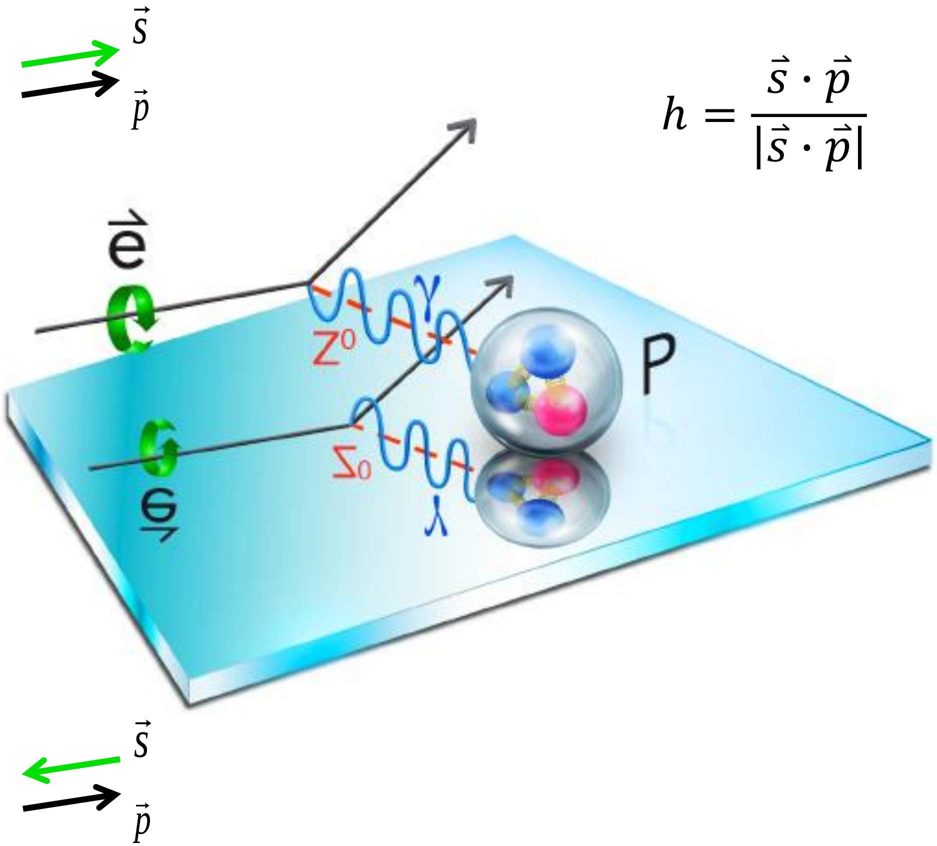
Measurements of the weak neutral current with parity violating electron scattering

Dr. Juliette Mammei

Parity violation in the weak interaction

Parity – quantum mechanical operator that reverses the spatial sign (P: x -> -x)



$$h = \frac{\vec{s}\cdot\vec{p}}{|\vec{s}\cdot\vec{p}|}$$

We describe physical processes as interacting currents by constructing the most general form which is consistent with Lorentz invariance

The the form of the currents is $\bar{\psi}(4 \times 4)\psi$

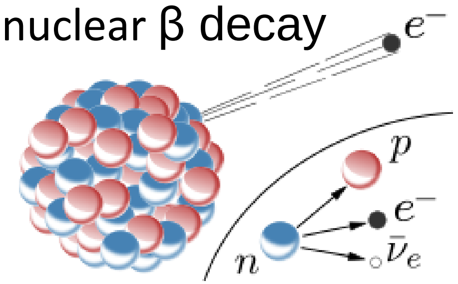
and they transform differently under different operators

Table of transformation of *independent* Dirac matrices

	$(\mathbf{4 \times 4})$	**Parity**	**Charge**	**Time**
Scalar	1	1	1	1
Pseudoscalar	γ^5	$-\gamma^5$	γ^5	γ^5
Vector	γ^μ	γ_μ	$-\gamma^\mu$	γ_μ
Axial vector	$\gamma^\mu\gamma^5$	$-\gamma_\mu\gamma^5$	$\gamma^\mu\gamma^5$	$\gamma_\mu\gamma^5$
Tensor	$\sigma^{\mu\nu}$	$\sigma_{\mu\nu}$	$-\sigma^{\mu\nu}$	$-\sigma_{\mu\nu}$

A brief history of parity violation

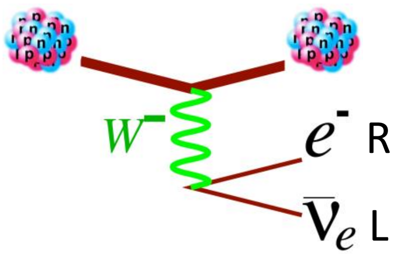
1930s – weak interaction needed to explain nuclear β decay

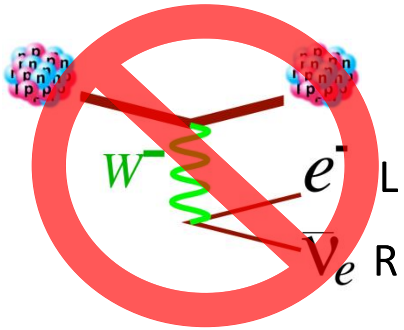


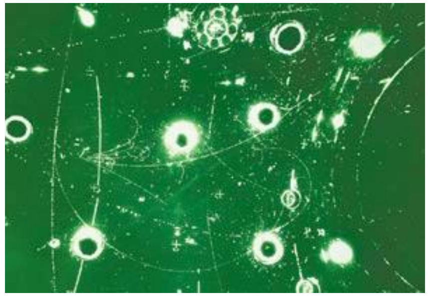
1950s – parity violation in weak interaction;

V-A theory

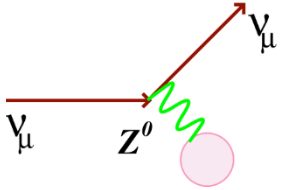
to describe ^{60}Co decay







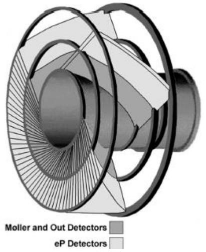
1970s – neutral weak current events seen at Gargamelle



late 1970s – parity violation observed in electron scattering - SLAC E122

1996 – atomic parity violation observed in atomic transitions of Cs

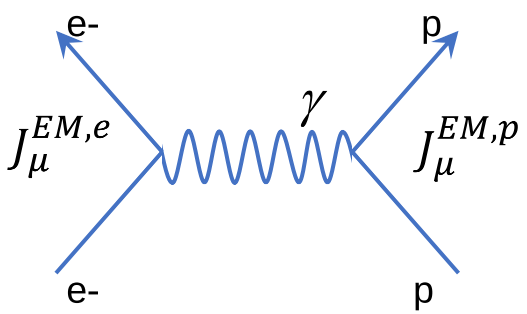
2005 – first measurement of the weak charge of the electron, Q_W^e



2013 – first measurement of the weak charge of the proton, Q_W^p

Precision Frontier

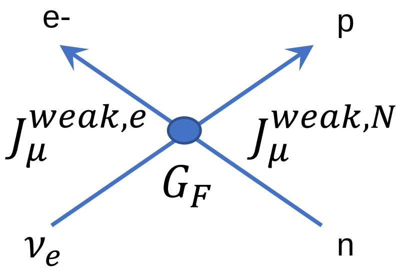
EM ⇒ Weak Interactions



EM: e + p → e + p elastic scattering

$$M = J_\mu^{EM,p}\left(-\frac{e^2}{Q^2}\right)J^{\mu,EM,e} = \left(\overline{\psi}_p\gamma_\mu\psi_p\right)\left(-\frac{e^2}{Q^2}\right)\left(\overline{\psi}_e\gamma^\mu\psi_e\right)$$

V x V



Weak: n → e^- + p + $\bar{\nu}_e$ neutron beta decay

Fermi (**1932**) : contact interaction, form inspired by EM

$$M = J_\mu^{weak,N}\ G_F\ J^{\mu,weak,e} = \left(\overline{\psi}_p\gamma_\mu\psi_n\right)G_F\ \left(\overline{\psi}_e\gamma^\mu\psi_{\nu_e}\right)$$

V x V

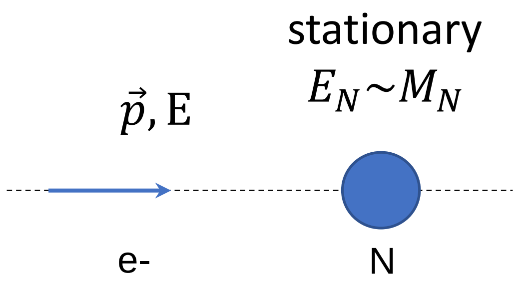
Parity Violation (1956, Lee, Yang; **1957**, Wu) required modification to form of current - need axial vector as well as vector to get a parity-violating interaction

$$M = J_\mu^{weak,N}\ G_F\ J^{\mu,weak,e} = \left(\overline{\psi}_p\gamma_\mu\left(1-\gamma^5\right)\psi_n\right)G_F\left(\overline{\psi}_e\gamma^\mu\left(1-\gamma^5\right)\psi_{\nu_e}\right)$$

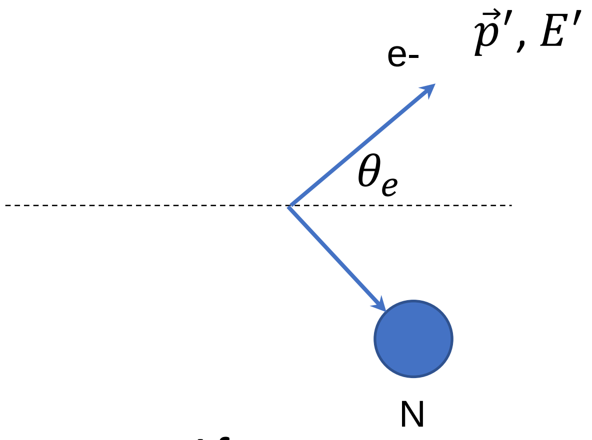
(V - A) x (V - A)

Note: weak interaction process here is charged current (CC)

