Acknowlegements:
HAPPEX, PREX/CREX, SLAC E158 and MOLLER Collaborations,
Numerous colleagues from whom I have borrowed pictures and ideas

The PVES Legacy that made MOLLER Feasible

The Hall A (Integrating) PVES Program

A personal recollection of the sequence of seminal measurements that likely would not have happened without Paul Souder's involvement

Krishna Kumar
University of Massachusetts, Amherst

Workshop on the Physics Program at High Luminosities
Jefferson Laboratory, October 8, 2026

Paul Souder Launched the Hall A PVES Program

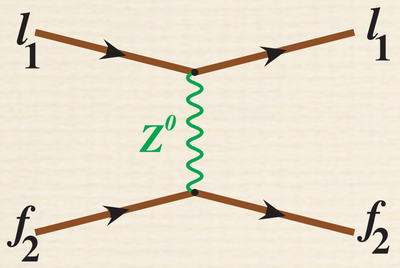
Outline

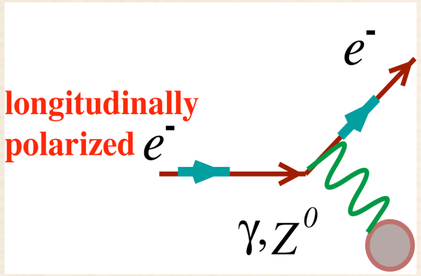
- **Historical Context**
  - *Parity-Violating Electron Scattering*
  - *The Stage for CEBAF Experiments to have Major Impact*
- **Strange Quarks in the Nucleon**
  - *The Hall A Program*
  - *Major Insights and Foundation for More Sensitivity*
- **Neutron Skin of a Heavy Nucleus**
  - *PREX and CREX*
  - *Impact Well Beyond Nuclear Physics*
- **Møller Scattering**
  - *SLAC E158*
  - *JLab and Hall A Primed for MOLLER*
- **Summary**

The combination of the success of the Hall A PVES program, including the contributions of the Hall A Collaboration, Hall A physics and technical staff, the Accelerator Division and especially the collaboration with the Injector Group, has set the stage for the MOLLER Experiment.

Historical Context

Semi-Leptonic and Leptonic Weak Neutral Currents at $Q^2 \ll M_Z^2$





Parity-violating Electron Scattering (PVES)

Weak Charge Q_W

g_V's are functions of $\sin^2\theta_W$

$$-A_{LR} = A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{\gamma}} \sim \frac{G_F Q^2}{4\pi\alpha} \left(g_A^e g_V^T + \beta\, g_V^e g_A^T\right)$$

$$A_{PV} \sim 10^{-5} \cdot Q^2 \text{ to } 10^{-4} \cdot Q^2$$

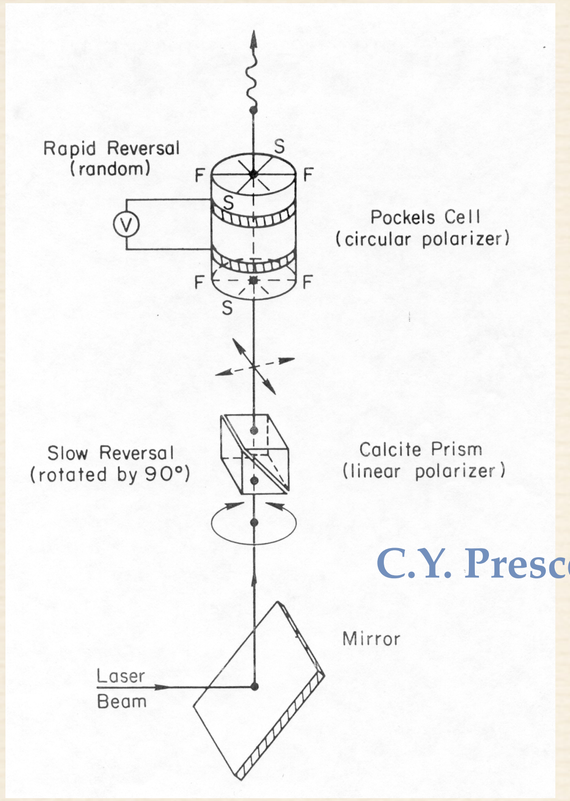
Specific choices of kinematics and target nuclei probe different physics:

- *Mid-70s to late-80's: goal was to establish the electroweak theory*
- *Early 90's to 2020's: target couplings probe novel aspects of hadron structure*
  - ✦ *strange quark form factors, neutron RMS radius of heavy nuclei*
- *Since late 90's: precision measurements with carefully chosen kinematics can probe physics at the multi-TeV scale via ultra-precise $\sin^2\theta_W$ measurements*

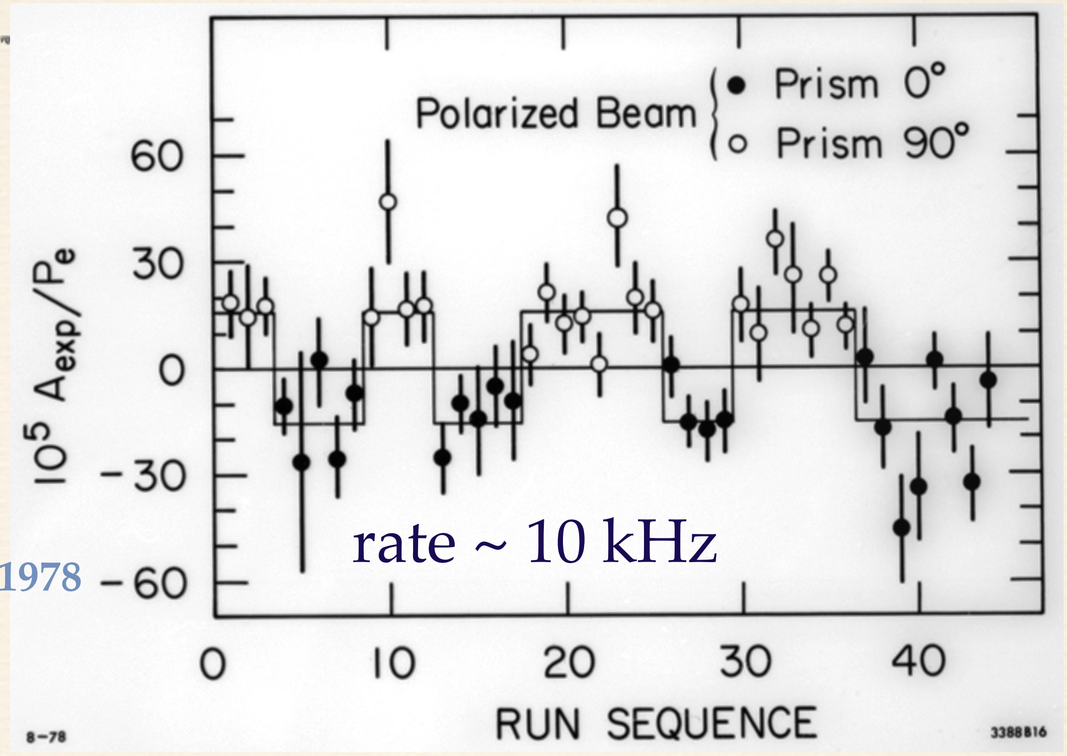
All 3 "applications" i.e. strange quarks, neutron skins and BSM searches, have their origins in ideas developed by around 1990

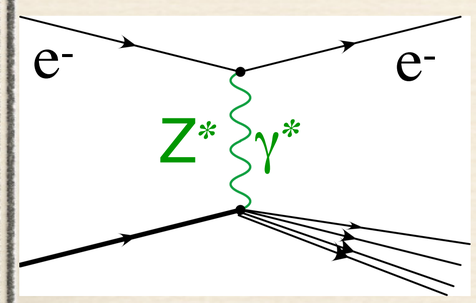
Does the weak neutral current amplitude interfere with the electromagnetic amplitude?

SLAC E122 Result



C.Y. Prescott et al, 1978





- ***Parity Violation in Weak Neutral Current Interactions***
- ***$\sin^2\theta_W$ = 0.224 ± 0.020: same as in neutrino scattering***

$$A_{PV} \sim 10^{-4}$$

$$\delta(A_{PV}) \sim 10^{-5}$$

Glashow, Weinberg, Salam Nobel Prize awarded in 1979

Nobel Press Release
October 15, 1979

"…Of special interest is a result, published in the summer of 1978, of an experiment at the electron accelerator at SLAC in Stanford, USA. In this experiment the scattering of high energy electrons on deuterium nuclei was studied and an effect due to a direct interplay between the electromagnetic and weak parts of the unified interaction could be observed…"

1980's **The ideas began at the same time as SLAC E122 but took much longer to complete**

Standard Model Tests on Nuclear Targets

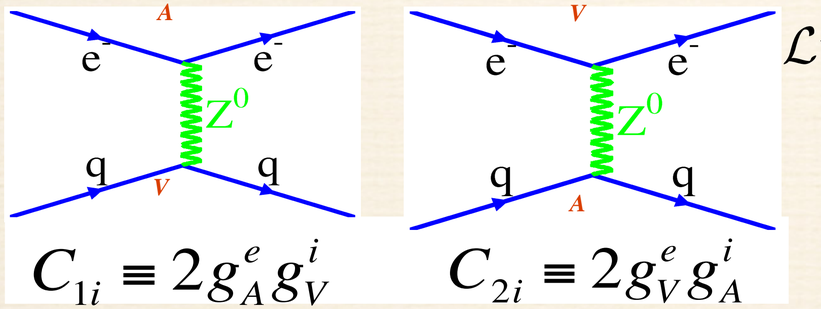
Elastic scattering from $(J^\pi, T) = (0^+, 0)$ *nuclei* *Feinberg (1975)*

For a simple nucleus like ^{12}C, A_{PV} in elastic scattering at forward angle insensitive to nuclear structure: clean measurement of $\sin^2\theta_W$

^{12}C at MIT-Bates: $A_{PV} = (1.69 \pm 0.39 \pm 0.06) \times 10^{-6}$ *Souder (1990)*

Quasi-elastic backward angle scattering from ^{9}Be

^{9}Be at Mainz: $A_{PV} = (-9.4 \pm 1.8 \pm 0.5) \times 10^{-6}$ *Heil (1989)*



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

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}} [\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$

- ***First measurements of electron-nuclear neutral weak interactions***
- ***Pushed experimental technology***
- ***Spawned a new generation of experimenters and experiments***

100 ppb systematics

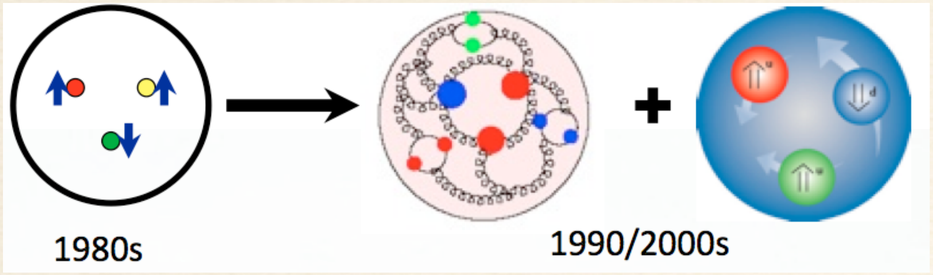
100's of MHz rates

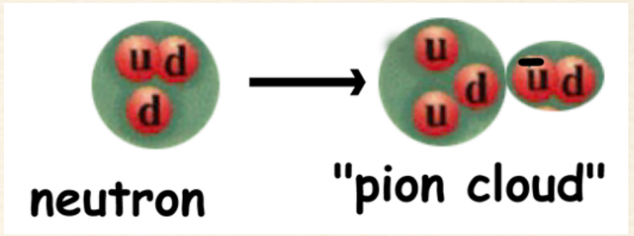
Strange Quarks in the Proton: The HAPPEX Program

Late 1970's onwards, Quantum Chromodynamics (QCD) began to tackle the challenge of fundamental understanding of nuclear systems

Sea Quarks in the Proton

It became clear that proton is an extraordinarily complex object at small length scales





Possible models to explain the electric charge form factor of the neutron were being explored

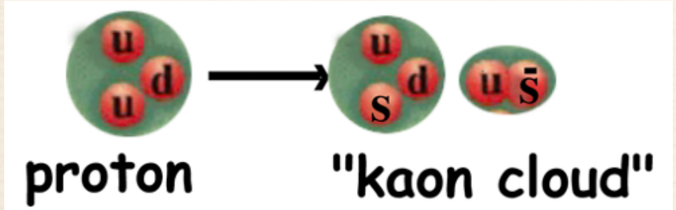
Polarized lepton scattering off polarized protons showed that only 25% of the proton spin was being carried by valence quarks!

Nucleon charge and magnetization distributions:

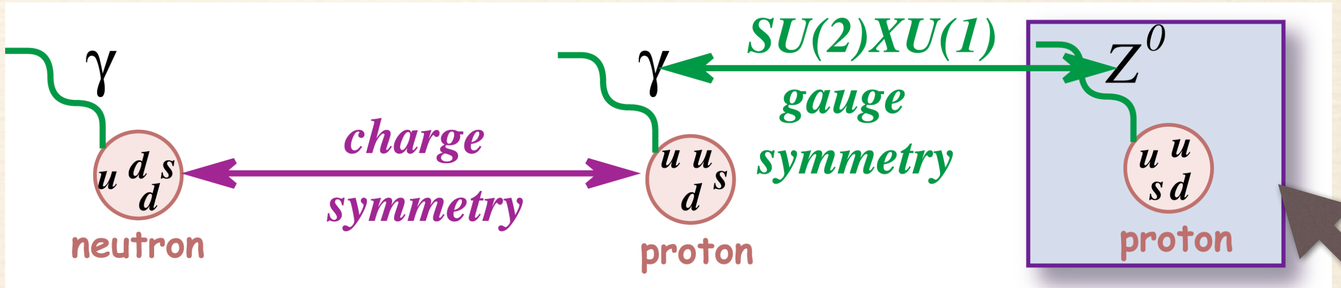
$G_E(Q^2), G_M(Q^2)$ — *electric and magnetic form factors*

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

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



Could it be that strange sea quarks also affect proton properties?



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

Parity-violating electron scattering

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

Jefferson Lab Prelude

- **Original CEBAF proposal did not mention polarized electrons!!!!**
- **Bill Bertozzi spearheaded the design the High Resolution Spectrometers (HRS) for e(e',p)**
- **Once polarized electrons were proposed, people started to think about parity-violating electron scattering (PVES), for strange quark form factors and Standard Model Tests**
  - Bob McKeown leveraged the "Bates C-12 Legacy" to propose SAMPLE at MIT-Bates
  - People were discussing elaborate and complex spectrometers for PVES at JLab
  - Paul was brought in by Jean Mougey (then Hall A Head) to review the STAR proposal
  - Legend has it that Paul ignored other committee members and started to work on something with pen and paper once he understood Bertozzi's HRS capabilities
  - He talked privately to Jean Mougey about it and then went home
  - Apparently, Jean was so impressed with whatever Paul told him that he called Paul the next day and asked him to write a proposal and submit it ot the JLab PAC

HAPPEX: Birth of the First PVES Run

and received on or before 1 October 1991.

A. TITLE: PARITY VIOLATION IN ELASTIC SCATTERING FROM THE PROTON AND ^{4}He

B. CONTACT PERSON: Paul Souder

PR-91-010

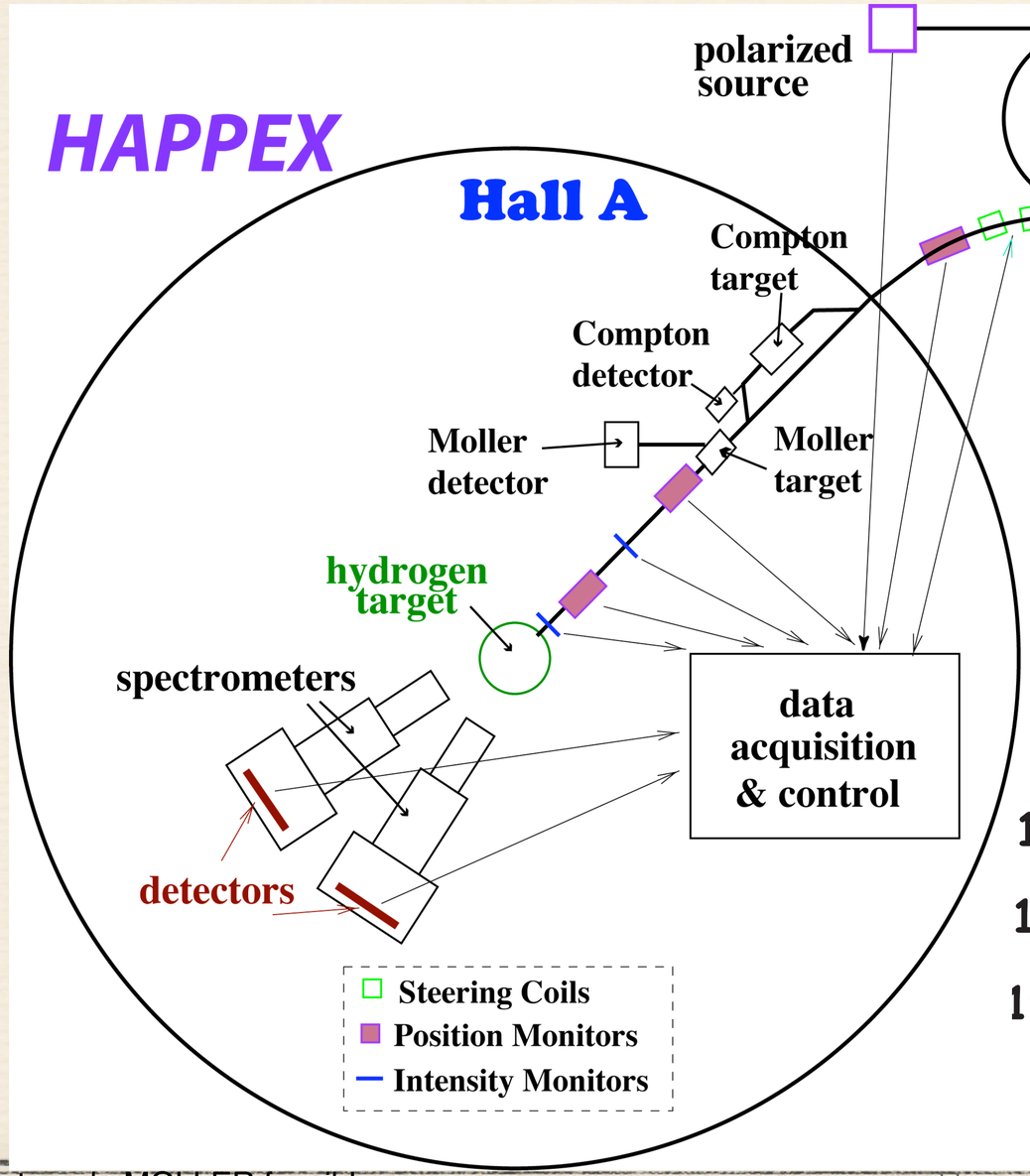
Spokespersons: Paul Souder and Mike Finn

First run was to be at 4 GeV on Hydrogen

Paul managed to lure THREE MIT-Bates ^{12}C graduate students back into the parity business!

- **I will tell you later how I came to get involved, but by 1995, I was building integrating electronics and playing with Pockels cells in my lab for HAPPEX**
- **Sometime in 1997, we were having a HAPPEX collaboration meeting**
  - **After the first hour, for the rest of the day, there were 6 people in the meeting… (Paul, Me, Mike Finn, two Phd students),**
  - **…and Kees De Jager, the new Head of Hall A!! He sat through the whole day, saying little, as I got increasingly worried…**
- **At the end of the meeting, Kees walked over to me and Paul….**
  - **"Can you run at 3.4 GeV?"…. silence from Paul… I am thinking (screaming internally) "Paul, say something!"**
  - **"You have until tomorrow morning to respond… Remember: it is YOUR experiment but positive response means you will get on the upcoming schedule 97-98 beam schedule"…. And he walked away**

HAPPEX at JLab

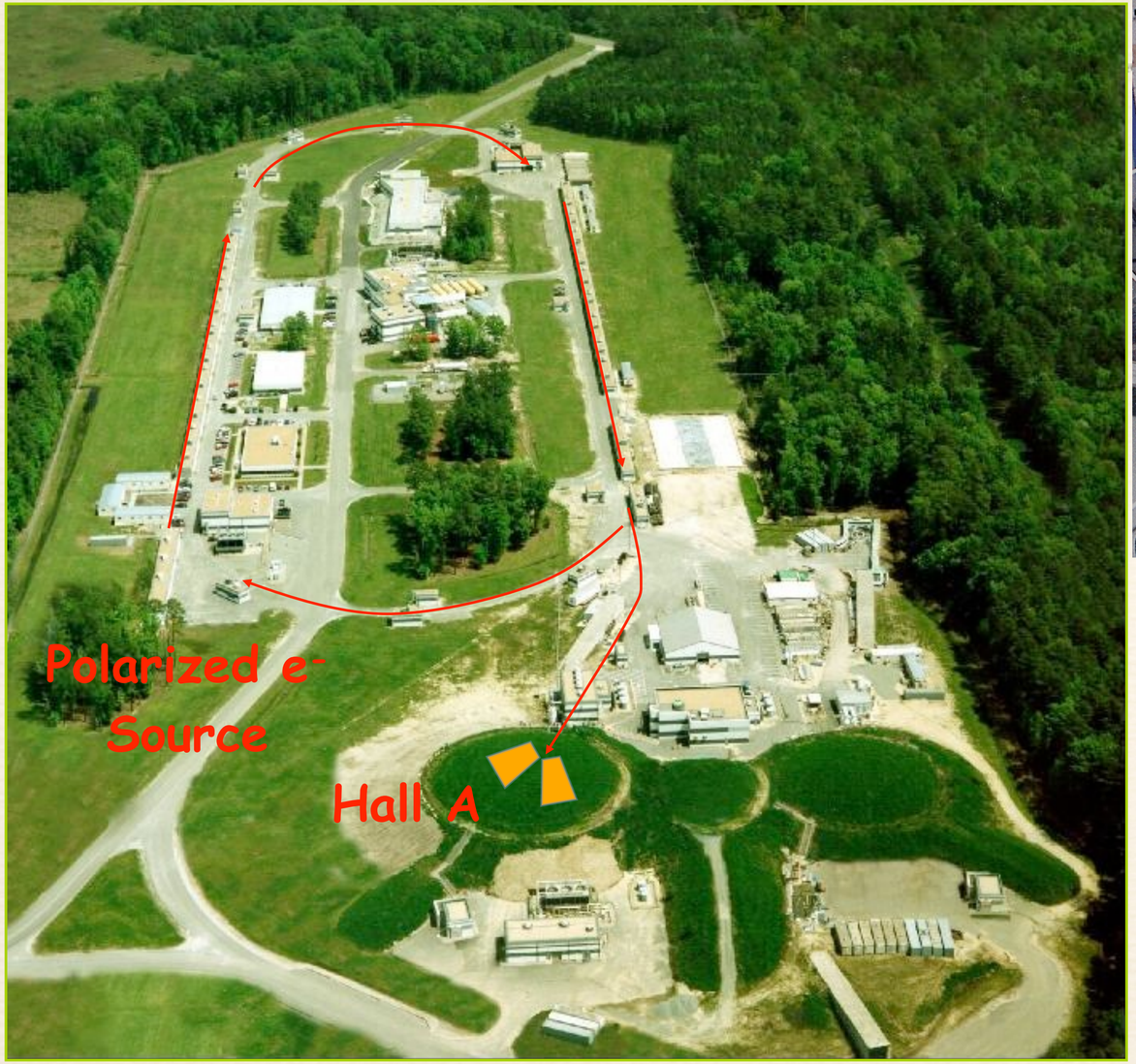


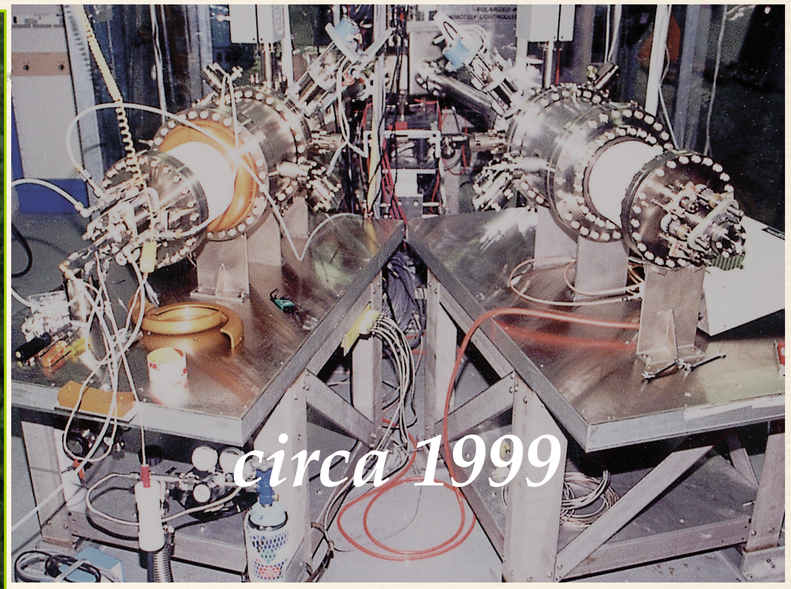
Jefferson Lab
Princeton
Syracuse
Saclay
William & Mary
& the Hall A collaboration

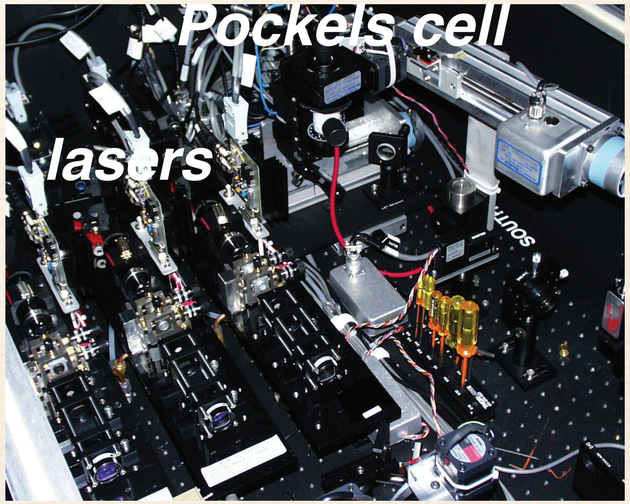
1998-99: Q^2=0.5 GeV^2, ^1H

1998:	37%	100 uA	80 C
1999:	70%	35 uA	75 C
1999 (II):	75%	45 uA	~ 10 C

Critical Polarized Source Development

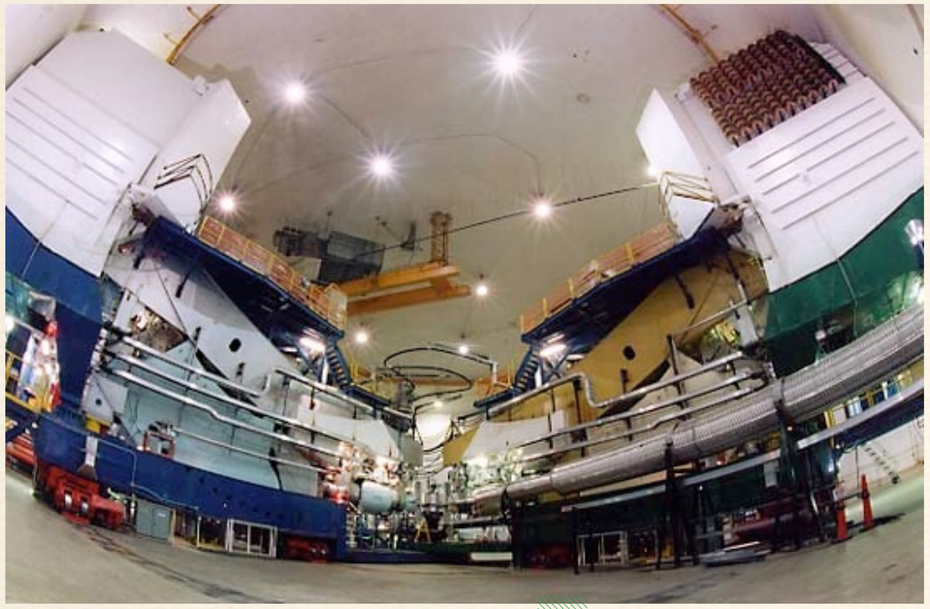


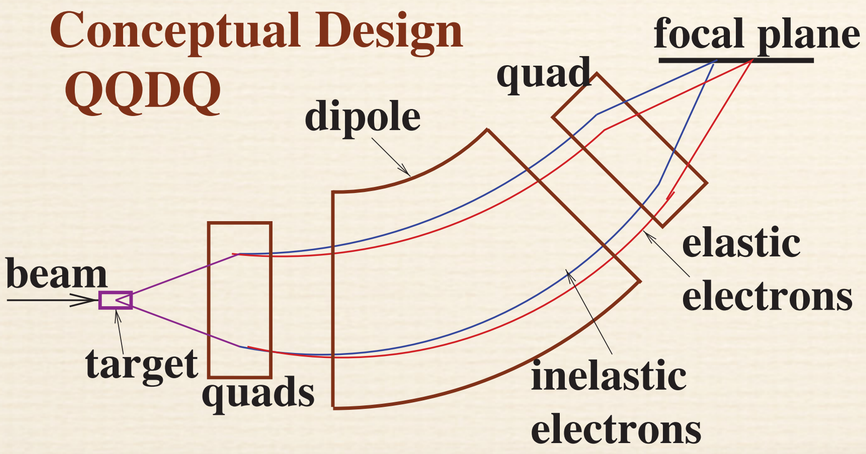


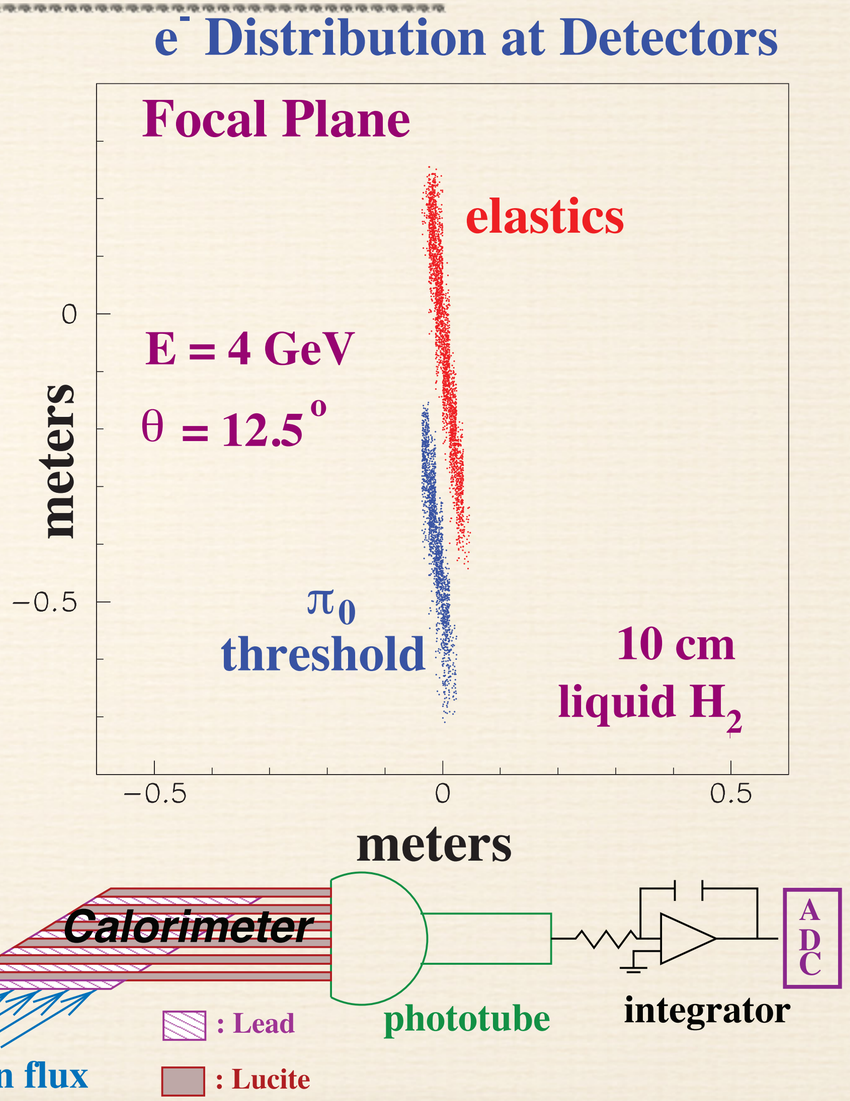


Charlie Sinclair and Matt Poelker were critical players during the early going

HRS in Hall A becomes a PVES Workhorse



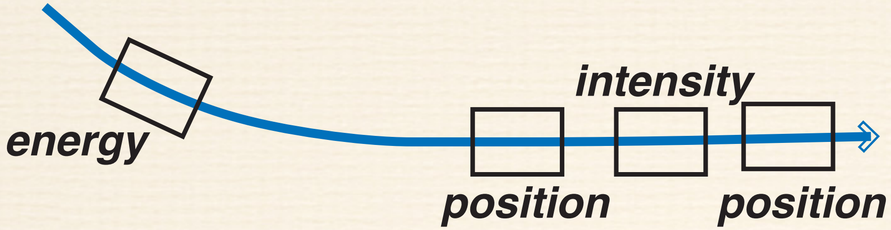




Goal: make parity experiments “routine”!

1998 Running: Bulk GaAs

Very successful, ongoing collaboration with accelerator division



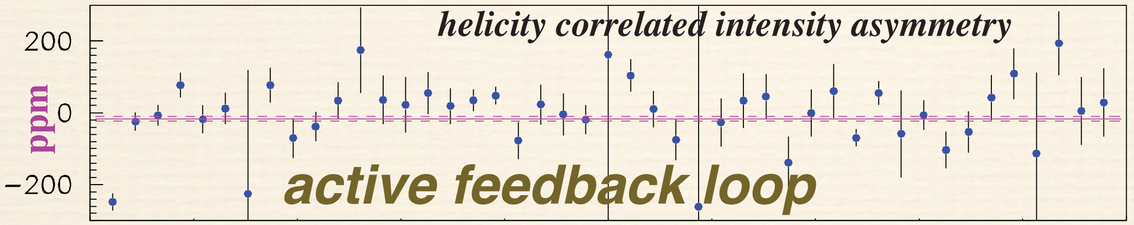
Integrator sampled at 30 Hz

$\Delta I/I : 5 \times 10^{-4}$

$\Delta E/E : 1 \times 10^{-5}$

$\Delta X, \Delta Y : 10$ microns

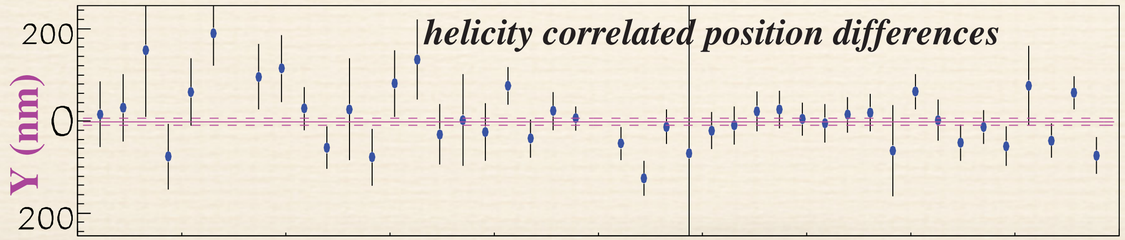
1998 running with bulk GaAs



for 1 month run:

$(-6 +/- 8) \times 10^{-8}$ **ppm**

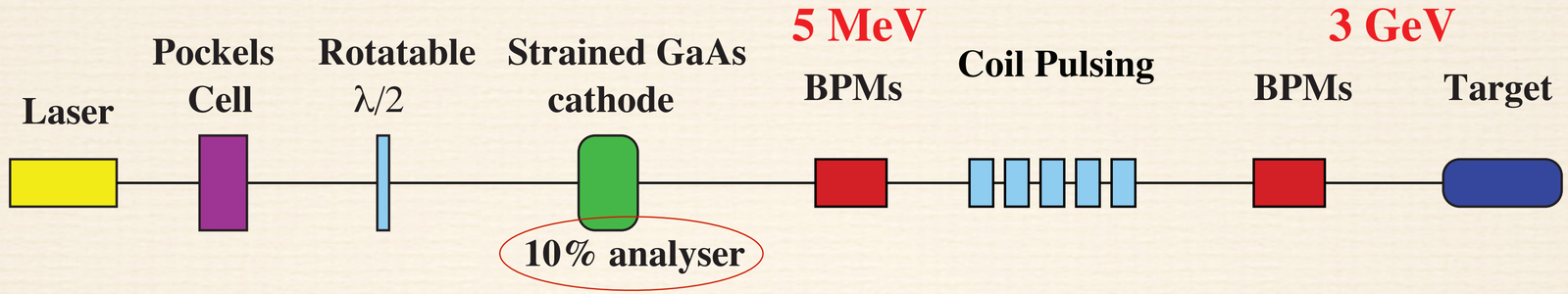
helicity correlated electron beam asymmetries for half hour runs



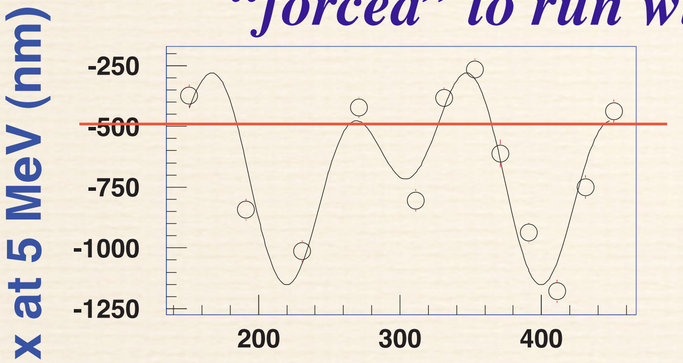
for 1 month run:

(0 +/- 3) nm

First Run with Strained GaAs

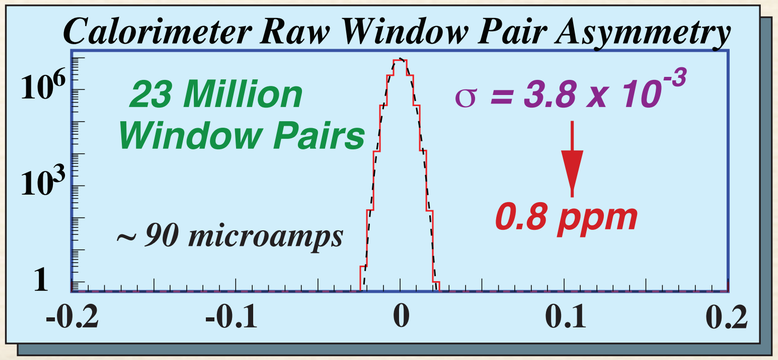


"forced" to run with strained GaAs in 1999...



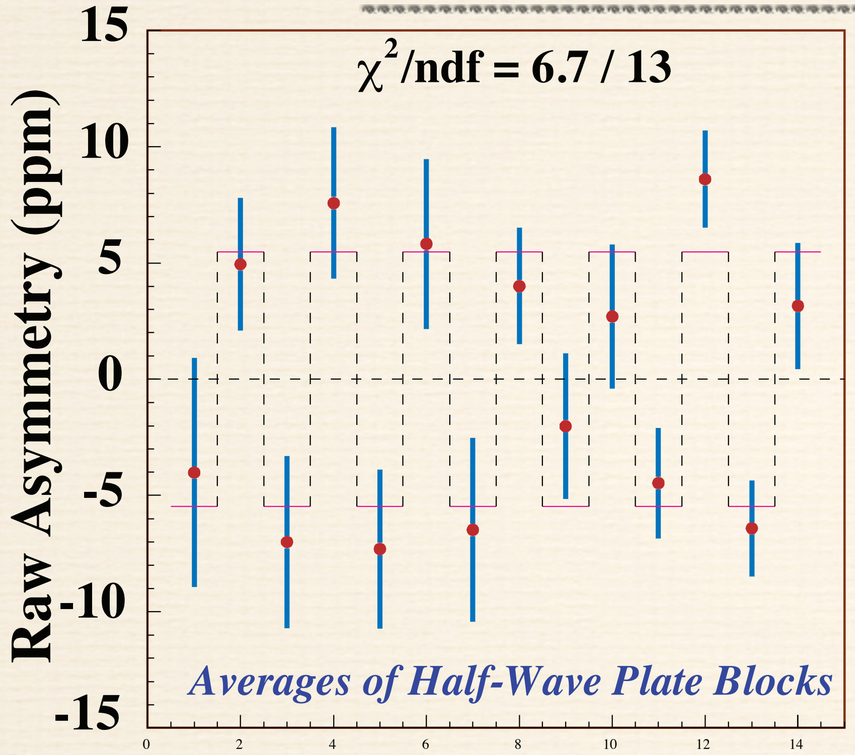
* *maintain < 500 nm at 5 MeV*
* *leads to < 20 nm in Hall A*
* *leads to 0.15 ppm systematic correction*

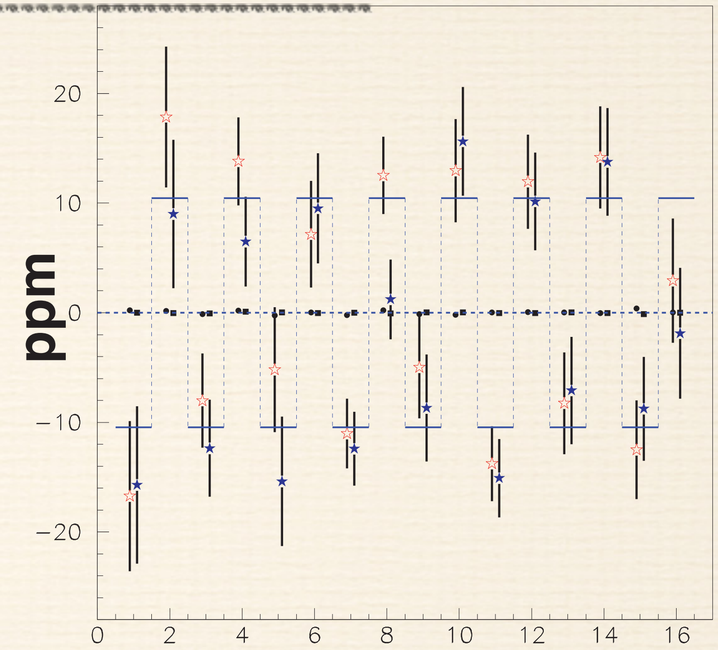
When we expressed concern to Larry Cardman at the limited beam time allotted to us, he told us: "you guys and Charlie Sinclair will figure it out… besides, take it or leave it…"

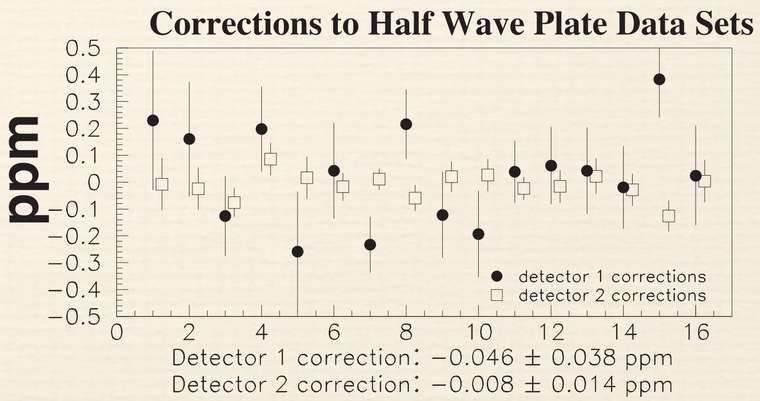


No non-gaussian tails to +/- 5σ

HAPPEX I Data







Online results virtually unchanged

HAPPEX was the third publication from Hall A

Strange Quarks Become Mainstream

More Q^2 points were motivated, building on the success

PERGAMON

Progress in Particle and Nuclear Physics

Progress in Particle and Nuclear Physics 45 (2000) S333–S395

http://www.elsevier.nl/locate/npe

Strange Quarks and Parity Violation

K. S. KUMAR

Department of Physics, University of Massachusetts, Amherst, MA 01003, USA

and

P. A. SOUDER

Department of Physics, Syracuse University, Syracuse, NY 13244, USA

Paul left HAPPEXII for youngsters to struggle with the smaller asymmetries, while he started to develop PREX with Chuck Horowitz and Bob Michaels

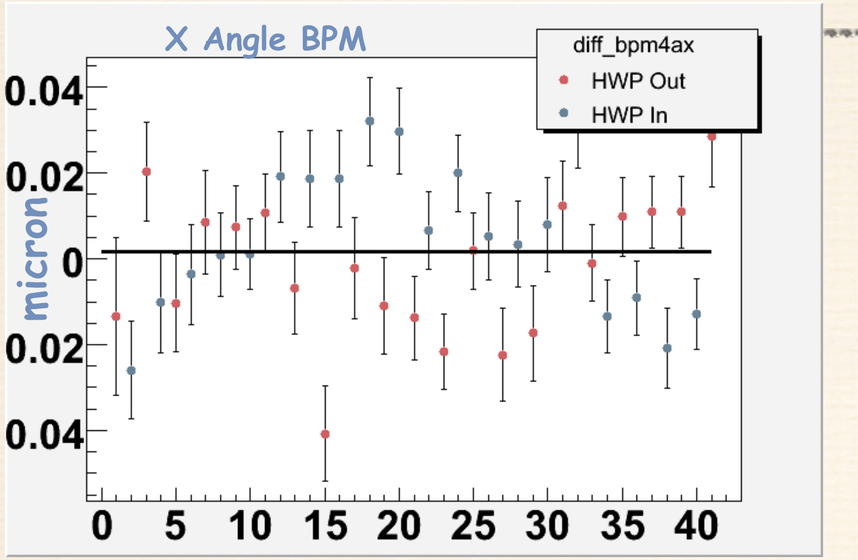
3 GeV, First Experiment with Septum Magnets, $Q^2 \sim 0.1$ GeV^2

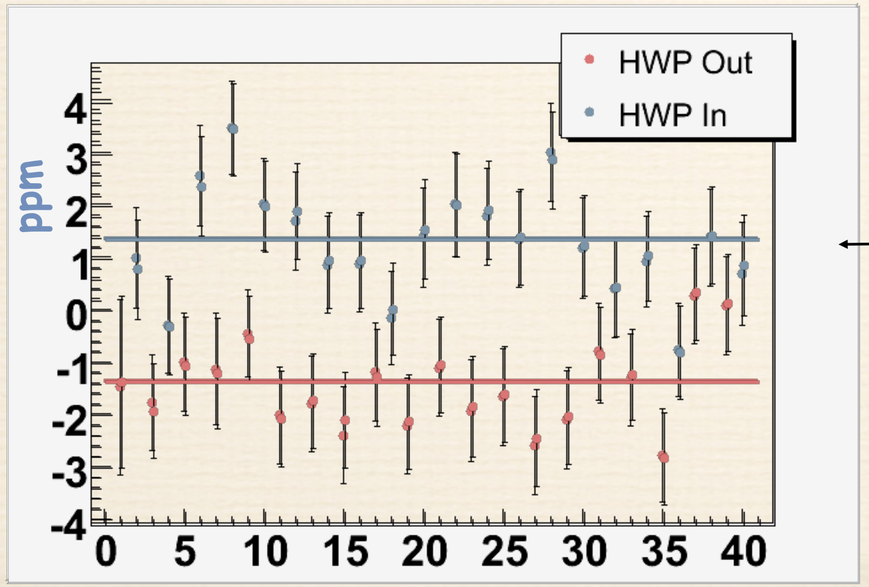
Mid-2000's

HAPPEXII Final results

Kent Paschke, Lead Postdoc

David Armstrong, Principal Spokesperson





Surpassed Beam Asymmetry Goals for Hydrogen Run

Hydrogen

Systematic control ~ 10^{-8}

$A_{PV} = -1.58 \pm 0.12$ *(stat)* ± 0.04 *(syst)* *ppm*

$A(G_s=0) = -1.66$ ppm $\pm$ 0.05 ppm

Energy: 0.25 ppb

X Target: 1 nm

X Angle: 2 nm

Helium

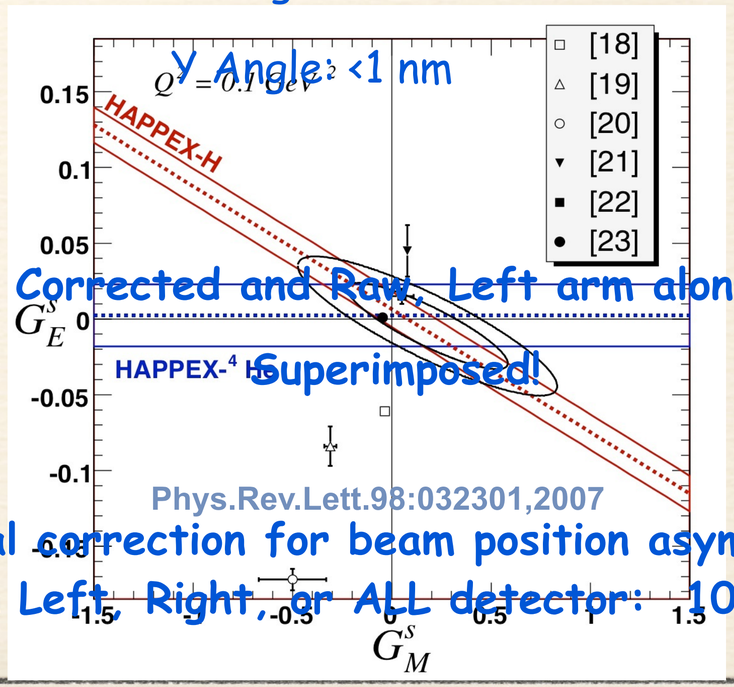
Normalization control ~ 2%

$A_{PV} = +6.40 \pm 0.23$ *(stat)* ± 0.12 *(syst)* *ppm*

$A(G_s=0) = +6.37$ ppm

Y Target : 1 nm

Y Angle: <1 nm



Corrected and Raw Left arm alone, Superimposed!

