Running of the Weak Mixing Angle

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Jefferson Lab

Electroweak and Beyond the Standard Model Physics at the EIC
INT, WU - Feb 12-16 2024

Outline

- Definition
- Running
- Past measurements
  - Z-pole measurements
  - Low-energy ($Q^2 \ll M_Z^2$) measurements
- Potential future measurements
- Summary

Acknowledgement: KK and Ciprian for providing slides and guidance

Weak Mixing angle - fundamental quantity of EW theory

EM force

Infinite-range

Massless mediator

Conserve parity

EW force

Having massive and massless mediator

Weak force

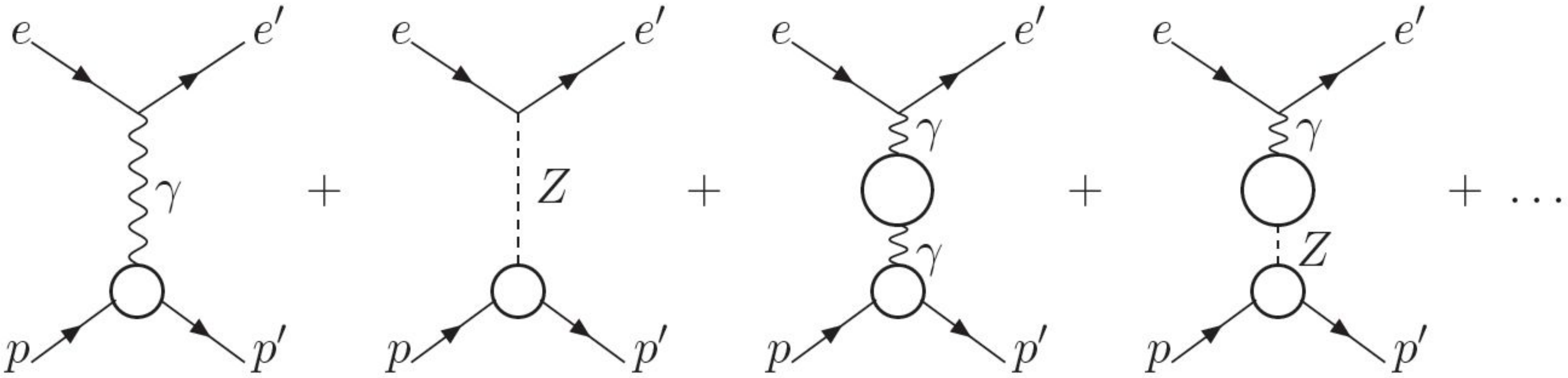
Short range

Massive mediator

Violate Parity

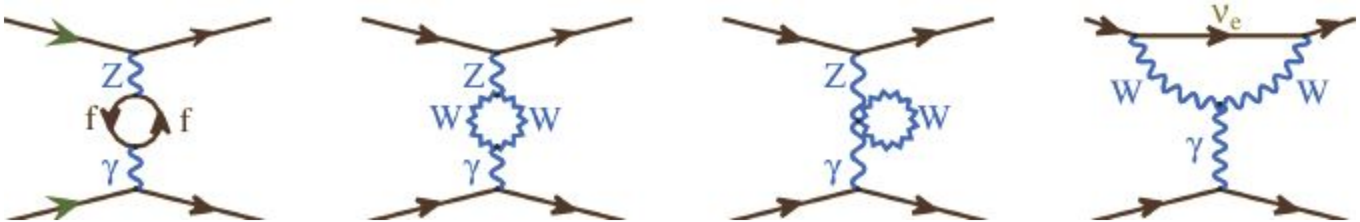
$$sin^2\theta_w = 1 - (M_W/M_Z)^2 = (e/g)^2$$

Quantum corrections



Tree-level **Running α** **Running $\sin^2\theta_W(\mu)$**

Universal quantum corrections can be absorbed into a scale dependent - “running” $\sin^2\theta_W(\mu)$



Schemes of Definition

- **On-shell scheme**
  - promotes Tree-level definition to a renormalized sin^2**ϴ**$_W$(**μ**) to all orders in perturbation theory

$$sin^2\theta_W \rightarrow s_W^2 \equiv 1 - M_W^2/M_Z^2$$

$$M_W = \frac{A_0}{s_W(1-\Delta r)^{1/2}}; M_Z = \frac{M_W}{c_W}$$

$$\Delta r \approx \Delta r_0 - \rho_t/tan^2\theta_w$$

$$\Delta r_0 = 1 - \alpha/\hat{\alpha}(M_z)$$

$$\rho_t = 3G_F m_t^2/8\sqrt{2}\pi^2$$

- Simple conceptually - relatively large (~3%) correction from $\boldsymbol{\rho}_t$ causes large spurious contributions in higher orders.

Schemes of Definition

- Modified Minimal Subtraction
  - Scale dependent scaling - choose **μ** = M_Z for many EW processes
  - Less sensitive to mt and new physics.

$$sin^2\hat{\theta}_W(\mu) \equiv \frac{\hat{g'}^2(\mu)}{\hat{g}^2(\mu)+\hat{g'}^2(\mu)}$$

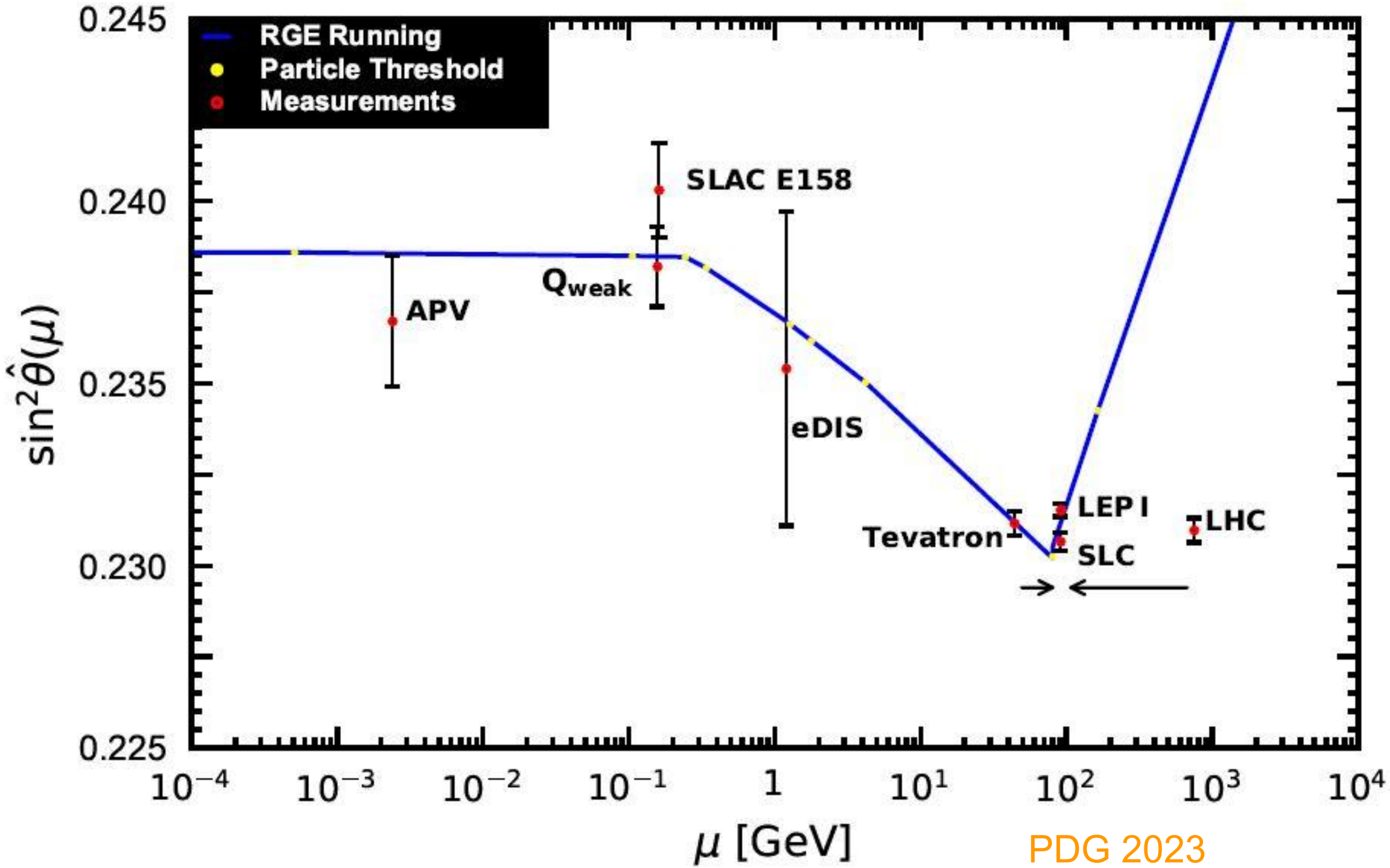
  - Theoretically nice - but unphysical
  - Good for GUT running

- Effective
  - Extensively used at LEP - defined by vector and axial vector couplings at the Z-pole - $Zf\bar{f}$
  - Good at Z-pole
  - Required to calculate renormalized counterterms for non-Z-pole applications

$$sin^2\theta_f^{eff} \equiv \kappa_f(q^2,\mu)sin^2\hat{\theta}_W(\mu)$$

$$sin^2\hat{\theta}_W(M_Z) - sin^2\theta_f^{eff} = 0.00028$$

Existing Measurements



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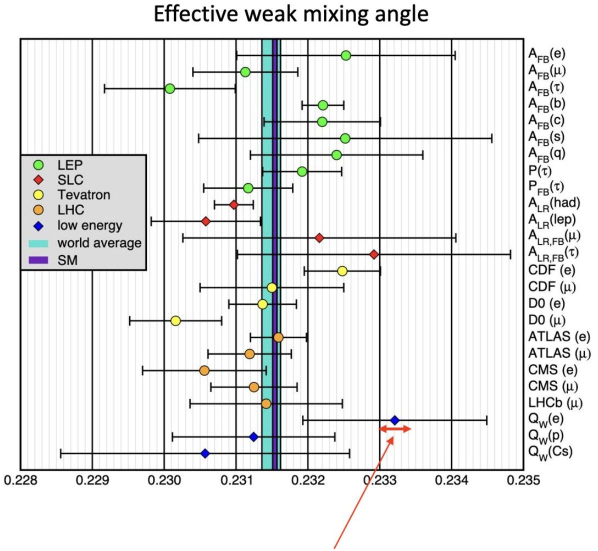
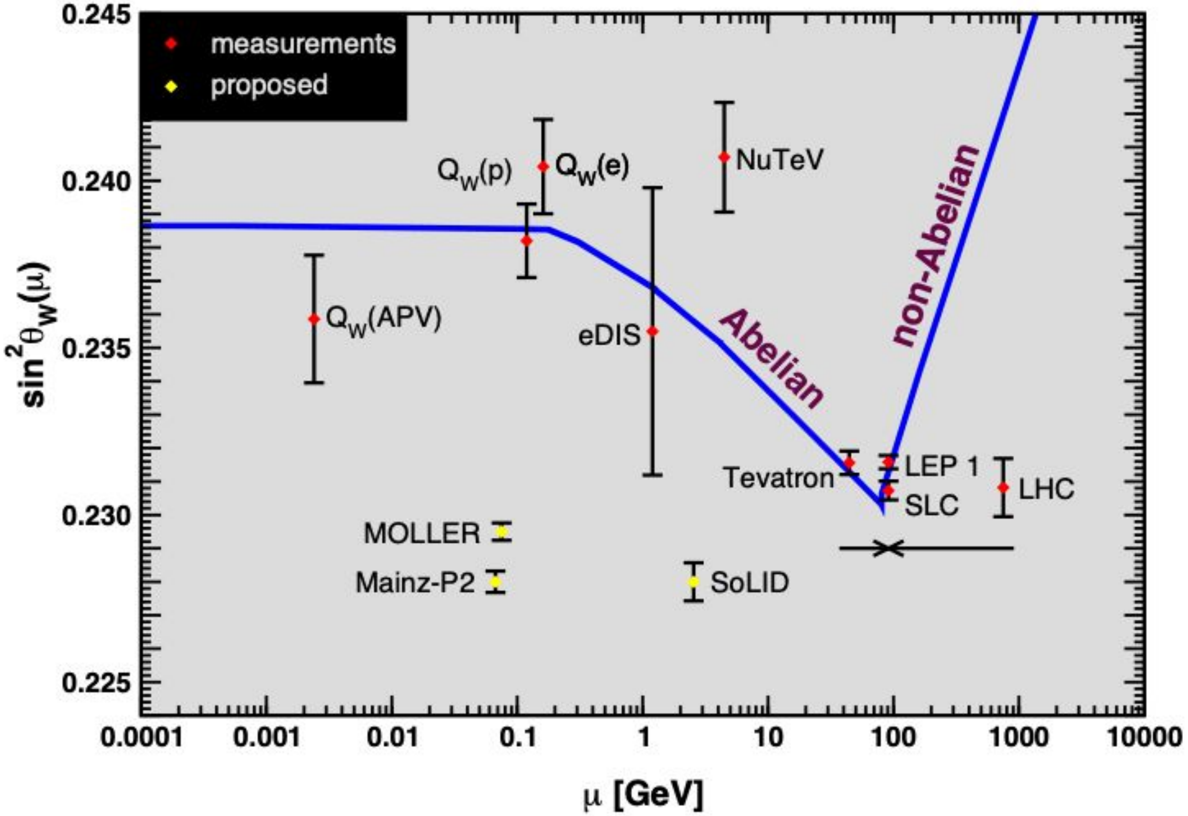
Future Measurements

