MOLLER Experiment

D.S. Armstrong

Nov. 9 2010

"Precision Tests of the Standard Model"
ECT* Workshop

- Moller scattering: intro
- Previous measurement: SLAC E158
- MOLLER: new physics reach
- Experimental Concept and Challenges
- Status & Timeline

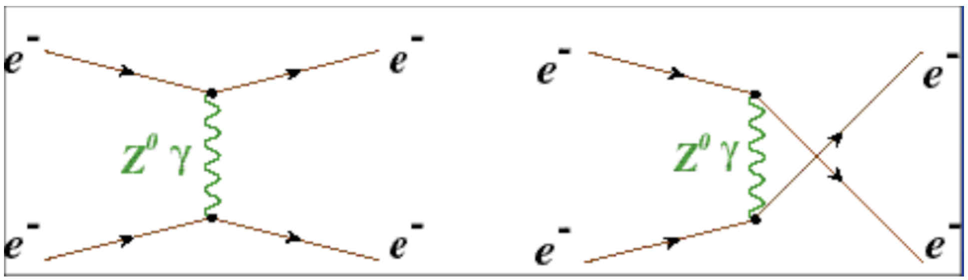
Many slides courtesy of *K. Kumar, K. Paschke, J. Mammei, M. Dalton, etc....*

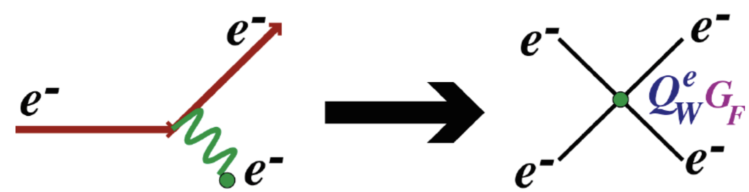
The College of WILLIAM & MARY

Jefferson Lab

Moller Scattering

MOLLER: **M**easurement **O**f **L**epton **L**epton **E**lastic **R**eaction
Proposed new experiment at 11 GeV at Jefferson Lab (after the upgrade)





Measure target weak vector coupling = weak charge: Q^e_W

$$A_{PV} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}Q^e_W$$

Derman and Marciano (1978)

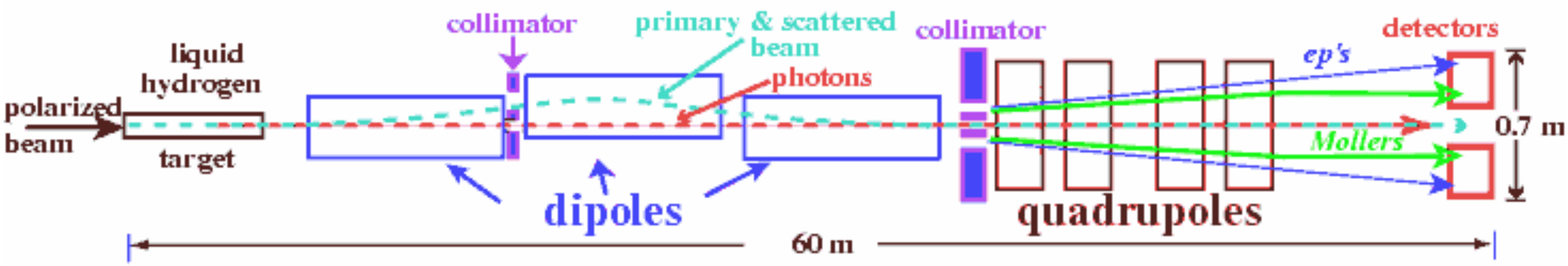
$$A_{PV} = \frac{N_R - N_L}{N_R + N_L} \propto m_e E_{lab}(1 - 4\sin^2\theta_W)$$

$$\frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \simeq 0.05\frac{\delta(A_{PV})}{A_{PV}}$$

Purely leptonic probe
- no hadronic corrections
- complementary to semileptonic expts

Pioneering Experiment: SLAC E158

- Spokespersons: *E. Hughes, K. Kumar, P. Souder*
- Stanford Linear Accelerator Center (SLAC):   used 45 and 48 GeV e^- beams
- electron beam ≈ 80% polarized (longitudinal)   120 Hz   11 μA
- 3 data-taking runs: 2002-2003
- A_{PV} ≈ 130 ppb   (280 ppb at tree level)

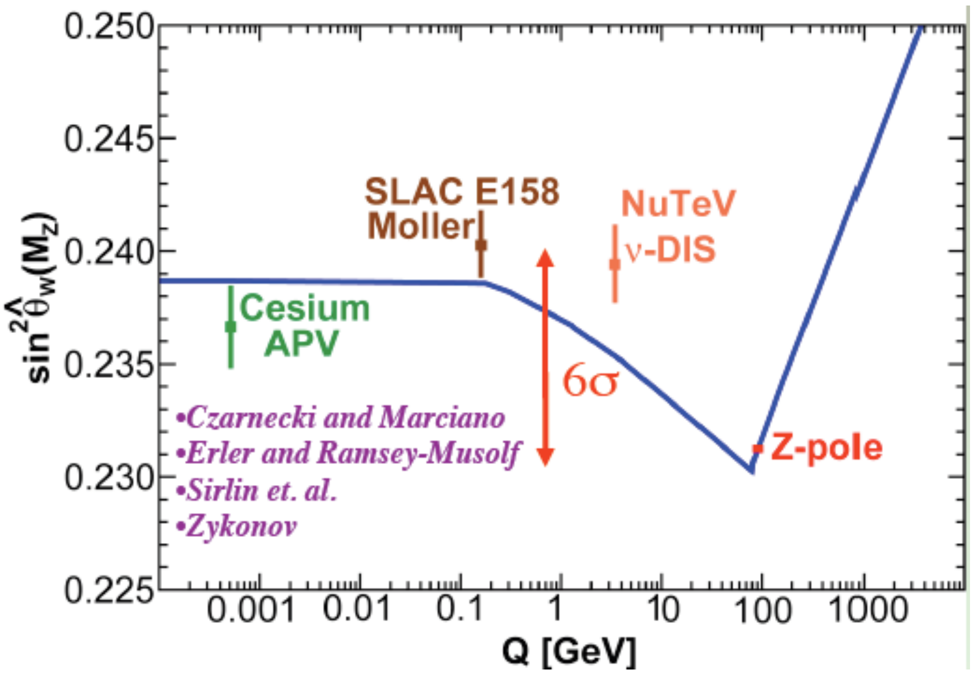


$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

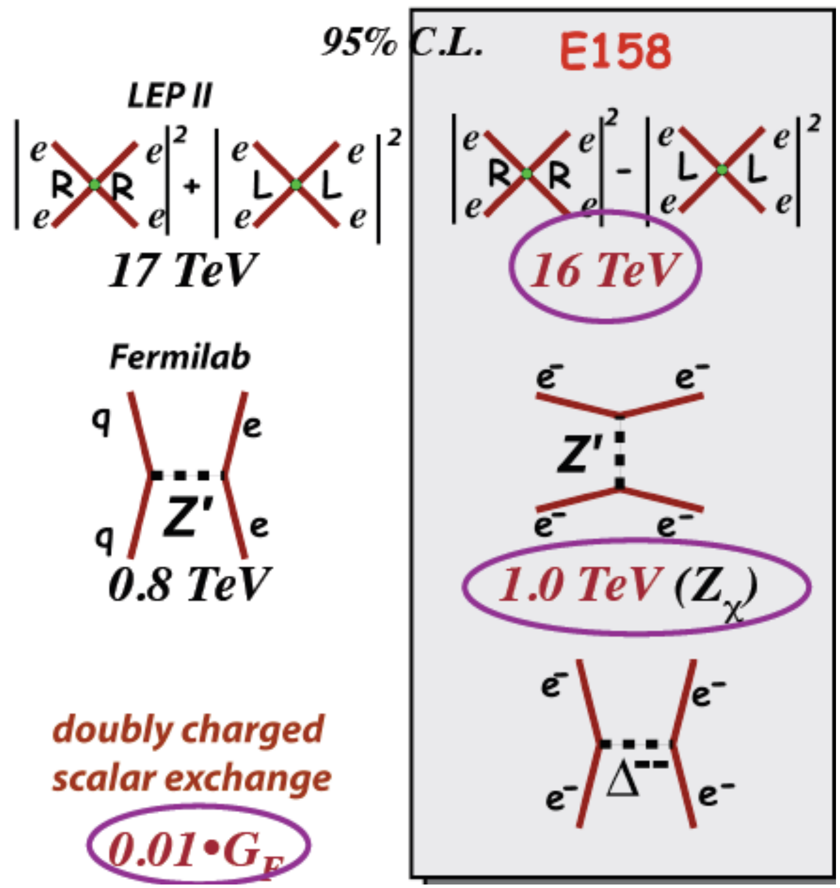
Phys. Rev. Lett. 95 *081601 (2005)*

E158: Implications

Running of $sin^2\theta_W$ established at 6σ level



if BSM physics: "bookkeeping" plot

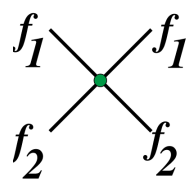


MOLLER: New Physics Reach

Flavor Diagonal Interactions

Consider $f_1 \bar{f}_1 \rightarrow f_2 \bar{f}_2$ or $f_1 f_2 \rightarrow f_1 f_2$

$$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda_{ij}^2} \eta_{ij} \bar{f}_{1i} \gamma_\mu f_{1i} \bar{f}_{2j} \gamma^\mu f_{2j}$$



Many new physics models give rise to such terms:
Heavy Z's, compositeness, extra dimensions, SUSY…

