# Benchmarking Air Light-Guide Cherenkov Detectors at SLAC ESTB

GHP Workshop

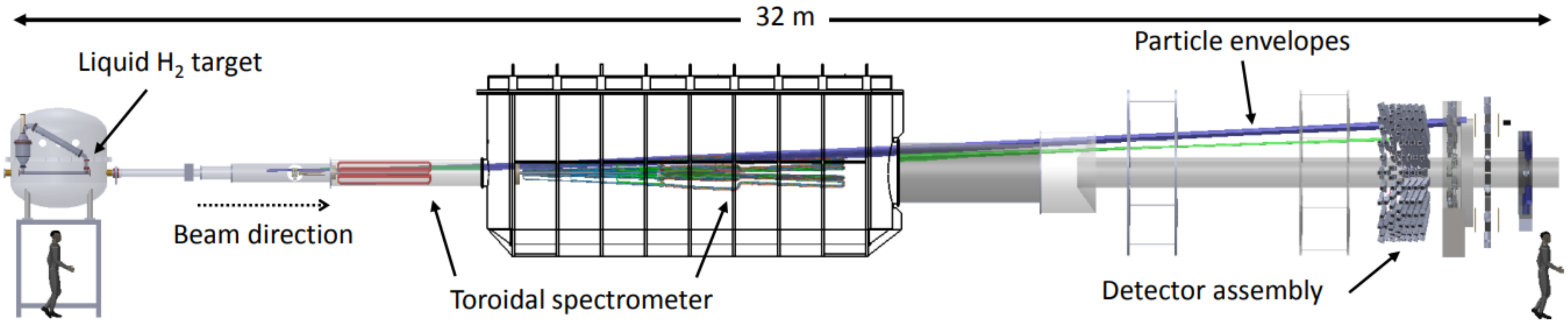
Cameron Clarke – April 10th, 2019

# Outline

- Integrating Cherenkov Detectors
  - What are we measuring?
  - What is the best way to measure it?
  - What’s new?
- SLAC ESTB Test Beam
- Cross Check with Simulation
- Looking to the Future

# What are we measuring?

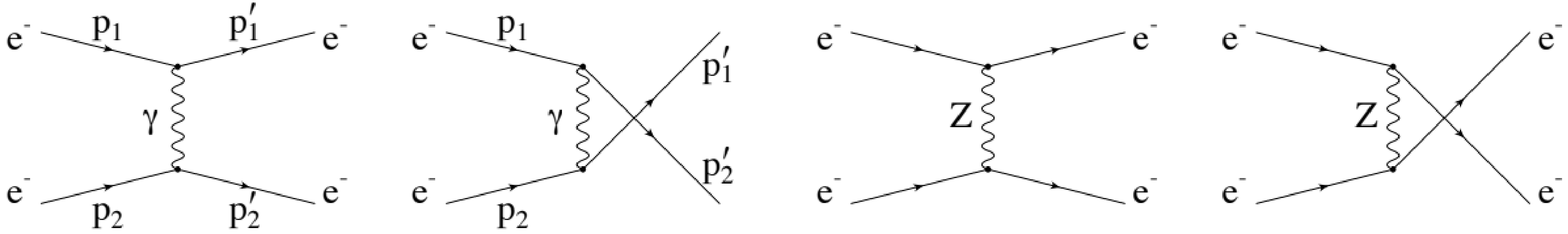
- The MOLLER experiment’s goal is to measure the parity violating asymmetry of Møller electron scattering
- Small asymmetries preclude directly measuring the asymmetric cross-sections or weak-force mediated interactions




The MOLLER experiment general layout in CAD

# What are we measuring?

Tree level EM and Weak Feynman diagrams for MOLLER Scattering




- Small effect of parity violation precludes directly measuring the asymmetric cross sections or weak-force mediated interactions → Measure asymmetries

- Fractional error in asymmetry is: $$\frac{\delta A_{PV}}{A_{PV}} = \frac{1}{P_e\sqrt{N}}$$
  N = # detected particles
  Pe = Measured polarization (another topic for another day)

# What is the best way to measure it?

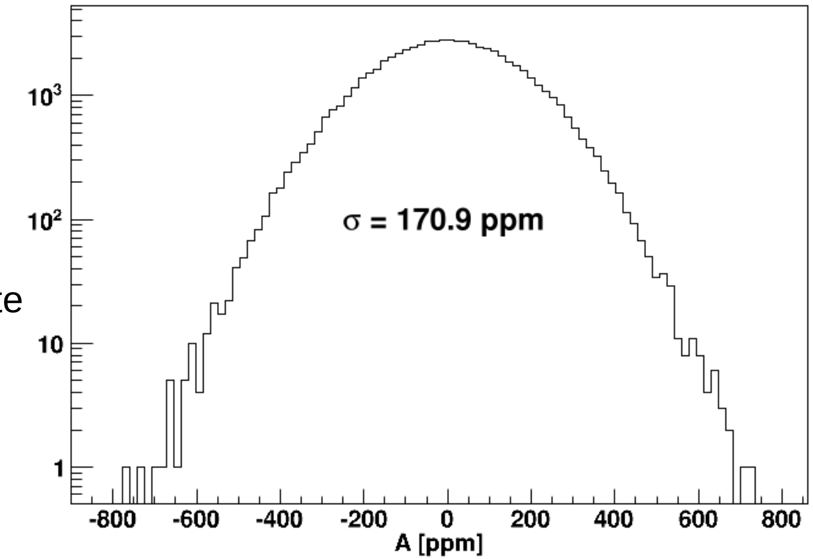
- To measure small asymmetries with good precision (large N) we therefore need to:
    - Be insensitive to low energy backgrounds
        - Pure Cherenkov detector
    - Achieve statistical precision with ~100+ GHz event rate
        - Integrate signal from unresolvable high rate
        - Need radiation-hard material

# What is the best way to measure it?

- To measure small asymmetries with good precision (large N) we therefore need to:
  - Be insensitive to low energy backgrounds
    - Pure Cherenkov detector
  - Achieve statistical precision with ~100+ GHz event rate
    - Integrate signal from unresolvable high rate
    - Need radiation-hard material
- Parity Violating Electron Scattering (PVES) experiments rely on high rates of electrons integrated over flipping helicity windows

# What is the best way to measure it?

- To measure small asymmetries with good precision (large N) we therefore need to:
  - Be insensitive to low energy backgrounds
    - Pure Cherenkov detector
  - Achieve statistical precision with ~100+ GHz event rate
    - Integrate signal from unresolvable high rate
    - Need radiation-hard material
- Parity Violating Electron Scattering (PVES) experiments rely on high rates of electrons integrated over flipping helicity windows



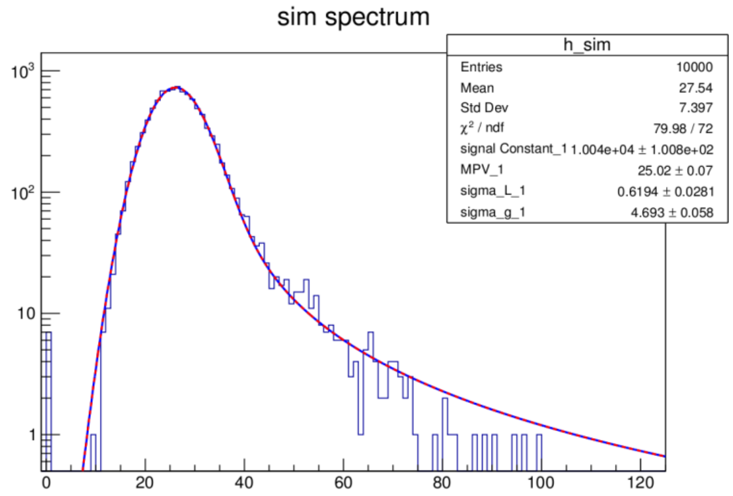

Typical distribution of corrected asymmetries (PREX I) per quadruplet, approximately consistent with counting statistics (~ 1 GHz at 70μA)