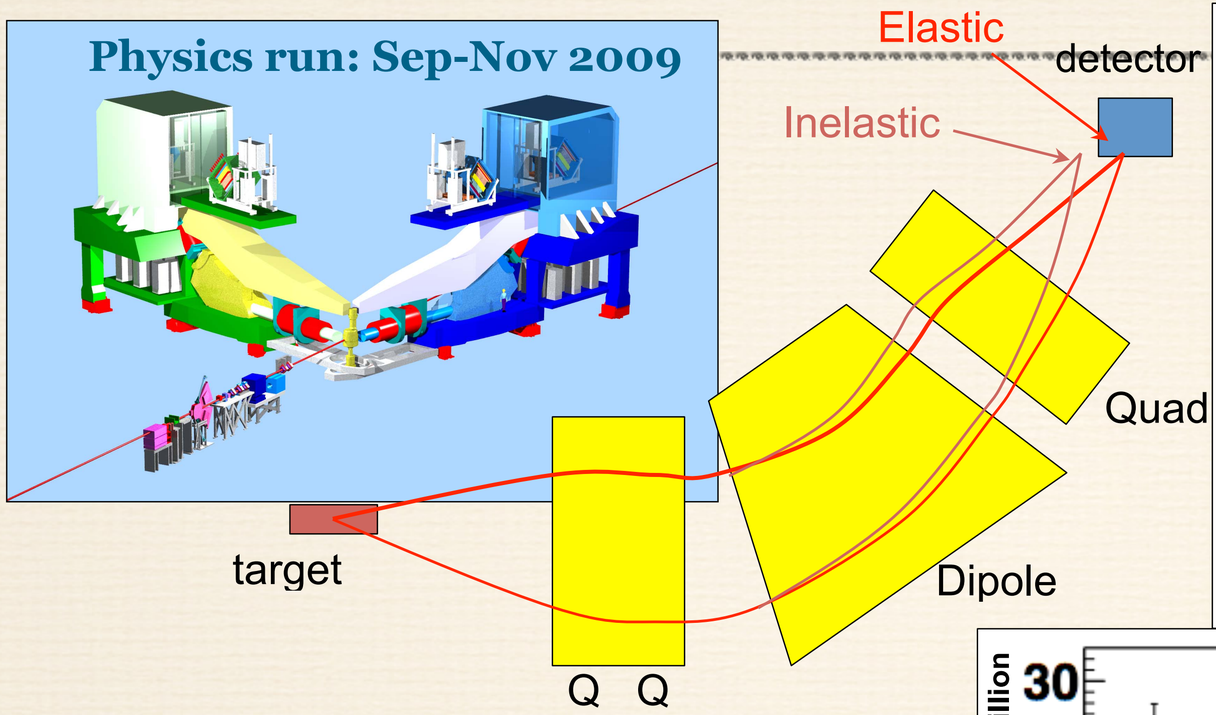
Phys.Rev.Lett.98:032301,2007

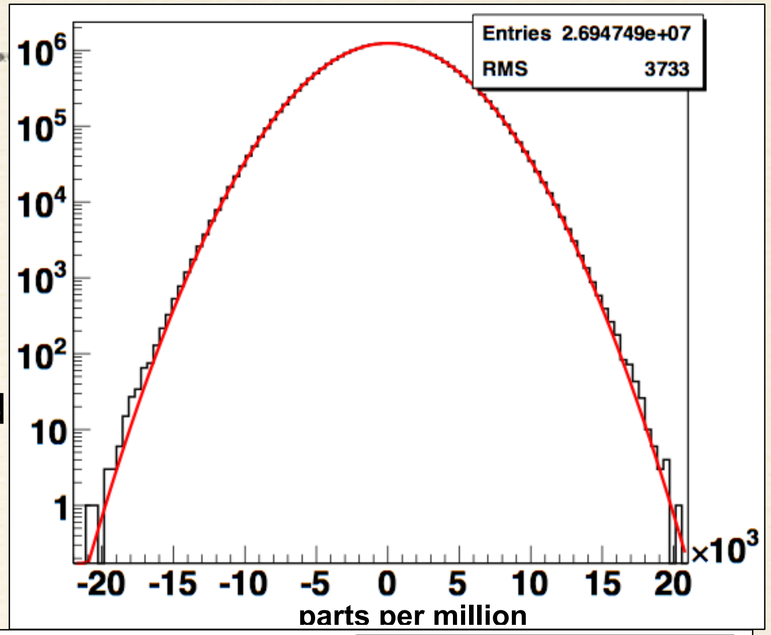
Total correction for beam position asymmetry on Left, Right, or ALL detector: 10 ppb

E = 3.3 GeV, θ_{lab} = 14^o , 100 μA with 85% P_e

HAPPEX III

Spokespersons:
Paul Souder and Kent Paschke



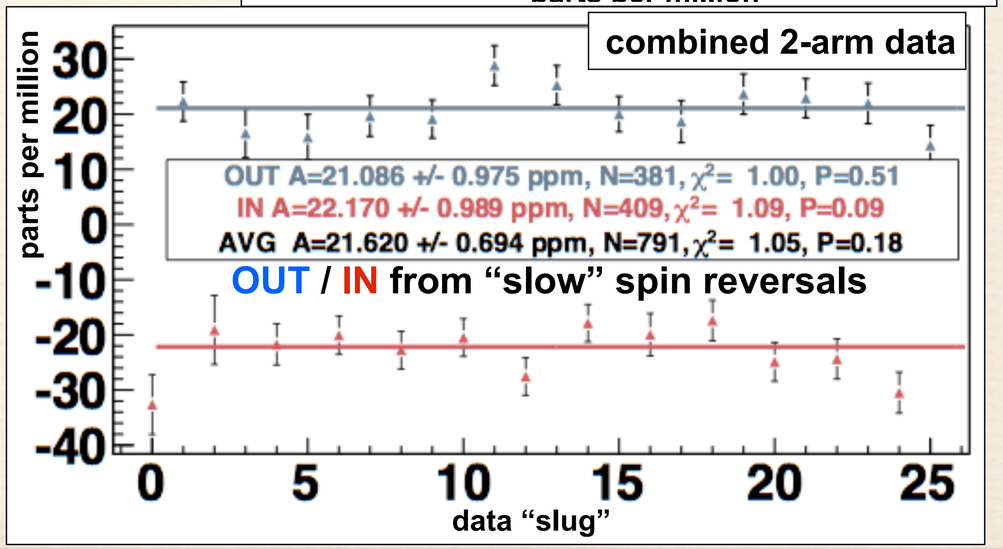


A_{RAW} = -21.591 ± 0.688 *(stat)* *ppm*

This includes
- **beam asymmetry correction (-0.01 ppm)**
- **charge normalization (0.20 ppm)**

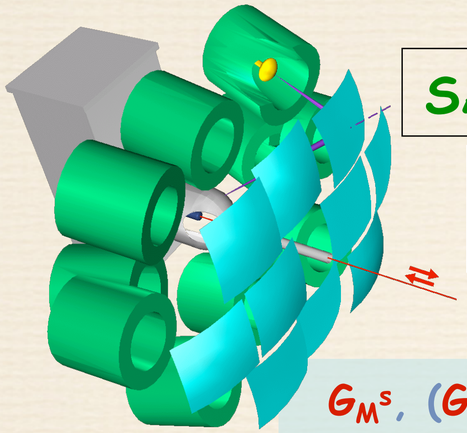
3.26% (stat)± 1.49% (syst)

total correction ~2.5% + polarization



PV Electron-Nucleon Elastic Scattering: The Experiments

1990s - 2010s

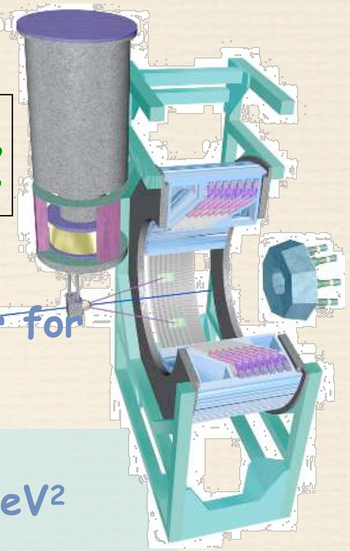


SAMPLE at MIT-Bates

open geometry, integrating

G_M^s, (G_A) at Q^2 = 0.1 GeV^2

A4 at Mainz



Open geometry

Fast counting calorimeter for background rejection

G_E^s + 0.23 G_M^s at Q^2 = 0.23 GeV^2

G_E^s + 0.10 G_M^s at Q^2 = 0.1 GeV^2

G_M^s, G_A^e at Q^2 = 0.23 GeV^2

HAPPEX at Jefferson Lab

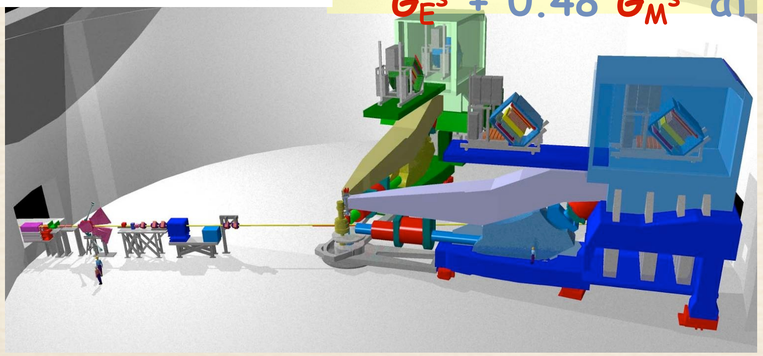
Precision spectrometer, integrating

G_E^s + 0.39 G_M^s at Q^2 = 0.48 GeV^2

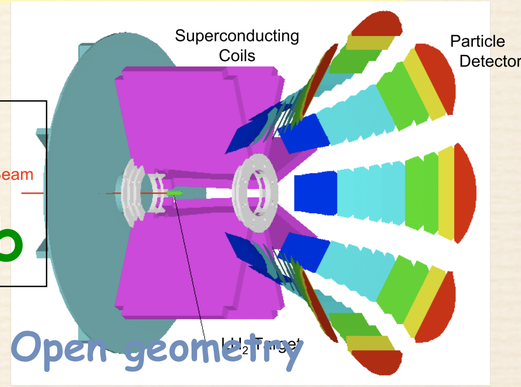
G_E^s + 0.08 G_M^s at Q^2 = 0.1 GeV^2

G_E^s at Q^2 = 0.1 GeV^2 (^{4}He)

G_E^s + 0.48 G_M^s at Q^2 = 0.62 GeV^2



G0 at Jefferson Lab



Open geometry

Fast counting with magnetic spectrometer + TOF for background rejection

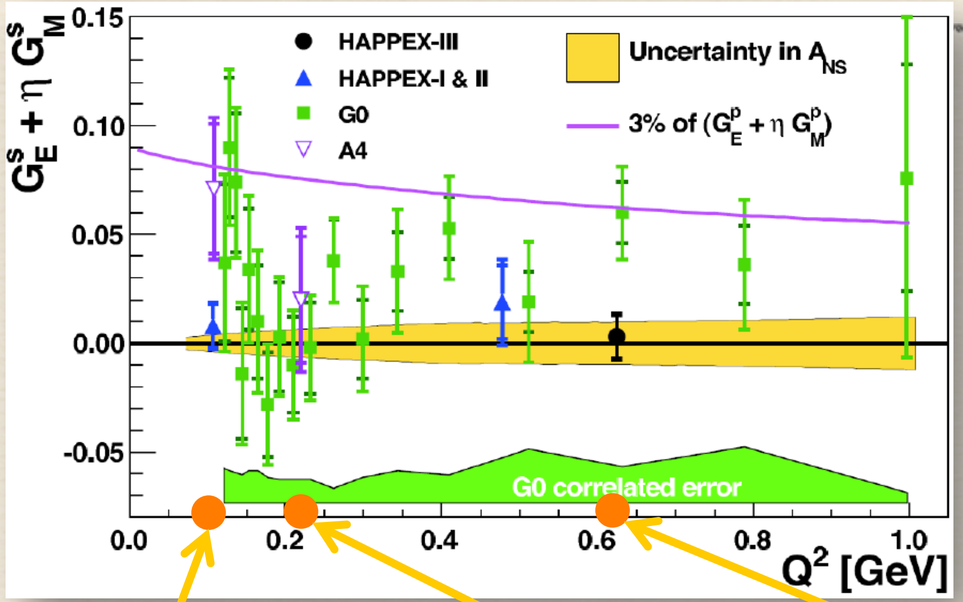
G_E^s + η G_M^s over Q^2 = [0.12,1.0] GeV^2

G_M^s, G_A^e at Q^2 = 0.23, 0.62 GeV^2

Typical asymmetries: 10's of ppm

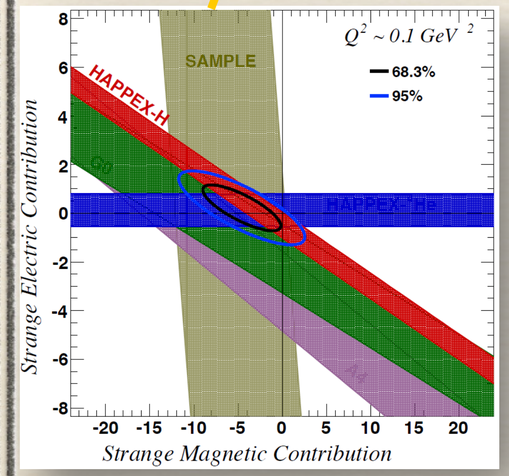
1990 - 2010

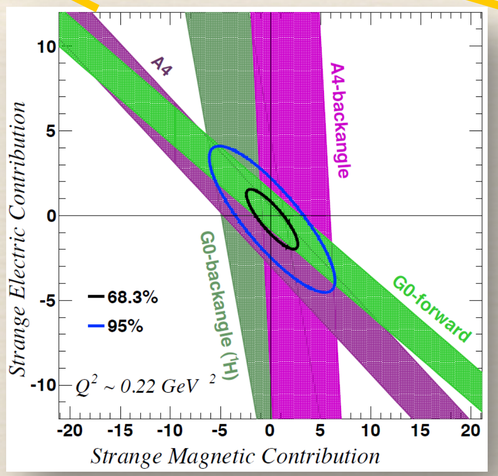
What have we learnt?

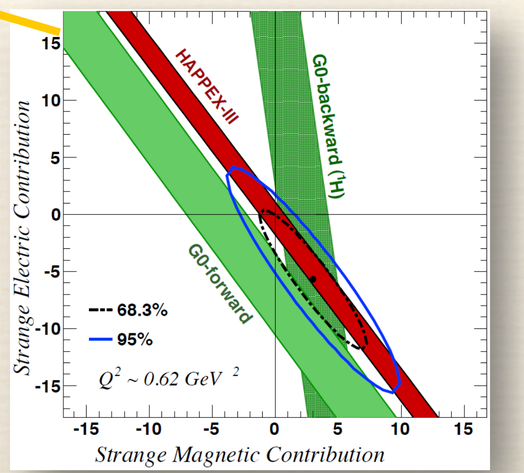


- Sensitive Flavor separation at three Q^2 values
- Strange quarks are no more than a few % of the proton's electromagnetic structure
- Modern lattice QCD results are in agreement

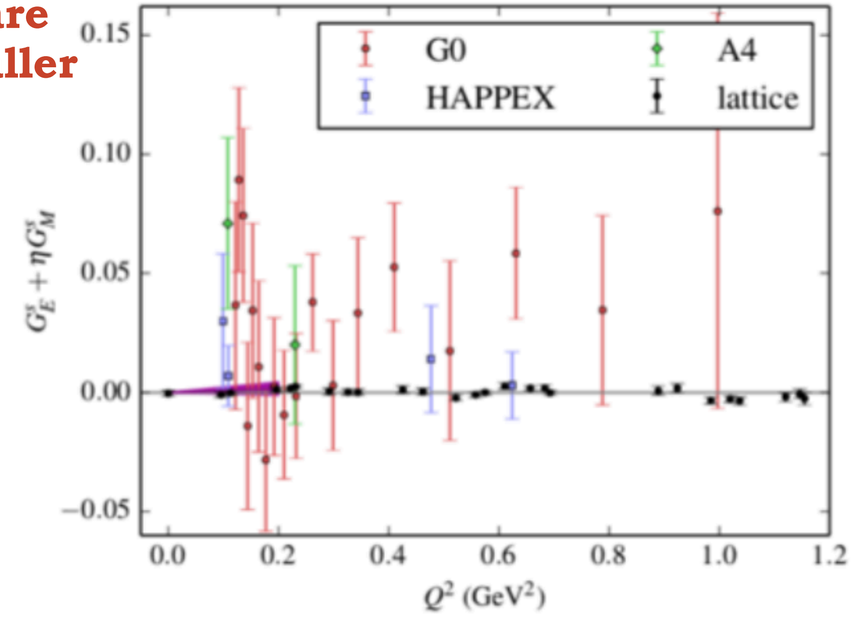
Latest lattice calculations say strange quark form factors are indeed non-zero but they are an order of magnitude smaller than these uncertainties







J.Green etal, 2015



Isospin Dependences in Parity Violating Electron Scattering

T.W. Donnelly (MIT, LNS), J. Dubach (Massachusetts U., Amherst and Jefferson Lab), Ingo Sick (Basel U.)

Mar, 1989

43 pages

Published in: *Nucl.Phys.A* 503 (1989) 589-631

Published: 1989

Neutron Skin of a Heavy Nucleus

First Proposal: 2000

PHYSICAL REVIEW C, VOLUME 63, 025501

Parity violating measurements of neutron densities

C. J. Horowitz*
Department of Physics and Nuclear Theory Center, Indiana University, Bloomington, Indiana 47405

S. J. Pollock†
Department of Physics, CB 390, University of Colorado, Boulder, Colorado 80309

P. A. Souder‡
Department of Physics, Syracuse University, Syracuse, New York 13244

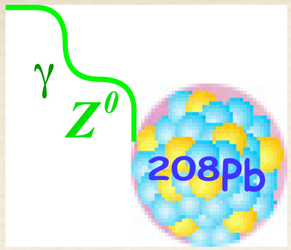
R. Michaels§
Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606

(Received 6 January 2000; revised manuscript received 12 July 2000; published 8 January 2001)

Proposal to Jefferson Lab PAC 17

A CLEAN MEASUREMENT OF THE NEUTRON SKIN OF ^{208}Pb THROUGH PARITY VIOLATING ELECTRON SCATTERING

Spokesmen: R. Michaels, P.A. Souder, G.M. Urciuoli



The success of HAPPEX II Made this Palatable to the PAC

PV Elastic Scattering off Heavy Nuclei: Neutron Densities

2010's

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n\left(Q^2\right)}{F_p\left(Q^2\right)}$$

Photon Exchange

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

$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

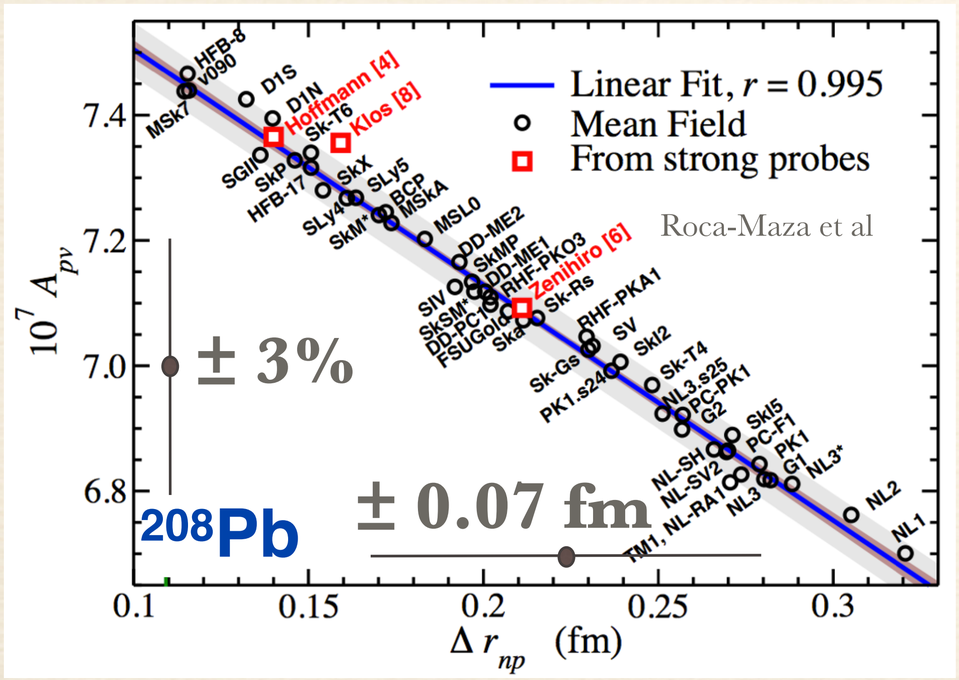
Z_0 exchange

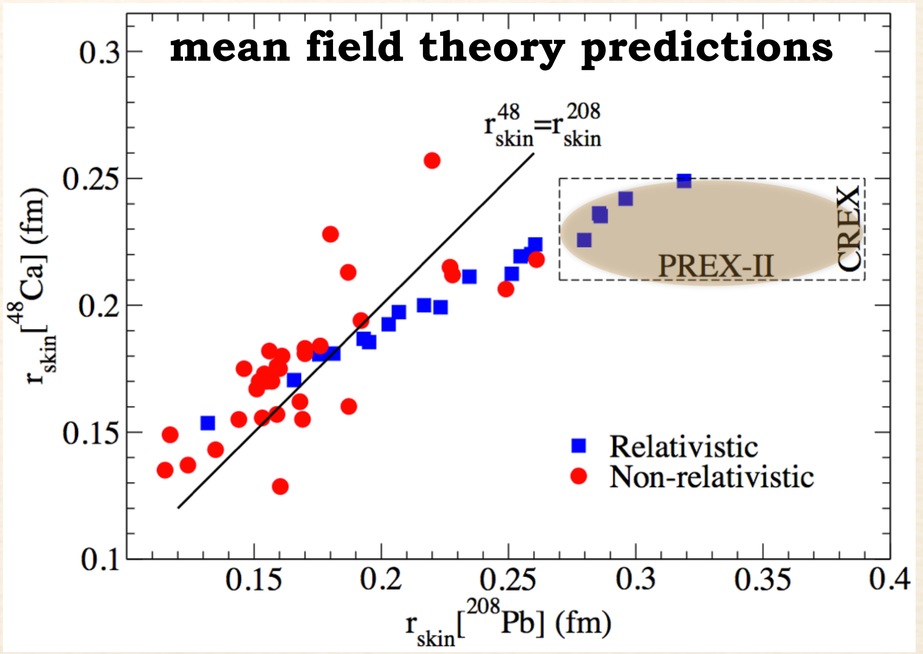
$$M^{NC}_{PV} = \frac{G_F}{\sqrt{2}}\left[\left(1 - 4\sin^2\theta_W\right)F_p\left(Q^2\right) - F_n\left(Q^2\right)\right]$$

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

$\delta(R_n)/R_n \sim 1\%$

$\delta(R_n)$: ± 0.07 fm (^{208}Pb)
± 0.03 fm (^{48}Ca)





PREX ^{208}Pb
&
CREX ^{48}Ca

PREX-2 Run:
Summer 2019

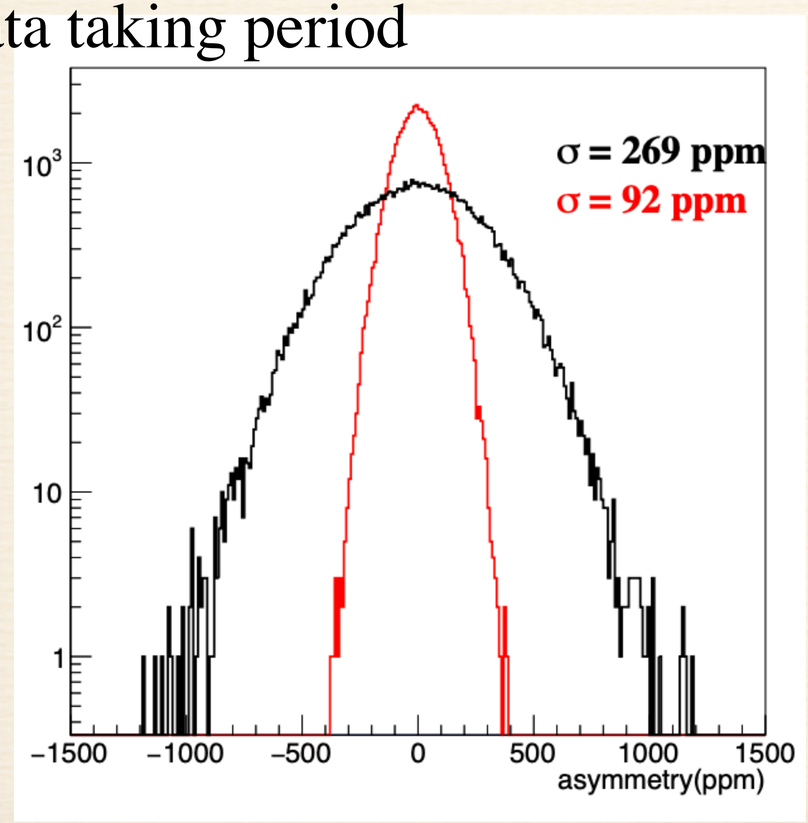
CREX runs:
Dec 19 to Sep 20
(Despite lockdowns!)

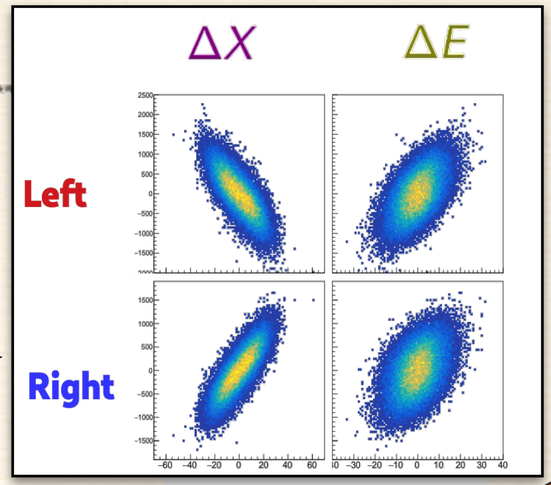
PREX-2 Beam Corrections

- To span the 5 dimension phase space of beam motion at the target (position, angle, energy) we made use of a set of 6 coils and an energy vernier
- This modulation is automated and was performed throughout the data taking period

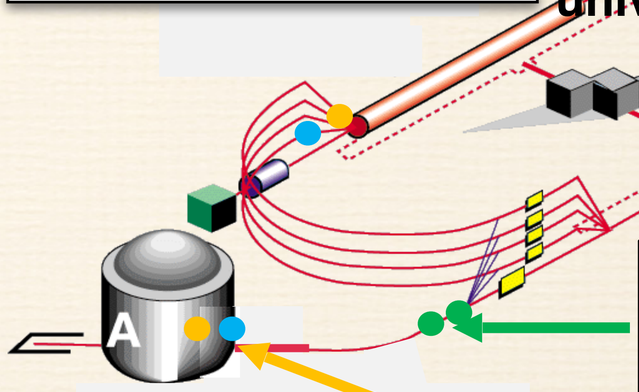
$$A_{corr} = A_{det} - A_Q + \alpha \Delta_E + \Sigma \beta_i \Delta x_i$$

$A_{corr} \sim 500$ ppb

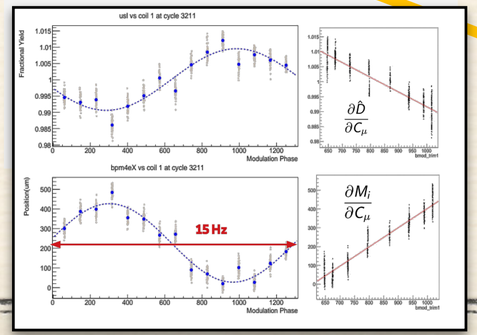




A number of talented young scientists contributed to the success of PREX2 and are now key members of the MOLLER team, both here among the JLab staff as well as at collaborating universities



Beam modulation system spans the phase space of beam motion



Beam monitors determine trajectory and parameters onto target

PREX and CREX Final Results

^{208}Pb

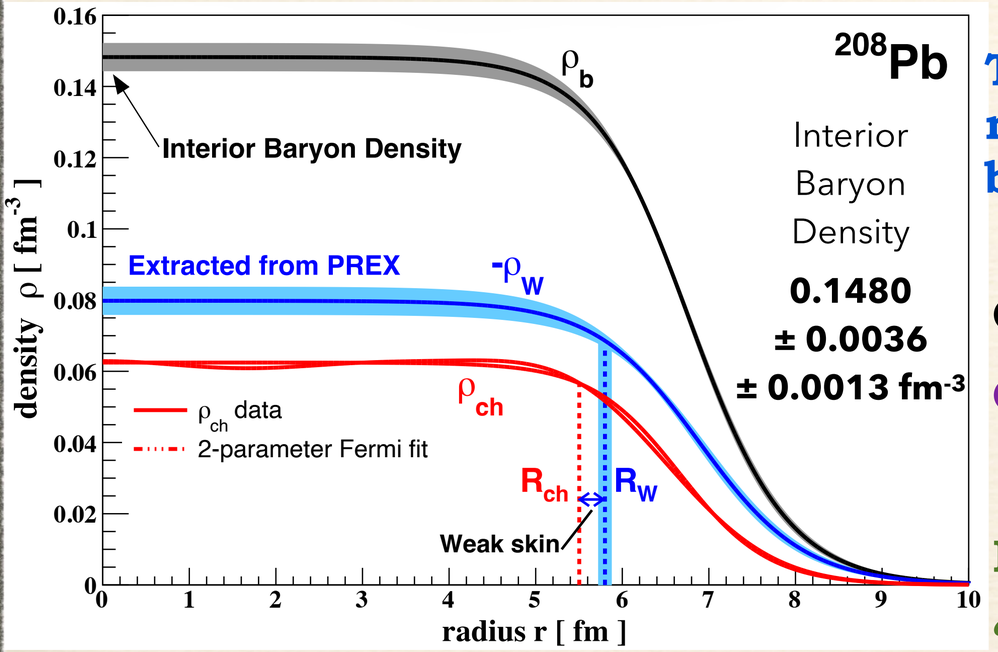
Phys.Rev.Lett. 126 (2021) 17, 172502

$$A_{PV} = 550 \pm 16(\text{stat}) \pm 8\ (\text{syst})\ \text{ppb}$$

F_W (Q^2 = 0.00616 GeV^2) = 0.368 ± 0.013

Implied neutron skin thickness PREX-1 and PREX-2

$$R_n - R_p = 0.283 \pm 0.071\ \text{fm}$$



The PREX ^{208}Pb measurement has very little model uncertainty

The CREX ^{48}Ca measurement will be hard to improve

Community "Lore":

Ca-48 skin:

"too thin"

Pb-208 skin:

"too thick"

^{48}Ca

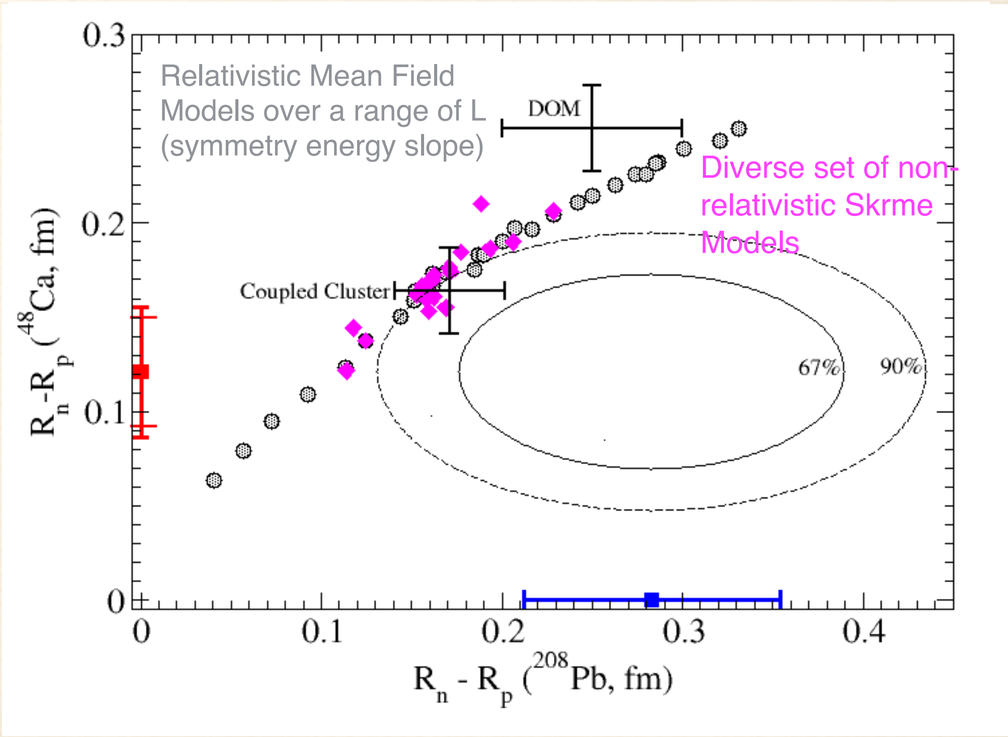
Phys.Rev.Lett. 129 (2022) 4, 042501

$$A_{PV} = 2668 \pm 106\ (\text{stat}) \pm 40\ (\text{sys})\ \text{ppb}$$

F_W (Q^2 = 0.0297 GeV^2) = 0.1304 ± 0.0055

Implied neutron skin thickness from CREX

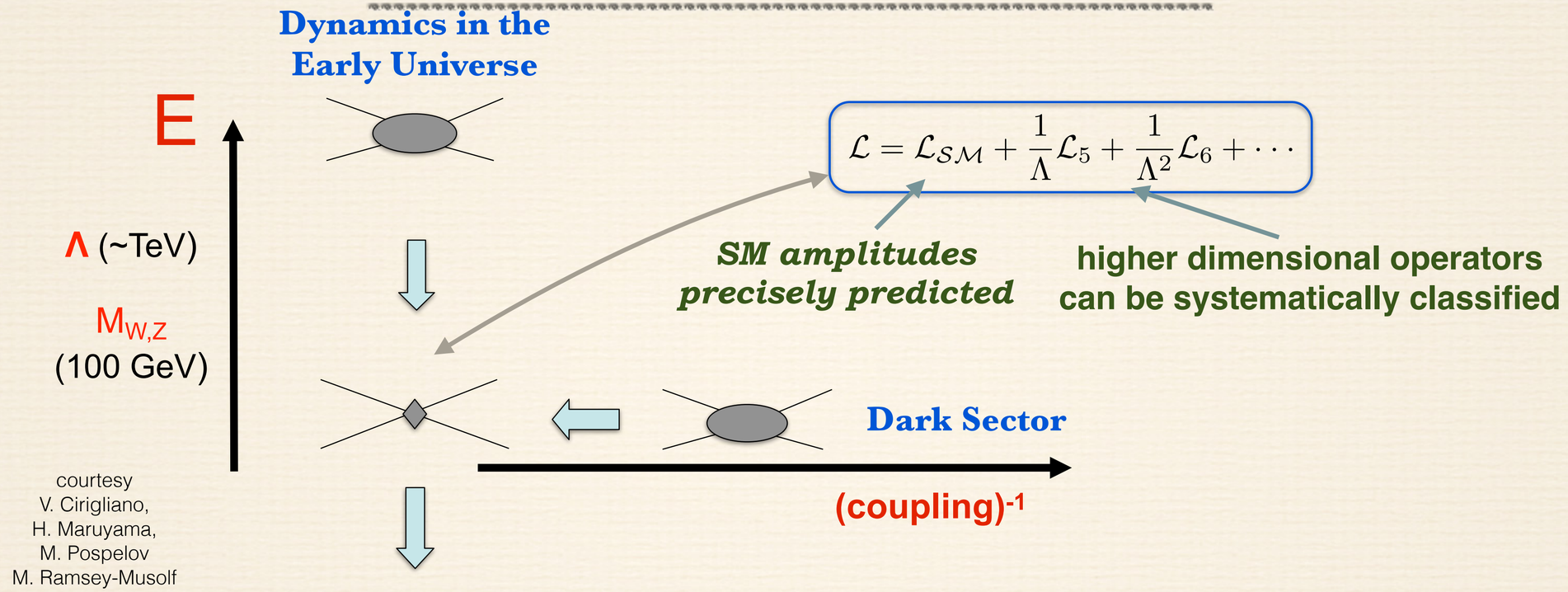
$$R_n - R_p = 0.121 \pm 0.026\ (\text{exp}) \pm 0.024\ (\text{model})$$



The Search for New Neutral Current Interactions

Observables at scales at or lower than the scale of EW Symmetry Breaking

Intensity Frontier Strategy



Discoveries and Insights about Big Questions

Measurements push several experimental parameters to the extreme such as intensity, luminosity, volume, radio-purity, resolution, precision, accuracy....

In most cases, observables exploit a symmetry principle

I was a HEP postdoc at CERN… How did I get here?

Getting me committed to the early JLab program….

If Parity Violation in atoms is sensitive to New Physics,

Parity Violating Electron Scattering can do better!

VOLUME 65, NUMBER 24 PHYSICAL REVIEW LETTERS 10 DECEMBER 1990

An Improved SLAC E122? PV Deep Inelastic Scattering?

William J. Marciano
Physics Department, Brookhaven National Laboratory, Upton, New York 11973

Jonathan L. Rosner
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637

Not the right x, Q² range to remove theoretical uncertainty at 1%

Need to measure 1-4sin²θ_W : elastic e-e or e-p scattering

(Received 30 August 1990)

Effects of physics beyond the standard model on electroweak observables are studied using the Peskin-Takeuchi spin-conserving S and T formalism. A parametrization of "new" quantum loop corrections. Experimental constraints on S and T are presented. Atomic parity-violating experiments are shown to be particularly sensitive to S with existing data giving $S = +2.7 \pm 2.0 \pm 1.1$. That constraint has important implications for generic technicolor models which predict $S \simeq 0.1 N_T N_D$ (N_T is the number of technicolors, N_D is the number of technidoublets).

In '93, I contacted Paul.. I hadn't spoken to him in ~ 3 years…

Paul: **Hmm, interesting… people are already working on this… Is it really worthwhile? too expensive….**

but at higher Q², one can probe strange quarks…

KK: ***What does e-p scattering have to do with strange quarks??!!!***

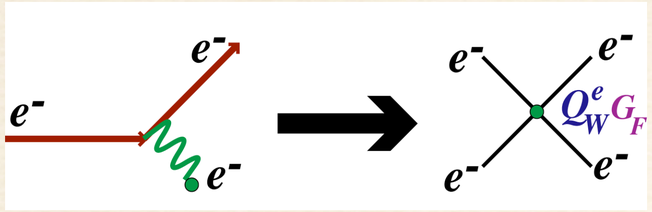
KK: ***We should look at electron-electron scattering…..***

Paul: ***Are you sure? There are two diagrams… So many minus signs…May be the asymmetry vanishes..***

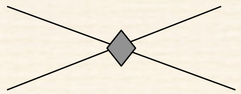
Depending on the day of the week, I get zero or 16/9ths times the e-p asymmetry ….

PV Electron-Electron (Møller) Scattering

A rare opportunity: a well-understood EW process below the scale of electroweak symmetry breaking that is purely leptonic



$+$



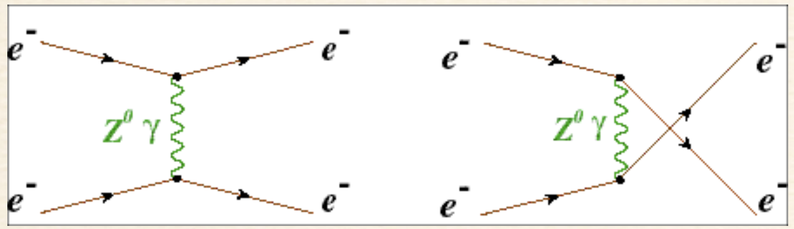
$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

electron target:

$$\mathbf{Q_W = 1 - 4\sin^2\theta_W}$$

$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

BSM Sensitivity Competitive with Colliders



$$\left|\mathbf{A_\gamma + A_Z + A_{new}}\right|^2 \rightarrow \mathbf{A_\gamma^2}\left[\mathbf{1} + \mathbf{2}\left(\frac{\mathbf{A_Z}}{\mathbf{A_\gamma}}\right) + \mathbf{2}\left(\frac{\mathbf{A_{new}}}{\mathbf{A_\gamma}}\right)\right]$$

$$A_{PV} \approx 8\times10^{-8}\, E_{beam}(1 - 4\sin^2\vartheta_W)$$

$$Q^2 = 2m_e E_{\text{beam}}$$

Tiny!

45 & 48 GeV Beam

85% longitudinal polarization

End Station A at SLAC

SLAC E158: 1997-2004

A_{PV} ~ 200 parts per billion

The Spectrometer… Out of our Price Range?

PRECISION LOW ENERGY WEAK NEUTRAL CURRENT EXPERIMENTS

K. S. KUMAR
Department of Physics, Princeton University, Princeton, NJ 08544, USA

E. W. HUGHES
Stanford Linear Accelerator Center, Stanford, CA 94309, USA

R. HOLMES and P. A. SOUDER
Department of Physics, Syracuse University, Syracuse, NY 13210, USA

Received 3 November 1995

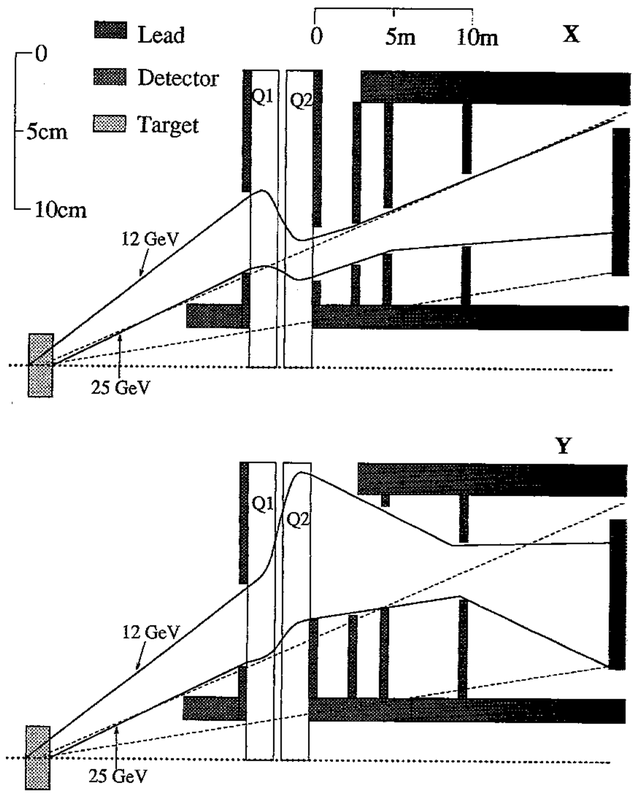


Fig. 2. The envelope of scattered electrons from the proposed quadrupole doublet spectrometer is shown, sectioned along horizontal and vertical planes. The solid lines trace the boundary of the scattered electron envelope. The dashed lines trace the line of sight from the center of the target.

