Parity-violating Electron Scattering and the Search for Strange Seas, New Physics and Quark Stars

Prof. Kent Paschke

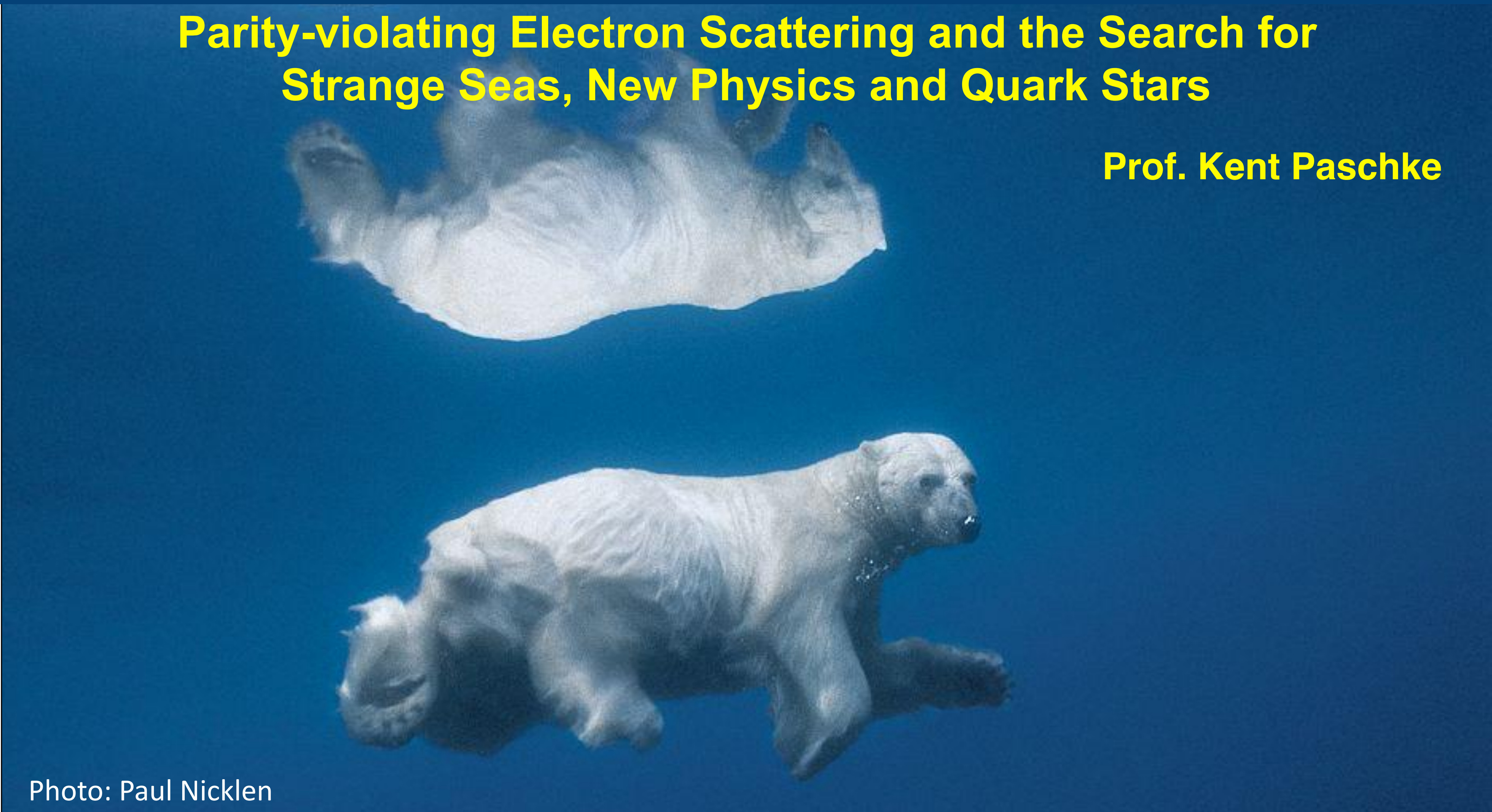


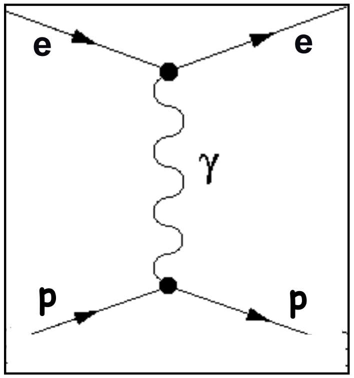
Photo: Paul Nicklen

Introduction to Electron Scattering

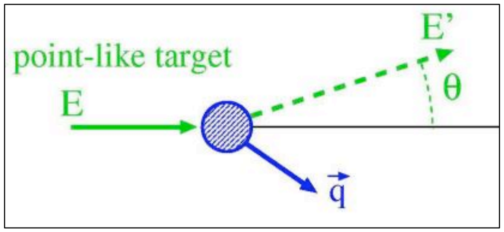
Introduction to electron scattering

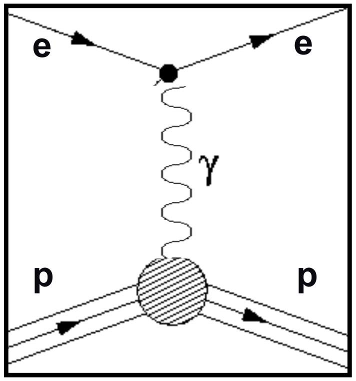
Electron scattering: electromagnetic interaction, described as an exchange of a virtual photon.

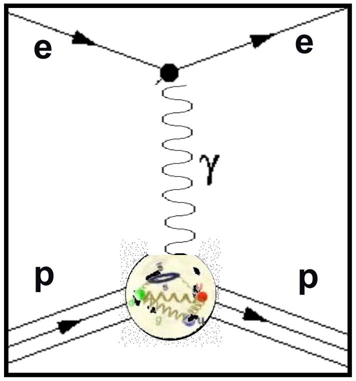
If photon carries low momentum
-> long wavelength
-> low resolution



Q^2: 4-momentum of the virtual photon



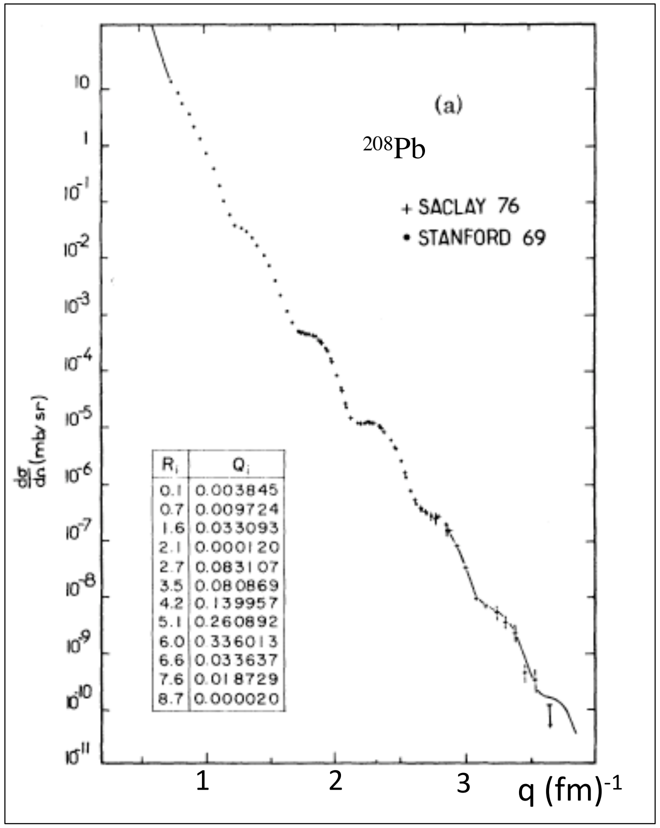




Increasing momentum transfer
-> shorter wavelength
-> higher resolution to observe smaller structures

Elastic Form Factors and Extended Targets

The point-like scattering probability for elastic scattering is modified to account for finite target extent by introducing the “form factor”



Assuming spherically symmetric (spin-0) target

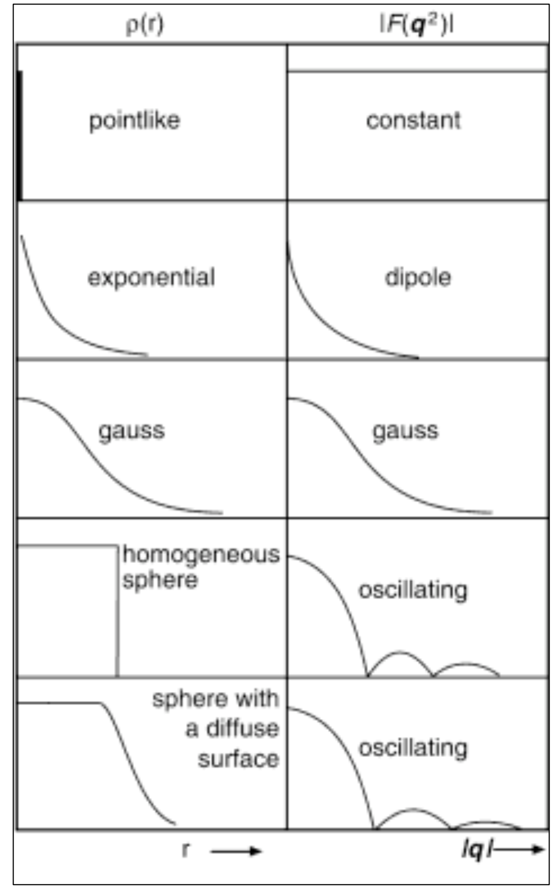
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} |\, F(q)\, |^2$$

point-like target, electron spin

$$F(q) = \int e^{iqr} \rho(r) d^3 r$$

Form factor is the Fourier transform of charge distribution

Figure from Particles and Nuclei, Povh *et al.*



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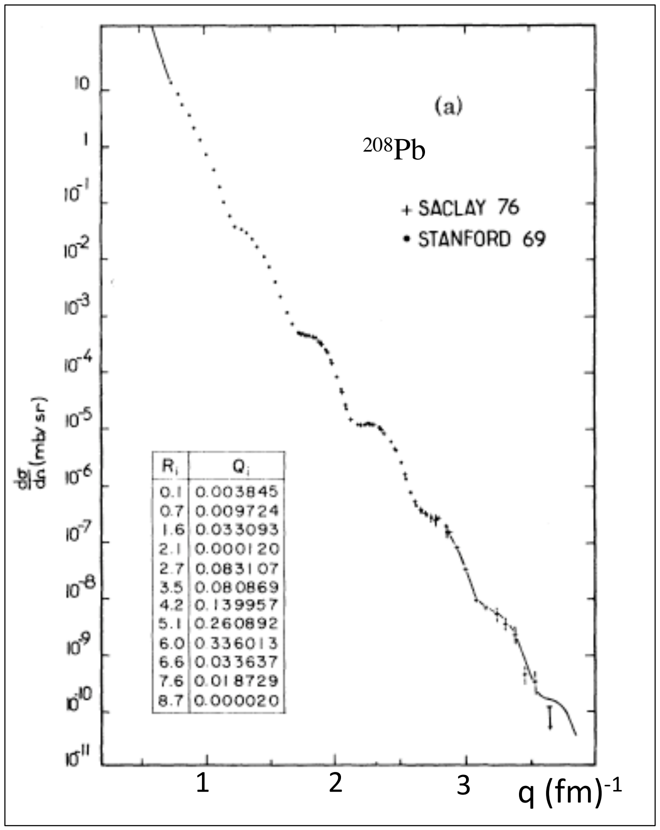

