Beyond the Standard Model: The Low & High Energy Interface

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U Mass Amherst

http://www.physics.umass.edu/acfi/

INT Workshop, Seattle, September 2015
Goals for this talk

- Set the context for the workshop
- Highlight (some) opportunities for low energy BSM discoveries
- Illustrate complementarity with BSM searches at the high energy frontier
- Underscore the need for on-going developments in nuclear and hadronic structure
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• Set the context for the workshop
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• Illustrate complementarity with BSM searches at the high energy frontier
• Underscore the need for on-going developments in nuclear and hadronic structure
Outline

I. Fundamental symmetries: the BSM context
II. LNV: $0\nu\beta\beta$ – decay & the LHC
III. CPV: EDMs, the LHC, & Baryon Asymmetry
IV. Precision Tests (if time)
V. Outlook
I. The BSM Context
Questions for Fundamental Physics*

• What is the origin of matter (luminous & dark) ?
• Why are neutrino masses so small ?
• Are fundamental interactions “natural” ?

*Partial List
BSM Physics: Where Does it Live?
BSM Physics: Where Does it Live?
BSM Physics: Where Does it Live?

- SUSY, LNV, extended Higgs sector…
- Sterile ν’s, axions, dark U(1)…

Diagram:
- Mass Scale
- Coupling
- BSM ?
Questions for Fundamental Physics*

- What is the origin of matter (luminous & dark) ?
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Discovering answers requires studies at three frontiers: energy, intensity, & cosmic.

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This talk
Low-Energy / High-Energy Interplay

Discovery

Low energy

“Diagnostic”

High energy
Low-Energy / High-Energy Interplay

Discovery

"Diagnostic"

Low energy

High energy
The Nuclear Physics Program

Targeted program of experiments & theory

- Nature of the neutrino & search for lepton number violation
- Yet unseen T-violation (CP-violation)
- Other key ingredients of the “New Standard Model”
### Four Components

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** 2012 NSAC Subcommittee Report
## Four Components

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If time
II. LNV: $0\nu\beta\beta$ – Decay & the LHC
$\beta\beta$-Decay: LNV? Mass Term?

\[ \mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \]

\[ \mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.} \]

Dirac  \hspace{1cm} \text{Majorana}
$0
\nu \beta \beta$-Decay: LNV? Mass Term?

\[ \mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \quad \text{Dirac} \]

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LNV Physics

\[ A(Z,N) \quad A(Z - 2, N + 2) \]
\(0\nu\beta\beta\)-Decay: LNV? Mass Term?

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**Dirac**

**Majorana**

**Impact of observation**

- Total lepton number not conserved at classical level
- New mass scale in nature, \(\Lambda\)
- Key ingredient for standard baryogenesis via leptogenesis
Ton Scale Experiments

0νββ decay Experiments - Efforts Underway

Thanks: J. Wilkerson
Why Might A “Ton-Scale” Exp’t See It?

A(Z,N) → Underlying Physics → A(Z+2, N-2) + e⁻ e⁻

- 3 light neutrinos only: source of neutrino mass at the very high see-saw scale
- 3 light neutrinos with TeV scale source of neutrino mass
- > 3 light neutrinos
Why Might A “Ton-Scale” Exp’t See It?

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- Dirac
- Majorana

“Standard” Mechanism

- Light Majorana mass generated at the conventional see-saw scale: \( \Lambda \sim 10^{12} - 10^{15} \text{ GeV} \)
- 3 light Majorana neutrinos mediate decay process

\[ A(Z,N) \rightarrow A(Z-2,N+2) \]
Why Might A “Ton-Scale” Exp’t See It?

Three active light neutrinos

Effective DBD neutrino mass (eV)

Lightest neutrino mass (eV) →

IH

NH
Why Might A “Ton-Scale” Exp’t See It?

Three active light neutrinos

Current generation

Effective DBD neutrino mass (eV)

Ton Scale

Inverted

Current generation

Lightest neutrino mass (eV) →

Normal
Interpreting the Result

Three active light neutrinos

Effective DBD neutrino mass (eV)

Current generation

Ton Scale

Inverted

Normal

Lightest neutrino mass (eV) →

Full implications require information on lightest mass & hierarchy
Interpreting a Positive Result

Three active light neutrinos

Effective DBD neutrino mass (eV)

Current generation

Current generation

Ton Scale

Inverted

Normal

Lightest neutrino mass (eV) →

Positive result would be consistent with 3 light active ν’s & IH or quasi-deg regime, but not definitive as to mechanism
Interpreting a Null Result

Three active light neutrinos

Effective DBD neutrino mass (eV)

Current generation

Inverted Normal

Ton Scale

Lightest neutrino mass (eV) →

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What Would a Null Result Imply?

Three active light neutrinos

Effective DBD neutrino mass (eV)

$^{3}\text{H}$ decay cur gen

Null result in NLDBD & non-zero $m_\nu$ from $^{3}\text{H}$ decay $\rightarrow$ Neutrinos are (pseudo) Dirac
What Would a Null Result Imply?

