Neutron and ^{3}He GDH at low Q^2 at Jefferson Lab HallA

F. Garibaldi

(for He-3 collaboration – Hall A Jefferson Lab)

- **Why**
- **How**
  - Polarized beam and target
  - Forward Angle -> Septum magnets
  - Kinematics
  - Neutron and ^{3}He
- **Conclusions**

why

Late 70's, polarized beams and targets.

→
- Further checks of pQCD.
- Spin structure of the nucleons.

SLAC, CERN, DESY

remaining problem

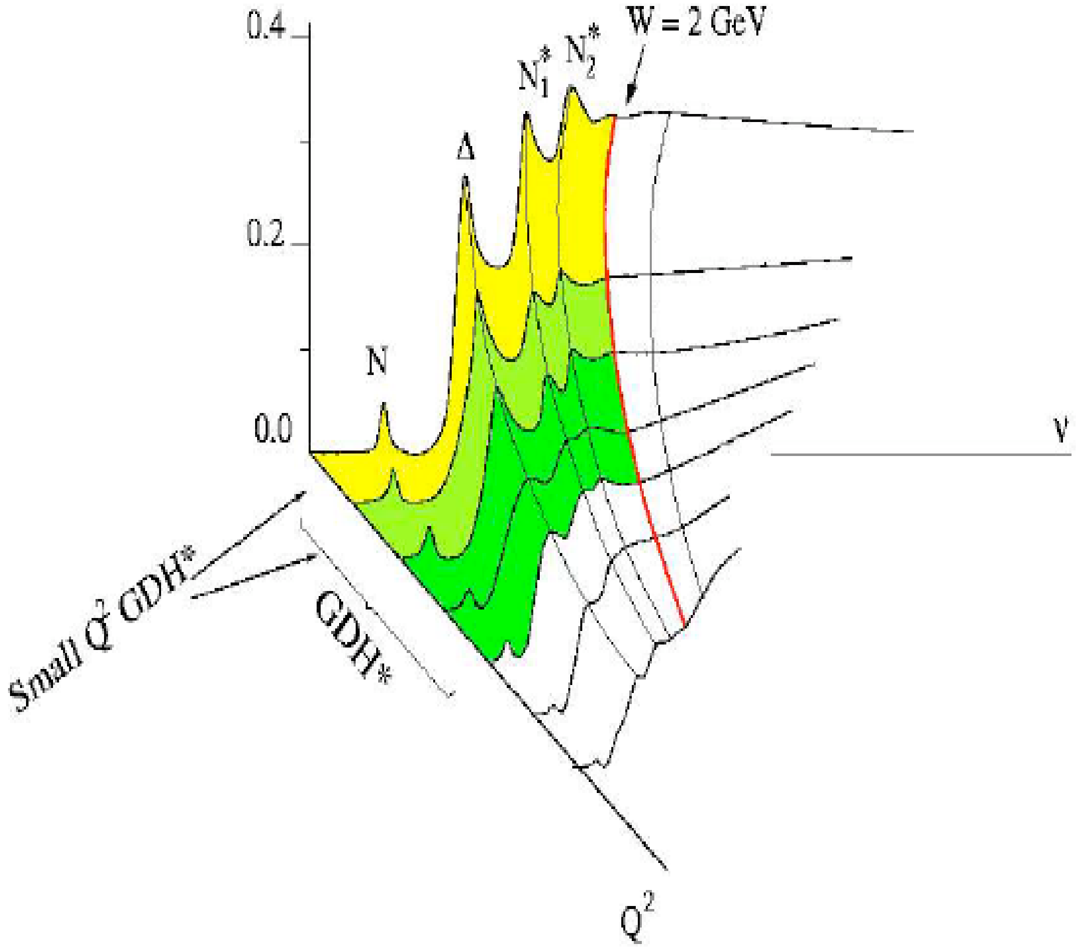
Jefferson Lab:
- Continuous polarized electron beam.
- Low to intermediate Q^2 range.

→ Precise study of the pQCD–npQCD transition. **(not understood)**

(pQCD: quarks & gluons; npQCD: nucleons & mesons)

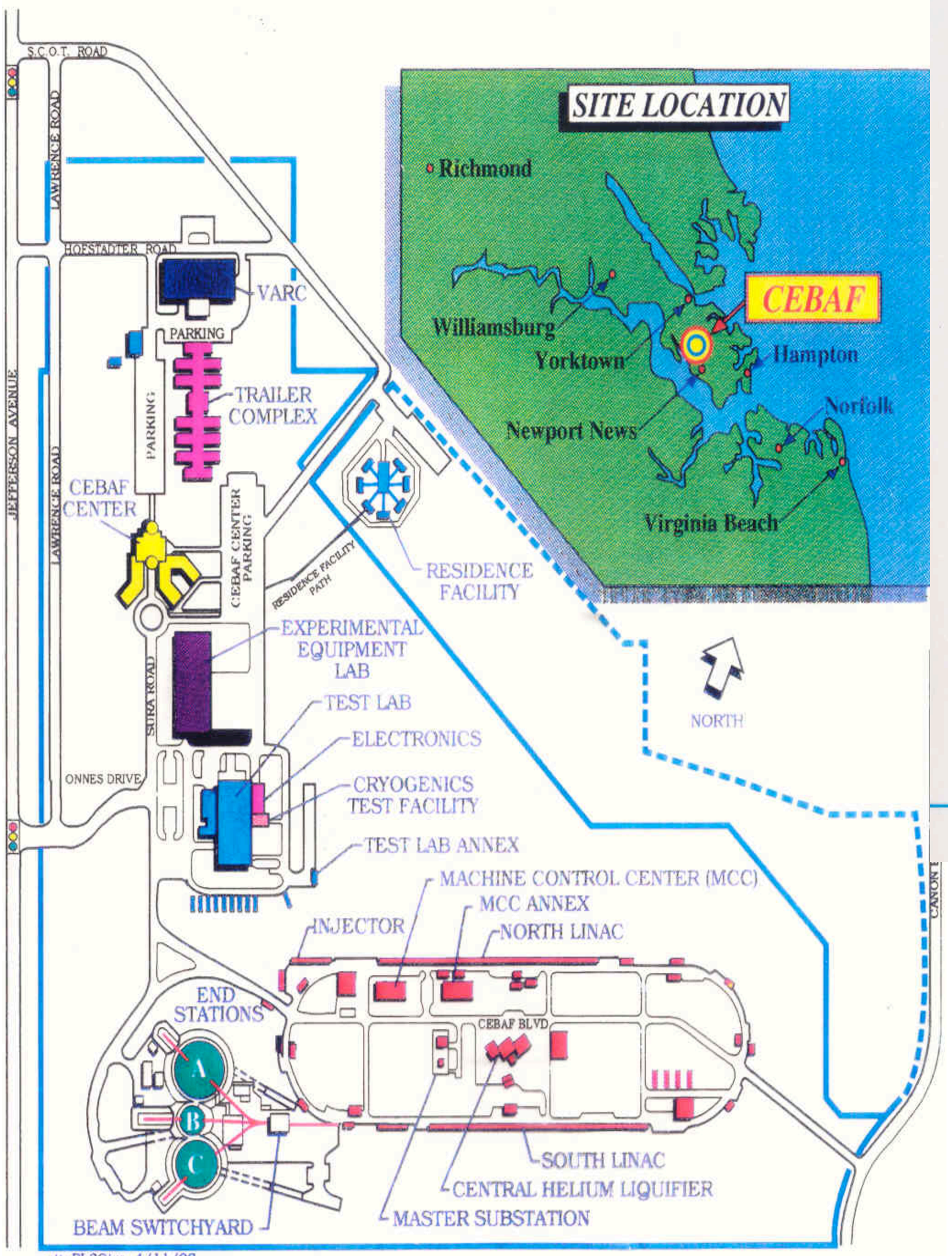
A unique tool to study this transition:
The extended GDH sum rule.

(connection with Bjorken SR)



SITE PLAN

CEBAF



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Boundaries of DOE Owned or Leased Property

Boundaries of SURA Property

0 500'

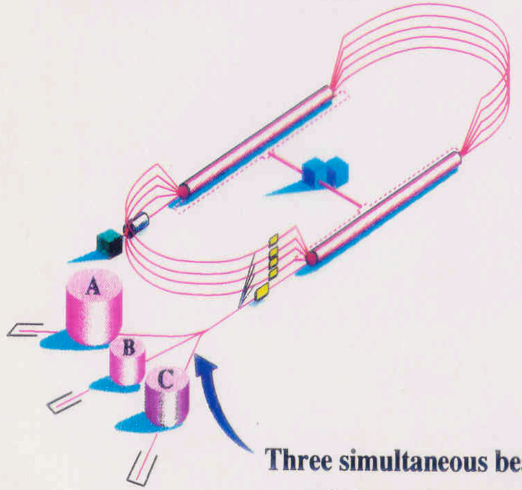
CEBAF

The Continuous Electron Beam Accelerator Facility

SCIENTIFIC MISSION

Investigate strongly interacting matter at the quark-gluon level.

- Nature of quark and gluon confinement
- Quark-gluon picture of the nucleus



MACHINE CHARACTERISTICS

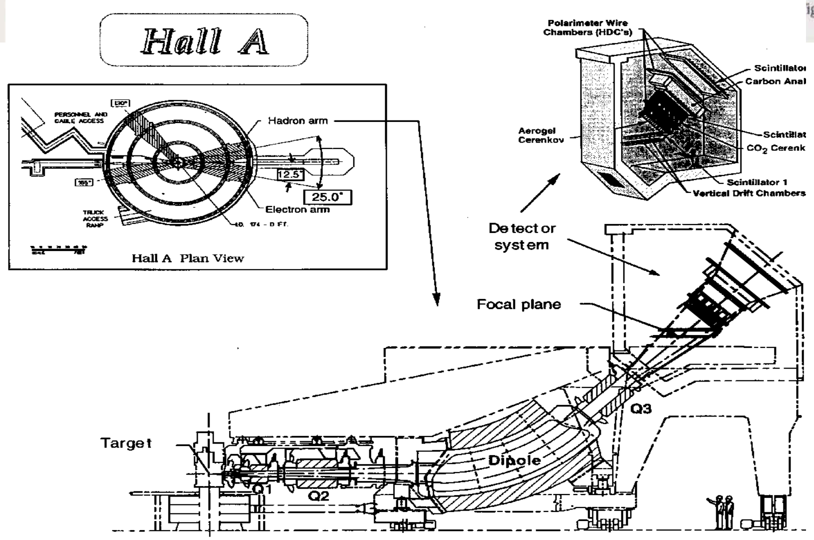
Energy:	.5-6 GeV
Current:	200 µA
Duty Factor:	cw
Emittance:	$\varepsilon \sim 2 \times 10^{-9}$ m·rad
Energy Spread:	$\frac{\sigma_E}{E} \sim 2.5 \times 10^{-5}$

