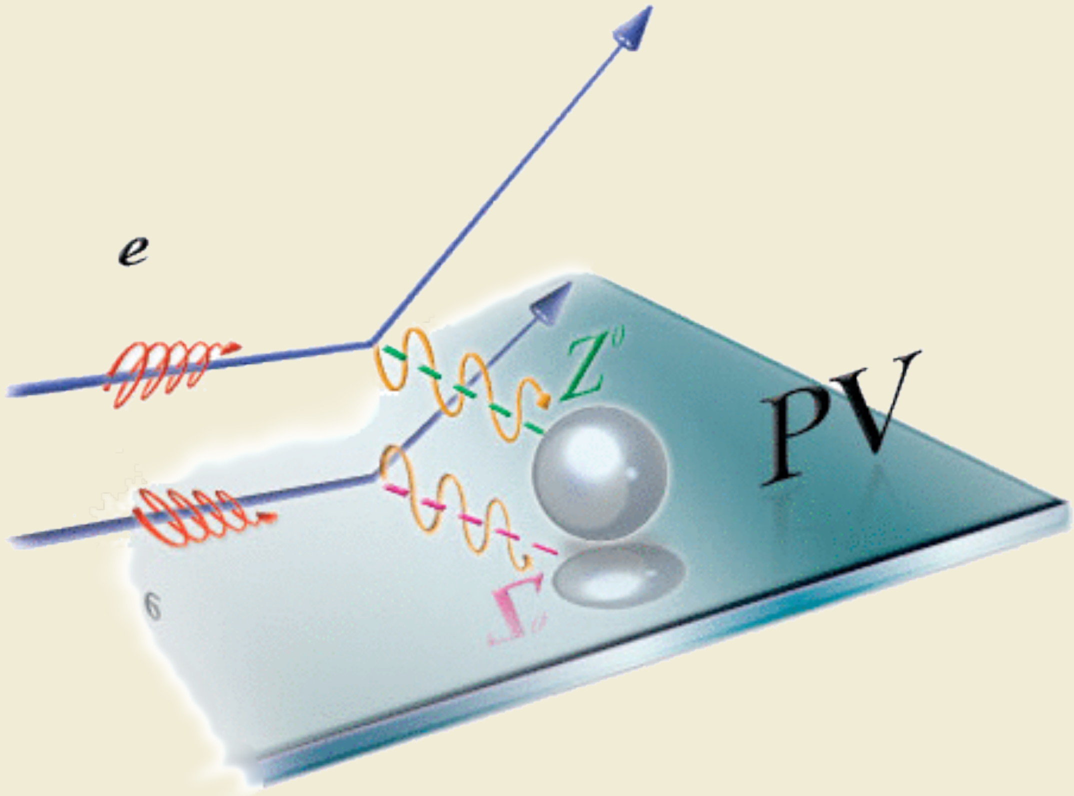
Electrons and Mirror Symmetry

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



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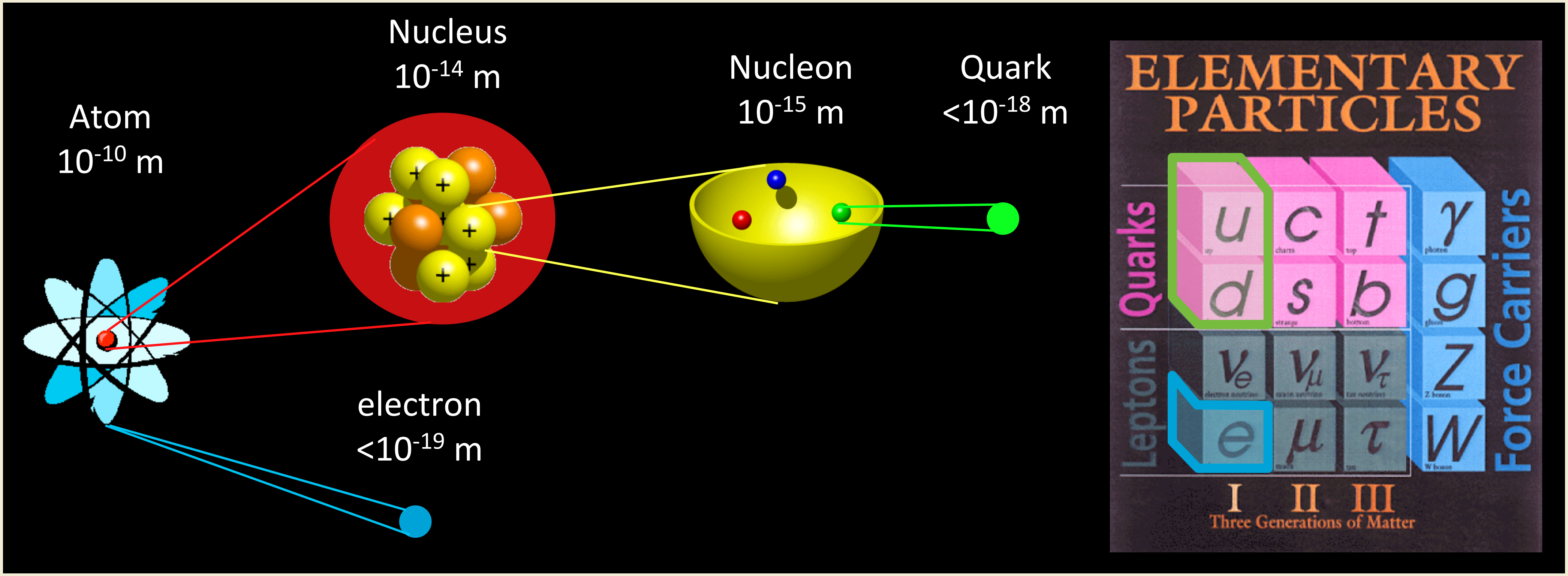
The present and future program of parity-violating electron scattering

- Framing the question: electron scattering, mirror symmetry, and the electroweak interaction
- Experimental Techniques
- An important question about VERY big nuclei
- Using parity-violation to fish in the nucleon sea
- Indirect searches for new physics

Matter and Interactions

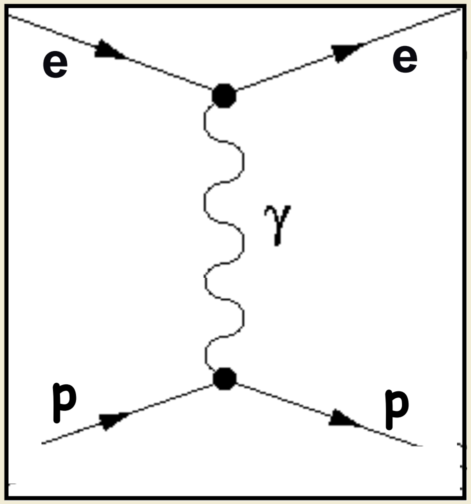
	Gravity	Weak	Electromagnetic	Strong
		Electroweak		
mediator	(not found)	W^+, W^-, Z^0	γ	gluons
acts on	all	quarks and leptons	Electrically charged	quarks and gluons
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

One unified framework for weak and electromagnetic interactions



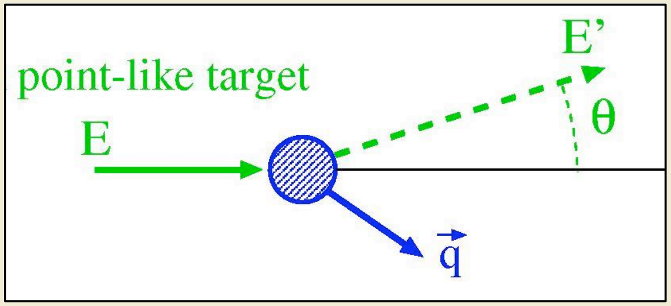
Introduction to electron scattering

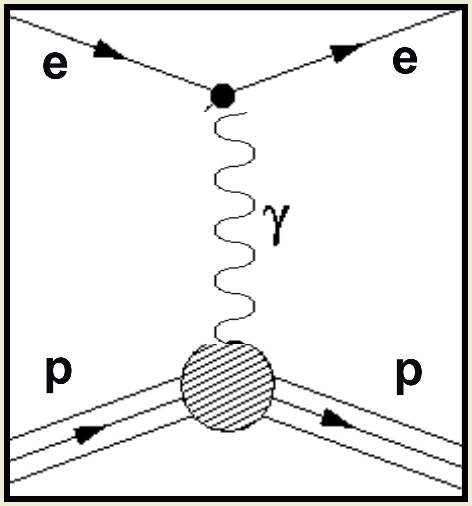
Electron scattering: electromagnetic interaction, described as an exchange of a virtual photon.



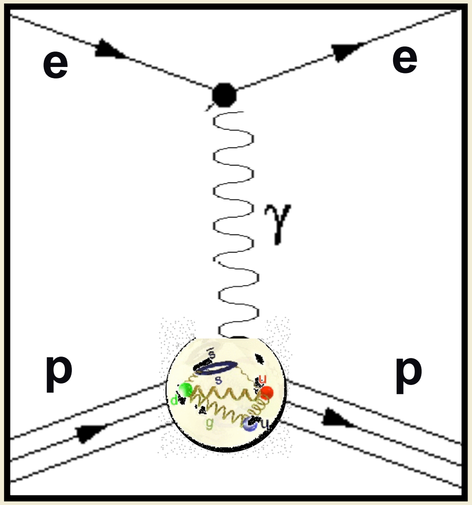
If photon carries low momentum
-> long wavelength
-> low resolution

Q^2: 4-momentum of the virtual photon





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

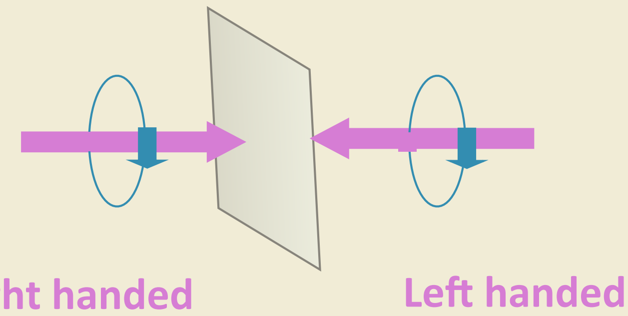


Parity Symmetry

Parity transformation

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

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



Helicity: spin in direction of motion

$$h = \vec{S} \cdot \vec{p} = \pm 1$$

Parity transformation is analogous to reflection in a mirror:

. . . reverses momentum but preserves angular momentum

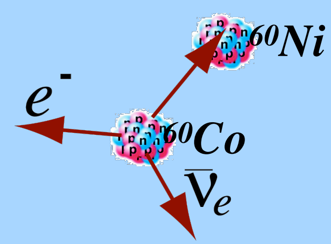
. . .takes right-handed (helicity = +1) to left-handed (helicity = -1).

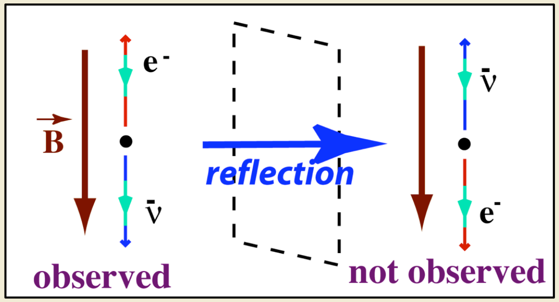
Parity symmetry:

interaction must be the same after parity transformation

1957 – Parity Violation observed

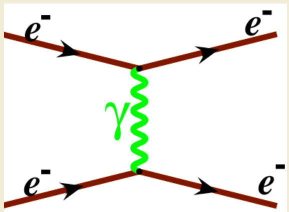
Weak decay of ^{60}Co Nucleus



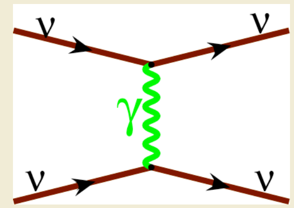


Charge and Handedness

Electric charge determines strength of electric force



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



observed

not observed

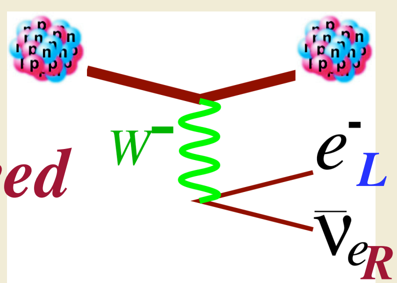
Weak charge determines strength of weak force

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

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

^{60}Co

observed

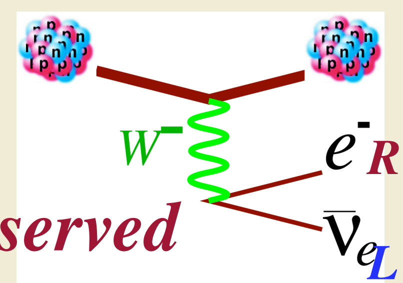


^{60}Ni

right-handed
anti-neutrino

^{60}Co

not observed

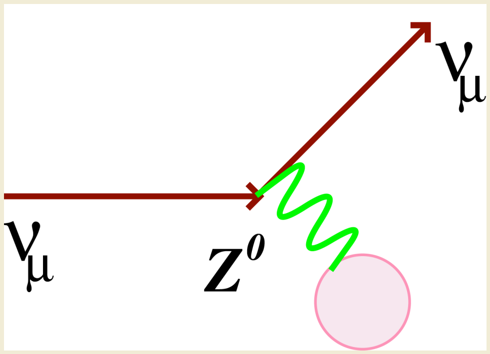


^{60}Ni

left-handed
anti-neutrino

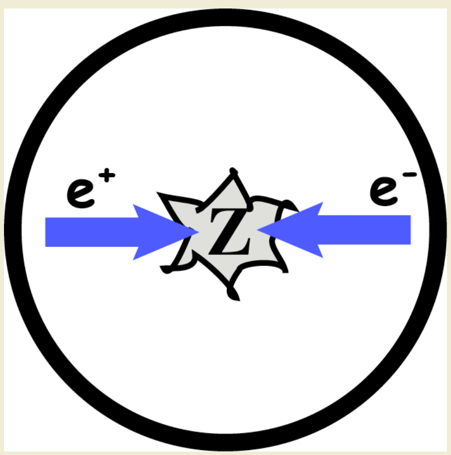
Neutral Weak Force

Electroweak unification implied a pattern of neutral weak charges with only one free parameter: θ_W



Neutral weak interaction first measured in the early '70s

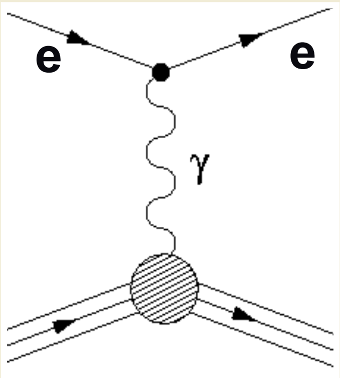
Z bosons produced in electron-positron collisions: precise measurements of Z charge of most fermions



	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	$T = \pm \frac{1}{2}$	0
Z Charge	$T - q \sin^2 \theta_W$	$-q \sin^2 \theta_W$

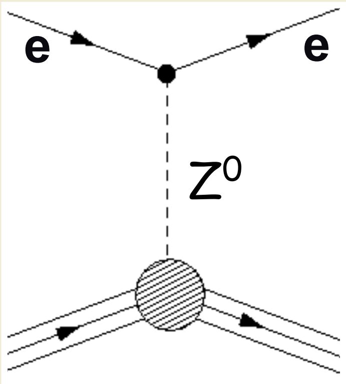
Measurements of Z mass, Z charges validated the electroweak theory

Electron scattering, weakly



Electron scattering is (mostly) electromagnetic scattering.

The weak amplitude is ~10^{-6} smaller.

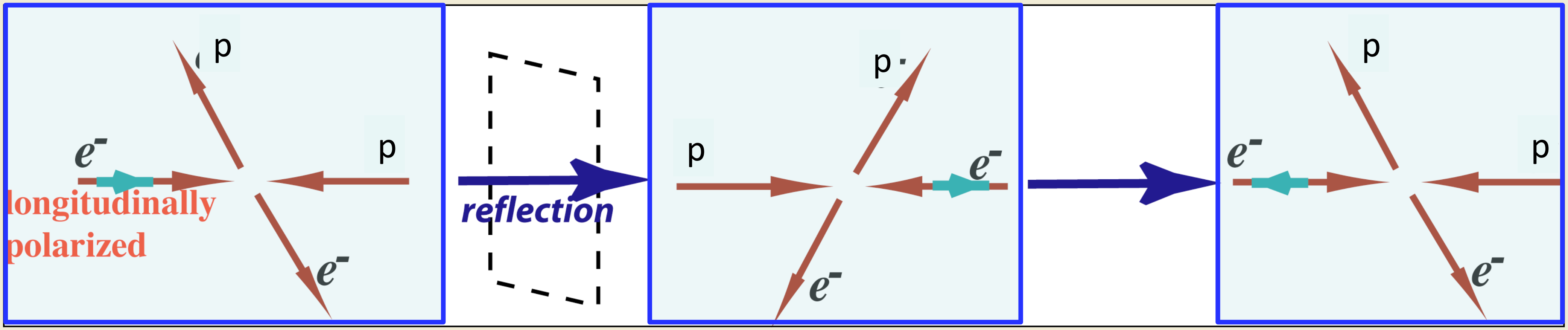


The weak quark charges are different than the EM charge. The weak interaction can be a valuable probe of nuclear matter, complementary to the extensive electromagnetic data set.

Fundamental Weak and EM interactions are predicted with very high precision, but with an apparently incomplete model. Can we find a crack in the Standard Model in precision measurements at low energy?

The challenge: Isolate the tiny effect of the weak interaction.

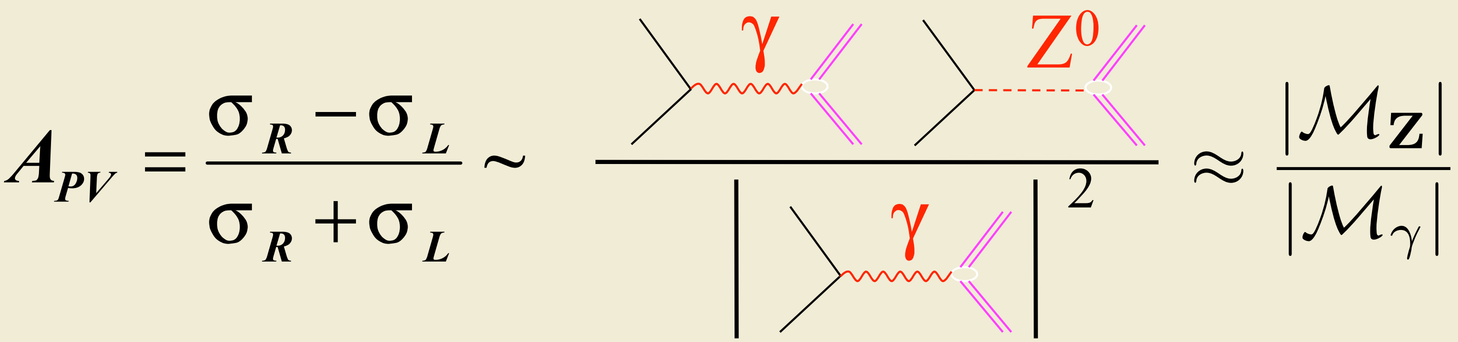
Mirror Asymmetry



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

$$\sigma = |\mathcal{M}_\gamma + \mathcal{M}_\mathbf{Z}|^2$$

Weak and EM amplitudes interfere:



A_{PV} ranges from 10^{-4}-10^{-7} (0.1-100 ppm)

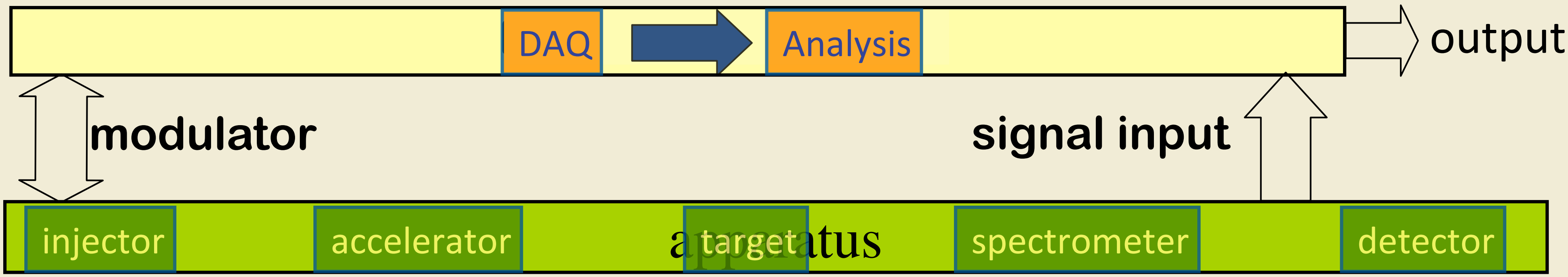
Experimental Technique

Experimental Technique

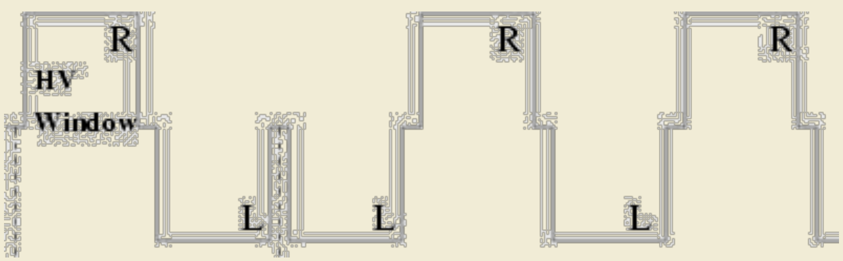
Goal: small asymmetry measured at the few percent level

$$A_{PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \approx 10^{-6} \quad \Rightarrow \quad \frac{\sigma_A}{A} = \frac{1}{A}\frac{1}{\sqrt{N}} = 10\% \quad \Rightarrow \quad N \sim 10^{14} \;!!!$$

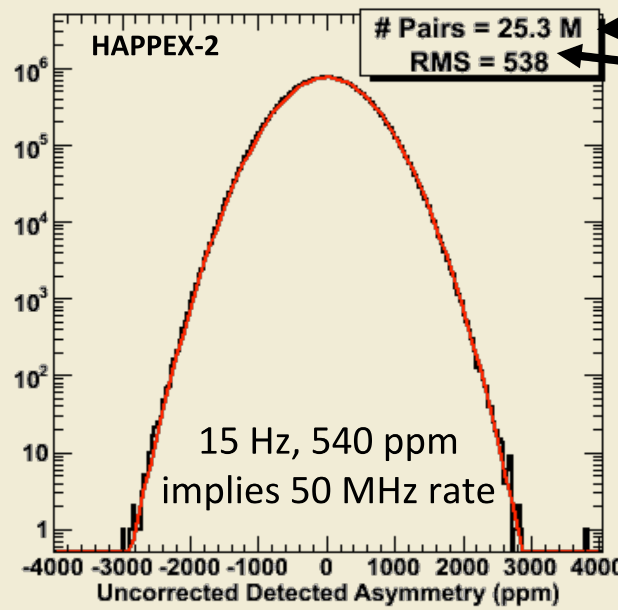
How do you pick a tiny signal out of a noisy environment?



