The MOLLER Experiment

Overview of the Physics Motivation

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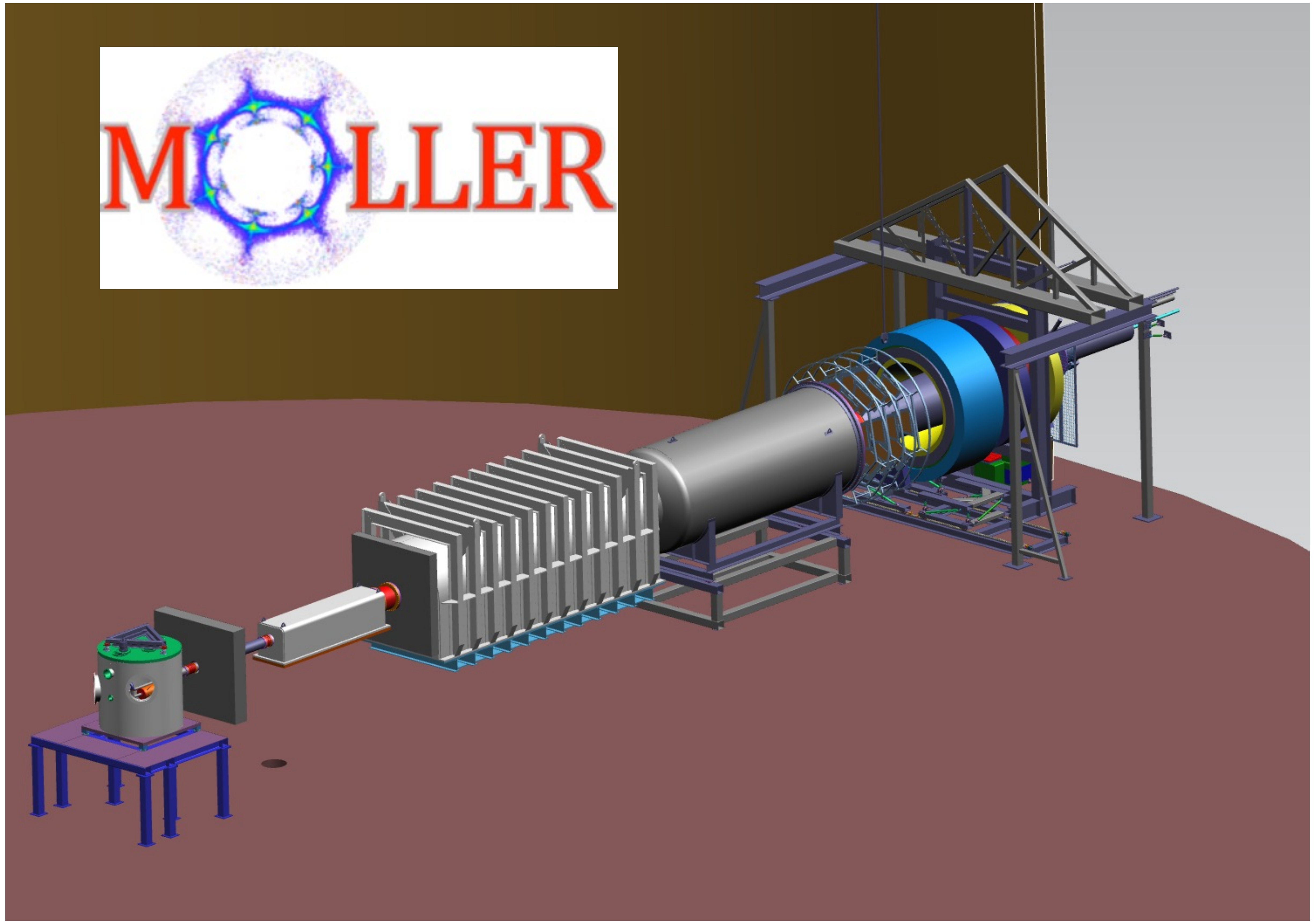
Tuesday, November 2, 2021



Outline

- **MOLLER Discovery Reach**
  - The MOLLER observable and New Interactions
- **Global Context for MOLLER**
  - Comparison to Collider Discovery Reach
  - Theoretical cleanliness and radiative corrections
  - Techniques to Measure the The Weak Mixing Angle at Low Energy
  - Lepton-Lepton Scattering at Existing, Planned or Potential Facilities
  - Equipment Alternatives

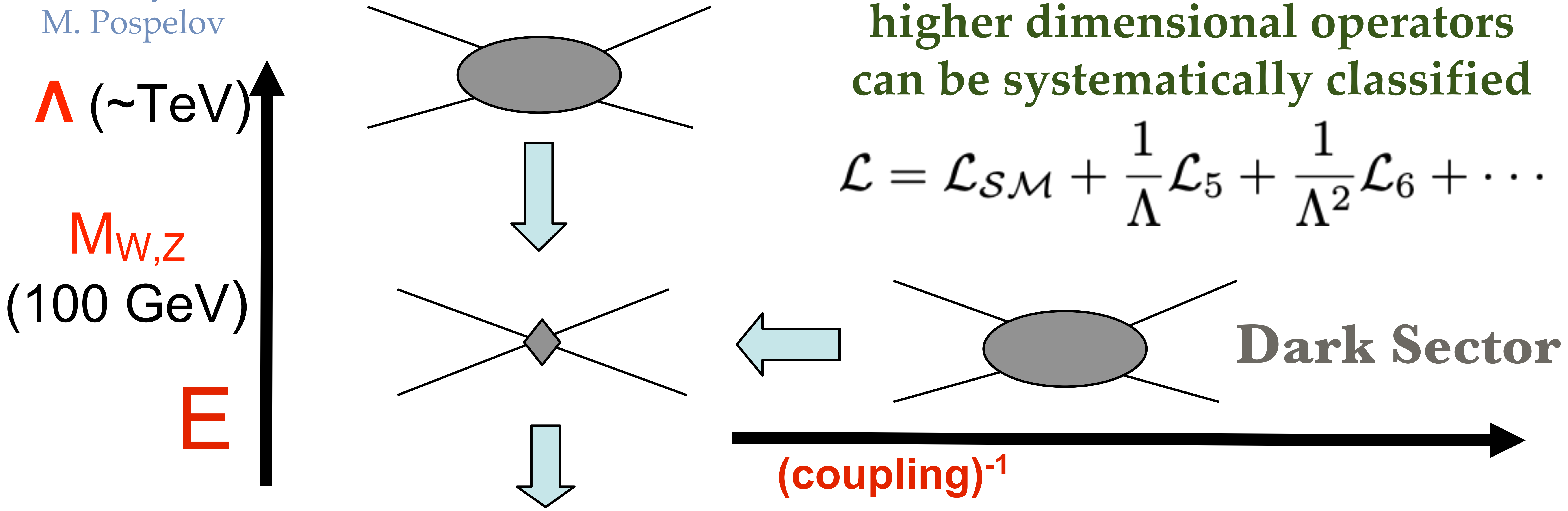
Physics Context for the Discovery Space of MOLLER

Unravelling "New Dynamics" in the Early Universe:
how did nuclear matter form and evolve?

Nuclear Physics Initiatives:
"Low" Energy: $Q^2 << M_Z^2$

courtesy
V. Cirigliano,
H. Maruyama,
M. Pospelov

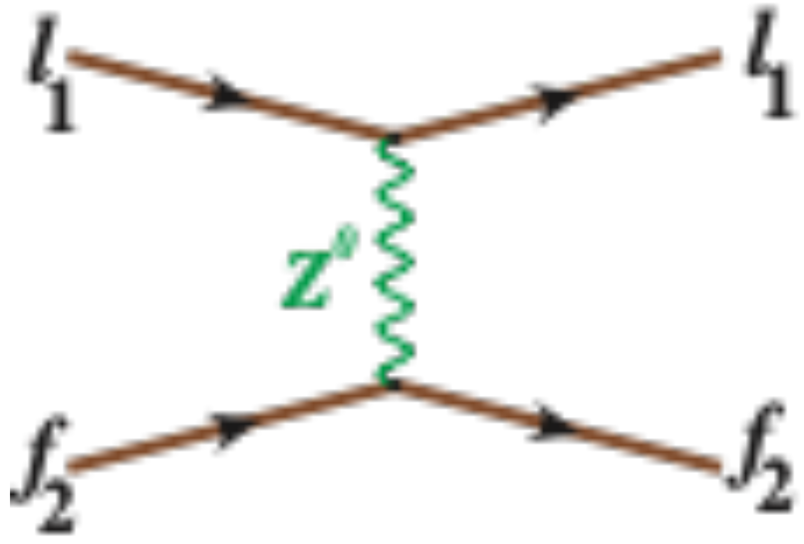
High Energy Dynamics



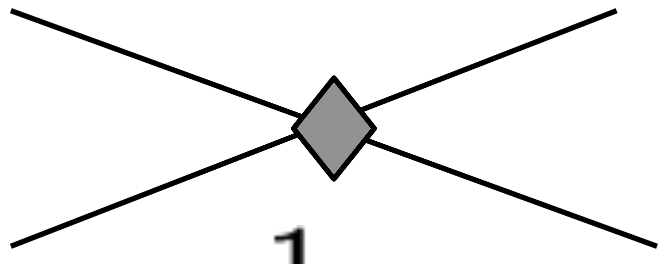
higher dimensional operators can be systematically classified

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

Leptonic and Semileptonic Weak Neutral Current Interactions

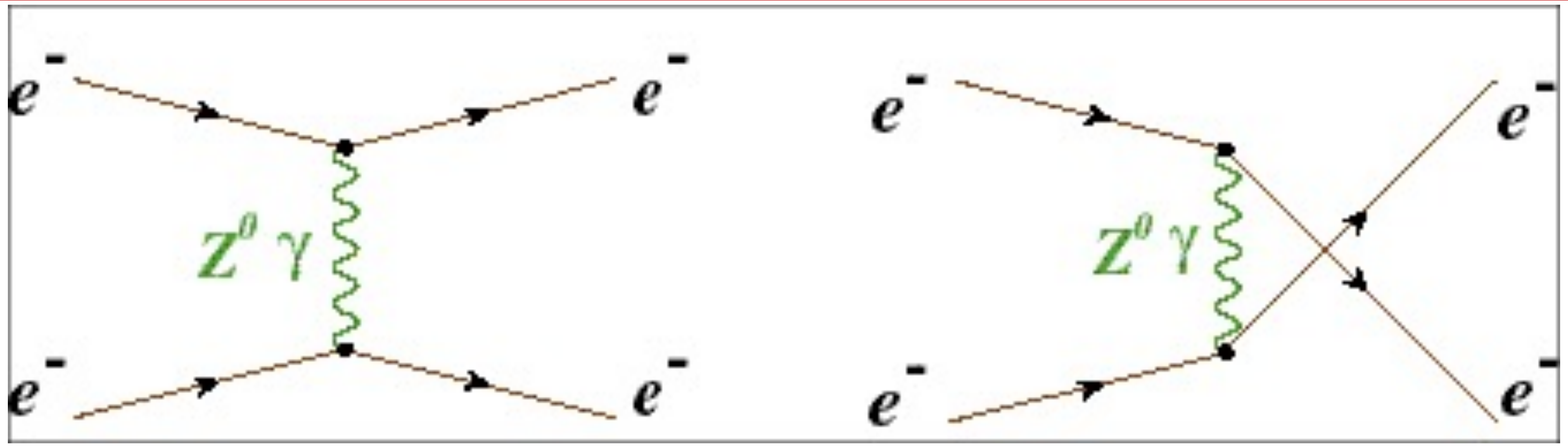


Search for new flavor diagonal neutral currents
Tiny yet measurable deviations from precisely calculable SM processes

