Fundamental Symmetries: The Low & High Energy Interface

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

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

Collaborators:, Chien-Yi Chen, Haolin Li, Tao Peng, Peter Winslow

PANIC, Beijing
September 2017

Key Theme for This Talk

- *Fundamental questions motivate the search for physics beyond the Standard Model*
- *Tests of fundamental symmetries at low- and high-energies are poised to*
  - *discover the BSM physics that answers several of these questions*
  - *determine its character*

Outline

I. The BSM Context

II. Lepton Number ←

III. CP (Flavor Conserving)

IV. Outlook

For another day: Parity, CPT, Charged Lepton Flavor, Baryon Number, Dark Photons…

I. The BSM Context

Fundamental Questions

MUST *answer*

SHOULD *answer*

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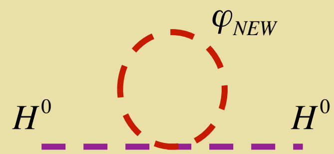
MUST *answer*

SHOULD *answer*

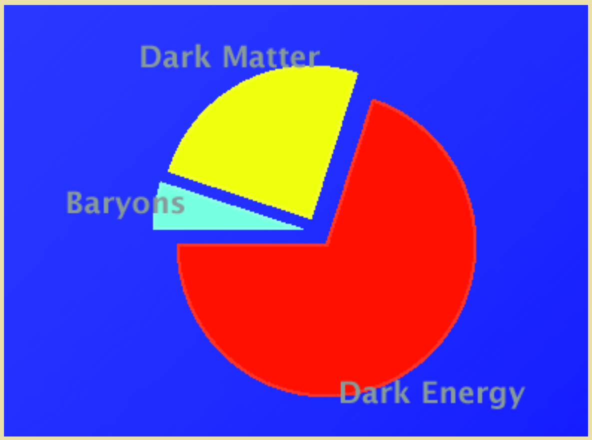


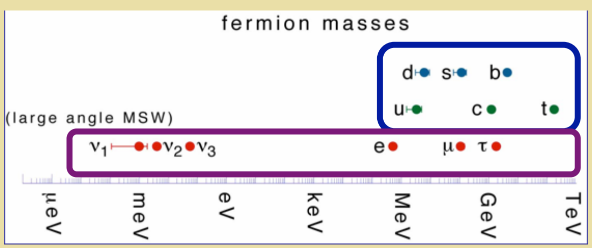
$\Delta m^2 \sim \lambda \Lambda^2$

$$\Lambda_{Cosmological}$$

Fundamental Questions

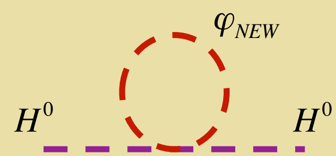
MUST *answer*





Origin of m_ν

SHOULD *answer*



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BSM Physics: Where Does it Live ?

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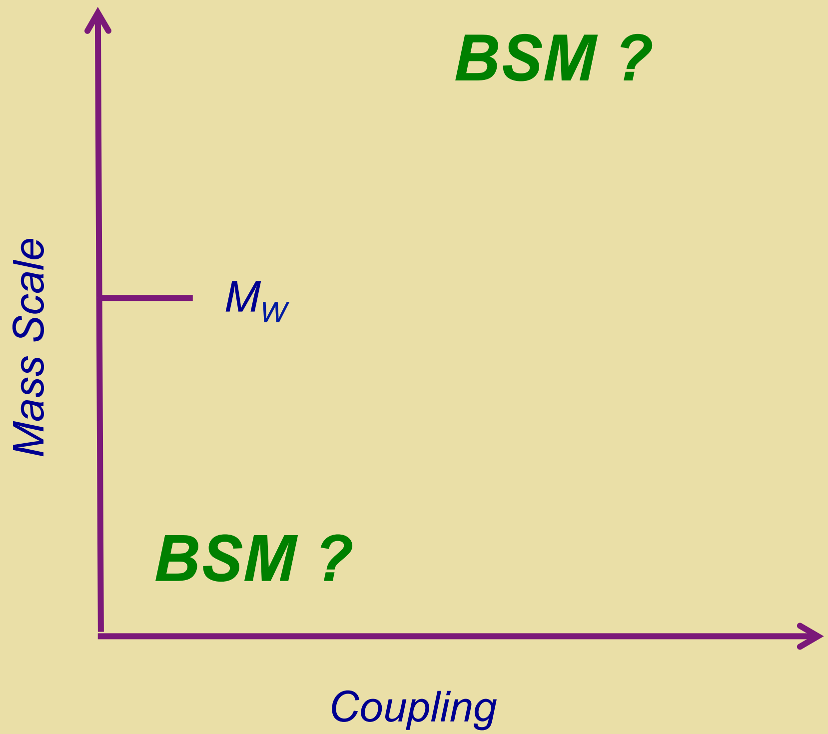

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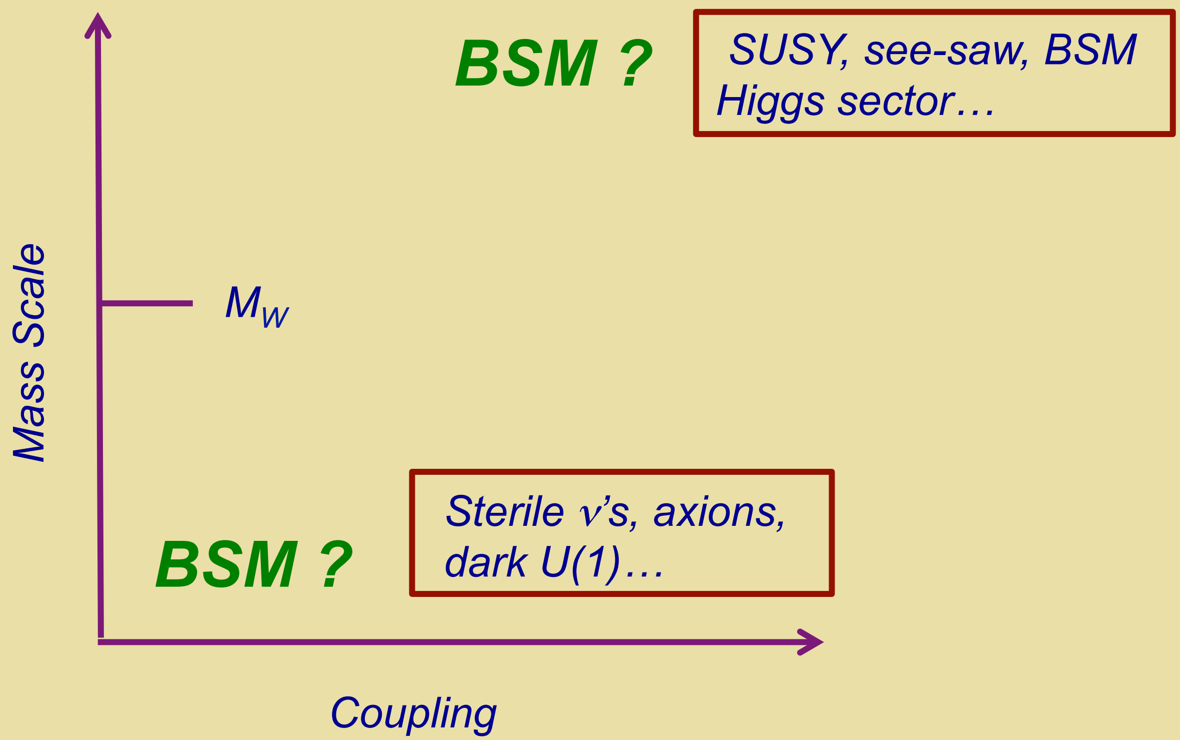

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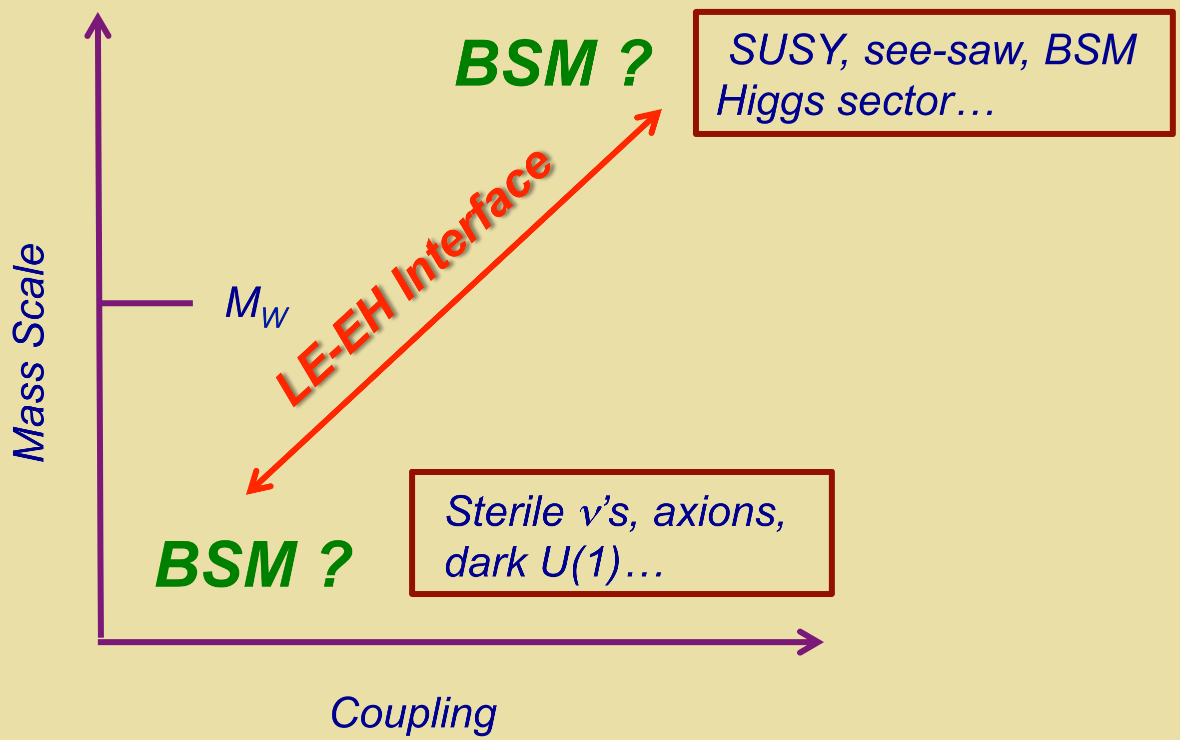


Low-Energy / High-Energy Interplay

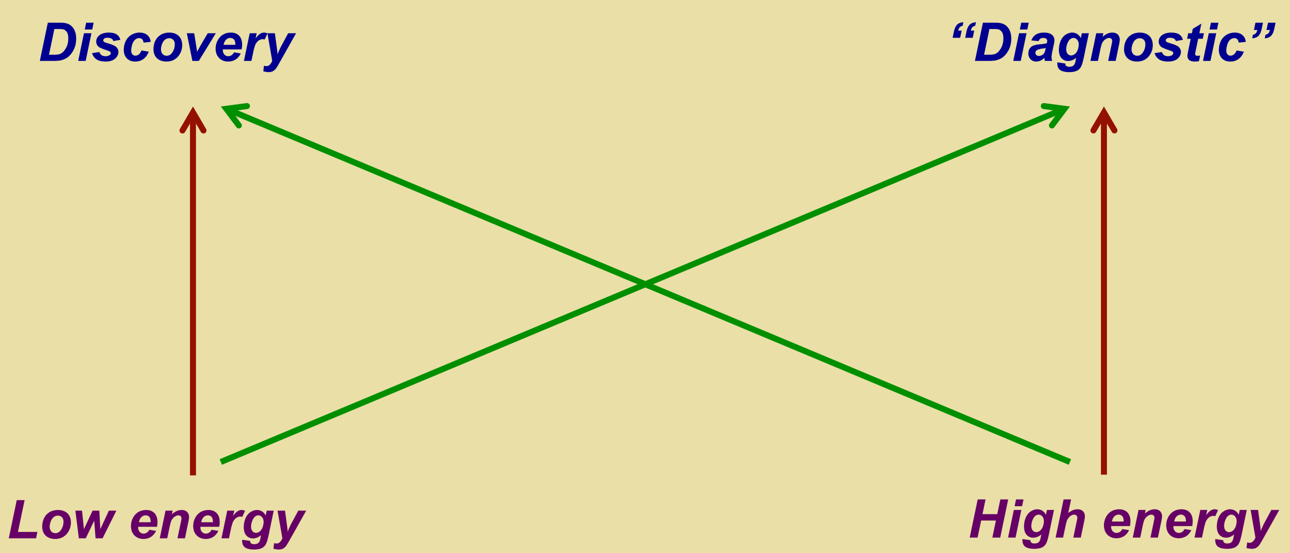
Discovery

Low energy

"Diagnostic"

High energy

Low-Energy / High-Energy Interplay



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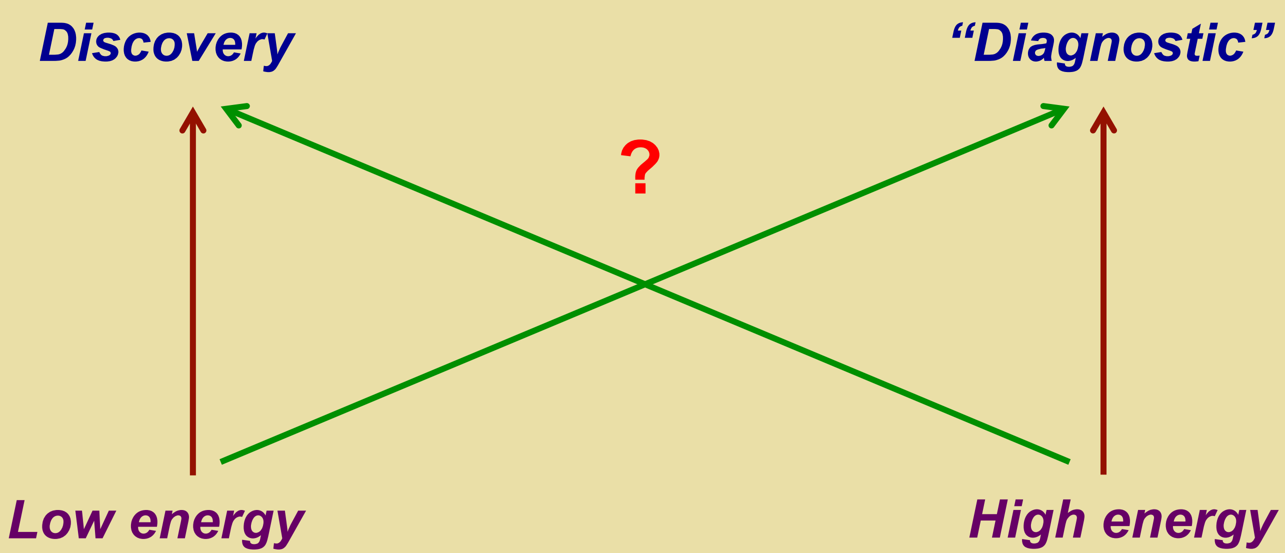

II. Lepton Number

Lepton Number: ν 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

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

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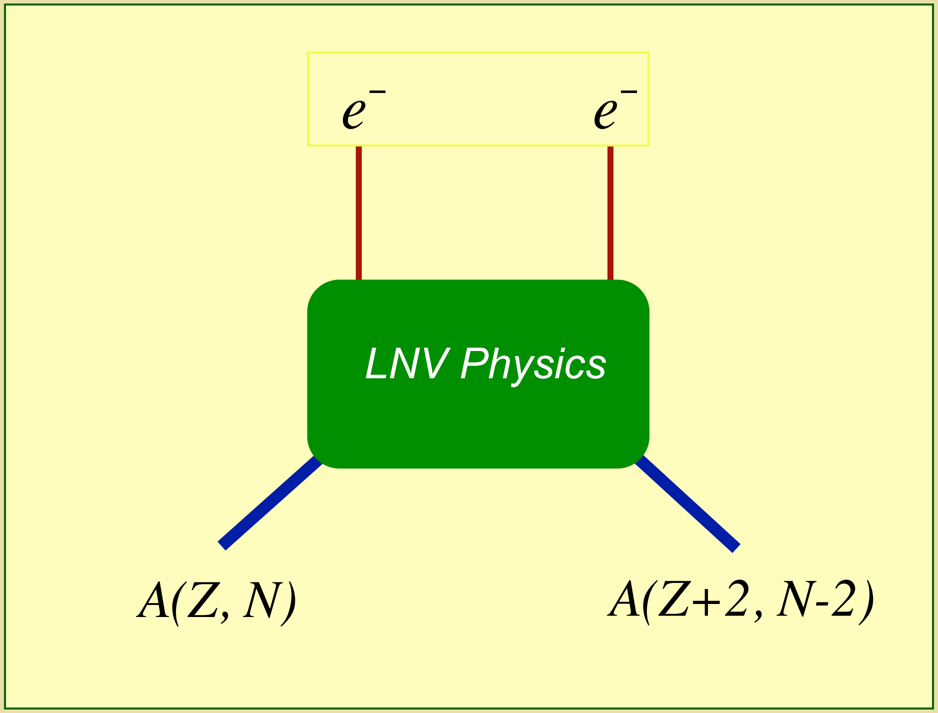

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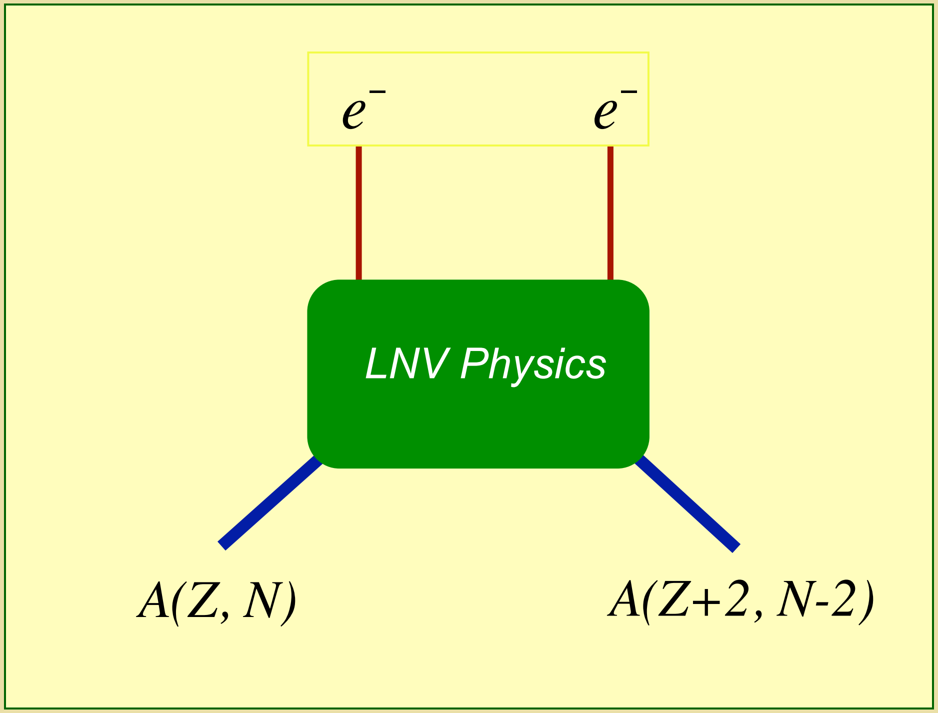
Impact of observation

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

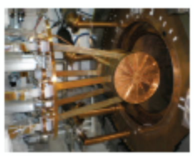


Ton Scale Experiments: Worldwide Quest

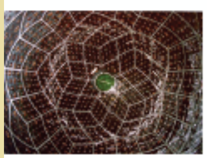
$0\nu\beta\beta$ decay Experiments - Efforts Underway

CUORE

EXO200



KamLAND Zen



Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT	Xe-136	High pressure Xe TPC	**100 kg - ton**	R&D
PandaX - 1k	Xe-136	High pressure Xe TPC	**~ ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

GERDA

MAJORANA

SNO+

The U.S. Context

NSAC Long Range Plan

RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

The Chinese Context

PandaX III

See X. Ji Talk 09/05

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

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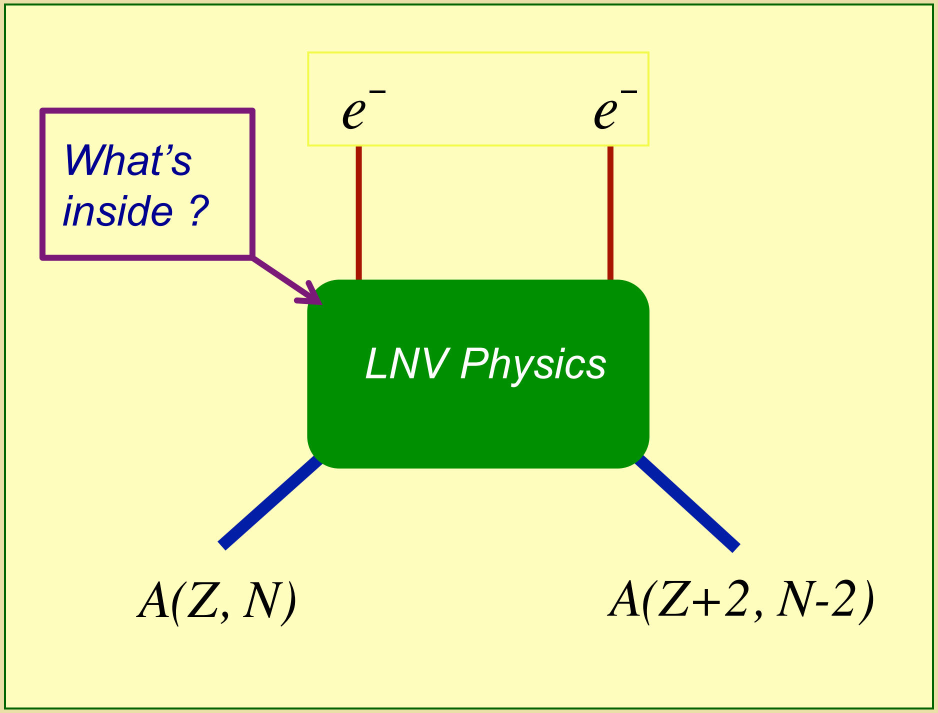
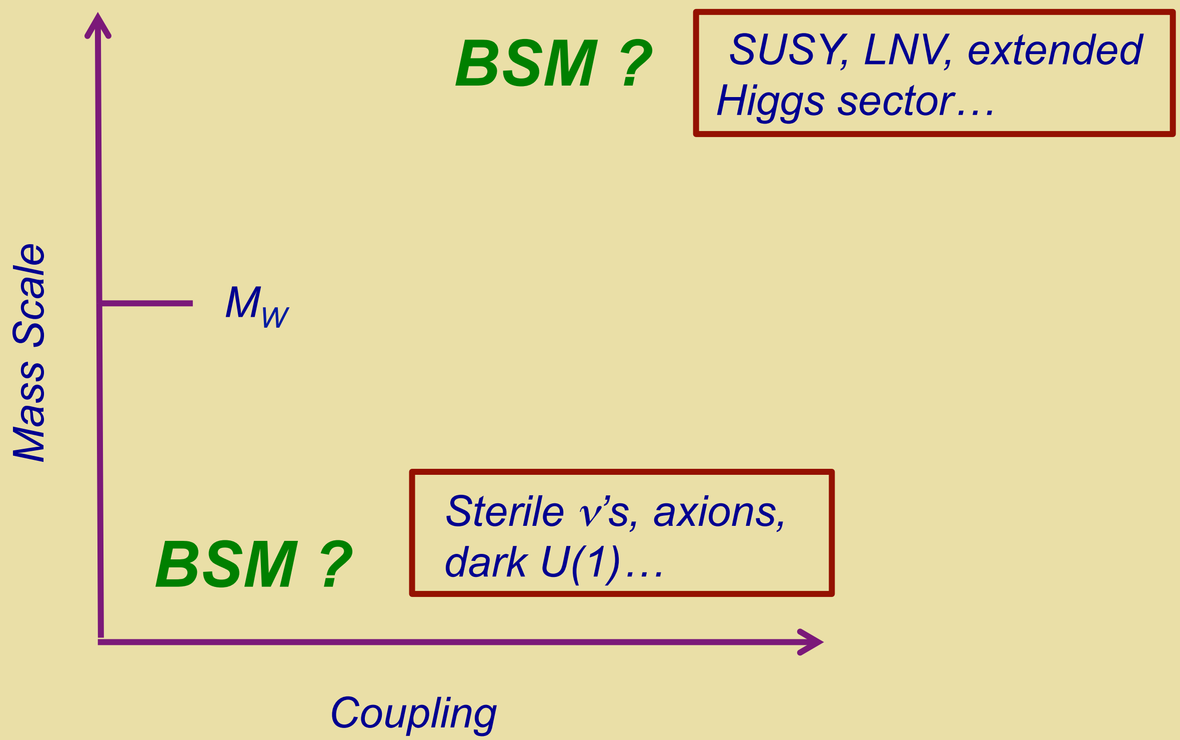


BSM Physics: Where Does it Live ?