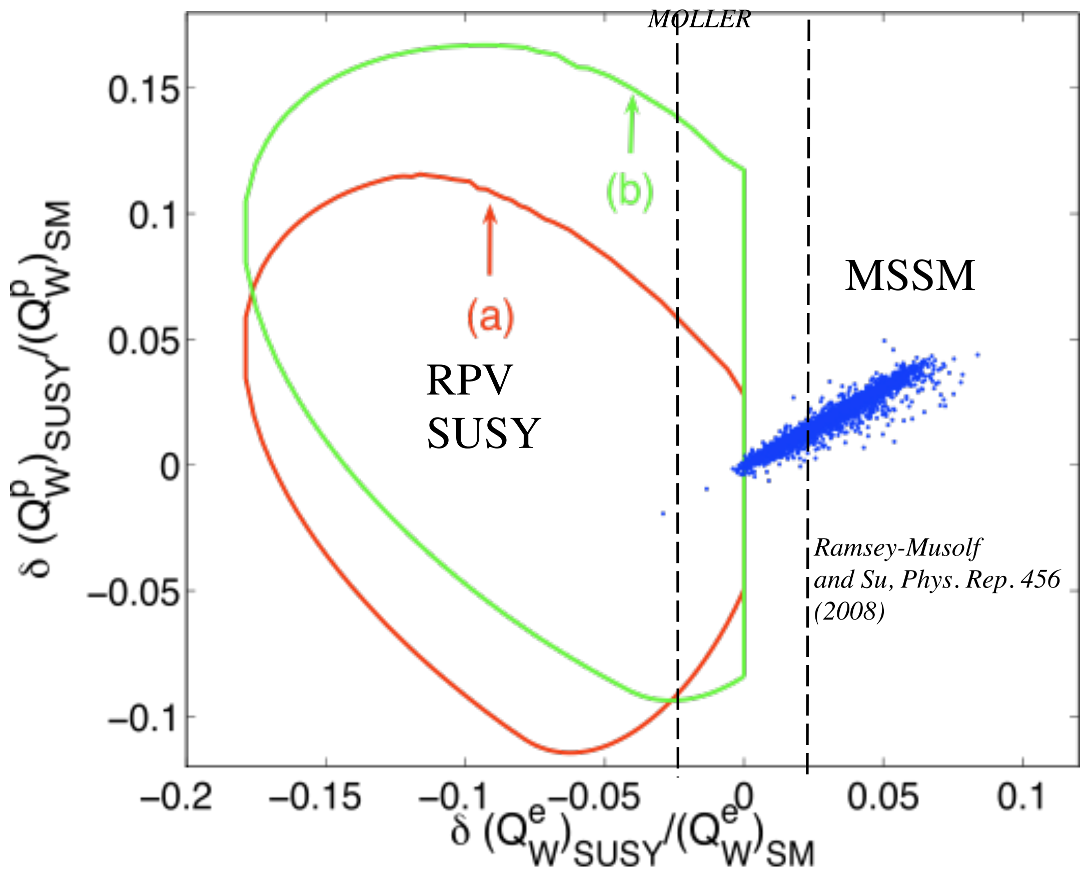
One goal of neutral current measurements at low energy AND colliders:
Access $\Lambda > 10$ TeV for as many $f_1 f_2$ and L,R combinations as possible

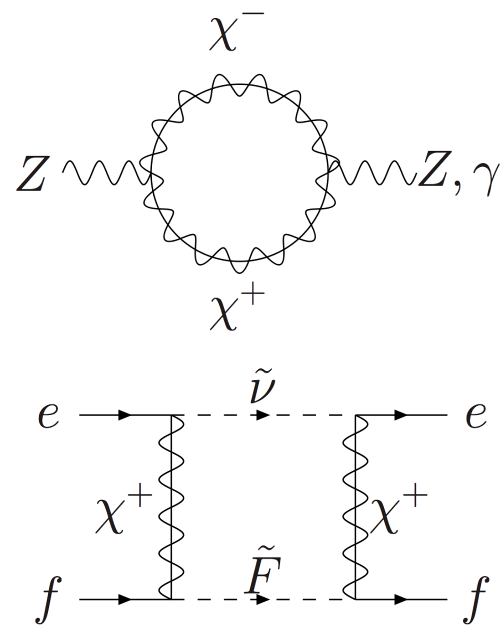
Precision of proposed experiment:

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

best contact interaction reach at low Q^2

MOLLER: if SUSY seen at LHC...

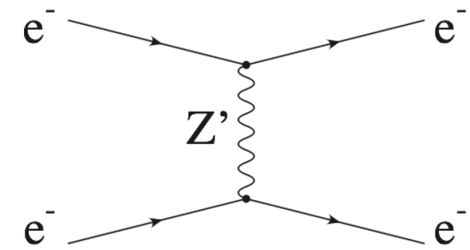




MSSM sensitivity if light super-partners

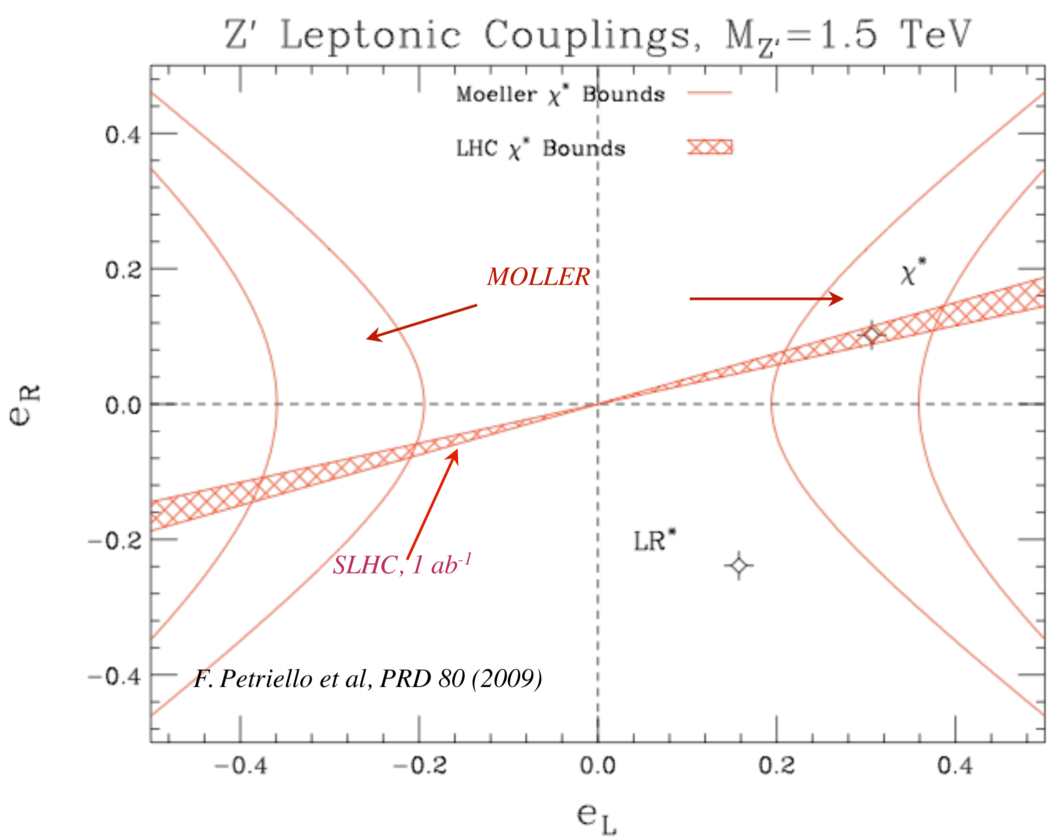
$$P_R = (-1)^{3(B-L)+2s}$$

MOLLER: if Z' seen at LHC…



- *Virtually all GUT models predict new Z's (E6, SO(10)…):*
  LHC reach ~ 5 TeV
- *With high luminosity at LHC, 1-2 TeV Z' properties can be extracted*

