# Parity Violating Electron Scattering
## An Overview of Integration Mode PV Measurements

**JGU CRC 1660 Annual Graduate School**

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With grateful acknowledgement of the support provided by these funding agencies:

DFG Deutsche Forschungsgemeinschaft
NSERC CRSNG
Canada Foundation for Innovation
Fondation canadienne pour l'innovation
Research Manitoba

# There is a lot of PV physics out there …

The stated topic of Parity Violation is huge!

Here is what I will **not** be talking about, but these are no less significant/important:

- Atomic parity violation
- Hadronic PV at low to very low energies
- PVES in nucleon structure physics (form factors, etc.)
- Hadronic PV measurements at higher energies are not discussed (collider physics, e.g. future EIC physics)
- PV measurements on resonances are also not discussed (LHC, e+e- colliders, etc.)

# Outline

- **Introduction / for context**
  - **Introduction to PV / some basic theory – brief summary (make you feel relaxed since you already know all this)**
  - **Motivation (why use PV:  BYSM tests, Astro-physics)**
  - **Experiments (historical view)**

- **Modern PVES experiments**
  - **Basic measurement principle (helicity reversal, detection mode, asymmetries)**
  - **Accelerators and sources (what qualities do we need)**
  - **Basic experimental components (the basics of how to take the measurement)**

- **Measurement details**
  - **Beam properties and diagnostics**
  - **Targets**
  - **Spectrometers**
  - **Acceptance defining collimators**
  - **Detectors**
  - **Asymmetries**
  - **Tracking**
  - **Systematic effects**
  - **Analysis**

# Parity Violation (a brief summary)

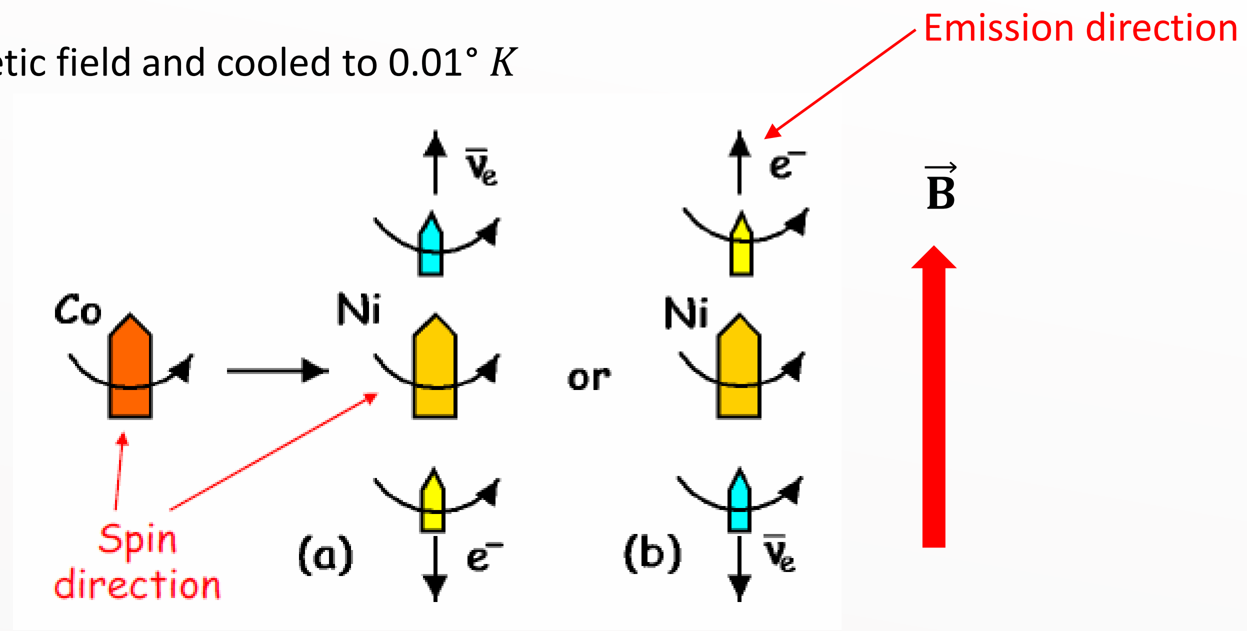
**Parity violation in beta decay (Columbia U.):**

- T-D. Lee and C-N. Yang proposed to test the weak interaction for parity violation (1956)
- C-S. Wu ("Madam" Wu) observes parity violation in beta decay of $^{60}Co$ (not the earliest observation – 1928 by R.T. Cox *et al.*)

In the decay of nuclei with spins aligned in a strong magnetic field and cooled to 0.01° $K$

$$^{60}\boldsymbol{Co} \rightarrow {}^{60}\boldsymbol{Ni} + \boldsymbol{e^-} + \boldsymbol{\bar{\nu}_e}$$

| $^{60}Co$ | $^{60}Ni$ | $e^-$ | $\bar{\nu}_e$ |
|---|---|---|---|
| $j = 5$ | $j = 4$ | $j = 1/2$ | $j = 1/2$ |
| $m_j = 5$ | $m_j = 4$ | $m_j = 1/2$ | $m_j = 1/2$ |




It was found that electrons were emitted predominantly in direction (a), opposite the $^{60}Co$ spin.

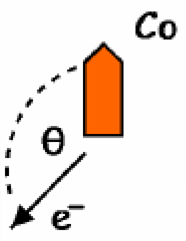
If parity were conserved one would expect (a) and (b) to be equally probable.

# Parity Violation (a brief summary)

**Parity violation in beta decay (Columbia U.):**

- The intensity of emitted electrons from $^{60}Co$ was found to be consistent with the angular distribution:

$$I(\theta) = 1 + f\frac{\vec{s}\cdot\vec{p}}{E} = 1 + f\frac{v}{c}\cos(\theta)$$




The polarization or helicity is defined as:

$$h \equiv \frac{I_+ - I_-}{I_+ + I_-} = \frac{I(0^\circ) - I(180^\circ)}{I(0^\circ) + I(180^\circ)} = f\frac{v}{c}$$

For $I_\pm$ denoting the detector signal intensity for emission parallel and anti-parallel to the momentum.

PV Experimental amplitudes are formed from a product axial and polar vectors: $\vec{s}\cdot\vec{p}$

We can induce a parity "transformation" either by spin reversal or momentum reversal, or both (not simultaneously).

# Parity Violation (a brief summary)

**Parity violation in beta decay (Columbia U.):**

Experimentally one finds:

$$f = +1 \text{ for } e^{+} \quad \rightarrow \quad h = \frac{v}{c}$$

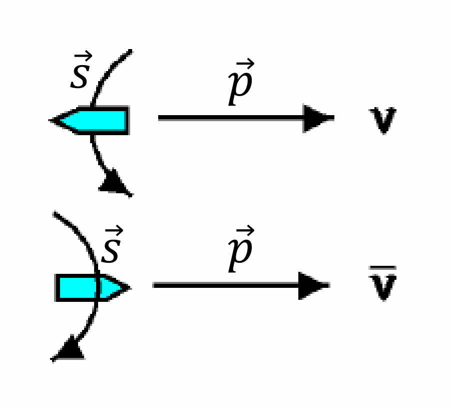
and

$$f = -1 \text{ for } e^{-} \quad \rightarrow \quad h = -\frac{v}{c}$$

Neutrinos (setting $m_\nu = 0 \ \rightarrow v = c$ ) are fully polarised along the axis of motion with $h = \pm 1$.

Experimentally find neutrinos are always $h = -1$ → 'Left-Handed'

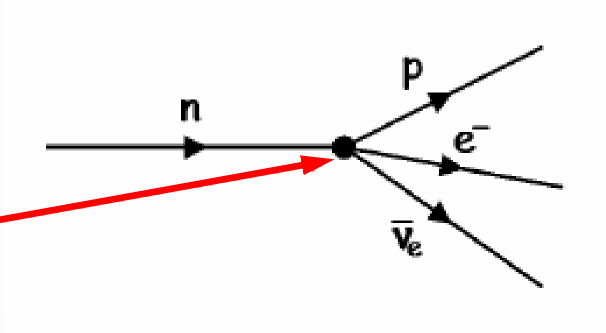
Anti-neutrinos have $h = +1$.



# Parity Violation (a brief summary)

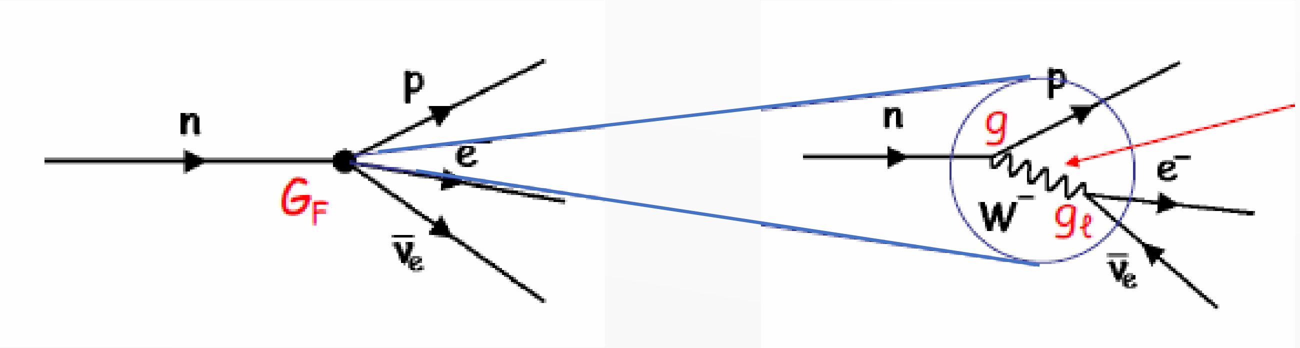
**A model to describe (some of) the observations:**

Fermi's theory of Weak
Interactions (1930s)
had a point-like interaction.




Fermi Coupling constant $G_F$
→ 'strength' of the Weak interaction

Modern interpretation:




$\approx \frac{1}{M_W^2}$

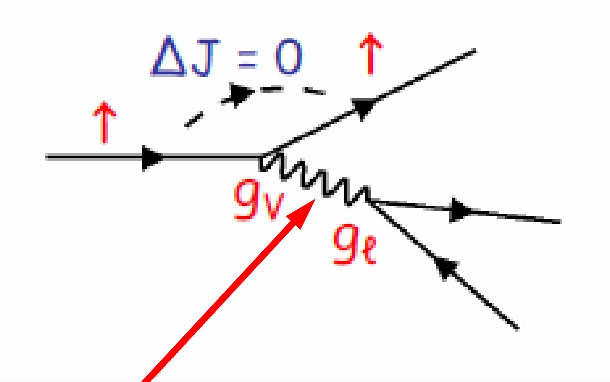
$$G_F \to g g_\ell \left(\frac{1}{M_W^2}\right)$$

Weak Interaction due to $W^{\pm}$ and $Z^0$(not shown) boson exchange. Short range (previously thought point-like) due to large ~80 GeV (~100 GeV for $Z^0$) mass.

# Parity Violation (a brief summary)

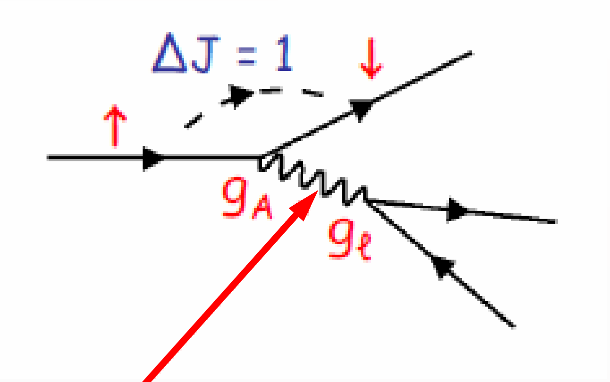
**A model to describe (some of) the observations:**

Either no spin transfer
Between initial and final state:




W has momentum but
no angular momentum
→ **Vector coupling**

or there is spin transfer
between initial and final state:




W has momentum and
angular momentum
→ **Axial Vector coupling**

Experimentally it is found that $g_V \approx -g_A$

→ **V-A interaction**

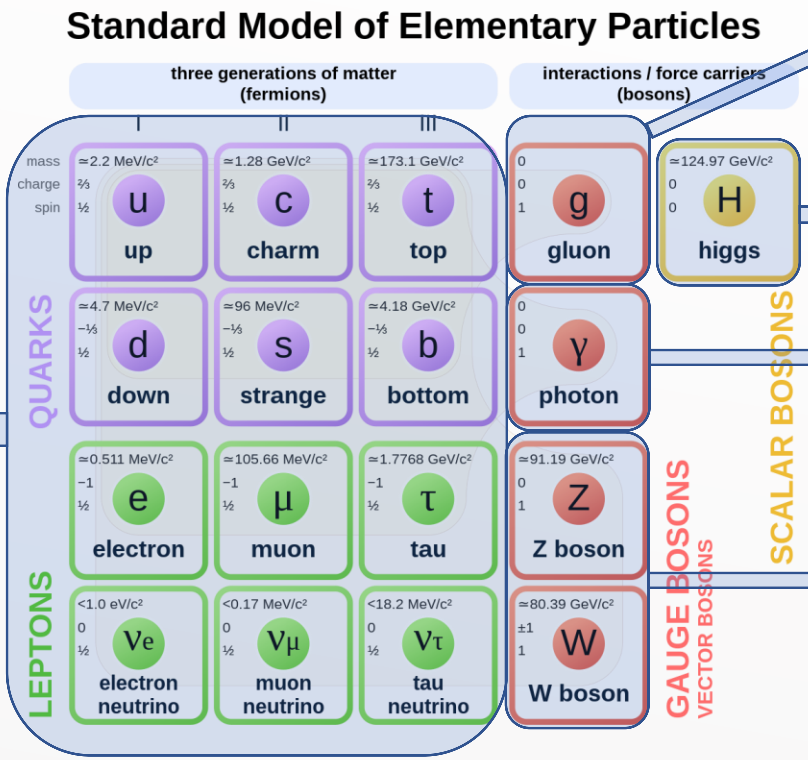
Charged current leptons

V+A not ruled out by current Standard Model

# Parity Violation (a brief summary)

**A model to describe (some of) the observations:**

Dirac equation
(Describes relativistic spin ½ particles)

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Maxwell-like Equations, but with a modified field strength tensor
(Describes "charged" mass-less spin 1 particles)

Klein-Gordon Equation
(Describes massive spin 0 particles)

Maxwell's Equations
(Describes neutral mass-less spin 1 particles)

Proca Equation (Klein-Gordon with sources or Maxwell with mass term) (Describes massive spin 1 particles)

# Parity Violation (a brief summary)

**A model to describe the observations:**

Experimental fact: The Weak interaction is not invariant under parity transformation. How to put this into the model?

**Left and right handedness:**

The Dirac equation turns out to have the correct transformation behavior under parity:

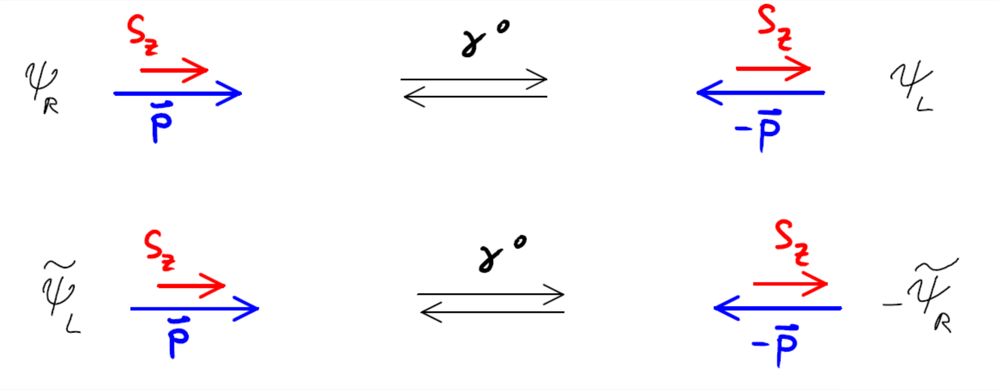
$$\boxed{P_R = \frac{1}{2}(1+\gamma_5) \qquad P_L = \frac{1}{2}(1-\gamma_5)}$$

$$P_R + P_L = I \;\Rightarrow\; \psi = (P_R + P_L)\psi = \psi_R + \psi_L = \frac{1}{2}(1+\gamma_5)\psi + \frac{1}{2}(1-\gamma_5)\psi$$

Turns out, the *left* and *right-handed* projections of the solutions to the Dirac equation have the "correct" behaviour:

Particles:

Anti-particles




$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

$$\hat{\Pi} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = \gamma^0$$

$$\hat{\Pi}\, \psi_\lambda(t, \vec{\boldsymbol{p}}, \vec{\boldsymbol{x}}) = \psi_\lambda(t, -\vec{\boldsymbol{p}}, -\vec{\boldsymbol{x}})$$

$$\hat{\Pi}\, \tilde{\psi}_\lambda(t, \vec{\boldsymbol{p}}, \vec{\boldsymbol{x}}) = -\tilde{\psi}_\lambda(t, -\vec{\boldsymbol{p}}, -\vec{\boldsymbol{x}})$$

# Parity Violation (a brief summary)

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Experimental fact: The Weak interaction is not invariant under parity transformation. How to put this into the model?

**Left and right handedness:**

Turns out, the *left* and *right-handed* projections of the solutions to the Dirac equation have the "correct" behaviour:

Particles:

$$\psi_R = \frac{1}{2}(1+\gamma_5)\psi$$

$$\psi_L = \frac{1}{2}(1-\gamma_5)\psi$$

$$\overline{\psi}_R = \overline{\psi}\frac{1}{2}(1-\gamma_5)$$

$$\overline{\psi}_L = \overline{\psi}\frac{1}{2}(1+\gamma_5)$$

Anti-Particles:

$$\tilde{\psi}_R = \frac{1}{2}(1-\gamma_5)\tilde{\psi}$$

$$\tilde{\psi}_L = \frac{1}{2}(1+\gamma_5)\tilde{\psi}$$

$$\overline{\tilde{\psi}}_R = \overline{\tilde{\psi}}\frac{1}{2}(1+\gamma_5)$$

$$\overline{\tilde{\psi}}_L = \overline{\tilde{\psi}}\frac{1}{2}(1-\gamma_5)$$

# Parity Violation (a brief summary)

**A model to describe the observations:**

**Intrinsic Parities of fundamental (Dirac) particles:**

Using the Dirac equation one can show that (within that model) all spin ½ particles have opposite parity to spin ½ anti-particles.

All spin-½ particles have $\Pi = +1$ : $\boxed{\boldsymbol{\Pi_\nu = \Pi_q = \Pi_{\tau^-} = \Pi_{\mu^-} = \Pi_{e^-} = +1}}$

And anti-particles have $\Pi = -1$ : $\boxed{\boldsymbol{\Pi_{\bar{\nu}} = \Pi_{\bar{q}} = \Pi_{\tau^+} = \Pi_{\mu^+} = \Pi_{e^+} = -1}}$

**Also,**

For the Spin 1 bosons: $\boxed{\boldsymbol{\Pi_\gamma = \Pi_{gluon} = \Pi_{W^+} = \Pi_{W^-} = \Pi_Z = -1}}$

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

$$\hat{\Pi} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = \gamma^0$$

$$\hat{\Pi}\,\psi_\lambda(t,\vec{\boldsymbol{p}},\vec{\boldsymbol{x}}) = \psi_\lambda(t,-\vec{\boldsymbol{p}},-\vec{\boldsymbol{x}})$$

$$\hat{\Pi}\,\tilde{\psi}_\lambda(t,\vec{\boldsymbol{p}},\vec{\boldsymbol{x}}) = -\tilde{\psi}_\lambda(t,-\vec{\boldsymbol{p}},-\vec{\boldsymbol{x}})$$

# Parity Violation (a brief summary)

**A model to describe the observations:**

**Particle currents:**

One can prove (W. Pauli) that the following bilinear currents are the only ones needed to form any particle interaction of this type (they are a complete set and form a basis):

| Type | Form | Parity |
|---|---|---|
| • Scalar | $\bar{\psi}\psi$ | even |
| • Pseudoscalar | $\bar{\psi}\gamma_5\psi$ | odd |
| • Vector | $\bar{\psi}\gamma^{\mu}\psi$ | even |
| • Pseudovector | $\bar{\psi}\gamma^{\mu}\gamma_5\psi$ | odd |
| • Tensor | $\bar{\psi}\sigma^{\mu\nu}\psi$ | even |

# Parity Violation (a brief summary)

**A model to describe the observations:**

**Parity violating particle currents:**

So we can write down the following currents that transform under parity in a well-defined way:

Particles → Particles: $\overline{\psi}_L\gamma^\mu\psi_L = \frac{1}{2}\overline{\psi}\gamma^\mu(1-\gamma_5)\psi \overset{\boldsymbol{\Pi}}{\rightleftarrows} \overline{\psi}_R\gamma^\mu\psi_R = \frac{1}{2}\overline{\psi}\gamma^\mu(1+\gamma_5)\psi$

Anti-Particles → Anti-Particles: $\overline{\tilde{\psi}}_L\gamma^\mu\tilde{\psi}_L = \frac{1}{2}\overline{\tilde{\psi}}\gamma^\mu(1+\gamma_5)\tilde{\psi} \rightleftarrows \overline{\tilde{\psi}}_R\gamma^\mu\tilde{\psi}_R = \frac{1}{2}\overline{\tilde{\psi}}\gamma^\mu(1-\gamma_5)\tilde{\psi}$

Anti-Particles → Particles: $\overline{\psi}_R\gamma^\mu\tilde{\psi}_L = \frac{1}{2}\overline{\psi}\gamma^\mu(1+\gamma_5)\tilde{\psi} \rightleftarrows \overline{\psi}_L\gamma^\mu\tilde{\psi}_R = \frac{1}{2}\overline{\psi}\gamma^\mu(1-\gamma_5)\tilde{\psi}$

Particles → Anti-Particles: $\overline{\tilde{\psi}}_R\gamma^\mu\psi_L = \frac{1}{2}\overline{\tilde{\psi}}\gamma^\mu(1-\gamma_5)\psi \rightleftarrows \overline{\tilde{\psi}}_L\gamma^\mu\psi_R = \frac{1}{2}\overline{\tilde{\psi}}\gamma^\mu(1+\gamma_5)\psi$

# Parity Violation (a brief summary)

**A model to describe the observations:**

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Particles → Anti-Particles: $$\bar{\tilde{\psi}}_R \gamma^\mu \psi_L = \frac{1}{2}\bar{\tilde{\psi}}\gamma^\mu(1-\gamma_5)\psi \quad \rightleftharpoons \quad \bar{\tilde{\psi}}_L \gamma^\mu \psi_R = \frac{1}{2}\bar{\tilde{\psi}}\gamma^\mu(1+\gamma_5)\psi$$

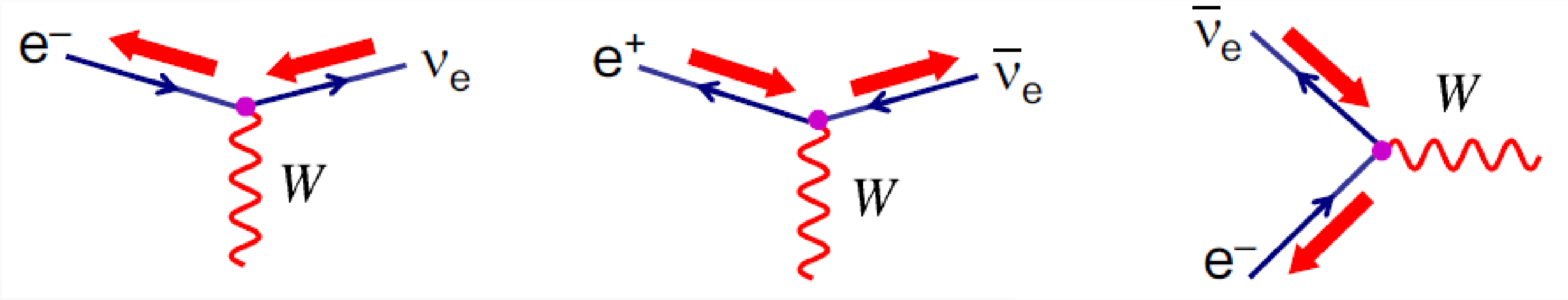
Only these are observed for the charged weak interactions $(W^{\pm})$ … the $V - A$ (vector – axial vector)

# Parity Violation (a brief summary)

**A model to describe the observations:**

**Parity violating particle currents:**

Example: In the relativistic limit, the only possible electron – neutrino interactions are:




| Left-handed | Right-handed | Left/Right-handed |
|---|---|---|
| $\overline{\psi}_L\gamma^\mu\psi_L = \frac{1}{2}\overline{\psi}\gamma^\mu(1-\gamma_5)\psi$ | $\overline{\tilde{\psi}}_R\gamma^\mu\tilde{\psi}_R = \frac{1}{2}\overline{\tilde{\psi}}\gamma^\mu(1-\gamma_5)\tilde{\psi}$ | $\overline{\tilde{\psi}}_R\gamma^\mu\psi_L = \frac{1}{2}\overline{\tilde{\psi}}\gamma^\mu(1-\gamma_5)\psi$ |

# Parity Violation (a brief summary)

$$M_{fi} = \frac{g}{2\sqrt{2}}\left[\bar{\psi}\gamma^{\mu}(1-\gamma_5)\psi\right]\frac{\left(g_{\mu\nu} - q_\mu q_\nu / M_{Z,W}^2\right)}{q^2 - M_{Z,W}^2}\frac{g}{2\sqrt{2}}\left[\bar{\psi}\gamma^{\nu}(1-\gamma_5)\psi\right]$$

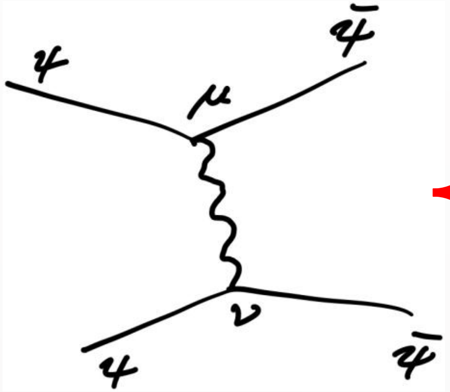
$$g_V \approx -g_A \equiv g$$

$$g \propto M_W\sqrt{G_F}$$

**A model to describe the observations:**

**Parity violating particle interactions:**

A linear combination of axial-vector and vector current (now with couplings).




$$J_1^{\mu}(x) = \bar{\psi}(g_V\gamma^{\mu} + g_A\gamma^{\mu}\gamma_5)\psi \equiv g_V J_{V_1}^{\mu} + g_A J_{A_1}^{\mu}$$

$$\frac{g_{\mu\nu}}{q^2 - m^2}$$

$$J_2^{\nu}(x) = \bar{\psi}(g_V\gamma^{\nu} + g_A\gamma^{\nu}\gamma_5)\psi \equiv g_V J_{V_1}^{\nu} + g_A J_{A_1}^{\nu}$$

$$M \propto J_1^{\mu} g_{\mu\nu} J_2^{\nu} = g_V^2\, J_{V_1}^{\mu} J_{\mu}^{V_2} + g_A^2\, J_{A_1}^{\mu} J_{\mu}^{A_2} + g_V g_A\left(J_{V_1}^{\mu}\, J_{\mu}^{A_2} + J_{A_1}^{\mu}\, J_{\mu}^{V_2}\right)$$

With a parity transformation we get: $\boxed{M \xrightarrow{\Pi} g_V^2\, J_{\mu}^{V_1}\, J_{V_2}^{\mu} + g_A^2\, J_{\mu}^{A_1}\, J_{A_2}^{\mu} - g_V g_A\left(J_{\mu}^{V_1}\, J_{A_2}^{\mu} + J_{\mu}^{A_1}\, J_{V_2}^{\mu}\right)}$

## Parity Violation (a brief summary)

**A model to describe the observations:**

**Problems:**

1. The left and right-handed fields do not satisfy the Dirac equation separately unless they are massless:

$$(i\gamma^\mu\partial_\mu - m)\psi^{L,R}(x) = \frac{1}{2}(i\gamma^\mu\partial_\mu - m)\psi(x) \mp \frac{1}{2}(i\gamma^\mu\partial_\mu - m)\gamma_5\psi(x) = \frac{1}{2}\gamma_5(-i\gamma^\mu\partial_\mu - m)\psi(x) \neq 0$$

2. The YM lagrangian for the vector bosons ($W^\pm, Z^0$) has not mass terms

$$\begin{aligned}\mathcal{L}_{YM} &= \frac{1}{4}\vec{E}_{\mu\nu}\cdot\vec{E}^{\mu\nu} \\ &= -\frac{1}{4}\left(\partial_\mu\vec{B}_\nu - \partial_\nu\vec{B}_\mu\right)\cdot\left(\partial^\mu\vec{B}^\nu - \partial^\nu\vec{B}^\mu\right) - 2g\left(\partial_\mu\vec{B}_\nu - \partial_\nu\vec{B}_\mu\right)\cdot\left(\vec{B}^\mu\times\vec{B}^\nu\right) + g^2\left(\vec{B}_\mu\times\vec{B}_\nu\right)\cdot\left(\vec{B}^\mu\times\vec{B}^\nu\right)\end{aligned}$$

The model so far describes a mass-less universe for weak interactions …

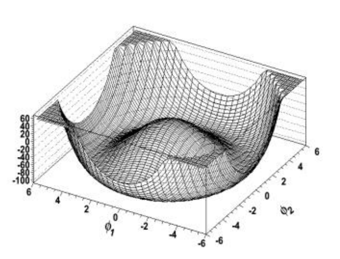
# Parity Violation (a brief summary)

**A model to describe the observations:**

- The Weak interaction is not invariant under parity transformation, which takes left-handed particles into right-handed particles and vice-versa.
- Left-handed particles are observed to only transform as iso-spinors, while right-handed particles are observed to transform only as iso-scalars (charged). The opposite is true for anti-particles. So there is a clear distinction in nature, between these two groups.
- Left- and right-handed fields are given by $\psi_L = \frac{1}{2}(1-\gamma_5)\psi$ and $\psi_R = \frac{1}{2}(1+\gamma_5)\psi$
- But $(i\gamma^\mu\partial_\mu\psi - m)\psi_{L,R} \neq 0$ . So the left-handed and right-handed fields do not satisfy the Dirac equation separately, unless the mass term is zero.
- We must keep the Dirac equation if we want to correctly describe spin ½ relativistic point particles
- But in this case we are then dealing with a theory of massless particles. The fact that the Weak interaction behaves differently for left-handed and right-handed particles forces us into this situation.
- Lagrangians for the massive bosons that have added mass terms violate the gauge invariance
- So we have to somehow generate the mass terms differently in the theory.

# Parity Violation (a brief summary)

**So we need some way to "generate" the masses in the theory !**



$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \upsilon + \sigma \end{pmatrix}$

**Spontaneous Symmetry Braking**

**Higgs Mechanism**

**Not discussed in detail here (see literature)**

$$\mathcal{L} = (D^\mu\Phi)^\dagger(D_\mu\Phi) - \mu^2|\Phi|^2 + \lambda|\Phi|^4 - \frac{1}{4}\vec{E}_{\mu\nu}\cdot\vec{E}^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$(D^\mu\Phi)^\dagger(D_\mu\Phi) = \frac{1}{2}\partial_\mu(\sigma+\upsilon)\partial^\mu(\sigma+\upsilon) + \frac{1}{4}(\sigma+\upsilon)^2 g^2 W_\mu^+ W_-^\mu + \frac{1}{8}(\sigma+\upsilon)^2 \begin{pmatrix} B_\mu^0 & A_\mu \end{pmatrix}\begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix}\begin{pmatrix} B_\mu^0 \\ A_\mu \end{pmatrix}$$

$$W_\mu^- = \frac{1}{\sqrt{2}}(B_\mu^1 - iB_\mu^2)$$

$$W_\mu^+ = \frac{1}{\sqrt{2}}(B_\mu^1 + iB_\mu^2)$$

$$Z_\mu = \frac{gB_\mu^0 - g'A_\mu}{\sqrt{g'^2 + g^2}}$$

Neutral Weak boson

$$\Gamma_\mu = \frac{g'B_\mu^0 + gA_\mu}{\sqrt{g'^2 + g^2}}$$

Photon

$$D_\mu\Phi = \partial_\mu\Phi + ig\left(\vec{B}_\mu\cdot\vec{T}\right)\Phi + \frac{1}{2}ig'A_\mu\Phi$$

# Parity Violation (a brief summary)

**So we need some way to "generate" the masses in the theory !**

- If we now use the following definitions

$$Z_\mu = \frac{gB_\mu^0 - g'A_\mu}{\sqrt{g'^2 + g^2}}$$ Neutral Weak vector boson

$$\Gamma_\mu = \frac{g'B_\mu^0 + gA_\mu}{\sqrt{g'^2 + g^2}}$$ Photon

we get ($\upsilon$ only)

$$(D^\mu \Phi)^\dagger (D_\mu \Phi) = M_W^2 W_\mu^+ W_-^\mu + \frac{1}{8}\upsilon^2 (\Gamma_\mu \quad Z_\mu) \begin{pmatrix} 0 & 0 \\ 0 & g'^2 + g^2 \end{pmatrix} \begin{pmatrix} \Gamma_\mu \\ Z_\mu \end{pmatrix}$$

$$= M_W^2 W_\mu^+ W_-^\mu + \frac{1}{8}\upsilon^2 (0) \Gamma_\mu \Gamma^\mu + \frac{1}{8}\upsilon^2 (g'^2 + g^2) Z_\mu Z^\mu$$

- So if we define the masses for the photon ($M_Y = 0$) and the neutral $Z$ boson ($M_Z = \frac{1}{2}\upsilon\sqrt{g'^2 + g^2}$), then we finally get

$$\boxed{(D^\mu \Phi)^\dagger (D_\mu \Phi) = M_W^2 W_\mu^+ W_-^\mu + \frac{1}{2} M_Z^2 Z_\mu Z^\mu}$$ $M_W = \frac{1}{2}\upsilon g$

# Parity Violation (a brief summary)

**So we need some way to “generate” the masses in the theory !**

- The gauge constants $g$ and $g'$ are clearly not independent now (they are coupled by the definitions of the photon and the neutral weak boson).

