Image C. Hambrock

Heavy Neutral Lepton Searches
Suggestions from a Theorist

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DESY Hamburg

Marco Drewes, Université catholique de Louvain

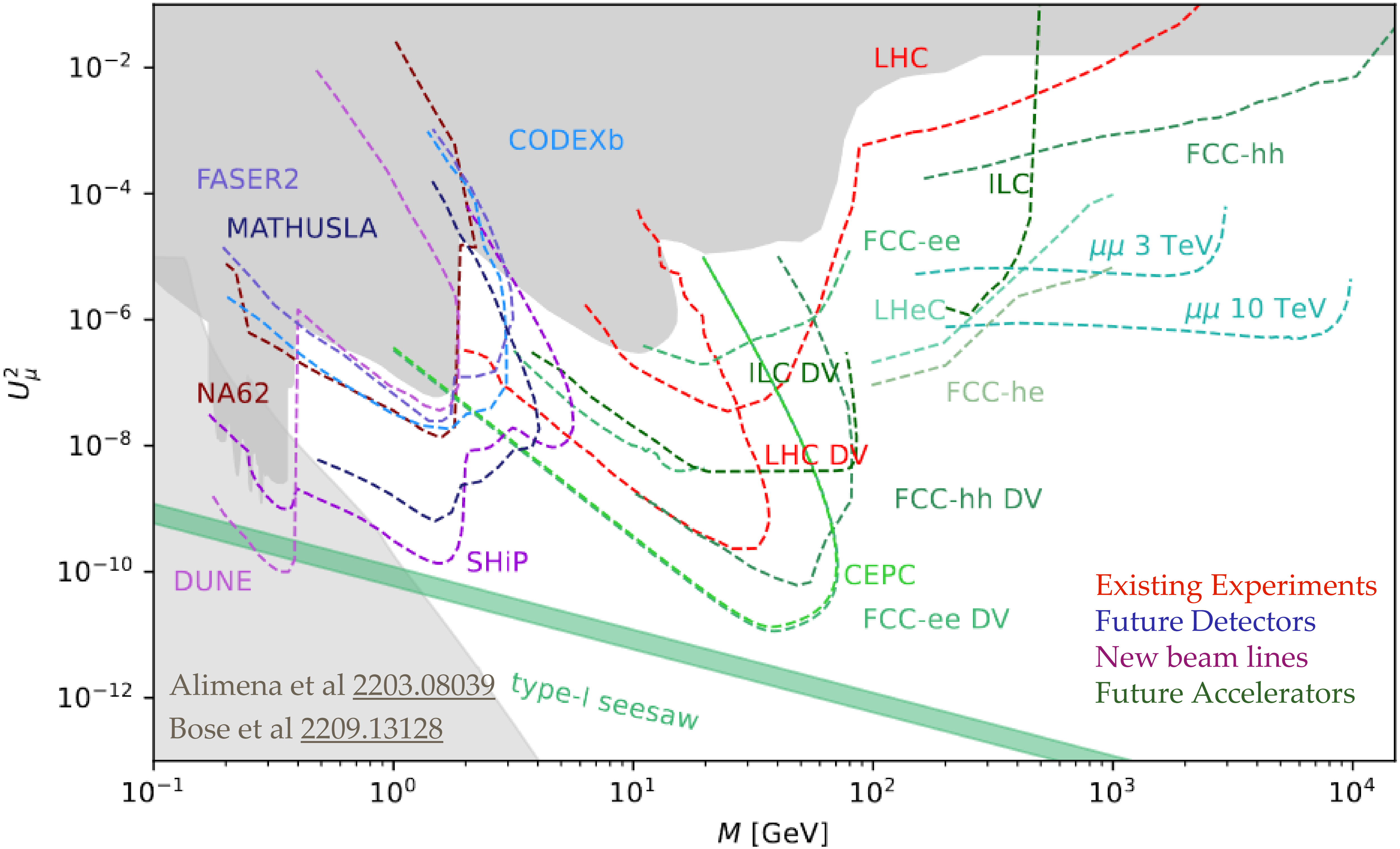
HNL SM Weak Interactions

Common phenomenological description: "Single HNL Model"

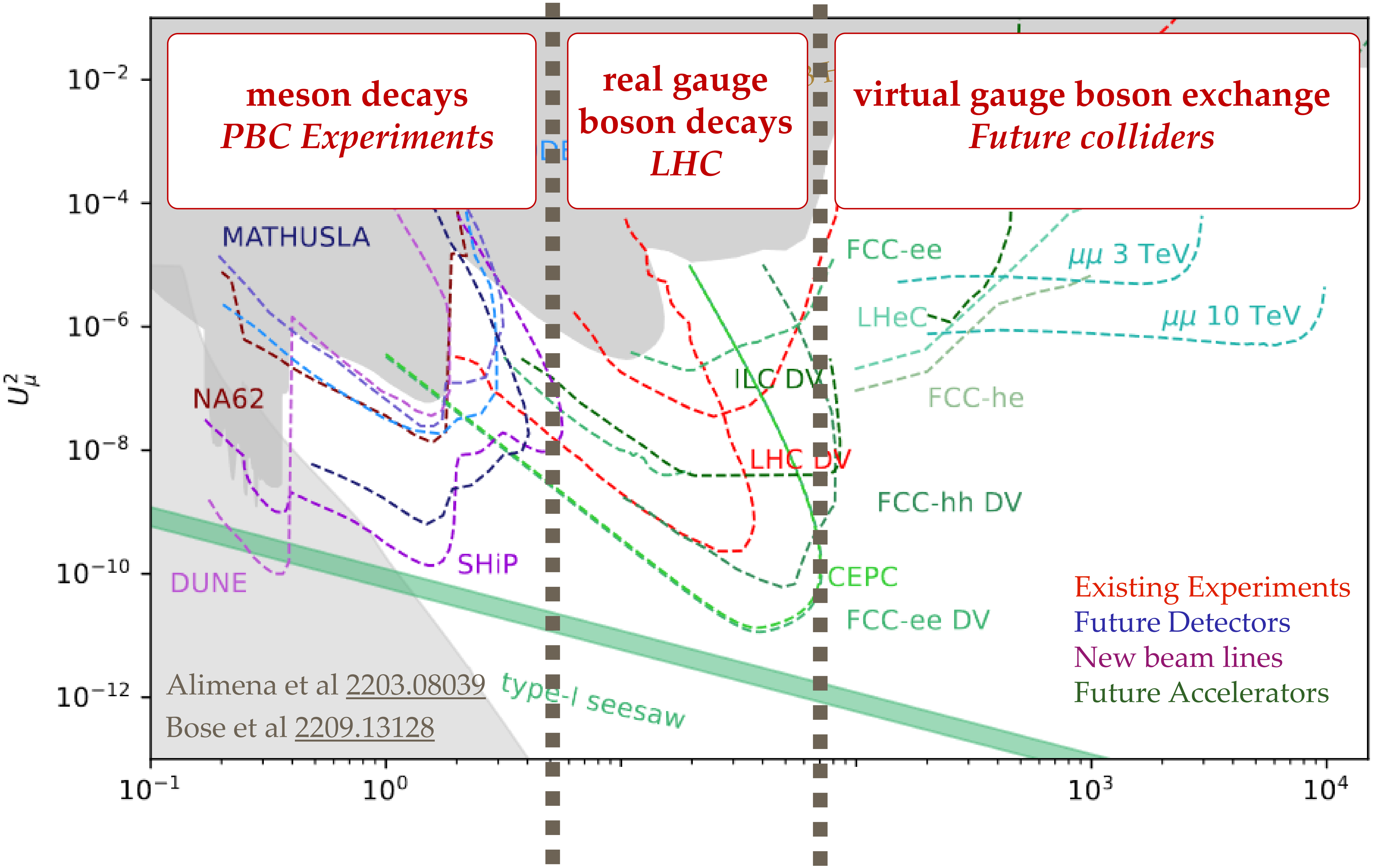
$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}\theta^*_\alpha\gamma^\mu e_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\overline{N}\theta^*_\alpha\gamma^\mu\nu_{L\alpha}Z_\mu - \frac{M}{v}\theta_\alpha h\overline{\nu_{L\alpha}}N + \text{h.c.}$$

- One flavour of HNLs N
- Couples to SM only through mixing θ_a with SM neutrinos, where a = e, μ, τ
- Model with five parameters : M, θ_e, θ_μ, θ_τ, and R_{ll}.
- **R_{ll} is ratio of lepton number violating (LNV) to lepton number conserving (LNC) N decays; $R_{ll} = 1$ for Majorana N and $R_{ll} = 0$ for Dirac N.**