Suppose a 1 to 2 TeV heavy Z' is discovered at the LHC…



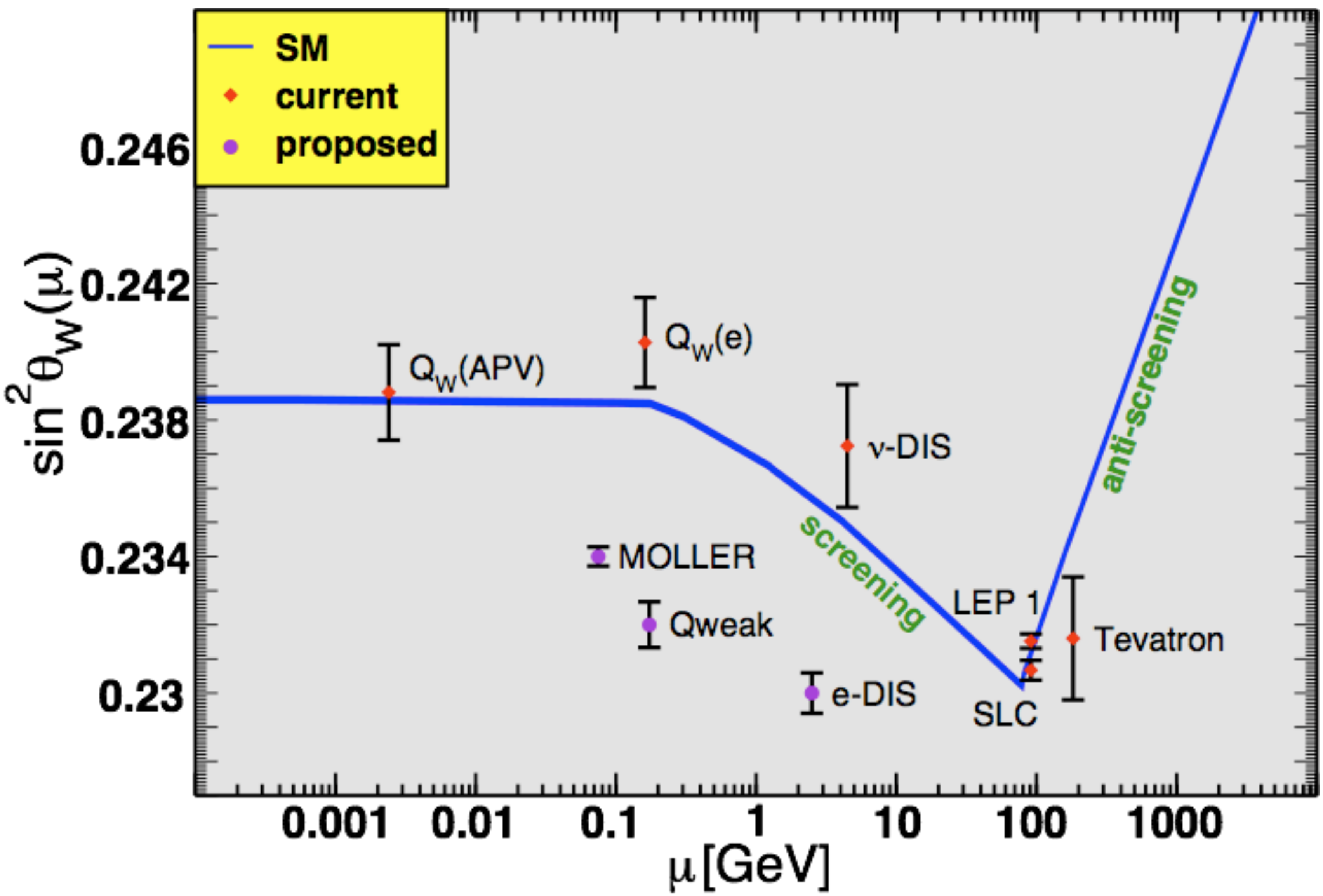
$$\sqrt{2}G_F\delta(Q_W^e) = \frac{1}{(7.5\ \mathrm{TeV})^2}$$

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

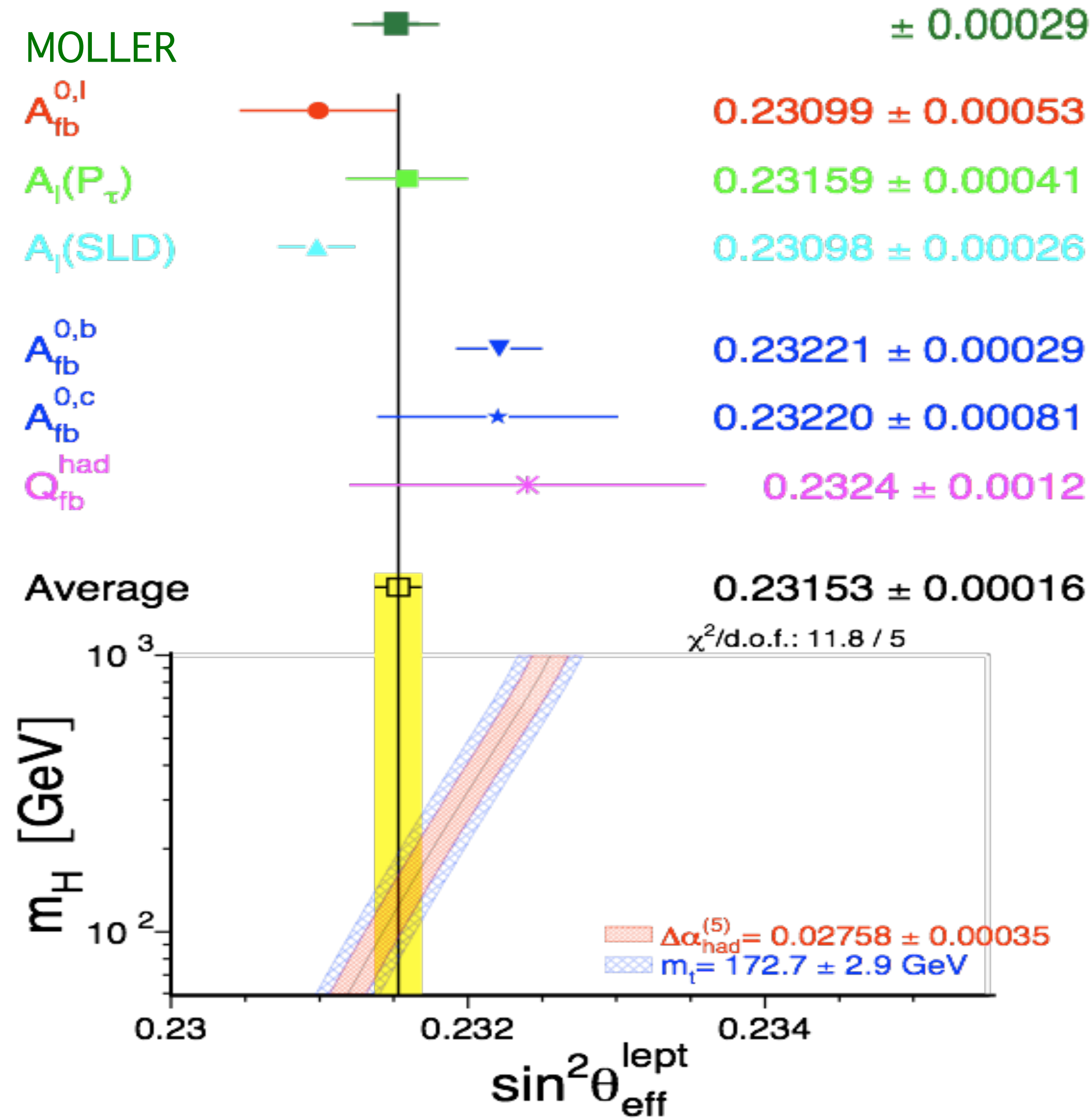
LHC data can extract the mass, width and $A_{FB}(s)$

MOLLER: resolve signs on e_R, e_L

MOLLER: Weak Mixing Angle (1)



MOLLER: Weak Mixing Angle (2)



Proposed MOLLER error bar ≈ most precise Z-pole data

Precise enough to affect the central value of the world average

MOLLER: Overview

How to improve on E158 precision?

Go to JLab @ 11 GeV (Hall A)

- take hit in figure of merit (factor 4) because of E_{lab}
- gain in Luminosity by order of magnitude (85 μA, 1.5 m target)
- gain in beam quality/stability
- spectrometer design: improve signal/background separation

$\theta_{lab} = 0.25° - 1.1°$ E' = 1.8 – 8.8 GeV

Detected Rate: 150 GHz!

$A_{PV} = 35.6$ ppb

Goal (5000 hrs running): $\delta(A_{PV}) = 0.73$ ppb

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

$\delta\sin^2\theta_W = \pm 0.00026$ (stat.) ± 0.00012 (syst.)

→ ~ 0.1%

MOLLER: Experimental Challenges

150 GHz Rate:

- flip Pockels cell at ~2 kHz
- 80 ppm pulse-to-pulse statistics
  - need 10 ppm or smaller electronic noise and target density fluctuations
  - need beam monitoring resolution at 10 ppm and few μm level at 1 kHz
- Flux integration; radiation-hard, highly-segmented detectors

85 μA on 150 cm ℓH_2 target

- 5 kW target *(twice power of QWeak target)*

Beam Quality

- 0.5 nm & 0.05 nrad helicity-correlated beam fluctuations on target

Electron Beam Polarimetry

- require 0.4% precision (SLD achieved 0.5%)
- redundant techniques: Compton and Atomic Hydrogen Moller polarimetry

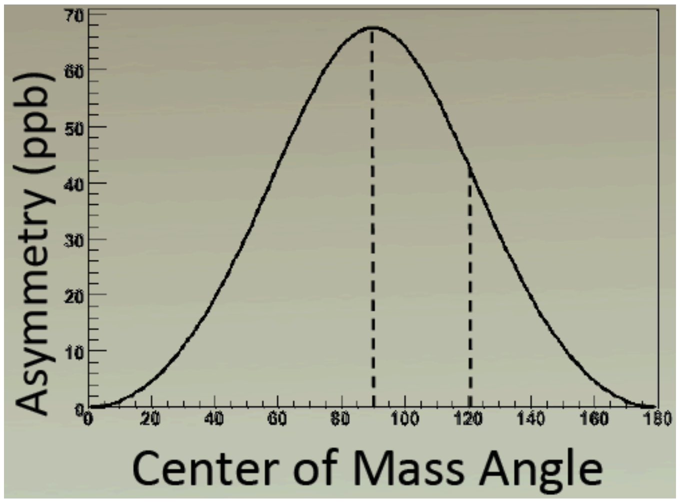
Full Azimuthal Acceptance

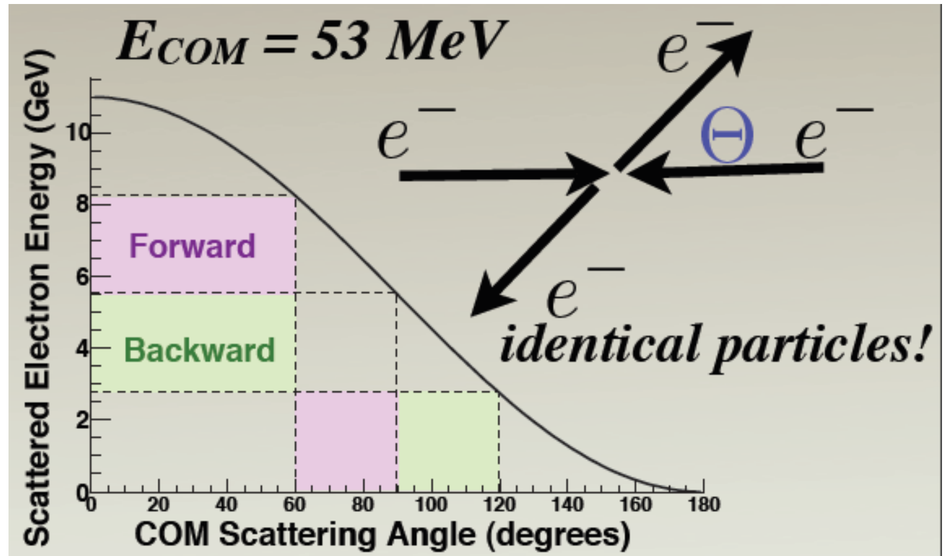
- small θ_{lab} wide range of scattered energies
- novel spectrometer magnet design: two toroids
- complicated collimation, alignment, shielding design