- **Clearly points out the precision of the future experiments: P2 and MOLLER - to the level of Z-pole measurements!**

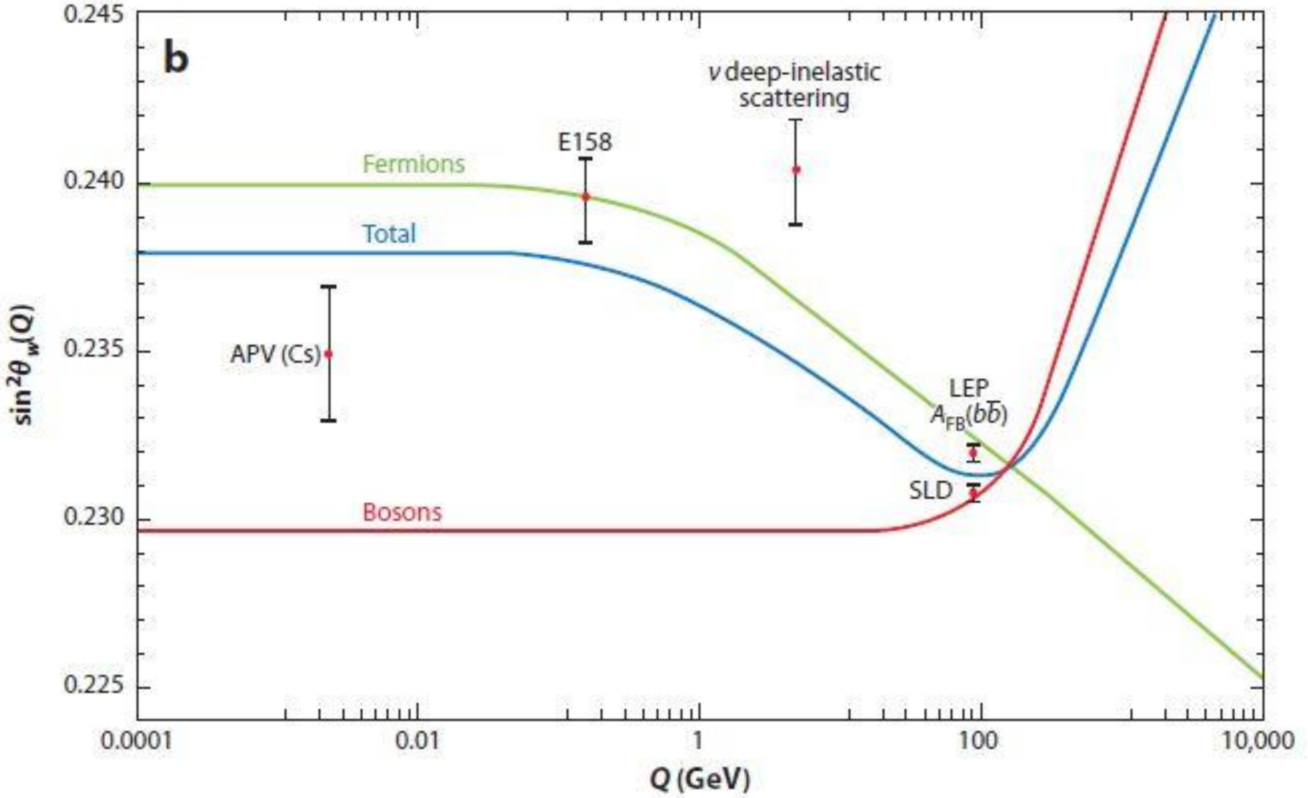


MOLLER expected precision

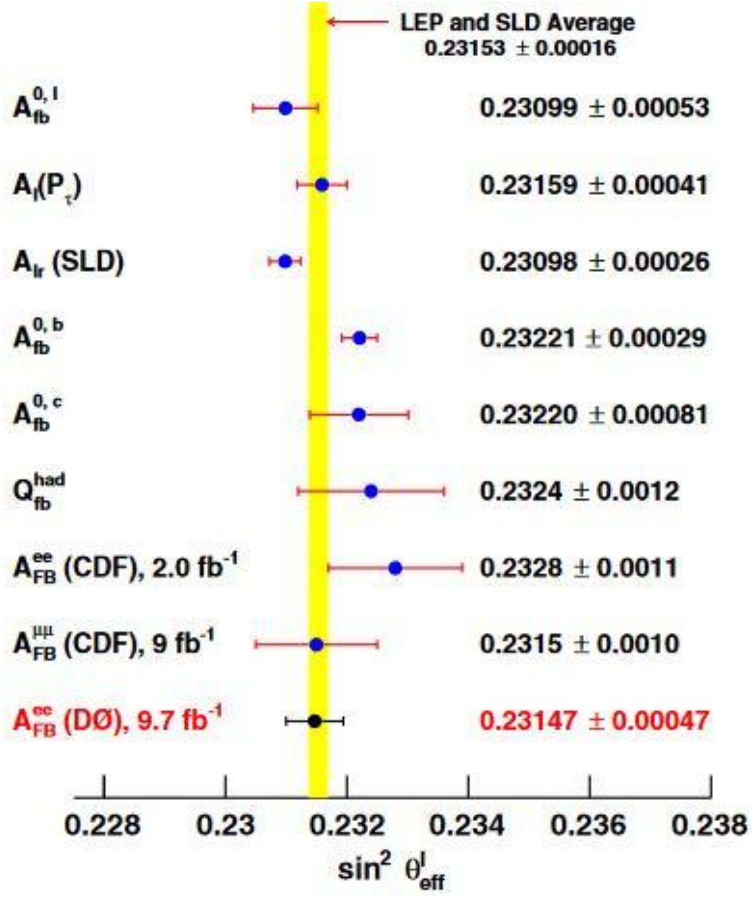


Running - fermionic and bosonic contributions

Annu. Rev. Nucl. Part. Sci. 63 237 (2013)



Z-pole measurements -CERN, SLAC, FermiLab



$$p\bar{p}/e\bar{e} \rightarrow Z \rightarrow q\bar{q}/l\bar{l}$$

Used left-right, forward-backward asymmetry of quark/leptons, polarization state of τ lepton

The two most precision measurements differ by 3.2σ.

PRL 115 041801 (2015)

INSTITUTE for NUCLEAR THEORY

Jefferson Lab
Exploring the Nature of Matter

Low Energy Measurements

$(Q^2 << M_z{}^2)$

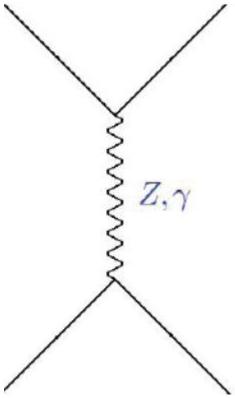
Sensitivity to new physics beyond the Standard Model

Unravelling “New Dynamics” in the Early Universe:

how did nuclear matter form and evolve?

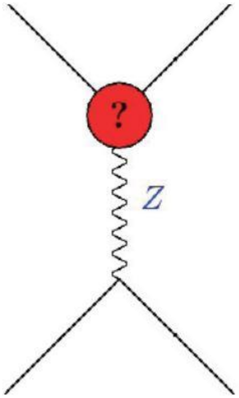
BSM: Symmetry violation with Electrons

- Lepton number
- Time reversal symmetry
- Charged Lepton Flavor
- **Parity violation with Flavor conservation**



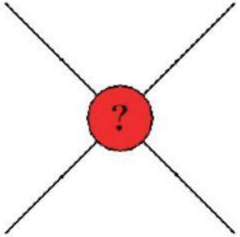
Extra Z

+



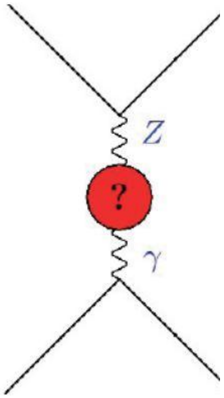
Mixing with Dark photon or Dark Z

+



Contact interaction

+

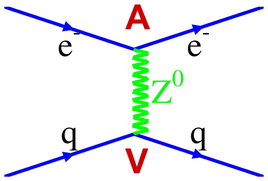


New Fermions

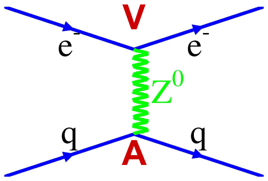
Look for tiny but measurable deviations from precisely calculable predictions from SM process

Observed PV: (SM+BSM) effect

Weak Neutral Current (WNC) Couplings



$$C_{1i} \equiv 2 g_A^e g_V^i$$



$$C_{2i} \equiv 2 g_V^e g_A^i$$

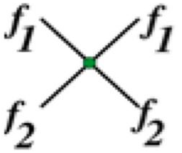
$$L^{PV} = \frac{G_F}{\sqrt{2}} [\bar{e}\gamma^\mu\gamma_5 e (C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e (C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)] + C_{ee}(e\gamma^\mu\gamma_5 e \bar{e}\gamma_\mu e)$$

SM relations

$$\begin{array}{lcrcr}
C_{1u} & = & -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W & \approx & -0.19 \\
C_{1d} & = & \frac{1}{2}-\frac{2}{3}\sin^2\theta_W & \approx & 0.35 \\
C_{2u} & = & -\frac{1}{2}+2\sin^2\theta_W & \approx & -0.04 \\
C_{2d} & = & \frac{1}{2}-2\sin^2\theta_W & \approx & 0.04
\end{array}$$

Precision weak-mixing angle measurements:
limits on the couplings

+ New Physics



$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

$$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

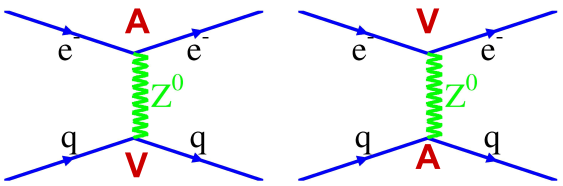
$$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2$$

$$L_{eff} = \frac{(g_{ij}^{12})^2}{(1+\delta)\Lambda^2} \sum_{i,j=L,R} \bar{f}_{1i}\gamma_u f_{1i} \bar{f}_{2i}\gamma^\mu f_{2j}$$

g - strength of the interaction

Λ - Scale of the new dynamics

Weak Neutral Current (WNC) Couplings



$C_{1i} \equiv 2 g_A^e g_V^i$ $\quad$ $C_{2i} \equiv 2 g_V^e g_A^i$

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

$$\begin{array}{lcrcr} C_{1u} & = & -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W & \approx & -0.19 \\ C_{1d} & = & \frac{1}{2}-\frac{2}{3}\sin^2\theta_W & \approx & 0.35 \\ C_{2u} & = & -\frac{1}{2}+2\sin^2\theta_W & \approx & -0.04 \\ C_{2d} & = & \frac{1}{2}-2\sin^2\theta_W & \approx & 0.04 \end{array}$$

$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$ $\rightarrow$ **Atomic parity violation, PV elastic e-N Scattering**

$$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$ $\rightarrow$ **PV deep inelastic scattering**

