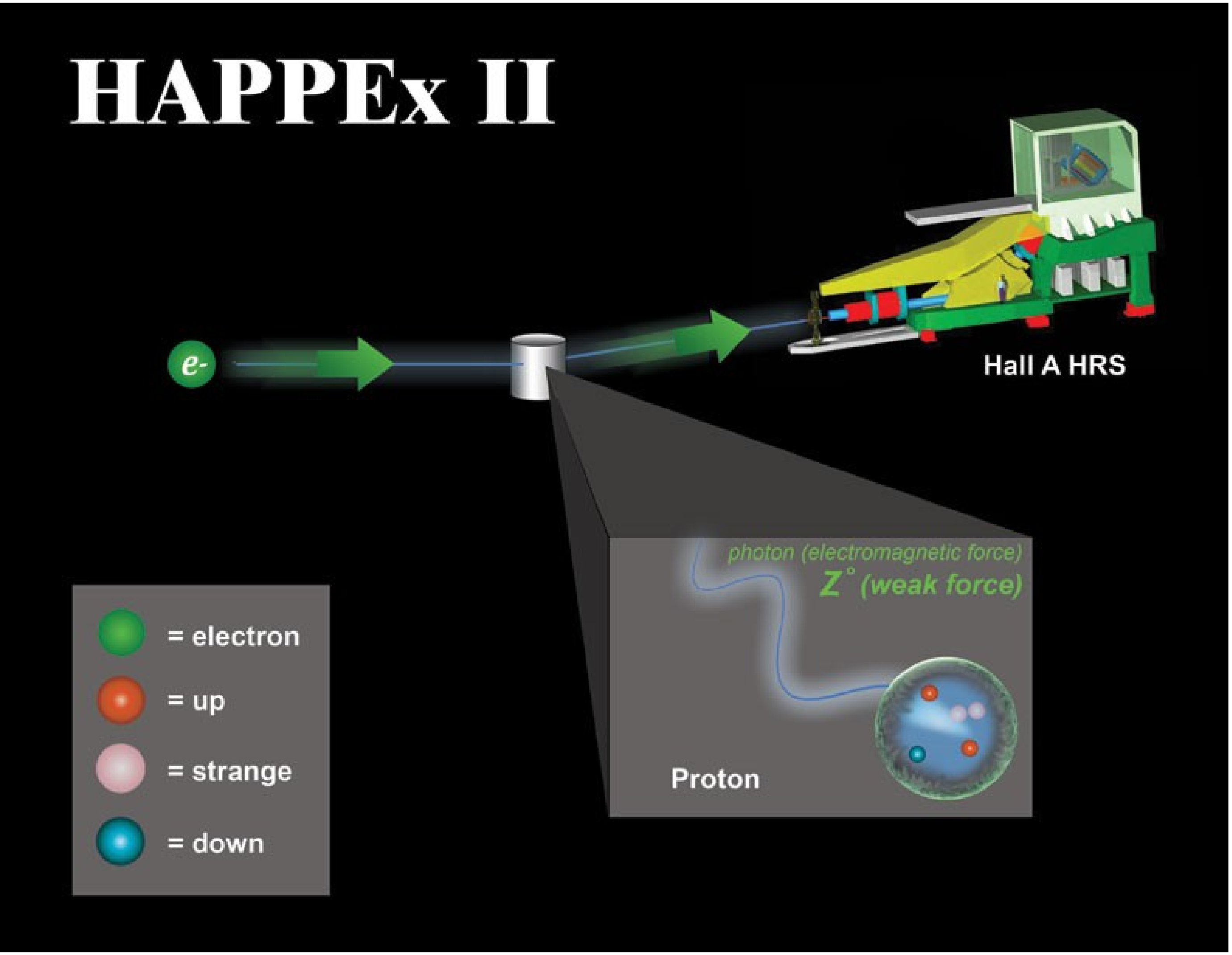
Parity-violating Electron Scattering and Strangeness in the Nucleon: Results from HAPPEX-II

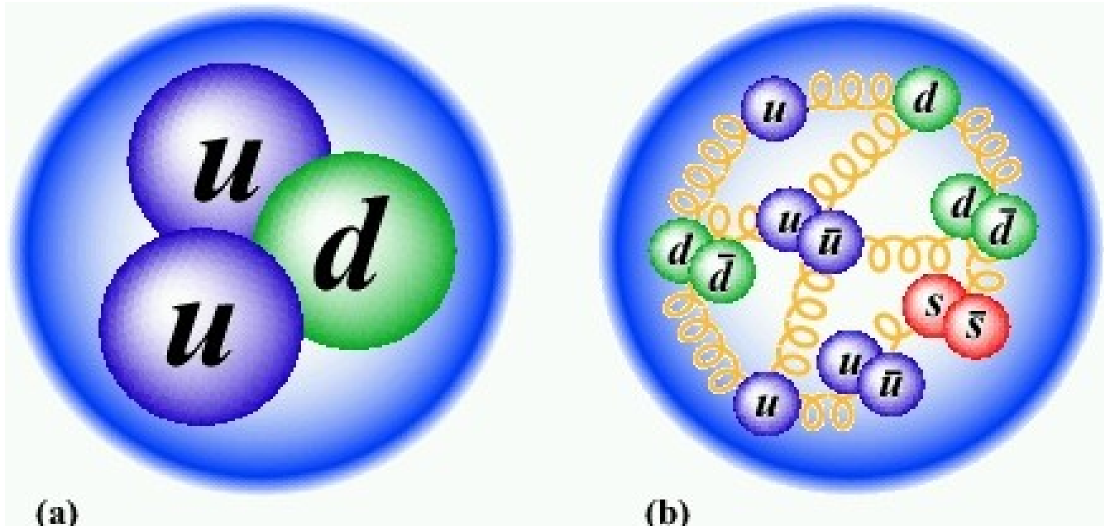


L. J. Kaufman
University of Massachusetts

The HAPPEX Collaboration

Thomas Jefferson National Accelerator Facility – Argonne National Laboratory – CSU, Los Angeles -William and Mary – Duke – DSM/DAPNIA/SPhN CEA Saclay - FIU – Harvard - INFN, Rome - INFN, Bari – IAE, Beijing – IPT Kharkov - Jozef Stefan Institute – Kent State - MIT – NPIRAS, St. Petersburg – ODU – Rutgers - Smith College – Syracuse – Temple – U. Blaise Pascal – U. of Illinois Urbana-Champaign – UMass, Amherst – U. of Kentucky – U. of Virginia – UST, Heifei

Strangeness of the Proton



- Quark Model: proton = *uud*
- QCD : proton = *uud* + “sea”
- Sea = $q\bar{q}$ pairs of *u*, *d*, *s* quarks

Probing strange quarks ⟶ Access only the Sea

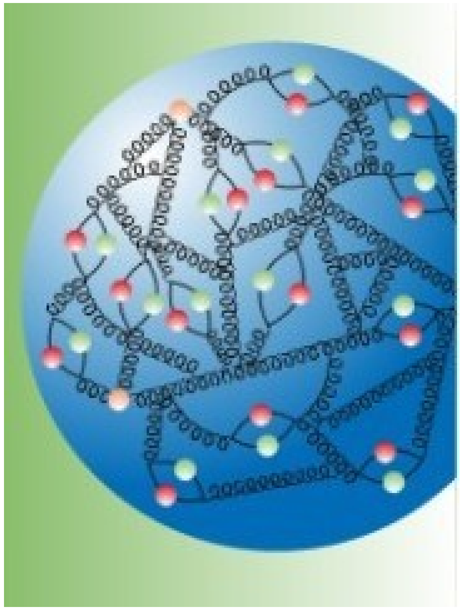
Compares Quark Model to QCD

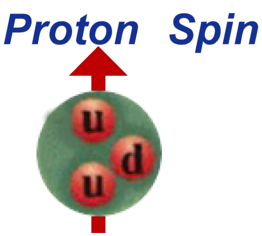
Sea Life

The three "constituent" quarks contribute

- only **1%** of the proton **mass**
- only **30%** of the proton **spin**

The sea provides the rest!





Measurements say that somewhere in the range of

- **0 to 20% of the proton mass**
- **0 to 10% of the proton spin**

may be due to strange quarks.

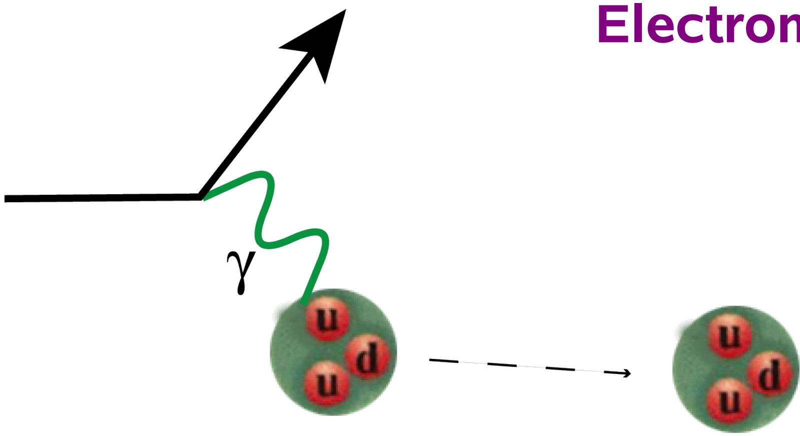
Dominant uncertainty is from messy details in interpreting the data.