Is the mass scale associated with m_ν far above M_W ? Near M_W ? Well below M_W ?

LNV Mass Scale & $0\nu\beta\beta$-Decay

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*

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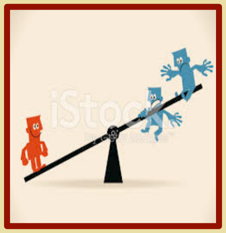

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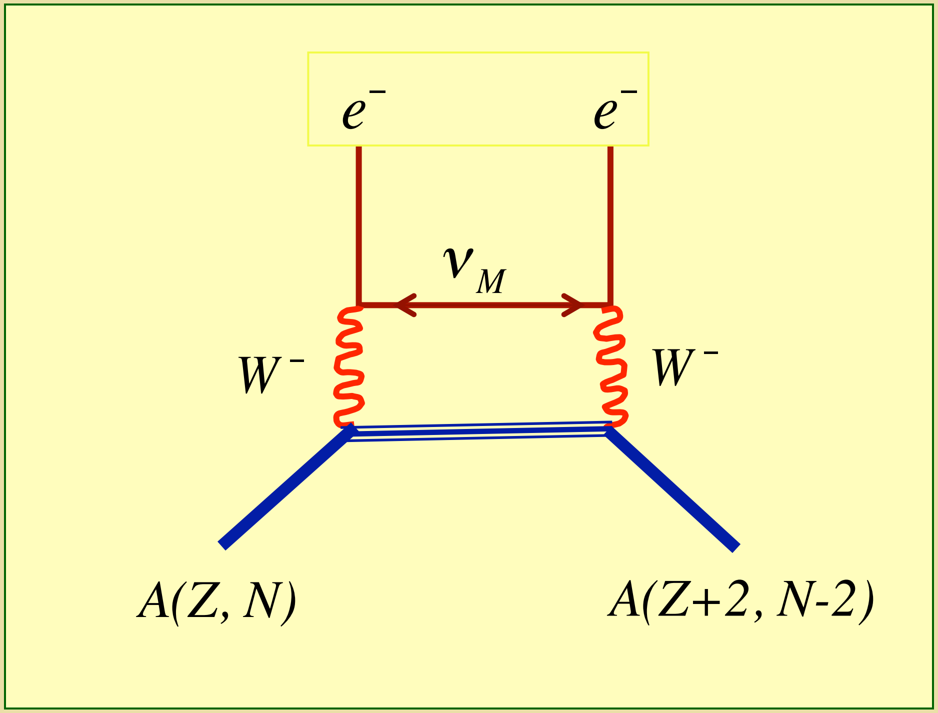
Majorana

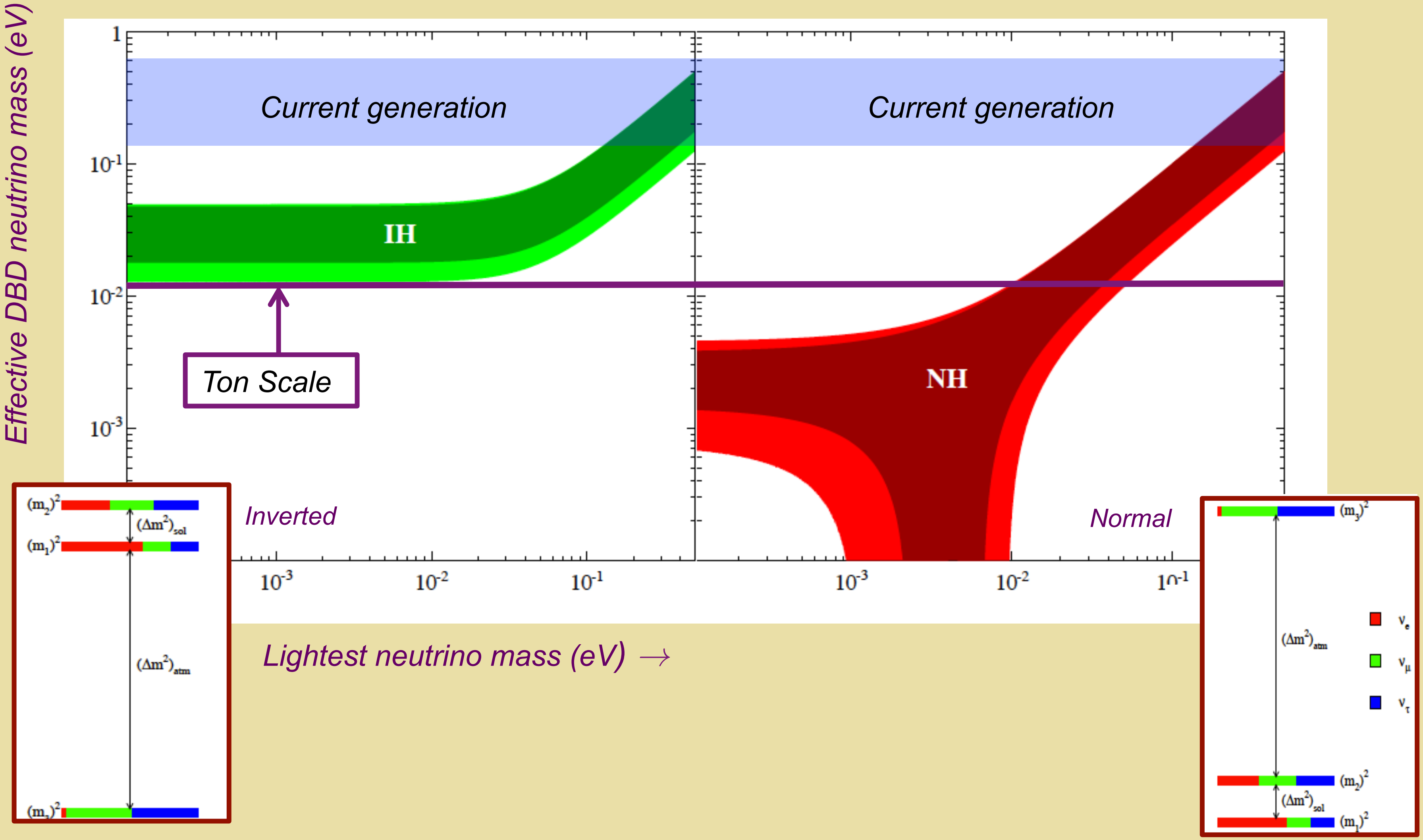
"Standard" Mechanism

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



High Scale LNV

Three active light neutrinos



High Scale LNV

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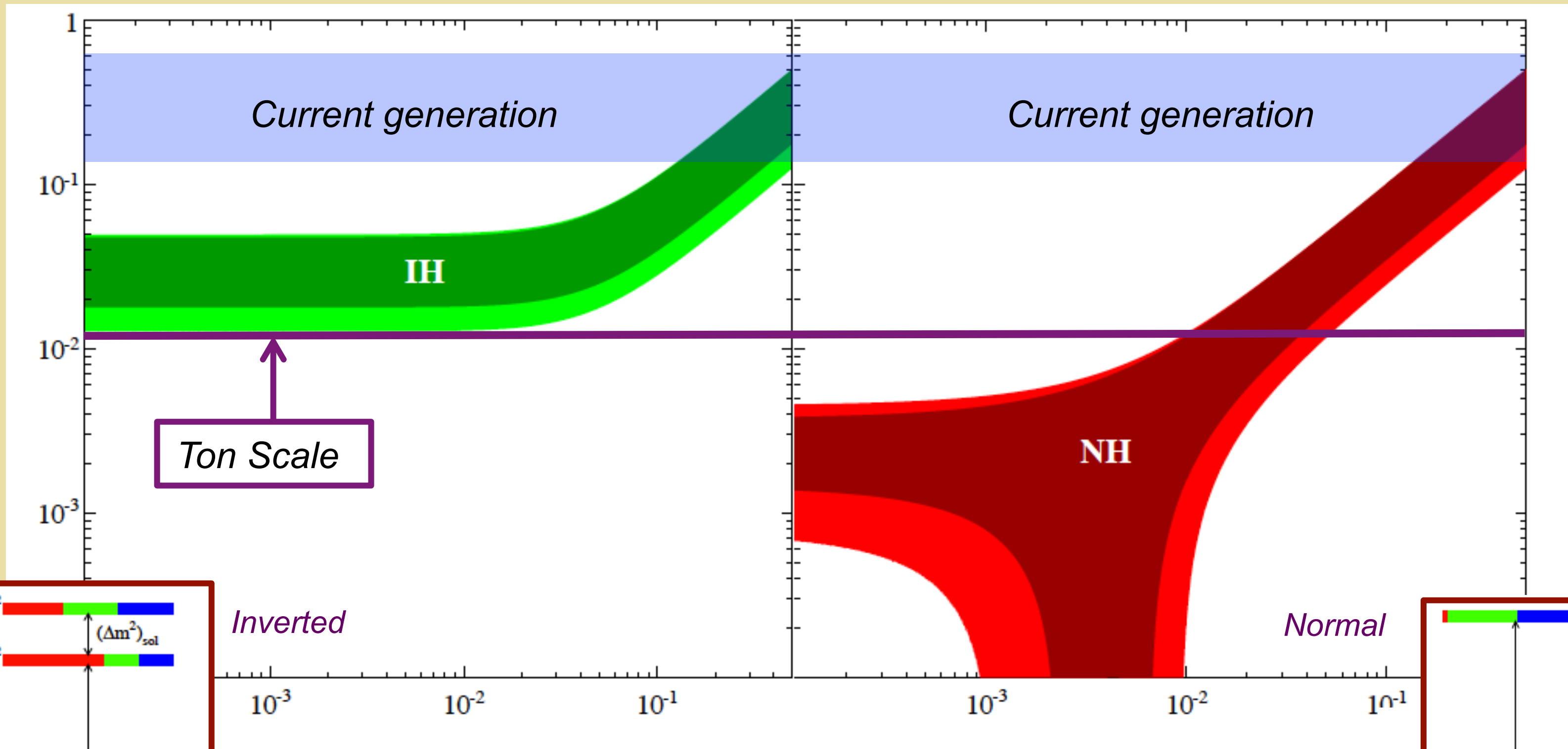
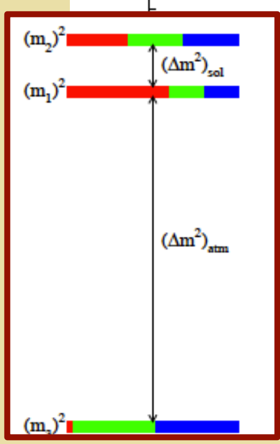
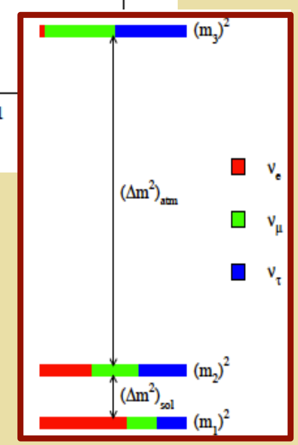
Effective DBD neutrino mass (eV)





Lightest neutrino mass (eV) →



Back up slides: interplay with other experiments

LNV Mass Scale & 0νββ-Decay

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Two parameters: Effective coupling & effective heavy particle mass

0νββ-Decay: LNV? Mass Term?

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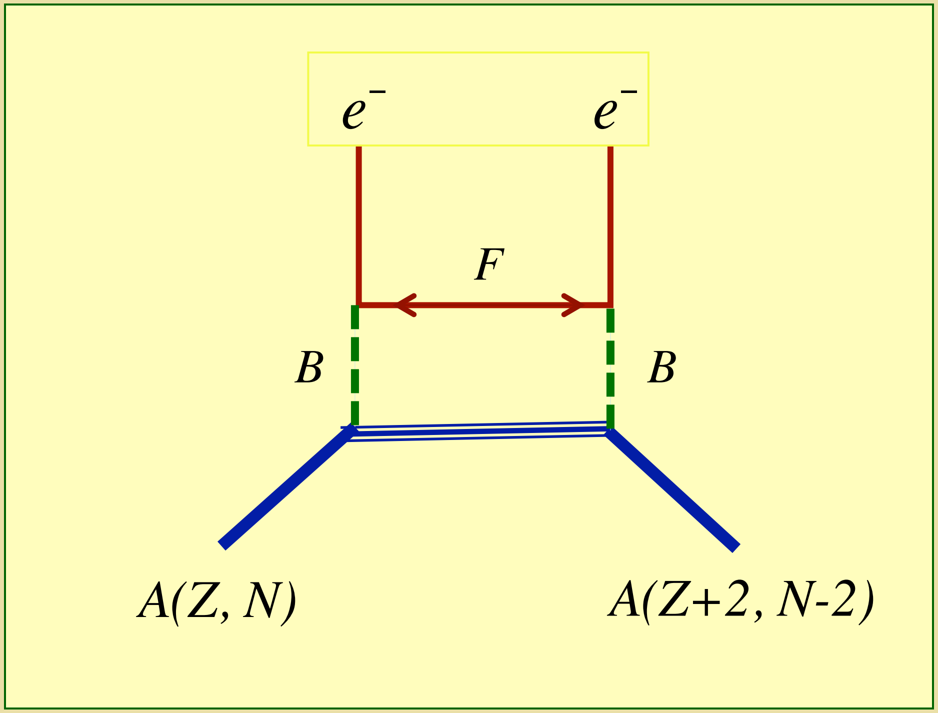
Majorana

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*



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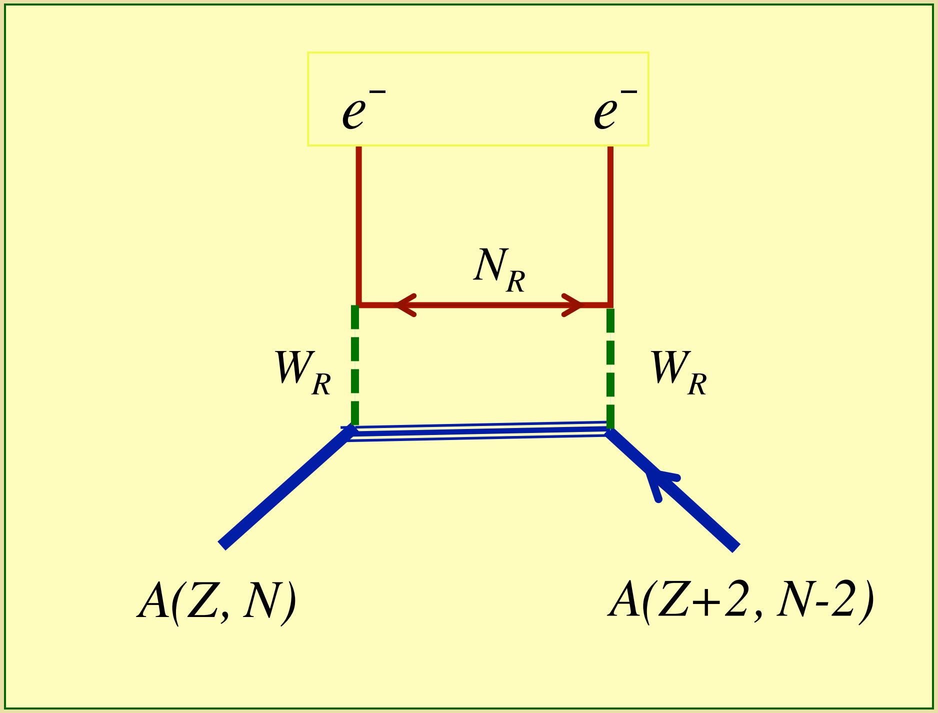

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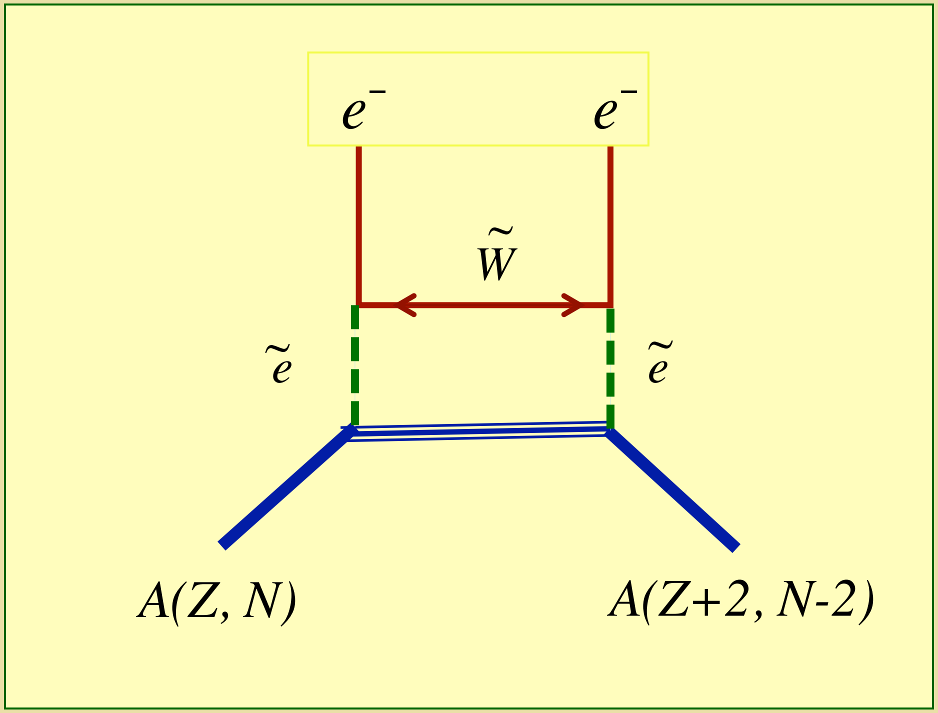

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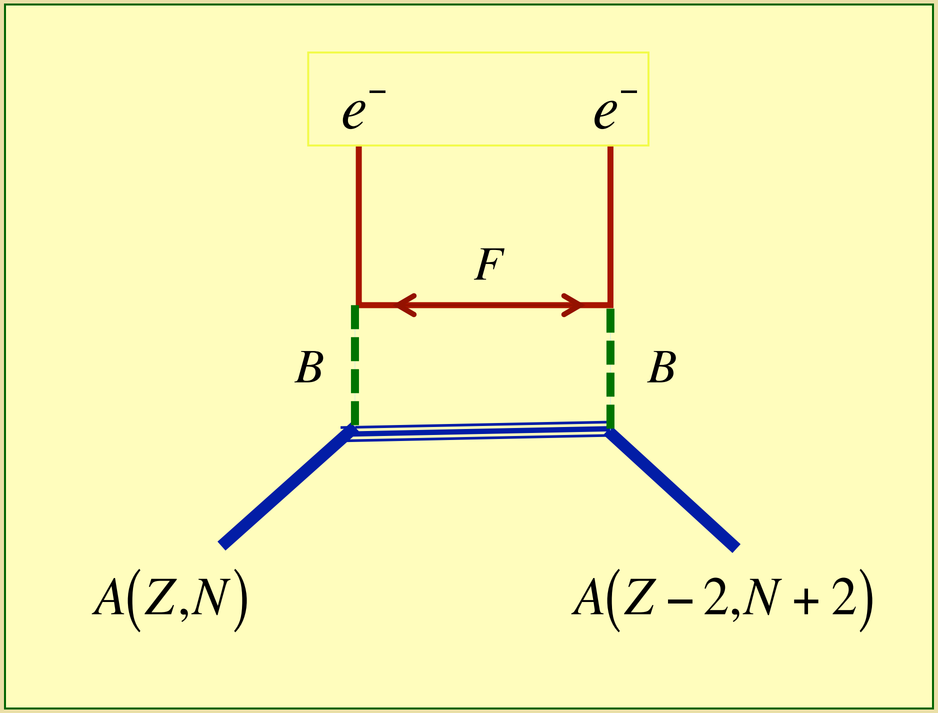
TeV LNV Mechanism

$$\boxed{\frac{A_H}{A_L} \sim \frac{M_W^4 \bar{k}^2}{\Lambda^5 m_{\beta\beta}}}$$

O(1) for Λ ~ 1 TeV



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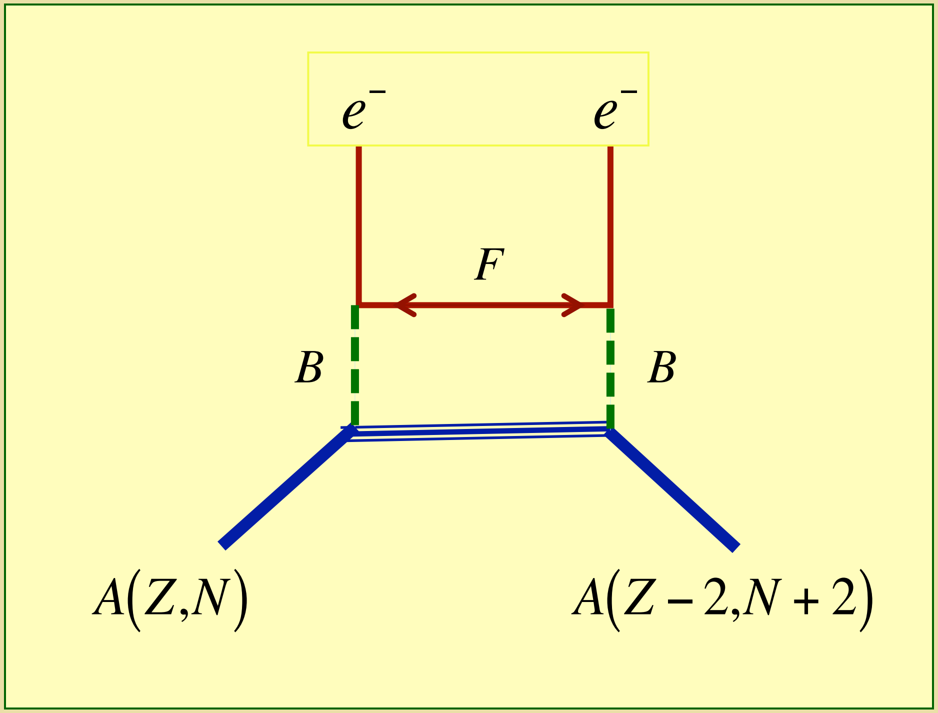
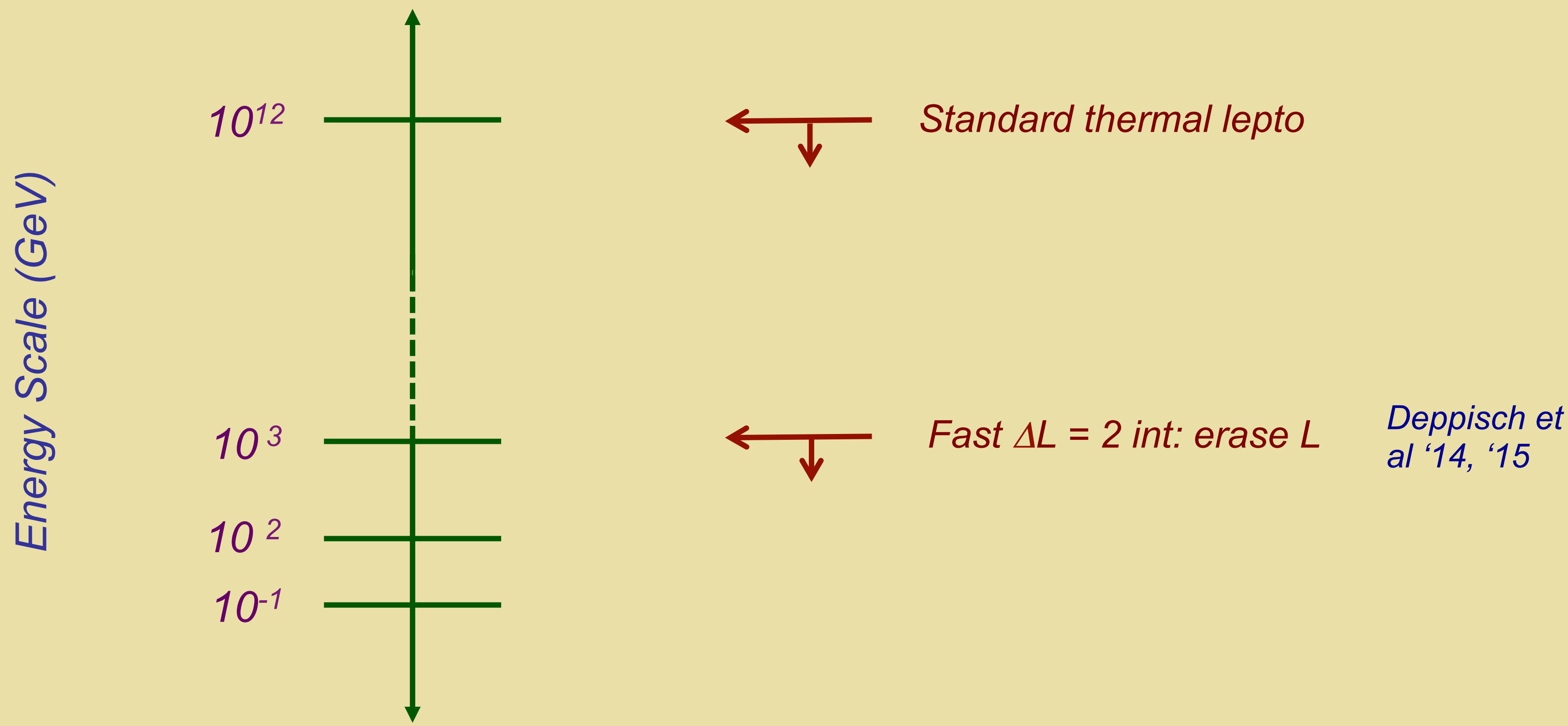
Implications



