Electroweak Physics

Lecture IV:

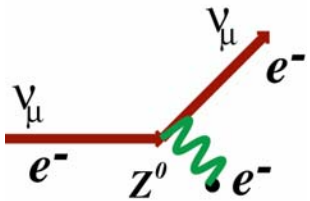
Weak Neutral Current Interactions (cont'd)

Review

- Progress beyond low energy electroweak theory requires:
  - Exploring the 1 TeV frontier
  - Exploring rare processes at lower energy
- Weak Neutral Current experiments play a central role in testing the electroweak theory
- SLAC E158 is the most sensitive test to date: what can we do next?
- Lower energy implies understanding of atoms, nuclei and nucleons

Future Possibilities (Leptonic)

SLAC E158



ν-e in reactor

- ***Parasitic to a neutrino oscillation search***
- ***can test neutrino coupling: $\sin^2\theta_W$ to ± 0.002***

Møller at 11 GeV at Jlab

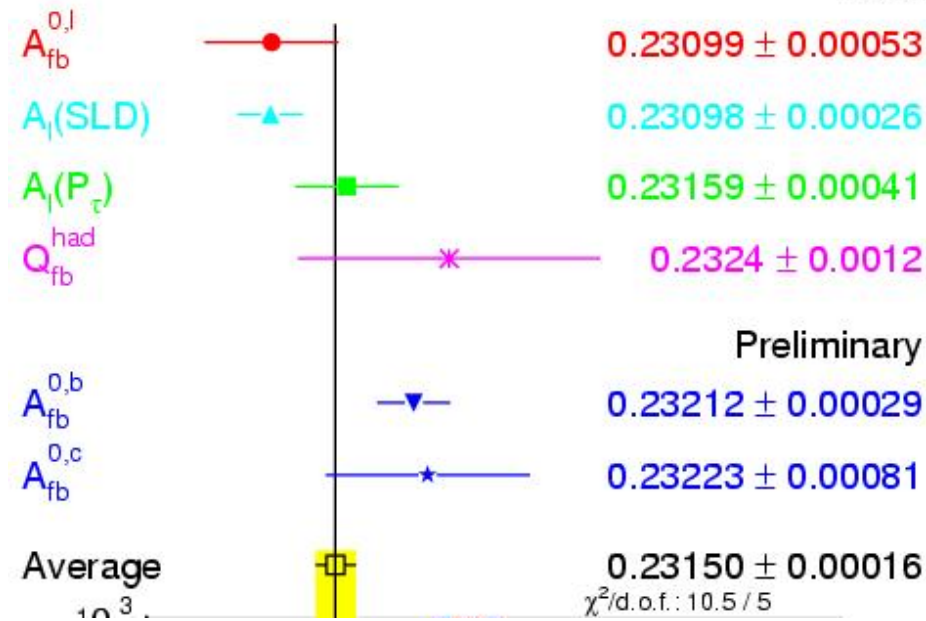
Higher luminosity and acceptance

$\sin^2\theta_W$ to ± 0.00025!

Λ_{ee} ~ 25 TeV reach!

Longstanding discrepancy between hadronic and leptonic Z asymmetries:

Z pole asymmetries



Design for 12 GeV

E': 3-6 GeV

θ_{lab} = 0.53°-0.92°

A_{PV} = 40 ppb

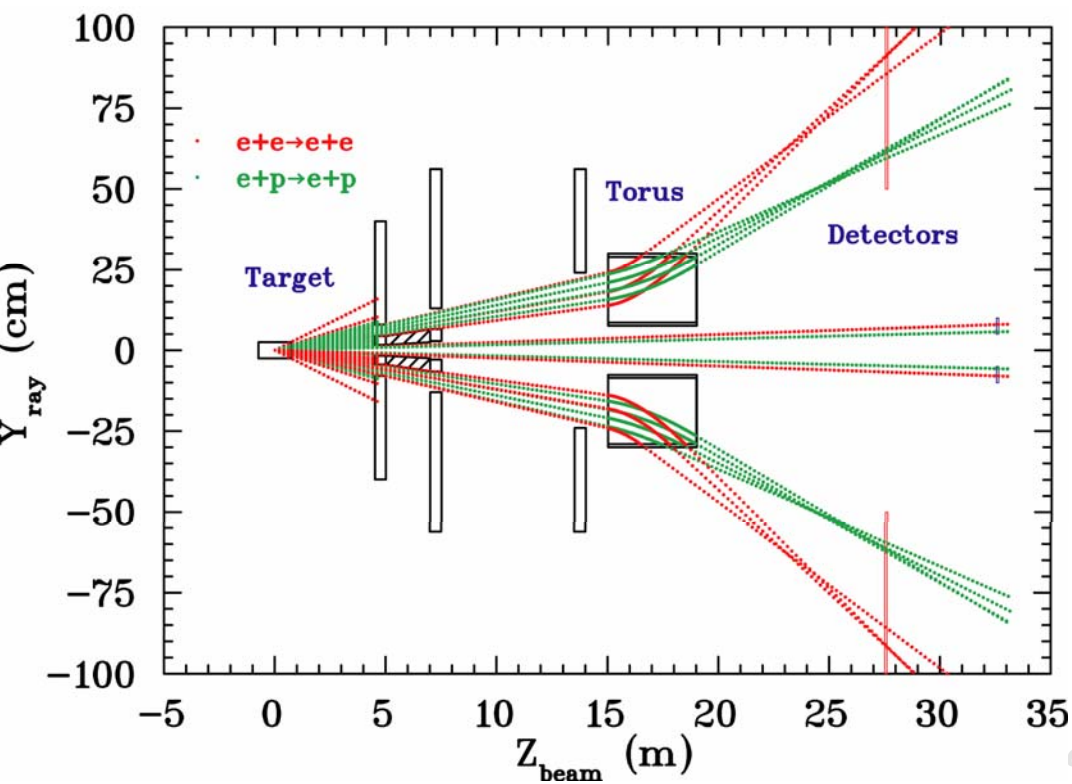
I_{beam} = 90 μA

150 cm LH_2 target

4000 hours

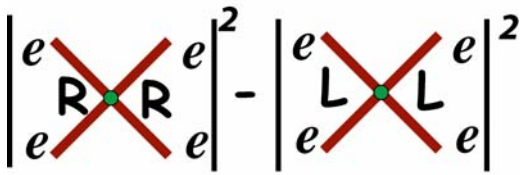
Toroidal spectrometer → ***ring focus***

$\delta(A_{PV})$=0.58 ppb



- *Beam systematics: steady progress (E158 Run III: 3 ppb)*
- *Focus alleviates backgrounds: $ep \rightarrow ep(\gamma)$, $ep \rightarrow eX(\gamma)$*
- *Radiation-hard integrating detector*
- *Normalization requirements similar to other planned experiments*
- *Cryogenics, density fluctuations and electronics will push the state-of-the-art*

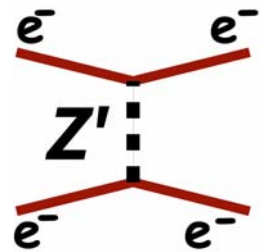
New Physics Reach

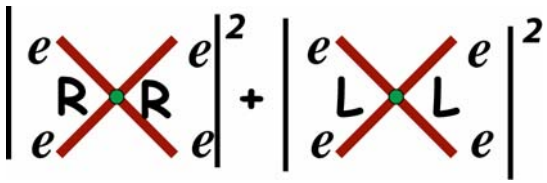


JLab Møller

$\Lambda_{ee} \sim 25$ TeV

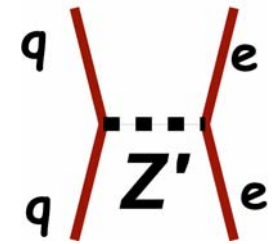
New Contact Interactions





LEP200

$\Lambda_{ee} \sim 15$ TeV



LHC

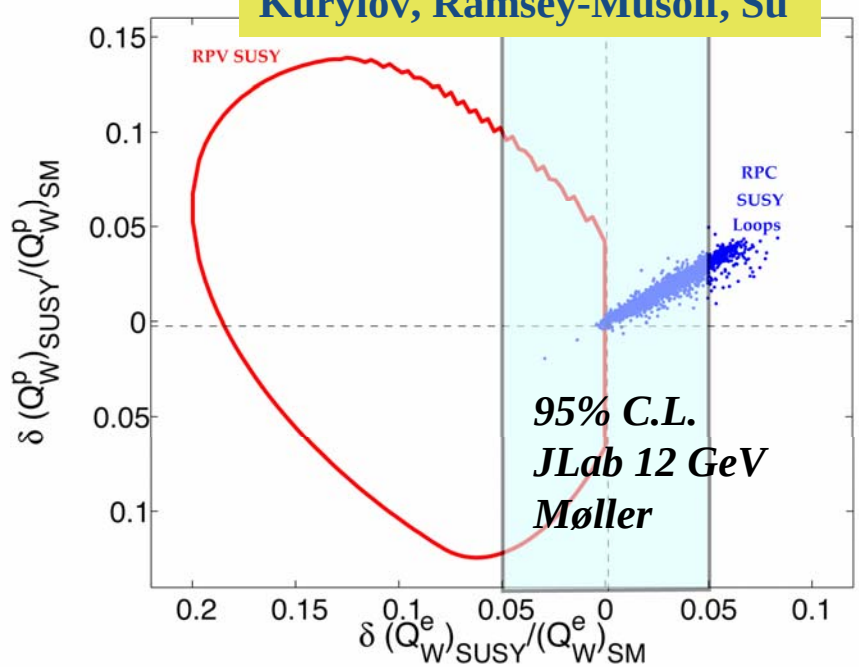
Complementary; 1-2 TeV reach

Does Supersymmetry (SUSY) provide a candidate for dark matter?

- **Lightest SUSY particle (neutralino) is stable if baryon (B) and lepton (L) numbers are conserved**

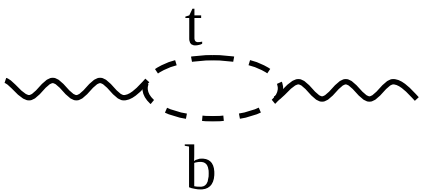
- **However, B and L need not be conserved in SUSY, leading to neutralino decay (RPV)**

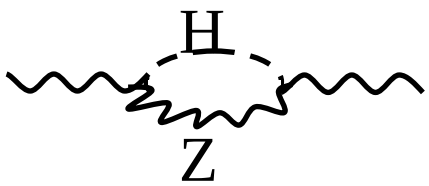
Kurylov, Ramsey-Musolf, Su

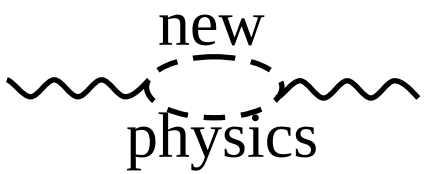


Ultrahigh Precision at an LC

Measure contribution from scalars to oblique corrections







$$\frac{\delta m_H}{m_H} \approx 10\% \text{ for } \delta \sin^2\theta_W \approx 0.00004$$ (world average ~0.00016)

Compare with masses of "bumps" at new colliders: *Critical crosscheck*

A_{LR} and M_W at future colliders:

Systematics extremely challenging!

