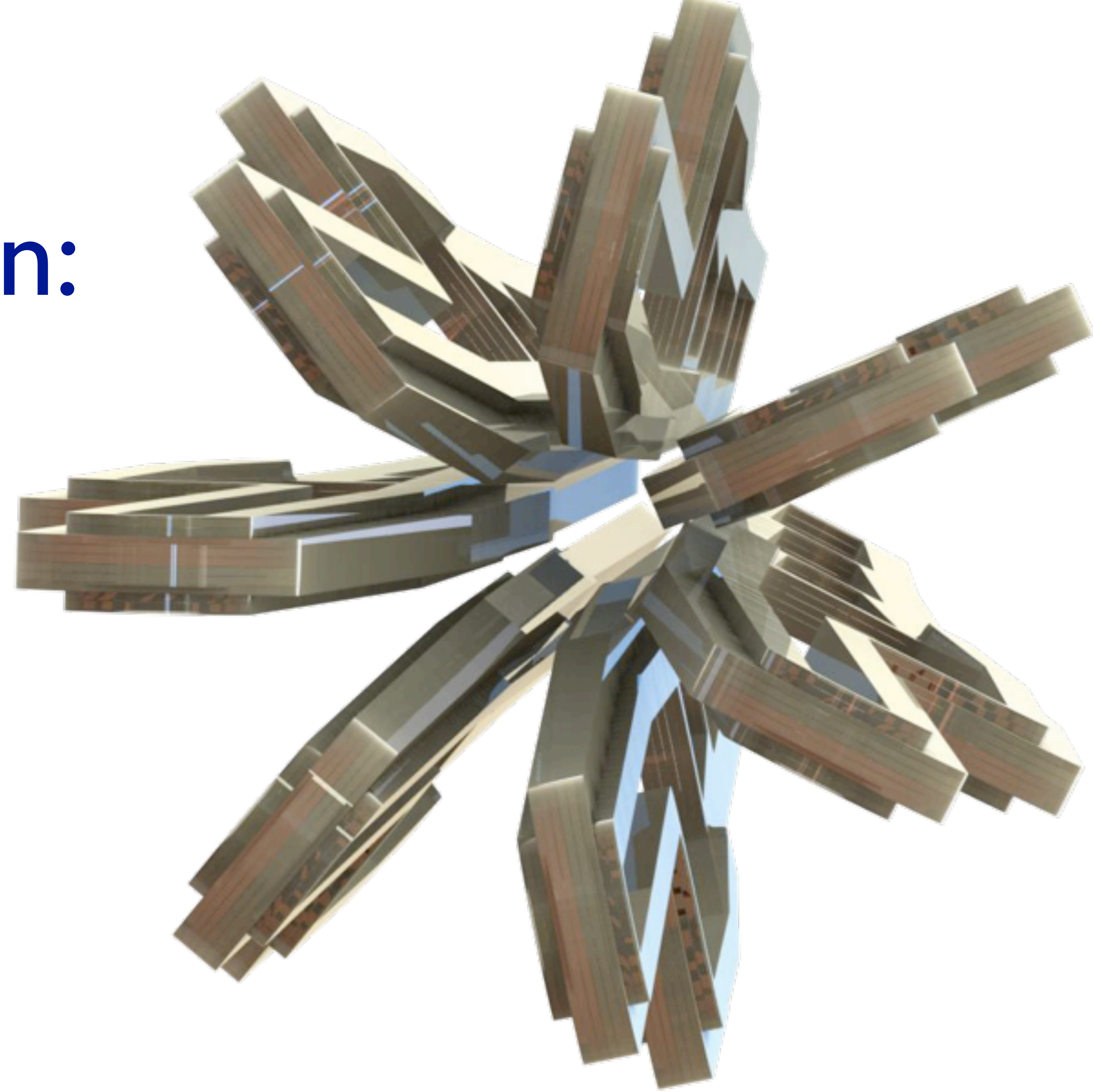
New Instrumentation: MOLLER



Mark Dalton for the MOLLER Collaboration

UNIVERSITY of VIRGINIA
ARTS & SCIENCES

Outline

Motivation
Experimental Overview
Recent Developments
- Spectrometer magnet design
- Simulation
- Detector design and tests

The Standard Model

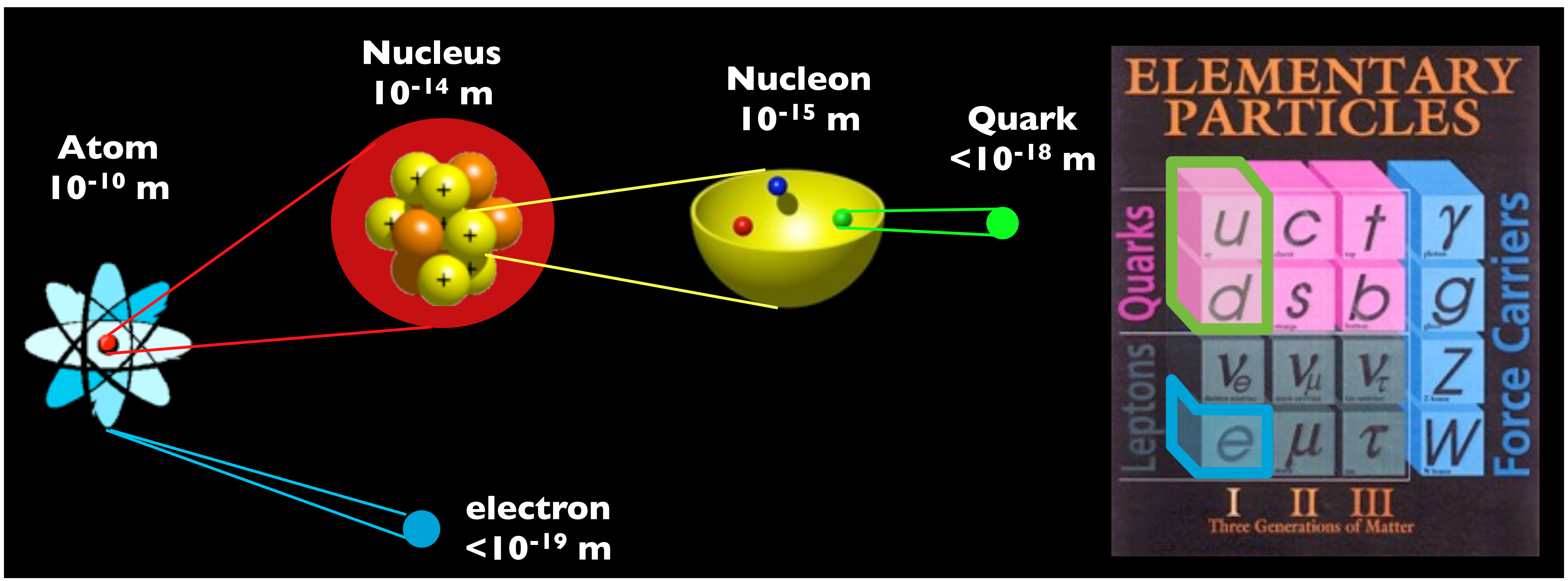
of particle physics

Quantum field theory framework

Forces …

	Gravity	Weak	Electromagnetic	Strong
mediator	(not found)	W^+, W^-, Z^0	γ	gluons
acts on	all	quarks and leptons	Electrically charged	quarks and gluons
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

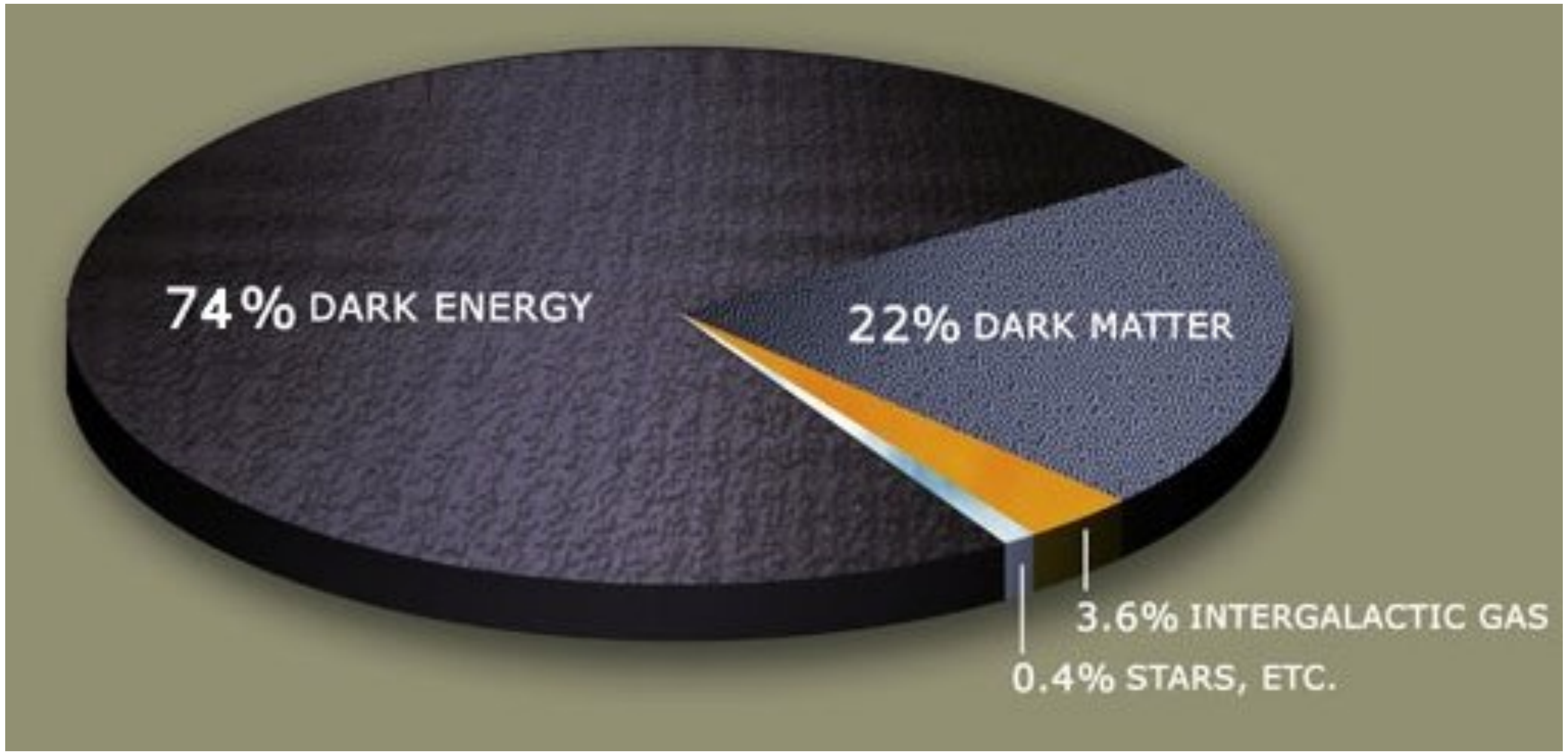
and particles



Should there be new physics?

Open SM Questions (a small subset)

What is dark matter?
What is dark energy, and what is the nature of the dark sector ?
Where is the anti-matter?



Ramsey-Musolf's list

What is the origin of matter (both visible and dark) ?
What is the dark energy and what is the nature of the dark sector ?
What is the origin of the dimensionful parameters of the SM ($m_{q,\nu}$, G_F, Λ_{QCD},...) and why are they stable against quantum corrections ?
What are the discrete symmetries of the early universe (P, **CP**, T, B, L,...) ?
When and how were they broken ? i.e. where is the anti-matter ?

Physics beyond the SM

Two lines of attack

Energy frontier

Tevatron and Large Hadron Collider

examples: See SUSY particles
see additional neutral Z'

Precision frontier

looking for tiny deviations from SM predictions or at phenomena that are highly-suppressed or forbidden by SM symmetries

Pattern of deviations:
guidance into nature of new physics

examples: Electric Dipole Moments
neutrino-less double beta decay ($0\nu\beta\beta$)
Baryon number or lepton flavor violation
Parity-Violating Electron Scattering

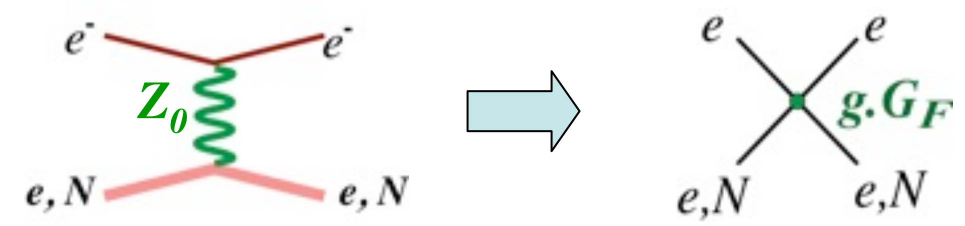
Neutral Current Beyond the SM

Many new physics models require new, heavy, neutral current interactions

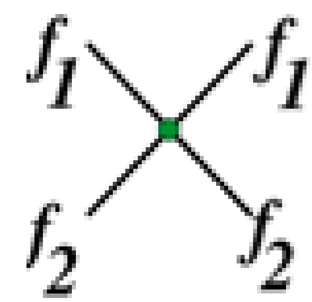
$$\mathcal{L} = \mathcal{L}_{\texttt{SM}} + \mathcal{L}_{\texttt{new}}$$

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

Low energy WNC interactions ($Q^2 << M_Z^2$)



Consider $f_1 f_1 \to f_2 f_2$ **or** $f_1 f_2 \to f_1 f_2$



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

Eichten, Lane and Peskin, PRL50 (1983)

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

Sensitivity to TeV-scale contact interactions if:

- $\delta(\sin^2\theta_W) \leq 0.5\%$
- away from the Z resonance

- Precision neutrino scattering
- PV couplings through interference with EM
  - opposite-parity transitions in heavy atoms
  - parity-violating electron scattering

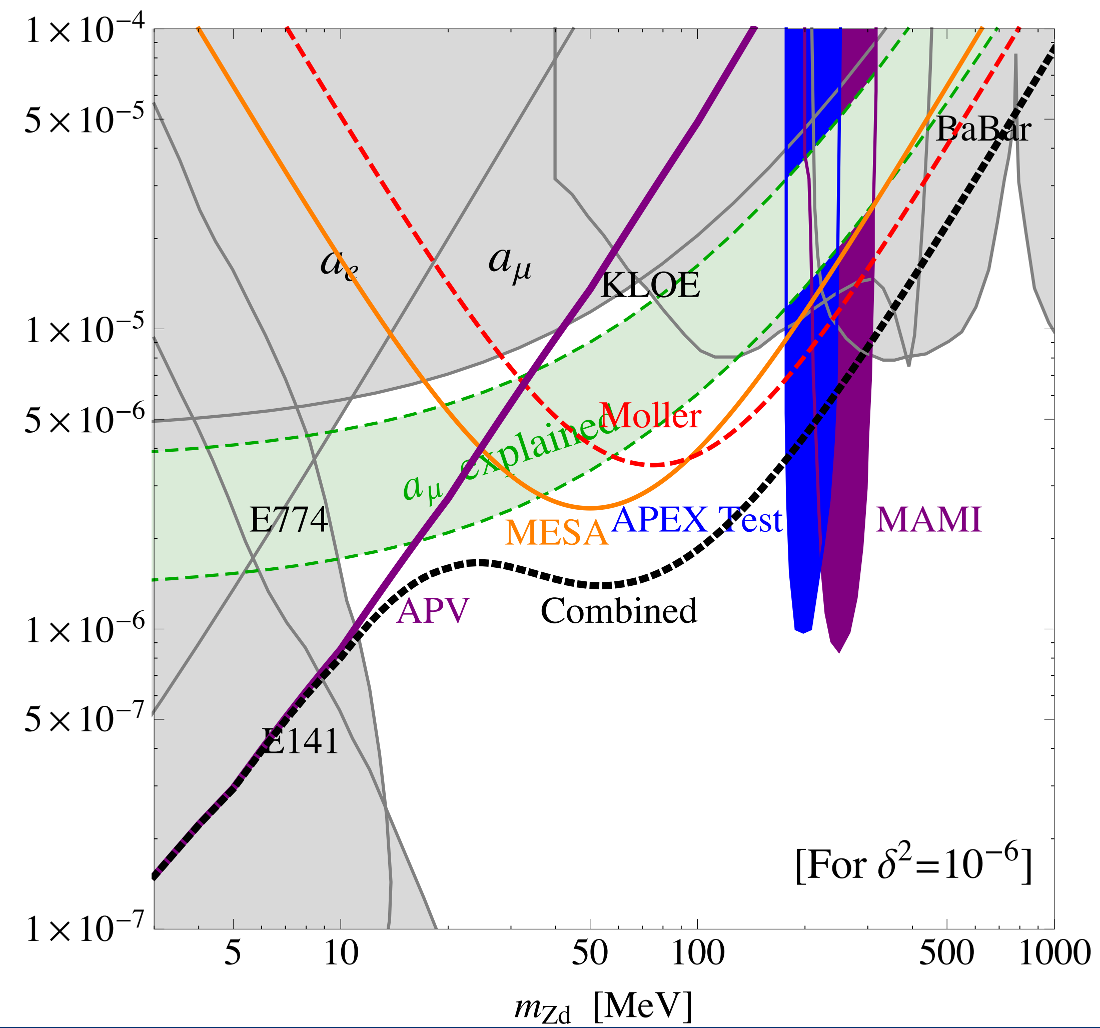
Physics Reach for MOLLER

$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j \quad \Rightarrow \quad \frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5 \text{ TeV}$$

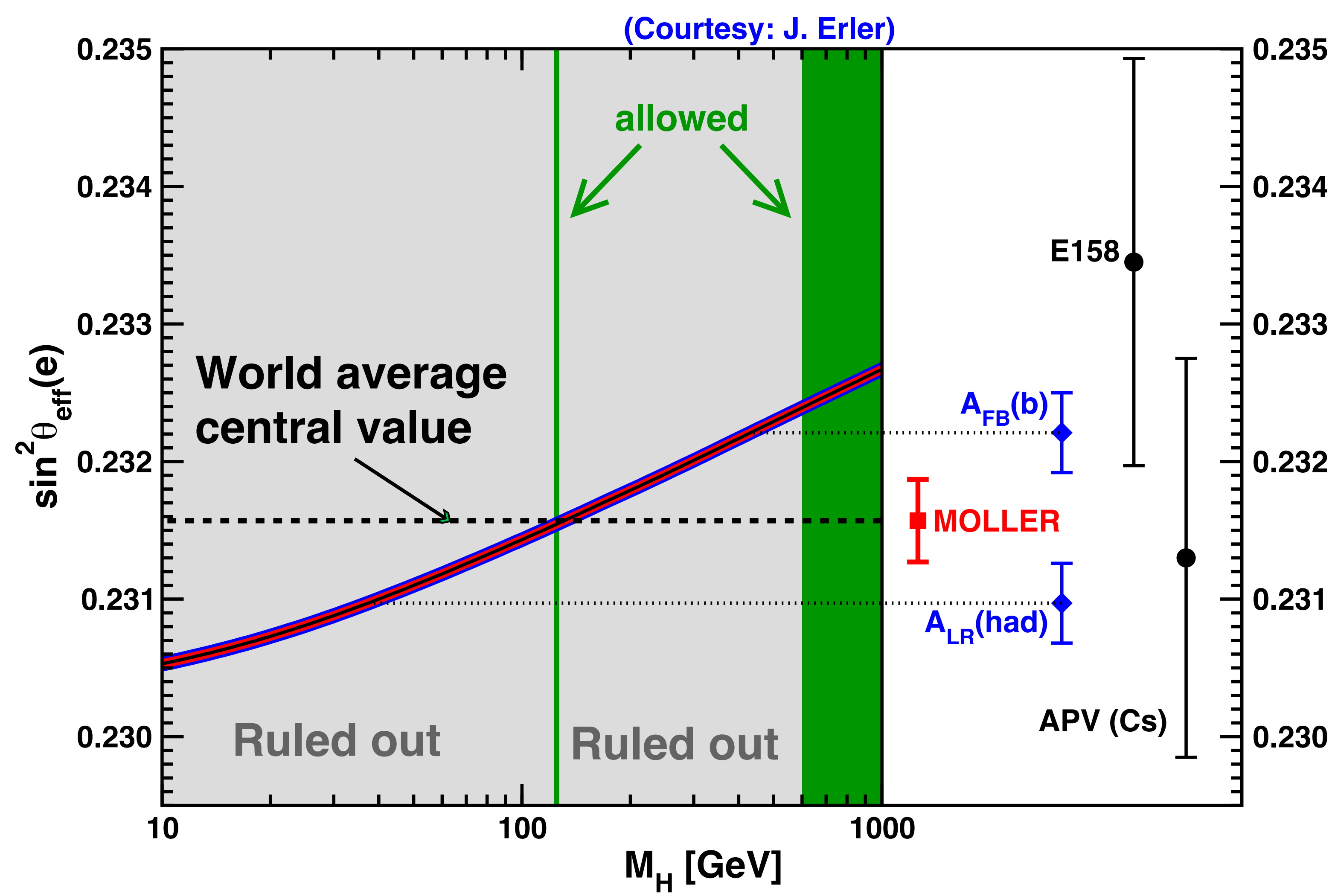
best contact interaction reach for leptons at low OR high energy

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

Complementary to direct heavy photon searches:



Test the consistency of the SM prediction, between directly measured m_H, m_W, m_t, $\sin^2\theta_W$



