An overview of the MOLLER experiment at Jefferson lab

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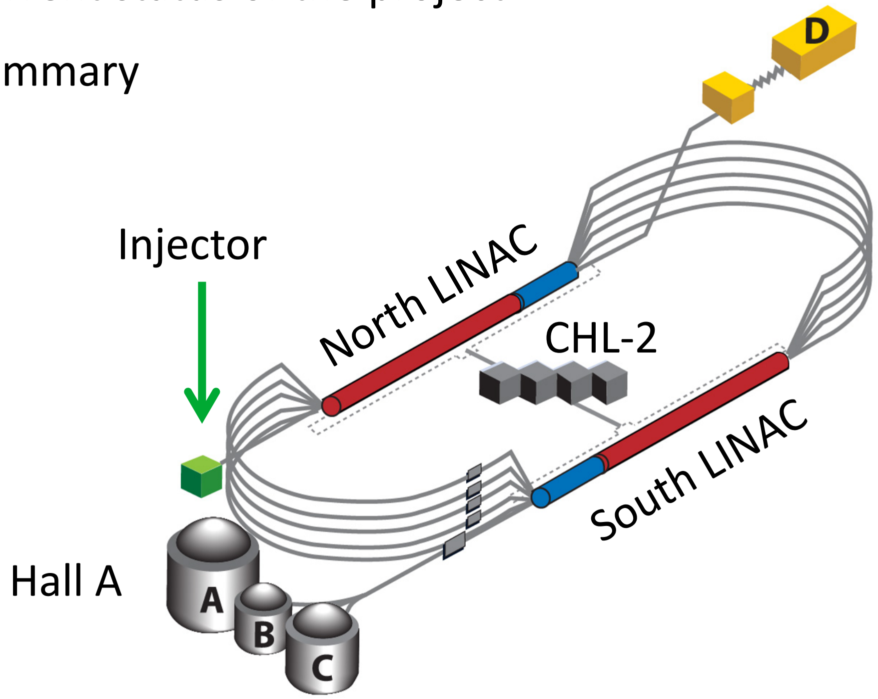
Outline

- Parity and its non-conservation in weak interaction
- Parity violating electron scattering (PVeS) introduction
- History of PVeS experiments
- MOLLER experiment overview
- Current status of the project
- Summary

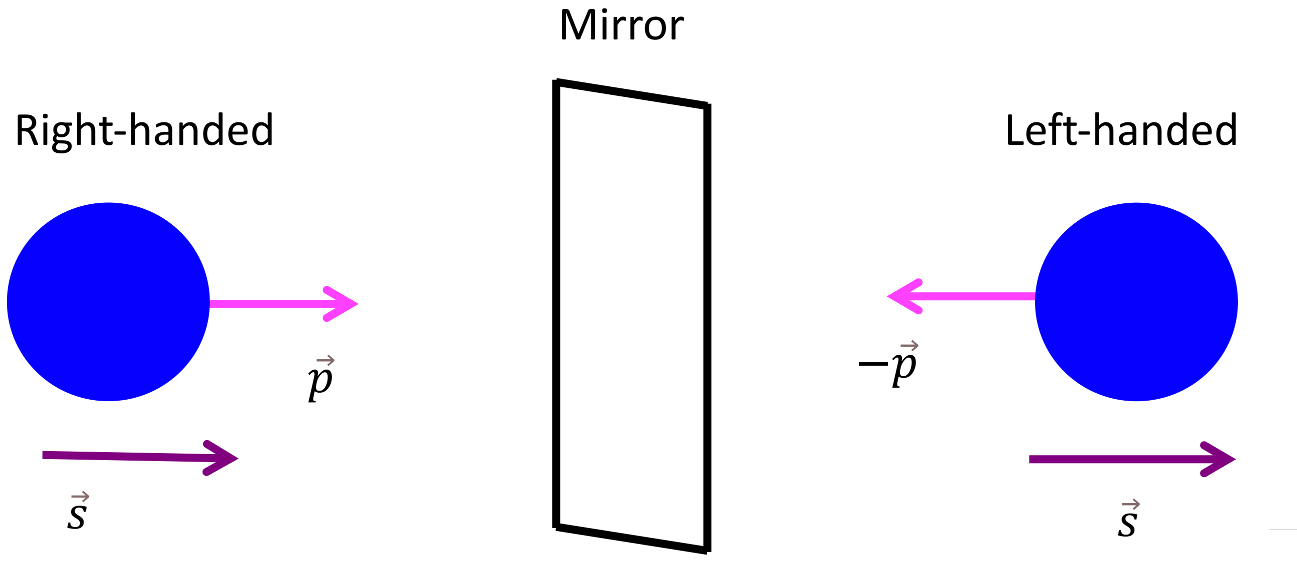


Parity Operation

- It is a mirror symmetry → inversion of spatial coordinates:

$$P(x, y, z) \Longrightarrow (-x, -y, -z)$$

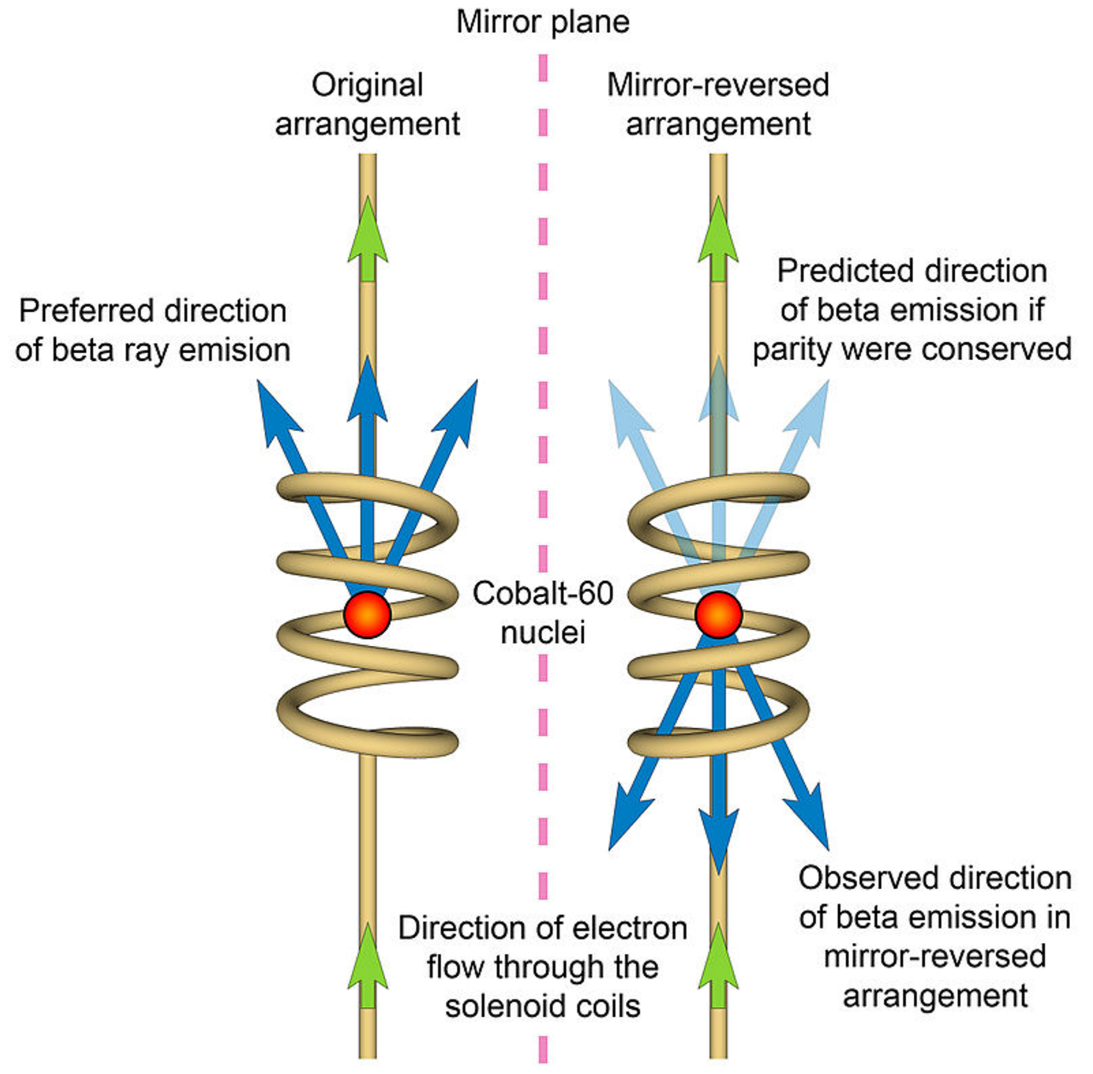
- It is not conserved in weak interactions. Why? (see next few slides)
- Parity operation is same as changing helicity.
- **We change electron's helicity to mimic parity operation.**
- **Parity-violation creates tiny asymmetry (A_{PV}) in the detected flux.**