  It is more convenient to have one neutral electro-weak coupling constant and let the other one vary continuously (over all possible values) relative to the first.

  Since $g$ is already used to define the mass of the $W$ boson, we keep it as the fundamental weak coupling constant and let the other one vary with respect to it. This is done by defining a trigonometric function of a “mixing angle”:

- Weak mixing angle (also called the Weinberg angle)

$$\boxed{\tan(\theta_W) = \frac{g'}{g}}$$

- With this we have

$$Z_\mu = \frac{gB_\mu^0 - g'A_\mu}{\sqrt{g'^2 + g^2}} \Rightarrow \boxed{Z_\mu = B_\mu^0 \cos(\theta_W) - A_\mu \sin(\theta_W)}$$

$$\Gamma_\mu = \frac{g'B_\mu^0 + gA_\mu}{\sqrt{g'^2 + g^2}} \Rightarrow \boxed{\Gamma_\mu = B_\mu^0 \sin(\theta_W) + A_\mu \cos(\theta_W)}$$

# Parity Violation (a brief summary)

**So we need some way to "generate" the masses in the theory !**

- Coupling the matter fields to the Weak bosons happens in a similar way (example for left-handed iso-spinors):

$$i\overline{\Psi}^L_\ell \gamma_\mu D^\mu_{L_\ell} \Psi^L_\ell \quad \rightarrow \quad \mathcal{L}_{CW,fI} = i\begin{pmatrix} \overline{\psi}^L_{\nu_\ell} & \overline{\psi}^L_\ell \end{pmatrix} \gamma_\mu \begin{pmatrix} 0 & \frac{1}{2} ig\left(B_1^\mu - iB_2^\mu\right) \\ \frac{1}{2} ig\left(B_1^\mu + iB_2^\mu\right) & 0 \end{pmatrix} \begin{pmatrix} \psi^L_{\nu_\ell} \\ \psi^L_\ell \end{pmatrix} = -\frac{g}{\sqrt{2}} \overline{\psi}^L_{\nu_\ell} \gamma_\mu W^{\mu -} \psi^L_\ell - \frac{g}{\sqrt{2}} \overline{\psi}^L_\ell \gamma_\mu W^{\mu +} \psi^L_{\nu_\ell}$$

Charged Current $$\boxed{\mathcal{L}_{W^\pm,fI} = -\frac{g}{2\sqrt{2}} \overline{\psi}_{\nu_\ell} \gamma_\mu (1-\gamma_5) \psi_\ell W^{\mu -} - \frac{g}{2\sqrt{2}} \overline{\psi}_\ell \gamma_\mu (1-\gamma_5) \psi_{\nu_\ell} W^{\mu +}}$$

$$i\overline{\Psi}^L_\ell \gamma_\mu D^\mu_{L_\ell} \Psi^L_\ell \rightarrow \quad \mathcal{L}_{NW,fI} = i\begin{pmatrix} \overline{\psi}^L_{\nu_\ell} & \overline{\psi}^L_\ell \end{pmatrix} \gamma_\mu \begin{pmatrix} ig'YA^\mu + \frac{1}{2} igB_0^\mu & 0 \\ 0 & ig'YA^\mu - \frac{1}{2} igB_0^\mu \end{pmatrix} \begin{pmatrix} \psi^L_{\nu_\ell} \\ \psi^L_\ell \end{pmatrix}$$

Neutral Current $$\boxed{\mathcal{L}_{NW,fI} = -\frac{g}{2\cos(\theta_W)} \overline{\psi}^L_{\nu_\ell} \gamma_\mu \psi^L_{\nu_\ell} Z_0^\mu + \frac{g}{2\cos(\theta_W)} \overline{\psi}^L_\ell \gamma_\mu \left(1 - 2\sin^2(\theta_W)\right) \psi^L_\ell Z_0^\mu}$$

And similarly for quarks …

$$D_\mu \Phi = \partial_\mu \Phi + ig\left(\vec{B}_\mu \cdot \vec{T}\right)\Phi + ig'YA_\mu\Phi$$

# Parity Violation (a brief summary)

**So we need some way to "generate" the masses in the theory !**

- Neutral Current Weak charges:

$$J^{\mu}_{NW} = \sum_f \bar{\psi}_f \gamma^{\mu} \left( g_V^f + g_A^f \gamma_5 \right) \psi_f$$

$$g_V^u = \quad 1 - \frac{8}{3} \sin^2 \theta_W \qquad g_A^u = -1$$

$$g_V^d = -1 + \frac{4}{3} \sin^2 \theta_W \qquad g_A^d = \quad 1$$

$$g_V^e = -1 + 4 \sin^2 \theta_W \qquad g_A^e = \quad 1$$

$Q_W^p = 2g_V^u + g_V^d = \ 1 - 4 \sin^2 \theta_W$ **QWeak , P2@Mainz**

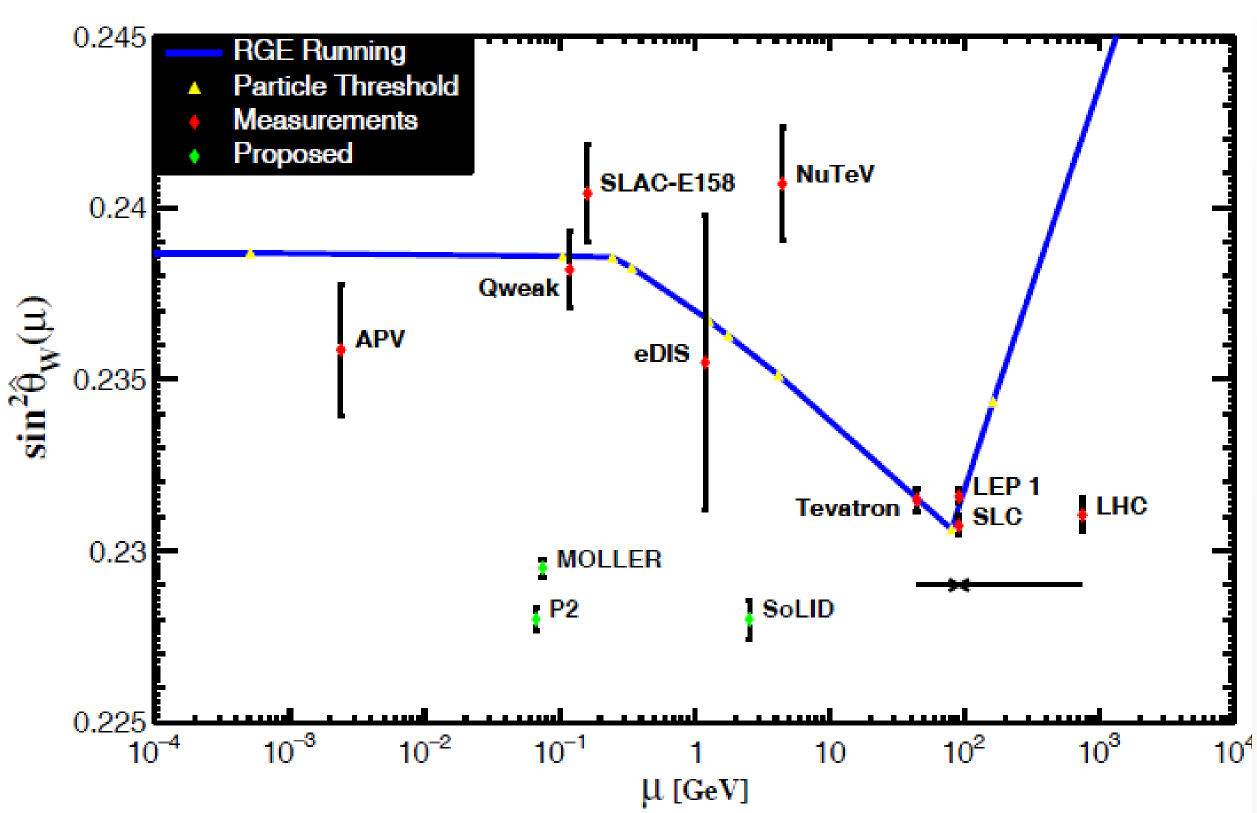
$Q_W^n = 2g_V^d + g_V^u = -1$ **PREX/CREX, MREX@Mainz**

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

# PVES Measurements (focus on BSM tests)

## The Weak Mixing Angle

J. Erler (JGU), reproduced with permission




The weak mixing angle is a central parameter of the electroweak part of the Standard Model:

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

SU(2): Gauge fields $(B^+, B^-, B^0)$ and coupling $g$

U(1): Gauge field $A$ and coupling $g'$

"On-shell" definition in terms of boson masses:

$$\sin^2(\theta_W) = 1 - \frac{m_W^2}{m_Z^2}$$

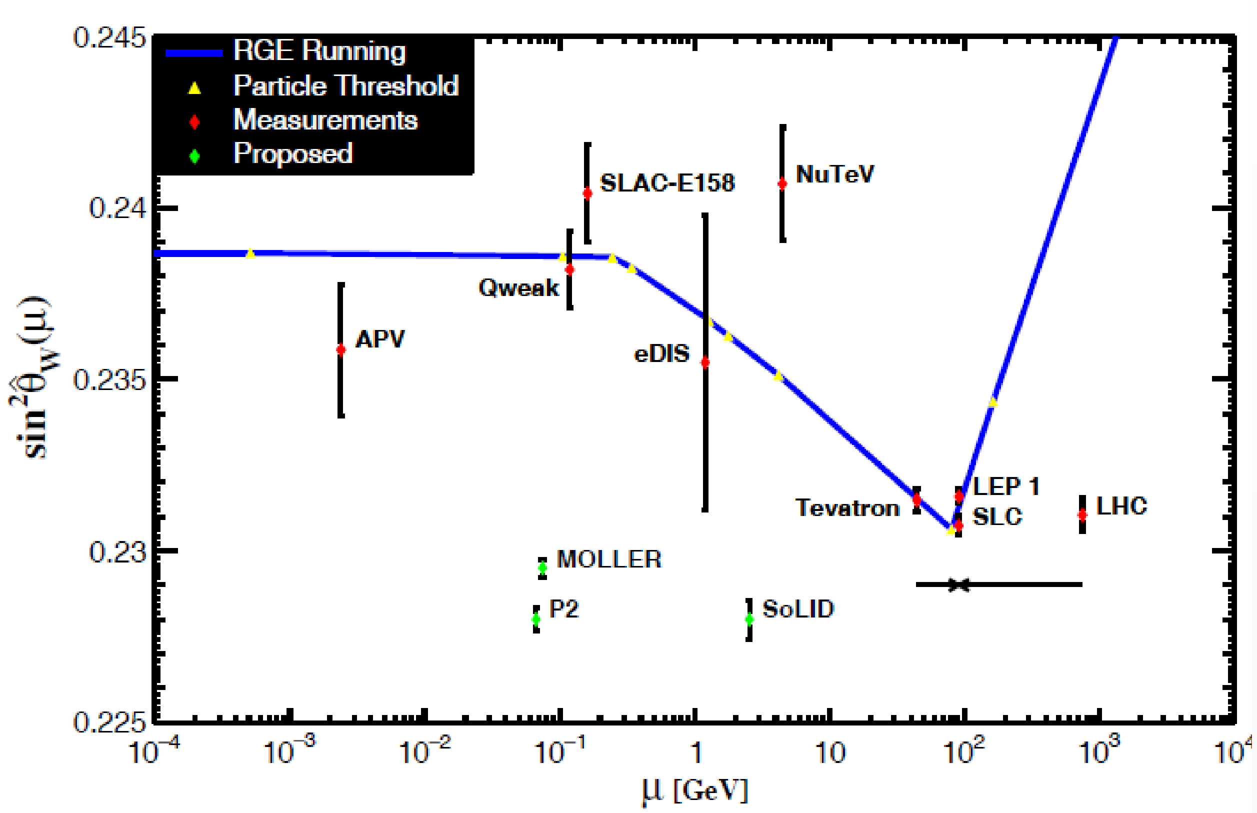
"$\overline{\mathrm{MS}}$-Scheme" definition in terms of (running) coupling constants:

$$\sin^2(\hat\theta_W) = \frac{g^2}{g^2 + g'^2}$$

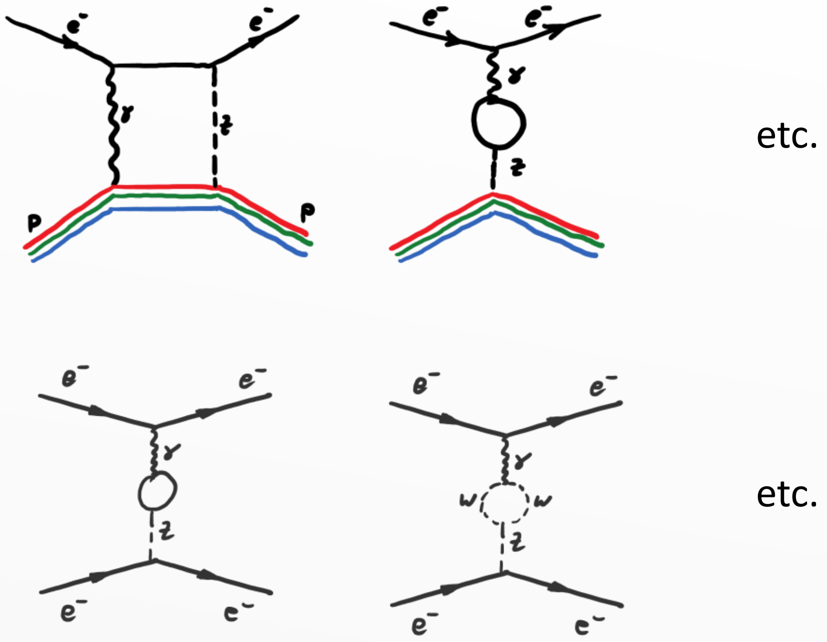
# PVES Measurements (focus on BSM tests)

## The Weak Mixing Angle

J. Erler (JGU), reproduced with permission




The weak mixing angle changes ("running") with interaction energy (e.g. momentum transfer), due to:




Different radiative correction apply to different particle interactions (e.g. electron with electrons vs. electron with quarks).

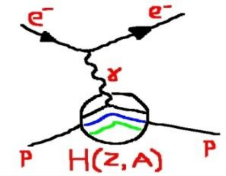
# PVES Cross-sections

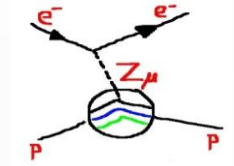
Parity Violating Cross-sections: Interference between indistinguishable $EM$ and $Weak$ amplitudes

$$\sigma_{\pm} \propto \left|S_{fi}\right|^2 = \left|S_{fi}^{EM}\right|^2 + \left|S_{fi}^{W}\right|^2 \pm \underbrace{\left(S_{fi}^{EM} S_{fi}^{W\dagger} + S_{fi}^{EM\dagger} S_{fi}^{W}\right)}_{\text{PV Signal}}$$

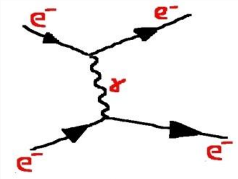
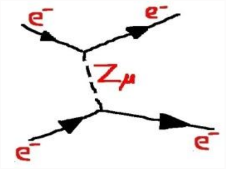
$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

- P2 @ Mesa: $$S_{fi}^{EM} S_{fi}^{W\dagger} + S_{fi}^{EM\dagger} S_{fi}^{W} \propto \frac{G_F}{\sqrt{2}} \sum_{i=u,d} \left[C_{1i}\bar{e}\gamma_\mu\gamma^5 e\bar{q}_i\gamma^\mu q_i + C_{2i}\bar{e}\gamma_\mu e\bar{q}_i\gamma^\mu\gamma^5 q_i\right]$$





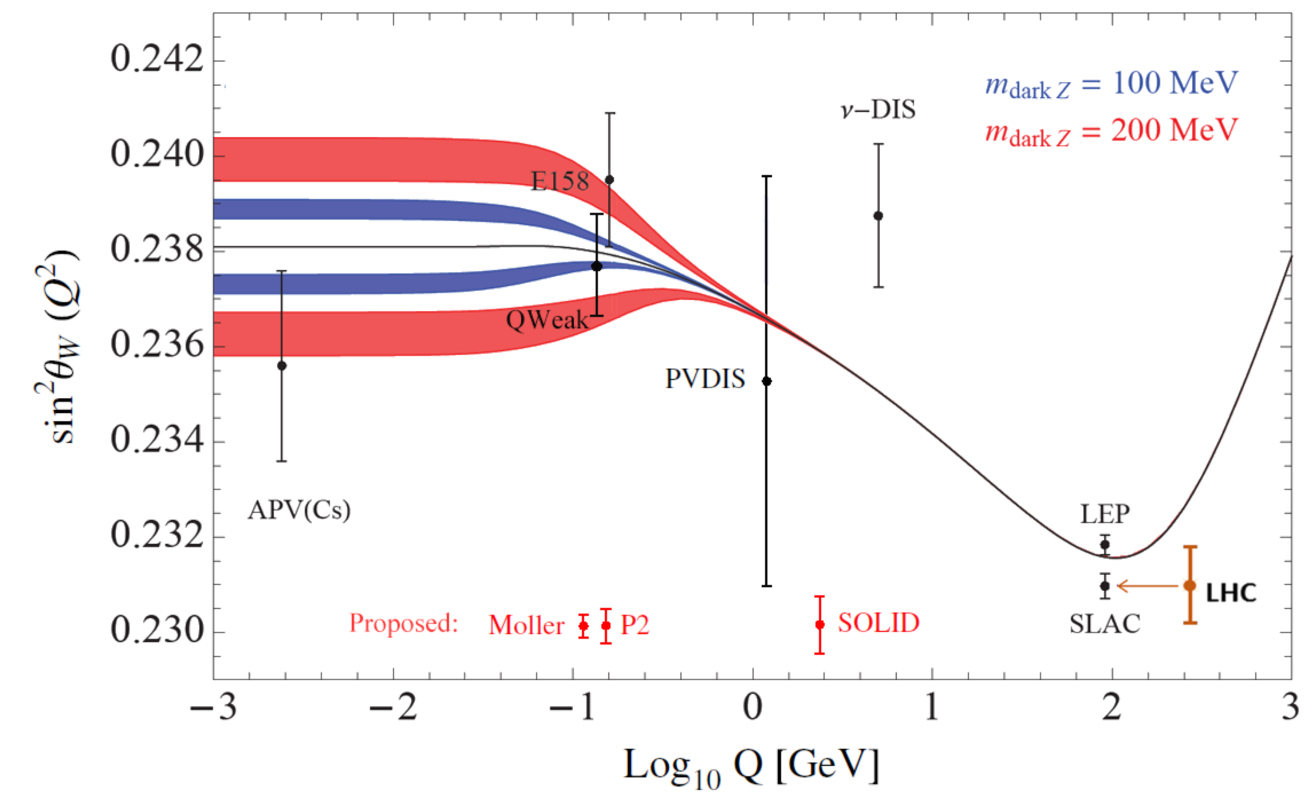
- MOLLER $$S_{fi}^{EM} S_{fi}^{W t} + S_{fi}^{EM t} S_{fi}^{W} \propto \frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu\gamma^5 e\bar{e}\gamma^\mu e$$

- New Physics ? $$\mathcal{L}_{e_1 e_2} = \sum_{i,j=LR} \frac{g_{ij}}{2\Lambda^2} \bar{e}_i\gamma_\mu e_i\bar{e}_j\gamma^\mu e_j$$ $$\frac{\Lambda}{\sqrt{\left|g_{RR}^2 - g_{LL}^2\right|}} = 7.5\ TeV$$

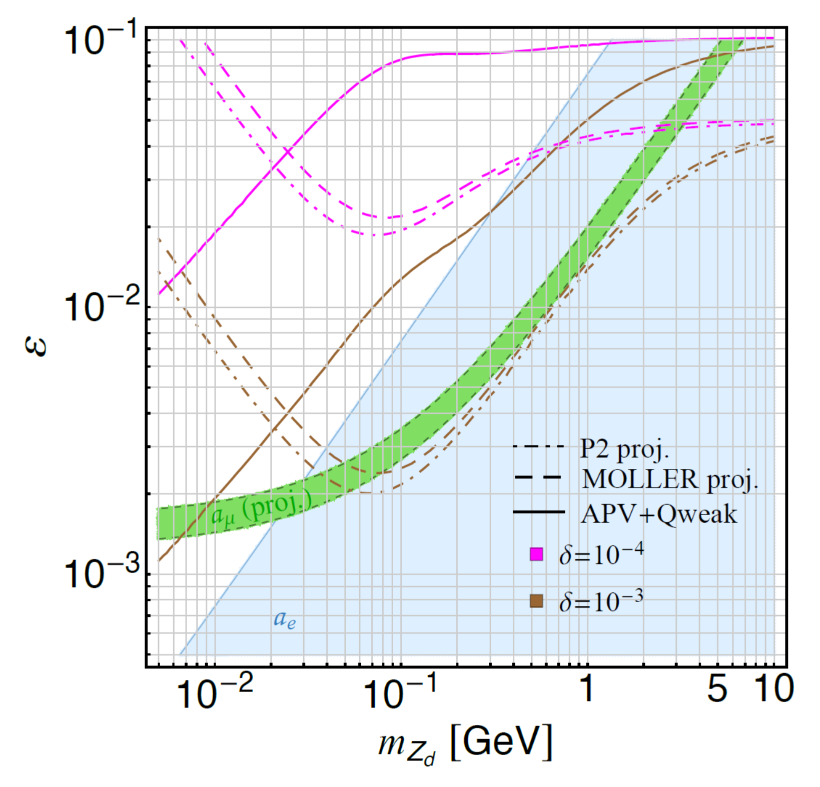
# The Weak Mixing Angle and New Physics

Adapted from Marciano, Davoudiasl, Lee (2014)




The running of the weak mixing angle away from the Z-Pole would change with the addition new physics models.

Dark matter Z bosons with different mass would produce different levels of deviation from the Standard Model prediction




M. Cadeddu et al. arXiv:2104.03280v3 [hep-ph]

$$\sin^2(\hat{\theta}_W) \longrightarrow \kappa_d \sin^2(\hat{\theta}_W)$$

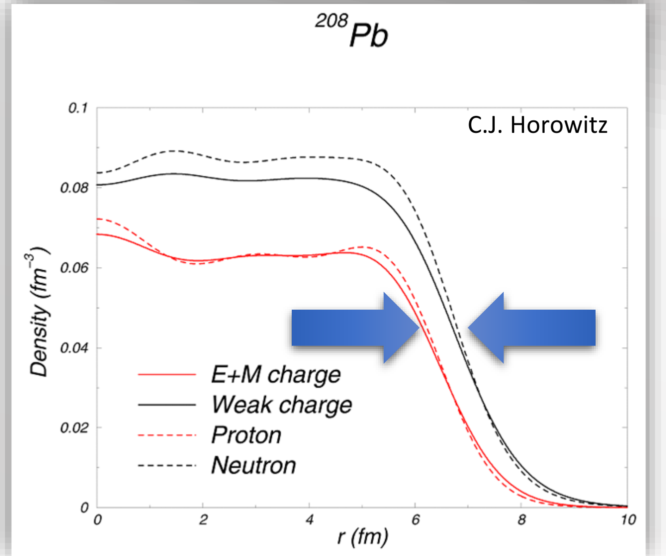
$$\kappa_d = 1 - \varepsilon\left(\frac{m_Z}{m_{Z_d}}\delta + \varepsilon\tan(\hat{\theta}_W)\right)\cot(\hat{\theta}_W) f\left(\frac{Q^2}{m_{Z_d}^2}\right)$$

## Parity Violating measurements for Astrophysics

The nuclear matter **equation of state** (EOS) is the pressure as a function of density: $P(\rho)$

Basis for understanding:

- Nuclear structure/matter stability
- Formation of elements
- Star collapse (neutron star or black hole)
- Neutron star structure

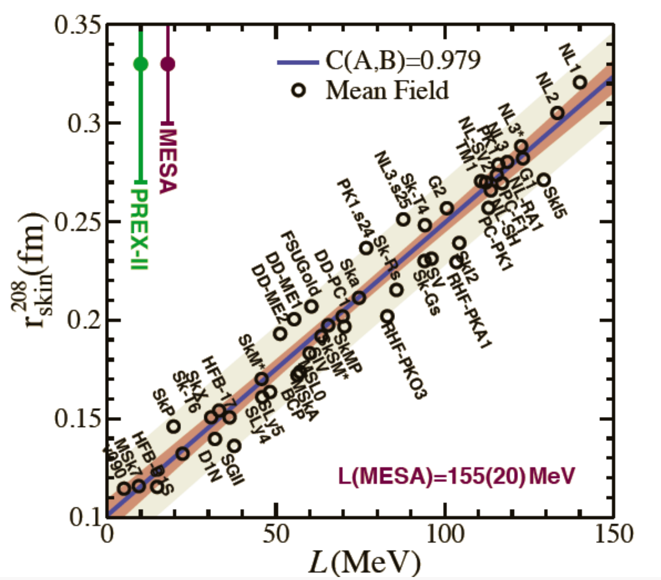



Present nuclear data does not yet constrain (symmetry energy density dependence):

$$L = 4\pi\sigma_B {r_{NS}}^2 T^4$$

- Strong correlation between $L$ and the neutron skin thickness $R_n - R_p$
- $R_n$ not yet well measured with previous methods

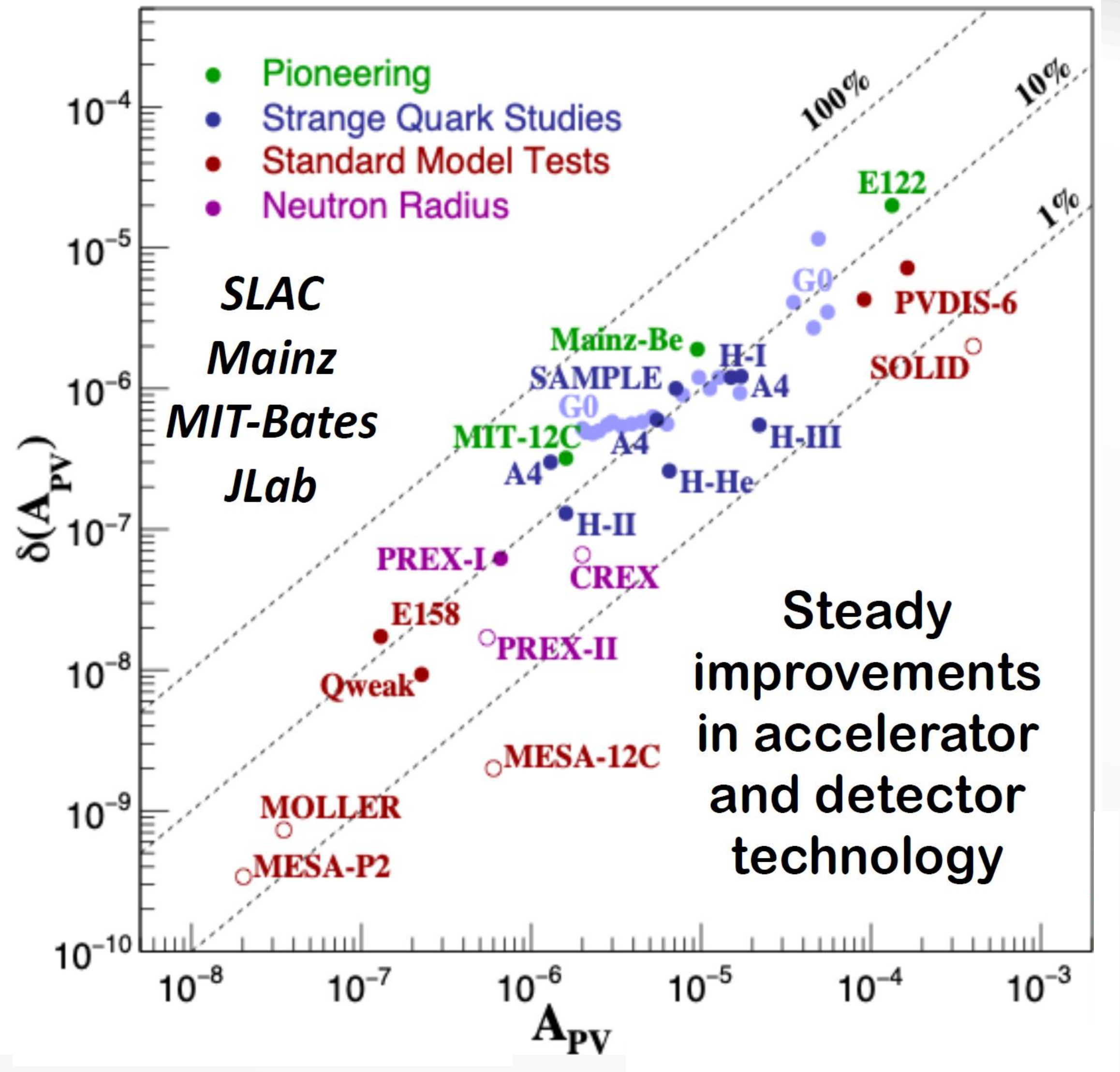
➡ Measure neutral weak form-factor $F_W$ in PVES $\quad A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\,\pi\alpha Z} Q_W^{Pb} \frac{F_W(Q^2)}{F_{ch}(Q^2)}$




arXiv:1305.7101v1 [nucl-th] 30 May 2013

# PVES Measurements in Time

- Long and active history of PVES measurements
- Asymmetries and errors now push on the (sub) ppb level
- Percent-level relative errors now allow for beyond two-loop level investigations of the SM and potential new physics
- Making such measurements requires:
  - High luminosity (beam and high-power targets)
  - Parity quality beam:
    High polarization with high beam stability and systematic control
  - High precision beam polarimetry measurements
  - Better and better detector systems with faster readout



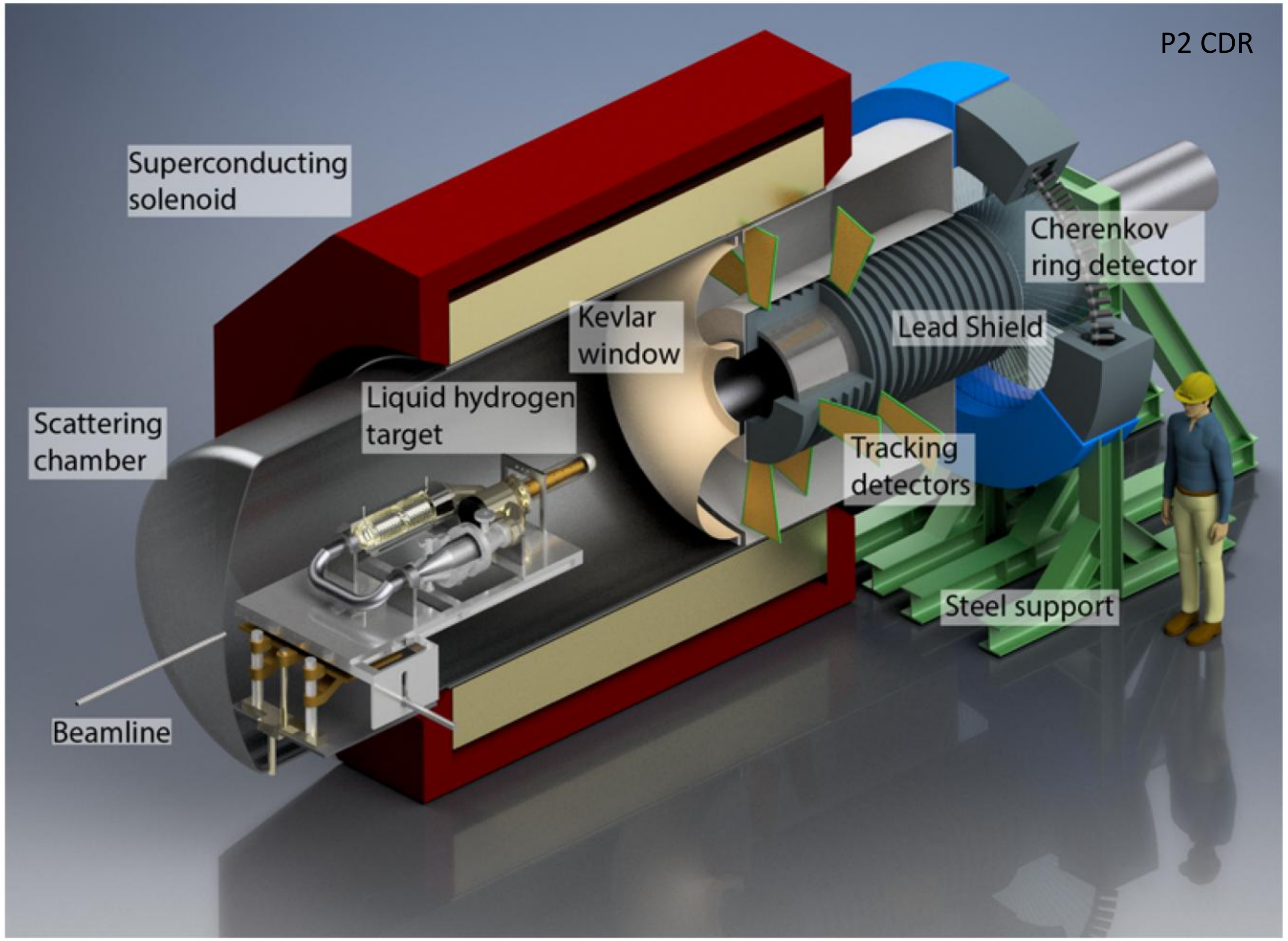
**Parity violation measurements**

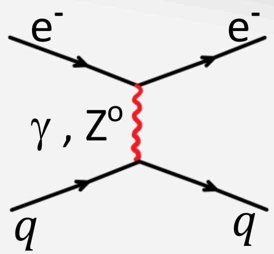
**~~almost~~ never work out exactly the way**

