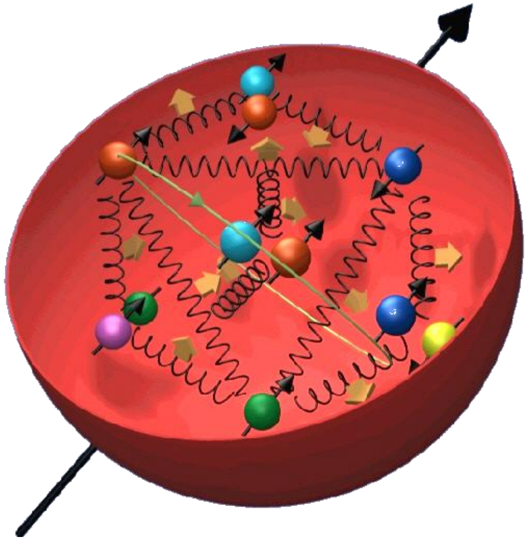


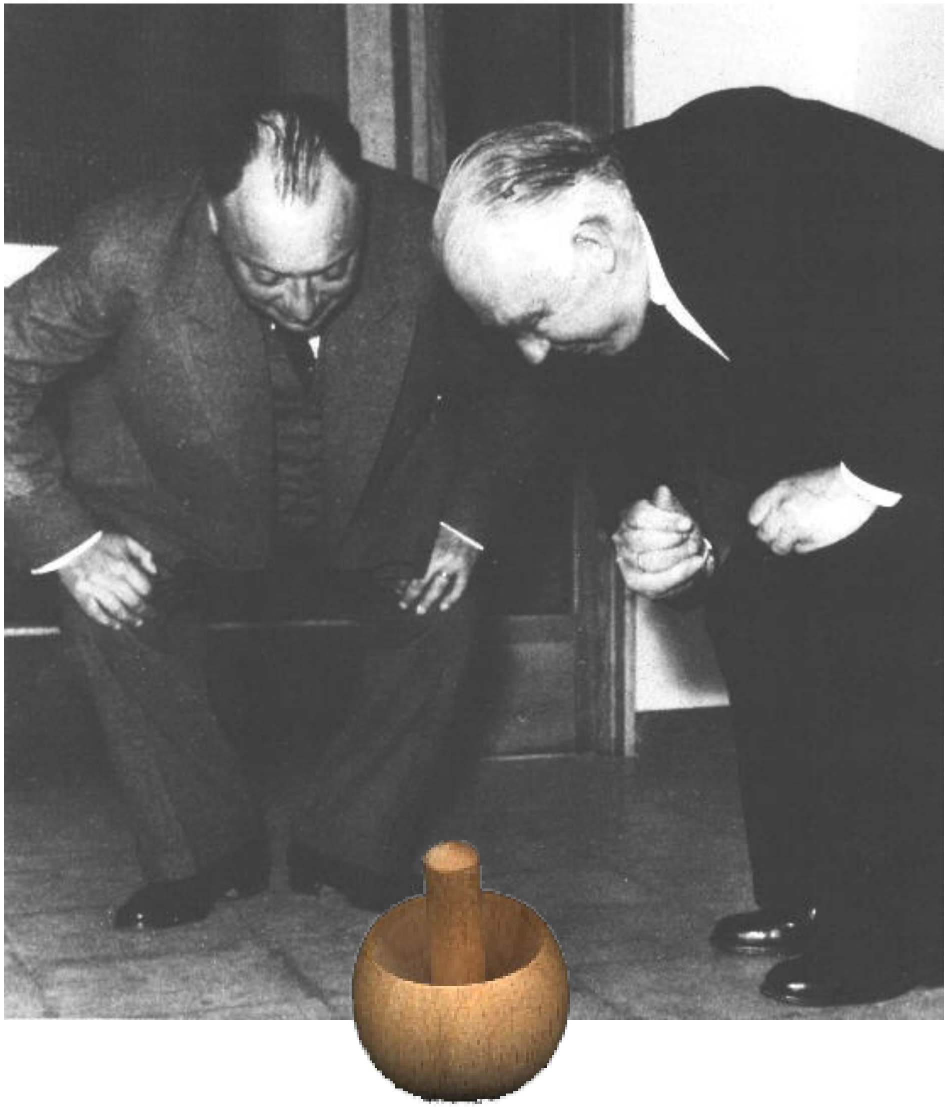
Experimental Overview of Nucleon Spin Structure I

Gerhard Mallot
CERN/PH

Plan

- Introduction
- DIS and structure functions
- Why is $\Delta\Sigma$ so small
- Experiments
- Inclusive results
- Semi-inclusive results
- ΔG from photon-gluon fusion
- RHIC pp collisions

Spin Experiments are Puzzling



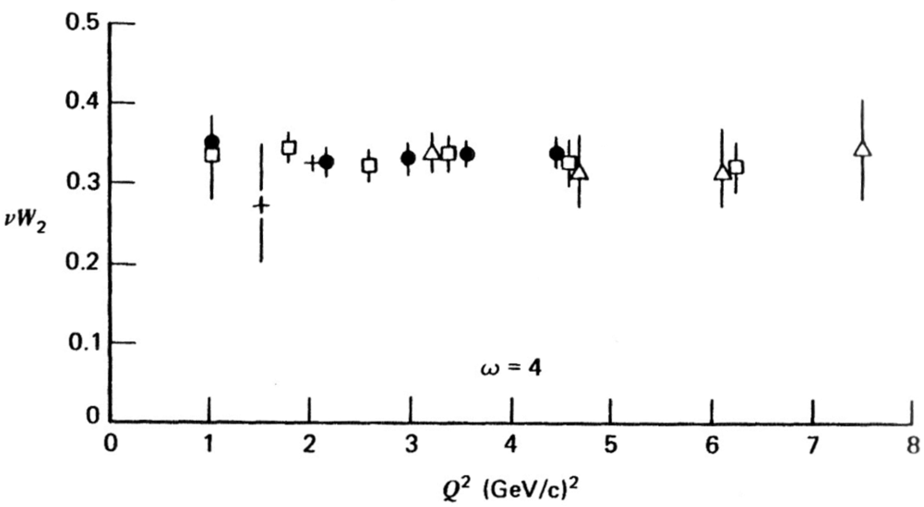
Wolfgang Pauli and Niels Bohr, 1954

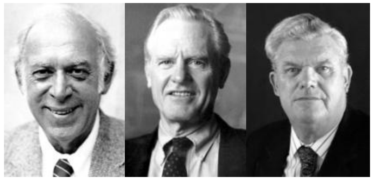
wondering about a tippe top toy

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

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

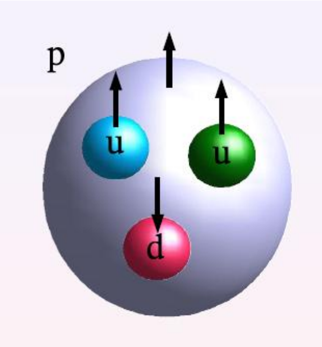
Static Quark model

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

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

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

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



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

→ up and down quarks carry the nucleon spin!

Baryon weak decays

The weak decay constants are linked to quark polarisations via the axial vector currents matrix elements, e.g.

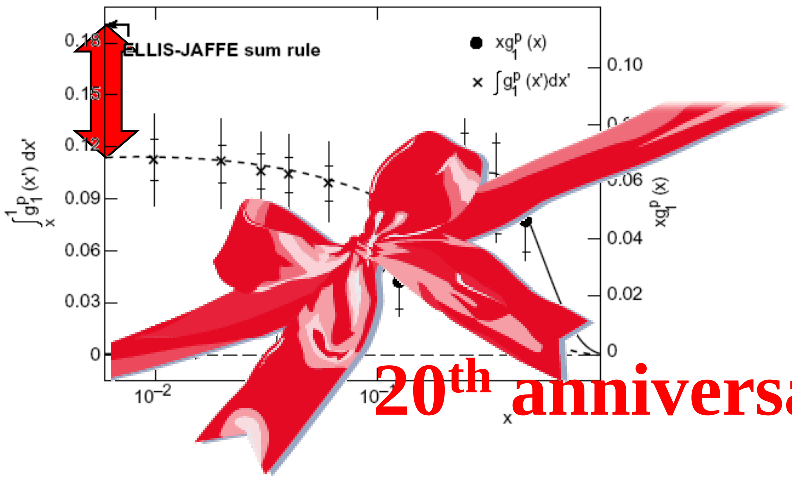
$$\Delta u + \Delta d - 2\Delta s = 0.58 \pm 0.03 \qquad (\Xi^- \to \Lambda)$$

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



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

20th anniversary (2007)

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \quad = \quad 0.12 \pm 0.17$$
$$\Delta s \quad = \quad -0.19 \pm 0.06$$

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

2. DIS and structure functions

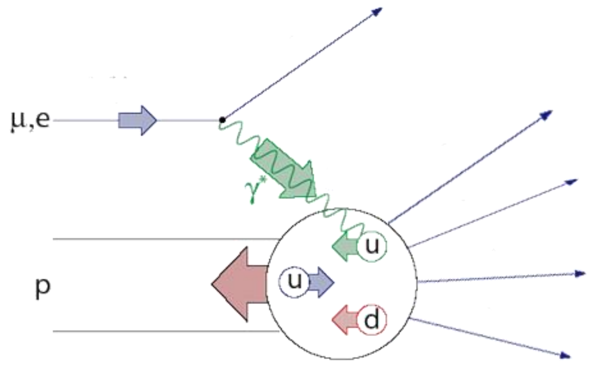
- What did the EMC actually measure?
- How severe is the spin puzzle?
- Can the Quark Model expectation

$$\Delta\Sigma = 0.6$$

be restored?

Deep inelastic scattering

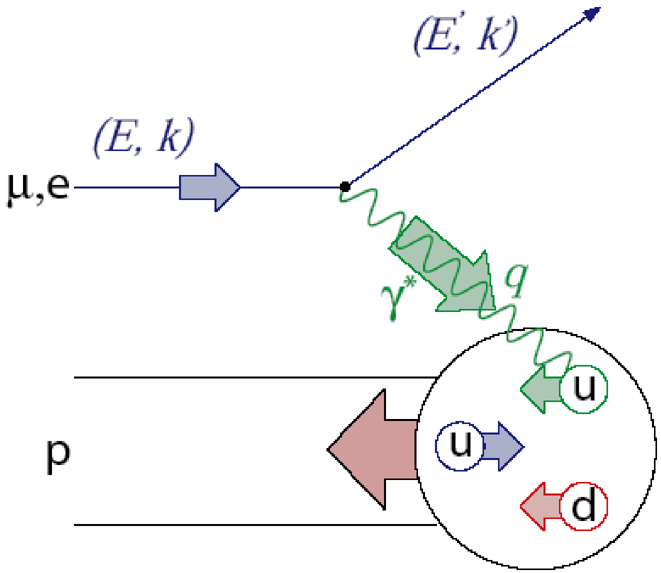
- probing partons



$$\ell N \to \ell' X$$

  - 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



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

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

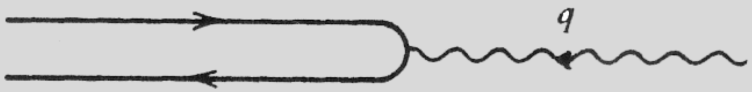
$$P\cdot k \stackrel{lab}{=} ME$$

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

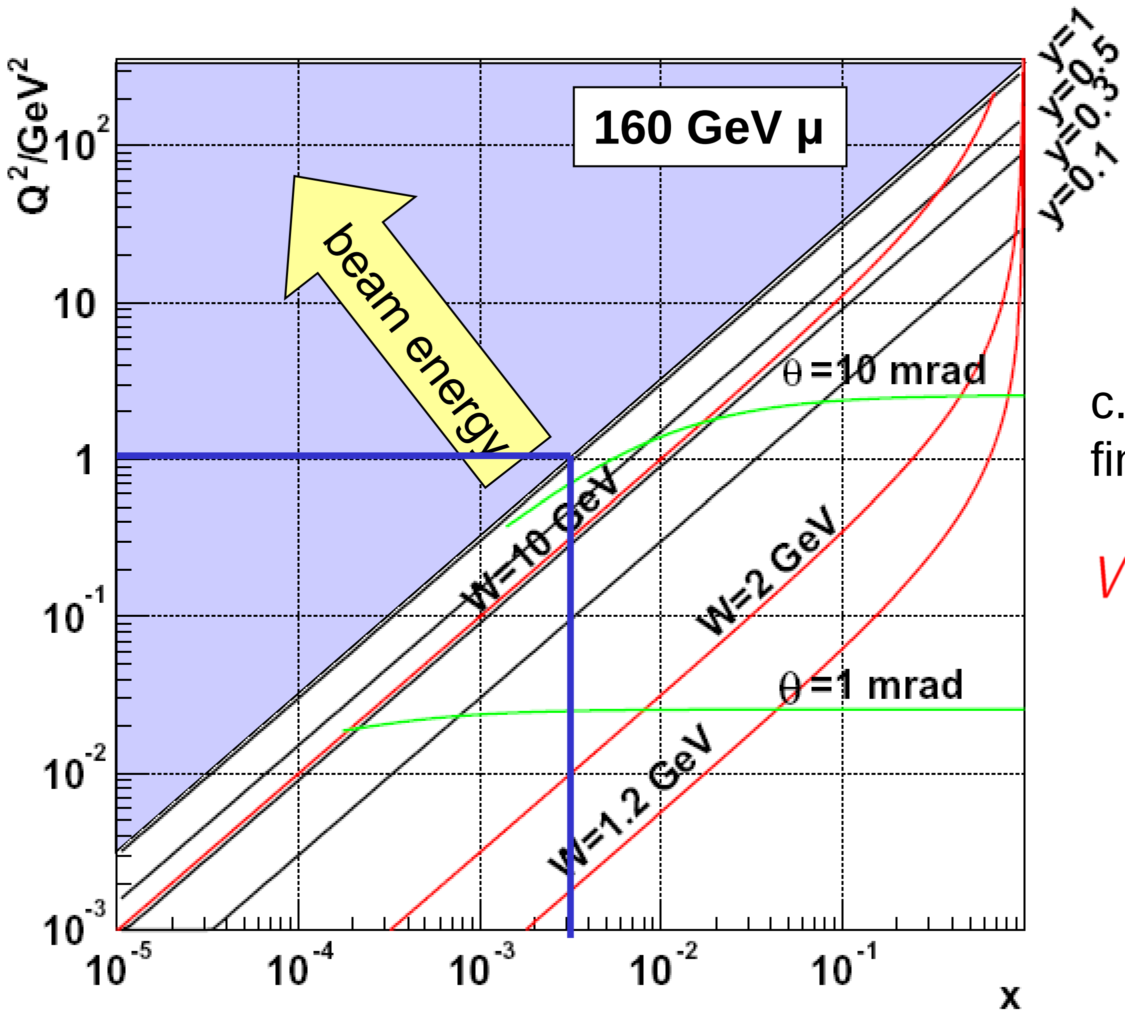
$$y \stackrel{lab}{=} \frac{\nu}{E} = \frac{P\cdot q}{P\cdot k}$$

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

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:

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

DIS: Q^2, W^2 large, 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

cross section:

lepton spin nucleon

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

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

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

factorise

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

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 $\Delta q = \int_0^1 \Delta q(x) \mathrm{d}x$

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

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

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

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

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

Ellis-Jaffe sum rule

PR D9 (1974) 1444

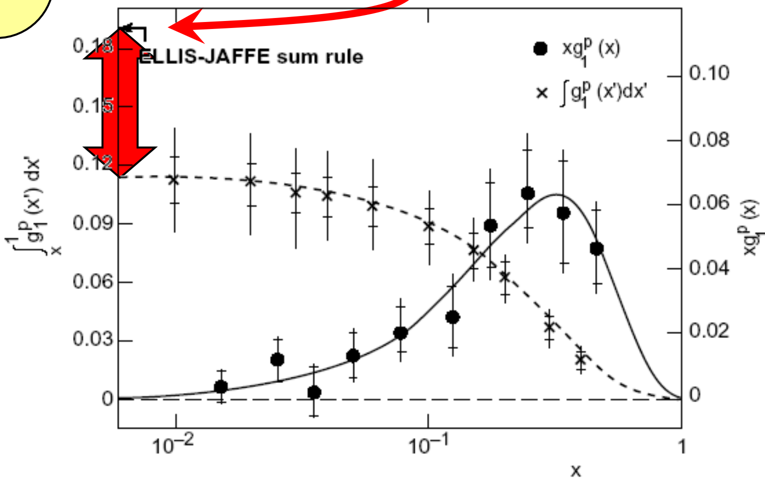
$$\Gamma_1^p = \frac{1}{12} g_a + \frac{5}{36}\sqrt{3} a_8 + \frac{1}{3}\Delta s \Rightarrow \Delta\Sigma \simeq 0.6$$

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

Consequences of violation:

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

EMC 1987



3. Why is $\Delta\Sigma$ so small

(1988)

CHIRAL SYMMETRY AND THE SPIN OF THE PROTON ☆

Stanley J. BRODSKY [a], John ELLIS [a,b1] and Marek KARLINER [a]
[a] *Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA*
[b] *CERN, CH-1211 Geneva 23, Switzerland*

PLB 206 (1988) 309

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

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Birkbeck College, University of London, London, UK
Dipartimento di Fisica Teorica, Universitá di Torino, I-10125 Torino, Italy

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

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CERN, CH-1211 Geneva 23, Switzerland

PLB 212 (1988) 391

Received 29 June 1988

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)

Lepton-Photon 1989

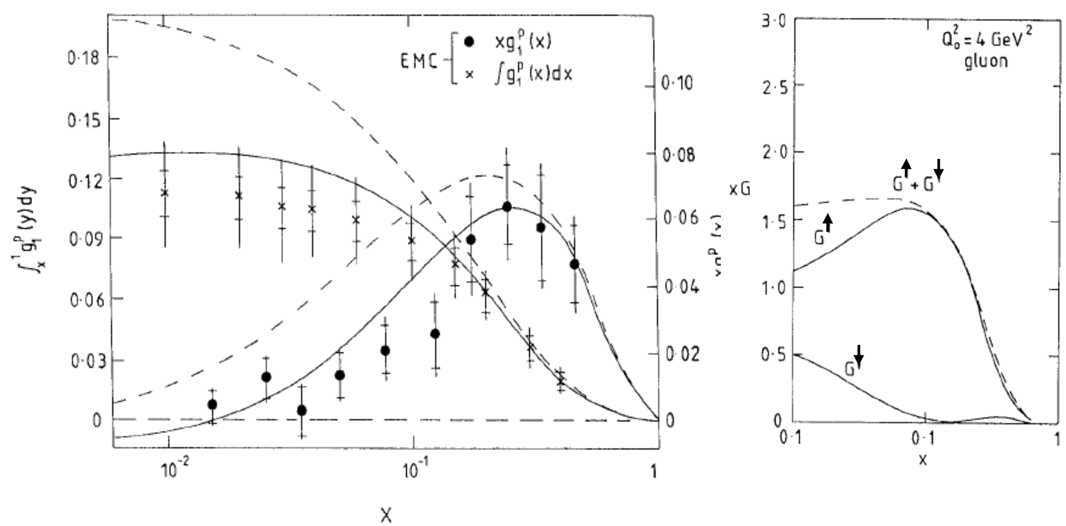
To summarise, let us return to the fit of Fig. 7 and 8. At Q^2=10GeV^2 this corresponds to Δg=6.3 and so the proton helicity is given by

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

$$= 0.35 + 6.3 - 6.15$$

G.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

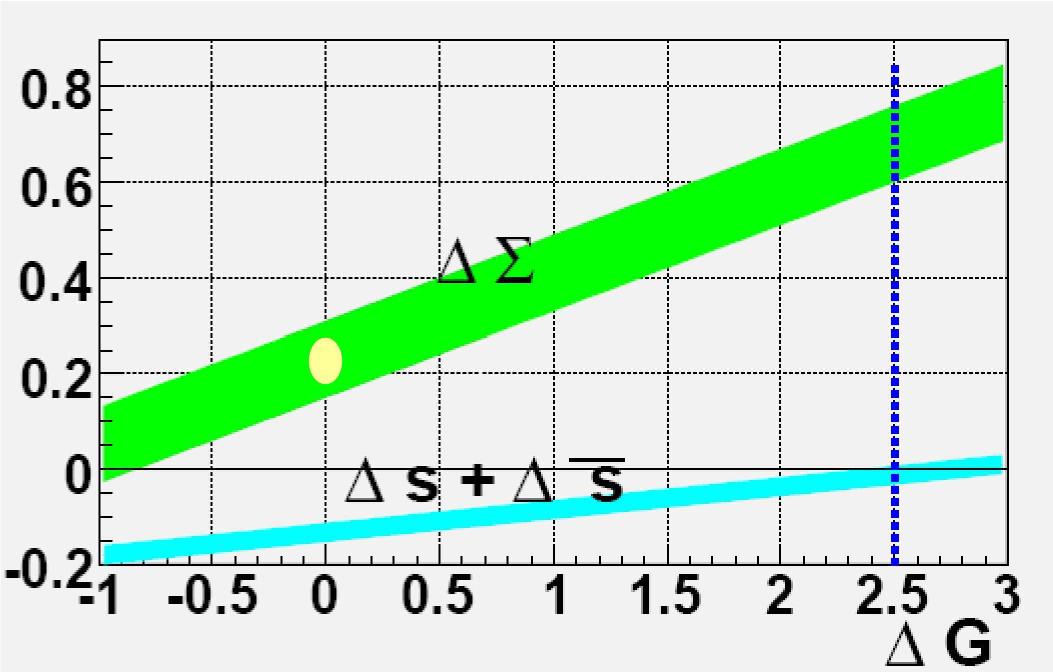


ΔG and $\Delta\Sigma$ in AB/jet scheme

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

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

α_s strong coupling constant



Now:

$a_0 \simeq 0.3$

Need:

$\Delta G \simeq 2.5$

Where is the proton spin?

