Beyond the Standard Model: The Low & High Energy Interface

M.J. Ramsey-Musolf

U Mass Amherst

Amherst Center for Fundamental Interactions
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts 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*

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*

Three Challenges

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

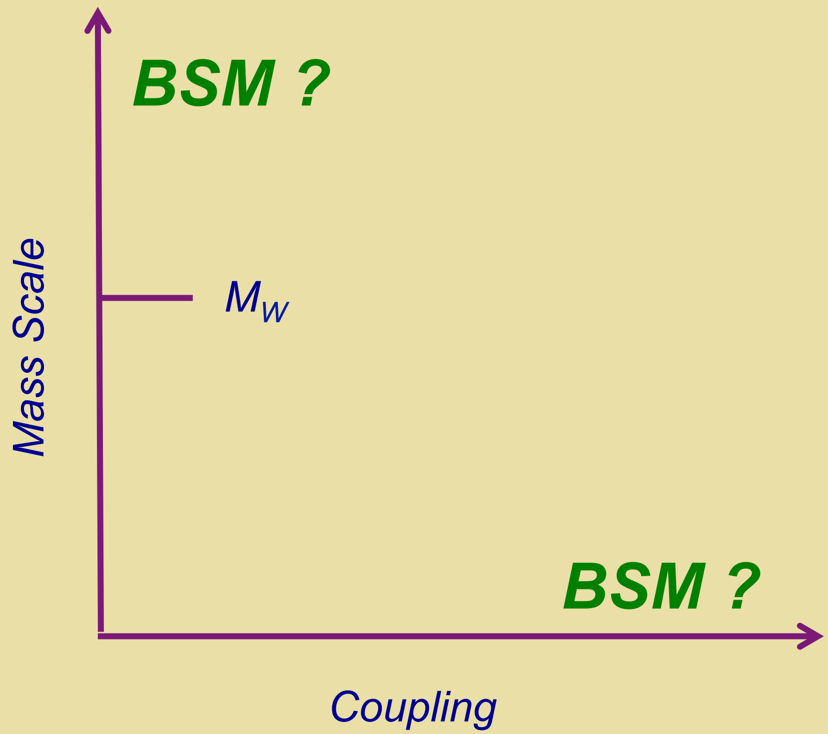
*Questions for Fundamental Physics**

- ***What is the origin of matter (luminous & dark) ?***
- ***Why are neutrino masses so small ?***
- ***Are fundamental interactions "natural" ?***

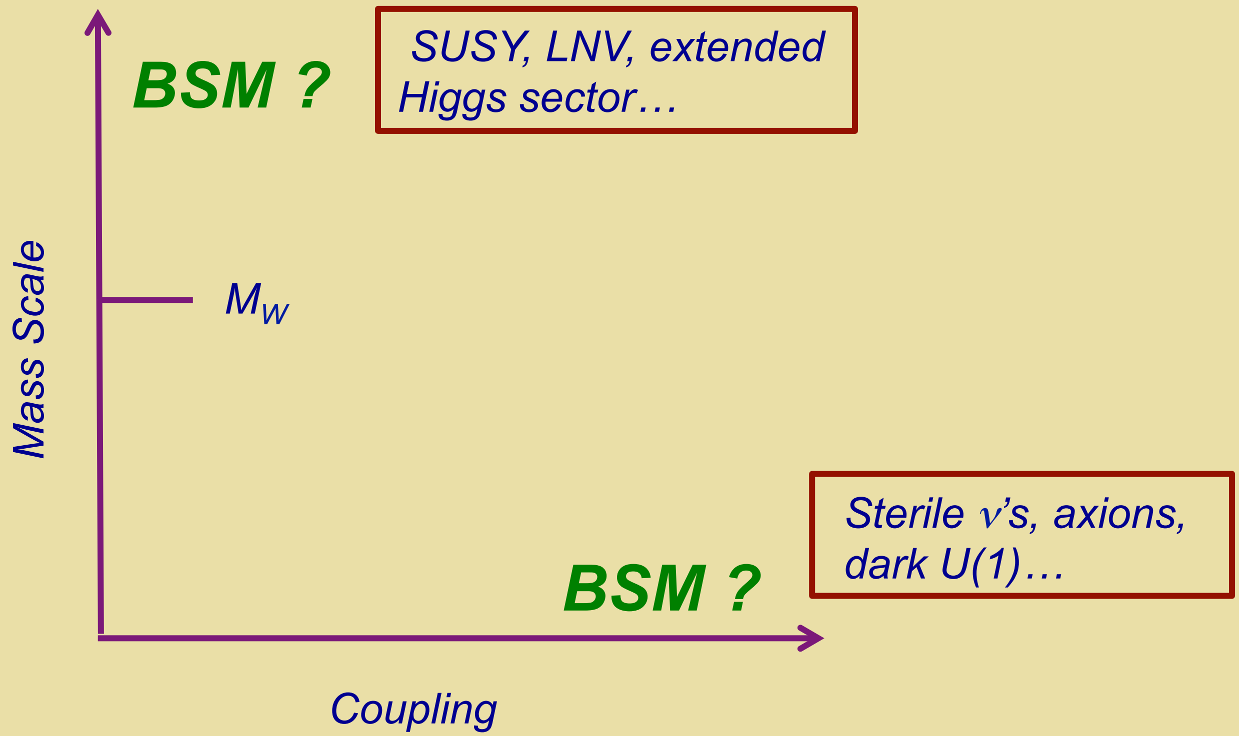
***Partial List**

BSM Physics: Where Does it Live ?

BSM Physics: Where Does it Live ?



BSM Physics: Where Does it Live ?



*Questions for Fundamental Physics**

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

Discovering answers requires studies at three frontiers: energy, intensity, & cosmic.

****Partial List***

*Questions for Fundamental Physics**

- ***What is the origin of matter (luminous & dark) ?***
- ***Why are neutrino masses so small ?***
- ***Are fundamental interactions "natural" ?***

Discovering answers requires studies at three frontiers: energy, intensity, & cosmic.

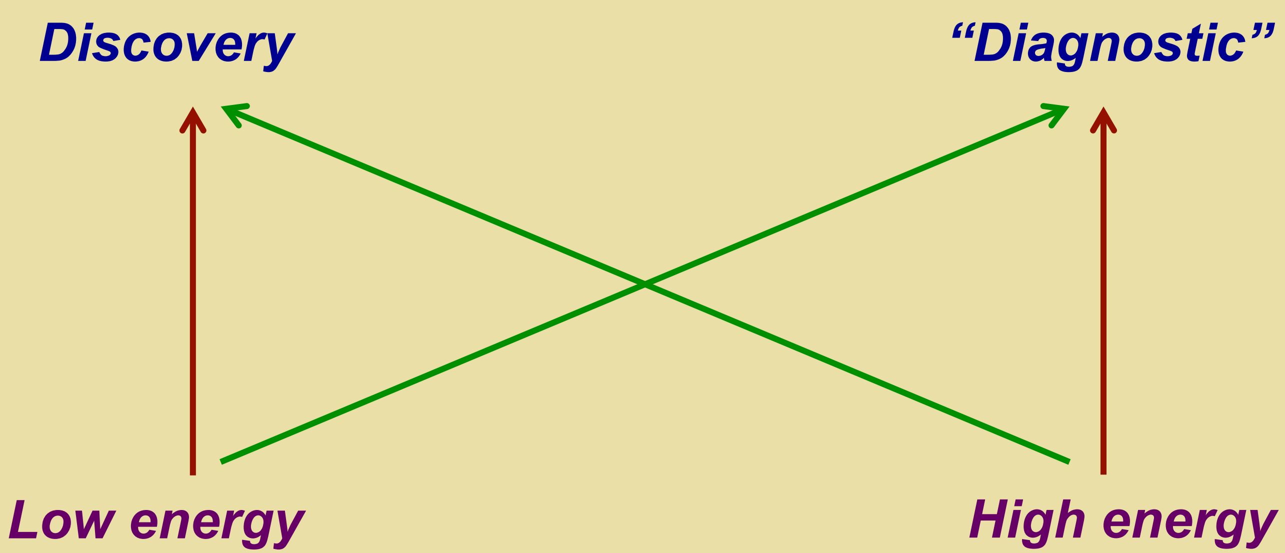
****Partial List*** *This talk*

Low-Energy / High-Energy Interplay

Discovery ↑ ***Low energy***

"Diagnostic" ↑ ***High energy***

Low-Energy / High-Energy Interplay



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 **

EDM searches: *BSM CPV, Origin of Matter*	*$0\nu\beta\beta$ decay searches:* *Nature of neutrino, Lepton number violation, Origin of Matter*
Electron & muon prop's & interactions: *SM Precision Tests, BSM "diagnostic" probes*	*Radioactive decays & other tests* *SM Precision Tests, BSM "diagnostic" probes*

*** 2012 NSAC Subcommittee Report*

Four Components

This talk

EDM searches: *BSM CPV, Origin of Matter*	*$0\nu\beta\beta$ decay searches:* *Nature of neutrino, Lepton number violation, Origin of Matter*
Electron & muon prop's & interactions: *SM Precision Tests, BSM "diagnostic" probes*	*Radioactive decays & other tests* *SM Precision Tests, BSM "diagnostic" probes*

Four Components

This talk

EDM searches: BSM CPV, Origin of Matter	$0\nu\beta\beta$ decay searches: Nature of neutrino, Lepton number violation, Origin of Matter
Electron & muon prop's & interactions: SM Precision Tests, BSM "diagnostic" probes	Radioactive decays & other tests SM Precision Tests, BSM "diagnostic" probes

If time

II. LNV: $0\nu\beta\beta$ – Decay & the LHC

$0\nu\beta\beta$-Decay: LNV? Mass Term?

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

Dirac

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

Majorana

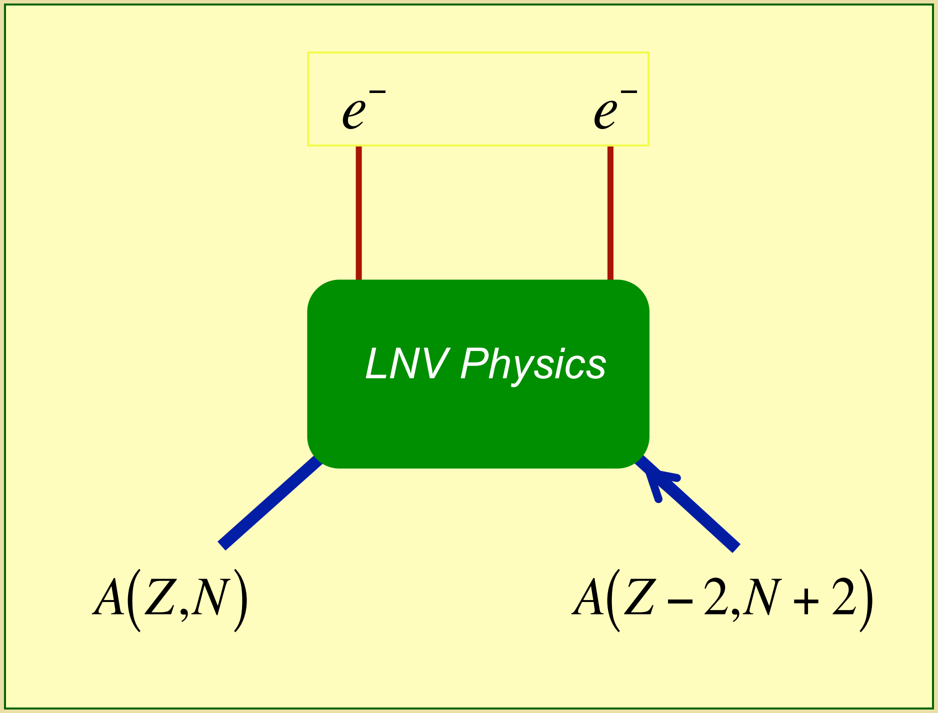
$0\nu\beta\beta$-Decay: LNV? Mass Term?

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

Dirac

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

Majorana



$0\nu\beta\beta$-Decay: LNV? Mass Term?

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

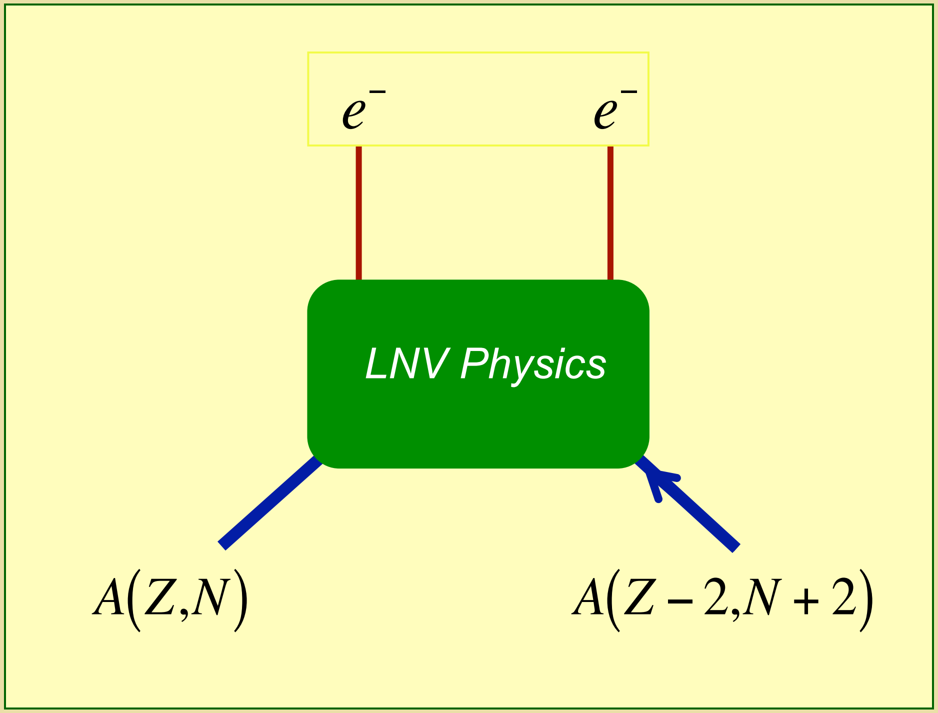
Dirac

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

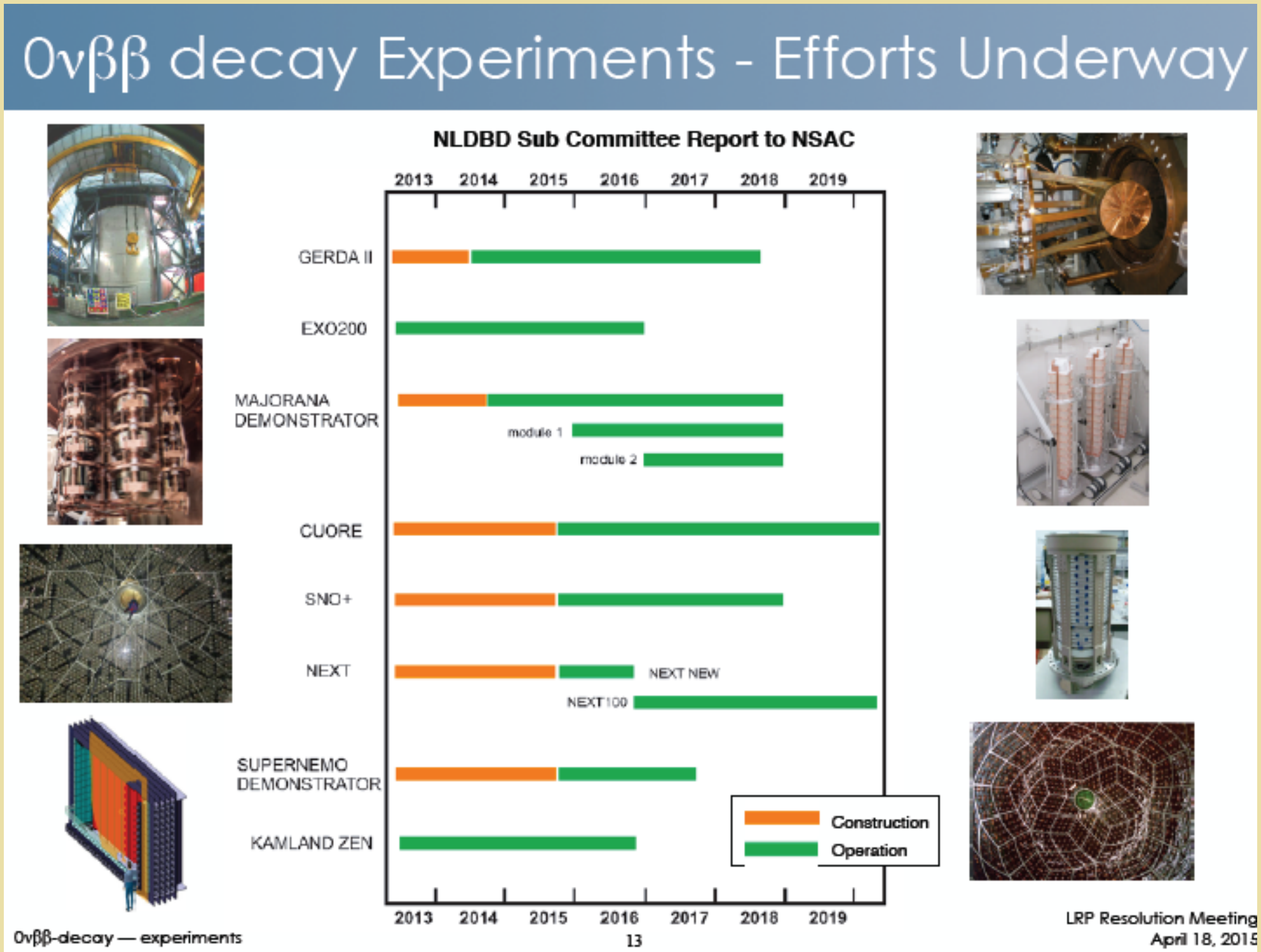
Majorana

Impact of observation

- *Total lepton number not conserved at classical level*
- *New mass scale in nature, Λ*
- *Key ingredient for standard baryogenesis via leptogenesis*



Ton Scale Experiments



Thanks: J. Wilkerson

Why Might A "Ton-Scale" Exp't See It?

$A(Z,N) \rightarrow$ **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?

$A(Z,N) \rightarrow$ *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*

0νββ-Decay: LNV? Mass Term?

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

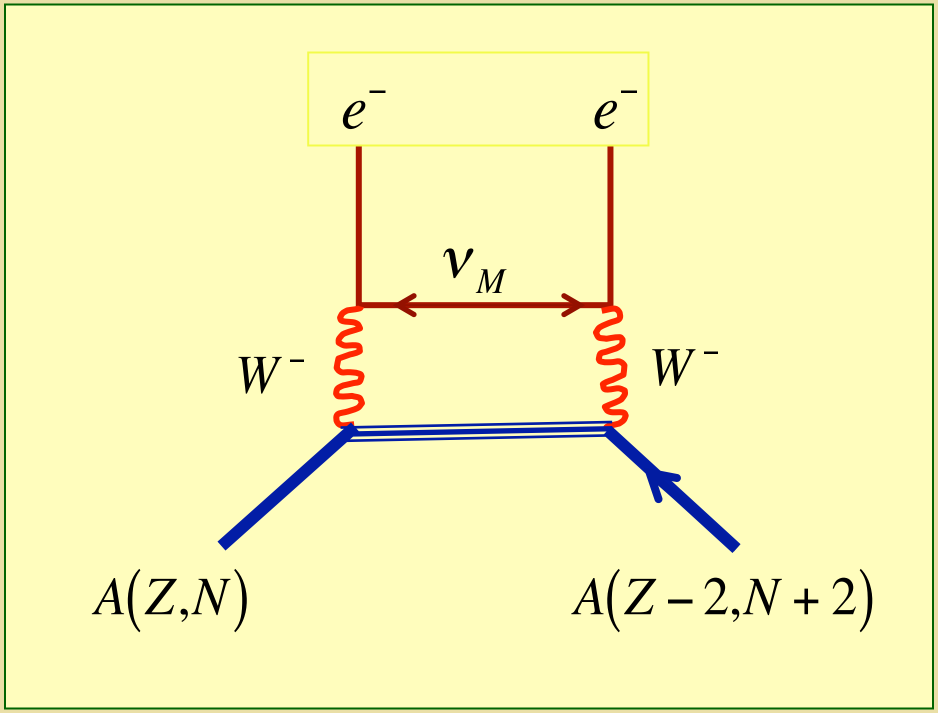
Dirac

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

Majorana

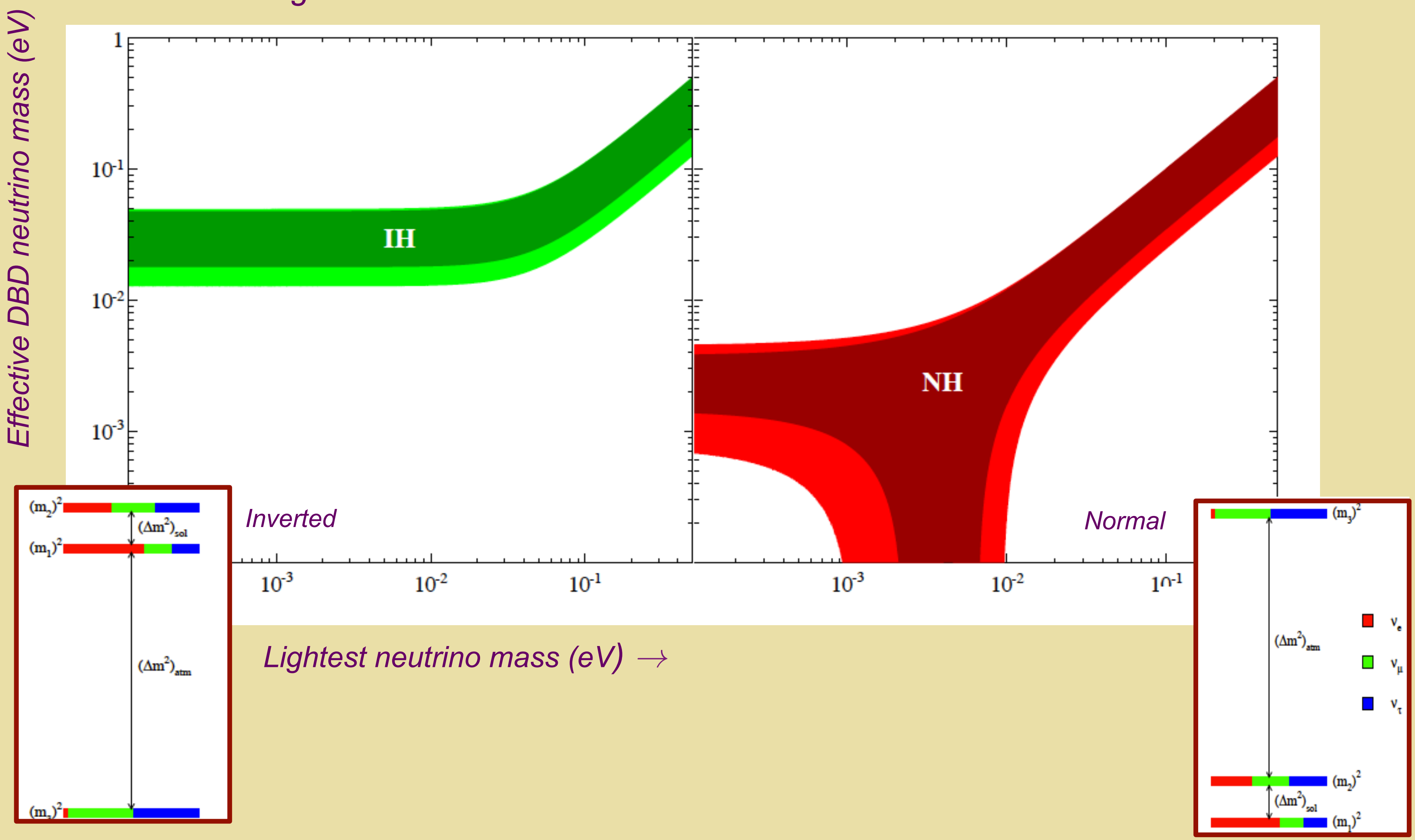
"Standard" Mechanism

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



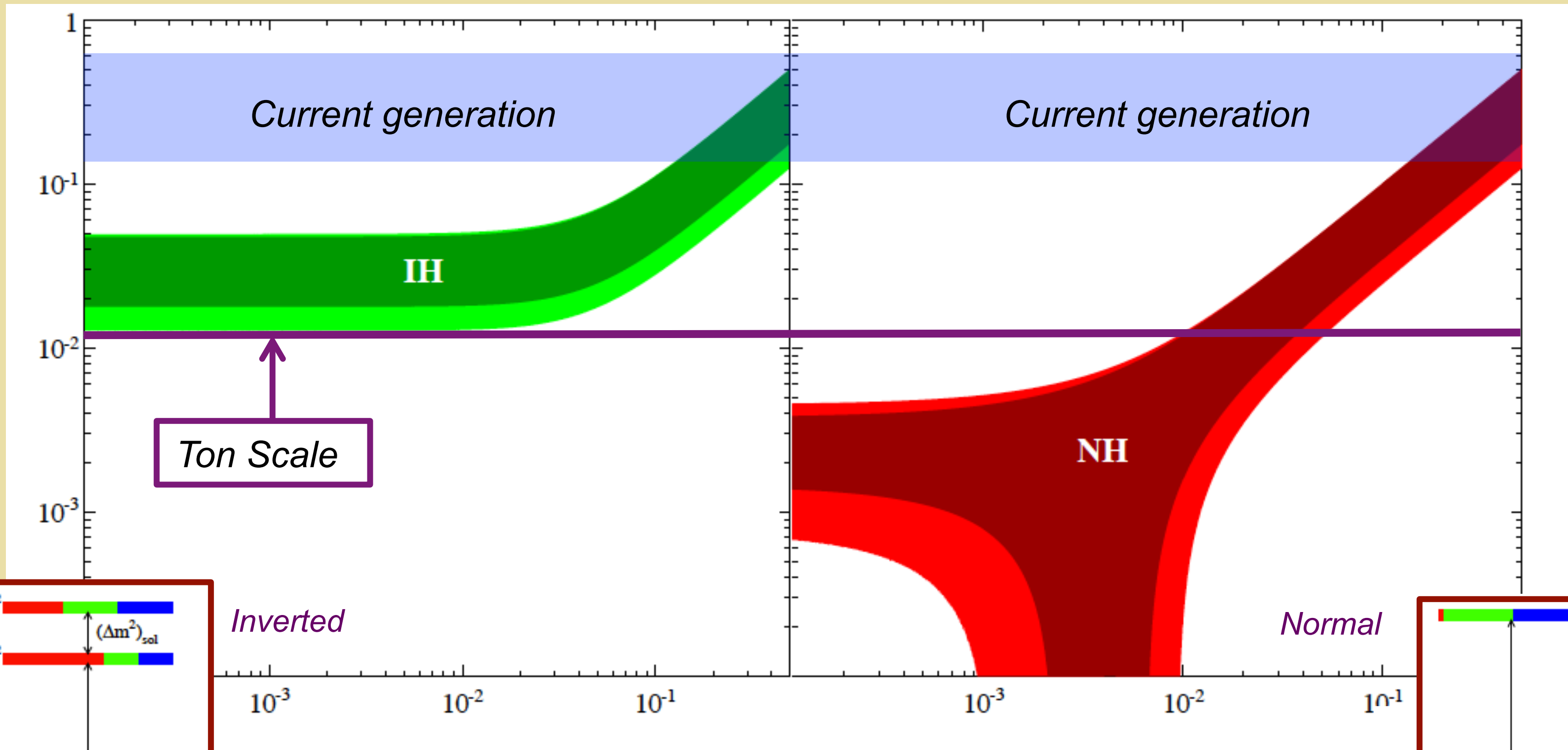
Why Might A "Ton-Scale" Exp't See It?