TeV LNV & Leptogenesis



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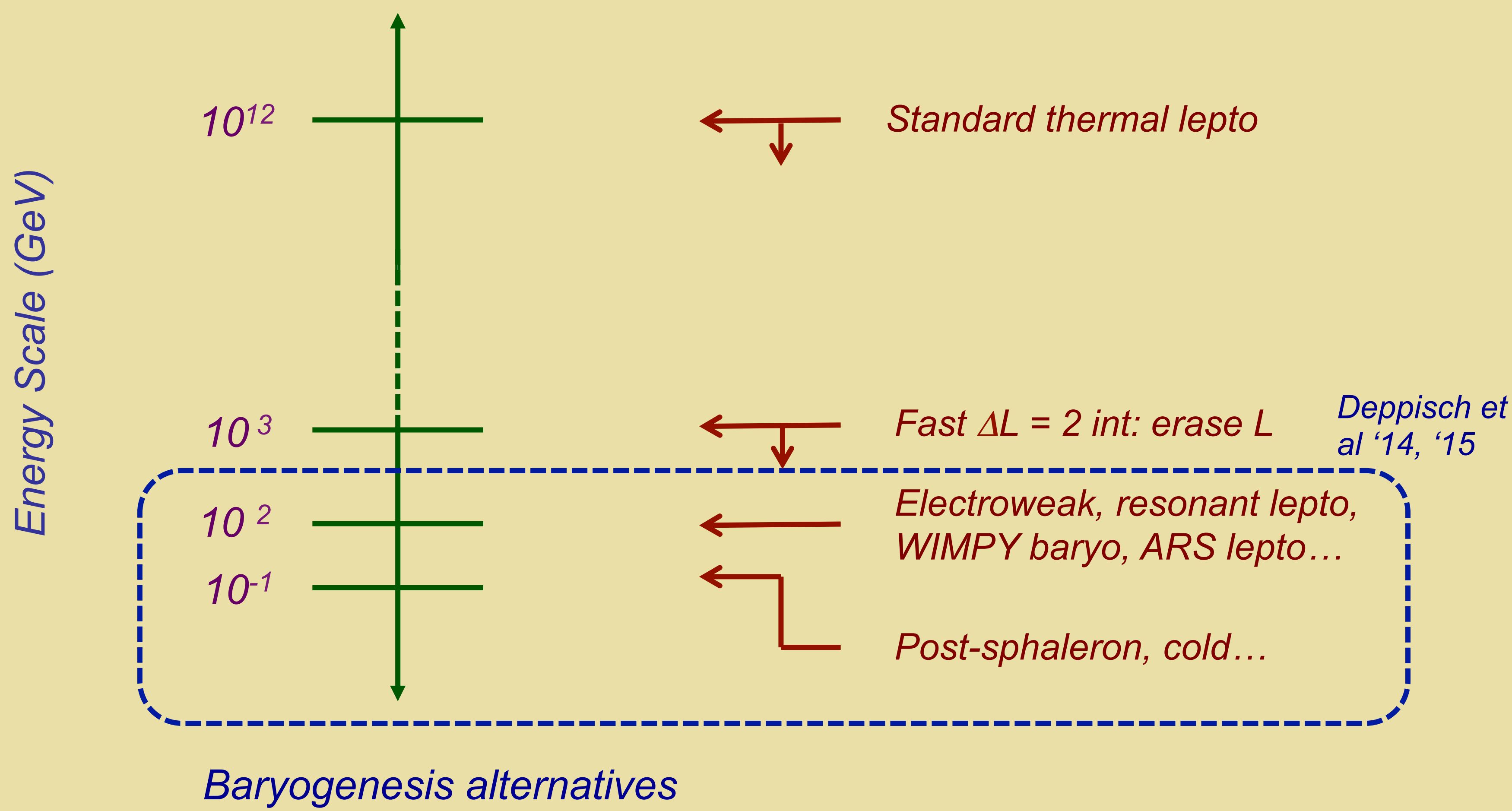

$0\nu\beta\beta$-Decay: TeV Scale LNV

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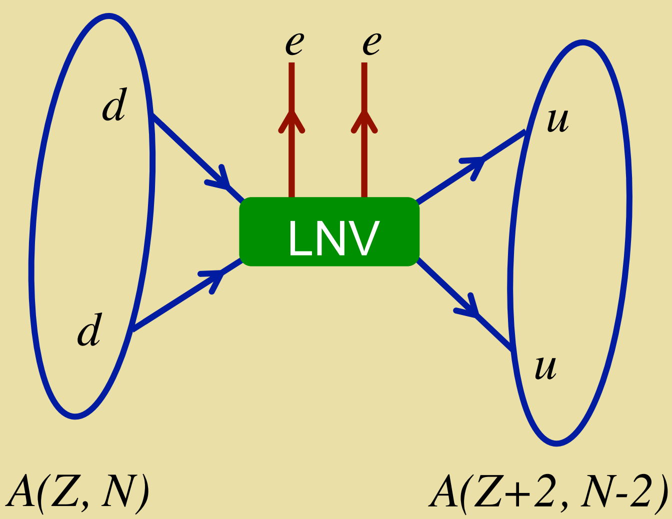
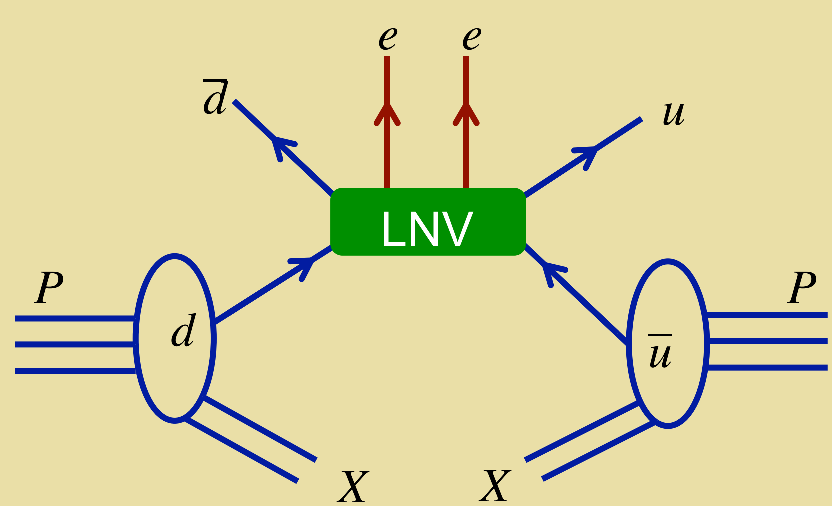
$0\nu\beta\beta$-Decay



pp Collisions



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LHC: SS Dilepton + Dijet

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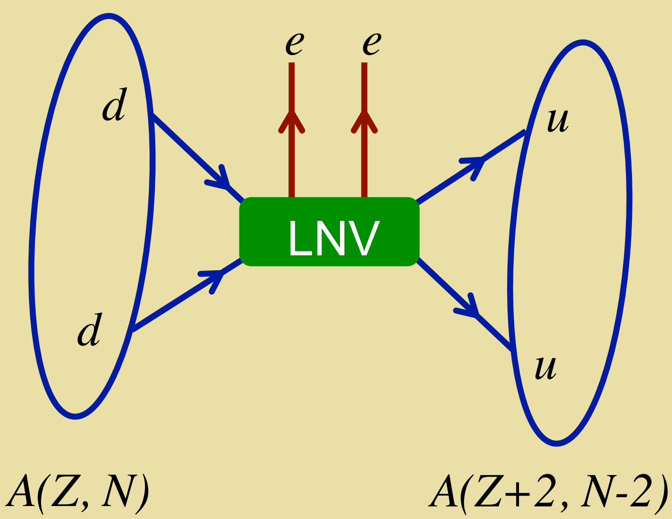
$0\nu\beta\beta$-Decay



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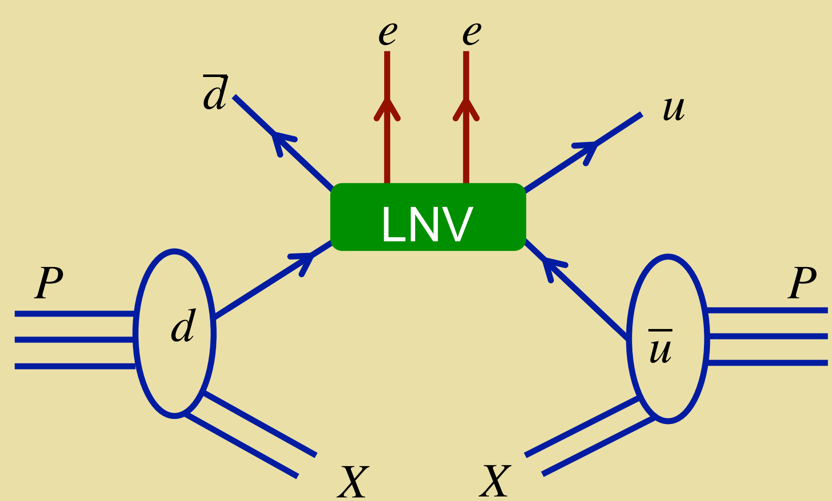

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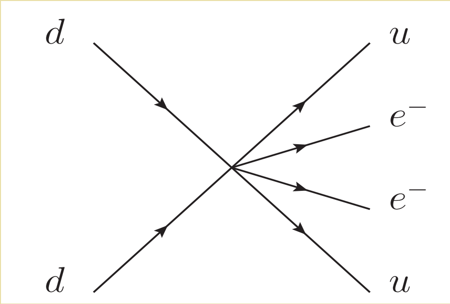
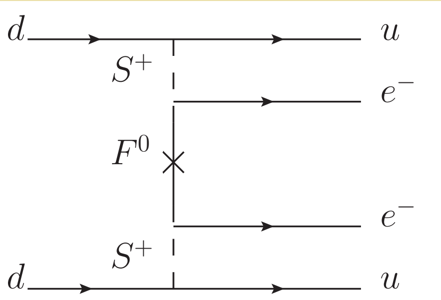
TeV Scale LNV

$0\nu\beta\beta$ - decay



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

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



Simplified models

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

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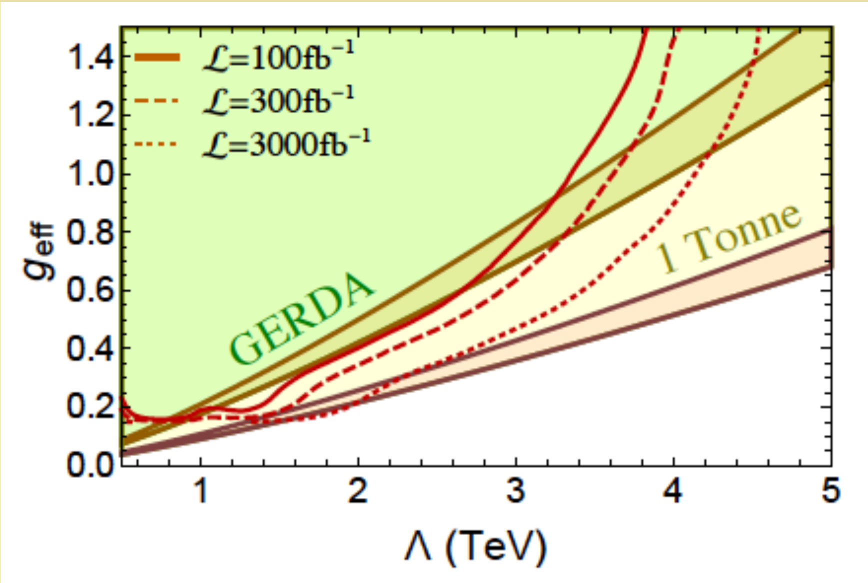
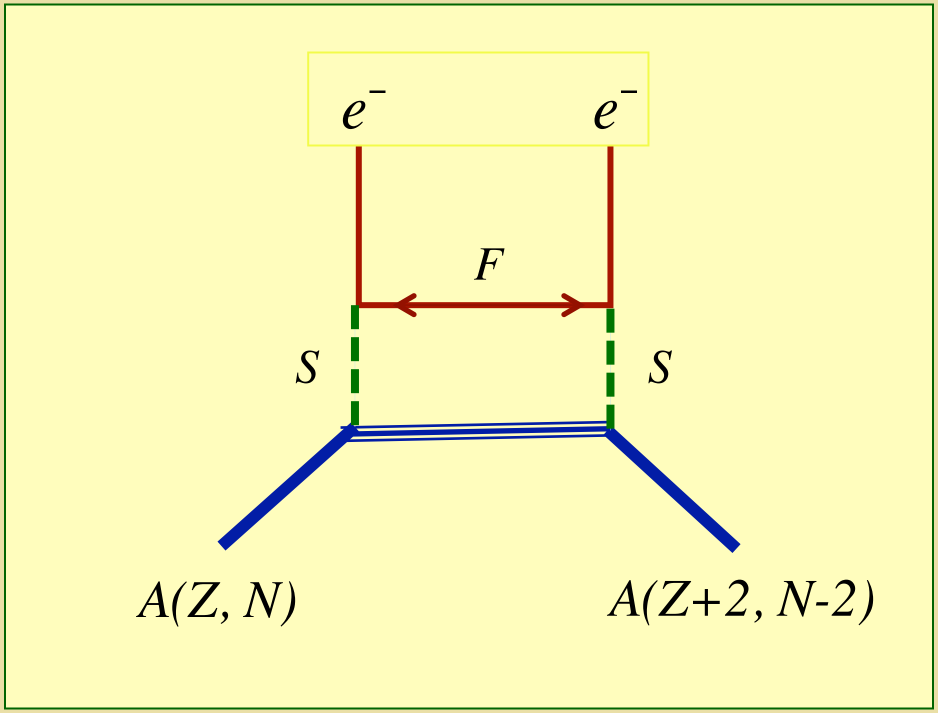
Benchmark Sensitivity: TeV LNV



T. Peng, MRM, P. Winslow 1508.04444



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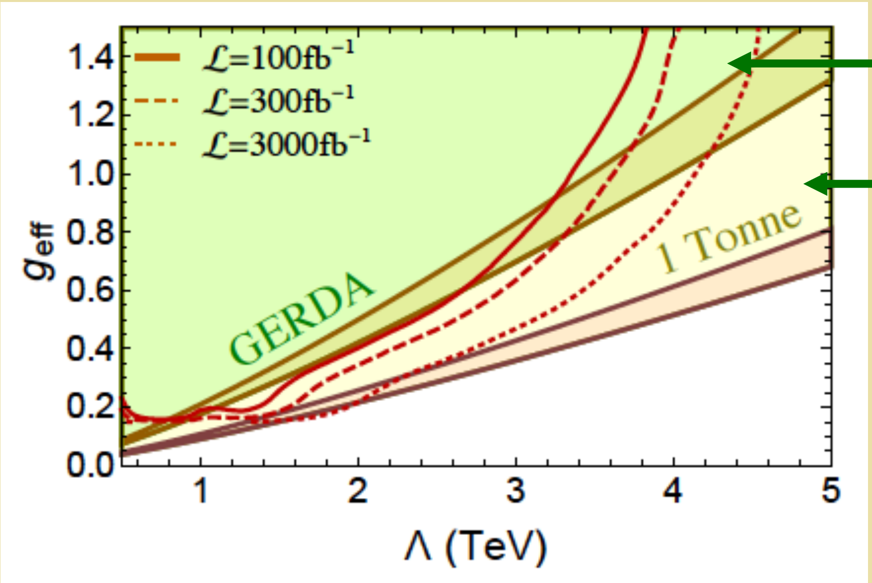

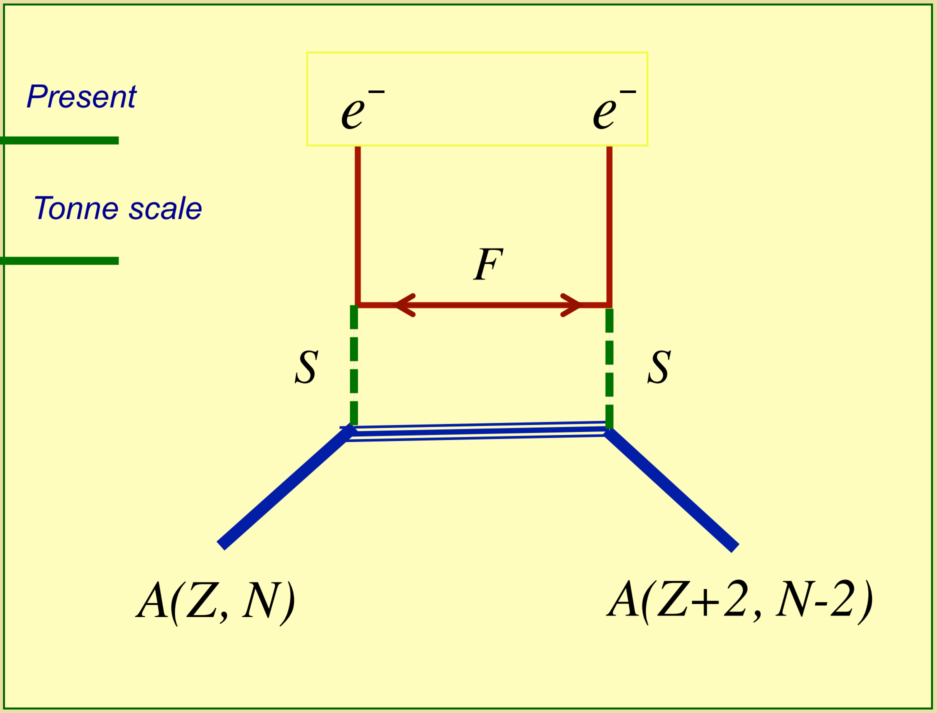

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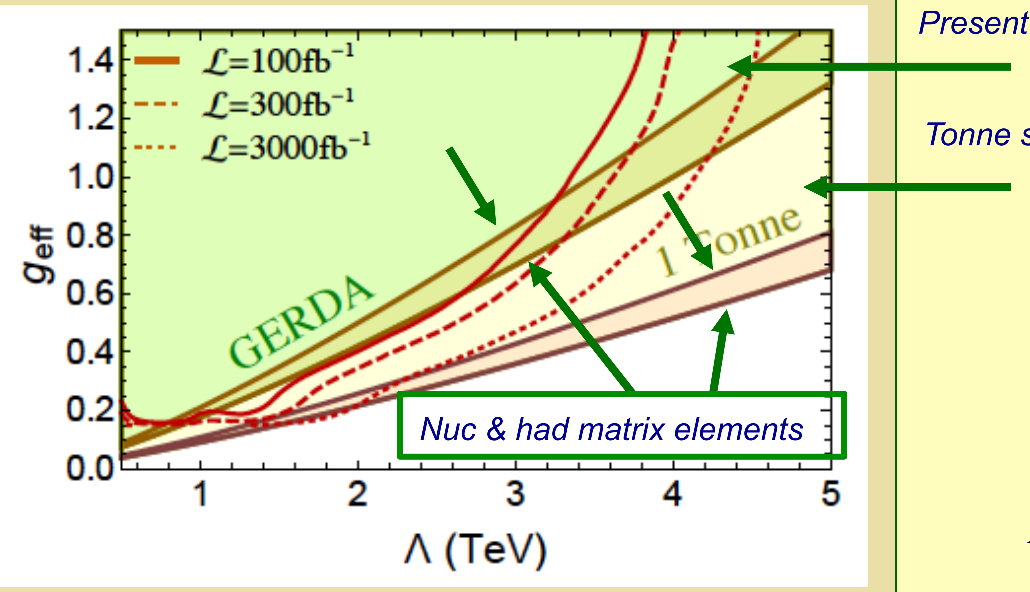
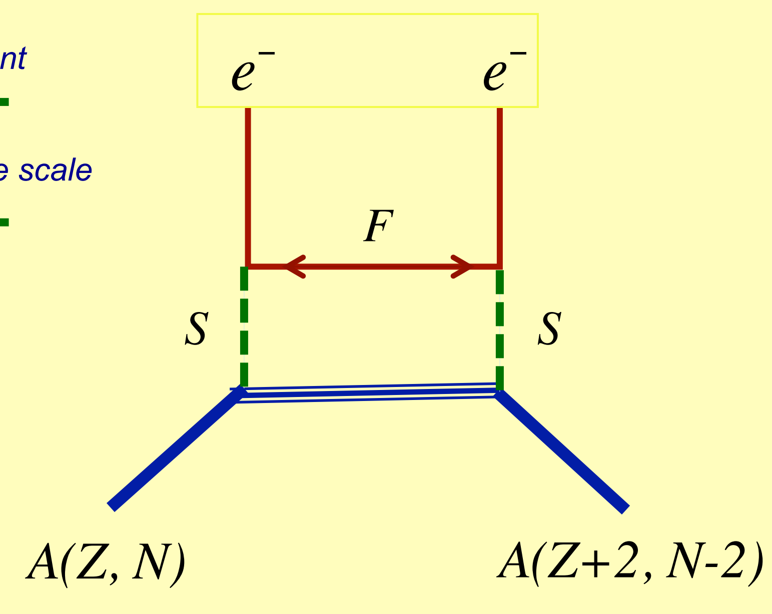




T. Peng, MRM, P. Winslow 1508.04444

0νββ-Decay: TeV Scale LNV

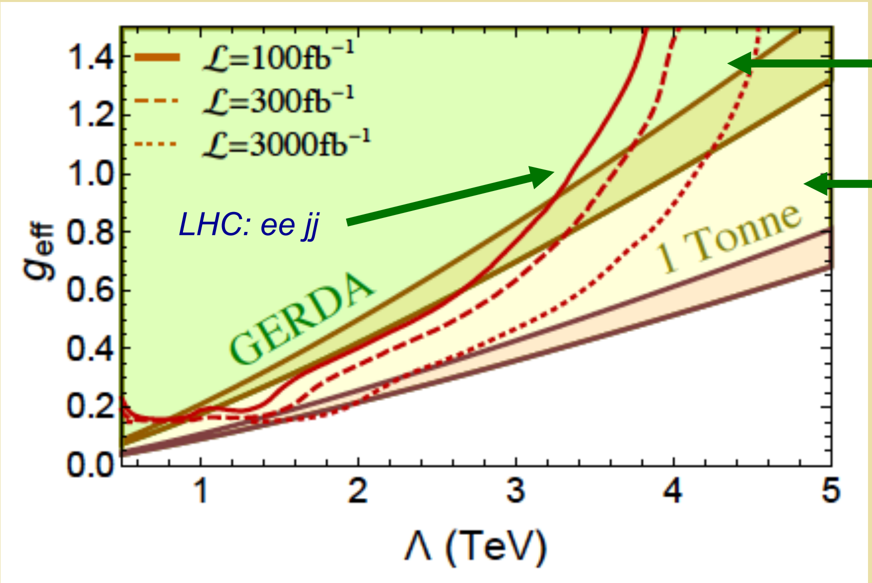
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

