Parity Violating Electron Scattering Experiments

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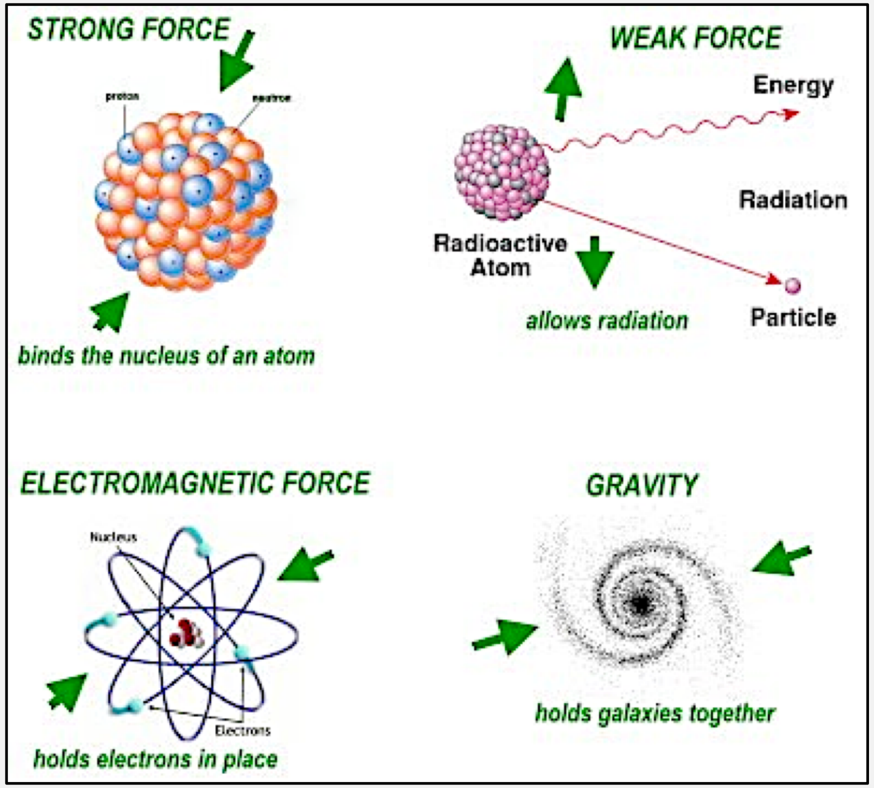
NNPSS IU

7/19/2024

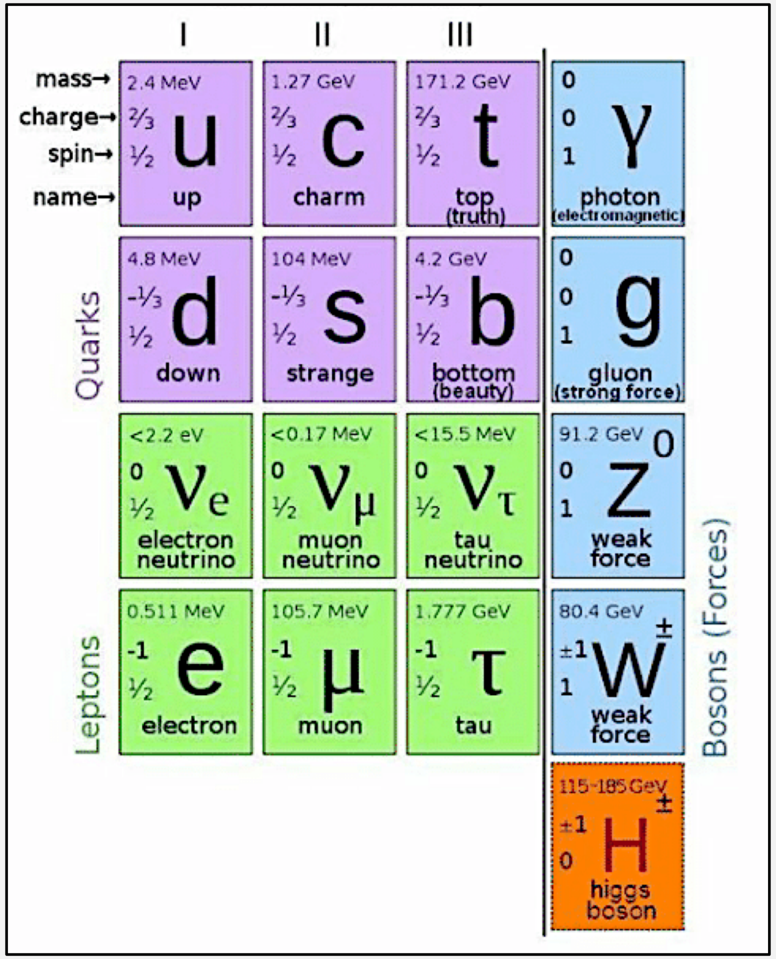
What do we think we know fundamentally?

Fundamental Forces

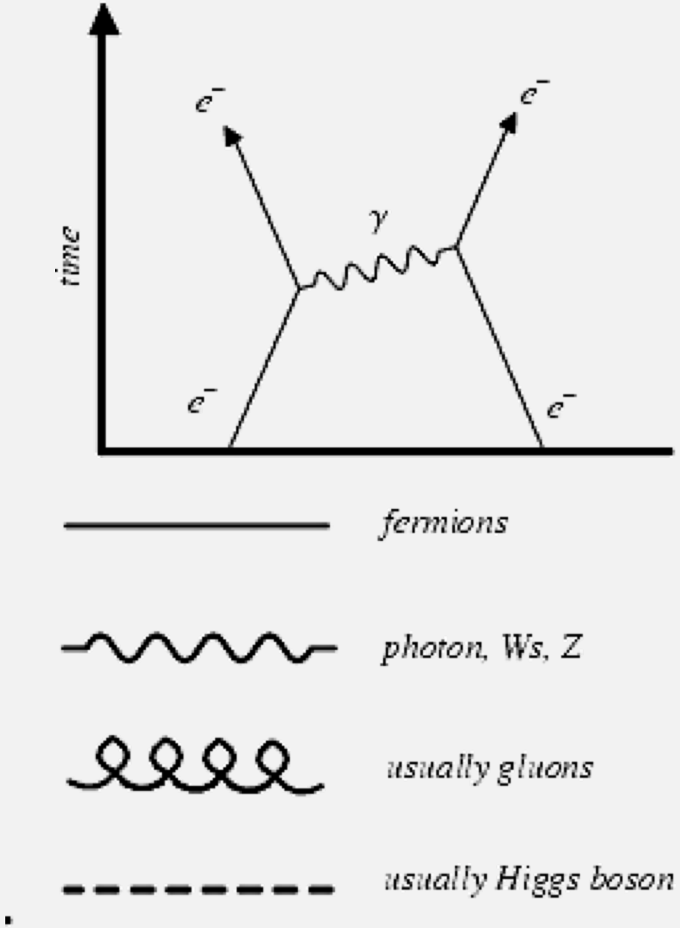


https://sites.google.com/site/joshlimlinganphysicslife/particle-physics/thefourforces

Standard Model Particles

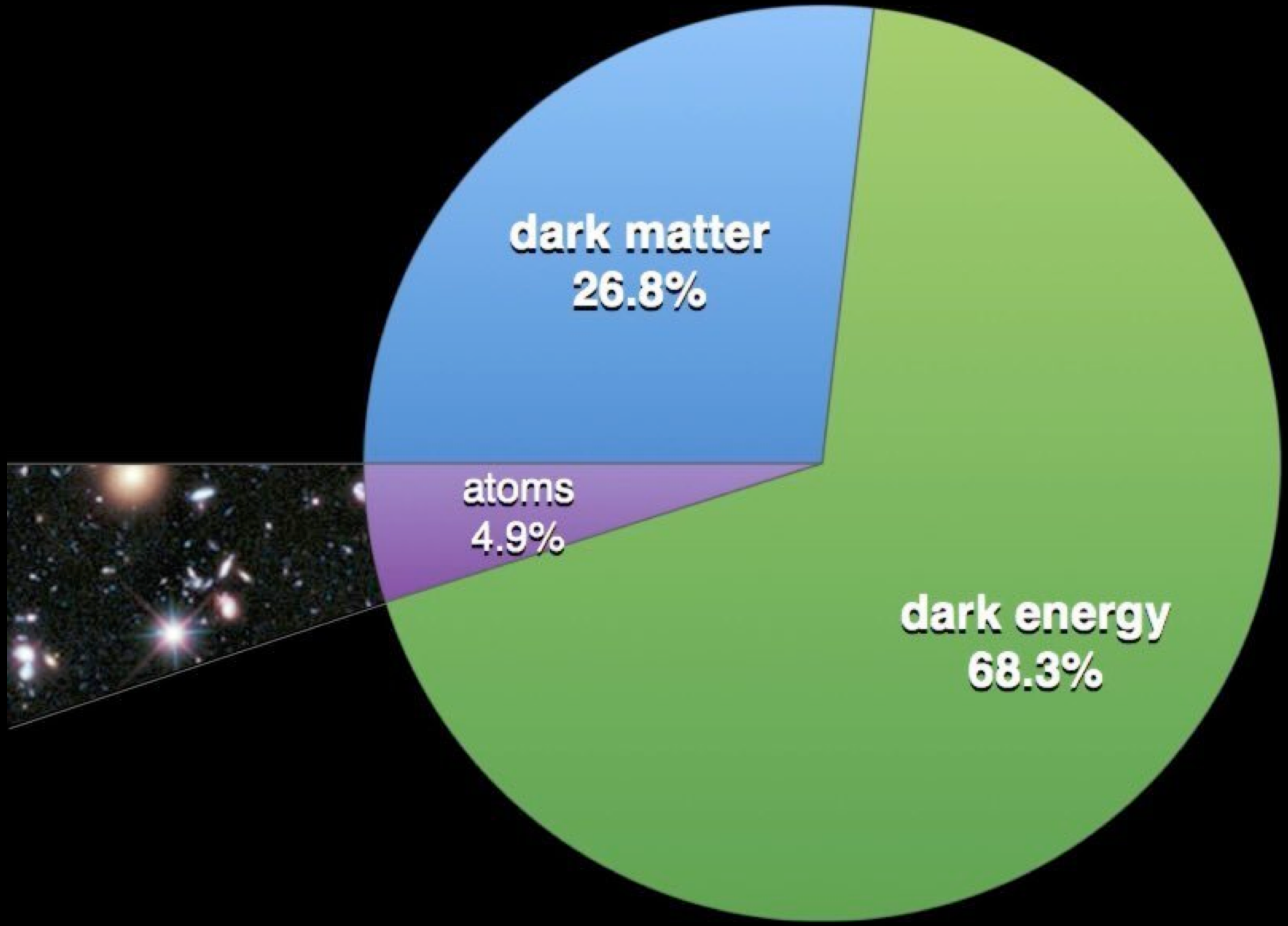


Feynman Diagrams



What do we NOT know?

It's a Dark World



@AstroKatie/Planck13

News

CDF collaboration at Fermilab announces most precise ever measurement of W boson mass to be in tension with the Standard Model

April 7, 2022

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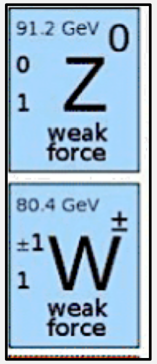
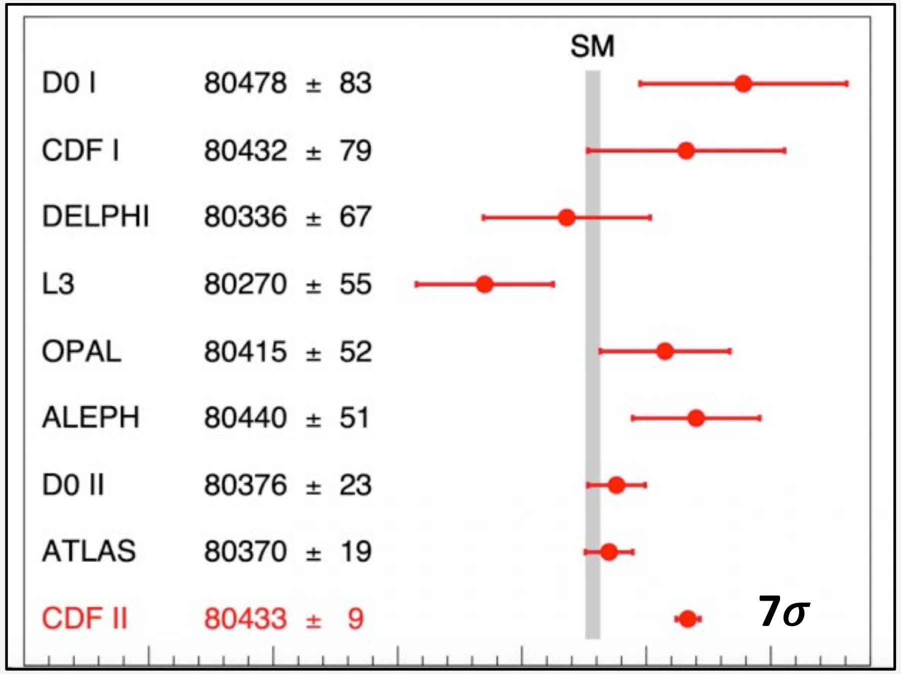
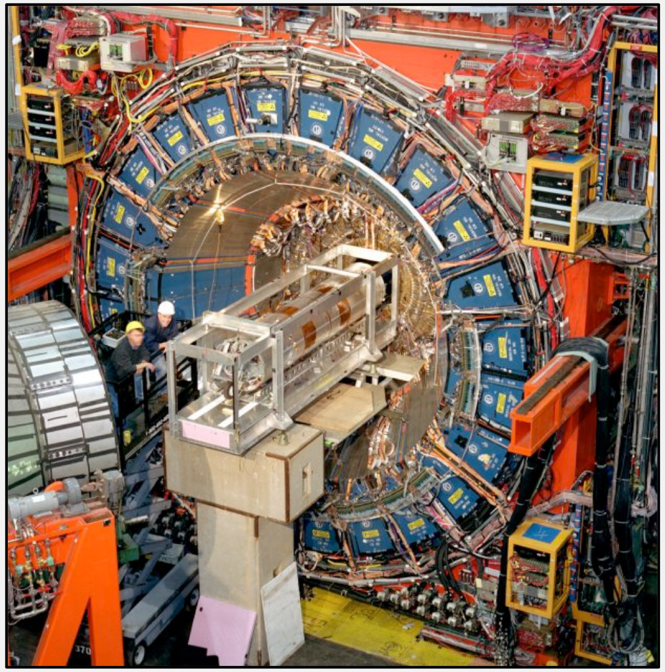


- CDF collaboration
- 2022
- Most precise measurement to date of the mass of the W boson

M_W 80,433 +/- 9 MeV/c^2.

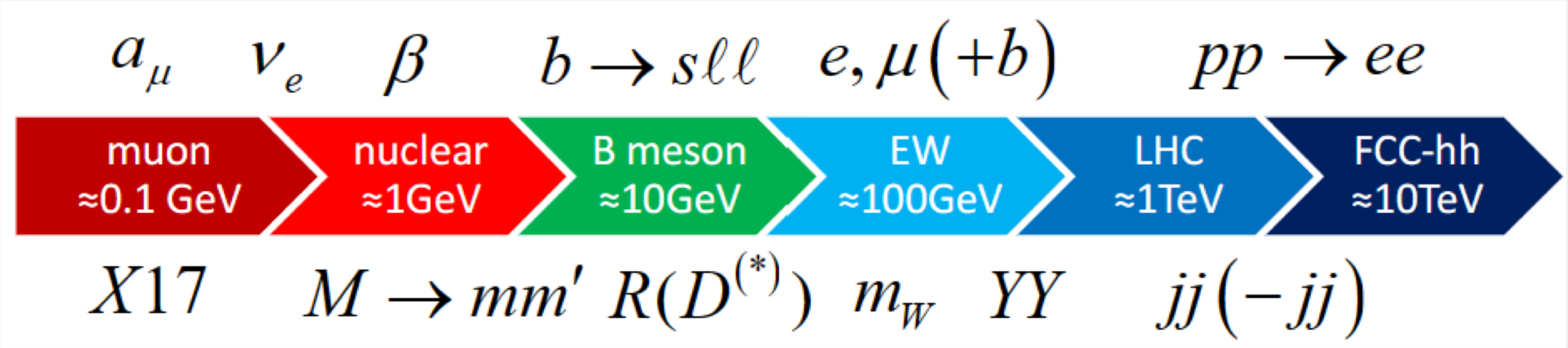
https://news.fnal.gov/2022/04/cdf-collaboration-at-fermilab-announces-most-precise-ever-measurement-of-w-boson-mass/





Anomalies

Andreas Crivellin DIS2024   Based on the Nature Physics Review arXiv:2309.03870



Combined significance of at least 3σ

- a_μ: Anomalous magnetic moment of the muon: [CDM-3, Electron g-2]
- X17: 17 MeV anomaly in excited nuclei decays [LSND & MiniBooNE]
- β: Anomalies related to β decays [neutron lifetime beam vs bottle]
- ν_e: Electron neutrino anomalies [LSND & MiniBooNE]
- b→sμμ & b→cτν: Semi-lepton B meson decays [LHCb, ATLIS, CMS]
- m_W: W mass [electroweak precision observables]
- eμ(+b): Multi-lepton anomalies [ATLAS]
- YY: New resonances at 95GeV, 152GeV and 650GeV [Hints for new Scalars]
- jj(-jj): Di-di-jets [ATLAS, CMS]
- pp→ee: non-resonant di-electrons [CMS, ATLAS,HERA]

- Leptoquarks with tau-loops
- Di-quarks (tau loops)
- Z'
- Z-Z' mixing
- SU(2) triplet scalar
- 2HDM
- Dark neutron decays
- Vector-like quarks
- MSSM
- H^+

How did we get here?

Our history informs our present and future.

What we do currently in research has its origins in 20^{th} century experiments.

History : Weak Interaction

- **1930's – Weak Interaction was needed to explain nuclear Beta decay**
- **A problem:** 1930, nuclear beta decay A->B+e- , E conservation violated
- Pauli – suggests a silent, neutral particle particle (neither the neutron or neutrino had yet been discovered)
- 1933 Fermi - the first theory of the weak forces - to explain beta decay-contact interaction-requiring no mediating particle (good approximation at low E)
- Widely recognized, at high E this approach would fail – needed theory with mediators (*intermediate vector bosons)*
- ***1950's – Discovery of Parity Violation in the Weak Interaction***
- ***What rules must be obeyed?***
- Prior to 1956 - taken for granted that parity is conserved in the weak interactions
- A paradox: 'τ-θ' puzzle, identical particles but distinct parity

$$\theta^+ \rightarrow \pi^+ + \pi^0 \ (P=1) \quad \tau^+ \rightarrow \pi^+ + \pi^0 + \pi^0 \ \textit{or} \ \pi^+ + \pi^+ + \pi^- \ (P=-1)$$

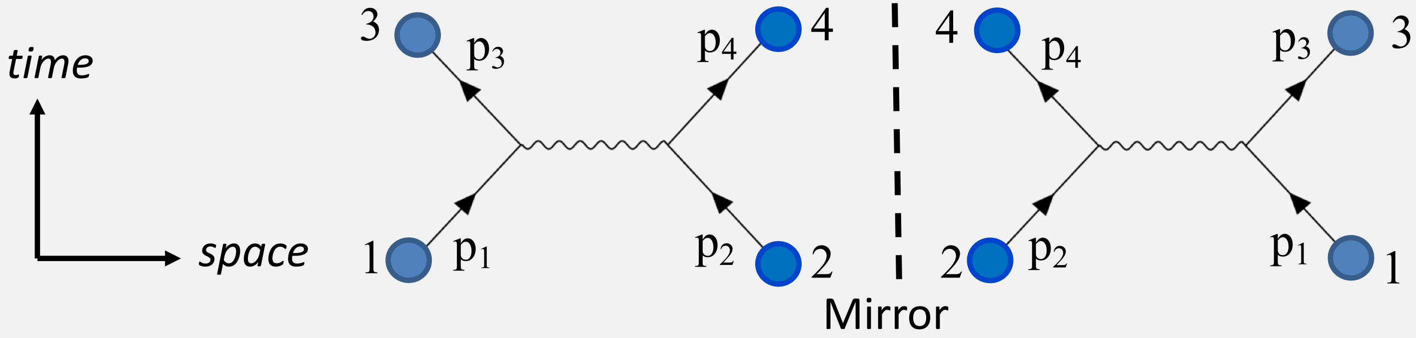
- Lee and Yang in 1956 suggest τ and θ the same (K^+) and parity not conserved the weak decay channel. Searched literature for evidence of parity conservation. Found none. Proposed experiment
- C.S. Wu carried out the experiment : famous Co-60 experiment

Fundamental Symmetries: Parity

Parity transformation

$$x, y, z \longrightarrow -x, -y, -z$$

$$\hat{P}\psi(\vec{x},t) = \psi(-\vec{x},t) \;\; =? \psi(\vec{x},t)$$



History of Weak Interaction: Parity Violation

- Principle of conservation of parity had been accepted physics doctrine for decades…
- *1950s: Lee and Yang ask C.S. Wu - has anyone ever proven the nucleus of a particle always behaves in a symmetrical way?*
- Goal: Test Parity Conservation
- Wu devised an experiment:

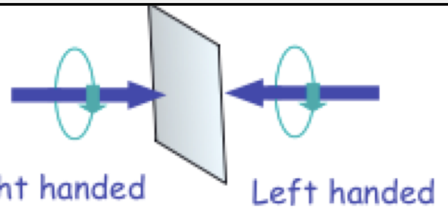
https://diversity.lbl.gov/2015/05/19/chien-shiung-wu-physicist-who-helped-change-the-world/

Parity transformation

$$x, y, z \longrightarrow -x, -y, -z$$

$$\vec{p} \rightarrow -\vec{p}, \quad \vec{L} \rightarrow \vec{L}, \quad \vec{S} \rightarrow \vec{S}$$

- *How does angular momentum behave under a parity transformation?*
- ***L*** *=* ***r*** *x* ***p***
- ***r*** → *-**r***
- ***p*** *= m**v** ,* ***v*** *= d**r**/dt* → *d(-**r**)/dt :* ***p*** → *-**p***
- ***L*** *=* ***r*** *x* ***p*** → *(-**r**)x(-**p**) =* ***r*** *x* ***p*** *=* ***L*** *! :* ***L*** → ***L***
- *Angular momentum doesn't reverse sign under a parity transformation,*



Parity transformation is analogous to reflection in a mirror:

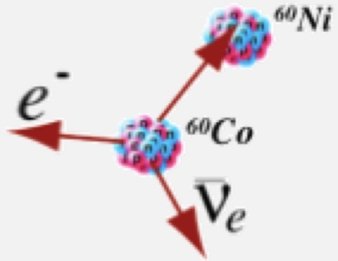
. . . reverses momentum but preserves angular momentum

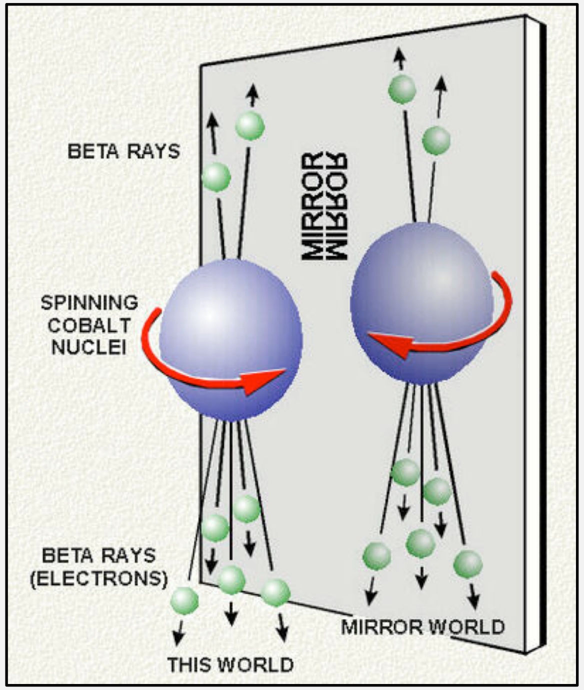
. . .takes right-handed (helicity = +1) to left-handed (helicity = -1).

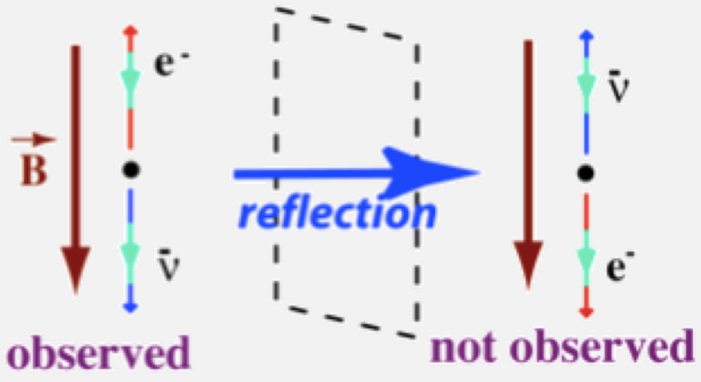
History of Weak Interaction: Wu experiment

Parity Transformation: Reverse space + Keep Spin Same = Reverse spin + Keep Space Same

Weak decay of ^{60}Co Nucleus







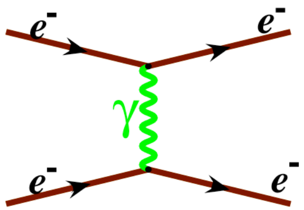
1956: C.S. Wu carried out famous Co-60 experiment – test Parity conservation

- Nuclei spin <u>aligned,</u> beta(e-) decay, recorded the direction of the emitted electrons.
- Observed: nuclei give off more e- in the direction of the nuclear spin
- *Proved an exception to the principle Parity conservation of, a fundamental symmetry, earned a Nobel Prize for Lee and Yang in 1957*
- **Established Parity violation - signature of the weak force**.