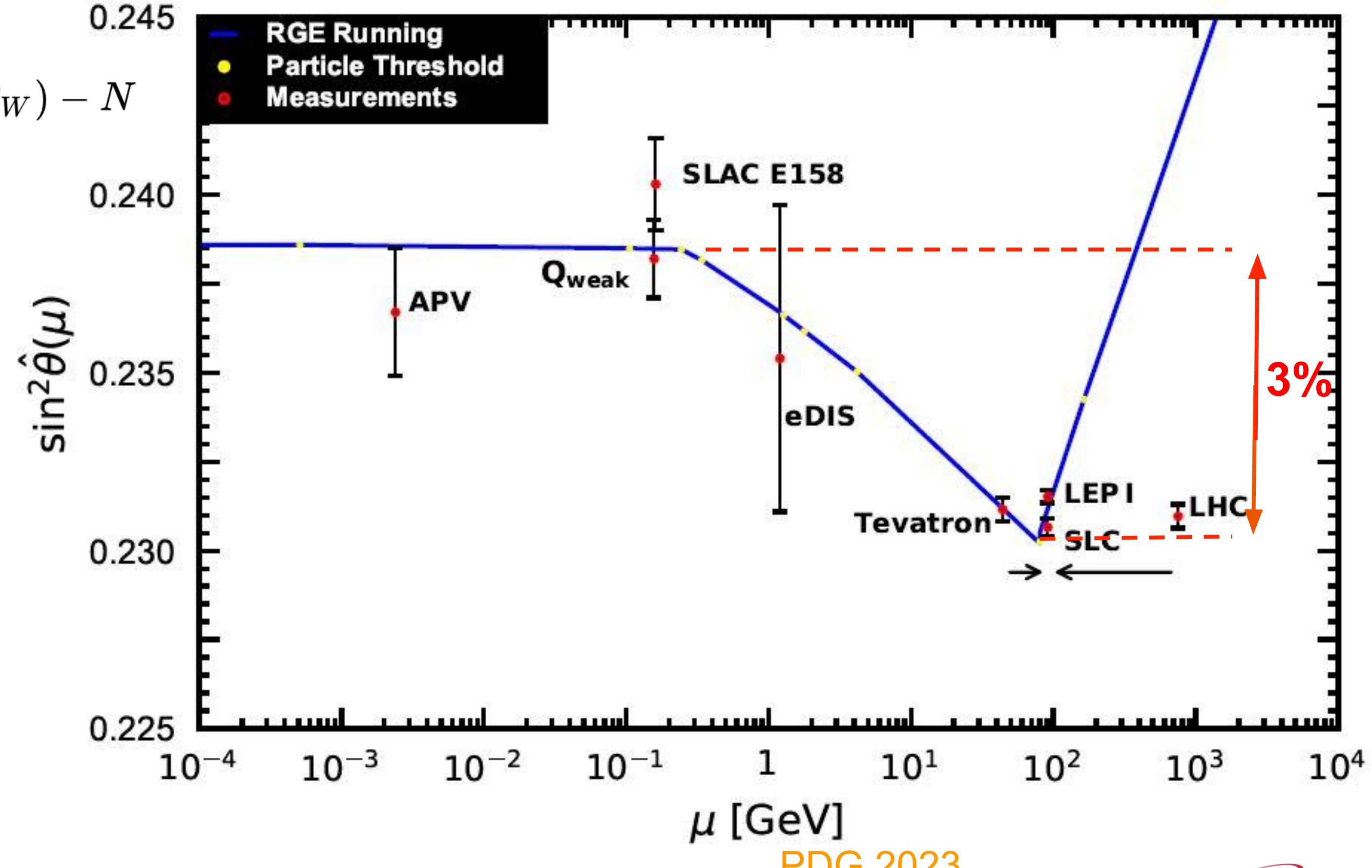
$$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2$$ $\rightarrow$ **PV Moller scattering**

Why low-energy ($Q^2 << M_Z^2$) measurements for the BSM search??

$$Q_W(Z,N) = Z(1 - 4sin^2\theta_W) - N$$

A 3% shift in $\sin^2\theta_W$ would imply 40% shift of $1\text{-}4\sin^2\theta_W$

Reduce the sensitivity of experimental uncertainty to the extracted quantity



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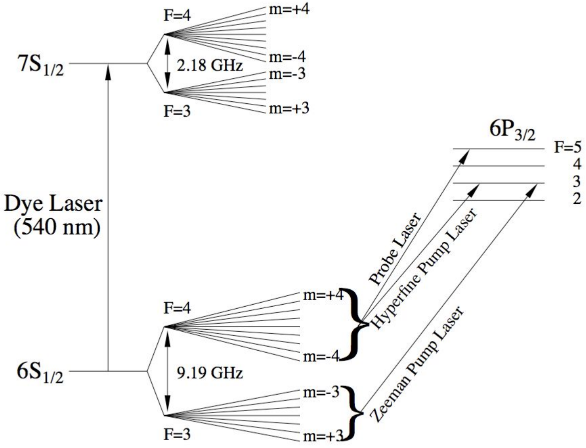
Existing Measurements:
Atomic Parity Violation: ^{133}Cs

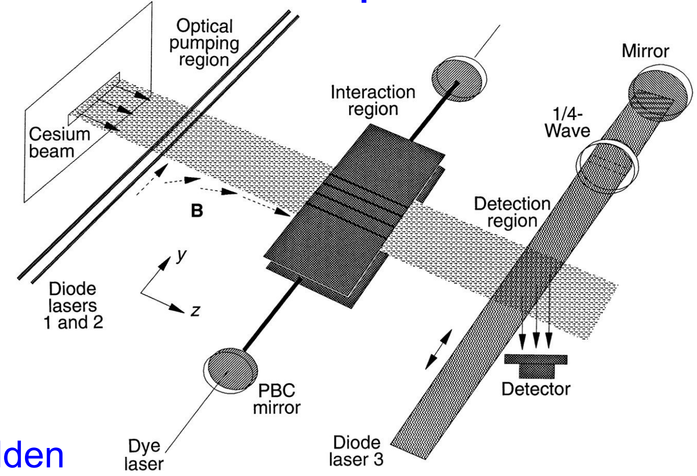
Atomic Parity Violation at Q=2.4 MeV

$$Q_W(Z,N) = Z(1-4sin^2\theta_W) - N$$

Partial Level Structure of Cs



Boulder Experiment



k_{PNC}

Atomic Theory

$0.9065\ (36) \times 10^{-11}\ ea_0$ -
1999

$0.8906\ (26) \times 10^{-11}\ ea_0$ -
2010

$0.8977\ (40) \times 10^{-11}\ ea_0$ -
2012

- 6S —>7S transition in ^{133}Cs is forbidden
- Weak charge - mixes S and P states
- Induced an E1 Stark transitions - measure the modulation of E1-PV interference

$Im(E1_{PNC})/\beta = 1.5935(56)$ mV/cm

$$Q_W = \left(\frac{E1_{PNC}/\beta}{M_{hf}/\beta}\right)\left(\frac{NM_{hf}}{k_{PNC}}\right)$$

$$sin^2\hat{\theta}_W(M_Z) = 0.2283(20)$$

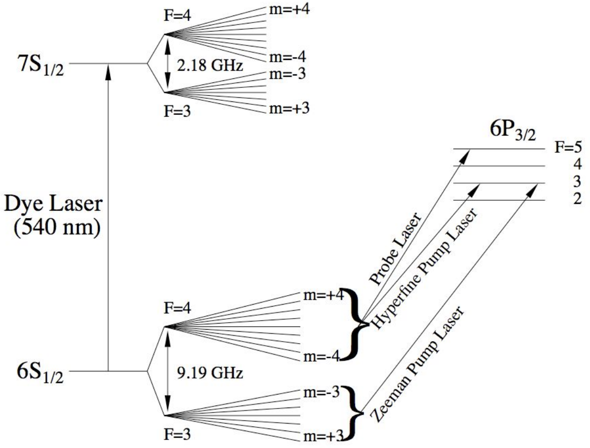
$$\frac{\delta(sin^2\hat{\theta}_W)}{sin^2\hat{\theta}_W} \sim 0.9\%$$

BSM mass sensitivity 9.9 TeV

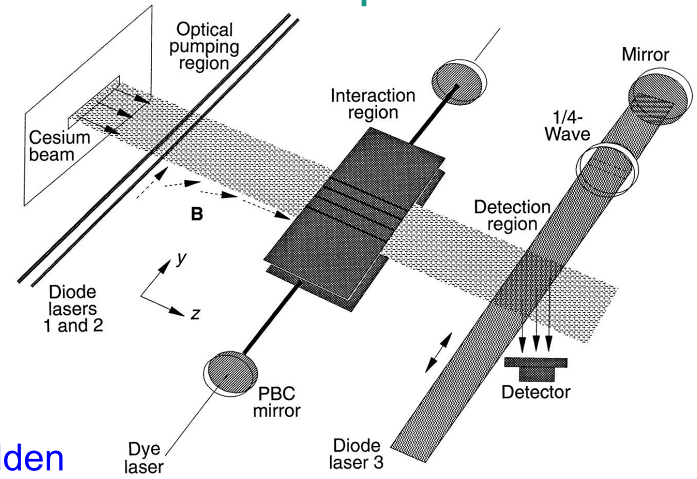
Atomic Parity Violation Q=2.4 MeV

$$Q_W(Z,N) = Z(1 - 4sin^2\theta_W) - N$$

Partial Level Structure of Cs



Boulder Experiment



New development

- **TRIUMF - Francium**
- **KVI - Ra+**
- **PREX/CREX results**
- **Theory - measurement on isotopic chain**

- 6S —>7S transition in ^{133}Cs is forbidden
- Weak charge - mixes S and P states
- Induced an E1 Stark transitions - measure the modulation of E1-PV interference

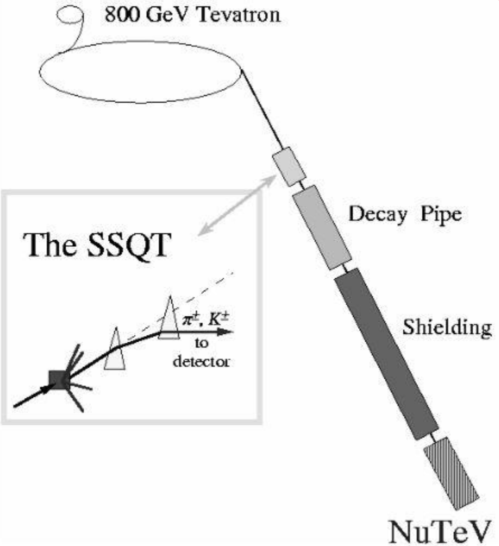
$\mathrm{Im}(E1_{PNC})/\beta = 1.5935(56)$ mV/cm

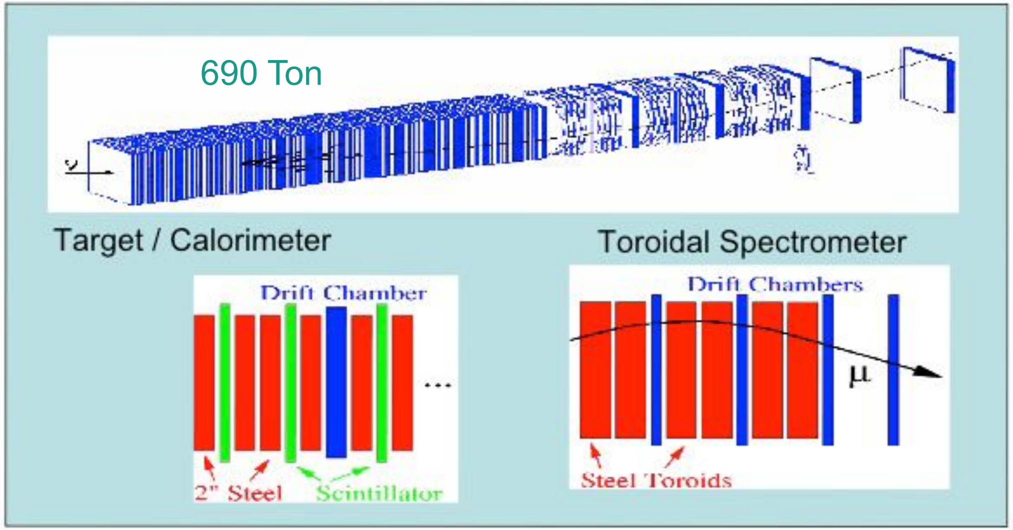
$$\frac{\delta(sin^2\hat{\theta}_W)}{sin^2\hat{\theta}_W} \sim 0.9\%$$

$$Q_W = (\frac{E1_{PNC}/\beta}{M_{hf}/\beta})(\frac{NM_{hf}}{k_{PNC}})$$

BSM mass sensitivity 9.9 TeV

NuTeV@ 4.47 GeV





- 800 GeV p at FNAL produce pi, K from interactions in BeO target;
- Decay of charged pi, K produces neutrinos, antineutrinos;
- Almost pure muon neutrinos;
- Only neutrinos penetrate shielding
- Dipoles select sign of charged meson:
  - Determine nu/nubar type

$$R^- = \frac{\sigma^{NC}_{\nu N} - \sigma^{NC}_{\bar{\nu} N}}{\sigma^{CC}_{\nu N} - \sigma^{CC}_{\bar{\nu} N}} \approx \rho^2\left(\frac{1}{2} - \sin^2\theta_W\right)$$

$$\boxed{\begin{aligned}\sin^2\theta_W^{(on-shell)} &= 0.2277 \pm 0.0013(stat.)\\ &\pm 0.0009(syst.)\end{aligned}}$$

Standard Model prediction is 0.2227
(3σ deviation)

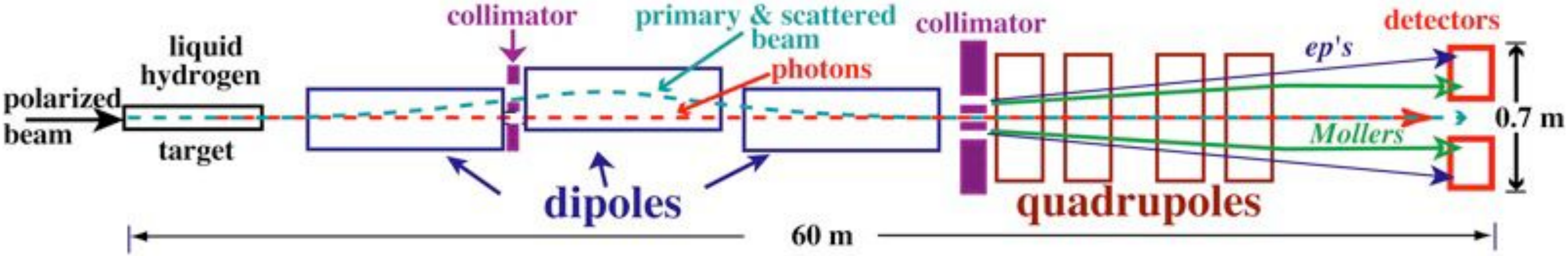
PRL 88 091802 (2002)

