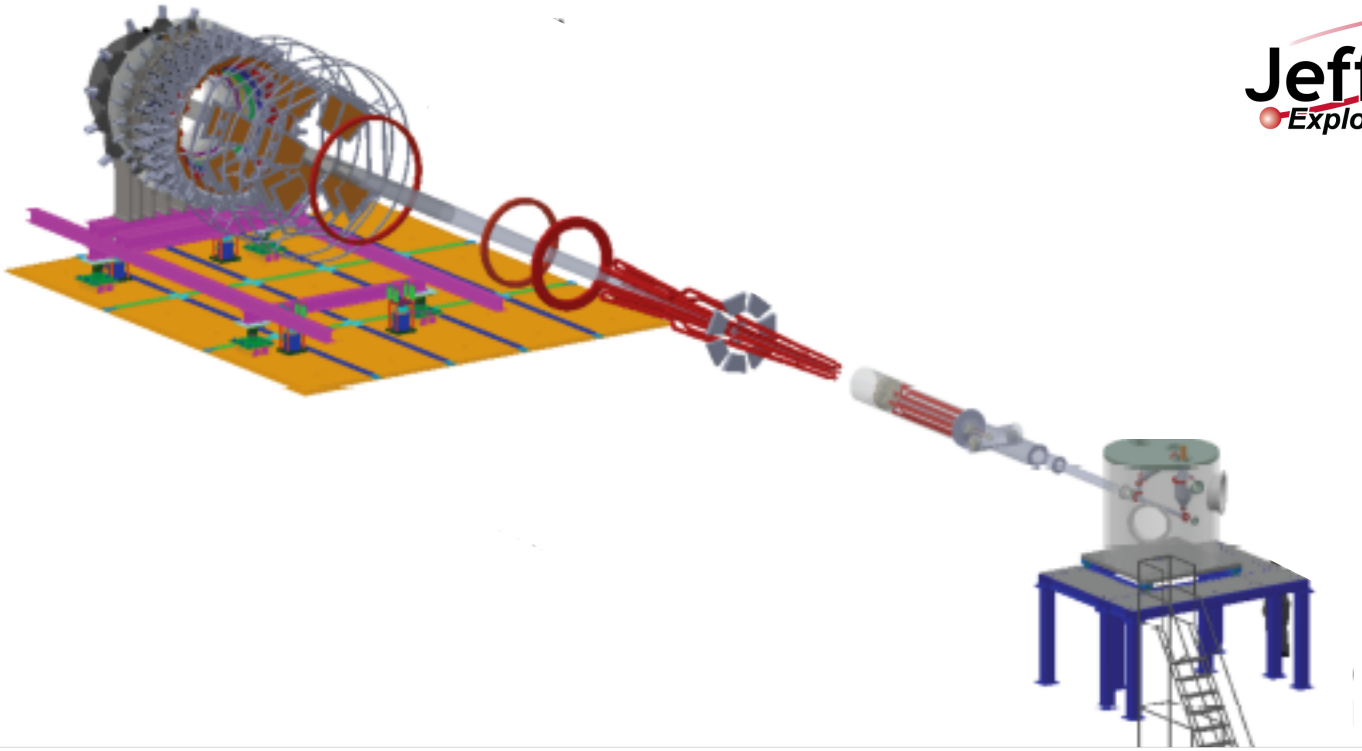


Jefferson Lab
Exploring the Nature of Matter

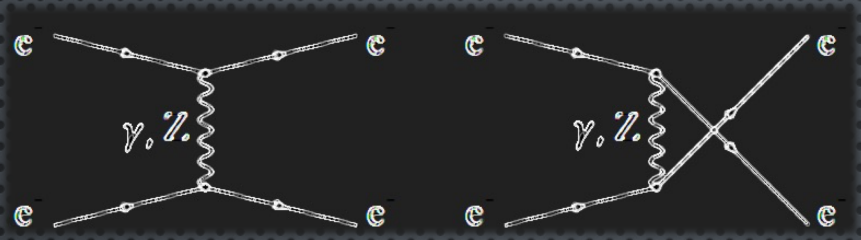
The MOLLER Experiment

Don Jones
for the MOLLER collaboration

TEMPLE UNIVERSITY

Hall A collaboration meeting Jan 31, 2020

MOLLER EXPERIMENT OVERVIEW

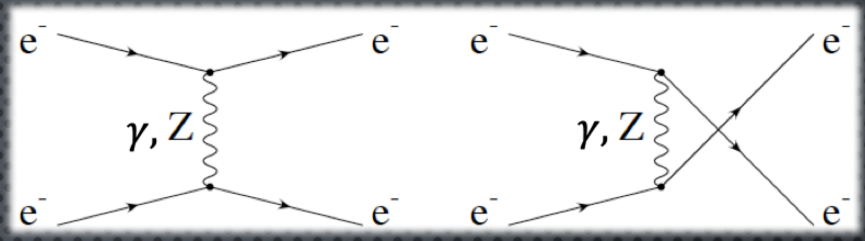


- POLARIZED ELECTRON SCATTERING ON UNPOLARIZED ATOMIC ELECTRONS IN LH2
- MEASURES PARITY-VIOLATING SCATTERING ASYMMETRY → PROPORTIONAL TO Q_w^e

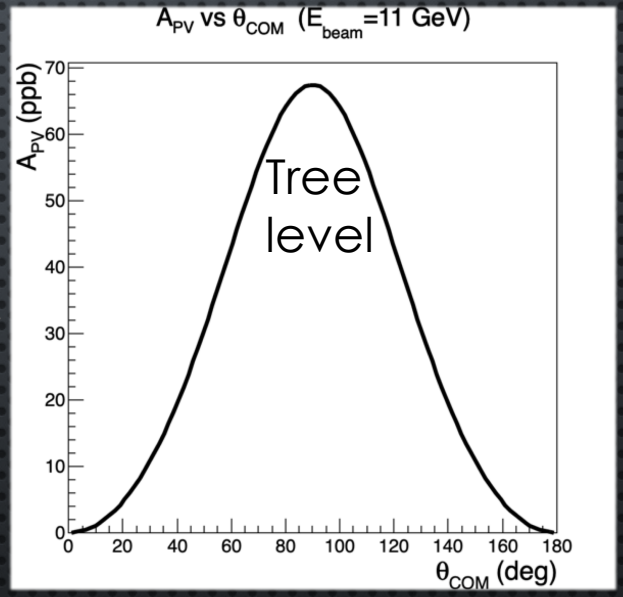
- PRECISE MEASUREMENT OF THE WEAK CHARGE OF THE ELECTRON (δQ_w^e ~2.4%)
- PRECISION TEST OF THE STANDARD MODEL PREDICTION FOR THE RUNNING OF THE WEAK CHARGE/WEAK MIXING ANGLE ($\delta \sin^2 \theta_W$ ~0.12%)
- SEARCH FOR PHYSICS BEYOND THE STANDARD MODEL

PARITY-VIOLATING MOLLER SCATTERING

PV MOLLER ASYMMETRY FROM INTERFERENCE TERMS γZ IN LAGRANGIAN $A_{PV} \propto \frac{M_\gamma M_Z}{M_\gamma^2}$



