Searches for BSM Physics at Low Energy

Krishna S. Kumar
University of Massachusetts, Amherst


(likely incomplete!)
Comprehensive Strategy
Direct and Indirect Searches for Physics Beyond the Standard Model

Compelling arguments for “New Dynamics” at the TeV Scale

A comprehensive search for clues requires:
Large Hadron Collider as well as Lower Energy: $Q^2 << M_Z^2$
Comprehensive Strategy

Direct and Indirect Searches for Physics Beyond the Standard Model

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Large Hadron Collider as well as Lower Energy: $Q^2 << M_Z^2$

- Violations of Accidental(?) Symmetries
  - CP, T (EDMs, Decays), CPT, Charged Lepton Flavor, Lepton Number

- Dark Matter Searches

- Neutrino Masses and Mixing
  - $0\nu\beta\beta$ decay, reactor $\theta_{13}$, long baseline experiments

- Precision Electroweak Measurements at $Q^2 << M_Z^2$
  - flavor conserving and flavor changing neutral current amplitudes, charged current amplitudes, muon $g-2$
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Intense beams, exotic nuclei, table-top experiments, rare processes....
**Intensity Frontier**

Electroweak Interactions at scales much lower than that of EWSB

Many theories predict new forces that disappeared when the universe cooled

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \sum_{d \geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} \hat{O}^{(d)}_n [\phi_{SM}] \]

• flavor changing as well as flavor diagonal
• charged current as well as neutral current

Many new physics models give rise to such terms:

Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY...

E

\[ \Lambda (= \text{TeV}) \]

\[ M_{W,Z} \]

courtesy V. Cirigliano

Dynamics involving particles with \( m > \Lambda \)
Many new physics models give rise to such terms:

Heavy Z’s and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

Measurements with the potential to indirectly access the TeV scale involve pushing one or more experimental parameters to the extreme such as intensity, luminosity, volume, radio-purity, precision, accuracy....

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\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d \geq 5} \frac{C_n^{(d)}}{\Lambda^{d-4}} \hat{O}_n^{(d)}[\Phi_{\text{SM}}] \]

- Electric Dipole Moment Searches
- Neutrinoless Double Beta Decay Searches
- Charged Lepton Flavor Violation Searches
- CP- and T-violating Weak Decay Searches
- Flavor-changing neutral currents
- Precision Weak Neutral Current Interactions

Dynamics involving particles with \( m > \Lambda \)

\[ \Lambda (\sim \text{TeV}) \]

\[ E \]

courtesy V. Cirigliano

\[ M_{W,Z} \]
Outline

The focus of this talk: flavor changing & conserving lepton currents

- Charged Lepton Flavor Violation
  - $\mu \rightarrow e\gamma$ (MEG at PSI)
  - $\mu N \rightarrow eX$ (Mu2e at Fermilab)

- Intensity Frontier Physics at Fermilab

- Precision Electroweak Measurements at Low Energy
  - muon $g-2$ at FNAL
  - Parity-violating Electron Scattering
    - Qweak & PVDIS at Jefferson Lab
    - MOLLER & SOLID after the 12 GeV Upgrade

- News on Double-Beta Decay Searches
  - EXO-200 is running!

Other Topics:
- Dark Matter (Thursday morning, parallel sessions)
- Neutrinos (this morning, parallel sessions)
- EDM searches (Parallel session this afternoon)
- Heavy Flavors (Plenary talk: Saturday morning)
- CP-Violation (Plenary talk: Saturday morning)
Lepton Flavor Violation

- $\nu$ oscillations: individual lepton family numbers ($L_e, \mu, \tau$) are not conserved
- SM + massive $\nu$'s: charged LFV allowed but negligible (GIM-suppression)

tiny standard model branching fraction

$$\text{BR}(\mu \to e \gamma) = \frac{3 \alpha}{32 \pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}$$

Extremely clean probe of "new" physics at the TeV scale
Lepton Flavor Violation

- $\nu$ oscillations: individual lepton family numbers ($L_e, \mu, \tau$) are not conserved
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$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ tiny standard model branching fraction

$\mu \rightarrow e + \gamma$

Extremely clean probe of “new” physics at the TeV scale

Example: SUSY interpretation of g-2 anomaly results in significant enhancement!

$$BR(\mu \rightarrow e\gamma) = \frac{3 \alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}$$

Supersymmetry
rate $\sim 10^{-15}$
Lepton Flavor Violation

- \( \nu \) oscillations: individual lepton family numbers \((L_e, \mu, \tau)\) are not conserved
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\]

Supersymmetry

rate \( \sim 10^{-15} \)

Tau Decays at \( e^+e^- \) colliders

At Colliders:

Large samples of \( \tau^+\tau^- \) pairs

New results from Babar/BELLE; future initiatives will try to push this by one or two orders of magnitude

\( e^- \gamma \) \( \mu^- \gamma \) \( e^- e^+ e^- \) \( e^- \mu^+ \mu^- \) \( e^+ \mu^- \mu^- \) \( \mu^- e^+ e^- \) \( \mu^+ e^- e^- \) \( \mu^- \mu^+ \mu^- \)
**MEG at PSI**

**Sensitive search for** $\mu^+ \rightarrow e^+ \gamma$ **using CW surface muon beam**

- Signal:
  - $\mu \rightarrow e \gamma$
  - $e^+ \mu^+ \rightarrow \gamma$
  - $\theta_{e\gamma} = 180^\circ$
  - $E_e = E_\gamma = 52.8$ MeV
  - $t_e = t_\gamma$

- Background:
  - Correlated:
    - $\mu \rightarrow e \gamma \nu \nu$
    - $e^+ \mu^+ \rightarrow \gamma$
  - Accidental:
    - $\mu \rightarrow e \nu \nu$
    - $ee \rightarrow \gamma \gamma$
    - $eZ \rightarrow eZ \gamma$