Beam helicity pairs with fixed time intervals are ordered pseudo-randomly



helicity reversal is rapid (30 Hz - 1 kHz)



25 million trials

0.05% precision

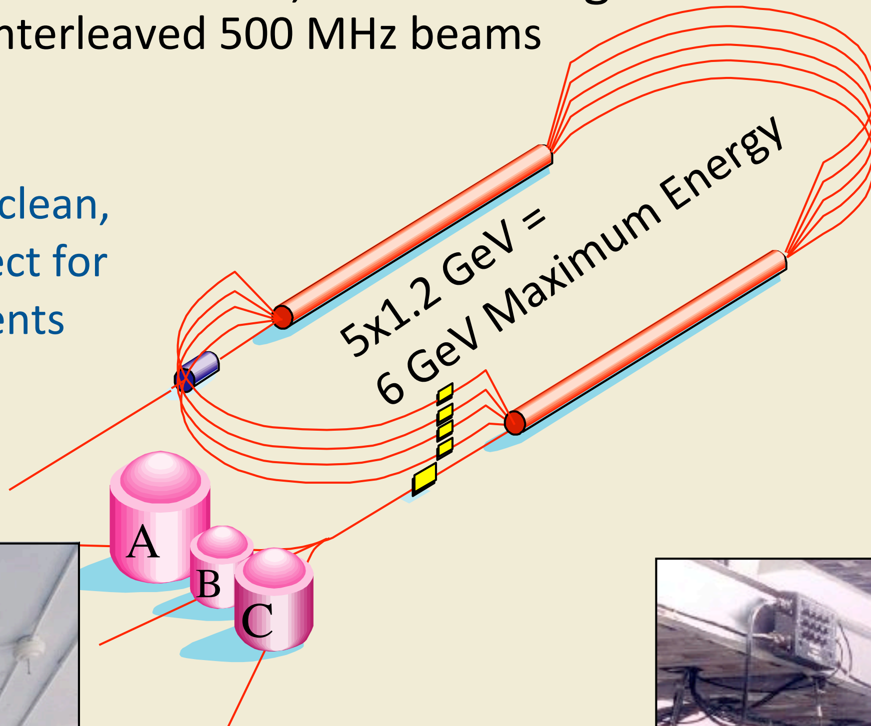
$$\delta(A_{PV}) = \frac{540 \text{ ppm}}{\sqrt{25.3 \times 10^6}} = 0.11 \text{ ppm}$$

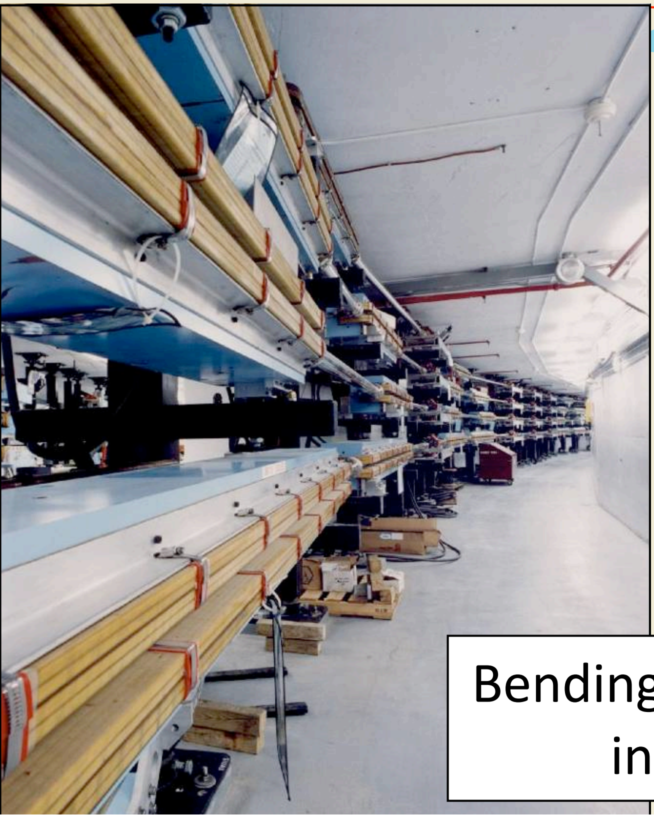
JLab: Continuous Electron Beam Accelerator Facility

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



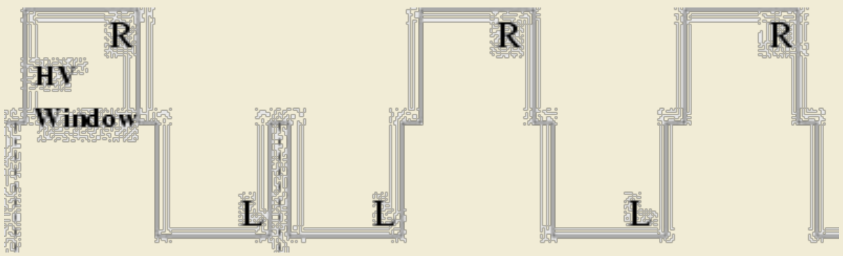


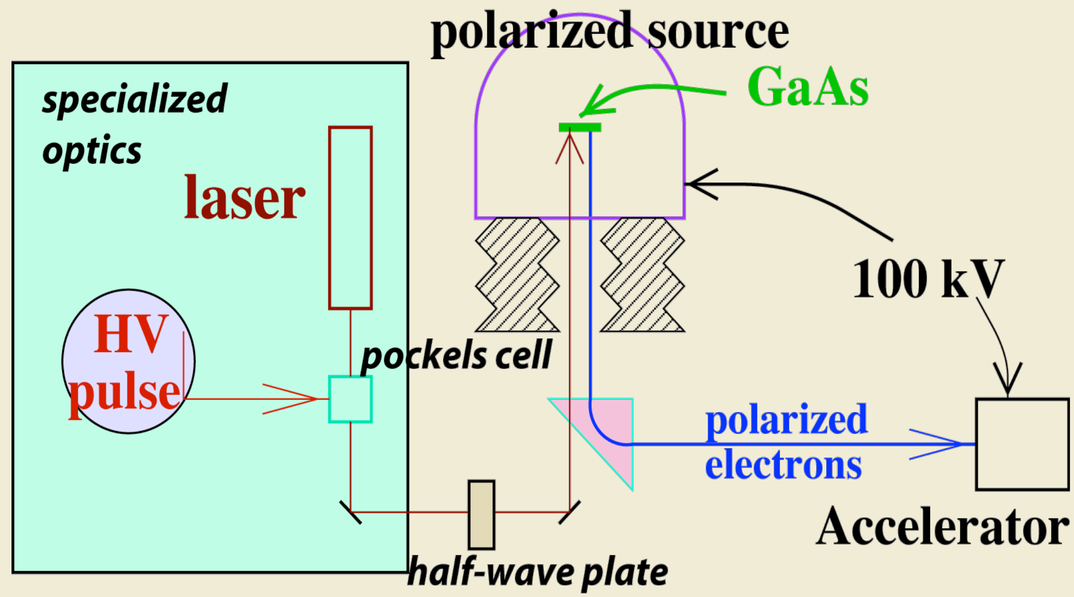
Bending magnets in arc

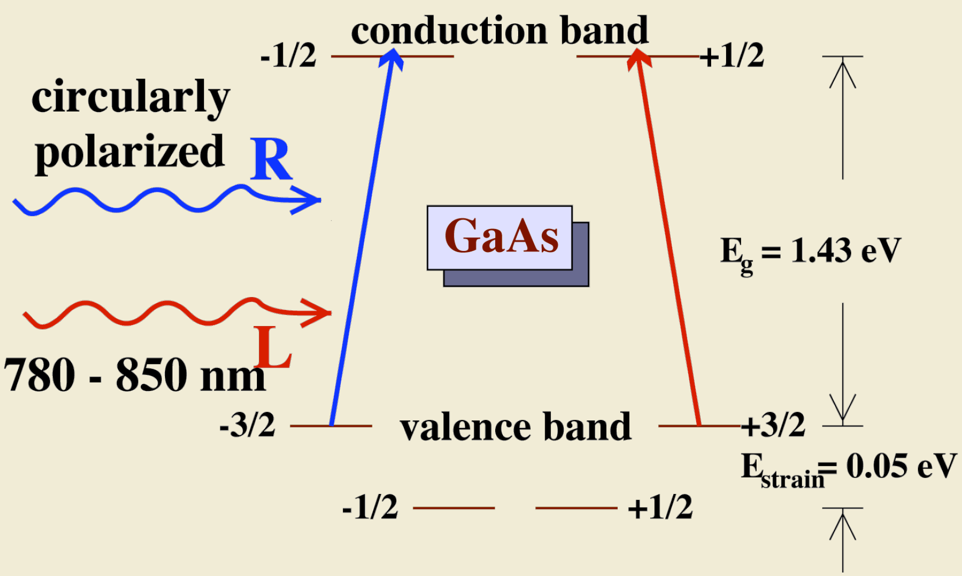
Linac tunnel

Polarized Electrons for Measuring A_{PV}

Photoemission from semiconductor cathode



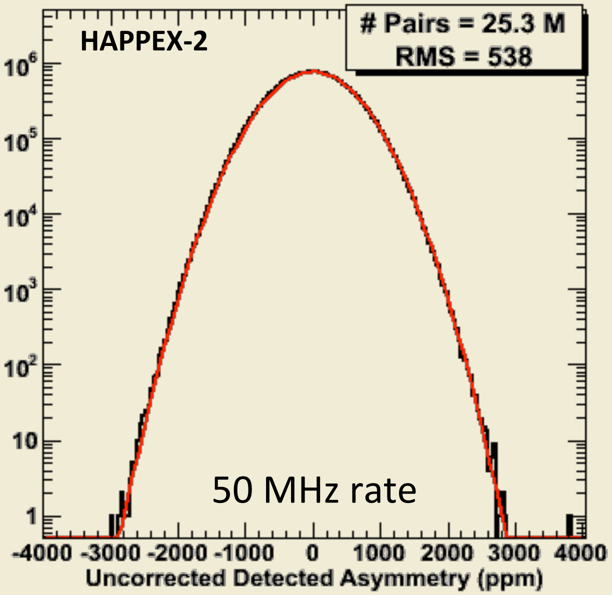




Strain gives high polarization (~85%)
but also introduces anisotropy

- High luminosity (200 μA, 80+C lifetime)
- High polarization (~90%)
- High stability / uptime
- Electro-optic Pockels cell enables rapid helicity flip

Measuring A_{PV}



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... ?

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}

Major effort toward reducing beam asymmetries at the polarized source

Corrections use measured sensitivities

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

Beam Asymmetries from the Source

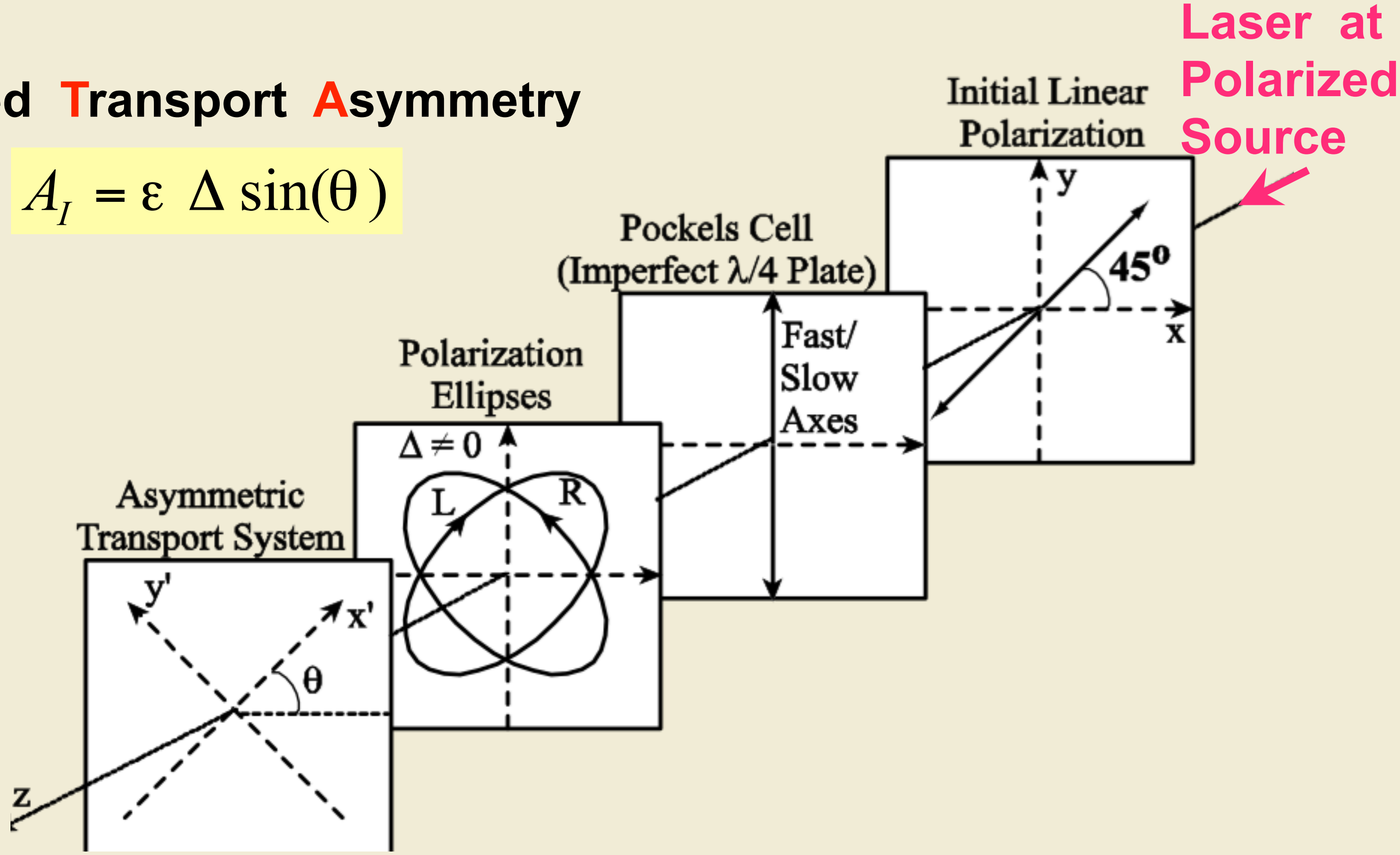
Uniformity of circular polarization: components, alignment techniques, diagnostics

PITA: Polarization Induced Transport Asymmetry

Intensity Asymmetry $A_I = \varepsilon \, \Delta \sin(\theta)$

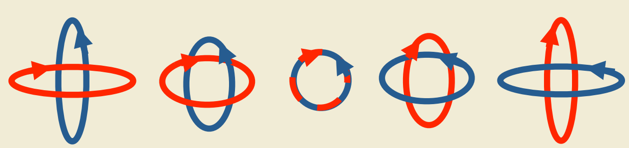
where $\varepsilon = \dfrac{T_x - T_y}{T_x + T_y}$

Quantum Efficiency Asymmetry

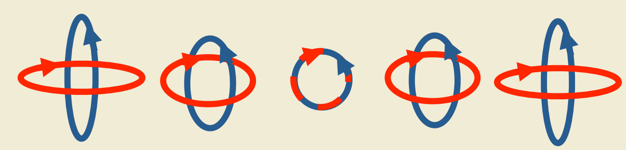


If on average linear polarization = 0, that doesn't mean that it is everywhere zero

A non-zero 1st moment creates a position difference

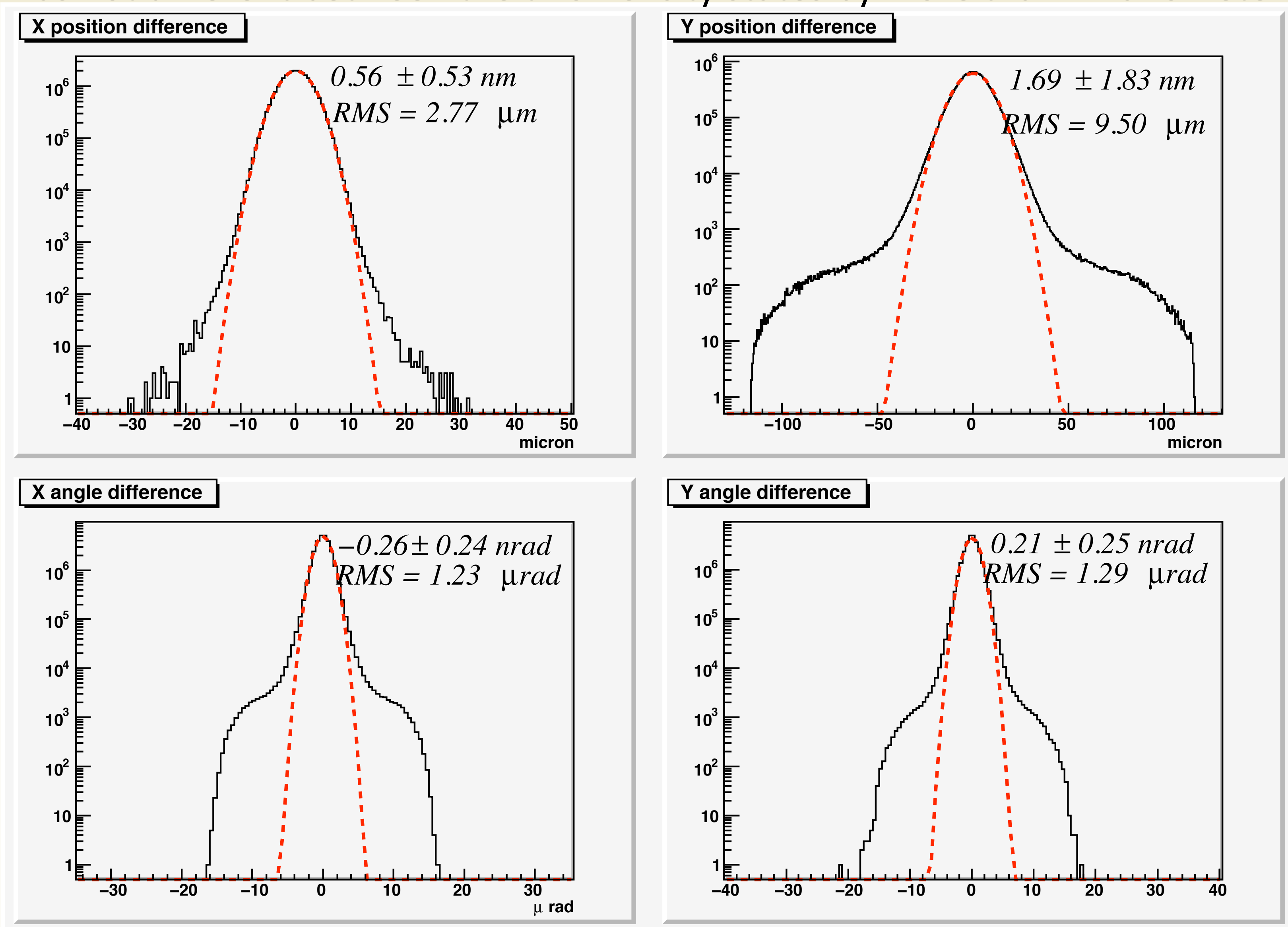


A non-zero 2nd moment creates a spot-size difference



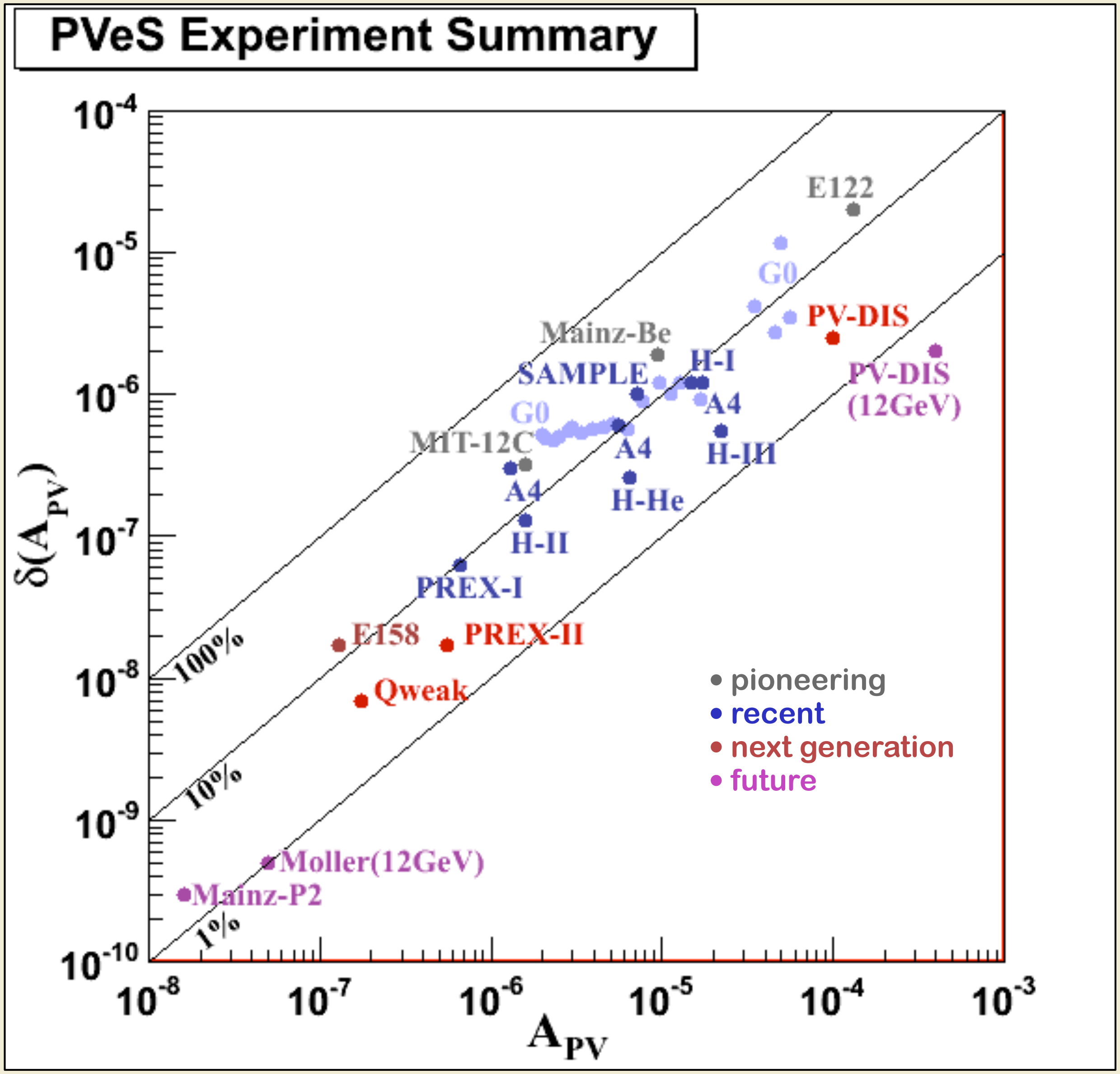
Helicity Correlated Position Differences

Over the ~20 million pairs measured in HAPPEX-II, the average position was not different between the two helicity states by more than 2 nanometers



This was still the leading source of systematic uncertainty in the asymmetry

Precision Electroweak Physics



Steady progress in technology:

- part per billion systematic control
- 1% systematic control
- Major developments in
  - photocathodes (I & P)
  - polarimetry
  - high power cryotargets
  - nanometer beam stability
  - precision beam diagnostics
  - low noise electronics
  - radiation hard detectors

Just how big are the really big nuclei?

Form Factors and Extended Targets

The point-like scattering probability is modified to account for
Finite Target Extent by introducing the "form factor"

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

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

Form factor is the Fourier transform of charge distribution

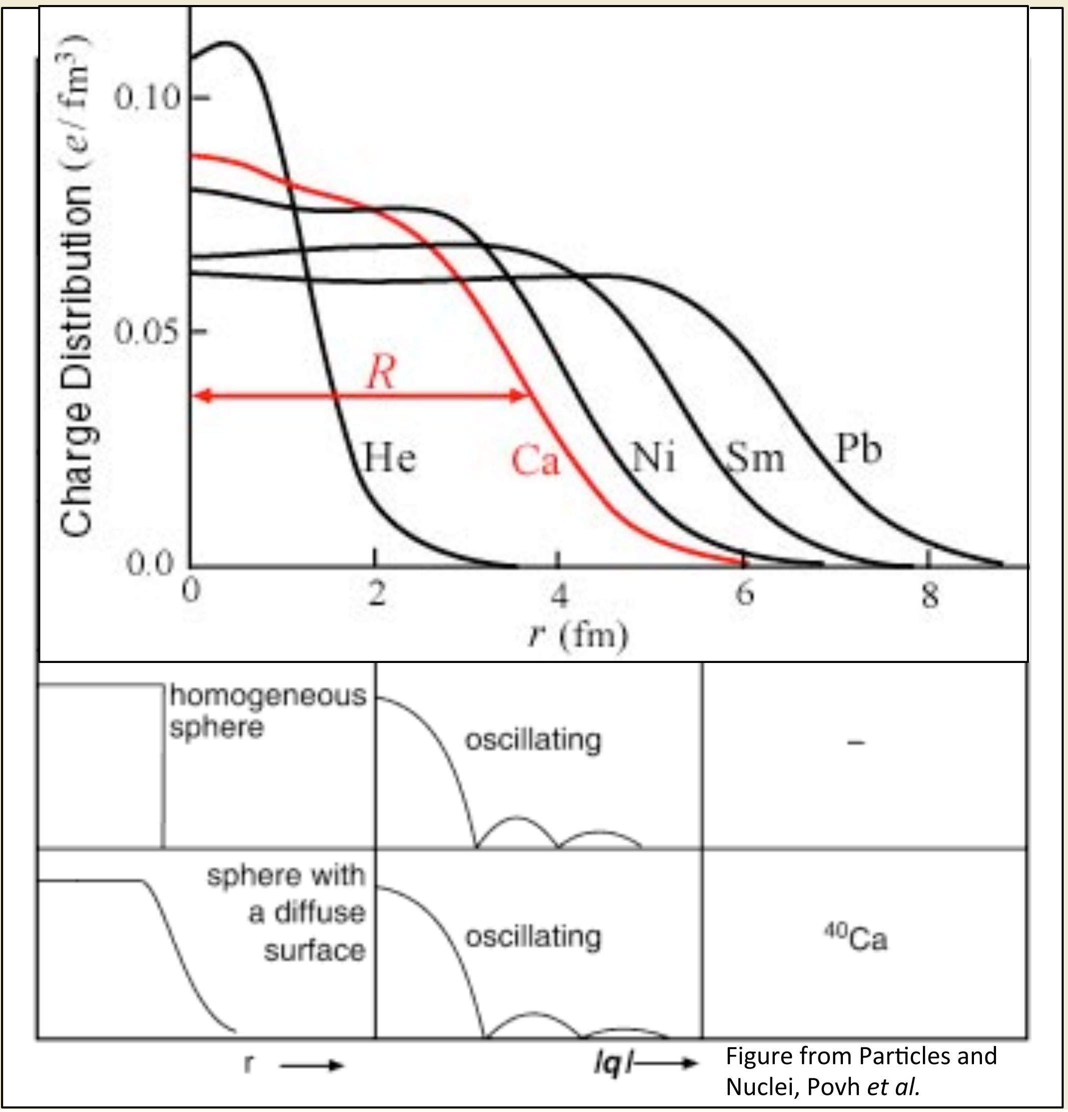
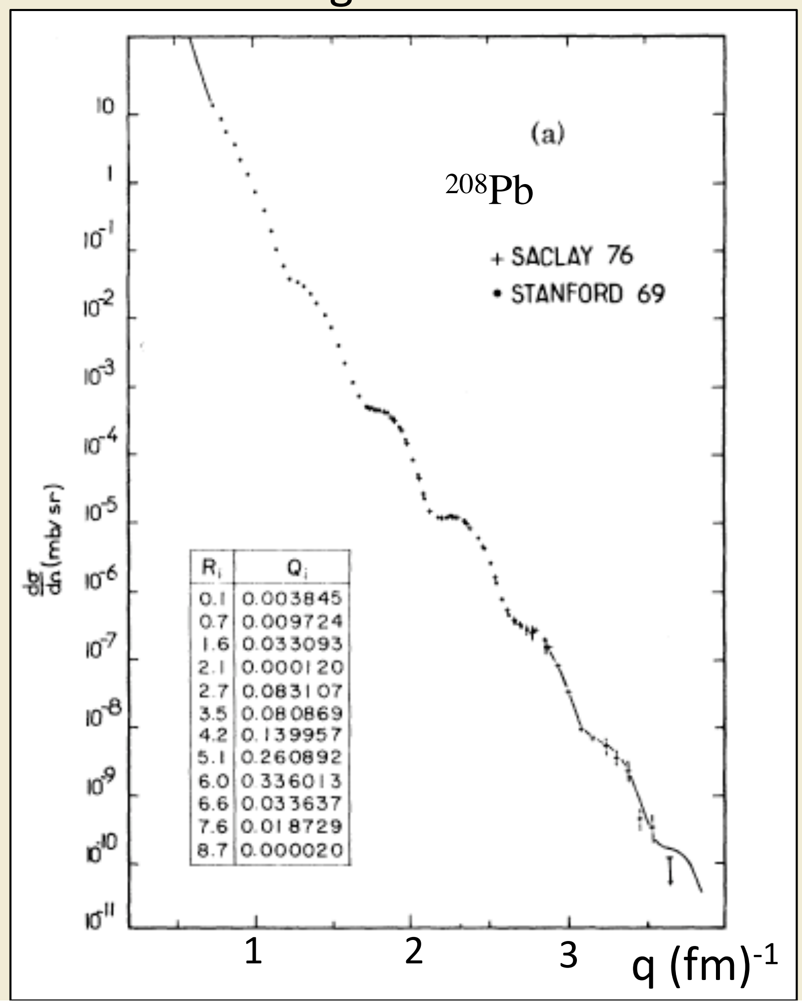