# What is the best way to measure it?

- Solution: integrate total Cherenkov response of many simultaneous electrons through a piece of fused silica (“quartz”)
- Narrow the pulse height distribution to optimize signal integration

  - Thinner radiator reduces shower fluctuations from delta rays, reducing Landau tail extent and overall RMS
  - Thicker radiator provides higher photon statistics, increasing mean and reducing relative Gaussian width
  - Non-zero (counting statistics) Gaussian width + tail broadens distribution and increases statistical uncertainty on N detected electrons
  - <S> = signal mean, σ = RMS width

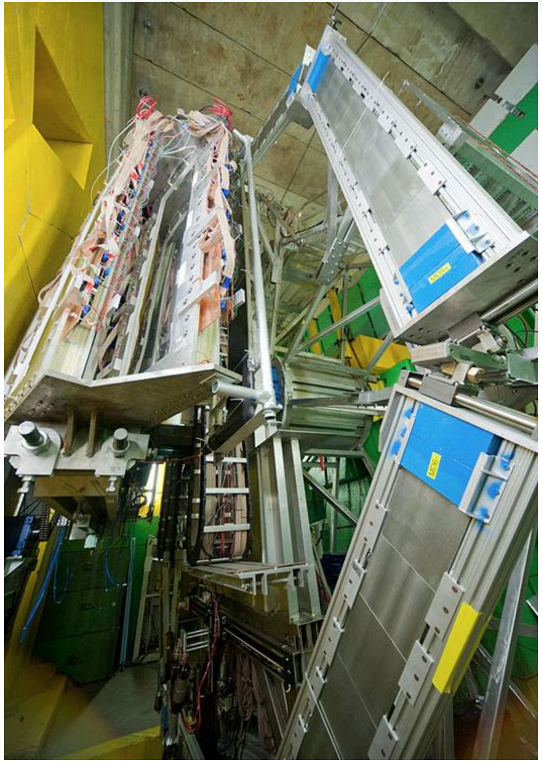
$$\frac{\Delta A_{PV}}{A_{PV}} = \frac{1}{\sqrt{N}}\sqrt{1+\frac{\sigma^2}{\langle S\rangle^2}}$$



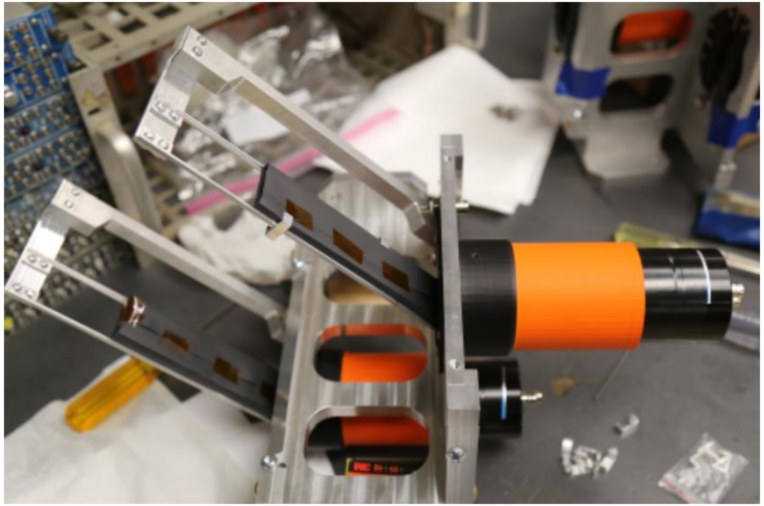

Simulated Data from “new” MOLLER Ring 5

# What is the best way to measure it?

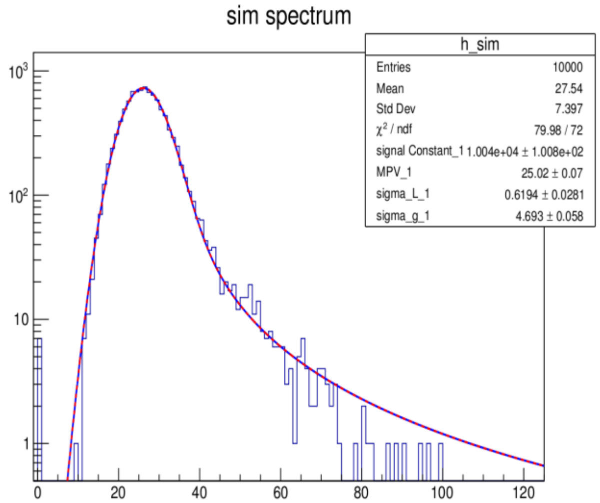
- Integrating flux over helicity states → measure small asymmetries
- Optimizing statistical precision with widths of integrating detector response has been done in a number of ways



Integrating large quartz with preradiator detectors (right) used for the QWeak experiment in Hall C



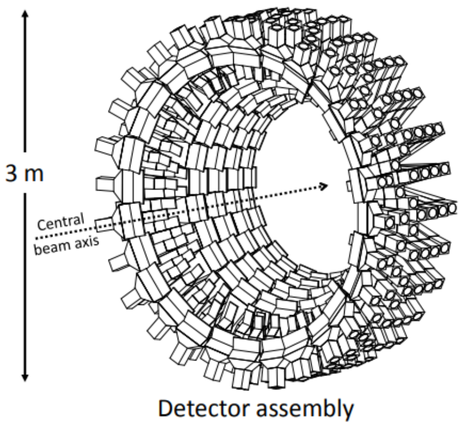
Integrating thin quartz detectors for use in PREX II/CREX



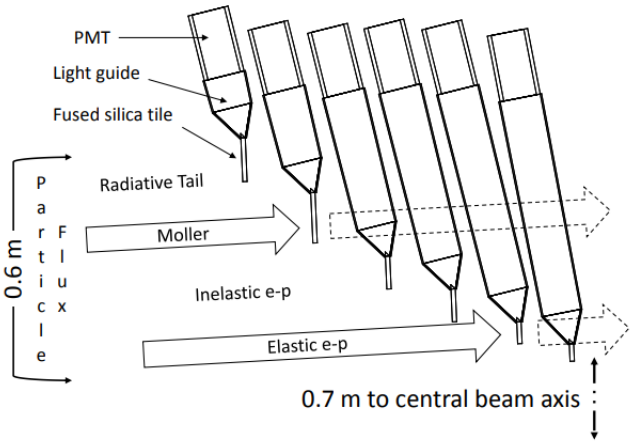

Simulated Data from “new” MOLLER Ring 5

# What’s new?

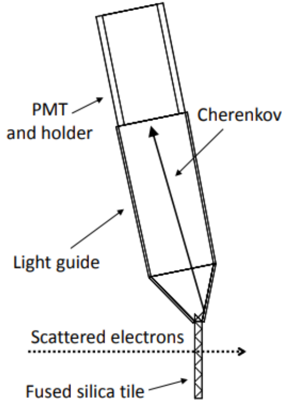
- The MOLLER experiment, with it’s novel 7-fold symmetric hybroid toroid spectrometer design, looks at a much larger range of kinematics than prior JLab Hall A High Resolution Spectrometer (HRS) experiments
- As a result the detectors need to span a large area with high segmentation and protect their electronics → utilize long, background optimized, air-core light guides