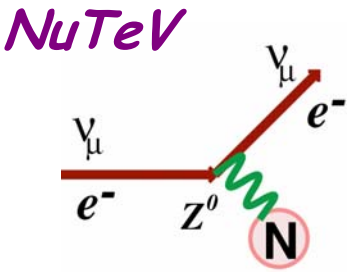
Energy scale to 10^{-4}, polarimetry to 0.15%

K.K, Snowmass 96	E158	LC
Energy (GeV)	48	250-500
Intensity/pulse	4.5×10^{11}	14×10^{11}
Pulse Rate (Hz)	120	120
P_e	85%	90%
Time (s)	5×10^6	2×10^7
A_{LR} (ppm)	0.15	1-2
δA_{LR} (ppm)	0.015	0.008
$\delta\sin^2(\theta_W)$	0.001	0.00008

Møller scattering at the ILC

- *Fixed target has advantages for systematics*
- *Could work with ILC "exhaust"beam*

Future Possiblities (Semileptonic)

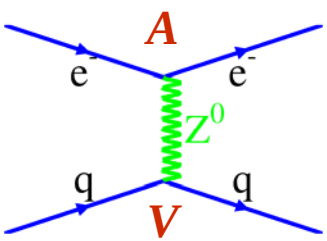


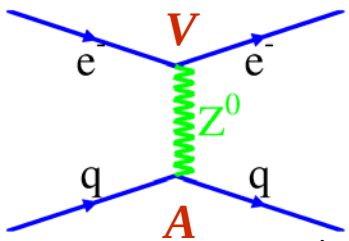
Qweak at Jlab

A_{PV} in elastic e-p scattering

- ***measure $\sin^2\theta_W$ to ± 0.0007***
- ***nail down fundamental low energy lepton-quark WNC couplings***

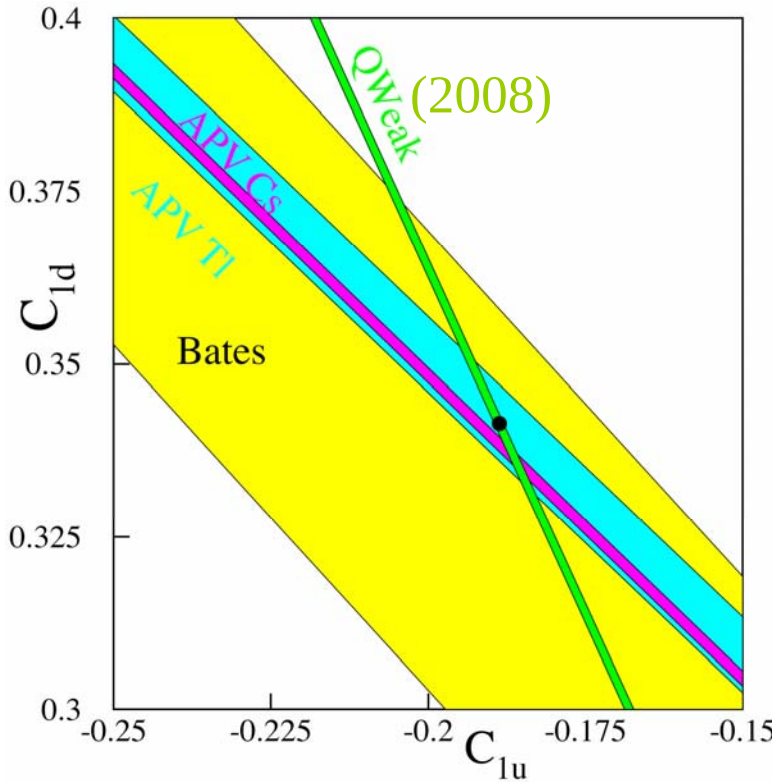
e-q WNC Lagrangian has 4 terms





$$C_{1i} \equiv 2 g_A^e g_V^i \qquad C_{2i} \equiv 2 g_V^e g_A^i$$

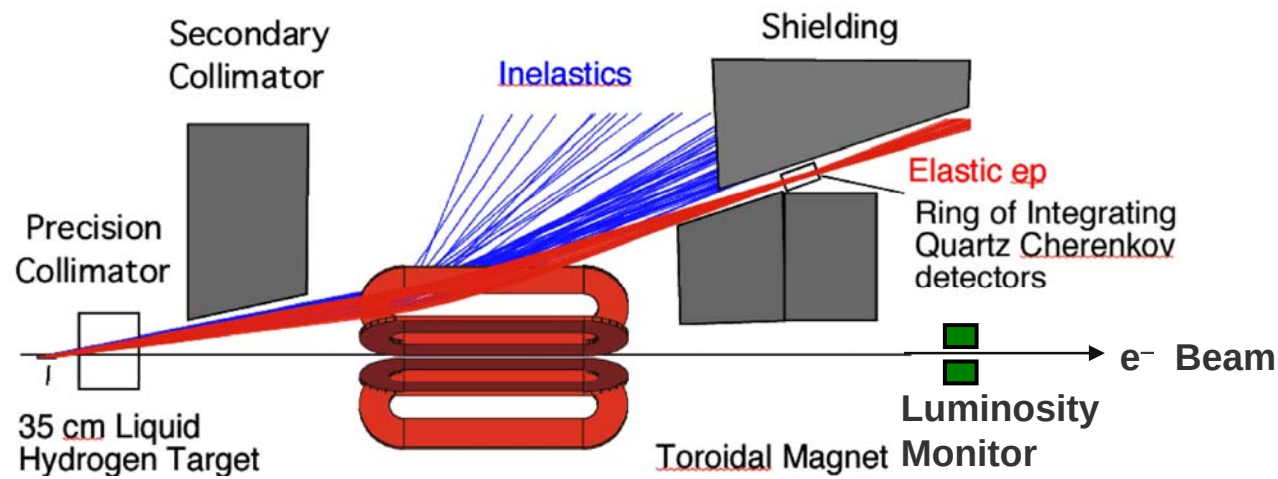
$$C_{1u} = -\tfrac{1}{2} + \tfrac{4}{3}\sin^2(\theta_W) \approx -0.19$$
$$C_{1d} = \tfrac{1}{2} - \tfrac{2}{3}\sin^2(\theta_W) \approx 0.35$$
$$C_{2u} = -\tfrac{1}{2} + 2\sin^2(\theta_W) \approx -0.04$$
$$C_{2d} = \tfrac{1}{2} - 2\sin^2(\theta_W) \approx 0.04.$$

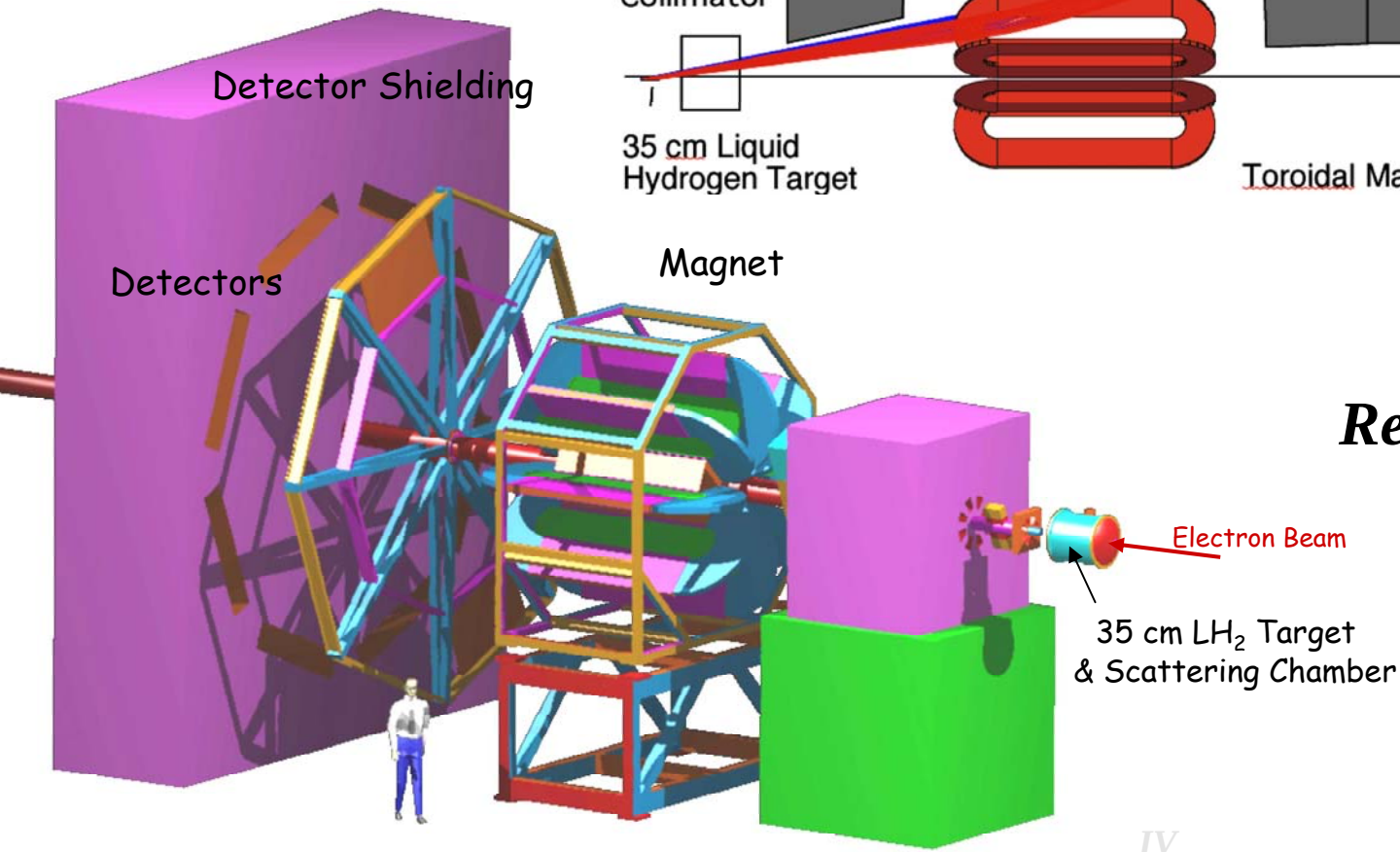


- ***C_{2i}'s small & poorly known: difficult to measure in elastic scattering***
- ***PV Deep inelastic scattering experiment with high luminosity 11 GeV beam***

Qweak Spectrometer

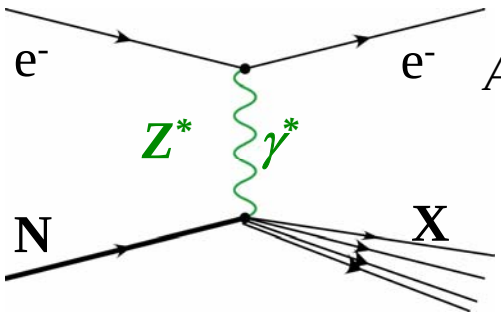
Hall C at JLab





Ready ~ 2008-9

PV DIS at 11 GeV with an LD_2 target



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

$$a(x) = \frac{\sum_i C_{1i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \qquad b(x) = \frac{\sum_i C_{2i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)}$$

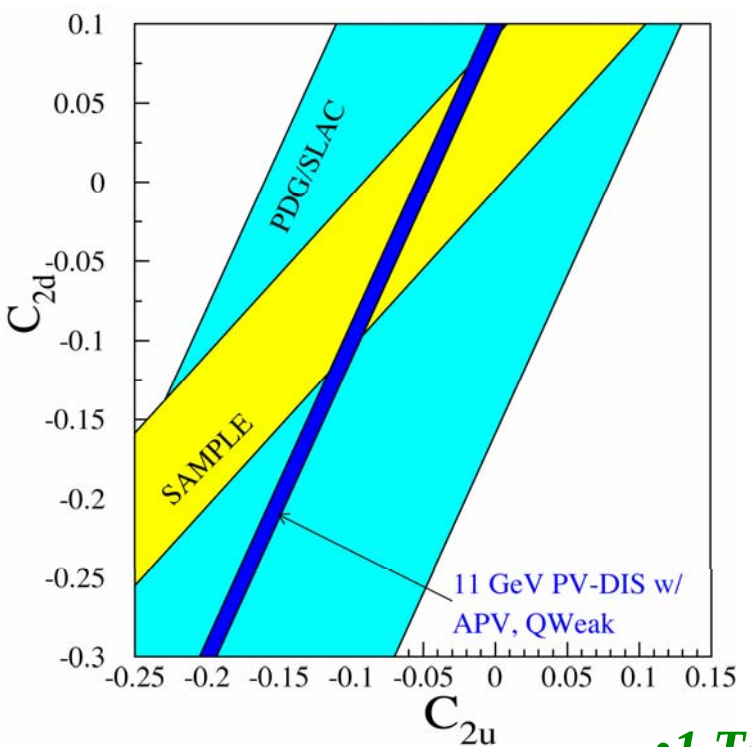
$$y \equiv 1 - E'/E$$

For an isoscalar target like ^2H, structure functions largely cancel in the ratio:

$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] + \cdots$$

$$b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right] + \cdots$$

($Q^2 >> 1$ GeV^2 , $W^2 >> 4$ GeV^2, $x \sim 0.2 - 0.4$)



$\delta(2C_{2u}-C_{2d})=0.012$ **$\delta(\sin^2\theta_W)=0.0009$**

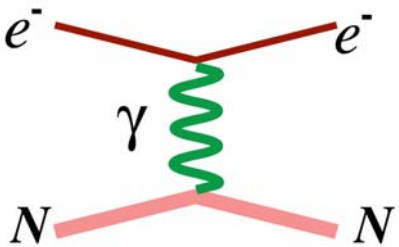
Complementary to LHC direct searches

Examples:

- ***1 TeV extra gauge bosons (model dependent)***
- ***TeV scale leptoquarks with specific chiral couplings***

Electron Scattering off Nucleons & Nuclei

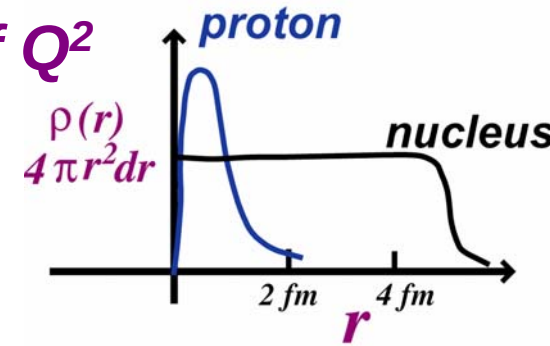
Elastic scattering



QED: precise predictions

Measure σ as a function of Q^2

Neglecting recoil and spin: Obtain Fourier transform of charge distribution



Nuclear charge distribution

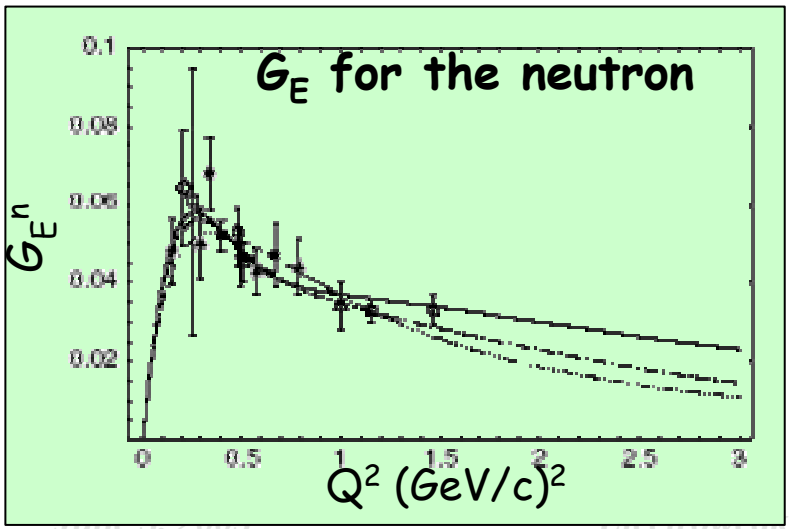
Nucleon charge and magnetization distributions:

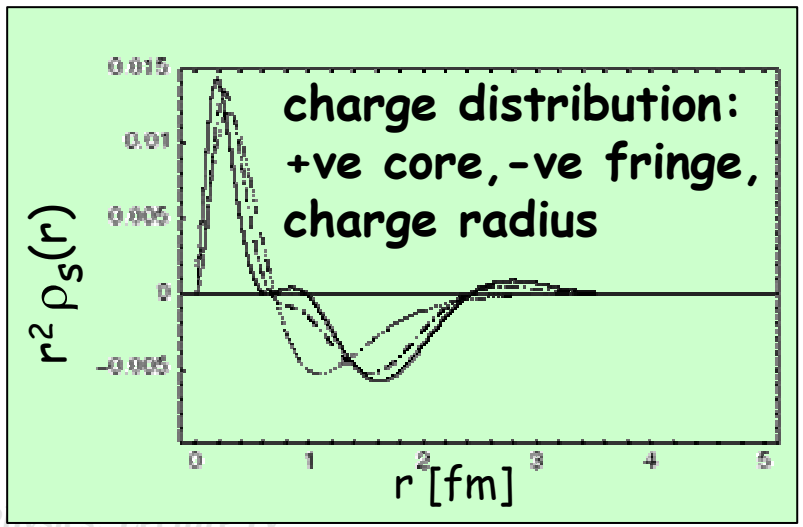
$G_E(Q^2)$, $G_M(Q^2)$

electric and magnetic form factors

$G_E^p(0) = 1$ $\quad$ $G_M^p(0) = +2.79 \equiv \mu_p$

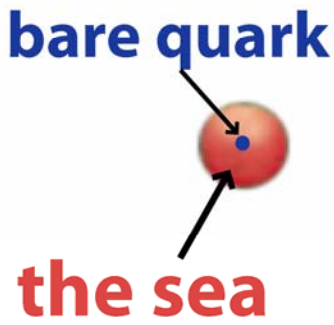
$G_E^n(0) = 0$ $\quad$ $G_M^n(0) = -1.91 \equiv \mu_n$





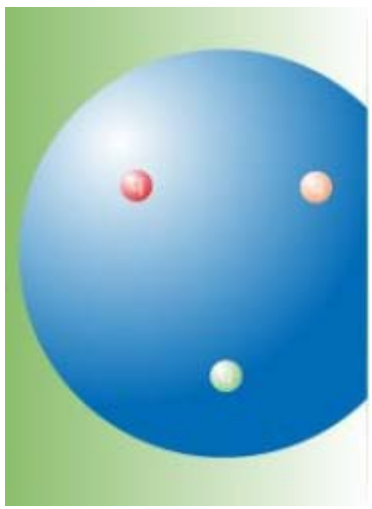
Dynamics of Low Energy QCD

Quantum Chromodynamics is intractable at low Q^2 (≥ 0.2 fm)



valence quark: bare quark "dressed" with quark-antiquark pairs and gluons

Why don't sea quarks destroy Quark Model predictions?

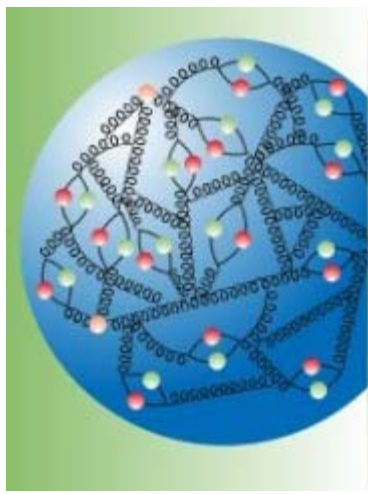


three flavors dominate: **u, d, s**

Strangeness Flavor:

- relatively light
- no valence contribution
- flavor separation now possible

Are proton properties modified?



Profound qualitative and quantitative implications!

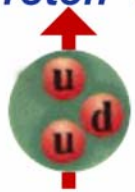
Strangeness in Nucleons

spin dependent deep inelastic scattering

$$S = \frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + \Delta L$$

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

Proton Spin



Experiments:
$\Delta\Sigma \sim 0.25$

+ Hyperon decay
+ $SU(3)_f$ Symmetry:

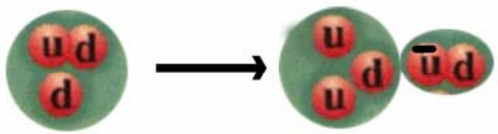
$\Delta s \sim -0.1$?

$$\Delta s \sim \langle N | \bar{s}\gamma_\mu\gamma_5 s | N \rangle$$

Breaking of SU(3) flavor symmetry introduces uncertainties

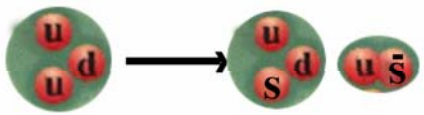
$$\langle N | \bar{s}\gamma_\mu s | N \rangle \neq 0\,?$$

neutron charge distribution

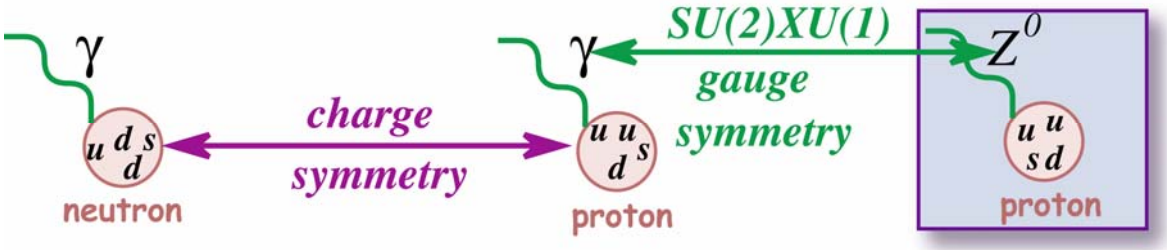


neutron "pion cloud"

proton flavor distribution



proton "kaon cloud"

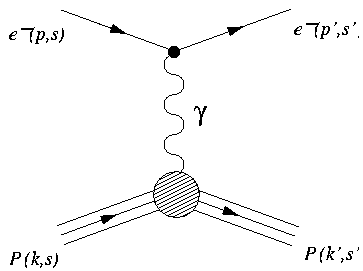


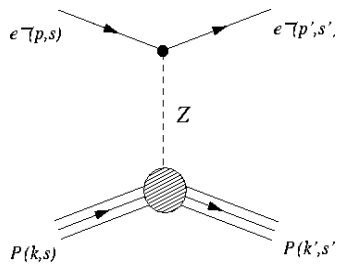
Kaplan & Manohar (1988)
McKeown (1990)

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

$\Rightarrow$ $G_E^s(Q^2)$, $G_M^s(Q^2)$

PV Electron Scattering to Measure Weak NC Amplitudes





$$M^{EM} = \frac{4\pi\alpha}{Q^2} \mathrm{Q}_{EM}\, \ell^{\mu} J_{\mu}^{EM}$$

$$M^{NC} = \frac{G_F}{2\sqrt{2}} \left[g_V \ell^{\mu} + g_A \ell^{\mu 5} \right] \left[J_{\mu}^{NC} + J_{\mu 5}^{NC} \right]$$

Parity Violating Amplitude dominated by NC terms:

$$M_{PV}^{NC} = \frac{G_F}{2\sqrt{2}} \left[g_A \ell^{\mu 5} J_{\mu}^{NC} + g_V \ell^{\mu} J_{\mu 5}^{NC} \right]$$

NC vector current probes same hadronic flavor structure, with different couplings:

$$J_{\mu}^{EM} = \sum_q \mathrm{Q}_q \left\langle \overline{N} \middle| \overline{u}_q \gamma_{\mu} u_q \middle| N \right\rangle$$

$$J_{\mu}^{NC} = \sum_q \mathrm{g}_{\mathrm{V}}^{\mathrm{q}} \left\langle \overline{N} \middle| \overline{u}_q \gamma_{\mu} u_q \middle| N \right\rangle$$

Flavor Decomposed Form Factors

$$J_\mu^{EM} = \sum_q Q_q \left\langle \overline{N} \left| \overline{u}_q \gamma_\mu u_q \right| N \right\rangle = \overline{N} \left[\gamma_\mu F_1^\gamma + \frac{i\sigma_{\mu\nu} q^\nu}{2M_N} F_2^\gamma \right] N$$

commonly used Sachs FF: $G_E^\gamma = F_1^\gamma + \tau F_2^\gamma$ $\quad G_M^\gamma = F_1^\gamma + F_2^\gamma$

Decompose by Quark Flavor:

	Q	g_V	g_A
e	–1	$-1 + 4\sin^2\theta_W$	+1
u	+2/3	$1 - 8/3\sin^2\theta_W$	–1
d,s	–1/3	$-1 + 4/3\sin^2\theta_W$	–1

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

$$G_{E/M}^Z = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G_{E/M}^u - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_{E/M}^d - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_{E/M}^s$$

Charge Symmetry

Charge symmetry: neglecting trivial breaking due to Coulomb force, one expects the neutron to be an isospin rotation of the proton

$$G^{p,u}_{E/M} = G^{n,d}_{E/M}, \qquad G^{p,d}_{E/M} = G^{n,u}_{E/M}, \qquad G^{p,s}_{E/M} = G^{n,s}_{E/M}$$

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

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

$G^{\gamma,p}_{E,M}$, $G^{\gamma,n}_{E,M}$, $G^{Z,p}_{E,M}$ $\xrightarrow[\text{symmetry}]{\text{Isospin}}$ $G^{u}_{E,M}$, $G^{d}_{E,M}$, $G^{s}_{E,M}$ $\xrightarrow[\text{Choose}]{\text{Pick 'n}}$ $G^{p}_{E,M}$, $G^{n}_{E,M}$, $G^{s}_{E,M}$

Well Measured

$\langle N | s\gamma^{\mu} s | N \rangle$

How Big are G_E^s, G_M^s?