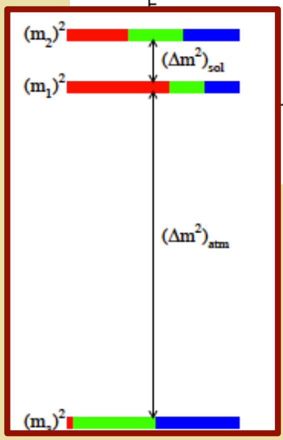
Three active light neutrinos

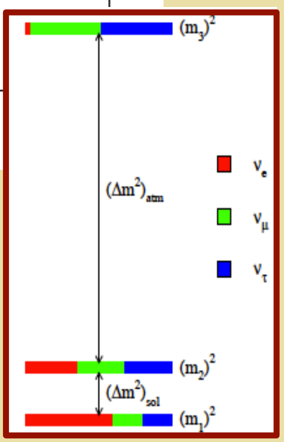


Why Might A "Ton-Scale" Exp't See It?

Three active light neutrinos

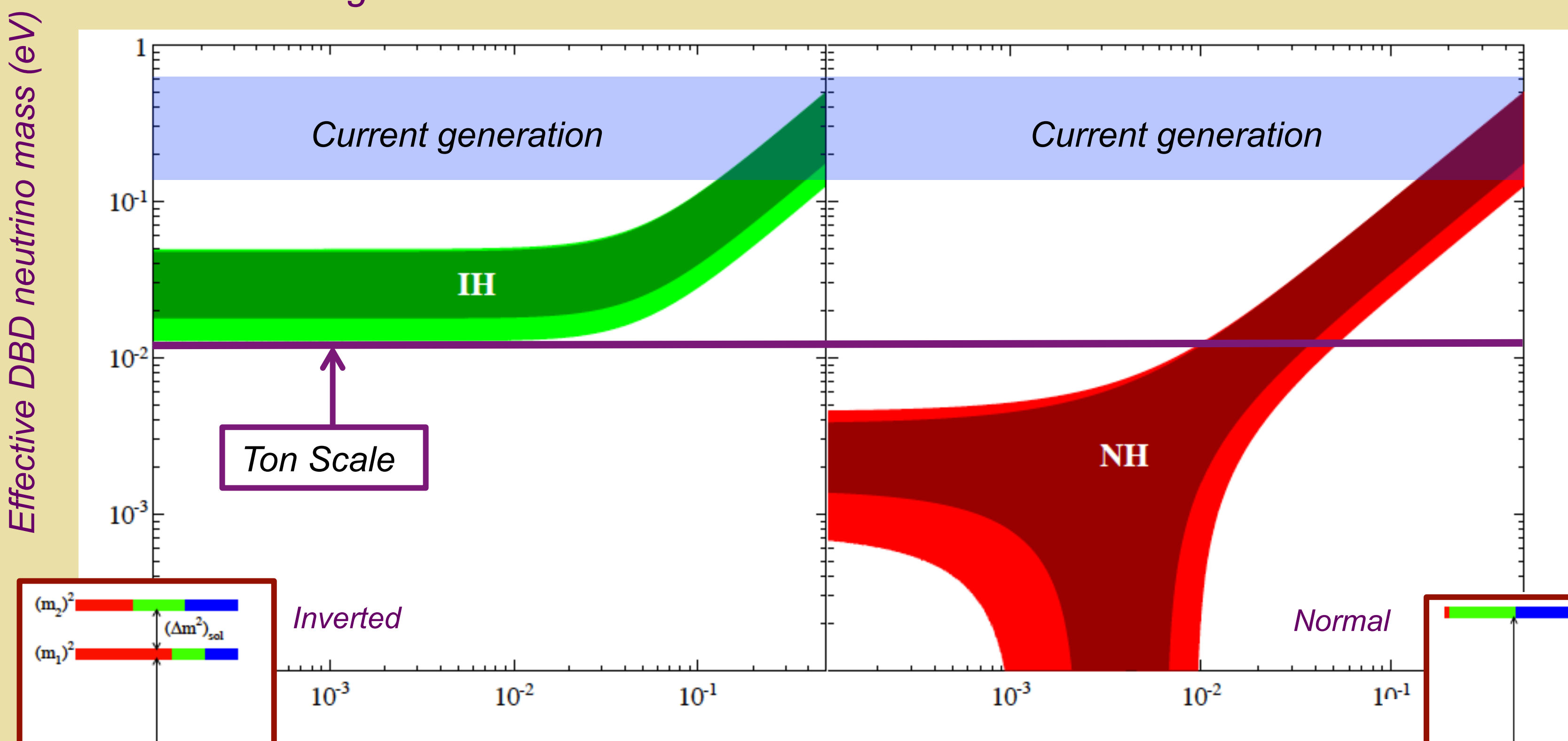


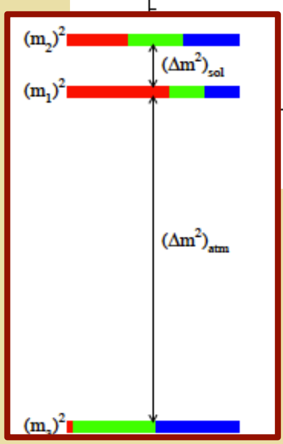


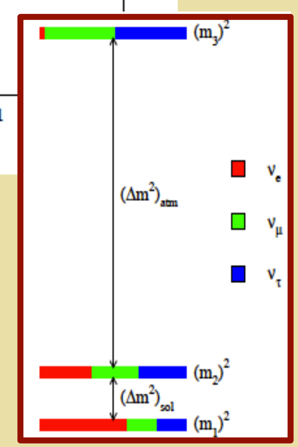


Interpreting the Result

Three active light neutrinos



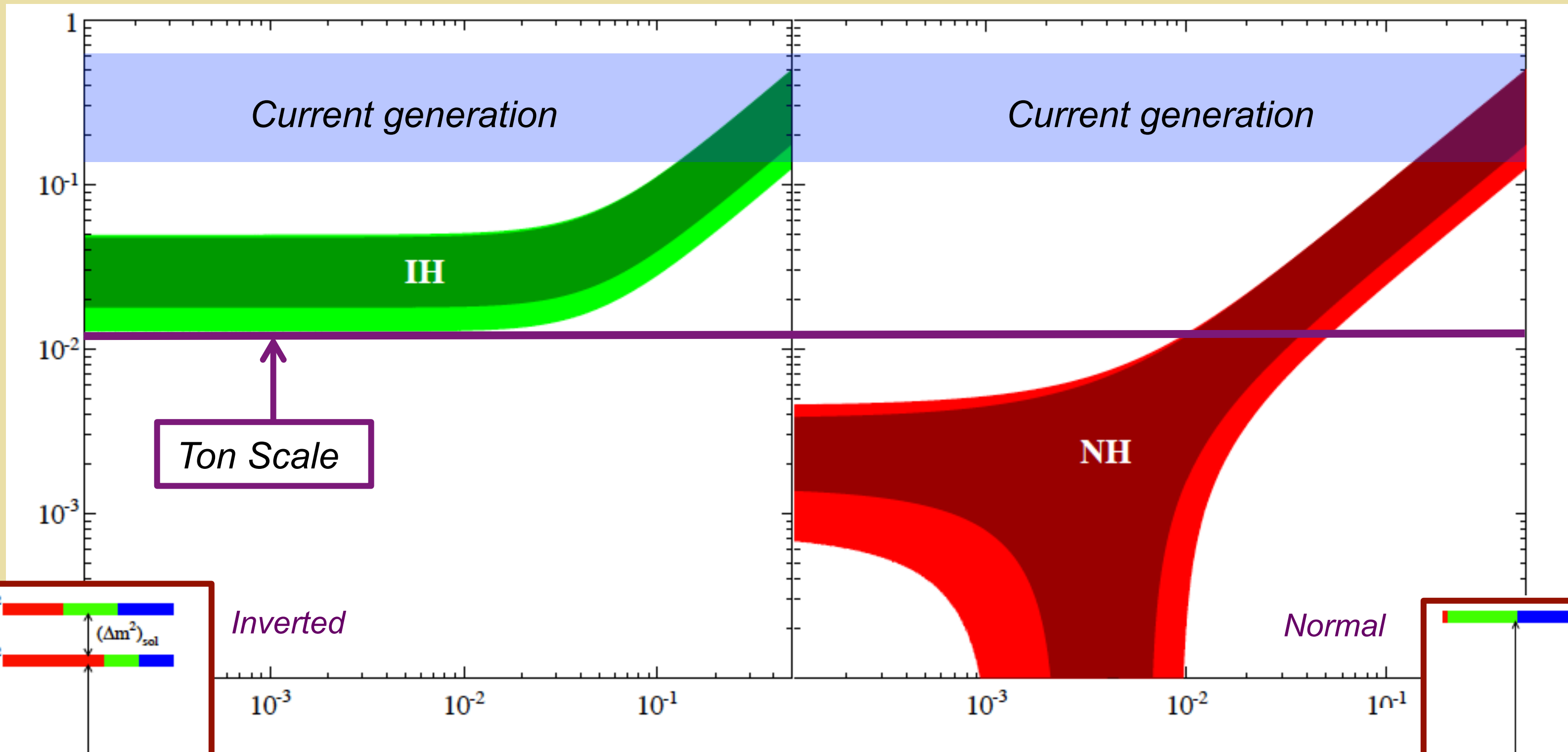


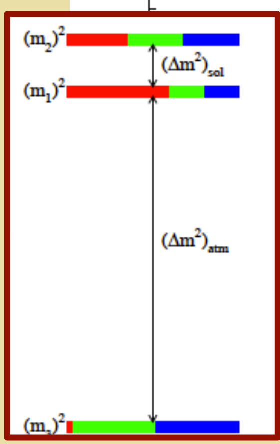


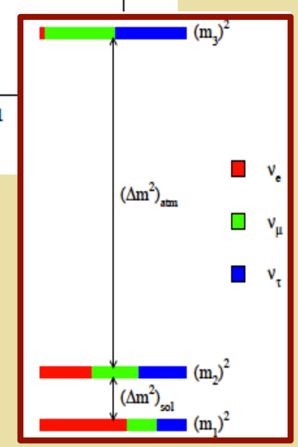
Full implications require information on lightest mass & hierarchy

Interpreting a Positive Result

Three active light neutrinos



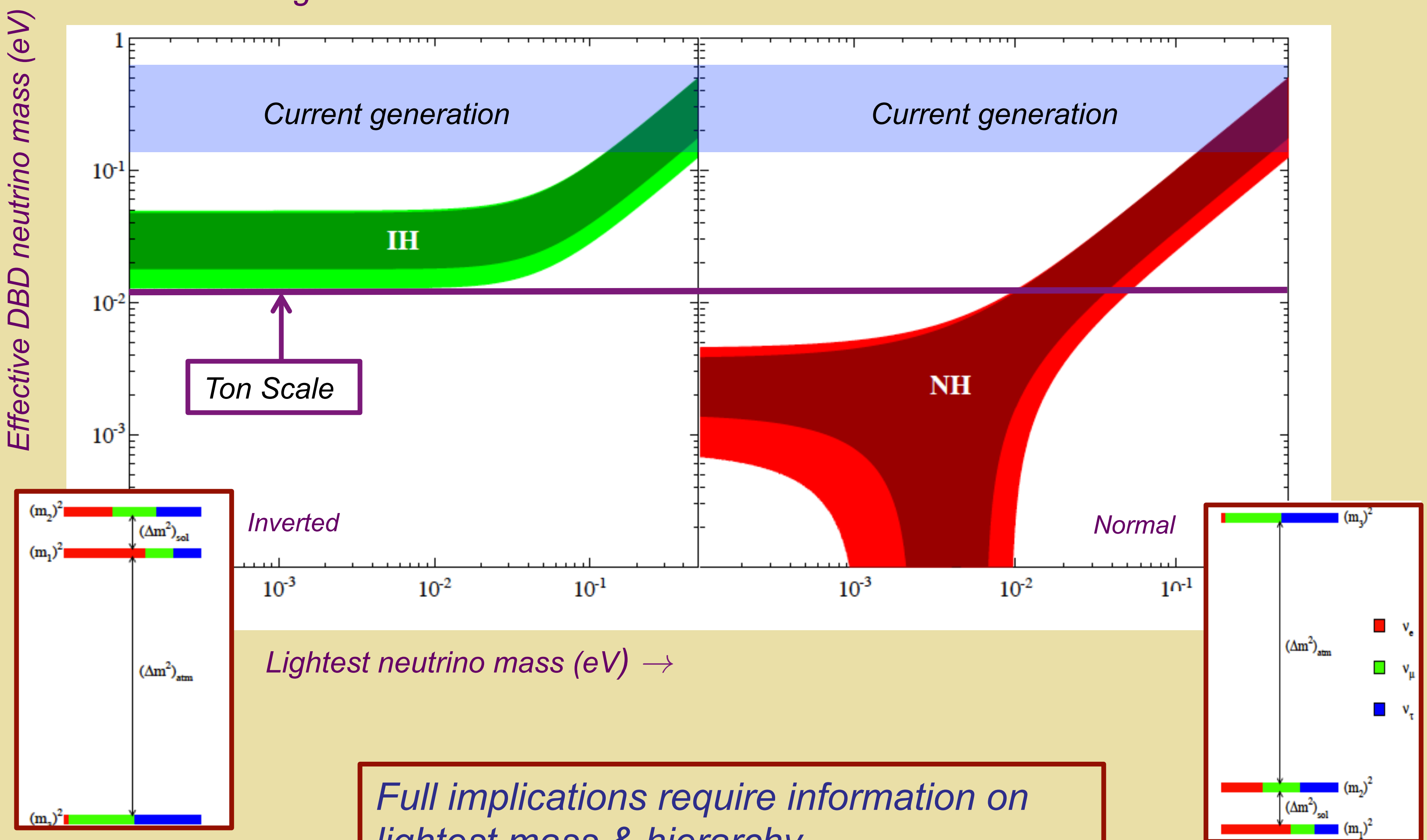




Positive result would be consistent with 3 light active ν's & IH or quasi-deg regime, but not definitive as to mechanism

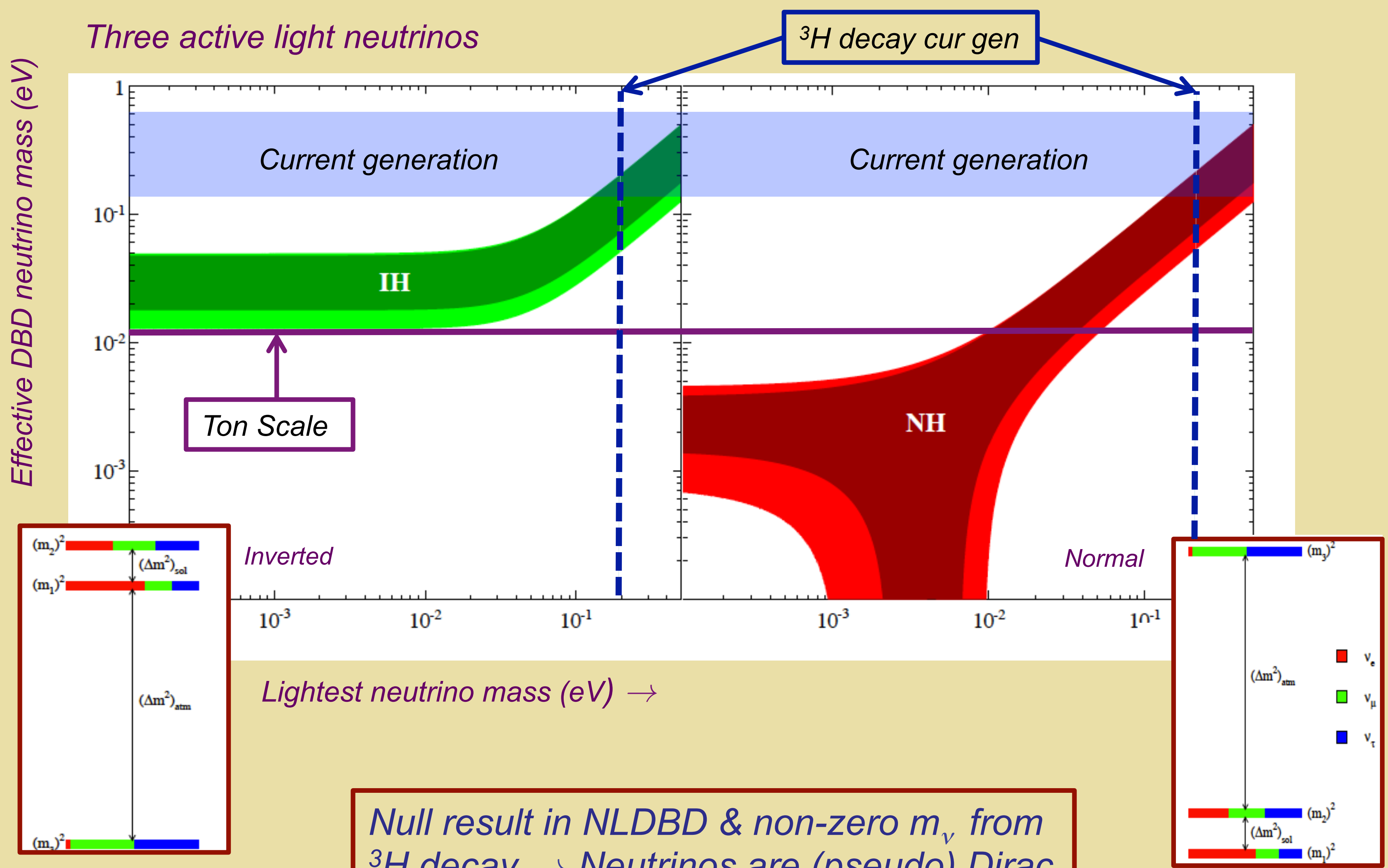
Interpreting a Null Result

Three active light neutrinos



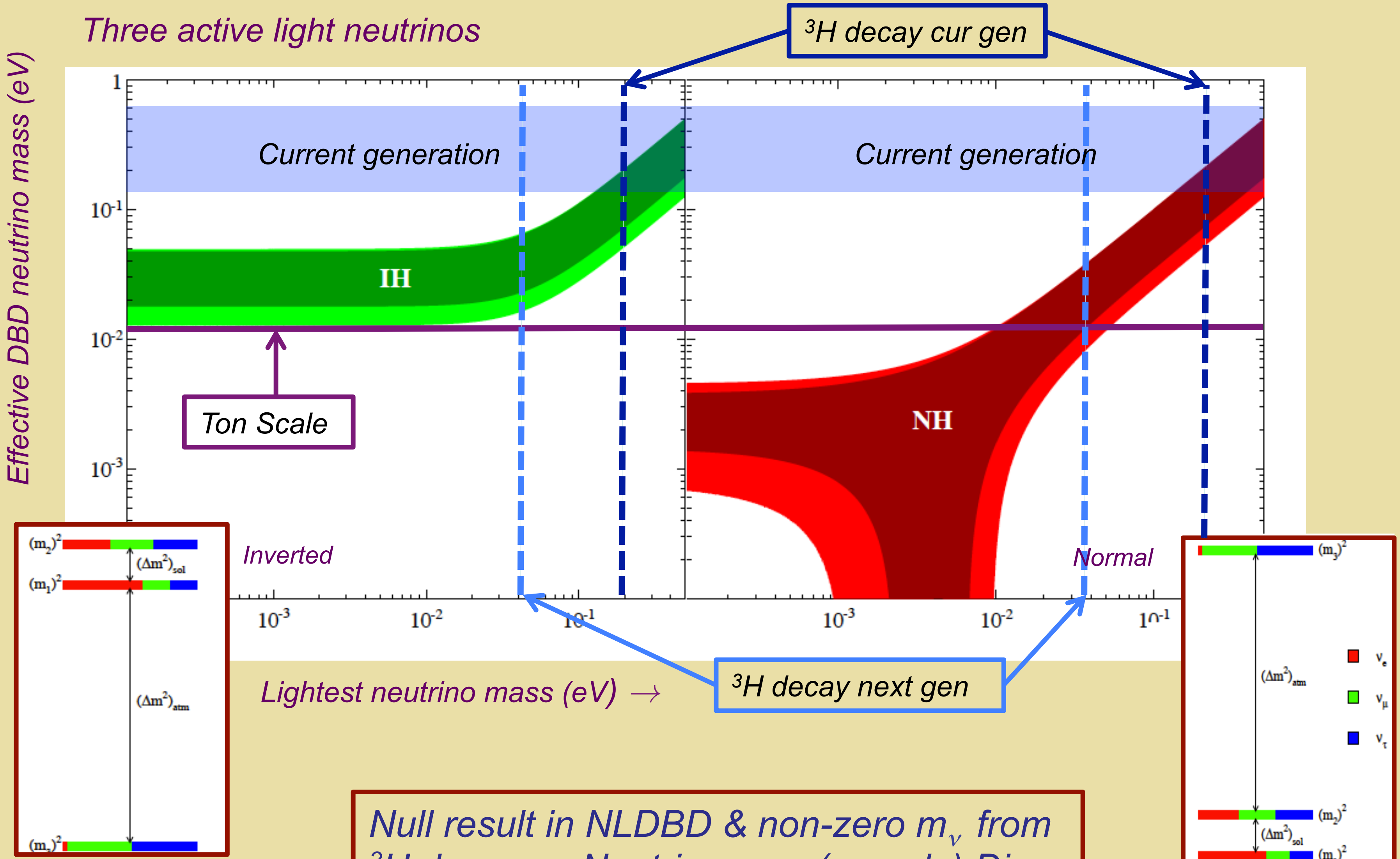
Full implications require information on lightest mass & hierarchy

What Would a Null Result Imply ?



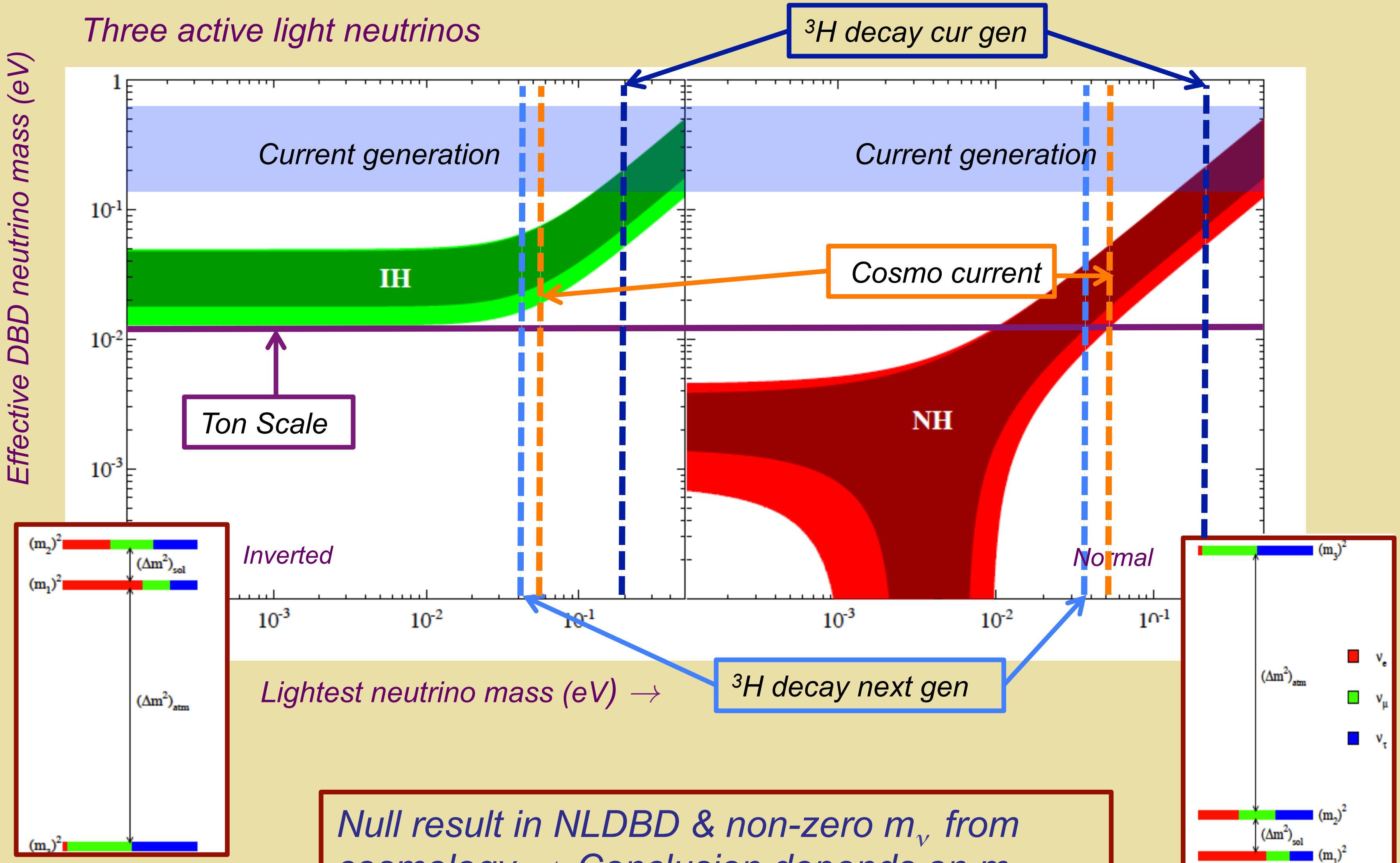
Null result in NLDBD & non-zero m_ν from ^{3}H decay → Neutrinos are (pseudo) Dirac

What Would a Null Result Imply ?