At JLab, we can make a VERY CLEAN measurement of the strange quark contributions to the proton's *Charge* and *Magnetization*

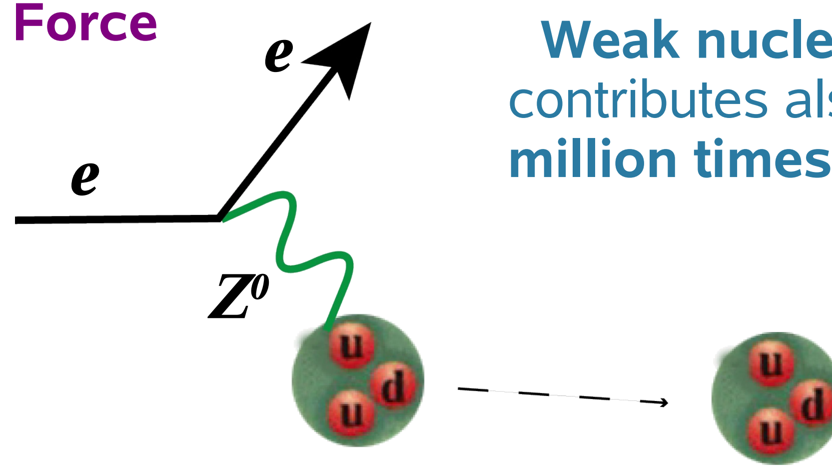
Strange Charge and Magnetism

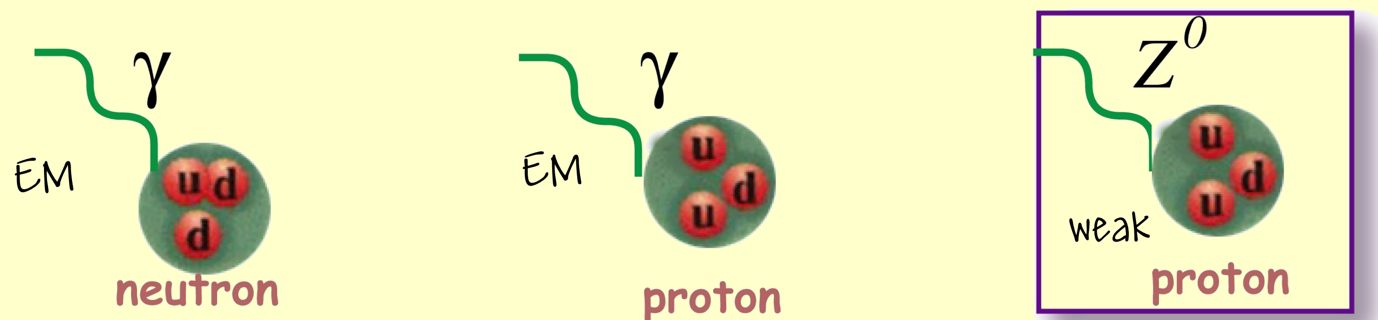
Elastic electron scattering from the nucleus measures *charge* and *magnetization* (average locations and motion of quarks).

Electron-nucleus scattering dominated by the **Electromagnetic Force**



Weak nuclear force contributes also, but a **million times weaker**





Measuring all three enables separation of up, down and strange contributions

Isolating Strange Form Factors

Electromagnetic elastic scattering (3 active quark flavors):

$$G_{E,M}^{p\gamma} = \frac{2}{3}G_{E,M}^{u} - \frac{1}{3}G_{E,M}^{d} - \frac{1}{3}G_{E,M}^{s}$$

Charge Symmetry: $p \leftrightarrow n$, $u \leftrightarrow d$, $s \leftrightarrow s$

$$G_{E,M}^{n\gamma} = \frac{2}{3}G_{E,M}^{d} - \frac{1}{3}G_{E,M}^{u} - \frac{1}{3}G_{E,M}^{s}$$

Need a third linear independent relationship between quark form factors $\Longrightarrow$ Weak neutral current

$$G_{E,M}^{pZ} = (\frac{1}{4} - \frac{2}{3}\sin^2\theta_W)G_{E,M}^{u} - (\frac{1}{4} + \frac{1}{3}\sin^2\theta_W)(G_{E,M}^{d} + G_{E,M}^{s})$$

Parity-Violating Electron Scattering

For a proton:

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{A_E + A_M + A_A}{\sigma_p}$$

~ few parts per million

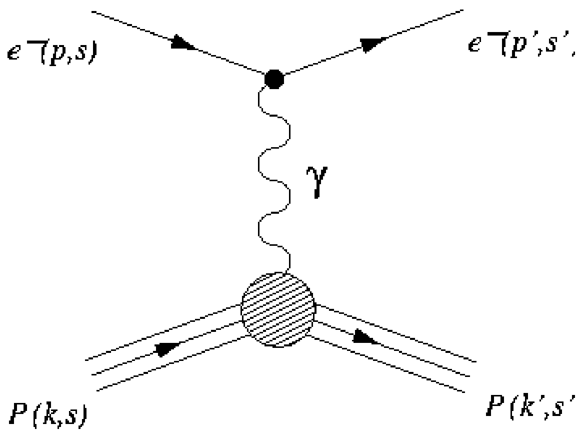
$$A_E = \varepsilon\, G_E^p G_E^Z, \qquad A_M = \tau\, G_M^p G_M^Z, \qquad A_A = -\left(1 - 4\sin^2\theta_W\right)\varepsilon'\, G_M^p G_A^e$$

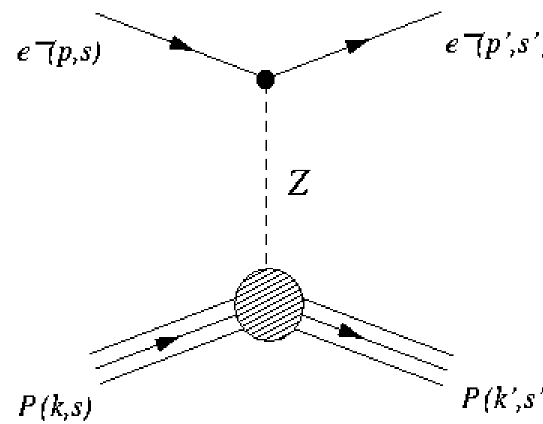
Forward angle — Backward angle

For ^{4}He: G_E^s alone

$$A^{PV} = -\frac{A_0}{2}\left(2\sin^2\theta_W + \frac{G_E^s}{G_E^{p\gamma} + G_E^{n\gamma}}\right)$$

PV Electron Scattering to Measure Weak NC Amplitudes

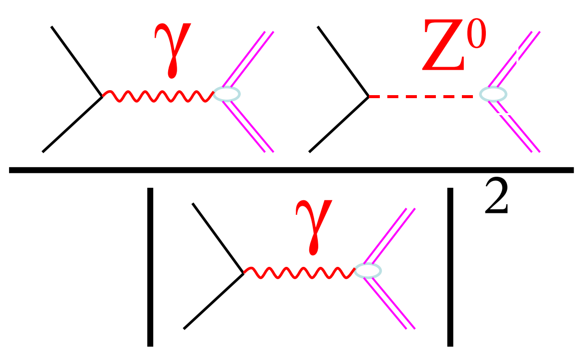




$$\sigma = \left|\mathcal{M}^{\gamma} + \mathcal{M}^{Z}\right|^2$$

Interference with EM amplitude makes NC amplitude accessible

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$



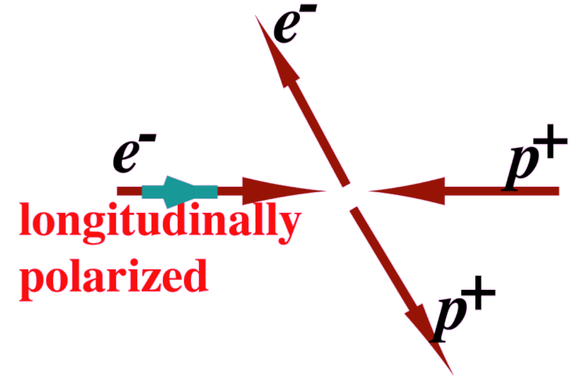
$$\sim \frac{\mathcal{M}^{Z}}{\mathcal{M}^{\gamma}} \sim \frac{Q^2}{(M_Z)^2}$$

Experimental Mirror

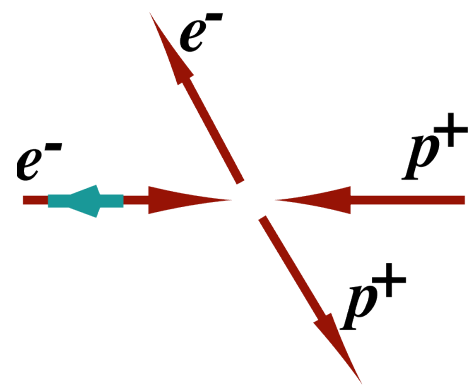
How to measure the weak scattering probability?