$h = \vec{s} \cdot \hat{p} \ = +s$

Parity operation

$h = \vec{s} \cdot (-\hat{p}) \ = -s$



Wu Experiment (1956)

Question on Parity Conservation

- If parity is conserved, the laws of physics should be observed the same in real and mirror world.
- Until 1950s parity was assumed to be a universal symmetry
- $\tau - \theta$ puzzle of early 50s suggested an experimental test of parity conservation in nuclear β-decay.

$$\theta^+ = \pi^+ + \pi^0$$

$$\text{parity:} (-1) \ (-1) \ \rightarrow (+1)$$

$$\tau^+ = \pi^+ + \pi^+ + \pi^-$$

$$\text{parity:} (-1) (-1) (-1) \ \rightarrow (-1)$$

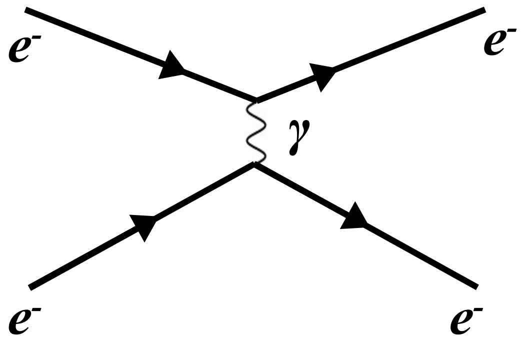
$$\text{parity}_{\theta^+} \neq \text{parity}_{\tau^+}$$

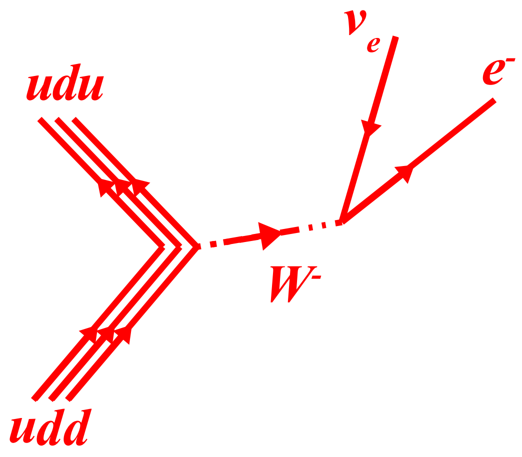
- Either parity is violated or θ and τ are the different particles.
- Lee and Yang suggested an experimental test of parity conservation in β-decay.

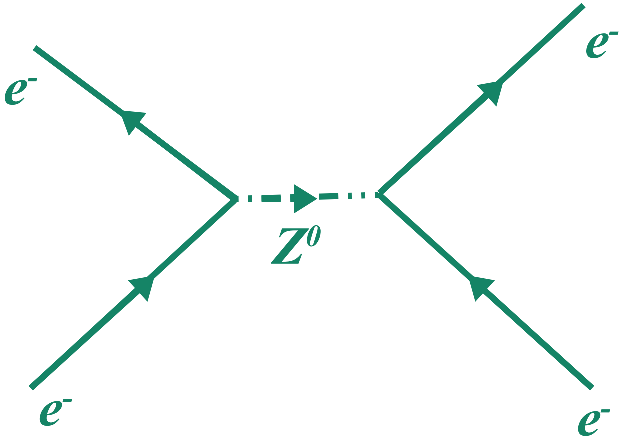
- In 1957, Chien-Shiung Wu observed β-decay in ^{60}Co nuclei.
- β particles emitted in a preferred direction.
- $\tau - \theta$ puzzle was resolved.
- Parity is no longer a universal symmetry.
- Weak interaction doesn't conserve parity. Why?

Electromagnetic and Weak Interactions

Electromagnetic interaction | Charged current weak interaction | Neutral current weak interaction







Vertex factor : $ig_e \gamma^\mu$ $\frac{-ig_w}{2\sqrt{(2)}}\gamma^\mu(1-\gamma^5)$ $\frac{-ig_z}{2}\gamma^\mu(c_V^f - c_A^f\gamma^5)$

$\gamma^\mu \rightarrow$ Odd

$\gamma^\mu\gamma^5 \rightarrow$ Even

Propagator : $\frac{-ig_{\mu\nu}}{q^2}$ $\frac{-i(g_{\mu\nu} - q_\mu q_\nu / M_w^2 c^2)}{q^2 - M_w^2 c^2}$ $\frac{-i(g_{\mu\nu} - q_\mu q_\nu / M_z^2 c^2)}{q^2 - M_z^2 c^2}$

$g_w = \frac{g_e}{\sin\theta_w}$ $g_z = \frac{g_e}{\sin\theta_w \cos\theta_w}$ $M_w = M_z \cos\theta_w$

- θ_w is an important parameter in the standard model.
- Experiments give: $\sin^2\theta_w \approx 0.23$.

