MOLLER

Measurement of Lepton-Lepton Electroweak Reaction

December 9, 2014

Kent Paschke
University of Virginia

white paper at arXiv:1411.4088v2

Fundamental Symmetries

A comprehensive search to understand the origin of matter requires:

The Large Hadron Collider **Astrophysical Observations** **Lower Energy: $Q^2 << M_Z^2$**

***Nuclear/Atomic* systems address several topics; unique & complementary:**

- ***Neutrino mass and mixing*** $0\nu\beta\beta$ *decay,* θ_{13}*,* β *decay, long baseline neutrino expts…*
- ***Rare or Forbidden Processes*** *EDMs, charged LFV,* $0\nu\beta\beta$ *decay…*
- ***Dark Matter Searches*** *direct detection, dark photon searches…*
- ***Precision Electroweak Measurements:*** *$(g-2)_\mu$, charged &* ***neutral current amplitudes***

LHC new physics signals likely will need additional indirect evidence

Parity-Violating Electron Scattering: *Low energy weak neutral current couplings, precision weak mixing angle (SLAC, Jefferson Lab, Mainz)*

MOLLER: an ultra-precise measurement of the weak charge of the electron

Weak Neutral Current Vector Charge

	Left	Right
γ Charge	$0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$	$0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$
W Charge	$T = \pm\frac{1}{2}$	zero
Z Charge	$T - q\sin^2\theta_W$	$-q\sin^2\theta_W$

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	EM Charge	WNC Vector Charge
u	$+\frac{2}{3}$	$1-\frac{8}{3}\sin^2\theta_W$
d	$-\frac{1}{3}$	$-1+\frac{4}{3}\sin^2\theta_W$
$p=2u+d$	$+1$	$1-4\sin^2\theta_W$
$n=u+2d$	0	-1
e	-1	$-(1-4\sin^2\theta_W)$

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$\sin^2\theta_W \sim \frac{1}{4}$ so $Q_W^e \sim 0$

suppression of Standard Model WNC vector coupling to the electron enhances the sensitivity to new physics

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$$\sin^2\theta_W \sim \frac{1}{4} \quad \text{so} \quad Q_W^e \sim 0$$

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Complementary Semi-Leptonic Measurements

^{133}Cs: Q_W^n

$$\delta[\mathbf{Q_W}(^{\mathbf{133}}\mathrm{Cs})/\mathbf{A}] \sim \mathbf{0.6\%} \Longrightarrow \mathbf{0.0033}\cdot\mathbf{G_F}$$

Qweak (JLab):

$$\delta[\mathbf{Q_W^p}] \sim \mathbf{4\%} \Longrightarrow \mathbf{0.003}\cdot\mathbf{G_F}$$

SOLID (JLab, unique reach to axial-quark couplings)

$$\delta[\mathbf{2C_{2u}}-\mathbf{C_{2d}}] \sim \mathbf{5\%} \Longrightarrow \mathbf{0.004}\cdot\mathbf{G_F}$$

MOLLER:

$$\delta(Q_W^e) \sim 2.4\% \Rightarrow \sim 0.001\cdot G_F$$

unprecedented sensitivity for new WNC interactions

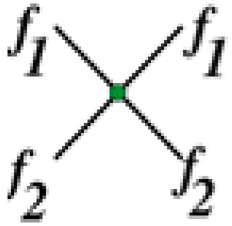
Search for, or study, new neutral currents

Many new physics models give rise to new heavy neutral current interactions

$$\mathcal{L} = \mathcal{L}_{\mathtt{SM}} + \mathcal{L}_{\mathtt{new}}$$

Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

Consider $f_1 f_1 \rightarrow f_2 f_2$ **or** $f_1 f_2 \rightarrow f_1 f_2$



$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g^{12}_{i\,j})^2}{\Lambda^2_{ij}} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

Eichten, Lane and Peskin, PRL50 (1983)

mass scale Λ, coupling g **for each fermion and handedness combination**

Sensitivity to TeV-scale **contact interactions** away from the Z resonance

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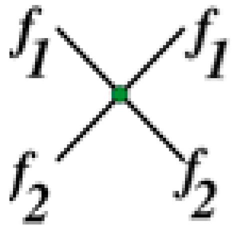

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Electromagnetic amplitude interferes with Z-exchange as well as any new physics

$$\left|\mathbf{A}_\gamma + \mathbf{A_Z} + \mathbf{A}_{\rm new}\right|^{\mathbf{2}} \to \mathbf{A}_\gamma^{\mathbf{2}}\left[\mathbf{1} + \mathbf{2}\left(\frac{\mathbf{A_Z}}{\mathbf{A}_\gamma}\right) + \mathbf{2}\left(\frac{\mathbf{A}_{\rm new}}{\mathbf{A}_\gamma}\right)\right]$$

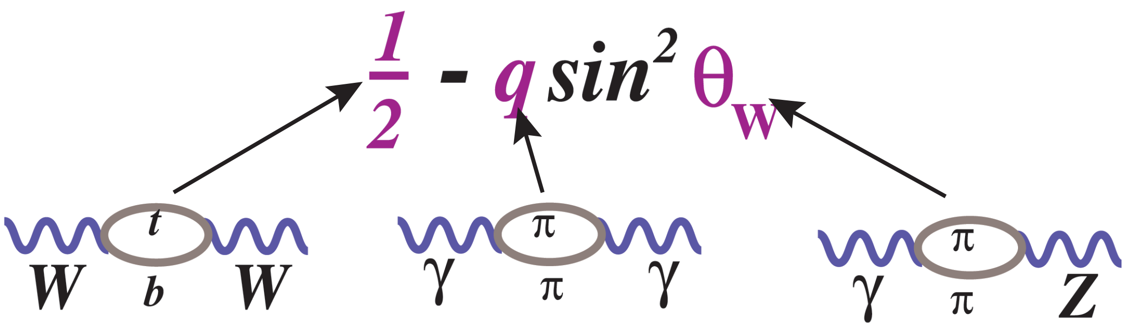
Conventional “mass limits” for contract interactions are defined using a compositeness scale $g^2=4\pi$.

MOLLER:

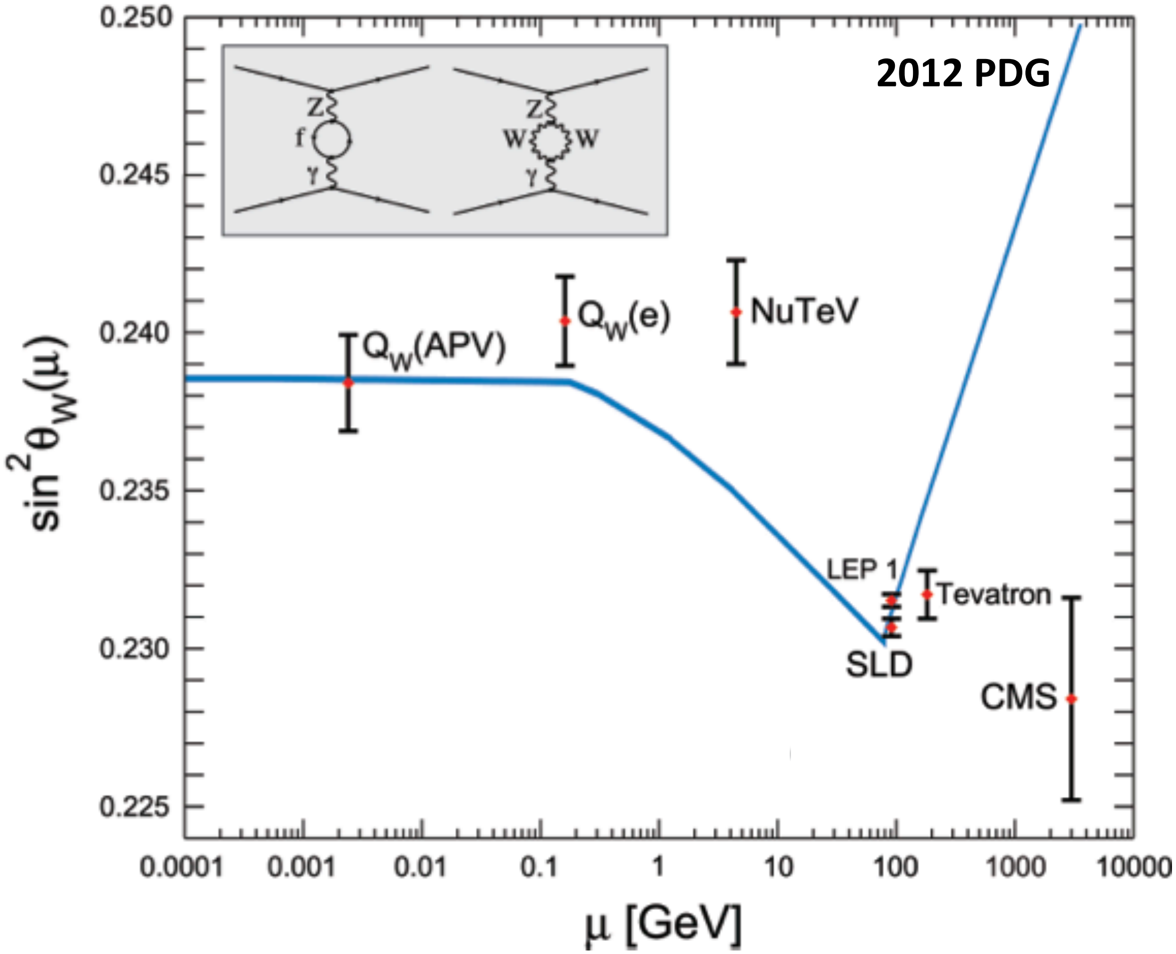
$$\delta(Q_W^e) \sim 2.4\% \Rightarrow \Lambda \sim 38 \text{ TeV}$$

Erler *et al.* (arXiv1401.6199)

Precision Standard Model Prediction



$$\frac{1}{2} - q \sin^2\theta_W$$



Improvement in SM prediction

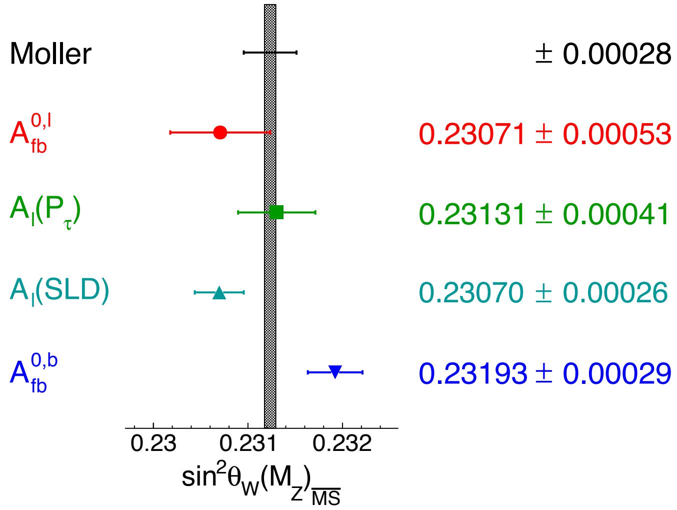
- *Czarnecki and Marciano (1995, 2000)*
- *Petriello (2002)*
- *Erler and Ramsey-Musolf (2004)*
- *Sirlin et. al. (2004)*
- *Zykonov (2004)*

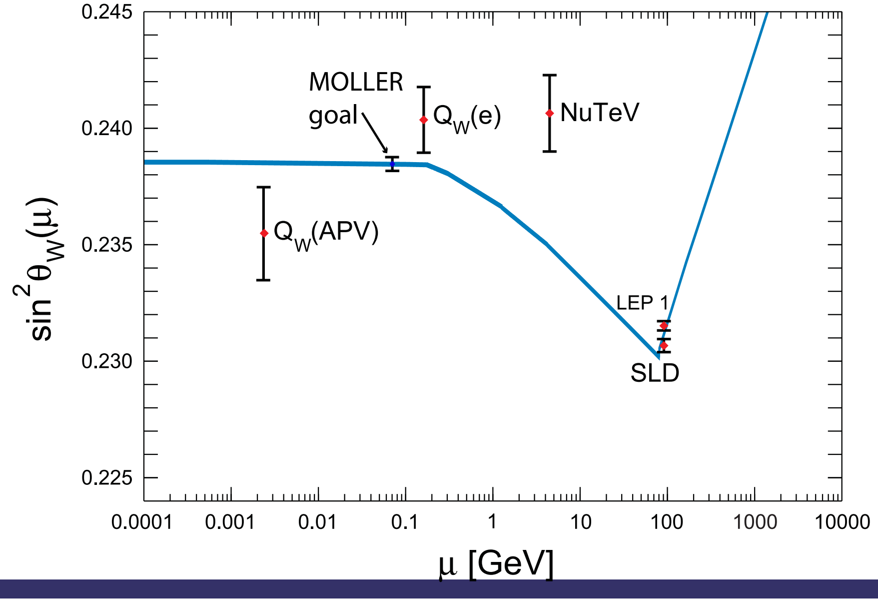
$\sin^2\theta_W$

A Fundamental Parameter of the Electroweak Theory

MOLLER Projection: $\delta(\sin^2\theta_W) = \pm\, 0.00024\ (\text{stat.}) \pm 0.00013\ (\text{syst.})$

Z resonance measurements: no interference term





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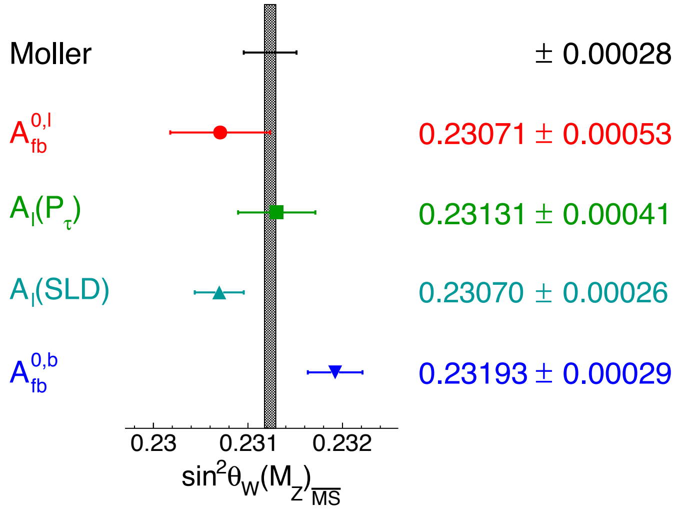

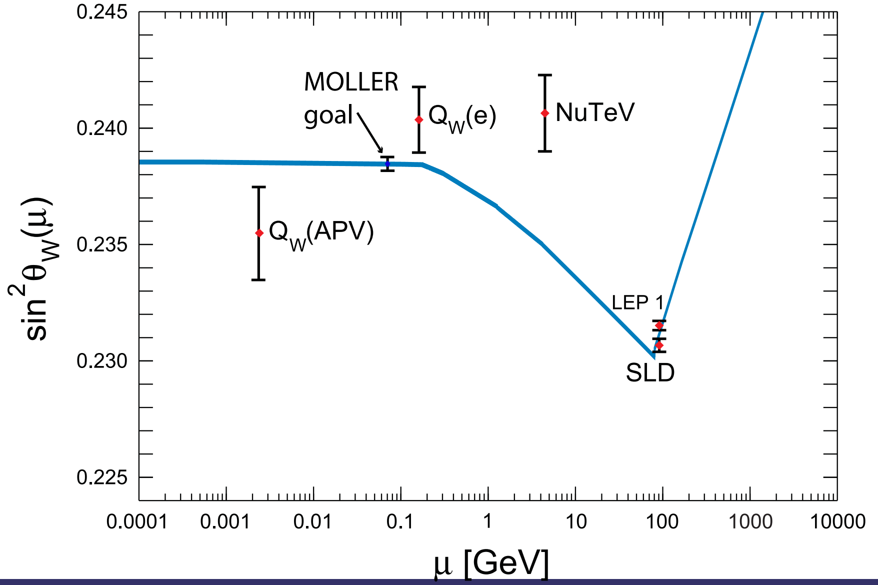

Future projections, similar time scale:

Mainz P2: ~ 0.00036

Final Tevatron: ~ 0.00041

LHC 14 TeV, 300 fb^{-1} : ~ 0.00036
Note: systematics-dominated (pdf uncertainties)

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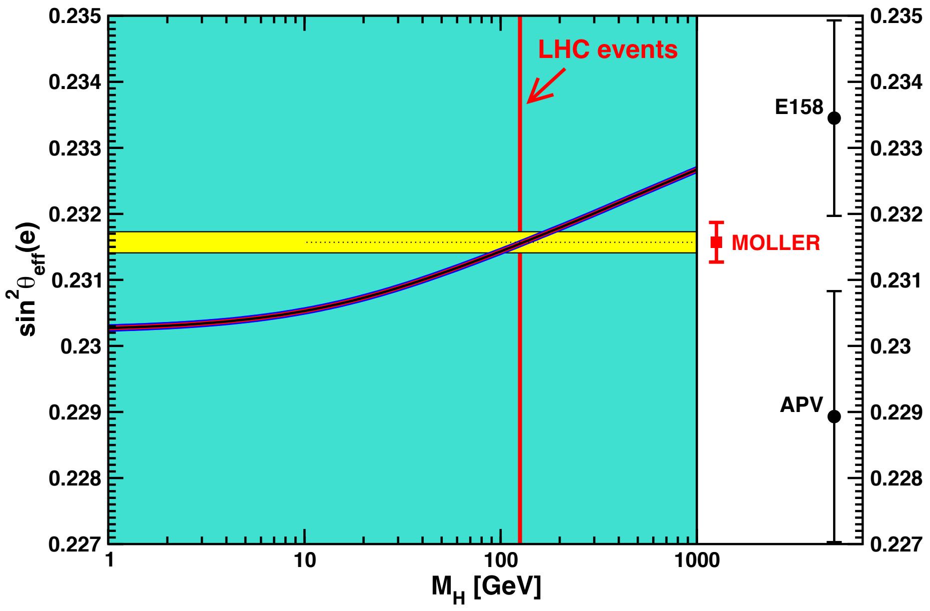
$\pm$ 10σ discovery potential at $Q^2 << M_Z^2$



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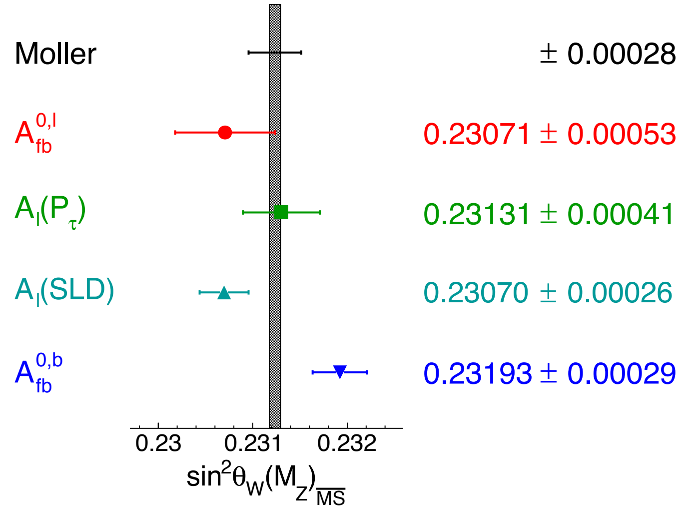