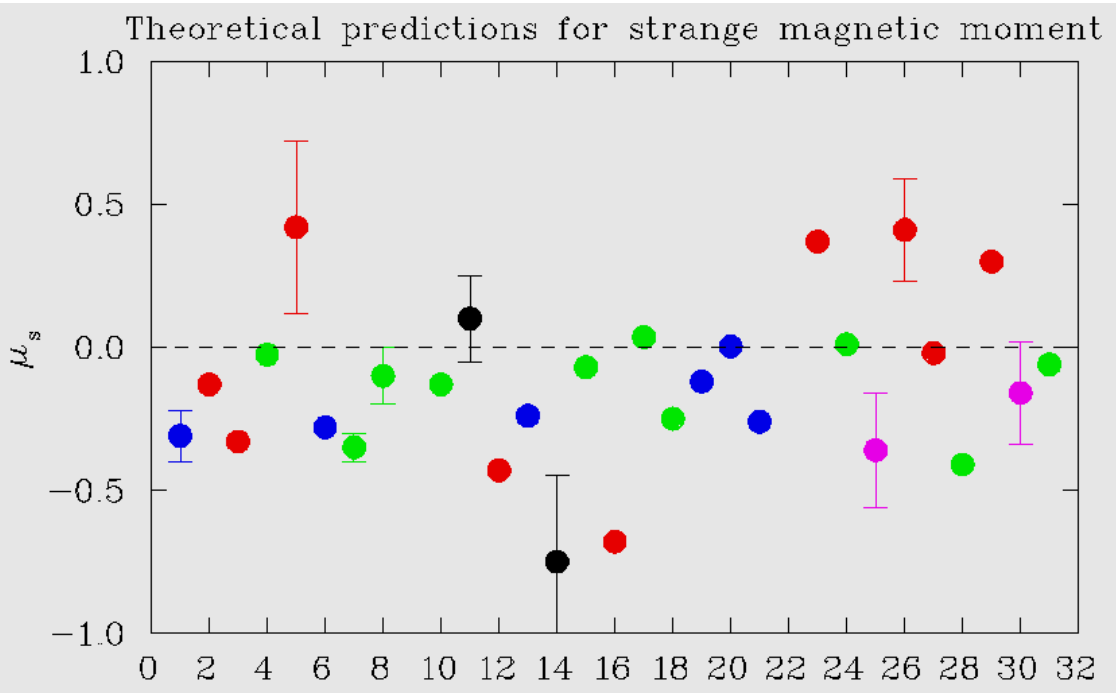
Various theoretical approaches:

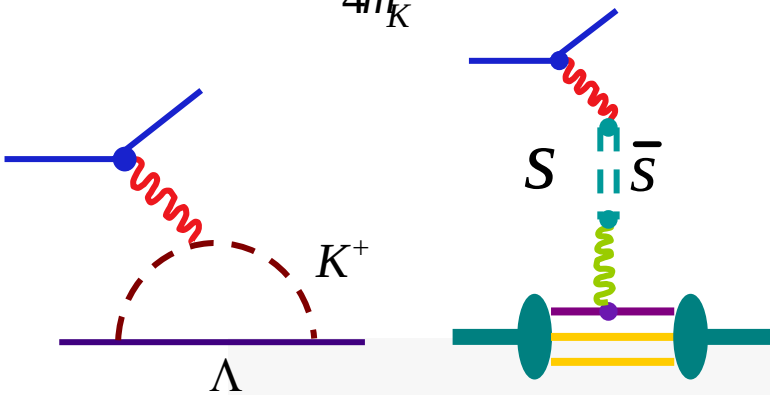
- *Quark models*
- *Dispersion Relations*
- *Lattice Gauge theory*
- *Skyrme models*

Dispersion Theory

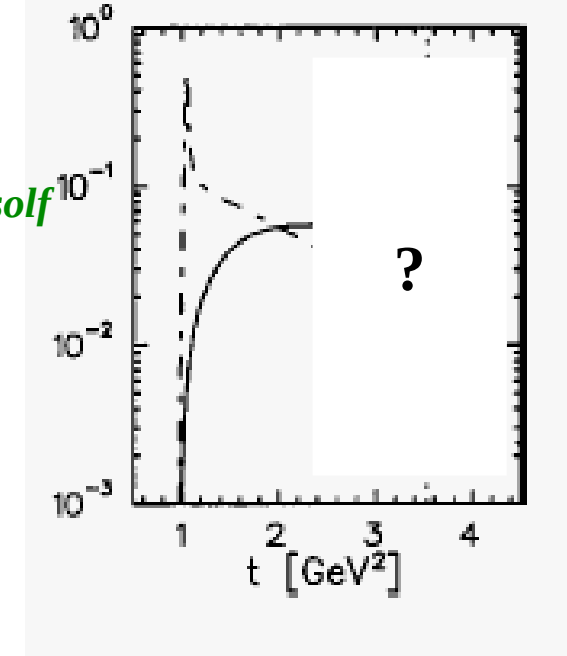
$$r_{s,M}^2 = \frac{6}{\pi}\int_{4m_K^2}^{\infty} dt \frac{\mathrm{Im}G_M^s(t)}{t^2}$$

$$\mu_s \equiv G_M^s(Q^2=0)$$

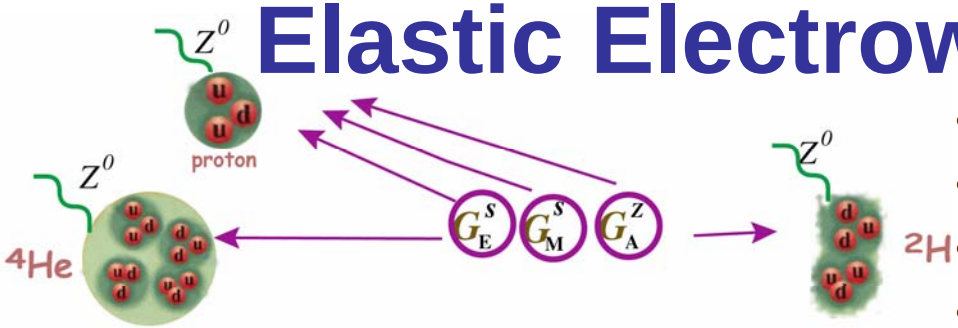




Hammer
Ramsey-Musolf

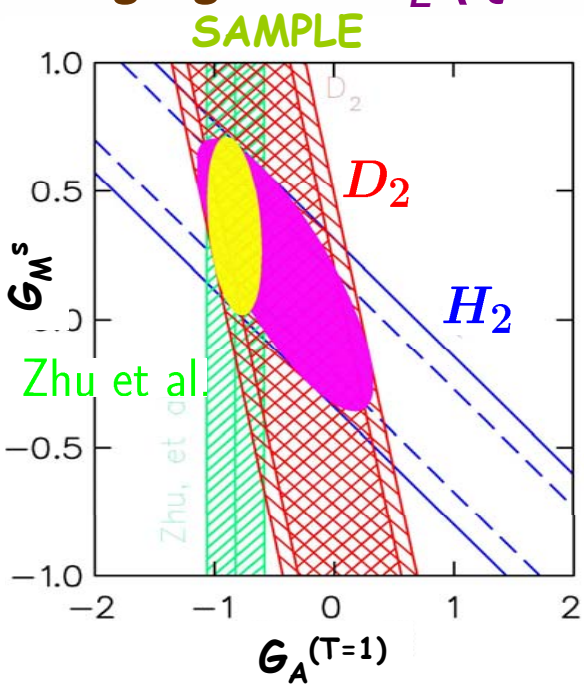


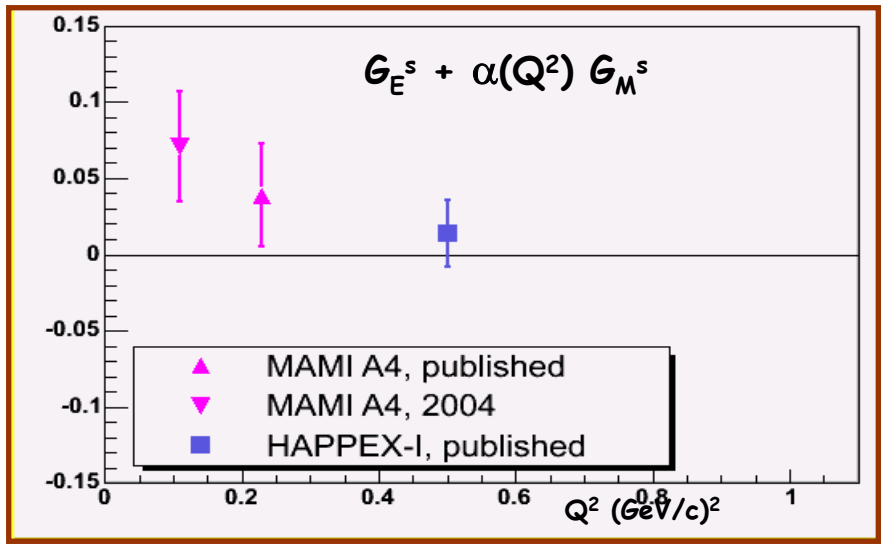
Elastic Electroweak Scattering



- *A_{PV} measurements ranging $0.1 < Q^2 < 1$*
- *forward and backward angles*
- *Hydrogen, Deuterium and Helium targets*
- *Statistical and systematic errors < 10%*

Rough guide: $G_E^n(Q^2=0.2) \sim 0.05$, $\mu_\Lambda \sim -0.6$





- *Cancellations?*
- *Q^2 dependence?*
- *Accuracy?*

HAPPEX: Second Generation

E=3 GeV, θ=6 deg, Q^2=0.1 (GeV/c)^2

^{1}H: A_{PV}=-1.4 ppm, goal ± 0.08 (stat.)