- Prompt branching ratio:
  - $B_{\text{prompt}} \approx 0.1 \times B_{\text{acc}}$

- Accidental branching ratio:
  - $B_{\text{acc}} \propto \frac{R_{\mu}}{D} \Delta E_e \Delta E_\gamma^2 (\Delta \theta_{e\gamma})^2 \Delta t_{e\gamma}$
MEG at PSI

Sensitive search for $\mu^+ \rightarrow e^+ \gamma$ using CW surface muon beam

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### Signal

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- $e^+ \rightarrow \mu^+ \gamma$

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### Background

- Correlated:
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  - $e^+ \rightarrow \mu^+ \nu \gamma$

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  - $e \rightarrow \gamma \gamma$
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$B_{\text{prompt}} \approx 0.1 \times B_{\text{acc}}$

\[ B_{\text{acc}} \propto \frac{R_{\mu}}{D} \Delta E_e \Delta E_\gamma^2 (\Delta \theta_{e\gamma})^2 \Delta t_{e\gamma} \]

---

### The Beam

- Located at Paul Scherrer Institut (CH)
- The most intense in the World ($>3 \times 10^8 \mu/s @ 2$ mA)
- Continuous (good for $B_{\text{acc}}$ suppression)
- Surface muons (28 MeV/c)

### The Detector

- Beam of $3 \times 10^7 \mu/s$ stopped in a 175 $\mu$m target
- Liquid Xenon calorimeter for $\gamma$ detection (scintillation)
- Solenoid spectrometer & drift chambers for $e^+$ momentum
- Scintillation counters for $e^+$ timing

Matter effects must be minimized in order not to spoil the resolution

---

Talk by N. Donato, Wed. afternoon
MEG at PSI
Sensitive search for $\mu^+ \rightarrow e^+ \gamma$ using CW surface muon beam

**The beam**
- Located at Paul Scherrer Institut (CH)
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**The detector**
- Beam of 3x10^7 μ/sec stopped in a 175 μm target
- Liquid Xenon calorimeter for γ detection (scintillation)
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New! 2009+10 Data:
Result: $< 2.4 \times 10^{-12}$
90% C.L. upper limit

2011 data taking has commenced
Final Goal (~2013):
Sensitivity: few $\times 10^{-13}$
Broader Sensitivity
The complementarity of muon-electron conversion

<table>
<thead>
<tr>
<th>$B_{\mu-e\gamma}$</th>
<th>$&lt; 1.2 \times 10^{-11}$</th>
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$10^{-13/14}$ (MEG at PSI, *now running*)

$10^{-14/17}$ Mu2e at Fermilab, DeeMe & COMET at J-PARC
muon converts to electron in the presence of a nucleus

Talk by M. Lancaster, Wed. afternoon
**Broader Sensitivity**

The complementarity of muon-electron conversion

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$10^{-13/14}$ (MEG at PSI, *now running*)

$10^{-14/17}$ Mu2e at Fermilab, DeeMe & COMET at J-PARC

Muon converts to electron in the presence of a nucleus

Signature: single $\sim 105$ MeV monoenergetic electron; beyond endpoint of DIO spectrum

Talk by M. Lancaster, Wed. afternoon
Broader Sensitivity
The complementarity of muon-electron conversion

\[
\begin{align*}
B_{\mu-e^\gamma} &< 1.2 \times 10^{-11} \\
B_{\mu-3e} &< 1.0 \times 10^{-12} \\
B_{T_i \mu-e} &< 4.3 \times 10^{-12} \\
B_{Au \mu-e} &< 8 \times 10^{-13} \\
B_{Pb \mu-e} &< 4.6 \times 10^{-11}
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\[10^{-13/14} \quad \text{(MEG at PSI, now running)}\]

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\[\Lambda (\text{TeV})\]

Signature: single ~105 MeV monoenergetic electron; beyond endpoint of DIO spectrum

Talk by M. Lancaster, Wed. afternoon
**Broader Sensitivity**

The complementarity of muon-electron conversion

- $B_{\mu\rightarrow e\gamma} < 1.2 \times 10^{-11}$
- $B_{\mu\rightarrow 3e} < 1.0 \times 10^{-12}$
- $B_{\mu_{Ti\rightarrow e}} < 4.3 \times 10^{-12}$
- $B_{\mu_{Au\rightarrow e}} < 8 \times 10^{-13}$
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Muon converts to electron in the presence of a nucleus

**Supersymmetry and Heavy Neutrinos**

\[
\mu^- \rightarrow e^- \nu \nu
\]

\[
\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1)
\]

**Signature:** single $\sim 105$ MeV monoenergetic electron; beyond endpoint of DIO spectrum

Talk by M. Lancaster, Wed. afternoon
Broader Sensitivity

The complementarity of muon-electron conversion

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→ \[10^{-13/14}\] (MEG at PSI, now running)

→ \[10^{-14/17}\] Mu2e at Fermilab, DeeMe & COMET at J-PARC

muon converts to electron in the presence of a nucleus

Contributes to \(\mu \rightarrow e\gamma\)

Supersymmetry and Heavy Neutrinos

\[\Lambda (\text{TeV})\]

Signature: single ~105 MeV monoenergetic electron; beyond endpoint of DIO spectrum

Talk by M. Lancaster, Wed. afternoon
Mu2e at Fermilab

A new project using intense, pulsed low energy proton beam

Supersymmetry

\[ \text{rate} \sim 10^{-15} \]

\[ \mu^- \rightarrow \gamma \mu^- \mu^- \gamma \]

Compositeness

\[ \Lambda_c \sim 3000 \text{ TeV} \]

\[ \mu^-, e^-, q \rightarrow e^- q \]

