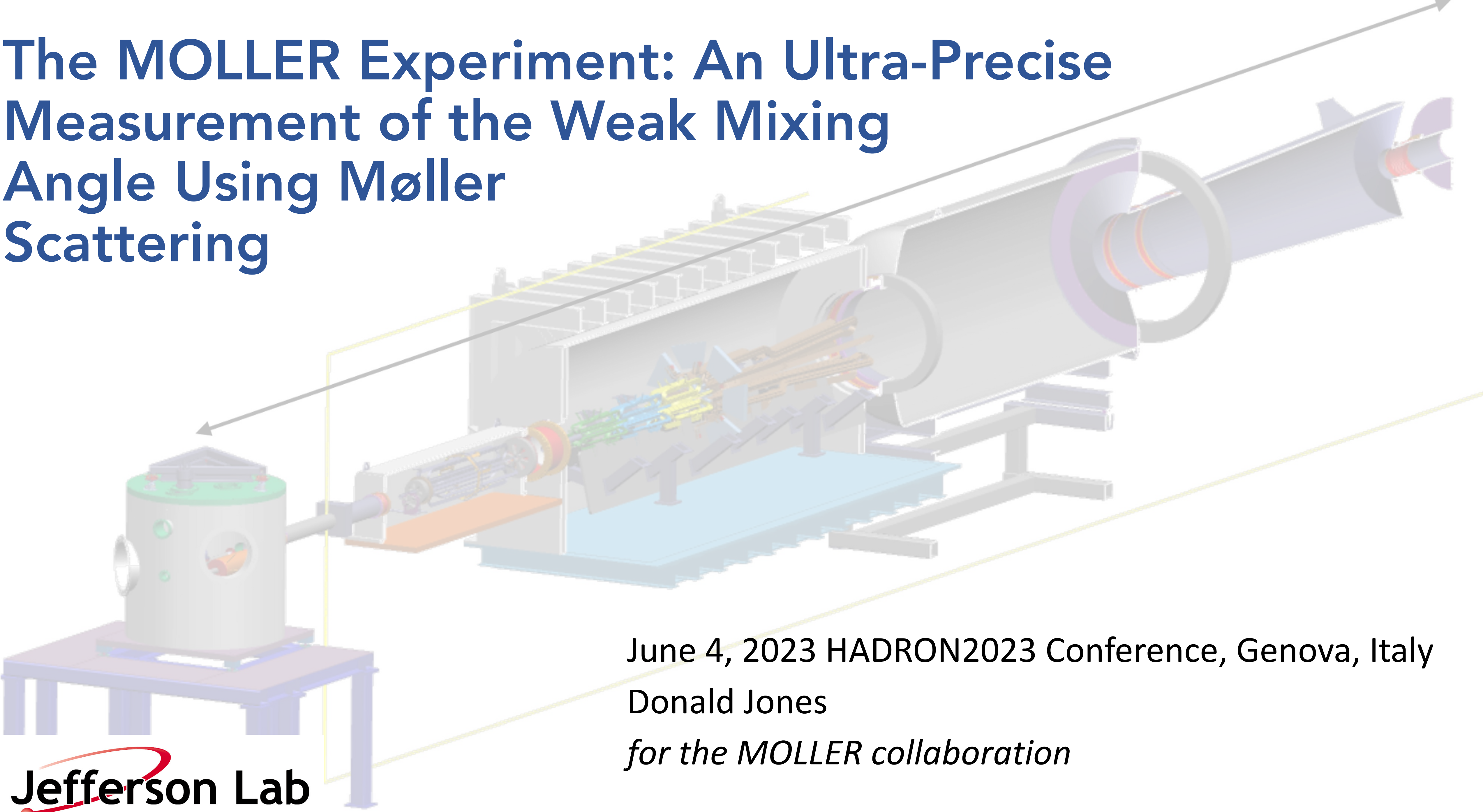
The MOLLER Experiment: An Ultra-Precise Measurement of the Weak Mixing Angle Using Møller Scattering



June 4, 2023 HADRON2023 Conference, Genova, Italy

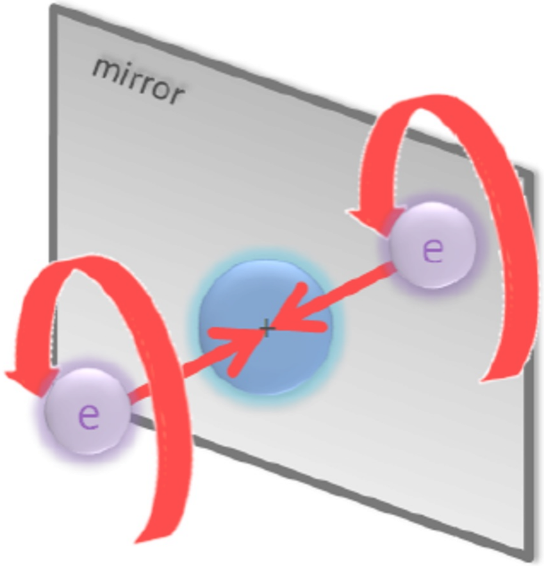
Donald Jones

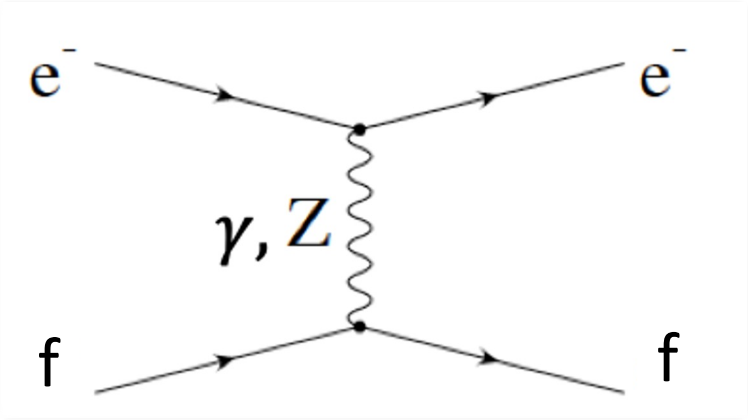
for the MOLLER collaboration

Jefferson Lab

Parity-violating electron scattering

- Parity violation in the Standard Model (SM) is a signature of the weak force only:
- $P(\vec{\mathbf{x}}) = -\vec{\mathbf{x}}$ but in practice a mirror inversion is sufficient
- Parity violation in electron scattering is measured by reversing the electron helicity and measuring the fractional difference in scattering rate, A_{PV}.
- This asymmetry A_{PV} arises from the interference between the electromagnetic and weak neutral current amplitudes and is proportional to the weak (vector) charge of the fermion.





EM term dominates

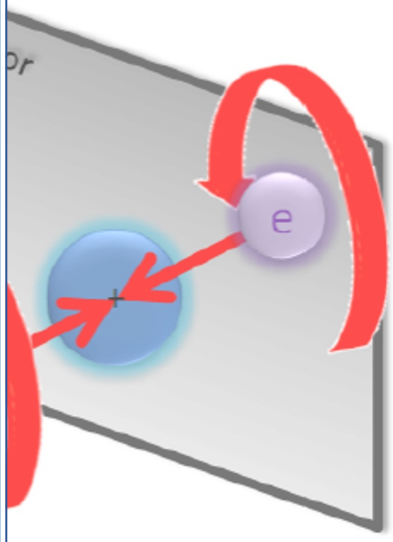
PV term

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

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

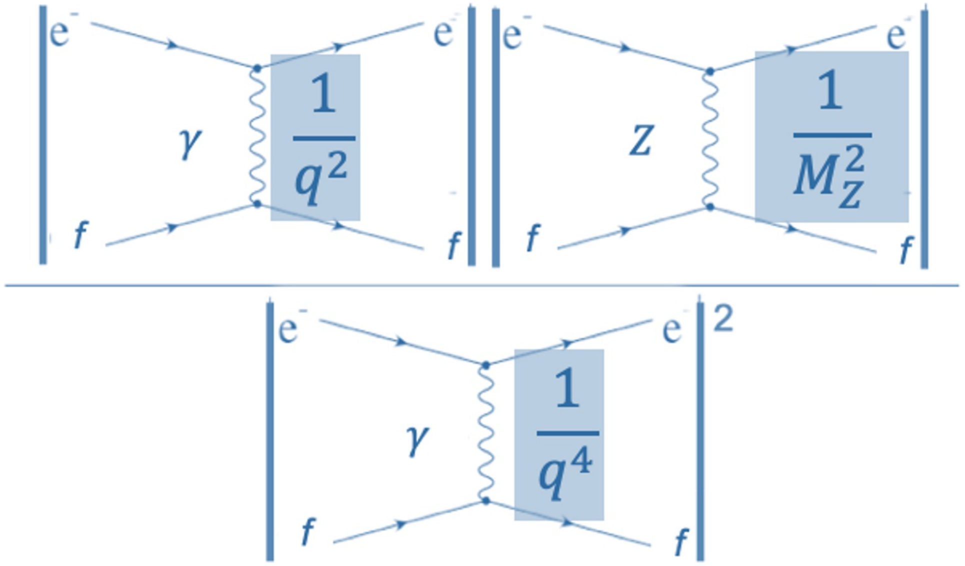
Parity-violating electron scattering

- Parity violation only:
- $P(\vec{\mathbf{x}}) = -\vec{\mathbf{x}}$ but
- Parity violation electron helicit rate, A_{PV}.
- This asymmetr electromagnet proportional to

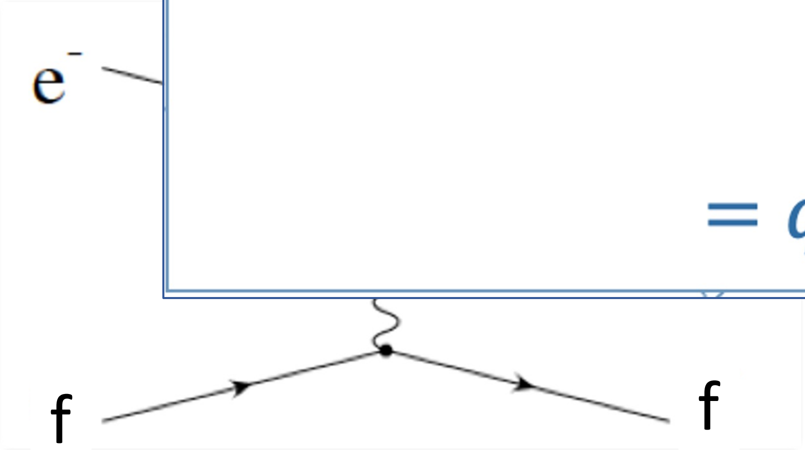


To estimate the size of the asymmetries

A_{PV} ~



$$= q^2\ (GeV^2)\times 10^{-4}$$



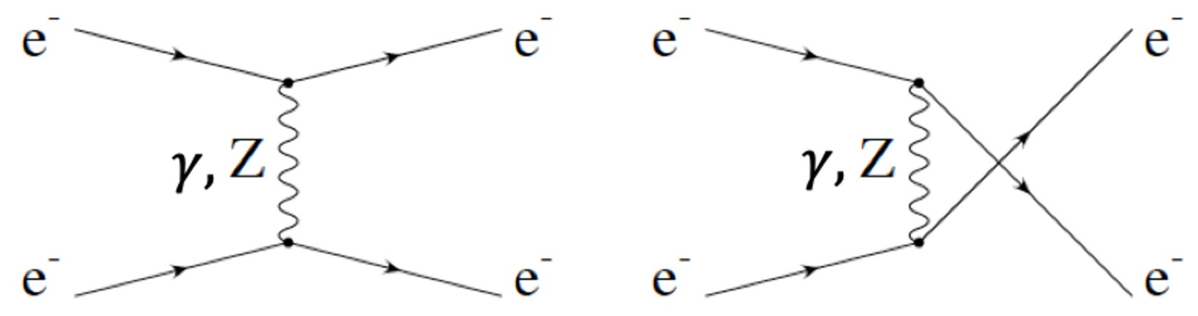
$|^2 + 2M_\gamma^* M_Z$

$\frac{M_Z^{PV}|}{|M_\gamma|^2} \propto Q_W$

Parity-violating Moller scattering

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \quad \text{(tree level)}$$

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



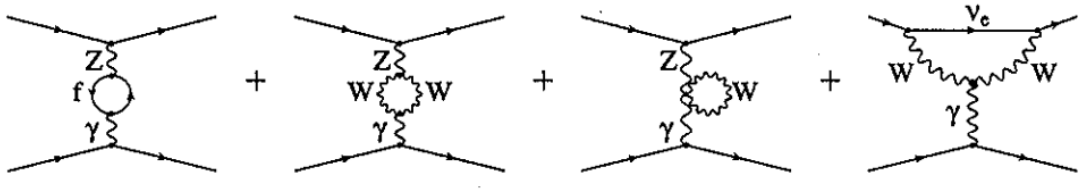
APV directly probes the weak charge which in the SM determines the weak mixing angle.

