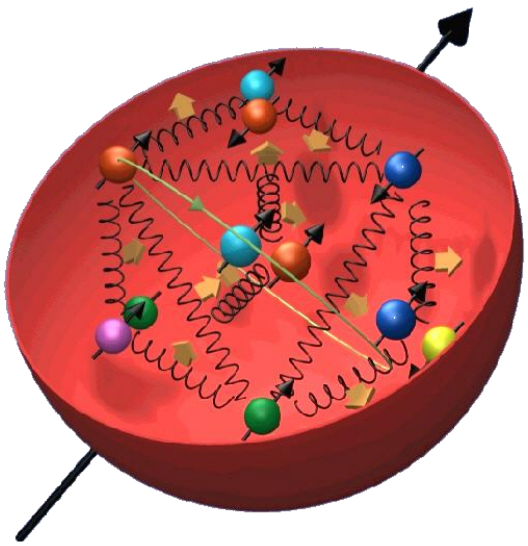
The Nucleon Spin Structure

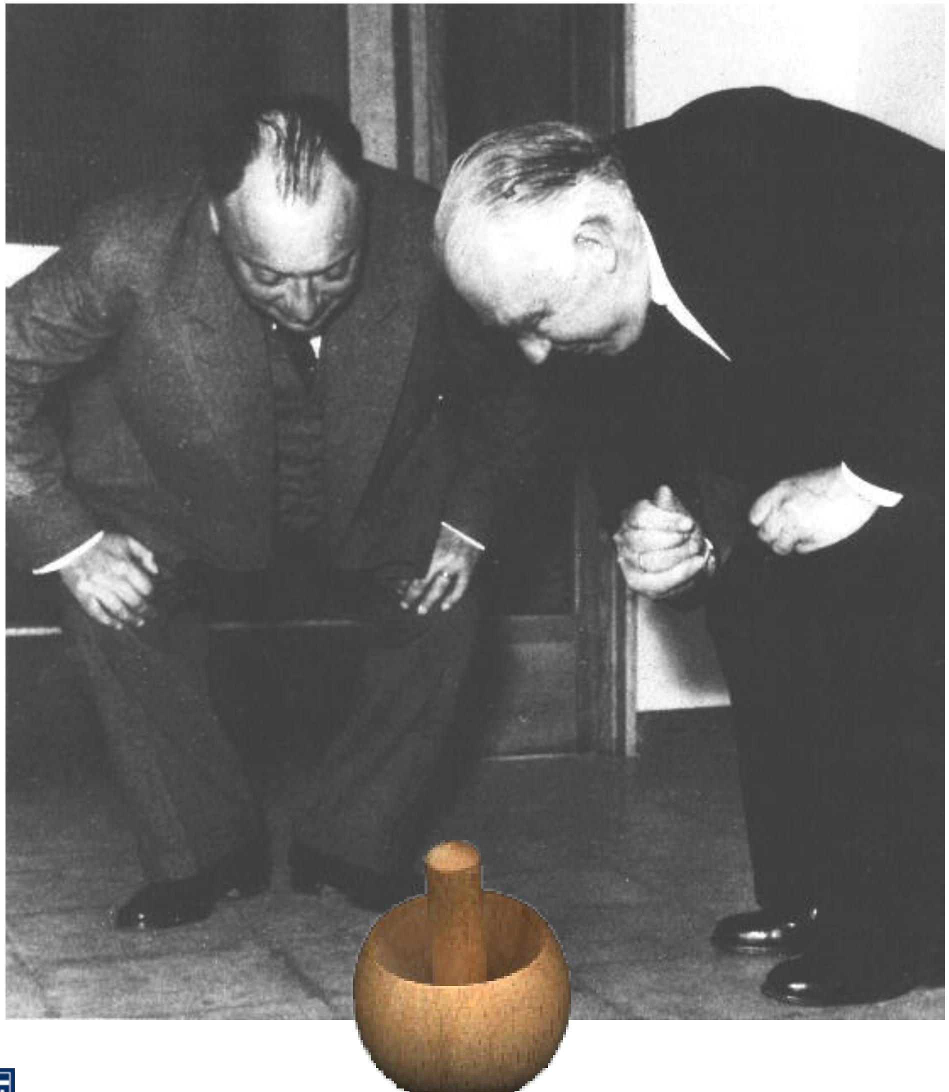


Gerhard Mallot

Plan

- Lecture I
  - Introduction
  - DIS and structure functions, sum rules
  - Why contribute the quark spin so little?
  - Principle of measurements, experiments

Spin Experiments are Puzzling



Wolfgang Pauli and Niels Bohr, 1954

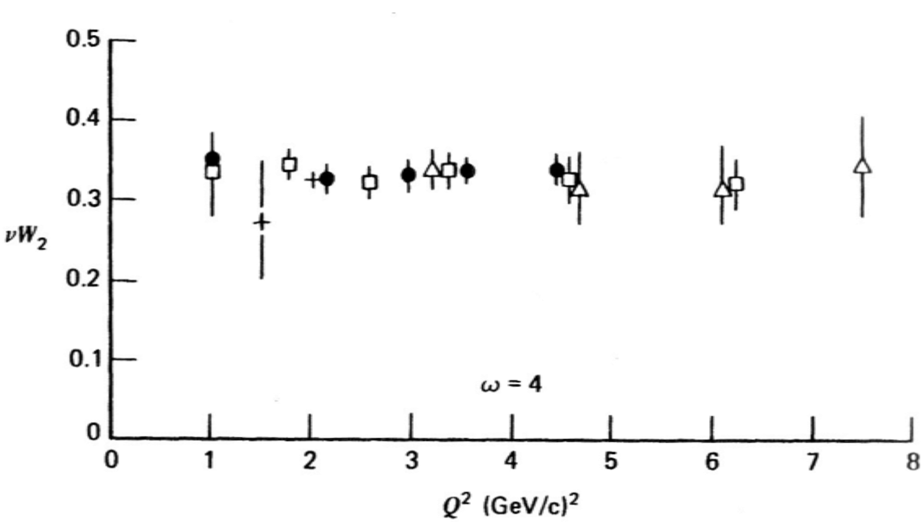
wondering about a tippe top toy

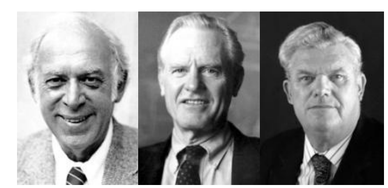
A theory of the nucleon needs to describe the dynamics of quarks and gluons including spin.

Imagine the theory of the atom without spin!

1. Introduction

- electron scattering at SLAC in the late 1960ies revealed point-like partons in the nucleon → quarks
- structure function is Q^2 independent (scaling)





Friedman, Kendall, Taylor

1990

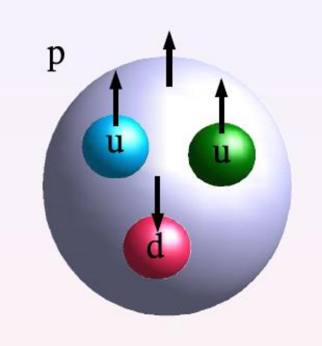
Quark model wave function

$SU_{spin}(2) \times SU_{flavour}(3)$

$$|p\uparrow\rangle = \frac{1}{\sqrt{18}}\Big\{2|u\uparrow u\uparrow d\downarrow\rangle - |u\uparrow u\downarrow d\uparrow\rangle - |u\downarrow u\uparrow d\uparrow\rangle + (u \leftrightarrow d)\Big\}$$

$$\Delta u = \langle p\uparrow|N_{u\uparrow} - N_{u\downarrow}|p\uparrow\rangle = \tfrac{3}{18}(10-2) = \tfrac{4}{3}$$

$$\Delta d = \langle p\uparrow|N_{d\uparrow} - N_{d\downarrow}|p\uparrow\rangle = \tfrac{3}{18}(2-4) = -\tfrac{1}{3}$$



$$\Delta\Sigma = \Delta u + \Delta d = 1$$

→ up and down quarks carry the nucleon spin!

Weak baryon decays

- weak decay constants are linked to quark polarisations via the axial vector currents matrix elements

$$2MS_\mu \Delta q = \langle P,S|\bar{q}\gamma_\mu\gamma_5 q|P,S\rangle$$

- SU(3) flavour symmetry assumed

Decay $A \to B\ell\nu$	Rate($10^6\,\mathrm{s}^{-1}$) $\ell = e^{\pm}$	Rate($10^6\,\mathrm{s}^{-1}$) $\ell = \mu^-$	g_1/f_1 $\ell = e^-$	
$n \to p$	1.1291 ± 0.0010		1.2670 ± 0.0030	$\Delta u - \Delta d$
$\Lambda^0 \to p$	3.161 ± 0.058	0.60 ± 0.13	0.718 ± 0.015	$2\Delta u - \Delta d - \Delta s$
$\Sigma^- \to n$	6.88 ± 0.23	3.04 ± 0.27	-0.340 ± 0.017	$\Delta d - \Delta s$
$\Sigma^- \to \Lambda^0$	0.387 ± 0.018			
$\Sigma^+ \to \Lambda^0$	0.250 ± 0.063			
$\Xi^- \to \Lambda^0$	3.35 ± 0.37	2.1 ± 2.1	0.25 ± 0.05	$\Delta u + \Delta d - 2\Delta s$
$\Xi^- \to \Sigma^0$	0.53 ± 0.10			$\Delta u - \Delta d$
$\Xi^0 \to \Sigma^+$	0.876 ± 0.071	0.012 ± 0.007 *	1.32 ± 0.21	$\Delta u - \Delta d$

P. Ratcliffe, Czech. J. Phys. 54 (2004)

From weak baryon decays

Fit to decay data:

$$\Delta u + \Delta d - 2\Delta s = 0.58 \pm 0.03 \qquad (\Xi^- \to \Lambda)$$

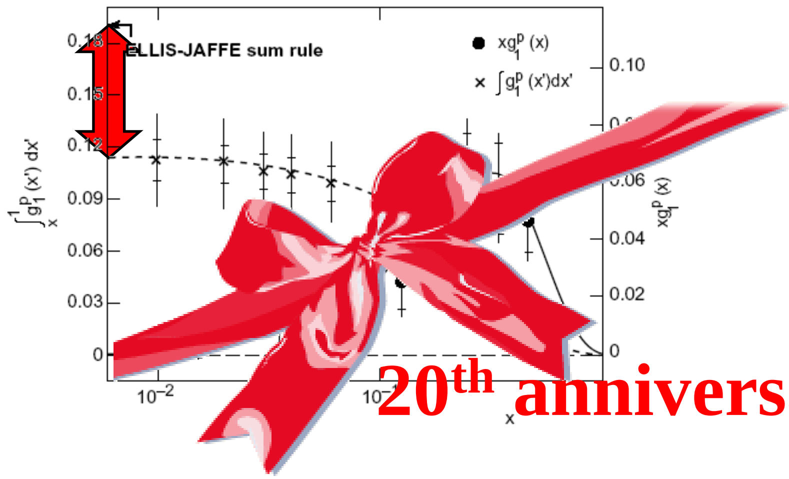
assuming $\Delta s = 0$:

$$\Delta\Sigma = \Delta u + \Delta d = 0.58 \pm 0.03$$

→ up and down quarks carry 58% of the nucleon spin!

deviation from 100% due to relativistic motion

Spin puzzle: EMC 1987



20th anniversary

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

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.12 \pm 0.17$$

$$\Delta s = -0.19 \pm 0.06$$

→ quark spin contribution to nucleon spin is consistent with zero! Strange quark polarisation negative.