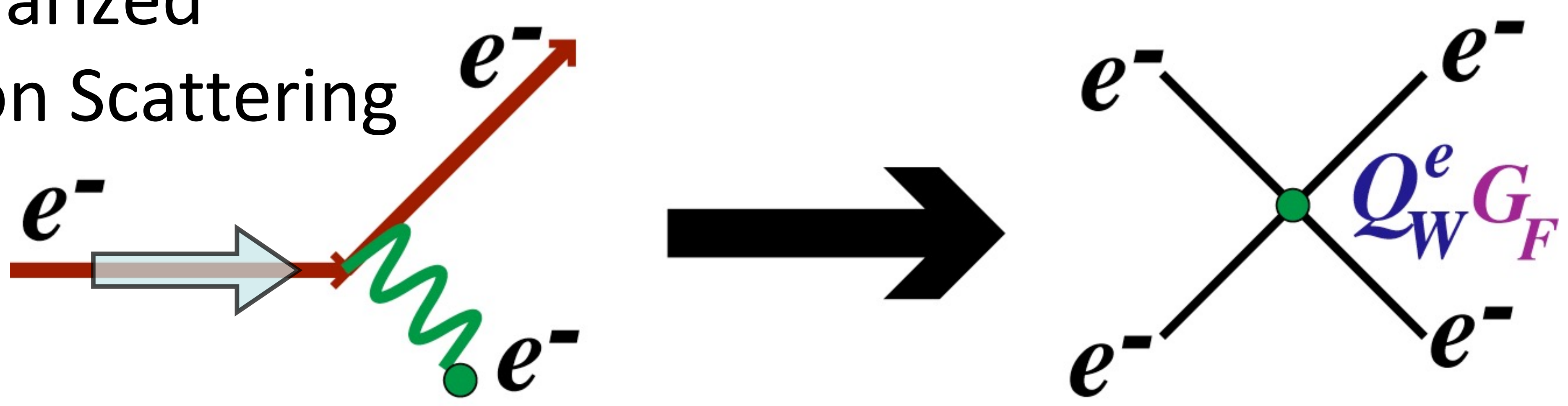


$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

Sensitivity of the Observable: PV Asymmetry in Møller Scattering

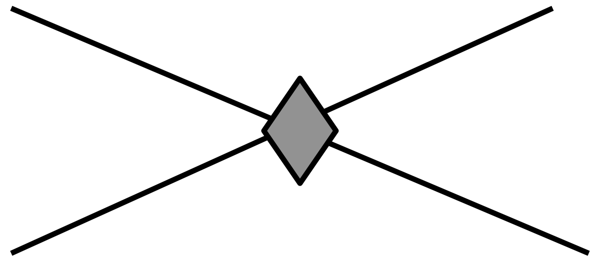


Fixed Target Polarized Electron-Electron Scattering



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

$$Q^e_W = 1 - 4\sin^2\theta_W \sim 0.075$$



$$+ \quad \frac{1}{\Lambda^2}\mathcal{L}_6$$

New Physics

11 GeV, 65 μA 90% beam polarization

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

$\delta(Q^e_W) = \pm 2.1$ % (stat.) ± 1.1 % (syst.)

$$\mathcal{L}_{e_1e_2} = \sum_{i,j=L,R}\frac{g^2_{ij}}{2\Lambda^2}\bar{e}_i\gamma_\mu e_i\bar{e}_j\gamma^\mu e_j$$

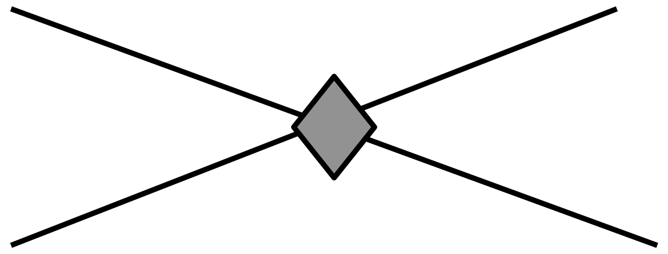
$\delta(\sin^2\theta_W) = \pm 0.00023$ (stat.) ± 0.00012 (syst.)

→ *~ 0.1%*

$$\frac{\Lambda}{\sqrt{|g^2_{RR} - g^2_{LL}|}} = 7.5\ \text{TeV}$$

Comparison with High Energy Colliders

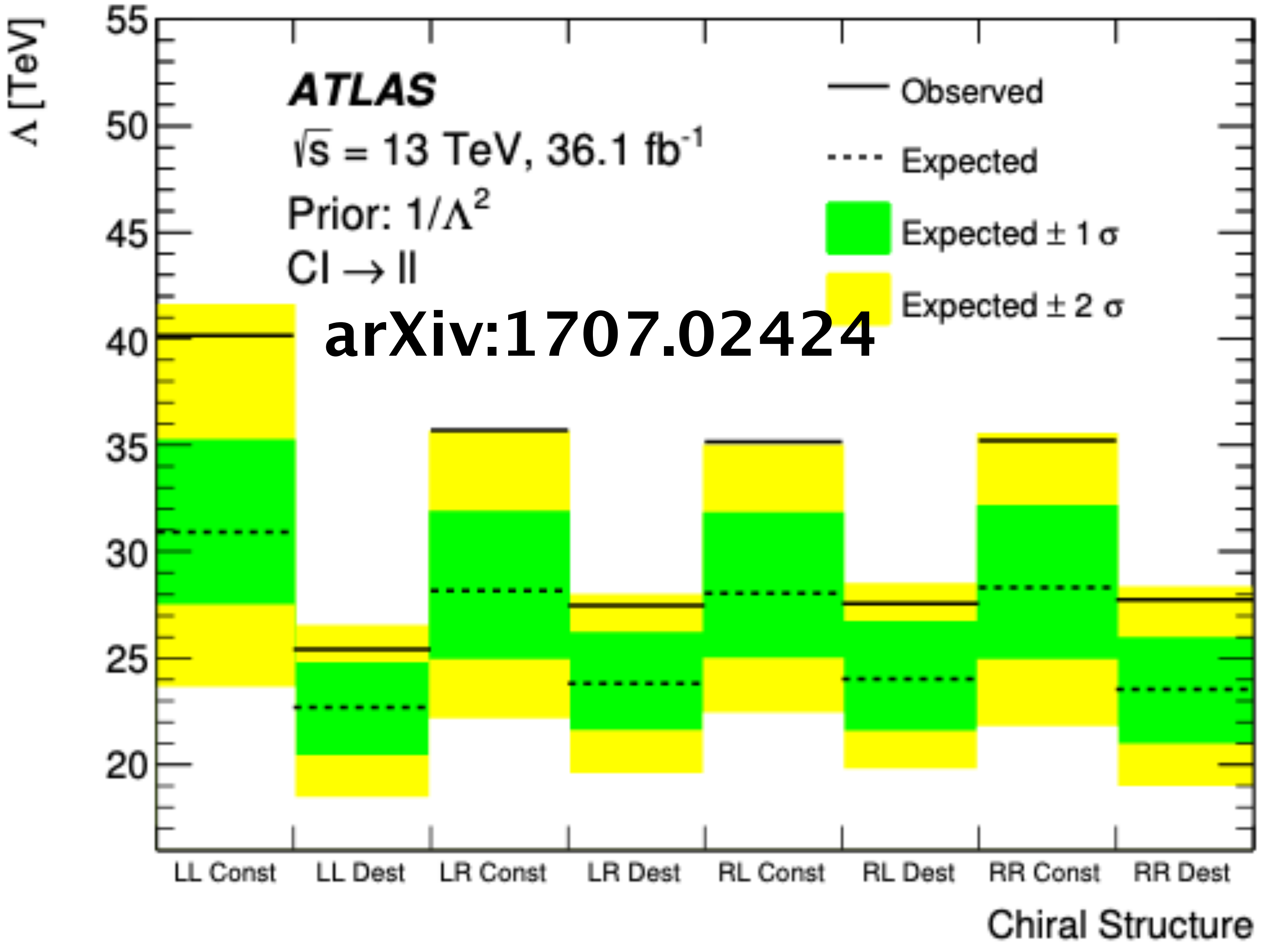
Carefully chosen low energy experiments complement direct searches



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

Lacking any direct evidence for new particles besides the Higgs, both colliders and fixed target experiments search for new physics by looking for deviations from Standard Model predictions

LHC searching for lepton-hadron interactions



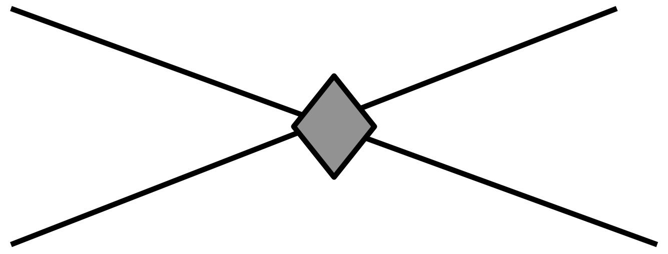
LEP200 searched for lepton-lepton interactions

95% C.L.

e^+e^- Collisions	LEP200 Reach	$\Lambda_{LL}^{ee} \sim 8.3$ TeV
Fixed Target	E158 Reach	$\Lambda_{LL}^{ee} \sim 12$ TeV
	MOLLER Reach	$\Lambda_{LL}^{ee} \sim 27$ TeV

MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory

Can MOLLER physics be done elsewhere in the world?



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

Search for New Interactions: carefully chosen low energy experiments complement direct searches

LHC and future EIC sensitive to new lepton-hadron interactions

New purely leptonic interactions: MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory

There are no concrete plans anywhere worldwide to build a next generation lepton collider or neutrino factory, both billion dollar class facilities that would take a decade or more to realize.

If the MOLLER measurement is not carried out, purely leptonic interactions will remain unexplored for at least another decade

Three other aspects:

- **Electroweak Physics**
- **New "Low" Energy Physics**
- **Capabilities of Existing Facilities**

Theory Prediction and Radiative Corrections

The Standard Model Prediction: Remarkably Well-Known

$$A_{PV} = \frac{\rho G_F Q^2}{\sqrt{2}\pi\alpha} \frac{1-y}{1+y^4+(1-y)^4}\{1 - 4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{\rm MS}}$$
$$+ \frac{\alpha(m_Z)}{4\pi\hat{s}^2} - \frac{3\alpha(m_Z)}{32\pi\hat{s}^2\hat{c}^2}(1-4\hat{s}^2)[1+(1-4\hat{s}^2)^2]$$
$$+ F_1(y,Q^2) + F_2(y,Q^2)\}$$

κ(0) known to 1% of itself

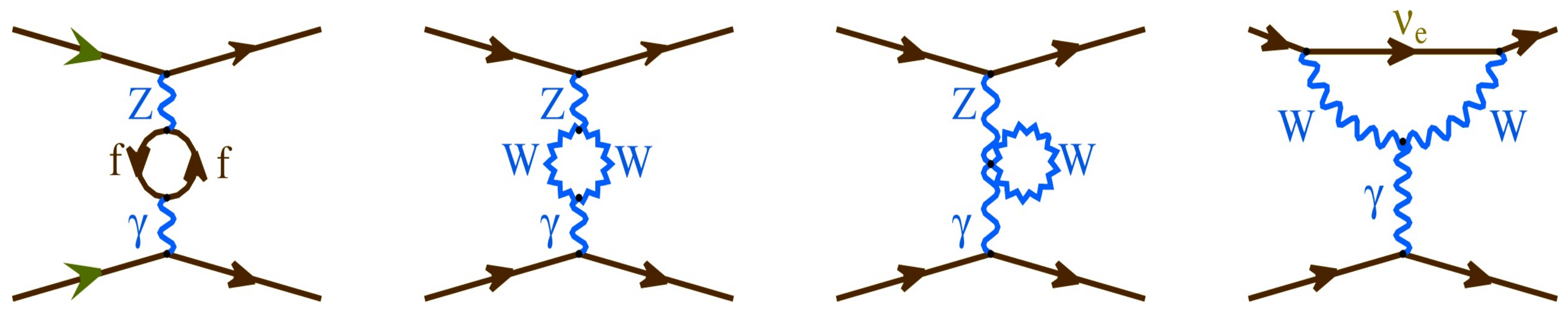
Erler and Ferro-Hernandez (2018)