Running of weak mixing angle

This is complicated "scheme dependent" many orders in loops of all particles

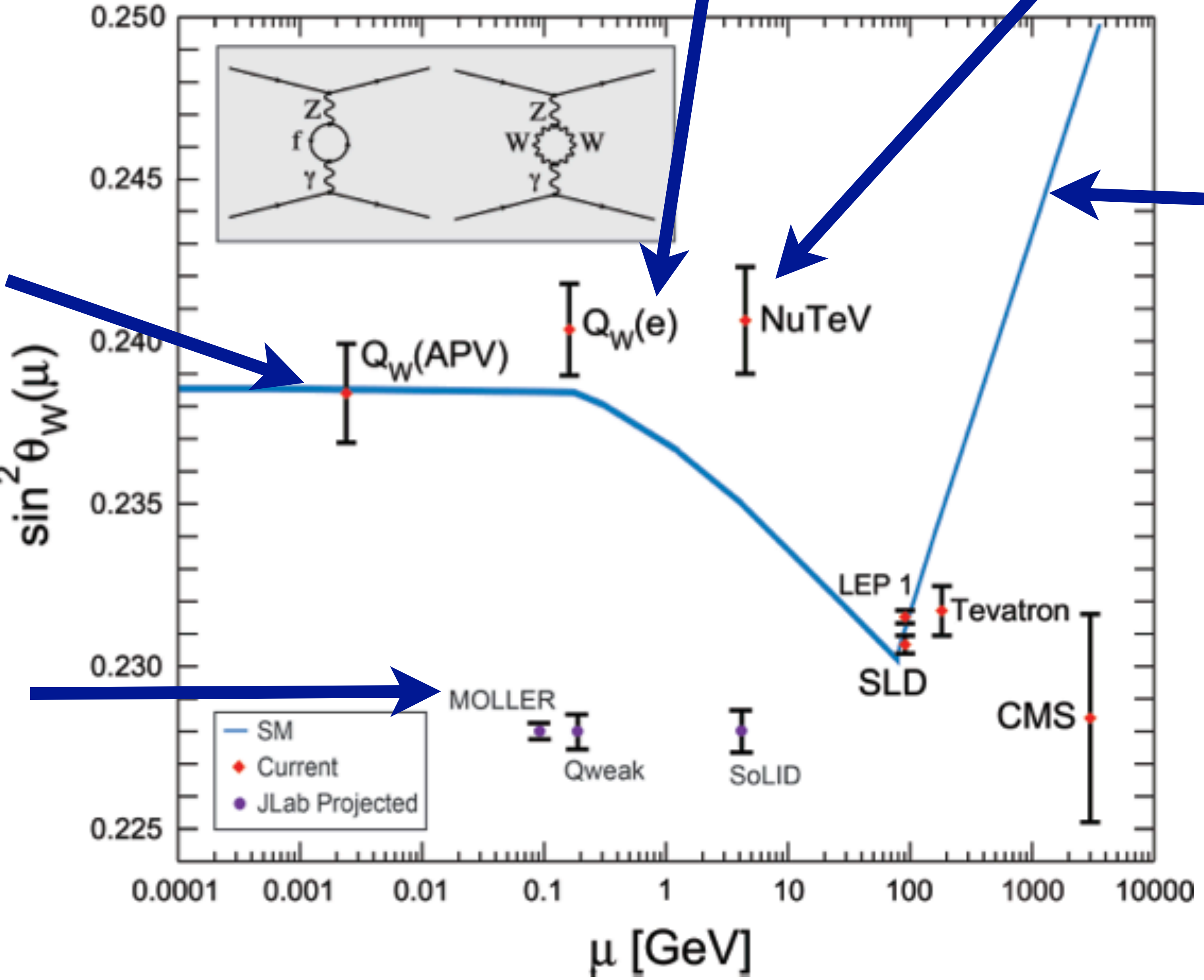
Parity violating Moller scattering

neutrino deep-inelastic scattering cross-sections

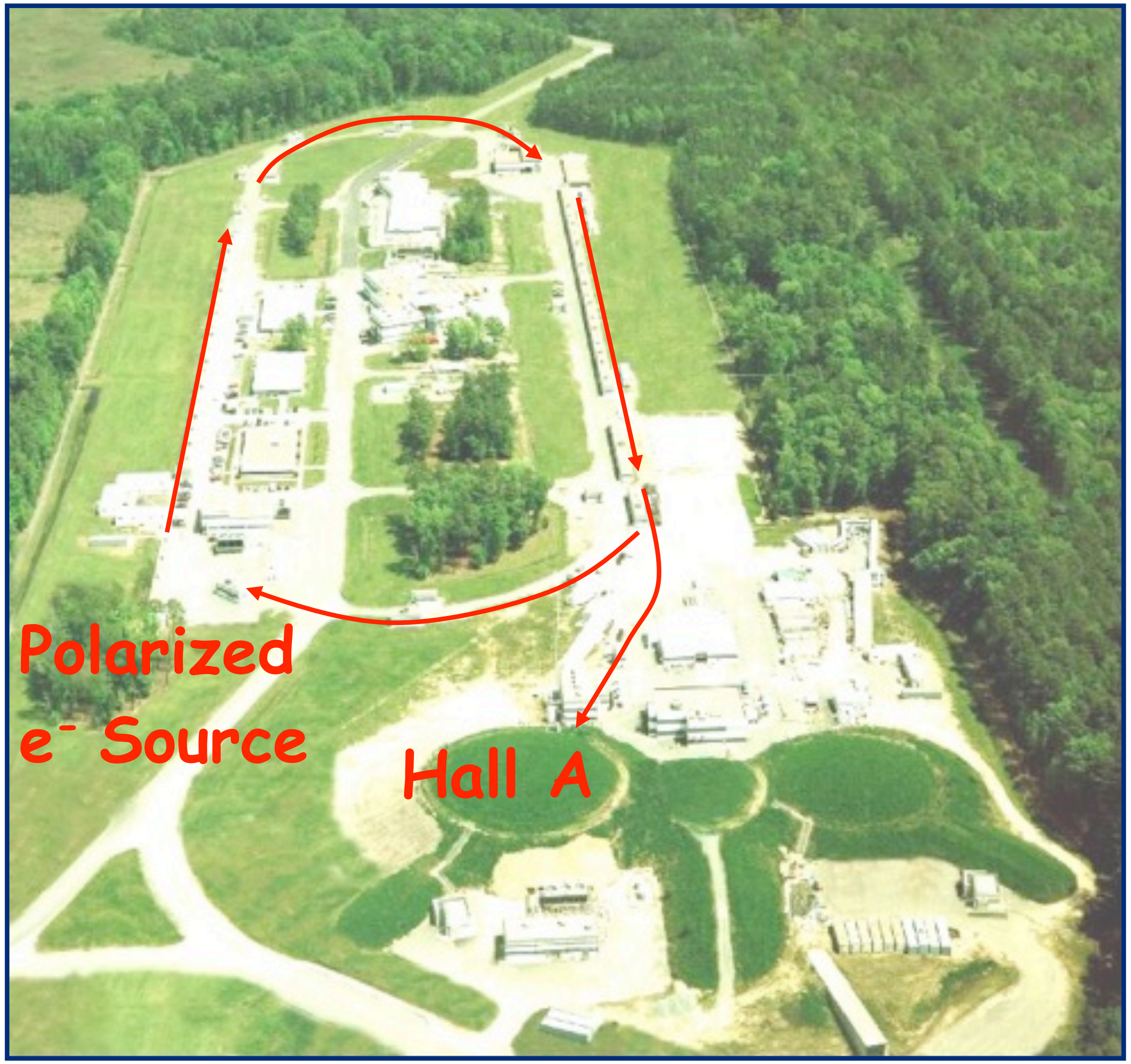
electroweak fit with uncertainty

6S → 7S ^{133}Cs atomic transition

Designed to be competitive with the best precision

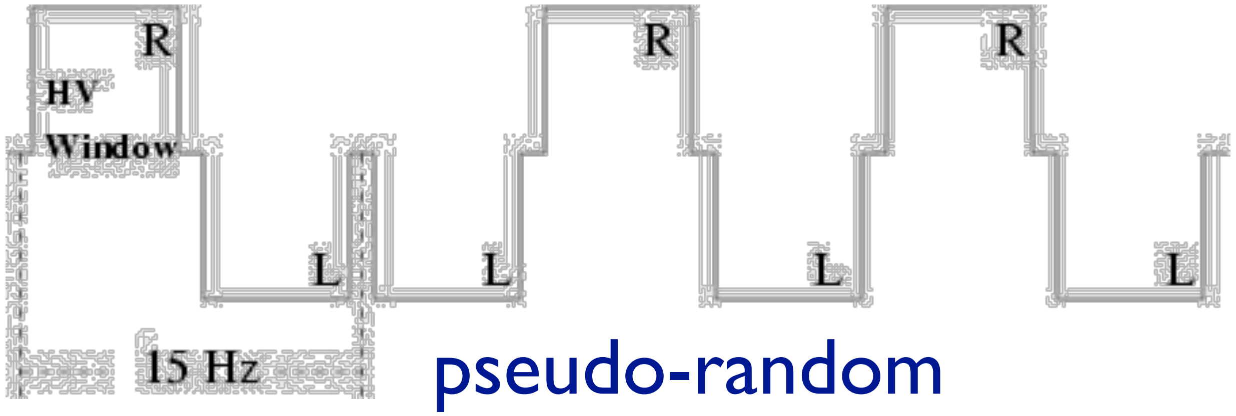


Parity Violating Electron Scattering



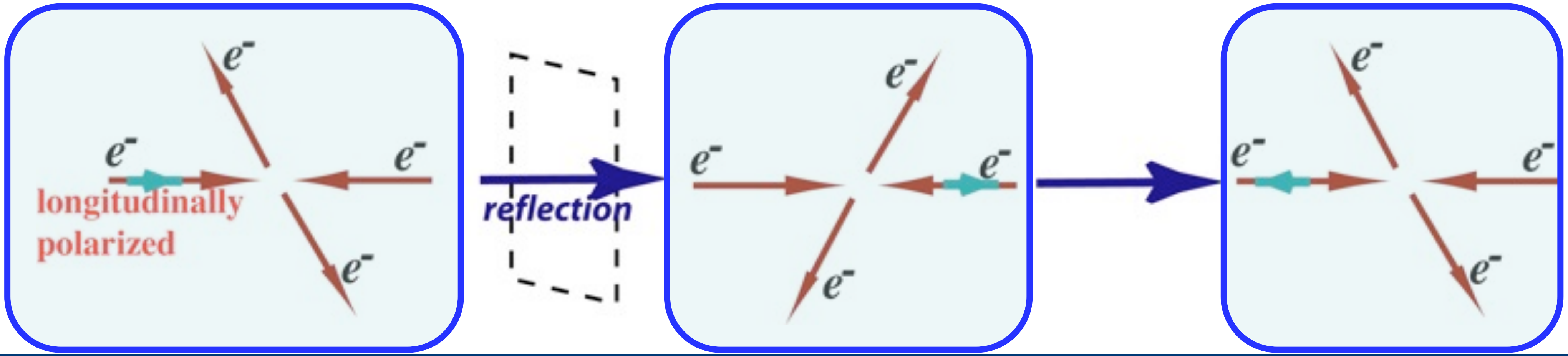
$$\sigma \propto |A_\gamma + A_{\text{weak}}|^2$$
$$\sim |A_\gamma|^2 + 2A_\gamma A^*_{\text{weak}}$$

interference between neutral weak and electromagnetic amplitudes

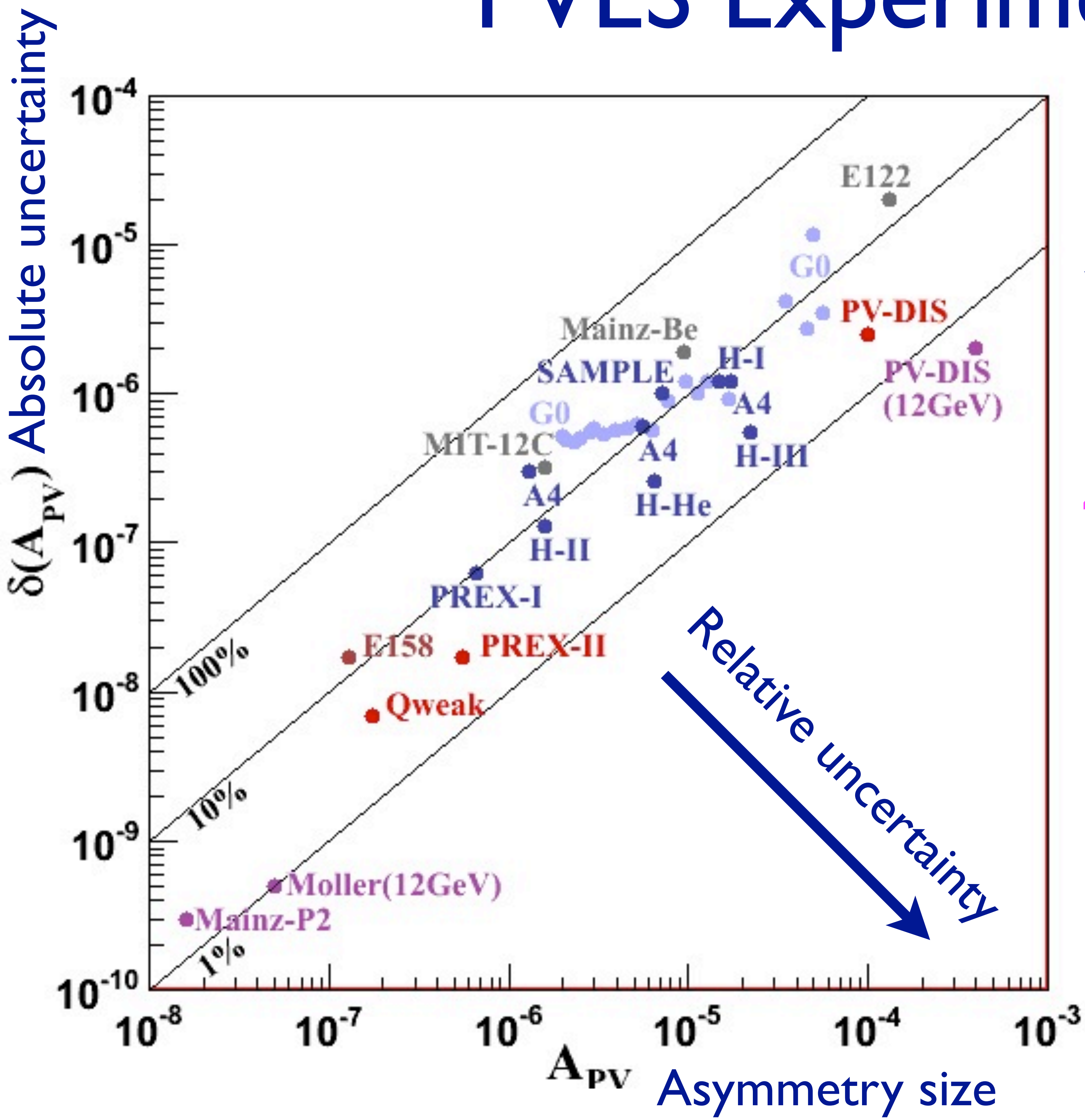


pseudo-random

Change helicity of beam - equivalent to changing parity



PVES Experiments



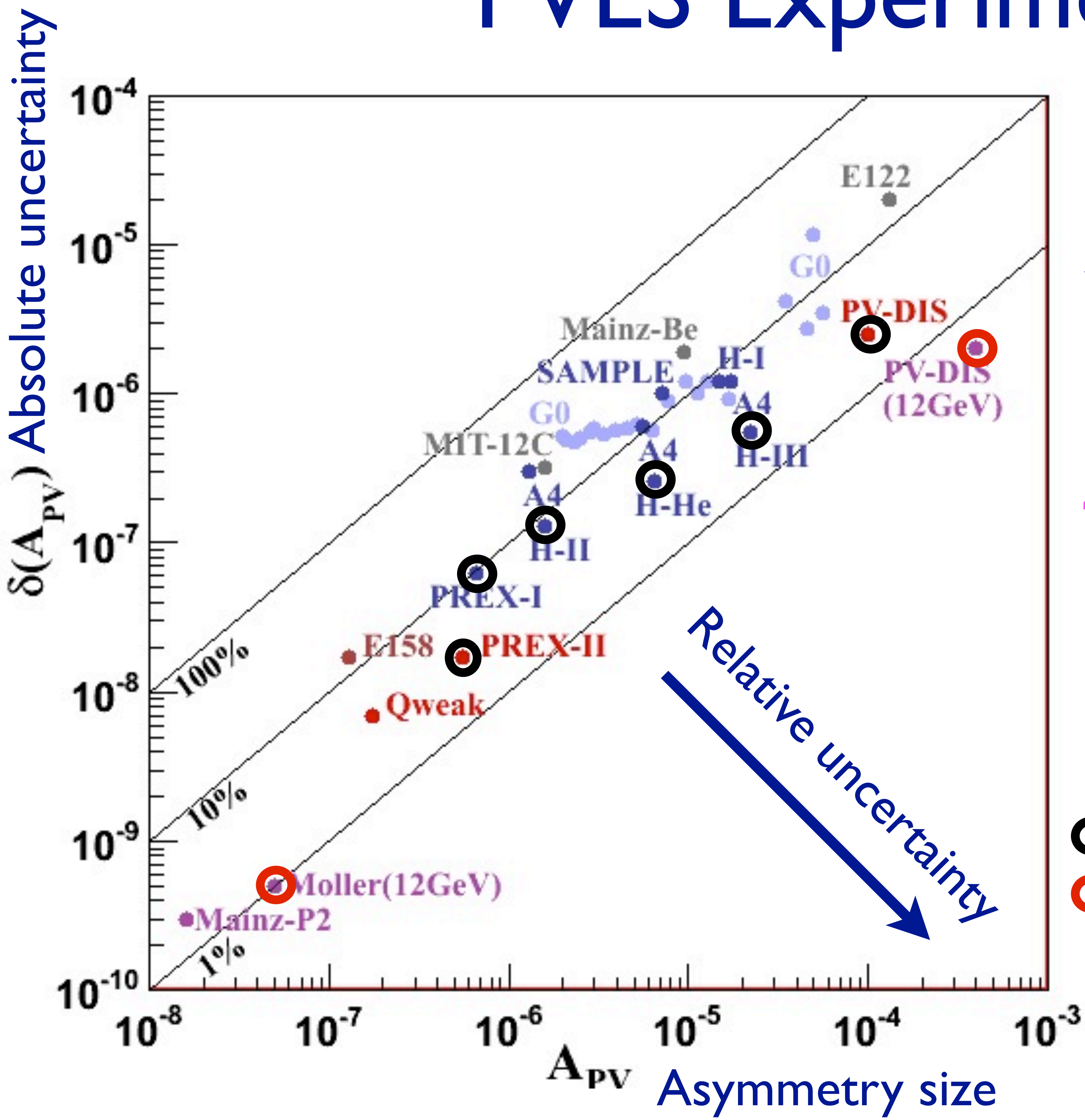
1st generation

2nd generation

3rd generation

4th generation

PVES Experiments



1st generation

2nd generation

3rd generation

4th generation

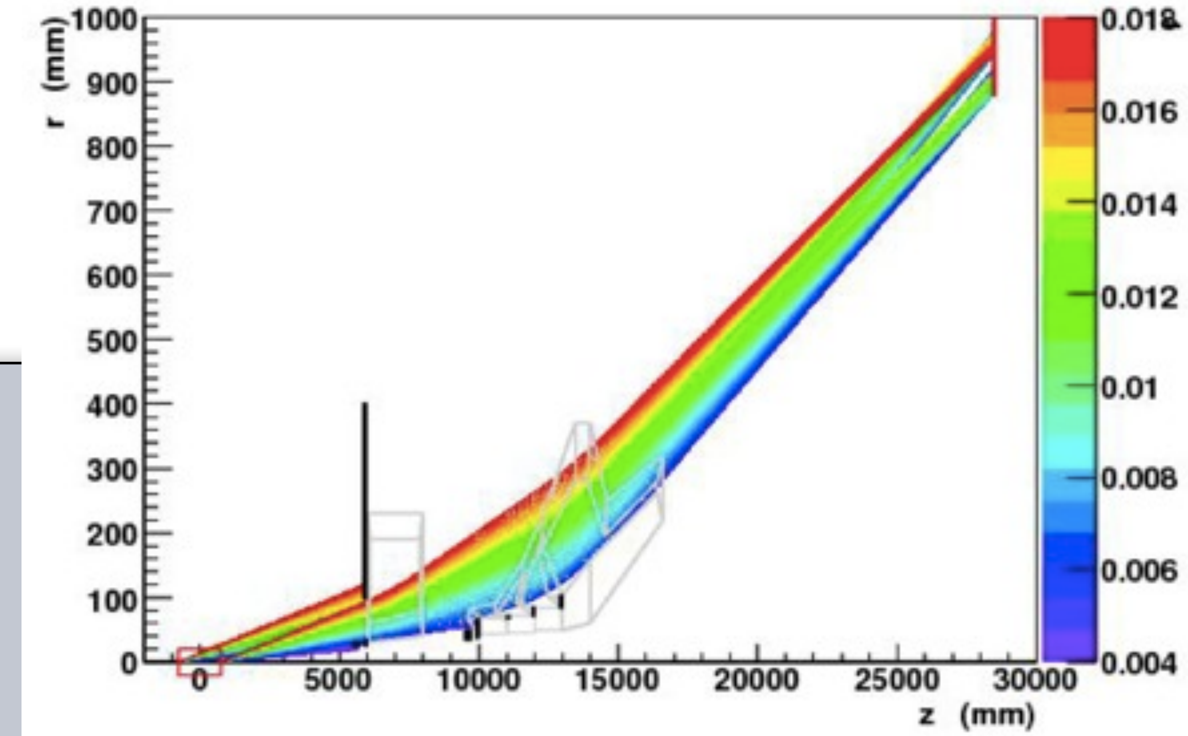
Jefferson Lab,
Hall A Experiments

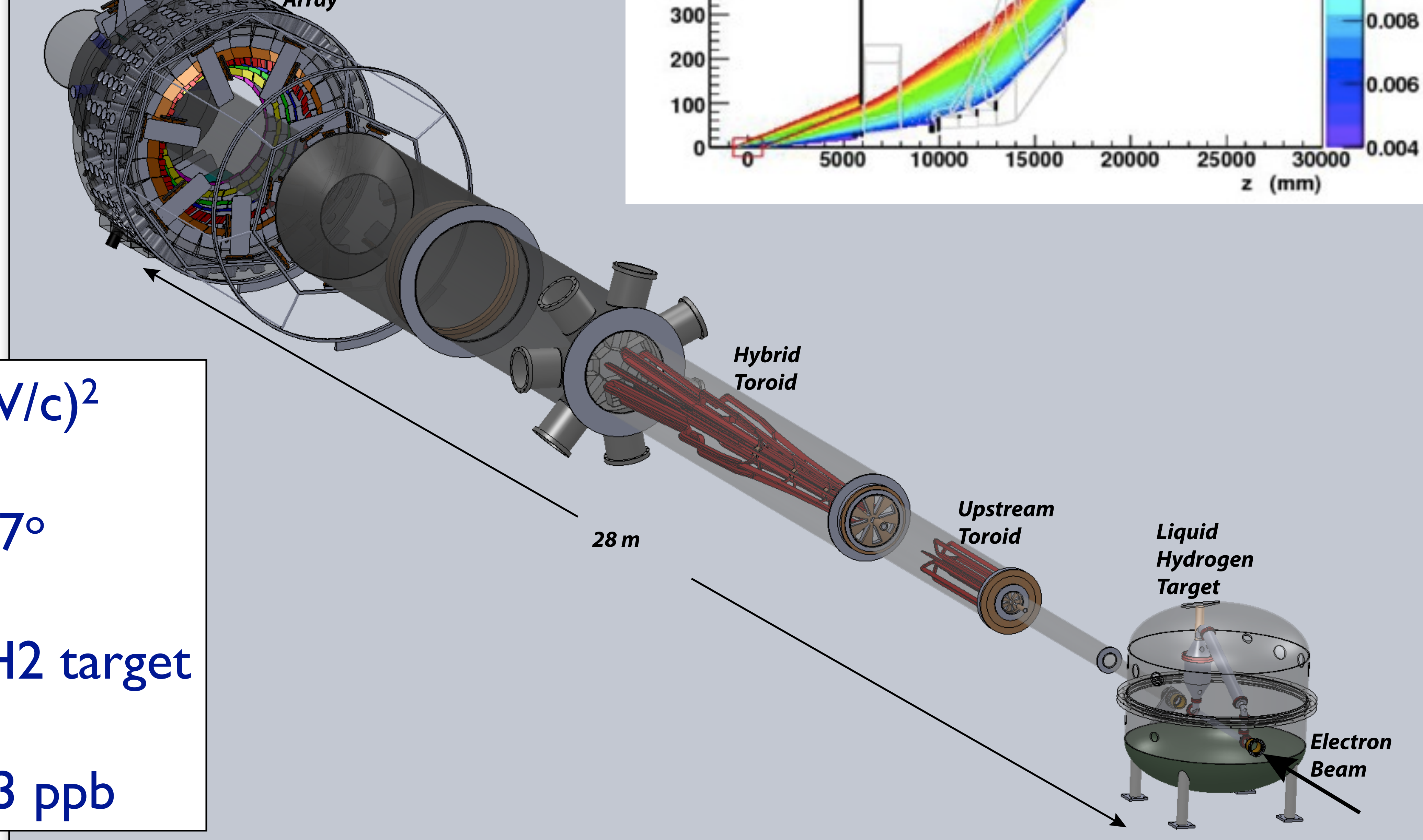
Standard Spectrometers
New Apparatus

MOLLER

An ultra-precise measurement of the weak mixing angle using Møller scattering

$\delta(Q_W^e) = \pm 2.1\ \%\ (\text{stat.}) \pm 1.0\ \%\ (\text{syst.})$





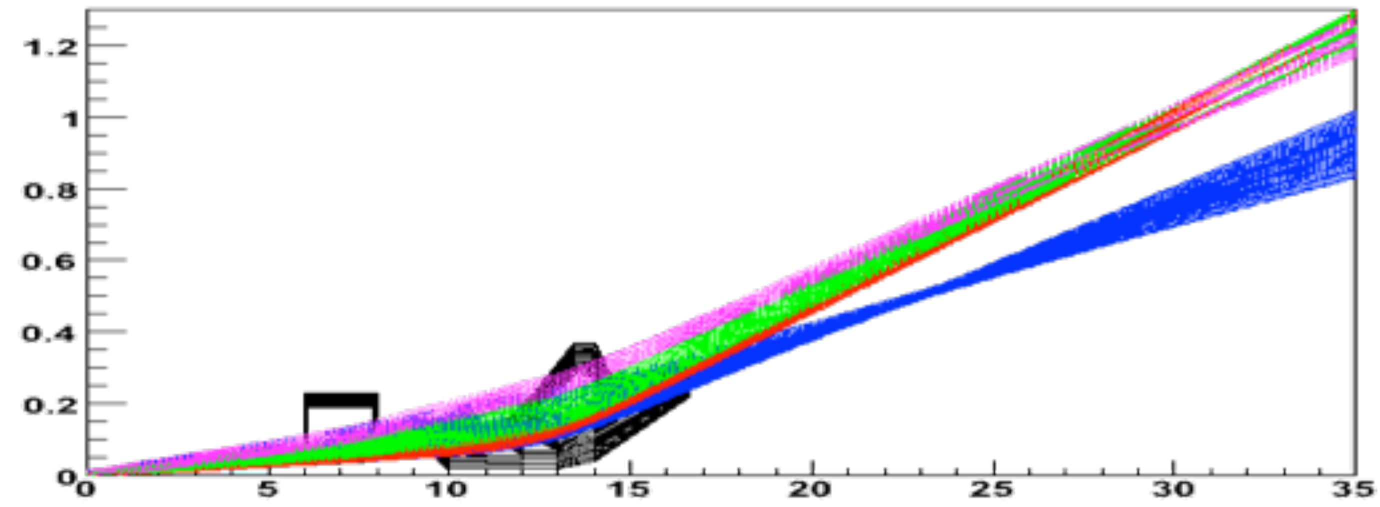
$Q^2 = 0.0056\ (\text{GeV/c})^2$
$E_{beam} = 11\ \text{GeV}$
$0.29^\circ < \theta_{lab} < 0.97^\circ$

~75 μA, 1.5 m LH2 target

$A_{PV} \approx 35.6 \pm 0.73\ \text{ppb}$

MOLLER Technical

Order of magnitude more precise than current state of the art.

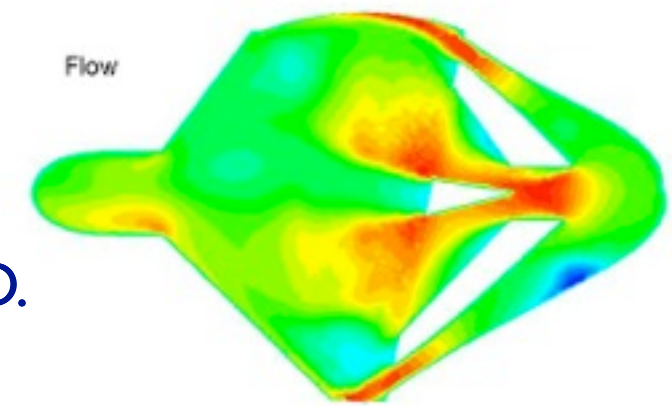


Polarized Beam

unprecedented polarized luminosity
unprecedented beam stability
helicity flip at 2 kHz

Liquid Hydrogen Target

5 kW dissipated power (2 X QWeak)
computational fluid dynamics



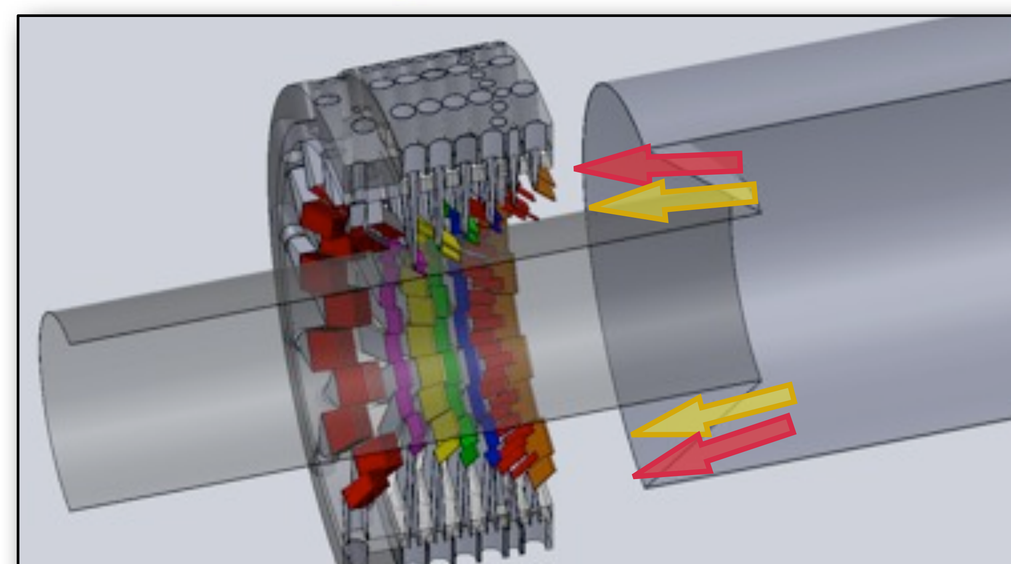
Qweak target designed with CFD.