PHYSICS START FALL 94

Three simultaneous beams into three experimental areas

- Independent energy and intensity
- Major equipment components procured in all halls

figscim6aaaCjm /mbs3 4/9



GDH Sum Rule: $Q^2=0$

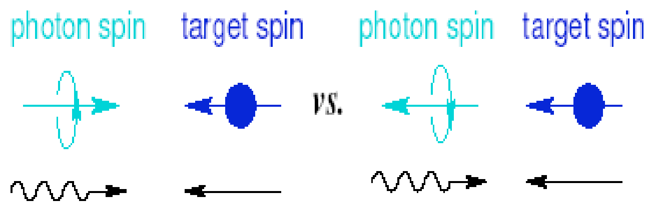
- Take classical Kramer–Kroenig dispersion relation (**causality**)
- Apply unitarity (**optical theorem**)
- Apply Relativity + gauge invariance (**low energy theorem**)

we get GDH:

$$\int_{\nu_0}^{\infty} (\sigma_{1/2}-\sigma_{3/2}) \frac{d\nu}{\nu} = -2\pi\alpha\frac{\kappa^2}{M^2}$$

κ: anomalous magnetic moment

$\sigma_{1/2}$ & $\sigma_{3/2}$:Photoproduction cross–sections



⇒**Based on solid assumptions (same as Bjorken SR)**

Only assumption open to question:
Validity of "**non subtraction hypothesis**"
(Cauchy integration)

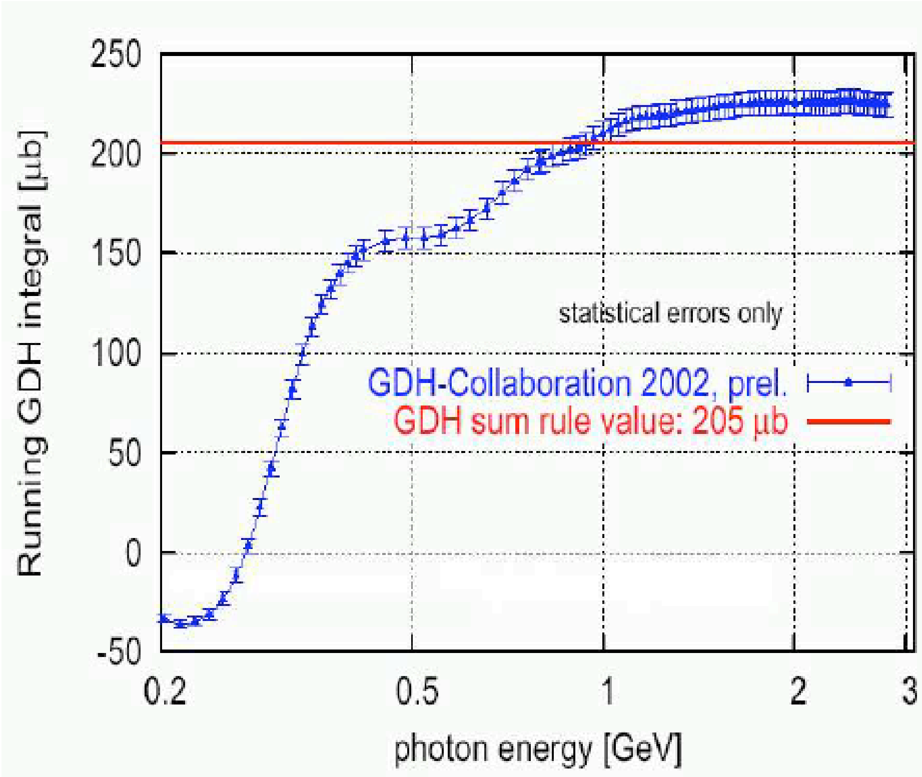
GDH: Fundamental quantity, never checked

- Need to check convergence
- Single π γ–production estimates violate GDH

Check on Proton at:

MAMI: 0.2< ν <0.8 MeV
ELSA : 0.7< ν <3 MeV

Ahrens *et al*
prl 87, 22003 (2001)



→ Need to check convergence (SLAC, JLAB)
Neutron: No data yet.

GDH Sum Rule: $Q^2=0$

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- Apply unitarity (**optical theorem**)
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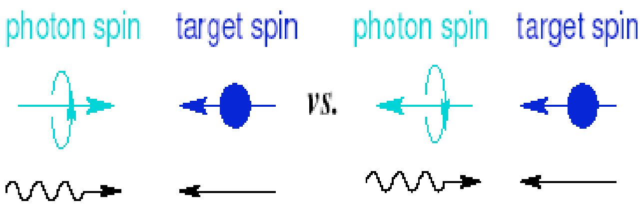

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Only assumption open to question:
Validity of "**non subtraction hypothesis**"
(Cauchy integration)

Generalized GDH sum rule (GDH*)

"Generalized": From photoproduction to electroproduction
$Q^2=0$ $Q^2>0$

Several ways to define the GDH* integral so that
$GDH^*(Q^2) \xrightarrow[Q^2 \to 0]{} GDH$
D. Drechsel et al., Phys. Rev D63 (2001 114010)

One definition of GDH* stands out:
X. Ji & J. Osborn. J.Phys G27 (2001) 127
- Extends the sum rule.
- Connects to the Bjorken sum rule.

$$\int_{\nu_1}^{\infty} G_{1(2)} \frac{d\nu'}{\nu'} = \overline{S}_{1(2)}$$

$\overline{S}_{1(2)}$: forward Compton amplitudes.

Calculable on the full QCD spectrum (χpT, lattice, Higher Twist Expansion).

Experiments: JLab Hall A: neutron (^{3}He)
JLab Hall B: proton, deuteron
HERMES: neutron (^{3}He), proton

Why the GDH sum rule important ?

It is a quantity as fundamental as, for ex., the Bjorken sum rule. It tests our understanding of QCD and of the Nucleon structure.

Why the extended GDH* sum rule important ?

The transition between the quark/gluon QCD degrees of freedom and the Nucleon/Meson degrees of freedom is still not understood.

The extended Gerasimov–Drell–Hearn (GDH*) sum rule, with its connection to the Bjorken sum rule, is ideal for studying such a transition.

Connection between the sum rules

$Q^2=0$

$$\int_{\nu_0}^{\infty} \left[\sigma^{1/2}(\nu)-\sigma^{3/2}(\nu)\right] \frac{d\nu}{\nu} = -2\pi^2\alpha\frac{\kappa^2}{M^2}$$ → GDH sum rule

Photoproduction → Electroproduction

$$\frac{M^2}{8\pi^2\alpha}\int_{\nu_0}^{\infty} \left[\sigma^{1/2}(\nu,Q^2)-\sigma^{3/2}(\nu,Q^2)\right] \frac{d\nu}{\nu}$$ → GDH* integral

$$= \frac{2M^2}{4\pi^2\alpha}\int_{\nu_0}^{\infty} \sigma^{TT}\frac{d\nu}{\nu}$$

$$= \frac{2M^2}{Q^2}\int_{0}^{1^-} g_1(x,Q^2) - 4M^2\frac{x^2}{Q^2} g_2(x,Q^2)\, dx$$ → Ji sum rules

$$\frac{1}{Q^2} g_2(\nu,Q^2) \xrightarrow[\substack{Q^2\to\infty \\ \nu\to\infty}]{} 0$$

$$\int_0^1 g_1^p(x)\,dx - \int_0^1 g_1^n(x)\,dx = \frac{1}{6}a_1$$ → Bjorken sum rule

$Q^2\to\infty$

Experiment E94010

Z.–E. Meziani, G. Cates, J.–P. Chen

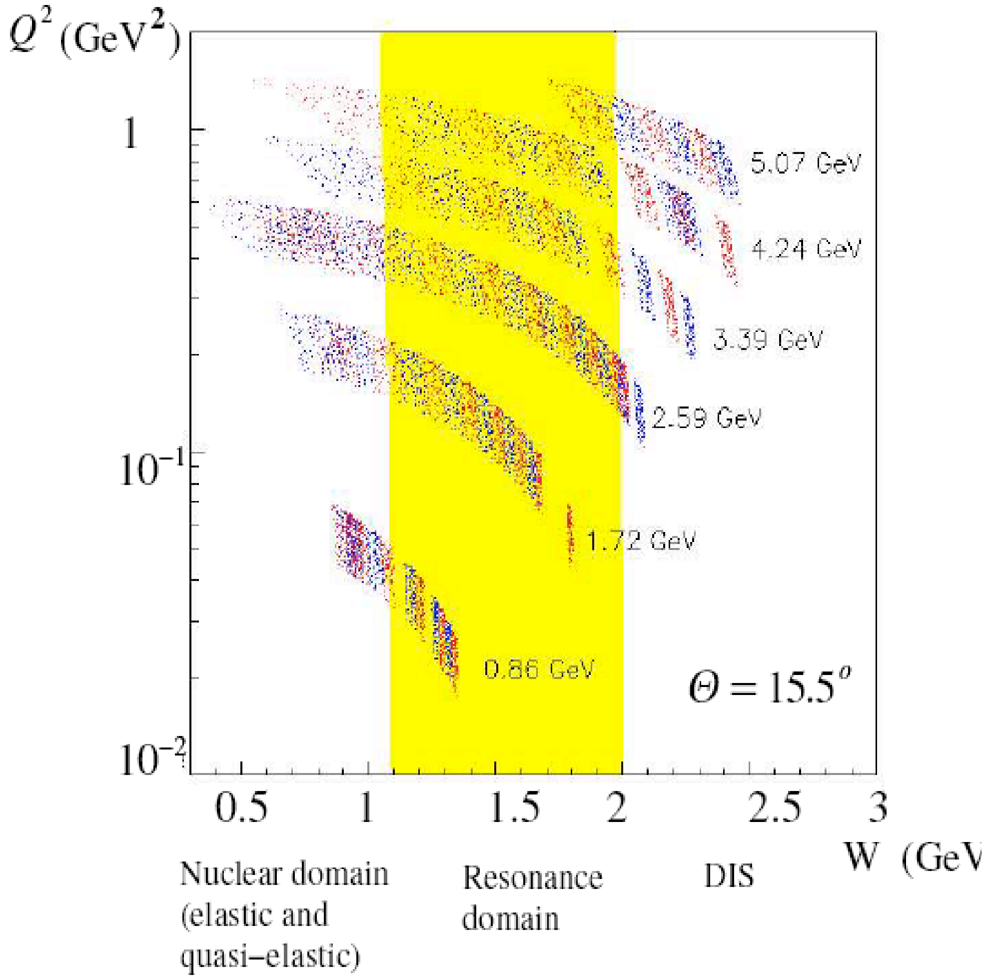
Inclusive $^3\vec{\mathrm{He}}(\vec{e}\rightarrow e')X$

We measured: $\sigma^{\Uparrow\uparrow}, \sigma^{\Uparrow\downarrow}, \sigma^{\Rightarrow\uparrow}, \sigma^{\Rightarrow\downarrow}$

$\Uparrow$:Target spin

$\uparrow$:electron spin

Linear combination gives extended GDH integrant.