Backgrounds

MOLLER: Kinematics

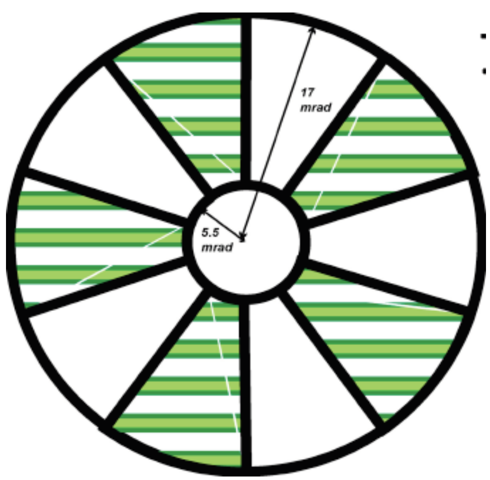
- Peak Figure of Merit at θ_{CM} = 90° (maximize A_{PV})





Normally: want to avoid double-counting (both electrons)
Instead, **exploit:** odd number of magnet coils: throw away half of φ acceptance!

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



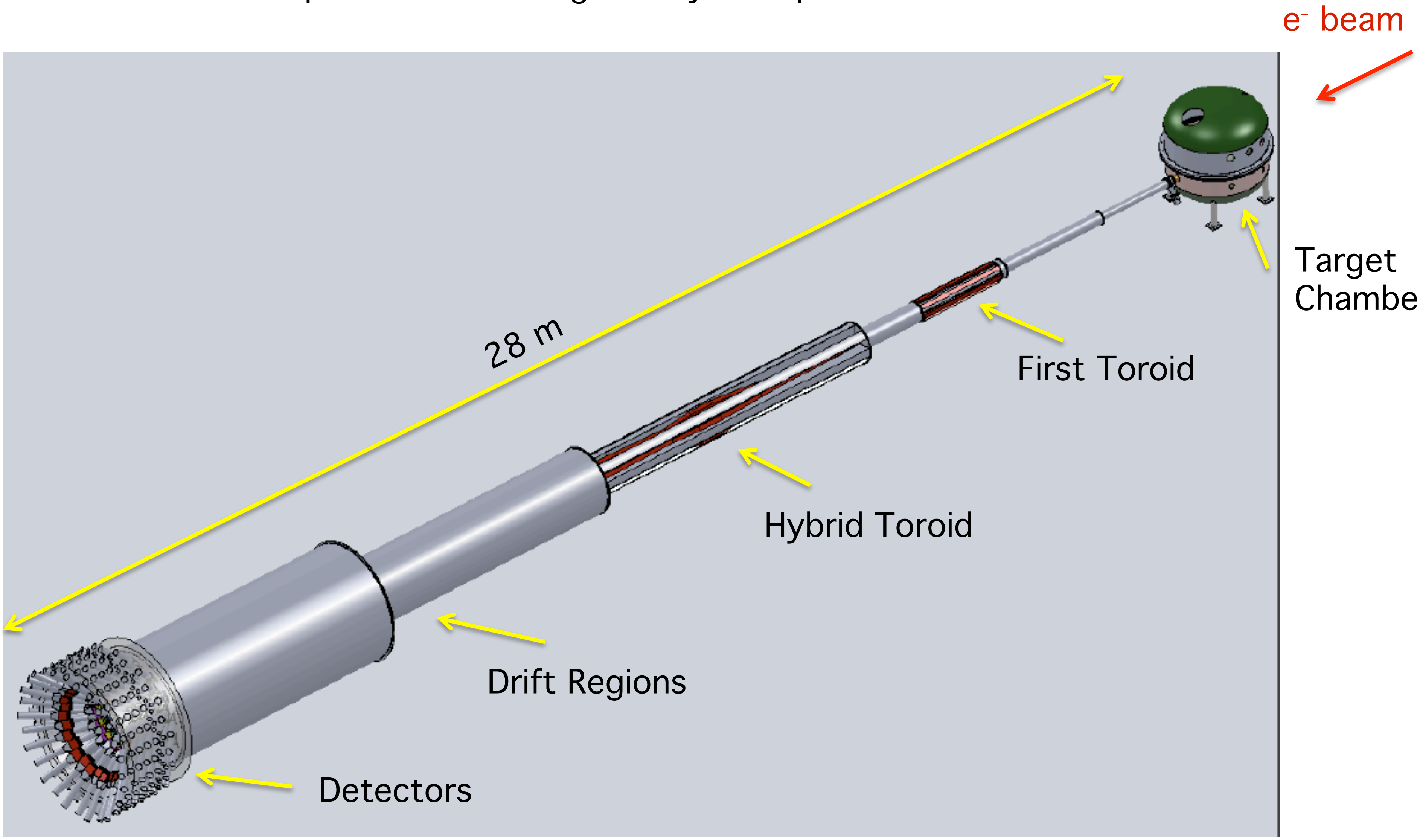
... are collected as θ_{CM} = [60,90] over here!