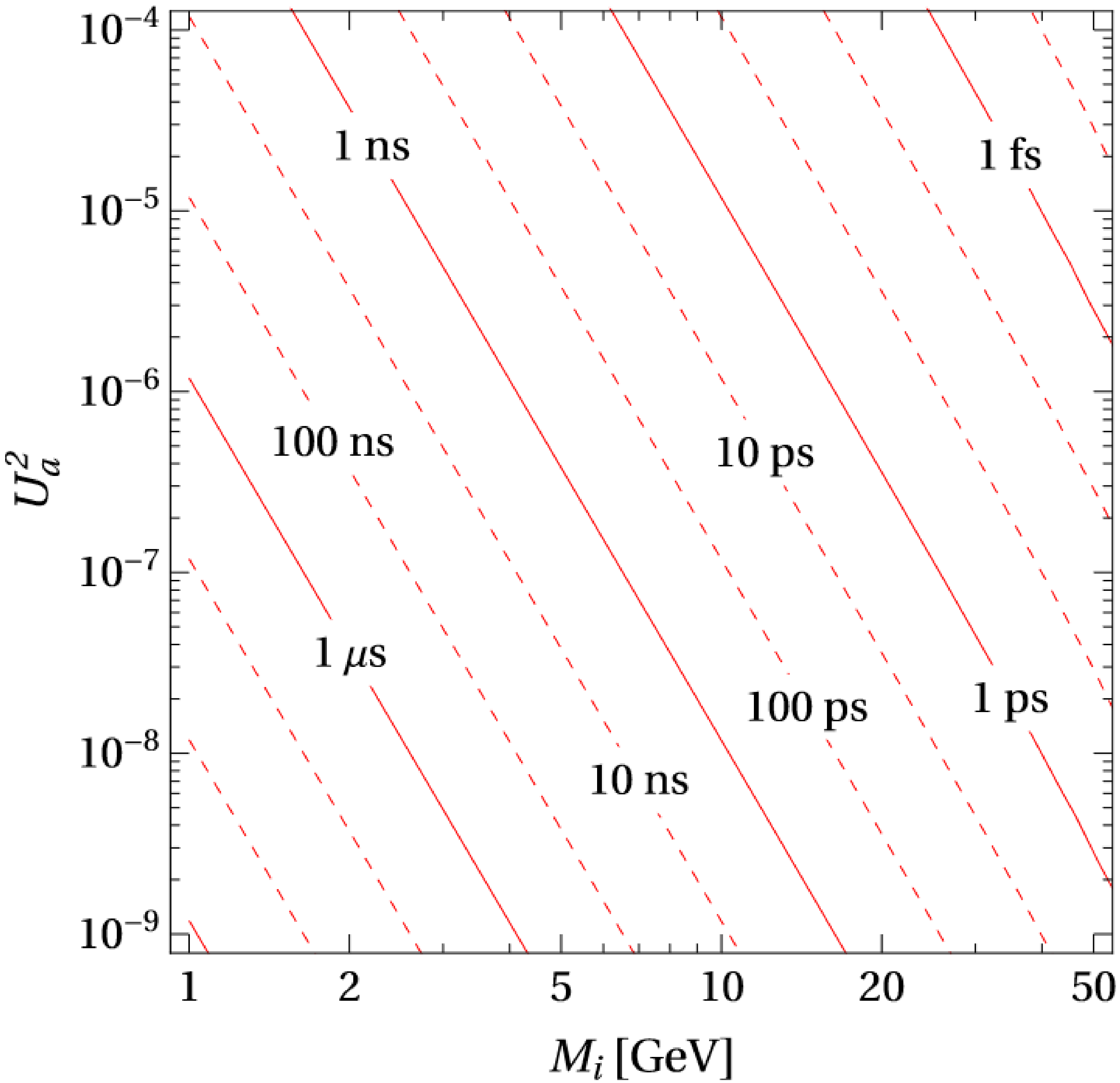
Search Summary



HNL Production



HNL Lifetime



- HNL decay width in rest frame scales as

$$\Gamma_N \sim U^2 M^5 G_F^2$$

- Decay length in lab frame

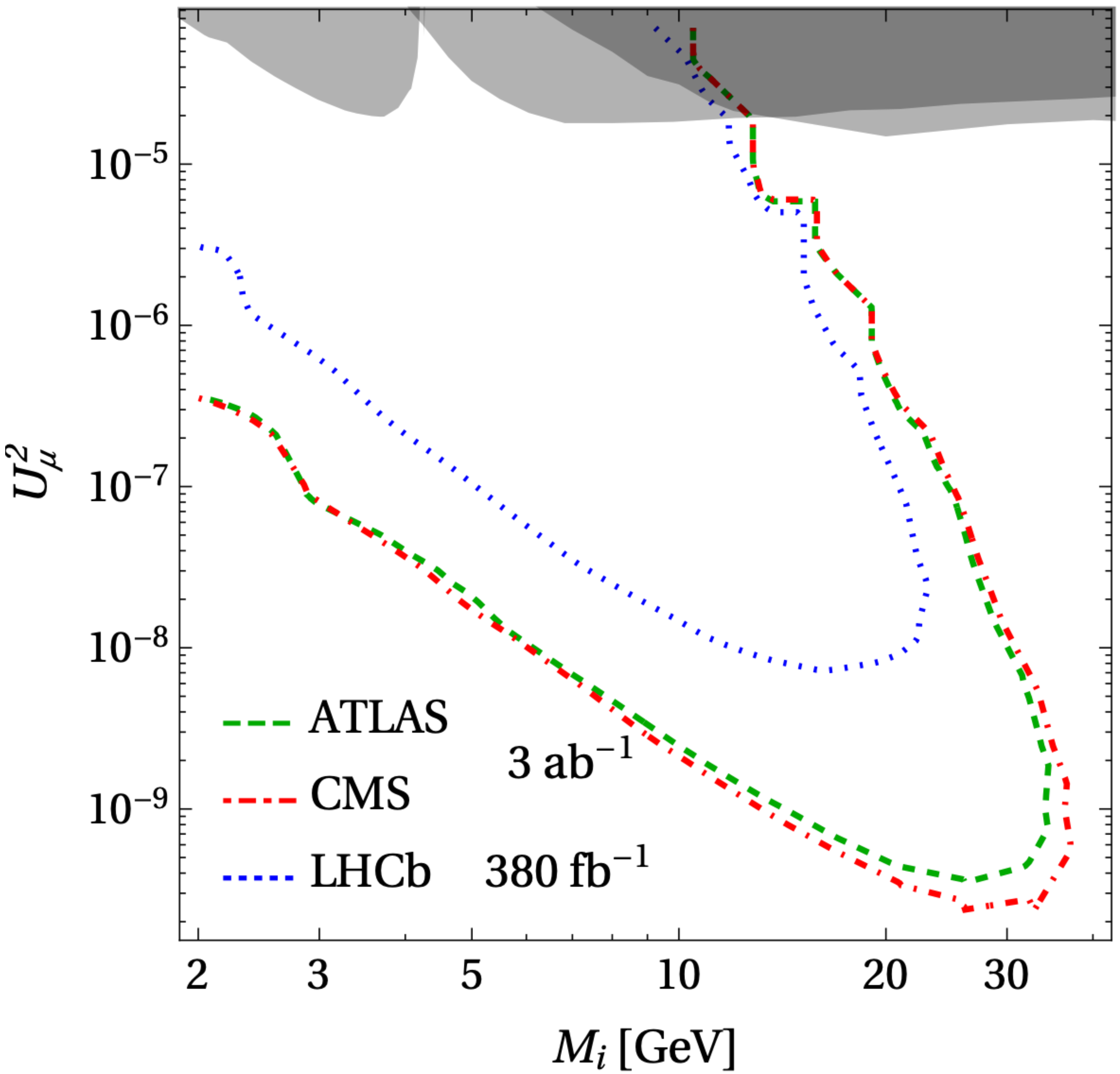
$$\lambda_N = \frac{\beta\gamma}{\Gamma_N} \sim \frac{\mathrm{p}}{U^2 M^6 G_F^2}$$

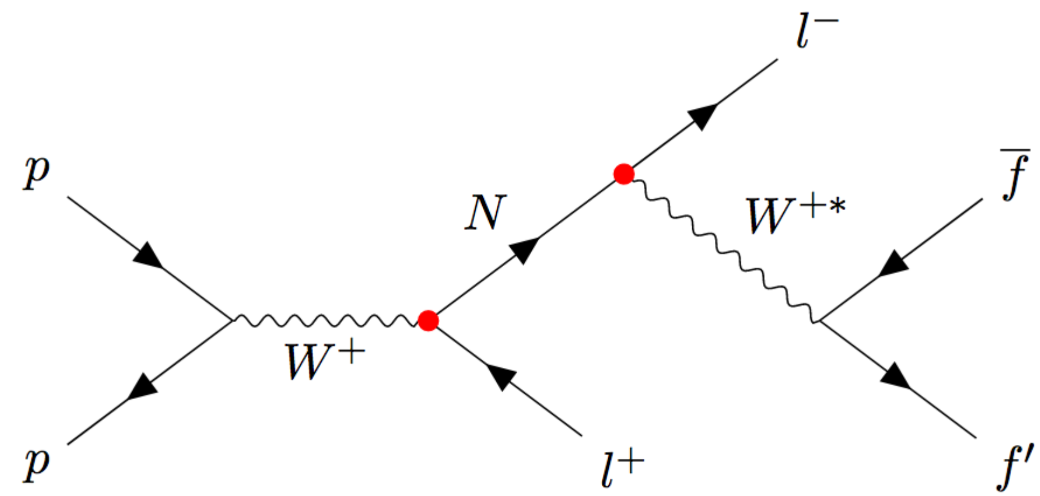
- For $M << m_W$

$$\lambda_N \simeq \frac{0.036}{U^2}\left(\frac{\mathrm{p}}{\mathrm{GeV}}\right)\left(\frac{M}{\mathrm{GeV}}\right)^{-6} \mathrm{cm}$$

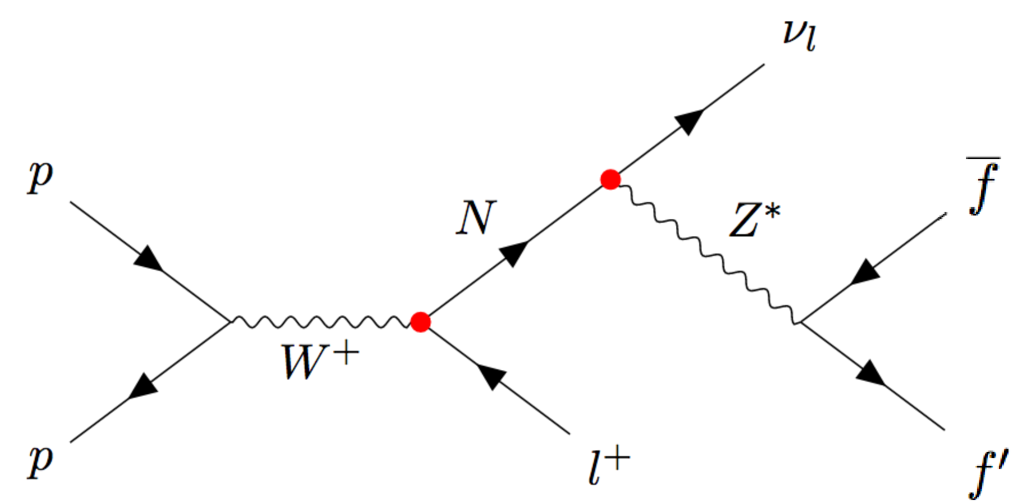
- In regime where HNLs can be produced efficiently they are often long-lived