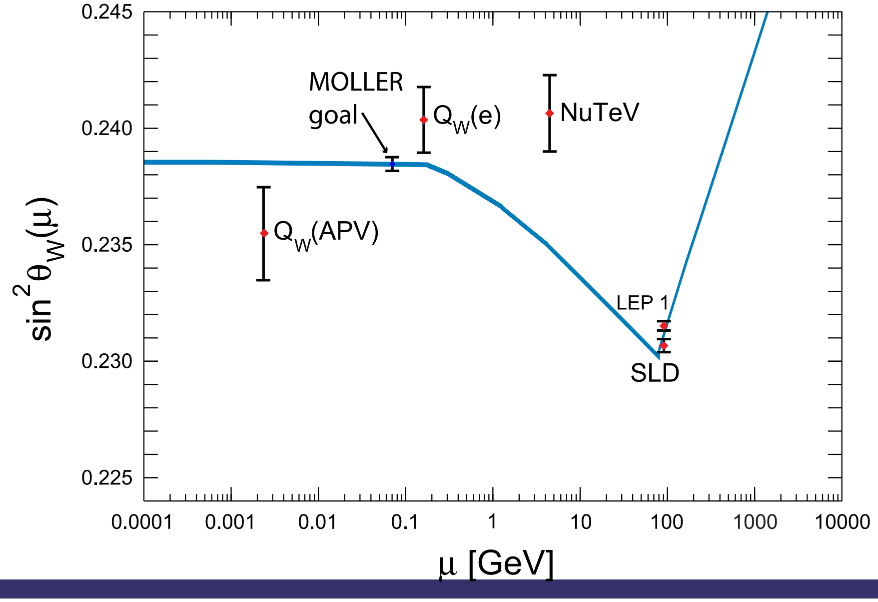

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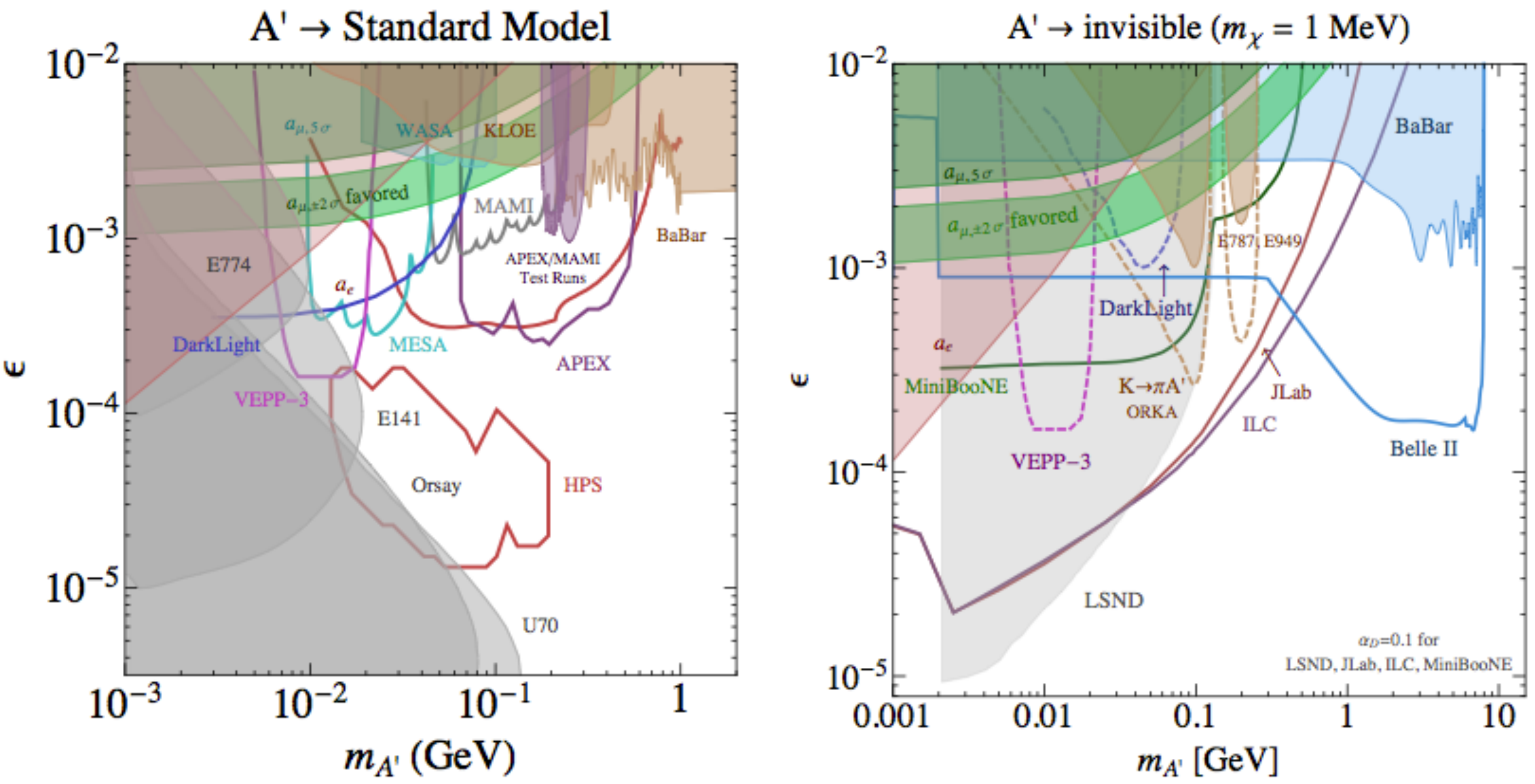
“Dark Z” - New Physics at *Low* Mass Scales

What if some U(1) gauge symmetry from the dark sector contains a light mediator (dark photon, heavy photon, U boson, hidden boson, dark Z)?

APEX, HPS, Darklight

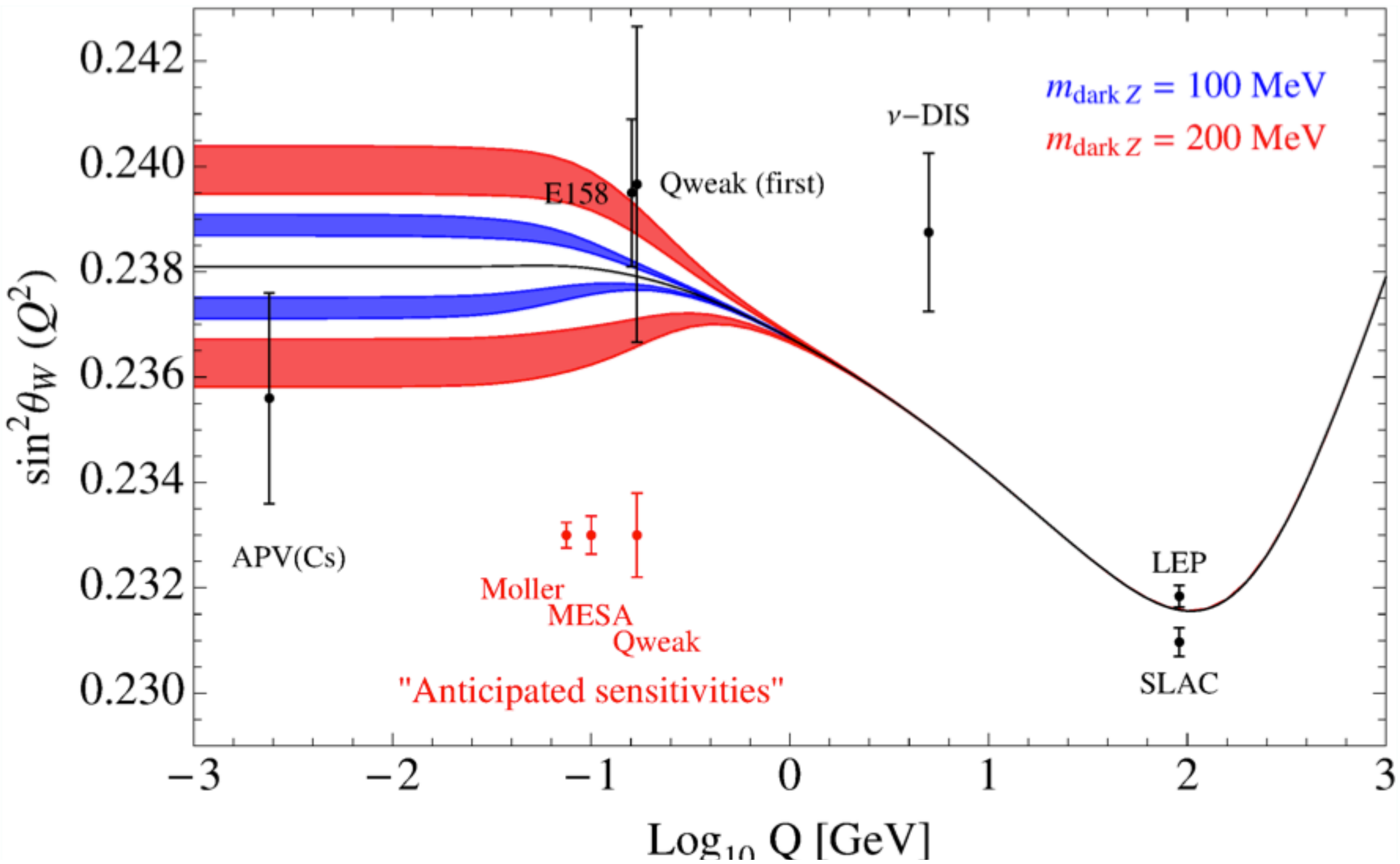


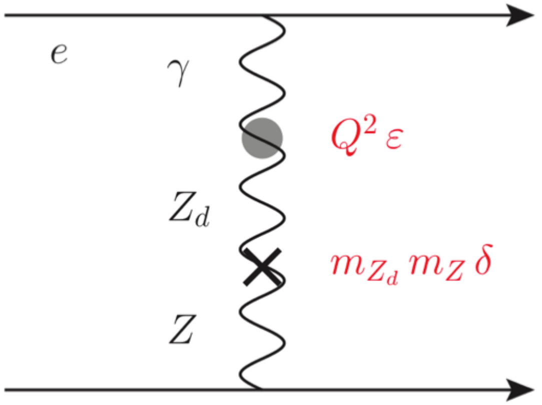
Existing measurements and new possibilities
(plots sensitive to models, A’ dark coupling, dark sector mass)
2013 Snowmass (1401.6077)

Dark Parity Violation

- Mass mixing of Z^0 and Z_d - observable changes to PV at low energies
- Complementary to direct searches for visible dark photons

“Dark Parity Violation”
Davoudiasl, Lee, Marciano, arXiv 1402.3620





mixing at level to match (still allowed) a_μ region

MOLLER and Fundamental Symmetries

best contact interaction reach for leptons at low OR high energy: similar to LHC reach with semi-leptonic amplitudes

To do better for a 4-lepton contact interaction would require: Giga-Z factory, linear collider, neutrino factory or muon collider

$$\delta(\sin^2\theta_W) = \pm\, 0.00024\ (stat.) \pm 0.00013\ (syst.) \Rightarrow \sim 0.1\%$$

Best projected uncertainties among projects being considered over next 10 years: worldwide and at any energy scale

If LHC sees ANY anomaly in Runs 2 or 3 (~2022)

- ➡ **there will be a pressing need for unique, complementary probes such as MOLLER, g-2, etc.**

Discovery scenarios beyond LHC signatures

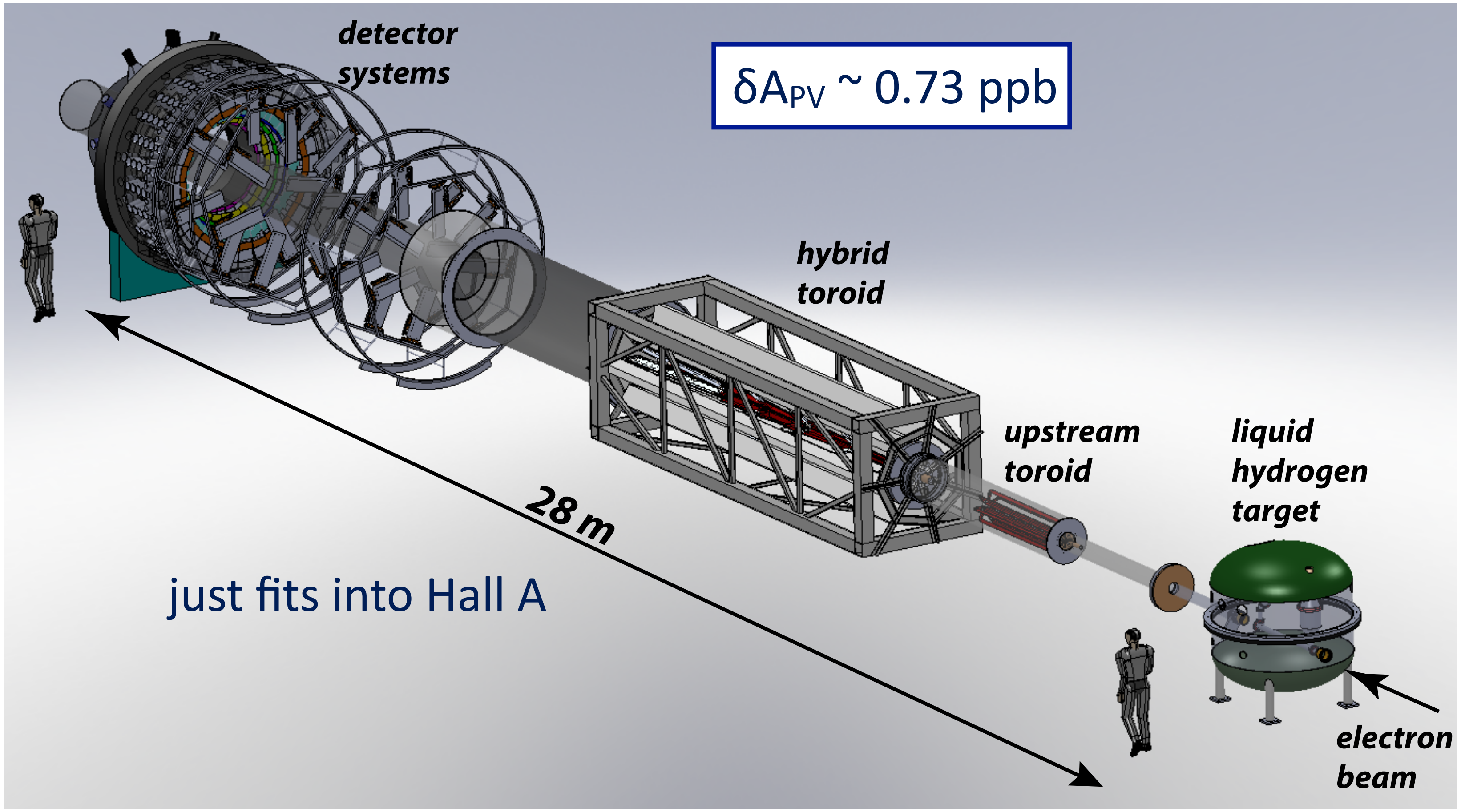
- ➡ **hidden weak scale mediators**
- ➡ **light dark matter mediators**
- ➡ **lepton number violating amplitudes**

Most sensitive discovery reach over the next decade for CP-/flavor-conserving or LNV scattering amplitudes

MOLLER Evolution

- E158 final result published in 2004
  - Major technical improvements incorporated
  - Highlighted in 2007 Long Range Plan
- MOLLER Concept Developed ~ 2007
  - Conceptual breakthrough: 100% acceptance toroidal spectrometer
  - Mentioned in 2007 LRP for Fundamental Symmetries investment
  - JLab PAC approval in 2009
    - "…outstanding physics reach….", "…potential JLab flagship experiment…"
  - JLab Director's Review chaired by C. Prescott in 2010
    - strongly endorsed physics case and commended experimental team and approach
  - JLab PAC Ranking and Beamtime allocation in 2011
    - enthusiastic endorsement, "…flagship…", full request (344 PAC days) allocated
  - Tribble Subcommittee Report in 2012 (LRP Implementation)
    - MOLLER listed in suite of recommended Fundamental Symmetries investments, along with Fermilab g-2, SOLID, nEDM, ton-scale double-beta decay, Nab and KATRIN
- MOLLER DOE Science Review - Sept 10-11, 2014, ACFI (UMass)
  - very positive feedback, awaiting official report

Experimental Overview

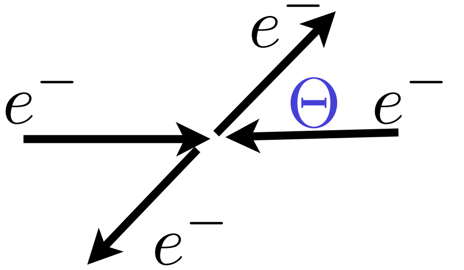


- 11 GeV, 90% polarized, 60 μA electron beam
- LH_2 target: 150 cm, 5 kW

Luminosity 3×10^{39}, rate ~ 130 GHz

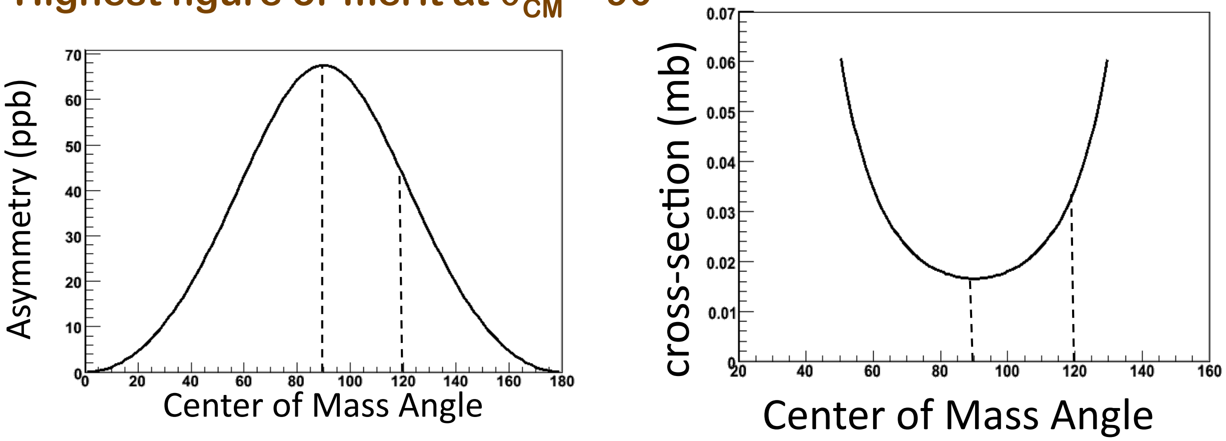
- Precision collimation (“2-bounce” design)
- Novel two (warm) toroid spectrometer (100% azimuth, E’ = 2.5-8.5 GeV, $\theta_{lab} = 0.3^{o}$-1.1^{o})
- Segmented integrating detectors, counting detectors (backgrounds, systematics)

Moller Kinematics



identical particles!

Highest figure of merit at θ_{CM} = 90°

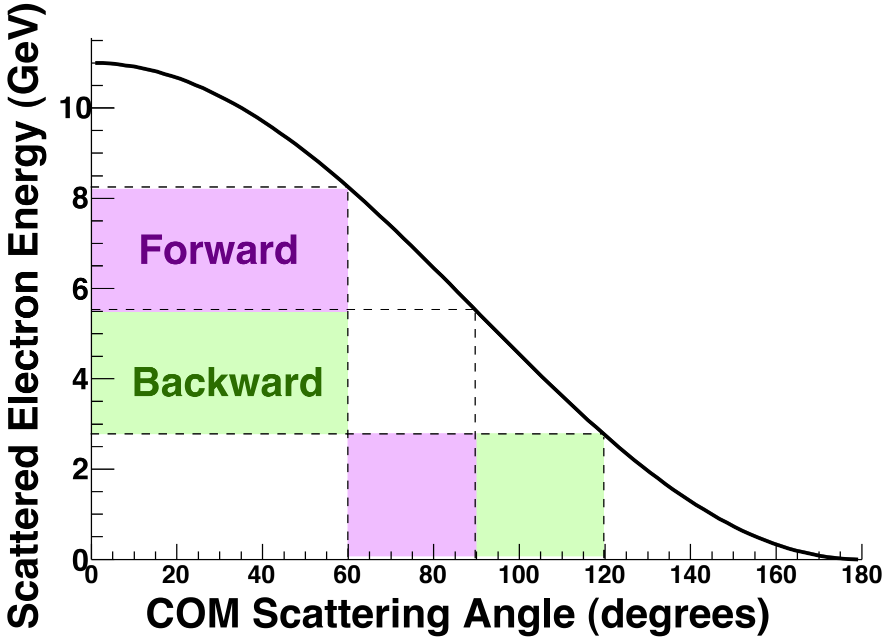


Toroid solution for 100% azimuthal coverage!