Full azimuthal acceptance, broad kinematic coverage

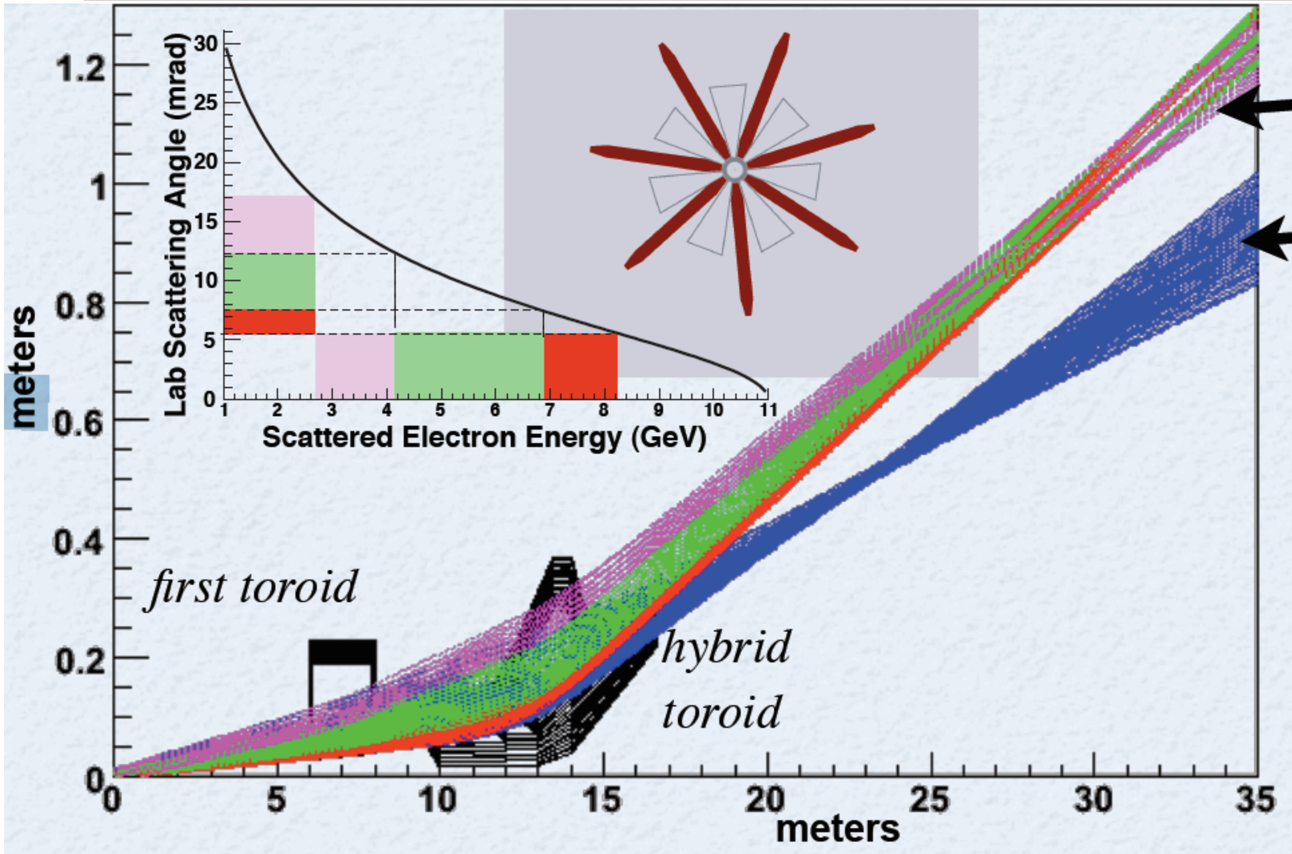
MOLLER: Schematic

Spectrometer: Two warm toroids

150 kW of photons from target – reject superconductors

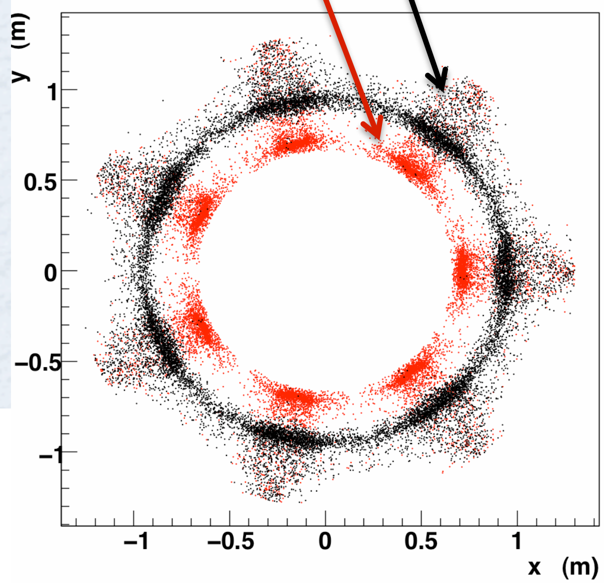


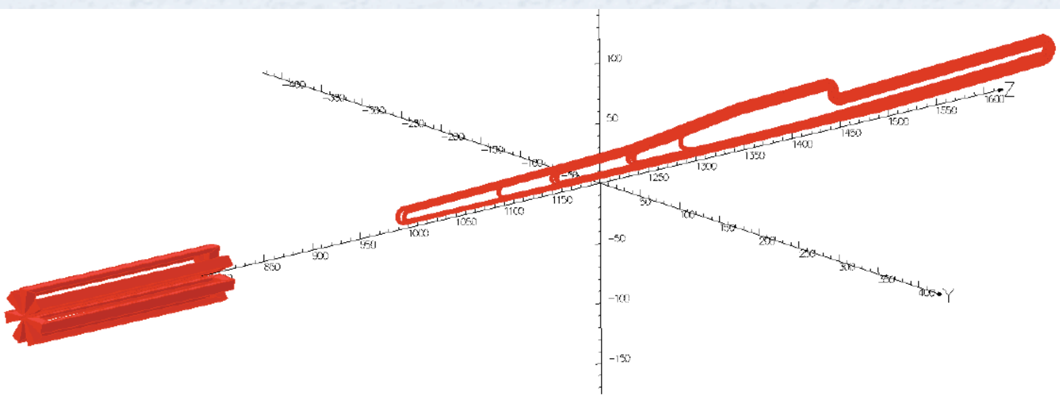
MOLLER: Spectrometer Concept



Mollers

e-p elastics



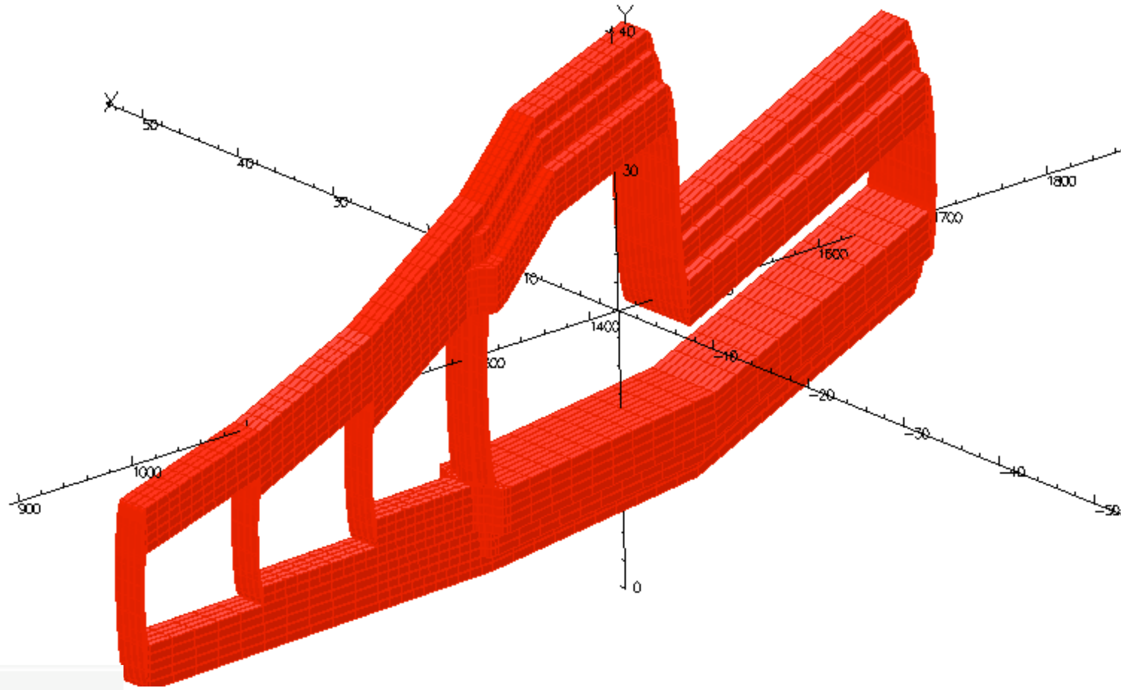


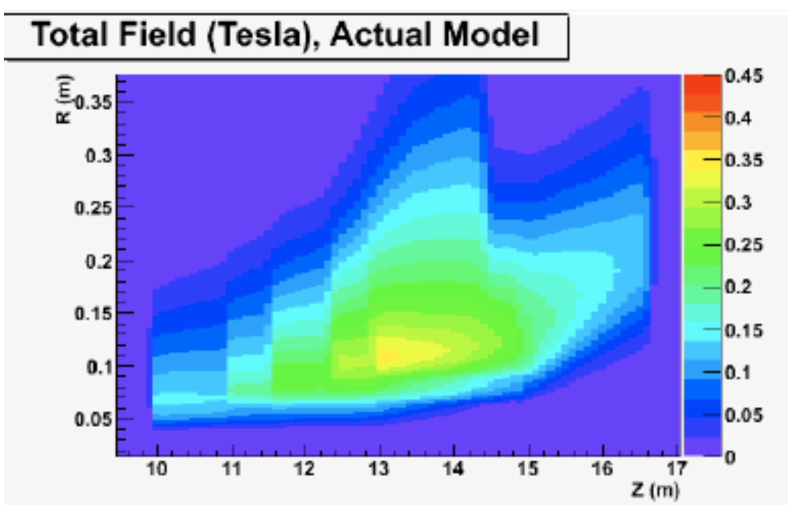
Also: azimuthal defocusing:
different φ – different θ_{CM} bins

MOLLER: Hybrid Toroid Design

Present design:

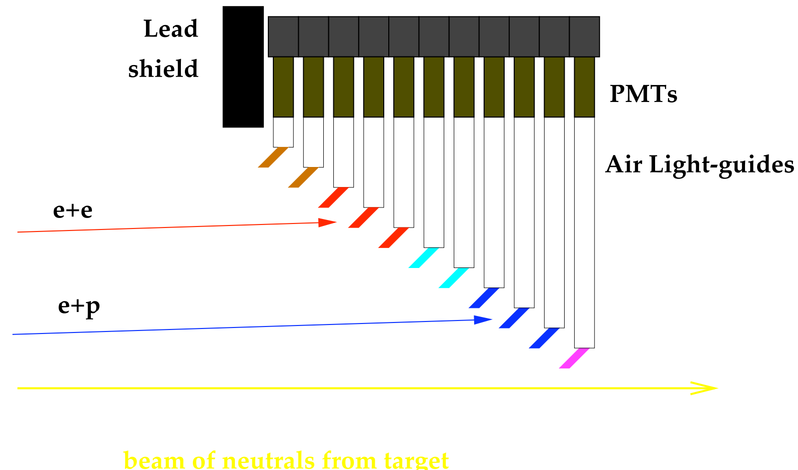
- 1.4 Tm
- 820 kW
- 243 A per conductor
- double pancake
- water cooling *(tricky...)*
- J = 1550 A/cm^2