Elastic scattering, $\vec{e} + N \rightarrow e + N$



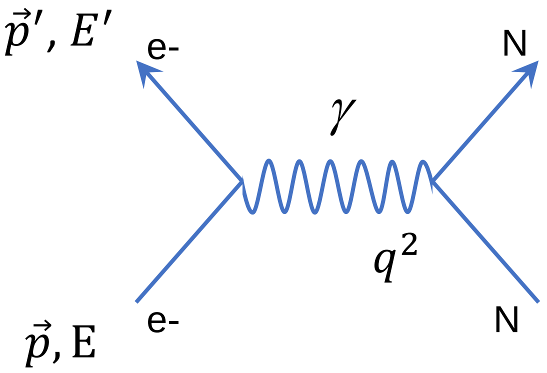
Before



After

"N" could be…

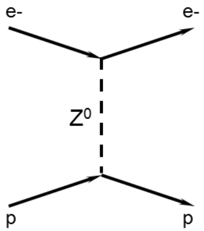
^{208}Pb *or* ^{48}Ca	(PREX/CREX)
p *or* d *or* He	(G0, HAPPEX)
or e^-	(MOLLER)

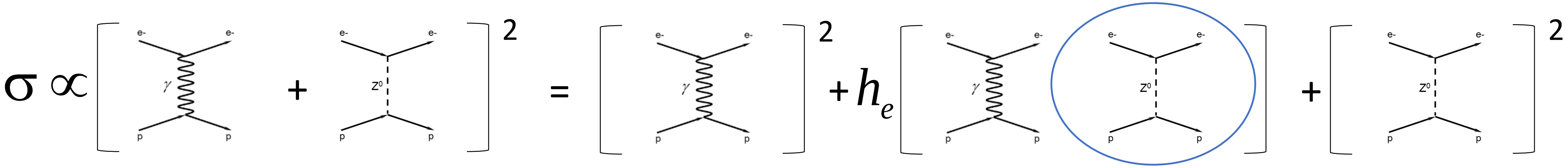


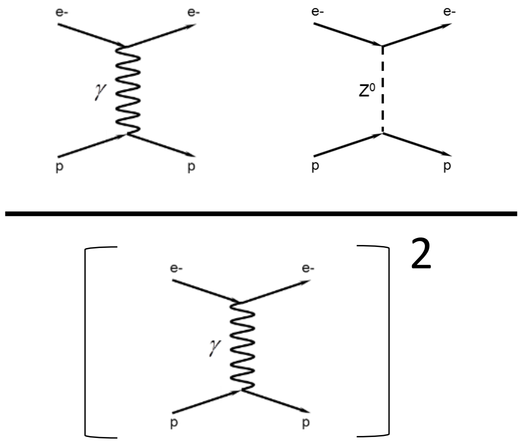
$$-q^2 = Q^2 = 4EE' \sin^2\left(\frac{\theta_e}{2}\right)$$

Q^2 is related to the wavelength of the virtual photon probe - $\lambda = \frac{h}{q}$

Using different targets and Q^2 (kinematics), can consider *elastic* scattering from nuclei, nucleons or electrons

How does PVES measure  ?

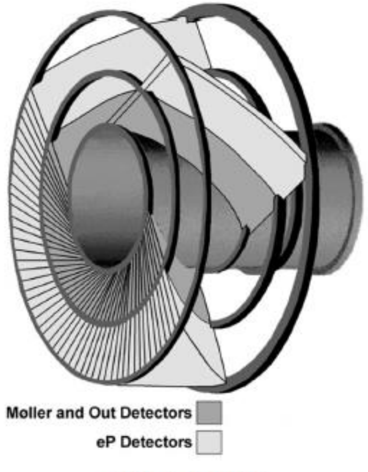


$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx$  $= \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\left[Q_W^p + B_4 Q^2 + \cdots\right]$

$\approx 10^{-6} - 10^{-5} \approx 1 - 10\, ppm$

PVES Experiments

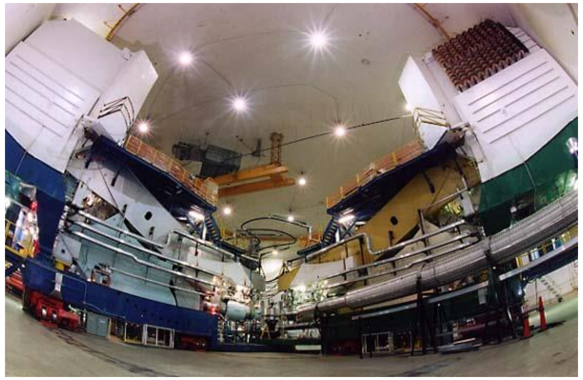
E158, SLAC



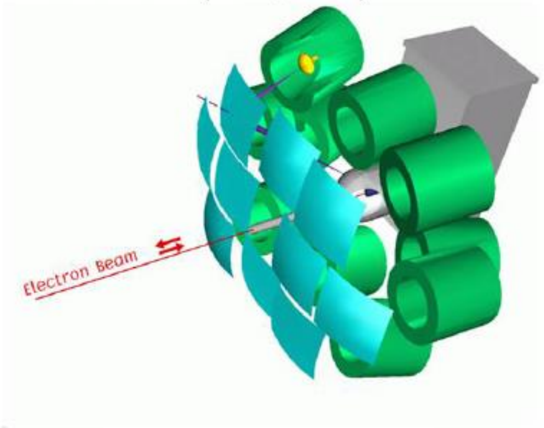
PVA4, Mainz

G0, JLAB

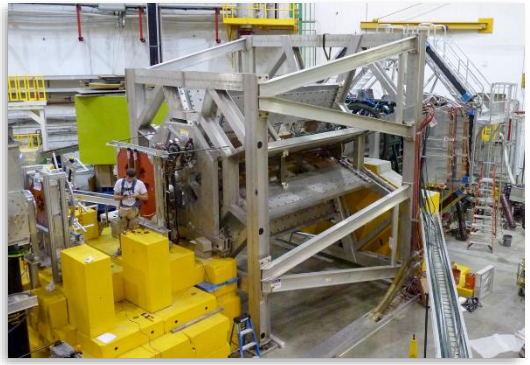
PREX, JLAB



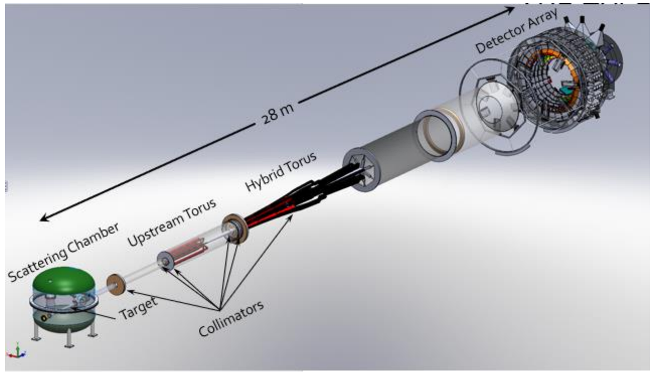
HAPPEX, JLAB



Sample, MIT-Bates



Qweak, JLAB



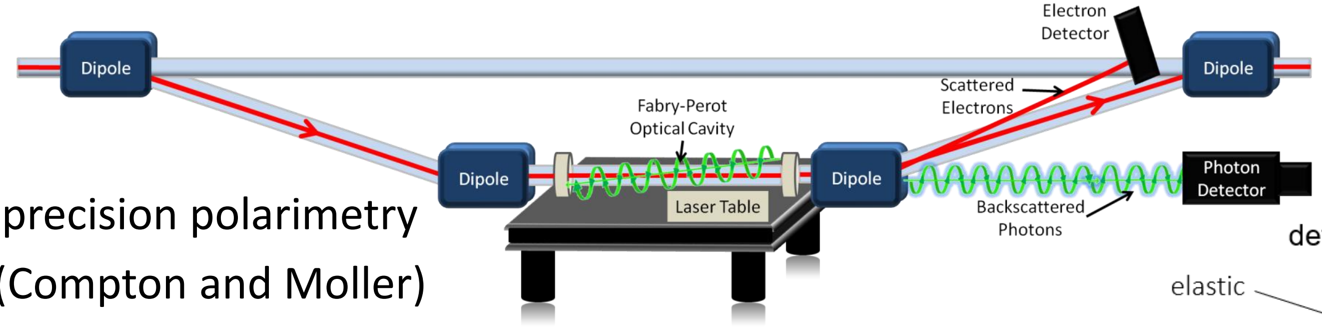
MOLLER, JLAB

⇒ SOLID, JLAB; P2, Mainz; EIC, BNL

Measuring A_{PV} with ES – *step by step*

unpolarized target

high current, highly polarized beam



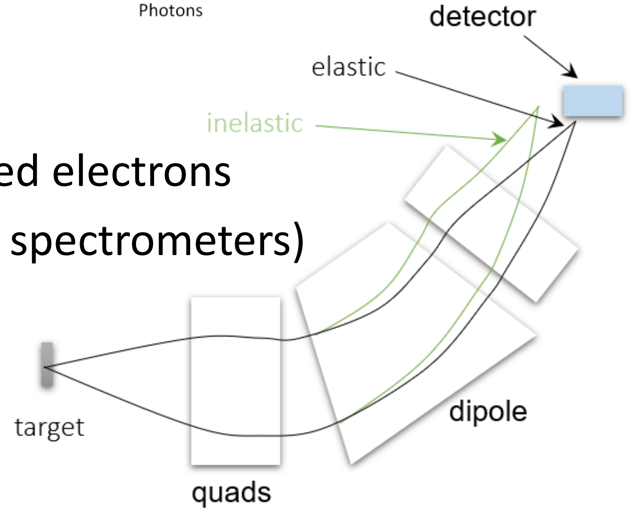
precision polarimetry

(Compton and Moller)