Hall A standard equipment + ^{3}He polarized target

$$\vec{e} + {}^3\vec{\mathrm{He}} \rightarrow e' + X$$

$\sigma_{\downarrow\Uparrow}$ $\sigma_{\uparrow\Uparrow}$ $\sigma_{\downarrow\Rightarrow}$ $\sigma_{\uparrow\Rightarrow}$

$$A_{\parallel} = \frac{1}{P_b P_t f} \frac{\sigma_{\downarrow\Uparrow} - \sigma_{\uparrow\Uparrow}}{\sigma_{\downarrow\Uparrow} + \sigma_{\uparrow\Uparrow}} \qquad A_{\perp} = \frac{1}{P_b P_t f} \frac{\sigma_{\downarrow\Rightarrow} - \sigma_{\uparrow\Rightarrow}}{\sigma_{\downarrow\Rightarrow} + \sigma_{\uparrow\Rightarrow}}$$

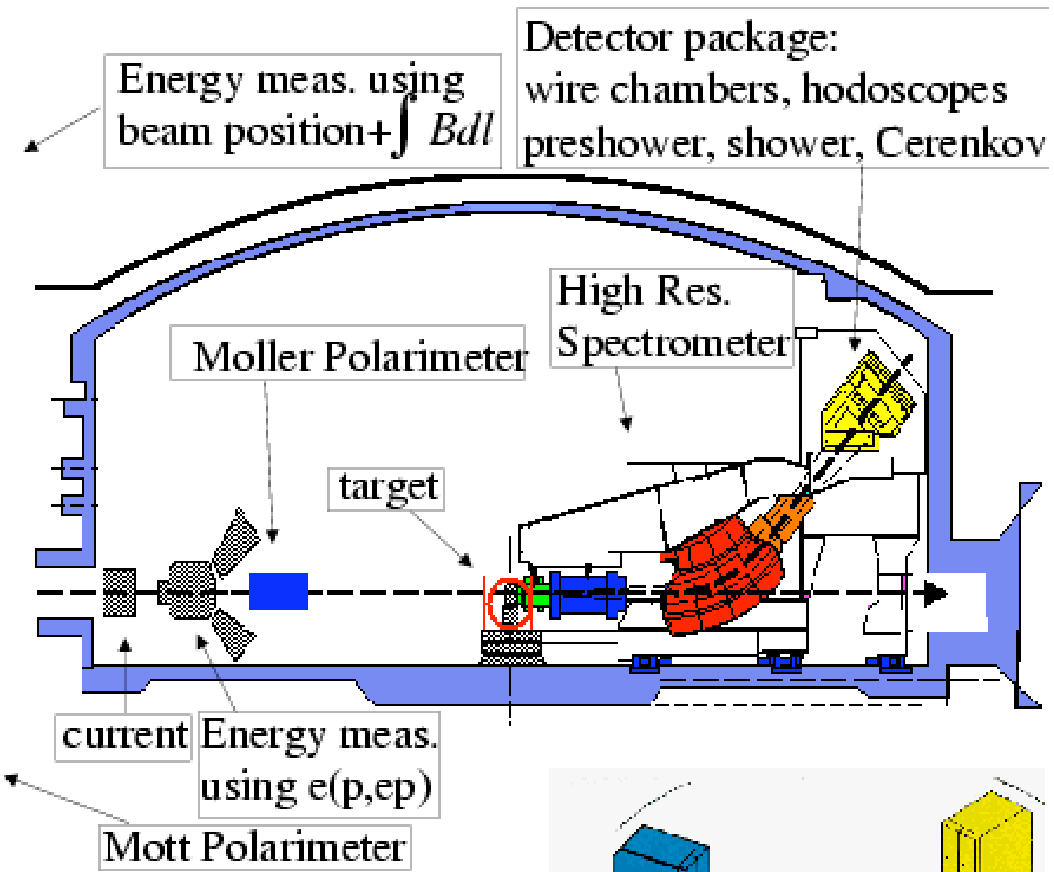
σ_0

$g_1, g_2, \sigma_{\mathrm{TT}}$

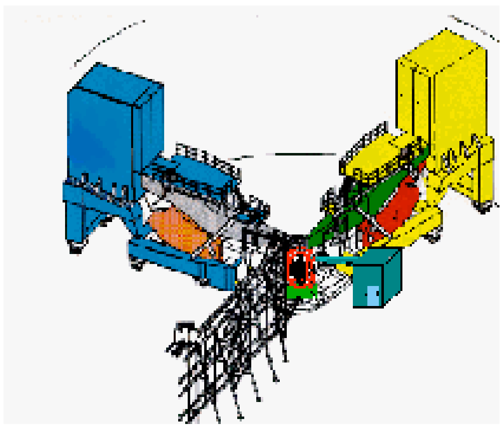
$\Downarrow$

$$I^{\mathrm{GDH}} = \int_{\nu_{\mathrm{th}}}^{\infty} (2\sigma_{\mathrm{T}} A_1) \frac{d\nu}{\nu}$$

Jefferson Lab Hall A.

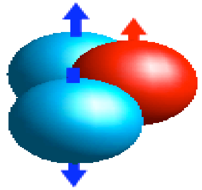


Beam characteristics:
- 1–15 µA
- 0.8–5.1 GeV
- 70% pol.



The ^{3}He polarized target

$^3\vec{He}$ at first order: $\vec{n}$ diluted by 2 p.



JLab target design: Similar to SLAC E142/E154.
Improvement: Optical pumping in any (in–plane) direction.

Successfully used in 4 experiments (GDH*, G_m^n, A_1^n, g_2^n).

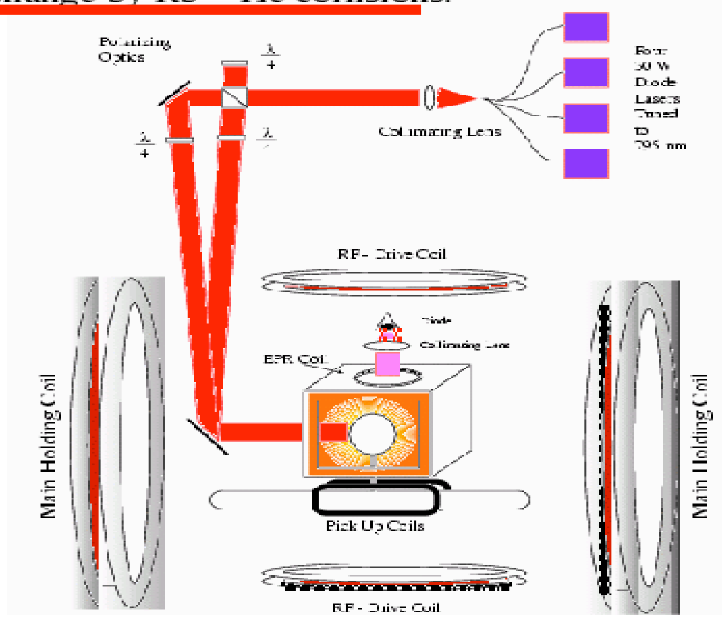
Polarization=35–40% (in running conditions).
Length=25 to 40 cm.

→ Luminosity 10^{36} cm^{-2}.s^{-1} (for 15 µA, 40 cm).

Polarimetry: NMR, EPR (and elastic).
ΔP/P= 4% (GDH*)

^{3}He Target Setup

Basic principles: Optical pumping of Rb, then spin exchange by Rb–^{3}He collisions.



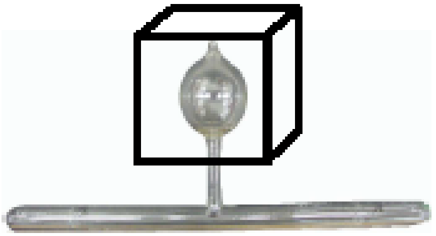
Collaboration: CalTech, Clermont–Ferrand, JLab, Univ. of Kentucky, MIT, Princeton, Temple, Univ. of Virginia, Col. of William & Mary.

^{3}He target heart: Two chamber glass cell

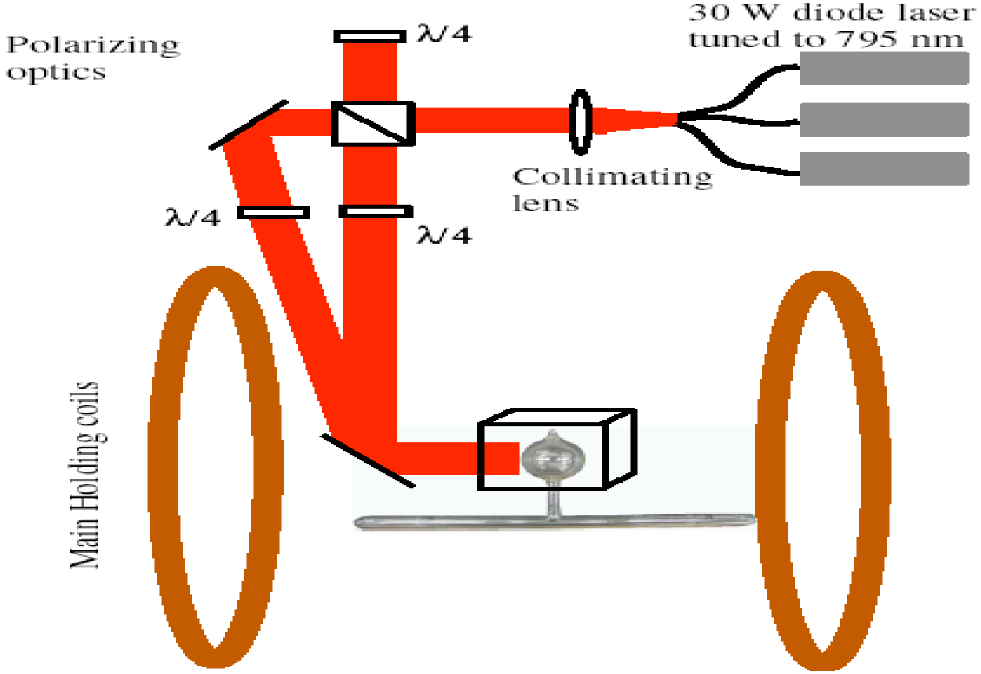
Cell filled with a mixture of Rb and ^{3}He