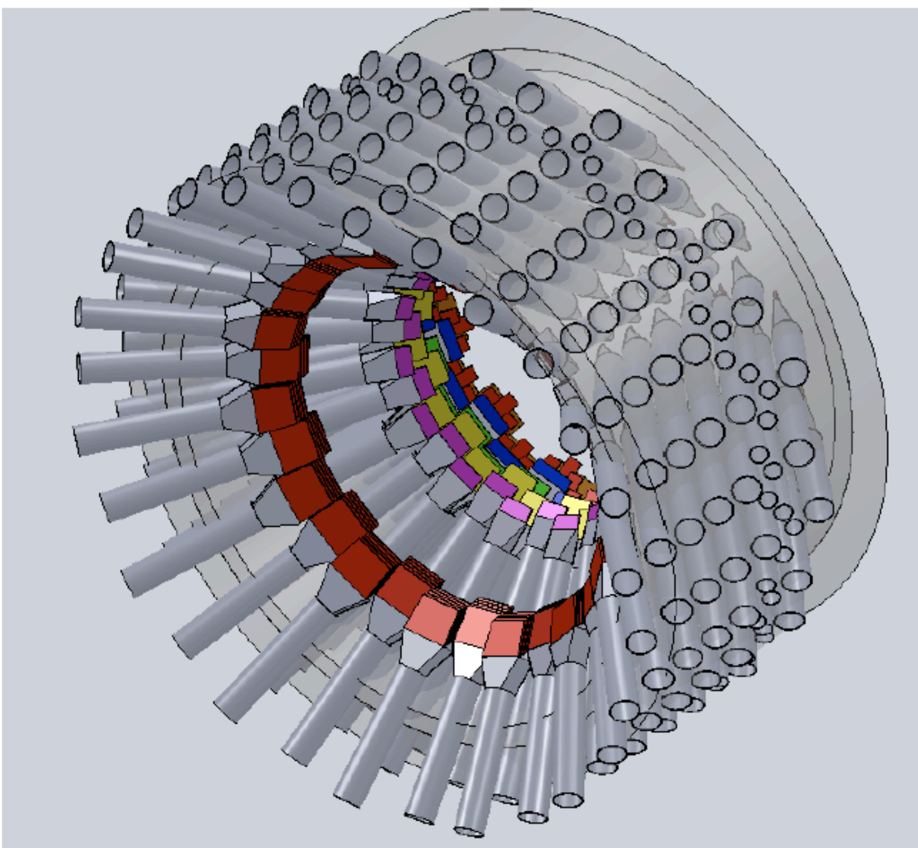


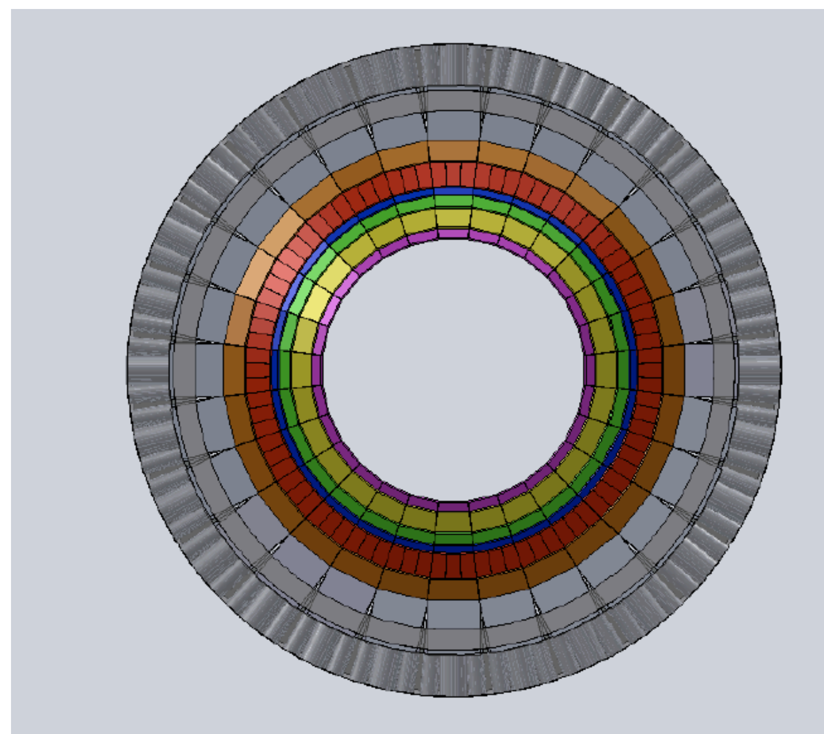


MOLLER: Detectors

Main Detectors:
- fused silica
- air lightguides & PMTs
- highly segmented in r and φ





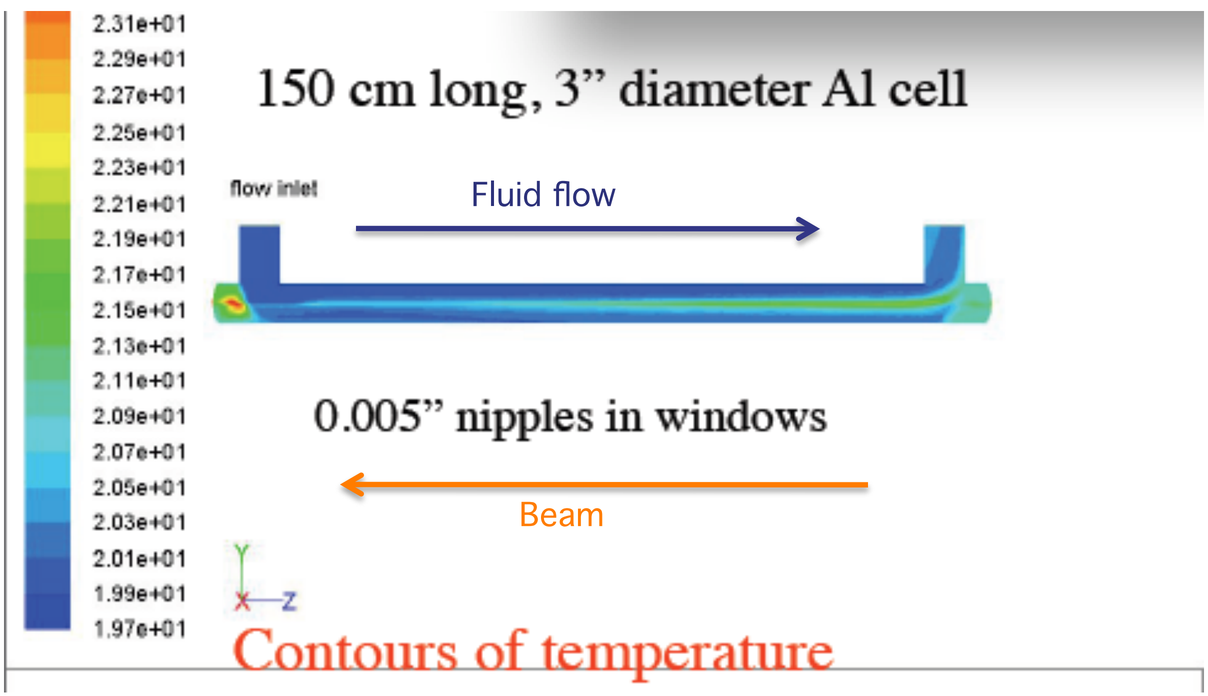


MOLLER: Target

Choose: **liquid hydrogen** *(as did E158)*

Why?
- Most thickness for least radiation length
- easy to assure is unpolarized
- no complex nucleus to scatter from

$10.7 \frac{g}{cm^2}$ $X_0 = 17.5\%$ → benchmark simulation with tracking detectors



7.8 litres
1 kg/s
35 psia 20 K
5000 W cooling power

Design with CFD (Fluent)
as was done for QWeak

Fluctuation scaling suggests:
26 ppm at 2 kHz

MOLLER: Backgrounds

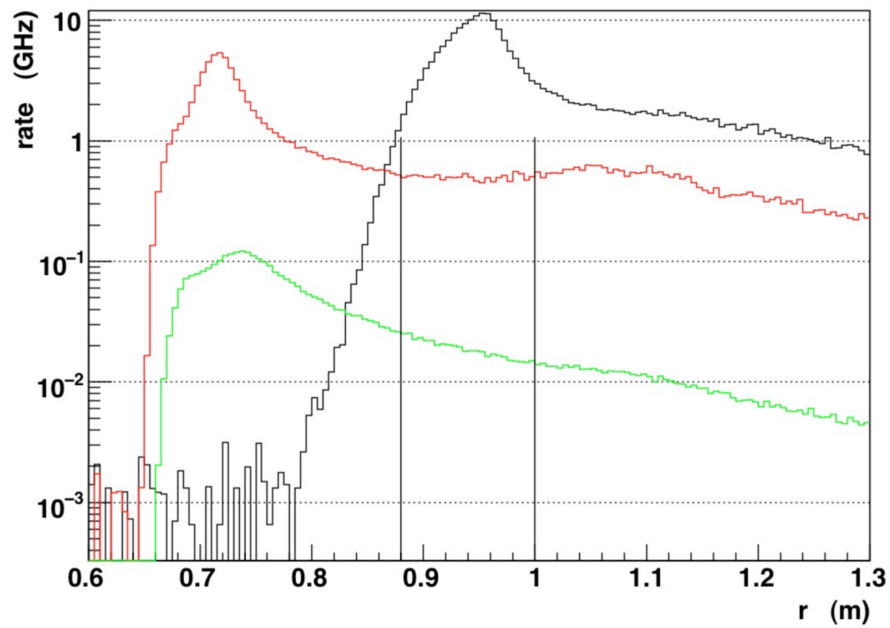
- Elastic e-p scattering
  - well-understood, measurable in data
  - 8% dilution, 7.5±0.3% correction

- Inelastic e-p scattering
  - <1% dilution
  - large EW coupling, 4.0±0.4% correction
  - A_{PV} varies with r and ϕ

- Photons and Neutrons
  - mostly 2-bounce collimation system
  - special runs to measure “blocked” response of detectors

- π’s and μ’s
  - real & virtual photo-production and DIS
  - continuous parasitic measurement
  - estimate: A_{PV} 0.5 ppm 0.1% dilution