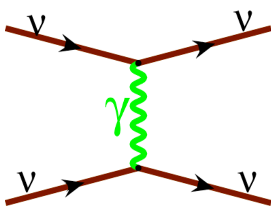
History : Weak Interaction

- The overthrow of parity had a profound effect on physics
- Parity violation - signature of the weak force.
- neutrino - Mid 50's - discovered all neutrinos are left-handed and all antineutrinos are right handed

Electric charge determines strength of electric force



observed



not observed

Neutrinos are "charge neutral": do not feel the electric force

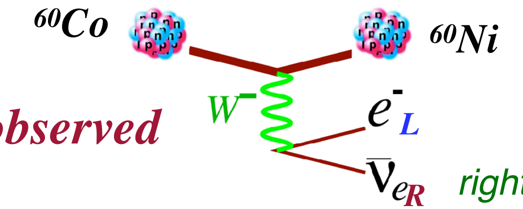
	Left	Right
γ **Charge**	$q = 0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$	$q = 0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$
W Charge	$T = \pm\frac{1}{2}$	**zero**

Weak charge determines strength of weak force

Left-handed particles (Right-handed antiparticles) have weak charge

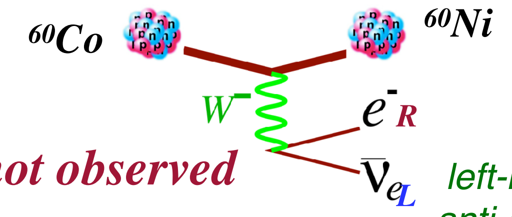
Right-handed particles (left-handed antiparticles) are "weak charge neutral"

observed



right-handed anti-neutrino

not observed



left-handed anti-neutrino

- 1958- Bludman suggests neutral weak interactions - Z^0 mediator

History : Weak Interaction

1960's – Glashow- Weinberg-Salam formulated theory unifying the weak and EM interaction – electroweak interaction – required W^{+-} and Z^0 - weak neutral currents

- 1961 - Glashow - unification of the weak and EM interaction – electroweak interaction – required W^{+-} and Z^0
- 1967 - Weinburg and Salam formulated Glashow's model as a spontaneously broken gauge theory. $\boldsymbol{\gamma}$ massless, W^{+-} and Z^0 heavy - Higgs mechanism

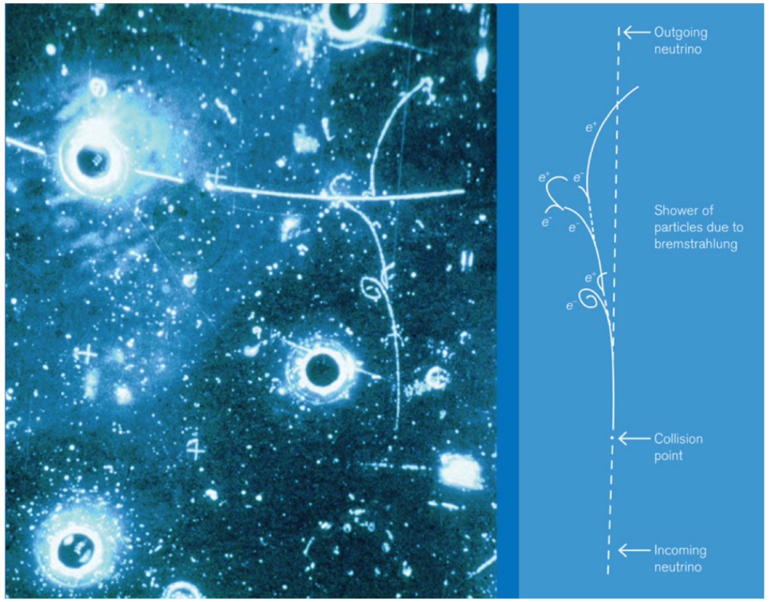
Electroweak Interaction

Until the 1970's, all known weak interactions could be explained by $W^{+/-}$ exchange

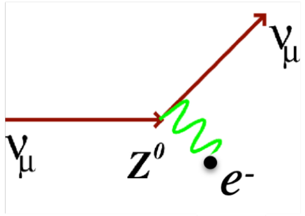
Weak neutral currents are proposed under electroweak unification (late '60s, Weinberg Salam Glashow, but others, also…)

$\Rightarrow$ The weak mixing angle θ_W introduced

1973 - the first observation of the neutrino reaction $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$



Gargamelle bubble chamber uncovers ν_μ e^- events in 1973, more convincingly in 1976. Suggested existence of the Z^0



This demonstrated the existence of the neutral current (Z^0) but not its nature

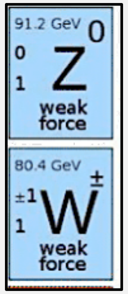
- What is the gauge structure of the underlying theory?
- Is this the electroweak unification of GWS?
- Another EW unification?
- A new interaction?

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

Landmark experiment (late 1970s): parity-violating electron scattering

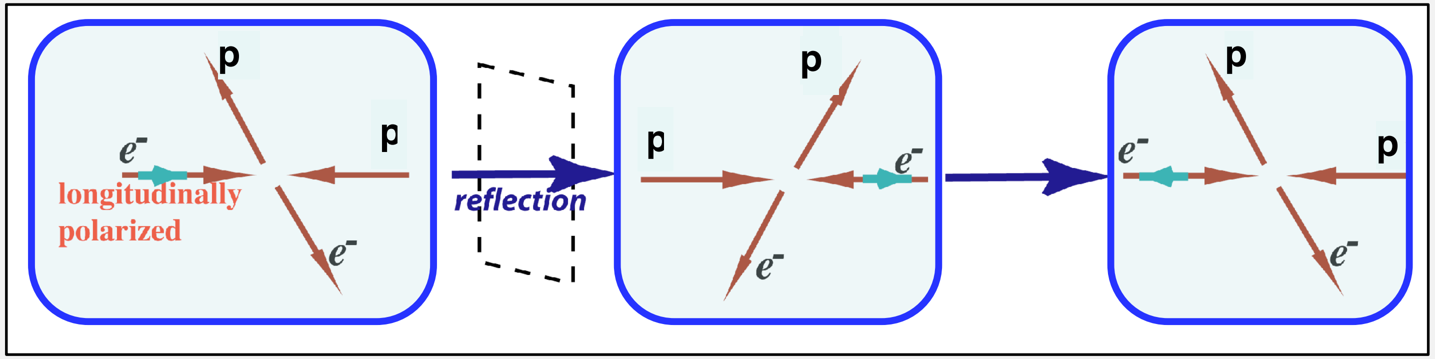
History of Weak Interaction: nature of Z^0

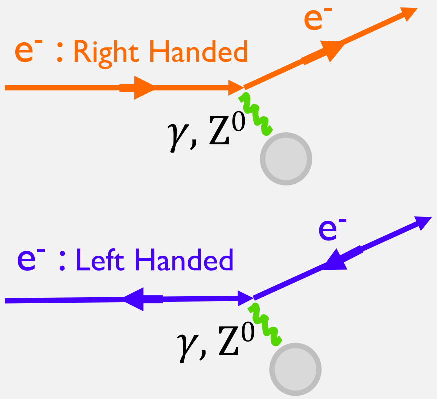
Theory
- GWS electroweak unification model – predictions of Z^0
  Couplings determined by the "weak mixing angle" θ_w
  Made possible firm prediction for mass of Z^0 : $M_w=M_z\cos\theta_w$
  In the early days it was hard to estimate θ_w - hence the Z^0 mass was quite uncertain



Indirect
- 1978 – E122 at SLAC
  - **Parity Violating Electron Scattering Experiment**
  - verified parity non-conservation - $\sin^2\theta_w = 0.2\pm.03$

Reverse space + Keep Spin Same = Reverse spin + Keep Space Same





Reverse Spin and measure rate asymmetry

1978 – E122 at SLAC

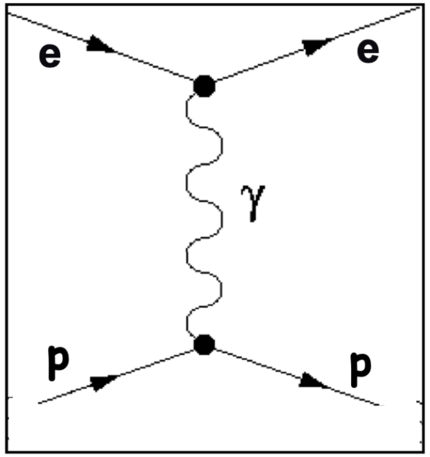
1st Parity Violating Electron Scattering Experiment

What is a PVES experiment?

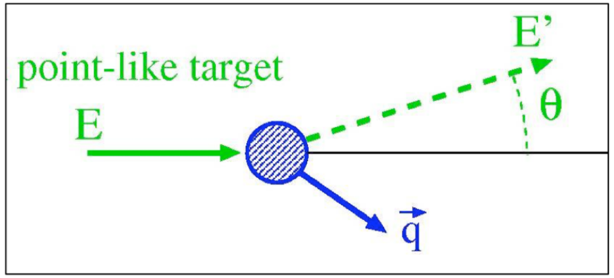
Introduction to electron scattering

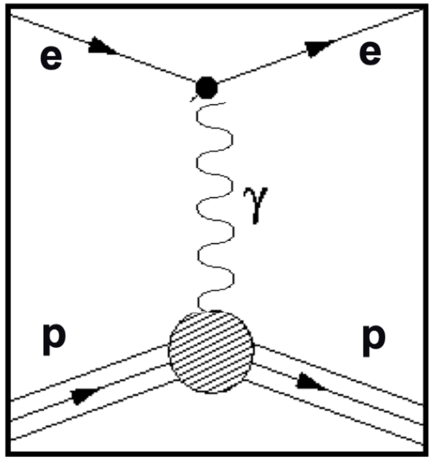
Electron scattering: electromagnetic interaction, described as an exchange of a virtual photon.

If photon carries low momentum
-> long wavelength
-> low resolution

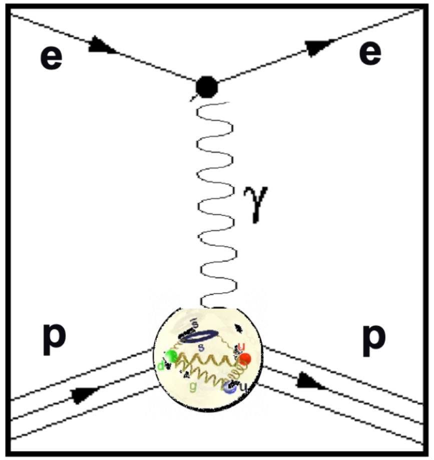


Q^2: 4-momentum of the virtual photon



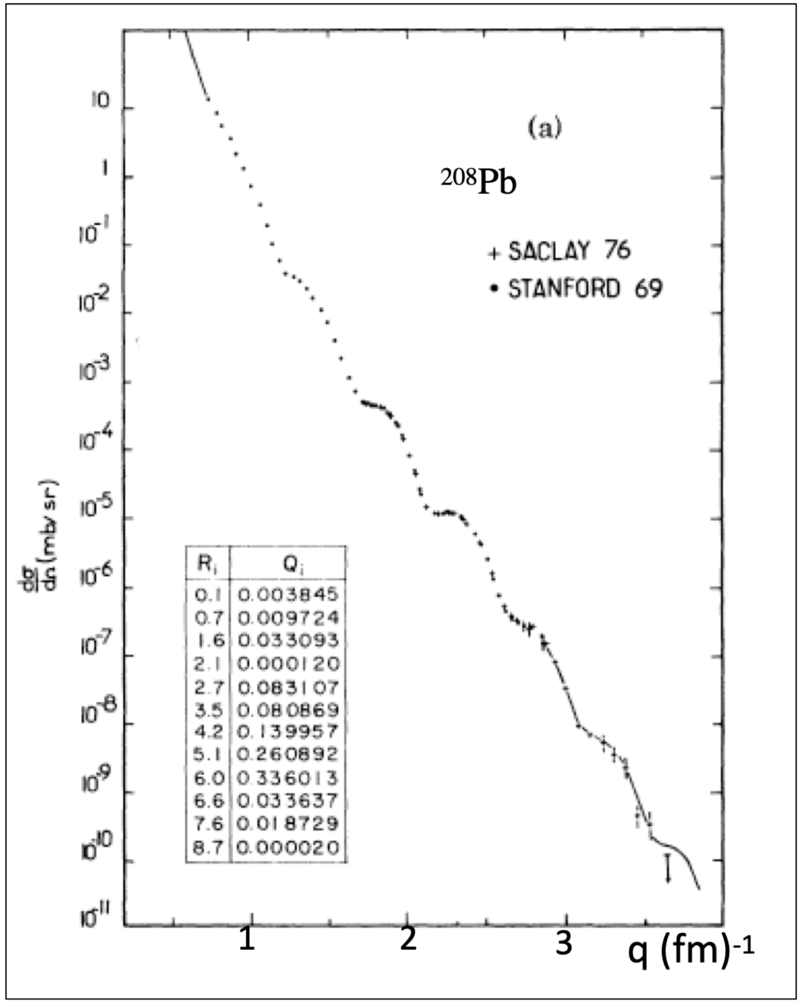


Increasing momentum transfer
-> shorter wavelength
-> higher resolution to observe smaller structures



Elastic Form Factors and Extended Targets

The point-like scattering probability for elastic scattering is modified to account for finite target extent by introducing the “form factor”



Assuming spherically symmetric (spin-0) target

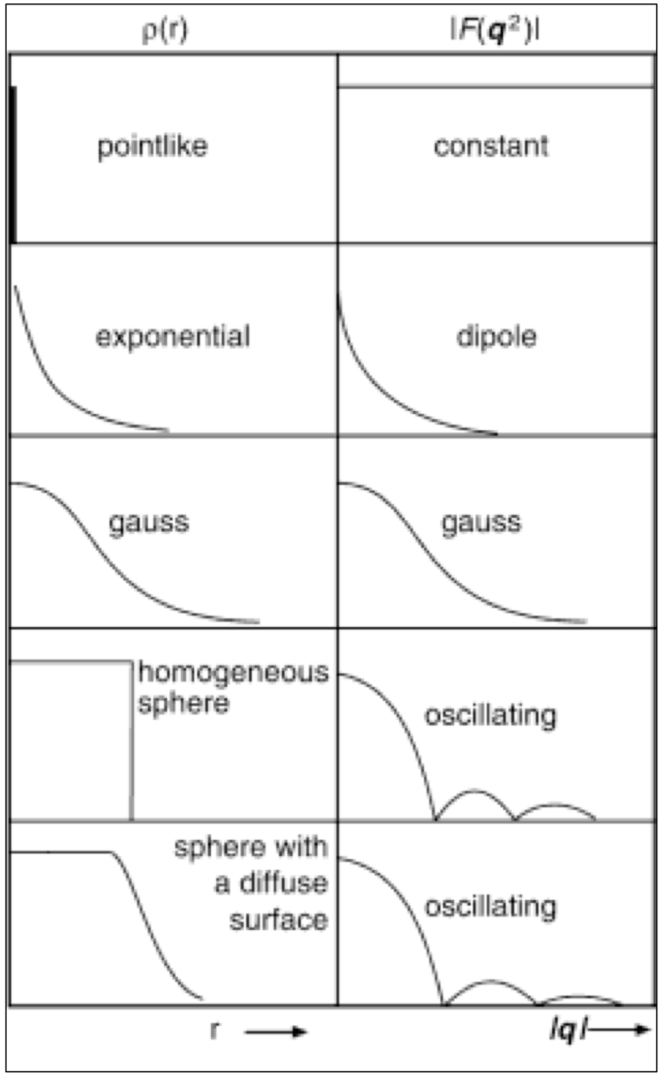
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left| F(q) \right|^2$$

point-like target, electron spin

$$F(q) = \int e^{iqr} \rho(r) d^3r$$

Form factor is the Fourier transform of charge distribution

Figure from Particles and Nuclei, Povh *et al.*



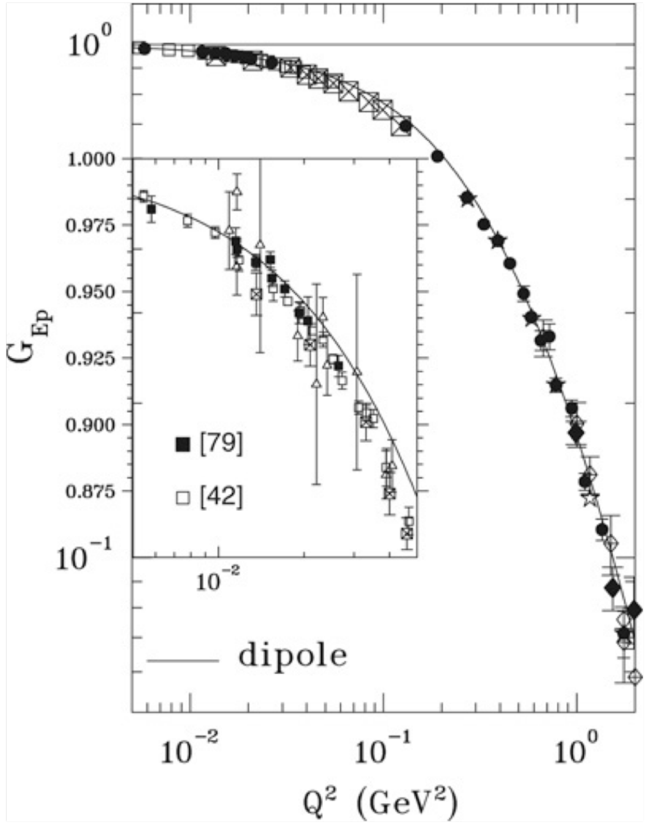
Elastic Electron-Nucleon Scattering

For targets with spin, must also account for magnetic moment

Electric and Magnetic form factors $G_E(Q^2)$ and $G_M(Q^2)$

$$\left.\frac{d\sigma}{d\Omega}\right|_{Rosenbluth} = \left.\frac{d\sigma}{d\Omega}\right|_{Mott} \left\{ \frac{(G_E^2 + \tau\, G_M^2)}{1+\tau} + 2\tau\, G_M^2 \tan^2(\theta/2) \right\}$$

Proton (and neutron magnetic) form-factors follow dipole form (exponential charge distribution)



With no structure

G_E = 1 (proton charge)

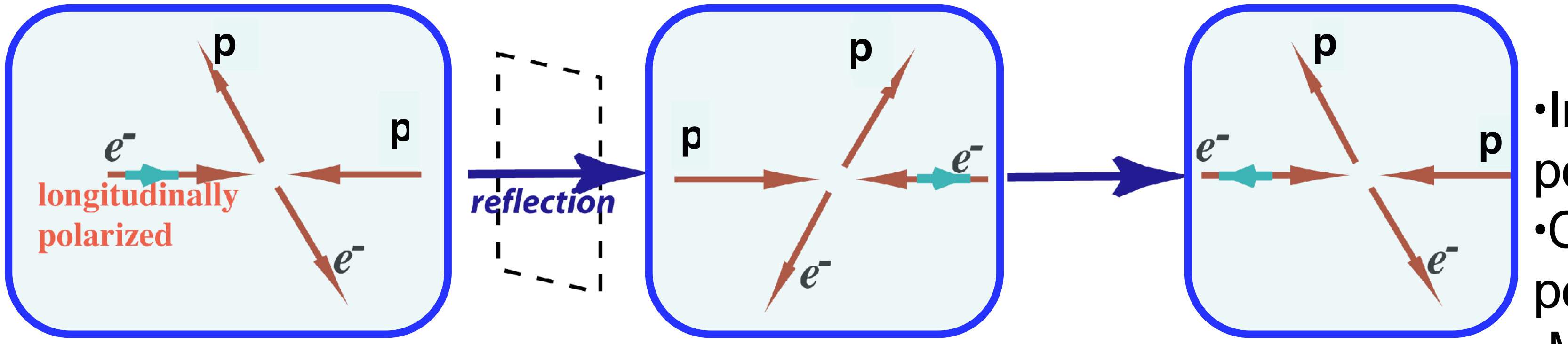
G_M = 1 (magnetic moment = μ_B).

At Q^2 = 0, the probe does not resolve the target

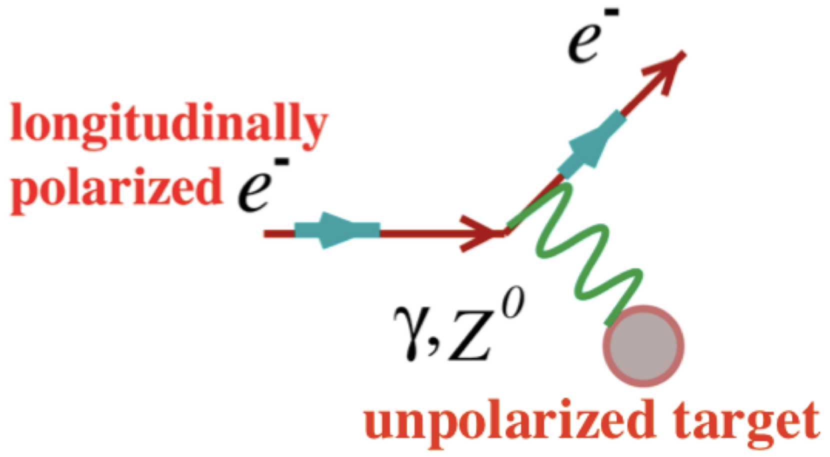
$G_E(0)$ = 1 (electric charge)

$G_M(0)$ = μ (magnetic moment in units of μ_B)

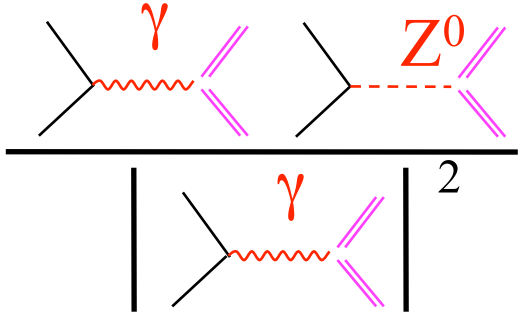
Electron Scattering and Parity-violation



- Incident beam is longitudinally polarized
- Change sign of longitudinal polarization
- Measure fractional rate difference



$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$



$$\propto \frac{|\mathcal{M}_Z|}{|\mathcal{M}_\gamma|}$$

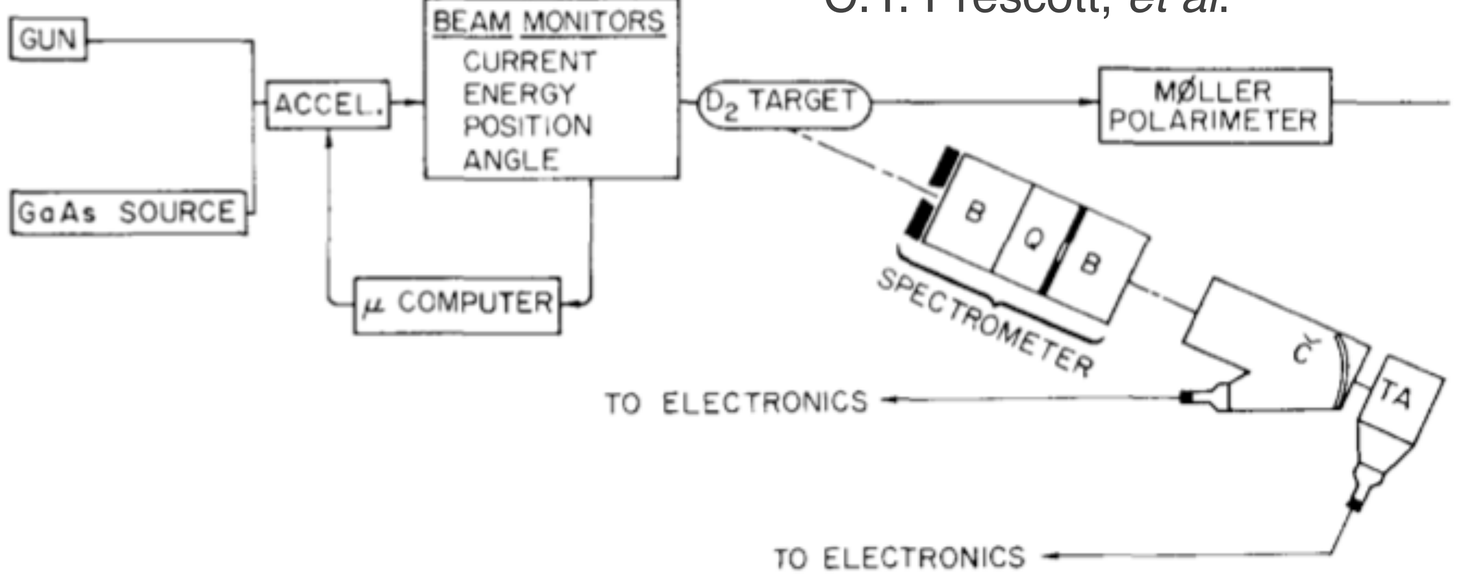
$$\sigma \propto |M_\gamma + M_{weak}|^2$$

$$\sim |M_\gamma|^2 + 2M_\gamma(M_{weak})^* + \ldots$$

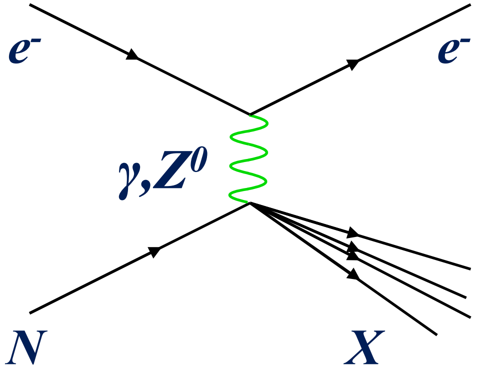
"Electroweak" models predicted
- interference of electromagnetic and weak amplitudes
- values for electron & quark weak neutral current coupling

E122 at SLAC (1978)

C.Y. Prescott, *et al.*

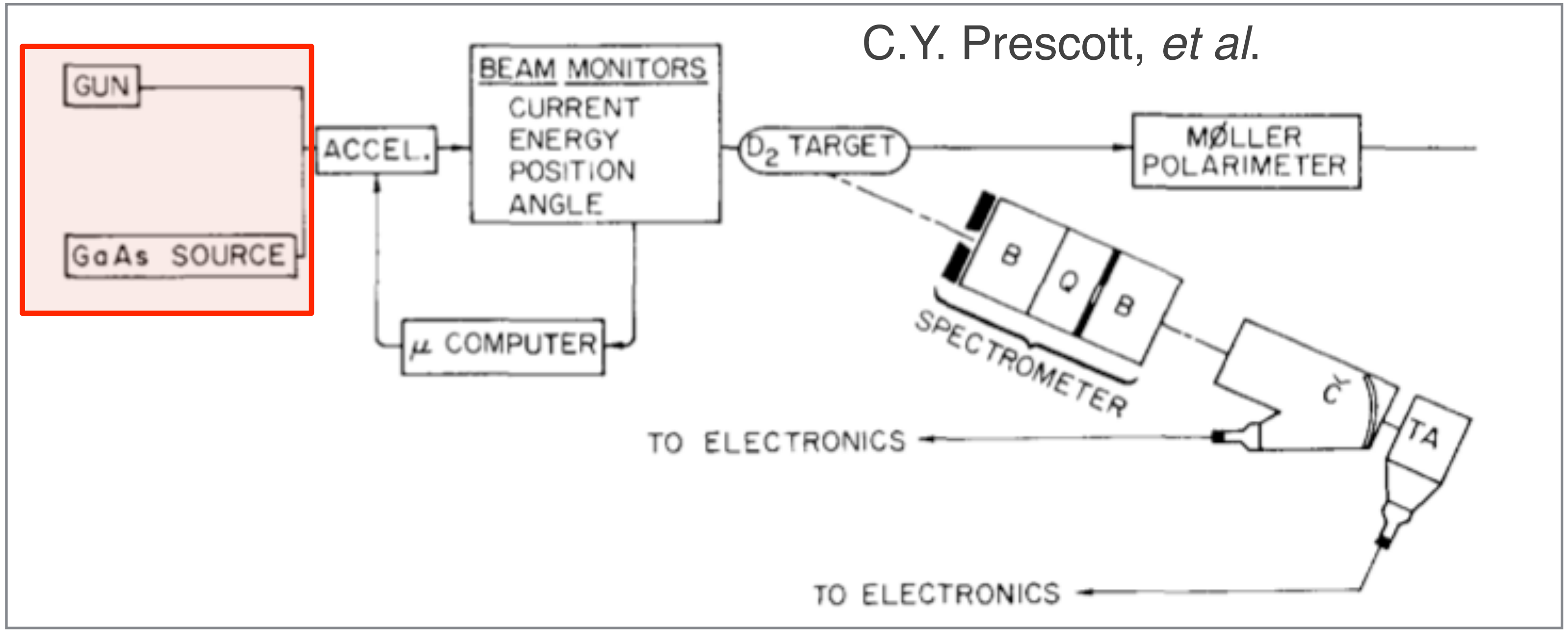


A_{PV} in Deep Inelastic Scattering from liquid Deuterium $Q^2 \sim 1$ GeV^2



Inclusive measurement
detect scattered electron only

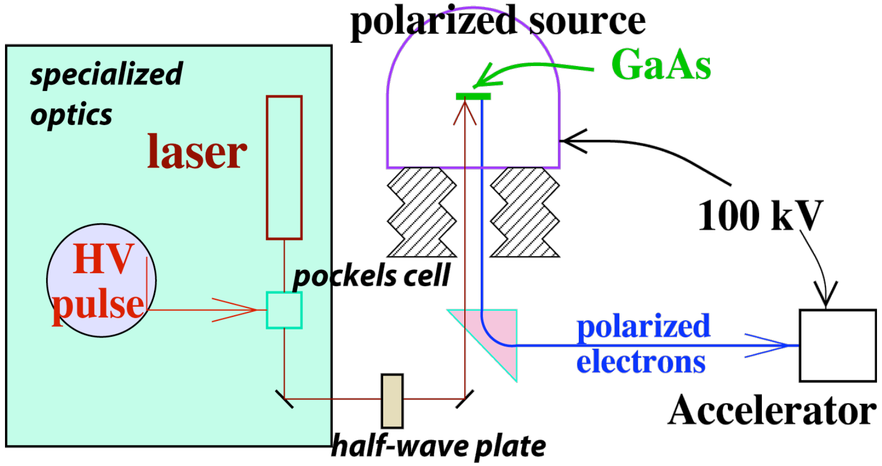
E122 at SLAC (1978)



