Hadron Physics

Lecture #1: The quark model, QCD, and hadron spectroscopy

Lecture #2: Internal structure of hadrons: momentum and spin

Lecture #3: Internal structure of hadrons: charge, magnetism, polarizability

Lecture #4: Hadrons as laboratories (weak interactions, fundamental symmetries, and other miscellaneous topics)

(much of this material is from my seminar at NNPSS 2008)

Hadrons as Laboratories

Weak interactions inside the nucleon

Weak NN interactions

Fundamental symmetry tests with A=1 (Z=1 or 0)

→ *see also seminars by Tim Chupp, John Hardy*

references for this section

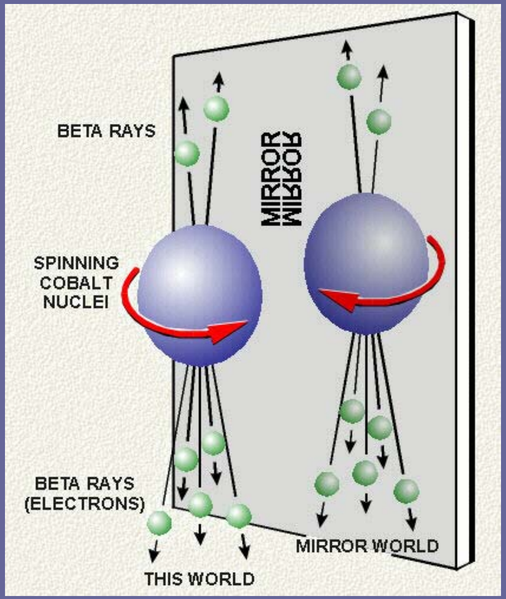
- General:
  - "Subatomic Physics 3rd edition", Henley & Garcia (2007)
  - "Quarks & Leptons", Halzen & Martin
  - "Experimental Foundations of Particle Physics", Cahn & Goldhaber
- PV electron scattering:
  - M.J. Musolf et al., Phys. Rep. 239 (1994) 1.
  - E. Beise, M.L. Pitt and D.T. Spayde, Prog. Part. Nucl. Phys. 54 (2005) 289.
  - M. Pitt, NNPSS 2004 Lecture notes (Bar Harbor, ME)
- Neutrons:
  - J. Nico and W.M. Snow, Ann. Rev. Nucl. Part. Sci. 55 (2005) 27.
  - M.J. Ramsey-Musolf & S. Page, Ann. Rev. of Nucl. Part. Sci. 56 (2006) 1.
  - NNPSS 2007 Lecture notes, G. Greene.

Thanks for slides, photos, etc.: B. Filippone, P. Mumm, J. Nico, K. Pashke, M. Pitt, X. Zheng, P. Reimer, H. Gao, J. Martin, and many others

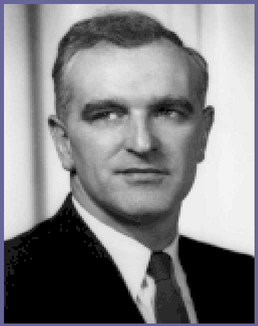
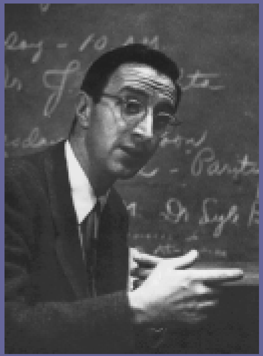
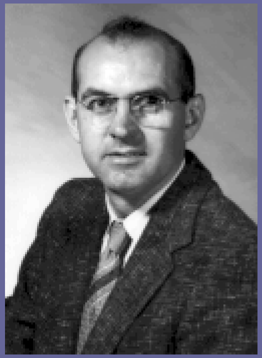
"The Fall of Parity"

from the NIST virtual museum
http://physics.nist.gov/GenInt/Parity/cover.html


T.D. Lee & C.N. Yang,
Phys. Rev. 104 (1956) 254.
(October 1956)



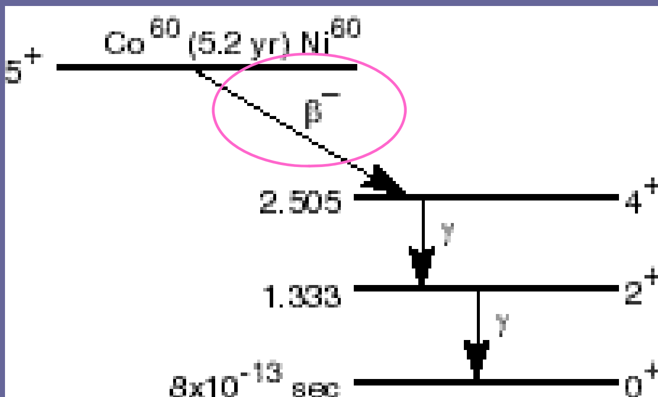
$$^{60}\vec{Co} \rightarrow {}^{60}Ni + e^{-} + \overline{\nu}_e$$


C.-S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,
Phys Rev 105 (1957) 1413. (January 1957)

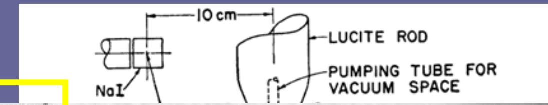
The ^{60}Co experiment

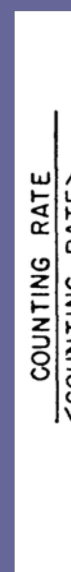
(see the NIST museum!)

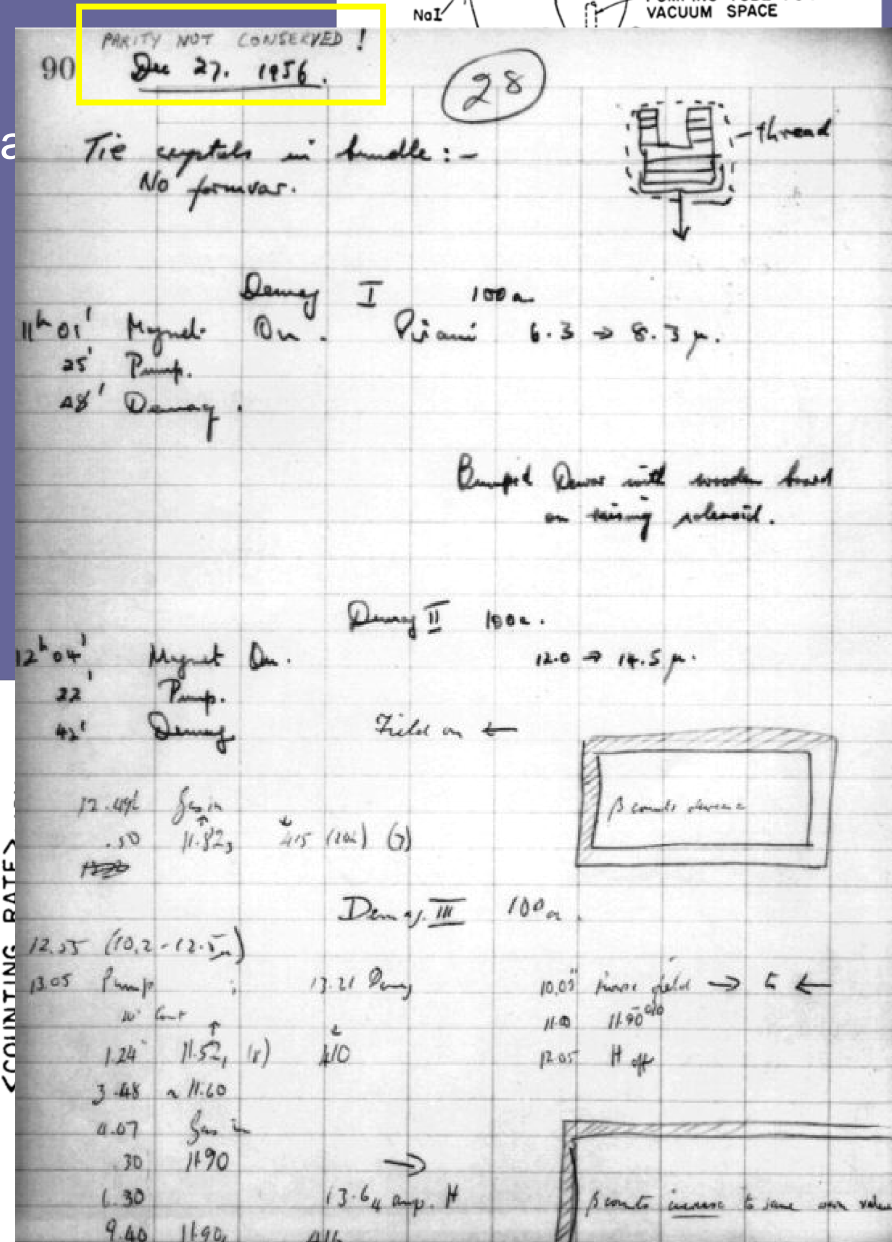


pseudosca

$$\langle \vec{J} \rangle \cdot \vec{p}_e$$





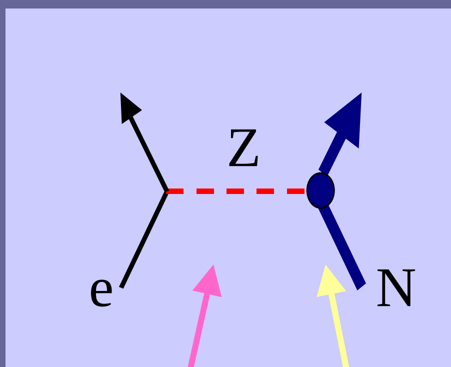


<J> = average nuclear polarization of ^{60}Co
(in B-field and low T (0.01K)

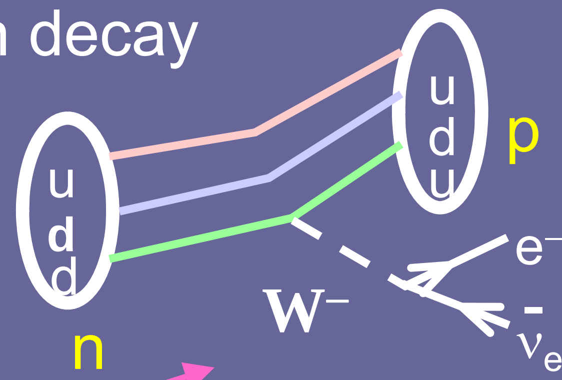
anisotropy of γ's measures the degree of pol'n of ^{60}Ni (now used for thermometry – see F. Pobell, "Matter and Methods at Low Temperature")

Weak interactions involving nucleons
(and electrons)

- electron scattering



- neutron decay

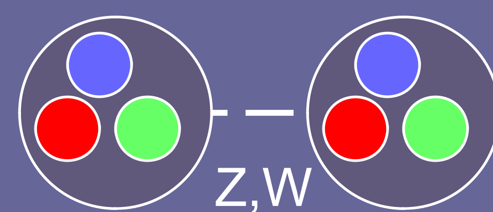


use well-understood target (nucleon) to perform precision test of EW physics

OR

use weak force to probe new aspects of strong interaction

- weak NN interactions



EXPERIMENTAL SIGNATURE IS VIOLATION OF PARITY

Neutral current e-quark interactions

$$L_{SM}^{PV} = -\frac{G_F}{\sqrt{2}} \sum_q \left[C_{1q} \bar{e} \gamma_\mu \gamma_5 e \boxed{\bar{q} \gamma^\mu q} + C_{2q} \bar{e} \gamma_\mu e \boxed{\bar{q} \gamma^\mu \gamma^5 q} \right]$$

A x V　　　　V x A

product of V and A violates parity

C_{iq}'s are "weak charges" of quarks (1="vector", 2="axial")
If scattering directly from quarks, can measure these, e.g.

$$C_{1u} = -\frac{1}{2} + \frac{4}{3} \sin^2 \theta_W$$

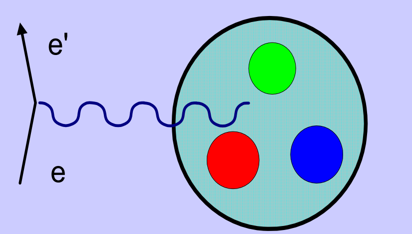
If scattering from a nucleon, have to take into account that quarks are bound inside nucleon via strong interaction to disentangle the C_{iq}'s: these are typically embedded in nucleon "form factors"

Elastic electron (electromagnetic) scattering from nucleons

$\tau = Q^2/4M^2$
$\varepsilon = [1+2(1+\tau)\tan^2(\theta/2)]^{-1}$

quark "charges" are buried in nucleon form factors

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott}\frac{E'}{E}\frac{1}{\varepsilon(1+\tau)}\left[\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right]$$



$Q = (\nu, \vec{q})$

$$G \to \left\langle N \left| \sum e_q \bar{q}\gamma^\mu q \right| N \right\rangle$$

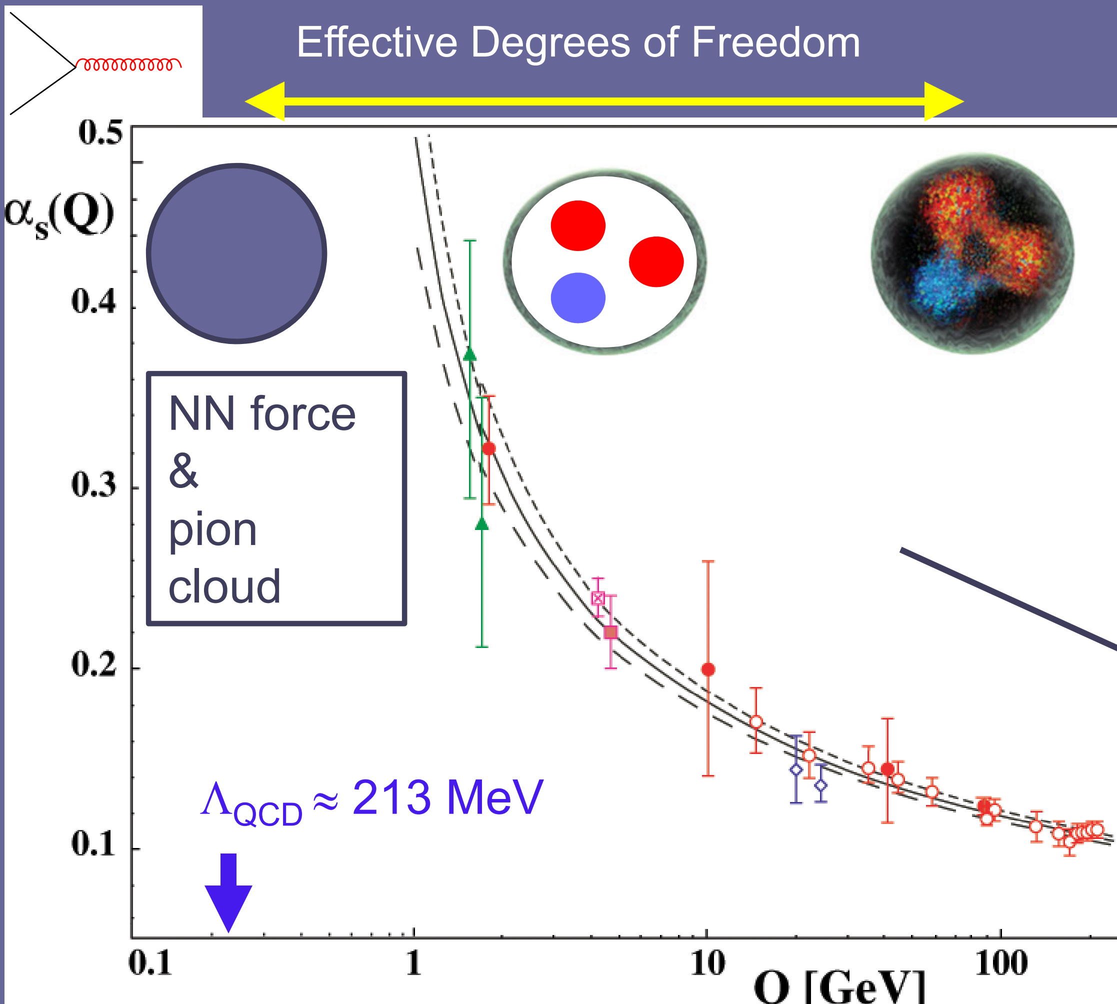
$$G_E^p = \frac{4}{3}G_E^u - \frac{1}{3}G_E^d - \frac{1}{3}G_E^s$$

$$G_E^n = \frac{2}{3}G_E^u - \frac{2}{3}G_E^d - \frac{1}{3}G_E^s$$

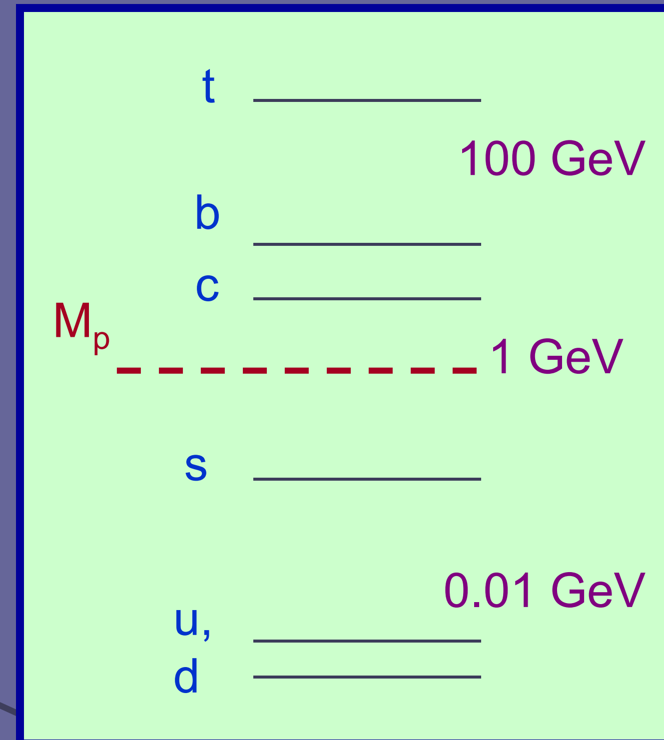
contributions to charge, similar for magnetism