Toroidal Spectrometer

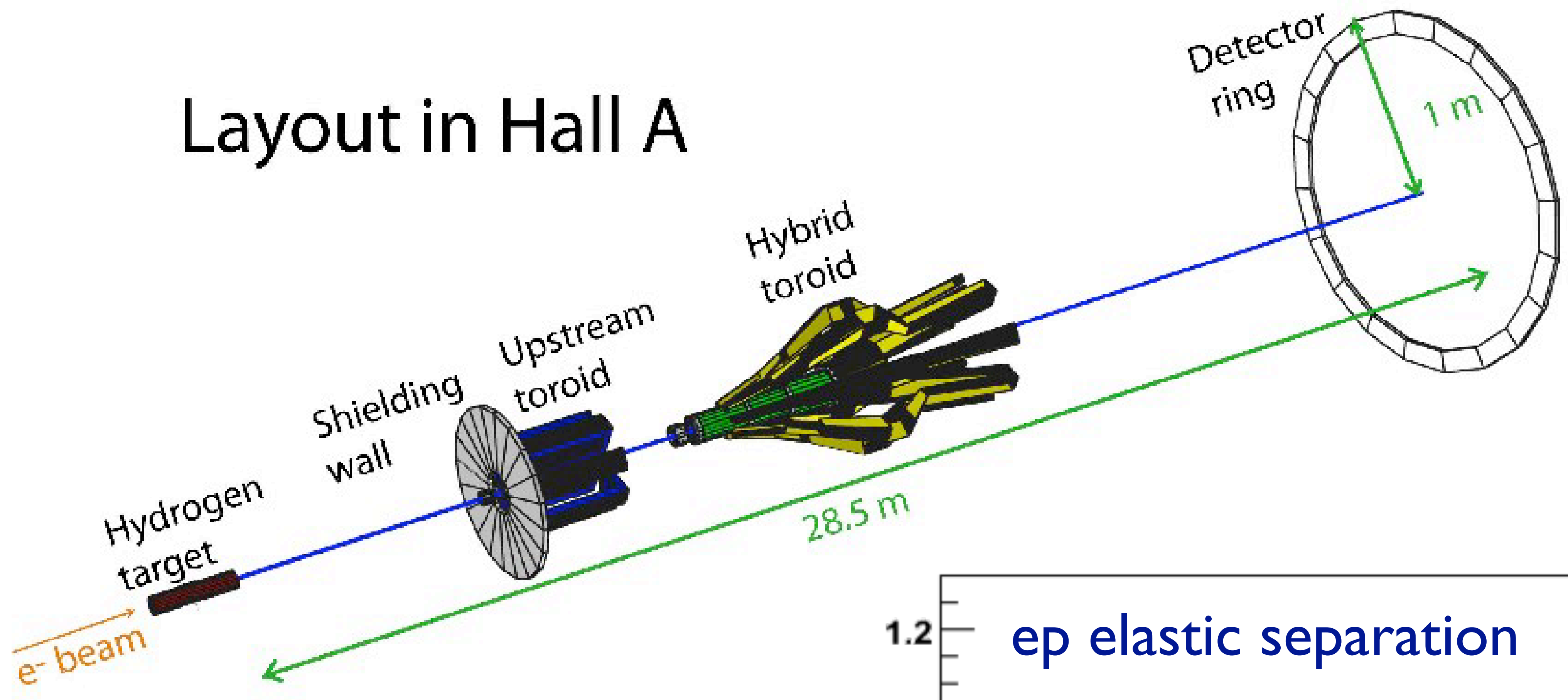
Novel 7 "hybrid coil" design
warm magnets, aggressive cooling

Integrating Detectors

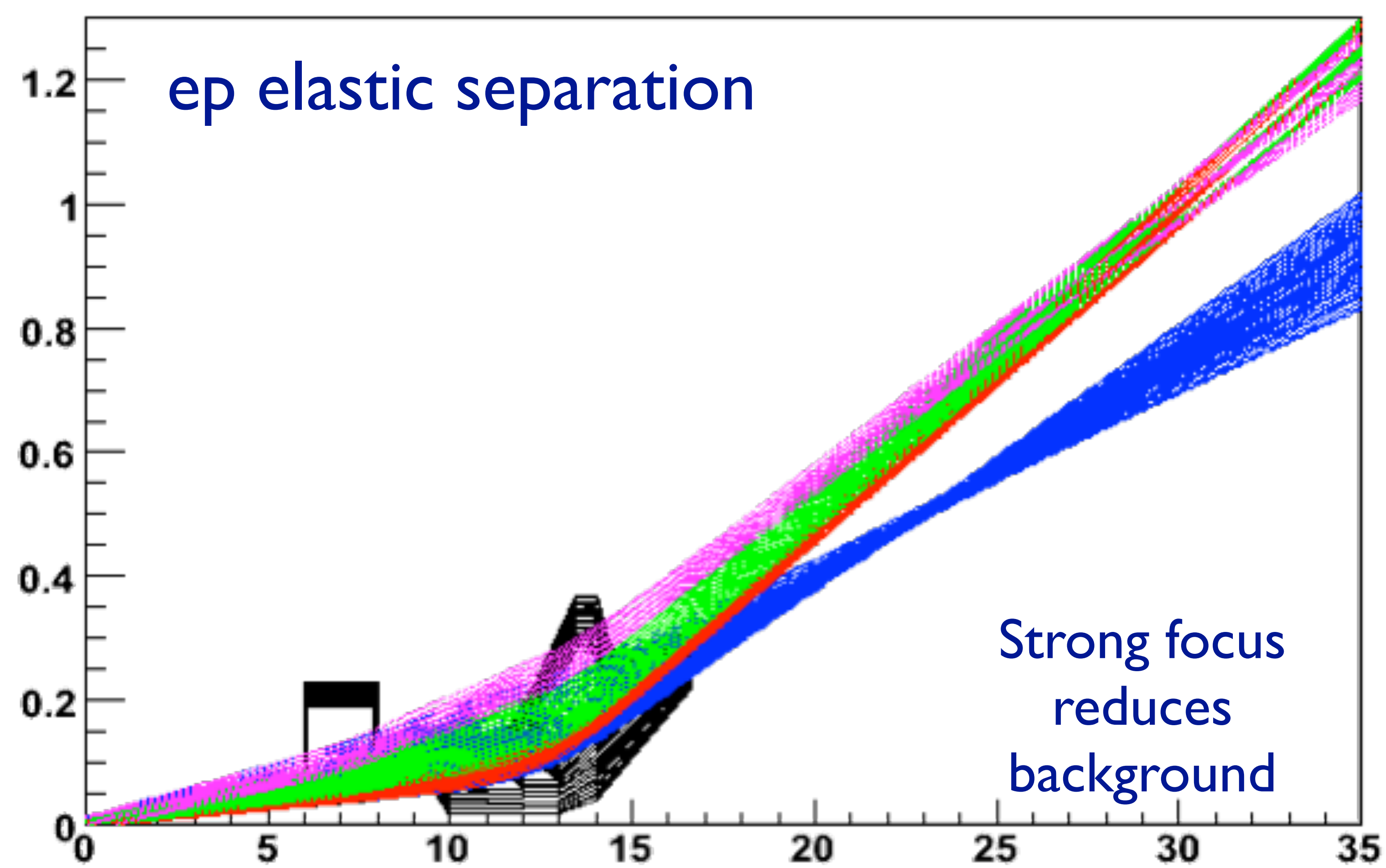
build on QWeak and PREX
intricate support & shielding
radiation hardness and low noise



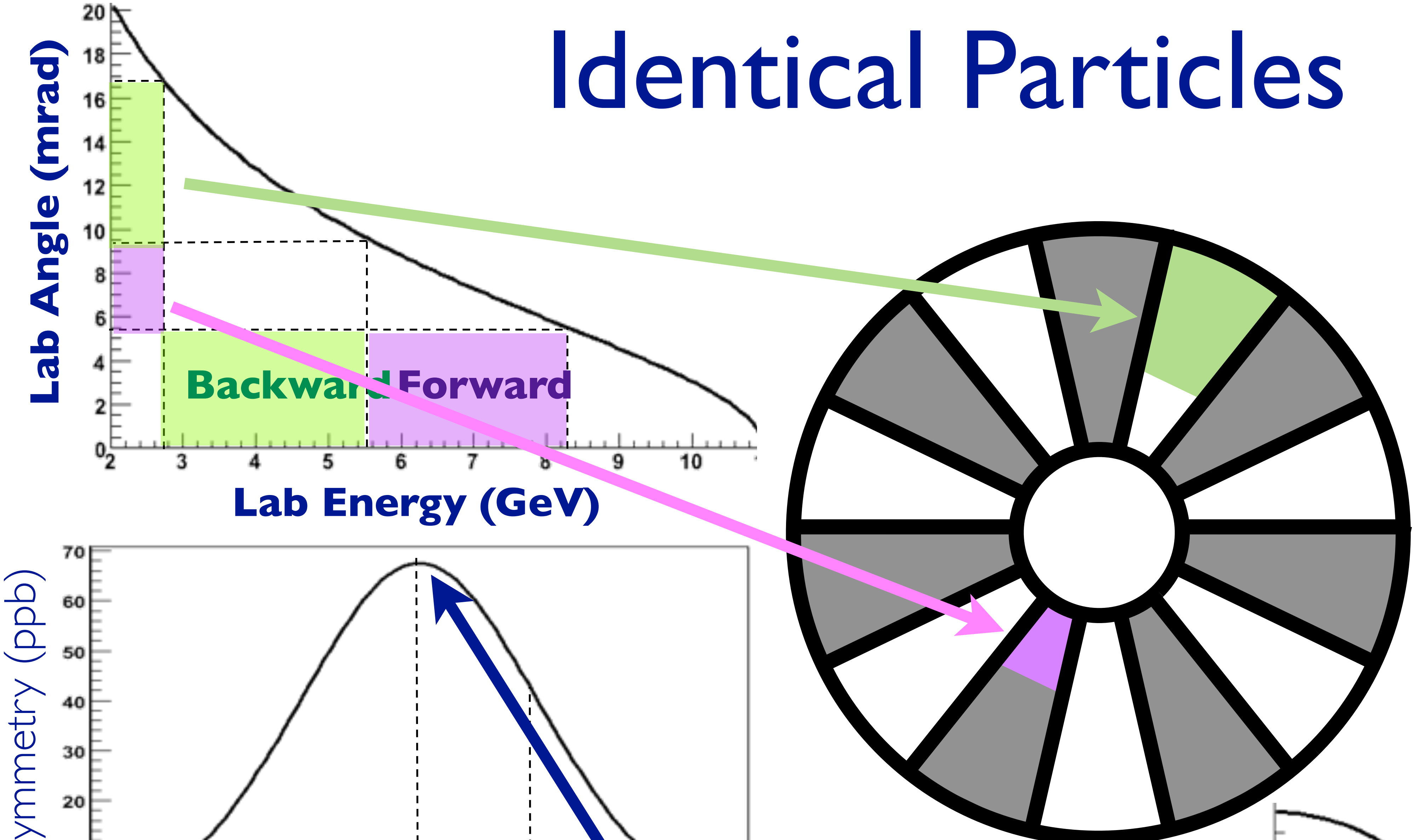
Unique New Spectrometer



Novel sculpted toroid coils designed to separate and focus Moller and Mott scattering.



Identical Particles



Collimate opposing sectors.

- Eliminates double counting.
- Plenty of space for coils with **full** azimuthal acceptance.

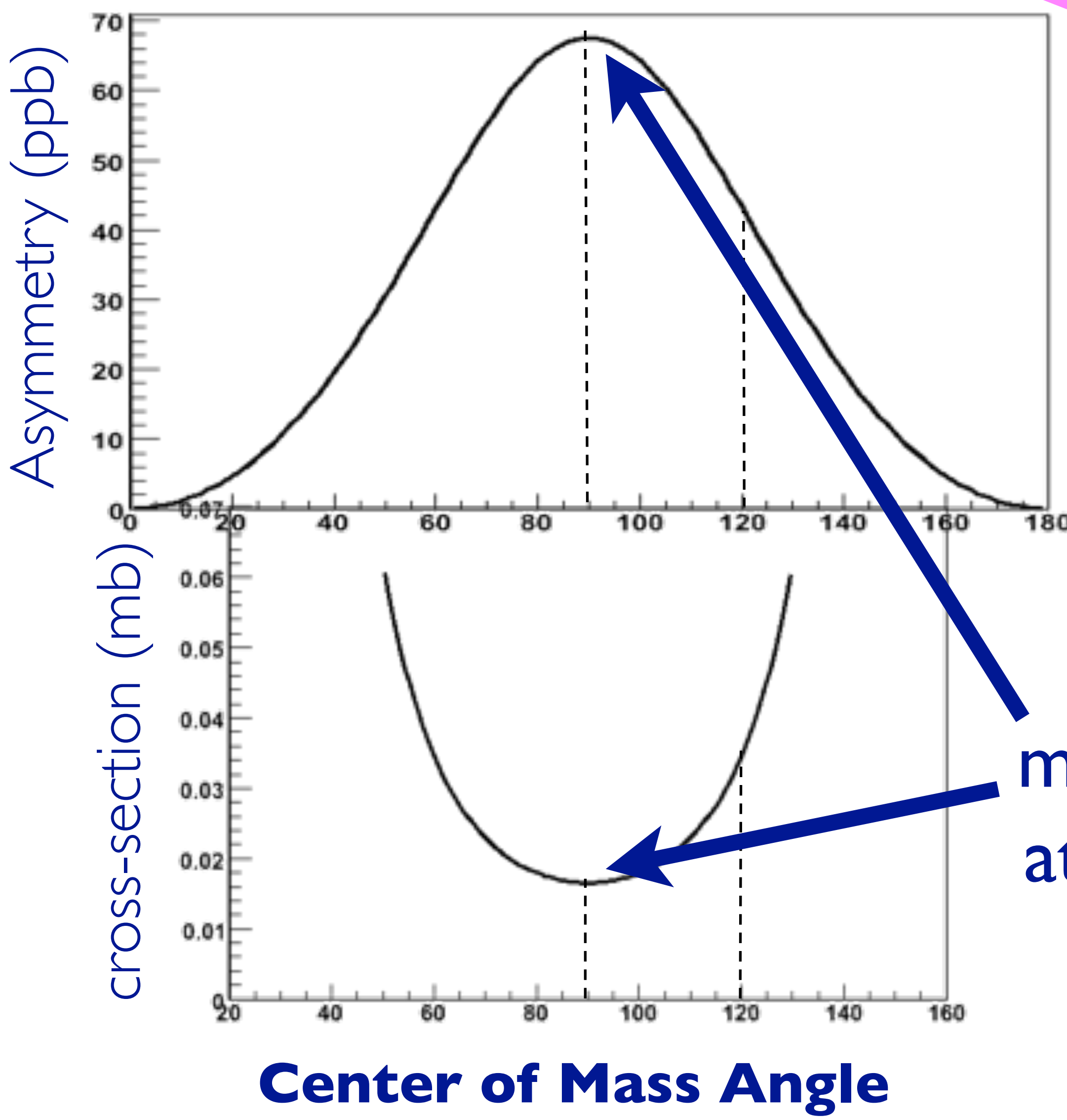
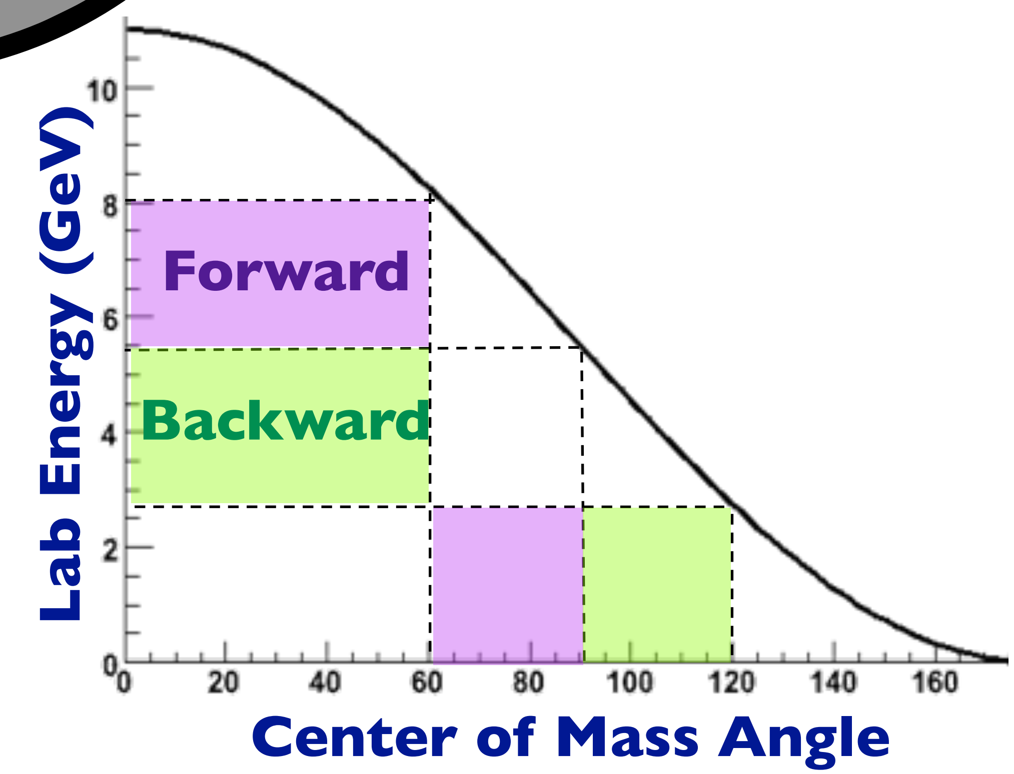


Figure of merit highest at $\theta_{CM} = 90^{o}$



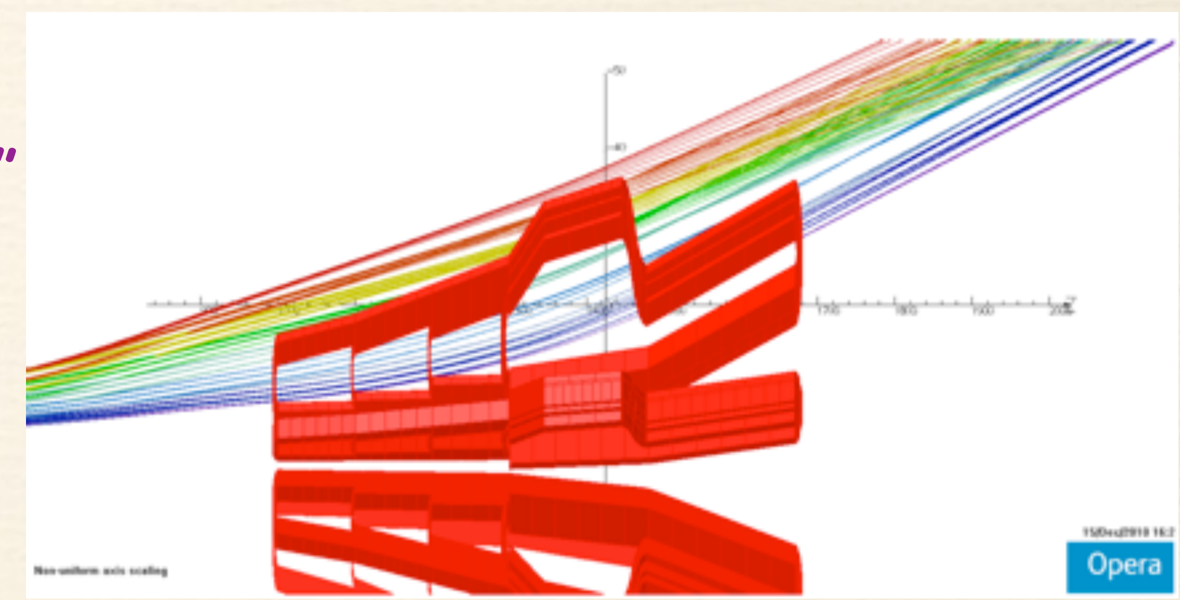
MOLLER Status

Director's Review chaired by C. Prescott: strong, positive endorsement

Technical Challenges

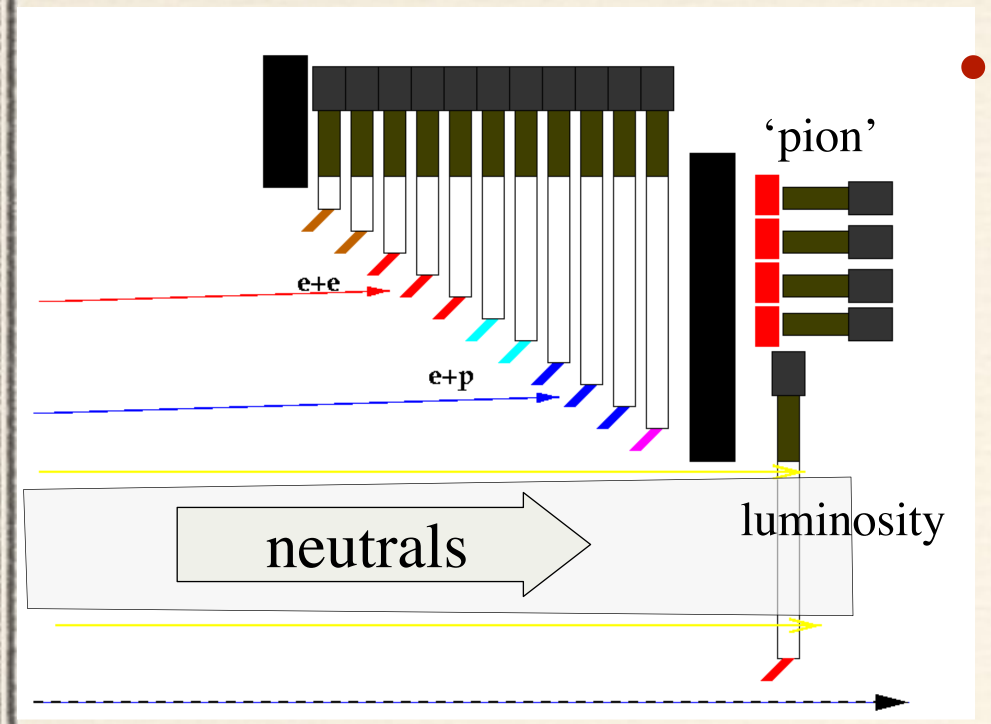
- **~ 150 GHz scattered electron rate**
  - Design to flip Pockels cell ~ 2 kHz
  - 80 ppm pulse-to-pulse statistical fluctuations
- **1 nm control of beam centroid on target**
  - Improved methods of "slow helicity reversal"
- **> 10 gm/cm^2 liquid hydrogen target**
  - 1.5 m: ~ 5 kW @ 85 μA
- **Full Azimuthal acceptance with θ_{lab} ~ 5 mrad**
  - novel two-toroid spectrometer
  - radiation hard, highly segmented integrating detectors
- **Robust and Redundant 0.4% beam polarimetry**
  - Pursue both Compton and Atomic Hydrogen techniques

- **MOLLER Collaboration**
  - ~ 100 authors, ~ 30 institutions
  - Expertise from SAMPLE A4, HAPPEX, G0, PREX, Qweak, E158
  - 4th generation JLab parity experiment

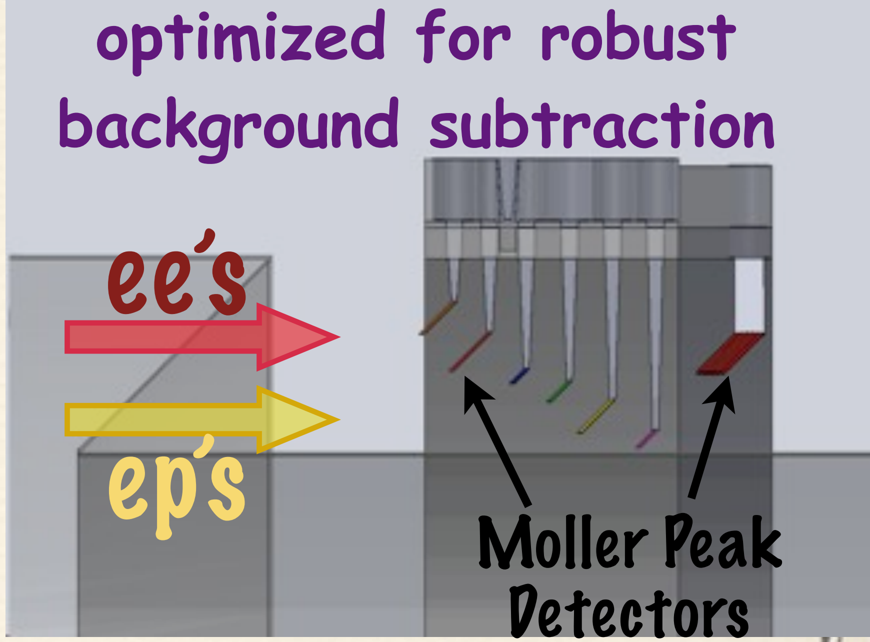


- **20M$ proposal to DoE NP**
- **3-4 years construction**
- **2-3 years running**

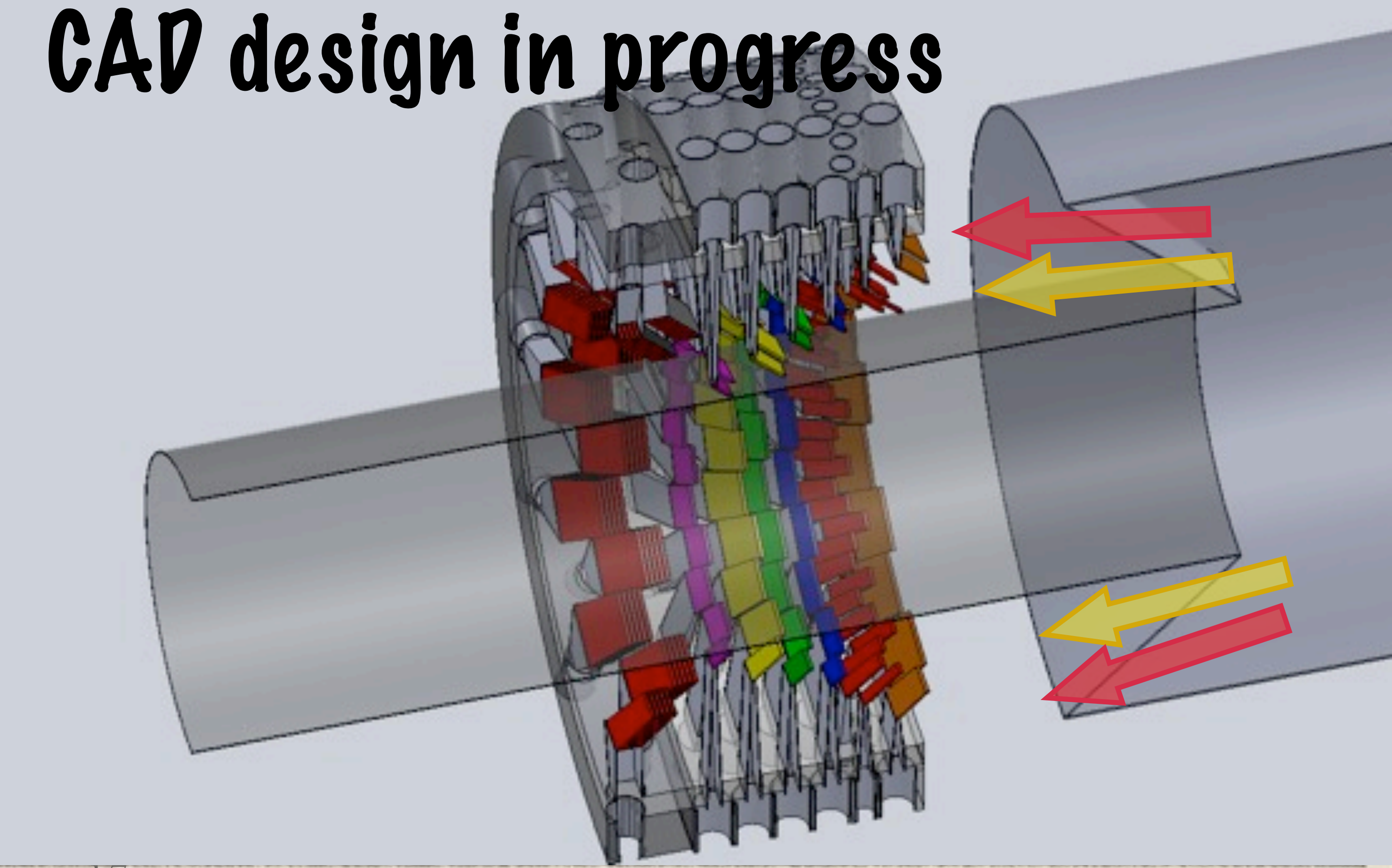
MOLLER Detectors



- Auxiliary Detectors
  - Tracking detectors
    - *3 planes of GEMs/Straws*
    - *Critical for systematics/ calibration/debugging*
  - Integrating Scanners
    - *quick checks on stability*