- ***Exploit a peculiar property of the weak force: it does not obey mirror ("parity") symmetry***

Flipping beam polarization creates mirror-symmetric configurations.



Compare scattering rate between mirror-symmetric configurations. Any difference is due to the Weak Force!



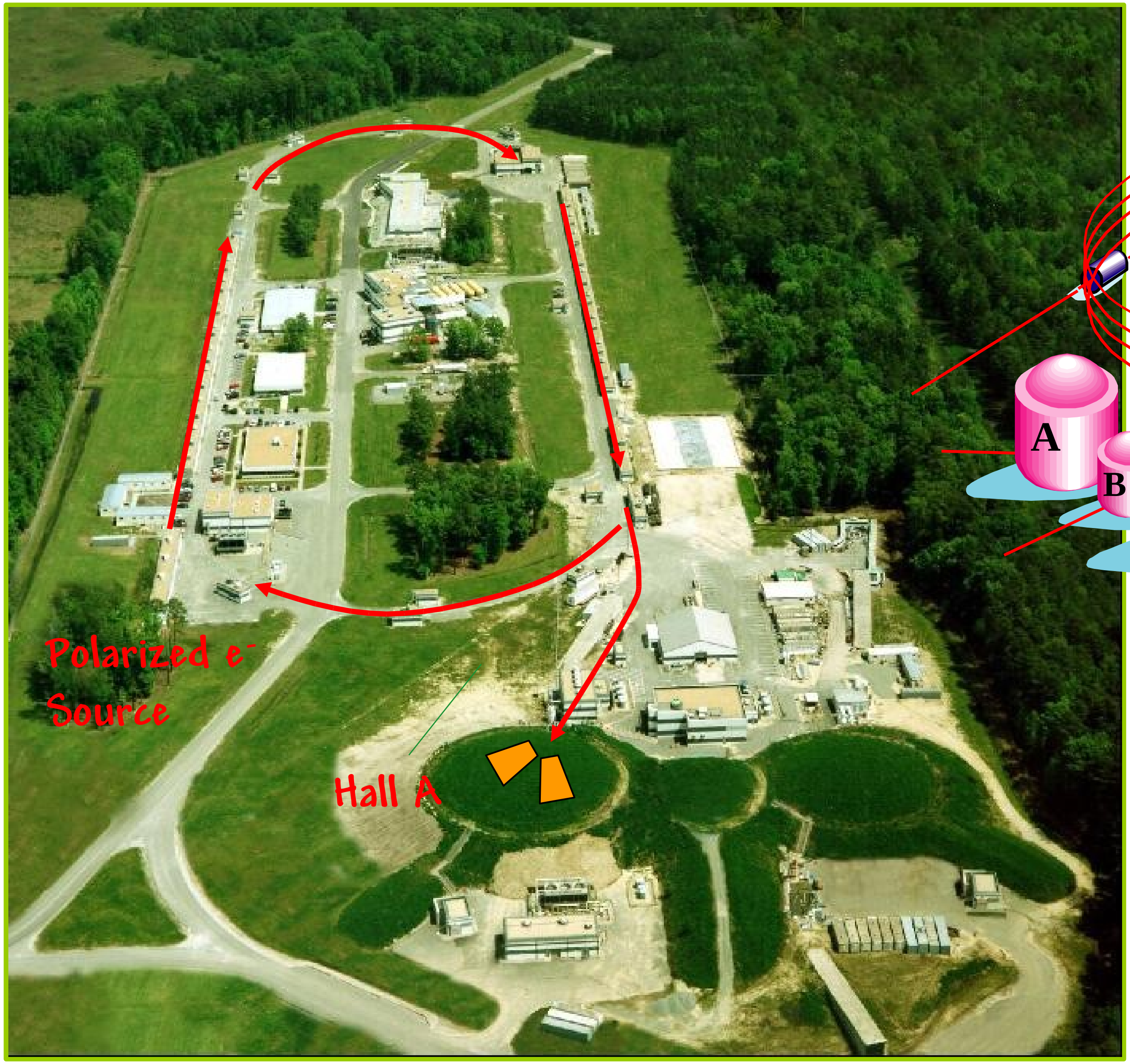
The difference is only 1 part in a million

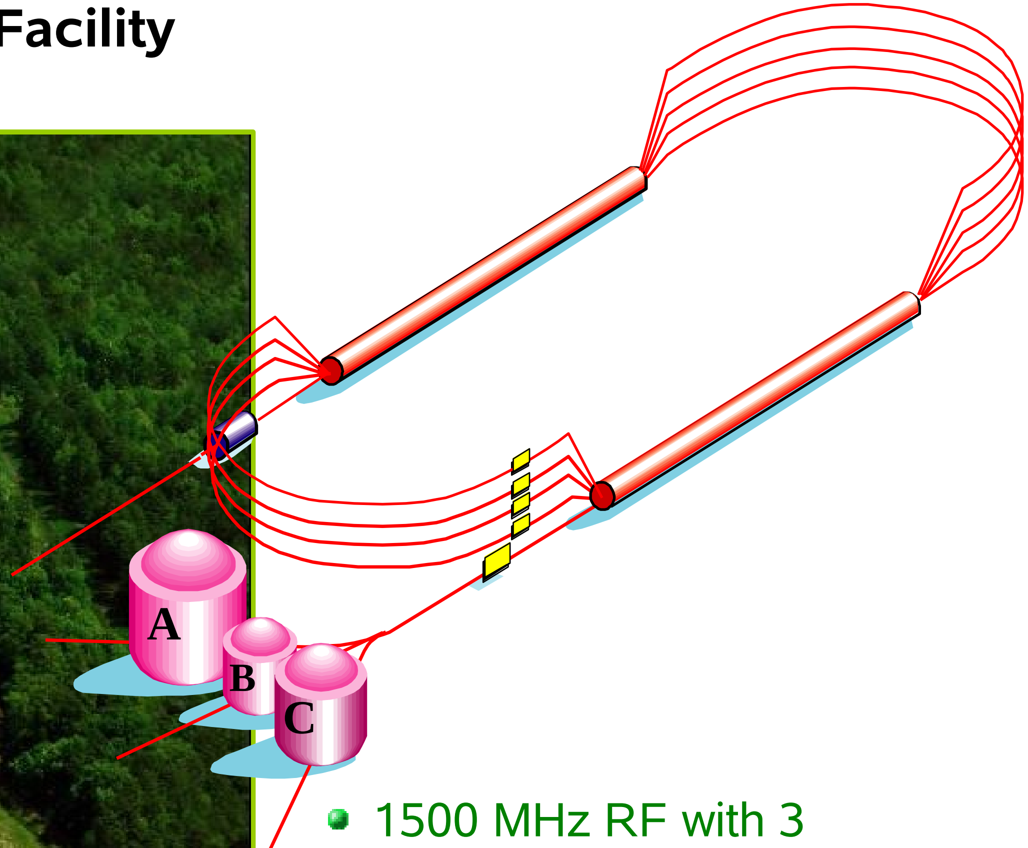
How do you measure such a small number with precision?
Flip polarization 30 times a second,
measure the asymmetry each time with 0.05% precision…
and do this mini-experiment 25 million times!