HL-LHC Displaced Vertex Search





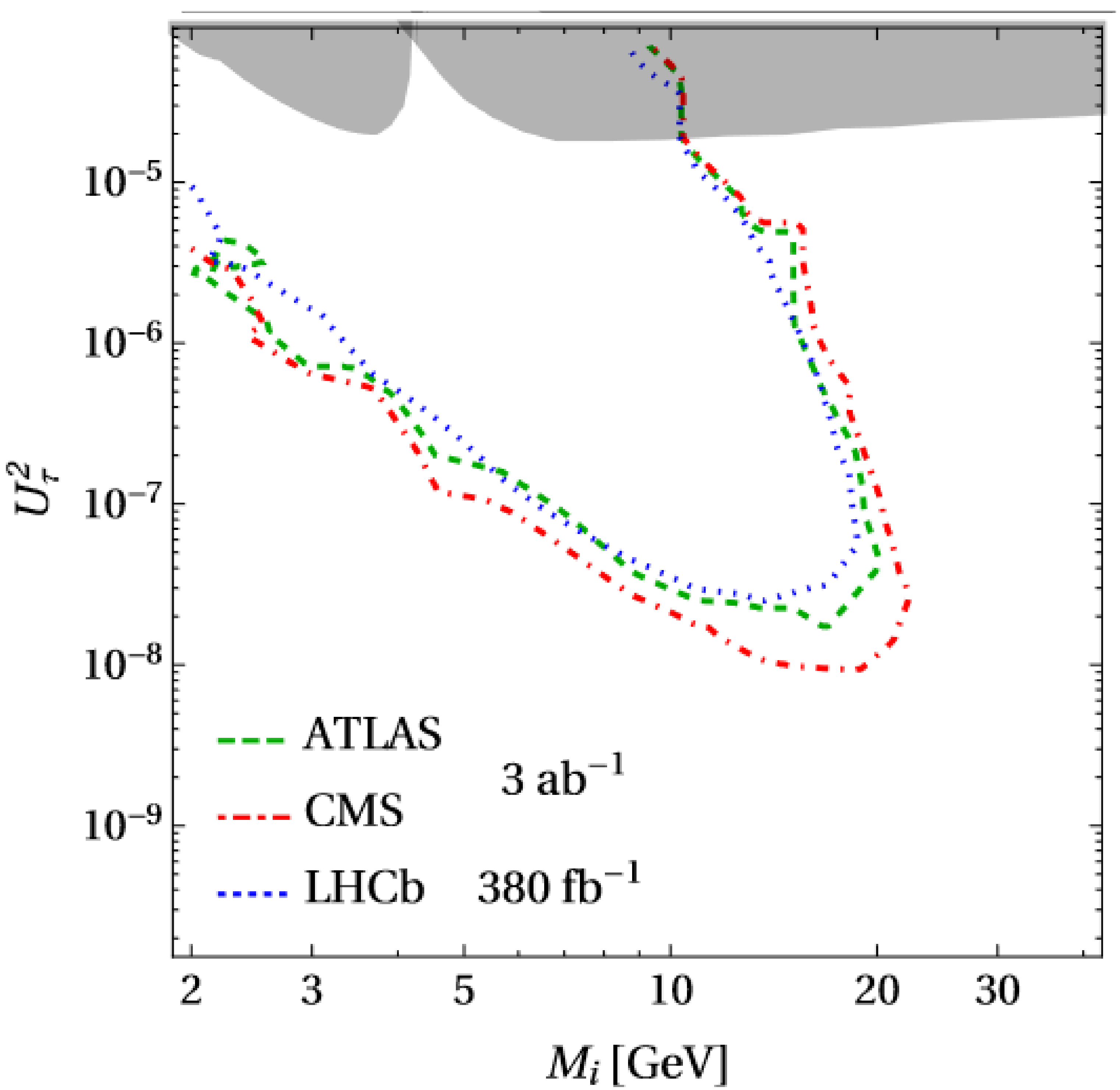
(a) Charged current decay

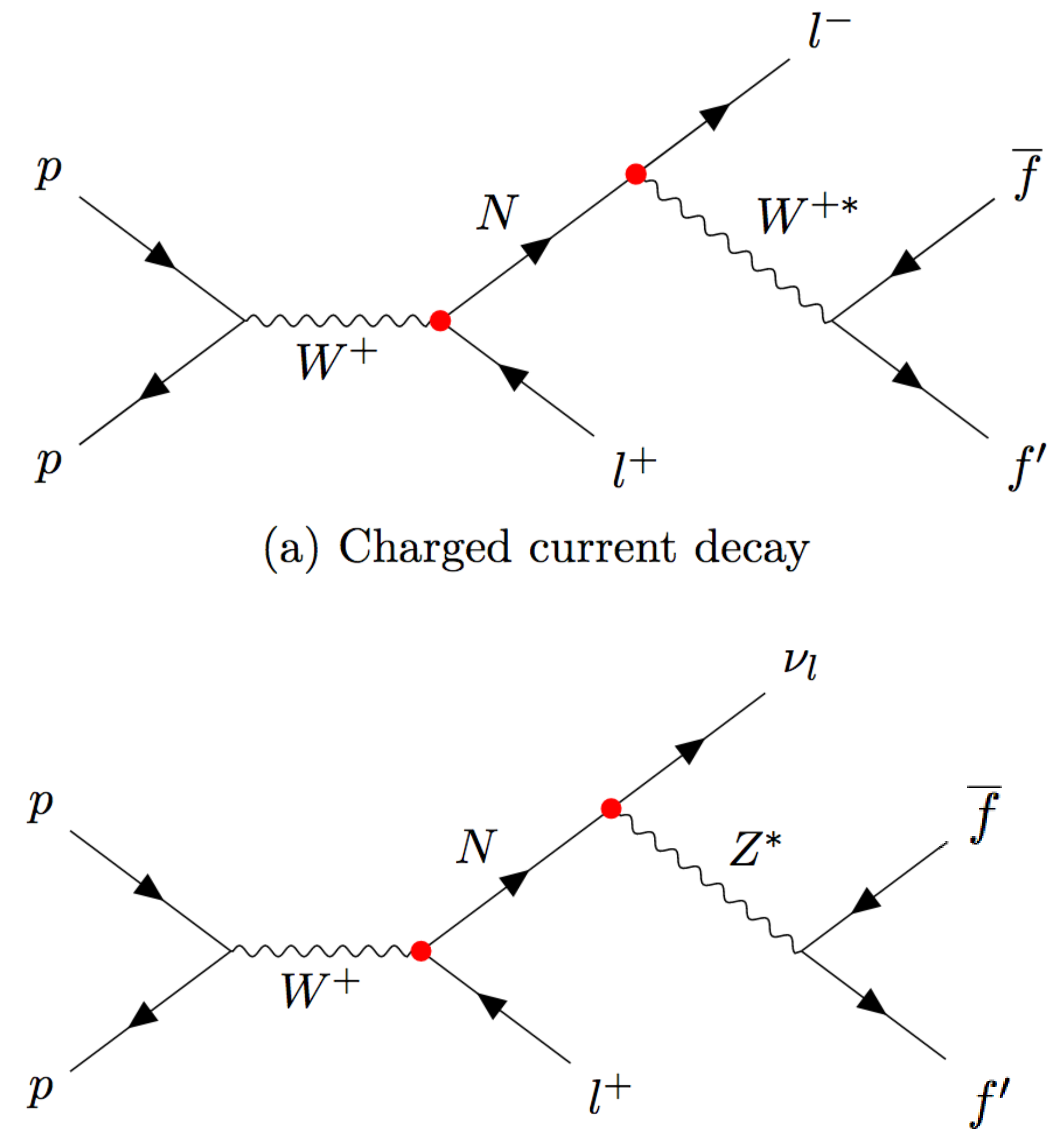


(b) Neutral current decay

MaD/Hajer 1903.06100

HL-LHC Displaced Vertex Search



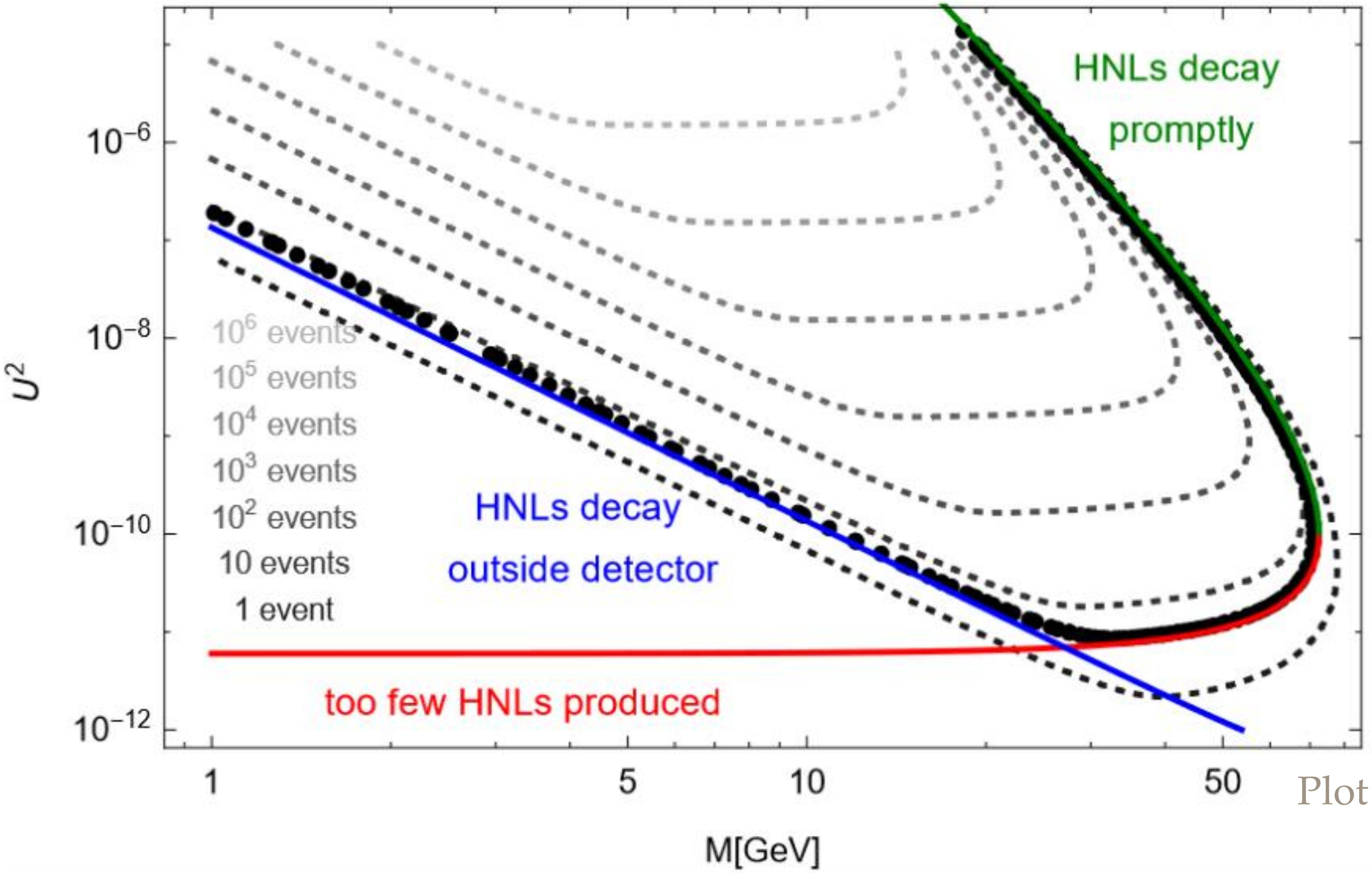


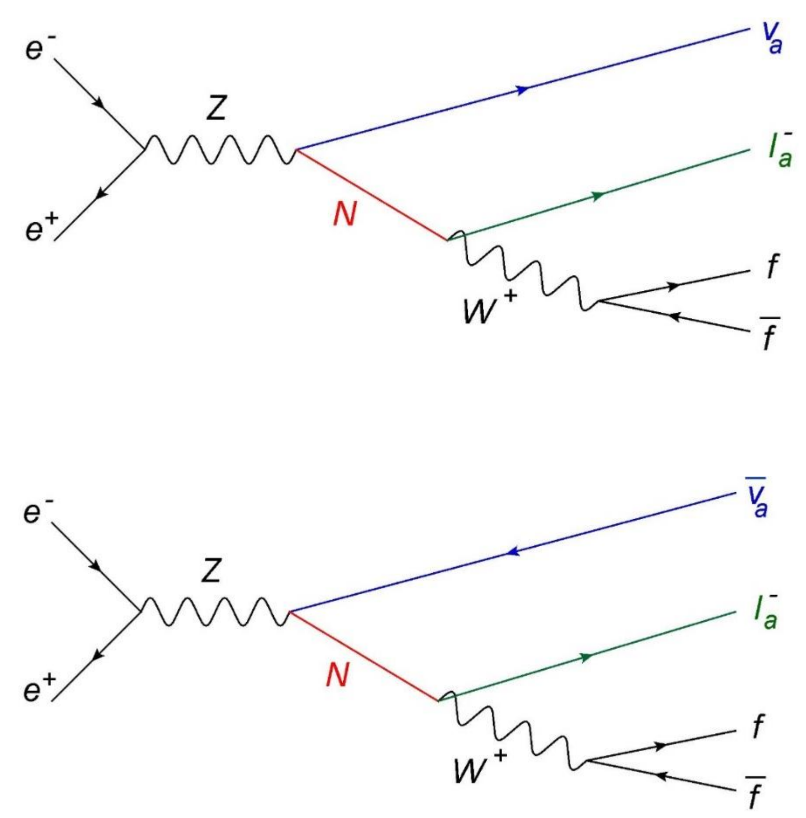
(a) Charged current decay

(b) Neutral current decay

MaD/Hajer 1903.06100

DV Vertex Searches during Z-pole Run





proposed in Blondel et al 1411.5230

Plot and estimates from MaD 2210.17110

$$\lambda_N = \frac{\beta\gamma}{\Gamma_N} \simeq \frac{1.6}{U^2 c_{\rm dec}} \left(\frac{M}{\rm GeV}\right)^{-6} \left(1 - (M/m_Z)^2\right) \text{cm.}$$

$c_{\rm dec} = 1 \ (c_{\rm dec} = 1/2)$ for Majorana (Dirac) HNL

Can one find HNLs at colliders?

Common phenomenological description: “Single HNL Model”

$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}\theta^*_\alpha\gamma^\mu e_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\overline{N}\theta^*_\alpha\gamma^\mu \nu_{L\alpha}Z_\mu - \frac{M}{v}\theta_\alpha h\overline{\nu_{L\alpha}}N + \text{h.c.}$$

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- ν-masses are key motivation for HNLs
- ν-masses naively scale $m_\nu \sim \theta^2 M$, implying tiny $U^2 = |\theta|^2 \sim m_\nu/M$
- production cross section at colliders scales as $\sigma_N \sim \theta^2 \sigma_\nu$

MUCH too low to be see at the LHC or HL-LHC!!!

Minimal vs Non-minimal Scenarios

minimal = literally only add HNLs

- generic EFT description of models with M < TeV << Λ
- can even be UV complete in the sense $\Lambda = M_P$
- … or at least up to the scale of inflation

non-minimal = anything else (gauge extensions, extended scalar sector, RHN as "portal" to dark sector…)

- can use generic EFT description for models with M < TeV < Λ
- need full dark sector description if M, Λ < TeV
- Common gauge-extensions: Left-right symmetric model, gauged $U(1)_{B-L}$

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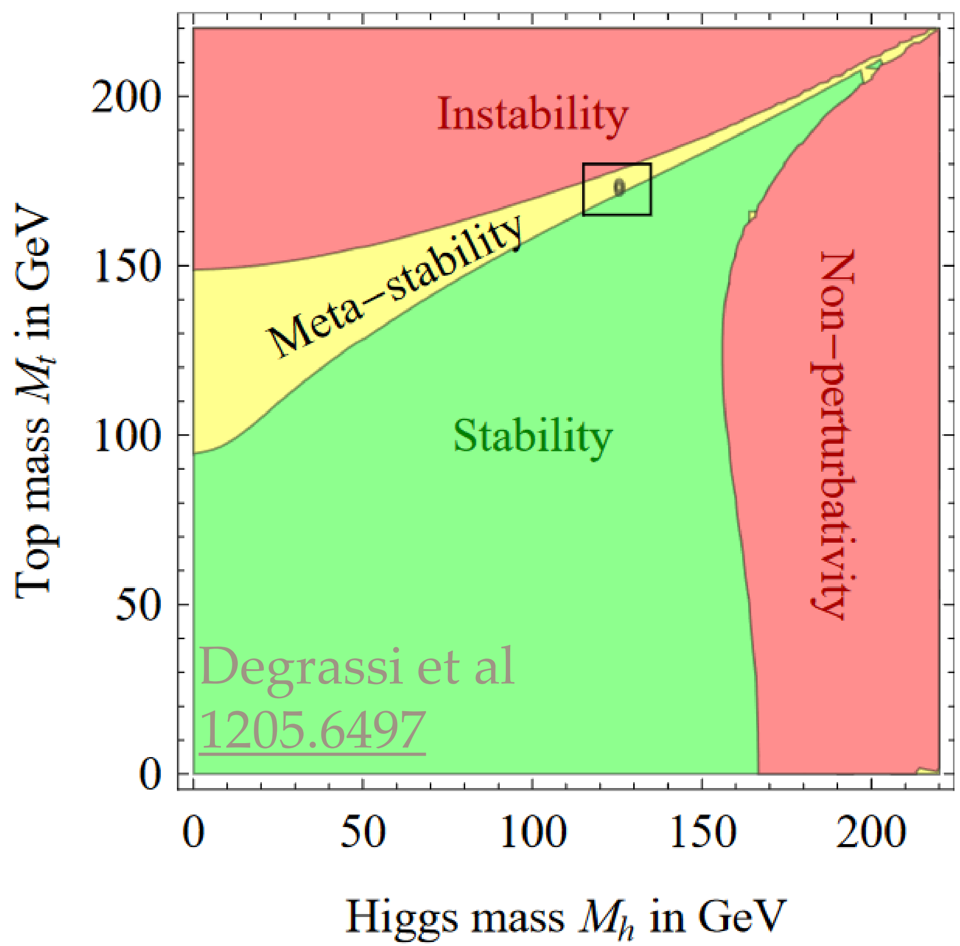
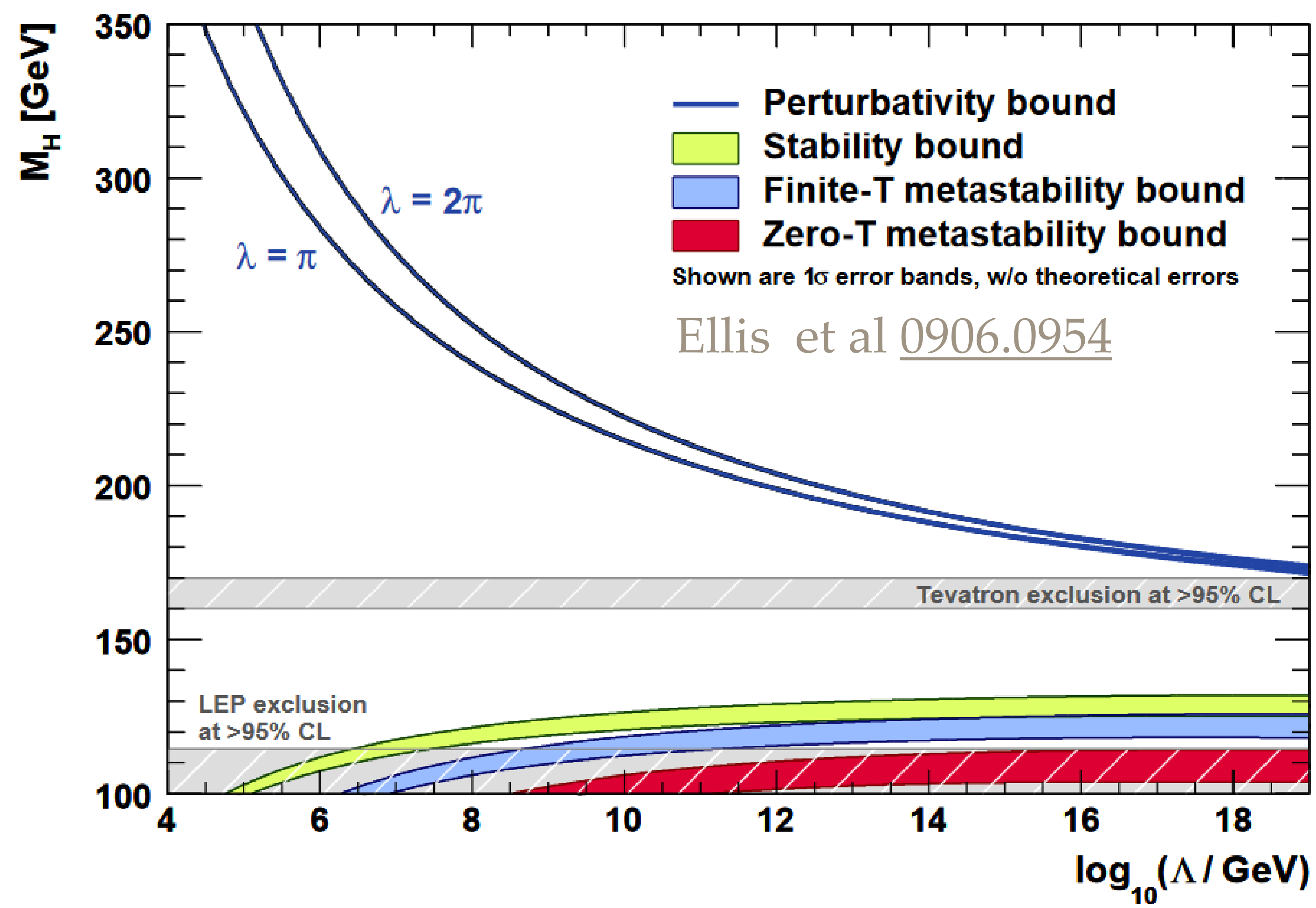
- This is not a realistic model of neutrino mass, but can effectively describe some pheno aspects of realistic models with suitable choices of : M, θ_e, θ_μ, θ_τ, R_{ll}.
- If coherent effects between production and decay can be neglected, one can consider the real quantities $U^2_\alpha = |\theta_\alpha|^2$

Why a Low Scale Seesaw?