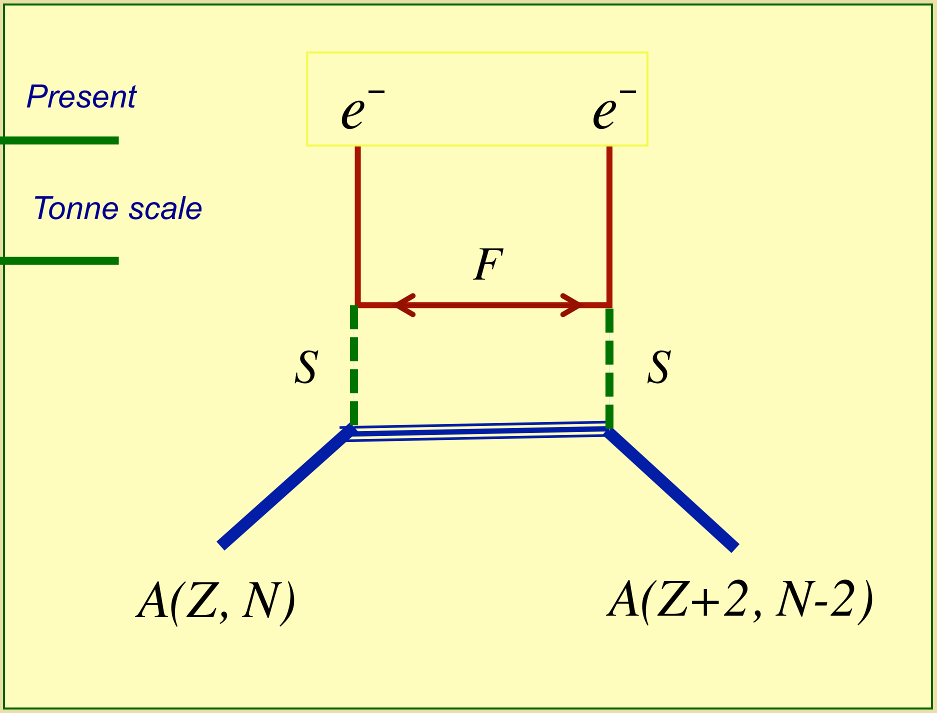
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

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

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

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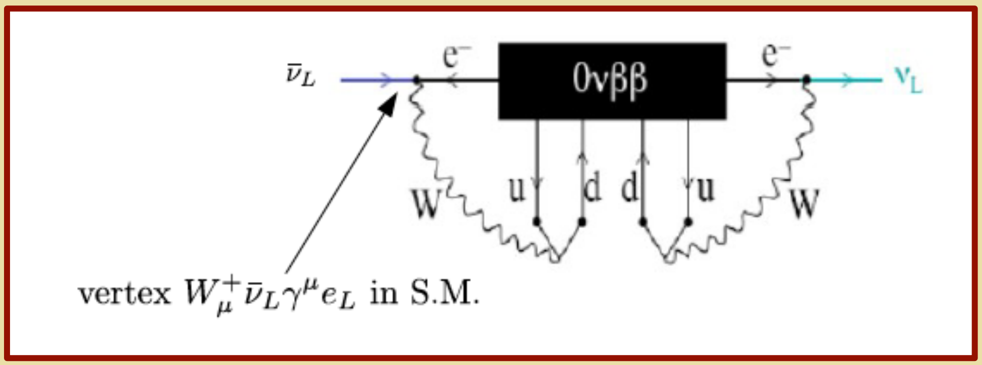
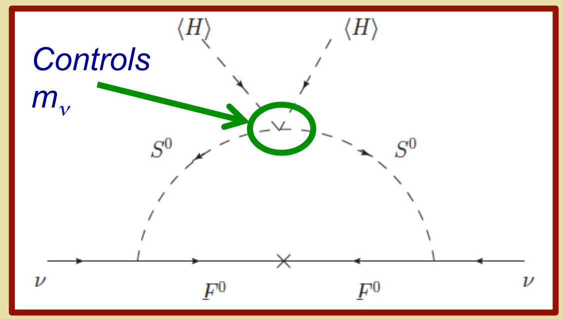
Majorana

Implications for m_ν:





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_ν

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

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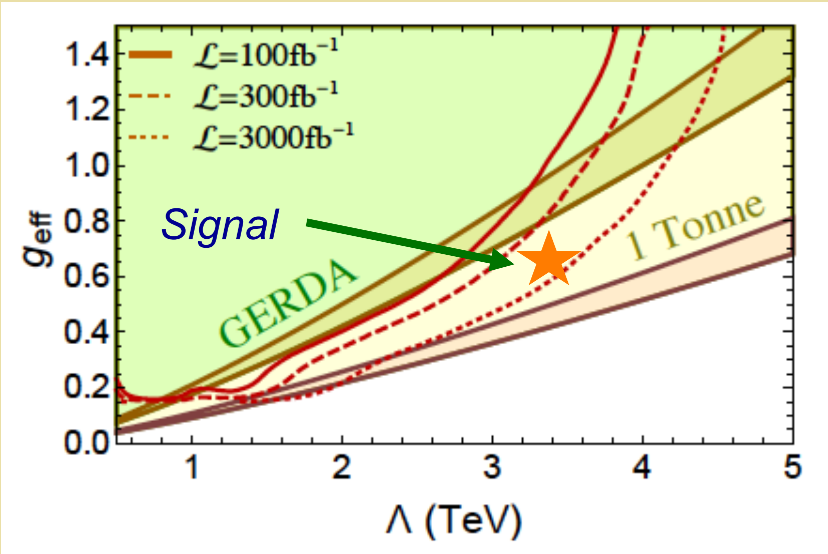
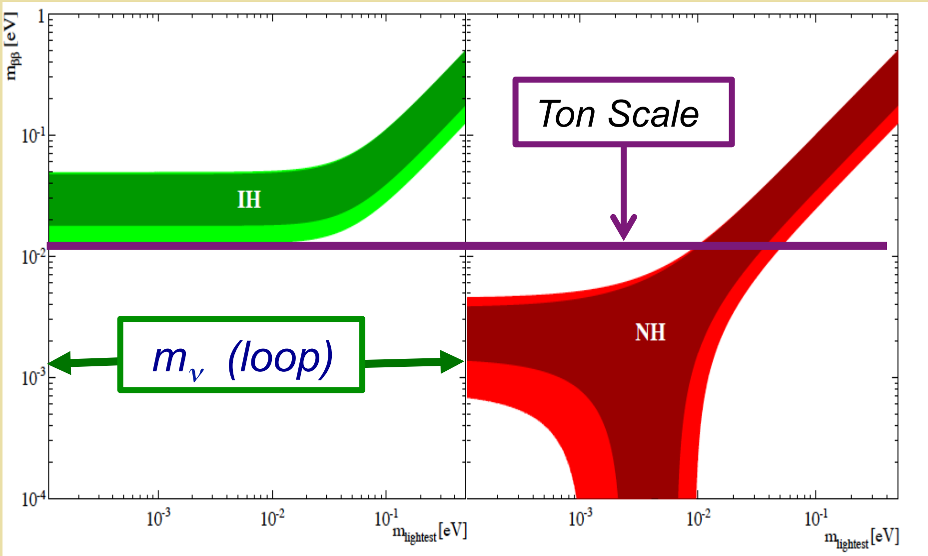




A hypothetical scenario

LNV Mass Scale & $0\nu\beta\beta$-Decay

A(Z,N) $\rightarrow$ *Underlying Physics* $\rightarrow$ *A(Z+2, N-2) +* $e^- e^-$

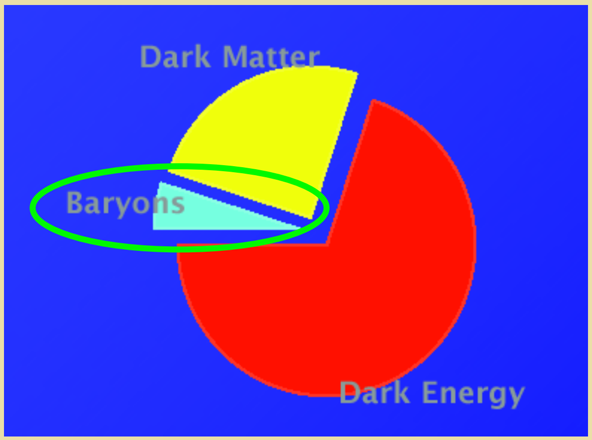
- *3 light neutrinos only: source of neutrino mass at the very high see-saw scale*
- *3 light neutrinos with TeV scale source of neutrino mass*
- *> 3 light neutrinos*

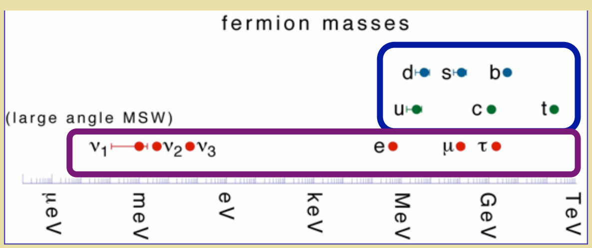
Back up slides

III. CP (Flavor Conserving)

Fundamental Questions

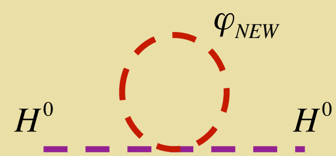
***MUST* answer**





Origin of m_ν

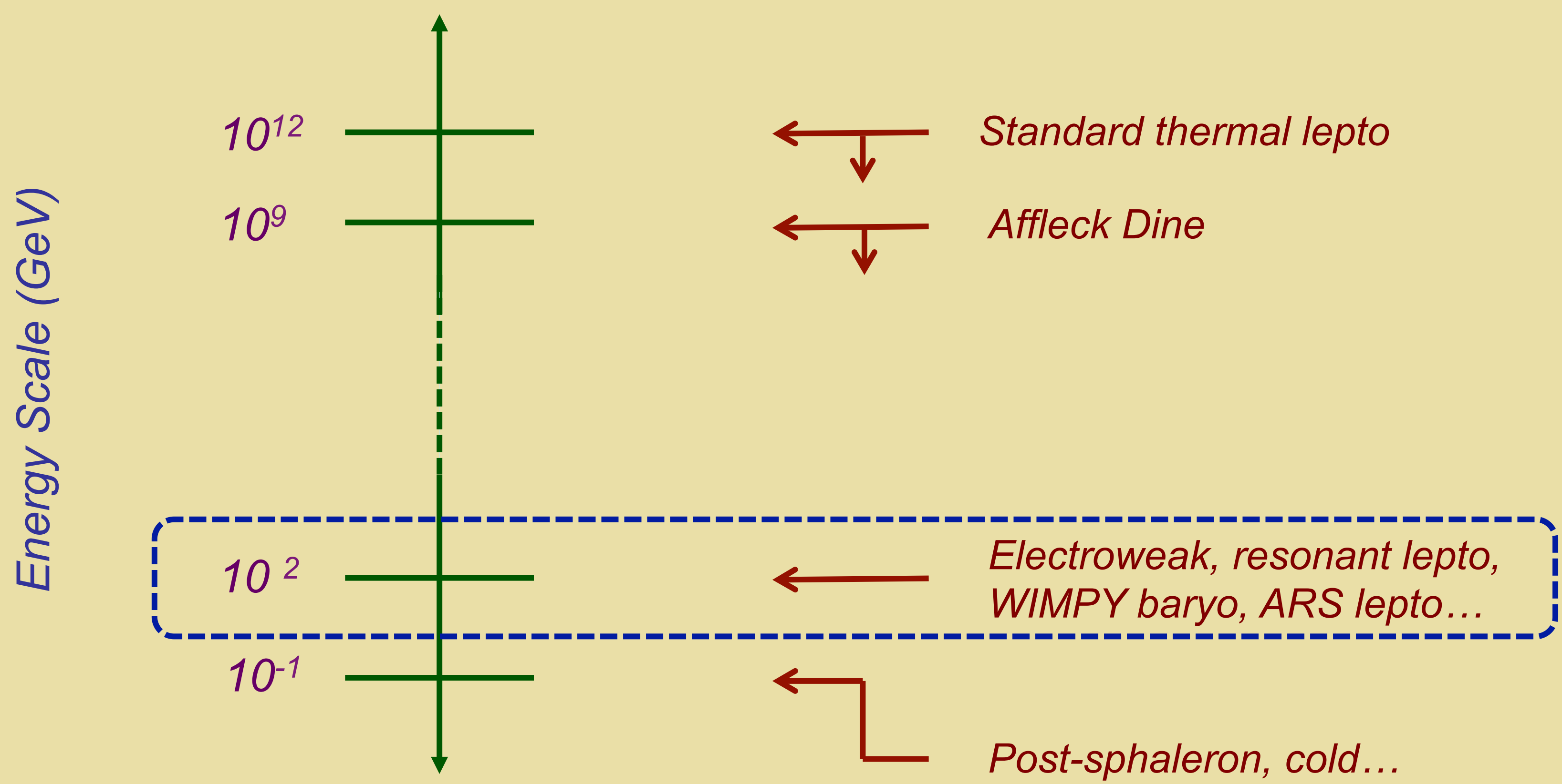
***SHOULD* answer**



$\Delta m^2 \sim \lambda \Lambda^2$

$\Lambda_{\mathit{Cosmological}}$

Baryogenesis Scenarios



Era of EWSB: t_{univ} ~ 10 ps

Electroweak Baryogenesis

- *Was Y_B generated in conjunction with electroweak symmetry-breaking?*
- *To what extent can EDM searches test this scenario?*

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	7.4×10^{-30}	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 *New Hf F^+ : 1.3×10^{-28} 1704.07928*

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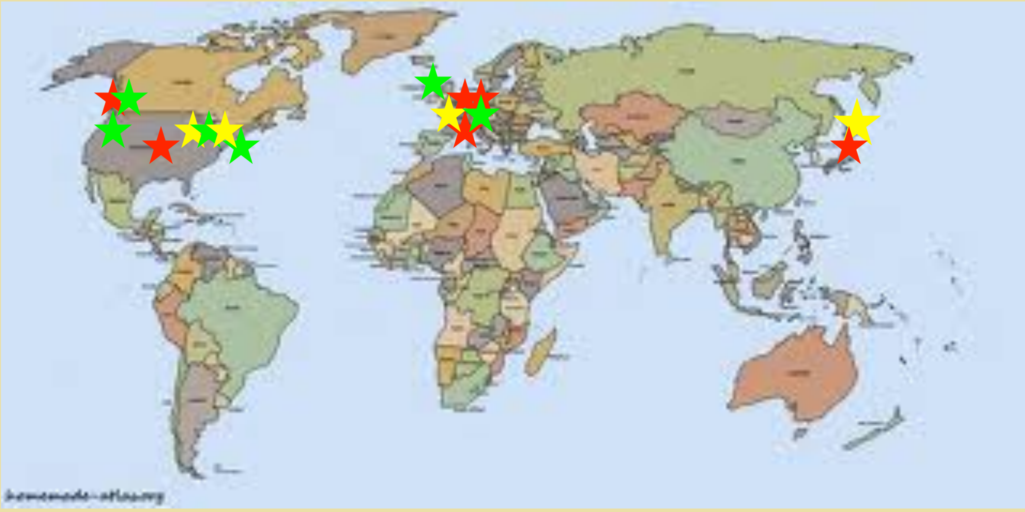

★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

EDMs: New CPV?

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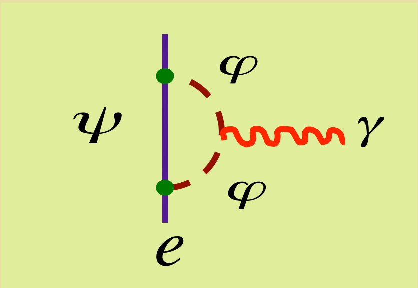
Mass Scale Sensitivity



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

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

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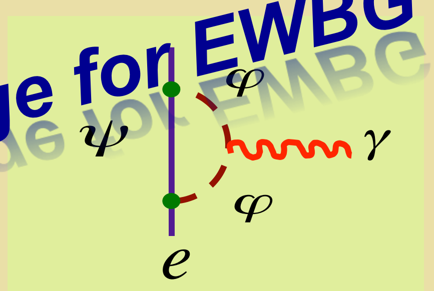
Mass Scale Sensitivity

Challenge for EWBG



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

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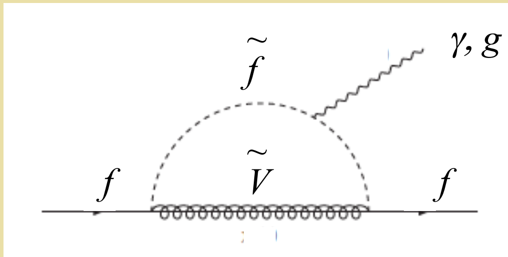
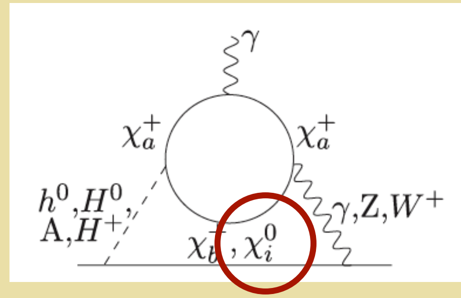
EDMs & EWBG: MSSM & Beyond

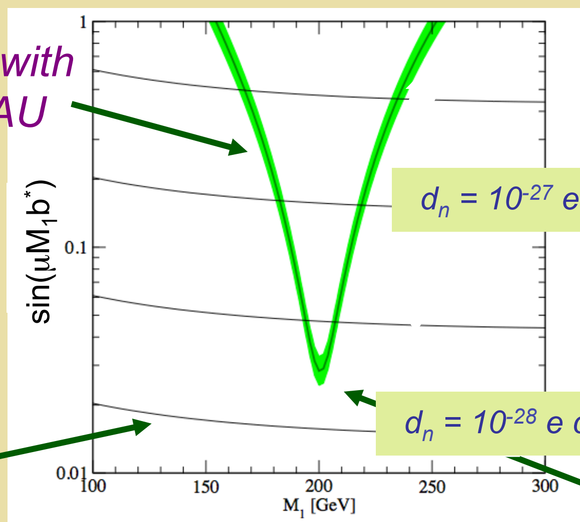


Heavy sfermions: LHC consistent & suppress 1-loop EDMs

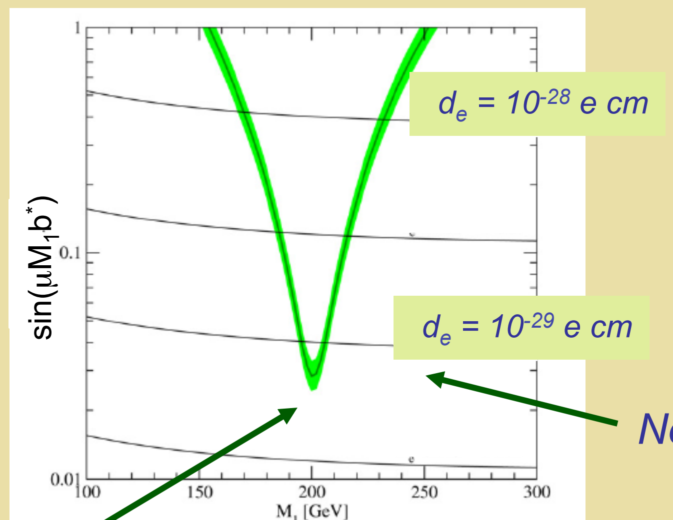


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU



Next gen d_n



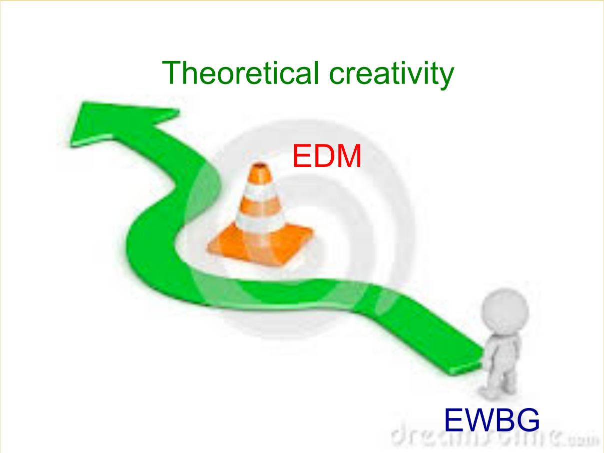
ACME: ThO

Next gen d_e

Li, Profumo, RM '09-'10

Compressed spectrum

CPV for EWBG



Back up slides

The Higgs Portal

What is the CP Nature of the Higgs Boson ?

What is the CP Nature of the Higgs Boson ?

- *Interesting possibilities if part of an extended scalar sector*

- *Two Higgs doublets ?*

$$H \to H_1 \,,\, H_2$$

- *New parameters:*

$$\tan\beta = \langle H_1 \rangle / \langle H_2 \rangle$$
$$\sin\alpha$$
$$\sin\alpha_b$$

What is the CP Nature of the Higgs Boson ?

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$$H \rightarrow H_1 \, , \, H_2$$

- *New parameters:*

$\tan\beta = \langle H_1 \rangle / \langle H_2 \rangle$

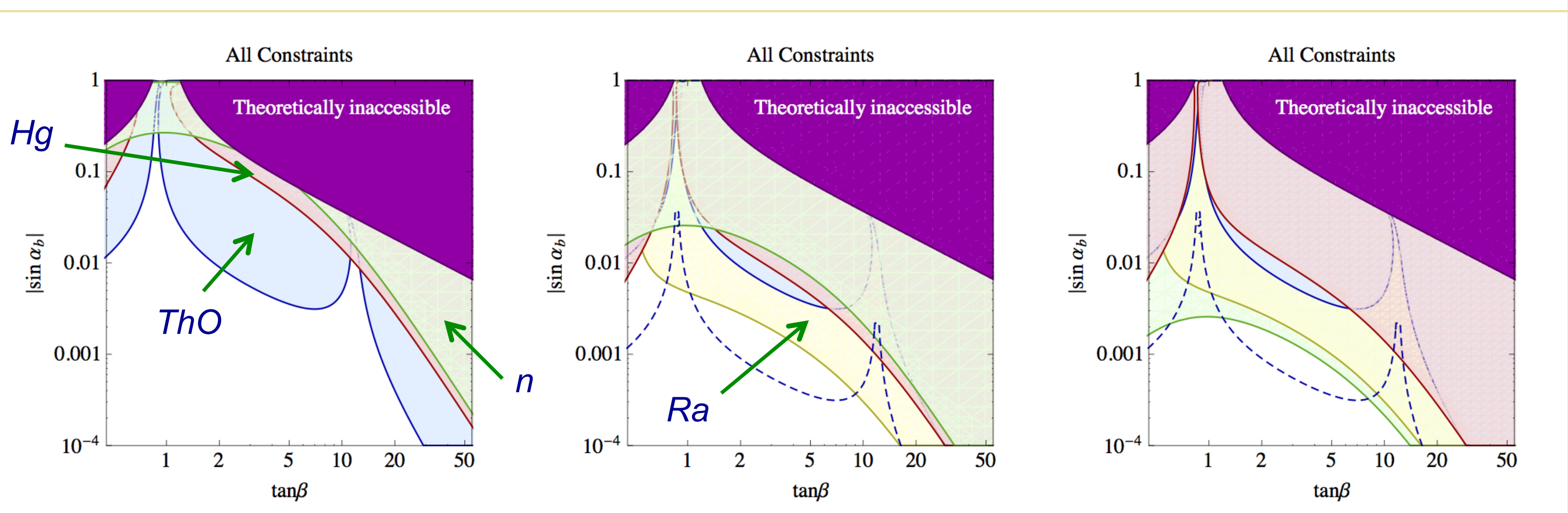
$\sin\alpha$

$\boxed{\sin\alpha_b}$

CPV : scalar-pseudoscalar mixing from $V(H_1, H_2)$

Future Reach: Higgs Portal CPV

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

$d_A(Ra)$ [10^{-27} e cm]