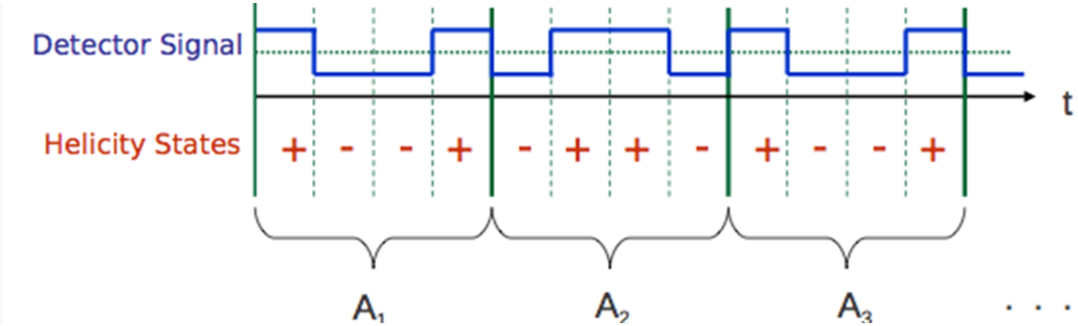
- **High polarized luminosity**

laser-driven photoemission from GaAs cathode

- First developed for E122
- NOW: superlattice cathodes for ~90% polarization, high QE and lifetime

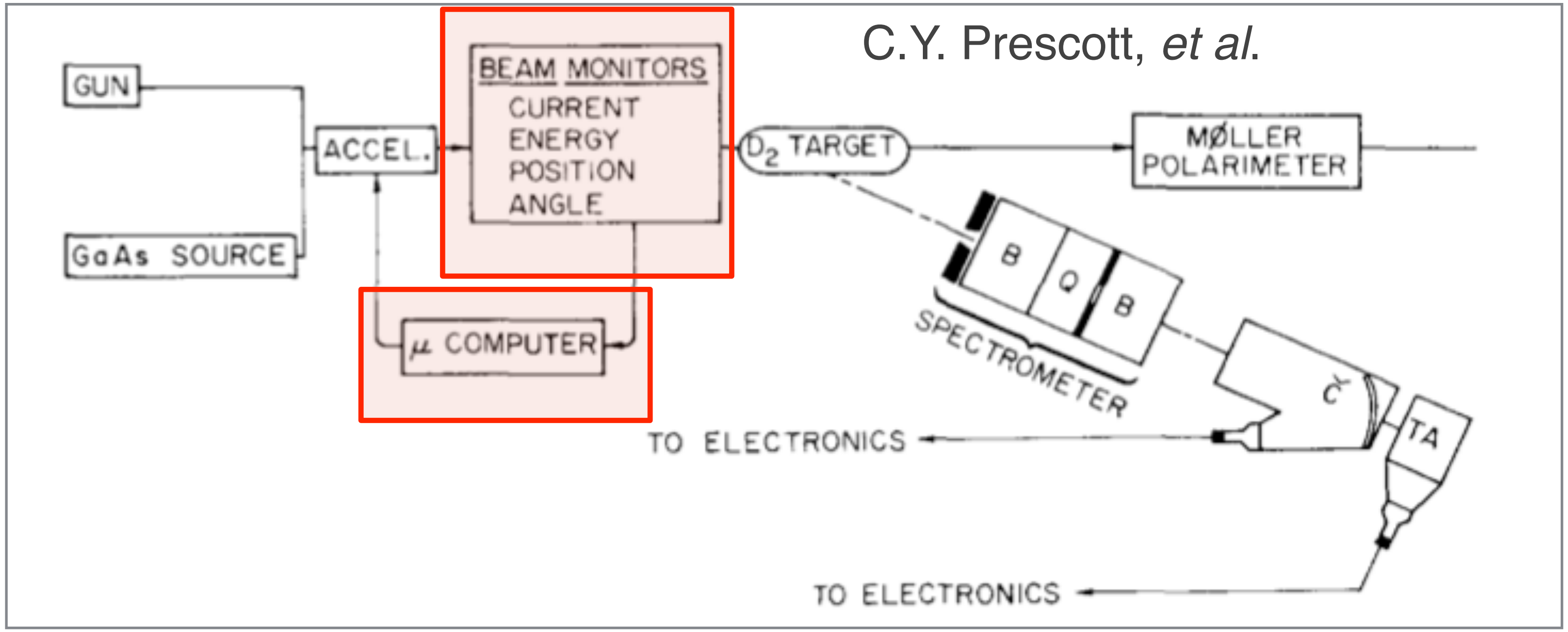


- **Rapid helicity-flip change sign of e^- polarization**
  - electro-optic Pockels cell in laser optics
  - NOW: up to 1kHz measurement over helicity reversal



- **Helicity-correlated beam asymmetries**
  - NOW: A_Q ~ few ppb, Δx ~ 1nm
  - both precision configuration and feedback

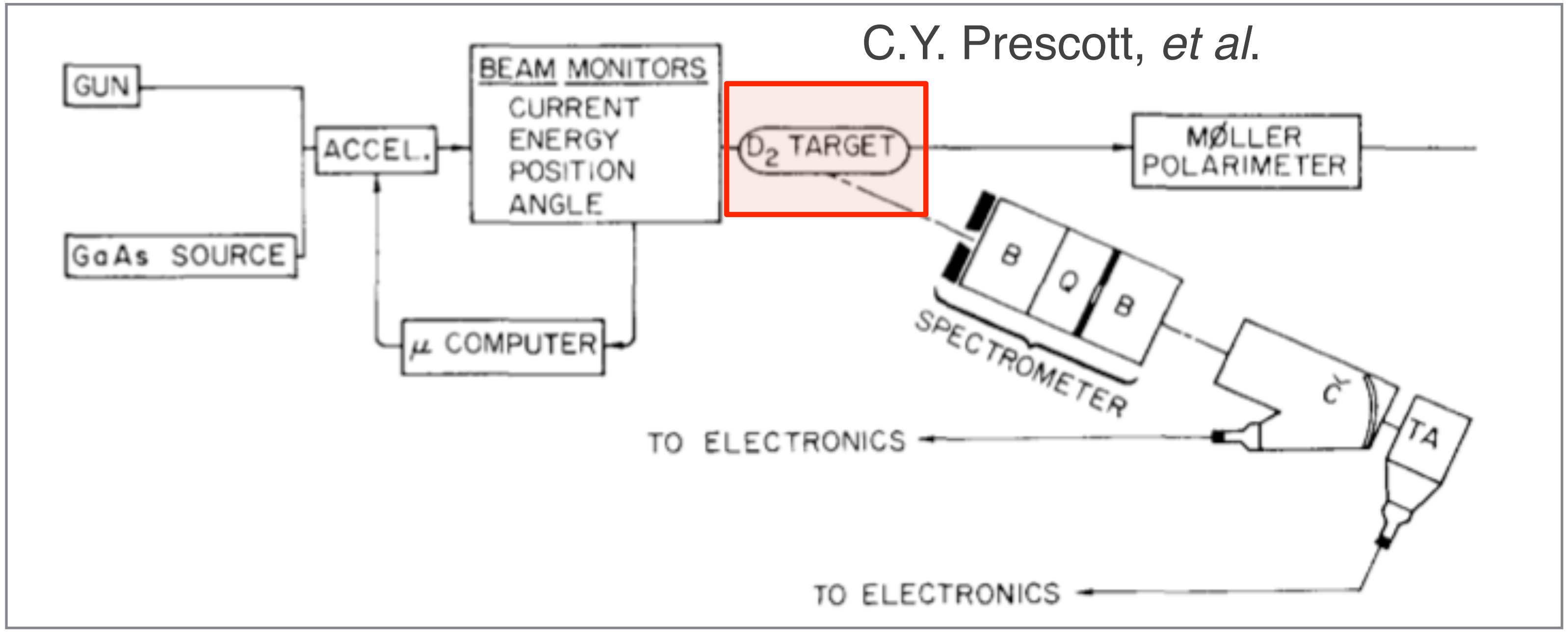
E122 at SLAC (1978)



- **Beam Monitors**
  - Measure helicity-dependent changes in current and position
  - NOW: usually RF antenna or RF resonant cavity
  - Precision: Q ~ 30 ppm , x ~ 1 micron at 250 Hz

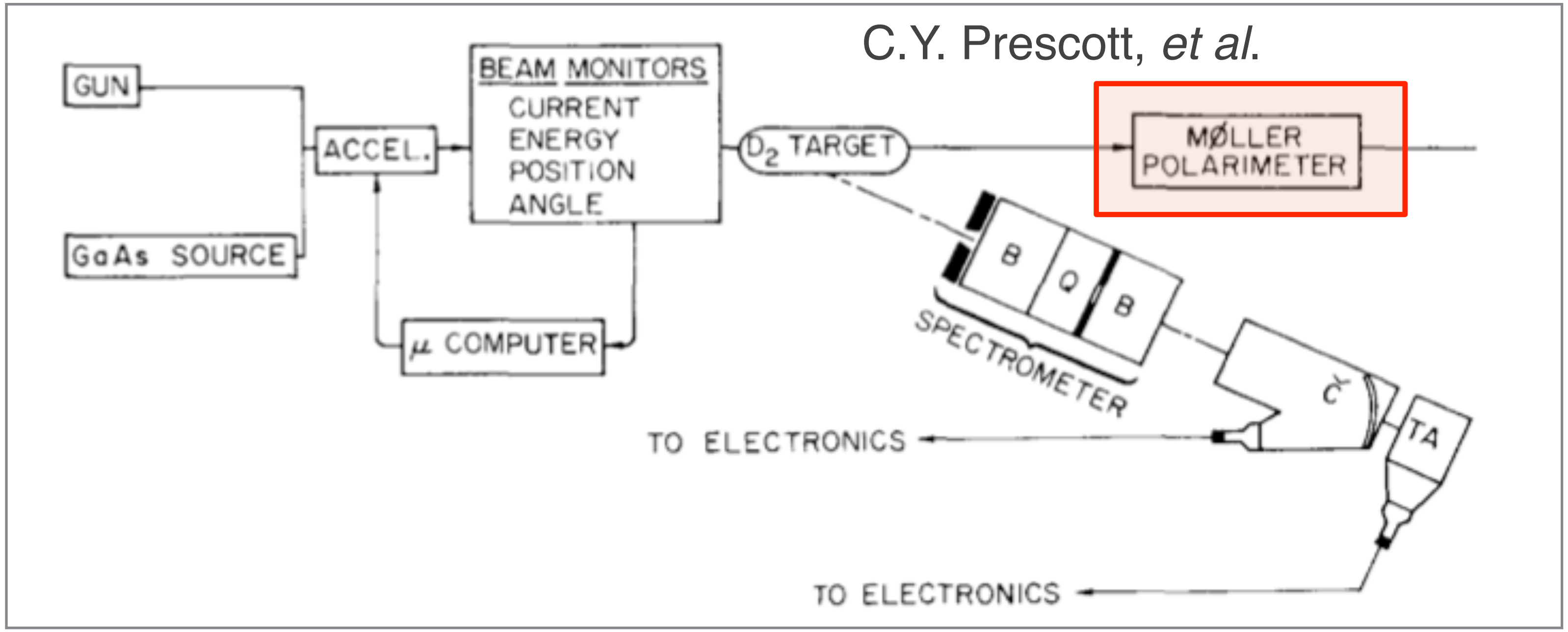
- **Fast Analysis**
  - Feedback to source to control beam asymmetries

E122 at SLAC (1978)



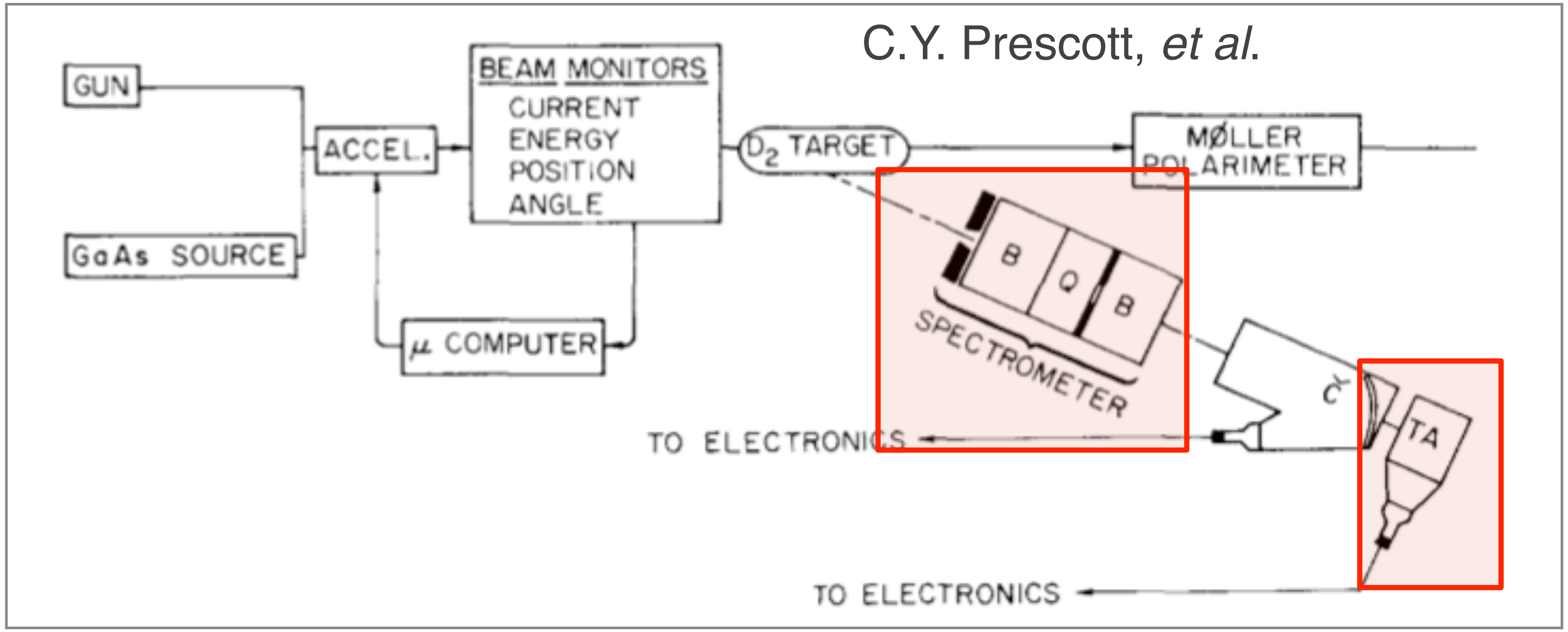
- **High-Power Cryogenic Target**
  - 30 cm long for high luminosity
  - NOW: power >2300 W, stability better than 40 ppm at 250 Hz
  - FUTURE: 1.5 meters, 4 kW, stability better than 25 ppm at 1kHz

E122 at SLAC (1978)

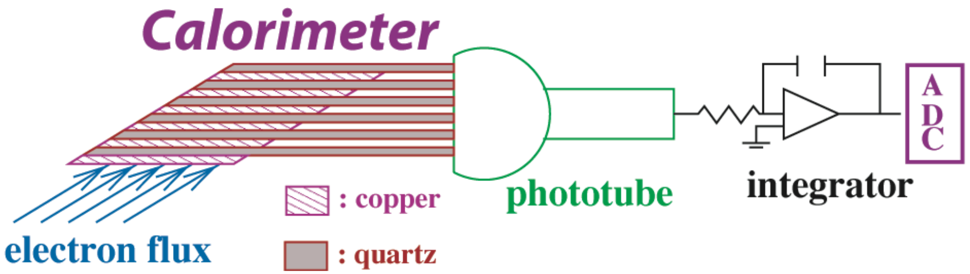


- **e-beam Polarimetry**
  - Møller polarimeter
  - NOW: Mott ~1%, Møller ~1%, Compton ~0.7% (continuous)
  - FUTURE: all three methods aim for 0.5%

E122 at SLAC (1978)



- **Magnetic Spectrometer**
  - directs scattered flux to background-free region
  - defines / calibrates kinematic acceptance



- **Integrating Detection**
  - integrate all signal during helicity window
  - measures high rate (>100 kHz) with no deadtime
  - NOW: ~6 GHz
  - FUTURE: ~500 GHz

PVeS Verifies the "Standard Model" (1978)

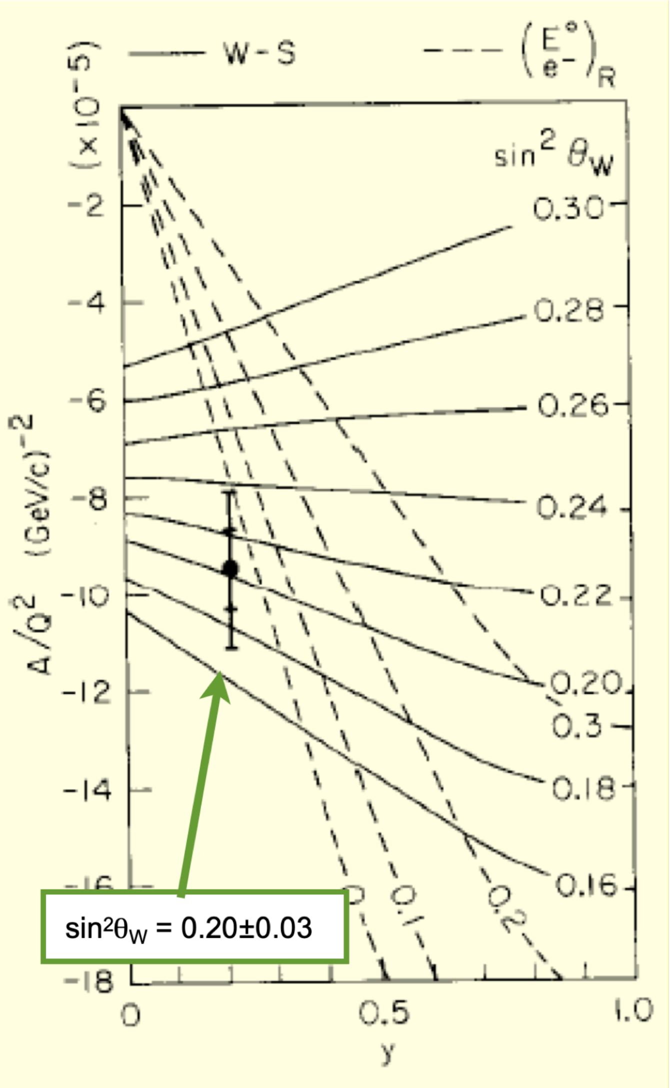
Indirect

*Parity Non-Conservation in Inelastic Electron Scattering, **C.Y. Prescott et. al, 1978***

$A_{PV} \sim 100 \pm 10$ ppm

Definitive answer on gauge structure of electroweak interaction

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



- GWS awarded the Nobel prize in 1979
  The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

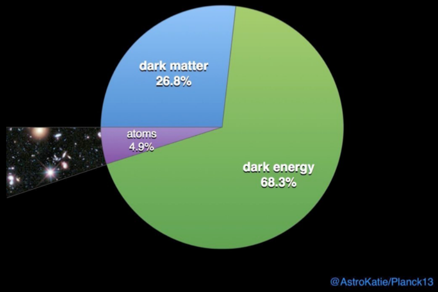
Direct

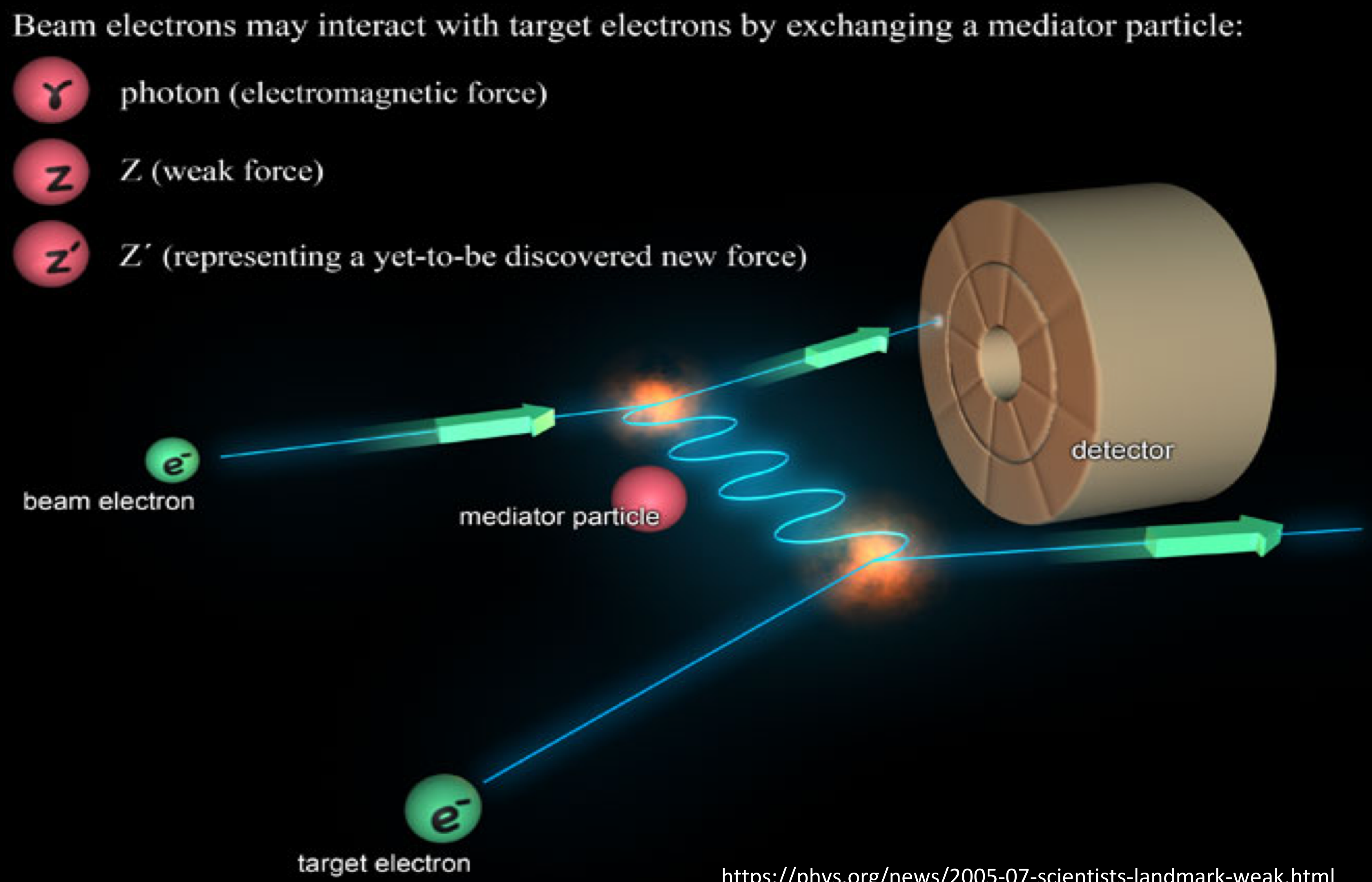
- 1983 – CERN made **direct** observation of the W(M_W=81±5GeV/c^2) and Z(M_Z=95±3GeV/c^2)

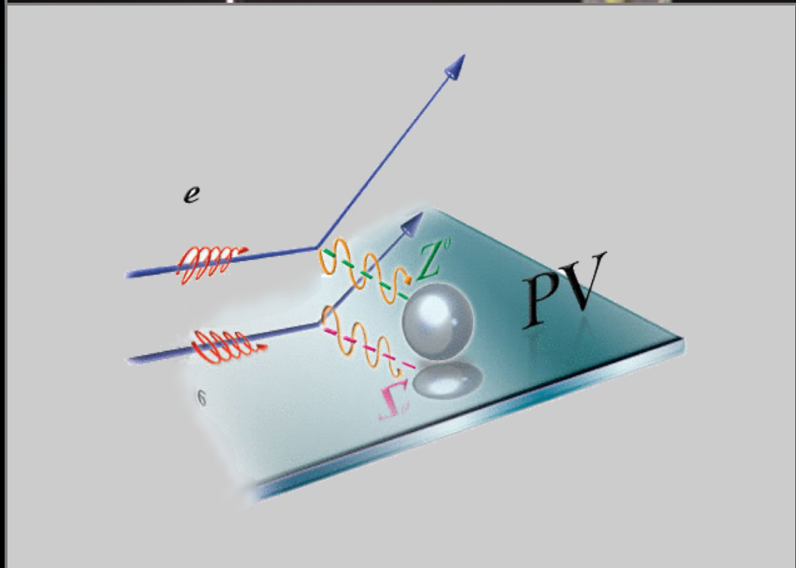
E122 at SLAC

Blue Print

Parity Violating Electron Scattering
Experiments Probing Symmetries in the Standard Model