- **Integrating Detectors:**
  - **Moller 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*



Spectrometer Magnet Design

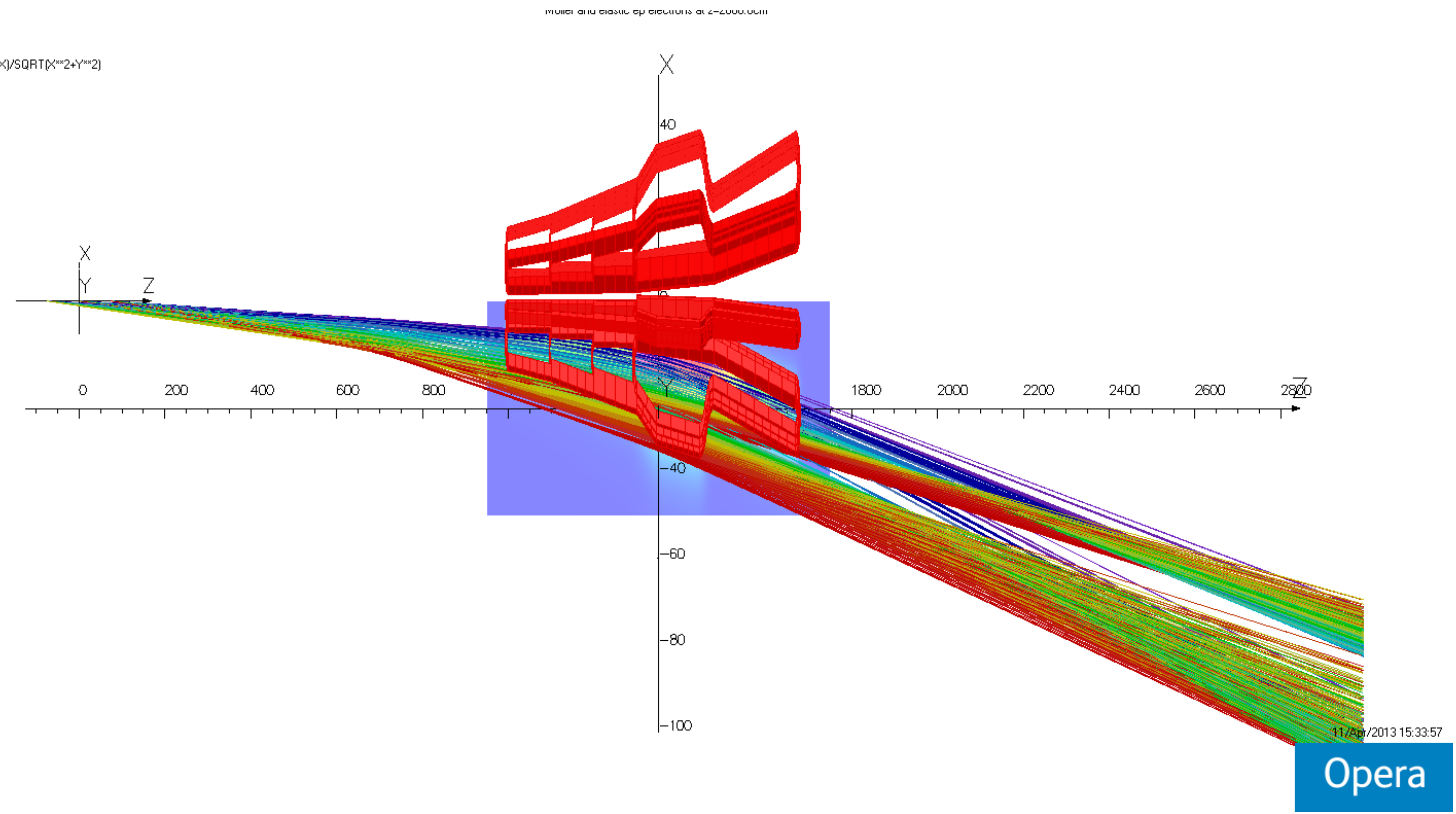
Advisory Group Meeting – July 2013
Internal and External advisory groups in place.

Development focus areas:

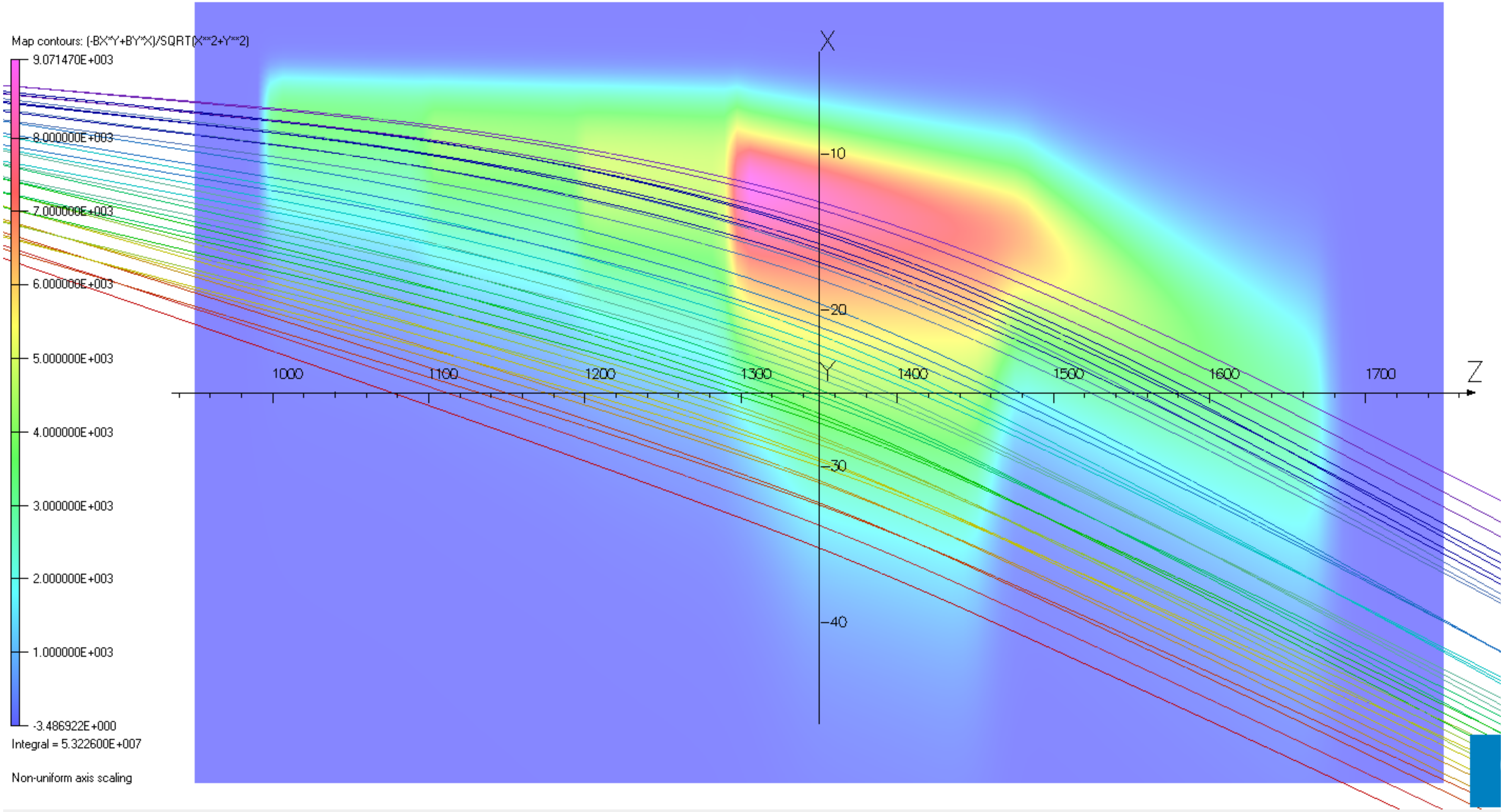
Conductor size and water hole size
Negative conductor bend angles
Coils in vacuum versus coils in air versus helium bag.
Potential 3 coil configuration.

Tosca Magnet Model

Realistic, realizable magnet design in progress.

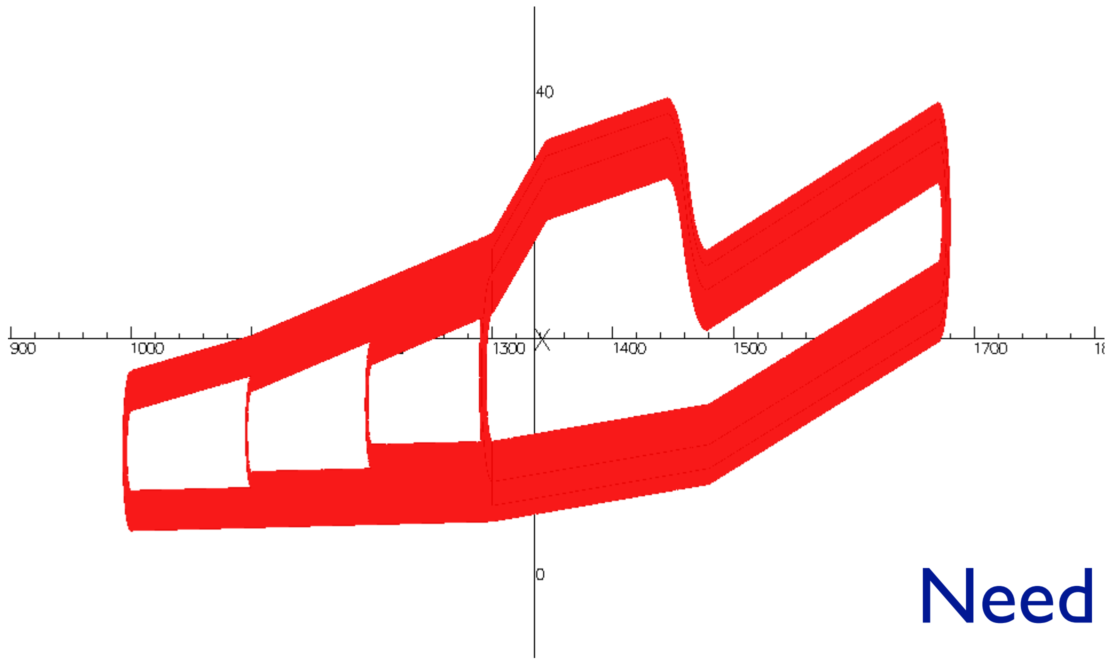


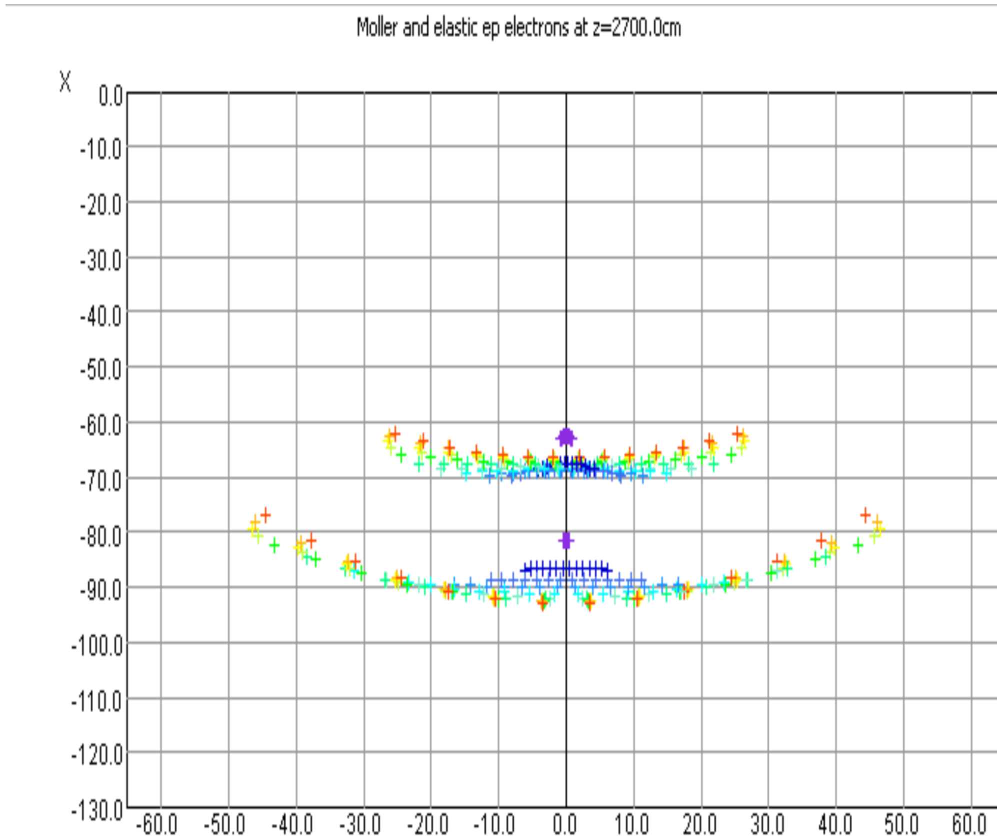
Field Strength



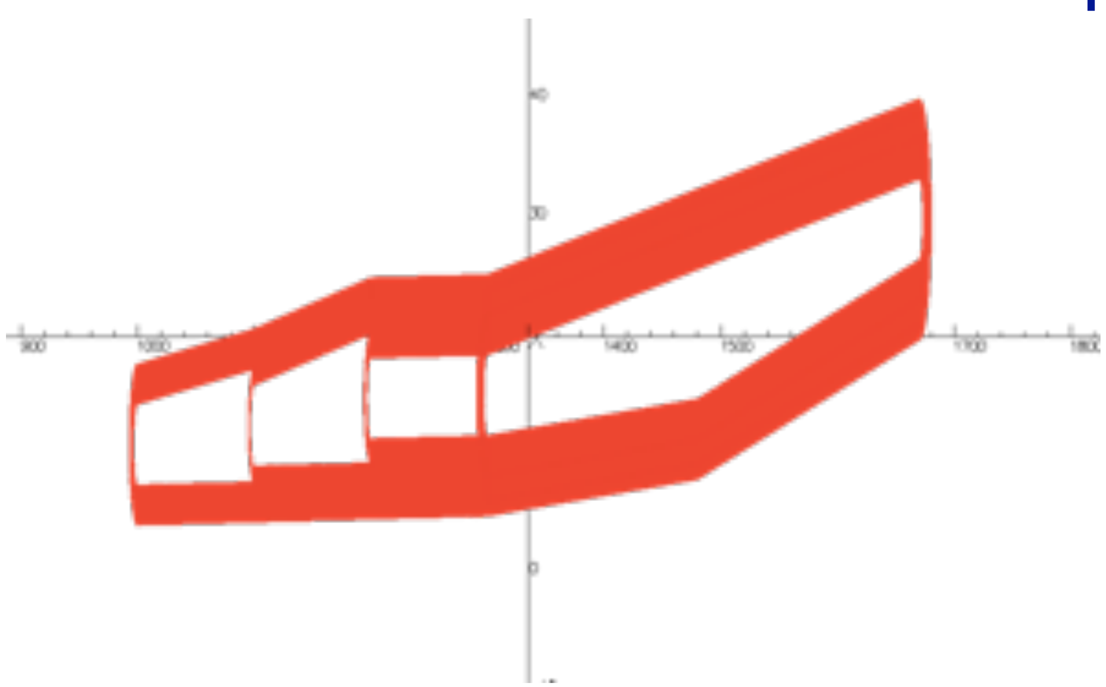
Magnet Design

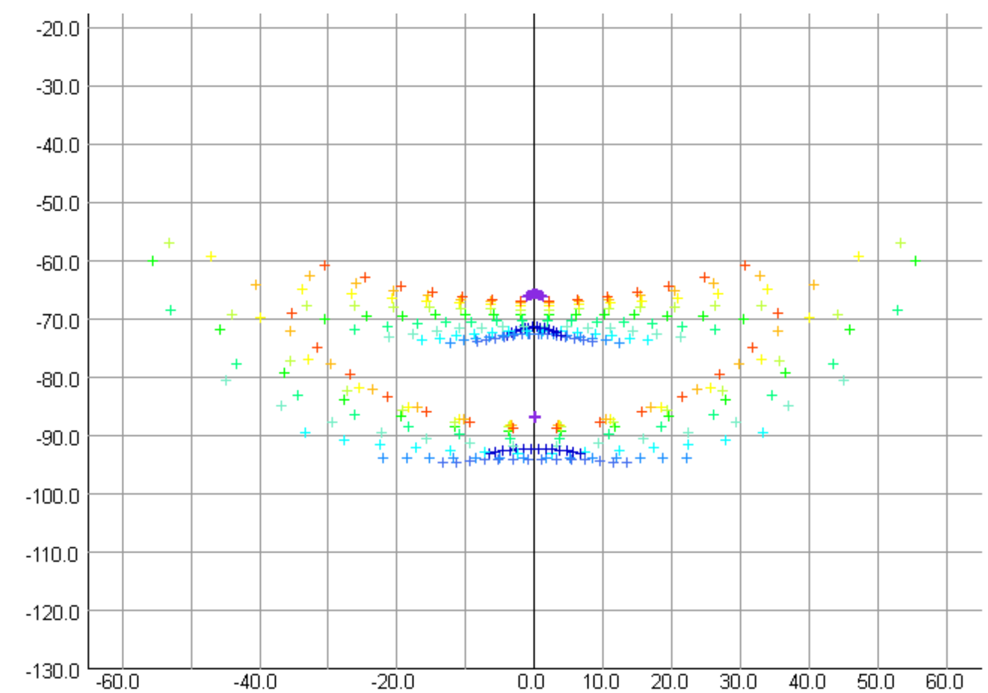
For example: what happens if you try to reduce the negative curvature?





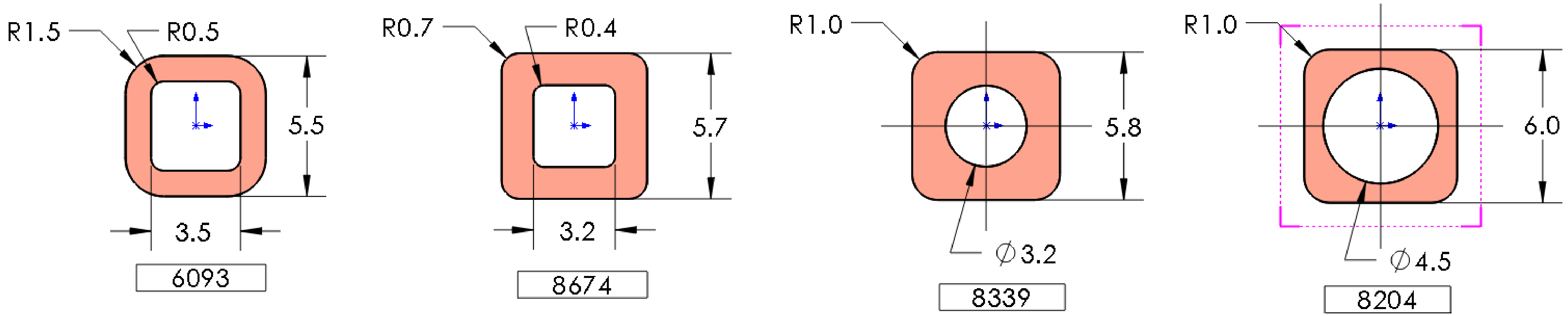
Need to optimize a complicated FOM





Conductors

- Hollow Cu conductors are available in a variety of standard sizes. I'm using data from Luvata; http://www.luvata.com/en/Products--Markets/Products/Hollow-Conductors/

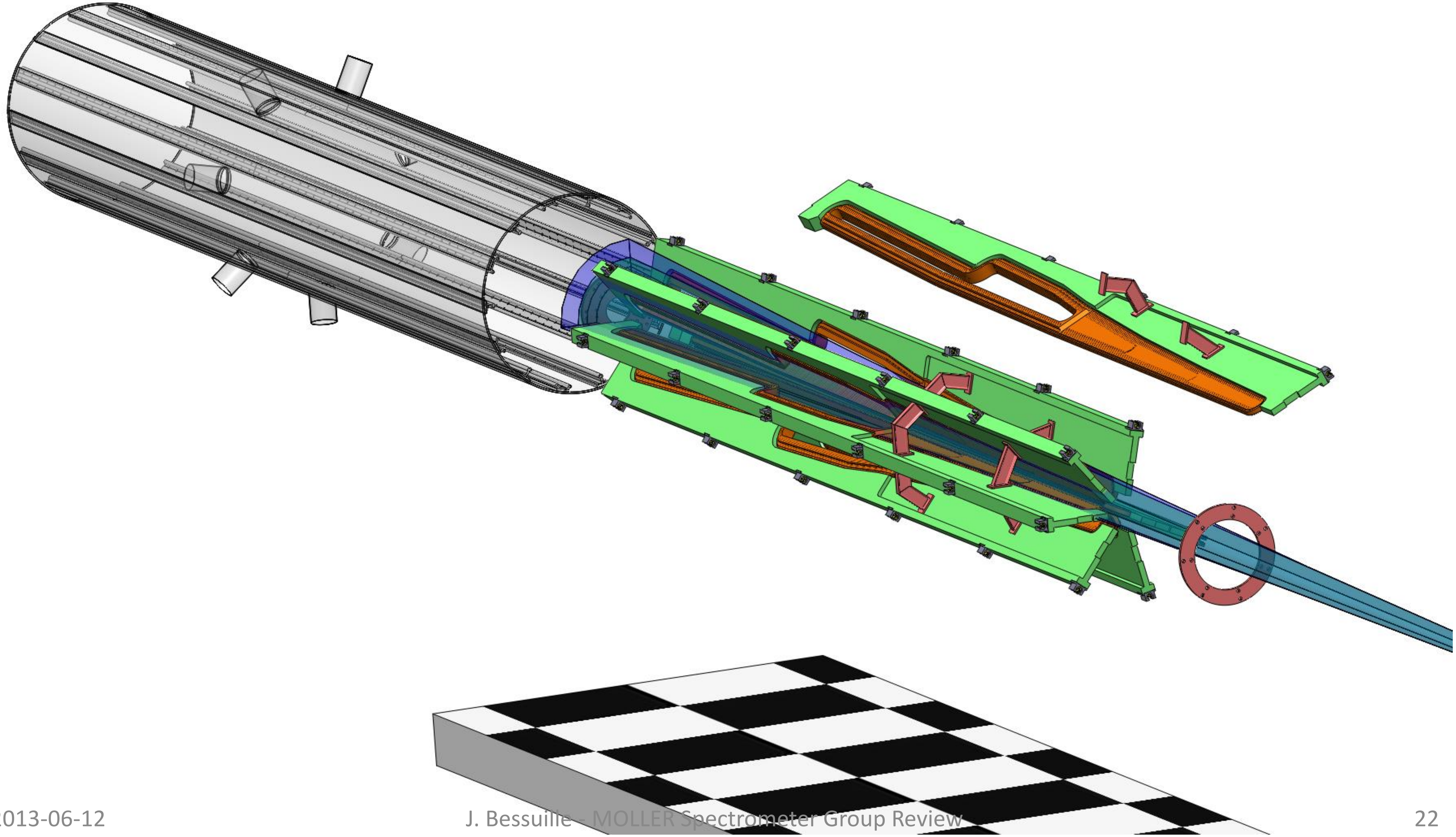


From original TOSCA design

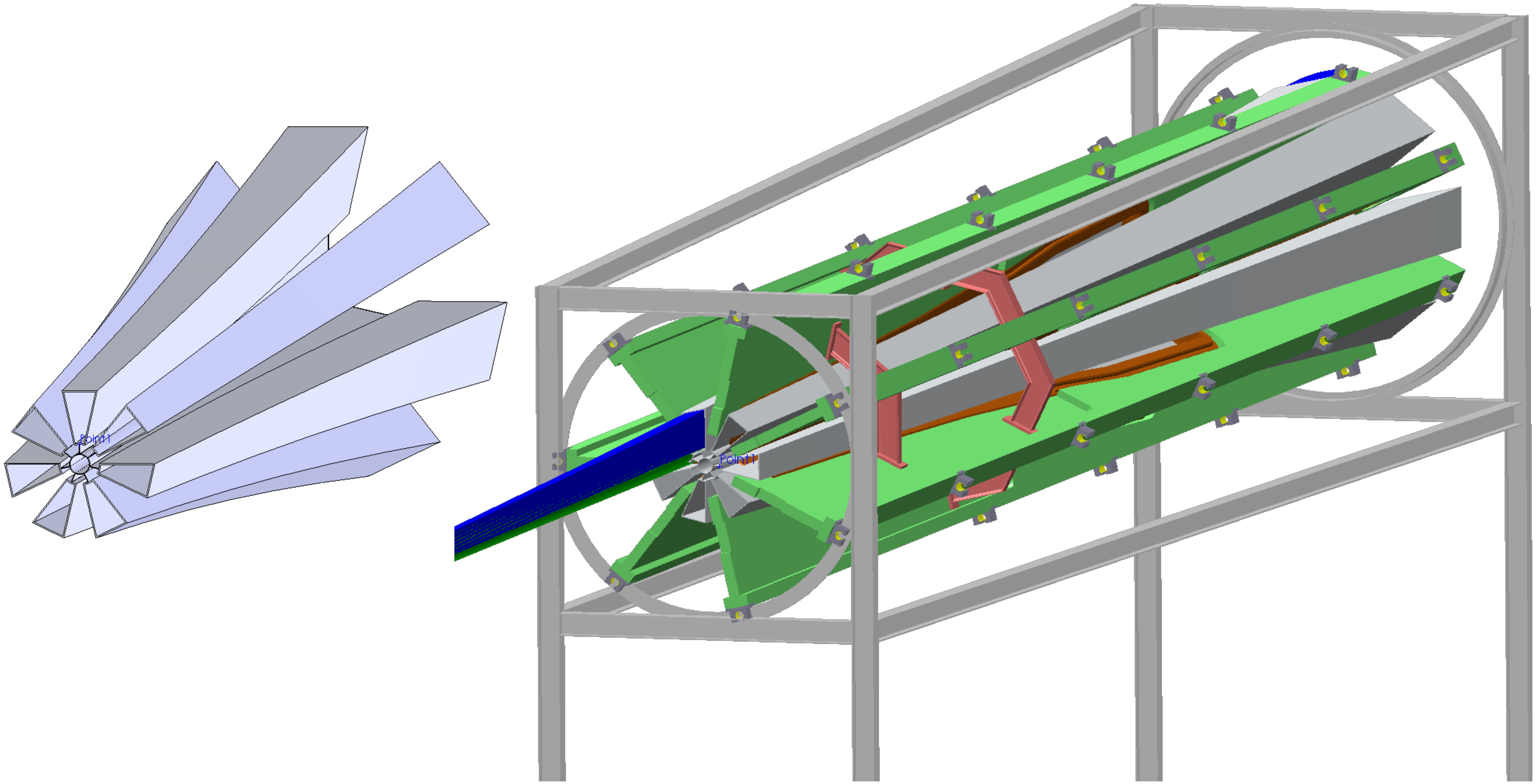
Conductor Style and Resulting Power and Voltage for I=384 A				Flow Properties assuming 4 average-length turns / cooling circuit; 45 deg C deltaT	
Part #	Current Density [A/cm^2]	Toroid Voltage Drop [V]	Toroid power [kW]	Velocity (4 turns in parallel) [m/s]	Pressure Drop (avg) [atm]
6093	*2358*	*2377*	*913*	*3.04*	*14*
8674	*1748*	*1762*	*677*	*2.68*	*13*
8339	*1553*	*1566*	*601*	*3.03*	*17*
8204	*1996*	*2012*	*773*	*1.95*	*5*

Coils in Vacuum

- Full assembly, Exploded



Coils in Air



- Collimated beams pass through 8 distinct volumes, comprising the "Tulip Pipe".