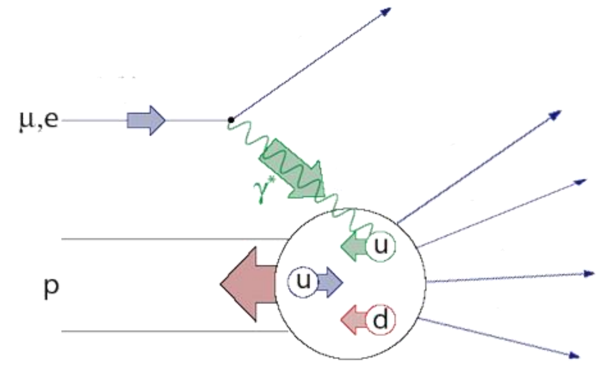
2. DIS and structure functions

- What did the EMC actually measure?
- How severe is the spin puzzle?
- Can the Quark Model expectation

$$\Delta\Sigma = 0.6$$

be restored?

Deep inelastic scattering

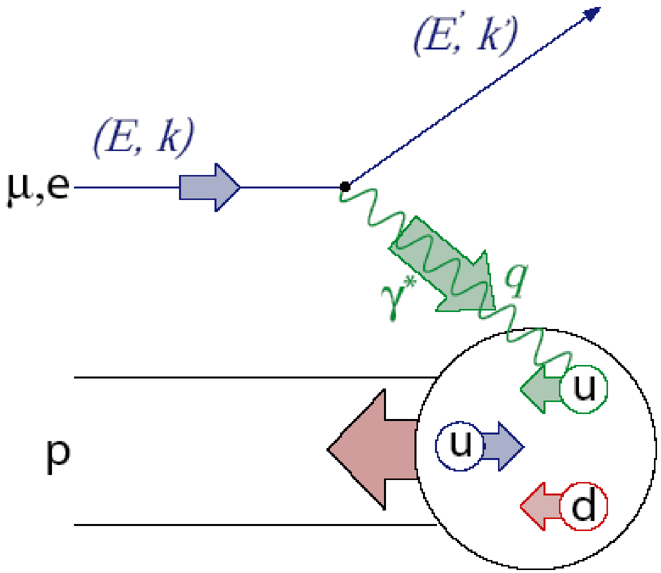


- probing partons

$$\ell N \rightarrow \ell' X$$

  - inclusive lepton – nucleon scattering
  - large momentum and energy transfer Q^2 and ν
  - finite ratio Q^2/ν
  - large c.m. energy of the hadronic final state $W > 2$ GeV

Deep Inelastic Scattering



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

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

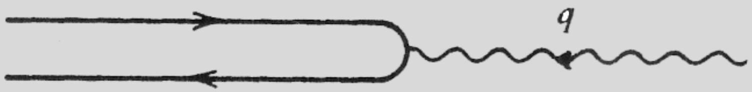
$$P\cdot k \stackrel{lab}{=} ME$$

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

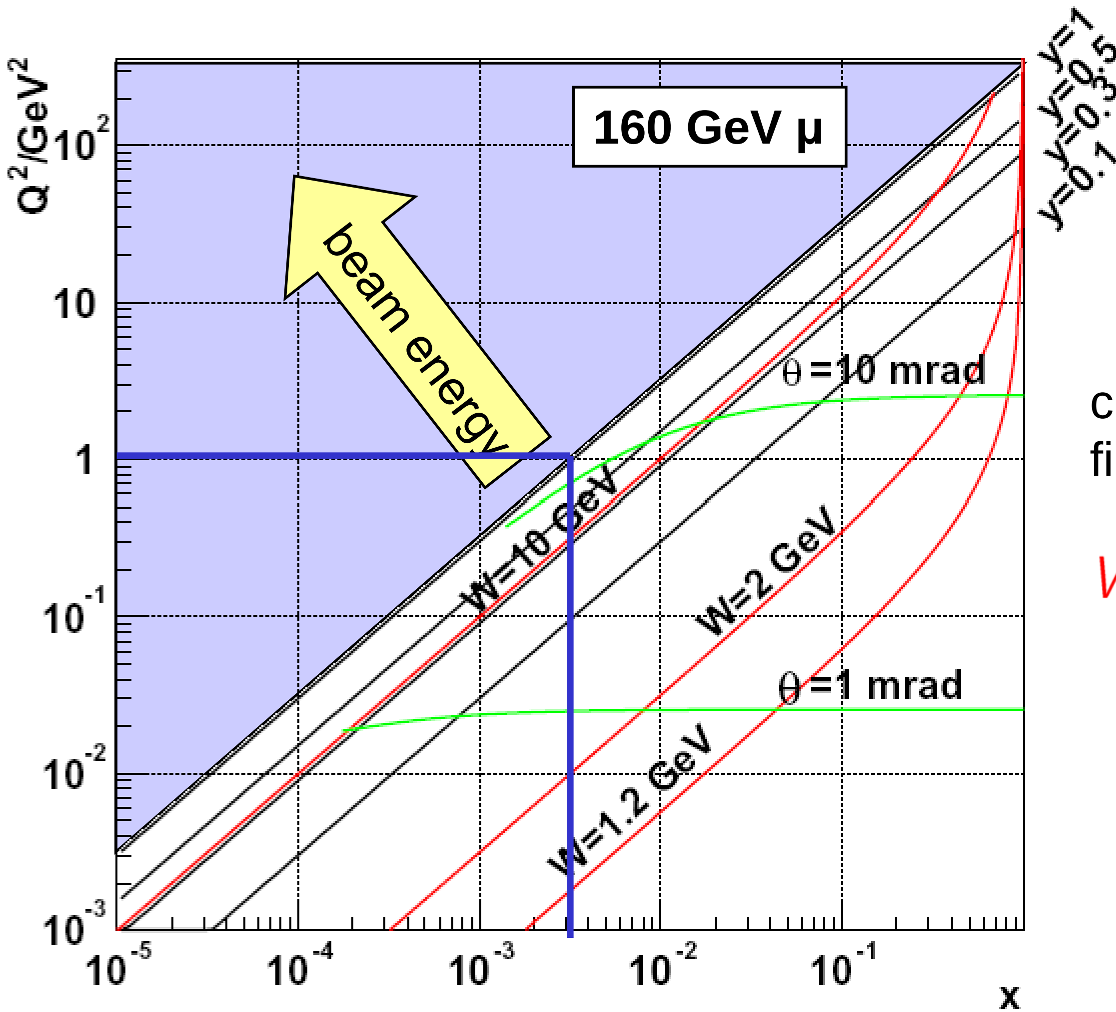
$$y \stackrel{lab}{=} \frac{\nu}{E} = \frac{P\cdot q}{P\cdot k}$$

$$0 \le x, y \le 1$$

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



Kinematics



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

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

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

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

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

Distance scales

- longitudial $1/Mx$
- transverse $1/\sqrt{Q^2}$

- for $x \simeq 0.2$ the longitudinal scale is 1 fm
- for $Q^2 = 1\ (\mathrm{GeV}/c)^2$ the transverse scale is 0.2 fm

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

factorise

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

Quark-Parton Model

- in the QPM: $W^{\mu\nu}$ for massless spin-½ partons

$$F_1(x) = \frac{1}{2} \sum_i e_i^2 \left\{ q_i^+(x) + q_i^-(x) \right\}$$

$$F_2(x) = x \sum_i e_i^2 \left\{ q_i^+(x) + q_i^-(x) \right\}$$

unpolarised SF,
momentum distributions

$$g_1(x) = \frac{1}{2} \sum_i e_i^2 \left\{ q_i^+(x) - q_i^-(x) \right\}$$

$$g_2(x) = 0$$

polarised SF,
spin distributions

- no Q^2 dependence (scaling)
- Calan−Gross relation $F_2(x) = 2xF_1(x)$
- g_2 twist-3 quark−gluon correlations

Sum rules for g_1

- first moment Γ_1 of g_1 with $\Delta q = \int_0^1 \Delta q(x)\mathrm{d}x$

$$\Gamma_1 = \int_0^1 g_1(x)\mathrm{d}x \overset{proton}{=} \frac{1}{2}\left\{\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right\}$$

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

Neutron decay
$a_3 = g_a$

Hyperon decay
(3F-D)/3

$\Delta\Sigma$

From Γ_1, a_3 and a_8 we obtain $\Delta\Sigma$ without assuming $\Delta s = 0$

Sum Rules

Bjorken sum rule

PR 148 (1966) 1467

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

if wrong ⇒ QCD wrong, “worthless equation”, needs neutron measurement

Ellis-Jaffe sum rule

PR D9 (1974) 1444

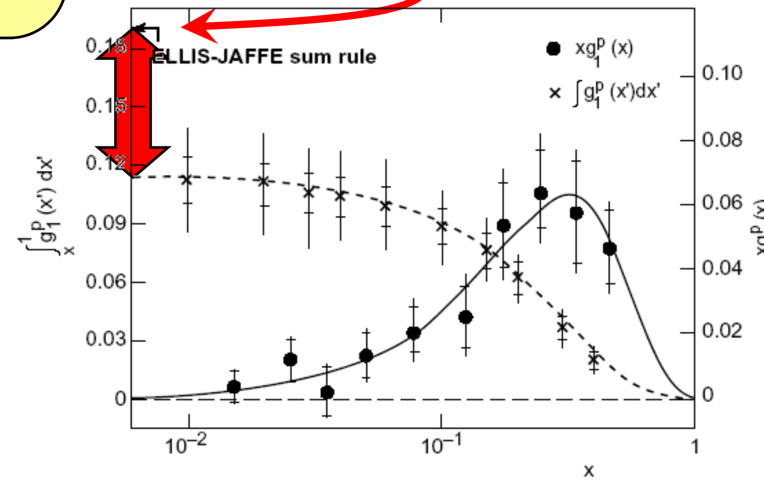
$$\Gamma_1^{\mathrm{p}} = \frac{1}{12} g_a + \frac{5}{36}\sqrt{3} a_8 + \frac{1}{3}\Delta s \quad \Rightarrow \quad \Delta\Sigma \simeq 0.6$$

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

Consequences of violation:

$$\begin{aligned} \Delta s &= -0.19 \pm 0.06 \\ \Delta\Sigma &= 0.12 \pm 0.17 \end{aligned}$$