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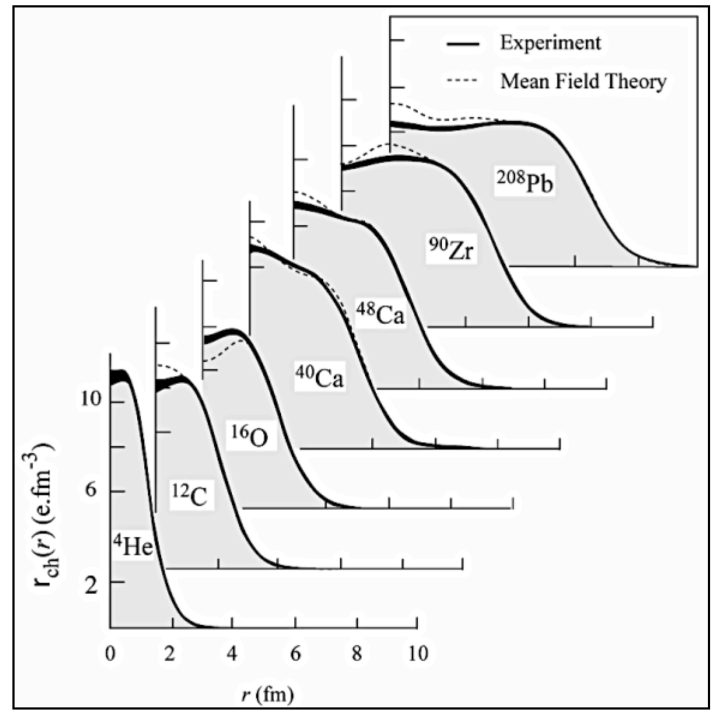


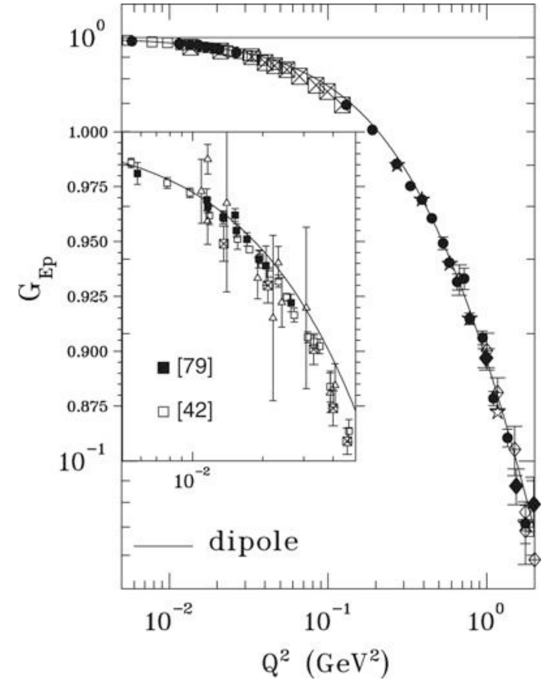
Elastic Electron-Nucleon Scattering

For targets with spin, must also account for magnetic moment

Electric and Magnetic form factors $G_E(Q^2)$ and $G_M(Q^2)$

$$\frac{d\sigma}{d\Omega}_{Rosenbluth} = \frac{d\sigma}{d\Omega}_{Mott} \left\{ \frac{(G_E^2 + \tau\, G_M^2)}{1+\tau} + 2\tau\, G_M^2 \tan^2(\theta/2) \right\}$$

Proton (and neutron magnetic) form-factors follow dipole form (exponential charge distribution)



With no structure

- **G_E = 1** (proton charge)
- **G_M = 1** (magnetic moment = μ_B).

At Q^2 = 0, the probe does not resolve the target

- **G_E(0) = 1** (electric charge)
- **G_M(0) = μ** (magnetic moment in units of **μ_B**)

Standard Model, Weak Interaction, Parity Symmetry, and Parity Violating Electron Scattering

Weak Interaction and parity

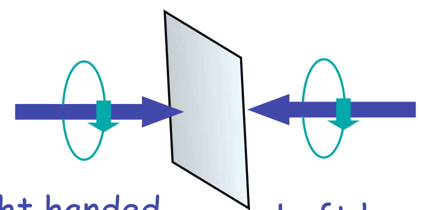
1930's - The weak nuclear interaction was needed to explain nuclear beta decay

1950's - Discovery of parity-violation by the weak interaction

Parity transformation

$$x, y, z \rightarrow -x, -y, -z$$

$$\vec{p} \rightarrow -\vec{p}, \quad \vec{L} \rightarrow \vec{L}, \quad \vec{S} \rightarrow \vec{S}$$

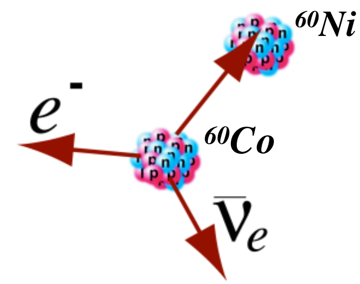


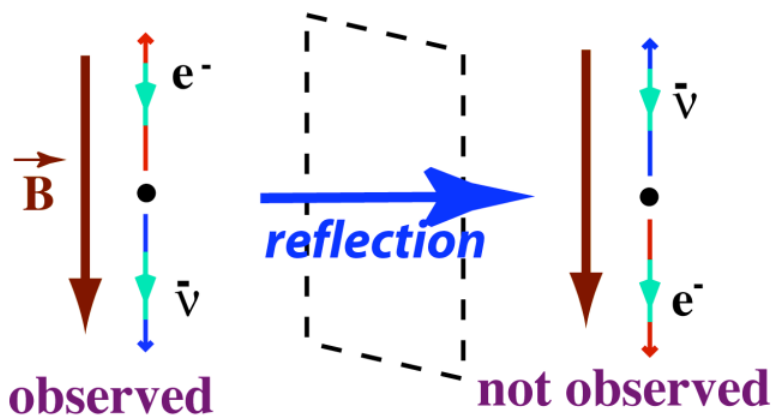
Parity transformation is analogous to reflection in a mirror:

. . . reverses momentum but preserves angular momentum

. . .takes right-handed (helicity = +1) to left-handed (helicity = -1).

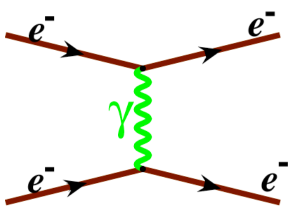
Weak decay of ^{60}Co Nucleus



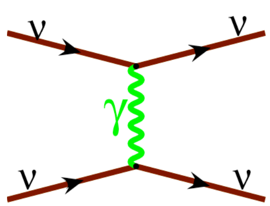


Charge and Handedness

Electric charge determines strength of electric force



observed



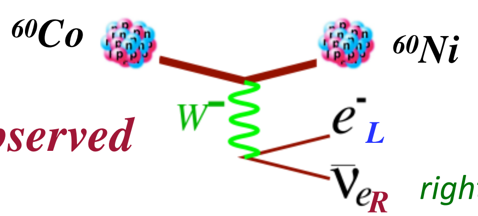
not observed

Neutrinos are "charge neutral": do not feel the electric force

	Left	Right
γ Charge	$q = 0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$	$q = 0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$
W Charge	$T = \pm\frac{1}{2}$	zero

Weak charge determines strength of weak force

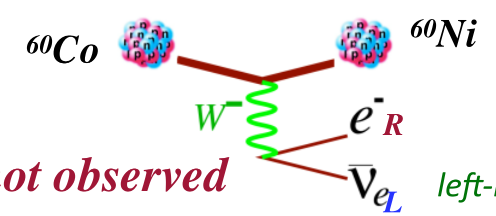
Left-handed particles (Right-handed antiparticles) have weak charge



observed

right-handed anti-neutrino

Right-handed particles (left-handed antiparticles) are "weak charge neutral"



not observed

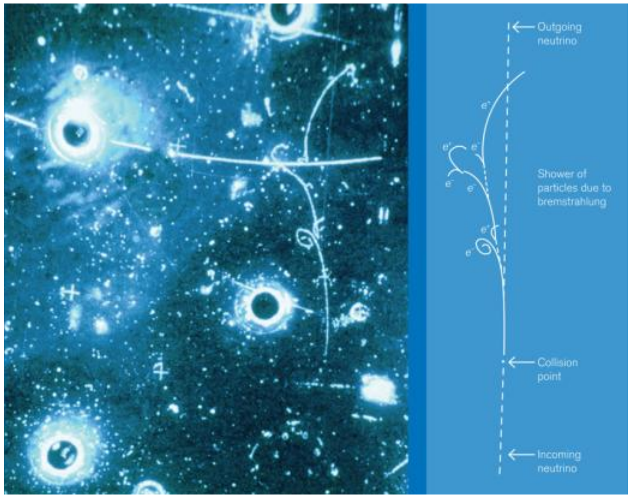
left-handed anti-neutrino

Electroweak Interaction

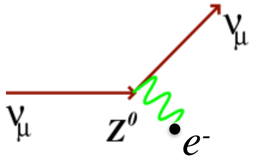
Until the 1970's, all known weak interactions could be explained by $W^{+/-}$ exchange

Weak neutral currents are proposed under electroweak unification (late '60s, Weinberg Salam Glashow, but others, also…)

⇒ The weak mixing angle θ_W introduced



Gargamelle bubble chamber uncovers ν_μ e^- events in 1973, more convincingly in 1976.



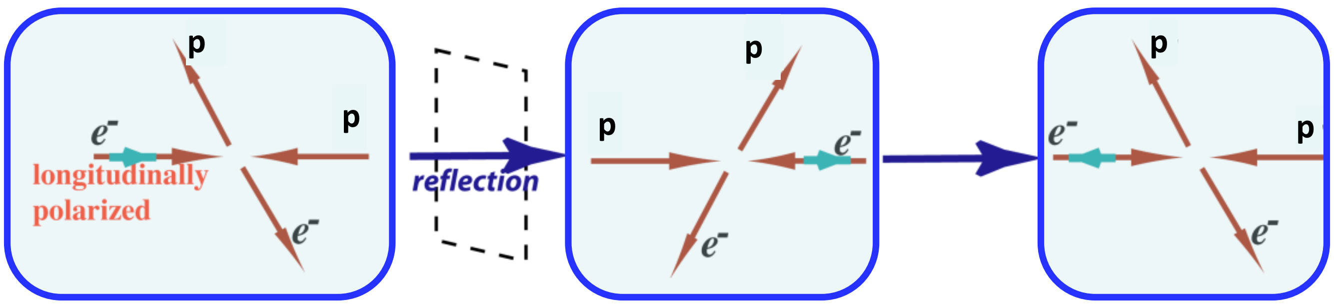
This demonstrated the existence of the neutral current (Z^0) but not its nature

- What is the gauge structure of the underlying theory?
- Is this the electroweak unification of GWS?
- Another EW unification?
- A new interaction?

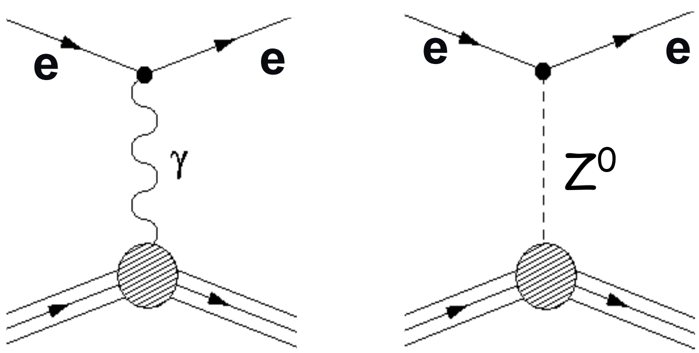
	Left	**Right**
γ Charge	$q = 0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$	$q = 0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$
W Charge	$T = \pm\frac{1}{2}$	**zero**
Z Charge		

Landmark experiment (late 1970s): parity-violating electron scattering

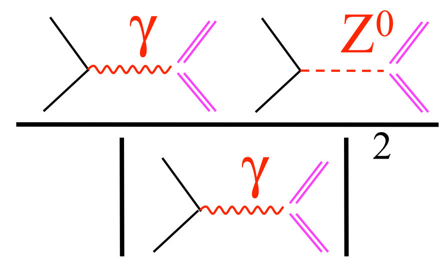
Electron Scattering and Parity-violation



- Incident beam is longitudinally polarized
- Change sign of longitudinal polarization
- Measure fractional rate difference



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



$$\propto \frac{|\mathcal{M}_Z|}{|\mathcal{M}_\gamma|}$$

Scattering cross-section

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

"Electroweak" models predicted
- interference of electromagnetic and weak amplitudes
- values for electron & quark weak neutral current coupling