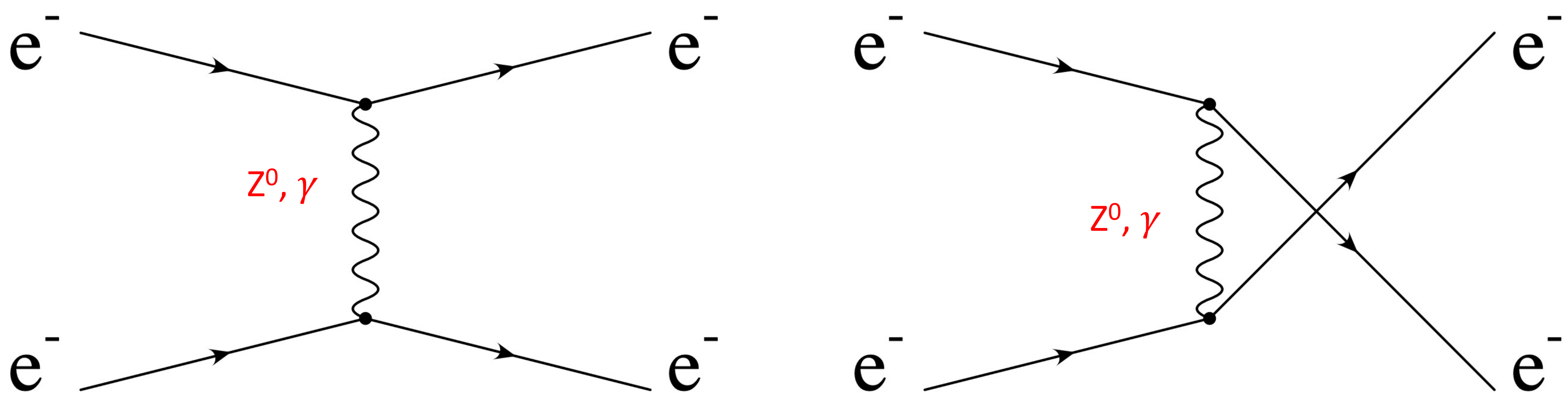
$$\underbrace{\begin{pmatrix}\gamma \\ Z^0\end{pmatrix} = \begin{pmatrix}\cos\theta_w & \sin\theta_w \\ -\sin\theta_w & \cos\theta_w\end{pmatrix}\begin{pmatrix}B^0 \\ W^0\end{pmatrix}}_{\text{Electroweak Unification}}$$

Parity Violation in Electron Scattering

- Scattering of longitudinally polarized electrons from unpolarized targets.
- **We change electron's helicity to mimic parity operation.**
- **Asymmetry (A_{PV}) of the detected rates between the beam's opposite helicity states.**

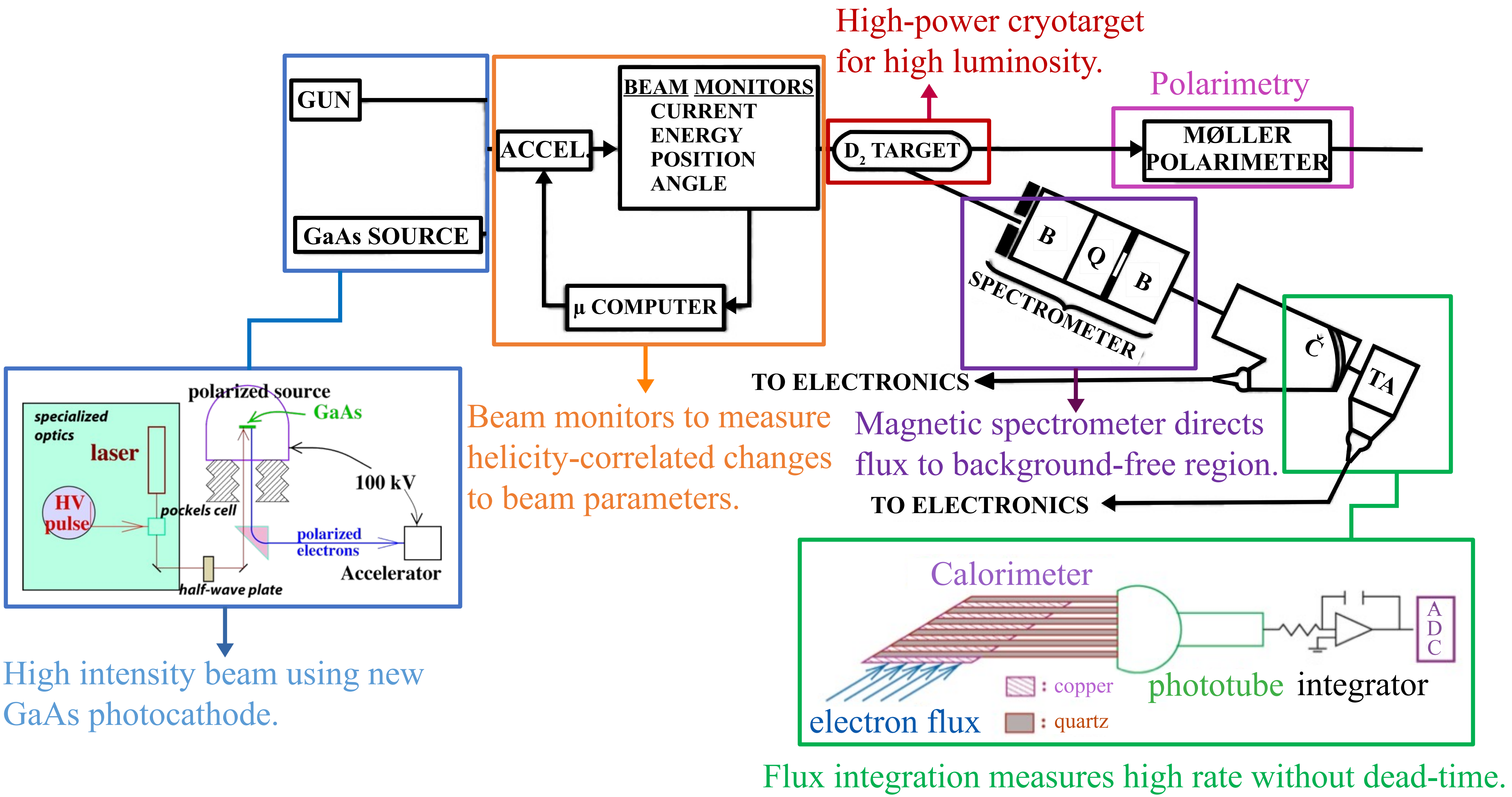
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \quad \text{where } \sigma \sim |\mathcal{M}_\gamma + \mathcal{M}_{Z^0}|^2 \quad \rightarrow A_{PV} \approx \frac{2\mathcal{M}_\gamma(\mathcal{M}_{Z^0})^*}{|\mathcal{M}_\gamma|^2}$$

- At $Q^2 \ll (M_{Z^0})^2$ A_{PV} is dominated by the interference between the weak and electromagnetic amplitudes.