Jefferson Laboratory

CEBAF

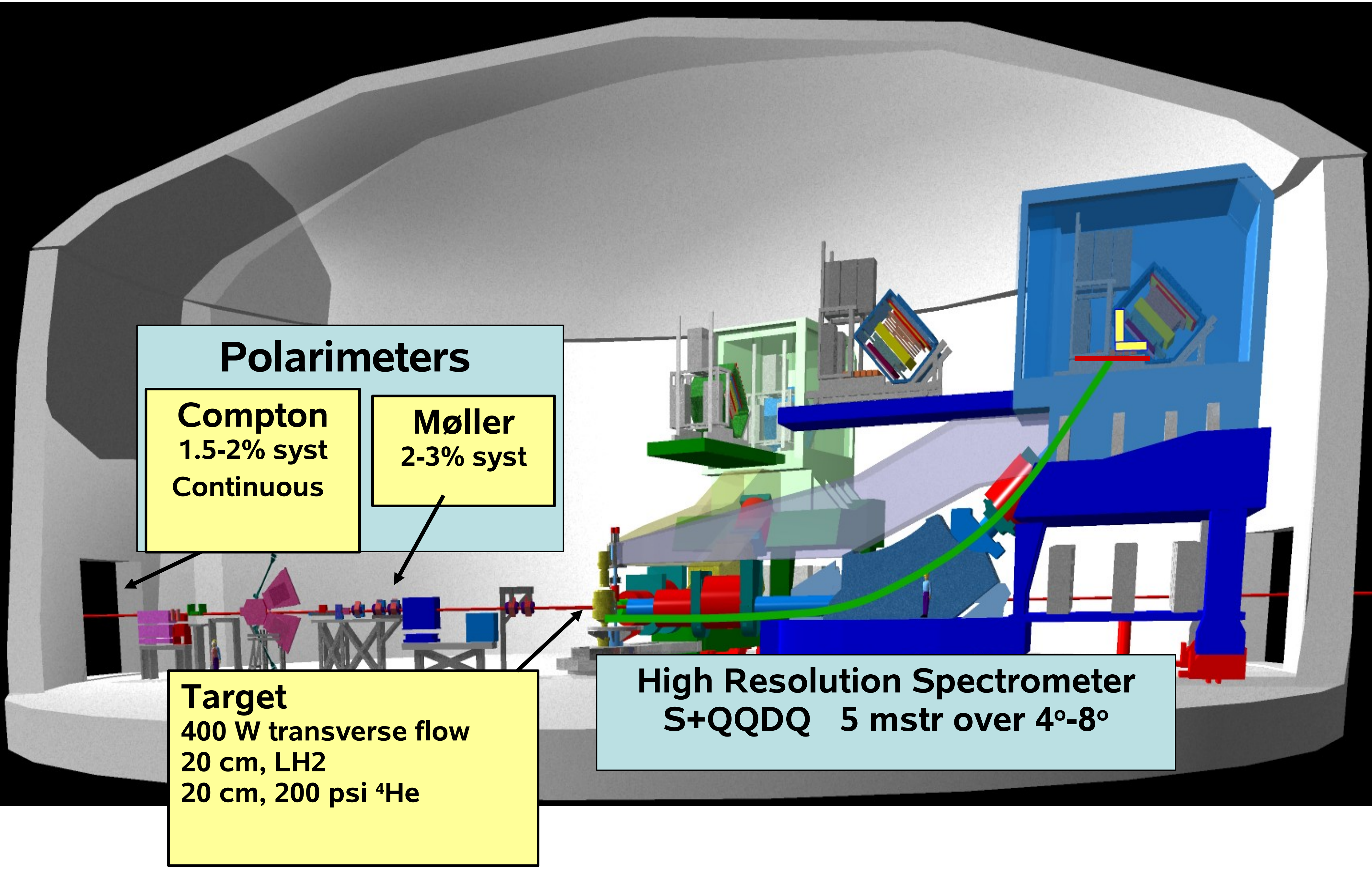
Continuous Electron Beam Accelerator Facility





- 1500 MHz RF with 3 interleaved 500 MHz beams
- Independent extraction to 3 experimental halls
- High current and polarization

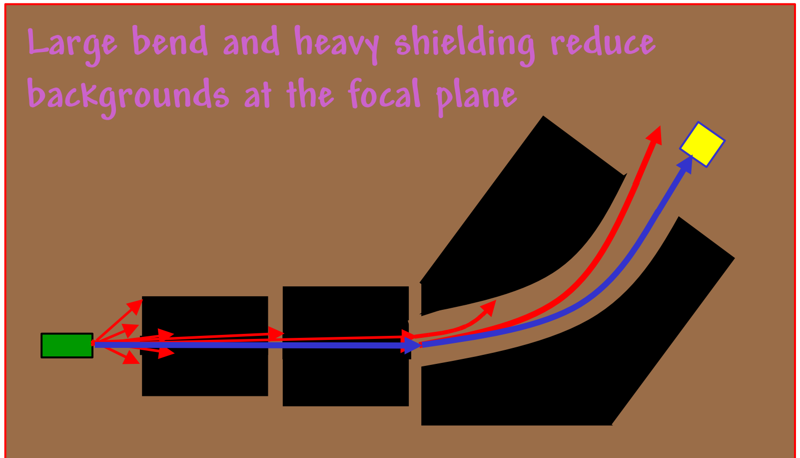
Hall A

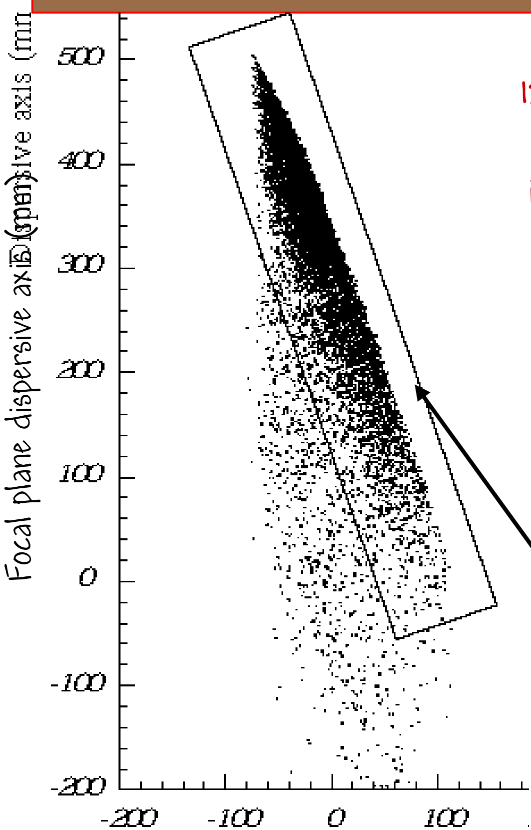


Polarimeters
Compton
1.5-2% syst
Continuous
Møller
2-3% syst
Target
400 W transverse flow
20 cm, LH2
20 cm, 200 psi 4He
High Resolution Spectrometer
S+QQDQ 5 mstr over 4o-8o

Spectrometer and Detector

Very clean separation of elastic events by HRS optics





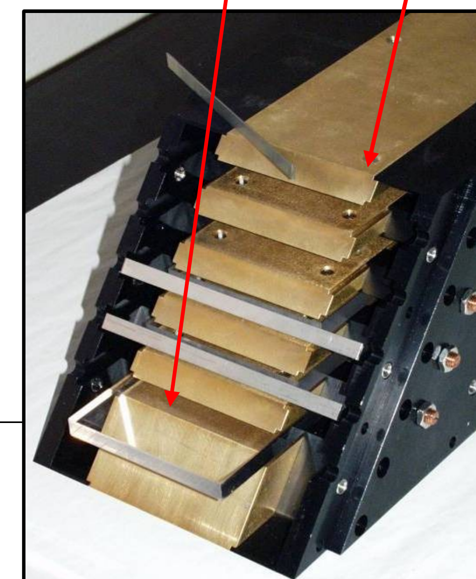
12 m dispersion
sweeps away
inelastic events

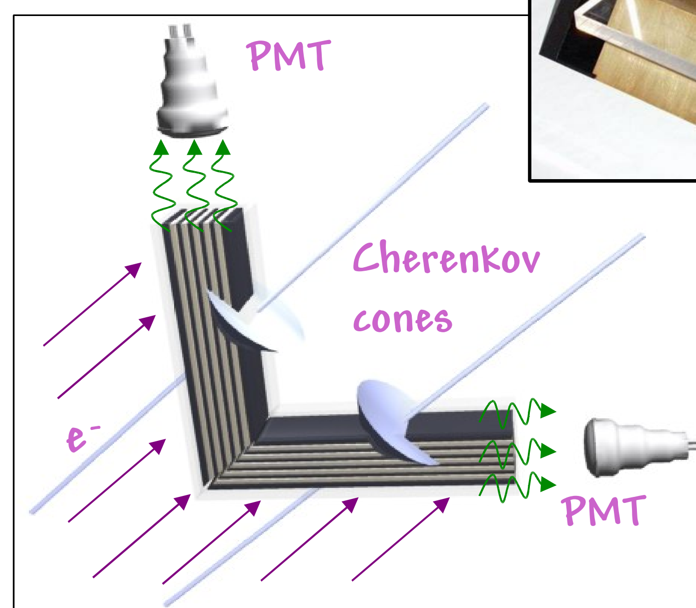
Overlap the elastic line and integrate the flux

Integrating Cerenkov Shower Calorimeter

- Electromagnetic shower through brass radiator
- Cerenkov light from shower in quartz layers
- **Analog integration** of PMT signal