Leptoquark

\[ M_{LQ} = 3000 (\lambda_{\mu d}^2 \lambda_{e d}^2)^{1/2} \text{ TeV}/c^2 \]

\[ \mu^- \rightarrow d LQ e^- \]

Heavy Neutrinos

\[ |U_{\mu N} U_{e N}|^2 \sim 8 \times 10^{-13} \]

\[ \mu^-, N \rightarrow W^+ e^- \]

Second Higgs Doublet

\[ g(H_{\mu \mu}) \sim 10^{-4} g(H_{\mu e}) \]

\[ \mu^-, H_1 \rightarrow e^- e^- e^- \]

Heavy Z'

Anomalous Z' Coupling

\[ M_{Z'} = 3000 \text{ TeV}/c^2 \]

\[ \gamma, Z', Z' \rightarrow e^- e^- \]

\[ q, q \]
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Supersymmetry
rate $\sim 10^{-15}$

Compositeness
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$M_{LQ} = 3000 (\lambda_{\mu \mu} \lambda_{dd})^{1/2}$ TeV/c$^2$

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Second Higgs Doublet
$g(H_{\mu\nu}) \sim 10^{-4} g(H_{\mu\mu})$

Heavy Z' Anomalous Z Coupling
$M_{Z'} = 3000$ TeV/c$^2$

A factor of $10^4$ sensitivity improvement:
Pulsed proton beam, superconducting magnets for intense muon beam, exquisite momentum resolution

Talk by C. Group, Wed. afternoon

Rate: $5 \times 10^{10}$ stopped muons/s

Krishna S. Kumar
Searches for BSM Physics at Low Energy, DPF2011, August 9 2011
Mu2e at Fermilab
A new project using intense, pulsed low energy proton beam

Supersymmetry
rate \sim 10^{-15}

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Heavy Z'
Anomalous Z Coupling

\[ M_{Z'} = 3000 \text{ TeV/c}^2 \]

A factor of $10^4$ sensitivity improvement:
Pulsed proton beam, superconducting magnets for intense muon beam, exquisite momentum resolution

In two years of running, fewer than one background event in the signal region.

If $R_{\mu e} = 10^{-15}$, 40 signal events
Mu2e: Ultimate Sensitivity

Monoenergetic single track signal: Detector and beam technology could potentially suppress backgrounds to required level.

Measurement can distinguish between PMNS and MFV.

Complementarity between Lepton Flavor Violation (LFV) and LHC experiments.
Mu2e: Ultimate Sensitivity

muon-electron conversion has potential to reach $10^{-18}$

monoenergetic single track signal:
Detector and beam technology could potentially suppress backgrounds to required level

- Test any single-operator model via target-dependence of $\mu \rightarrow e$ rate

Neutrino-Matrix Like (PMNS)    Minimal Flavor Violation (CKM)

BR($\mu \rightarrow e \times 10^{12}$)

measurement can distinguish between PMNS and MFV

Complementarity between Lepton Flavor Violation (LFV) and LHC experiments

Cirigliano-Kitano-Okada-Tuzon 2009

Mu2e: Ultimate Sensitivity

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*monoenergetic single track signal:*

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Current $\mu e$ conversion

Neutrino-Matrix Like (PMNS)  Minimal Flavor Violation (CKM)

BR$(\mu \rightarrow e) \times 10^{12}$

measurement can distinguish between PMNS and MFV

complementarity between Lepton Flavor Violation (LFV) and LHC experiments

Cirigliano-Kitano-Okada-Tuzon 2009

If signal found in Phase I ($10^{-16}$):
change targets

If no signal: Phase II reach well beyond LHC
Mu2e: Ultimate Sensitivity

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Neutrino-Matrix Like (PMNS) \ Minimal Flavor Violation (CKM)

BR($\mu \rightarrow e$) $\times 10^{12}$

Measurement can distinguish between PMNS and MFV

Complementarity between Lepton Flavor Violation (LFV) and LHC experiments
• Physics Reach Across Intensity Frontier:
  – Physics of Flavor
• Neutrinos (NOvA→LBNE)
• Muons
• Other: Kaons, EDMs

Multiple beams could cater to a broad physics program
Project X: Physics Topics

Parallel Session: 12:30 pm Wednesday

- Physics Reach Across Intensity Frontier:
  - Physics of Flavor
- Neutrinos (NOvA→LBNE)
- Muons
- Other: Kaons, EDMs

Multiple beams could cater to a broad physics program

- $b, s \rightarrow s, d$
- $b \rightarrow s$: $V_{tb} \cdot V_{ts} \approx \lambda^2$, 100 TeV
- $b \rightarrow d$: $V_{tb} \cdot V_{td} \approx \lambda^3$, 500 TeV
- $s \rightarrow d$: $V_{ts} \cdot V_{td} \approx \lambda^5$, 1000 TeV

$\lambda = \sin \theta_C = 0.226(1)$ Isidori, Nir, Perez 2010

Kaons provide critical complementarity

Flavor changing neutral currents highly motivated by virtually all BSM scenarios

New Physics $\Lambda$

Talk by R. Tschirhart
Wed. afternoon

construction of first stage: 2016-2020?
Precision EW Physics
Search for New Flavor Conserving Contact Interactions

Start with 3 fundamental inputs needed: $\alpha_{em}$, $G_F$ and $M_Z$

Other experimental observables predicted at 0.1% level:
sensitive to heavy particles via higher order quantum corrections

4th and 5th best measured parameters: $\sin^2\theta_W$ and $M_W$

courtesy: Jens Erler

Muon decay
$\Pi_{WW} - \Pi_{ZZ} \propto m_t^2 - m_b^2$

Z production

Start with 3 fundamental inputs needed: $\alpha_{em}$, $G_F$ and $M_Z$

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**Precision EW Physics**

**Search for New Flavor Conserving Contact Interactions**

*Talk by D. Webber, Fri. morning*

_**Start with 3 fundamental inputs needed:** \( \alpha_{em}, G_F \text{ and } M_Z \)_