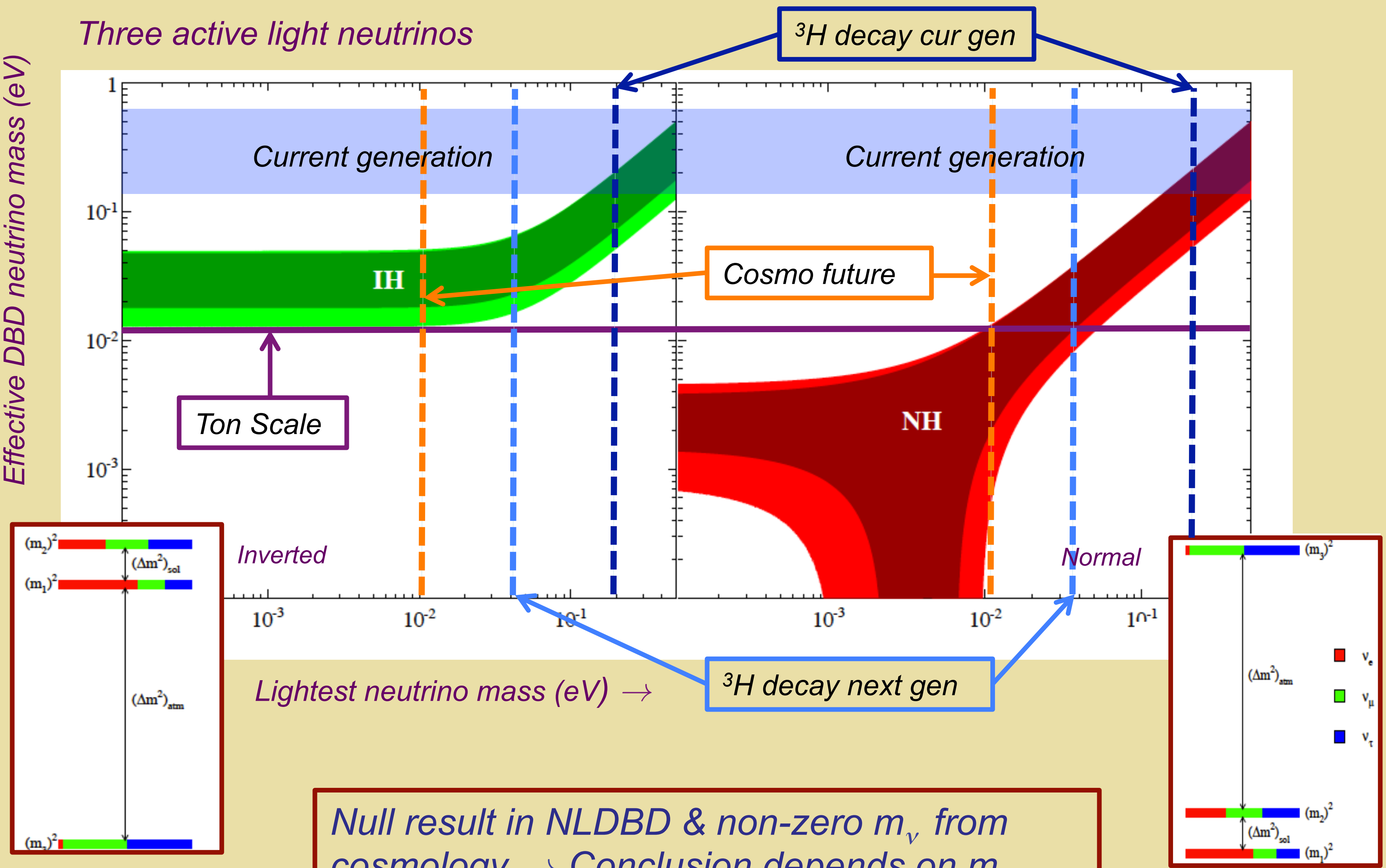
Null result in NLDBD & non-zero m_ν from ^3H decay $\rightarrow$ Neutrinos are (pseudo) Dirac

What Would a Null Result Imply ?



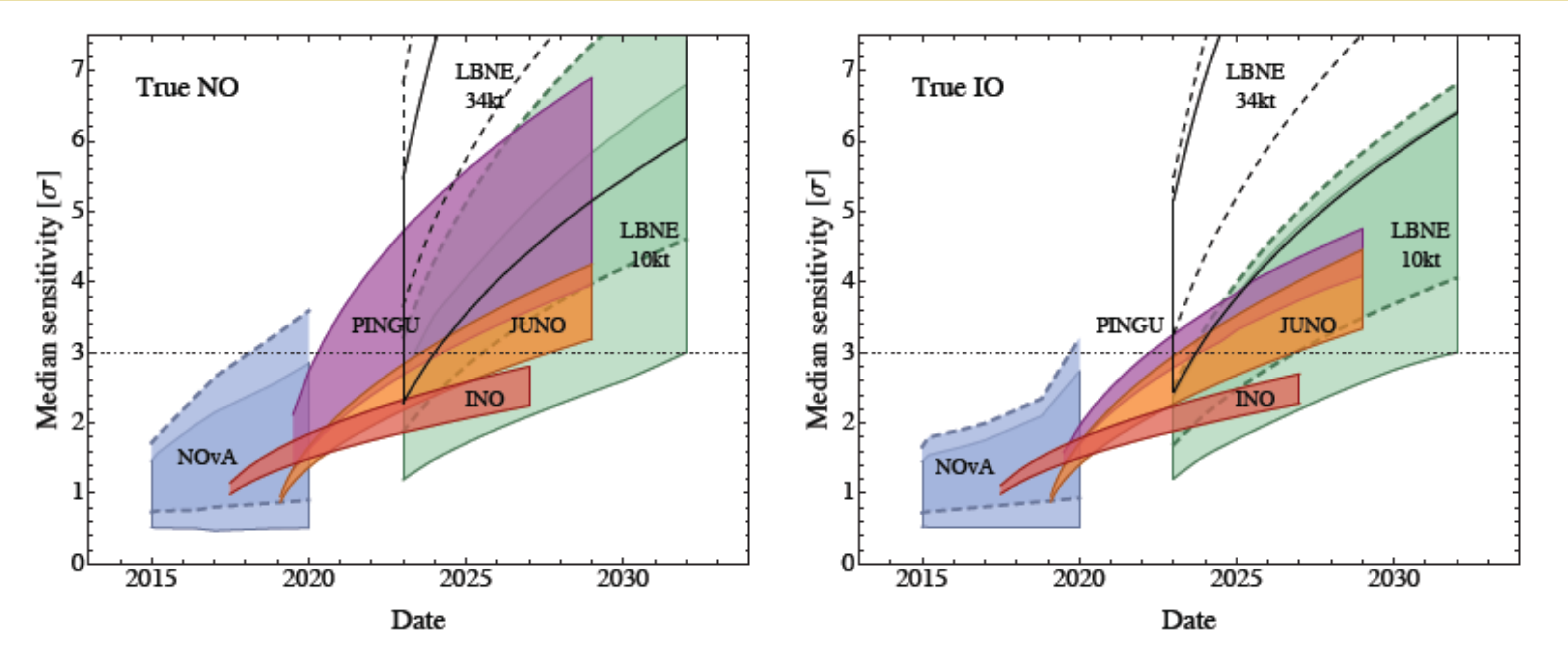
Null result in NLDBD & non-zero m_ν from cosmology $\rightarrow$ Conclusion depends on $m_{lightest}$ & hierarchy

What Would a Null Result Imply ?



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

Neutrino Mass Hierarchy

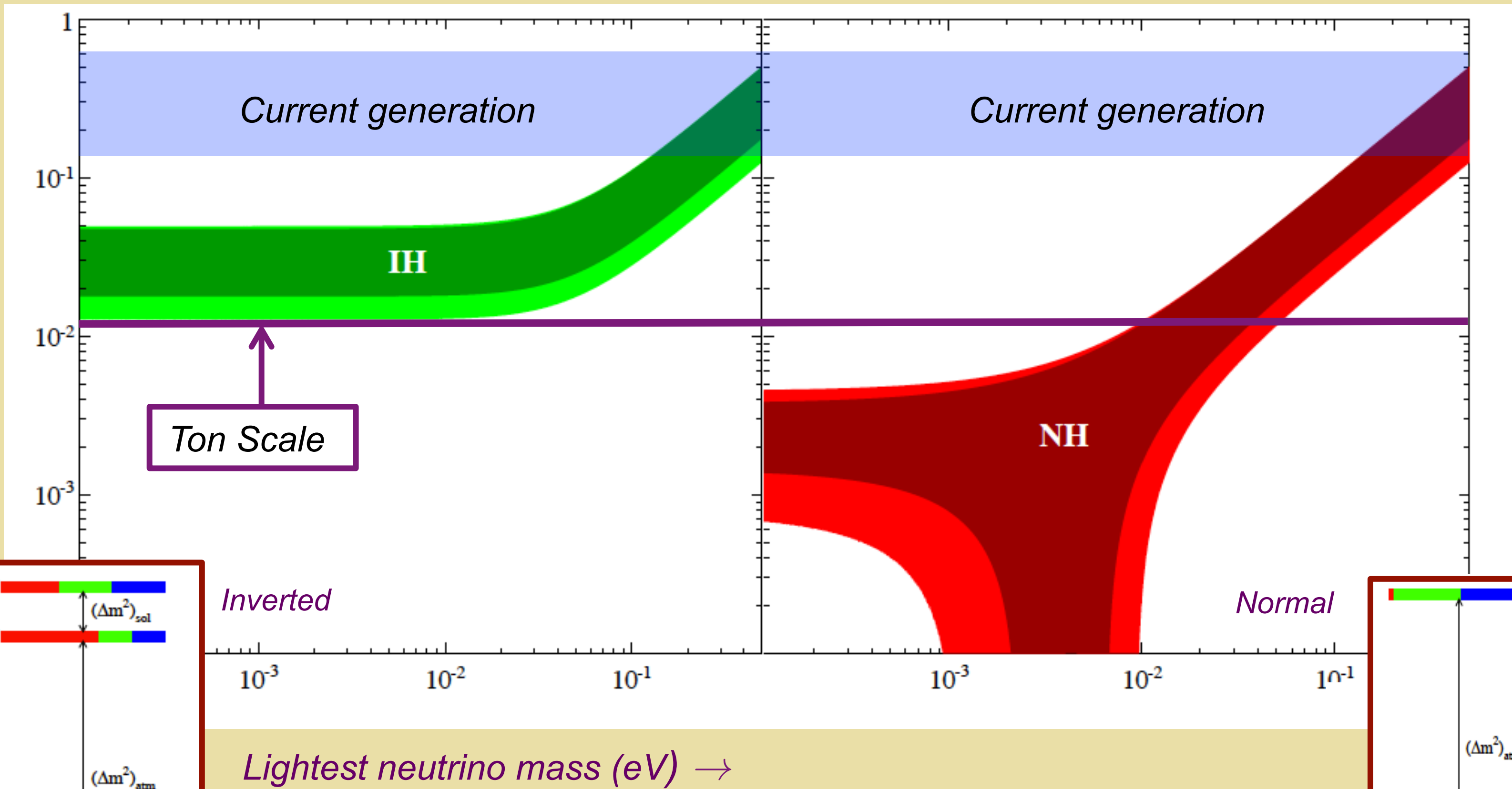


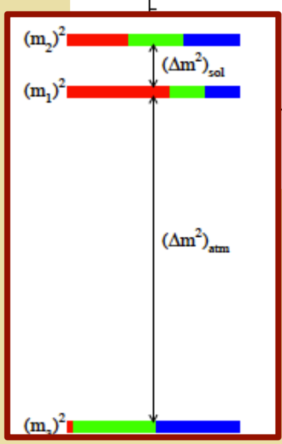
Expected significance for rejecting wrong hierarchy hypothesis

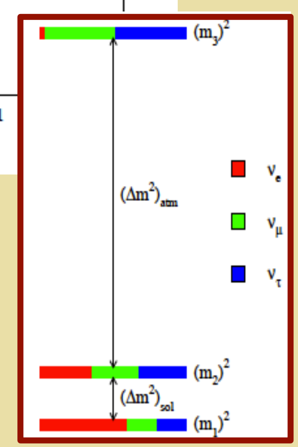
Blennow et al, 1311.1822

Interpreting a Positive Result

Three active light neutrinos







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

Why Might A "Ton-Scale" Exp't See It?

A(Z,N) $\rightarrow$ **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*

Two parameters: Effective coupling & effective heavy particle mass

0νββ-Decay: LNV? Mass Term?

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

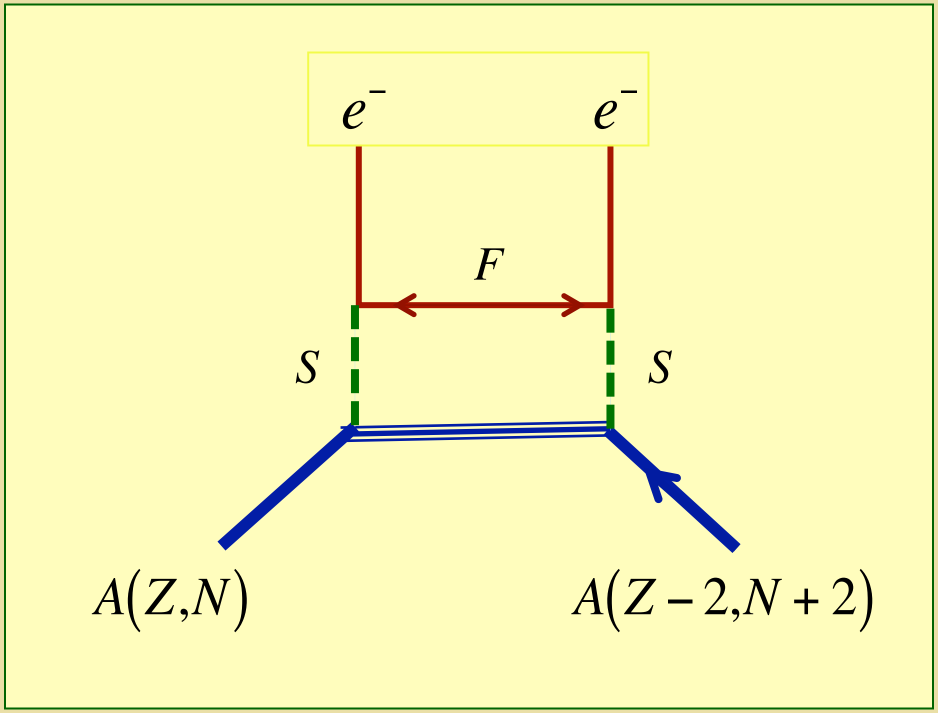
Dirac

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

Majorana

TeV LNV Mechanism

- *Majorana mass generated at the TeV scale*
  - *Low-scale see-saw*
  - *Radiative m_ν*
- *m_{MIN} << 0.01 eV but 0νββ-signal accessible with tonne-scale exp'ts due to heavy Majorana particle exchange*



$0\nu\beta\beta$-Decay: TeV Scale LNV

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

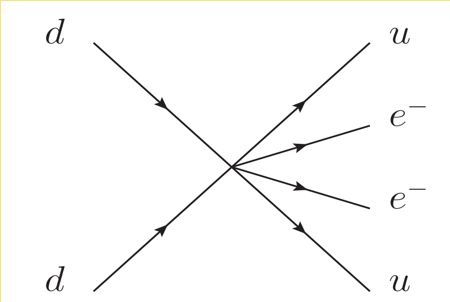
Dirac

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

Majorana

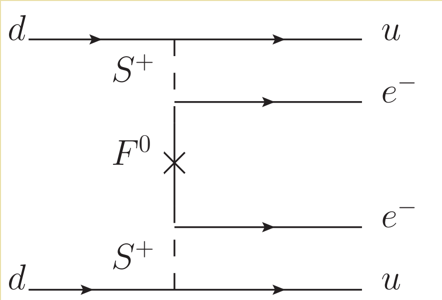
TeV Scale LNV

$0\nu\beta\beta$ - decay



Can it be discovered with combination of $0\nu\beta\beta$ & LHC searches ?

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



Simplified models

0νββ-Decay: TeV Scale LNV

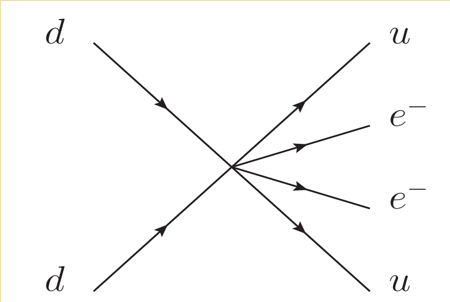
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

Dirac

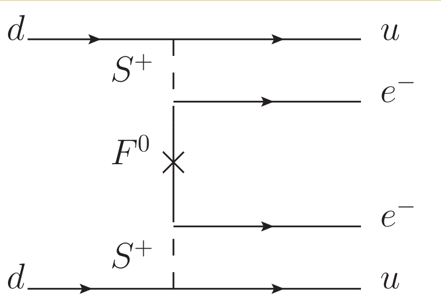
$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; \text{h.c.}$$

Majorana

0νββ - decay



LHC: pp → jj e⁻e⁻



TeV Scale LNV

Comparing 0νββ & LHC sensitivities:

- *LHC backgrounds*
- *Running effective op's to low energy*
- *Matching onto hadronic d.o.f.*
- *Long range NME contributions*

$0\nu\beta\beta$-Decay: TeV Scale LNV

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

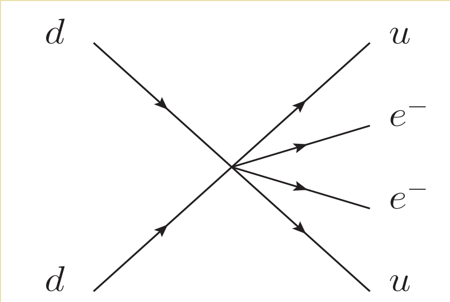
Dirac

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

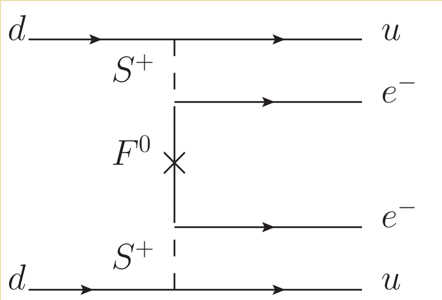
Majorana

TeV Scale LNV

$0\nu\beta\beta$ - decay



LHC: pp $\rightarrow$ jj e⁻e⁻



Effective operators:

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

$$\mathcal{O}_1 = \bar{Q}\tau^+ d\bar{Q}\tau^+ d\bar{L}L^C$$

$$g_{\rm eff} \ = \ C_1(\Lambda)^{1/4}$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

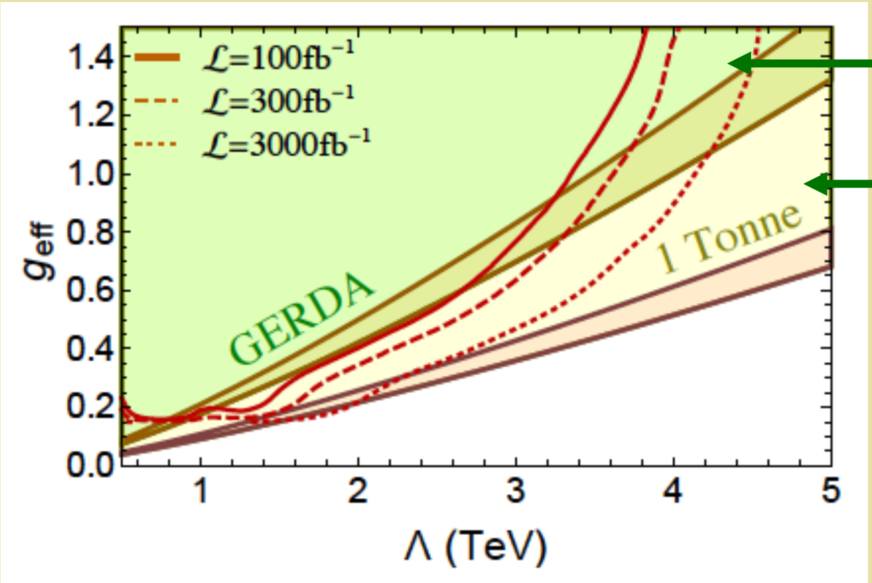
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

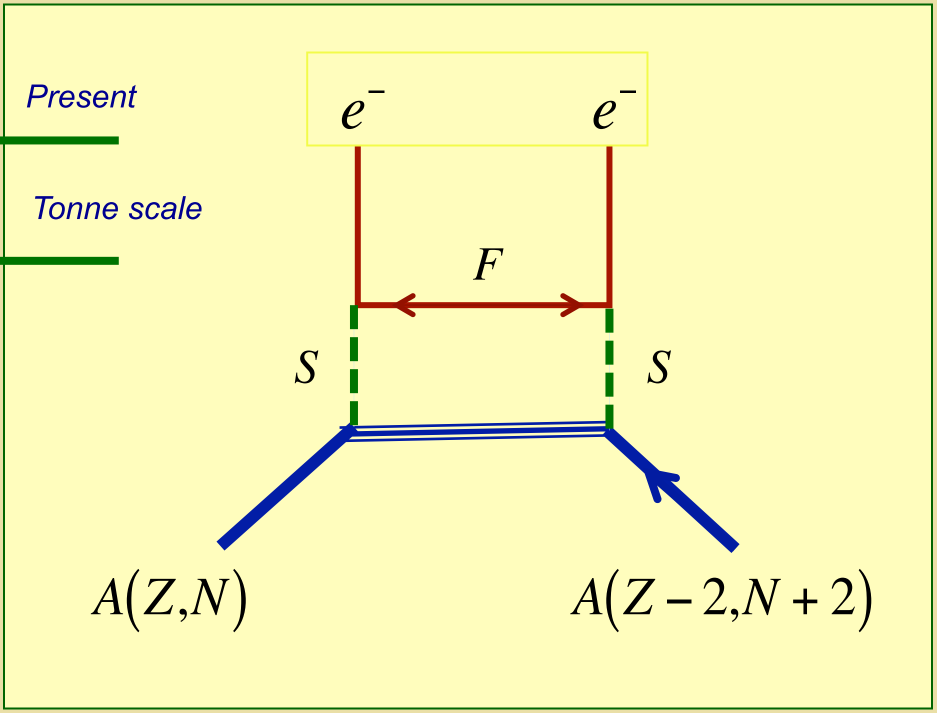
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

$0\nu\beta\beta$-Decay: TeV Scale LNV

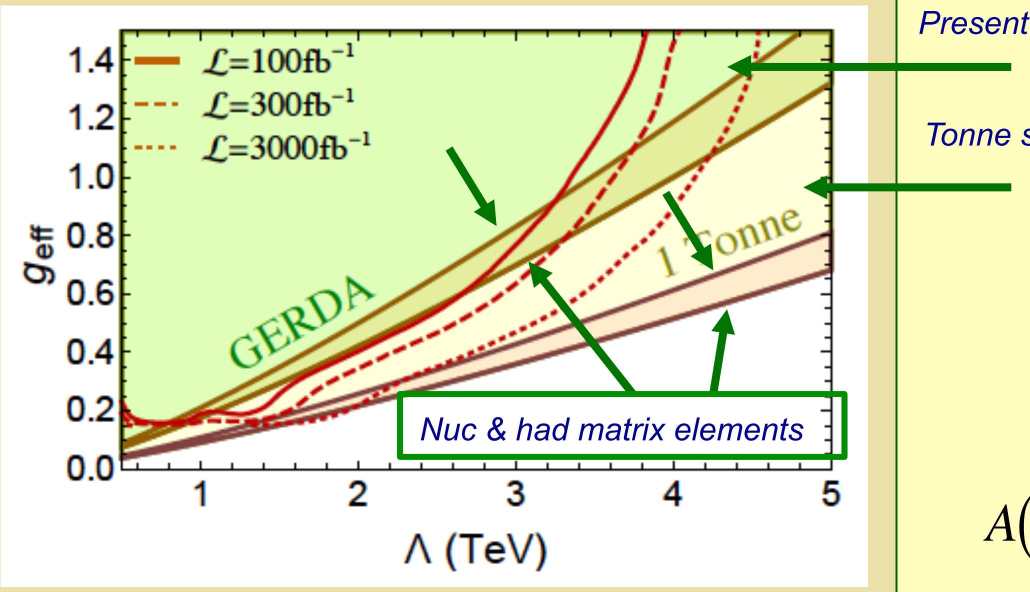
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

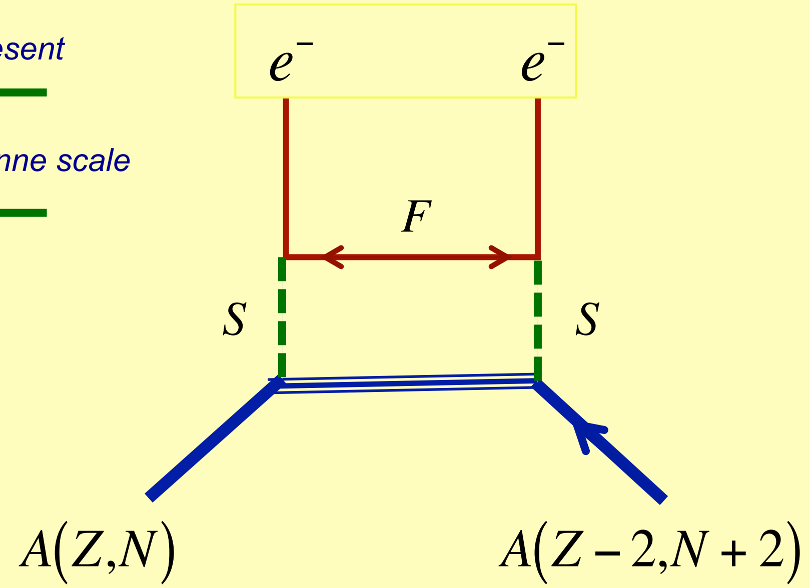
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

0νββ-Decay: TeV Scale LNV

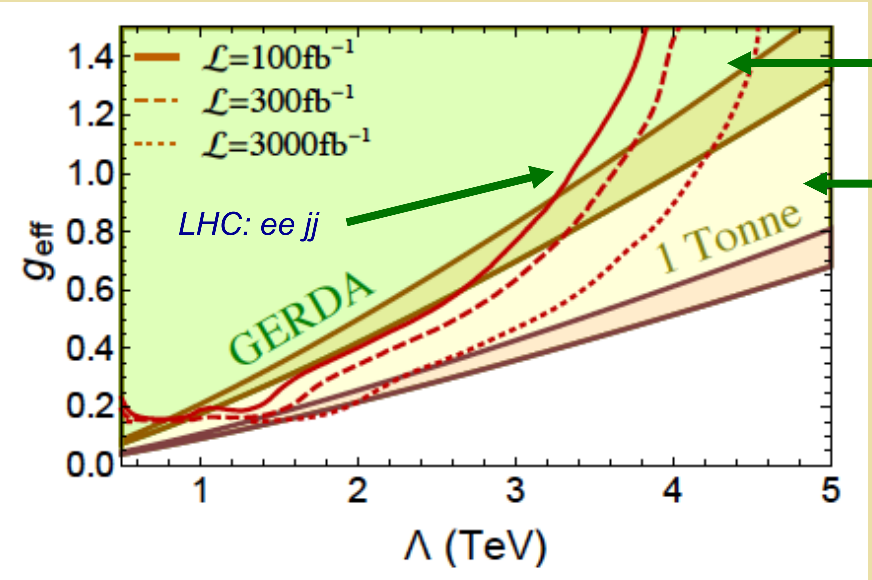
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