- Weak charge of electrons and protons is accidentally suppressed in the SM due to proximity of $\sin^2\theta_W$ to ¼.
- Provides an optimal place for precision tests of the SM
- For MOLLER 2.4% error on APV provides a measurement of $\sin^2\theta_W$ at 0.12% ($\pm$0.00028)
- SM prediction for $\sin^2\theta_W$ known to much higher precision

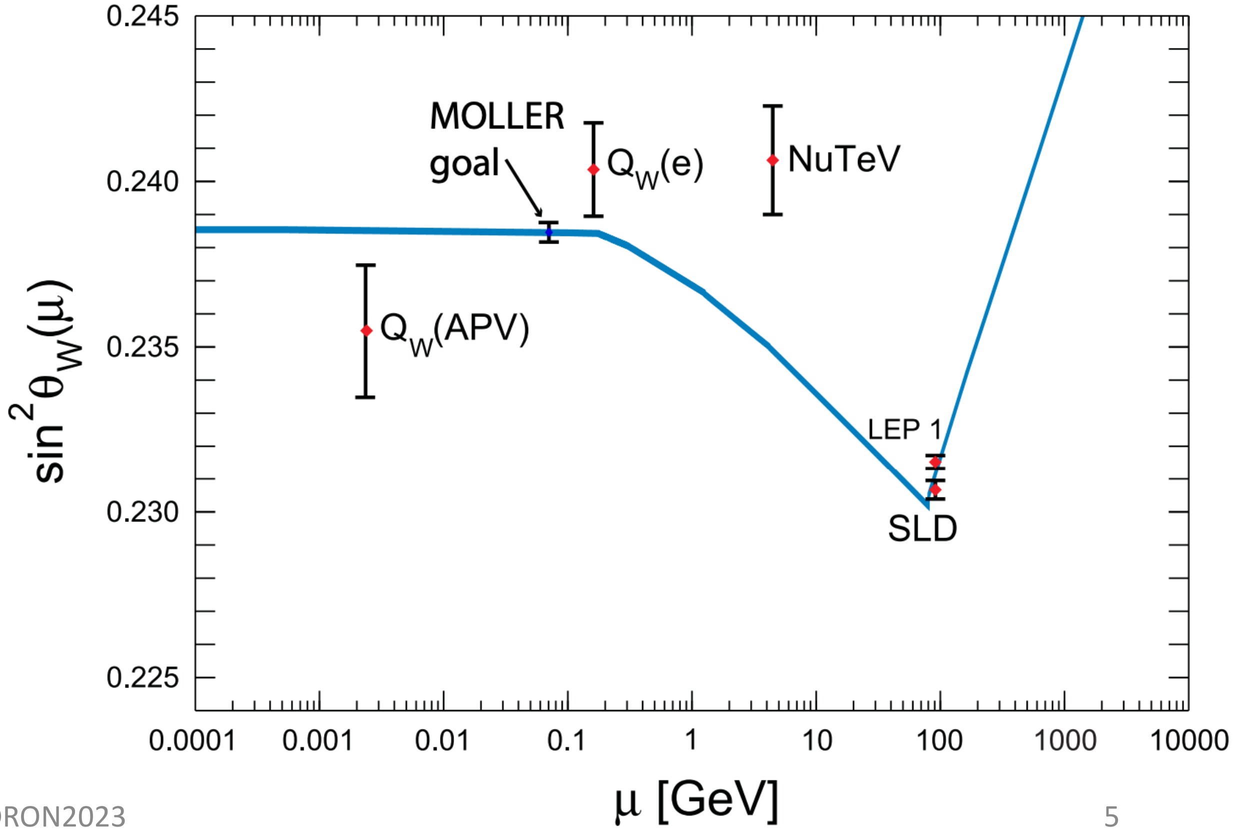
Particle	q_{EM}	$g_V = Q_w/2$
e^-	-1	$-\frac{1}{2} + 2\sin^2\theta_W$
u	$\frac{2}{3}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$
d, s	$-\frac{1}{3}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$
p	1	$\frac{1}{2} - 2\sin^2\theta_W$
n	0	$-\frac{1}{2}$

Running of $\sin^2\theta_W$

- Defining $\sin^2\theta_W = \frac{g'^2}{g^2+g'^2}$ in terms of weak and EM running couplings done in renormalization schemes like $\overline{\text{MS}}$
- Vacuum polarization diagrams and other quantum corrections absorbed into couplings makes makes $\sin^2\theta_W$ "run" with mass scale
- At Z-pole measuring SM Z-boson properties → low sensitivity to new physics
- Off Z-pole sensitivity to new (PV) physics is in the quantum loops
- MOLLER precision matches the best Z-pole measurement!



Weak mixing angle running in $\overline{\text{MS}}$ renormalization scheme



Running of $\sin^2\theta_W$

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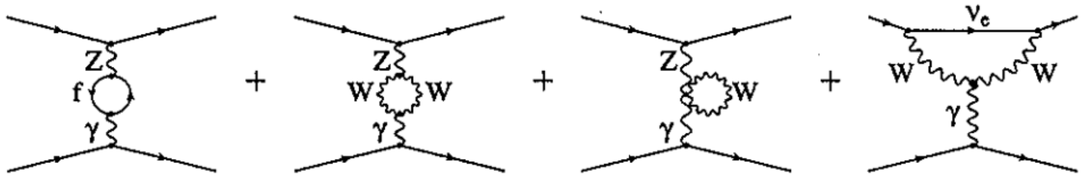
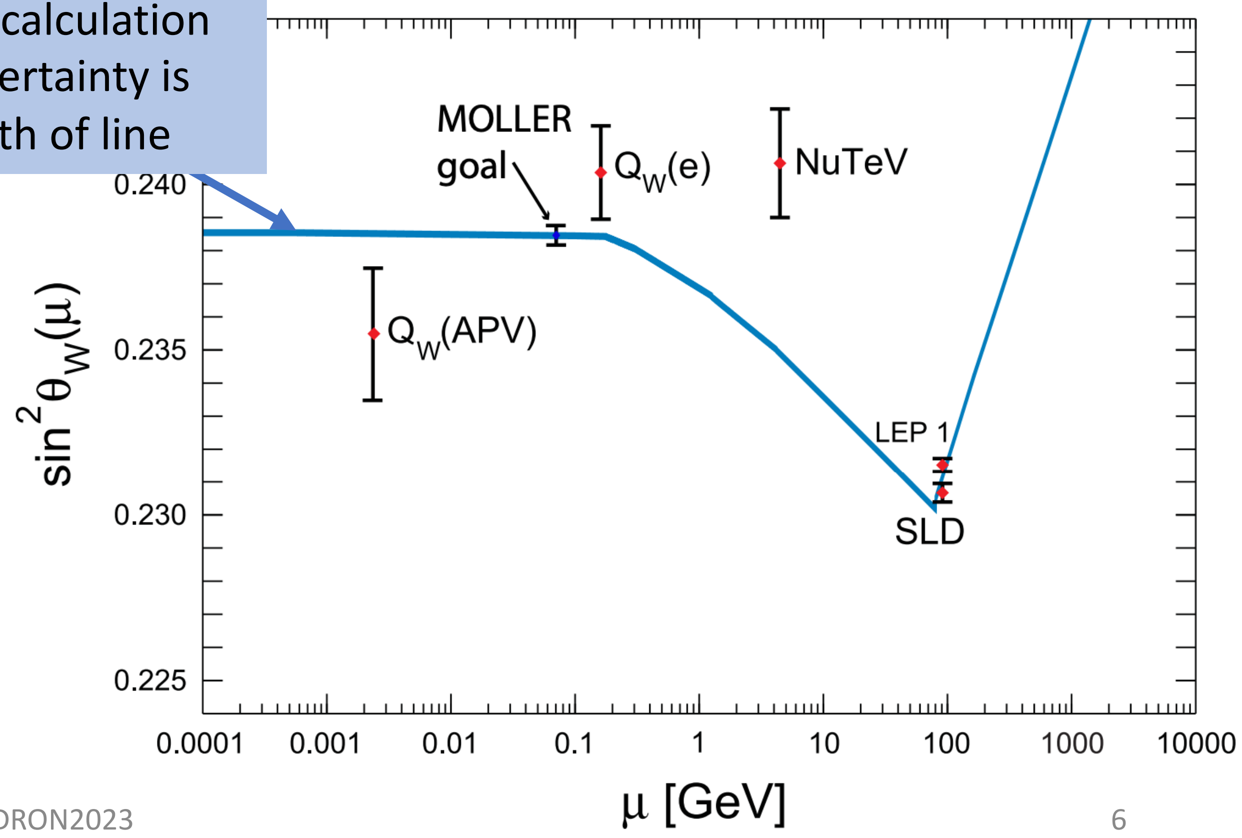


Weak mixing angle running in $\overline{\text{MS}}$ renormalization scheme

SM calculation uncertainty is width of line

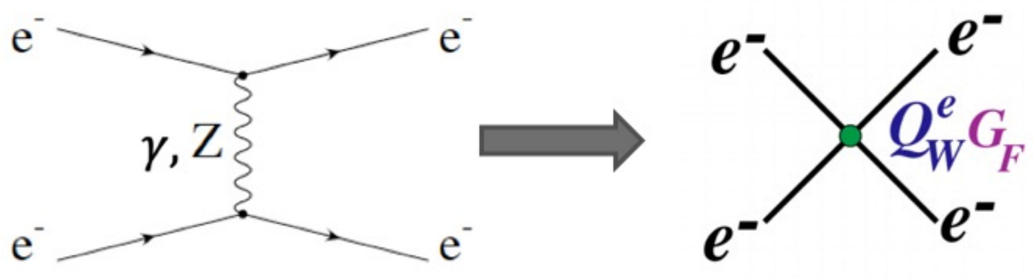


Sensitivity to New Physics at TeV scales

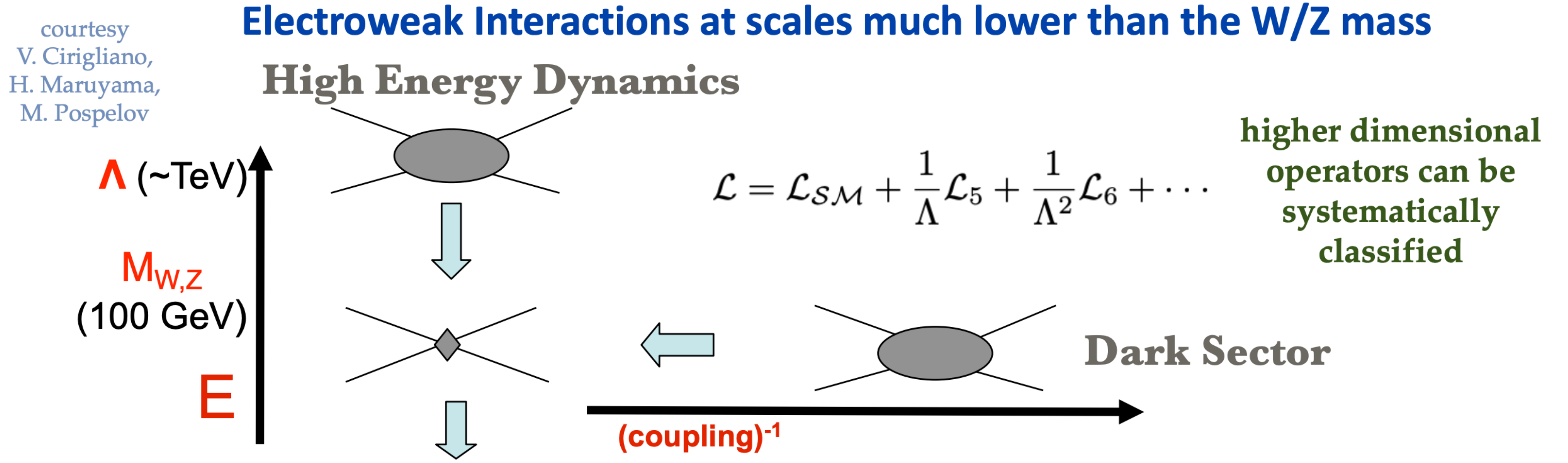
Well off the Z-pole ($Q^2 \ll M_Z$) interactions modeled as contact interactions with new physics entering in loops at $\frac{g}{\Lambda}$ (mass scale Λ, coupling g)

$$\frac{\delta A_{PV}}{A_{PV}} = 2.4\% \longrightarrow \qquad g\sim 1 \longrightarrow \Lambda \sim 7 \text{ TeV}$$