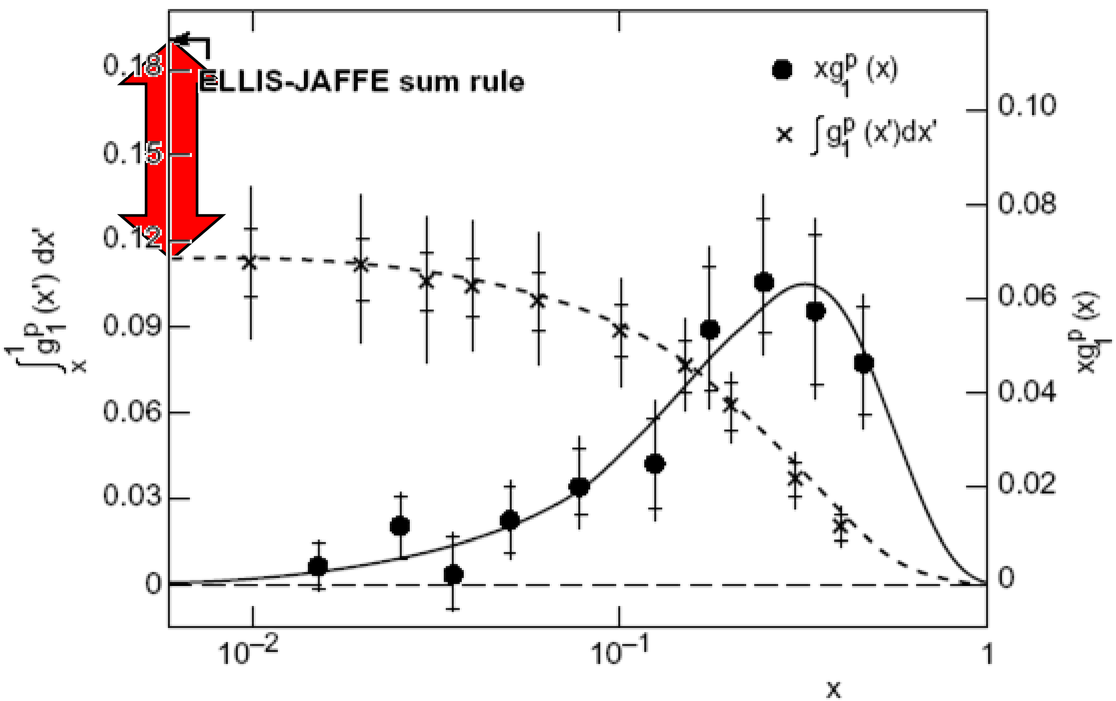
EMC 1987



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

3. Why is ΔΣ so small

(1988)

CHIRAL SYMMETRY AND THE SPIN OF THE PROTON ☆

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PLB 206 (1988) 309

A crisis in the parton model: where, oh where is the proton's spin?

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Received 18 March 1988

ZPC 41 (1988) 239

E2-88-287

A.V.Efremov, O.V.Teryaev*

SPIN STRUCTURE OF THE NUCLEON AND TRIANGLE ANOMALY

THE ANOMALOUS GLUON CONTRIBUTION TO POLARIZED LEPTOPRODUCTION

G. ALTARELLI and G.G. ROSS [1]
CERN, CH-1211 Geneva 23, Switzerland

Received 29 June 1988

PLB 212 (1988) 391

Considered Options

- Skyrmions: model,
  all orbital angl. mom. (BEK) maybe

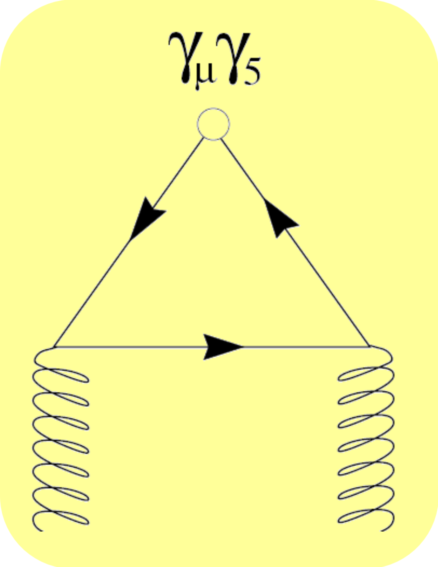
- Bjorken sum rule broken?
  Measurement wrong? (LA) no!

- Large ΔG ~ 2-3-6 at EMC Q^2 could mask quark spin via axial anomaly (ET, AR) measure gluon!

requires fine tuning of cancelation of ΔG and orbital angular momentum (orb. ang. mom. is generated at gluon emision)

Axial anomaly contribution

- The contribution of the quark spins $\Delta\Sigma$ is NOT an observable. The observable is a_0, the flavour-singlet axial vector ME.
- The singlet axial vector current is not conserved and receives a gluon contribution via the **axial anomaly** (à la $\pi^0 \rightarrow 2\gamma$). The contribution vanishes for the triplet and octet currents.
- A conserved current can be constructed in next-to-leading order QCD by subtracting the anomalous gluon contribution, however , not in a gauge invariant way.
- The corresponding ME is then independent of Q^2.



Axial anomaly (continued)

- in the $\overline{\text{MS}}$ renormalisation scheme

$$a_0 = \Delta\Sigma_{\text{MS}}$$

- in the so-called Alder–Bardeen and the jet scheme:

$$a_0 = \Delta\Sigma_{\text{AB}} - n_f \frac{\alpha_s}{2\pi} \Delta G$$

- thus a large gluon polarisation could mask the quark spin contribution to the nucleon spin and the parton model value of 0.6 could be restored by $\Delta\Sigma_{\text{AB}}$

Lepton-Photon 1989

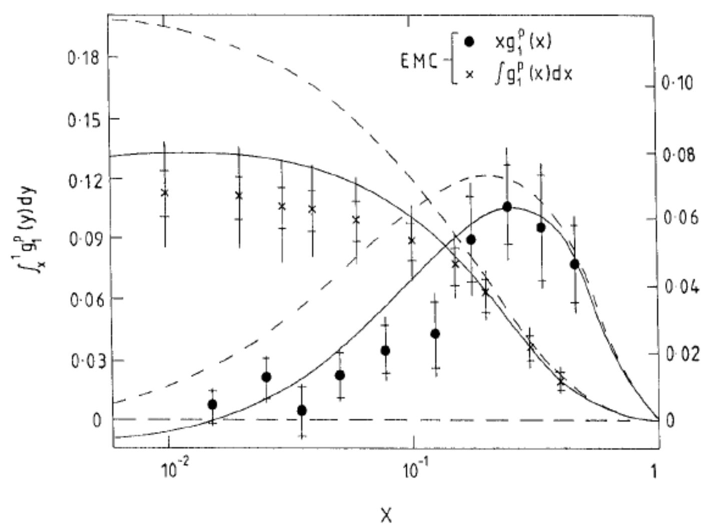
To summarise, let us return to the fit of Fig. 7 and 8. At Q^2=10GeV^2 this corresponds to Δg=6.3 and so the proton helicity is given by

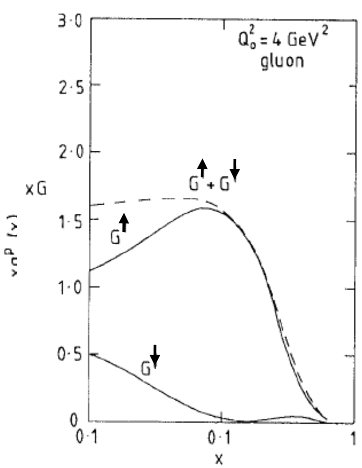
$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta g + L_z$$

$$= 0.35 + 6.3 - 6.15$$

R.G. Ross 1989

Need $\Delta G \approx 6$ at
$Q^2 = 10$ GeV^2
for $\Delta\Sigma = 0.7$,
to be compared to ½
=> measure ΔG



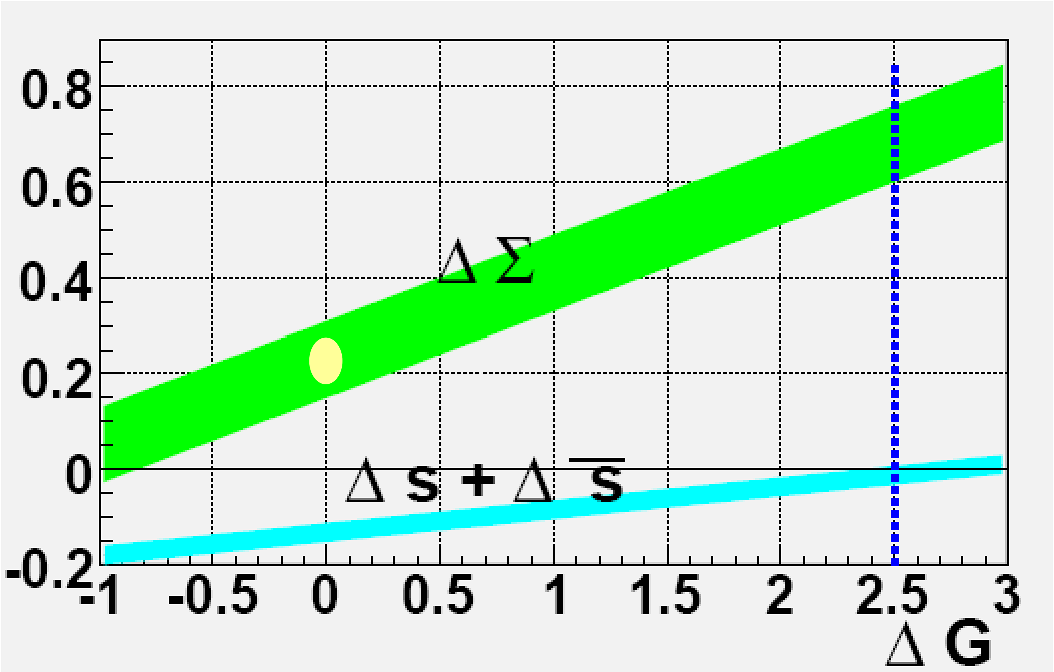


ΔG and ΔΣ in AB/jet scheme

$$\Delta\Sigma \leftarrow a_0 + \frac{3\alpha_s}{2\pi}\Delta G$$

$$\Delta s \leftarrow \Delta s + \frac{3\alpha_s}{2\pi}\Delta G$$

α_s strong coupling constant



Now:

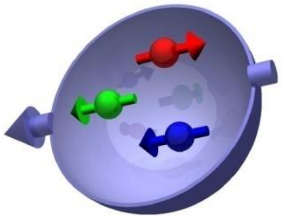
$a_0 \simeq 0.3$

Need:

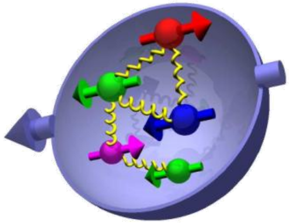
$\Delta G \simeq 2.5$

Spin sum rule

- naive QPM: only valence quarks Δq_v

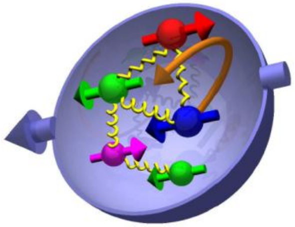


- QCD: sea quarks and gluons $\Delta q_s, \; \Delta g$



gluons carry 50% of momentum!

- orbital angular momentum: $L_q, \; L_g$



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

Where is the proton spin?

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

small

poorly known
certainly not 6

unknown

Riddle

What is similar and what is different between the following two sets?:
The first set consists of a farmer, his pig and the truffles:

The second set consists of the theorist, the experimentalist and the big discoveries

A. De Rújula

not an experimentalist!