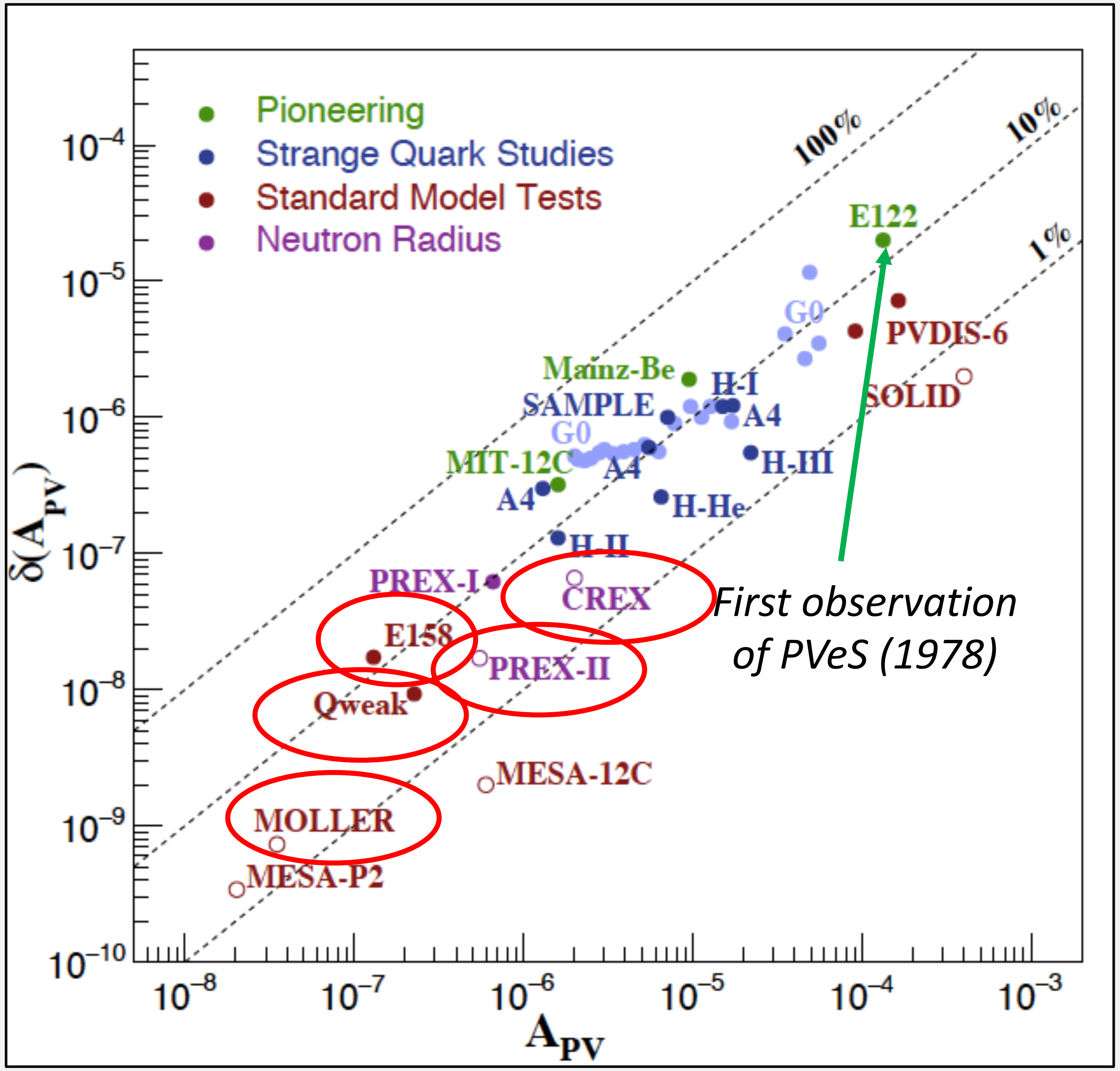






https://phys.org/news/2005-07-scientists-landmark-weak.html

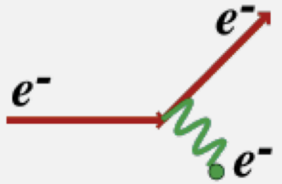
PVES has become a precision tool



Broad program studying the structure of protons and nuclei, and searching for new (beyond Standard Model) physics

Searches for New Neutral Currents

Møller (*ee*) scattering : Weak charge of the electron



SLAC-E158 1997-2004

MOLLER

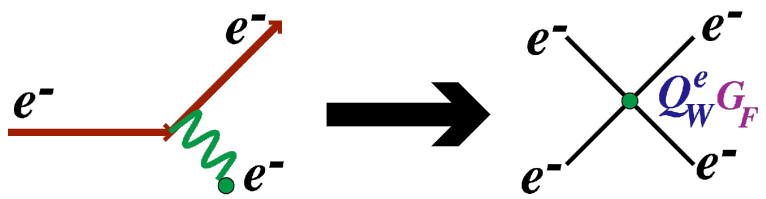
Q_W^e Weak charge of the electron

- Perform ultra-precise measurements sensitive to new parity-violating interactions
- Measure the **weak charge of the electron** to extremely high precision (E158 & Moller)

SLAC- E158: Weak charge of the electron

Møller (ee) scattering

1997-2004



+ new

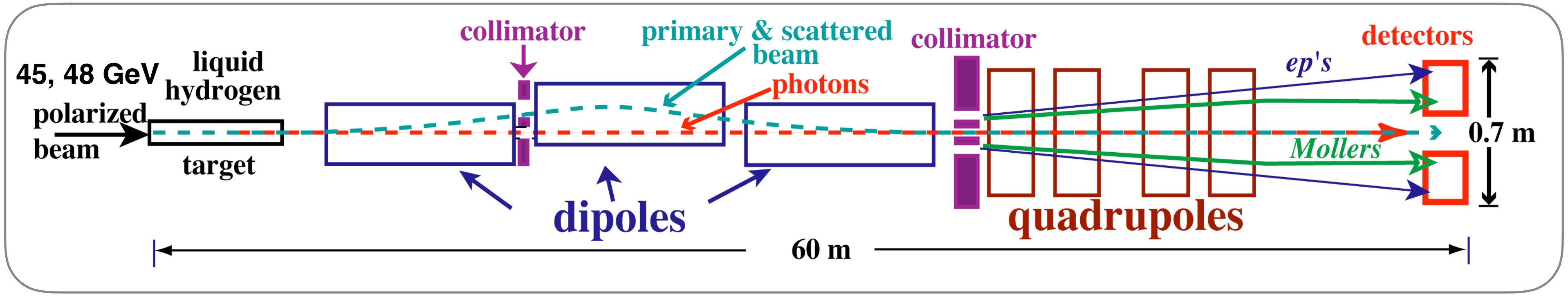
$$Q_W = 1 - 4\sin^2\theta_W$$

SM highly suppressed, so even a weakly-coupled or heavy new physics scenario can stand out

High-power (1kW) LH_2 target, 18% radiator

Dipole chicane + quadrupole spectrometer 45, 48 GeV, 4-7 mrad scattering angle

High beam polarization and current



First Measurement of the electron-electron weak interaction

A_{PV} = (-131 ± 14 ± 10) ppb

$$\frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

LEP200

$$\Lambda^{ee}_{VV} \sim 17.7\ \text{TeV}$$

E158 Reach

$$\Lambda^{ee}_{RR-LL} \sim 17\ \text{TeV}$$

High Precision of Moller: improve E158 by a factor of 5

The weak charge of the electron

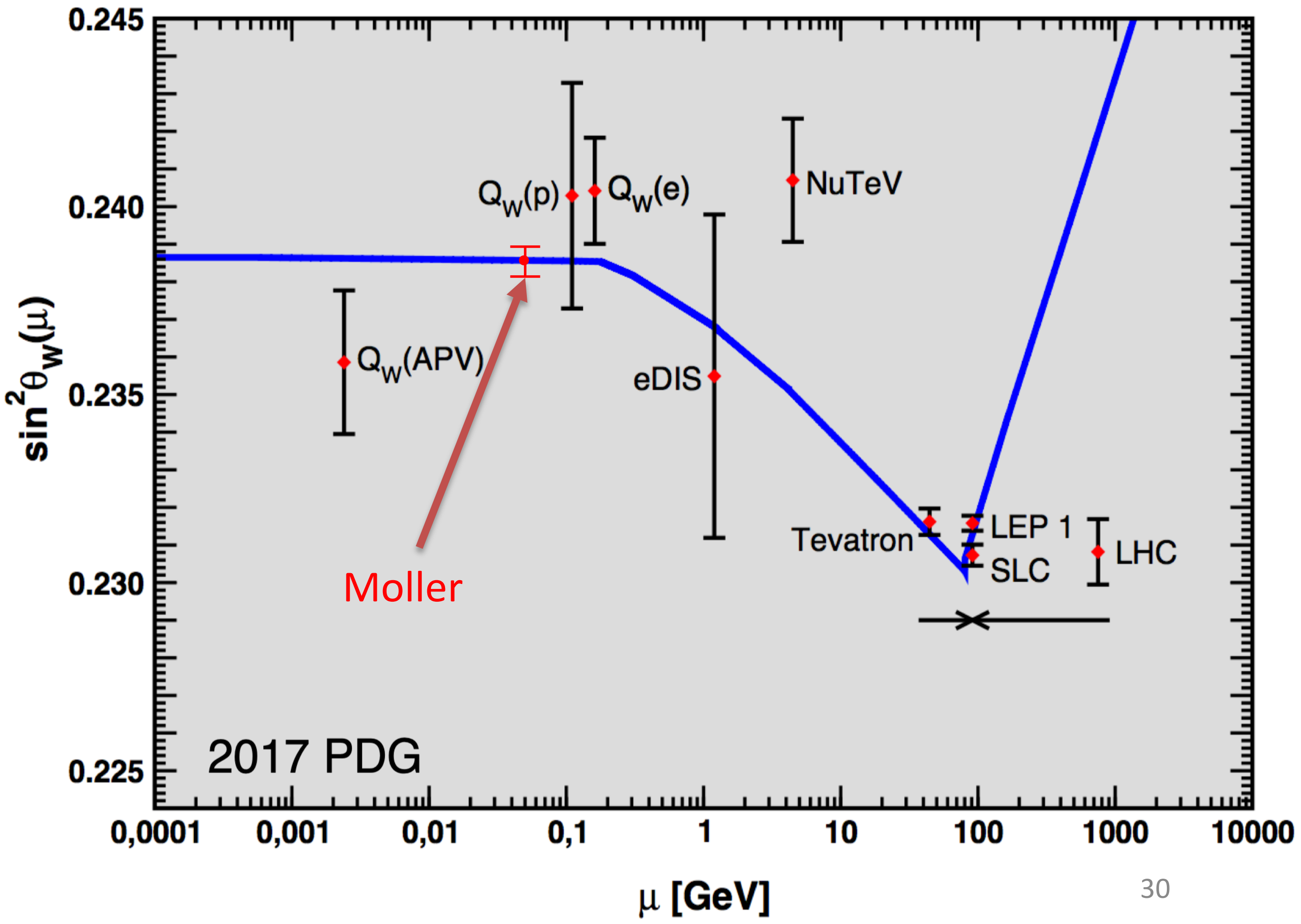
Search for Deviations from the Standard Model

Interference term between the electro-magnetic and weak amplitudes.

Parity-violating asymmetry is measured by comparing left and right helicity state and relates directly to the electron weak charge and weak mixing angle

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \Rightarrow Q_W^e \Rightarrow \sin^2\theta_W$$

$$Q_W^e = 1 - 4\sin^2\theta_W$$



Extreme Precision Moller Measurement

- A_{PV} *35.6ppb* to 0.73 ppb precision
- $\sin^2\theta_W$: ±0.00026(stat)±0.00013(sy
- Mass Reach scales up to 47TeV

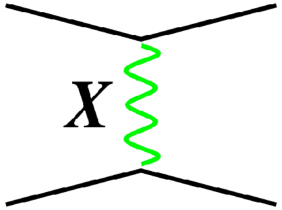
Defining Mass "Reach" of Precision Experiment

Need model independent way to:

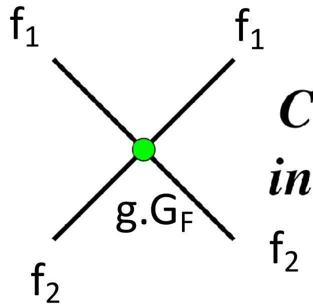
- Quantify the effects of new high energy dynamics in low E processes
- Translate high precision at low E into high energy regime
- Express the "reach" of precision experiment

Low energy new NC interactions ($Q^2 \ll M_x^2$)

Heavy mediators = contact interactions



$$A_X \propto \frac{1}{Q^2 - M_X^2} \longrightarrow \sim \frac{4\pi}{\Lambda^2}$$



Contact interaction

For each fermion and handedness combination, reach characterized by mass scale Λ, coupling g

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

<u>Moller Experiment Example</u>

Sensitivity: 2.3% uncertainty gives

$$\frac{\Lambda}{\sqrt{|g^2_{RR} - g^2_{LL}|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q^e_W|}} = 7.5\text{TeV}$$

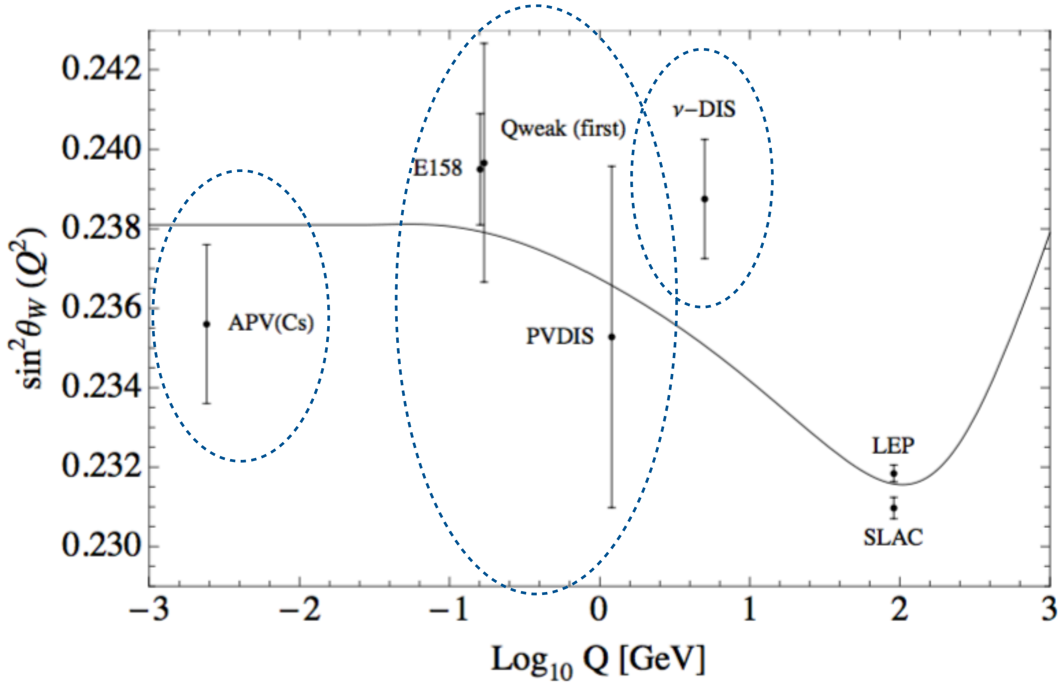
Mass Reach:

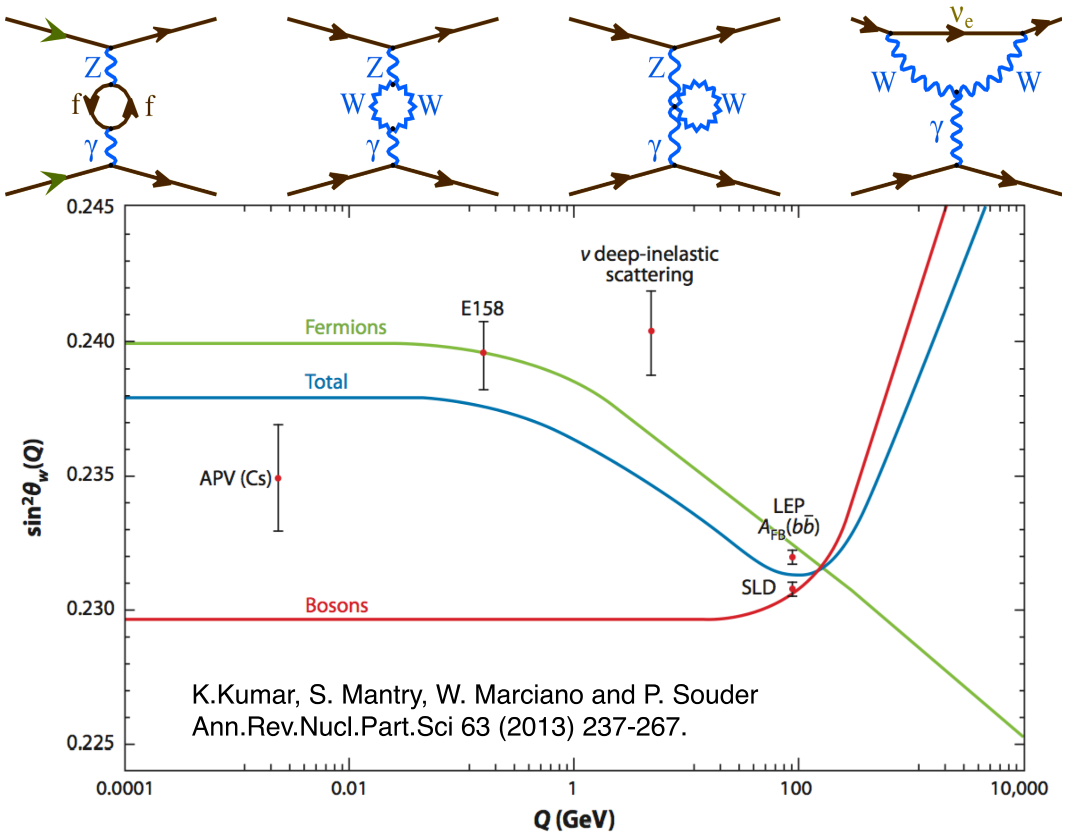
Conventional "mass limits" for new contact interaction: assume coupling with compositeness scale $g^2=4\pi$

Gives mass reach scale of Λ=47TeV

Running of $\sin^2\theta_W$

Czarnecki and Marciano (1995)
1-loop calculation

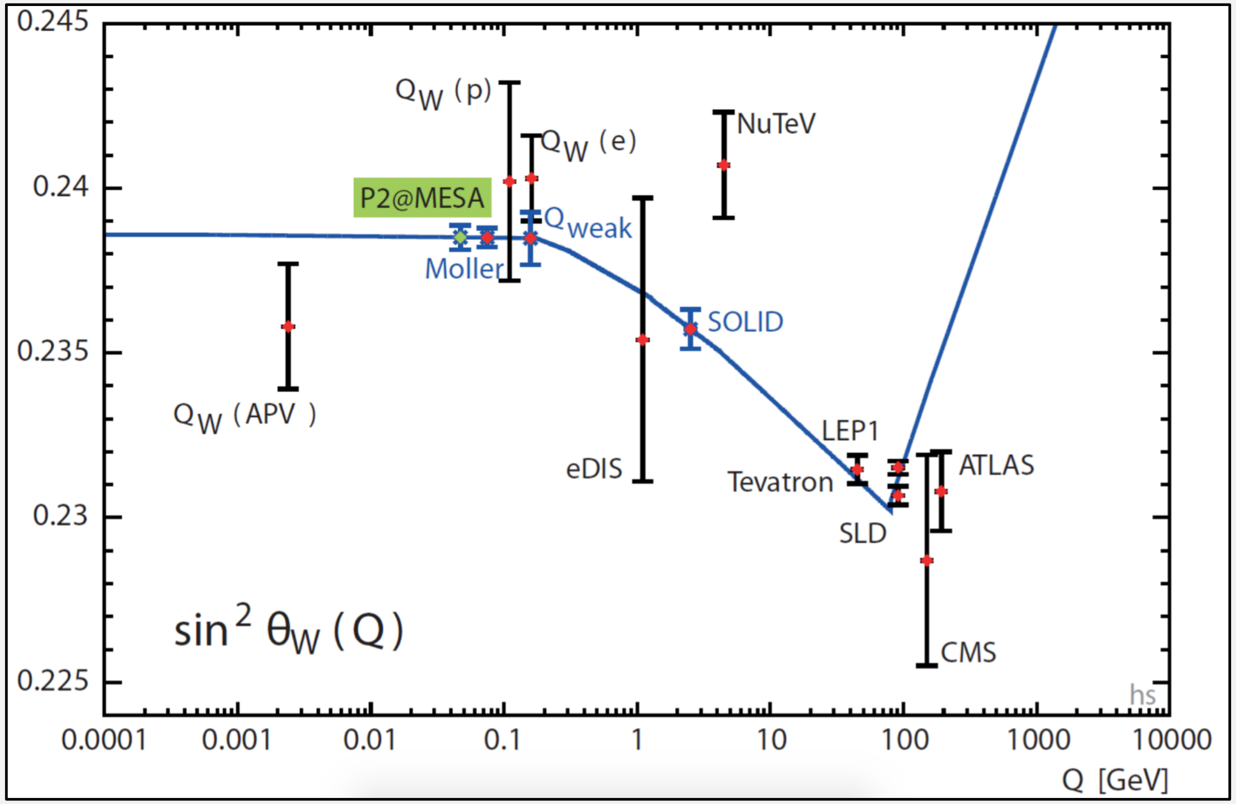




- **Atomic Parity Violation** (^{133}Cs)
  Theory challenging (atomic)
- **Neutrino DIS**
  Controversial interpretation (QCD)
- ***e-e* & *e-p* PV Elastic Scattering**
  statistics limited, theory robust
- ***e-D* PV-DIS**
  axial-vector quark coupling

PVeS at low energies provides a method for searching for *new* neutral currents

Recent Weak Interaction measurements



- Recent experiments continue to measure the "weak mixing angle" θ_w
- Including an upcoming experiment called:

  MOLLER

- Calculating θ_w to increasingly high precision still currently stands as a major challenge for any theory going beyond the Standard Model
- Measuring θ_w in different energy regimes stands as a test of the Standard Model

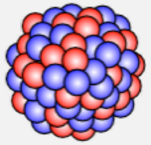
PVES Experiments: Probing Weak Interaction

WEAK CHARGE DISTRIBUTION IN NUCLEI

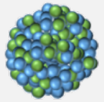
CREX

PREX

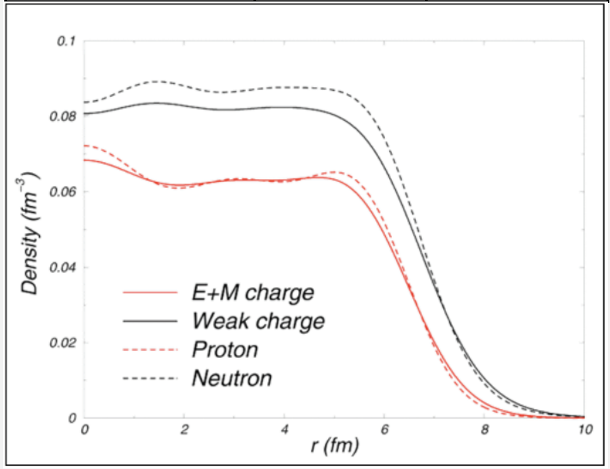
^{208}Pb



^{48}Ca



	proton	neutron
Electric charge	**1**	**0**
Weak charge	**~0.08**	**1**



Ca48

Thin neutron skin

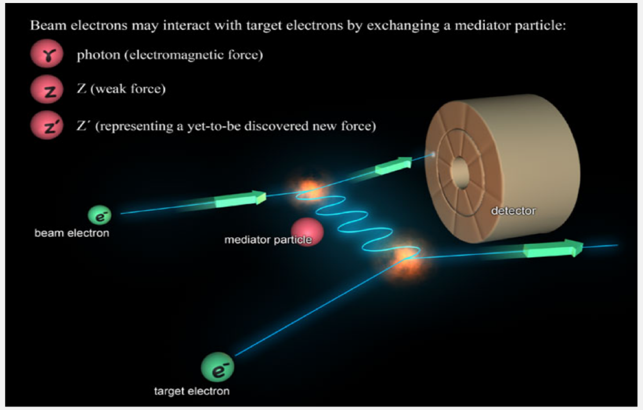
Pb208

Thick neutron skin $R_n - R_p = 0.283 \pm 0.071$ fm

WEAK CHARGE OF THE ELECTRON

MOLLER, SLAC E158

e-



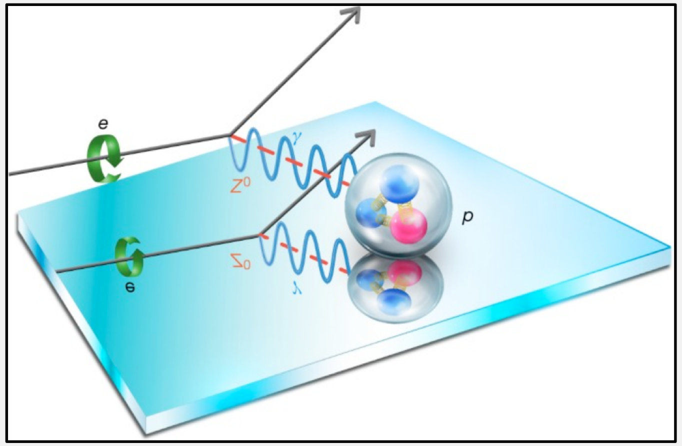
$$Q_W^e = 1 - 4\sin^2\theta_W$$

JLAB

WEAK CHARGE OF THE PROTON

P2, QWEAK

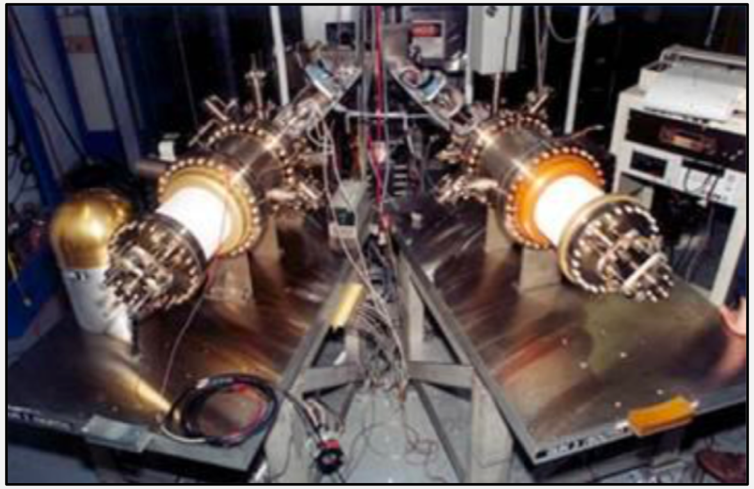
p

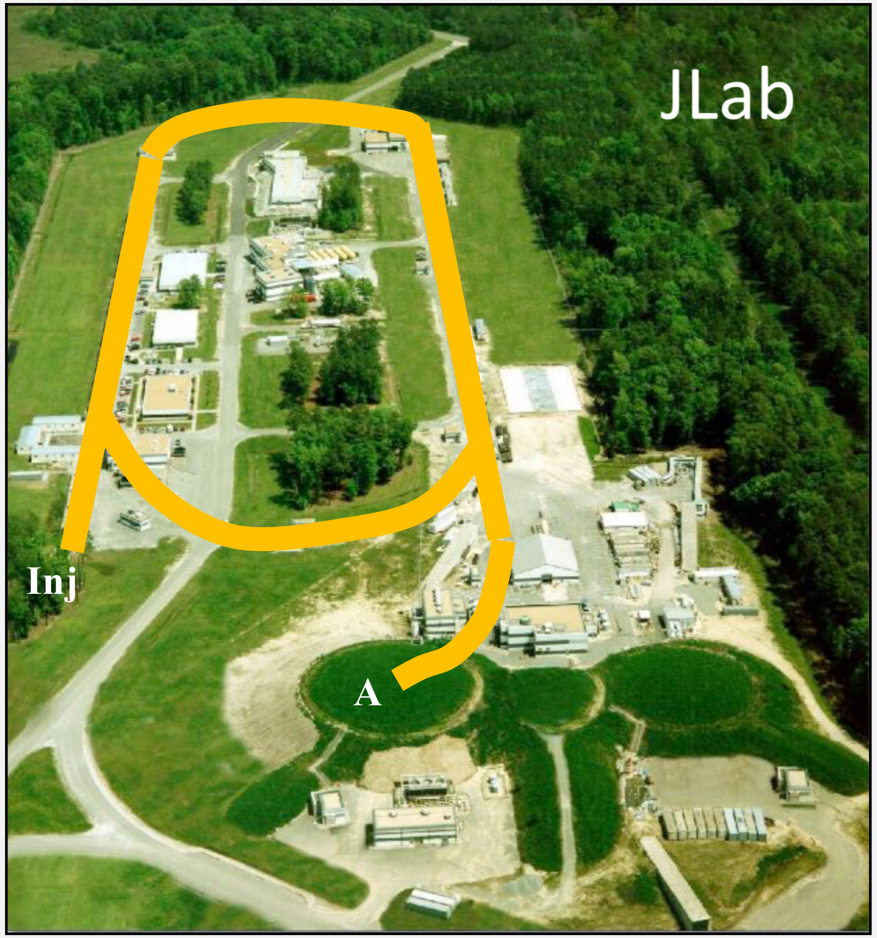


MAINZ

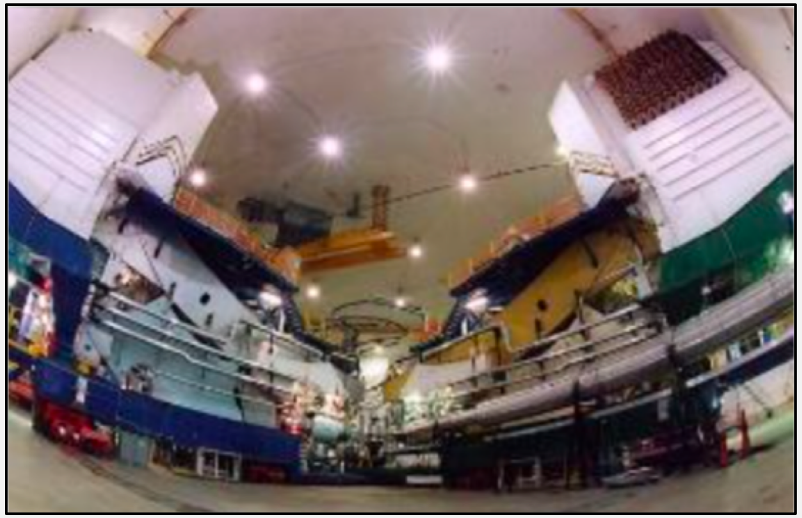
Experimental Overview

Polarized Source





Hall A

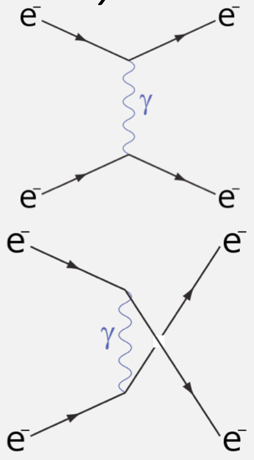


CEBAF is the ONLY operating facility in the world where such an experiment could be attempted