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



PARITY-VIOLATING MOLLER SCATTERING

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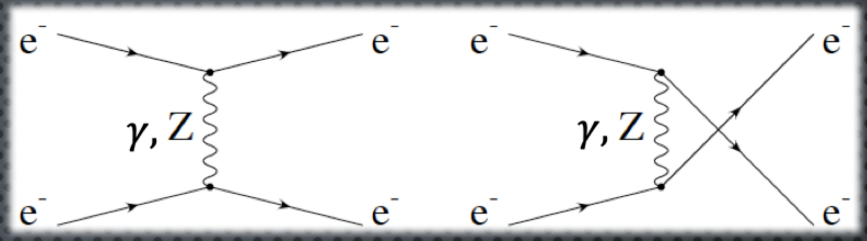
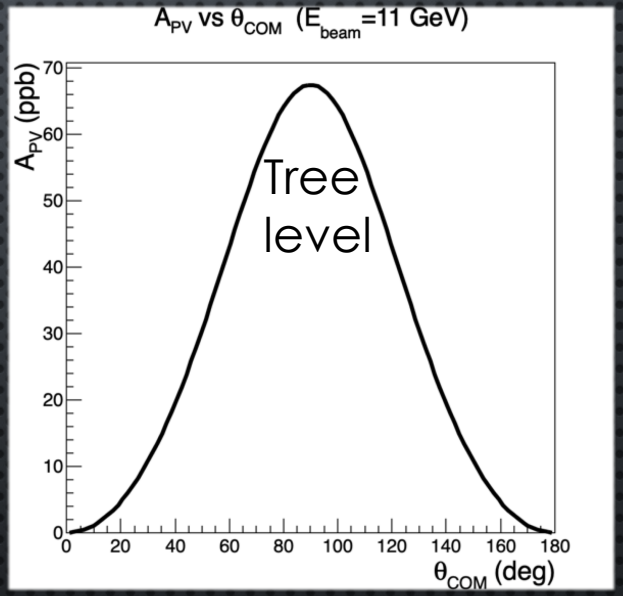


$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$
$$= mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4\sin^2\theta}{(3+\cos^2\theta)^2} Q_W^e$$



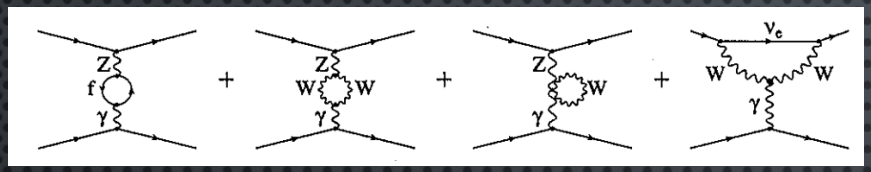
Electroweak corrections in the SM

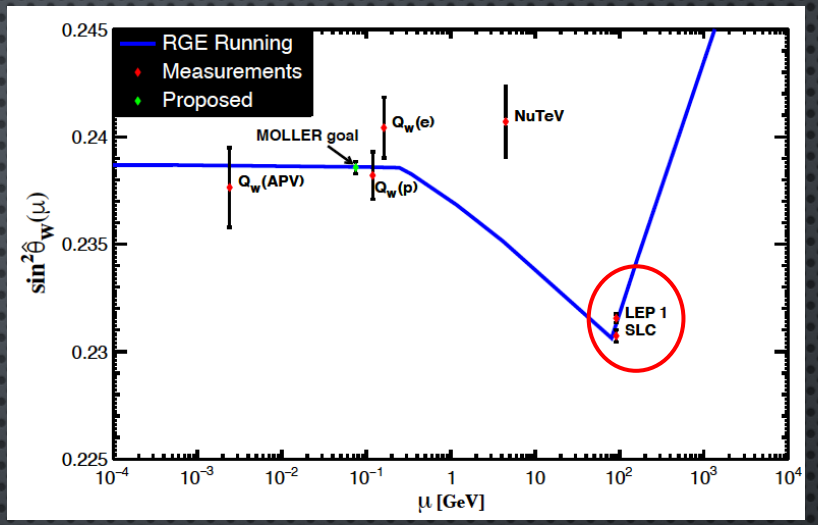
- couplings run (weak mixing angle/weak charge)
- A_{PV} loop contributions depend on energy scale

PARITY-VIOLATING MOLLER SCATTERING

tree level 1 loop EW corrections

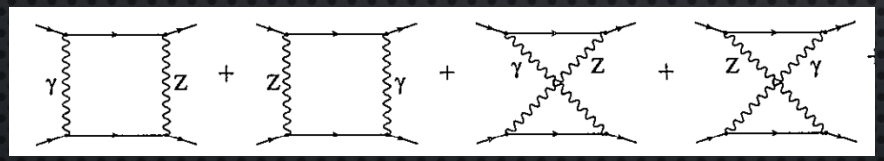
$Q_w^e = 1 - 4\sin^2\theta_w \sim 0.075 \longrightarrow 0.0435$

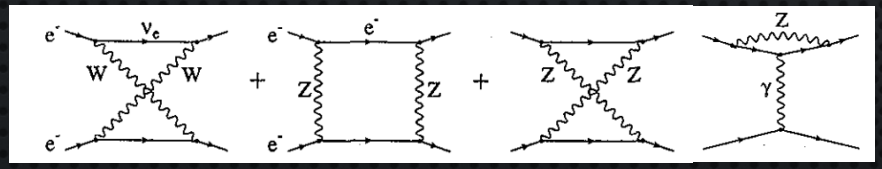




tree level 1 loop EW corrections

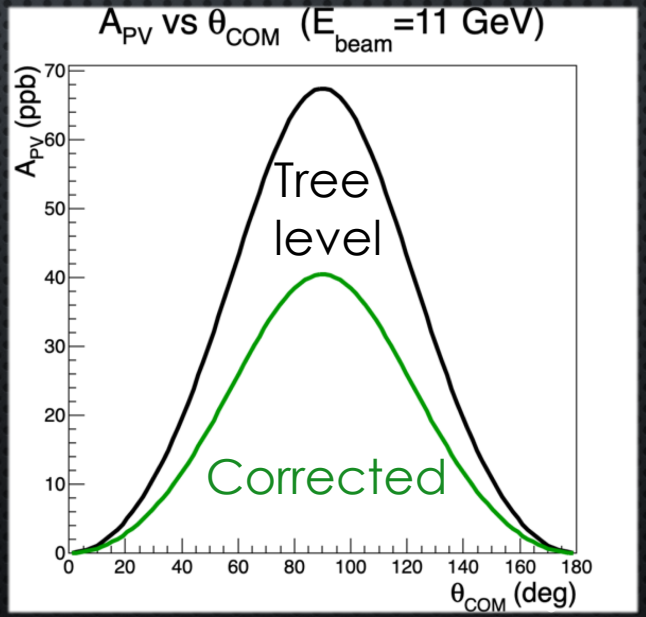
$A_{PV}(\theta_{CM} = 90°) = 67$ ppb $\longrightarrow$ 40 ppb





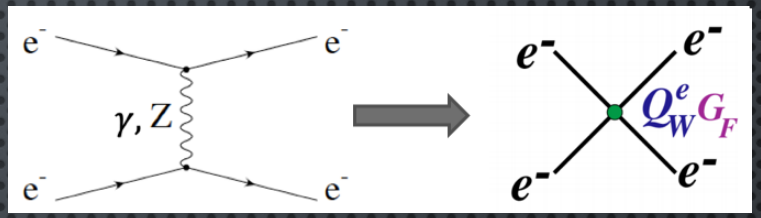
2 Loop corrections calculations underway!