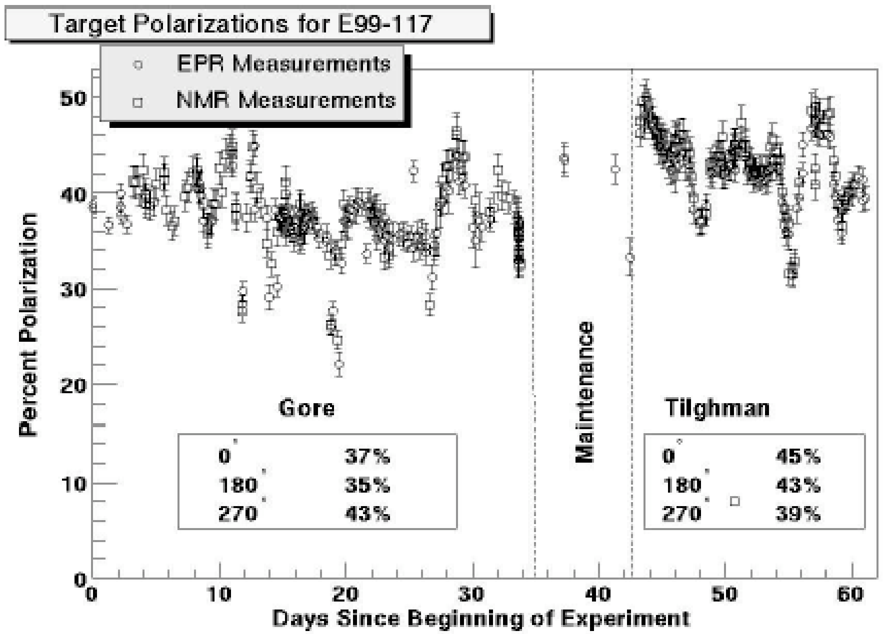
Oven: Vaporizes Rb

⇒ Top Chamber: Rb–^{3}He Mixture
Bottom Chamber: Pure ^{3}He gas

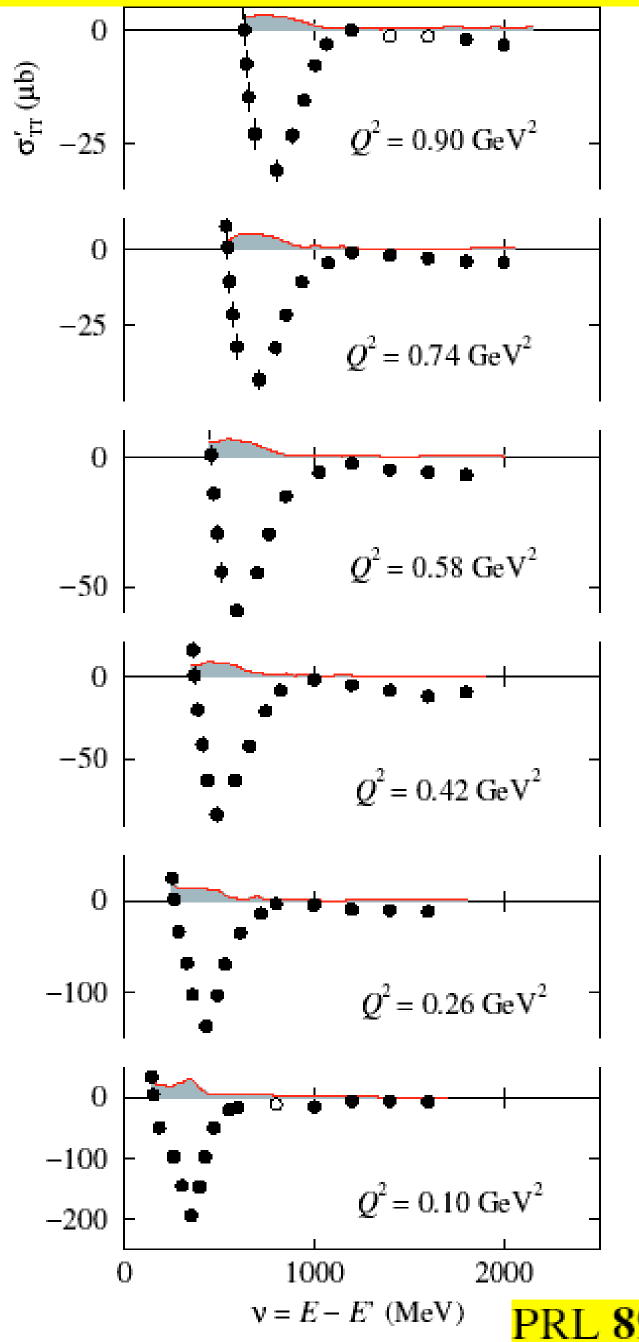


Optical pumping of Rb.
Polarization of ^{3}He by Rb–He spin exchange collisions



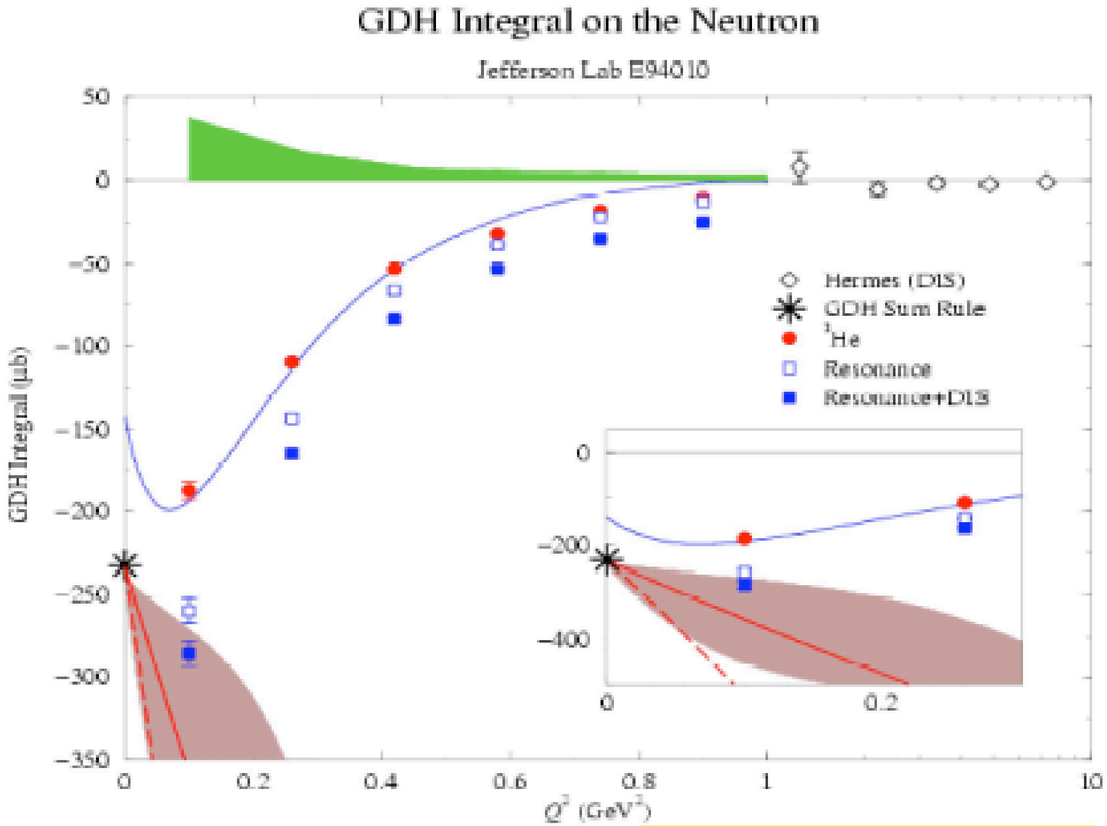


The GDH* integrant: $(\sigma_{1/2} - \sigma_{3/2})/2$



PRL **89**, 242301 (

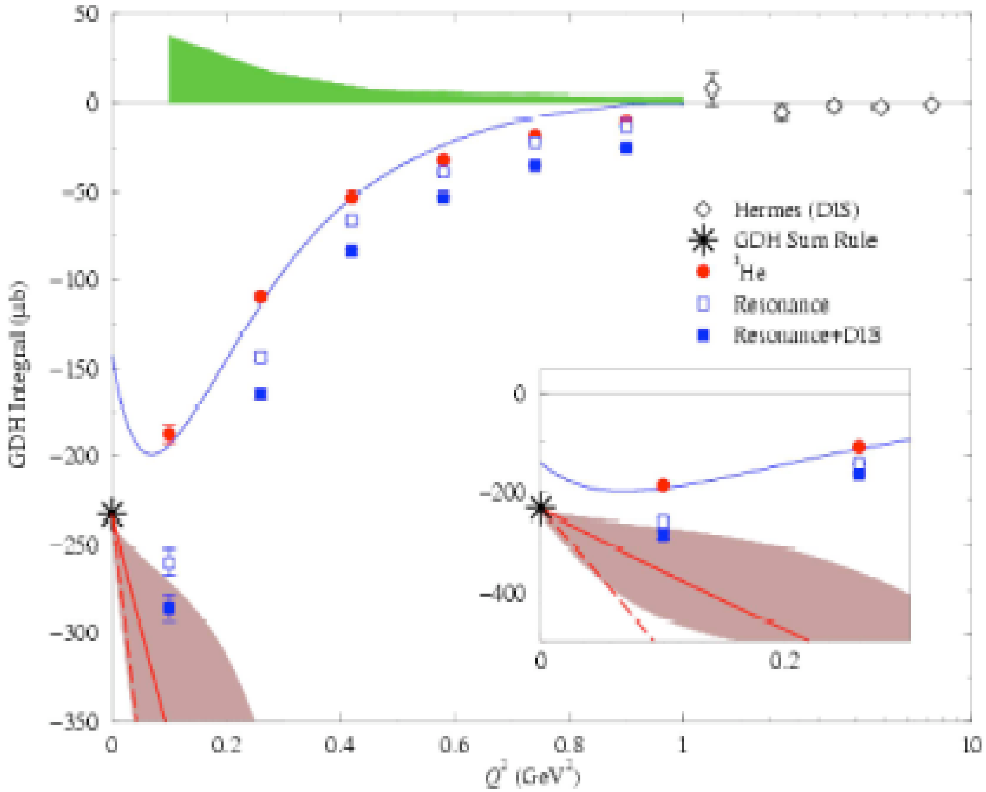
Evolution of the GDH*(Q^2) Integral (neutron)



PRL **89**, 242301 (2002)

Nuclear corrections: degli Atti et al, Phy Rev **C48** 968 (1993)
Phys Let **B404** 223 (1997)

DIS contribution: N. Bianchi & E. Thomas,
Phys. Lett B **450** 439 (1999)