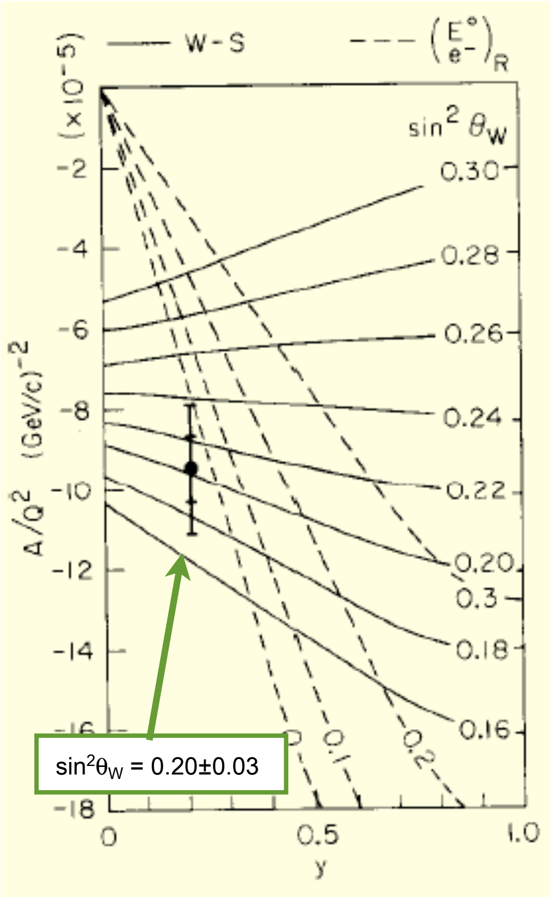
PVeS Verifies the "Standard Model" (1978)

Parity Non-Conservation in Inelastic Electron Scattering, ***C.Y. Prescott et. al, 1978***

A_{PV} ~ 100 ± 10 ppm

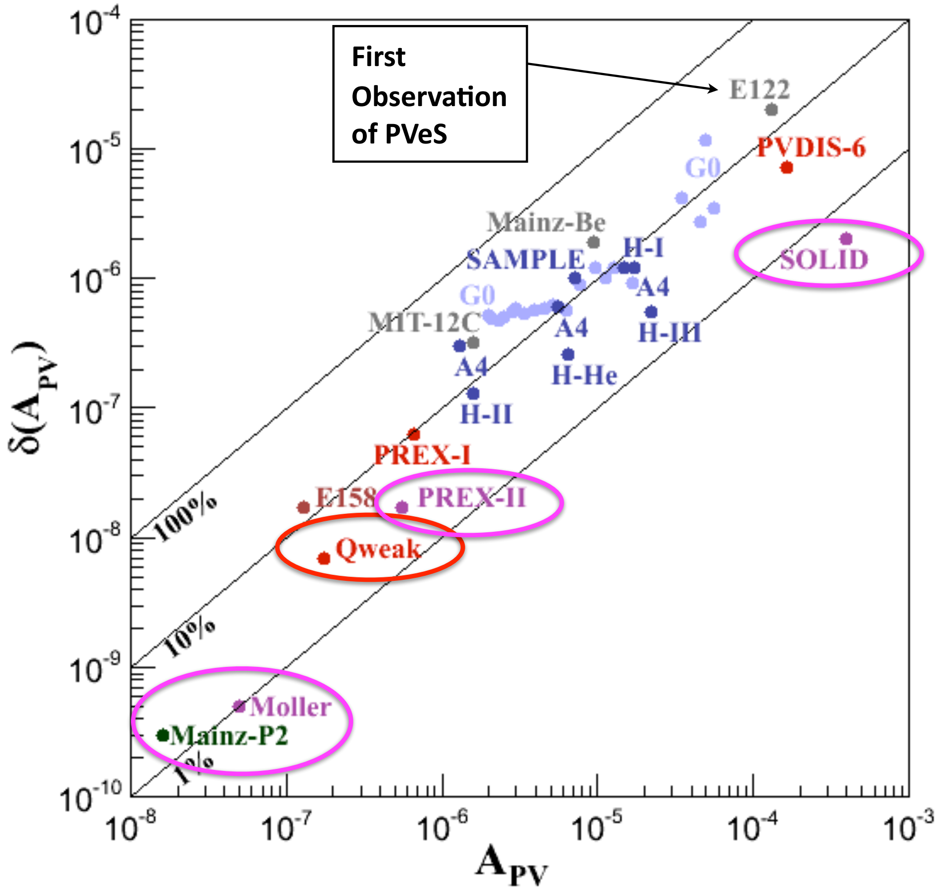
Definitive answer on gauge structure of electroweak interaction

	Left	Right
γ Charge	$q=0,\pm1,\pm\frac{1}{3},\pm\frac{2}{3}$	$q=0,\pm1,\pm\frac{1}{3},\pm\frac{2}{3}$
W Charge	$T=\pm\frac{1}{2}$	zero
Z Charge	$T-q\sin^2\theta_W$	$-q\sin^2\theta_W$



The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

Progress in PVeS studies

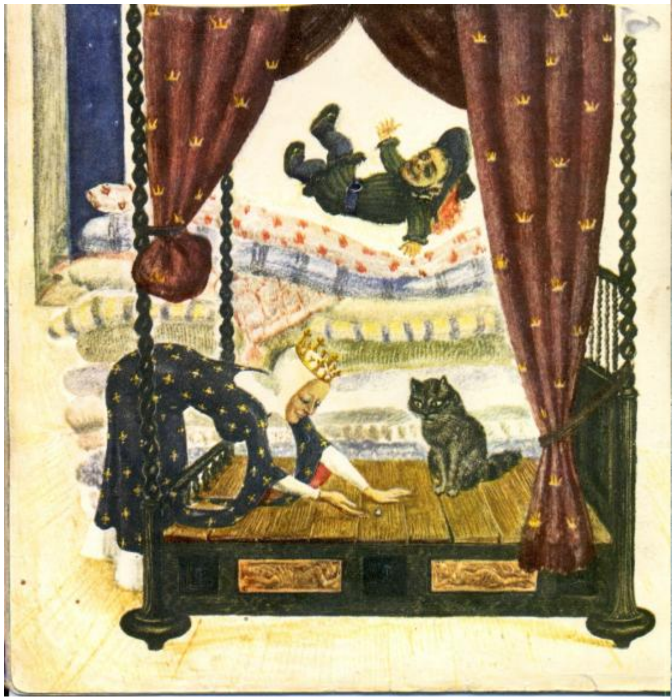
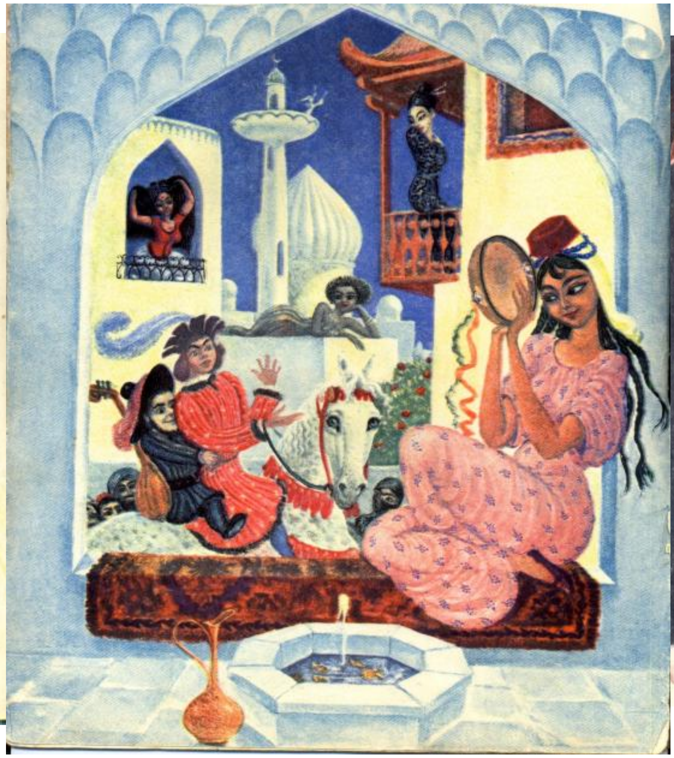


Broad program studying the structure of protons and nuclei, and searching for new (beyond Standard Model) physics

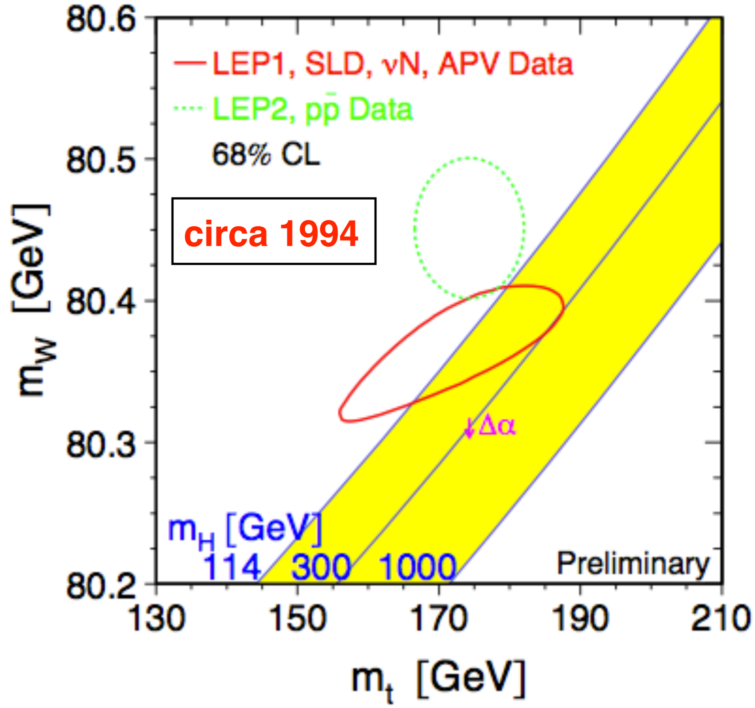
Beyond the Standard Model with Precision at Low Energies

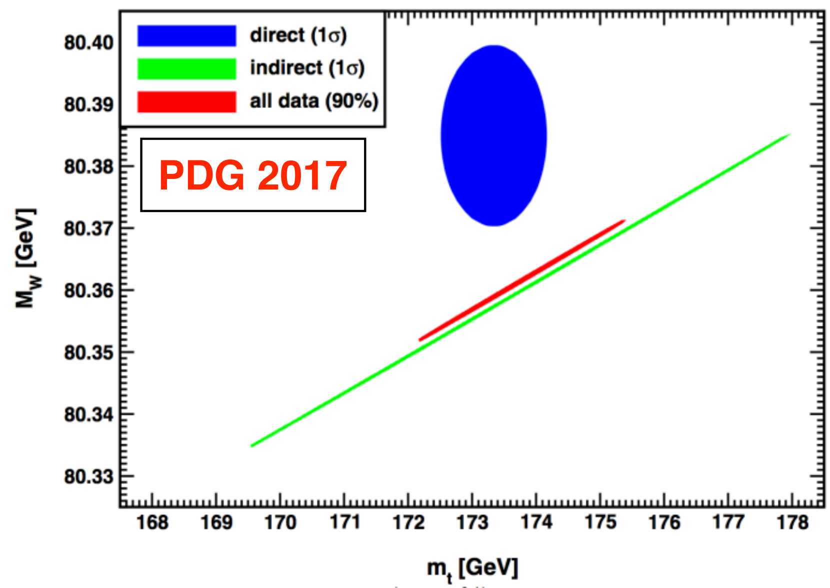
Direct vs Indirect Searches

(according to Hans Christian Andersen)