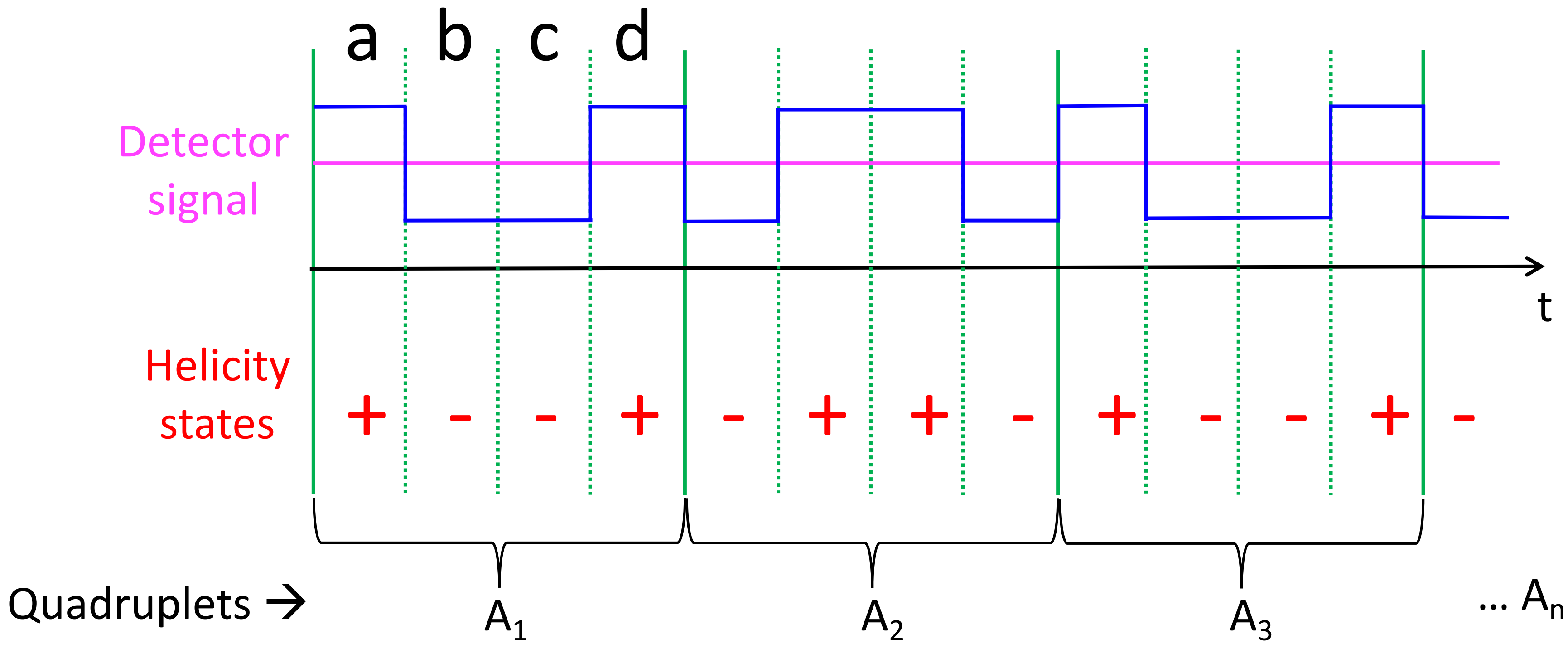


Feynman diagrams for Møller scattering at tree level

PVeS Technique (SLAC E122 Experimental Blueprint)



PVeS Technique Contd.