Hall A collaboration meeting Jan 2020



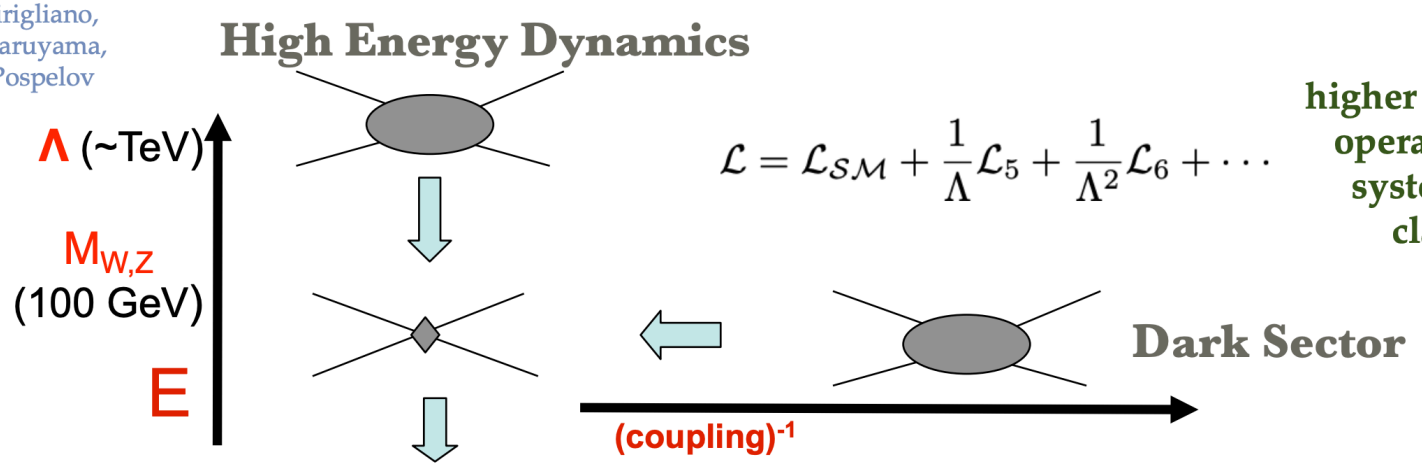
SENSITIVITY TO NEW PHYSICS

- 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
  - $\frac{\delta A_{PV}}{A_{PV}} = 2.4\% \longrightarrow$ $g \sim 1 \longrightarrow \Lambda \sim 7\ \mathrm{TeV}$; $\Lambda \sim 100\ \mathrm{MeV} \longrightarrow g \sim 10^{-3}\alpha_{QED}$



courtesy V. Cirigliano, H. Maruyama, M. Pospelov

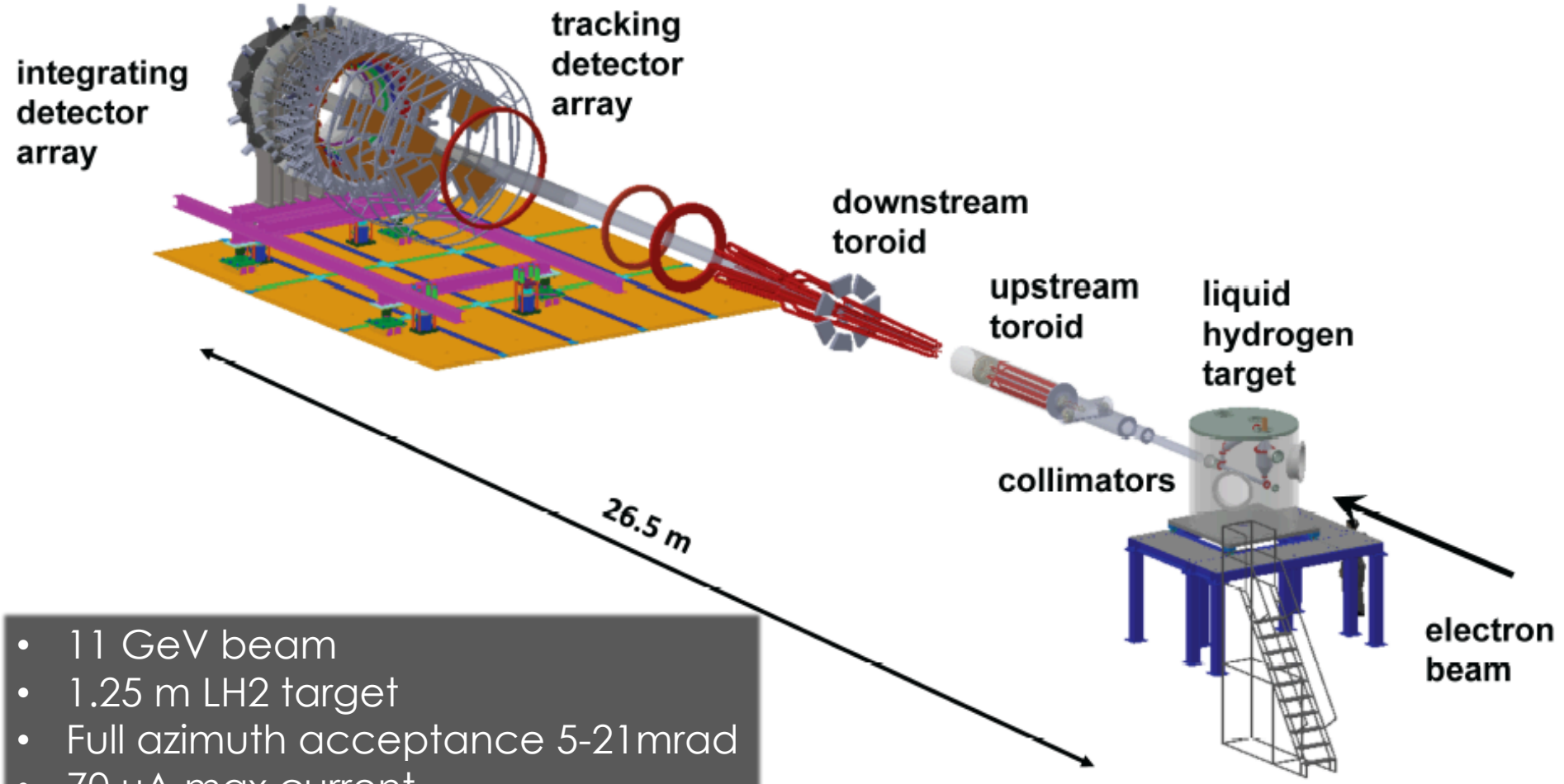
Electroweak Interactions at scales much lower than the W/Z mass