Answer

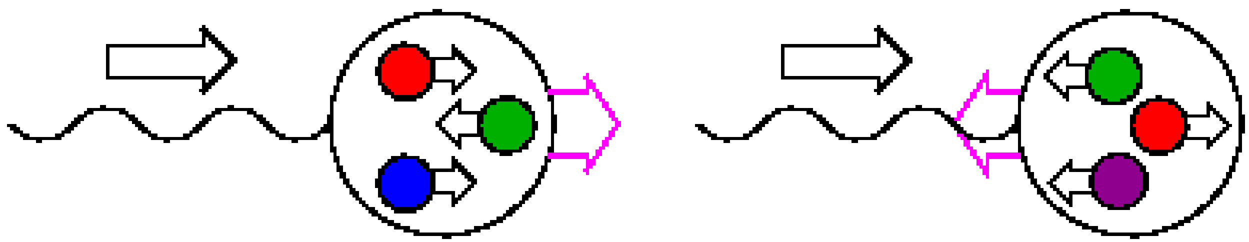
- The farmer takes his pig to the woods. The pig snifs around looking for a truffle. When the pig gets it and is about to eat it, the farmer kicks the pig on the head with his club and steals the truffle. Those are the similarities…
- The difference is that the farmer always takes the pig to woods where there are truffles, while more often than not, the suggestions by the theorists take the experimentalists to "woods" where there are no “truffles”…
- … often while looking for the theorists' “truffles” the experimentalists find “gold”…

http://public.web.cern.ch/Public/Content/Chapters/AboutCERN/WhoWorksThere/ThinkersMakers/Theorists/Theorists-en.html

4. Principle of measurements

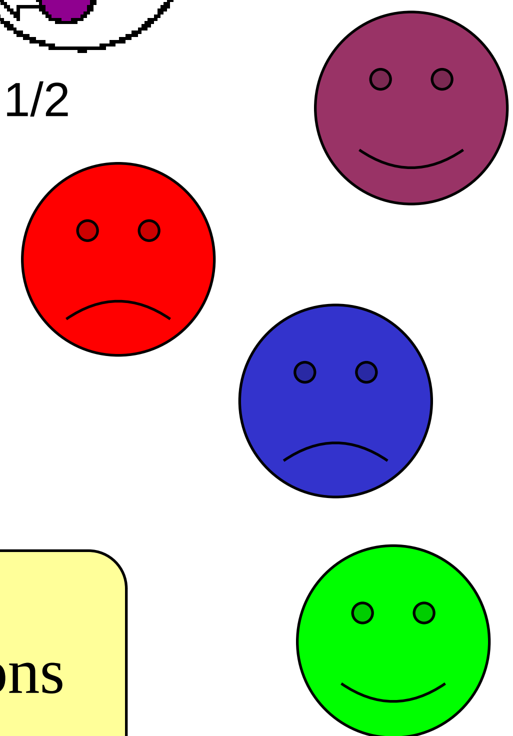
- Photoabsorption:

(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

Cross Section Asymmetries

unpolarised:

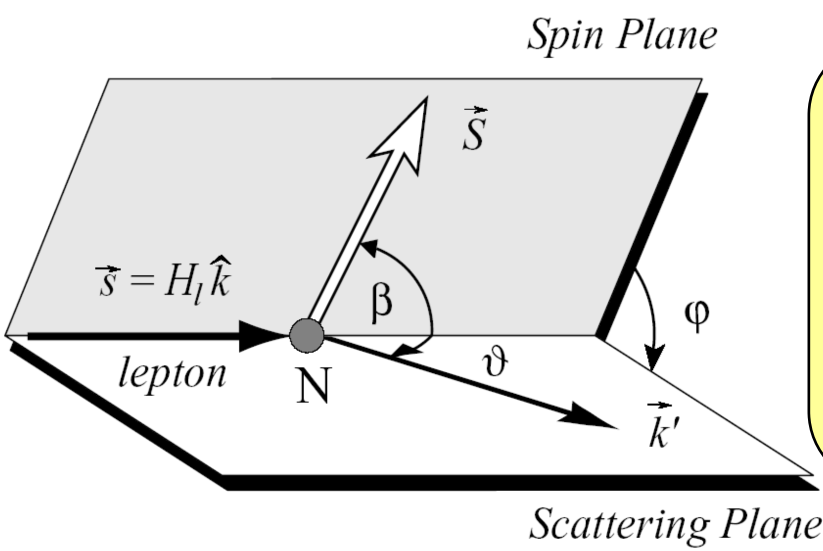
$$\frac{d^3\overline{\sigma}}{dx\,dy\,d\varphi} = \frac{4\alpha^2}{Q^2}\left\{\frac{y}{2}F_1 + \frac{1}{2xy}\left(1-y-\frac{y^2\gamma^2}{4}\right)F_2\right\}$$

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:

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

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

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
  - measurable asymmetries very small
  - need excellent control of fake asymmetries, e.g. time variations of detector efficiency

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
(RHIC	100 – 100 GeV		pp collider	)

- fake asymmetries:
  - rapid variation of beam polarisation (SLAC)
  - rapid variation of target polarisation (HERMES)
  - simultaneous measurement of two oppositely polarised targets (CERN)
  - bunch trains of different polarisation (RHIC)

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

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

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

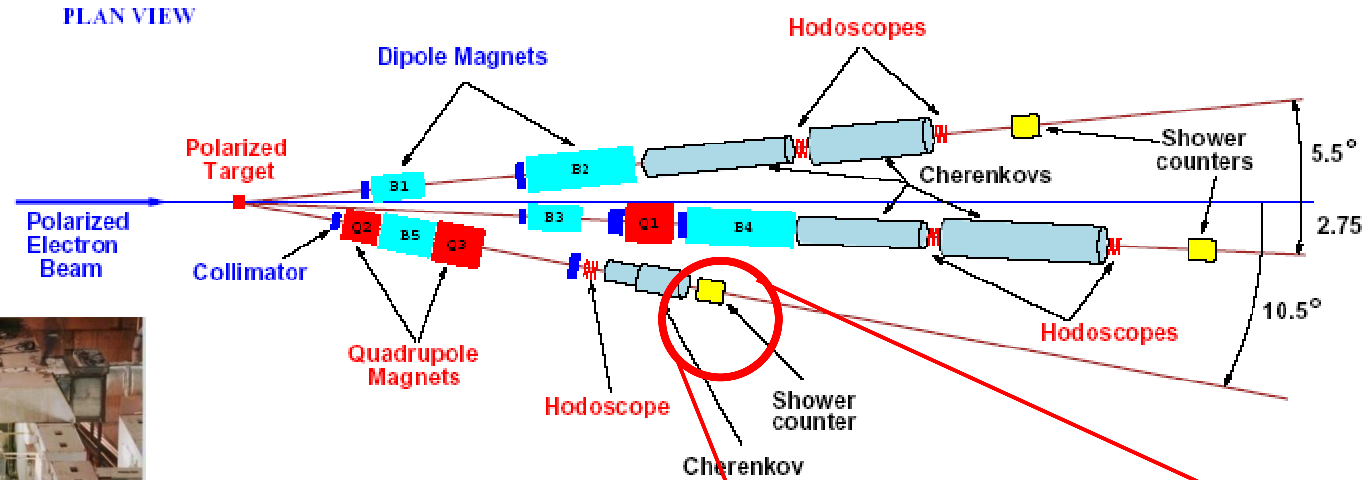
Pol. DIS experiments

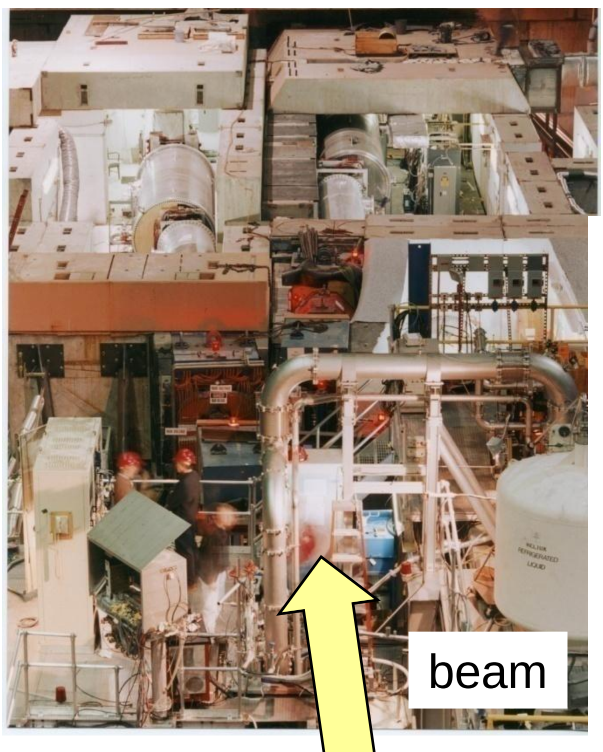
Spin Crisis

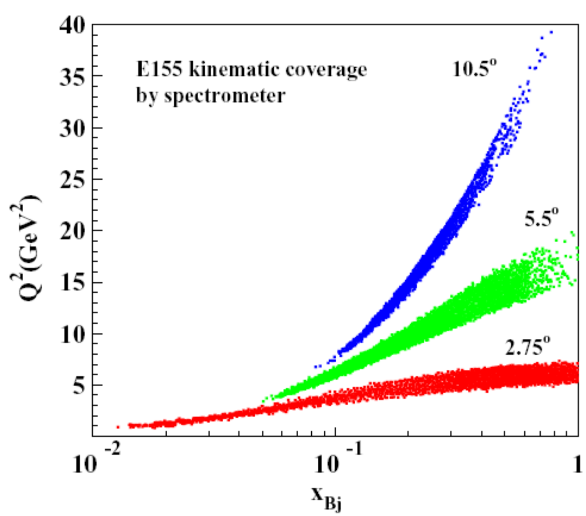
running

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	$\geq$ 01	28 GeV	$e^\pm$	0.55	H/D	0.85	1.00	
CERN	COMPASS	$\geq$ 01	160 GeV	μ^+	0.80	^6LiD	0.50	0.40	
BNL	RHIC	$\geq$ 01	coll.	p		p		1.00	