CAD rendering of proposed MOLLER detector array



Different fluxes passing through integrating Quartz and air light guides



Schematic of primary signal path

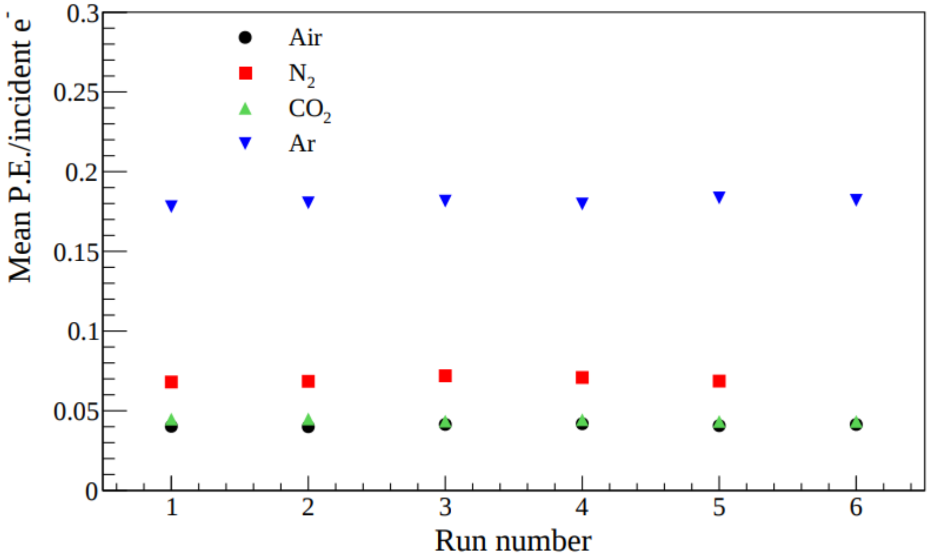
# What’s new?

- So we must mitigate air-Cherenkov and scintillation signals from air-core light guide backgrounds → Tests at MAMI Mainz in 2016 characterized gas response

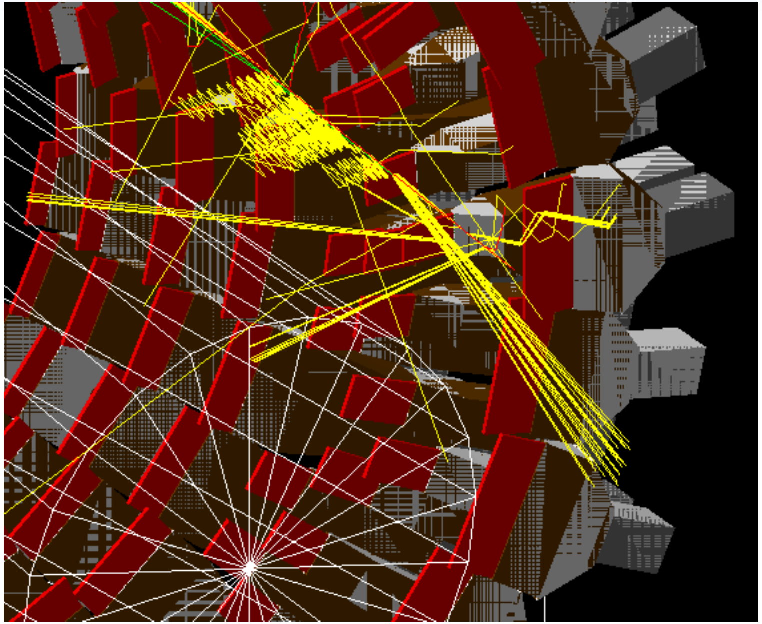
S. Riordan, et al. NIM A, 896, **11** 2018 (arXiv: 1710.07100)

- Geant4 simulations have been developed for simulating many, parametrized, easily modified detector geometries, and it now fully includes optical physics properties
  - Geometry simulation updates and constraints from CAD implementation require an “updated” geometry
  - We’ve learned the key air-core light guide background mitigation techniques from prior beam tests
  - This prompted us to perform a test at SLAC of an “updated” design that matches prior tests’ signal quality

# What's new?



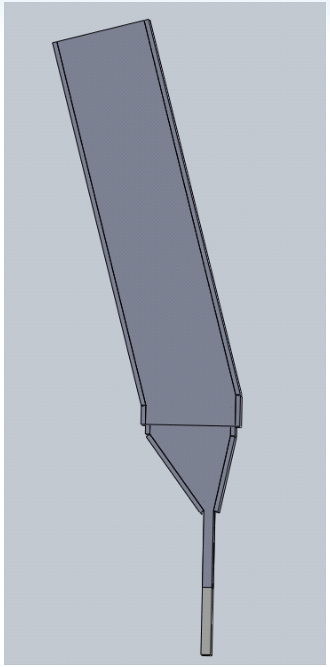

Scintillation yield of gasses inside the light guides at Mainz test beam in 2016 indicates that air is sufficiently background reducing



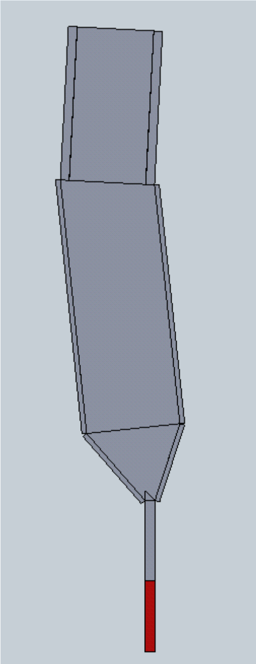
New simulation techniques for optimizing full array of detectors together, allow for systematic background reducing geometry optimization with full optical physics

# SLAC ESTB Test Beam

- Built the “old” Mainz 2016 prototype test design
- Built a “new” practical G4/GDML design
  - Optimized in Geant4 simulation
- Took to SLAC to test alongside PREX, ShowerMax, & GEMs
  - 8 GeV, 5 Hz low-multiplicity electron beam
  - 8 GeV is similar to the proposed MOLLER beam energy



“Old” Mainz 2016 test beam prototype CAD



“New” G4 and engineering constraint optimized CAD

“New” model in SLAC test beam setup (GEMs not shown)

# Cross Check with Simulation

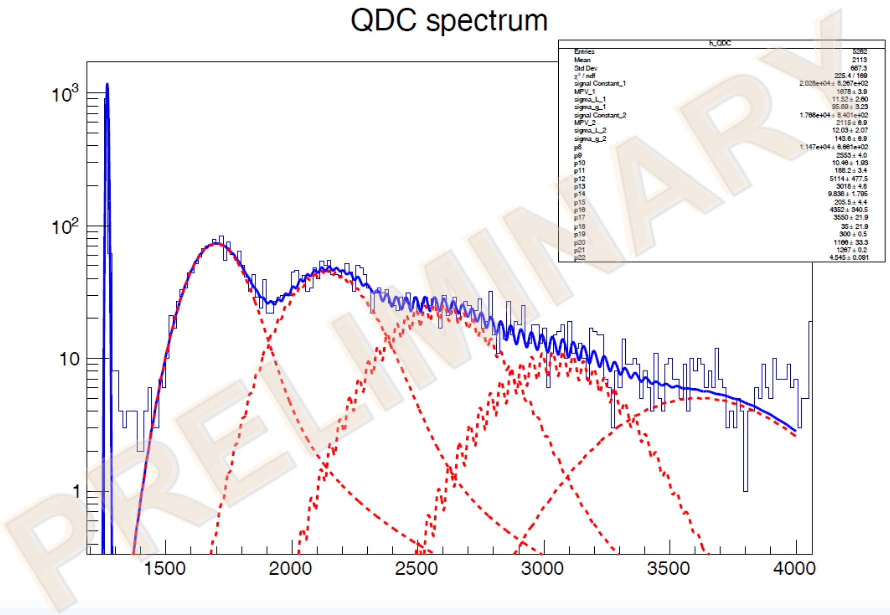
- Simulated with optical physics:
  - A close approximation of the “old” Mainz 2016 prototype test design that was built
  - An exact geometry copy of the optimized “new” G4/GDML produced design
- Simulation shows no appreciable difference between these two configurations
  - “Old” mean  PEs = 26.6 +- 0.1, RMS = 7.25 +- 0.06, resolution = 0.272 +- 0.029
  - “New” mean Pes = 26.9 +- 0.1, RMS = 7.20 +- 0.06, resolution = 0.267 +- 0.028
- Preliminary SLAC test data agrees with simulation on similarity of two designs
- The same geometry simulation and optimization procedure yields the same results with different sets of constraints

