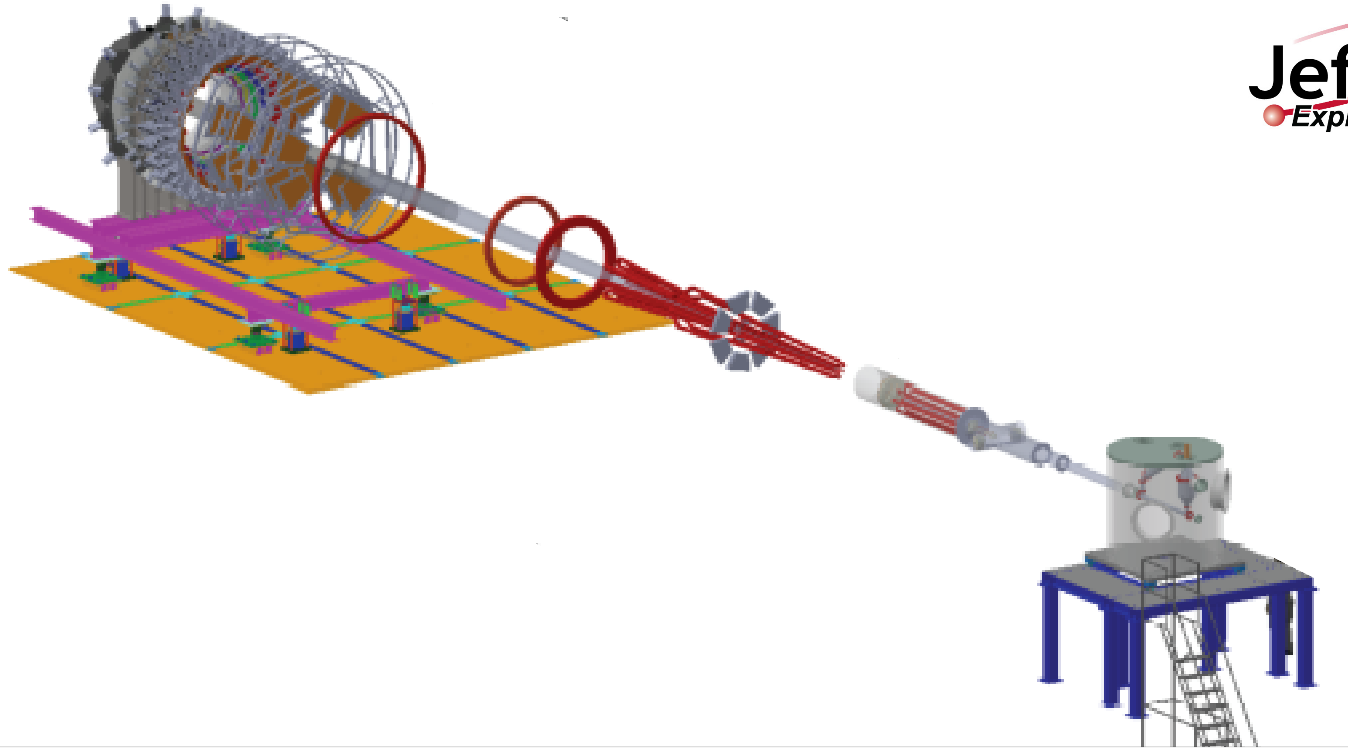


Jefferson Lab
Exploring the Nature of Matter

The MOLLER Experiment

Don Jones
for the MOLLER collaboration

SBS weekly meeting

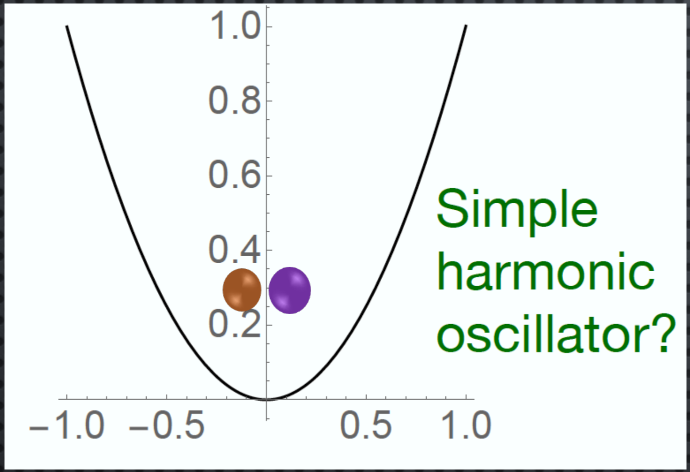
Dec 12, 2022

MOLLER EXPERIMENT OVERVIEW

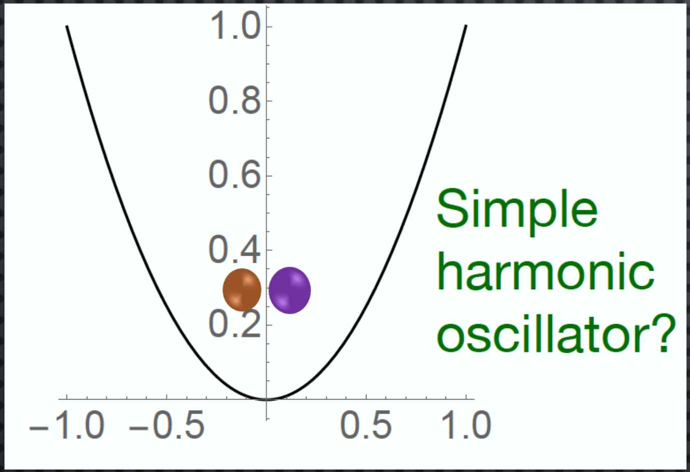
- Polarized electron scattering on unpolarized atomic electrons in LH2
- Measures parity-violating scattering asymmetry → proportional to Q_w^e

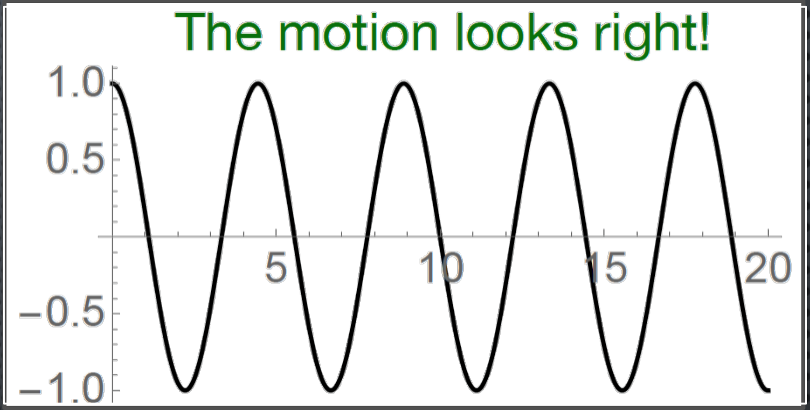
- Precise measurement of the weak charge of the electron (δQ_w^e ~2.4%)
- Precision test of the Standard Model prediction for the running of the weak charge/weak mixing angle ($\delta \sin^2 \theta_W \sim 0.12\%$)
- Search for physics beyond the Standard Model at the Precision Frontier

HIGH ENERGY PHYSICS @ LOW ENERGY = PRECISION



HIGH ENERGY PHYSICS @ LOW ENERGY = PRECISION





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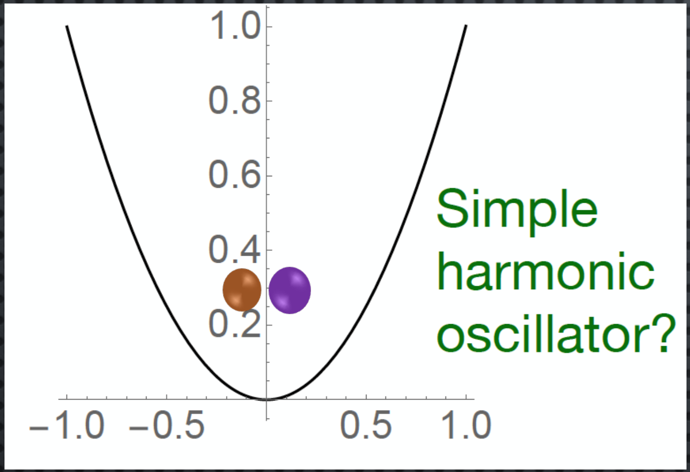