**you plan them!**

# The P2 Experiment (Mainz MESA Facility – See Malte Wilfert's Talk)

P2@MESA




$E_{beam} = 155\ MeV$

$I_{beam} = 150\ \mu A$

$\mathcal{L} = 2.4 \times 10^{39}\ cm^{-2} \cdot s^{-1}$

$P_{beam} \geq 80 \pm 0.4\ \%$

$A_{PV} = -40\ ppb$

$\delta A_{PV} = 0.6\ ppb$

$Q_W^p = (1 - 4sin^2\theta_W)$

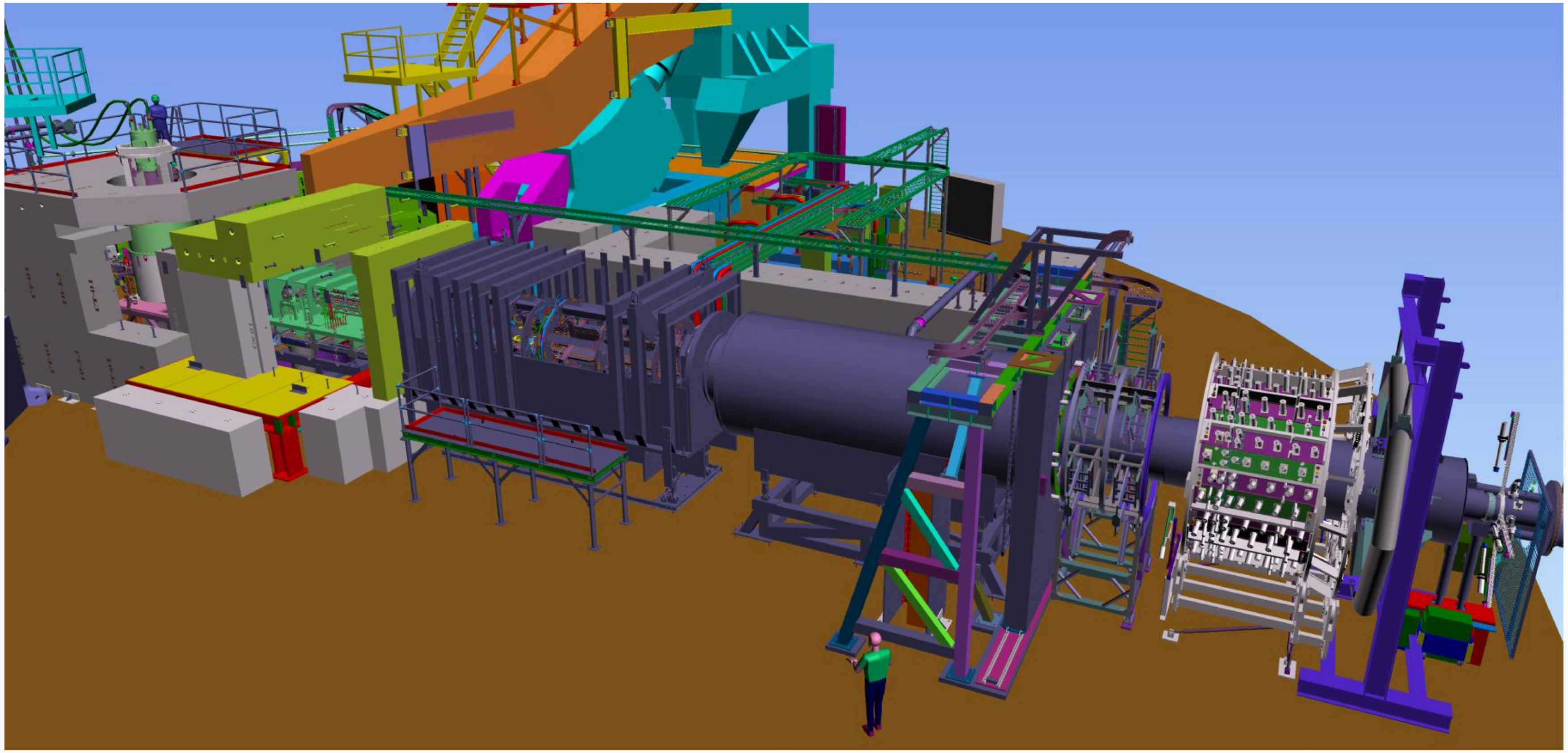
$\Delta Q_W^p = 1.83\%$

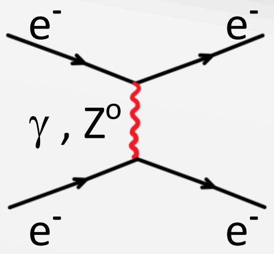
$\Delta sin^2\theta_W = 0.14\%$

Main Observable:
PV asymmetry with detectors
Weak Charge of the proton

$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\ \pi\alpha}\left(Q_W^e - F(Q^2)\right)$$

# The MOLLER experiment (Jefferson Lab)






$E_{beam} = 11\ GeV$

$I_{beam} = 65\ \mu A$

$\mathcal{L} = 3 \times 10^{39}\ cm^{-2} \cdot s^{-1}$

$2.75 \leq E_{scat} \leq 8.25\ GeV$

$P_{beam} \geq 90 \pm 0.5\ \%$

$A_{PV} = 32\ ppb$

$\delta A_{PV} = 0.8\ ppb$

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

$\Delta Q_W^e = 2.4\%$

$\Delta sin^2\theta_W = 0.1\%$

Main Observable:
PV asymmetry with detectors
Weak Charge of the electron

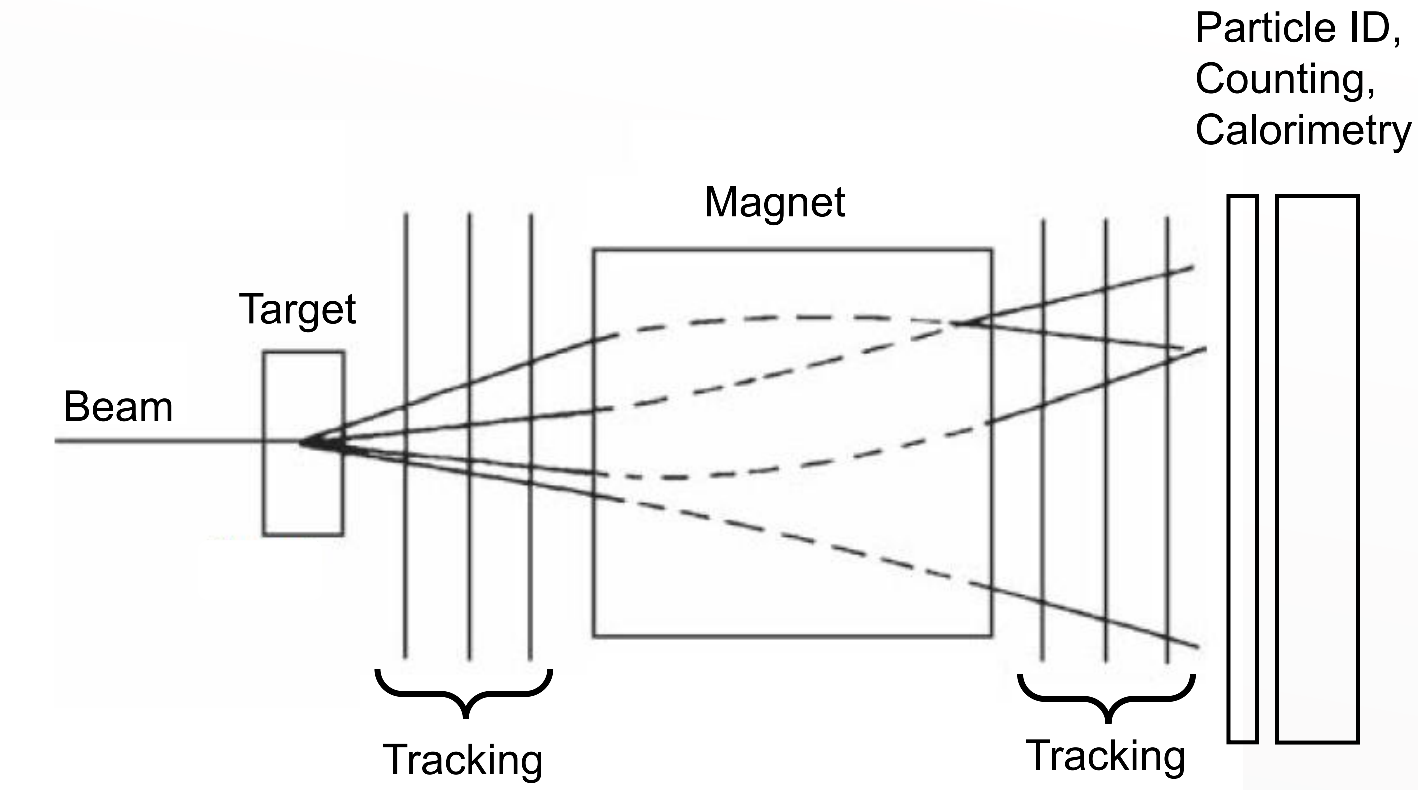
$$A_{PV} = m_e E \frac{G_F}{\pi\alpha\sqrt{2}} \frac{4sin^2\theta}{(3 + cos^2\theta)^2} Q_W^e$$

# Basic Experimental Components

## Critical factors in experimental design for PV experiments:

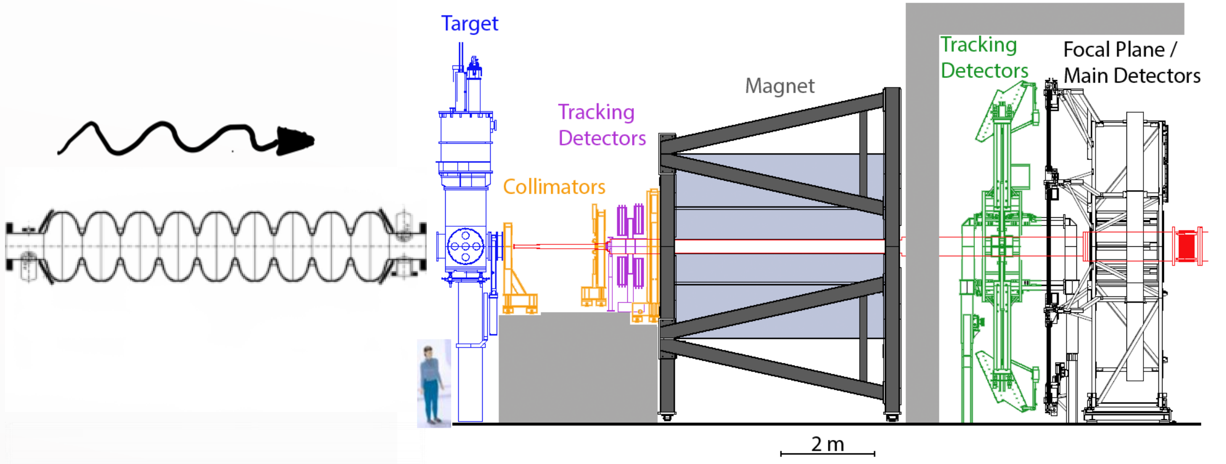
- A stable, high intensity, highly polarized beam, optimized for asymmetry measurements
- A highly stable target that maximizes luminosity and simultaneously minimizes excess noise (e.g. a long LH2 cryogenic target)
- A set of precise collimators that define the acceptance.
- A magnet system (“spectrometer”) optimized for high acceptance, but able to “focus chosen events” onto a system of detectors
- A set of detectors capable of deadtime-less precision measurements at extreme rates
- A set of detectors for tracking individual scattered electrons to characterize the experimental performance
- A set of detectors to determine sources of background and characterize beam conditions (e.g. polarization)

### Generic Fixed Target Experiment

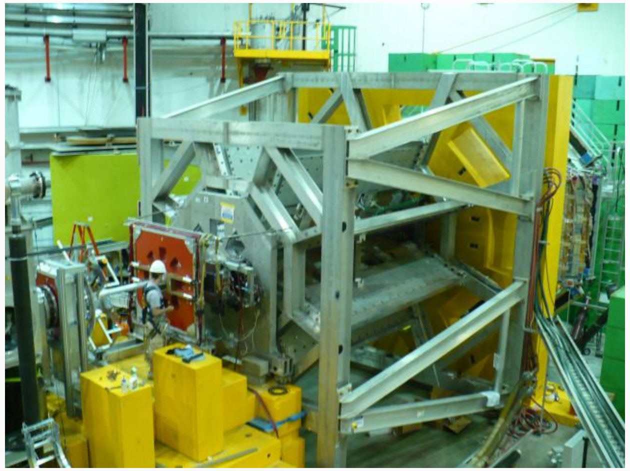


# Basic Experimental Components

**Example: QWeak**




Jefferson Lab Continuous Electron Beam Accelerator Facility



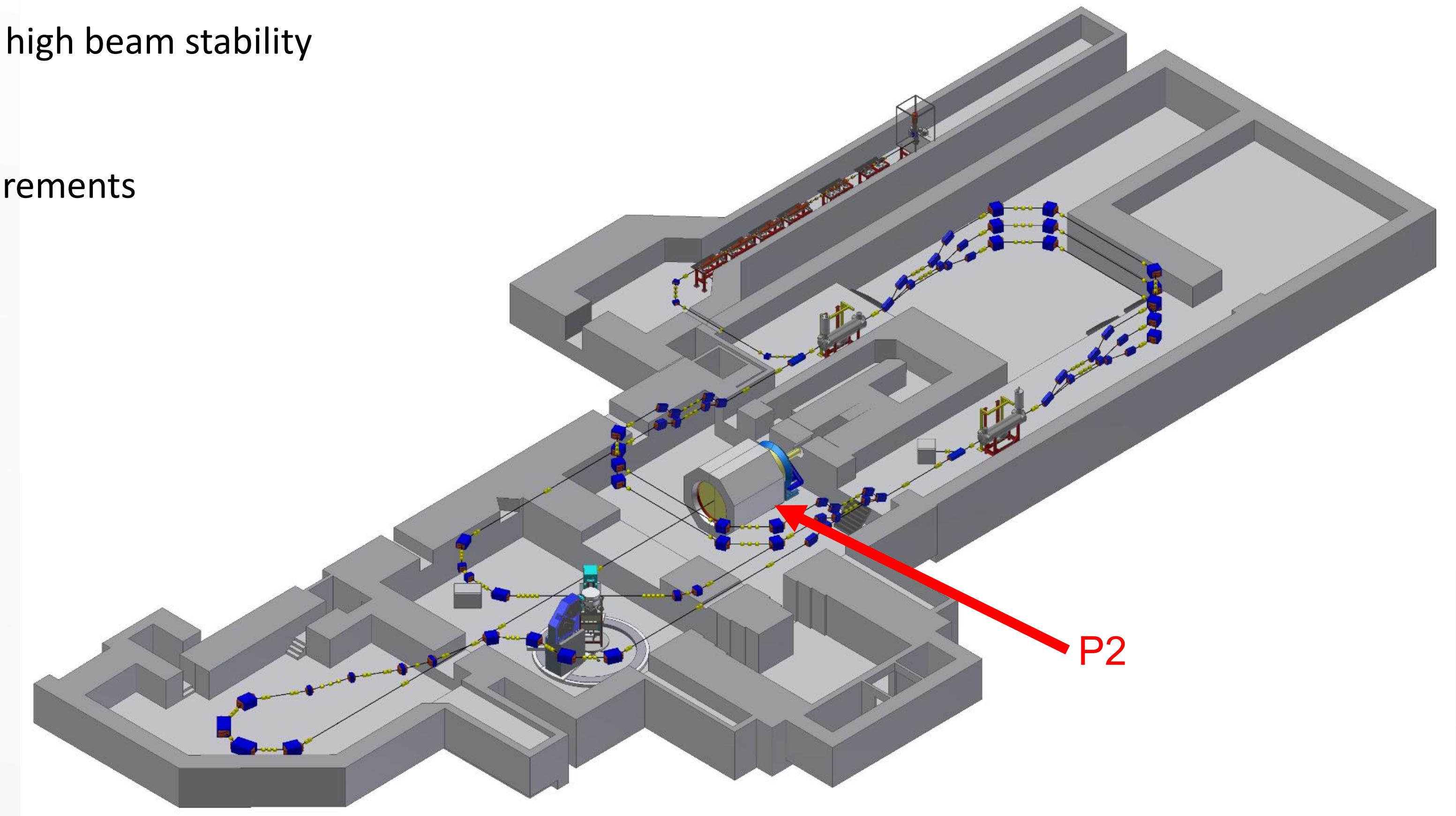
JLab QWeak Experiment

P2@MESA

# The P2 Experiment (Mainz MESA Facility – See Talk by Kurt Aulenbacher)

Particular beam properties that are important include:

- High luminosity
- Parity quality beam: High polarization with high beam stability and systematic control
- Highest precision beam polarimetry measurements

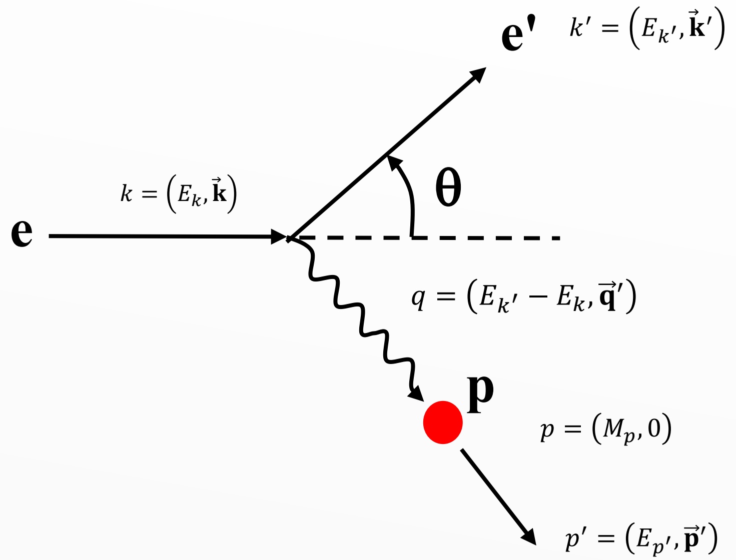


# Integration Mode Asymmetry Measurements

**Parity violating elastic scattering of polarized electrons:**

- Prepare electron beam with a given helicity (spin)
- Scatter electrons and measure cross-section
- Flip spin and measure cross-section again
- Calculate the difference for the period of measurement
- Extract an asymmetry:

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$




- The rest is all about picking the right kinematics and controlling backgrounds and systematic effects

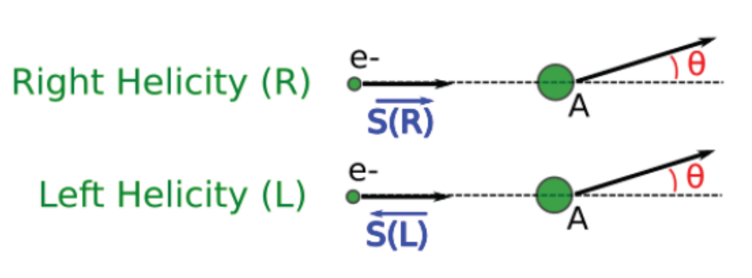
- **Okay "easy peesy" … so what's the problem ??**

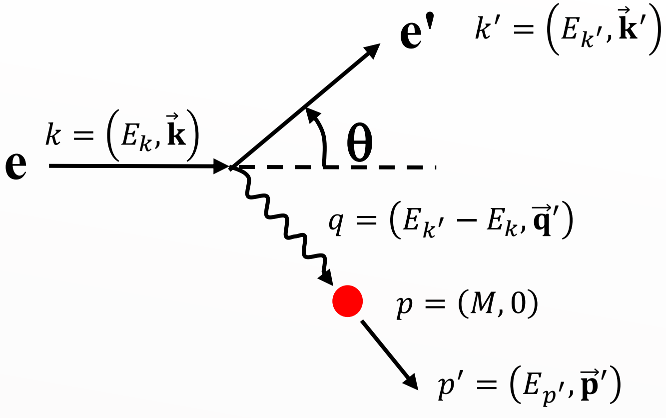
  **It's just elastic scattering …**

# Integration Mode Asymmetry Measurements

The experiments measure the asymmetry in the number of scattered electrons as a function of beam helicity.

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

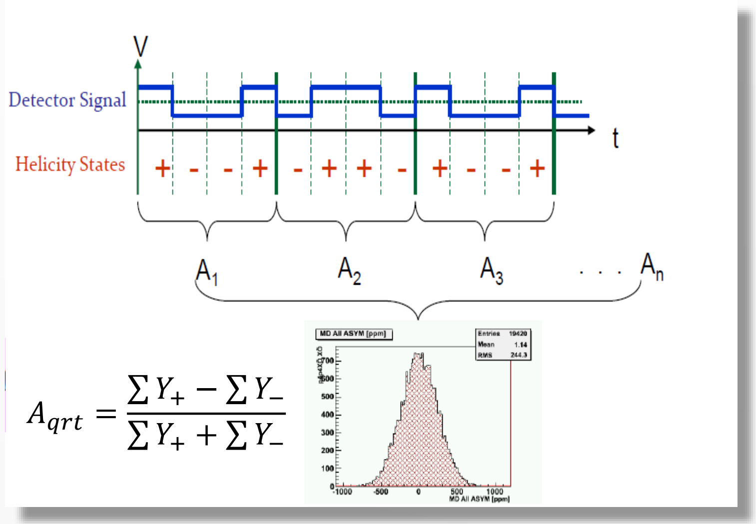



At high rates (to collect enough statistics) the measured flux is integrated (both spatially and in time) over the helicity window, to form the measured asymmetry at the pair, quartet, or octet level (see later).

All systematic effect must be taken into account:

$$A_{msr} = \frac{Y^+ - Y^-}{Y^+ + Y^-} = P_e \left( f_p A_{PV} + \sum_b A_b f_b \right) + A_{beam} + A_{inst}$$



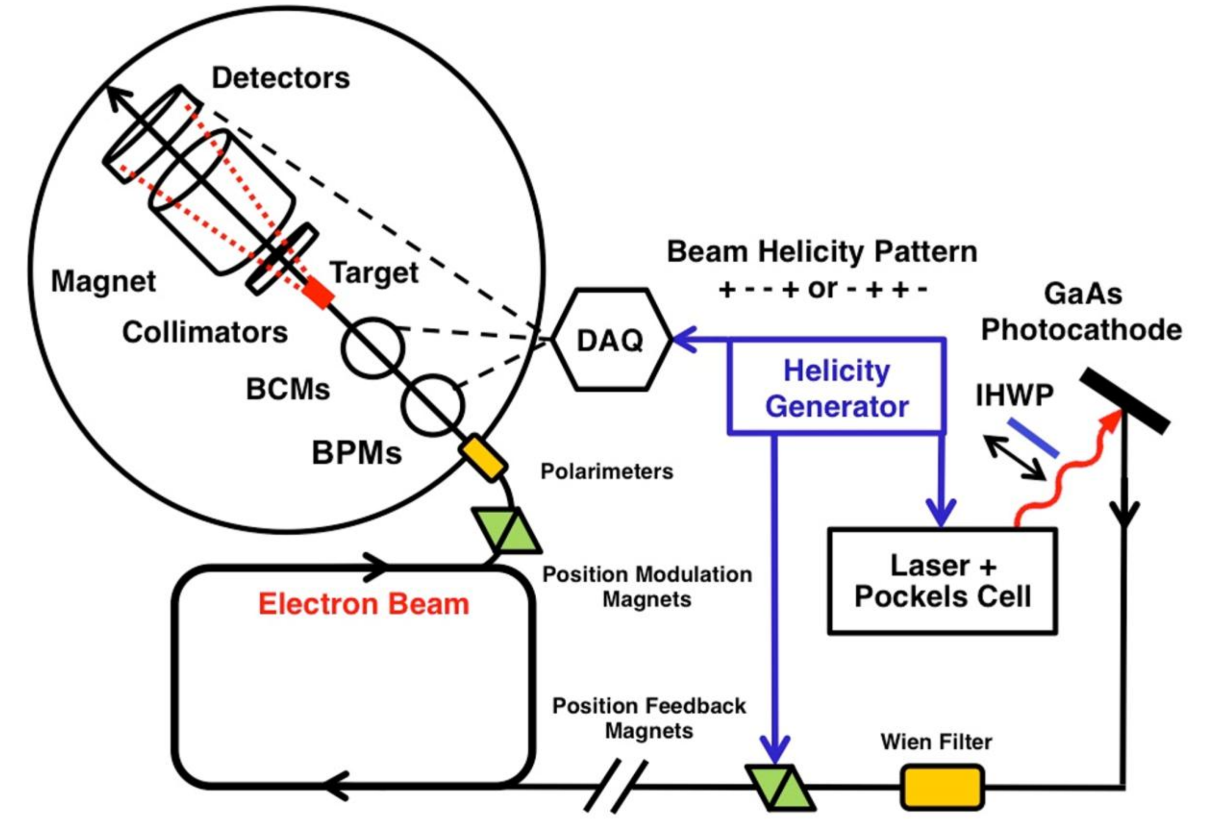

Then there are additional experimental factors to go from $Y \rightarrow \sigma$

# Integration Mode Asymmetry Measurements

## Measurement Methodology

We need multiple pieces of instrumentation, before the target.

- **Helicity Generator:** Everything is synched to this frequency, defining the integration window.
- **Laser and Pockels cell**: Allowing rapid reversal of helicity, preferably with minimum deadtime (ringing) between stable helicity states.
- **Source Photocathode:** High efficiency electron source – beam spot movable.
- **Helicity Reversal:** Several ways to reverse the beam helicity (fast and slow).
- **Beam Monitoring:** Beam position (BPM) and beam current (BCM) measurements.
- **Beam Modulation and Feedback:** Move (modulate) the beam to study false asymmetries. Feedback on BM data to stabilize beam.

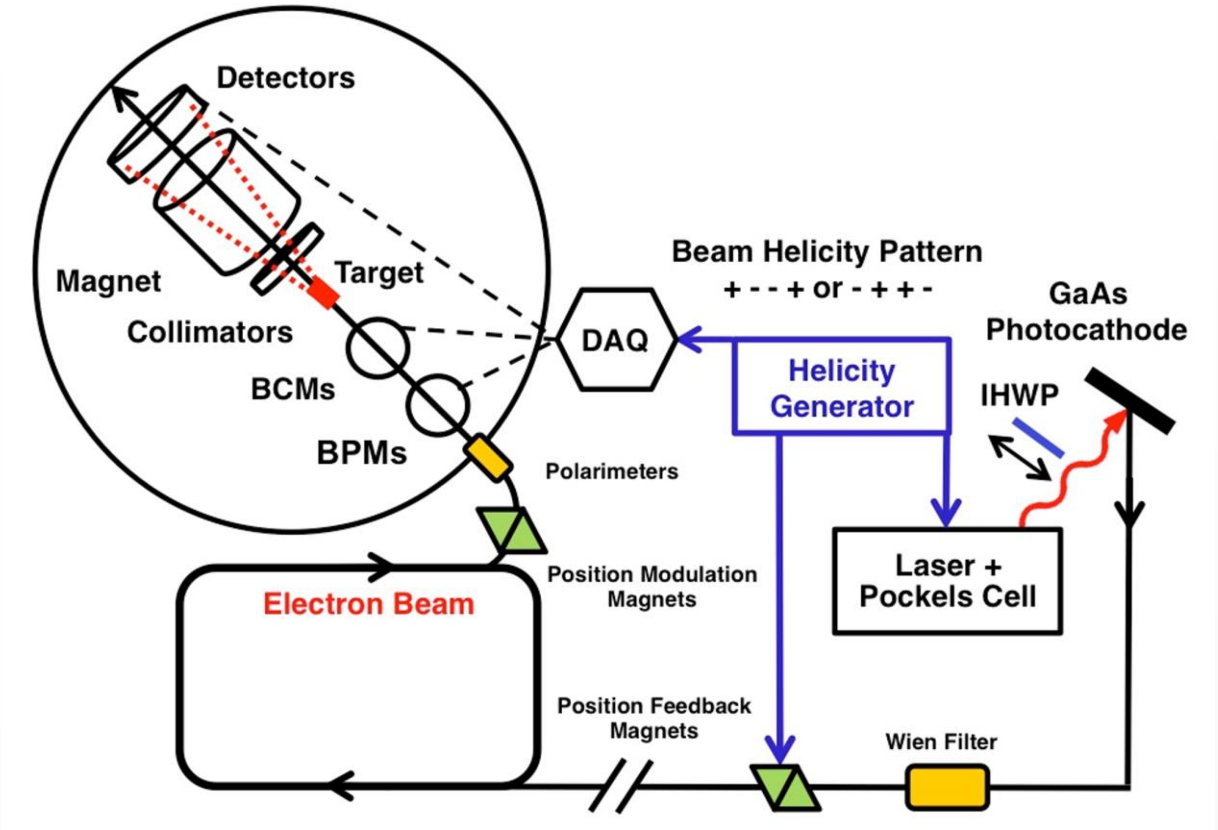



QWeak collaboration, unknown source

## Measurement Methodology

We ideally have three independent techniques for helicity reversal of a longitudinally polarized beam:

- **Rapid pseudo-random reversal:** (~ 1 kHz). Rejects LH2 target "boiling noise".
- **IHWP at ~8-hour intervals:** Mechanical action unable to induce electrical or magnetic induced false asymmetries.
- **Wien filter at monthly intervals:** Rejection of beam size (or focus) modulation induced false asymmetry and suppression of slow drifts in apparatus linearity.
- **Also as check construct NULL:** "out-of-phase" quantity from the two slow reversal techniques to bound unaccounted for false asymmetries.

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# Integration Mode Asymmetry Measurements

## Measurement Methodology

Main experimental components:

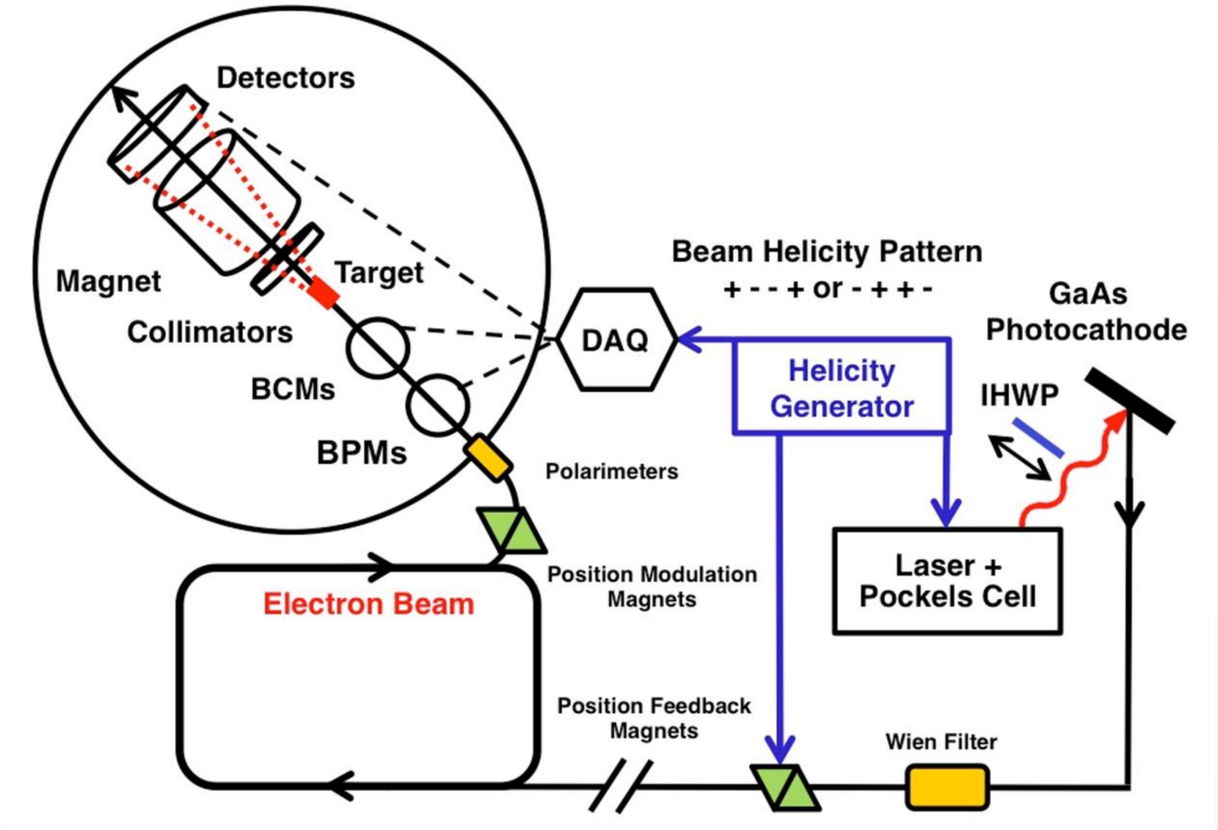
- **Target:** High power capable (high beam currents) LH2 target with low target boiling.

- **Collimation:** Define the acceptance of the experiment.

- **Magnet:** Not really a spectrometer – used to “focus” the scattered electrons on the detectors, maximizing event rate (at the chosen kinematics). Reject background events.

- **Detectors:** Experiment needs to run in two modes: data production in integration mode and tracking for kinematics determination and background/efficiency checks. Requires two different sets of detectors (tracking and integration). Set of auxiliary detectors for systematics and monitoring.

- **Data acquisition:** High precision, low noise data acquisition integrated accurately in the helicity synchronization. Low noise amplifiers - linear electronics - fast, high-resolution ADCs.




QWeak collaboration, unknown source

## Beam Characteristics and Linearity

High rates require signal integration (timing and spatial) and a detector that produces a response that is strictly proportional to the number of electrons detected.