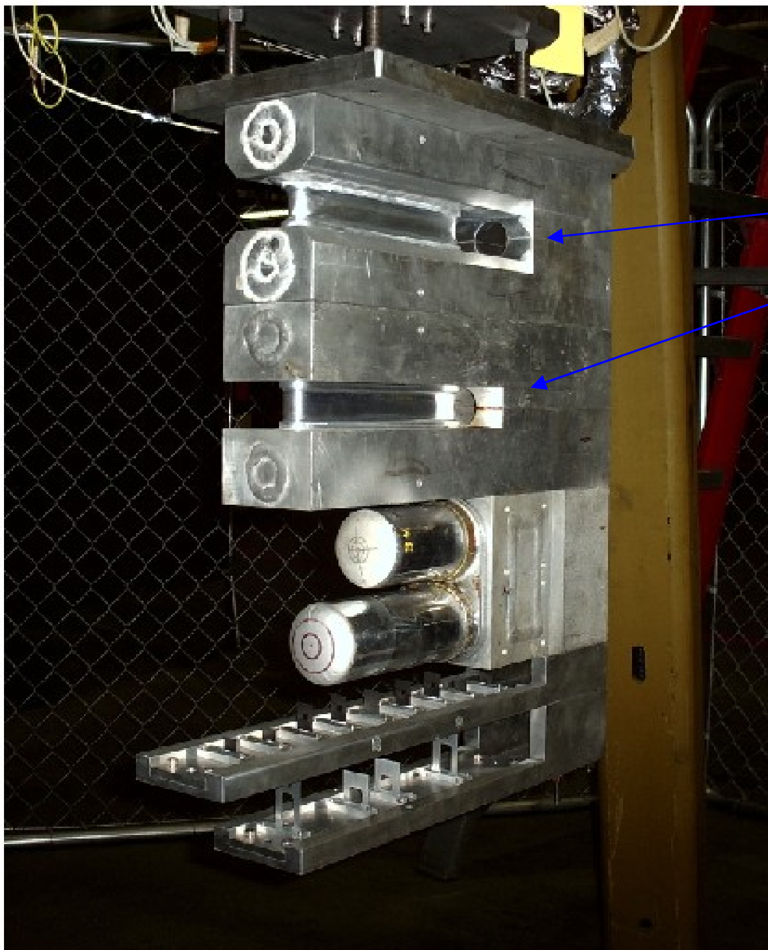
- Insensitive to background
- Directional sensitivity
- High-resolution
- Rad hard

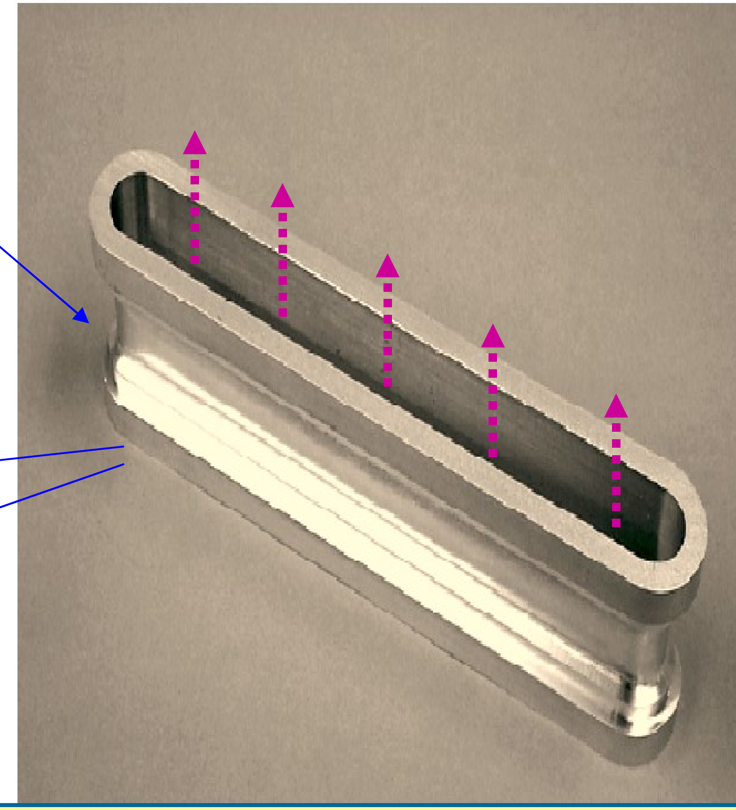




High-Power Cryogenic Target

New "race track" design – 20 cm (transverse cryogen flow)





20 cm 1.8% R.L. LH_2

20 cm 2.2% R.L. ^{4}He gas cell

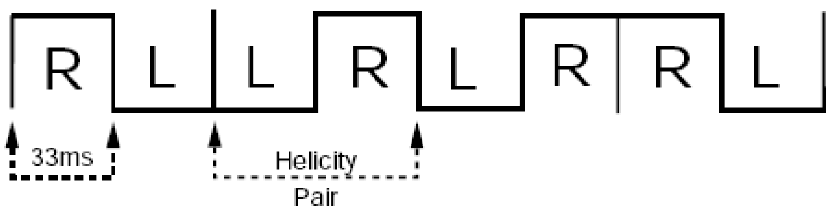
- Cold (6.6K), dense (230 psi)

Al wall thickness

- 4 mils (H)
- 10 mils (He)

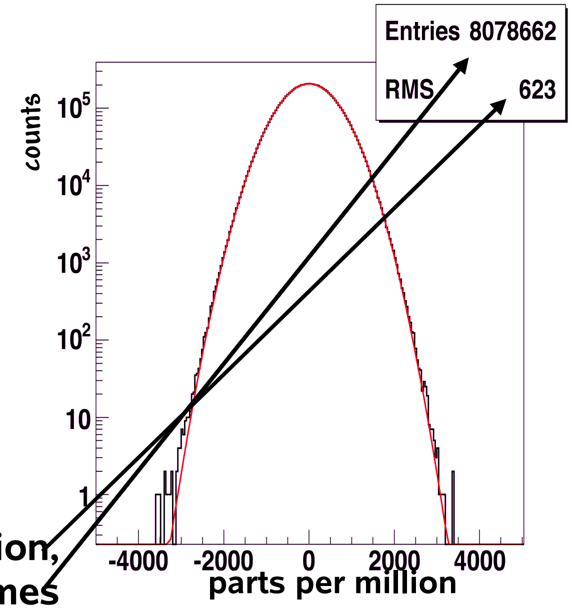
Measuring A_{PV}

- **Beam helicity is chosen pseudo-randomly at 30 Hz**
  - Helicity state, followed by its complement
  - Data analyzed as "pulse-pairs"



$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

calculated at 15Hz



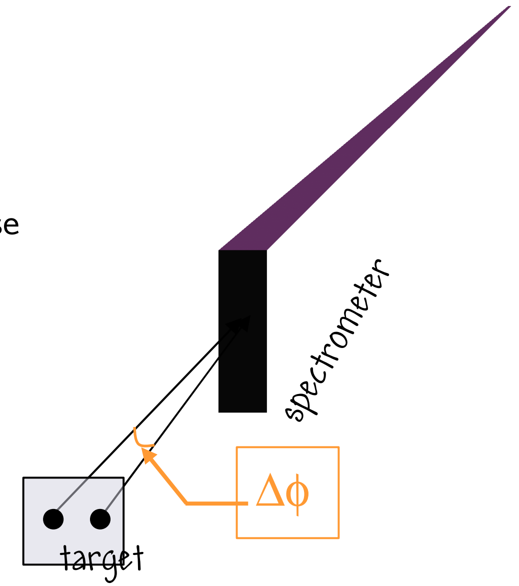
Measure the asymmetry with 0.06% precision, millions of times

Beam must look the same for the two helicity states!

- More beam = more signal: so intensity change -> A_{false}
- Cross-section vs angle is very steep: position change -> A_{false}

Corrections are made using measured sensitivities.

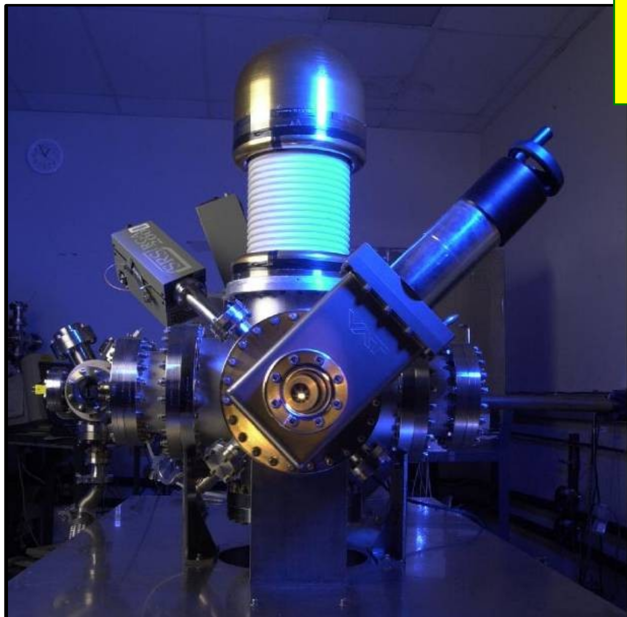
$$A_{cor} = A_{det} - A_Q + \sum_{i=1}^{5} \beta_i \Delta x_i$$