Other experimental observables predicted at 0.1% level:
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**Allows searches for new physics at the TeV scale via small measurement deviations**

![Graph showing T_{WW} - T_{ZZ} \propto m_t^2 - m_b^2](image)

*4th and 5th best measured parameters: \( \sin^2 \theta_W \) and \( M_W \)*

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**Talk by D. Webber, Fri. morning**

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**courtesy: Jens Erler**
**Precision EW Physics**

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**Talk by D. Webber, Fri. morning**

- **All data (90% CL)**
- **LEP 2 excluded (95% CL)**
- **Tevatron excluded (95% CL)**

Allows searches for new physics at the TeV scale via small measurement deviations

- $\Gamma_Z$, $\sigma_{had}$, $R_l$, $R_q$
- $Z$ pole asymmetries
- $M_W$
- $m_t$

**4th and 5th best measured parameters:** $\sin^2 \theta_W$ and $M_W$

All flavor-conserving weak neutral current amplitudes are functions of $\sin^2 \theta_W$
sensitive to TeV-scale contact interactions iff:

- $\delta (\sin^2 \theta_W) \leq 0.5\%$
- away from the Z resonance

Muon decay and $Z$ production:

$$\Pi_{WW} - \Pi_{ZZ} \propto m_t^2 - m_b^2$$

courtesy: Jens Erler
Precision EW Physics
Search for New Flavor Conserving Contact Interactions

Talk by D. Webber, Fri. morning

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one very special observable:
muon g-2 anomaly

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courtesy: Jens Erler
Muon $g-2$ at Fermilab

The New Muon $(g - 2)$ Experiment (Fermilab E989): $a_\mu$ to 0.14 ppm

Status: 3.6 $\sigma$

unique sensitivity to SUSY among low energy observables
Muon $g-2$ at Fermilab

The New Muon ($g - 2$) Experiment (Fermilab E989): $a_\mu$ to 0.14 ppm

- JN 09 ($e^+e^-$-based w/o BABAR): $-299 \pm 65$
- HLMNT 10 ($e^+e^-$-based): $-259 \pm 48$
- DHMZ 10 ($\tau$-based): $-195 \pm 54$
- DHMZ 10 ($e^+e^-$-based): $-287 \pm 49$

BNL-E821 (world average): $0 \pm 63$

Status: 3.6 $\sigma$

Help discriminate among scenarios if SUSY-like signature at LHC

Discriminating SUSY models

- $\sim$ factor of 4 improvement

The Snowmass Points and Slopes showing the present region favored by the E821 $\Delta a_\mu$, and the projected sensitivity of E989 ($UED$ is a universal extra dimension calculation; clearly unfavored)

Status: Obtained Stage-1 Approval, applying for CD-0

From BNL

New installation at FNAL

Krishna S. Kumar

Searches for BSM Physics at Low Energy, DPF2011, August 9 2011
Muons, Neutrinos and Beyond

- Fermilab plan for the next decade
  - Neutrinos: NOvA to explore the PMNS matrix
  - Muons: Mu2e and g-2

- Neutrinos and Muons can run simultaneously
  - Mu2e and g-2 must alternate but complex accommodates both
  - neither conflicts with NOvA
  - planning assumes all three will run in the next decade

- Significant improvement in intensity with Project X
  - x100 muons for mu2e to reach $10^{-18}$ or study $Z$ dependence
  - Many other ideas for rare mu, $K$ decays, EDMs....
Weak Neutral Currents
Search for New Flavor Conserving Contact Interactions

◆ Precision Neutrino Scattering
◆ New Physics/Weak-Electromagnetic Interference
  • opposite parity transitions in heavy atoms
  • Spin-dependent electron scattering
Weak Neutral Currents
Search for New Flavor Conserving Contact Interactions

- **Precision Neutrino Scattering**
- **New Physics/Weak-Electromagnetic Interference**
  - opposite parity transitions in heavy atoms
  - Spin-dependent electron scattering

**Parity-violating Electron Scattering**

\[-A_{LR} = A_{PV} = \frac{\sigma_{L}-\sigma_{R}}{\sigma_{L}+\sigma_{R}} \sim \frac{A_{\text{weak}}}{A_{\gamma}} \sim \frac{G_{F} Q^{2}}{4 \pi \alpha} (g_{A} e g_{V} T + \beta g_{V} e g_{A} T)\]

\[g_{V} \text{ and } g_{A} \text{ are function of } \sin^{2}\theta_{W}\]

\[A_{PV} \sim 10^{-5} \cdot Q^{2} \text{ to } 10^{-4} \cdot Q^{2}\]
Weak Neutral Currents
Search for New Flavor Conserving Contact Interactions

- Precision Neutrino Scattering
- New Physics/Weak-Electromagnetic Interference
  - opposite parity transitions in heavy atoms
  - Spin-dependent electron scattering

**Parity-violating Electron Scattering**

\[ -A_{LR} = A_{PV} = \frac{\sigma_{\uparrow \rightarrow \uparrow} - \sigma_{\uparrow \rightarrow \downarrow}}{\sigma_{\uparrow \rightarrow \uparrow} + \sigma_{\uparrow \rightarrow \downarrow}} \sim \frac{A}{A_{\gamma}} \sim \frac{G_F Q^2}{4 \pi \alpha} (g_A e V_T + \beta g_V e g_A T) \]

\[ g_V \text{ and } g_A \text{ are function of } \sin^2 \theta_W \]

Thumb rule: measure \( \delta(\sin^2 \theta_W) \lesssim 0.002 \) or better to access the multi-TeV scale

\[ A_{PV} \sim 10^{-5} \cdot Q^2 \text{ to } 10^{-4} \cdot Q^2 \]