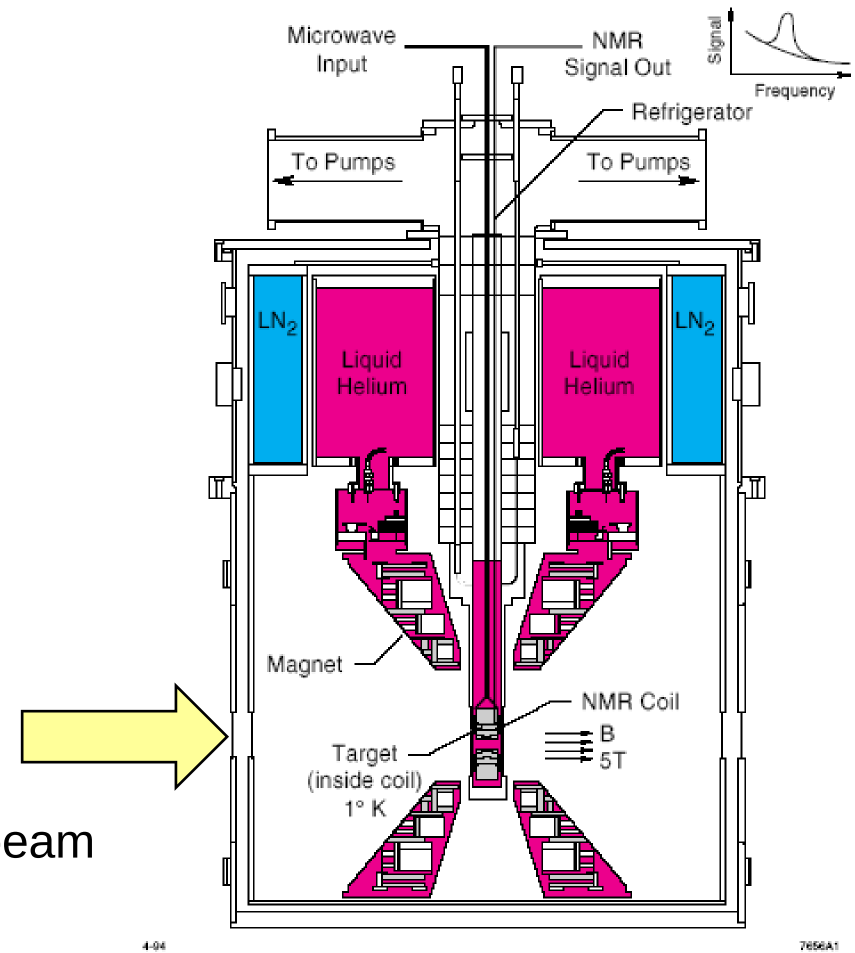
SLAC E155 Spectrometer







E155 Target

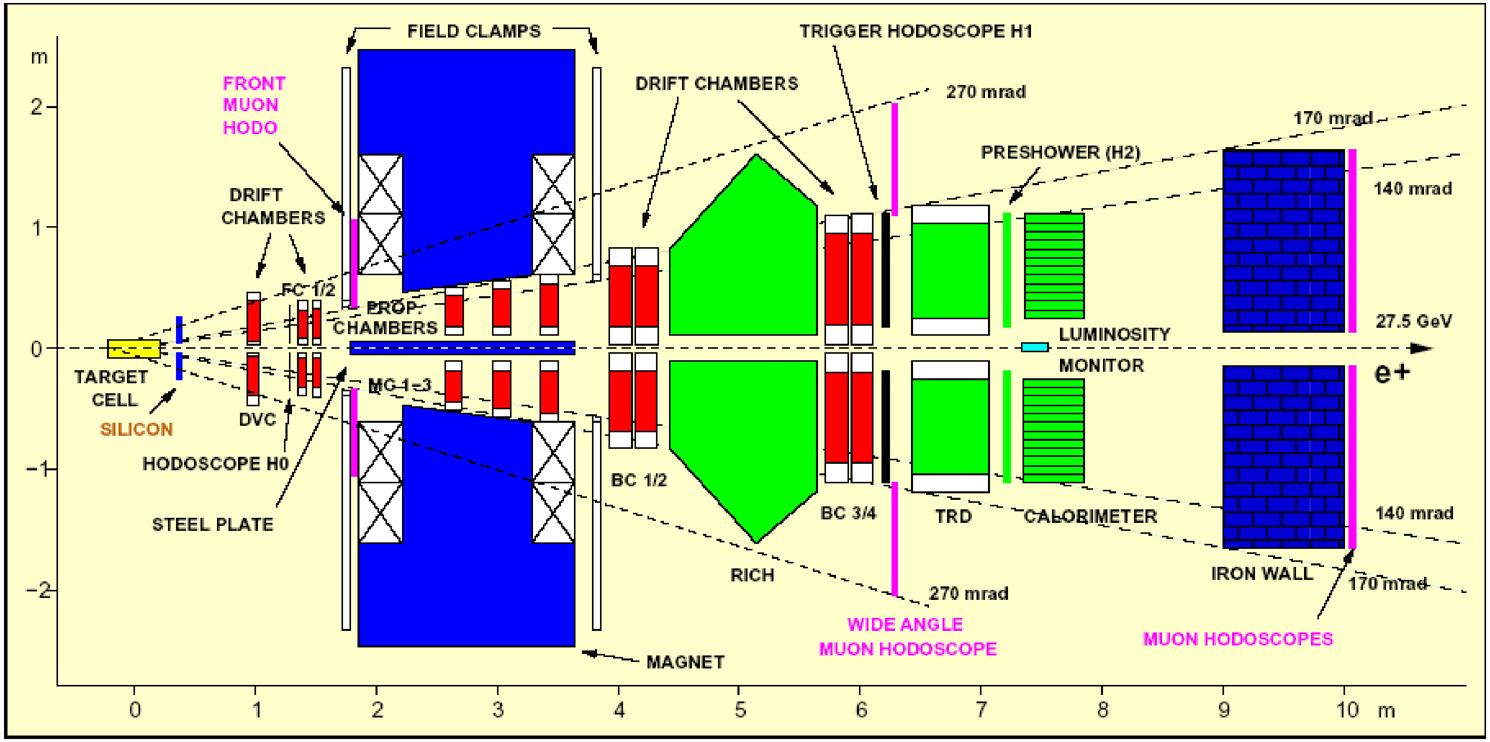


beam

cryogenic target
^{6}LiD, NH_3

1K evaporator fridge
5 T magnetic field

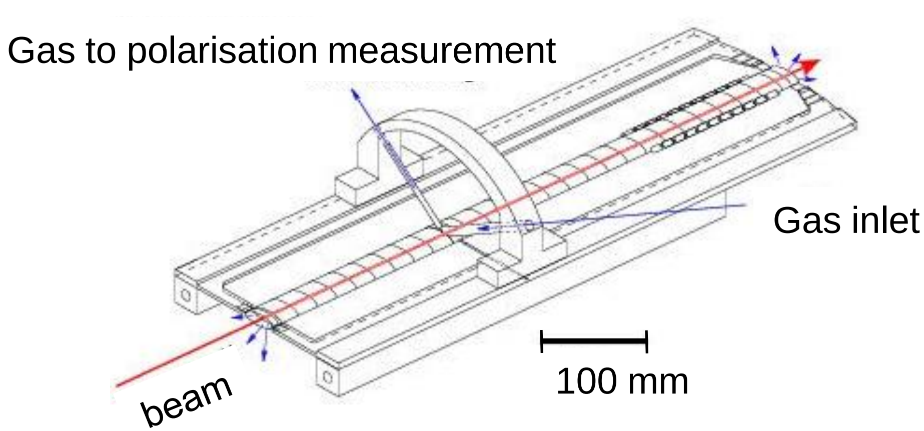
HERMES

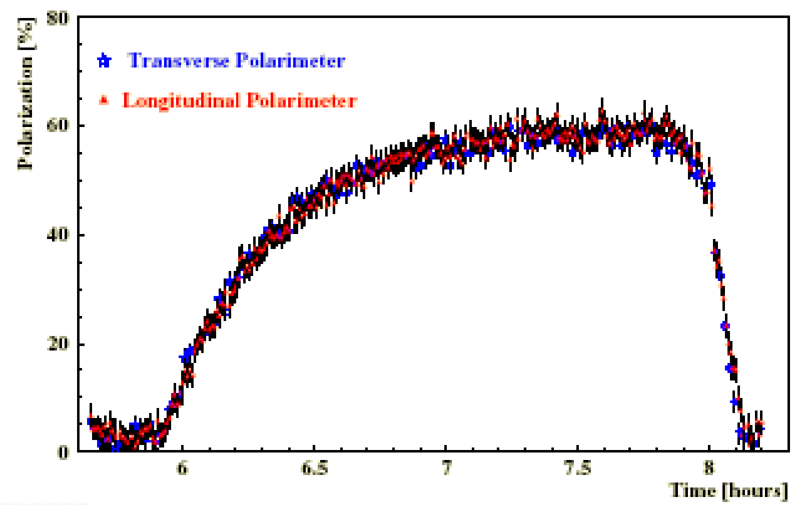


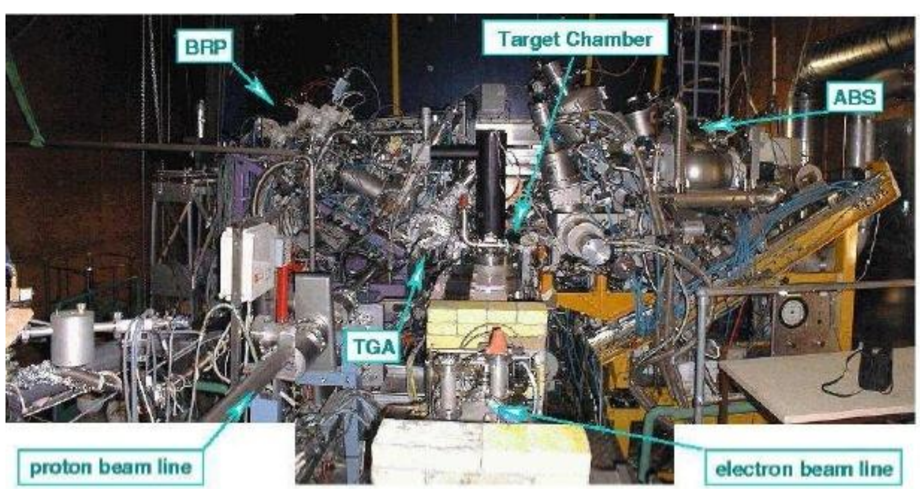
FIELD CLAMPS
TRIGGER HODOSCOPE H1
DRIFT CHAMBERS
270 mrad
170 mrad
FRONT MUON HODO
PRESHOWER (H2)
140 mrad
DRIFT CHAMBERS
FC 1/2
PROP. CHAMBERS
27.5 GeV
LUMINOSITY MONITOR
e+
TARGET CELL
SILICON
DVC
MC 1-3
HODOSCOPE H0
BC 1/2
BC 3/4
TRD
CALORIMETER
140 mrad
STEEL PLATE
RICH
IRON WALL
170 mrad
270 mrad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