- collect both forward and back scatters

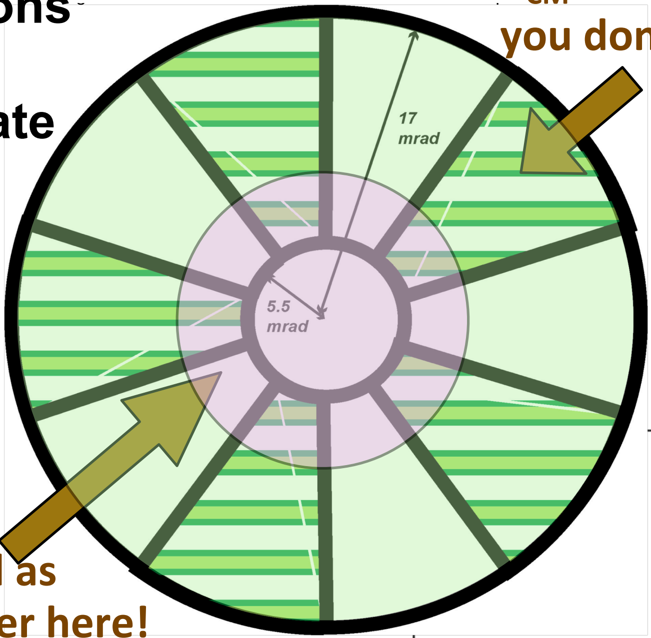
Avoid superconductors

- ~150 kW of photons from target
- collimation extremely challenging (0.3° minimum acceptance angle)



100% acceptance

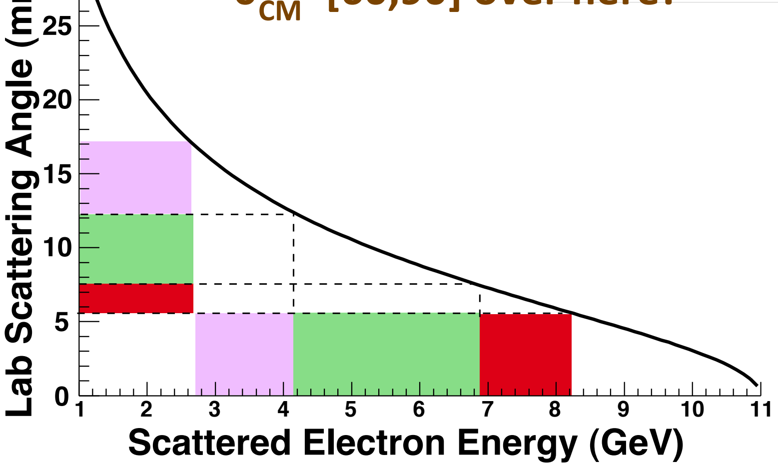
Electrons from elastic scattering off target protons separated from elastic scattering off target electrons (Møllers); electrons from inelastic scattering dominate in between two “rings”

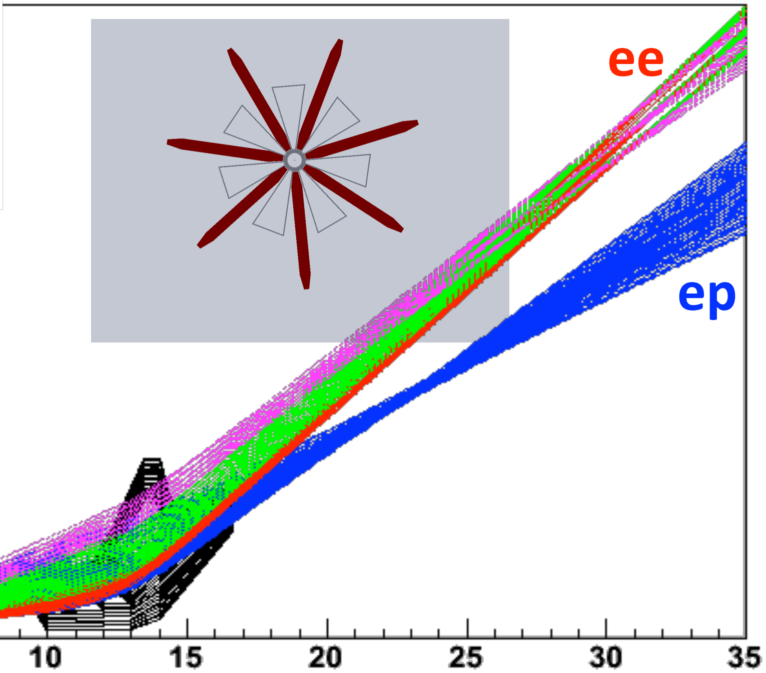


All of those rays of θ_{CM}=[90,120] that you don’t get here...

... are collected as θ_{CM}=[60,90] over here!

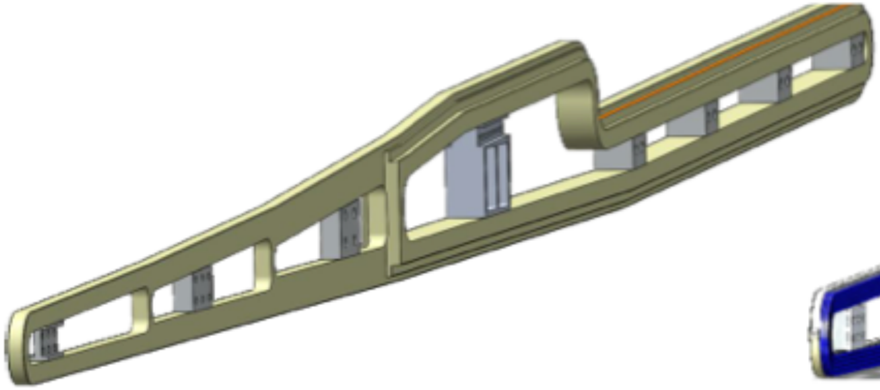
Odd number of coils: each segment accepts forward scattered Møllers, & backward (from forwards at opposite phi)

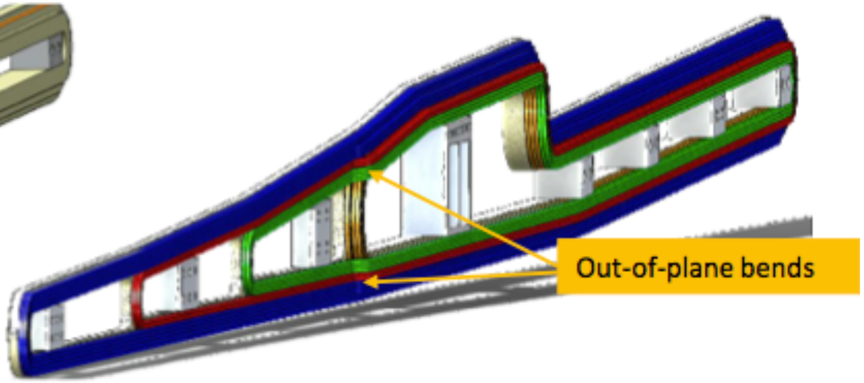




“nested” Toroidal Coils

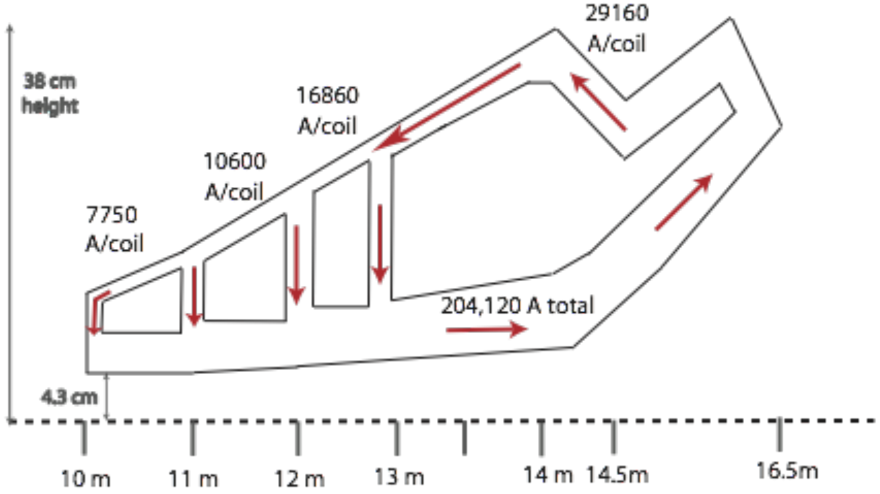
challenging engineering, but a real, buildable design



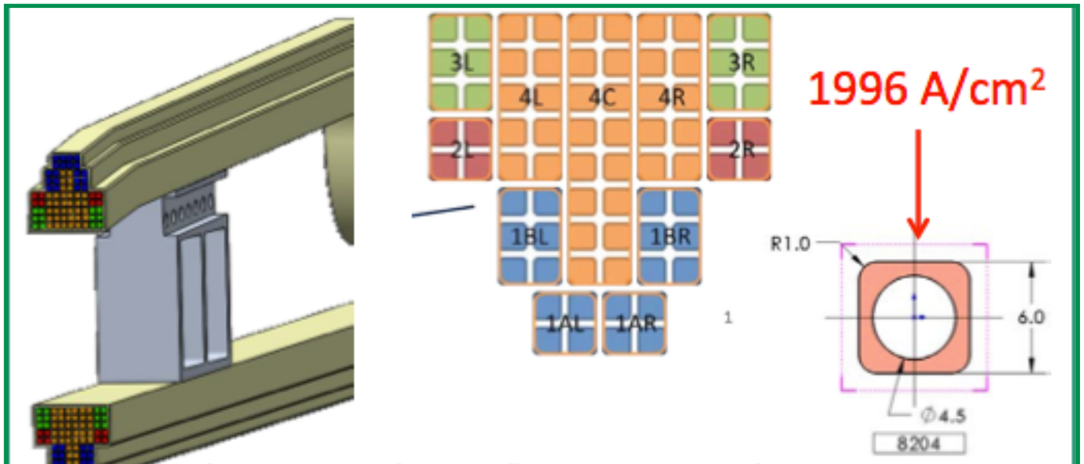


UMass / Manitoba & MIT engineering

100% azimuth “line current” near beamline
14-17 degree azimuthal fill for coil limbs

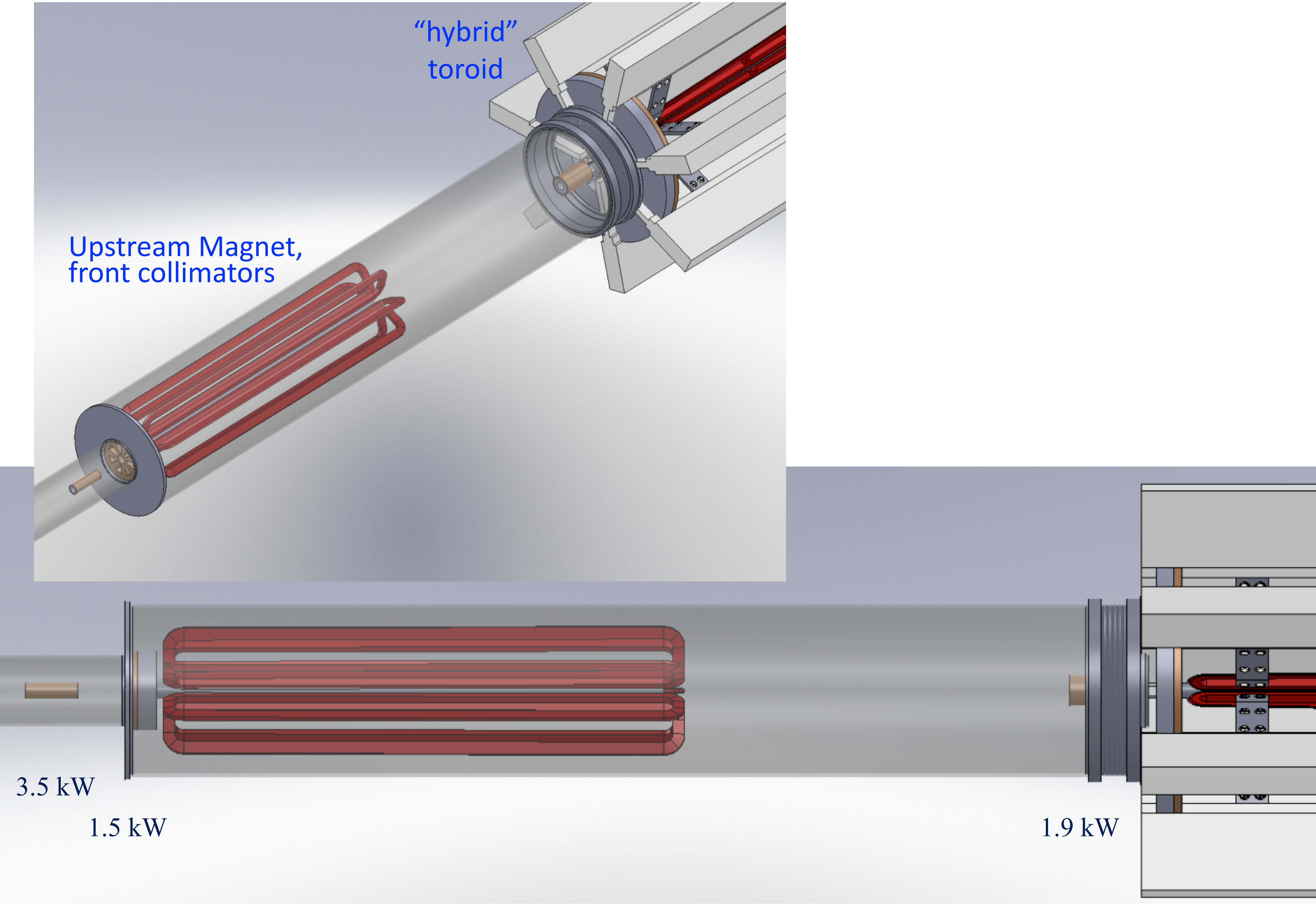


UVa conceptual design

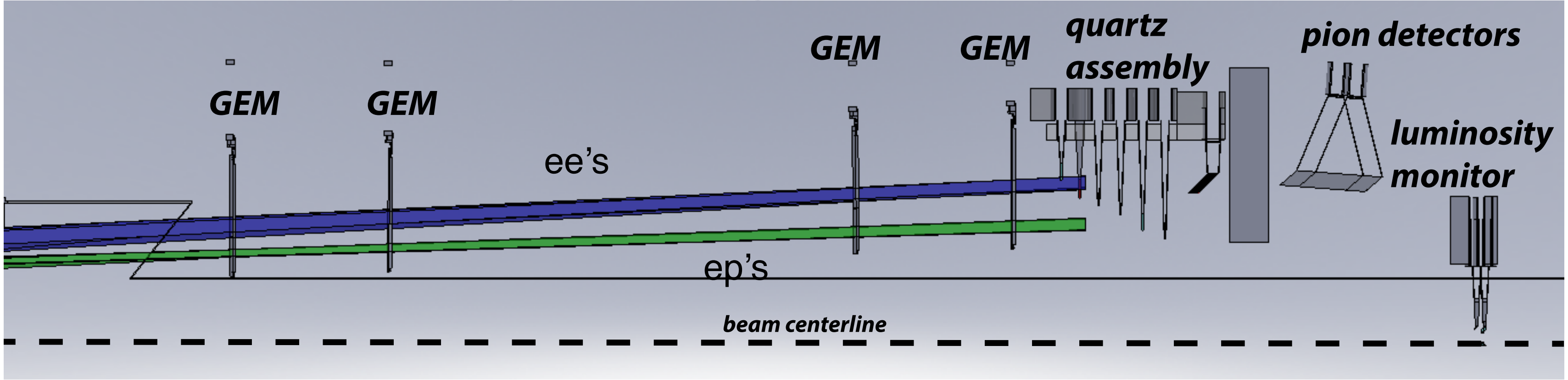


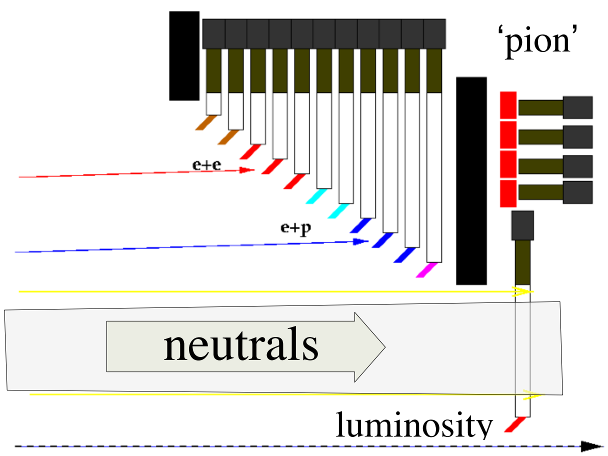
Coil cross section showing all 76 turns, 11 pancake shapes, and tentatively chosen conductor

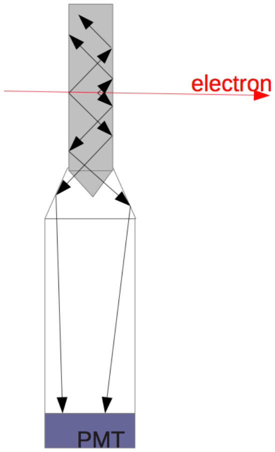
Collimation



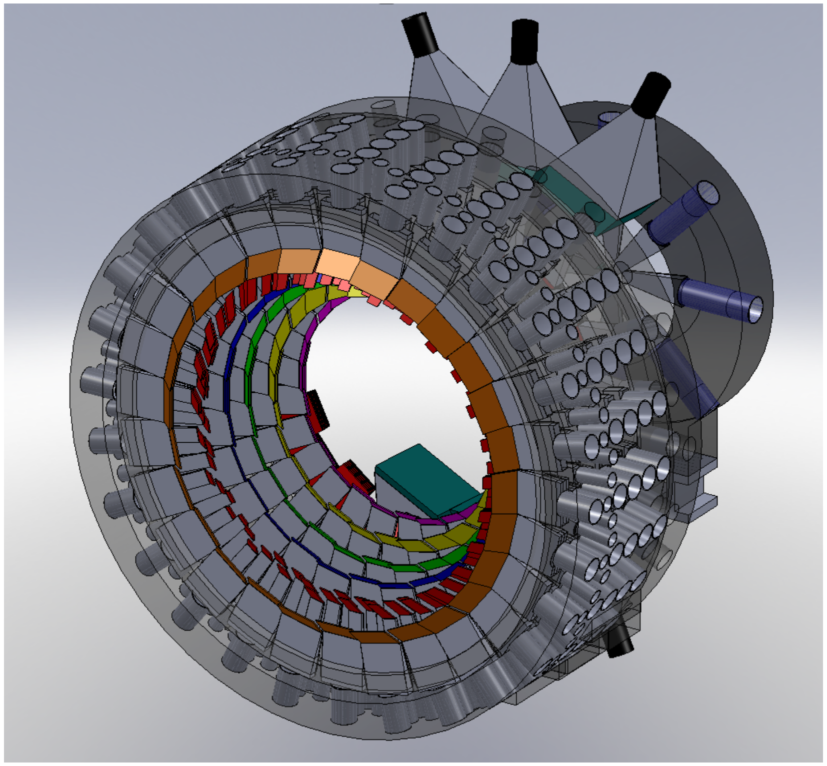
Integrating Detectors







azimuthal defocusing in radial fields, so detector must cover full azimuth



- **Møller and e-p electrons:**
  - radial and azimuthal segmentation
  - quartz with air lightguides & PMTs
- **Pions and muons:**
  - quartz sandwich behind shielding
- **Luminosity monitors**
  - beam & target density fluctuations

Measurement

- Incident beam is longitudinally polarized
- Change sign of longitudinal polarization
- Measure fractional rate difference
- 130 GHz - integrating (not counting)

$$A_{pair} = \frac{F_R - F_L}{F_R + F_L} \qquad \sigma_{A_{expt}} = \frac{\sigma_{\mathtt{pair}}}{\sqrt{N}}$$