Future:

d_n x 0.01

$d_A(Hg)$ x 0.1

d_{ThO} x 0.1

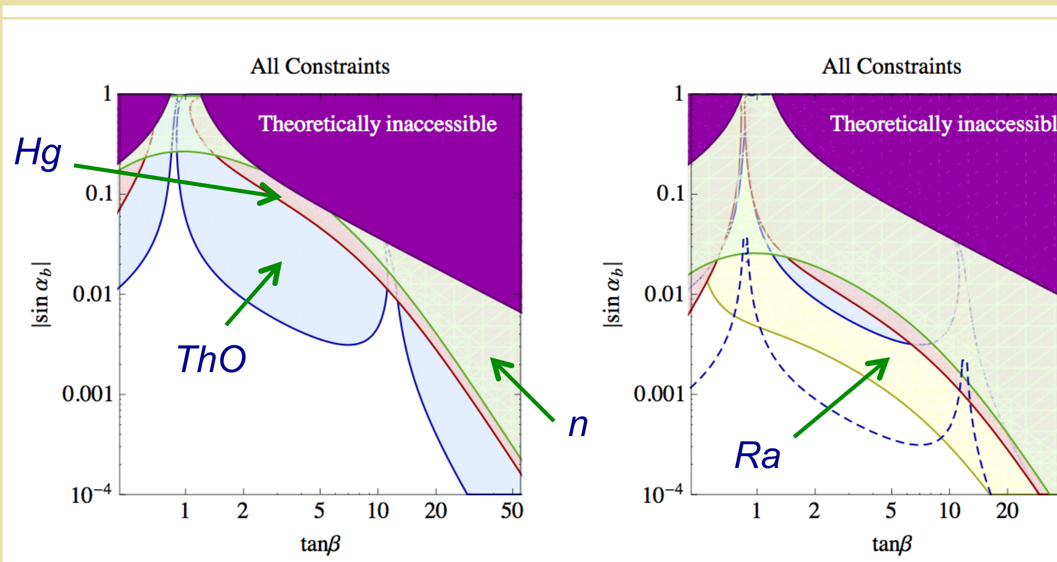
$d_A(Ra)$

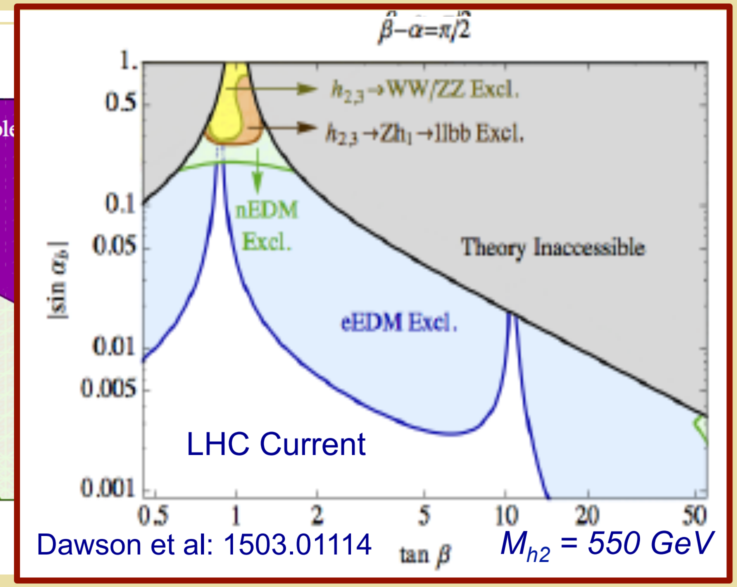
Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration

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





Present

sin α_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*
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Inoue, R-M, Zhang: 1403.4257

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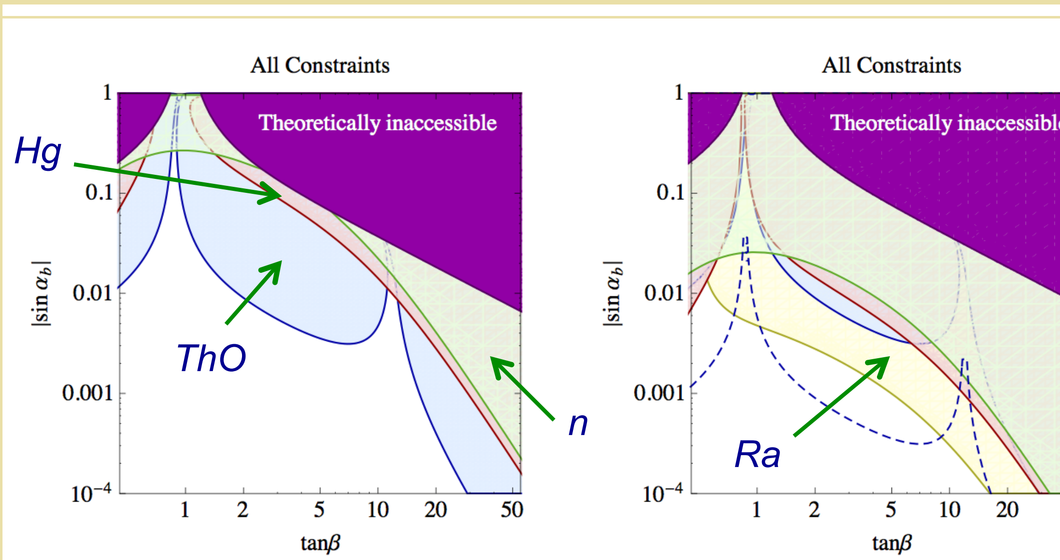

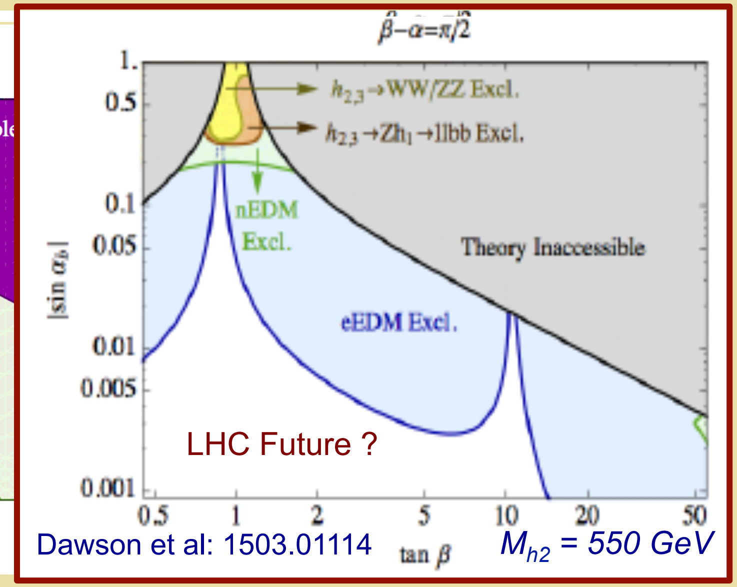

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d_n x 0.1

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

Future:

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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

Chien-Yi Chen, Haolin Li, MJRM 1708.00435

$h_{2,3} \to Z\, h_1 \to bb\ \ell\ell$

Z h_a h_b couplings

$$g_{2z1} \propto -\alpha_b + O(\alpha_b\theta)$$ ← *Vanishes in CP conserving limit*

$$g_{3z1} \propto -\theta + O(\alpha_b^2)$$ ← *Vanishes in alignment limit*

$\theta = \beta - \alpha - \pi/2$

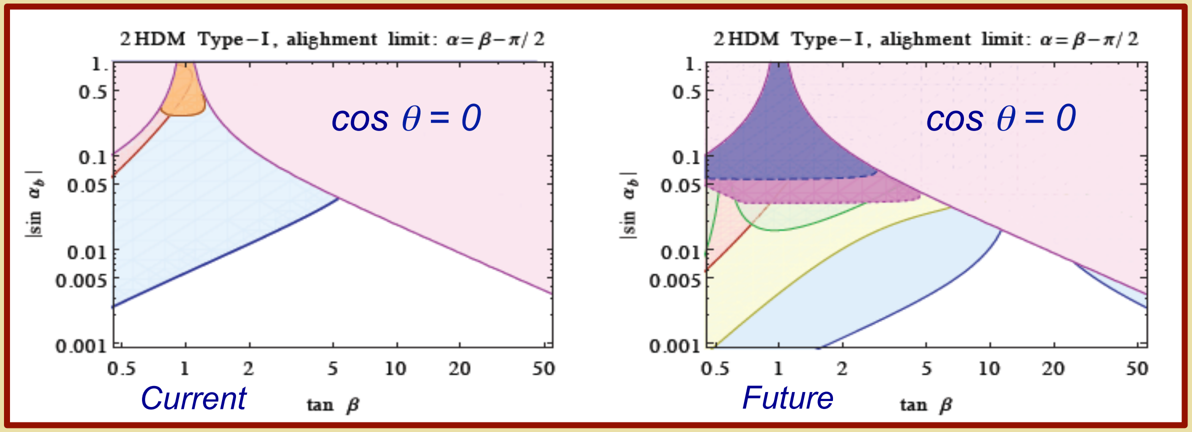
"Alignment": $\theta = 0$

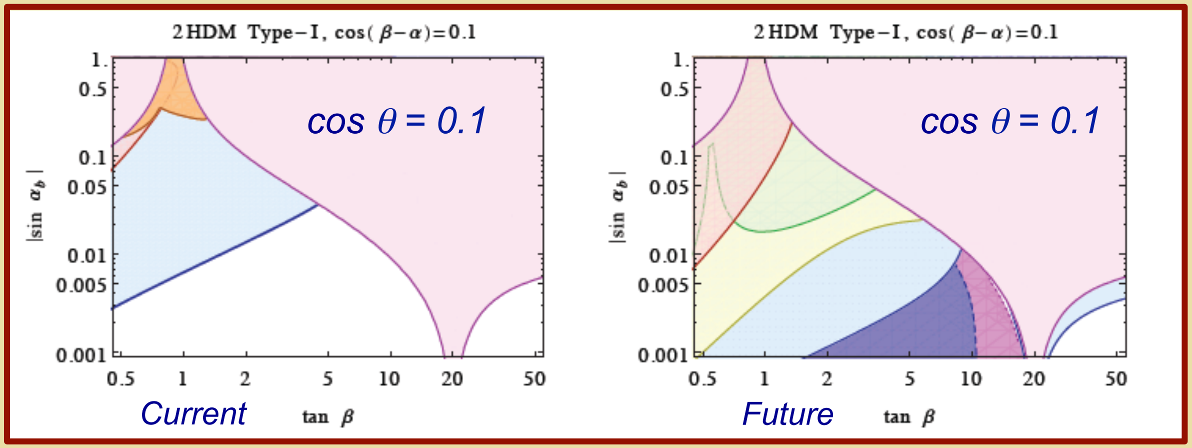
Higgs Portal CPV: EDMs & LHC

Chien-Yi Chen, Haolin Li, MJRM 1708.00435

$$\boxed{h_{2,3} \to Z\, h_1 \to bb\ \ell\ell}$$

LHC & EDM Future





- *Orange: LHC 8 TeV*
- *Blue: 300 fb^{-1}*
- *Magenta: 3 ab^{-1}*

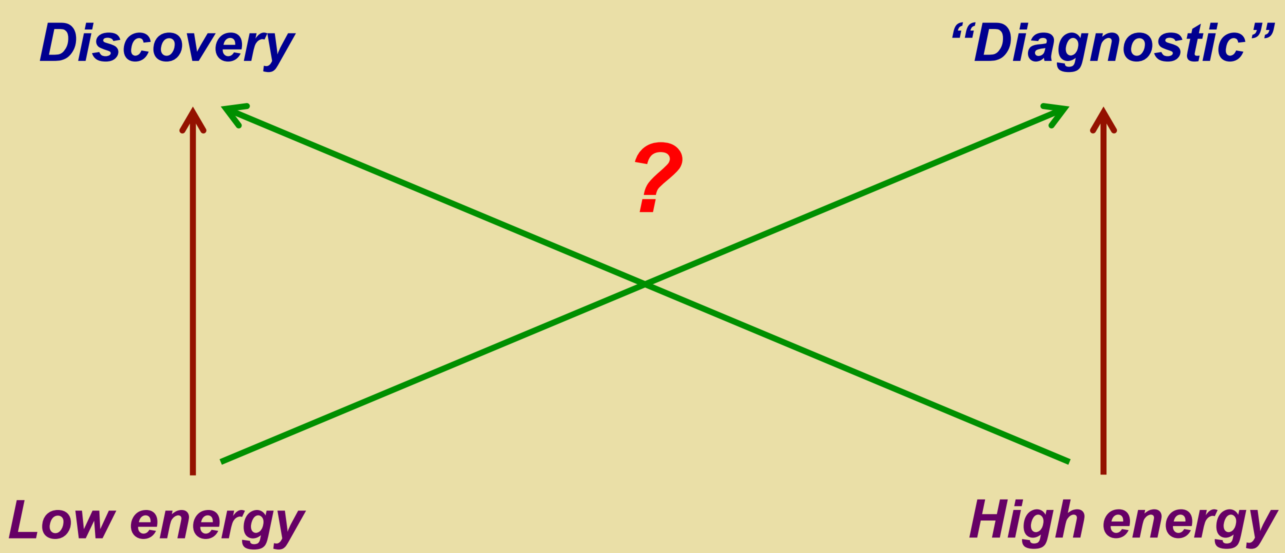
- *Validated vs. ATLAS 8 TeV: 1502.04478*
- *Apply BDT for 14 TeV*

$$g_{2z1} \propto -\alpha_b + O(\alpha_b \theta)$$

$$g_{3z1} \propto -\theta + O(\alpha_b^2)$$

Low-Energy / High-Energy Interplay

Higgs Portal CPV



Low-Energy / High-Energy Interplay

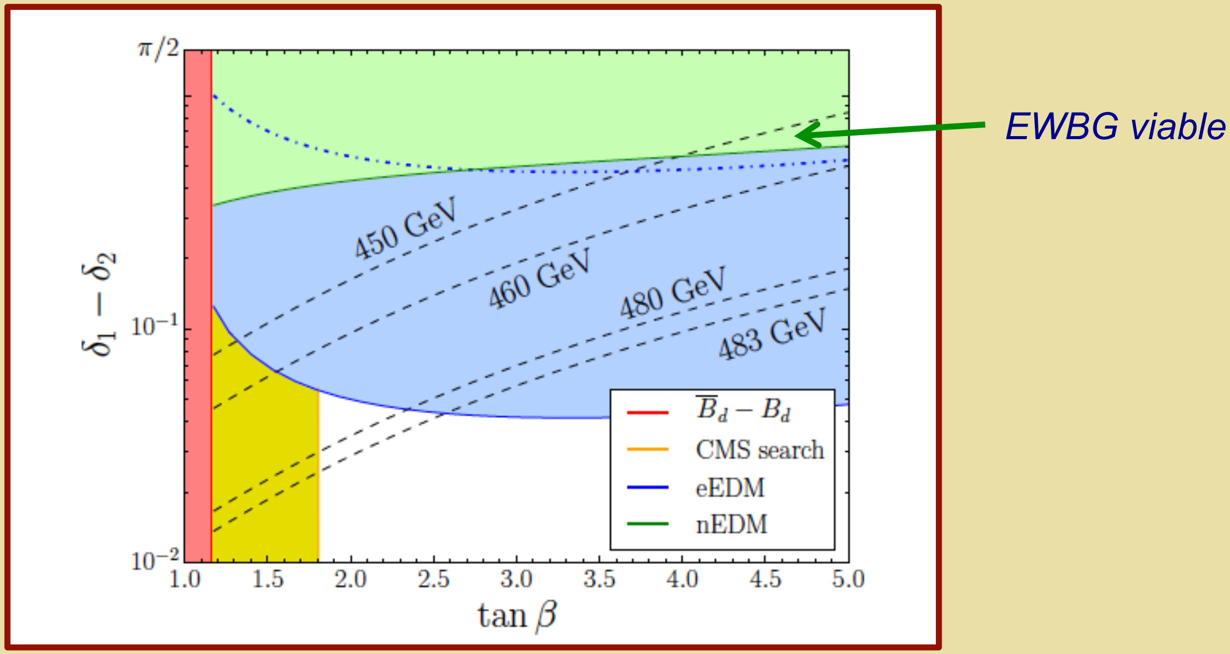
Higgs Portal CPV

- *Alignment limit: LHC discovery $\rightarrow$ Non-zero radium and electron (paramagnetic) EDMs should be observed*
- *Away from alignment: Non-zero EDM $\rightarrow$ LHC null result would preclude CPV 2HDM for > modest deviation from alignment*

Low-Energy / High-Energy Interplay

Higgs Portal CPV: Source for EWBG?

Dorsch et al, 1611.05874



$$\alpha_b \propto \delta_1 - \delta_2$$

V. Outlook

- ***Low-energy tests of fundamental symmetries 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***