HERMES

Target cell

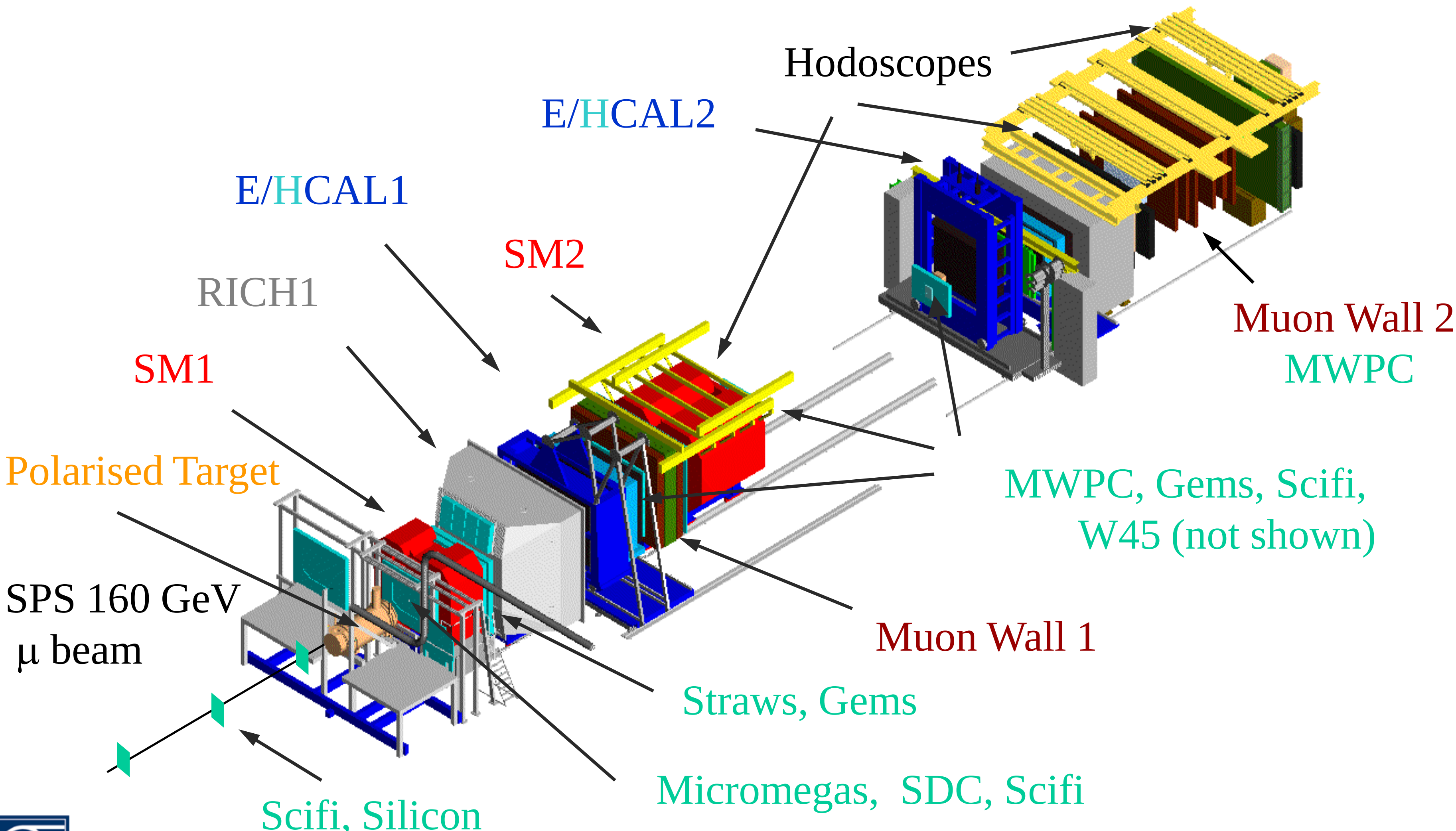




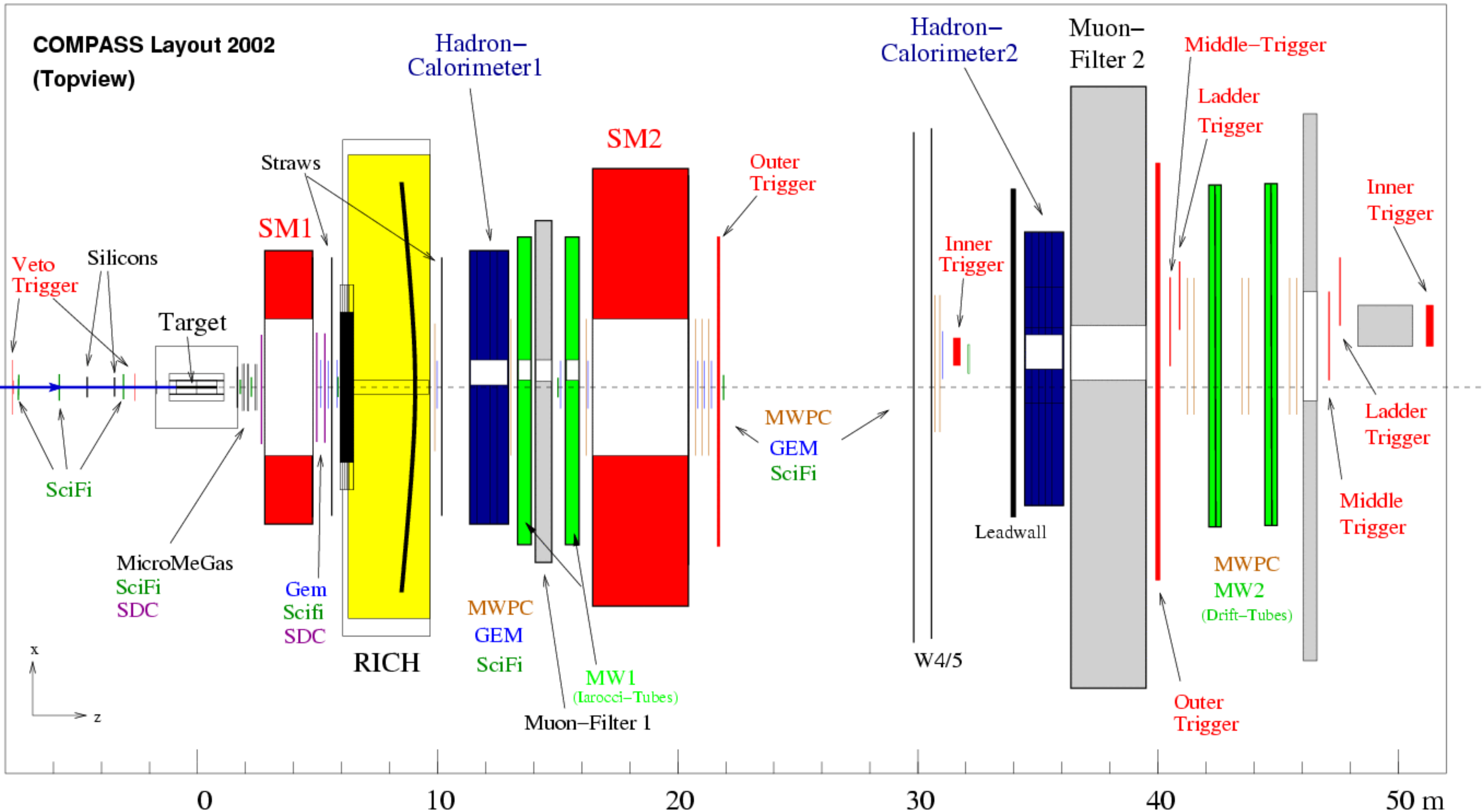


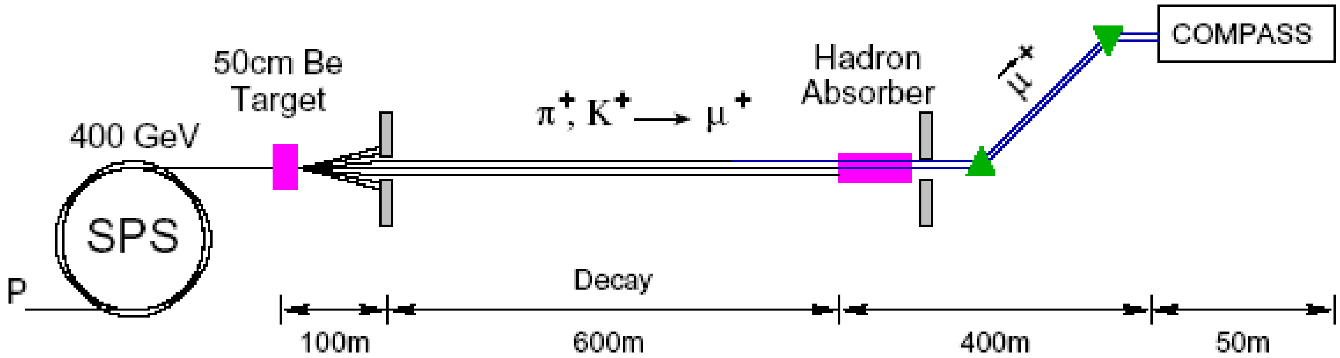
beam polarisation built-up by Sokolov-Ternov effect