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

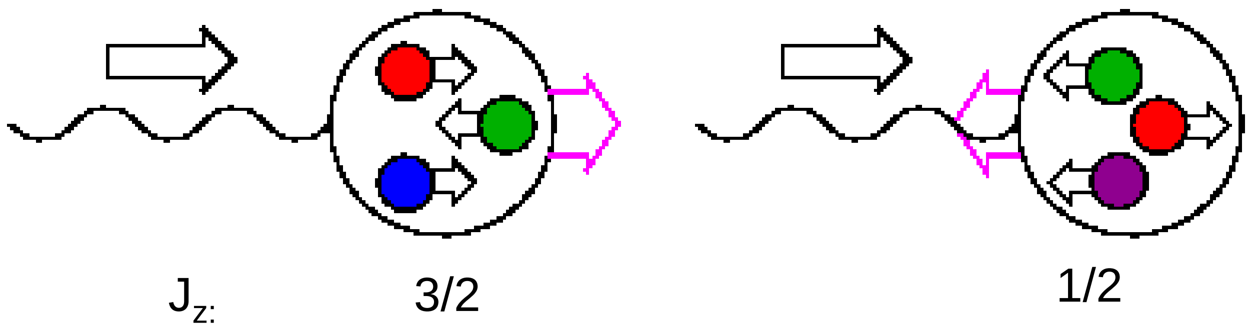
small

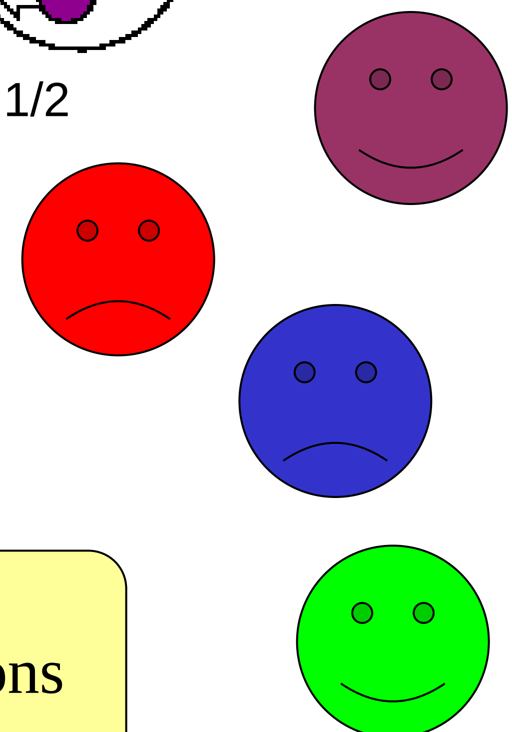
Still poorly known
certainly not 6

unknown

4. Experiments

- Photoabsorption: (flavours ignored)





- only quarks with opposite helicity can absorb the polarised photon via spin-flip

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

need polarised photons & nucleons

Cross Section Asymmetries

unpolarised:

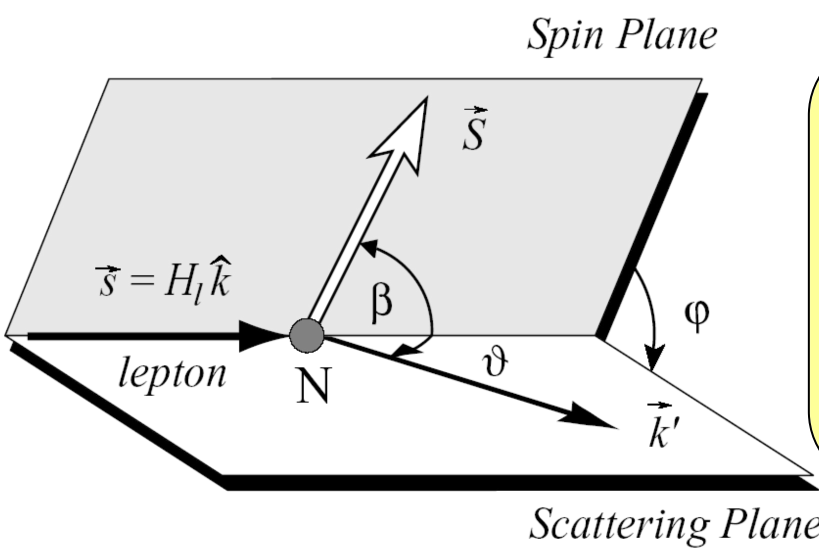
$$\frac{d^3\overline{\sigma}}{dx\,dy\,d\varphi} = \frac{4\alpha^2}{Q^2}\left\{\frac{y}{2}F_1 + \frac{1}{2xy}\left(1 - y - \frac{y^2\gamma^2}{4}\right)F_2\right\}$$

longitudinally polarised nucleon: β=0,π

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

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:

$$A_{\|}(x, Q^2; E) = \frac{\Delta_{\|}\sigma}{\overline{\sigma}} = \frac{\sigma^{\overset{\rightarrow}{\leftarrow}} - \sigma^{\overset{\rightarrow}{\Rightarrow}}}{\sigma^{\overset{\rightarrow}{\Leftarrow}} + \sigma^{\overset{\rightarrow}{\Rightarrow}}},$$

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

Experimental essentials I

- up to now only pol. DIS experiments with fixed-target geometry
- need polarised targets and beams
- need detection of scattered lepton (or all hadrons), energy, direction, identification
- need to know energy and direction of incoming lepton
  - detection or given by accelerator
- measurable asymmetries very small
  - need excellent control of fake asymmetries, e.g. time variations of detector efficiencies

Experimental essentials II

- Beams & targets:

		target	beam pol	$x_{min}(1\ \text{GeV}^2)$
• 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	100/250 GeV	pp collider	pol. Source	-)

- 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 causes very small asymmetries

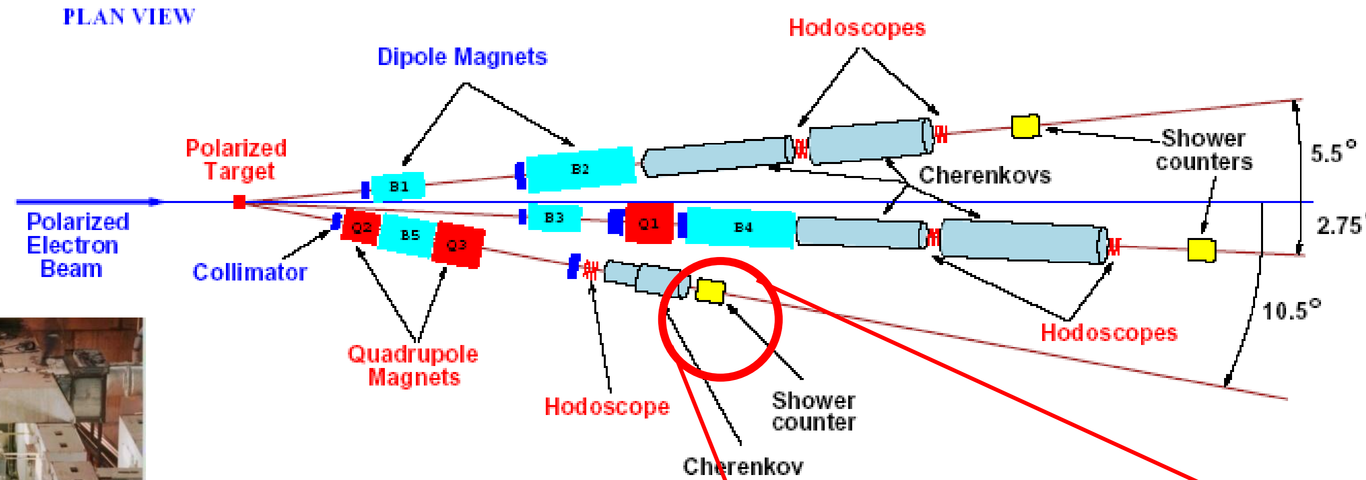
Pol. DIS experiments

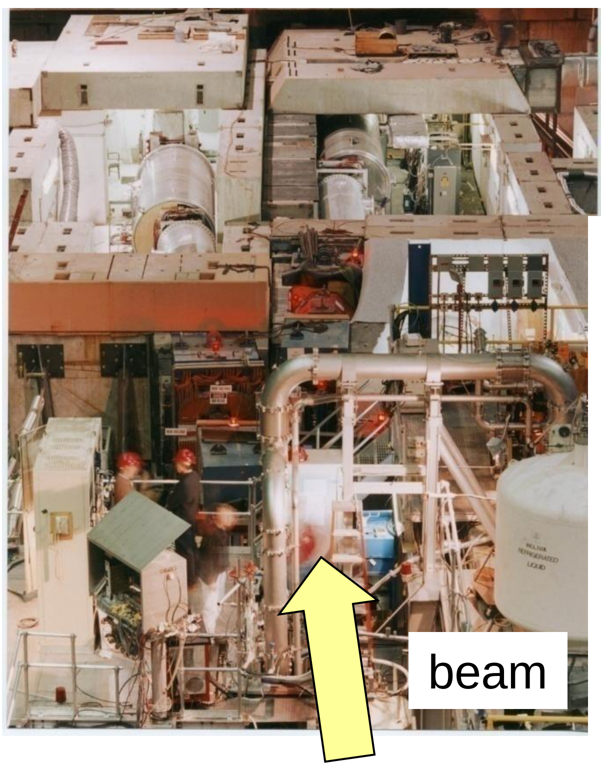
Spin Crisis

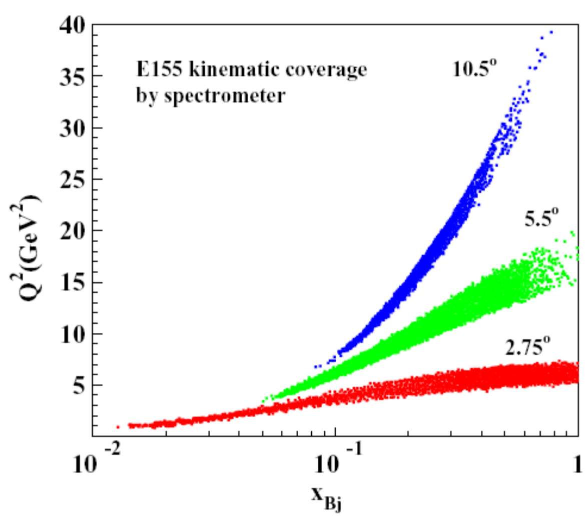
Lab	Exp	Year	Energy	Beam	P_b	target	P_t	f	result
SLAC	E80	75	10–16 GeV	e^-	0.85	H-butanol	0.50	0.13	A_1^p
SLAC	E130	80	16–23 GeV	e^-	0.81	H-butanol	0.58	0.15	A_1^p
CERN	EMC	85	200 GeV	μ^+	0.79	NH_3	0.78	0.16	g_1^p
CERN	SMC	92	100 GeV	μ^+	0.81	D-butanol	0.40	0.19	g_1^d
SLAC	E142	92	19–26 GeV	e^-	0.39	^{3}He	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	^{3}He	0.38	0.18	g_1^n
DESY	HERMES	95	28 GeV	e^+	0.55	^{3}He	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	^{6}LiD	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	^{6}LiD	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	^{6}LiD	0.50	0.40	
BNL	RHIC	$\geq$ 01	coll.	p		p		1.00	