**In this mode you integrate every single noise source into your signal (within your defined bandwidth).**

$$A_{corr} = \left(\frac{Y^+ - Y^-}{Y^+ + Y^-}\right) - A_{beam} \qquad A_{beam} = \left(\frac{I^+ - I^-}{I^+ + I^-}\right)_i + \sum_j \frac{\partial A_i}{\partial \delta X_j} (\delta \mathrm{X}_j)_i \; = +A_{beam} + A_{inst}$$

We are trying to make highly precise relative measurements of average/mean signal levels to form asymmetries.

Any non-linearity in the experimental response to the variation in the scattering rate (for +/- helicity states) is a problem.

Normally drifts caused by diurnal variations, general temperature fluctuations, slow electronics drifts, etc. would preclude any chance of such a measurement, but …

⇒ Fast helicity reversal , fast (over)sampling, signal integration mitigate this to levels we can handle

The spectrometer has to separate wanted events from background since there is no way to implement amplitude threshold cuts, timing cuts, or tracking cuts (at highest rates).

Some conditions which can change rapidly during these measurements – notably the electron beam trajectory, energy, and intensity – must be averaged over the same integration periods and used to correct the measured asymmetry for the changing conditions.

# Asymmetry Corrections

Measured asymmetry:

$$A_{msr} = \frac{Y_+ - Y_-}{Y_+ + Y_-} \approx \underbrace{P\left(f_p A_{PV} + \sum_b f_b A_{Bgr}^b + A_{Trans}\right)}_{\text{Polarization Dependent}} + A_{Beam} + A_{Lin}$$

Regressing out systematic effects (e.g. beam motion)

$$A_{Beam} = A_{Beam}(E, x, y, x', y') = \sum_i^{E,x,y,x',y'} \left(\frac{\partial A_{msr}}{\partial \delta X_i}\right) \delta X_i$$

Removing the backgrounds and applying radiative corrections

$$A_{PV} = R\frac{(A_{msr} - A_{Beam} - A_{Lin})/P - \sum_b f_b A_{Bgr}^b - A_{Trans}}{f_P}$$

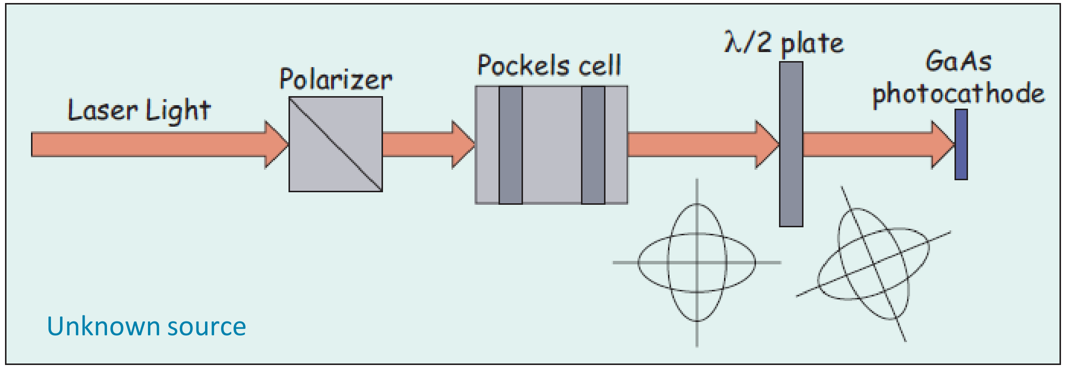
# Polarized beam

The accuracy of a PV experiment is ultimately limited by the degree and knowledge of the electron beam polarization.

$$P_e = \frac{R_e^{\uparrow} - R_e^{\downarrow}}{R_e^{\uparrow} + R_e^{\downarrow}}$$

**The source:**

- The most important aspects (including almost all systematic beam effects) are determined at the source
- The polarized electron beam is generated using photoemission due to circularly-polarized light on a photocathode.
- The circular polarization is created in a Pockels cell and determines the spin of the emitted electrons
- The Pockels cell allows fast flipping of the laser polarization, by reversing the applied high voltage - providing for the important fast flipping of the beam helicity

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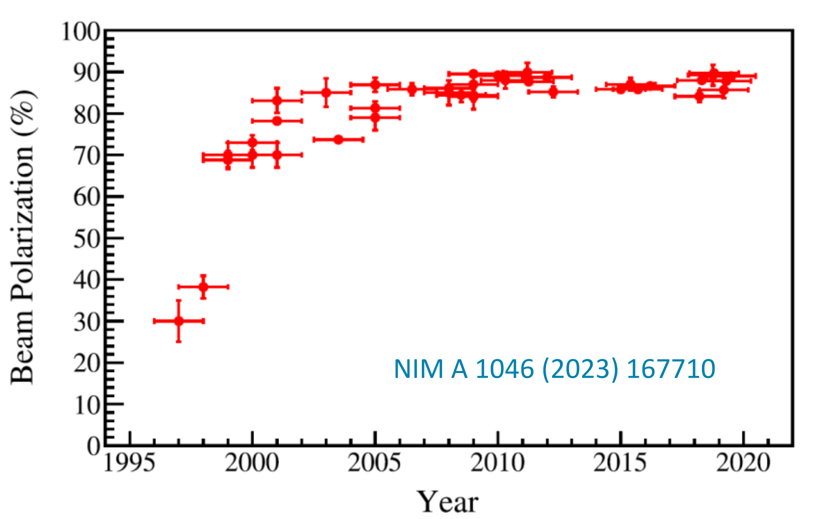



NIM A 1046 (2023) 167710

# Polarized beam

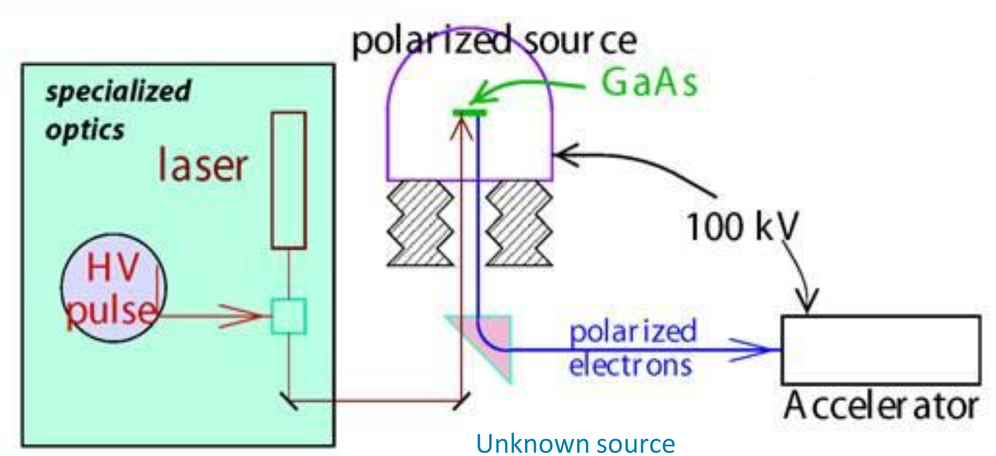
**The source:**

**Photoemission of electrons from GaAs:**

- Bulk GaAs typical $P_e \simeq 37\%$
  Theoretical maximum: $P_e = 50\%$

- Strained GaAs = typical $P_e \simeq 80\%$
  Theoretical maximum: $P_e = 100\%$

Figure of Merit: $IP_e^2$

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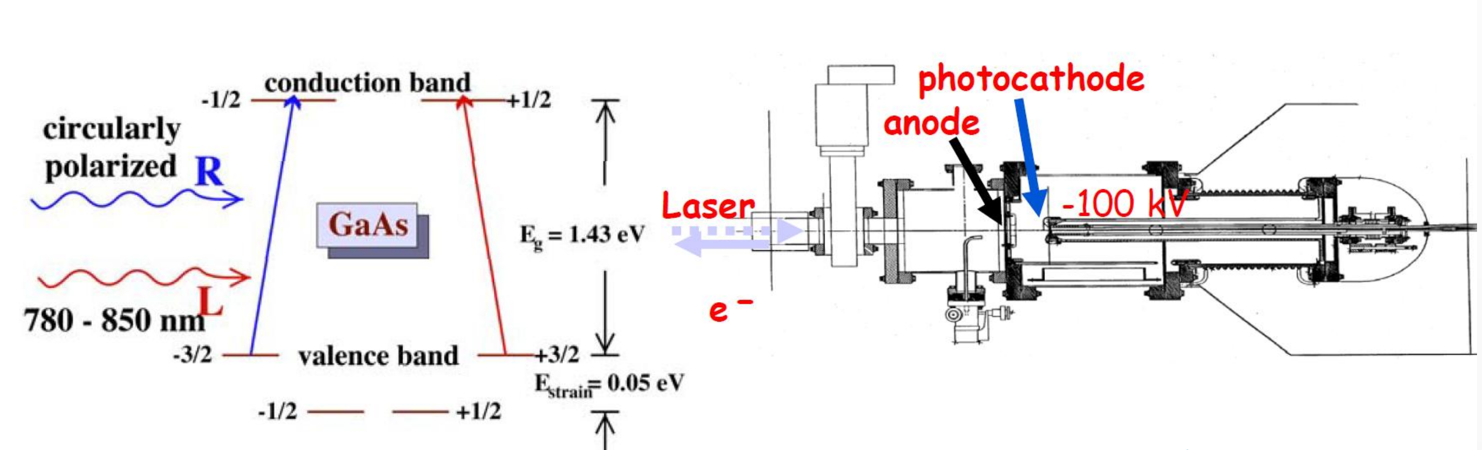


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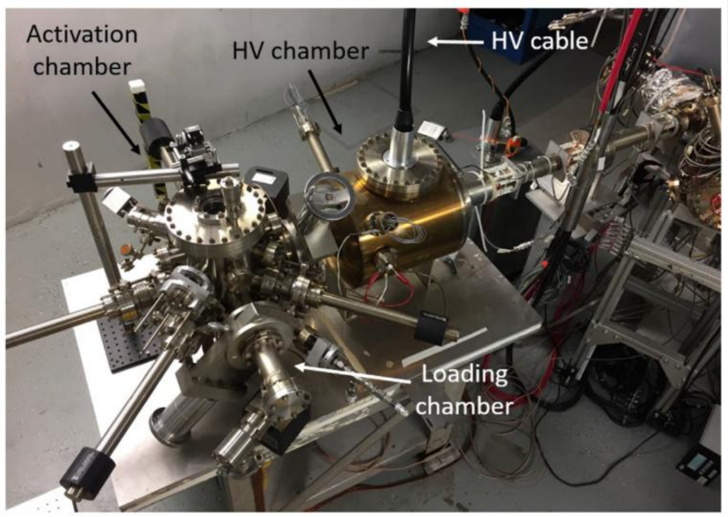
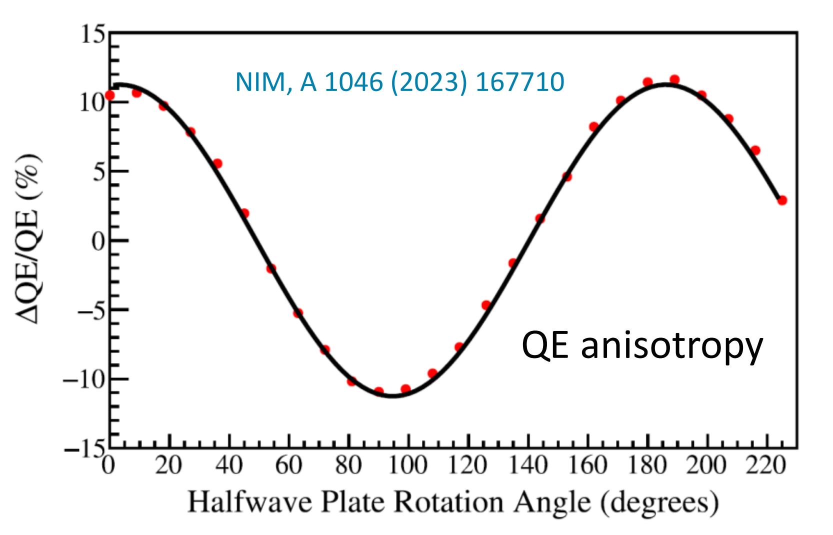
# Polarized beam

**The source:**

- The voltage applied to the Pockels cell is the only change in the electron beam generation or transport that is correlated to beam helicity.
- The photocathode quantum efficiency has an analyzing power for linear polarized light, but is the same for right- and left-handed circular polarization.
- Helicity-correlated asymmetries in the electron beam are directly related to the voltage applied to the Pockels cell or the polarization-sensitive transport of the laser light to the photocathode.
- Residual linear polarization on the cathode is impossible to completely eliminate (Pockels cell alignment, vacuum windows, etc.)
- The residual linear light polarization is the major reason for beam charge asymmetries
- The cathode QE is also position dependent and changes over time, requiring laser spot changes.



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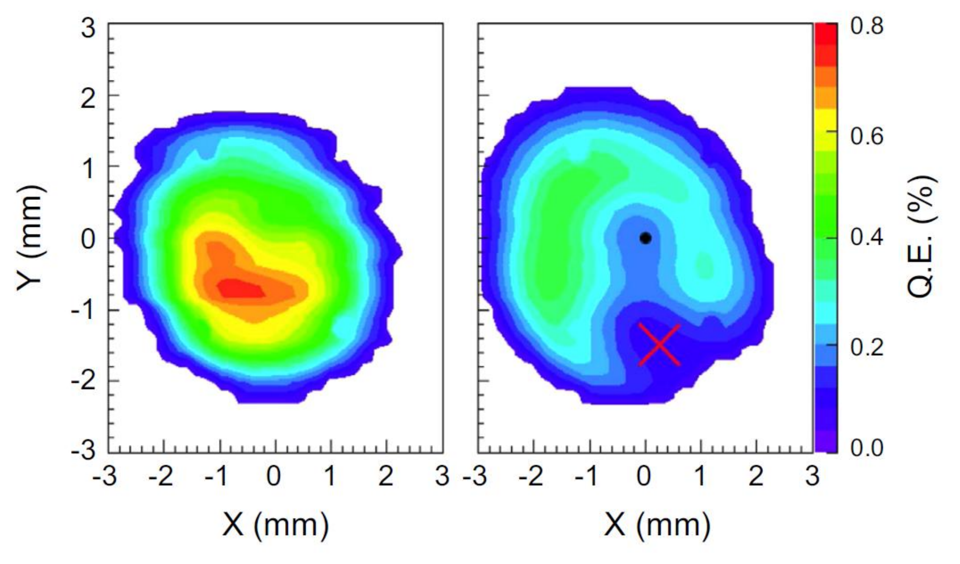



QWeak ,Unknown source

# Polarized beam

## The source:

### Position Differences

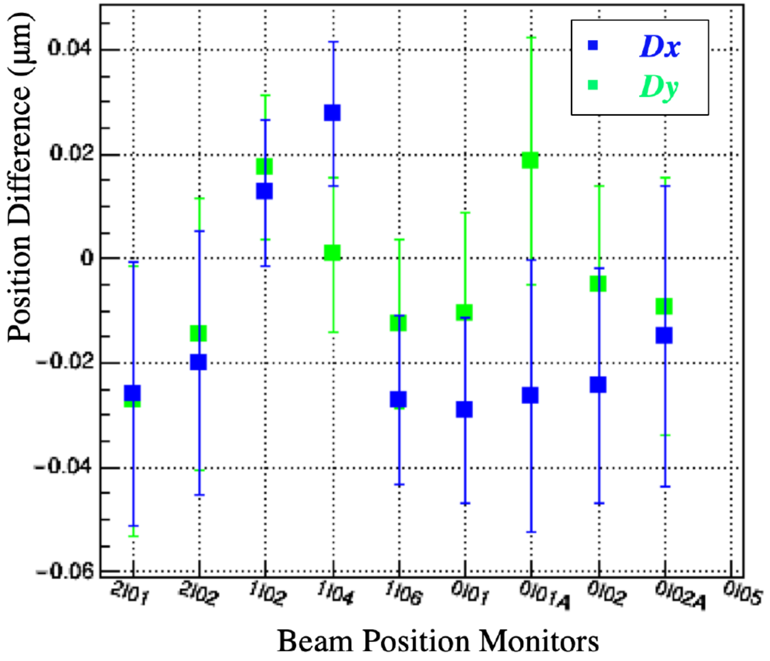
- Pockels cell electric-field non-uniformity + Pockels cell alignment errors creates a polarization gradient.

- Gradient causes helicity correlated changes in electron beam spatial profiles and result in electron beam ‘‘position difference’’.

- Position differences can also emerge from physical modification of the cell dimensions when voltage is applied

  leading to helicity-correlated beam steering or focusing
  (helicity-correlated “spot size asymmetry”)

B. Waidyawansa , QWeak Ph.D. Thesis




### Energy Asymmetry

- Caused as a side-effect of beam charge differences and **beam loading**: The beam in each helicity state extracts energy from the SRF cavities depending on the beam charge , reducing the field .

- If there is a charge asymmetry, the helicity state with the higher charge will draw more energy, leaving less for the next state.

# Polarized beam

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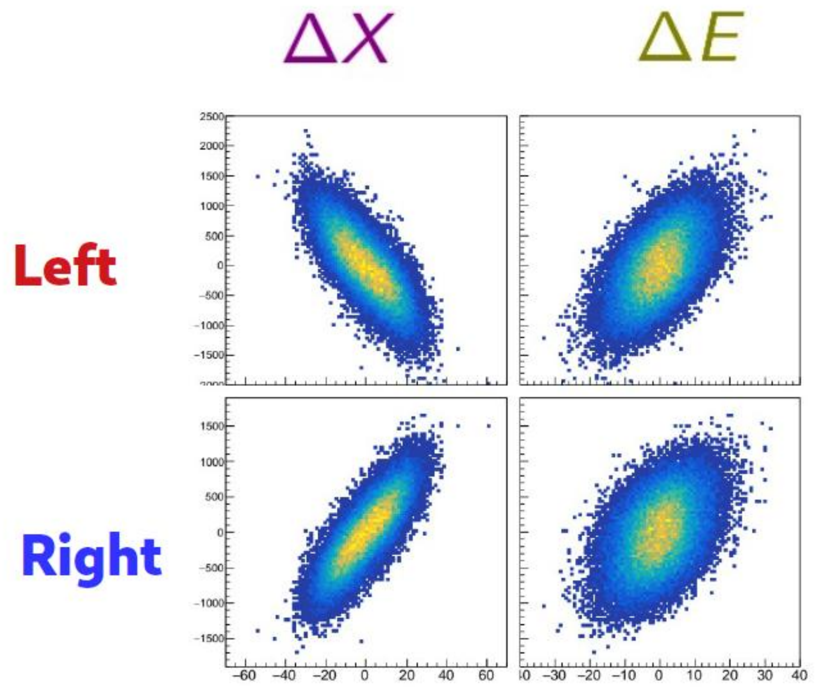


QWeak, Unknown source

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- If there is a charge asymmetry, the helicity state with the higher charge will draw more energy, leaving less for the next state.

- the energy is treated as a position because the energy differences are measured as a position difference in the dispersive transport lines.

# Polarized beam

**The source:**

- PV experiments usually rely on longitudinal beam polarization, which is how it is emitted from the cathode (but spin precesses in the accelerator dipoles)

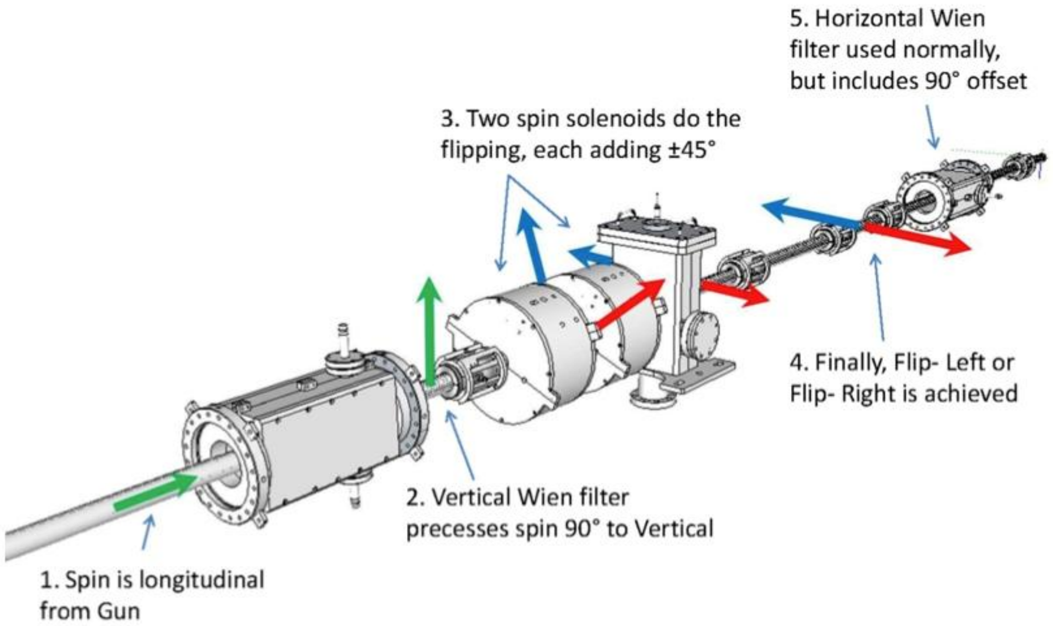
- We need a way to mitigate this – spin manipulation in the injector – create the opposite spin position to what is expected to be caused by precession in the accelerator

- Horizontal Wien – ration from longitudinal to transverse in the accelerator plane

- Vertical Wien added to allow for slow helicity reversal

- Vertical Wien also used for transverse asymmetry measurements

- The g-2 rotation can also be used as a slow reversal tool to study systematics, since all sources of HCBAs will be reversed under this operation.




MOLLER collaboration: Unknown source

# Polarized beam

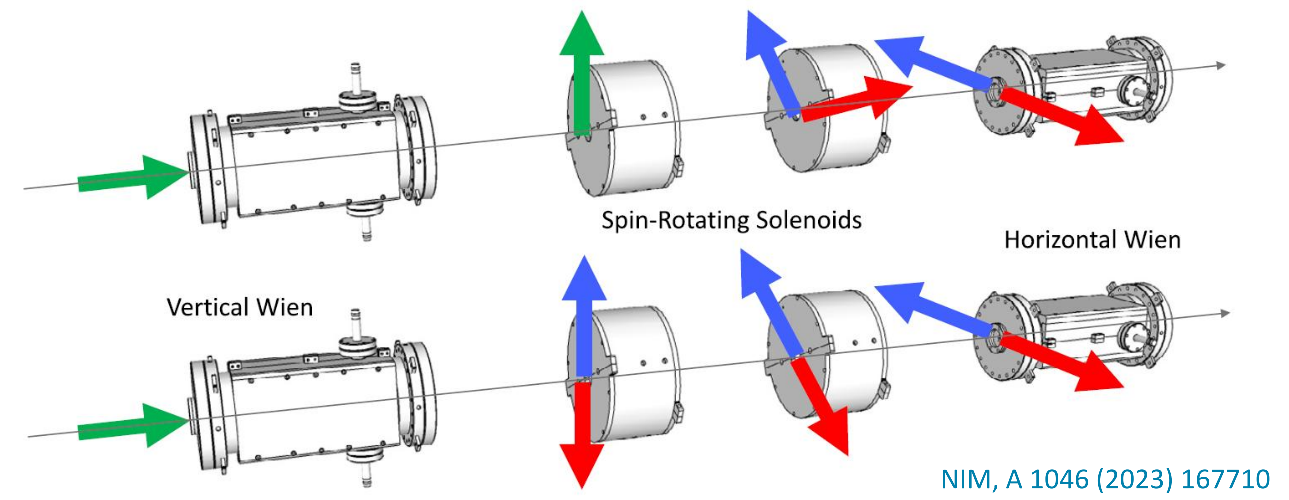
**The source:**

Use a combination of Wien filters and solenoids to rotate and focus the beam.

Top:

- $1^{st}$ Wien rotates the spin vertical
- (out of horizontal plane)
- Solenoids focus and rotate back into the horizontal plane, but transverse
- Solenoids are used to flip the spin
- $2^{nd}$ Wien rotates by angle opposite to g-2 precession

This method is quick, with low downtime, but introduces helicity correlated beam changes



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Bottom:

- $1^{st}$ Wien is used to flip the spin (transverse)
- Solenoids rotate spin back into horizontal plane
- Solenoids current remains the same (no flip)
- $2^{nd}$ Wien rotates by an angle opposite to g-2 precession

This method is slow, requires beam tuning (8 hour downtime), but does not add helicity correlated beam changes

# Polarized beam

## Beam Monitoring

The fact that helicity correlated beam parameter changes (intensity, position, angle, energy) are unavoidable means that we have to monitor these parameters continuously and correct the main detector data with the information we get from the beam monitors.

- Measure the beam current, position, angles (at the target) with special detectors placed at various positions along the beam.
- Normalize the detector signal by the beam current for each helicity state: $\boldsymbol{Y^{\pm} = S_D^{\pm} / I^{\pm}}$
- Subtract out the false asymmetry

$$\boldsymbol{A_{corr} = \left(\frac{Y^+ - Y^-}{Y^+ + Y^-}\right) - A_{beam}}$$

$$\boldsymbol{A_{beam} = \left(\frac{I^+ - I^-}{I^+ + I^-}\right)_i + \sum_j \frac{\partial A_i}{\partial \delta X_j} \left(\delta X_j\right)_i}$$

$\boldsymbol{i =}$ Detector , $\boldsymbol{j =}$ Measured beam parameter

- The false asymmetry includes the measured beam current asymmetry (in-situ) as well the other parameters which are determined from asymmetry dependence studies and removed in linear regression.

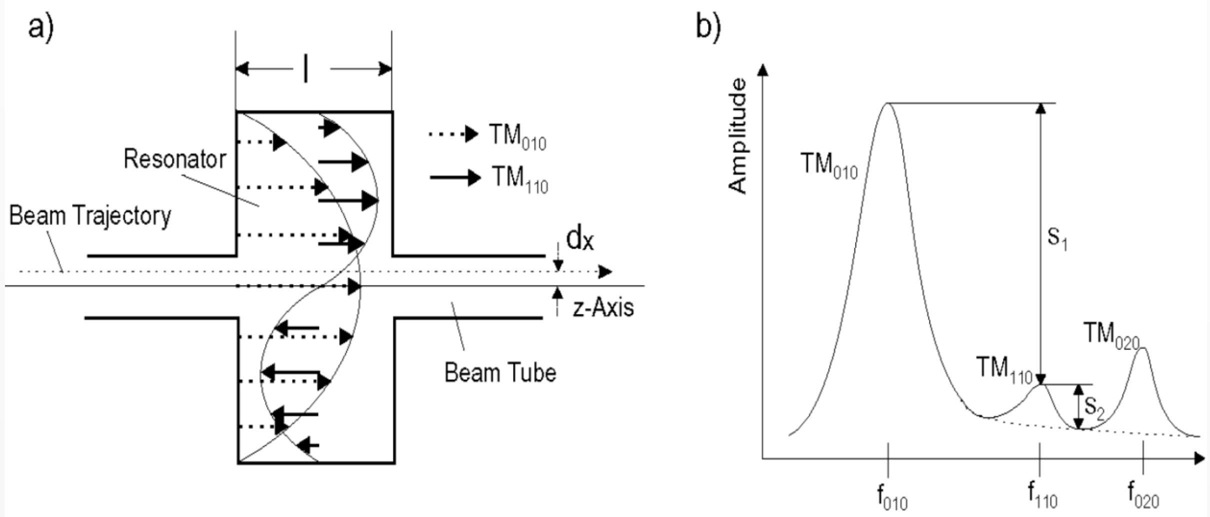
# Polarized beam

## Beam Monitoring

### Current Monitors:

For example: Using ''pillbox''-style $TM_{010}$ mode resonant RF cavity beam-current monitors (BCMs)

The signal measured from each BCM is proportional to the cavity's electric field, which falls off non-linearly from the central axis of a $TM_{010}$ resonant cavity

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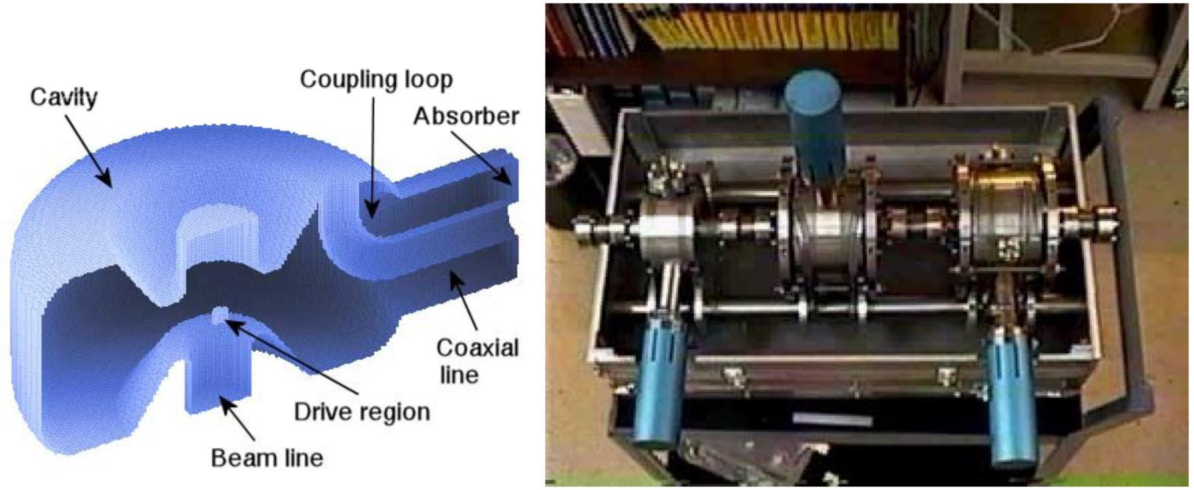


# Polarized beam

## Beam Monitoring

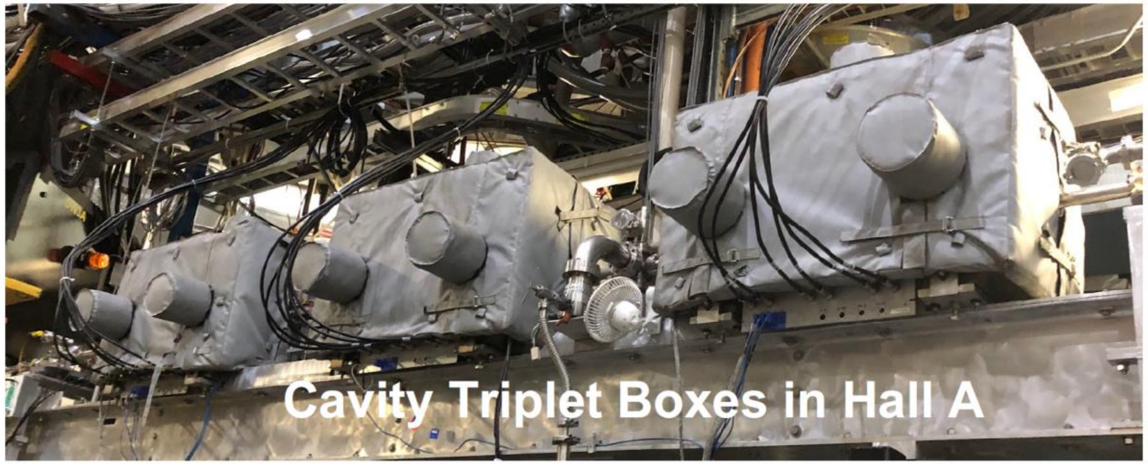
**Current Monitors:**

Need multiple beam monitors (e.g. 7 BCMs used for MOLLER)

The Measured beam charge is slightly different for each BCM due to beam trajectory differences

Displacement from monitor central axis causes a drop in sensitivity

- Beam steering needed to center the beam on target 1 or 2 mm, and the displacement will be different in each BCM.
- Beam raster causes the beam to traverse each BCM at a different radius as a function of time and position along the beamline
- Beam jitter

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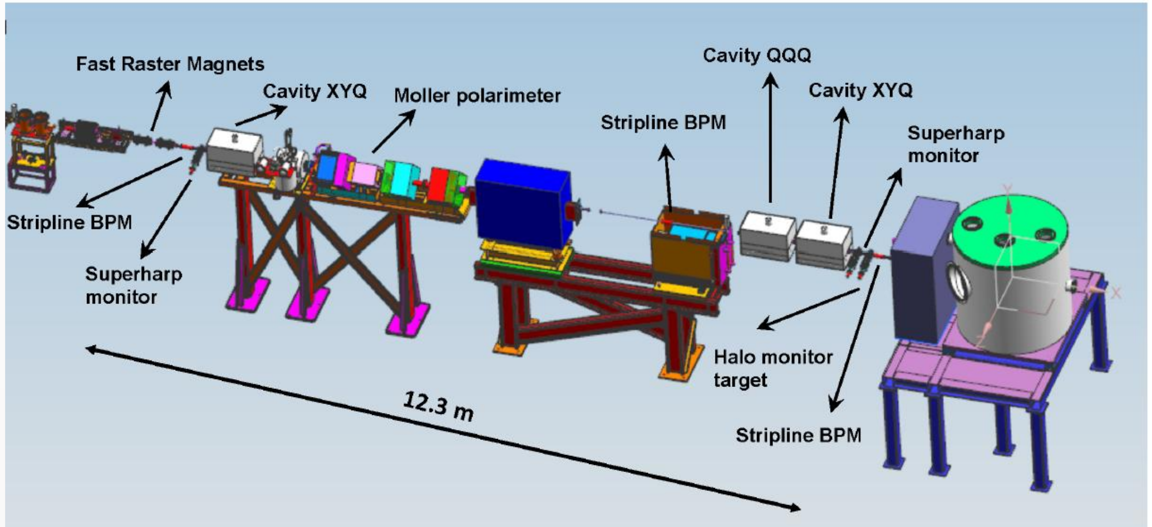



**For a precision PV experiment, a sensitivity of $1\ ppb/nm$ ( at $2\ mm$ from the central BCM axis) can become a limiting uncertainty.**

Need dedicated measurements to explore the BCM sensitivity to beam position for each BCM separately (induce deliberate beam position and charge changes at the source/injector)

# Polarized beam

## Beam Monitoring

$$A_{beam} = \left(\frac{I^+ - I^-}{I^+ + I^-}\right)_i + \sum_j \frac{\partial A_i}{\partial \delta X_j} (\delta X_j)_i$$

**Precision:**

BCM asymmetries and differences and their widths are measured continuously

The precision of the beam monitors is limited by their resolution

The resolution is measured using the BCM double-difference, which is independent of accelerator fluctuations:

$$DD_{ij} = \left(\frac{I_i^+ - I_i^-}{I_i^+ + I_i^-}\right) - \left(\frac{I_j^+ - I_j^-}{I_j^+ + I_j^-}\right) = A_{I_i} - A_{I_j} \qquad R = \frac{RMS(DD_{ij})}{\sqrt{2}}$$

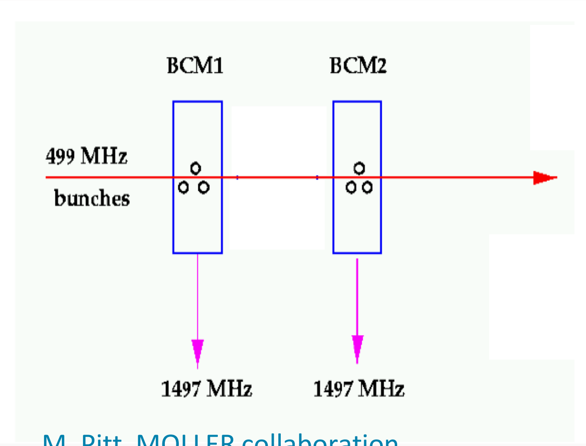
The additional uncertainty should normally be a small percentage ( $< 10\%$ ) of the detector counting statistics width for a single detector.