# Cross Check with Simulation

- Preliminary results from SLAC test beam

- The single electron data can be fit out from under the higher multiplicity data
- But we can also apply GEM tracking detector cuts to the data
- Both need work to obtain the high PE tails

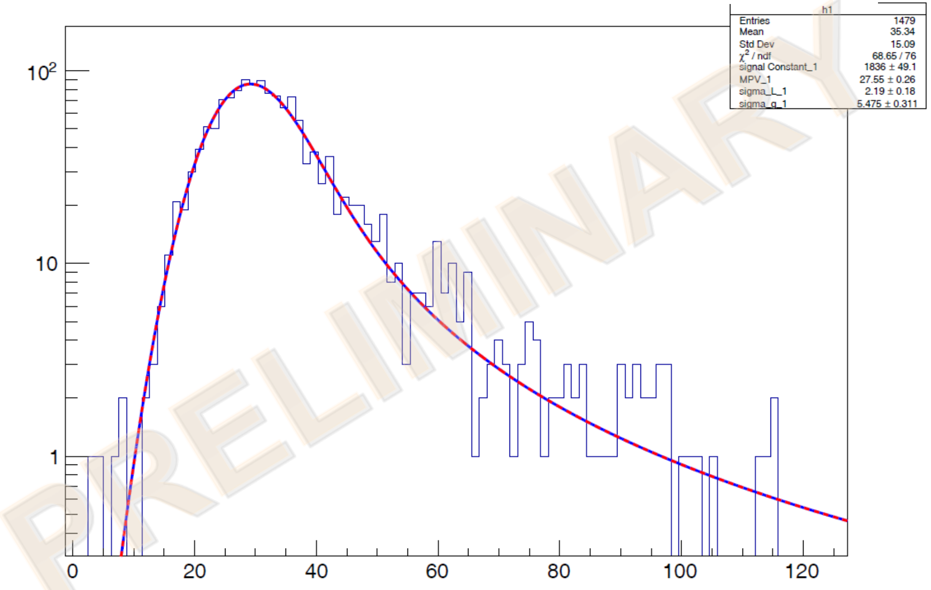
Raw Data from “new” MOLLER Ring 5



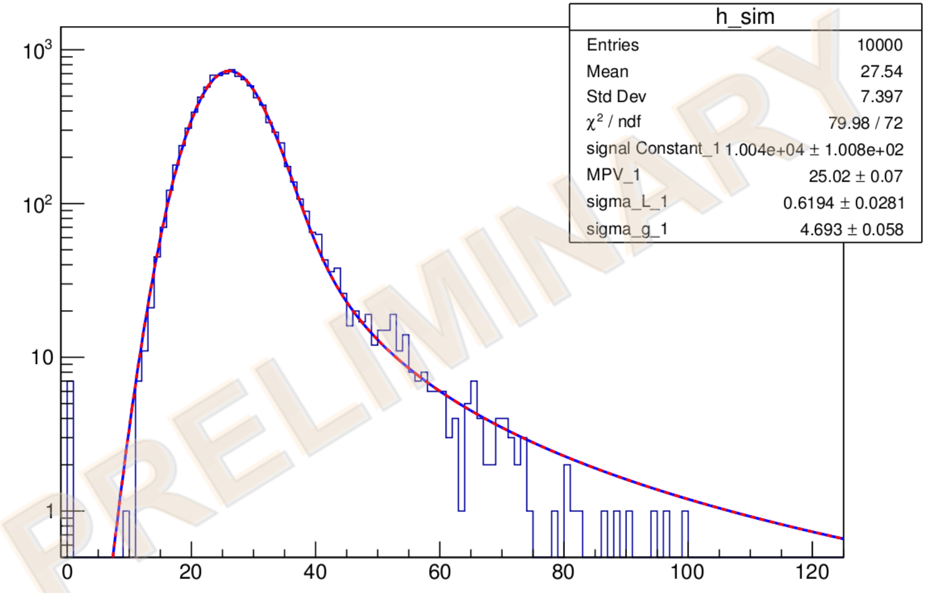
# Cross Check with Simulation

- Preliminary results from SLAC test beam
- Apply GEM tracking detector cuts to try to remove higher multiplicity spectrum

GEM cut Data from “new” MOLLER Ring 5

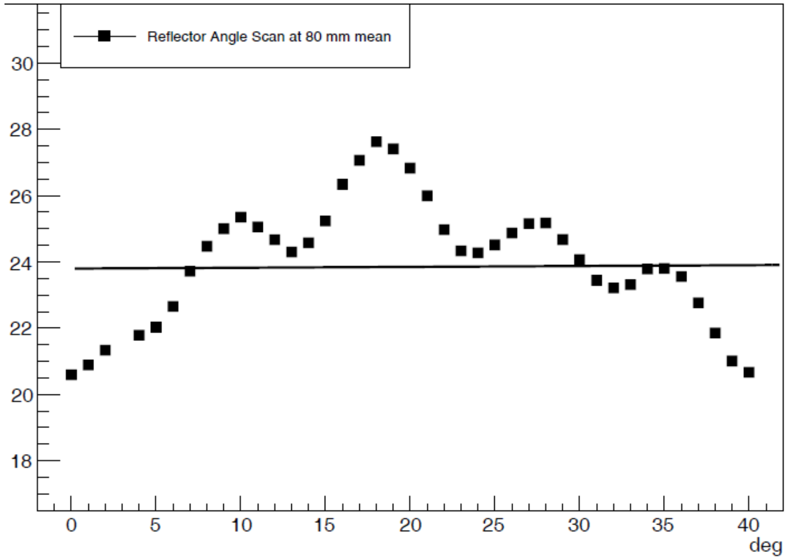



Simulated Data from “new” MOLLER Ring 5

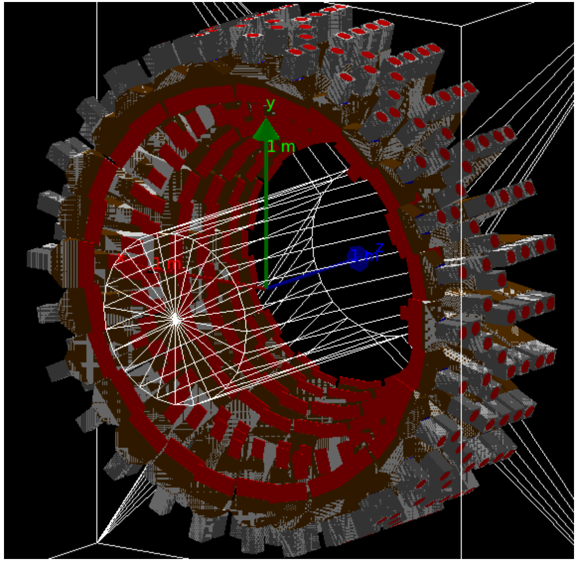


# Looking to the Future

- This test beam serves as a verification of the simulation
- The “new” design performs similarly to the “old” one in simulation and in test data
- We can now move forward with simulating and optimizing the rest of the array




A simulation parameter scan used to pick 18 degrees reflector angle for “new” design




The rest of the MOLLER detector array can now be optimized

# Thank You!

# Backups

# Abstract

The MOLLER experiment proposed at the Thomas Jefferson National Accelerator Facility plans a precision low energy determination of the weak mixing angle via the measurement of the parity-violating asymmetry in longitudinally polarized beam electron scattering on the unpolarized electrons in a liquid hydrogen target (Møller scattering). The scattered electrons are measured by a circular array of thin fused silica tiles which generate Cherenkov photons and transport them to photomultiplier tubes (PMTs) through air light-guides. The detector design must balance constraints of machining, structural support, maximizing the PMTs' optical photon yield and resolution, and minimizing the backgrounds from neighboring separated fluxes. Prior tests at the MAMI facility at Johannes Gutenberg University, Mainz, Germany characterized the effects of Cherenkov and scintillation light generated by flux passing through the air of the detectors' light guides. We report on tests performed at the SLAC End Station A Test Beam (ESTB), Geant4 optical physics simulations, and ongoing studies of optimized detector geometry prototypes for the MOLLER experiment.