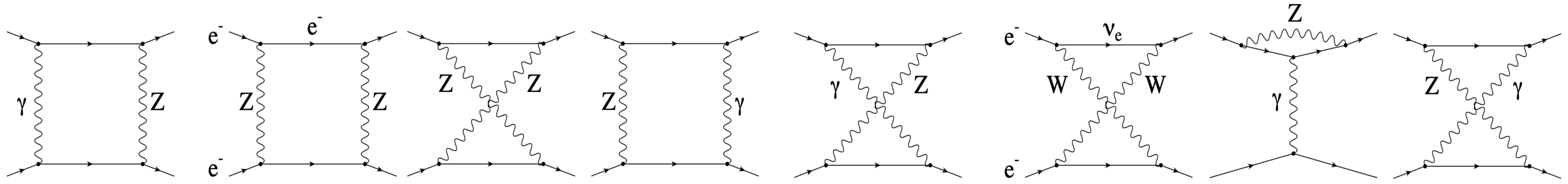
$$\mathbf{Q^e_W = 1 - 4\sin^2\theta_W \sim 0.075 \Longrightarrow 0.045}$$

$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

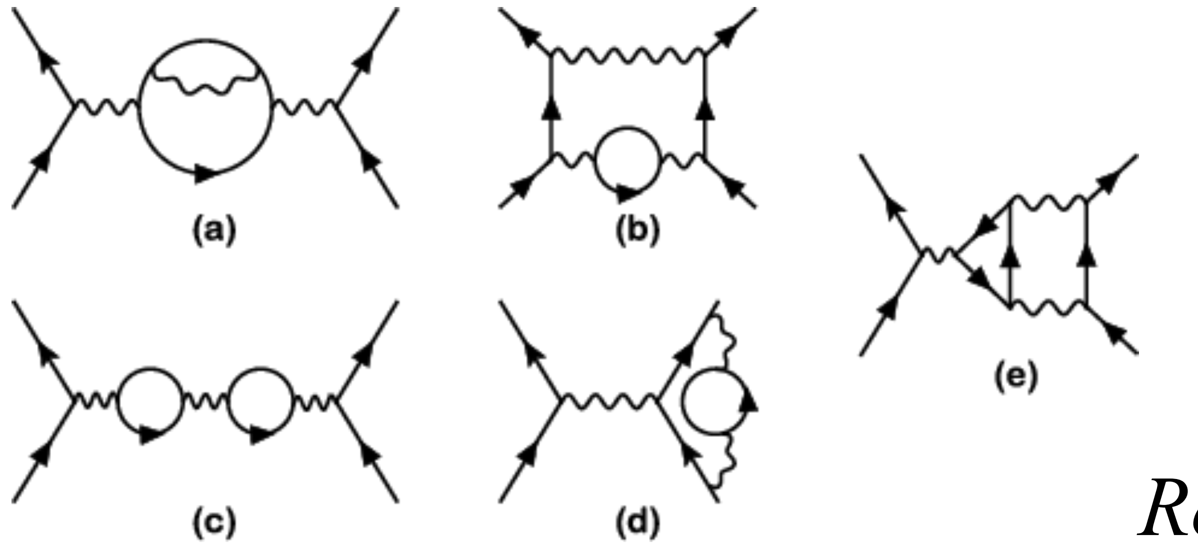
$\delta(Q^e_W) \lesssim 0.4\%$

Czarnecki and Marciano (1995)





2 groups working on 2-loop Calculations

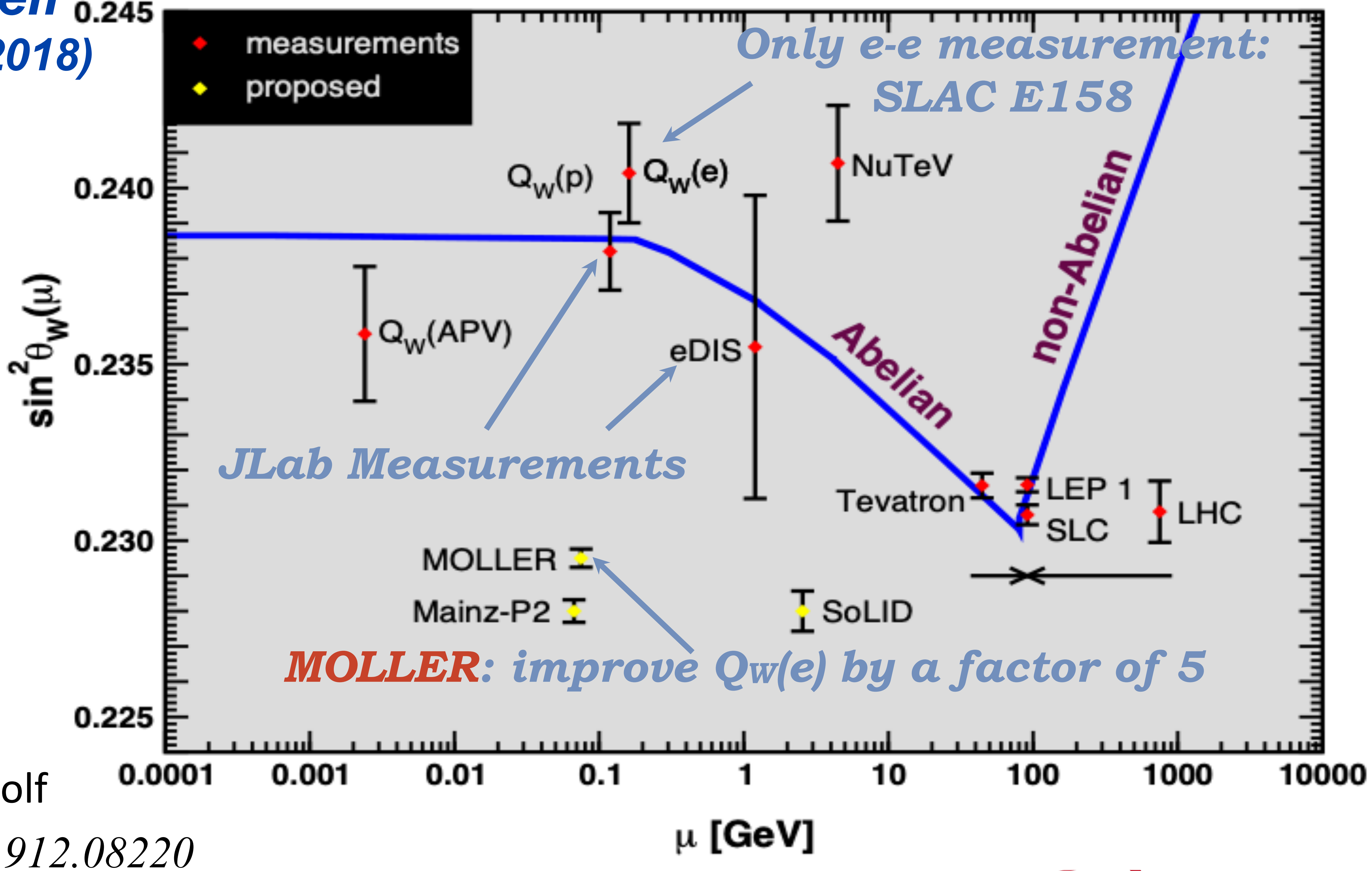


Aleksejevs and Barkanova

Series of publications

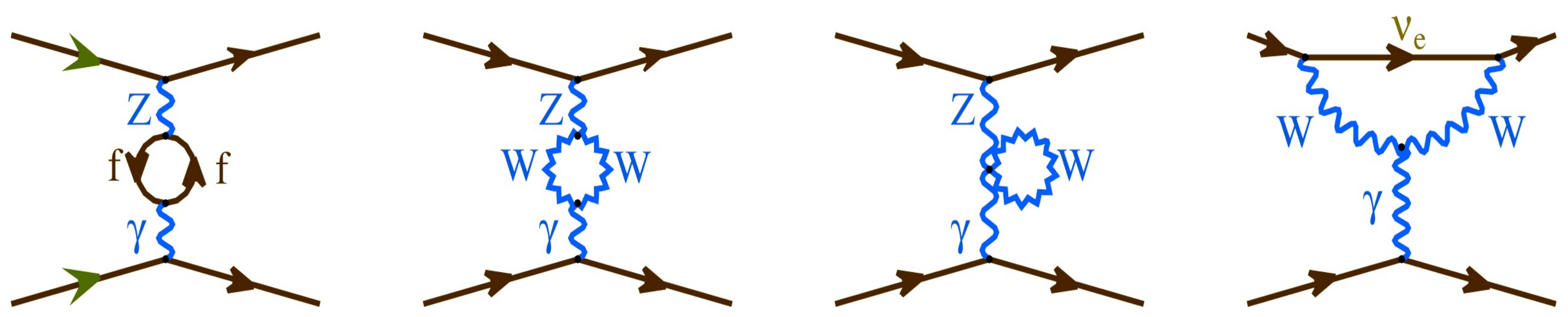
Du, Freitas, Patel and Ramsey-Musolf

Recent closed-fermion loops: arXiv:1912.08220

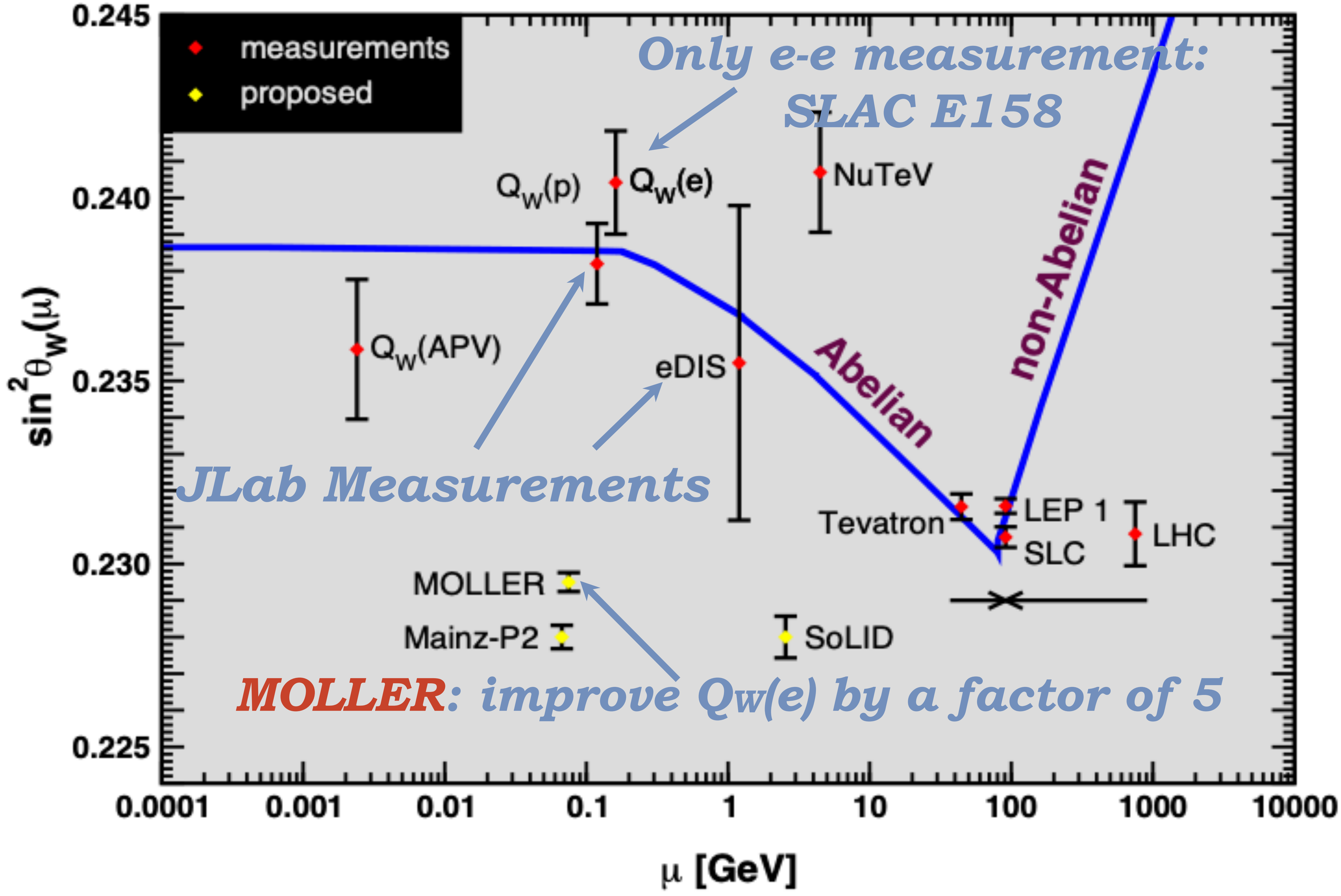


Weak Mixing Angle Measurements at Low Energy

Czarnecki and Marciano (1995)