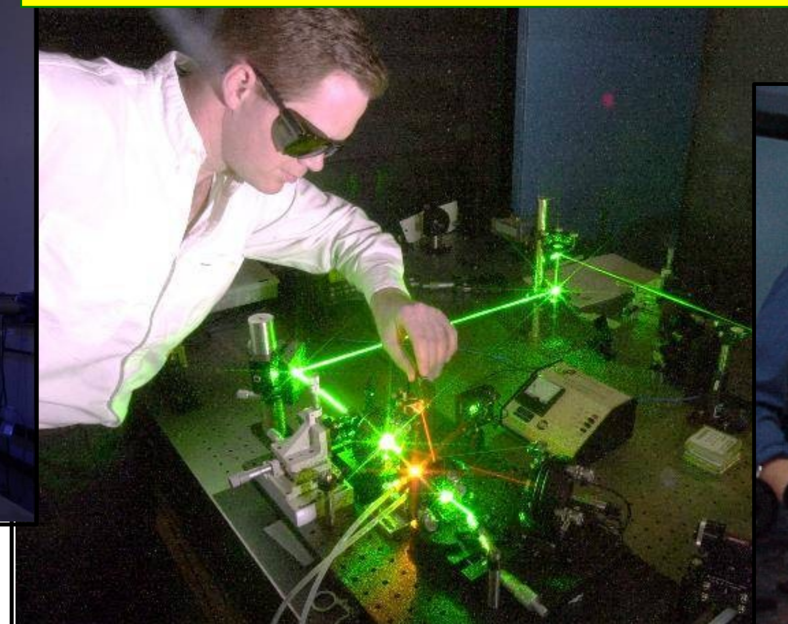


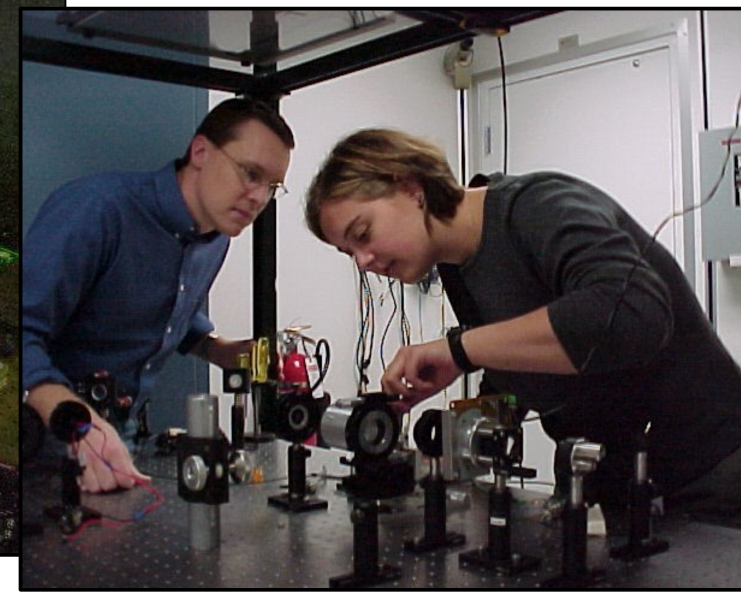
Major effort was applied to reducing beam asymmetries at the polarized source

Beam must look the same for the two polarization states!

Close Collaboration with the Electron Gun Group to reduce differences at the polarized source!







Also, major work on by Center for Advanced Studies of Accelerators (CASA) on beam transport to avoid amplifying beam asymmetry.

Result: Average position the same to ~1 nanometer
for hydrogen measurement

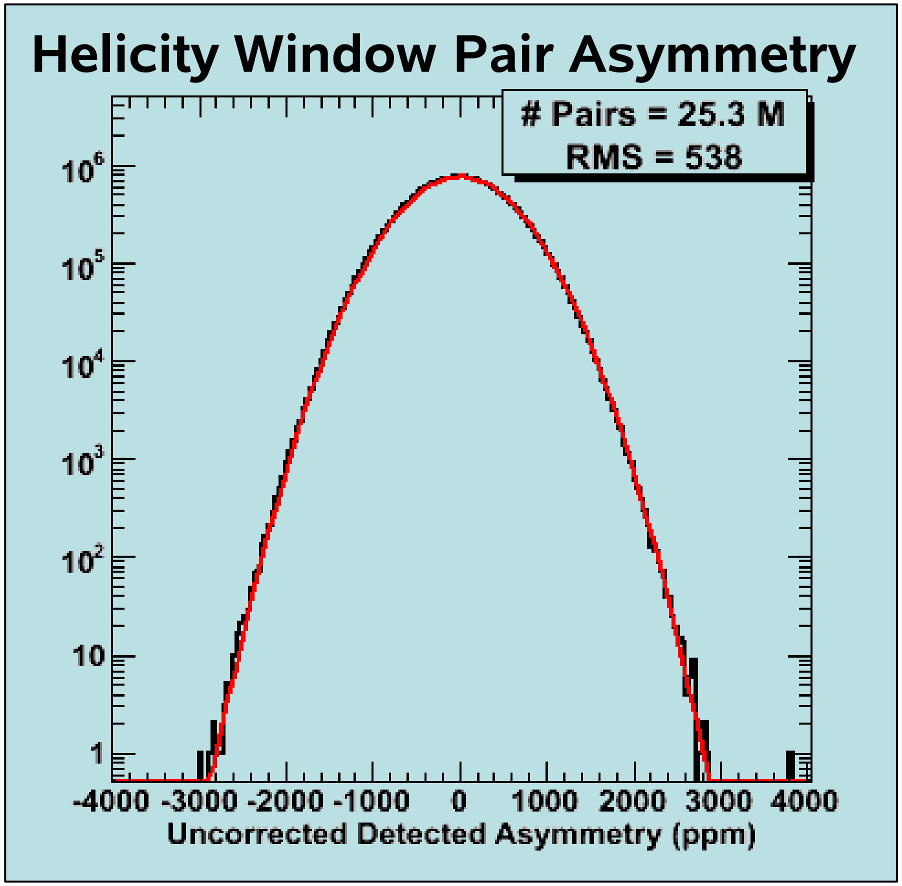
Major achievement from close collaboration between nuclear and accelerator scientists