Quiet JLab beam, high-flow target, and low-noise electronics keeps precision high

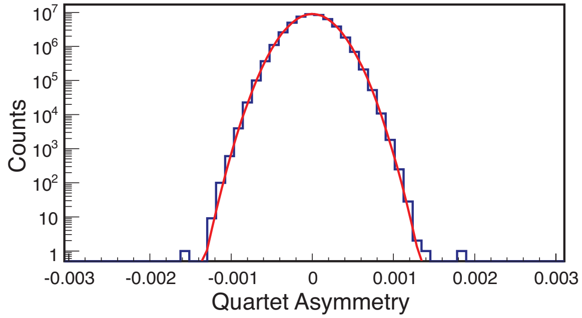
Noise Budget (1kHz pairs)

Parameter	Noise (60 µA)
Statistical Width (0.5 ms)	**~89 ppm**
Target Density Fluctuation	21 ppm
Beam Intensity Resolution	10 ppm
Beam Position Noise	7 ppm
Detector Resolution (25%)	3.1%
Electronics Noise	10 ppm
Measured Width	**95 ppm**

Qweak

~6 GHz total rate

230 ppm at 240 Hz



1ppm precision in 4 minutes

MOLLER: 1 ppm in 10 seconds

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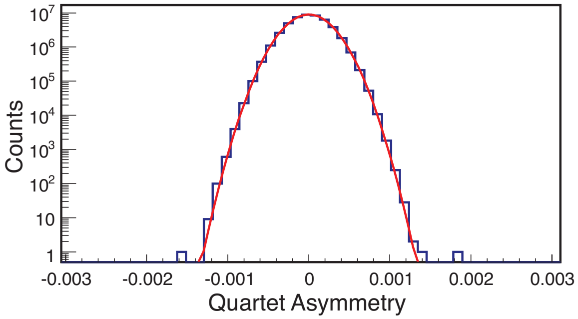

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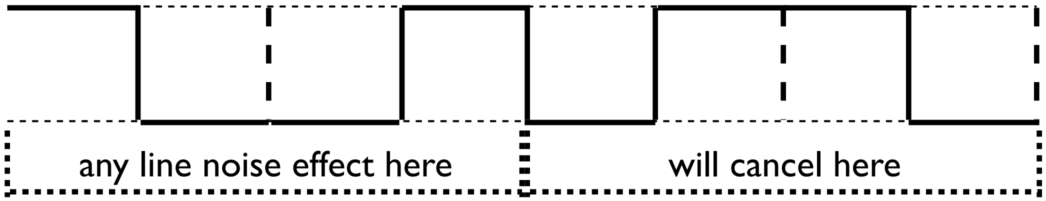
Use multiplets to control 60 Hz noise

Example: at 240 Hz reversal



MOLLER will flip at 2 kHz, with 64-plet to control noise

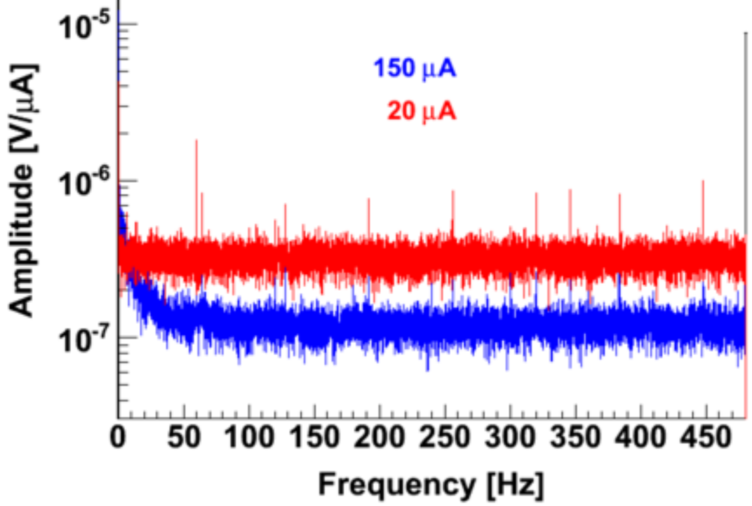
Target

MOLLER goal: up to 85 A on 150 cm LHw - 5 kW power

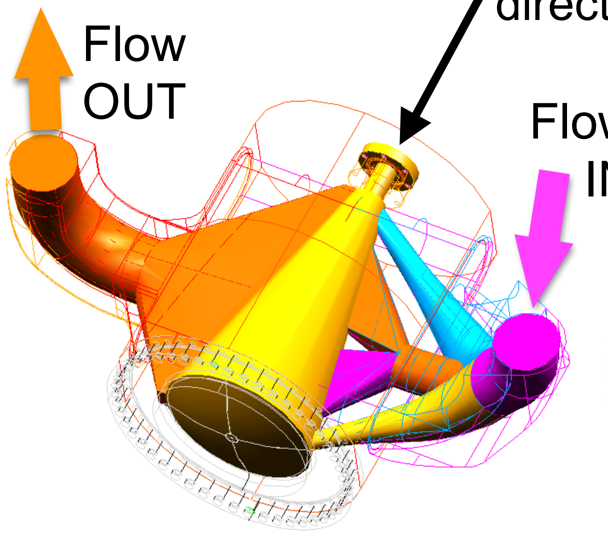
Build on Qweak success using CFD for target design

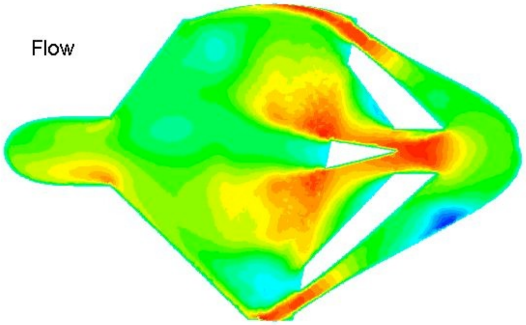
Silviu Covrig, 2012 DOE Early Career Award

Fast helicity reversal (1 ms) cancels density fluctuations



Qweak Target:
180 µA, 35 cm, 2.2 kW





Designed with CFD simulation

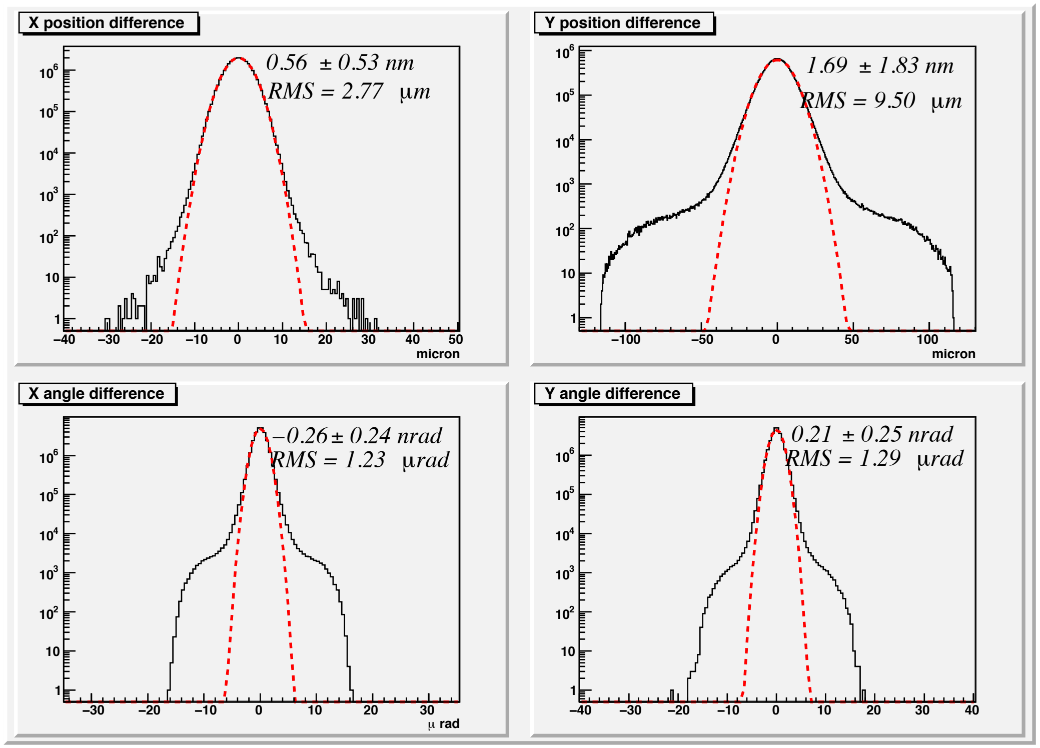
Polarized Source

Helicity correlated Beam asymmetries (intensity, position, size/shape)
can introduce “false” asymmetry

Require: Δx~1nm, size asymmetry ~5×10^{-6}

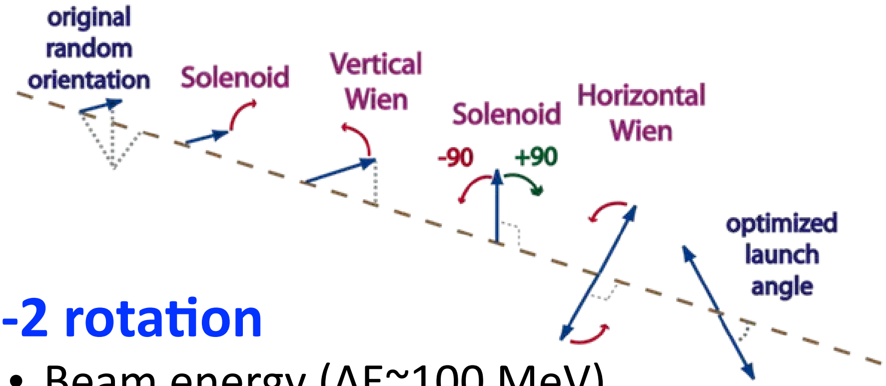
- Injector source laser
- e- beam delivery (adiabatic damping)
- cancellation with “slow” reversals
- detector symmetry
- correction calibration (beam modulation)

HAPPEX-II: “Zero” position differences



Injector Spin Manipulation

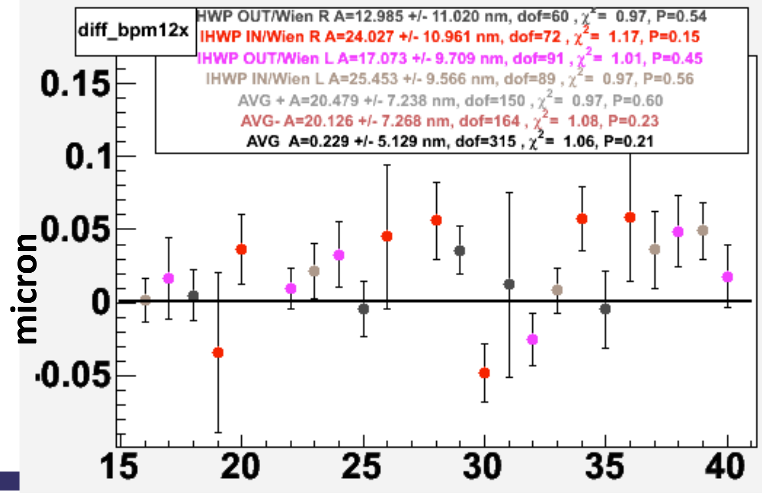
- Solenoids + 2 Wien rotations
- weekly reversals



g-2 rotation

- Beam energy (ΔE~100 MeV)
- ~few reversals during run phases 2 and 3

PREX-II showed ISM cancellation of position differences

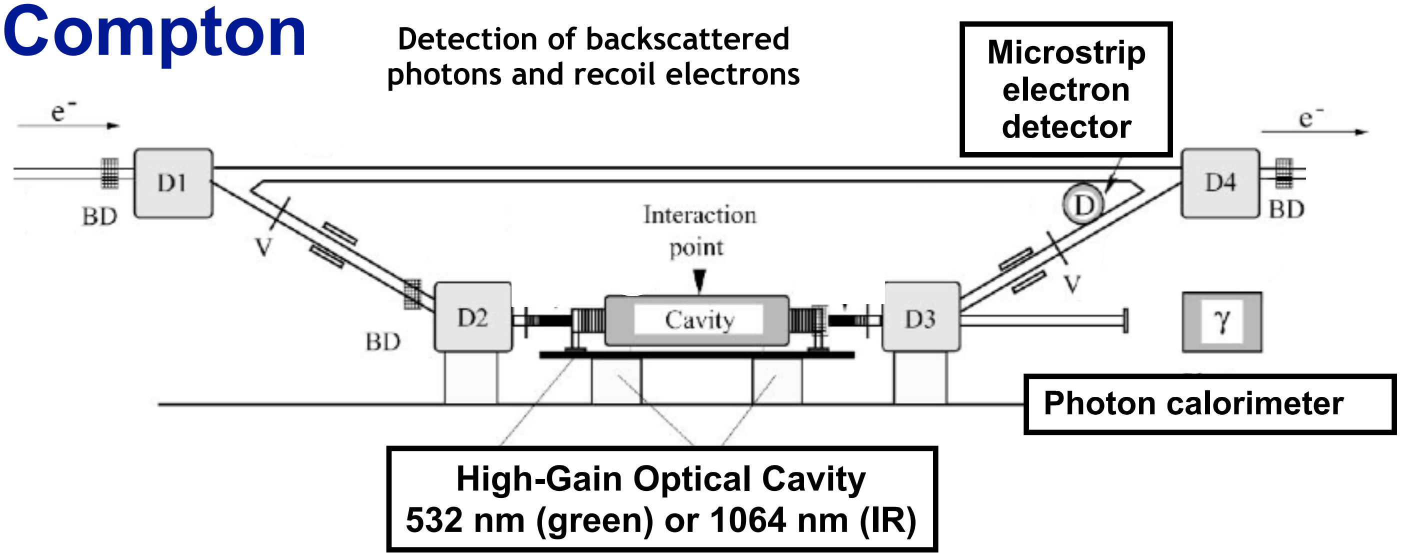


Beam Polarization

- Unimpeachable credibility for 0.4% polarimetry
- Two independent measurements which can be cross-checked
- Continuous monitoring during production (protects against drifts, precession...)
- Statistical power to facilitate cross-normalization (get to systematics limit in about 1 hour)
- High precision operation at 11 GeV

Compton

Detection of backscattered photons and recoil electrons



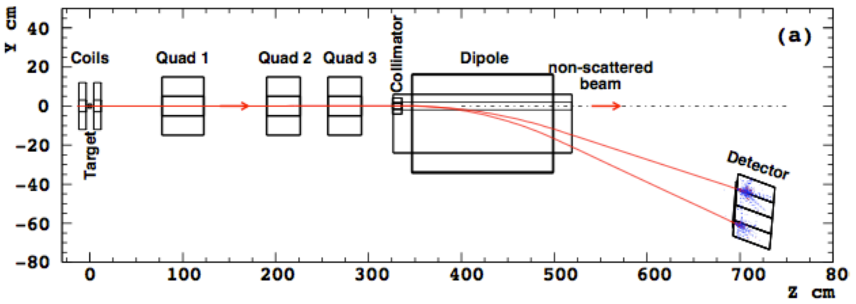
Microstrip electron detector

Photon calorimeter

High-Gain Optical Cavity 532 nm (green) or 1064 nm (IR)

- continuous measurement with high precision
- state-of-the-art: 0.5% (SLD), 0.8% (JLAB)
- laser polarization to 0.2%
- Independent electron/photon analyses, each expected to reach 0.4%

Møller

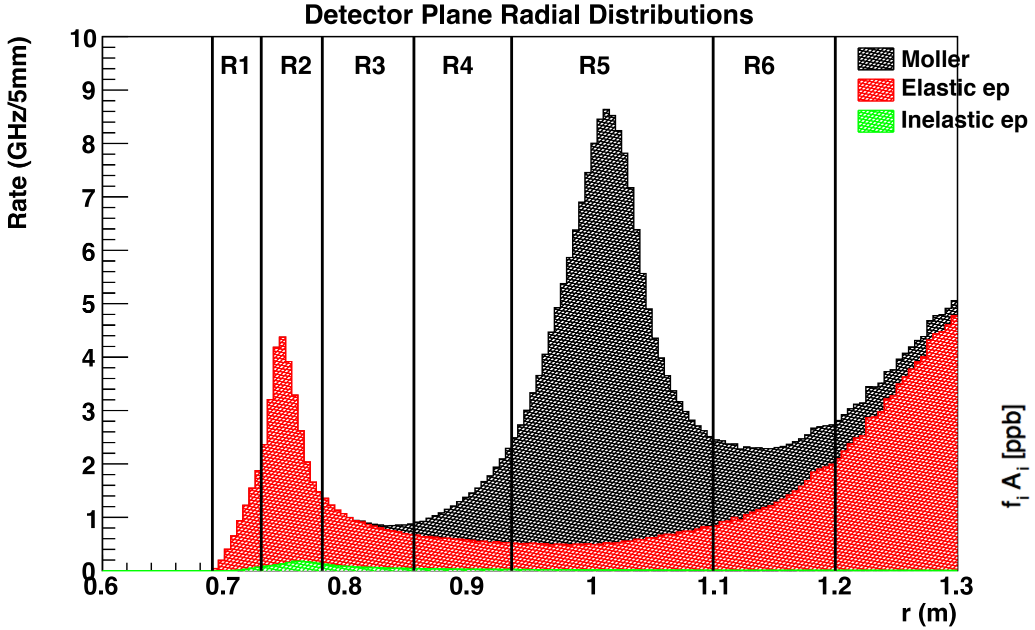


Pure Iron at High Field

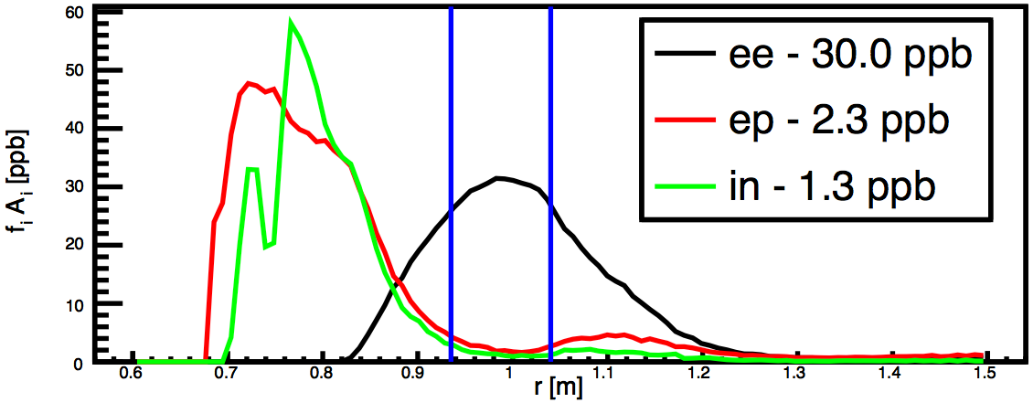
- Magnetized perpendicular to foil
- 3-4 T applied field - magnetization saturated
- Spin polarization, known to 0.25%

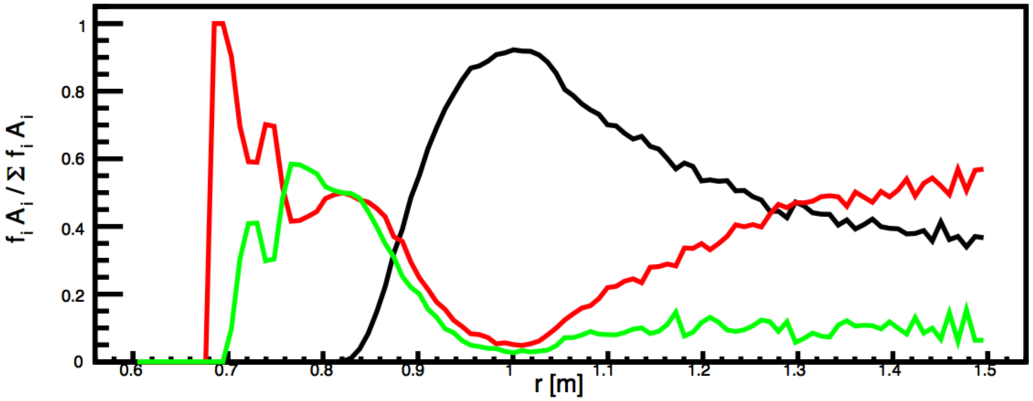
- 0.5% precision already claimed on Hall C polarimeter
- Low-current, invasive measurement
- Spin polarization can not be independently verified