$$A_{PV} = \frac{A_{sig}}{P_{beam}}$$

elastically scattered electrons

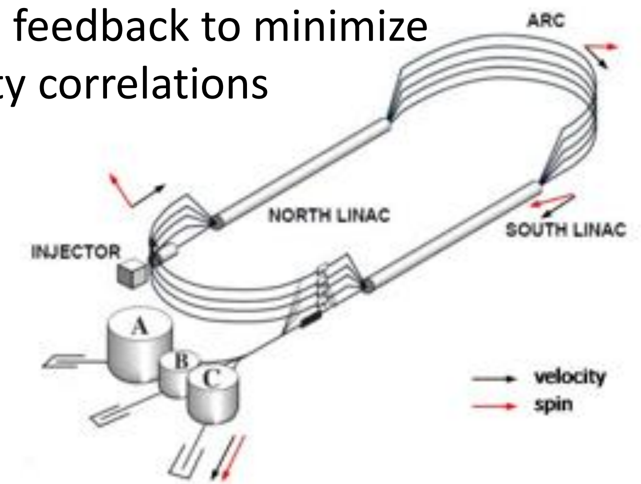
(resolution of the spectrometers)



$$A_{sig} = \frac{A_{corr} - A_{back}\, f_{back}}{f_{sig}}$$

beam property monitoring

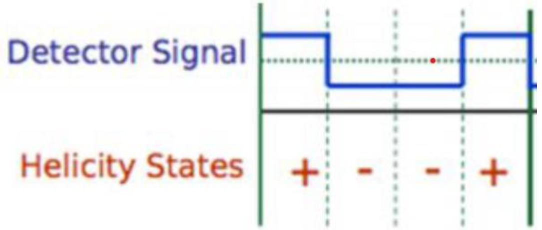
active feedback to minimize helicity correlations



$$A_{corr} = A_{meas} - \sum_{i=1}^{N} \frac{1}{2Y}\left(\frac{\partial Y}{\partial P_i}\right)\Delta P_i$$

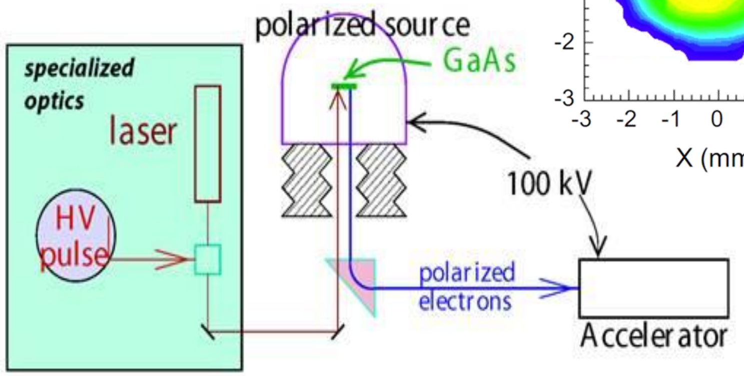
where $\Delta P_i = P_+ - P_-$

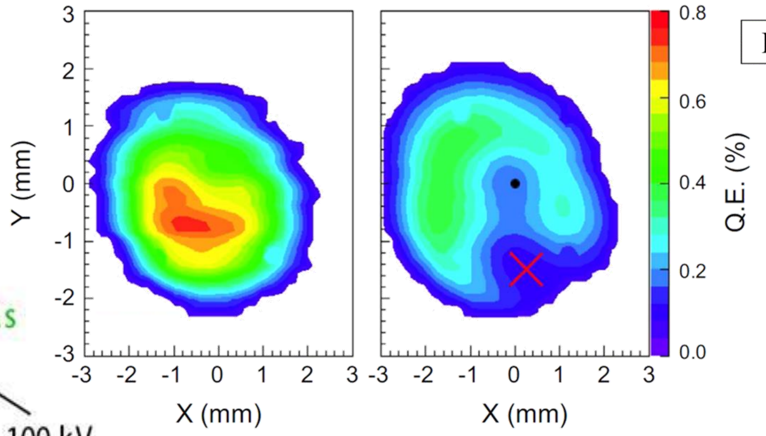
both slow and rapid helicity reversals

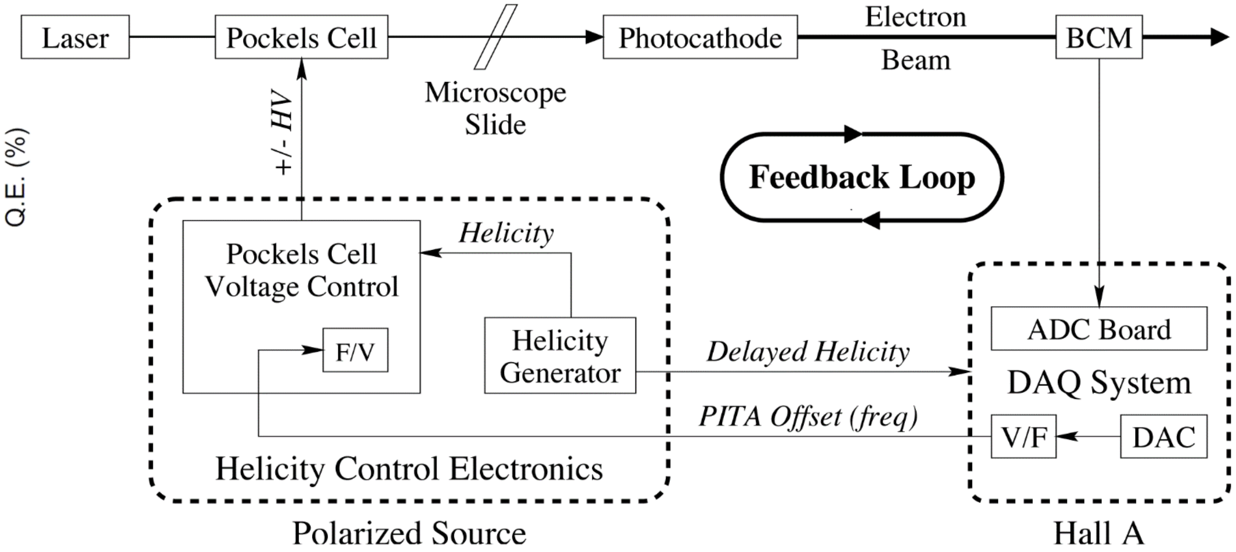


$$A_{meas} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

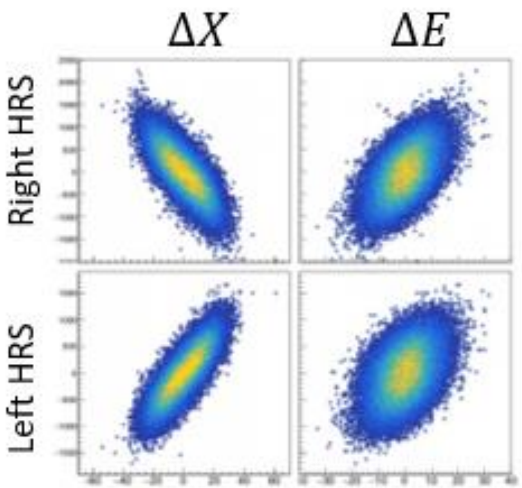
Helicity correlated beam properties







detector correlations

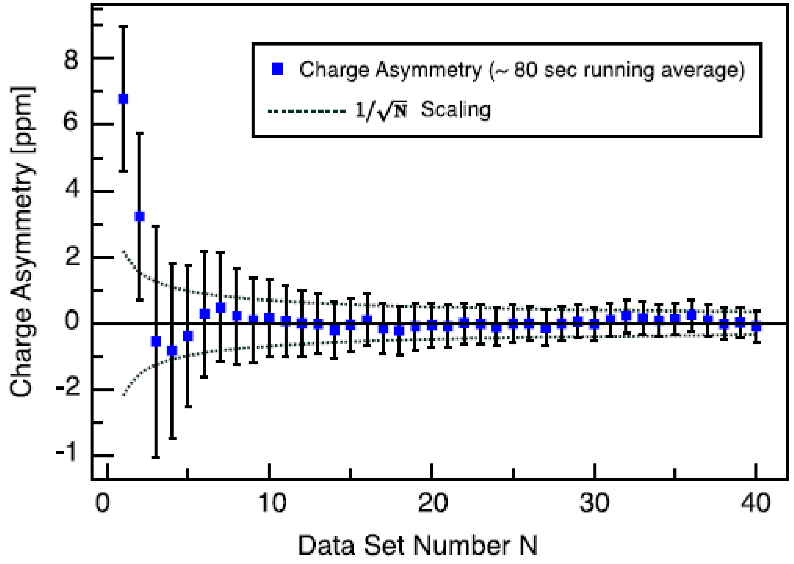


Measure and correct for position (X, Y) and position angle (δX, δY) as well as charge and energy differences

Average position differences at the target controlled to better than 10 nm

The width of human hair is 50,000 nanometers!!!

Effect of intensity feedback



Measuring the electroweak couplings

The parity-violating part of the Standard Model Lagrangian is

nucleon target — electron target

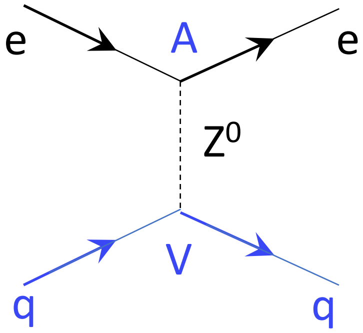
$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}\left[\bar{e}\gamma^{\mu}\gamma_5 e\left(C_{1u}\bar{u}\gamma_{\mu}u + C_{1d}\bar{d}\gamma_{\mu}d\right) + \bar{e}\gamma^{\mu}e\left(C_{2u}\bar{u}\gamma_{\mu}\gamma_5 u + C_{2d}d\gamma_{\mu}\gamma_5 d\right) + C_{ee}\bar{e}\gamma^{\mu}\gamma_5 e\left(\bar{e}\gamma_{\mu}e\right)\right]$$

EM coupling: $e\gamma^{\mu}$ (not parity violating)

The charged current violates parity maximally: $\frac{g}{2\sqrt{2}}\gamma^{\mu}(1-\gamma^5)$

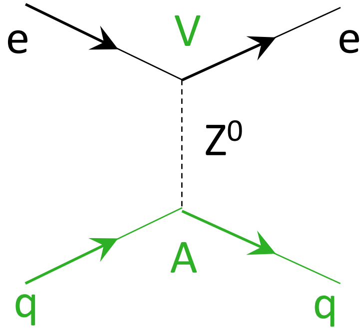
The neutral current coefficients need to be determined:

$$\frac{g}{2cos\theta_W}\left(c_V^f\gamma^{\mu} - c_A^f\gamma^{\mu}\gamma^5\right)$$