Three active light neutrinos

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$^3$H decay cur gen

$^3$H decay next gen

Lightest neutrino mass (eV) $\rightarrow$
What Would a Null Result Imply?

Three active light neutrinos

Effective DBD neutrino mass (eV)

Current generation

Inverted

Ton Scale

NH

Cosmo current

Normal

Null result in NLDBD & non-zero $m_\nu$ from cosmology $\rightarrow$ Conclusion depends on $m_{\text{lightest}}$ & hierarchy
What Would a Null Result Imply?

Three active light neutrinos

Lightest neutrino mass (eV)

Effective DBD neutrino mass (eV)

$^3H$ decay cur gen

Cosmo future

Ton Scale

Inverted

Normal

Current generation

Current generation

Null result in NLDBD & non-zero $m_\nu$ from cosmology → Conclusion depends on $m_{\text{lightest}}$ & hierarchy

$^3H$ decay next gen
Neutrino Mass Hierarchy

Expected significance for rejecting wrong hierarchy hypothesis

Blennow et al, 1311.1822
Interpreting a Positive Result

Three active light neutrinos

Effective DBD neutrino mass (eV)

Positive result would be consistent with 3 light active $\nu$'s & IH or quasi-deg regime, but not definitive as to mechanism
Why Might A “Ton-Scale” Exp’t See It?

A(Z,N) → Underlying Physics → A(Z+2, N-2) + e⁻ e⁻

- 3 light neutrinos only: source of neutrino mass at the very high see-saw scale
- 3 light neutrinos with TeV scale source of neutrino mass
- > 3 light neutrinos

Two parameters: Effective coupling & effective heavy particle mass
0νββ-Decay: LNV? Mass Term?

\[ \mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \]

Dirac

\[ \mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.} \]

Majorana

TeV LNV Mechanism

- Majorana mass generated at the TeV scale
- Low-scale see-saw
- Radiative \( m_\nu \)
- \( m_{\MIN} \ll 0.01 \text{ eV} \) but 0νββ-signal accessible with tonne-scale exp’ts due to heavy Majorana particle exchange
0νββ-Decay: TeV Scale LNV

\[ \mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \quad \text{Dirac} \]

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0νββ - decay

TeV Scale LNV

Can it be discovered with combination of 0νββ & LHC searches?

Simplified models

LHC: \( pp \rightarrow jj e^-e^- \)
$0\nu\beta\beta$-Decay: TeV Scale LNV

$\mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.}$  

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**Dirac**  

**Majorana**

$0\nu\beta\beta$ - decay

LHC: $pp \rightarrow jj e^- e^-$

TeV Scale LNV

Comparing $0\nu\beta\beta$ & LHC sensitivities:

- LHC backgrounds
- Running effective op’s to low energy
- Matching onto hadronic d.o.f.
- Long range NME contributions
0νββ-Decay: TeV Scale LNV

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Majorana

0νββ - decay

LHC: pp → jj e⁺e⁻

Effective operators:

\[ \mathcal{L}_{\text{LNV}}^{\text{eff}} = \frac{C_1}{\Lambda^5} \mathcal{O}_1 + \text{h.c.} \]

\[ \mathcal{O}_1 = \bar{Q}_\tau^+ d \bar{Q}_\tau^+ d \bar{L} L^C \]

\[ g_{\text{eff}} = C_1 (\Lambda)^{1/4} \]
\(0\nu\beta\beta\)-Decay: TeV Scale LNV

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**Benchmark Sensitivity: TeV LNV**

\[A(Z,N) \quad A(Z - 2, N + 2)\]

T. Peng, MRM, P. Winslow 1508.04444
\(0^\nu\beta\beta\)-Decay: TeV Scale LNV

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Benchmark Sensitivity: TeV LNV

T. Peng, MRM, P. Winslow 1508.04444
**0νββ-Decay: TeV Scale LNV & $m_\nu$**

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\]

**Implications for $m_\nu$:**

*Schecter-Valle: non-vanishing Majorana mass at (multi) loop level*

*Simplified model: possible (larger) one loop Majorana mass*
\(0\nu\beta\beta\)-Decay: TeV Scale LNV & \(m_\nu\)

\[
\mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \quad \text{Dirac}
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**Implications for \(m_\nu\):**

A hypothetical scenario
Low-Energy / High-Energy Interplay

TeV LNV

Discovery → "Diagnostic"

Low energy → High energy

?
$0\nu\beta\beta / LHC$ Interplay: Matrix Elements

$$\mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \quad \mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.}$$

**Dirac**

**Majorana**

Benchmark Sensitivity: TeV LNV

Assume GERDA present limit & different Nuc/Had MEs

T. Peng, MRM, P. Winslow 1508.04444
**0νββ / LHC Interplay: Matrix Elements**

\[ \mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \quad \text{Dirac} \]

\[ \mathcal{L}_{\text{mass}} = y \frac{\Lambda}{\Lambda} \bar{L}^c H H^T L + \text{h.c.} \quad \text{Majorana} \]