Simulation Developments

New simulation framework.

Improved readability, streamlined output; version, parameter and input tracking; uniform generators for Moller, ep elastic and ep inelastic (Christy/Bosted)

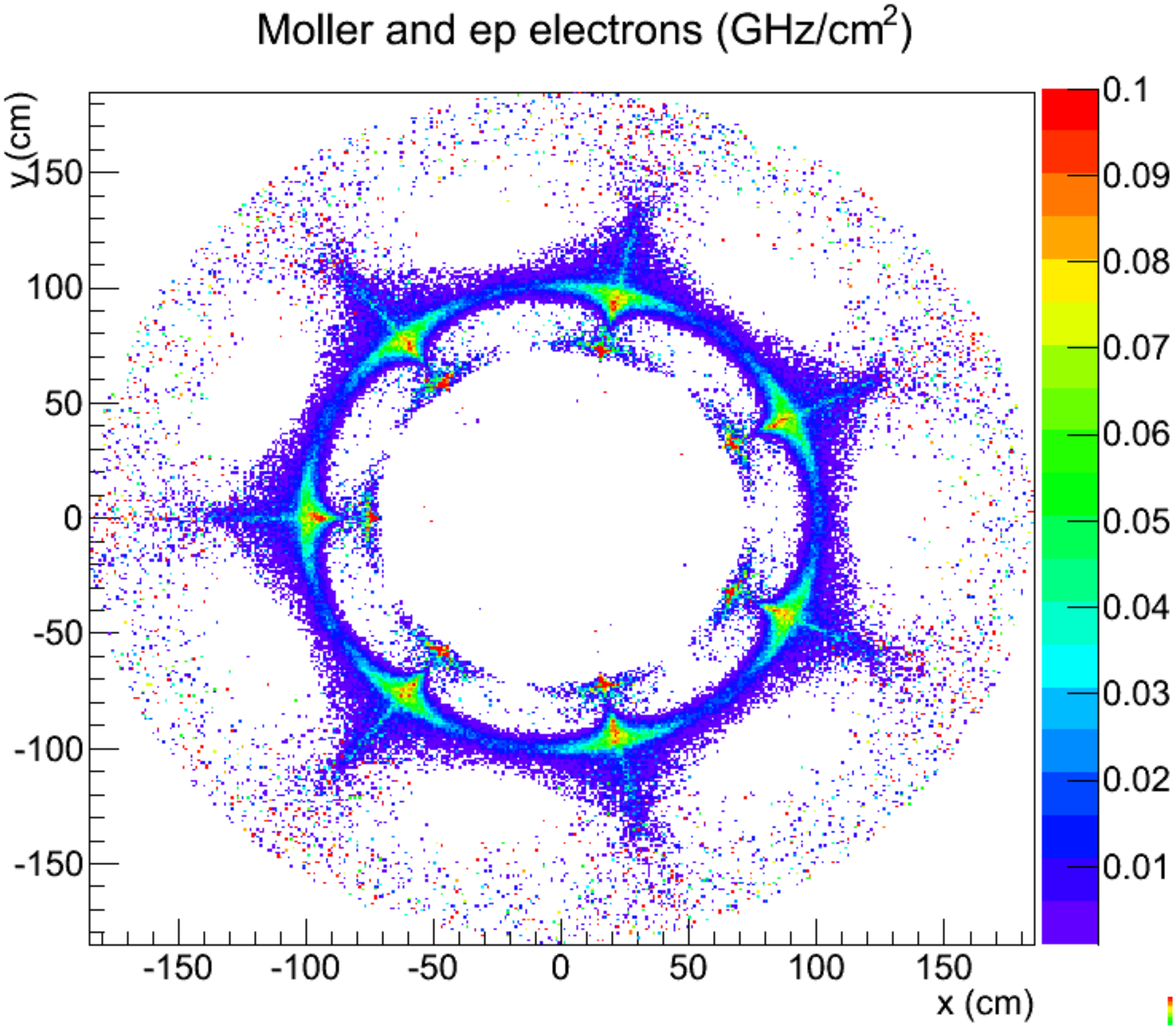
Study "phi-sculpting" collimation to block photons while preserving FOM.

New 2D photon bounce code for rapid prototyping.

Hyperon background generator in development.

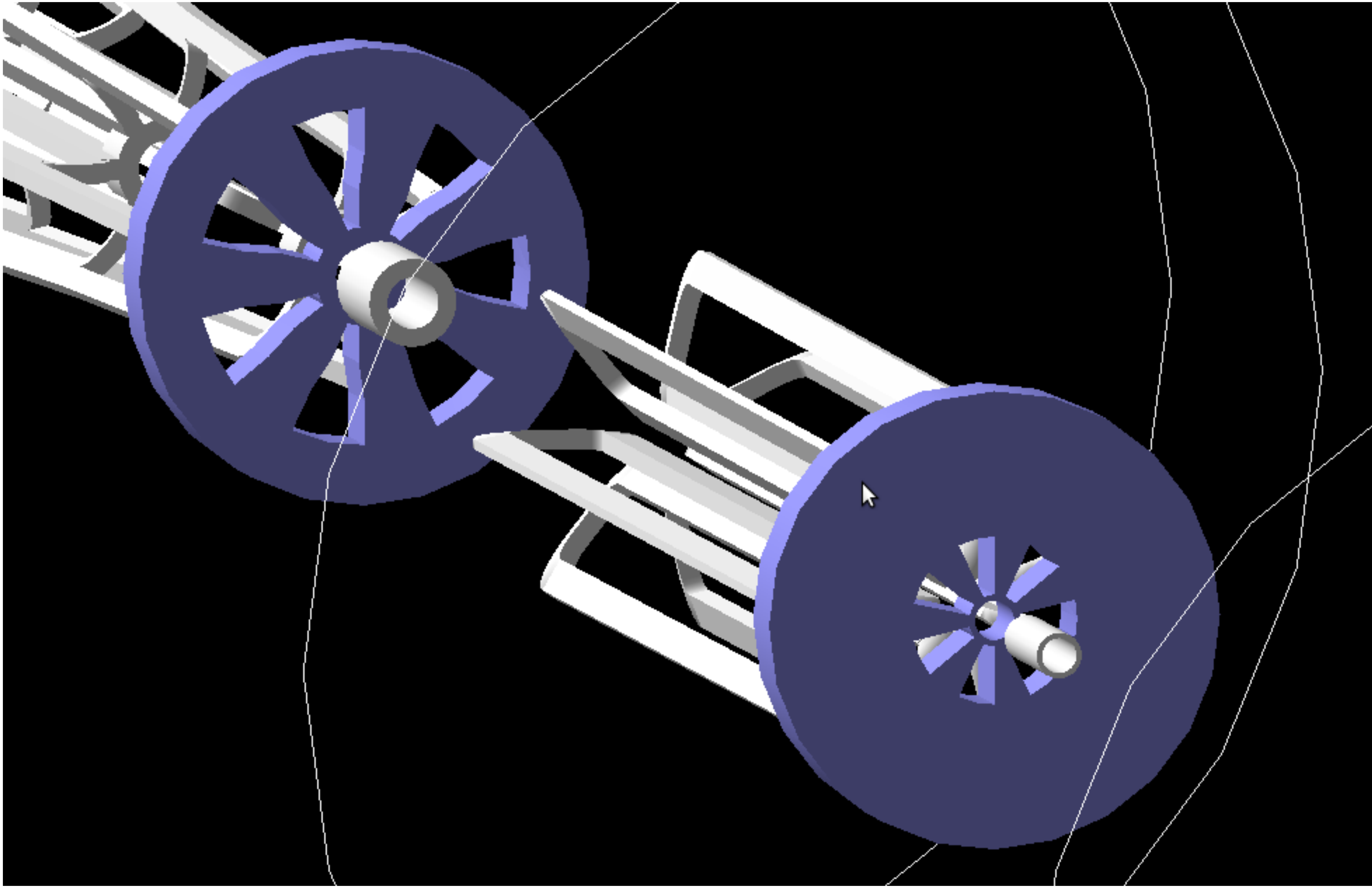
Target window studies in progress.

Recent rate map



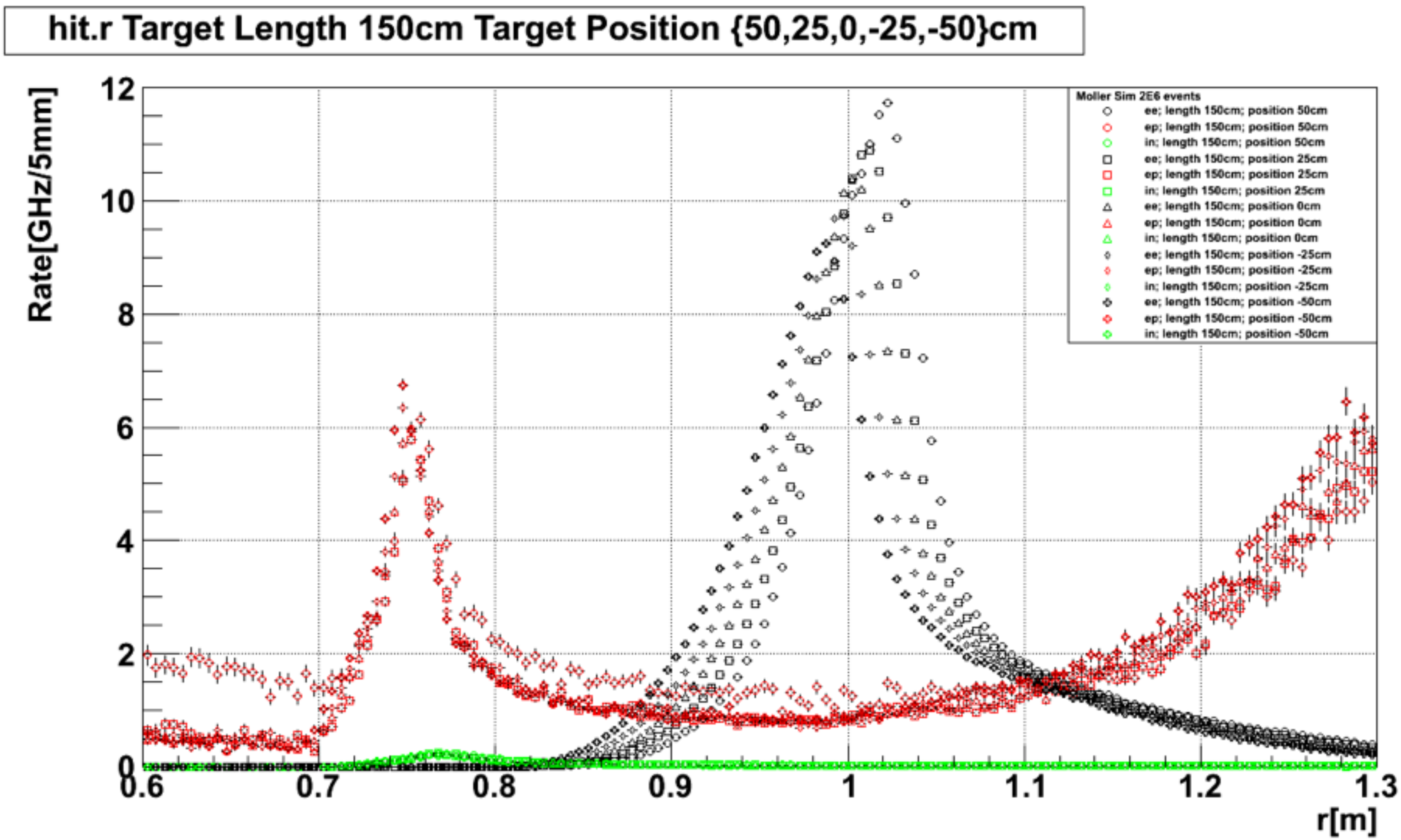
Geant 4 used to simulate effects of radiation and background physics processes.

Sculpted Collimators

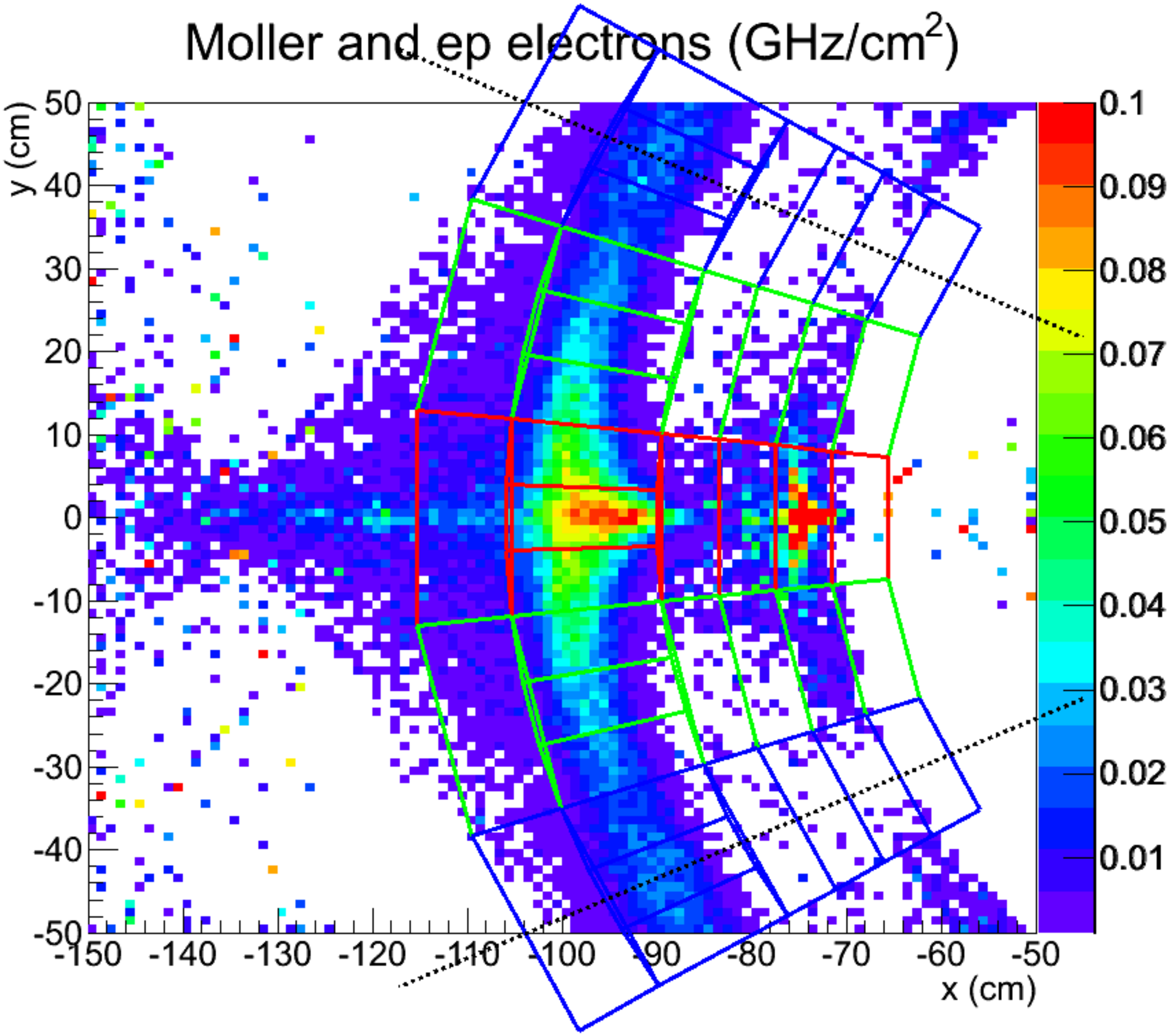


Target Length and Position

Study the effect of changing target geometry.



Conceptual detector tile layout



Multiple detectors allow the separation of signal by kinematics and production process.

Necessary to disentangle background processes.

FOM must ultimately be calculated from yields and asymmetries in detectors.

Detector Development

Basic design is 1.5 cm thick quartz, 3" PMT and air-core light guide.

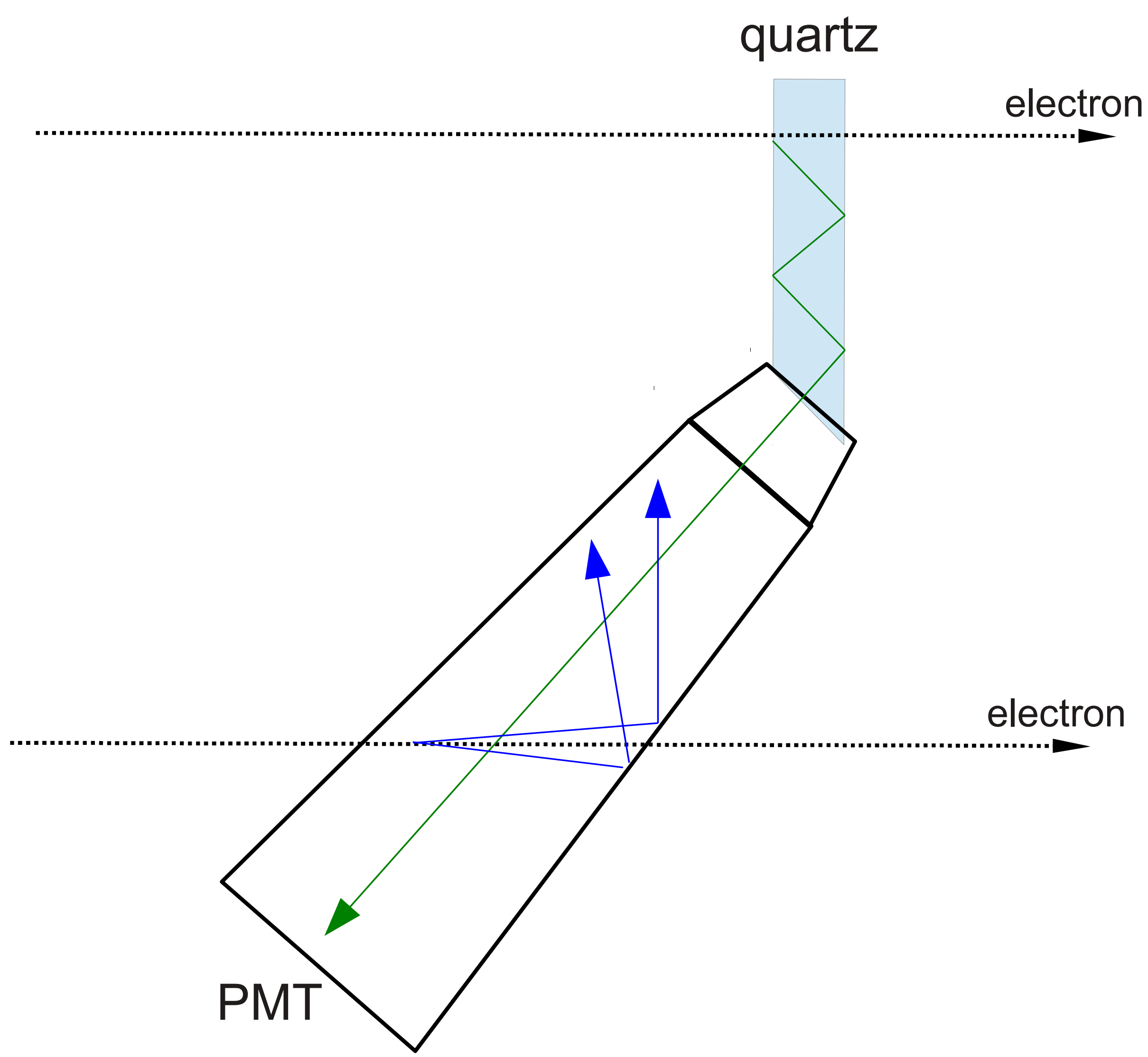
Independent detector simulation of individual detectors and full detector rings used to optimize detector geometry and study background and interference.

Trying to find:
Best geometry of quartz, lightguide and shielding to maximize signal per electron and minimize background.
Best procedures for low wavelength photons.
Best material for lightguide.

Detector test stands now exist at Manitoba, UMass and Idaho.
In beam detector tests being planned at Mainz.

Potential Detector Design

Favorable Model



Bottom wedge cut:

- Allowing the Cerenkov light to escape easily from quartz with specific direction, and to reduce the loss due to bouncing in quartz

Tilting light guide towards beam:

- Matching the angle of escaping Cerenkov light from quartz (**green**), so as to minimize the loss due to bouncing on light guide inner surface
- Directing the Cerenkov light in air (**blue**) to the opposite side of PMT, so that these interferences can be reduced by bouncing in light guide

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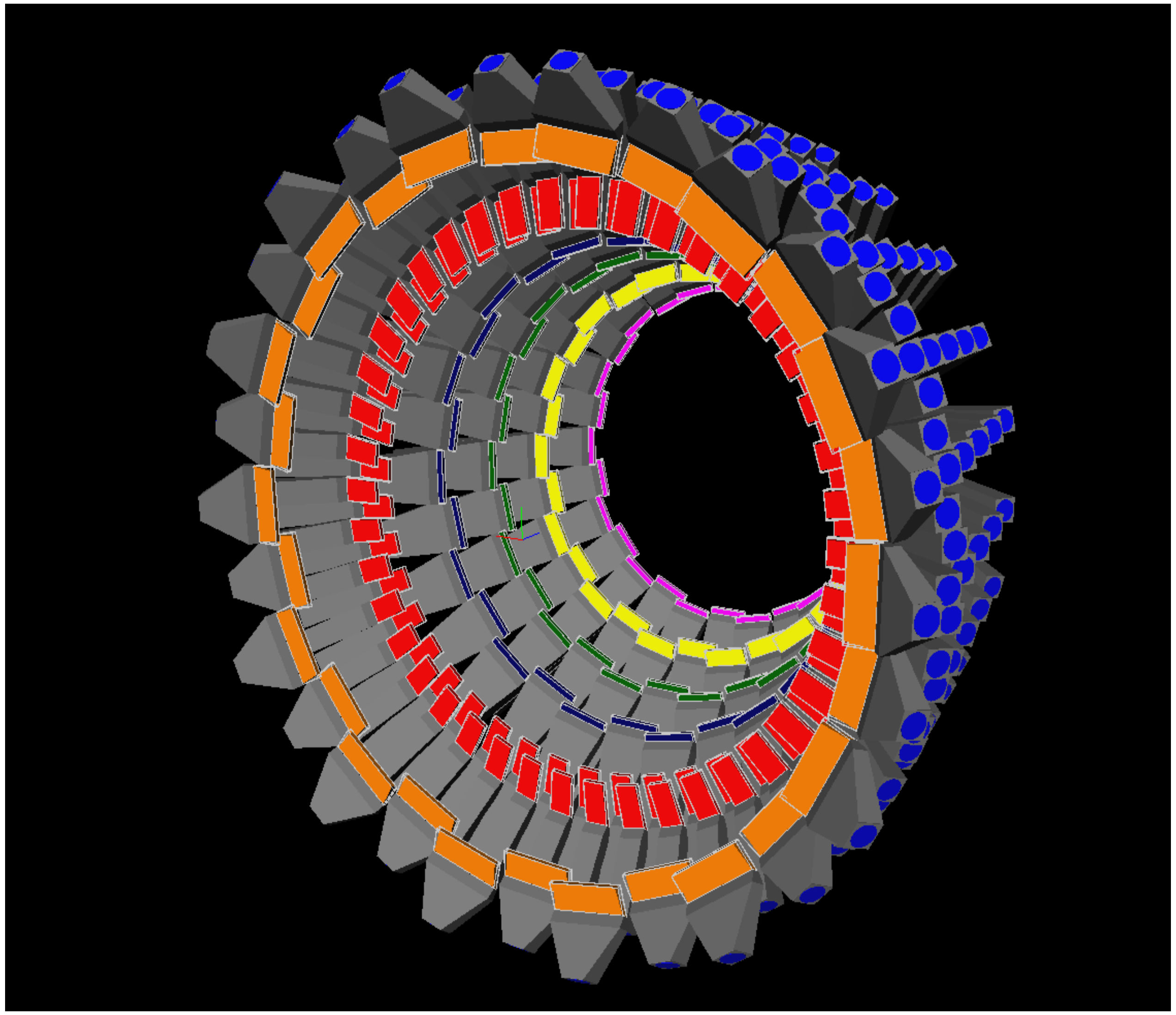
Detector Simulation
Implementation