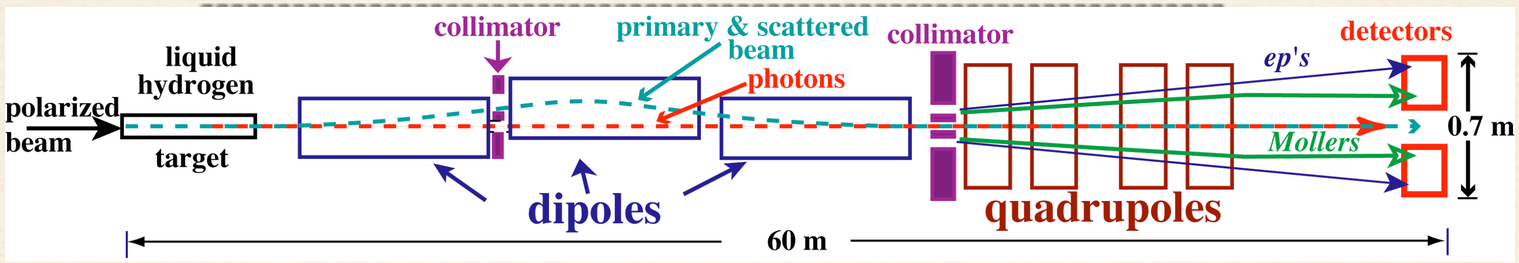
Major Breakthrough:
The Famous 8 GeV and 20 GeV spectrometers could be scavenged for some spectacularly well-made magnets

Goal: error small enough to probe TeV scale physics

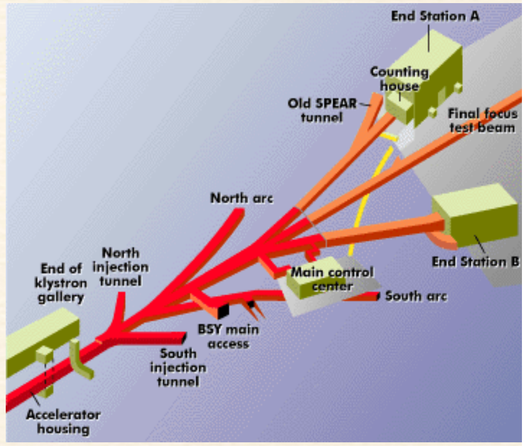
SLAC E158

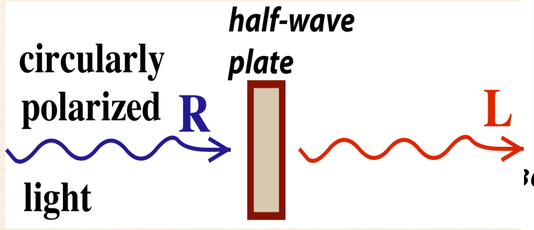
1997-2004

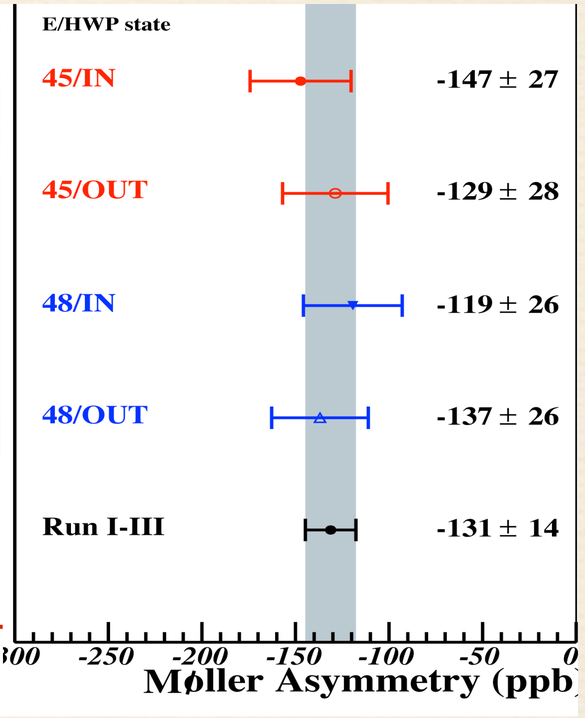
~ 10 ppb statistical error at highest E_{beam}, ~ 0.5% error on weak mixing angle



A large number of technical challenges





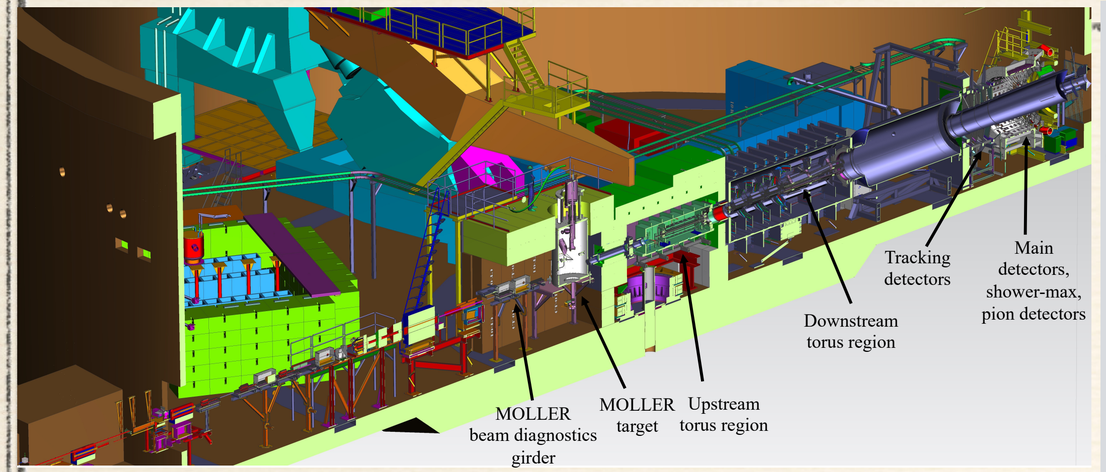


$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

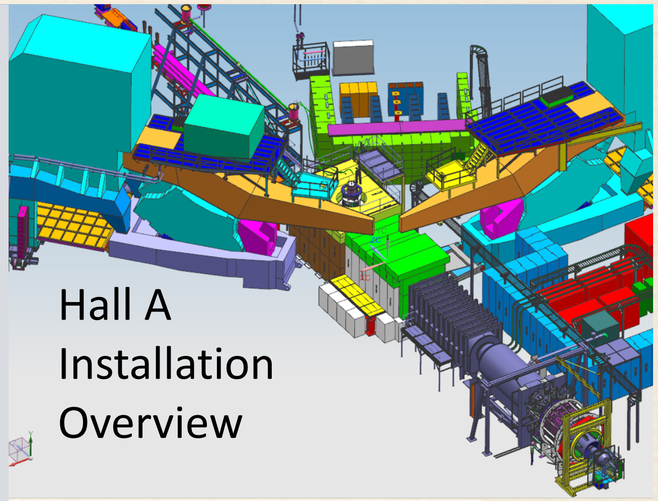
Phys. Rev. Lett. **95** 081601 (2005)

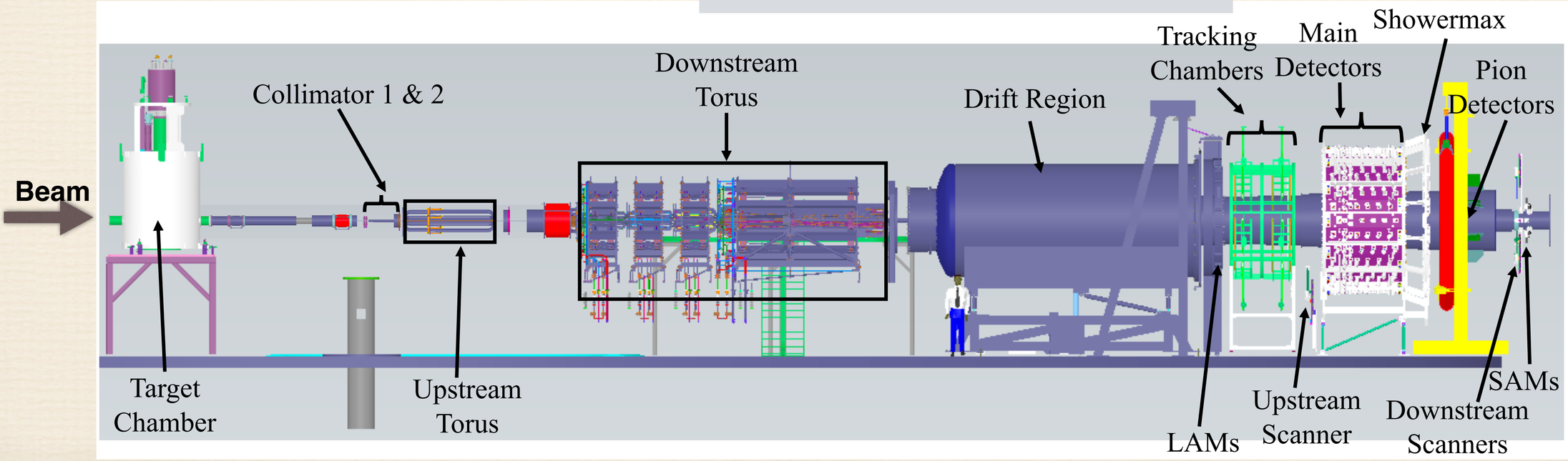
MOLLER Experiment

Improve on the E158 Sensitivity by a further factor of 5 to make the definitive low Q^2 Measurement



- **~ 50M$ MIE by US DOE NP**
- **~ 12M$: US NSF and Canada CFI/Research Manitoba**
- **CD-1 granted in Dec 2020**
- **CD-2/3 granted May 2024**
- **Construction: 2024-25**
- **Installation late ’25 - early ’27**
- **Commissioning: Summer 2027**
- **Physics thru 2030**





MOLLER is going to be fun! (Challenge)

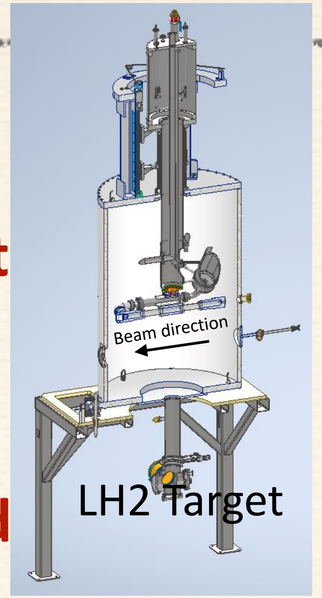
Paul: You are not going to be able to stay away! Besides, we need you; there are going to be mysteries to solve!!

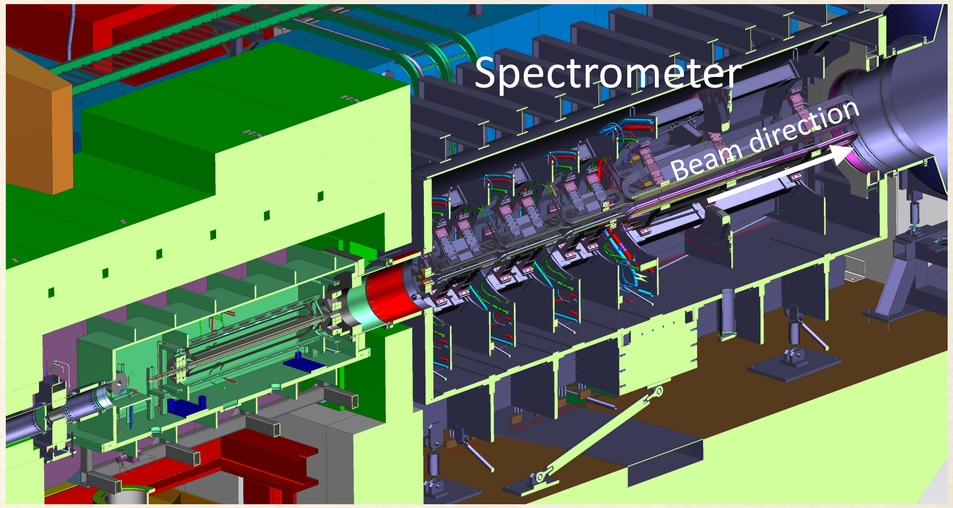
	SLAC E122	Bates C-12	E158/PREX/ Qweak	MOLLER
A_{PV}	10 ppm	1 ppm	300 ppb	33 ppb
$\delta(A_{PV})$	1 ppm	100 ppb	10 ppb	0.7 ppb
Instantaneous Rate	10 kHz	1 MHz	Few GHz	100s of GHz
Beam Stability Goal	1 micron	0.1 micron	Few nm	0.5 nm
Polarimetry Uncertainty Goal	3%	3%	1%	0.4%

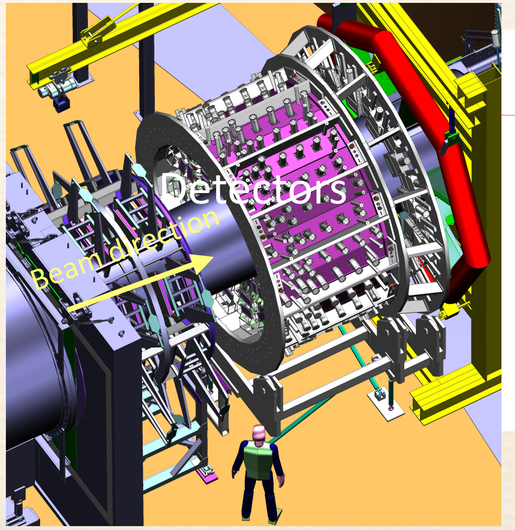
MOLLER Technical Challenges

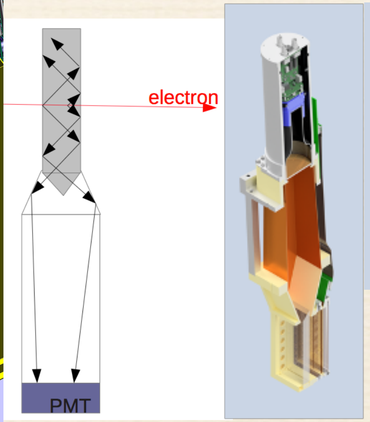
Evolutionary Improvements from Technology of Third Generation Experiments

- **High intensity polarized electron source**
- **~ 134 GHz scattered electron rate**
- **sub-nm control of beam centroid on target**
- **~ 9 gm/cm² liquid hydrogen target**
  - **1.25 m: ~ 3.7 kW @ 70 μA**
- **Full Azimuthal acceptance w/ θ_{lab} ~ 5 mrad**
  - **novel toroidal spectrometer assemblies**
  - **radiation hard, segmented integrating detectors**
- **Robust & Redundant 0.4% beam polarimetry**

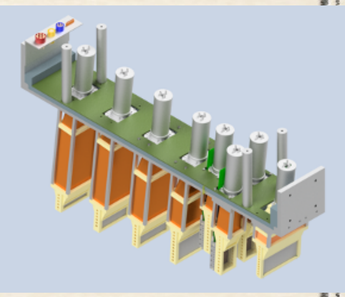








Single channel



1/28th Segment

Over the course of decades pursuing the science, Paul Souder has had an impact on every one of these technical items, all of it finally coming together in MOLLER

Now, for some insight into Paul….

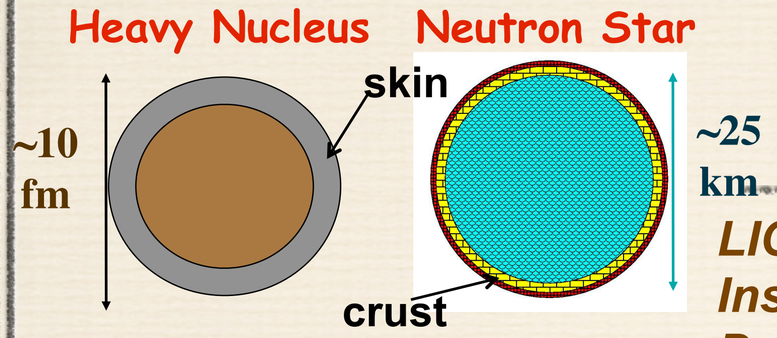
24/7 WORRYING about DATA, (or lack thereof), and solving MYSTERIES/PUZZLES in the experiment

Thank you Paul for decades of contributions to JLab science and looking forward to solving new MOLLER puzzles together!

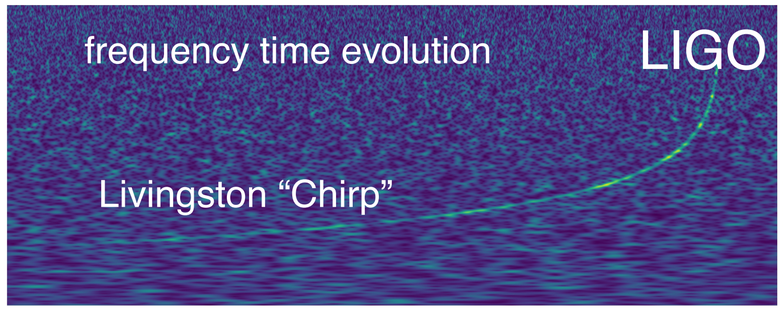
Backup

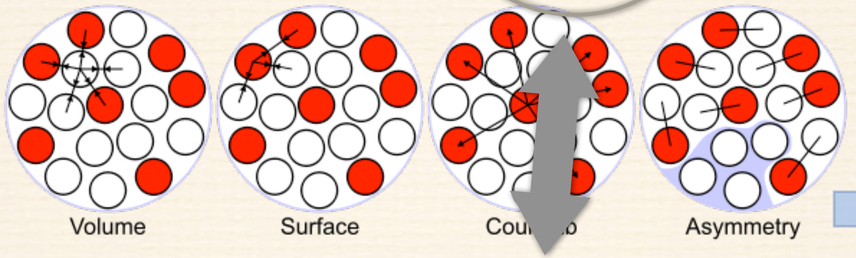
Neutron Radius: Broader Context

- *Nuclear Structure Physics*
- *Neutron Star Physics*
- *Atomic Parity Violation*
- *Coherent Neutrino Scattering*



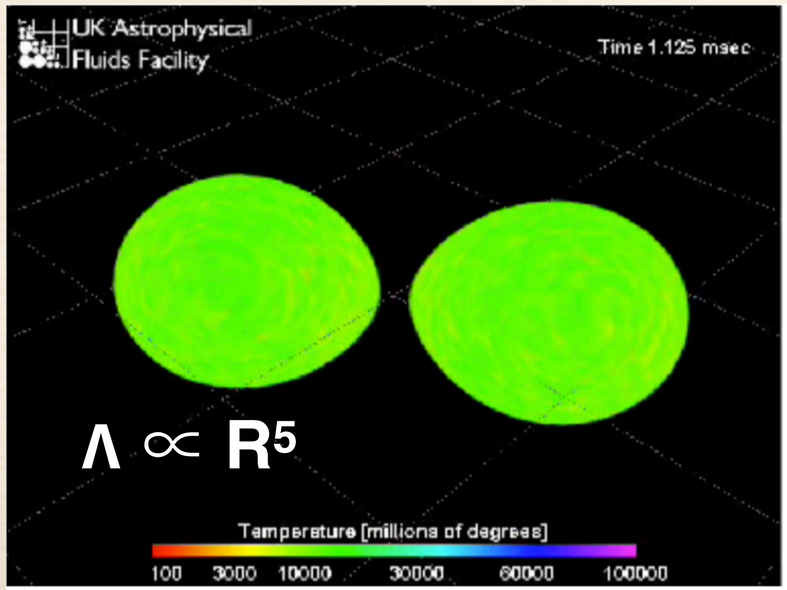
LIGO Binary Inspiral Tidal Deformability ⟷ **Neutron Star Radius** ⟷ *NICER Measurements of Pulsar X-rays*





MREX at MESA: *Use of a solenoidal spectrometer with a 200 MeV beam*

$\delta(A_{PV})/A_{PV} \sim 1.5\%$ → $\delta(R_n)$: ± 0.03 fm



pressure pushes against surface tension

208Pb Neutron Skin

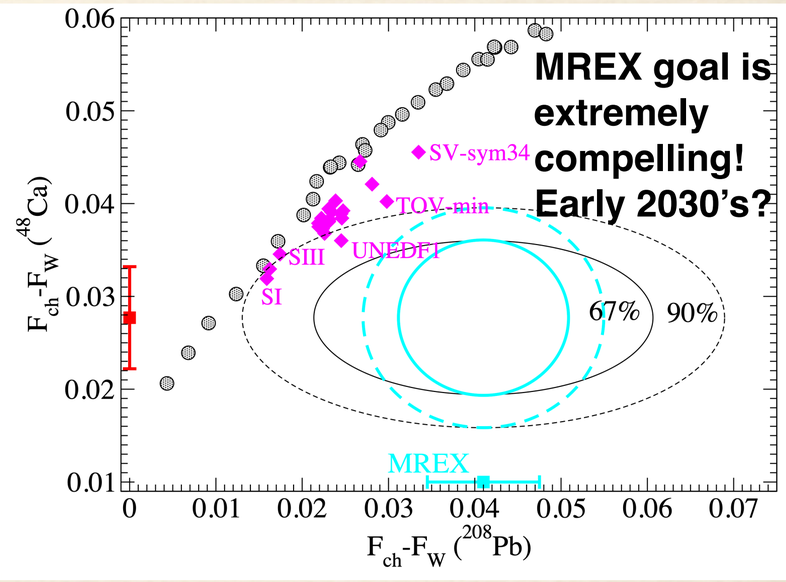
Equation of state (EOS) of dense nuclear matter

$$E(\rho,\delta) = E_0(\rho,\delta=0) + S(\rho)\delta^2$$

$$\delta = \frac{(\rho_n - \rho_p)}{\rho}$$

size of neutron skin → pressure → density dependence of symmetry energy at subnuclear densities

Symmetry Energy



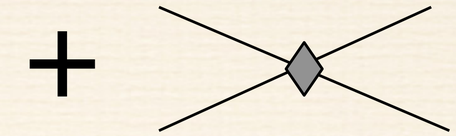
The MOLLER Sensitivity

11 GeV, 65 μA 90% beam polarization

A_{PV} ~ 32 ppb *$\delta(A_{PV})$ ~ 0.8 ppb*

$\delta(Q^e_W) = \pm 2.1$ % (stat.) ± 1.1 % (syst.)

A new experiment to measure parity-violating Møller scattering at Jefferson Lab



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

New Physics

$\delta(\sin^2\theta_W) = \pm 0.00023$ (stat.) ± 0.00012 (syst.)

~ 0.1%

$$\frac{\Lambda}{\sqrt{|g^2_{RR} - g^2_{LL}|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q^e_W|}} \simeq \frac{246.22\ \text{GeV}}{\sqrt{0.023 Q^e_W}} = 7.5\ \text{TeV}.$$

Conventional Collider Contact Interaction Analysis: $\left|g^2_{RR} - g^2_{LL}\right| = 4\pi$

LEP200: 200 GeV e+e- collider (before LHC)

Simultaneous fits to cross-sections and angular distributions

$\Lambda^{ee}_{LL} \sim 8.3$ TeV

$\Lambda^{ee}_{RR} \sim 8.2$ TeV

$\Lambda^{ee}_{VV} \sim 17.7$ TeV

95% C.L. Limits

MOLLER Reach

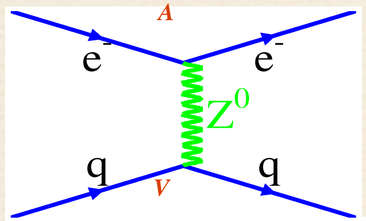
$\Lambda^{ee}_{LL} \sim 27$ TeV

$\Lambda^{ee}_{RR-LL} \sim 38$ TeV

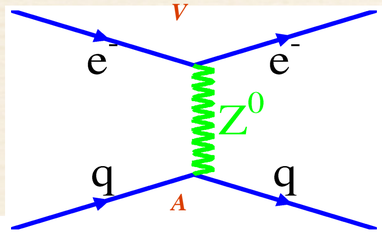
LEP-200 insensitive

MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider

Weak Neutral Current (WNC) Couplings



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



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

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)] + C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

$$\begin{array}{lcll} C_{1u} & = & -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W & \approx -0.19 \\ C_{1d} & = & \frac{1}{2}-\frac{2}{3}\sin^2\theta_W & \approx 0.35 \\ C_{2u} & = & -\frac{1}{2}+2\sin^2\theta_W & \approx -0.04 \\ C_{2d} & = & \frac{1}{2}-2\sin^2\theta_W & \approx 0.04 \end{array}$$

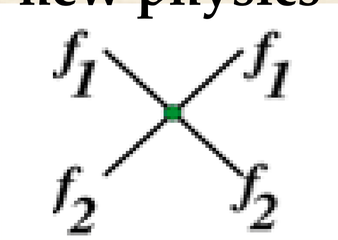
$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$ ***PV elastic e-N scattering, Atomic parity violation***

$$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$ ***PV deep inelastic scattering***

$$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2 \Rightarrow$$ ***PV Møller scattering***

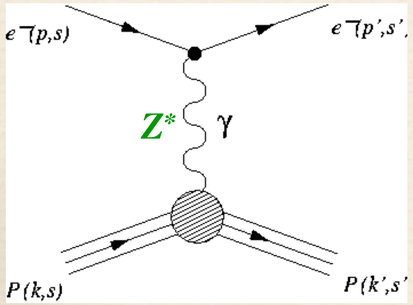
+

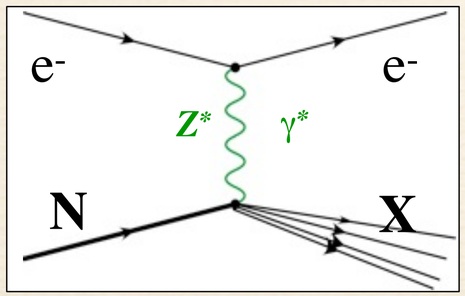
new physics



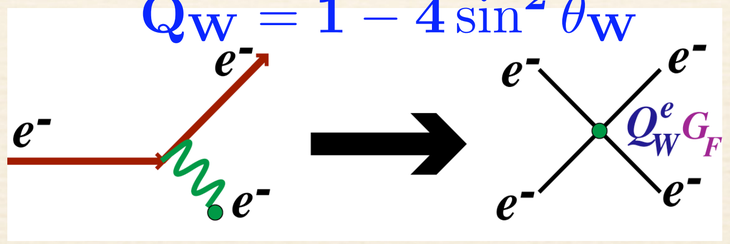
$$\mathcal{L}_{f_1 f_2} =$$

$$\sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$





$Q_W = 1 - 4\sin^2\theta_W$



PREX/CREX Data Summary

^{208}Pb

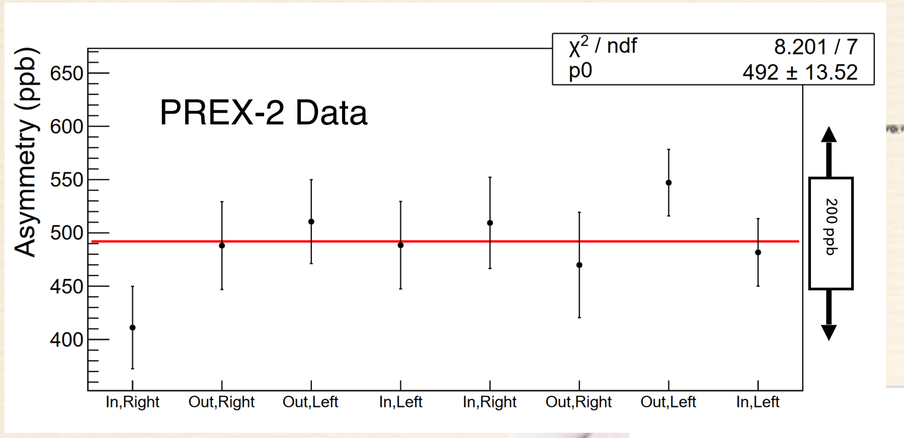
$Q^2 \sim 0.006$ GeV^2

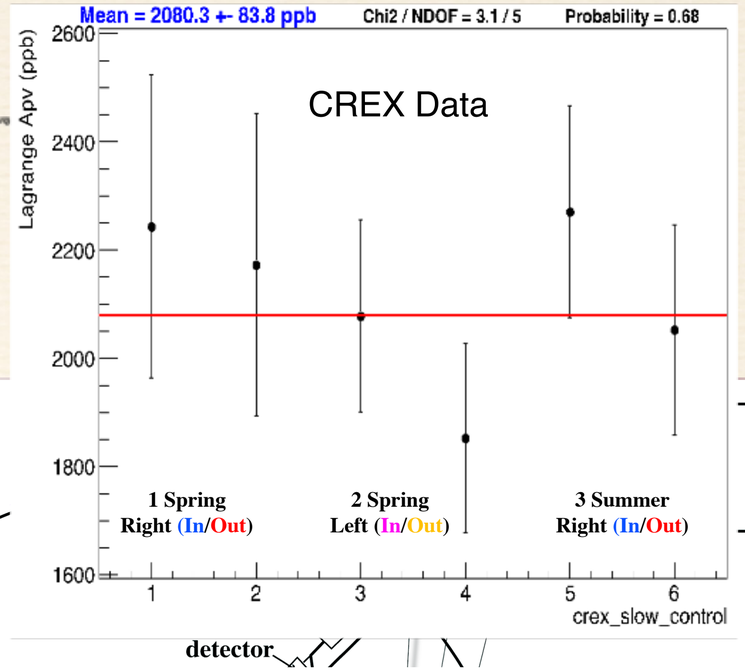
$A_{PV} \sim 0.6$ ppm

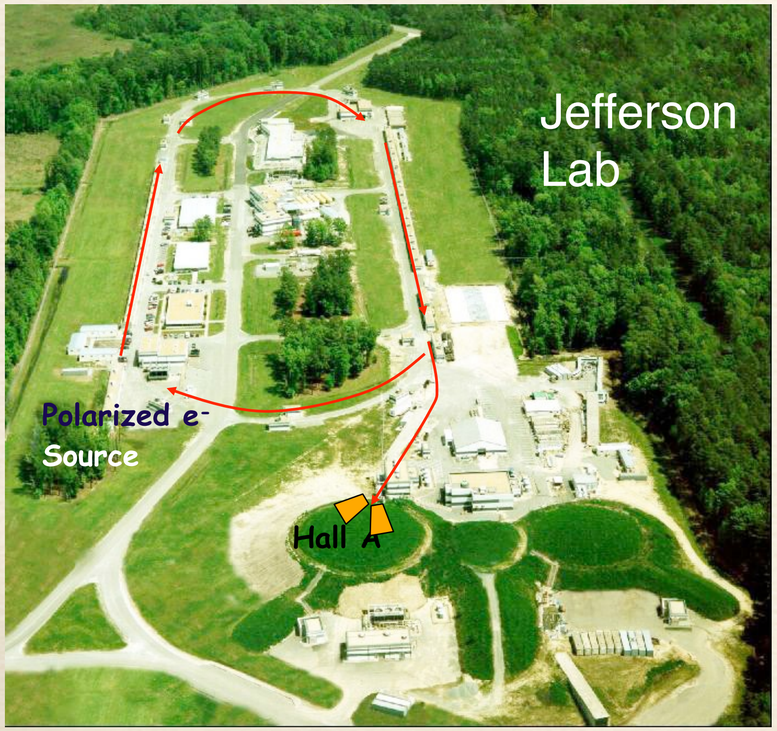
Rate ~ 4 GHz

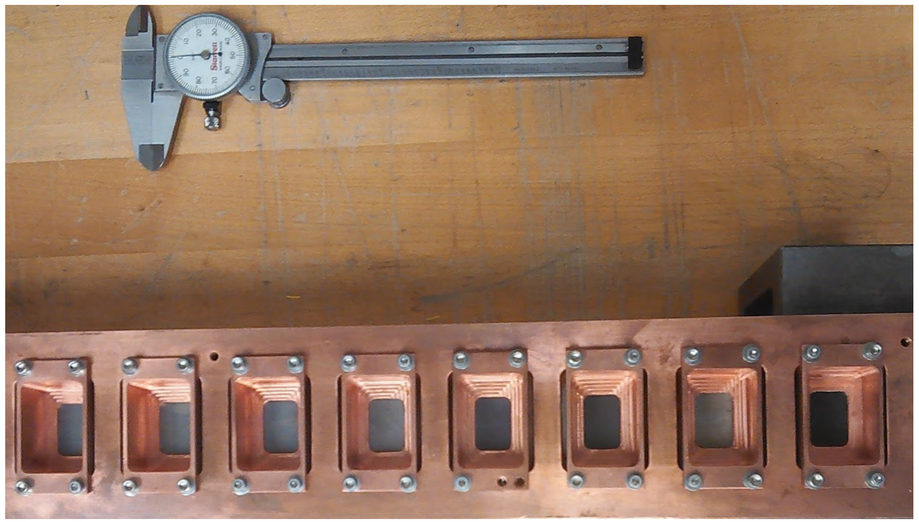
$\Delta(A_{PV}) \sim 16$ ppb

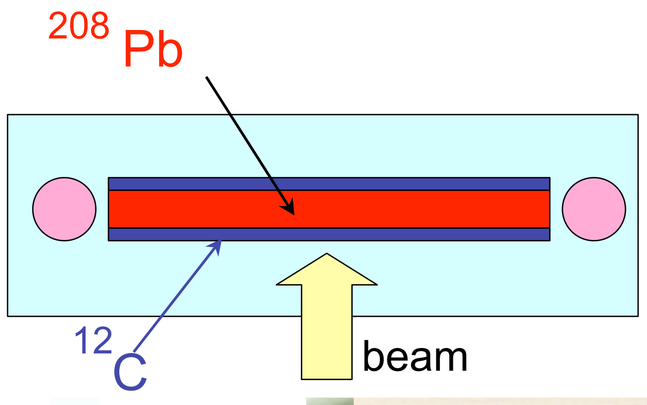
$\Delta(R_n) \sim 0.07$ fm











^{48}Ca

$Q^2 \sim 0.03$ GeV^2

$A_{PV} \sim 2$ ppm

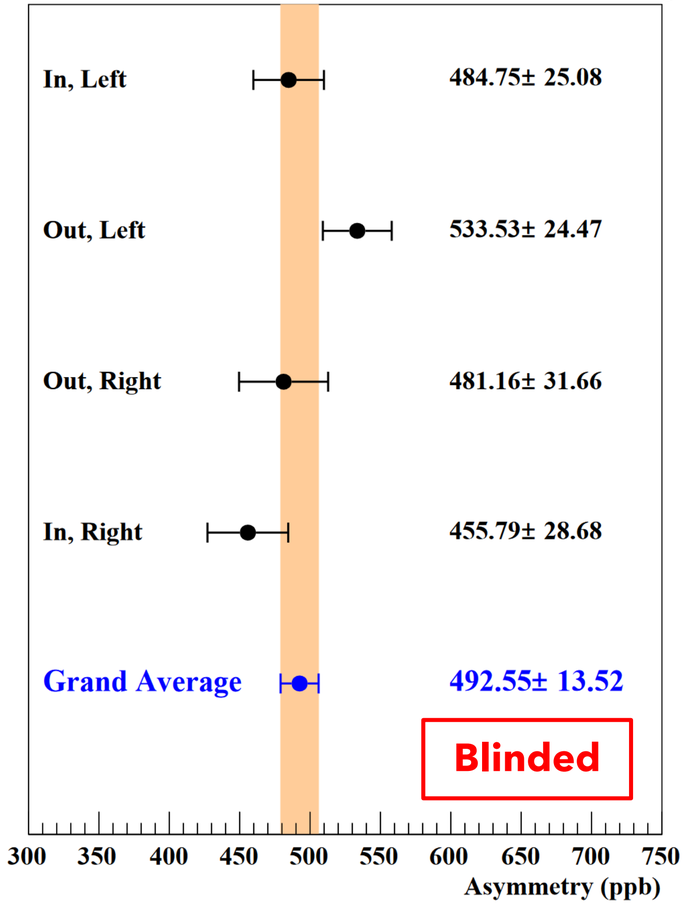
Rate ~ 56 MHz

$\Delta(A_{PV}) \sim 100$ ppb

$\Delta(R_n) \sim 0.03$ fm

Summary of Systematics

The final result is dominated by counting statistics



$$A_{PV} = R_{acceptNorm}\frac{A_{corr}/P_e - \sum_i A_i f_i}{1 - \sum_i f_i}$$

$$A_{corr} = A_{raw} + A_{beam} + A_{nonLin} - A_{blind}$$

Blinded A_{PV}:

(549.4 ± 16.1)ppb

	A_{PV} uncertainty contribution [ppb]	A_{PV} uncertainty contribution [%]
Polarization	5.23	0.95%
Acceptance normalization	4.56	0.83%
Beam correction	2.98	0.54%
Non-linear detector response	2.69	0.49%
Carbon dilution	1.45	0.26%
Charge correction	0.25	0.04%
Inelastic contamination	0.12	0.02%
Total	**8.16**	**1.48%**

When taken all into account the experimental systematic uncertainty comes to just shy of 1.5%

Tree-level prediction: ~ 250 ppb

$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

E158 Implications and Status

Final E158 Result

Nature
Vol 435 26 May 2005

Phys. Rev. Lett. **95** 081601 (2005)

NEWS AND VIEWS

PARTICLE PHYSICS

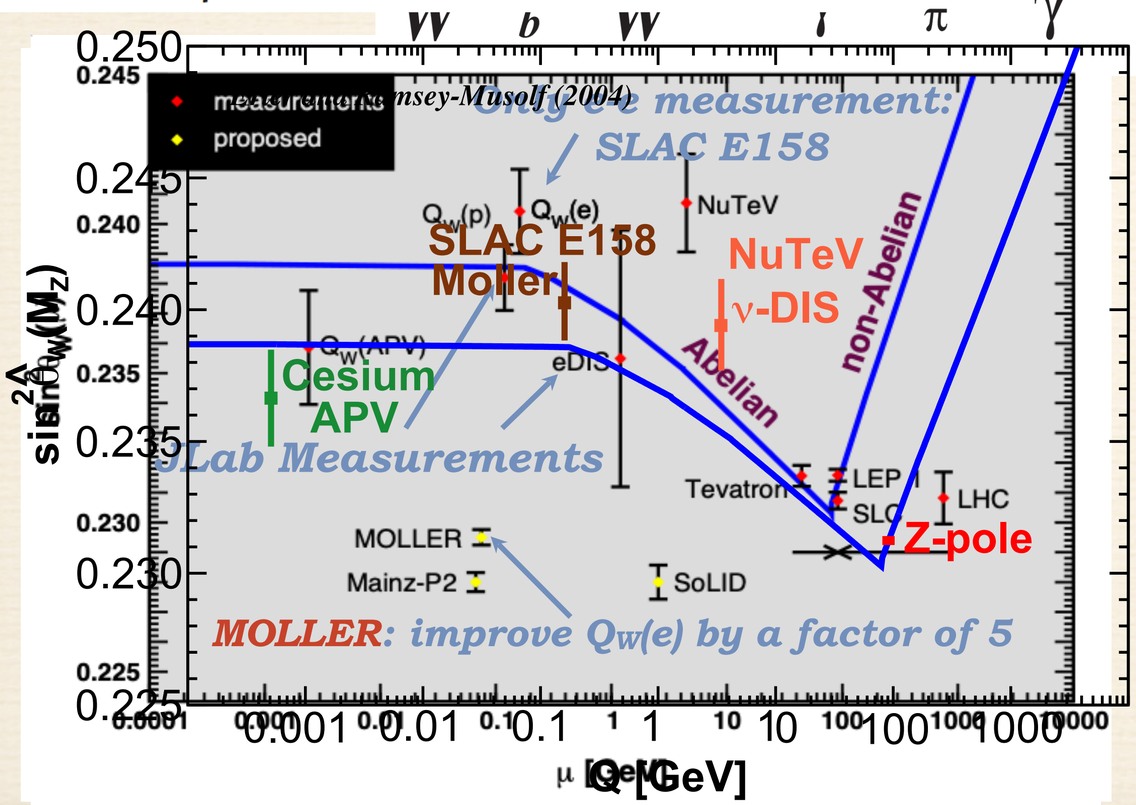
Electrons are not ambidextrous

Andrzej Czarnecki and William J. Marciano

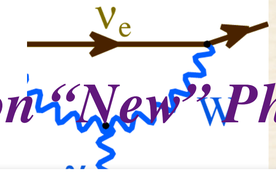
The best low-energy measurement yet obtained of the electroweak mixing angle — a central parameter of the standard model of particle physics — is the last hurrah for Stanford's powerful two-mile linear accelerator.

i and Marciano (1995)

$q \sin^2 \theta_W$

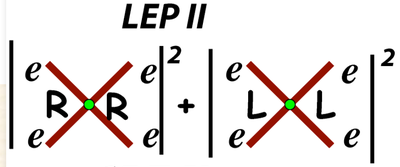


Limits on "New" Physics



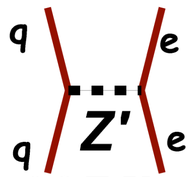
95%

LEP II



17 TeV

Fermilab

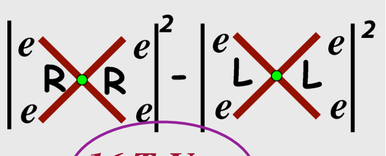


0.8 TeV

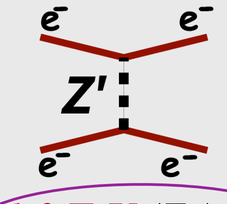
doubly charged scalar exchange

$0.01 \cdot G_F$

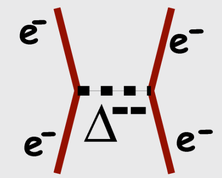
E158



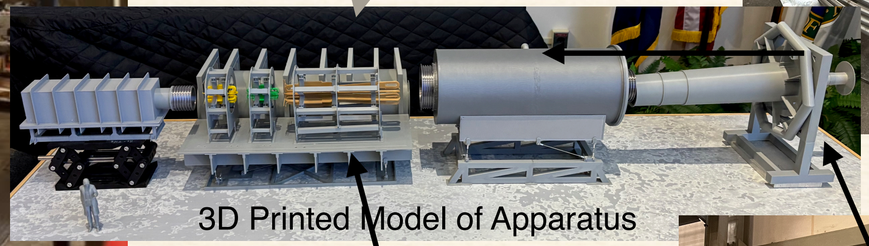
16 TeV

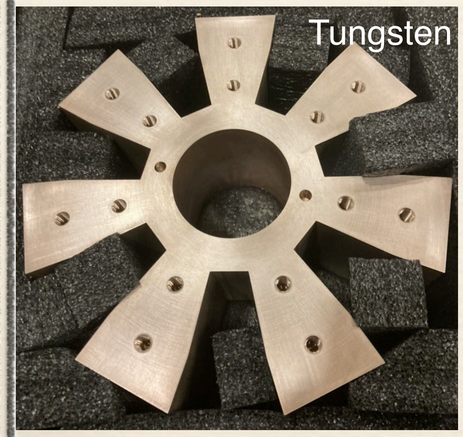


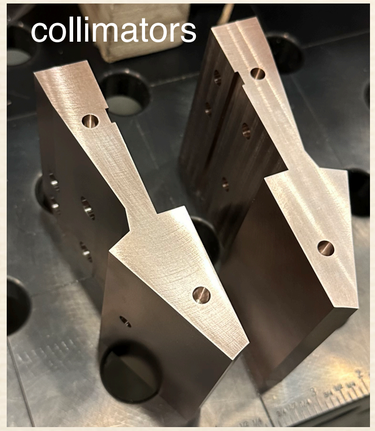
1.0 TeV (Z_χ)



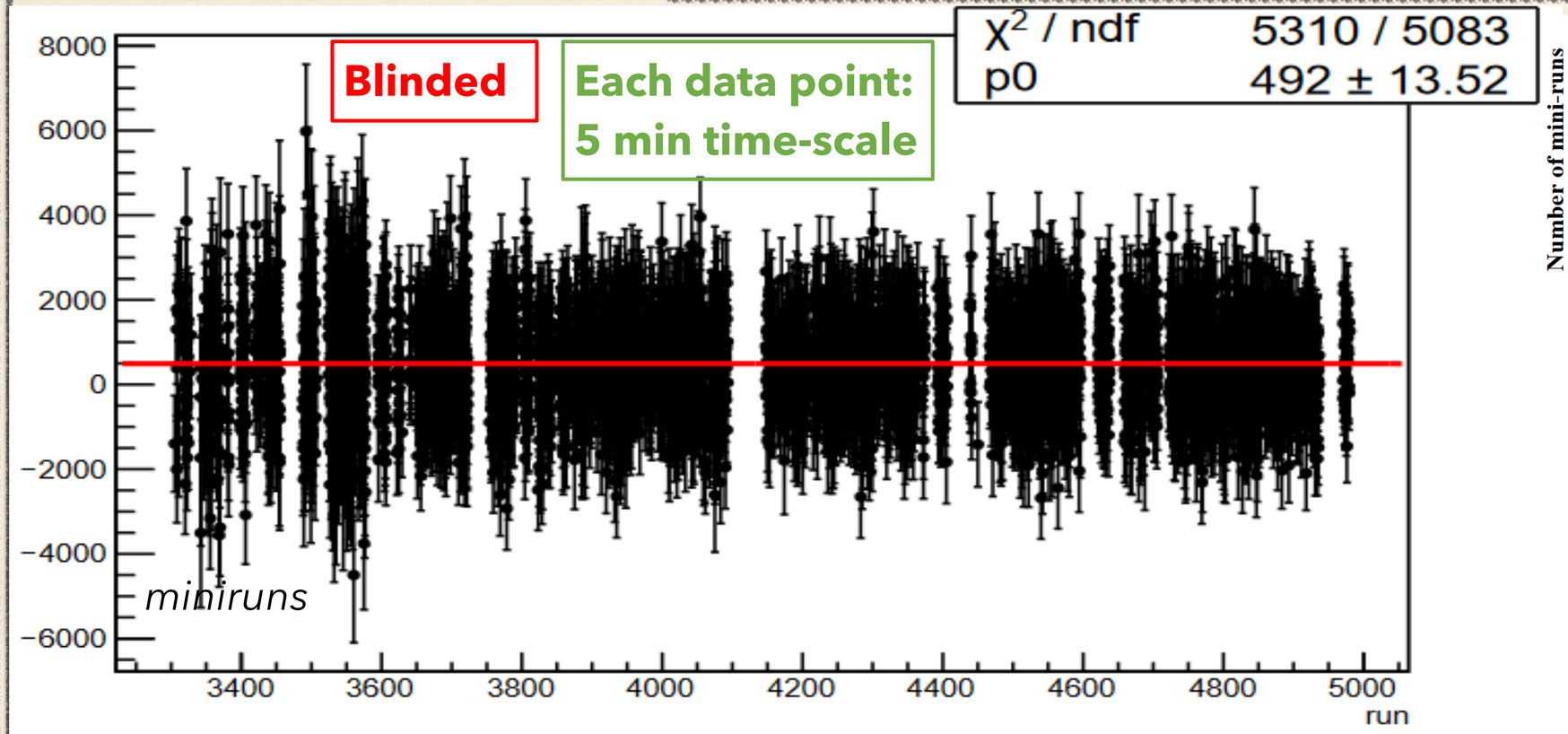
MOLLER Under Construction!