**Benchmark Sensitivity: TeV LNV**

Assume GERDA present limit & different Nuc/Had MEs

\[ \frac{S}{\sqrt{S+B}} \]

T. Peng, MRM, P. Winslow 1508.04444
III. CPV: EDMs, LHC, & $Y_B$
**EDMs: New CPV?**

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* 95% CL  ** e⁻ equivalent
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Mike Pendlebury: 1936-2015

The Guardian 9/23/15
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**Mass Scale Sensitivity**

$$\sin\phi_{CP} \sim 1 \rightarrow M > 5000 \text{ GeV}$$

$$M < 500 \text{ GeV} \rightarrow \sin\phi_{CP} < 10^{-2}$$
**EDMs: New CPV?**

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* 95% CL  
** e⁻ equivalent

- ★ neutron
- ★ proton & nuclei
- ★ atoms

~ 100 x better sensitivity

Not shown: muon
Complementarity: Three Illustrations

• **CPV in an extended scalar sector (2HDM): “Higgs portal CPV”**

• **Weak scale baryogenesis (MSSM)**

• **Model-independent**
What is the CP Nature of the Higgs Boson?

• *Interesting possibilities if part of an extended scalar sector*
Higgs Portal CPV

CPV & 2HDM: Type I & II

\[ V = \frac{\lambda_1}{2} (\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{2} (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1) (\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2) (\phi_2^\dagger \phi_1) + \frac{1}{2} \left[ \lambda_5 (\phi_1^\dagger \phi_2)^2 + \text{h.c.} \right] \]

\[ -\frac{1}{2} \left\{ m_{11}^2 (\phi_1^\dagger \phi_1) + \left[ m_{12}^2 (\phi_1^\dagger \phi_2) + \text{h.c.} \right] + m_{22}^2 (\phi_2^\dagger \phi_2) \right\} . \]

**EWSB**

\[ \delta_1 = \text{Arg} \left[ \lambda_5^* (m_{12}^2)^2 \right], \]
\[ \delta_2 = \text{Arg} \left[ \lambda_5^* (m_{12}^2) v_1 v_2^* \right] \]

\[ \delta_2 \approx \frac{1 - \left| \frac{\lambda_5 v_1 v_2}{m_{12}} \right|}{1 - 2 \left| \frac{\lambda_5 v_1 v_2}{m_{12}} \right|} \delta_1 \]

Inoue, R-M, Zhang: 1403.4257

\[ \lambda_{6,7} = 0 \text{ for simplicity} \]
Future Reach: Higgs Portal CPV

CPV & 2HDM: Type II illustration

$\lambda_{6,7} = 0$ for simplicity

Inoue, R-M, Zhang: 1403.4257
**Higgs Portal CPV: EDMs & LHC**

CPV & 2HDM: Type II illustration

\[ \lambda_{6,7} = 0 \text{ for simplicity} \]

**FIG. 10:** Current and prospective future constraints from electron EDM (blue), neutron EDM (green), Mercury EDM (red) and Radium (yellow) in flavor conserving 2HDMs.

- **First row:** type-I model.
- **Second row:** type-II model. The model parameters used are the same as Fig. 6. Central values of the hadronic and nuclear matrix elements are used.

**Left:** Combined current limits.

**Middle:** combined future limits if the Mercury and neutron EDMs are both improved by one order of magnitude. Also shown are the future constraints if electron EDM is improved by another order of magnitude (in blue dashed curves).

**Right:** combined future limits if the Mercury and neutron EDMs are improved by one and two orders of magnitude, respectively.

Matrix elements, there is guidance from naïve dimensional analysis, which takes into account the chiral structures of the operators in question. However, the precise value of matrix elements involving quark CEDMs and the Weinberg three-gluon operator are only known to about an order of magnitude, and dimensional analysis does not tell us the signs of the matrix elements. We highlight two places where these uncertainties can change our results.

- **In Figs. 7 and 8,** we see that the Weinberg three-gluon operator is always subdominant as a contribution to the neutron and mercury EDMs. It is possible, though, that the actual matrix element may be an order of magnitude larger than the current best value. Then, the Weinberg operator would make the largest contribution to the neutron and mercury EDMs at large \( \tan \beta \) in the type-II model.

- **In the left panel of Fig. 7,** the quark EDM and CEDM contributions to \( n_{EDM} \) in the type-I model are shown to be nearly equal, but with opposite signs, suppressing the total neutron EDM in the type-I model. If overall sign of the CEDM matrix element is opposite to that used here, the two effects would add constructively, making the neutron EDM limit much stronger.

In the absence of hadronic and nuclear matrix element uncertainties, improvements in neutron and diamagnetic atom searches will make them competitive with present ThO result when in constraining CPV in 2HDM. At present, however, theoretical uncertainties are significant, making it difficult to draw firm quantitative conclusions regarding the impact of the present and prospective neutron and diamagnetic EDM results.