running

SLAC E155 Spectrometer

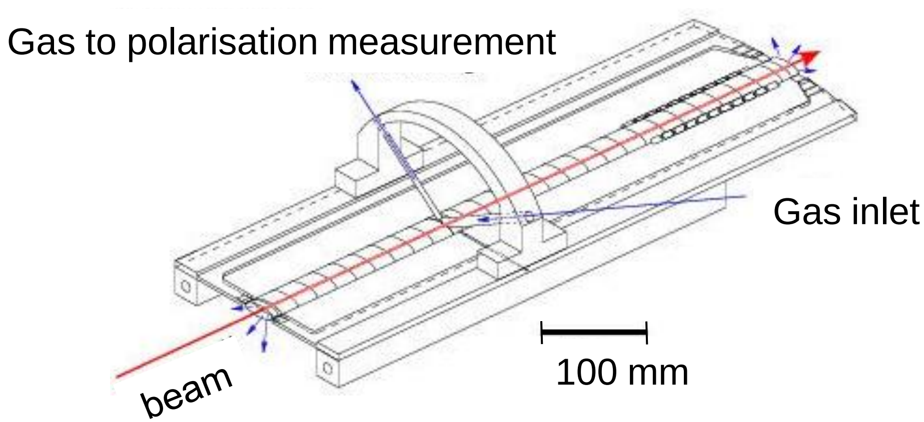


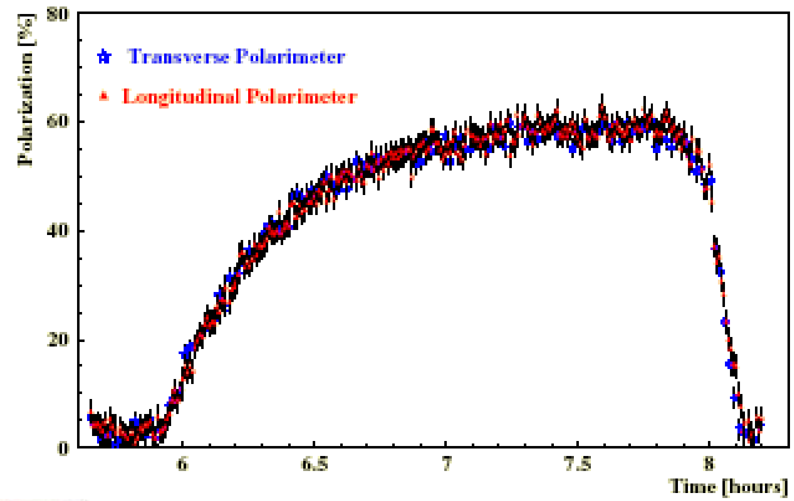


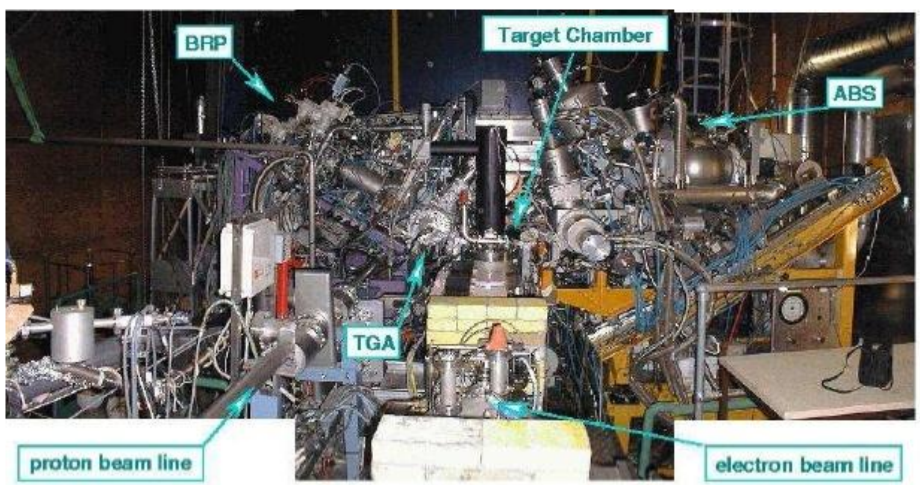


HERMES

Target cell

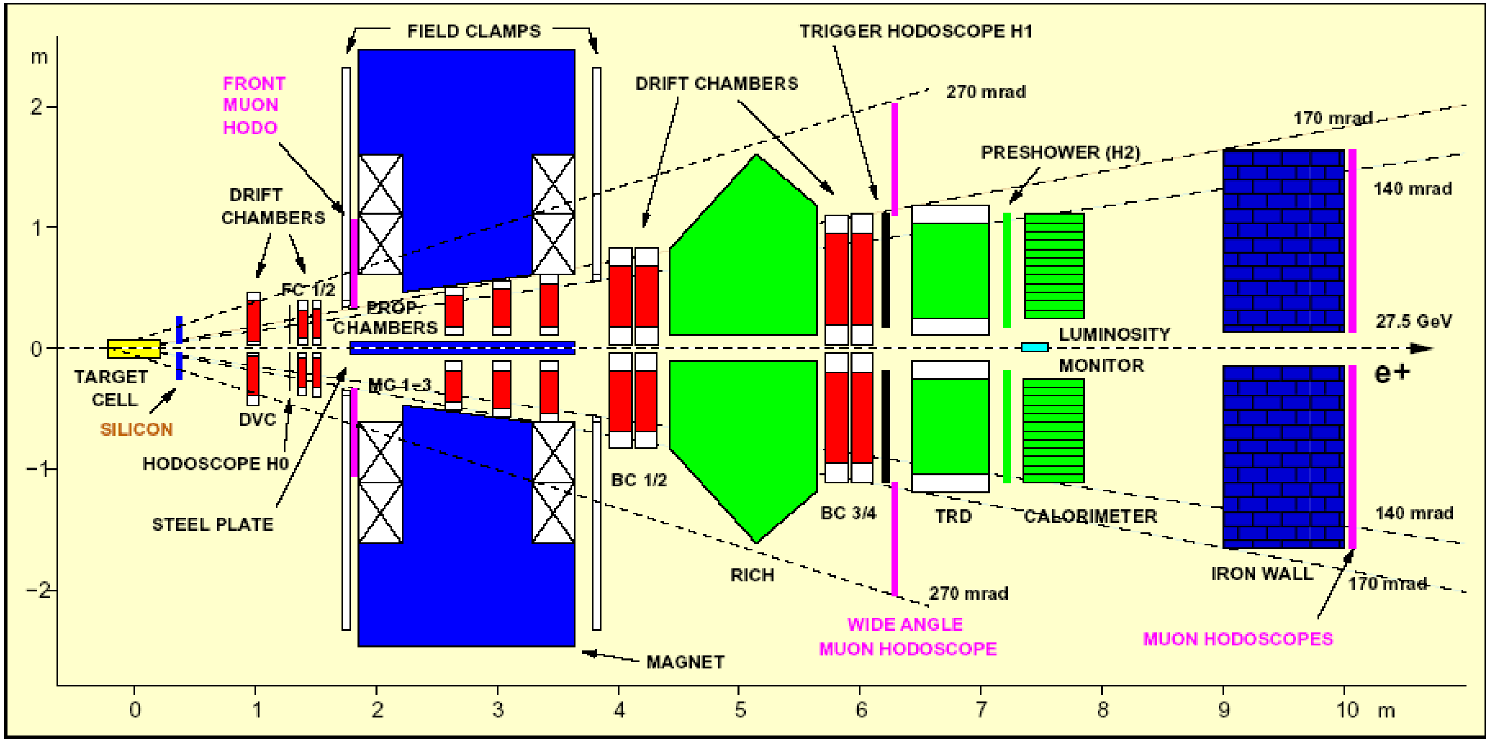






beam polarisation built-up by Sokolov-Ternov effect

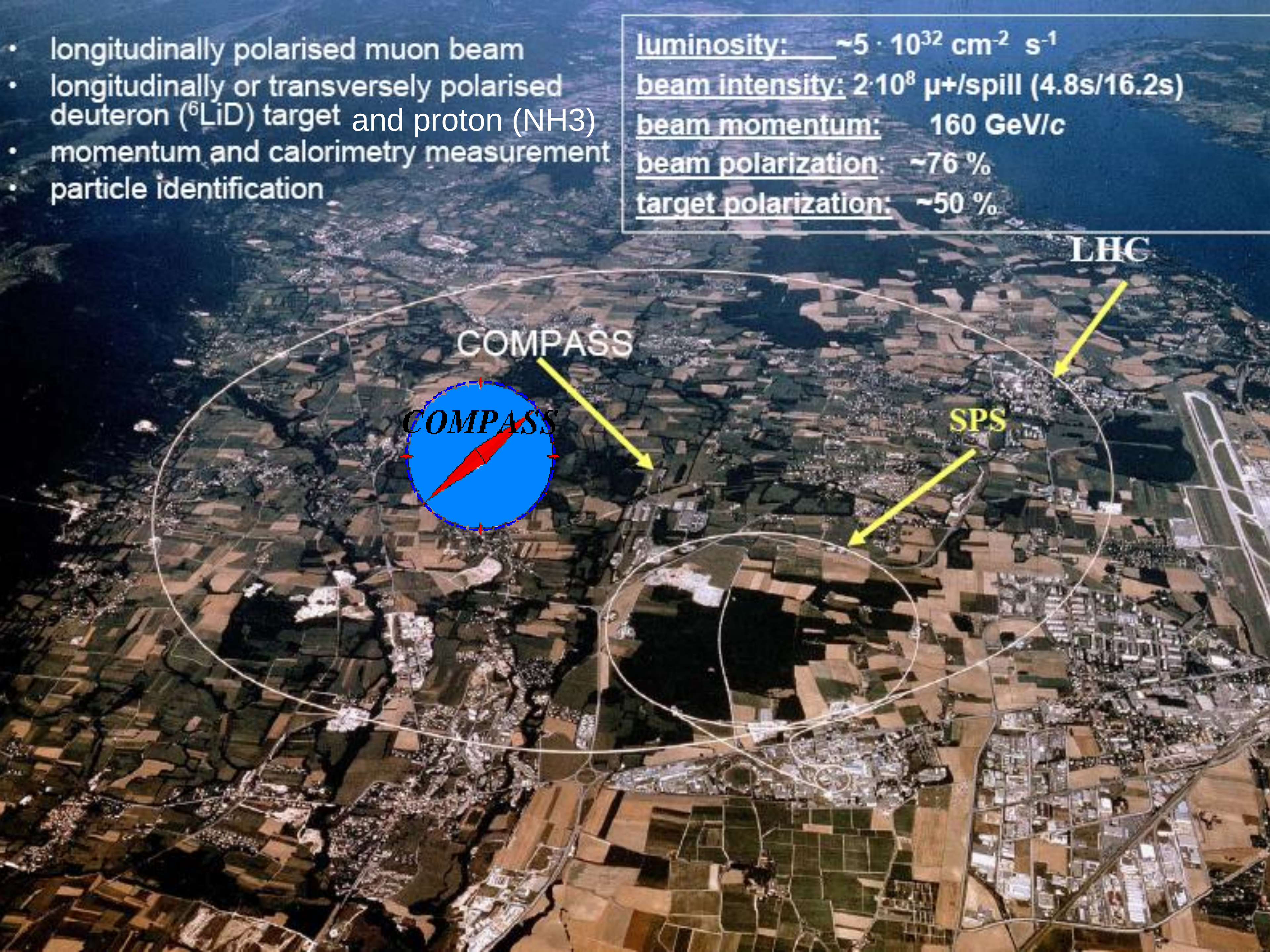
HERMES



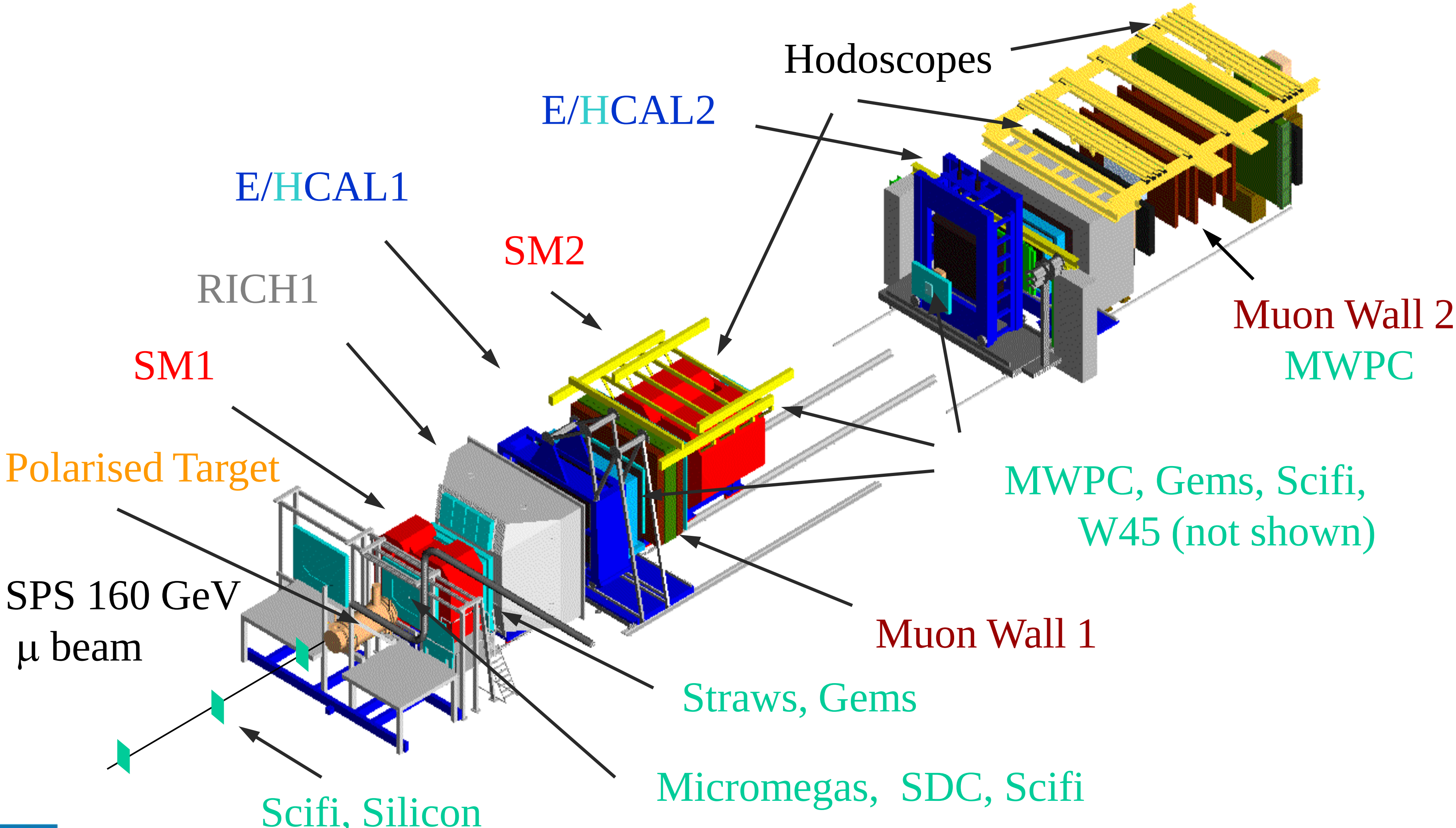
FIELD CLAMPS
TRIGGER HODOSCOPE H1
FRONT MUON HODO
DRIFT CHAMBERS
270 mrad
170 mrad
PRESHOWER (H2)
140 mrad
DRIFT CHAMBERS
FC 1/2
PROP. CHAMBERS
27.5 GeV
LUMINOSITY MONITOR
e+
TARGET CELL
SILICON
DVC
MC 1-3
HODOSCOPE H0
STEEL PLATE
BC 1/2
BC 3/4
TRD
CALORIMETER
140 mrad
RICH
IRON WALL
170 mrad
270 mrad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

- longitudinally polarised muon beam
- longitudinally or transversely polarised deuteron (^{6}LiD) target and proton (NH3)
- momentum and calorimetry measurement
- particle identification

luminosity:	~5 · 10^{32} cm^{-2} s^{-1}
beam intensity:	2·10^8 μ+/spill (4.8s/16.2s)
beam momentum:	160 GeV/*c*
beam polarization:	~76 %
target polarization:	~50 %



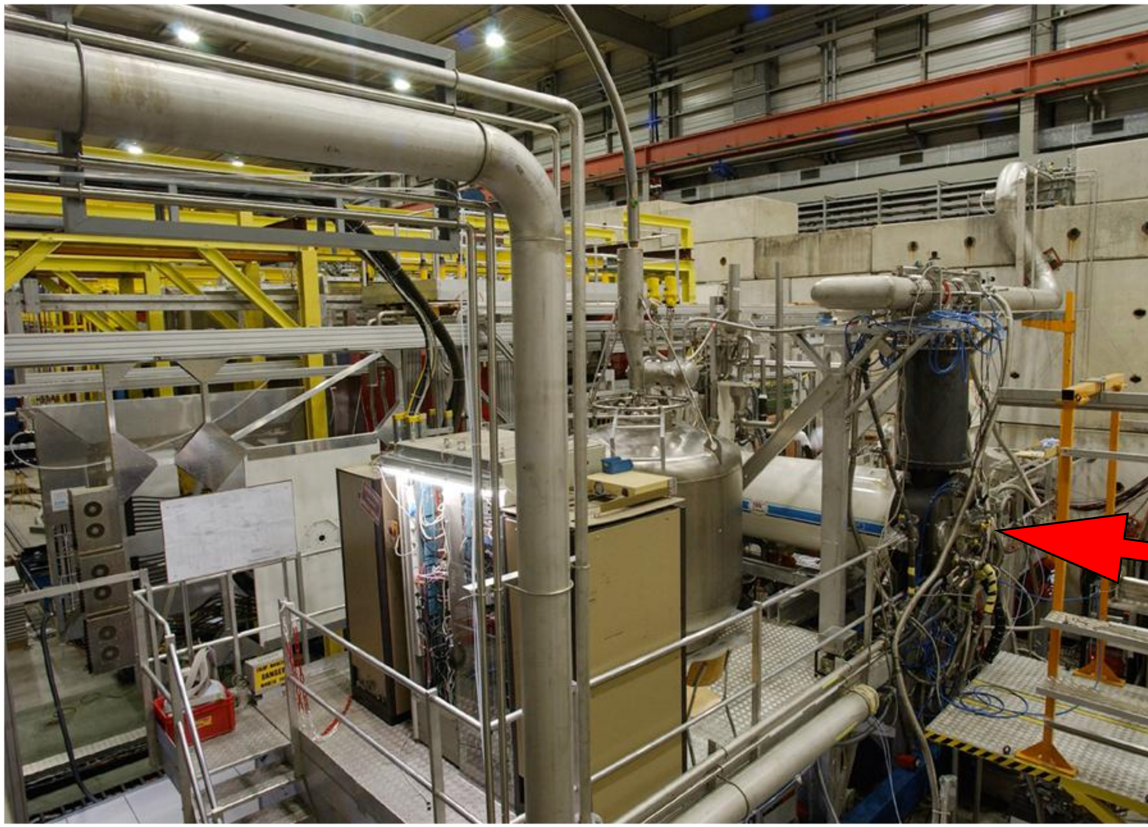
COMPASS



Hodoscopes
E/HCAL2
E/HCAL1
SM2
RICH1
SM1
Polarised Target
SPS 160 GeV
μ beam
Muon Wall 2,
MWPC
MWPC, Gems, Scifi,
W45 (not shown)
Muon Wall 1
Straws, Gems
Micromegas, SDC, Scifi
Scifi, Silicon