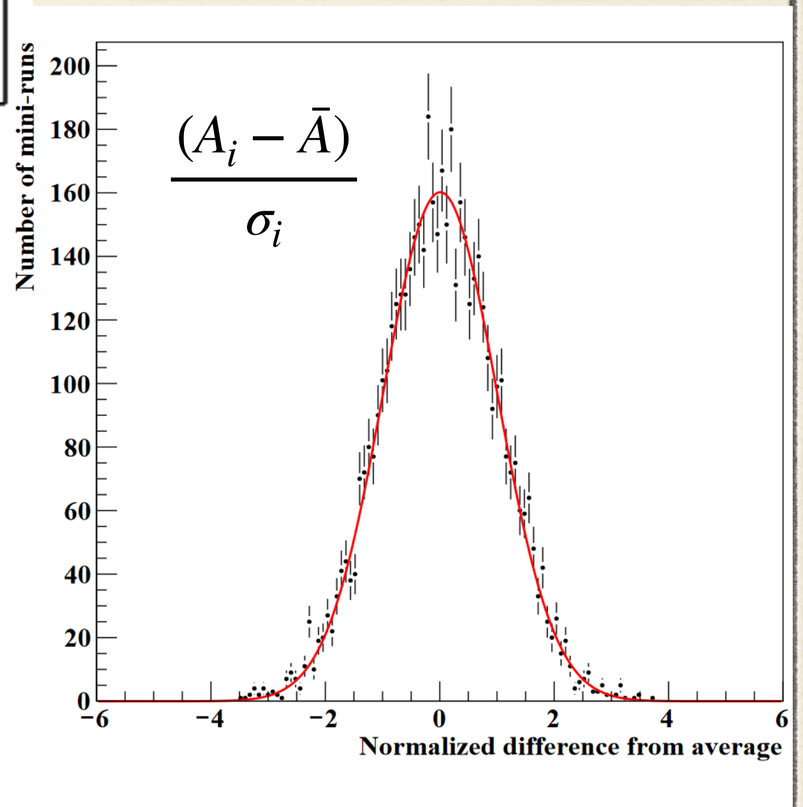




5 minute time scale

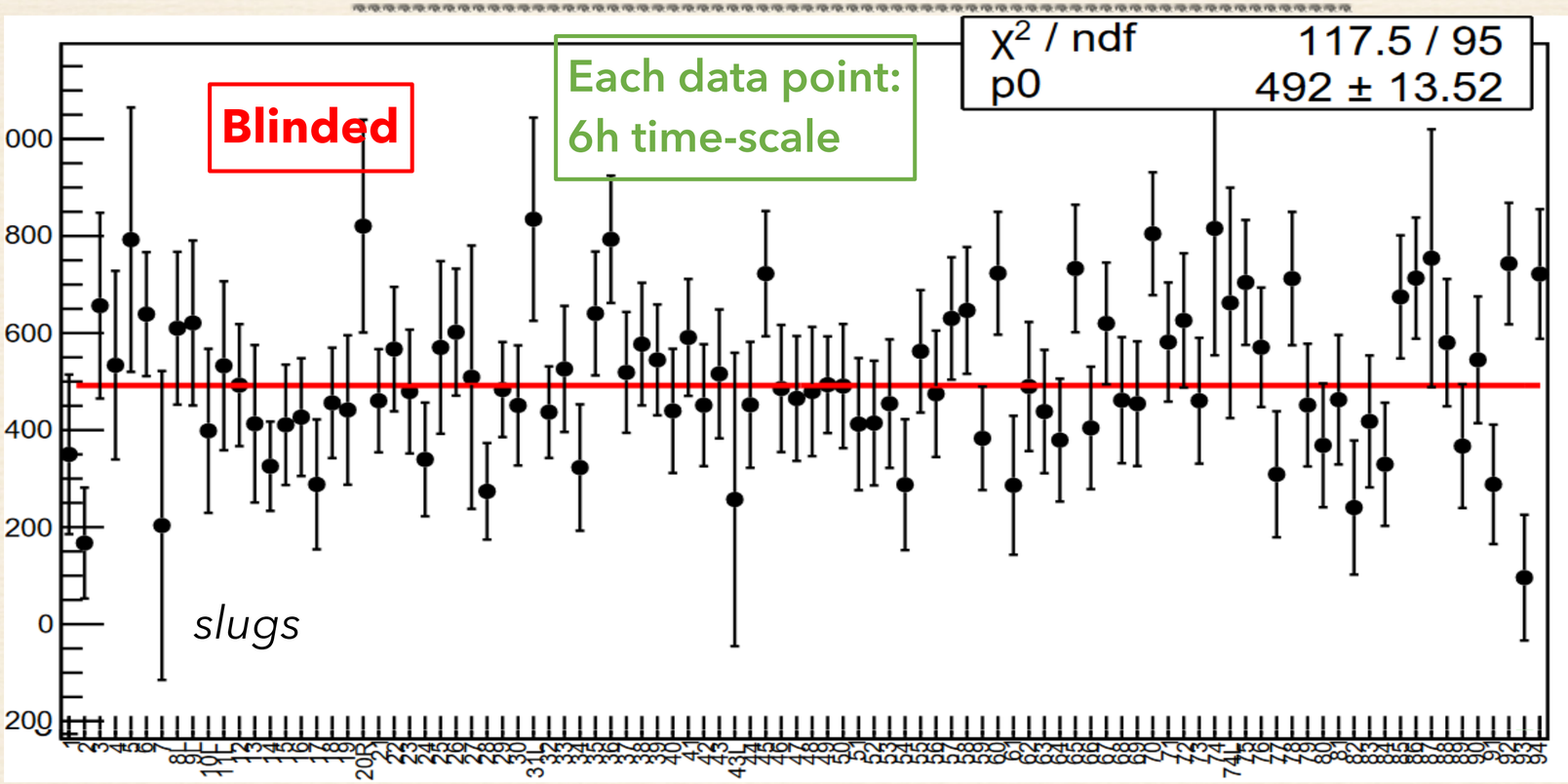


"pull" plot



- The corrected asymmetry removed effects from beam asymmetries and noise
- Still to come: polarization and background corrections

6 hour time scale

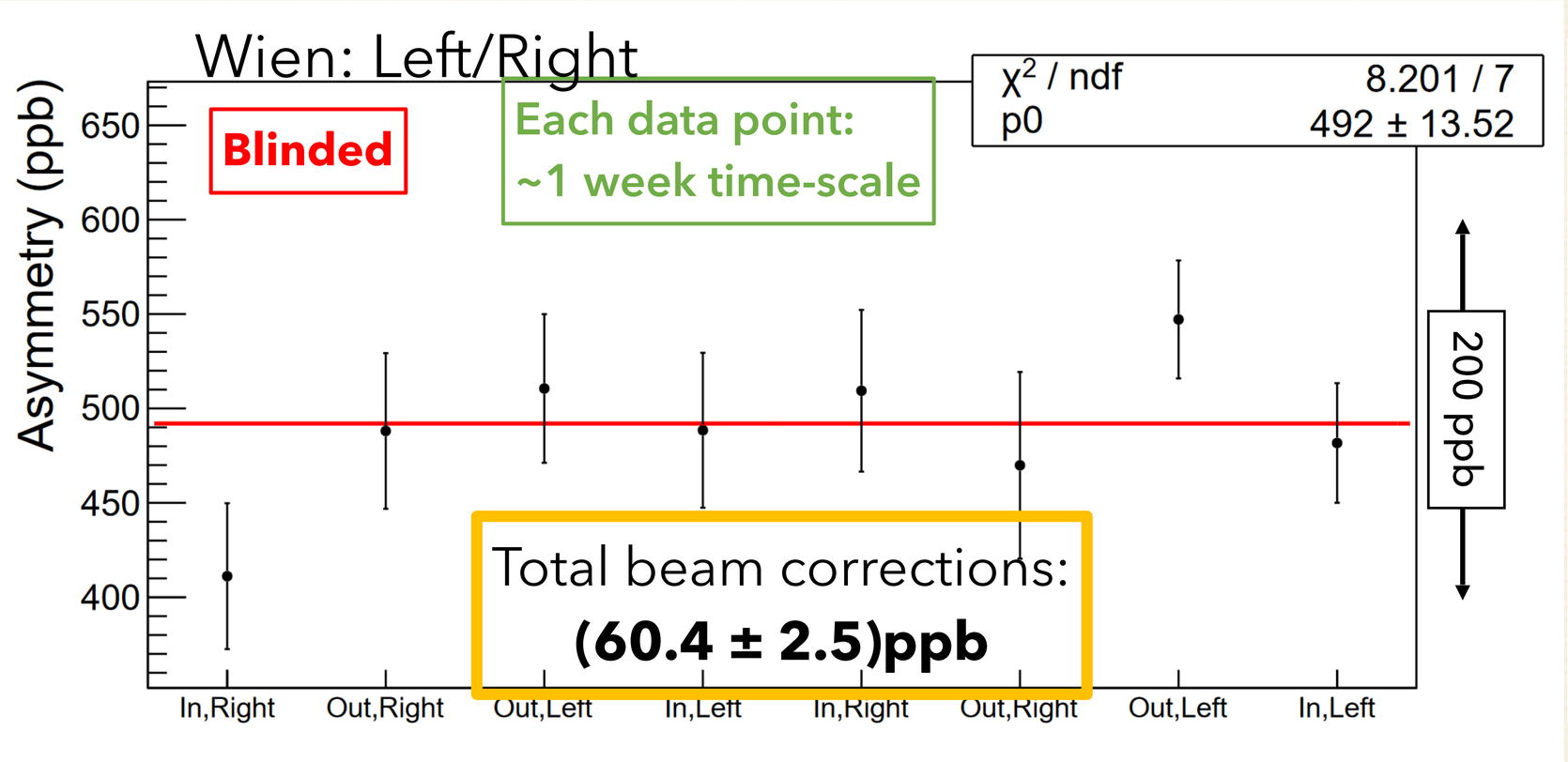


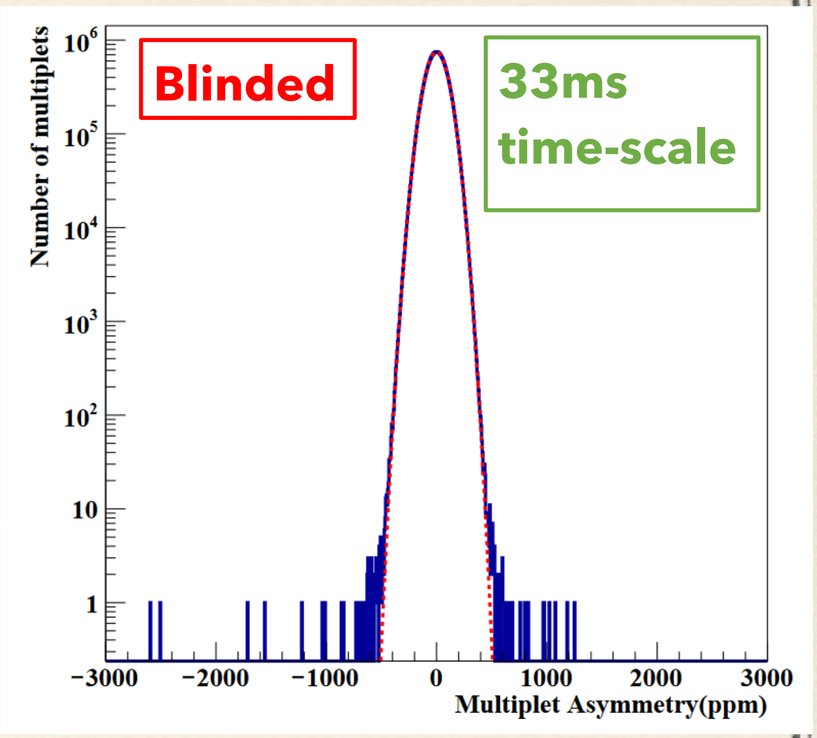
- The corrected asymmetry removed effects from beam asymmetries and noise
- Still to come: polarization and background corrections

Data Overview: Corrected Asymmetry

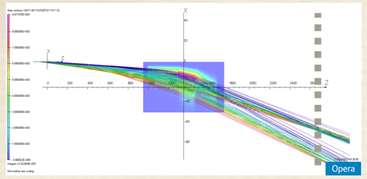
Half Wave Plate: IN/OUT

Wien: Left/Right





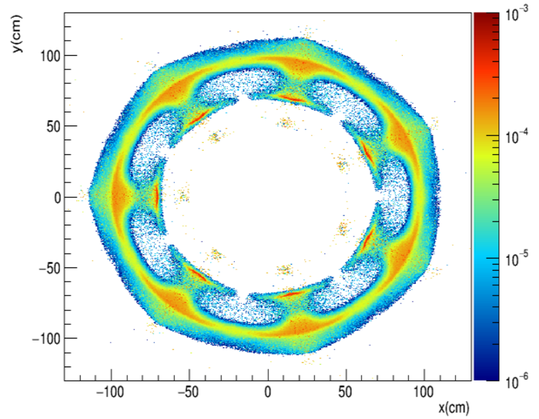
- The corrected asymmetry removed effects from beam asymmetries and noise
- Still to come: polarization and background corrections



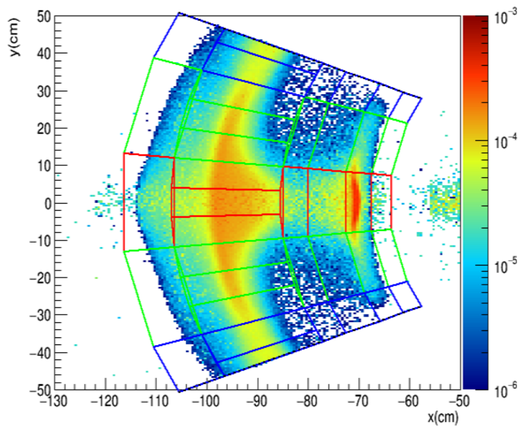
Capturing the Scattered Flux

Time check

Heat map on transverse plane 26.5 m from target center

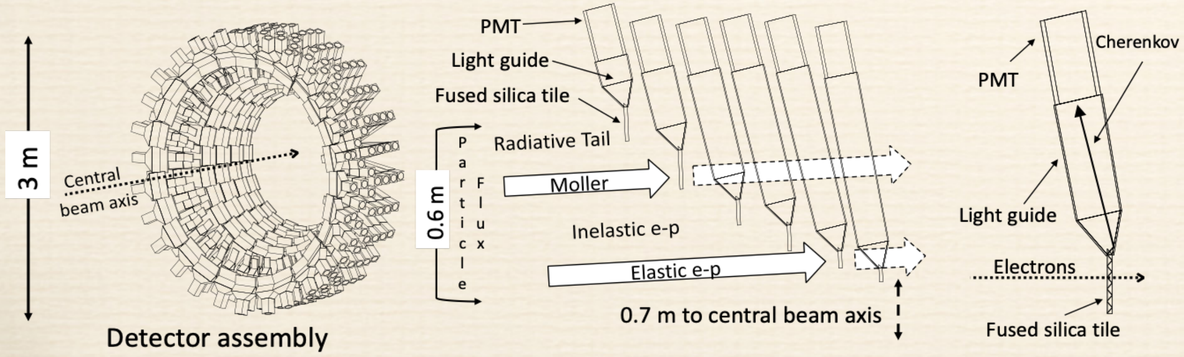


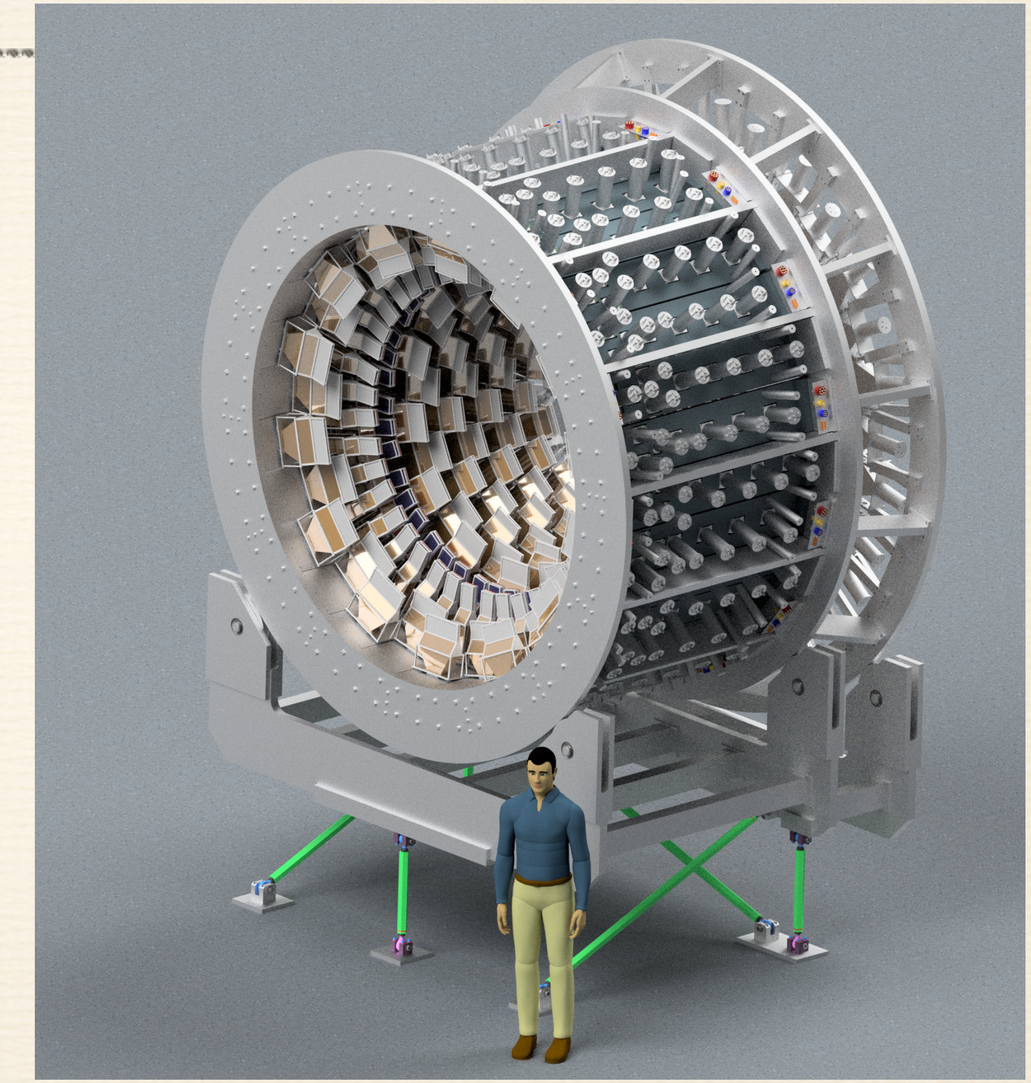
1/7 of the azimuth showing tiling segmentation



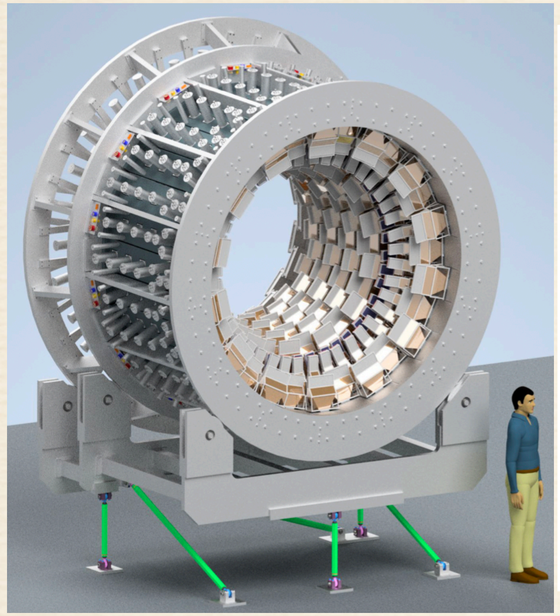
Wide variation in flux intensity and weights of different scattering processes: 1) e-e, 2) elastic e-p, 3) inelastic e-p

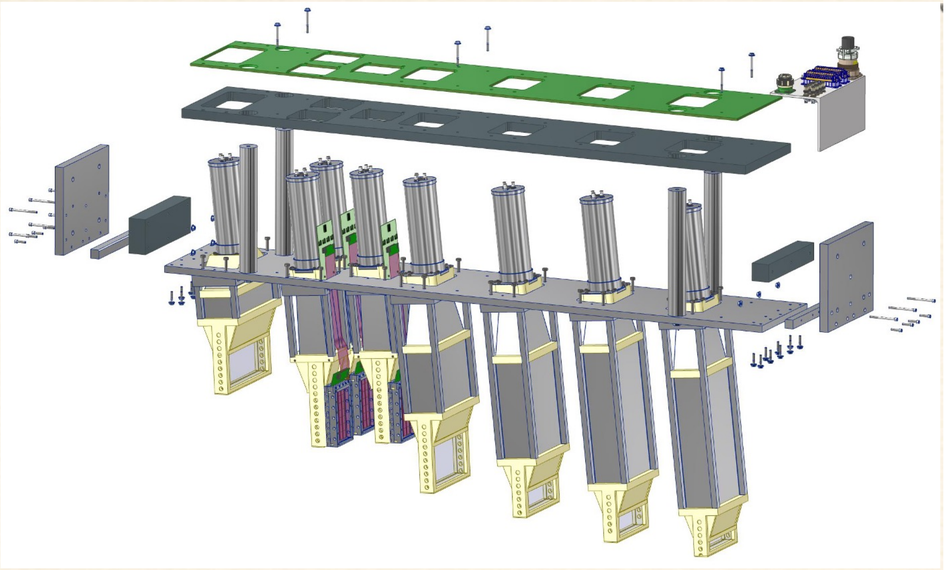
Both radial and azimuthal segmentation in scattered flux measurements required

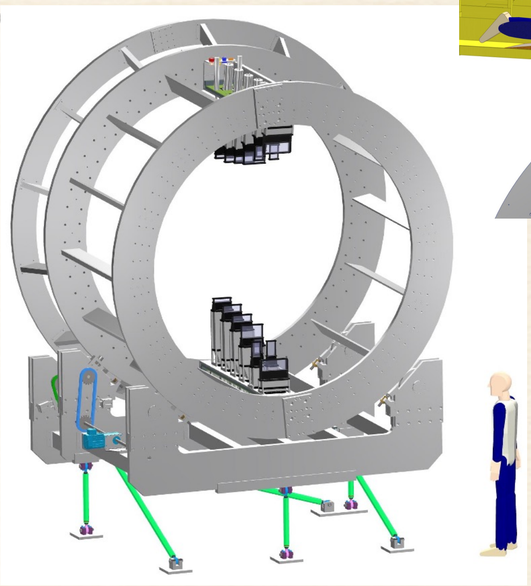


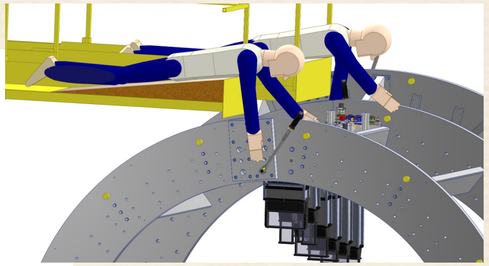


Integrating Detector Assembly

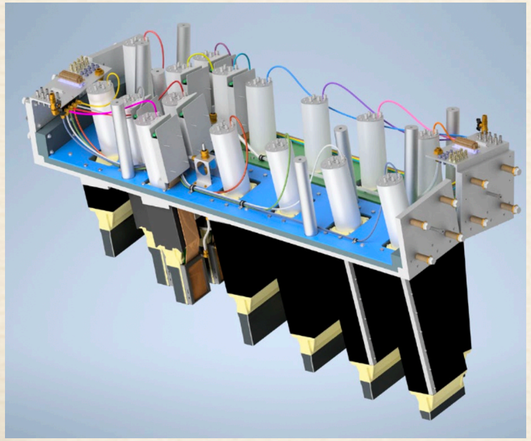


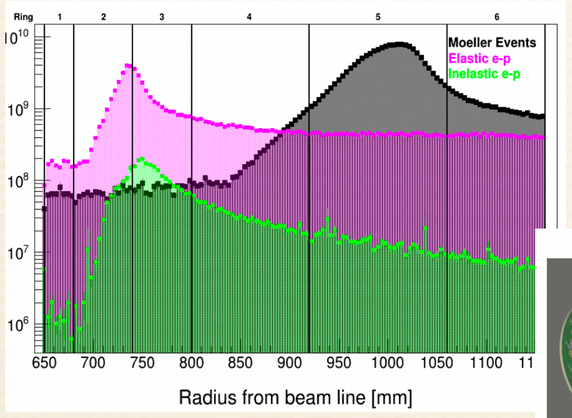


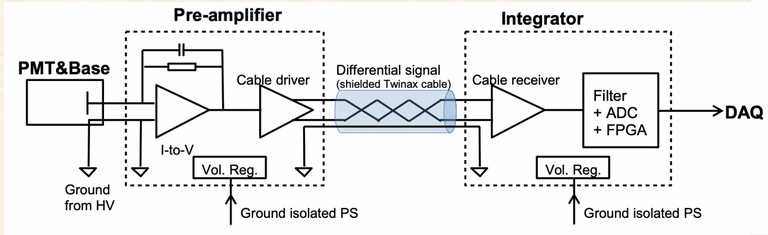


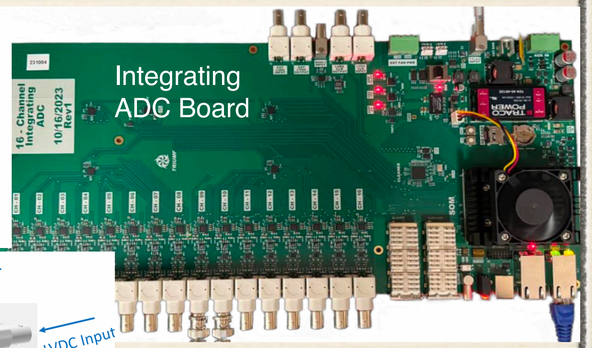


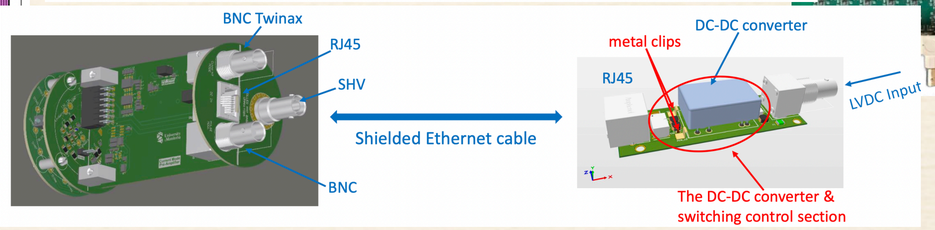
Idaho State University
University of Manitoba
University of Massachusetts
Bartoszek Engineering











Glashow, Weinberg and Salam: $SU(2)_L X\ U(1)_Y$

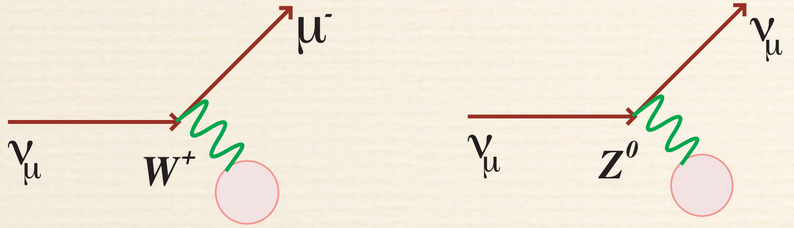
Electroweak Interactions

One free parameter: weak mixing angle θ_W

$$\tan\theta_W = \frac{g'}{g} \qquad A_\mu = B^0_\mu \cos\theta_W + W^0_\mu \sin\theta_W$$

$$Z_\mu = W^0_\mu \cos\theta_W - B^0_\mu \sin\theta_W .$$

$$e = g \sin\theta_W$$



Charged Current

Neutral Current

Higgs Mechanism + Renormalizability

$$\sin^2\theta^0_W = \left(\frac{e^0}{g^0}\right)^2 = 1 - \left(\frac{M^0_W}{M^0_Z}\right)^2$$

- **Why is the weak boson scale 100 GeV?**
- **Why are there 3 generations of particles?**
- **How did matter come to dominate over anti-matter?**
- **Were there as yet unobserved new forces in the early universe?**
- **Is there a unifying framework to describe all forces?**
- **Why are neutrinos so light?**
- **Why is the top so heavy?**
- **...**

Physics Beyond the Standard Model (BSM)

BSM Searches must be as model-independent as possible

The Global Search for New Physics

The High Energy Frontier: Collider Physics

The Cosmic Frontier: Particle, Nuclear and Gravitational Astrophysics

A comprehensive search for clues requires, in addition:

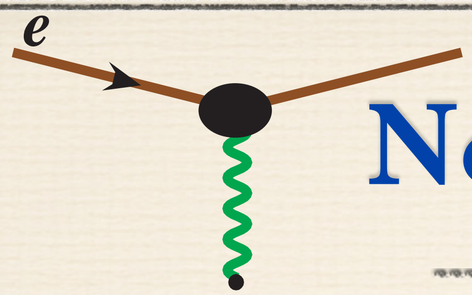
The Intensity/Precision Frontier

★ **Measurements of Neutrino Properties**

★ **Direct and Indirect Searches for Dark Matter**

★ **Searches for Violation of Accidental (?) Symmetries**

★ **Precise Measurements of SM observables**

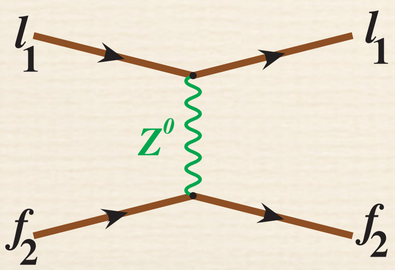


Modern Day Electroweak Physics

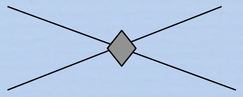
New Electron Operators

- **Violation of Lepton Number** — $\frac{1}{\Lambda}\mathcal{L}_5$, 10^{15} GeV; $\frac{1}{\Lambda^5}\mathcal{L}_9$, multi-TeV
  - ★ Neutrinoless Double-Beta Decay?
- **Violation of Time Reversal Symmetry**
  - ★ Non-zero Electric Dipole Moment of the Electron?
- **Violation of Charged Lepton Flavor** — 100s of TeV; $\frac{1}{\Lambda^2}\mathcal{L}_6$
  - ★ muon-to-electron conversion in muon decay or nuclear muon capture?
- **Violation of Parity with Flavor Conservation** — multi-TeV
  - ★ new contributions to parity-violating electron scattering?

Search for new flavor-diagonal superweak forces



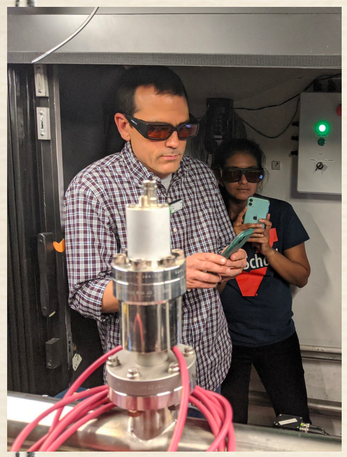
Look for tiny but measurable deviations from precisely calculable predictions for SM processes



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

Congratulations to the PREX crew

Students: **Devi Adhikari**, Devaki Bhatta Pathak, Quinn Campagna, Yufan Chen, **Cameron Clarke**, Catherine Feldman, **Iris Halilovic**, **Siyu Jian**, **Eric King**, Carrington Metts, Marisa Petrusky, **Amali Premathilake**, **Victoria Owen**, **Robert Radloff**, **Sakib Rahman**, **Ryan Richards**, Ezekiel Wertz, **Tao Ye**, **Adam Zec**, **Weibin Zhang**



Post-docs and Run Coordinators: Rakitha Beminiwattha, Juan Carlos Cornejo, Mark-Macrae Dalton, Ciprian Gal, Chandan Ghosh, Donald Jones, Tyler Kutz, Hanjie Liu, Juliette Mammei, Dustin McNulty, Caryn Palatchi, Sanghwa Park, Ye Tian, Jinlong Zhang

Spokespeople: Kent Paschke (contact), Krishna Kumar, Robert Michaels, Paul A. Souder, Guido M. Urciuoli

Thanks to the Hall A techs, Machine Control, Yves Roblin, Jay Benesch and other Jefferson Lab staff

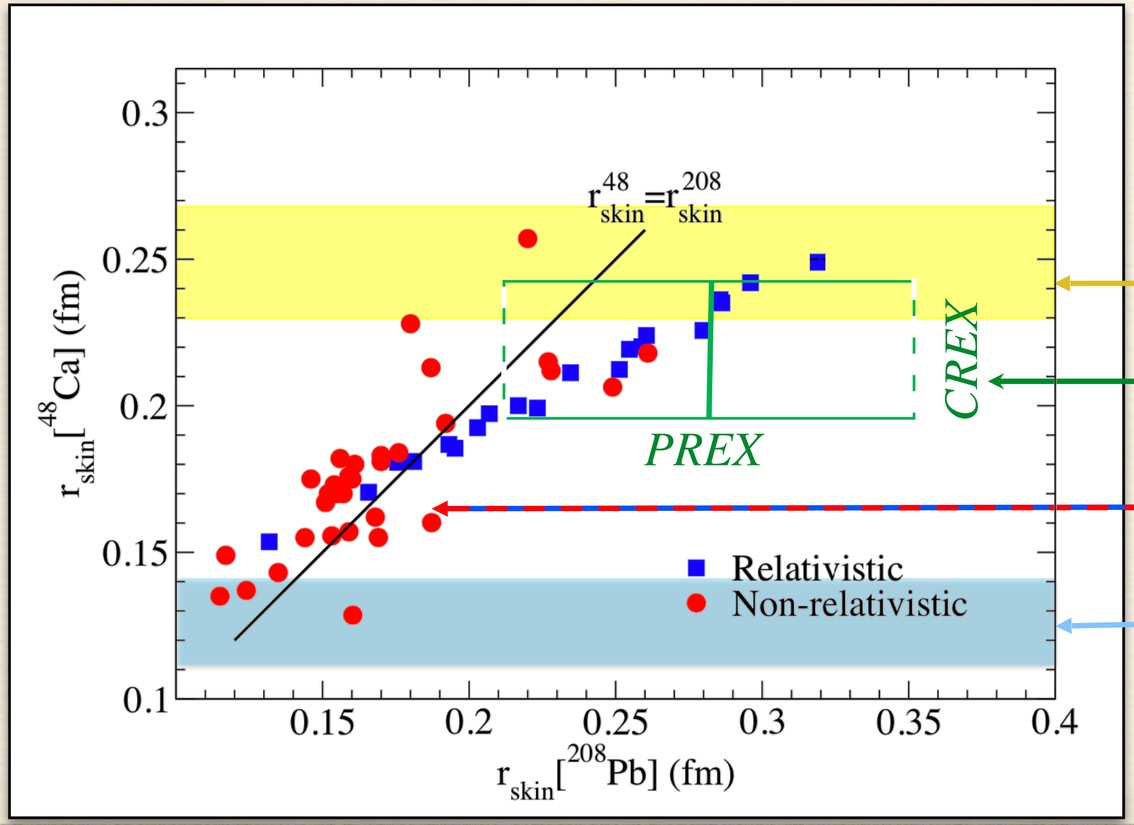
Special thanks to: Charles Horowitz and Jorge Piekarewicz for support and insightful conversations
Especially Chuck and grad student Brendan Reed who have worked to help us interpret our results

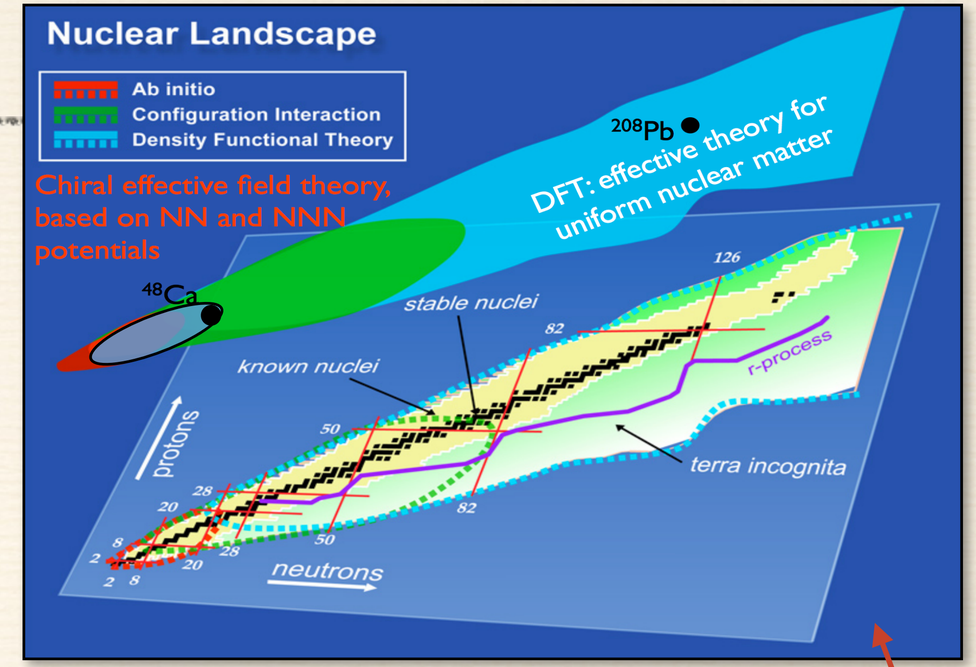
Motivation for Measuring a Second Nucleus

PREX: ^{208}Pb large, uniform nucleus, DFT

CREX: neutron FF ^{48}Ca

- moderate size system
- finite size effects
- Within reach of microscopic calculations (which suggest the importance of 3-nucleon forces)





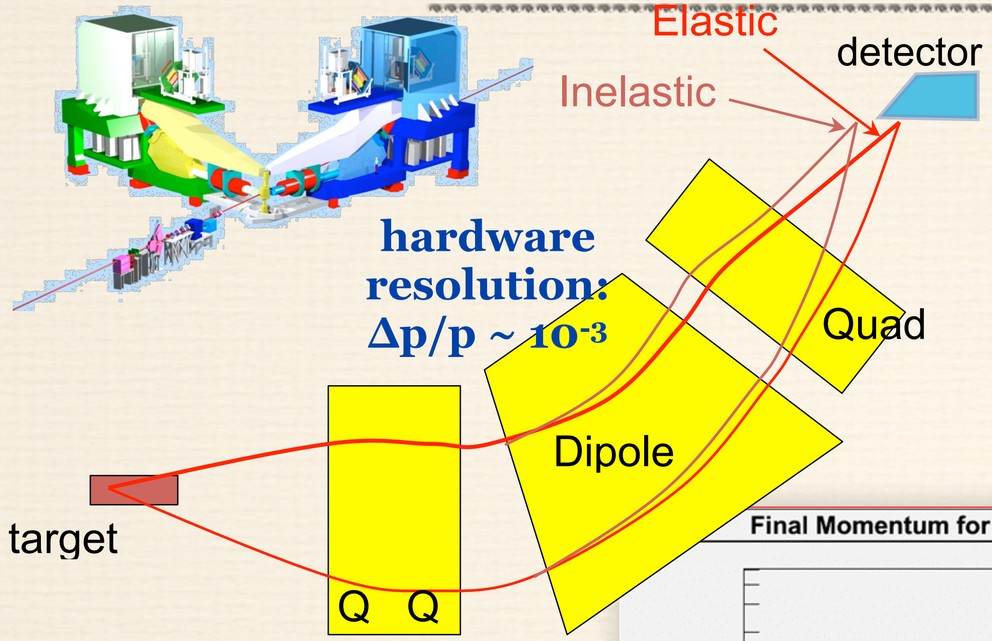
- DOM (Dispersive Optical Model)
  W. Dickoff *et al*, PRL 119, 222503(2017)
- *Arbitrary CREX central value*
- DFT (Relativistic, Non-relativistic)
  Fattoyev, Piekarewicz, PRC 85, 015802 (2012)
- Coupled cluster calculations predict a neutron skin of: $0.12 \leqq R_{skin} \leqq 0.15$ fm
  G. Hagen *et al*, Nature Physics **12**, 186–190 (2016)

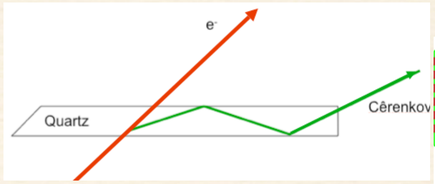
Picture likely "stolen" from someone in this audience!!