# Polarized beam

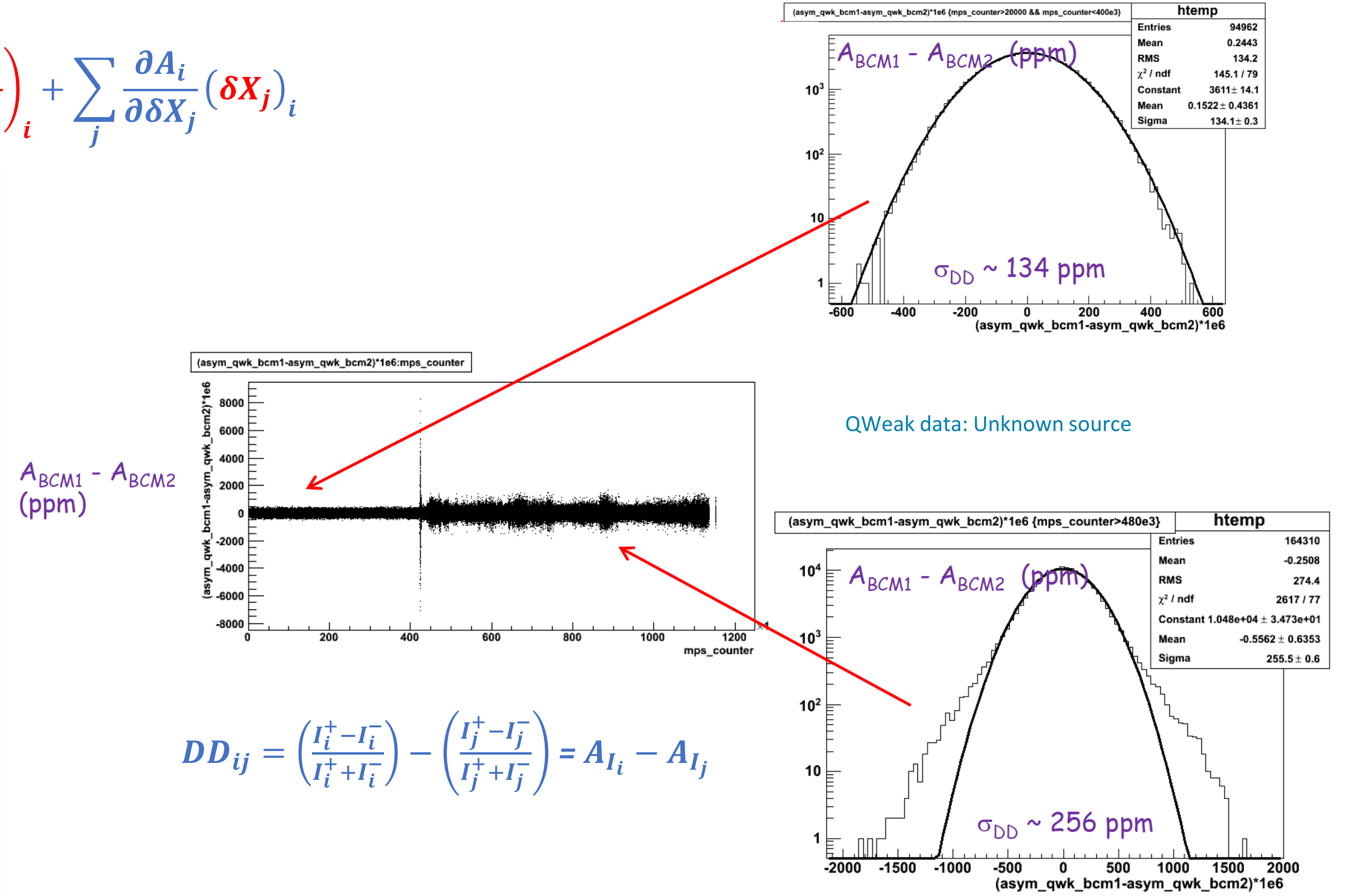
## Beam Monitoring

$$A_{beam} = \left(\frac{I^+ - I^-}{I^+ + I^-}\right)_i + \sum_j \frac{\partial A_i}{\partial \delta X_j}\left(\delta X_j\right)_i$$

## Precision:




M. Pitt, MOLLER collaboration




QWeak data: Unknown source

$$DD_{ij} = \left(\frac{I_i^+ - I_i^-}{I_i^+ + I_i^-}\right) - \left(\frac{I_j^+ - I_j^-}{I_j^+ + I_j^-}\right) = A_{I_i} - A_{I_j}$$

# Polarized beam

## Beam Monitoring

$$A_{beam} = \left(\frac{I^+ - I^-}{I^+ + I^-}\right)_i + \sum_j \frac{\partial A_i}{\partial \delta X_j} \left(\delta X_j\right)_i$$

**Systematic uncertainty:**

Systematic differences between beam current measured with different BCMs can be investigated by looking at the detector sensitivity to each BCM

$$\delta A_{sys}^M = \sqrt{\frac{\sum_j \left(A_j^{det} - \langle A^{det} \rangle\right)^2}{n(n-1)} - \sigma_M^2}$$

With $n$ different beam current monitors, for each detector. $\langle A^{det} \rangle = \frac{1}{n} \sum A_j^{det}$

One can establish these sensitivities by:

1. Measuring detector sensitivity do natural beam jitter (random fluctuations of the beam)

2. Modulating the beam charge and position deliberately

# Polarized beam

## Beam Monitoring

$$A_{beam} = \left(\frac{I^+ - I^-}{I^+ + I^-}\right)_i + \sum_j \frac{\partial A_i}{\partial \delta X_j} \left(\delta X_j\right)_i$$

**Beam Jitter:**

- Exploit experiment/detector symmetry to measure detector sensitivity to natural beam parameter changes at or above the line frequency
- This sensitivity can (in principle) be measured continuously, during production data taking.

**Beam modulation (see later):**

- Reduce the uncertainty in the measured detector sensitivity to beam parameter changes.
- This is done by actively modulating the beam position and angles on target using steering coils in front of the target
- Can also be done for current monitoring
- Requires dedicated runs during which the detectors are not taking regular asymmetry data
- Usually done for 5-10% of the run time, short runs every few minutes

# Polarized beam

## Beam Monitoring

$$A_{pos} = \sum_j \frac{\partial A_i}{\partial \delta X_j} (\delta X_j)_i$$

**Beam Position Monitors (BPMs):**

Used to verify beam tune (steer the beam through the different elements of the beamline onto the experimental target).

Experiments also use position locks using BPMs and corrector magnets to keep the beam centered on the experimental target, especially at the higher beam currents characteristic of PV experiments.

Measure energy variations, using the beam position for two monitors separated by some distance (e.g. $\sim 10\ m$) to measure position and angle and at a third point at the maximum beam dispersion to measure energy variations

Also required to measure helicity-correlated beam asymmetries (exploit the detector symmetry)

Usually require a resolution of about $\leq 3\ \mu m$ per helicity pair

This is mostly driven by the requirement to reduce the jitter contribution to $\leq 10\%$ (see earlier), and

study the detector sensitivity to beam motion, and to precisely measure the azimuthal asymmetry contribution.

# Polarized beam

## Beam Monitoring

$$A_{pos} = \sum_j \frac{\partial A_i}{\partial \delta X_j}(\delta X_j)_i$$

**Beam Position Monitors (BPMs):**

Different styles of BPMs: Antenna-wire BPMs (right), strip-line BPMs (left) and cavity BPMs.

The majority of BPMs used for PV experiments are antenna BPMs with four equally-spaced antennas which detect the presence of the beam via capacitive coupling to the electron beam's electric field.

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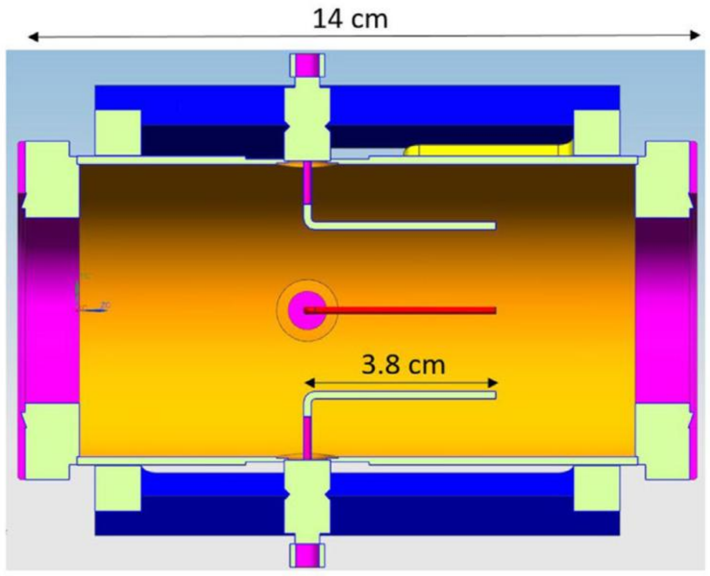
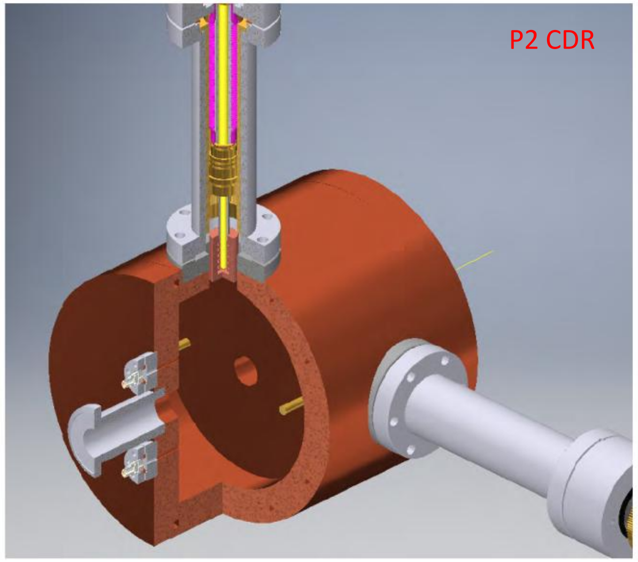



Need several BPMs to:

- monitor beam position and angle at the target,
- measure beam energy

The beam position and the angle at the target are determined from a linear least squares fit of 4 or 5 BPMs located in a magnetic field-free drift region between ~1 and 10 m upstream of the target.

# Polarized beam

## Beam Monitoring

$$A_{pos} = \sum_j \frac{\partial A_i}{\partial \delta X_j} (\delta X_j)_i$$

**Beam Position Monitors (BPMs):**

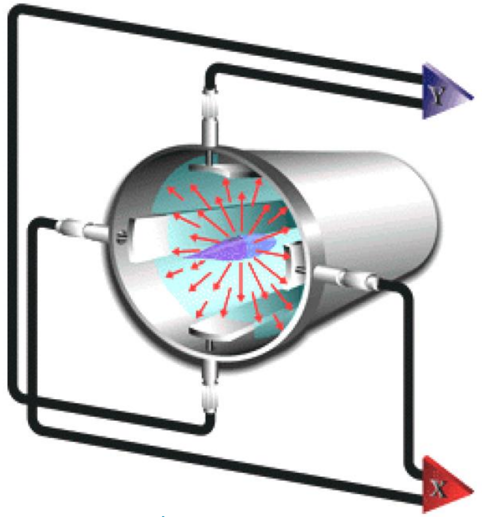
The stripline BPMs are used for their

- Ability to measure the electron beam absolute position relative to a mechanical fix-point or to any other absolutely known axis e.g. the symmetry axis of a quadrupole magnet.

- The stripline BPM sensors are CNC machined, complete with external fiducial dimples on the main corpus to facilitate precise placement on the beamline, and directly traceable from the prints to within CNC tool accuracy.

- Typical measurement offsets of $200 - 400\ \mu m$.

- Intrinsic BPM resolution can be extracted by using two (or more) upstream monitors to project to downstream monitor



MOLLER, unknown source

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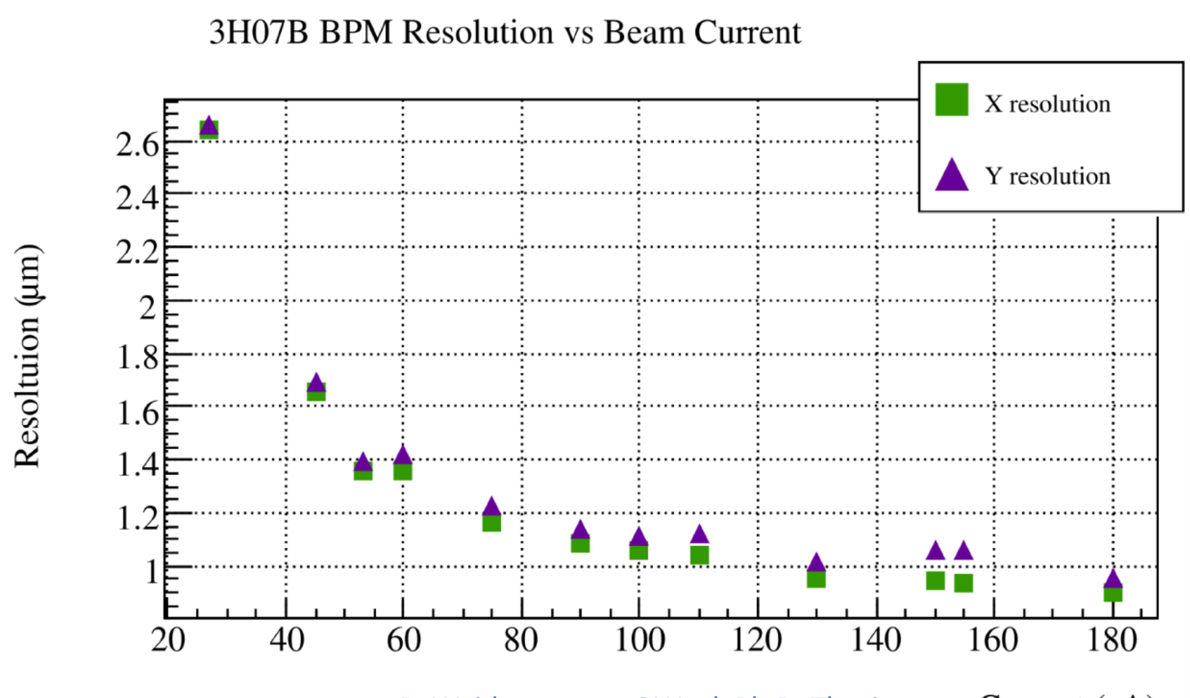
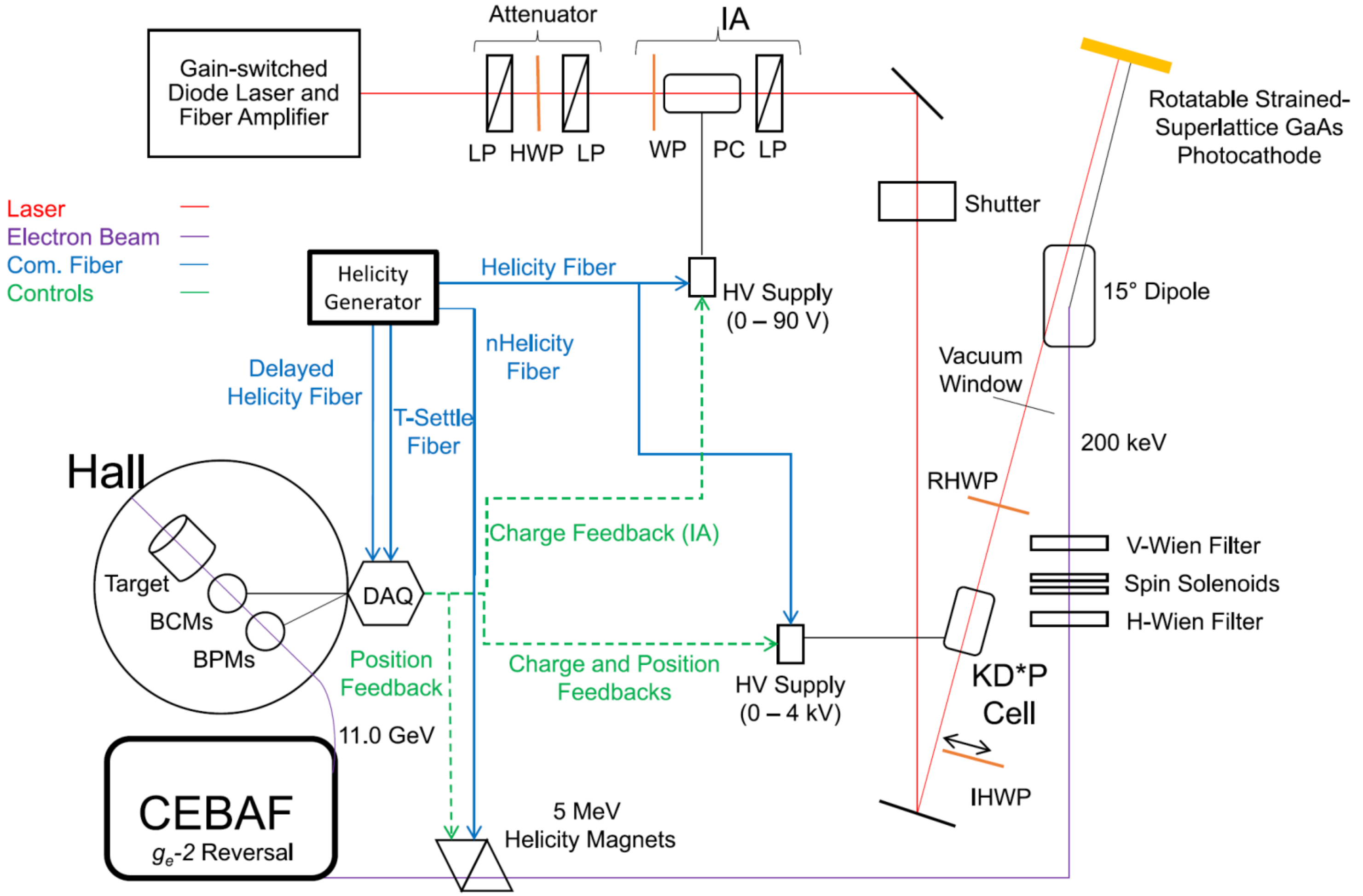



B. Waidyawansa , QWeak Ph.D. Thesis

# Polarized Beam

**Active Beam Feedback:**

- One can reduce beam effects with active/fast feedback on the charge and position differences.
- The associated noise is known to converge faster with active feedback than the statistical detector noise.
- The charge jitter can be suppressed by applying small changes to the voltage setpoints for the source Pockels cell, based on the measured charge asymmetry width.
- Position differences can also be reduced using active feedback on both, the Pockels cell, as well as helicity magnets in the injector

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# Polarized Beam

**Experiment Sensitivity**

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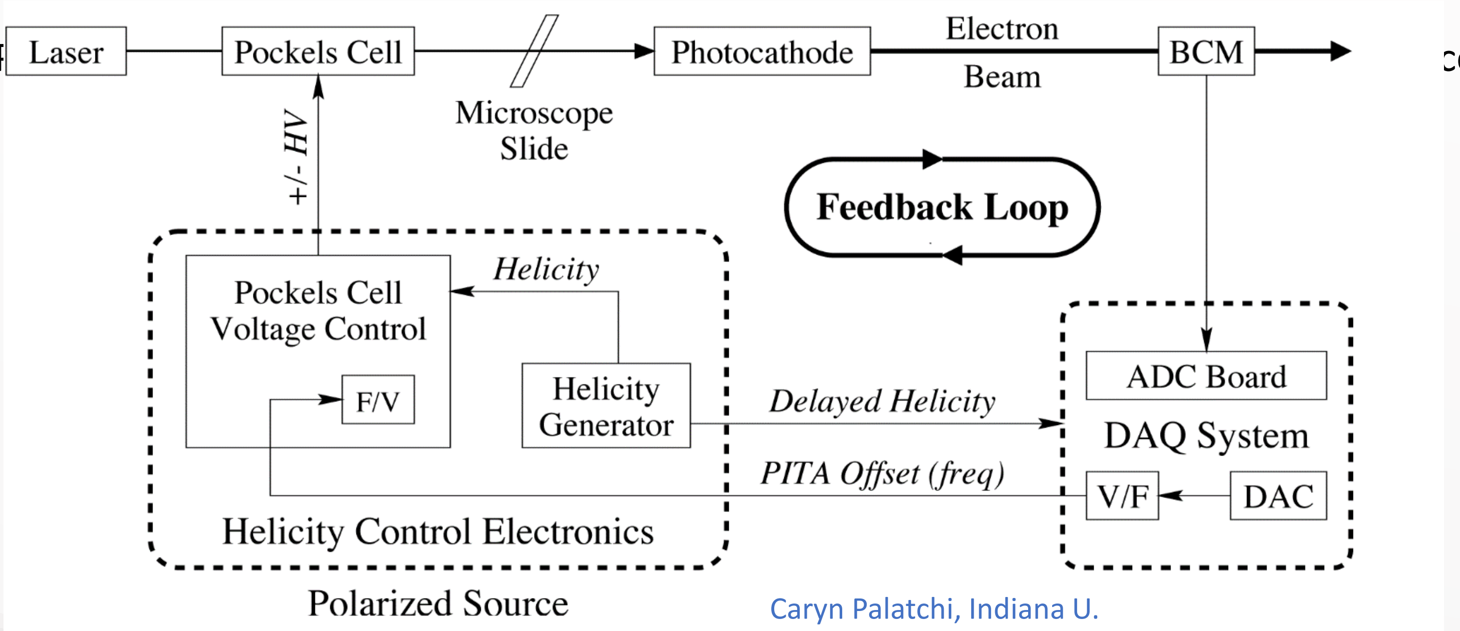
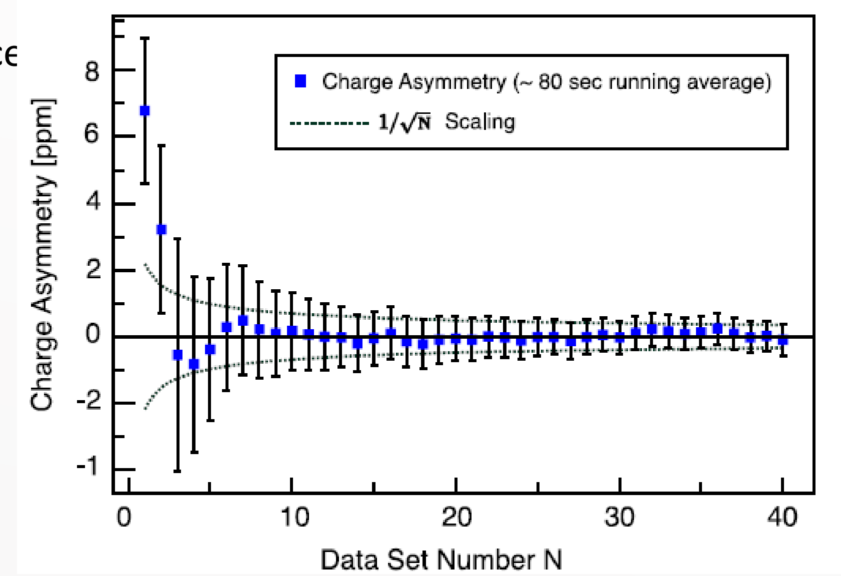
- F




Caryn Palatchi, Indiana U.

Qweak, unknown source



# Polarized Beam

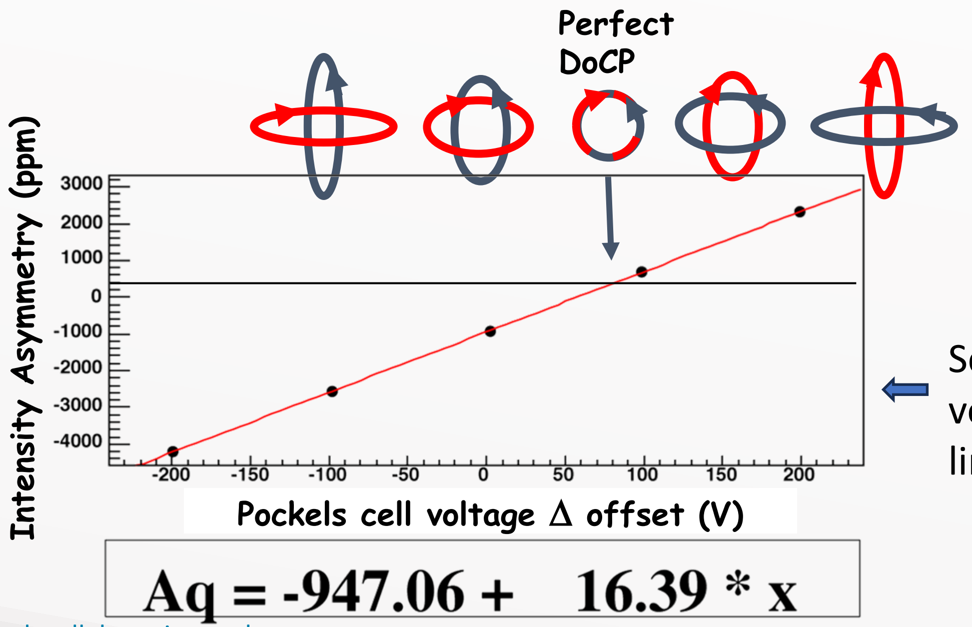
**Experiment Sensitivity**

**Pockels cell feedback:**

**P**hase **I**nduced **T**ransport **A**nomaly **(PITA)**

This is a driven beam intensity asymmetry : $A_I \ = \ \varepsilon \ \Delta \ \ sin(\ \theta)$

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

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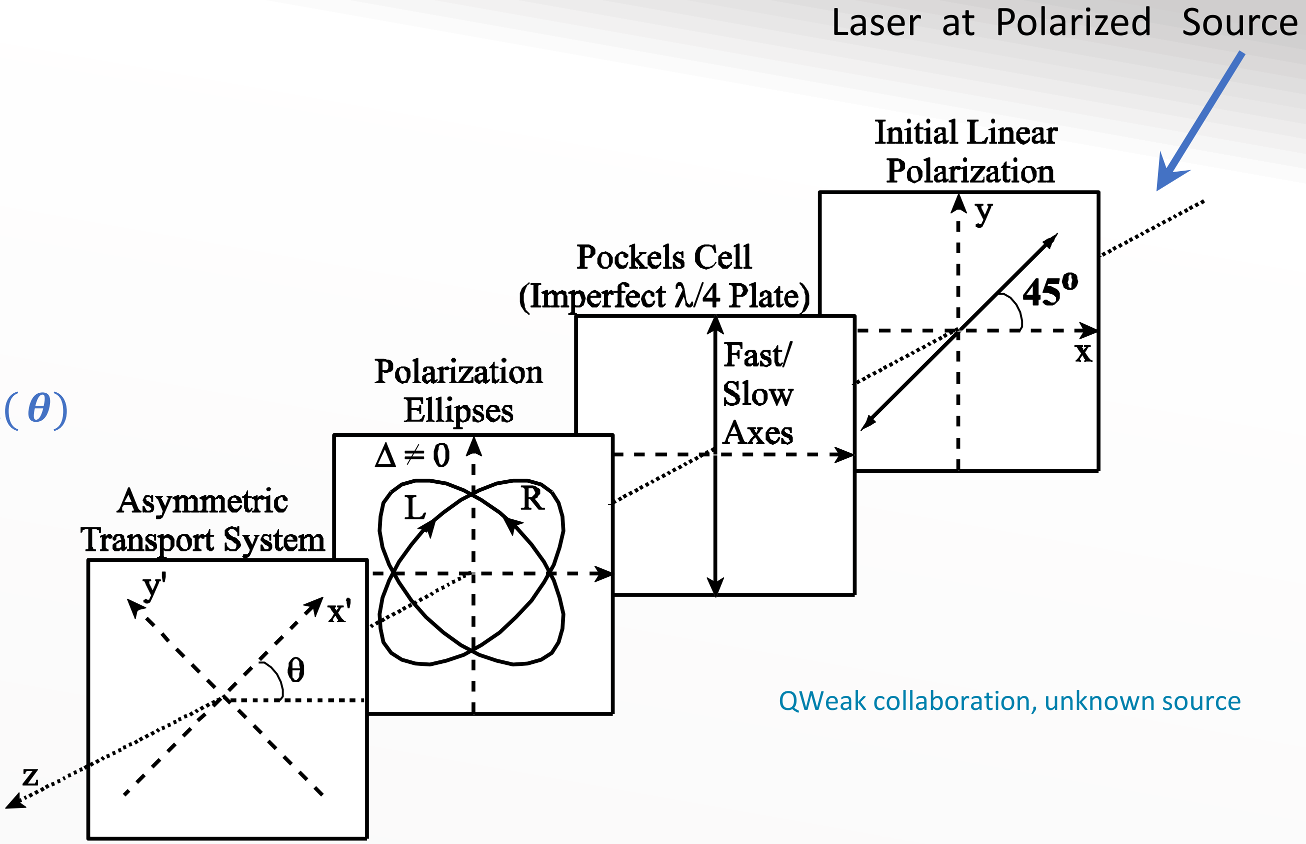
Scanning the Pockels Cell voltage = scanning the residual linear polarization (DoLP)

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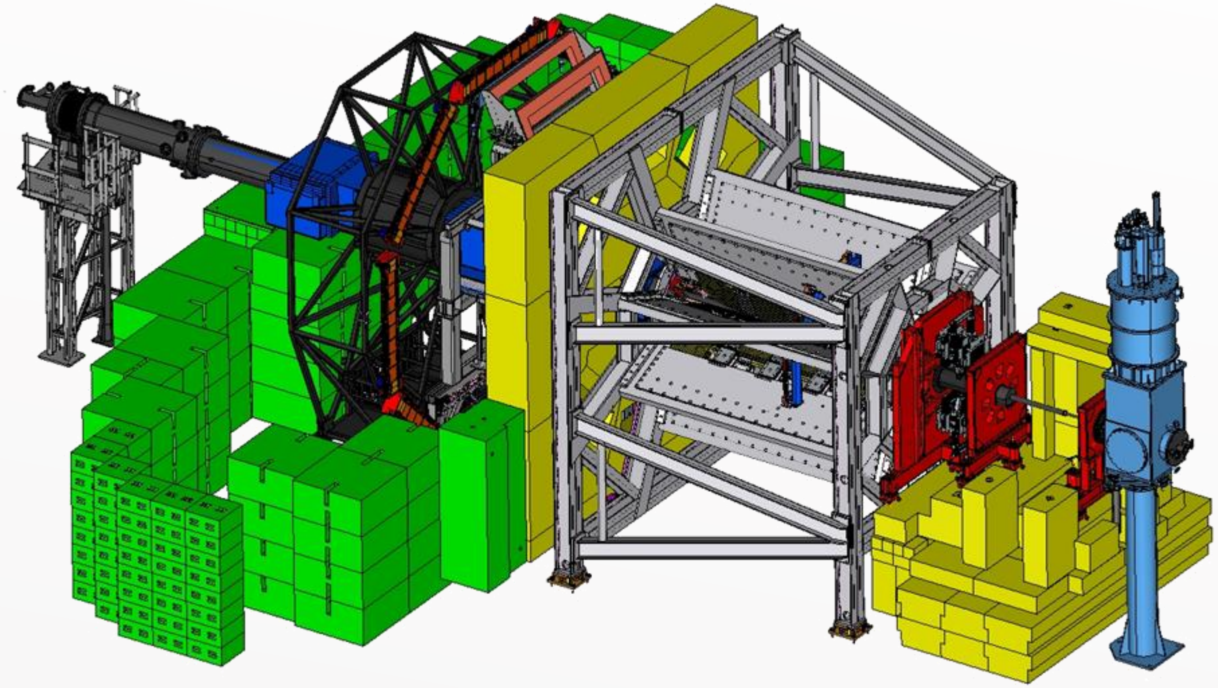
Δ drifts, but slope is ~ stable