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



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



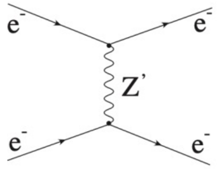
Heavy Z's, light (dark) Z's, L-R models, compositeness, extra dimensions, SUSY…

Slide courtesy K. Kumar to illustrate thinking on MOLLER reach for various new physics scenarios

New (Low Energy) Physics Examples

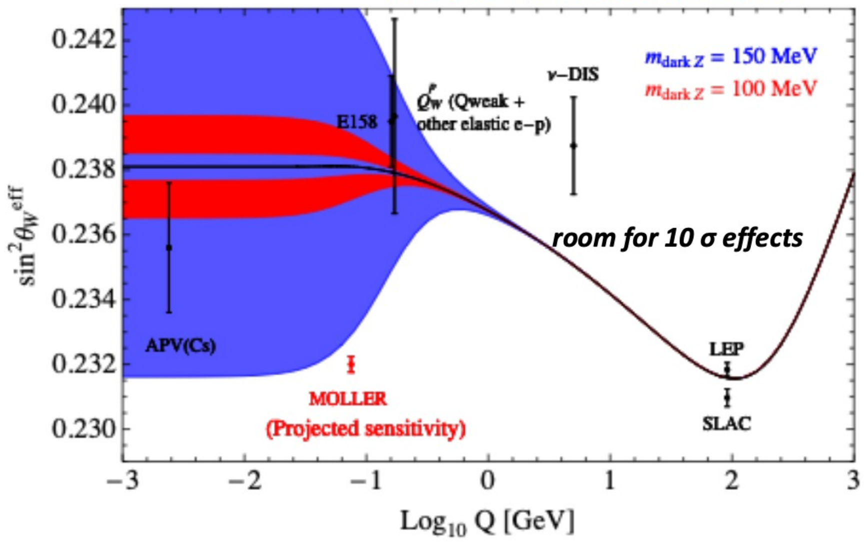
Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential



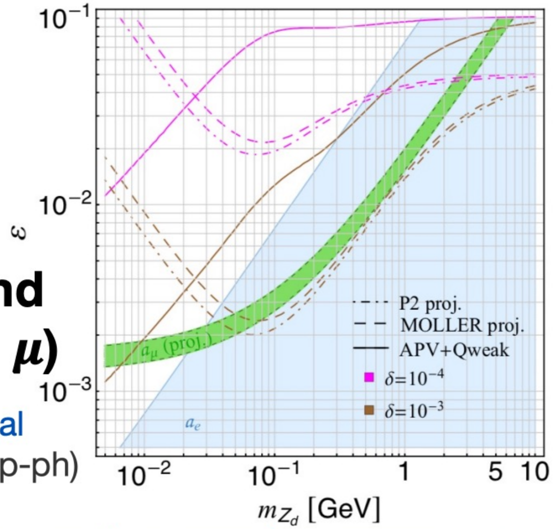
Heavy Photons (A' mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano

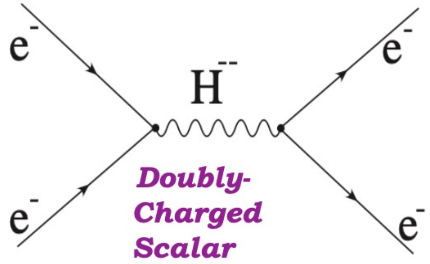


Specific Scenario folding in Cs APV and g-2 (e and μ)

M. Caddedu et al
2104.03280 (hep-ph)



Lepton Number Violation

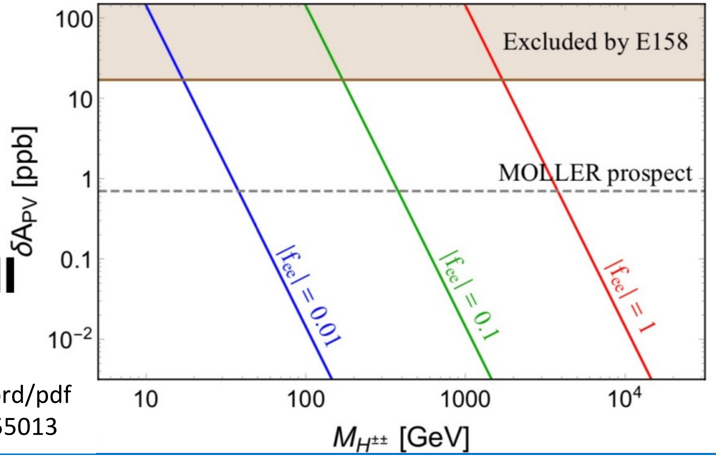


$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\frac{|h_{ee}|^2}{(M_\Delta/1\ \text{TeV})^2}$$