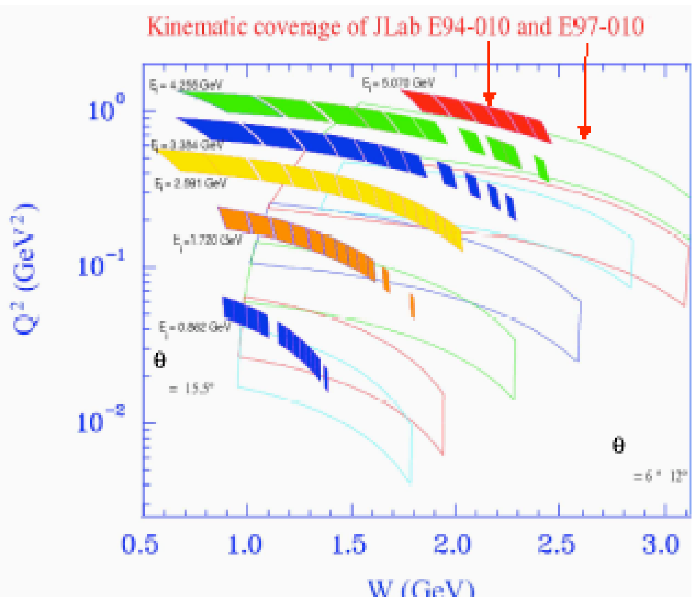


data not conclusive with regard to

the turn over at small Q^2

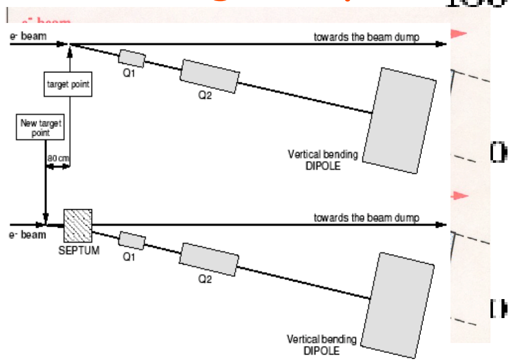
the validity of GDH at $Q^2=0$

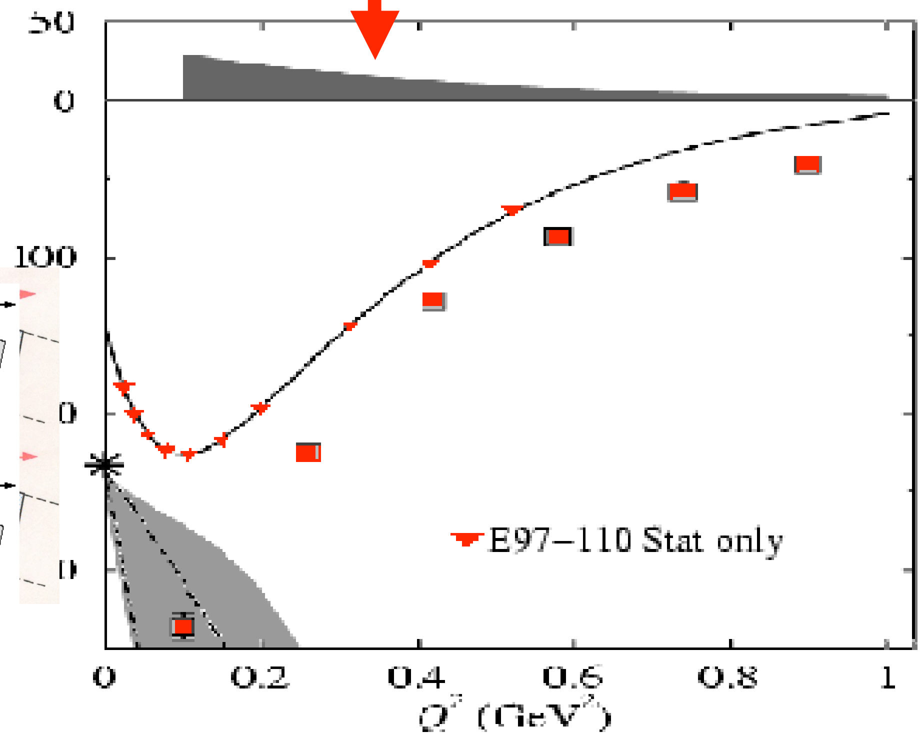
- 2 □pt calculations (large error)
- sum rule
  - → calculations
  - → measurements



forward angle detection capability

-> adding 2 septa



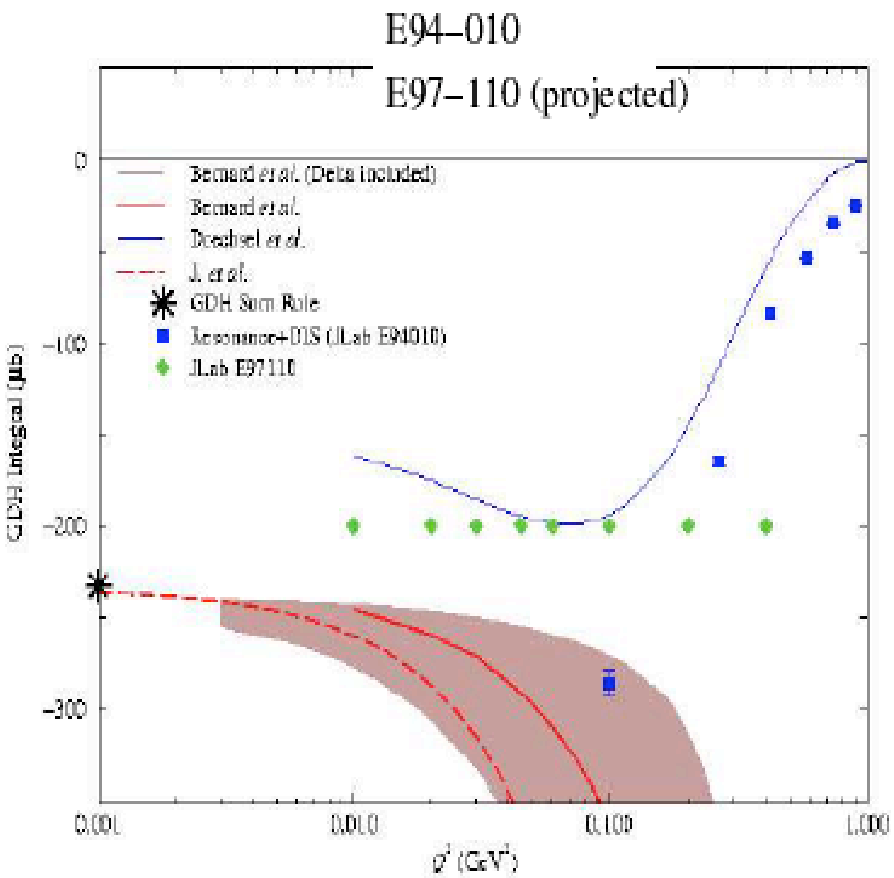


Small Q^2 GDH

Experiment E97110, Hall A
J.-P. Chen, A. Deur, F. Garibaldi

Septum magnet: scattering angles: 6° and 9°

Lower $<Q^2>=0.02$ GeV^2



Target challenges with forward angle detection

With the former ^{3}He target hardware:

Large radiative tails:
Forbids detection at $E_{beam} < 2$ GeV

- "2 step process":
Forbid detection at $Q^2<0.3$ GeV^2 and
for $Q^2>0.3$, forbid detection at $\nu > 2$ GeV

Septum gradient magnetic field:
Forbid the use of high performance cells

The GDH Sum Rule and the Spin Structure of ^{3}He and *n* using Nearly Real Photons

Spokespersons: JP Chen, A. Deur, F. Garibaldi

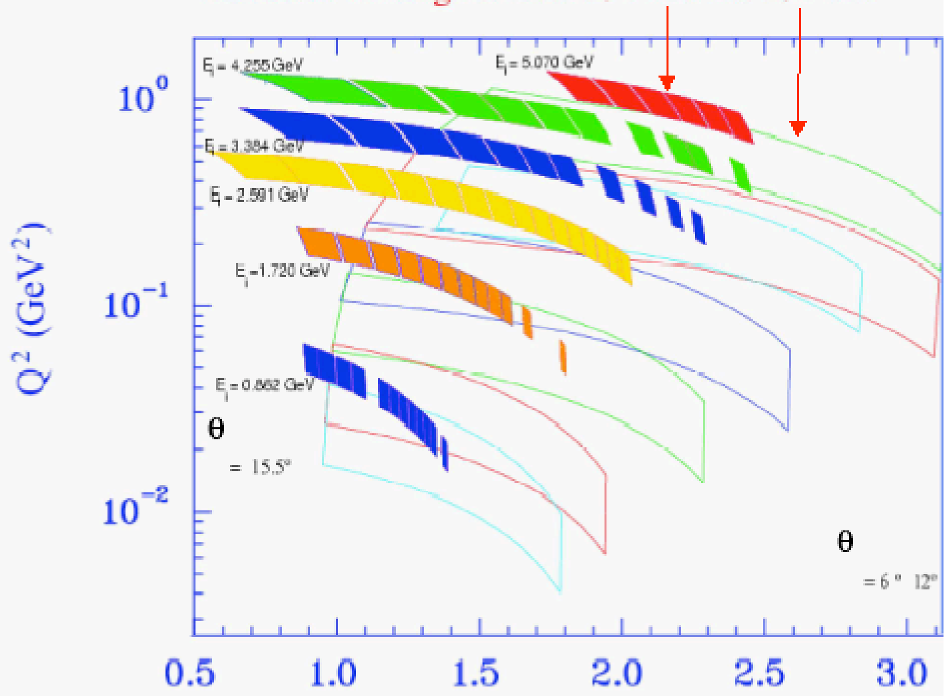
Goals of the experiment

- measure GDH sum at Q^2 near 0 for ^{3}He and *n*
- $Q^2 = 0.02 - 5\ (GeV/c)^2$
    - below "turn around" point
    - slope at $Q^2 = 0$
    - extrapolate to the real photon point
- Virtual photon energy: thr.- 4.5 Gev
    - test convergence
- Comparison ^{3}He and *n* sum
    - study nuclear physics effects

New septum magnets:

data as low as $<Q^2>=0.02\ GeV^2$ (scattering angles: 6 and 9 degrees).