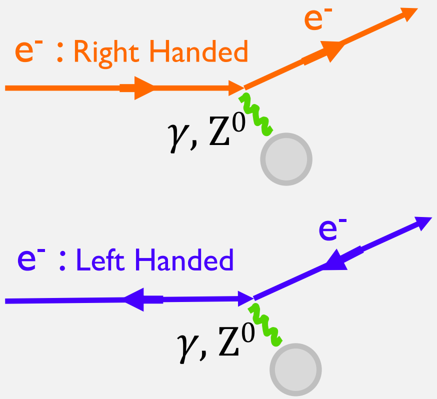
MOLLER PVES Measurement Purpose

Extend the reach of new physics beyond the Standard Model

Feynman

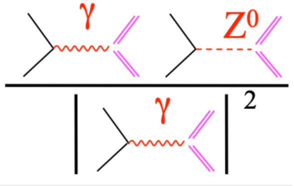


Lab Frame

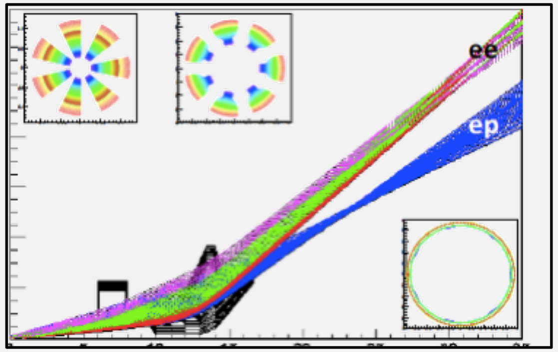


$$\sigma \propto |M_\gamma + M_{weak}|^2 \sim |M_\gamma|^2 + 2M_\gamma (M_{weak})^*$$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$



$$\propto \frac{|M_Z|}{|M_\gamma|}$$



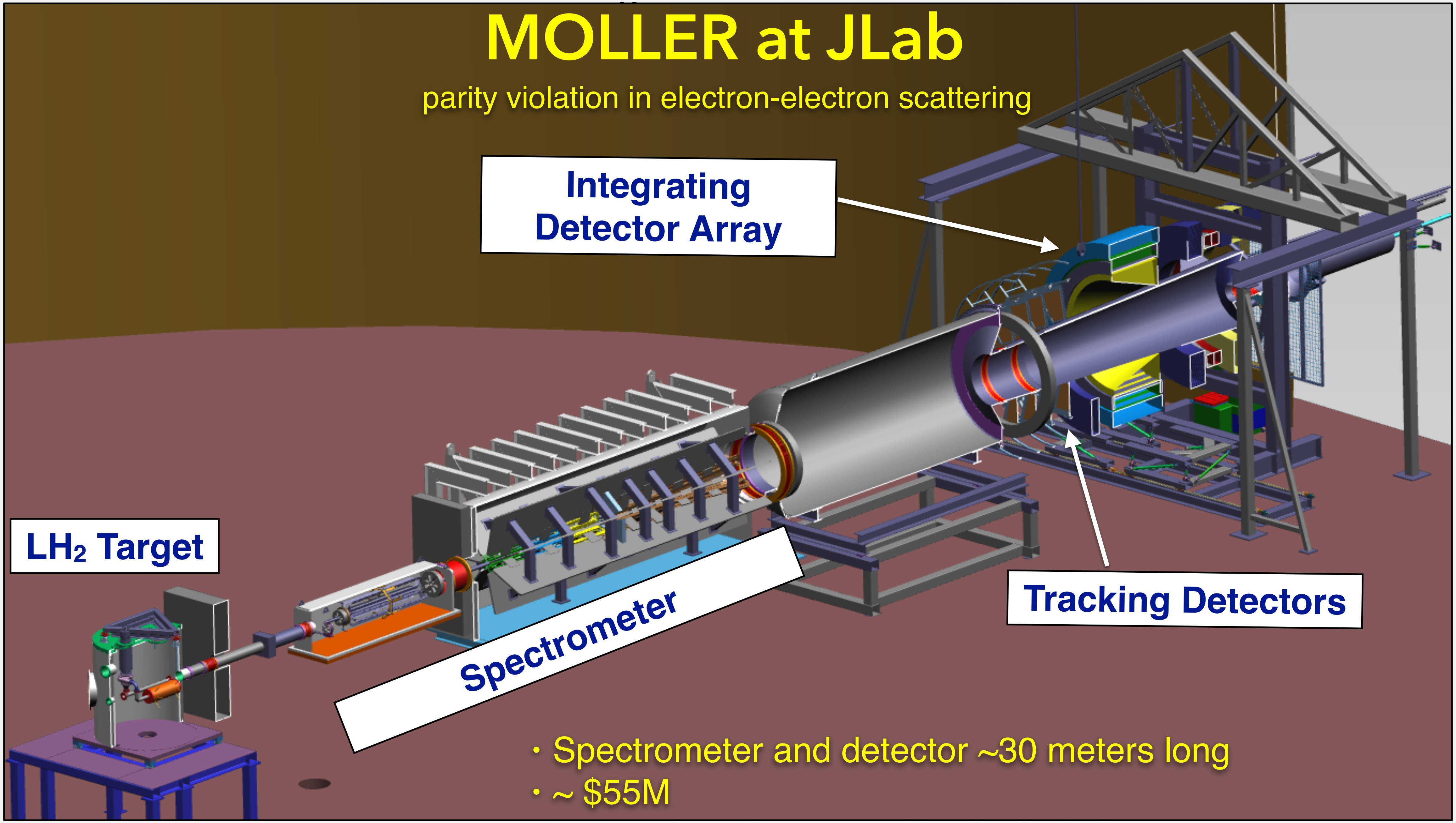
- *Moller scattering is electron-electron scattering*
- *Longitudinally polarized beam is incident on an unpolarized target*
- *Change sign of longitudinal polarization*
- *Measure fractional rate difference*
- *Interference term between the electro-magnetic and weak amplitudes gives rise to parity-violating asymmetry which relates directly to the electron weak charge and weak mixing angle*

$$A_{PV} \Rightarrow Q_W^e \Rightarrow sin^2\theta_W$$

Mass reach scale of Λ=47TeV

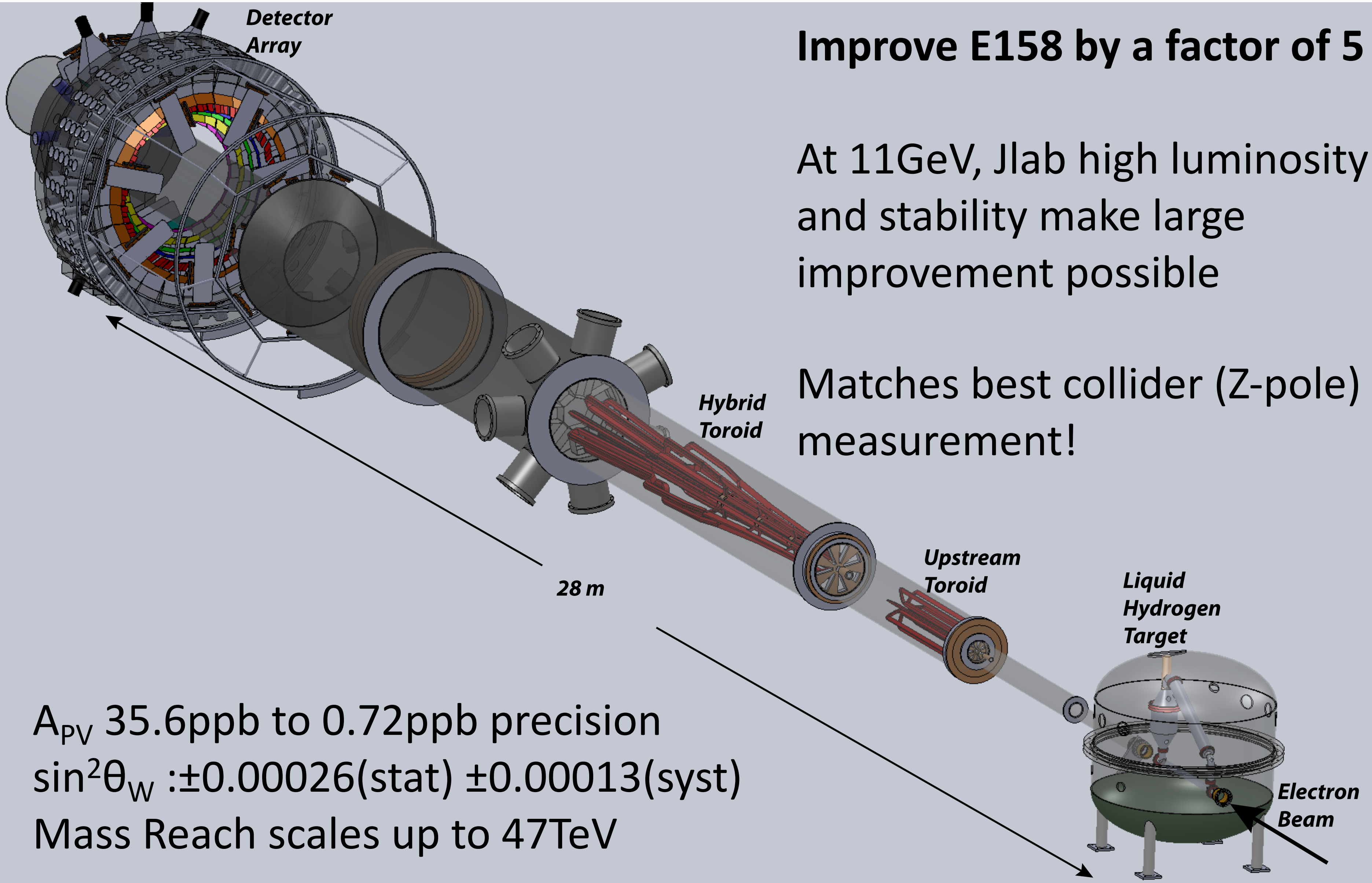
MOLLER at JLab

parity violation in electron-electron scattering



- Spectrometer and detector ~30 meters long
- ~ $55M

Design for precision beyond E158: Moller experiment



Improve E158 by a factor of 5

At 11GeV, Jlab high luminosity and stability make large improvement possible

Matches best collider (Z-pole) measurement!

A_{PV} 35.6ppb to 0.72ppb precision
$\sin^2\theta_W$:±0.00026(stat) ±0.00013(syst)
Mass Reach scales up to 47TeV

Mass Reach is ~600X the mass of the W mediator, ~400X the Higgs Mass

Statistics and Systematics: Summary

Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Normalization of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \rightarrow e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \rightarrow e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \rightarrow (\pi, \mu, K) + X$	0.3
Transverse polarization	0.2
Neutral background (soft photons, neutrons)	0.1
Total systematic	**1.1**

Beam Property	Assumed Sensitivity	Accuracy of Correction	Required 2 kHz random fluctuations	Required cumulative helicity-correlation	Systematic contribution
Intensity	1 ppb / ppb	$\sim$1%	$<$ 1000 ppm	$<$ 10 ppb	$\sim$ 0.1 ppb
Energy	-1.4 ppb / ppb	$\sim$10%	$<$ 108 ppm	$<$ 0.7 ppb	$\sim$ 0.05 ppb
Position	0.85 ppb / nm	$\sim$10%	$<$ 47 μm	$<$ 1.2 nm	$\sim$ 0.05 ppb
Angle	8.5 ppb / nrad	$\sim$10%	$<$ 4.7 μrad	$<$ 0.12 nrad	$\sim$ 0.05 ppb

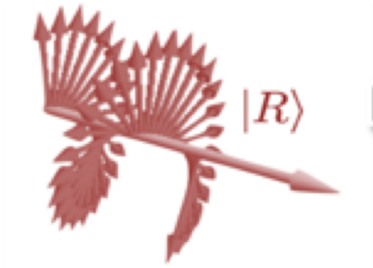
Obtaining High Precision of Moller

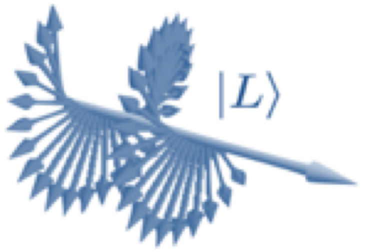
- **Beam from source to target:** An opto-electric device called a Pockels cell controls the spin of the electron beam by switching the polarization state of the laser beam generating it. There's a **new type of crystal**, RTP (Rubidium Titanyle Phosphate), which can switch states extremely quickly

Laser Beam

Pockels Cell (+- HV)

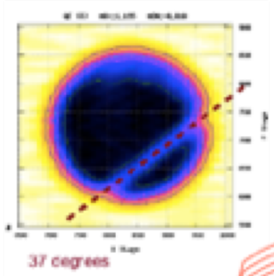
Circularly polarized light

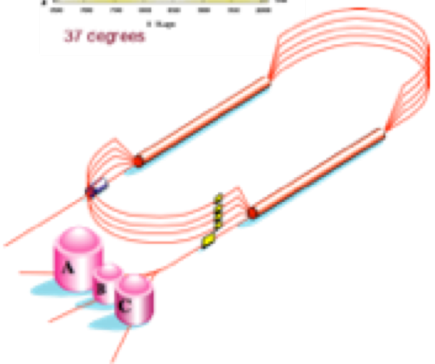




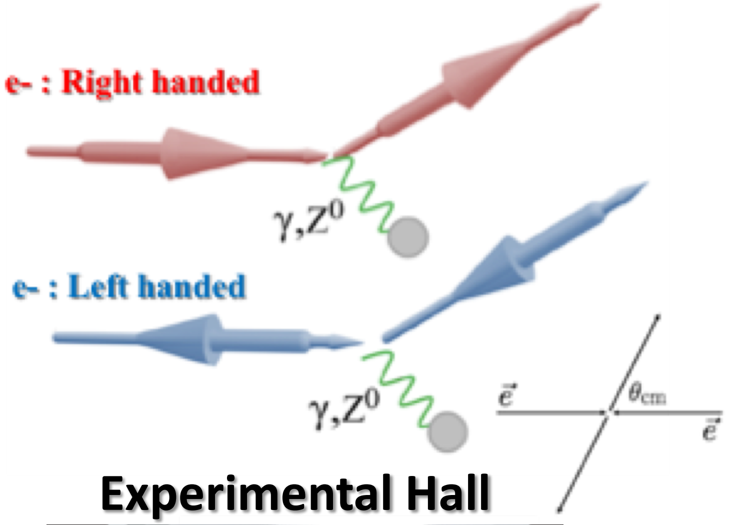
Electron Beam

Photocathode (GaAs)

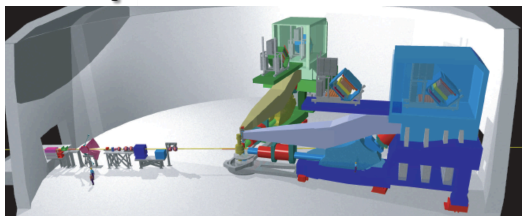




Polarized electrons



Experimental Hall



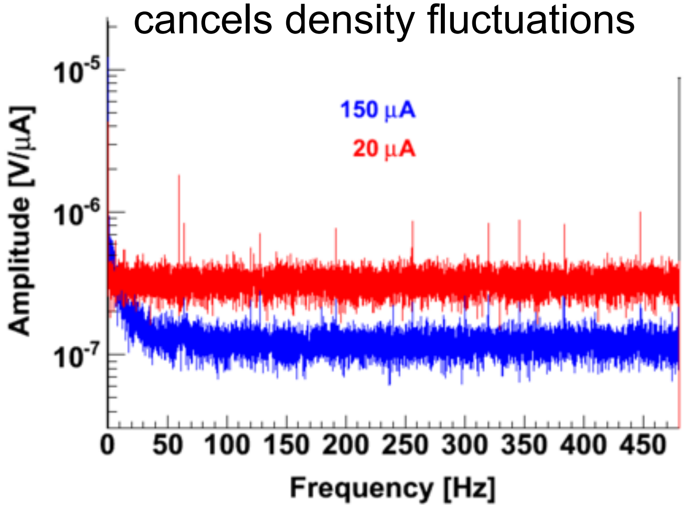
Target

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

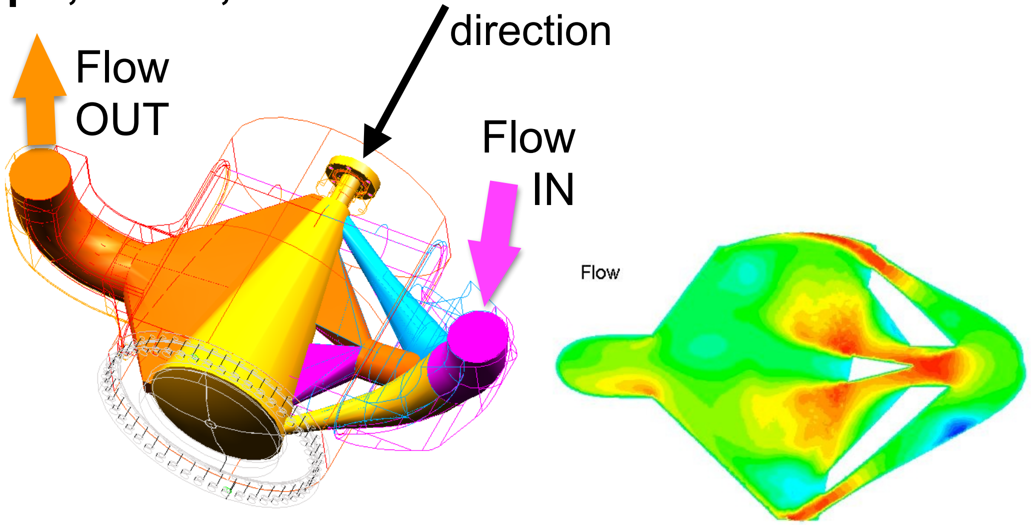
Build on Qweak success using CFD for target design

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

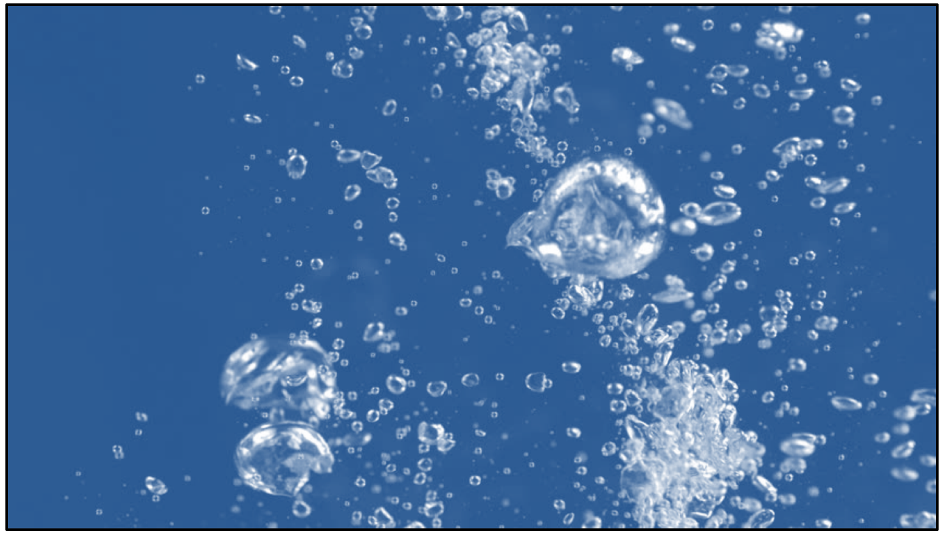
Target

LH2 (~20 Kelvin) – hit it with 60uA of electrons at 11GeV - 5kW of power!

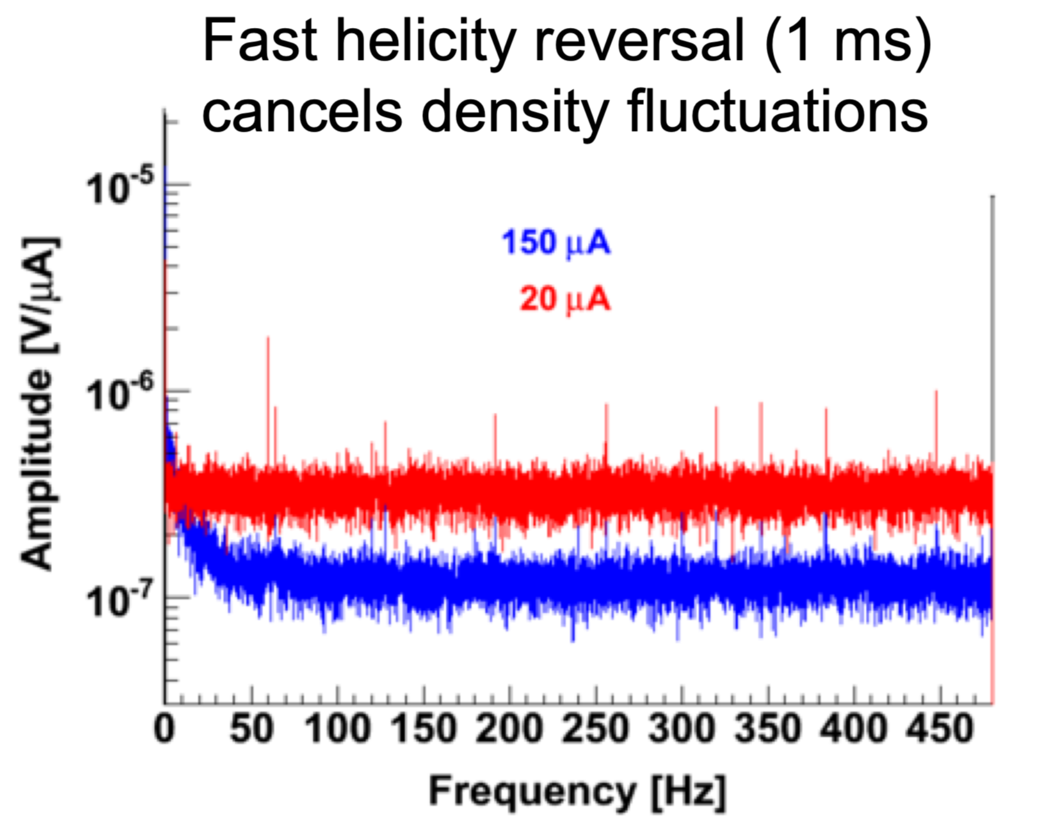
It boils! →Noisy Data ☹

So…increase the data rep. rate

Target Boiling

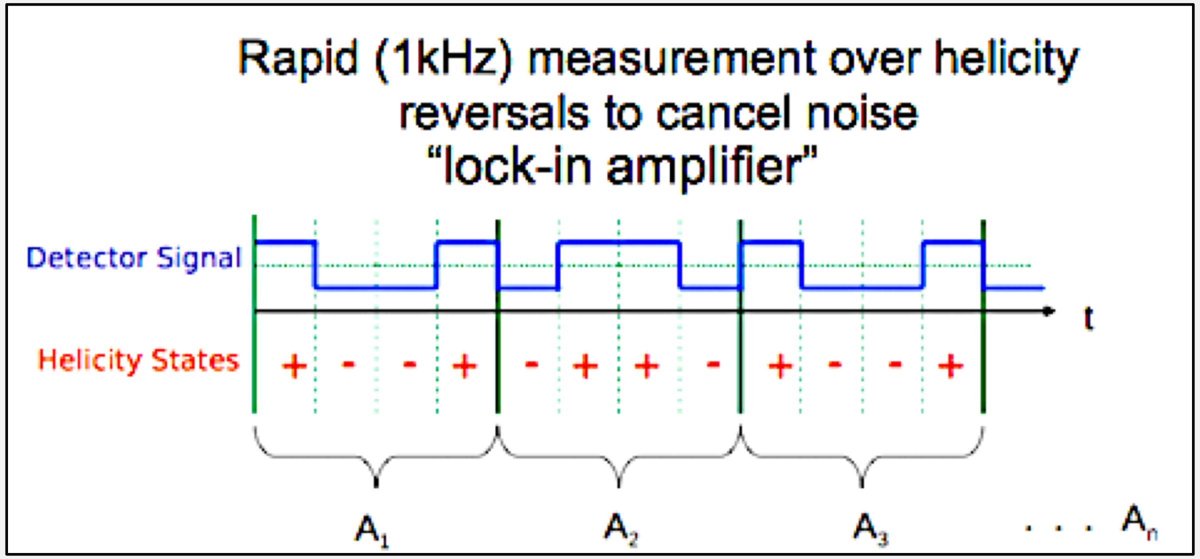


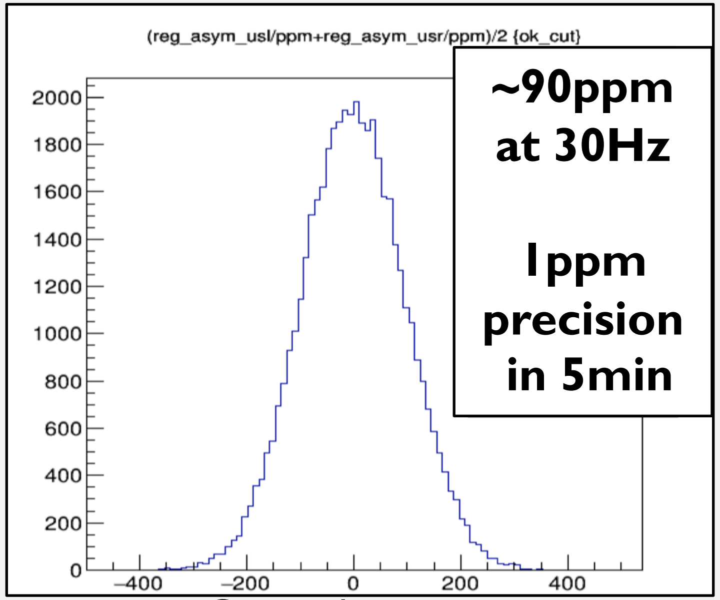
Fast helicity flipping = high speed camera



Fast Reversals: Statistical Uncertainty & Helicity Flipping

Choosing your data rate wisely is important





Octet Asymmetry

- *Helicity switching: Time "windows" are generated in the electron bunch train at a selected flip rate, with the sign of the beam's polarization in each window assigned on a pseudo-random basis.*
- Frequency selection for helicity flipping – noise, widths, statistical errors
- MOLLER is designed around a flip rate of at least 2 kHz *… hmmm this is hard to do…*
- MOLLER Goal: flip polarization within 10 µs

Motivated new Pockels cell design!