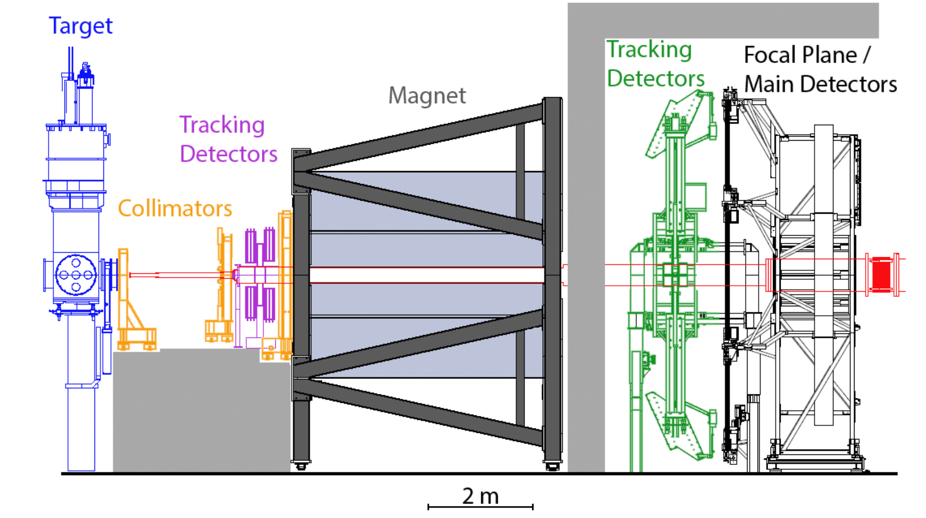
⟹ Feedback on Δ

# Polarized Beam

## The QWeak Experiment

## Experiment Sensitivity





# Polarized Beam

**Experiment Sensitivity**

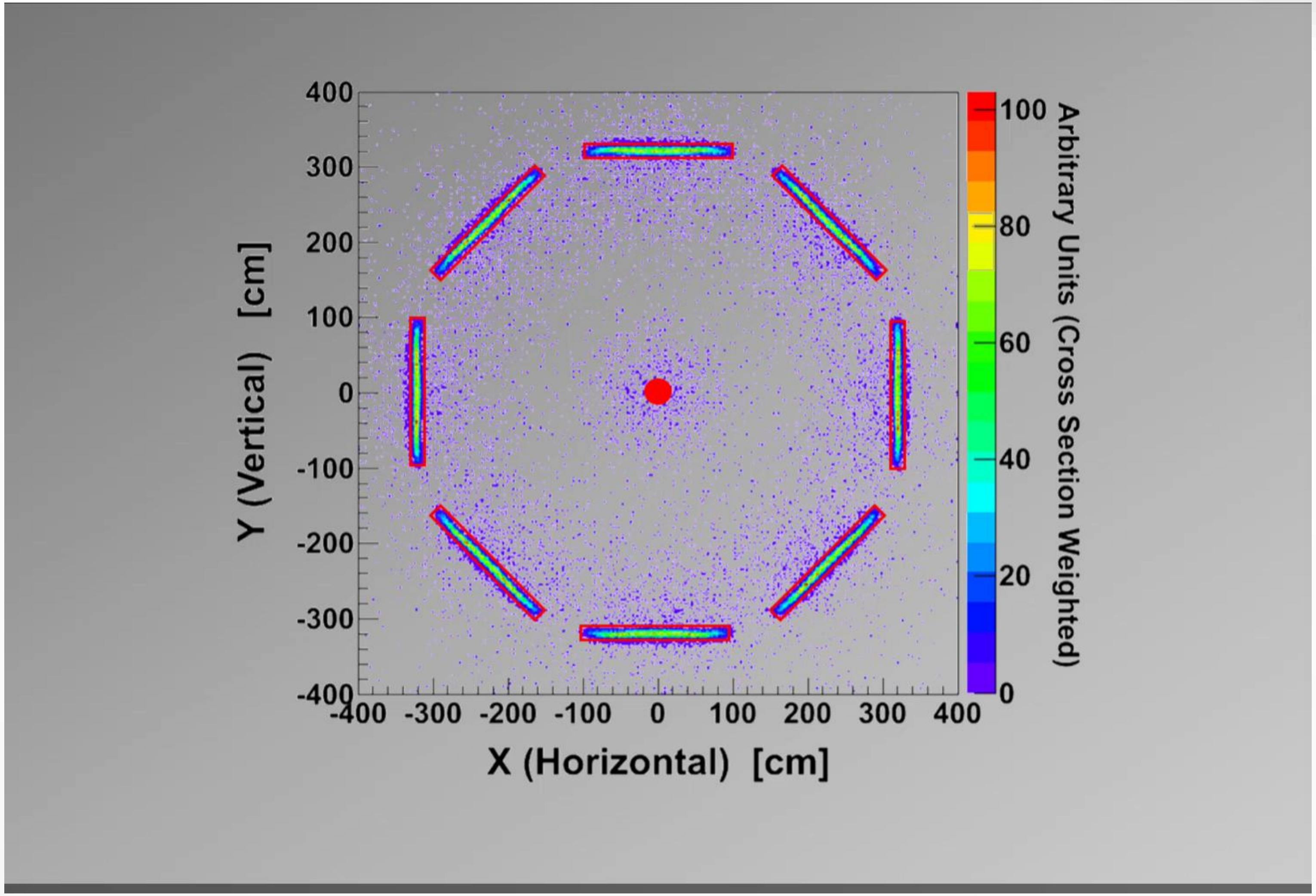
**Modulation:**

Beam modulation refers to the deliberate variation of beam parameters, such as

- Beam current
- Beam position
- Beam angle/energy

Performing detector studies that measure the correlation between the detector signal and beam parameters is used to remove the corresponding false asymmetries.

Detector symmetry can also be used to measure transverse spin asymmetry (later).



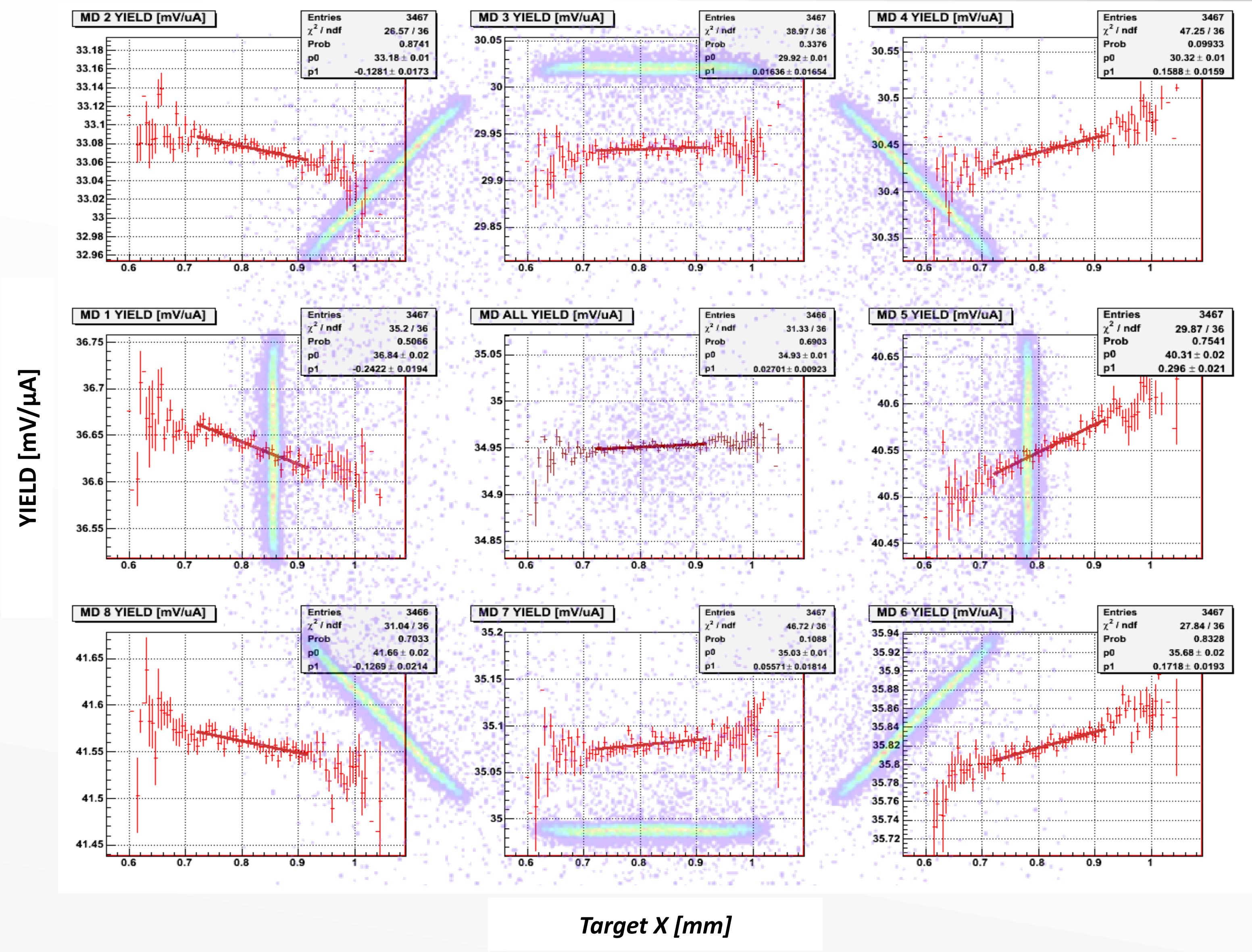
# Examples of experimental effects

Detector symmetry allows measurement of:

- Beam motion
- Beam position
- Beam angle

Performing detector studies that measure the correlation between the detector signal and beam parameters (deliberate variation) is used to remove the corresponding false asymmetries.

Detector symmetry can also be used to measure transverse spin asymmetry.



# Polarized Beam

## Experiment Sensitivity

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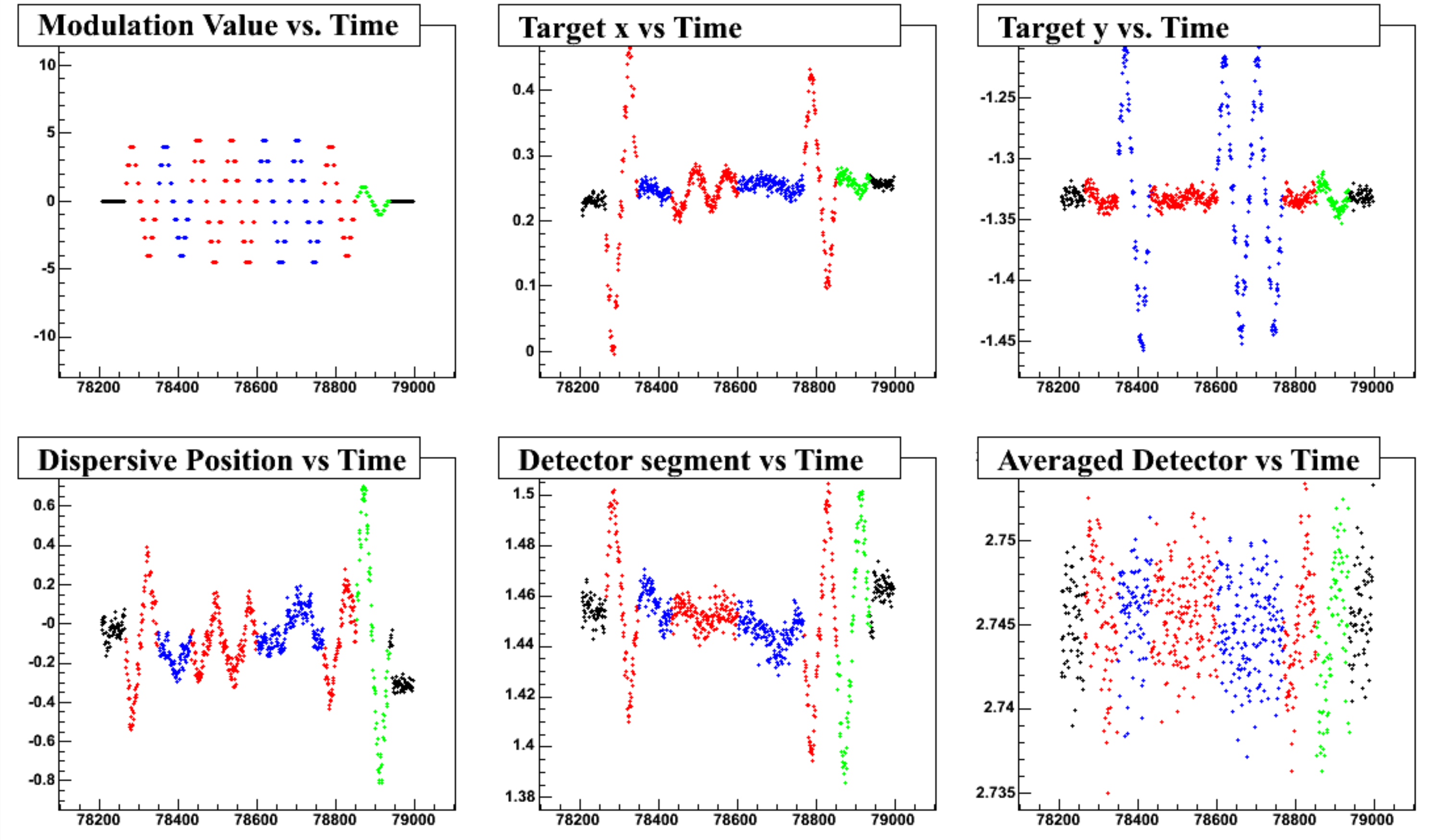


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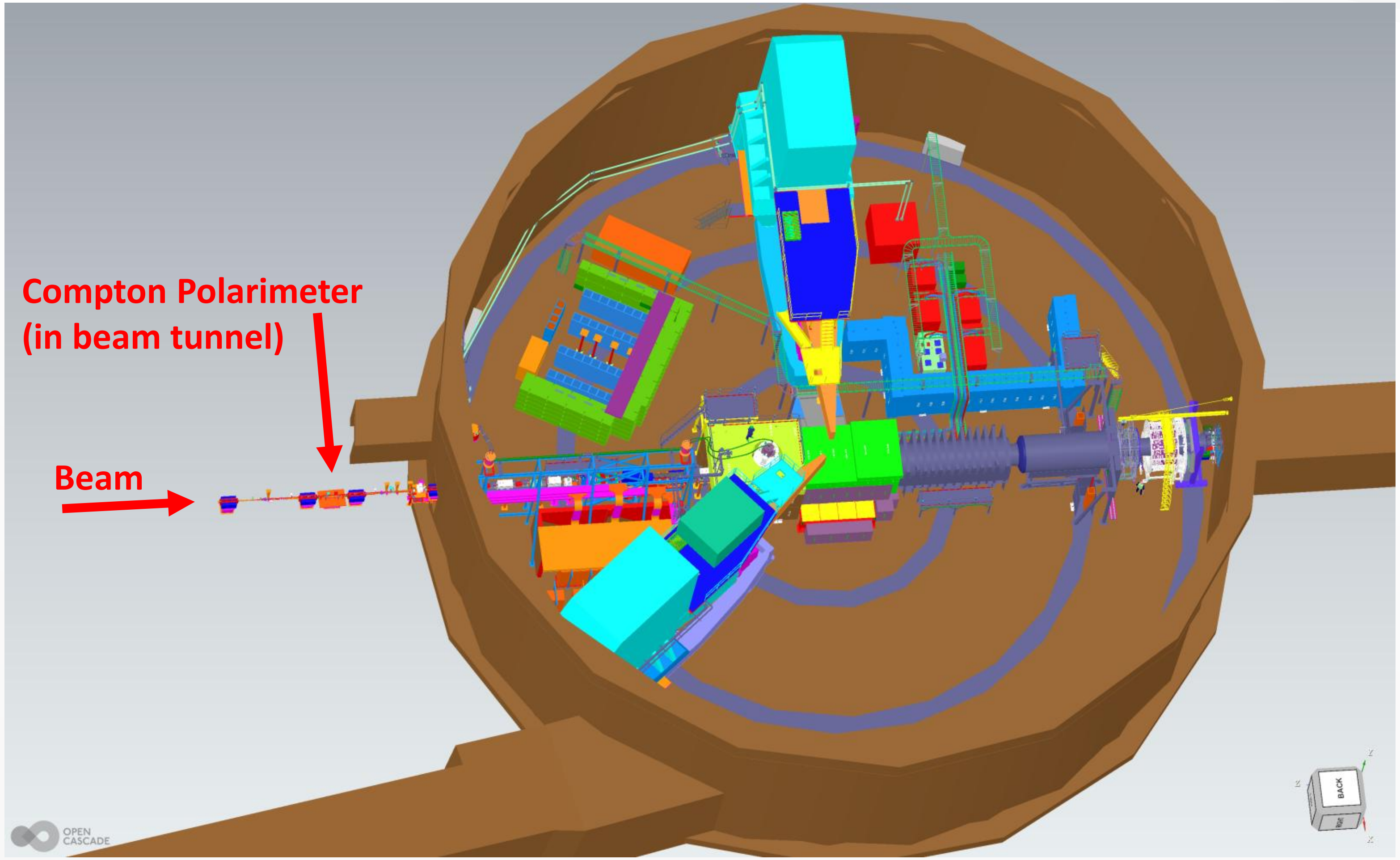
# Polarized Beam

**Example: MOLLER Beam Line**

- The first component dedicated to the experiment is the Compton polarimeter

**The “in-Hall” components include:**

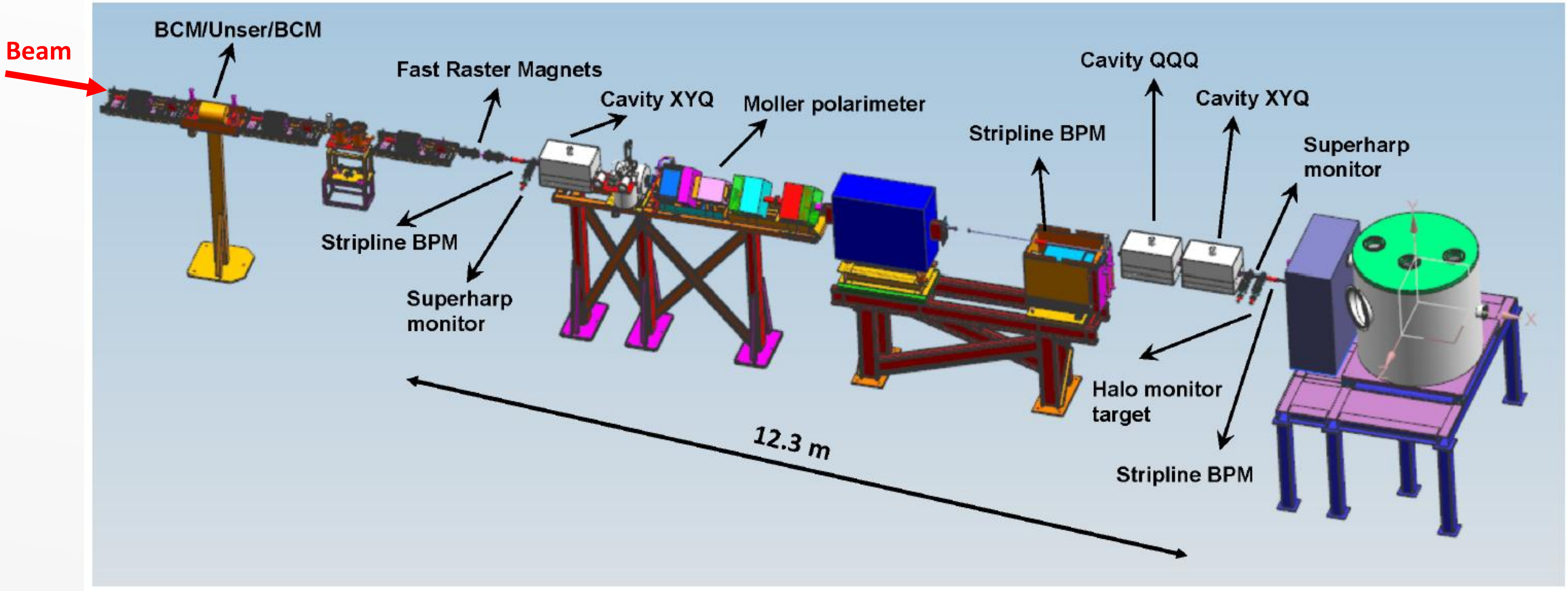
- Quadrupole and corrector magnets, for position lock at both the Møller polarimeter the targets
- BCM/Unser/BCM combination
- Fast raster magnets
- Stripline BPMs, microwave cavity XYQ box, and superharp beam profile monitor
- The Møller polarimeter
- Additional BCMs, BPMs, profile monitors, and halo monitors



# Polarized Beam

**Example: MOLLER Beam Line**

**The "in-Hall" components include:**

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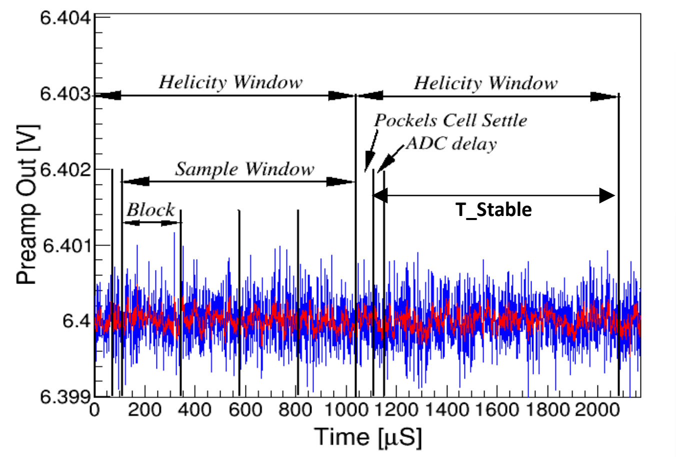
# Polarized beam

## Helicity State Generation

Fast helicity reversal is the single most important technique we need to make a successful measurement.




The reversal frequency and pattern should be chosen such that it

- suppresses systematic effects from coherent pick-up of fixed-frequency noise
- suppresses pickup of line noise
- suppresses effects (false asymmetry) from slow drifts in the experiment or beam line

The helicity flip process and window much satisfy the following requirements:

- the flip must be robust,
- The flip must be completed significantly before the next integration period begins,
- The helicity timing must be consistent over a given pattern (precisely timed)
- The window must be long enough to allow statistics to dominate any potential electronics noise sources (counting statistics)

Helicity flipping can be

- ‘‘line locked’’ to the power company 60 Hz (50 Hz) alternating current (AC) voltage or
- free running, with
- repetitive or pseudo-random flipping in pairs, quartets or octets,
- and with direct or delayed reporting of the helicity information to the experiment

It is vital to prevent electronic cross-talk that could transmit real-time helicity information to the experiment, including via ground loops, that could produce false raw (detector) asymmetries.

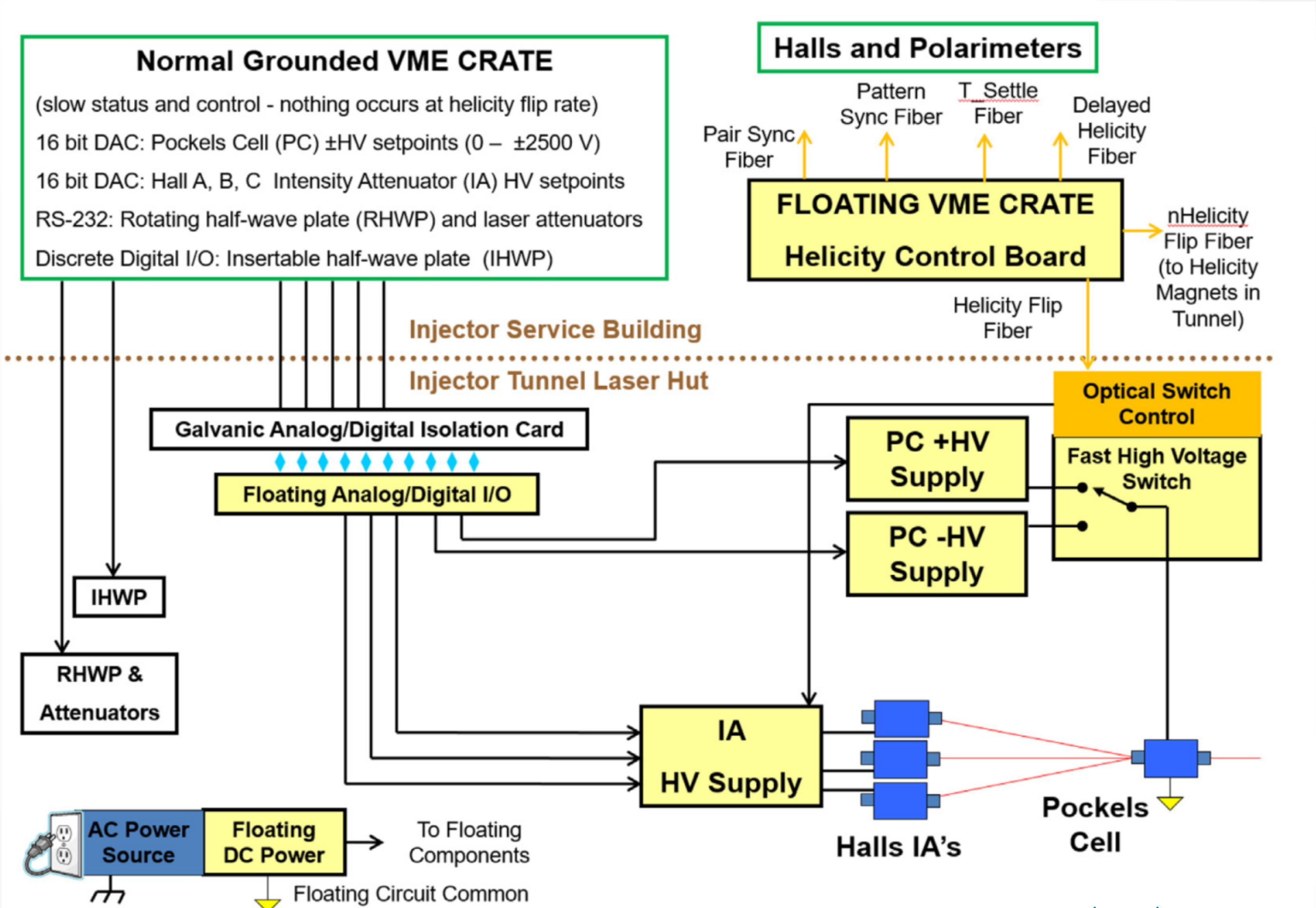
# Polarized beam

## Helicity State Generation

### Helicity Control

- A helicity-control board/device – electrically-isolated
- generate two real time helicity signals:
  - $f$ Helicity flip signal
  - $\sim f$ NOT Helicity Flip signal (power balance)
- The Pockels cell and the so-called IA charge-asymmetry controllers at the laser table are the only devices that receive a real-time helicity signal (Helicity flip). The signals are galvanically isolated.
- The beam helicity signal is generated by a pseudo-random bit generator
- All other experimental components receive only a delayed helicity signal so there is no knowledge of the real time helicity

Jefferson Lab Setup

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# Polarized beam

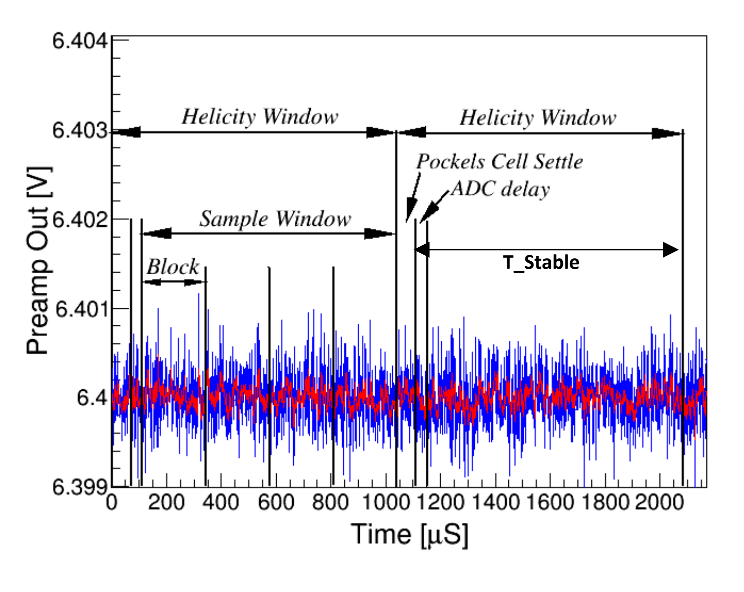
## Helicity State Generation

### Helicity Control

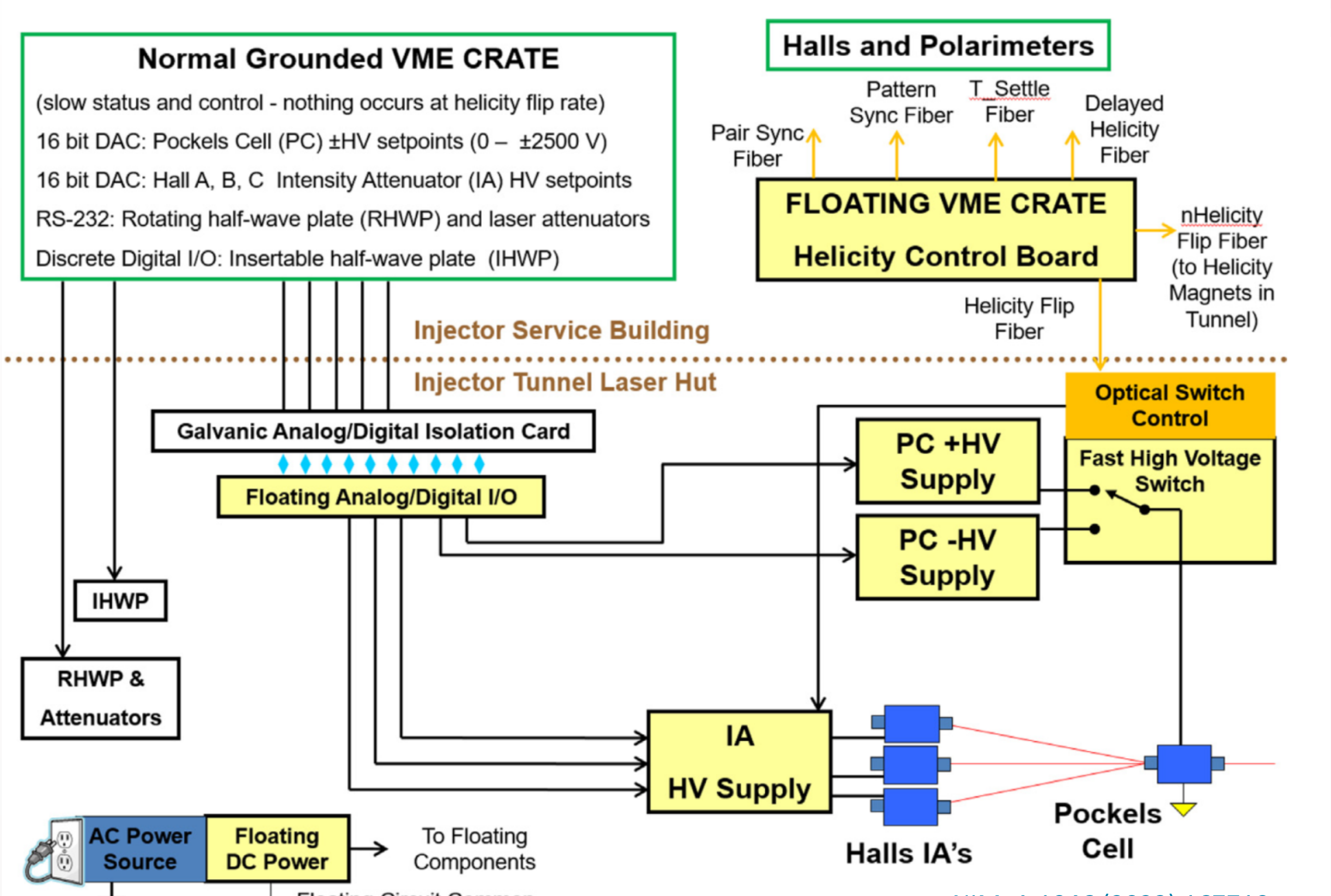
Generates the following additional signals:

- $T_{Settle}$ (Pockels cell ringing)
- Pair Sync
- Pattern Sync
- Clock (reference clock for experiment)
- Maybe delayed helicity

$$f_h = \frac{1}{T_{settle} + T_{stable}}$$




Jefferson Lab Setup




NIM, A 1046 (2023) 167710

# Polarized beam

## Helicity State Generation

### Helicity Control

Reduction of line noise issues (60 Hz/ 50 Hz etc.)