Physics Letters B 693 (2010) 462–466

Charge symmetry violation $+s\bar{s}$

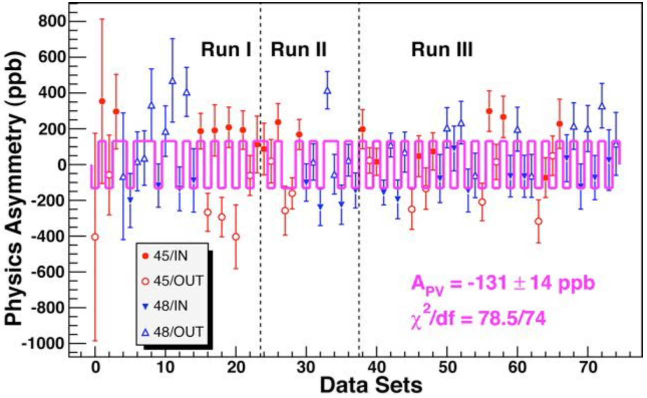
C_{ee}:
The purely leptonic interaction

SLAC E158 2002-2003

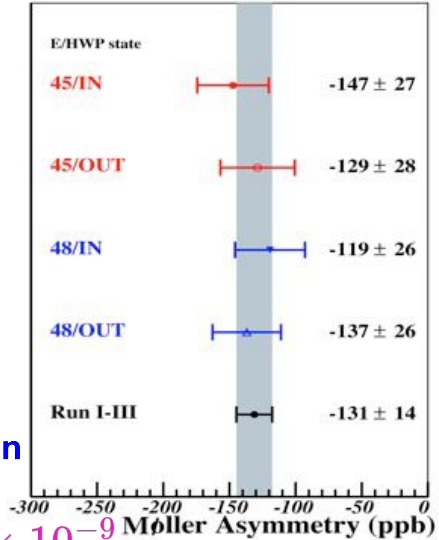


45/48 GeV Beam
85% long. Polarization

PRL 95 081601 (2005)



Slow reversal: IHWP, (g-2) precession



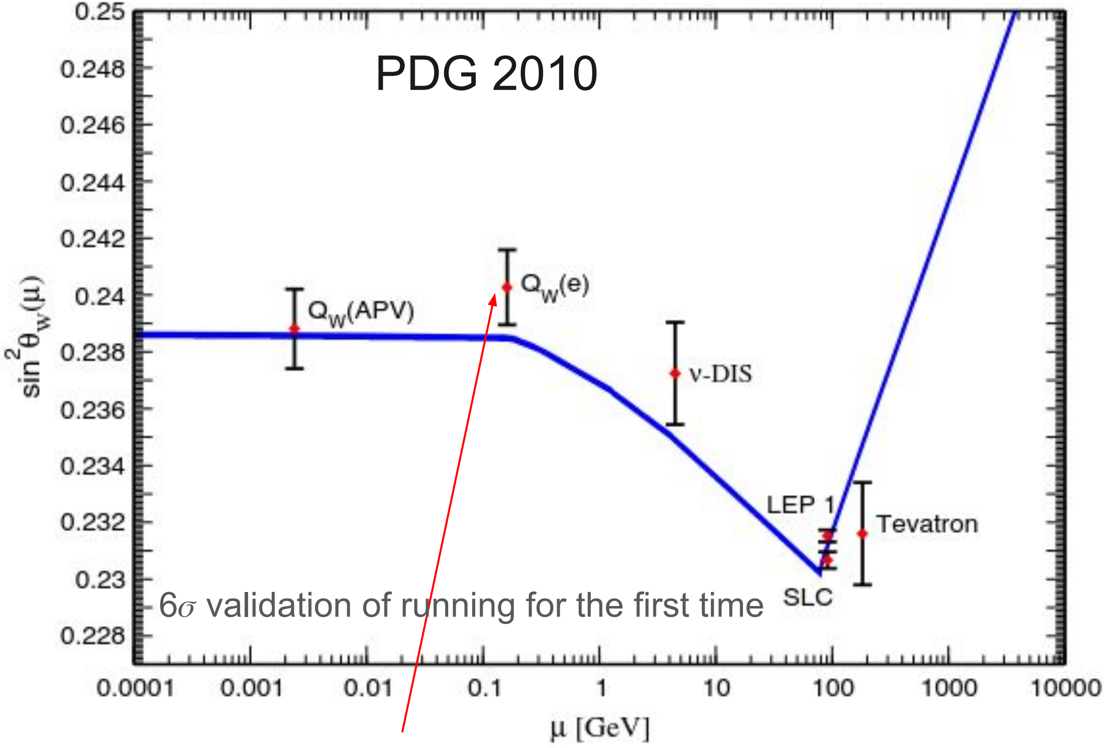
Technical challenges overcome: 10 nm beam position control, Max. beam current limit, Radiation dose, high rates

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

SLAC E158 -Results @ Q = 161 MeV

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

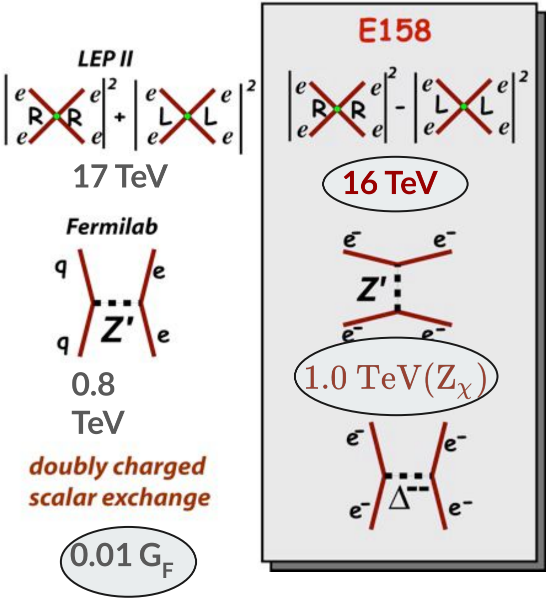
$$sin^2\hat{\theta}_W(M_Z) = 0.2330 \pm 0.0011(stat) \pm 0.0009(syst.) \pm 0.0006(theo.)$$



6σ validation of running for the first time

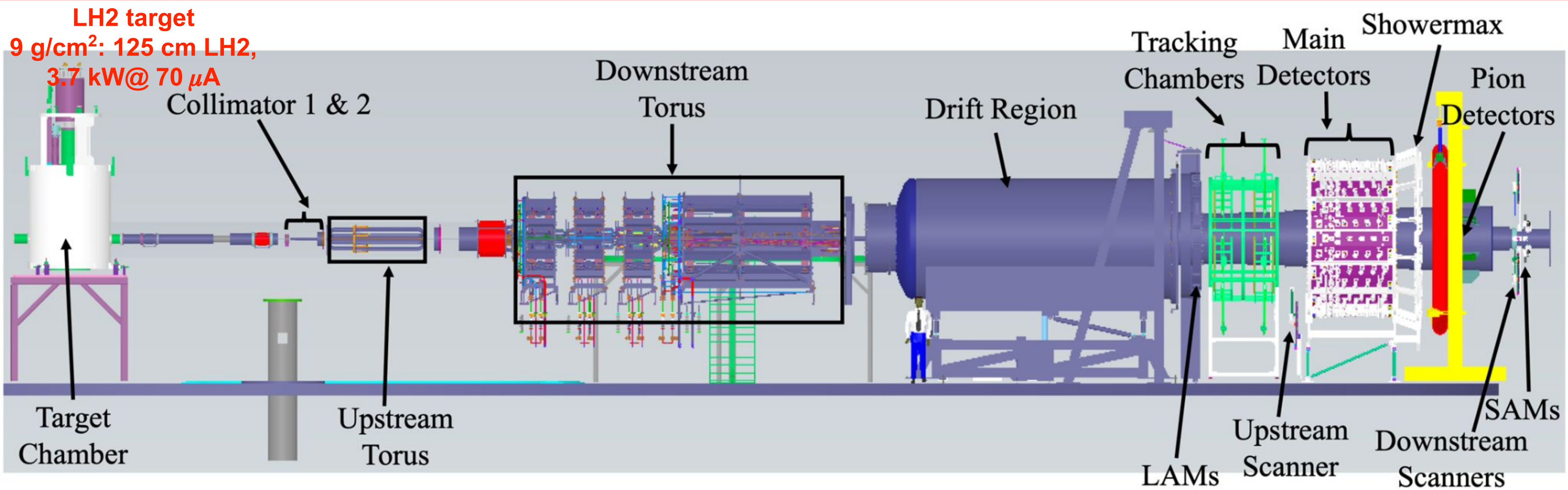
MOLLER: 5x improvement

- Statistics limited
- Theory uncet. under control.



MOLLER at JLab

MOLLER at JLab - A Special purpose installation in HallA



- Full Azimuthal acceptance ~ 5 mrad lab frame.
- 134 GHz Electron rate
- 1 nm control of beam centroid on target
- Robust and redundant 0.4% polarization
- Multiple slow reversals: IHWP, Wien filter, spin precession

A_{PV} ~ 32 ppb $\delta(A_{PV})$ ~ 0.8 ppb

$$\frac{\delta Q^e_W}{Q^e_W} = 2.4\%$$

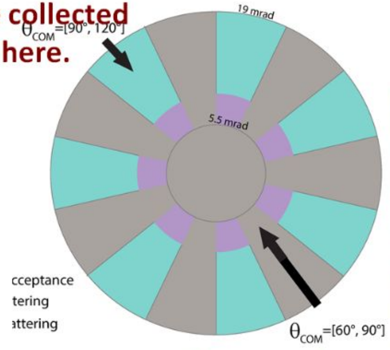
$$\delta(\sin^2\theta_W) = \pm\, 0.00023\ (stat.) \pm 0.00012\ (syst.)$$

~0.1% measurement

MOLLER measurement is the best among projected sensitivities for new measurements at low Q^2 or colliders over the next decade

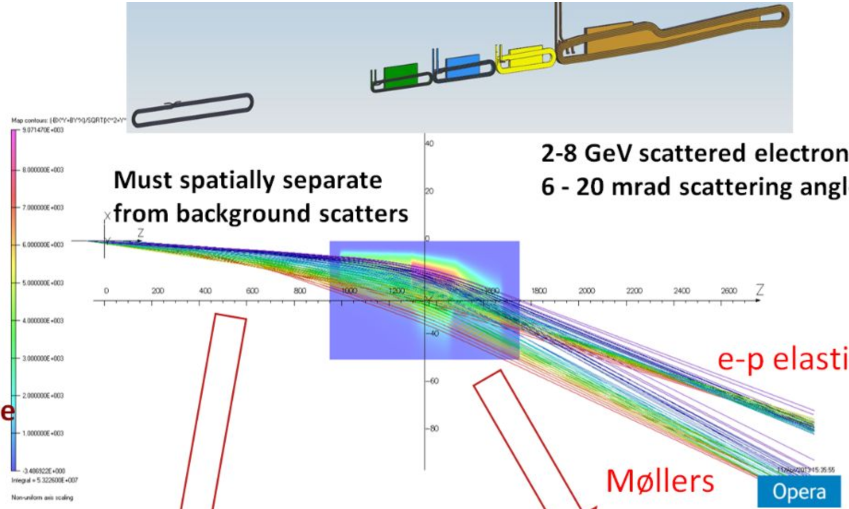
Spectrometer Acceptance and Collimation

- Accept all Møller scattered electrons in range Θ_{CM} = 50° – 130°
- **Exploit identical particle nature for 100% azimuthal acceptance**; needs odd number of coils



...are collected over here.

The rays that are blocked here...