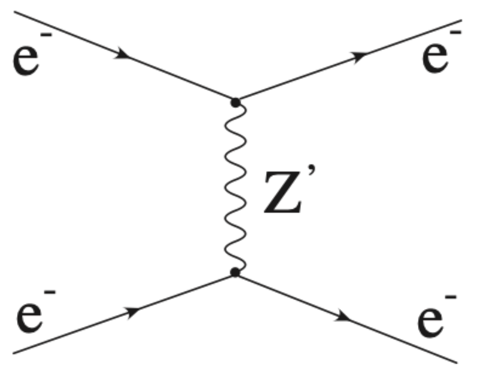
- ✦ **Atomic Parity Violation: Cs-133**
  - future measurements and theory challenging
- ✦ **Neutrino Deep Inelastic Scattering: NuTeV**
  - future measurements and theory challenging
- ✦ **PV Møller Scattering: E158 at SLAC**
  - statistics limited, theory robust
  - next generation: MOLLER (factor of 5 better)
- ✦ **PV elastic e-p scattering: Qweak**
  - theory robust at low beam energy
  - next generation: P2 (factor of 3 better)
- ✦ **PV Deep Inelastic Scattering: PVDIS**
  - theory robust for ^{2}H in valence quark region
  - factor of 5 improvement: SOLID



New (Low Energy) Physics Examples

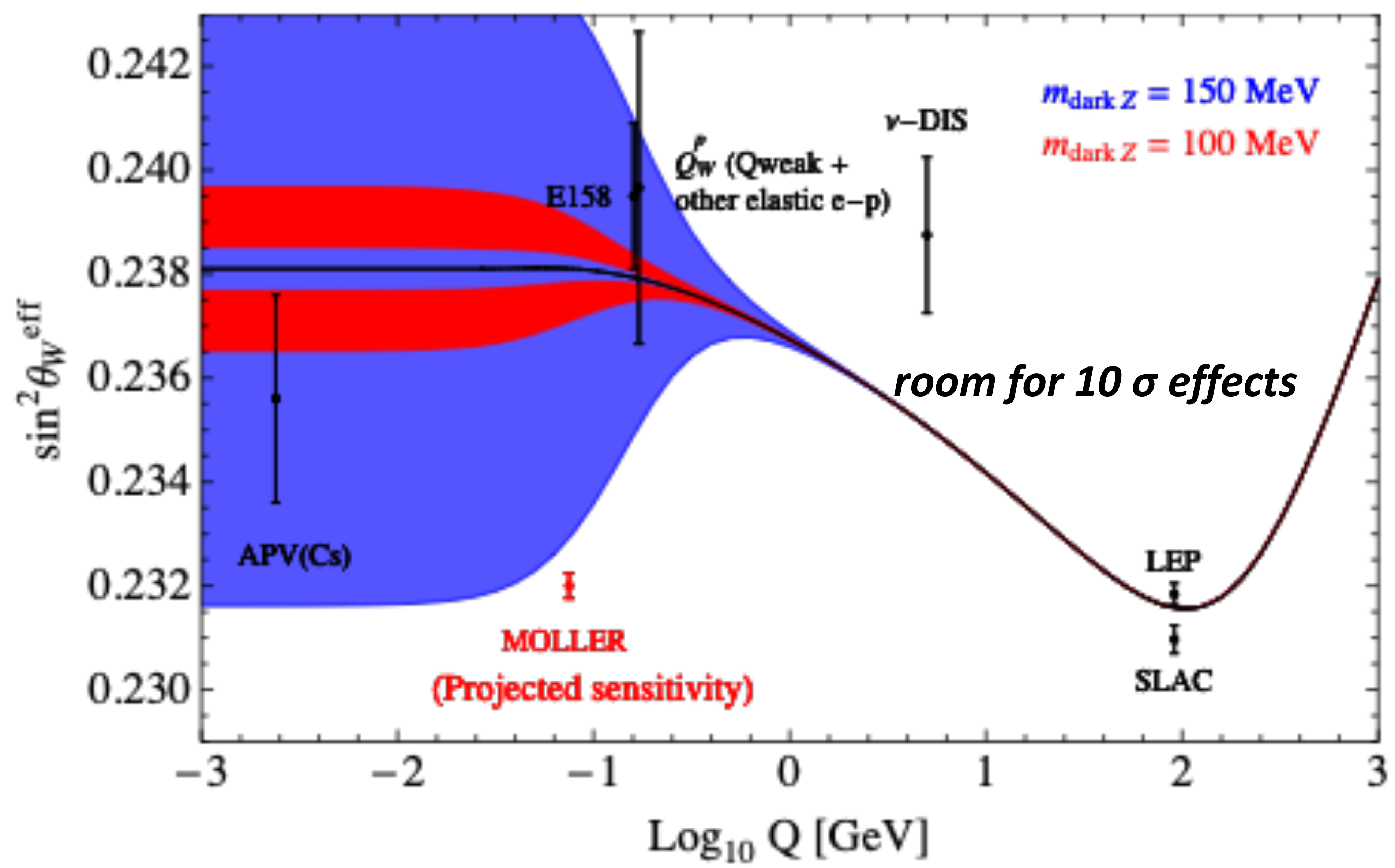
Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential



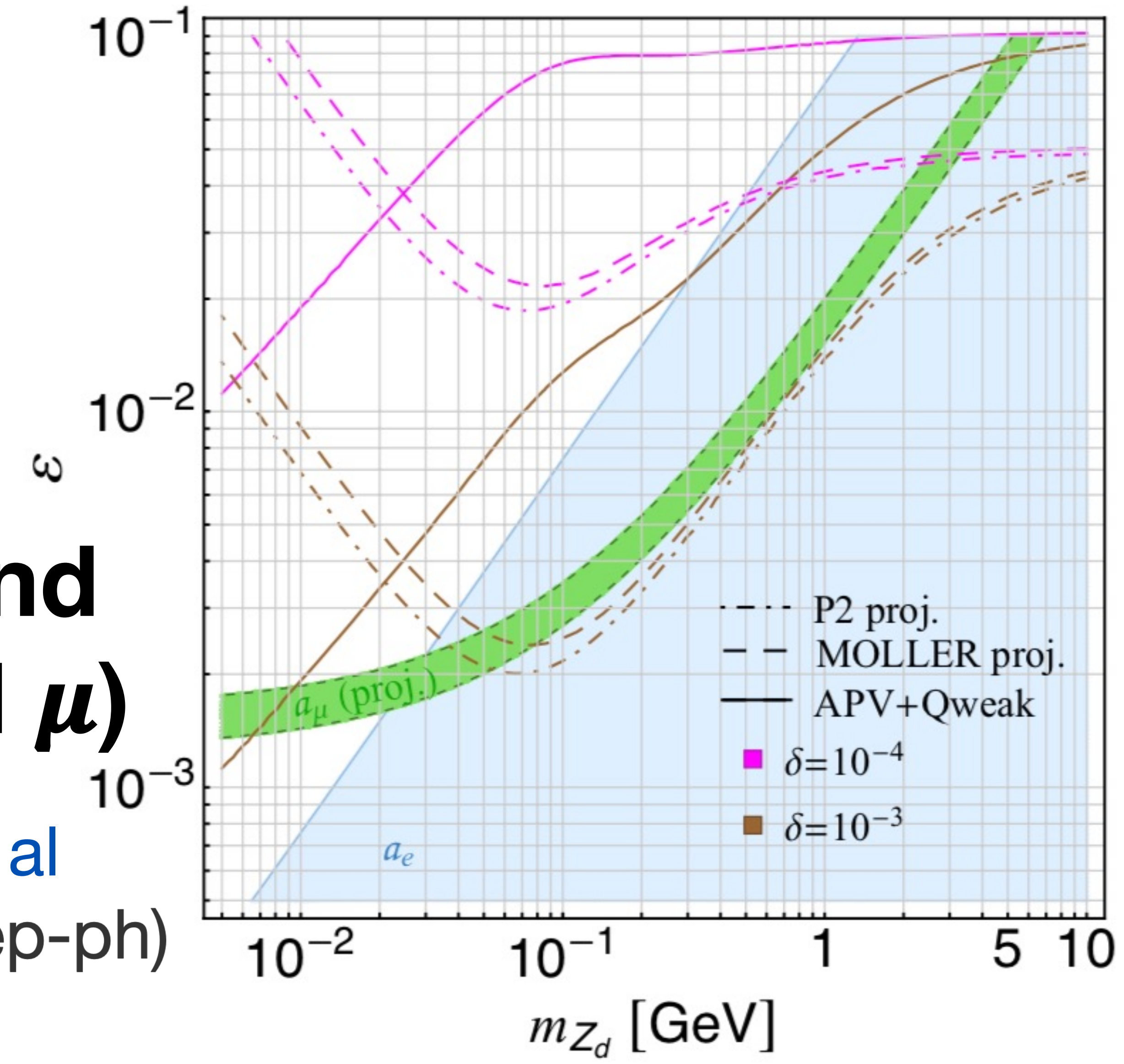
Heavy Photons (A' mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano

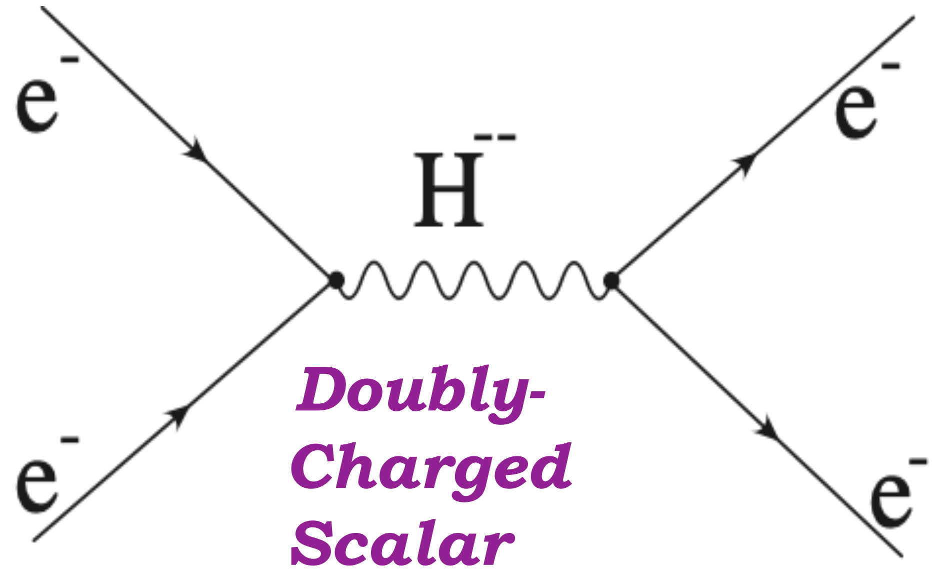


Specific Scenario folding in Cs APV and g-2 (e and μ)