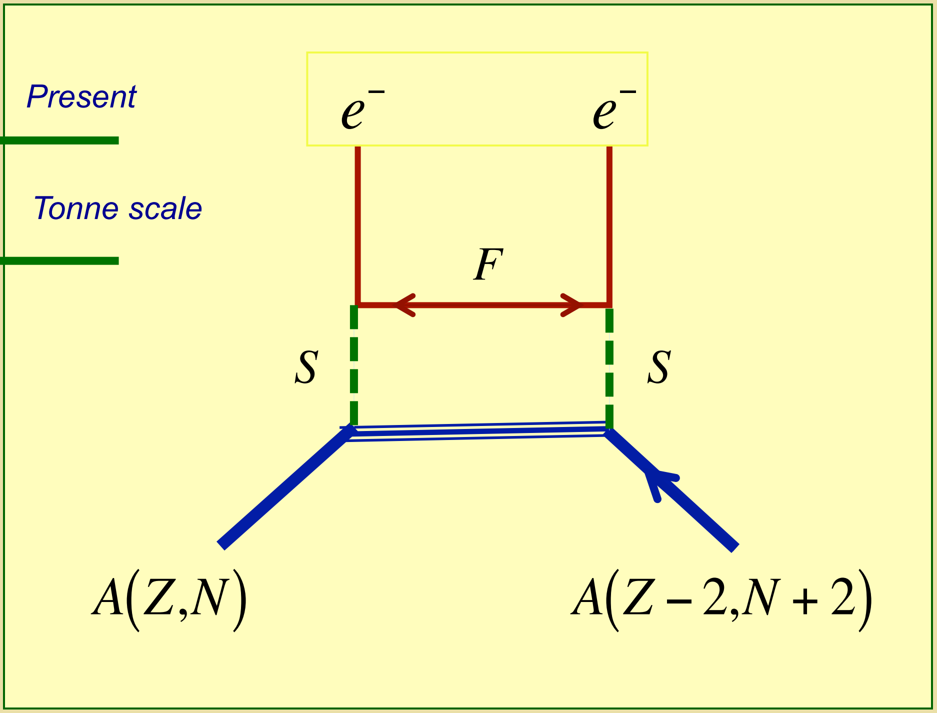
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

$0\nu\beta\beta$-Decay: TeV Scale LNV

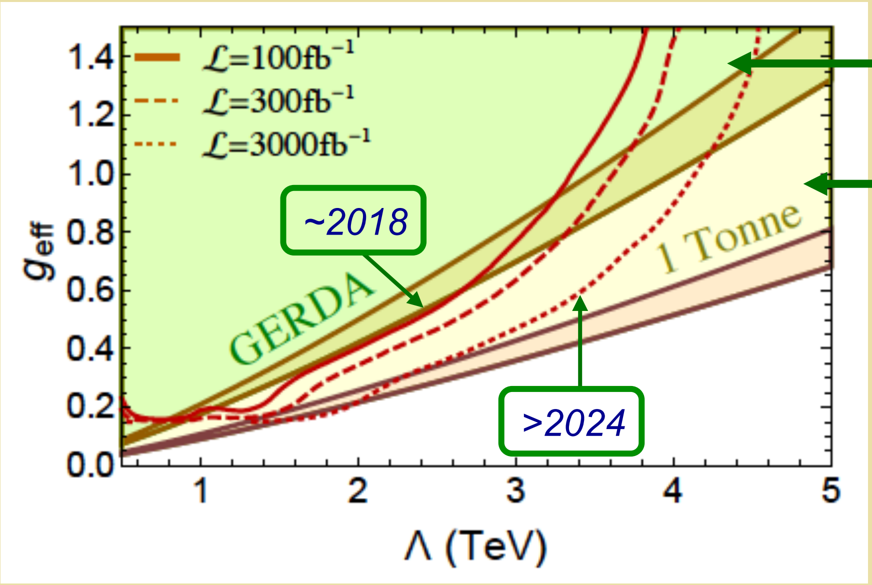
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

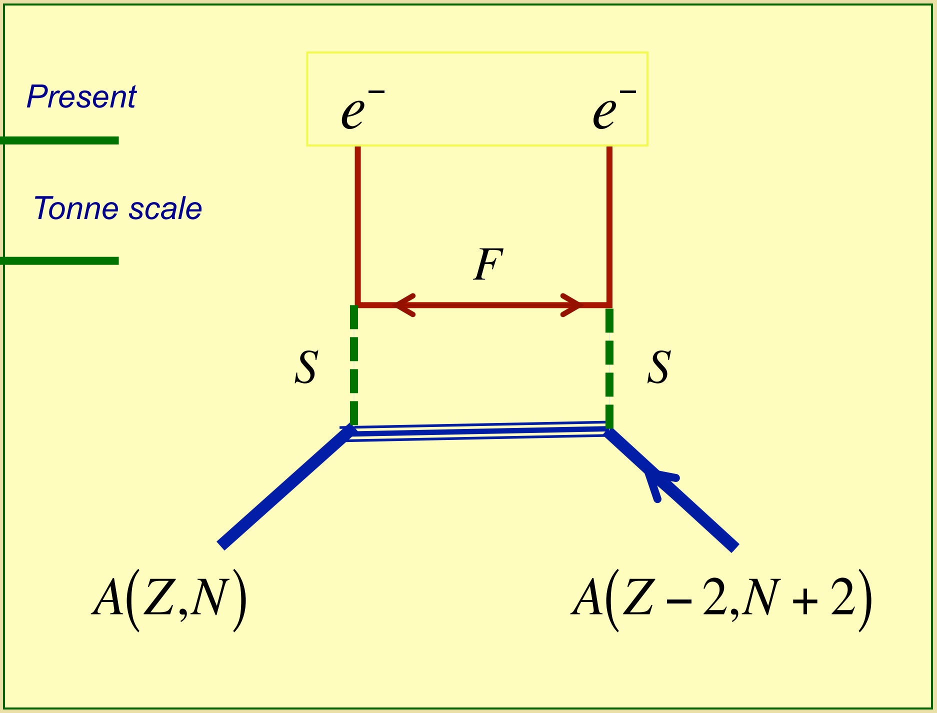
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

$0\nu\beta\beta$-Decay: TeV Scale LNV & m_ν

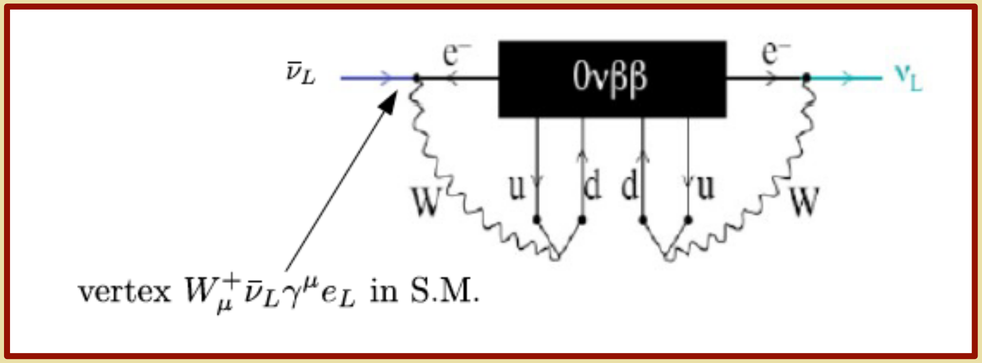
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

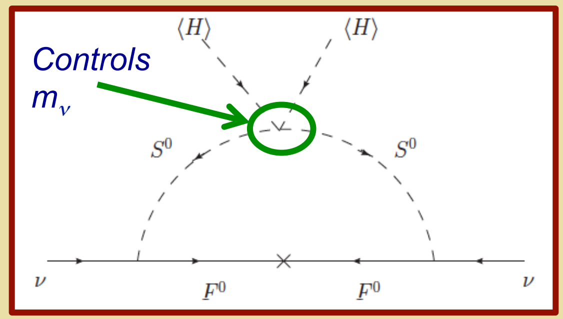
Dirac

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

Majorana

Implications for m_ν:





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

Simplified model: possible (larger) one loop Majorana mass

0νββ-Decay: TeV Scale LNV & m_ν

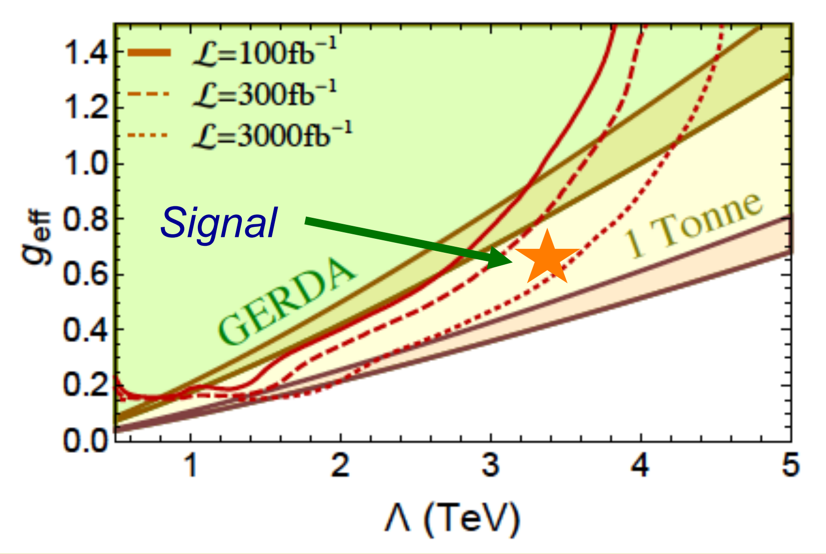
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

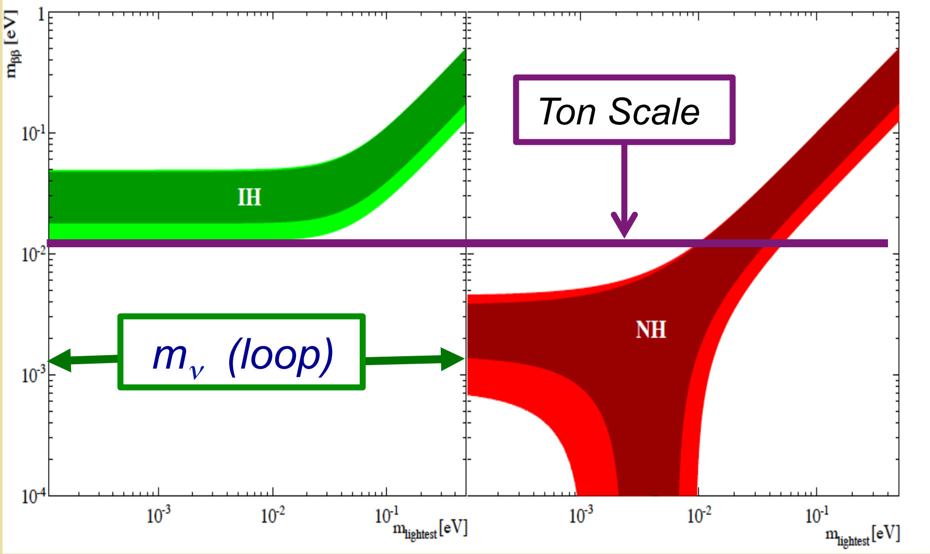
Dirac

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

Majorana

Implications for m_ν:

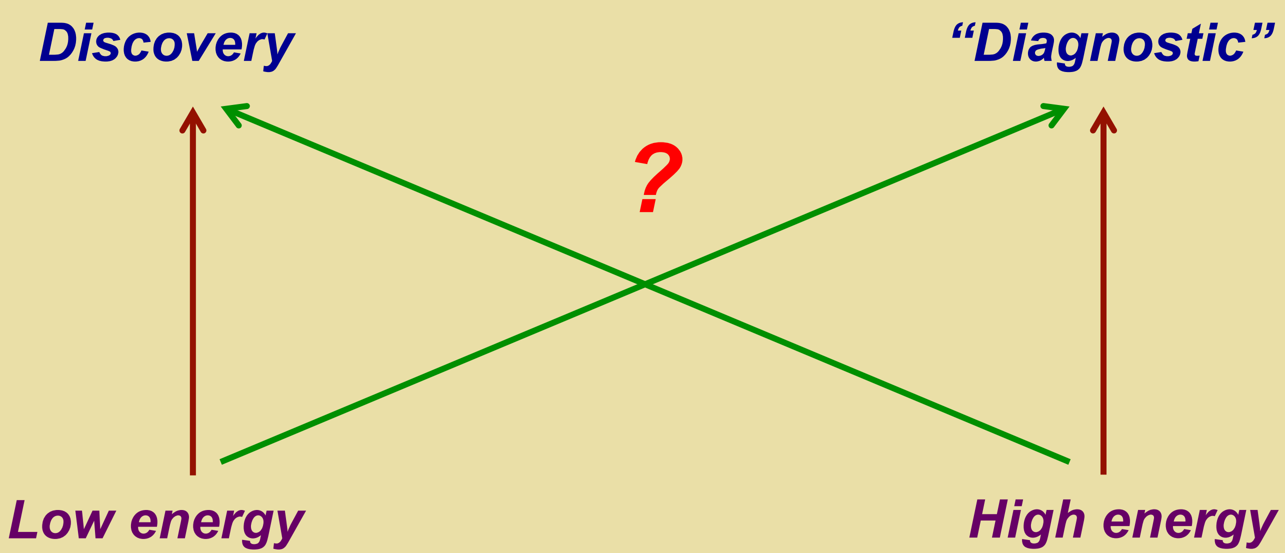




A hypothetical scenario

Low-Energy / High-Energy Interplay

TeV LNV



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

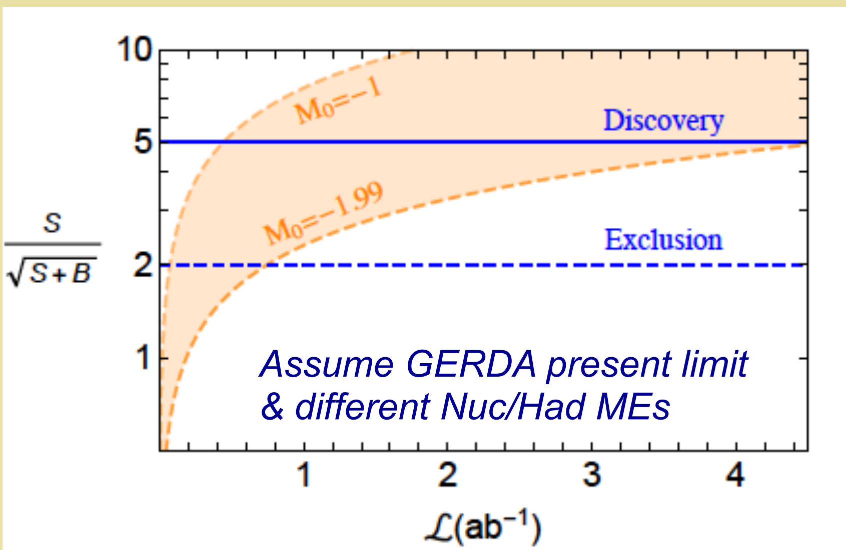
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

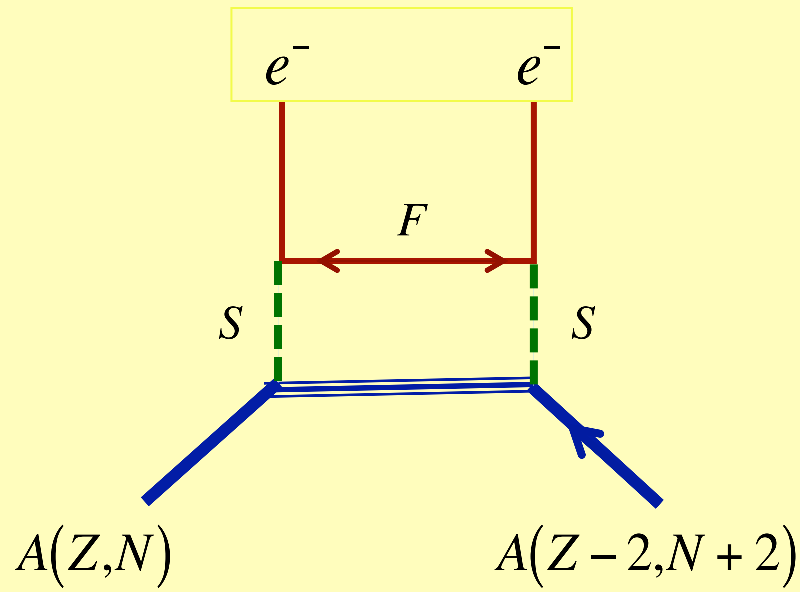
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

0νββ / LHC Interplay: Matrix Elements

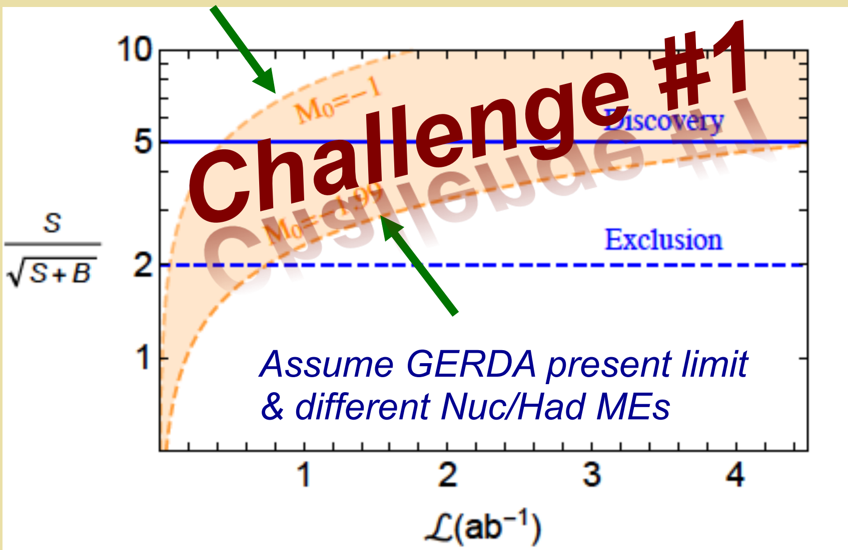
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

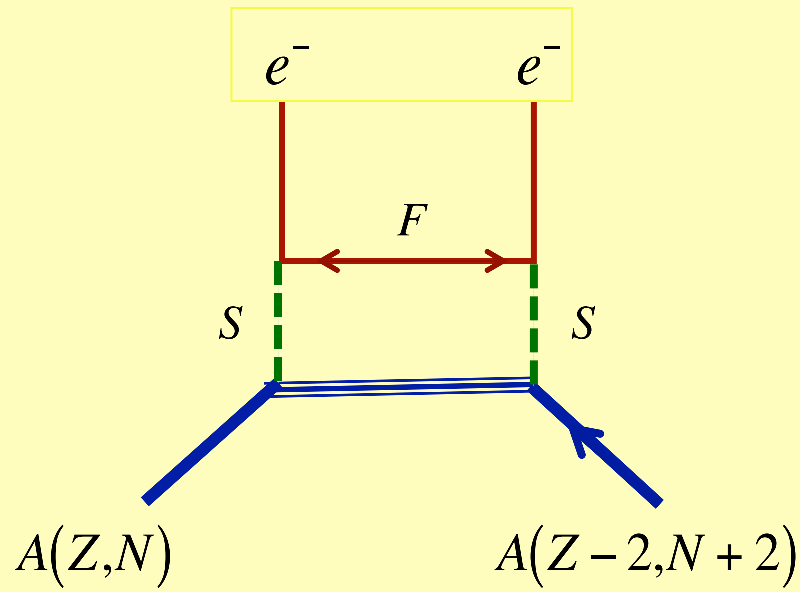
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

III. CPV: EDMs, LHC, & Y_B

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	3.1×10^{-29}	10^{-33}	10^{-29}
ThO	8.7×10^{-29} **	10^{-38}	10^{-28}
n	3.3×10^{-26}	10^{-31}	10^{-26}

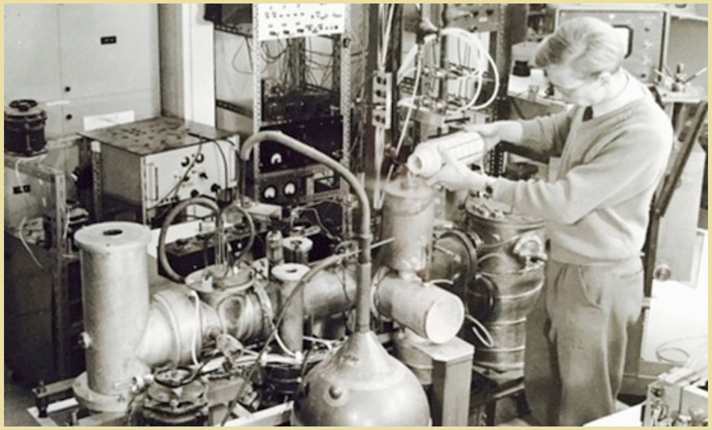
* 95% CL   ** e^- equivalent

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	3.1×10^{-29}	10^{-33}	10^{-29}
ThO	8.7×10^{-29} **	10^{-38}	10^{-28}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL ** e^- equivalent

Mike Pendlebury: 1936-2015



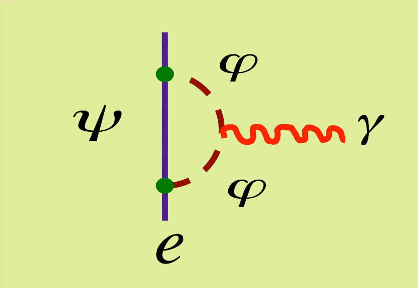
The Guardian 9/23/15

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	3.1×10^{-29}	10^{-33}	10^{-29}
ThO	8.7×10^{-29} **	10^{-38}	10^{-28}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL   ** e^- equivalent

Mass Scale Sensitivity



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

M < 500 GeV $\rightarrow \sin\phi_{CP} < 10^{-2}$

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	3.1×10^{-29}	10^{-33}	10^{-29}
ThO	8.7×10^{-29} **	10^{-38}	10^{-28}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 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

Inoue, R-M, Zhang:
1403.4257

CPV & 2HDM: Type I & II

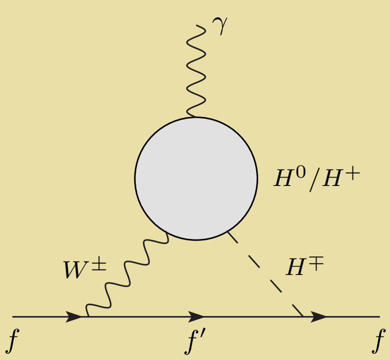
$\lambda_{6,7}$ = 0 for simplicity

$$V = \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right]$$
$$-\frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}.$$

$$\delta_1 = \text{Arg}\left[\lambda_5^*(m_{12}^2)^2\right],$$
$$\delta_2 = \text{Arg}\left[\lambda_5^*(m_{12}^2)v_1v_2^*\right]$$

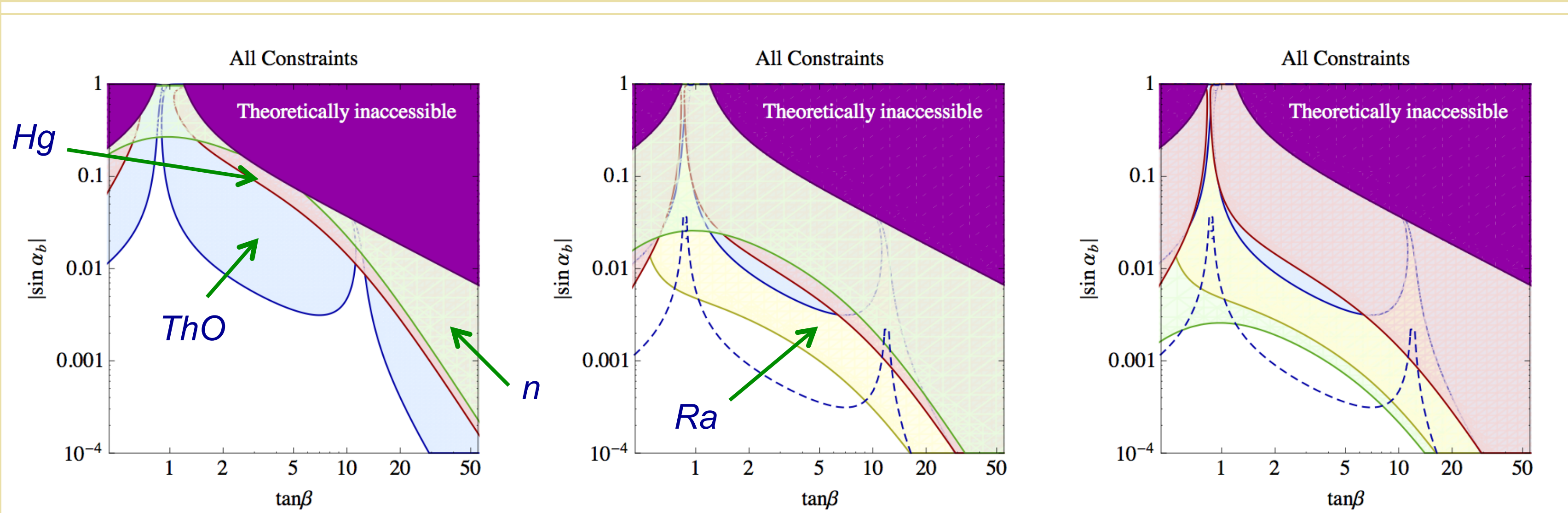
EWSB →

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



Future Reach: Higgs Portal CPV

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*



Present

Future:

d_n x 0.1

$d_A(Hg)$ x 0.1

d_{ThO} x 0.1

$d_A(Ra)$

Future:

d_n x 0.01

$d_A(Hg)$ x 0.1

d_{ThO} x 0.1

$d_A(Ra)$

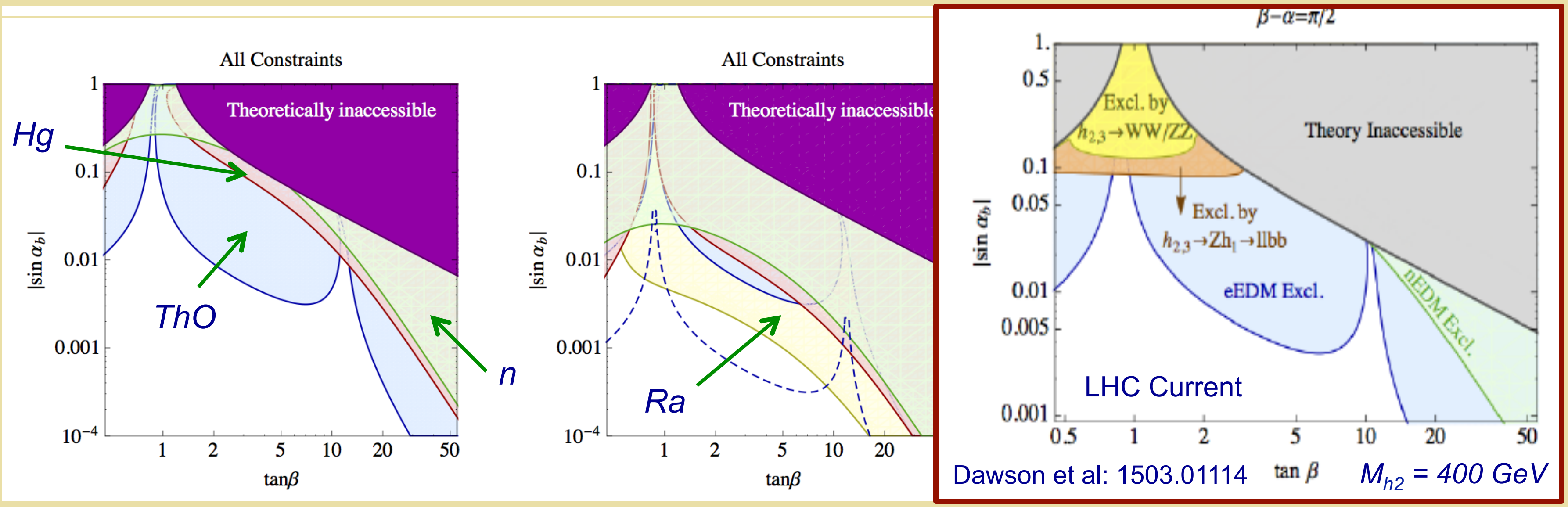
$\sin\alpha_b$: CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration

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



Present

Future:

d_n x 0.1

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

Future:

d_n x 0.01

d_A(Hg) x 0.1

d_{ThO} x 0.1

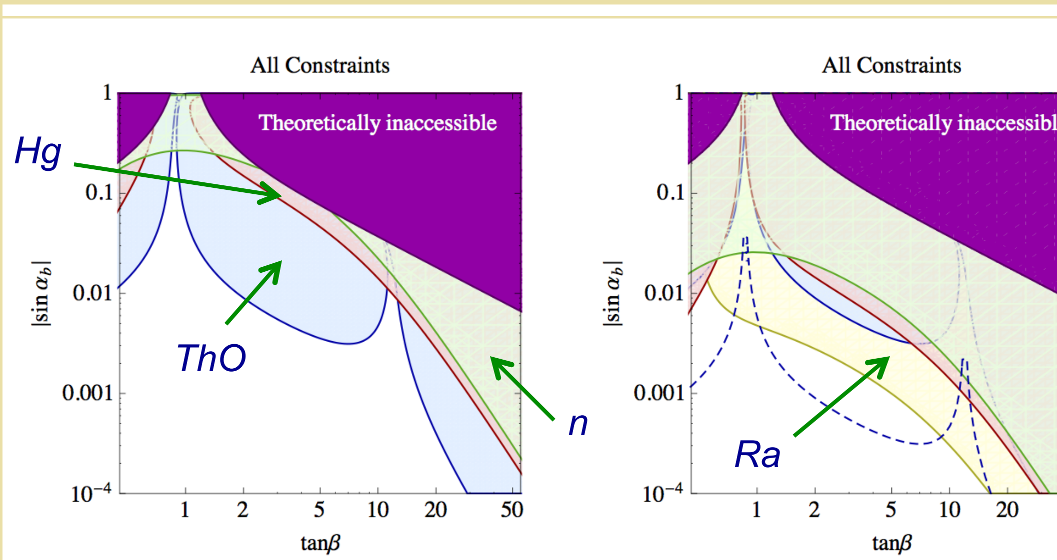
d_A(Ra)

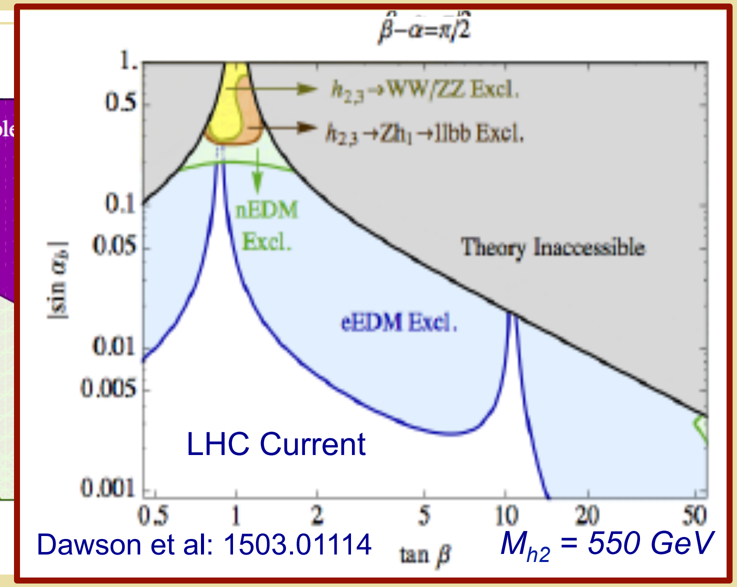
sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*





Present

$\sin \alpha_b$: CPV scalar mixing

Future:

d_n x 0.1

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

Future:

d_n x 0.01

d_A(Hg) x 0.1

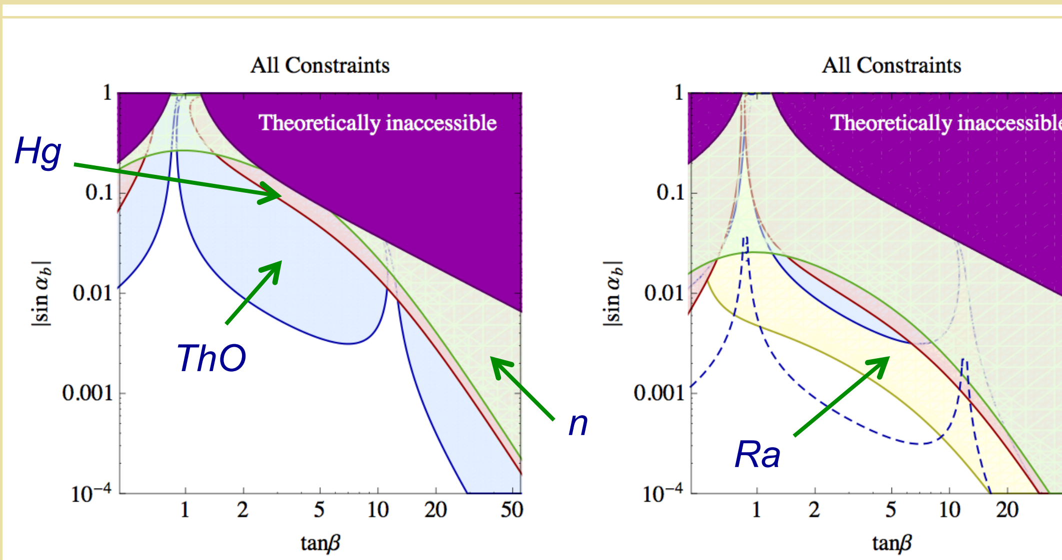
d_{ThO} x 0.1

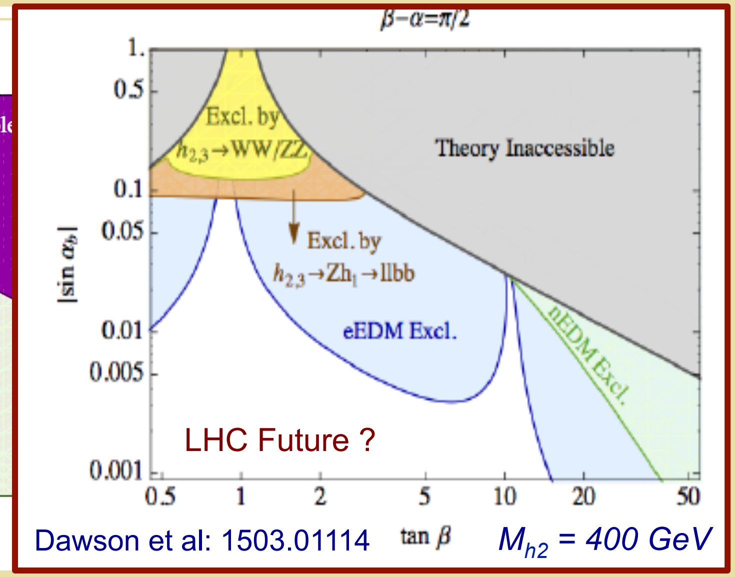
d_A(Ra)

Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*



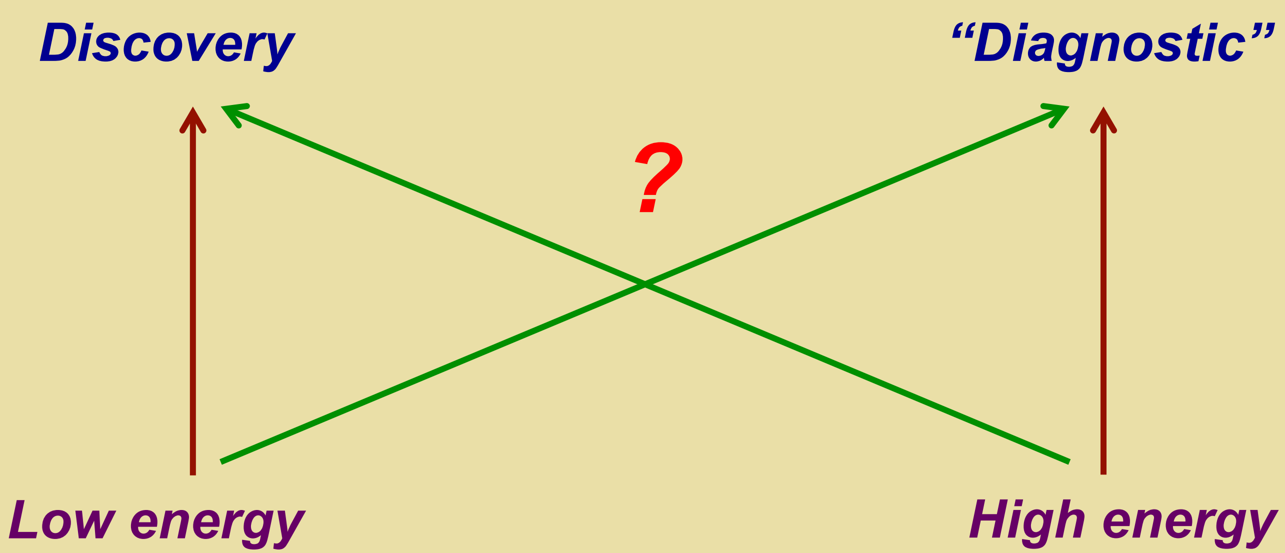


Present	*Future:*	*Future:*
	d_n x 0.1	d_n x 0.01
	d_A(Hg) x 0.1	d_A(Hg) x 0.1
sin α_b : CPV scalar mixing	d_{ThO} x 0.1	d_{ThO} x 0.1
	d_A(Ra)	d_A(Ra)

Inoue, R-M, Zhang: 1403.4257

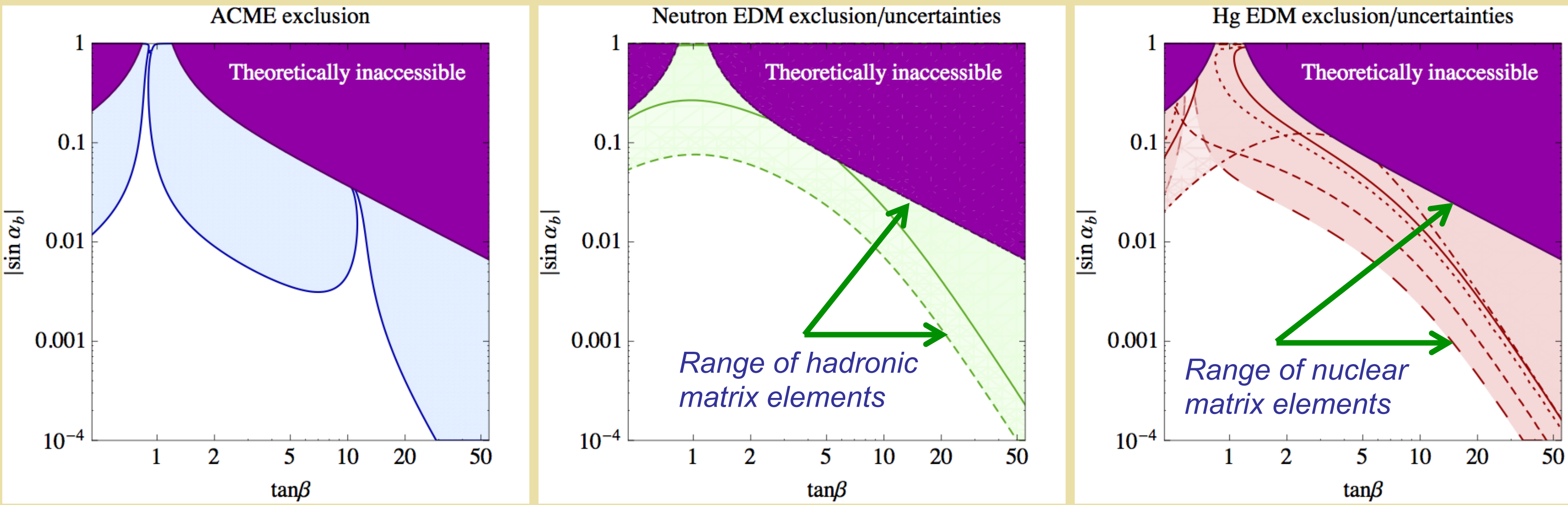
Low-Energy / High-Energy Interplay

Higgs Portal CPV



Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*



Present

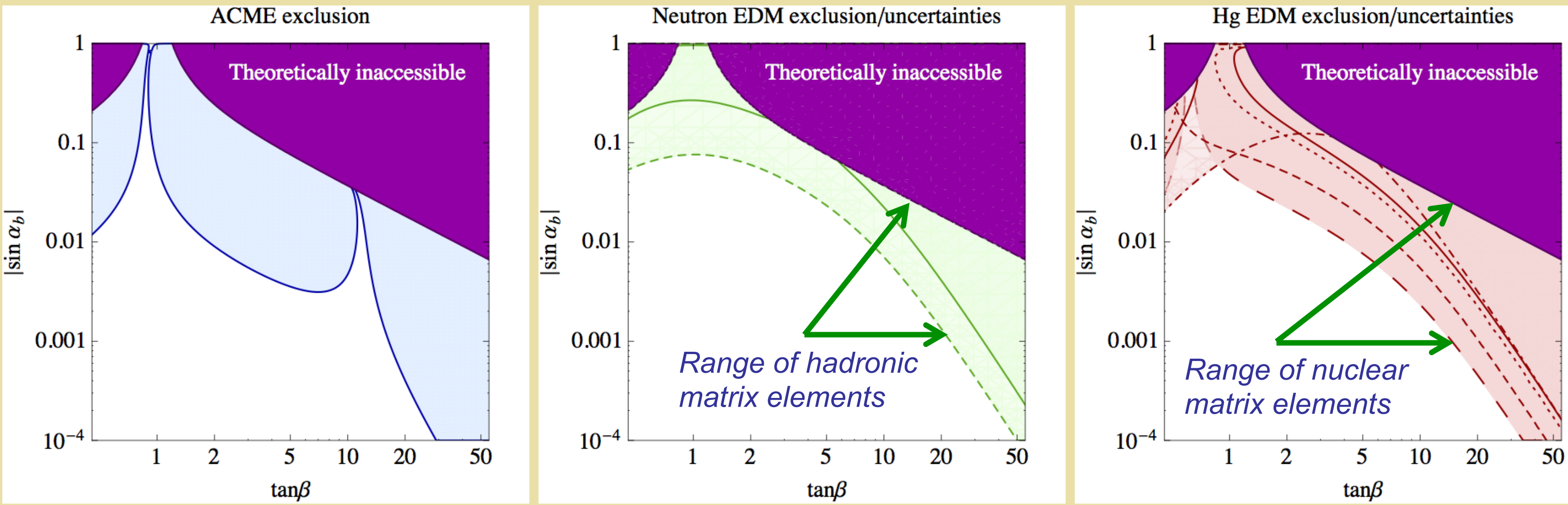
sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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



Present

Challenge #2

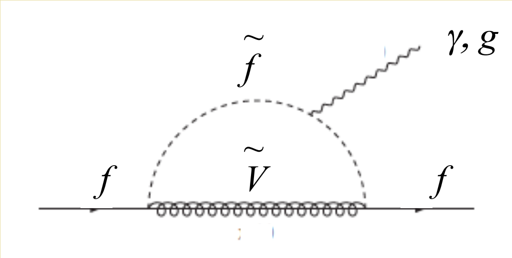
$\sin \alpha_b$: CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

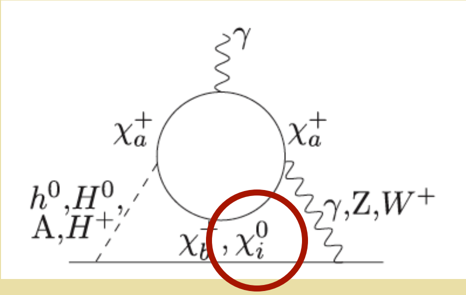
Was the baryon asymmetry produced during electroweak symmetry-breaking ?

- *EDMs provide most powerful probe of CPV*
- *Phase transition $\rightarrow$ Separate talk (back up slides)*

EDMs & EW Baryogenesis: MSSM

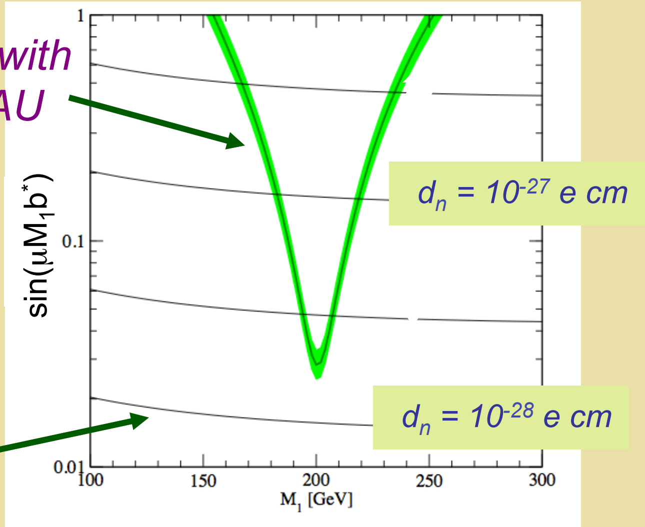


Heavy sfermions: LHC consistent & suppress 1-loop EDMs

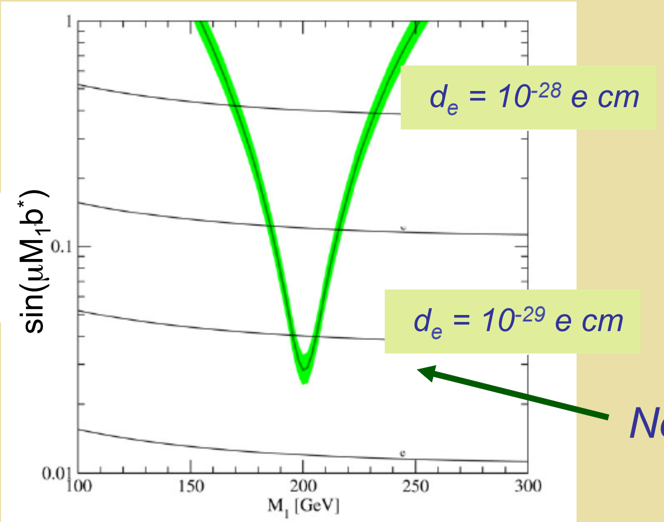


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU



Next gen d_n

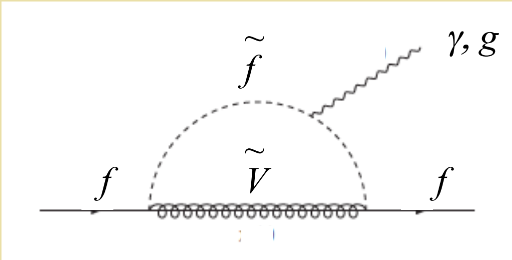


ACME: ThO

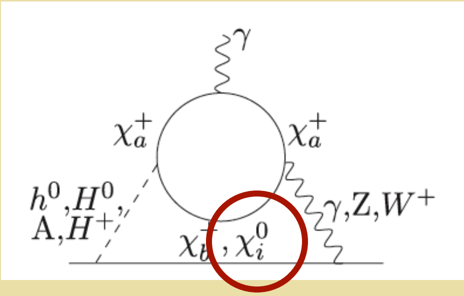
Next gen d_e

Li, Profumo, RM '09-'10

EDMs & EW Baryogenesis: MSSM

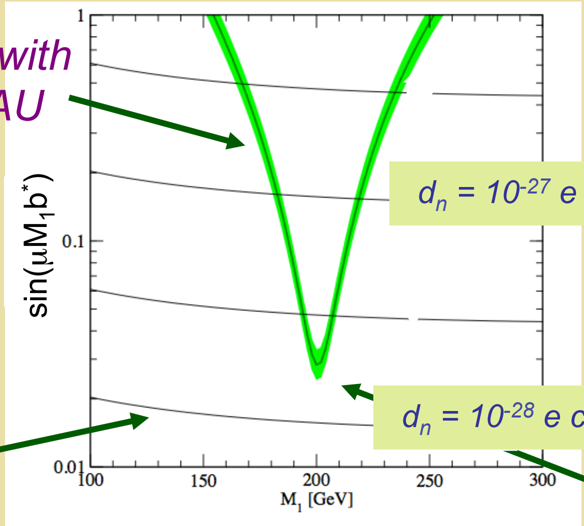


Heavy sfermions: LHC consistent & suppress 1-loop EDMs



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

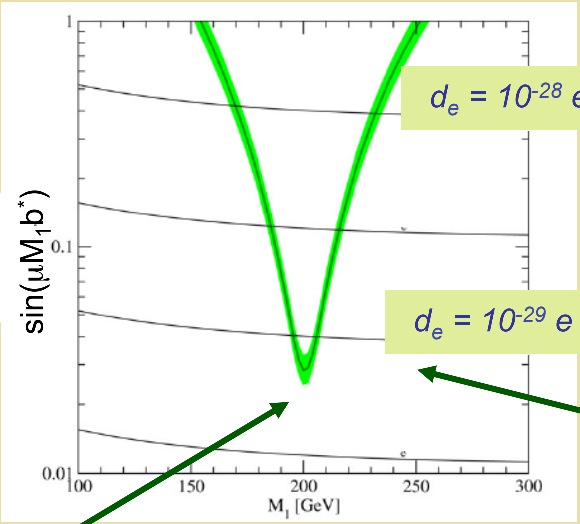
Compatible with observed BAU



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

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

Next gen d_n



$d_e = 10^{-28}$ e cm ACME: ThO

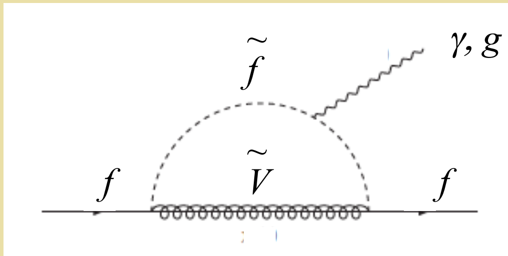
$d_e = 10^{-29}$ e cm

Next gen d_e

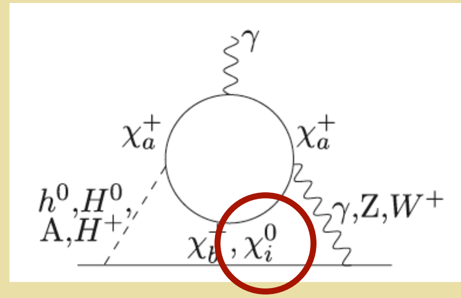
Li, Profumo, RM '09-'10

Compressed spectrum (stealthy SUSY)

EDMs & EW Baryogenesis: MSSM

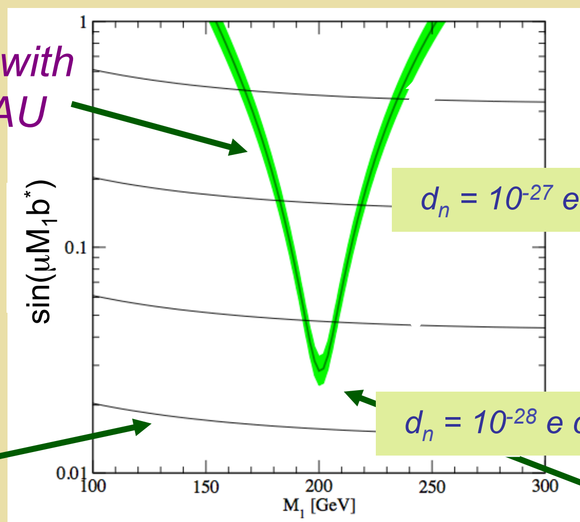


Heavy sfermions: LHC consistent & suppress 1-loop EDMs



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

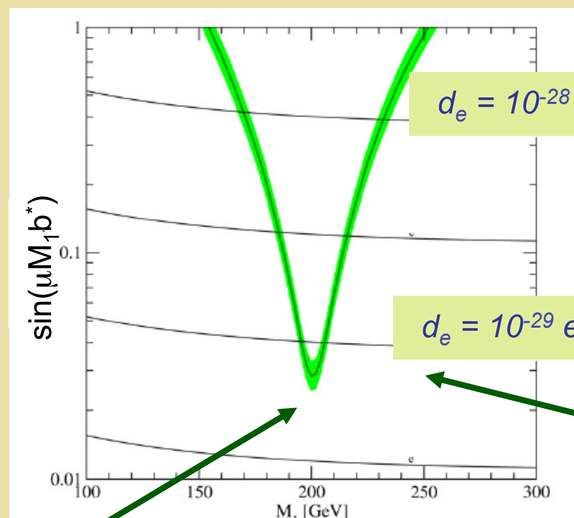
Compatible with observed BAU



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

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

Next gen d_n



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

ACME: ThO

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

Next gen d_e

Li, Profumo, RM '09-'10

Compressed spectrum (stealthy SUSY)

Next gen lepton collider

Low-Energy / High-Energy Interplay

EWB for Compressed SUSY

Discovery	***"Diagnostic"***
↑	↑
Low energy	***High energy***

Model Independent: Effective Operators

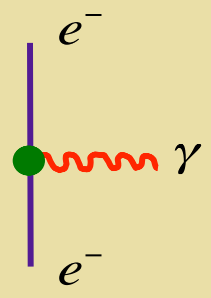
δ_f	*fermion EDM*	*(3)*
$\tilde{\delta}_q$	*quark CEDM*	*(2)*
$C_{\tilde{G}}$	*3 gluon*	*(1)*
C_{quqd}	*non-leptonic*	*(2)*
$C_{lequ,\, ledq}$	*semi-leptonic*	*(3)*
$C_{\varphi ud}$	*induced 4f*	*(1)*

12 total + $\bar{\theta}$

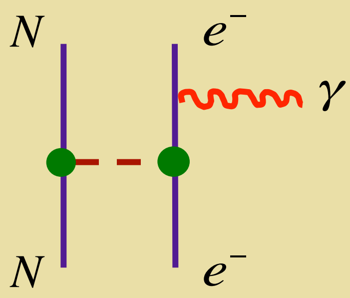
light flavors only (e,u,d)