Mollers, elastic e-p’s inelastic e-p’s

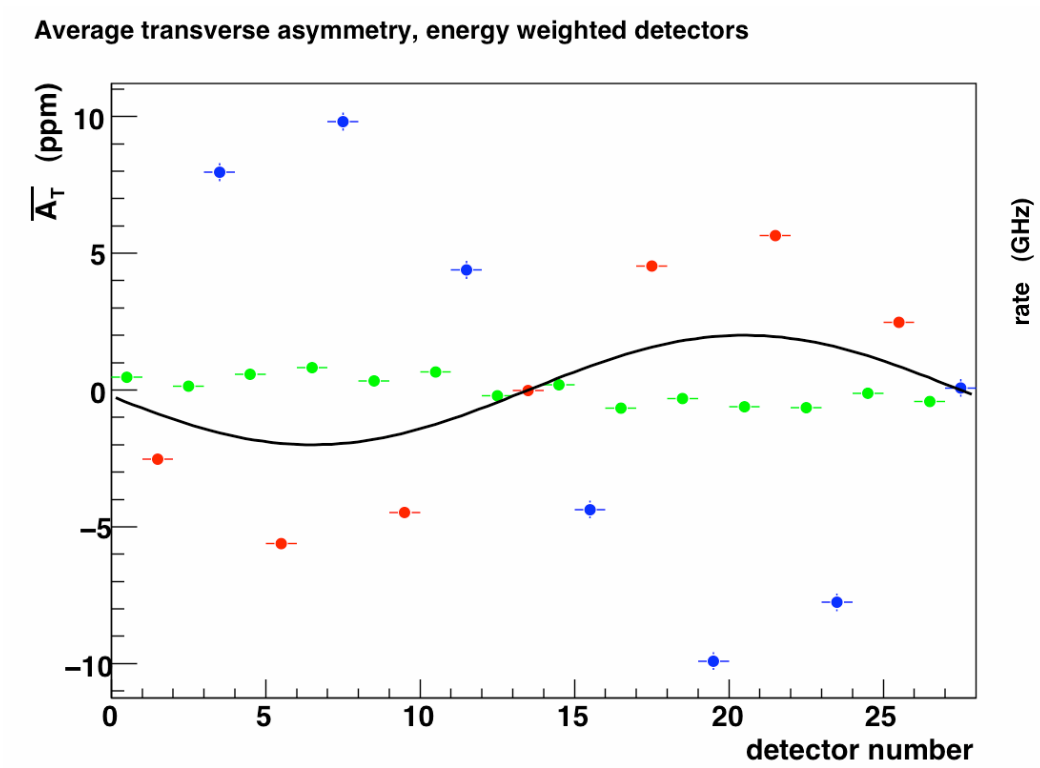


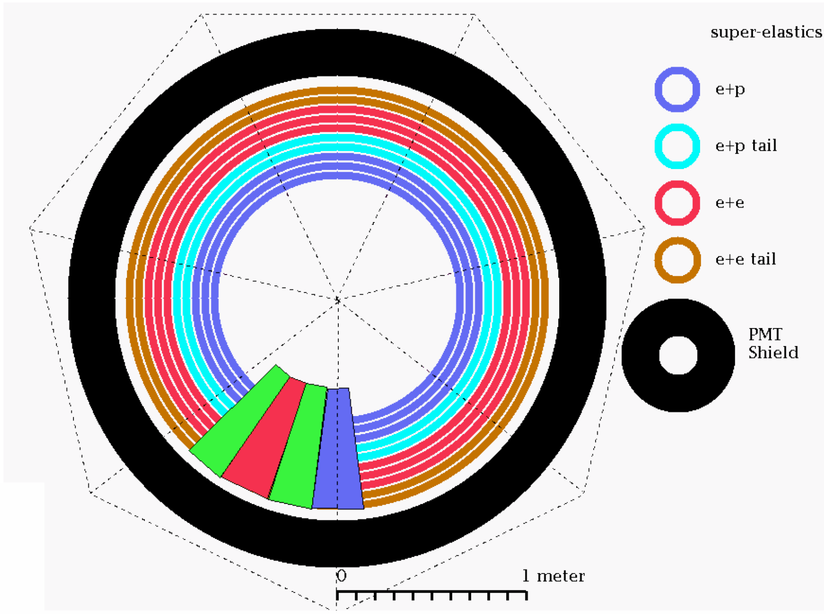
MOLLER: Transverse Asymmetry

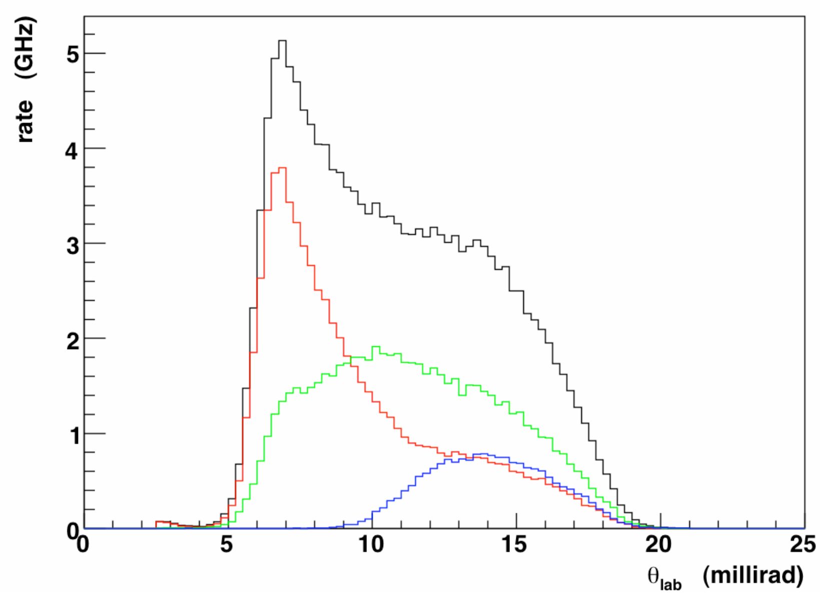
Two Photon Exchange: Beam normal single spin asymmetry; if electron beam has transverse component → φ dependence

$A_T \sim 14$ ppm (>10^4 our precision goal)

- need to average this down to tolerable correction...







MOLLER: Systematics

source of error	% error
absolute value of Q^2	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**

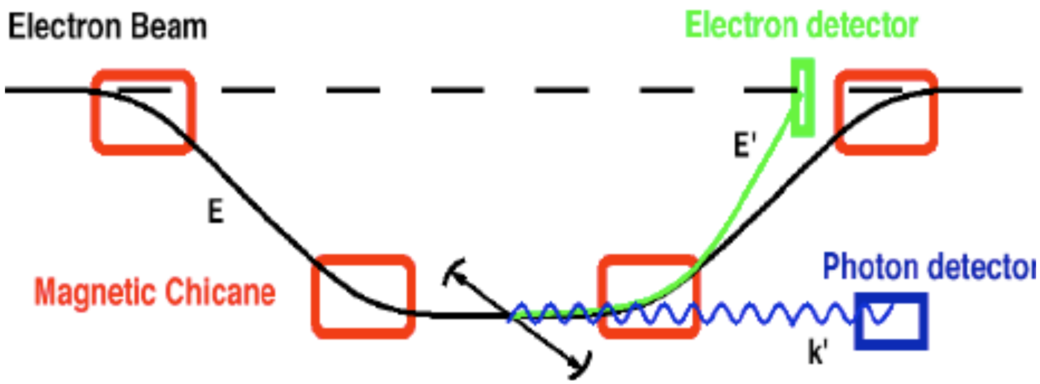
Dedicated Tracking & Scanner detectors

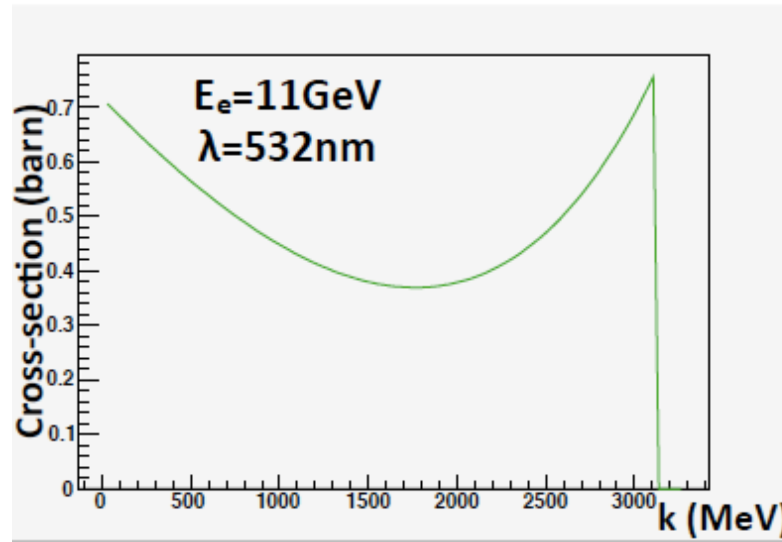
Laser spot-size control at 10^{-4} level
Slow flips via Wien-filter & g-2 beam energy

Active feedback:
intensity, position and angle

Monitor online: kinematic separation
Slow feedback using Wien-filter

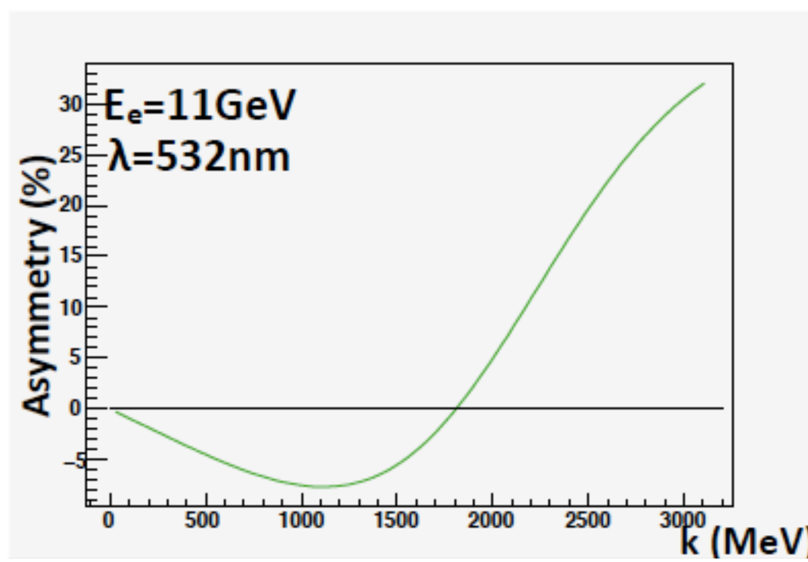
MOLLER: Compton Polarimetry





SLD: achieved 0.5% precision

Systematics: 2 points of well-defined energy:
end-point and A=0 crossing
- electron detector: integrate between these to minimize error on analyzing power
- photon detector: independent analysis normalizable to 0.5% (tag via e detector) (SLD did not have)



Techniques being developed (PREx, Qweak...)