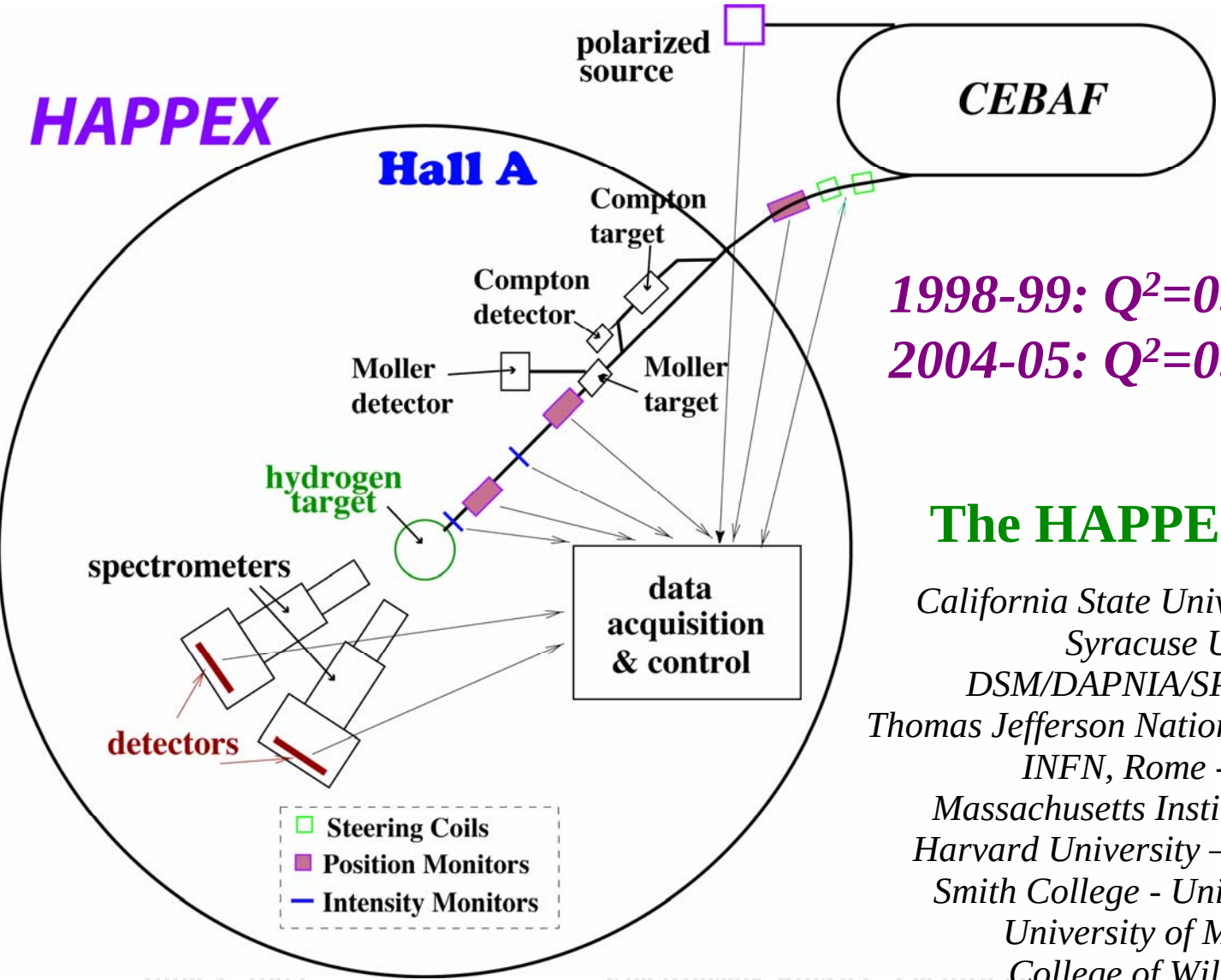
⇨ $\delta(G^s_E + 0.08 G^s_M) = 0.010$

^{4}He: A_{PV}=+7.6 ppm, goal ± 0.18 (stat.)

⇨ $\delta(G^s_E) = 0.014$

HAPPEX at JLab

Hall A Proton Parity EXperiment



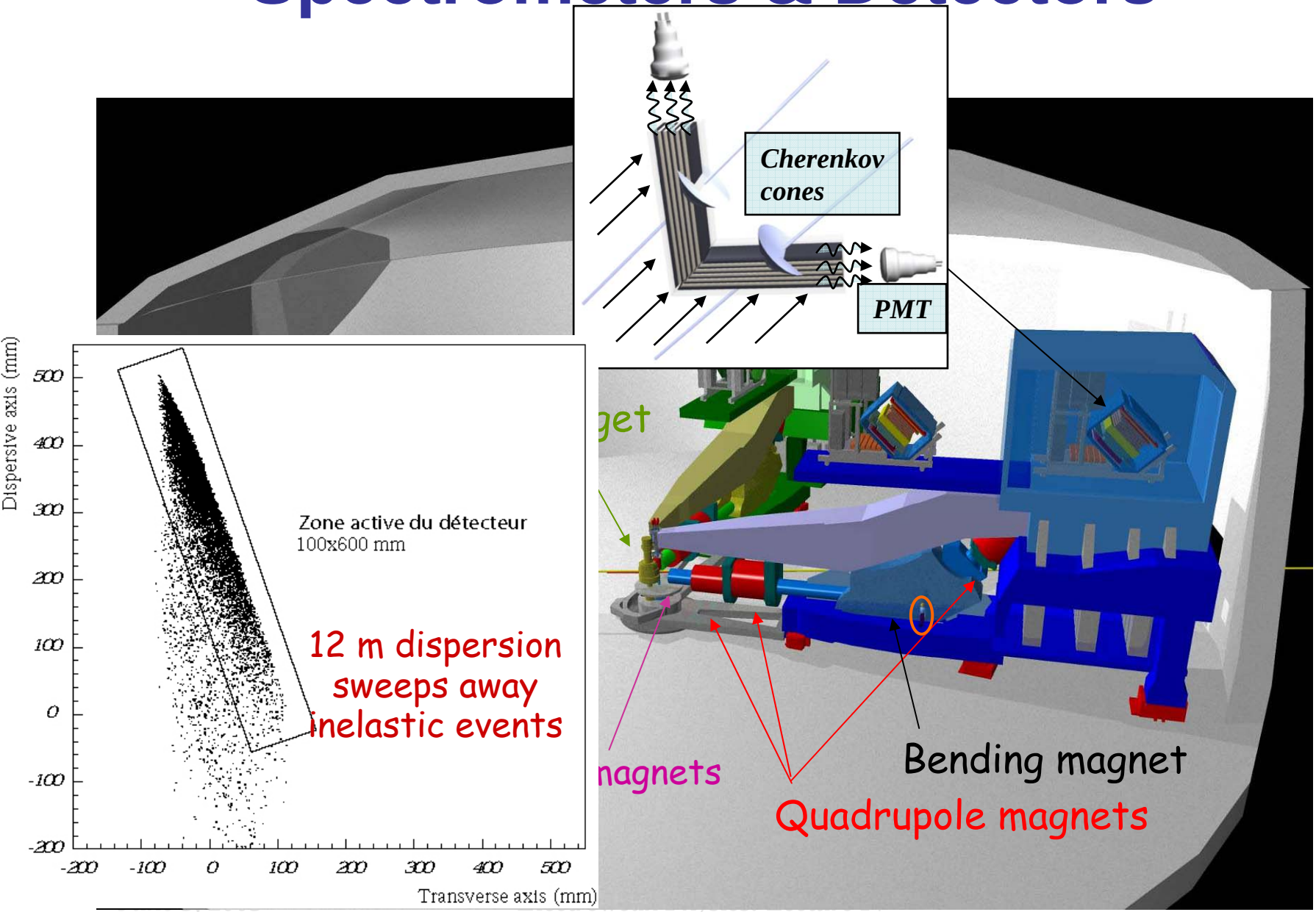
1998-99: Q^2=0.5 GeV^2, ^1H

2004-05: Q^2=0.1 GeV^2, ^1H, ^4He

The HAPPEX Collaboration

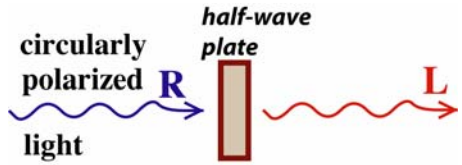
California State University, Los Angeles - Syracuse University - DSM/DAPNIA/SPhN CEA Saclay - Thomas Jefferson National Accelerator Facility- INFN, Rome - INFN, Bari - Massachusetts Institute of Technology - Harvard University – Temple University – Smith College - University of Virginia - University of Massachusetts – College of William and Mary

Spectrometers & Detectors



^{4}He Asymmetry Result

June 8-22, 2004

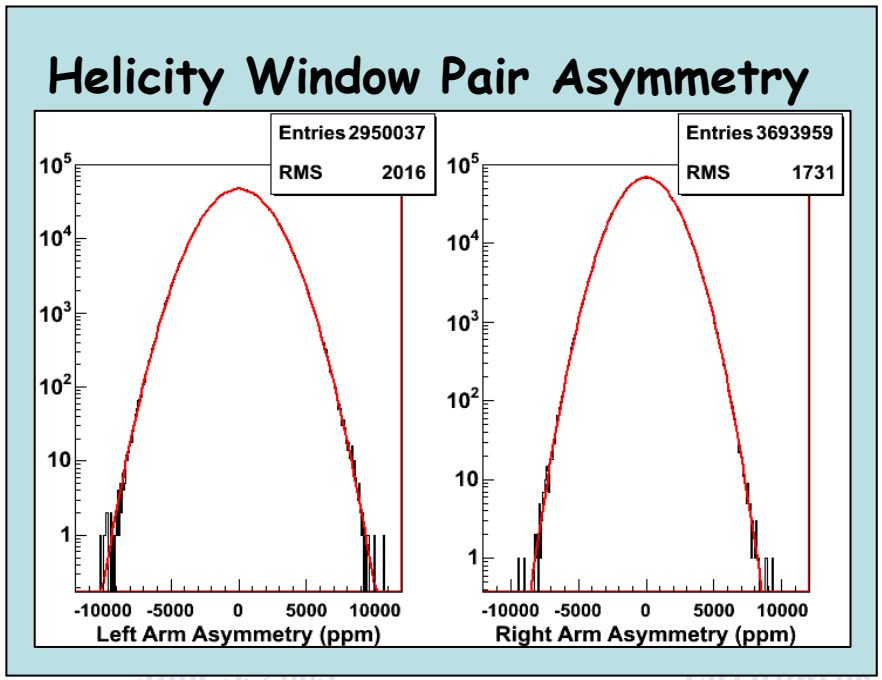


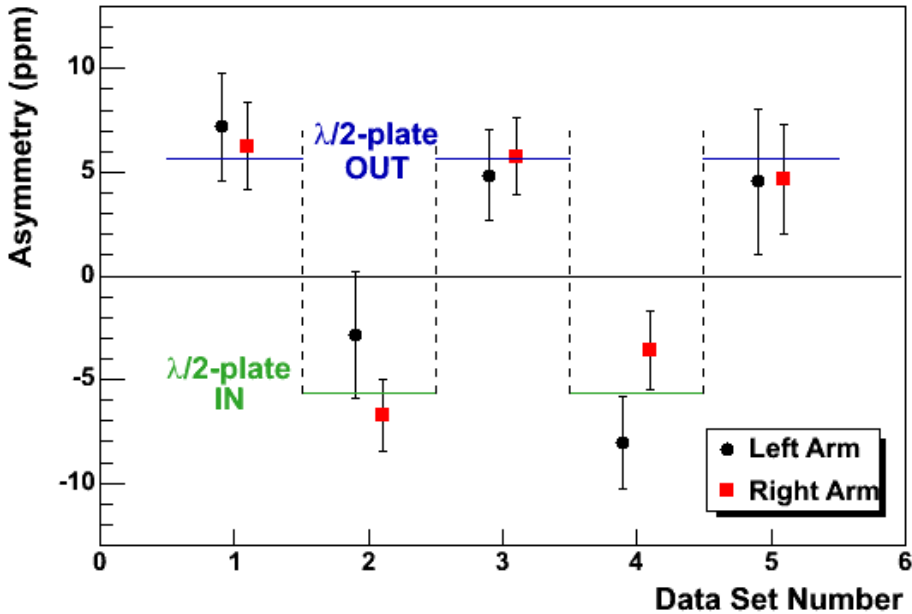
3.3 M pairs, total width ~1300 ppm

A_{raw} correction < 0.2 ppm

$Q^2 = 0.091\ (GeV/c)^2$

$A_{raw} = 5.63\ ppm \pm 0.71\ ppm\ (stat)$





Theory

$A(G^s=0) = +7.51 \pm 0.08$ ppm

Data: (after all corrections)