Paramagnetic Systems: Two Sources

Electron EDM



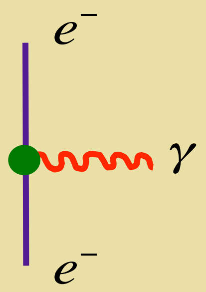
(Scalar q) x (PS e^-)



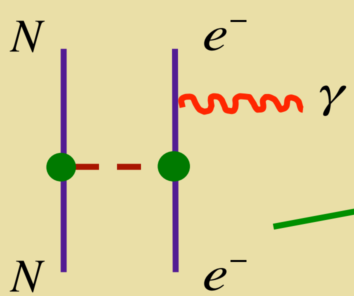
Tl, YbF, ThO…

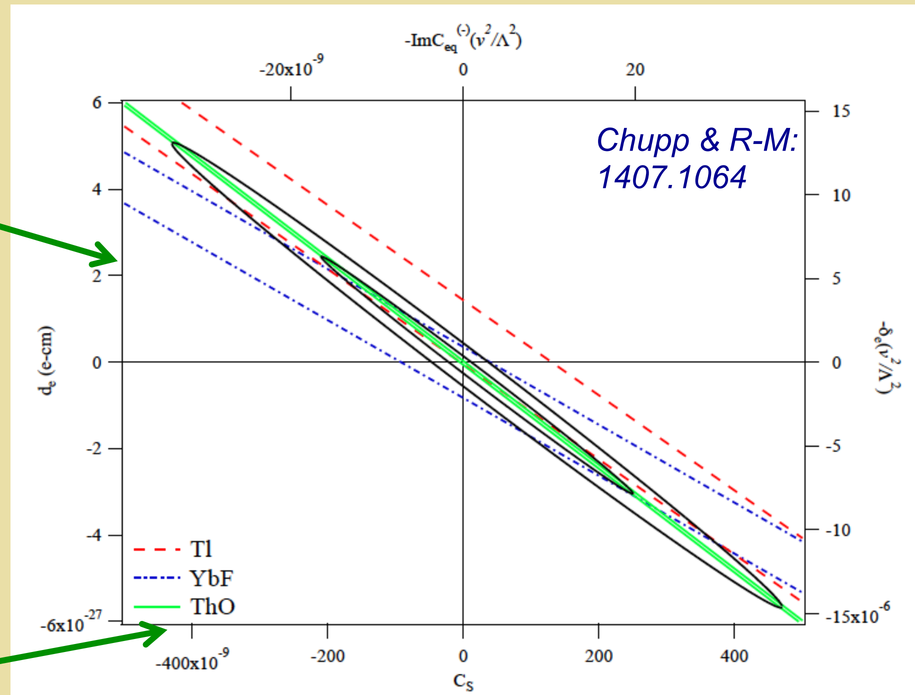
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e⁻)

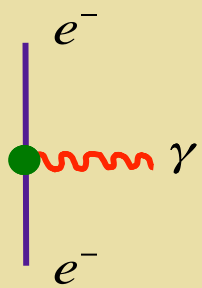




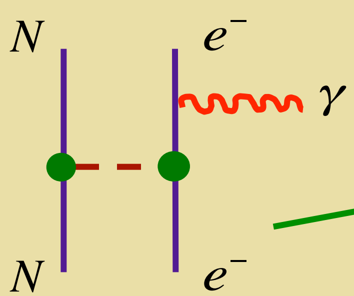
Tl, YbF, ThO…

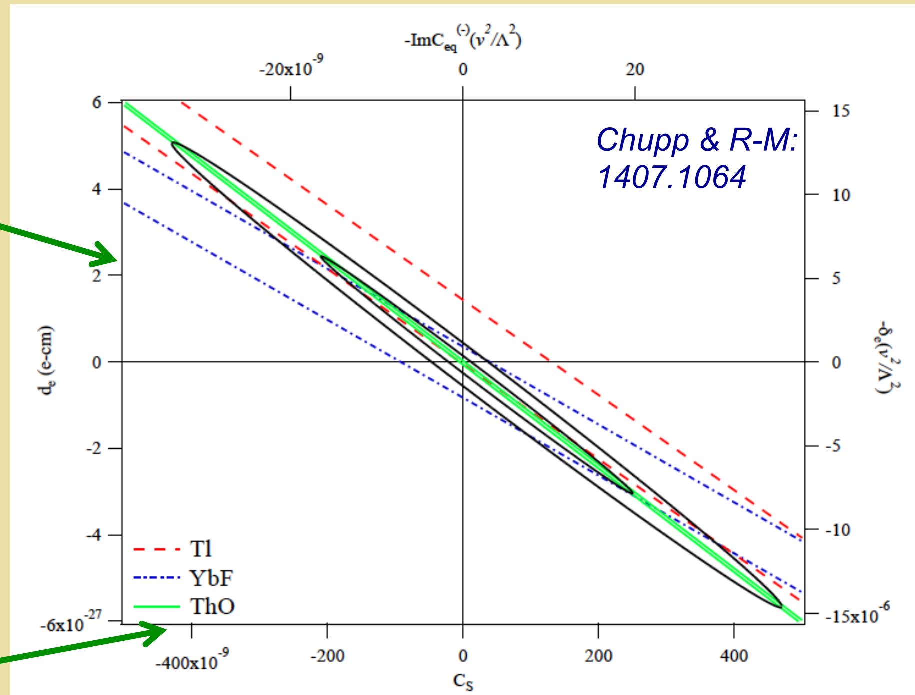
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e-)





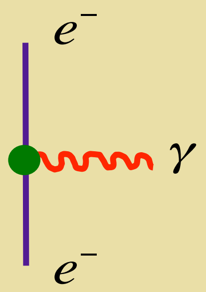
$$\Lambda \gtrsim (1.5\ \text{TeV}) \times \sqrt{\sin\phi_{\rm CPV}} \qquad \text{Electron EDM (global)}$$

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

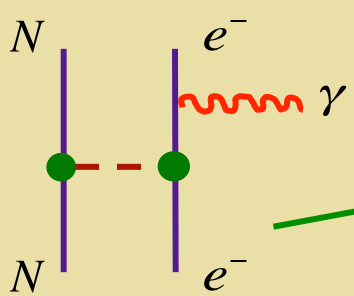
Tl, YbF, ThO…

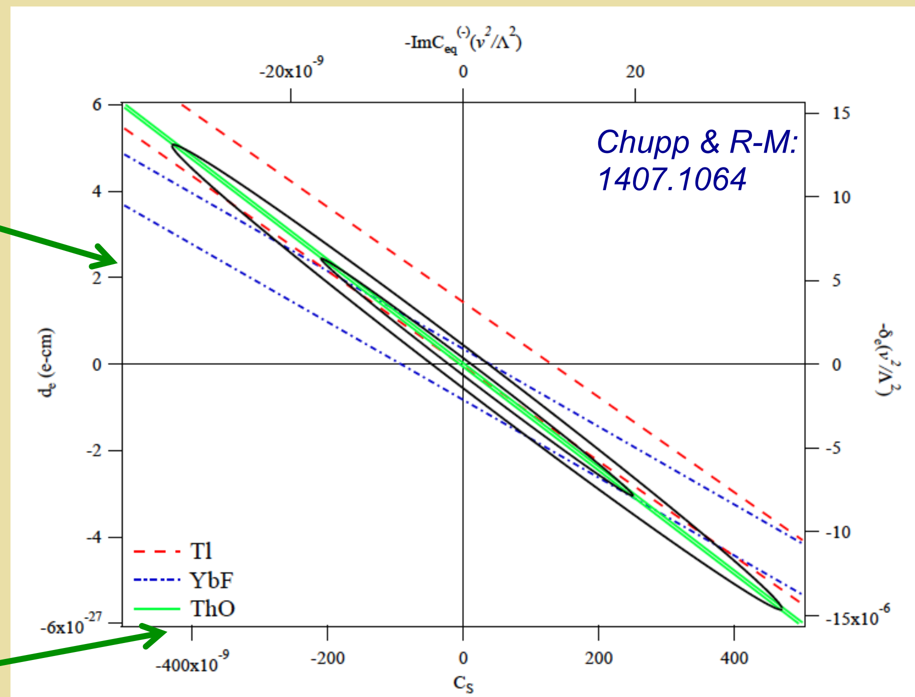
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e⁻)



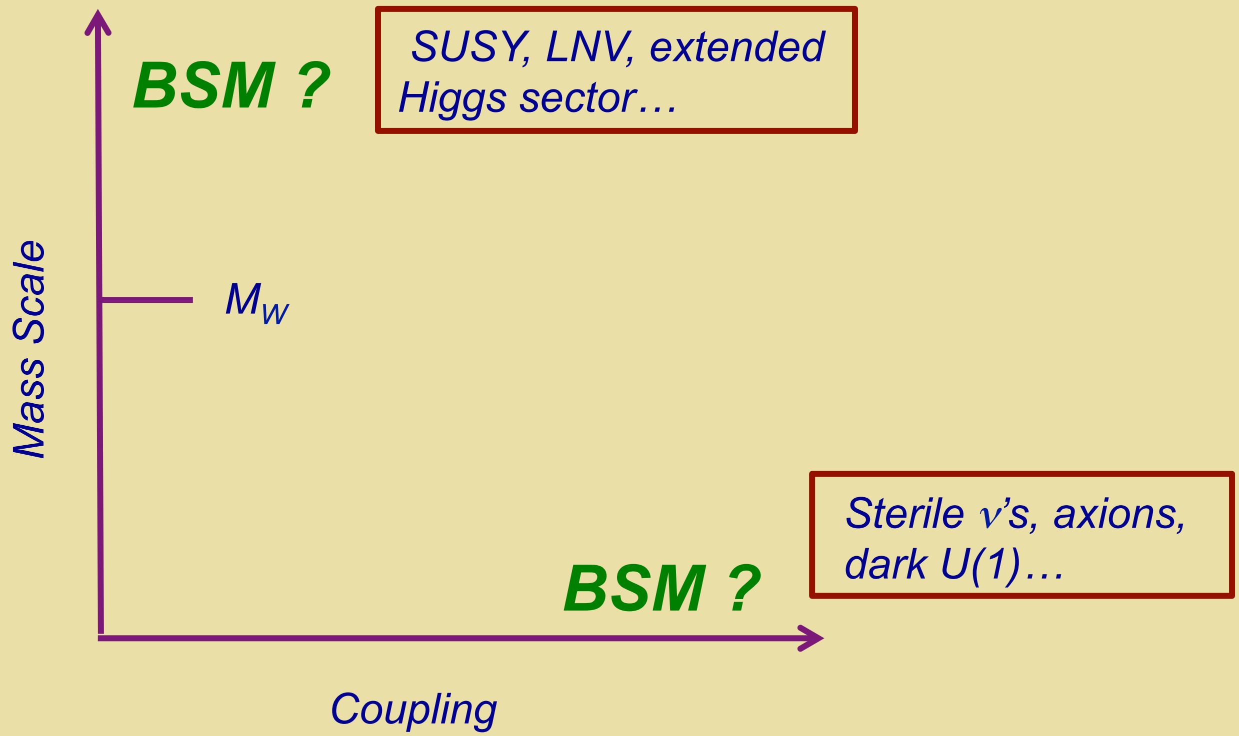


$\Lambda \gtrsim (1.5\ \text{TeV}) \times \sqrt{\sin\phi_{\text{CPV}}}$	Electron EDM (global)
$\Lambda \gtrsim (1300\ \text{TeV}) \times \sqrt{\sin\phi_{\text{CPV}}}$	C_S (global)

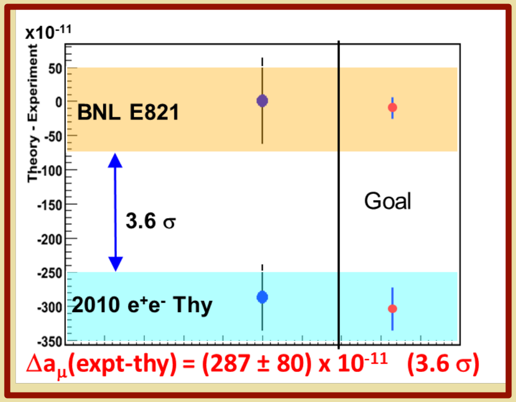
LHC accessible?

Tl, YbF, ThO…

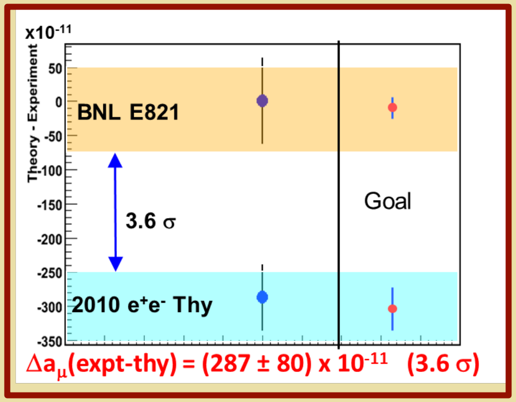
IV. Precision Tests



Muon Anomalous Magnetic Moment



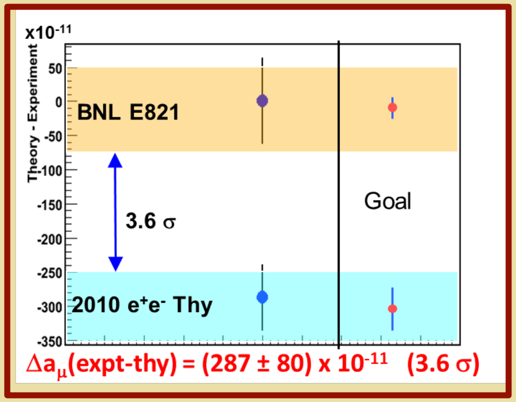
Muon Anomalous Magnetic Moment

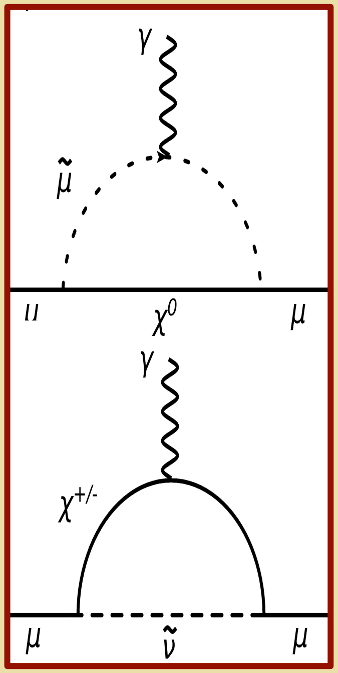


True deviation from SM ?

Challenge #3

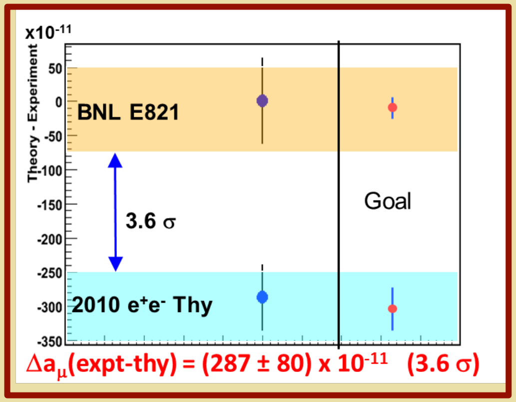
Muon Anomalous Magnetic Moment

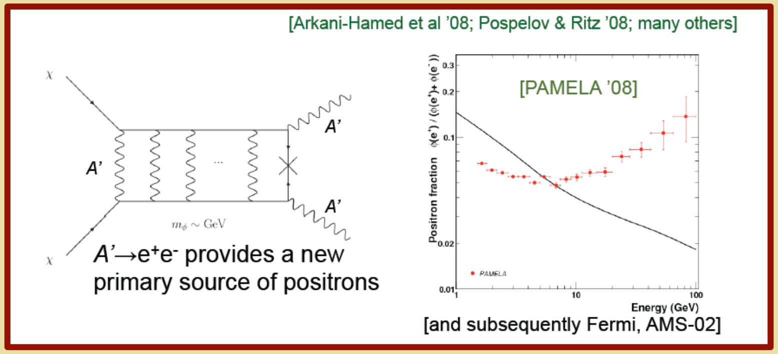


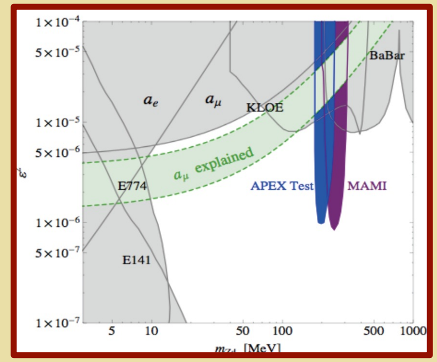


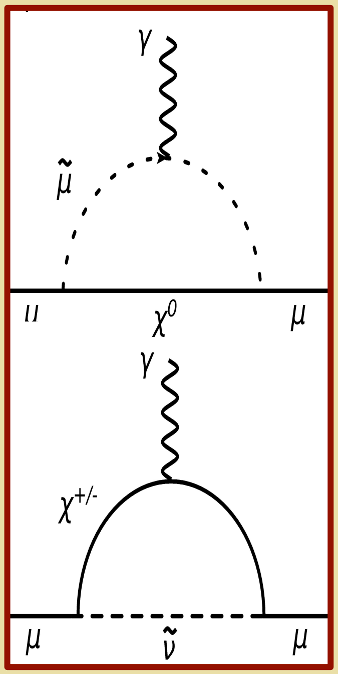
New TeV Physics (SUSY)

Muon Anomalous Magnetic Moment







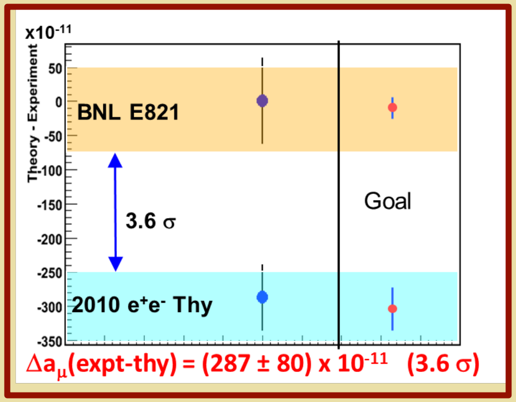


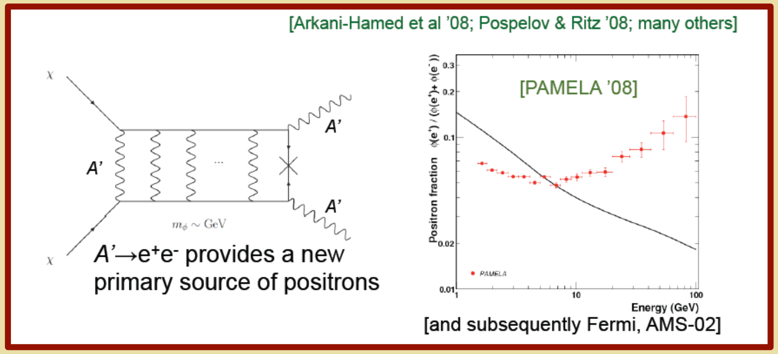
New TeV Physics (SUSY)

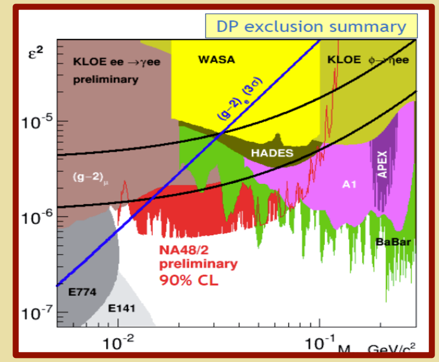
New Ultralight Physics (Dark γ)

New excitement since 2008

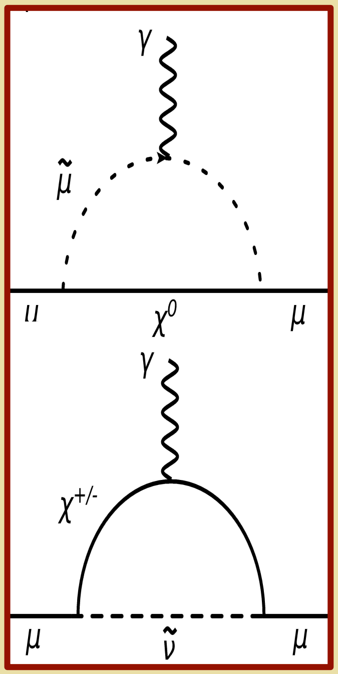
Muon Anomalous Magnetic Moment







Muon g-2 region essentially ruled out (assumptions)

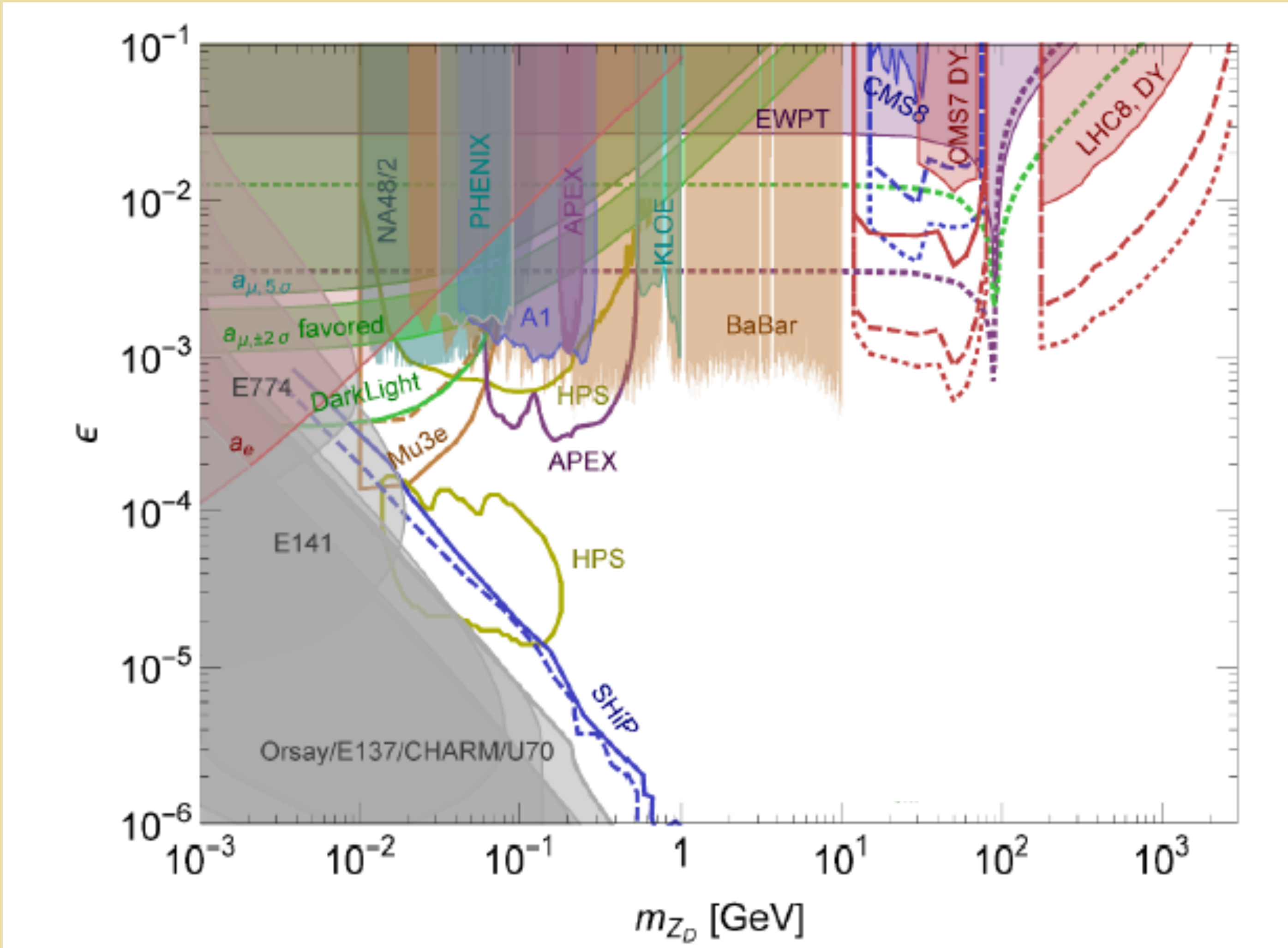


New TeV Physics (SUSY)

New Ultralight Physics (Dark γ)