**Present**

- \( \sin \alpha_b : CPV \)
- scalar mixing

**Future:**

- \( d_n \times 0.1 \)
- \( d_A(Hg) \times 0.1 \)
- \( d_{ThO} \times 0.1 \)
- \( d_A(Ra) \)

**Future:**

- \( d_n \times 0.01 \)
- \( d_A(Hg) \times 0.1 \)
- \( d_{ThO} \times 0.1 \)
- \( d_A(Ra) \)

*Inoue, R-M, Zhang: 1403.4257*
**Higgs Portal CPV: EDMs & LHC**

**CPV & 2HDM: Type II illustration**

$\lambda_{6,7} = 0$ for simplicity

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- In the left panel of Fig. 7, the quark EDM and CEDM contributions to $n$EDM in the type-I model are shown to be nearly equal, but with opposite signs, suppressing the total neutron EDM in the type-I model. If overall sign of the CEDM matrix element is opposite to that used here, the two effects would add constructively, making the neutron EDM limit much stronger.

---

In the absence of hadronic and nuclear matrix element uncertainties, improvements in neutron and diamagnetic atom searches will make them competitive with present ThO result when in constraining CPV in 2HDM. At present, however, theoretical uncertainties are significant, making it difficult to draw firm quantitative conclusions regarding the impact of the present and prospective neutron and diamagnetic EDM results.

**Present**

- $\sin \alpha_b$ : CPV scalar mixing

**Future:**

- $d_n \times 0.1$
- $d_{A(Hg)} \times 0.1$
- $d_{ThO} \times 0.1$
- $d_A(Ra)$

**Future:**

- $d_n \times 0.01$
- $d_{A(Hg)} \times 0.1$
- $d_{ThO} \times 0.1$
- $d_A(Ra)$

Inoue, R-M, Zhang: 1403.4257
**Higgs Portal CPV: EDMs & LHC**

**CPV & 2HDM: Type II illustration**

\[ \lambda_{6,7} = 0 \text{ for simplicity} \]

**FIG. 10:** Current and prospective future constraints from electron EDM (blue), neutron EDM (green), Mercury EDM (red) and Radium (yellow) in flavor conserving 2HDMs.

First row: Type-I model; Second row: Type-II model. The model parameters used are the same as Fig. 6. Central values of the hadronic and nuclear matrix elements are used.

Left: Combined current limits. Middle: combined future limits if the Mercury and neutron EDMs are both improved by one order of magnitude. Also shown are the future constraints if electron EDM is improved by another order of magnitude (in blue dashed curves).

Right: combined future limits if the Mercury and neutron EDMs are improved by one and two orders of magnitude, respectively.

In the absence of hadronic and nuclear matrix element uncertainties, improvements in neutron and diamagnetic atom searches will make them competitive with present ThO result when in constraining CPV in 2HDM. At present, however, theoretical uncertainties are significant, making it difficult to draw firm quantitative conclusions regarding the impact of the present and prospective neutron and diamagnetic EDM results.

- **• In Figs. 7 and 8, we see that the Weinberg three-gluon operator is always subdominant as a contribution to the neutron and mercury EDMs. It is possible, though, that the actual matrix element may be an order of magnitude larger than the current best value. Then, the Weinberg operator would make the largest contribution to the neutron and mercury EDMs at large tan \( \beta \) in the type-II model.**

- **• In the left panel of Fig. 7, the quark EDM and CEDM contributions to nEDM in the type-I model are shown to be nearly equal, but with opposite signs, suppressing the total neutron EDM in the type-I model. If overall sign of the CEDM matrix element is opposite to that used here, the two effects would add constructively, making the neutron EDM limit much stronger.**

\[ \sin \alpha_b : \text{CPV scalar mixing} \]

**Present**

- \( d_n \times 0.1 \)
- \( d_{A(Hg)} \times 0.1 \)
- \( d_{ThO} \times 0.1 \)
- \( d_A(Ra) \)

**Future:**

- \( d_n \times 0.01 \)
- \( d_{A(Hg)} \times 0.1 \)
- \( d_{ThO} \times 0.1 \)
- \( d_A(Ra) \)

**Future:**

- \( d_{n} \times 0.1 \)
- \( d_{A(Hg)} \times 0.1 \)
- \( d_{ThO} \times 0.1 \)
- \( d_A(Ra) \)

**Dawson et al: 1503.01114**

**\( M_{h^2} = 400 \text{ GeV} \)**

**Inoue, R-M, Zhang: 1403.4257**
Low-Energy / High-Energy Interplay

Higgs Portal CPV

Discovery

“Diagnostic”

Low energy

High energy
Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

$\lambda_{6,7} = 0$ for simplicity

$\sin \alpha_b$: CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257
Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

\[ \lambda_{6,7} = 0 \text{ for simplicity} \]

\[ \sin \alpha_b : \text{CPV scalar mixing} \]

Inoue, R-M, Zhang: 1403.4257
Was the baryon asymmetry produced during electroweak symmetry-breaking?