Weak Charge \( Q_w \)

\[ e \& p: \quad Q_w = 1 - 4 \sin^2 \theta_W \]
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Parity-violating Electron Scattering

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Thumb rule: measure \(\delta (\sin^2 \theta_W) \lesssim 0.002\) or better to access the multi-TeV scale

Electromagnetic amplitude interferes with Z-exchange as well as any new physics

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

Weak Charge \(Q_W\)

\[e \& p: \quad Q_W = 1 - 4 \sin^2 \theta_W\]
Parity-Violating Electron-Electron (Møller) Scattering

SLAC E158

Purely leptonic reaction

\[ Q^e_W G_F \]
Parity-Violating Electron-Electron (Møller) Scattering

\[ A_{PV} \propto m_e E_{lab} (1 - 4 \sin^2 \vartheta_W) \]

\[ \frac{\delta(\sin^2 \vartheta_W)}{\sin^2 \vartheta_W} \approx 0.05 \frac{\delta(A_{PV})}{A_{PV}} \]

50 GeV at SLAC:
\[ \sim 150 \text{ ppb!} \]
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\(~ 150 \) ppb!

**Standard Linear Accelerator Center (SLAC)**

45 & 48 GeV Beam
85% longitudinal polarization

Final Result:

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

*Phys. Rev. Lett.* 95 081601 (2005)*
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**Standard Linear Accelerator Center (SLAC)**

**Major technical challenges**

45 & 48 GeV Beam

85% longitudinal polarization

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The Weak Mixing Angle

**Running of** $\theta_W$: Bookkeeping for off-resonance measurements

- $\gamma-\gamma$ loop is the running of $\alpha_{EM}$
- $W-W$ loop provides indirect $m_t$
- $\gamma-Z$ loop is the running of $\sin^2\theta_W$
The Weak Mixing Angle

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---

**Atomic Parity Violation**
- $^{133}\text{Cs}$: Best result to date
- *Future initiatives: Fr, Yb, Ra+.... (TRIUMF, Berkeley, Seattle, KVI...)*

**Deep Inelastic Neutrino Scattering**
- *NuTeV result requires careful consideration of nuclear corrections*
- *Improved measurements require new facilities*
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Precision Weak Charges
Current and future measurements of parity-violating asymmetries

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

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

4 e-q couplings and the e-e coupling
**Precision Weak Charges**

Current and future measurements of parity-violating asymmetries

- **Elastic Electron-Proton Scattering**
  - *Qweak has accumulated more than 25% of production data*
  - *New proposal to improve Qweak by factor of 3 at Mainz, Germany*

- **Deep Inelastic Scattering off Deuterium**
  - *6 GeV experiment completed: analysis ongoing*
  - *SoLID: New Apparatus with a large solenoid using 11 GeV beam*

- **Møller Scattering**
  - *MOLLER: New project to improve E158 by a factor of 5*
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---

Talk by J-P Rajotte
Friday morning

After Jlab energy upgrade in 2013; physics 2015-20
**Precision Weak Charges**

Current and future measurements of parity-violating asymmetries

\[ C_{1i} = 2g_A^e g_V^i \]
\[ C_{2i} = 2g_V^e g_A^i \]

4 e-q couplings and the e-e coupling

LHC new physics signals will have multiple interpretations: weak charge measurements can discriminate among scenarios

- **Elastic Electron-Proton Scattering**
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Talk by J-P Rajotte Friday morning

After Jlab energy upgrade in 2013; physics 2015-20
**MOLLER at Jefferson Lab**

An ultra-precise measurement of the weak mixing angle using Møller scattering

- \( E_{\text{beam}} = 11 \text{ GeV} \)
- 75 \( \mu \text{A} \)
- 80% polarized
- \( \Delta(A_{PV}) = 0.73 \text{ ppb} \)
- \( A_{PV} = 35.6 \text{ ppb} \)
- \( \delta(Q_{eW}) = \pm 2.1 \text{ (stat.)} \pm 1.0 \text{ (syst.) \%} \)
- \( \delta(\sin^2\theta_W) = \pm 0.00026 \text{ (stat.)} \pm 0.00012 \text{ (syst.)} \) ~ 0.1\%

\[ \text{δ(sin}^2\text{θ}_W\text{)} = \pm 0.00026 \text{ (stat.)} \pm 0.00012 \text{ (syst.)} \Rightarrow \sim 0.1\% \]
MOLLER at Jefferson Lab

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\[ \sim 0.1\% \]

\[ \Lambda = 7.5 \text{ TeV} \]

**best contact interaction reach for leptons at low OR high energy**

To do better for a 4-lepton contact interaction would require:

- Z factory,
- linear collider,
- neutrino factory or muon collider

---

Krishna S. Kumar

Searches for BSM Physics at Low Energy, DPF2011, August 9 2011
MOLLER at Jefferson Lab

An ultra-precise measurement of the weak mixing angle using Møller scattering

\[ E_{\text{beam}} = 11 \text{ GeV} \quad 75 \mu \text{A} \quad 80\% \text{ polarized} \quad \sim 38 \text{ weeks} \quad (\sim 2 \text{ yrs}) \quad \delta(A_{PV}) = 0.73 \text{ ppb} \]

\[ A_{PV} = 35.6 \text{ ppb} \quad \delta(Q^e_W) = \pm 2.1 \text{ (stat.)} \pm 1.0 \text{ (syst.)} \% \]

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

\[ \begin{align*}
L_{e_1e_2} &= \sum_{i,j=L,R} \frac{g^2_{ij}}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j \\
\Lambda &= \frac{\sqrt{g_{RR}^2 - g_{LL}^2}}{g_{RR}} = 7.5 \text{ TeV}
\end{align*} \]