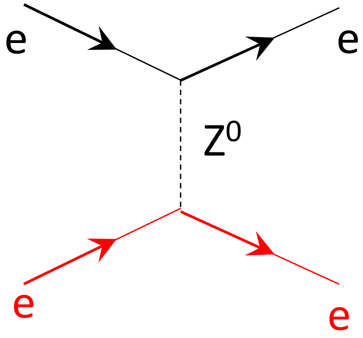
$C_{1q} = 2g_A^e g_V^q$

Small θ



$C_{2q} = 2g_V^e g_A^q$

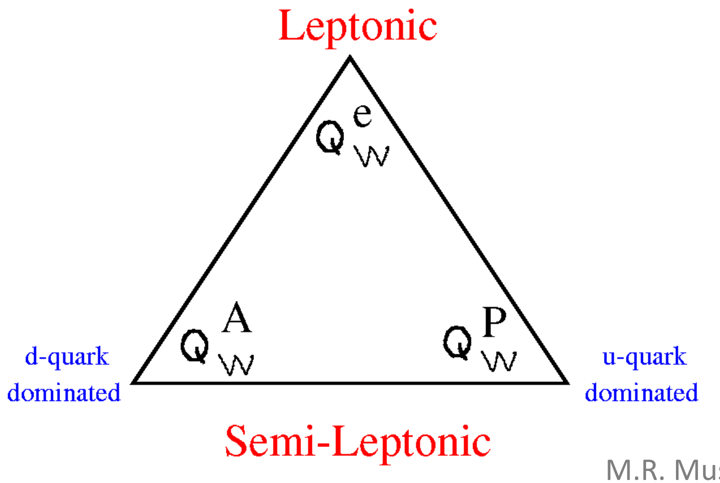
Large θ



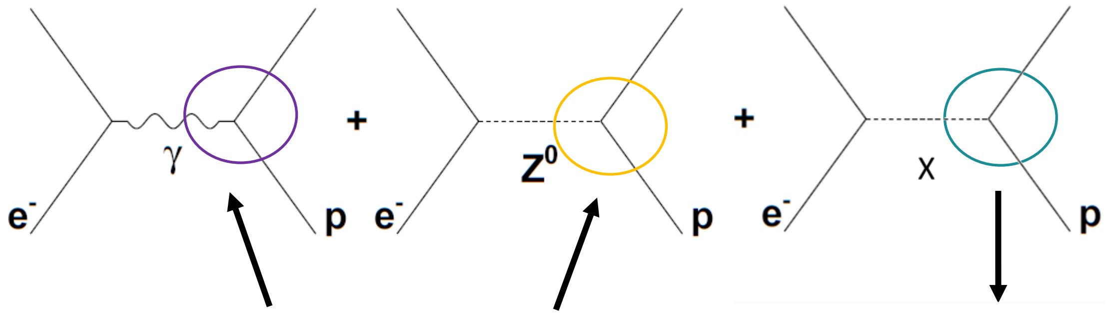
Testing the Standard Model

with Qweak as an example, $\vec{e} + p \rightarrow e + p$

$E_{beam} = 1.165$ GeV
$\theta \sim 7.9°$
$Q^2 \sim 0.025$ GeV^2/c^2



M.R. Musolf



Standard Model processes

Standard Model Test
possible new exchange particle X

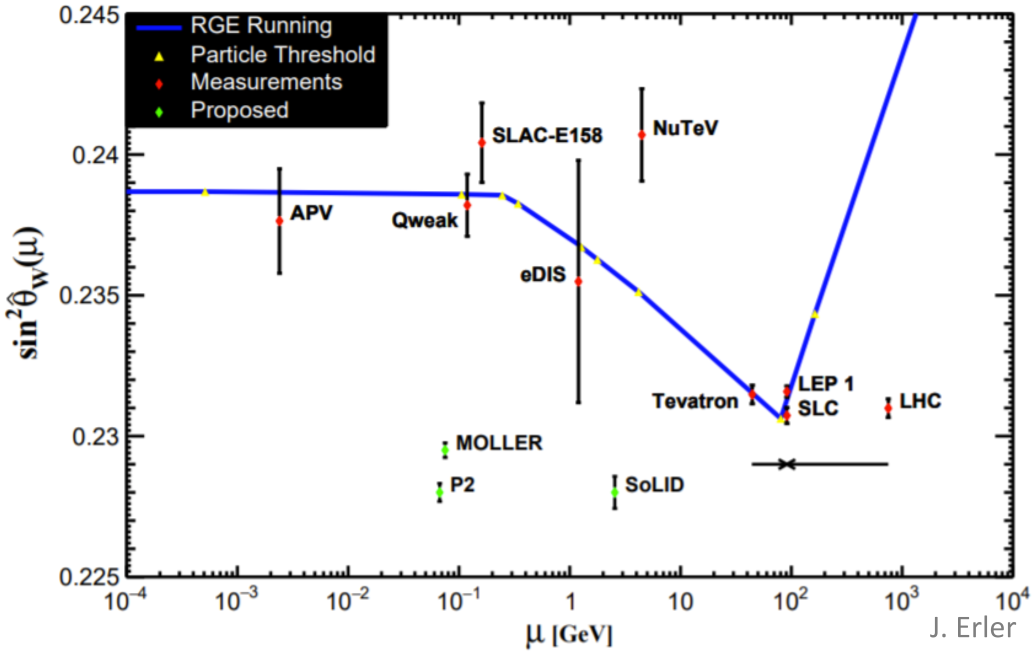
$Q^2 \rightarrow 0$
measure charge of proton

$Q^2 \rightarrow 0$
measure weak charge of proton

$Q^2 \rightarrow 0$
measure coupling of new physics to proton

$$Q^p = 2Q^u + Q^d = 2\left(+\tfrac{2}{3}\right) + \left(-\tfrac{1}{3}\right)$$

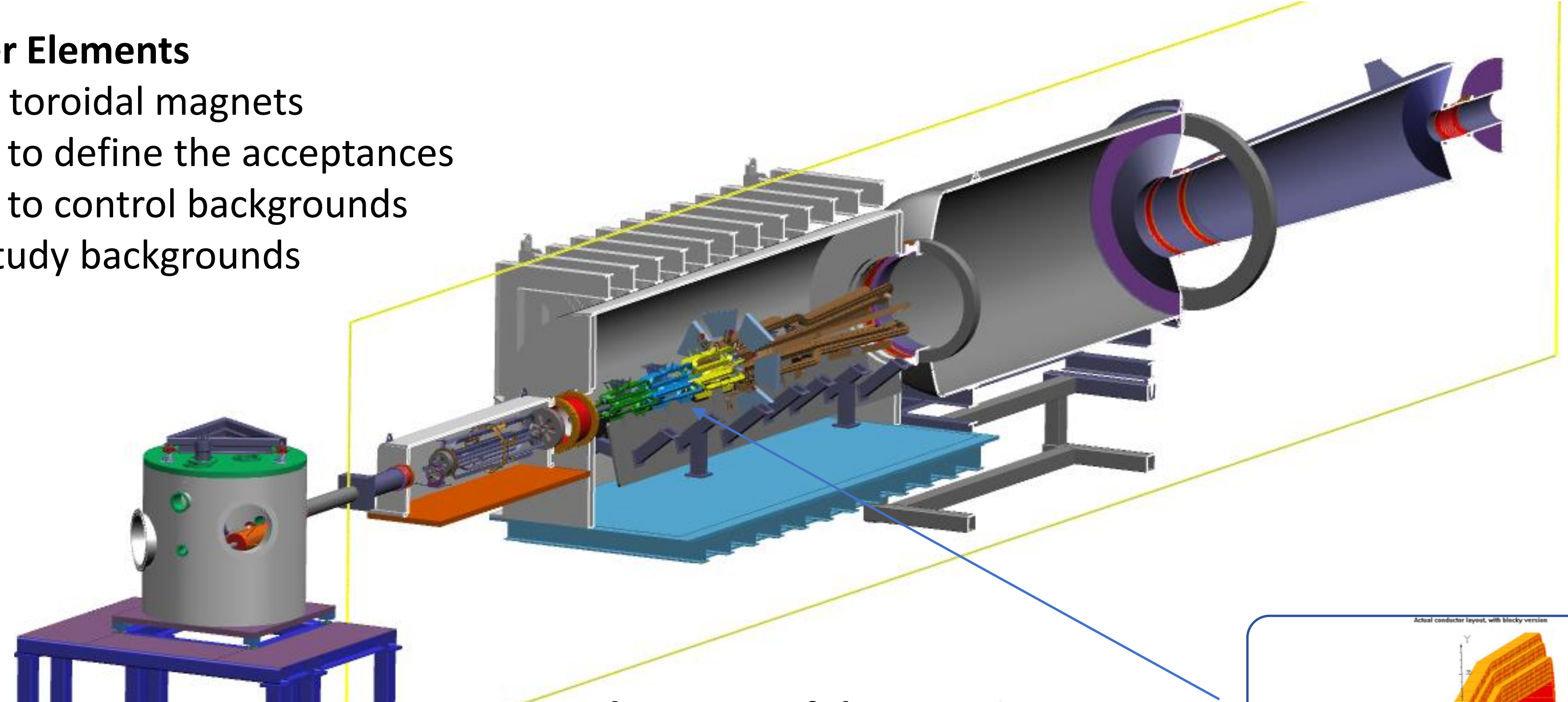
$$Q_W^p = 2Q_W^u + Q_W^d = 2\left(1 - \tfrac{8}{3}\sin^2\theta_W\right) + \left(-1 + \tfrac{4}{3}\sin^2\theta_W\right) \approx 0$$