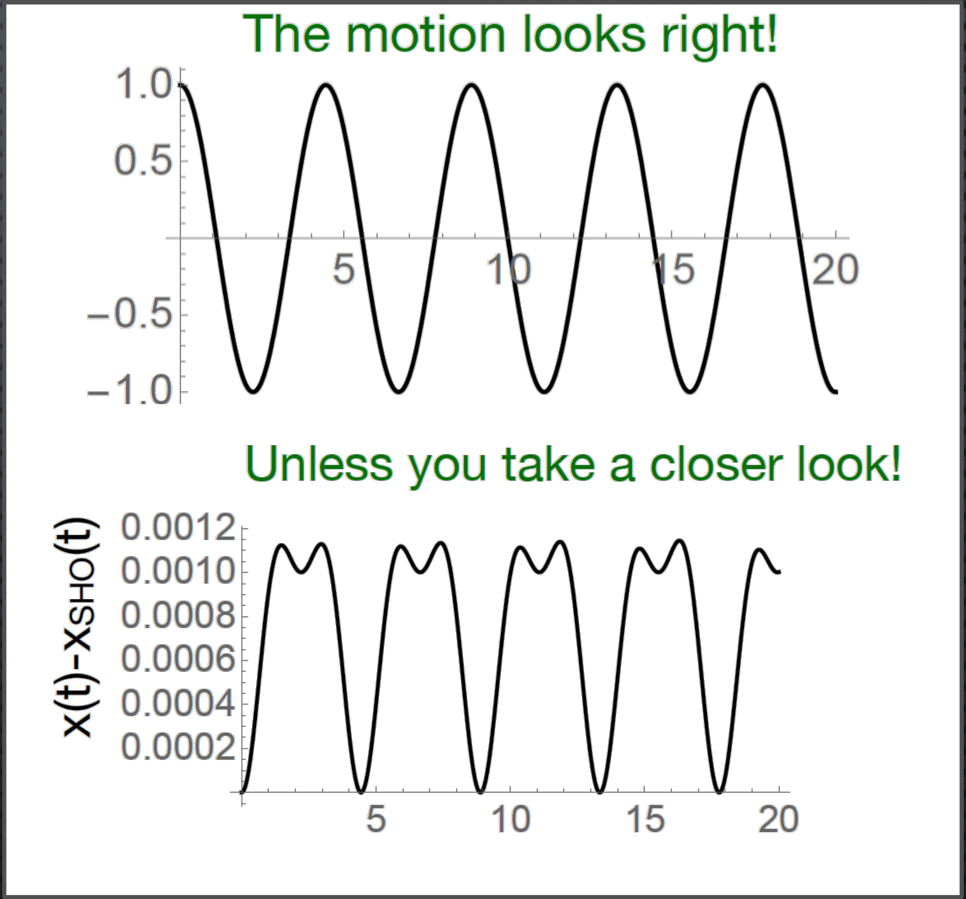

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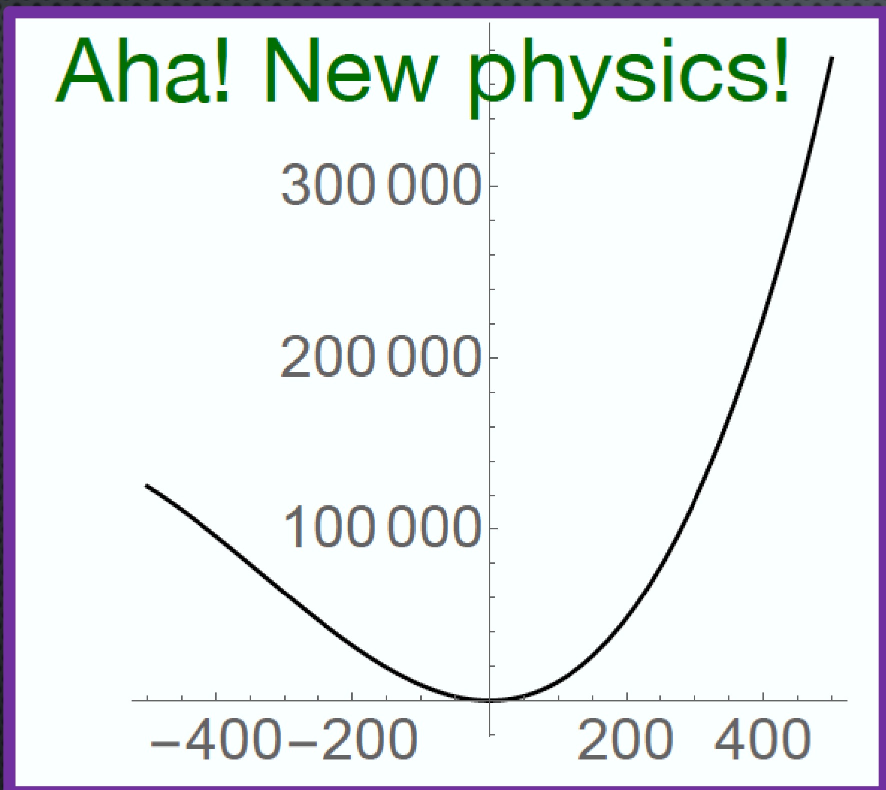
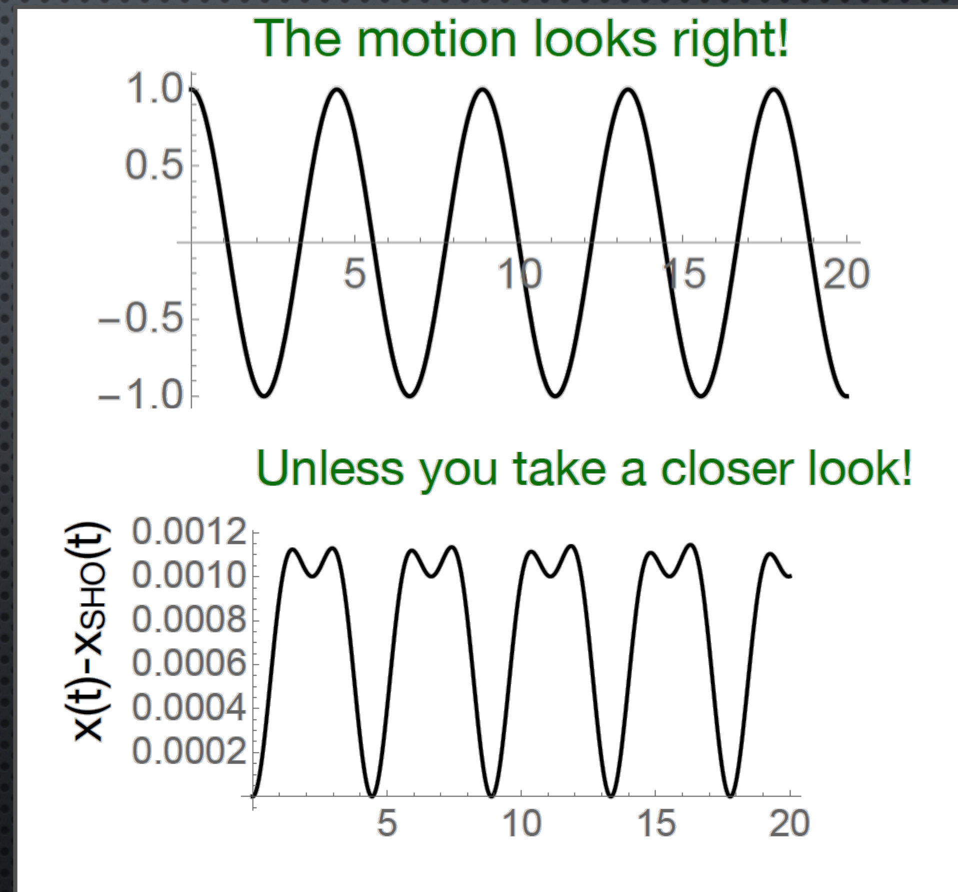


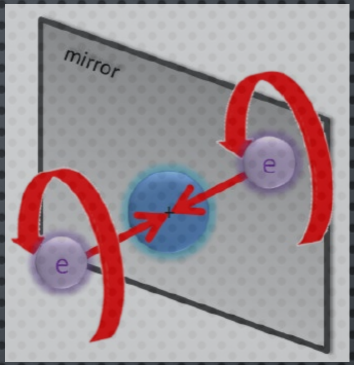


HOW ARE PARITY EXPERIMENTS DIFFERENT?

Some folks groan when they hear Parity experiments are on the schedule. They are quite different in their demands and the way they extract their physics.

- They are typically measuring tiny asymmetries (ppm level) so they obsess over beam quality to the annoyance of MCC and other Halls
  - (eg. differences in average beam position between left and right helicity states needs to be at the nm scale)
  - Incessantly measure beam characteristics and detector sensitivities to them
  - Continuously monitor distribution widths: Eg. a small increase in asymmetry width from target boiling and noisy instrumentation could easily lead to an effective loss of 50% in statistics.
- Usually pushing precision boundaries and require creativity to eliminate unknown errors not previously encountered.
- Statistical requirements are such that event counting is impossible and you have to resort to measuring integrated PMT current instead.
  - Pedestals are a big deal
  - Go to great lengths to prevent any crosstalk or ground loops that might be correlated with Helicity
- Carefully account for even tiny backgrounds
  - Precision of MOLLER requires we replace many beamline components. Even "non-magnetic" stainless (316L) is too magnetic for use in some places due to its magnetic polarization in ambient fields ~1G with the potential to introduce parity conserving asymmetries at ppb levels

Parity violating electron scattering (PVES)

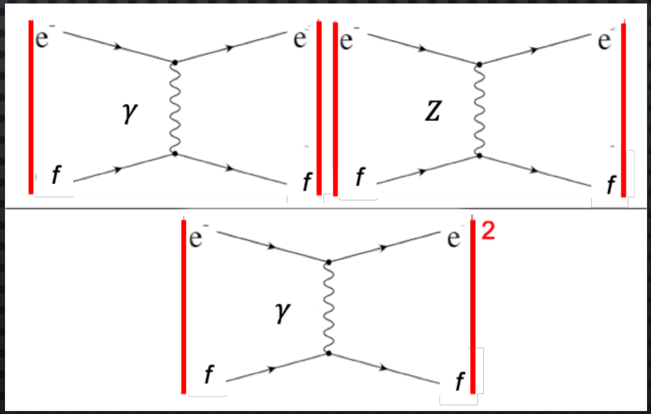


- Electron beam scattering from fixed target
- Reverse electron beam helicity = mirror exp

- PV asymmetry in scattering rates arises from interference between EM and neutral current amplitudes

$$\sigma \propto |M_\gamma + M_Z|^2 \approx |M_\gamma|^2 + 2M_\gamma^* M_Z$$

$$A_{PV} \sim \frac{2|M_\gamma^* M_z^{PV}|}{|M_\gamma|^2} \propto Q_W$$



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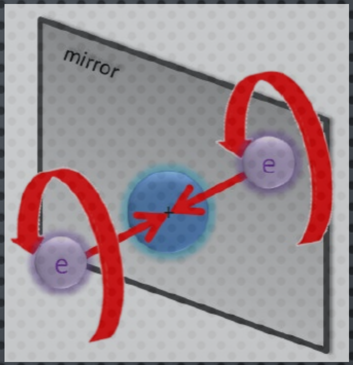