# Bethe-Bloch Semi-Empirical Mass Formula

- The distributions of protons and neutrons in an atomic nucleus are hard to find
- Parametrizing energy cost in the nucleus as a bag or liquid drop is effective

$$B(A,Z,N) = a_v A - a_s A^{2/3} - a_C \frac{Z^2}{A^{1/3}} + a_p \frac{\delta}{A^{1/2}} + a_a \frac{(N-Z)^2}{A}$$

Where Z is the atomic number, N is the number of neutrons, and A is Z + N. [1]
The coefficients represent:

- ➢ $a_v$ = Liquid drop <u>v</u>olume term
- ➢ $a_s$ = Bag <u>s</u>urface term
- ➢ $a_C$ = Core <u>C</u>oulombic repulsion term
- ➢ $a_p$ = Spin coupling and fermi exclusion <u>p</u>airing energy term, where $2\delta = (-1)^N + (-1)^Z$
- ➢ $a_a$ = Isospin <u>a</u>symmetry term

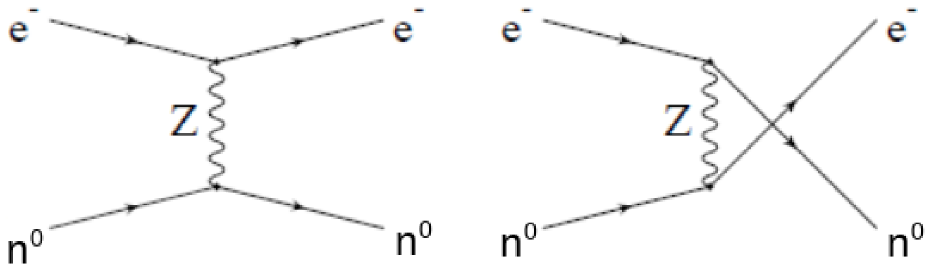
# The Weak Force as a probe of Neutrons

- So, how can we look at neutron skins in neutron rich nuclei?

Parity Violation

- The weak force gives us a tool:
  - Before SSB, weak bosons only couple to the left handed components of SM fermion fields
  - This maximally violates parity in the weak interactions, showing up in the neutral current as

$$\mathcal{L}_{NC} = e j_\mu^{em} A^\mu + \frac{g}{\cos\theta_W}(J_\mu^3 - \sin^2\theta_W J_\mu^{em}) Z^\mu$$




Feynman diagrams for tree level weak neutral current interactions

# The Weak Force as a probe of Neutrons

- So, how can we look at neutron skins in neutron rich nuclei?

  Parity Violation
- The weak force gives us a tool:
  - Before SSB, weak bosons only couple to the left handed components of SM fermion fields
  - This maximally violates parity in the weak interactions, showing up in the neutral current as

$$\mathcal{L}_{NC} = e j_\mu^{em} A^\mu + \frac{g}{\cos\theta_W}(J_\mu^3 - \sin^2\theta_W J_\mu^{em}) Z^\mu$$

- Constructing a parity violating asymmetry $A_{PV}$ to cancel the large EM part and focus on the weak contribution needs P odd:

$$\mathcal{M}^L = -\mathcal{M}^R$$

  - Converting to the scattering Vector + Axial Vector framework
    - $\gamma^\mu$ Vectors are P odd, $\gamma^\mu\gamma^5$ axial vectors are even: a parity odd observable can be V*A
    - The Z boson couples preferentially to left handed particles, whose $J^3$ current projection $\psi_L = \frac{1}{2}(1-\gamma^5)\psi$ gives a $\gamma^5$ that can be used to make an axial vector term
    - Therefore weak interactions can provide parity violation in scattering experiments

# The Weak Force as a probe of Neutrons

- How can we use Parity Violation?
  - With P odd observables, unpolarized weak charge of the proton and neutron ≃ valence quark vector charges

$$Q_w^u = 1 - \tfrac{8}{3}\sin^2\theta_w \text{ and } Q_w^d = -1 + \tfrac{4}{3}\sin^2\theta_w, \text{ with } \sin^2\theta_w \simeq 0.223$$

  - Including radiative corrections, the proton has $Q_W \simeq 1 - 4\sin^2\theta_w \simeq 0.0721$, and the neutron ≃ -0.9878 [4]
  - Since $Q_W$ of the neutron is larger than in the proton, weak nuclear scattering is sensitive to neutrons

# The Weak Force as a probe of Neutrons

- How can we use Parity Violation?
  - With P odd observables, unpolarized weak charge of the proton and neutron ≃ valence quark vector charges

$$Q_w^u = 1 - \tfrac{8}{3}\sin^2\theta_w \text{ and } Q_w^d = -1 + \tfrac{4}{3}\sin^2\theta_w, \text{ with } \sin^2\theta_w \simeq 0.223$$

  - Including radiative corrections, the proton has $Q_W \simeq 1 - 4\sin^2\theta_w \simeq 0.0721$, and the neutron ≃ -0.9878 [4]
  - Since $Q_W$ of the neutron is larger than in the proton, weak nuclear scattering is sensitive to neutrons
  - Following the Born approximation in nuclear elastic scattering + weak interactions, and P odd[1]:

$$\frac{d\sigma^{L,R}}{d\Omega} = \frac{dQ}{F}\left|\mathcal{M}_Z^{L,R} + \mathcal{M}_\gamma\right|^2 \qquad A_{PV} = \frac{\frac{d\sigma_L}{d\Omega} - \frac{d\sigma_R}{d\Omega}}{\frac{d\sigma_L}{d\Omega} + \frac{d\sigma_R}{d\Omega}}$$

$$A_{PV} \approx \frac{\left[\mathcal{M}_\gamma^2 + 2\mathcal{M}_Z\mathcal{M}_\gamma + \mathcal{M}_Z^2\right] - \left[\mathcal{M}_\gamma^2 - 2\mathcal{M}_Z\mathcal{M}_\gamma + \mathcal{M}_Z^2\right]}{\left[\mathcal{M}_\gamma^2 + 2\mathcal{M}_Z\mathcal{M}_\gamma + \mathcal{M}_Z^2\right] + \left[\mathcal{M}_\gamma^2 - 2\mathcal{M}_Z\mathcal{M}_\gamma + \mathcal{M}_Z^2\right]} = \frac{2\mathcal{M}_Z\mathcal{M}_\gamma}{\mathcal{M}_\gamma^2}$$

Where, in nuclear matter, the matrix element for scattering off of a charge is modified by the form factor, the Fourier transform of the charge distribution:

$$F_p(Q^2) = \int Z\rho(x)\,\mathrm{e}^{-\mathrm{iq}\cdot\mathrm{x}}\mathrm{d}^3\mathrm{x}$$

# The Weak Force as a probe of Neutrons

- How can we use Parity Violation?
  - With P odd observables, unpolarized weak charge of the proton and neutron ≃ valence quark vector charges

    $$Q_w^u = 1 - \tfrac{8}{3}\sin^2\theta_w \text{ and } Q_w^d = -1 + \tfrac{4}{3}\sin^2\theta_w, \text{ with } \sin^2\theta_w \simeq 0.223$$

  - Including radiative corrections, the proton has $Q_W \simeq 1 - 4\sin^2\theta_w \simeq 0.0721$, and the neutron ≃ -0.9878 [4]
  - Since $Q_W$ of the neutron is larger than in the proton, weak nuclear scattering is sensitive to neutrons
  - Following the Born approximation in nuclear elastic scattering + weak interactions, and P odd[1]: $A_{PV} \approx \frac{2\mathcal{M}_Z\mathcal{M}_\gamma}{\mathcal{M}_\gamma^2}$
  - Then plugging in the matrix elements, $A_{PV} = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\frac{F_W(Q^2)}{F_p(Q^2)}$