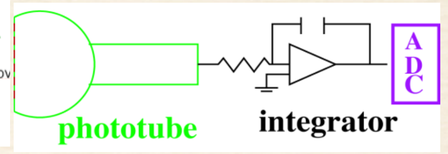
second major SLAC E122 innovation: “flux integration”

High Flux, Low Background

Hall A High Resolution Spectrometers



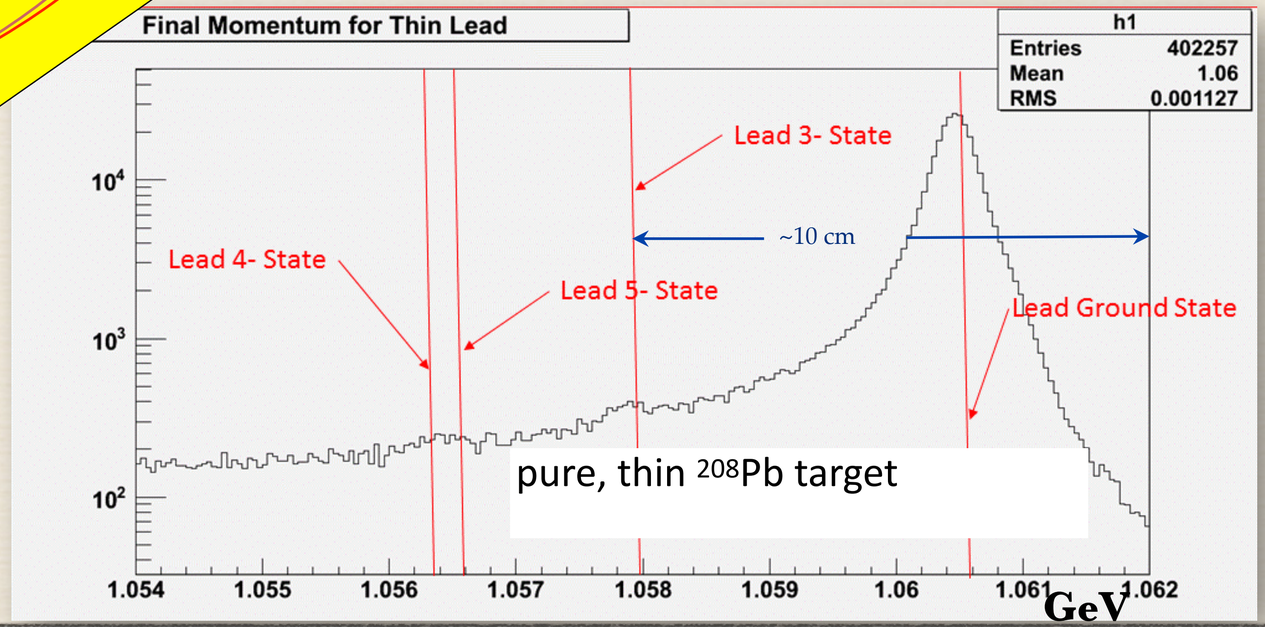




1 GHz scattered flux

1 x 10^{-4} statistical uncertainty
30 times per second

Inelastic backgrounds negligible



CREX Result Summary

Unblinded Corrected Asymmetry A_{corr}:

2336.0 ± 84.8ppb

$$A_{phys} = R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L(1 - \sum_i f_i)}$$

$$A_{corr} = A_{det} - A_{beam} - A_{trans} - A_{nonlin} - A_{blind}$$

Unblinded A_{PV}:

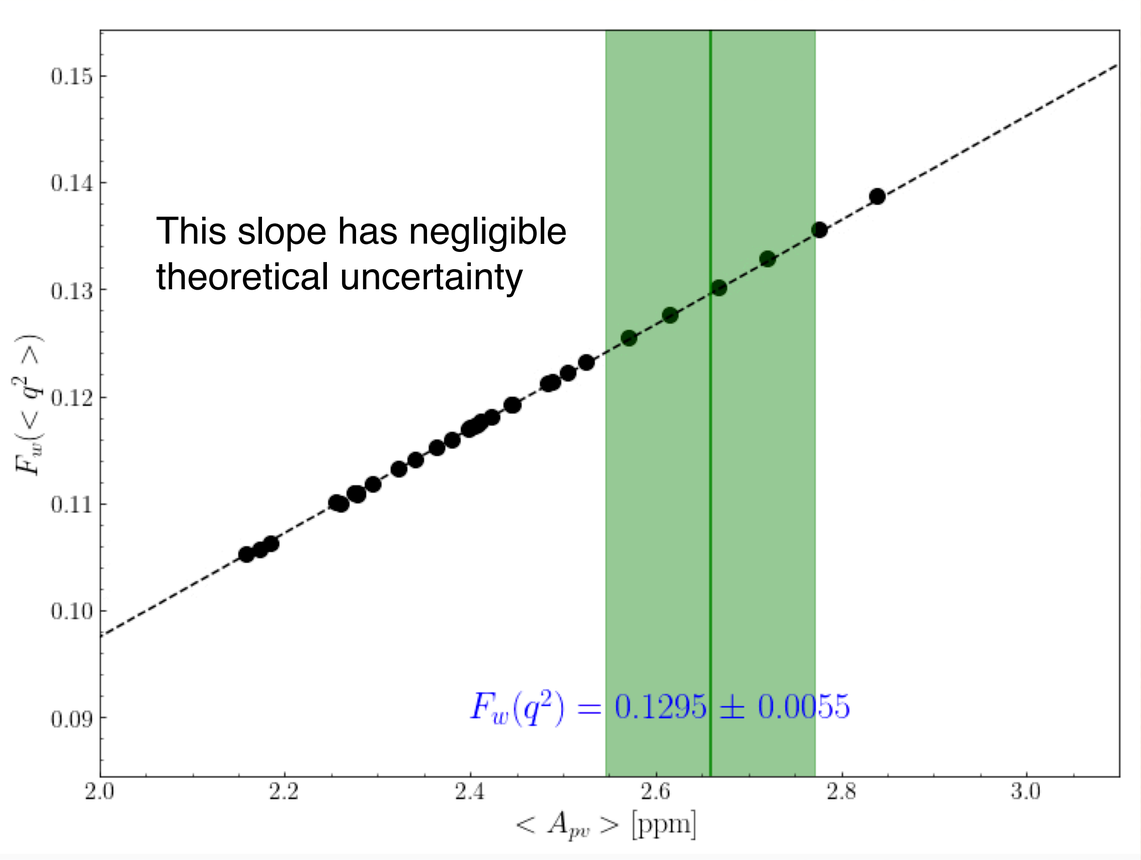
2658.6 ± 106.1(stat) ± 39.4(sys)ppb

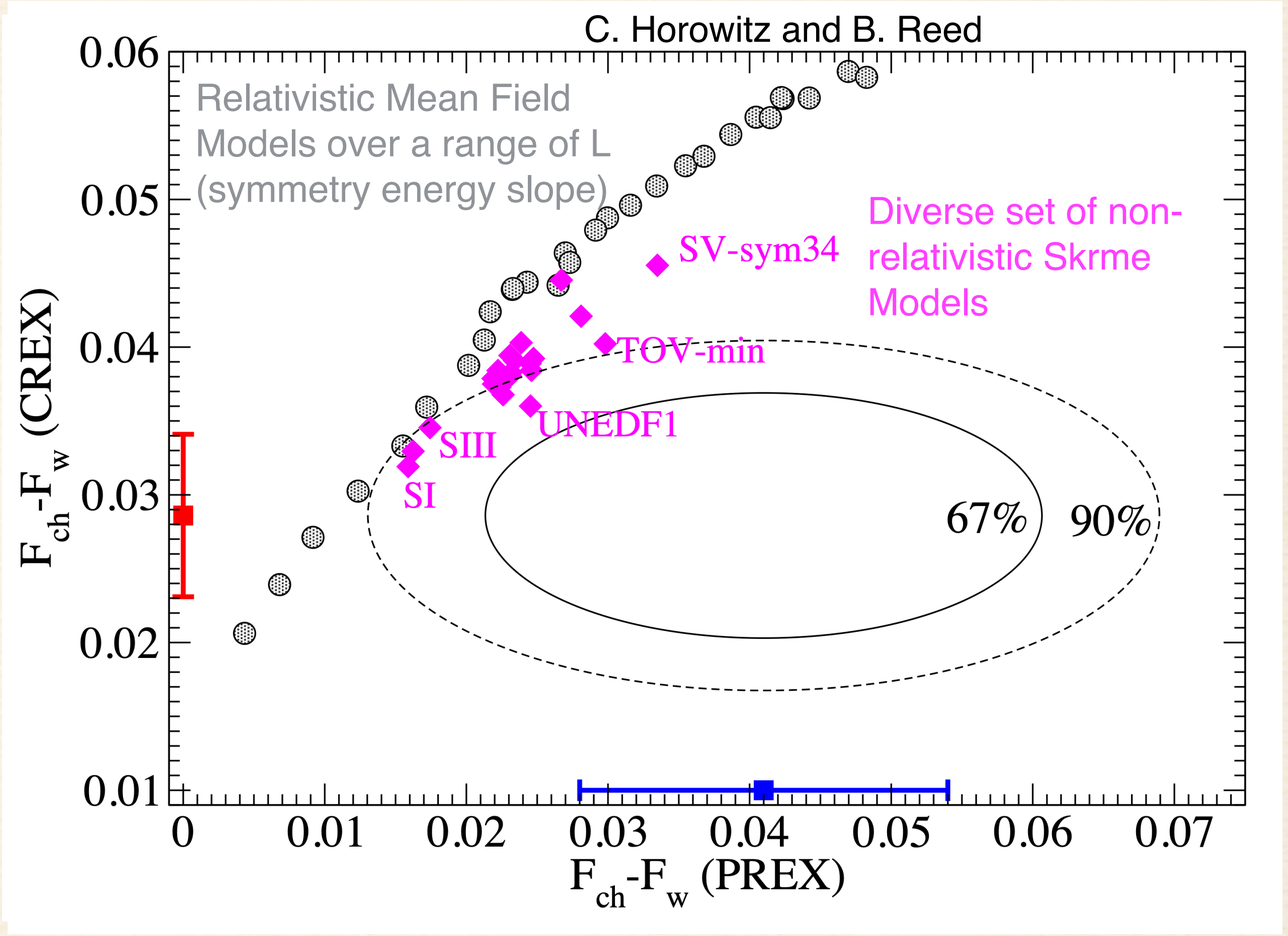
[± 113.2ppb(tot) (4.3%)]

	A_{PV} uncertainty contribution [ppb]	A_{PV} uncertainty contribution [%]
Polarization	13.1	0.49%
Horizontal Polarization	12.7	0.48%
Vertical Polarization	0.9	0.03%
Acceptance normalization	23.9	0.90%
Beam correction	6.9	0.26%
Non-linear detector response	6.7	0.25%
Ca40 background	8.8	0.33%
Charge correction	1.1	0.04%
Inelastic contamination 2+	18.9	0.71%
Inelastic contamination 3-(1)	10.2	0.38%
Inelastic contamination 3-(2)	3.6	0.13%
Rescattering	0.5	0.02%
Total	**39.4**	**1.5%**

- When taken all into account the experimental systematic uncertainty comes to 1.5%, less than half the 4.0% statistical uncertainty
- Total uncertainty of is 113.2ppb (4.3%)

Main Derived Parameter: The Weak Form Factor at $Q^2 = 0.0297$ GeV^2

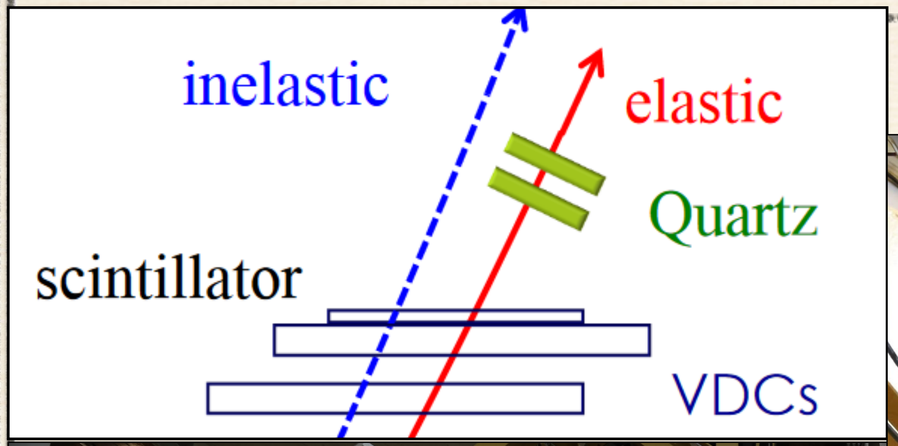


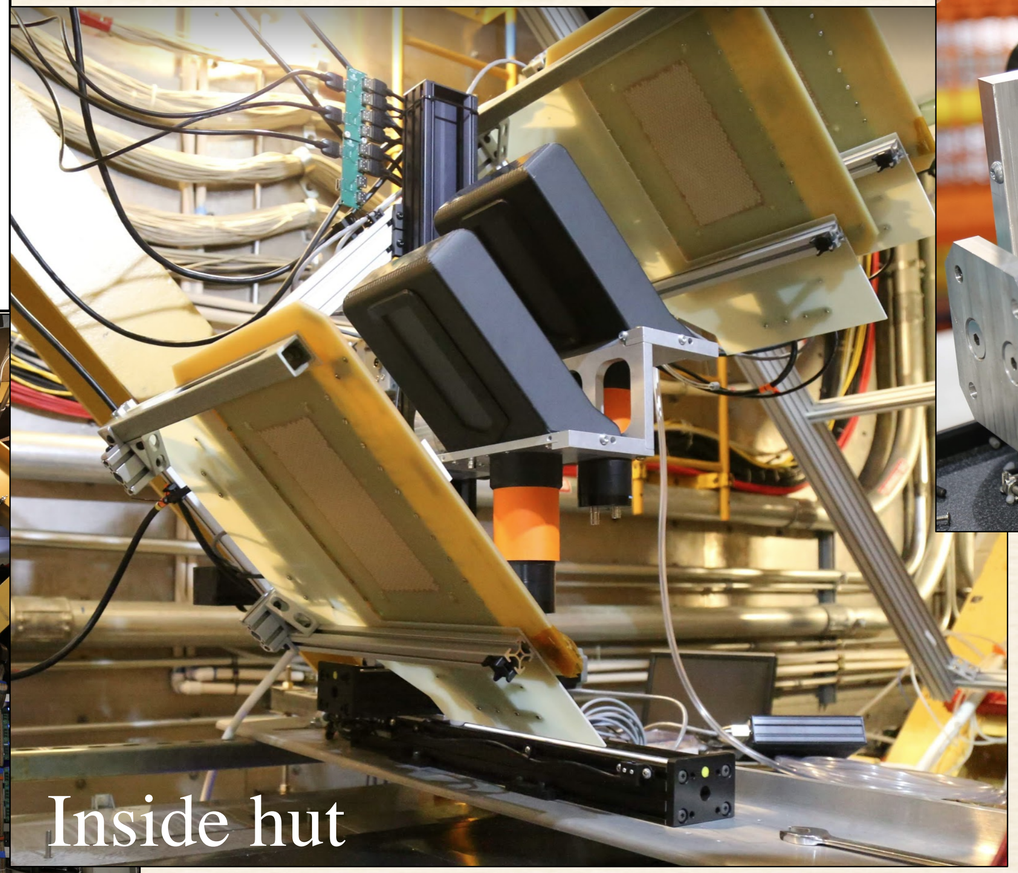


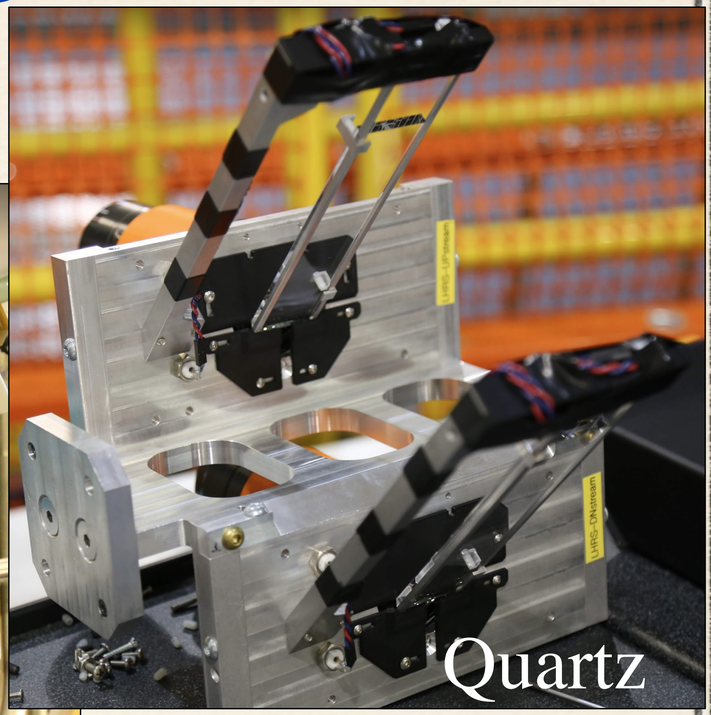
F_W: 0.1295 ± 0.0055

Observation:
CREX result is consistent with a thin neutron skin prediction (e.g. coupled cluster calculations) and is strongly inconsistent with predictions of a very thick skin

Inside the HRS "Counting Hut"

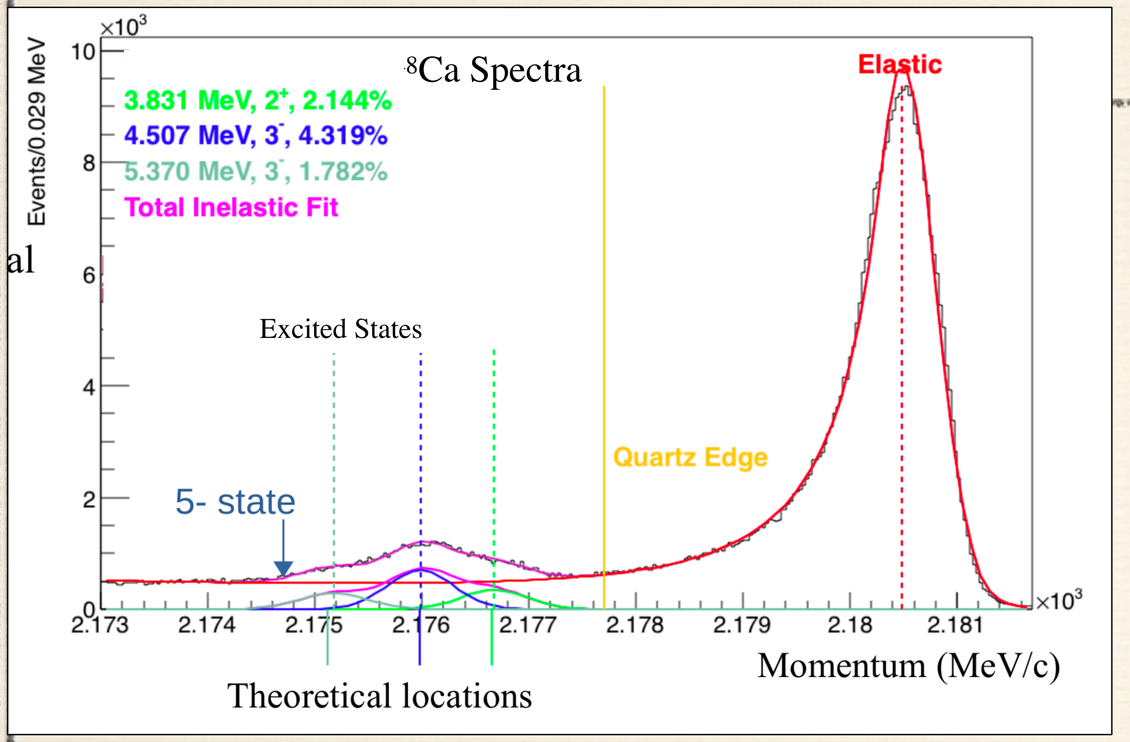






- Integrating detectors (reduce deadtime effects)
- Thick and thin quartz bars (different systematics)

^{48}Ca Target

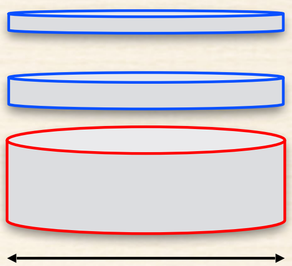


Target 1

Element: Calcium
Symbol: Ca
Isotope: 48
Series: LO
Batch: 140042

- Single puck
- 5mm thick
- 96% ^{48}Ca
- 3.84% ^{40}Ca

Target 2



Element: Calcium
Symbol: Ca
Isotope: 48
Series:
Batch: 900242

*Oak Ridge

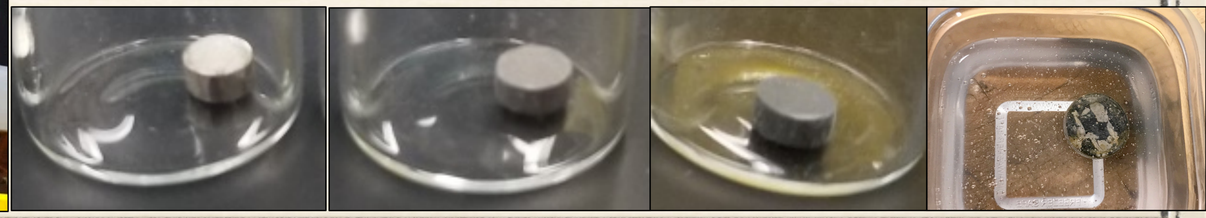
- 1puck+2 foils sandwiched
- ~5.7mm thick total
- ~91.7% ^{48}Ca
- ~7.96% ^{40}Ca

Stored in mineral oil until installed
Protected against oxidation

Delicate Installation

Cooled Copper Target Ladder

sanded | Oxidized 1hr | Oxidized 24hr | mineral oil



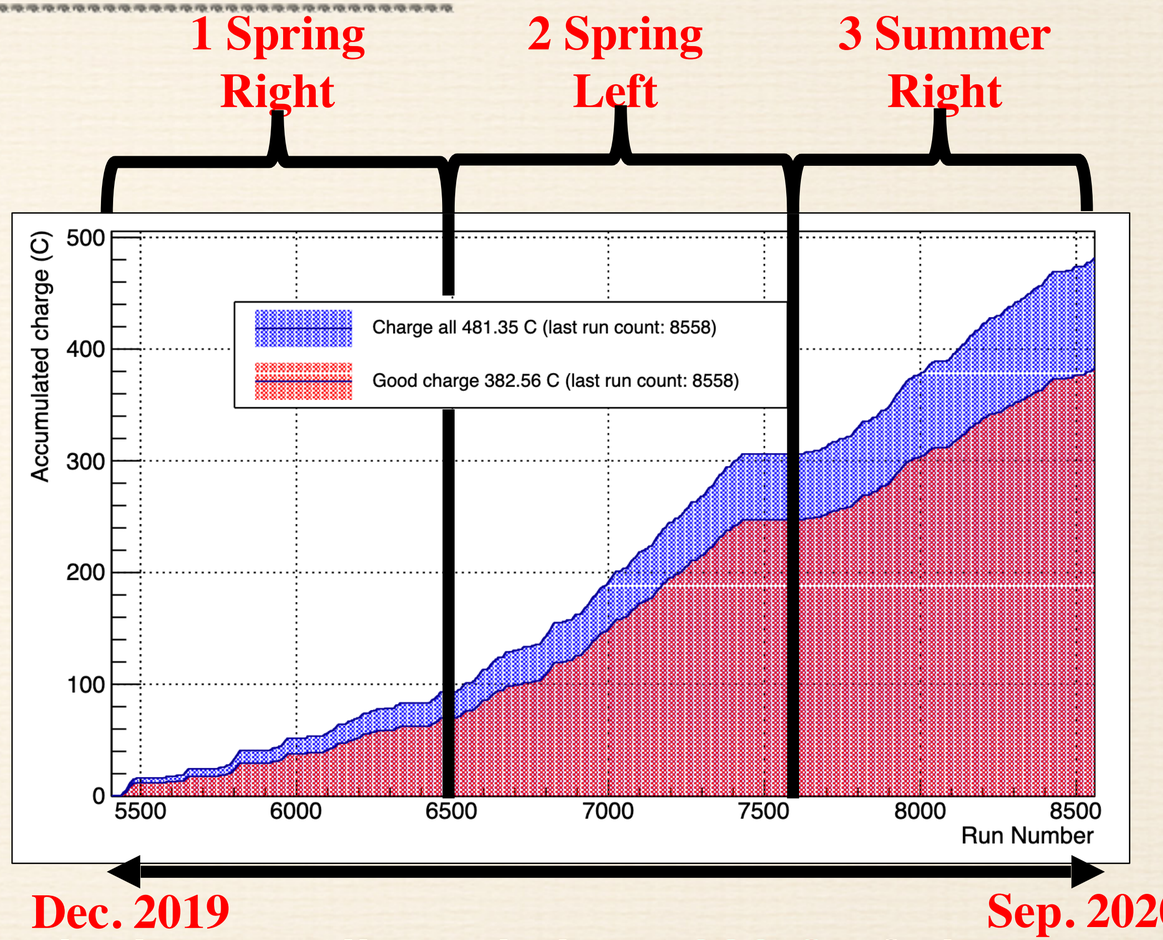
The CREX Physics Runs

13 Ph.D. students, 7 postdocs, a total of about 80 scientists

Data Divided Into 3 Run Periods

- Part 1) Wien* Right Spring
- Part 2) Wien* Left Spring
  …Covid hit….
- Part 3) Wien* Right Summer
- * “Wien” = Spin Manipulator

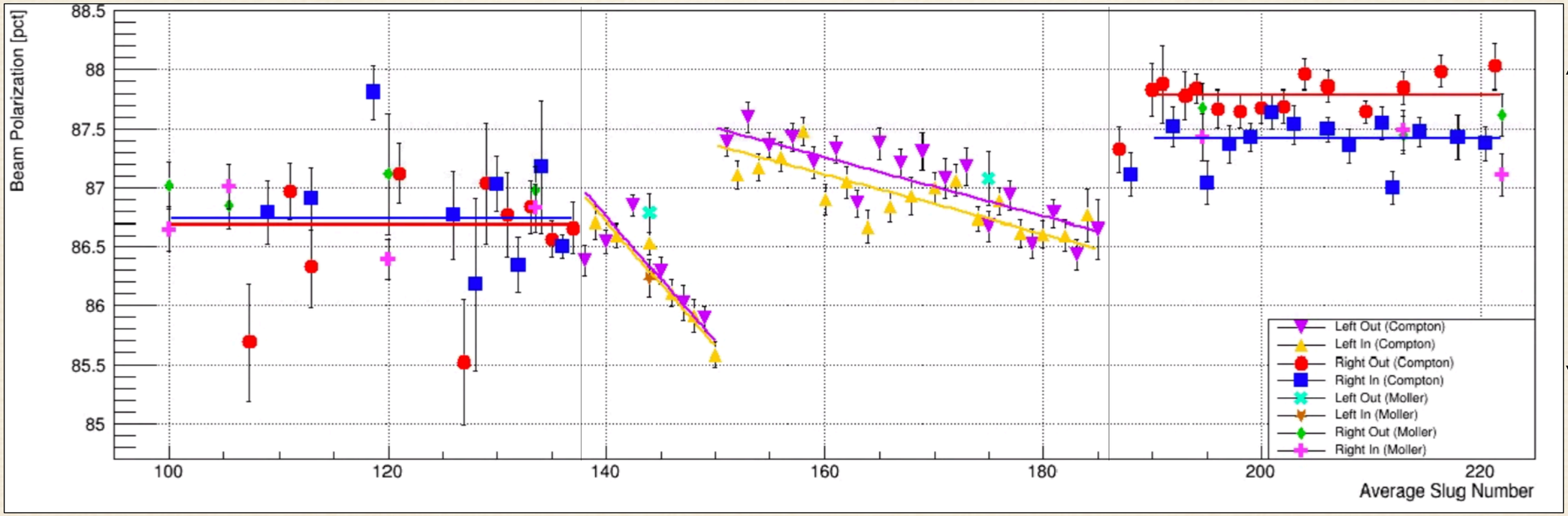
- Very close watch on-line data stream - beam conditions, detector response, etc.
- Frequent contact with MCC operators to maintain running conditions
- “prompt" analysis process flagged more subtle problems
- Daily grooming and review in "WAC" process
- (analysis development leader Paul King)



- **At the end of the experiment after our realtime analysis we collected about 383 C of charge on target which passed online analysis cuts(i.e. not excluded in calibrations or due to poor beam conditions, trip recovery, beam excursions, or beam monitor issues)**

Beam Polarimetry

1 Spring Right (In/Out) | **2 Spring Left (In/Out)** | **3 Summer Right (In/Out)**



Spans ~ +-1.3% relative error

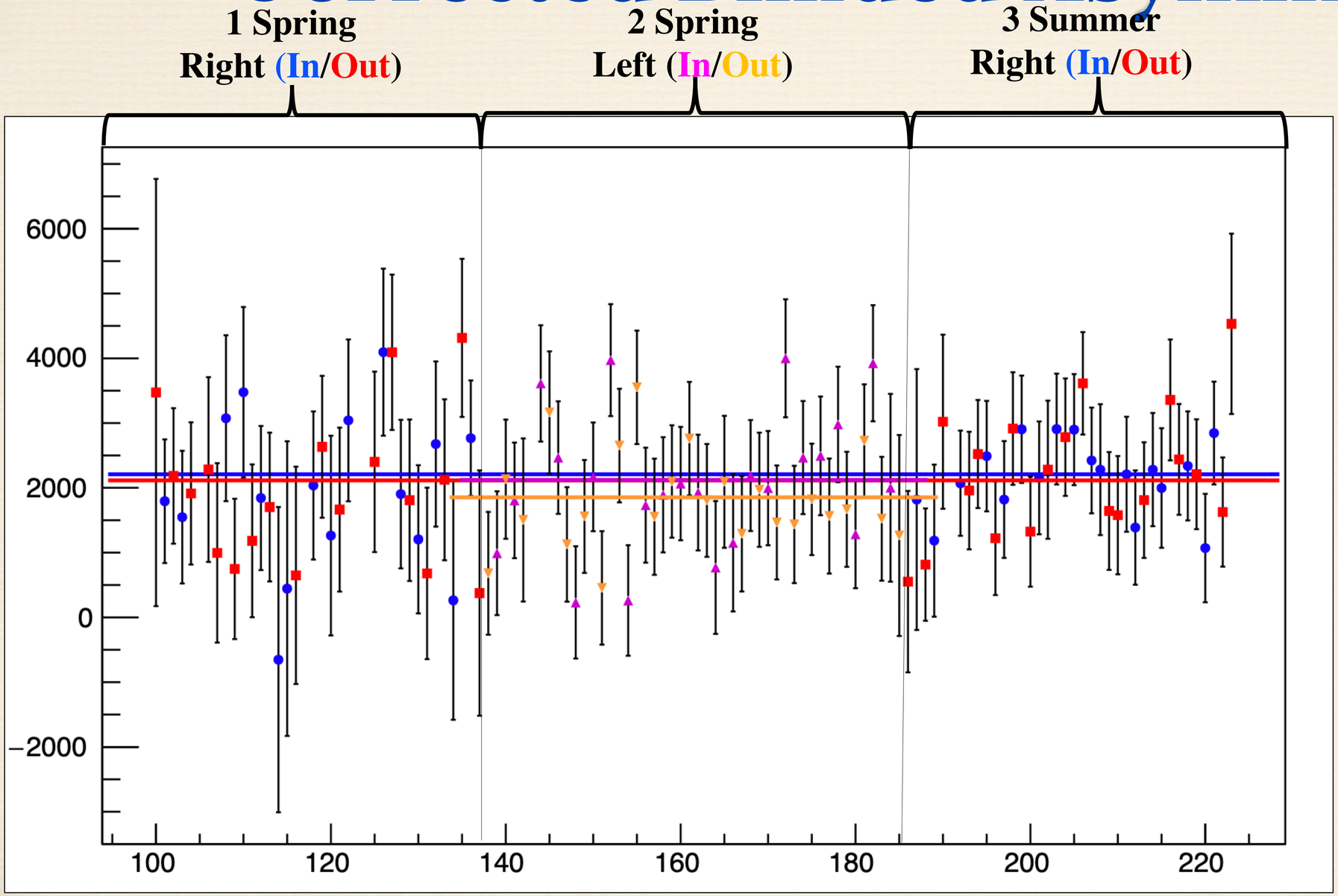
Acknowledgments: A.J. Zec, J. C. Cornejo, M. Dalton, C. Gal, D. Gaskell, C. Palatchi, K. Paschke, A. Premithilake, B. Quinn

Average Compton polarization:
87.10 ± (0.52% dP/P)

CREX Polarimetry Result:
P_e=87.09 +/- (0.44% dP/P)

Average Moller polarization:
87.06 ± (0.85% dP/P)

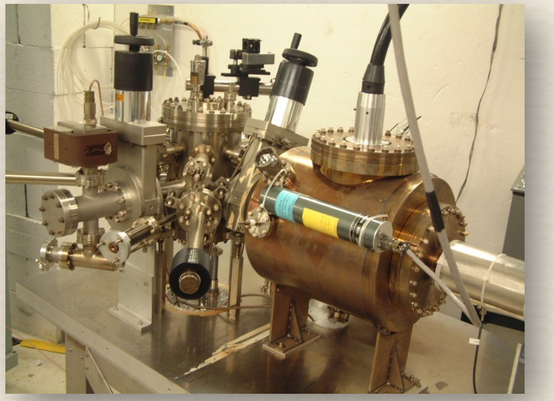
Corrected Blinded Asymmetries



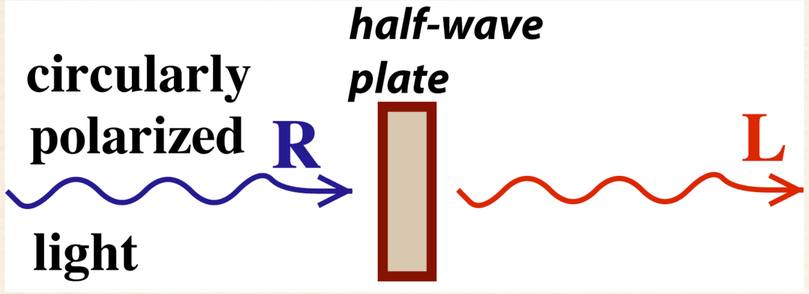
We were looking at the final data set after carefully removing unstable run periods with multiple checks on log books by about the middle of Summer 2021

Statistical Uncertainty: 80 to 90 parts per billion

Stability of Polarized Beam at JLab



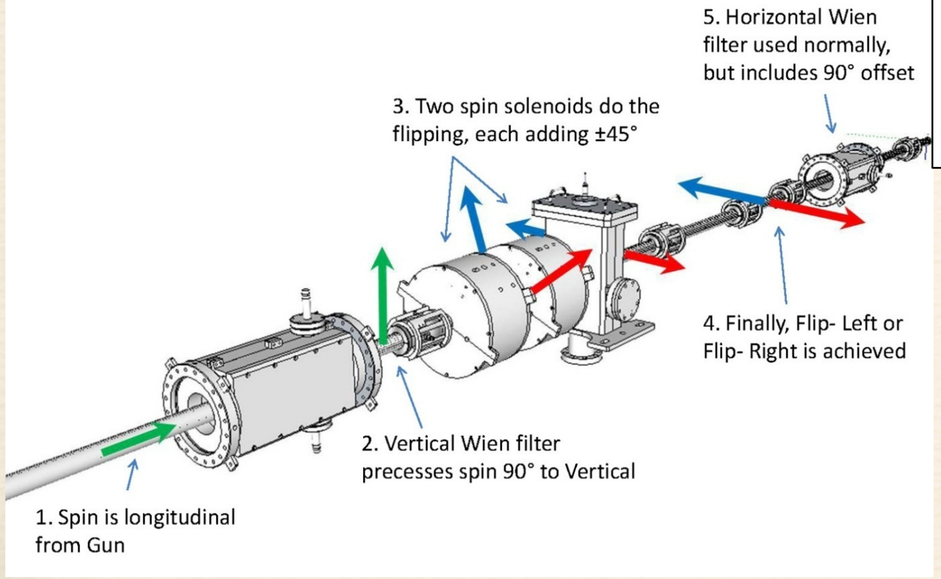
Beam helicity is chosen pseudo-randomly at 30 Hz



$$A_{corr} \sim 2000 \text{ ppb}$$

$$A_{corr} = A_{det} - A_Q + \alpha \Delta_E + \Sigma \beta_i \Delta x_i$$

Injector Two Wien Flipper – QWeak setup (Nov-Dec, 2011) – J. Grames



Wien	Weight	X (nm)	Y (nm)	θ X (nrad)	θ Y (nrad)	E dpp
R 1	18.0%	1.6 ± 3.7	-2.4 ± 2.0	-0.26 ± 0.17	-0.11 ± 0.12	$-2.0 \pm 2.0e^{-9}$
Left	45.2%	-4.1 ± 1.6	0.3 ± 1.1	0.08 ± 0.04	-0.024 ± 0.10	$0.32 \pm 1.5e^{-9}$
R 2	36.9%	-2.8 ± 4.1	-0.2 ± 1.7	-0.06 ± 0.09	-0.28 ± 0.17	$0.84 \pm 1.9e^{-9}$
	Avg	-2.6 ± 1.8	-0.4 ± 0.9	-0.03 ± 0.05	-0.13 ± 0.08	$0.09 \pm 1.0e^{-9}$

- Three independent techniques agree across 3-parts of data set
- For beam correction, decided to use 12 BPM Lagrange Multiplier 3-part eigenvector correction, 5% slope uncertainty
- Left/right symmetric detectors, so correction dominated by E

Total beam corrections:

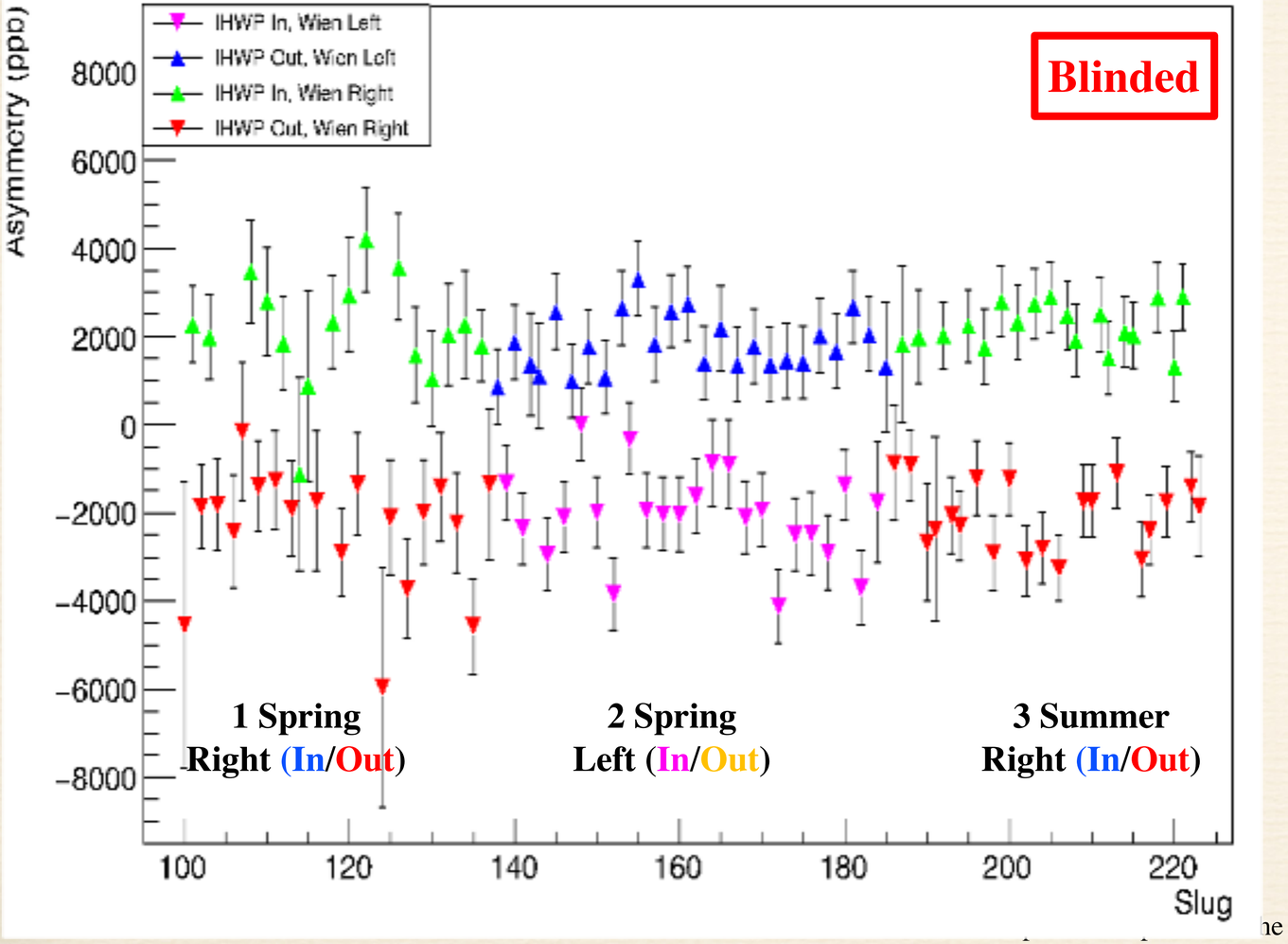
$A_{beam} = (53.5 \pm 5.4)$ ppb

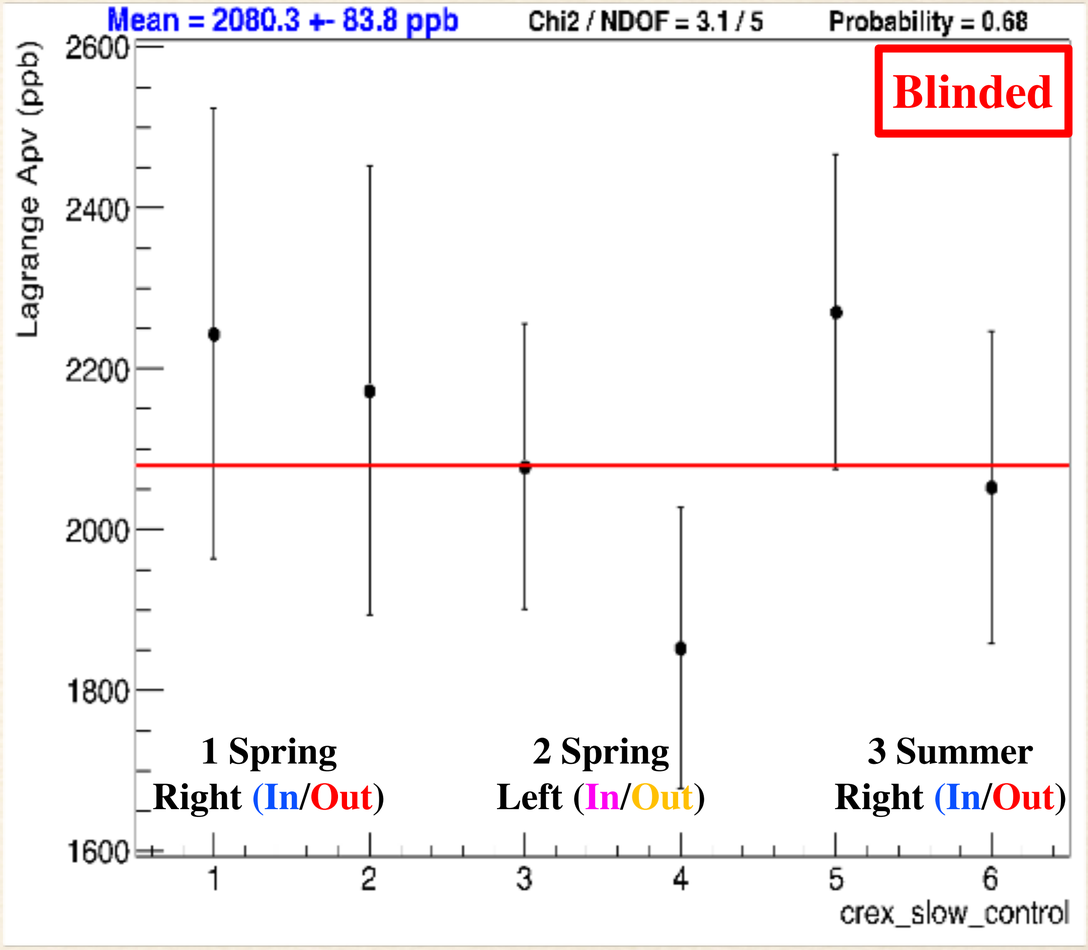
Half Wave Plate: IN/OUT Wien(Spin Manipulator): Left/Right

Demonstration of Systematic Control

Sign-uncorrected, Each point: 8h time-scale

Sign-corrected, Each point: ~1week time-scale





he right (zoomed in y-scale)

- Measuring continuously flipping sign by 2 methods (IHWP, Wien)
- The corrected asymmetry removed effects from beam asymmetries and noise

Grand Corrected Asymmetry

Final result averaging over all IHWP and 3 Part Wien flip configurations

C. Clarke

Wien	Weight	A_{raw} (ppb)	A_{det} (ppb)	A_Q (ppb)
Right 1	17.9%	2460.15 ± 391.95	2207.90 ± 197.69	-94.1 ± 69.6
Left	45.2%	1871.06 ± 278.39	1963.65 ± 124.64	148.1 ± 40.1
Right 2	36.9%	2006.57 ± 335.29	2160.94 ± 137.95	-376.3 ± 38.7
Weighted Average		2026.81 ± 189.88	2080.26 ± 83.77	-88.8 ± 26.2

1 Right (In/Out)
2 Left (In/Out)
3 Right (In/Out)

Blinded Corrected Asymmetry A_{corr}:
2080.3 ± 83.8ppb

Careful and painstaking analyses by multiple students on each of the small corrections to extract the physics asymmetry

$$A_{corr} = A_{det} - A_{beam} - A_{trans} - A_{nonlin} - A_{blind}$$

$$A_{phys} = R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L(1 - \sum_i f_i)}$$

Unblinding!! Week before Fall DNP Meeting

Blinded A_{PV}:

2334.8 ± 112.4ppb (4.8%)

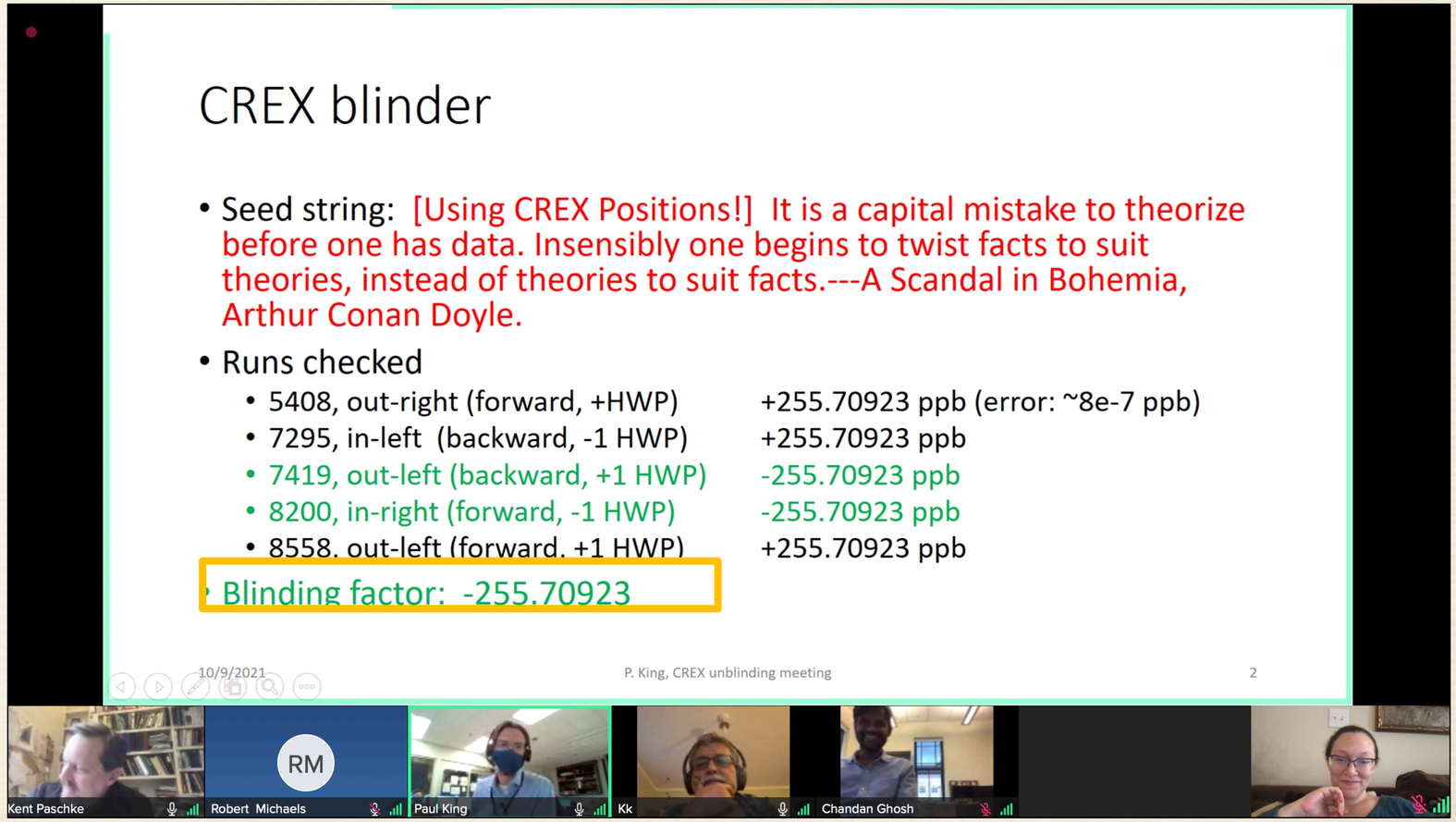
"Blinding box": an additive term on every quartet asymmetry, randomly selected (flat) at the start of the run, from ± 900 ppb

$$A_{phys} = R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L(1 - \sum_i f_i)}$$

$$A_{corr} = A_{det} - A_{beam} - A_{trans} - A_{nonlin} - A_{blind}$$

Unblinded A_{PV}:

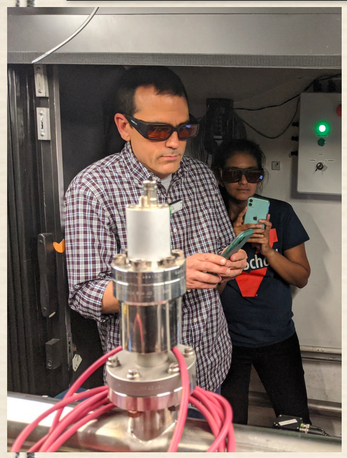
2658.6 ± 113.2ppb (4.3%)