- EDMs provide most powerful probe of CPV
- Phase transition $\rightarrow$ Separate talk (back up slides)
EDMs & EW Baryogenesis: MSSM

Heavy sfermions: LHC consistent & suppress 1-loop EDMs

Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU

Next gen $d_n$

$\sin(\mu M_1 b) = 10^{-27} \text{ e cm}$

$\sin(\mu M_1 b) = 10^{-28} \text{ e cm}$

$\sin(\mu M_1 b) = 10^{-29} \text{ e cm}$

$\gamma, g$

$\gamma, \gamma$

$\chi^+_0, \chi^-_0$

$\chi^{0, \pm}_0$

$\chi_0$

$\chi^+_0, \chi^-_0$

$\chi^{0, \pm}_0$

$\chi_0$

$\chi^+_0, \chi^-_0$

$\chi^{0, \pm}_0$

$\chi_0$

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EDMs & EW Baryogenesis: MSSM

Heavy sfermions: LHC consistent & suppress 1-loop EDMs

Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU

Next gen $d_n$

$Li, Profumo, RM '09-'10$

Compressed spectrum (stealthy SUSY)

$ACME: ThO$

$d_n = 10^{-27} \text{ e cm}$

$d_n = 10^{-28} \text{ e cm}$

$d_e = 10^{-28} \text{ e cm}$

$d_e = 10^{-29} \text{ e cm}$

Next gen $d_e$
EDMs & EW Baryogenesis: MSSM

Heavy sfermions: LHC consistent & suppress 1-loop EDMs

Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU

Next gen $d_n$

Next gen $d_e$

Li, Profumo, RM ‘09-’10

Compressed spectrum (stealthy SUSY)

Next gen lepton collider

$\sin(\mu \, M)$

$M_1$ (GeV)

$\sin(\mu \, M)$

$M_1$ (GeV)

$\gamma, g$

$\gamma^\prime, Z, W^+$

$d_n = 10^{-27} \text{ e cm}$

$d_n = 10^{-28} \text{ e cm}$

$d_e = 10^{-28} \text{ e cm}$

$d_e = 10^{-29} \text{ e cm}$

ACME: ThO
Low-Energy / High-Energy Interplay

EWB for Compressed SUSY

Discovery

Low energy

High energy

“Diagnostic”
### Model Independent: Effective Operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_f$</td>
<td>fermion EDM</td>
<td>(3)</td>
</tr>
<tr>
<td>$\tilde{\delta}_q$</td>
<td>quark CEDM</td>
<td>(2)</td>
</tr>
<tr>
<td>$C_G\tilde{G}$</td>
<td>3 gluon</td>
<td>(1)</td>
</tr>
<tr>
<td>$C_{quqd}$</td>
<td>non-leptonic</td>
<td>(2)</td>
</tr>
<tr>
<td>$C_{lequ, ledq}$</td>
<td>semi-leptonic</td>
<td>(3)</td>
</tr>
<tr>
<td>$C_{\varphi ud}$</td>
<td>induced 4f</td>
<td>(1)</td>
</tr>
</tbody>
</table>

12 total + $\theta$ light flavors only (e,u,d)
Paramagnetic Systems: Two Sources

Electron EDM

$e^{-} \gamma$

$N$ $(\text{Scalar } q)$

$x (\text{PS } e^{-})$

$N$

$e^{-} \gamma$

$e^{-}$

$Tl, YbF, ThO…$
Paramagnetic Systems: Two Sources

Electron EDM

(Scalar q) x (PS e⁻)

Tl, YbF, ThO...
**Paramagnetic Systems: Two Sources**

Electron EDM

(Scalar q) \(\times\) (PS e⁻)

\(\Lambda \gtrsim (1.5 \text{ TeV}) \times \sqrt{\sin \phi_{\text{CPV}}} \)  
Electron EDM (global)

\(\Lambda \gtrsim (1300 \text{ TeV}) \times \sqrt{\sin \phi_{\text{CPV}}} \)  
\(C_S\) (global)

**TL, YbF, ThO...**

Chupp & R-M: 1407.1064
**Paramagnetic Systems: Two Sources**

Electron EDM

$(-1.5 \, \text{TeV}) \times \sqrt{\sin \phi_{CPV}}$

$(-1300 \, \text{TeV}) \times \sqrt{\sin \phi_{CPV}}$

$\Lambda \gtrsim (1.5 \, \text{TeV}) \times \sqrt{\sin \phi_{CPV}}$

$\Lambda \gtrsim (1300 \, \text{TeV}) \times \sqrt{\sin \phi_{CPV}}$

**LHC accessible?**
IV. Precision Tests

- **BSM?**

  - SUSY, LNV, extended Higgs sector…

  - Sterile ν’s, axions, dark U(1)…

- Mass Scale

- Coupling

- $M_W$
Muon Anomalous Magnetic Moment

\[ \Delta a_\mu (\text{expt-thy}) = (287 \pm 80) \times 10^{-11} \ (3.6 \sigma) \]
Muon Anomalous Magnetic Moment