Why should the seesaw scale be low?





- Apart from explaining data extremely well, the SM is also a fully consistent effective field theory up to the Planck scale
- Existence of new scales in between would spoil this and e.g. de-stabilise the vacuum (though this can of course in principle be fixed, as in SUSY)
- Together with current experimental bounds (e.g. flavour physics etc) this may be interpreted as indirect evidence for absence of a new scale!?!

e.g. Bezrukov et al 1205.2893

Why are the Neutrino masses small?

$$\frac{1}{2}\overline{\ell_L}\tilde{\Phi}c^{[5]}\Lambda^{-1}\tilde{\Phi}^T\ell_L^c + h.c. \qquad\qquad m_\nu = -v^2 c^{[5]}\Lambda^{-1}$$

a) Suppression by heavy scale (classic high scale seesaw mechanism)

- Smallness is result of $v/\Lambda << 1$
- Wilson coefficients $c_{[n]}$ can be O[1]
- Need no small numbers…
- …but contribute to hierarchy problem (unless SUSY or so added
- …can destabilises Higgs potential

b) Small numbers

- Smallness is result of small Wilson coefficients $c_{[n]}$
- Generally considered "tuned" unless smallness has a reason (breaking of symmetry by flavons, radiative breaking, gravitational origin…)

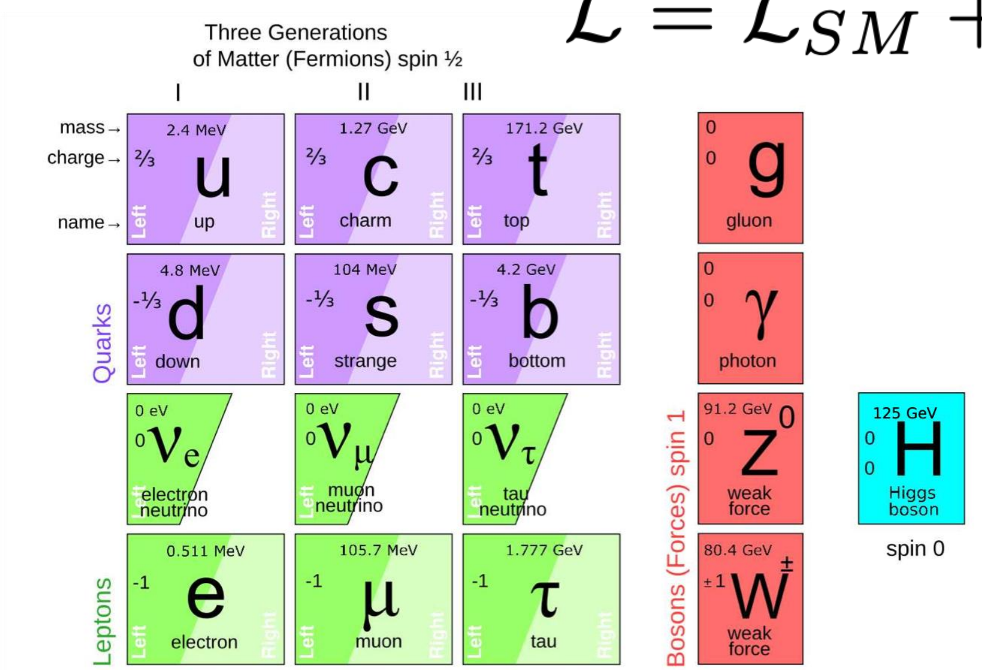
c) Protecting symmetry

- Ratio v/Λ and Wilson coefficients $c_{[n]}$ can both be O[1] if a flavour symmetry in $m\nu$ keeps the eigenvalues small
- Prime example: Approximate global $U(1)_{B-L}$, as in SM
- Low Λ and large couplings $c_{[n]}$ ideal for experimental searches!

section 5.1 in 2102.12143

The Seesaw Mechanism (type I)

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L$$
$$-\frac{1}{2}(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$



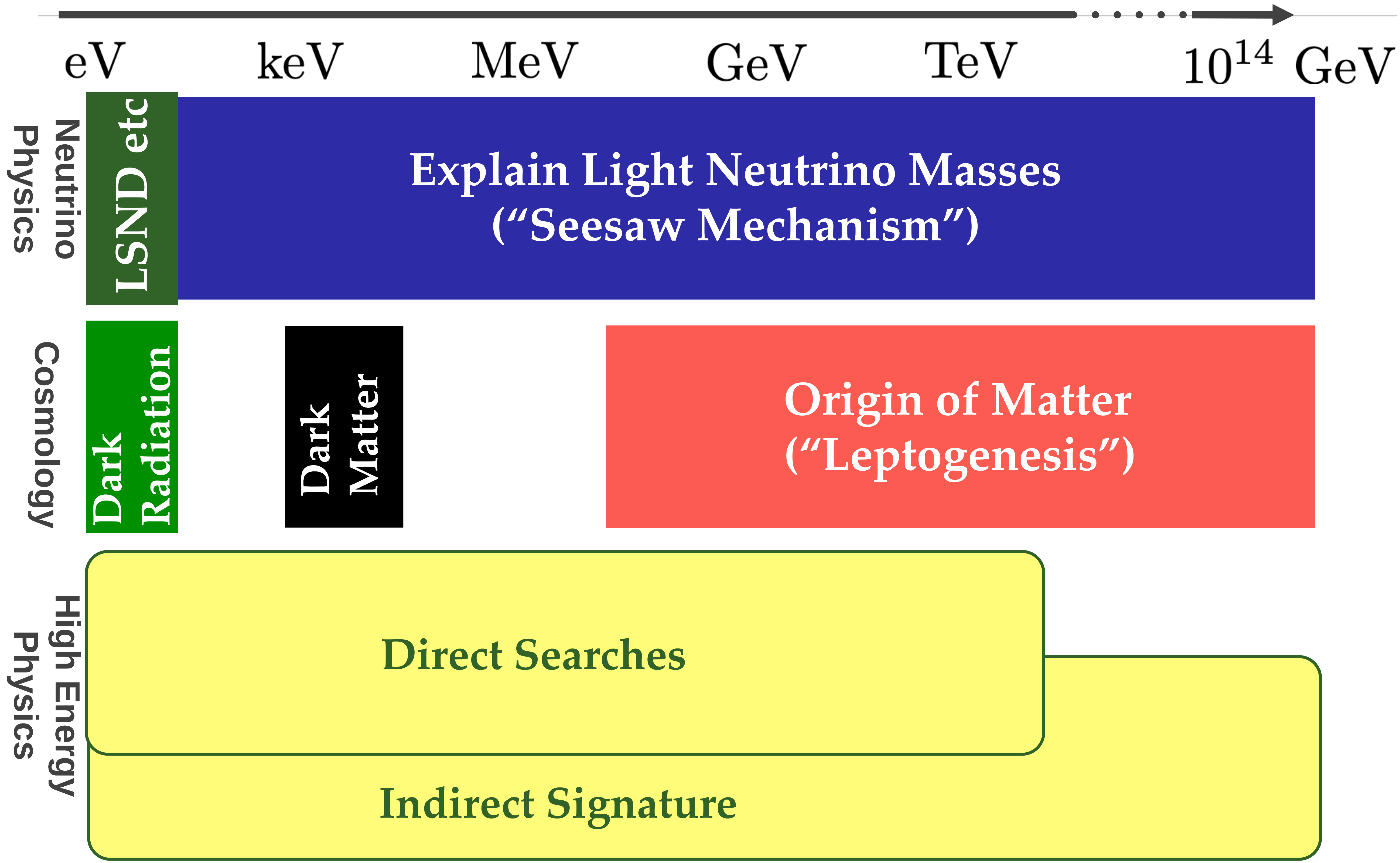
three light neutrinos mostly "active" SU(2) doublet
$\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
with masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$

three heavy mostly singlet neutrinos
$N \simeq \nu_R + \theta^T \nu_L^c$
with masses $\boldsymbol{M_N \simeq M_M}$

Minkowski 79, Gell-Mann/Ramond/Slansky 79, Mohapatra/Senjanovic 79, Yanagida 80, Schechter/Valle 80

- Can simultaneously explain light neutrino masses ("seesaw mechanism") and matter-antimatter asymmetry of the universe ("leptogenesis")
- Heavy mass eigenstate N are type of heavy neutral lepton (HNL) that can be searched for at colliders

Heavy Neutrino Mass Scale



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B-L Symmetry protected Scenarios

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Shaposhnikov 06, Kersten/Smirnov 07

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix}, \quad M_M = \begin{pmatrix} \bar{M}(1-\mu) & 0 & 0 \\ 0 & \bar{M}(1+\mu) & 0 \\ 0 & 0 & M' \end{pmatrix}$$

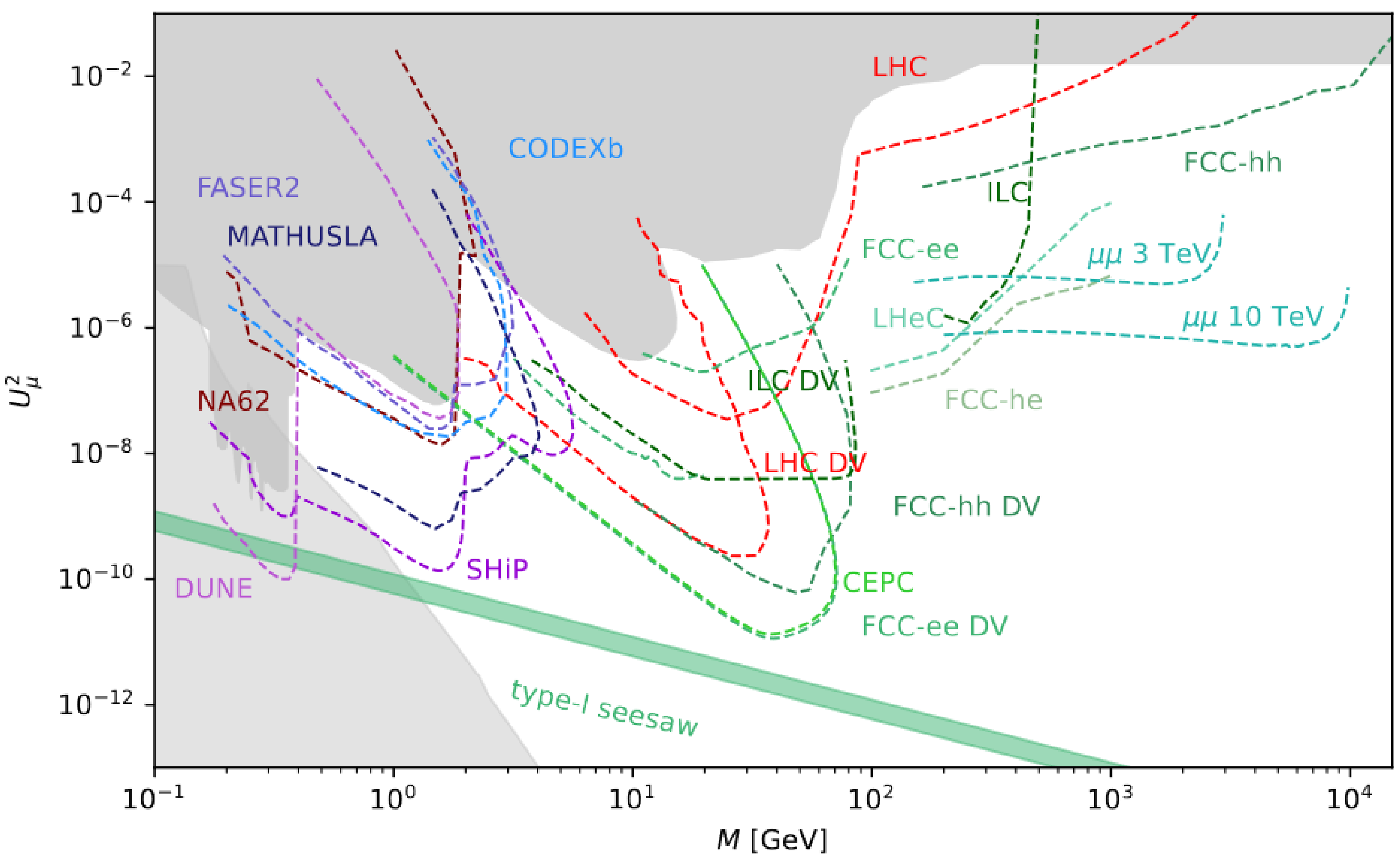
- Technically natural seesaw with O[1] Yukawas and M < TeV
- Resonant enhancement in leptogenesis comes for free due to $\mu \ll 1$
- Possible realisations:
  - **Inverse-seesaw-like** $\epsilon, \epsilon' \ll \mu \ll 1$ Mohapatra 86, Mohapatra /Valle 86, …
  - **Linear-seesaw-like** $\mu \ll \epsilon, \epsilon' \ll 1$ Akhmedov/Lindner/Schnapka/Valle 95
  - **νMSM-like** : $\epsilon, \epsilon', \mu \ll 1$ Asaka/Shaposhnikov 05
  - **"mass communism"**: $\mu \ll 1$ and $M' \rightarrow M$

section 5.1 in 2102.12143

Absolute Neutrino Mass as a Guideline [defines a floor for the searches]