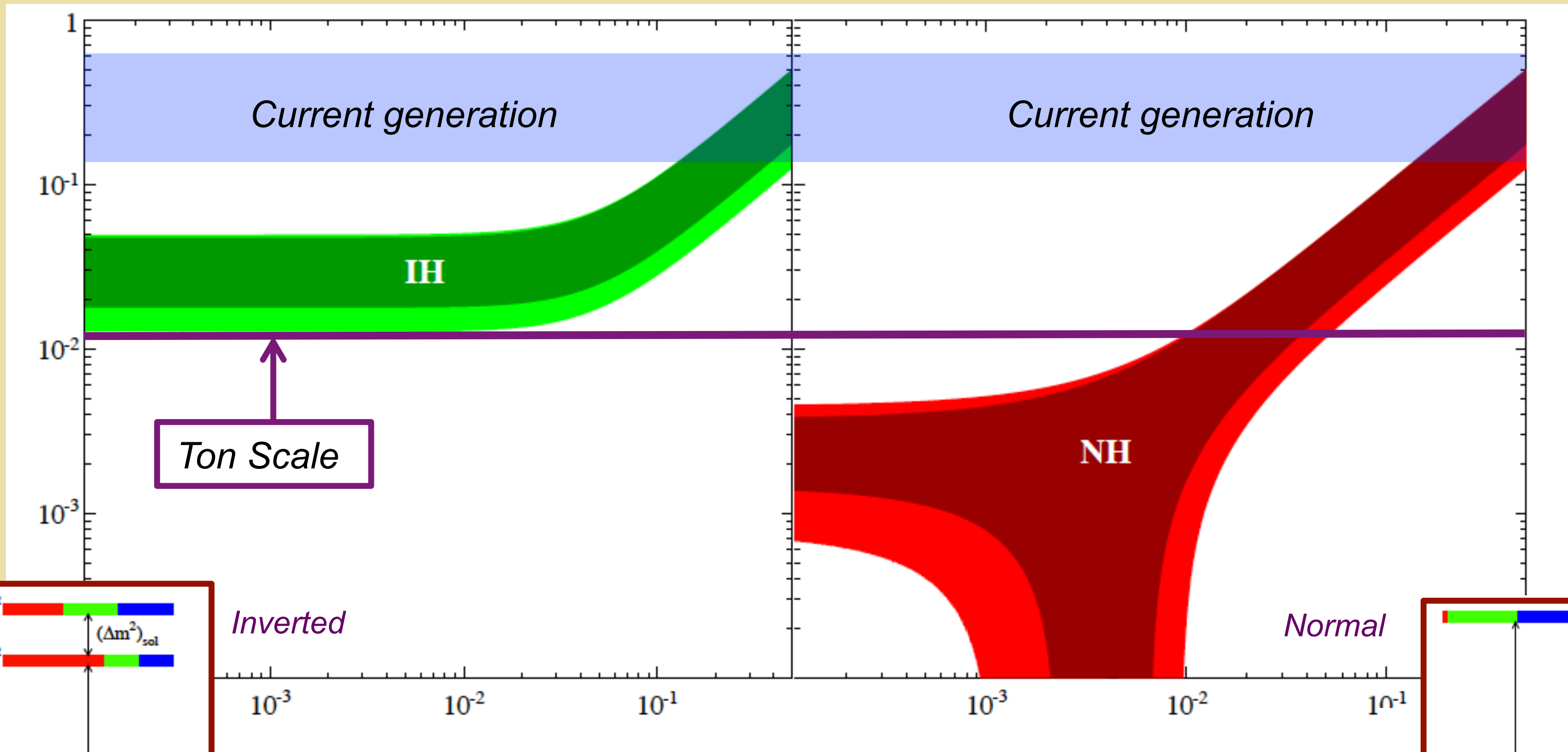
谢谢

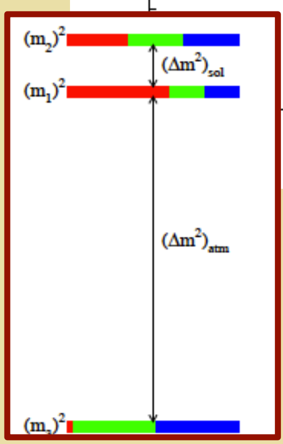
Back Up Slides

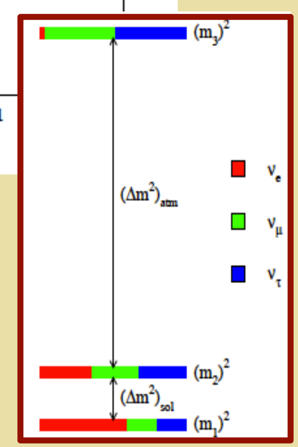
Lepton Number

Interpreting the Result

Three active light neutrinos



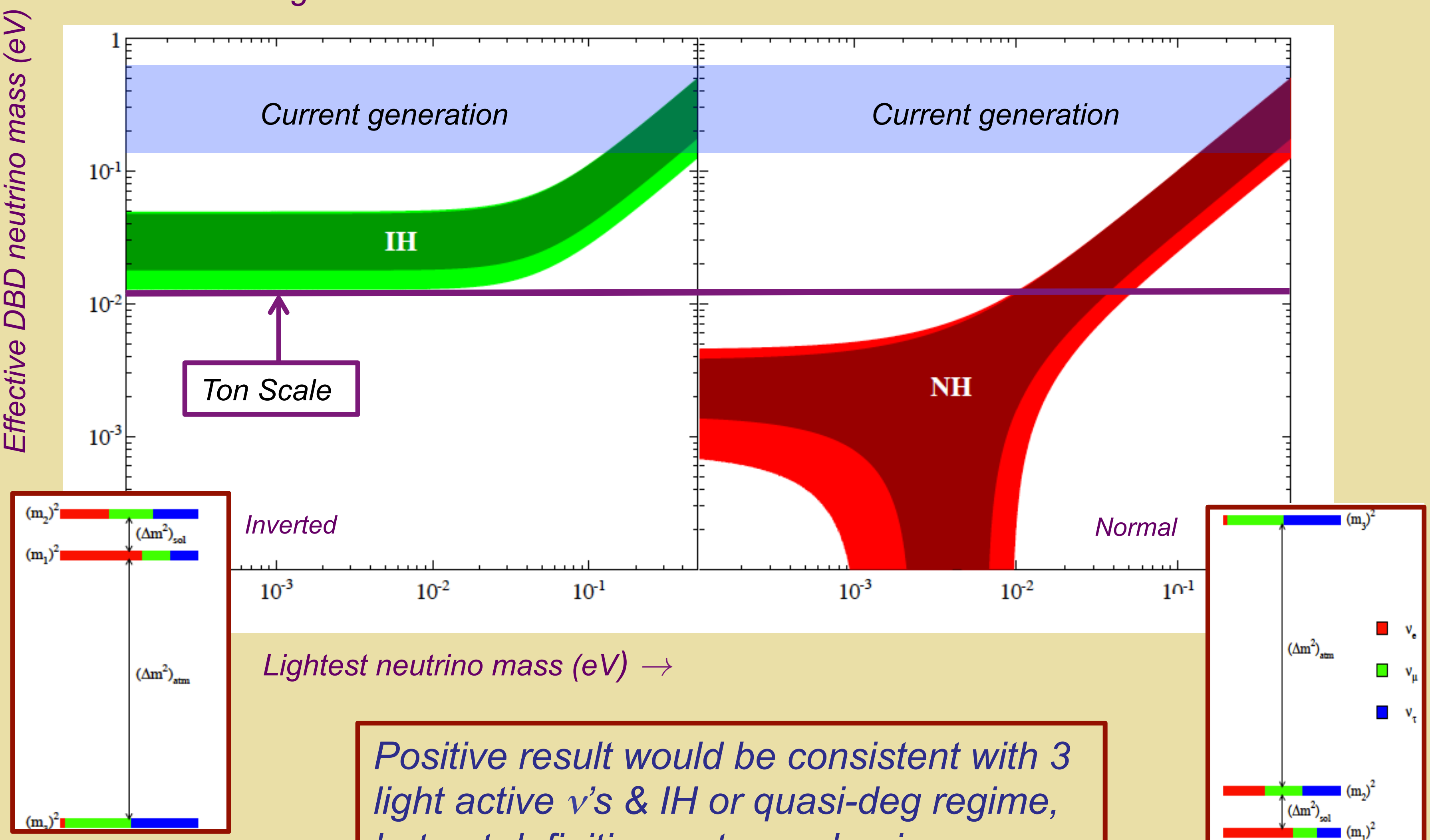




Full implications require information on lightest mass & hierarchy

Interpreting a Positive Result

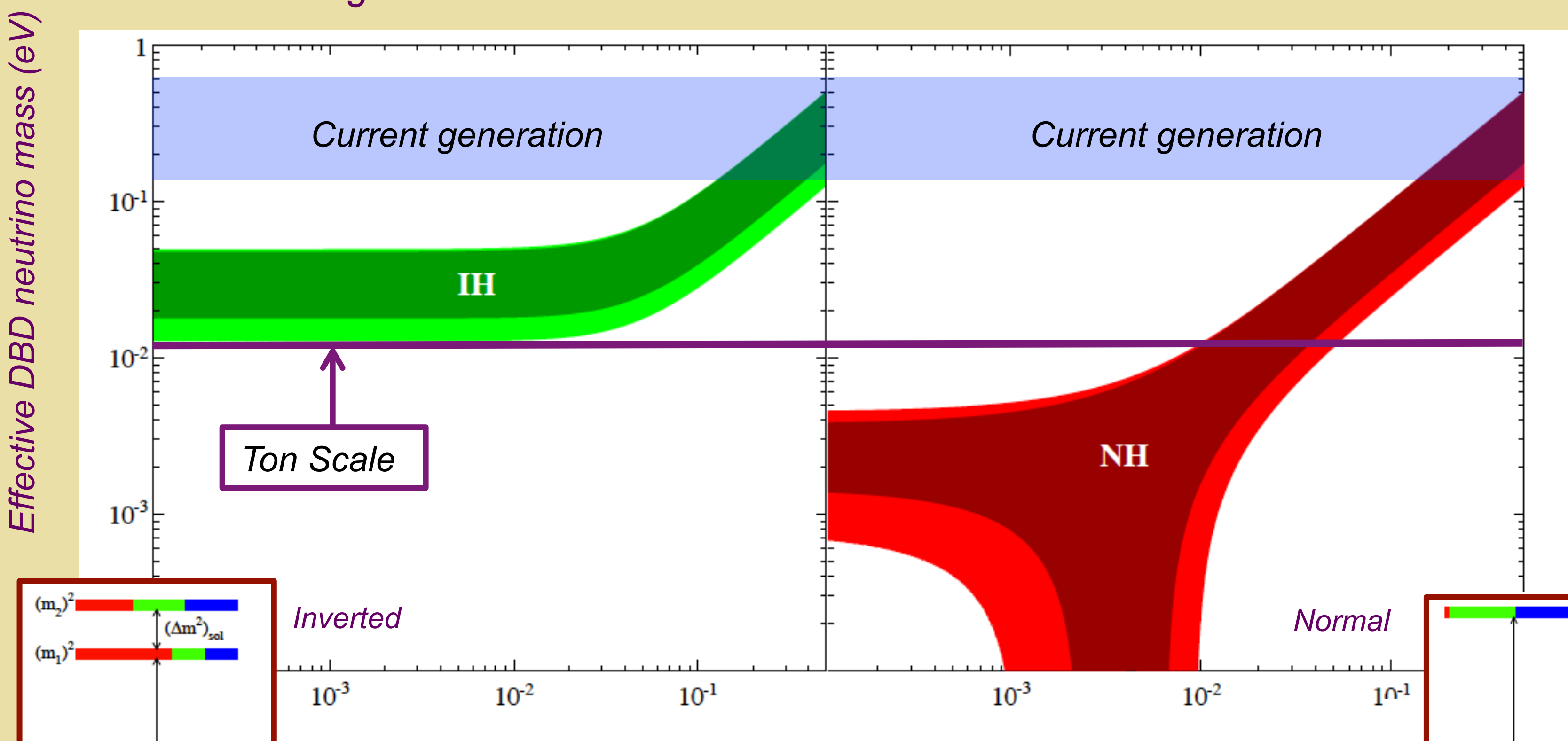
Three active light neutrinos

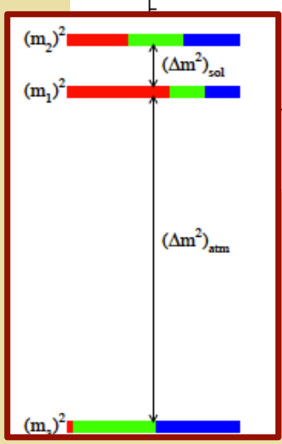


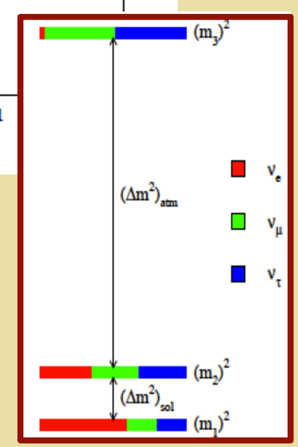
Positive result would be consistent with 3 light active ν's & IH or quasi-deg regime, but not definitive as to mechanism

Interpreting a Null Result

Three active light neutrinos

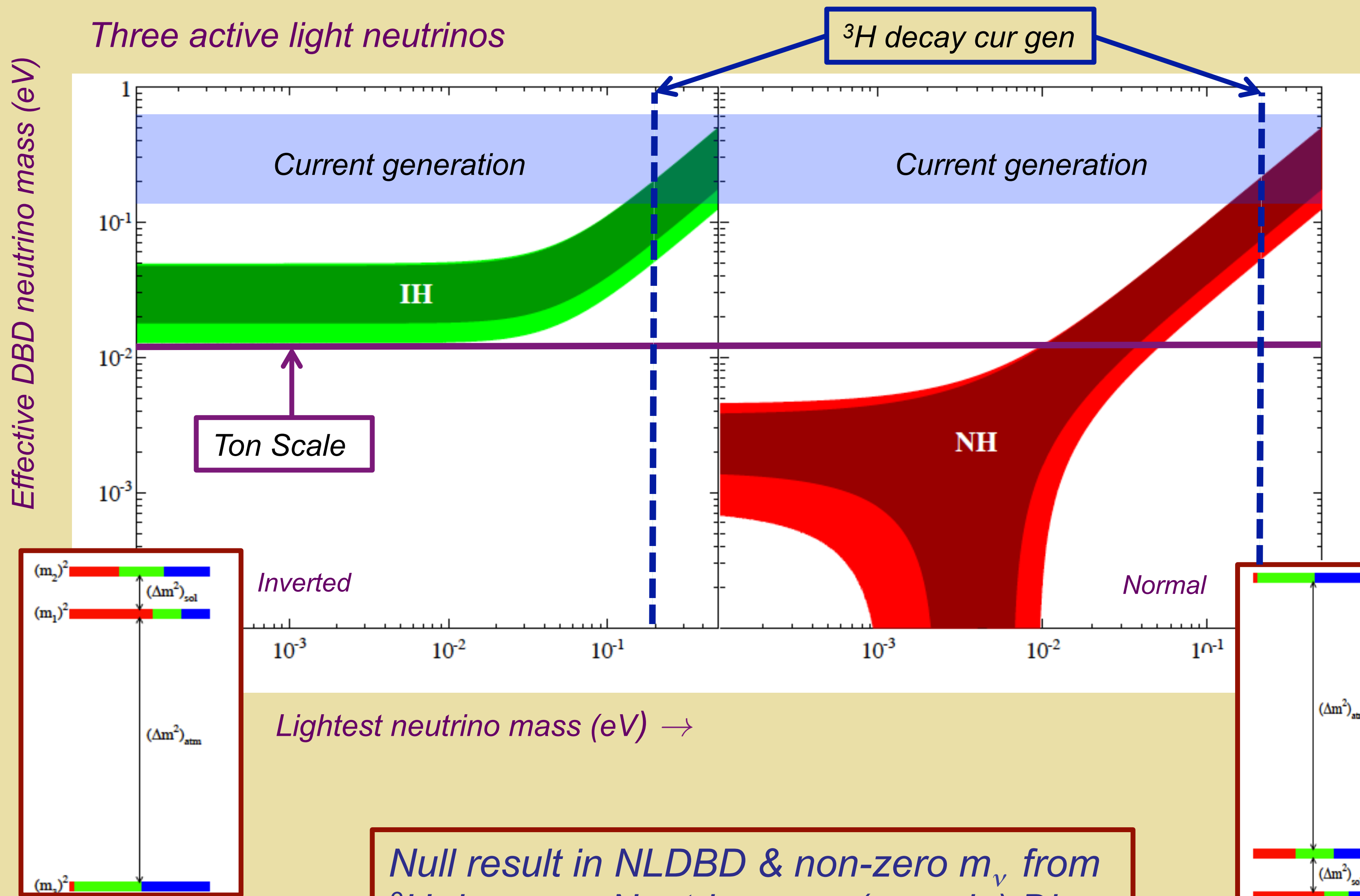






Full implications require information on lightest mass & hierarchy

What Would a Null Result Imply ?



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

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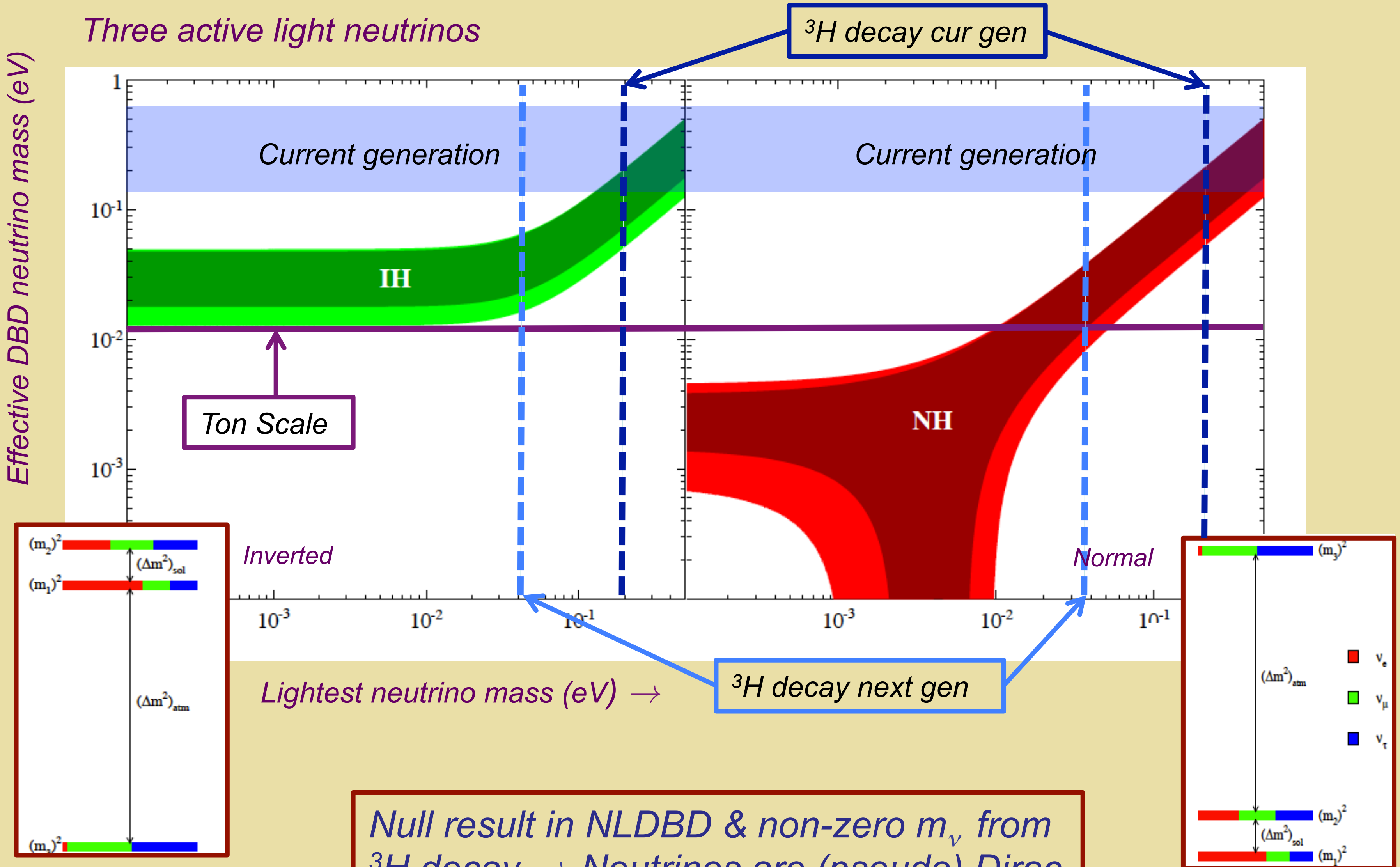

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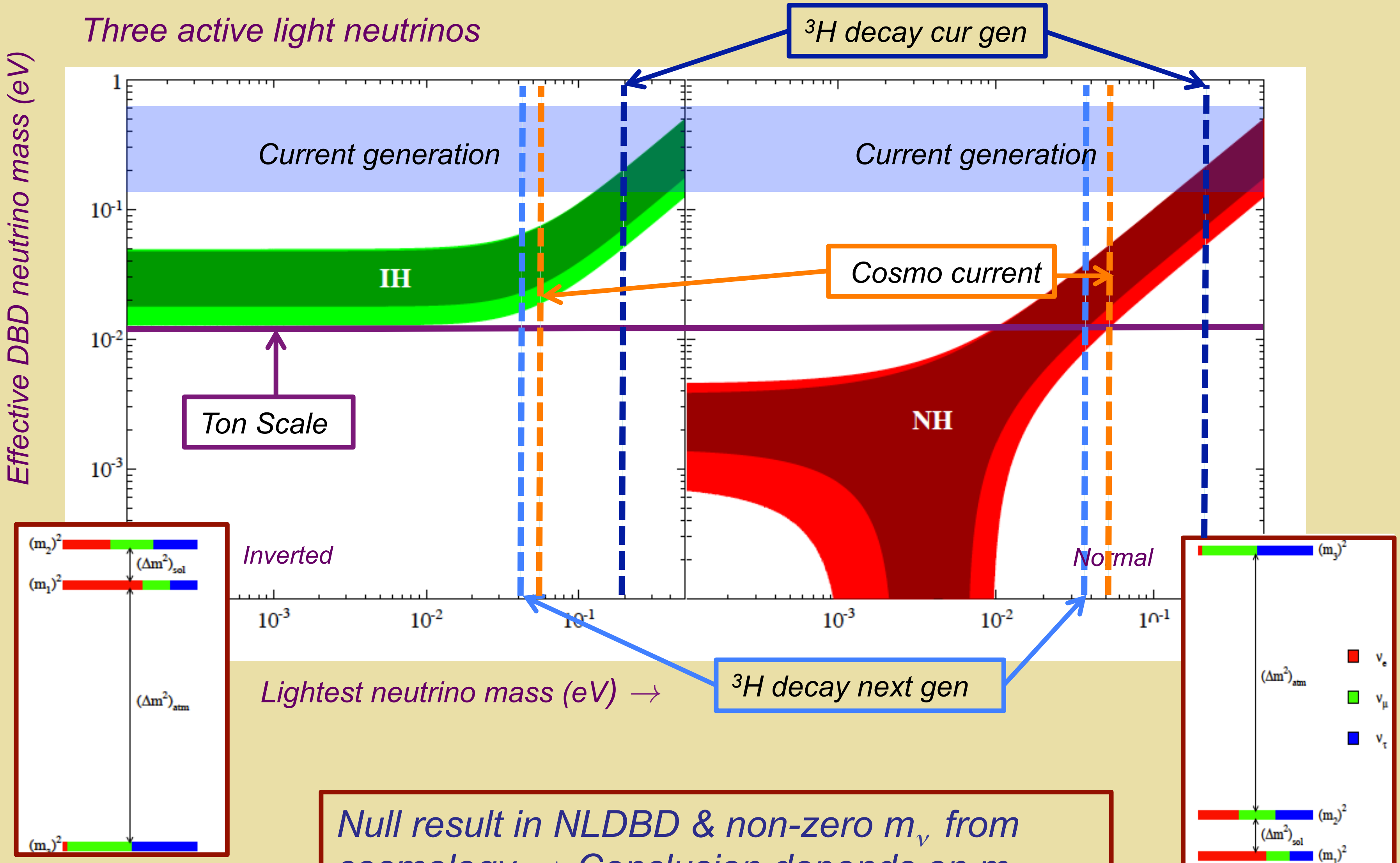
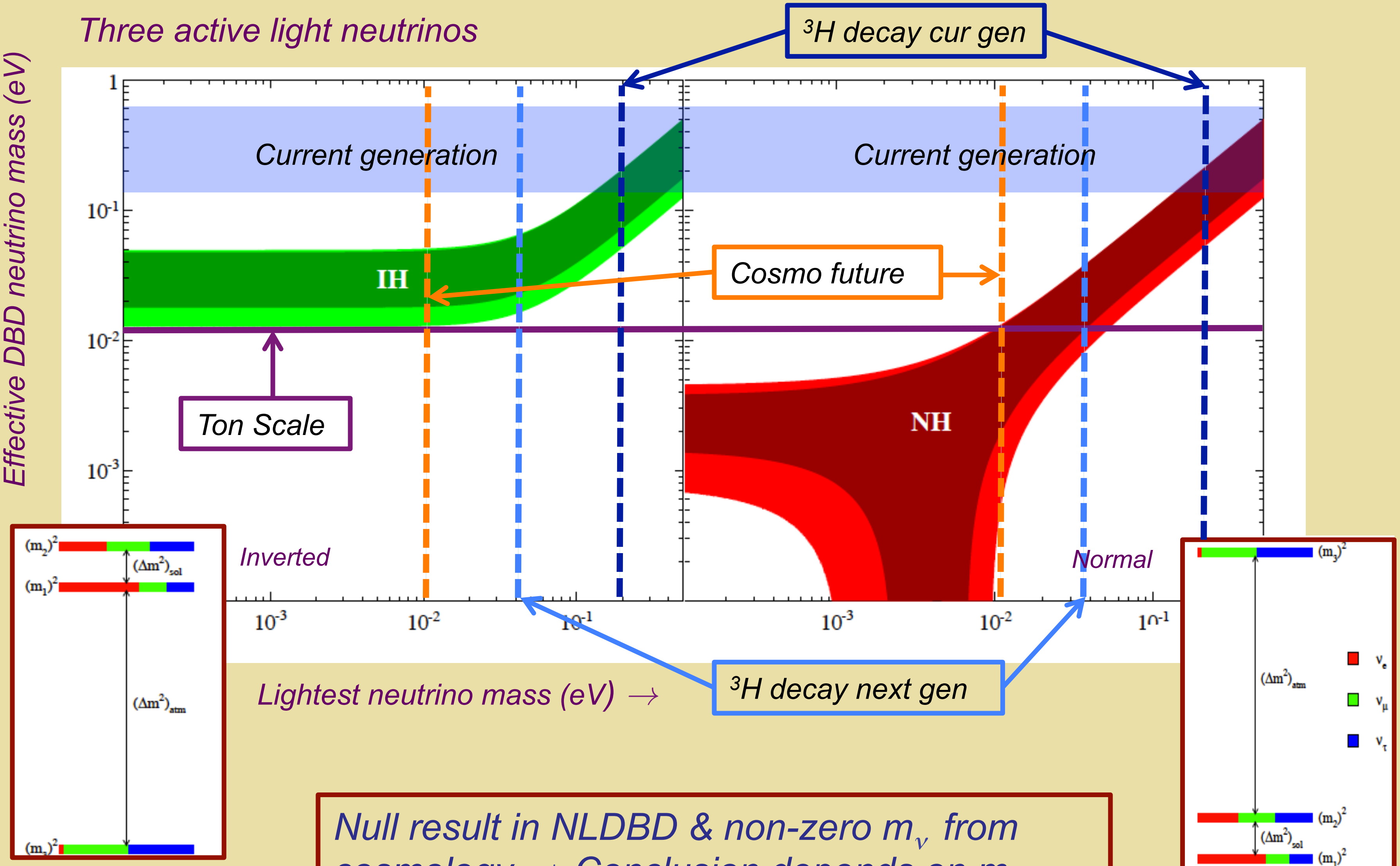


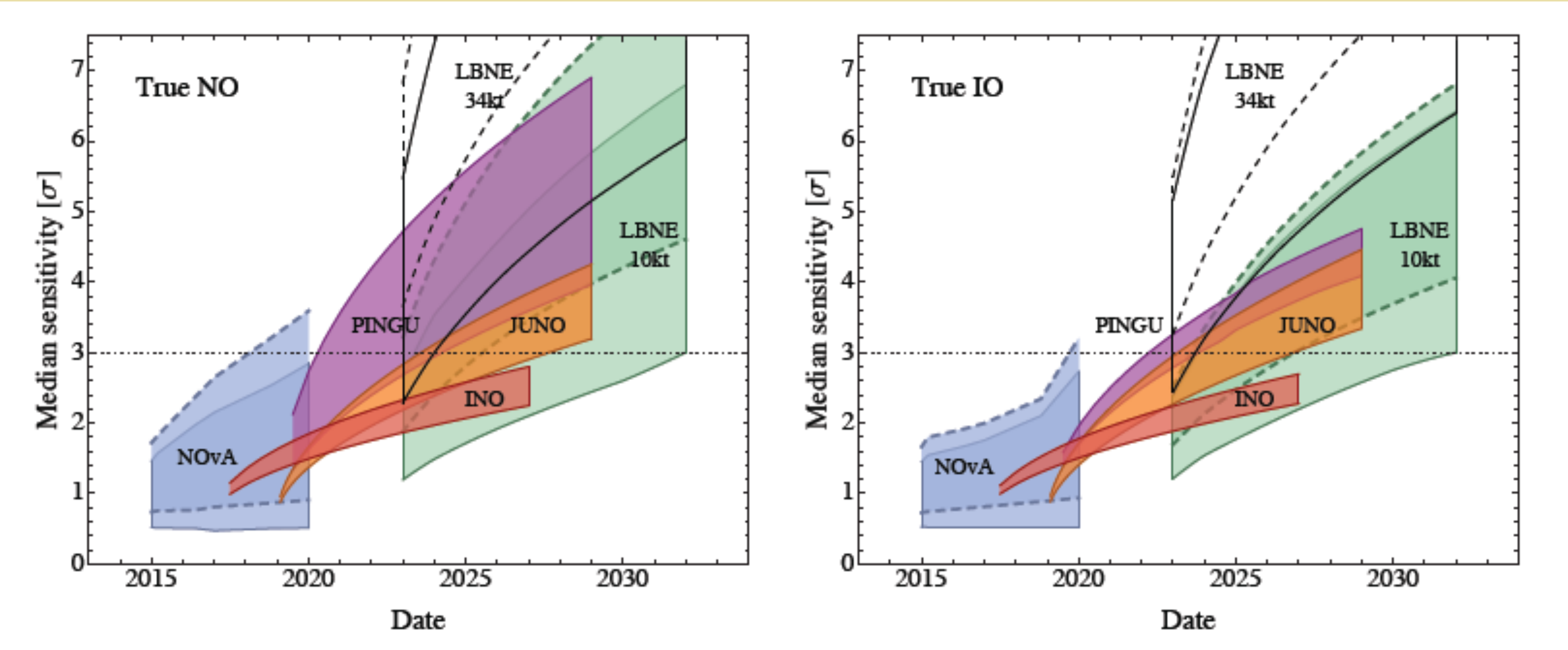
Null result in NLDBD & non-zero m_ν from cosmology → Conclusion depends on $m_{lightest}$ & hierarchy

What Would a Null Result Imply ?