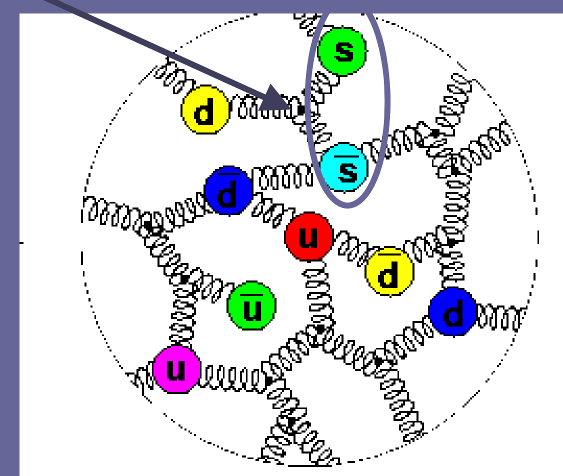
G_E and G_M for both proton and neutron are now very well known via precision electron scattering exps. But not enough information to disentangle individual quark pieces from these alone.

Inside the Nucleon



(from R. Ent)





Weak nucleon form factors

point-like fermions:

$$\text{EM}: \quad ieQ_f\gamma_\mu$$

$$\text{Weak}: \; i\frac{gM_Z}{4M_W}\gamma_\mu\left(g_V^f + g_A^f\gamma_5\right)$$

	Q_f	$g_V^{\,f}$	$g_A^{\,f}$
ν	0	1	-1
e, μ^-	-1	$-1 + 4\sin^2\theta_W$	$+1$
u,c,t	$+2/3$	$1 - 8/3\sin^2\theta_W$	-1
d,s,b	$-1/3$	$-1 + 4/3\sin^2\theta_W$	$+1$

nucleons:

$$G_{E,M}^{u,p} = \left(3 - 4\sin^2\theta_W\right)G_{E,M}^{\gamma,p} - G_{E,M}^{Z,p}$$

$$G_{E,M}^{d,p} = \left(2 - 4\sin^2\theta_W\right)G_{E,M}^{\gamma,p} - G_{E,M}^{\gamma,n} - G_{E,M}^{Z,p}$$

$$G_{E,M}^{s,p} = \left(1 - 4\sin^2\theta_W\right)G_{E,M}^{\gamma,p} - G_{E,M}^{\gamma,n} - G_{E,M}^{Z,p}$$

combine weak and EM information to separate (u,d,s) contributions to proton's charge and magnetism

$$J_{\mu 5}^{Z} = \bar{u}_N\left[G_A^Z(q^2)\gamma_\mu + \cancel{\frac{1}{M_N}G_P(q^2)q_\mu}\right]\gamma_5 u_N$$

ignore

axial part is related to proton's spin

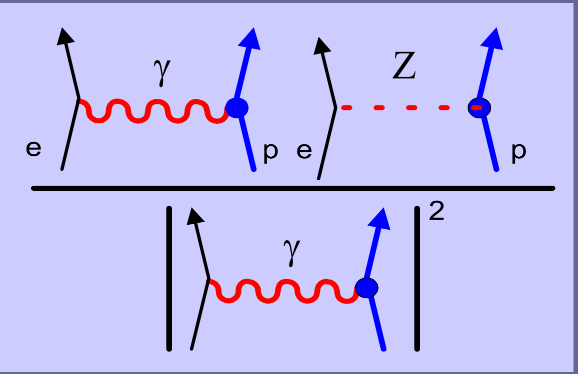
Parity Violating Electron-Proton Scattering

polarized electrons, unpolarized target

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

~ few parts per million

and want to measure to ~ 5%



Statistics : 10^{13}-10^{14} counts for precision measurement

high beam intensity, very thick targets, large acceptance detector
(sometimes can't count individually scattered particles....)

Systematic Effects:

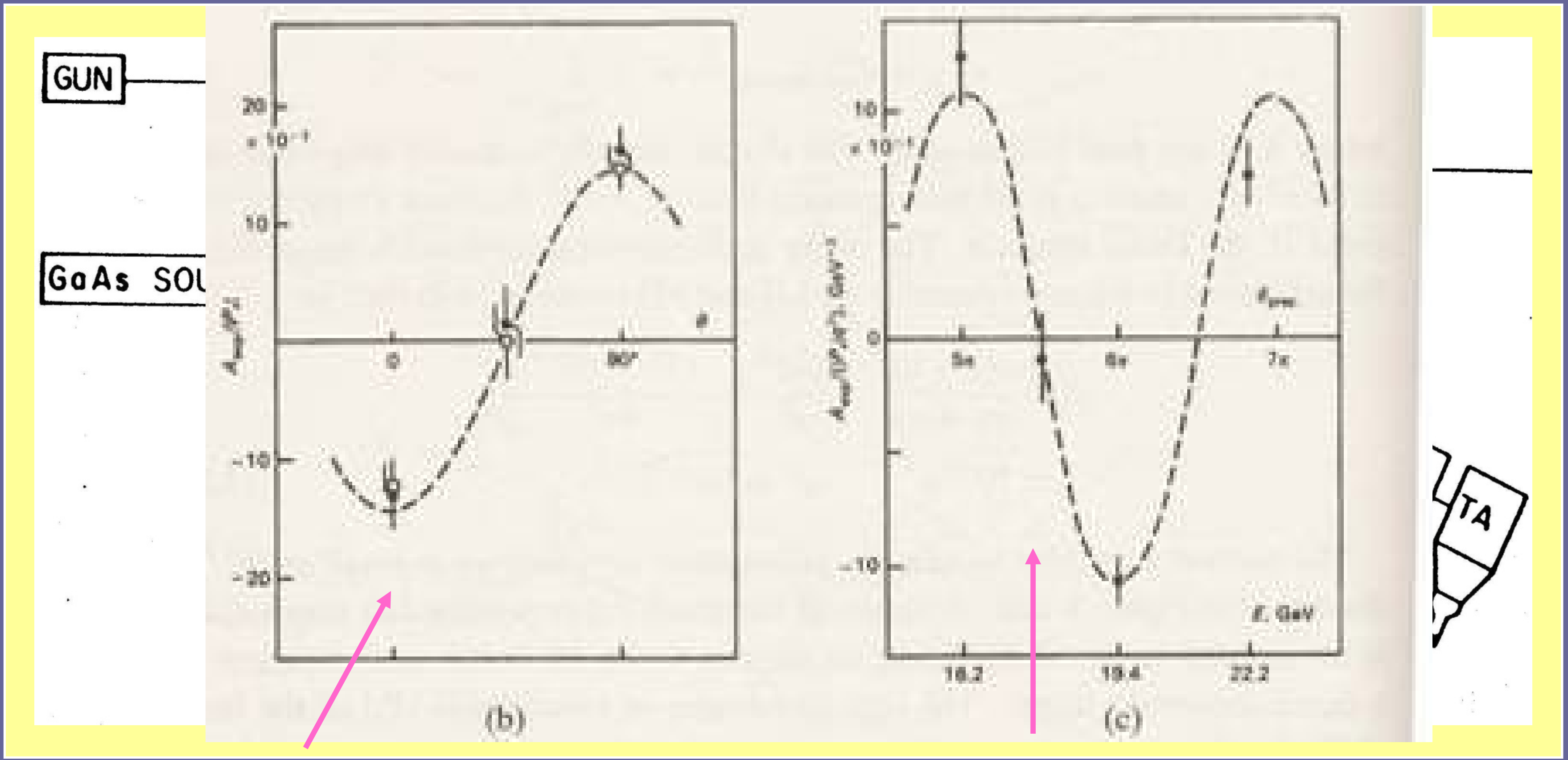
High quality beam (intensity, position, energy) over a long time
Minimize systematic effects in detection that depend on initial beam state
(feedback on energy, position, angle and intensity of incident beam)

Deep inelastic e-D scattering

C.Y. Prescott, et al, PL 77B (1978) 347

SLAC 1978: e + d (DIS) : A ~ –60 ± 10 ppm

led to correct description of neutral weak force: $\sin^2\theta_W = 0.20 \pm 0.03$

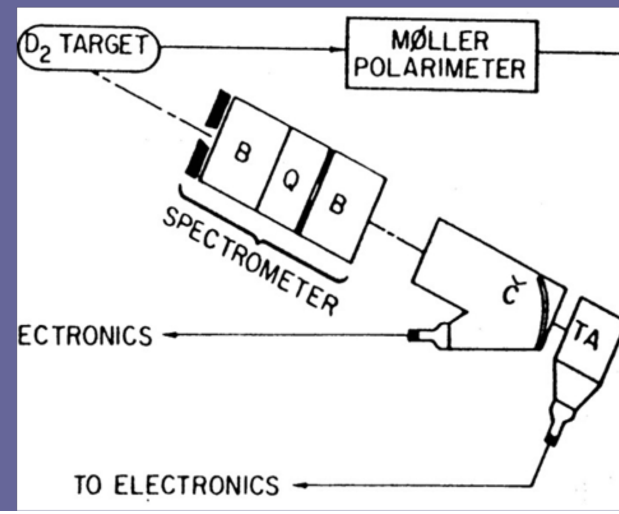


reverse handedness of electron beam

reverse beam via g-2 precession

SLAC 1978 and JLab 2006

1.5 μs/pulse, 120 Hz

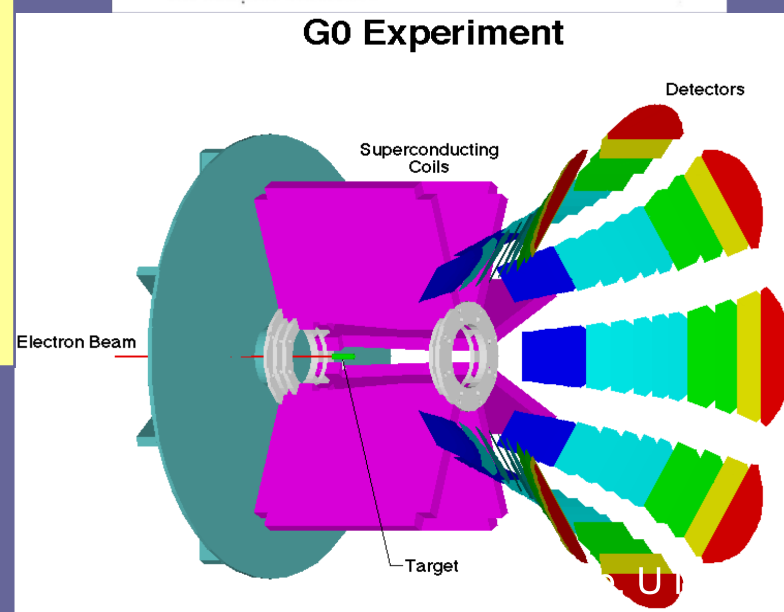


Prescott et al., SLAC DIS e-d:

P = 37%
L = (7 μA, pulsed) x (30 cm target)
$\Delta\Omega$ = 5 x 10^{-4} sr
1000 scattered electrons/pulse
→ integrate

JLAB G0 Experiment (representative):

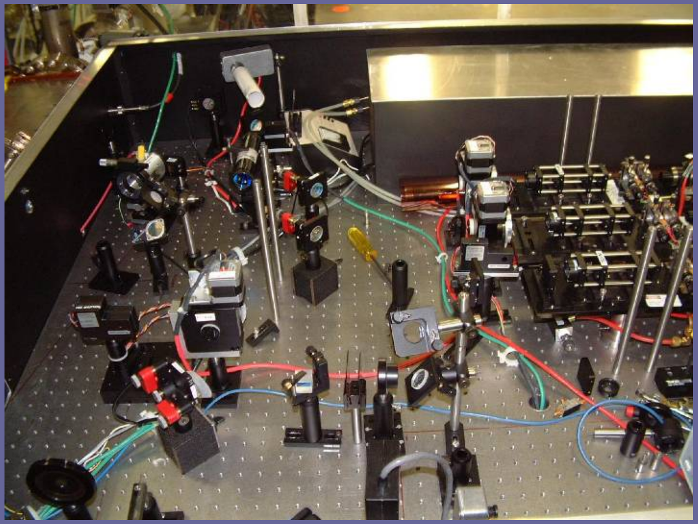
P = 83%
L = (60 μA, CW) x (20 cm target)
$\Delta\Omega$ = 2 sr
rate ~ maximum few MHz per detector
→ count

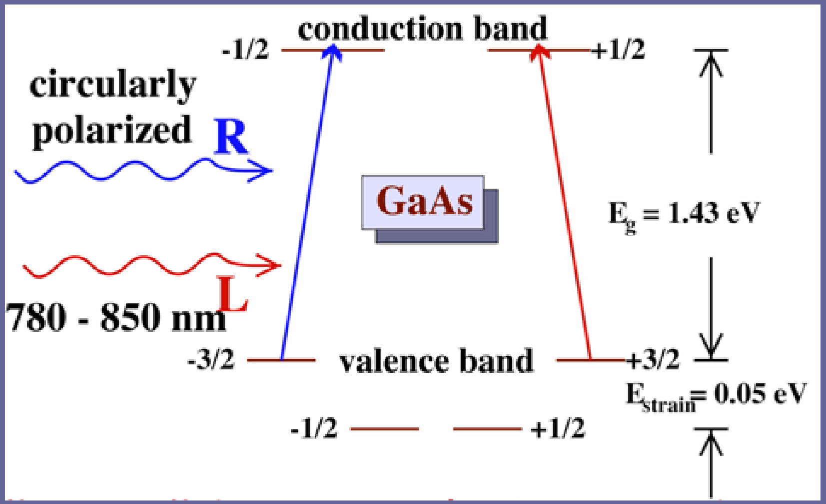


P^2 (L) ($\Delta\Omega$) = (JLAB/SLAC) = 10^5

Polarized Electrons

D.T. Pierce et al., Phys. Lett. 51A (1975) 465.