Implemented in the independent detector simulation package:



Configuration:

- Quartz thickness: 1.5 cm
- Length of e-e ring light guide : 34 cm
- Light guide mateial: Anolux-UVS
- PMT: 3” round quartz window

#PE yield of e-e ring detector:

- ~37 PE
- rms: 8.7

To see the the background/interference, an implementation in the full MOLLER simulation environment is needed (not done yet)

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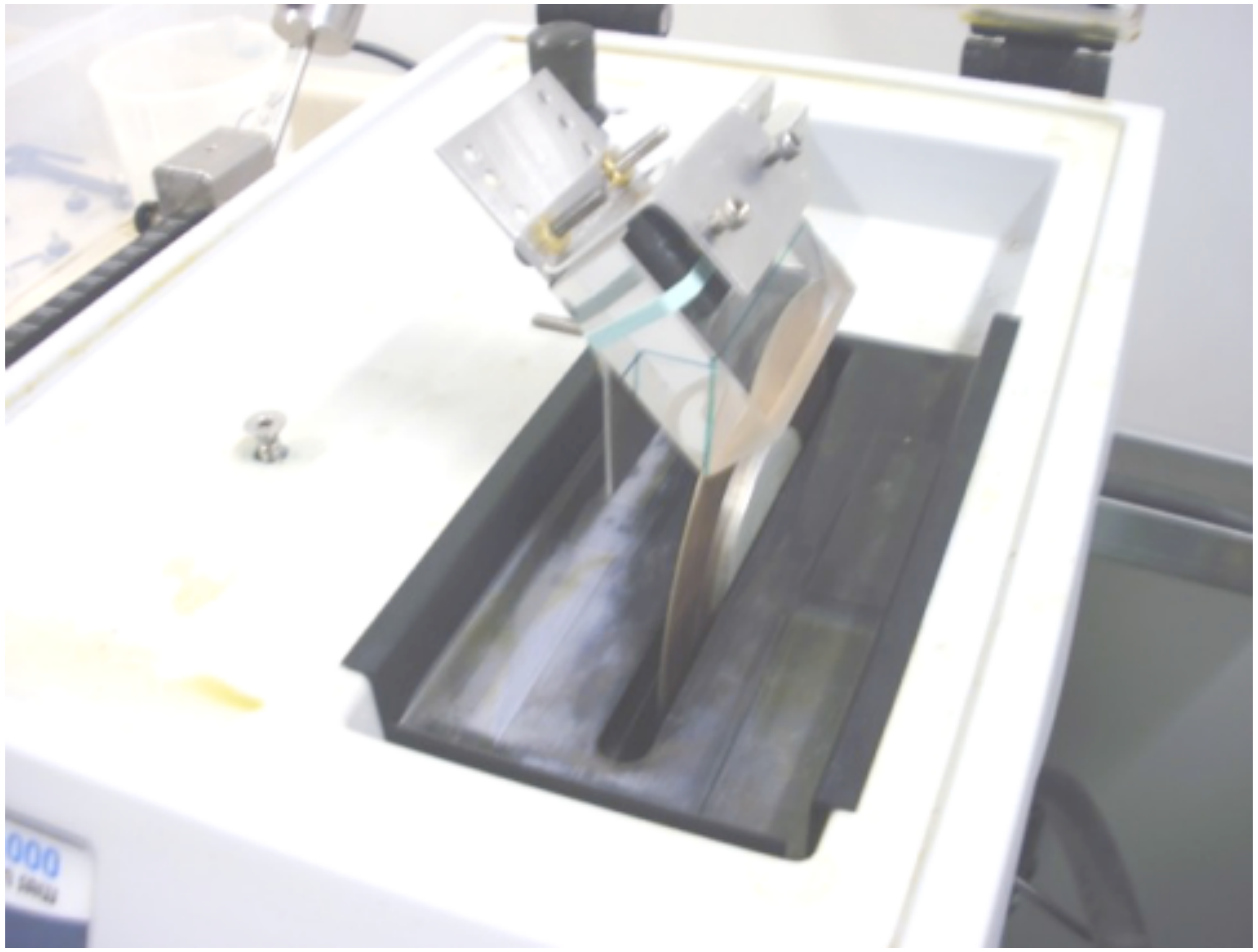
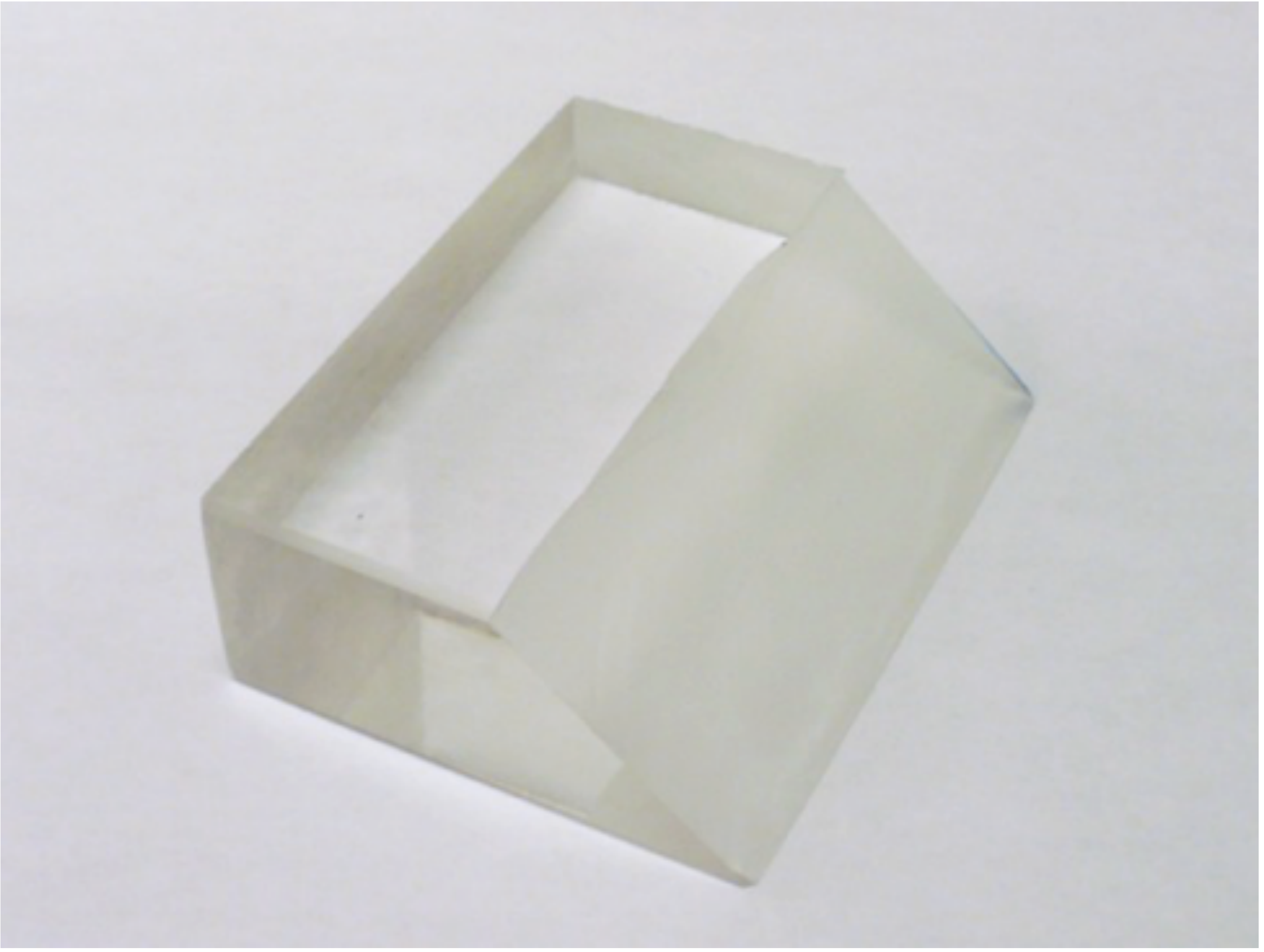
8

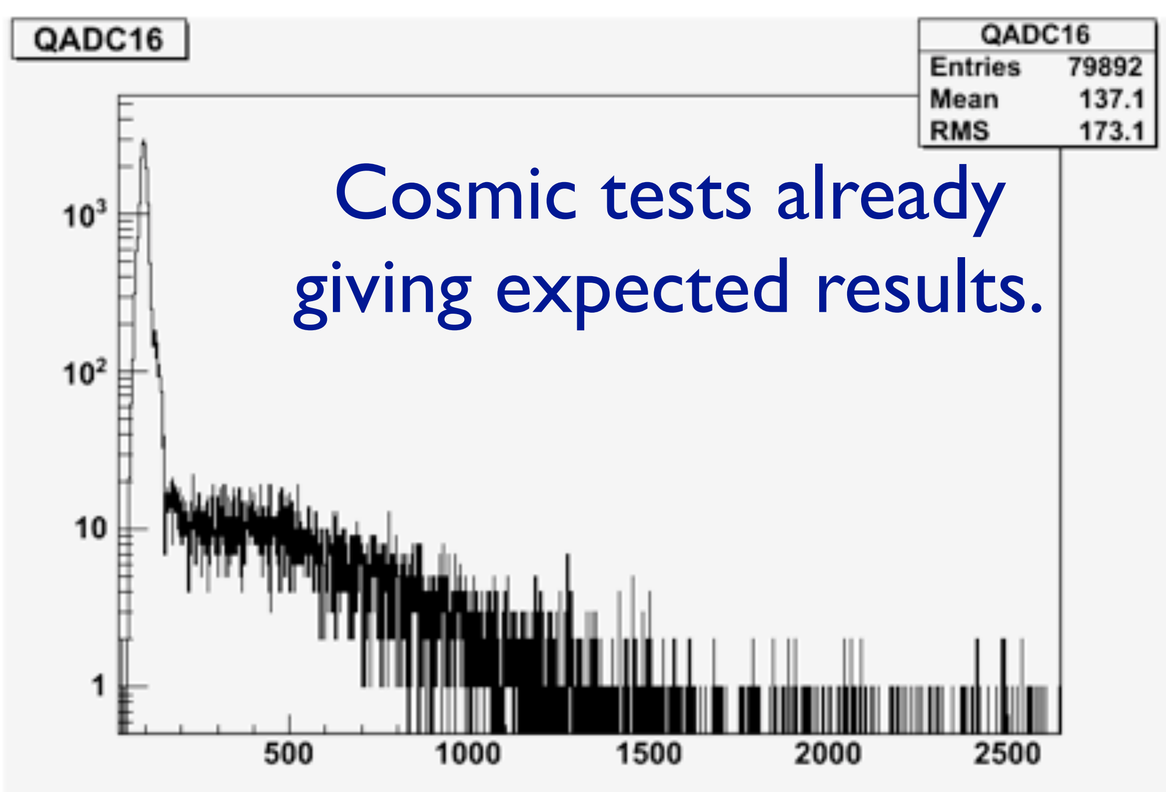
Detector Tests

Prototype detectors being prepared for beam tests at Mainz.





Cosmic Tests



Cosmic tests already giving expected results.

PREX detector testing with cosmic rays at UMass

Conclusion

MOLLER is a Hall A experiment with New Physics discovery potential.

Experiment design has made significant advancements since the last Hall A meeting.

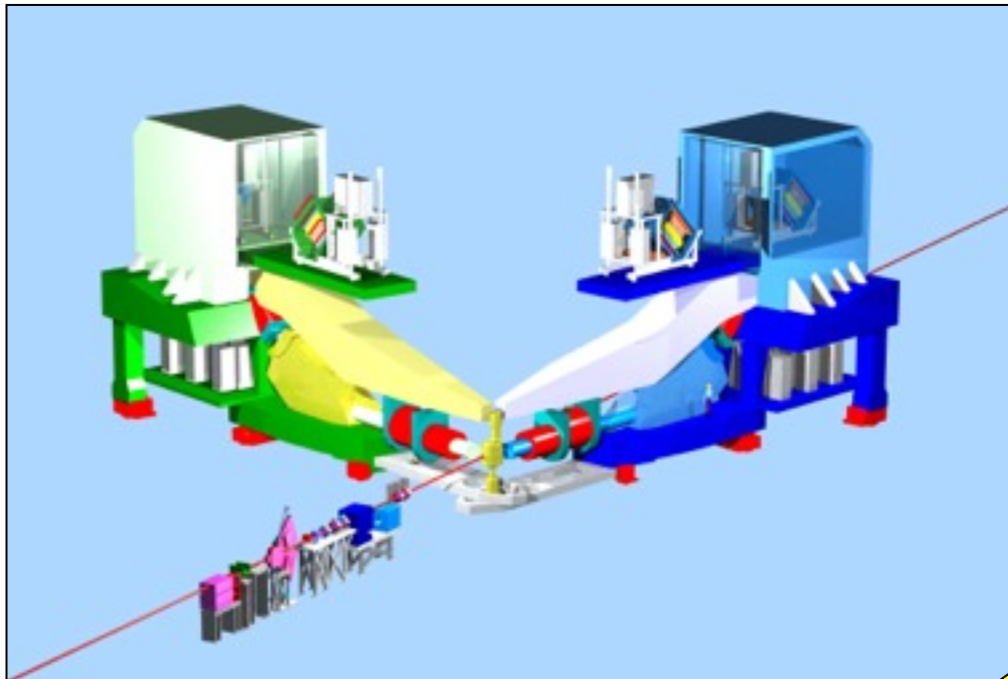
A proposal has been delivered to DOE and is awaiting action. A writing group is working on updating relevant sections in anticipation of a Fall science review.

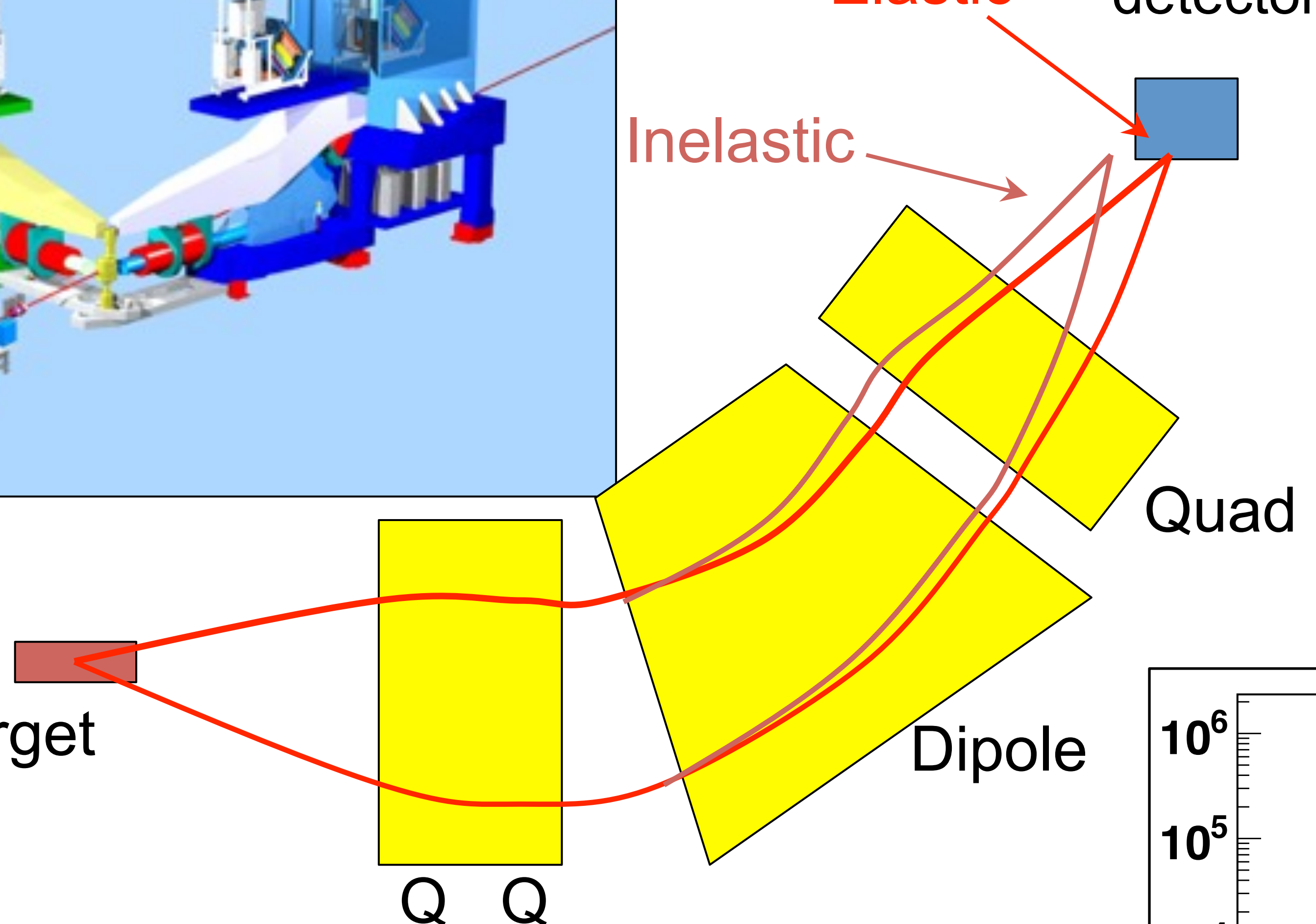
Backup

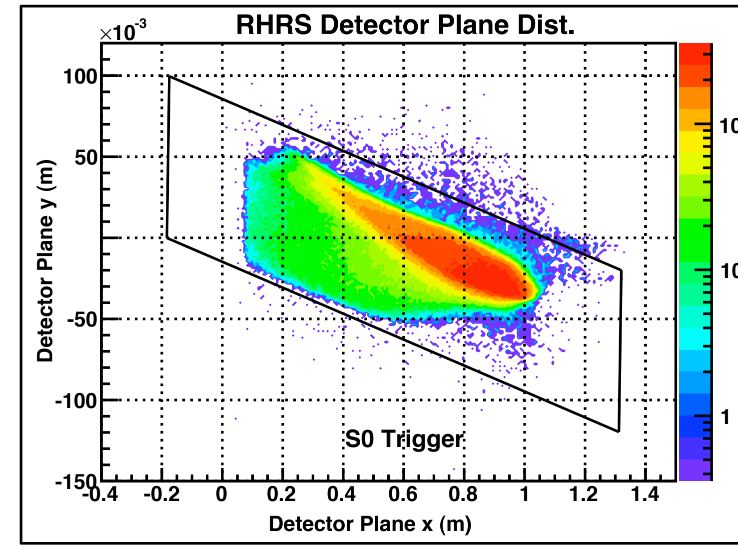
In-Air vs. In-Vacuum

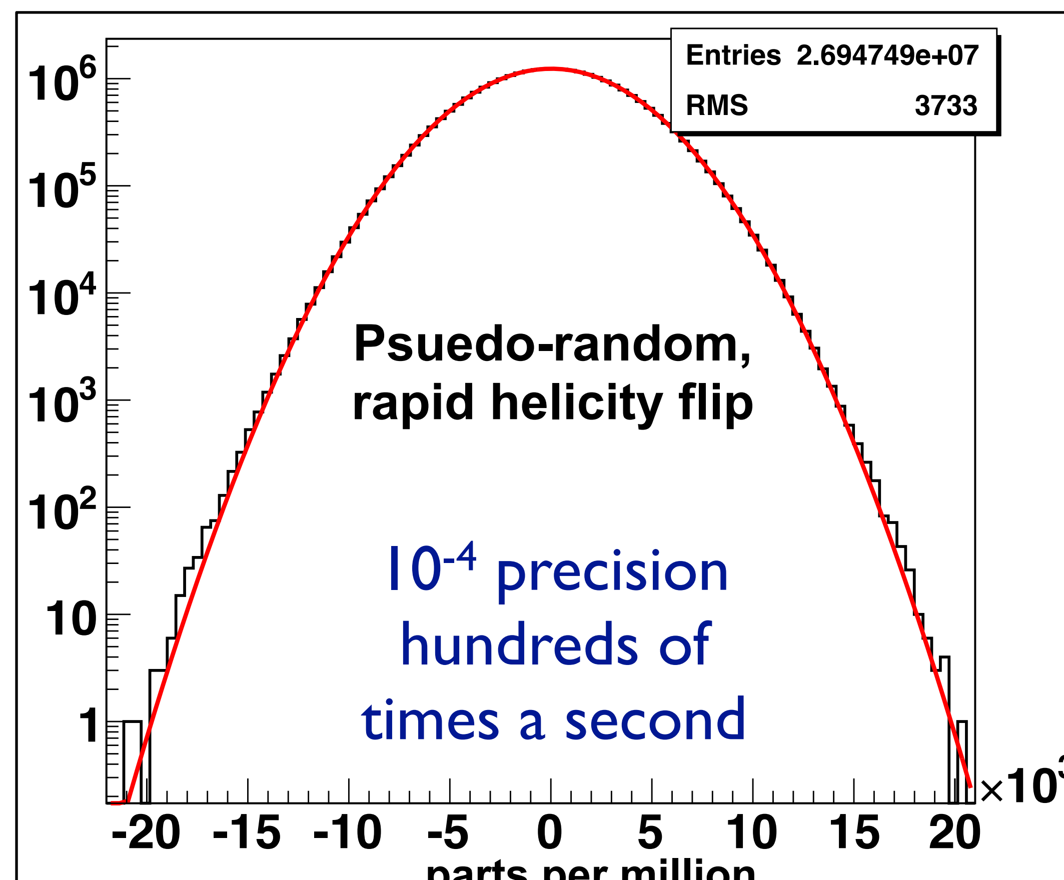
	Coils in Vacuum	Coils in Air
Beampipe / vacuum system	• Large vacuum chamber to hold all coils – could have issues with pressure vessel code @ JLab • Need water system interlocked to vacuum system	• Needs complex beampipe system, which could incur the wrath of pressure vessel inspectors. • Central beampipe needs to be capable of absorbing 1000 W of photon flux over 6 m.
Coil Support	• Inter-coil supports could be implemented easily, due to absence of beam pipe	• Inter-coil supports could be more difficult; would require tulip petal pipe with circumferential holes or as 8 separate pipes.
Physics Acceptance	• Only determined by coils	• Beampipe cuts into acceptance, figure at least 4 mm thick.
Attachment of services	• More difficult… would likely need to rout these all to one end or the other. • Would need flexible lines in vacuum – metal due to radiation → $$$	• Can access services directly at outer radius.
Maintenance	• More difficult	• Less difficult
Alignment	• Much more difficult, JLab laser tracking system would be used.	• Laser tracking system is easier to use for this configuration.