$A_{PV} = 6.72 \pm 0.84_{(stat)} \pm 0.21_{(syst)}$ ppm

PRL in preparation

^{1}H Asymmetry Result

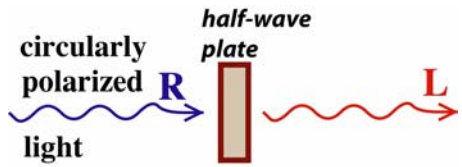
June 24-July 25, 2004

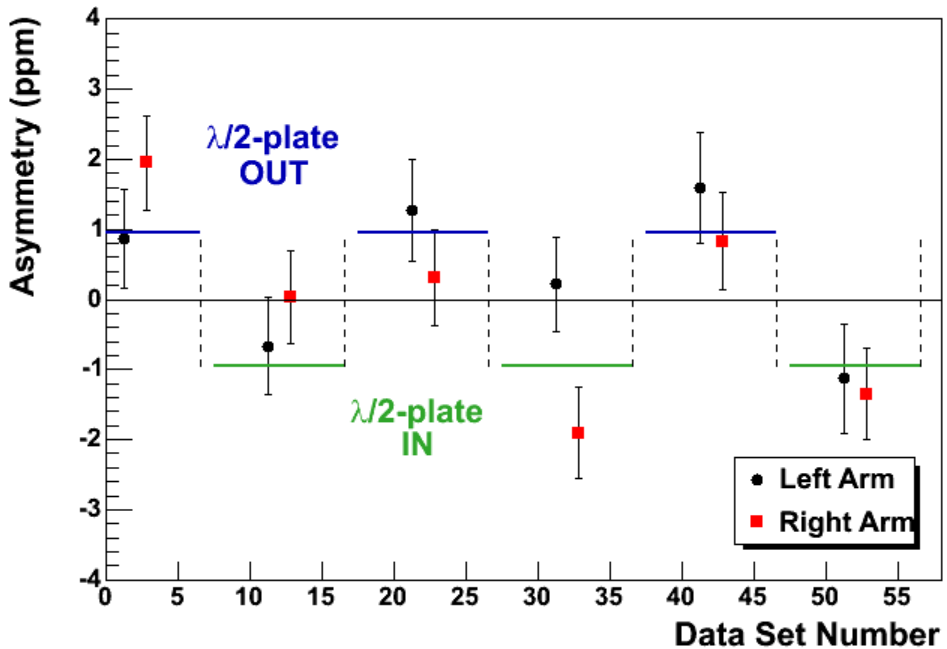
9.5 M pairs, total width ~620 ppm

A_{raw} correction ~ 0.06 ppm

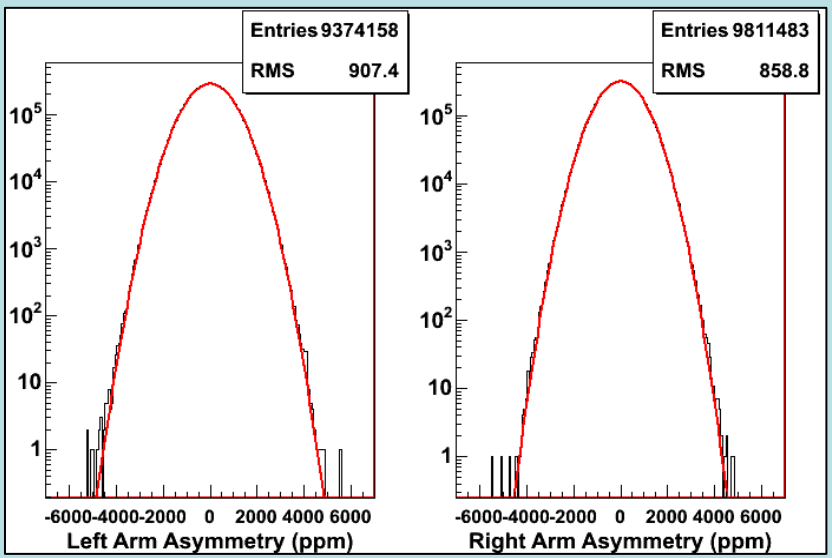
$Q^2 = 0.099\ (GeV/c)^2$

$A_{raw} = -0.95\ ppm \pm 0.20\ ppm\ (stat)$





Helicity Window Pair Asymmetry



Theory

$A(G^s=0) = -1.44\ ppm \pm 0.11\ ppm$

Data: (after all corrections)

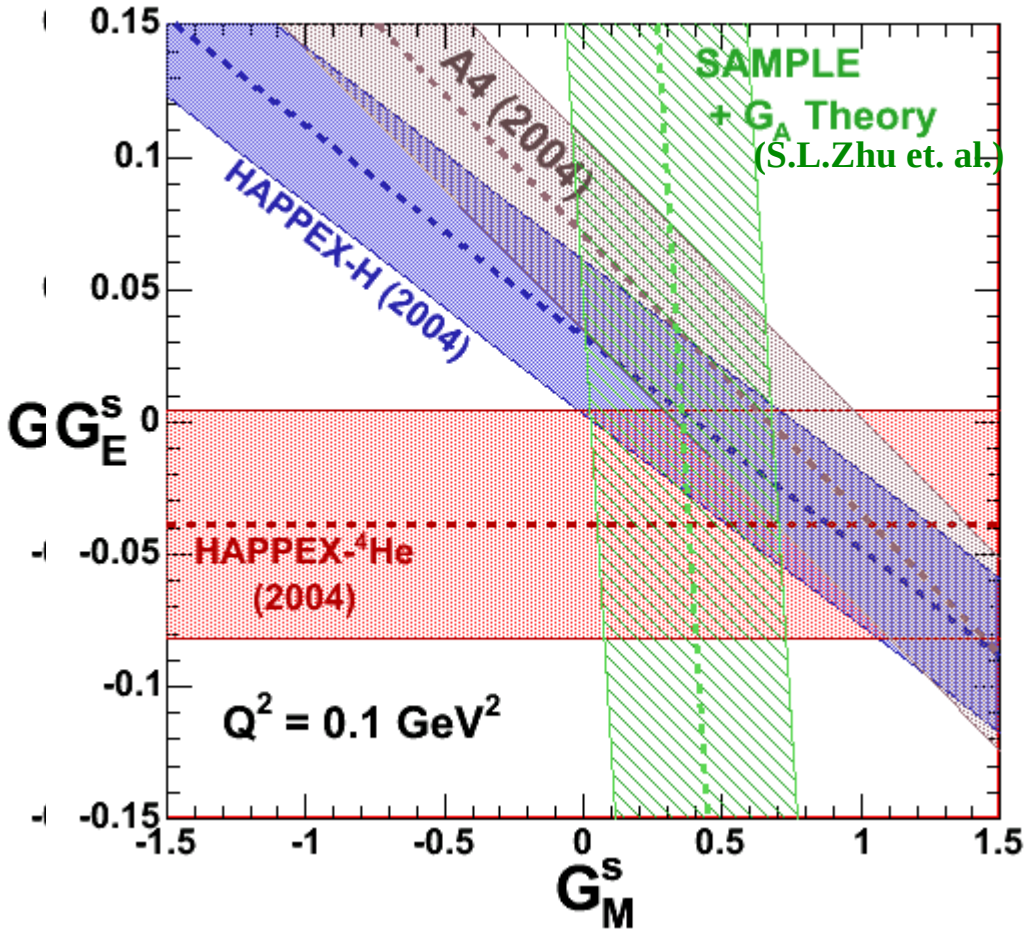
$A_{PV} = -1.14 \pm 0.24_{(stat)} \pm 0.06_{(stat)}\ ppm$

PRL in preparation

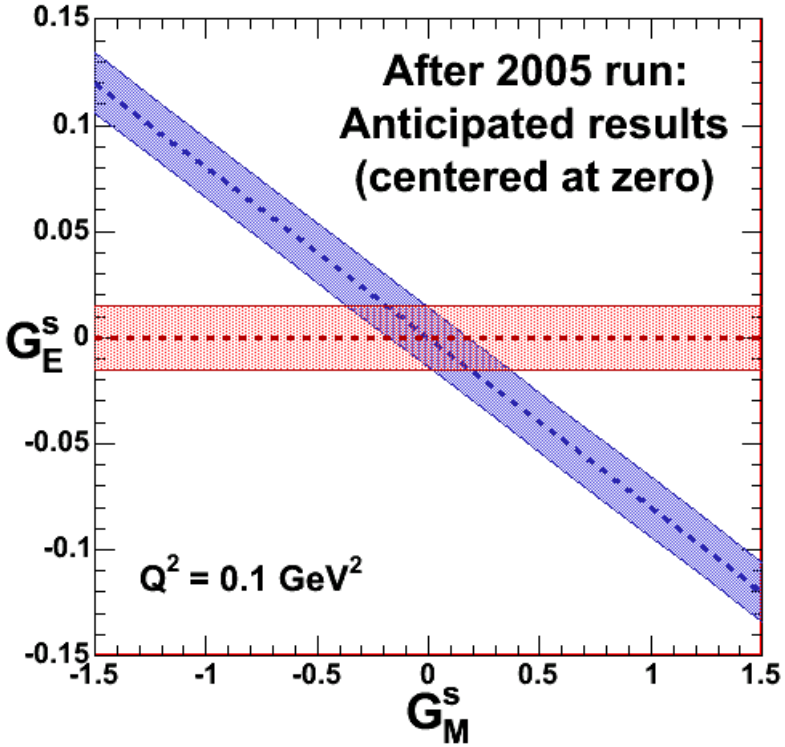
Summary of ^{1}H and ^{4}He Results

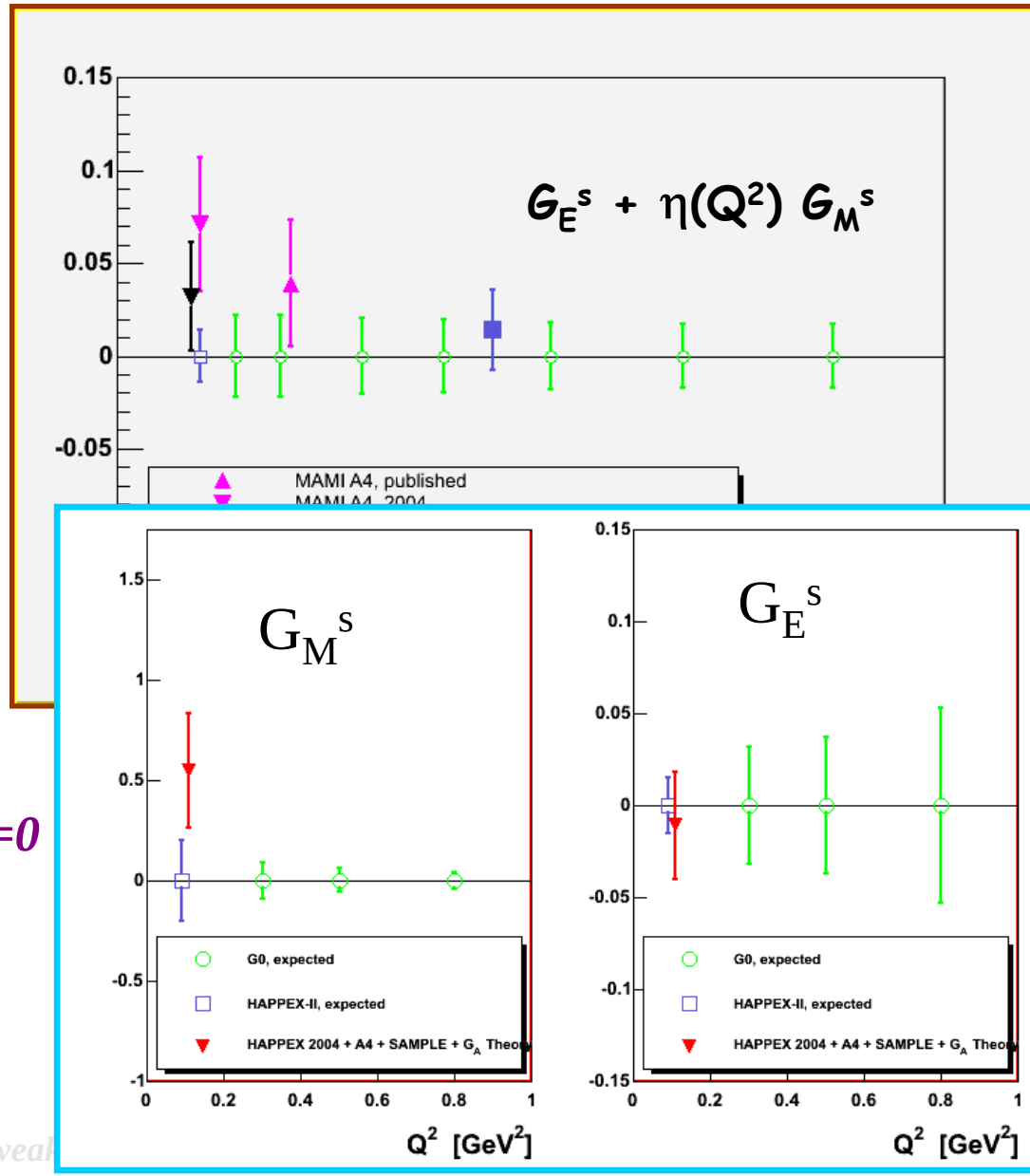
$$G^s_E = -0.039 \pm 0.041_{(stat)} \pm 0.010_{(syst)} \pm 0.004_{(FF)}$$

$$G^s_E + 0.08\, G^s_M = 0.032 \pm 0.026_{(stat)} \pm 0.007_{(syst)} \pm 0.011_{(FF)}$$