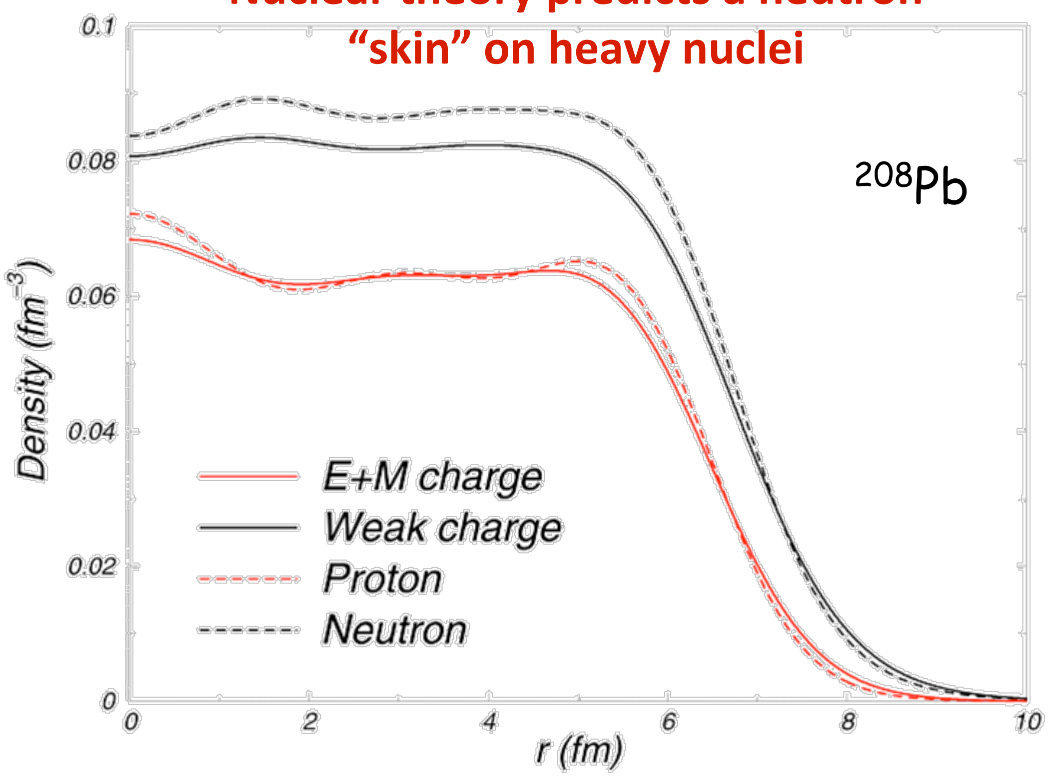
Figure from Particles and Nuclei, Povh *et al.*



R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
2.1	0.000120
2.7	0.083107
3.5	0.080869
4.2	0.139957
5.1	0.260892
6.0	0.336013
6.6	0.033637
7.6	0.018729
8.7	0.000020

Weak Charge Distribution of Heavy Nuclei

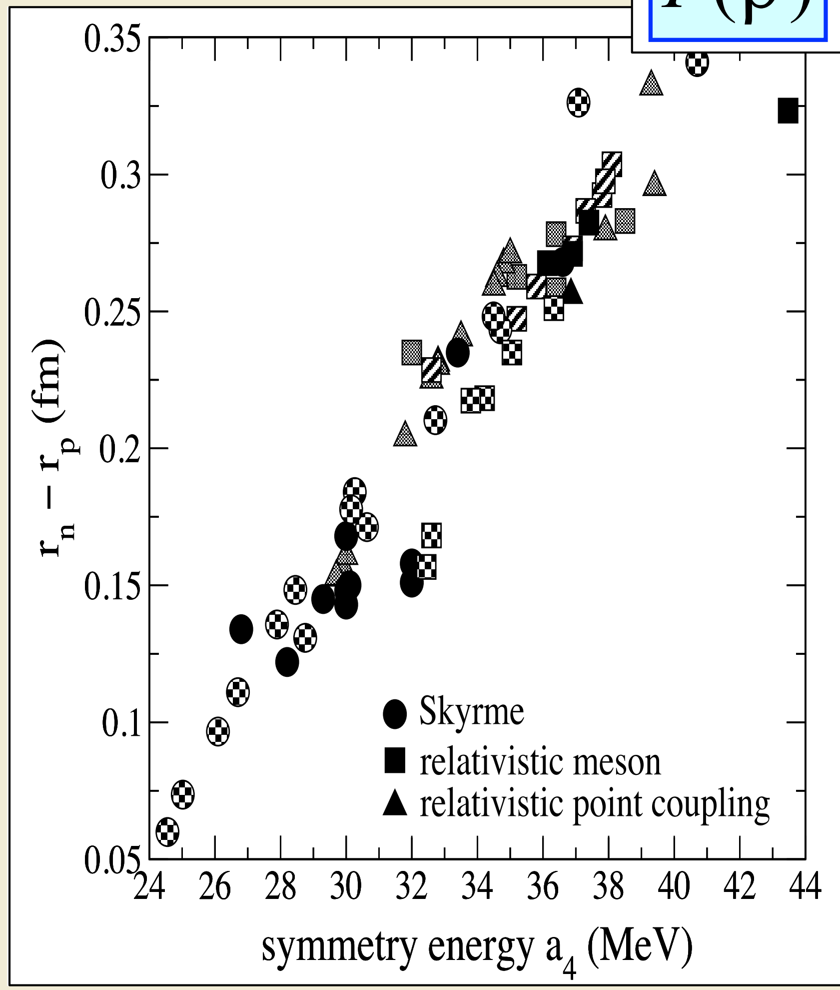
Nuclear theory predicts a neutron "skin" on heavy nuclei



R_n calibrates the **Equation of State** of neutron rich matter

pressure density

$P(\rho)$



Uncertainty in R_n reflects poor understanding of symmetry energy of nuclear matter = the energy cost of $N \neq Z$

$$E(n,x) = E(n, x = 1/2) + S_\upsilon(n)(1 - 2x^2)$$

n = n.m. density

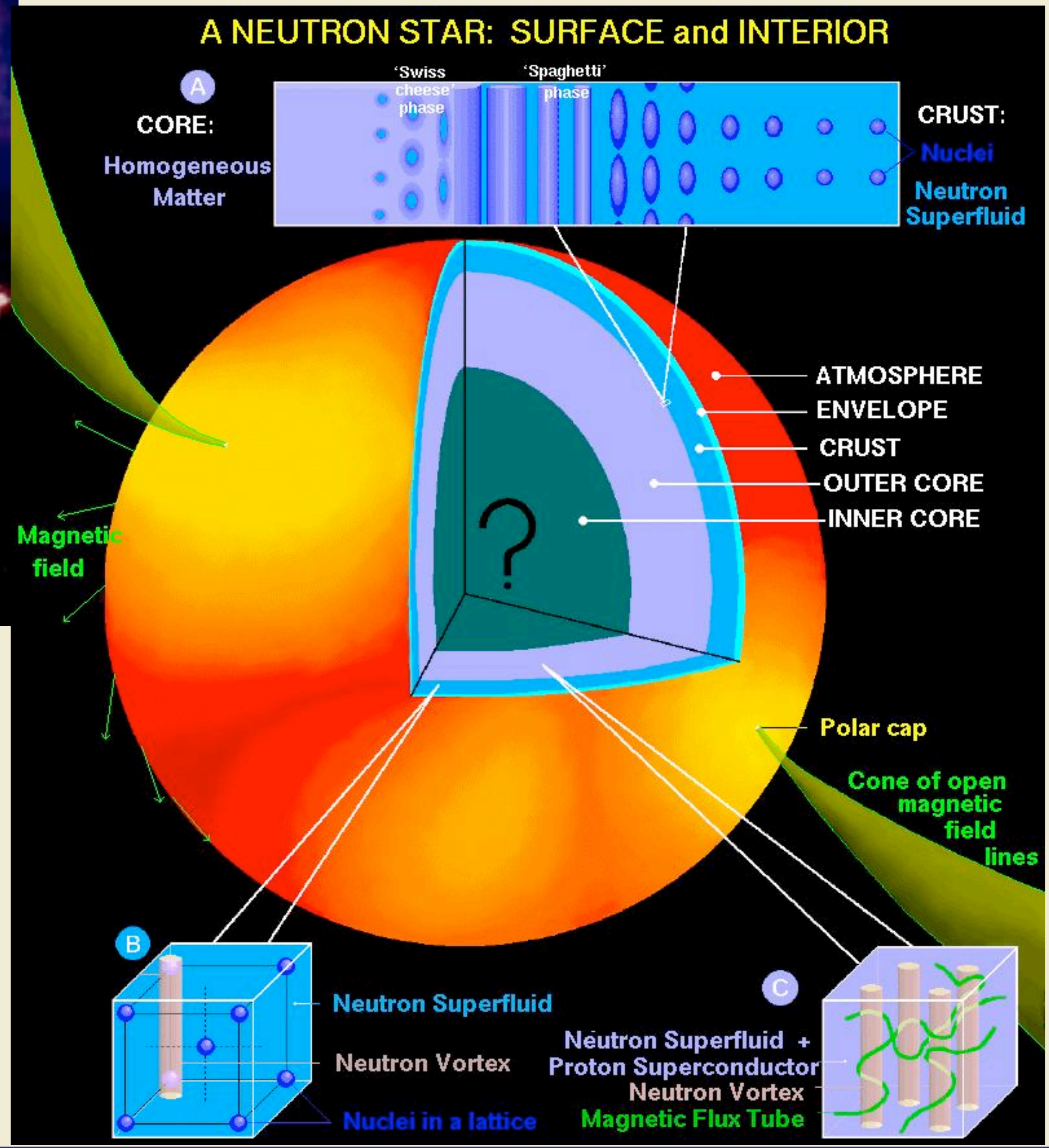
x = ratio proton/neutrons

From ^{208}Pb to a Neutron Star

Crab Nebula

Crust Thickness

Explain Glitches in Pulsar Frequency ?



Combine PREX R_n with observed neutron star radii

Phase Transition to "Exotic" Core ?

Strange star ? Quark Star ?

Some neutron stars seem too cold

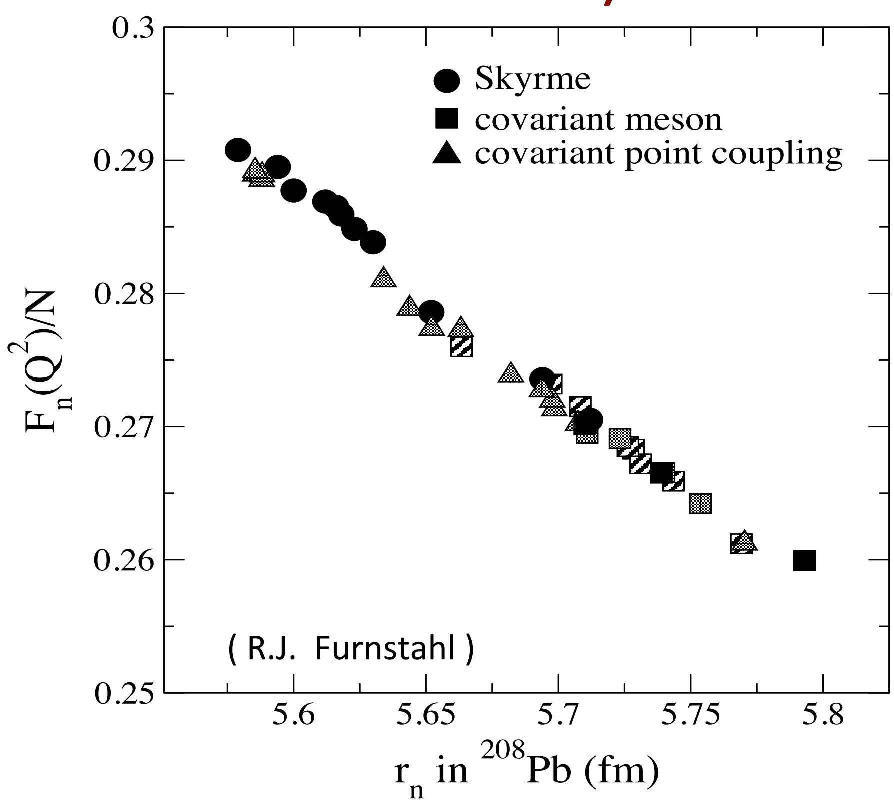
Cooling by neutrino emission (URCA)

$R_n - R_p > 0.2$ fm URCA probable, else not

Weak Charge Distribution of Heavy Nuclei

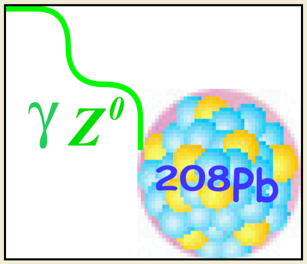
Nuclear theory predicts a neutron "skin" on heavy nuclei

The single measurement of F_n translates to a measurement of R_n (via mean-field nuclear models)



Neutron distribution is not accessible to the charge-sensitive photon.

	proton	neutron
Electric charge	1	0
Weak charge	~0.08	1



for the spin-0 ^{208}Pb nucleus

$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$$M_{PV}^{NC} = \frac{G_F}{\sqrt{2}}\left[\left(1-4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

Measurements of neutron skin

- Proton-Nucleus Elastic
- Pion, alpha, d Scattering
- Pion Photoproduction
- Heavy ion collisions
- Rare Isotopes (dripline)

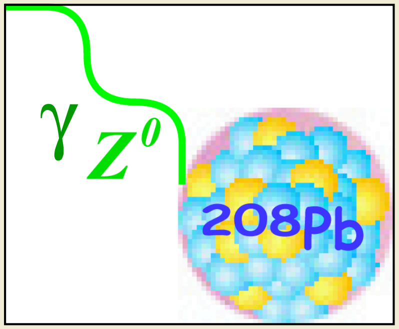
} Involve strong probes

- Magnetic scattering → Most spins couple to zero.

- A_{PV} Electroweak probe

- Theory → MFT fit mostly by data *other than* neutron densities

PREX (Pb-Radius Experiment)



Q^2 ~ 0.01 GeV^2 ⇨ **A_{PV} ~ 0.6 ppm**

5^o scattering angle — **Rate ~1.5 GHz**

Ultimate goal:

$\delta(A_{PV})/A_{PV} \sim 3\%$ — **Stat. Error ~ 15 ppb (3%)**

$\delta(R_n)/R_n \sim 1\%$ — **Syst. Error ~ 5 ppb (1) %**

First Run (early 2010)

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = 0.6571 \pm 0.0604(stat) \pm 0.0130(syst)$$

ppm — 9.2 % — 2.0 %

- **The most precise measurement of electron-nuclear scattering asymmetry yet: 62 ppb**
- **Demonstrated control of random noise, to get full precision**
- **Demonstrated control of systematic error for full precision**

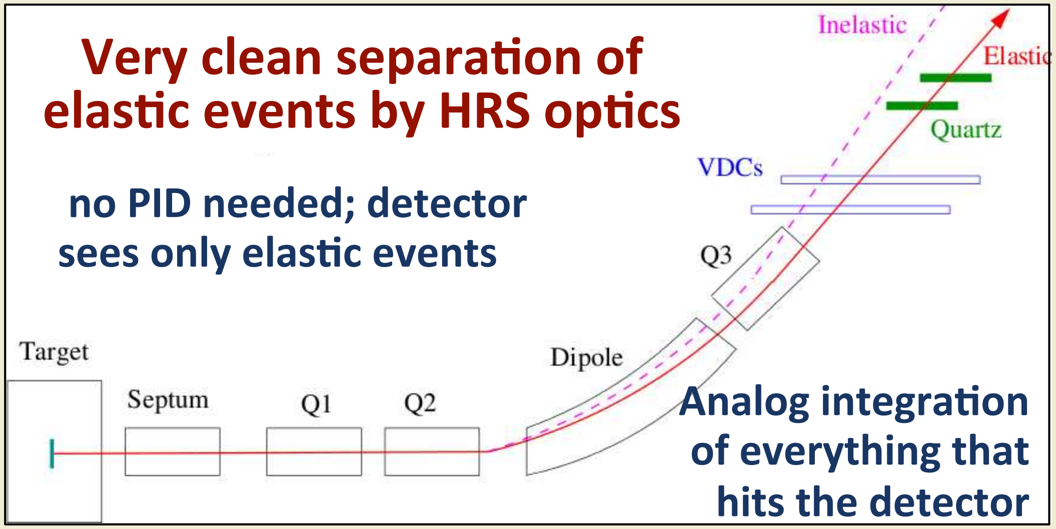
High Resolution Spectrometers in JLab Hall A

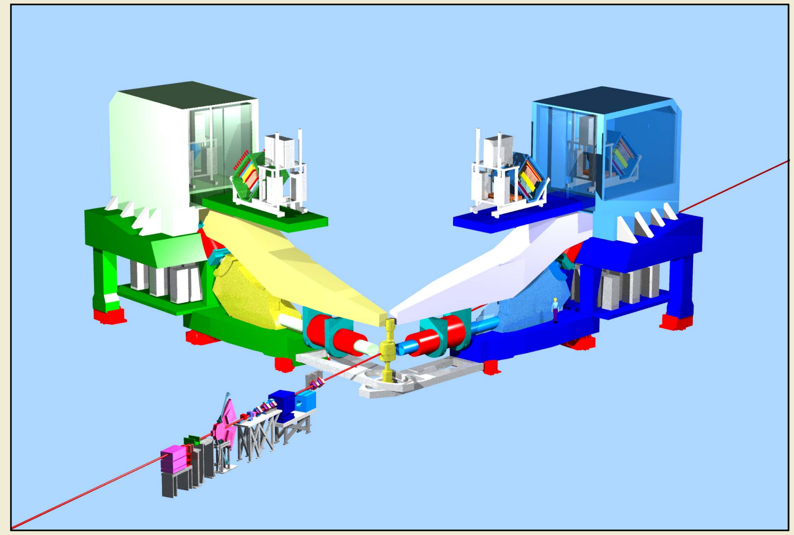
Twin spectrometers built for HIGH precision

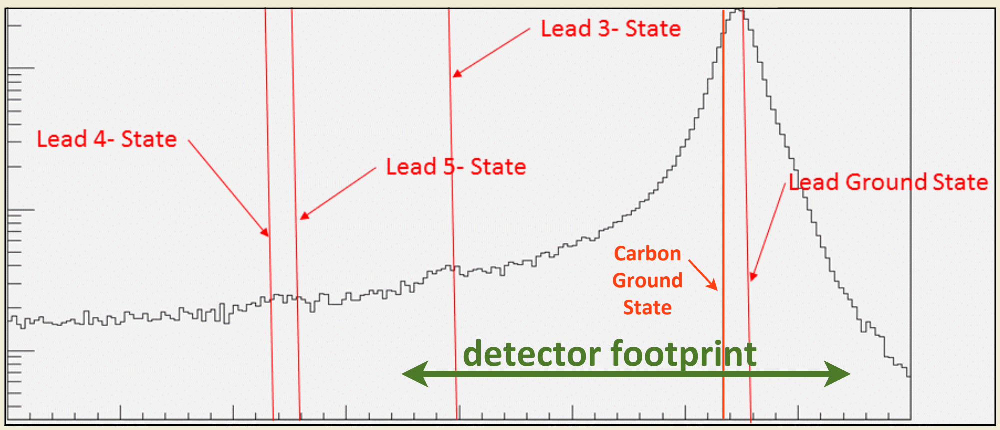
- Bending (dipole) magnet – 450 tons
- 1.6 T magnetic field
- 45^0 bend angle
- 3,500,000 J stored energy
- up to 3 GeV central momentum
- 12 meter dispersion
- Resolution (momentum) – 0.01%

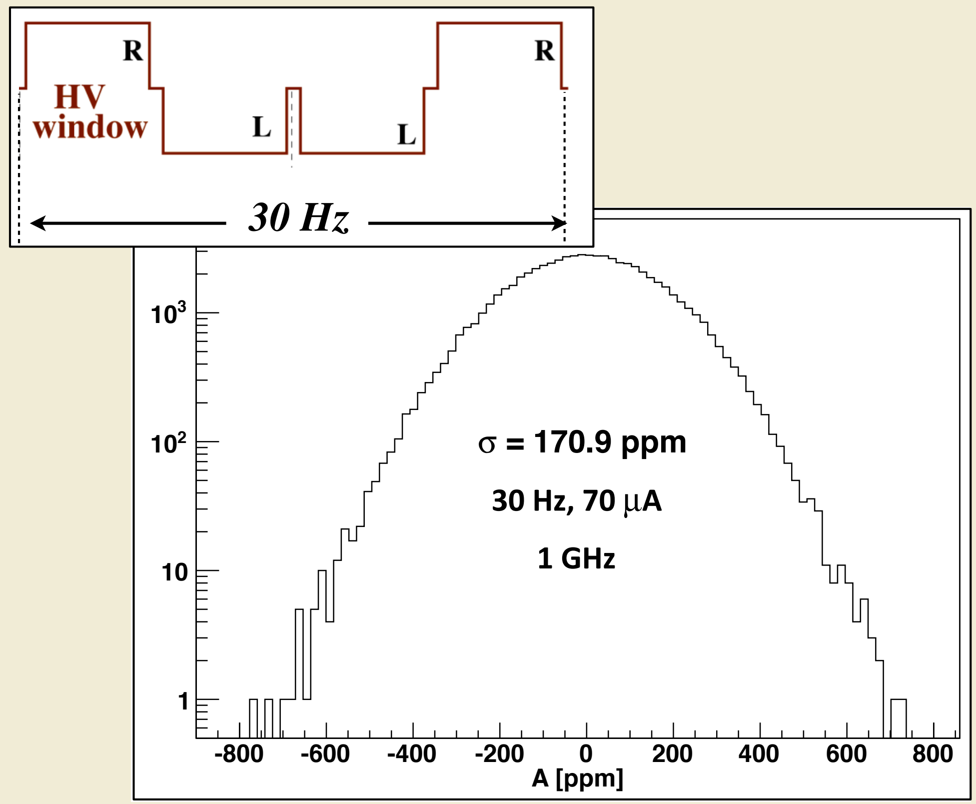
- Total spectrometer – 1000 tons

Integrating in the High Resolution Spectrometers



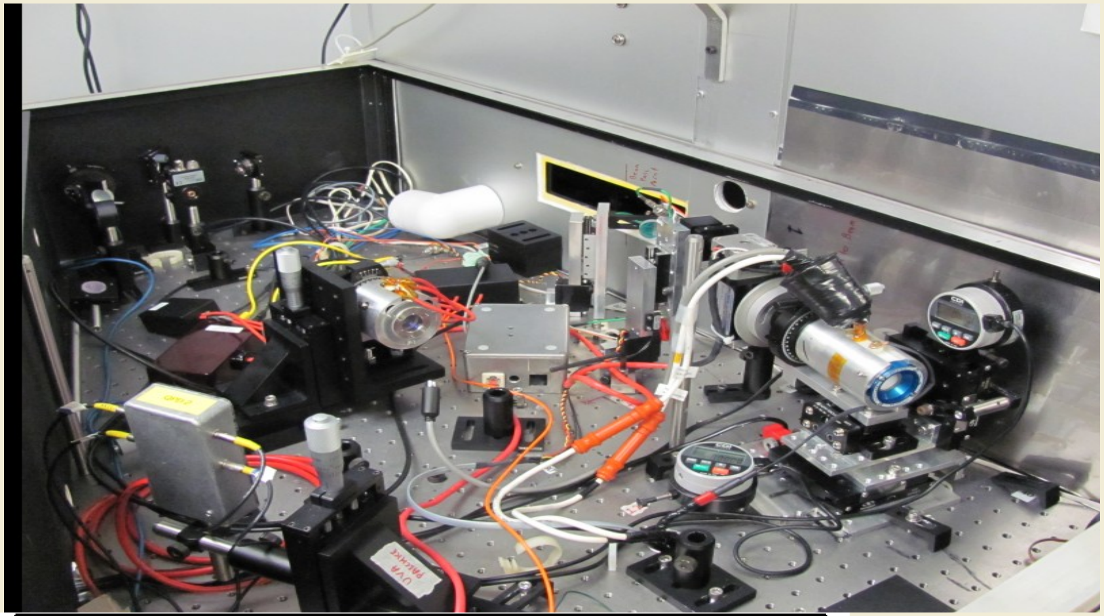




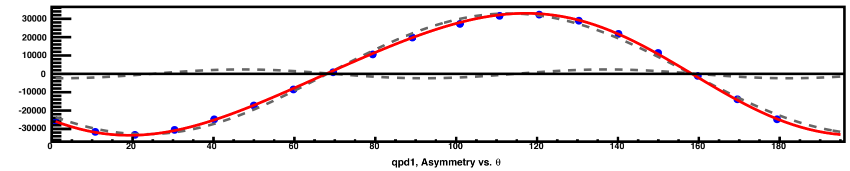


Polarimetry: 1%
Scattering Angle: 0.4%
Backgrounds: well known, 0.4%
Beam Asymmetries: 1%