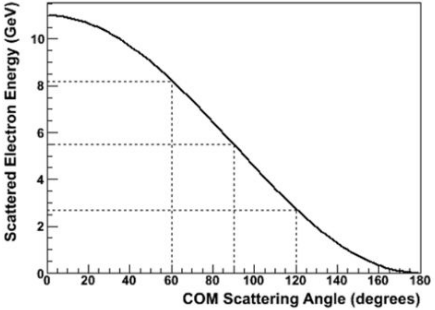


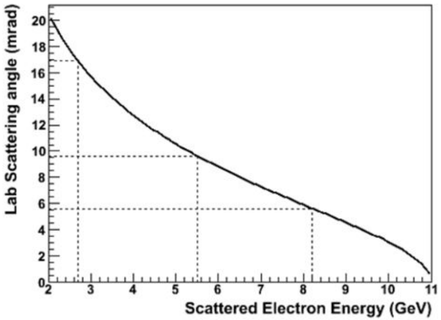
Must spatially separate from background scatters

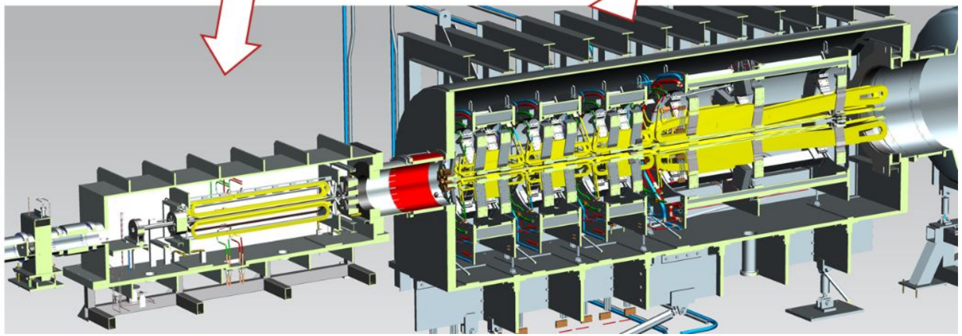
2-8 GeV scattered electrons
6 - 20 mrad scattering angle

e-p elastic

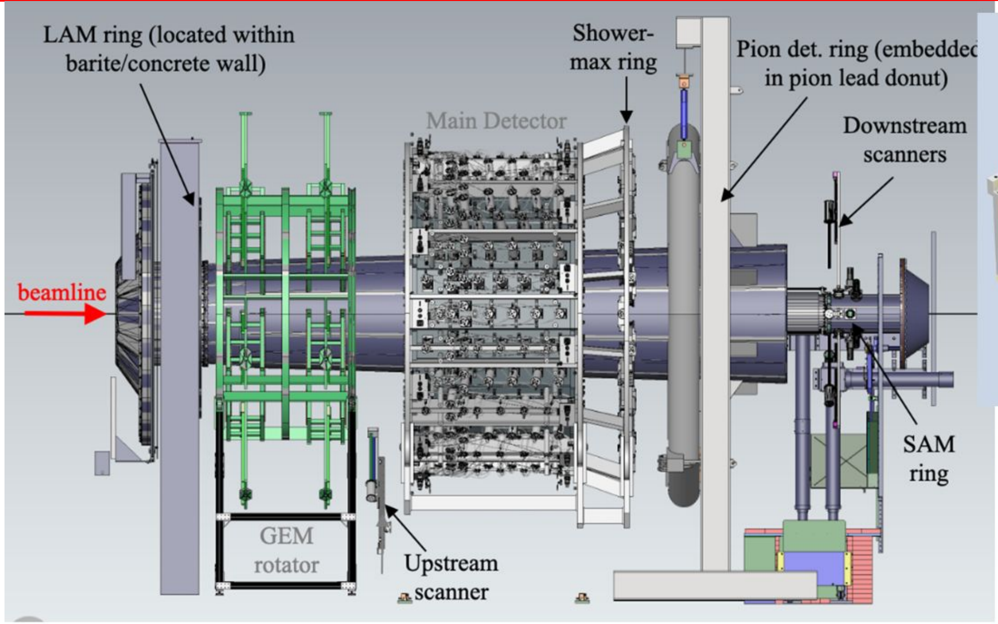
Møllers

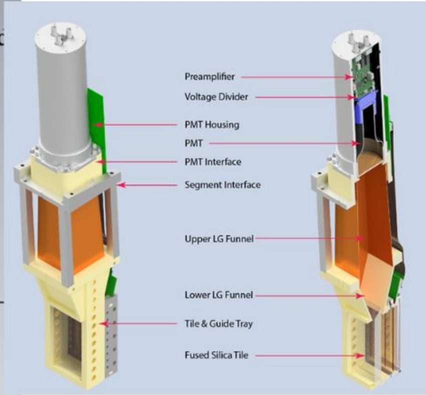




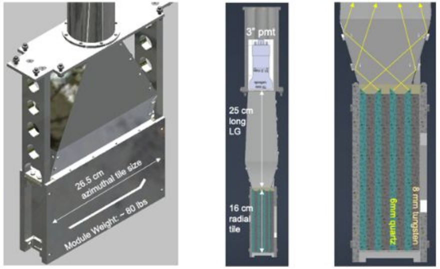


MOLLER Detectors





Requirement for Ring 5:
Detector resolution < 25%
excess noise < 4%



Integrating (current mode) detectors:

asymmetry measurements of both signal and background, and beam and target monitoring

Tracking (counting mode) detectors:

spectrometer calibration, electron scattering angle distribution, and background measurements

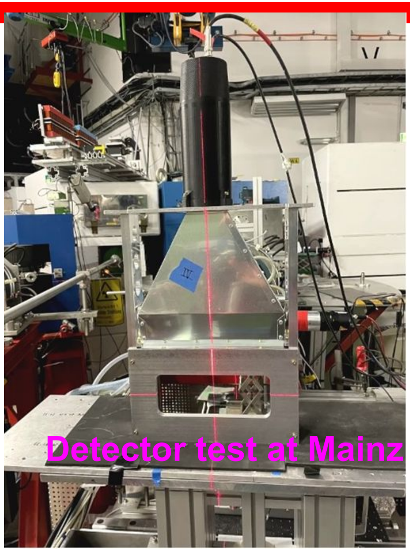
- Gas electron multipliers (GEM) detectors
- "Pion" acrylic Cherenkov detectors

Readout Electronics:

- Integration mode DAQ & trigger
  - *Collect & analyaize100% of the helicity windows*
- Counting mode DAQ & trigger
  - *input rates between 10~kHz and 300~kHz*

MOLLER Status - Currently at construction phase

- ~50M$ MIE by US DOE
- CD-1 granted on Dec-2020
- CD-2/3 review on Oct 2023.
- **Construction:2024-2025**
- Installation: 2026
- Commissioning: Summer 2026
- **Physics run: thru 2028**



Detector test at Mainz

Prototype Frame for DS Magnet

Pressure test

INSTITUTE for NUCLEAR THEORY

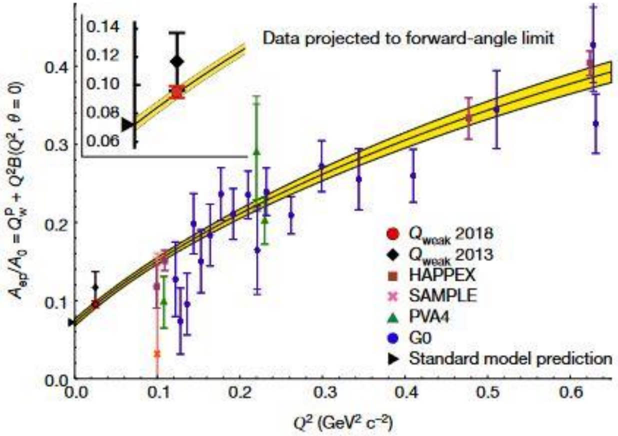
Jefferson Lab
Exploring the Nature of Matter

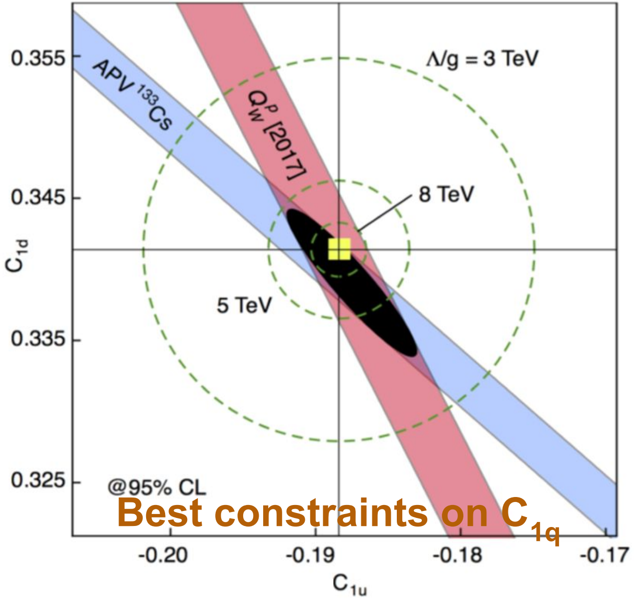
Qweak:
The axial-vector coupling

Qweak @ JLab - 4% measurement

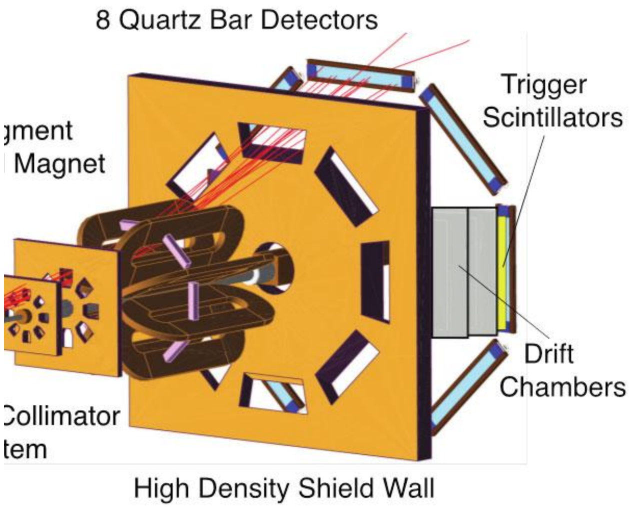
$$A_{eP}/A_0 = Q_W^p + Q^2 B(Q^2,\theta)$$

Beam energy = 1.165 GeV, 180 uA
5.8 - 11.6 deg scattered electrons





Best constraints on C_{1q}



$$A_{eP} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = 226.5 \pm 8.3(stat) \pm 5.8(syst)ppb$$

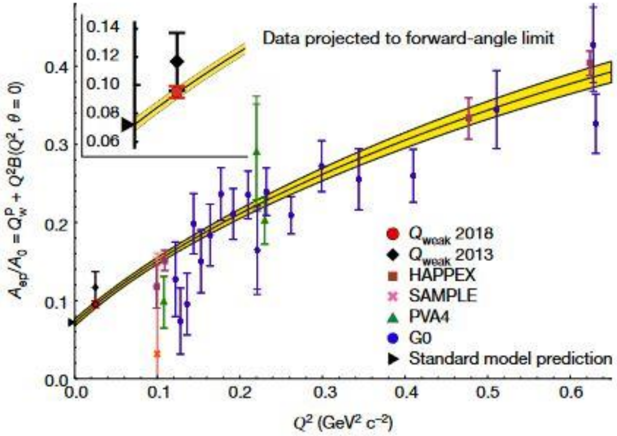
$$Q_W^p = -2(2C_{1u} + C_{1d}) = 0.0719 \pm 0.0045$$

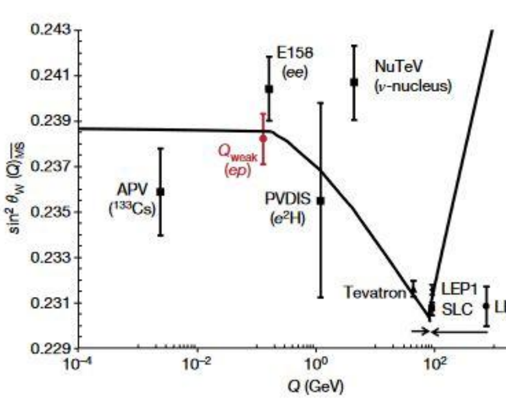
Nature 557 207 (2018)

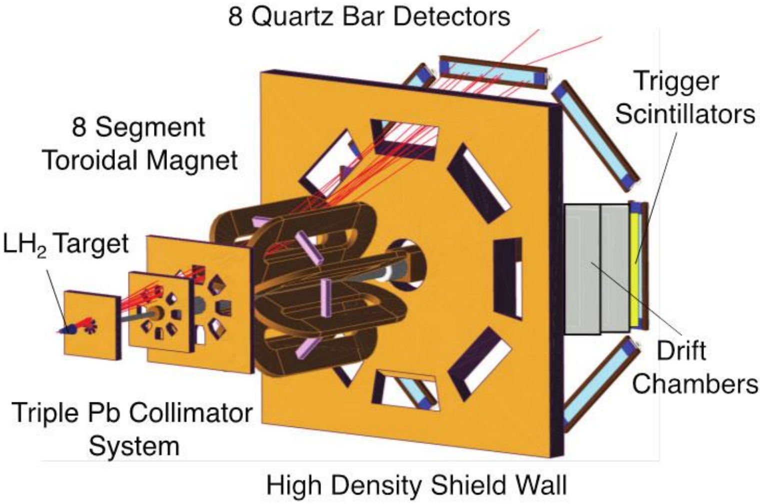
Qweak @ JLab - 4% measurement

$$A_{eP}/A_0 = Q_W^p + Q^2 B(Q^2, \theta)$$

Beam energy = 1.165 GeV, 180 uA 35 cm LH2 target (3 kW), 5.8 - 11.6 deg scattered electrons, Q = 158 MeV







