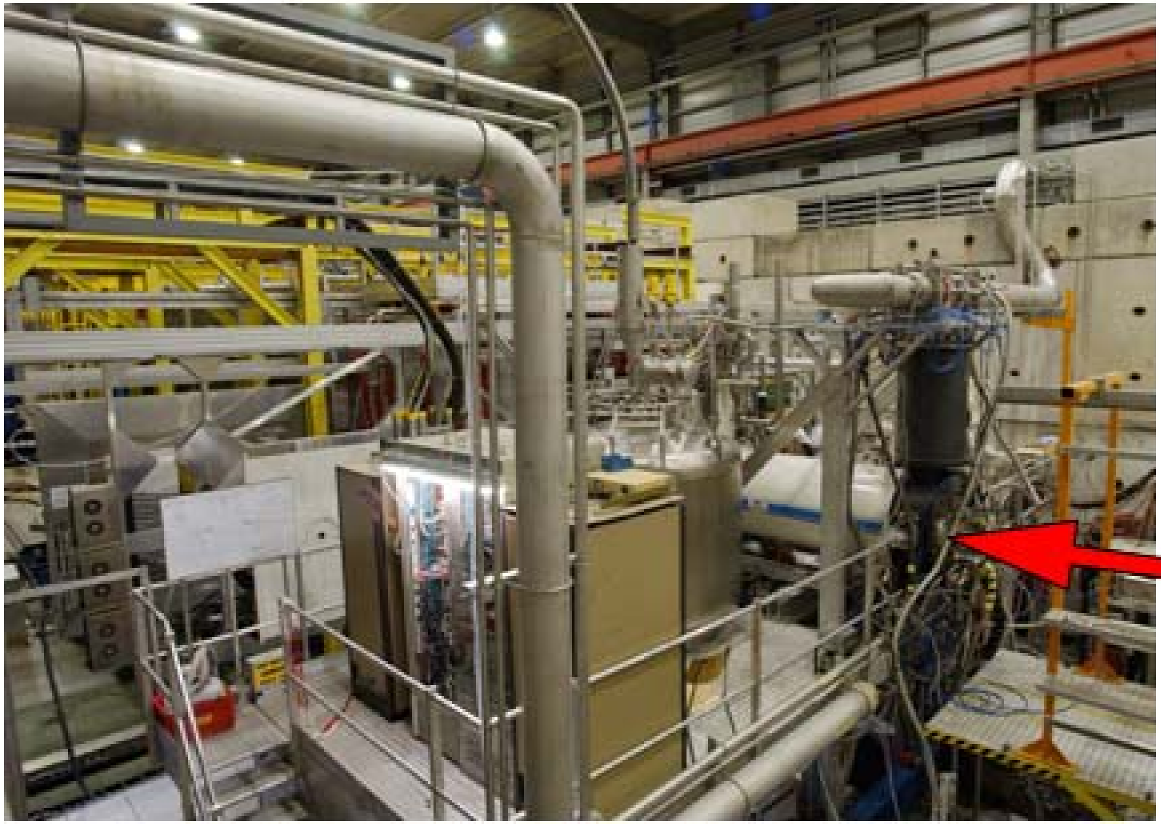






Energy	160 GeV
Intensity	$2 \cdot 10^8 \mu$/Spill
Polarisation	$\approx 76\,\%$

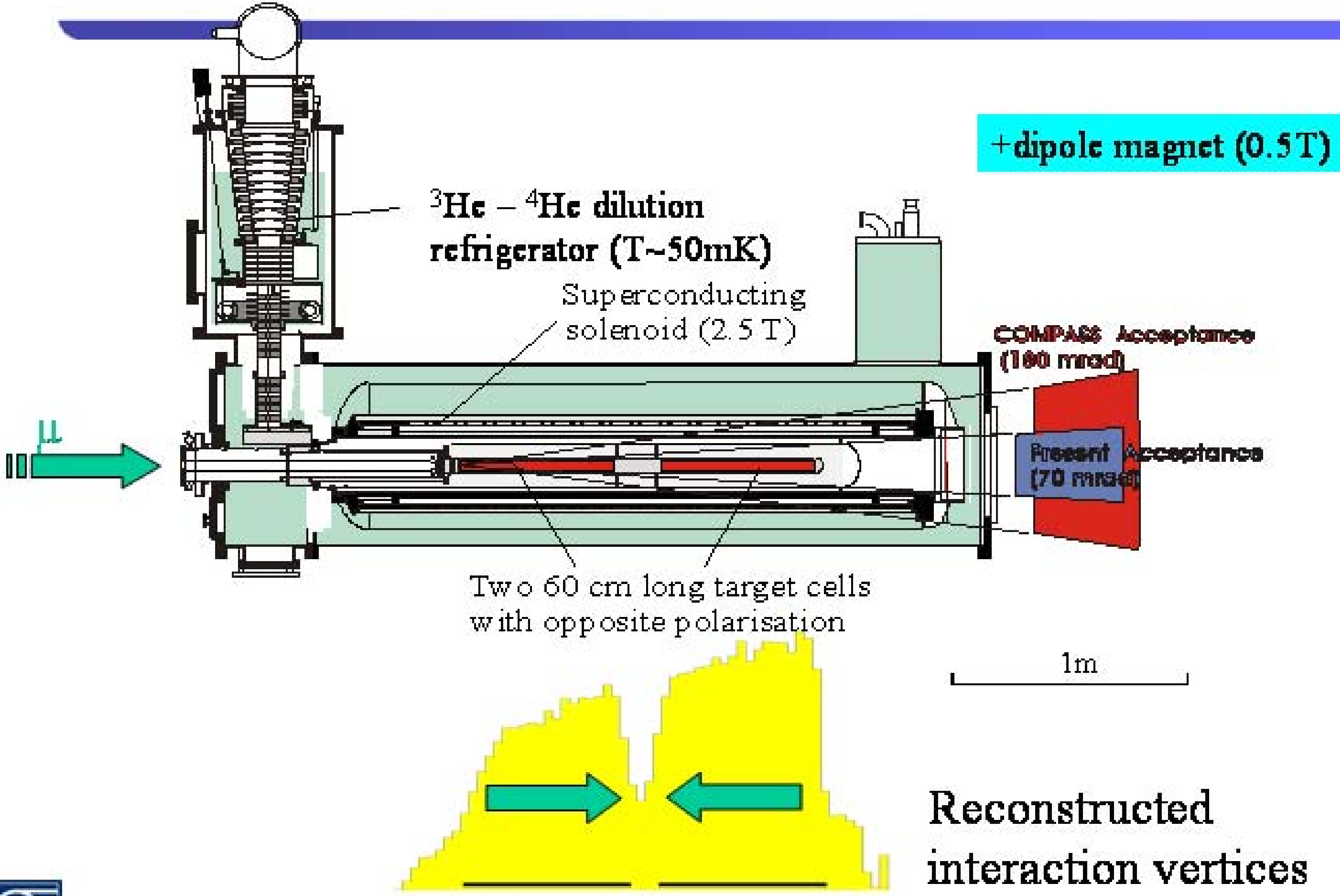
Polarised target



- ^{6}LiD
- ± 50 % polarisation
- 50 % dilution factor
- 2.5 T
- 50 mK

μ

Target system



Pol. DIS experiments

Spin Crisis → CERN EMC 85

Lab	Exp	Year	Energy	Beam	P_b	target	P_t	f	result
SLAC	E80	75	10–16 GeV	e^-	0.85	H-butanol	0.50	0.13	A_1^p
SLAC	E130	80	16–23 GeV	e^-	0.81	H-butanol	0.58	0.15	A_1^p
CERN	EMC	85	200 GeV	μ^+	0.79	NH_3	0.78	0.16	g_1^p
CERN	SMC	92	100 GeV	μ^+	0.81	D-butanol	0.40	0.19	g_1^d
SLAC	E142	92	19–26 GeV	e^-	0.39	^3He	0.35	0.12	g_1^n
CERN	SMC	93	190 GeV	μ^+	0.80	H-butanol	0.86	0.12	g_1^p, g_2^p
SLAC	E143	93	10–29 GeV	e^-	0.85	NH_3	0.70	0.15	g_1^p