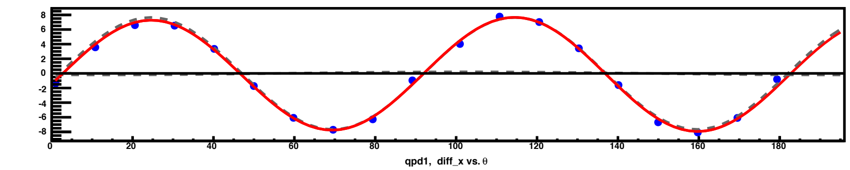
PREX source setup



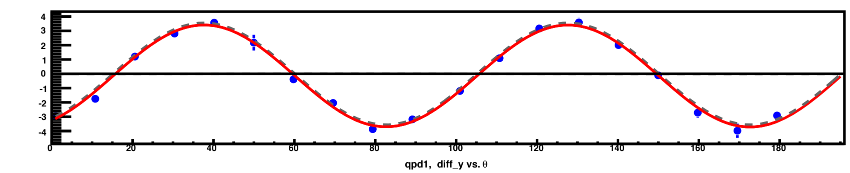
RHWP Scan, Run 1667, IHWP IN, qpd1, PITA = 0



Aq = -7.25 + -32896.33 sin (2θ + 43.77) + -2397.50 sin (4θ + 81.55)

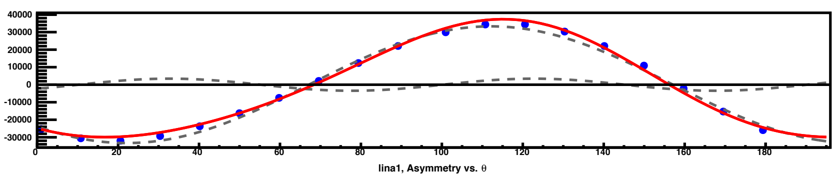


Dx = -0.19 + -0.22 sin (2θ + 66.12) + -7.66 sin (4θ + 171.88)

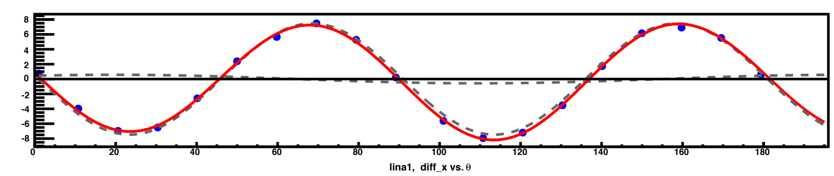


Dy = -0.15 + -0.01 sin (2θ + 122.27) + -3.56 sin (4θ + 119.40)

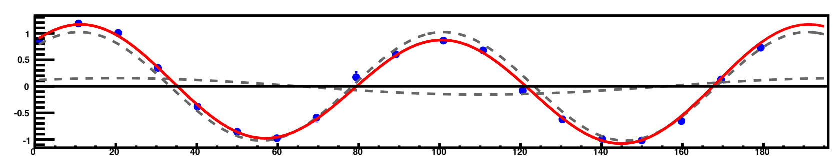
RHWP Scan, Run 1626, IHWP IN, lina1 horizontal, PITA = 0



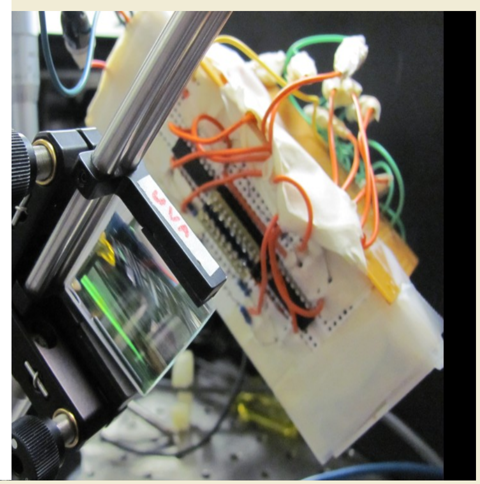
Aq = 1270.40 + -33304.00 sin (2θ + 45.74) + -3452.41 sin (4θ + 139.13)



Dx = -0.15 + 0.57 sin (2θ + 50.56) + 7.48 sin (4θ + 176.00)



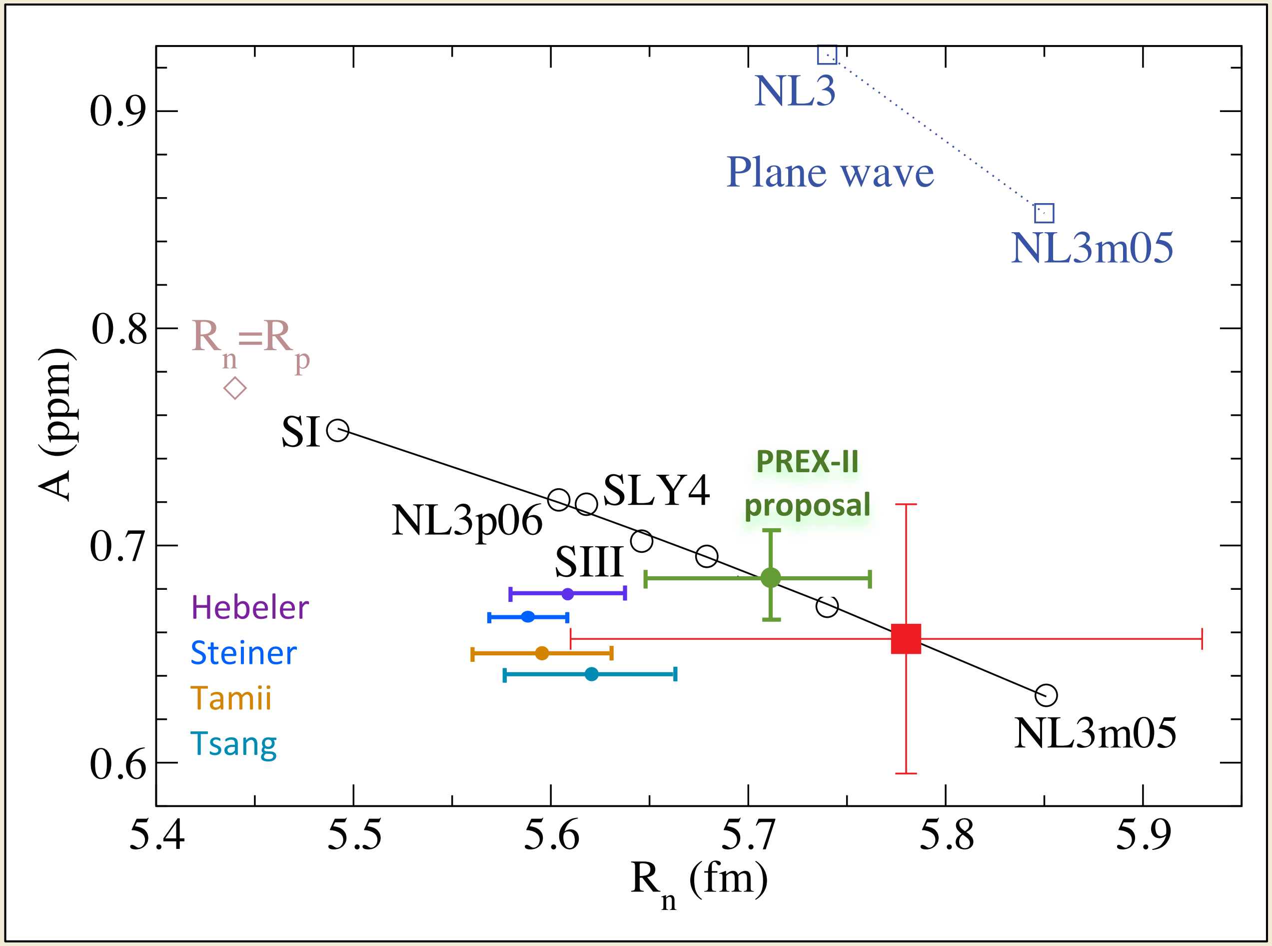
Drms = -0.00 + 0.15 sin (2θ + 49.44) + 1.02 sin (4θ + 46.45)



First time at JLab: an empirical bound on possible spot-size asymmetries, <1e-4

Recent R_n Predictions Can Be Tested By PREX at Full Precision

PREX could provide an electroweak complement to R_n predictions from a wide range of physical situations and model dependencies



Recent R_n predictions:

Hebeler *et al.* Chiral EFT calculation of neutron matter. Correlation of pressure with neutron skin by Brown. Three-neutron forces!

Steiner *et al.* X-Ray n-star mass and radii observation + Brown correlation. (Ozel *et al* finds softer EOS, would suggest smaller R_n).

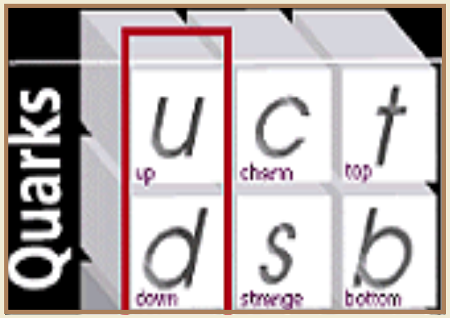
Tamii *et al.* Measurement of electric dipole polarizability of ^{208}Pb + model correlation with neutron skin.

Tsang *et al.* Isospin diffusion in heavy ion collisions, with Brown correlation and quantum molecular dynamics transport model.

Fishing the strange sea

The Simple Nucleon

The nucleon is composed of three quarks (up and down flavors) interacting via the Strong force (Quantum Chromodynamics)



Increasing mass

The quark flavor content determines the nucleon properties

It's simple: the nucleon is three marbles in a bag!

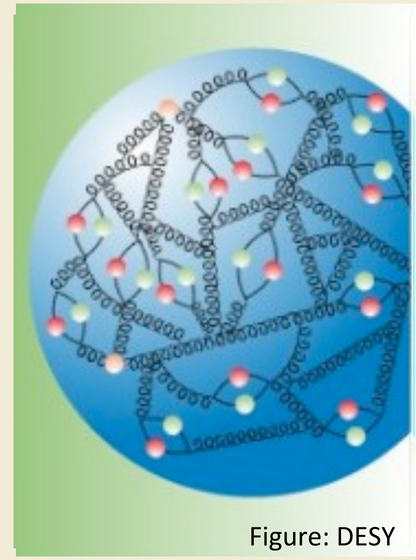


Figure: DESY

<u>Not so fast. The strong force is weird!</u>

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

It grows with distance, and is huge at "large" distances (10^{-15} m).
Gluons (strong carriers) interact with themselves.

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

So why does the simple quark model work so well?

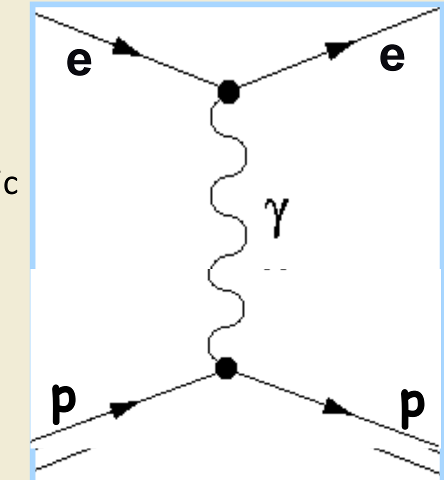
Sea contributions to nucleon static properties are unsettled

mass, spin, charge radius, magnetic moment

By analogy with the electron shell structure that determines the chemical properties of an atom, the three dominant quarks are referred to as "valence" quarks. The rest of the quarks and gluons are called the "sea".

Elastic Electron-Nucleon Scattering

If proton is point-like: The differential cross-section (scattering probability) is given by simple scattering theory



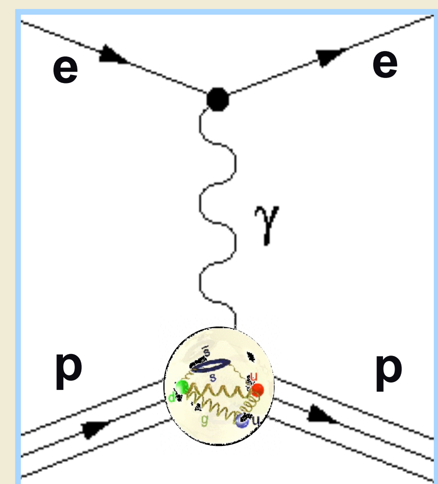
Function of (E,θ).
Cross-section for infinitely heavy proton

$\tau = Q^2/4M^2$ is a convenient kinematic factor

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

If proton is not point-like: The **electric and magnetic form factors G_E and G_M** parameterize the effect of proton structure.

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



If the proton were like the electron:

G_E = 1 (proton charge)

G_M = 1 (and the magnetic moment would be 1 Bohr magneton).

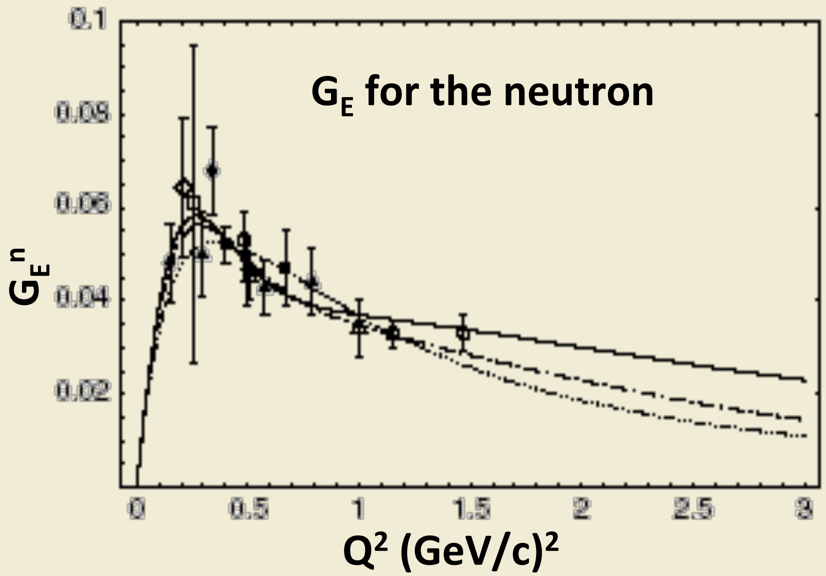
$\mu_p = 2.79\ \mu_B$ (Stern, 1932)

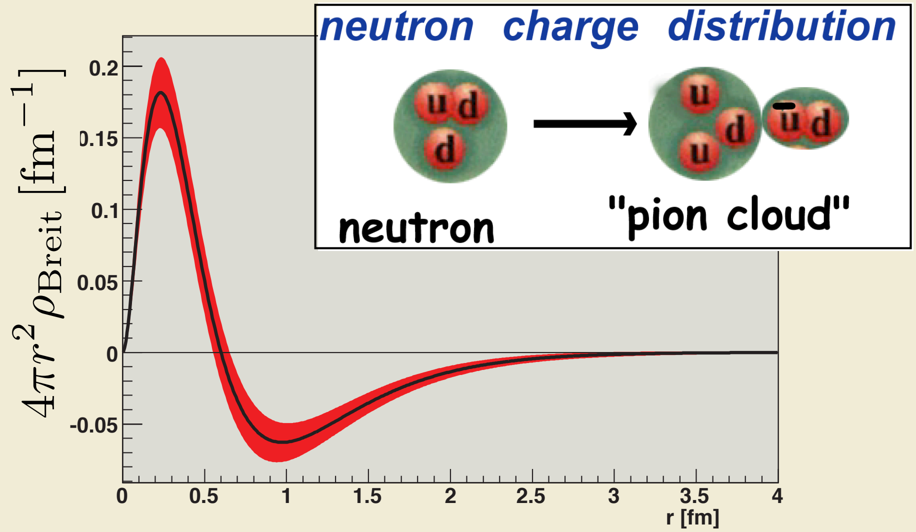
Charge & Current Distributions

Form factors G_E, G_M are functions of Q^2

-> they measure scattering probability as a function of wavelength

Where recoil can be neglected (low Q^2): Fourier transform of the charge and magnetic current distributions





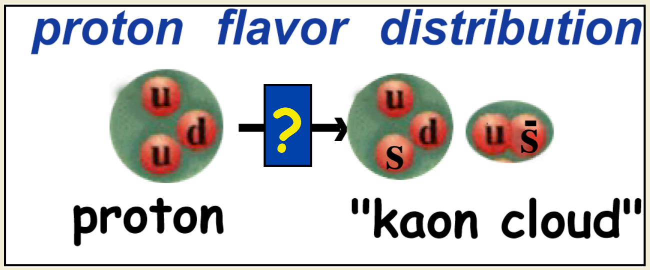
At Q^2 = 0, the form factor represents an integral over the nucleon

At Q^2=0	G_E	G_M
proton	1	2.79
neutron	0	-1.91

anomalous magnetic moment

charge

Do strange sea quarks play a significant role in the electric/magnetic charge distributions in the nucleon?



Strangeness in the Sea

The sea contains all flavors, but

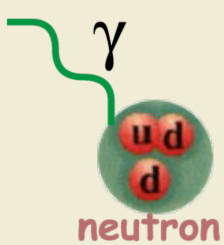
- the u and d sea can't be distinguished from the valance
- the heavier quarks (c,b,t) are too heavy to contribute much

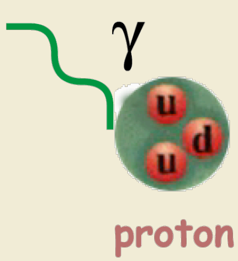
From hard-scattering, we know that the strange sea exists.

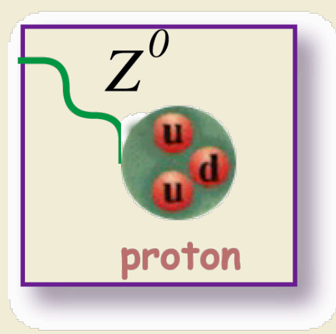
~4% of the momentum of the nucleon is carried by strange quarks

But this is a "deep" probe... Do the strange quarks affect the static properties of the nucleon?

Low-Q^2 Elastic electron scattering from the nucleus measures charge radius and magnetic moment



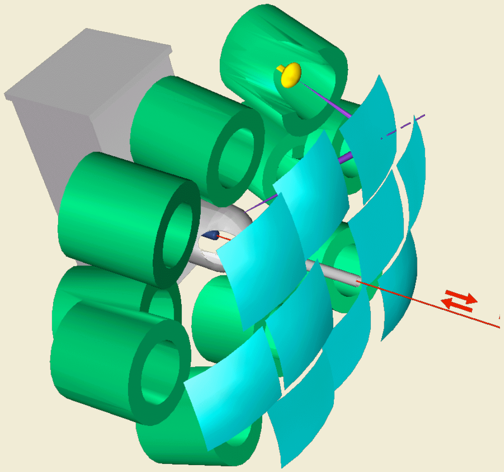




A strange contribution would be the first unambiguous low-energy failure of the naïve quark model

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

Experimental Overview



SAMPLE

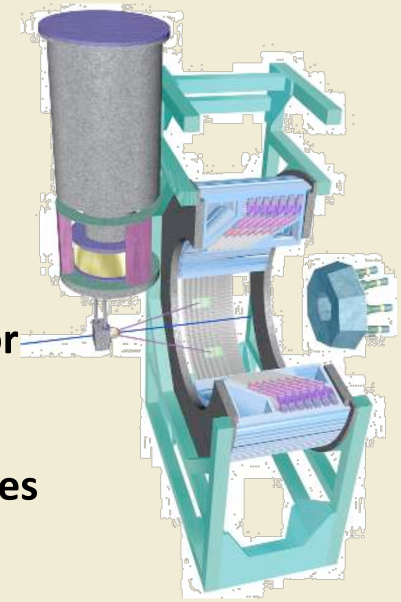
open geometry,
integrating,
back-angle only

A4

Open geometry

Fast counting calorimeter for background rejection

Forward and Backward angles

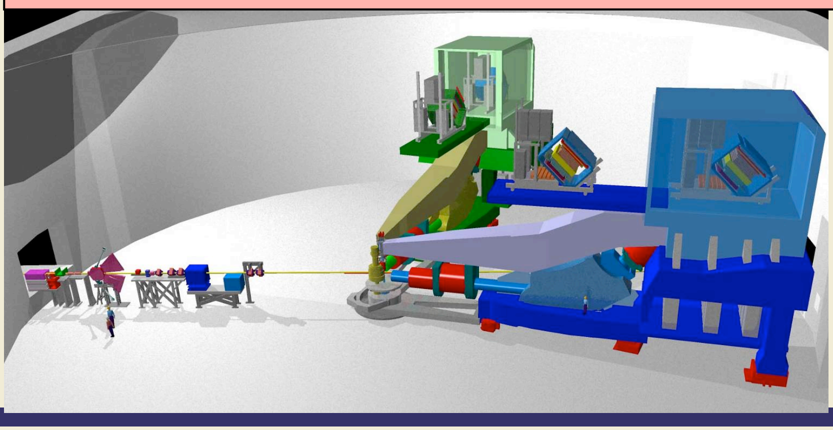


HAPPEX

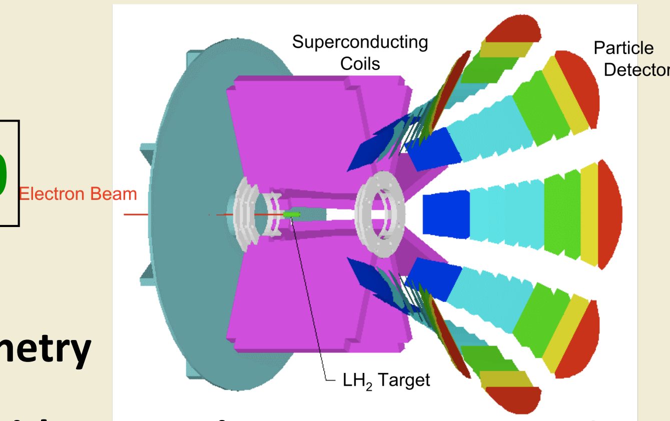
Precision spectrometer, integrating

Forward angle, also
^{4}He at low Q^2

HAPPEX-3: $G_E^s + 0.52\ G_M^s$ at $Q^2 = 0.62\ \text{GeV}^2$



G0

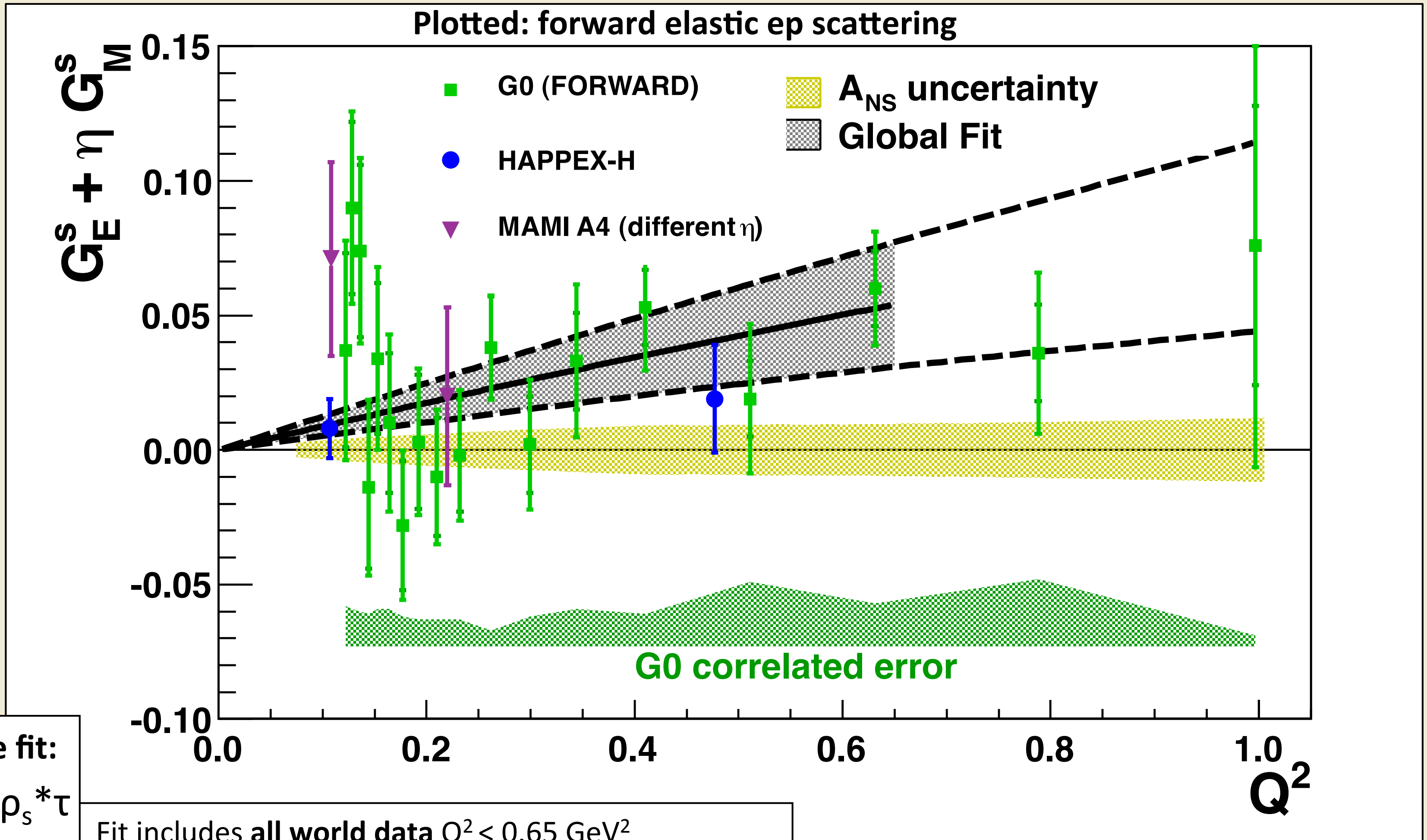


Open geometry

Fast counting with magnetic spectrometer + TOF for background rejection

Forward and Backward angles over a range of Q^2

Global fit of all world data



Simple fit:

$G_E^s = \rho_s * \tau$

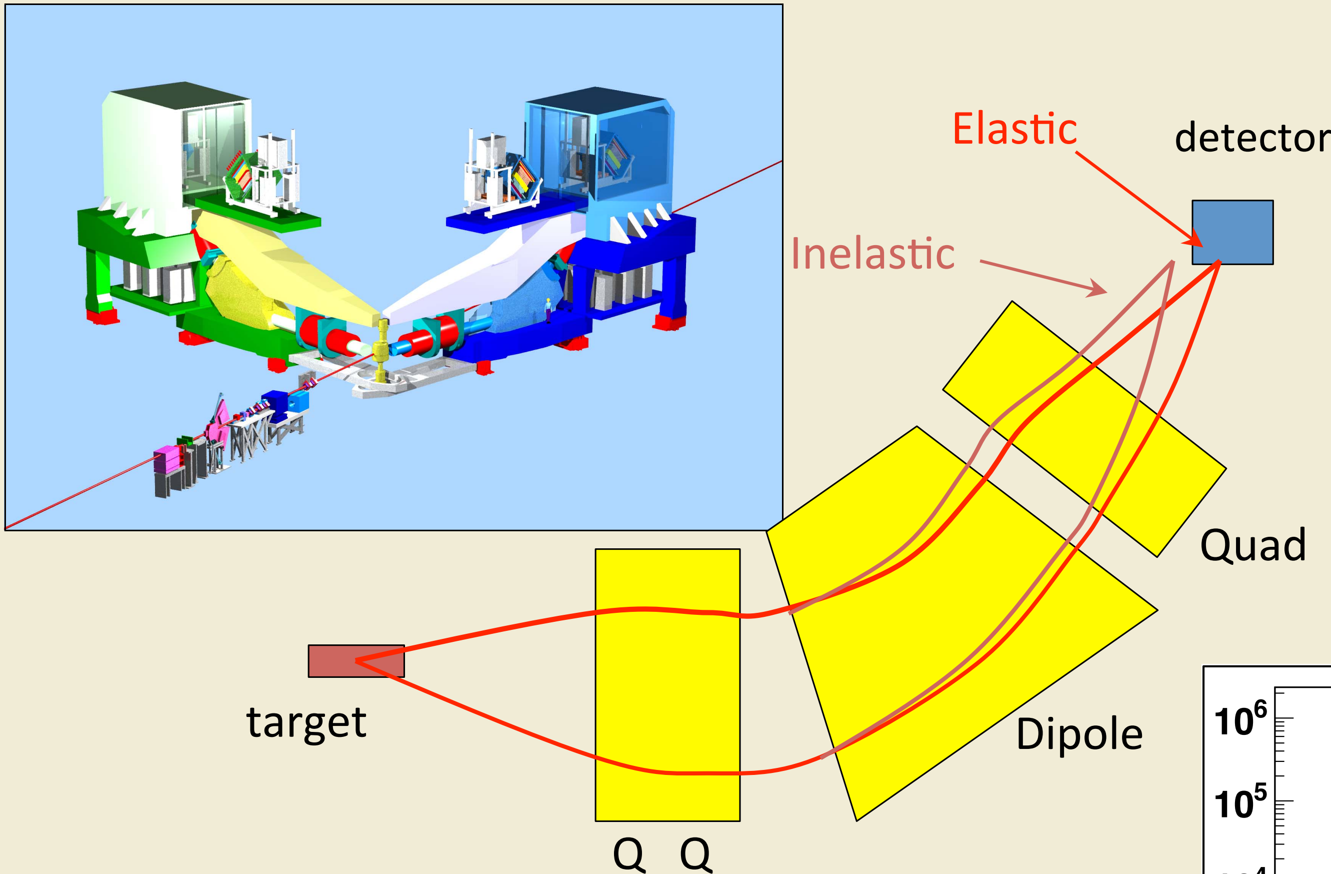
$G_M^s = \mu_s$

Fit includes **all world data** $Q^2 < 0.65\ GeV^2$

G0 Global error allowed to float with unit constraint

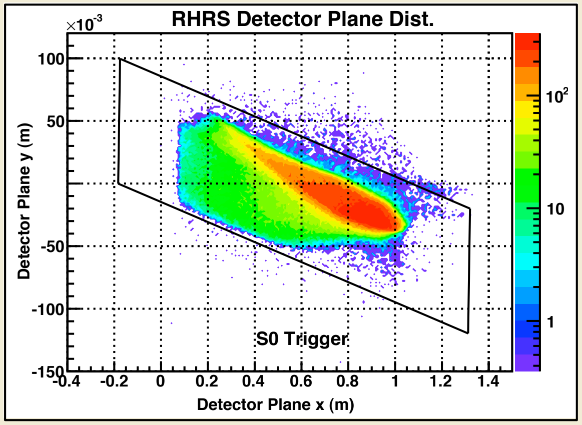
- **Data set appears to show consistent preference for positive effect**
- **Significant contributions at higher Q^2 are not ruled out.**

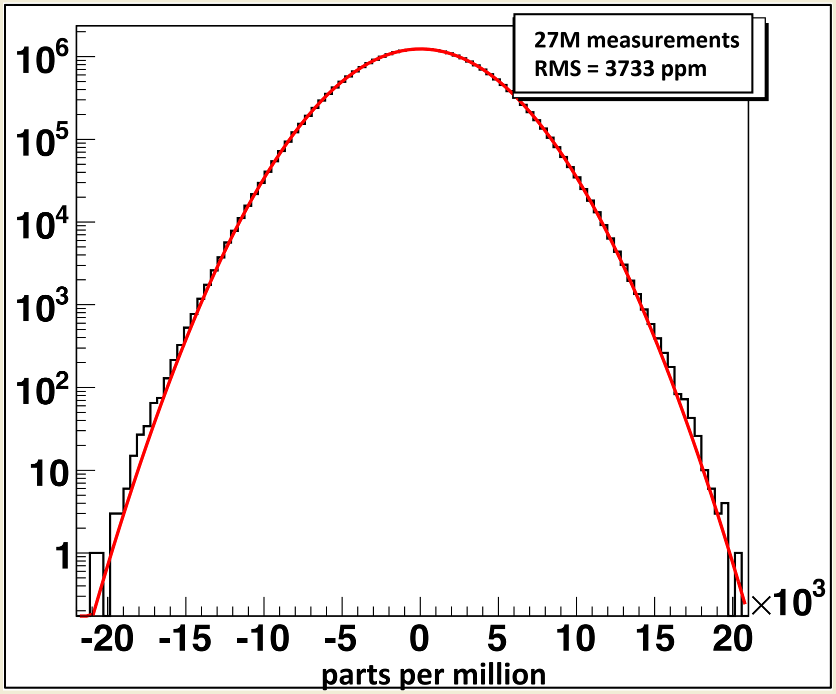
Integrating in the High Resolution Spectrometers



Very clean separation of elastic events by HRS optics

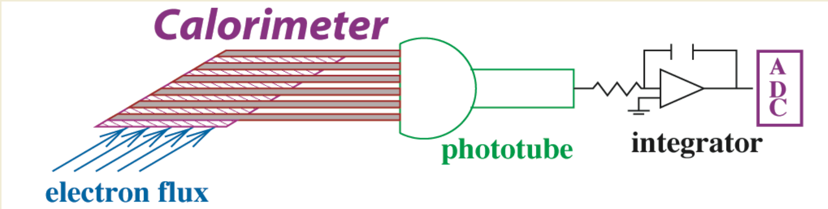
no PID needed; detector sees only elastic events





Lead - Lucite Cerenkov Shower Calorimeter

- phototube current integrated over fixed time periods



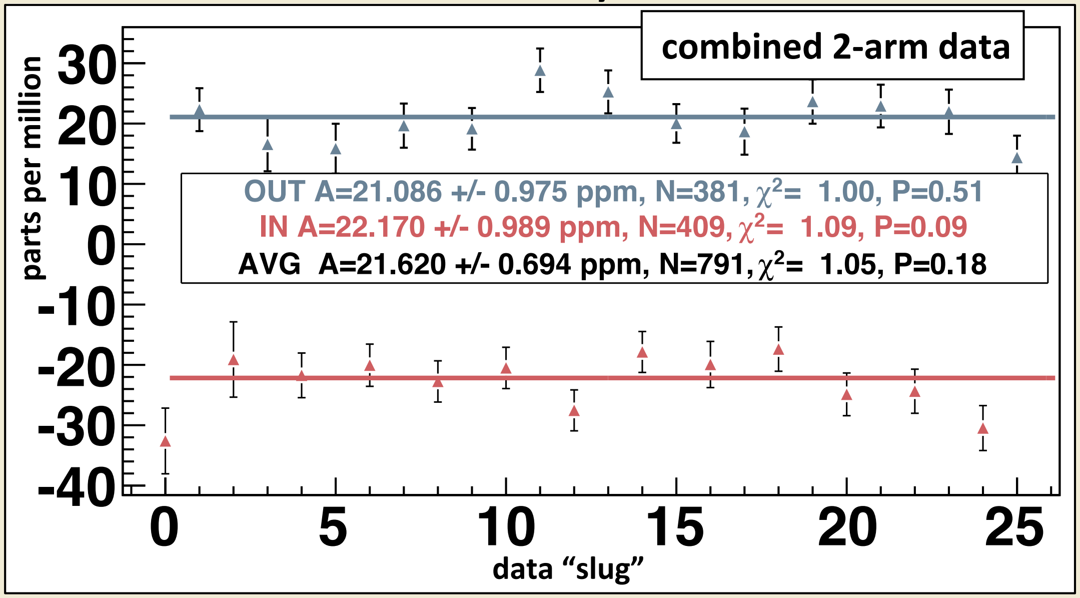
HAPPEX-III Error Budget

	δA_{PV} (ppm)	$\delta A_{PV} / A_{PV}$
Polarization	0.202	0.85%
Q^2 Measurement	0.160	0.67%
Backgrounds	0.194	0.82%
Linearity	0.129	0.54%
Finite Acceptance	0.048	0.20%
False Asymmetries	0.041	0.17%
Total Systematic	0.353	1.49%
Statistics	0.776	3.27%
Total Experimental	0.853	3.59%

total correction ~2.5% + polarization

Systematic uncertainties are well controlled - experiment is statistics dominated