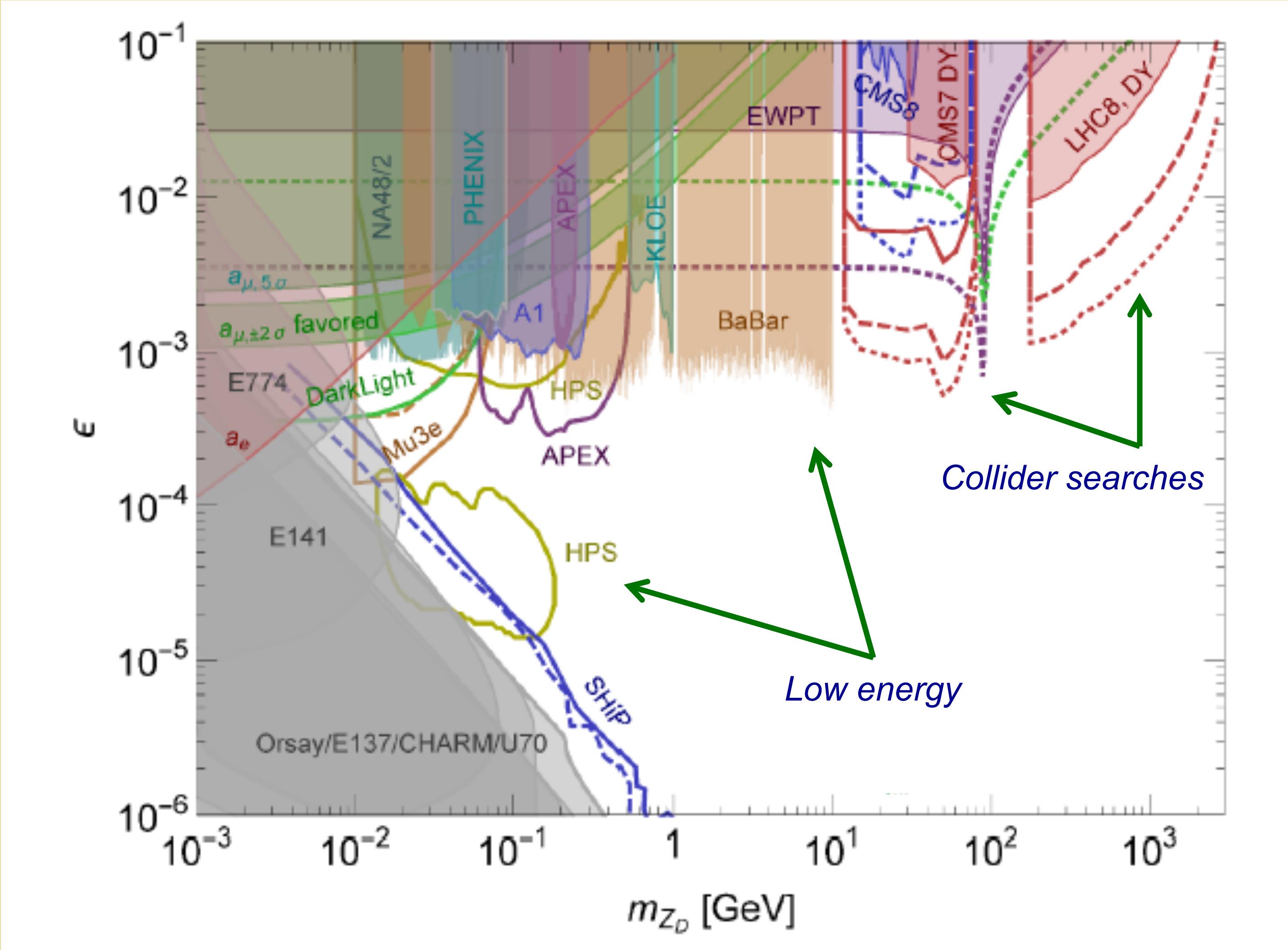
New excitement since 2008

The Hunt for a Dark Z



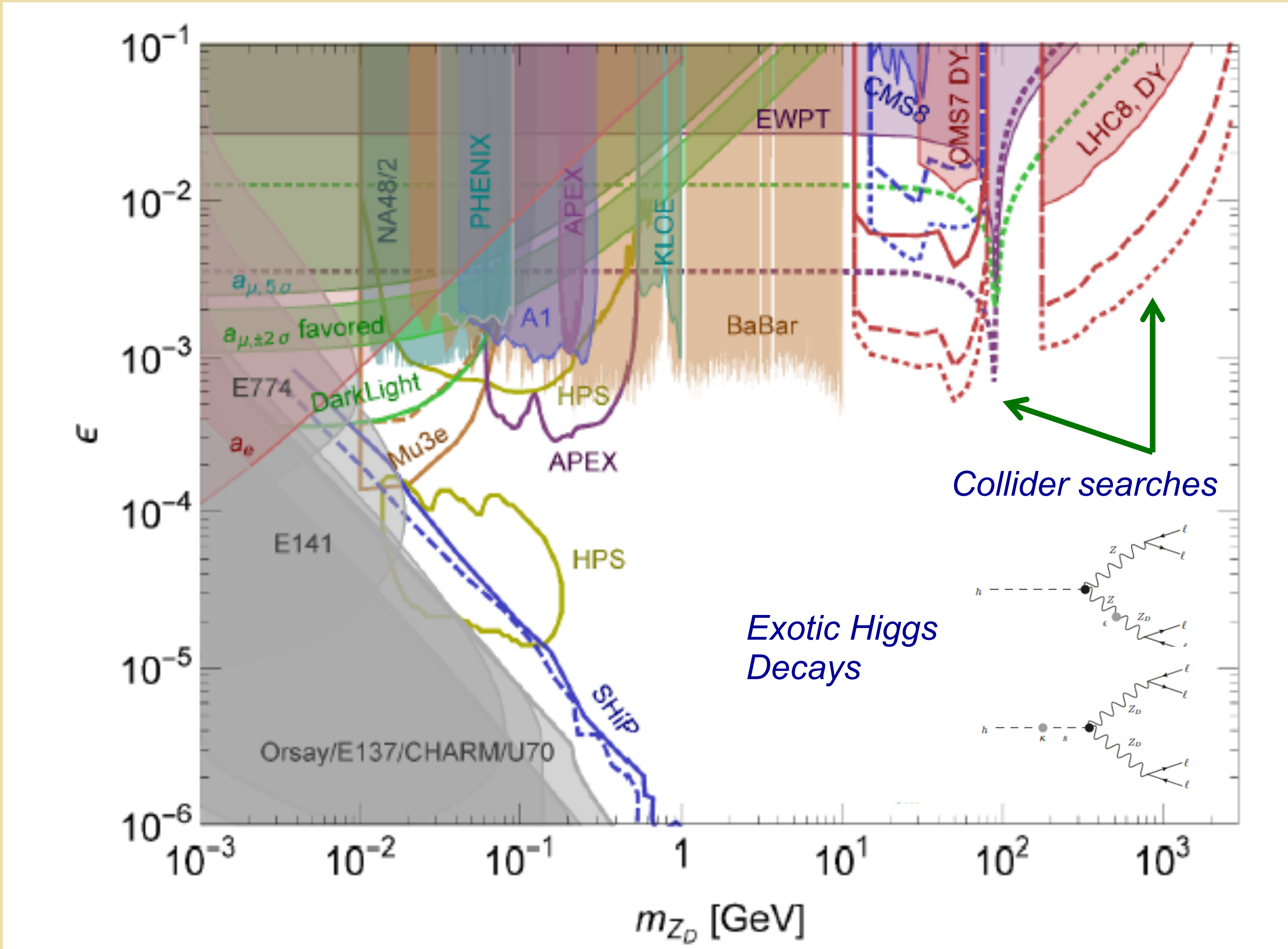
Curtin et al, '14

The Hunt for a Dark Z



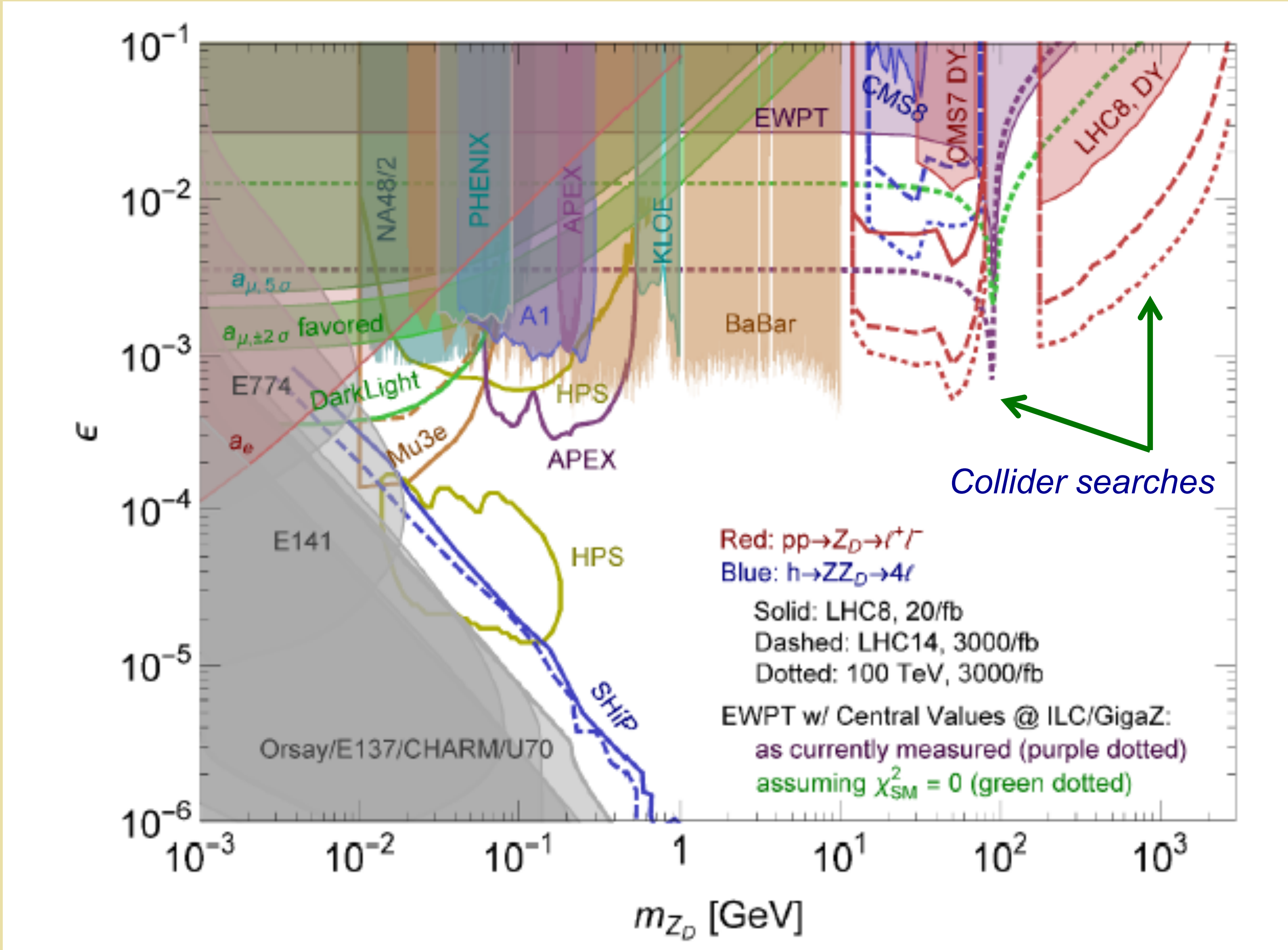
Curtin et al, '14

The Hunt for a Dark Z



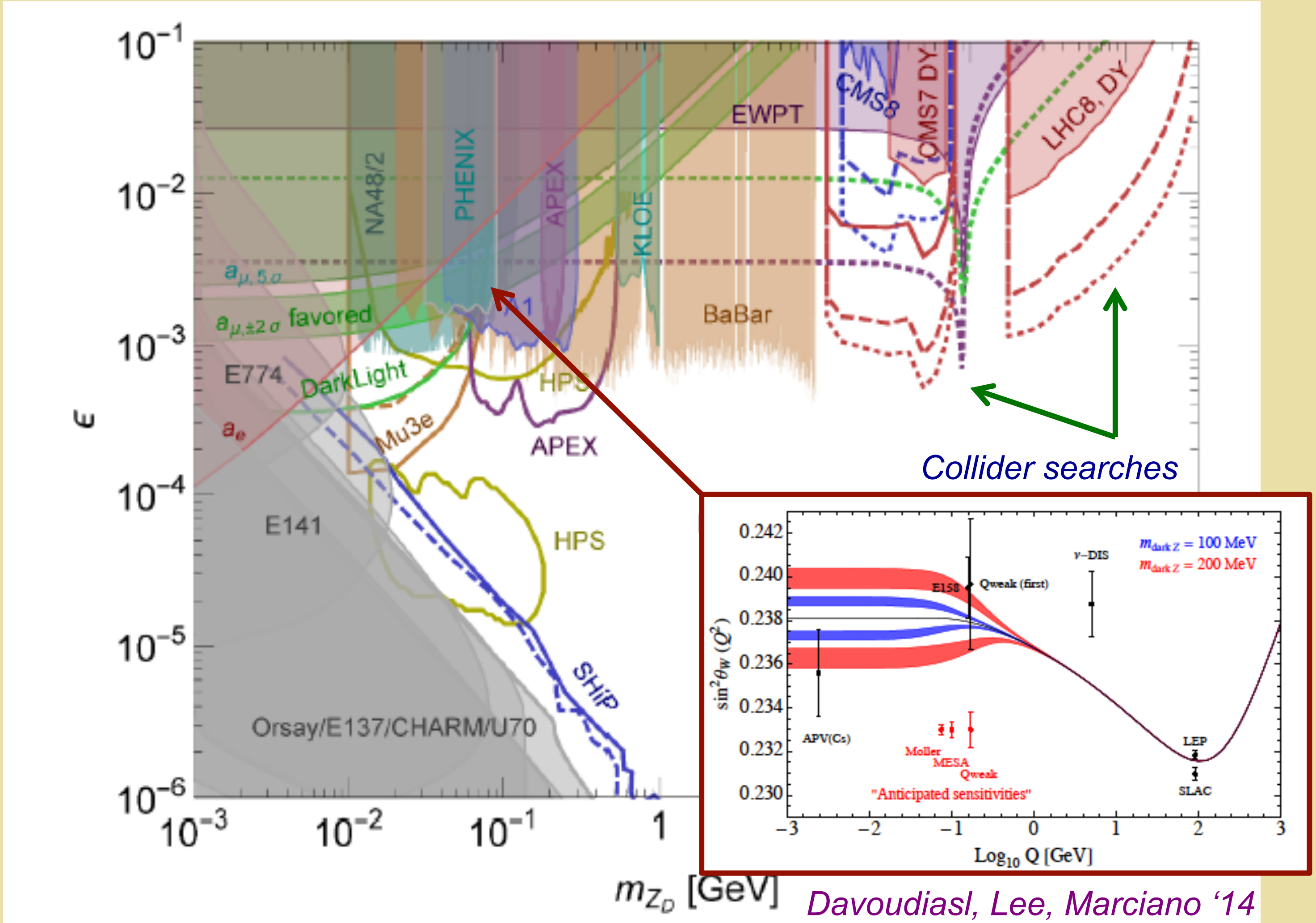
Curtin et al, '14

The Hunt for a Dark Z



Curtin et al, '14

The Hunt for a Dark Z: PVES



Davoudiasl, Lee, Marciano '14

Dark Z: Mechanism

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

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

Dark Z: Mechanism

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

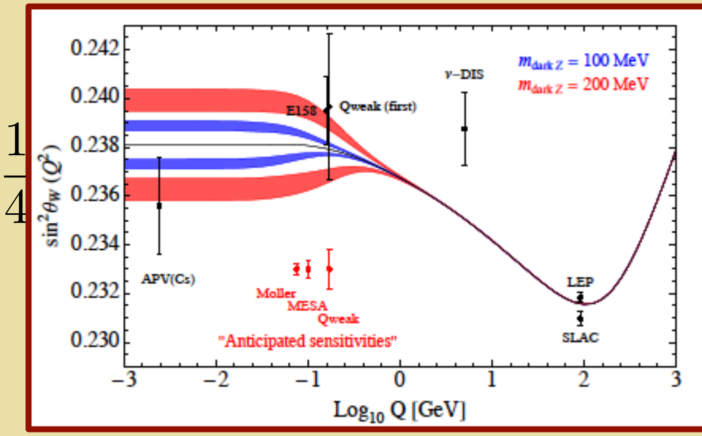
Kinetic Mixing *Mass Mixing*

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

Higgs Mixing

Dark Z: Mechanism

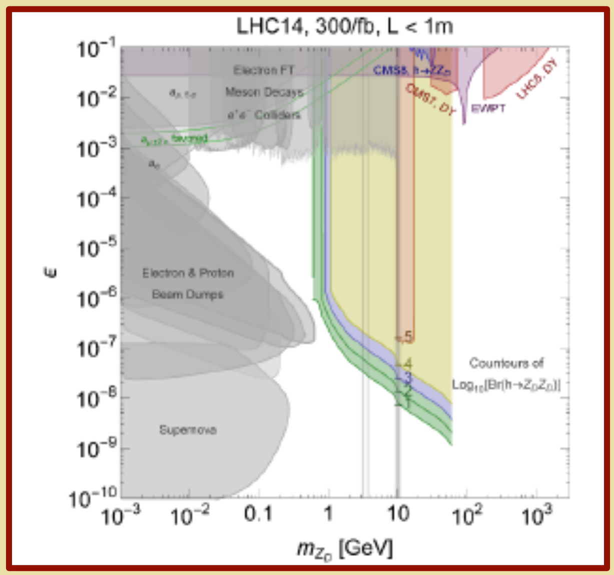
$$\mathcal{L} \subset -\frac{1}{4}\,\hat{B}_{\mu\nu}\,\hat{B}^{\mu\nu} - \frac{1}{4} \cdots + \frac{1}{2}\,m^2_{D,0}\,\hat{Z}^{\mu}_{D}\,\hat{Z}_{D\mu}$$



PVES

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

$h \to Z_D\, Z_D$

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

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

Dirac

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

Majorana

Our analysis:

- *Include backgrounds*
- *Incorporate QCD running*
- *Include long-distance contributions to nuclear matrix elements*

$0\nu\beta\beta$-Decay: TeV Scale LNV

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

Dirac

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

Majorana

Backgrounds:

- *Charge flip*
- *Jet faking electron*

$0\nu\beta\beta$-Decay: TeV Scale LNV

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

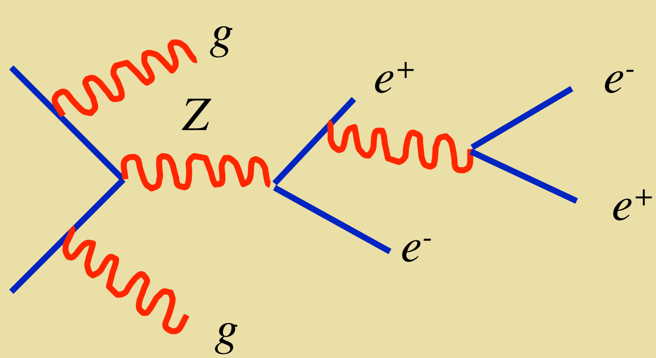
Dirac

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

Majorana

Backgrounds:

- *Charge flip*
- *Jet faking electron*



e^+ transfers most of p_T to conversion e^- ;
Z / γ^* + jets $\rightarrow$ apparent $e^- e^-$ jj event

$0\nu\beta\beta$-Decay: TeV Scale LNV

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

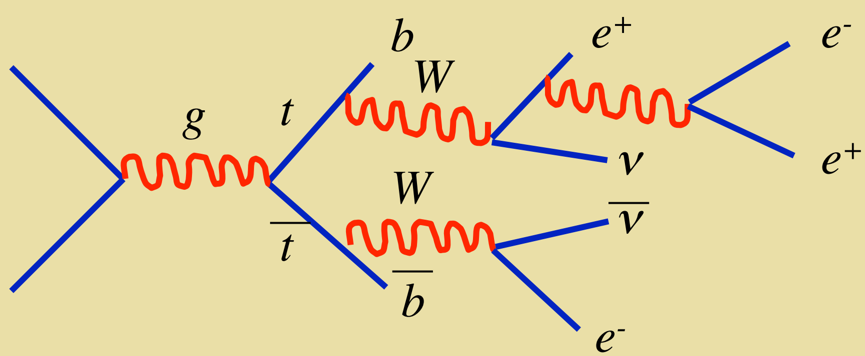
Dirac

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

Majorana

Backgrounds:

- *Charge flip*
- *Jet faking electron*



e^+ transfers most of p_T to conversion e^- ;
b's not tagged $\rightarrow$ apparent e^- e^- jj event

$0\nu\beta\beta$-Decay: TeV Scale LNV

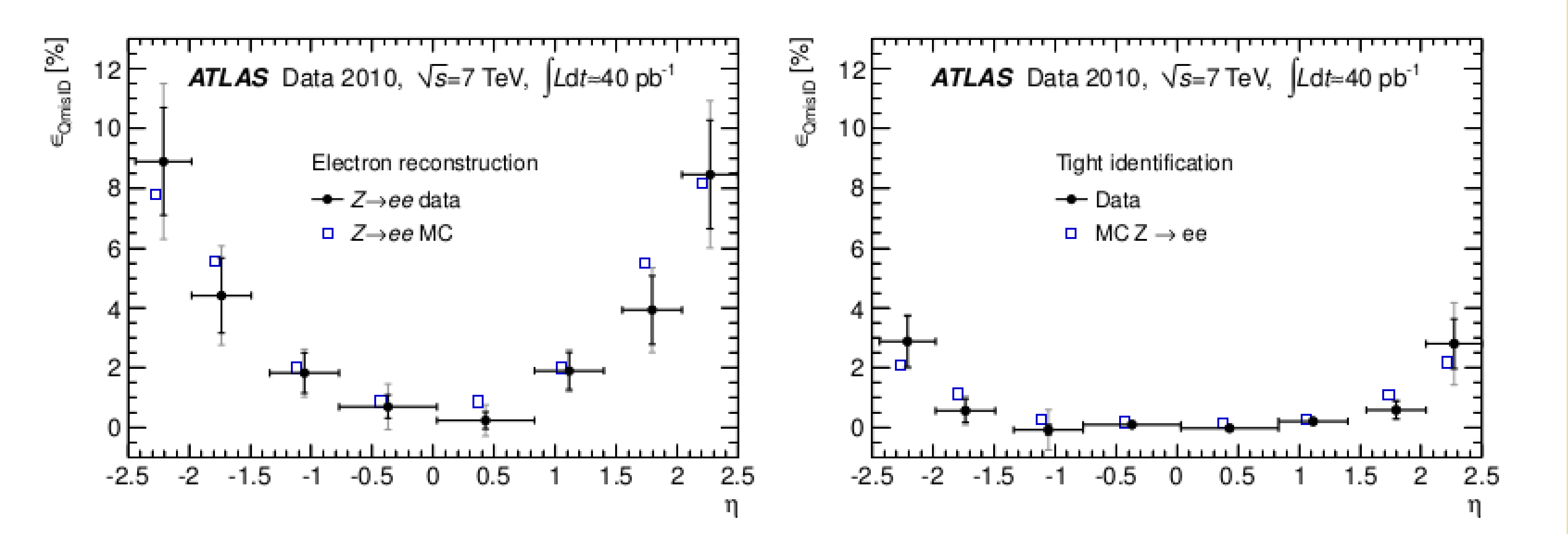
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

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

Majorana

Backgrounds: *Bin in η and apply charge flip prob*



$0\nu\beta\beta$-Decay: TeV Scale LNV

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

Dirac

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

Majorana

Backgrounds: Jet fakes

$$\sigma_{JF} \text{ before cuts} = \sigma_{JF,MG+Pythia+PGS} \times (1/5000 \times 1/2)^{\#\text{ of jet-fakes}} \times \begin{pmatrix} \#\text{ of jets} \\ \#\text{ of jet-fakes} \end{pmatrix}$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

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

Dirac

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

Majorana

Backgrounds: *Cuts*

- H_T
- *MET*
- M_{ll}

$0\nu\beta\beta$-Decay: TeV Scale LNV

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

Dirac

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

Majorana

Backgrounds: *Cuts*

σ(fb)	Signal	Backgrounds									$\frac{S}{\sqrt{S+B}}$ ($\sqrt{\mathrm{fb}}$)
		Diboson			Charge Flip		Jet Fake				
		W^-W^-+2j	W^-Z+2j	ZZ+2j	Z/γ^*+2j	$t\bar{t}$	$t\bar{t}$	$\bar{t}$+3j	W^-+3j	4j	
Before Cuts	0.142	0.541	6.682	0.628	903.16	68.2	6.7	0.45	15.09	362.352	0.0038
Signal Selection	0.091	0.358	4.66	0.435	721.7	28.9	2.37	0.22	11.73	72.03	0.0031
H_T(jets) > 650 GeV	0.054	0.04	0.187	0.015	5.6	0.266	0.025	0.0003	0.102	0.027	0.0213
$m_{\ell_1\ell_2} > 130$ GeV	0.039	0.029	0.105	0.008	0.163	0.127	0.024	3x10^{-4}	0.101	0.027	0.0493
$\not{E}_T < 40$ GeV	0.036	0.005	0.036	0.007	0.126	0.014	0.005	3x10^{-5}	0.03	0.017	0.0684
$(\eta_{j_{1,2}} - \eta_{\ell_{1,2}})_{max} < 2.2$	0.033	0.003	0.022	0.005	0.093	0.009	0.004	2x10^{-5}	0.019	0.011	0.0738

T. Peng, MRM, P. Winslow 1508.04444

0νββ-Decay: TeV Scale LNV

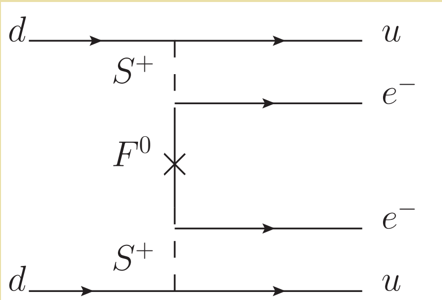
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

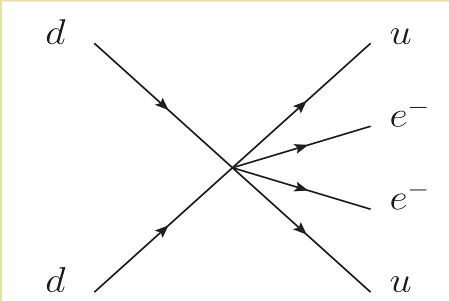
$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

Low energy: *Matching*



Match onto O_{eff} at Λ_{BSM}



0νββ-Decay: TeV Scale LNV

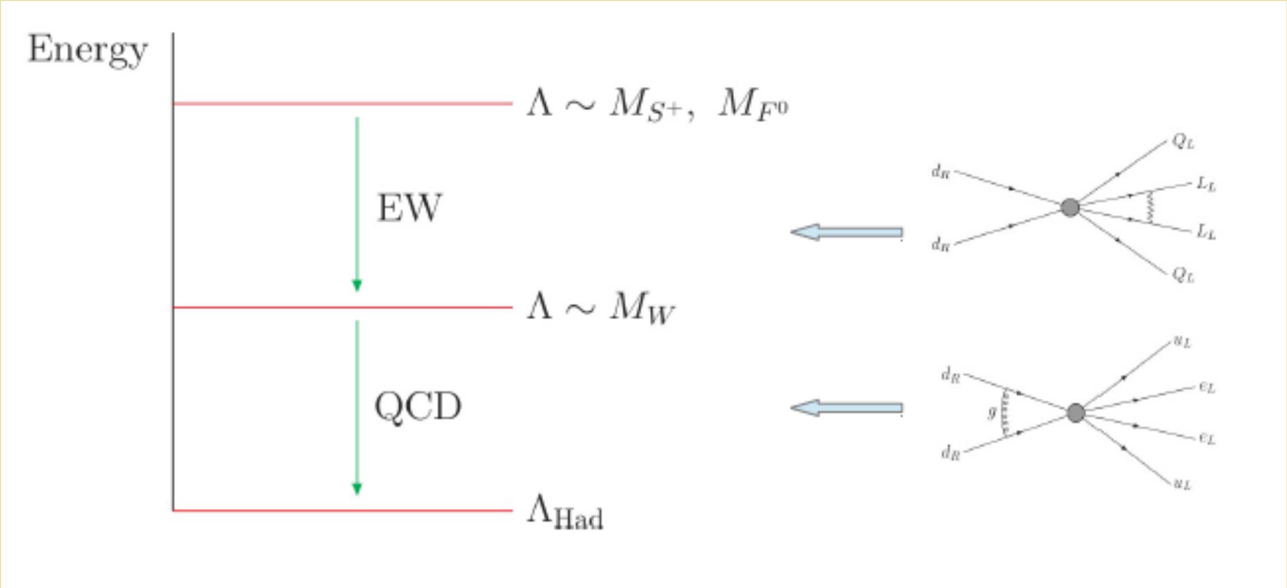
$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

Dirac

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

Majorana

Low energy: *Running*



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

Low energy: *QCD Running*

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

$$\gamma^{ij} = -\frac{\alpha_s}{2\pi}\begin{pmatrix} 8 & 0 & 0 & 1 \\ 0 & -8/3 & 48 & 0 \\ 0 & 2/9 & -1 & 5/12 \\ 32/3 & 0 & 20 & 19/3 \end{pmatrix}$$