1. Either choose integration window such that $T_{stable} = 40000\ \mu s$ (or $T_{stable} = 3333\bar{3}\ \mu s$)

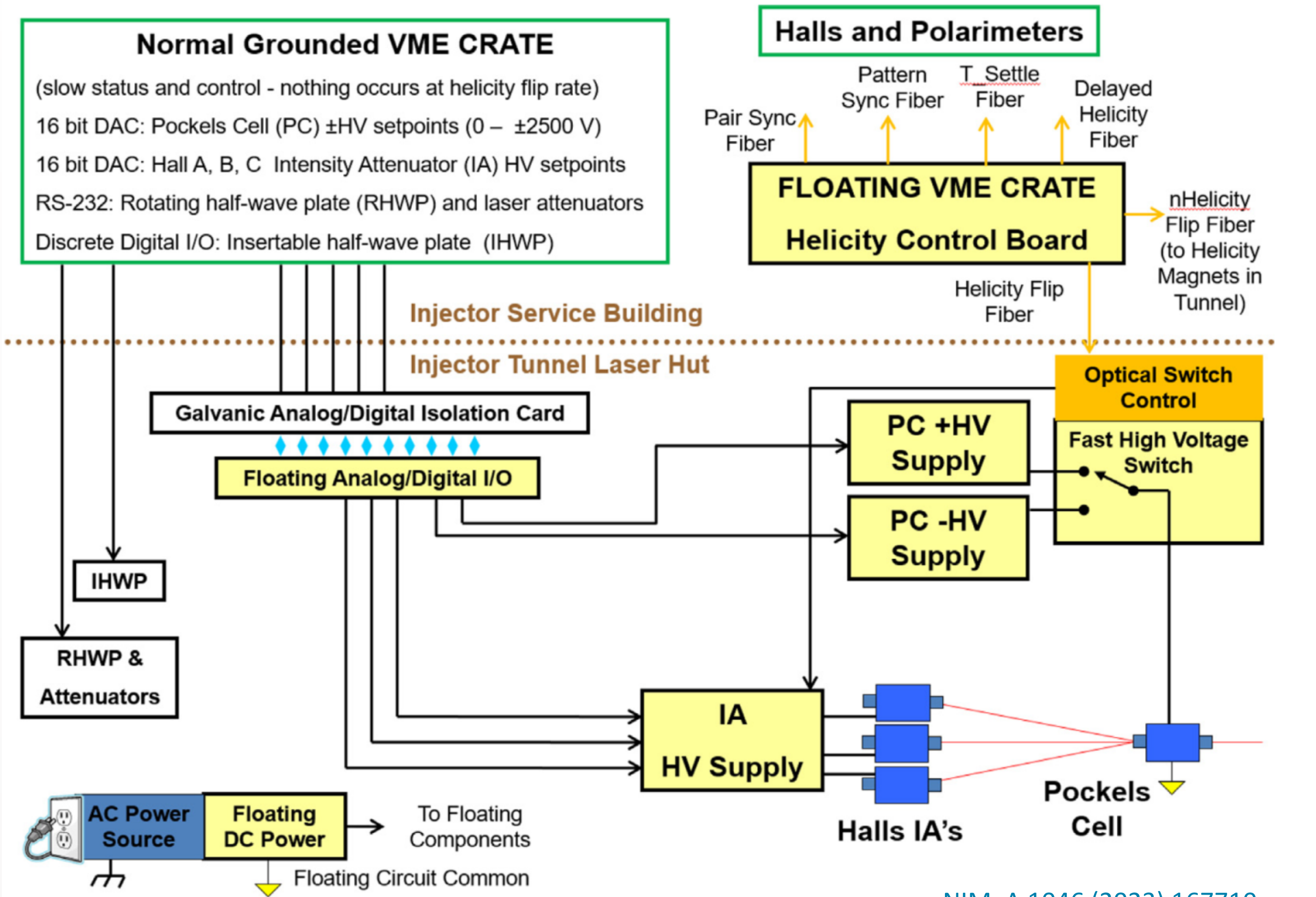
   This is too slow for other reasons. See later …

2. Or choose $f_h > 1\ kHz$ (far from harmonics) in free clock mode with specified pattern (see next slide) Also cancels other, low frequency noise.

3. Or operate in line-synch mode and choose a helicity pattern that cancels line noise in the asymmetry formation. This can be done at high frequencies $f_h > 1\ kHz$. The start of each pattern is line-phase locked. Does not remove other noise sources.

Fast reversal suppresses other low frequency components.

Jefferson Lab Setup

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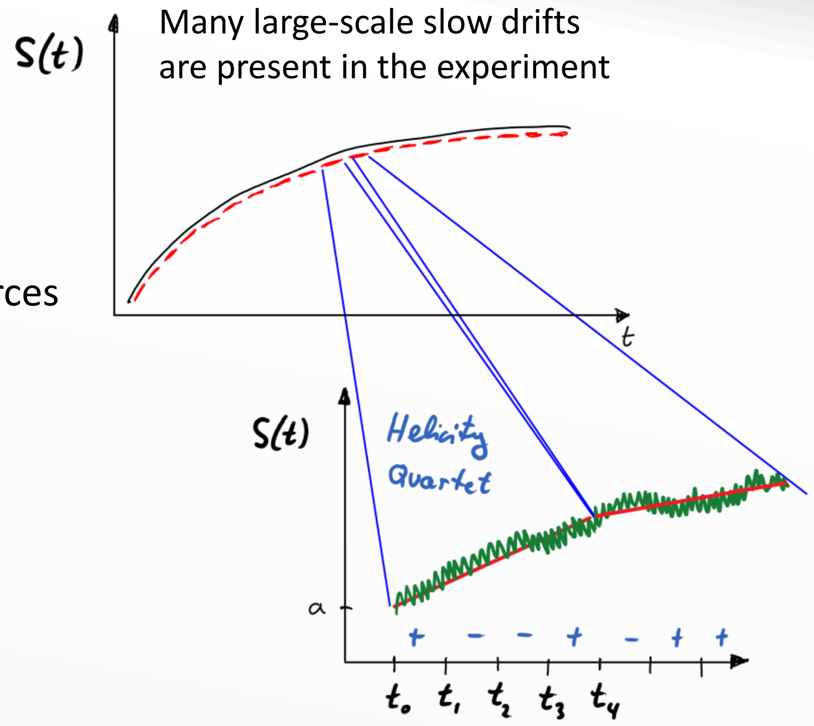
# Polarized beam

**Helicity State Generation**

**Helicity Control Device**

Helicity Patterns:

- Pattern can be chosen to cancel drifts and certain noise sources
- Pattern length should be consistent with line frequency




Example (MOLLER)

- Reversal frequency: $1920\ Hz = 32 \times 60\ Hz$
- Option 2 on the previous slide (free running clock / no line synch)
- 64 state pattern with random initial state sign and 128 window delay:

1. Thu-Morse ($32 + \overline{32}$ or complement): $(+ - - + - + + -)\ (- + + - + - - +)\ (- + + - + - - +)\ (+ - - + - + + -)$ $(- + + - + - - +)\ (+ - - + - + + -)\ (+ - - + - + + -)\ (- + + - + - - +)$
2. 16 Quad (or complement) $(+ - - + + - - +)\ (- + + - - + + -)\ (+ - - + + - - +)\ (- + + - - + + -)$ $(+ - - + + - - +)\ (- + + - - + + -)\ (+ - - + + - - +)\ (- + + - - + + -)$
3. 32 Pair (or complement) $(+ - + - + - + -)\ (+ - + - + - + -)\ (+ - + - + - + -)\ (+ - + - + - + -)$ $(+ - + - + - + -)\ (+ - + - + - + -)\ (+ - + - + - + -)\ (+ - + - + - + -)$

poor low frequency noise cancelation

# Polarized beam

## Helicity State Generation

The faster the helicity reversal the better the approximation of the signal as a linear drift for many experimental effects.

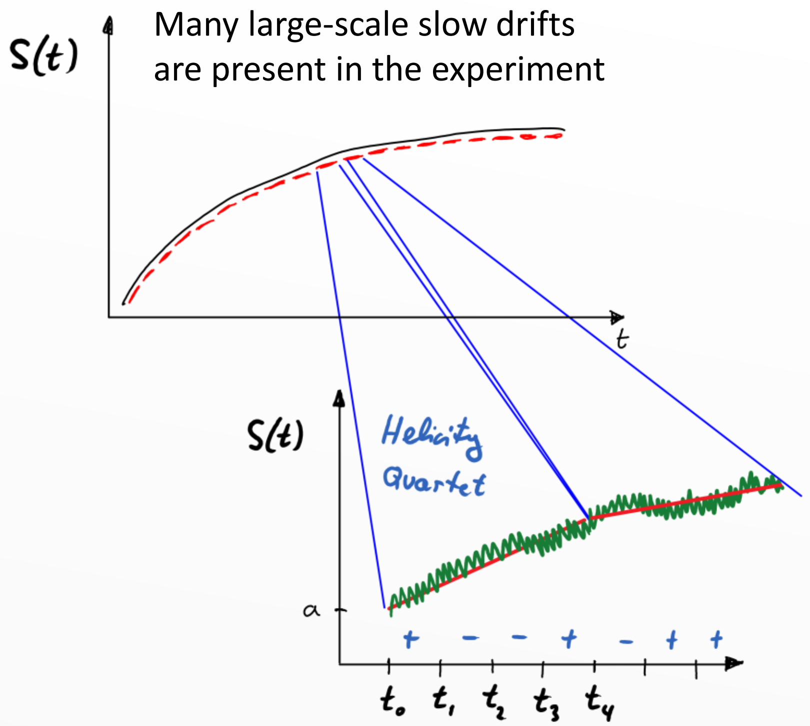
So, locally, the signal behaves like a linear function of time:

$$Y(t) \approx \left( a + \frac{dY}{dt}\bigg|_{t_i} t \right)(1 + A_{msr})$$

- The quartet helicity pattern removes linear drifts +--+ or -++-
- An octet helicity pattern removes quadratic drifts +--+-++-
- Pseudo random reversal of the fist sign in quartet patterns removes higher order drifts

Example of these drifts:

- Target drifts (e.g. diurnal variations)
- Detector gain and electronics drifts
- Spectrometer field drifts
- Slow beam drifts




The smaller the helicity window (faster reversal) the better this approximation becomes.

The faster the reversal the faster the ADC has to be.
The ADC resolution is driven by the size of the asymmetry.

# Polarized beam

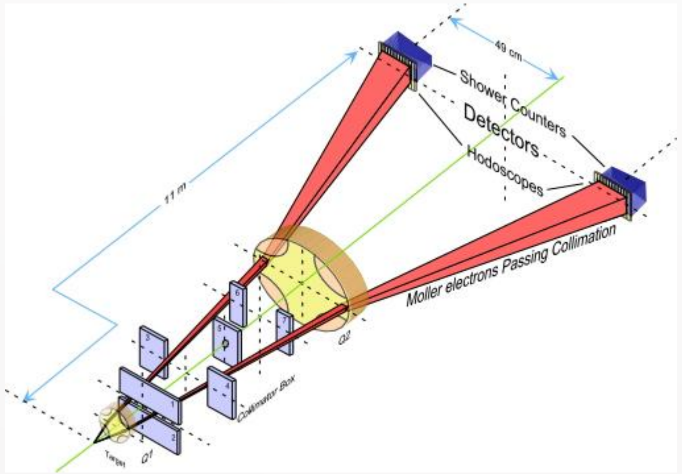
## Polarimetry

### Moller polarimeter

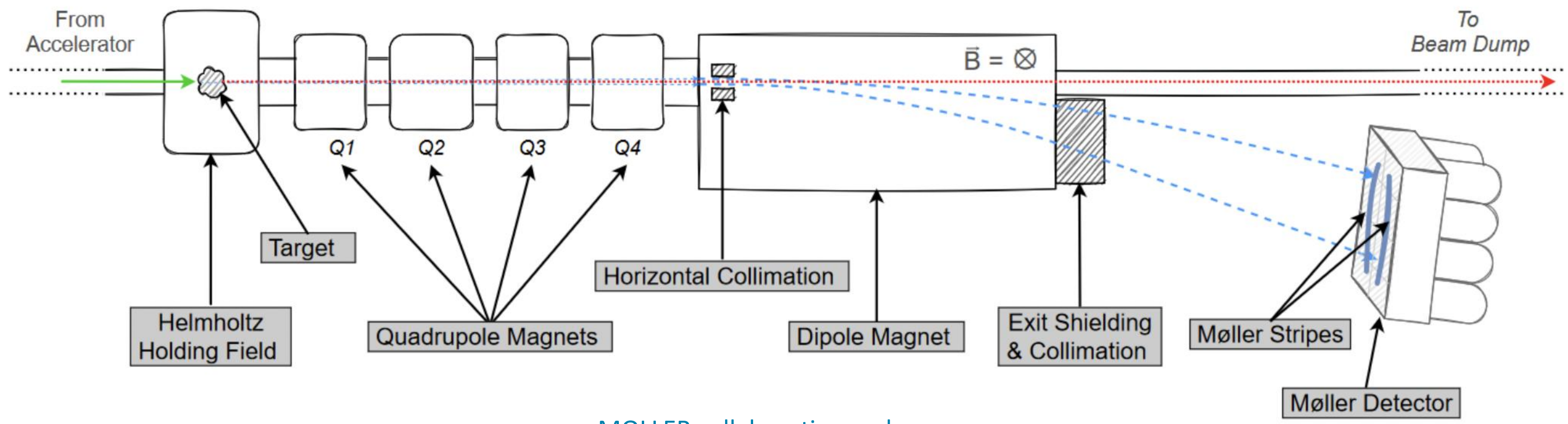
Measure the parity conserving Moller scattering asymmetry from an iron foil target (polarized along beam direction) with a required coincidence between the left and right detectors.

Four quadrupoles select the events of interest focusing them through left/right slits in the dipole onto a calorimeter.

Moller polarimetry is invasive and must be taken at low current during dedicated period of running: added difficulty of trying to assess effects from any changes in beam properties between the measurement and the experiment production data.




MOLLER collaboration, unknown source

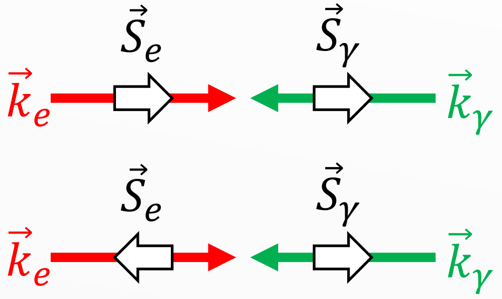



MOLLER collaboration, unknown source

# Polarized beam

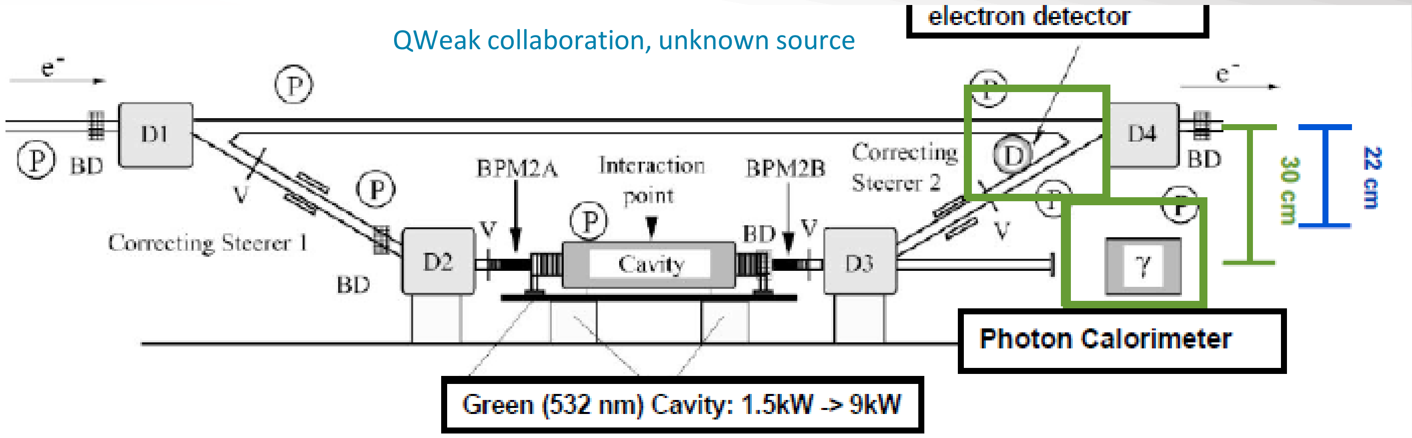
## Polarimetry

### Compton polarimeter ($E_{beam} > 1GeV$)




$n^+$ counts in this mode

$n^-$ counts in this mode



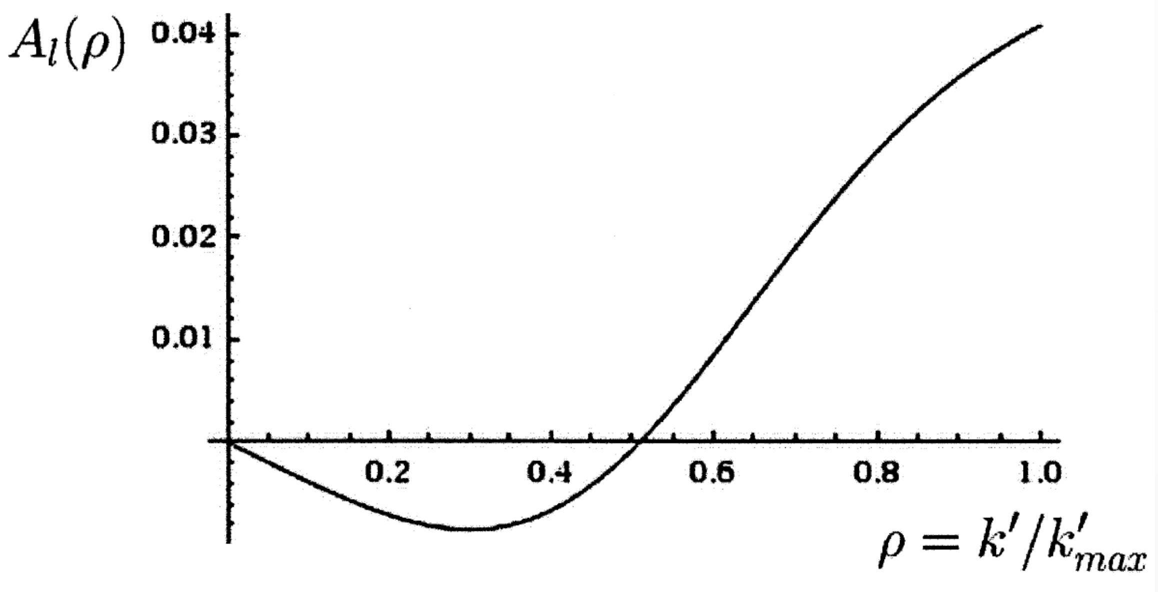

QWeak collaboration, unknown source

- Measure the number counts in each mode over equal time periods
- For the experimental asymmetry from detector measurements:

$$A_{exp} = \frac{n^+ - n^-}{n^+ + n^-} = P_\gamma P_e A_l$$

- $P_\gamma$ : Photon polarization (from laser)
- $A_l$ : Theoretical Compton asymmetry (precisely known)
- $P_e$ : Electron (beam) polarization: $P_e = \frac{A_{exp}}{P_\gamma A_l}$

QWeak collaboration, unknown source



# Polarized beam

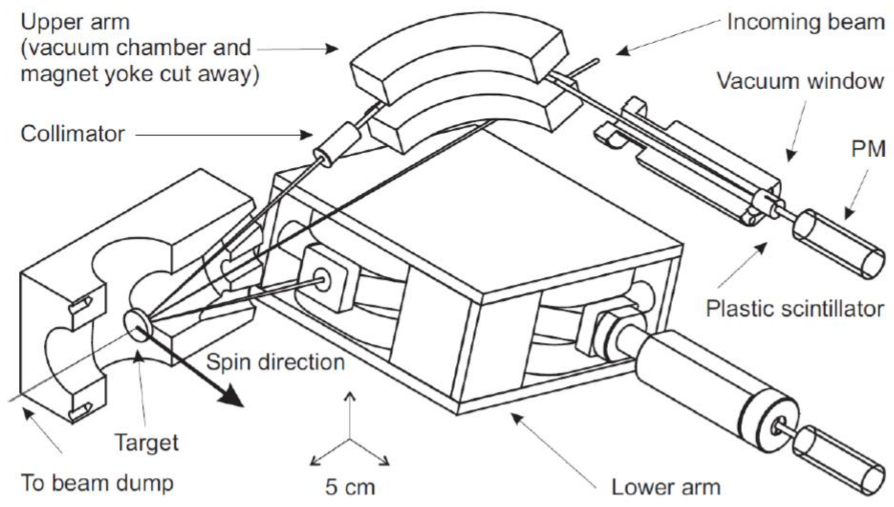
## Polarimetry

### Mott polarimeter

Measure beam polarization from transverse spin dependent Mott scattering cross-section.

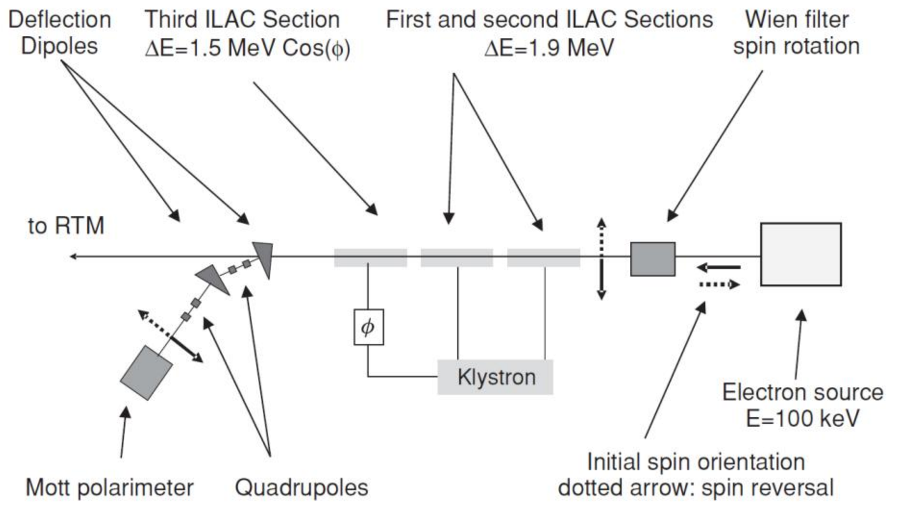
Measurement done at low energies ($\sim 5\ MeV$) in the injector.

$$Q = \frac{R_1^+ R_2^-}{R_1^- R_2^+} \qquad A_{exp} = \frac{1-\sqrt{Q}}{1+\sqrt{Q}} = S_{eff} P_e$$




MAMI Mott Polarimeter: Rev. Sci. Instrum. 82, 033303 (2011)

Like Møller scattering, this is an invasive measurement.



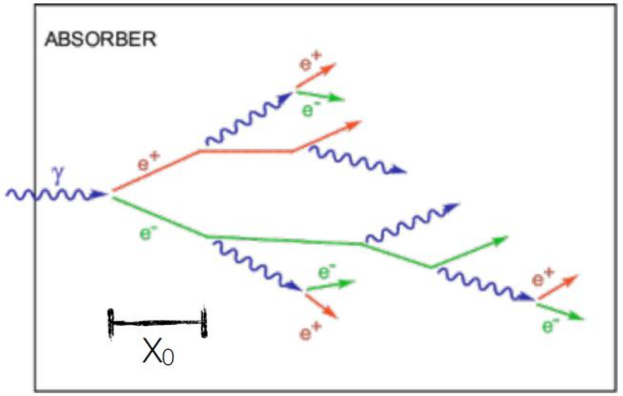

Can use this together with an in-situ measurement close to the experiment at the design energy.

E.g. A standard Møller polarimeter or perhaps a Hydro-Møller (for P2) or a Compton polarimeter at higher energies (MOLLER).

# Target

**Requirements:**

For the precise measurement of a small asymmetry, it is paramount that a given target remains highly stable at the timescale of the helicity flip rate.



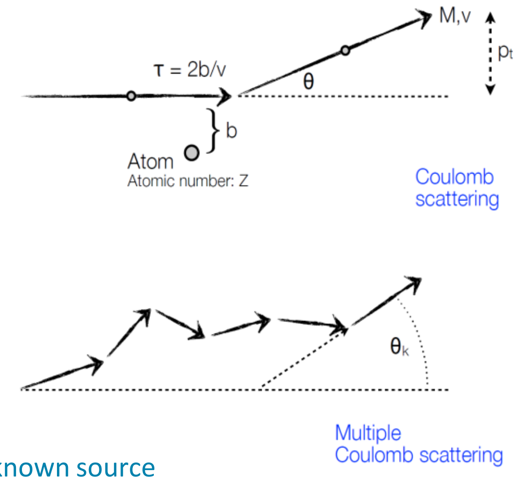

Things to consider:

- Density fluctuations (liquid)
- Temperature fluctuations / target heating (solid)
- Radiation length
- Luminosity
- Background production/reduction

Want to maximize the detector rate of desired events for a given beam current $\boldsymbol{\mathcal{L} = \Phi \rho l}$

Naively would increase target length/density (for a given material), but:

- we get shower development $e^{\pm} + N \rightarrow N + e^{\pm} + \gamma \Rightarrow \gamma + N \rightarrow N + e^{+} + e^{-}$
- multiple scattering (undefined vertex for $Q^2$ determination, complicates design, …)
- more background (aside from Bremsstrahlung)




Unknown source

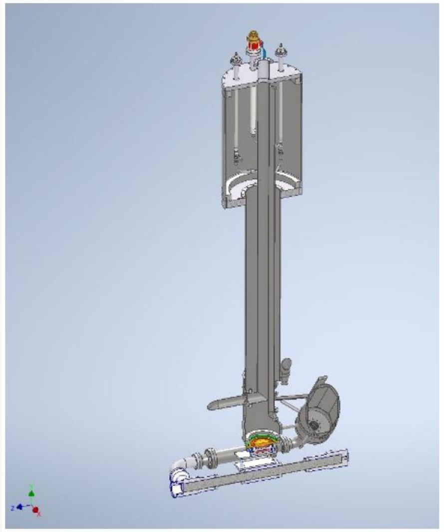
# Target

## Liquid Hyrogen Target

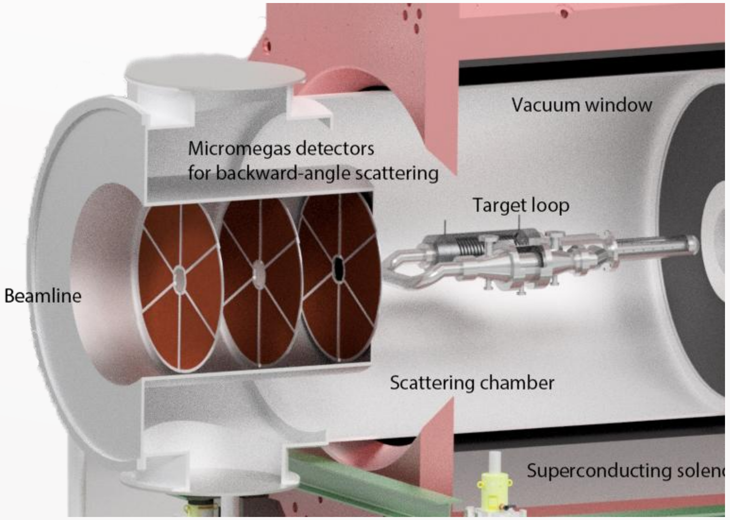
- For $e \to e$ or $e \to p$ scattering, a liquid hydrogen target is ideal, because it provides the greatest target length with the lowest radiation length, thus reducing background and multiple scattering.

- Irreducible backgrounds are confined to radiative electron-proton elastic and inelastic scattering, which are relatively well-understood

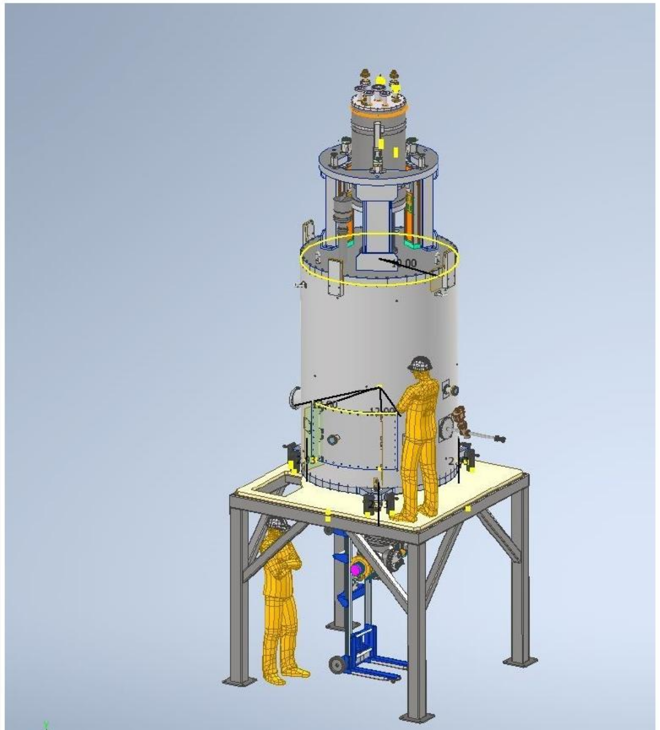
- Precision PV experiments requires that target density variation must be small (e.g. $< 30\ ppm$ at the millisecond timescale used for the asymmetry measurement) to keep the corresponding excess noise small relative to counting statistics.



MOLLER collaboration, Unknown source




P2 collaboration, Unknown source



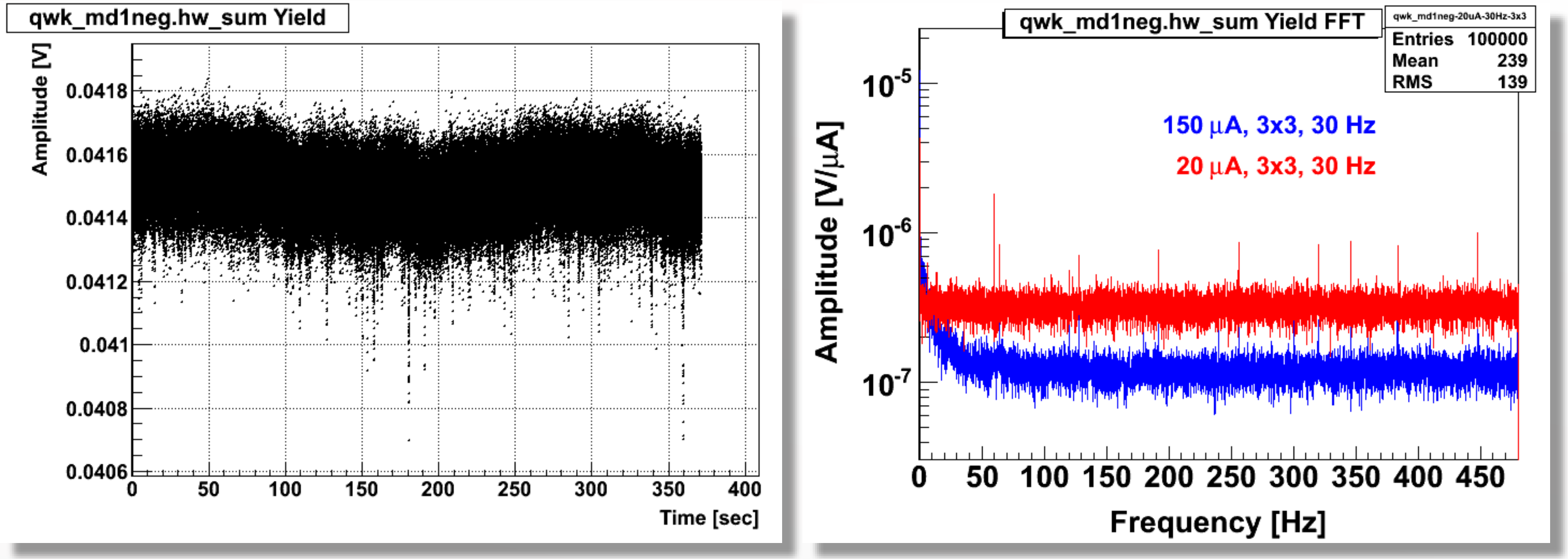
MOLLER collaboration, Unknown source

# Target

## Liquid Hyrogen Target

### Target performance

- At high beam current (power) target boiling is inevitable
- Starts around $100\ \mu A$ (energy dependent)
- This has a $1/f$ frequency dependence, which dominates at low frequency
- Fast helicity reversal (e.g. $1920\ Hz$) reduces this effect
- Higher LH2 pump speeds can also reduce this effect




QWeak data

# Target

## Liquid Hyrogen Target

### Target performance

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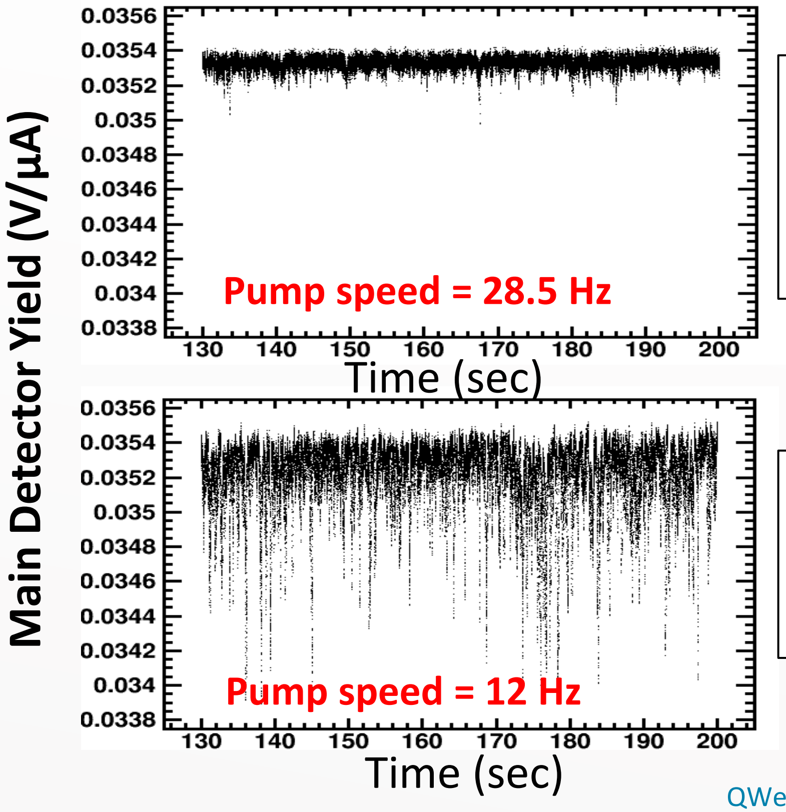
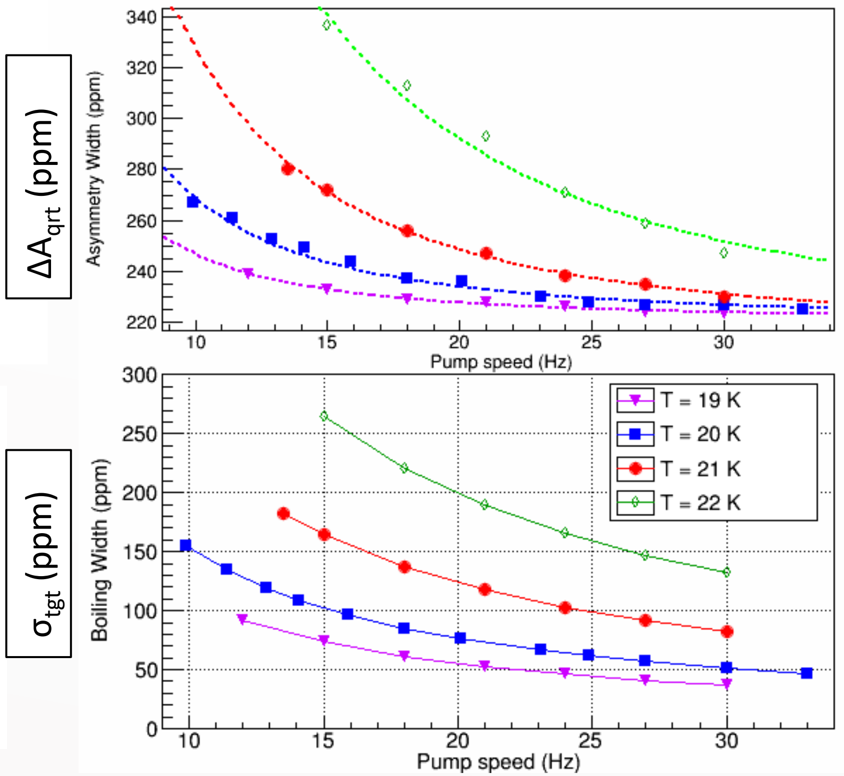