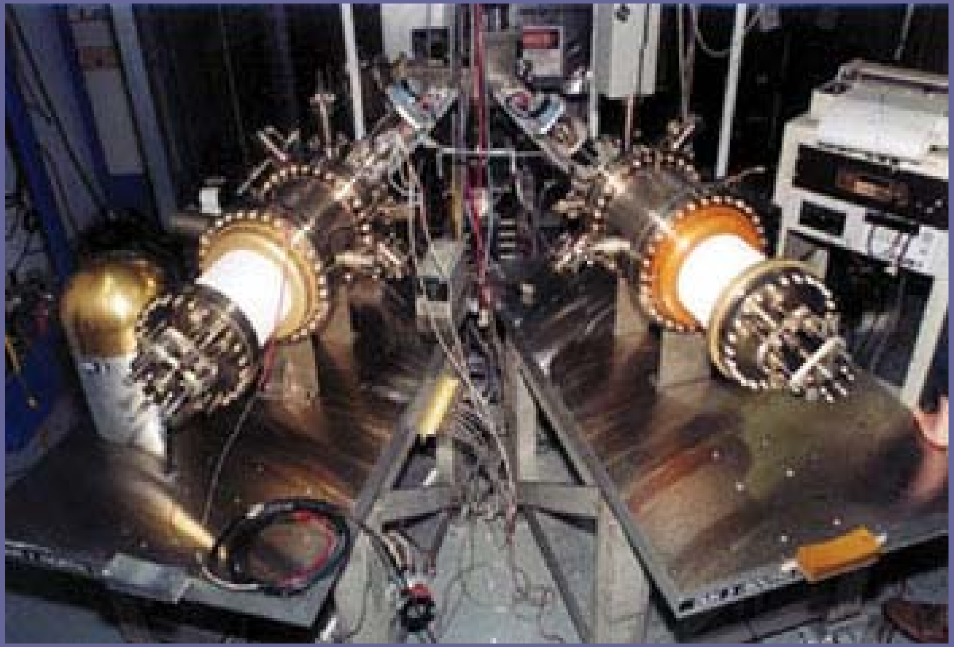




Electron retains circular polarization of laser beam: $P_e \sim 85\%$

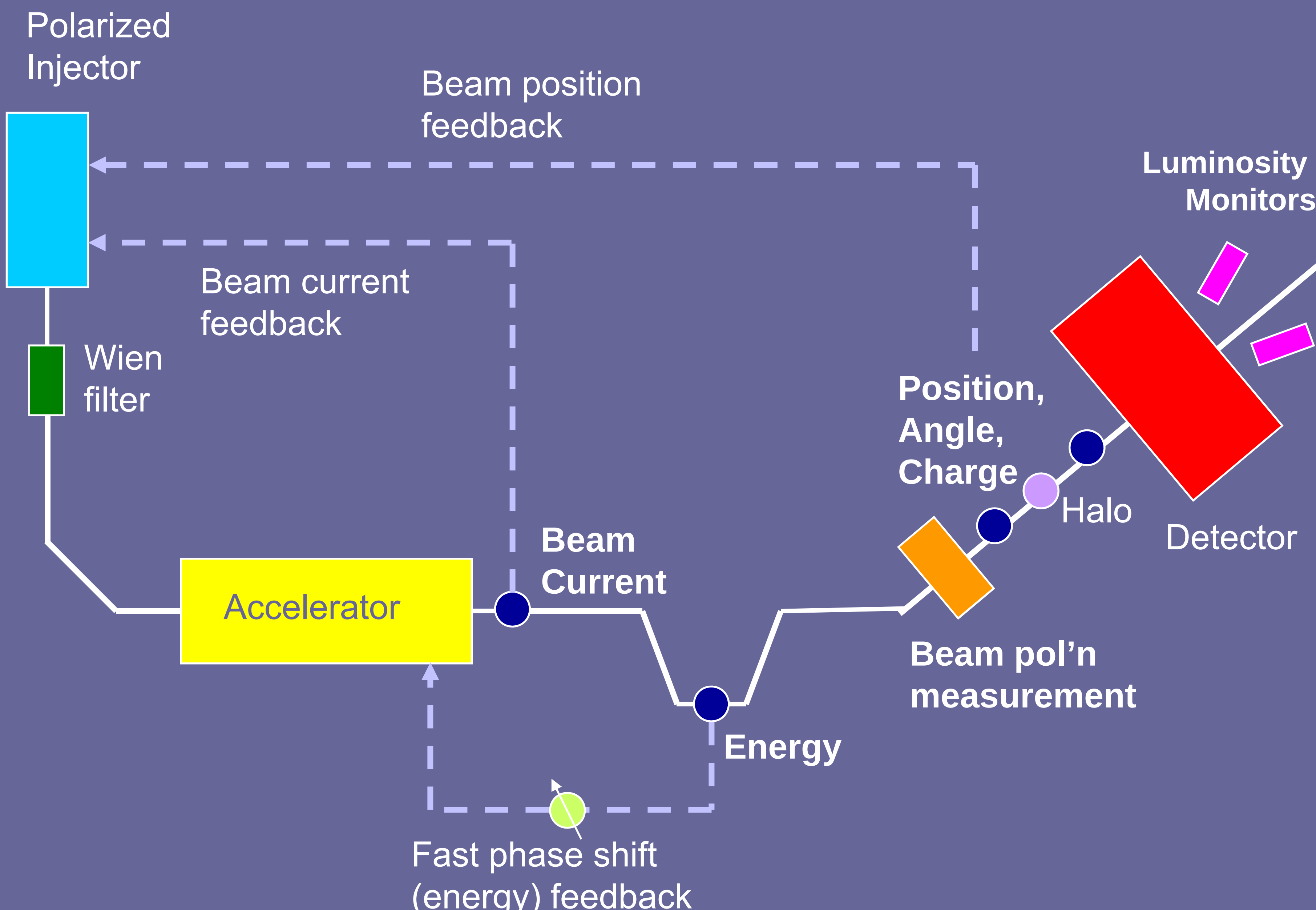
Reverse pol'n of beam at rate of 30 Hz

Feedback on laser intensity and position at high rate



See also Physics Today, Dec 2007

A Typical beam line for PV experiments



False asymmetries from the beam

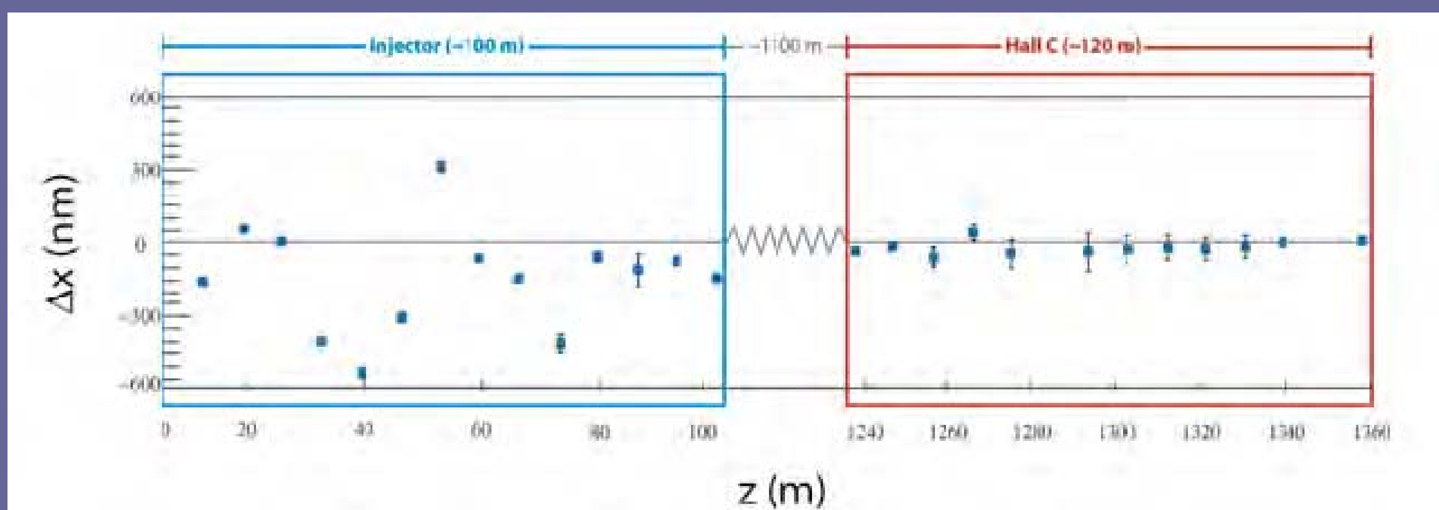
$$A_{meas} = A_{phys} + \sum_{i=1}^{N} \frac{1}{2Y}\left(\frac{\partial Y}{\partial P_i}\right)\Delta P_i$$

detector sensitivity

beam property (x,θ,E,intensity)

At the injector:
$\Delta x < 1$ micron

Measurement at > 1 km:
$\Delta x \sim 5 – 10$ nm



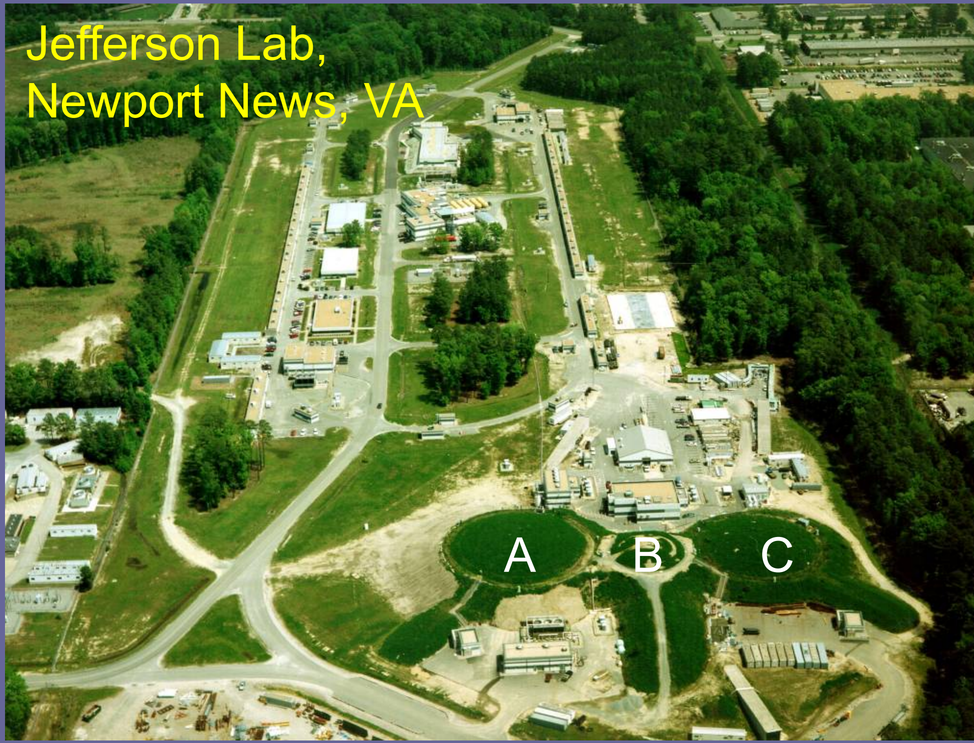
JLab polarized beam : 2005

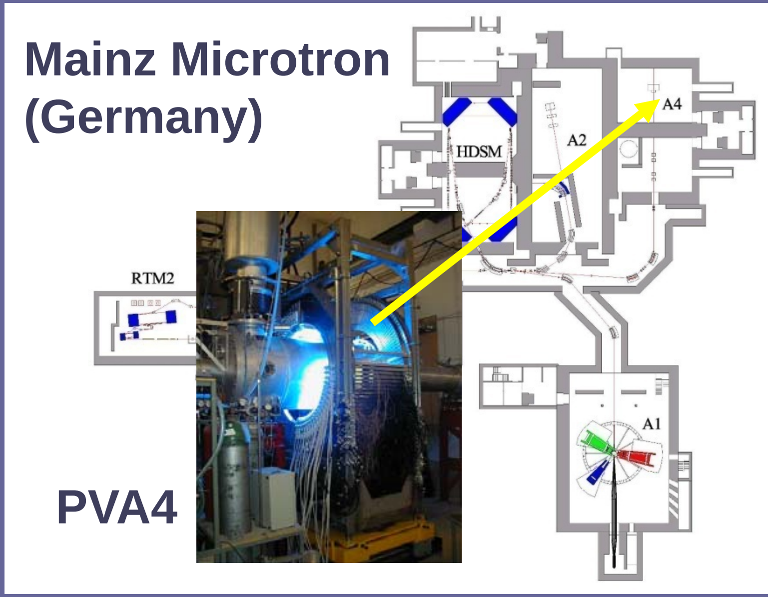
G0 beam:
- strained GaAs (P_B ~ 73%)
- 32 ns pulse spacing
- 40 μA beam current

HAPPEX-II beam:
- superlattice (P_B > 85%)
- 2 ns pulse spacing
- 35 μA beam current

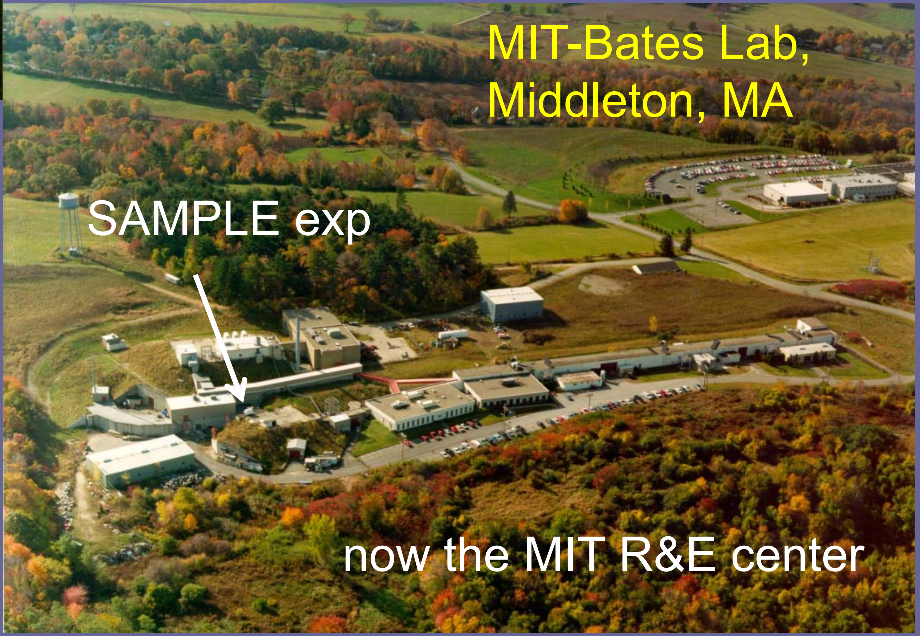
Beam Parameter	G0 beam	HAPPEX beam
Charge asymmetry	**–0.14 ± 0.32 ppm**	**–2.6 ± 0.15 ppm**
Position difference	**4 ± 4 nm**	**–8 ± 3 nm**
Angle difference	**1.5 ± 1 nrad**	**4 ± 2 nrad**
Energy difference	**29 ± 4 eV**	**66 ± 3 eV**
Total correction to Asymmetry	**–0.02 ± 0.01 ppm**	**0.08 ± 0.03 ppm**

Electron accelerators (for nuclear physics)



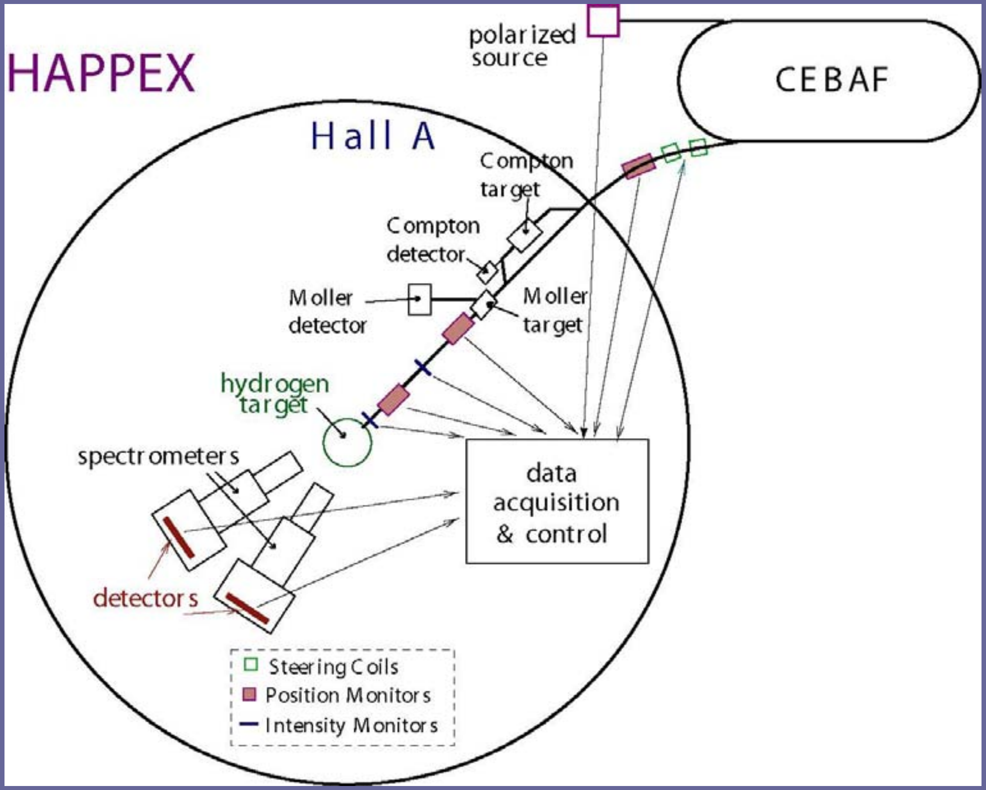


JLab: 6 GeV beam, getting ready for upgrade to 12 GeV



Also, parity-violating Moller scattering (E158) carried out at SLAC….