Current Status and Prospects





- *Each experiment consistent with $G^s=0$*
- *Some indication of positive G_M^s*
- *More data forthcoming!*
- *Cancellations might play a role*

PVA4 at Mainz

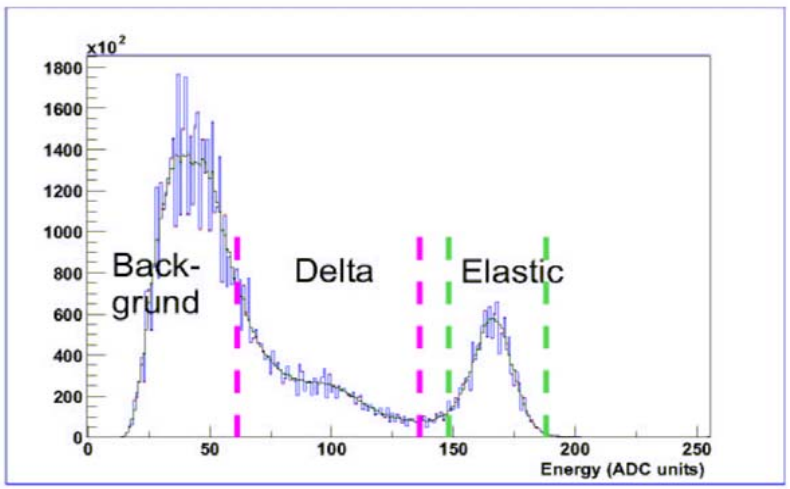
Forward angle, Hydrogen, Q^2 = 0.23, 0.1 GeV^2

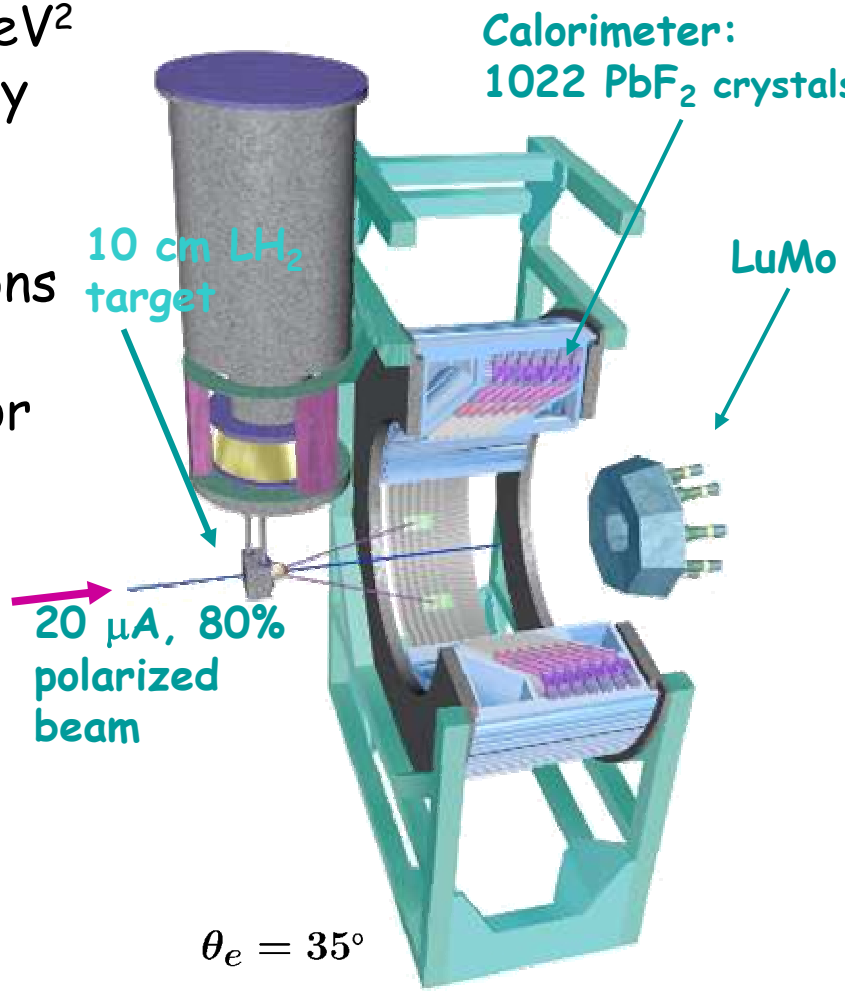
Calorimeter distinguishes elastic via energy resolution

Specialized fast counting electronics self-trigger and histogram energy distributions in overlapping 3x3 modules

Integrate "elastic region" in histograms for each helicity window

Elastic rate: 10 MHz, total rate 100 MHz





$\theta_e = 35^\circ$

$E = 854,\ 570$ MeV

Significant density flucuation in target, normalized to luminosity monitor.

G0

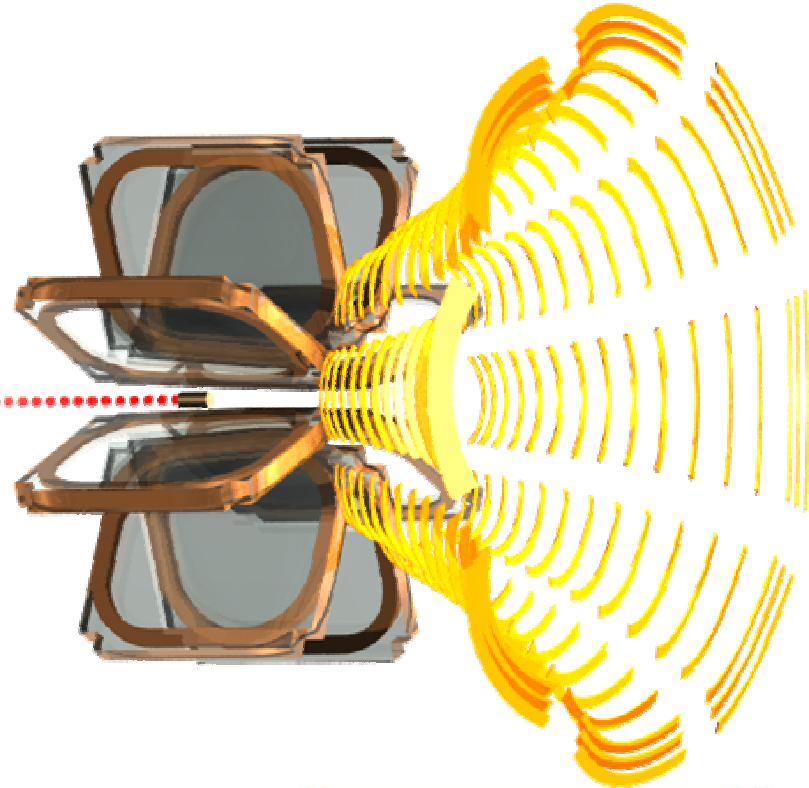
TJNAF, 2004 Forward angle H

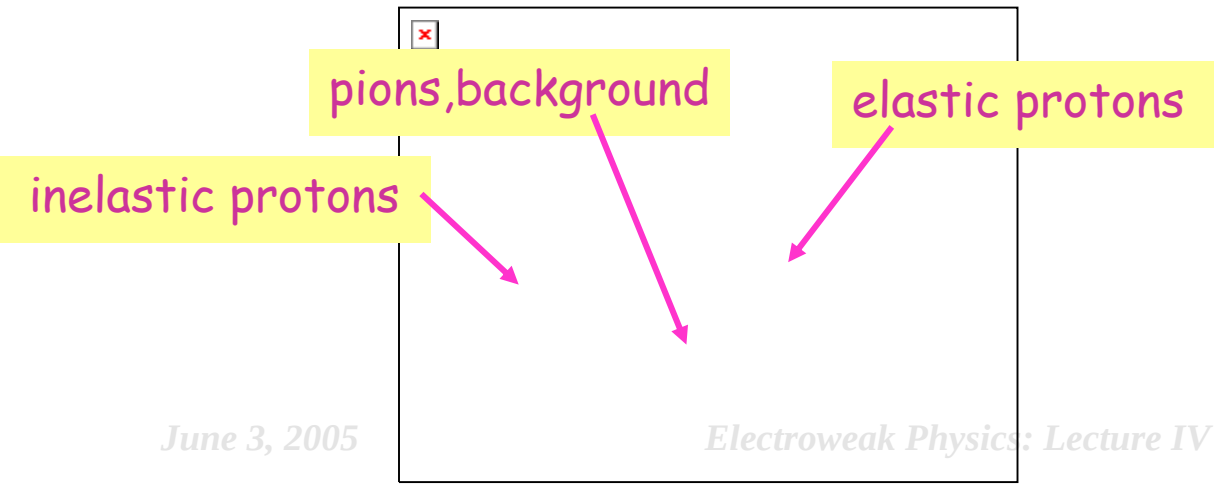
Duty factor of 499 MHz CEBAF beam reduced to 31 MHz

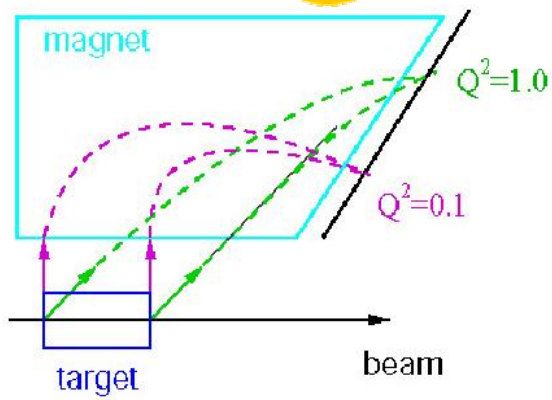
Recoil protons detected in scintillators, segmentation defines Q^2 point

T.o.F on path through torroidal spectrometer,Time histogram from specialized electronics