Discovery of the Top

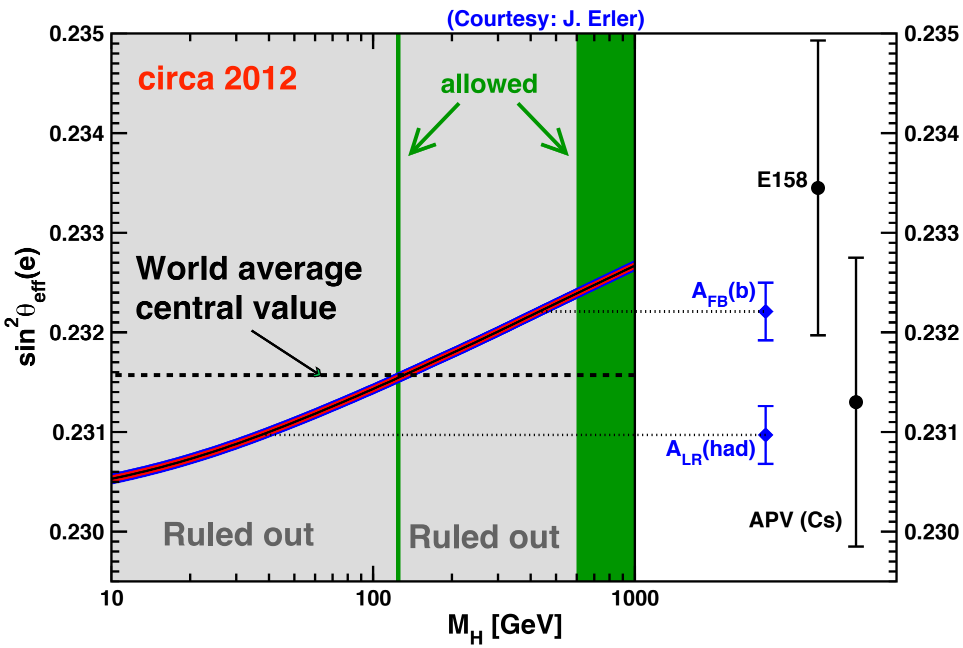




Glashow (spoke at UH, in 1995)

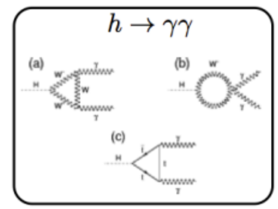
The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman *"for elucidating the quantum structure of electroweak interactions in physics"*

Discovery of the Higgs Boson

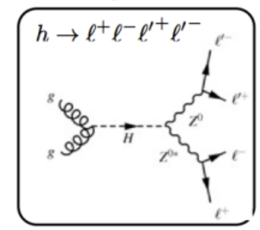


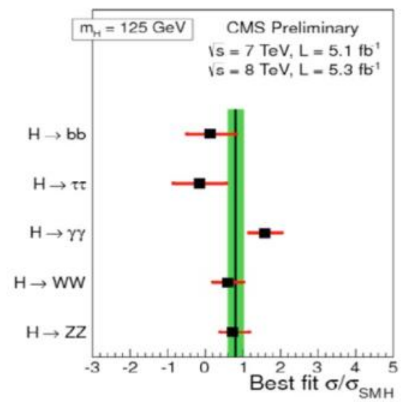
Good match to SM Higgs predicted signals

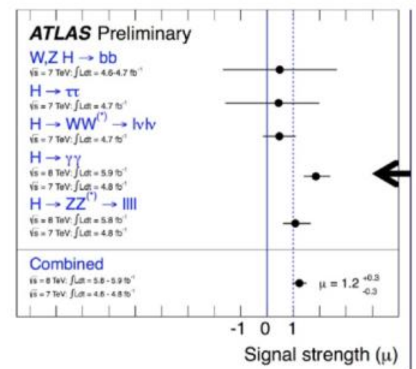
- H →γγ



- H → ZZ* → 4 leptons





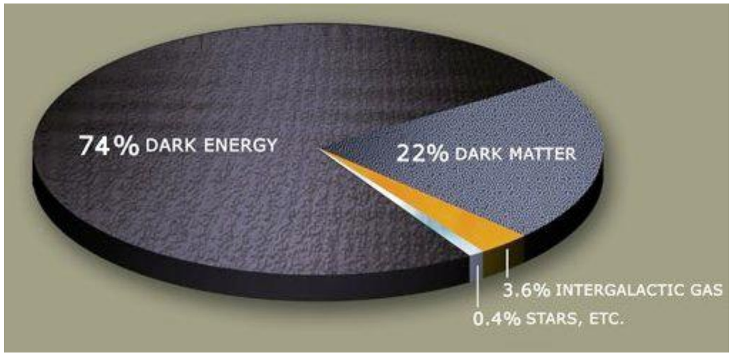


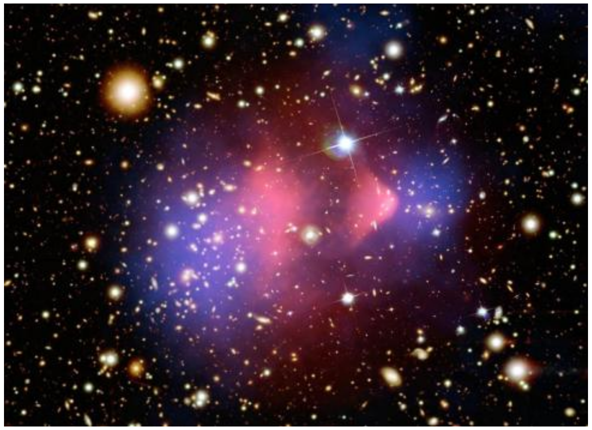
Amazing consistency of the SM prediction, between directly measured m_H, m_W, m_t, $\sin^2\theta_W$

So, what's wrong with the Standard Model?

Too many parameters, so much fine-tuning...

Cosmology says that we know nothing about most everything!





Neutrino mass - not incorporated, not known, not explained

Baryon asymmetry - where is the antimatter corresponding to our matter?

No role for gravity, even though gravity is fundamental to space-time

Fundamental Interactions at UVa

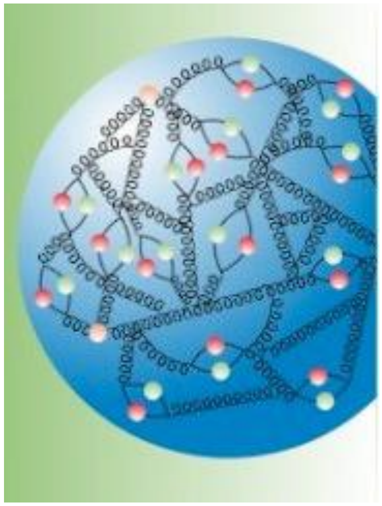
- Cox, Hirosky, Neu - CMS at CERN
- Dukes, Group - NOvA, Mu2e (Fermilab)
- Baessler, Pocanic - neutrons at SNS and ILL, mesons at PSI
- Paschke, Zheng, Cates, Liyanage - PVeS at JLab
- Arnold, Hung, Thacker, Vaman - Electroweak and QCD theory

What else don't we know?

A lot of physics focuses on extracting effective degrees of freedom from complex systems, that is, an attempt to model systems that cannot be calculated from the fundamental interactions

The complete Langrangian describing the strong force - Quantum Chromodynamics - is known.

At low (i.e. real-world) energies, it cannot be calculated.



The nucleon contains three quarks… embedded in a teeming sea of gluons, quarks, and anti-quarks.

The bare mass of the three quarks ~1% of the proton mass.
99% of the mass of the proton is in the sea!

The Higgs particle relates to the origin of mass for fundamental particles... but 99% of the mass of the proton lies in the excited vacuum!

With the discovery of the Higgs, 1% of 4% of the mass of the universe is explained...

Probing QCD in nucleon and nuclear structure:
Cates, Crabb, Day, Liyanage, Norum, Paschke, Zheng
Theory: Liuti

The QWeak Experiment: Peering Beyond the Standard Model with PVeS

New Physics with Precision at Low Energies

Low Q^2 offers complementary probes of new physics at multi-TeV scales

EDM, g_μ-2, weak decays, β decay, $0\nu\beta\beta$ decay, DM, LFV…

Parity-Violating Electron Scattering: *Low energy weak neutral current couplings (SLAC, Jefferson Lab, Mainz)*

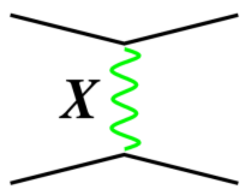
Many new physics models give rise to new neutral current interactions

Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

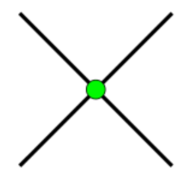
$$\mathcal{L} = \mathcal{L}_{\mathtt{SM}} + \mathcal{L}_{\mathtt{new}}$$

Low energy NC interactions ($Q^2 << M_Z^2$)

Heavy mediators = contact interactions



$$A_X \propto \frac{1}{Q^2 - M_X^2} \sim \frac{4\pi}{\Lambda^2}$$



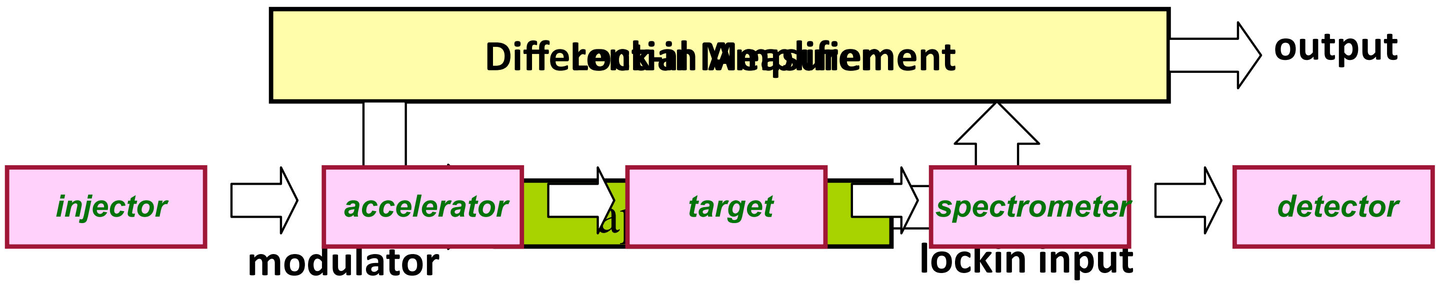
Contact interaction

for **each fermion** and **handedness** combination
reach, characterized by mass scale Λ, coupling g

Measuring APV

Goal: 10^{-7} asymmetry measurement at the few percent level

How do you pick a tiny signal out of a noisy environment?



Measure fractional rate difference between opposing helicity states

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

A_{measured} ~ -200 ppb with 4% precision
N ~ 1×10^{16} electrons!

High rates to get statistical precision, but also:

Control Noise - quiet electronics, luminosity stability

Low backgrounds - must be known PV asymmetry

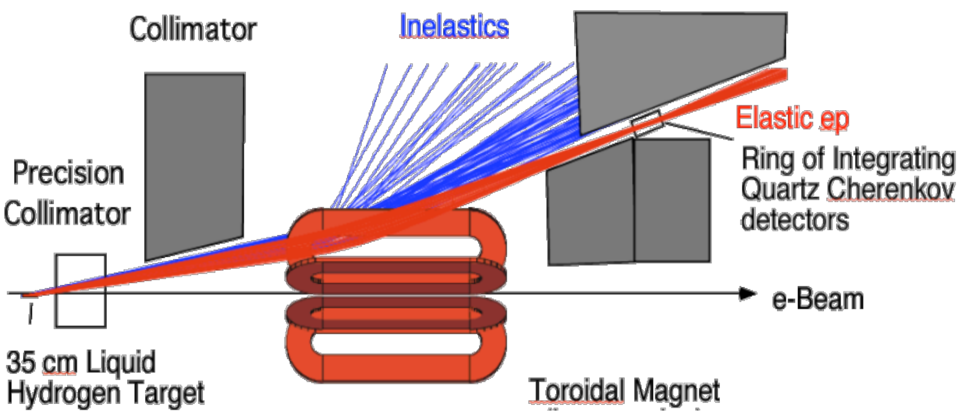
Polarimetry - Can't do better on A_{PV} than on P_{beam}

Kinematics - Interpretation requires Q^2 precision

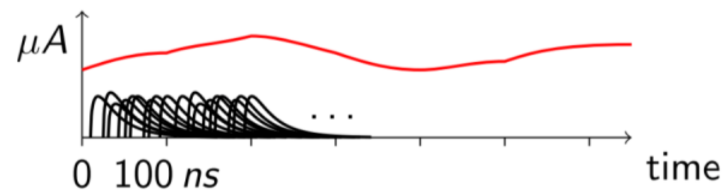
False Asymmetries - electronics, beam motion... ?