Cirigliano et al
Phys.Rev. D70 (2004) 075007

5 σ for h_{ee} ~ 1 and M_Δ ~ 1 TeV

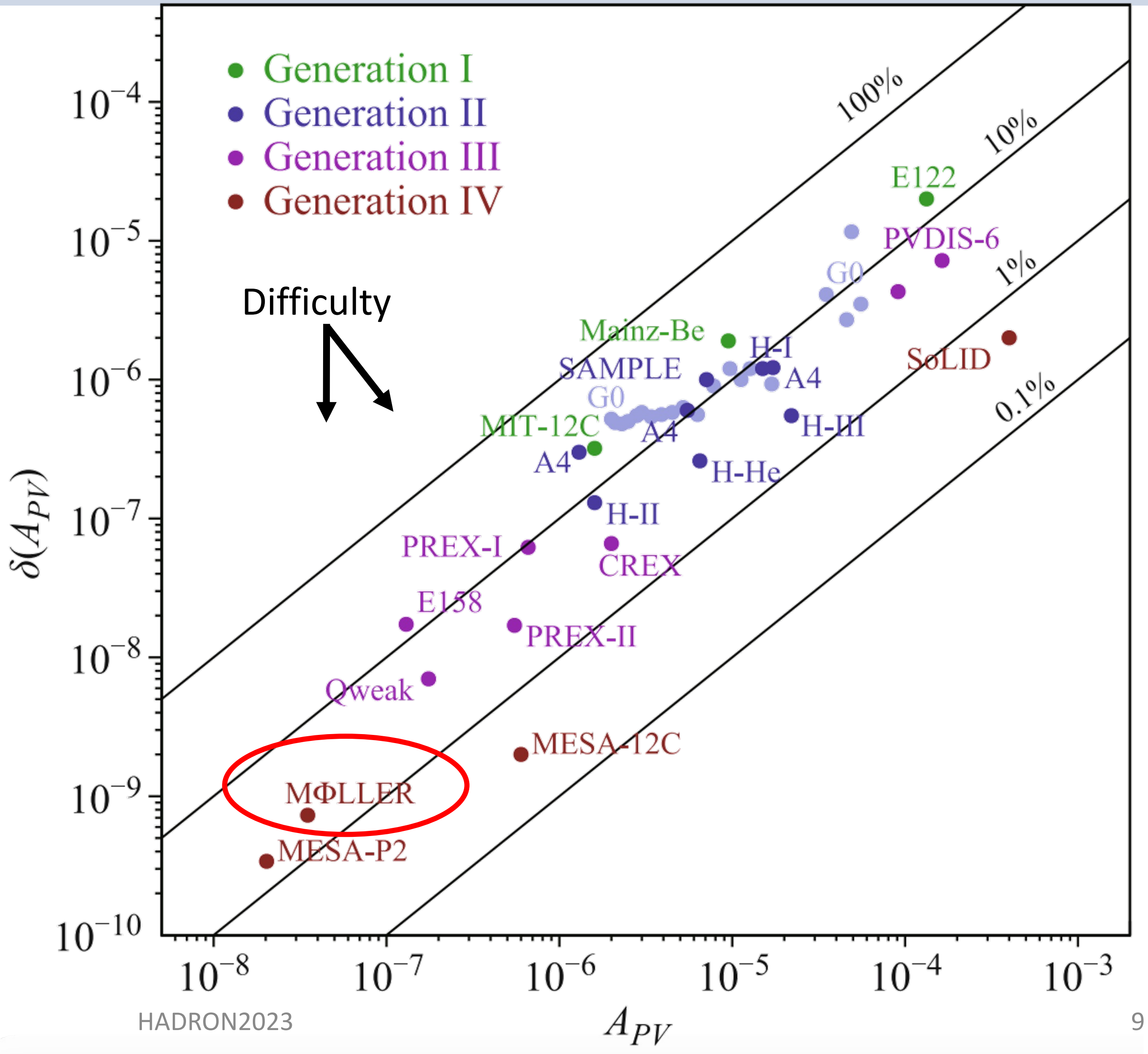
Specific Scenario for Type-II SeeSaw



https://journals.aps.org/prd/pdf/10.1103/PhysRevD.98.055013

PVES past and proposed

Range of >4 orders of magnitude in size and uncertainty



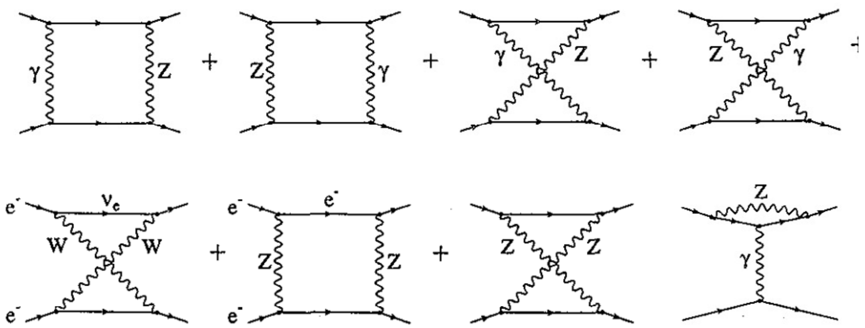
Parity-violating Moller scattering

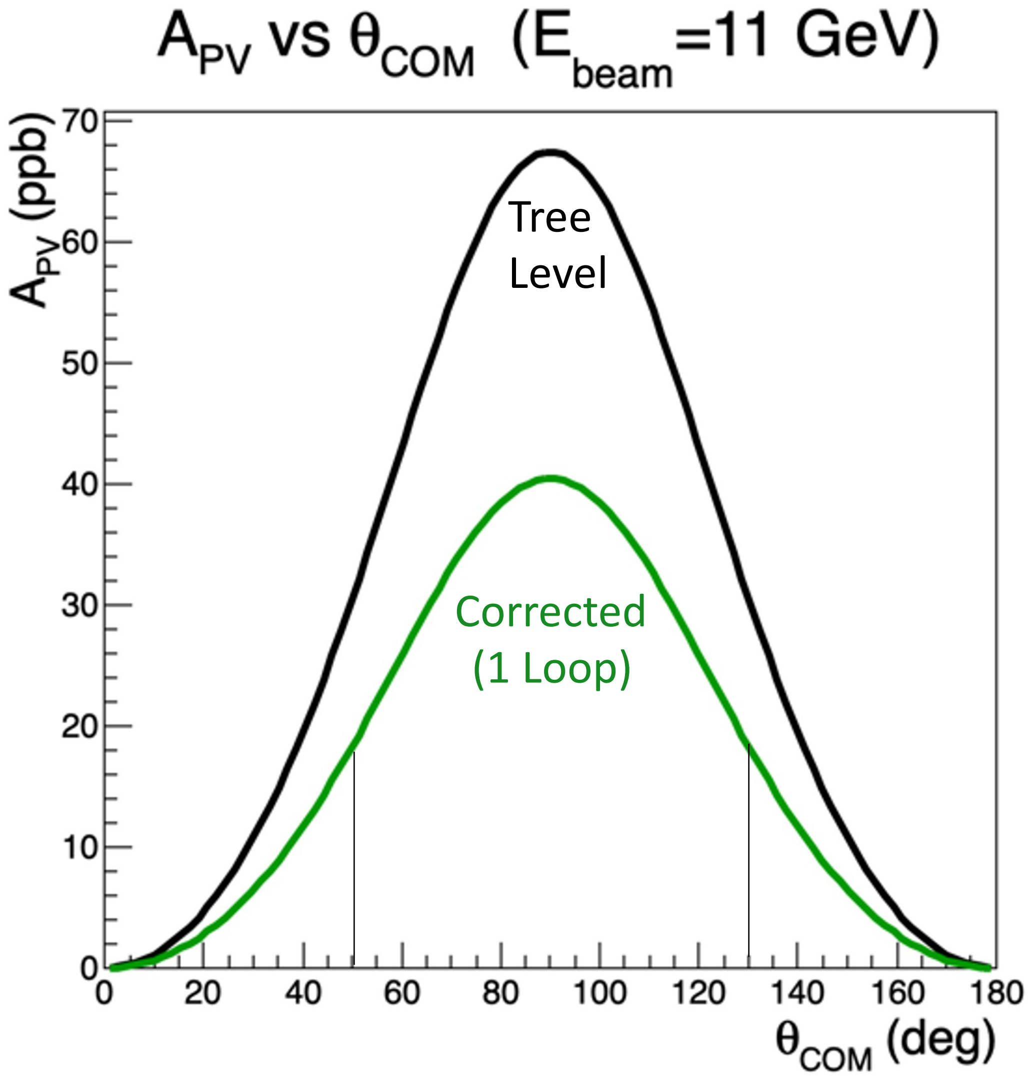
tree level — 1 loop EW corrections

$$Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075 \longrightarrow 0.0435$$

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

2 Loop corrections calculations required for accuracy of MOLLER and are underway!





MOLLER (Measurement Of A Lepton-Lepton Electroweak Reaction)

$A_{PV} = 35.6$ *ppb*

$\delta(A_{PV}) = 0.73$ *parts per billion*

$\delta(Q^e_W) = \pm 2.1\ \%\ (stat) \pm 1.0\ \%\ (syst)$

$\langle Q^2 \rangle = 0.0056\ \mathrm{GeV}^2$

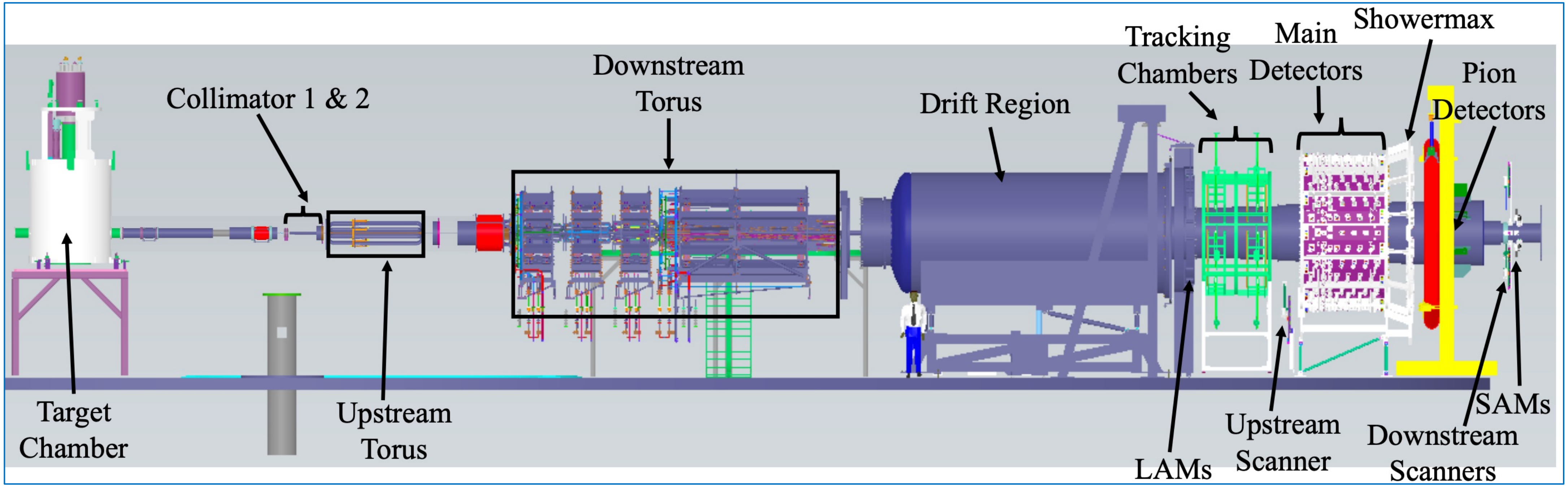
signal rate: 134 GHz

run time: 8200 hours

~$3\mathrm{x}10^{18}$ electrons detected

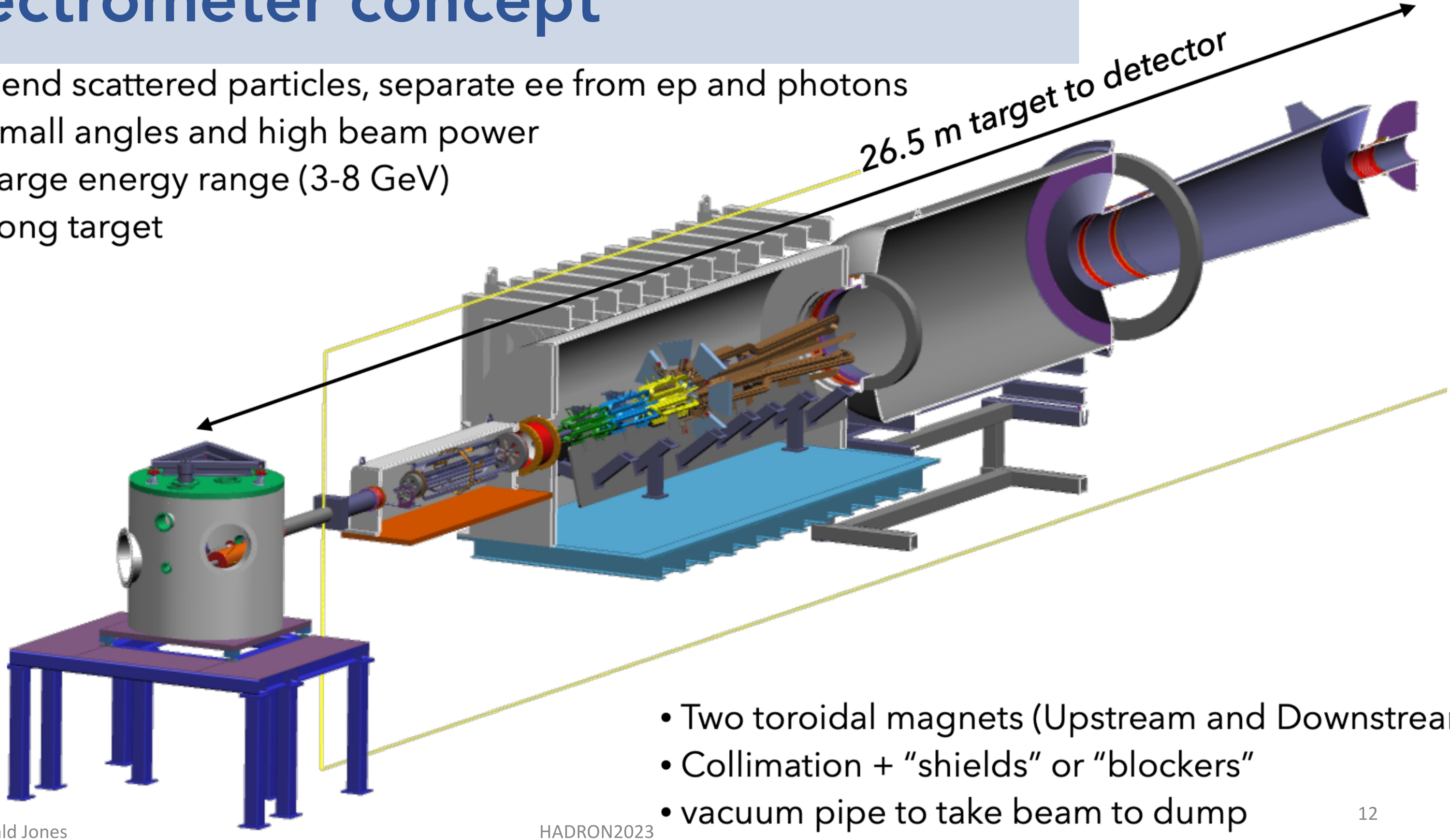
Target 1.25m long LH2

65 μA electron beam 85% polarized



Spectrometer concept

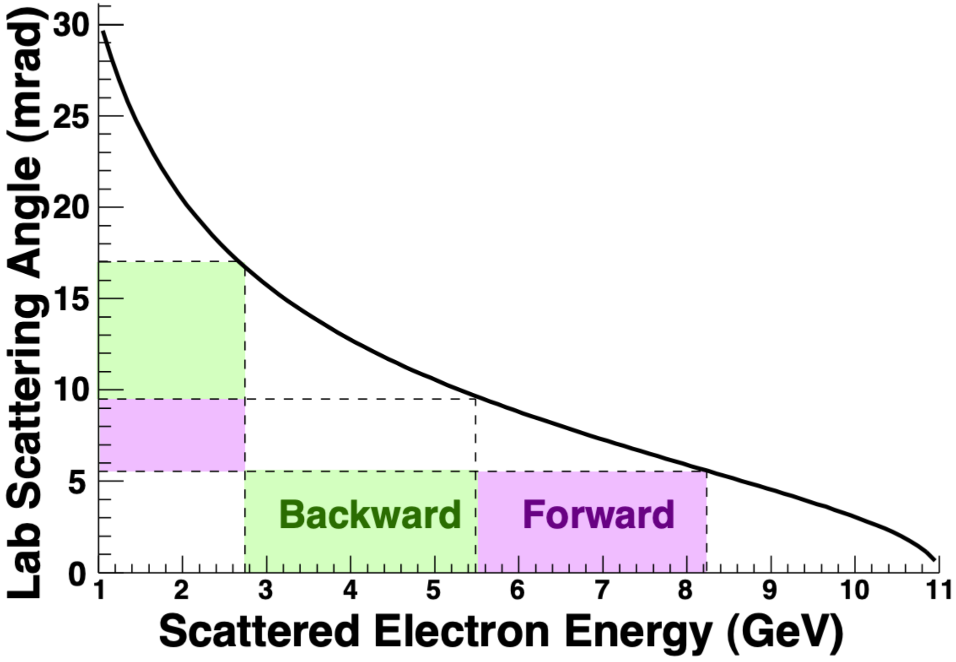
- Bend scattered particles, separate ee from ep and photons
- Small angles and high beam power
- Large energy range (3-8 GeV)
- Long target