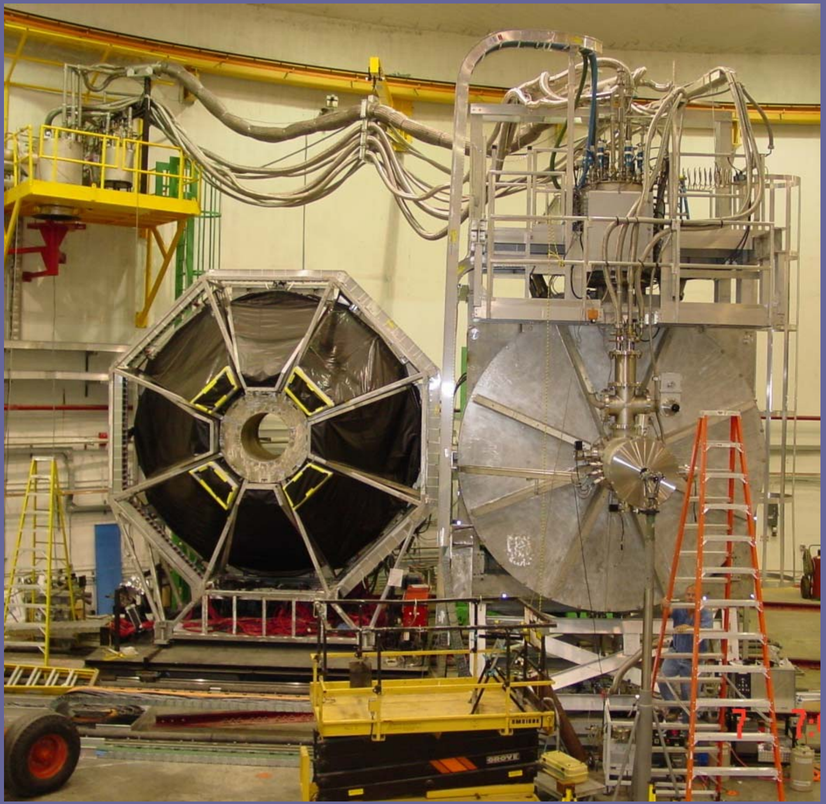
Weak form factors at JLAB



High precision,
forward angles,
selected Q^2
H and ^{4}He targets

G-Zero in Hall C

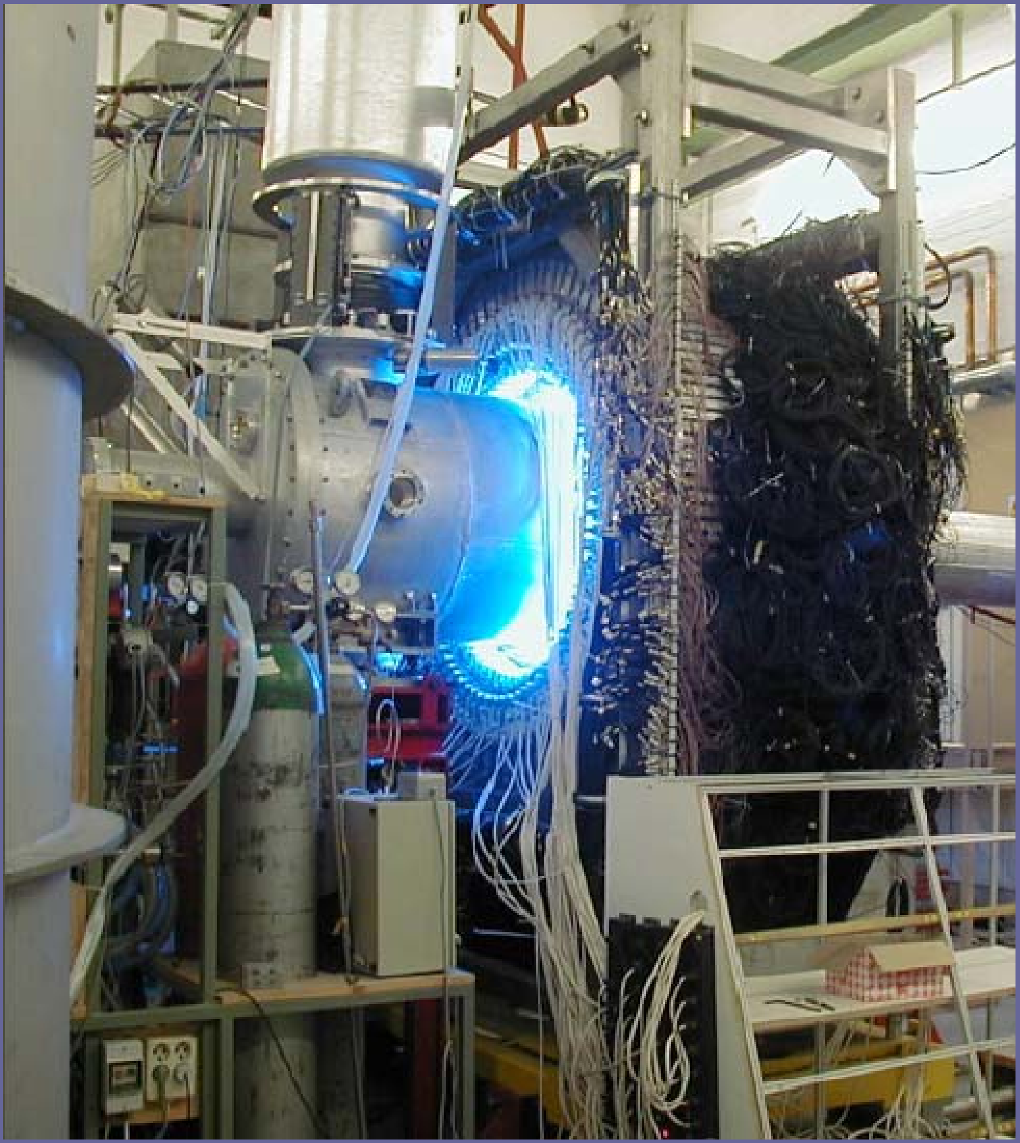
G_E^s , G_M^s and G_A^e separated over range $Q^2 \sim 0.1 - 1.0\ (\mathrm{GeV/c})^2$



H and D targets,
forward/backward angles

PV-A4 at Mainz

PbF$_2$ Calorimeter



phases I &II:
forward angles, H target

$$\mathrm{I:}\ A_{\mathrm{exp}} = -5.6 \pm 0.6 \pm 0.2\ \mathrm{ppm}$$

$$\mathrm{II:}\ A_{\mathrm{exp}} = -1.36 \pm 0.29 \pm 0.13\ \mathrm{ppm}$$

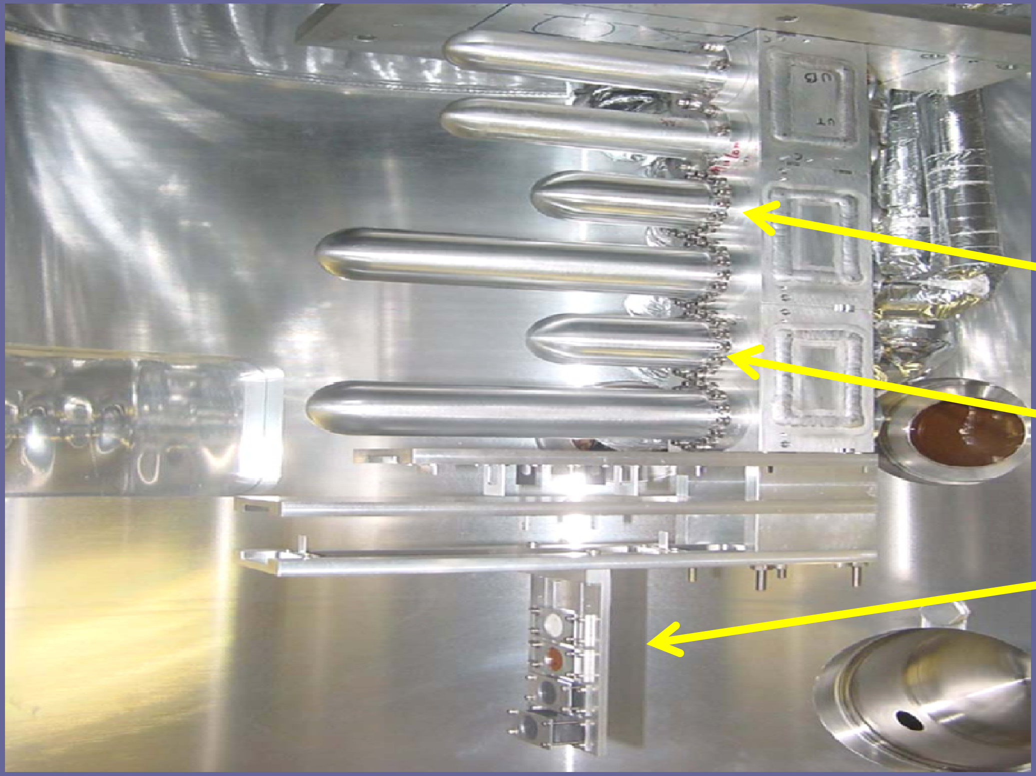
F. Maas et al.,
PRL 93 (2004) 022002,
PRL 94 (2005) 152001

phase III:
backward angles, higher E

$$\mathrm{III:}\ A_{\mathrm{exp}} = -17.23 \pm 0.82 \pm 0.89\ \mathrm{ppm}$$

Cryogenic Targets

Hall C targets



liquid Hydrogen

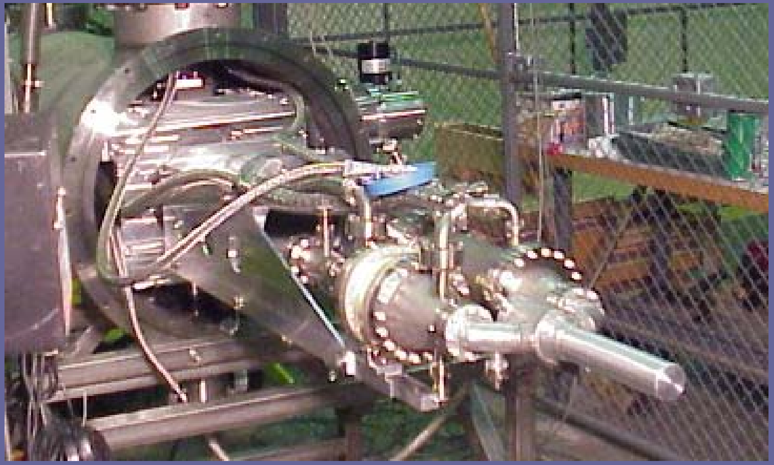
liquid deuterium

solid targets

$$\Delta E = \left(4.5\ \mathrm{MeV\text{-}cm^2/g}\right) \times \left(0.07\,\mathrm{g/cc}\right) \times \left(20\,\mathrm{cm}\right) = 6\,\mathrm{MeV}$$

$$\Delta P = (10\,\mathrm{MeV}) \times (100\,\mu\mathrm{A}) = 1\,\mathrm{kW}$$

G0 target

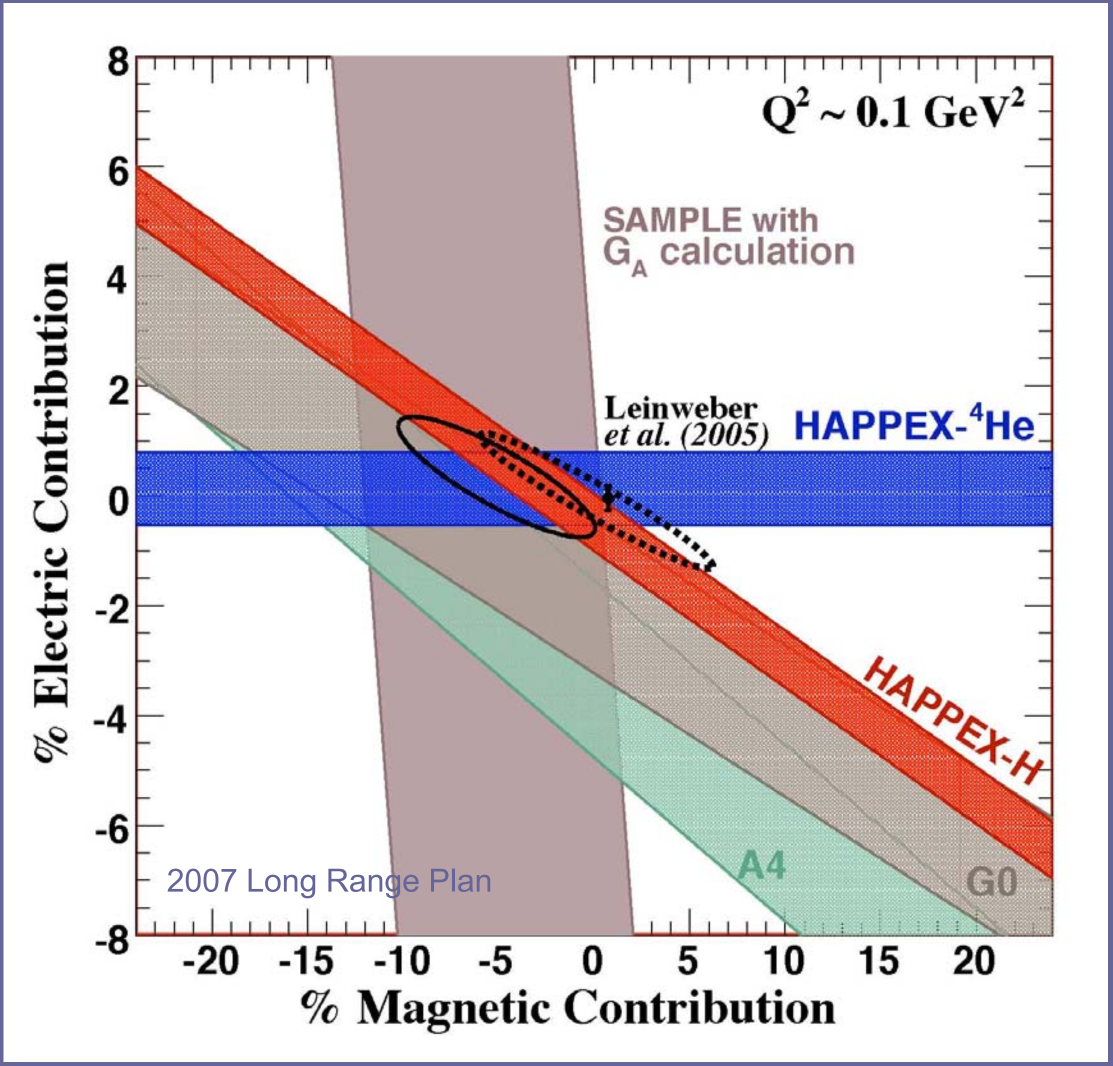


Summary of data at Q^2 =0.1 GeV^2

Solid ellipse:
K. Pashke, private comm, [same as J. Liu, et al
PRC 76, 025202 (2007)],
uses theoretical constraints on the axial form factor