SLAC	E143	93	10–29 GeV	e^-	0.85	ND_3	0.25	0.24	g_1^d
CERN	SMC	94/5	190 GeV	μ^+	0.80	D-butanol	0.50	0.20	g_1^d, g_2^d
SLAC	E154	95	48 GeV	e^-	0.83	^3He	0.38	0.18	g_1^n
DESY	HERMES	95	28 GeV	e^+	0.55	^3He	0.46	0.33	g_1^n
CERN	SMC	96	190 GeV	μ^+	0.80	NH_3	0.89	0.16	g_1^p
DESY	HERMES	96/97	28 GeV	e^+	0.55	H	0.88	1.00	g_1^p
SLAC	E155	97	48 GeV	e^-	0.81	NH_3	0.80	0.15	g_1^p
SLAC	E155	97	48 GeV	e^-	0.81	^6LiD	0.22	0.36	g_1^d
DESY	HERMES	98–00	28 GeV	$e^\pm$	0.55	D	0.85	1.00	g_1^d, b_1^d
SLAC	E155X	99	29/32 GeV	e^-	0.81	NH_3	0.70	0.16	g_2^p
SLAC	E155X	99	29/32 GeV	e^-	0.81	^6LiD	0.22	0.36	g_2^d
DESY	HERMES	≥ 01	28 GeV	$e^\pm$	0.55	H	0.85	1.00	
CERN	COMPASS	≥ 01	160 GeV	μ^+	0.80	^6LiD	0.50	0.40	
BNL	RHIC	≥ 01	coll.	p		p		1.00	

running (DESY HERMES, CERN COMPASS, BNL RHIC)