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

Neutrino Mass Hierarchy

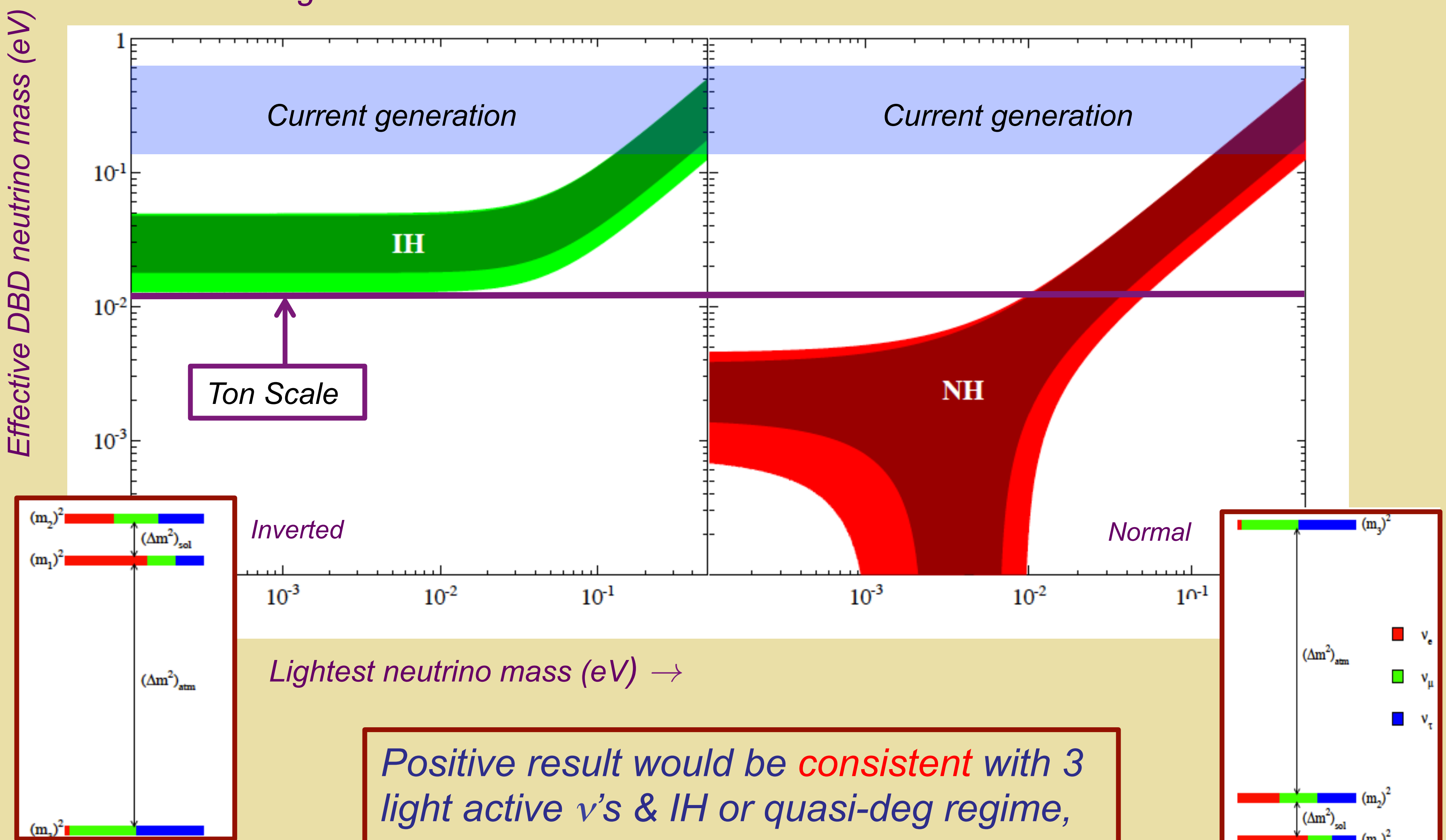


Expected significance for rejecting wrong hierarchy hypothesis

Blennow et al, 1311.1822

Interpreting a Positive Result

Three active light neutrinos



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

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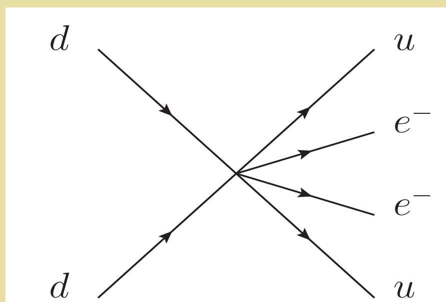
Dirac

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

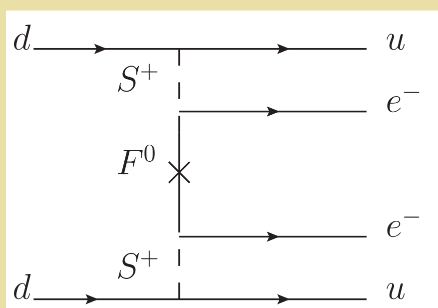
Majorana

TeV Scale LNV

$0\nu\beta\beta$ - decay



LHC: pp $\rightarrow$ jj e⁻e⁻



Effective operators:

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

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

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

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

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Dirac

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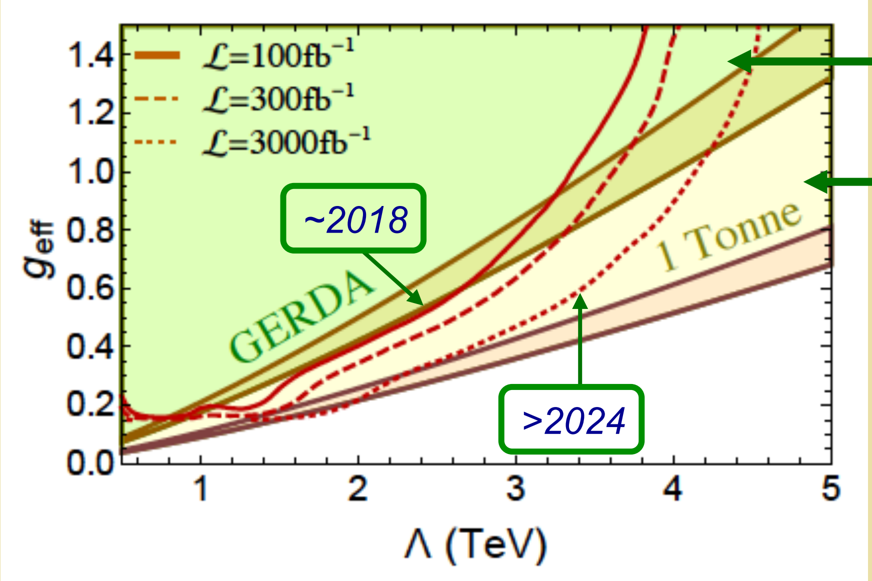
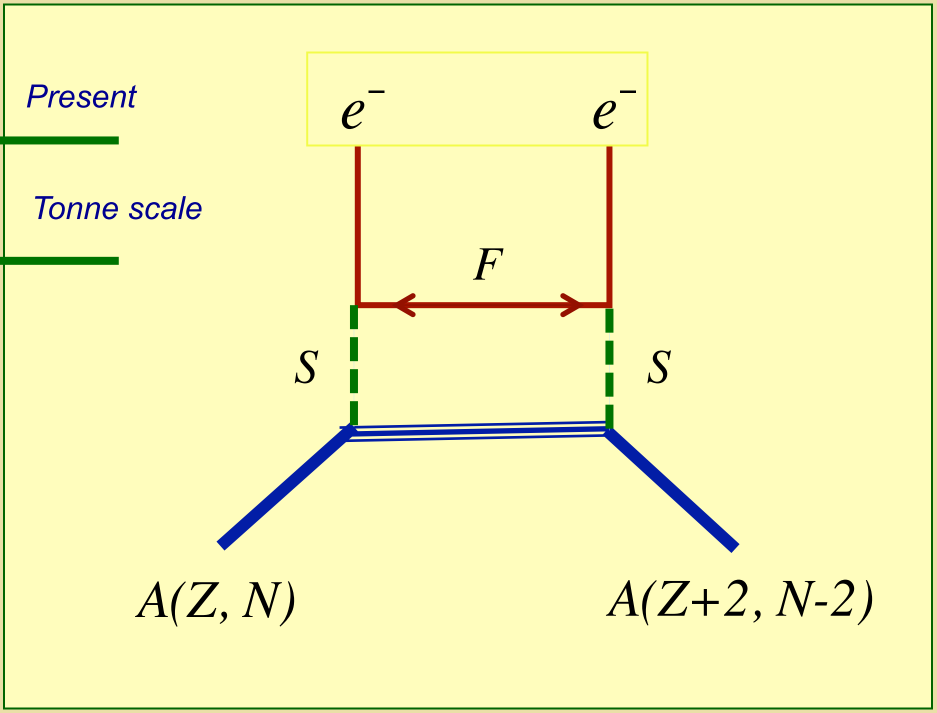
Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

0νββ / LHC Interplay: Matrix Elements

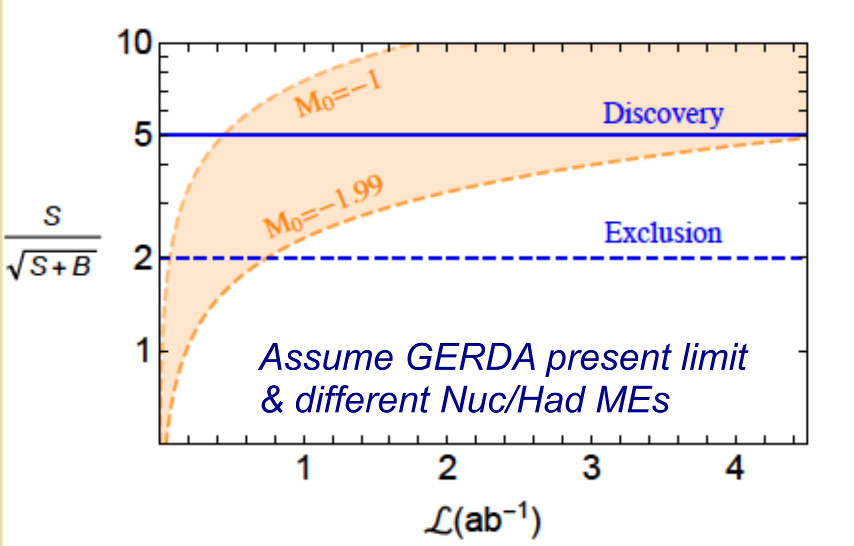
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

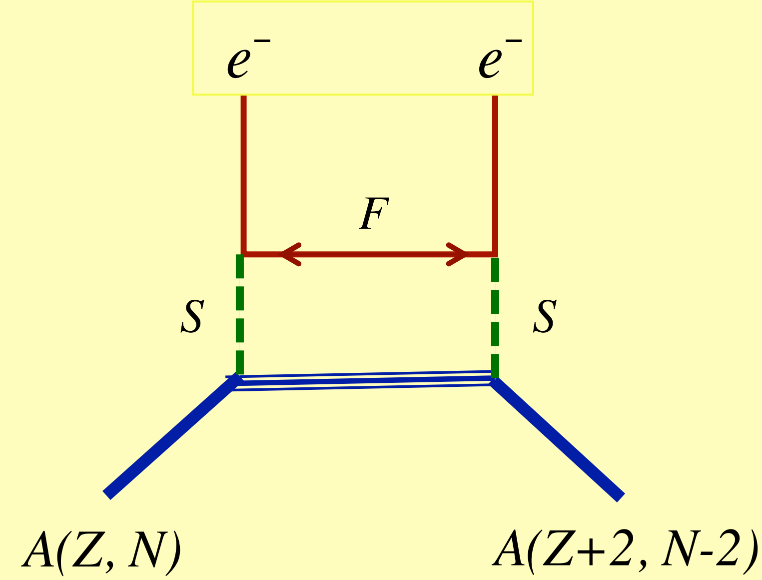
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

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

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Majorana

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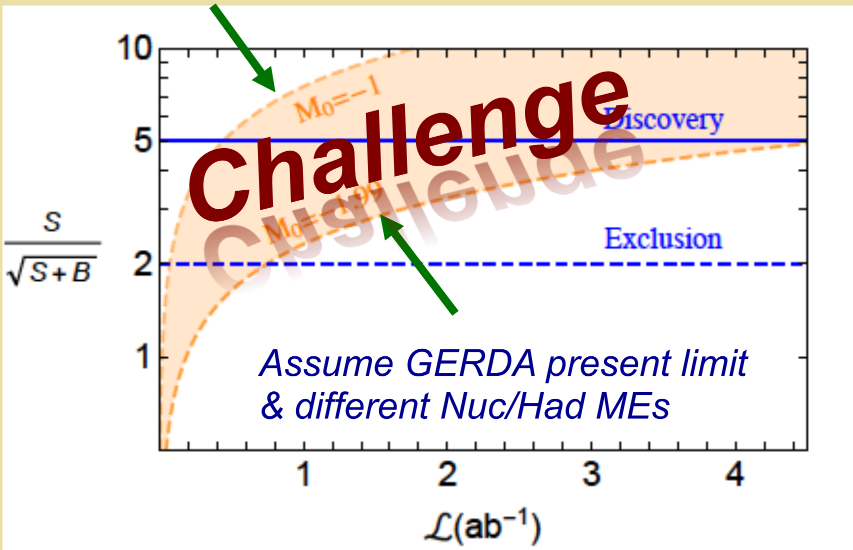
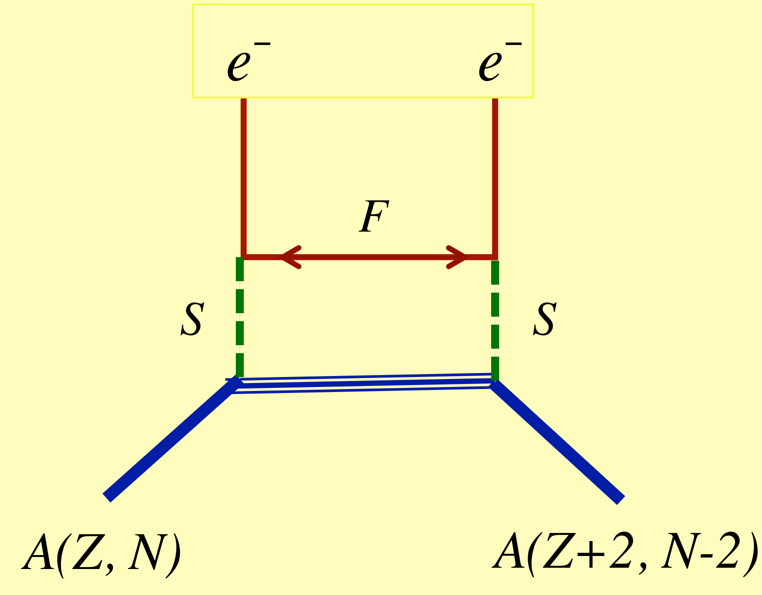




T. Peng, MRM, P. Winslow 1508.04444

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

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

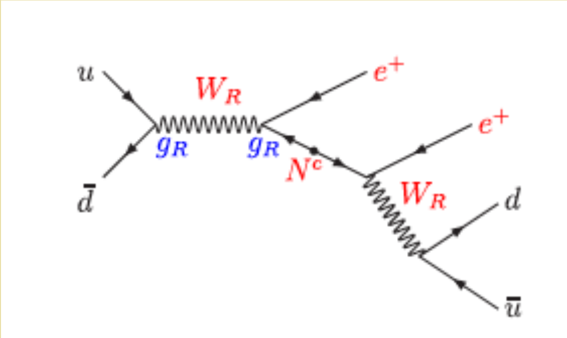
Dirac

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

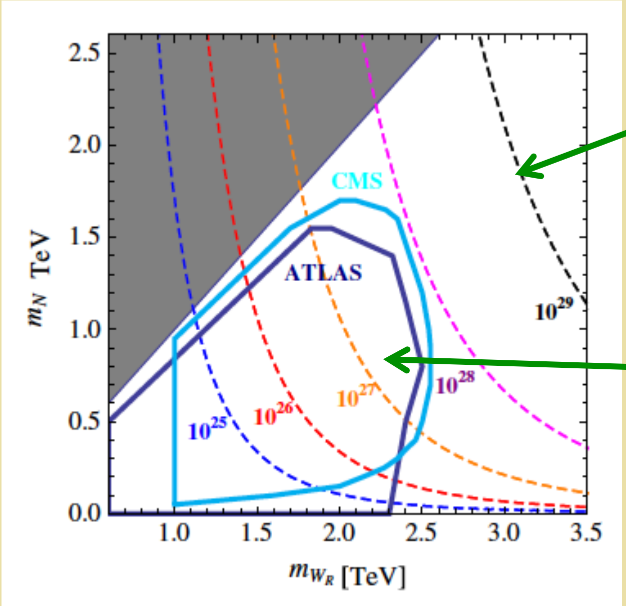
Majorana

LHC: SS Dilepton + Dijet

LHC Production & $0\nu\beta\beta$-Decay



Helo et al, PRD 88.011901, 88.073011



$0\nu\beta\beta$-Decay Sensitivity

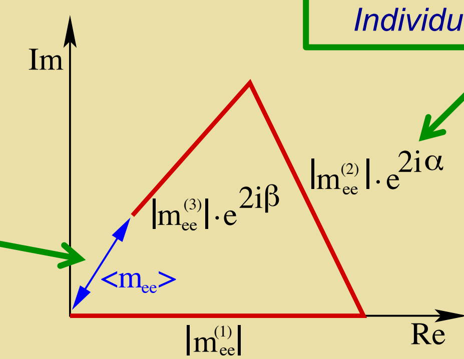
2ν DBD: $A(Z,N) \rightarrow A(Z+2, N-2) + e^- e^- \boxed{\bar{\nu}\,\bar{\nu}}$

If own antiparticle, can be emitted then absorbed during decay

0ν DBD: $A(Z,N) \rightarrow A(Z+2, N-2) + e^- e^-$

Individual contributions

All three light neutrinos participate $\rightarrow$ Rate governed by an effective mass

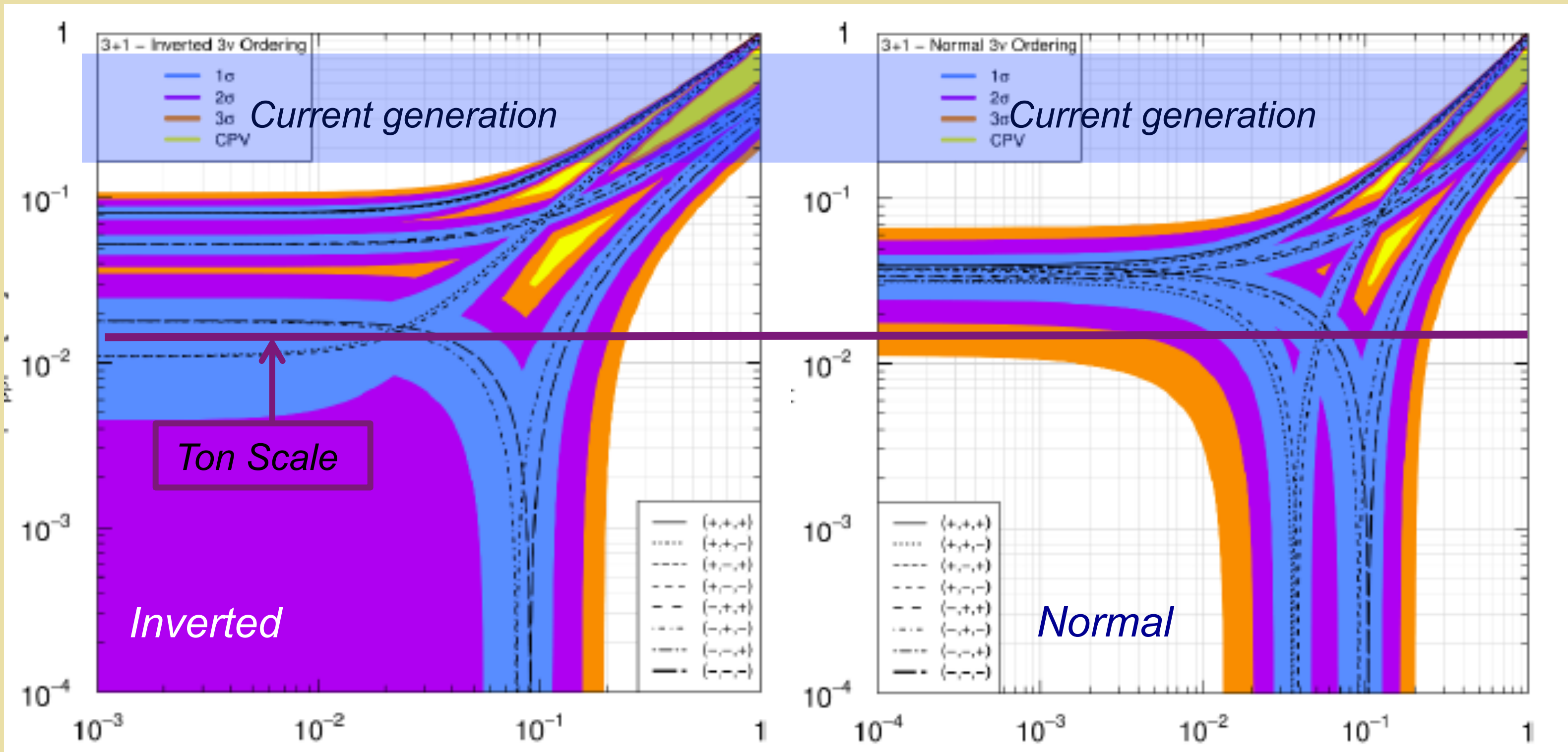


> 3 Light Neutrinos

3+1 active light neutrinos

Giunti & Zavanin, JHEP07 (2015) 171

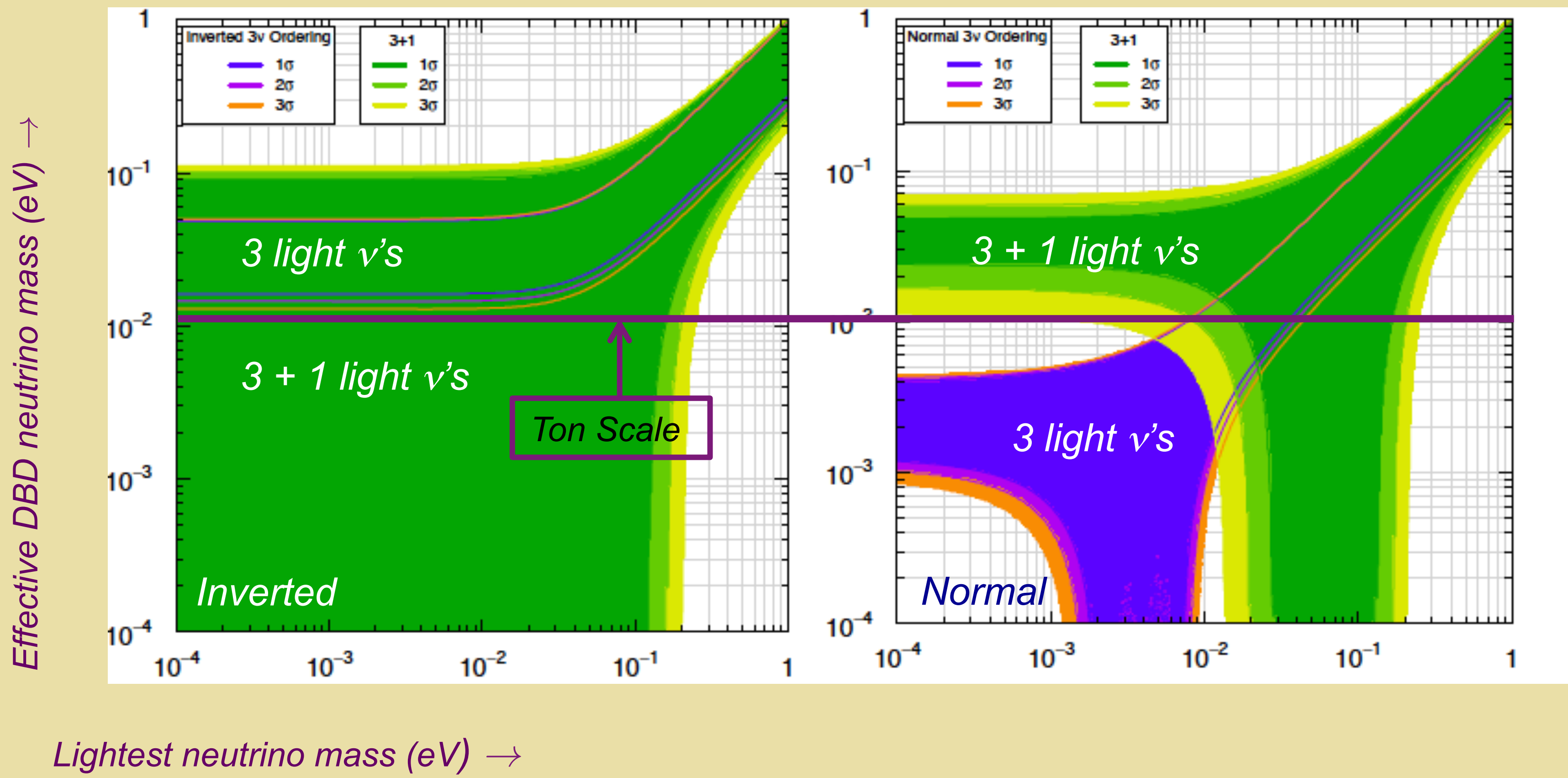
Effective DBD neutrino mass (eV)



Lightest neutrino mass (eV) $\rightarrow$

Positive result would be consistent with 3+1 light active ν's & NH, IH, or quasi-deg regime, but not definitive as to mechanism