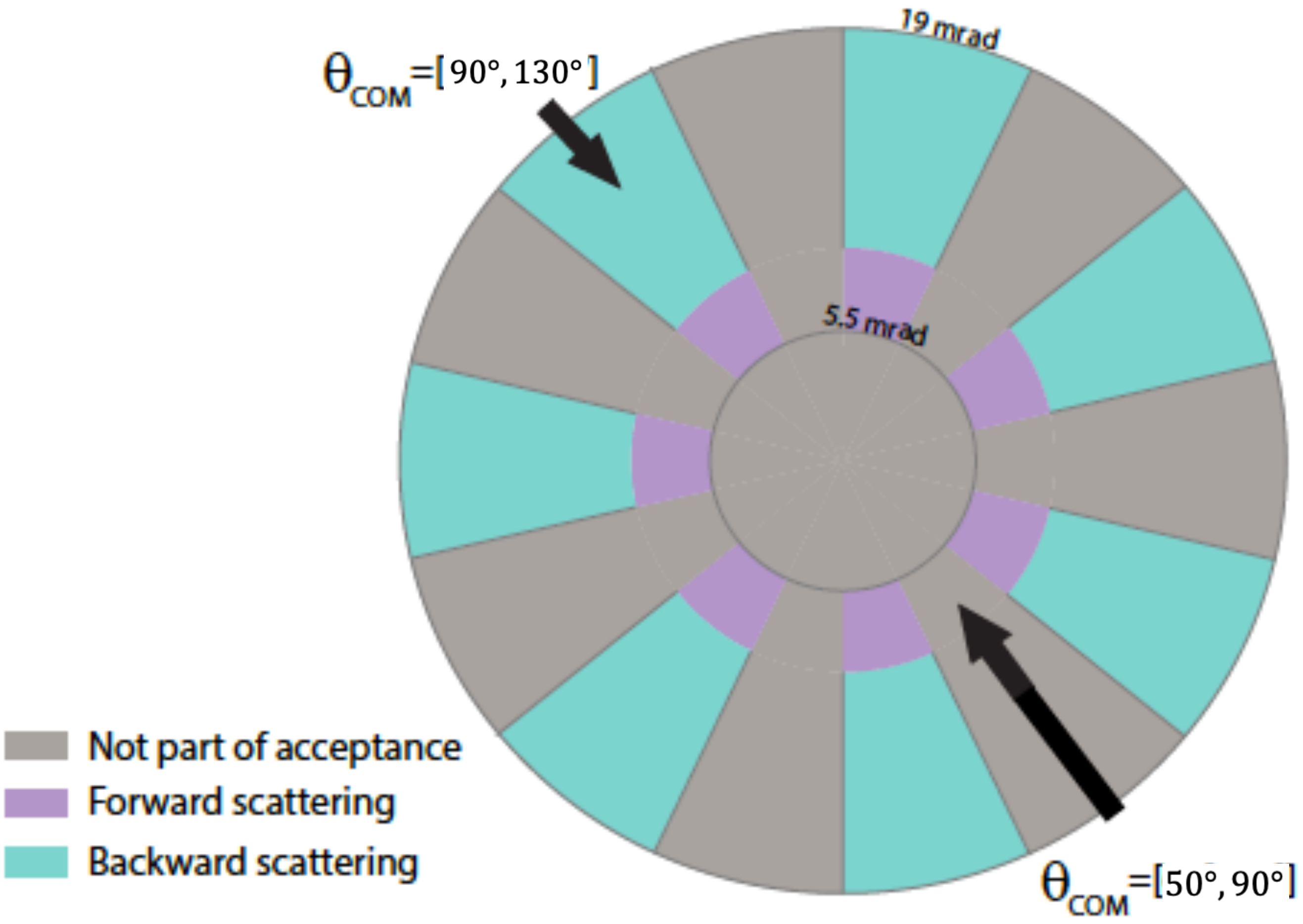


- Two toroidal magnets (Upstream and Downstream)
- Collimation + "shields" or "blockers"
- vacuum pipe to take beam to dump

Heptagonal spectrometer design

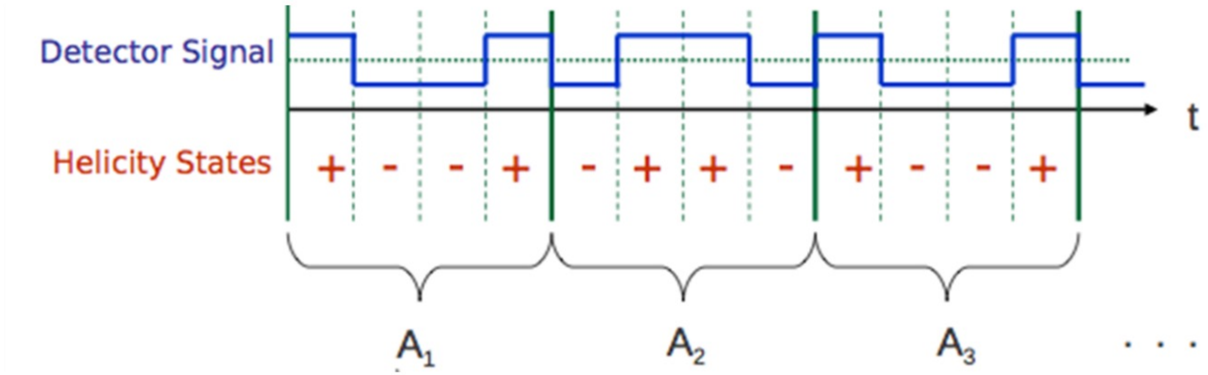
- Provides open and blocked sectors directly opposite each other
- Effective full azimuthal acceptance due to identical particles accept one from each scattered pair either backward or forward
- Acceptance:
  - $\theta_{COM} = 50° - 130°, \theta_{LAB} = 0.26° - 1.2°$





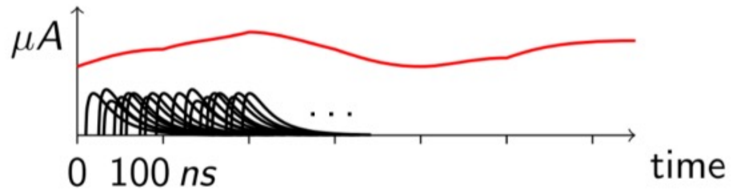
Measuring the tiny asymmetry

Rapid (2kHz) helicity reversals



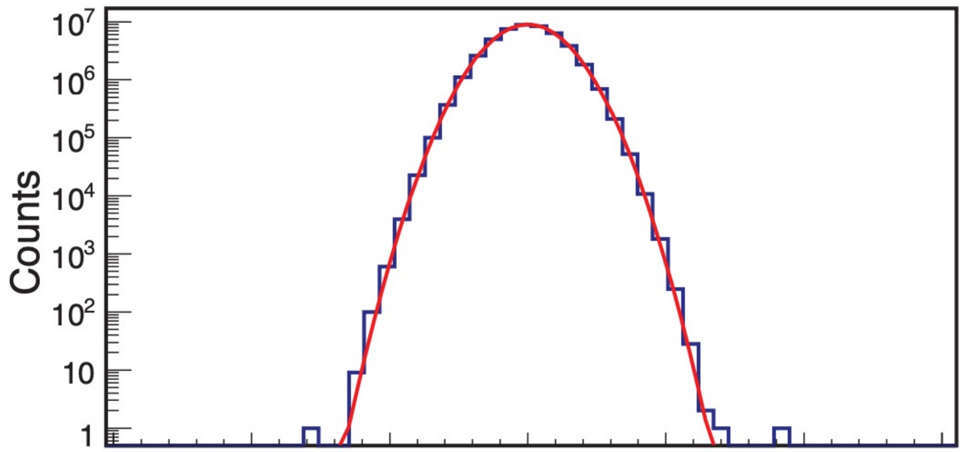
134 GHz MOLLER rate→can't count events so…

Analog integrate detector current



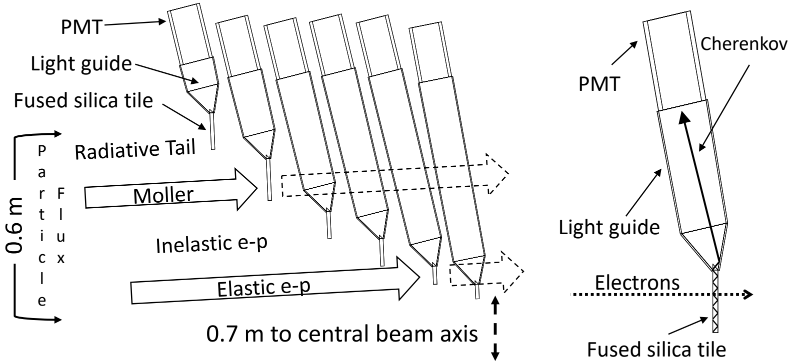
Form an asymmetry over the helicity reversal

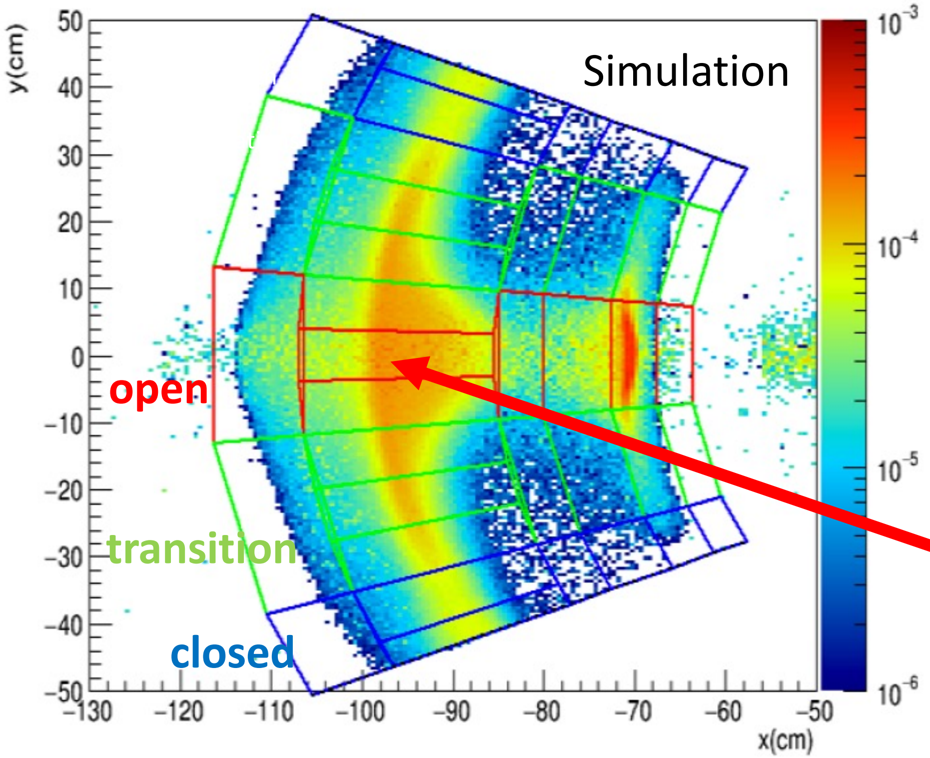
Measure to 0.01% at 1 kHz,
repeat for a year straight (8200 hrs)

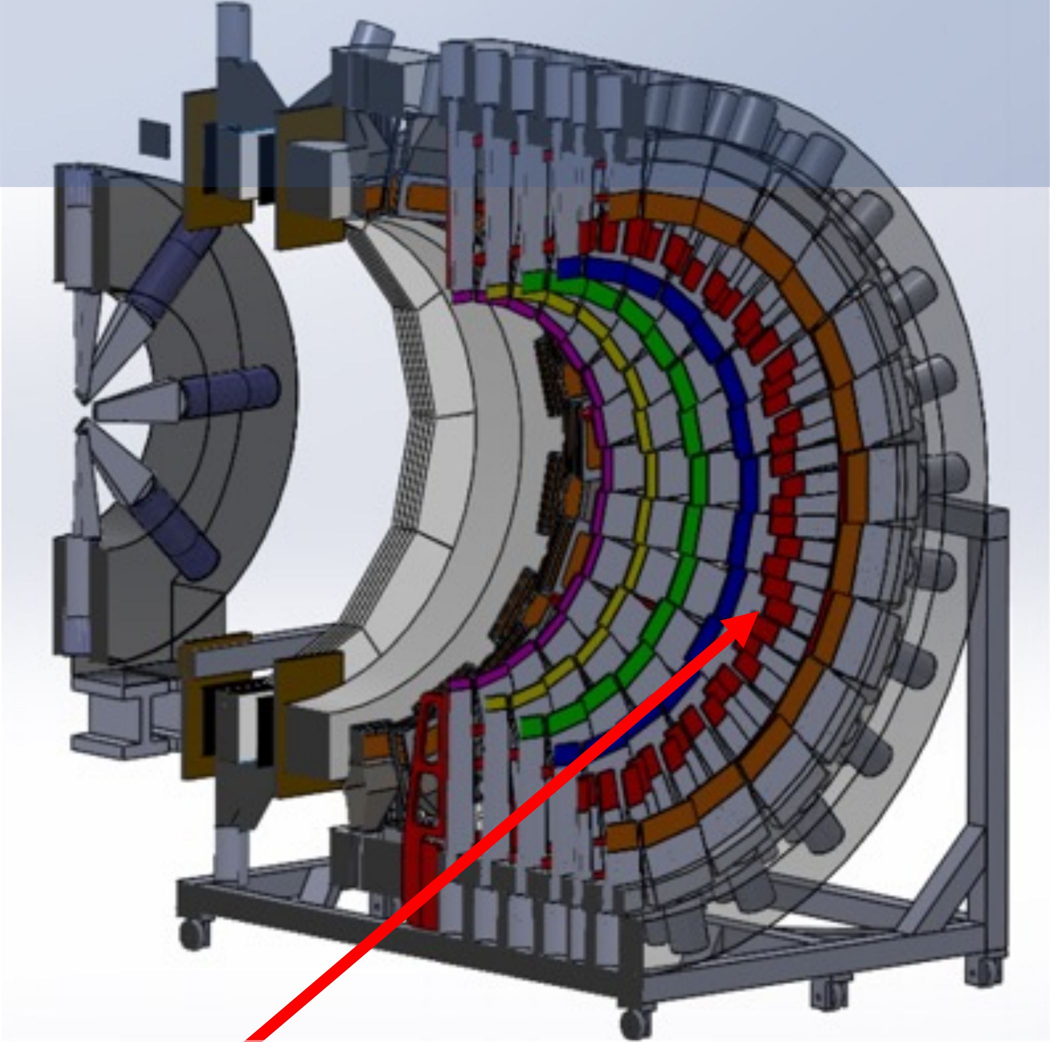


- Backgrounds must be determined and removed
- Measure and remove pedestal signal
- Careful to isolate from spurious asymmetries arising from things like electronic pickup
- Lots of built up experience so known failure modes will be monitored 24/7