M. Caddedu et al
2104.03280 (hep-ph)



Lepton Number Violation



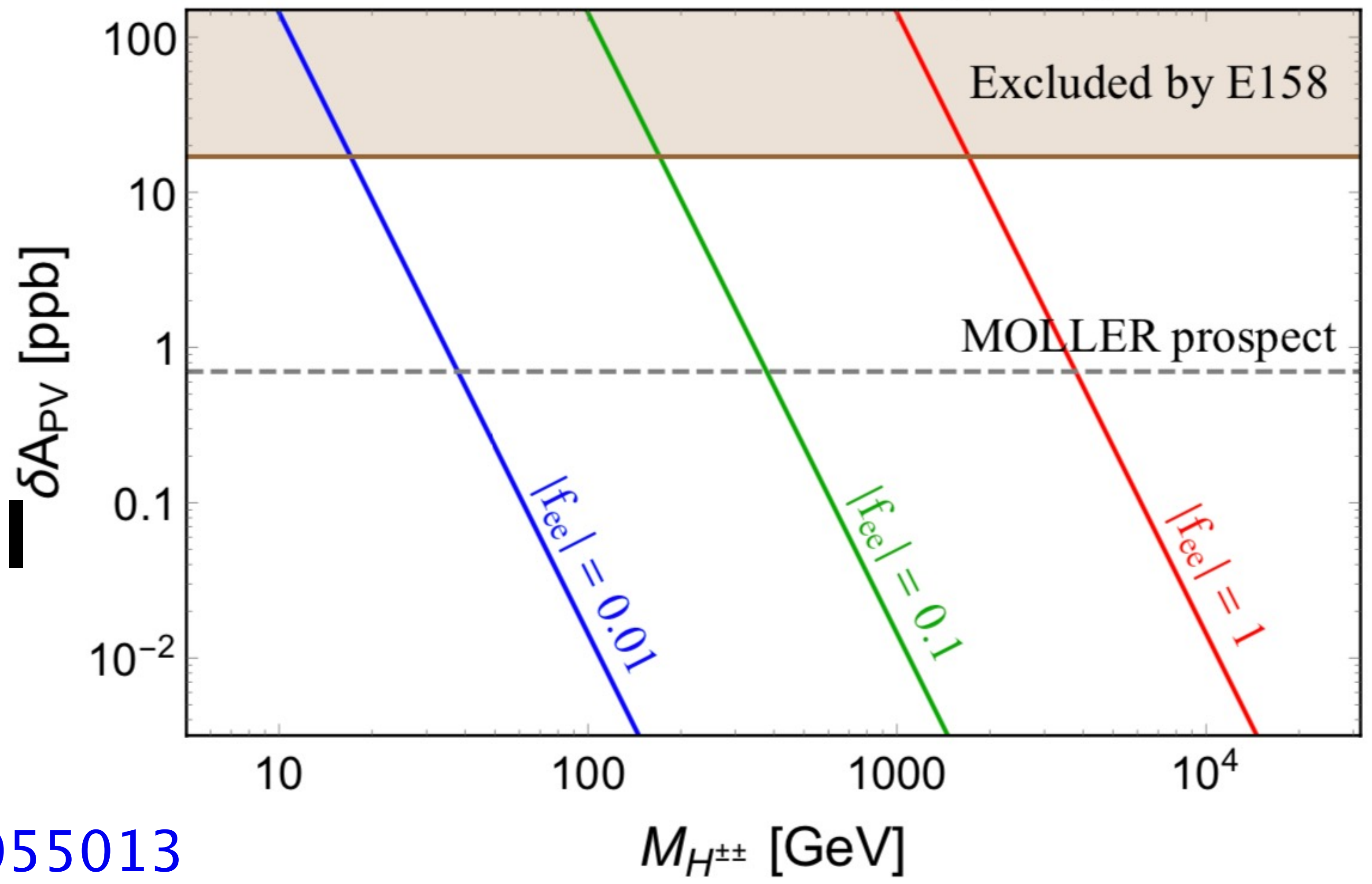
$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\frac{|h_{ee}|^2}{(M_\Delta/1\ \mathrm{TeV})^2}$$

Cirigliano et al
Phys.Rev. D70 (2004) 075007

5 σ for h_{ee} ~ 1 and M_Δ ~ 1 TeV

Specific Scenario for Type-II SeeSaw

B. Dev et al
PhysRevD.98.055013



Global Context Summary

best contact interaction reach for leptons at low OR high energy:
similar to LHC reach with semi-leptonic amplitudes

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

$$\delta(\sin^2\theta_W) = \pm\, 0.00023\ (\text{stat.}) \pm 0.00012\ (\text{syst.}) \Rightarrow \sim 0.1\%$$

Best projected uncertainties among projects being considered over next 10 years worldwide

- **If LHC sees ANY anomaly in the mid-2020s**
  - The unique MOLLER discovery space becomes pressing, with a few others (e.g. g-2 anomaly)
- **Discovery scenarios beyond LHC signatures**
  - Hidden weak scale scenarios
  - Lepton Number Violating Amplitudes
  - Light Dark Matter Mediators
  - …

Most sensitive discovery reach over the next decade for CP-/flavor-conserving or LNV scattering amplitudes

Alternatives Analysis Summary Table

	Reaction	$\sin^2\theta_W$ Precision	Technical Requrements	Feasibliity	Cost	Possible Timeline	Comments
MOLLER	**ee-ee**	**0.1%**	**11 GeV, polarimetry**	**reviewed**	**~ 40M$**	**2025**	
Other Møller	ee-ee	0.5%?	> 10 GeV e-e collider with spin	unknown	>> 100M$	N/A	Possible JLEIC figure-8 modification
Other PVES	ee-qq	0.15 - 0.25 %	MESA P2 JLab SOLID	likely studied	30 - 70 M$	2024 2027	additional hadronic uncertainties studied
Hadron Collider	qq-ee	0.1% 0.3%	> 300 inv. fb at LHC 250 inv. fb at EIC	> likely likely	-	2025 2030s	Requires pdf uncertainty reduction
Lepton Collider	ee-$\mu\mu$	0.1%?	> 500 GeV electron-positron collider	studied	> 1B$	> 2035	No current plans to move forward
Neutrino DIS	$\nu\nu$-qq $\nu\mu$-q_1q_2	0.2%?	fine-grained large calorimeter + ν beam	studied	> 100 M$	~ 2030	DUNE Near-Detector upgrade, QCD uncertainties
Elastic Neutrino	νe-νe $\nu\nu$-qq	0.5%?	Reactor neutrino experiments	studied	unknown	unknown	Requires upgrades of existing plans
Atomic PV	ee-qq	0.3%?	Ra+, Cs, Fr or Th beams, custom apparatus	studies ongoing	unknown	unknown	Feasibility studies ongoing (Mainz, TRIUMF, KVI, Purdue)

Equipment Alternatives

- **Option A: Upgrade of Existing Detector**
  - E158 at SLAC: quadrupole spectrometer concept insufficient for background rejection
  - Qweak at JLab: Toroid particle acceptance at much larger scattering angles
- **Option B: Fabrication of Entirely New Apparatus**
  - Design flexibility to achieve combined precision and accuracy to meet scientific objectives
  - 7-fold toroidal symmetry; carefully sculpted field; highly segmented integrating detectors; upgraded hydrogen target
- **Option C: No Action**
  - Not considered: scientific goal and hence mission need cannot be addressed elsewhere

Recommended Alternative: Modified version of Option B
Analysis of option A revealed that a few existing components can be reused, such as some elements of the electronics and data acquisition systems

MOLLER Physics Summary

- MOLLER represents an outstanding opportunity to take advantage of the unique instrument (11 GeV CEBAF beam) enabled by the 12 GeV upgrade
- The science case remains compelling and the plan is to run physics at about the time that precision results from high luminosity phases of 14 TeV LHC are becoming available
- The science goals cannot be accomplished in existing or planned facilities elsewhere worldwide

Appendix

Sensitivity to 4-Lepton Contact Interactions from Low Energy and Colliders

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W^e|}}$$

$$\simeq \frac{246.22\text{ GeV}}{\sqrt{0.023 Q_W^e}} = 7.5\text{ TeV}.$$

Model	η_{LL}^f	η_{RR}^f	η_{LR}^f	η_{RL}^f
$LL^\pm$	±1	0	0	0
$RR^\pm$	0	±1	0	0
$LR^\pm$	0	0	±1	0
$RL^\pm$	0	0	0	±1
$VV^\pm$	±1	±1	±1	±1
$AA^\pm$	±1	±1	∓1	∓1
$VA^\pm$	±1	∓1	±1	∓1

Conventional Collider Contact Interaction Analysis: → $\left|g_{RR}^2 - g_{LL}^2\right| = 4\pi$

Simultaneous fits to cross-sections and angular distributions

95% C.L. Limits

LEP200

$\Lambda_{\mathrm{LL}}^{\mathrm{ee}} \sim 8.3$ TeV　　$\Lambda_{\mathrm{LL}}^{\mathrm{ll}} \sim 12.8$ TeV

$\Lambda_{\mathrm{RR}}^{\mathrm{ee}} \sim 8.2$ TeV　　$\Lambda_{\mathrm{RR}}^{\mathrm{ll}} \sim 12.2$ TeV

$\Lambda_{\mathrm{VV}}^{\mathrm{ee}} \sim 17.7$ TeV　　$\Lambda_{\mathrm{VV}}^{\mathrm{ll}} \sim 22.2$ TeV

E158 Reach (actual limits asymmetric)

$\Lambda_{\mathrm{LL}}^{\mathrm{ee}} \sim 12$ TeV　　$\Lambda_{\mathrm{RR-LL}}^{\mathrm{ee}} \sim 17$ TeV

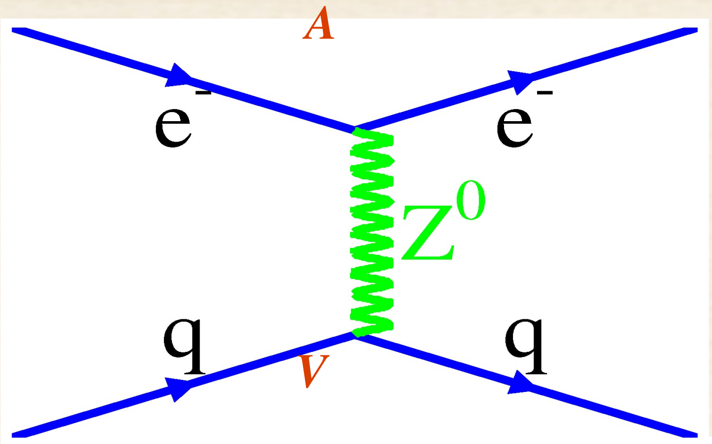
LEP-200 insensitive

MOLLER Reach

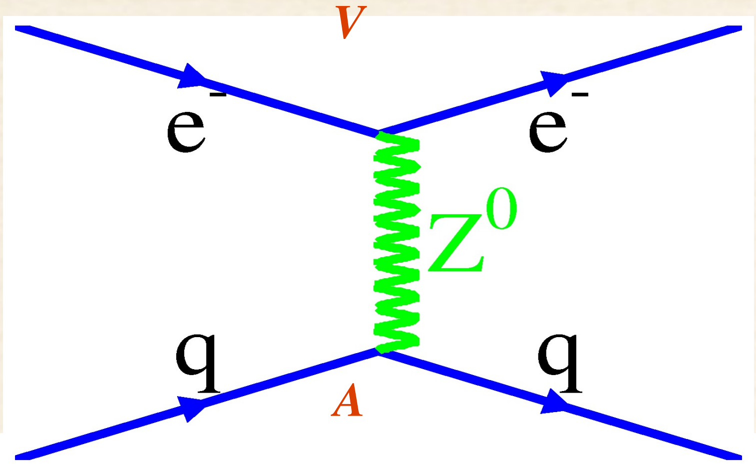
$\Lambda_{\mathrm{LL}}^{\mathrm{ee}} \sim 27$ TeV　　$\Lambda_{\mathrm{RR-LL}}^{\mathrm{ee}} \sim 38$ TeV

MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider

Weak Neutral Current (WNC) Couplings



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



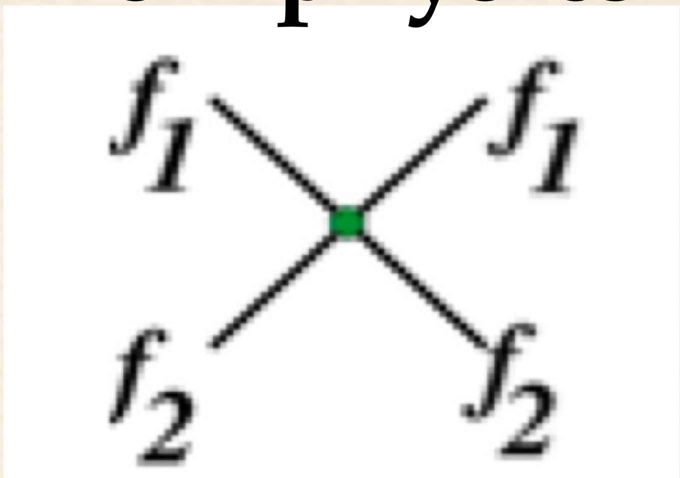
$C_{2i} \equiv 2 g_V^e g_A^i$

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

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

+

new physics

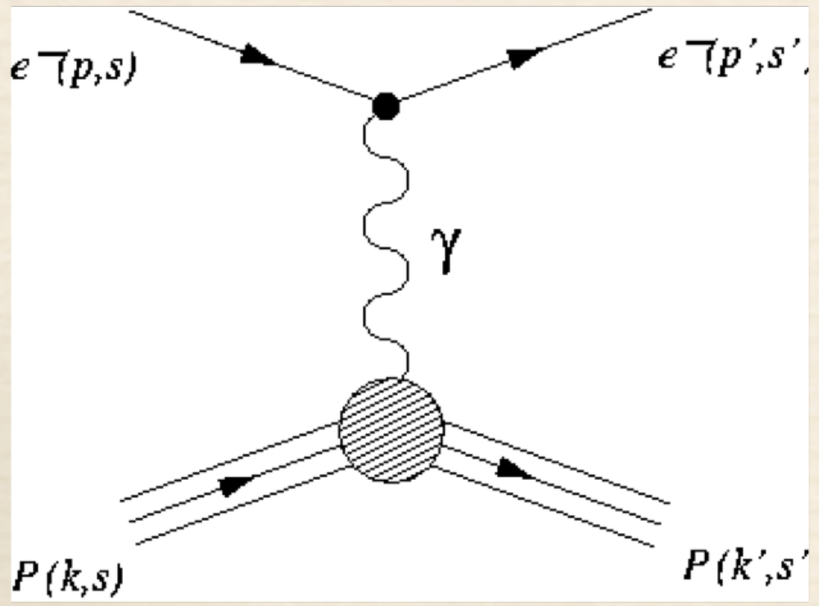


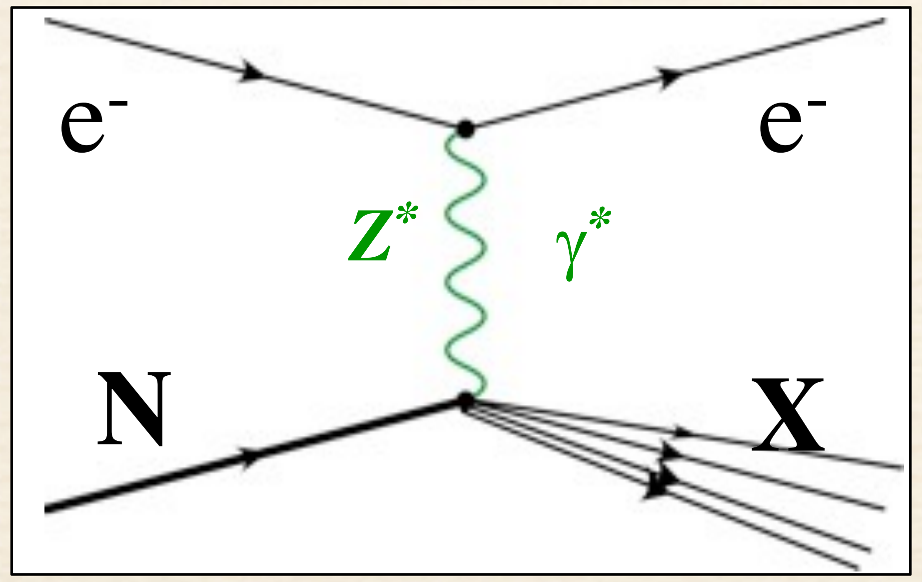
$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$ ⇨ ***PV elastic e-N scattering, Atomic parity violation***

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

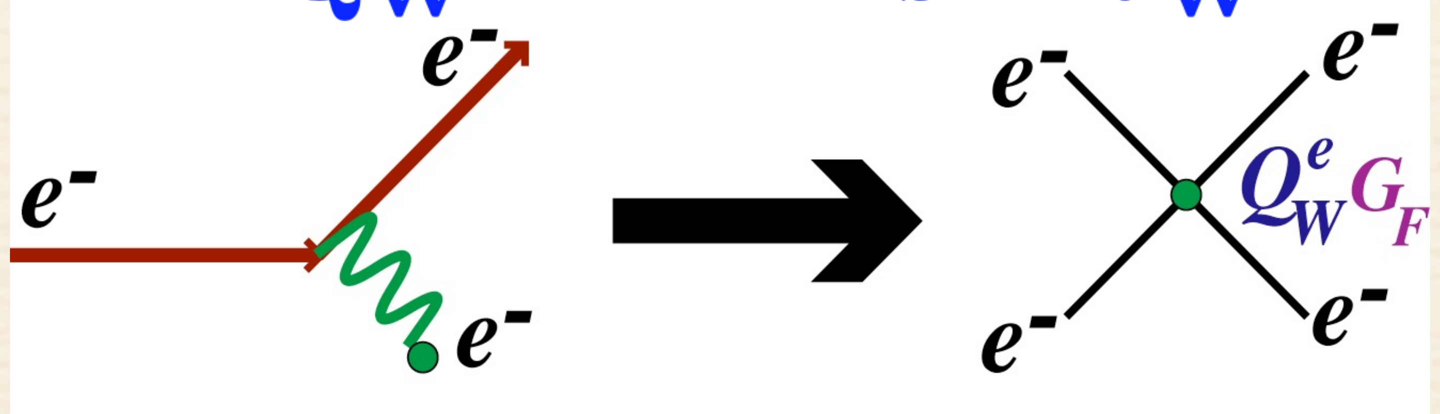
$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2$ ⇨ ***PV Møller scattering***