Backgrounds

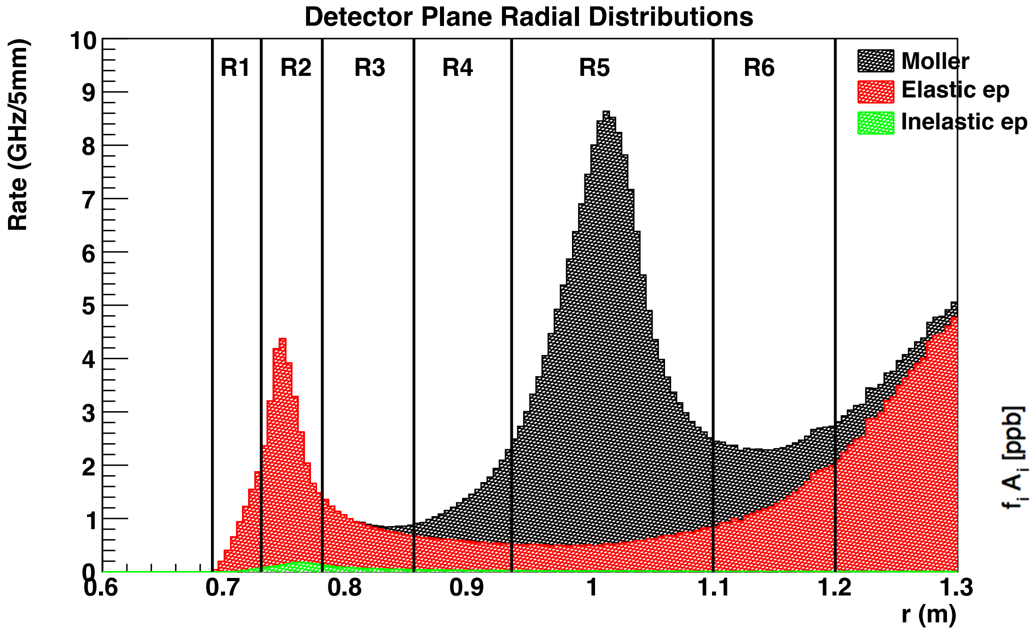


The primary irreducible backgrounds are from electrons scattering elastically and inelastically off target protons

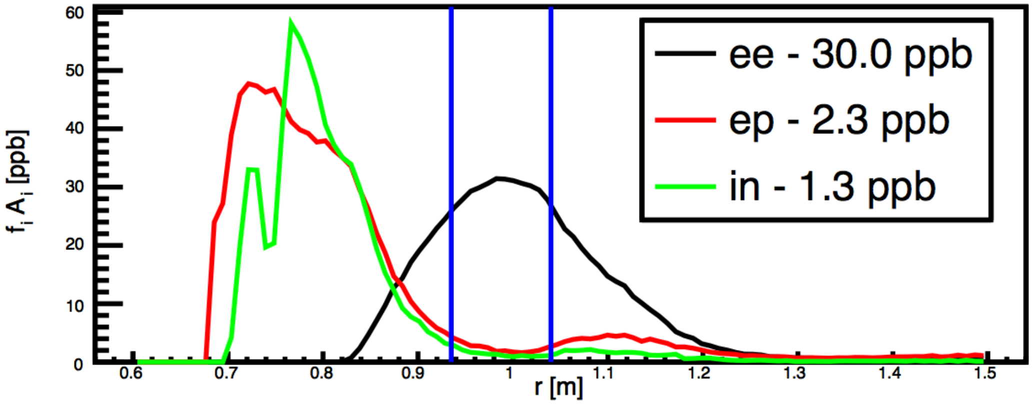




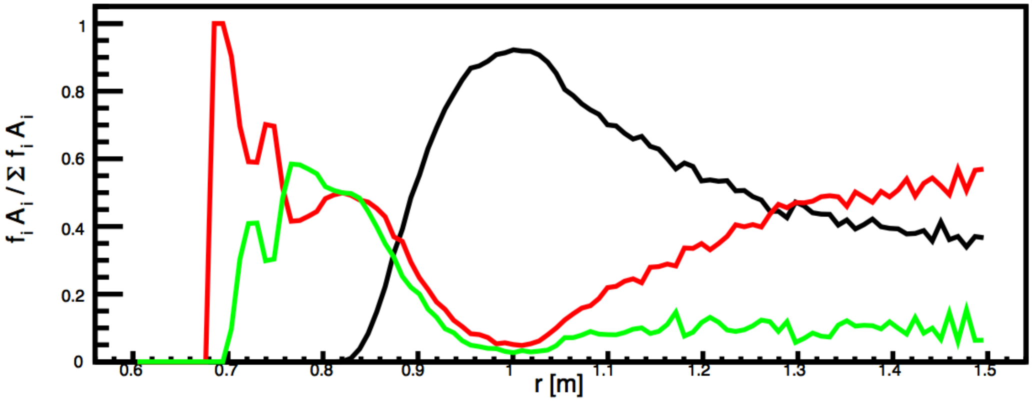
Backgrounds



The primary irreducible backgrounds are from electrons scattering elastically and inelastically off target protons



- photons and neutrons
  - **- 2-bounce collimation system**
- pions and muons
  - **- real and virtual photo-production and DIS**
  - **- continuous parasitic measurement: guards against potential hyperon background**



Summary Table

60 µA, 90% polarization

Run Phases	1 kHz Width	PAC Days (prod)	Stat Error (ppb)	Stat Error (%)	Eff %	Calendar Weeks (prod.)	Comm Weeks	Total Weeks
I	105	14	3.09	10.9	40	5	6	11
II	100	95	1.13	3.9	50	27	3	30
III	95	235	0.68	2.4	60	56	4	60
Total		**344**	**0.57**	**2.01**			**13**	**101**

Uncertainty Source	Ultimate Fractional Error (%)
Statistical	**2.0**
kinematic normalization	0.5
Beam Polarization	0.4
Transverse beam polarization	0.2
Beam Asymmetries	0.6
Backgrounds	0.7
Total systematic	**1.1**

Run Phase 1

near precision of SLAC-E158

Run Phase 2

2.5x beyond SLAC-E158,

$\delta(\sin^2\vartheta_W)$=0.00044 (stat), 0.00047 (stat+syst)

Run Phase 3

$\delta(\sin^2\vartheta_W)$=0.00024 (stat), 0.00028 (stat+syst)

Collaboration and Subsystems

Collaboration still growing, structure evolving into project shape

~120 Collaborators, 30 institutions, 6 countries

Expertise from several generations of successful parity experiments

Spokesperson: K. Kumar, Stony Brook U.

Executive Board Chair and Deputy Spokesperson: M. Pitt, Virginia Tech

Other Executive Board Members

Dave Armstrong (William and Mary)
Javier Gomez (JLab)
Cynthia Keppel (JLab)
Frank Maas (U. Mainz)
Juliette Mammei (U. Manitoba)
Kent Paschke (U. Virginia)
Paul Souder (Syracuse U.)

MOLLER Subsystem Leaders

Polarized Source: G. Cates (U. Virginia)
Beam Instrumentation: M. Pitt (Virginia Tech)
Hydrogen Target: S. Covrig (JLab)
Spectrometer: J. Mammei (Manitoba)
Integrating Detectors: M. Gericke (Manitoba)
Tracking Detectors, D. Armstrong (William and Mary)
Polarimetry: K. Paschke (U. Virginia)
Electronics/DAQ: R. Michaels (JLab) and P. King (Ohio)
Simulations: S. Riordan (UMass) and D. McNulty (Idaho State)

Progress Towards MOLLER

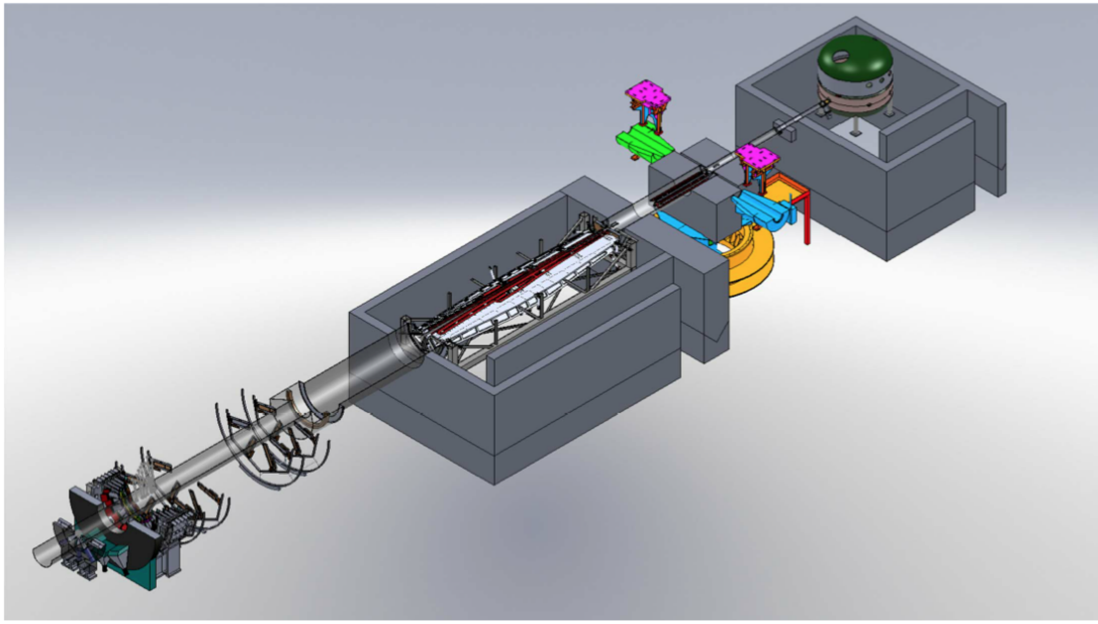
The motivation for MOLLER is very strong

$\delta(\sin^2\theta_W) = \pm\, 0.00024\ (\text{stat.}) \pm 0.00013\ (\text{syst.}) \Rightarrow \sim 0.1\%$

- unchallenged best prospect for improving precision on weak mixing angle, probing lepton-lepton contact interactions, flavor conserving or lepton-number-violating “ultra”-weak amplitudes

MOLLER is moving forward with an active collaboration

- Detailed engineering design work on challenging magnet, collimation, vacuum, and detection systems
- Simulation work continues to optimize collimation, understand the expected backgrounds, design radiation shielding
- Additional evolutionary research on detector design, source laser, polarimetry, beam monitoring
- Collaboration is growing, with plenty of room for more!



Backup

Modular Experimental Design

Modular design and moderate alignment tolerances

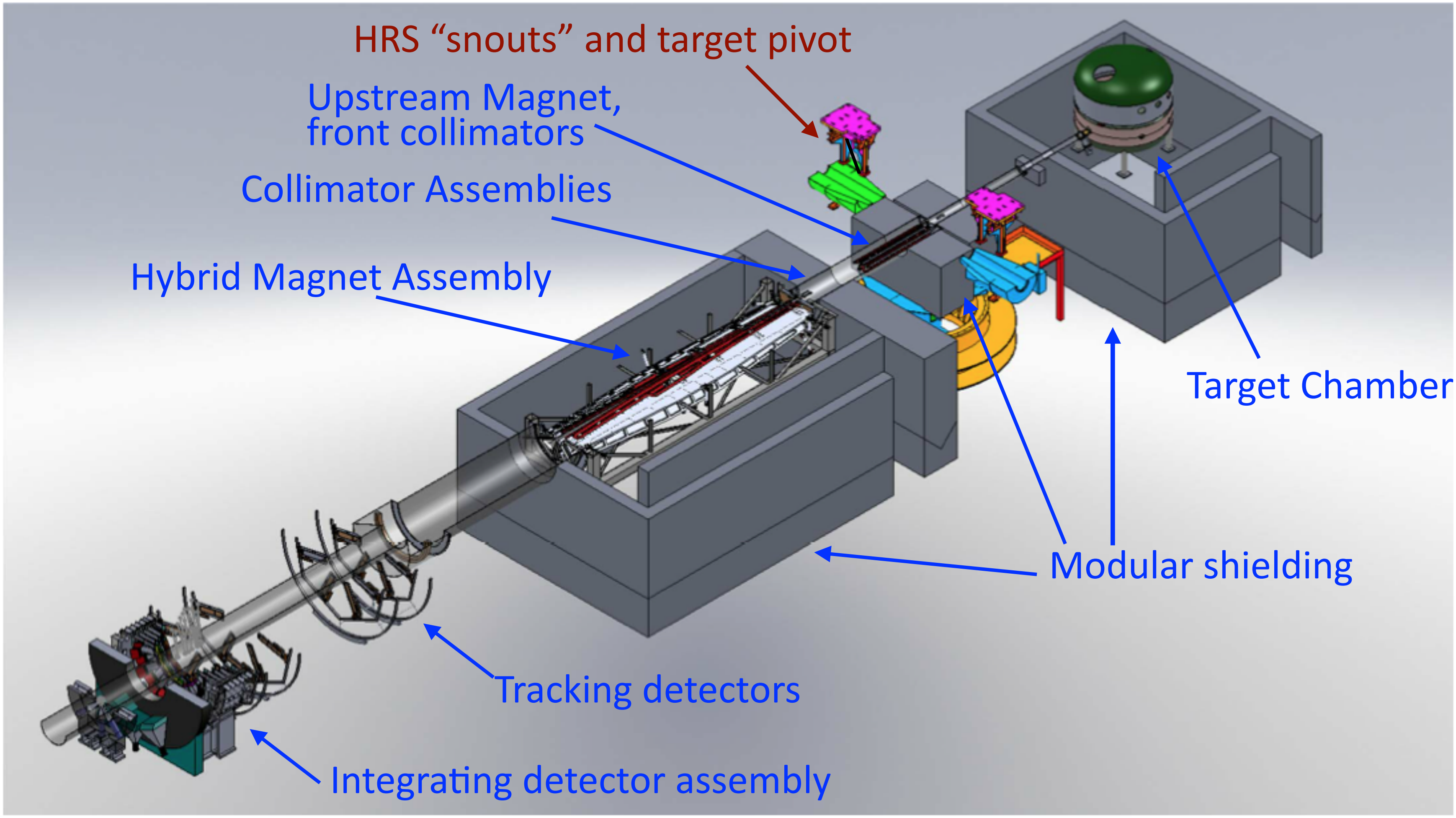
HRS/BigBite experiments need:

- pivot region
- upstream beamline
- open aperture to beam dump
- room for HRS in forward direction

MOLLER: modular assemblies protect critical alignments

- Target chamber
- collimator assemblies
- Hybrid Magnet assembly

Alignment tolerances for positioning of assemblies ~ 1mm



HRS "snouts" and target pivot

Upstream Magnet, front collimators

Collimator Assemblies

Hybrid Magnet Assembly

Target Chamber

Modular shielding

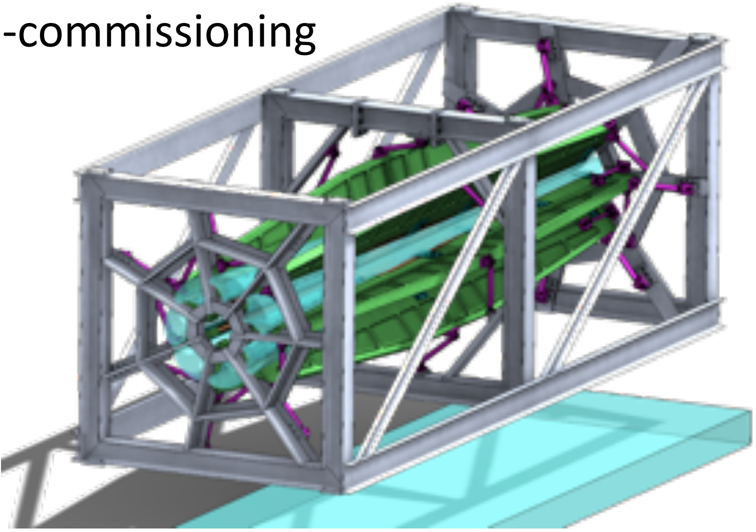
Tracking detectors

Integrating detector assembly

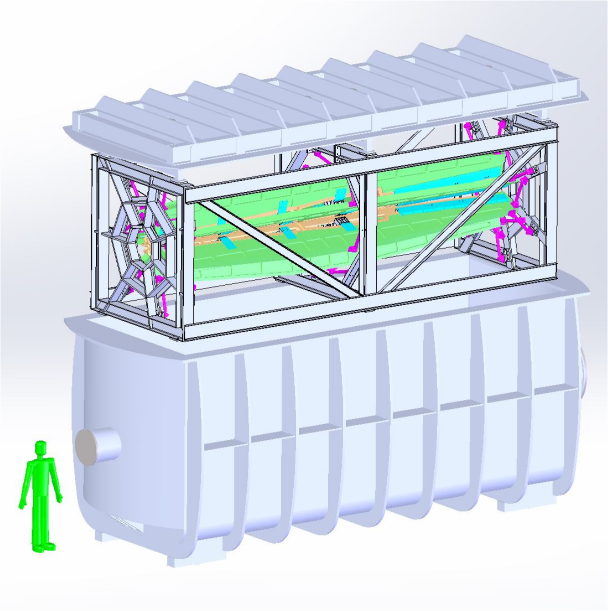
Critical Alignments in Fixed Assemblies

Hybrid Magnet Assembly

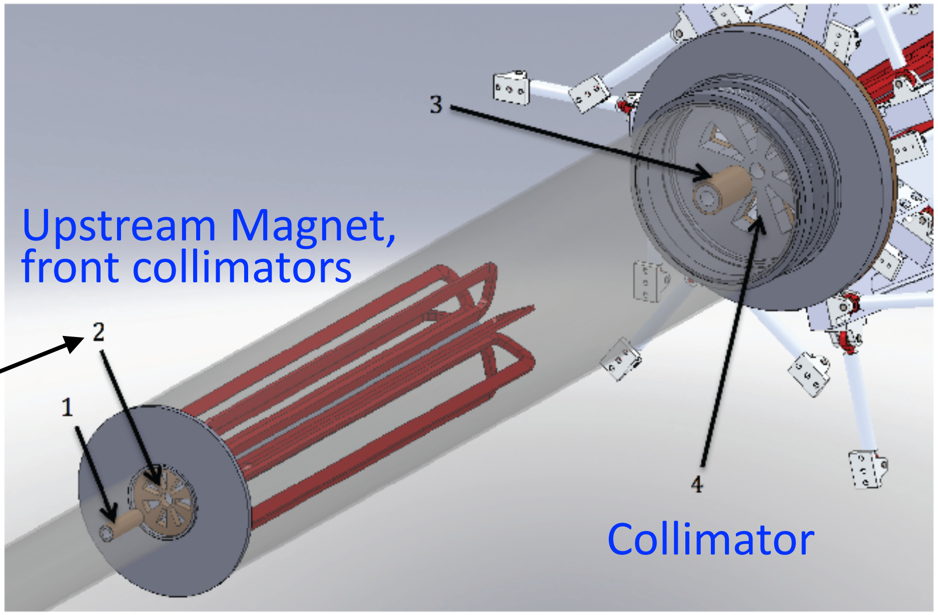
Coils in assembly, relative alignment preserved to simplify re-commissioning