$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

higher dimensional operators can be systematically classified

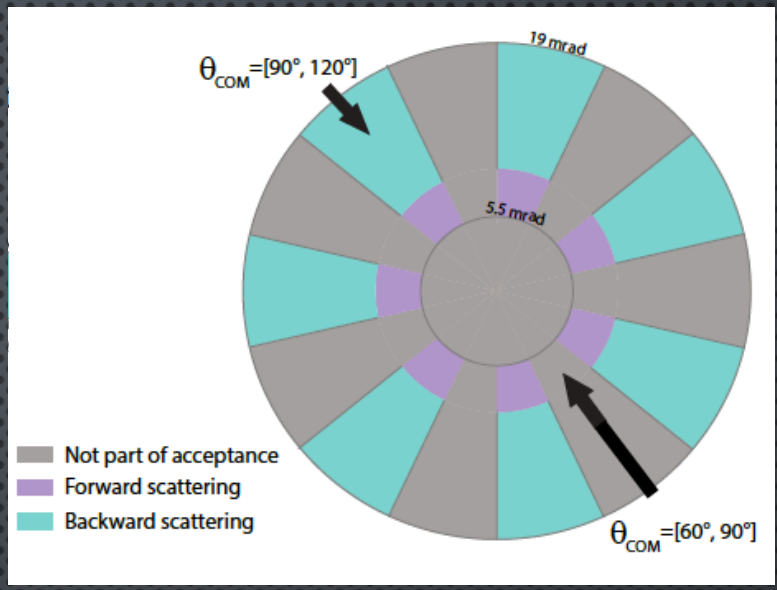
Heavy Z's, light (dark) Z's, L-R models, compositeness, extra dimensions, SUSY…

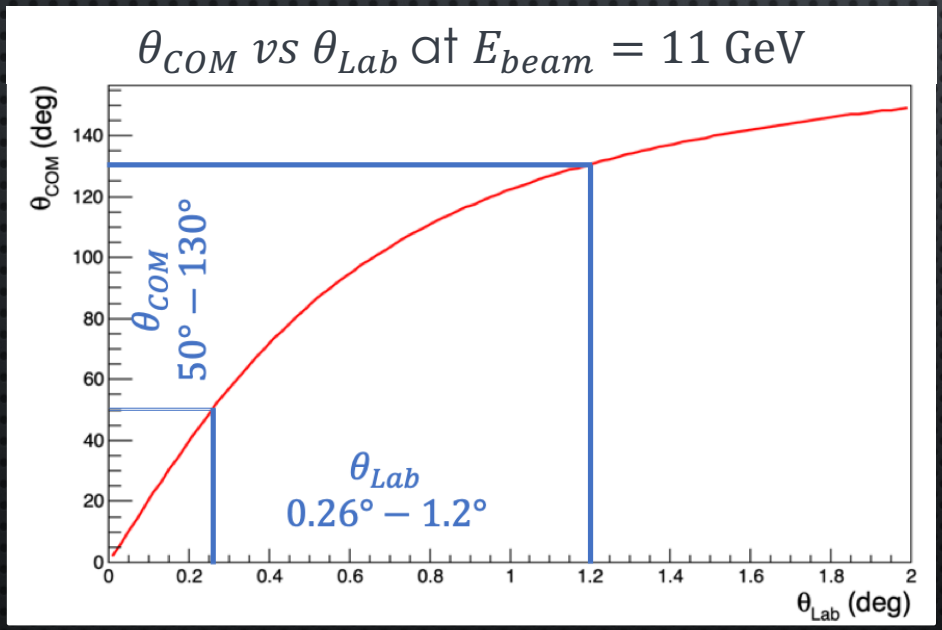


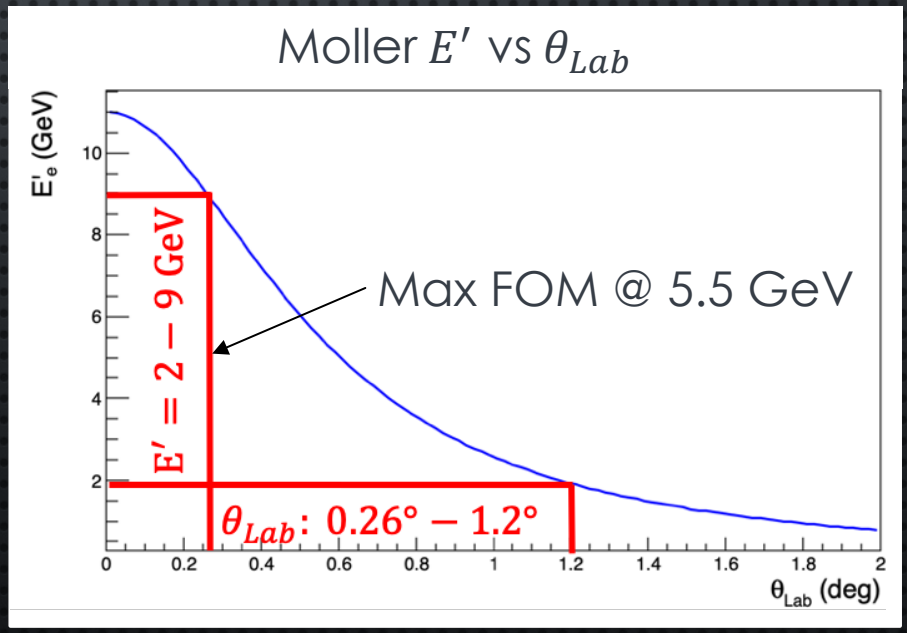
- 11 GeV beam
- 1.25 m LH2 target
- Full azimuth acceptance 5-21mrad
- 70 μA max current
- Moller rate ~2 GHz/ μA
- 344 PAC days→8256 hours spread over 3 running periods