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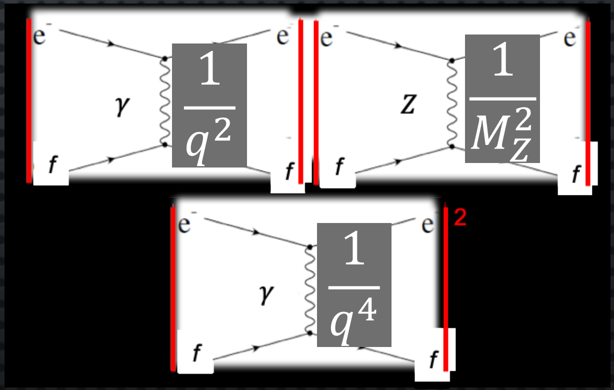
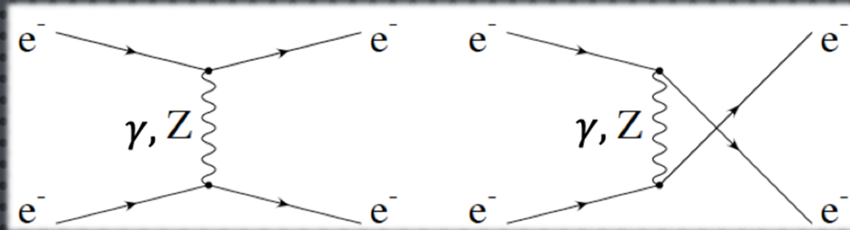


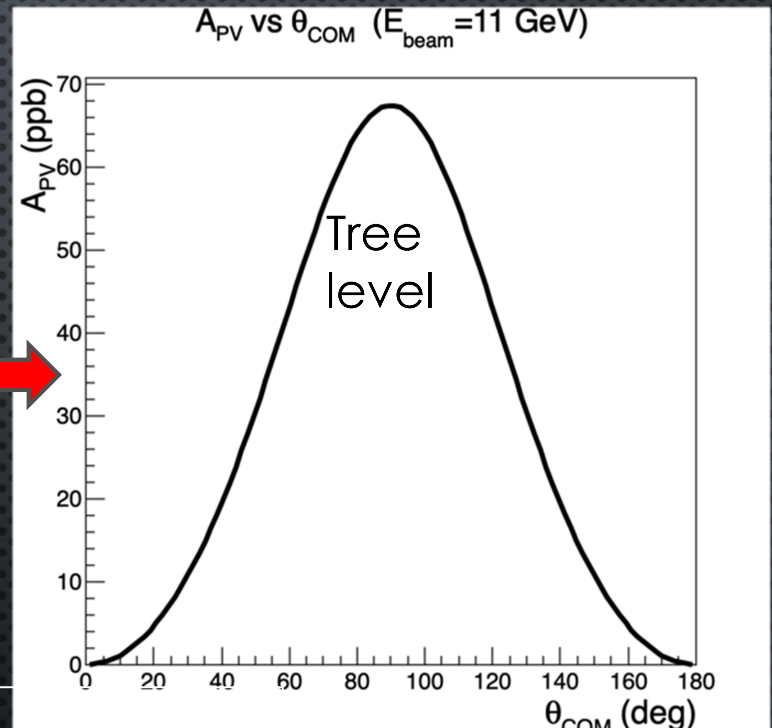
GeV/c

$$A_{PV} \sim \frac{q^2}{M_Z^2} \approx q^2 \times 10^{-4}$$

PARITY-VIOLATING MOLLER SCATTERING



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



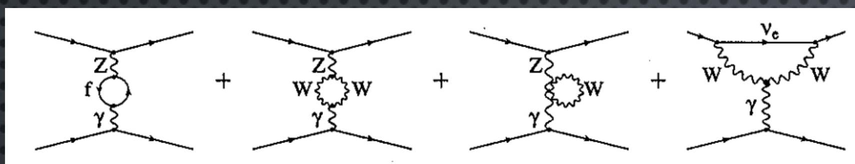
Electroweak corrections in the SM

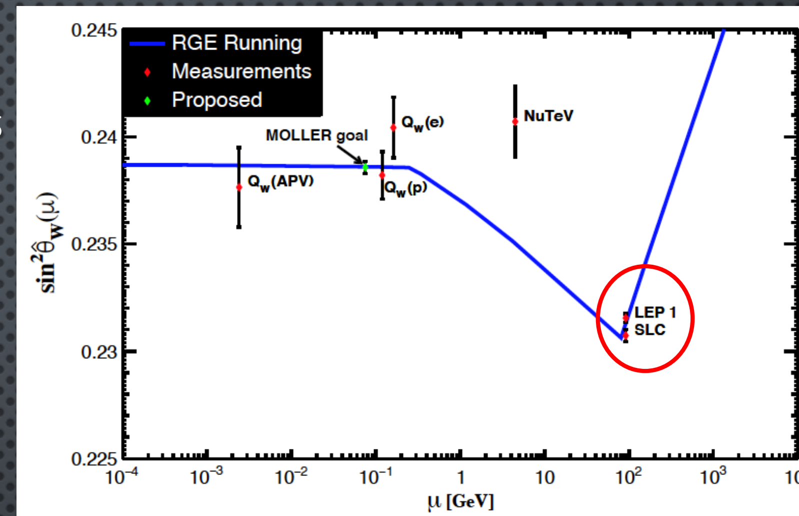
- couplings run (weak mixing angle/weak charge)
- A_{PV} loop contributions depend on energy scale

PARITY-VIOLATING MOLLER SCATTERING

tree level — 1 loop EW corrections

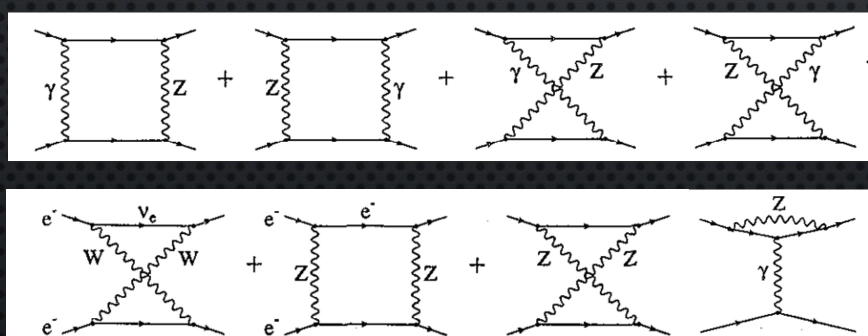
$$Q_w^e = 1 - 4\sin^2\theta_w \sim 0.075 \longrightarrow 0.0435$$

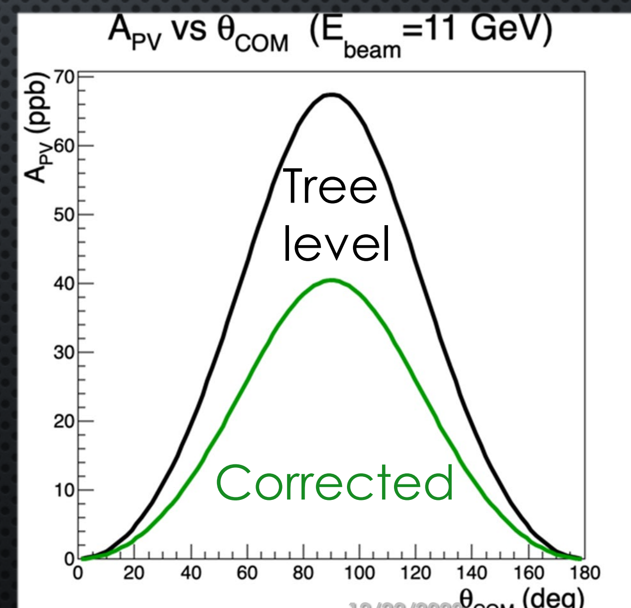




tree level — 1 loop EW corrections

$$A_{PV}(\theta_{CM} = 90°) = 67 \text{ ppb} \longrightarrow 40 \text{ ppb}$$





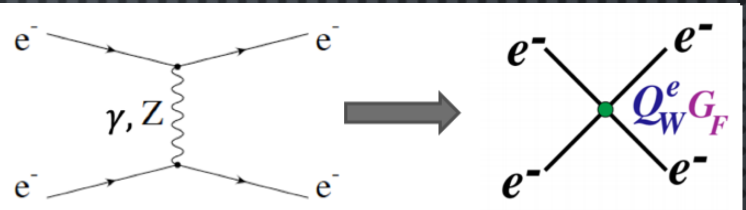
2 Loop corrections calculations underway!