Position Tolerance ~1mm

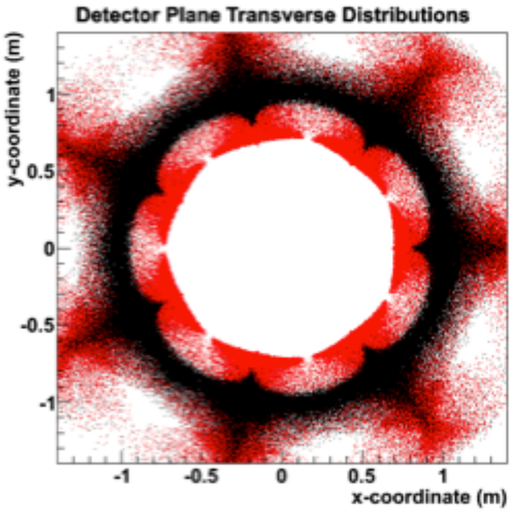


Machining tolerance on acceptance defining collimator: 200 µm



Detector Plane Segmentation

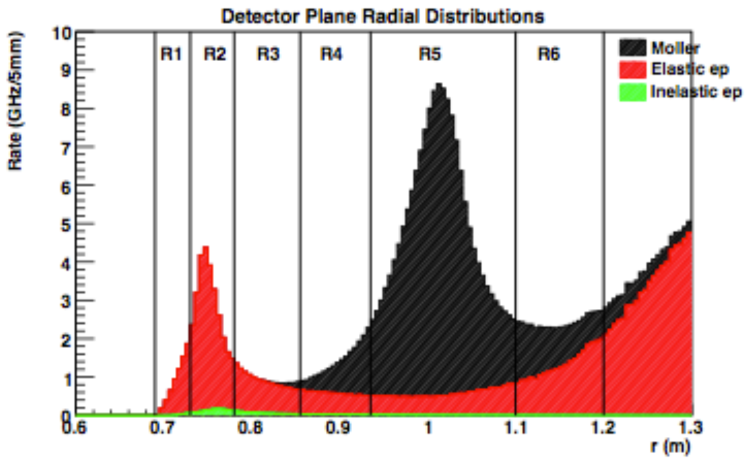
Quartz Cerenkov detectors will have radial and azimuthal segmentation



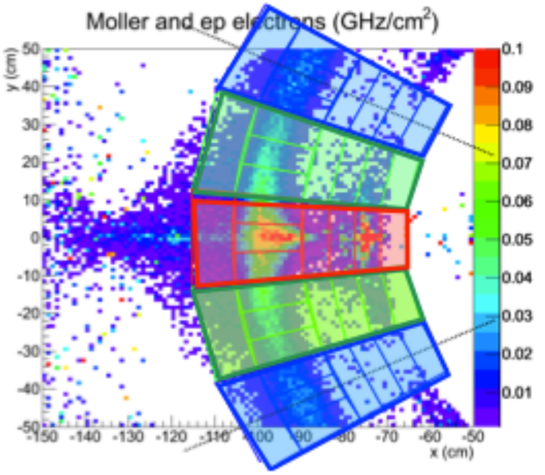
Azimuthal defocusing –

Different φ, different θ_{CM} bins

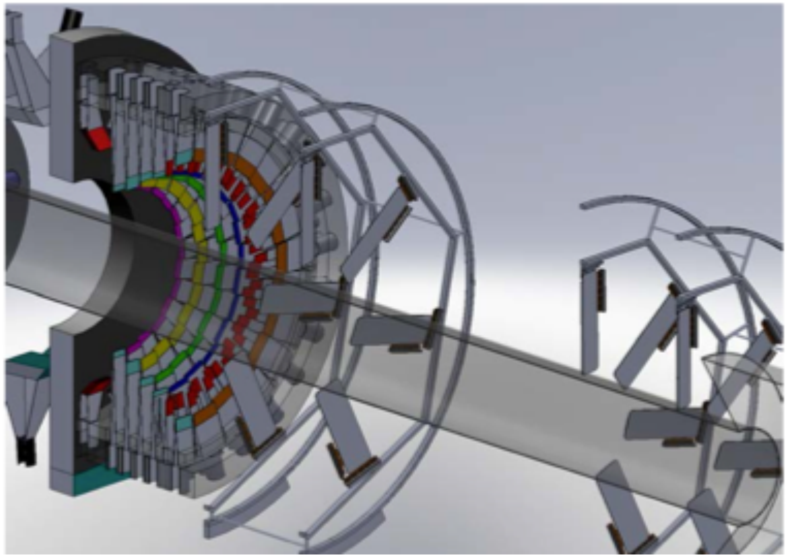
Detector Plane Radial Distribution



Main Moller peak in Region 5



Proposed Segmentation



28 azimuthal channels per radial bin

Moller peak (region 5): 84 azimuthal channels per radial bin

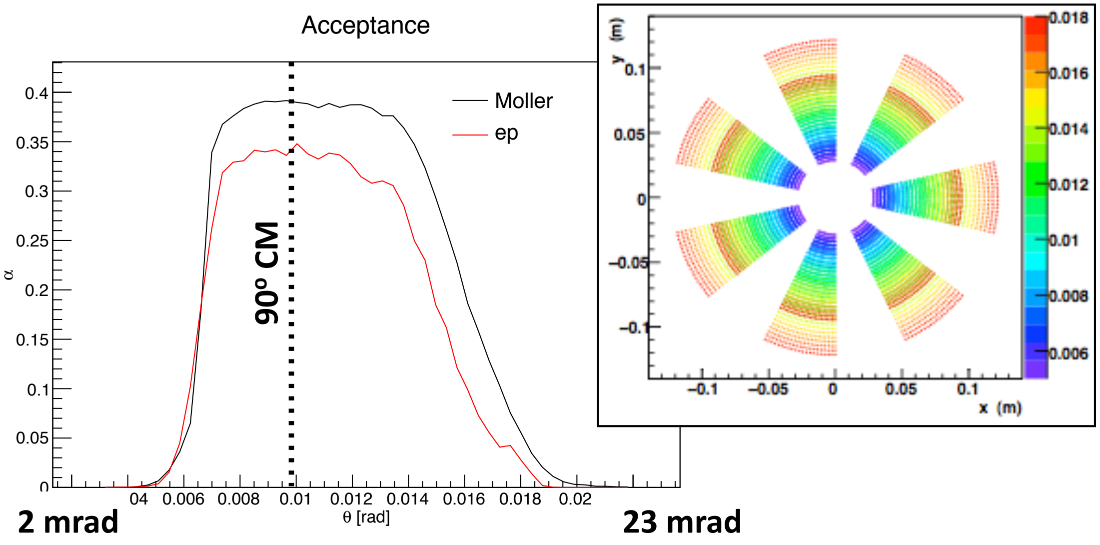
224 total channels

Rate per channel ~ few MHz – GHz

(overall rate ~ 159 GHz)

slide: M. Pitt, DOE Science Review, Sept '14

Rates, Noise Budget, and Statistical



High Rate, high precision

150 cm cell, up to 85 µA

38% ⇒ 70% (CM) acceptance

@ 75 µA: 144 GHz Mollers, 159 GHz total

Quiet JLab beam, high-flow target, and low-noise electronics keeps precision high

Noise Budget

Parameter	Noise (75 µA)	Noise (60 µA)
Statistical Width (0.5 ms)	**~79 ppm**	**~89 ppm**
Target Density Fluctuation	26 ppm	21 ppm
Beam Intensity Resolution	10 ppm	10 ppm
Beam Position Noise	7 ppm	7 ppm
Detector Resolution (25%)	3.1%	3.1%
Electronics Noise	10 ppm	10 ppm
Measured Width	**88 ppm**	**95 ppm**

$$\sigma_{A_{expt}} = \frac{\sigma_{\mathtt{pair}}}{\sqrt{N}}$$

$N_{pair} = (8.3\times10^{7})\, N_{days}$

$$A_{PV} \sim \frac{1}{P_b}\frac{1}{(1 - f_{bkgd})} A_{expt}$$

A_{PV} ~ 35 ppb $\Longrightarrow$ 9.5% irreducible background fraction
80% polarization $\Longrightarrow$ A_{expt} ~ 25 ppb

Run Phases

Multiple Run Phases Optimizes Statistical and Systematic Precision

- Hardware changes (beamline, collimation, electronics, detectors…)
- Detailed analysis
- Improved run planning / test planning
- Publication of intermediate results

E158

Run 1: 2001
- collimator upgrade

Run 2: 2002
- “slice” bpm upgrade
- 1st physics publication

Run 3: 2003
- 75% of total statistics

Qweak

Commissioning: Oct 2010
- BCM electronics
- detector radiators, new collimators
- background detectors
- 1st publication

Run 1: Oct 2010 - May 2011
- Dump beamline rebuild
- BCM electronics upgrade

Run 2: Nov 2011 - May 2012
- >50% of statistics

Plan for Approaching 2% Precision

60 µA, 90% polarization

Run Phases	1 kHz Width	PAC Days (prod)	Stat Error (ppb)	Stat Error (%)	Eff %	Calendar Weeks (prod.)	Comm Weeks	Total Weeks
I	105	14	3.09	10.9	40	5	6	11
II	100	95	1.13	3.9	50	27	3	30
III	95	235	0.68	2.4	60	56	4	60
Total		**344**	**0.57**	**2.01**			**13**	**101**

Run Phase 1

- Spectrometer optics, acceptance, alignment
- First look at backgrounds
- Test sufficiency of beam correction tools and analysis
- beam quality (asymmetry and halo)

Result: near precision of SLAC-E158

Run Phase 2

- statistical behavior of beam asymmetries, measured asymmetry
- quality of "slow" reversals (Wien, g-2)
- precision on background, normalization, beam corrections, polarization

Result: 2.5x beyond SLAC-E158,

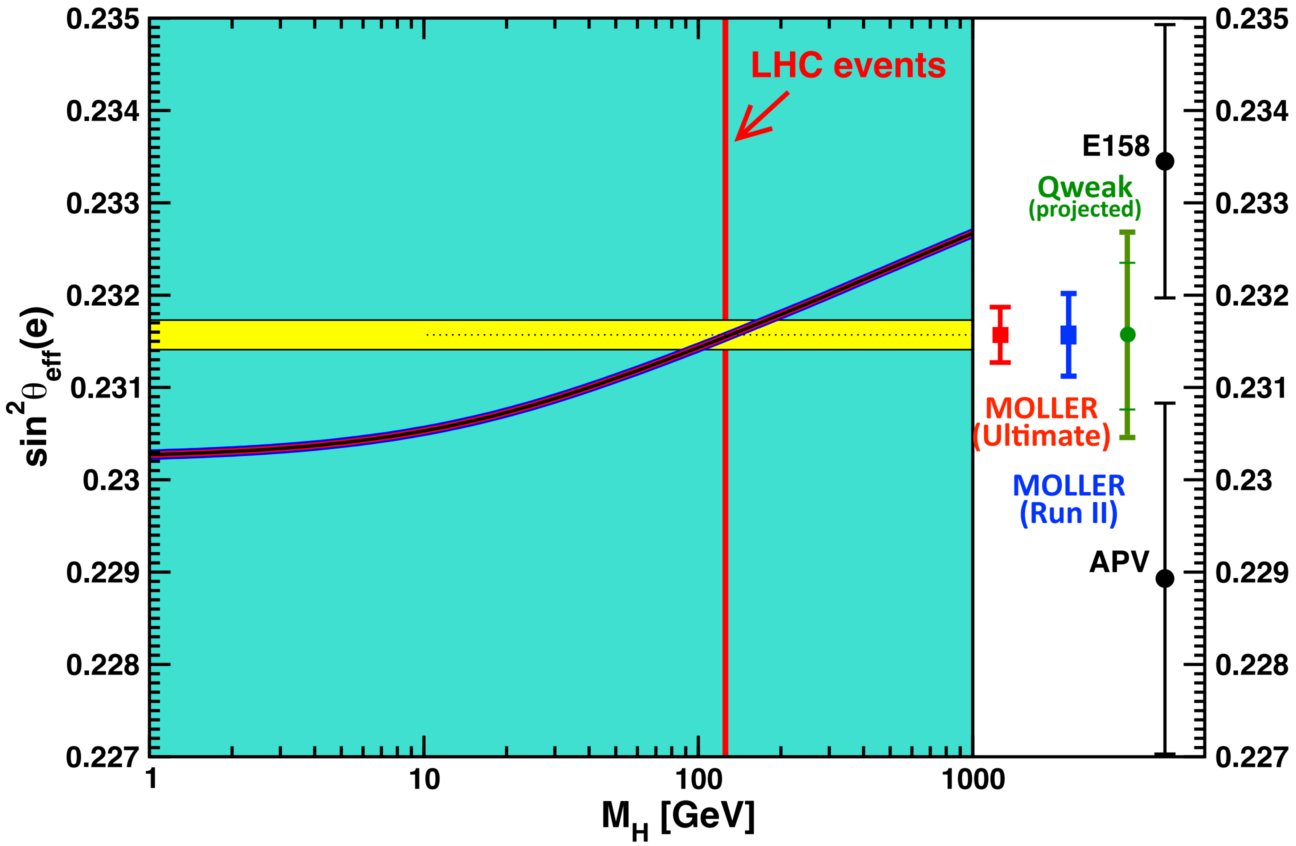
$\delta(\sin^2\vartheta_W)=0.00044$ (stat), 0.00047 (stat+syst)

Run Phase 3

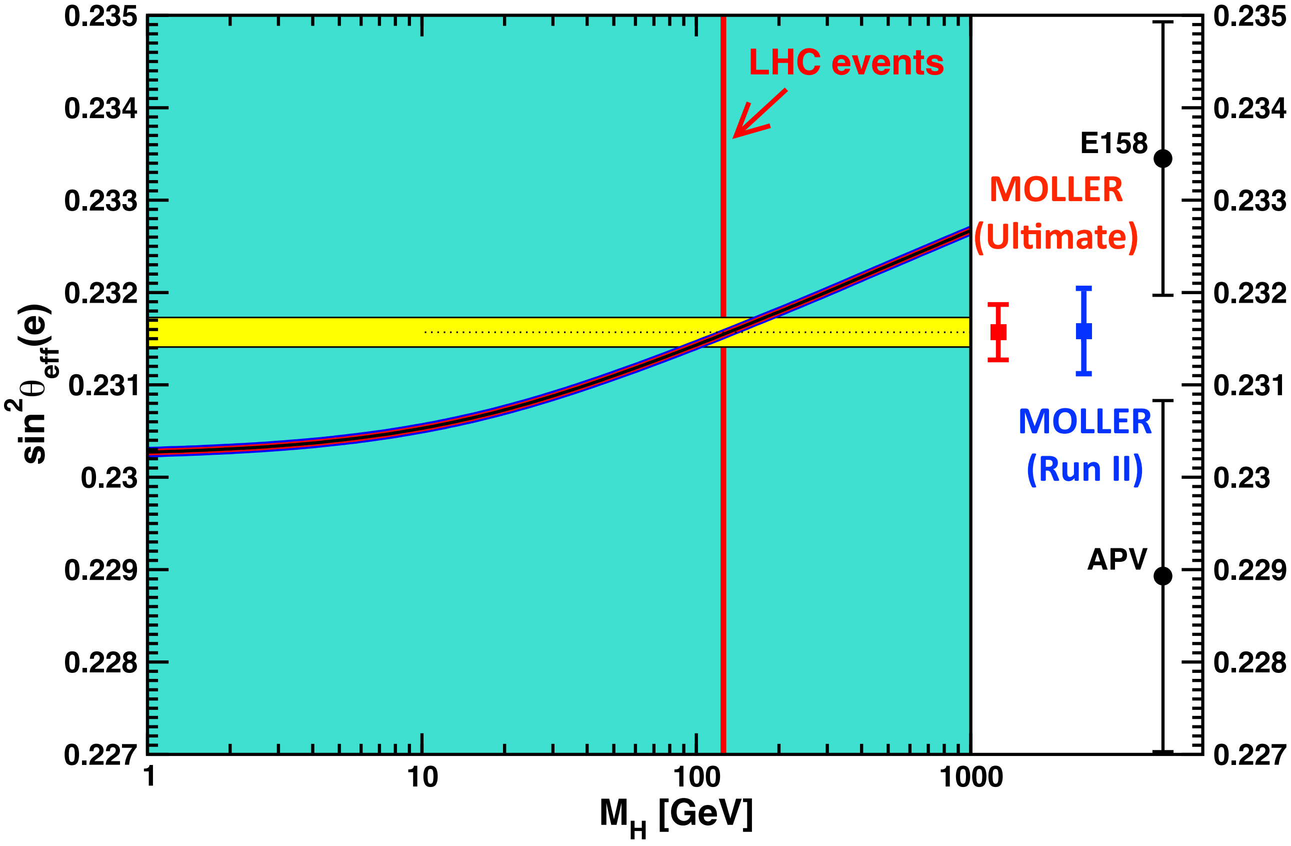
- ultimate precision, ultimate systematic uncertainty

Result: $\delta(\sin^2\vartheta_W)=0.00024$ (stat), 0.00028 (stat+syst)

Physics Impact of Run 2 result



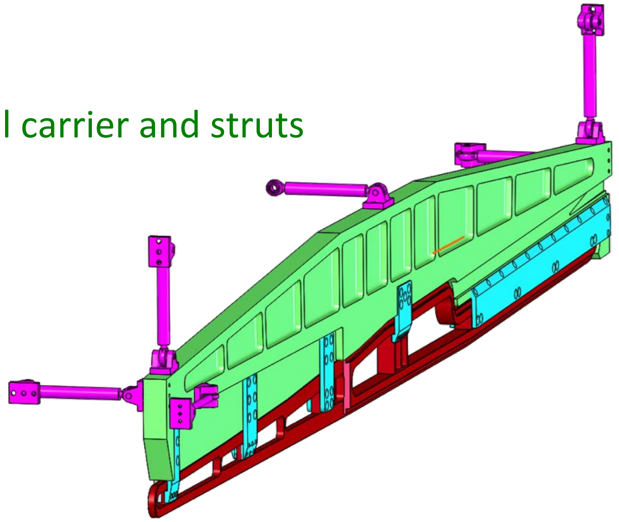
Physics Impact of Run 2 result



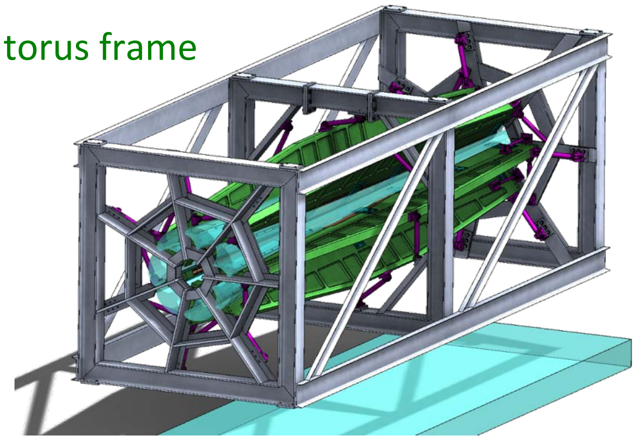
Spectrometer – Coil Carriers, Frame, Vacuum Chamber

- MIT-Bates engineers have designed coil carriers, mounting struts, frame, and vacuum chamber for the hybrid torus
- Finite element analysis (FEA) studies of deflection/stress have been carried out – results predict deflections within the tolerance of < 3 mm allowed by GEANT4 simulated coil mis-positioning studies