Our Crew

PhD Student

Students: Devi Adhikari, Devaki Bhatta Pathak, Quinn Campagna, Yufan Chen, Cameron Clarke, Catherine Feldman, Iris Halilovic, Siyu Jian, Eric King, Carrington Metts, Marisa Petrusky, Amali Premathilake, Victoria Owen, Robert Radloff, Sakib Rahman, Ryan Richards, Ezekiel Wertz, Tao Ye, Allison Zec, Weibin Zhang



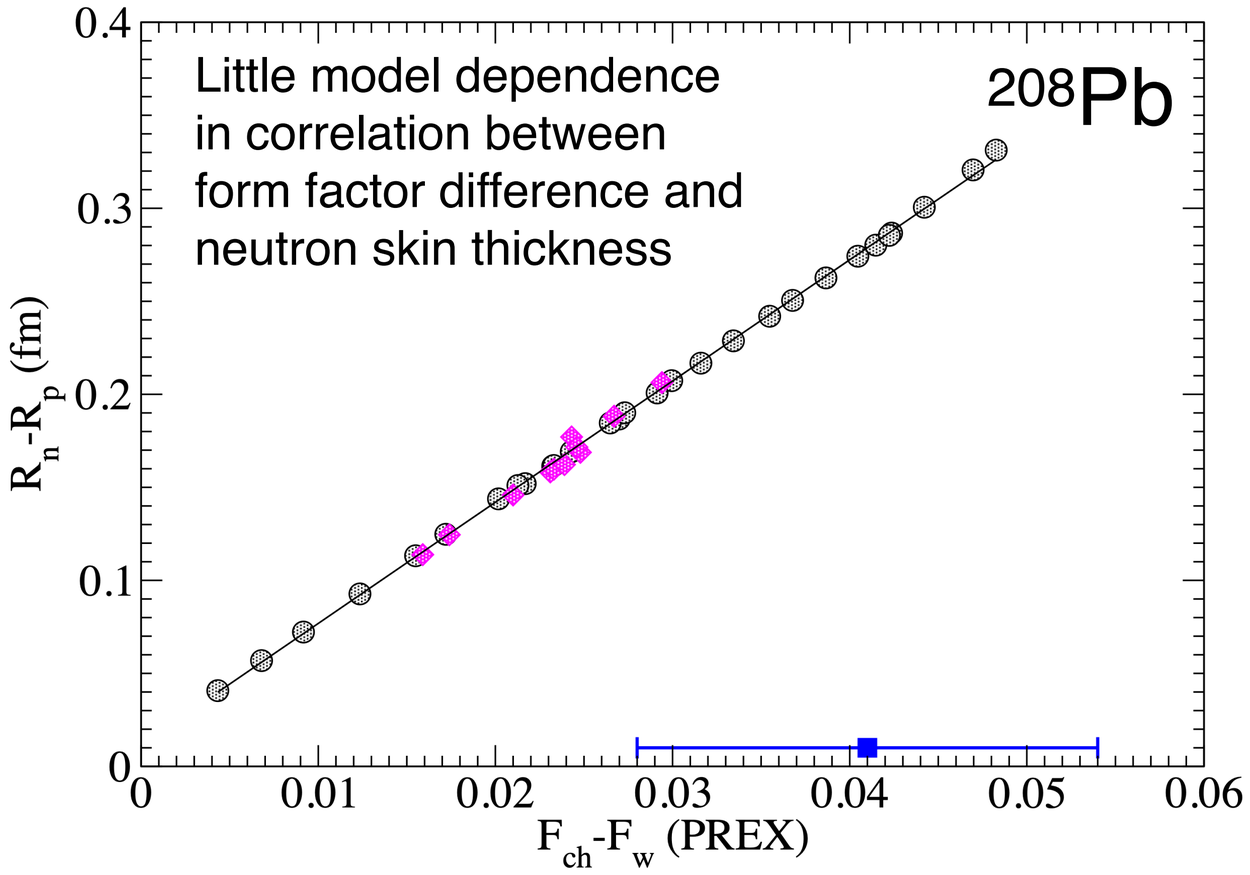
Post-docs and Run Coordinators: Rakitha Beminiwattha, Juan Carlos Cornejo, Mark-Macrae Dalton, Ciprian Gal, Chandan Ghosh, Donald Jones, Tyler Kutz, Hanjie Liu, Juliette Mammei, Dustin McNulty, Caryn Palatchi, Sanghwa Park, Ye Tian, Jinlong Zhang

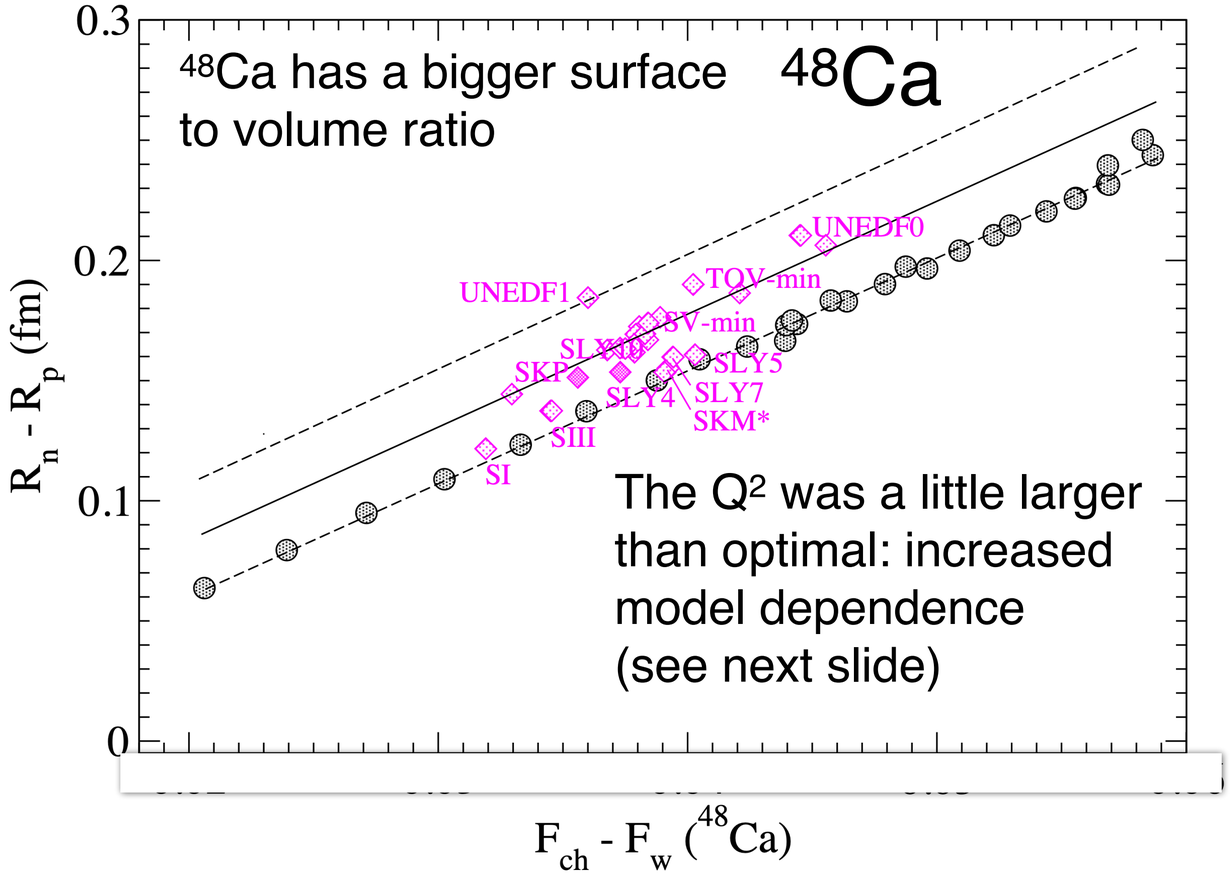
Spokespeople: D. McNulty, J. Mammei, P. Souder, S. Covrig Dusa, R. Michaels, K. Paschke, S. Riordan

Thanks to the Hall A techs, Machine Control, Yves Roblin, Jay Benesch and other Jefferson Lab staff

Special thanks to: Charles Horowitz and Jorge Piekarewicz for support and insightful conversations
Especially Chuck and grad student Brendan Reed who have worked to help us interpret our results

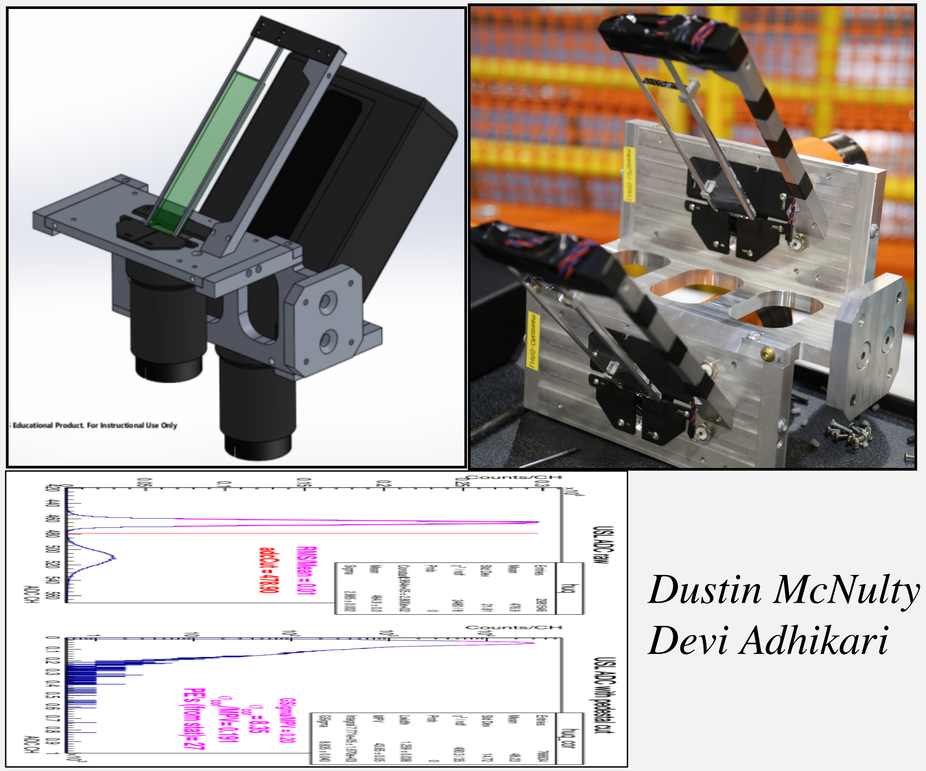
Neutron Skin Extraction: Model Dependence





^{48}Ca: Projected experimental skin thickness uncertainty ~ 0.026 fm
Projected skin thickness model uncertainty ~ 0.023 fm

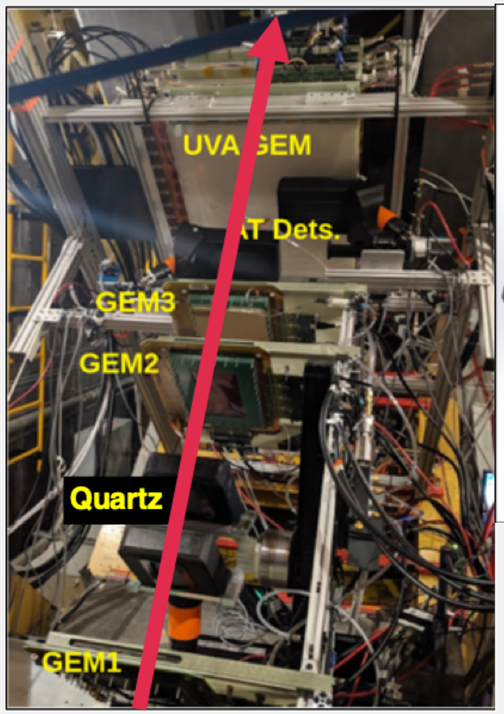
Integrating Detectors

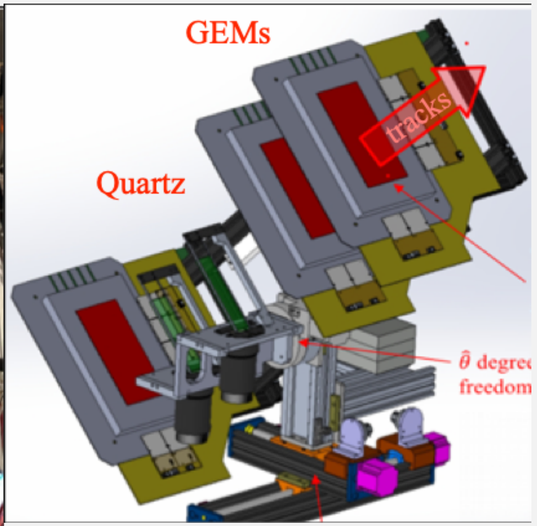


Dustin McNulty
Devi Adhikari

- The challenge: all electrons need to count the same - high photon statistics but low shower fluctuations
- Fused silica Cerenkov radiator, 5mm thick, 3.5x16 cm^2 area, mated to a single PMT
- ~56 MHz signal rate in a 3x3 cm^2 area at the end of the detector
- Non-linearity of detector response was tested on the bench and with beam during the experiment

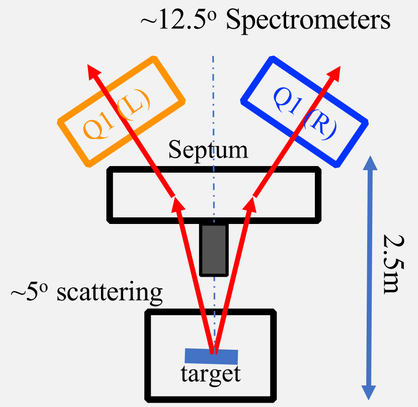
Counting Detectors

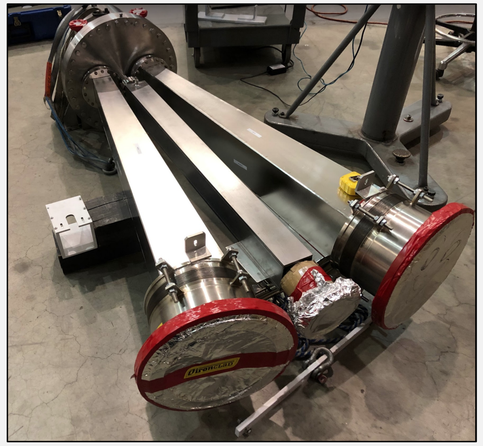


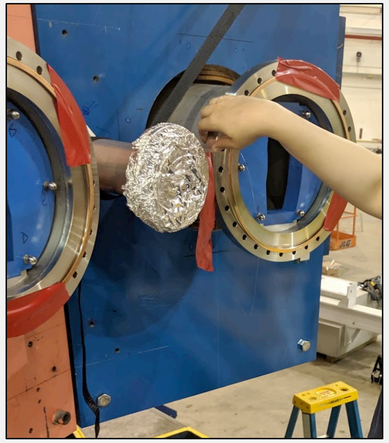


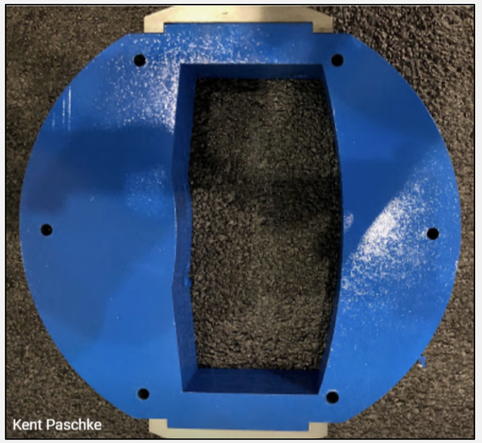
- The HRS Vertical Drift Chambers (VDCs) below the quartz detectors
- GEMs that we installed upstream and downstream of our quartz detectors (*N. Liyanage*)
- Used to align the elastic peak on the quartz and to measure accepted kinematics
- Used at very low beam currents (<1uA) “counting experimental mode”

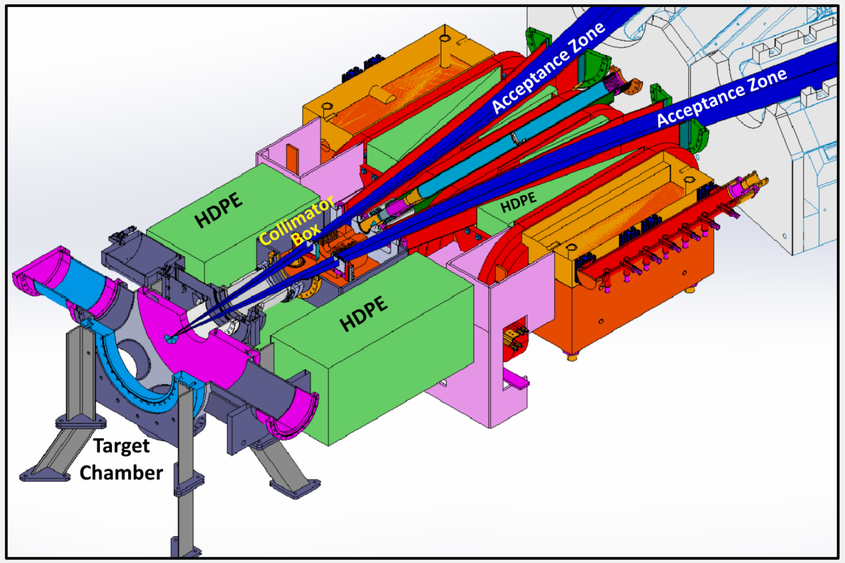
Hardware Downstream of Target









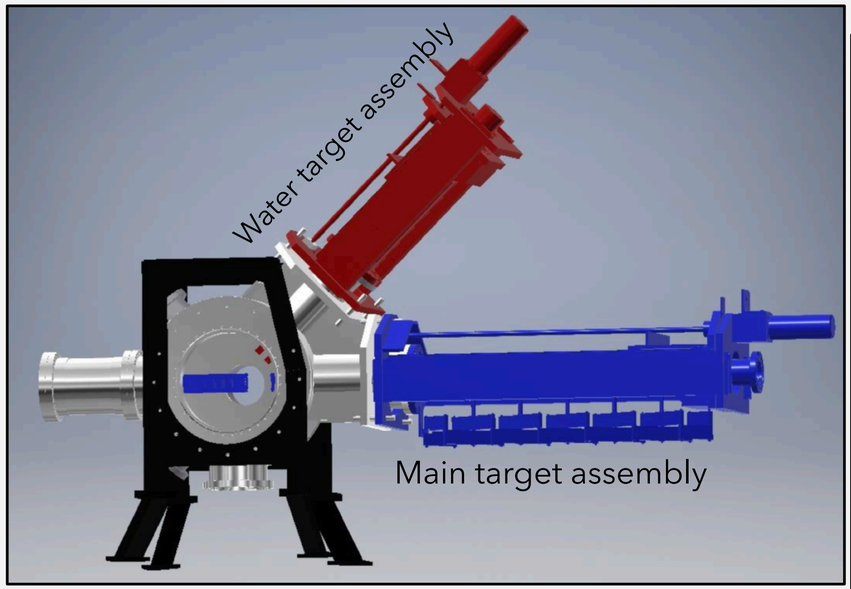


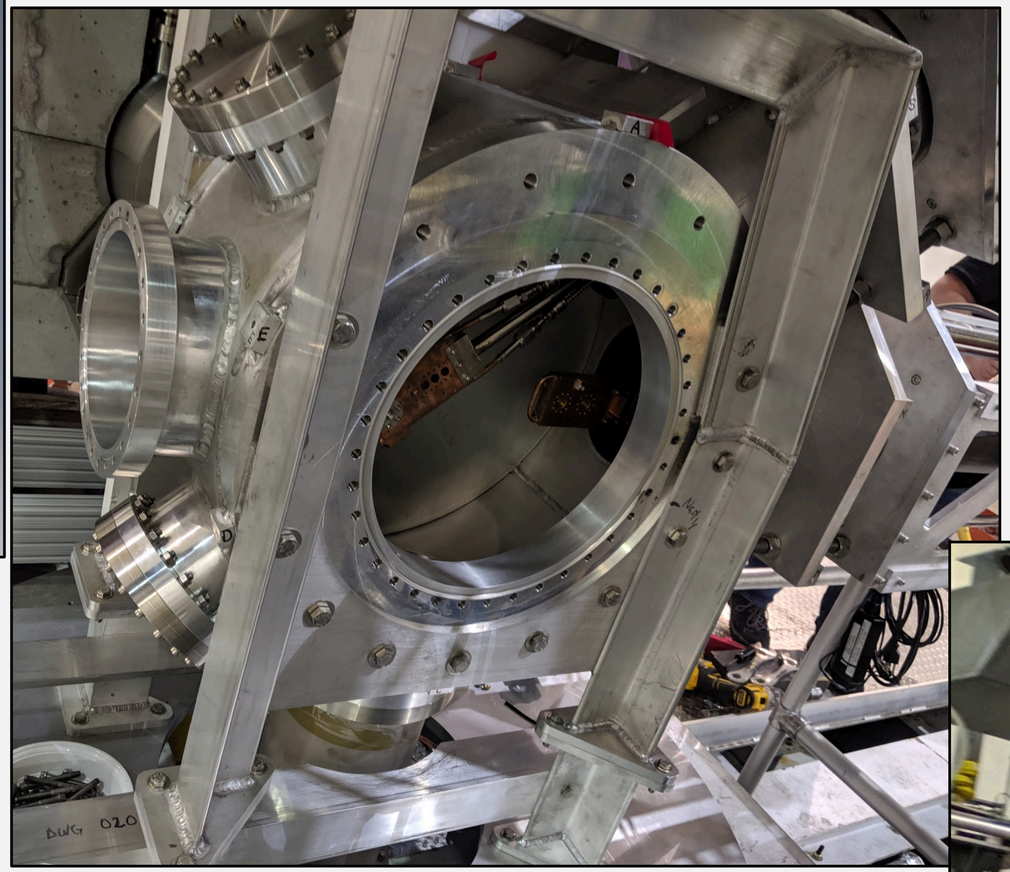
- Septum magnet needed to reach the low angles
- Vacuum vessel to transport scattered electrons in vacuum to detector hut
- Precision collimators to define the acceptance
- The experimental hall provides unique challenges for a high luminosity, high Z, low energy experiment
- Large angle scattered electrons need to be stopped close to the target and that region needs to be heavily shielded
- Electronics inside the hall need to be protected from both the electromagnetic and neutron radiation damage that will stop it from functioning properly

- Tight acceptance, space requirements, collimator power, shielding made for tricky installation

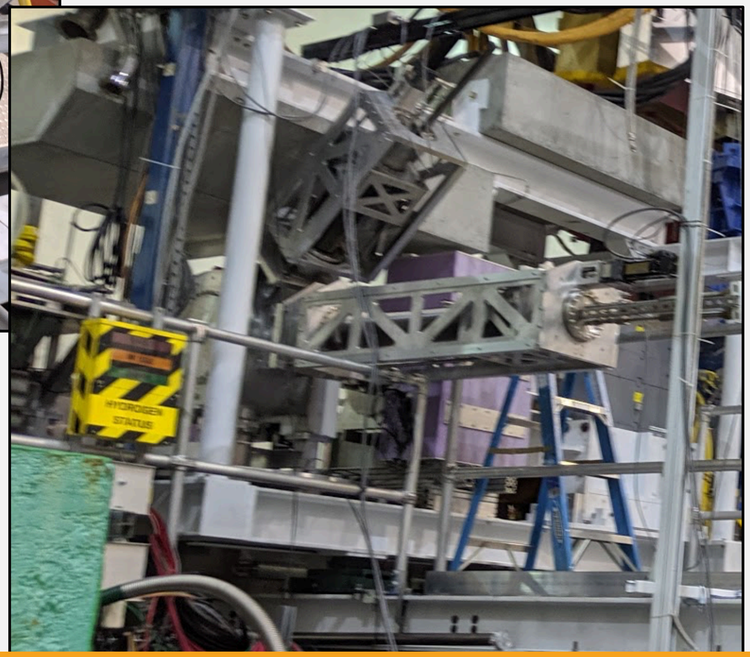
(acknowledgements to Hall A designers and the Hall A technical staff)

Target Chamber Design





Watercell target

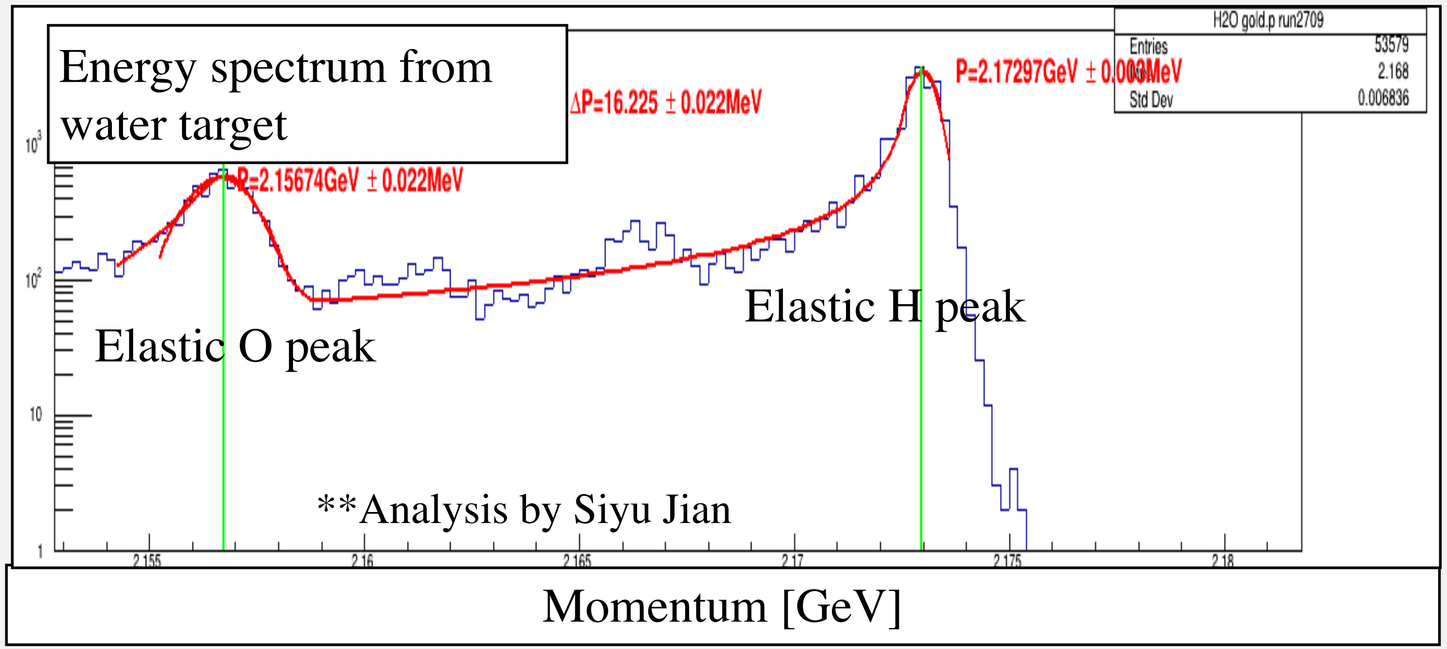


- Long horizontal target ladder
- 45^0 optics ladder

An important addition is the water cell absolute angle calibration

Challenging system, successfully implemented by the target group (esp. Dave Meekins)

Absolute Angle Calibration - Watercell



- Critical to measure the absolute scattering angle to high precision
- Nuclear recoil method
- ^{1}H and ^{16}O in one target (same E-loss) provides straightforward measurement of angle, insensitive to other calibrations

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W F_W(Q^2)}{Z F_{ch}(Q^2)}$$

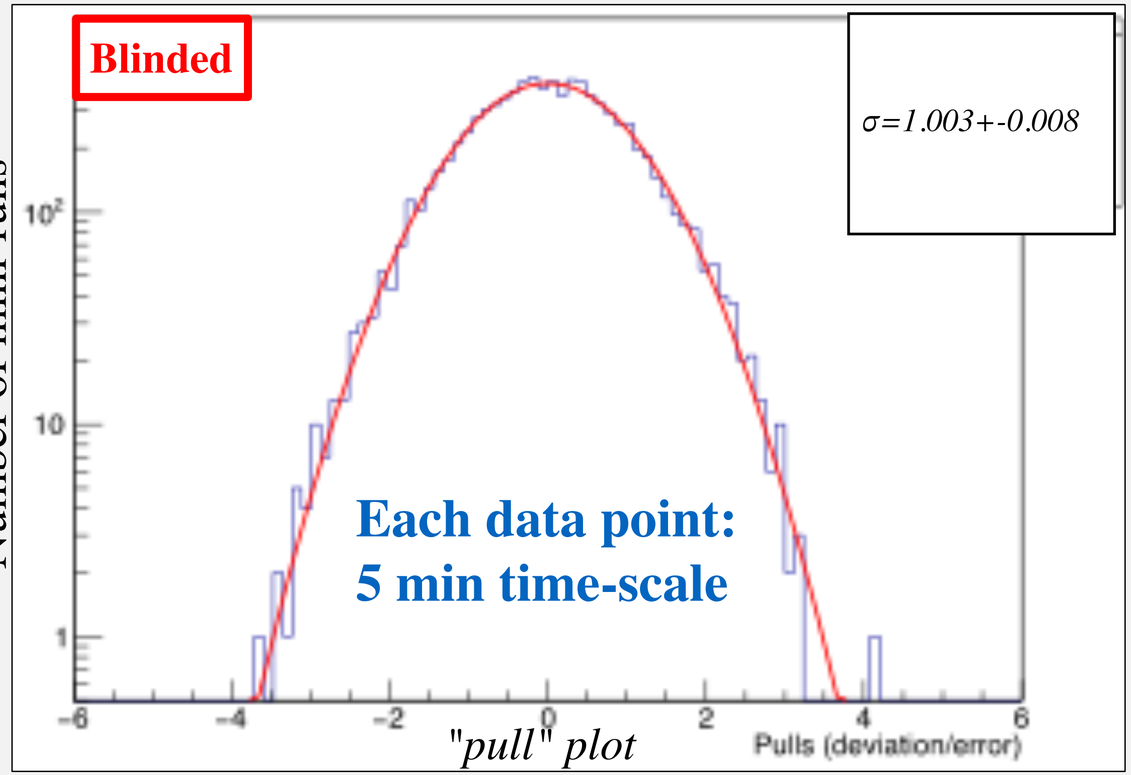
recoil momentum difference ⟶ scattering angle

$$\Delta E' = E'_O - E'_H = E\left(\frac{1}{1+\frac{2E\sin^2(\frac{\theta}{2})}{M_O}} - \frac{1}{1+\frac{2E\sin^2(\frac{\theta}{2})}{M_H}}\right)$$

Determined central angle with pointing with precision of
$\delta\theta = 0.02^{0}$ (0.45%)

Data Overview: Corrected Asymmetry

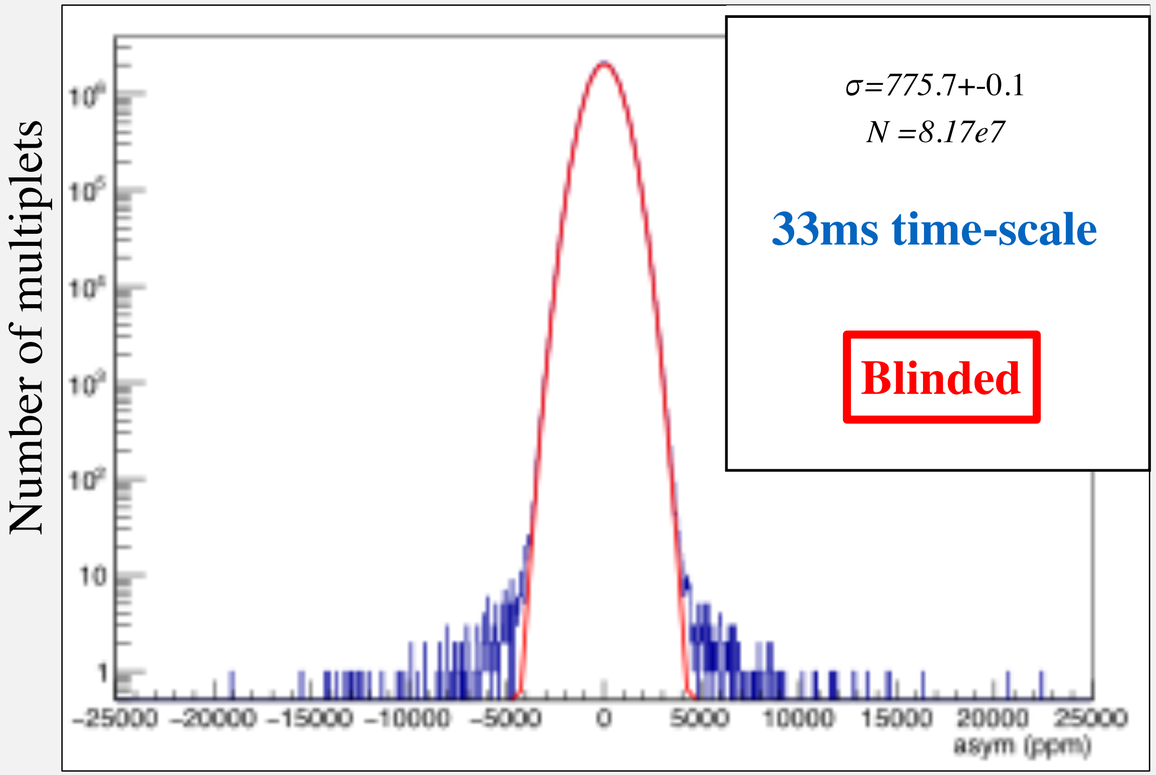
Miniruns



Normalized difference from average

- Check that we know how to calculate statistical errors
- 1σ pull plot width confirms we do

Individual quartets (>135μA, 120Hz)



Multiplet Asymmetry(ppm)

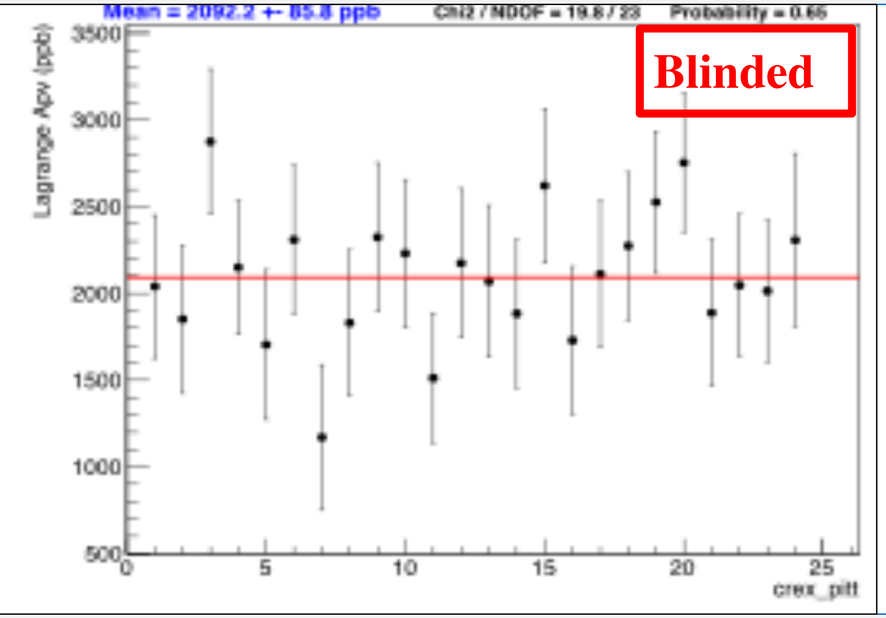
- Check at time scale of helicity flips, we don't have bizarre tails
- Extremely consistent widths, negligible tails, gaussian up to 5 OOM

Data Overview: Corrected & Null Asymmetry

Each data point: 2 days time-scale

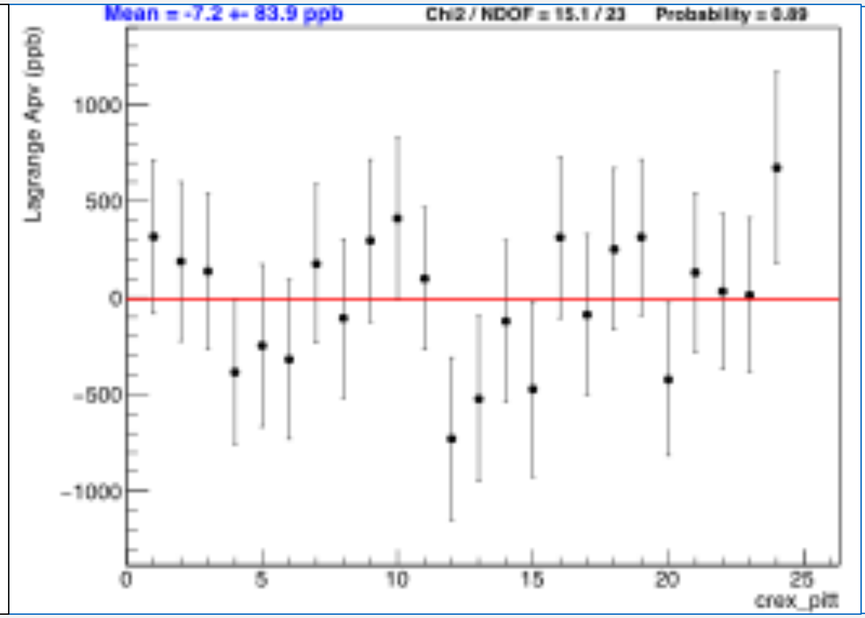
Corrected Asymmetry

Averaged over IHWP states

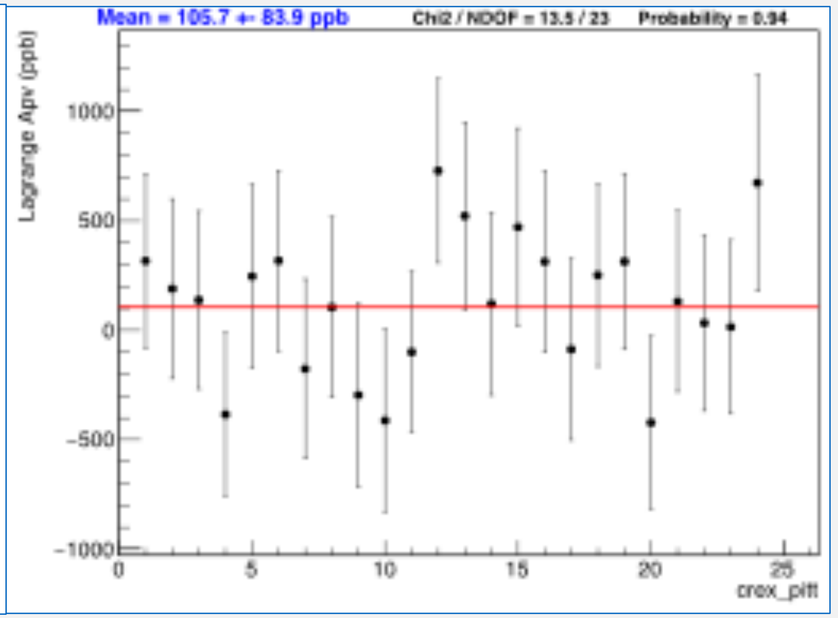


Null Asymmetry

Null Pitt (no Wien flip)



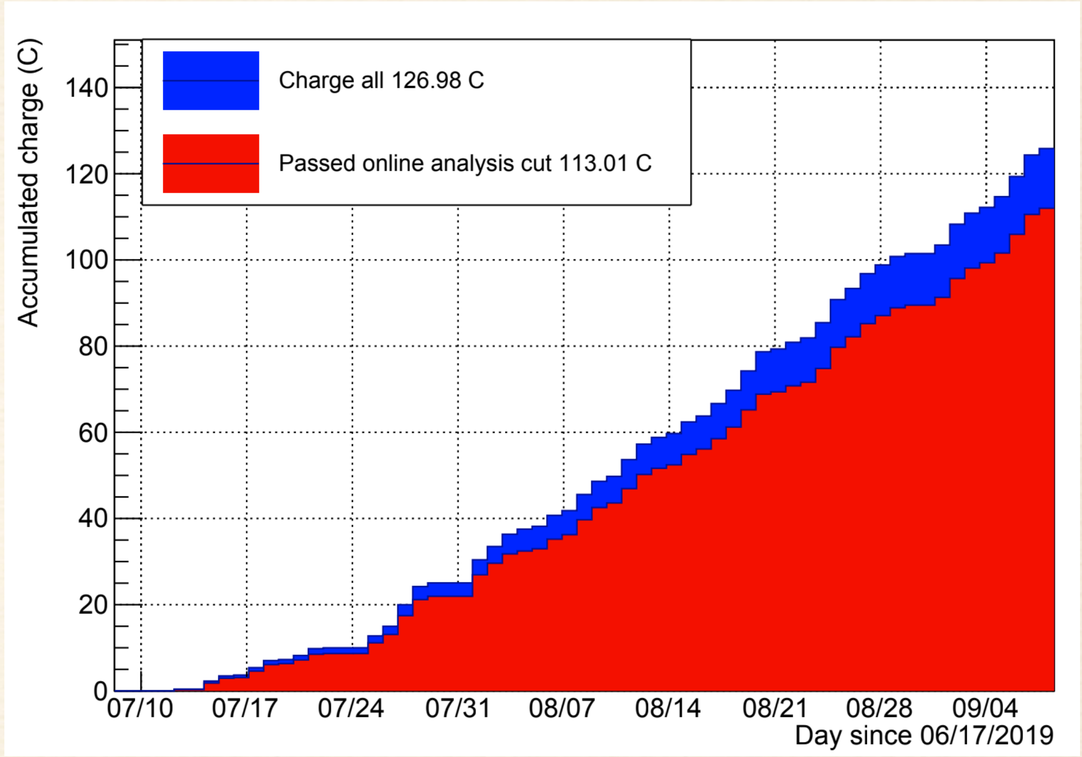
Null Pitt (Wien flip)



$$A_{null} = \frac{A_{IN} - A_{OUT}}{2}$$

PREX-II Run: Summer 2019

- 13 Ph.D. students, 7 postdocs, a total of about 80 scientists
- Very close watch on-line data stream - beam conditions, detector response, etc.
- Frequent contact with machine operators to maintain running conditions
- “prompt" analysis flagged subtle problems: review of beam performance by PhD students in weekly shifts



- At the end of the experiment after our realtime analysis we collected about 113 C of charge on target with only about 14 C being excluded in calibrations or due to poor beam conditions (mostly, trip recovery, beam excursions, or beam monitor issues)

MOLLER Context Summary

best contact interaction reach for leptons at low OR high energy: similar to LHC reach with semi-leptonic amplitudes

To do better for a 4-lepton contact interaction would require:
Giga-Z factory, linear collider, neutrino factory or muon collider

$$\delta(\sin^2\theta_W) = \pm 0.00024\ (stat.) \pm 0.00013\ (syst.) \quad \Rightarrow \quad \sim 0.1\%$$

Best projected uncertainty among fixed target experiments over next 10 years

- **If LHC sees ANY anomaly in next run (results ~2023?)**
  - The unique discovery space probed by MOLLER will become a pressing need, like other sensitive probes (e.g. g-2 anomaly)
- **Discovery scenarios beyond LHC signatures**
  - Hidden weak scale scenarios
  - Lepton Number Violating Amplitudes
  - Light Dark Matter Mediators
  - ...