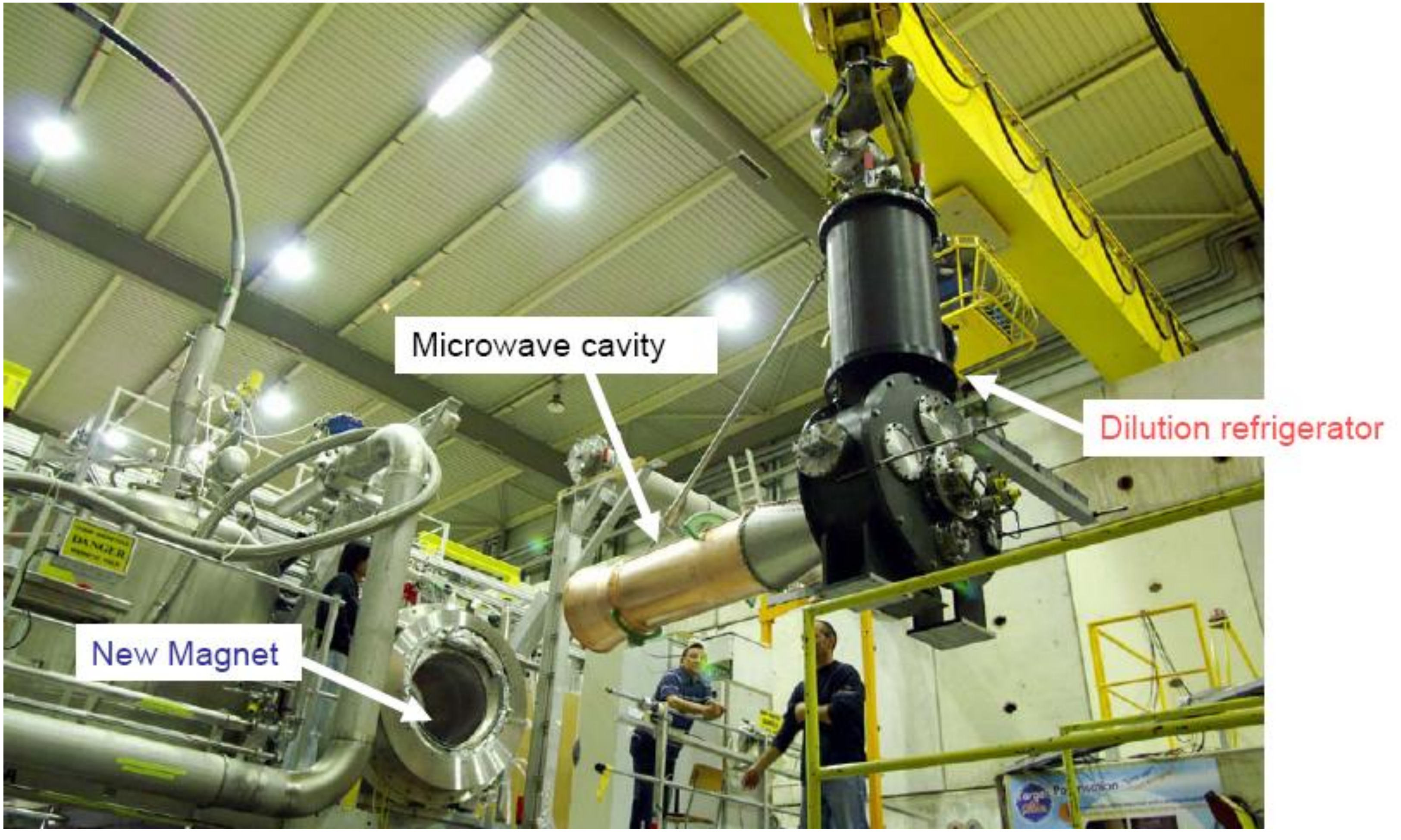
COMPASS Spectrometer

Polarised target

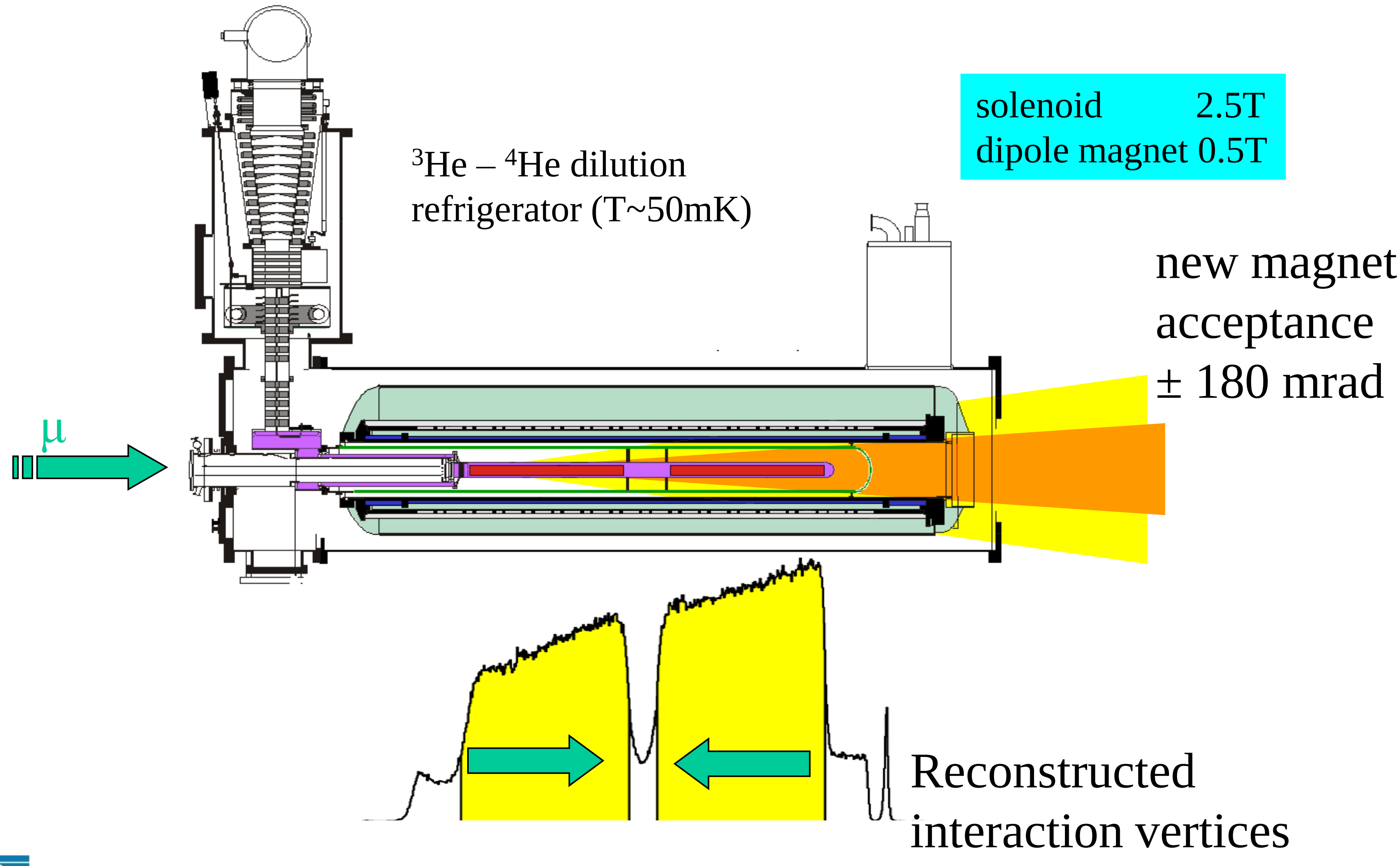


μ

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

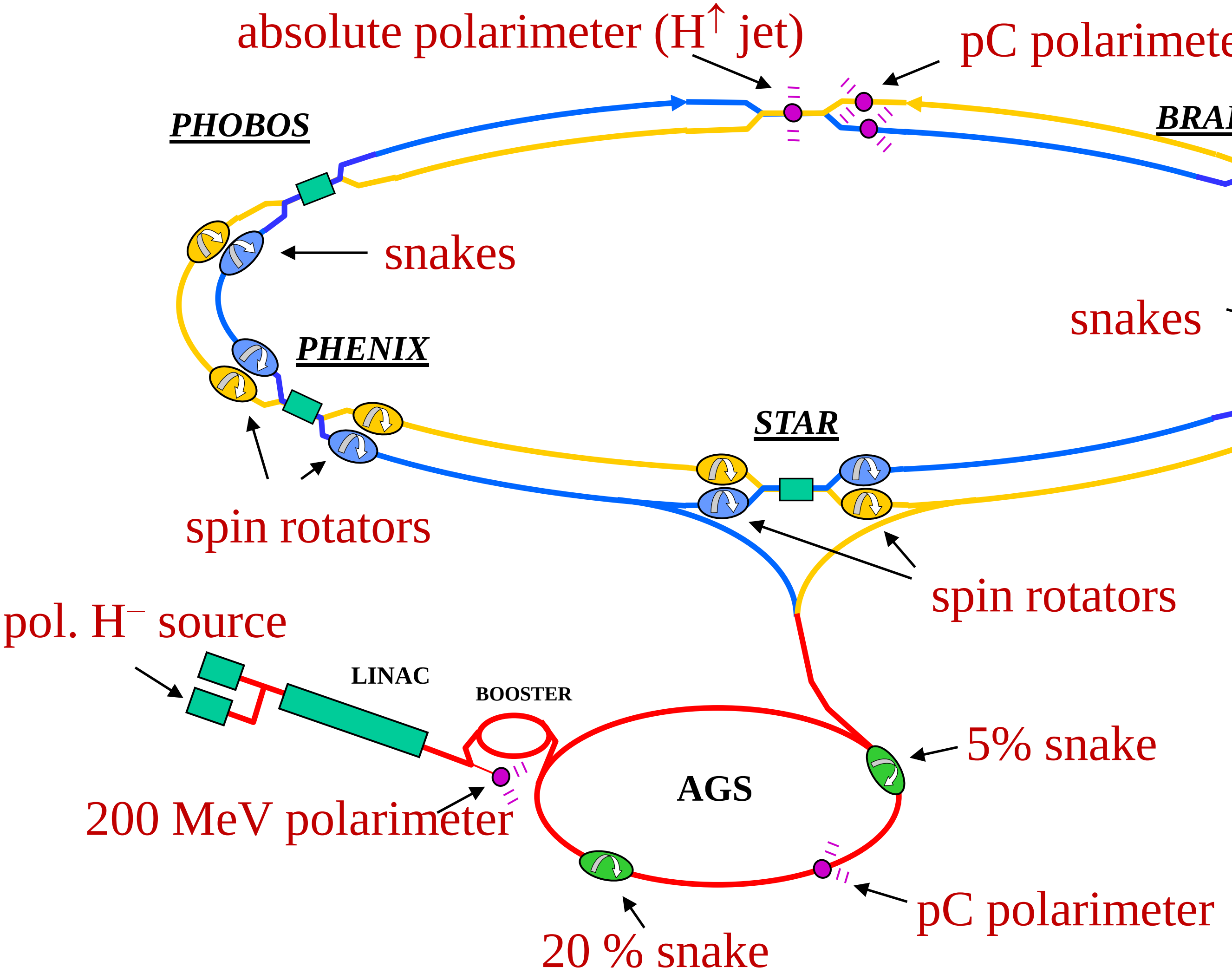

Microwave cavity
Dilution refrigerator
New Magnet

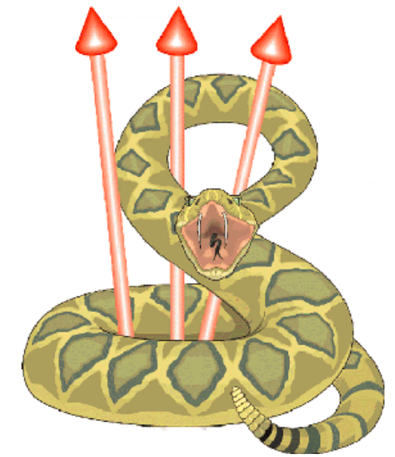
Target system



RHIC $\vec{p}\vec{p}$

RHIC polarised $\vec{p}\vec{p}$ Collider



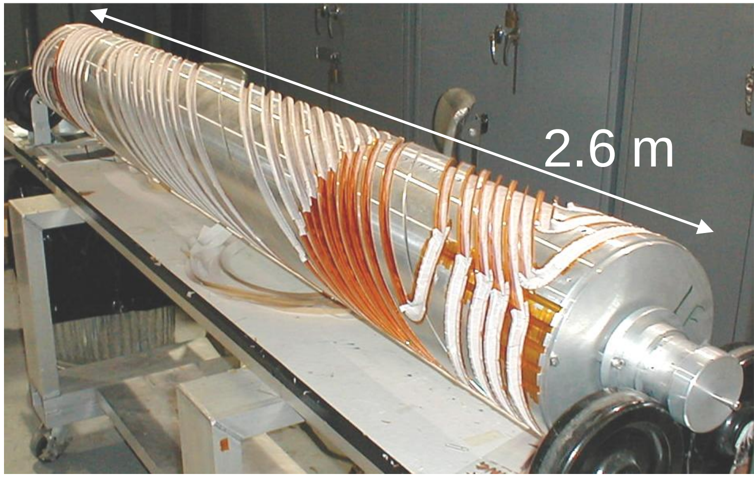


Siberian Snake

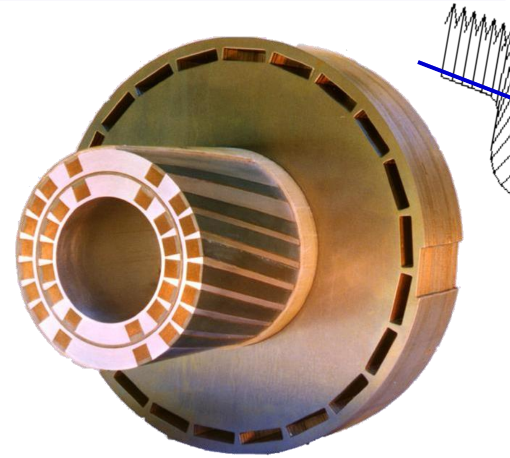
Siberian Snakes (helical dipoles)

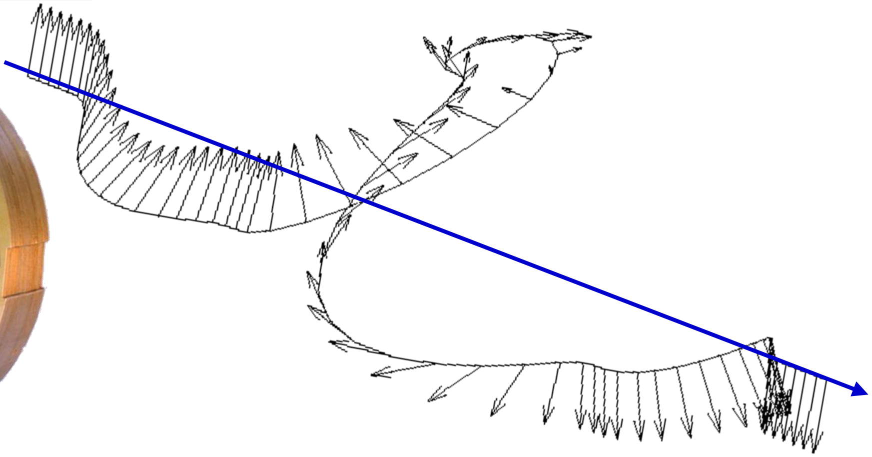
from Th. Roser

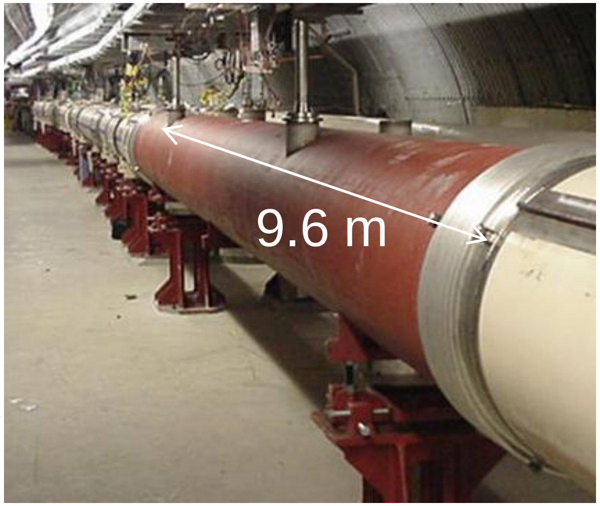
AGS partial snakes, 1.5T (RT) & 3T(SC)



RHIC full Siberian Snakes: 4 x 4 T (SC), each 2.4

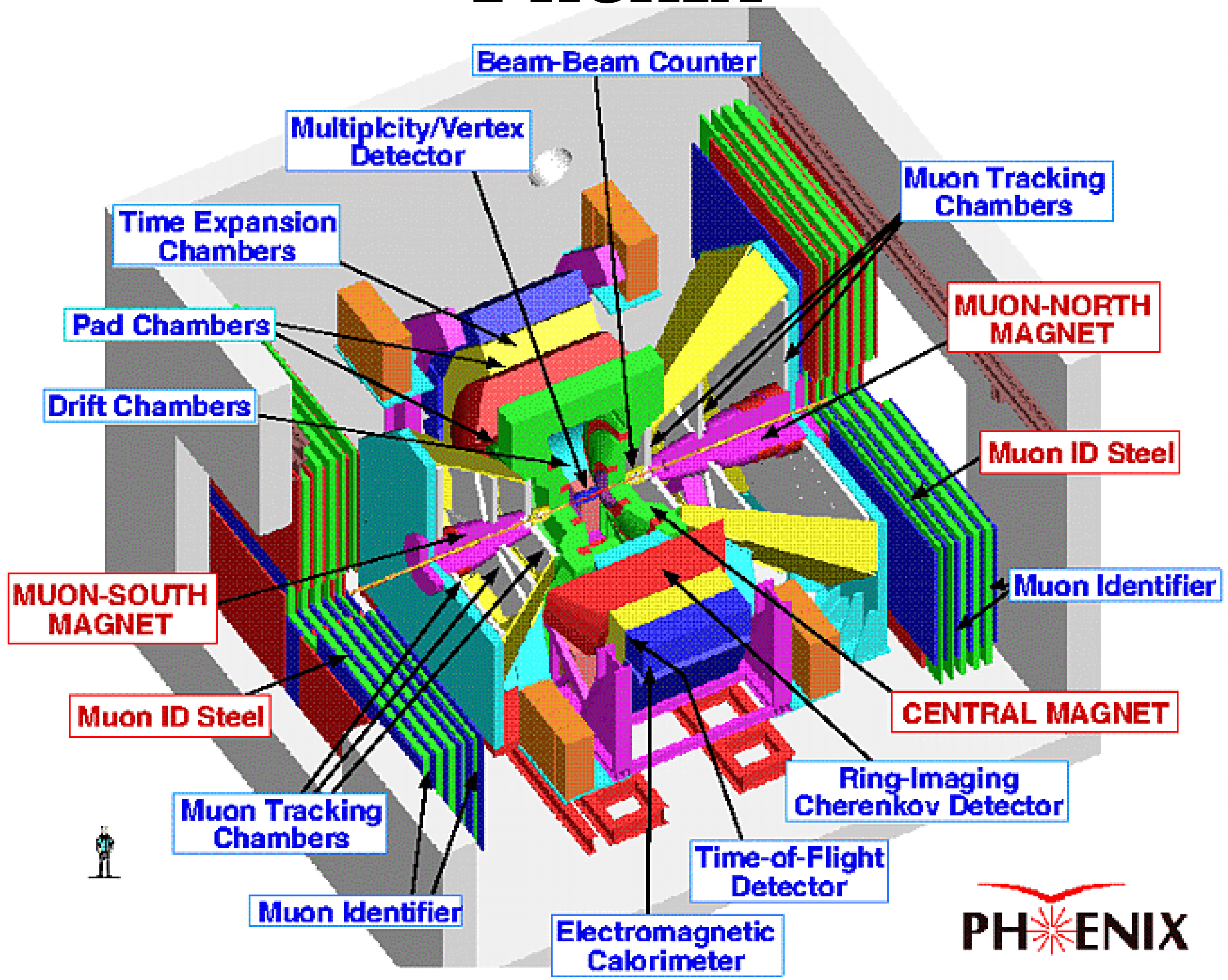




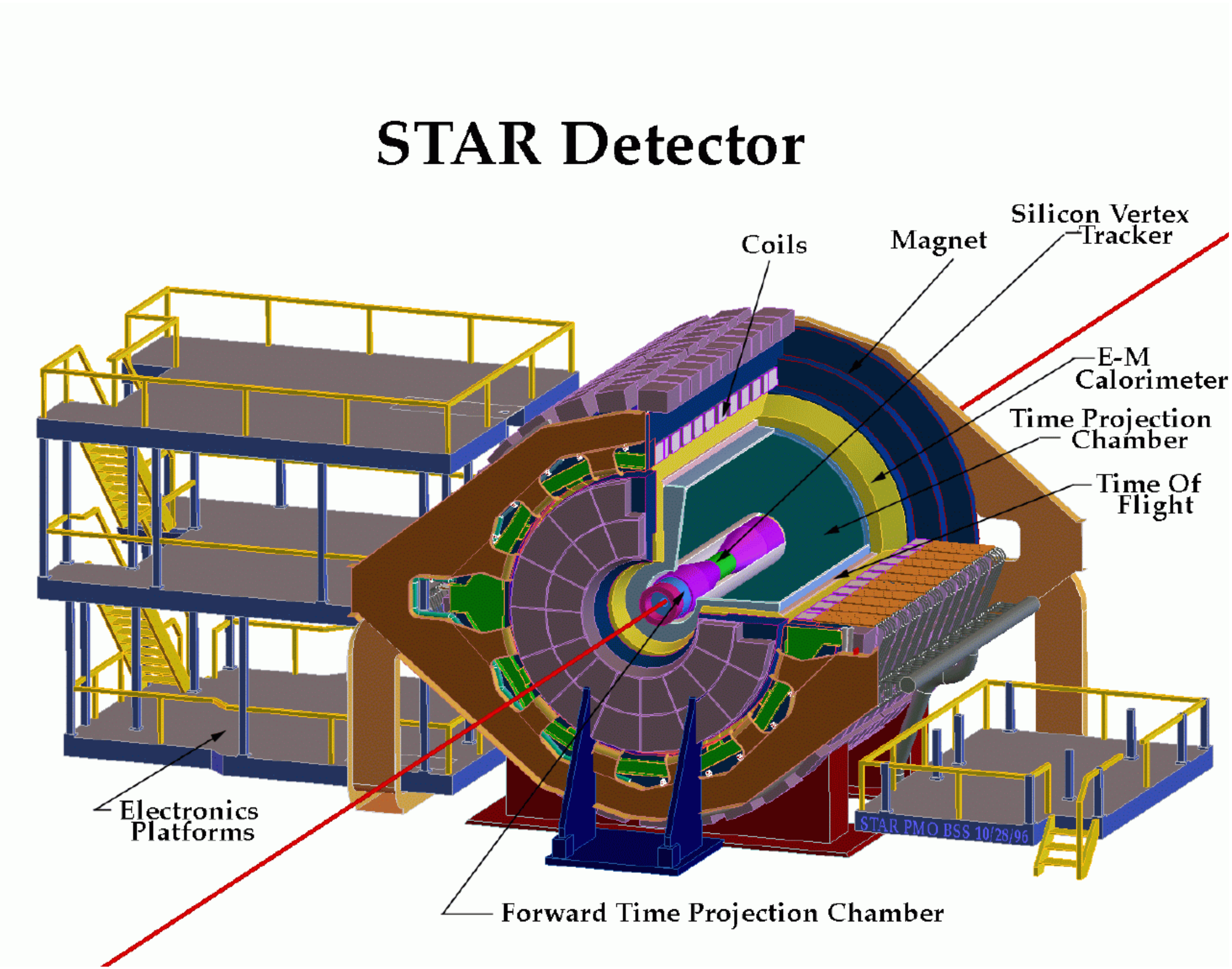


w/o: 1000 depolarising resonances

Phenix



Beam-Beam Counter
Multiplcity/Vertex Detector
Time Expansion Chambers
Pad Chambers
Drift Chambers
Muon Tracking Chambers
MUON-NORTH MAGNET
Muon ID Steel
Muon Identifier
MUON-SOUTH MAGNET
Muon ID Steel
CENTRAL MAGNET
Ring-Imaging Cherenkov Detector
Muon Tracking Chambers
Time-of-Flight Detector
Muon Identifier
Electromagnetic Calorimeter
PHENIX