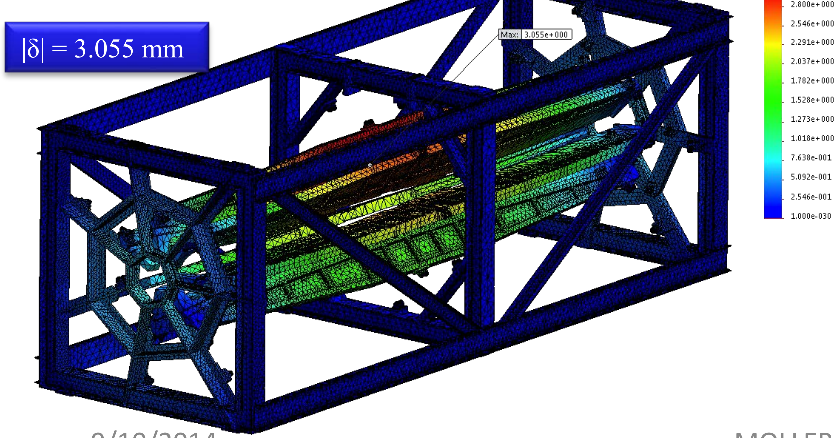
Coil carrier and struts



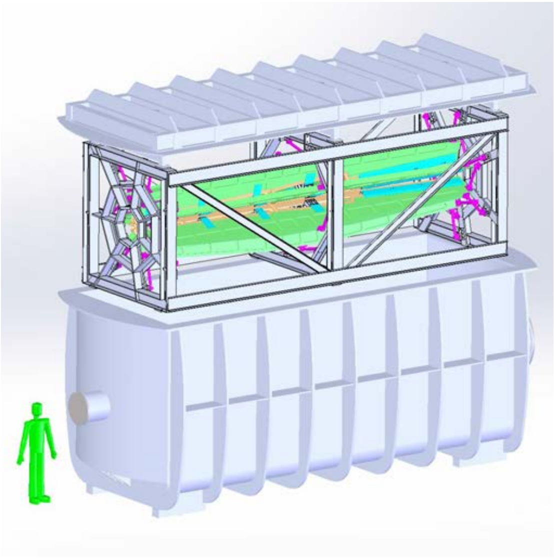
Hybrid torus frame



FEA Deflection



Vacuum chamber

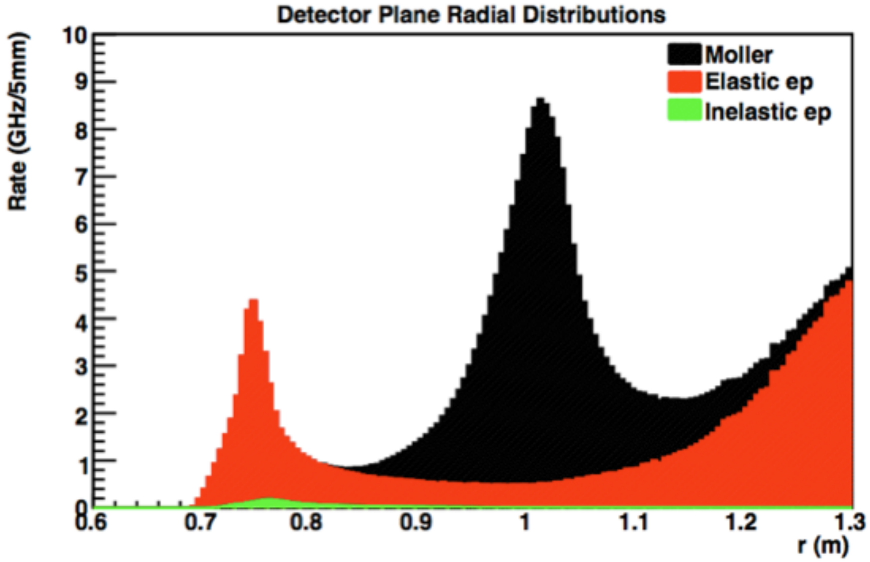


slide: M. Pitt, DOE Science Review, Sept '14

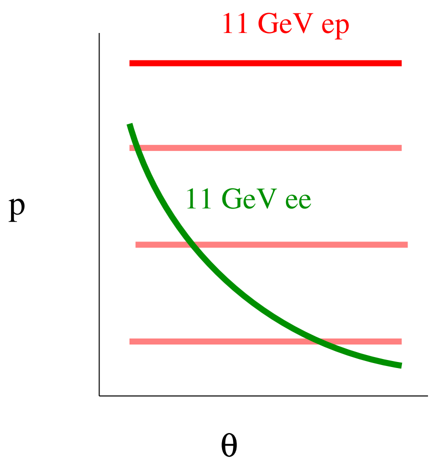
Kinematic Normalization

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

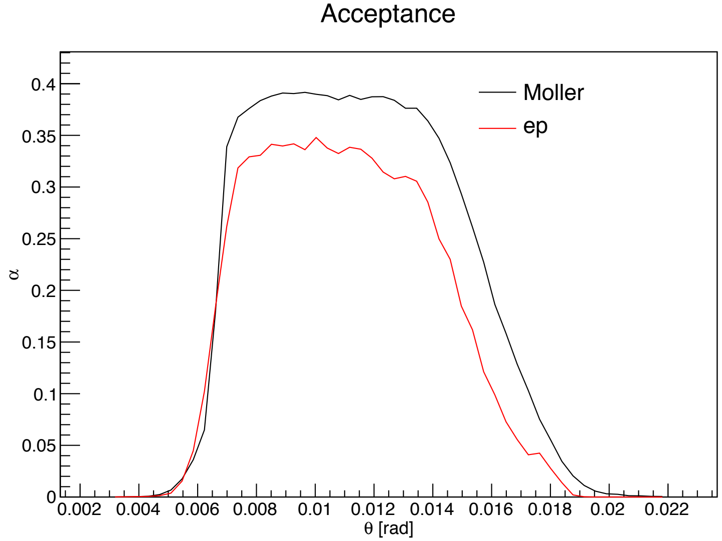
Need $\dfrac{4\sin^2\theta}{(3+2\cos^2\theta)^2}$ to within 0.5% of itself



Map acceptance using GEM chambers between the hybrid magnet and integrating detector stack



Optics calibration using lower beam energy, sieve slit, optics target



Ultimately estimated using simulation, benchmarked to tracking runs

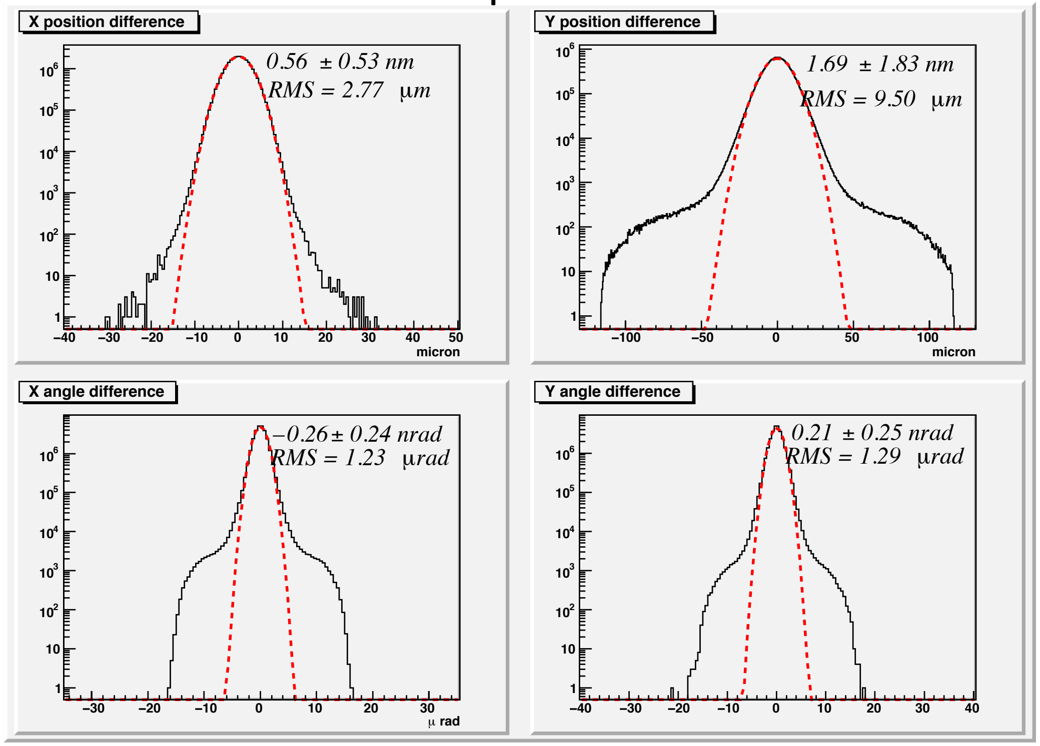
Calibrations and tracking studies will recur through all run phases

Beam Asymmetries

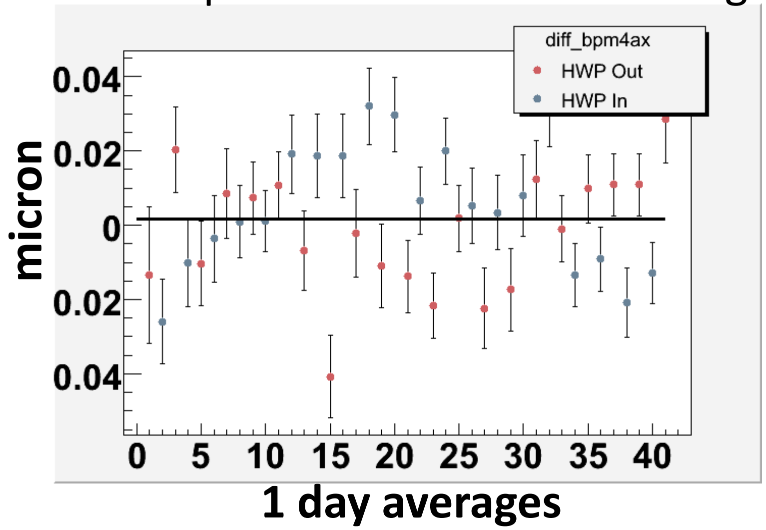
beam position, angle, energy variation with helicity causes an experimental asymmetry

• Injector source laser	20-50 nm in 5MeV injector
• e- beam delivery (adiabatic damping)	factor of 10-100 from adiabatic damping
• cancellation with “slow” reversals	factor of 2-10
• detector symmetry	Factor >10 in sensitivity
• correction calibration (beam modulation)	10% precision

HAPPEX-II: Zero position differences



HAPPEX-II: position difference convergence



Beam Asymmetries - “2nd order”

Helicity-correlated Beam Spot Size variation creates false asymmetry

Source configuration

- Bounds <10^{-4} from laser configuration
- must be maintained throughout run

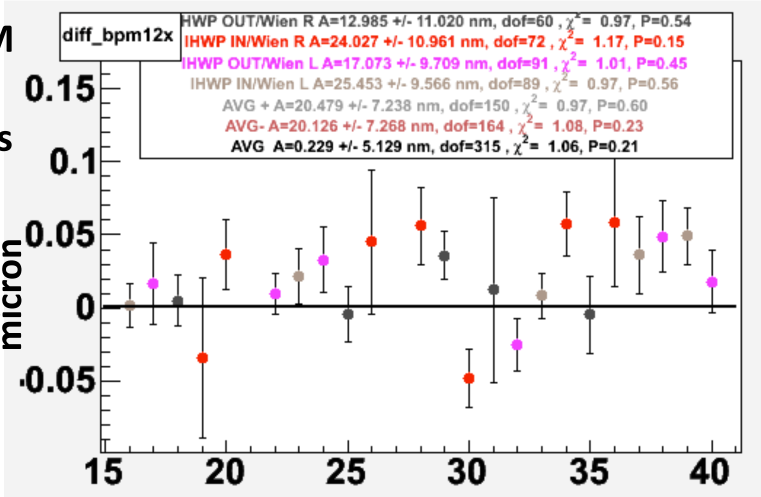
Adiabatic Damping

- Good beam match keeps variation small

Slow Reversals

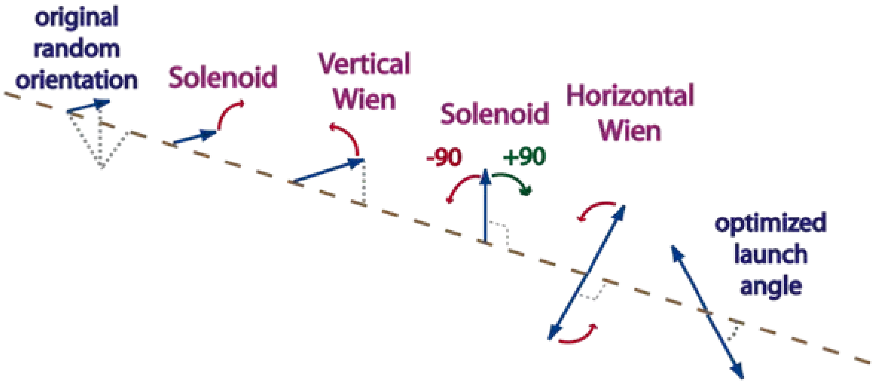
- Laser optics reversals (e.g. IHWP) do not cancel expected sources of spot-size differences
- Helicity reversal on e^- beam will be incoherent with spot-size differences
- Net factor ~10 suppression of beam asymmetries

PREX-II showed ISM cancellation of position differences



Injector Spin Manipulation

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



g-2 rotation

- Beam energy (ΔE~100 MeV)
- ~few reversals during run phases 2 and 3

Beam Polarization - Evolution to 0.4%

Projected Performance:

Analysis improvements, beam tests, hardware evolution needed to improve from baseline upgrade

Run Phase 1:

projecting to completed upgrades in progress, from current state-of-the-art:

- Compton electron - 0.8%
- Compton photon - 0.7%
- Compton correlated error: 0.2%
- Moller: 1%

Run Phase 2:

- Compton electron: 0.4%
- Compton photon: 0.4%
- Compton correlated error: 0.2%
- Moller: 0.5%

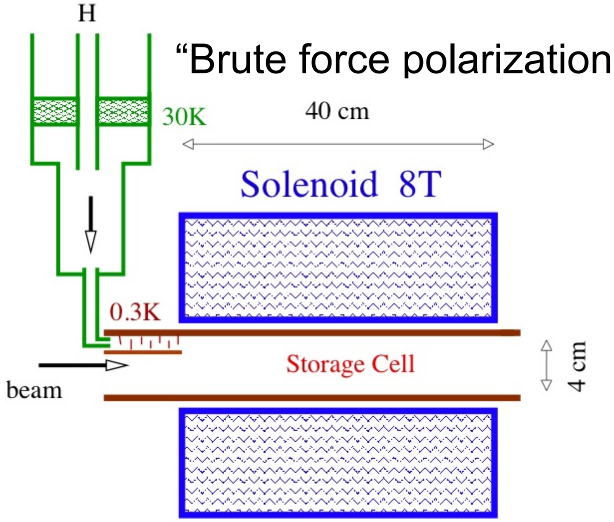
Detailed, high-precision cross-check in Run 2

Alternative: Atomic H Møller

Moller polarimetry from polarized atomic hydrogen gas in an ultra-cold magnetic trap

- P_e =100% ± 10^{-4}
- high beam currents
- Non-invasive, continuous

E. Chudakov and V. Luppov, IEEE Transactions on Nuclear Science, v 51, n 4, Aug. 2004, 1533-40

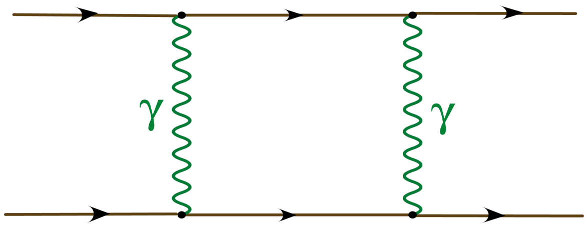


Development at Mainz underway for P2 at MESA

possible alternative if needed to resolve controversial results in Compton and high-field Moller

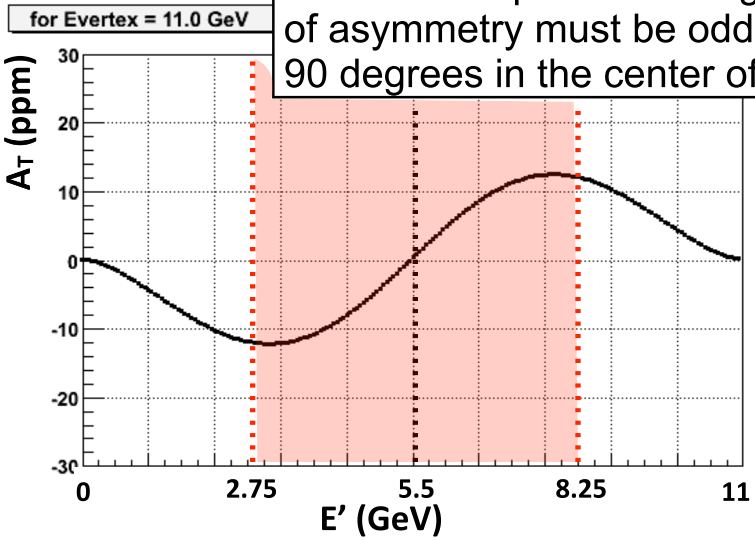
Transverse Asymmetry

Interference between one- and two-photon exchange



electron beam polarized
transverse to beam direction

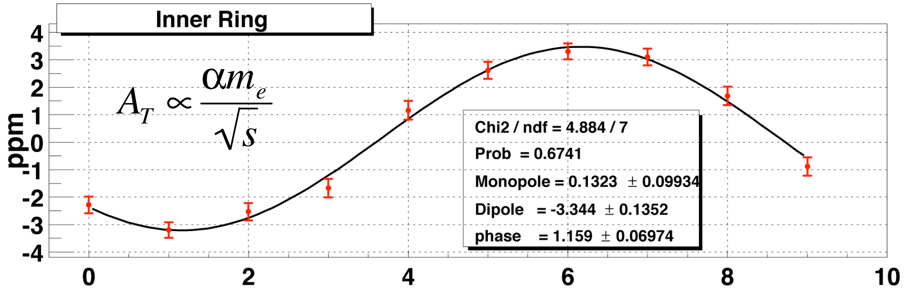
$$A_T \equiv \frac{2\pi}{\sigma^{\uparrow}+\sigma^{\downarrow}}\frac{d(\sigma^{\uparrow}-\sigma^{\downarrow})}{d\phi} \propto \vec{S}_e \bullet (\vec{k}_e \times \vec{k}'_e)$$



For identical particles: magnitude of asymmetry must be odd around 90 degrees in the center of mass

Potential systematic error in A_{PV}.
Suppressed by
- small transverse polarization
- azimuthal acceptance symmetry
- acceptance symmetry in c.m.s. polar angle

Measured at E158

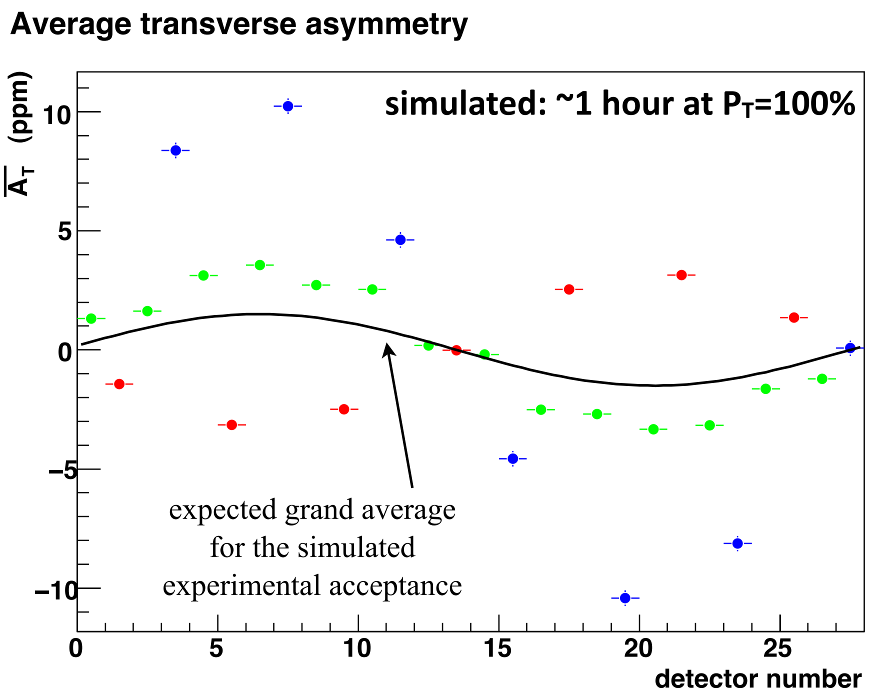


$$A_T \propto \frac{\alpha m_e}{\sqrt{s}}$$

Theory References:

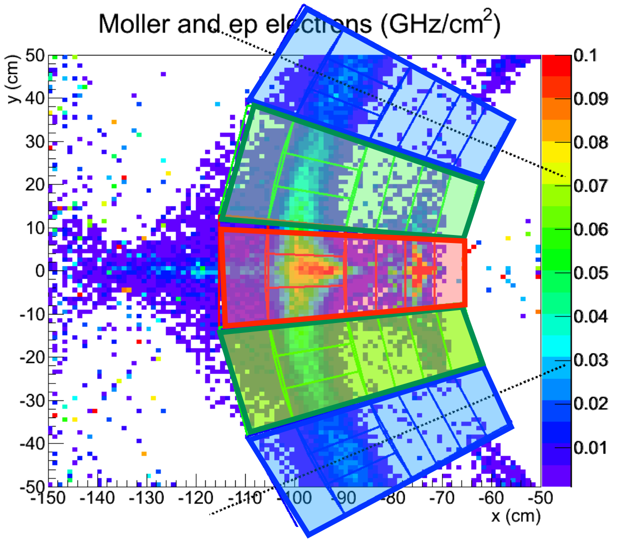
1. **A. O. Barut and C. Fronsdal, (1960)**
2. **L. L. DeRaad, Jr. and Y. J. Ng (1975)**
3. **Lance Dixon and Marc Schreiber:hep/ph-0402221**

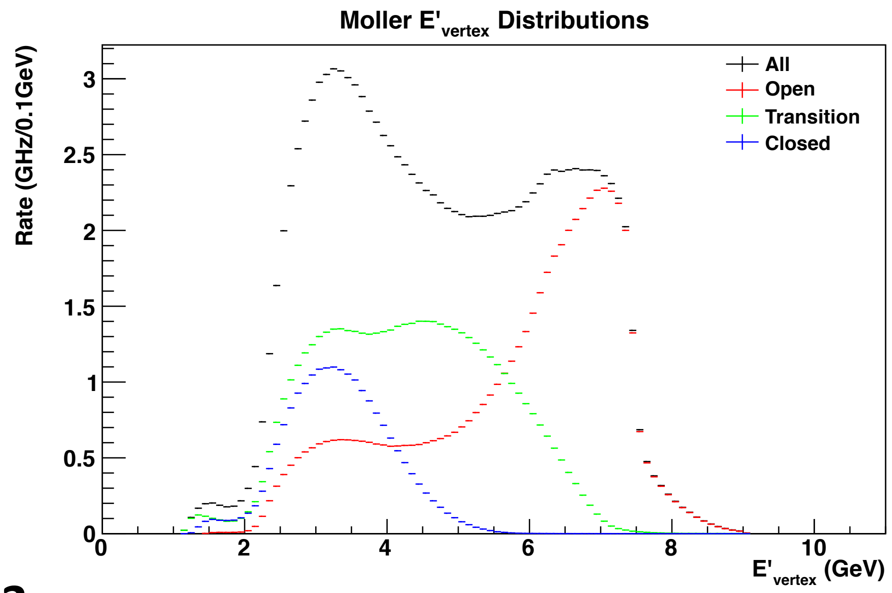
Transverse Beam Polarization


Average transverse asymmetry

simulated: ~1 hour at P_T=100%

expected grand average for the simulated experimental acceptance




Moller E'$_{vertex}$ Distributions

- Initial beam setup ~ 1-2 degrees
- Unique signature of transverse beam polarization
- 50 ppb error on A_T*P_b in 4 hours: 1 degree precision
- Over entire run: feedback will hold transverse polarization small (<<1 degree)

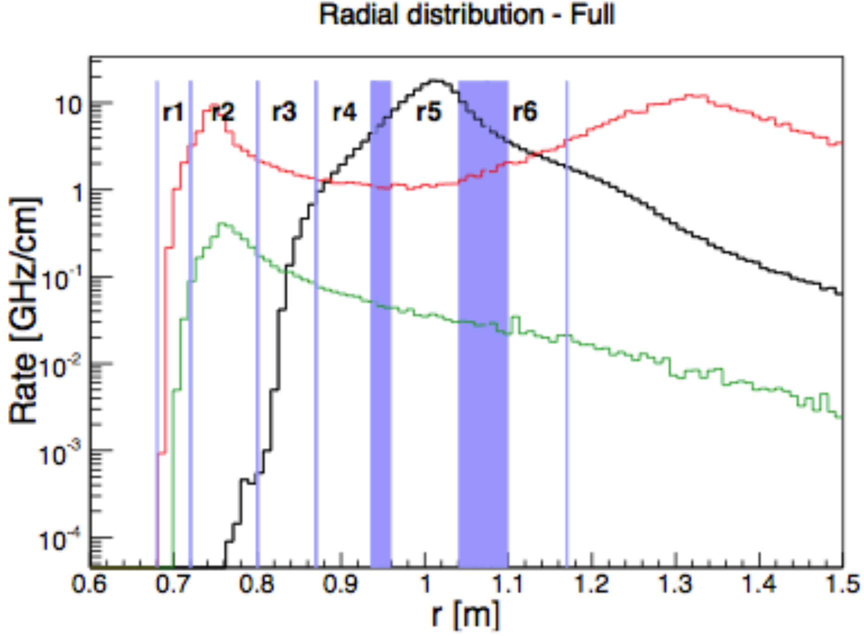
Run Phase 1:

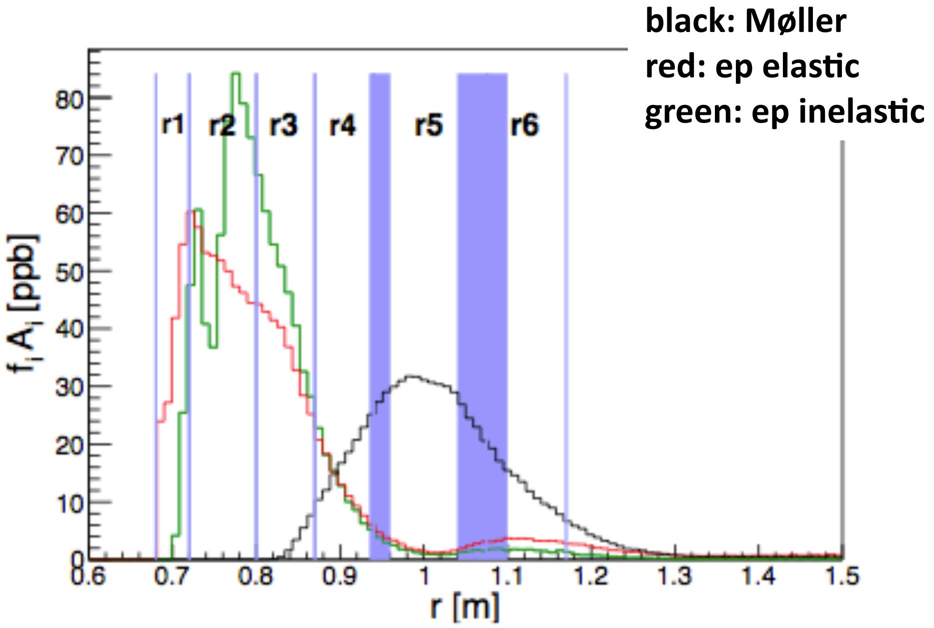
- A_T measurement
- Feedback technique tested

Run Phases 2 and 3:

- Routine feedback

ep Backgrounds





black: Møller
red: ep elastic
green: ep inelastic

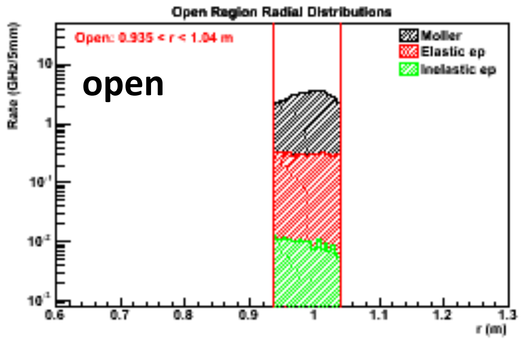
ep elastics: 8.9% under Møller peak, asymmetry well known

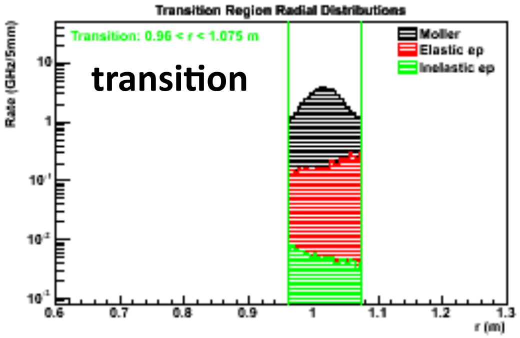
ep inelastics: <0.5% of signal but asymmetry not well known

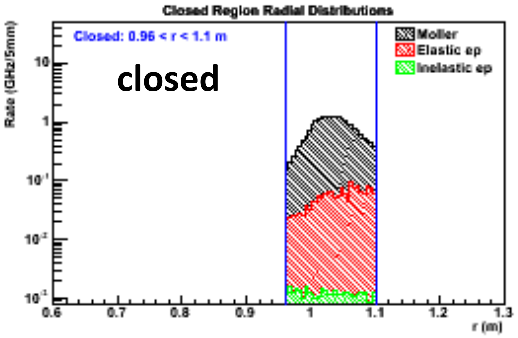
Al elastics: ~0.3% of signal, elastic from target windows

Radial and Azimuthal binning - measure asymmetries under the Møller peak

- R4, R3, R2: inelastic contribution dominant
- R4: best measure. W^2 distribution matches signal region R5 at low W^2
- Test using radial and azimuthal variations







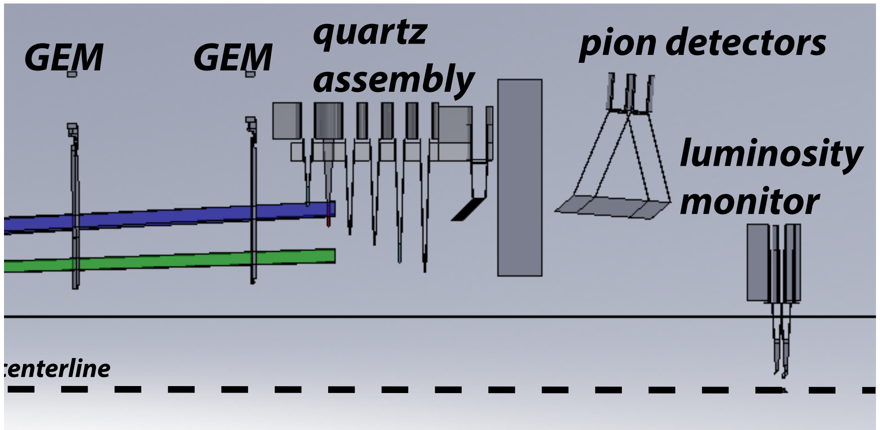
R5 Azimuthal segments

black: Møller
red: ep elastic
green: ep inelastic

Other Backgrounds

π/μ:

- direct scaling from E158 suggests ~0.1% fraction, simulation confirms 0.13%
- asymmetry ~500 ppb
- hyperon decay could contribute significantly
- direct measurement with pion detector required
- After run 3: known to within ~150ppb.

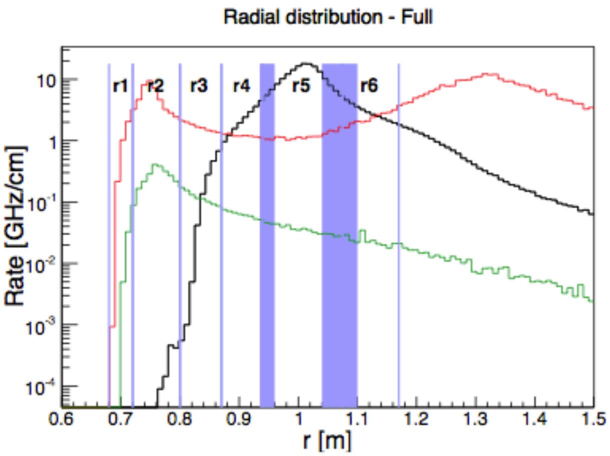


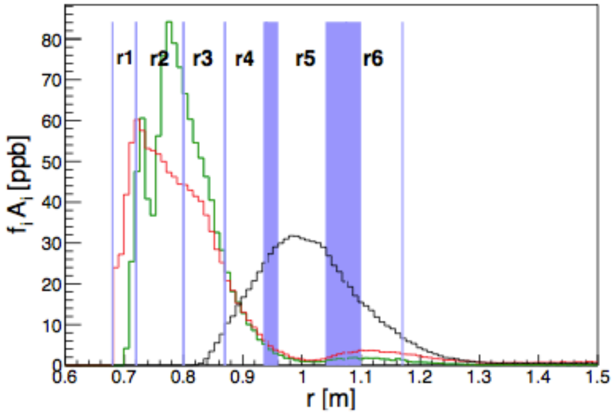
Neutrals:

- suppressed by thin quartz, lead-shielded PMT assemblies
- blinded tube, spectrometer-off runs
- Expected contribution ~0.1%, will be well measured
- Expected asymmetry negligible, will be well measured with auxiliary detectors

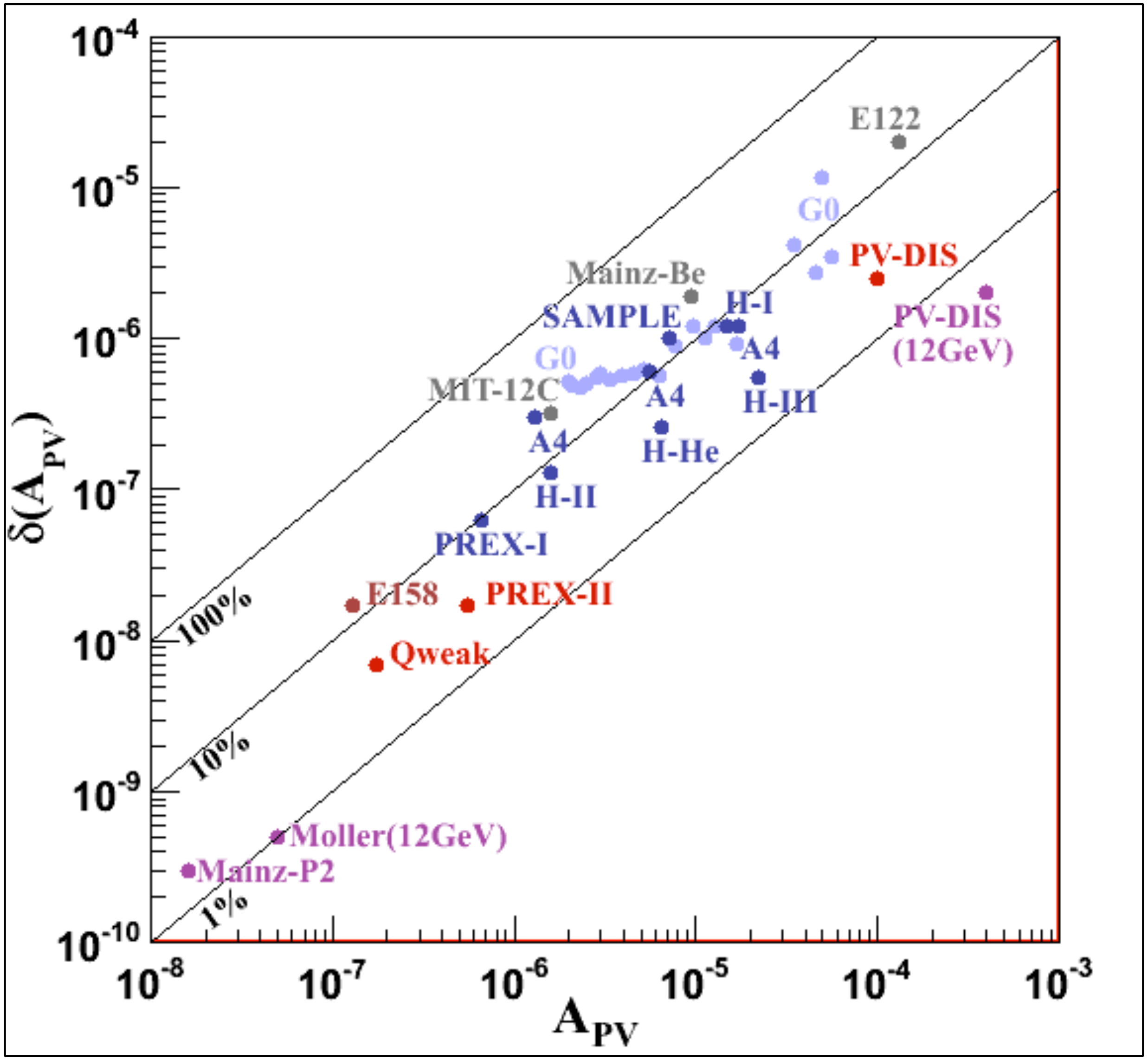
Background Summary

Background	Fraction of total signal (%)	Asymmetry (ppb)	correction (ppb)	Note
e+p (+γ) → e+p (+γ)	8.9	~40	~3.6	A_{ep}
e+p (+γ) → e+X (+γ)	<0.5	~300	~1.4	Measured in azimuthal/radial dependence
γ + p → (π,μ,K) + X	~0.1	~500*	~0.7	Estimated from E158. Hyperon decay would show up here. Direct measurement in pion detector.
Al elastic (target)	~0.3	~440	1.3	simulation, QWeak measurement
neutral backgrounds	<0.1	0	0.1	measured with blinded tube and other auxiliary measurements

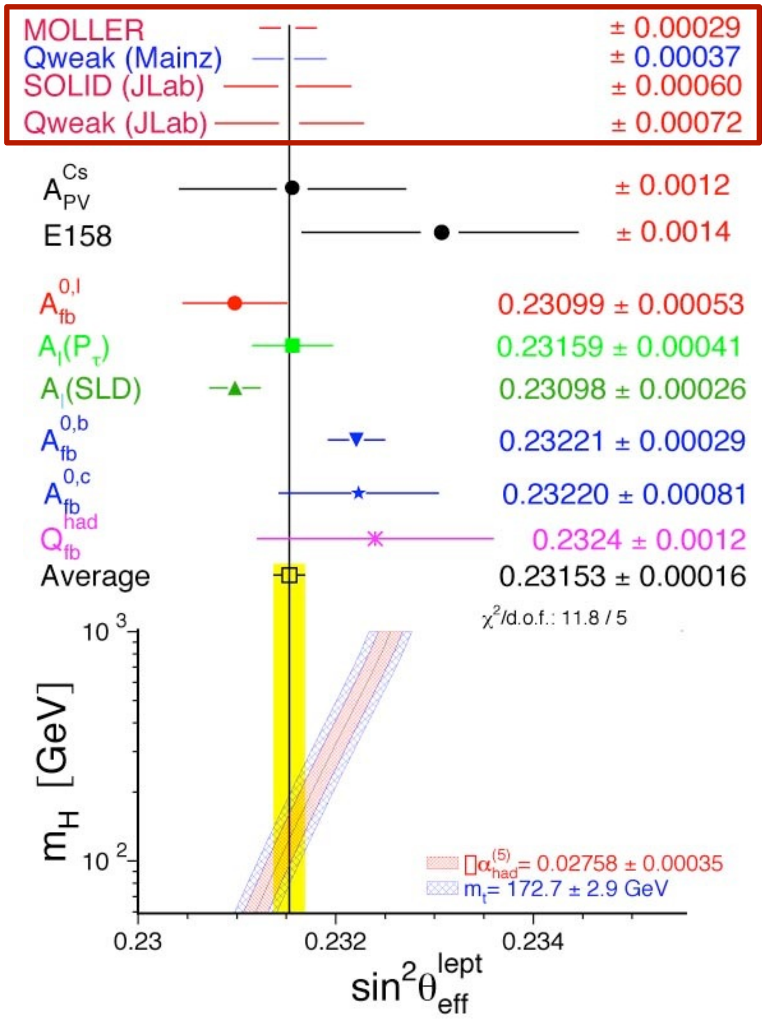




Precision PVES is a powerful probe of new



New *precision-frontier* measurements in PVES may cast a wide net over the parameter space available to new neutral current interactions...



...and open a new program of structure function study to explore the nucleon partonic structure and QCD