Dashed ellipse:
R. Young ,et al.
PRL 97 (2006) 102002,
does not constrain G_A

Placement of SAMPLE band on the graph depends on choice for G_A

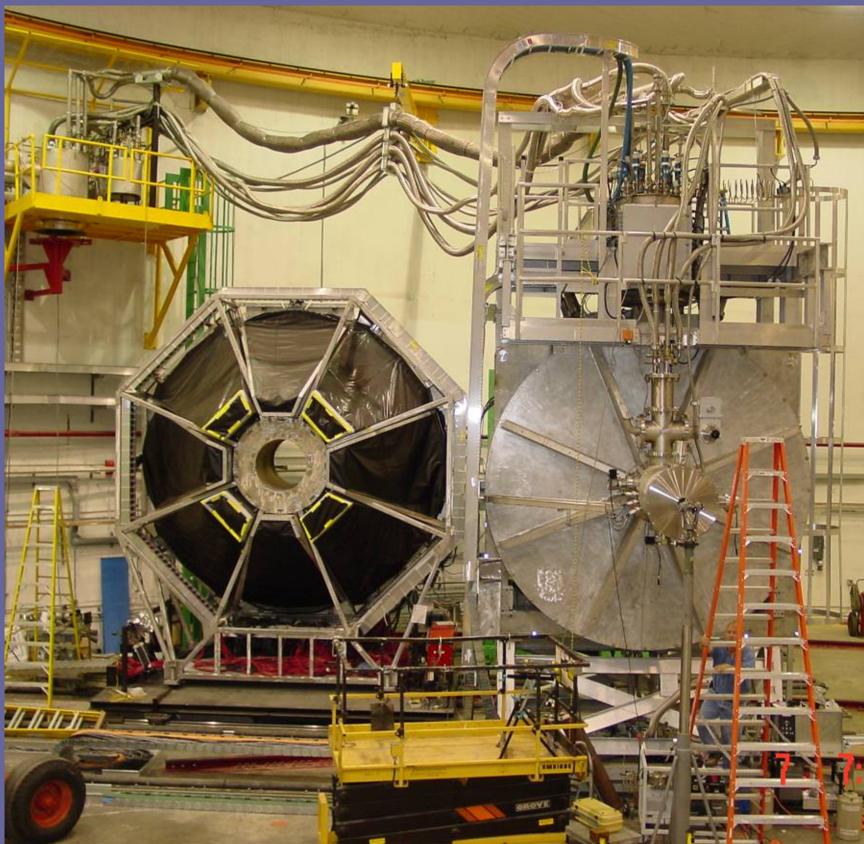


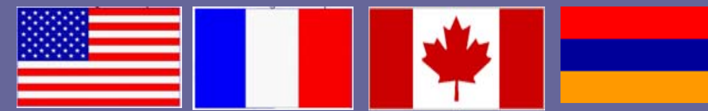
at Q^2=0.23 GeV^2
% contribution to proton:
electric: -3.0 ± 2.5 %
magnetic: $+2.9 \pm 3.2$ %

Similar to Q^2=0.1 GeV^2

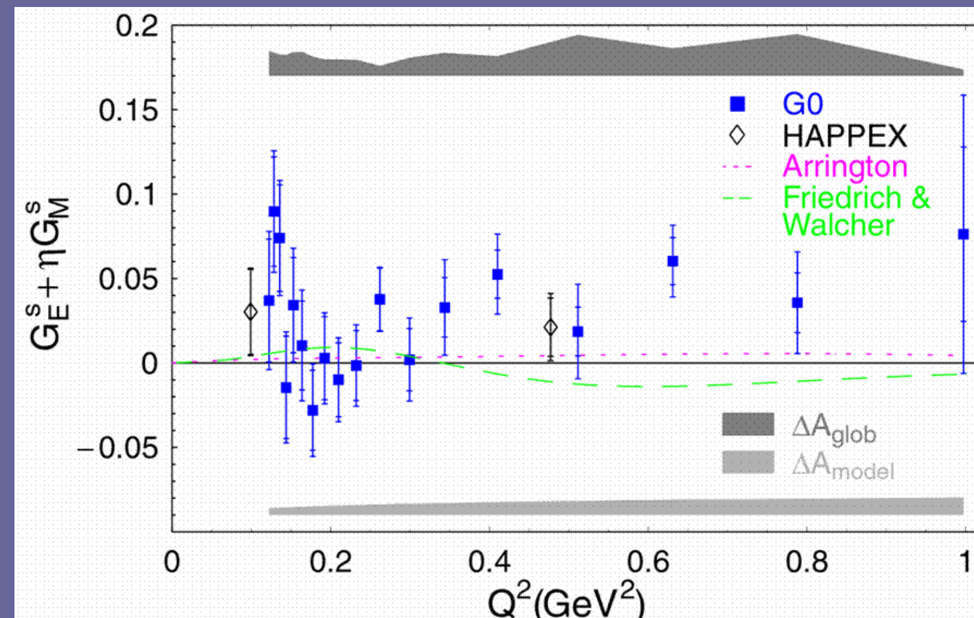
$$\% \text{ contrib} = \frac{G^s_{E,M}}{G^p_{E,M}} \times \left(-\frac{1}{3}\right) \times 100$$

The “G0” experiment at JLab





D.S. Armstrong etal, PRL 95 (2005) 092001



smaller distance

- H and D targets, wide range of distance scales
- Independently determine neutral weak charge, magnetism and axial form factors

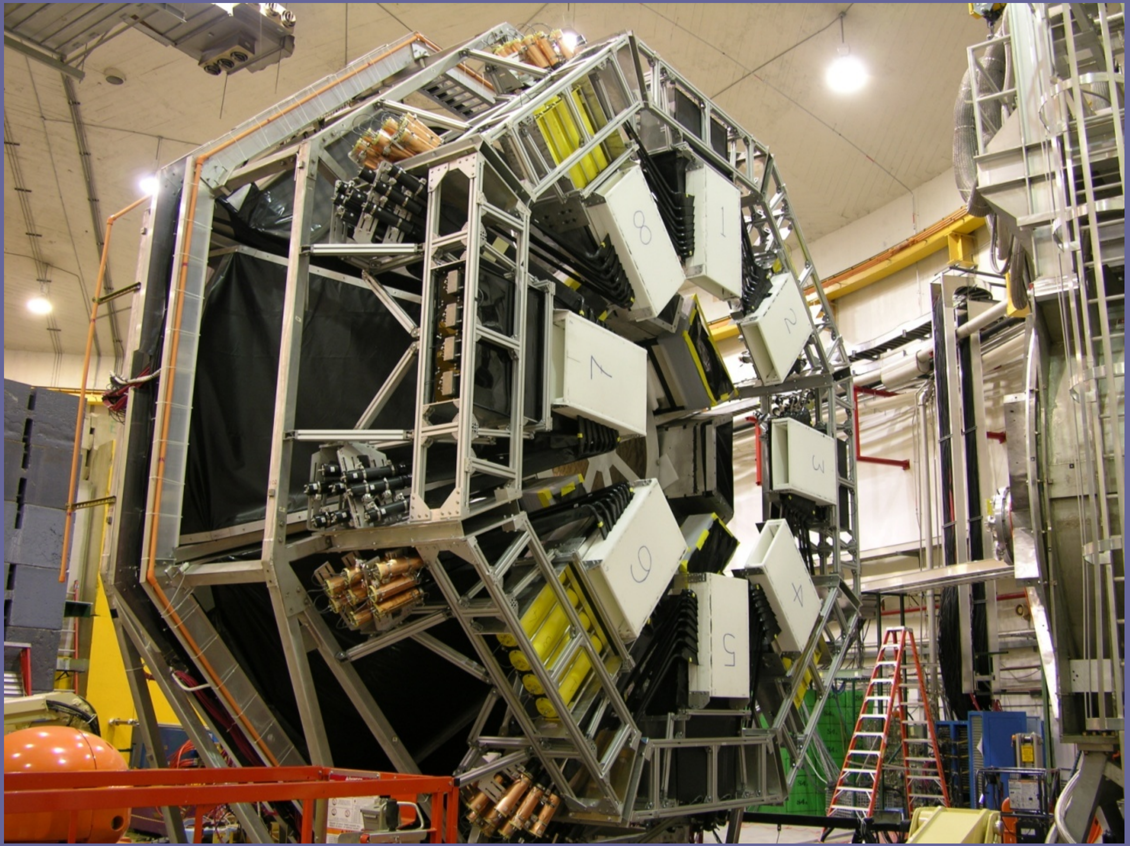
G0 Backward Angle (at Jlab)

Electron detection: $\theta = 108°$, H and D targets
Add Cryostat Exit Detectors (CED) to define electron trajectory
Aerogel Cerenkov detector for π/e separation ($p_\pi < 380$ MeV/c)
1 scaler per channel FPD/CED pair (w/ and wo/ CER)

E_e (MeV)	Q^2 (GeV^2)
362	0.23
687	0.62

Both H and D
at each kinematic setting

Common Q^2 with
HAPPEX-III and PVA4



G0 fun facts

Run start to run end ~ 8940 hours, 330 C of beam, 3.5 Tb of data

$$A = \frac{Y_1 + Y_4 - Y_2 - Y_3}{Y_1 + Y_2 + Y_3 + Y_4}; \quad 1,4 = "+" \quad 2,3 = "-"$$

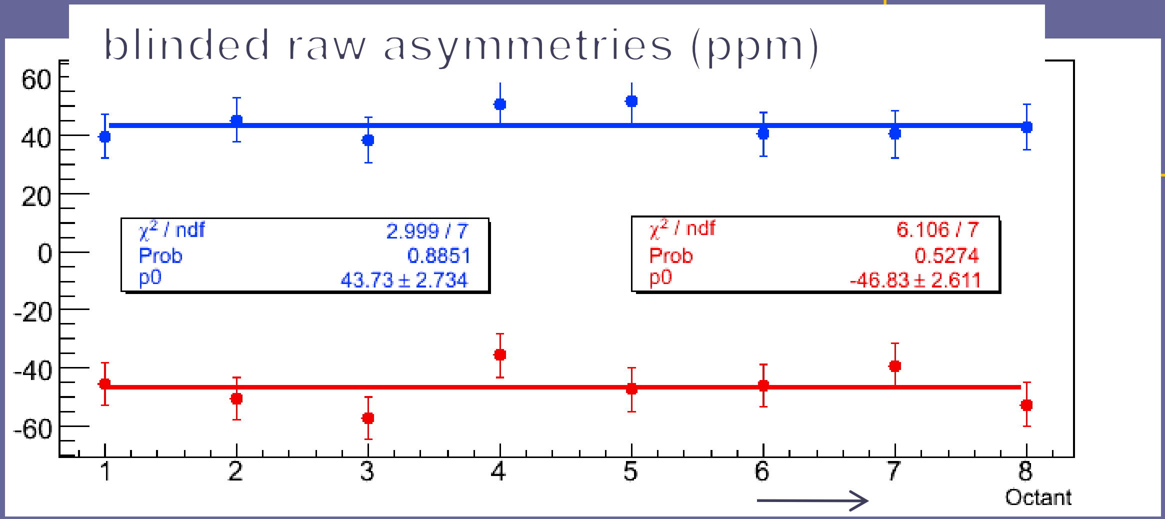
measured 2,000 asymmetries 15 times / second

In 2400 hours, we measured 250 billion asymmetries
(or, each asymmetry is measured 13 million times)

3.5 Tb ~ 5.5 x 10^8 inches of 6250 bpi tape
~ 14,000 km

distance from Newport News, VA to Katmandu, Nepal

~ 14,000 data tapes



octant # (azimuthal distribution)

H-687 MeV data sample

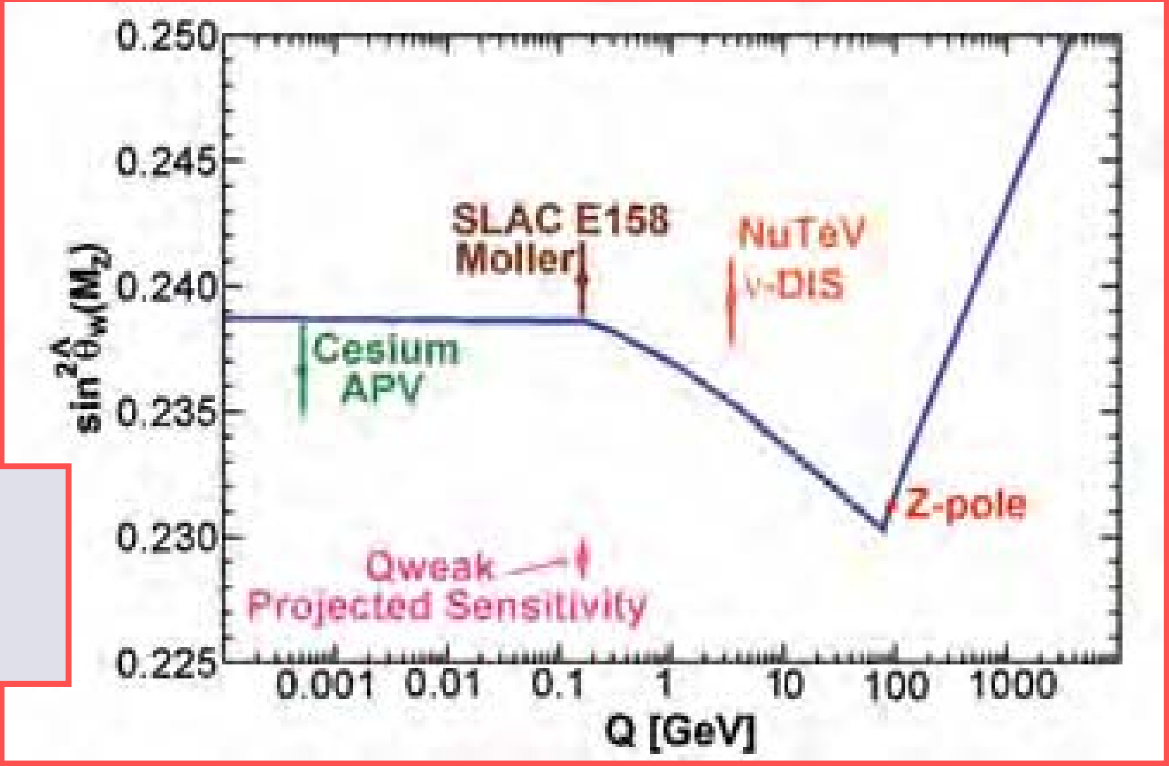
Precision tests of TeV-scale Electroweak Physics

Indirect searches for extensions to Standard Model of particle physics using precision measurements of $\sin^2\theta_W$ at several energy scales are complementary to experiments at the LHC.