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





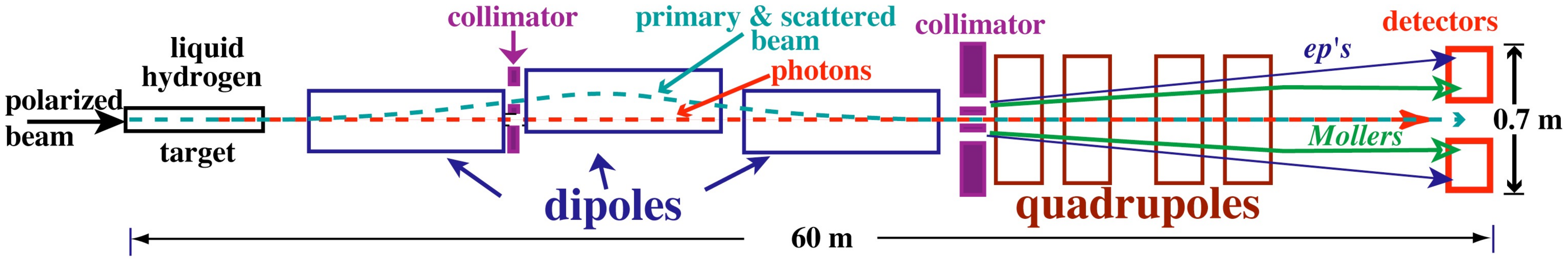
$\mathbf{Q_W = 1 - 4\sin^2\theta_W}$

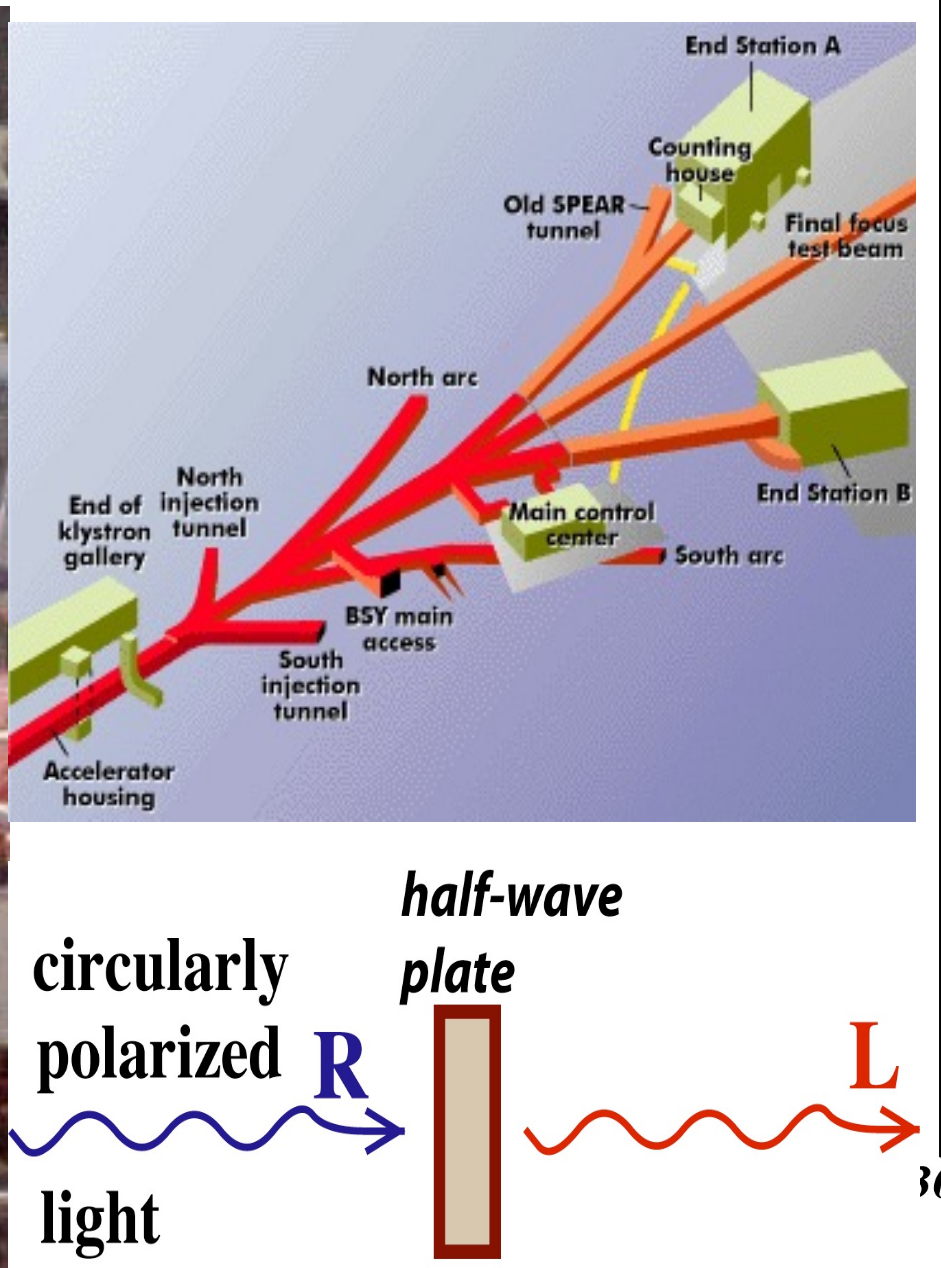


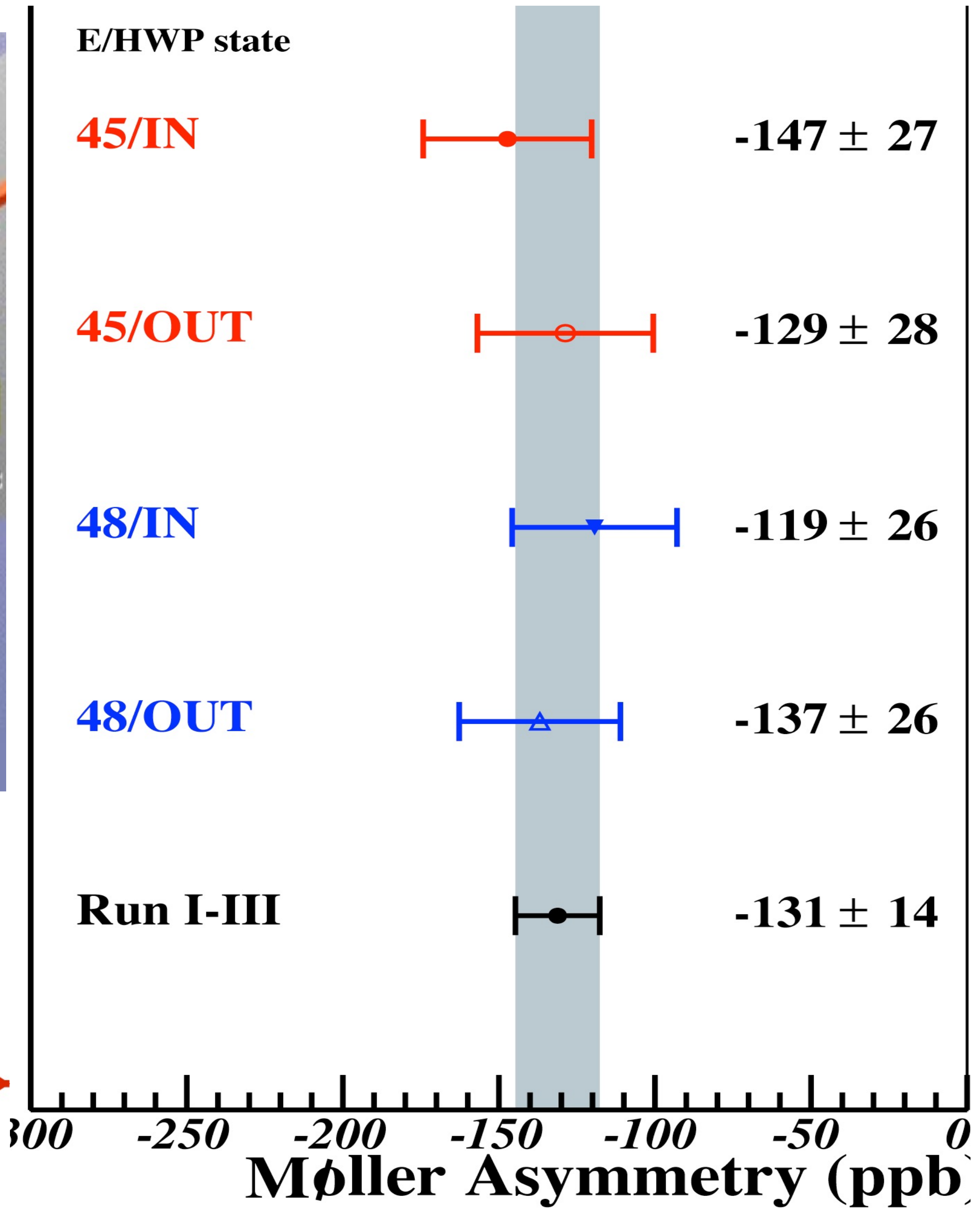
Previous Measurement: SLAC E158

1997-2004

~ 10 ppb raw sensitivity at highest E_{beam}, ~ 0.5% error on weak mixing angle



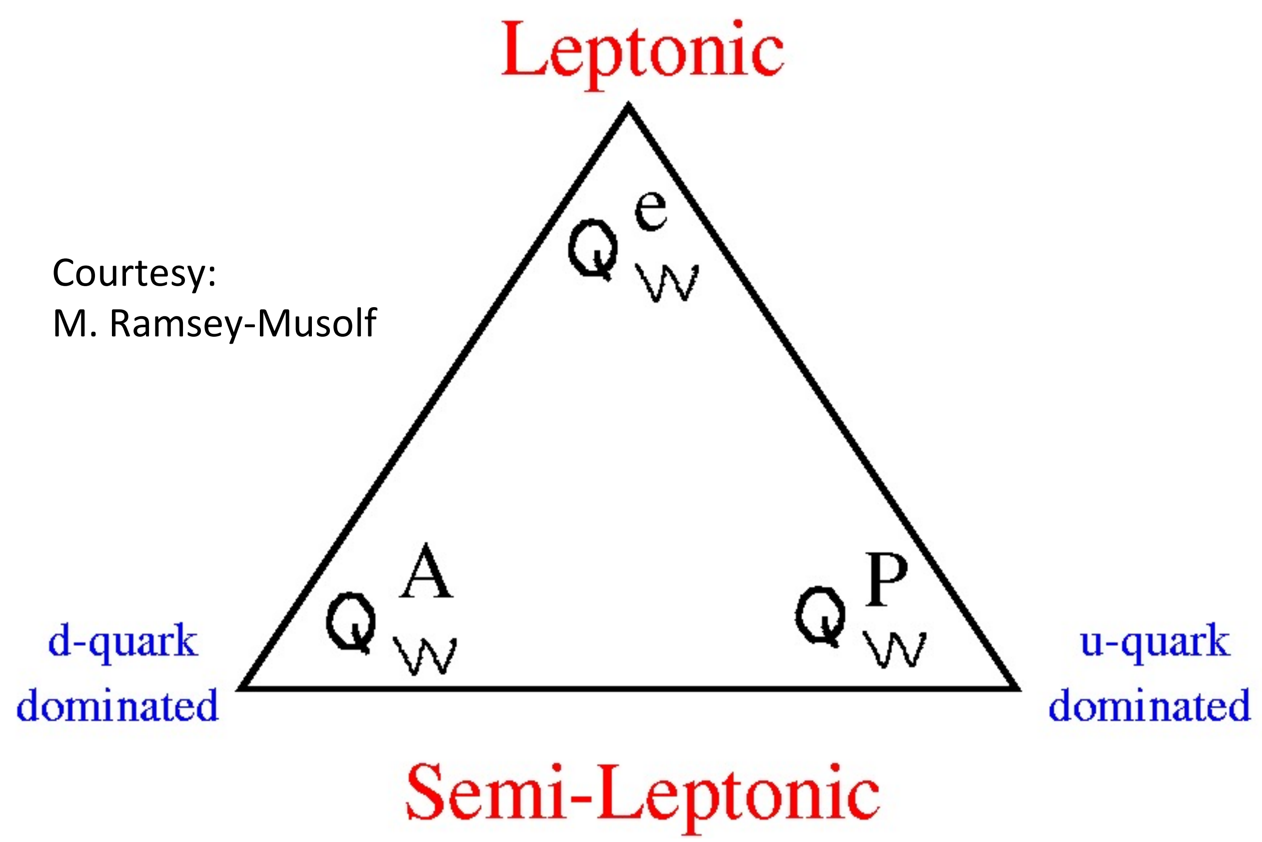




$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

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

PVES Initiatives: Complementarity



vector-quark couplings

$$[2C_{2u} - C_{2d}]$$

axial-quark couplings

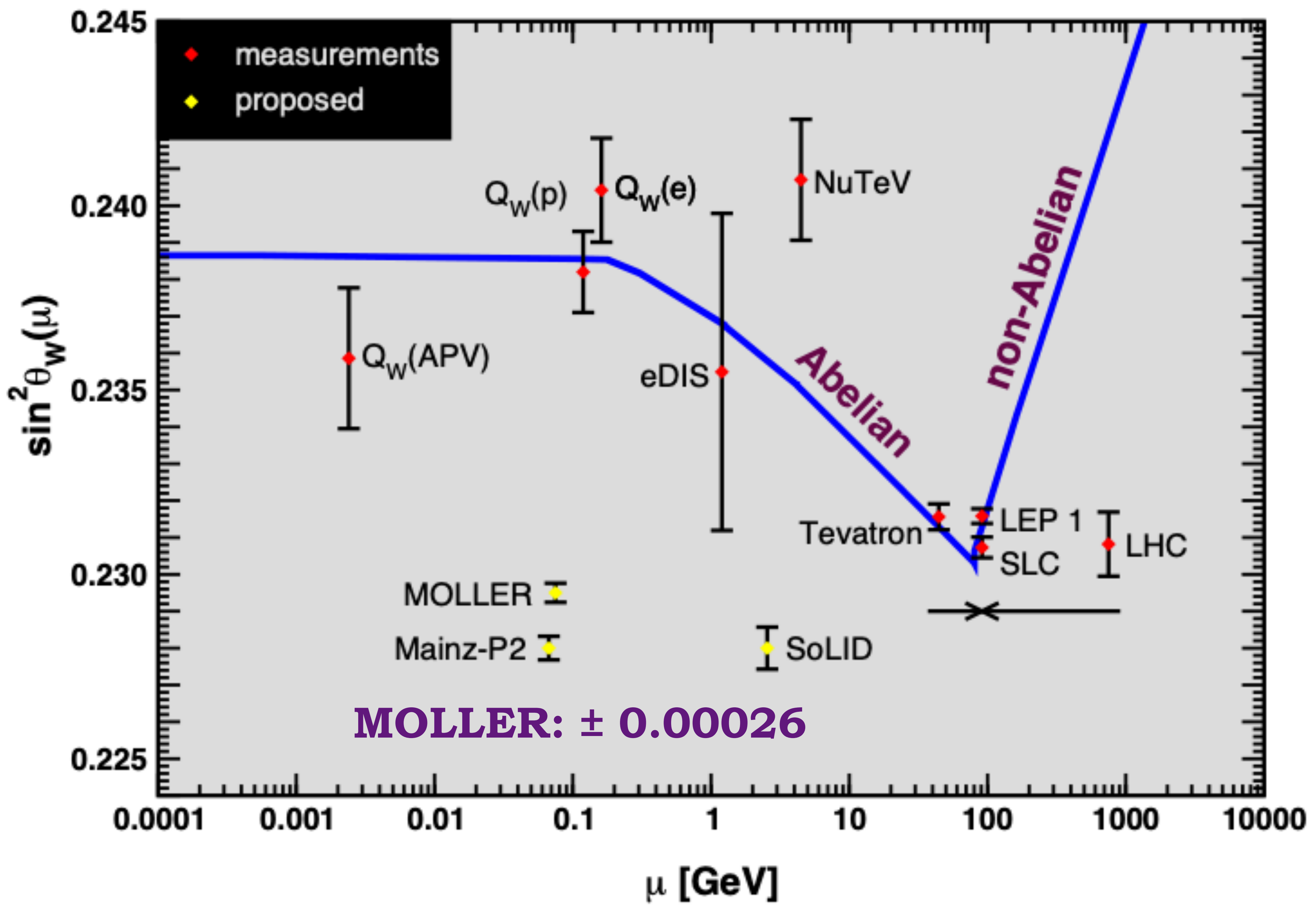
SUSY Loops	→	Q_W^e and Q_W^{p}:same absolute shift, smaller for others
GUT Z'	→	High for Q_W(Cs), Q_W^e(relative), smaller for others
Leptophobic Z'	→	axial-quark couplings (C_2's) only
RPV SUSY	→	Different for all four in sign and magnitude
Leptoquarks	→	semi-leptonic only; different sensitivities
Lepton Number Violation	→	Q_W^e only