**Challenge #3**

True deviation from SM?

\[ \Delta a_{\mu}(\text{expt-thy}) = (287 \pm 80) \times 10^{-11} \ (3.6 \sigma) \]
Muon Anomalous Magnetic Moment

\[ \Delta a_\mu (\text{expt-thy}) = (287 \pm 80) \times 10^{-11} \ (3.6 \sigma) \]

New TeV Physics (SUSY)
Muon Anomalous Magnetic Moment

$\Delta a_\mu (\text{expt-thy}) = (287 \pm 80) \times 10^{-11} (3.6 \sigma)$

New TeV Physics (SUSY)

New Ultralight Physics (Dark $\gamma$)

New excitement since 2008
Muon Anomalous Magnetic Moment

New TeV Physics (SUSY)

New Ultralight Physics (Dark $\gamma$)

New excitement since 2008

Muon g-2 region essentially ruled out (assumptions)
The Hunt for a Dark Z

Curtin et al, '14
The Hunt for a Dark Z

Curtin et al, '14
The Hunt for a Dark Z

Curtin et al, '14
The Hunt for a Dark Z

Collider searches
The Hunt for a Dark Z: PVES

Collider searches

Davoudiasl, Lee, Marciano ‘14
**Dark Z: Mechanism**

\[
\mathcal{L} \subset -\frac{1}{4} \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} - \frac{1}{4} \hat{Z}_{D\mu\nu} \hat{Z}^{\mu\nu}_D + \frac{1}{2} \epsilon \frac{1}{\cos \theta} \hat{Z}_{D\mu\nu} \hat{B}^{\mu\nu} + \frac{1}{2} m_{D,0}^2 \hat{Z}^\mu_D \hat{Z}_D\mu
\]

\[
V_0(H, S) = -\mu^2 |H|^2 + \lambda |H|^4 - \mu_S^2 |S|^2 + \lambda_S |S|^4 + \kappa |S|^2 |H|^2
\]
**Dark Z: Mechanism**

\[ \mathcal{L} = -\frac{1}{4} \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} - \frac{1}{4} \hat{Z}_{D\mu\nu} \hat{Z}^{\mu\nu}_D + \frac{1}{2} \epsilon \frac{\hat{Z}_{D\mu\nu}}{\cos \theta} \hat{B}^{\mu\nu} + \frac{1}{2} m_{D,0}^2 \hat{Z}_D^\mu \hat{Z}_D^\mu \]

- Kinetic Mixing
- Mass Mixing

\[ V_0(H, S) = -\mu^2 |H|^2 + \lambda |H|^4 - \mu_S^2 |S|^2 + \lambda_S |S|^4 + \kappa |S|^2 |H|^2 \]

- Higgs Mixing
**Dark Z: Mechanism**

\[ \mathcal{L} \subset -\frac{1}{4} \hat{B}_{\mu \nu} \hat{B}^{\mu \nu} - \frac{1}{4} \partial^2 \phi (\phi) \]

\[ V_0(H, S) = -\mu^2 |H|^2 + \lambda |H|^4 - \mu_S^2 |S|^2 + \lambda_S |S|^4 + \kappa |S|^2 |H|^2 \]

**PVES**

\[ \frac{1}{2} m_{D,0}^2 \hat{Z}_D^\mu \hat{Z}_{D\mu} \]

**Mass Mixing**

**Higgs Mixing**

\[ h \rightarrow Z_D Z_D \]
V. Outlook

• Tests of fundamental symmetries & neutrino properties provide powerful windows into key open questions in fundamental physics

• There exists a rich interplay with BSM searches at the high energy frontier & both frontiers are essential

• Exciting opportunities for discovery and insight lie at the frontier interface

• Fully realizing them poses new challenges for hadronic & nuclear structure theory
Stay Tuned!
Back Up Slides
LNV
$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \quad \mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.}$$

**Dirac**

**Majorana**

**Our analysis:**

- Include backgrounds
- Incorporate QCD running
- Include long-distance contributions to nuclear matrix elements
# $0\nu\beta\beta$-Decay: TeV Scale LNV

\[ \mathcal{L}_{\text{mass}} = y \bar{L} H \nu_R + \text{h.c.} \]

\[ \mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.} \]

**Dirac**

**Majorana**

**Backgrounds:**

- Charge flip
- Jet faking electron
$\nu\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.}$$

- **Dirac**

$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.}$$

- **Majorana**

**Backgrounds:**

- Charge flip
- Jet faking electron

$e^+$ transfers most of $p_T$ to conversion $e^-$; $Z / \gamma^*$ + jets $\rightarrow$ apparent $e^- e^- jj$ event
\[ \mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \]

\[ \mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.} \]