Measuring A_{PV}

Elastic signal focused on detector



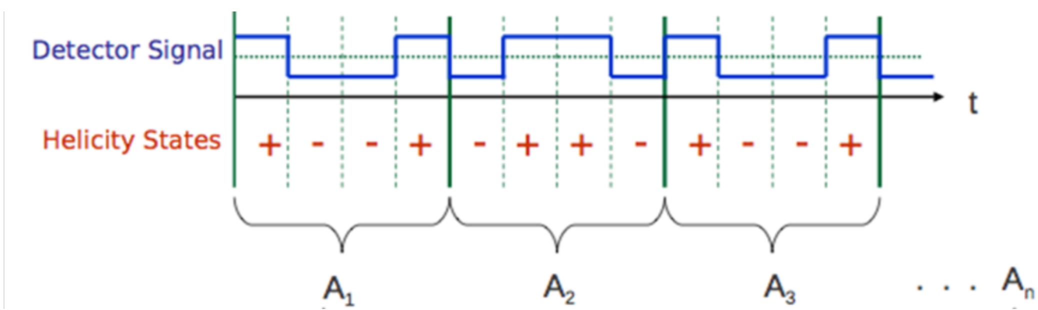
Analog integration of detector current

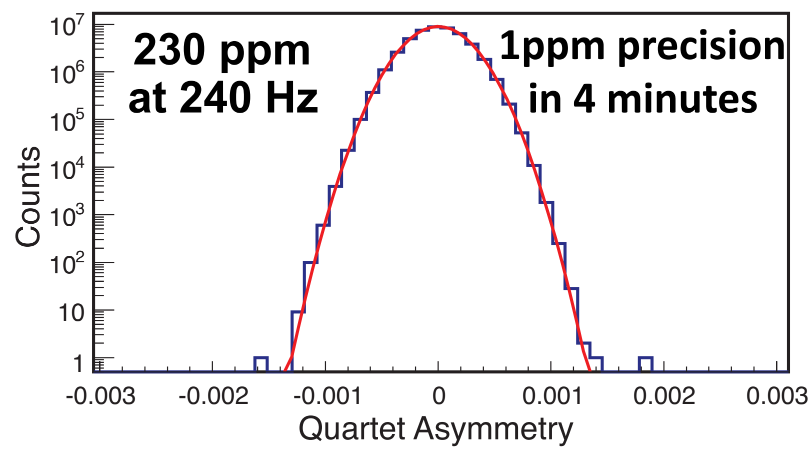


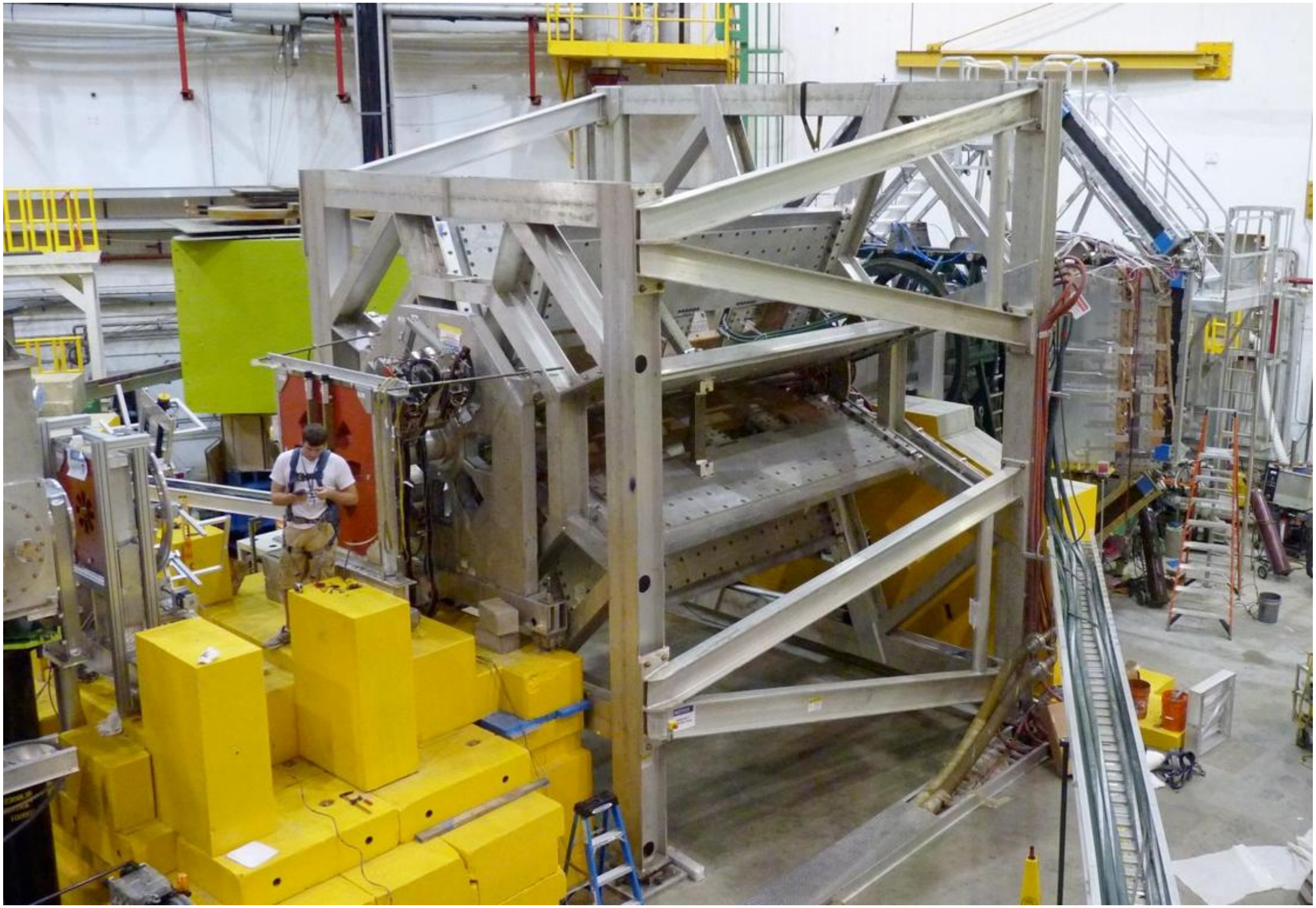
~6 GHz total rate

1 GeV, 180 μA, 1.5 years

Rapid (1kHz) measurement over helicity reversals to cancel noise





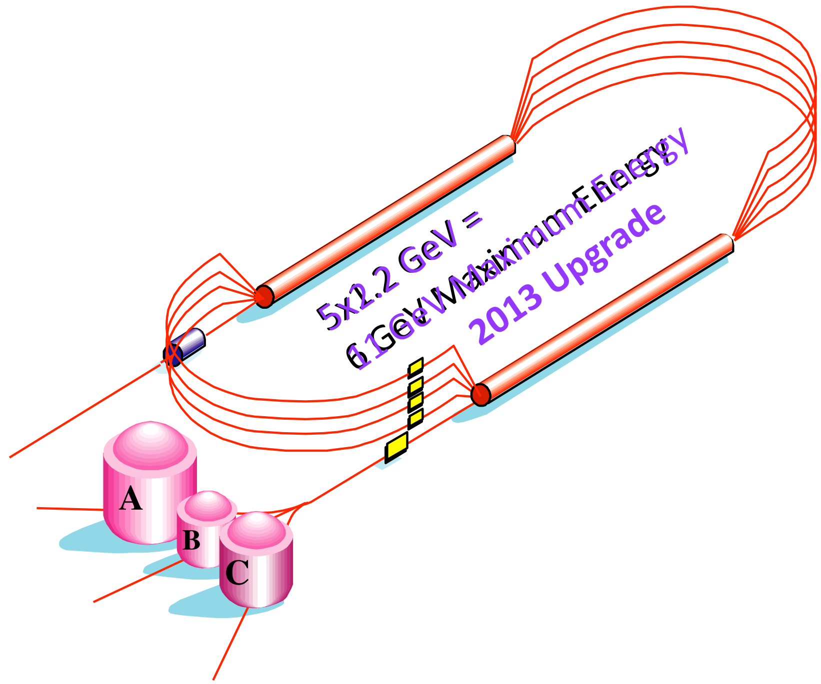


CEBAF at JLab

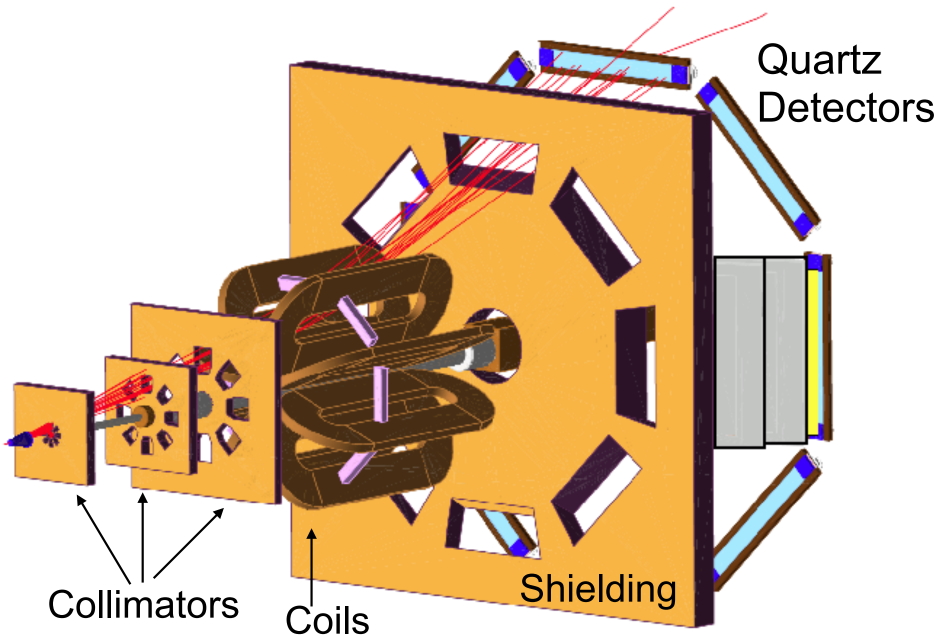
Superconducting, continuous wave, recirculating linac

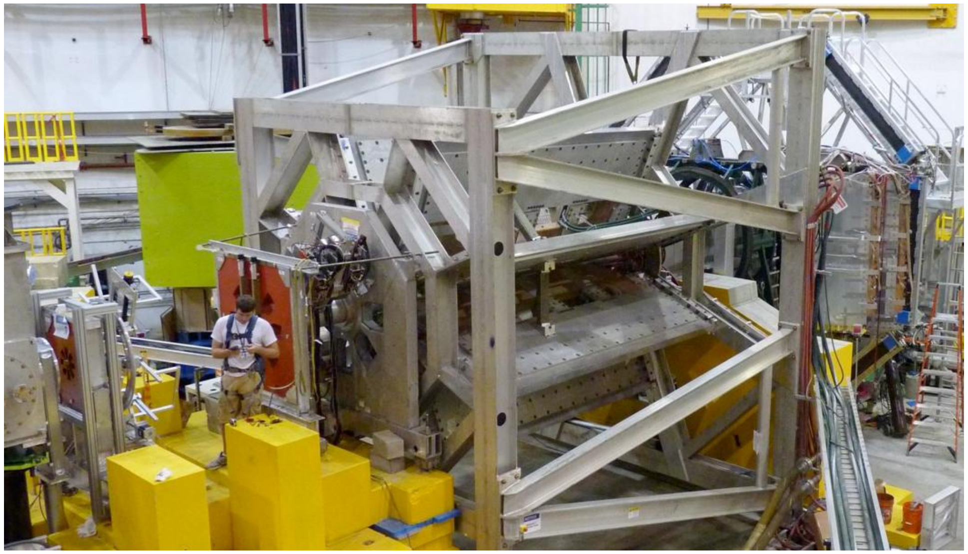
1500 MHz RF, with 3 interleaved 500 MHz beams