    Decomposing $F_W$ into P + N: $F_W(Q^2) = \int e^{-iq\cdot x}\rho_W(x)\,d^3x = \int e^{-iq\cdot x}\left[\left(1 - 4\sin^2(\theta_W)\right)\rho_p(x) - \rho_n(x)\right]d^3x$

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

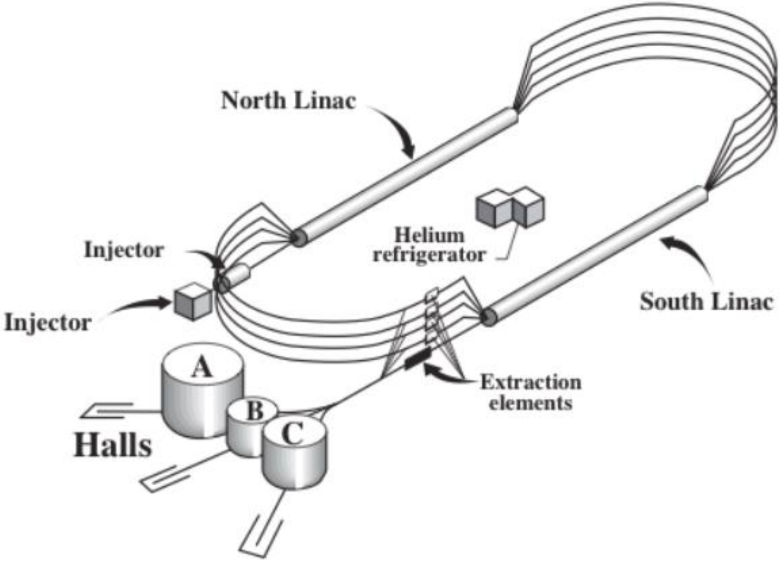
    which <u>measures the neutron form factor</u>
  - Pick a convenient $Q^2$ to measure $F_n(Q^2)$ and use models get to the RMS radius $\langle r^2\rangle = -6\hbar^2 \left.\frac{dF_n(Q^2)}{dQ^2}\right|_{Q^2=0}$
  - This is how we can use parity violation in the electroweak sector to measure nuclear properties

# Detecting tiny asymmetries at JLab

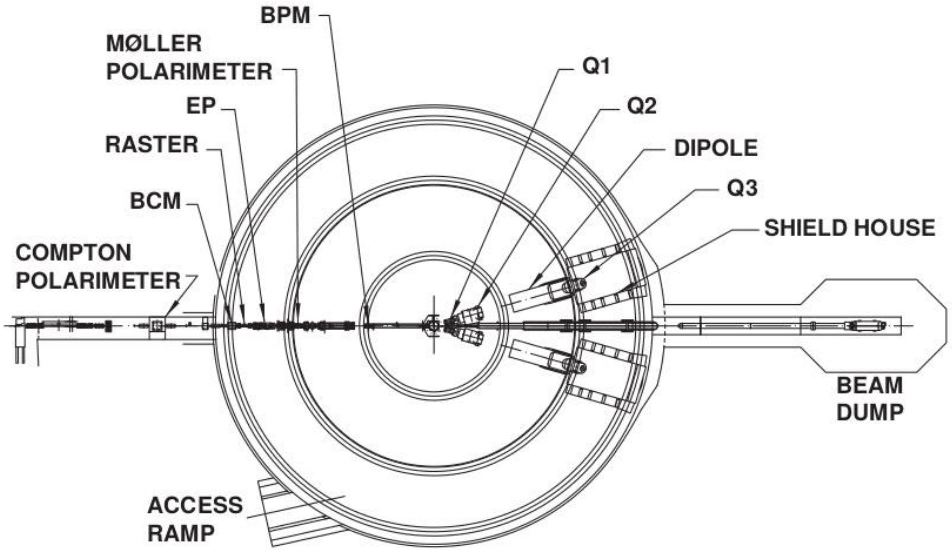
Where do we measure such small asymmetries?

# Detecting tiny asymmetries at JLab

The Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility (JLab) provides GeV energy polarized electrons to fixed target experimental halls




CEBAF schematic




Hall A aerial schematic view

# Backups

- History of Parity Violation
  - 1961 – Weak mixing angle formalism developed by Sheldon Glashow.

$$\begin{pmatrix}\gamma \\ Z^0\end{pmatrix} = \begin{pmatrix}\cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W\end{pmatrix}\begin{pmatrix}B^0 \\ W^0\end{pmatrix}$$

Where $\tan\theta_W = \frac{g'}{g}$, for the theory's coupling constants $g$ and $g'$, or in terms of the electromagnetic coupling, $e = \frac{gg'}{\sqrt{g^2+g'^2}}$, such that $\sin\theta_W = \frac{e}{g}$, $\cos\theta_W = \frac{e}{g'}$

# Backups

- History of Parity Violation
  - 1961 – Weak mixing angle formalism developed by Sheldon Glashow.
  - 1967 – Weinberg adds Higgs mechanism and relates gauge boson masses by $\theta_W$.

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

Where $\tan\theta_W = \frac{g'}{g}$, for the theory's coupling constants $g$ and $g'$, or in terms of the electromagnetic coupling, $e = \frac{gg'}{\sqrt{g^2+g'^2}}$, such that $\sin\theta_W = \frac{e}{g}$, $\cos\theta_W = \frac{e}{g'}$

$$m_W = m_{Z^0}\cos\theta_W$$

# Backups

- History of Parity Violation
  - 1961 – Weak mixing angle formalism developed by Sheldon Glashow.
  - 1967 – Weinberg adds Higgs mechanism and relates gauge boson masses by $\theta_w$.
  - 1971 – T'Hooft proves renormalizability for gauge theories with spontaneous symmetry breaking.
  - 1973 – Weak neutral current ($Z^0$ mediated interaction) in neutrino scattering is discovered at CERN's Gargamelle bubble chamber.
  - 1978 – Parity Violation was first observed in neutral current by the SLAC E122 experiment measuring polarized electron scattering off of deuterium.
  - E122 found $\sin^2\theta_w = 0.22(2)$, matching theoretical predictions, establishing the Standard Model (SM) of particle physics.

# Backups

- History of Parity Violation
  - 1980s – It was determined that $\sin^2\theta_W$ was needed to high precision to verify predictions of theoretical calculations.

$$\sin^2\theta_W(Q^2) = \kappa(Q^2)\sin^2\theta_W(m_Z)$$

where $\kappa(Q^2)$ carries the 1-loop radiative corrections with it. $\kappa(Q^2 = m_Z^2) \equiv 1$, and $\kappa(Q^2 = 0) \simeq 1.03$, which is a nearly 3% shift. Experiments that measure the weak charge of the electron