**Dirac**

**Majorana**

**Backgrounds:**

- Charge flip
- Jet faking electron

\[ e^+ \text{ transfers most of } p_T \text{ to conversion } e^-; \]
\[ b's \text{ not tagged } \rightarrow \text{ apparent e}^- e^- jj \text{ event} \]
\(0\nu\beta\beta\)-Decay: TeV Scale LNV

\(\mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \quad \mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.} \)

Dirac \quad \text{Majorana}

Backgrounds: \quad \text{Bin in } \eta \text{ and apply charge flip prob}

Electron reconstruction:
- \(Z\to ee\) data
- \(Z\to ee\) MC

Tight identification:
- Data
- MC \(Z\to ee\)
0νββ-Decay: TeV Scale LNV

\[ \mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \]

Dirac

\[ \mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.} \]

Majorana

Backgrounds: Jet fakes

\[ \sigma_{JF \text{ before cuts}} = \sigma_{JF, MG+Pythia+PGS} \times \left(1/5000 \times 1/2\right)^\# \text{of jet-fakes} \times \left(\begin{array}{c} \# \text{of jets} \\ \# \text{of jet-fakes} \end{array}\right) \]
\( \beta \beta \text{-Decay: TeV Scale LNV} \)

\[
\mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \\
\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L} c H H^T L + \text{h.c.}
\]

**Backgrounds:** Cuts

- \( H_T \)
- \( \text{MET} \)
- \( M_{\parallel} \)
0νββ-Decay: TeV Scale LNV

\[ \mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \quad \mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.} \]

**Backgrounds:**

- Dirac
- Majorana

**Cuts**

<table>
<thead>
<tr>
<th>( \sigma (\text{fb}) )</th>
<th>Signal</th>
<th>Diboson</th>
<th>Charge Flip</th>
<th>Jet Fake</th>
<th>( \frac{S}{\sqrt{S+B}} (\sqrt{\text{fb}}) )</th>
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</thead>
<tbody>
<tr>
<td>( W^- W^- + 2j )</td>
<td>0.142</td>
<td>0.541</td>
<td>6.682</td>
<td>0.628</td>
<td>903.16</td>
</tr>
<tr>
<td>( W^- Z^0 + 2j )</td>
<td>0.091</td>
<td>0.358</td>
<td>4.66</td>
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<td>721.7</td>
</tr>
<tr>
<td>( Z/\gamma^* + 2j )</td>
<td>0.034</td>
<td>0.029</td>
<td>0.187</td>
<td>0.015</td>
<td>5.6</td>
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<tr>
<td>( t\bar{t} )</td>
<td>0.054</td>
<td>0.04</td>
<td>0.15</td>
<td>0.017</td>
<td>0.266</td>
</tr>
<tr>
<td>( t\bar{t} + 3j )</td>
<td>0.036</td>
<td>0.005</td>
<td>0.036</td>
<td>0.007</td>
<td>0.126</td>
</tr>
<tr>
<td>( W^- + 3j )</td>
<td>0.039</td>
<td>0.033</td>
<td>0.022</td>
<td>0.005</td>
<td>0.093</td>
</tr>
<tr>
<td>( 4j )</td>
<td>0.036</td>
<td>0.005</td>
<td>0.022</td>
<td>0.005</td>
<td>0.093</td>
</tr>
</tbody>
</table>

T. Peng, MRM, P. Winslow 1508.04444
**0νββ-Decay: TeV Scale LNV**

\[ \mathcal{L}_{\text{mass}} = \gamma \tilde{L} \tilde{N} \nu_R + \text{h.c.} \]

**Dirac**

\[ \mathcal{L}_{\text{mass}} = \frac{\gamma}{\Lambda} \tilde{L}^c H H^T L + \text{h.c.} \]

**Majorana**

**Low energy: Matching**

Match onto \( O_{\text{eff}} \) at \( \Lambda_{\text{BSM}} \)
$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R + \text{h.c.} \quad \mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^cHH^TL + \text{h.c.}$$

Low energy: Running

![Diagram showing energy levels and their corresponding scales: EW, QCD, $\Lambda_{\text{Had}}$, $\Lambda \sim M_{S^+}, M_{F^0}$, $\Lambda \sim M_W$.]
$0\nu\beta\beta$-Decay: TeV Scale LNV

\[ \mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \]

*Dirac*

\[ \mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.} \]