Precision & Systematic Error Goals

Any change in the polarized beam, correlated to helicity reversal, can be a potential source for a false asymmetry

$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

Expectation: Helicity-correlated changes in the beam are expected to contribute *~0.14 ppb*

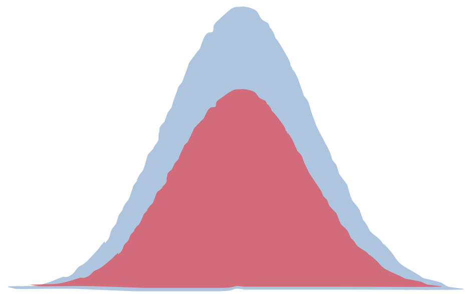
Goals

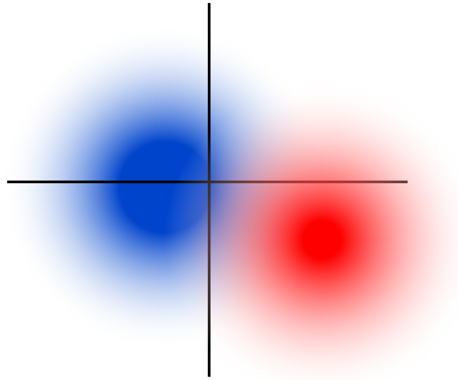
- The beam trajectory must remain unchanged with respect to the sign of the electron beam polarization at the sub-nanometer level (*0.5nm,0.05 nrad* in the experimental Hall)
- Electron beam **position differences** in the injector, before acceleration, must approach *~ 20nm*.
- Helicity-correlated laser **spot-size asymmetries** *~10^{-4}*
- **Achieving these goals all depends on the laser and Pockels Cell**

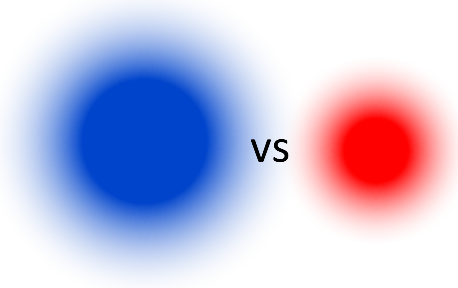
Intensity Asymmetry

Position Difference

Spot-size *Asymmetry*



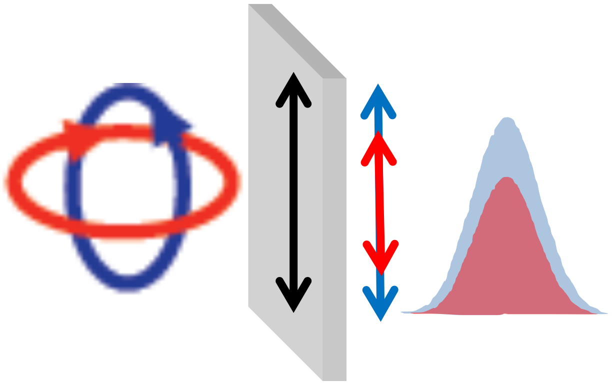




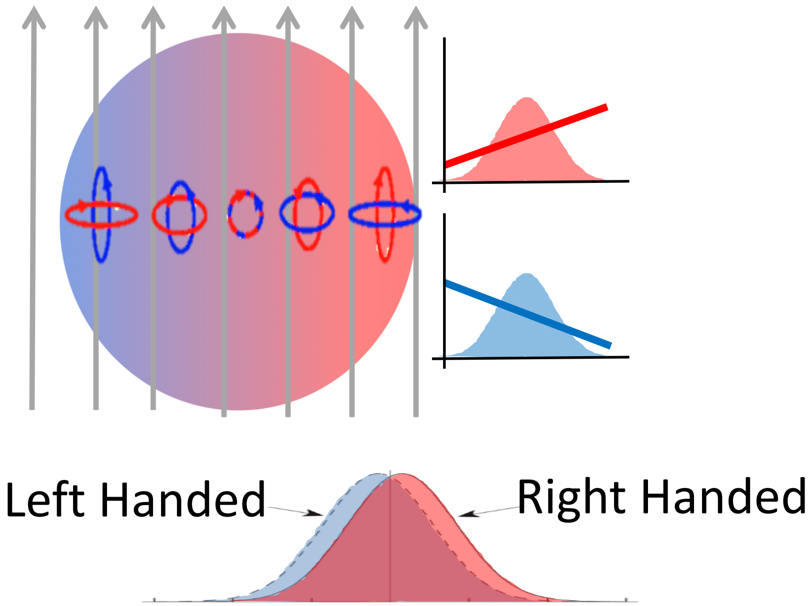
Intensity Asymmetry from Laser Polarization Asymmetry

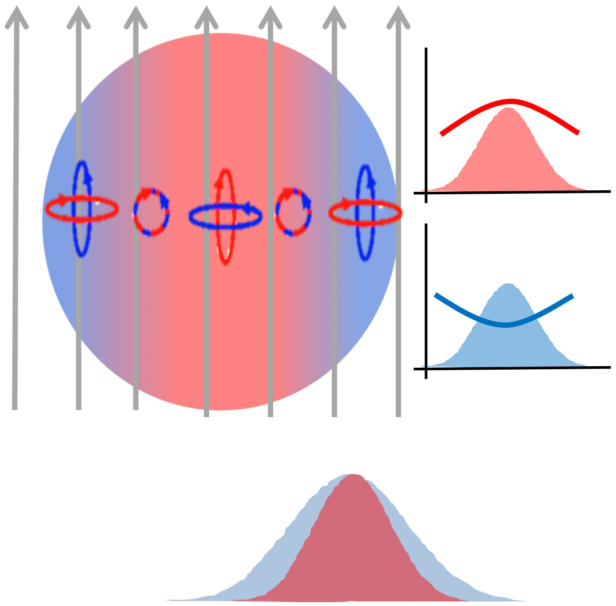
Position Difference from Polarization Gradient

Spot-size Asymmetries from 2^{nd} moment Polarization Gradient



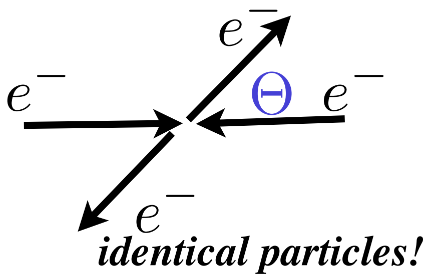
Polarizing element
(i.e. photocathode)





- The electron beam must be very **symmetric** to make this comparison, both forwards and backwards facing electron beams must have the same intensity and the same direction, position, and spot-size.

High Luminosity, High Rate… ***High Acceptance***

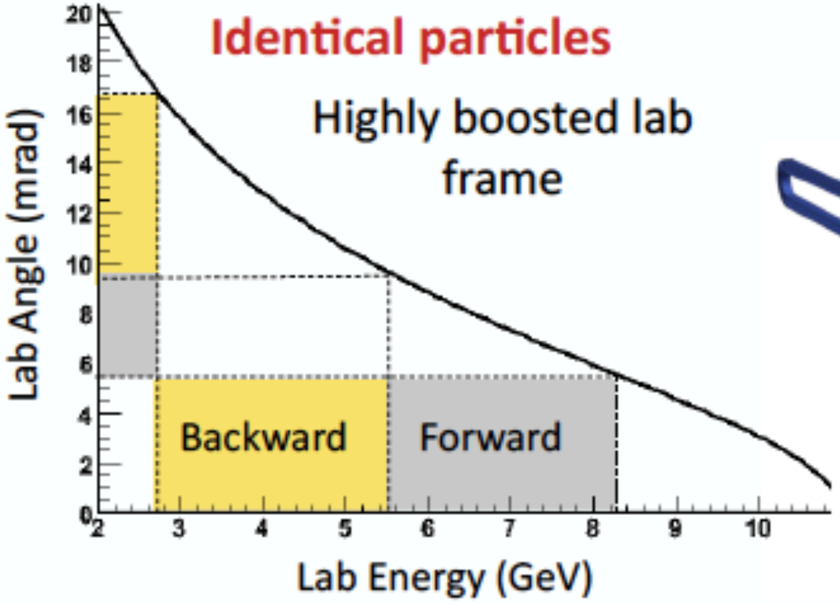


How do you maximize the azimuthal acceptance of the spectrometer?

Idea: 50% Azimuth, 100% Acceptance

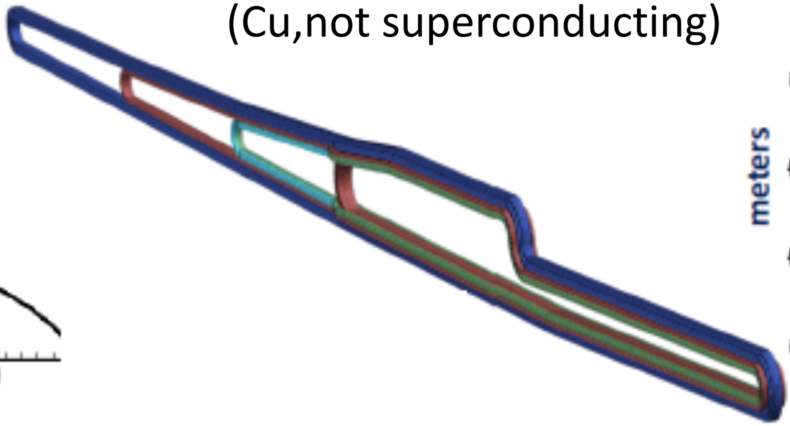
Odd number of octants: accept CM[60º,120º] so you always get one of the electrons from each event

Figure of merit highest at θ_{CM} = 90º
Optimum Acceptance [90º,120º]

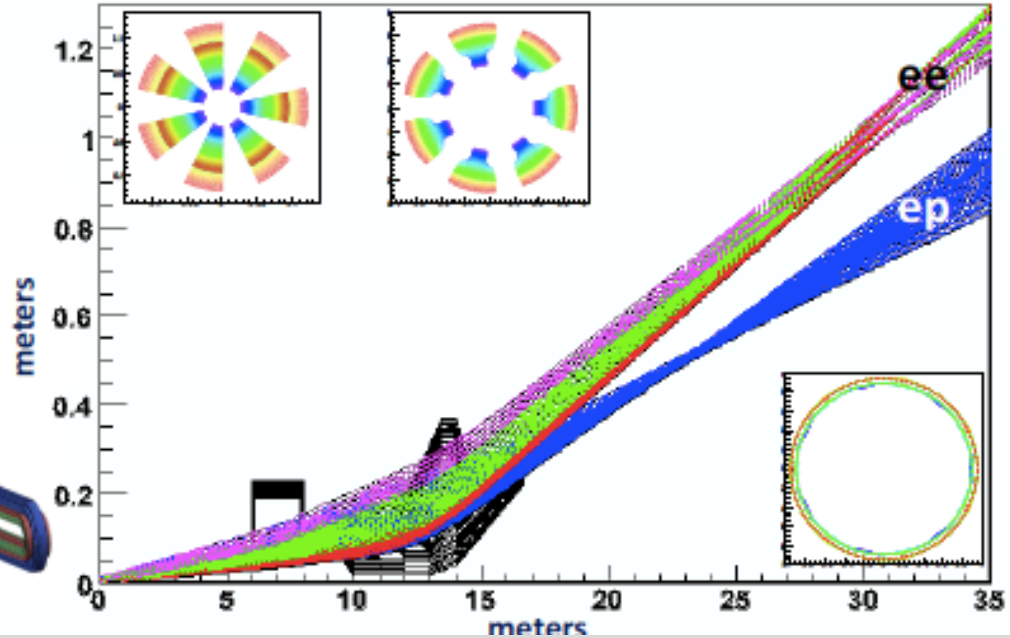


Toroid spectrometer
- E′ = 2.5-8.5 GeV
- θ_{lab} = 0.3º-1.1º
- Two resistive torroids

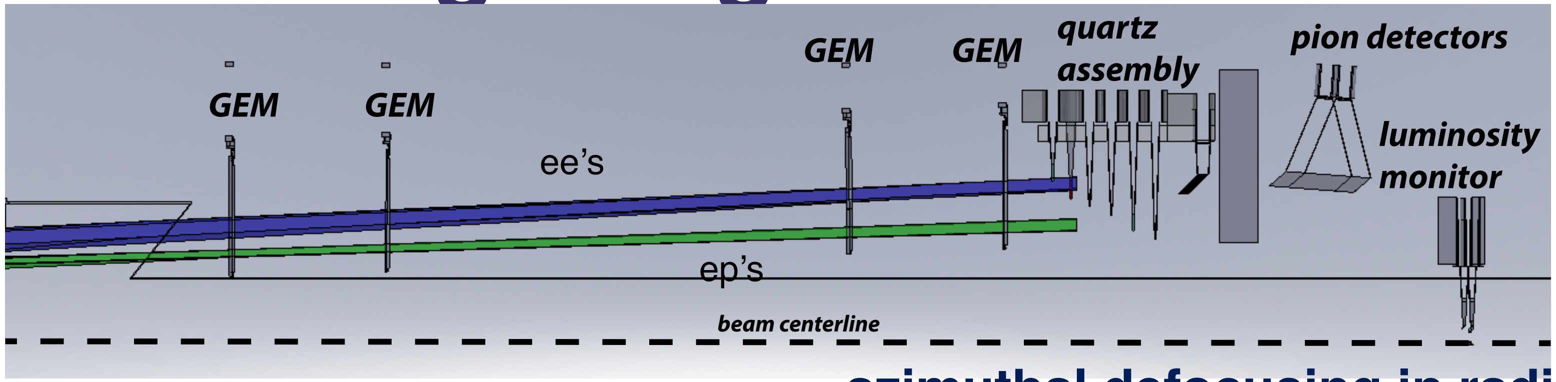
(Cu,not superconducting)

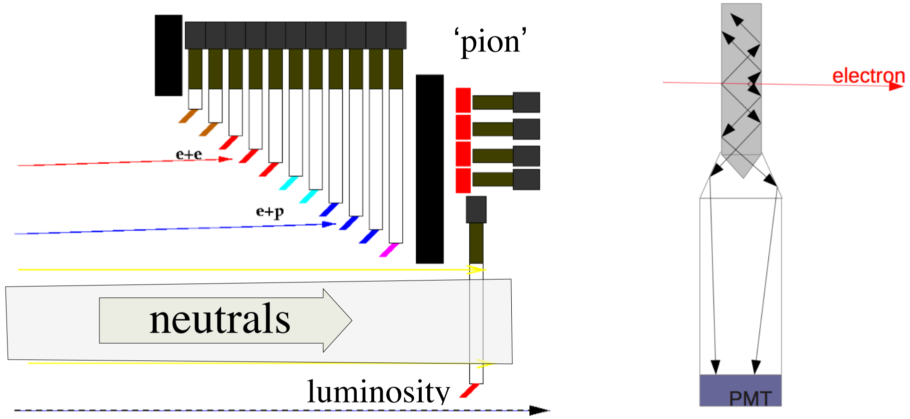


Radial Fields defocus azimuthally.
Full detector ring

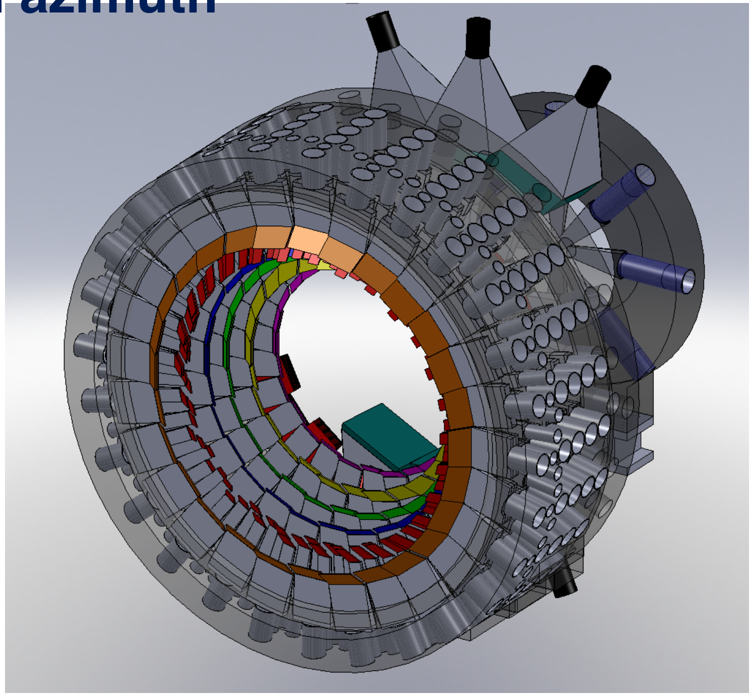


Integrating Detectors





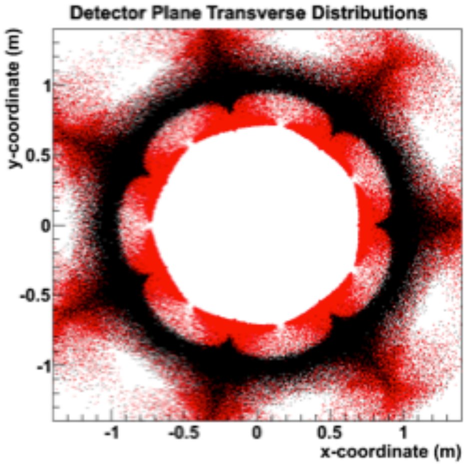
azimuthal defocusing in radial fields, so detector must cover full azimuth



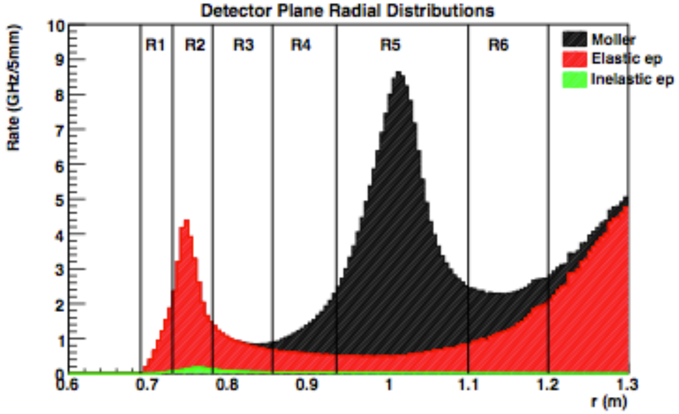
- Møller and e-p electrons:
  - radial and azimuthal segmentation
  - quartz with air lightguides & PMTs
- Pions and muons:
  - quartz sandwich behind shielding
- Luminosity monitors
  - beam & target density fluctuations

Detector Plane Segmentation

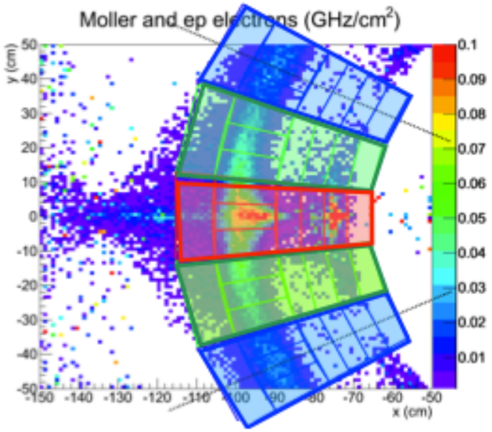
Quartz Cerenkov detectors will have radial and azimuthal segmentation



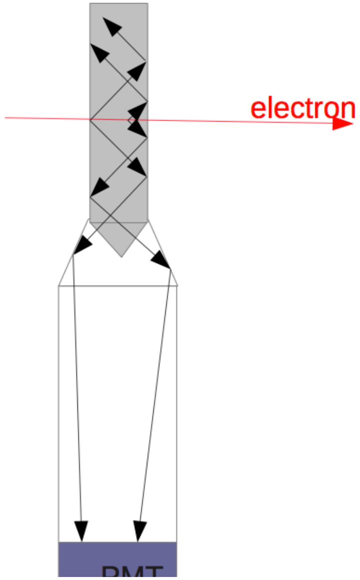
Azimuthal defocusing – Different φ, different θ_{CM} bins

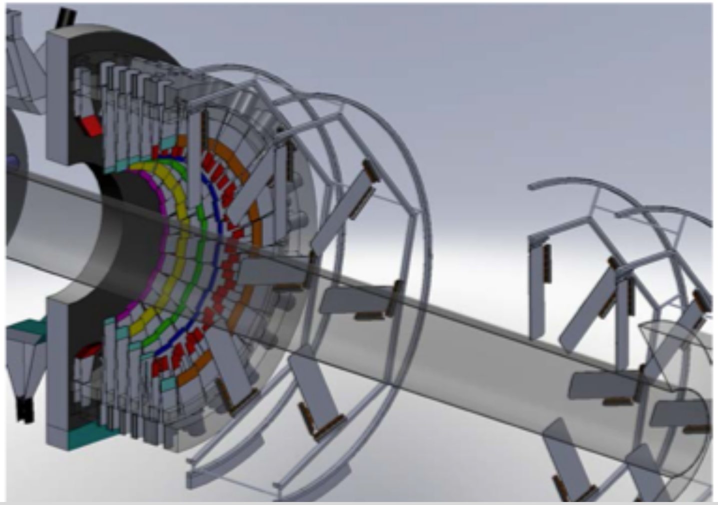


Main Moller peak in Region 5



Proposed Segmentation



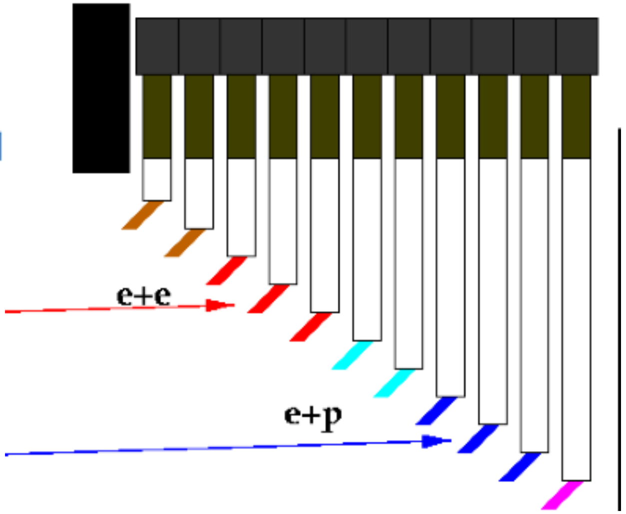


28 azimuthal channels per radial bin

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

224 total channels

Rate per channel ~ few MHz – GHz (overall rate ~ 159 GHz)