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$$Q_W^p = -2(2C_{1u} + C_{1d}) = 0.0719 \pm 0.0045$$

$$sin^2\hat{\theta}_W(0) = 0.2383 \pm 0.0011$$

Agreement with SM prediction

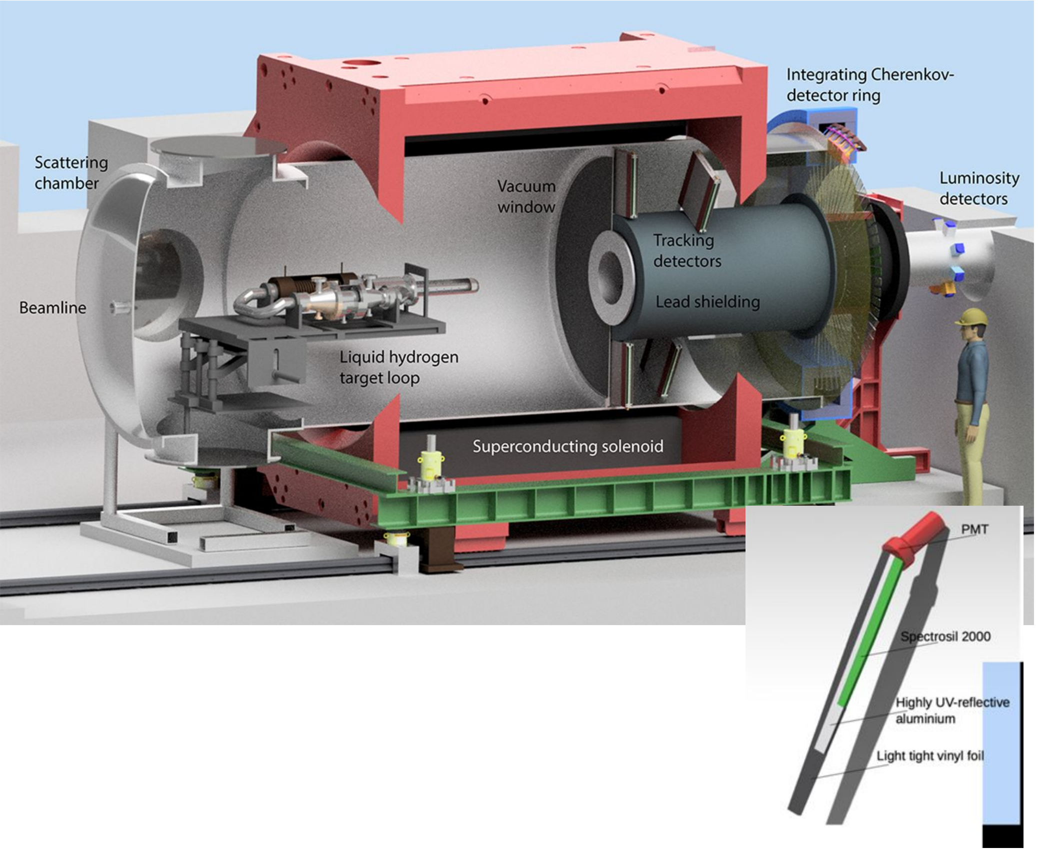
Nature 557 207 (2018)

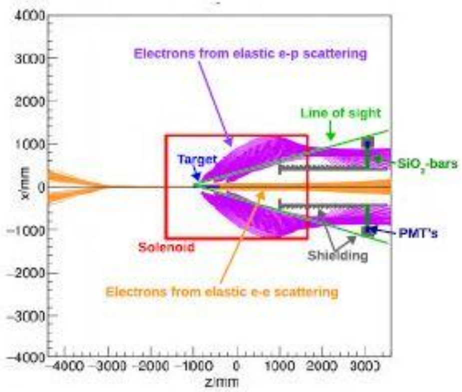
INSTITUTE for NUCLEAR THEORY

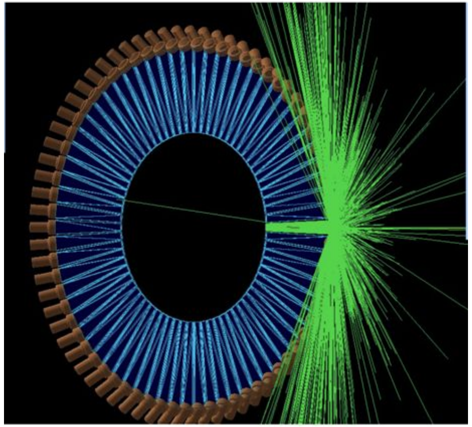
Jefferson Lab
Exploring the Nature of Matter

P2 at MESA:
3x better Proton weak charge measurement

P2 at MESA @ Q = 67 MeV



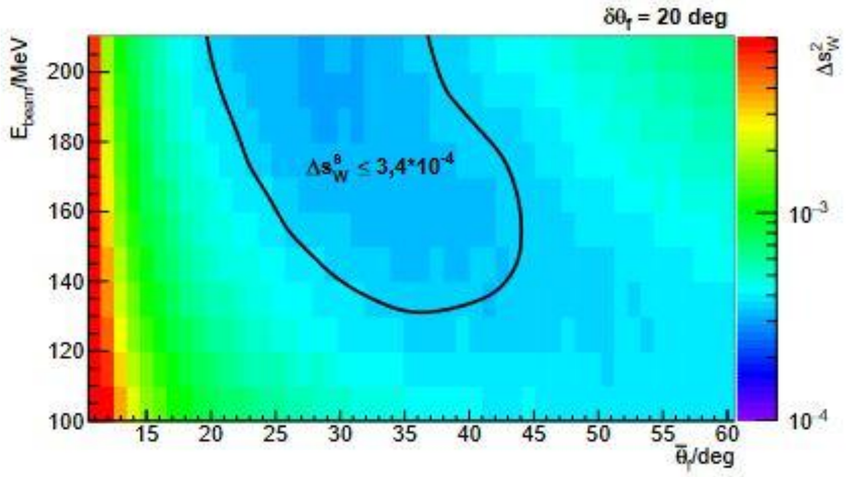


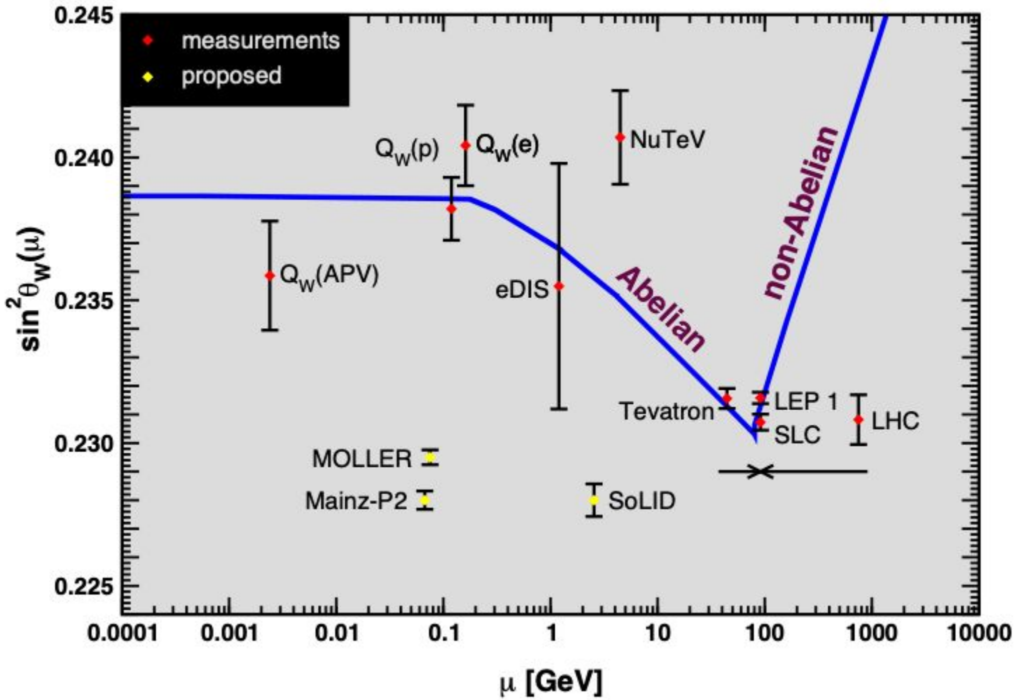


P2@MESA hydrogen
A_{ep}=-28 ppb
ΔA_{ep}= 0.5 ppb ppb=1/√N Factor 19 After 11,000 h
$\Delta A_{ep}/A_{ep}$= 1.8 %
$\Delta\sin^2\theta_W/\sin^2\theta_W$= 0.15 %

60 cm LH2 target *155 MeV, 150 μA* *90% beam polarization*

P2 at MESA



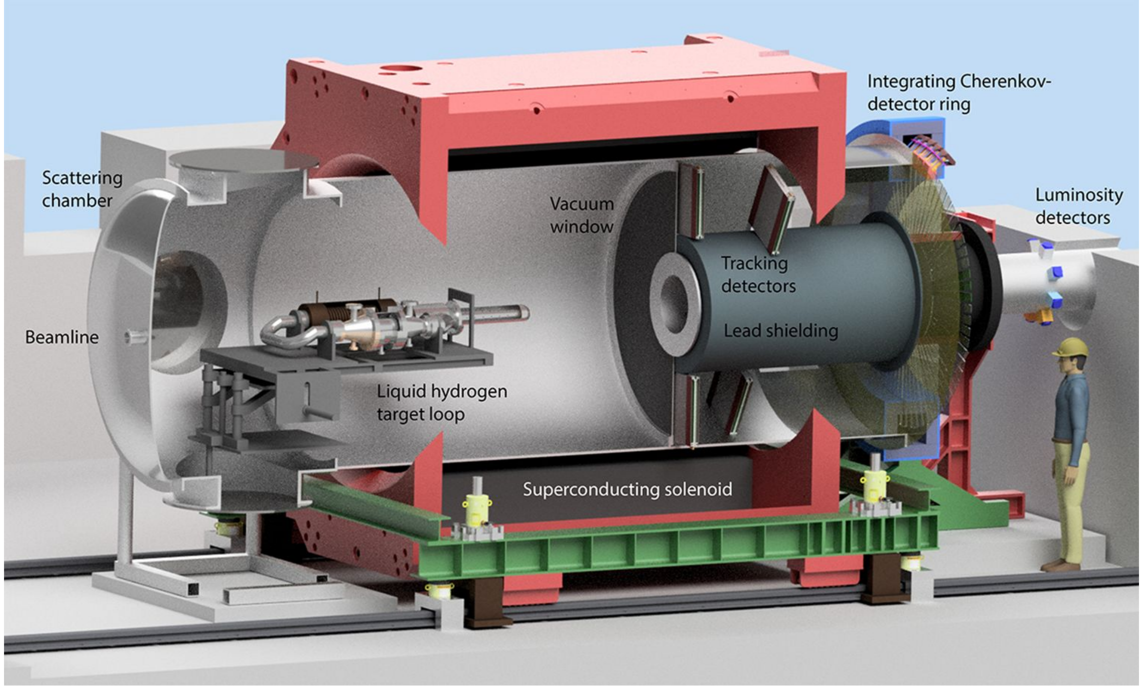


155 MeV - 150 uA beam on 60 cm LH2 target - 35 deg central scattering angle (Q = 67 MeV) - 10000h of data taking

Sensitivity test of SM ~ 50 TeV - extendable to 60 TeV

Eur. Phys. J. A. 54 208 (2018)

C12 Weak charge measurement at MESA



P2@MESA hydrogen	P2@MESA carbon
A_{ep}=-28 ppb	A_{ep}= 416.3 ppb
ΔA_{ep}= 0.5 ppb ppb=1/√N Factor 19 After 11,000 h	ΔA_{ep}^{stat}= 2.7 ppb after 300 h ΔA_{ep}^{stat}= 0.9 ppb after 2500 h
$\Delta A_{ep}/A_{ep}$= 1.8 %	$\Delta A_{ep}/A_{ep}^{stat}$= 0.6 % (0.2 %) Polarimetry!
$\Delta \sin^2\theta_W/\sin^2\theta_W$= 0.15 %	$\Delta \sin^2\theta_W/\sin^2\theta_W$= 0.6 %

MIT-Bates C12 Weak measurement ~ 25%

EBeam = 150 MeV,
Scatt. Angle =40 deg.

Sensitive to light dark Z-boson

A Decade-Long Ring PVES Program at MESA!!