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Searches for BSM Physics at Low Energy, DPF2011, August 9 2011

18
MOLLER at Jefferson Lab

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\[ \delta(Q^{eW}) = \pm 2.1 \text{ (stat.)} \pm 1.0 \text{ (syst.)} \% \]

\[ \delta(\sin^{2}{\theta_{W}}) = \pm 0.00026 \text{ (stat.)} \pm 0.00012 \text{ (syst.)} \% \]

\[ \approx 0.1\% \]

Proposal to be submitted to DoE (Nuclear Physics) to obtain CD-0

\[ \Lambda = 7.5 \text{ TeV} \]

\[ \frac{\Lambda}{\sqrt{g_{RR}^{2} - g_{LL}^{2}}} \]

\textbf{best contact interaction reach for leptons at low OR high energy}

To do better for a 4-lepton contact interaction would require:

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Krishna S. Kumar

Searches for BSM Physics at Low Energy, DPF2011, August 9 2011
Neutrinoless Double-Beta Decay

Are neutrinos Majorana particles? What is the absolute neutrino mass?

- **Need both helicities**, so $\nu_e$ must be massive
- Neutrino mass mechanism for double beta decay
- $\text{amplitude } \sim \frac{m(\nu)}{E(\nu)}$, $E(\nu) \sim 100 \text{ MeV}$

Talk by F. Avignone, Friday morning

- $2\nu\beta\beta$
- $0\nu\beta\beta$
- 2% energy resolution

- **N(Z,A)**
- **N(Z+2,A)**

[N(Z,A)]

[$N(Z,A)$]

[$N(Z+2,A)$]
**EXO-200**

Physics run ongoing with 200 kg of 80% enriched $^{136}\text{Xe}$

- Copper cryostat filled with HFE heat transfer fluid
- Lead shielding
- TPC

- at WIPP (1600 mwe)
- Liquid Xe TPC
- scintillation (APDs)
- ionization from wires
- $2-\nu$: > 40K evts/yr at current limit
- $0-\nu$ reach with 2 year run: 109 - 135 meV

Stay tuned!

$^{214}\text{Bi}$ undergoes $\beta$-decay into $^{214}\text{Po}$ which then undergoes $\alpha$-decay with a half-life of 164 $\mu$s.

Talk by T. Daniels, Wed. afternoon

source calibration data

source positions for calibration runs

single-site energy deposition

two-site Compton scattering event
Take-Away Message

- **Charge Lepton Flavor Violation Searches**
  - *MEG will push into the interesting region (10^{-13}) in a couple of years*
  - *Mu2e, DeeMe and COMET will improve sensitivity by 10^{3-4} over the next decade*
  - *Tau decays aim to improve sensitivity by 10 to 100 at super-B factories*

- **Muon g-2**
  - *Plans are being made for x4 improvement with a new experiment at Fermilab*

- **Fermilab Project X offers the potential to expand portfolio of Intensity Frontier physics**

- **Parity-Violating Electron Scattering**
  - *Qweak will produce the best low energy weak mixing angle measurement in 2 years*
  - *MOLLER and SOLiD will push sensitivity into the multi-TeV scale in the next decade*

- **Neutrinoless Double-Beta Decay**
  - *EXO-200 has begun a physics run with 160 kg of^{136}Xe*
  - *Several other projects at the scale of 100s of kg-yr will start data collection in the next few years: probe the 100 meV absolute mass scale*
Mature Technique
Parity-Violating Longitudinal Beam Spin Asymmetry

*Parity-violating electron scattering has become a precision tool*

- Beyond Standard Model
- Strange quark form factors
- Neutron skin of a heavy nucleus
- QCD structure of the nucleon

Mainz & MIT-Bates in the mid-80s
JLab program launched in the mid-90s:
focus on strange quarks

- part per billion systematic control
- 1% normalization control

- photocathodes, polarimetry, high power cryotargets,
nanometer beam stability, precision beam diagnostics,
low noise electronics, radiation hard detectors
Potential Isotopes

Candidate nuclei with Q>2 MeV

<table>
<thead>
<tr>
<th>Candidate</th>
<th>(Q) (MeV)</th>
<th>Abund. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{48}\text{Ca} \rightarrow ^{48}\text{Ti})</td>
<td>4.271</td>
<td>0.187</td>
</tr>
<tr>
<td>(^{76}\text{Ge} \rightarrow ^{76}\text{Se})</td>
<td>2.040</td>
<td>7.8</td>
</tr>
<tr>
<td>(^{82}\text{Se} \rightarrow ^{82}\text{Kr})</td>
<td>2.995</td>
<td>9.2</td>
</tr>
<tr>
<td>(^{96}\text{Zr} \rightarrow ^{96}\text{Mo})</td>
<td>3.350</td>
<td>2.8</td>
</tr>
<tr>
<td>(^{100}\text{Mo} \rightarrow ^{100}\text{Ru})</td>
<td>3.034</td>
<td>9.6</td>
</tr>
<tr>
<td>(^{110}\text{Pd} \rightarrow ^{110}\text{Cd})</td>
<td>2.013</td>
<td>11.8</td>
</tr>
<tr>
<td>(^{116}\text{Cd} \rightarrow ^{116}\text{Sn})</td>
<td>2.802</td>
<td>7.5</td>
</tr>
<tr>
<td>(^{124}\text{Sn} \rightarrow ^{124}\text{Te})</td>
<td>2.228</td>
<td>5.64</td>
</tr>
<tr>
<td>(^{130}\text{Te} \rightarrow ^{130}\text{Xe})</td>
<td>2.533</td>
<td>34.5</td>
</tr>
<tr>
<td>(^{136}\text{Xe} \rightarrow ^{136}\text{Ba})</td>
<td>2.479</td>
<td>8.9</td>
</tr>
<tr>
<td>(^{150}\text{Nd} \rightarrow ^{150}\text{Sm})</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>

\[m_{\nu}^{\text{eff}} \approx 50\text{ meV}: \sim 10^{27}\text{ years}\]