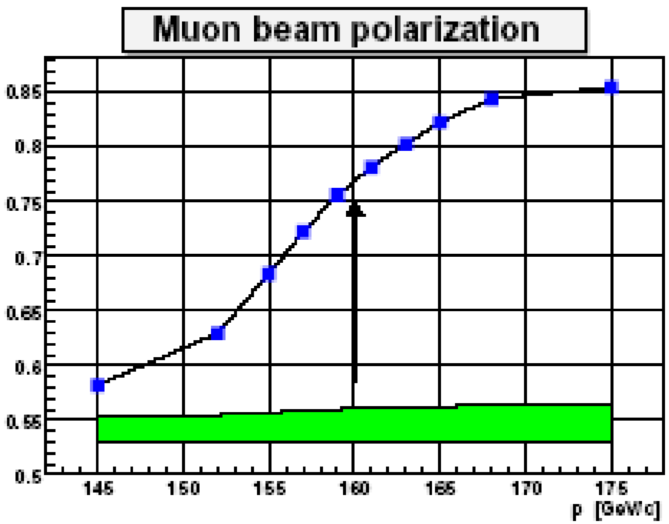
The COMPASS Spectrometer

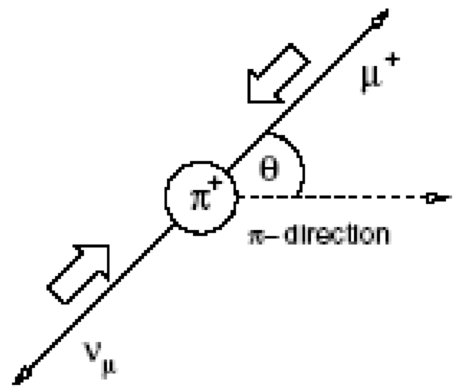


Spectrometer





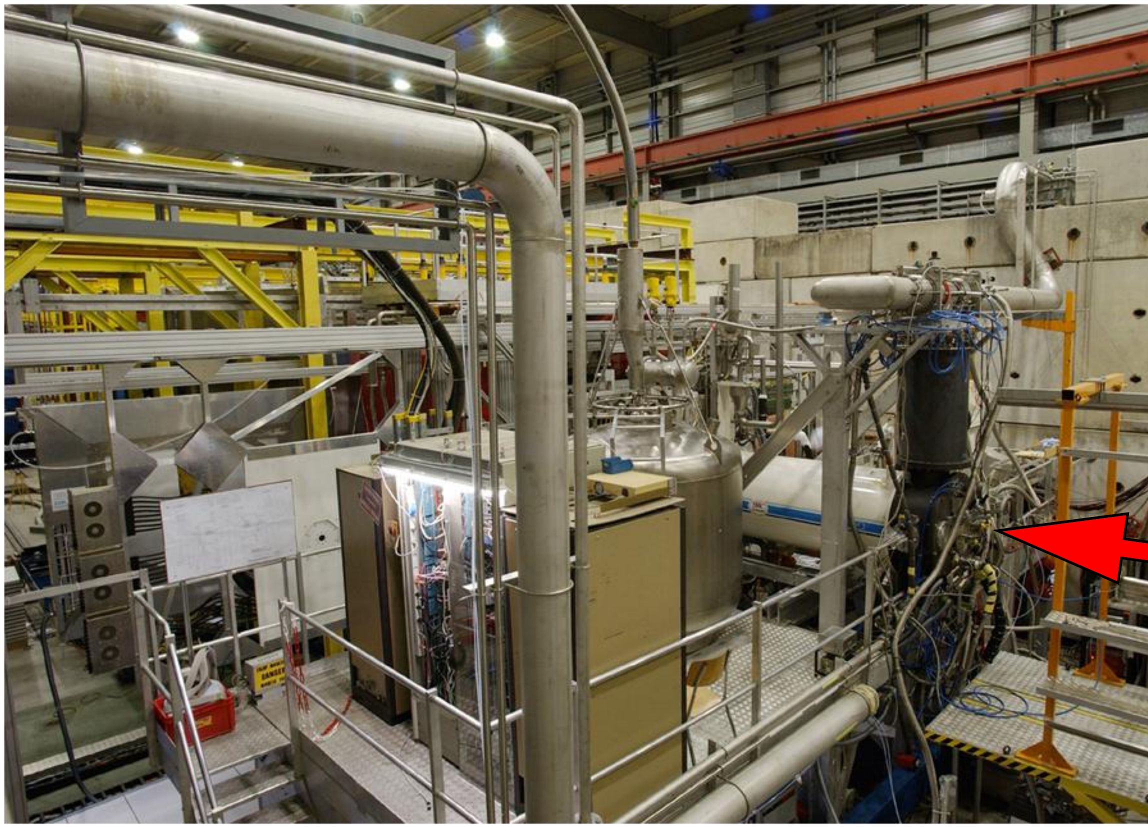




Energy	160 GeV
Intensity	$2 \cdot 10^8 \mu/\text{Spill}$
Polarisation	$\approx 76\,\%$

COMPASS Spectrometer

Polarised target



- $^6LiD/NH_3$
- 50/90% polarisation
- 50/16% dilution fact.
- 2.5 T
- 50 mK

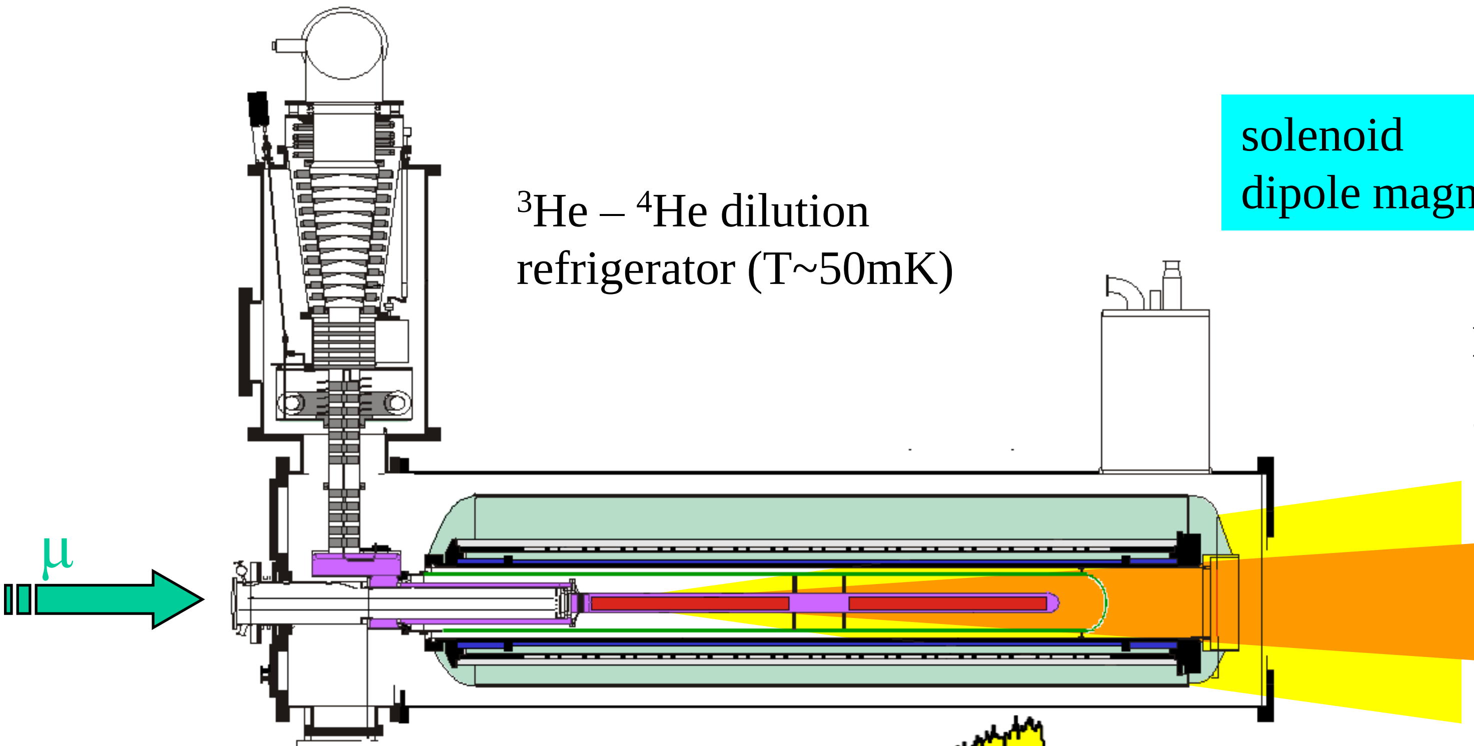
μ


Microwave cavity
Dilution refrigerator
New Magnet

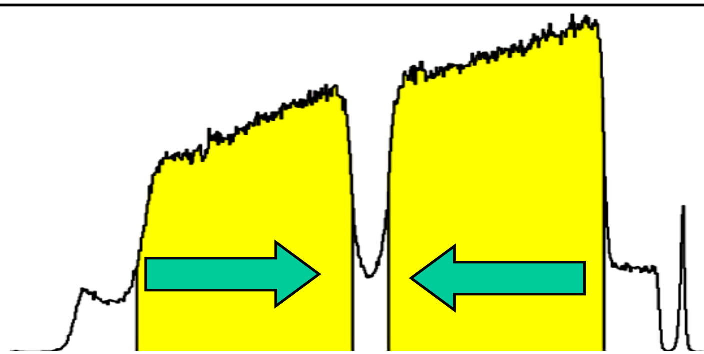
Target system

^3He – ^4He dilution refrigerator (T~50mK)