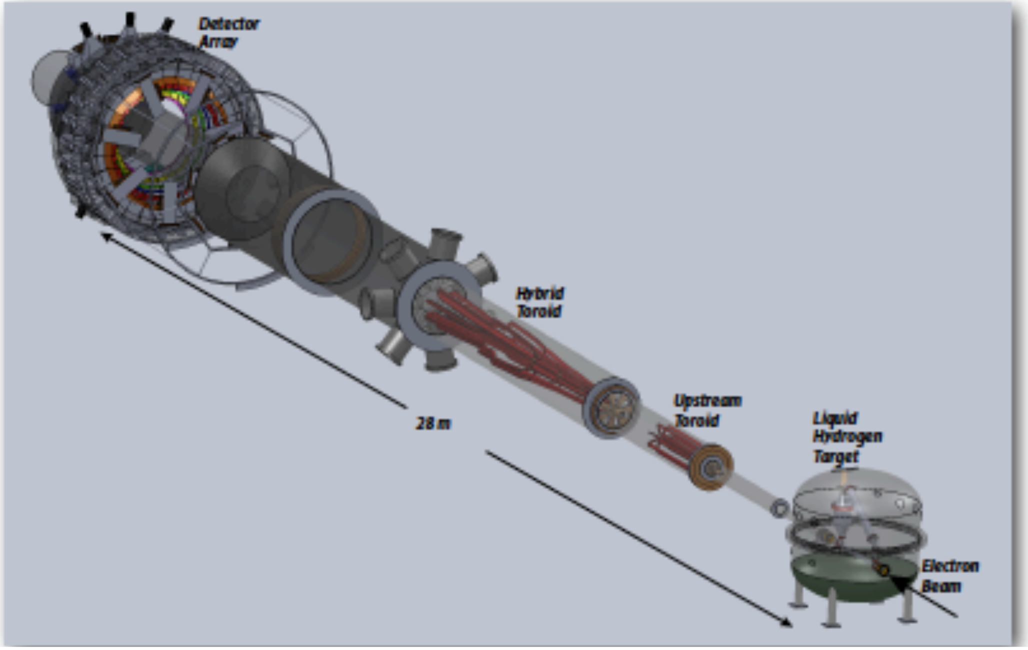
MOLLER Status

Broad range of technical challenges

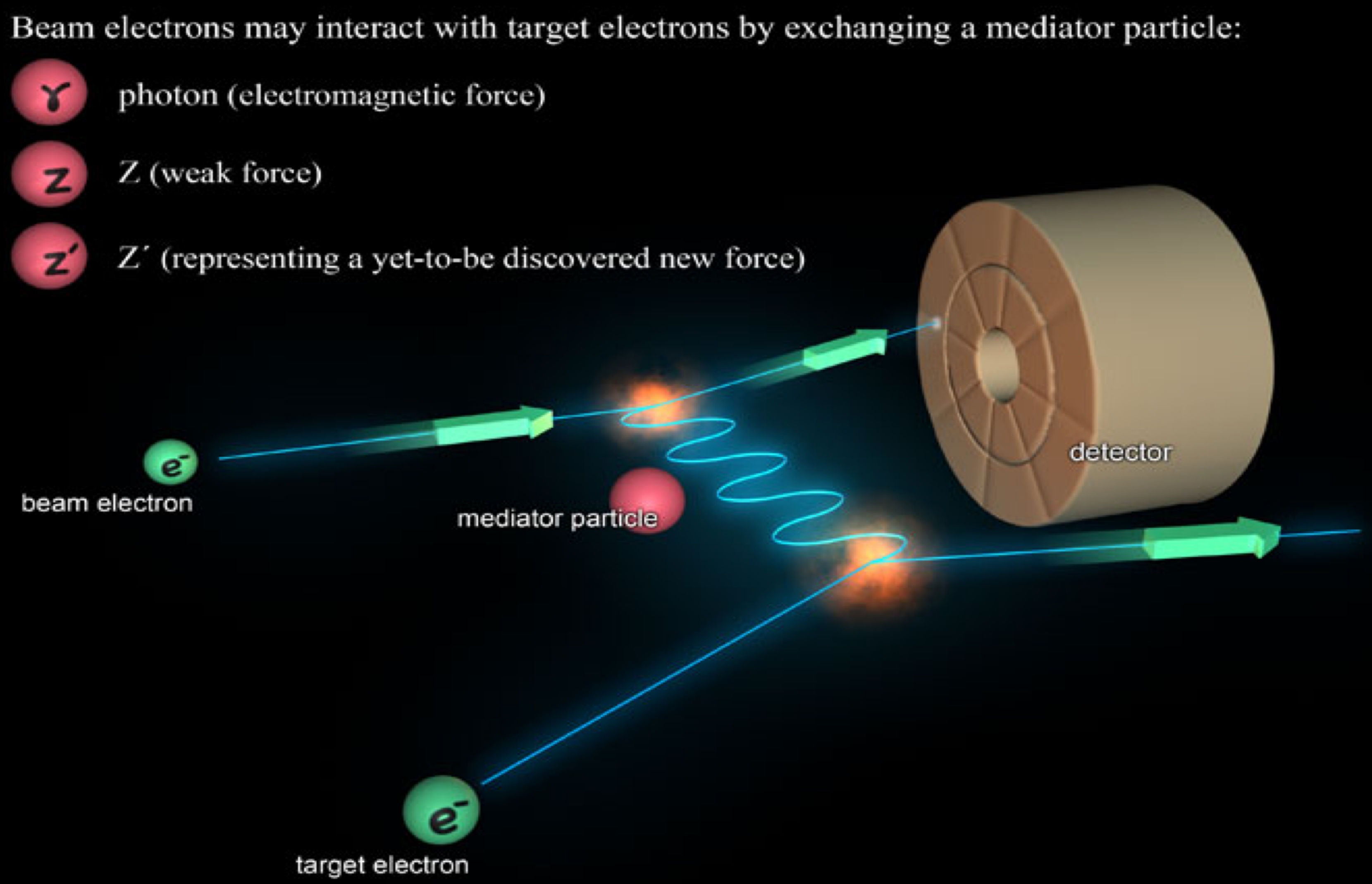
- Full Azimuthal coverage with to ~5° lab angle
  - Magnet construction and engineering
  - collimation
  - backgrounds
  - calibration procedures
- 1.5 m LH_2 target
  - up to 5 kW power
  - Boiling / density fluctuations <25ppm
- Polarized Source
  - Flip at 2 kHz, 10 µs deadtime
  - beam position stable (<1nm) with reversal
  - Improved slow reversal to cancel beam asymmetries
- Robust 0.4% beam polarimetry
  - Compton
  - Iron foil and atomic hydrogen target Møller
- Detector development
  - resolution, rad hard
  - Ancillary (background and tracking)

Collaboration:

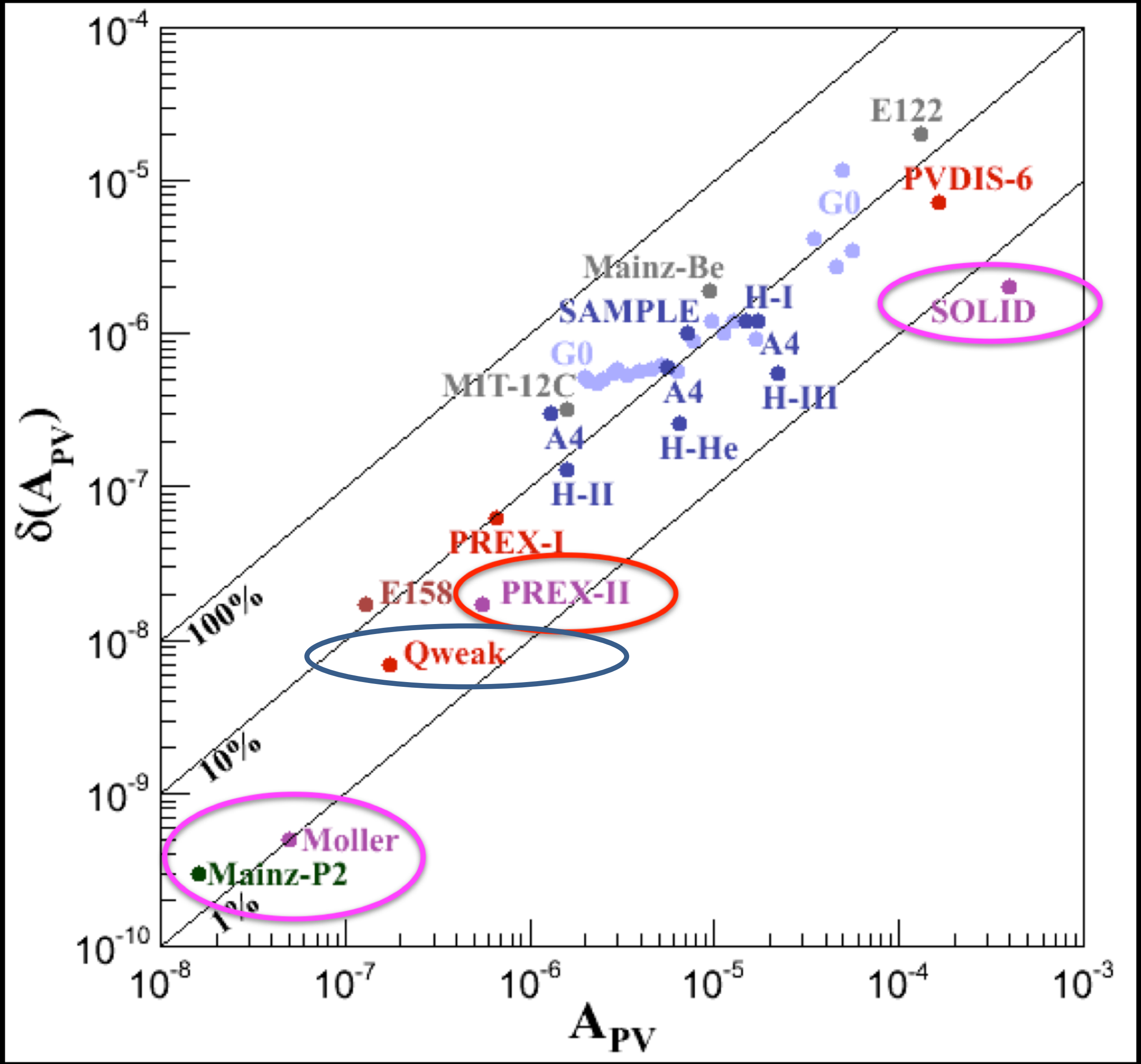
~100 scientists, ~ 30 institutions, expertise from Qweak, E158, HAPPEX, PREX, A4, G0



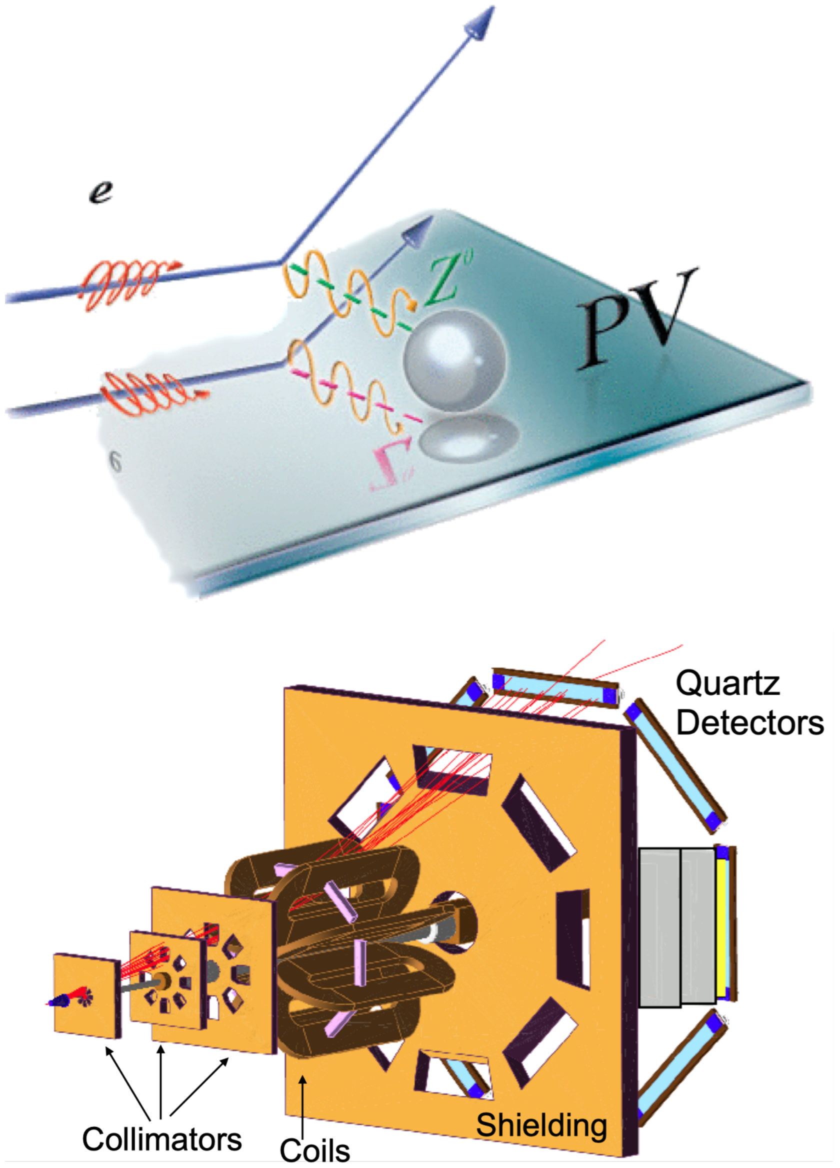
MOLLER Precision: BSM Physics Search



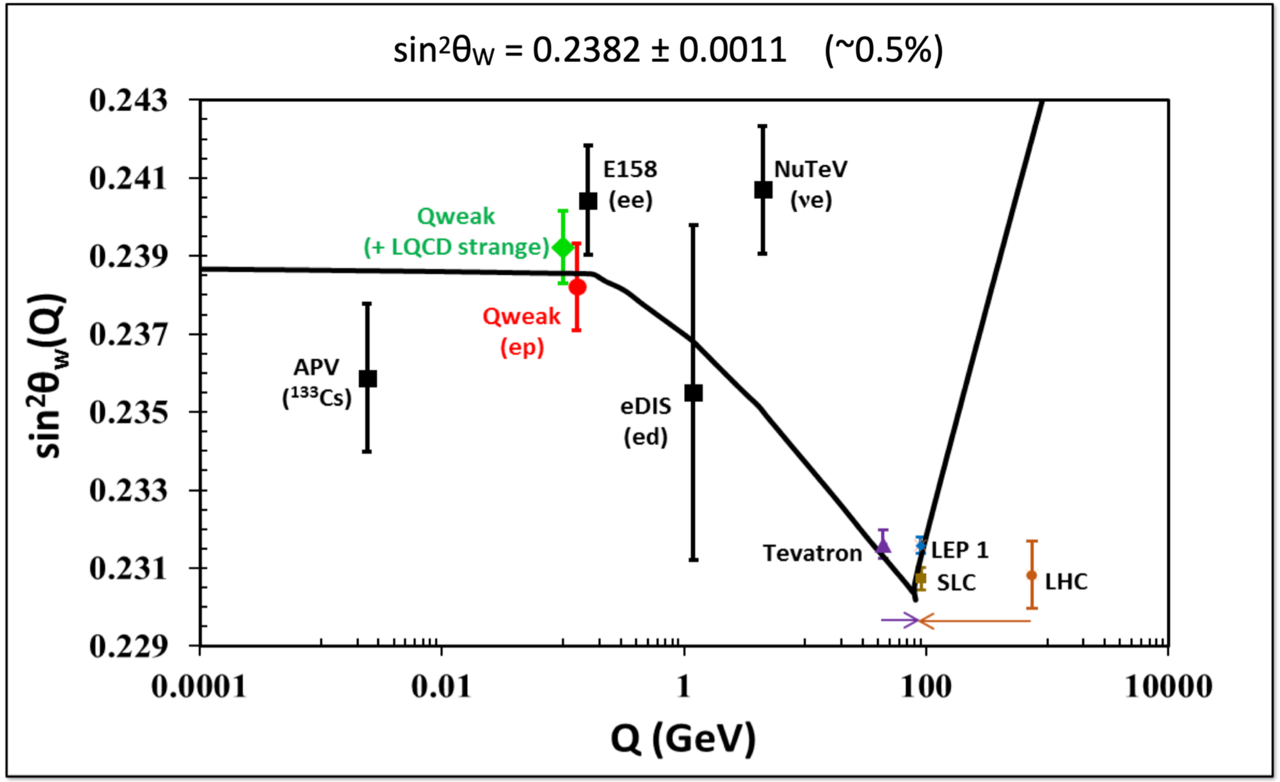
Other PVES Experiments



Qweak



Weak Mixing Angle



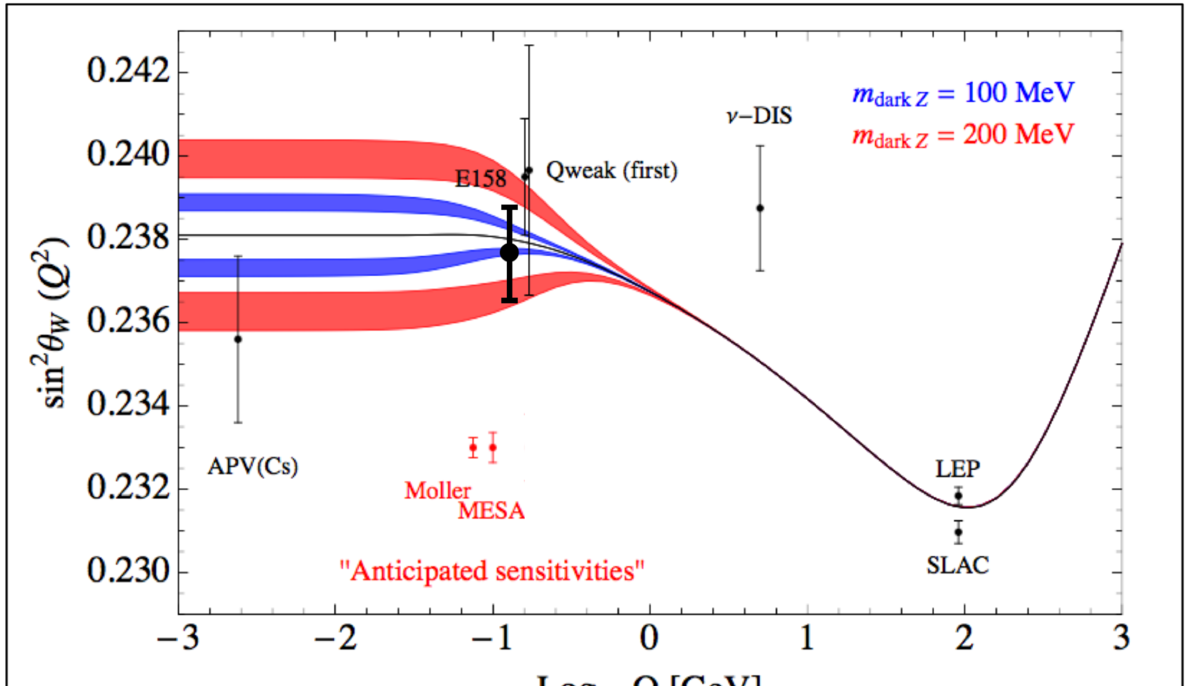
Solid Curve by: J. Erler, M. Ramsey-Musolf and P. Langacker

Dark Z

Dark photon, couples to Dark Sector massive particles but with small E&M couplings to known matter

511keV line in galactic core, Pamela high energy positron excess, $(g\text{-}2)_{\mu}$ discrepancy

New model: a dark Z_d^0 with no coupling to the 3 known generations of matter,
but mass mixing with the Z^0



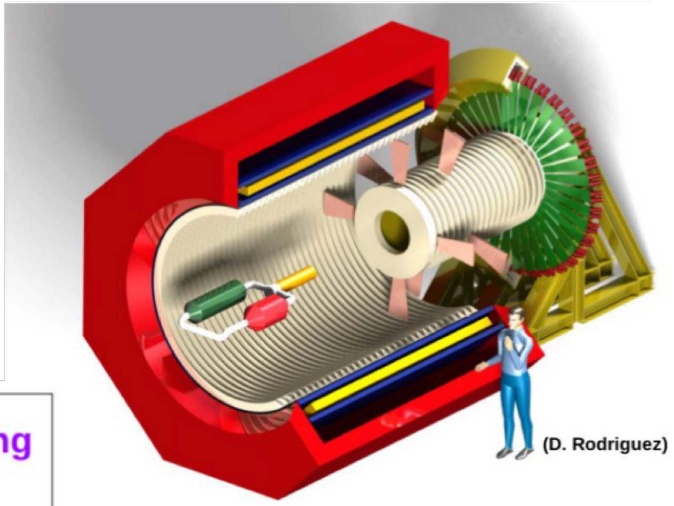
Phys.Rev. D89 (2014) 9, 095006

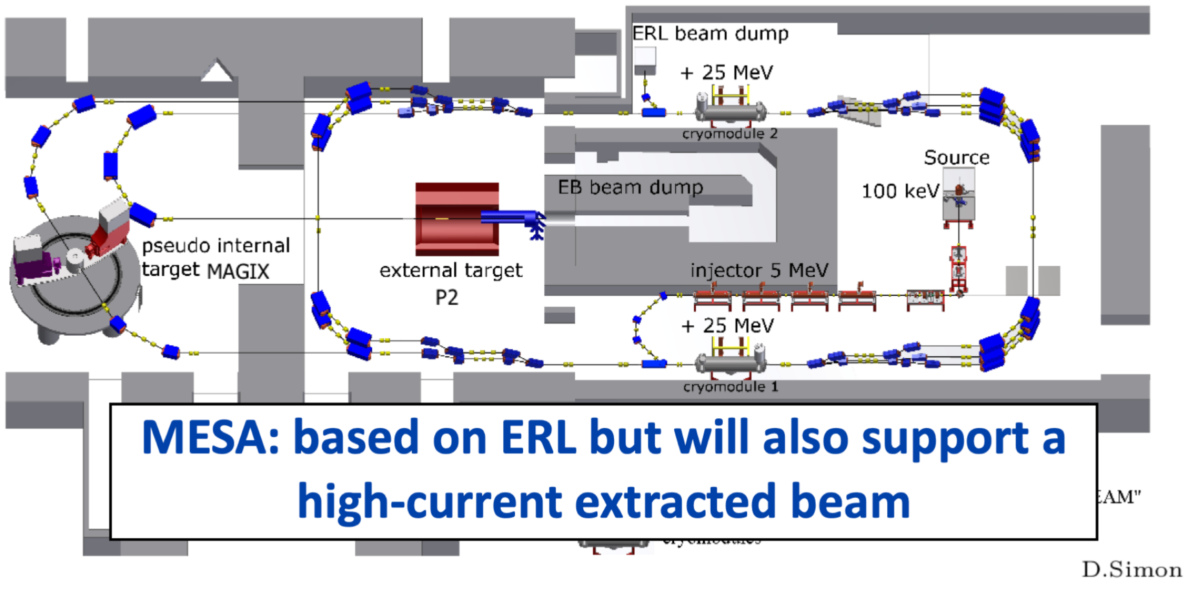
Davoudiasl, Lee, Marciano
Phys.Rev.Lett. 109 (2012) 031802
Phys.Rev. D85 (2012) 115019
Phys.Rev. D92 (2015) 5, 055005

P2 at MESA / Mainz

Qweak: proton structure F contributes ~30% to asymmetry, ~2% to $\delta(Q_W^p)/ Q_W^p$

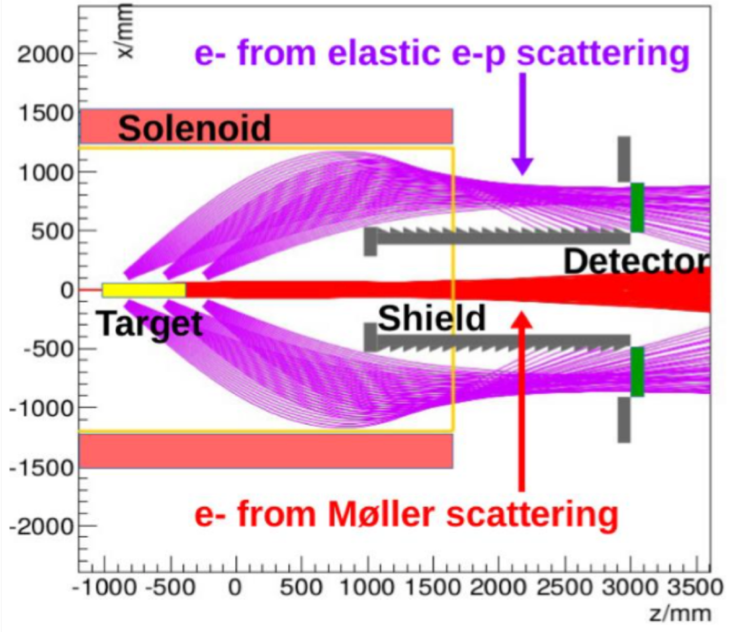
Negligible for significantly lower Q^2





MESA: based on ERL but will also support a high-current extracted beam

Solenoid Spectrometer



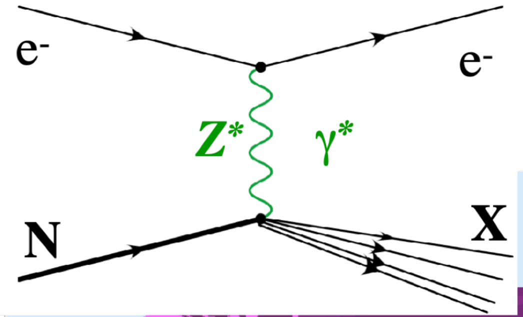
- E_{beam} = 155 MeV, 25-45°
- Q^2 = 0.0048 GeV^2
- 60 cm target, 150 uA, 10^4 hours

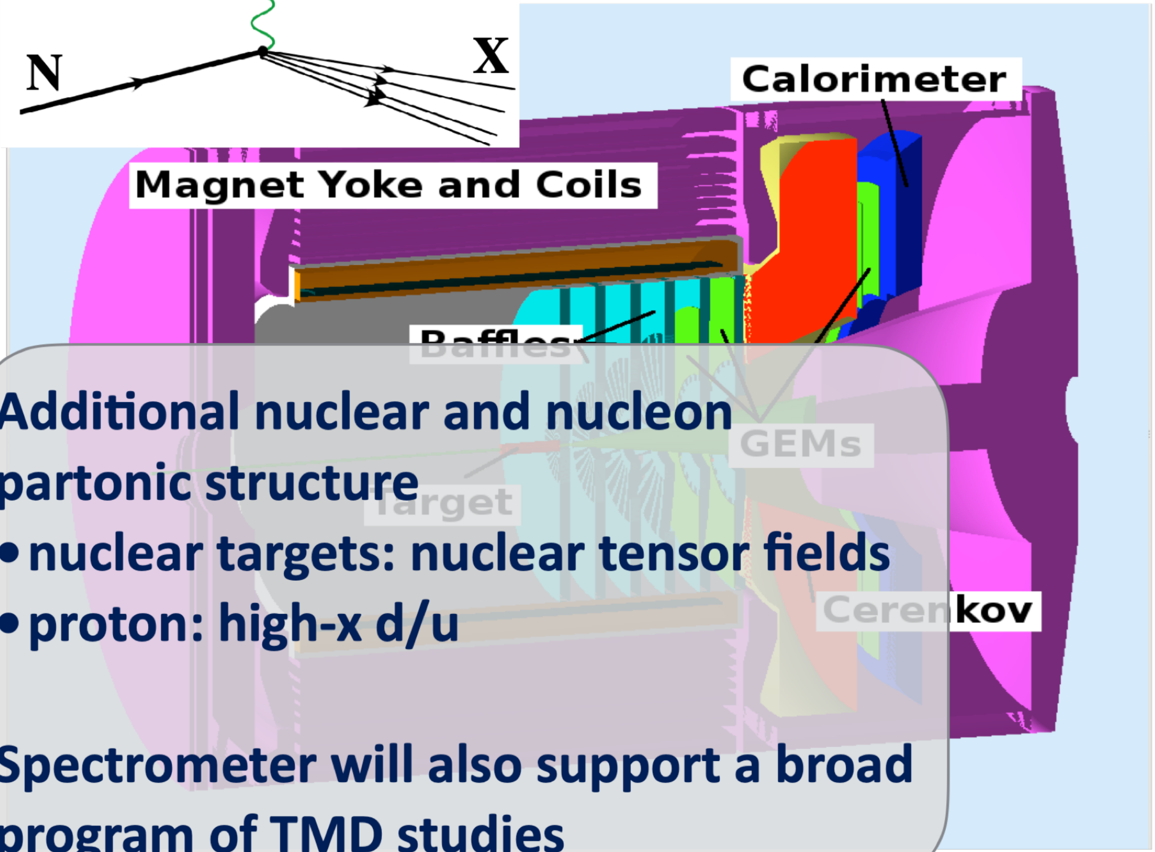
- A_{PV} = -29 ppb to 1.5% (0.44ppb)
- **$\delta(\sin^2\theta_W)$ = 0.00031 (0.13%)**

- **Development underway**
- **Funding approved**
- **start 2020+**

SOLID

PV-DIS: controlling hadronic contributions requires precise kinematics and broad range