J. Erler
arXiv:1908.07346v1

The Experiment

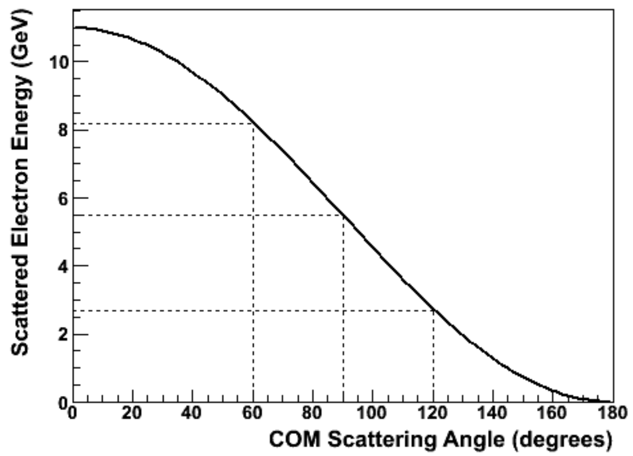
Spectrometer Elements
Two resistive toroidal magnets
2 collimators to define the acceptances
2 collimators to control backgrounds
Blockers to study backgrounds
Beamline

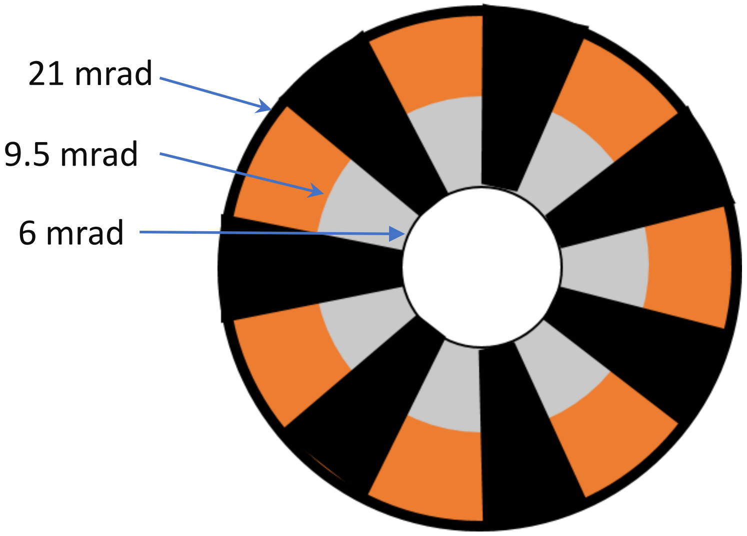


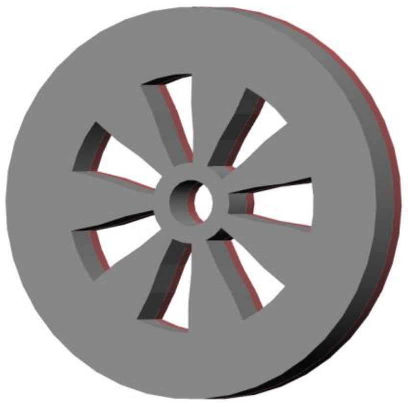
Other parts of the experiment
Integrating detectors
Tracking detectors
Target
Shielding
Beam monitors

Single coil of downstream **(hybrid torus)**

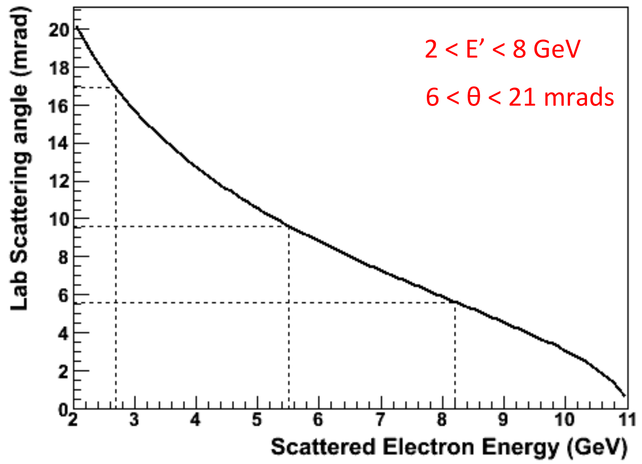
100% Azimuthal Acceptance Possible

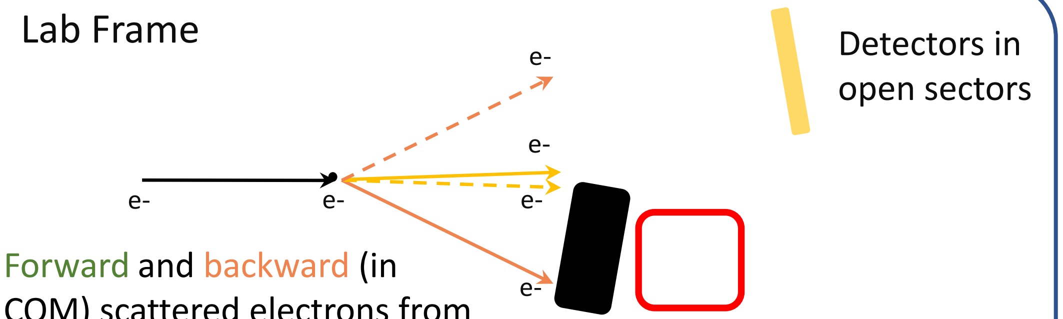






Acceptance defining collimator





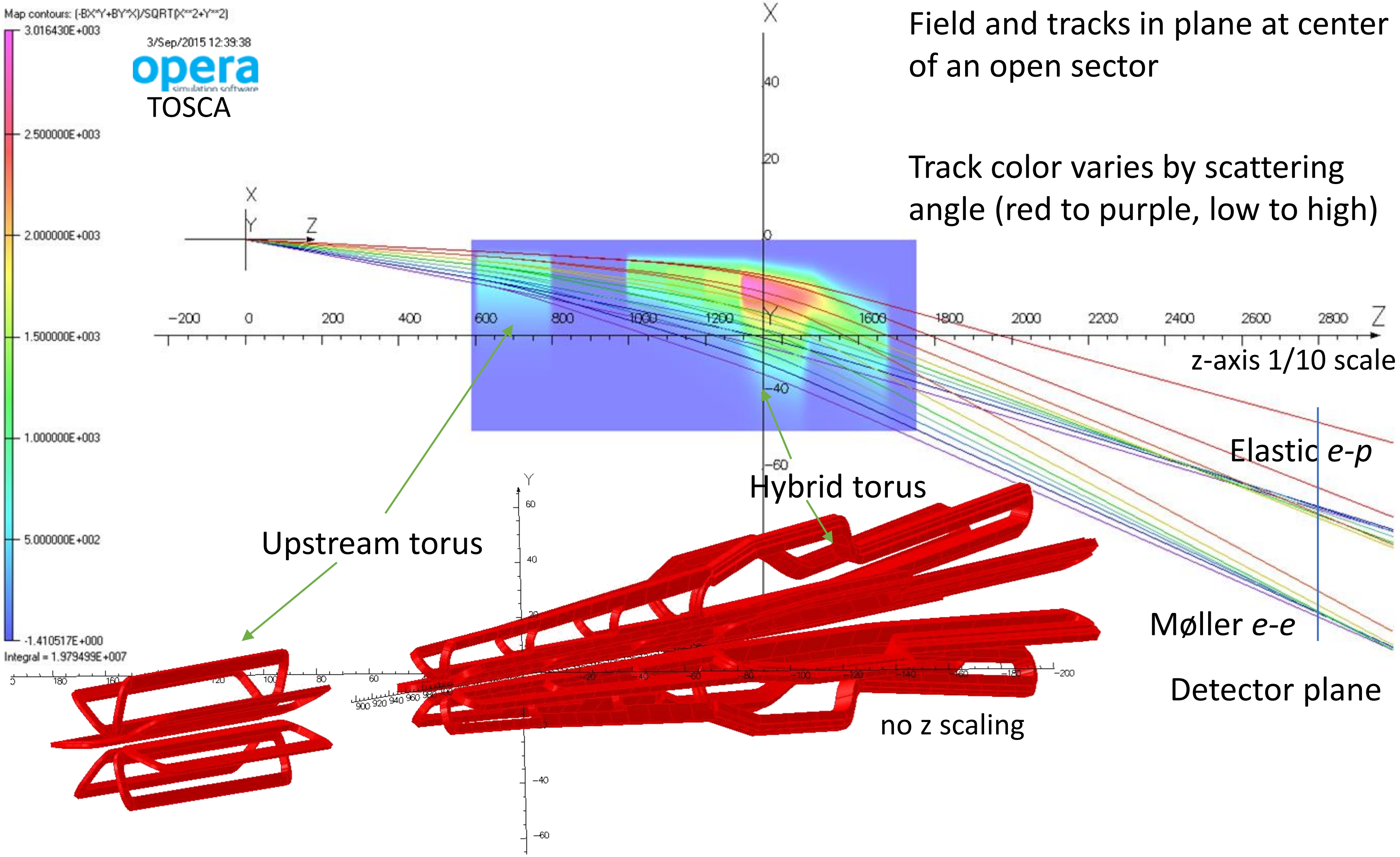
Forward and backward (in COM) scattered electrons from two events (line type links electrons from same event)