Lower Limits on the Mixings

- The **Seesaw line** is indicates the lower bound on the mixing from the requirement to explain the light neutrino masses
- In general there is no lower bound on the mixing between individual flavours of light and heavy neutrinos



- For three HNLs: lower bound on

$$U_i^2 = \sum_a U_{ai}^2 > \frac{m_{\text{lightest}}}{M_i}$$

MaD 1904.11959

- For 2 HNLs: lower bounds on

$$U_\alpha^2 = \sum_i U_{\alpha i}^2$$

MaD/Garbrecht/Gueter/Klaric 1609.09069

- For mass-degenerate HNLs

$$U^2 = \sum_i U_i^2 > \frac{\sum_i m_i}{M}$$

Varying lightest neutrino mass gives "seesaw band" used in Snowmass plots

Neutrino Mixings Parameters as a Guideline [tells us about branching ratios]

Additional Global Symmetries

Agnostic approach:

- Treat Yukawa matrices *F* and Majorana mass *M* as free parameters, allowing all values that are not excluded experimentally
- Sizeable couplings require approximate B-L symmetry to protect neutrino masses, but other than that no assumptions about flavour structure/texture

Symmetry-based approach:

- UV-completions can motivate specific structures in *F* and *M*

  See e.g. King 1701.04413, Xing 1909.09610,

- We consider groups $\Delta(3n^2)$ and $\Delta(6n^2)$ with CP symmetry   Hagedorn et al 1408.7118
  - Model with three degenerate HNLs and six parameters M, y_1, y_2, y_3, θ_R, θ_L
  - Two parameters κ, λ break mass degeneracy
  - Discrete parameters describe implementation of symmetry group in three cases, namely (n,s), (n,s,t), (n,m,s)
- Symmetries reduce parameter space, make the model more testable

  MaD/Georis/Hagedorn/Klaric 2203.08538, 2xxx.xxxxx

B-L Symmetric Limit

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- production cross section at colliders scales as $\sigma_N \sim \theta^2 \sigma_\nu$

Shaposhnikov 06, Kersten/Smirnov 07

***B-L* violating parameters** $\mu, \ \epsilon, \ \epsilon'$

$$M_M = \begin{pmatrix} \bar{M}(1-\mu) & 0 & 0 \\ 0 & \bar{M}(1+\mu) & 0 \\ 0 & 0 & M' \end{pmatrix}$$

Explains mass degeneracy favourable for leptogenesis

***B-L* symmetry dictates structure in sterile flavours**

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix},$$

ν oscillation data constrains structure in SM flavours

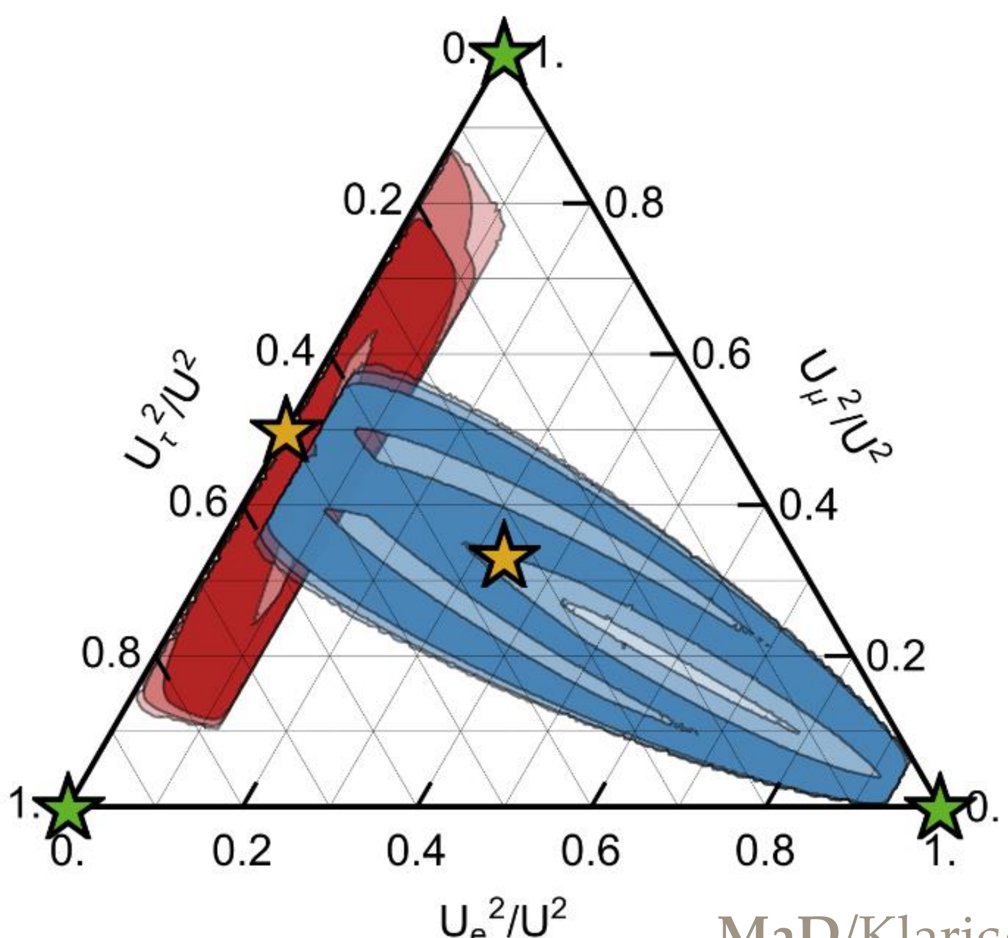
Majorana Phases

- Position in the triangle is basically given by parameters in PMNS

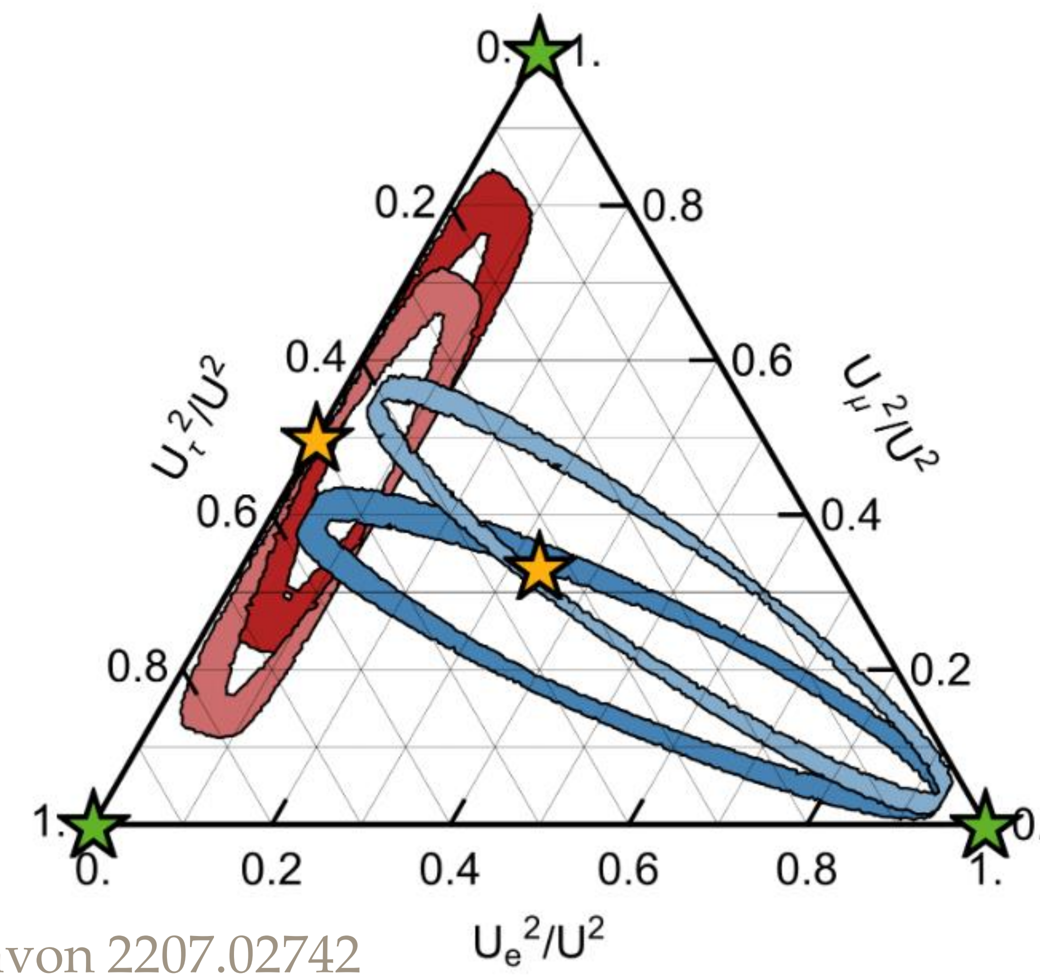
Hernandez et al 1606.06719 MaD et al 1609.09069

- After measuring Dirac phase at DUNE of HyperK, Majorana phase is only unknown
- Hence: branching ratios provide indirect probe of Majorana phase