Additional nuclear and nucleon partonic structure

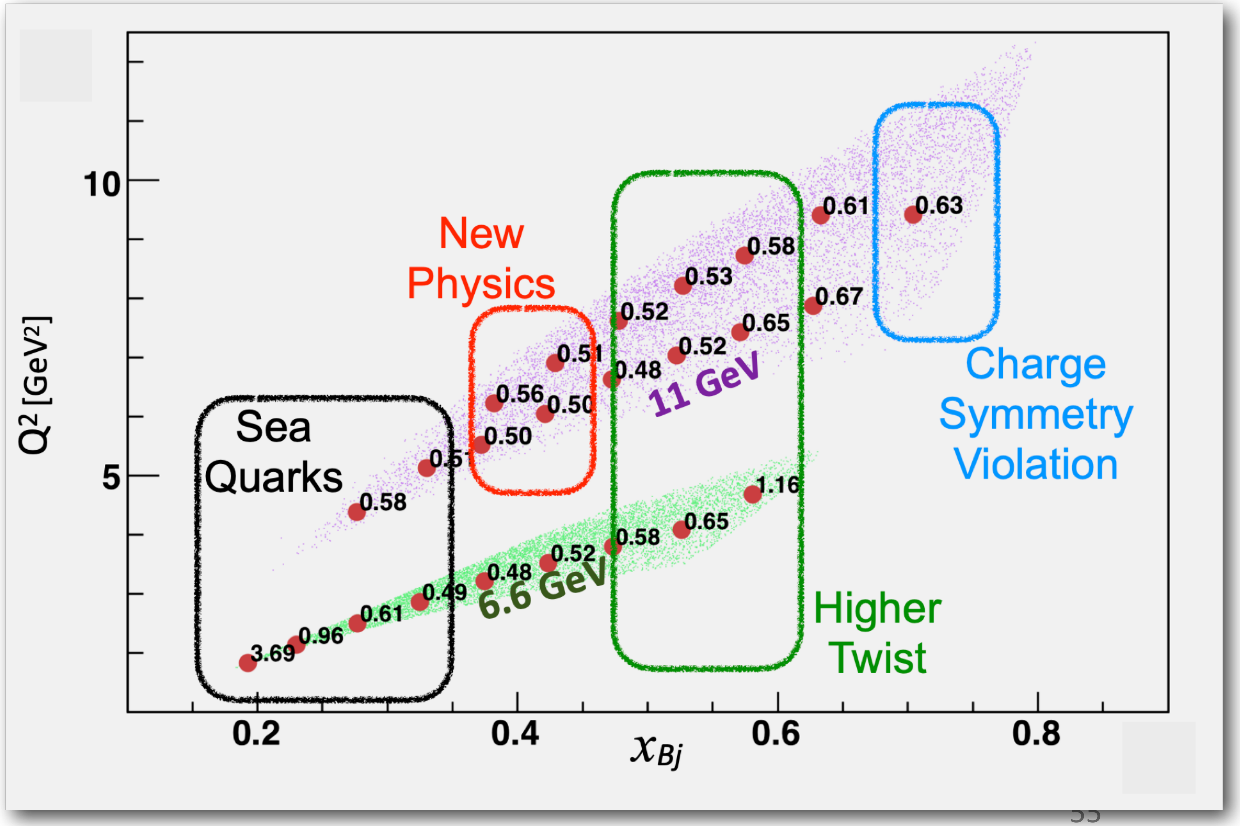
- **nuclear targets: nuclear tensor fields**
- **proton: high-x d/u**

Spectrometer will also support a broad program of TMD studies

- **high luminosity, large acceptance**
- **repurpose the CLEO solenoid**

<u>**Strategy:**</u> **sub-1% precision** over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**

Requires 0.4% *e-* polarimetry

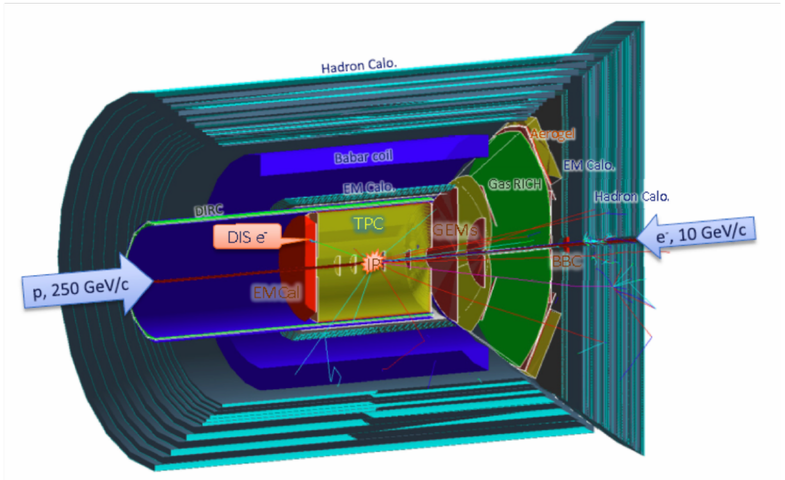


PV-DIS at EIC

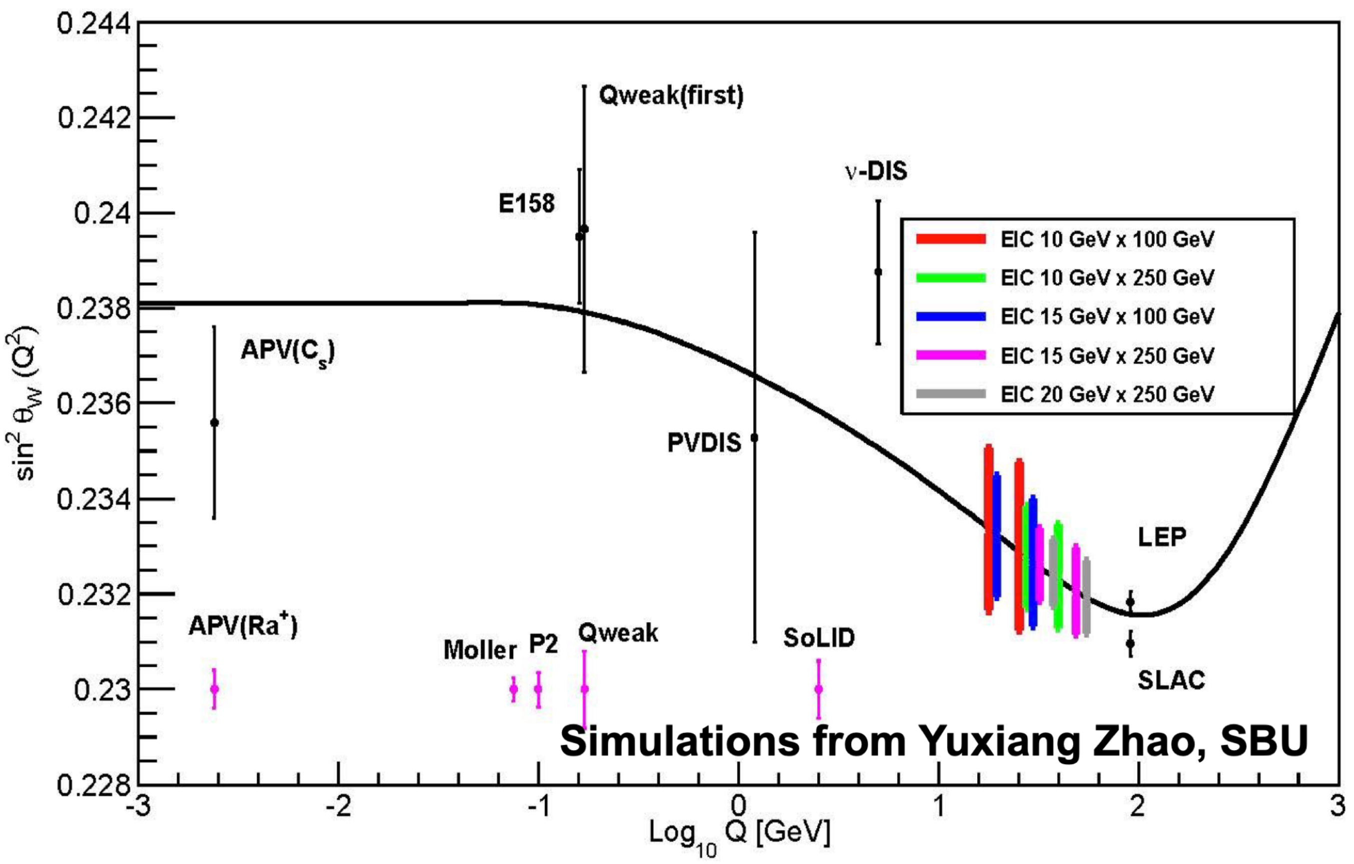
EIC can access interesting Q^2 region with PV-DIS - no past or planned measurements

Assumptions:

- Dedicated deuterium run
- This measure will average over ^2H polarization
- 200 days of beam time
- Int. Lumi. ~267 fb^{-1}(incl. eff.)



Simulated using "Day-1 EIC detector" described in ePHENIX LOI

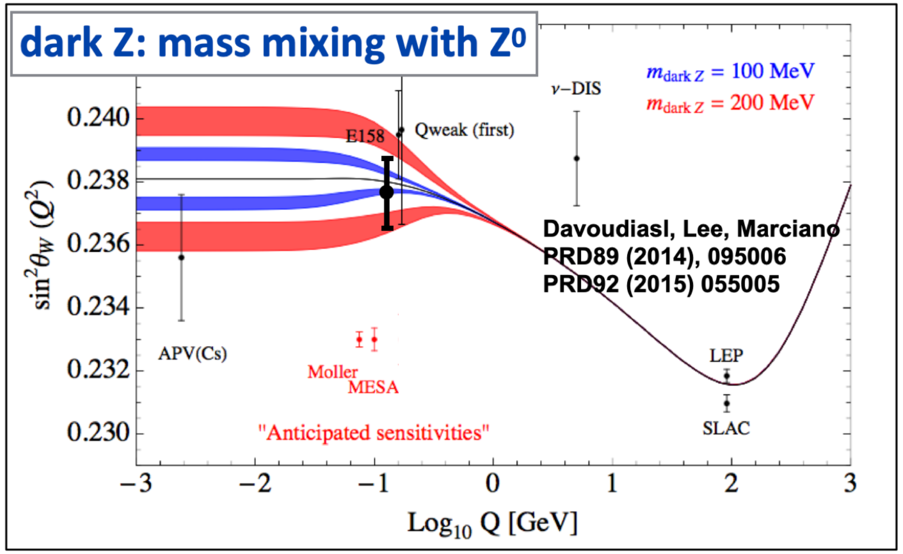


- Polarimetry ~0.5% for highest energy, luminosity
- Differential luminosity precision ~5×10^{-4}

New Physics Complementarity

Best Collider $\delta(\sin^2\theta_W)$:
- A_l(SLD): 0.00026
- A_{fb}(LEP): 0.00029

Future projections, similar time scale:
- Final Tevatron: ~ 0.00046
- LHC 14 TeV, 300 fb^{-1} : ~ 0.00036
- Note: pdf uncertainties
- MOLLER: ~ 0.00028
- Mainz P2: ~ 0.00032



mass reach

assumptions on isospin structure, strong coupling

E158	~17 TeV
PV-DIS-6	~8 TeV
Qweak	~27 TeV
MOLLER	~39 TeV
P2	~49 TeV
SOLID	~22 TeV

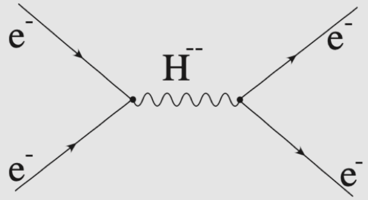
Erler *et al.*, Ann.Rev.Nucl.Part.Sci. (2014)

MOLLER: e^-e^- scattering

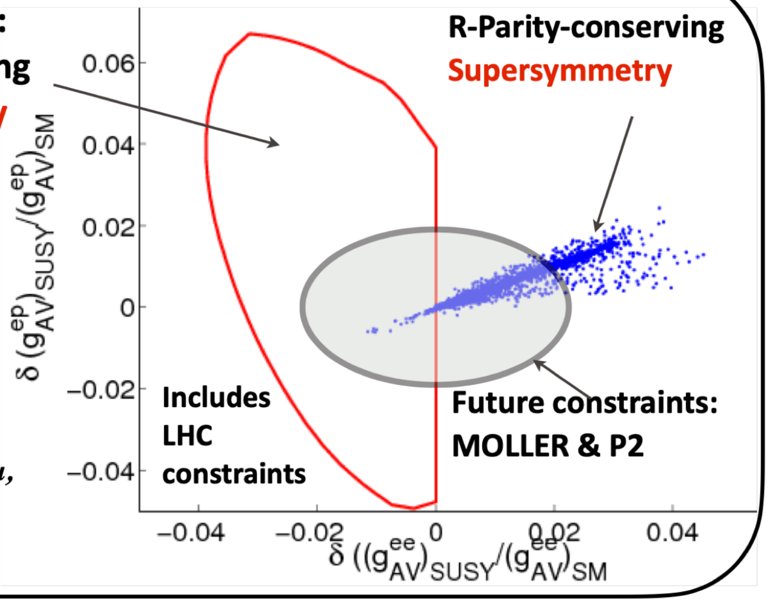
Lepton Number Violation

Λ > *5 TeV*

Doubly-Charged Scalars



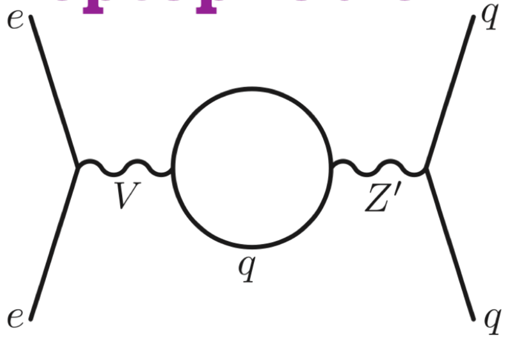
Significant reach beyond LEP-200



Erler and Su, arXiv:1303.5522

Ramsey-Musolf and Su, Phys. Rep. 456 (2008)

SOLID: Leptophobic Z'



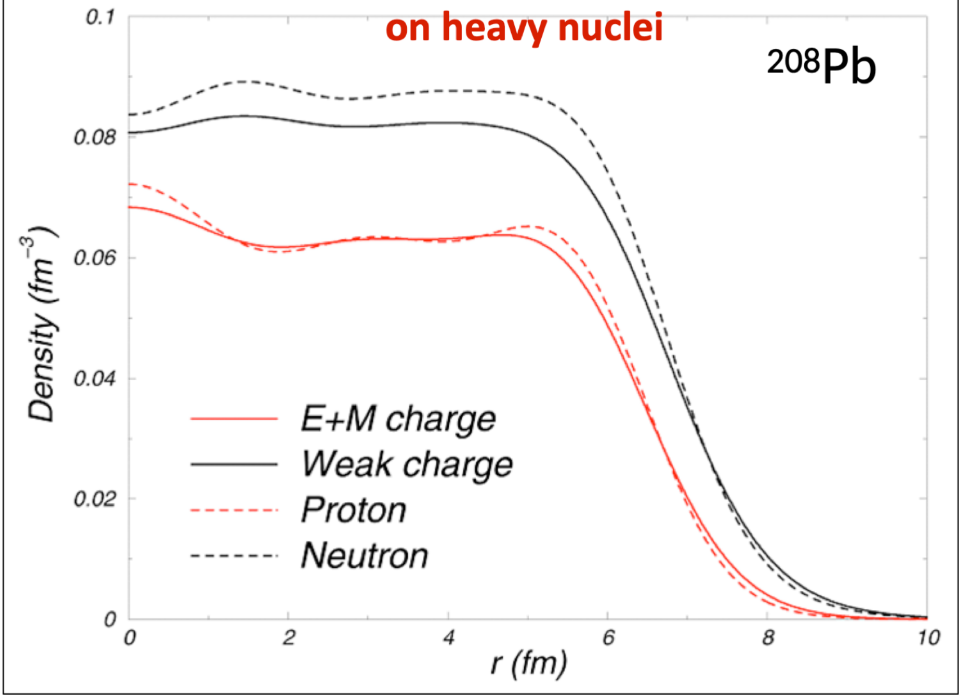
SOLID: 100-200 GeV range

Buckley and Ramsey-Musolf Phys.Lett. B712 (2012) 261-265

PREX

Weak Charge Distribution of Heavy Nuclei

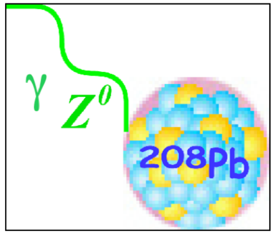
Nuclear theory predicts a neutron "skin" on heavy nuclei



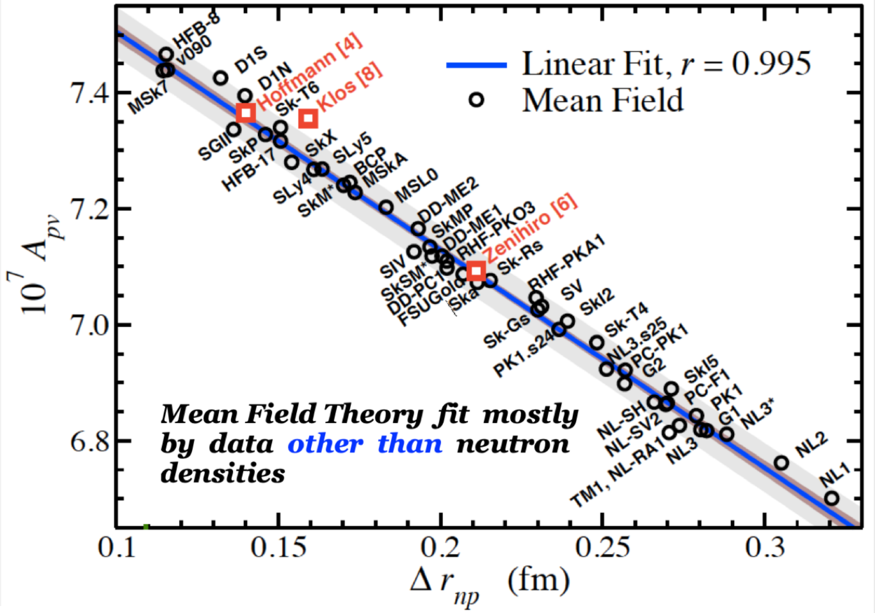
	proton	neutron
Electric charge	**1**	**0**
Weak charge	**~0.08**	**1**

for spin-0 nucleus

$$A_{\rm PV} \approx \frac{G_{\rm F} Q^2}{4\pi\alpha\sqrt{2}} \frac{F_{\rm W}}{F_{\rm ch}}$$



Mean-field model predictions of A_{PV} correlate with the neutron skin of a heavy nucleus



Rocal-Maza et al, PRL106, 252501 (2011)

- Neutron skin thickness is highly sensitive to the pressure in neutron-rich matter.
- The greater the pressure, the thicker the skin as neutrons are pushed out against surface tension.

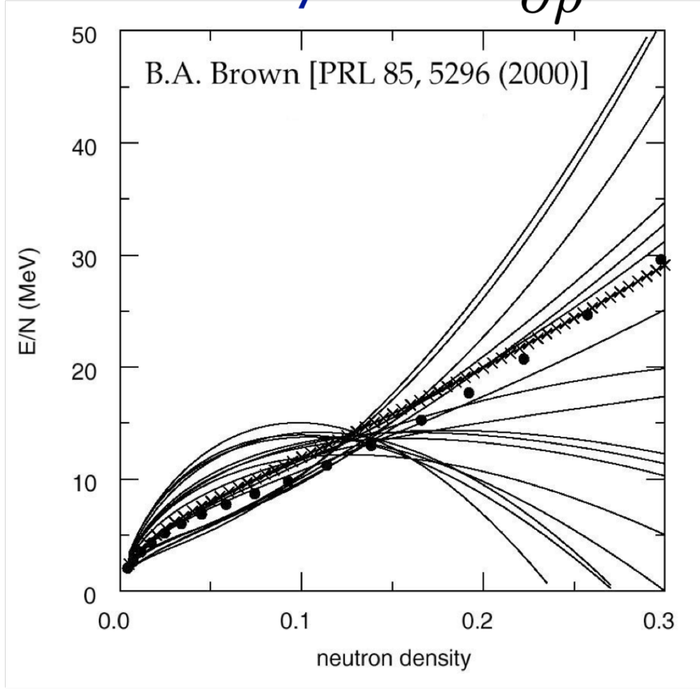
Knowledge of r_n highly model dependent, not well constrained by robust measurements

R_n of ^{208}Pb: Equation of state for neutron-rich nuclear matter

Density Dependence of Symmetry Energy

Energy penalty for breaking n=Z symmetry $S = \frac{E}{N}$

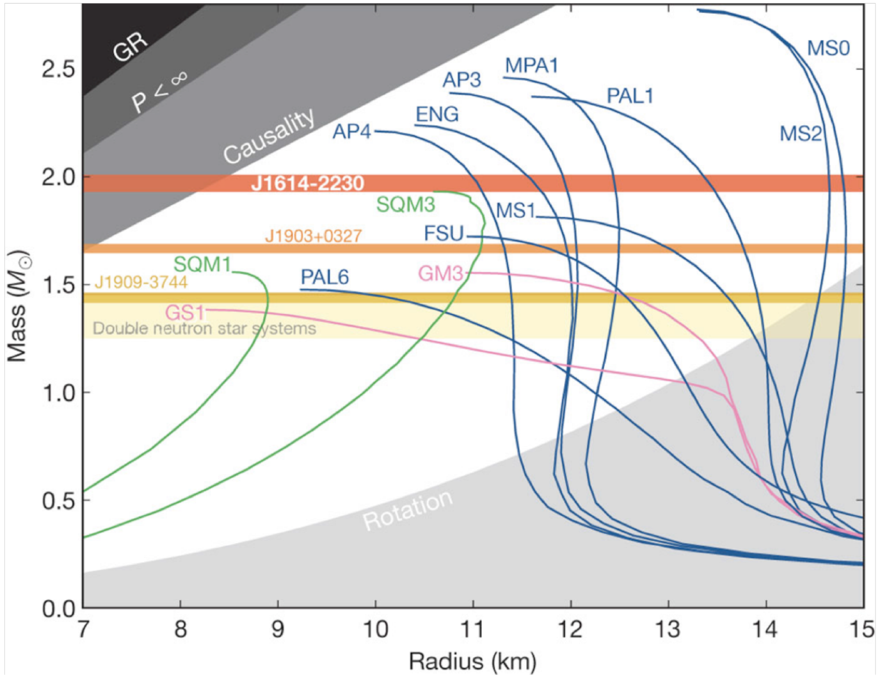
Slope at saturation density $L \propto \frac{\partial S(\rho)}{\partial \rho}|_{\rho_0}$

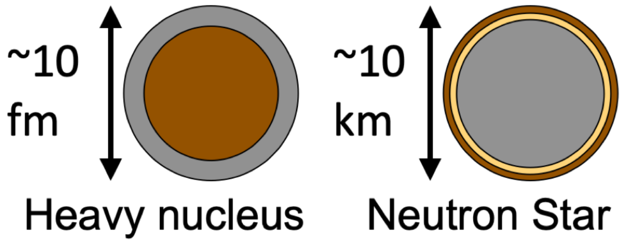


A_{PV} from ^{208}Pb provides a clean measure of L, testing the description of nuclear matter

Isovector properties are not well measured.

Models informed mostly by measurements of properties sensitive to *p+n*.





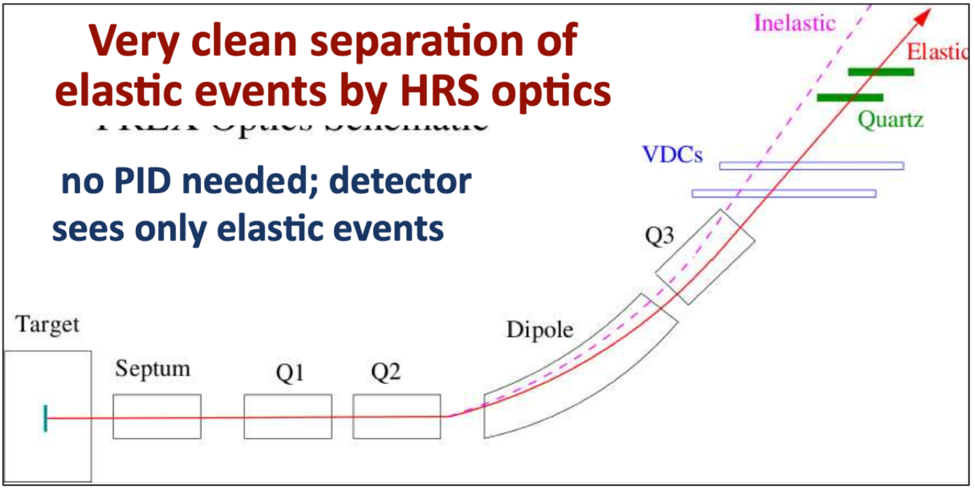
- Stiffness vs core collapse
- Mass/radius
- cooling mechanisms (URCA or not)

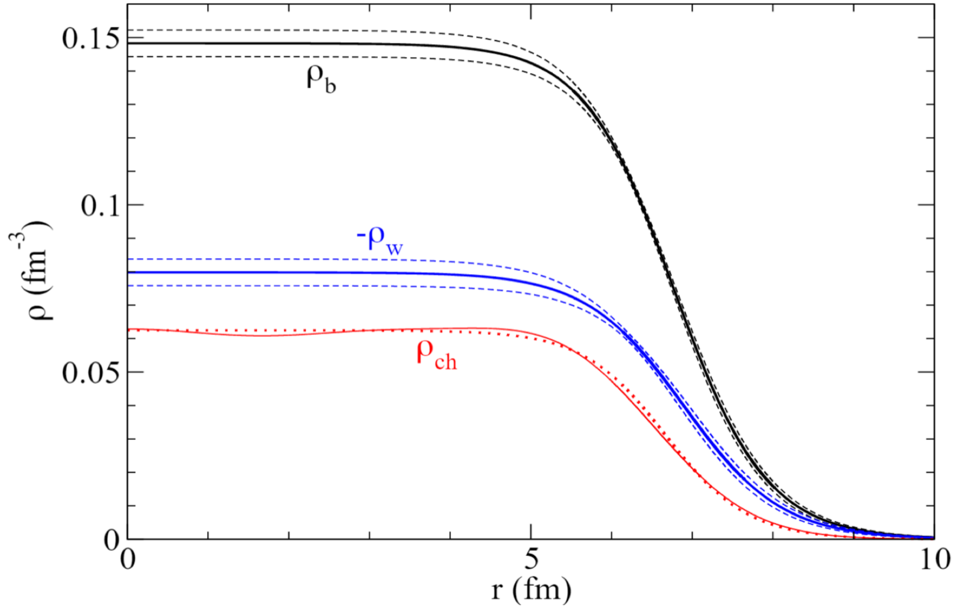
Measuring Neutron Skins at JLab

PREX (^{208}Pb)
- important check on nuclear structure data set
- uniform nuclear matter
- terrestrial laboratory for n-star matter

CREX (^{48}Ca)
- isovector probe in moderate size system
- finite size effects
- Within reach of microscopic calculations

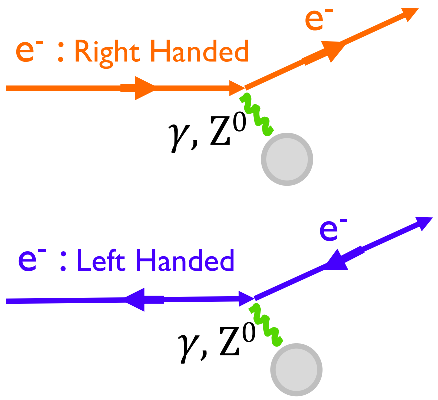
Spring 2019:
PREX (3% APV, rn to 0.06 fm)
CREX (2.5% APV, rn to 0.02 fm)





Calculations by Chuck Horowitz following PRC 102(2020) 044321

Summary



PVES Experiments

New challenges arise with increasing precision. The experiments are hard, but worth it.

Unprecedented precision enabled by technological advances, preparing for the next generation of PVES experiments

Electroweak Physics with PVES is a powerful component of the low energy fundamental symmetries program

- P2, SOLID, MOLLER: Future Flagship experiments for electron beam facilities
- Search for new interactions from 100 MeV to 10s of TeV

Neutron skin provides a crucial check on nuclear structure theory

A rich experimental program is envisioned over the next 10 years at Jefferson Lab and Mainz MESA facility