Any odd number of coils will allow for 100% φ acceptance

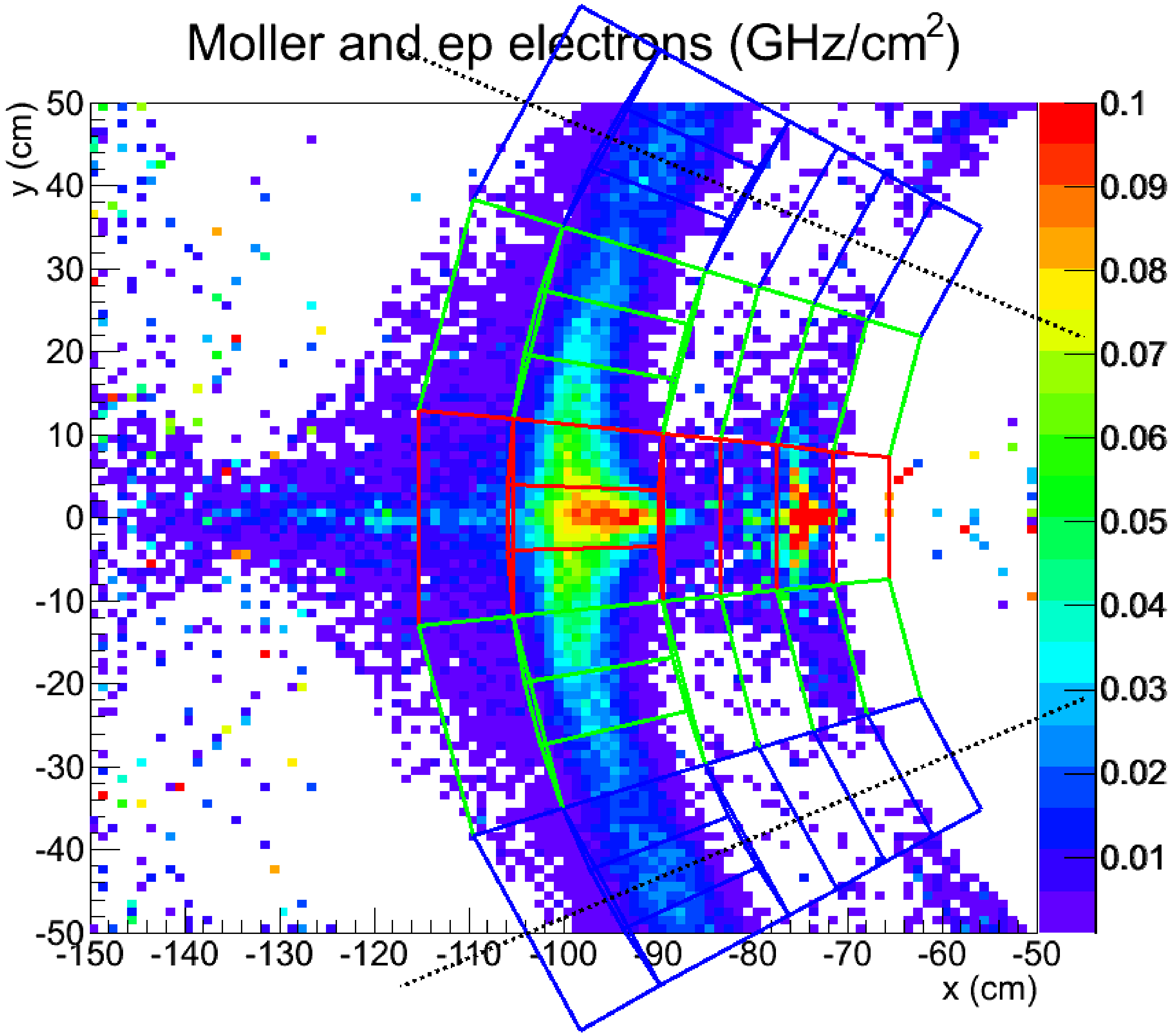
MOLLER Spectrometer

Field and tracks in plane at center of an open sector

Track color varies by scattering angle (red to purple, low to high)

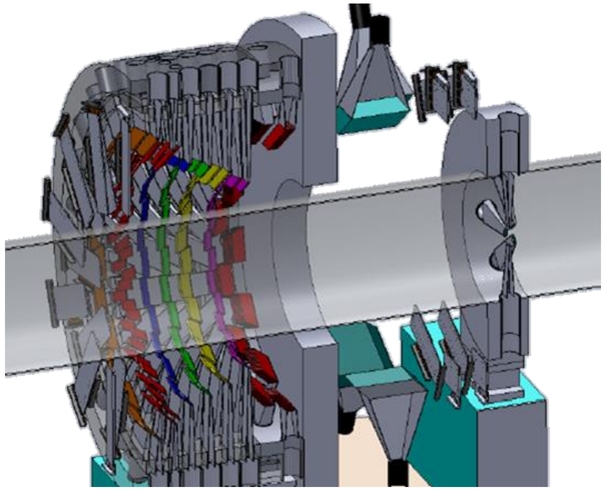


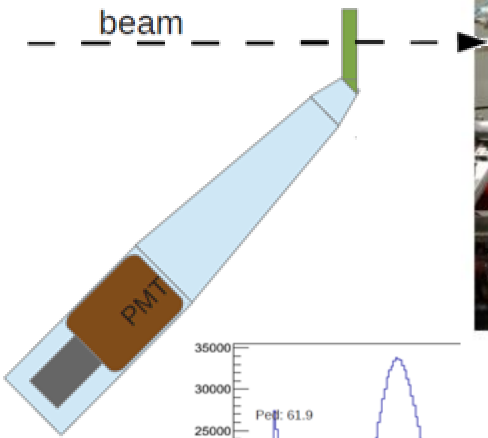
Detector Array

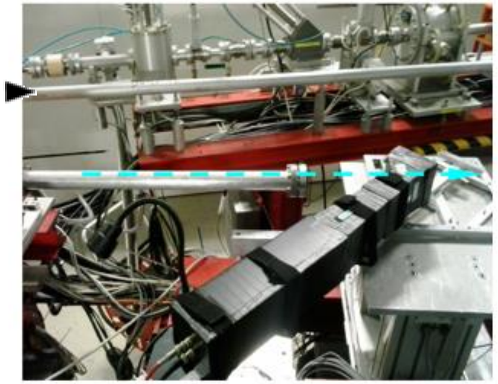


x (cm)

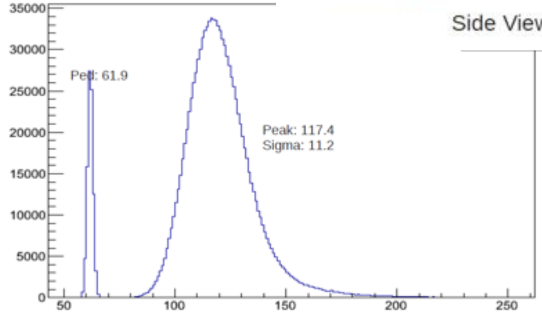
(Rate weighted 1x1cm^2 bins)







Side View

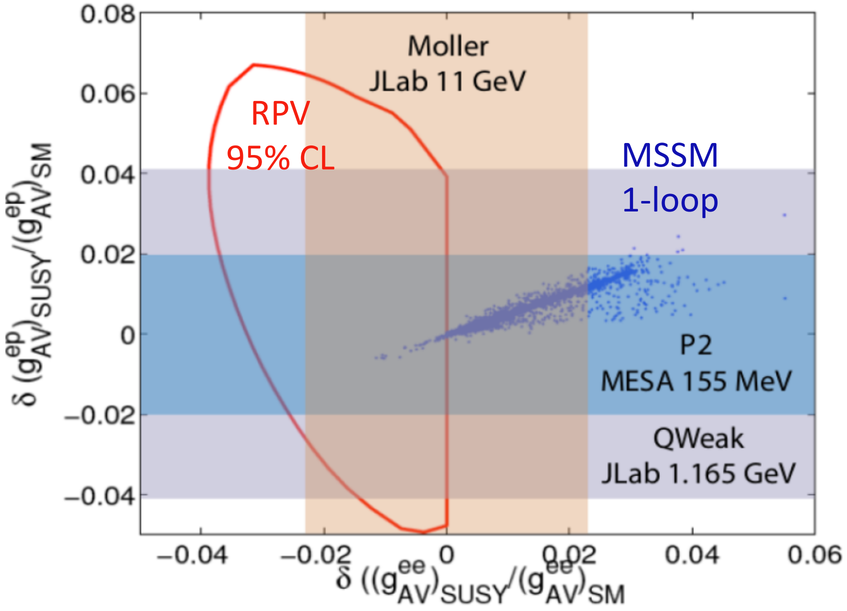


- Simulation expectation: 37 PE (for 1.5 cm thick quartz)
  25 PE (for 1.0 cm thick quartz)
  (ref. p.21, DocDB#76-v1)

MOLLER

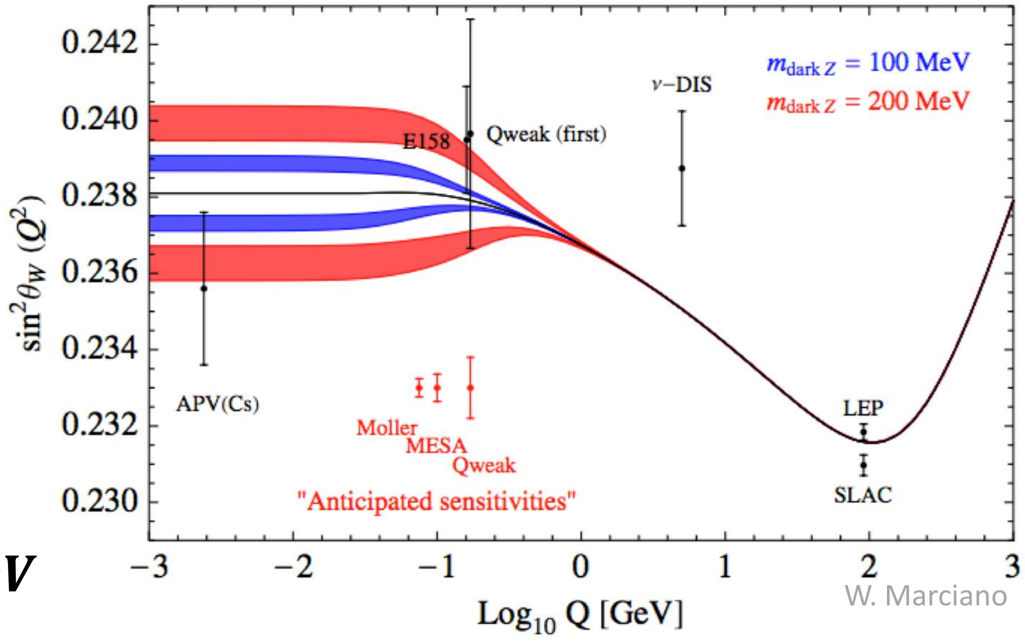
Shufeng Su

- Science need has long been demonstrated
- Recent review recommended to proceed to CD1
- Design and construction expected 2021 – 2024
- First physics in 2025