Main detector rings





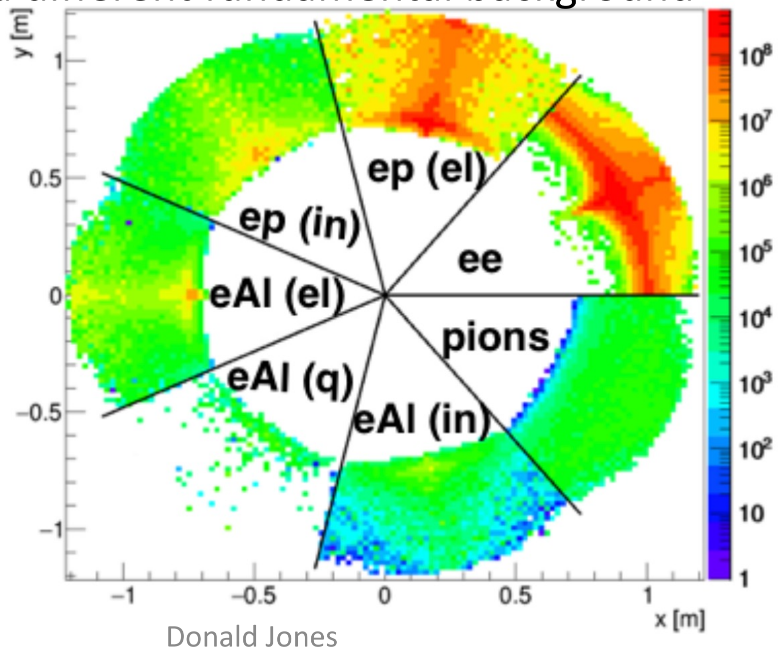


- Six main detector rings over full azimuth measuring different parts of signal and background
- Integrating in current mode
  - Ring 5 primary Moller signal @ 134 GHz

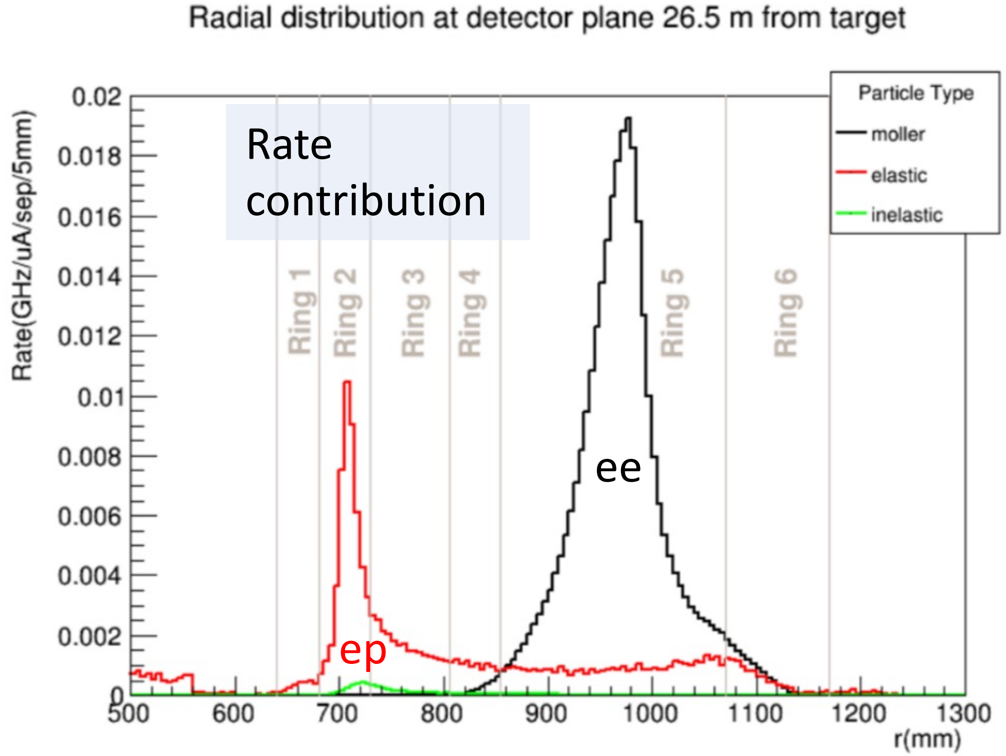
Background distributions on the detector

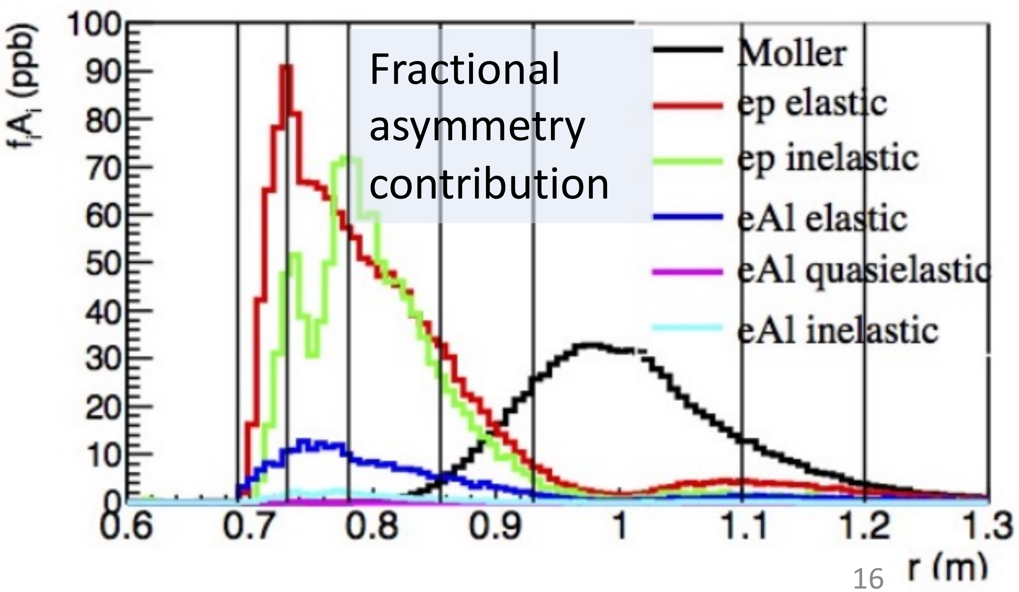
Various sources of background from the target that make it through the spectrometer to the detector

Illustration with each septant showing a different fundamental background



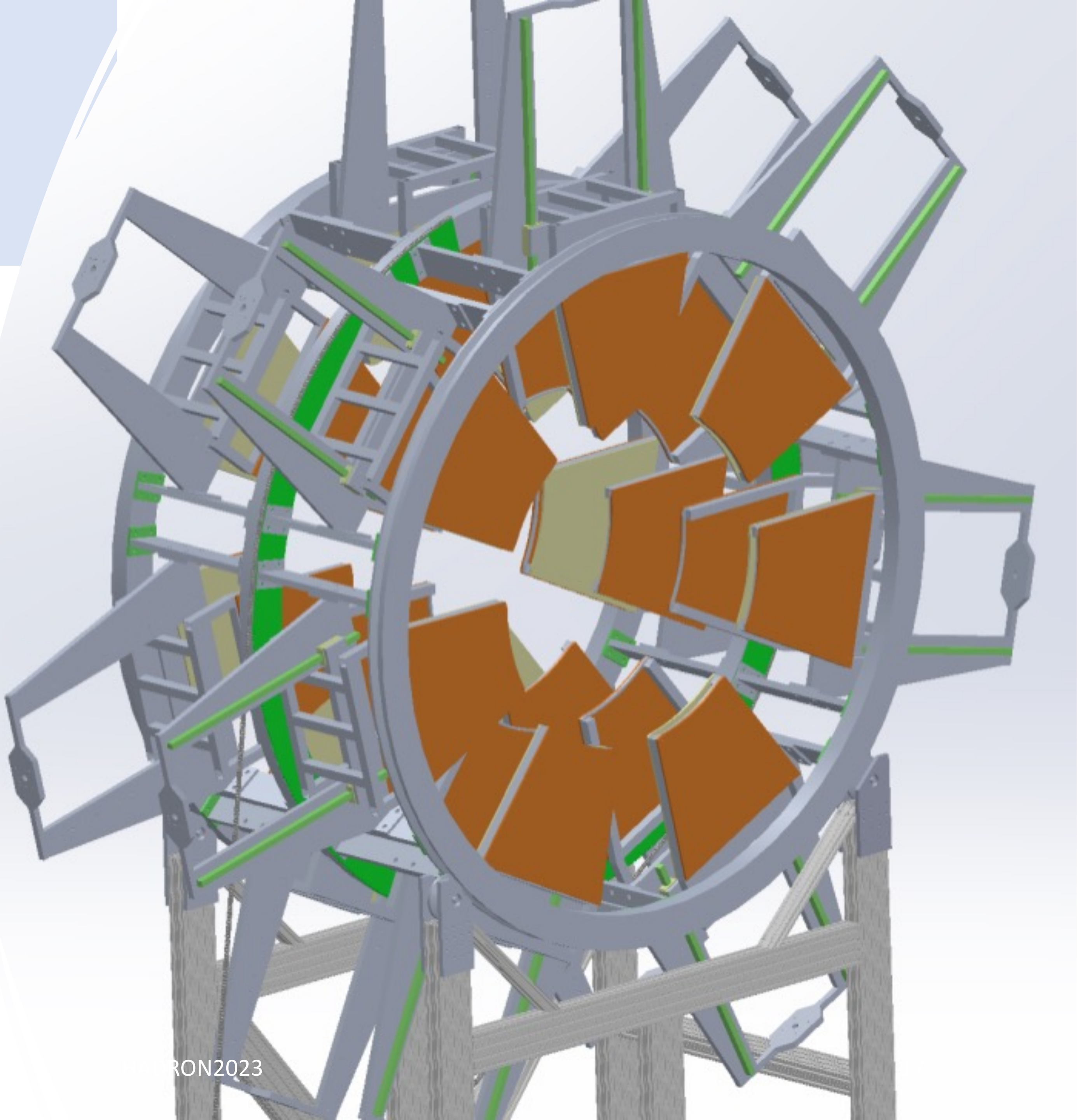
Must understand backgrounds and their contributions to the measured asymmetry and deconvolute from signal