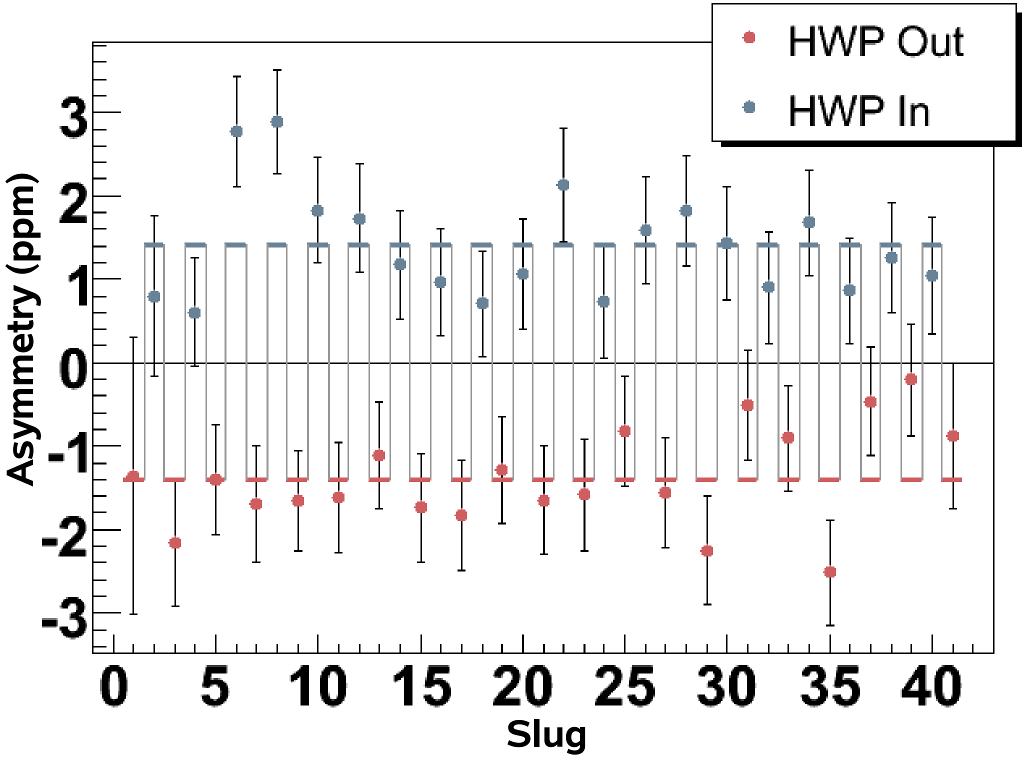
^{1}H Preliminary Results

Raw Parity Violating Asymmetry

~25 M pairs, width ~540 ppm

A_{raw} correction ~11 ppb





$Q^2 = 0.1089 \pm 0.0011 \text{GeV}^2$

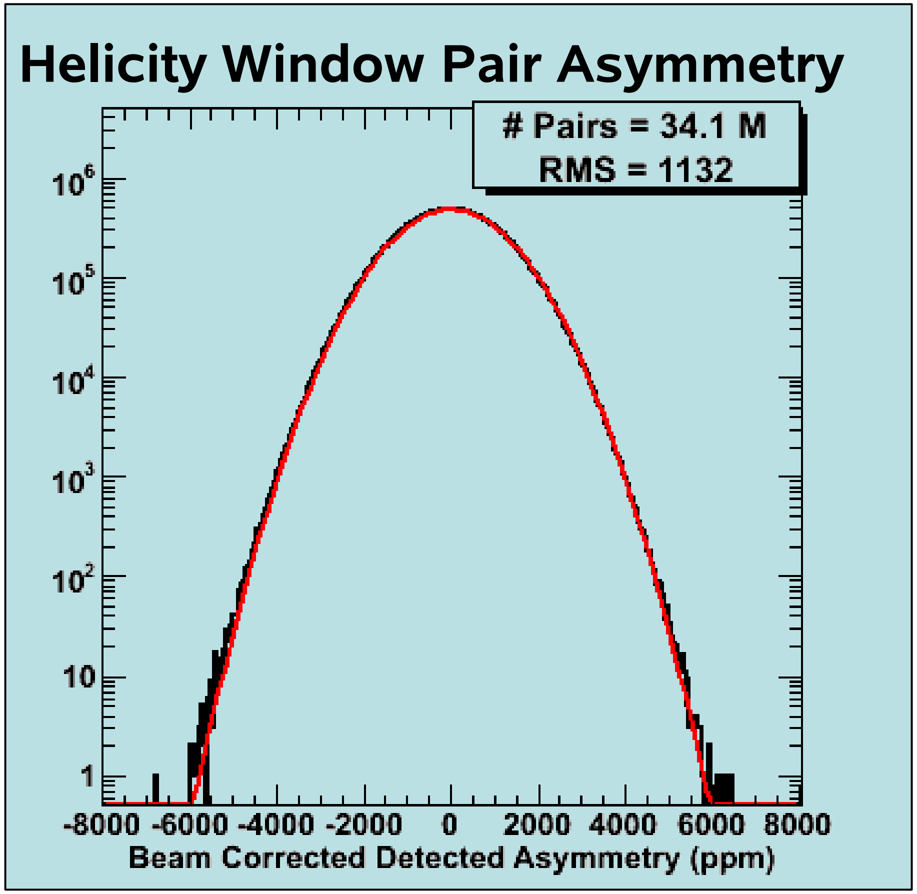
$A_{raw} = -1.418$ ppm $\pm$ 0.105 ppm (stat)

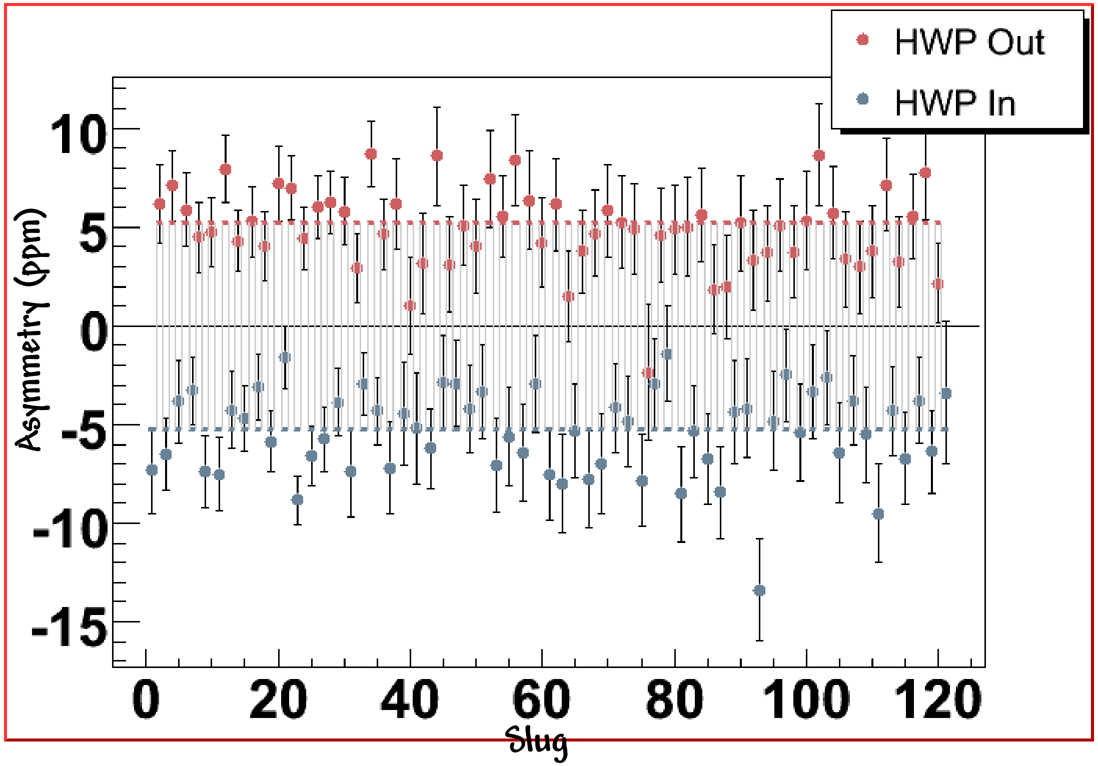
^{4}He Preliminary Results

Raw Parity Violating Asymmetry

35 M pairs, total width ~1130 ppm

A_{raw} correction ~ 0.12 ppm





$Q^2 = 0.07725 \pm 0.0007\ \mathrm{GeV}^2$

$A_{raw} = 5.253$ ppm $\pm$ 0.191 ppm (stat)

HAPPEX-II 2005 Preliminary Results

HAPPEX-^{4}He:

$Q^2 = 0.0772 \pm 0.0007\ (\mathrm{GeV}/c)^2$

$A_{PV} = +6.43 \pm 0.23\ (\mathrm{stat}) \pm 0.22\ (\mathrm{syst})\ \mathrm{ppm}$

$A(G^s=0) = +6.37\ \mathrm{ppm}$

$G^s_E = 0.004 \pm 0.014_{(\mathrm{stat})} \pm 0.013_{(\mathrm{syst})}$

HAPPEX-H:

$Q^2 = 0.1089 \pm 0.0011\ (\mathrm{GeV}/c)^2$

$A_{PV} = -1.60 \pm 0.12\ (\mathrm{stat}) \pm 0.05\ (\mathrm{syst})\ \mathrm{ppm}$

$A(G^s=0) = -1.640\ \mathrm{ppm} \pm 0.041\ \mathrm{ppm}$

$G^s_E + 0.088\ G^s_M = 0.004 \pm 0.011_{(\mathrm{stat})} \pm 0.005_{(\mathrm{syst})} \pm 0.004_{(\mathrm{FF})}$