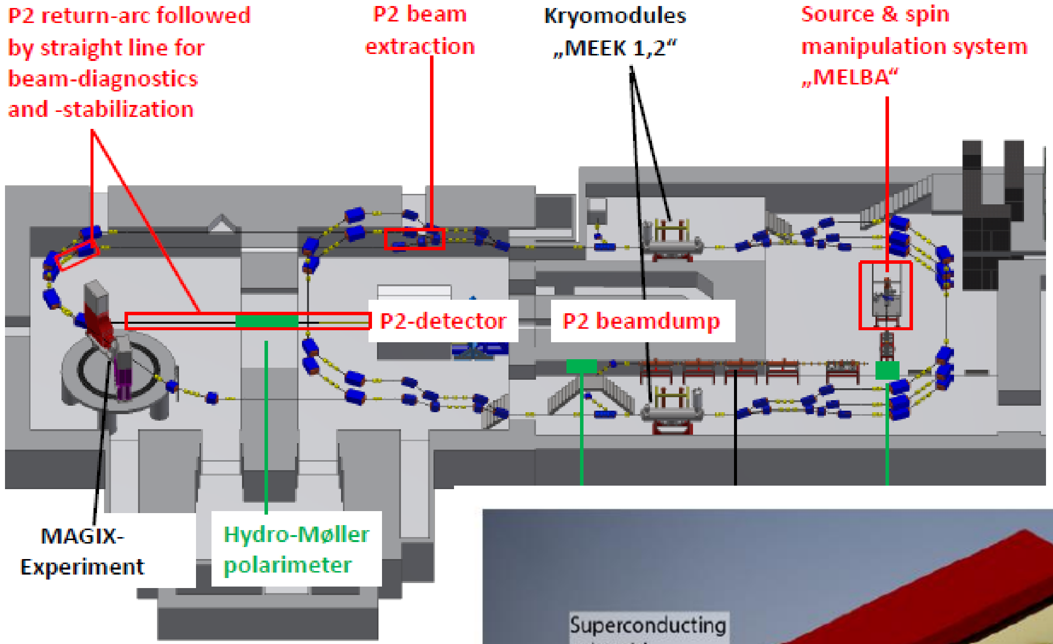
$$\frac{\delta \sin^2\theta_W}{\sin^2\theta_W} \simeq .05\frac{\delta A_{PV}}{A_{PV}} \quad \Rightarrow \quad \delta Q_W^e = 2.3\%, \sim 5\times smaller\ than\ E158$$

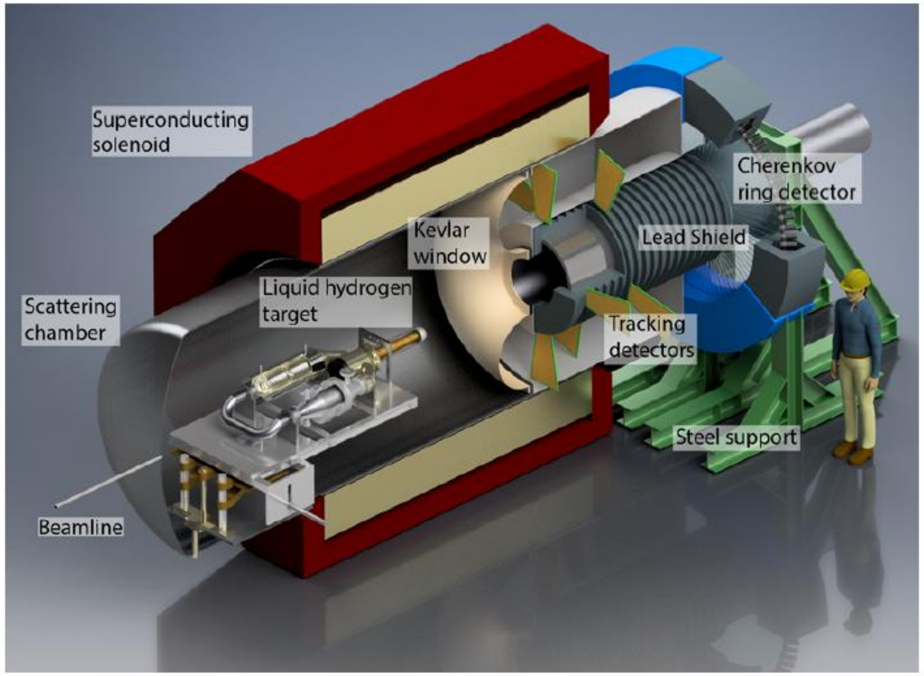
$$\mathcal{L}^{PV}_{e_1e_2} = \sum_{i,j=L,R}\frac{g_{ij}^2}{2\Lambda_{ij}^2}\bar{e}_i\gamma_\mu e_i\bar{e}_j\gamma^\mu e_j \quad \Rightarrow \quad \frac{\Lambda}{\sqrt{|g_{RR}^2-g_{LL}^2|}} = 7.5\ TeV$$

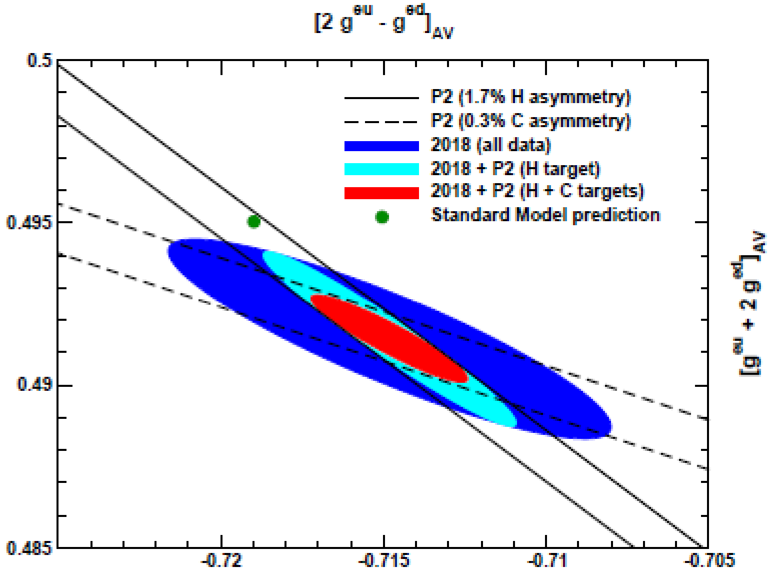


2.3% MOLLER uncertainty → 7.5 to 27 *TeV*

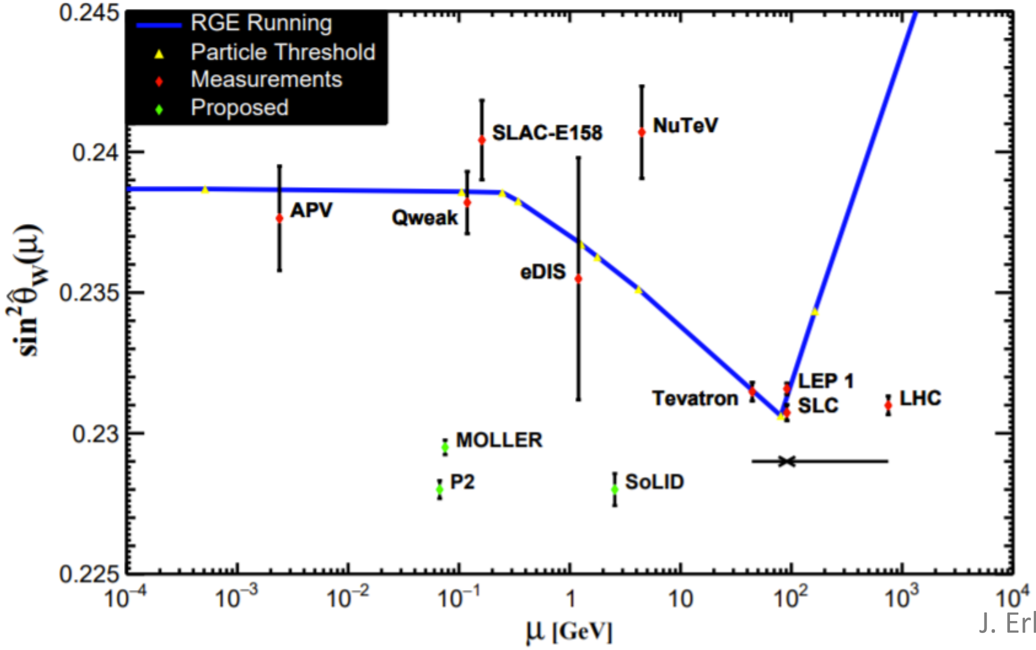
P2 at MESA - Q_W^p







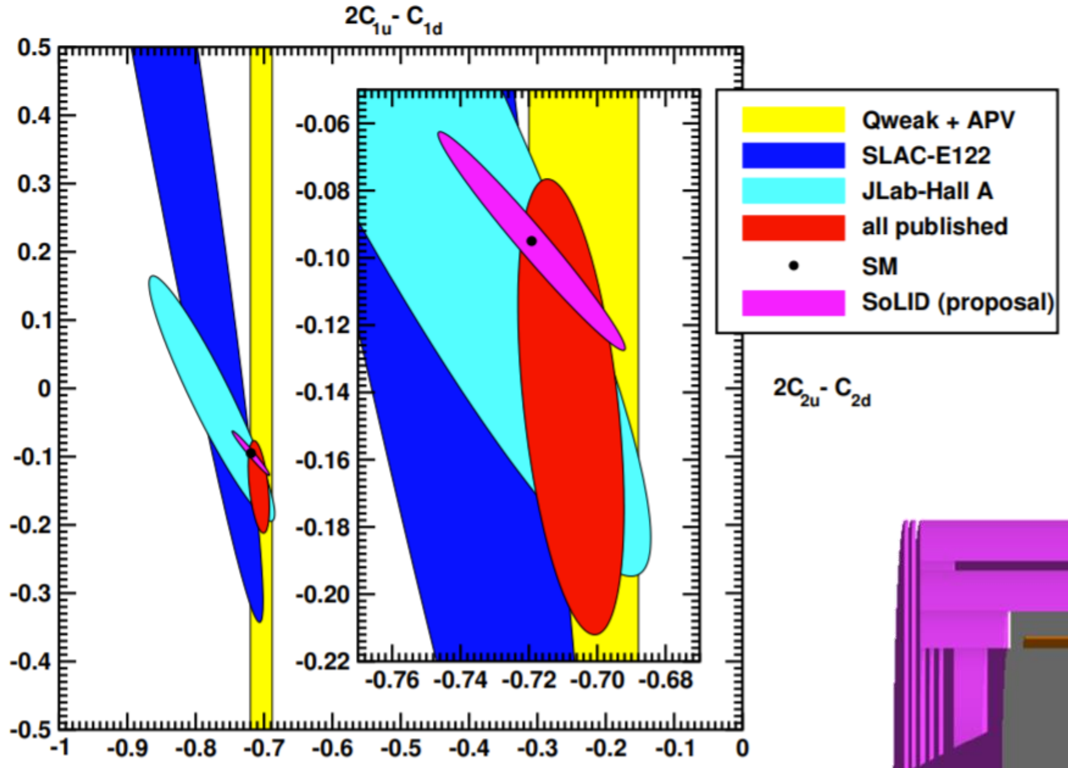
Blue includes Qweak projected with APV
Cyan adds future P2 H
Red ellipse includes possible C measurement