OUT / IN from "slow" spin reversals to cancel systematics

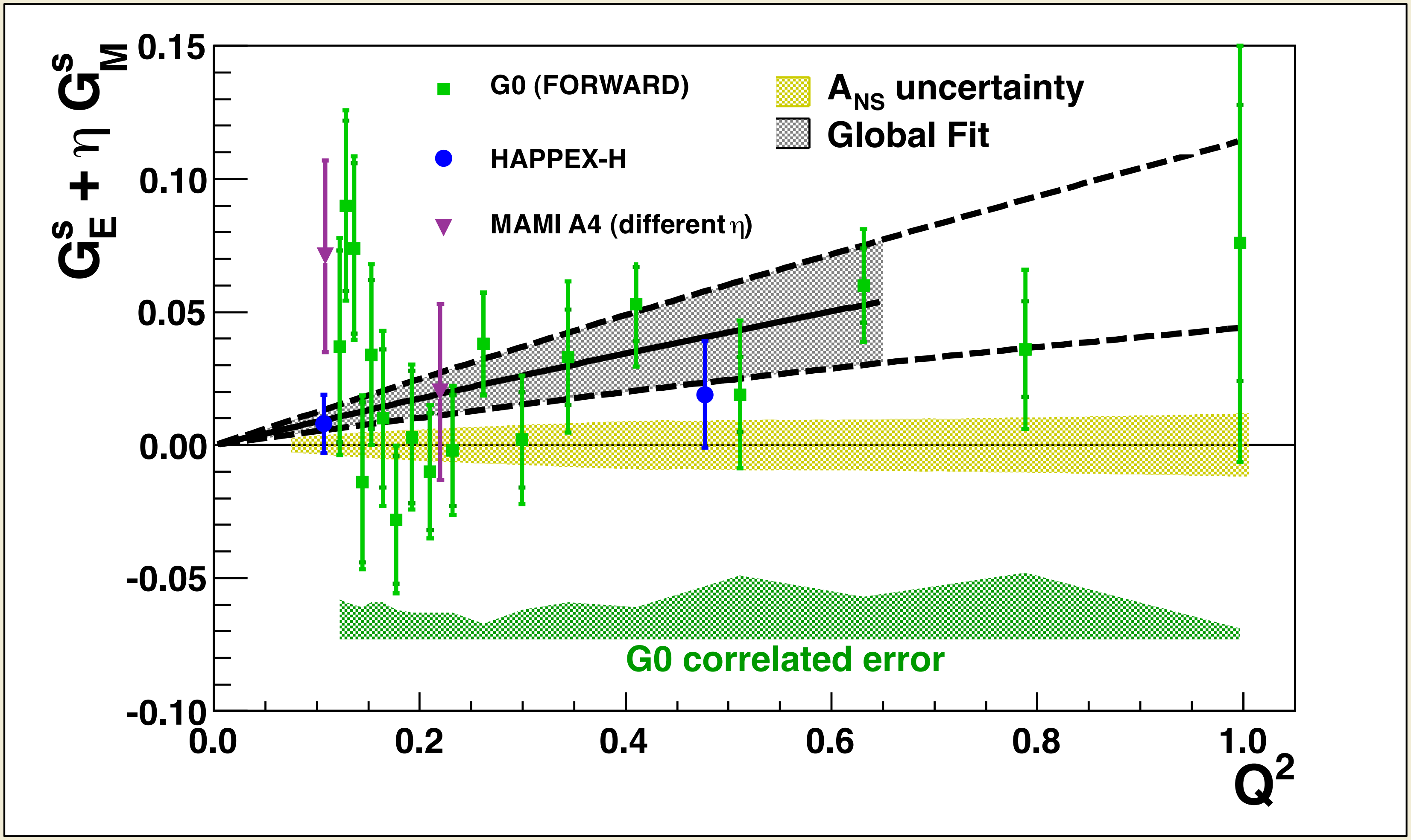


HAPPEX-III Result

A_{PV} = -23.803 ± 0.778 (stat) ± 0.362 (syst) ppm

Q^2 = 0.6241 ± 0.0032 $(GeV/c)^2$

A(G^s=0) = -24.062 ppm ± 0.734 ppm

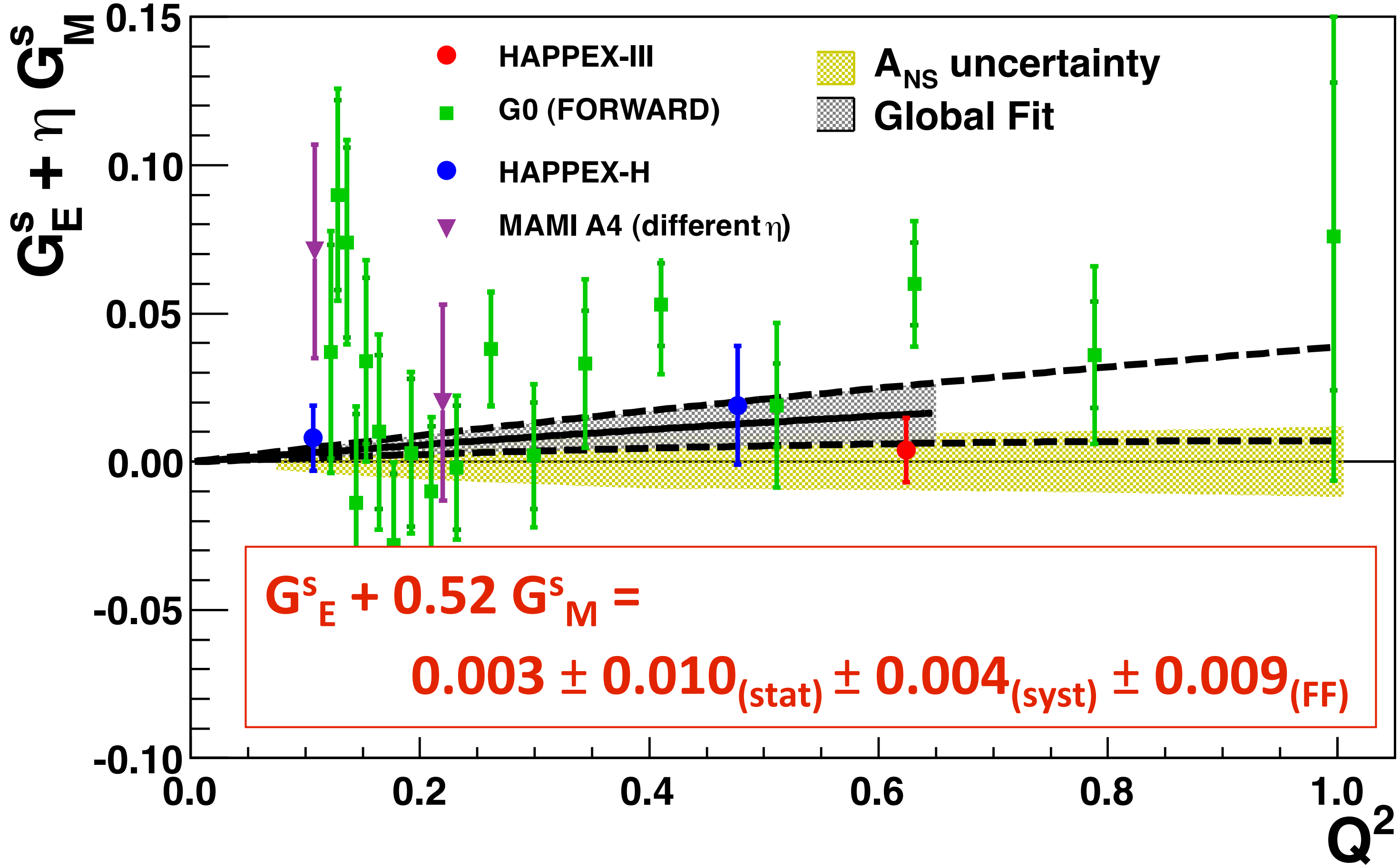


HAPPEX-III Result

$A_{PV} = -23.803 \pm 0.778$ (stat) ± 0.359 (syst) ppm

$Q^2 = 0.6241 \pm 0.0032\ (GeV/c)^2$

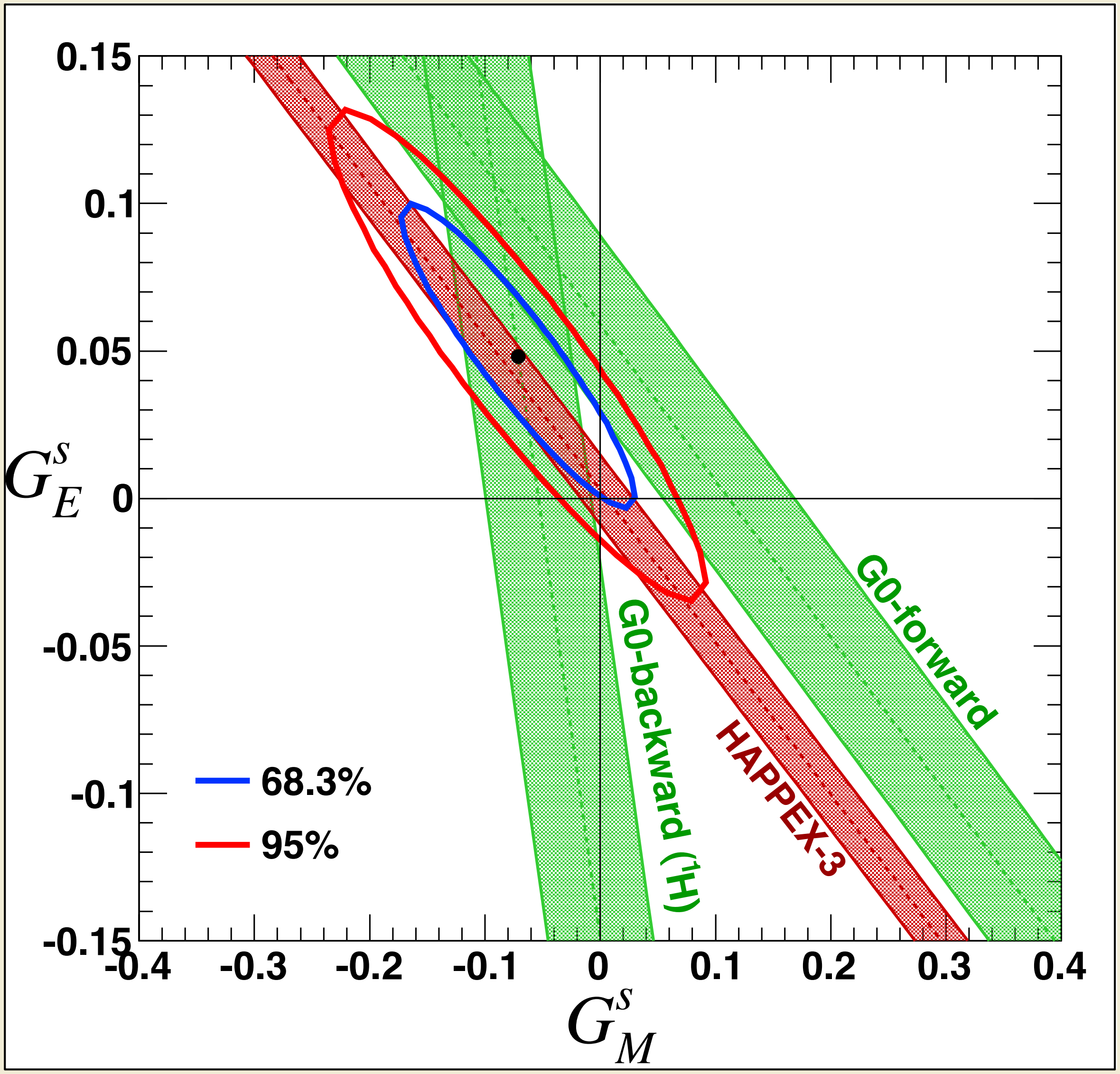
$A(G^s=0) = -24.062$ ppm ± 0.734 ppm



$G^s_E + 0.52\, G^s_M =$

$0.003 \pm 0.010_{(stat)} \pm 0.004_{(syst)} \pm 0.009_{(FF)}$

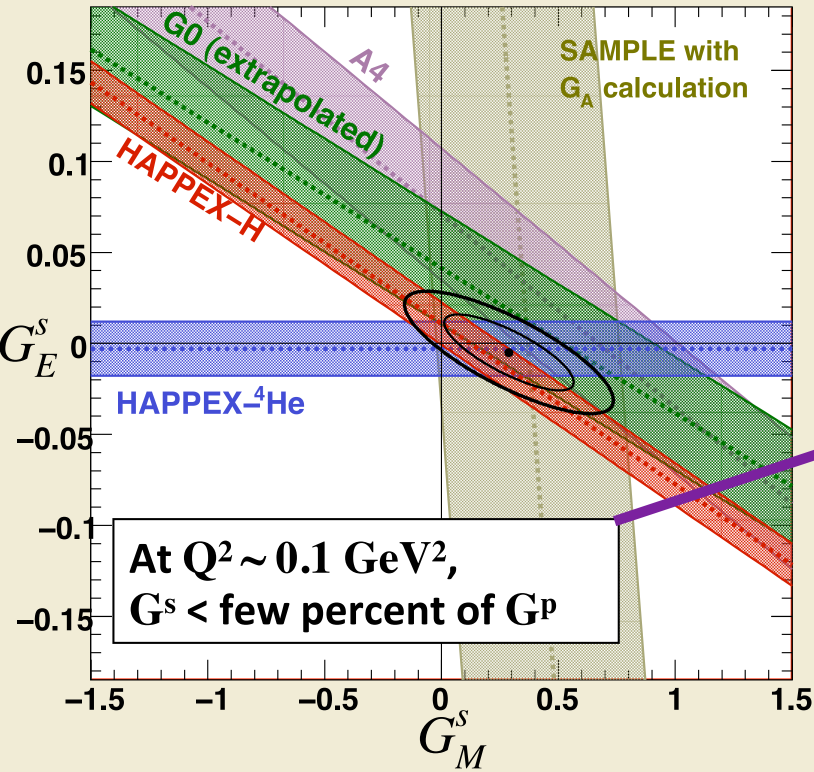
$Q^2 = 0.62\ GeV^2$ in combination

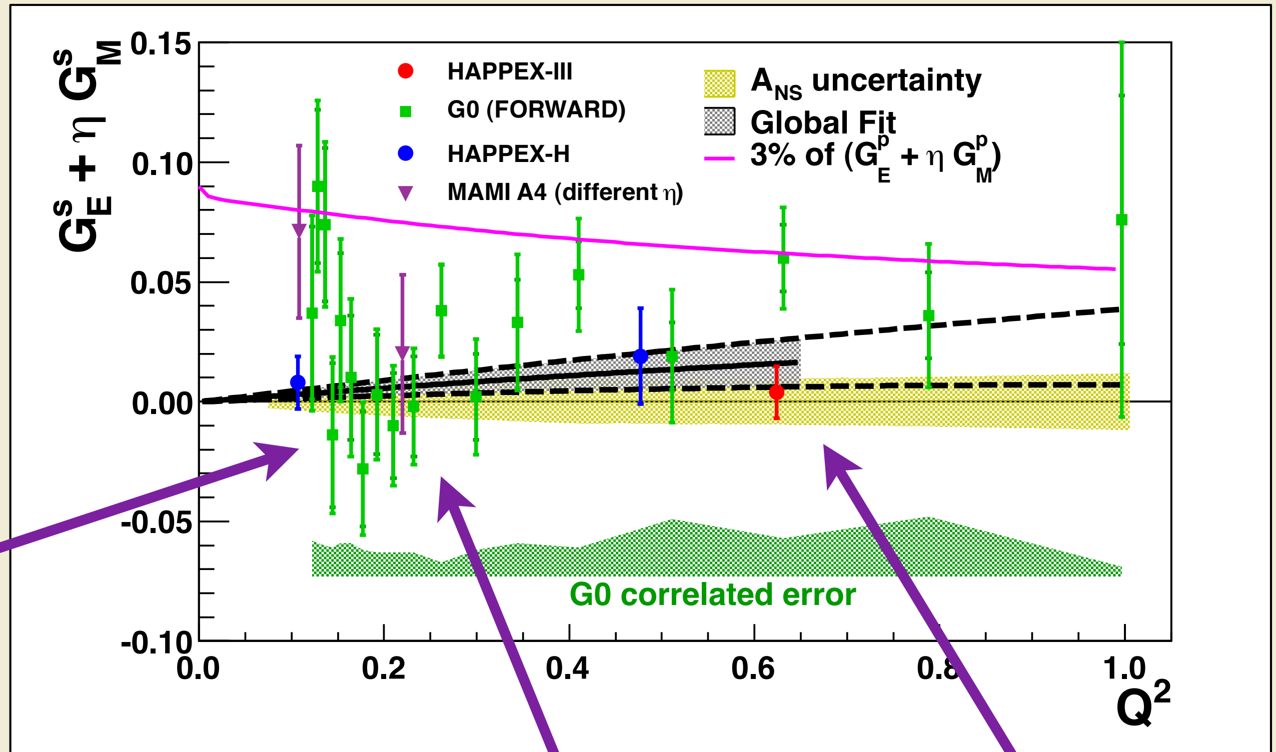


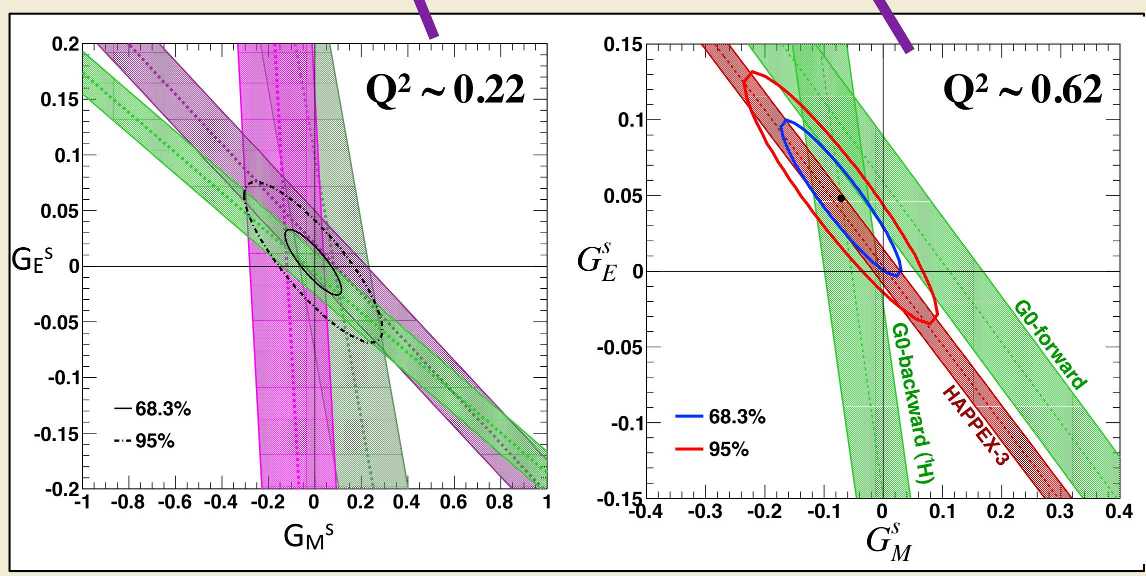
Zhu constraint is used for axial form-factor

Combined fit includes form-factor uncertainties, experimental bands do not

Strange Vector Form Factors Are Small







- HAPPEX-III provides a clean, precise measure of A_{PV} at Q^2=0.62 GeV^2, consistent with no strangeness contribution
- Further improvements in precision would require additional theoretical and empirical input for interpretation

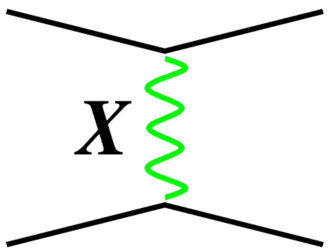
Peering Beyond the Standard Model

Direct vs Indirect Searches

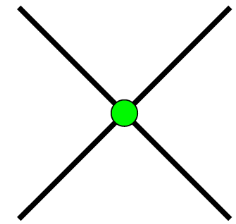
(according to Hans Christian Andersen)

Electroweak Physics Away from Z pole

consider



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



Contact interaction

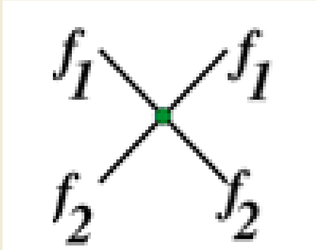
at $\mathbf{Q^2 = M_Z^2}$

On Z resonance, A_Z dominates. Interference with other contact interactions is not visible!

Precision Z observables establish anchor points for the Standard Model

For low energy measurements, interference with New Physics terms can be found

Consider $f_1 f_1 \rightarrow f_2 f_2$ **or** $f_1 f_2 \rightarrow f_1 f_2$



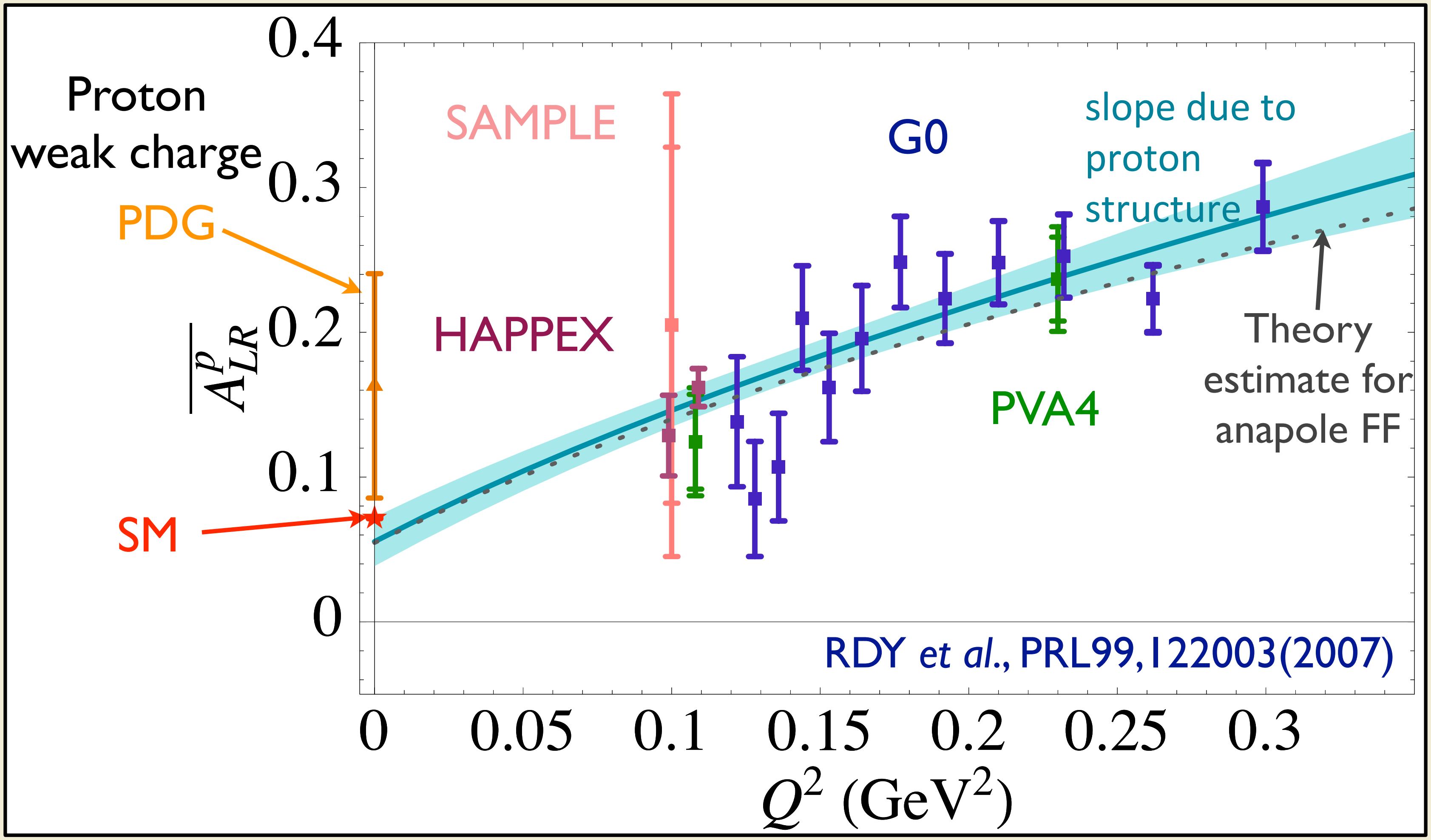
$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g^{12}_{i\,j})^2}{\Lambda^2_{ij}} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

Eichten, Lane and Peskin, PRL50 (1983)

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

New terms arise in models for new physics with Λ's at the TeV scale

Proton Weak Charge



Proton weak charge precisely known from EW gauge theory and precision EW at the Z-pole

If measurement at low energy comes up different, indicates proton charged for some other (parity-violating) interaction

Global fit of existing strange-quark program data provides constraint on Standard Model

QWeak

Measuring the proton ~~form-factor~~ weak charge

Small angle, low $Q^2 \sim 0.03\ GeV^2$ to suppress target structure

$$A_{PV} = -\frac{Q^2 G_F}{4\sqrt{2}\pi\alpha}\left[Q_W^p + F(\theta, Q^2)\right]$$

Proton structure F, constrained by strange quark program, contributes ~30% to asymmetry, **~2% to $\delta(Q_W^p)/Q_W^p$**

$$F \sim \frac{Q^2}{4M_P^2}(1+\mu_p)\mu_n + \text{ strange quarks } \mathcal{O}(Q^2) + \mathcal{O}(Q^4)$$

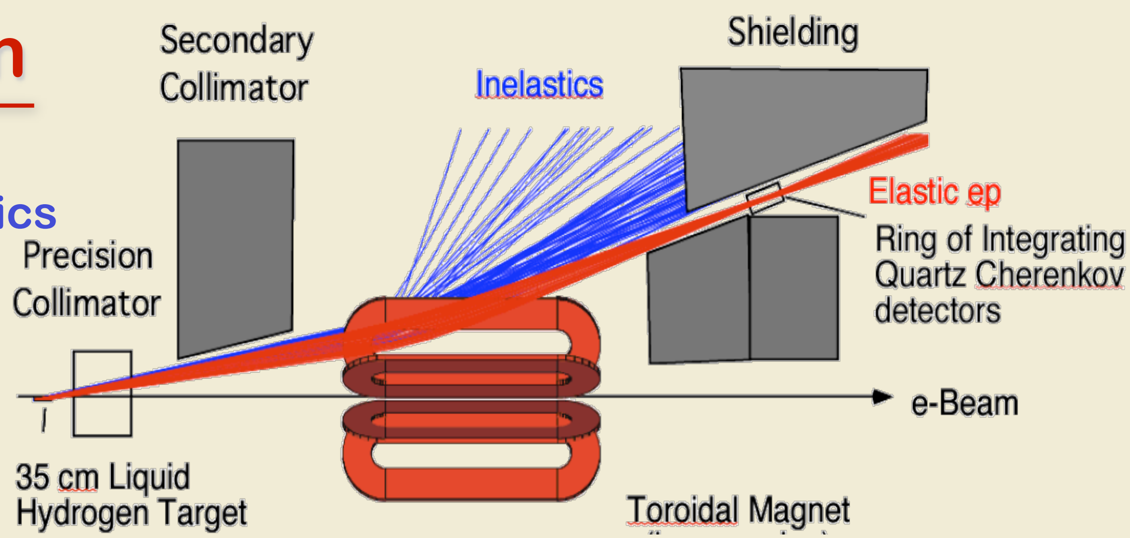
$$A_{PV} \approx -230 \pm 5 \pm 4\ ppb$$

$$\delta Q_W^p = \pm 4\% \quad \Rightarrow \quad \delta(\sin^2\theta_W) = \pm\ 0.3\%$$

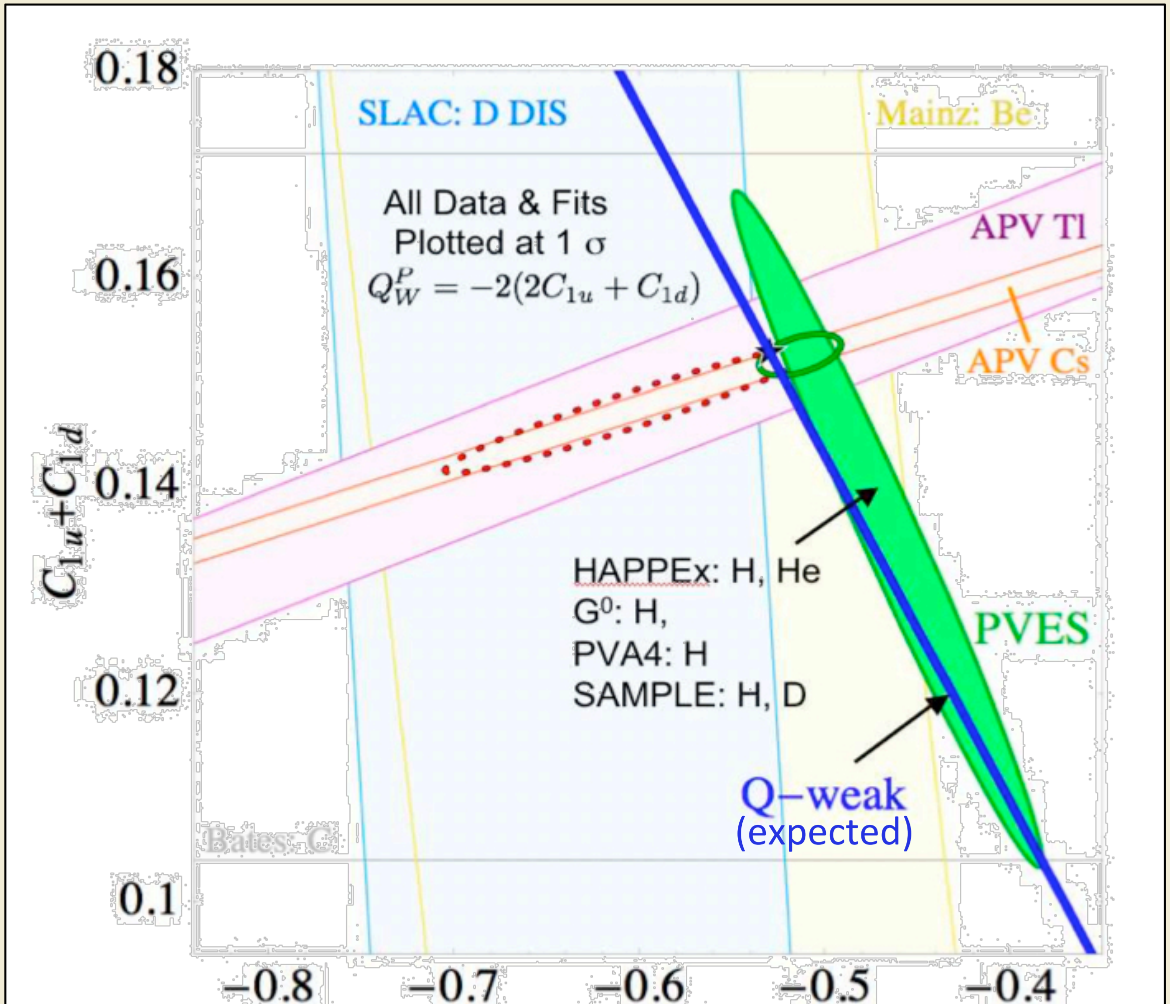
A new standard in precision

- New Spectrometer system
- Control and correction for beam systematics
- Polarimetry approaching 1% (new)
- Low system noise - 5 GHz rate!
- High rate, radiation hard readout
- Background and calibration precision

mid-2010 through 2012



Proton Weak Charge with Qweak



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

$Q^p_W = 2\ C_{1u} + C_{1d}$

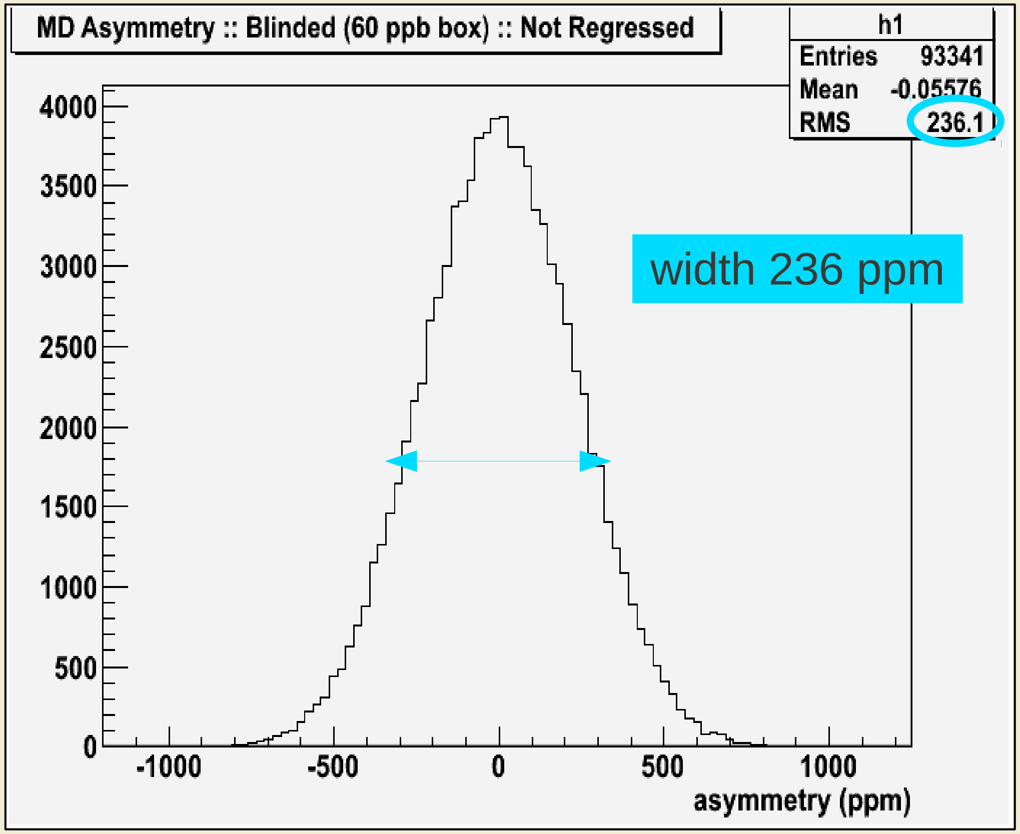
$$C_{1q} = (g^{eq}_{RR})^2 + (g^{eq}_{RL})^2 - (g^{eq}_{LR})^2 - (g^{eq}_{LL})^2$$

$\delta Q_W{}^p$=4%

$$\frac{\Lambda}{g} \sim \frac{1}{\sqrt{\sqrt{2}G_\mu |\Delta Q^p_W|}} \sim 4.6\text{TeV}$$

- Non-perturbative theory **g ~ 2π   Λ ~ 29 TeV**
- Extra Z' **g ~ 0.45   m $_{Z'}$ ~ 2.1 TeV**

Qweak



Width well understood

Counting statistics:	215 ppm
Detector Resolution:	232 ppm
Current normalization and estimate of target boiling:	236 ppm

width at 240 Hz: 236 ppm

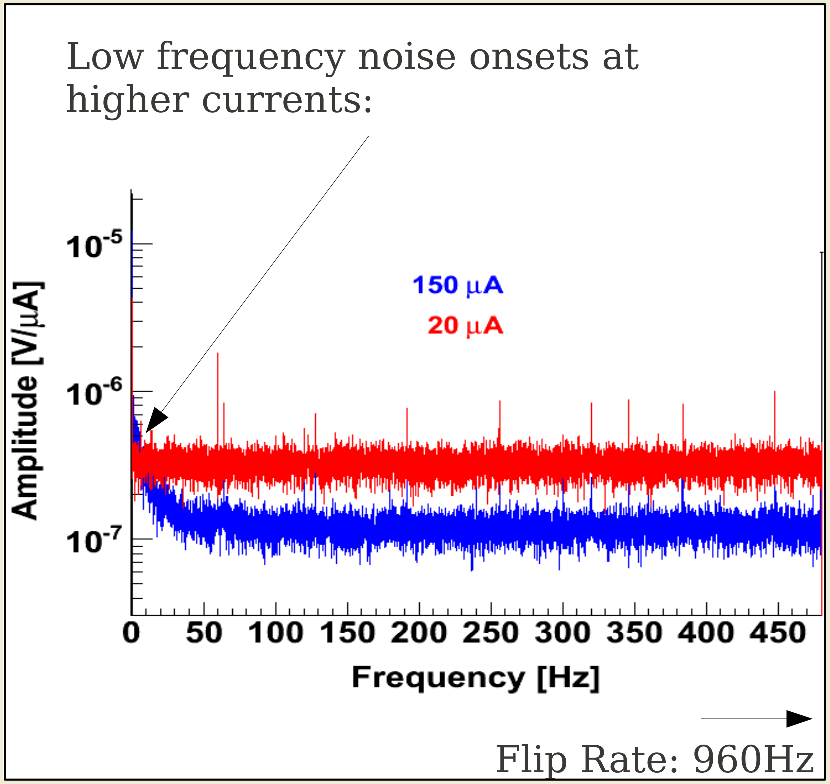
1ppm precision in 4 minutes

~25% data collected: final run starting November 2011

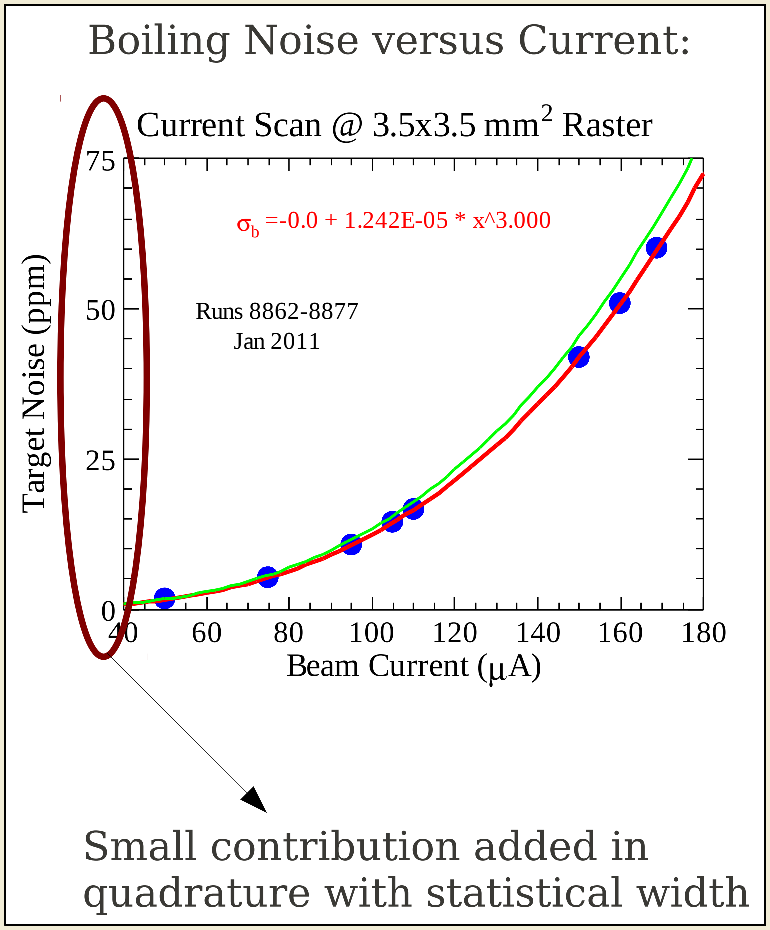
Cryotarget

Liquid Hydrogen: 35cm cell, 180 μA

2300 Watts



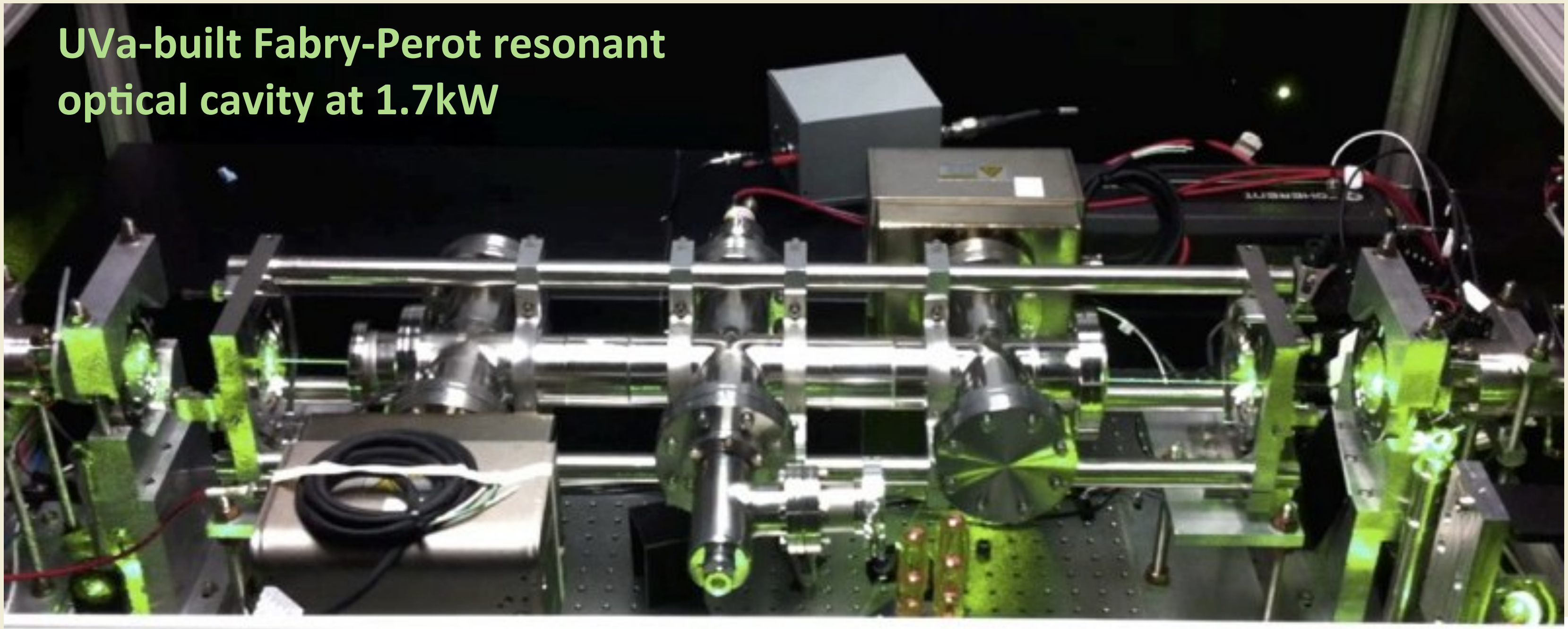
Doesn't "boil" (much)