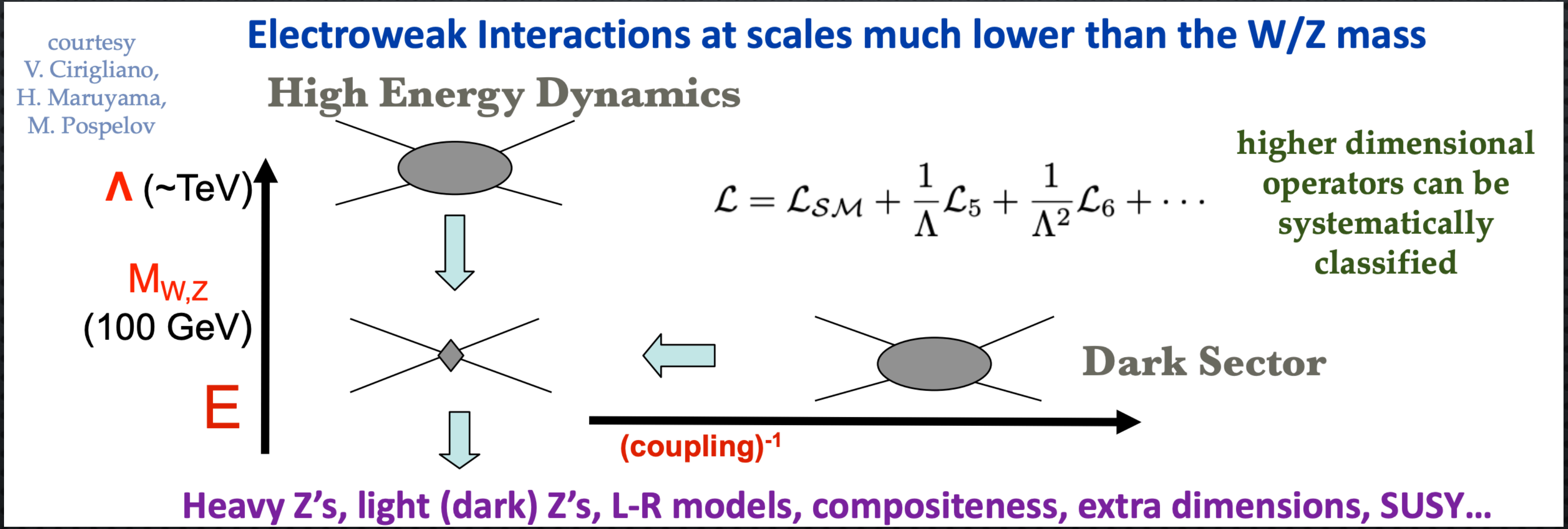
SENSITIVITY TO NEW PHYSICS

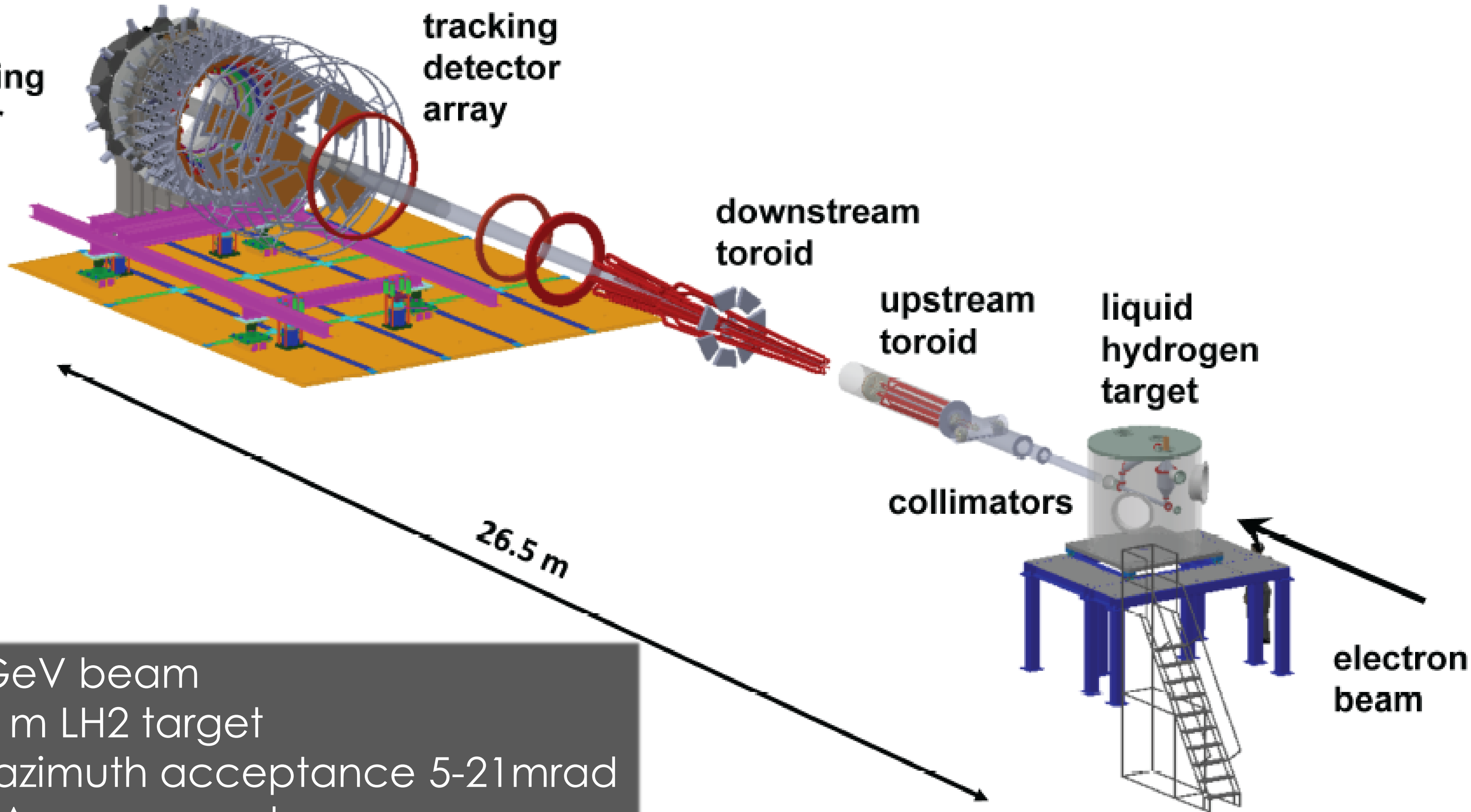
- PRECISE MEASUREMENT OF PV ASYMMETRY PROBES CERTAIN MODELS OF NEW PHYSICS AT TEV SCALES
  - INTERACTIONS MODELED AS CONTACT INTERACTIONS WITH NEW PHYSICS ENTERING IN LOOPS AT MASS SCALE Λ AND COUPLING g
  - $\frac{\delta A_{PV}}{A_{PV}} = 2.4\% \longrightarrow$

$$g \sim 1 \longrightarrow \Lambda \sim 7 \text{ TeV}$$

$$\Lambda \sim 100 \text{ MeV} \longrightarrow g \sim 10^{-3} \alpha_{QED}$$



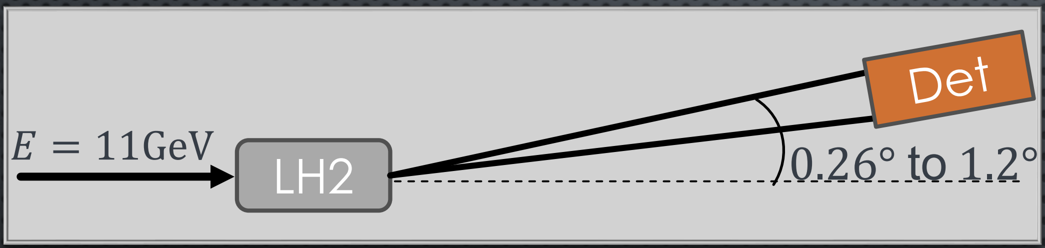


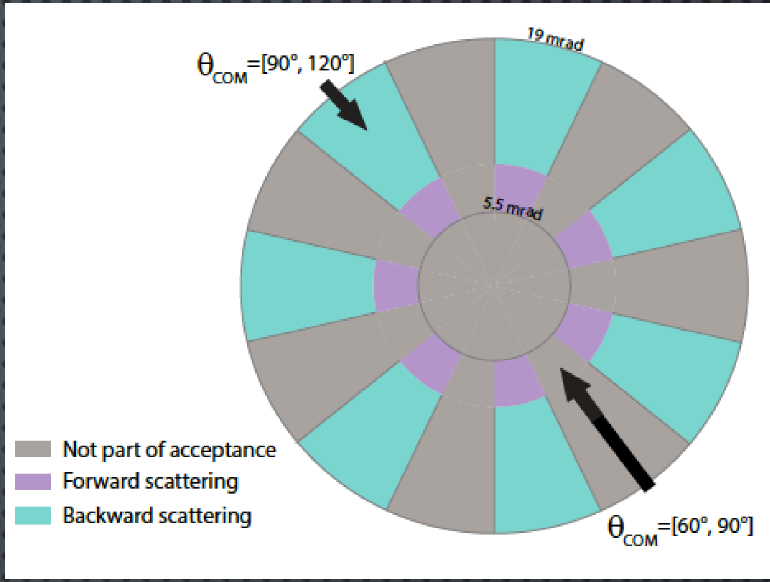


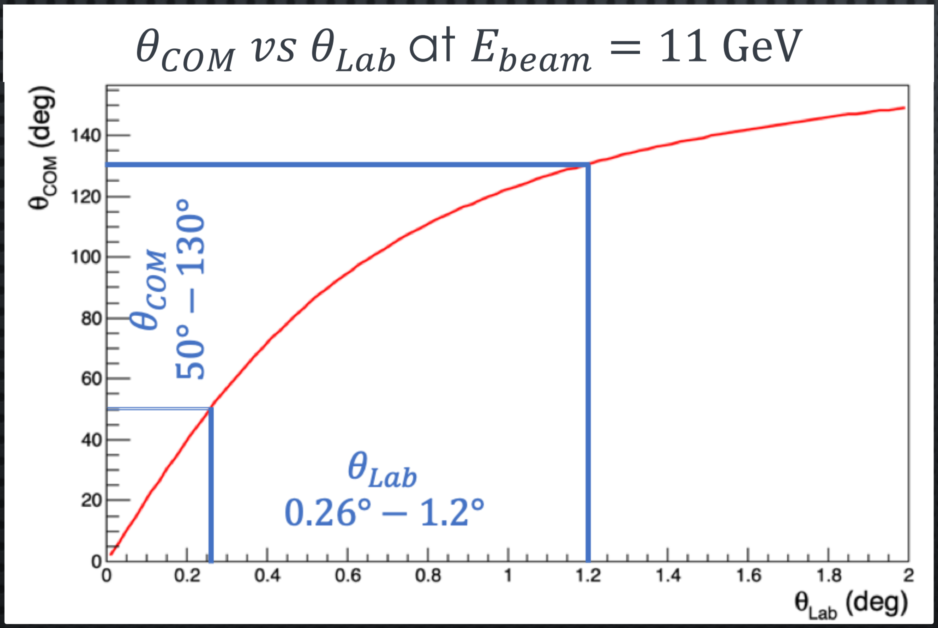
- 11 GeV beam
- 1.25 m LH2 target
- Full azimuth acceptance 5-21mrad
- 65 μA max current
- Moller rate ~2 GHz/ μA
- 344 PAC days (688 calendar days) spread over 3 running periods