- **Hydrogen** at **forward** **angles:**
  $A_{PV} \rightarrow Q_W(p) \rightarrow \sin^2\theta_W \rightarrow$ BSM physics?

$$\sin^2\theta_W \approx \frac{1-Q_{\rm W}}{4}$$

Proton structure - << 1 at small Q^2

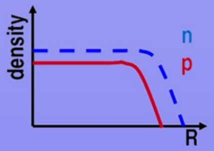
$$A_{\rm PV} = \frac{G_{\rm F}Q^2}{4\sqrt{2}\pi\alpha_{\rm em}}\left(Q_{\rm W} - F(Q^2)\right)$$

Hadronic structure of proton sizable at not-so-small Q^2

- **Hydrogen + Deuterium** at **backward** **angles:**
  $A_{PV} \rightarrow$ axial FF + strange contribution to magnetic FF

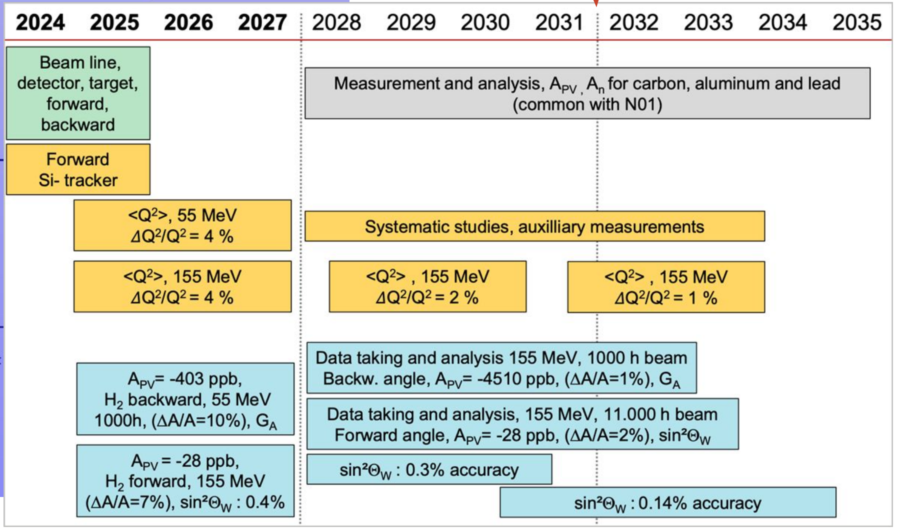
- **Carbon:**
  $A_{PV} \rightarrow Q_W(^{12}C) = -24 \sin^2\theta_W$
  Complementary sensitivity to BSM physics

- **Lead:**
  $A_{PV} \rightarrow F_{weak}(Q^2)$
  → neutron radius
  → neutron skin thickness
  related to the
  → symmetry energy - nuclear Equation of State,
  e.g., → modeling of neutron stars



$A_{\rm PV} = -$
4

Notional Schedule of physics measurement campaign



2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035

Beam line, detector, target, forward, backward

Forward Si- tracker

Measurement and analysis, A_{PV}, A_n for carbon, aluminum and lead (common with N01)

$<Q^2>$, 55 MeV $\Delta Q^2/Q^2 = 4$ %

Systematic studies, auxilliary measurements

$<Q^2>$, 155 MeV $\Delta Q^2/Q^2 = 4$ %

$<Q^2>$, 155 MeV $\Delta Q^2/Q^2 = 2$ %

$<Q^2>$, 155 MeV $\Delta Q^2/Q^2 = 1$ %

A_{PV}= -403 ppb, H_2 backward, 55 MeV 1000h, ($\Delta A/A$=10%), G_A

Data taking and analysis 155 MeV, 1000 h beam Backw. angle, A_{PV}= -4510 ppb, ($\Delta A/A$=1%), G_A

Data taking and analysis, 155 MeV, 11.000 h beam Forward angle, A_{PV}= -28 ppb, ($\Delta A/A$=2%), $\sin^2\Theta_W$

A_{PV} = -28 ppb, H_2 forward, 155 MeV ($\Delta A/A$=7%), $\sin^2\Theta_W$: 0.4%

$\sin^2\Theta_W$: 0.3% accuracy

$\sin^2\Theta_W$: 0.14% accuracy

PVDIS:
Measurements of the Vector-Axial couplings

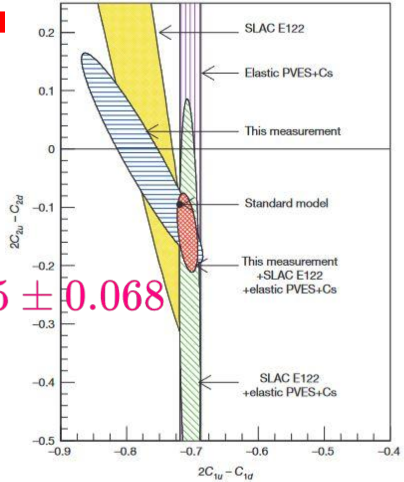
First measurement: E122

PVDIS - Existing Data (e,D) from 6 GeV JLab era

$$A_{PV}(PVDIS) = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$
$$= \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{EM}}\left[a_1(x,Q^2)Y_1(x,y,Q^2) + a_3(x,Q^2)Y_3(x,y,Q^2)\right]$$

$$a_1 = \frac{6}{5}(2C_{1u} - C_{1d})$$
$$a_3 = \frac{6}{5}(2C_{2u} - C_{2d})$$

$$(2C_{2q} - C_{2d})|_{Q^2=0} = -0.145 \pm 0.068$$



At large $y = (E-E')/E$, the A_{PV} is sensitive to C_{2q}

selectively chosen DIS region

$A_{PV} = -91.1(3.1(\text{stat}),3.0(\text{sys.})) \times 10^{-6}$ (4.3%)

Nature 506 67 (2014)

PVDIS - Existing Data (e,D) from 6 GeV JLab era

$$A_{PV}(PVDIS) = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$= \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{EM}}\left[a_1(x,Q^2)Y_1(x,y,Q^2) + a_3(x,Q^2)Y_3(x,y,Q^2)\right]$$

$$a_1 = \frac{6}{5}(2C_{1u} - C_{1d})$$

$$a_3 = \frac{6}{5}(2C_{2u} - C_{2d})$$

$$(2C_{2q} - C_{2d})|_{Q^2=0} = -0.145 \pm 0.068$$

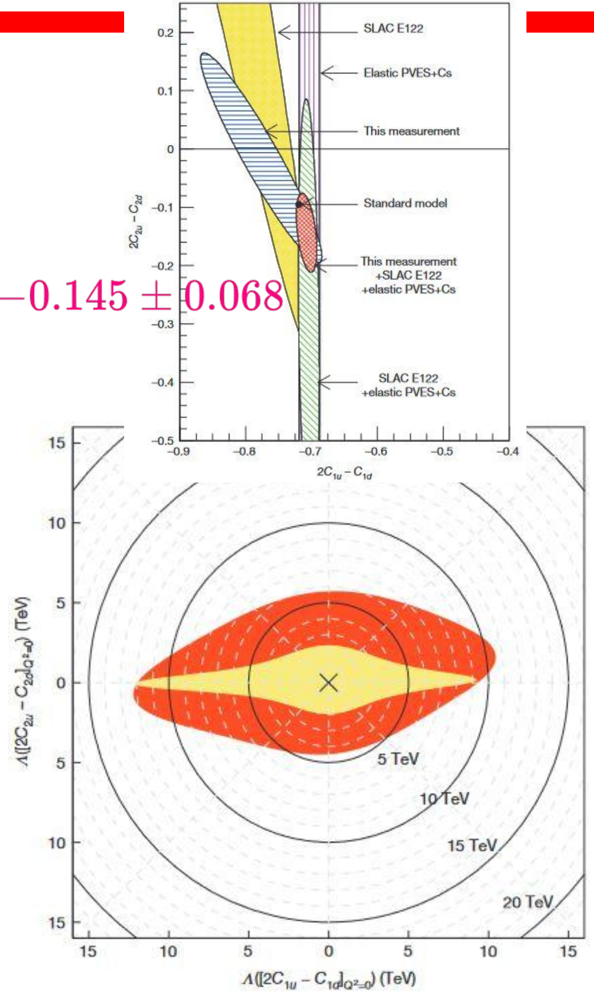
At large *y* = *(E-E')/E*, the A_{PV} is sensitive to C_{2q}

selectively chosen DIS region

A_{PV} = -91.1(3.1(stat),3.0(sys.)) x 10^{-6} (4.3%)

$$\sin^2\hat{\theta}_w = 0.2299 \pm 0.0043 (1.9\%)$$

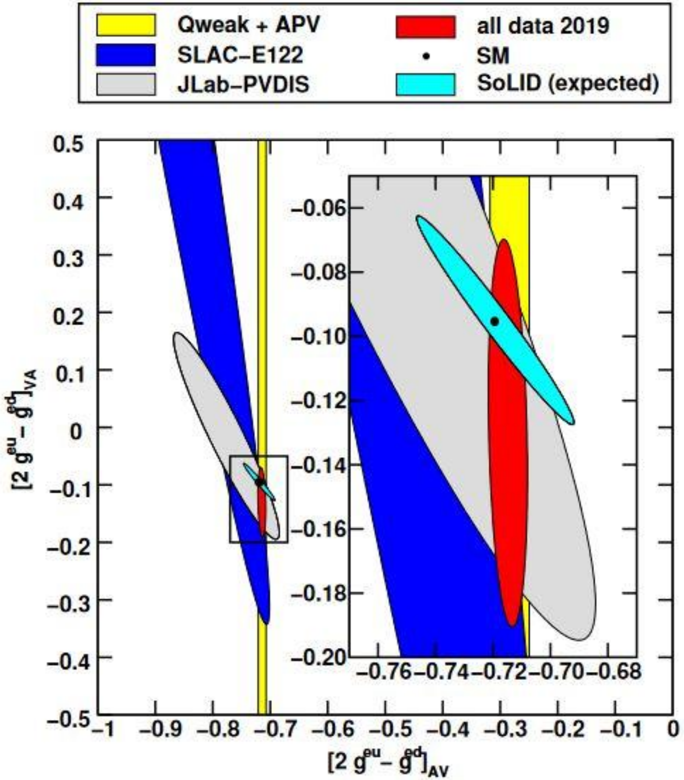
Mass scale of new physics ~ 10 TeV!

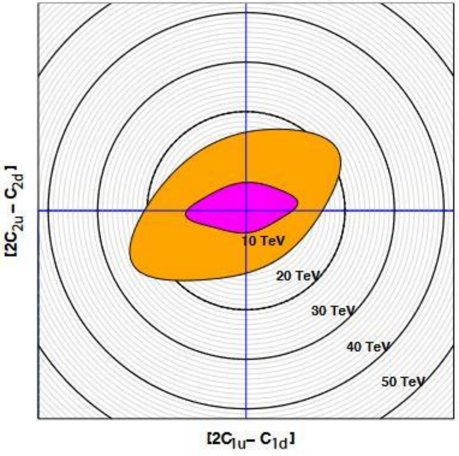


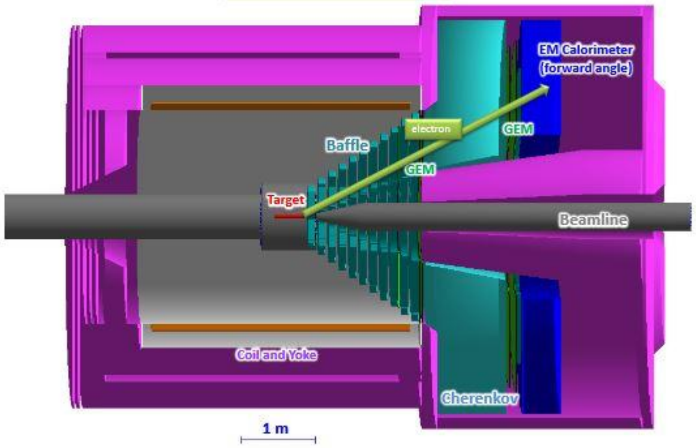
Nature 506 67 (2014)

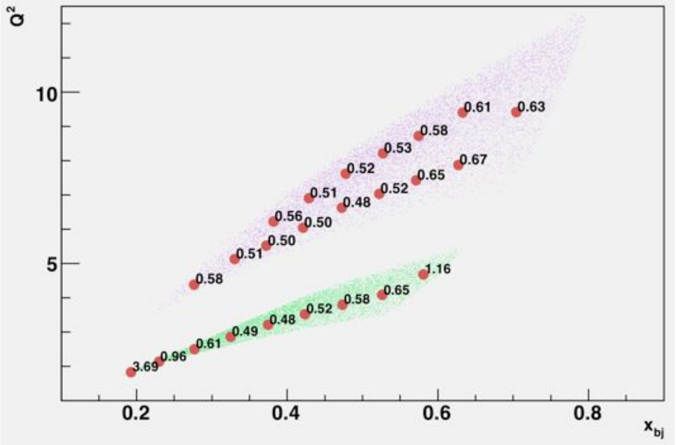
PVDIS @ SoLID:
Large Kinematic Coverage

PVDIS @ SoLID



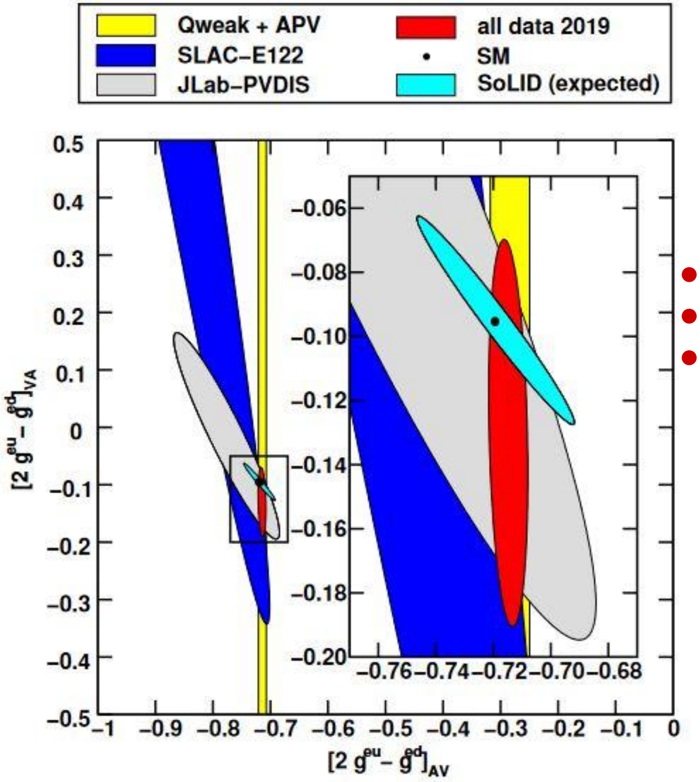




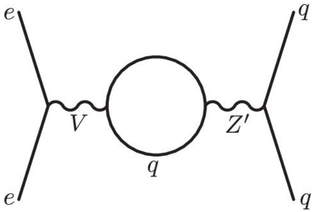


New physics reach of SoLID (with existing data) ~ 20 TeV

PVDIS @ SoLID - Installation will start just after MOLLER.