Jefferson Lab

A Fundamental Parameter of the Electroweak Theory

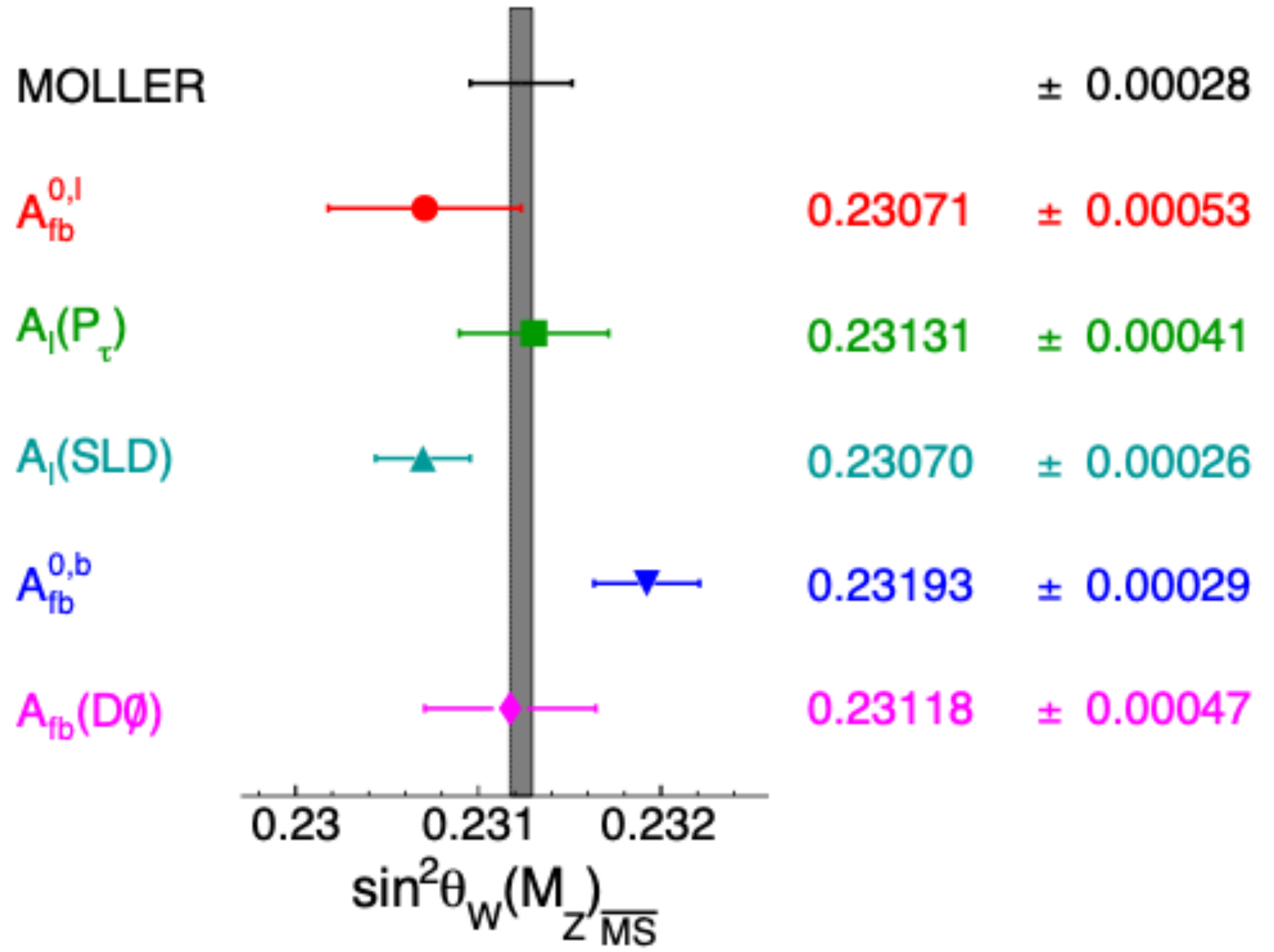
The Weak Mixing Angle

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



± 10σ discovery potential at $Q^2 << M_Z^2$

Z resonance measurements:
no interference term



Tevatron: 0.00033 (combined)

Mainz P2: 0.00031 (projected)

LHC (combined) : ~ 0.00036

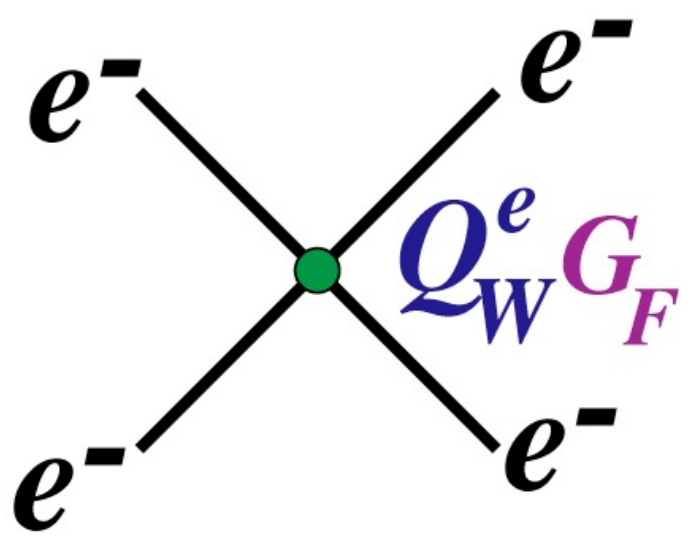
systematics-dominated (pdf uncertainties)

LHC (combined) and MOLLER/P2 (combined) will provide two combinations with uncertainties ~ 0.0002 in late-2020's

Best Sensitivity among Weak Charge Measurements

leptonic and semi-leptonic weak neutral current amplitudes

$$\left|\mathbf{A}_\gamma + \mathbf{A_Z} + \mathbf{A}_{\text{new}}\right|^2 \rightarrow \mathbf{A}_\gamma^2\left[1 + 2\left(\frac{\mathbf{A_Z}}{\mathbf{A}_\gamma}\right) + 2\left(\frac{\mathbf{A}_{\text{new}}}{\mathbf{A}_\gamma}\right)\right]$$



$$\mathbf{Q_W^e} \sim \mathbf{0.045}$$

$$\frac{\delta \mathbf{Q_W^e}}{\mathbf{Q_W^e}} = \mathbf{2.4\%}$$

$$\mathbf{A}_{\text{new}} \sim \mathbf{0.001 \cdot G_F}$$

unprecedented sensitivity

Complementary PVES measurements off Quarks:

$$\delta[\mathbf{Q_W}(^{133}\text{Cs})/\mathbf{A}] \sim \mathbf{0.6\%} \Longrightarrow \mathbf{0.0033 \cdot G_F}$$

Atomic Parity Violation Future ???

JLab Qweak

$$\delta[\mathbf{Q_W^p}] \sim 6\,\% \Longrightarrow \mathbf{0.0045\,G_F}$$

Future Mainz P2: improve by factor of 3

$$\delta[\mathbf{2C_{2u} - C_{2d}}] \sim \mathbf{5\%} \Longrightarrow \mathbf{0.004 \cdot G_F}$$

SOLID: Unique sensitivity to axial-quark couplings

(Anti-)Neutrino Scattering

Deep Inelastic Scattering:

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

NuTeV measured a neutrino W/Z amplitude ratio to ~0.1%

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

Standard Model prediction is 0.2227 (3σ deviation)

Future improvements remain challenging to design: e.g. NuSONG proposal at Fermilab; fine-grained near detector at DUNE; coherent neutrino scattering detectors: none of the ideas come close to MOLLER in terms of weak mixing angle error projections.

Elastic $\bar{\nu}$-electron Scattering: best direct comparison to MOLLER as a purely leptonic low Q^2 measurement

The most aggressive reactor experiment projections have fallen significantly short of the proposed MOLLER goal

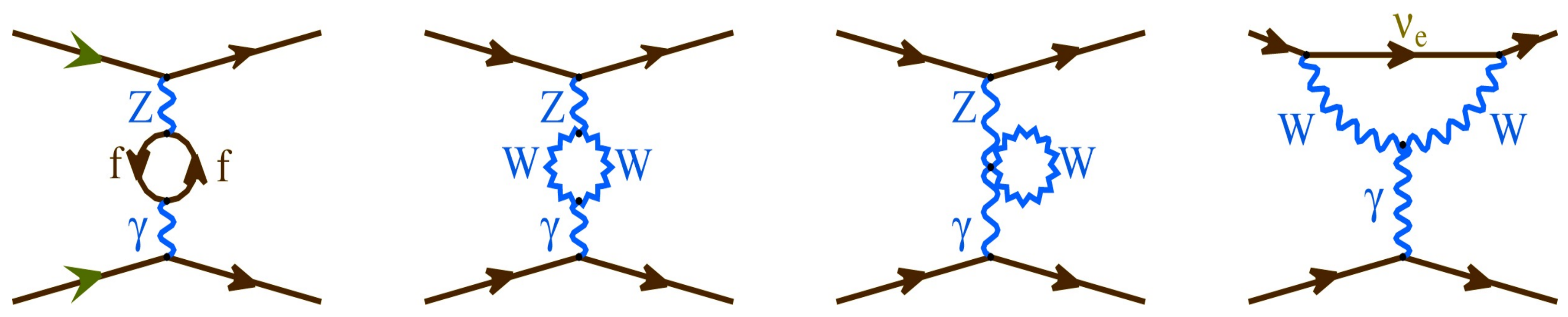
Matching MOLLER precision and accuracy likely requires beta-beams and neutrino factories

Radiative Corrections

The Standard Model Prediction: Remarkably Well-Known

$$A_{PV} = \frac{\rho G_F Q^2}{\sqrt{2}\pi\alpha}\frac{1-y}{1+y^4+(1-y)^4}\{1-4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{\rm MS}}$$
$$+\frac{\alpha(m_Z)}{4\pi\hat{s}^2}-\frac{3\alpha(m_Z)}{32\pi\hat{s}^2\hat{c}^2}(1-4\hat{s}^2)[1+(1-4\hat{s}^2)^2]$$
$$+F_1(y,Q^2)+F_2(y,Q^2)\}$$

Czarnecki and Marciano (1995)



$$\mathbf{Q^e_W = 1 - 4\sin^2\theta_W \sim 0.075 \Longrightarrow 0.045}$$

$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

The small size of the coupling, further reduced by radiative corrections, will be a recurring theme: it eases the pressure on “normalization” errors