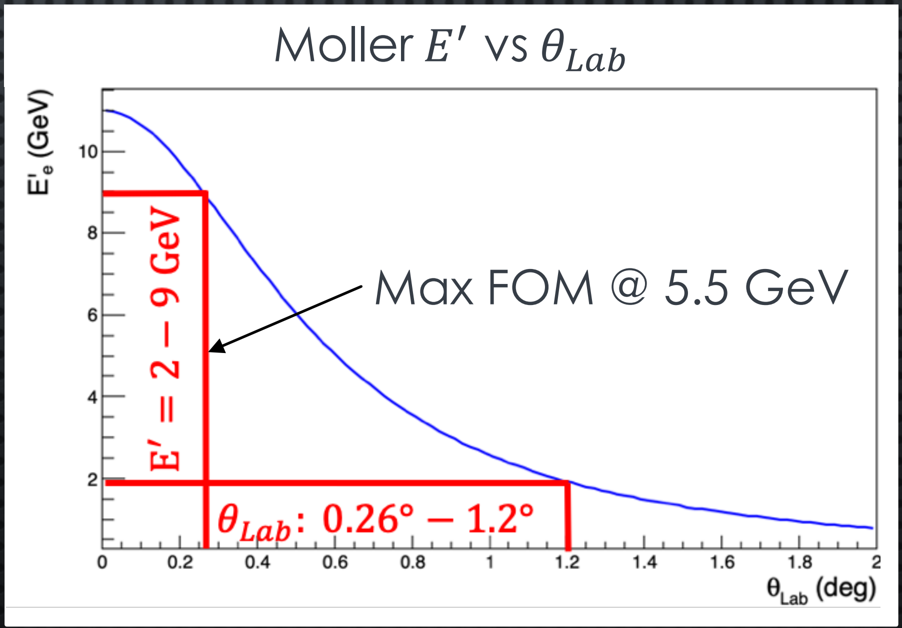
ACCEPTANCE

- Effective full azimuthal acceptance due to identical particles
- Acceptance from $\theta_{COM} = 50° - 130°$



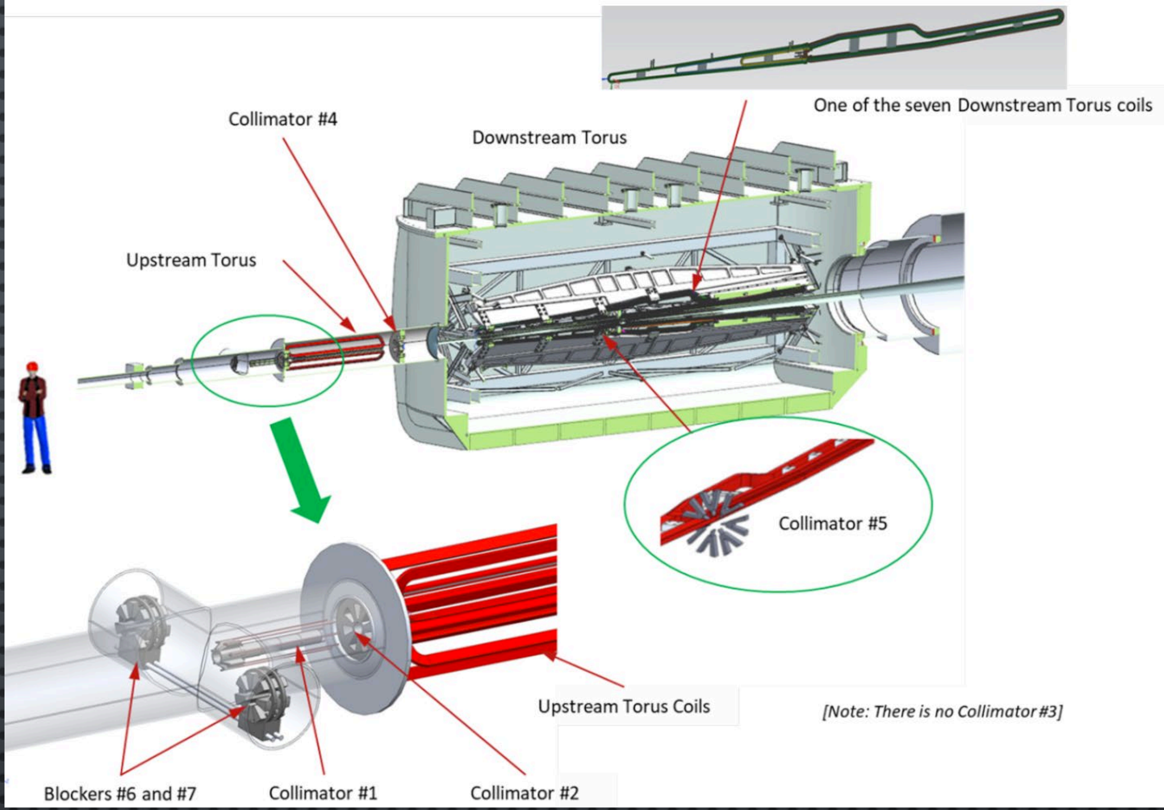


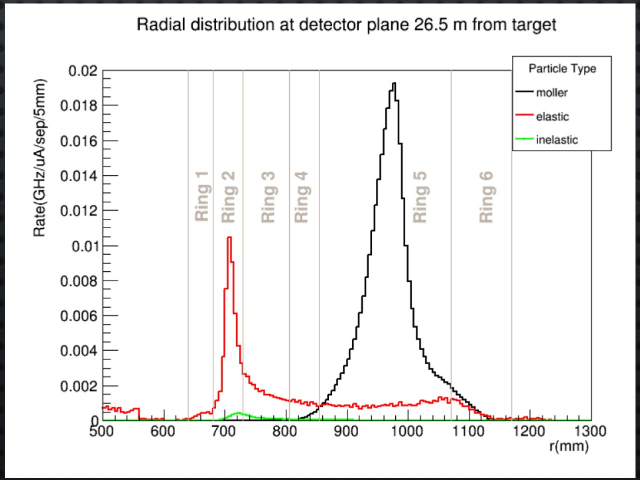




SPECTROMETER

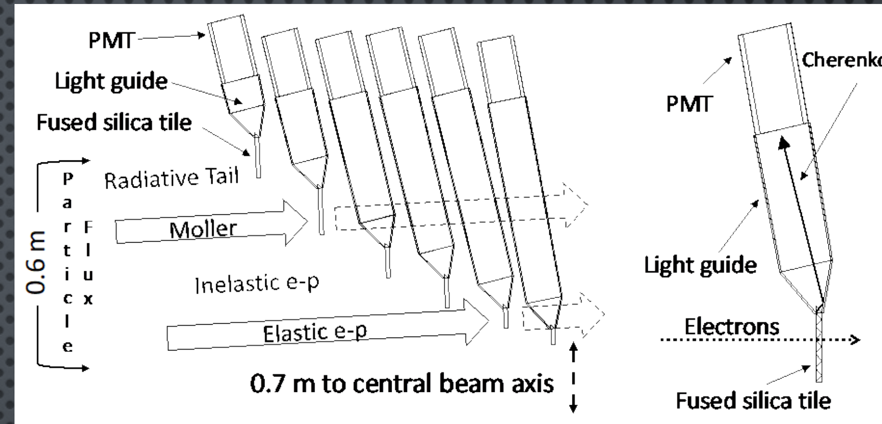
- DEFINING COLLIMATOR (2) UPSTREAM OF MAGNETIC OPTICS
- COMPRISES AN UPSTREAM AND DOWNSTREAM TORUS WITH 7-FOLD SYMMETRY
- FOCUSES ELASTIC *ee* ONTO DETECTOR ARRAY WHILE SEPARATING ELASTIC *ep*