“Cold” RF is makes a clean, quiet beam...
perfect for precision experiments

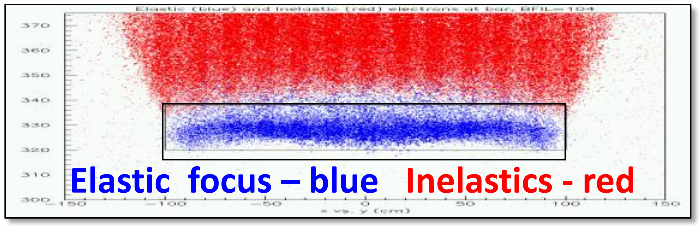


The Qweak Spectrometer



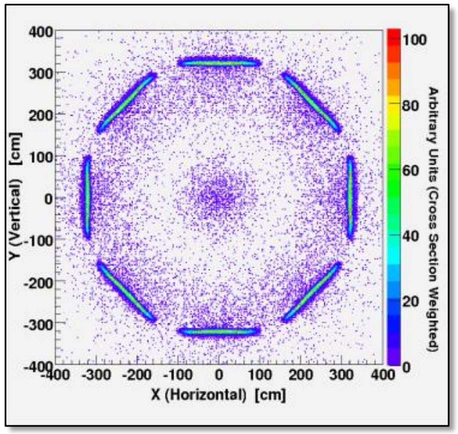


Toroidal Spectrometer separates elastics into each of 8 detectors

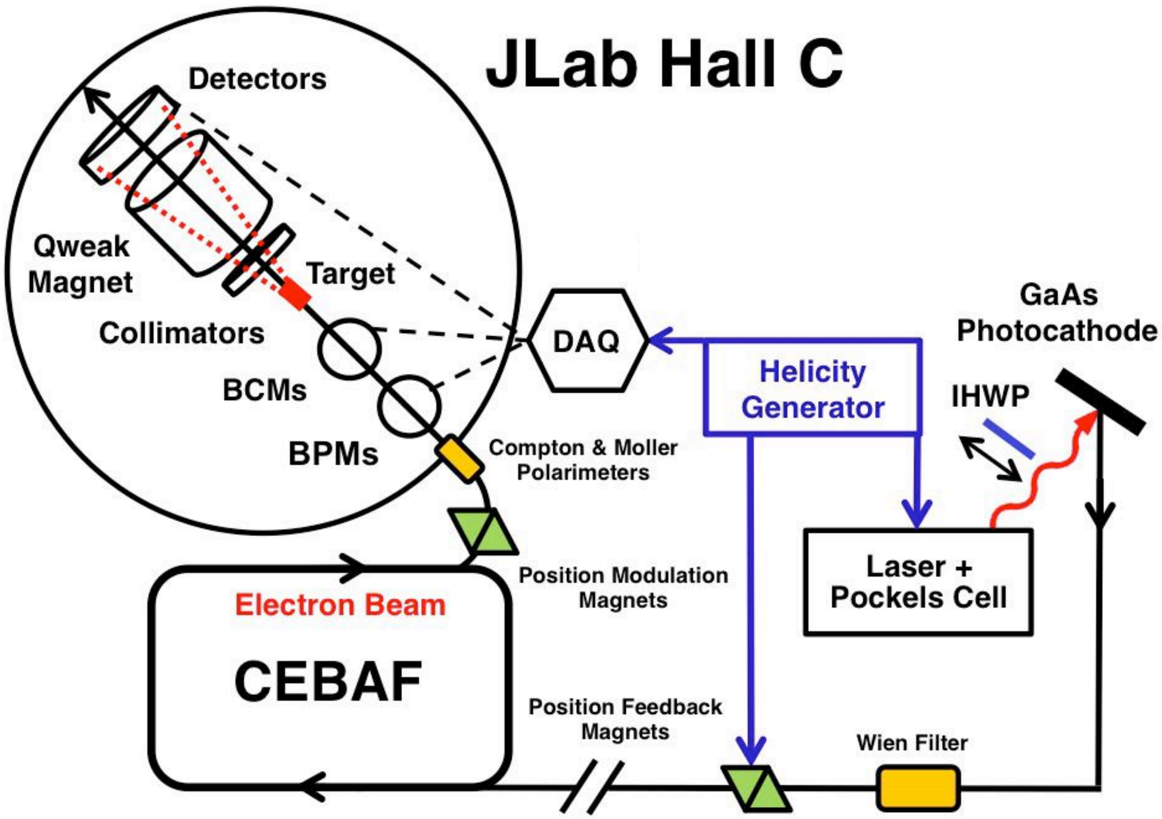


Each detector:

- 2 meters long
- lead radiator, fused silica
- Cerenkov light from shower
- collected by phototube at each end

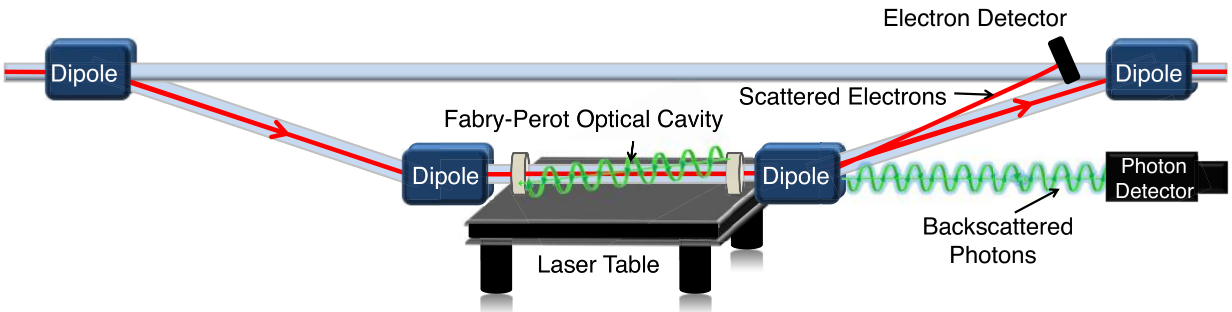


The Entire Accelerator Complex is our Apparatus

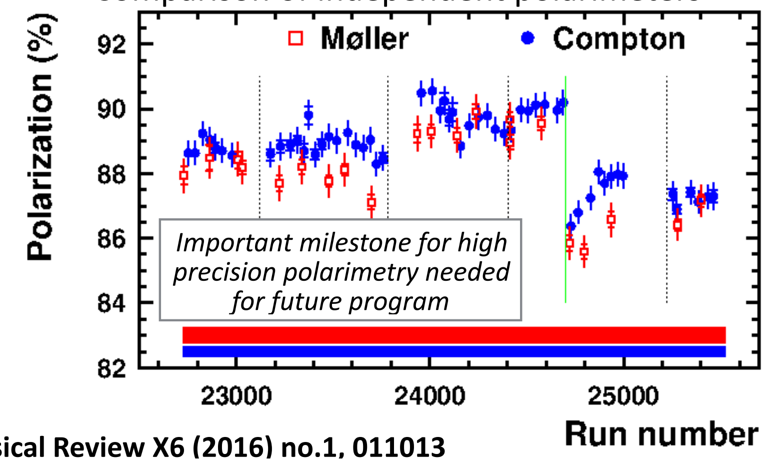


- Polarized Source Laser - rapid reversal, keep spin states the same intensity, position, shape…
- Spin Manipulation - crossed E and B fields, to rotate spin in low energy injector
- Position/Energy Modulation - for calibrating detector sensitivity
- Polarimeters
- Precise monitors for beam current and position