ACCEPTANCE

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

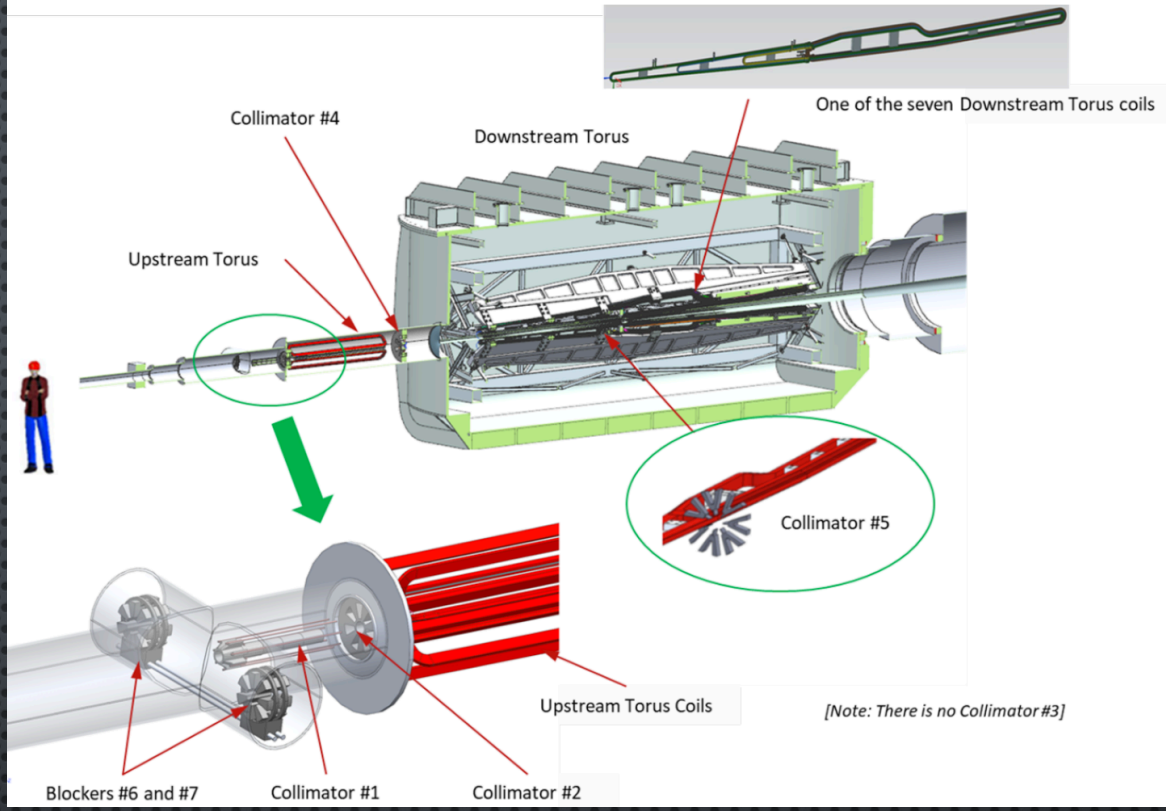


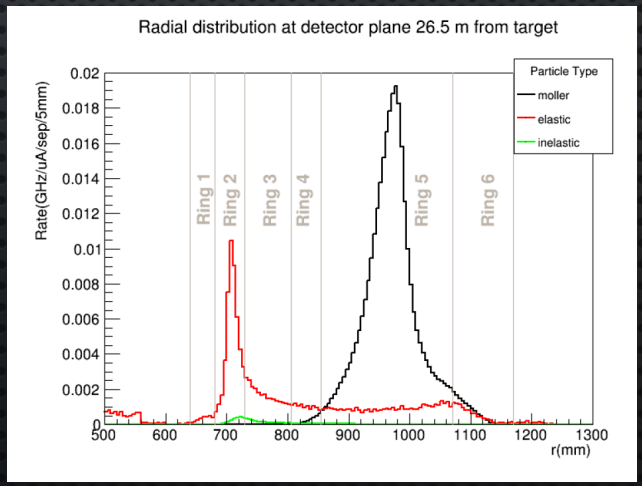




SPECTROMETER

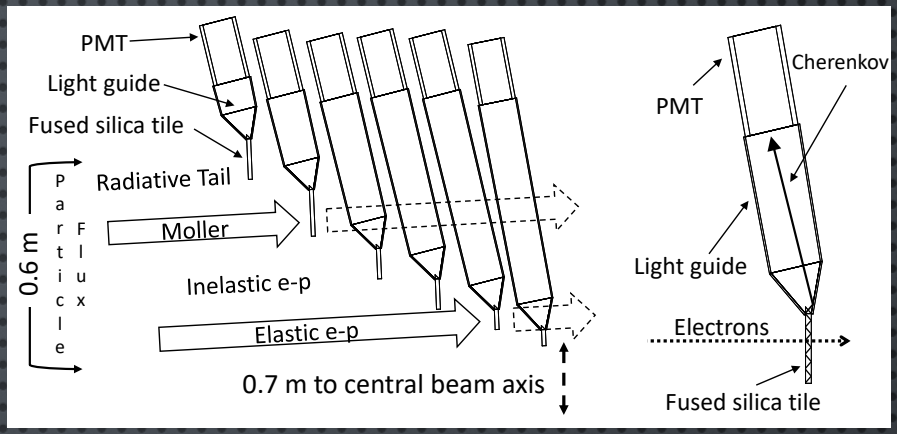
- Defining collimator (2) upstream of magnetic optics
- Comprises an upstream and downstream torus with 7-fold symmetry
- Focuses elastic *ee* onto detector array while separating elastic *ep*