STAR Detector
Coils
Magnet
Silicon Vertex Tracker
E-M Calorimeter
Time Projection Chamber
Time Of Flight
Electronics Platforms
Forward Time Projection Chamber
STAR PMO BSS 10/28/96

5. Inclusive Results

Unpolarised structure function:

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

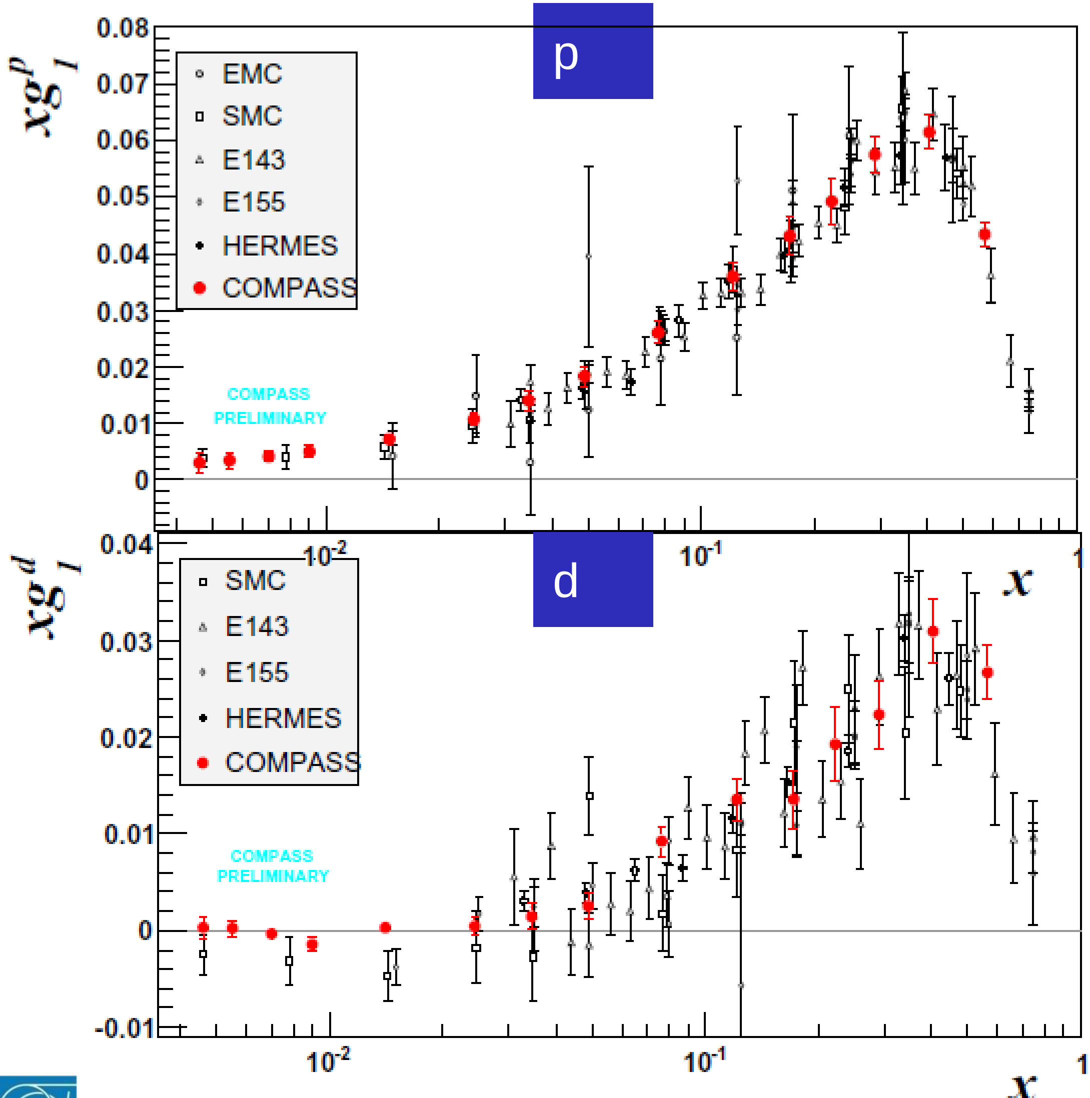
Polarised structure function :

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

Experiments often present data as A_1:

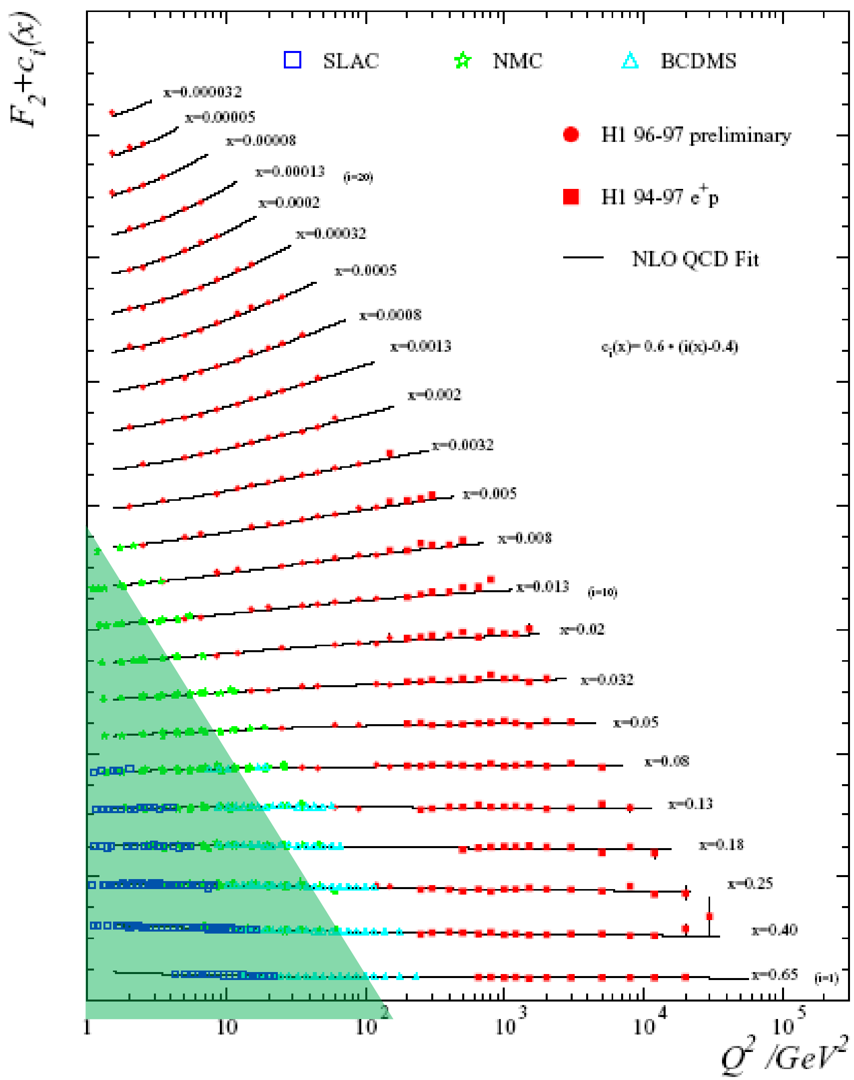
$$A_1 \cong \frac{A_{II}}{D} \cong g_1 \frac{2x}{F_2}$$

Structure function $xg_1(x,Q^2)$

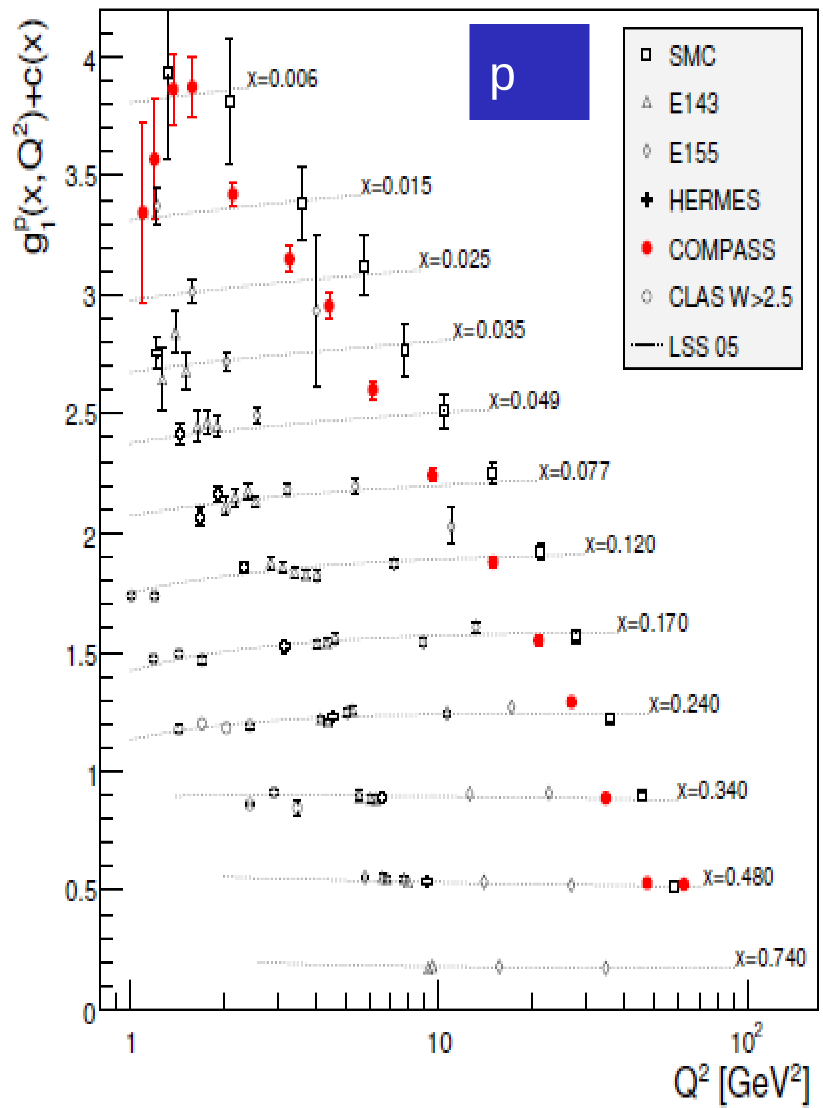


- COMPASS deuteron data:
  a_0 ___ = 0.33 0.03 0.05
  $\Delta s + \Delta s$ = −0.08 0.01 0.02
- Hermes similar
- (evol. to $Q^2 = \infty$)

$F_2(x,Q^2)$ $g_1(x,Q^2)$

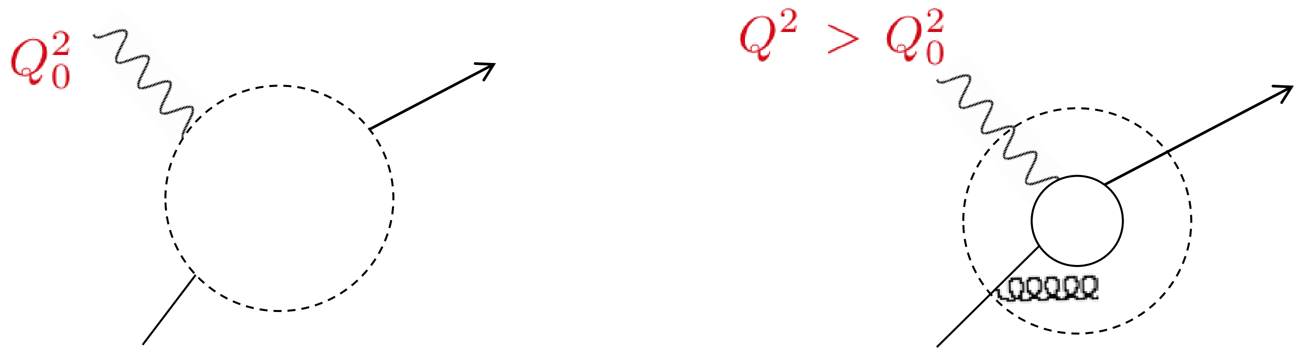


SLAC
NMC
BCDMS
H1 96-97 preliminary
H1 94-97 e+p
NLO QCD Fit
$F_2+c_i(x)$
Q^2 /GeV^2



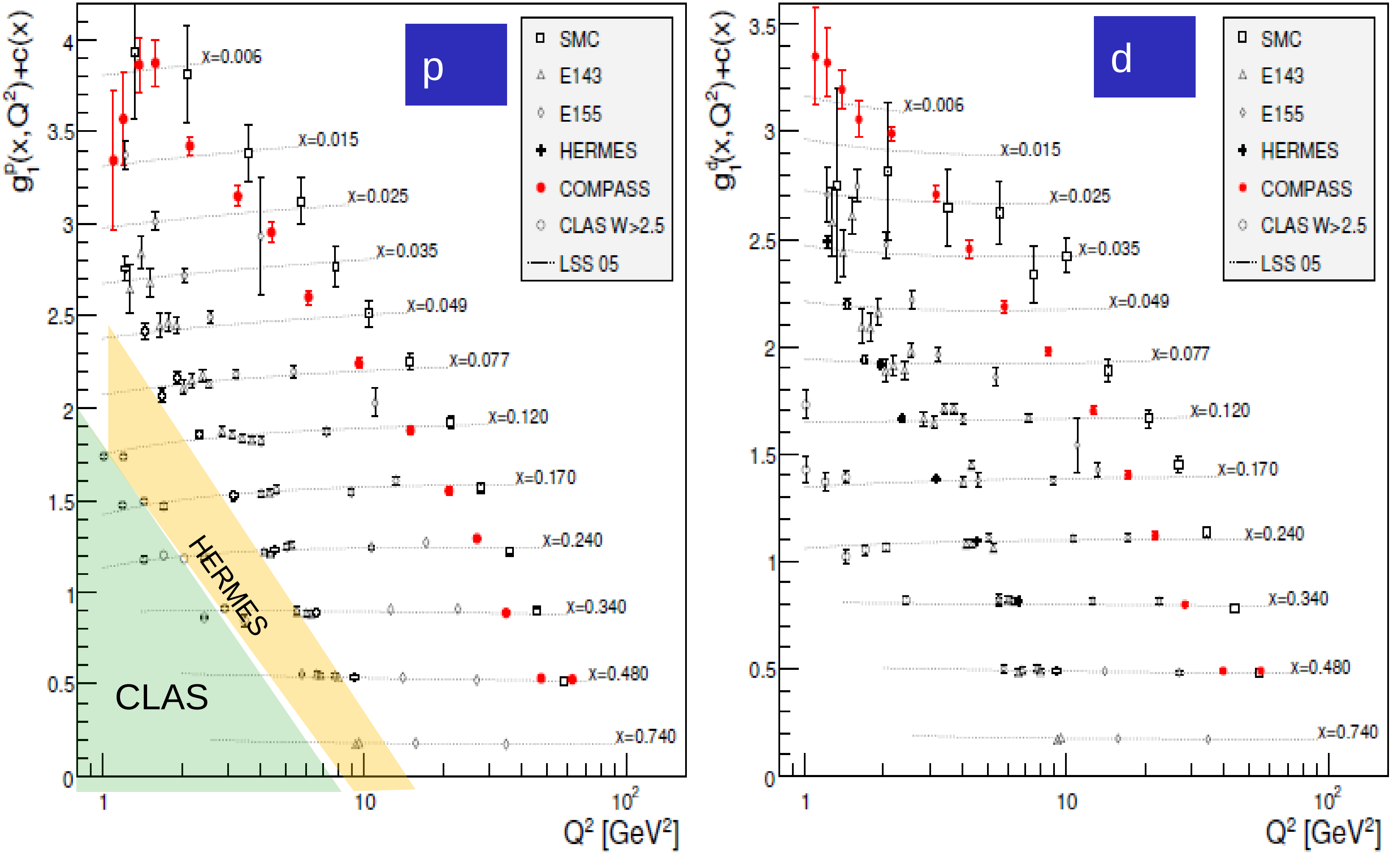
p
SMC
E143
E155
HERMES
COMPASS
CLAS W>2.5
LSS 05
$g_1^p(x,Q^2)+c(x)$
Q^2 [GeV^2]

Scaling violations

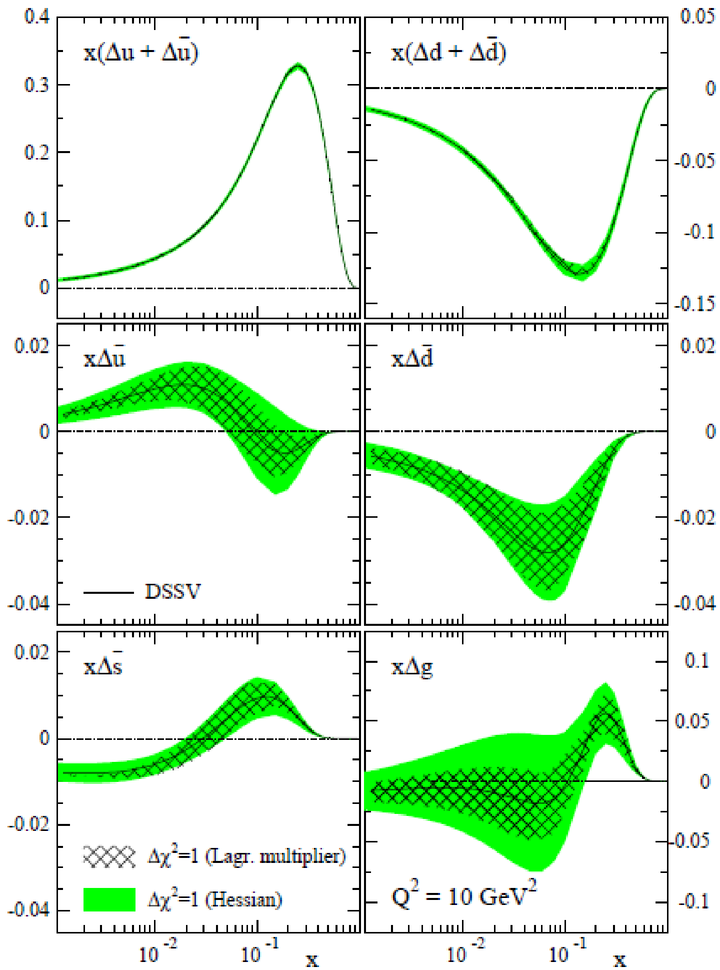


- with increasing Q^2 more details are resolved
- quarks/gluons split and produce more partons
- the 'new' partons have smaller x-Bjorken
- PDFs and SFs became functions of Q^2: $P(x) \rightarrow P(x,Q^2)$
- the Q^2 evolution is calculable in perturbative QCD, if the PDFs $P(x,Q^2_0)$ are known at some Q^2_0 (DGLAP equations)
- x dependence is non-perturbative and not described in pQCD
- The gluon distribution can be deterimined from these "scaling violations"

Proton & deuteron $g_1(x,Q^2)$

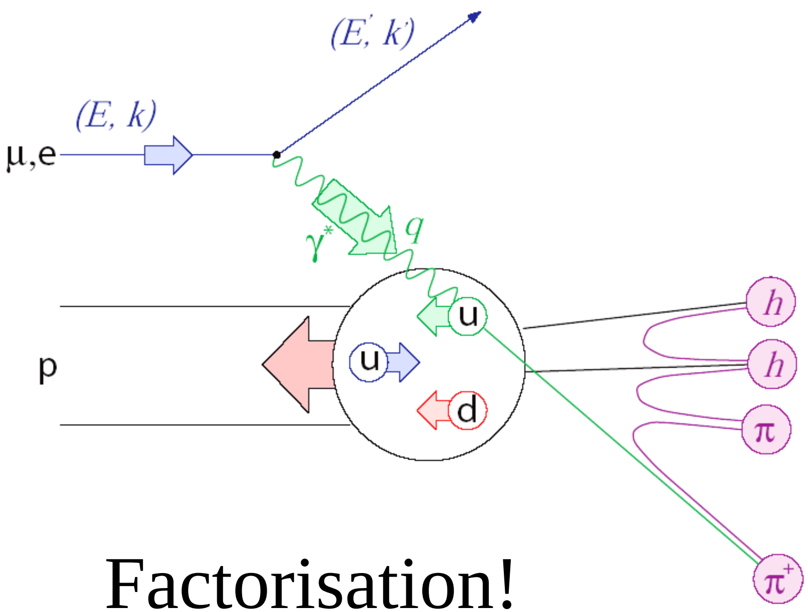


QCD Fits



Marco Stratmann (tomorrow)

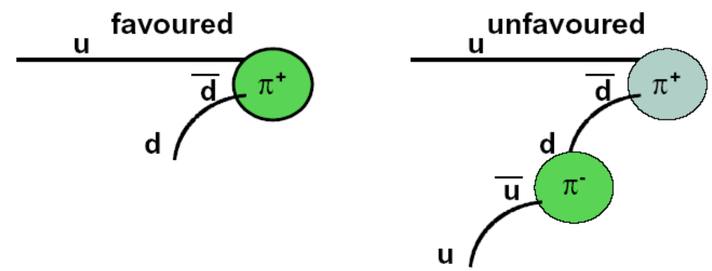
6. Semi-inclusive results



Factorisation!