QWeak data

# Target

## Solid Targets

Solid targets ($e \rightarrow N$ scattering) are required for specialized calibration measurements and are regularly used for specific physics measurements

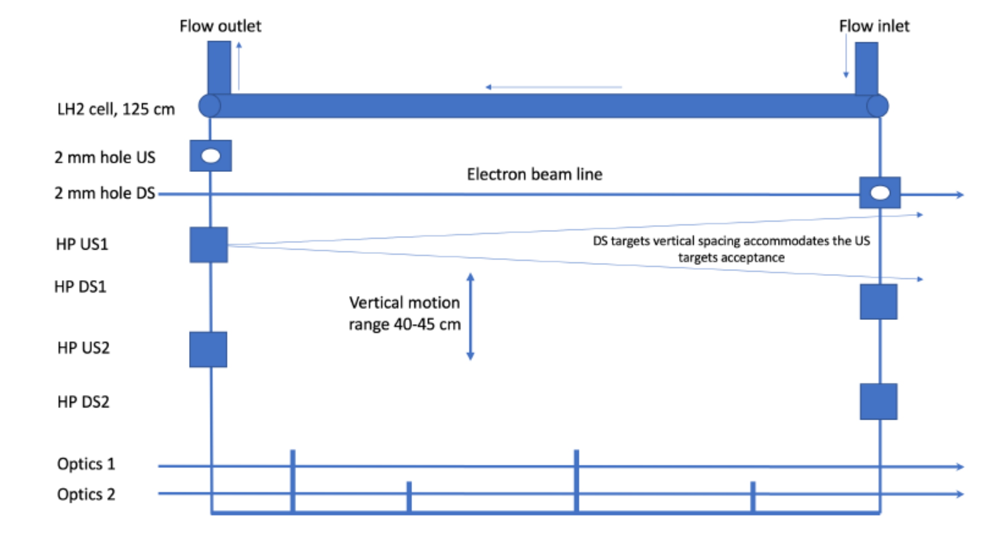
- Neutron radius measurements ($^{208}Pb$, $^{12}C$)
- Weak mixing angle from $^{12}C$
- Calibration measurements (materials found in the $LH2$ target windows)

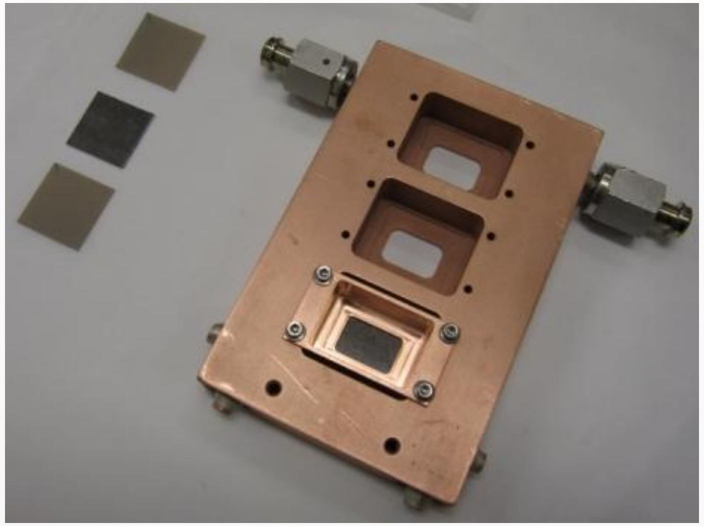
For the physics measurements the target composition/purity and thickness has to be carefully studied and designed (preferably no melting $^{208}Pb$).

- For calibration (target/spectrometer background studies) use (e.g.) $Al$ or whatever the target windows are made of

- Sometimes implemented with a motion mechanism to swap between the $LH2$ and solid targets.

MOLLER target arrangement (TDR)



PREX target (From a talk by J. Mammei)

# Magnet(s) / Spectrometers

**Requirements:**

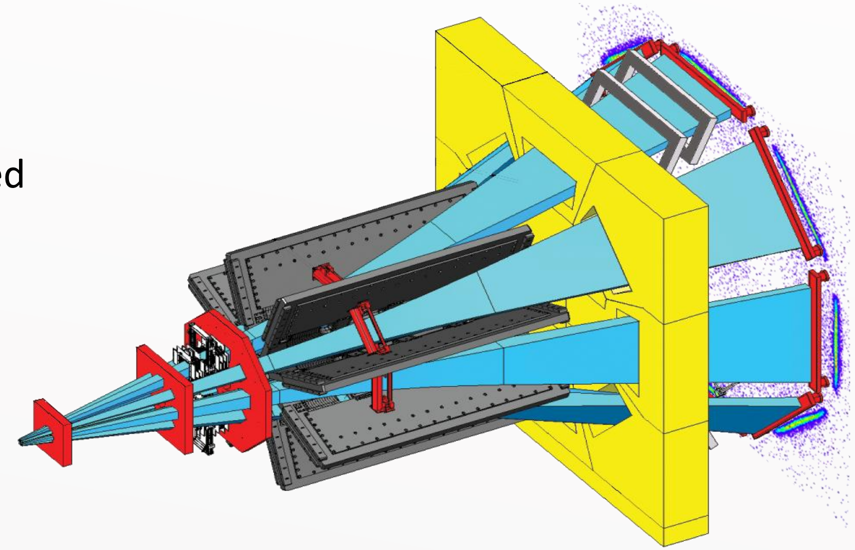
- For some counting/event mode experiments the magnets are real (i.e. momentum analyzing) spectrometers (e.g. G0 “G-Zero”) with a reasonably good momentum resolution.

- At very high beam currents, with detectors operating in integration mode, the magnets are usually not very good spectrometers.

  For these cases the primary goals of the magnet system are:

  - Separation of main physics events from background events
  - Moderate focusing of physics events onto a set of detectors
  - Kinematics determination (i.e. momentum transfer measurements required for some elastic and all inelastic signal contributions)

GZero Experiment



QWeak experiment

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

$ep$ PV requires $Q^2$ measurement

$$A_{PV} = m_e E \frac{G_F}{\pi\alpha\sqrt{2}} \frac{4\sin^2\theta}{(3+\cos^2\theta)^2} Q_W^e$$

$ee$ PV requires (moderate) $E$ measurement but not $Q^2$

# Magnet(s) / Spectrometers

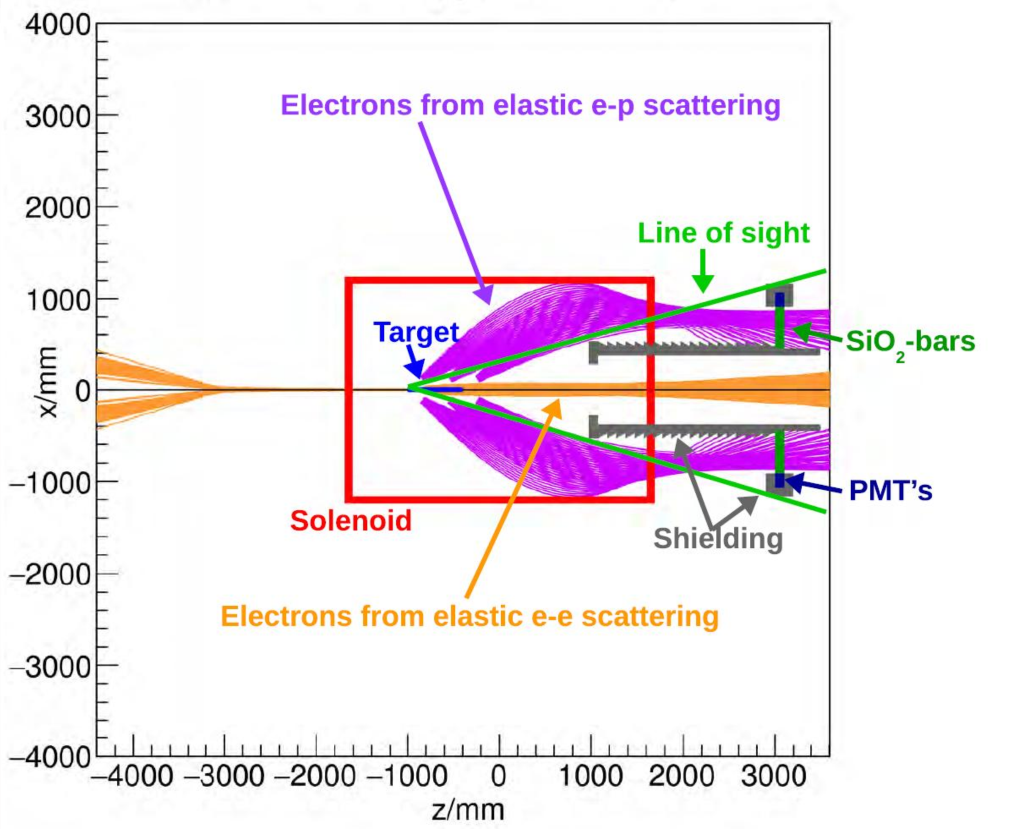
$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\ \pi\alpha}\left(Q_W^p - F(Q^2)\right)$$

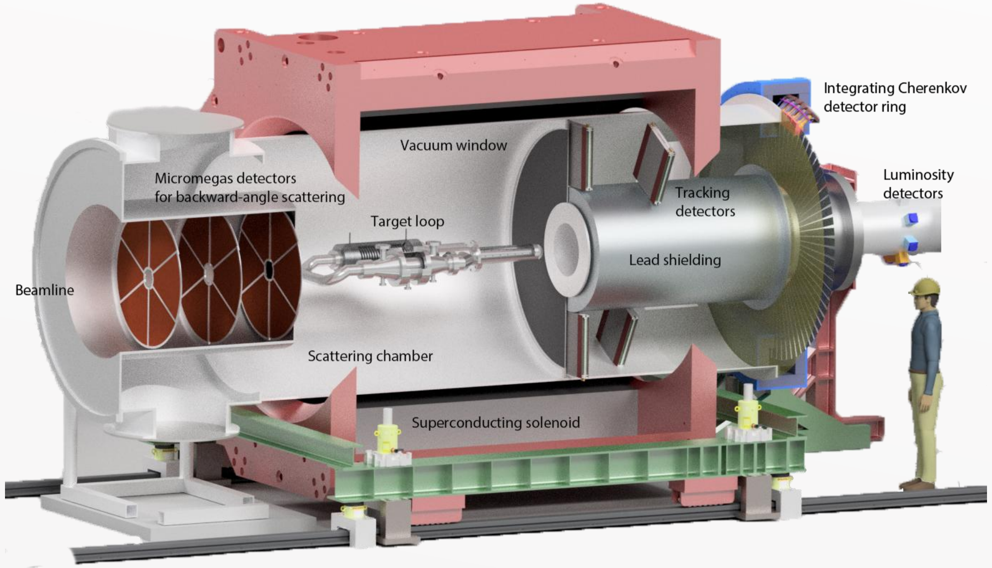
$ep$ PV requires $Q^2$ measurement

**Example: P2 @ MESA**

- $ep$ / $ee$ separation
- moderate focusing of $ep$ events
- tracking and $Q^2$ measurement
- focusing for back-angle measurement ($^{12}C$ measurement)

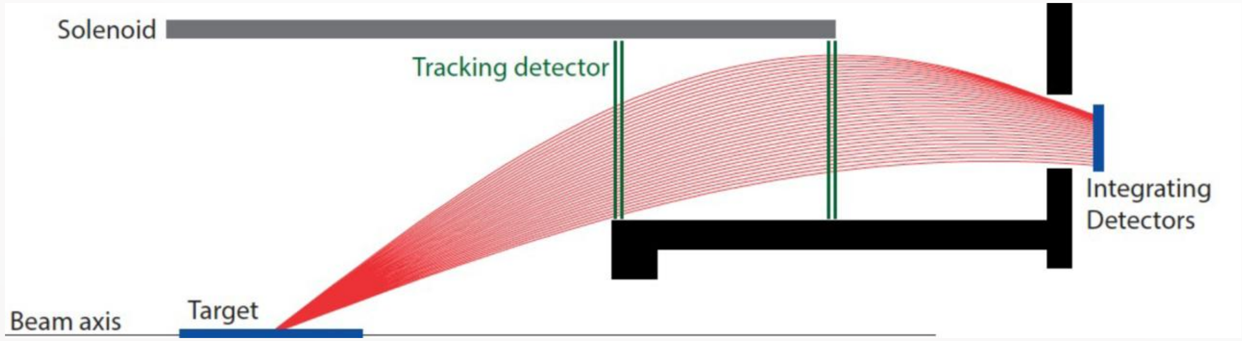
(See Malte's talk on P2 for details)




P2, unknown source

From the CDR



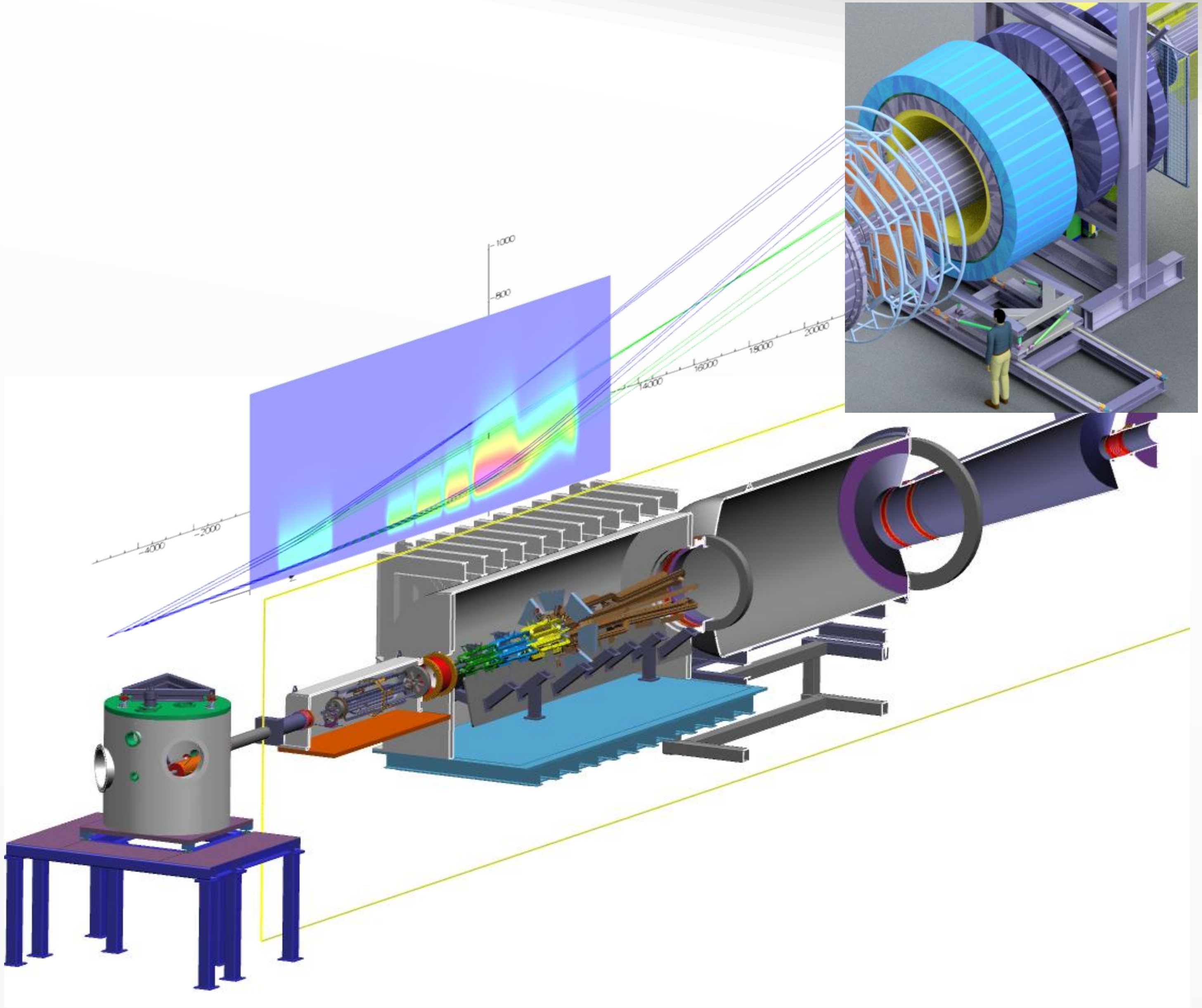
# Magnet(s) / Spectrometers

**Example: MOLLER**

- $ep$ / $ee$ / $eX$ event separation
- moderate focusing of events
- tracking

The scattering profile in the detector planes has to be separated into a suitable number of radial and azimuthal bins to allow:

- Event separation,
- Statistics collection
- Control of systematic effects, such
- Beam motion
- Backgrounds



# Magnet(s) / Spectrometers

**Example: MOLLER**

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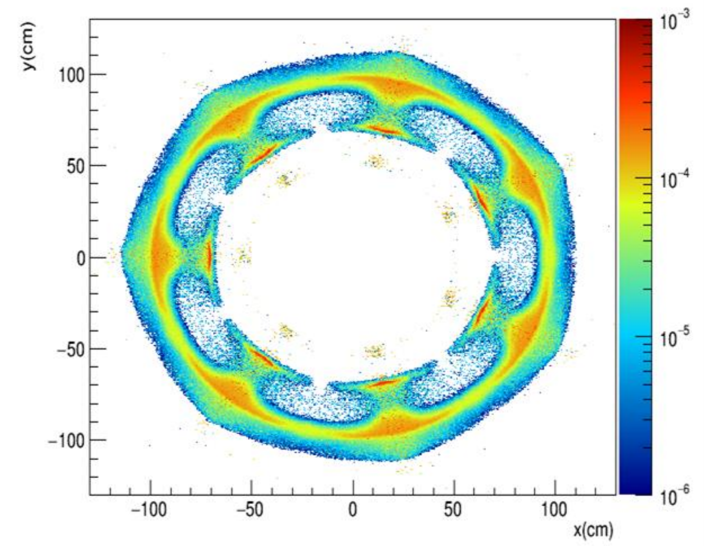
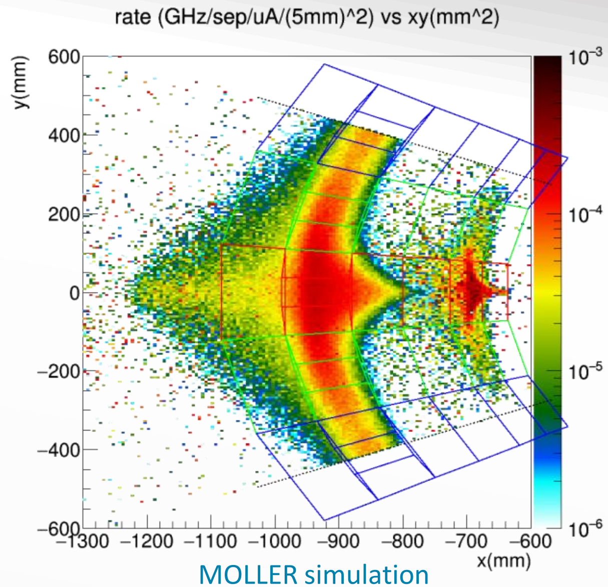
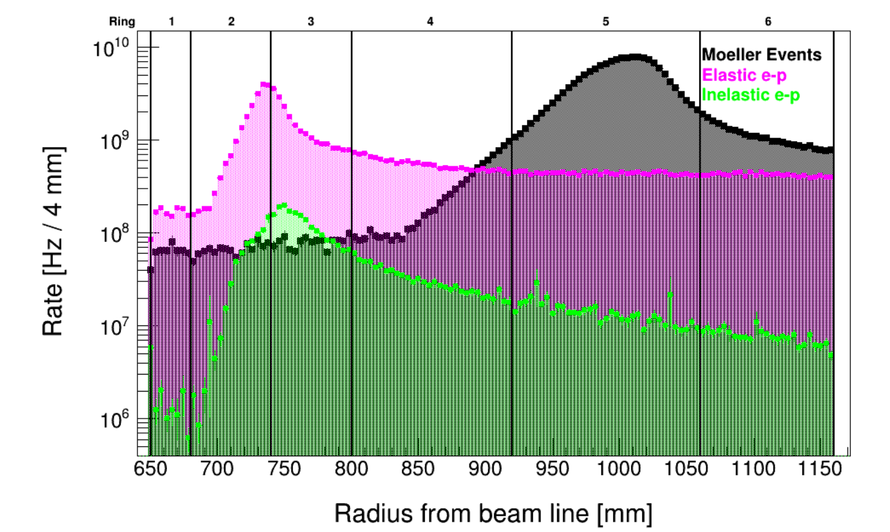


MOLLER simulation



MOLLER simulation



# Collimators, Shielding, and Blocking

**Defining the experimental acceptance:**

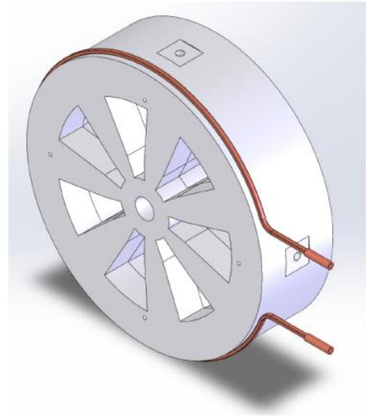
As already mentioned, integration mode experiments cannot use analysis methods to reject specific events in the data stream.

It is extremely important to design the experiment such that backgrounds are rejected by construction.

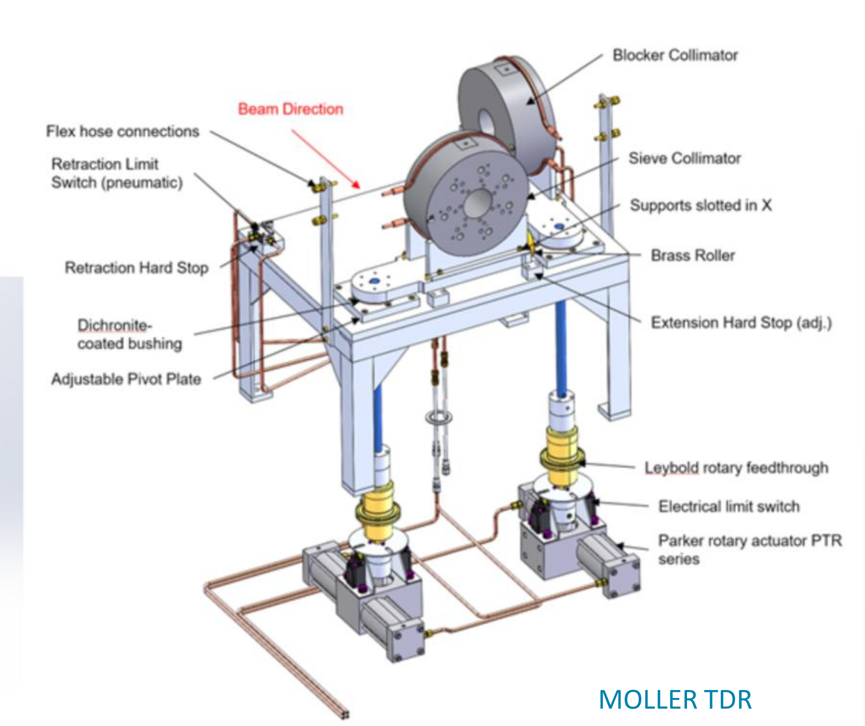
Spectrometer design, collimators, and detectors all contribute to the acceptance definition.

Collimators are used to:

- Define the acceptance window of primary scattered events
- To help with spectrometer optics calibration (sieve)
- To help measure beamline and inelastic background contributions (blocking the primary beam)
- To help measure beam motion effects
- To block photon background (two-bounce shield)
- Remove lower energy electrons (target - radiative) before they hit and irradiate other parts of the experiment



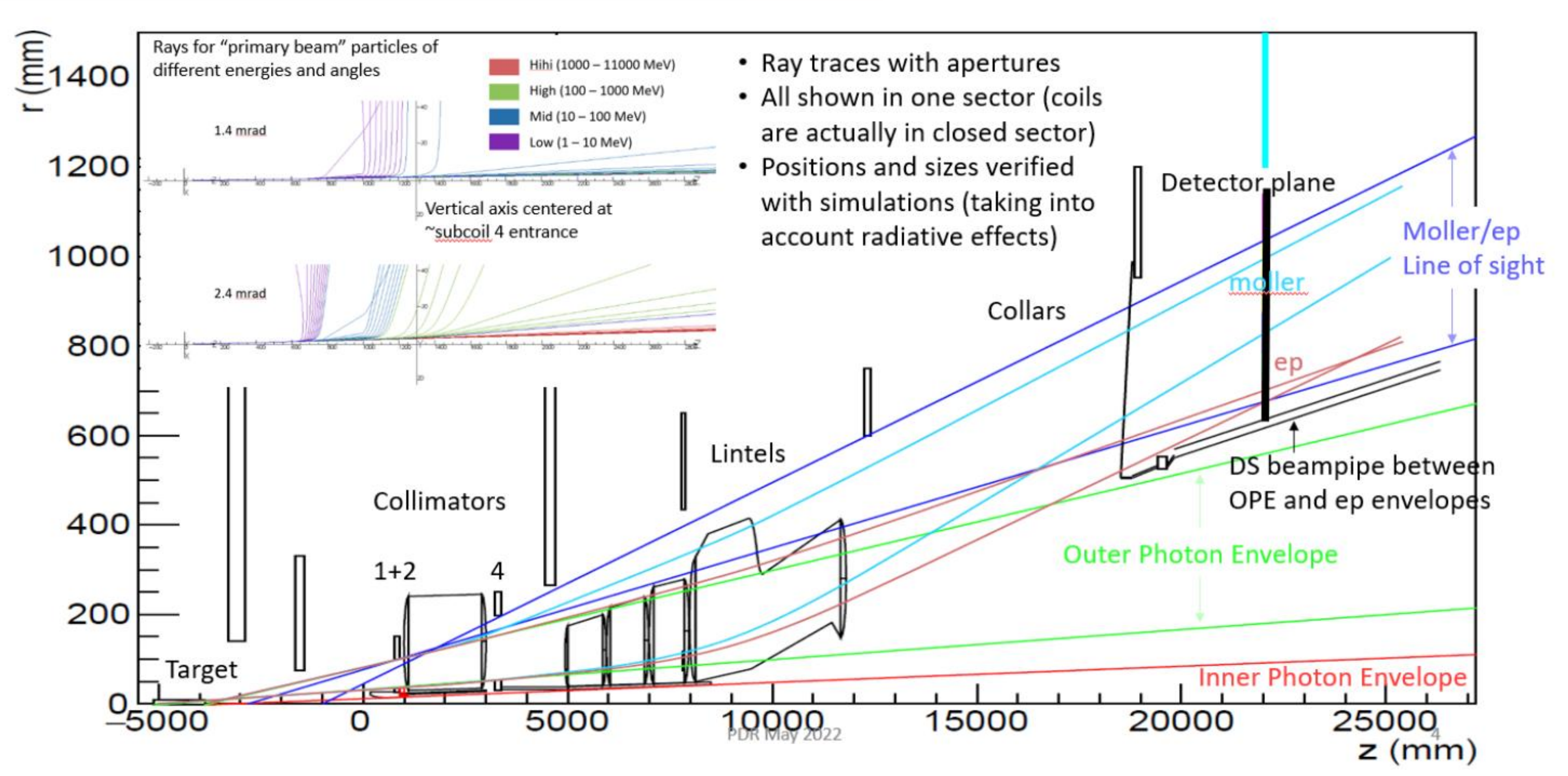
(a) “Cleanup” collimator 4




MOLLER TDR

# Collimators, Shielding, and Blocking

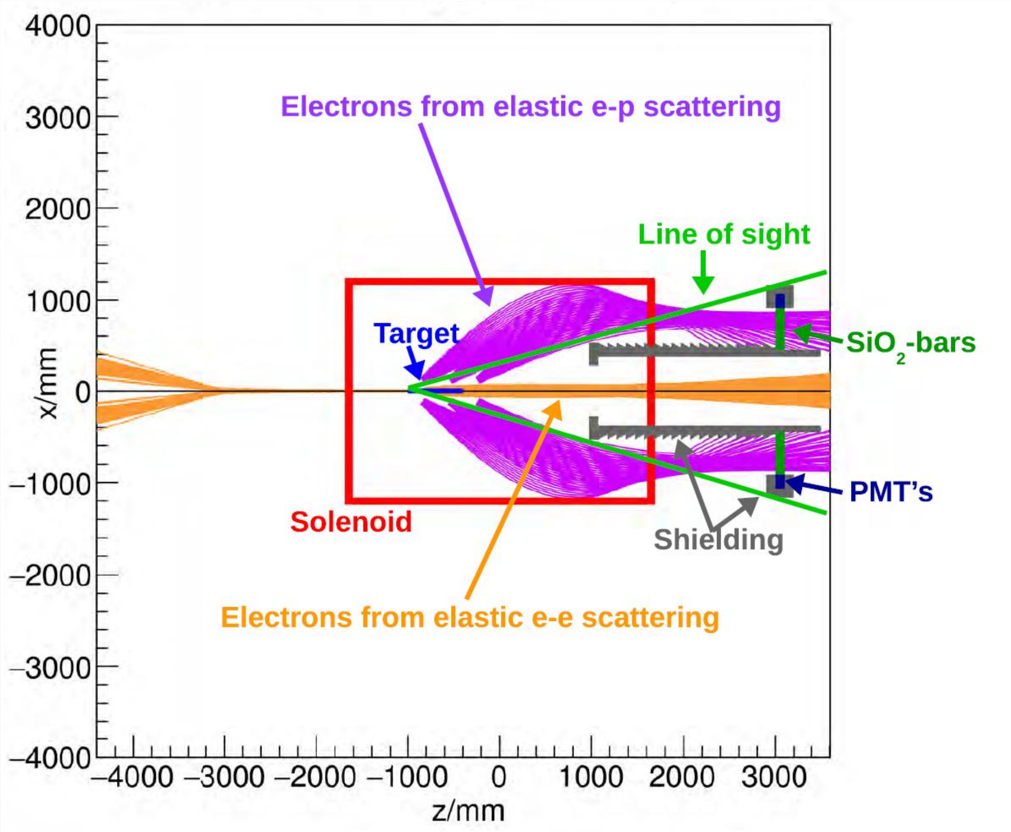
**Defining the experimental acceptance:**

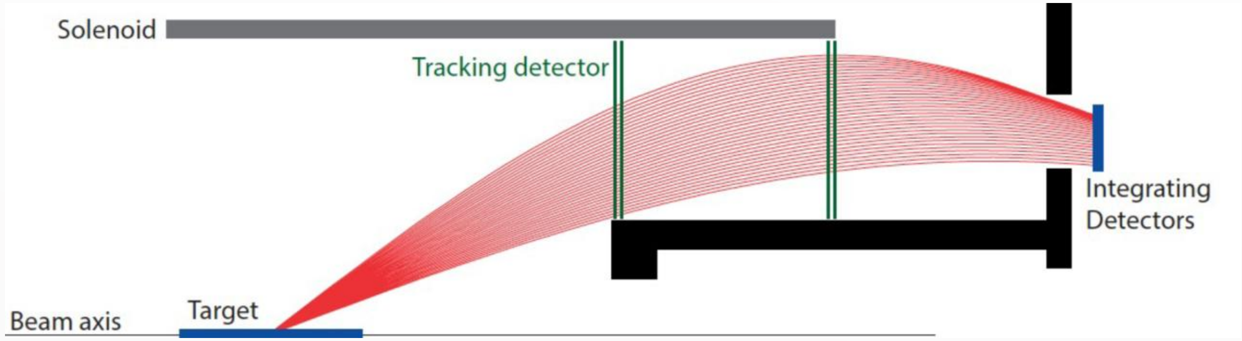



MOLLER collaboration (Kent Paschke)

# Collimators, Shielding, and Blocking

**Defining the experimental acceptance:**




From the CDR