Kinematic coverage of JLab E94-010 and E97-010



SEPTUM MAIN CHARACTERISTICS

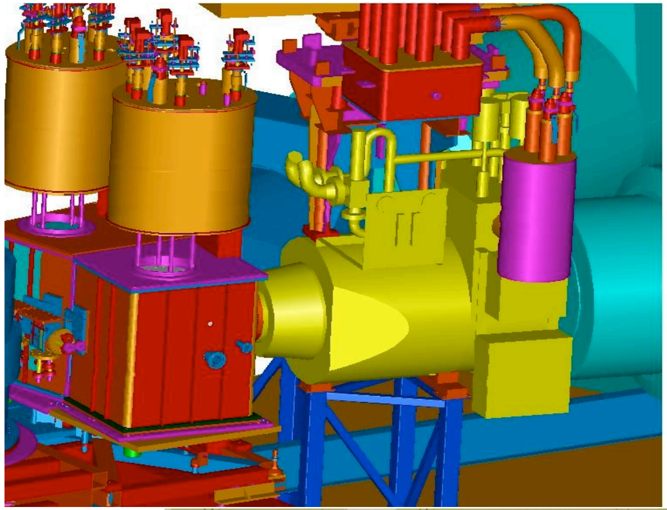
Table 3: HRS + Septum performances

Solid angle	4.5	(msrd)
Angular range	6 — 12.5	(deg)
Momentum range	0.4-4	(GeV/c)
Momentum acceptance	9.9	(%)
Momentum resolution	$1 \cdot 10^{-4}$	*
Angular horizontal resolution	0.96	* (mr)
Angular vertical resolution	1.26	* (mr)

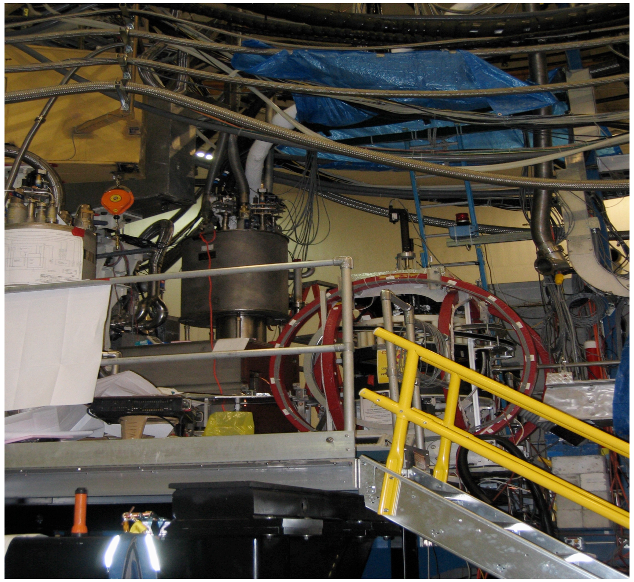
* FWHM

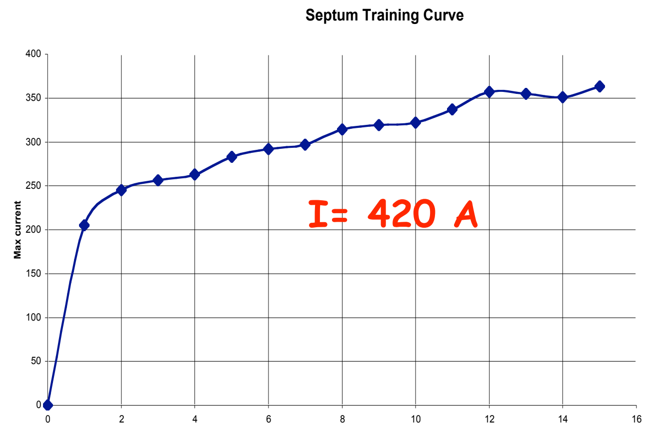
Magnetic lenght 84 cm.

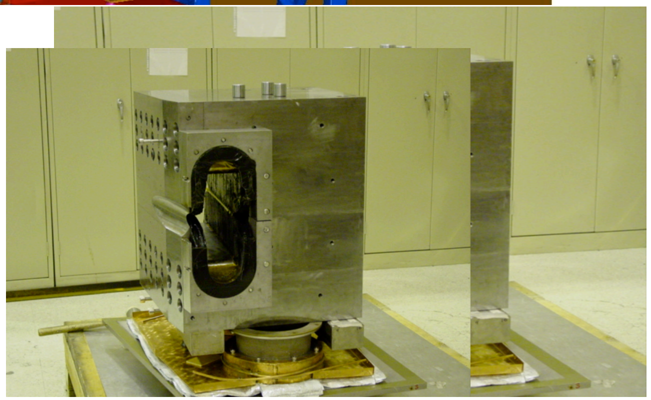
p (GeVc)	□ (degrees)	□ (degrees)	R (cm)	□B. dl (Tesla .m)	B0 (Tesl)
2	6	6.5	740.8	0.76	0.9
2	12.5	11.9	404.6	1.39	1.65
4	6	6.5	740.8	1.51	1.8
4	12.5	11.9	4046	2.77	3.3

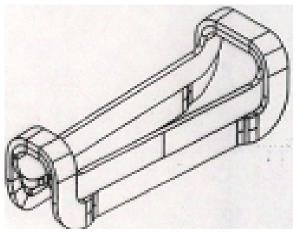


INFN









Small Q^2 GDH

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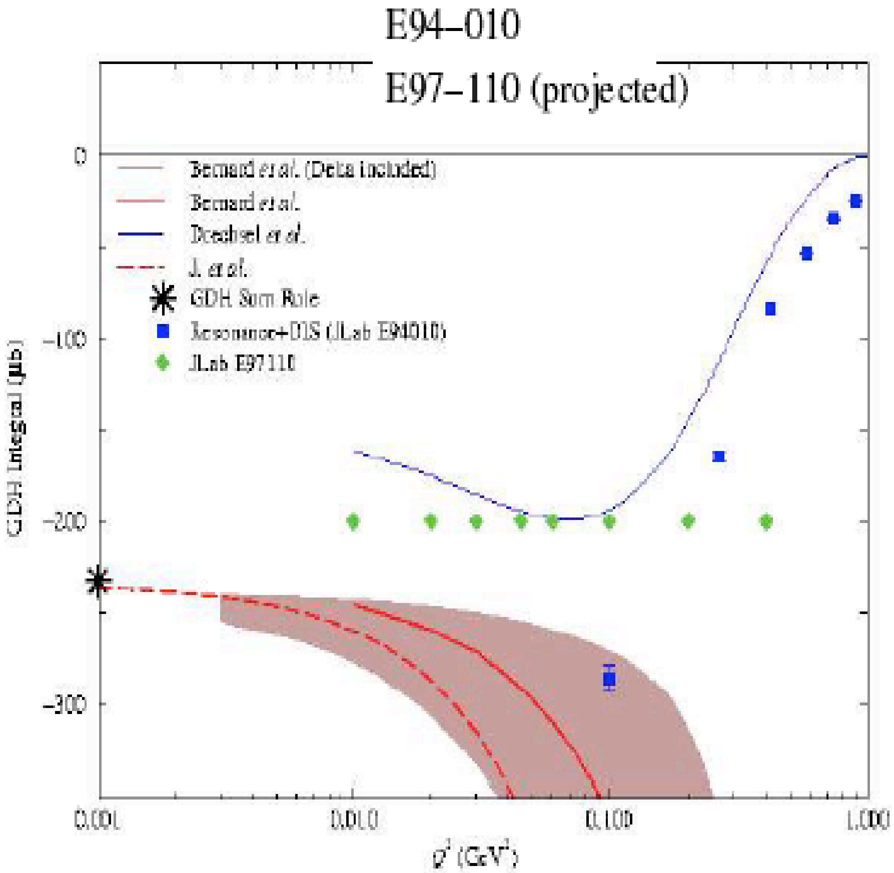
Lower $\langle Q^2 \rangle = 0.02\ GeV^2$



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Septum gradient magnetic field:

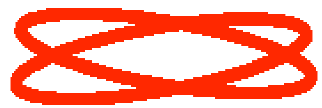
Forbid the use of high performance cells

What do small angles imply ?

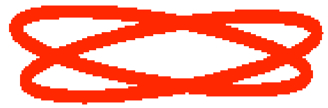
- Septum magnets ✗
- High rates ✓
- Large elastic radiative tails
  - Cell design change ✗
  - → Minimize matter in the beam path ✓
- Target design changes ✓
- Collimation of the target windows ✓

Experimental issues & solutions:

- New Septum Magnets
- Magnetic field gradients

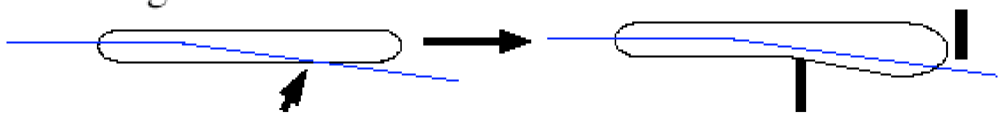


  - Field clamps
  - 2 sets of tilted Helmholtz coils:



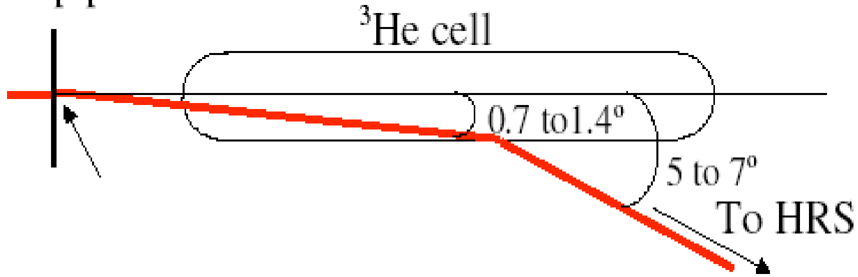
- Radiative corrections

Regular ^{3}He cell



- Double scattering

Beam pipe window



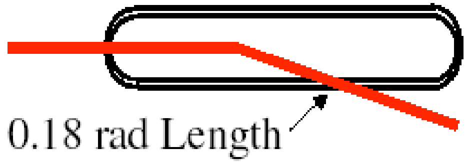
- "Ice cream cone cell"
- Thin beam line windows

Large radiative tails

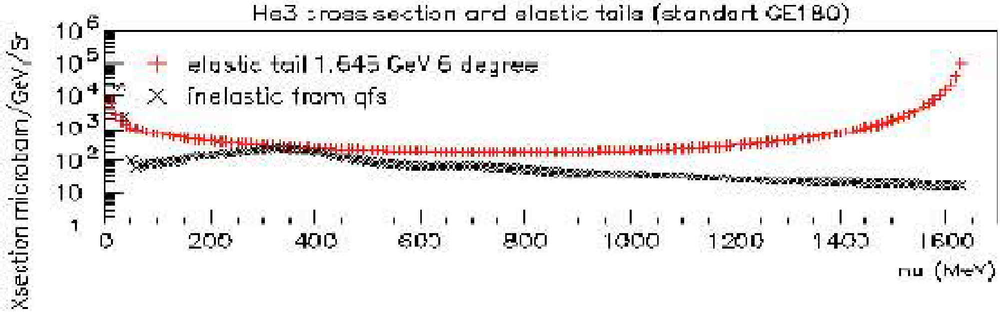
Low beam energy: Start at 1.1 GeV

Small scattering angle 6^{o} and 9^{o}

Large radiation length



⇒Large radiative tails



Solutions:

Less dense aluminosilicate glass:

Before GE180. RL=7.03 cm

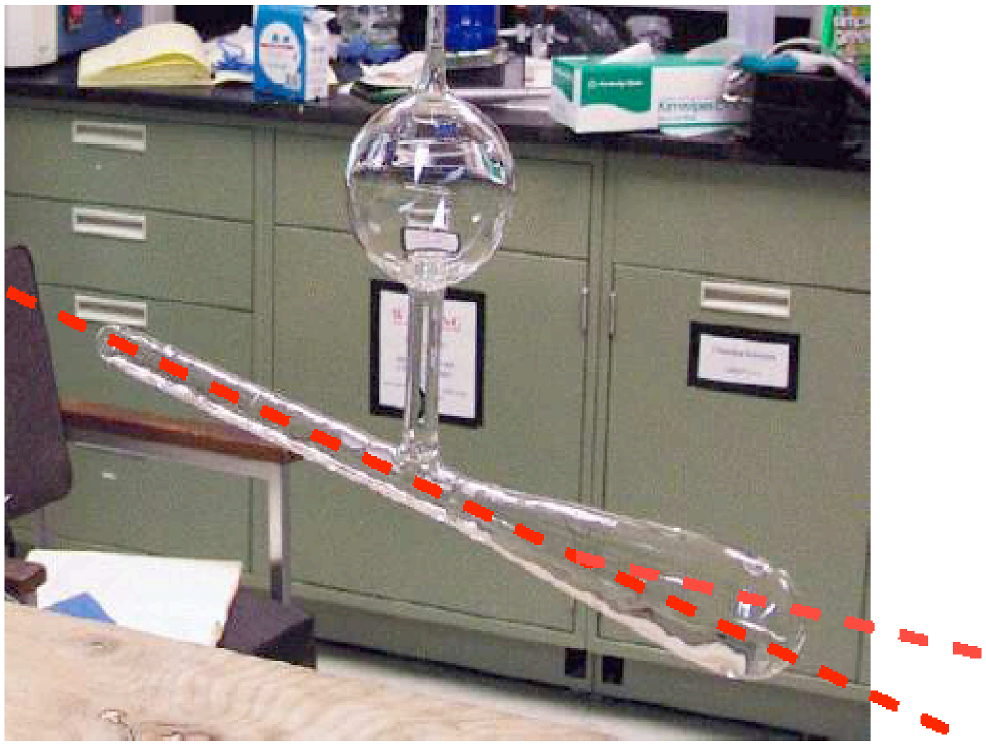
Now C1720. RL=10.6 cm

(also studied: Coated Pyrex. RL:12.7 cm)

- Less matter on beam path
- New cell geometry

New cell geometry

Design to allow exit through thin window:

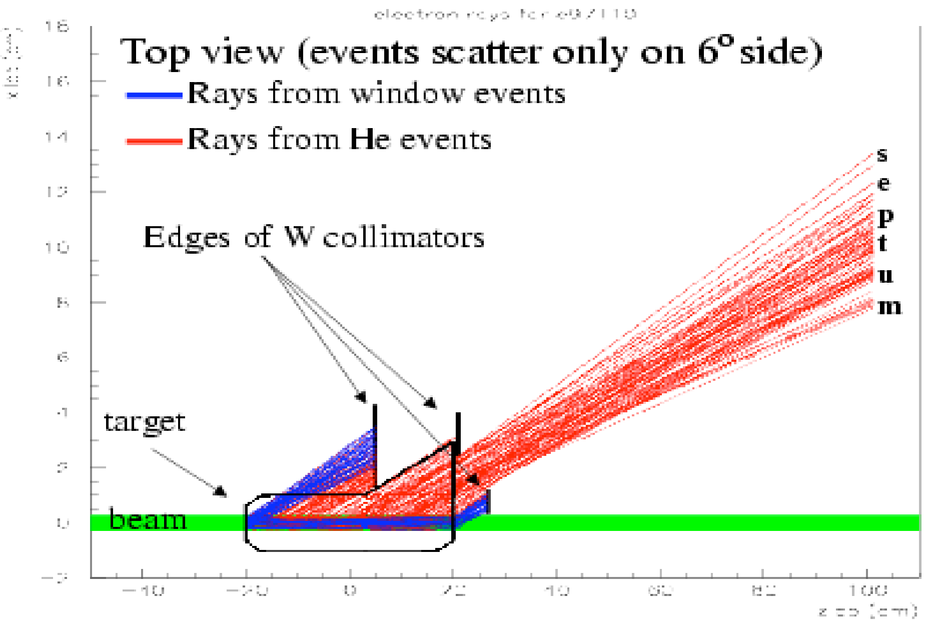


Challenges :

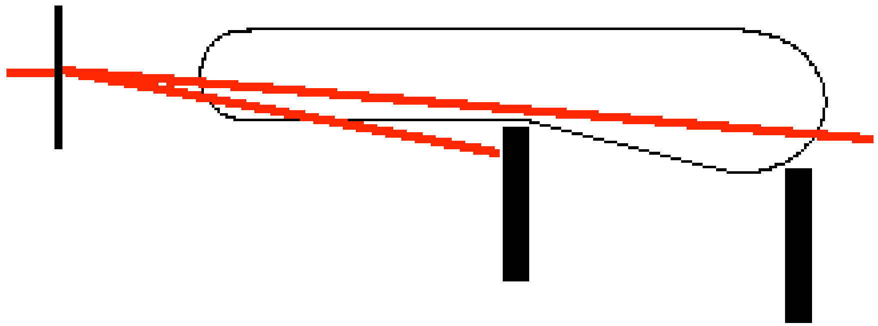
Complicated geometry with aluminosilicate glass

Need thin (250 μ) but large radius exit window

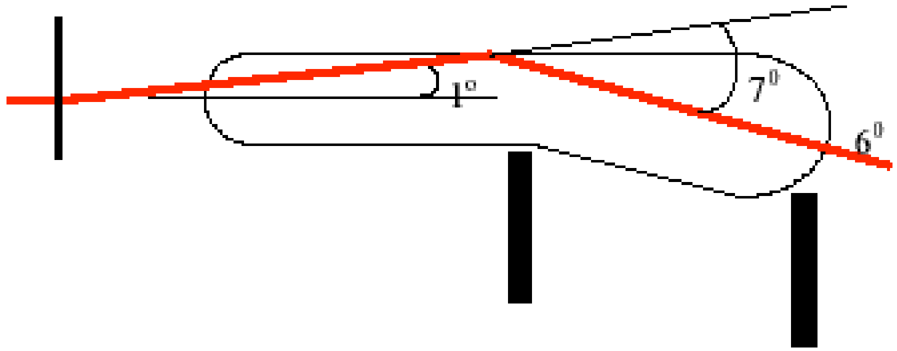
Good glass surface quality to allow polarization



The new cell improves the situation:



Although we still have:



This background may still be a limitation for the experiment but it is not an issue anymore

New cell geometry

After a year of struggle:

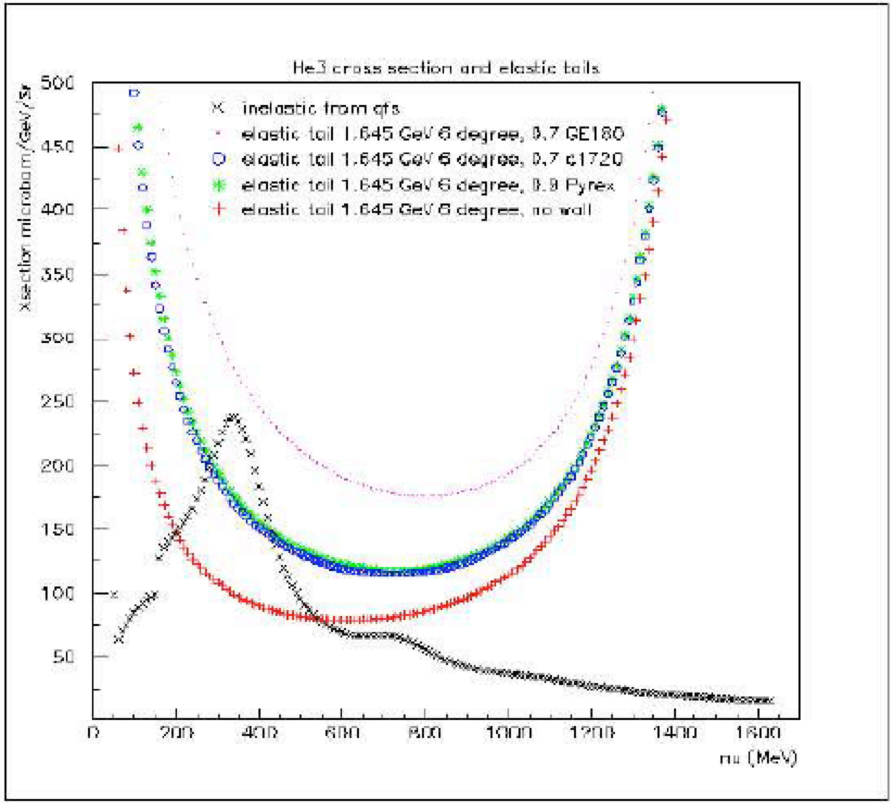
Steady production of new cells

Longest lifetime cells ever made: 72 h

SLAC E142 (Princeton) :63 h

SLAC E154 (Princeton) :68 h

^{3}He exp @ JLAB (UVa) :69 h



→ Radiative tails are significantely reduced

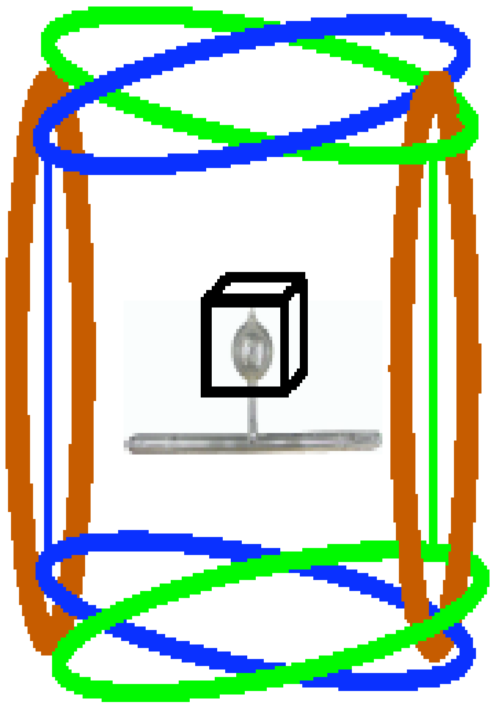
Gradient issue

Reduce the maximal polarization

Increase the polarization loss during polarimetry

Solution: Specially designed correction coils.