Projected Uncertainty Tables

$$\sigma_{A_{cxpt}} = \frac{\sigma_{pair}}{\sqrt{N_{pair}}}$$

Contributions to σ_{pair} - "Pair width"

Parameter	Random Noise (65 μA)
Statistical width (0.5 ms)	~ **82 ppm**
Target Density Fluctuation	30 ppm
Beam Intensity Resolution	10 ppm
Beam Position Noise	7 ppm
Detector Resolution (25%)	21 ppm (3.1%)
Electronics noise	10 ppm
Measured Width (σ_{pair})	**91 ppm**

$$A_{PV} = \frac{\frac{A_{cxpt}}{P_b} - f_{bkgd}A_{bkgd}}{1 - f_{bkgd}}$$

Uncertainty budget for A_{PV}

Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Norm. of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \rightarrow e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \rightarrow e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \rightarrow (\pi, \mu, K) + X$	0.3
Transverse polarization	0.2
Neutral background (soft photons, neutrons)	0.1
Linearity	0.1
Total systematic	**1.1**

All systematics required at sub-1% level

$$\sigma_{A_{cxpt}} = 0.54\,\text{ppb} \quad A_{cxpt} \sim 26\,\text{ppb} \quad \frac{\sigma_{A_{cxpt}}}{A_{cxpt}} = 2.1\%$$

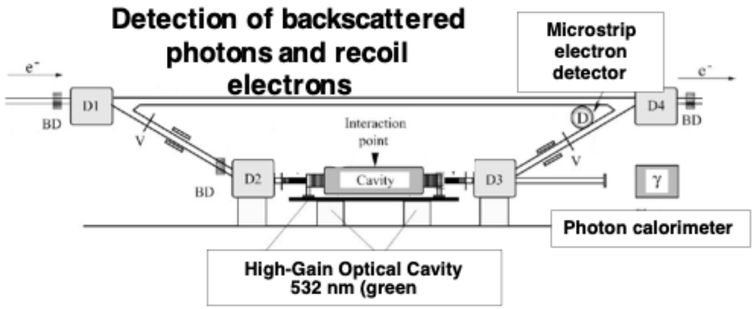
Experimental design driven by these goals:

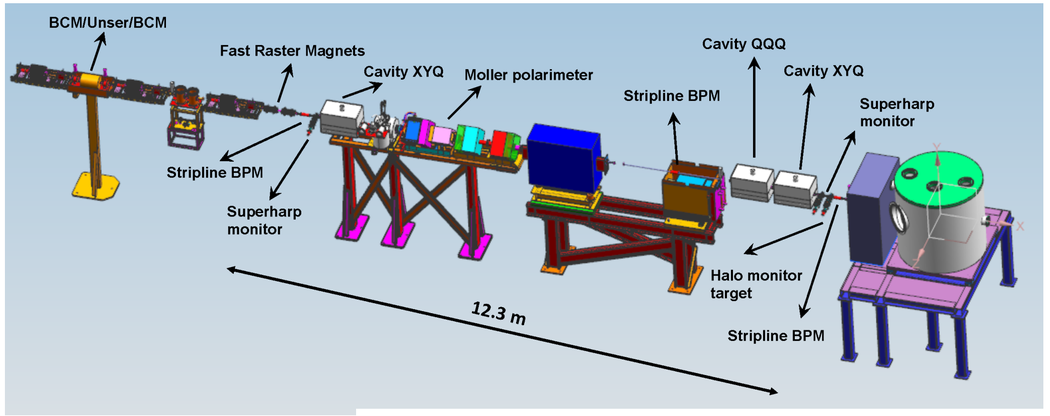
Statistical error: Measure A_{expt} with precision ~ 2%

$$\text{Combined } \frac{\delta A_{PV}}{A_{PV}} = 2.4\%$$

Systematic error: Measure and/or minimize all systematic error sources so their individual contributions are < 1%, resulting in statistics limited experiment

Beamline, Target and Polarimetry



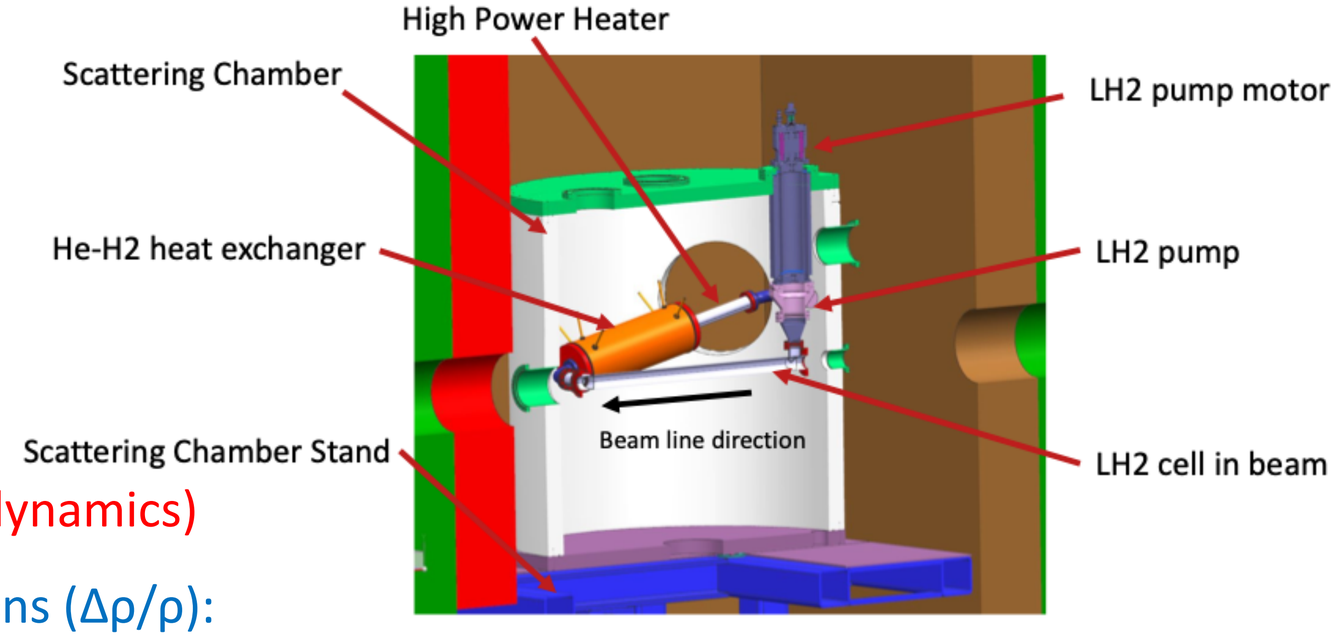


Beamline and Beam Monitoring

- Redundant position, angle, intensity monitoring
- Intensity, position monitor resolution requirements

Electron Beam Polarimetry

- Two independent measurements
- Compton: continuous monitor
- Møller: invasive at low beam current



Liquid Hydrogen Target

- up to 70 μA on 125 cm LH_2 target - 3.7 kW
- Q_{weak} experience: use of CFD (computational fluid dynamics)

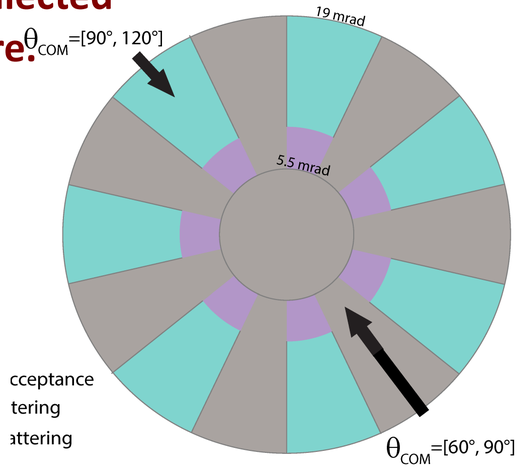
Main requirement: minimize target density fluctuations ($\Delta\rho/\rho$):

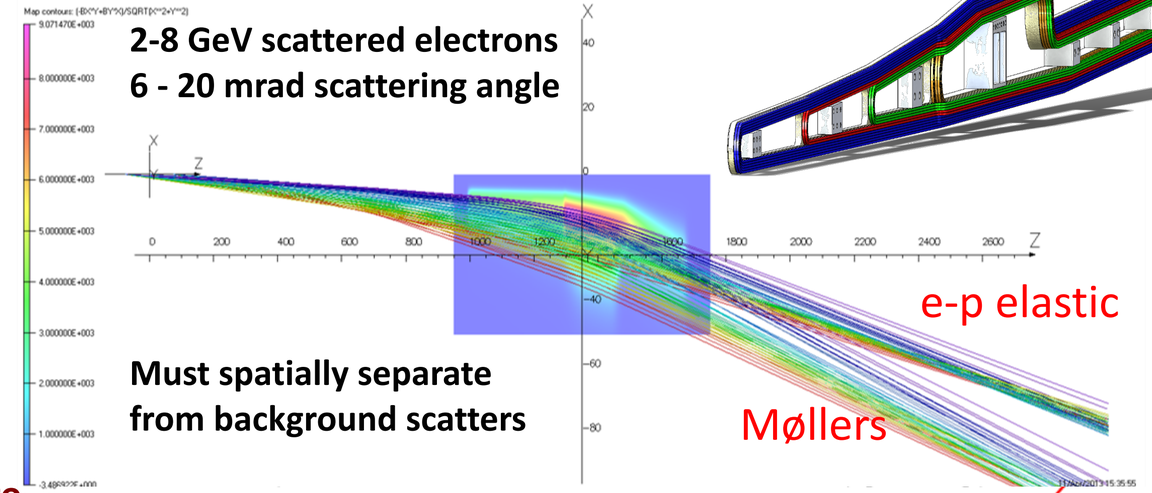
$\Gamma_{target} < 30$ ppm for 70 μA, 5x5 mm^2 raster, 1.92 kHz flip

Spectrometer and Collimation

- Accept all Møller scattered electrons in range Θ_{CM} = 50^o – 130^o
- **Exploit identical particle nature for 100% azimuthal acceptance**; needs odd number of coils

…are collected over here.





The rays that are blocked here…

Collimation system requirements:

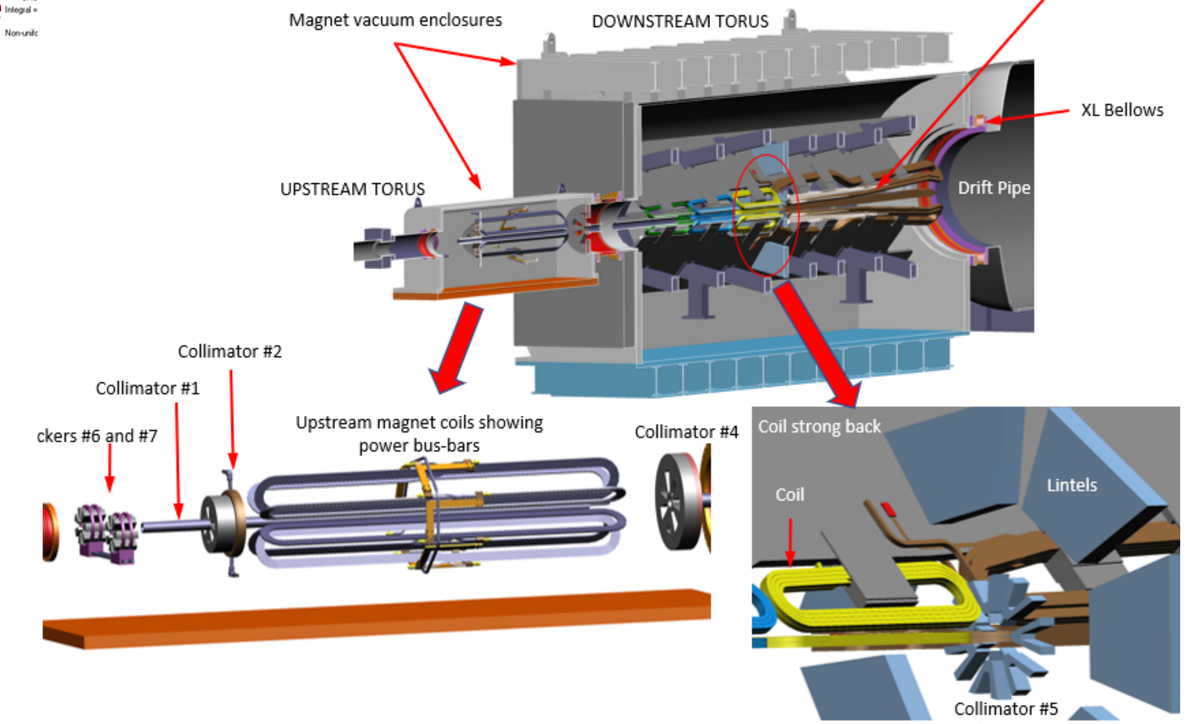
- define Møller electron acceptance
- block detector line-of-sight to target and localize backgrounds
- shield the toroid coils

Designed to achieve “two-bounce” criteria for low energy neutral backgrounds

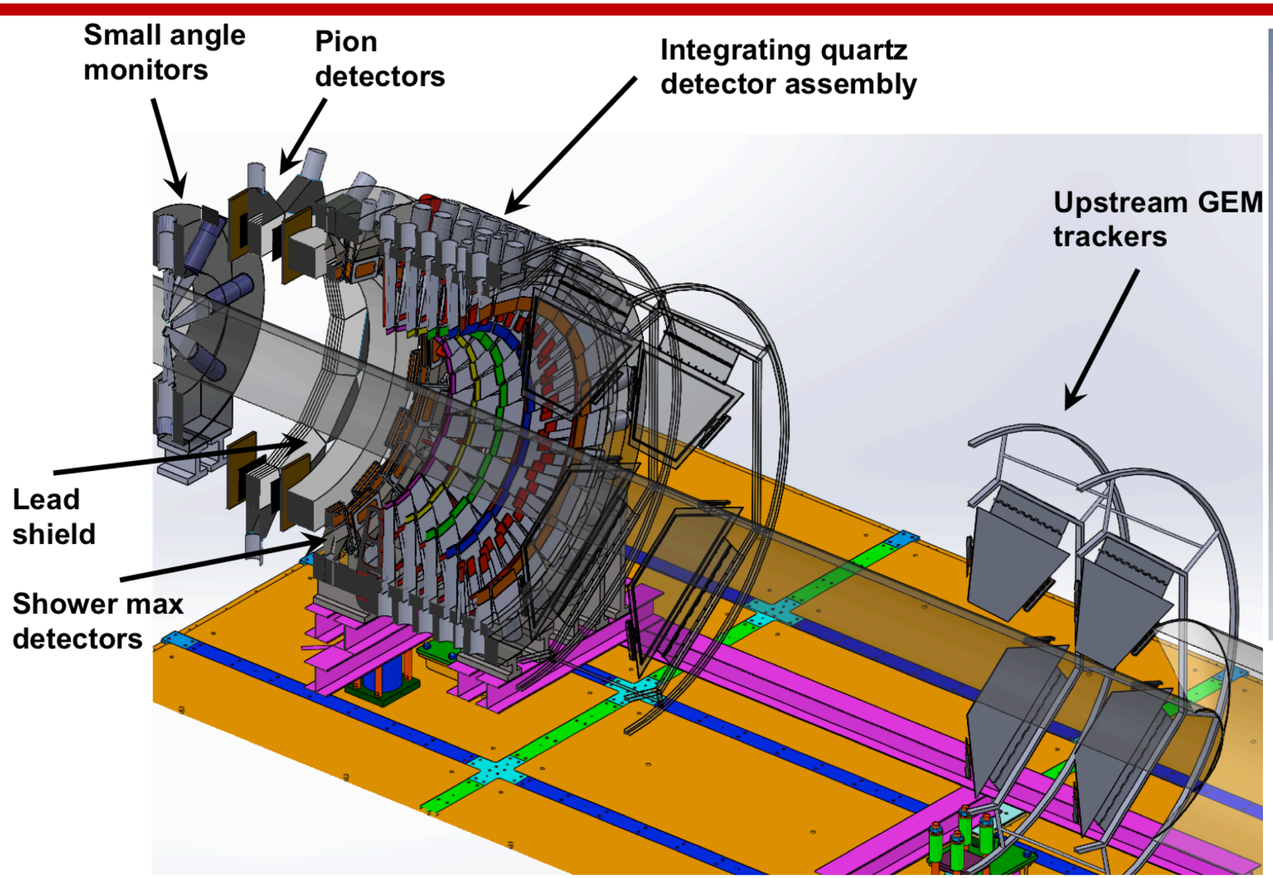
Most critical required tolerances:

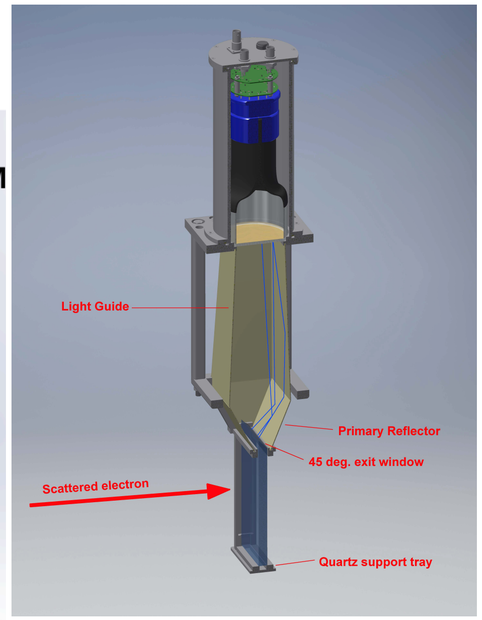
±200 µm machining tolerance on defining inner edge

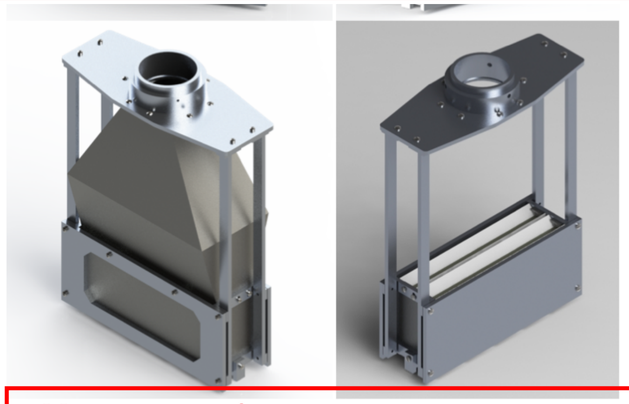
±1 mm positioning tolerance for most critical collimators



Primary and Auxiliary Integrating and Tracking Detectors







Key requirement:

Detector resolution < 25%

for detector excess noise < 4%

Integrating (current mode) detectors:

asymmetry measurements of both signal and background, and beam and target monitoring

Tracking (counting mode) detectors:

spectrometer calibration, electron scattering angle distribution, and background measurements

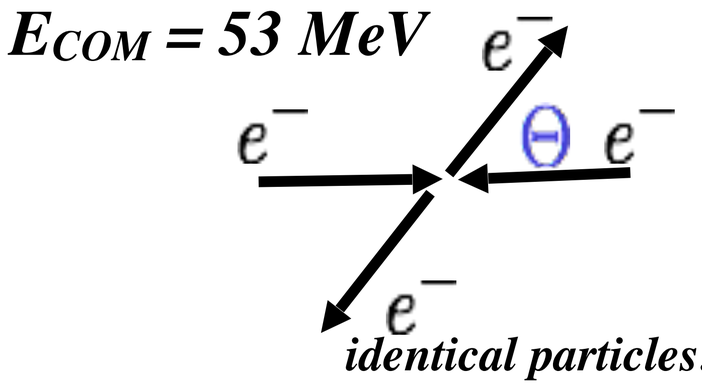
- Gas electron multipliers (GEM) detectors
- "Pion" acrylic Cherenkov detectors

Readout Electronics:

WBS 1.07 DAQ & Trigger

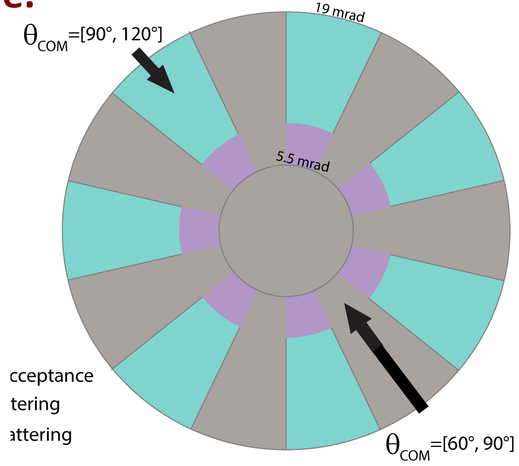
- Integration mode DAQ & trigger
  - *Collect & analyaize100% of the helicity windows*
- Counting mode DAQ & trigger
  - *input rates between 10~kHz and 300~kHz*

100% Azimuthal Acceptance

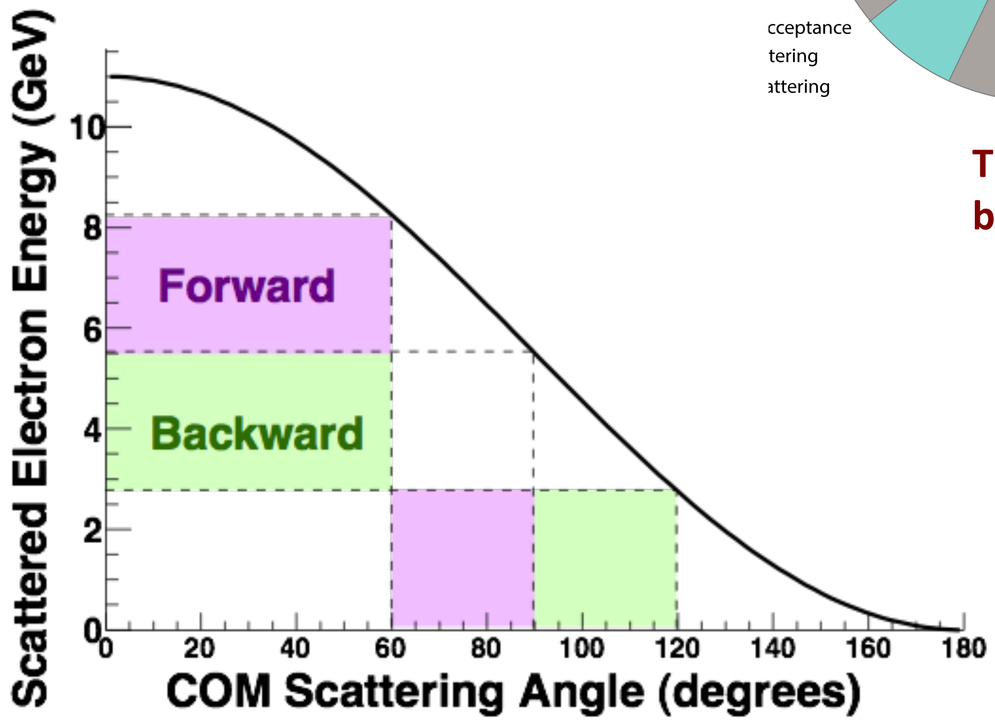


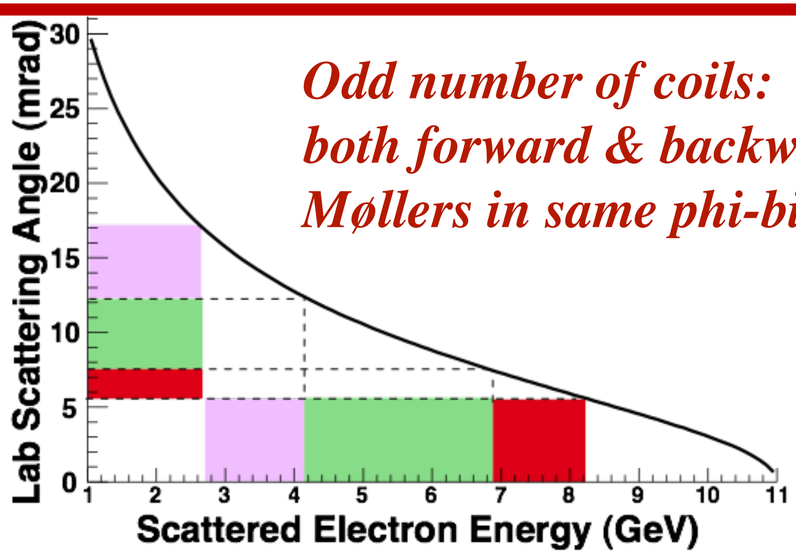
identical particles!

...are collected over here.

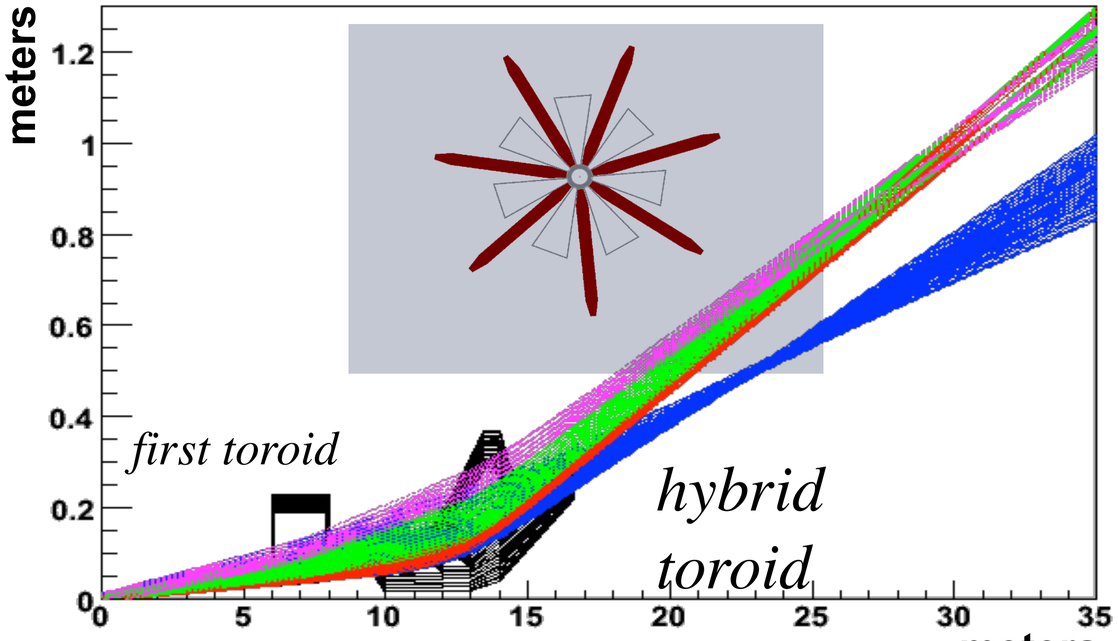


The rays that are blocked here...





Odd number of coils: both forward & backward Møllers in same phi-bite



Theory Prediction and Radiative Corrections

The Standard Model Prediction: Remarkably Well-Known

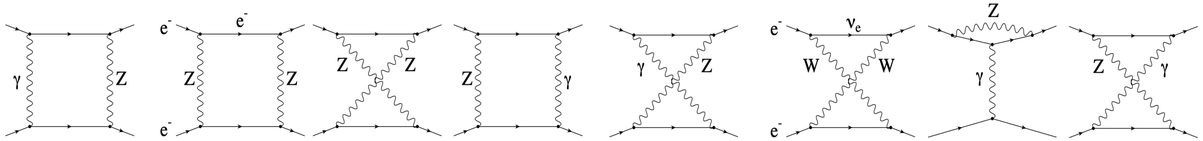
$$A_{PV} = \frac{\rho G_F Q^2}{\sqrt{2}\pi\alpha}\frac{1-y}{1+y^4+(1-y)^4}\left\{1-4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{\rm MS}}\right.$$
$$+ \frac{\alpha(m_Z)}{4\pi\hat{s}^2} - \frac{3\alpha(m_Z)}{32\pi\hat{s}^2\hat{c}^2}(1-4\hat{s}^2)[1+(1-4\hat{s}^2)^2]$$
$$\left. + F_1(y,Q^2) + F_2(y,Q^2)\right\}$$

κ(0) known to 1% of itself
Erler and Ferro-Hernandez (2018)

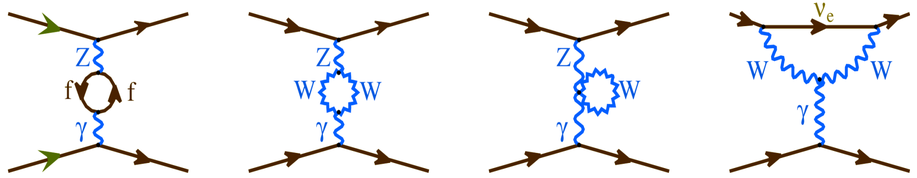
$$Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075 \Longrightarrow 0.045$$

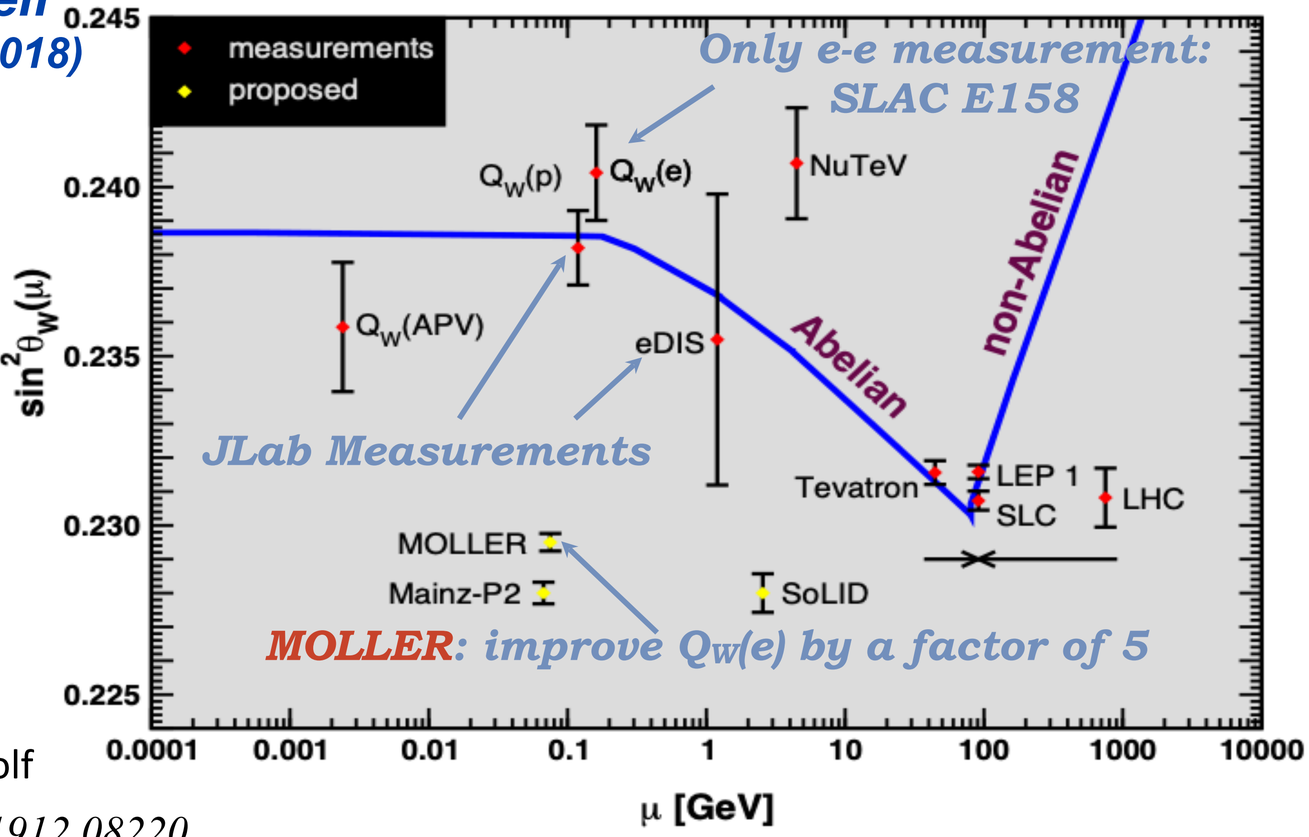
$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

δ(Q^e_W) ≈ 0.4%

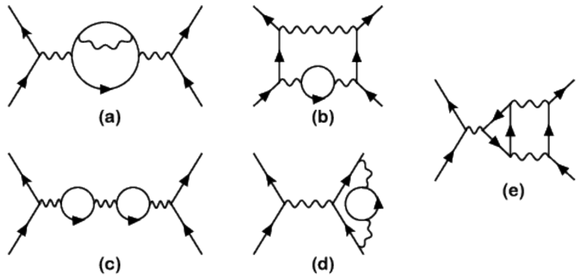


Czarnecki and Marciano (1995)





2 groups working on 2-loop Calculations



Aleksejevs and Barkanova

Series of publications

Du, Freitas, Patel and Ramsey-Musolf

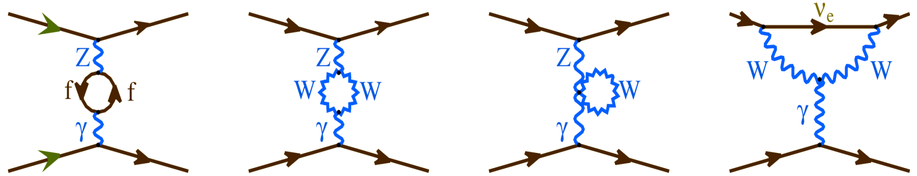
Recent closed-fermion loops: arXiv:1912.08220

Radiative Corrections

The Standard Model Prediction: Remarkably Well-Known

$$
\begin{aligned}
A_{PV} &= \frac{\rho G_F Q^2}{\sqrt{2}\pi\alpha}\frac{1-y}{1+y^4+(1-y)^4}\left\{1-4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{\rm MS}}\right. \\
&+ \frac{\alpha(m_Z)}{4\pi\hat{s}^2}-\frac{3\alpha(m_Z)}{32\pi\hat{s}^2\hat{c}^2}(1-4\hat{s}^2)[1+(1-4\hat{s}^2)^2] \\
&+ \left. F_1(y,Q^2)+F_2(y,Q^2)\right\}
\end{aligned}
$$

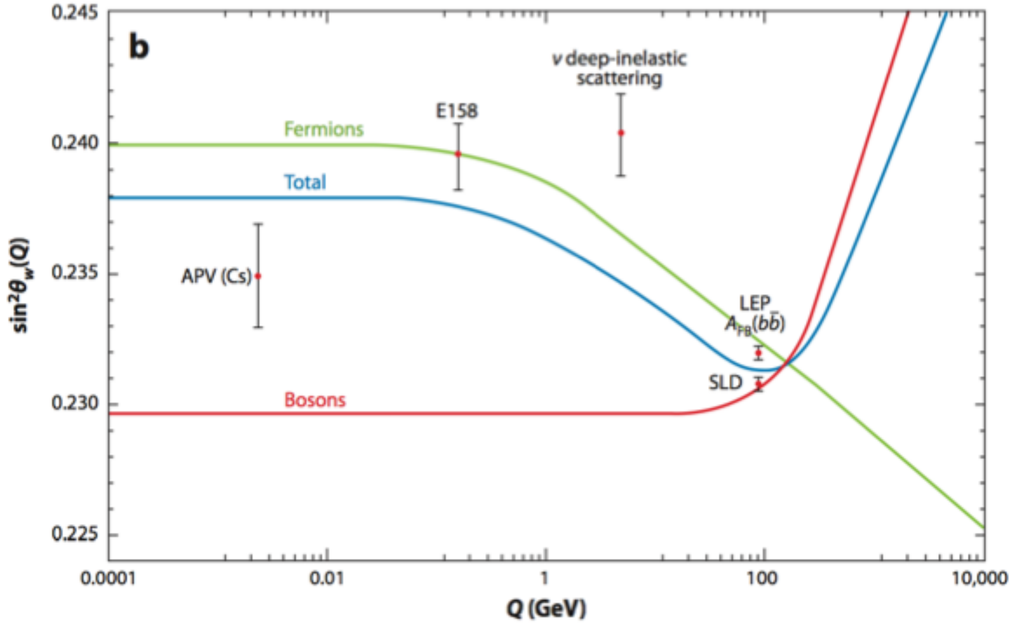
Czarnecki and Marciano (1995)



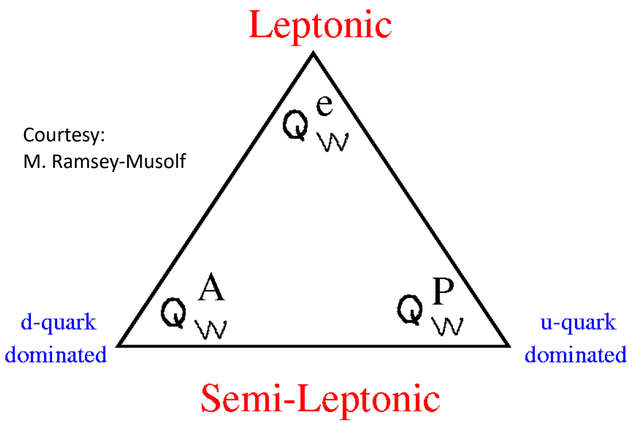
$$\mathbf{Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075 \Longrightarrow 0.045}$$

$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

The small size of the coupling, further reduced by radiative corrections, will be a recurring theme: it eases the pressure on "normalization" errors



PVES Initiatives: Complementarity



vector-quark couplings

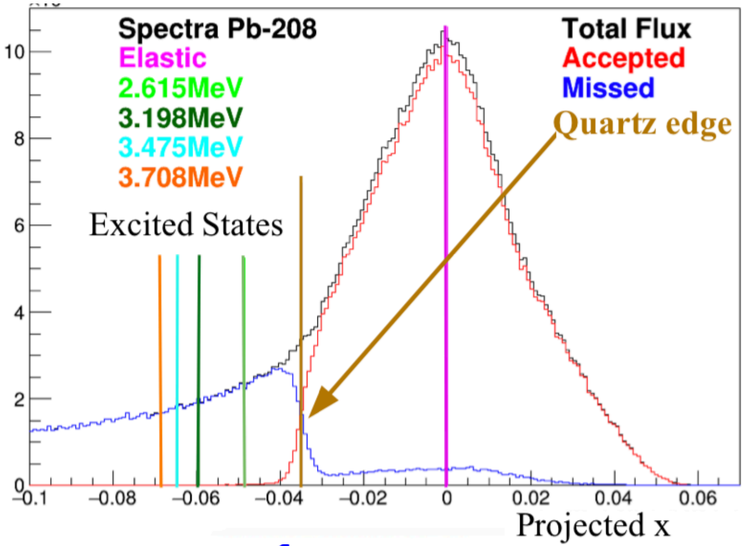
$$[2C_{2u} - C_{2d}]$$

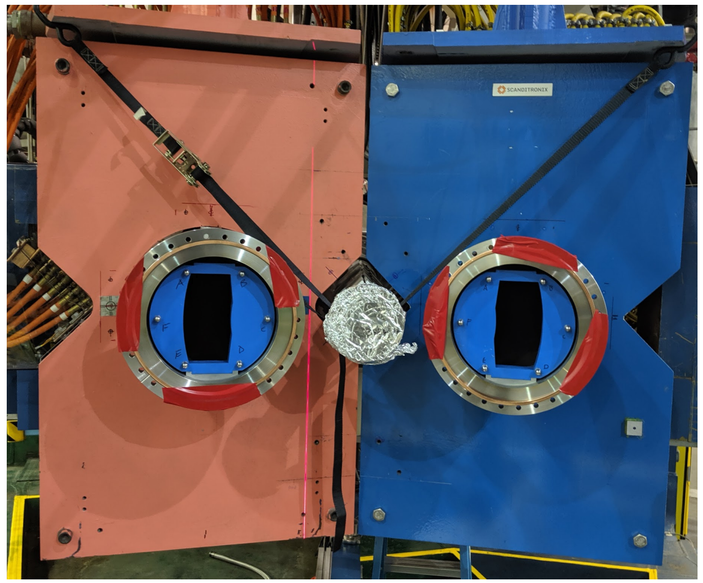
axial-quark couplings

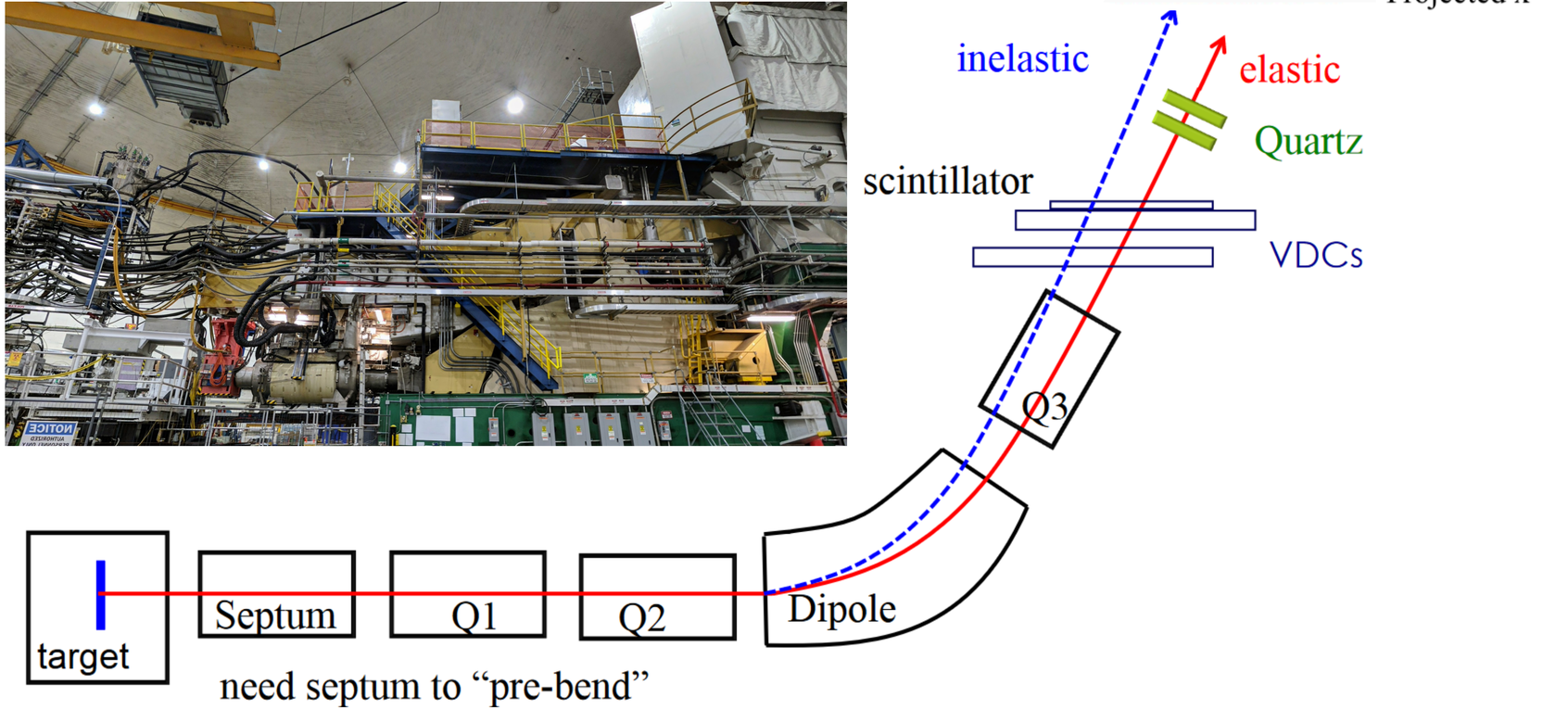
SUSY Loops	➡	**Q_W^e and Q_W^p:same absolute shift, smaller for others**
GUT Z'	➡	**High for Q_W(Cs), Q_W^e(relative), smaller for others**
Leptophobic Z'	➡	**axial-quark couplings (C_2's) only**
RPV SUSY	➡	**Different for all four in sign and magnitude**
Leptoquarks	➡	**semi-leptonic only; different sensitivities**
Lepton Number Violation	➡	**Q_W^e only**

HRS Spectrometers

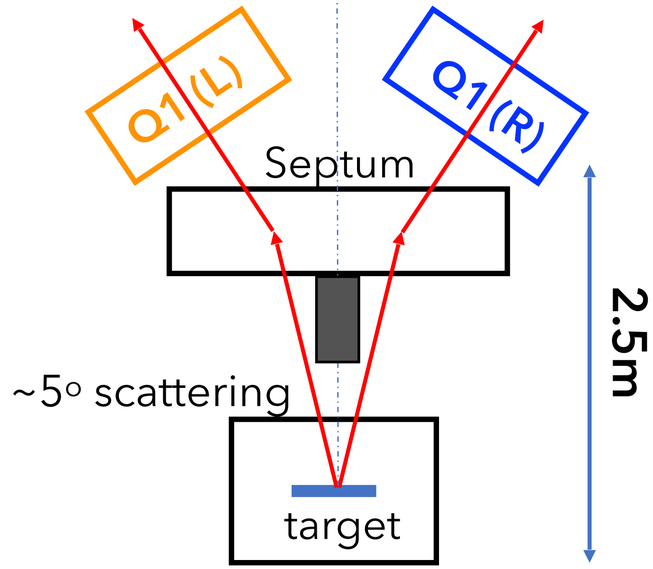
- Spectrometer separates elastic peak, directs it onto integrating detector
- Integrate detector in each of the spectrometer pair independently