Hall A Parity - Standard Setup



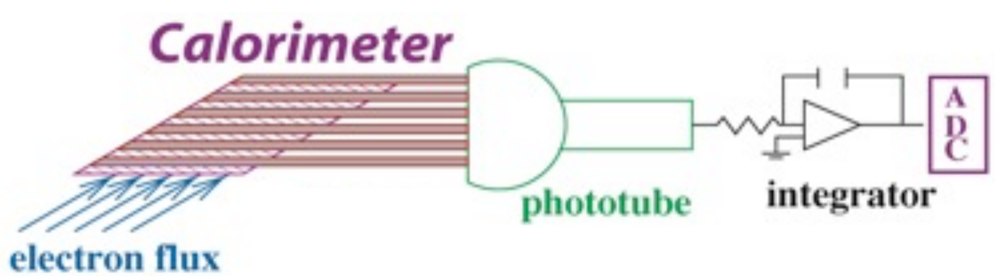




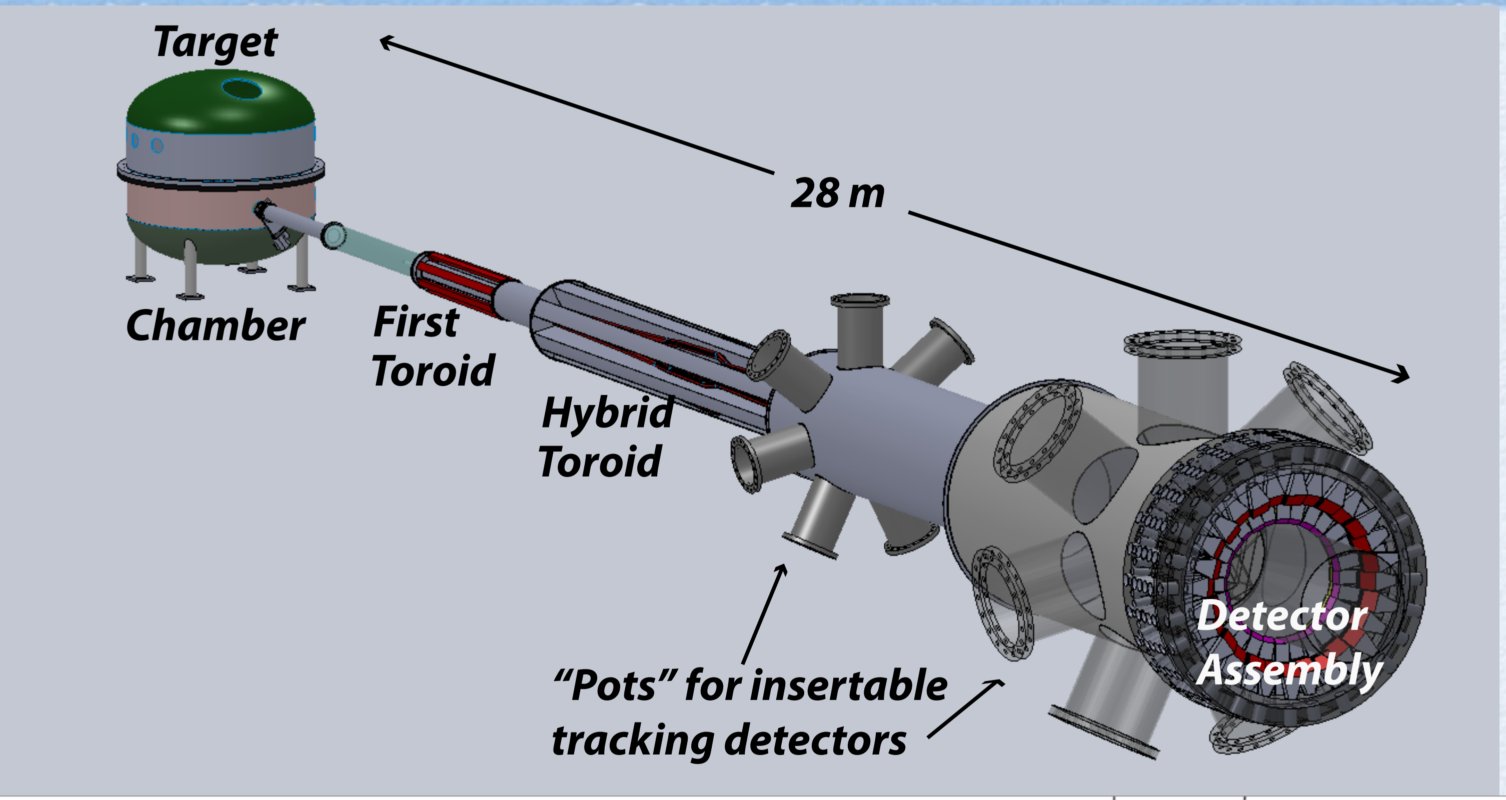


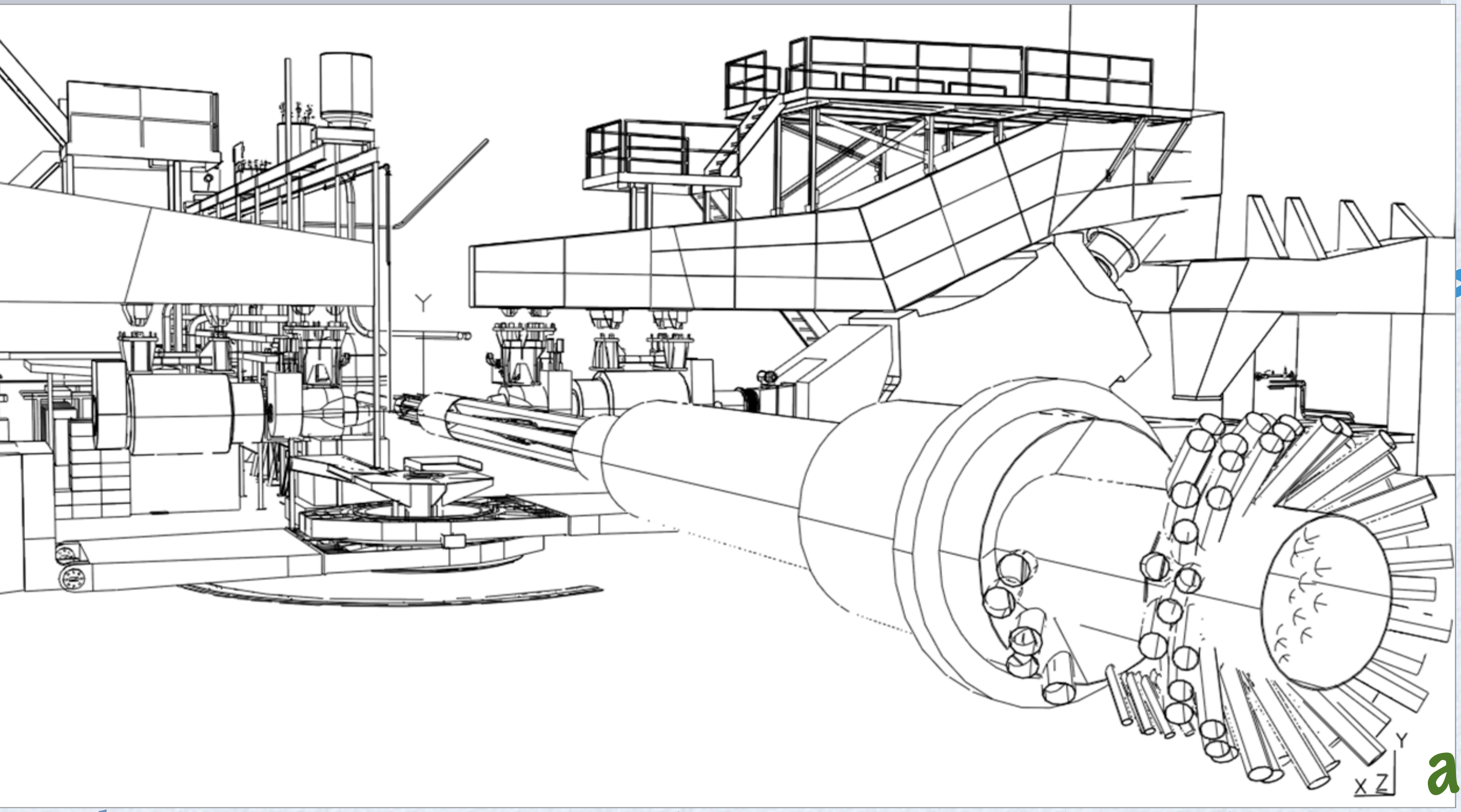
Lead - Lucite Cerenkov Shower Calorimeter

phototube current integrated over fixed time periods



MOLLER Apparatus





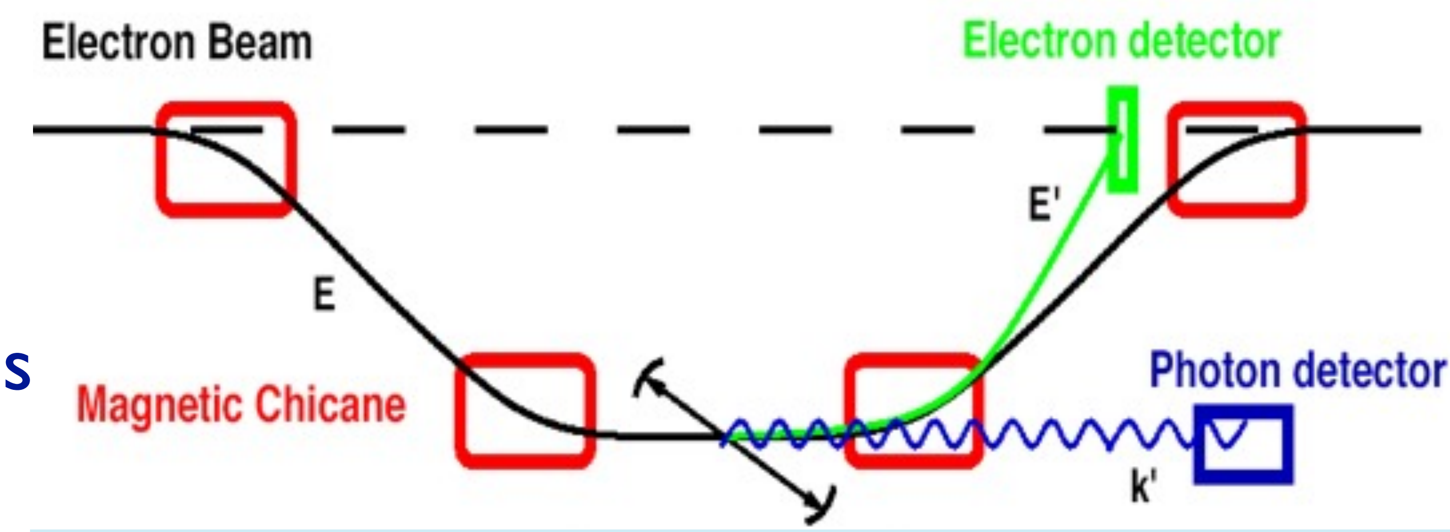
* **Polarized Beam**
  - Unprecedented polarized luminosity
  - unprecedented beam stability
* **Liquid Hydrogen Target**
  - 5 kW dissipated power (2 X Qweak)
  - computational fluid dynamics
* **Toroidal Spectrometer**
  - Novel 7 "hybrid coil" design
  - warm magnets, aggressive cooling
* **Integrating Detectors**
  - build on Qweak and PREX
  - intricate support & shielding
  - radiation hardness and low noise

compact structure: plan to make apparatus and sheilding easily removable

Technical Challenges

Polarization enters result directly

$$A_{PV} = \frac{A_{\rm raw}}{P_e}$$

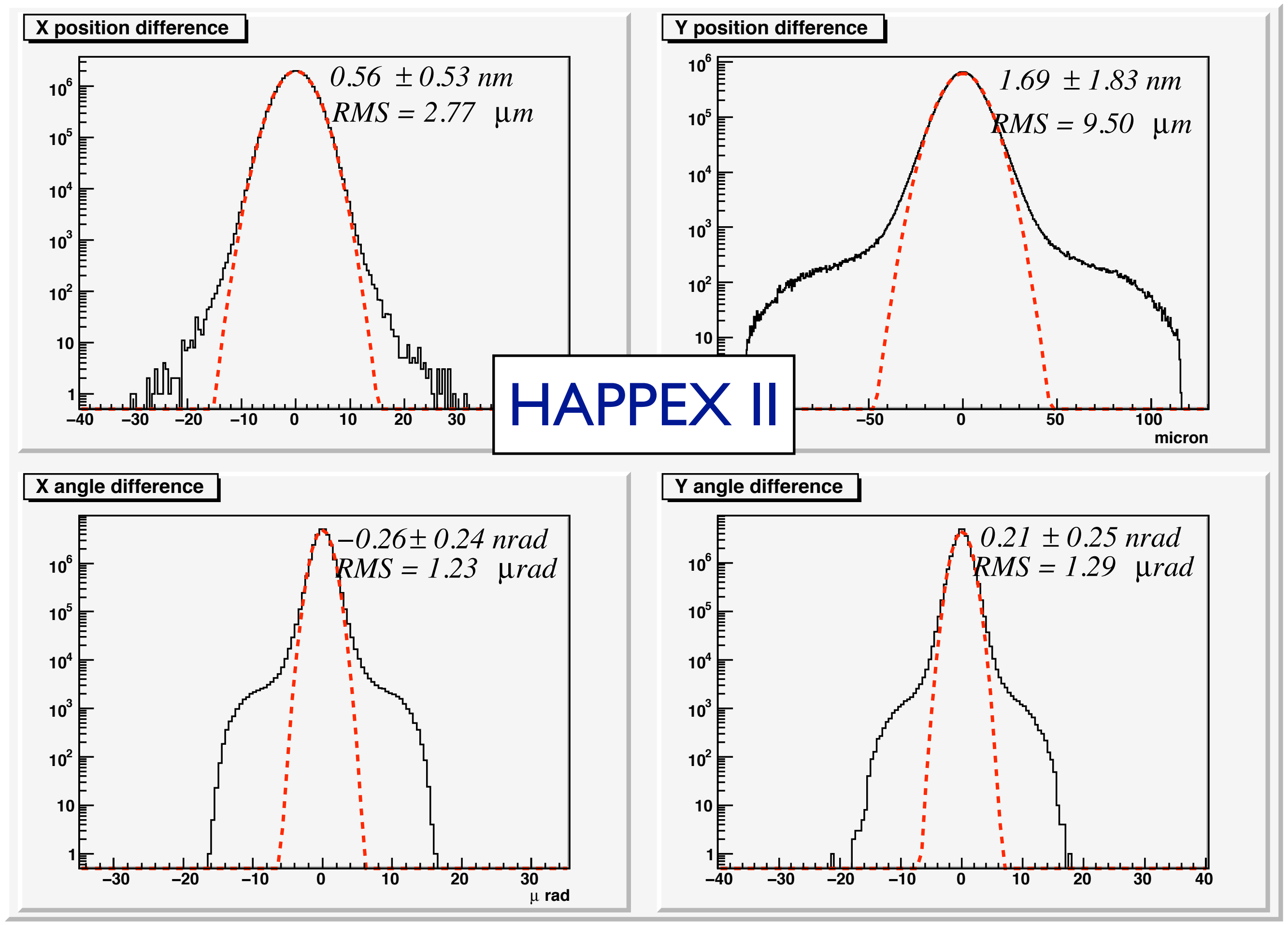


Resonant cavity "photon target", up to 2kW intensity

Precision must be better than statistics

V.Tvaskis DLNP building, Thursday16:50

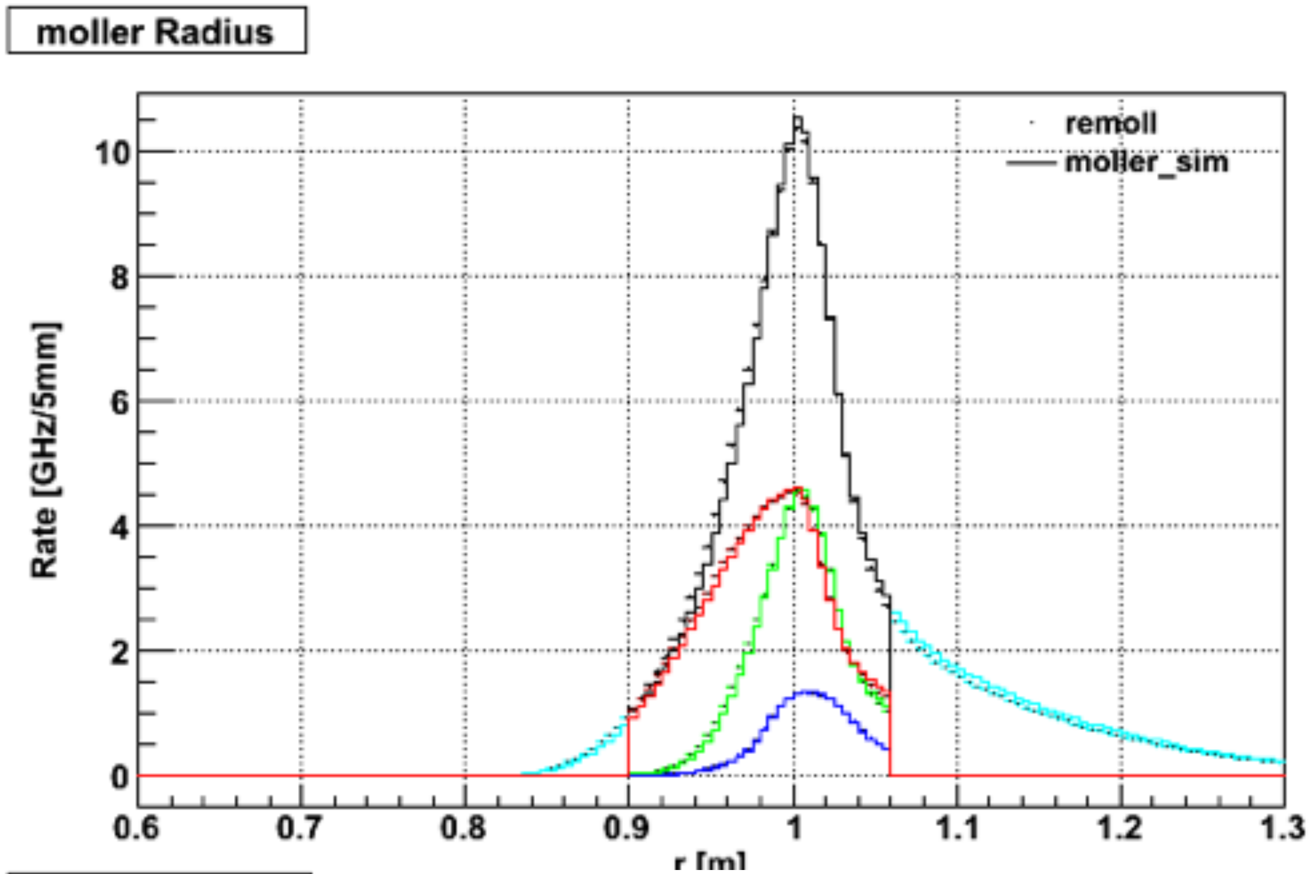
Beam false asymmetries must be kept small

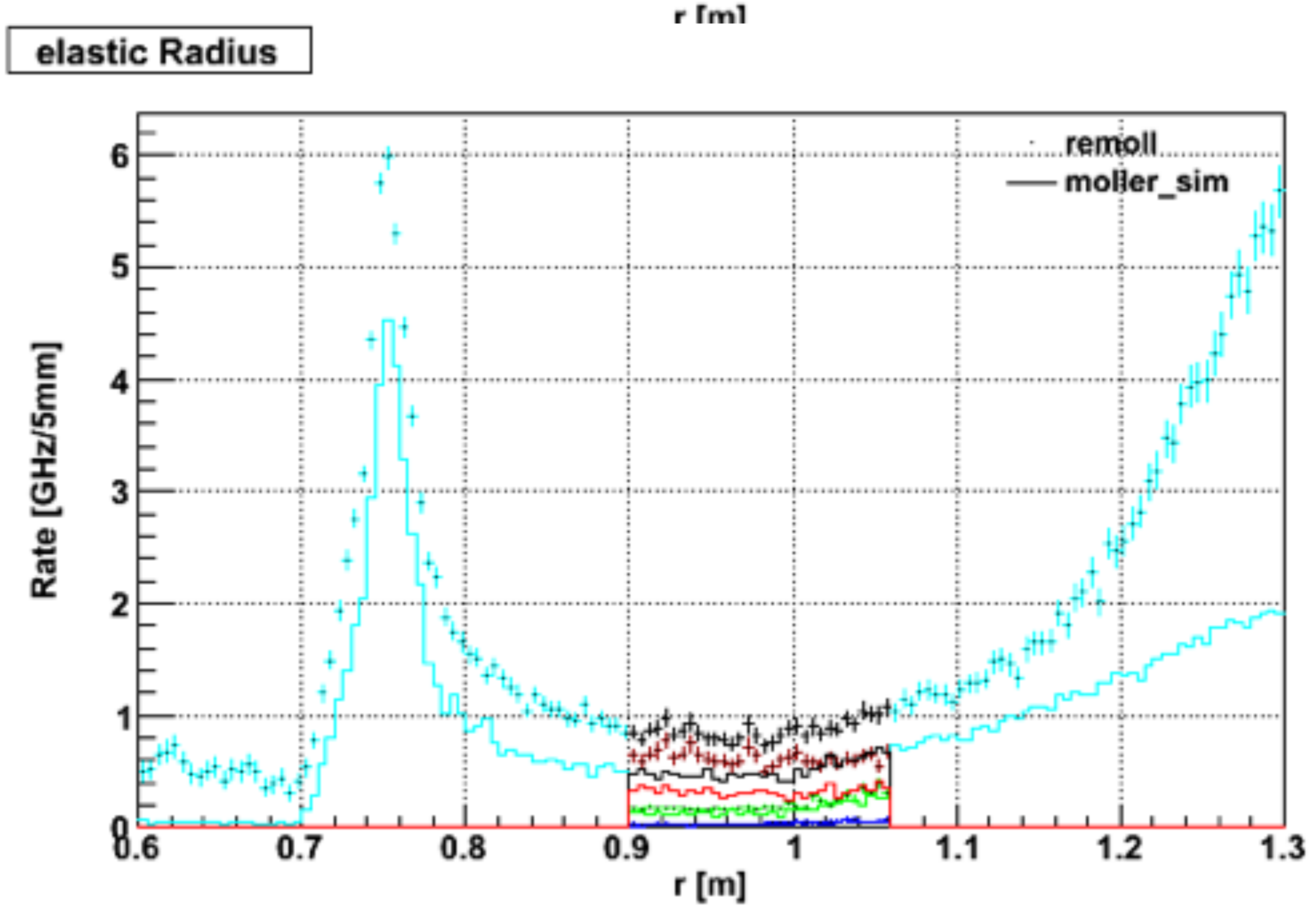


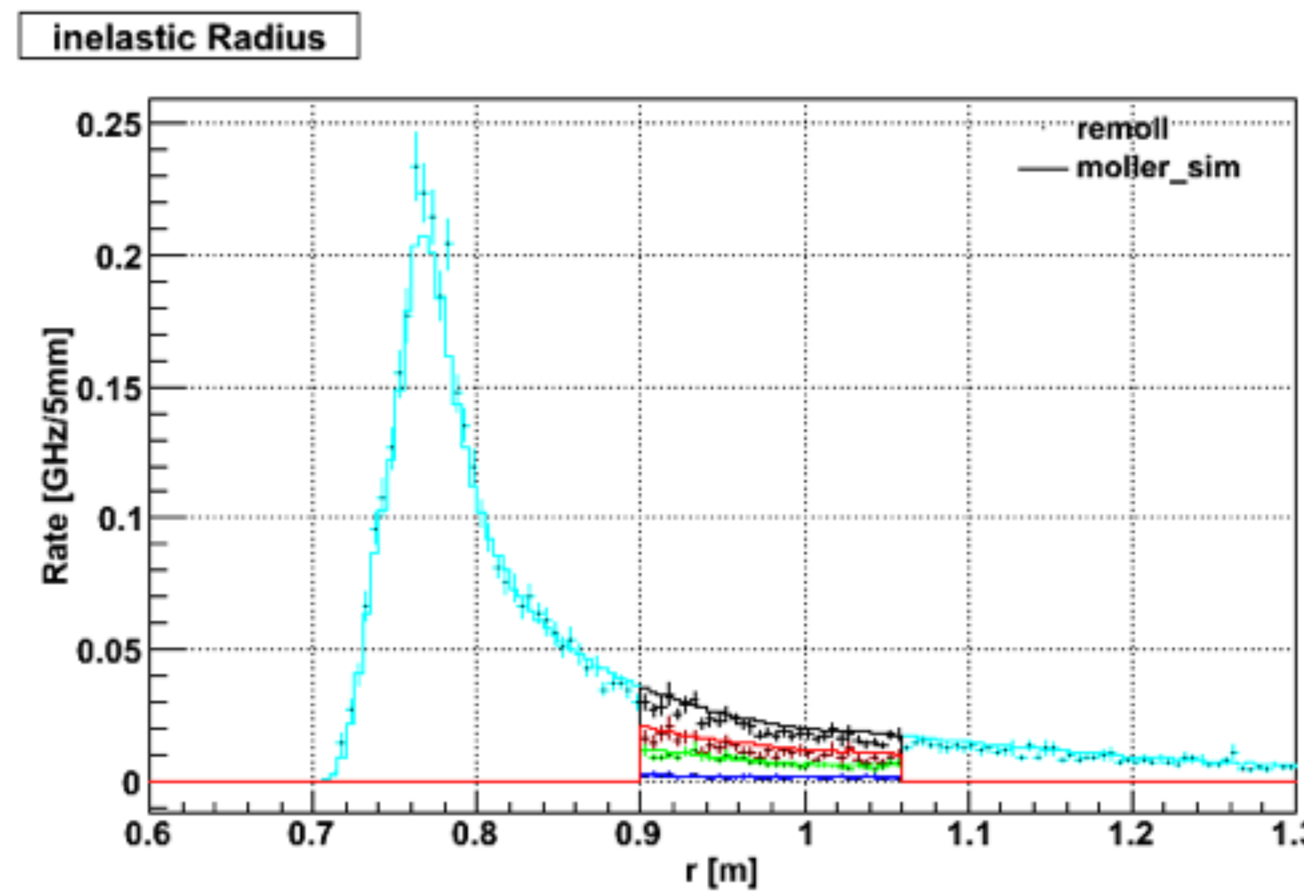
Currently we achieve ~1nm position differences and <1nrad angle differences

These need to be improved for future experiments!

New Simulation Benchmarking







Beam modulation "Dithering" system

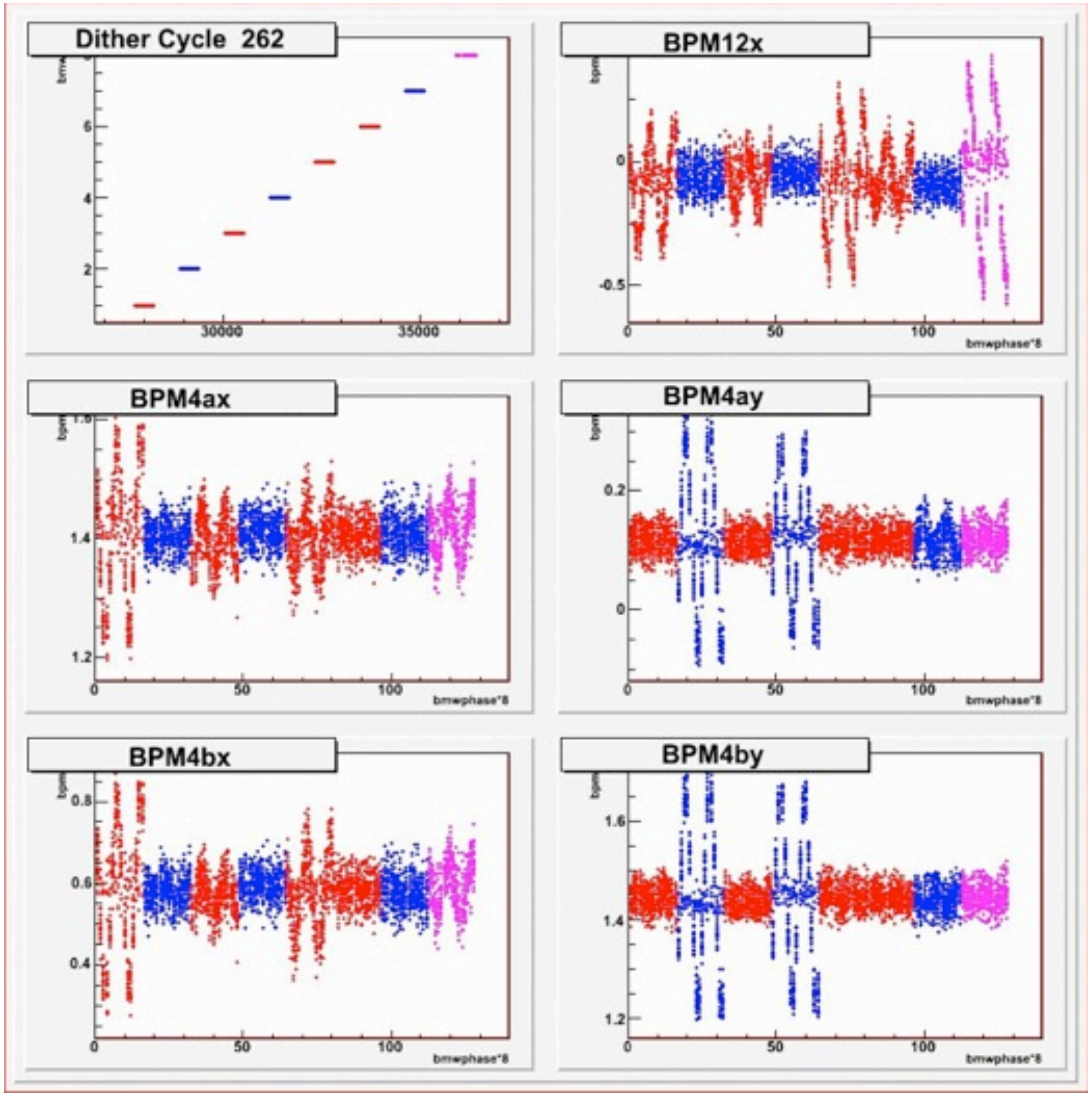
Avoids slow drifts with differential measurement

VME function generators drives sine waves

Slower than DAQ readout frequency (i.e. 15 Hz)

FFB must still be disabled

Uses standard Trim magnet P.S. cards drive readout in DAQ

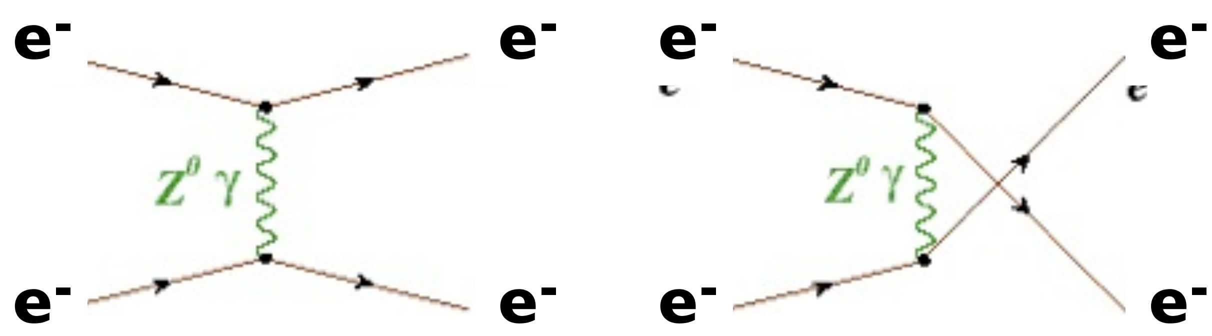


- Reasonable orthogonality
- Reasonable stability
- Hardware working well
- Slopes change with optics
- energy independent fit more constant

MOLLER Experiment

Measurement
Of
Lepton-
Lepton
Electroweak
Reaction

Measuring weak charge on the electron to very high precision with "low" energy Moller scattering.