MaD et al 1609.09069 Caputo et al 1611.05000



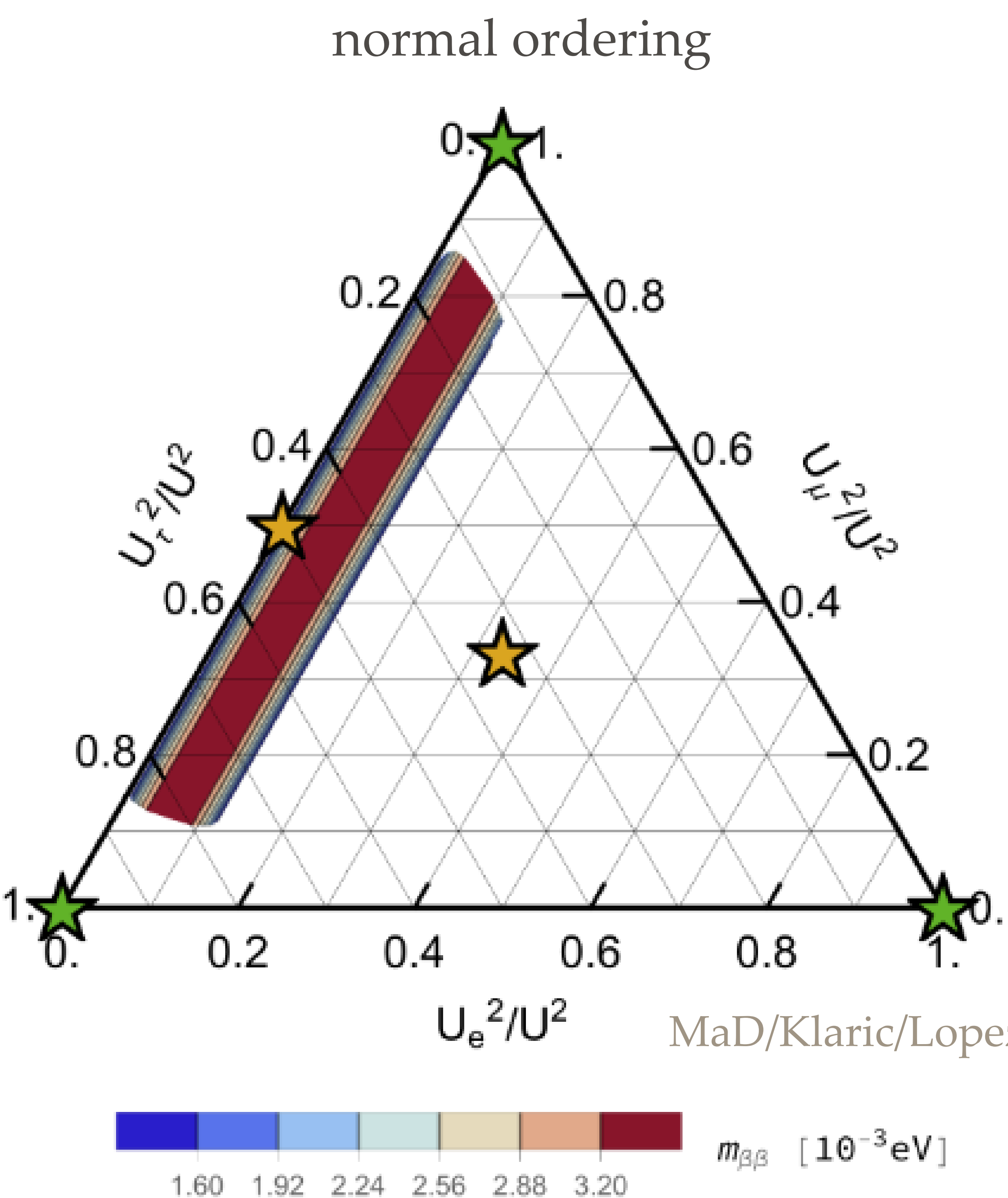
Current constraints

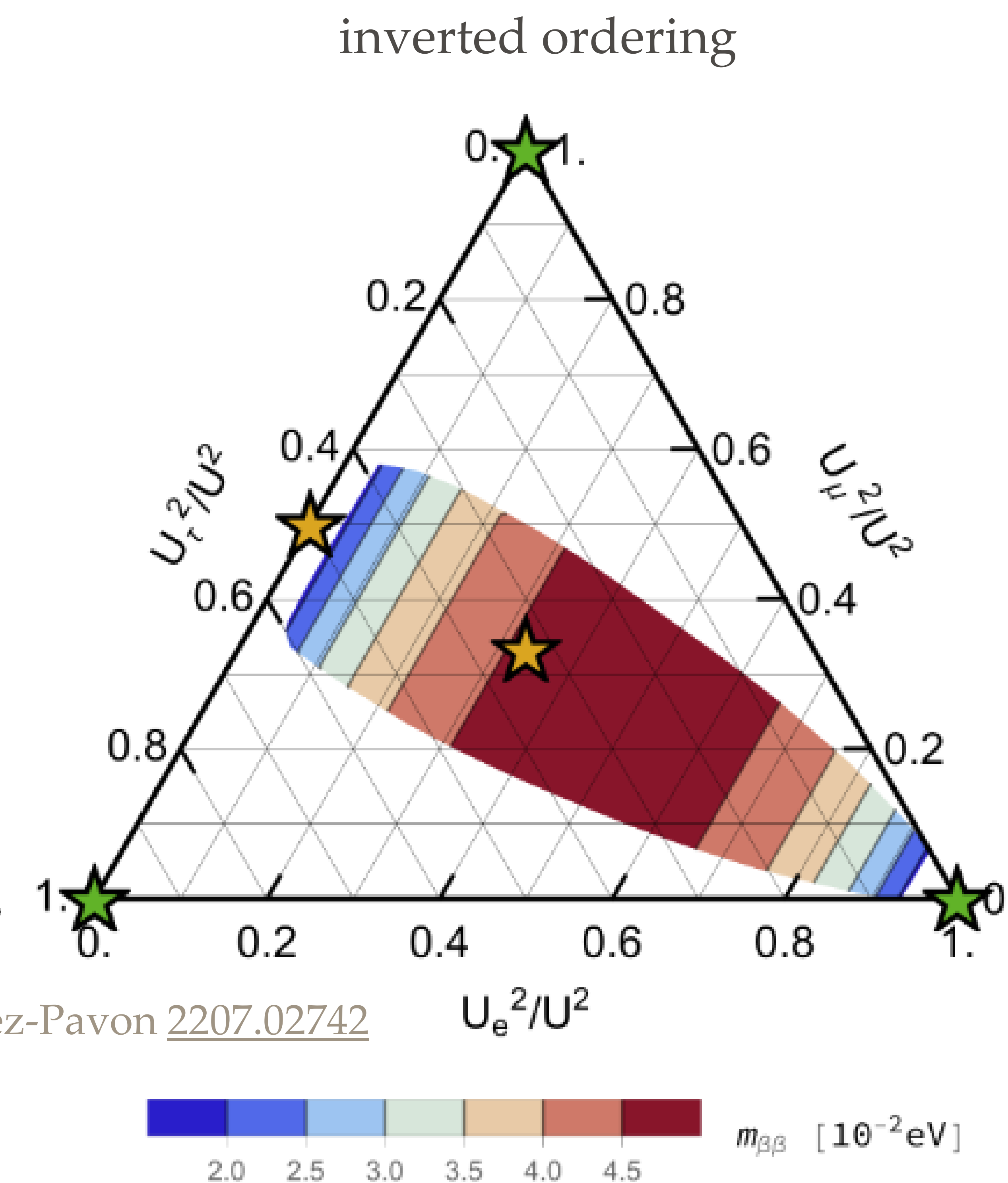


MaD/Klaric/Lopez-Pavon 2207.02742

DUNE projection

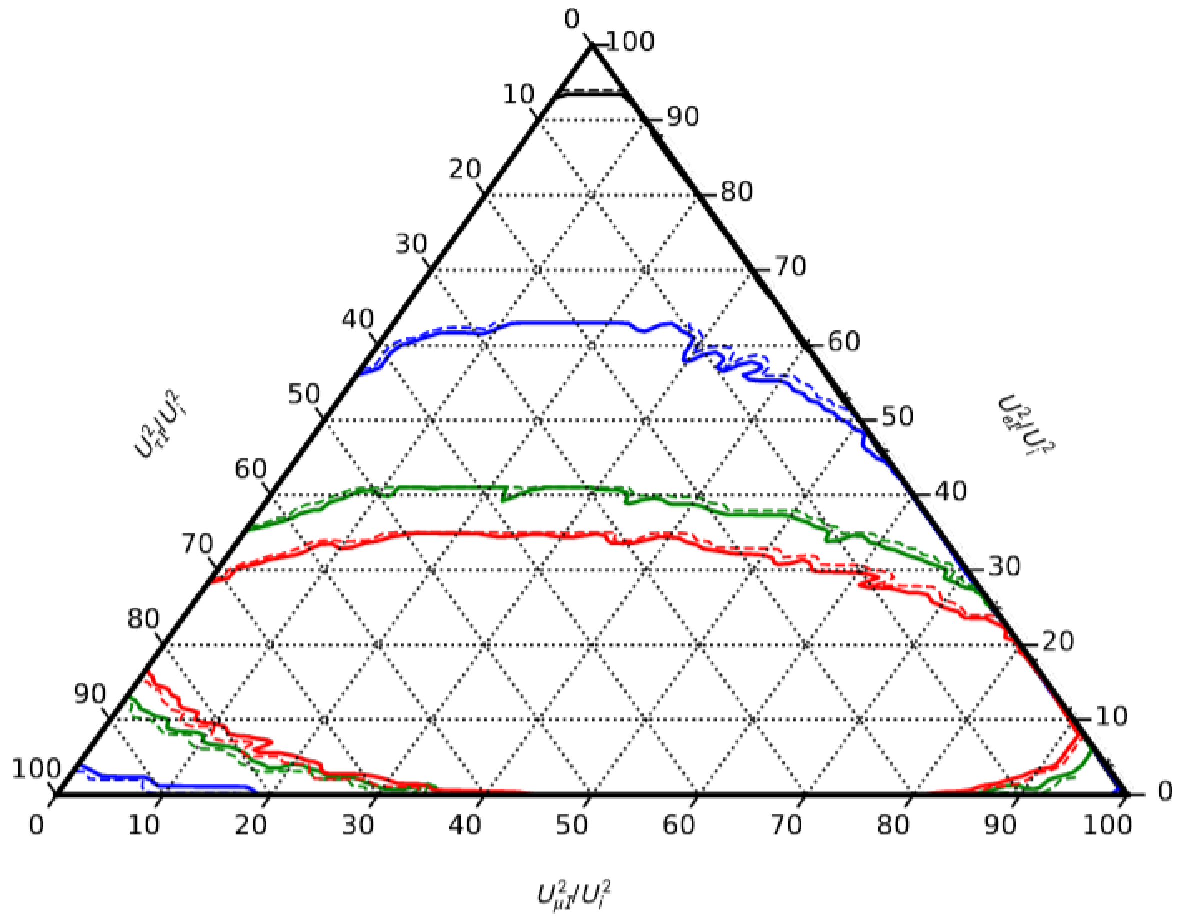
Predictions for 0νββ Decay



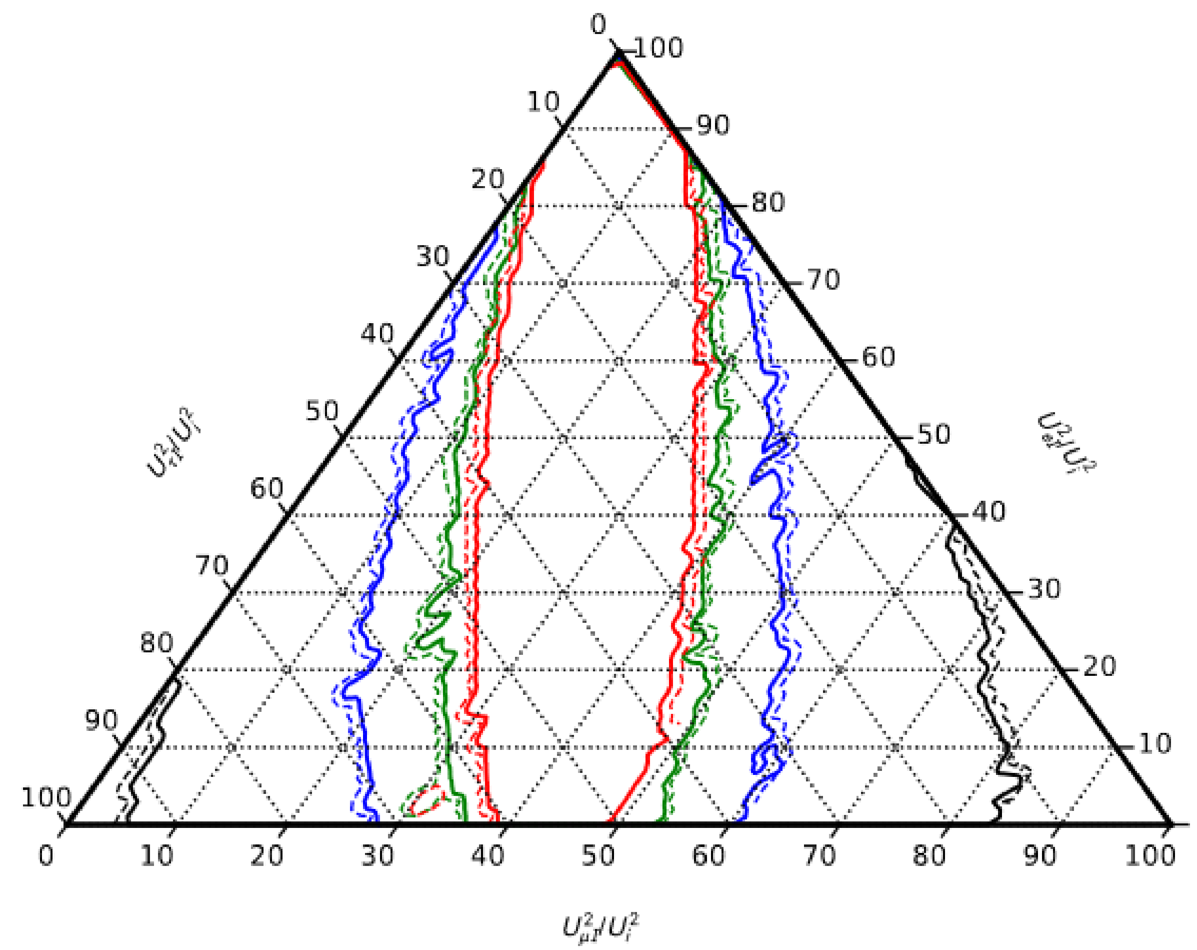


MaD/Klaric/Lopez-Pavon 2207.02742

Constraints from ν-Oscillation Data in Model with 3 Heavy Neutrinos



normal ordering



inverted ordering

$m_{\text{lightest}} < 10$ meV

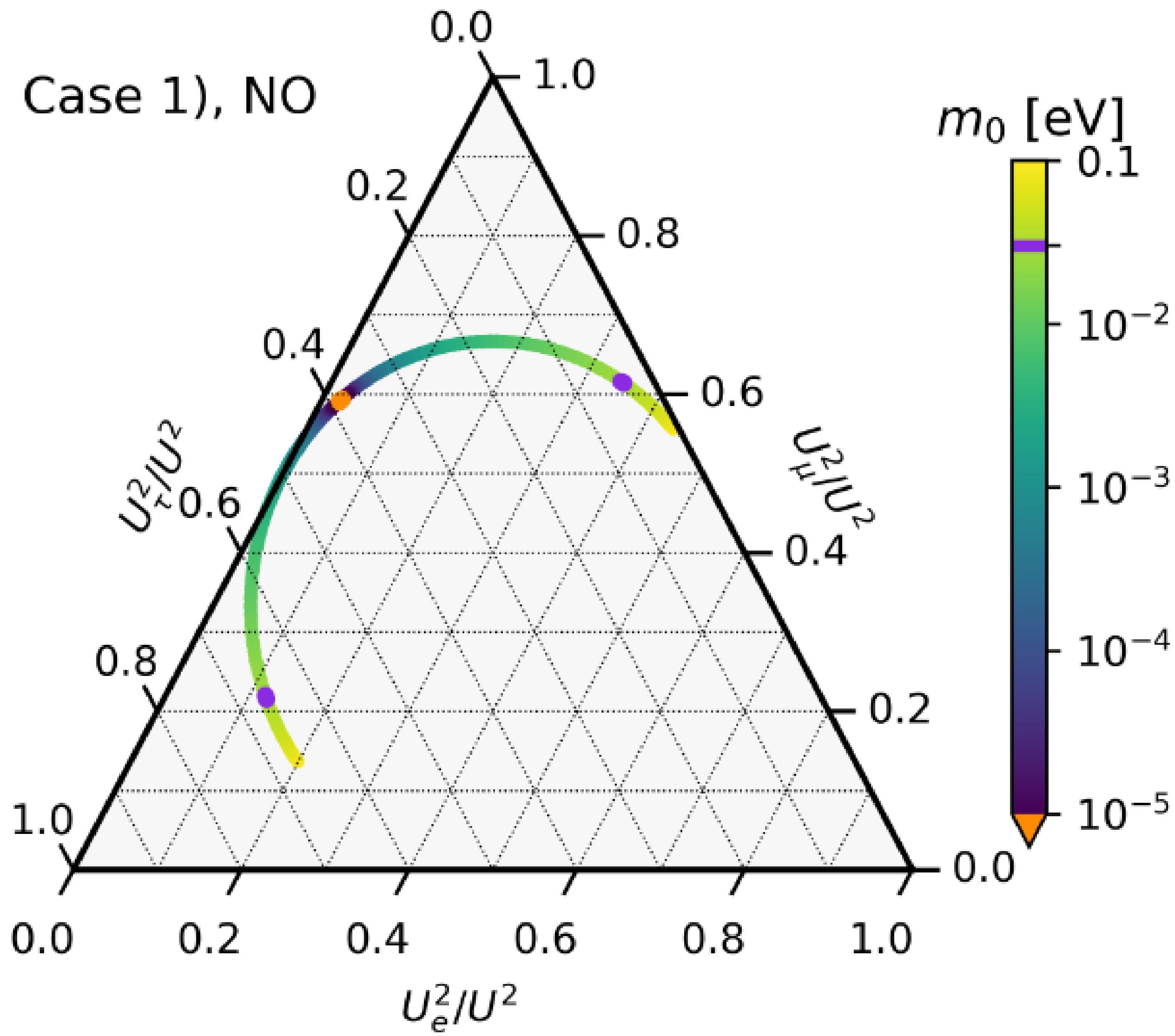
$m_{\text{lightest}} < 1$ meV

$m_{\text{lightest}} < 0.1$ meV

$m_{\text{lightest}} < 0.01$ meV

Chrzaszcz et al 1908.02302

Flavour Mixing Pattern with Discrete Symmetries



- With discrete flavour and CP symmetries: Mixing pattern very predictive

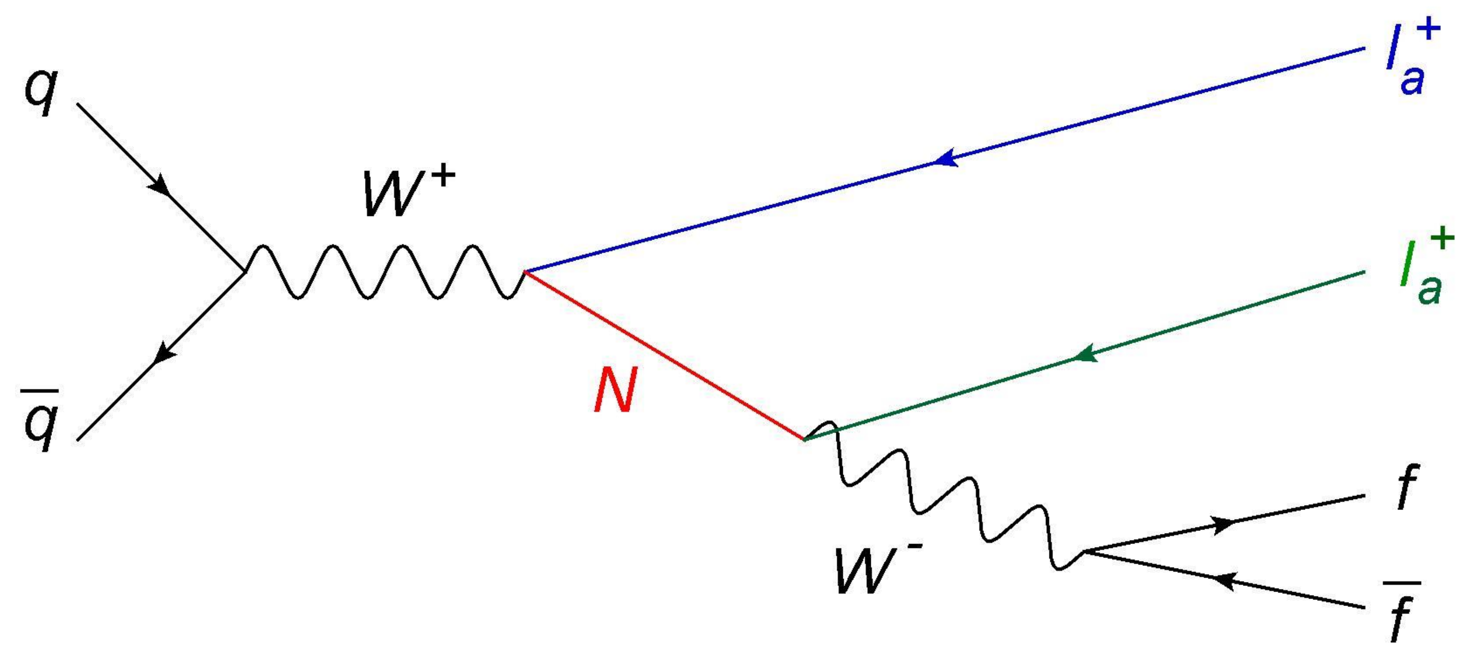
- Even more predictive if lightest neutrino mass is measured

Plot from Georis 2401.04840
Based on MaD/Georis/Hagedorn/Klaric 2203.08538

Neutrino Mass Splittings as a Guideline [tells us about LNV branching ratio or “Dirac vs Majorana”]