solenoid 2.5T
dipole magnet 0.5T

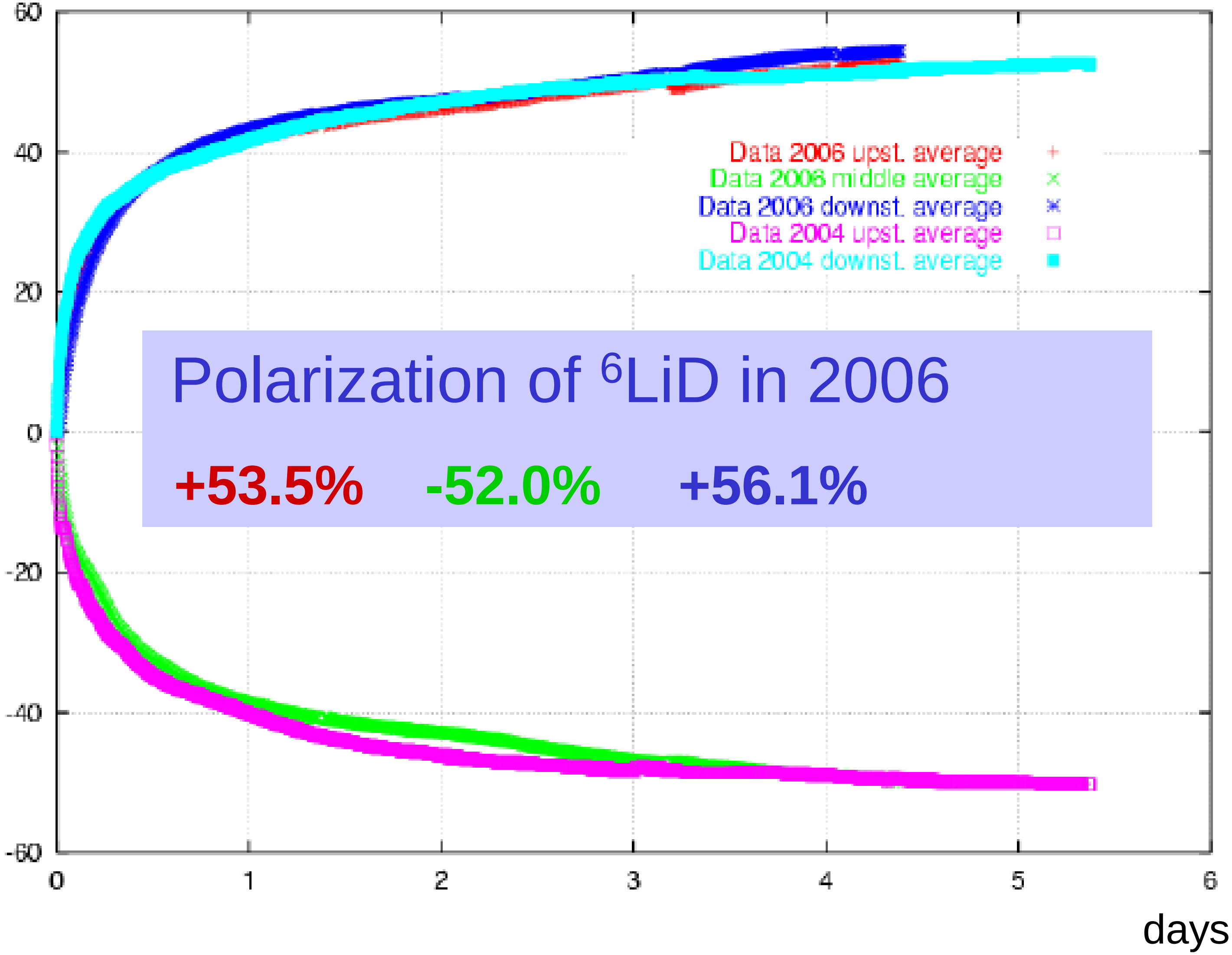


new magnet acceptance ± 180 mrad

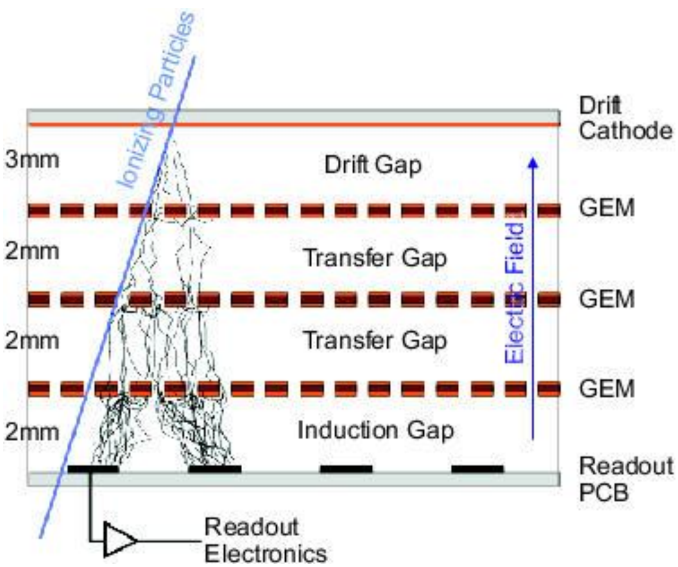


Reconstructed interaction vertices

Polarized target performances



Gems



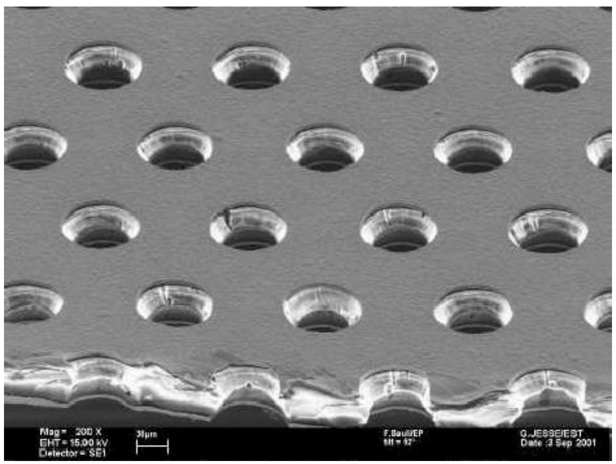
-4100 V

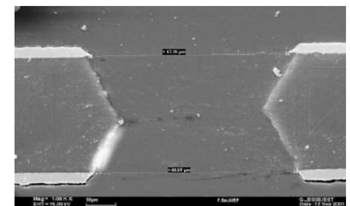
0V

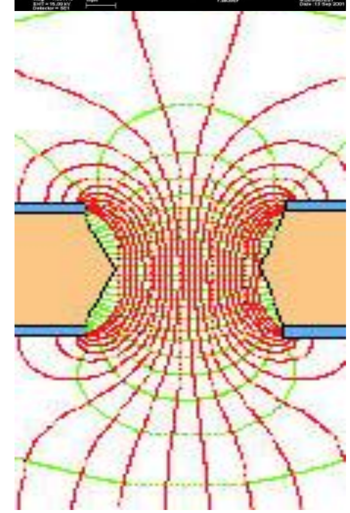
- 20 triple Gems detectors
- in 10 stations
- 40 coordinates
- size 30x30 cm^2
- 12 ns time resolution
- 50 µm space resolution
- efficiency ~ 97 %
- Ar/CO_2 70/30 %

Gems

Gem foil

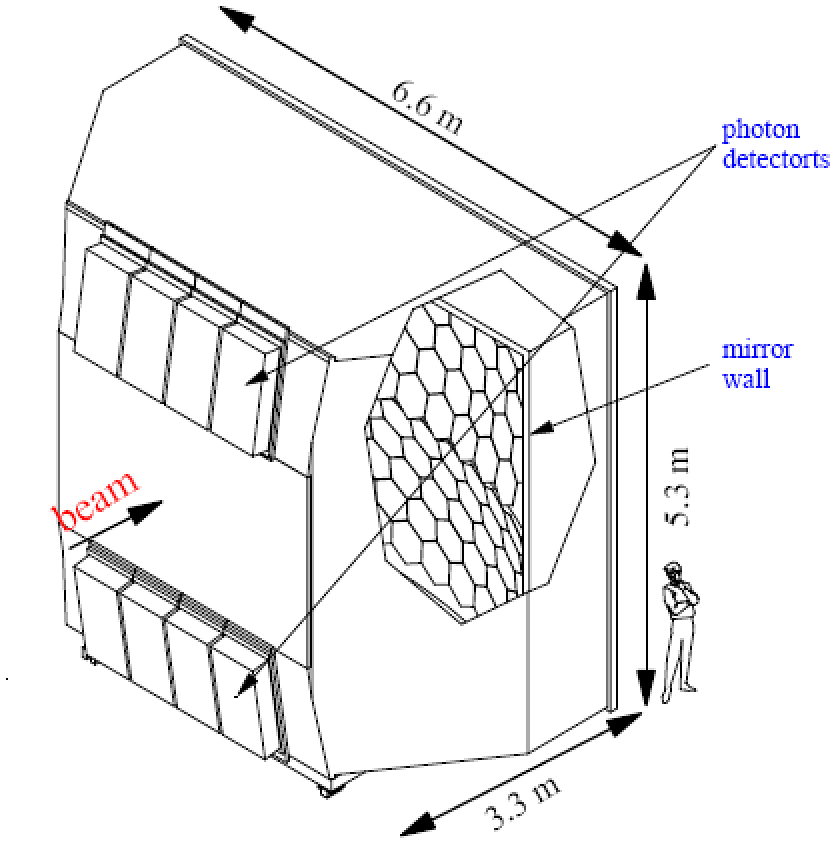






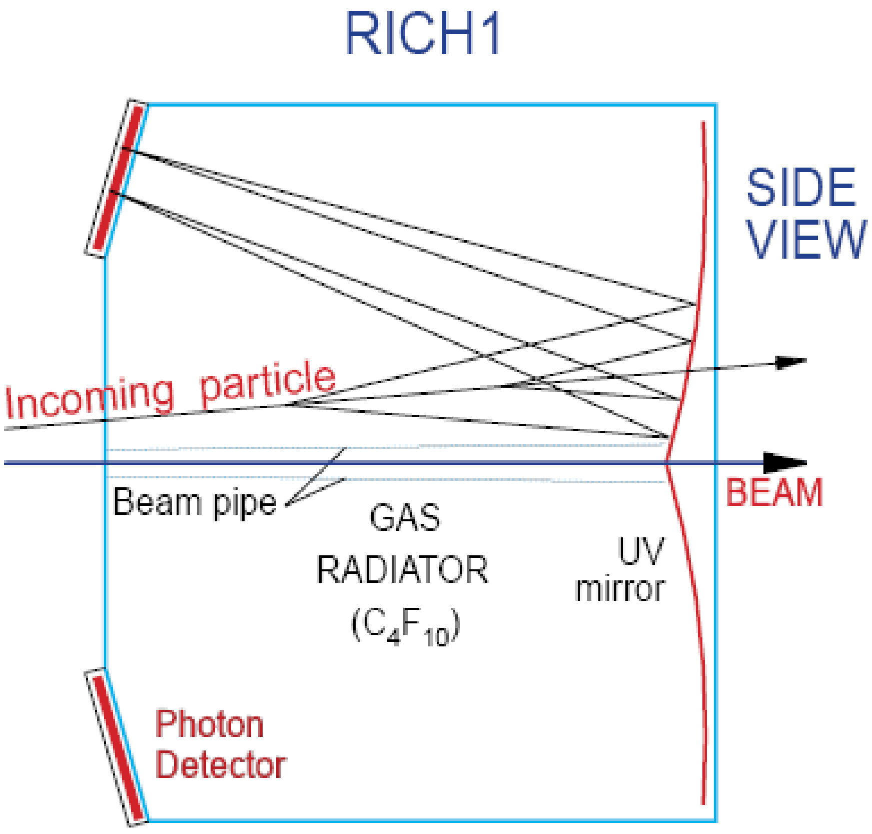
RICH

- 80 m^3 (3 m C_4F_{10} radiator)
- 116 VUV mirrors
- 5.3 m^2 VUV detectors
  - MWPC CsI photo-sensitive cathodes
  - 8x8 mm^2 pads
- 84k analog r/o channels
- 2006 inner quarter with maPMTs

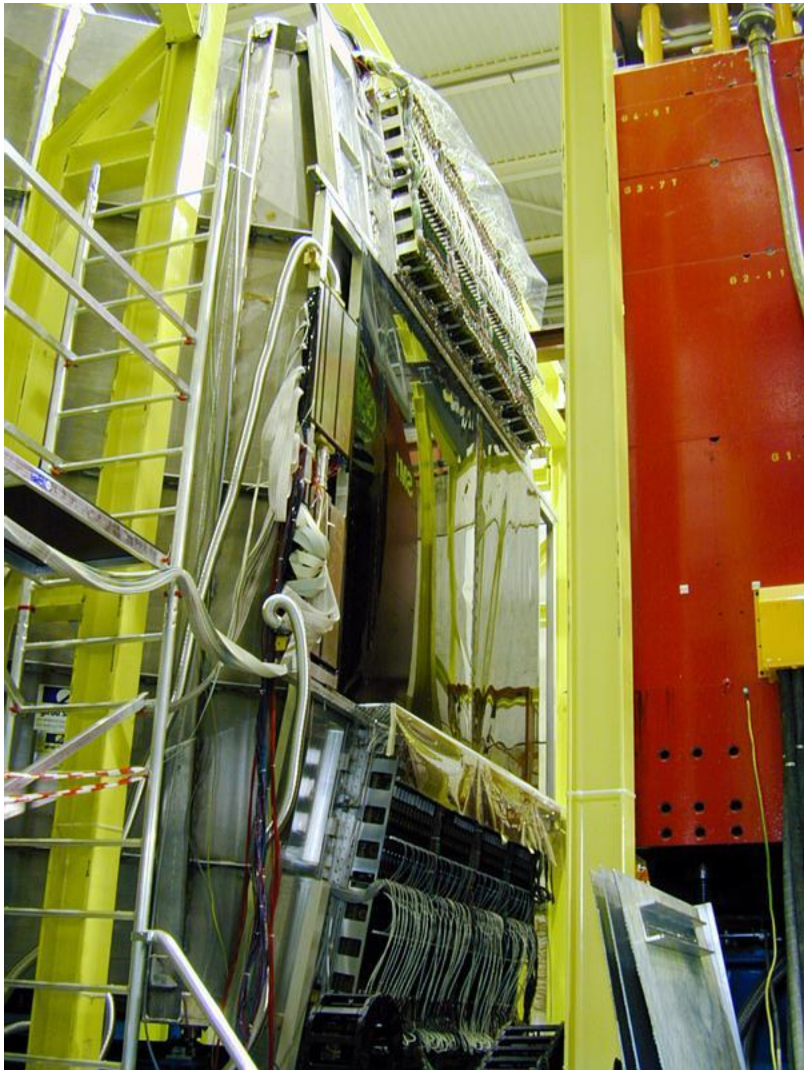


RICH

1. π/K separation up to ~ 60 GeV/c
2. Large angular acceptance:
   ± 250 mrad (H), ± 200 mrad (V)
3. Minimize materials



RICH



Lecture 2

- Experimental status
  - Q^2 evolution, scaling violations, DGLAP
  - status of g_1 and QCD analyses
  - interplay: g_2
  - semi-inclusive data
  - ΔG from hadron pairs