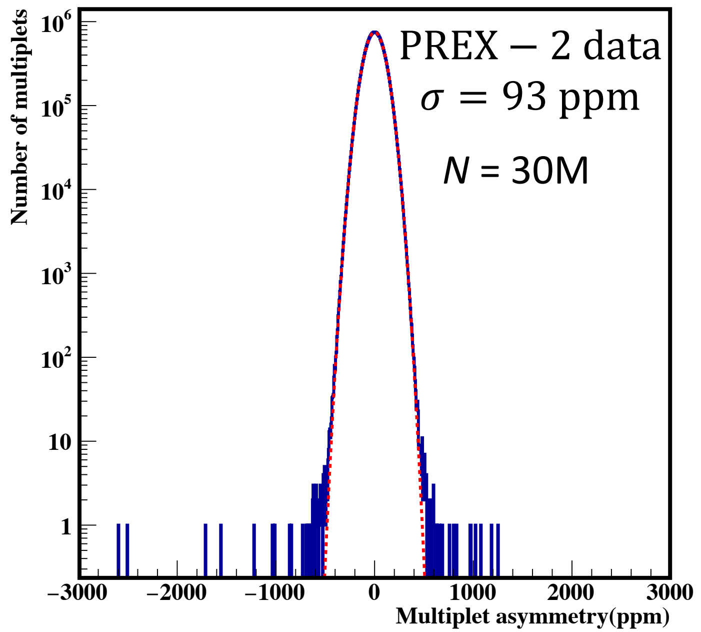
$$A_1 = \frac{(a+d)-(b+c)}{a+b+c+d}$$

Measure flux *F* for each helicity window

$$A_{pair} = \frac{F_R - F_L}{F_R + F_L}$$

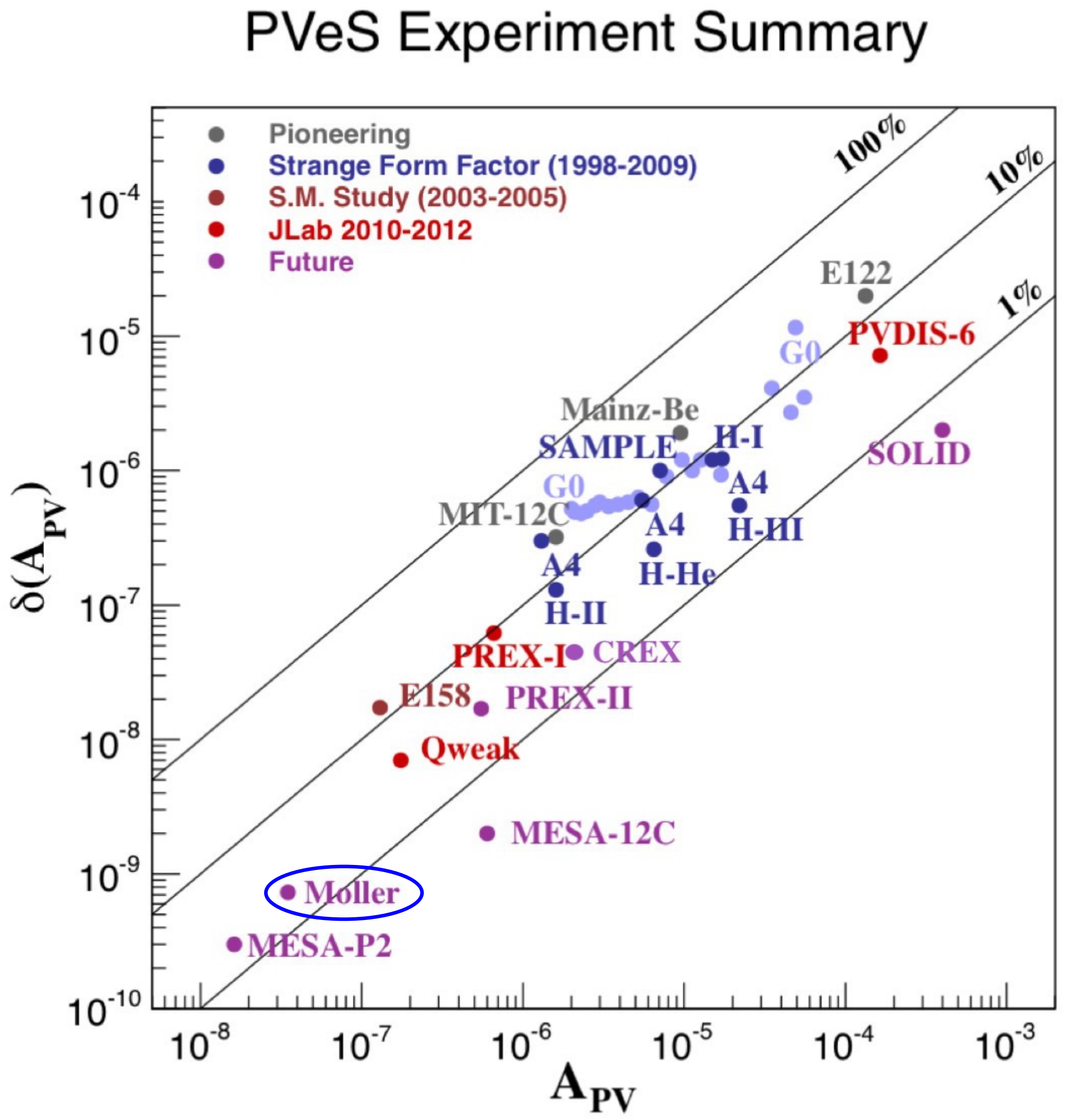
For N window pairs: $A \pm \frac{\sigma}{\sqrt{N}}$

For MOLLER, *N* = 30B



PVeS Experiments Summary

- E122 – 1st PVeS exp. (late 70's) at SLAC
- Jlab program launched in 90's
- E158 – measured PV in Møller scattering at SLAC (2007)
- Significant improvement in experimental components over time:
  - ➢ Photocathodes
  - ➢ Polarimetry
  - ➢ Cryotargets
  - ➢ Beam stability to nanometer level
  - ➢ Low noise electronics
  - ➢ Radiation-hard detectors

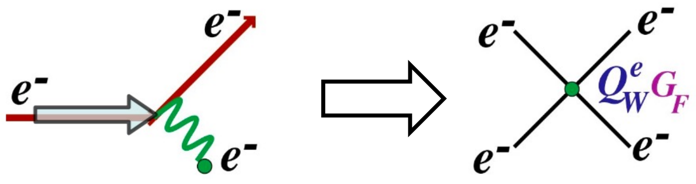


MOLLER Experiment Overview

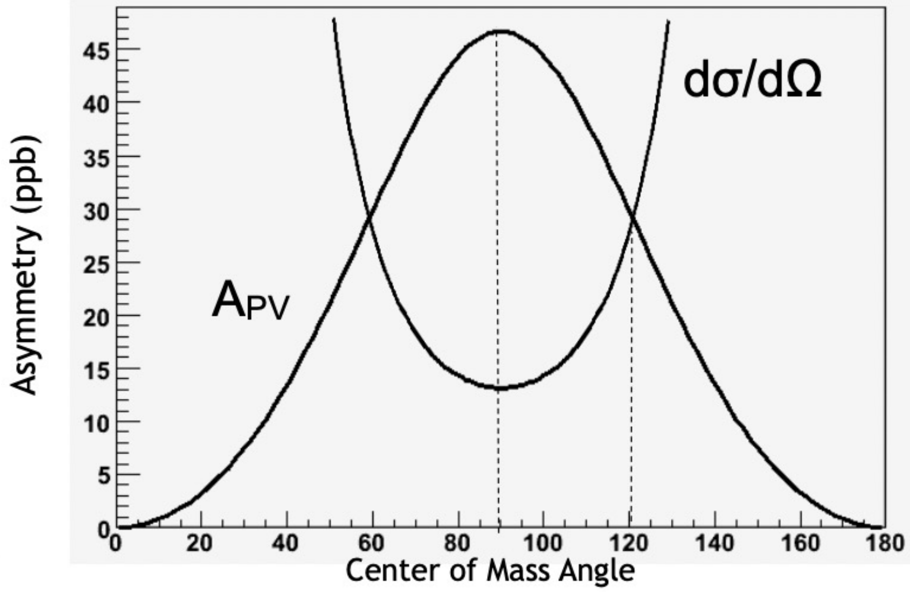
- MOLLER: Measurement Of Lepton Lepton Electroweak Reaction
  - will have a factor of 5 improvement over E158 measurement

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

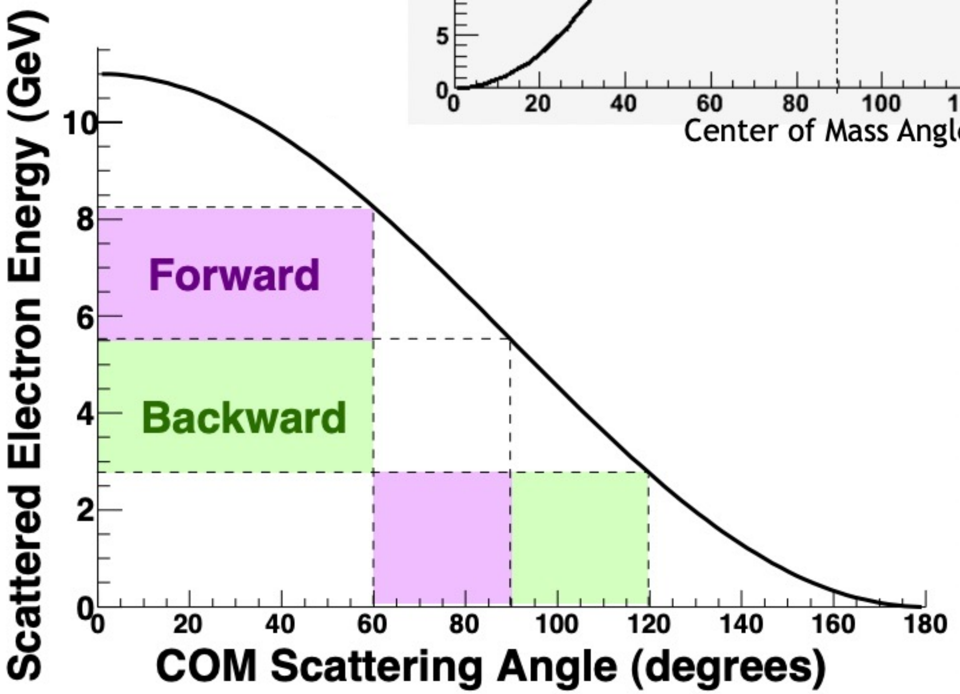
$$Q_W^e = 1 - 4\sin^2\theta_W \approx 0.075$$