Case 1: electron-electron scattering (Moller) → SLAC E158

A_{meas} = $-131 \pm 14 \pm 10$ parts per billion

P. Anthony et al., PRL 95 (2005) 081601



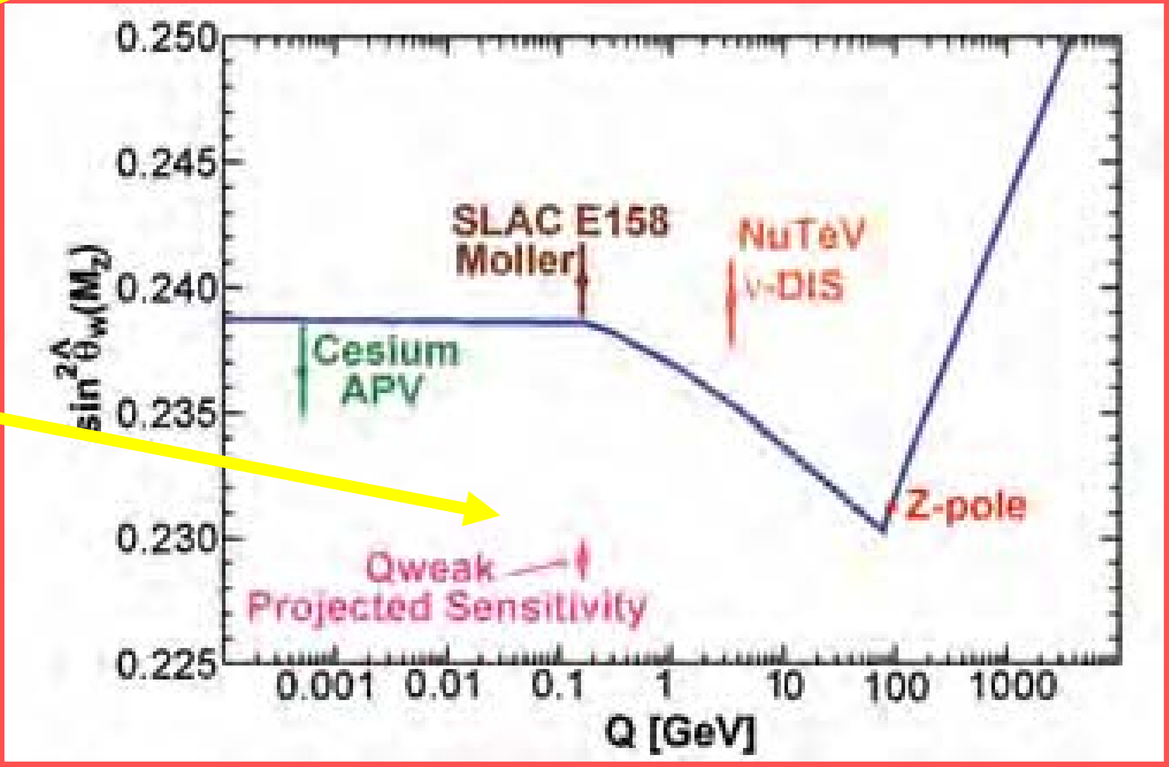
Limits existence of new e-e interactions on scale of 7-16 TeV

Precision tests of TeV-scale Electroweak Physics

Case 2: e-p scattering: Weak Charge of the Proton

$$L = L_{SM}^{PV} + L_{NEW}^{PV} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e\sum_q C_{1q}\bar{q}\gamma^\mu q + \boxed{\frac{g^2}{4\Lambda^2}}\bar{e}\gamma_\mu\gamma_5 e\sum_q h_V^q\bar{q}\gamma^\mu q$$

precise measurement of known e-q interactions (C_{1u}, C_{1d}) can place limits on existence of new ones on scale of a few TeV



Weak charge of the nucleon

As $Q^2 \rightarrow 0$, for far forward angles,

$$A_{LR} = \frac{-G_\mu \; Q^2}{4\pi\alpha\sqrt{2}}\left[(1-4\sin^2\theta_W) + \frac{-\varepsilon G_E^{\gamma,p}(G_E^{\gamma,n}+G_E^s) - \tau G_M^{\gamma,p}(G_M^{\gamma,n}+G_M^s) + A_A}{\varepsilon (G_E^{\gamma,p})^2 + \tau (G_M^{\gamma,p})^2}\right]$$

$$\boxed{A_{LR} = \frac{-G_\mu}{4\pi\alpha\sqrt{2}}\left[Q^p_{weak}\, Q^2 + B_4 Q^4 + \ldots\right]}$$

$$Q^p_{weak} = 1 - 4\sin^2\theta_W$$

$$Q^p_{weak} = -2\left(2C_{1u} + C_{1d}\right)$$

e axial-vector, q vector couplings

P.M. King, CIPANP2009 6

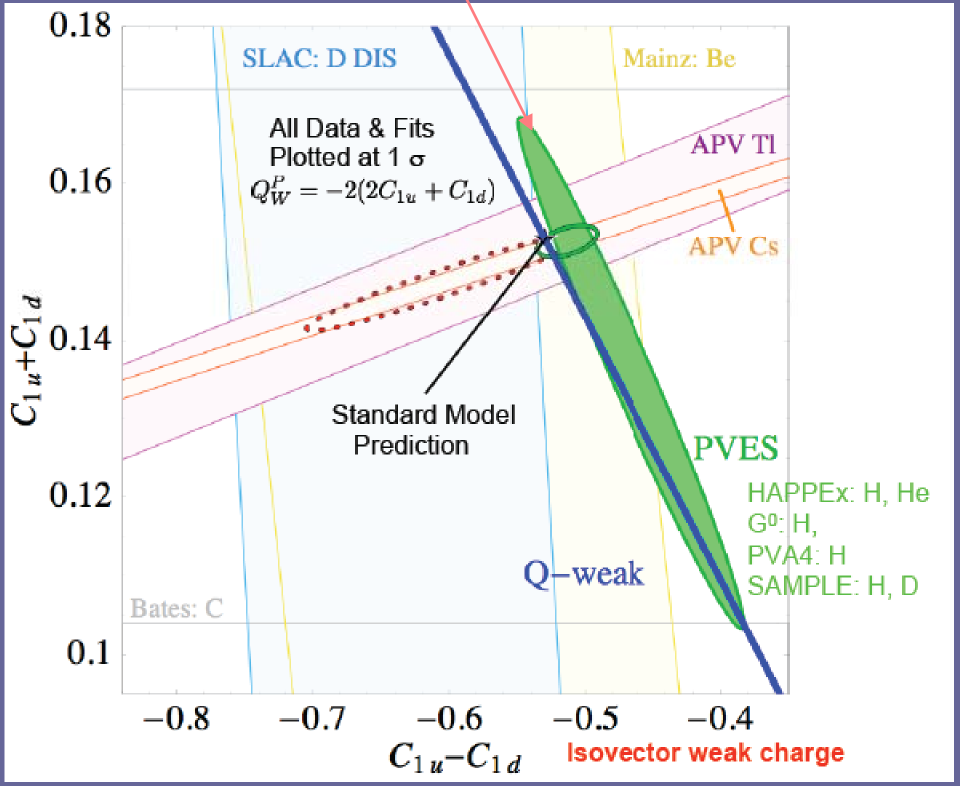
QWeak: Parity violating e-p scattering

R. Carlini, etal

QWeak toroidal magnet at MIT-Bates lab

expected asymmetry ~ 0.3 ppm
measure to few %.

combined existing PV electron scattering data provide most precise experimental limit on proton's weak charges

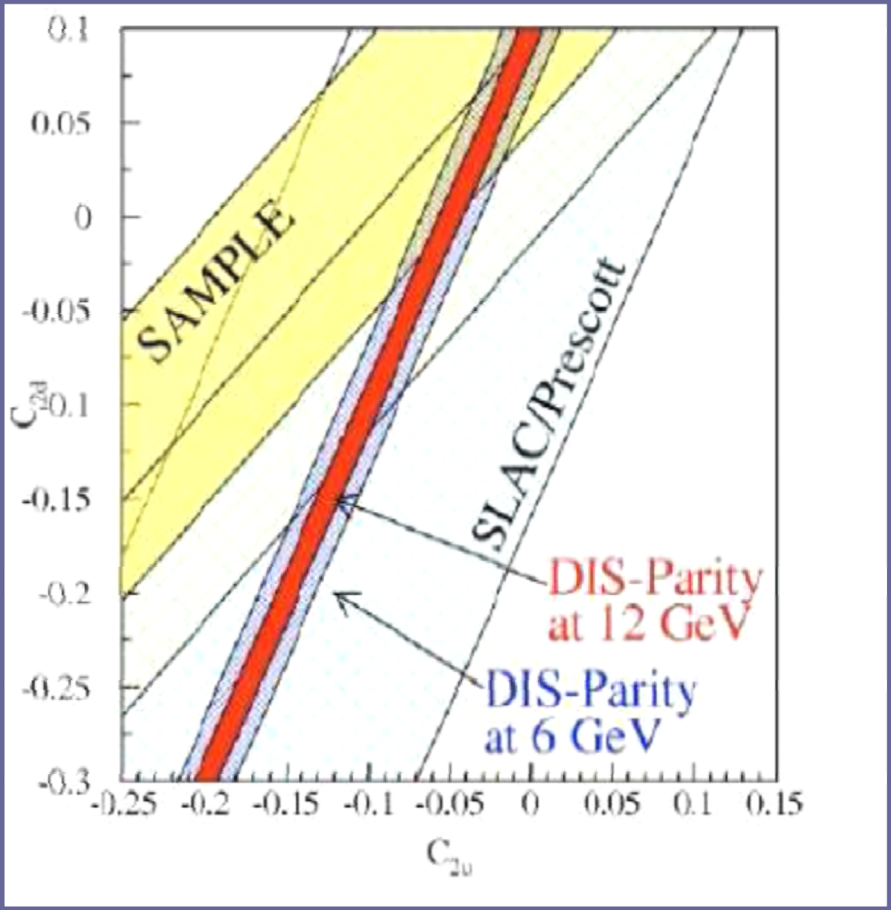


R. Young et al., PRL 99 (2007) 122003

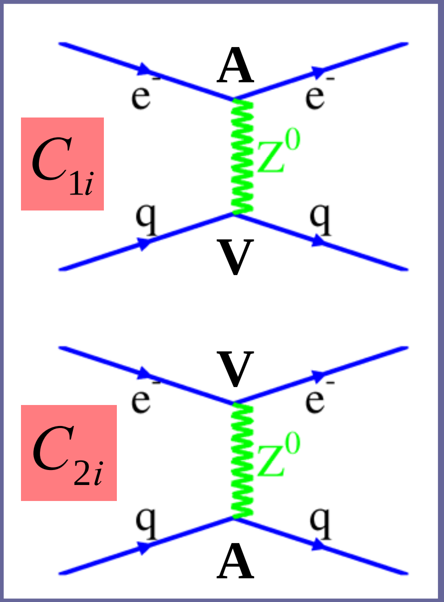
Precision tests of TeV-scale Electroweak Physics

Case 3: Direct electron-quark scattering

high precision return to SLAC 1978 measurement



X. Zheng, U Va & P.Reimer, ANL



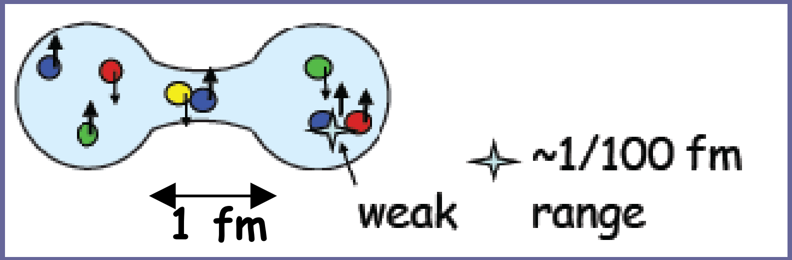
$$y = \frac{E - E'}{E}$$

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

$$b(x) \rightarrow \left[2C_{2u} - C_{2d}\right]$$

w/ 6 GeV, strong interaction important

Weak interactions between nucleons



from P. Mumm, NIST

Fundamental interaction is q-q weak interactions, but these are buried inside strongly bound systems

$\rightarrow$ typical size of effect < 10^{-7}
5 leading contributions

see H. Griesshammer, NNPSS 2008

• need a minimum of 5 experiments (more is better, and preferably without too many nucleons)

• need a theoretical framework to interpret the results → chiral EFT

Required Experimental program

- Asymmetry in $\vec{p}$-p and $\vec{p}$-^{4}He scattering

  p-p measurement from TRIUMF

- spatial γ asymmetry in $\vec{n}$+p$\rightarrow$ d+γ and $\vec{n}$+d $\rightarrow$ t+γ

  n+p$\rightarrow$ d+γ underway, moved from LANSCE to SNS

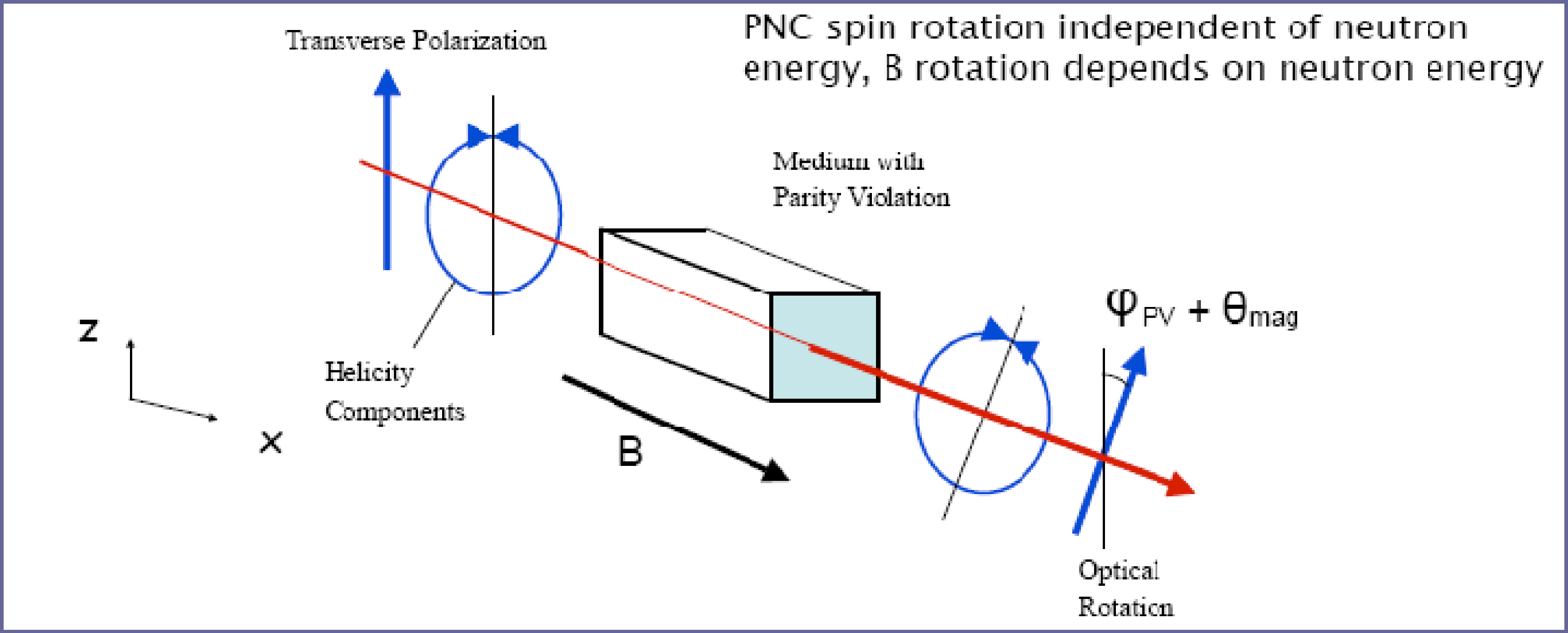
- circular pol'n of γ in n+p $\rightarrow$ d+γ

- spin rotation of $\vec{n}$ in ^{4}He and $\vec{n}$ in p

  recently completed at NIST

- Also: laser spectroscopy on heavy rare isotopes (e.g., Francium) installation in progress at TRIUMF (L. Orozco, et al.)

neutron spin rotation in ^{4}He
(at NIST, Gaithersburg, MD)