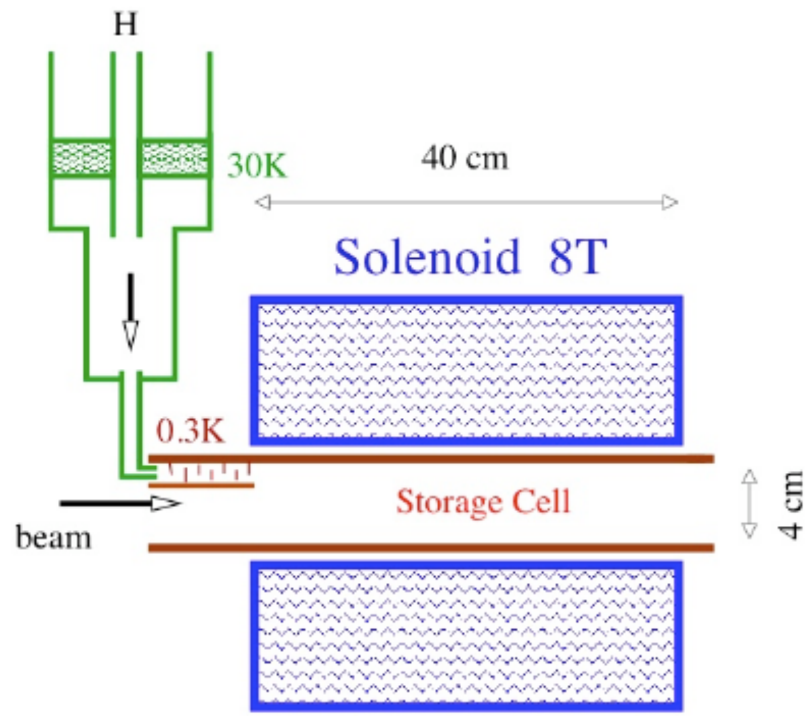
MOLLER: Atomic Hydrogen Moller Polarimetry

Virgin territory: Redundant technique, equal precision to Compton

E. Chudakov and V. Luppov, IEEE Trans. Nucl. Sci., vol 51, no. 4, Aug 2004 1533

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

- 100% electron polarization - Brute force
- tiny error on polarization
- thin target (sufficient rates but no dead time)
- Non-invasive
- high beam currents allowed
- no Levchuk effect



10 cm ρ = 3x10^{15}/cm^3
B = 7T T=300 mK

$$\frac{n_+}{n_-} = e^{-2\mu B / kT} \approx 10^{-14}$$

Ambitious development project
Adopt high-field solid target Moller as fall-back plan

MOLLER: Collaboration

Proposal: ~100 authors, 30 institutions;
experience from E158, HAPPEx, PV-A4, G0, PREx, Qweak

Steering Committee:
– D. Armstrong, R. Carlini, G. Cates, K. de Jager, Y. Kolomensky, K. Kumar (chair), F. Maas, D. Mack, K. Paschke, M. Pitt, G. Smith, P. Souder, W. van Oers

Working Groups & Conveners:
- Polarized Source: *G. Cates*
- Beam & Beam Instrumentation: *M. Pitt*
- Target: *G. Smith*
- Spectrometer: *K. Kumar*
- Integrating Detectors: *D. Mack*
- Tracking Detectors: *D. Armstrong*
- Polarimetry: *K. Paschke*
- Electronics/DAQ: *R. Michaels*
- Simulations: *N. Simicevic / K. Grimm*

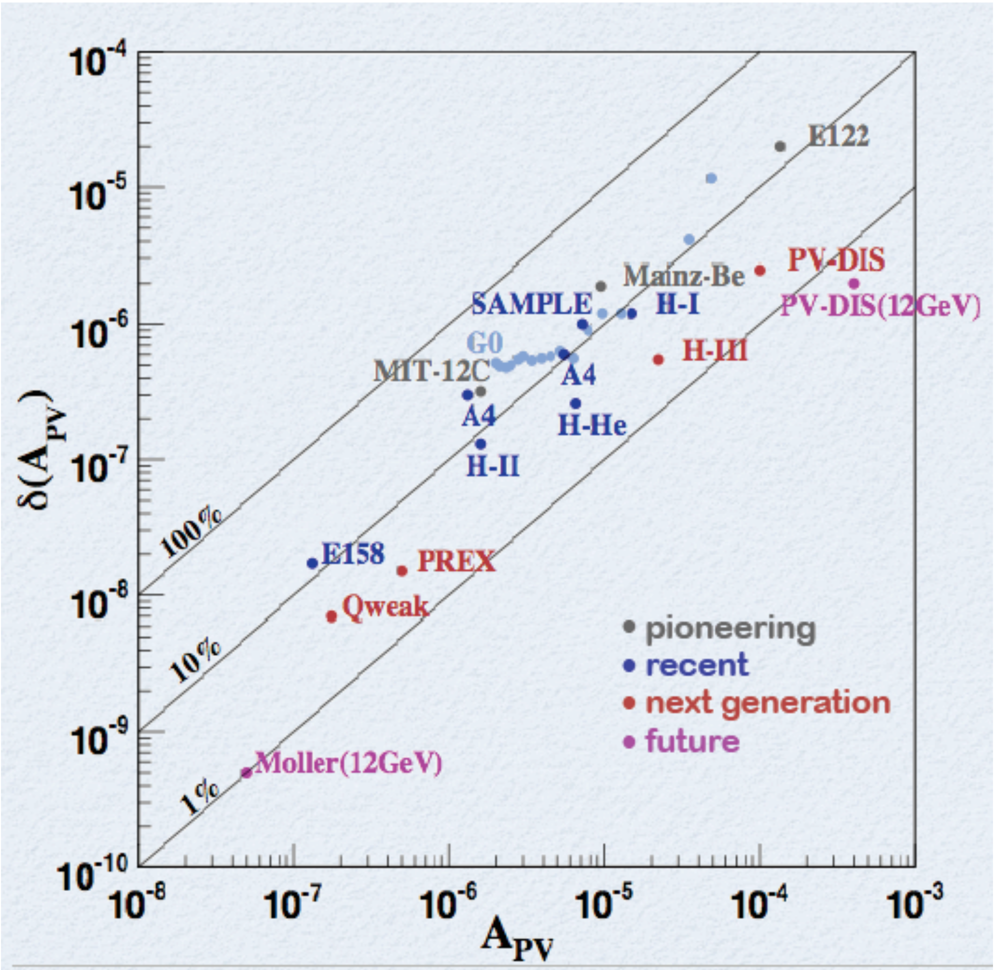
Collaboration seeks to grow!

Expressions of interest – not finalized

sub-system	Institutions
polarized source	UVa, JLab, Miss. St.
Target	JLab, VPI, Miss. St.
Spectrometer	Canada, ANL, MIT, UVa
Integrating Detectors	Syracuse, Canada, JLab, FIU, UNC A&T, VPI
Luminosity Monitors	VPI, Ohio U.
Pion Detectors	UMass/Smith, LATech
Tracking Detectors	William & Mary, Canada, INFN Roma
Electronics	Canada, JLab
Beam Monitoring	VPI, UMass, JLab
Polarimetry	UVa, Syracuse, JLab, CMU, ANL, Miss. St., Claremont-Ferrand, Mainz
Data Acquisition	Ohio U., Rutgers U.
Simulations	LATech, UMass/Smith, Berkeley, UVa

MOLLER: Timeline

- Project received PAC approval: Jan 2009
- Director's review of physics goals and concept: Jan 2010
- Aim to develop project funding (US + foreign):   2011-12
- Aim to install at JLab after 12 GeV upgrade: late 2015



Daunting challenges...
pushes precision in both
absolute and relative terms

MOLLER: Summary

- Projected Result from an A_{PV} measurement in Moller Scattering:

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

$$\delta(\sin^2\theta_W) = \pm 0.00026 \text{ (stat.)} \pm 0.00012 \text{ (syst.)} \quad \sim 0.1\%$$

- Opportunity with high visibility and large potential payoff
  - **The weak mixing angle is a fundamental parameter of EW physics**
  - **A cost-effective project has been elusive until now**
    - ***expensive ideas reach perhaps 0.2% (reactor or accelerator ν's, LHC Z production...)***
    - ***sub-0.1% requires a new machine (e.g. Z- or ν-factory, linear collider....)***
  - **physics impact on nuclear physics, particle physics and cosmology**
    - ***pin down parameter for other precision low energy measurements***
    - ***help decipher new physics signals at LHC***
    - ***critical part of the web of "Precision Frontier" measurements (e.g. see MRM's talk)***

- 11 GeV JLab beam is a unique instrument that makes this feasible

Grazie !