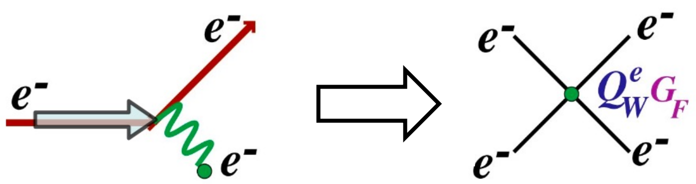
Highest figure of merit at $\theta_{CM} = 90°$



Parameter	Value
E	11 GeV
E'	2 – 9 GeV
θ_{CM}	60° – 90°
Target	120 cm long LH_2
Max. Luminosity	2.4×10^{39} cm^{-2} sec^{-1}
Moller Rate @ 65 μA beam current	134 GHz
Run Time	344 PAC-days
Polarization	≈ 90 %
$< A_{PV} >$	33 ppb



MOLLER Experiment Overview (contd.)

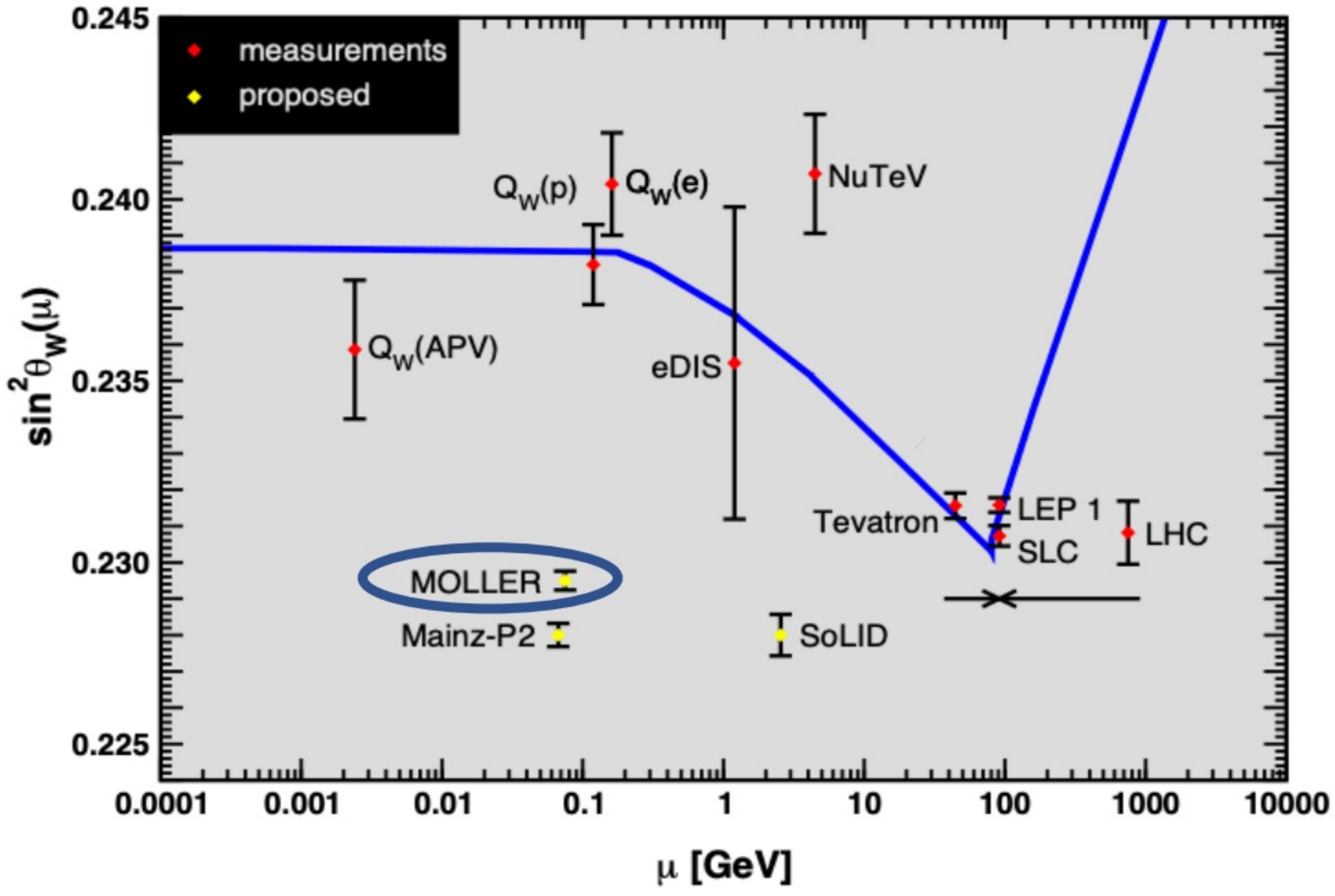


$$\mathcal{L}_{e_1e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\,\Lambda^2} \bar{e}_i\gamma_\mu e_i \bar{e}_j \gamma^\mu e_j$$

- Sensitive to $\frac{\Lambda}{g}$ up to 7.5 TeV

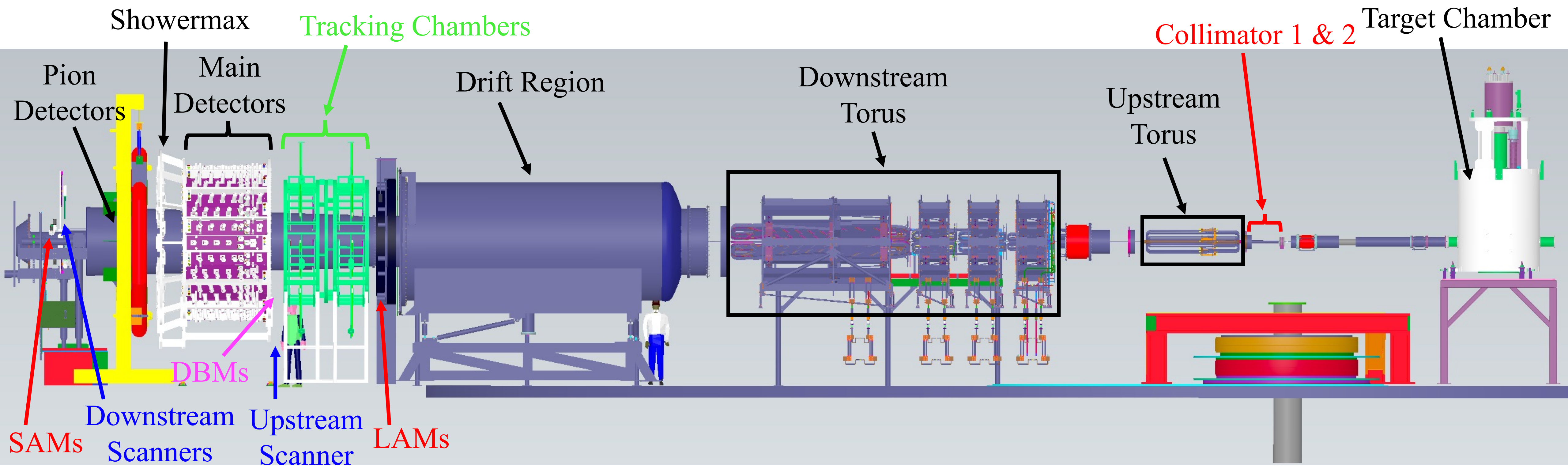
- MOLLER precision:

  $\delta(\sin^2\theta_W) \Rightarrow 0.1\ \%$

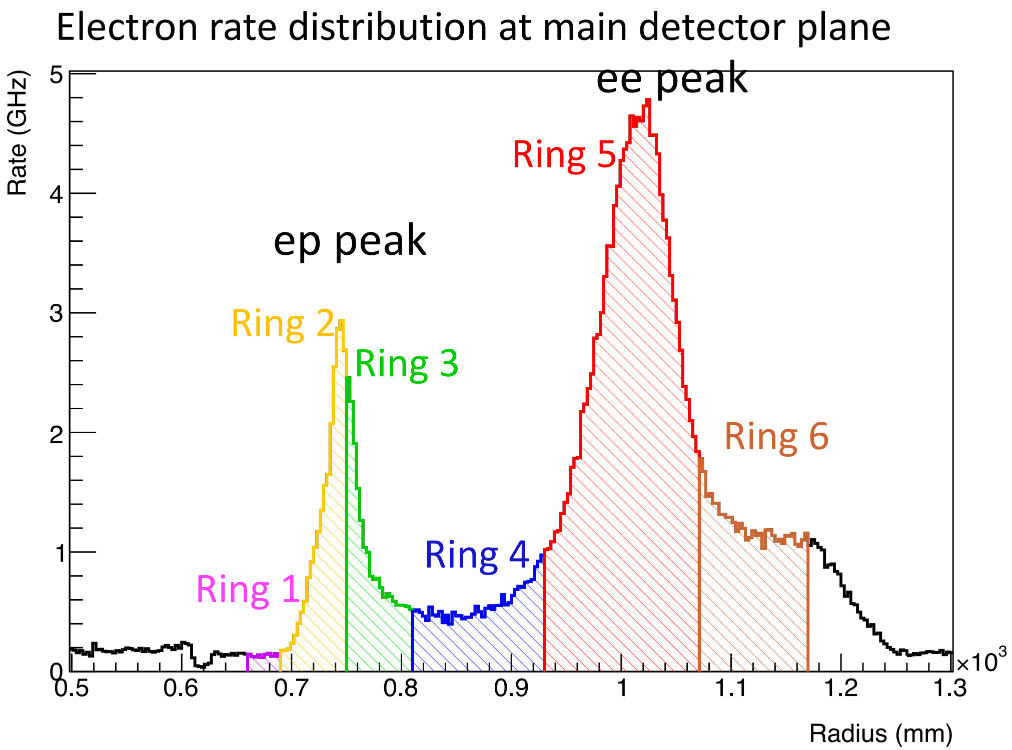


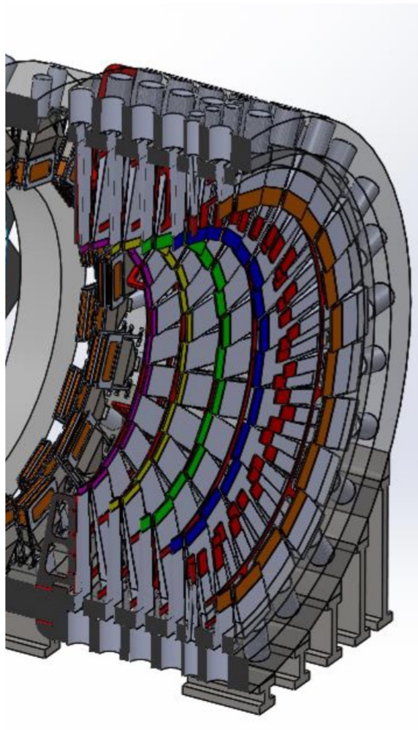
MOLLER Equipment

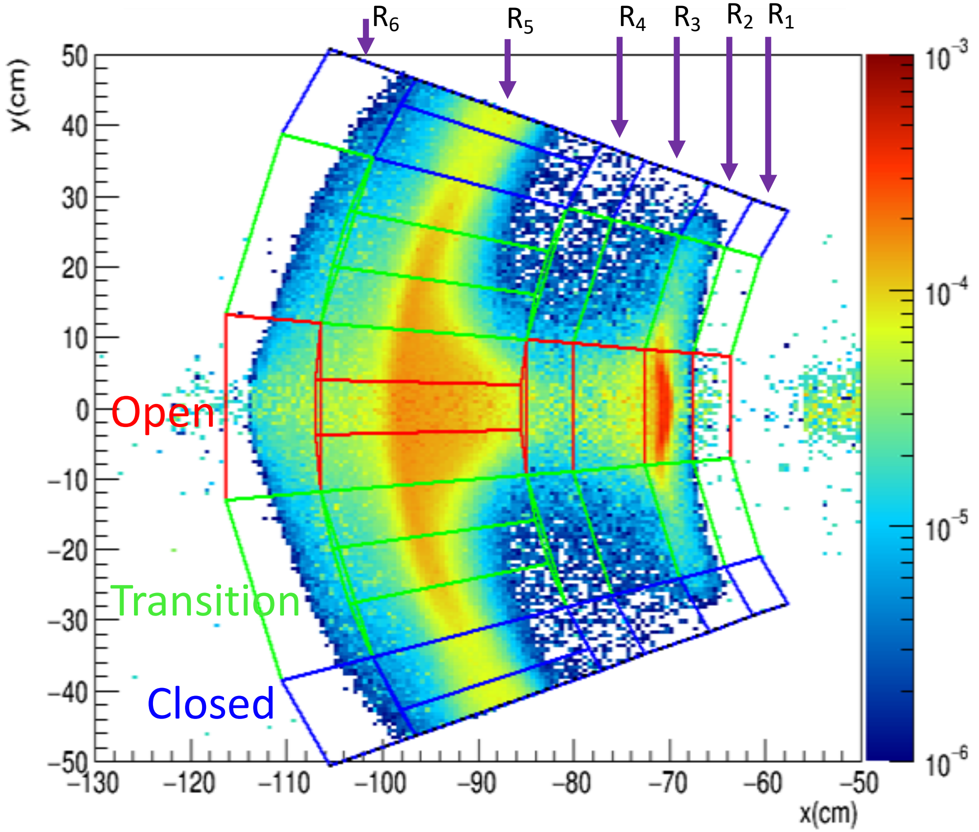
MOLLER full CAD



MOLLER Detector Acceptance







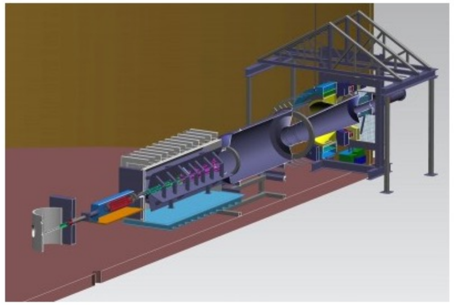
- Magnetic spectrometer separates signal from background and radially focuses to detector plane
- Six radial rings and 28 phi segments per ring
- Ring 5 intercepts MOLLER peak (~135 GHz full azimuth)
- 224 total quartz tiles in main detector to cover entire azimuth and signal processes