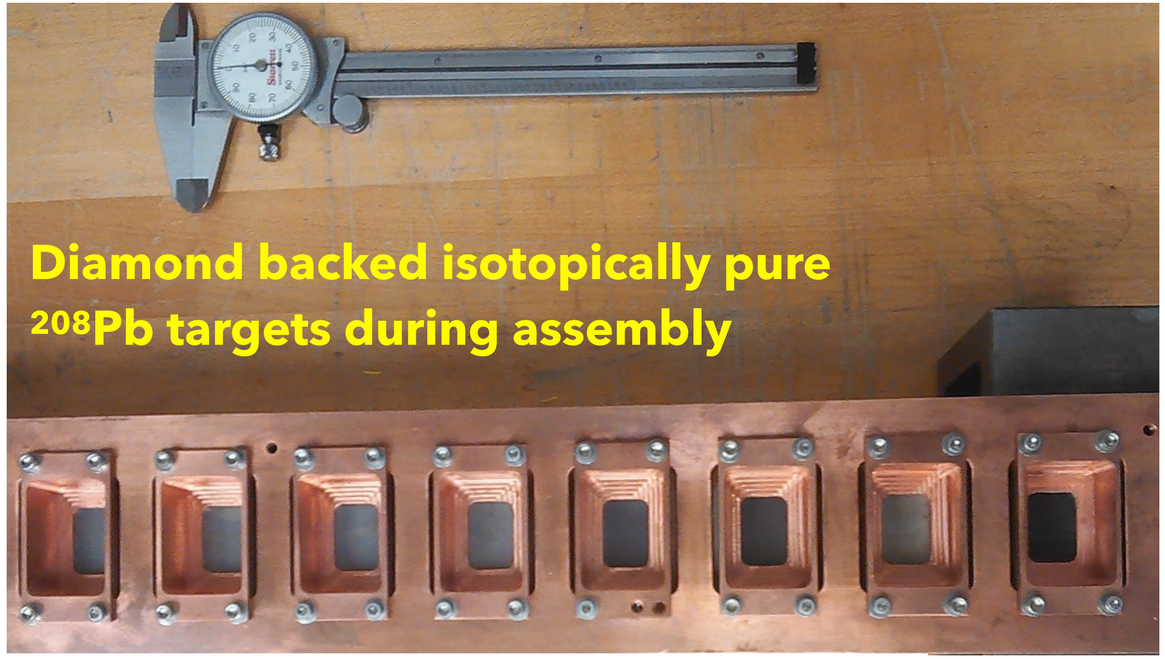




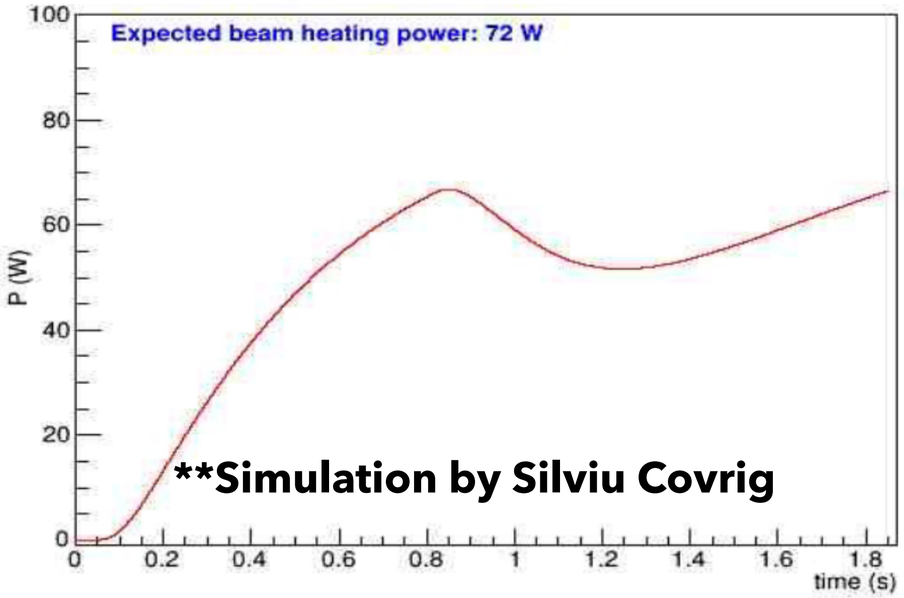
~12.5° Spectrometers

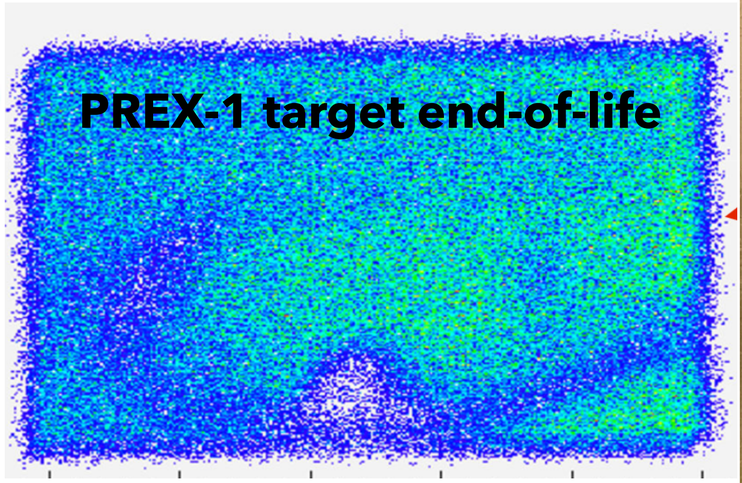


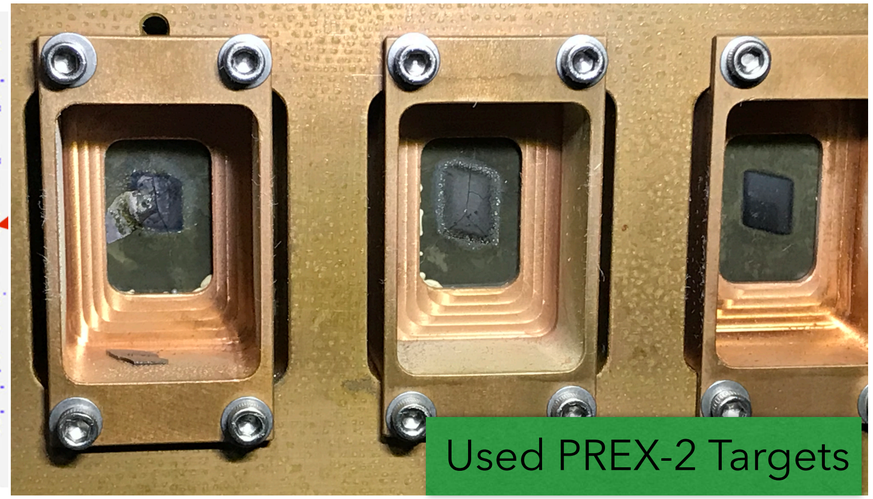
^{208}Pb Target



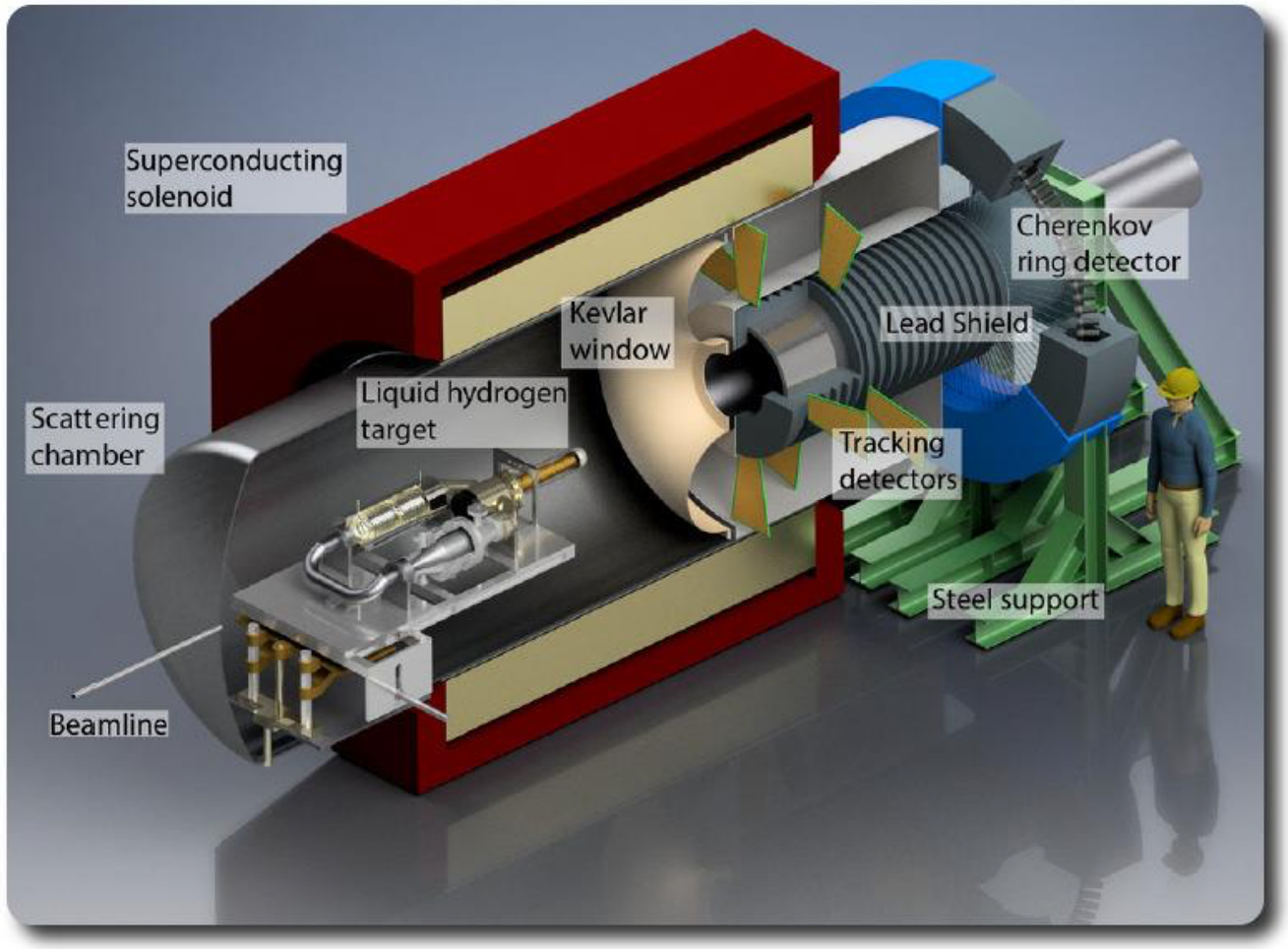
- Diamond-lead-diamond sandwich targets were used to get heat out of the target to cryocooling
- Diamond eventually breaks down, and lead is damaged
- PREX-1 proved concept and demonstrated target lifetime
- For PREX-2 we prepared a complement of 10 isotopically pure targets (used 6, as expected)
- Simulations predicted approximately 72 W of power deposition from the 70 μA rastered beam



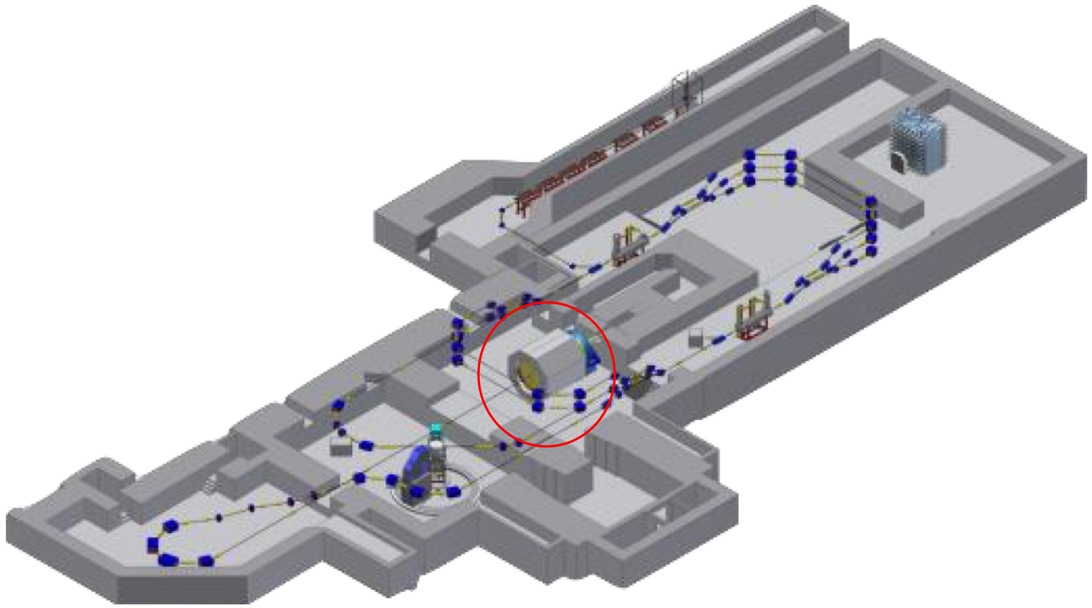




Future: MREX at MESA (Mainz)



MREX



$\Delta\theta$=4° : expected rate = 8.25 GHz, A_{pv} = 0.66 ppm, P = 85%, Q ≈ 86 MeV

1440h → $\delta R_n/R_n$ = 0.52% (^{208}Pb @ 155 MeV)

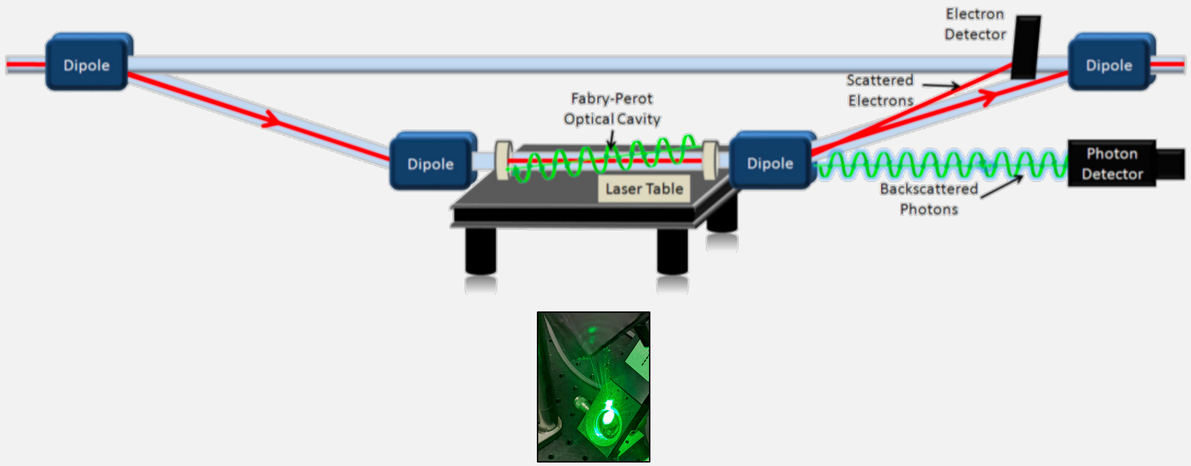
➢ $\delta R_n/R_n$ = 0.5%
→ L ± 20 MeV

Concettina Sfienti, Michaela Thiel

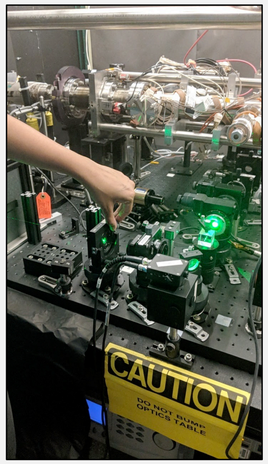
Goal: $\delta R_{n\text{-}p} \sim 0.03$ fm

Beam Polarization

Compton Polarimetry

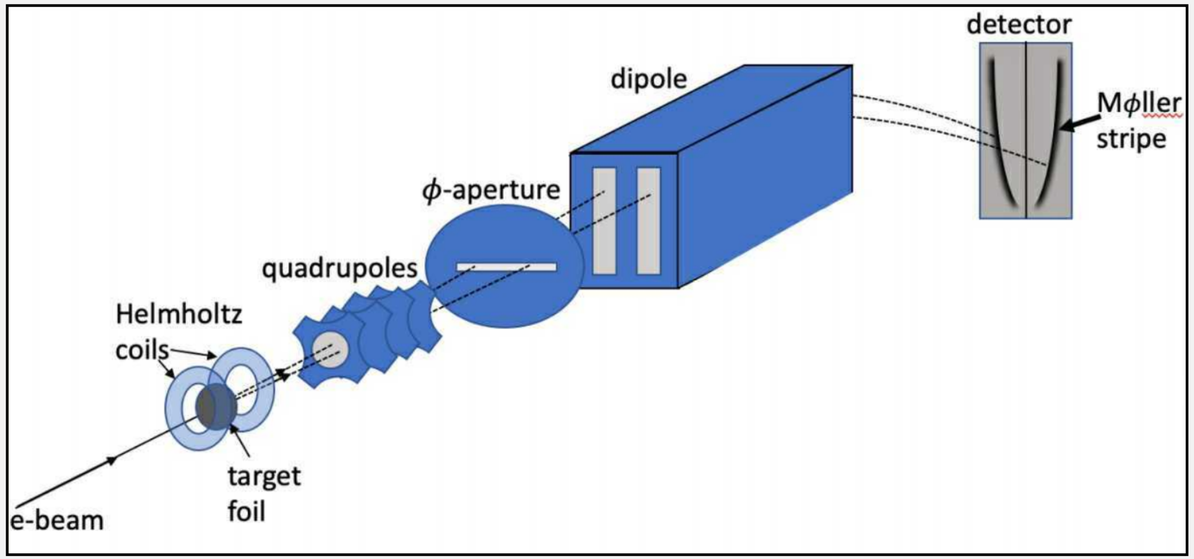


Acknowledgments: D. Gaskell, A. Premithilake A.J. Zec, J. C. Cornejo, M. Dalton, C. Gal, C. Palatchi, K. Paschke,, B. Quinn



- Continuous, non-invasive measurement
- Utilized integrating technique with photon detector
- Evaluated systematic uncertainty
- Polarimeter runs taken continuously alongside main detector data

Moller Polarimetry



Acknowledgments: S. Malace, E. King, D. Jones, P. Souder

- Low-current, invasive measurement
- 3-4T field provides saturated magnetization perpendicular to the foil
- Spectrometer redesigned for 11 GeV
- CREX reoptimized the spectrometer tune (and detector configuration), to provide high precision and sensitivity to systematic effects
- Polarimeter runs were taken approximately every week

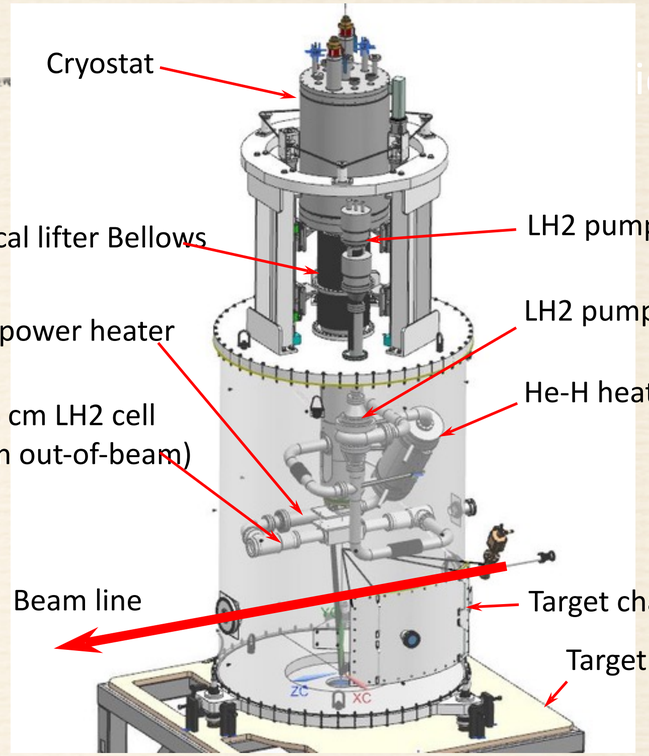
Liquid Hydrogen Target

- up to 70 μA on 125 cm LH_2 target - 3.7 kW
- Q_{weak} experience: use of CFD (computational fluid dynamics)

Main requirement: minimize target density fluctuations (Δρ/ρ):

$\Gamma_{target} < 30$ ppm for 70 μA, 5x5 mm^2 raster, 1.92 kHz flip

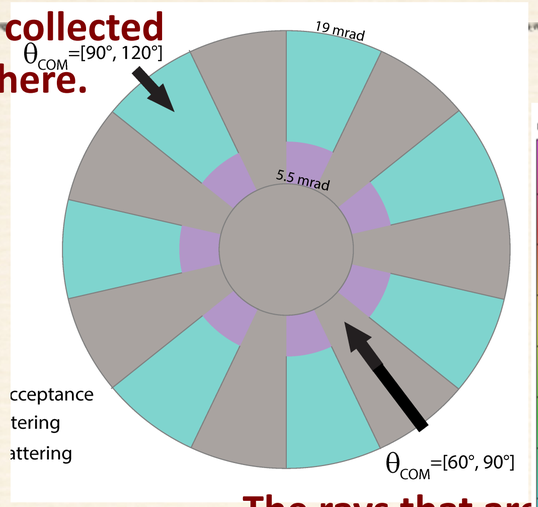
Test fit of scattering chamber completed

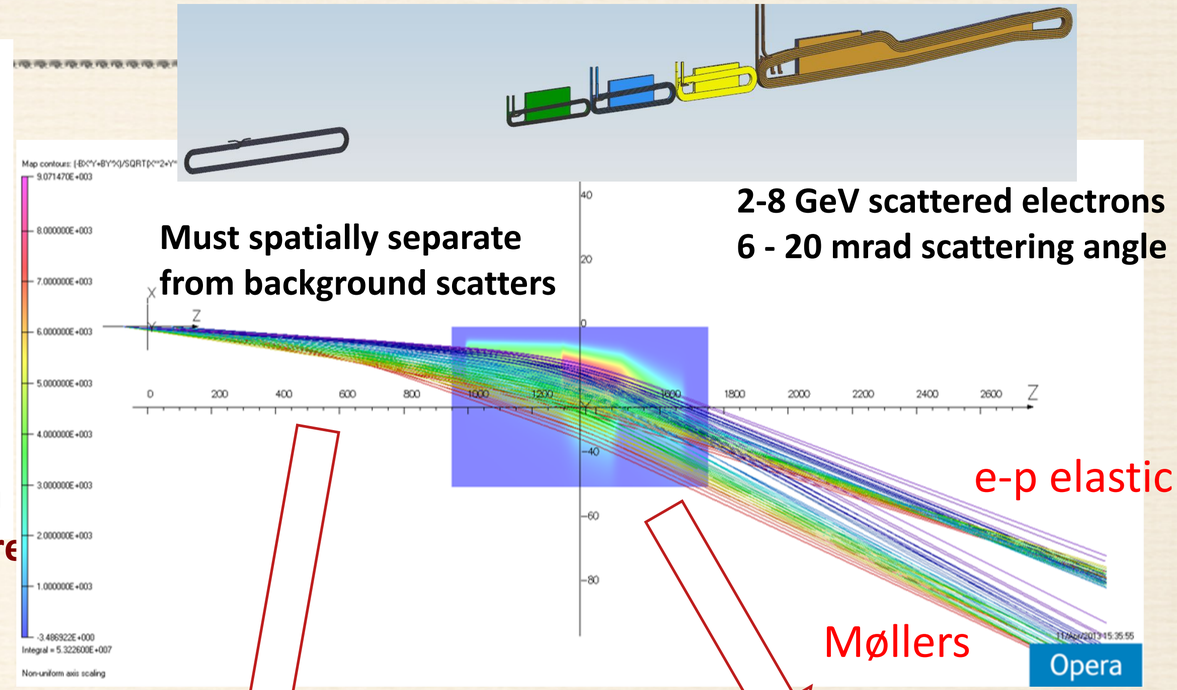


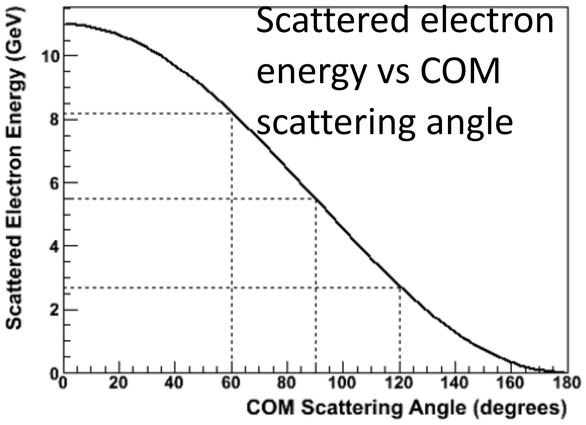
Cryostat components

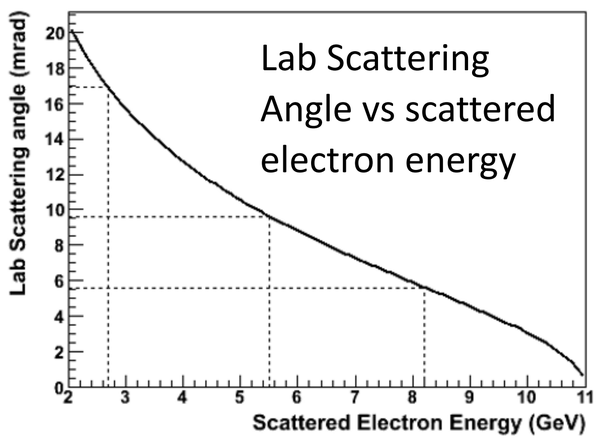
Spectrometer Design

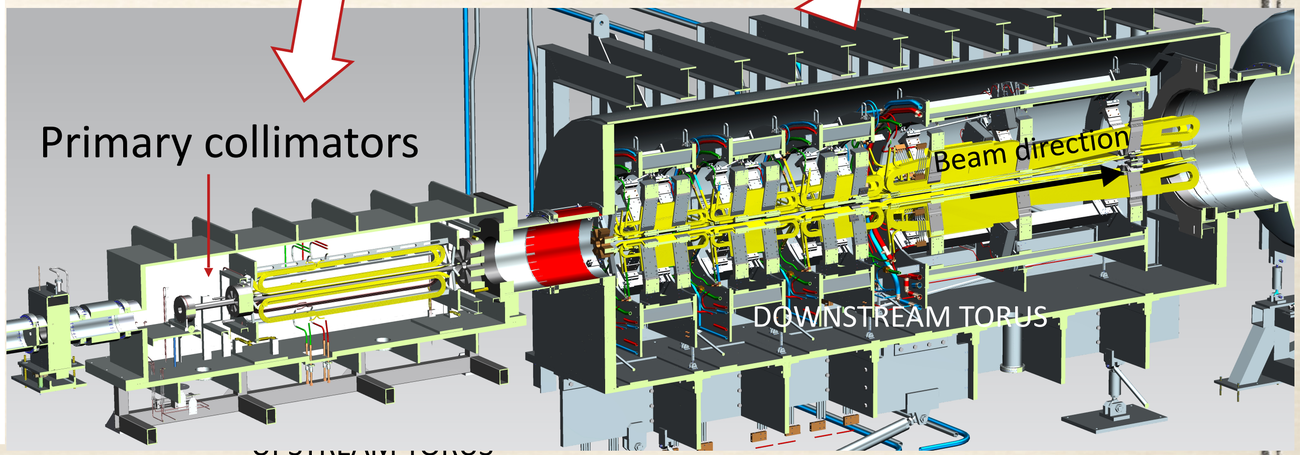
- Accept all Møller scattered electrons in range Θ_{CM} = 50^o – 130^o
- **Exploit identical particle nature for 100% azimuthal acceptance**; needs odd number of coils



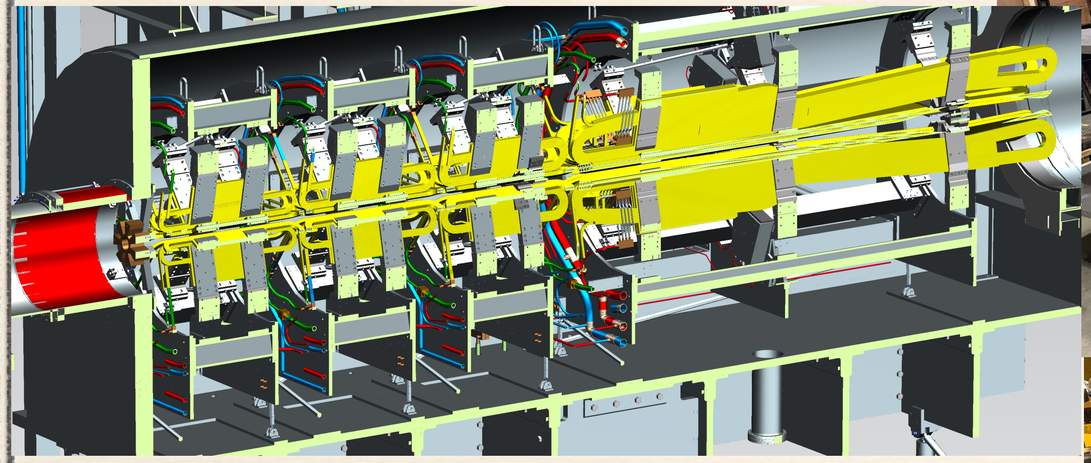






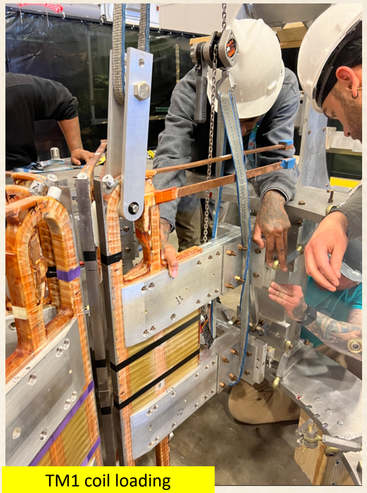


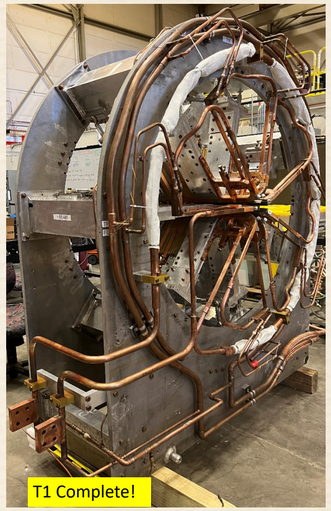
Spectrometer Construction

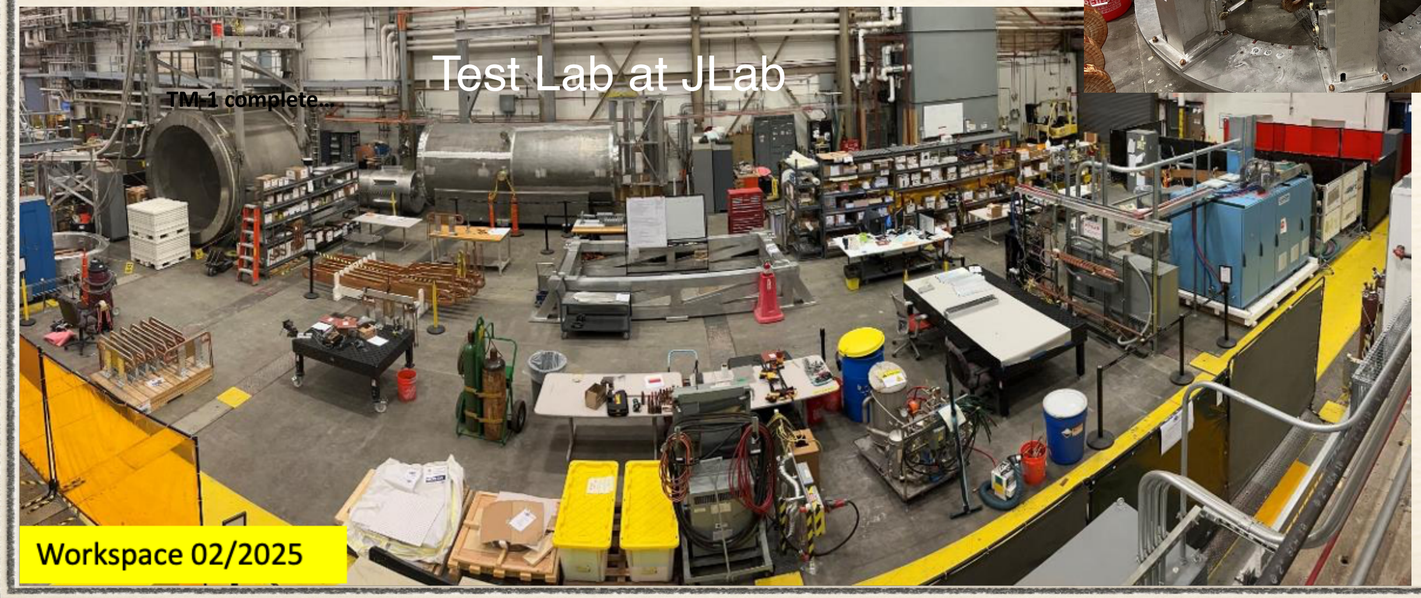


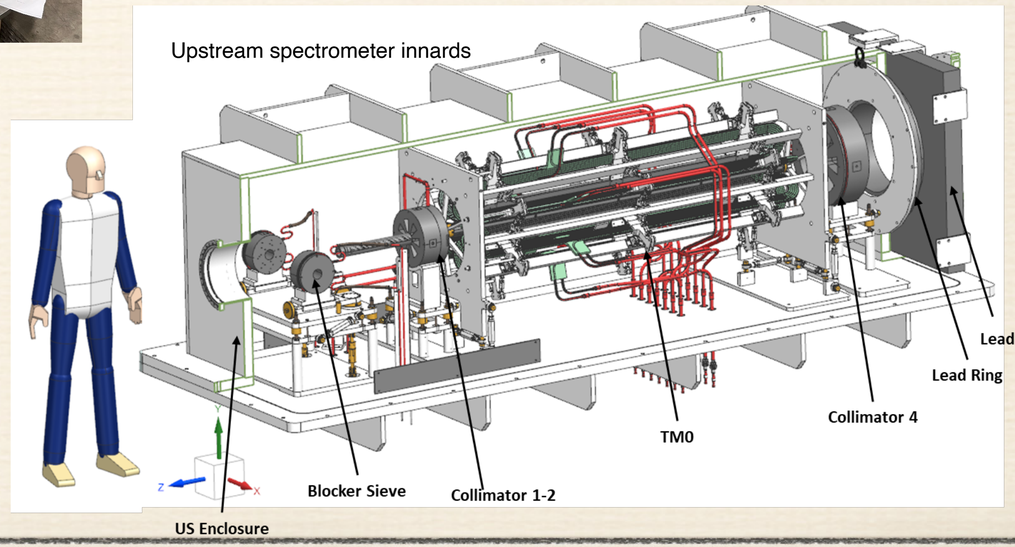
TM2 frame ready for loading

TM1 coil rigging test

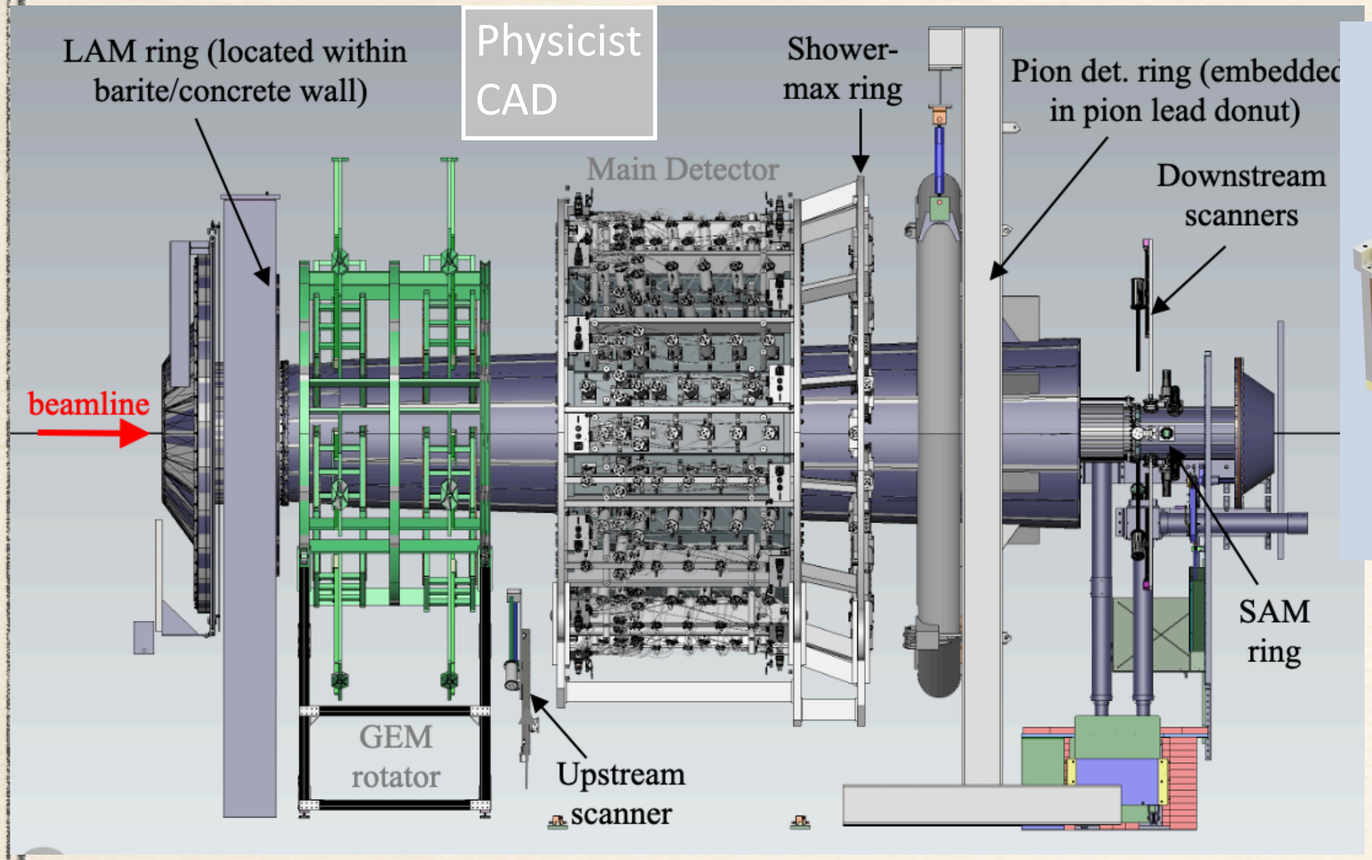

TM1 coil loading

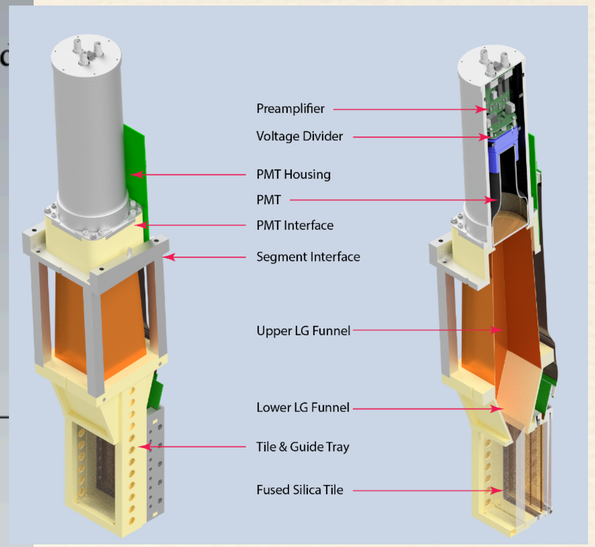

T1 Complete!





MOLLER Detection Overview

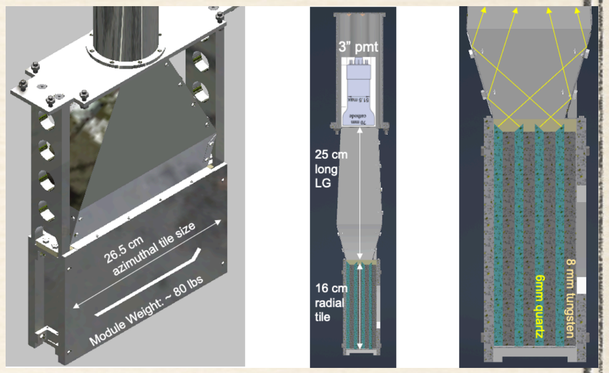




Requirement for Ring 5:

Detector resolution < 25%

excess noise < 4%



Integrating (current mode) detectors:

asymmetry measurements of both signal and background, and beam and target monitoring

Tracking (counting mode) detectors:

spectrometer calibration, electron scattering angle distribution, and background measurements

- Gas electron multipliers (GEM) detectors
- "Pion" acrylic Cherenkov detectors

Readout Electronics:

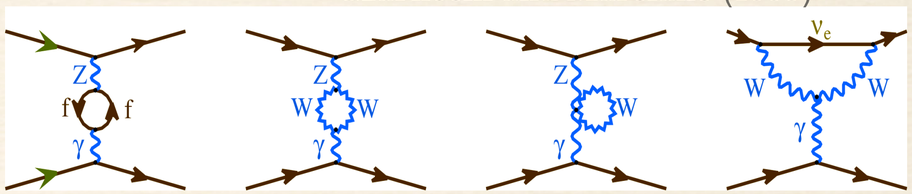
- Integration mode DAQ & trigger
  - *Collect & analyaize100% of the helicity windows*
- Counting mode DAQ & trigger
  - *input rates between 10~kHz and 300~kHz*

Thumb Rule: Weak mixing angle must be measured to sub-0.5% precision

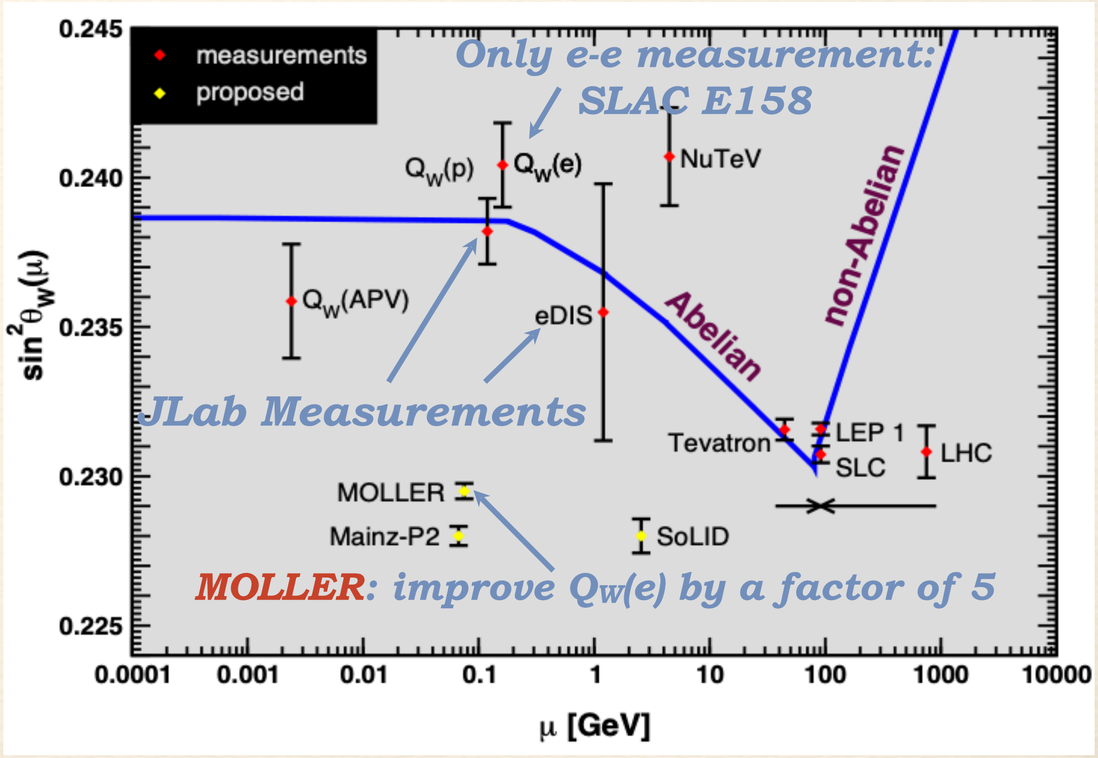
WNC "Bookkeeping"

Electroweak Radiative Corrections causes weak mixing angle to "run"

Czarnecki and Marciano (1995)

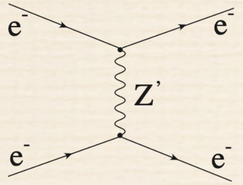


- **Atomic Parity Violation: Cs-133**
  - future measurements and theory challenging
- **Neutrino Deep Inelastic Scattering: NuTeV**
  - future measurements and theory challenging
- **PV Møller Scattering: E158 at SLAC**
  - statistics limited, theory robust
  - next generation: MOLLER (factor of 5 better)
- **PV elastic e-p scattering: Qweak**
  - theory robust at low beam energy
  - next generation: P2 (factor of 3 better)
- **PV Deep Inelastic Scattering: PVDIS**
  - theory robust for ^{2}H in valence quark region
  - factor of 5 improvement: SOLID



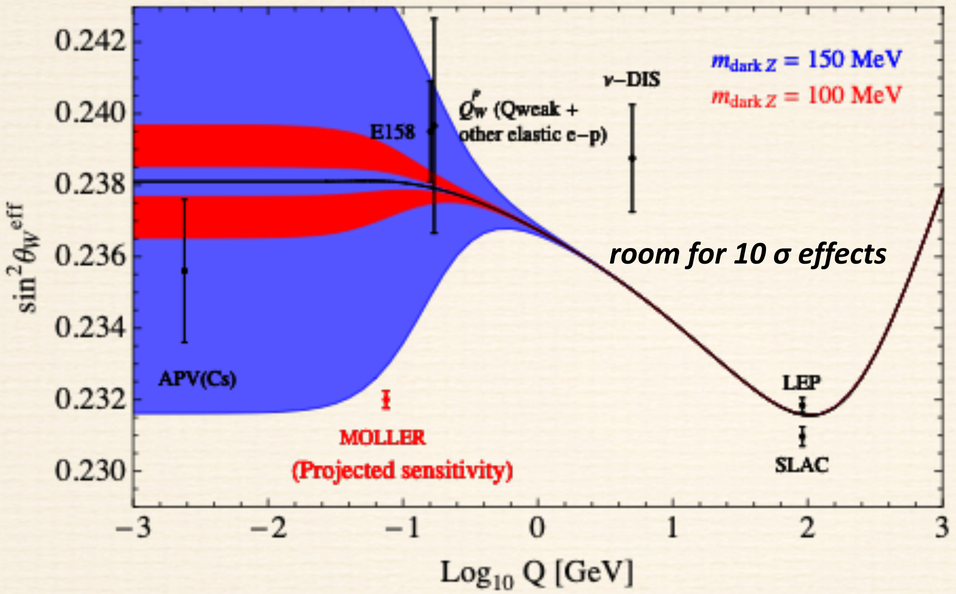
New Physics Examples

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential



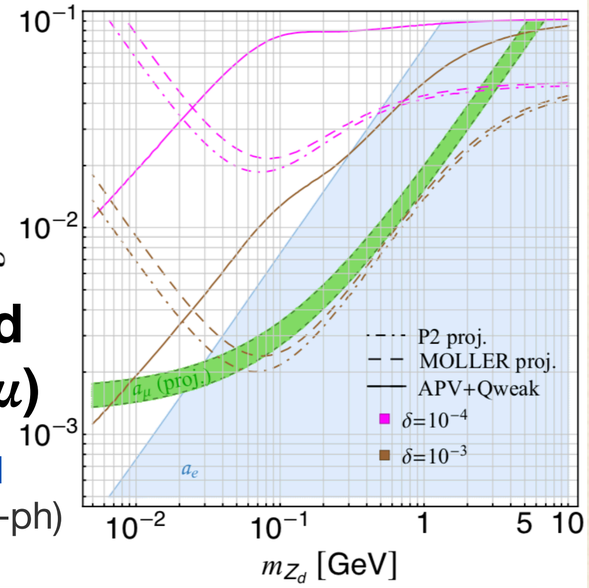
Heavy Photons (A' mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano

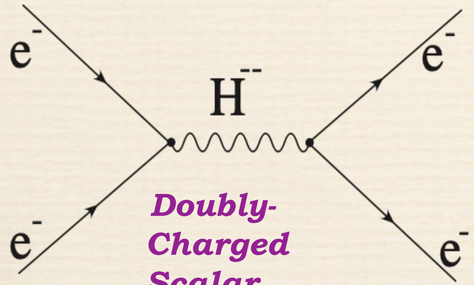


Specific Scenario folding in Cs APV and g-2 (e and μ)

M. Caddedu et al
2104.03280 (hep-ph)



Lepton Number Violation



$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\,\frac{|h_{ee}|^2}{(M_\Delta/1\ \mathrm{TeV})^2}$$

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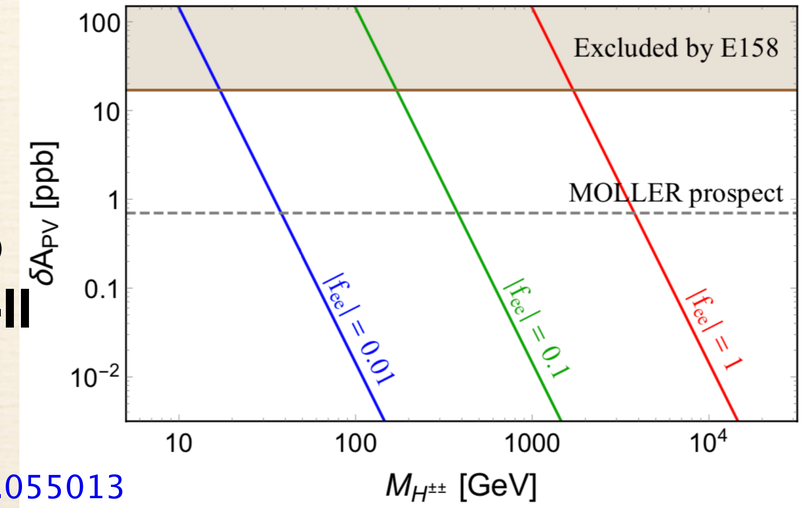
5 σ for h_{ee} ~ 1 and M_Δ ~ 1 TeV

Specific Scenario for Type-II SeeSaw

B. Dev et al
PhysRevD.98.055013