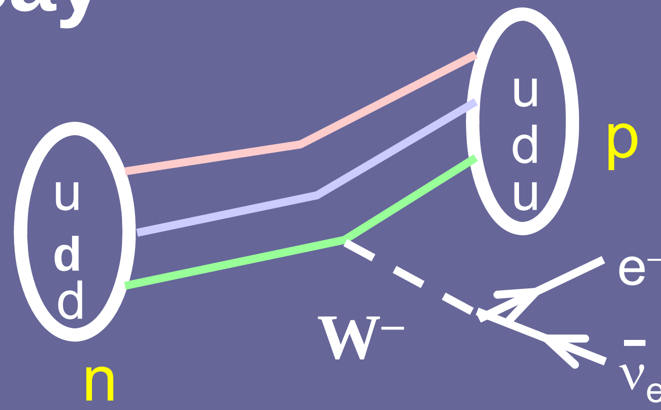


ϕ_{PV} from $\sigma \cdot p$ term in forward scattering amplitude (P odd)

$$\boxed{\frac{d\phi}{dz} \sim 10^{-7} \text{ rad/m}}$$

Polarized neutron beta decay

G_F from μ-decay, apparently the same for quarks and leptons



$$g_V^2 \propto \left(G_F V_{ud}\right)^2$$

$$\text{define } \lambda = \frac{g_A}{g_V} = 1.2695 \pm 0.0029$$

$$n \longrightarrow p + e^- + \overline{\nu}_e + 782 \text{ keV}$$

decay rate

$$dW \propto \left(g_V^2 + 3g_A^2\right) F(E_e) \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \vec{\sigma}_n \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right]$$

measurable and non-zero

T odd, P even

neutron lifetime measures this piece

a, b, B, and A each depend differently on λ

"cold" and "ultracold" neutrons

"cold":

$$\text{temperature} = \frac{K.E.}{\frac{1}{40}\,eV} \times 300K = 36\,K$$

$$\beta = \sqrt{\frac{2 \times K.E.}{m_n}} \rightarrow v = 760 \text{ m/s}$$

$$\lambda = \frac{h}{p} = 0.5 \text{ nm}$$

Produce by moderating thermal neutrons from reactor or spallation source

Can be transported long distances by total internal reflection

"ultra-cold":

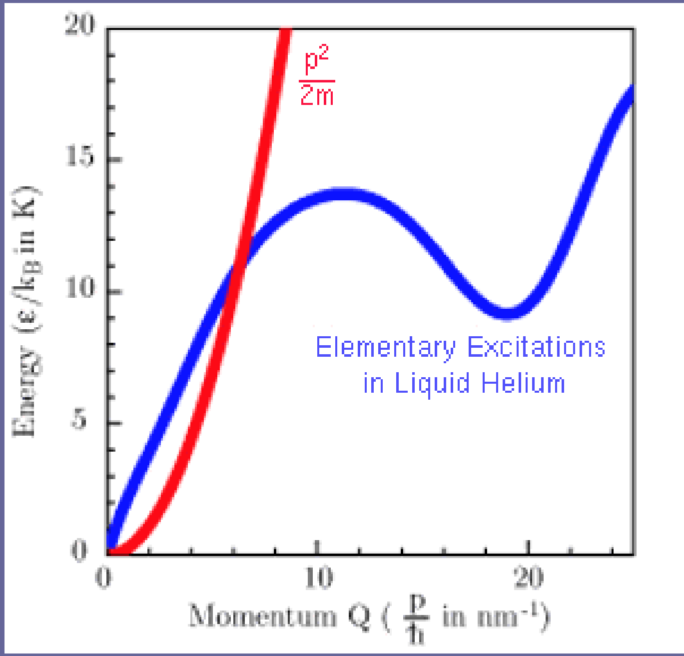
$$v = 5 \text{ m/s}$$

$$\text{T} \sim \text{few mK}$$

$$\lambda \sim 50 \text{ nm}$$

Scatter cold neutrons from solids, liquids, etc., that can absorb bulk of neutron KE into a "phonon" resonance

Can be trapped:
- material walls
- magnetic fields
- gravity!



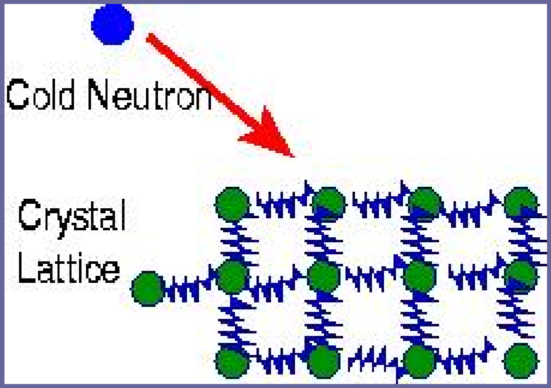
Golub & Pendelbury, 1977

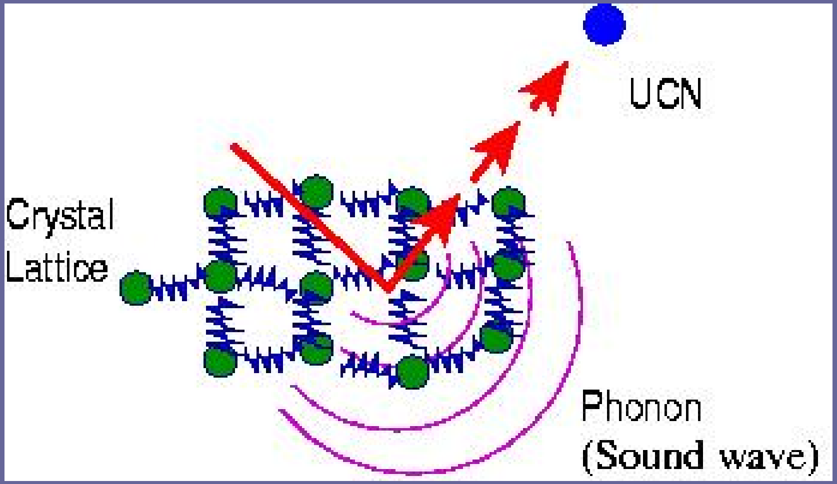
Ultracold Neutrons: Superthermal Process

slide from C.-Y. Liu, Indiana Univ.

R. Golub and J. M. Pendlebury, Phys. Lett, A53, 133 (1975)

- Cold neutrons downscatter in the solid, giving up almost all their energy, becoming UCN.

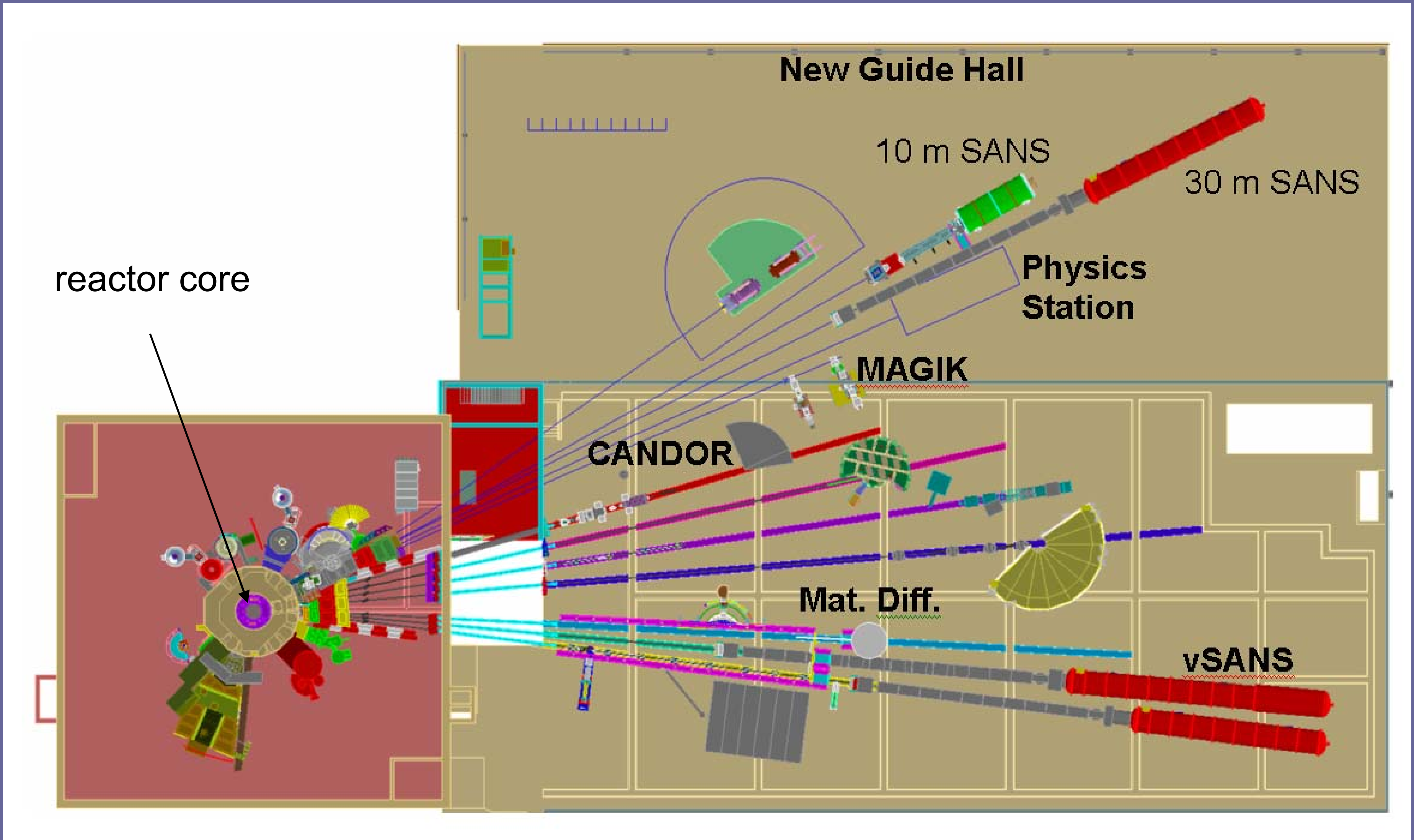




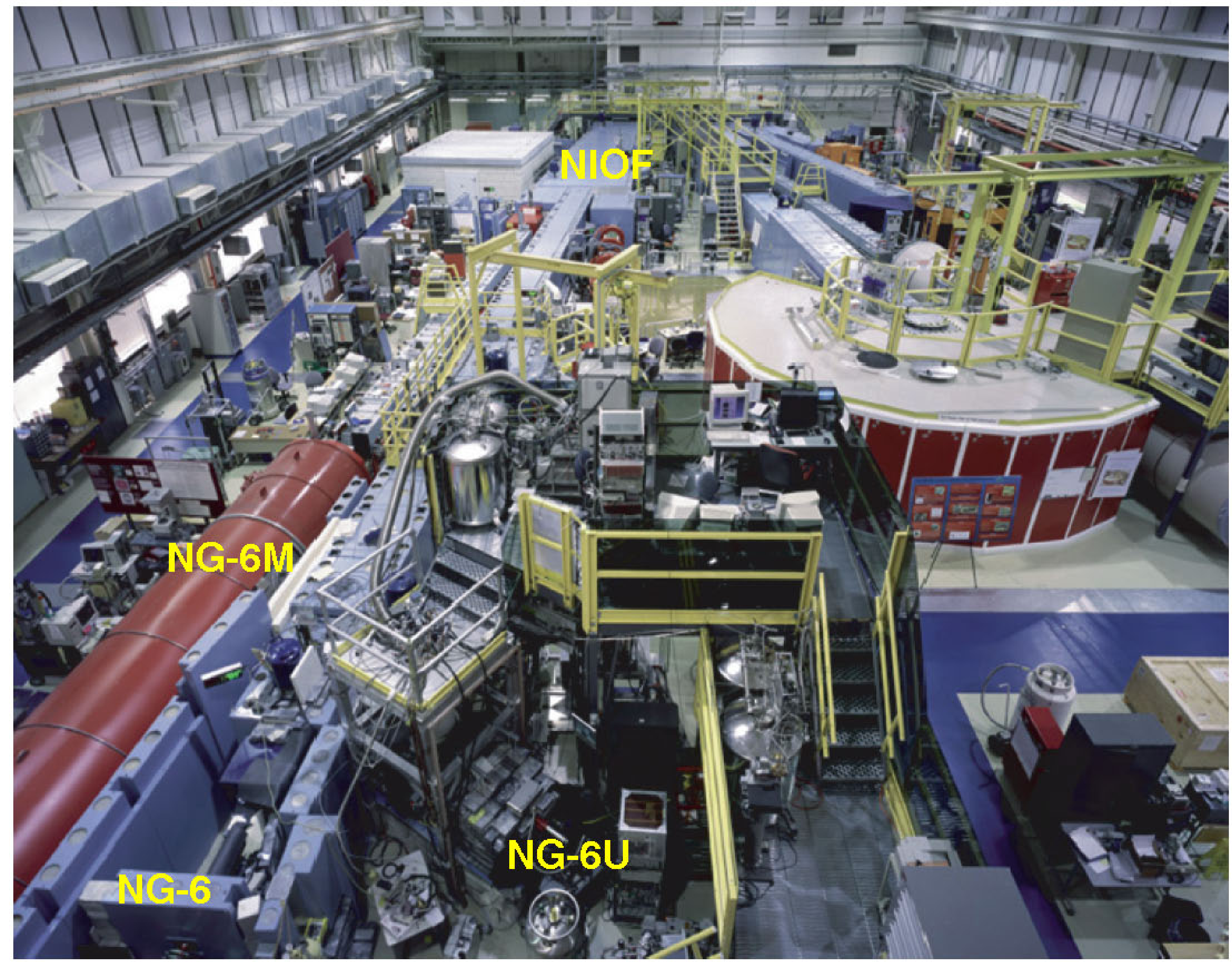
- UCN upscattering (the reverse process) is suppressed by cooling the moderator to low temperatures.

NIST Center for Neutron Research

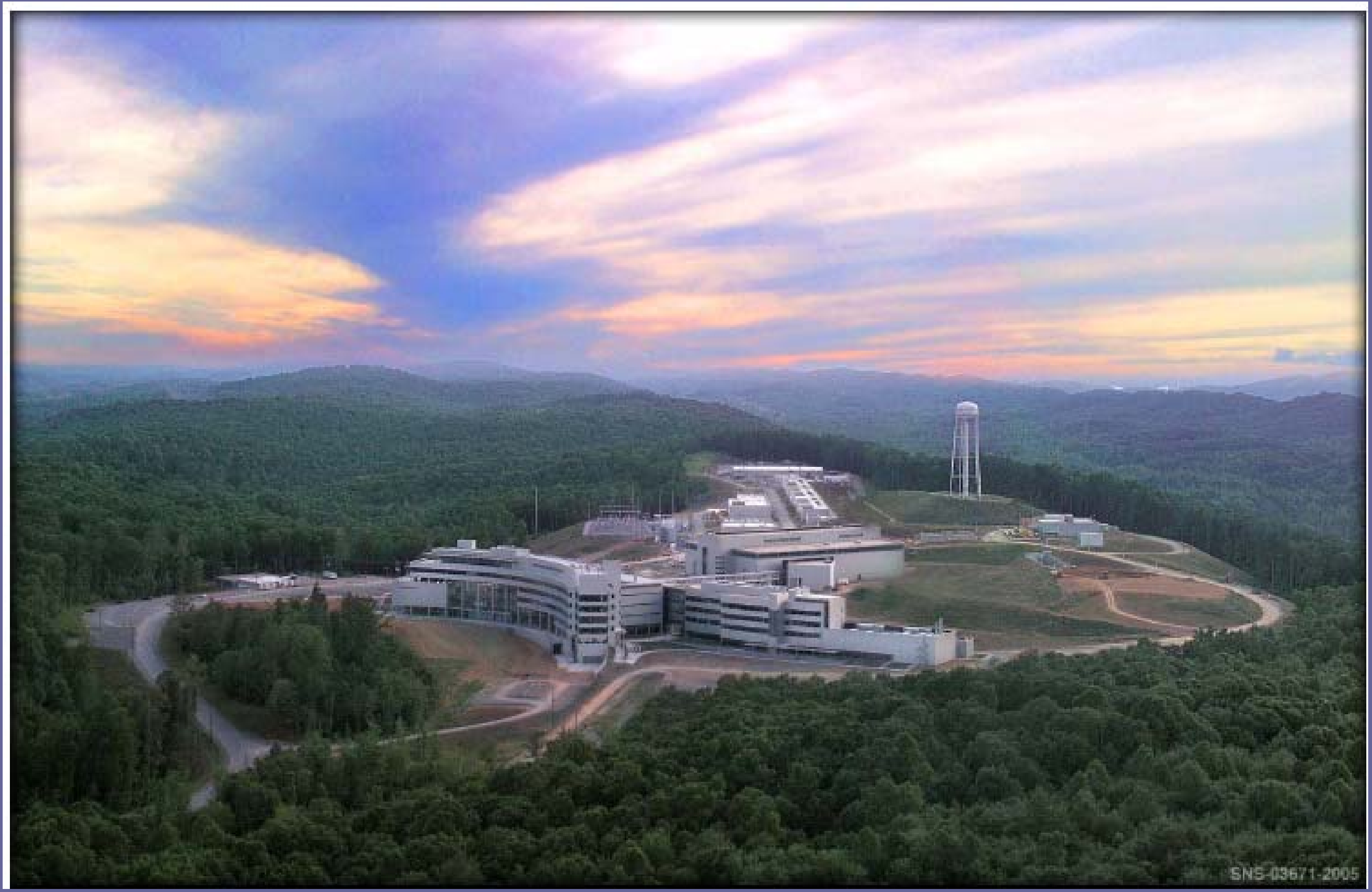
20 MW reactor is source of "cold" neutrons: $T_n \sim 10^{-5}$-10^{-2} eV