\((10^{27}\text{ nuclei} \sim 10^3\text{ moles} \sim 100\text{ kg})\)

\[T_{1/2}^{0\nu\beta\beta} = 2.23^{+0.44}_{-0.31} \times 10^{25}\text{ years}\]

\[m_{\nu}^{\text{eff}} = 0.32 \pm 0.03\text{ eV}\]

\[\Delta m_{23}^2 < 0\]

\[\Delta m_{23}^2 > 0\]

\(99\%\text{ CL (1 dof)}\)

\([\text{Strumia and Vissani, hep-ph/0606054}]\)
## Ongoing Projects

<table>
<thead>
<tr>
<th>Technique</th>
<th>Location</th>
<th>Mass kg</th>
<th>start</th>
<th>Bckg Cts/keV/kg/yr</th>
<th>$T_{1/2}(0\nu)$ 5 yr</th>
<th>$&lt;m_{ee}&gt;$ meV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EXO</strong></td>
<td>Liquid Xe $^{136}$Xe</td>
<td>WIPP (USA)</td>
<td>200</td>
<td>0.002</td>
<td>$6.4 \times 10^{25}$</td>
<td>$&lt; 109 - 135$</td>
</tr>
<tr>
<td><strong>GERDA</strong></td>
<td>Diode Ge $^{76}$Ge</td>
<td>Gan sasso (Italy)</td>
<td>18</td>
<td>0.01</td>
<td>$3.0 \times 10^{25}$</td>
<td>$&lt; 250 - 380$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>0.001</td>
<td>$3.0 \times 10^{26}$</td>
<td>$&lt; 80 - 120$</td>
</tr>
<tr>
<td><strong>CUORE-0</strong></td>
<td>Bolometers $^{130}$Te</td>
<td>Gan sasso (Italy)</td>
<td>13</td>
<td>0.12</td>
<td>$8.0 \times 10^{25}$</td>
<td>$&lt; 100 - 200$</td>
</tr>
<tr>
<td><strong>CUORE</strong></td>
<td></td>
<td></td>
<td>200</td>
<td>0.01</td>
<td>$2.1 \times 10^{26}$ $6.5 \times 10^{26}$</td>
<td>$&lt; 41 - 82$ $&lt; 23 - 47$</td>
</tr>
<tr>
<td><strong>SN module0</strong></td>
<td>Tracko-calorimeter $^{82}$Se, $^{150}$Nd</td>
<td>Modane (France)</td>
<td>7</td>
<td>0.0001</td>
<td>$6.0 \times 10^{24}$</td>
<td>$&lt; 200 - 600$</td>
</tr>
<tr>
<td><strong>SuperNEMO</strong></td>
<td></td>
<td></td>
<td>100</td>
<td>0.0001</td>
<td>$1.0 \times 10^{26}$</td>
<td>$&lt; 53 - 145$</td>
</tr>
<tr>
<td><strong>SNO+</strong></td>
<td>Liq. Scint. $^{150}$Nd</td>
<td>SNOLAB (Canada)</td>
<td>44</td>
<td></td>
<td></td>
<td>$&lt; 100$</td>
</tr>
<tr>
<td><strong>KamLAND</strong></td>
<td>Liq. Scint. $^{136}$Xe</td>
<td>Kamioka (Japan)</td>
<td>400</td>
<td></td>
<td></td>
<td>$&lt; 60$ (2 yr)</td>
</tr>
</tbody>
</table>

F. Picquemal, ICHEP2010
Xenon is Attractive

Xenon isotopic enrichment is easier:  \( Xe \) is a gas and \( ^{136}Xe \) is the heaviest isotope.

Xenon is “reusable”:  can be re-purified and easily recycled into a different detector (no crystal growth).

Monolithic detector:  \( LXe \) is self shielding, surface contamination minimized.

Minimal cosmogenic activation:  no long lived radioactive isotopes of \( Xe \).

Energy resolution in \( LXe \) improved:  scintillation light + ionization anti-correlation.

… admits a novel coincidence technique:  background reduction by \( Ba \) tagging.
EXO-200 Overview

EXO-200 is a large LXe TPC with scintillation light readout. It uses a source of 200 kg of enriched xenon (80% $^{136}$Xe).

→ EXO-200 has no $^{136}$Ba$^+$ identification ←

Goals:

- look for $0\nu\beta\beta$ decay of $^{136}$Xe with competitive sensitivity
  $(T^{0\nu}_{1/2} > 6 \times 10^{25} \text{ y}, \text{ current limit: } T^{0\nu}_{1/2} > 2.8 \times 10^{24} \text{ y})$

- measure the standard $2\nu\beta\beta$ decay of $^{136}$Xe $(Q = 2457.8 \pm 0.4 \text{ keV})$ and measure its lifetime
  (best upper limit to date: $T^{2\nu}_{1/2} > 1 \times 10^{22} \text{ y}$)

- test backgrounds of large LXe detector at $\sim$2000 m.w.e. depth
- test LXe technology and enrichment on a large scale
- test TPC components, light readout (518 LAAPDs), and radioactivity of materials, xenon handling and purification, energy resolution
The EXO-200 detector

- Refrigeration and HFE feedthroughs
- Hermetic lead enclosure (25 cm, low activity Pb)
- Double, vacuum-insulated cryostat (low-background copper)
- Xe and TPC copper chamber
- Class 100 clean room
- 50 cm of ultra pure cryofluid, providing large thermal bath for uniform temperature (3M HFE-7000, hydrofluoroether C₃F₇OCH₃)
Principal Backgrounds