HAPPEX-II 2005

Hydrogen

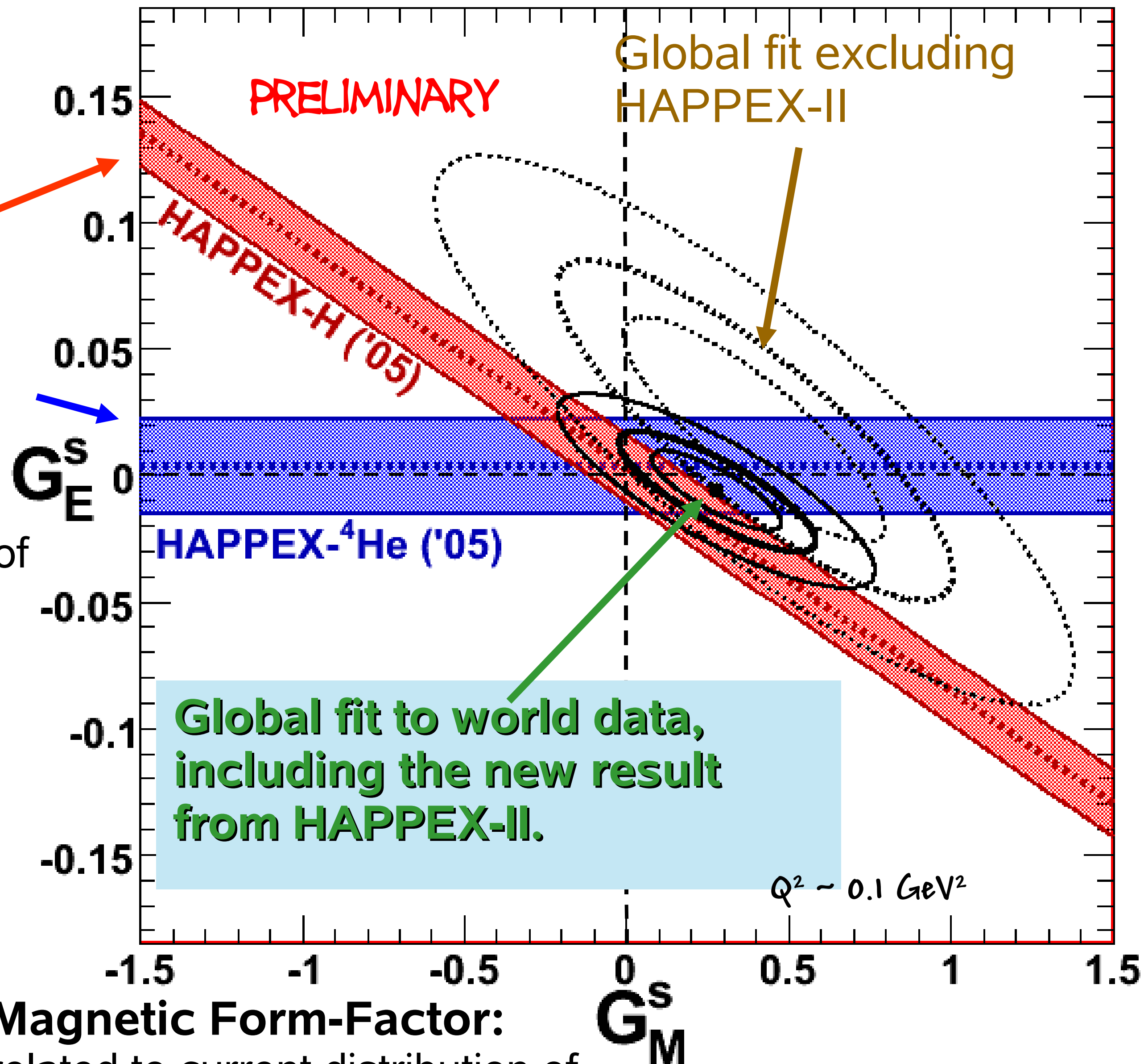
(electric + magnetic)

Helium-4

(electric contribution only)

Electric Form-Factor:

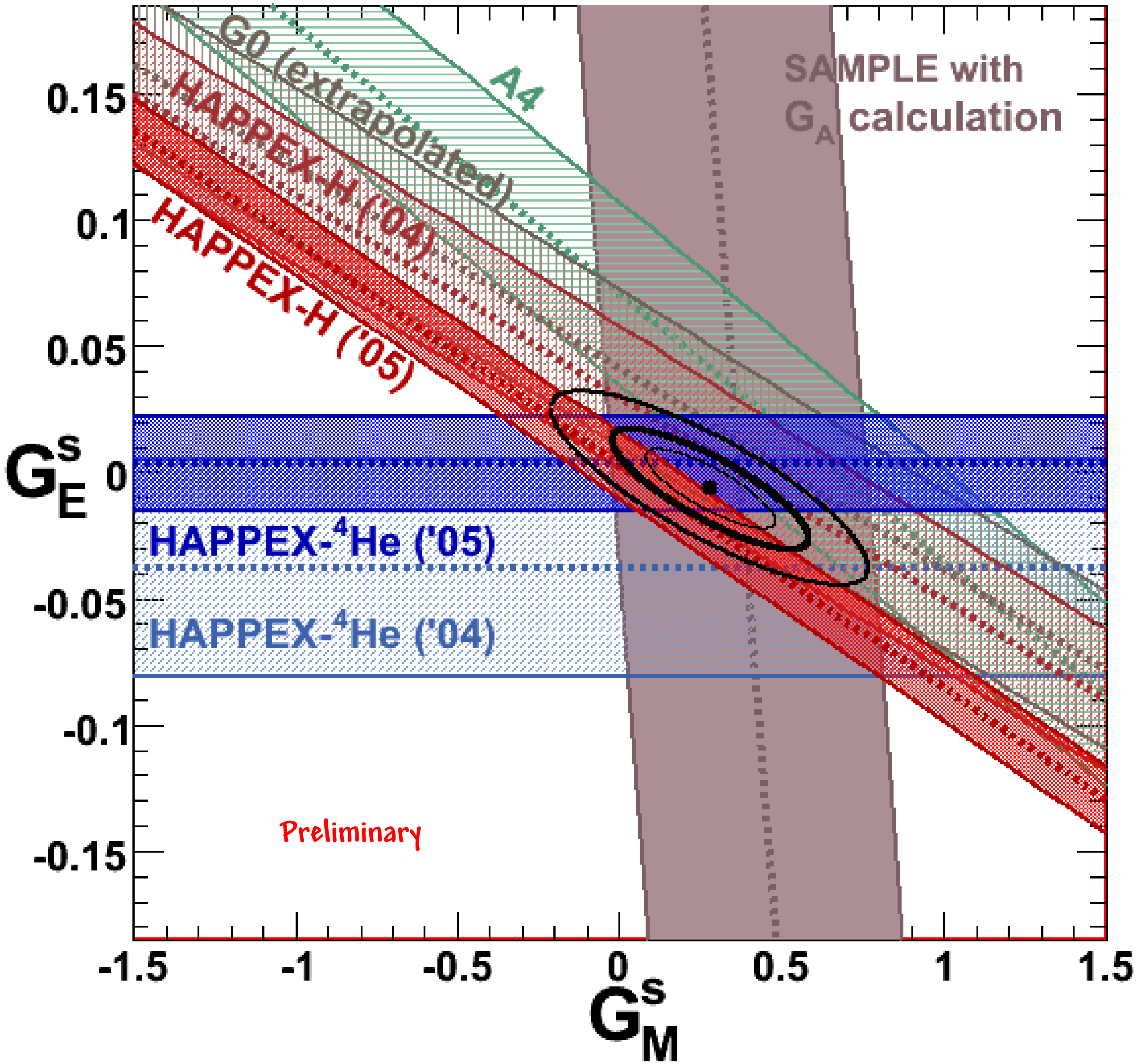
related to charge distribution of strangeness



Magnetic Form-Factor:

related to current distribution of strangeness

World Data near Q^2 ~0.1 GeV^2



G_M^s = 0.28 +/- 0.20

G_E^s = -0.006 +/- 0.016

~3% +/- 2.3% of proton magnetic moment

~0.2 +/- 0.5% of Electric distribution

HAPPEX-only fit suggests something even smaller:

G_M^s = 0.12 +/- 0.24

G_E^s = -0.002 +/- 0.017

Caution: the combined fit is approximate. Correlated errors and assumptions not taken into account

High precision of HAPPEX-II places very tight bounds on strange contributions

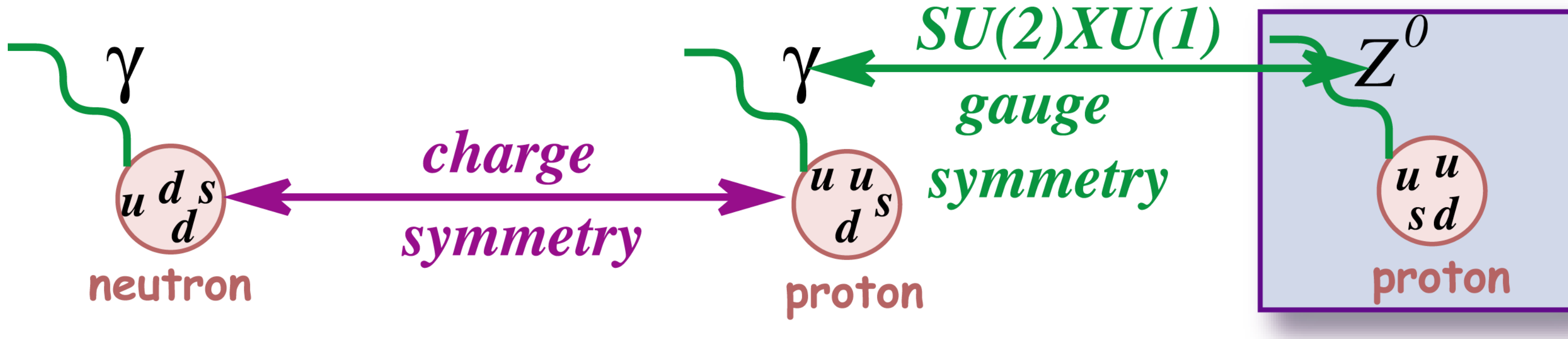
<1% of proton charge density
<5% of proton magnetic density

The strange quarks are in there… but all measurements of static properties (mass, charge, spin, etc…) are consistent with **zero!**

There is no known fundamental reason why this should be!

Is there an unknown symmetry of the Strong Force that requires this contribution to be small?

Can We Measure the Contribution of Strange Quarks to Form Factors?



$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$