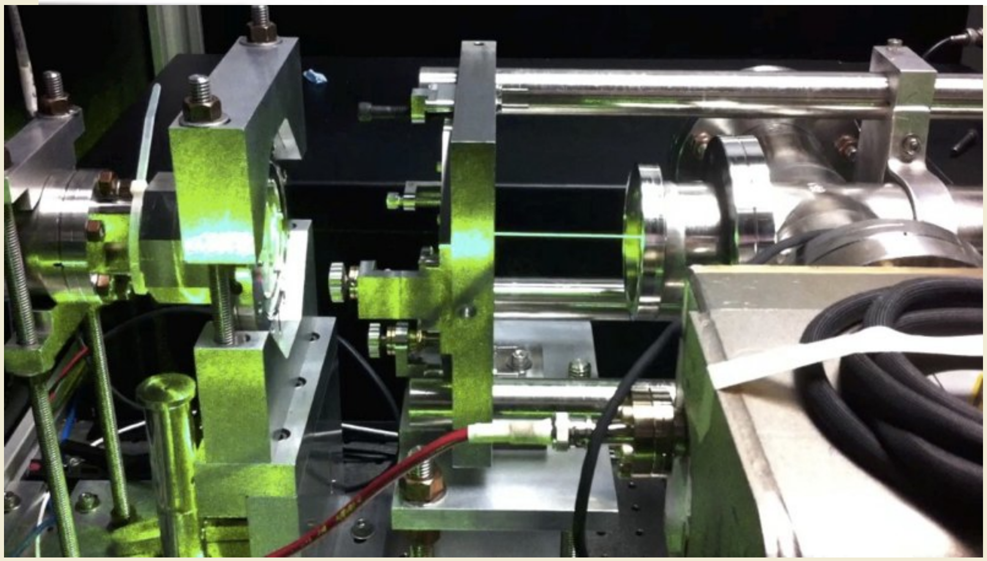


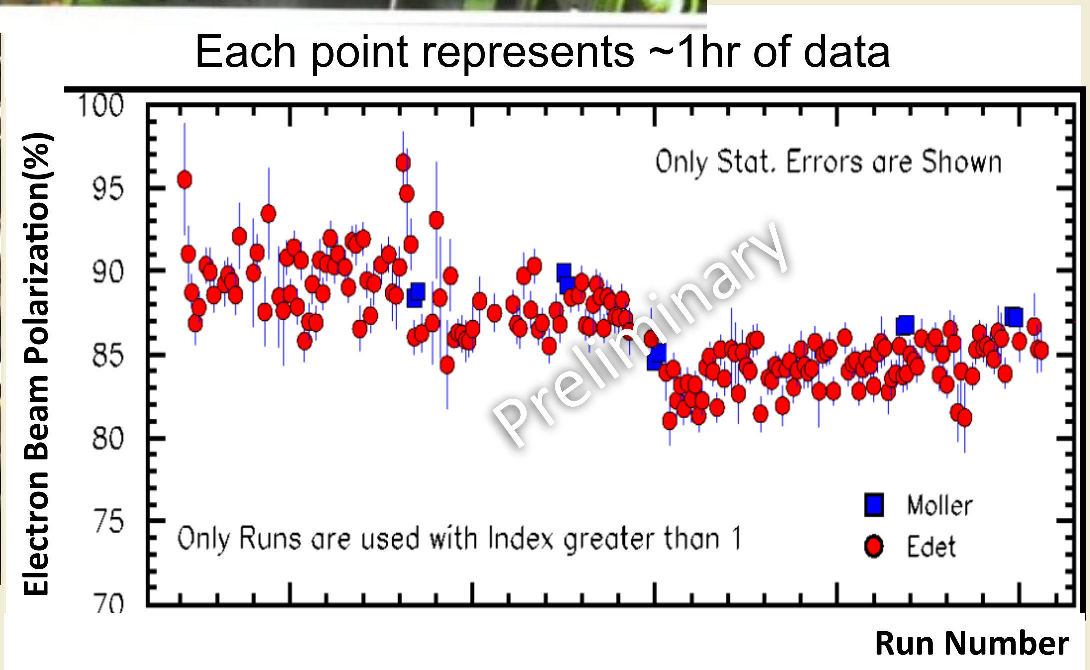
Boiling <60ppm = about 4% excess noise

Compton Polarimeter

1% electron beam polarimetry

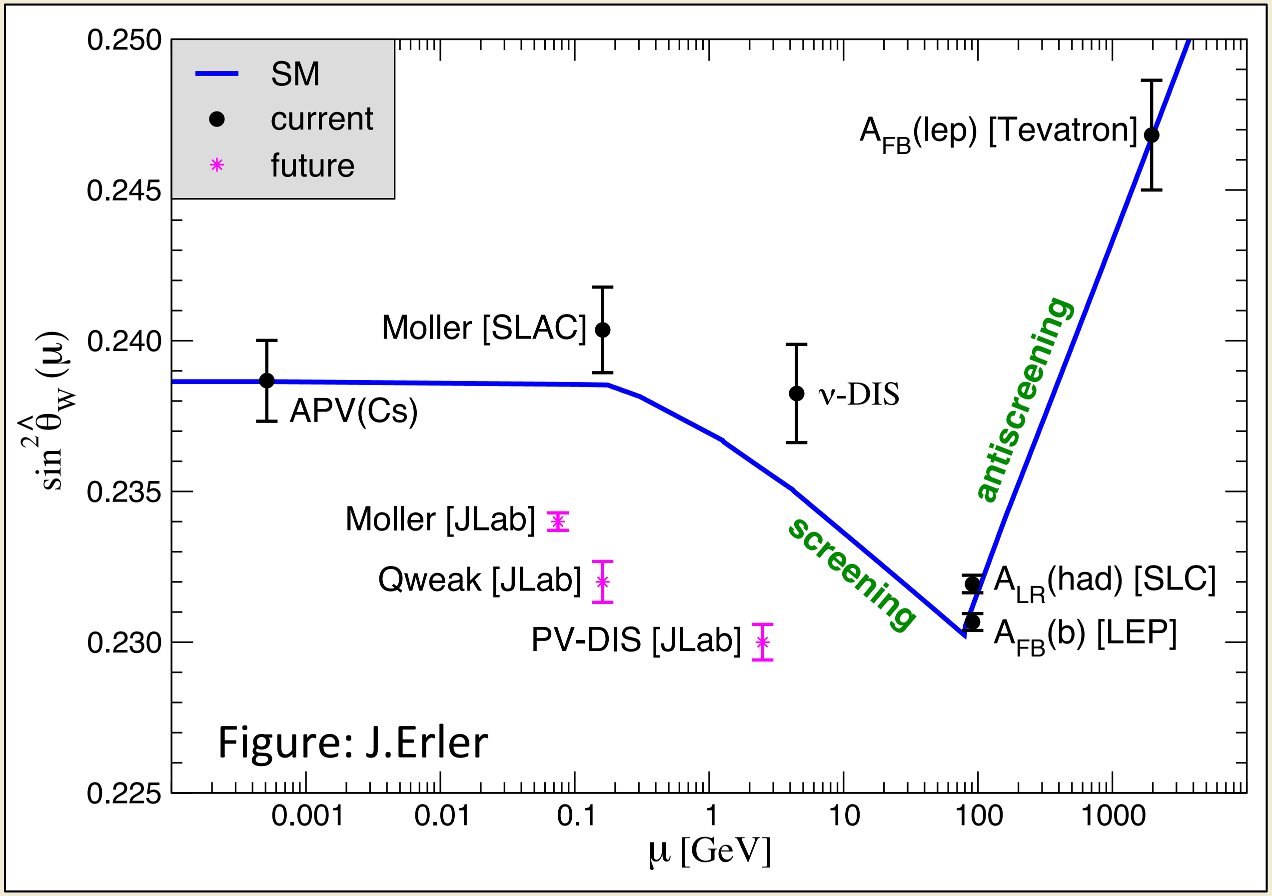






Weak mixing angle $\sin^2\theta_W$

Weak mixing angle defines weak neutral-current charges



Renormalization scheme defines $\sin^2\theta_W$ at the Z-pole.

γ-Z mixing and other diagrams are absorbed into the coupling constant

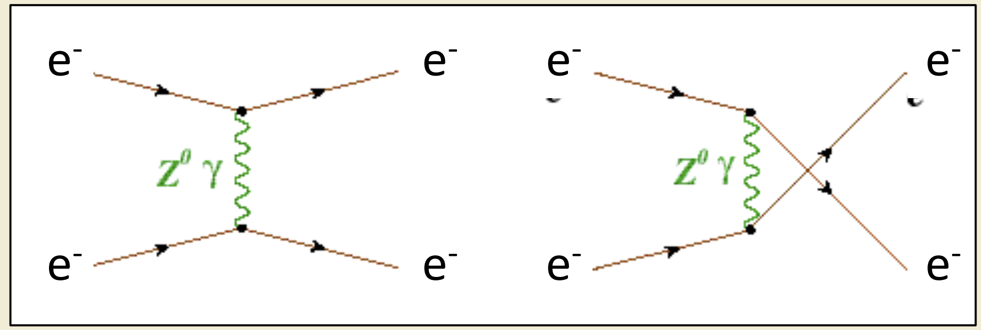
Off the Z-pole, Qweak measures for (new) parity-violating interactions

Qweak will be the most precise low-energy measurement... until...

The Future of Parity-Violation Electron Scattering

Møller Scattering at 11 GeV

MOLLER: Measurement Of a Lepton-Lepton Electroweak Reaction



A_{PV} = -35.6 ppb δA_{PV} = 0.73 ppb

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

$\delta (\sin^2\theta_W) = \pm 0.00026$ (stat) ± 0.00012 (syst)

$$A_{PV} \propto E_{lab} Q^e_W \qquad Q_W^e \sim 1 - 4\sin^2\theta_W$$

~150 GHz !

$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g^2_{ij}}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j \Rightarrow \frac{\Lambda}{\sqrt{|g^2_{RR} - g^2_{LL}|}} = 7.5 \text{ TeV}$$

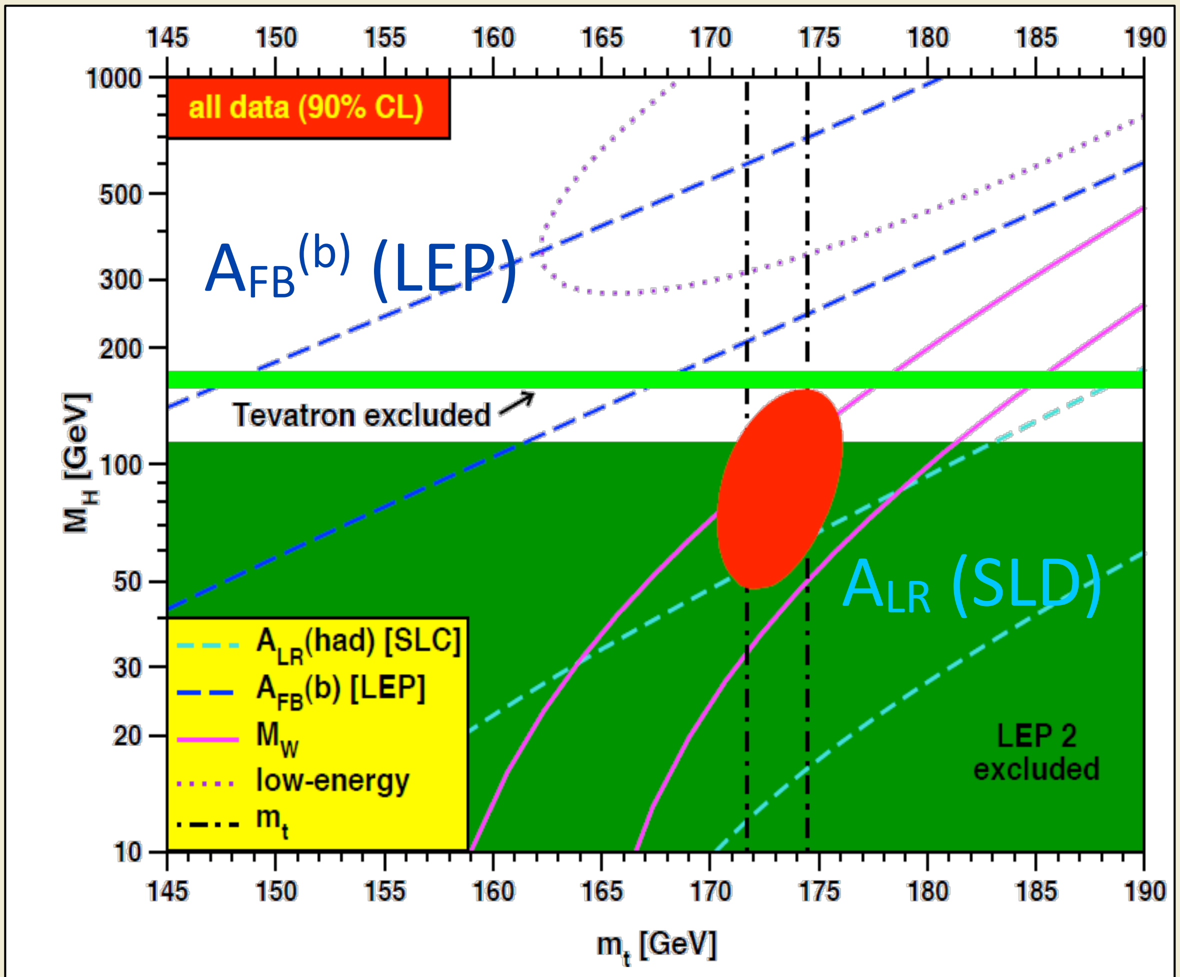
- Address important ambiguity in existing electroweak data
- Provide important complementary sensitivities to make sense of emerging LHC data
- Test for new parity-violating interactions to mass scales >25 TeV

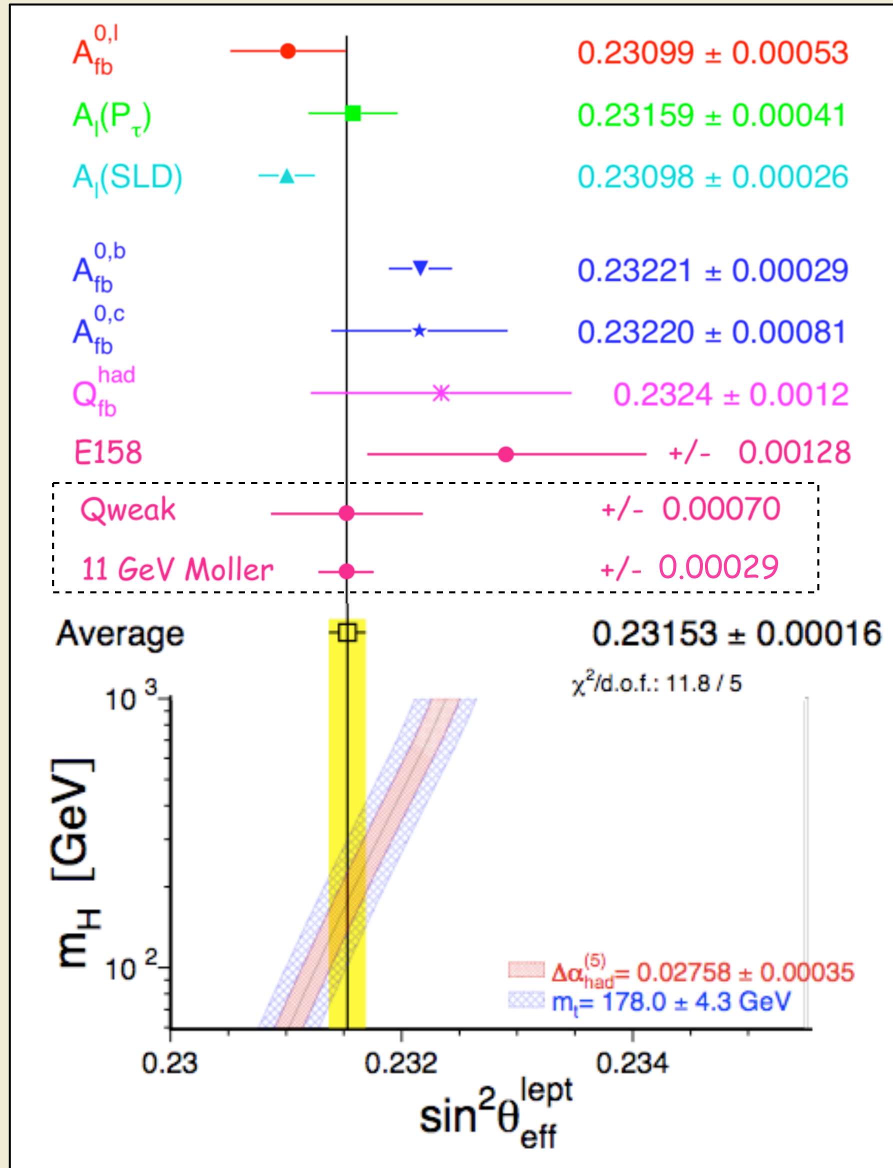
Best contact interaction reach for leptons at low OR high energy, without Z factory, linear collider, neutrino factory, or muon collider

$\sin^2\theta_W$ in Electroweak Fits

There are only 3 fundamental parameters in the electroweak Standard Model
(plus a few others from loop corrections)

Fits over global data set show good consistency (with a few sore points)





Example of Complementarity to LHC

- Most unified theories predict additional neutral Z’
- LHC can find these ~5 TeV, can determine properties 1-2 TeV
- 11 GeV Moller can help pin down couplings

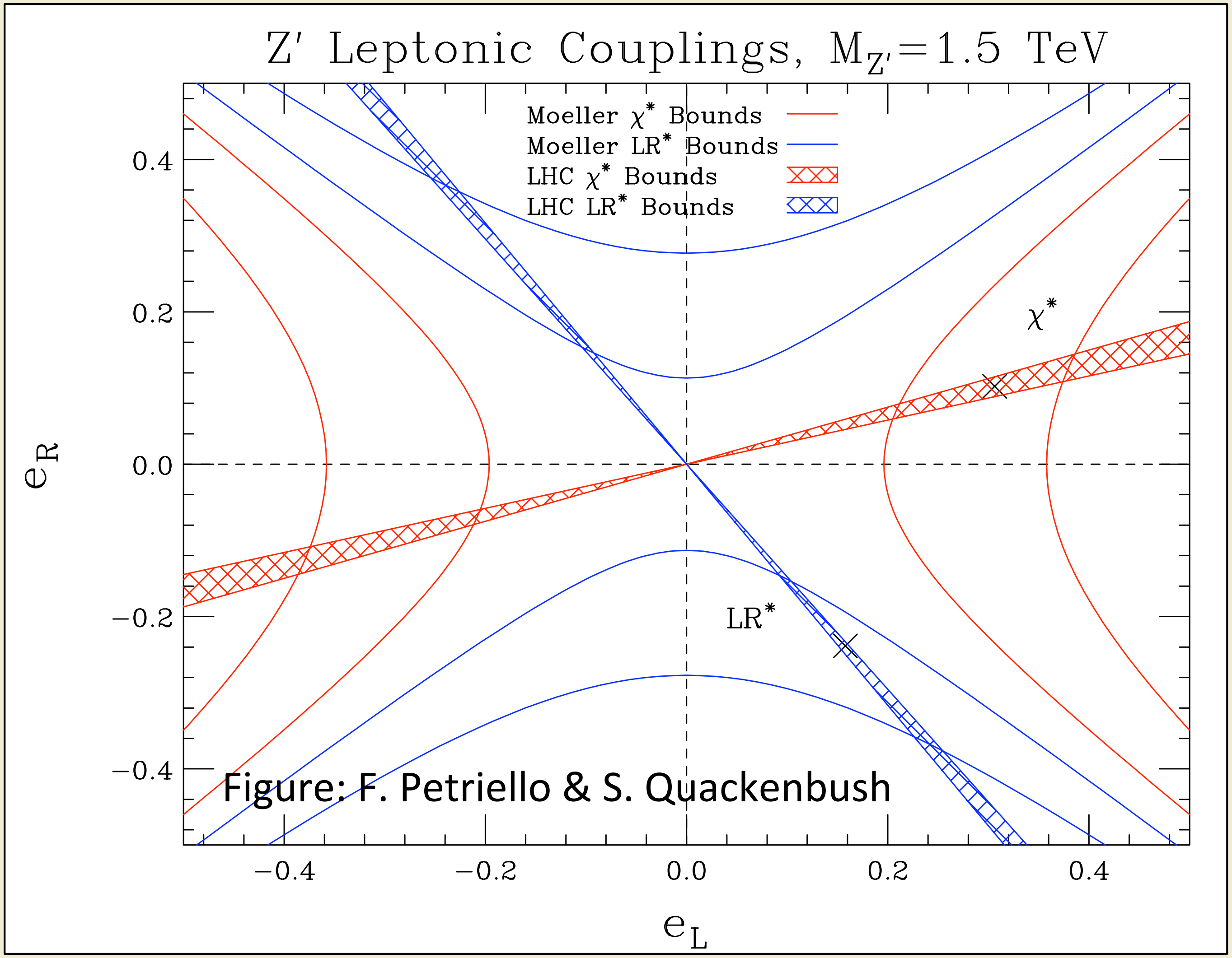


Figure: F. Petriello & S. Quackenbush

Moller sensitivity:

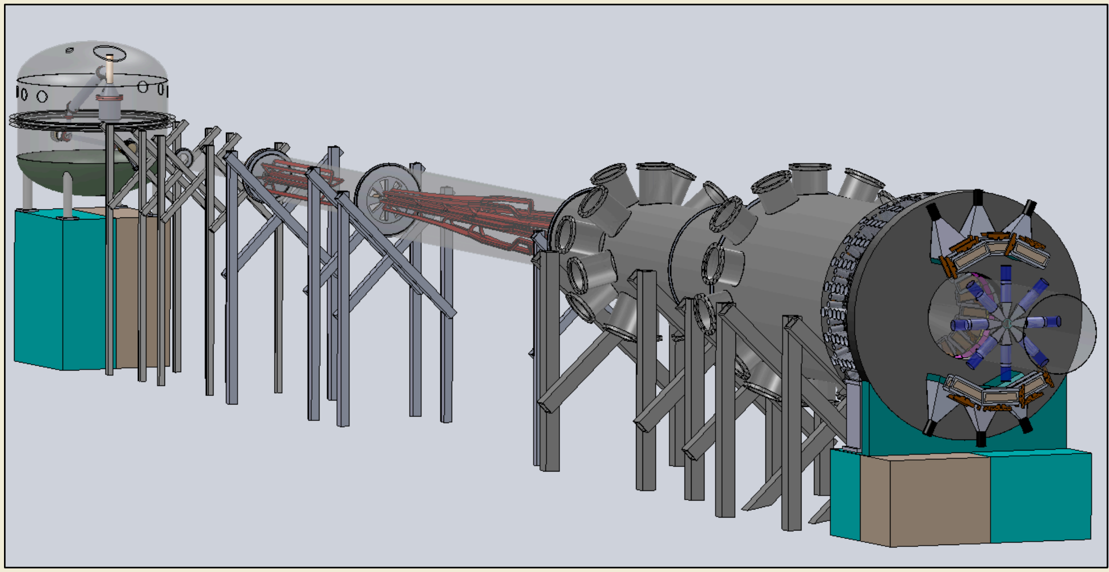
$$\frac{g_{RR}^2 - g_{LL}^2}{\Lambda^2} = \frac{e_R^2 - e_L^2}{M_{Z'}^2}$$

$$\sim \frac{1}{(7.5\mathrm{TeV})^2}$$

With mass, width, and A_{FB} LHC can constrain ratio

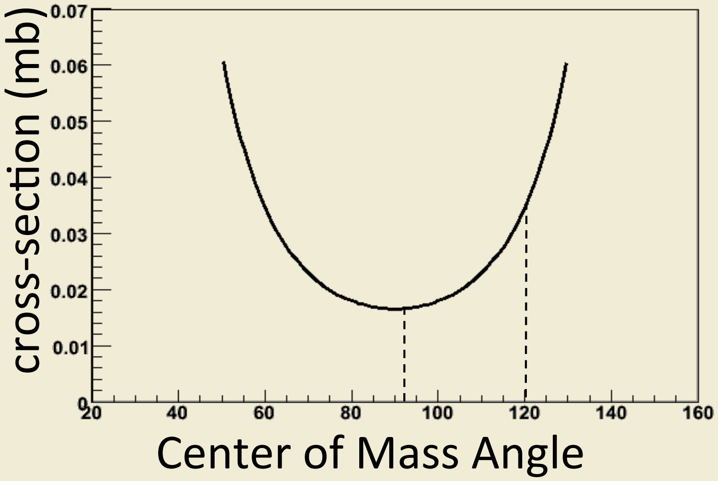
$$\frac{e_R}{e_L}$$

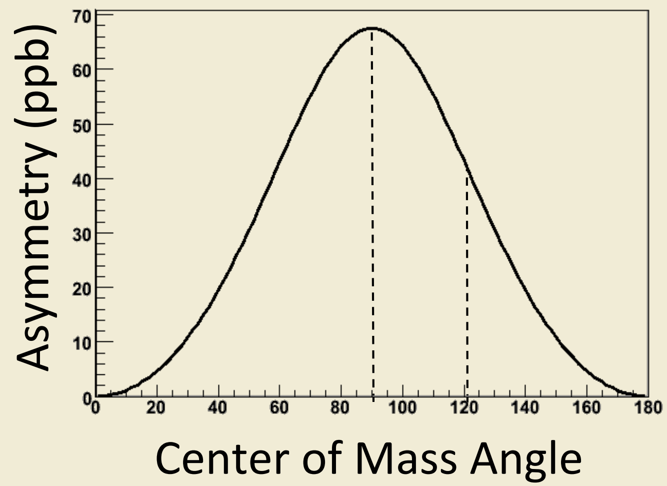
MOLLER Aparatus

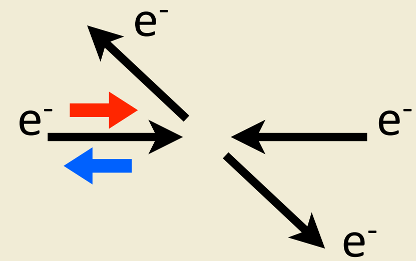


- Polarized Beam
  - Unprecedented stabililty
  - Requires best-ever JLab polarimetry
  - Beam monitoring (RF, optical techniques?)
- Liquid Hydrogen Target
  - 5kW dissipated power
  - unprecedented luminosity stability, 1.5meters length
- Toroidal Spectrometer
  - Novel 2-toroid, 7 coil "hybrid" design, 100% azimuthal acceptance
  - warm magnets, but aggressive engineering
  - background supression/study
- Integrating Detectors
  - Novel 2-toroid, 7 coil "hybrid" design
  - 135 GHz rate, 83 ppm/1kHz measurement

Spectrometer Concept







identical particles

Highly boosted lab frame

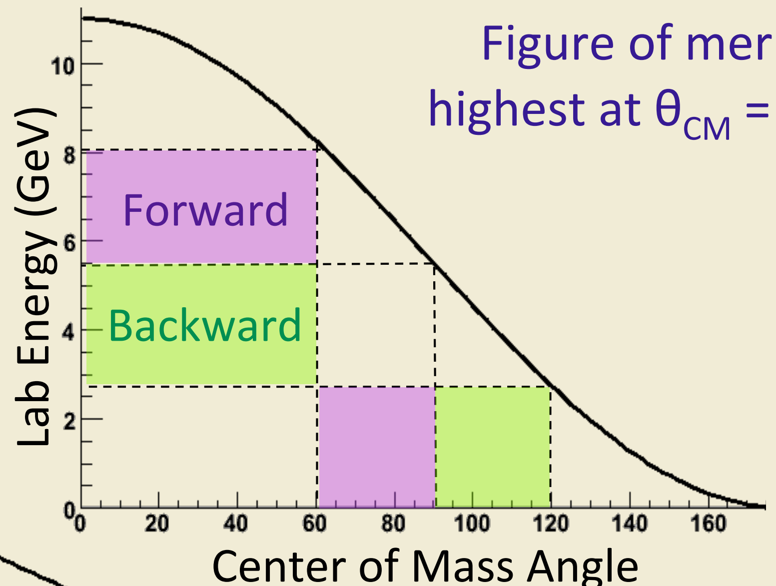
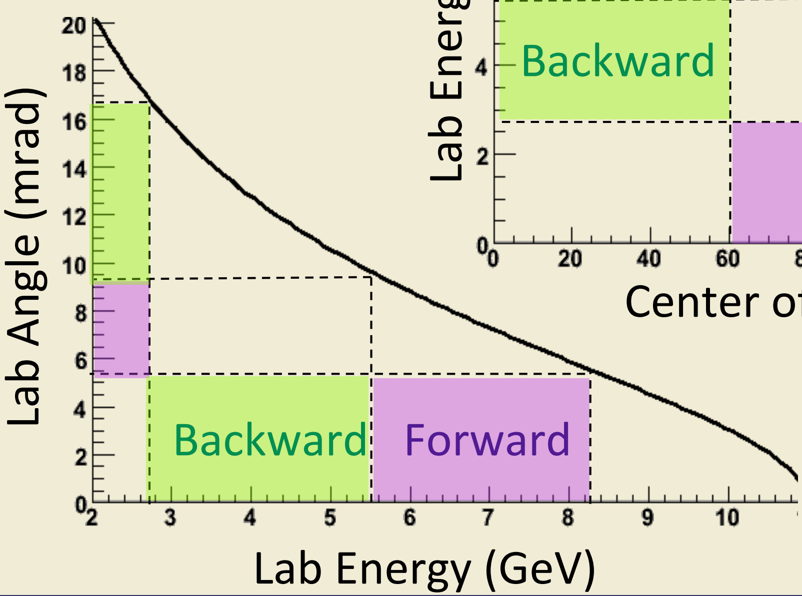
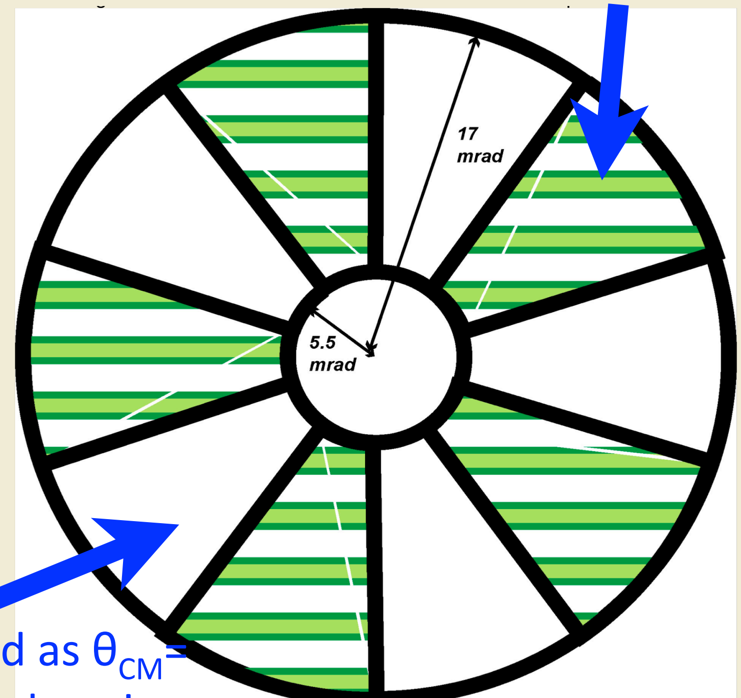


Figure of merit highest at θ_{CM} = 90^o

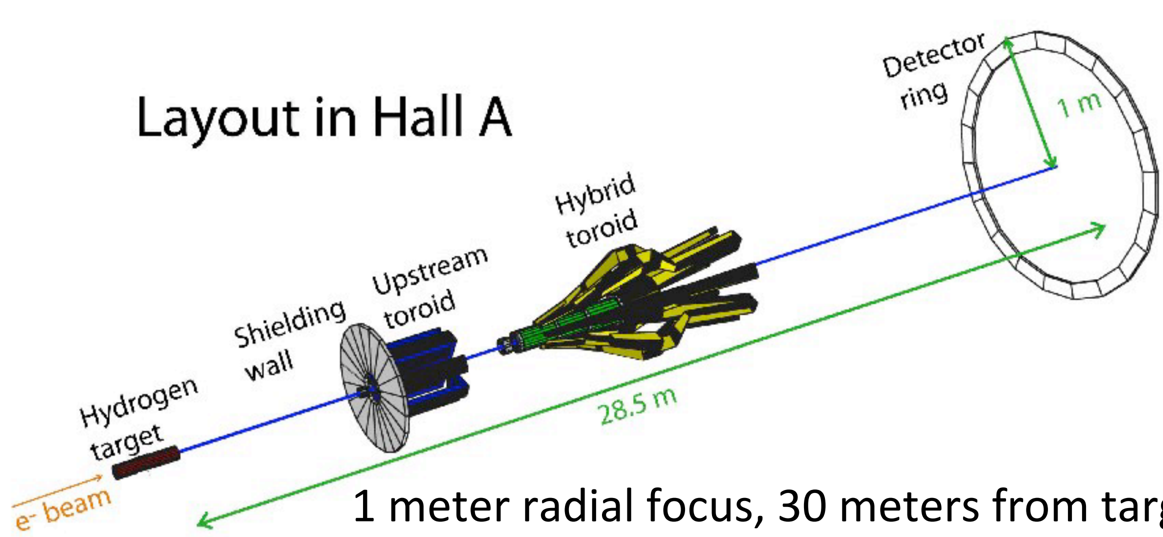


All of those rays of θ_{CM}=[90,120] that you don't get here...

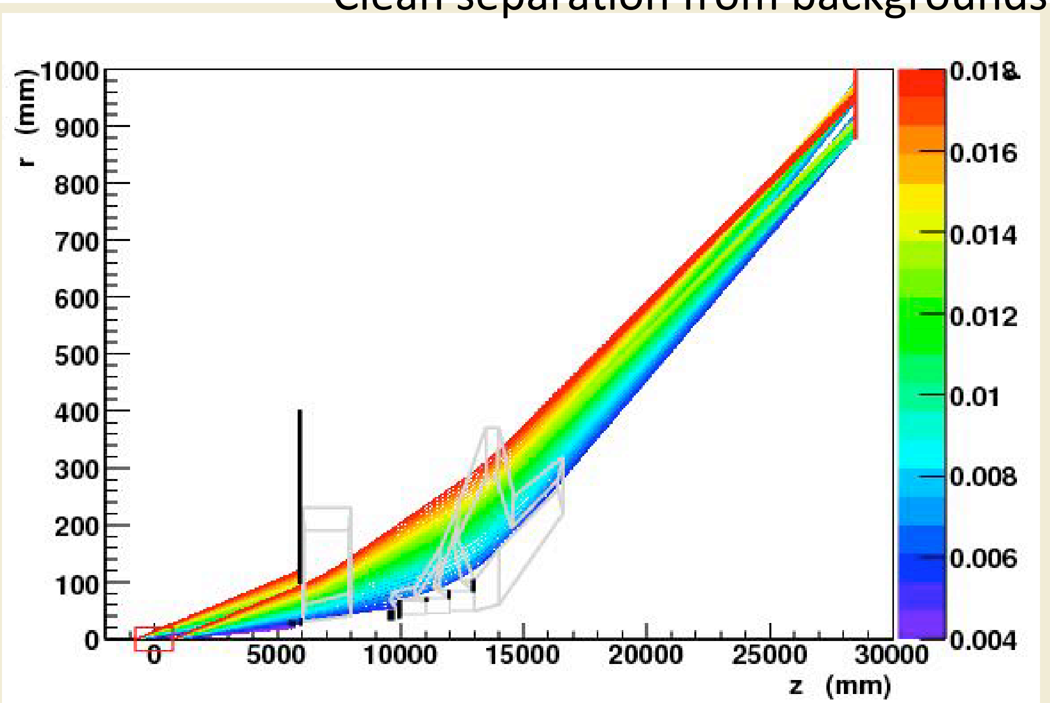


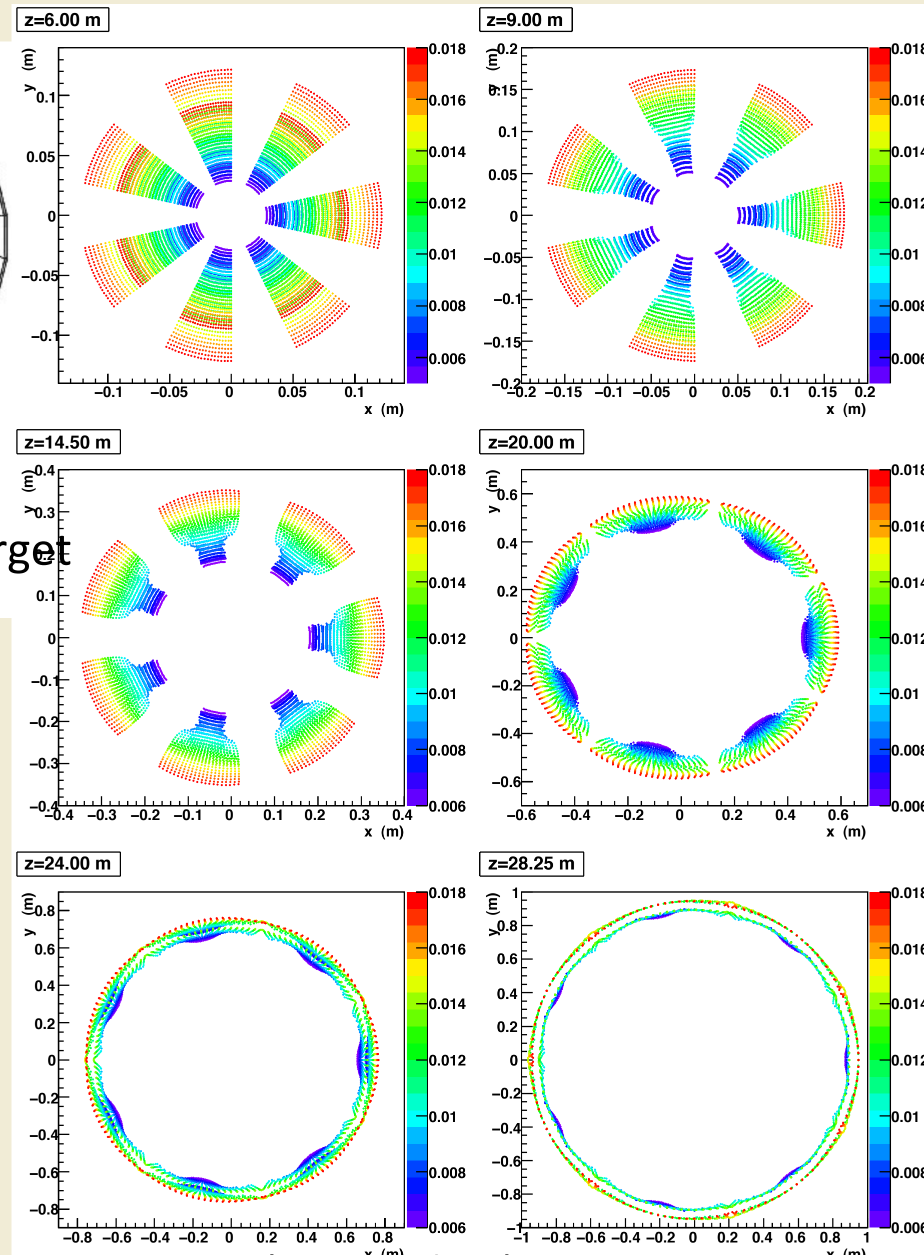
... are collected as θ_{CM}= [60,90] over here!

Two Toroid Spectrometer



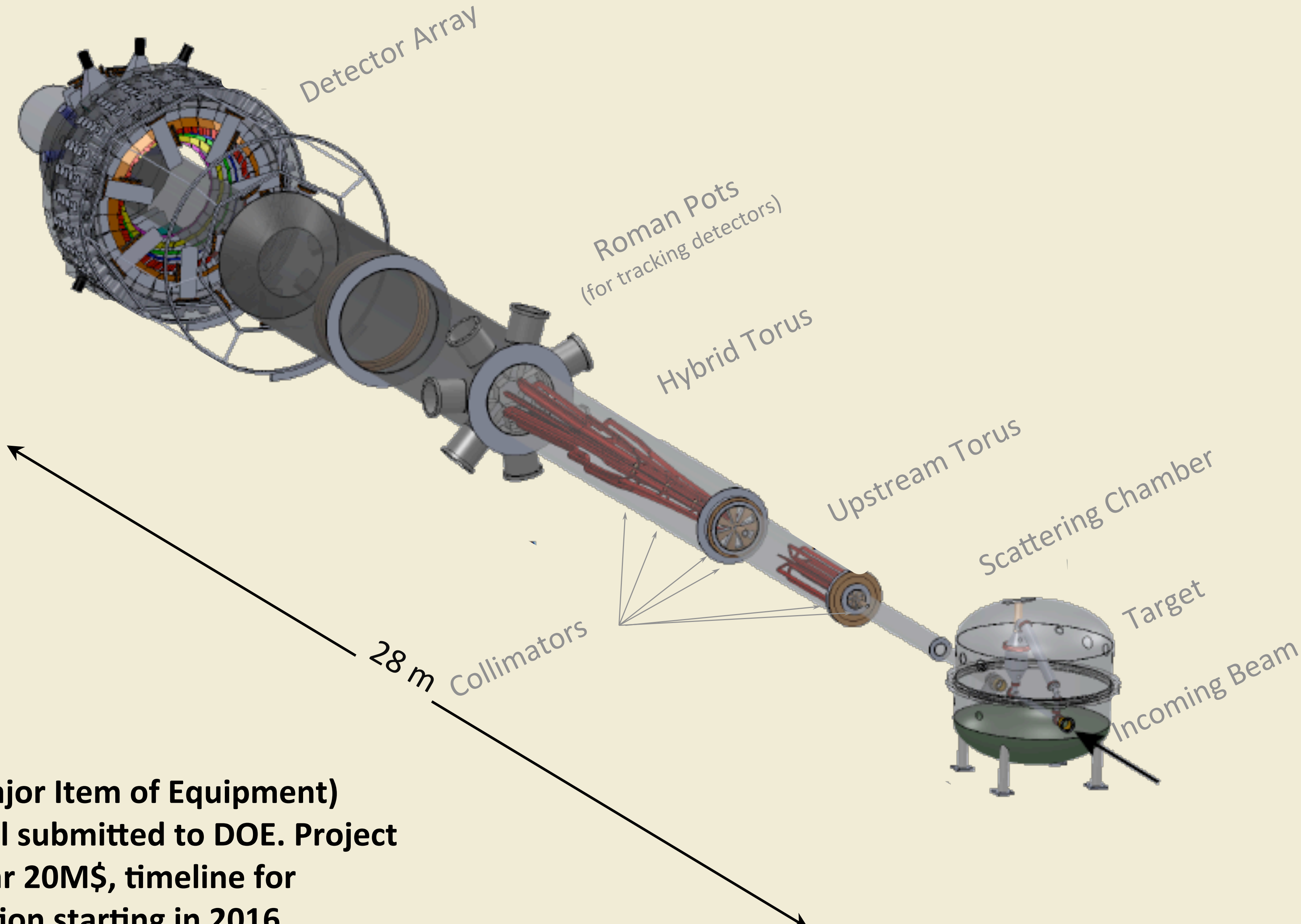
1 meter radial focus, 30 meters from target
Clean separation from backgrounds





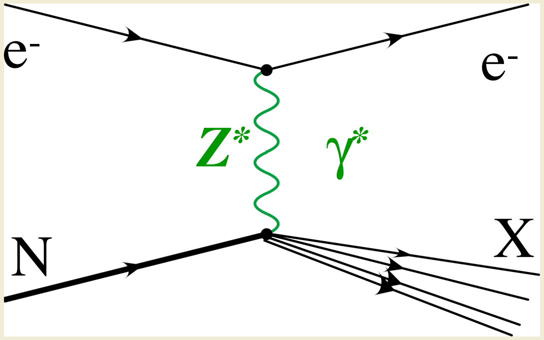
Designed by UVa (Clayton Davis)

Radial Fields (edge effect) creates azimuthal defocussing which populates the full ring at the detector



MIE (Major Item of Equipment) proposal submitted to DOE. Project cost near 20M$, timeline for installation starting in 2016

Deep Inelastic Scattering: SoLID



Deep Inelastic Regime: Scattering from quarks

Parity-violation in DIS is uniquely sensitive to the poorly known quark axial charges C_{2u} and C_{2d}

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

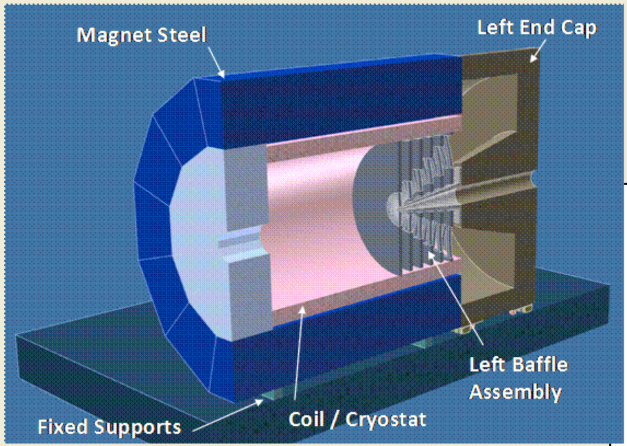
$$a(x) = (2C_{1u} - C_{1d})$$

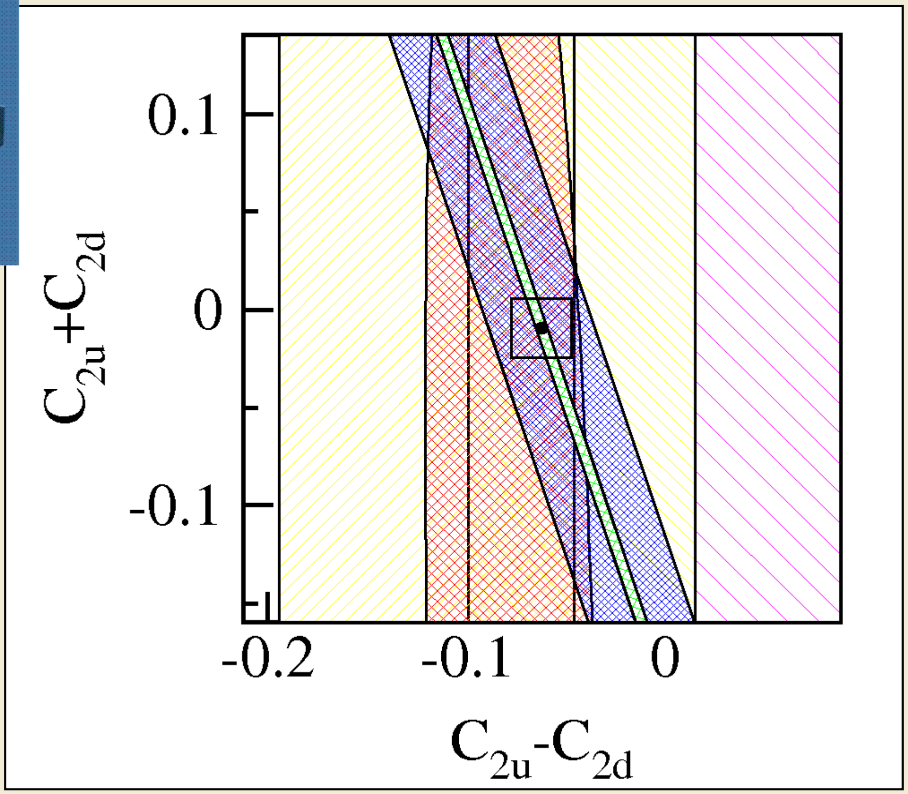
$$b(x) = (2C_{2u} - C_{2d})$$

$$C_{1q} = (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

$$C_{2q} = (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

Requires Dedicated New Spectrometer System and a broad program of study to separate hadronic and electroweak physics





Proposed design provides sufficient acceptance, resolution, and shielding for broad PVDIS program

- charge symmetry violation
- C_{2q}'s and new physics
- higher twist and quark correlations
- d/u in proton at high x
- PV analog of EMC, nuclear media induced charge asymmetry

Discussed in detail in X.Zheng's colloquium Oct. 31

Summary

Parity-violating electron scattering has a record of accomplishment

... and a very bright future