Leptophobic z’

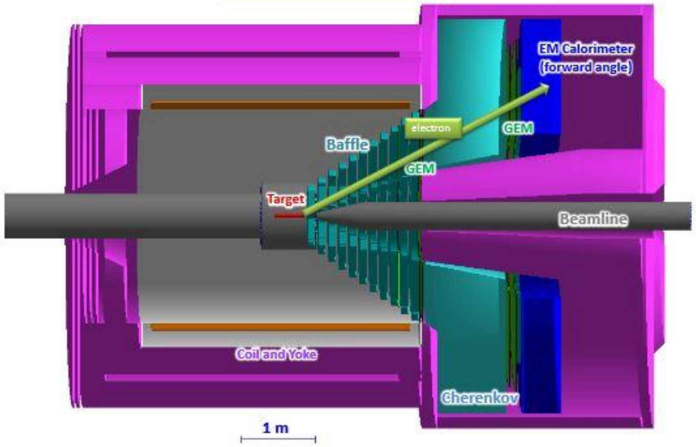


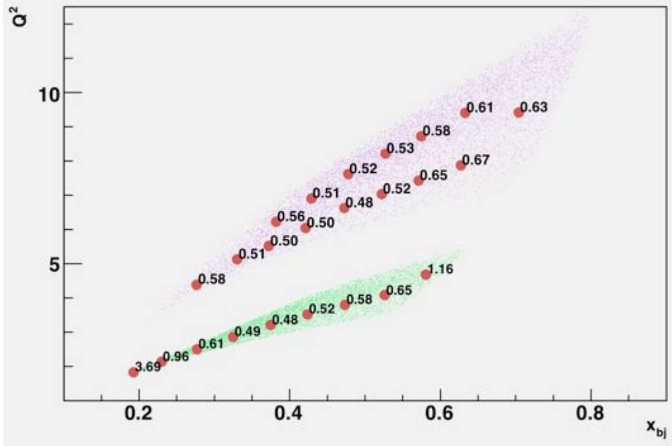
- Virtually all GUT models predict
- LHC reach ~ 5TeV
- Little sensitivity if Z’ doesn’t couple to leptons

Since e-vertex must be vector, the Z’ can’t couple to the C_{1q} if there is no electron coupling: can only affect C_{2q}’s

Current limit <100 GeV

SoLID can improve sensitivity: 100-200 GeV range





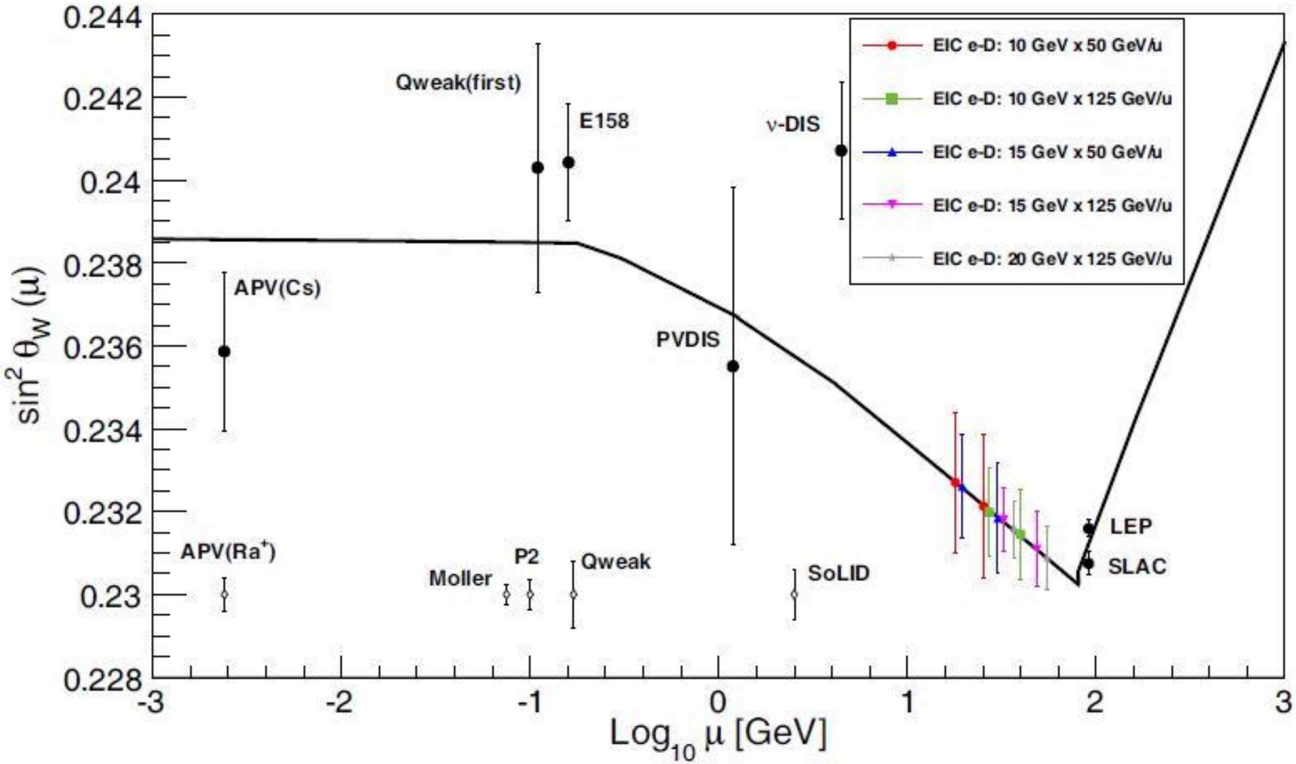
Running of Weak-mixing angle at EIC - PVDIS

- Polarized e on p
  - DIS regime (not like P2)
  - Required precise knowledge of PDFs
- Polarized e on d
  - Isoscalar target - Reduced need for precision PDF input

Zhao, Deshpande, Huang, Kumar, Riordan

-Performed Simulations at EIC

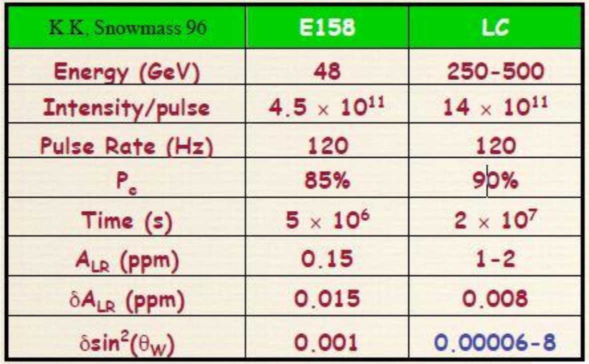
Talk from Michael Nycz



Eur. Phys. J. A 53 55 (2017)

Other possibilities

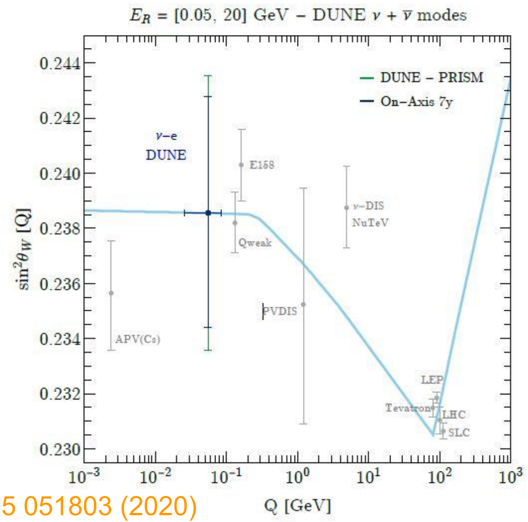
- Moller scattering at an ILC
    - Fixed target Moller scattering - Order of magnitude better than MOLLER.
    - Timeline????



K.K. Snowmass 96	E158	LC
Energy (GeV)	48	250-500
Intensity/pulse	4.5×10^{11}	14×10^{11}
Pulse Rate (Hz)	120	120
P_e	85%	90%
Time (s)	5×10^6	2×10^7
A_{LR} (ppm)	0.15	1-2
δA_{LR} (ppm)	0.015	0.008
$\delta \sin^2(\theta_W)$	0.001	0.00006-8

- Weak mixing angle at DUNE:
    - High neutrino beam intensities
    - Relatively smaller uncertainty for neutrino-electron than neutrino-nucleus scattering
- Challenges:
    - Neutrino-electron cross-section is three order smaller than neutrino-nucleus scattering - statistics
    - Flux and energy distribution of neutrinos
        - PRISM (near detector) - moves perpendicular to the beam - on- and off- axis measurements

75 ton LAr TPC; 1.2MW proton beam with 7 yrs of data taking -2% measurement of $\sin^2\theta_W$

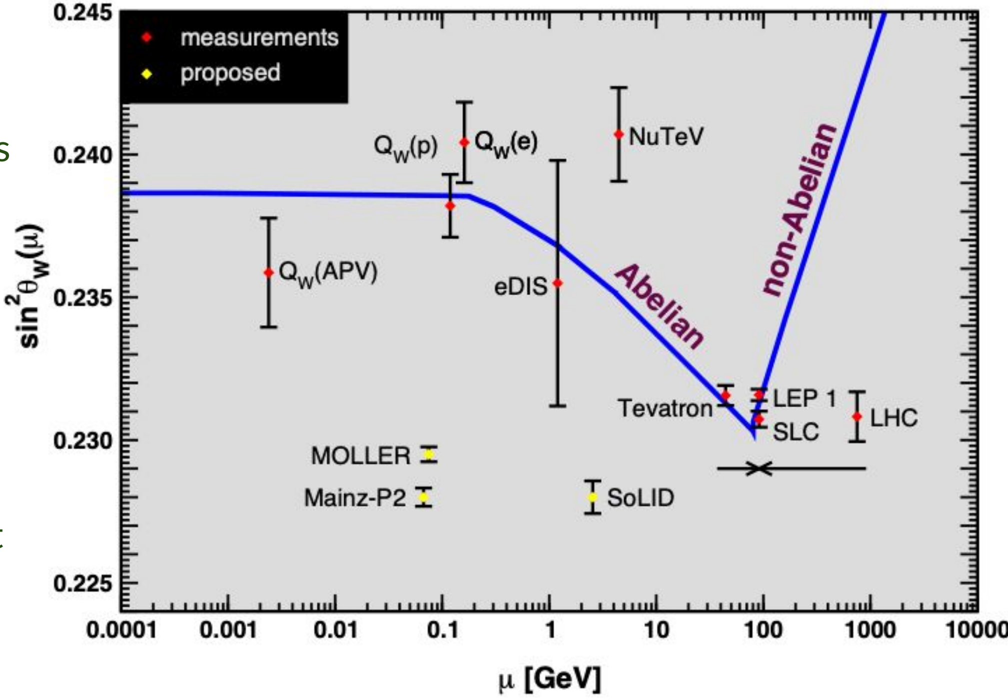


PRL 125 051803 (2020)

- FEC-ee, CEPC - timeline..

Summary

- **Measurements of the Weak Mixing Angle**
  - ➢ Central to our understanding of the SM
  - ➢ Likely remain central in our search for new physics
- **A problem involving (both experimentalists and theorists) - Atomic, nuclear, higher-energy, neutrino..**
  - ➢ Challenging and exciting future for everyone..
- **Upcoming facilities, upgrade**
  - ➢ Pushing measurements to well below sub-percent levels
  - ➢ Reaching to limits where more robust theory calculation required



A remarkably productive research program that will continue to flourish over the next decade