NIST Center for Cold Neutron Research



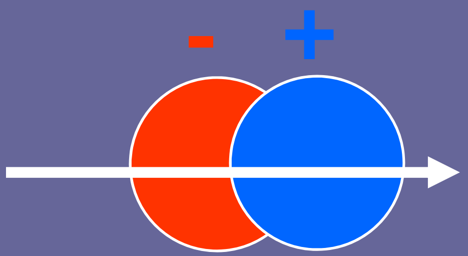
The Spallation Neutron Source



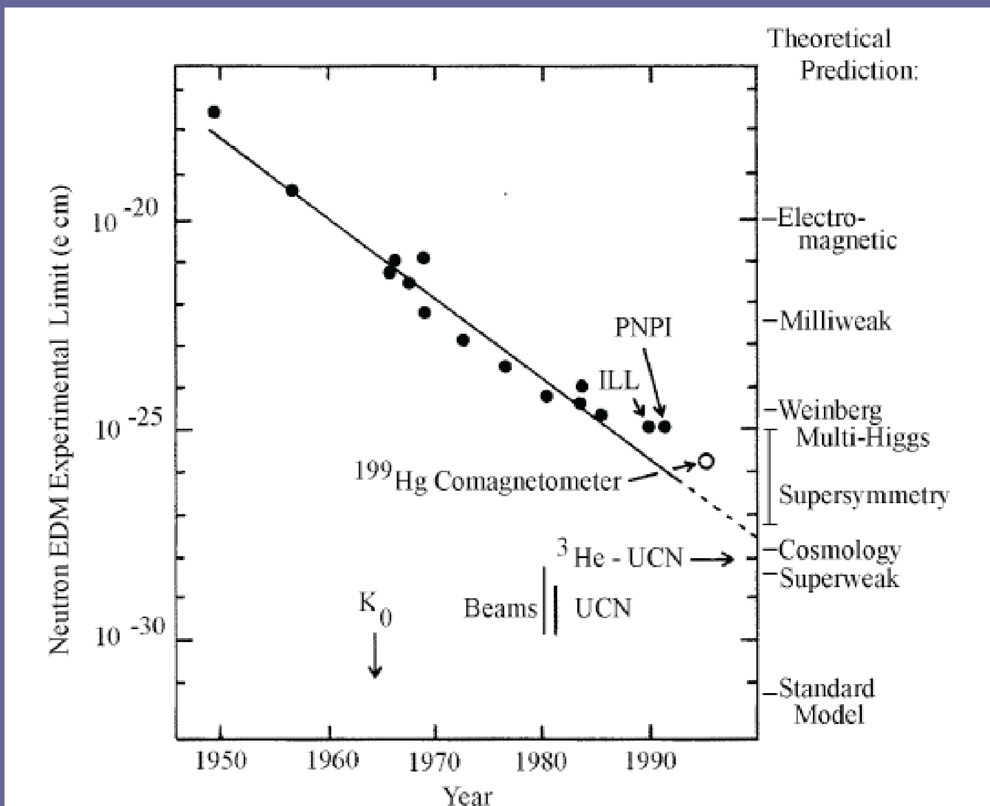
T-odd → CP odd: neutron EDM

CP-violation is important to understanding of original of matter (vs antimatter)

$\vec{d} \bullet \vec{E}$



$s = 1/2$



If neutron possesses an electric dipole moment, then, in an electric field:

$$H_E = -d_n \vec{\sigma} \cdot \vec{E}$$

will reverse sign under reversal of E. This is CP-odd observable.

many EDM experiments underway or proposed, in many systems.

New U.S. experiment planned using ultracold neutrons at SNS –Oak Ridge

http://p25ext.lanl.gov/edm/edm.html

Origin of Matter

from P. Huffman, NSCU

- Sakharov conditions: [JETP 5 (1967) 24]
  - A violation of baryon number
  - A violation of both C and CP
  - A departure from thermal equilibrium

A. Sakharov, 1943
(from Wikipedia)

- Could occur in several points during BBN
  - T~10^{29} K (GUT scale)
  - 10^{29} K >> T >> 10^{15} K (leptogenesis)
  - T~10^{15} K (Electroweak)

- One can test Electroweak Baryogenesis (EWB) and parts of leptogenesis experimentally

neutron EDM and CP in the strong interaction

QCD Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{QCD}} + \boxed{\frac{\theta\, g_s^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}}$$

→ Violates P and T

Conserves Flavor

No T-violation Observed in Static Quark System, i.e. neutron EDM → $\theta < 10^{-9}$ → "Strong CP Problem" $\Rightarrow$ Axion ?

CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†

Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

(Received 31 March 1977)

We give an explanation of the CP conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

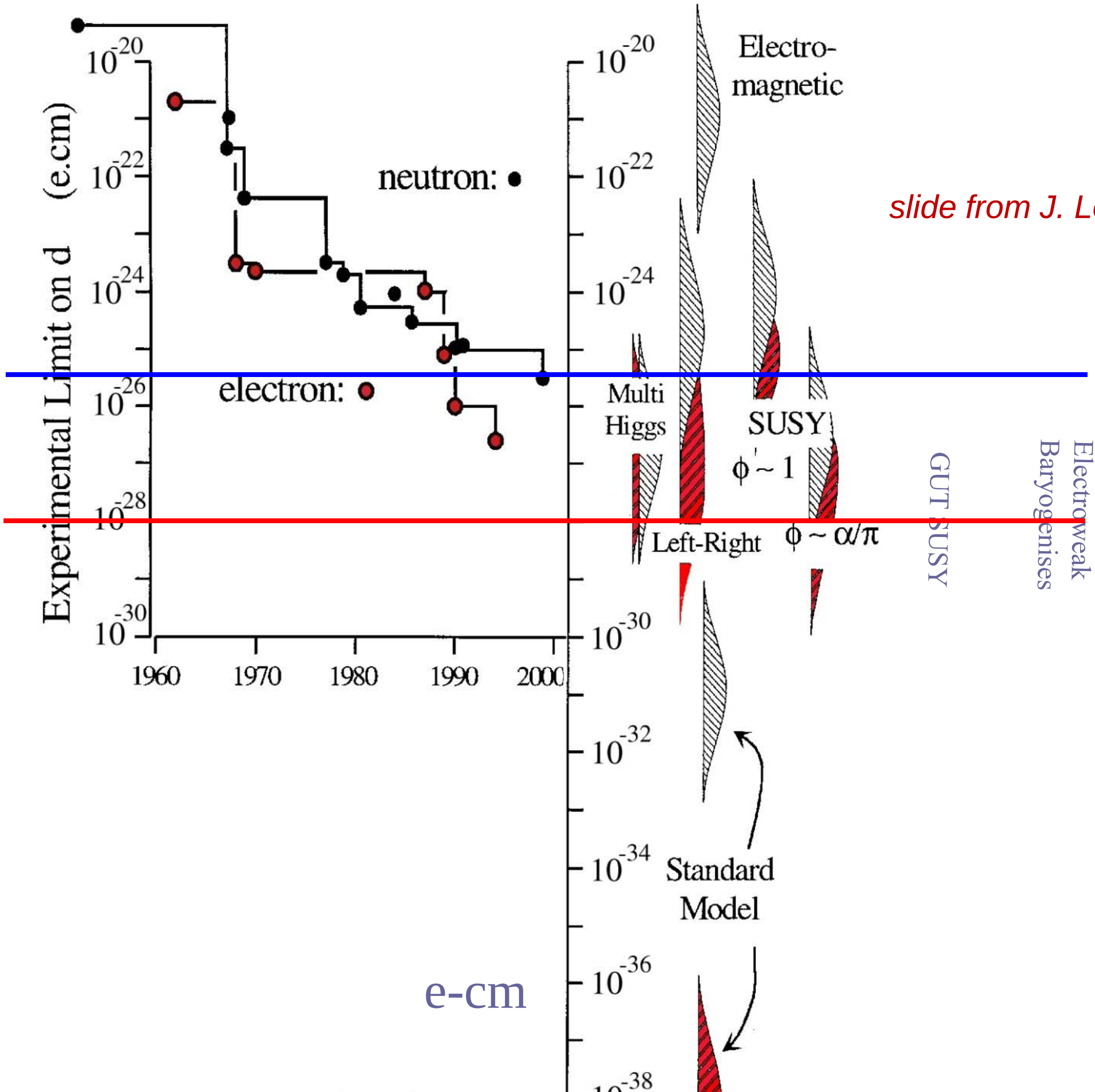
Model Sensitivity to EDM

Gray: Neutron
Red: Electron

slide from J. Long, CIPANP 2009

neutron
current
limit

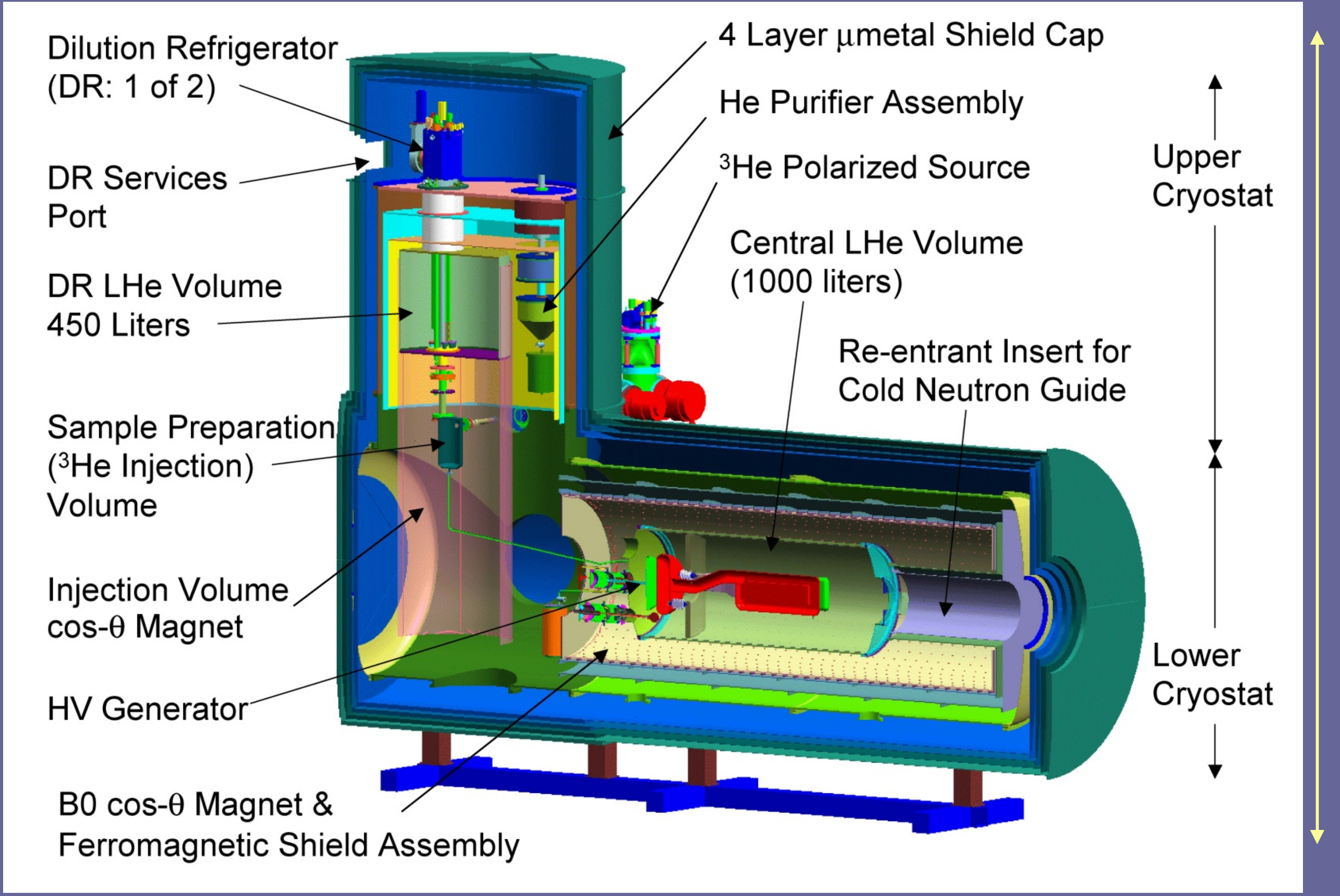
SNS target



J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

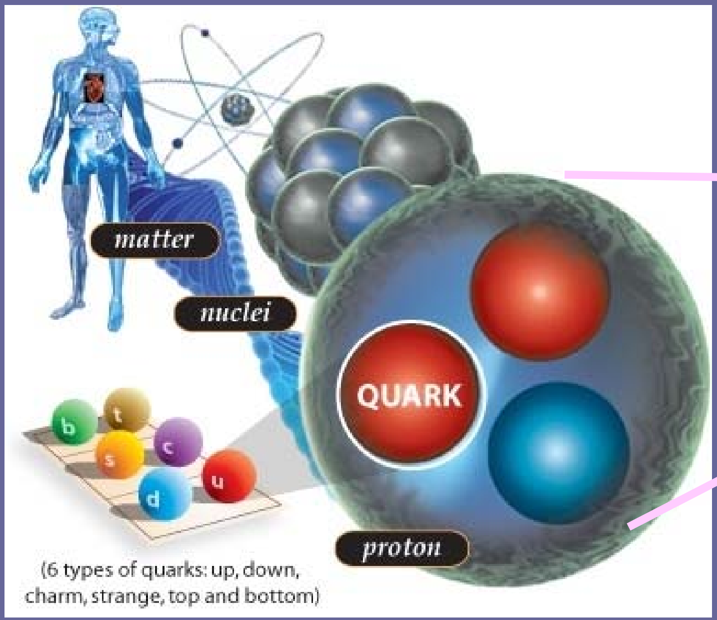
proposed n-EDM experiment at the SNS

slide from J. Long, CIPANP 2009

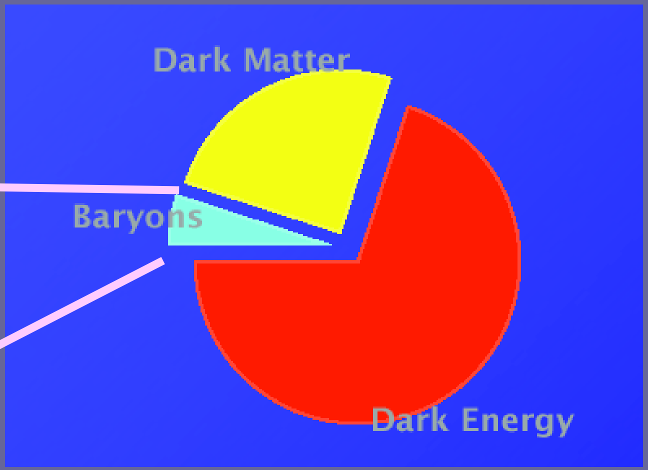


stay tuned → 2016….

Thanks for your attention



picture courtesy of Jefferson Lab



and enjoy the NSCL tour….