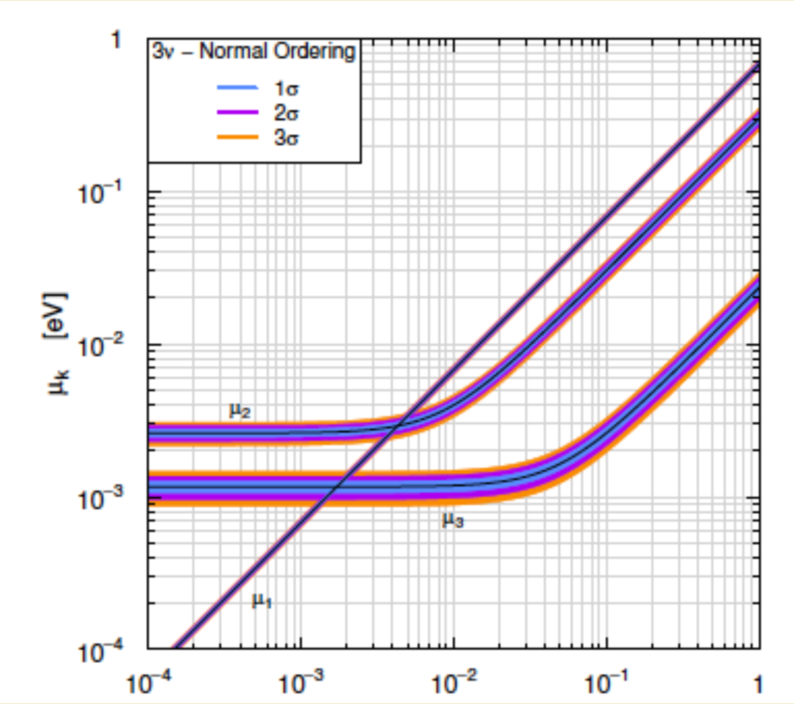
> 3 Light Neutrinos



Sterile Neutrinos & $0\nu\beta\beta$−Decay

Effective DBD neutrino mass (eV)

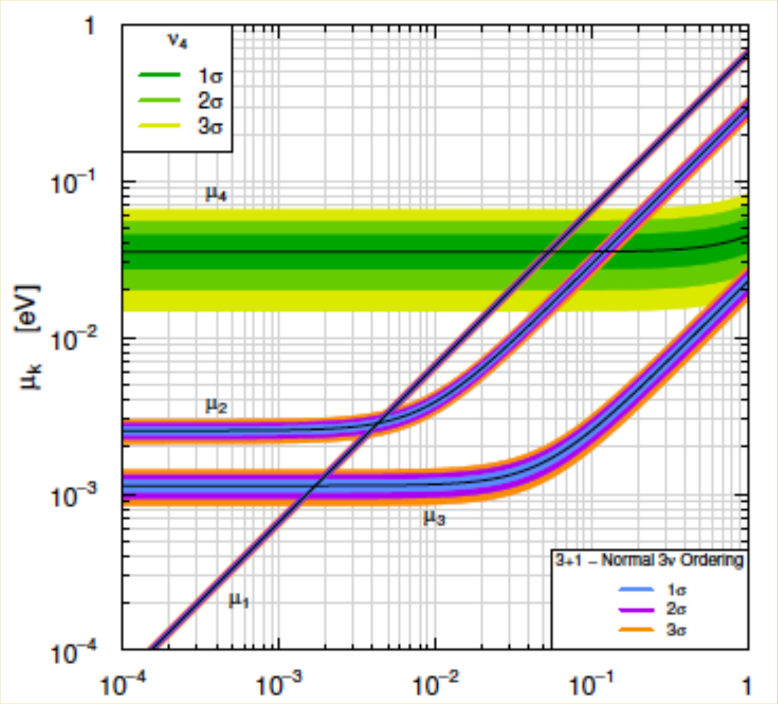
3 active light neutrinos



Lightest neutrino mass (eV) →

$$|m_{\beta\beta}| = \left|\mu_1 + \mu_2 e^{i\alpha_2} + \mu_3 e^{i\alpha_3}\right|$$

3+1 active light neutrinos



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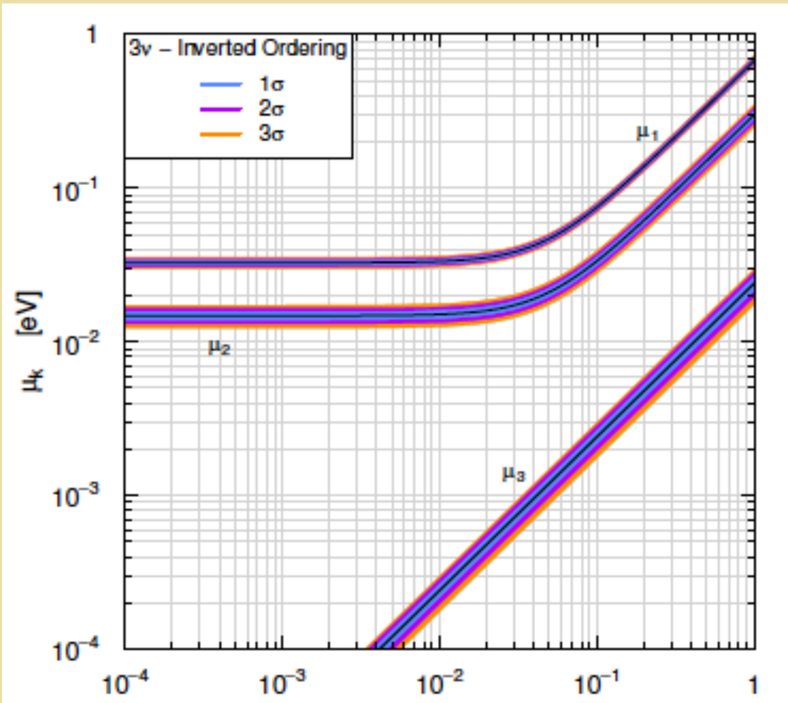
Giunti & Zavanin, JHEP07 (2015) 171

Sterile Neutrinos & $0\nu\beta\beta$−Decay

Effective DBD neutrino mass (eV)

3 active light neutrinos



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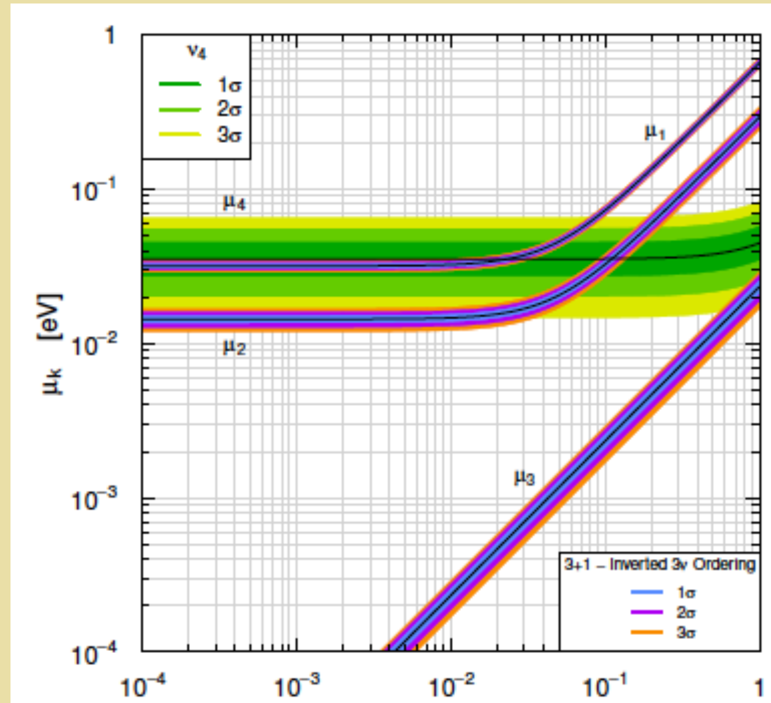


Lightest neutrino mass (eV) $\rightarrow$

$$|m_{\beta\beta}| = \left|\mu_1 + \mu_2 e^{i\alpha_2} + \mu_3 e^{i\alpha_3} + \mu_4 e^{i\alpha_4}\right|$$

Giunti & Zavanin, JHEP07 (2015) 171

CP

Higgs Portal CPV

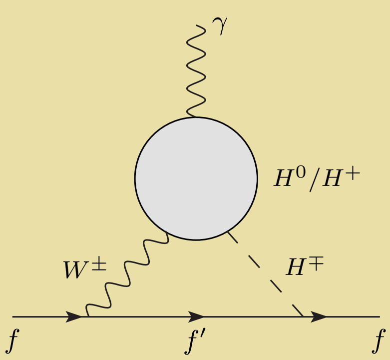
Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

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

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

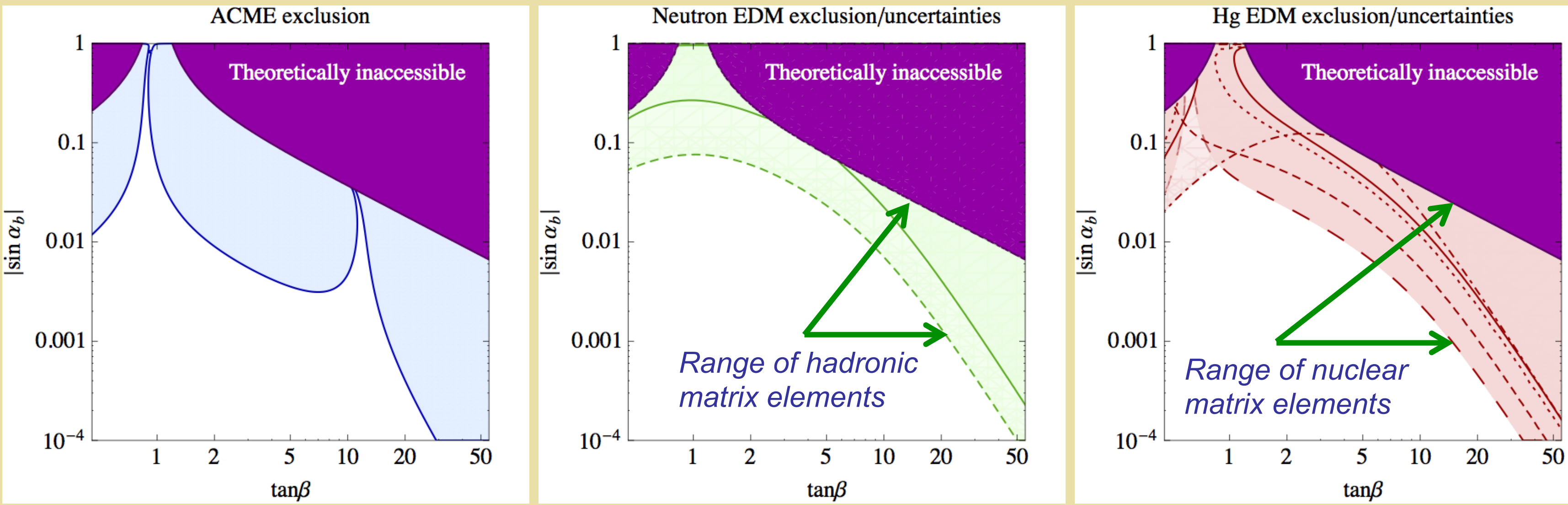
$$\boxed{\begin{aligned} \delta_1 &= \mathrm{Arg}\left[\lambda_5^*(m_{12}^2)^2\right] \ , \\ \delta_2 &= \mathrm{Arg}\left[\lambda_5^*(m_{12}^2)v_1 v_2^*\right] \end{aligned}} \xrightarrow{\textit{EWSB}} \boxed{\delta_2 \approx \frac{1 - \left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}{1 - 2\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}\delta_1}$$



Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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



Present

$\sin \alpha_b$: CPV scalar mixing

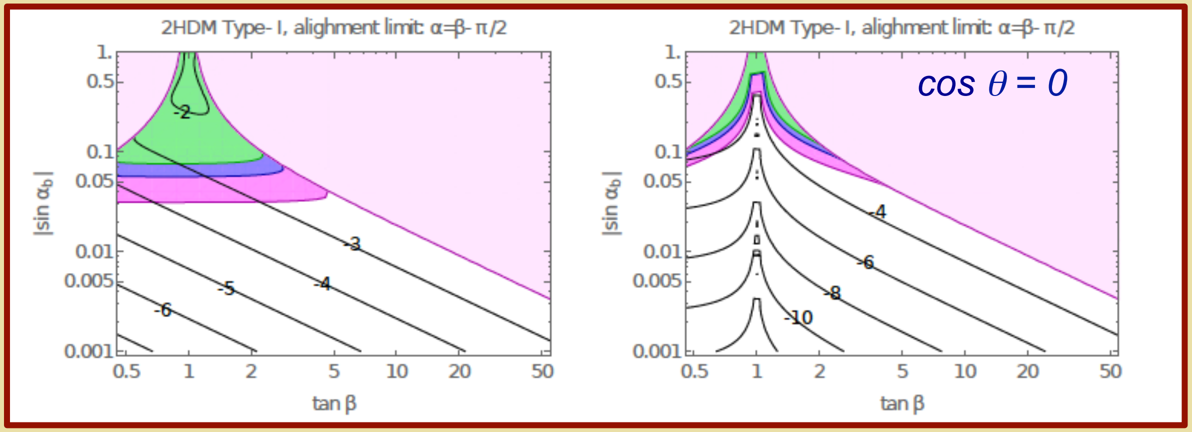
Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

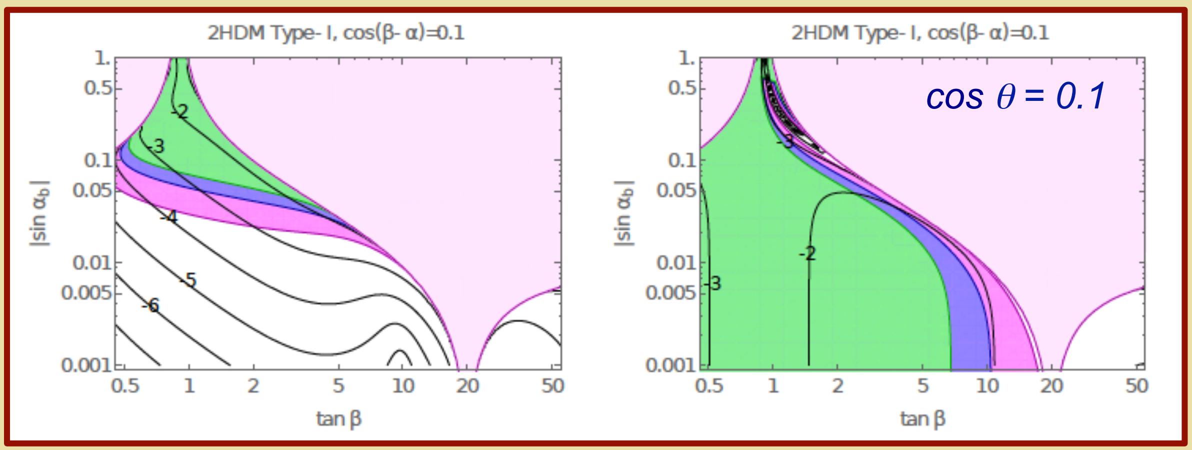
Chien-Yi Chen, Haolin Li, MJRM 1708.00435

$\boxed{h_{2,3} \to Z\, h_1 \to bb\ \ell\ell}$

LHC Future



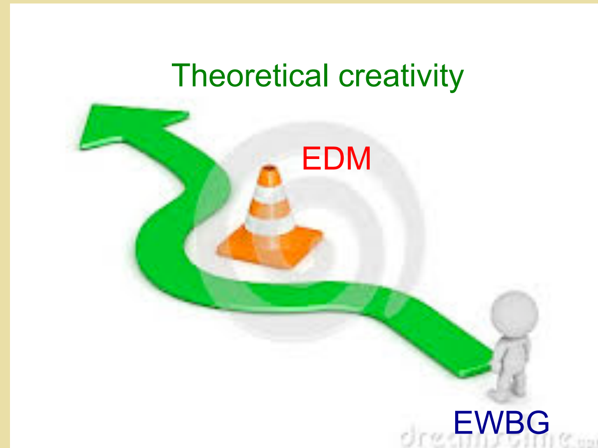
- Green: $100\ fb^{-1}$
- Blue: $300\ fb^{-1}$
- Magenta: $3\ ab^{-1}$



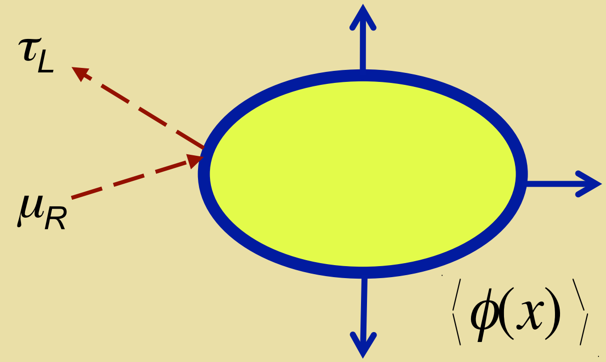
- Validated vs. ATLAS 8 TeV: 1502.04478
- Apply BDT for 14 TeV

$$g_{2z1} \propto -\alpha_b + O(\alpha_b \theta)$$
$$g_{3z1} \propto -\theta + O(\alpha_b^2)$$

CPV for EWBG



Flavored EW Baryogenesis



Flavor basis (high T)

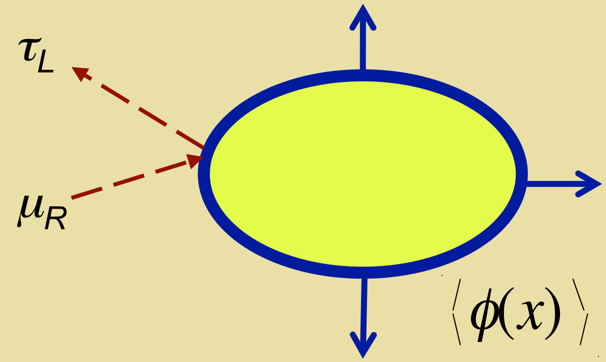
$$\mathscr{L}^{\text{Lepton}}_{\text{Yukawa}} = -\overline{E^i_L}\left[(Y_1^E)_{ij}\Phi_1 + (Y_2^E)_{ij}\Phi_2\right] e^j_R + h.c.$$

Mass basis (T=0)

$$\frac{m_f}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)h$$

Guo, Li, Liu, R-M, Shu 1609.09849
Chiang, Fuyuto, Senaha 1607.07316

Flavored EW Baryogenesis



CPV $h \to \tau\tau$

$\Delta\phi_\tau \sim 10^o$:

3 ab^{-1} @ LHC 14

Flavor basis (high T)

$$\mathscr{L}^{\text{Lepton}}_{\text{Yukawa}} = -\overline{E^i_L}\left[(Y^E_1)_{ij}\Phi_1 + (Y^E_2)_{ij}\Phi_2\right] e^j_R + h.c.$$

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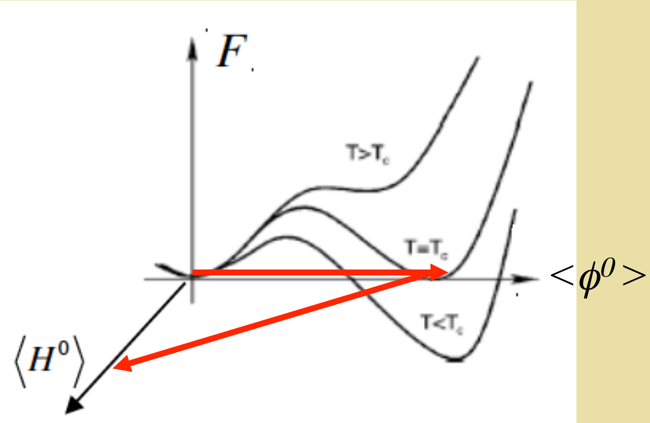
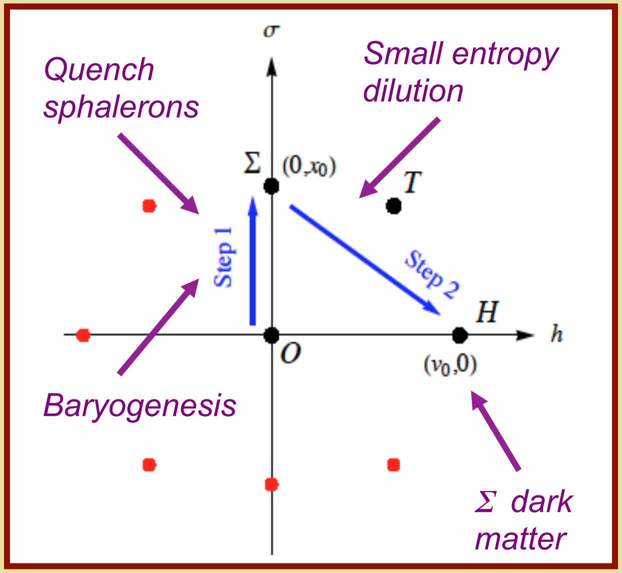
Chiang, Fuyuto, Senaha 1607.07316

Two-Step EW Baryogenesis





Inoue, Ovanesyan, R-M: 1508.05404

Illustrative Model:

New sector: "Real Triplet" Σ
Gauge singlet S

$H \rightarrow$ Set of "SM" fields: 2 HDM

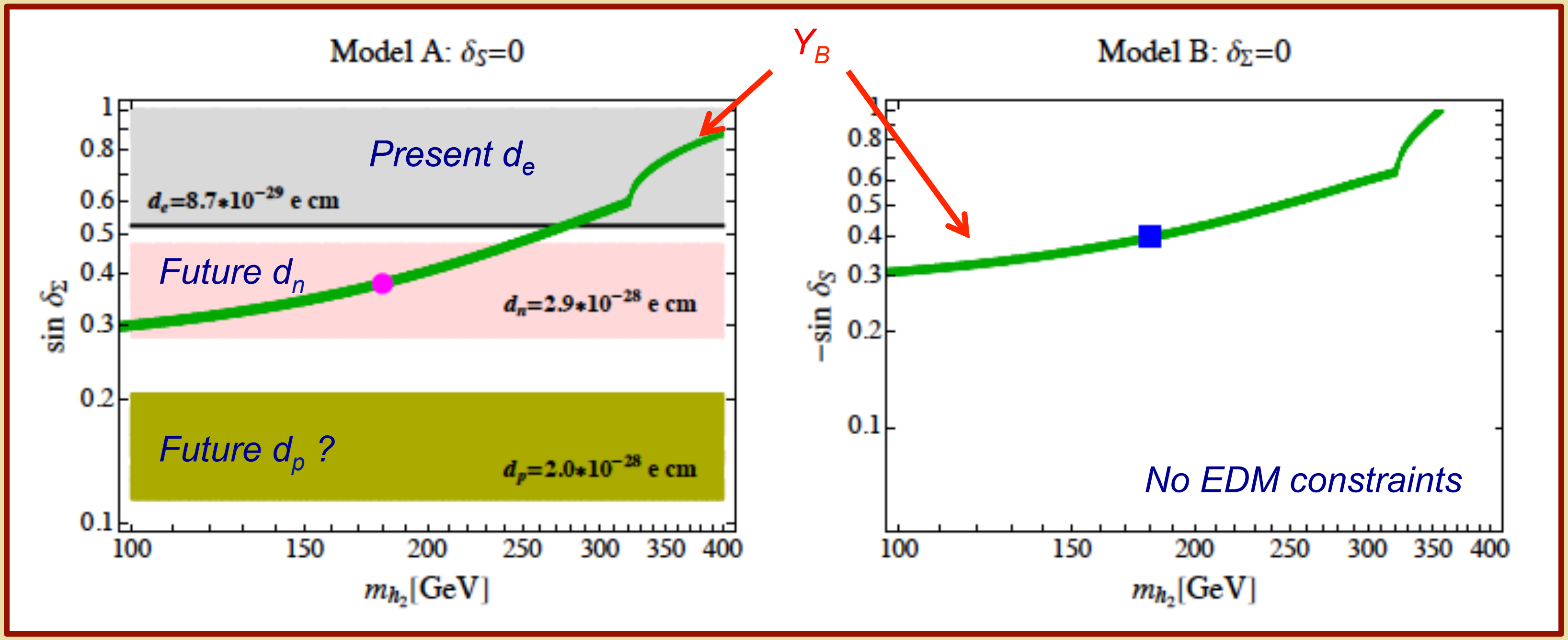
(SUSY: "TNMSSM", Coriano…)

Two CPV Phases:

δ_Σ : *Triplet phase*
δ_S : *Singlet phase*

Two-Step EW Baryogenesis & EDMs

Two cases: (A) $\delta_S = 0$ (B) $\delta_\Sigma = 0$



Inoue, Ovanesyan, R-M: 1508.05404