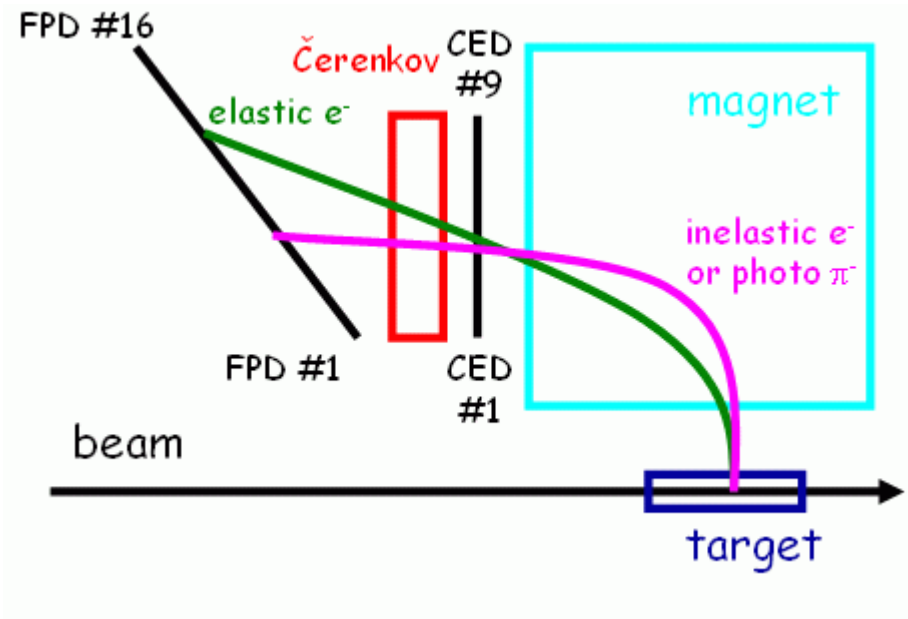
Simultaneous Q^2 = [0.16,1] GeV^2





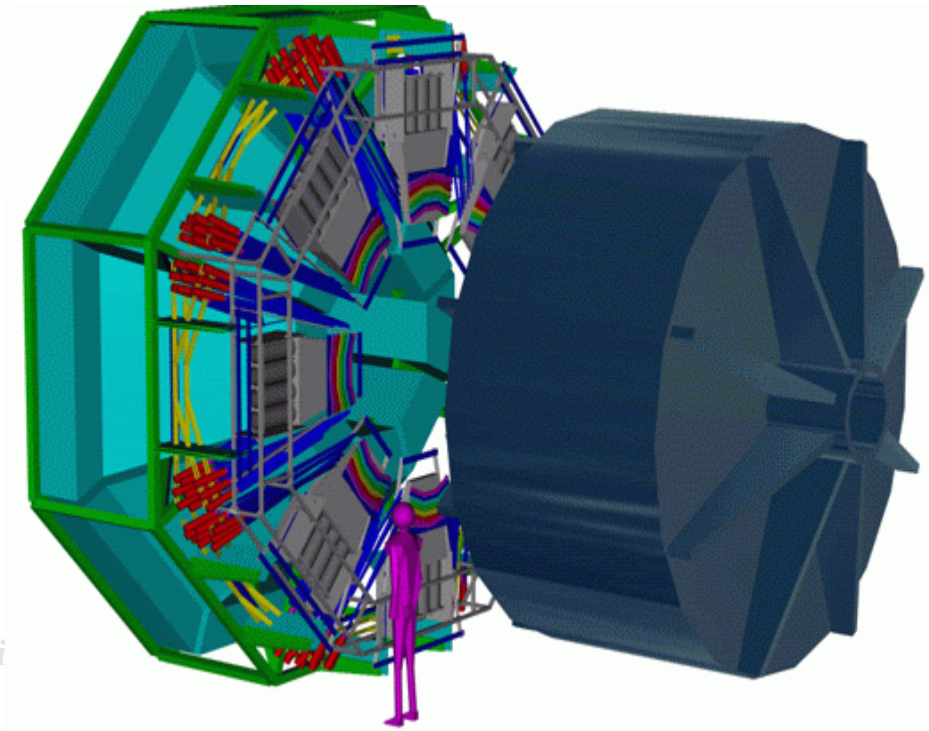


G0 Backward Angle



Electron detection
- Turn magnet/detector package around
- Add Cryostat Exit Detectors ("CEDs") to define electron trajectory
- Add aerogel Cerenkovs to reject pions

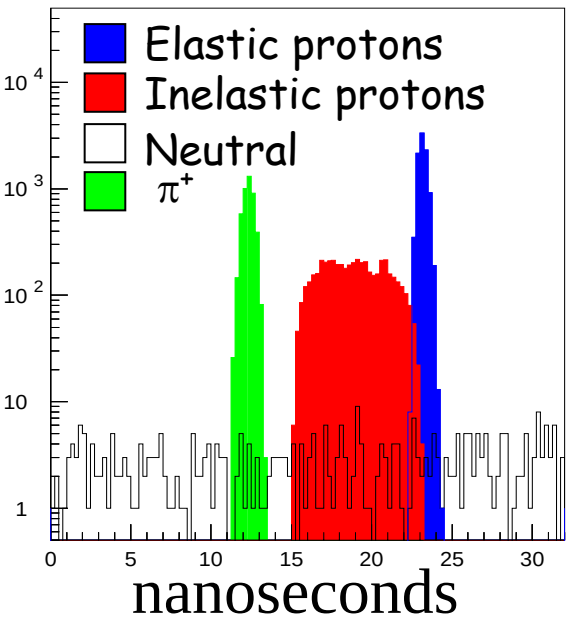
Begin Backward Angle installation in 2005



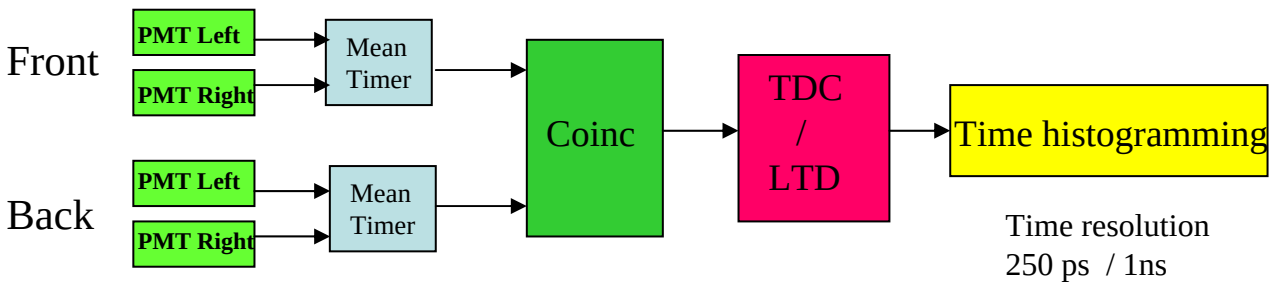
Planned measurements of H, ^{2}H Q.E.

Combine with forward angle to separate G^s_E, G^s_M, G_A at 3 Q^2 points

G0 Electronics



Time of Flight measurement



Beam structure: 32 ns between pulses

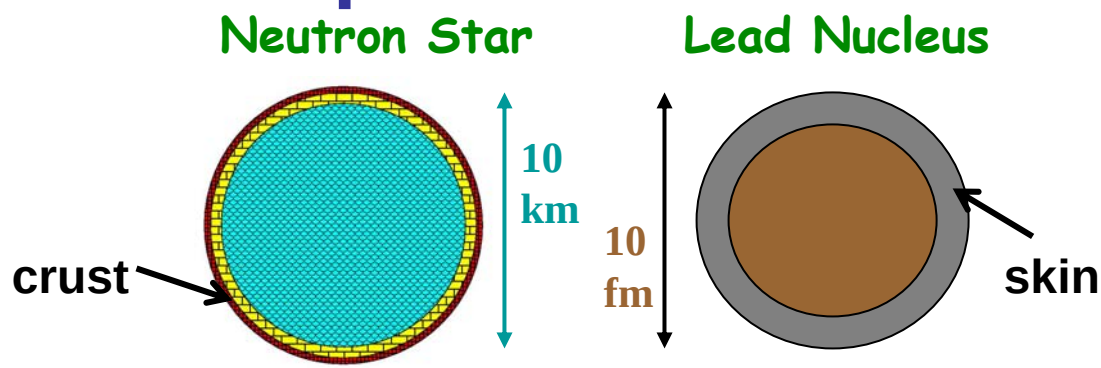
FR octants: flash TDCs (0.25 ns over 32 ns range)

NA octants: Latching Time Digitizer (500 MHz)
→ scalers (1 ns over 24 ns range)

Time histogramming read out at 30 Hz (polar. reversal)

Crust of a Neutron Star; Neutron Skin of a Spinless Nucleus

- Neutron star has solid crust over liquid core.
- Heavy spinless nucleus has neutron skin.



$R_p \sim 5.5$ fm

$R_n - R_p \sim 0.1$ to 0.3 fm?

Both neutron skin and neutron star crust are made out of neutron rich matter at similar densities.

•A neutron skin is expected: how thick is it?

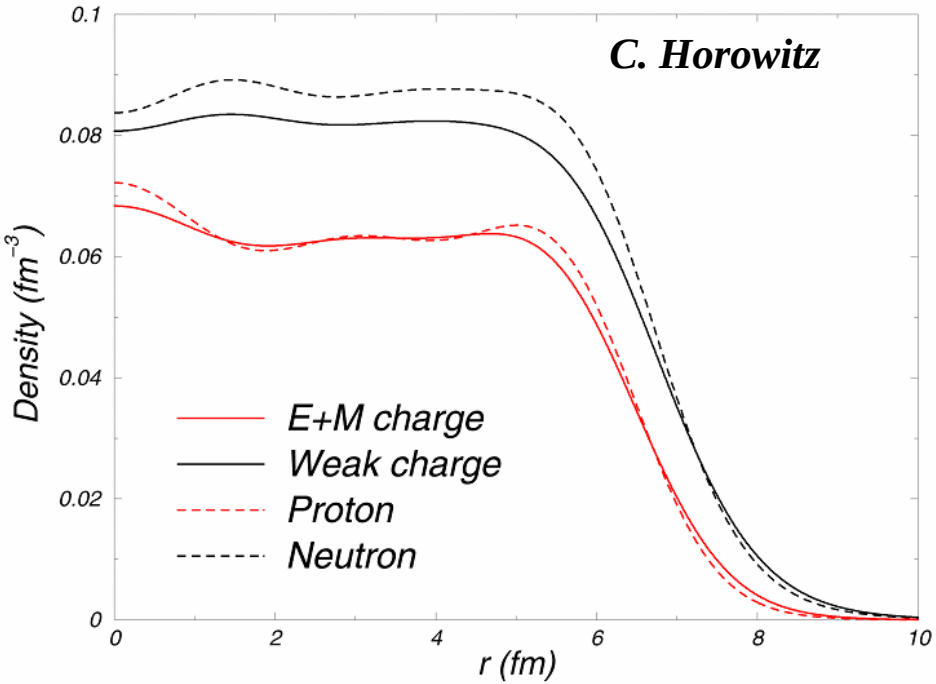
•The extent of the skin constrains the transition density from solid crust to liquid core in a neutron star

•The density dependence of the symmetry energy constrains the composition of the neutron star core: important implications for rate of neutron star cooling

An experimentally clean measurement of skin is now viable:

PREX at JLab

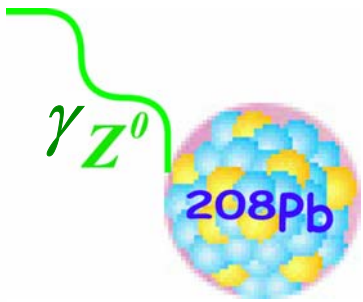
^{208}Pb



Donnelly, Dubach & Sick (1988)

$Q^p_{EM} \sim 1$ $\quad$ $Q^n_{EM} \sim 0$

$Q^p_W \sim 1 - 4\sin^2\theta_W$ $\quad$ $Q^n_W \sim 1$



$\delta(A_{PV}) \sim 3\%$

$\delta(R_p - R_n) \sim 1\%$

$Q^2 \sim 0.01$ GeV^2 → $A_{PV} \sim 0.5$ ppm

A technically demanding measurement:

- Rate ~ 2 GHz
- Separate excited state at 2.6 MeV
- Stat. Error ~ 15 ppb
- Syst. Error ~ 1 to 2 %

Data collection at JLab Hall A within 2 years

Summary

- Weak Neutral Current experiments with fixed targets will continue to play a role in the search for new physics at TeV scales
- The tools developed allow us to focus on other important issues
  - strangeness in nucleons
  - neutron skin of a heavy nucleus
- In the final lecture, we will survey electroweak experiments at other laboratories