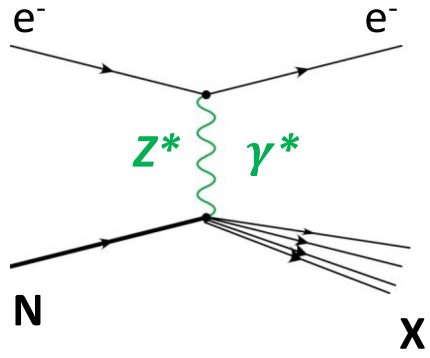
J. Erler
arXiv:1908.07346v1

SOLID – Large Acceptance Device

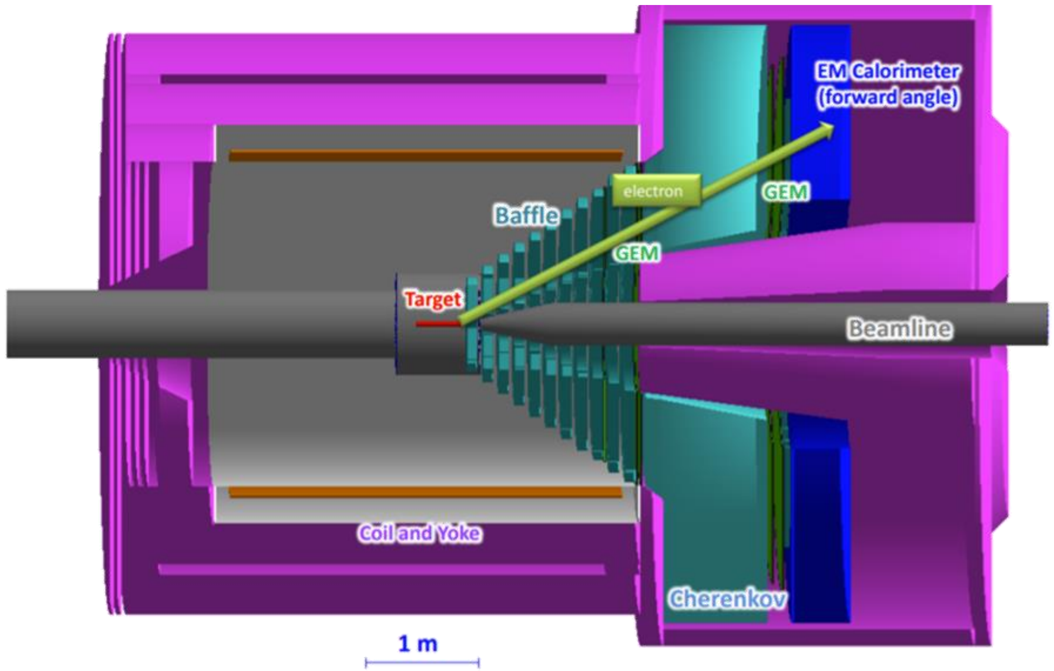
- Large acceptance
- High luminosity
- < 1% errors for small bins
- Large Q^2 coverage
- $0.25 < x < 0.75$
- $W^2 > 4$ GeV^2



Y. X. Zhao
arXiv:1701.02780v1



- Requirements
  - Solenoid contains low energy backgrounds
  - Baffling to limit backgrounds
  - Measure trajectories after baffles
  - Fast tracking – GEM, particle ID, colorimetry and pipleline electronics
  - Precision polarimetry (0.4%) Compton and atomic hydrogen Moller



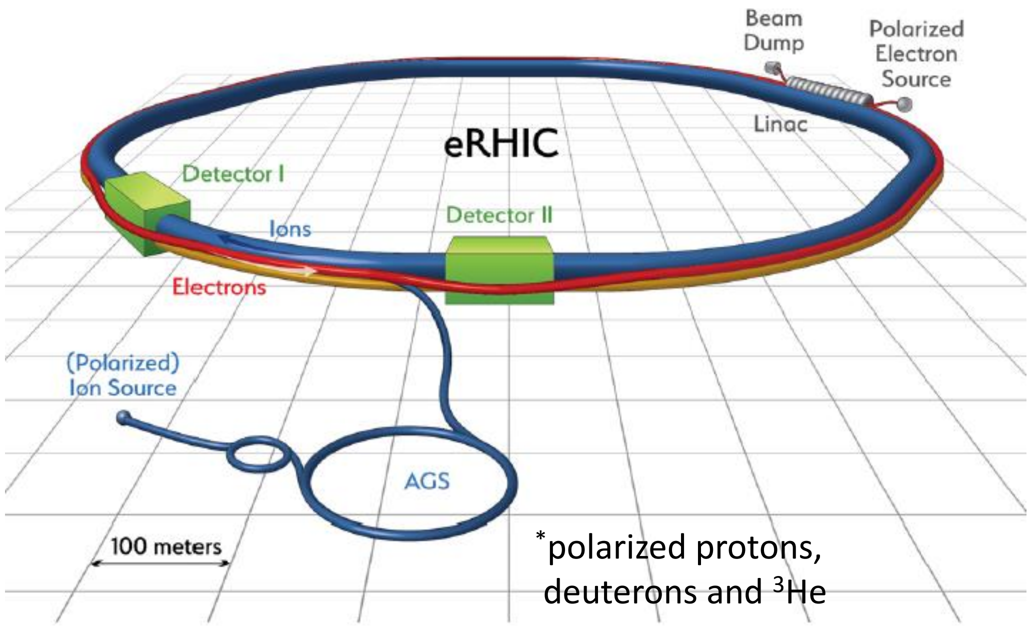
DOE Science Review – early 2021

Electron Ion Collider

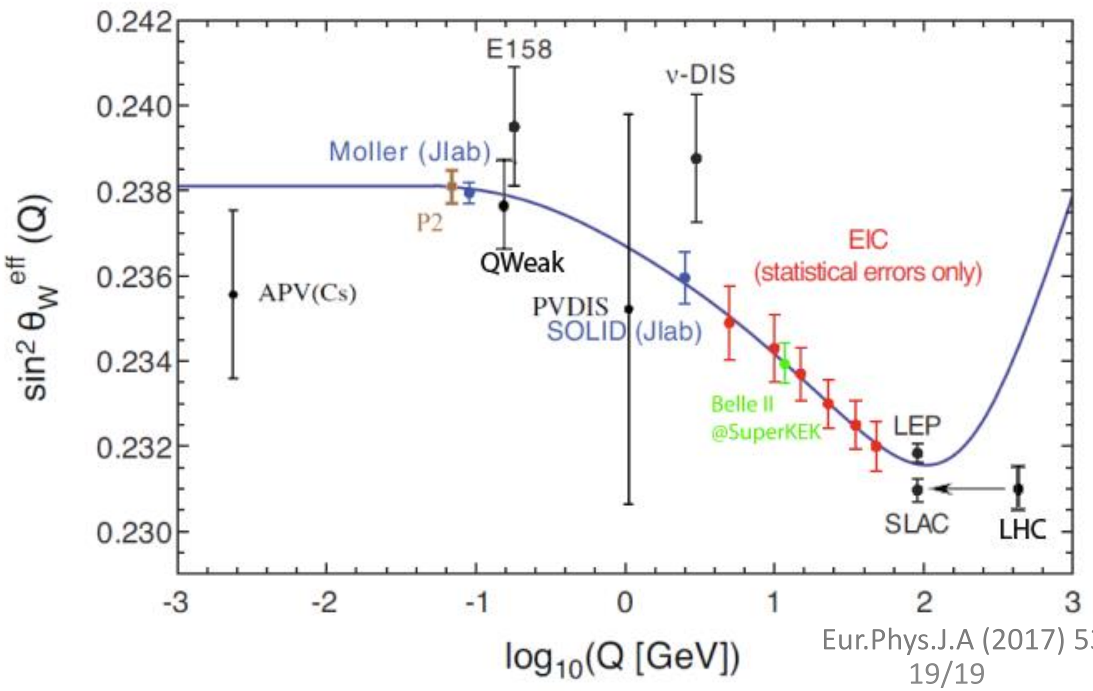
- Center of mass energies from 20 to 100 GeV
  - Polarized electron ring with $10 < E_{beam} < 20$ GeV
  - Ion ring* with $50 < E_{ion} < 250$ GeV

- Measurements of
  - weak vector and weak axial-vector quark couplings from interference of $F_1^{\gamma Z}$ and $F_3^{\gamma Z}$ and structure functions in $\vec{e} + d$ scattering
  - determination $sin^2\theta_W$ between 10 and 70 GeV
  - $F_3^{\gamma Z}$ informs V_{ud} – another avenue for Standard Model tests

- Discovery potential in $e^- \to \tau^-$ decays for BSM physics
  - leptoquarks
  - R-parity violating supersymmetry
  - leptophobic Z^0 bosons
  - other charged lepton flavor violation theories.



*polarized protons, deuterons and ^{3}He



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PVES Experiment Summary

- Program of PVES to measure
  - nuclear and nucleon properties
  - weak couplings
  - test the Standard Model
- Each new "generation" leverages
  - improvements to technology
  - advances in theory
- Future measurements will
  - continue the search for BSM physics
  - improve our understanding of nuclear structure