D_q^h from quark q into hadron h

$z = \frac{E_h}{\nu}$ energy fraction carried by h

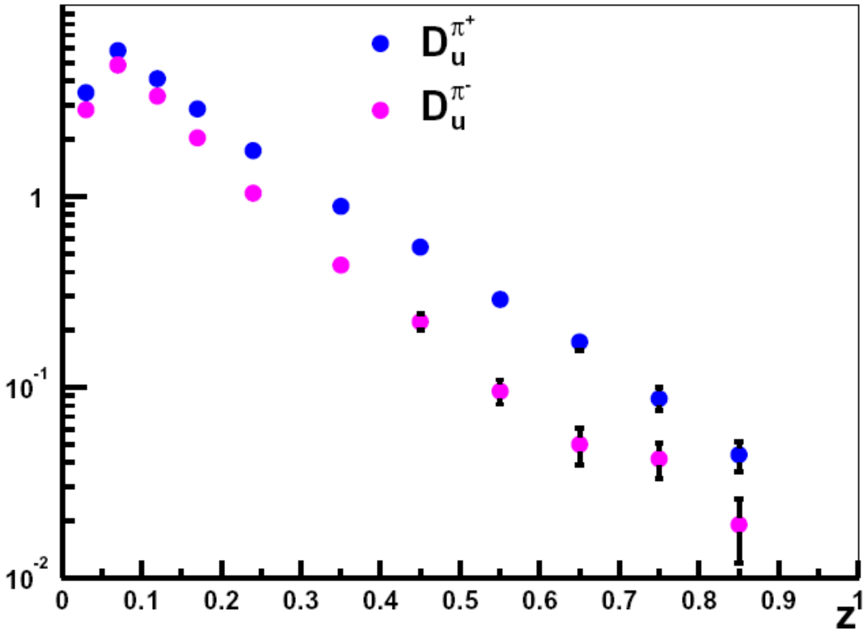


$$D_u^{\pi^+} \underset{\text{CC}}{=} D_{\bar{u}}^{\pi^-} \underset{\text{IS}}{=} D_{\bar{d}}^{\pi^+} \underset{\text{CC}}{=} D_d^{\pi^-}$$

$$D_d^{\pi^+} = D_{\bar{d}}^{\pi^-} = D_{\bar{u}}^{\pi^+} = D_u^{\pi^-}$$

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

Fragmentation functions



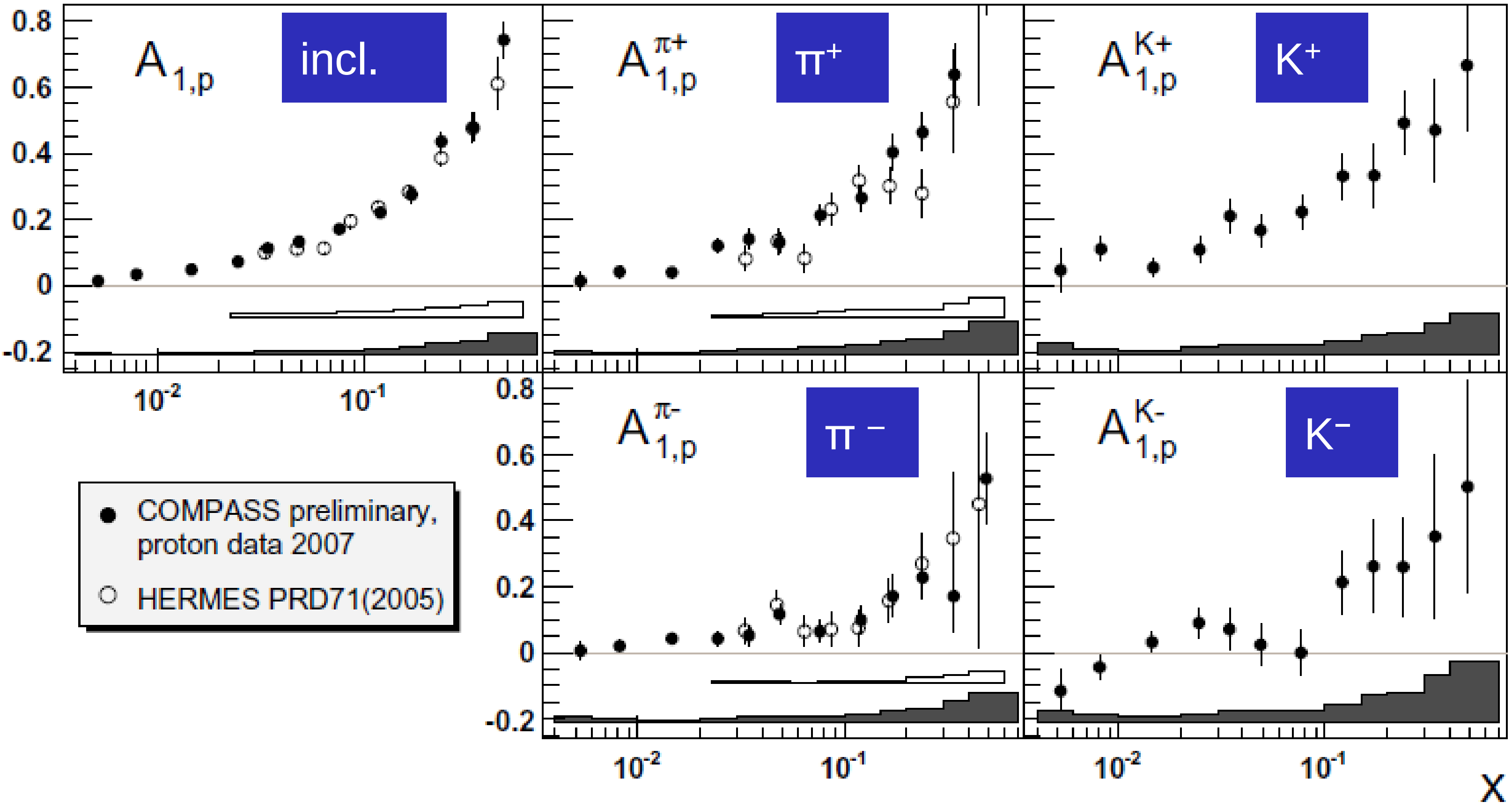
final hadron remembers flavour of initially struck quark

Integrate over used *z* region

$$A_1^h(x, Q^2) = \frac{\int \mathrm{d}z \sum_f e_f^2 \Delta q_f(x, Q^2) \cdot D_f^h(z, Q^2)}{\int \mathrm{d}z \sum_f e_f^2 \; q_f(x, Q^2) \cdot D_f^h(z, Q^2)}$$

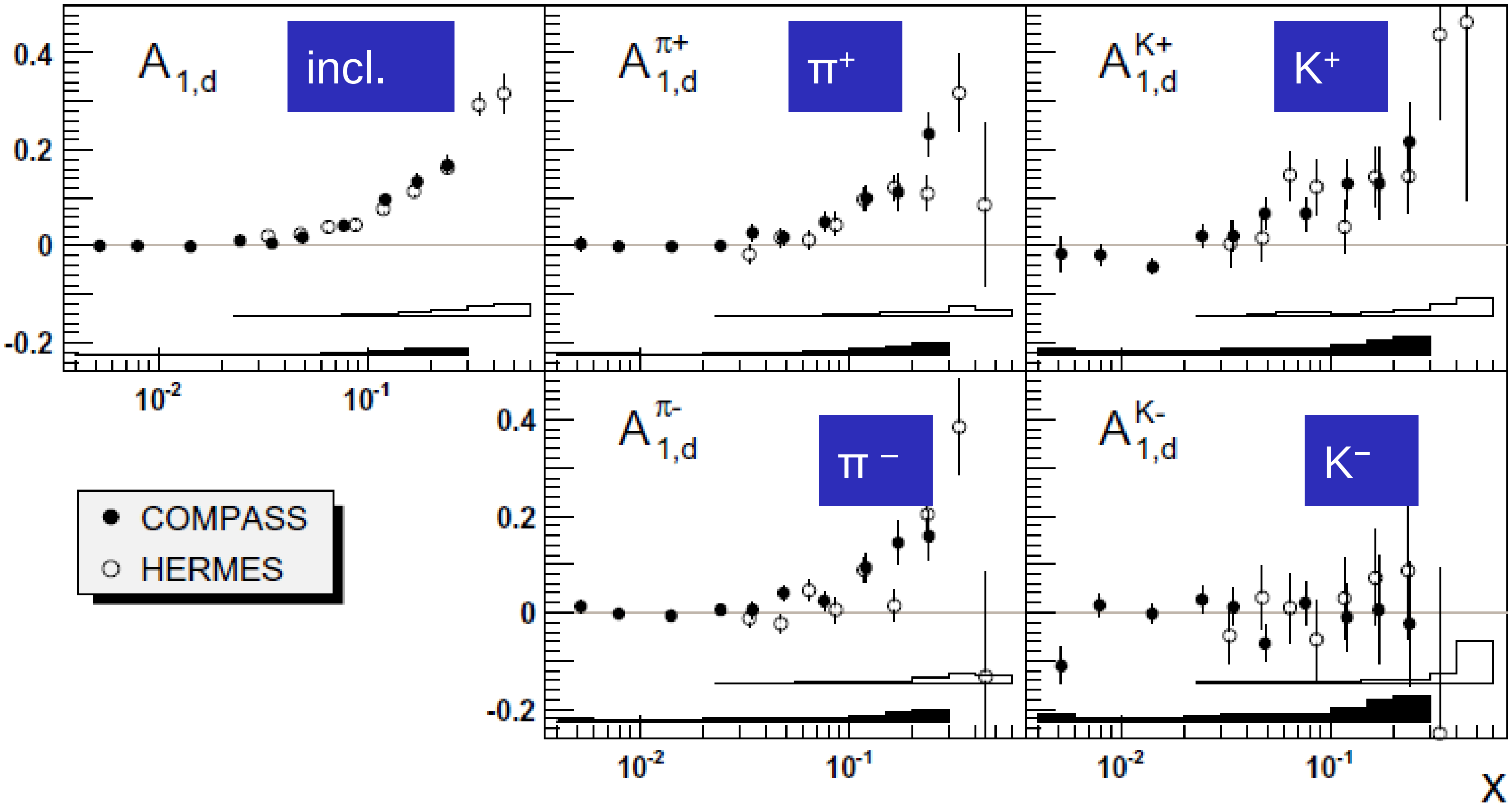
Incl. & semi-incl. A_1

- proton

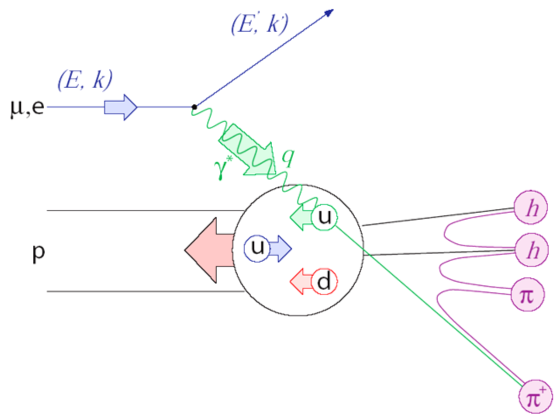


Incl. & semi-incl. A_1

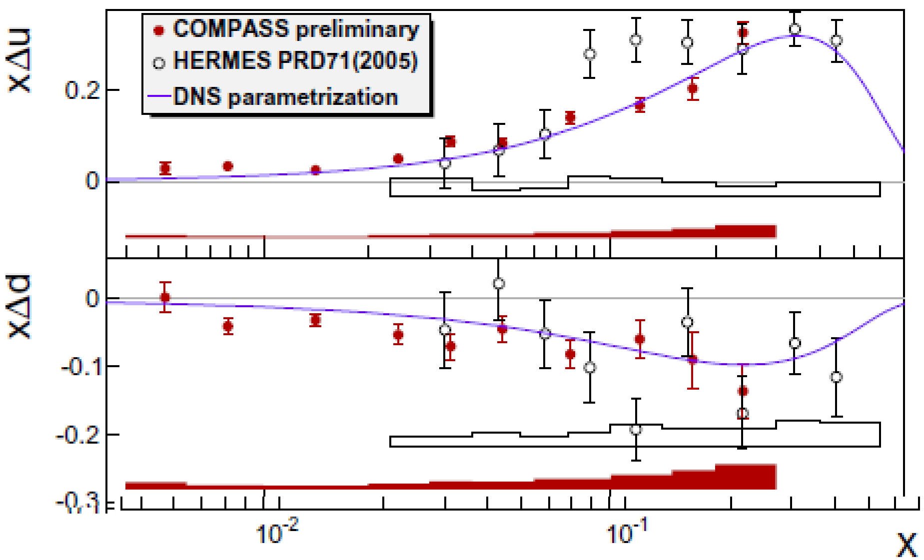
- deuteron

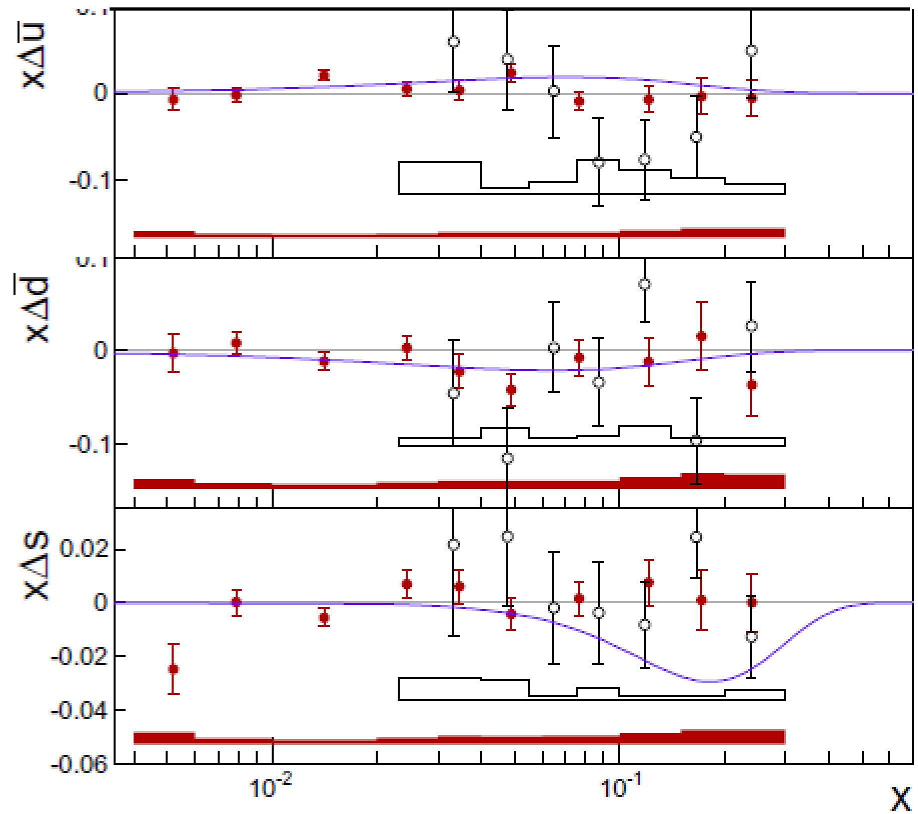


The role of quark flavours



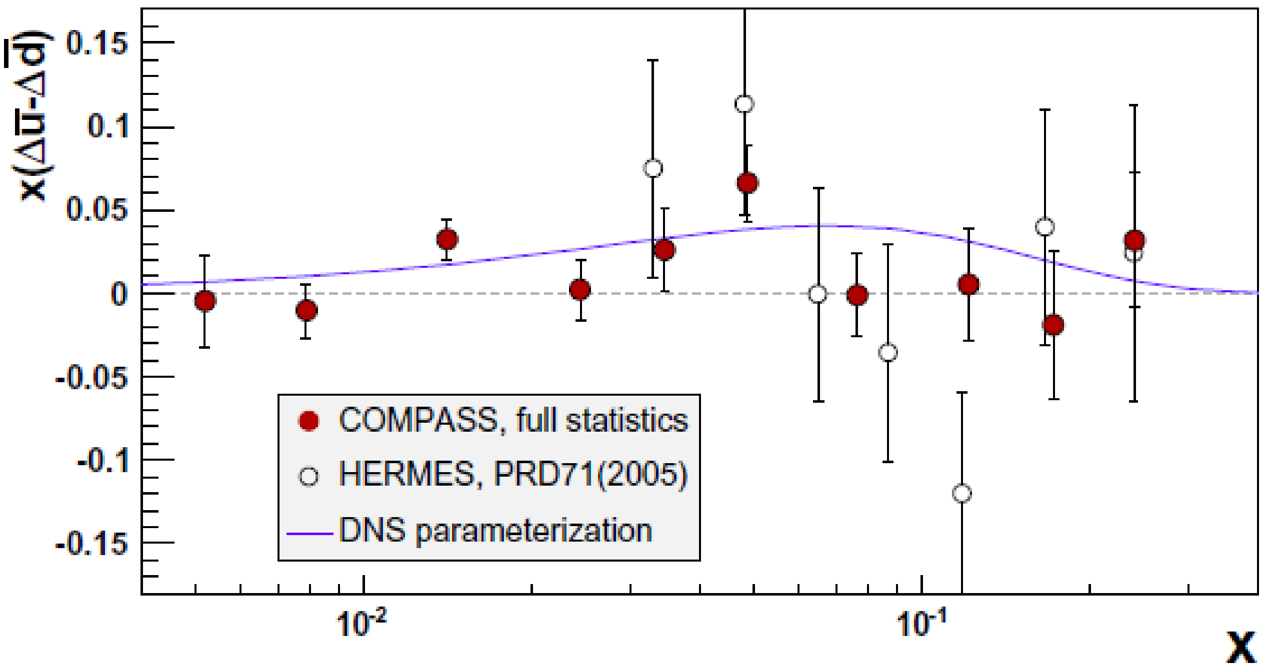
- LO analysis, preliminary





Flavour asymmetry? $\Delta\overline{u} - \Delta\overline{d}$

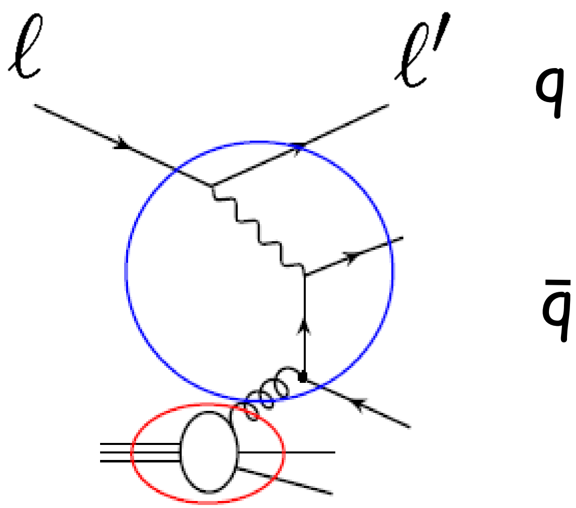
- considerable asymmetry in the unpolarised case
- model predicts naturally asymmetry for pol. case
- only small effect (if at all)