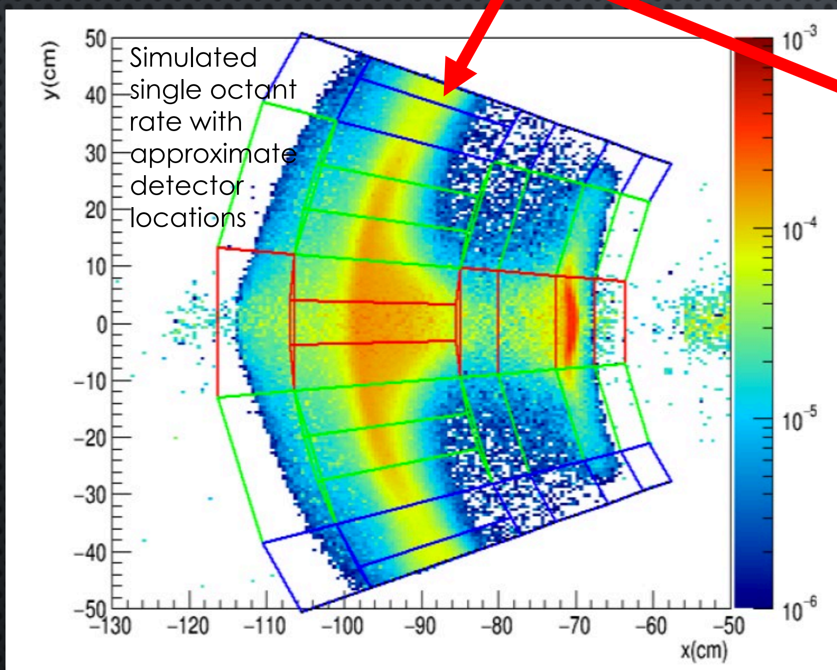


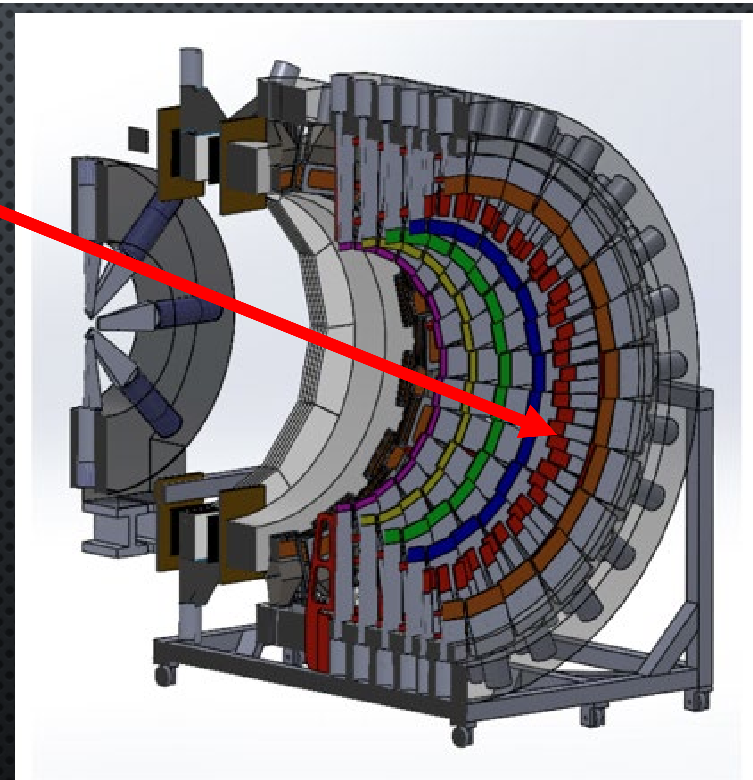


DETECTORS

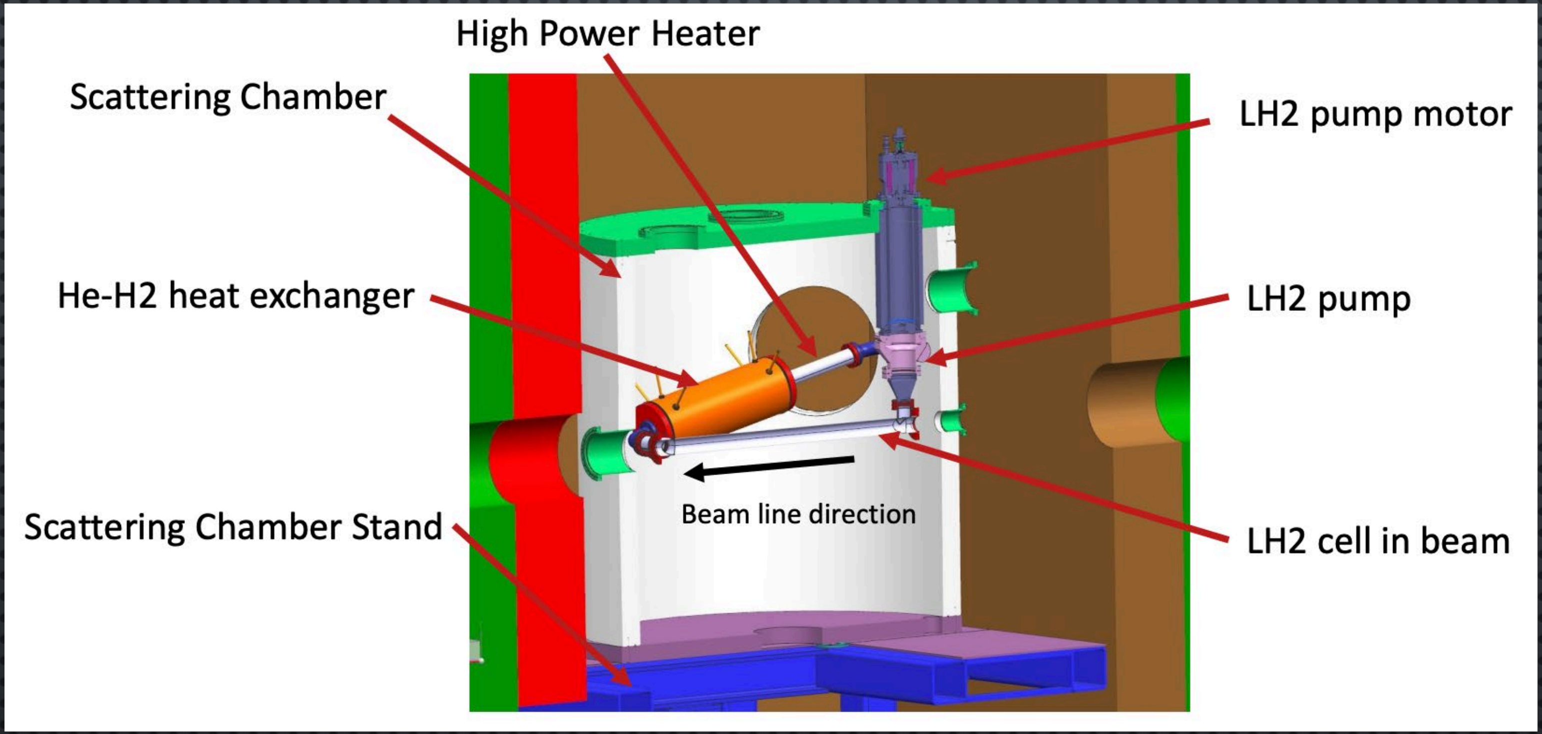
- Six main detector rings over full azimuth measuring different parts of signal
- Integrating in current mode
  - 122 GHz for Moller ring







LIQUID HYDROGEN TARGET

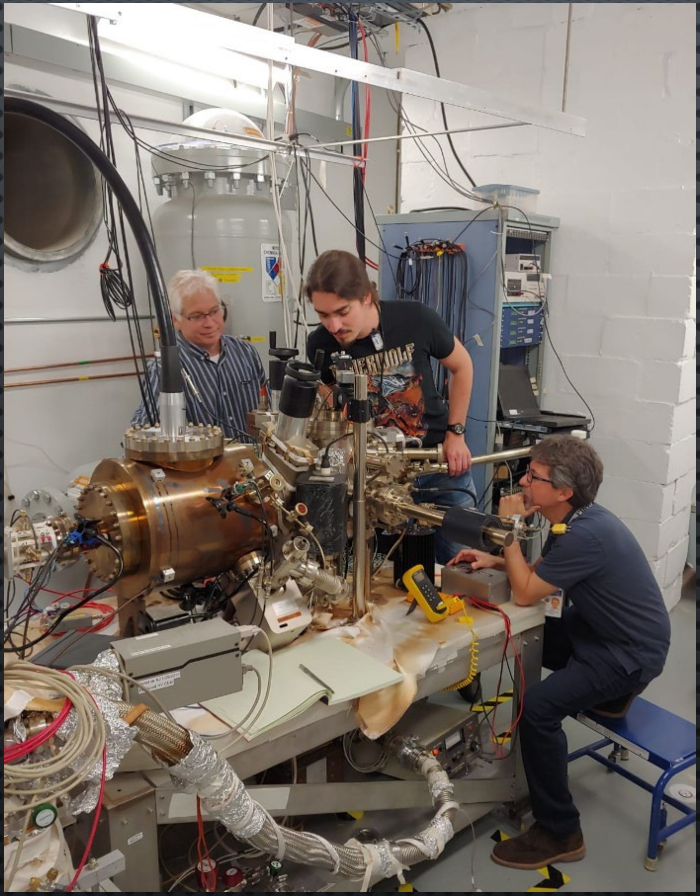


- 1.25 m long target
- Designed with extensive CFD

- Qweak target precursor
  - 47 ppm → 30 ppm
  - Flow 17 l/s → 25 l/s
  - Cooling 3 kW → 4 kW