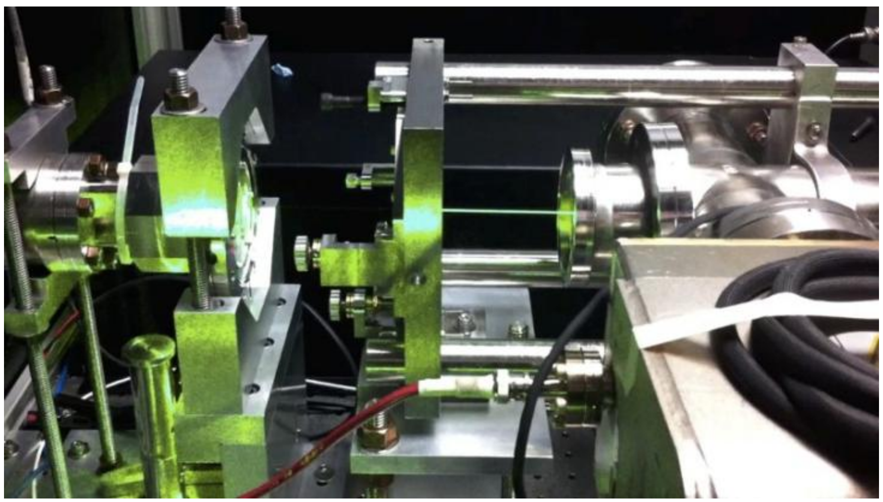
Compton Polarimeter

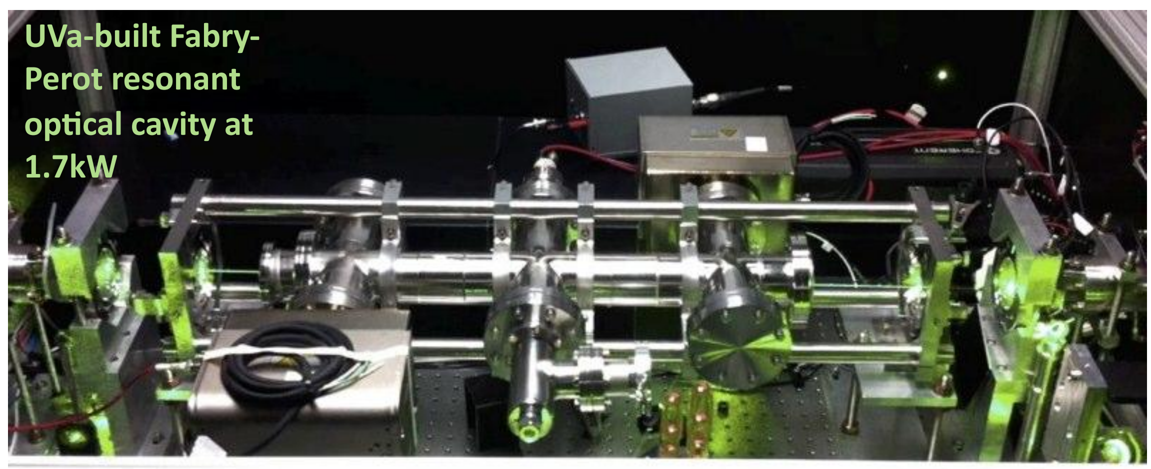


Comparison of independent polarimeters



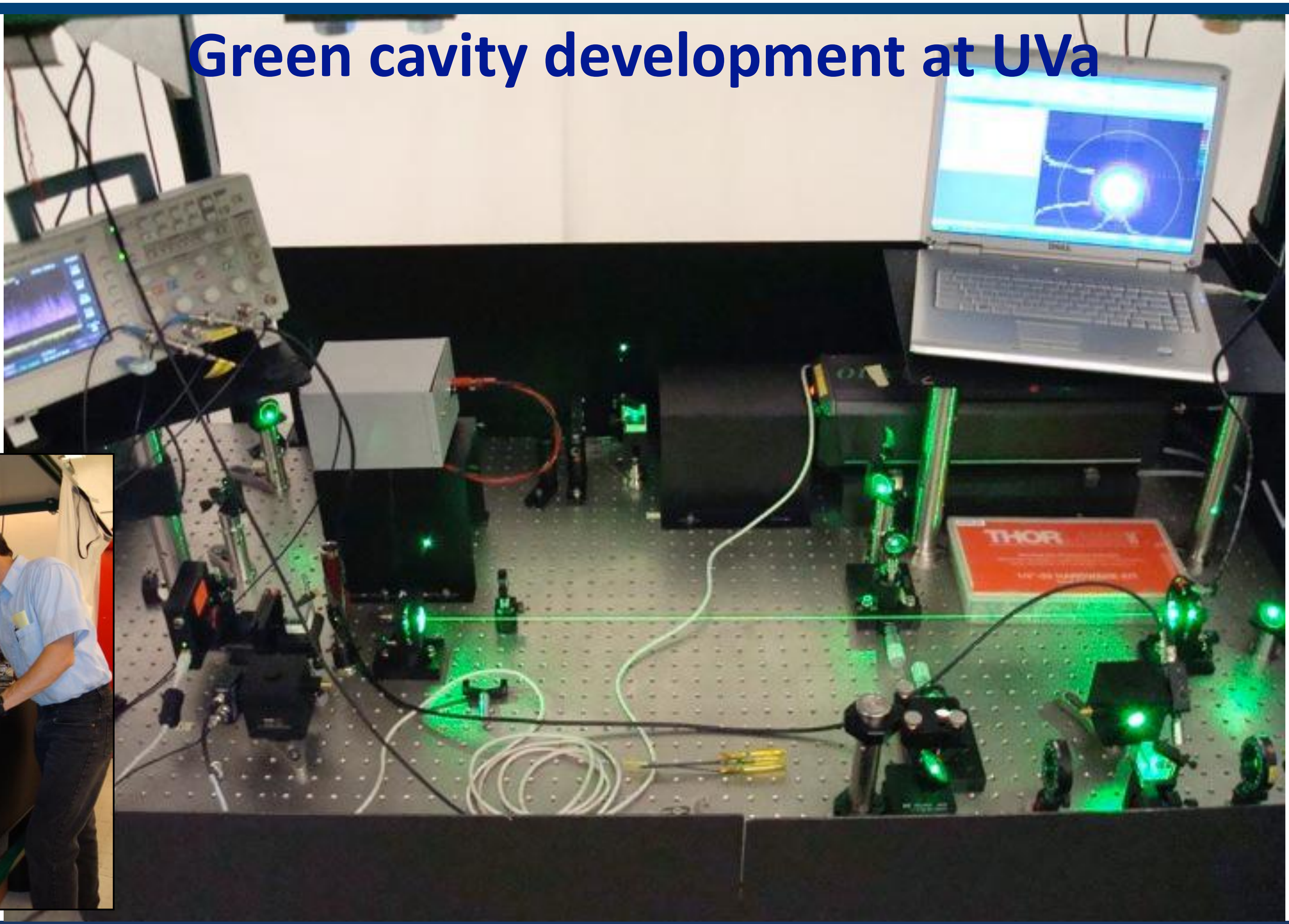
Physical Review X6 (2016) no.1, 011013





Result: ~0.6% precision on 89% polarization

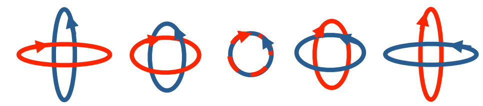
Green cavity development at UVa

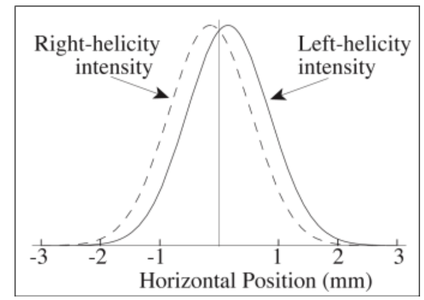


Controlling Beam Asymmetries

- •Photoemission from GaAs photocathode
- •Rapid-flip of beam helicity by reversing laser polarization
- •Pockels cell to flip laser polarization
- •Beam must look the same for the two polarization states
- •Photocathode has preferred axis: analyzing power for linear light

A non-zero 1st moment creates a position difference

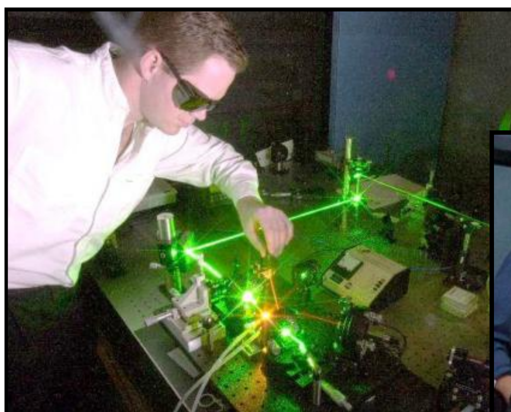


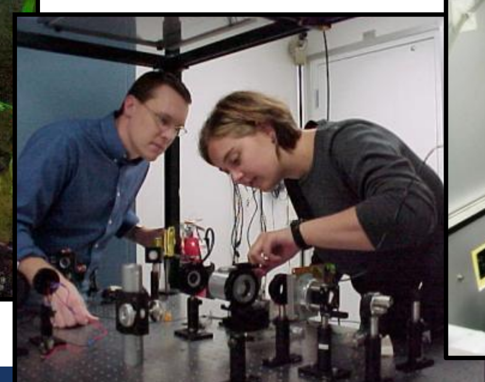


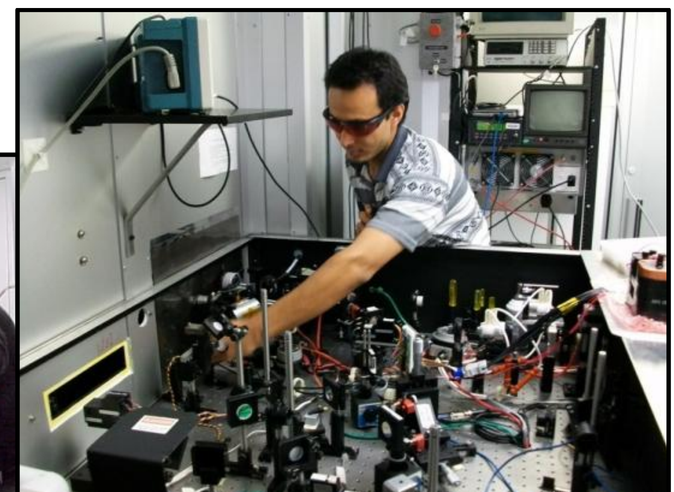
Qweak

X	-2.7 nm
X’	-0.14 nrad
Y	-1.9 nm
Y’	-0.05 nrad
Energy	-0.6 ppb

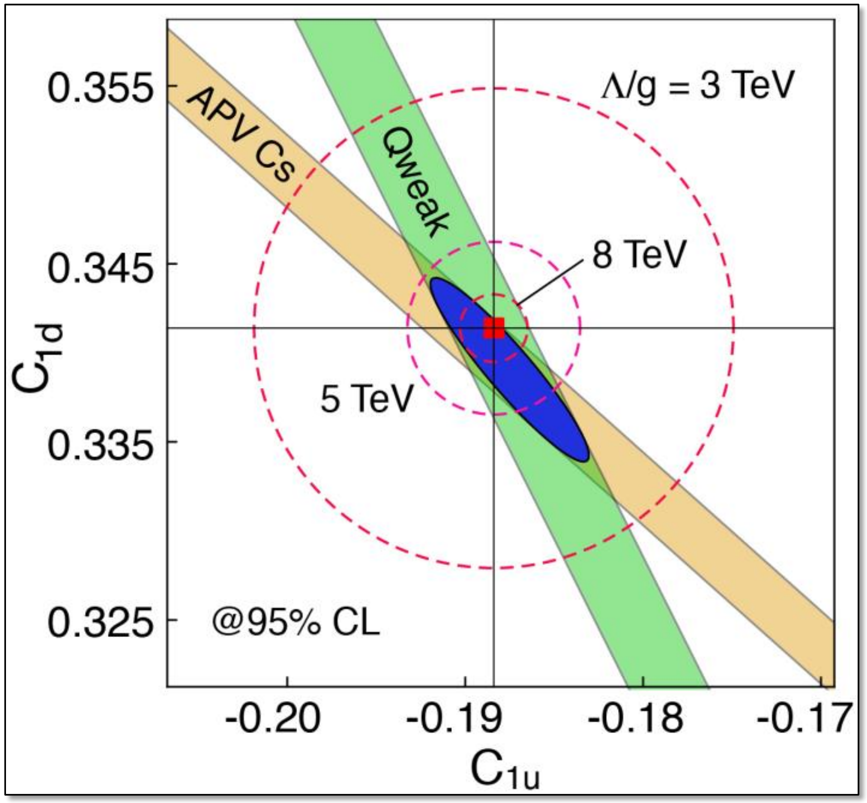
Manolis Kargiantoulakis







New Result from Qweak



Fit with APV in ^{133}Cs

with usual convention for contact interactions

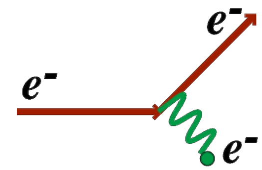
$$g = \sqrt{4\pi}$$

the exclusion limits are

$$\frac{\lambda}{g} \approx 7.5\ \mathrm{TeV} \rightarrow \lambda \approx 27\ \mathrm{TeV}$$

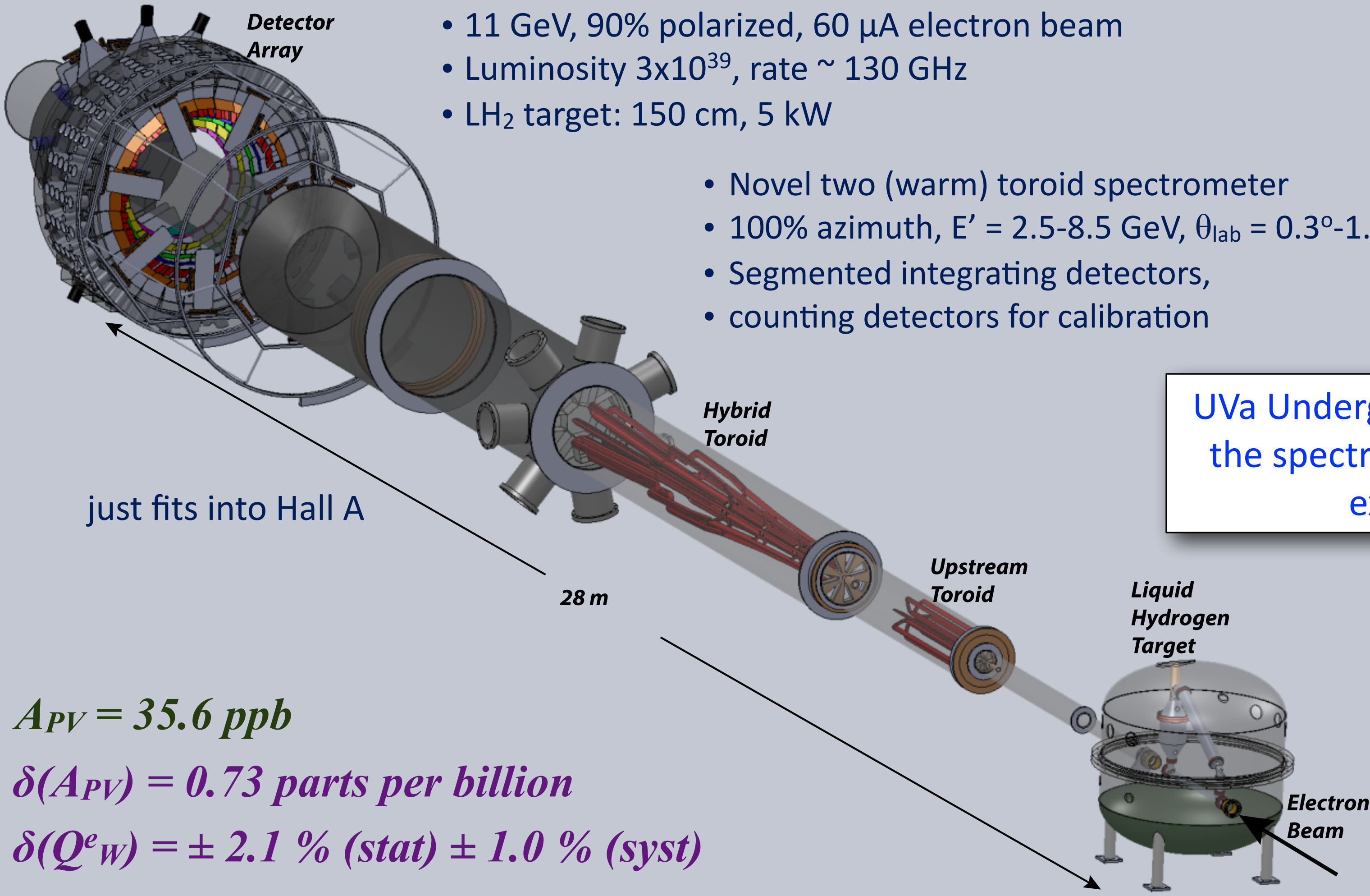
Future: MOLLER at 11 GeV JLab

- 11 GeV, 90% polarized, 60 µA electron beam
- Luminosity 3×10^{39}, rate ~ 130 GHz
- LH_2 target: 150 cm, 5 kW