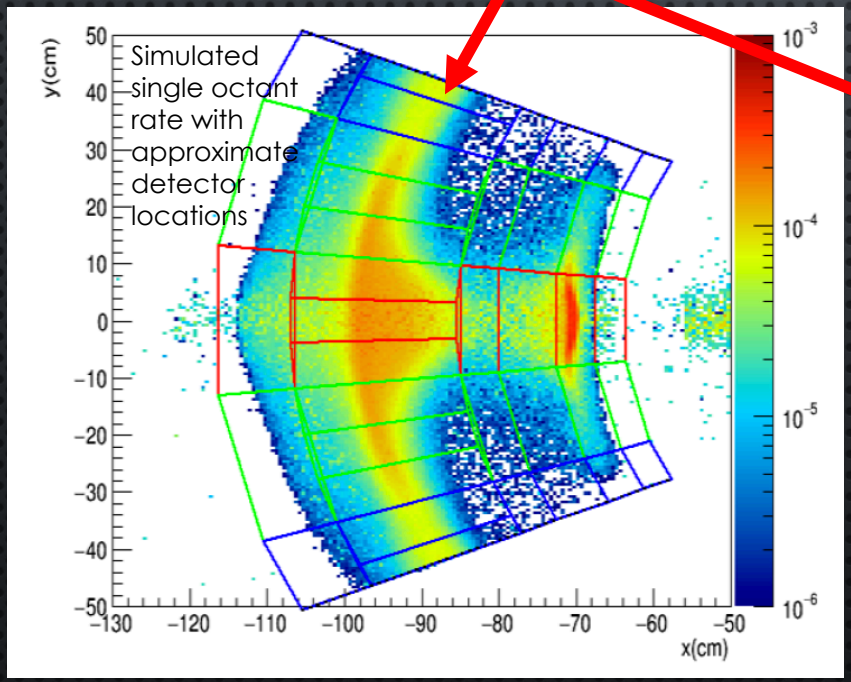


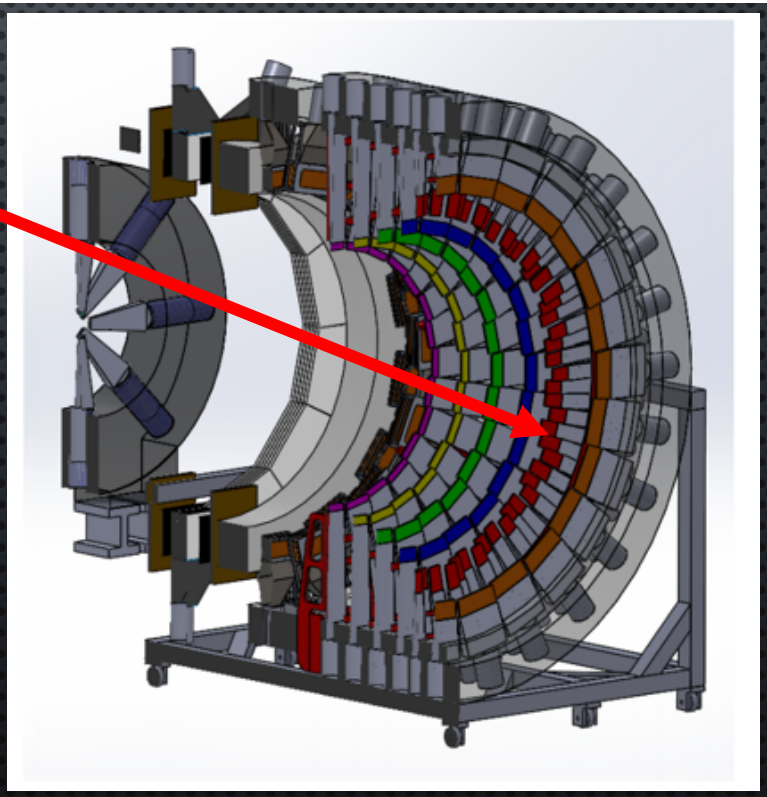


DETECTORS

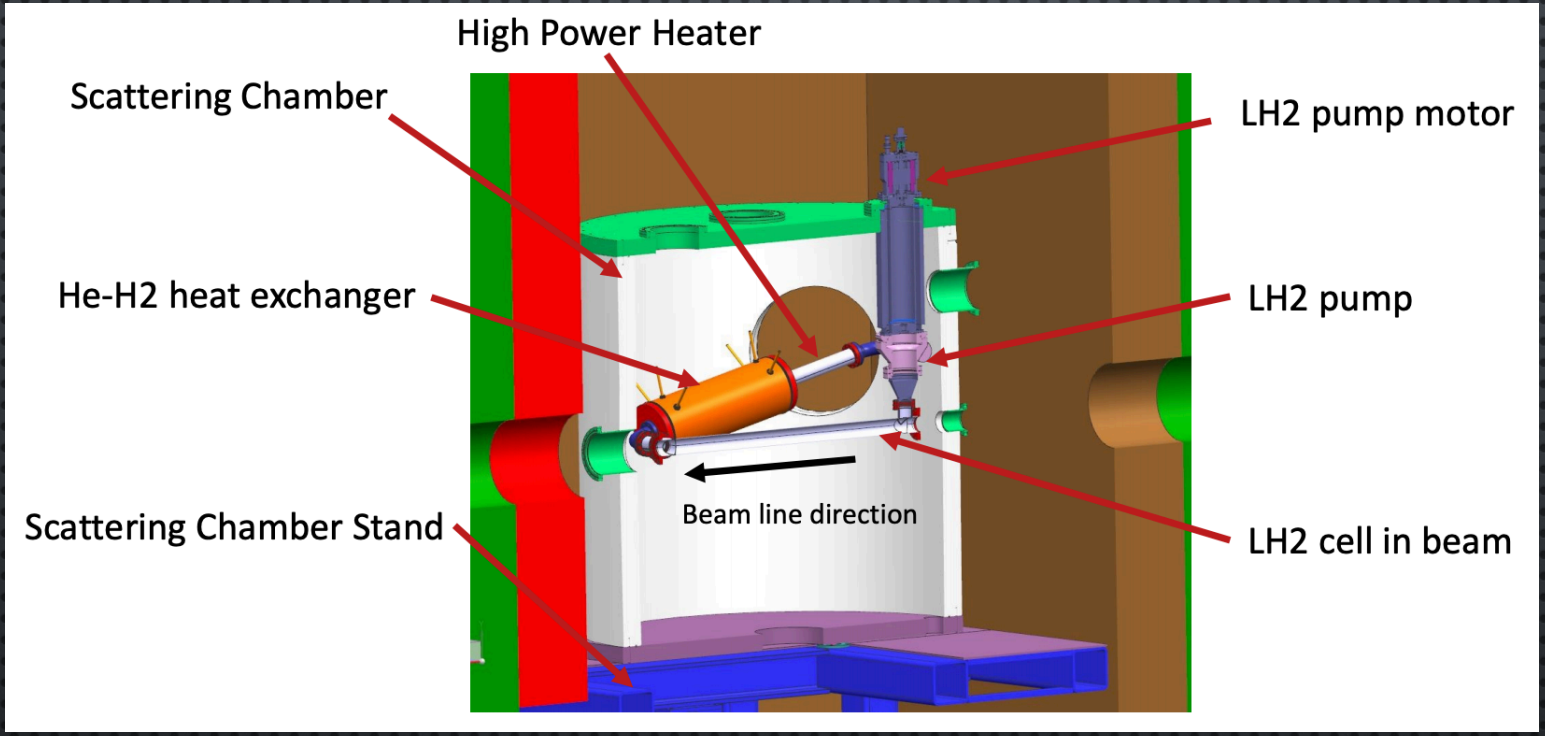
- Six main detector rings over full azimuth measuring different parts of signal
- Integrating in current mode
  - 122 GHz for Moller ring







LIQUID HYDROGEN TARGET

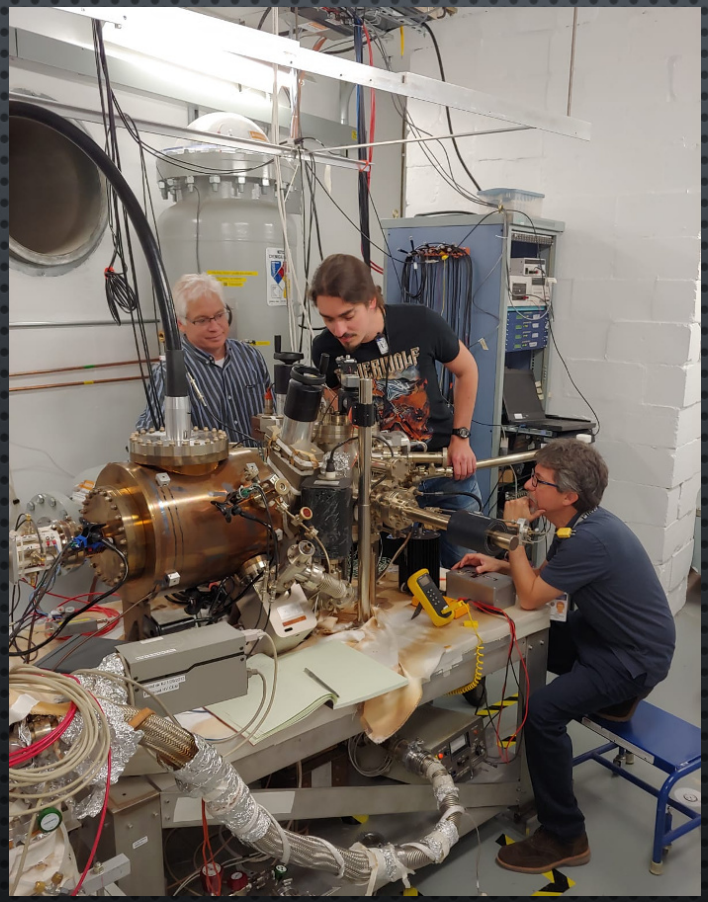


- 1.25 m long target
- Design with extensive CFD expected complete by end of year

- 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**

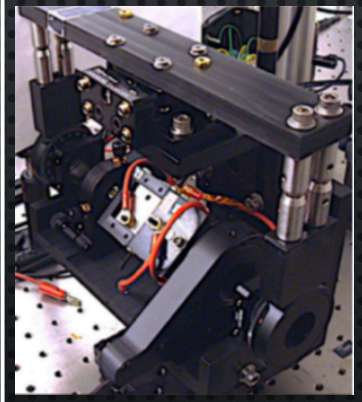


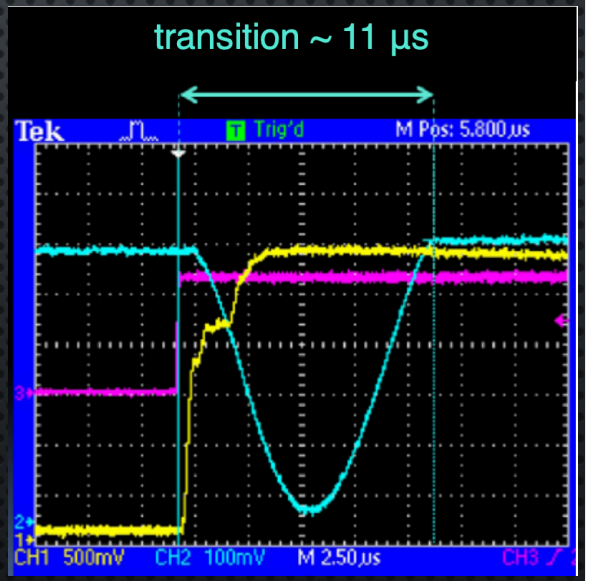
PARITY QUALITY ELECTRON BEAM

- 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

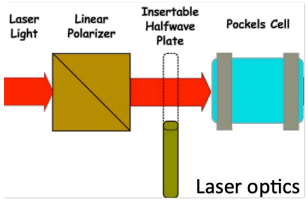
1. Injector upgrade including new Wien filter and 200 keV gun with no RF prebuncher
   - Reduced space charge effects (beam halo)
   - Better matching = adiabatic damping
   - No x/y coupling
2. RTP cell provides ability to feed back on position and intensity differences