MOLLER Experiment History and Current Status

MOLLER collaboration: ~ 160 authors, 37 institutions, 6 countries; Spokesperson: K. Kumar, U. Mass, Amherst

- JLab PAC approval Jan. 2009, JLab Director's review Jan. 2010
- JLab PAC37 Ranking/Beam Allocation Jan. 2011 (A rating, 344 PAC days)
- Strong endorsement from DOE Science Review in Sept. 2014
- Second Director's Review in Dec. 2016
- DOE CD-0 status achieved in Dec. 2016; paused in Jan. 2017
- Project team formed in Jan. 2019
- Director's Review in April 2019 – Technical Readiness, Risk, Cost
- Director's Review in January 2020
- CD-1 Director's Review in August 2020
- DOE MOLLER CD-1 Independent Project Review, October 2020
- MOLLER-NSF Midscale Technical and Cost Review, October 2020
- MOLLER-NSF Midscale Funding Awarded, February 2021, VT lead institution
- MOLLER CD-1 approved
- DOE OPA IPR Annual Review, November 2021
- Next goal is CD-2 approval in calendar 2022

PARTNERSHIP CONTRIBUTES TOWARD SHARP EYES FOR MOLLER EXPERIMENT



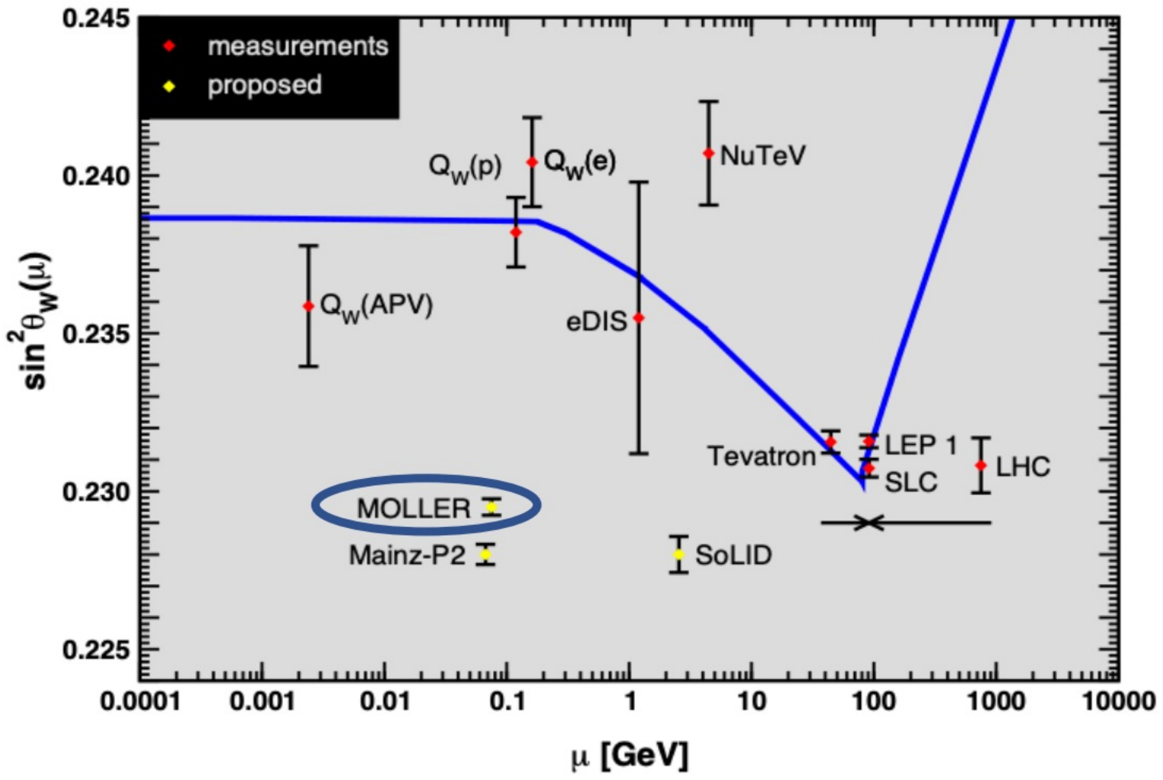
The MOLLER experiment has received additional grants totaling $9 million

NEWPORT NEWS – Thirteen universities working on a new experiment to be carried out at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility have recently been awarded new grants totaling more than $9 million. The grants come from the National Science Foundation and the Canadian Foundation for Innovation, with a matching award for the CFI grant from Research Manitoba. The grants benefit the Measurement of a Lepton-Lepton Electroweak Reaction Experiment, called MOLLER.

MOLLER is an experiment designed to precisely measure the electron's weak charge, a gauge of how much influence the weak force exerts on the electron. MOLLER's precision measurement will test the theory that describes the particles and interactions that make up everyday matter.

Summary

- PVeS has become a precision tool for neutron distribution measurement and standard model test
- The MOLLER experiment will use PVeS to search new dynamics
  - ➢ 0.1% precision on $\sin^2_{\theta W}$
- MOLLER is currently working on final design of all subsystem and anticipates DOE CD-2 near the end of 2022



Thank You
🙏

Weak Neutral Current

- In Glashow-Weinberg-Salam (GWS) model, the weak neutral current V-A couplings for electron and three light quarks are:

f	c_V	c_A
e^-	$-1/2 + 2\sin^2\theta_W$	-1/2
u	$1/2 - 4/3 \sin^2\theta_W$	1/2
d, s	$-1/2 + 2/3 \sin^2 \theta_W$	-1/2

- Weak neutral current:

$$J^\mu(e) = \bar{u}(e)\left[\frac{-ig_Z}{2}\gamma^\mu\left(c_V^f - c_A^f\gamma^5\right)\right]u(e)$$

$\gamma^\mu \rightarrow$ odd under parity

$\gamma^\mu \gamma^5 \rightarrow$ even under parity

Sum of the two leads to the parity violation in weak interactions.

1970s – weak neutral current events at Gargamelle