- $\gamma$ (2449 keV) from $^{214}$Bi decay  (from $^{238}$U and $^{222}$Rn decay chains)
- $\gamma$ (2615 keV) from $^{208}$Tl decay  (from $^{232}$Th decay chain)
- $\gamma$ (1.4 MeV) from $^{40}$K  (a concern for the $2\nu\beta\beta$)
- $^{60}$Co: 1173 + 1333 keV simultaneous $\gamma$’s  (from $^{63}$Cu($\alpha$,n)$^{60}$Co)
- other $\gamma$’s in $^{238}$U and $^{232}$Th chains
- other cosmogenic products of Cu  (a concern for the $2\nu\beta\beta$)
- in situ cosmogenic products in Xe, neutron capture de-excitations, ...
- $^{222}$Rn anywhere (Xe, HFE, air gaps inside lead shield)

**very extensive material screening campaign:**

<table>
<thead>
<tr>
<th>Component</th>
<th>K $10^{-9}$ g/g</th>
<th>Th $10^{-12}$ g/g</th>
<th>U $10^{-12}$ g/g</th>
<th>$^{210}$Po Bq/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M Novec HFE-7000, 1-methoxyheptafluoropropane</td>
<td>&lt;1.08</td>
<td>&lt;7.3</td>
<td>&lt;6.2</td>
<td></td>
</tr>
<tr>
<td>Lead shielding</td>
<td>&lt;7</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>17-20</td>
</tr>
<tr>
<td>Copper</td>
<td>&lt;55</td>
<td>&lt;2.4</td>
<td>&lt;2.9</td>
<td></td>
</tr>
<tr>
<td>Acrylic</td>
<td>&lt;2.3</td>
<td>&lt;14</td>
<td>&lt;24</td>
<td></td>
</tr>
<tr>
<td>TPC grid wires</td>
<td>&lt;90</td>
<td>47 +/- 2</td>
<td>320 +/- 2</td>
<td></td>
</tr>
</tbody>
</table>


Krishna S. Kumar

Searches for BSM Physics at Low Energy, DPF2011, August 9 2011
### Assumptions
1. 200 kg of $^{136}$Xe, 80% enrichment
2. Low but finite radioactive background: 20 events/yr in ±2σ interval around Q=2.481 MeV
3. Negligible background from $2\nu\beta\beta$ ($T_{1/2} > 1\times10^{22}$ yr, Bernabei et al.)

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass [ton]</th>
<th>Efficiency [%]</th>
<th>Run time [yr]</th>
<th>$\sigma_{E}/E @ 2.5$ MeV [%]</th>
<th>Radioactive background [events]</th>
<th>$T_{1/2}^{0\nu\beta\beta}$ [yr, 90% CL]</th>
<th>Neutrino majorana mass [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXO-200</td>
<td>0.2</td>
<td>70</td>
<td>2</td>
<td>1.6</td>
<td>40</td>
<td>6.4x10^{25}</td>
<td>0.135 (1)</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td></td>
<td>0.109 (2)</td>
</tr>
</tbody>
</table>

If Klapdor’s observations are correct, EXO-200, 2-yr runtime:
1. 46 events on top of 40 (QRPA) $\rightarrow$ 5σ measurement
2. 170 events on top of 40 (NSM) $\rightarrow$ 11.7σ measurement

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass [ton]</th>
<th>Efficiency [%]</th>
<th>Run time [yr]</th>
<th>$\sigma_{E}/E @ 2.5$ MeV [%]</th>
<th>$2\nu\beta\beta$ background [events]</th>
<th>$T_{1/2}^{0\nu\beta\beta}$ [yr, 90% CL]</th>
<th>Neutrino majorana mass [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservative</td>
<td>1</td>
<td>70</td>
<td>5</td>
<td>1.6 (3)</td>
<td>0.5 (~1)</td>
<td>2.0x10^{27}</td>
<td>19 (1)</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24 (2)</td>
</tr>
<tr>
<td>Aggressive</td>
<td>10</td>
<td>70</td>
<td>10</td>
<td>1.0 (4)</td>
<td>0.7 (~1)</td>
<td>4.1x10^{28}</td>
<td>4.3 (1)</td>
</tr>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>5.3 (2)</td>
</tr>
</tbody>
</table>
E158 Data

**g-2 spin precession**
- 45 GeV: 14.0 revs
- 48 GeV: 14.5 revs

**A_{PV} = -131 \pm 14 \text{ ppb}**

\[ \chi^2/df = 78.5/74 \]

**Run I-III**

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

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

\[ A_{PV} \approx -1 \times 10^{-7} \times E_{beam} \times P_{beam} \times (1 - 4 \sin^2 \theta_W) \]

\[ \approx 250 \text{ ppb} \]
Qweak @ Jefferson Lab
Precision Measurement of the Proton’s Weak Charge

- Design and construction over past several years
- Successful installation and commissioning
- Data ~ 2010 thru mid-2012
- 25% of production data accumulated

New, complementary constraints on lepton-quark interactions at the TeV scale
Deep Inelastic Scattering

With Qweak and APV, $C_{1i}$’s measured, but $C_{2i}$’s still unconstrained

**$A_{PV}$ in Electron-Nucleon DIS:**

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha} \left[ a(x) + f(y)b(x) \right]$$

$Q^2 >> 1 \text{ GeV}^2$, $W^2 >> 4 \text{ GeV}^2$

For a $^2H$ target, assuming charge symmetry, structure functions largely cancel in the ratio

Must measure $A_{PV}$ sub-1% fractional accuracy! → luminosity $> 10^{38}/\text{cm}^2/\text{s}$ at JLab

- First experiment at 6 GeV: ran Oct-Dec ’09; 3-4% accuracy @ $Q^2 \sim 1-2 \text{ GeV}^2$
- SOLID: New large acceptance solenoidal spectrometer approved for Hall A