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**

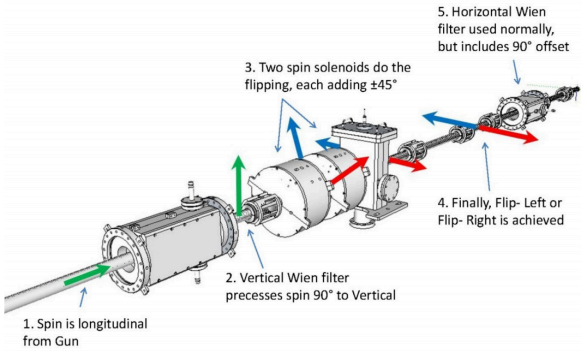
Insertable Halfwave Plate

- 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

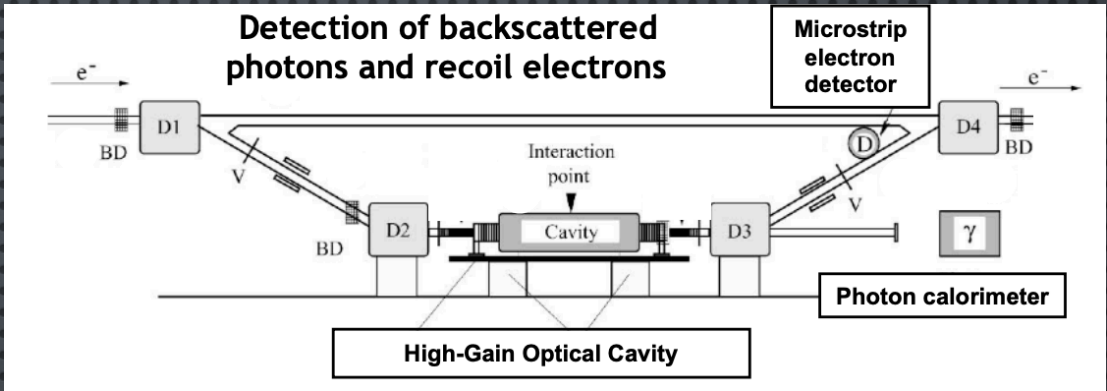
Suppressing:

- electronics pickup
- beam asymmetries
- Spot size asymmetry

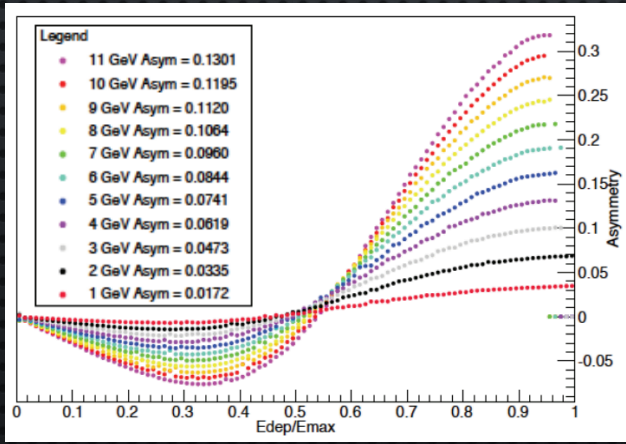
Courtesy K. Paschke

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%

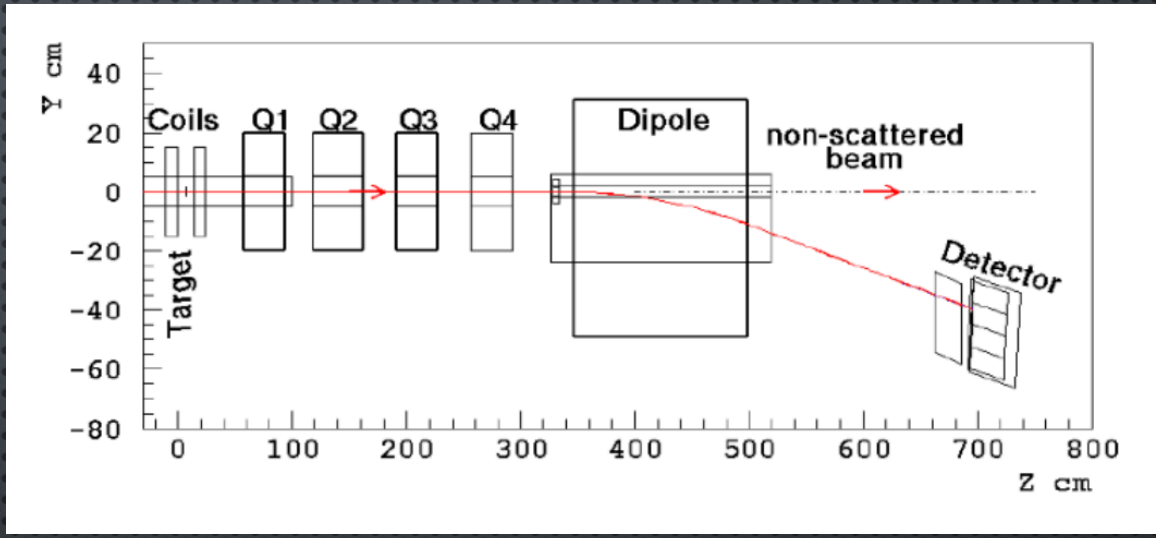
- Elastic ee scattering from a Fe foil polarized | | beam
- Parity conserving Moller asym