θ_{lab} ~ 0.3°-1.03°

I_{beam} = 75 μA

150 cm LH_2 target

~150 GHz !

Small angle

Huge rate

Tiny asymmetry

High precision

$$A_{PV} = -35 \text{ ppb}$$
$$\delta(A_{PV}) = 0.73 \text{ ppb}$$
$$\delta(Q_W^e) = \pm 2.1\% \pm 1.0\%$$

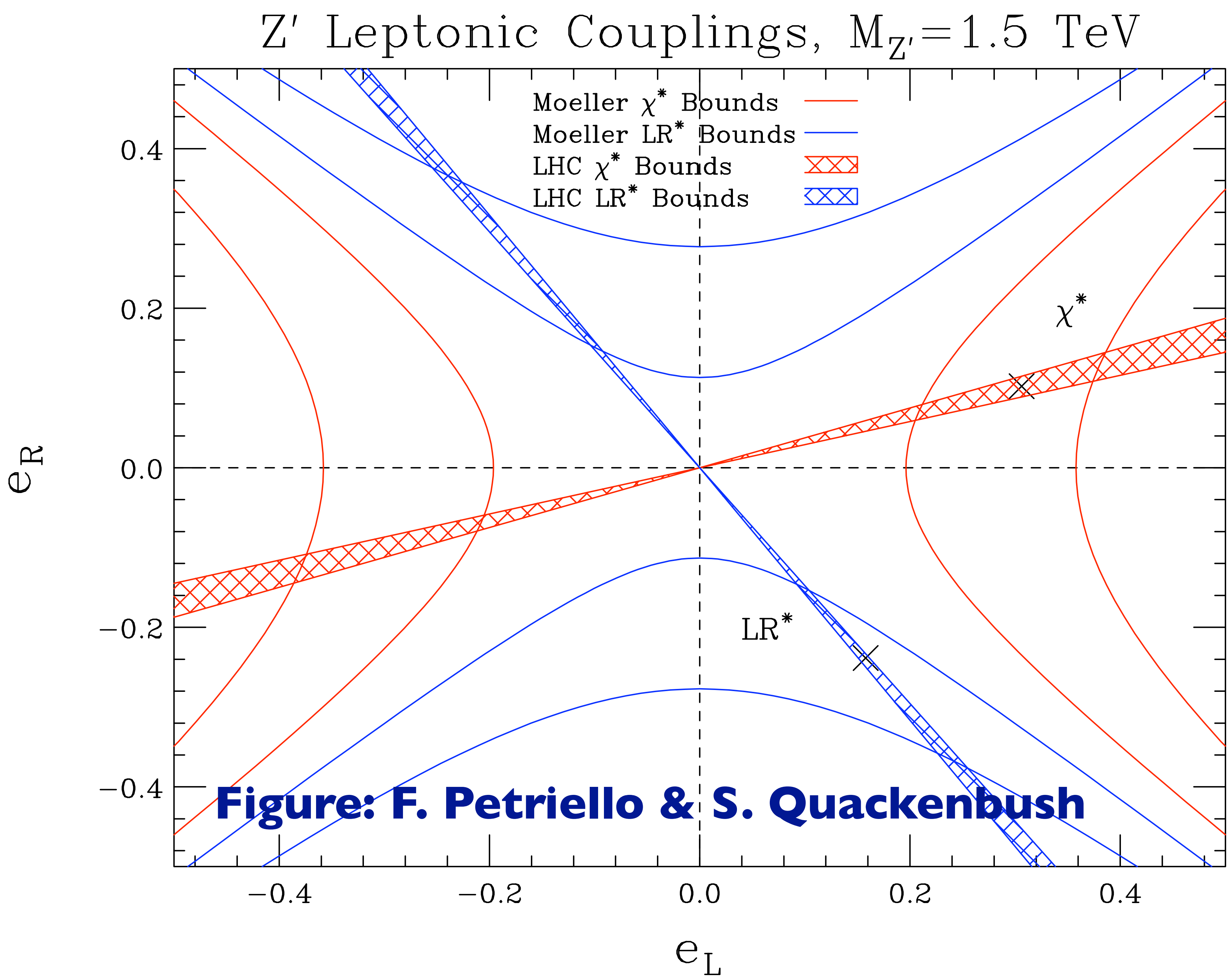
Matches best collider (Z-pole) measurement!

$$\delta(\sin^2\theta_W) = \pm 0.00029$$

Complementary to LHC

For the additional neutral Z' scenario:
LHC sensitive to ~5 TeV, properties to 1-2 TeV
MOLLER can help pin down couplings

lepton coupling only: could break degeneracy between q and e couplings to Z'
QWeak can get sign of q×e



MOLLER sensitivity:

$$\frac{g_{RR}^2 - g_{LL}^2}{\Lambda^2} = \frac{e_R^2 - e_L^2}{M_{Z'}^2}$$

$$\sim \frac{1}{(7.5\text{TeV})^2}$$

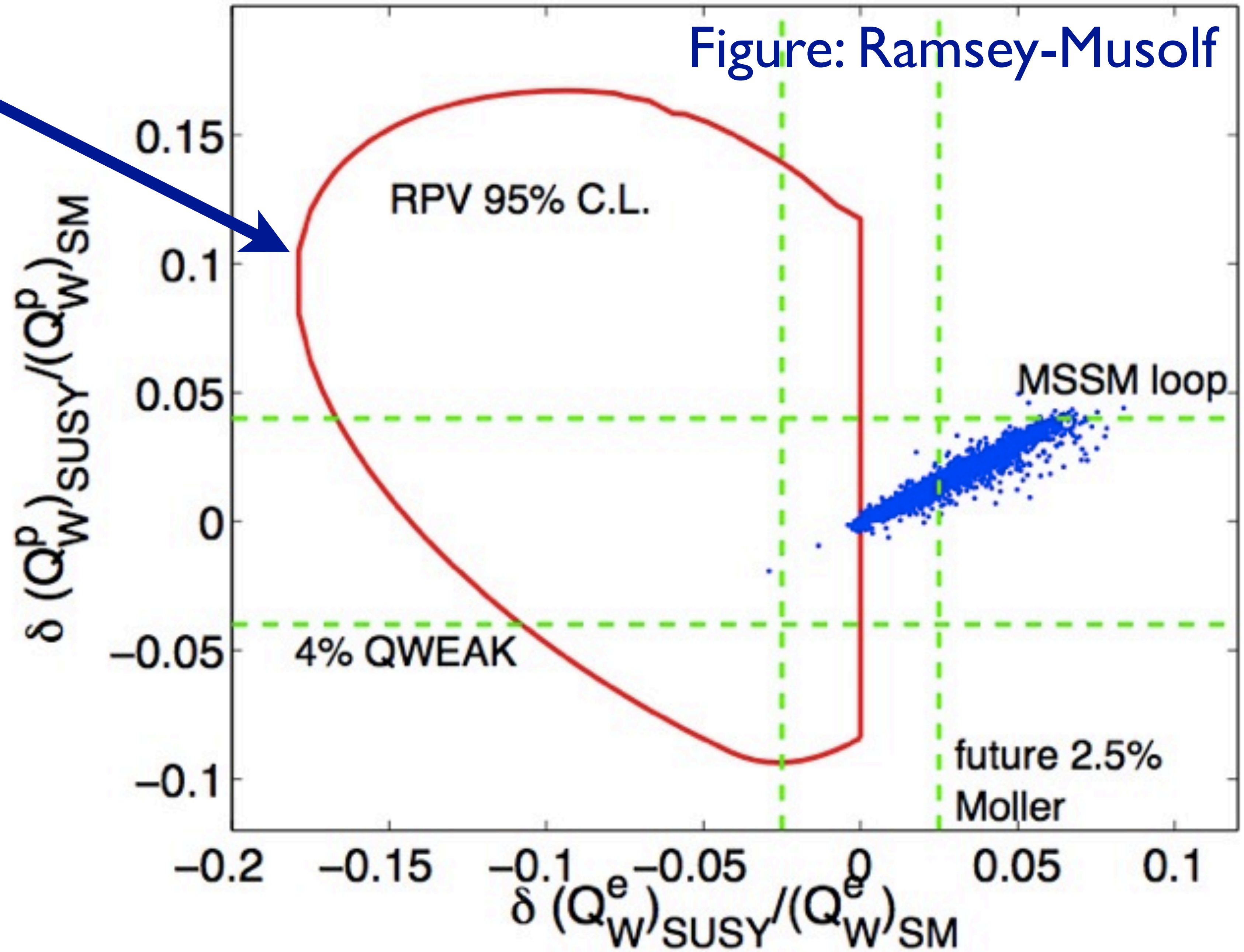
With mass, width, and A_{FB}, LHC can get constraint on e_R/e_L

PVES access to New Physics

Including global fit constraints

⇒ νs are Majorana

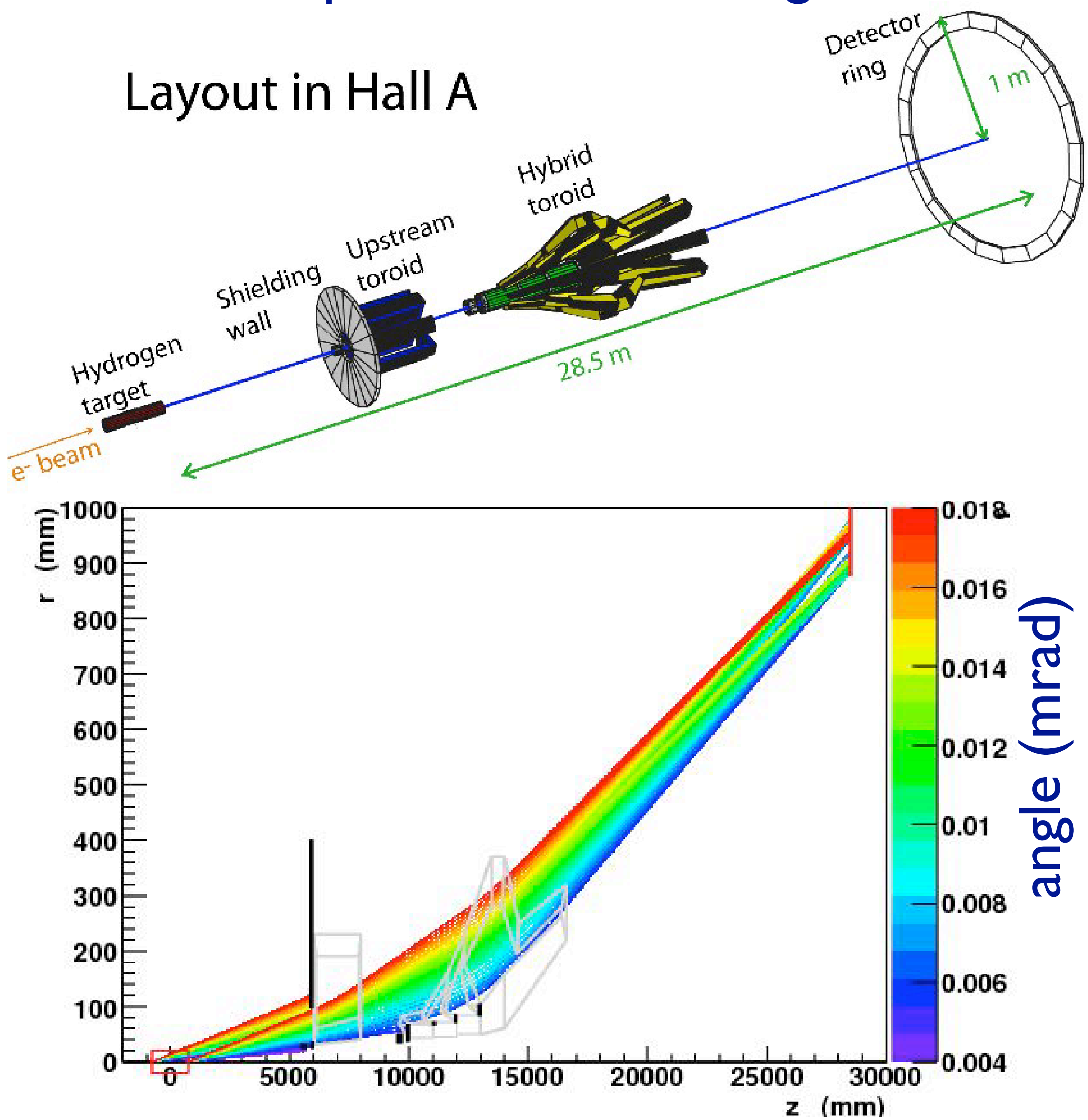
⇒ Lightest Supersymmetric Particle can't be Dark Matter

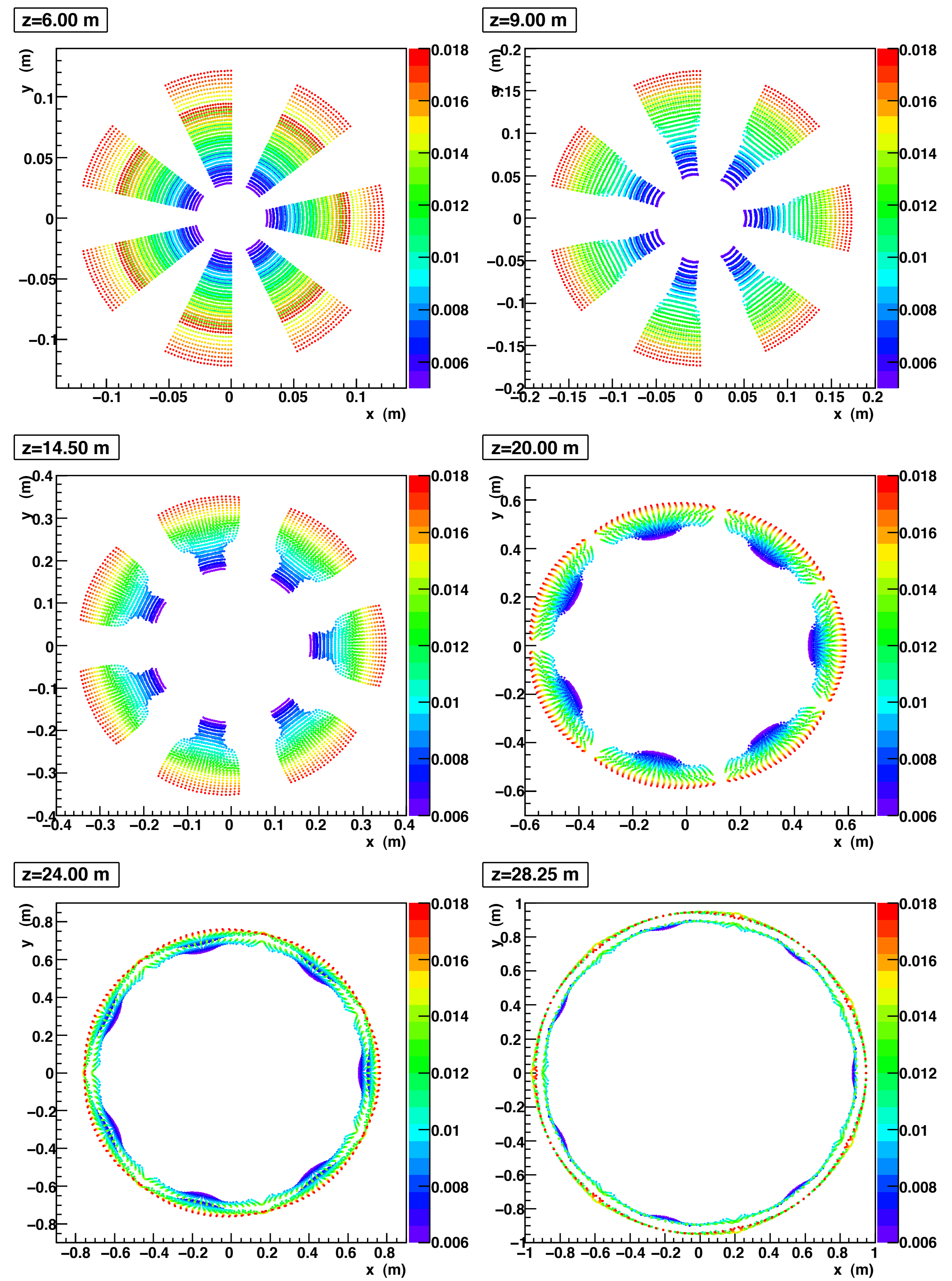


Tension between E158 and (g-2)μ ← (if interpreted in SS, favors large loop effects)

Two Toroid Configuration

1 meter radial focus, 30 meters from target
Clean separation from backgrounds



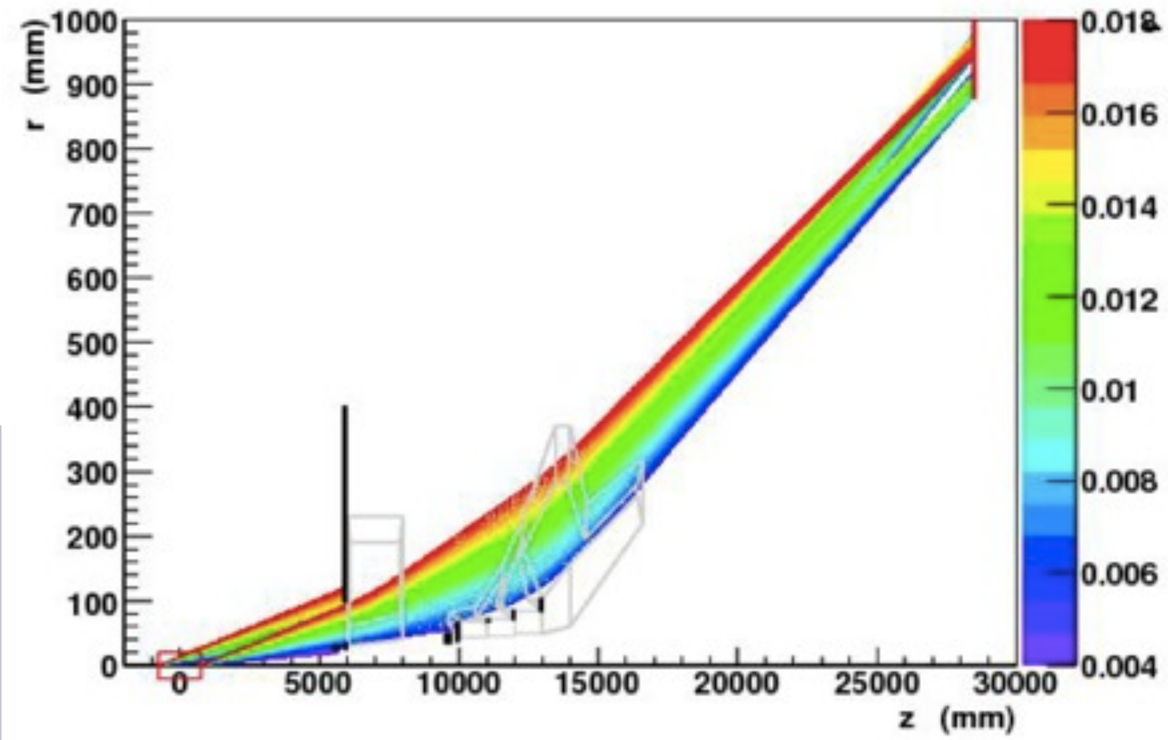


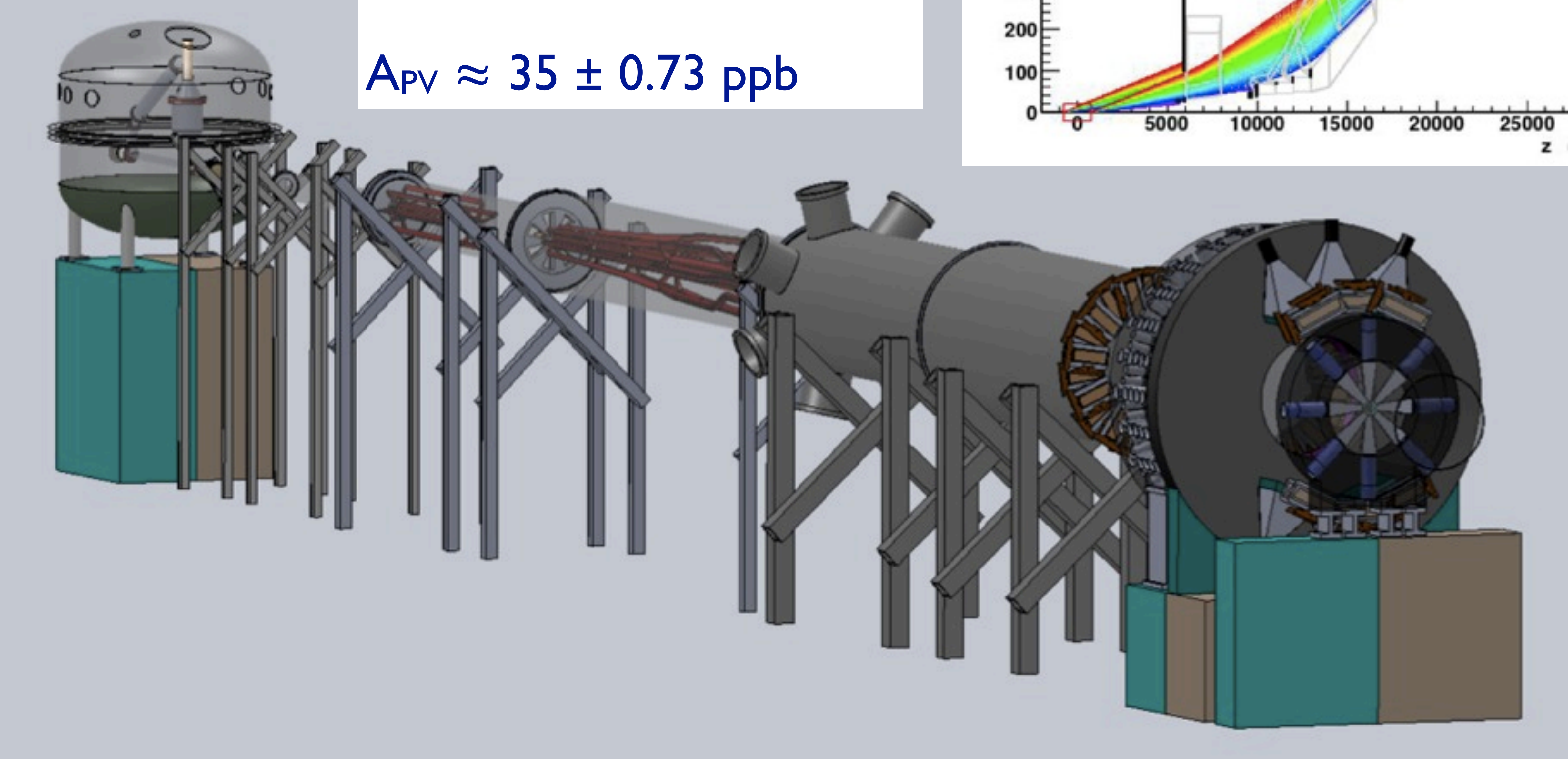
MOLLER Experiment

$Q^2 = 0.0056\ (\mathrm{GeV}/c)^2$
$E_{beam} = 11$ GeV
$0.29^\circ < \theta_{lab} < 0.97^\circ$

~85 µA, 1.5 m LH2 target

$A_{PV} \approx 35 \pm 0.73$ ppb





Statistics and Systematics Comparison

Accuracy goals for MOLLER are factors of 2 to 10 beyond those of E158 & Qweak

parameter	E158	Qweak	MOLLER
Rate	3 GHz	6 GHz	135 GHz
reversal rate	120 Hz	960 Hz	1920 Hz
pair stat. width	200 ppm	400 ppm	82.9 ppm
$\delta(A_{raw})$	11 ppb	4 ppb	0.544 ppb
$\delta(A_{stat})/A$	10%	3%	2.1%
$\delta(\sin^2\theta_W)_{stat}$	0.001	0.0007	0.00026

Extremely narrow width increases sensitivity to noise sources e.g. electronics noise

MOLLER apparatus

Enormous technical challenges: MOLLER is a IV Generation Expt at JLab

Polarized Beam
- unprecedented polarized luminosity
- unprecedented beam stability

Liquid Hydrogen Target
- 5 kW dissipated power (2 X QWeak)
- computational fluid dynamics

Toroidal Spectrometer
- Novel 7 "hybrid coil" design
- warm magnets, aggressive cooling

Integrating Detectors
- build on QWeak and PREX
- intricate support & shielding
- radiation hardness and low noise

MOLLER error budget

source of error	% error
absolute value of Q2	0.5
beam second order	0.4
longitudinal beam polarization	0.4
inelastic e-p scattering	0.4
elastic e-p scattering	0.3
beam first order	0.3
pions and muons	0.3
transverse polarization	0.2
photons and neutrons	0.1
Total	**1.0**

Very little room for uncertainties from HC beam properties

Technical Challenges

~150 GHz Scattered Rate

Must flip Pockels cell ~ **2 kHz**

- **80 ppm** pair statistical fluctuations
  - electronic noise and density fluctuations <10^{-5}
  - beam jitter ~10 microns or less
  - beam monitoring resolution ~ few micron

~1 nm / 0.1 nrad beam position change with helicity

>10 gm/cm^2 target, 1.5 meter LH2, ~**5kW**

Full azimuthal acceptance for 0.3° scattering

- **novel** two-toroid spectrometer
- radiation hard integrating detectors

Robust and redundant **0.4% beam polarimetry**

- Both atomic hydrogen Moller and improved Compton