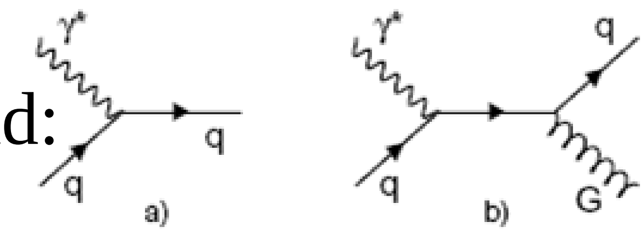
7. ΔG from photon-gluon fusion

Principle: Gluon polarisation enters via photon-gluon fusion (PGF), use

- light quark with high p_T or
- charm quarks



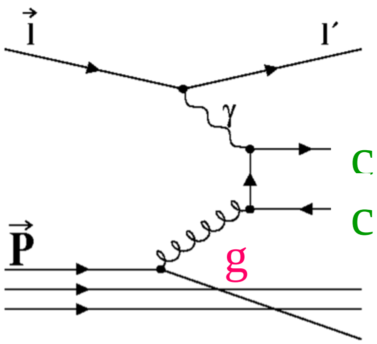
- Background:



- measure $$A_{||} = R_{pgf}\langle \hat{a}_{pdf}\rangle \left\langle \frac{\Delta g}{g} \right\rangle$$
- calculate R_{pgf} , $\langle \hat{a}_{pgf}\rangle$ and background by Monte Carlo

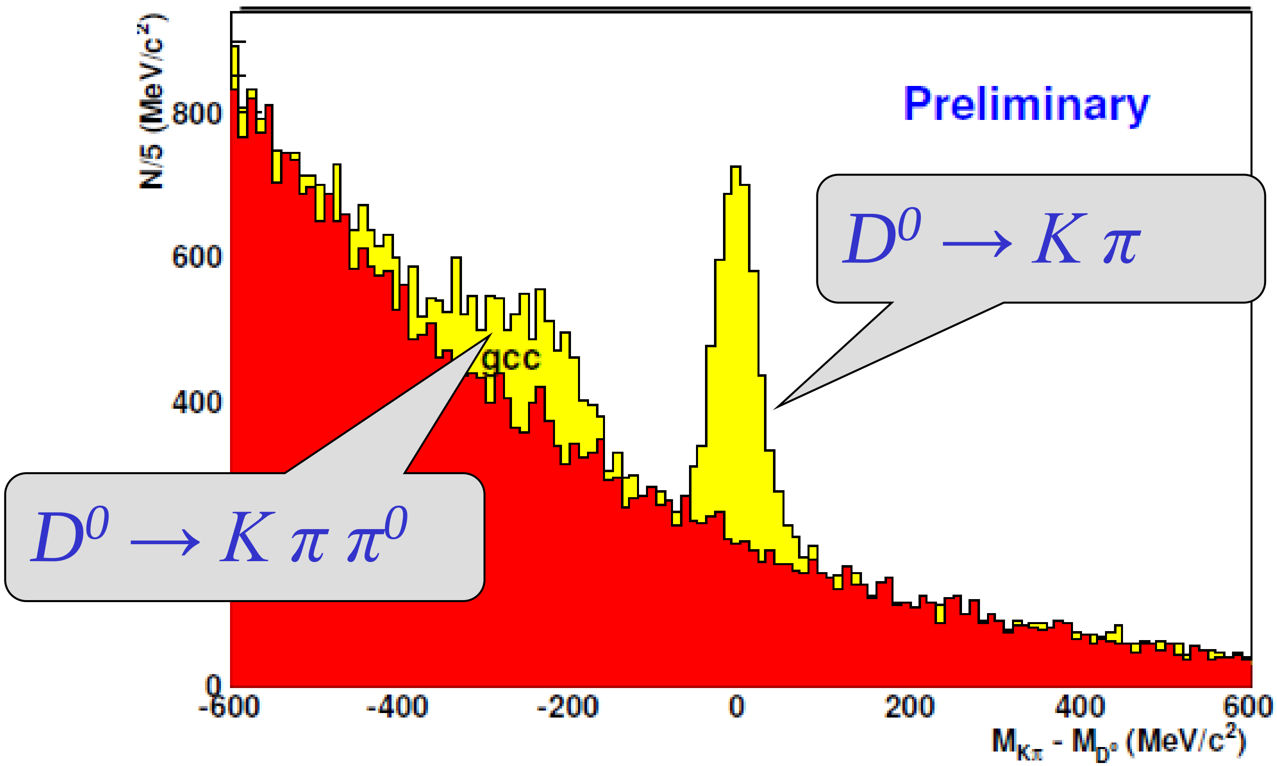
Δg/g from open charm

- cleanest process
  - little physics background (LO, QCDC)
- observe asymmetry in *D* meson production
  - statistics limited
  - only one *D* meson via $D \to \pi K$ (BR ~ 4%)
  - combinatorial background large
  - drastically reduced when looking to *D** decay in coincidence with slow pion



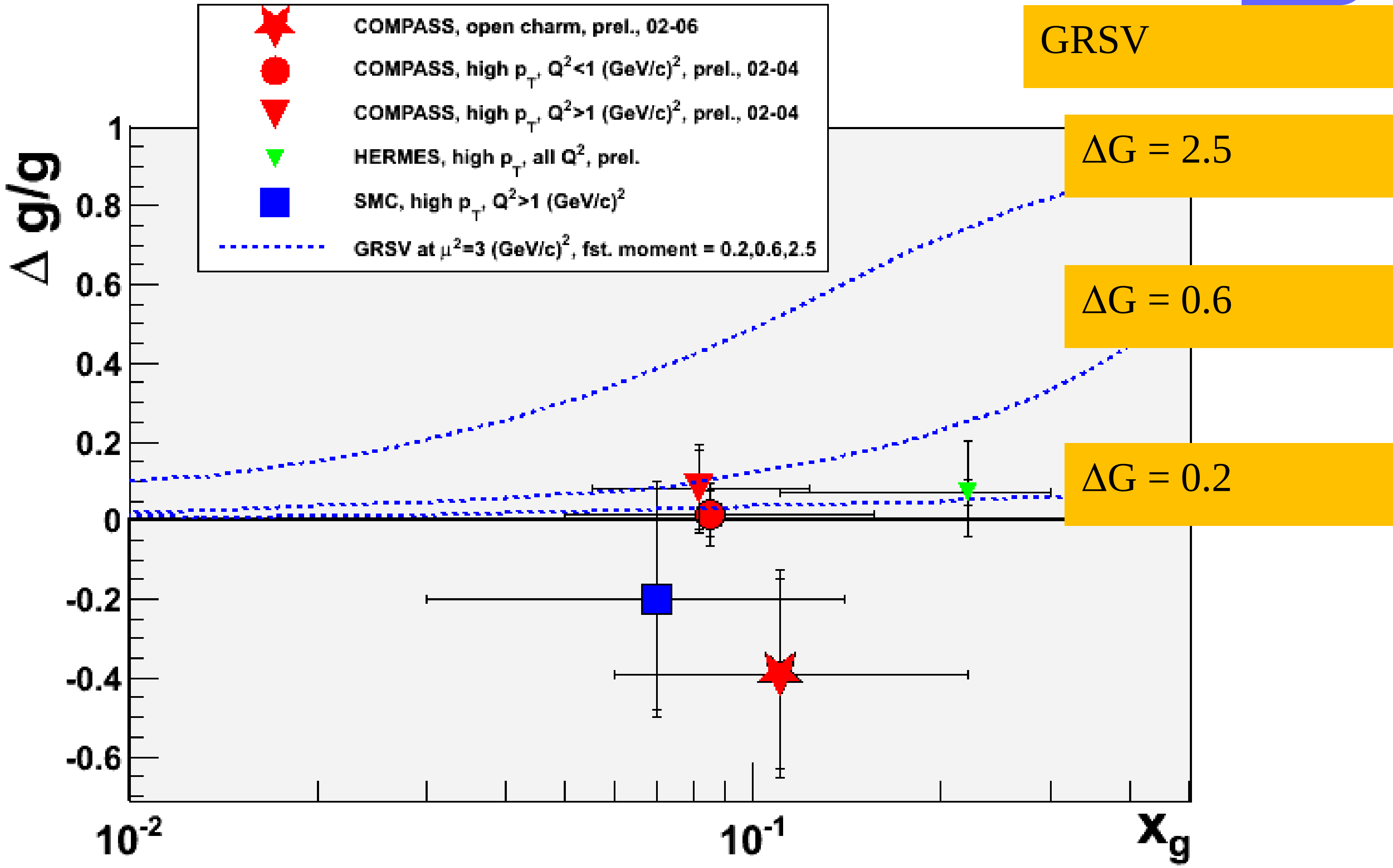
$$D^* \to D^0 + \pi_s \to K + \pi + \pi_s$$

Δg/g from open charm

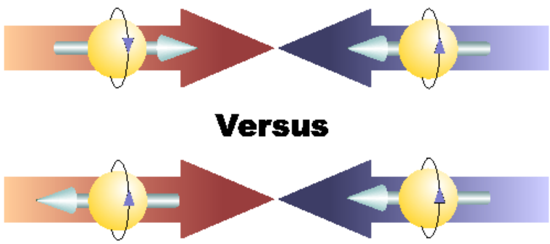


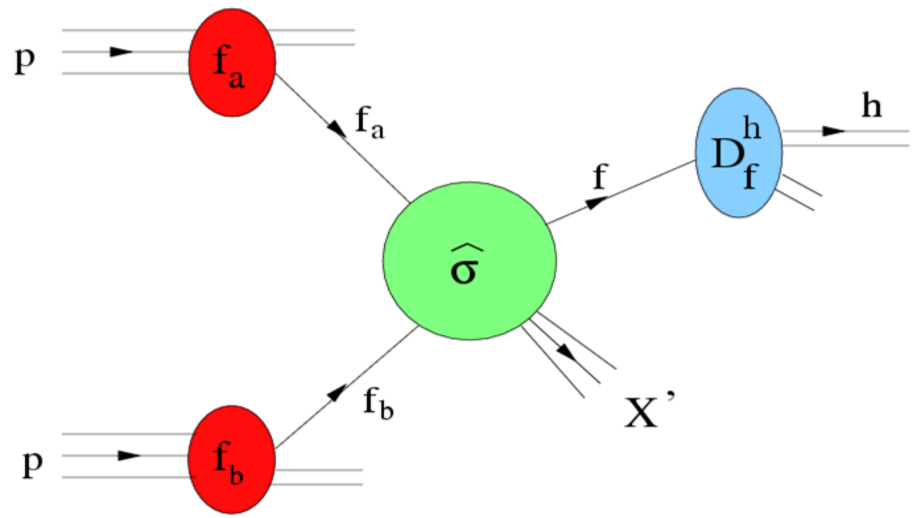
$$\langle \Delta g/g \rangle_x = -0.39 \pm 0.24\,(\text{stat.})$$