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

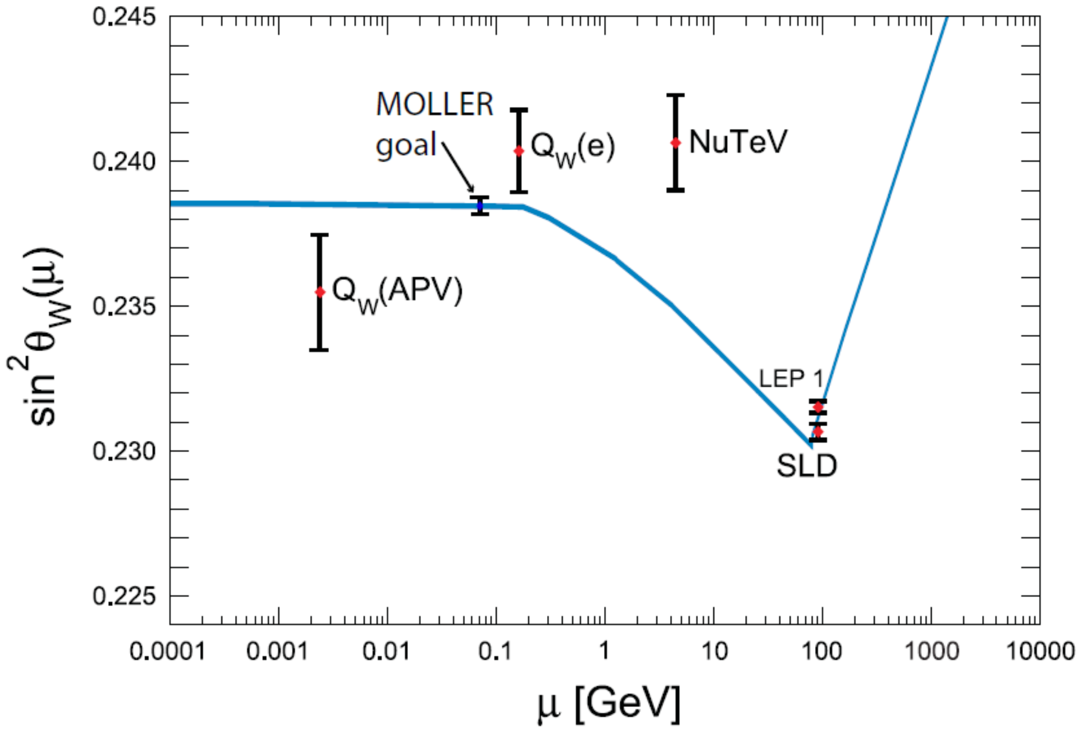
see a 40% shift, from 0.075 to 0.46 (at $Q \simeq 0.1 GeV$)

# Backups

- History of Parity Violation
  - 1961 – Weak mixing angle formalism developed by Sheldon Glashow.
  - 1967 – Weinberg adds Higgs mechanism and relates gauge boson masses by $\theta_w$.
  - 1971 – T'Hooft proves renormalizability for gauge theories with spontaneous symmetry breaking.
  - 1973 – Weak neutral current ($Z^0$ mediated interaction) in neutrino scattering is discovered at CERN's Gargamelle bubble chamber.
  - 1978 – Parity Violation was first observed in neutral current by the SLAC E122 experiment measuring polarized electron scattering off of deuterium.
  - E122 found $\mathrm{Sin}^2\theta_w = 0.22(2)$, matching theoretical predictions, establishing the Standard Model (SM) of particle physics.
  - 1980s – It was determined that $\mathrm{Sin}^2\theta_w$ was needed to high precision to verify predictions of theoretical calculations.
  - Radiative corrections cause $\mathrm{Sin}^2\theta_w$ to change as a function of energy scale (typically taken to be $Q^2$, the momentum transfer of a reaction).

# Backups

- History of Parity Violation

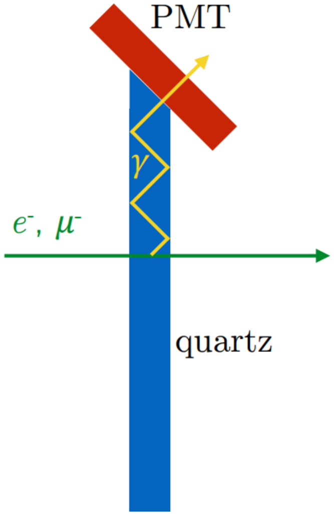


# The Weak Force as a probe of Neutrons

- Weak Interactions in the Standard Model:
    - The Standard Model is a specific theory of Lorentz invariant SO(3,1) fermion fields (4 component spinors) interacting via gauge boson fields, where the gauge group empirically is $SU(3)_c \times SU(2)_L \times U(1)_Y$
    - Spontaneous symmetry breaking of a $SU(2)_L$ doublet scalar Higgs field provides the separation of scales and mass yukawa couplings, and breaks $SU(2)_L \times U(1)_Y$ down to $U(1)_{EM}$ plus three massive weak bosons
    - The weak bosons only couple to the left handed components of SM fermion fields
    - The SO(3,1) spinors can be written as $SU(2)_L \times SU(2)_R$ combined spinors, which allows us to look at the $SU(2)_L$ weak gauge field as acting only on the L handed chiral spinor fields, $\psi_L = ½(1-\gamma^5)\,\psi$ in our field content
    - This maximally violates parity (there is no reason a matching $SU(2)_R$ gauge field couldn't exist, and they are postulated, with their own Higgs's, to restore L-R parity symmetry, and to solve the mass hierarchy of neutrinos through the see-saw mechanism)
    - After SSB the $W^3$ and B mix to give an unbroken and massless $U(1)_{EM}$ boson A (the $\gamma$), and massive $W^\pm$ and $W^0$ (the Z)
    - The Weak Isospin and Hypercharge charges in our field content work together to provide equal electric charges $Q = T_3 + ½Y$ for both the singlet right handed fields and doublet left handed fields, while the weak charge is different, meaning that parity is conserved by the electromagnetic force by construction, but not for any fundamentally evident reason in the standard model, and weak scattering violates parity

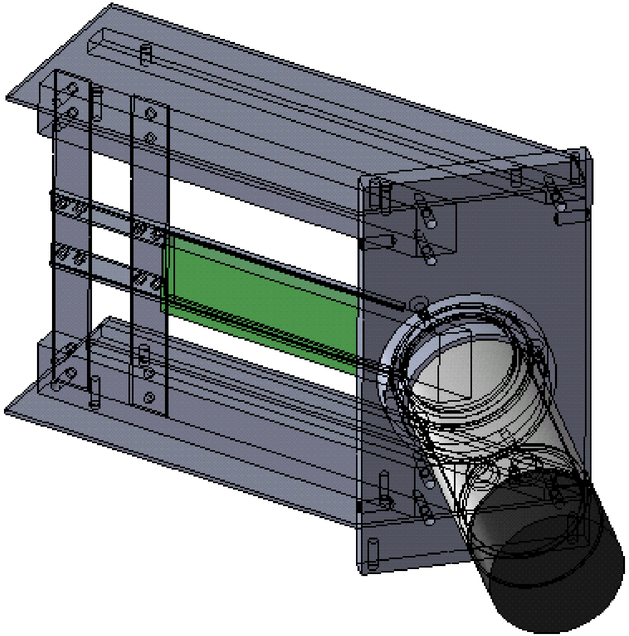
# Designing and Optimizing Detectors

- Cherenkov radiating fused silica ("Quartz") detectors integrate electron flux
- Optimal quartz parameters balance large gaussian photo-electron (PE) yield vs. narrow signal width
- Thicker quartz yields more PEs, but also more delta electrons, falsely indicating more $e^-$ flux than exists