Majorana nature of HNLs: Can LNV decay be observed?

- Protecting symmetry parametrically suppresses LNV processes
- But symmetry must be broken to give masses to neutrinos
- Is this breaking enough?



- **Quasi-degenerate HNLs kinematically indistinguishable**
- **behave like one particle with non-integer *Rll*!**

e.g. Anamiati et al 1607.05641

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\text{phys}}}{2\Gamma^2_N + \Delta M^2_{\text{phys}}}$$

- suppression happens by destructive interference between exchange of different HNLs
- interference can be avoided if quantum coherence is lost between production and decay
- This happens if HNLs oscillate many times during their lifetime
- Hence, the relevant quantity is the ratio between their lifetime and oscillation frequency

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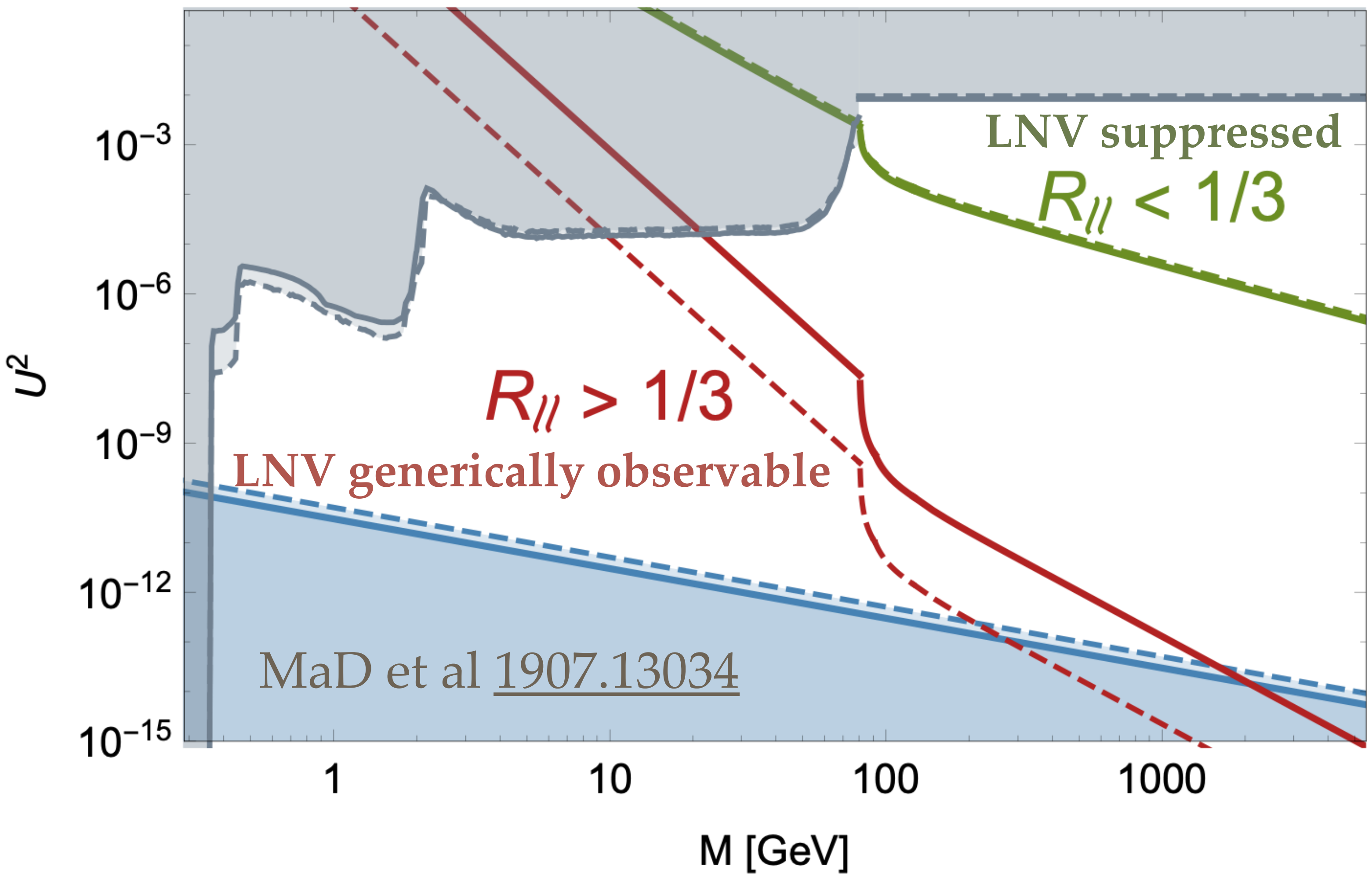

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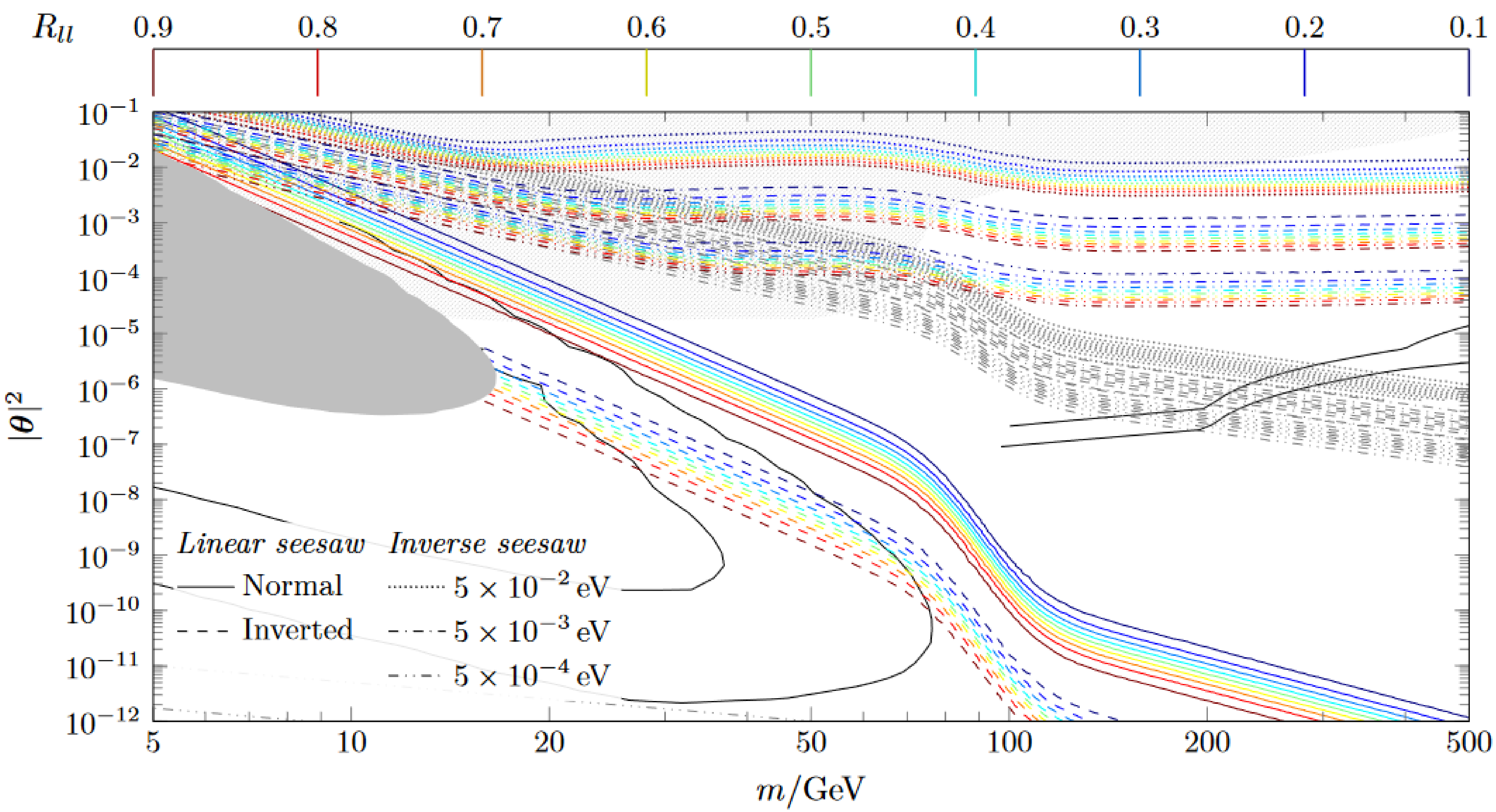
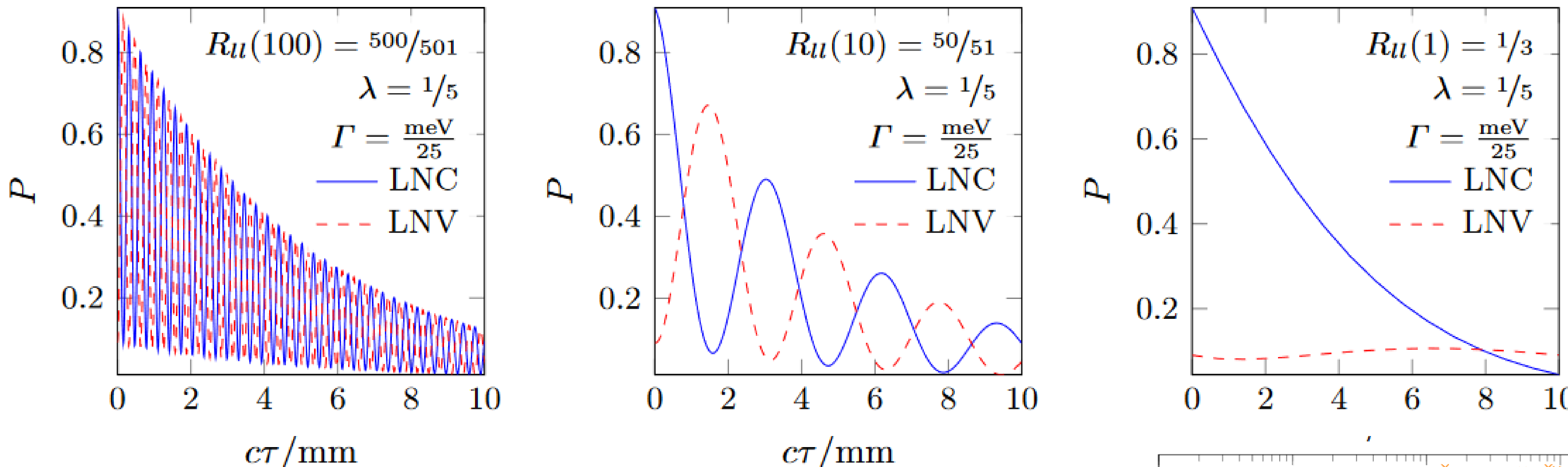
Impact of Wave Packets' Finite size