Q^e_W

- Novel two (warm) toroid spectrometer
- 100% azimuth, E' = 2.5-8.5 GeV, $\theta_{lab} = 0.3^o$-1.1^o
- Segmented integrating detectors,
- counting detectors for calibration



just fits into Hall A

UVa Undergrad Clayton Davis designed the spectrometer at the heart of this experimental effort

$A_{PV} = 35.6$ *ppb*

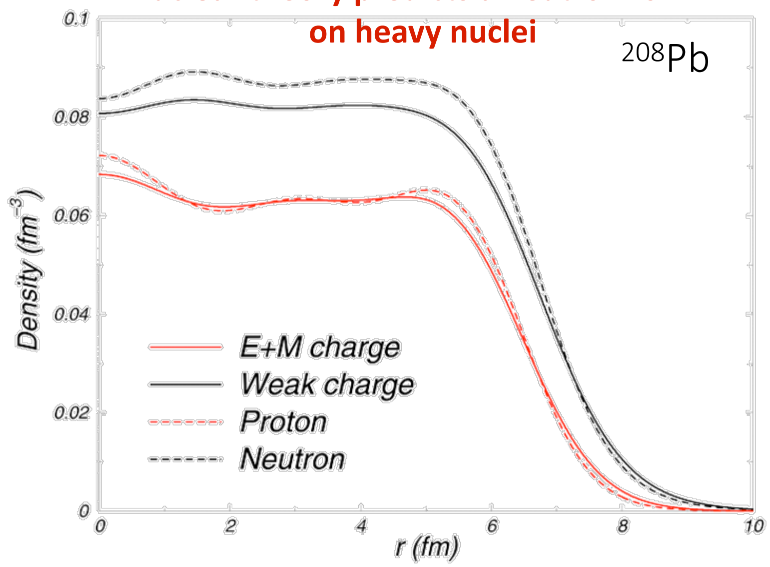
$\delta(A_{PV}) = 0.73$ *parts per billion*

$\delta(Q^e_W) = \pm 2.1\ \%\ (stat) \pm 1.0\ \%\ (syst)$

Outlook:
- **~25M$ required**
- **2-3 years construction**
- **3-4 years running**

Weak Charge Distribution of Heavy Nuclei

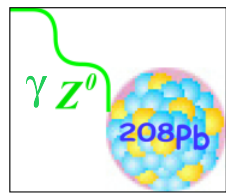
Nuclear theory predicts a neutron "skin" on heavy nuclei

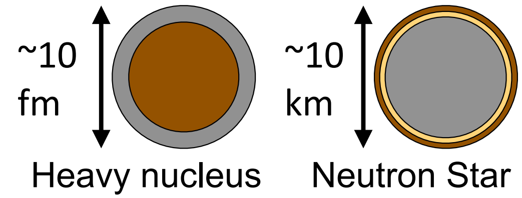


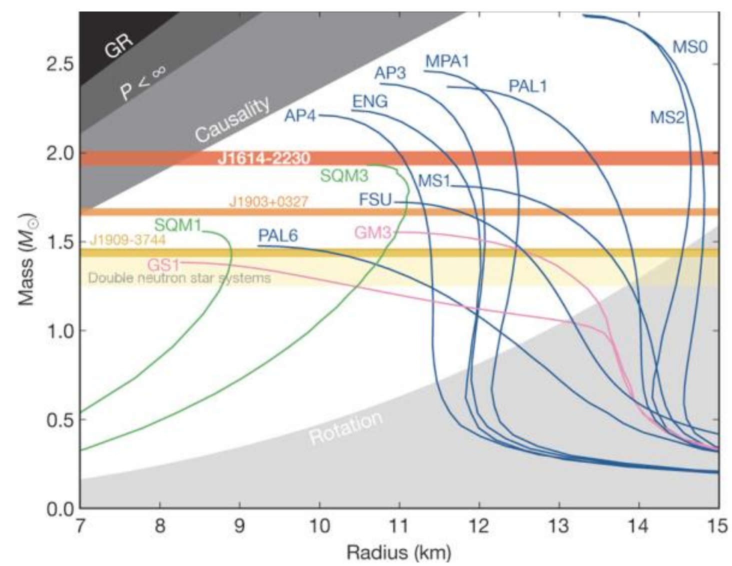
	proton	neutron
Electric charge	**1**	**0**
Weak charge	**~0.08**	**1**

for spin-0 nucleus

$$A_{\rm PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_W}{F_{ch}}$$



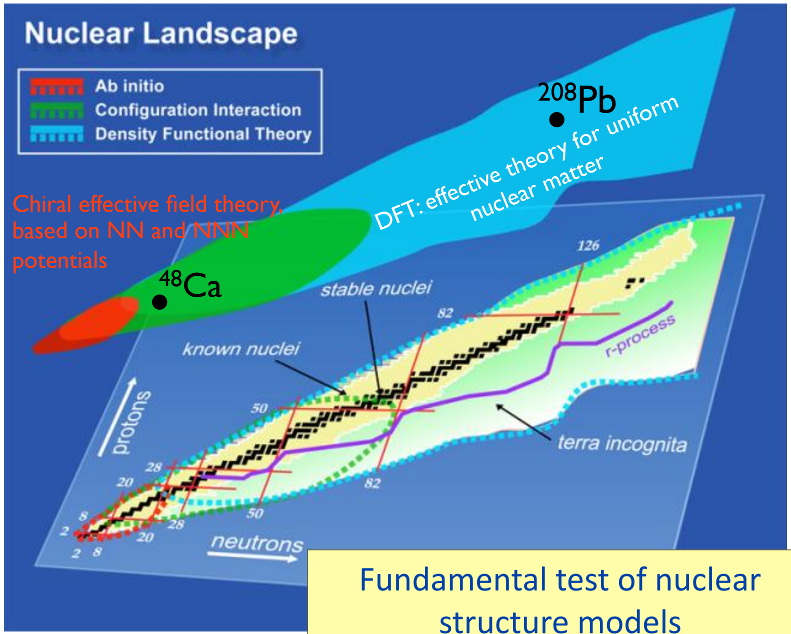




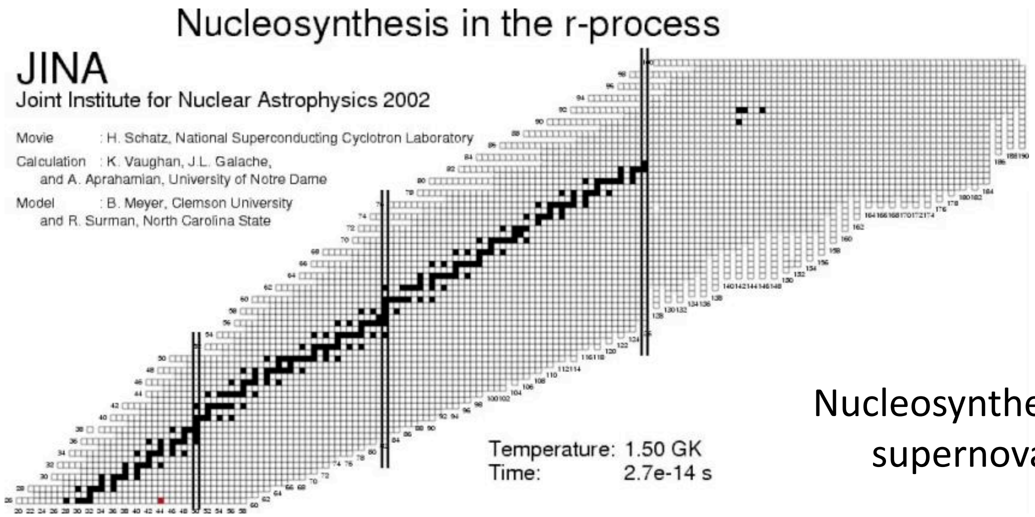
- Neutron skin thickness is highly sensitive to the pressure in neutron-rich matter.
- The greater the pressure, the thicker the skin as neutrons are pushed out against surface tension.

Knowledge of r_n highly model dependent, not well constrained by robust measurements

Nuclear Structure Models Reach Back to the Cradle of Our Raw Material



Fundamental test of nuclear structure models



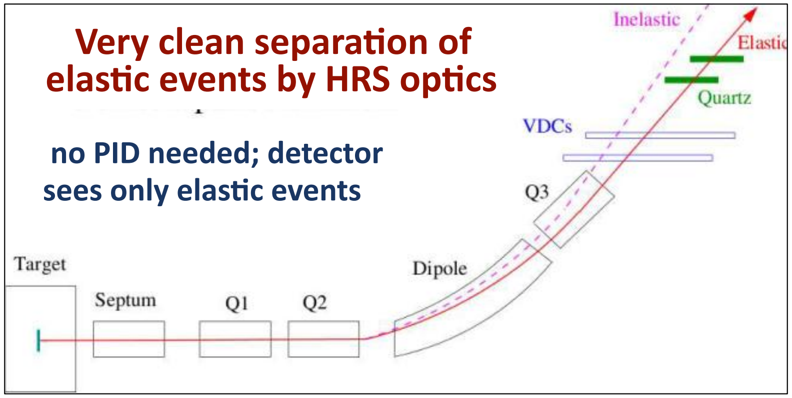
Nucleosynthesis in supernovae

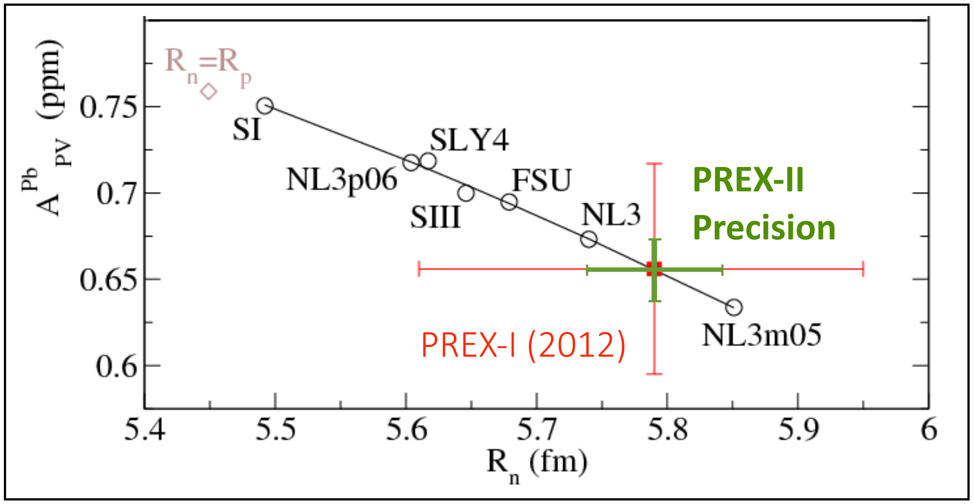
Measuring Neutron Skins at JLab

PREX (^{208}Pb)
- important check on nuclear structure data set
- uniform nuclear matter
- terrestrial laboratory for n-star matter

CREX (^{48}Ca)
- isovector probe in moderate size system
- finite size effects
- Within reach of microscopic calculations

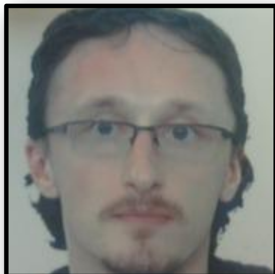
Spring 2019:
PREX (3% APV, rn to 0.06 fm)
CREX (2.5% APV, rn to 0.02 fm)

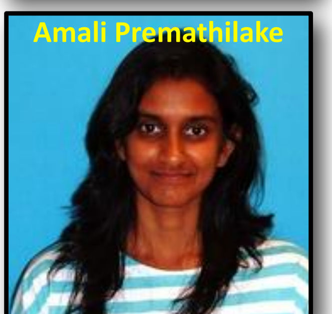




Nuclear and Electroweak Symmetries Group

Ciprian Gal
(postdoc)





Not pictured:
Paul Landini

Technical R&D and analysis techniques for polarimetry and control of false asymmetries

Development of future experiments (PREX, CREX, MOLLER and PV-DIS)

<u>Former Group Members</u>

Recent Undergrads:
Ricky Elwell
Ben Gilbert