*Majorana*

Low energy: QCD Running

\[ \mathcal{O}_1 = (\bar{u}_L d_R)(\bar{u}_L d_R)(\bar{e}_L e_R^c), \]
\[ \mathcal{O}_2 = (\bar{u}_L \sigma^{\mu\nu} d_R)(\bar{u}_L \sigma_{\mu\nu} d_R)(\bar{e}_L e_R^c), \]
\[ \mathcal{O}_3 = (\bar{u}_L t^a d_R)(\bar{u}_L t^a d_R)(\bar{e}_L e_R^c), \]
\[ \mathcal{O}_4 = (\bar{u}_L t^a \sigma^{\mu\nu} d_R)(\bar{u}_L t^a \sigma_{\mu\nu} d_R)(\bar{e}_L e_R^c). \]

\[ \mathcal{L}_{\text{eff}} = \sum_j \frac{C_j(\mu)}{\Lambda^5} \mathcal{O}_j(\mu) + \text{h.c.}, \]

\[ \mu \frac{d}{d\mu} C = \gamma^T C \]
$0\nu\beta\beta$-Decay: TeV Scale LNV

\begin{align*}
\mathcal{L}_{\text{mass}} &= y \bar{L} \tilde{H} \nu_R + \text{h.c.} \\
\mathcal{L}_{\text{mass}} &= \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.}
\end{align*}

\text{Dirac} \quad \text{Majorana}

**Low energy:**  
**QCD Running**

\begin{align*}
\mathcal{O}_1 &= (\bar{u}_L d_R)(\bar{u}_L d_R)(\bar{e}_L e_R^c), \\
\mathcal{O}_2 &= (\bar{u}_L \sigma^{\mu\nu} d_R)(\bar{u}_L \sigma_{\mu\nu} d_R)(\bar{e}_L e_R^c), \\
\mathcal{O}_3 &= (\bar{u}_L t^a d_R)(\bar{u}_L t^a d_R)(\bar{e}_L e_R^c), \\
\mathcal{O}_4 &= (\bar{u}_L t^a \sigma^{\mu\nu} d_R)(\bar{u}_L t^a \sigma_{\mu\nu} d_R)(\bar{e}_L e_R^c).
\end{align*}

Assuming $C_k = 1$ at $\mu = 5 \text{ GeV}$ \rightarrow 
Effective DBD amplitude for $\mathcal{O}_1$ substantially weaker for given LHC constraints
$0\nu\beta\beta$-Decay: TeV Scale LNV

\[
\mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R + \text{h.c.} \quad \mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L + \text{h.c.}
\]

**Dirac** \quad **Majorana**

**Low energy:** Nuclear Matrix Elements: Long Range Effects

Exploit Chiral Symmetry & EFT ideas
$0\nu\beta\beta$-Decay: TeV Scale LNV

\[
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\]

Low energy: Nuclear Matrix Elements: Long Range Effects

Our work
Exploit Chiral Symmetry & EFT ideas

Helo et al
Why Might A “Ton-Scale” Exp’t See It?

\[ A(Z,N) \rightarrow \text{Underlying Physics} \rightarrow A(Z+2, N-2) + e^- e^- \]

- 3 light neutrinos only: source of neutrino mass at the very high see-saw scale
- 3 light neutrinos with TeV scale source of neutrino mass
- > 3 light neutrinos
Why Might A “Ton-Scale” Exp’t See It?

Lightest neutrino mass (eV) →
**EW Phase Transition: St’d Model**

- **1st order**
- **2nd order**

**Lattice: Endpoint**

<table>
<thead>
<tr>
<th>Lattice</th>
<th>Authors</th>
<th>$M_h^C$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>[76]</td>
<td>80 ± 7</td>
</tr>
<tr>
<td>4D Anisotropic</td>
<td>[74]</td>
<td>72.4 ± 1.7</td>
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<tr>
<td>3D Isotropic</td>
<td>[70]</td>
<td>72.4 ± 0.9</td>
</tr>
</tbody>
</table>

**Increasing $m_h$**

*S’td Model: 1st order EWPT requires light Higgs*
EW Phase Transition: MSSM

Increasing $m_h$  
New scalars

MSSM: Light RH stops

Carena et al 2008: Higgs phase metastable
**EW Phase Transition: MSSM**

**Increasing** $m_h$  

**New scalars**

**MSSM: Light RH stops**

Inconsistent w/ Higgs data:

Curtin et al `12, Katz et al `15

---

Katz, Perelstein, R-M, Winslow 1509.02934
**EW Phase Transition: Higgs Portal**

- Renormalizable
- $\phi$: singlet or charged under $SU(2)_L \times U(1)_Y$
- Generic features of full theory (NMSSM, GUTS...)
- More robust vacuum stability
- Novel patterns of SSB
Precision Tests
Electron Scattering

Continuous interplay between probing hadron structure and electroweak physics

4 Decades of Progress
Parity-violating electron scattering has become a precision tool

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

PVeS Experiment Summary

State-of-the-art:
- sub-part per billion statistical reach and systematic control
- sub-1% normalization control

Physics Topics
- Strange Quark Form Factors
- Neutron skin of a heavy nucleus
- Indirect Searches for New Interactions
- Novel Probes of Nucleon Structure
- Electroweak Structure Functions at the EIC
- Charge Lepton Flavor Violation at the EIC

K. Kumar
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Search for additional neutral weak force that is inaccessible to the Large Hadron Collider