Allow a remote control of a compensating gradient



Nuclear Study on ^3He

GDH(^{3}He) ~ −496 μb

If $^3\vec{He} \sim \vec{n}$

Then GDH(^{3}He) ~ GDH(n) + quasi−elastic contribution
(−233 μb) (−263 μb)

→ The measurement of the quasi−elastic part can be used as a check of our understanding of the ^{3}He nuclear description.

From ^{3}He to Neutron

degli Atti et al
Phy Rev C48 968 (1993)
Phys Let B404 223 (1997)

^{3}He: not in a pure S wave. → The proton spins contribute to the nucleus spin.

$$g^{3He} = 2P_p g^p + P_n g^n$$

with: $P_p = -0.028$
$P_n = 0.86$

Further nuclear effects (Fermi motion and binding) are taken into account with a convolution model.

This method has proven reliable for:

- the DIS domain.
- the resonance and DIS domains (integrated quantities).

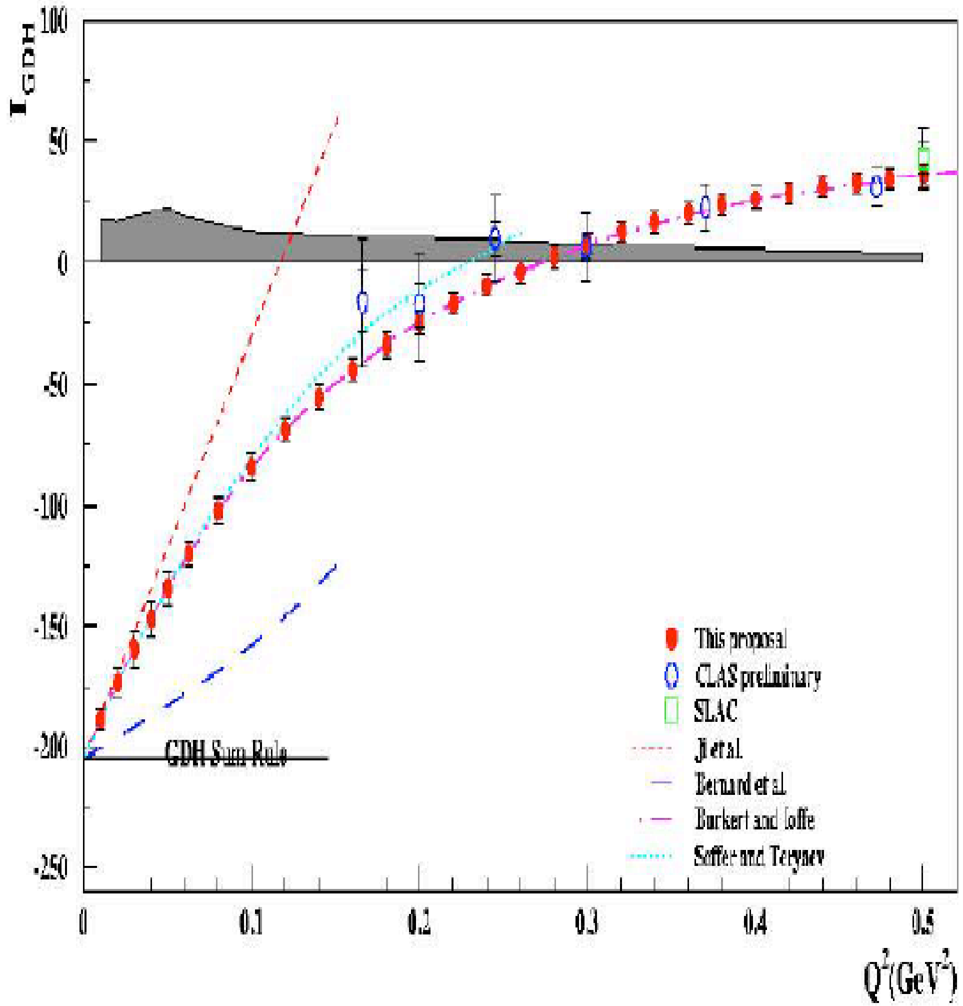
Our experiments: integrated quantities or DIS
→ The neutron extraction should be fine.

However, it is highly desirable to have an extraction procedure working everywhere for any quantities (open challenge for theorists !).

New generalized GDH experiment

M. Battaglieri A. Deur,
R. DeVita, M. Ripani

GDH at low Q^2 for proton.
In Hall B. Approved by PAC23 (A)



Conclusions

- Very good characteristics of the Jlab *polarized* beam

  and Hall A

  - ^3He polarized target
  - septum magnets

→ measure of GDH sum rule for ^3He and neutron

- $Q^2 = 0.02 - 0.5\ (GeV/c)^2$
  - below "tun around" point
  - slope at Q2 = 0
  - extrapolate to real photon point

- virtual photon energy, from threshold up to 4.5 GeV/c

- comparison of ^3He and neutron GDH sum rule

- High precision data on the transition region.
- Benchmark measurement for Chiral perturbation theory and future lattice calculations.
- Check and refinement of models describing the transition from QCD to pQCD and the neutron structure.
- Test of Nuclear ^3He wave functions.
- low Q^2 sequel of the experiment.

Formalism

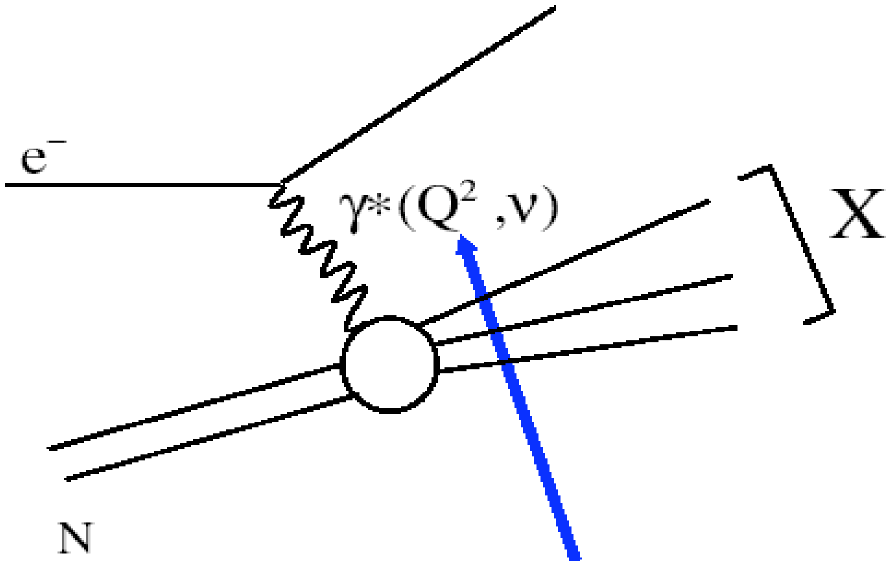
Inclusive electron scattering

ν: virtual photon energy

$Q^2 = -q^2$: 4−momentum transfer

$W^2 = M^2 + 2p.q - Q^2$: Invariant mass

$x = Q^2/(2p.q)$: Scaling variable



The probe depends upon 2 variables
Question: How the nucleon structure changes with them ?

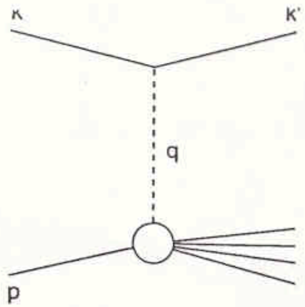


Figure 1 The lowest order Feynman diagram for deep inelastic lepton scattering.

e + N -> e + X

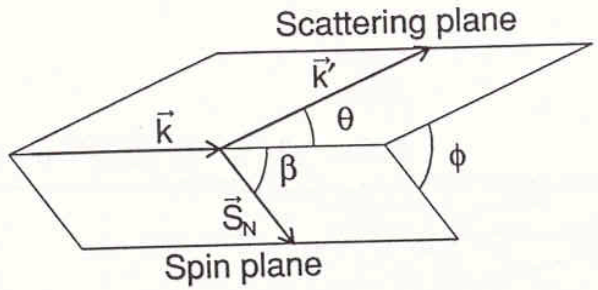


Figure 2 Scattering of longitudinally polarized leptons in the laboratory frame.

$$\frac{d^3\sigma(\beta)}{dQ^2\,dx\,d\phi} = \frac{d^3\sigma_0}{dQ^2\,dx\,d\phi} - \frac{d^3\Delta\sigma(\beta)}{dQ^2\,dx\,d\phi}$$

unpol. pol

$$\frac{d^2\sigma}{dQ^2dx} = \frac{4\pi\alpha^2}{Q^4}\frac{1}{x}\left[xy^2F_1(x,Q^2) + \left(1 - y - \frac{Mxy}{2E}\right)F_2(x,Q^2)\right]$$

$$\frac{d^3\Delta\sigma(\beta)}{dQ^2\,dx\,d\phi} = \frac{4\alpha^2}{Q^4}y\left\{\cos\beta\left[\left(1 - \frac{y}{2} - \frac{\gamma^2y^2}{4}\right)g_1(x,Q^2) - \frac{\gamma^2y}{4}g_2(x,Q^2\right.\right.$$
$$- \cos\phi\sin\beta\frac{\sqrt{Q^2}}{\nu}\left(1 - y - \frac{\gamma^2y^2}{4}\right)^{\frac{1}{2}}$$
$$\times\left.\left[\frac{y}{2}g_1(x,Q^2) + g_2(x,Q^2)\right]\right\},$$

- target ∥ beam sen β = 0 → g_1 (g_2 suppressed by $\frac{Mx}{2E}$)
- target ⊥ beam cos β = 0 → g_1, g_2

asymmetries

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

$$A_\parallel = D[A_1 + \eta A_2]$$

$D = \frac{1-\epsilon E'/E}{1+\epsilon R}$

$$A_\perp = \frac{\sigma^{\downarrow\rightarrow} - \sigma^{\uparrow\rightarrow}}{\sigma^{\downarrow\rightarrow} + \sigma^{\uparrow\rightarrow}}$$

$$A_2(x) = \gamma\frac{g_1(x) + g_2(x)}{F_1(x)} \qquad A_1(x) = \frac{g_1(x)}{F_1(x)},$$

$$A_{exp} = f_t P_t P_b A$$

$$A_\perp = d\left[A_2 - \gamma\left(1 - \frac{y}{2}\right)A_1\right]$$

where A represents either $A_\parallel$ or $A_\perp$. In this expression, P_b is the beam polarization, P_t the polarization of the target nucleons, and f_t the target dilution factor, i.e. the fraction of polarized nucleons in the target material.