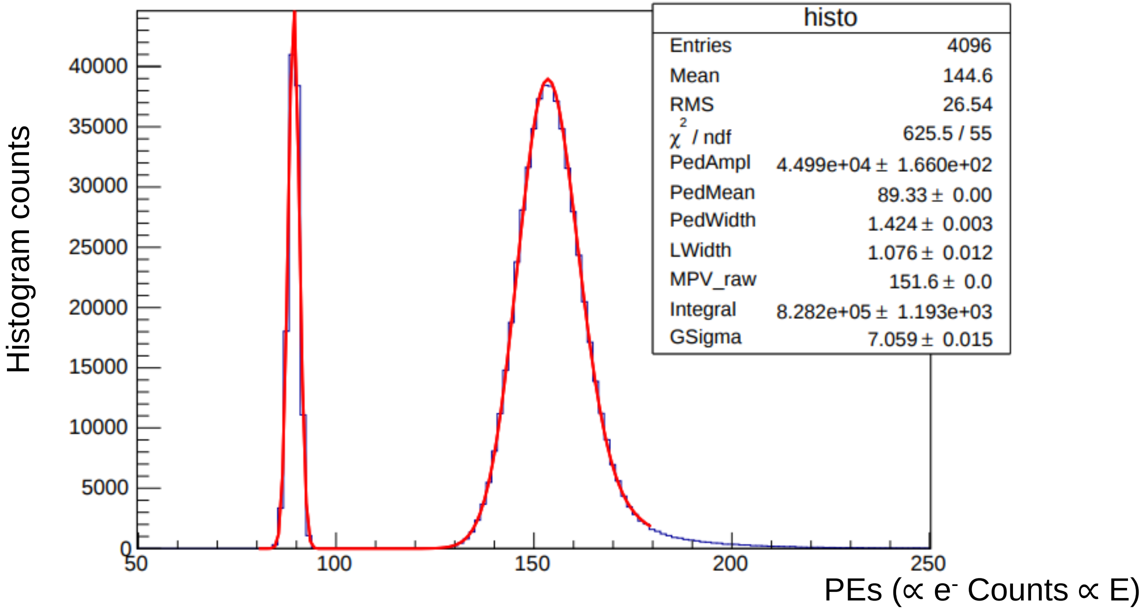

CAD model of new Prex detector design ⇨

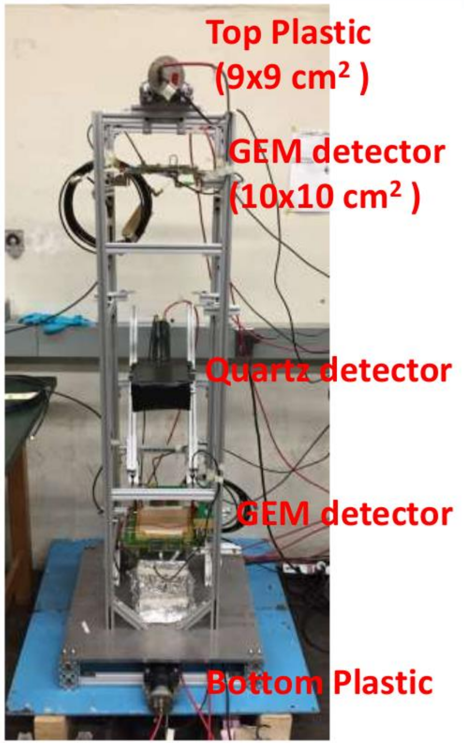
⇦ Cartoon of new Prex detector in action



# Cosmic Stand

Sample Prex detector data from 2015 Mainz test beam




Cosmic test stand I built at SBU, in use to calibrate new Prex detector design with cosmics

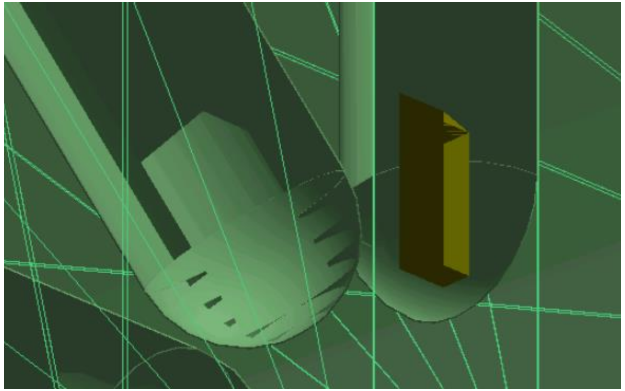
- Fit of Gaussian pedestal and Gaussian convoluted with Landau delta ray tail
- Optimize mean PE yield - maximize counting mode PMT readout signal
- Optimize signal RMS width - detector resolution: $\sigma = \sigma_0\sqrt{1+(\frac{\Delta E}{E})^2} \simeq 1.06$

# Small Angle Monitors (SAMs)

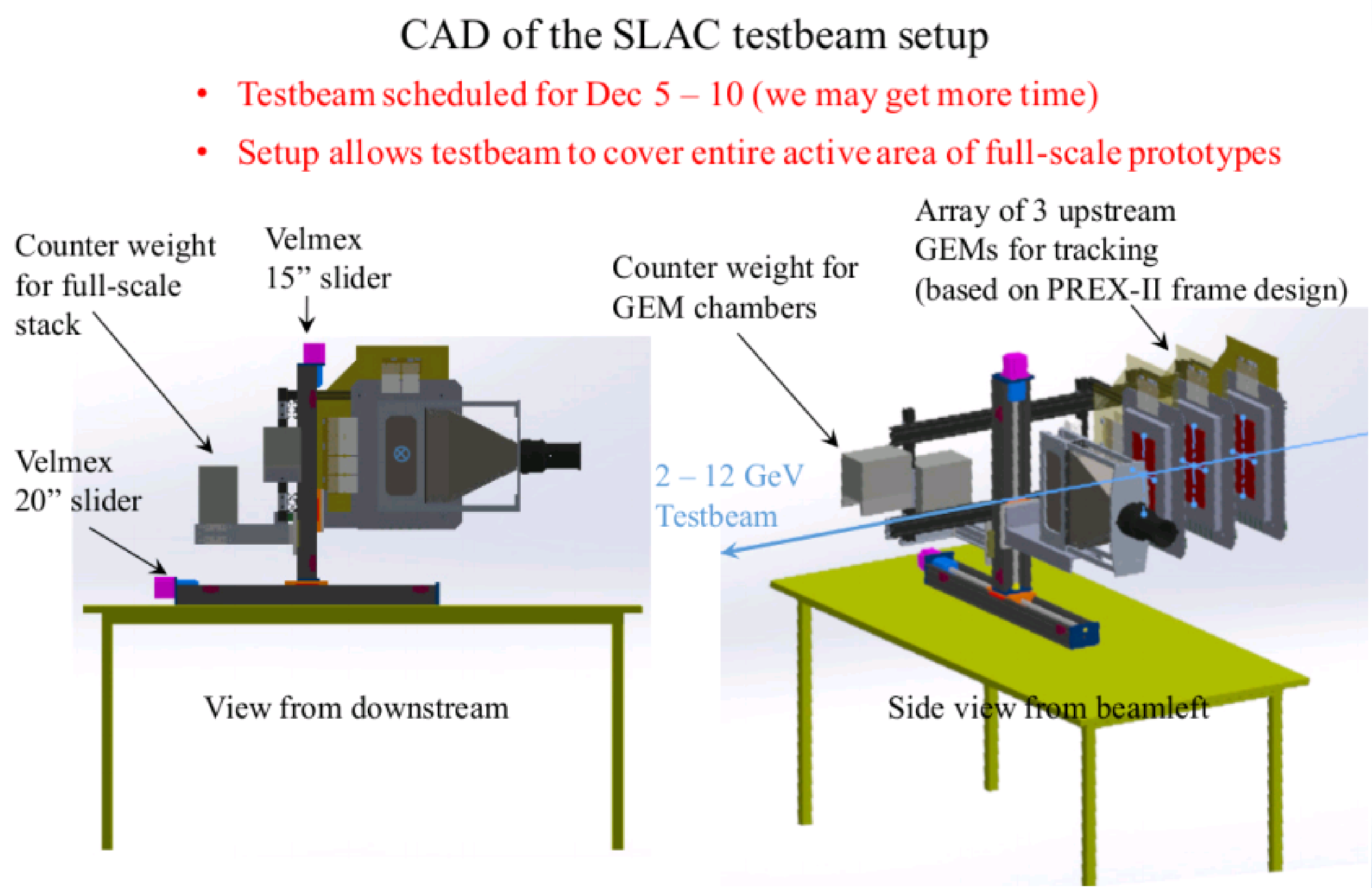
- Also working on Small Angle Monitor (SAM) quartz detectors downstream of the target
  - Function like the main integrating detectors, but with much higher rate → very high statistics check
  - Serve as a diagnostic for problems upstream, as well as indicator of noise floor and stability

⇦ CAD model of SAM detector array design

Simulation visualization of some SAM geometry improvements ⇨



# SLAC Test Pictures



# SLAC Test Pictures

# SLAC Test Pictures