PARITY QUALITY ELECTRON BEAM

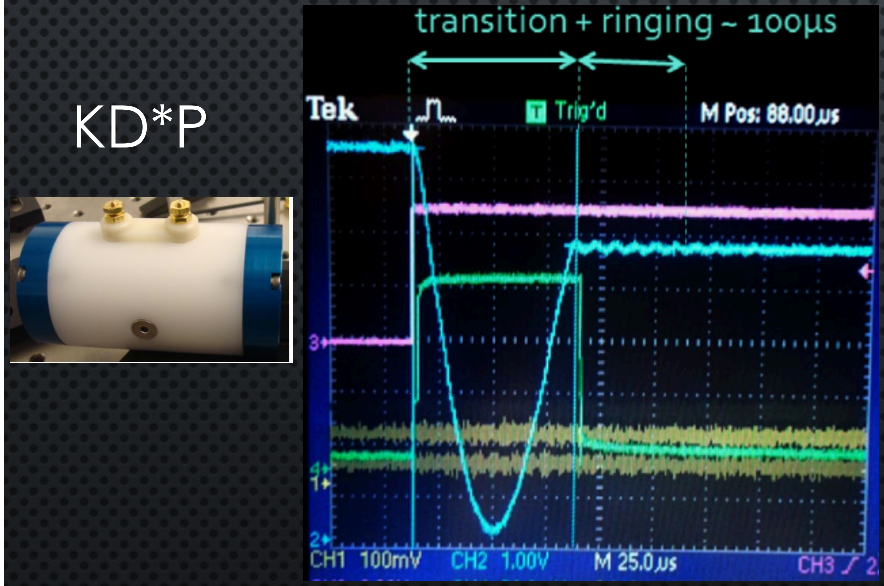
- **HIGH POLARIZATION (~85%)→ ROUTINELY ACCOMPLISHED WITH GAAS PHOTOCATHODE**



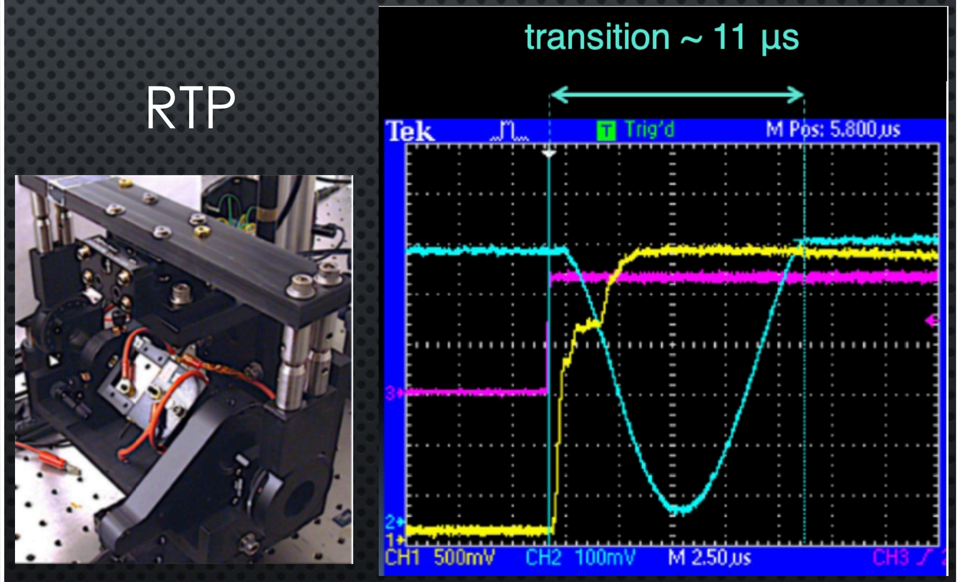
Parity Quality Electron Beam

- High polarization (~85%)→ routinely accomplished with GaAs photocathode
- **Rapid helicity reversal (~2kHz) to reduce random noise from target density fluctuations**
  - Helicity reversal of laser polarization in source provided by Pockels cell
  - Previous KD*P cell limited to ~100 μs deadtime for each reversal due to ringing
  - Ringing eliminated and 10 μs reversal time possible with new RTP crystal cell developed by UVA

KD*P



RTP



PARITY QUALITY ELECTRON BEAM

- High polarization (~85%)→ routinely accomplished with GaAs photocathode
- Rapid helicity reversal (~2kHz) to minimize random noise (eg. Target density fluctuations and slow drifts
- **Helicity correlated (HC) Differences suppressed**

	PREX-2 (achieved)	MOLLER (required)
Intensity asymmetry	25 ppb	10 ppb
Energy asymmetry	1 ± 0.6 ppb	< 0.7 ppb
position differences	$< 2 \pm 2$ nm	1.2 nm
angle differences	$< 0.2 \pm 0.4$ nrad	0.12 nrad
size asymmetry (quoted)	$< 10^{-5}$	$< 10^{-5}$

Achieving Moller Requirements

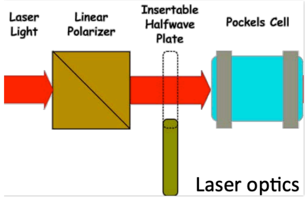
1. Injector upgrade including new Wien filter and 200 keV gun with no RF prebuncher
   - Reduced space charge effects (beam halo)
   - Better matching = adiabatic damping
   - No x/y coupling
2. RTP cell provides ability to feed back on position and intensity differences

PARITY QUALITY ELECTRON BEAM

- HIGH POLARIZATION (~85%)→ ROUTINELY ACCOMPLISHED WITH GAAS PHOTOCATHODE
- RAPID HELICITY REVERSAL (~2KHZ) TO MINIMIZE RANDOM NOISE (EG. TARGET DENSITY FLUCTUATIONS AND SLOW DRIFTS
- HELICITY CORRELATED (HC) DIFFERENCES SUPPRESSED
- **CANCELATION OF REMAINING HC FALSE ASYMMETRIES = SLOW REVERSALS**

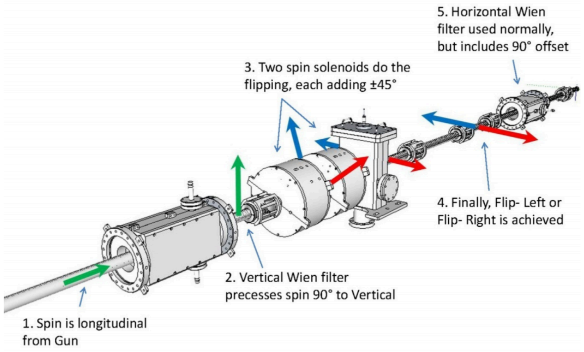
Insertable Halfwave Plate

- Reverses circular polarization relative to PC voltage
- frequent changes (few hours)
- some HCBA cancel (many do not)



Injector Spin Manipulation

- Solenoids + 2 Wien rotations
- ~80 reversals during run phase 2&3 (weekly)



g-2 rotation

- precession in accelerator arcs
- Modest shift in beam energy (ΔE~100 MeV)
- intend a few reversals per annual run period

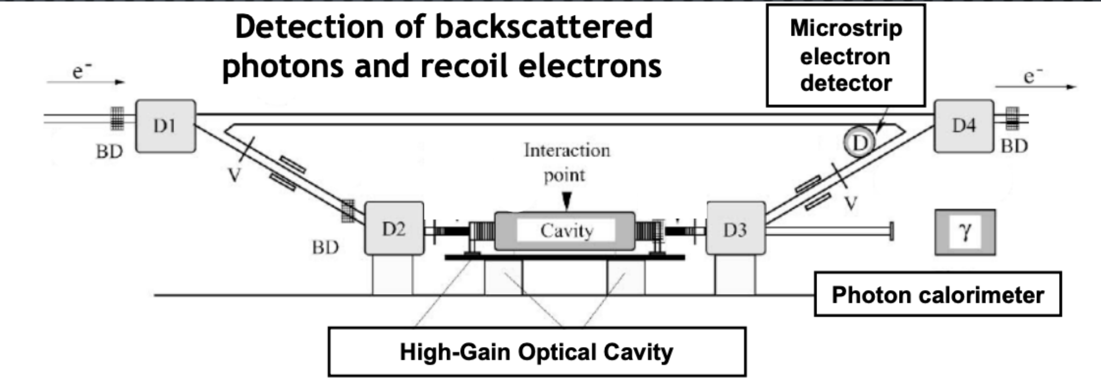
Suppressing:

- electronics pickup
- beam asymmetries
- Spot size asymmetry

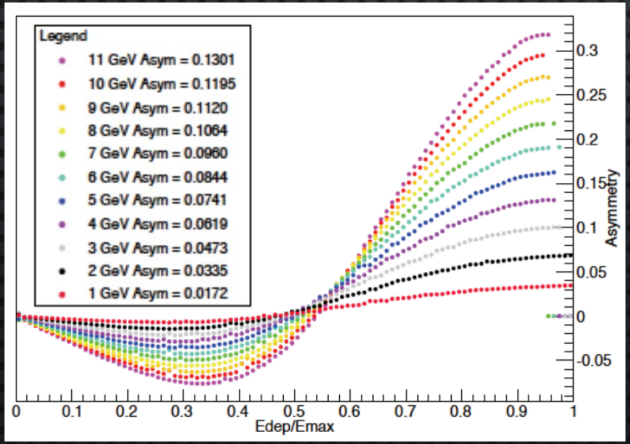
Courtesy K. Paschke

POLARIMETRY: COMPTON ~0.4%

Scattering ~3kW circularly polarized green laser from electron beam and detecting both back-scattered γ and e-



- γ-DETECTOR
  - NO-THRESHOLD INTEGRATION 200 MHZ
  - OPERATING DURING PREXII-CREX



- E-DETECTOR
  - 3RD DIPOLE MOMENTUM ANALYZES SCATTERED ELECTRONS
  - SPECTRUM FORMED AS FUNCTION OF DISPLACEMENT FROM BEAM
  - SILICON DETECTOR NOT CURRENTLY FUNCTIONING BUT PLANS TO REPLACE WITH DIAMOND STRIP OR HVMAPS (HIGH VOLTAGE MONOLITHIC ACTIVE PIXEL SENSORS) DETECTOR
  - MOST INDEPENDENT FROM γ BUT SHARES LASER POLARIZATION