ΔG from PDF analyses

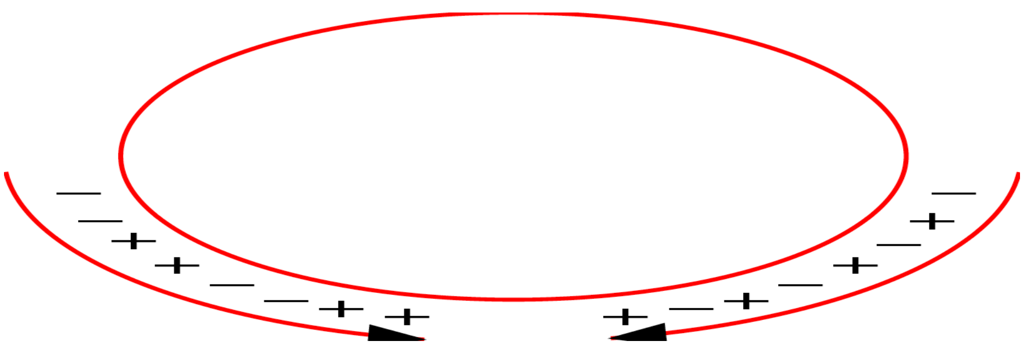


8. RHIC $\vec{p}\vec{p}$ collisions



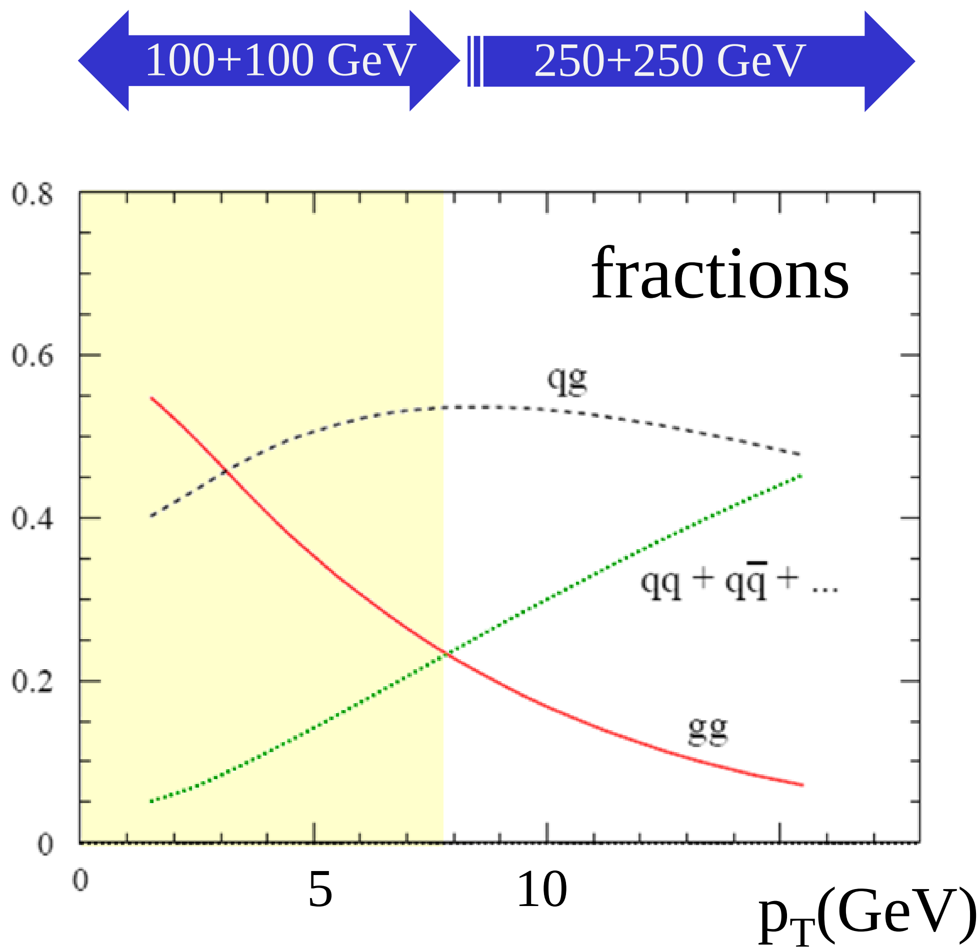


polarisation ~ 45 % in 2005
~ 60 % ≥ 2006



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

qg - qq - gg processes

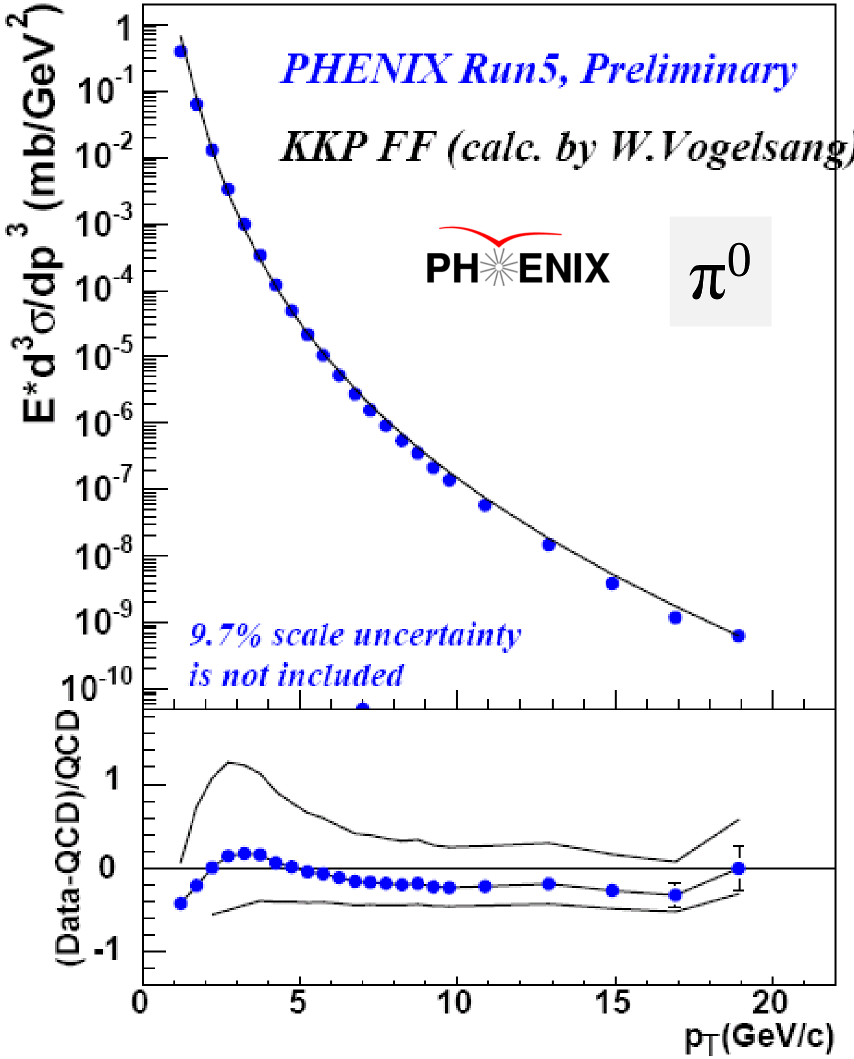


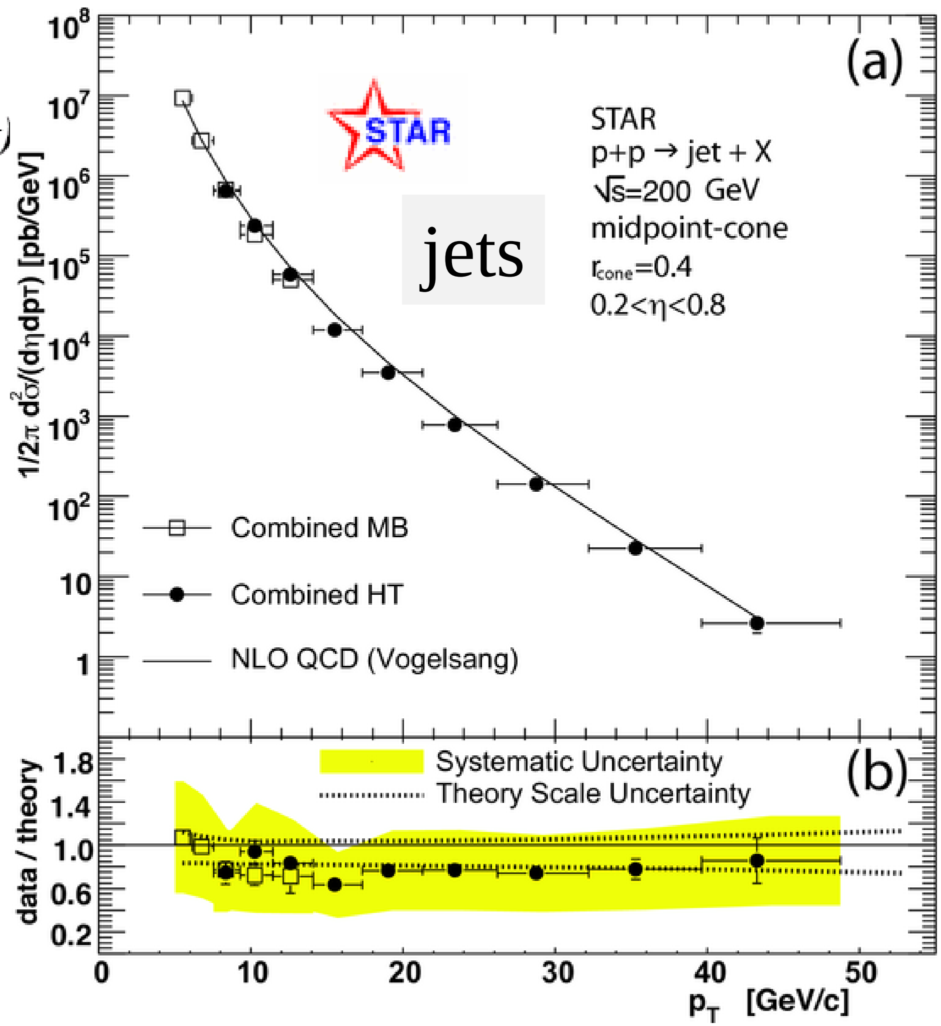
energy:
100 on 100 GeV
2009:
250 on 250 GeV

$\propto \Delta g^2$

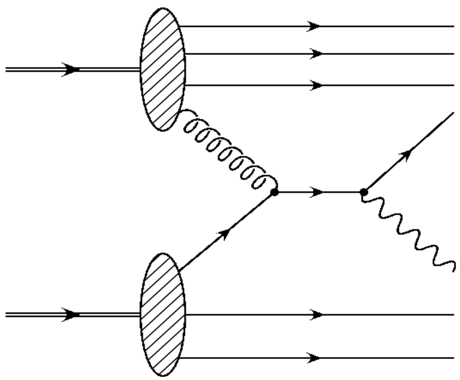
gg processes dominate at 100 on 100 GeV
sign ambiguity

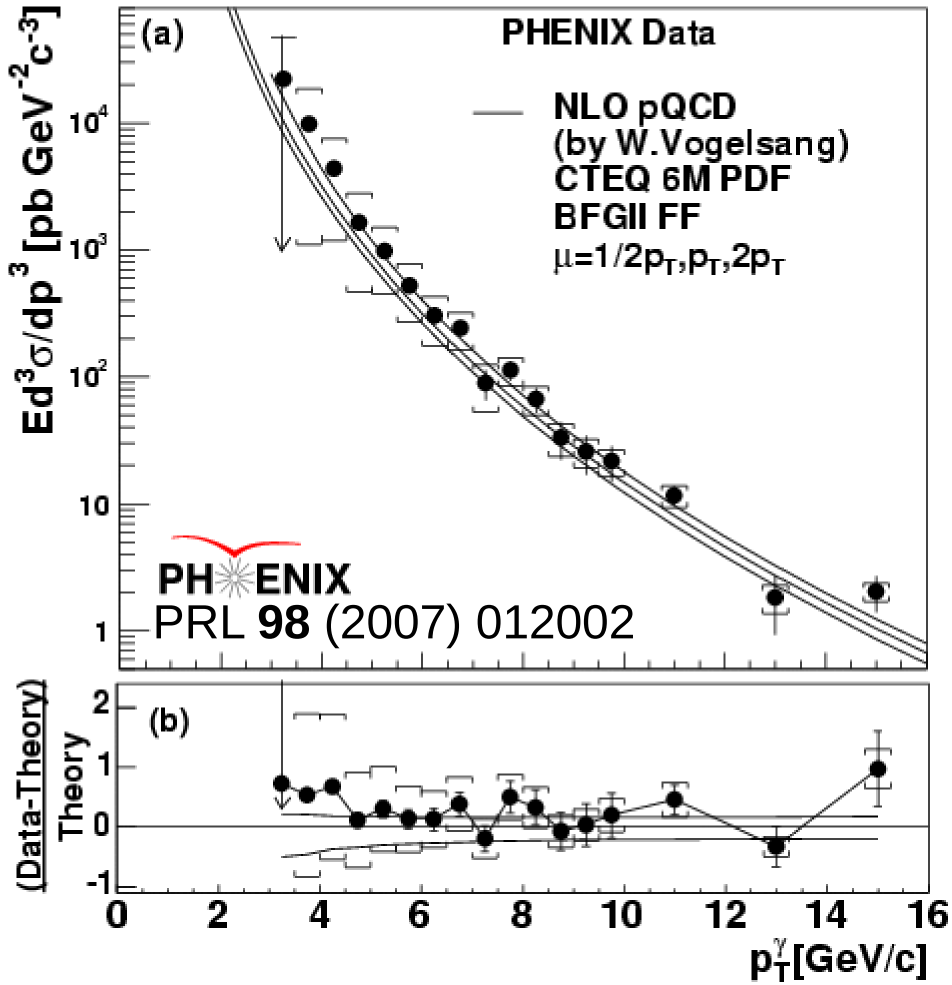
NLO vs data (unpol)





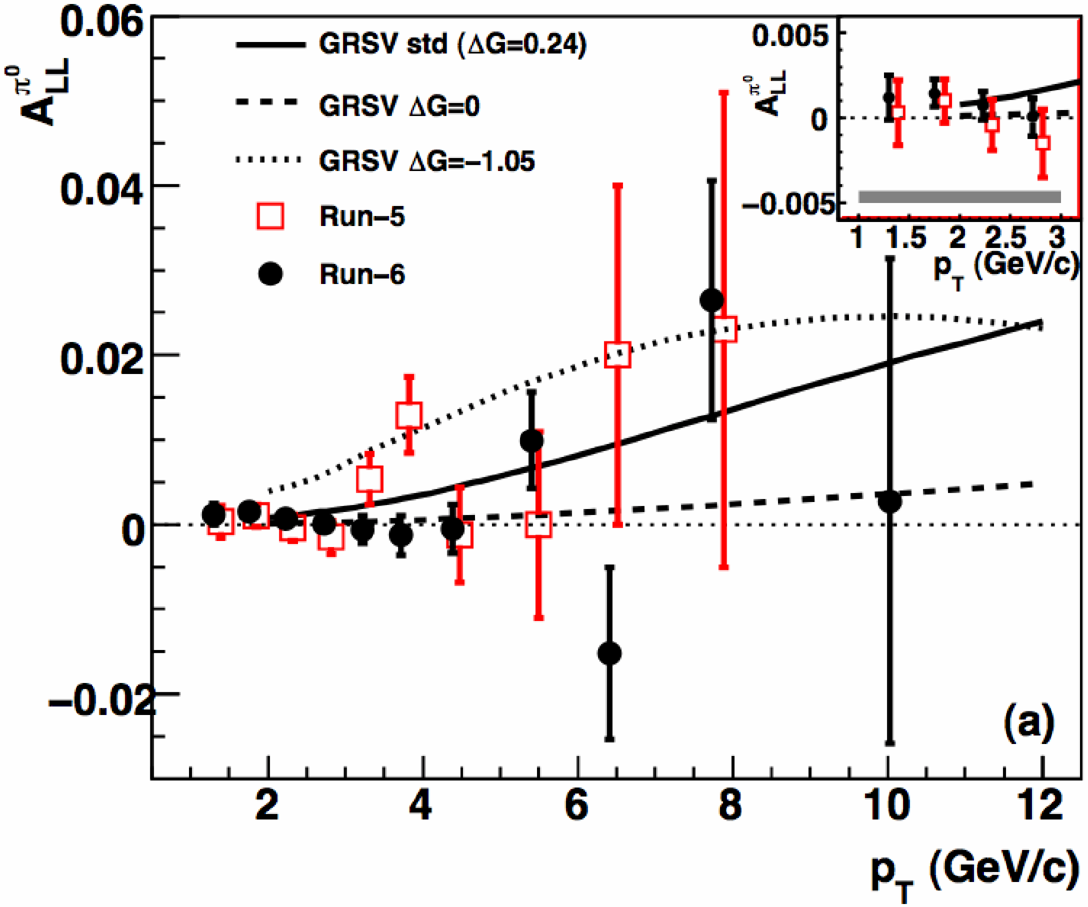
Direct photons



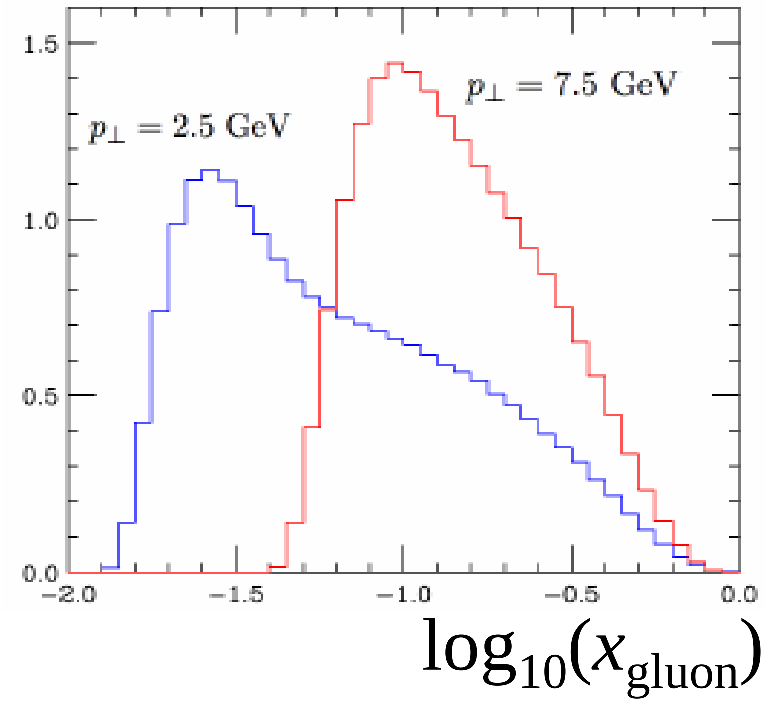


- good agreement of calc. and data at collider energies

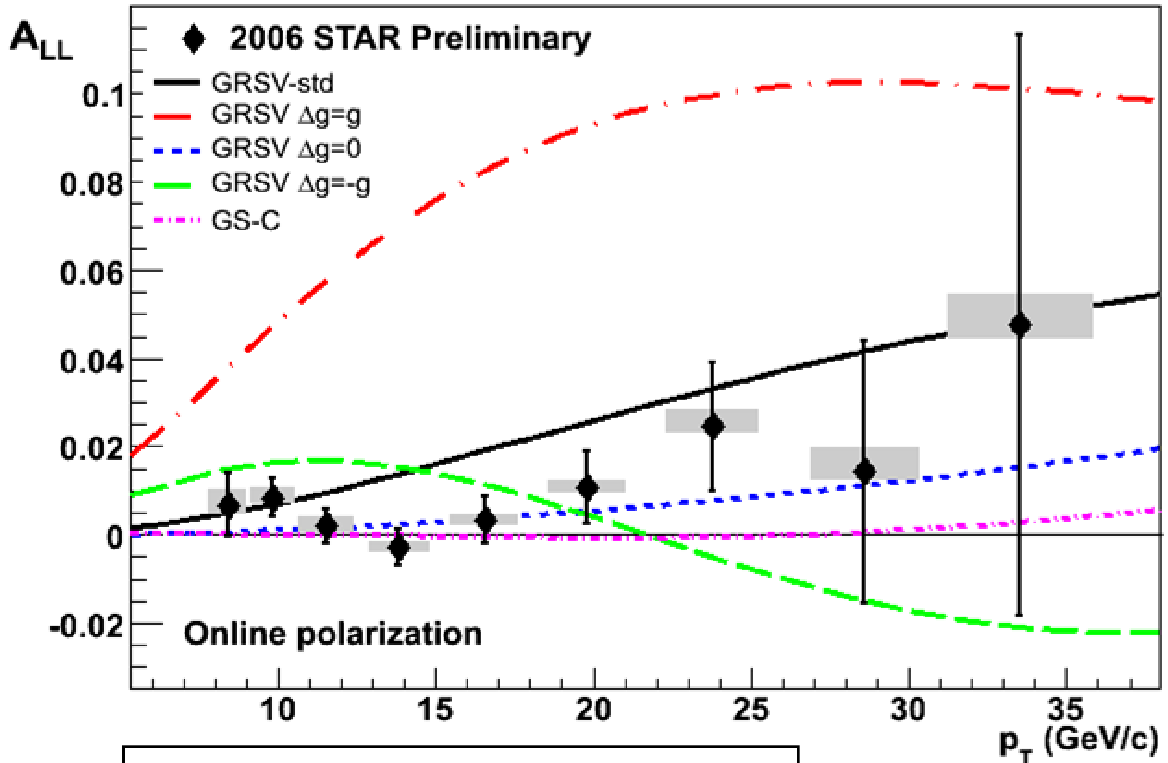
Phenix π^0 asymmetries



PHENIX



STAR incl. jet asymmetries



GRSV Models:

$\Delta G = G$: $\Delta G(Q^2=1\,GeV^2) = 1.9$

$\Delta G = -G$: $\Delta G(Q^2=1\,GeV^2) = -1.8$

$\Delta G = 0$: $\Delta G(Q^2=1\,GeV^2) = 0.1$

$\Delta G = std$: $\Delta G(Q^2=1\,GeV^2) = 0.4$

2-jet events will give information on the kinematics on the parton level event by event (x_g)

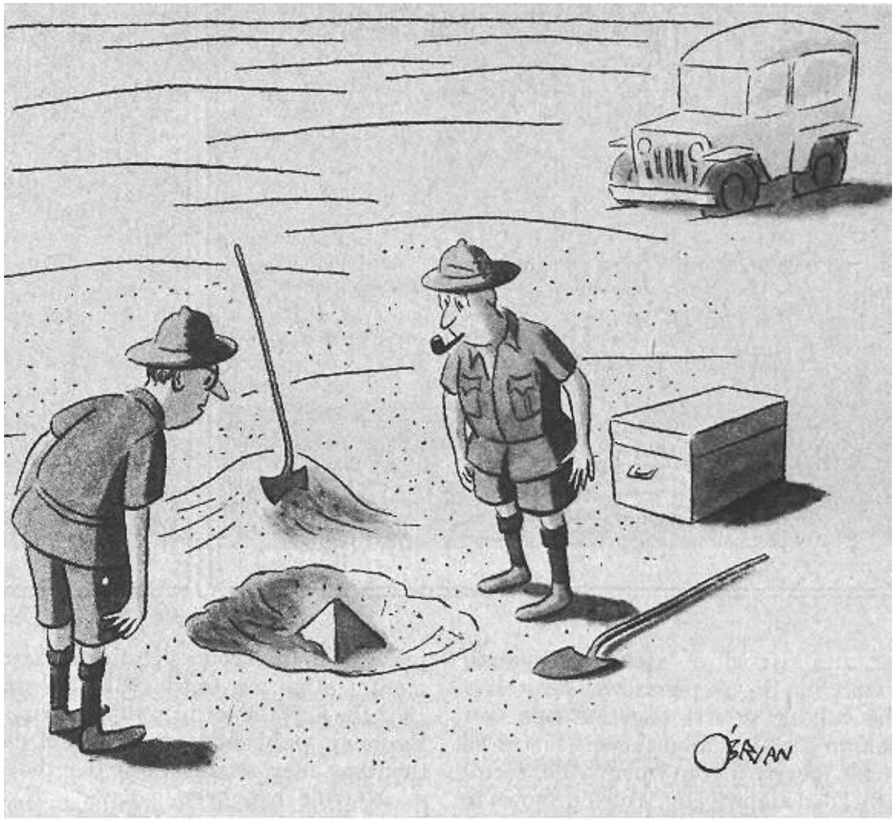
Remark

- More than two decades passed since the so-called spin-puzzle was discovered.
- Very fruitful investigations, both experimental and theoretical, led to a much deeper understanding.
- However, the spin structure of the nucleon and the role of orbital angular momentum remains to be understood.

- "You think you understand something…, now add spin"

R. Jaffe

It seems, spin goes pretty far down…



"This could be the discovery of the century. Depending, of course, on how far down it goes."