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

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

- 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

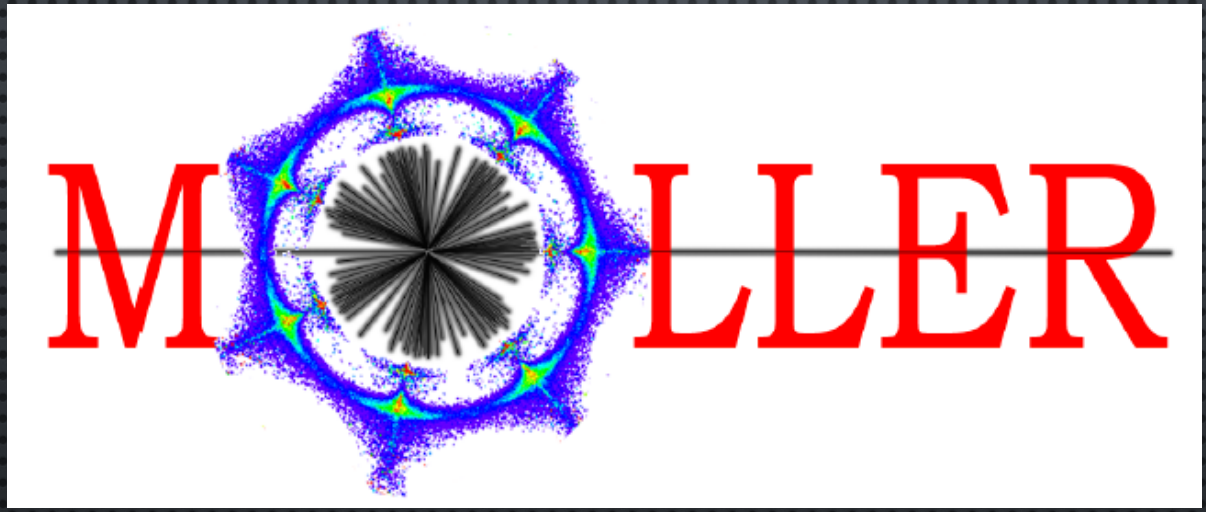
MOLLER Project Team has been very active

- Thanks to the leads who have helped shepherd MOLLER through Several reviews
  - Project Manager: H. Fenker
  - Deputy Project Manager: J. Butler
  - Project Engineer: R. Wines
  - Safety Lead: E. Folts
- The MOLLER collaboration owes much thanks to Howard Fenker who just retired
- Grateful to Steve Woods for stepping in as interim Project Manager
- Jim Fast (currently at PNNL) moving to JLab in May to become permanent Project Manager

STATUS

- Underwent internal conceptual design review dec 12-13, 2019
- Completed director's pre-cd1 review jan 14-16, 2020
- Expect doe cd-1 review to be scheduled soon
- Optimistic to achieve cd-1 status by start of 3rd quarter of fy20

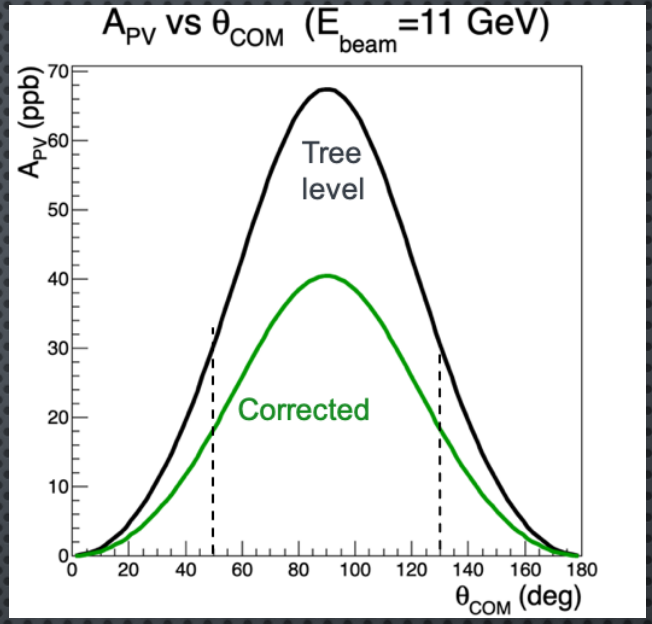
The MOLLER collaboration consists of ~160 authors, 37 institutions from 6 countries

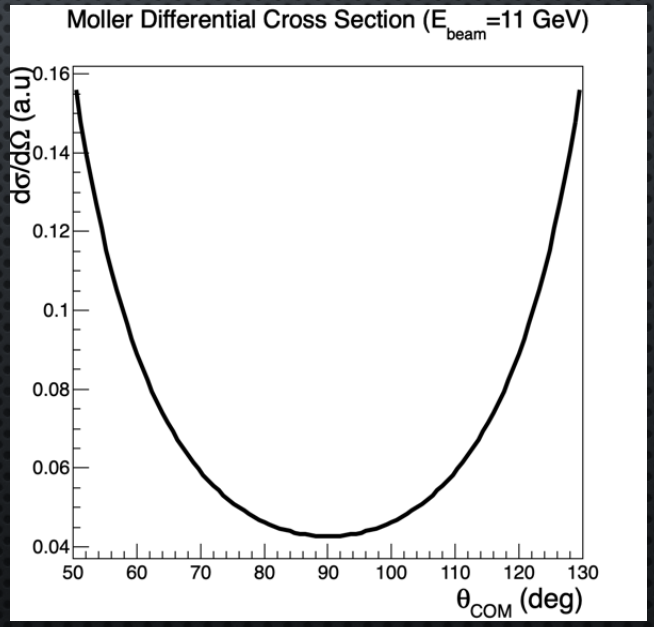


THANK YOU

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

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

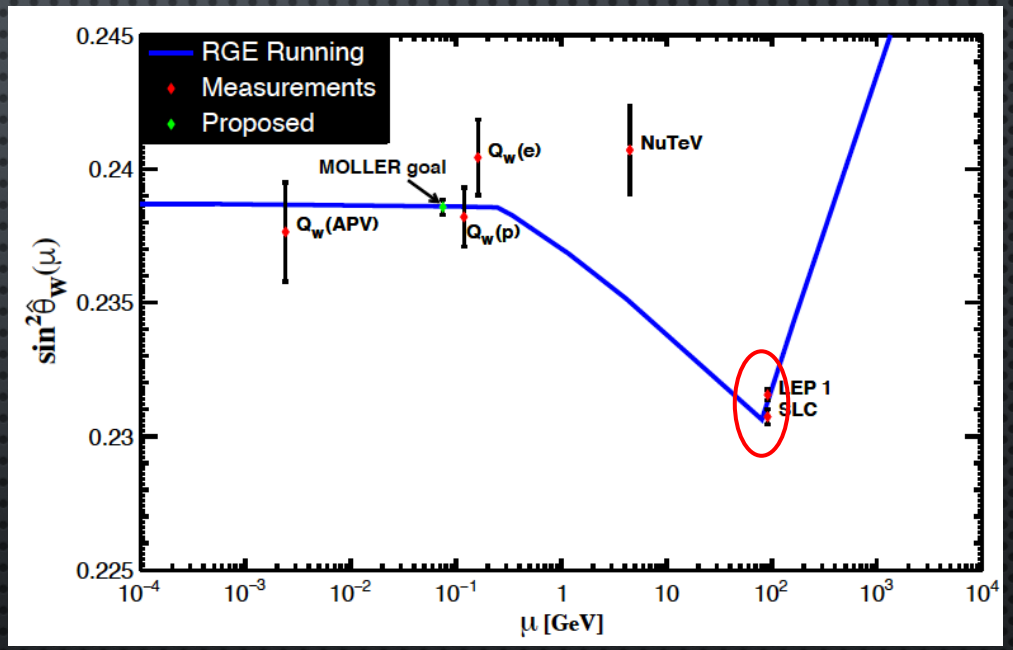
- VARYING SENSITIVITY TO DIFFERENT COUPLINGS
  - MOLLER PART OF LARGER PROGRAM TO PROBE PHASE SPACE OF DIFFERENT MODELS OF NEW PHYSICS
  - WITH $\frac{g}{4\pi} = 1$ AS IN HIGH ENERGY PHYSICS GIVES MOLLER SENSITIVITY TO $\Lambda_{LL}^{ee} = 27$ TEV

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^2 or at collider over next decade.