POLARIMETRY: MOLLER ~0.4%

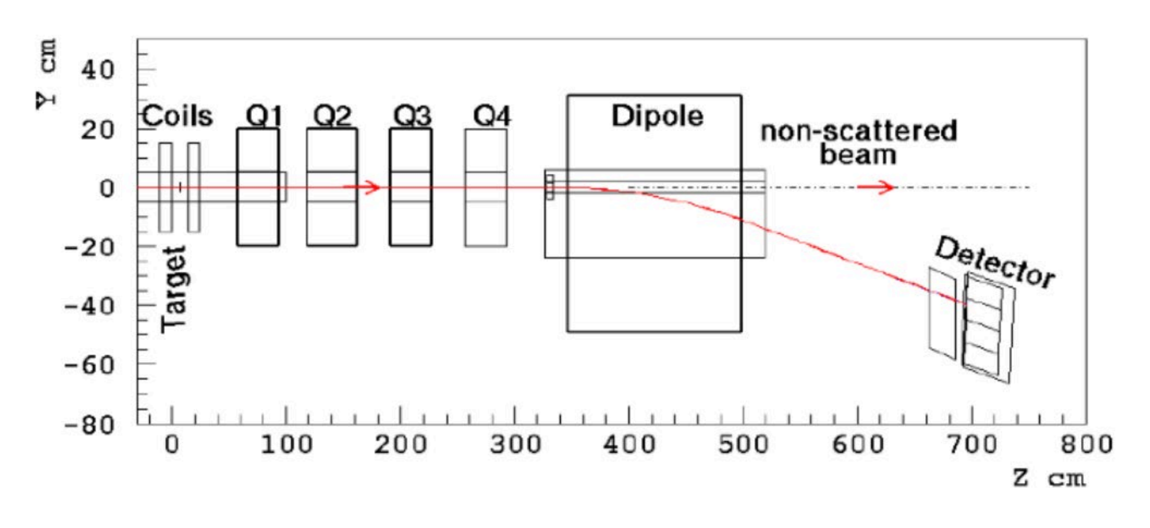
- Elastic ee scattering from a Fe foil polarized || beam
- Parity conserving Moller asym

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

$$A_{meas} = \sum_{i,j=x,y,z} P_i^t A_{ij} P_j^b$$

- Measured asymmetry for us

$$A_{long} = P_z^t A_{zz} P_z^b$$



- KEY SYSTEMATICS BEING STUDIED: LEVCHUK EFFECT, TARGET POLARIZATION, SENSITIVITY TO OPTICS
- LOTS OF LESSONS LEARNED DURING PREXII/CREX
- MAY ADD GEM TRACKER TO REDUCE SYSTEMATICS FROM OPTICS UNCERTAINTY

MOLLER Project Team has been very active

- Thanks to the leads who have helped shepherd MOLLER through Several reviews
  - Project Manager: J. Fast
  - Deputy Project Manager: J. Butler
  - Project Engineer: R. Wines
  - Safety Lead: E. Folts

STATUS

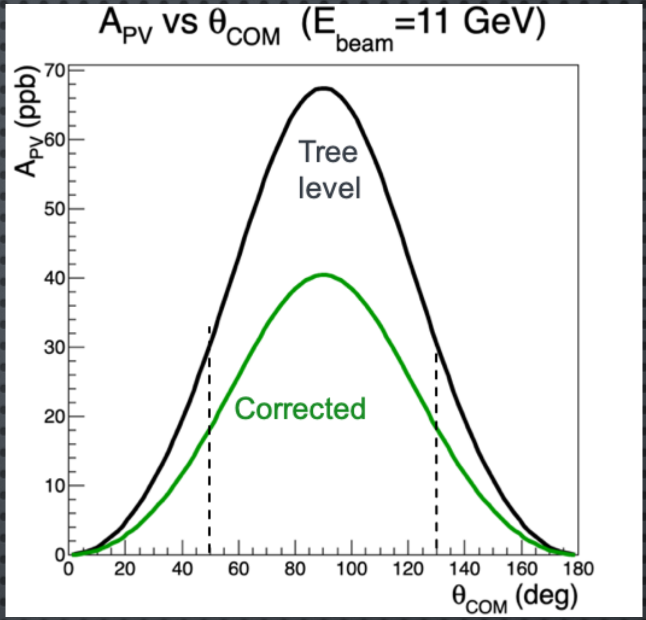
- Achieved CD1 in Dec 2020
- Going through reviews now expecting CD2-3 in early 2023
- Expect to begin installation in Fall of 2024 with first physics beam in 2025

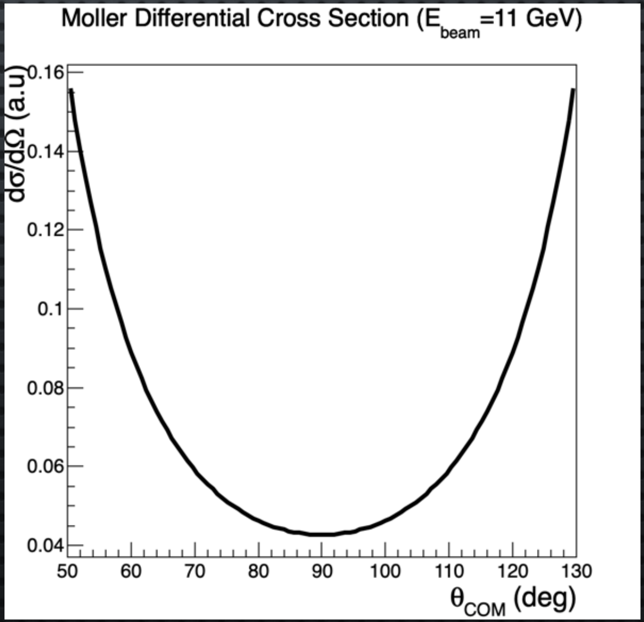
The MOLLER collaboration consists of ~160 authors, 37 institutions from 6 countries

THANK YOU

FIGURE OF MERIT

- A_{pv} varies over acceptance from 40 to 27 ppb → $\langle A_{pv}\rangle$~32 ppb
- Cross section minimum at $\theta_{COM} = 90°$
- FOM = $\langle A_{PV}^2 R_{ee}\rangle$ maximum at $\theta_{COM} = 90°$ and varies slowly away from 90 deg





SENSITIVITY TO NEW PHYSICS

- NEW PHYSICS CAN BE PARAMETRIZED BY CONTACT INTERACTIONS IN AN EFFECTIVE LAGRANGIAN

$$\mathcal{L}_{\text{eff}} = \frac{g^2}{(1+\delta)\Lambda^2} \sum_{i,j=L,R} \eta_{ij}^{f} \bar{e}_i \gamma_\mu e_i \bar{f}_j \gamma^\mu f_j$$

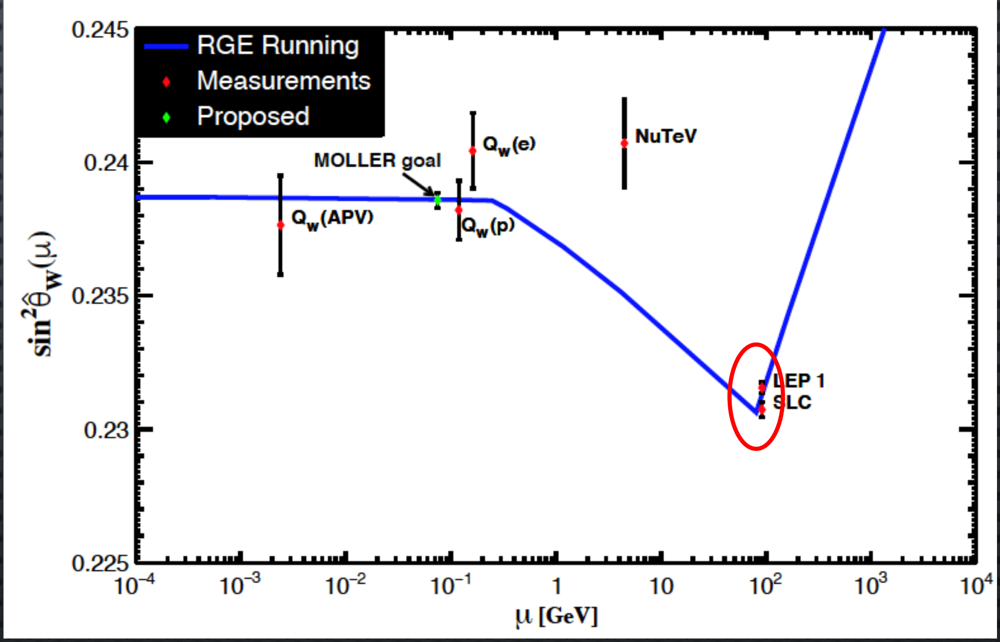
- VARYING SENSITIVITY TO DIFFERENT COUPLINGS
    - MOLLER PART OF LARGER PROGRAM TO PROBE PHASE SPACE OF DIFFERENT MODELS OF NEW PHYSICS
    - WITH $\frac{g}{4\pi} = 1$ AS IN HIGH ENERGY PHYSICS GIVES MOLLER SENSITIVITY TO $\Lambda_{LL}^{ee} = 27$ TEV

Model	η_{LL}^f	η_{RR}^f	η_{LR}^f	η_{RL}^f
$LL^\pm$	±1	0	0	0
$RR^\pm$	0	±1	0	0
$LR^\pm$	0	0	±1	0
$RL^\pm$	0	0	0	±1
$VV^\pm$	±1	±1	±1	±1
$AA^\pm$	±1	±1	∓1	∓1
$VA^\pm$	±1	∓1	±1	∓1

https://arxiv.org/abs/1302.6263

RUNNING OF WEAK MIXING ANGLE

- Running of $\sin^2\theta_W$ precisely given by Standard Model and anchored absolutely by Measurements at the Z-pole resonance
- 3 sigma difference between LEP 1 and SLC measurements with nearly equal precision
  - Average agrees well with Higgs boson mass of 126 GeV
  - Choosing one or the other has ruins agreement with different implications for high energy dynamics
- MOLLER proposal to measure $\delta\sin^2\theta_W = 0.00028$ has same level of precision and interpretability



Best projected sensitivity to $\sin^2\theta_W$ at low Q^2or at collider over next decade.