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

$$\mu\frac{d}{d\mu}C = \gamma^T C$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

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

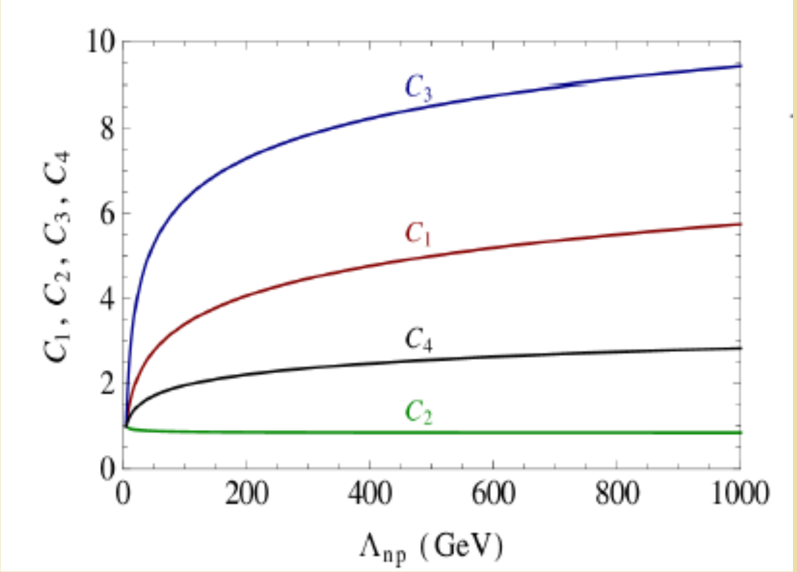
Dirac

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

Majorana

Low energy: *QCD Running*

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



Assuming C_k = 1 at μ = 5 GeV $\rightarrow$ Effective DBD amplitude for $\mathcal{O}_1$ substantially weaker for given LHC constraints

$0\nu\beta\beta$-Decay: TeV Scale LNV

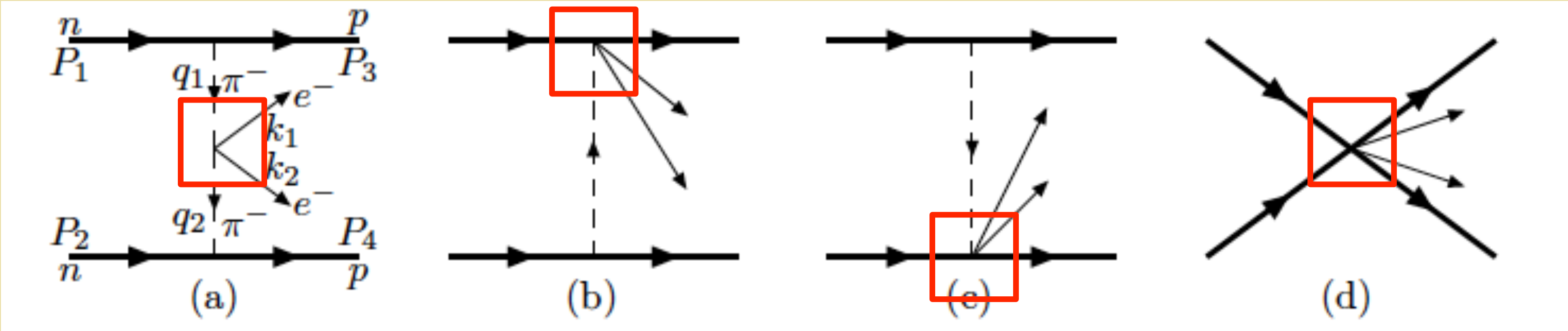
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

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

Majorana

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



Exploit Chiral Symmetry & EFT ideas

$0\nu\beta\beta$-Decay: TeV Scale LNV

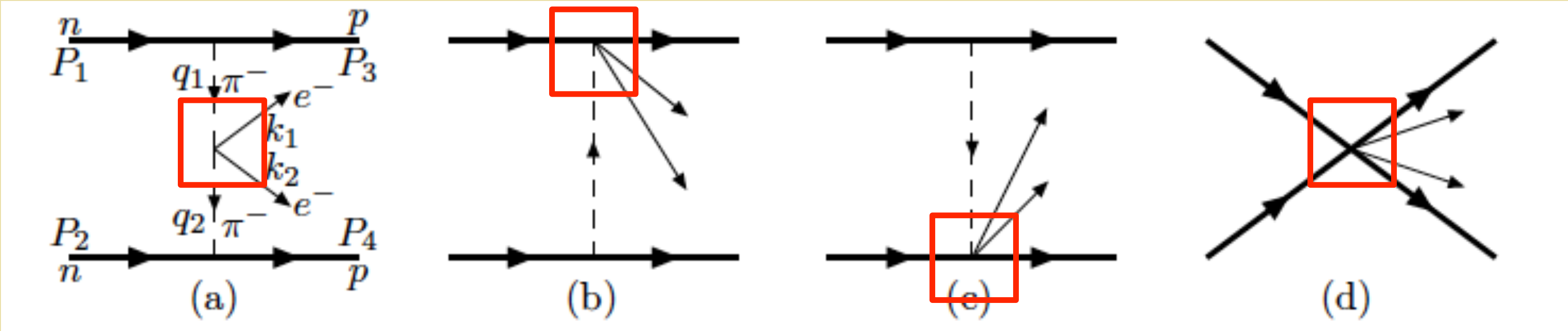
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

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

Majorana

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



Our work *Helo et al*

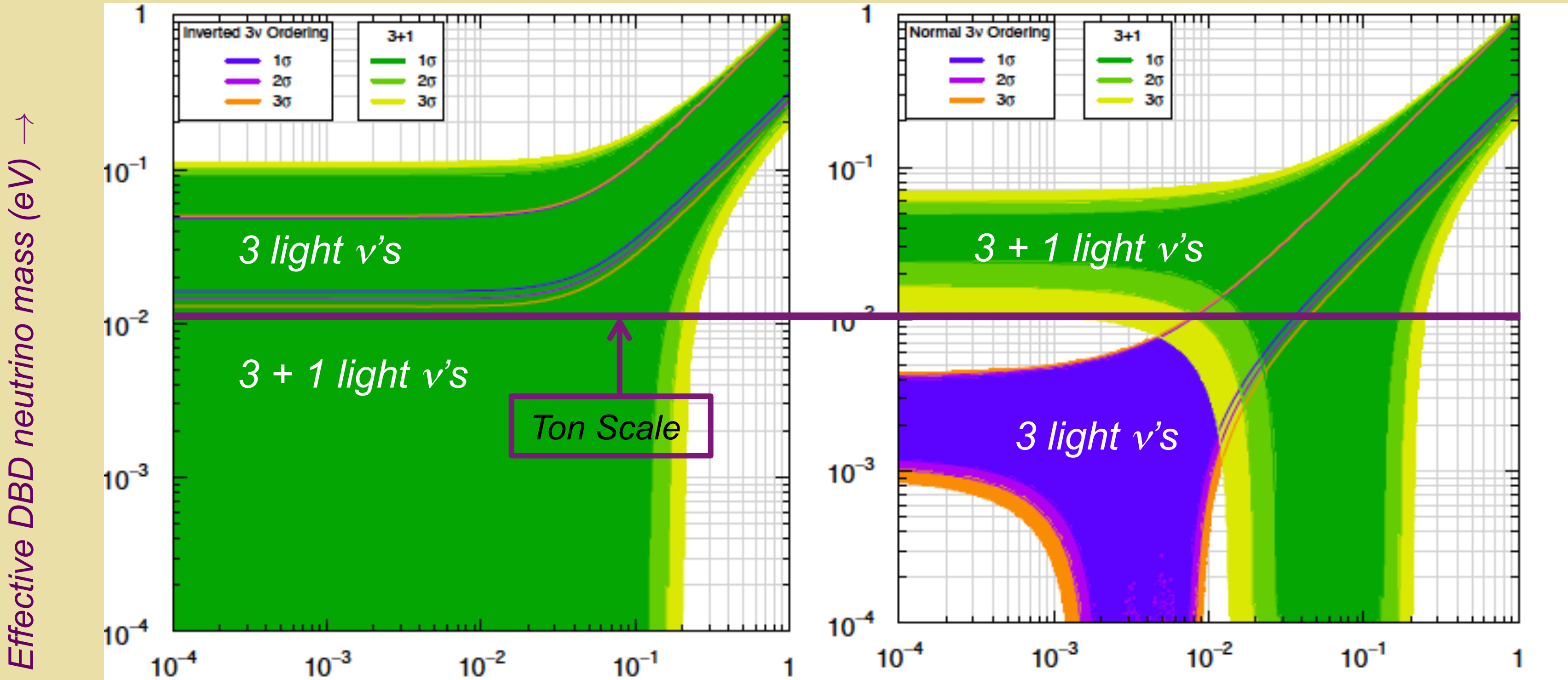
Exploit Chiral Symmetry & EFT ideas

Why Might A "Ton-Scale" Exp't See It?

$A(Z,N) \rightarrow$ 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

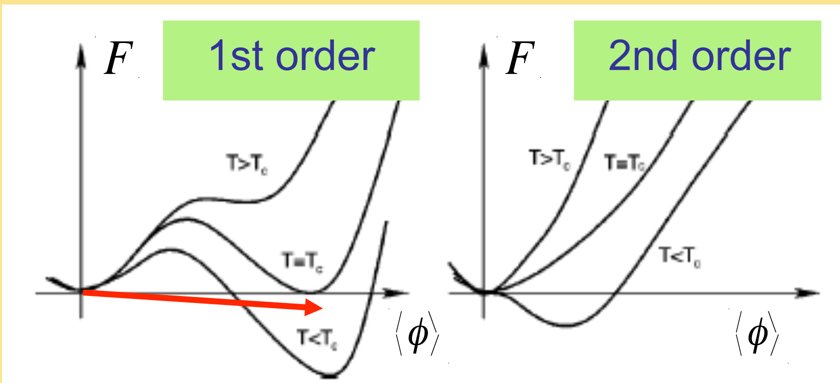
Why Might A "Ton-Scale" Exp't See It?



Lightest neutrino mass (eV) →

EWPT

EW Phase Transition: St'd Model



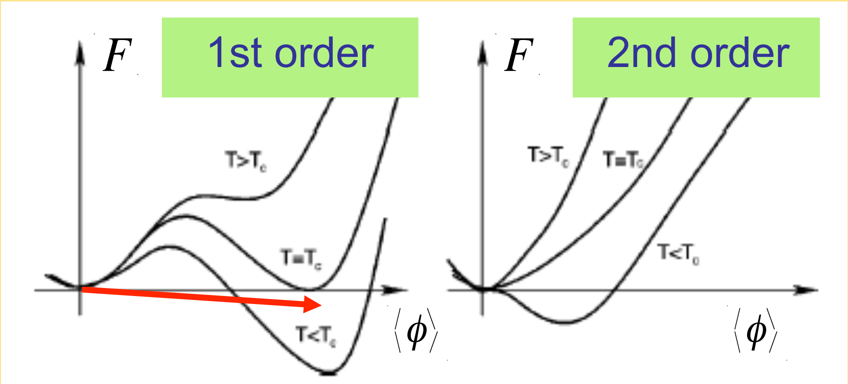
Increasing m_h →

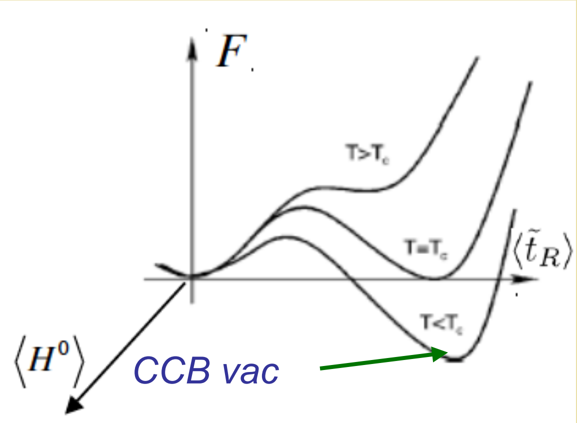
Lattice: Endpoint

Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

S'td Model: 1st order EWPT requires light Higgs

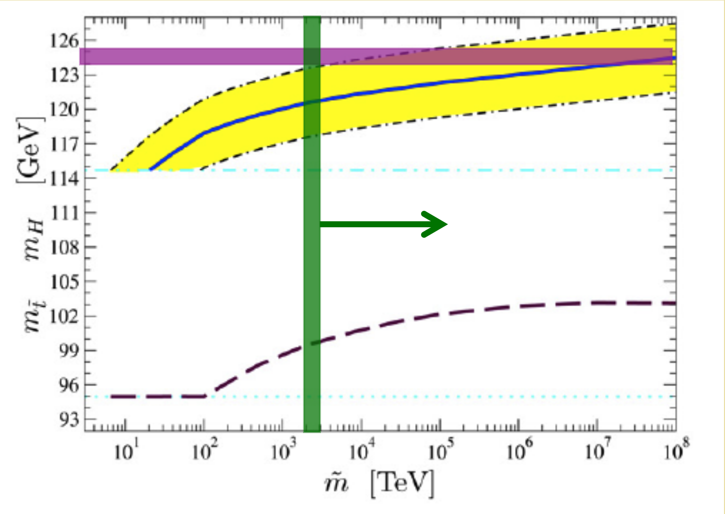
EW Phase Transition: MSSM





Increasing m_h →

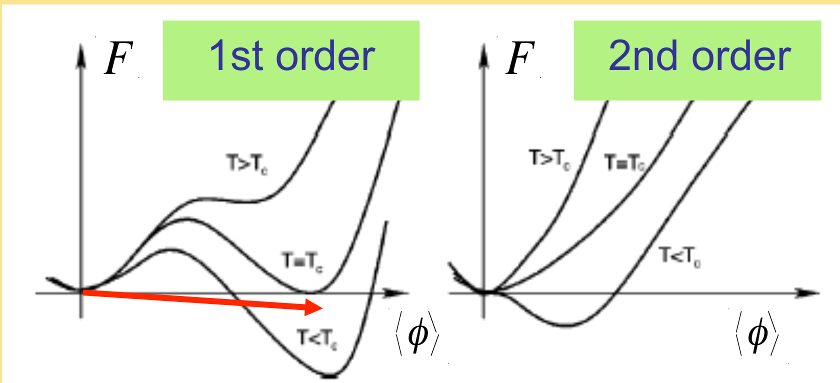
← *New scalars*



MSSM: Light RH stops

Carena et al 2008: Higgs phase metastable

EW Phase Transition: MSSM



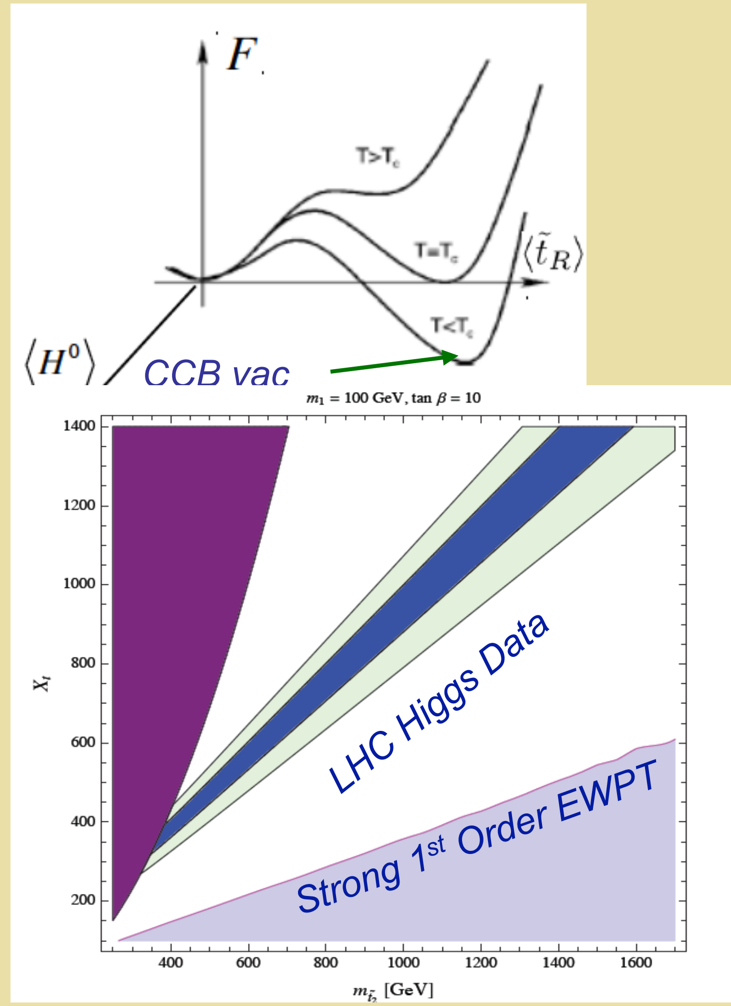
Increasing m_h →

← New scalars

MSSM: Light RH stops

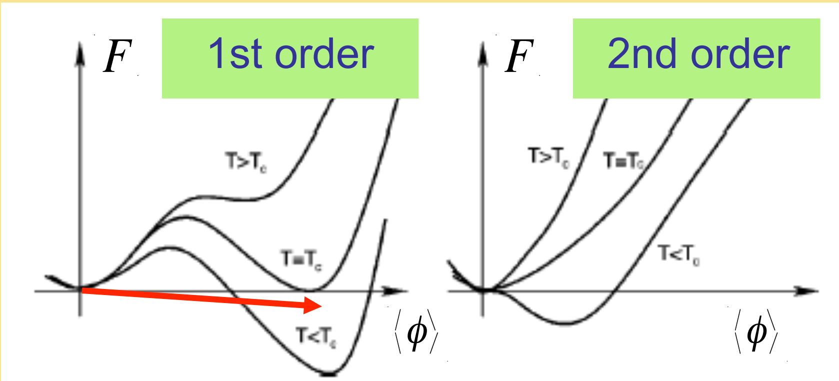
Inconsistent w/ Higgs data:

Curtin et al ‘12, Katz et al ‘15



Katz, Perelstein, R-M, Winslow 1509.02934

EW Phase Transition: Higgs Portal

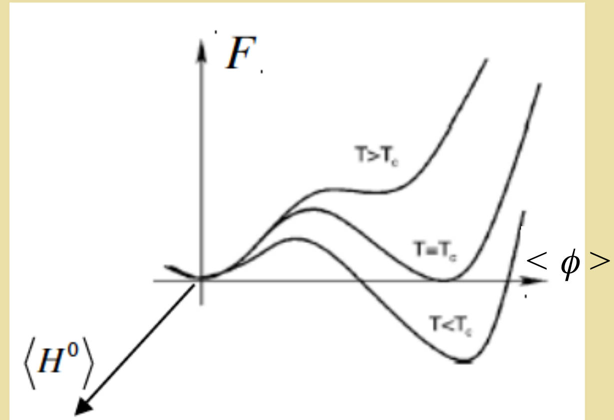


Increasing m_h →

← *New scalars*

$$\mathcal{O}_4 = \lambda_{\phi H}\ \phi^\dagger \phi\ H^\dagger H$$

+…



- *Renormalizable*
- *ϕ : singlet or charged under $SU(2)_L$ x $U(1)_Y$*
- *Generic features of full theory (NMSSM, GUTS…)*
- *More robust vacuum stability*
- *Novel patterns of SSB*

Precision Tests

Electron Scattering

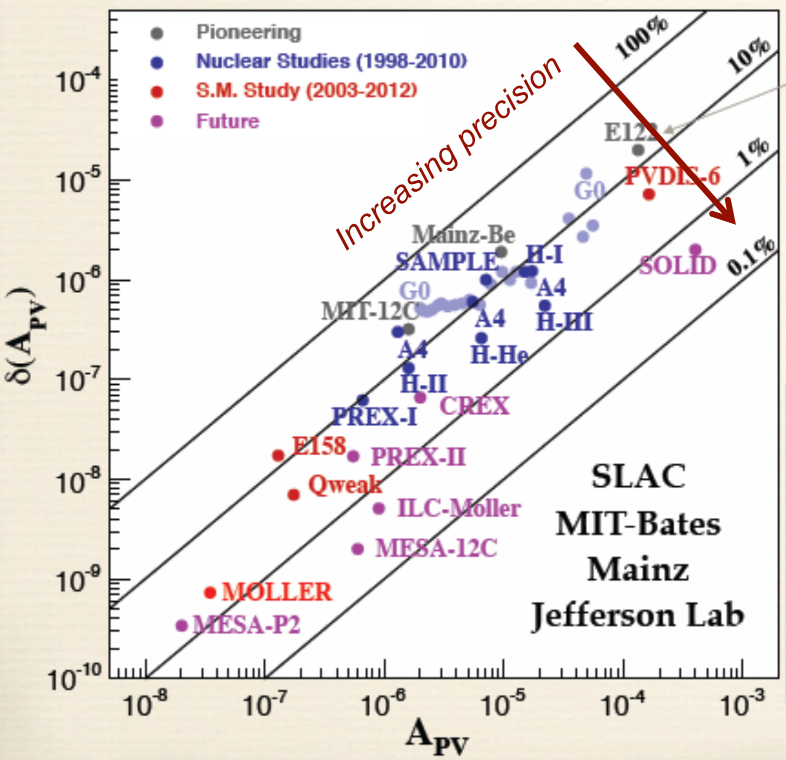
Continuous interplay between probing hadron structure and electroweak physics

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



Pioneering electron-quark PV DIS experiment SLAC E122

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

Electron Scattering

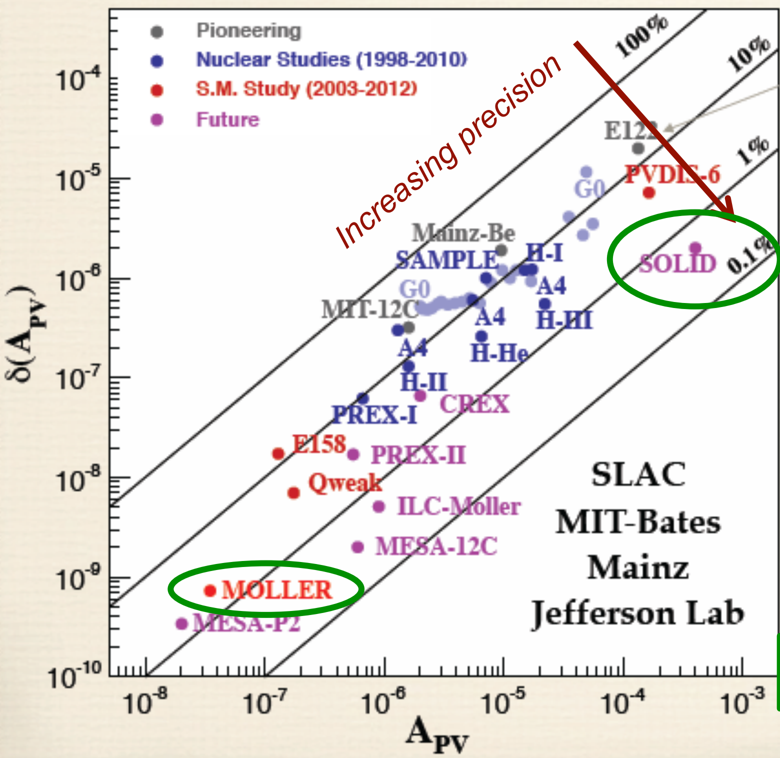
Continuous interplay between probing hadron structure and electroweak physics

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



Pioneering electron-quark PV DIS experiment SLAC E122

State-of-the-art:

- *sub-part per billion statistical reach and systematic control*
- *sub-1% normalization control*

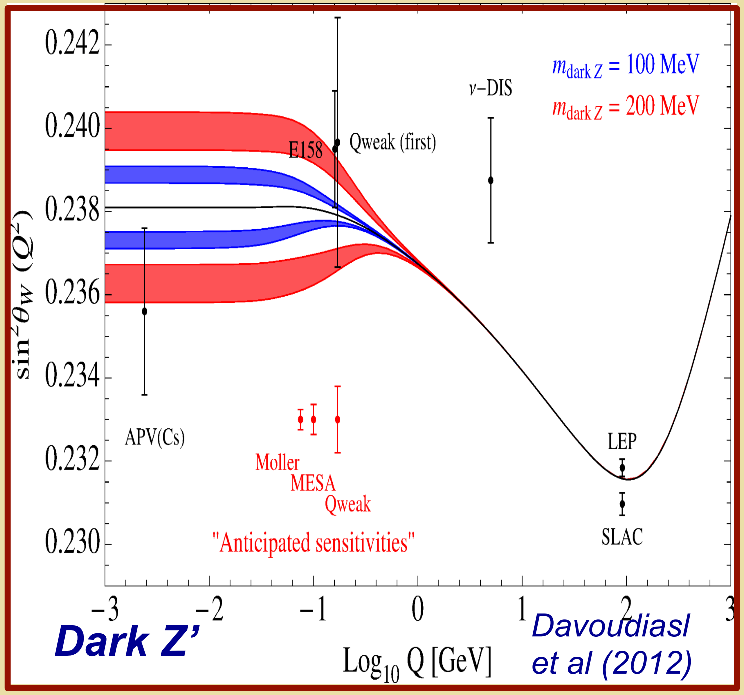
Physics Topics

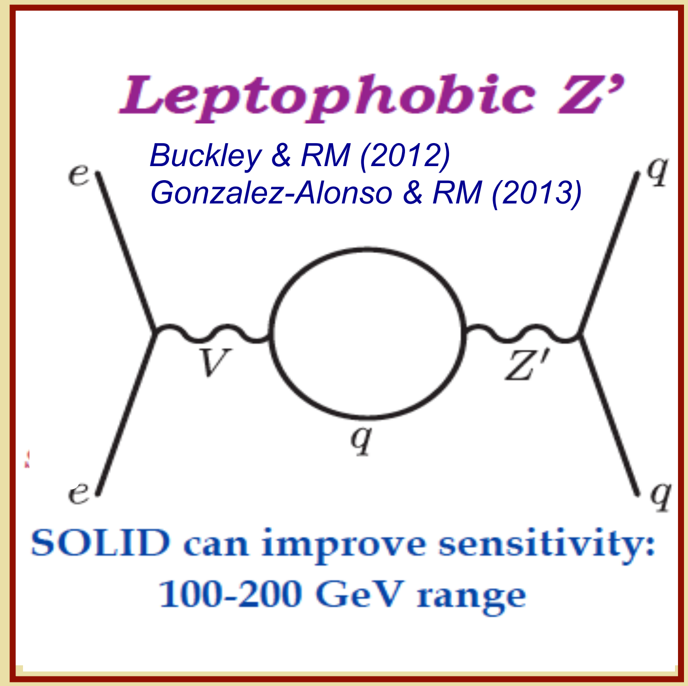
- *Strange Quark Form Factors*
- *Neutron skin of a heavy nucleus*
- *Indirect Searches for New Interactions*
- *Novel Probes of Nucleon Structure*
- *Electroweak Structure Functions at the EIC*
- *Charge Lepton Flavor Violation at the EIC*

K. Kumar

Electron Scattering

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





MOLLER: PV ee

SoLID & EIC: PV eD