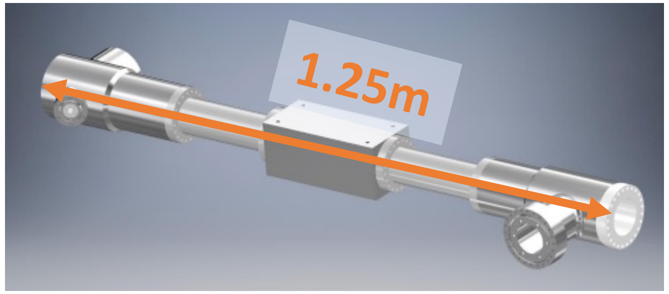
GEM high-rate tracking planes

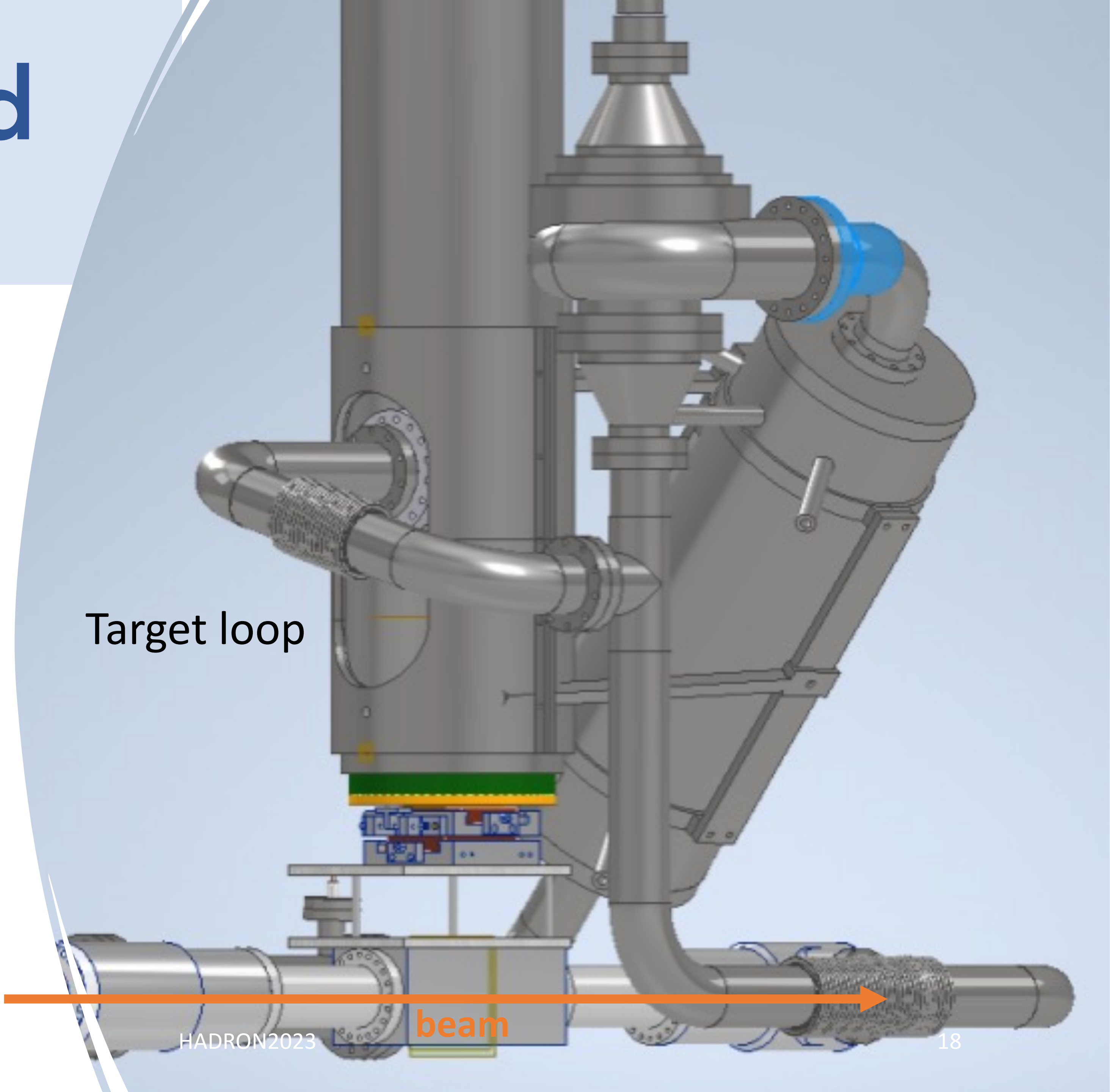
- Verify/benchmark optics model by comparing rate distributions during dedicated periods of low current running
- Determine precision Q-squared for experiment in combination with insertable sieve collimator
- Rotator allows overlapping measurements to reduce sensitivity to efficiency differences septant to septant



High-power liquid hydrogen target

- 1.25 m target cell
- 4kW: highest power LH2 target in the world
- Designed with extensive CFD





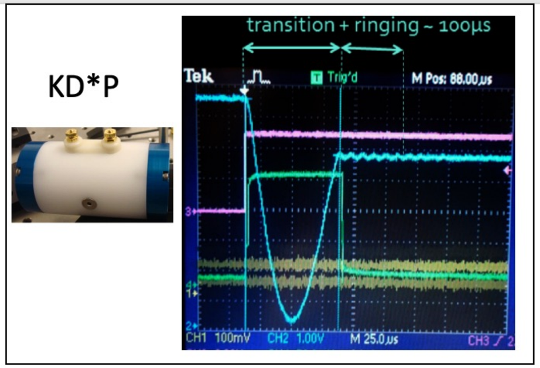
Beam quality and false asymmetries

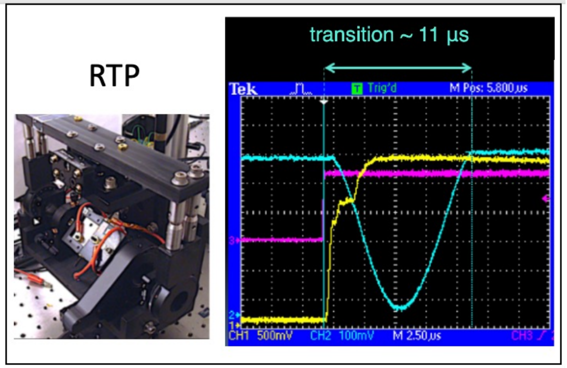
A family of spurious asymmetries mimicking but unrelated to the physics A_{PV} arise from differences in beam parameters between left and right beam helicities

Strategy:

1. **Minimize** known sources from beam differences. (dX, dX’, dY, dY’, dE)
    - Injector upgrade to 200 keV gun removes X/Y coupling, reduces space charge effects, improved optics matching
    - Careful setup of laser in the source to remove position and intensity differences.
    - New RTP Pockels cell for rapid flipping of beam helicity provides only 10us of dead time at helicity reversal (KDP was 10x longer) and allows simultaneous active feedback on position and intensity differences

	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)	$< 10^{-5}$	$< 10^{-5}$



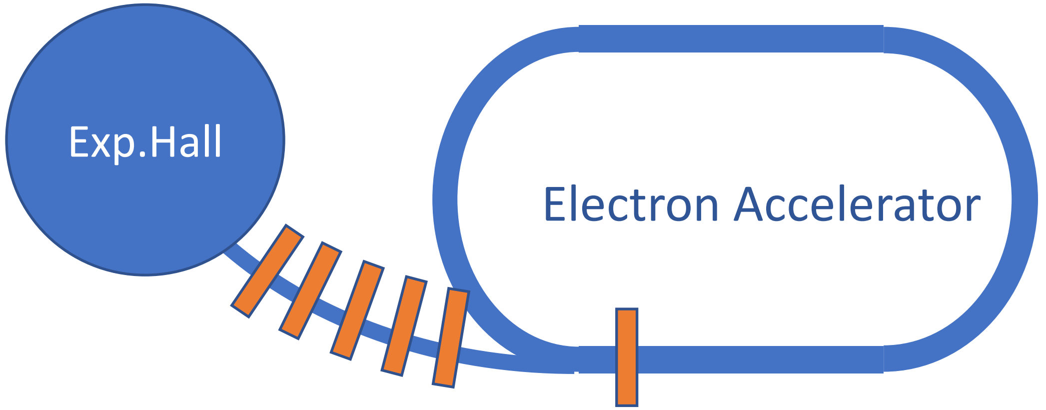


Beam quality and false asymmetries

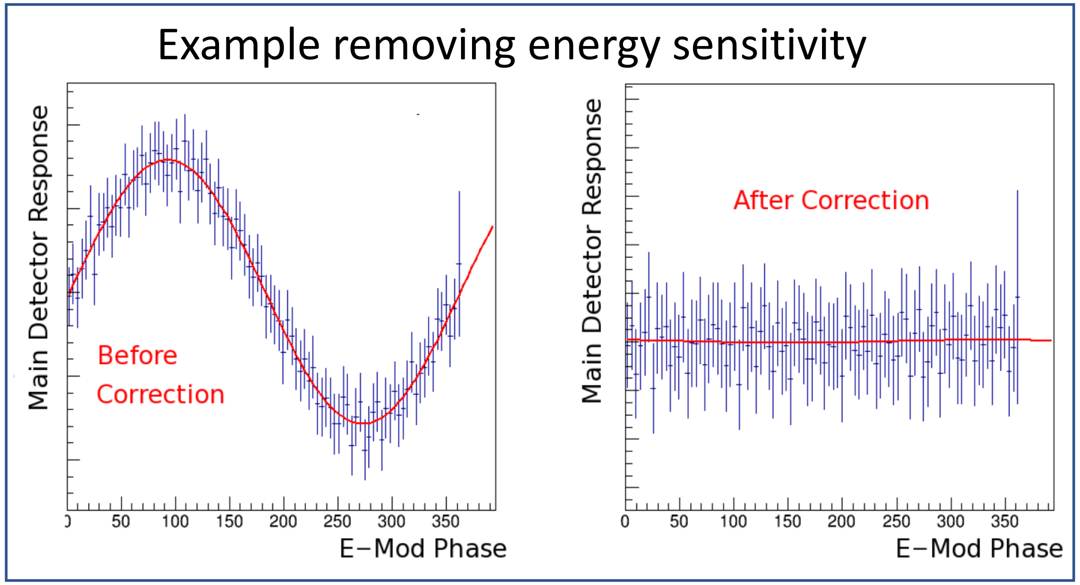
A family of spurious asymmetries mimicking but unrelated to the physics A_{PV} arise from differences in beam parameters between left and right beam helicities

Strategy:

2. **Measure** sensitivities $\frac{\partial A}{\partial X_i}$ **and remove** known remaining false asymmetries from beam differences ΔX, ΔX', ΔY, ΔY', ΔE
   - Using regression (natural beam motion)
   - Using modulation (regular controlled excursions well outside natural beam motion envelope) to measure sensitivities
   - Using a combination of the two: Lagrange Multiplier Regression



$$A_{PV} = A_{meas} - \sum \frac{\partial A}{\partial x_i} \Delta x_i,$$



Beam quality and false asymmetries

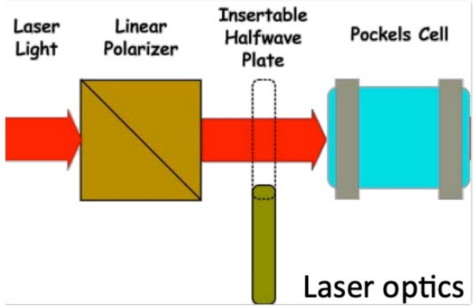
A family of spurious asymmetries mimicking but unrelated to the physics A_{PV} arise from differences in beam parameters between left and right beam helicities

Strategy:

3. **Cancel** remaining false asymmetries with spin rotations

Insertable Halfwave Plate

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

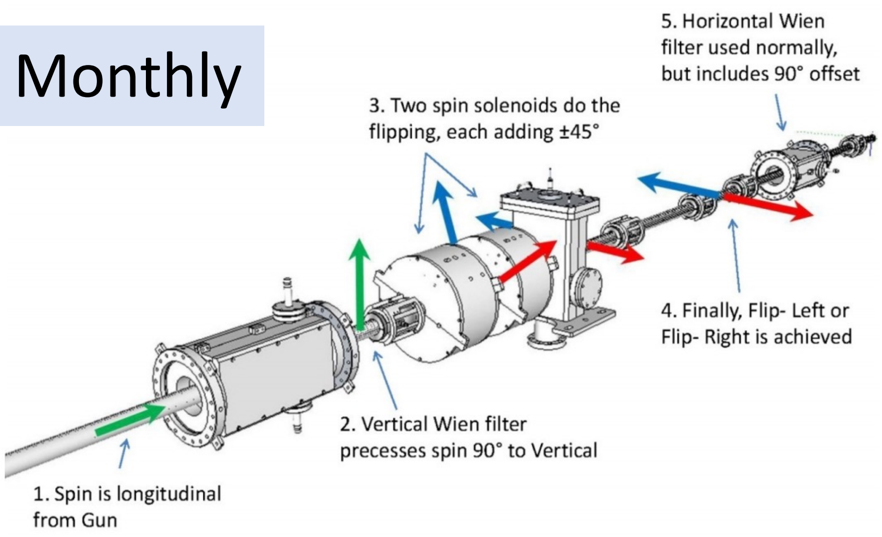


Daily

Injector Spin Manipulation

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

Monthly



g-2 rotation

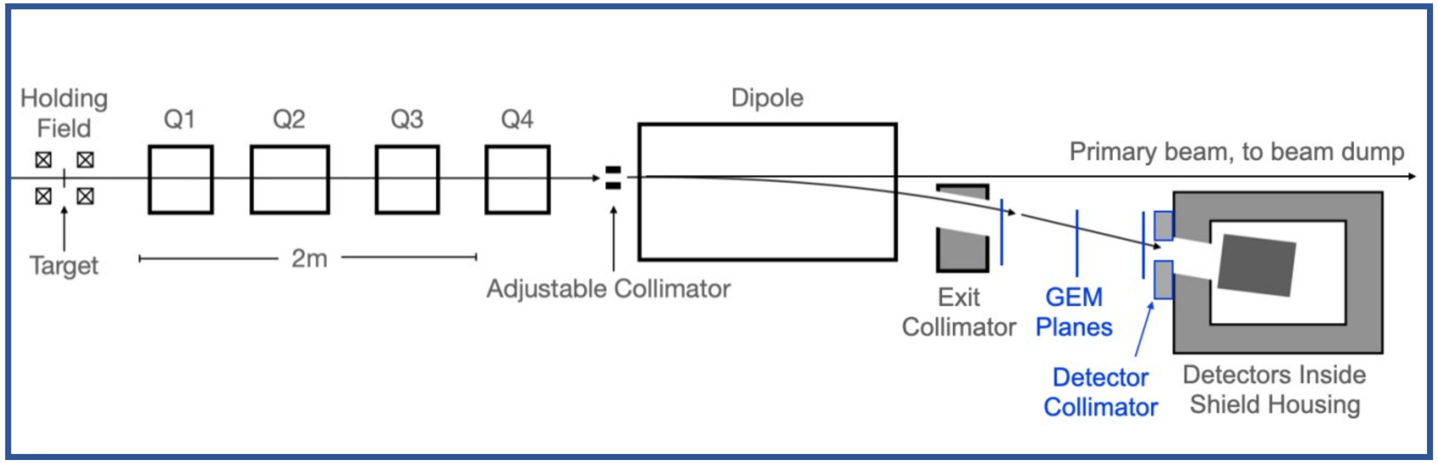
Yearly

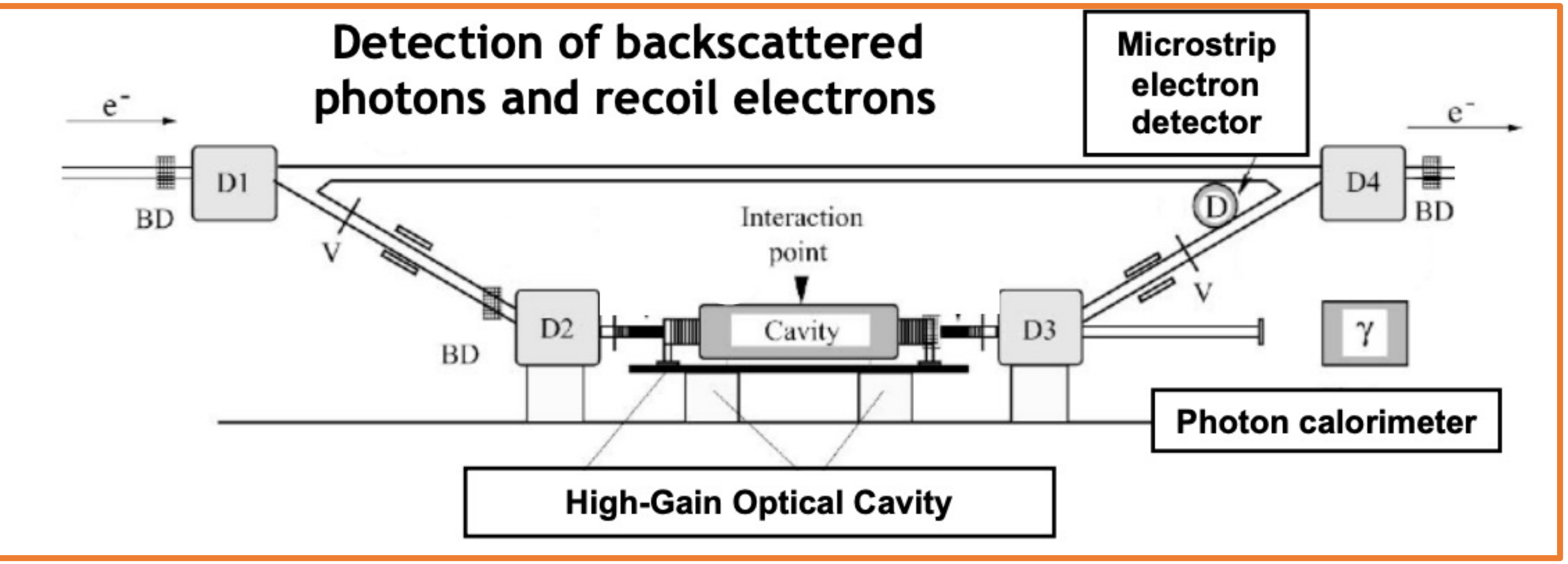
- precession in accelerator arcs
- Modest shift in beam energy (ΔE~100 MeV)
- intend a few reversals per annual run period

0.4% electron beam polarimetry: 2 types

Moller polarimetry

- Elastic ee scattering from a Fe foil polarized (magnetized) parallel to beam direction
- Parity conserving Moller asym $A = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\downarrow\uparrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\uparrow}}$
- For longitudinally polarized e
  - $A_{long} = A_{zz} P_{beam} P_{target}$





Compton polarimetry

- eγ scattering: green laser amplified in Fabry-Perot cavity ~3kW
- 100% circularly polarized photons Compton scatter from electron
- Backscattered photon rate depends on electron polarization
- Reached 0.44% with photon detector only during recent CREX experiment!
- Diamond plane electron detector under devel

Projected schedule

- Now: design nearly complete. Order components. Construct and test as appropriate.
- End of 2024 to end of 2025 installation
- 2026-2028 data taking.

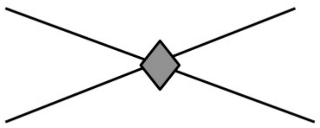
Things appear to be going according to schedule.
DOE CD2/3 funding review coming this October.

Thank you!
Questions?

Backup Slides

Comparison with High Energy Colliders

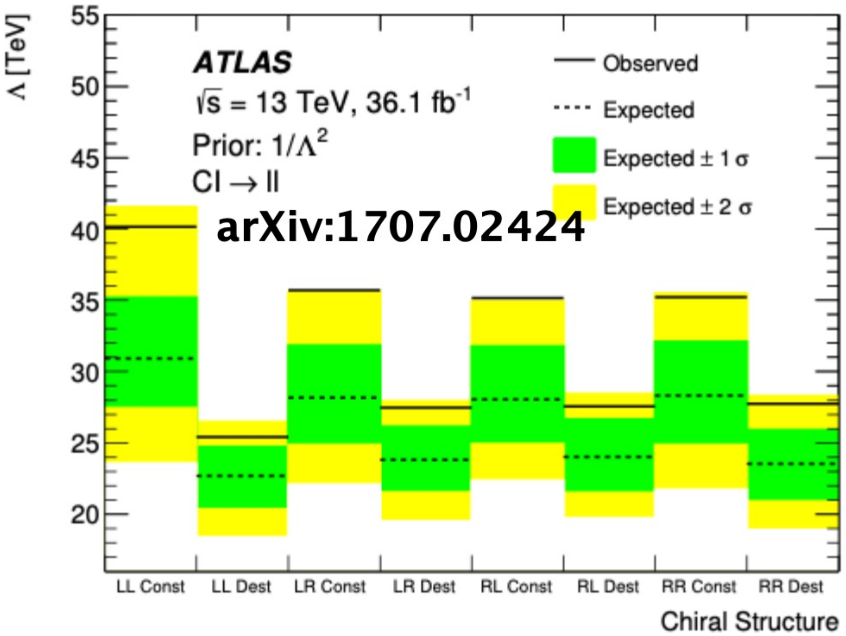
Carefully chosen low energy experiments complement direct searches



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

Lacking any direct evidence for new particles besides the Higgs, both colliders and fixed target experiments search for new physics by looking for deviations from Standard Model predictions

LHC searching for lepton-hadron interactions



LEP200 searched for lepton-lepton interactions

95% C.L.

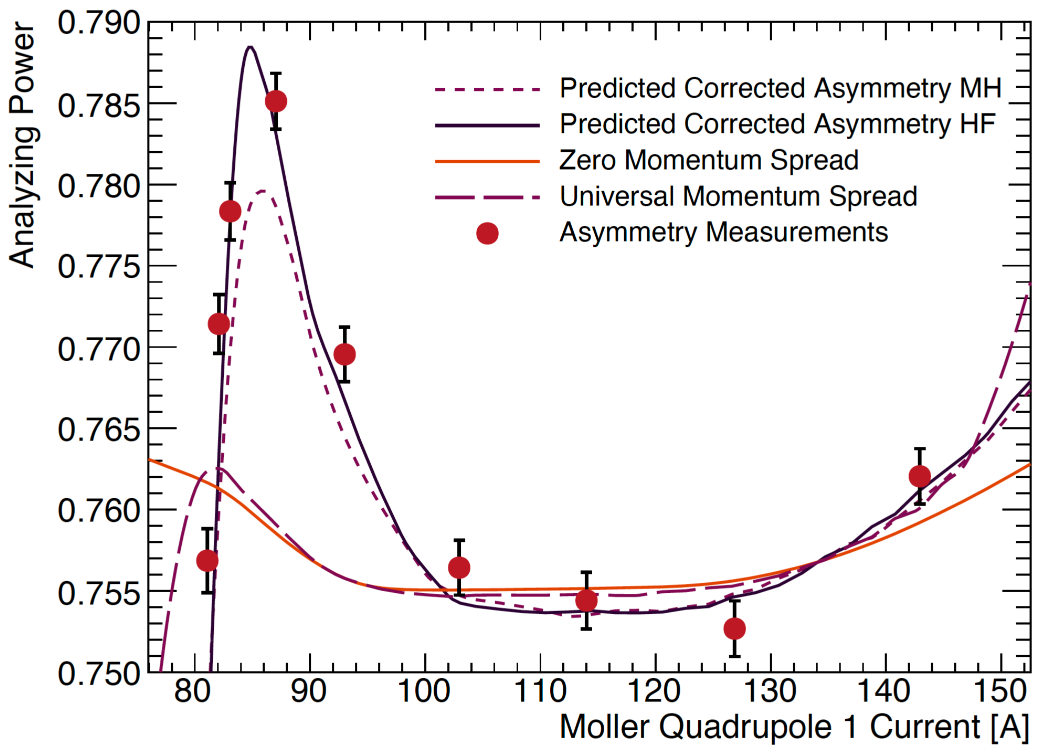
e^+e^- **Collisions**	**LEP200 Reach**	$\Lambda_{LL}^{ee} \sim 8.3$ TeV
Fixed Target	**E158 Reach**	$\Lambda_{LL}^{ee} \sim 12$ TeV
	MOLLER Reach	$\Lambda_{LL}^{ee} \sim 27$ TeV

MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory

Polarimetry technical progress highlights

Moller polarimetry

- Demonstrated improved model for Levchuk asymmetry correction (corrects for effect of intrinsic momentum of electrons in Fe target)



Compton polarimetry

- +/-0.44% electron beam polarimetry during recent CREX experiment a world's best and nearly meeting future goal using photon detector only
- New diamond plane electron detector under development and expected ready for use in MOLLER