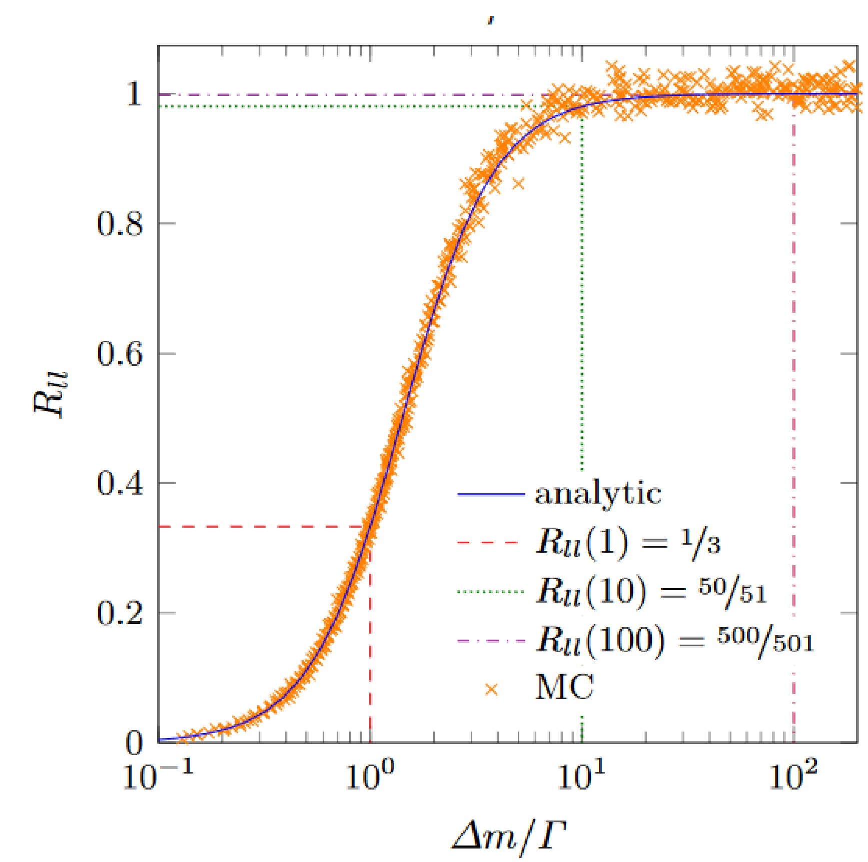


- Parameter *Rll* only captures inherent decherence due to HNL oscillations
- LNV region increases if finite size of proton wave packages is taken into account
  Antusch/Hajer/Rosskopp 2307.06208

Simulating Heavy Neutrino Oscillations



- Oscillations of pseudo-Dirac HNLs in the detector may be observed by studying *Rll* as function of displacement
- Current framework of [MadGraph] and [HeavyN FeynRules] only allows to simulate single "Dirac" or "Majorana" HNL
- MadGraph patch to simulate oscillations has been published in Antusch/Hajer/Rosskopp 2210.10738



Defining Benchmarks

Common phenomenological description: "Single HNL Model"

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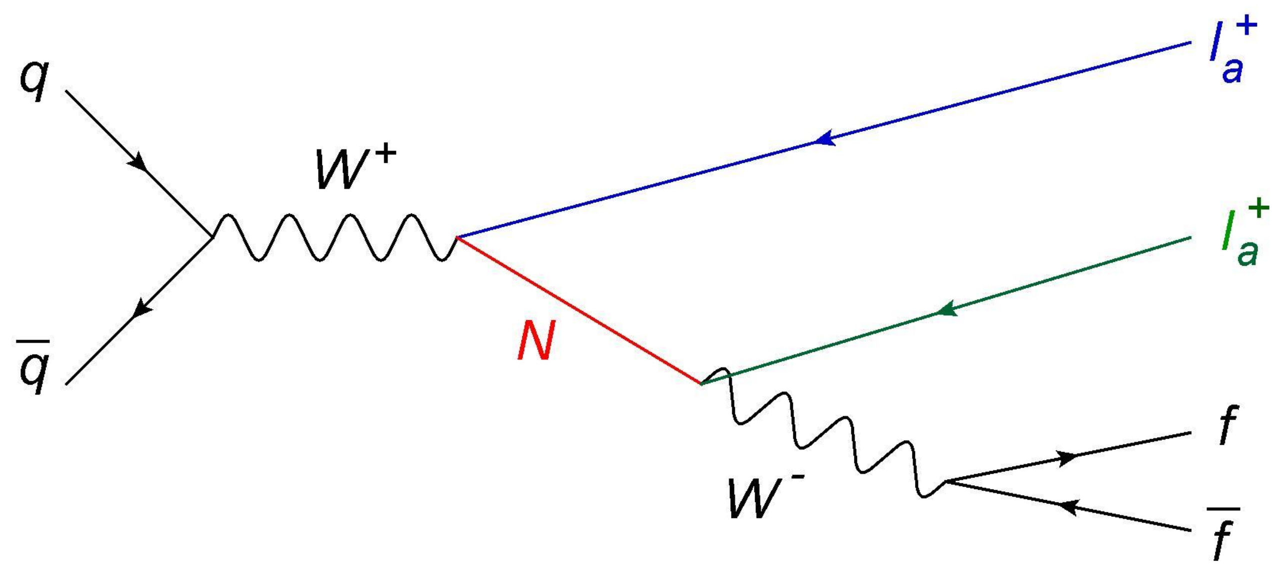
- can effectively describe some phenomenological aspects of realistic models with suitable choices of : M, θ_e, θ_μ, θ_τ, R_{ll}., with R_{ll} interpolating between 0 and 1.
- To be a bit more realistic one can introduce two more parameters c_{prod} and c_{dec}:

$$\sigma_N \sim U^2 c_{\text{prod}}\sigma_\nu \qquad\qquad \Gamma_N \simeq c_{\text{dec}}\frac{a}{96\pi^3}U^2 M^5 G_F^2$$

mass spectrum	c_{prod}	c_{dec}	R_{ll}	appearance
$\Delta M > \delta M_{\text{exp}} \gg \Gamma_N$	1	1	1	two Majorana HNLs with mixing U^2 each
$\delta M_{\text{exp}} > \Delta M \gg \Gamma_N$	2	1	1	one HNL, mixing $2U^2$, lifetime as Dirac, R_{ll} as Majorana
$\delta M_{\text{exp}} > \Gamma_N \gg \Delta M$	2	1	0	one Dirac HNL with mixing $2U^2$

How to observe LNV?



How to practically distinguish Dirac from Majorana *N*?

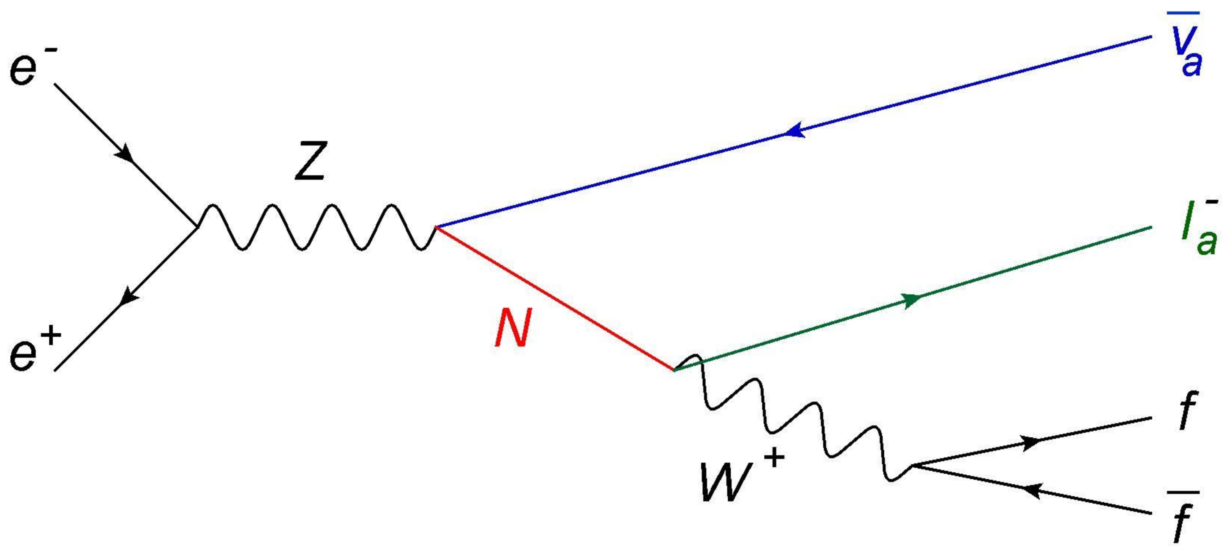
1) Direct observation of LNV in fully reconstructed final state
2) Angular distribution of final state particles
3) Polarisation of final state particles
4) Lifetime of N

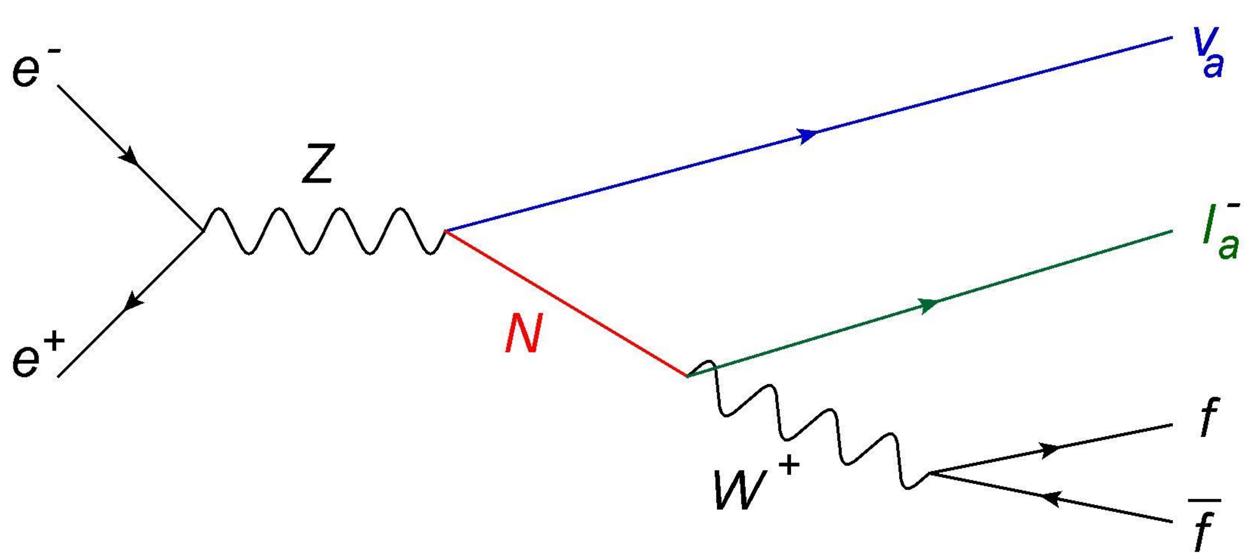
Signature 1) in general cleanest, but not always observable

- Neutrinos in the final state
- First vertex not visible (fixed target…)

I use FCC-ee as a clean example, similar considerations apply at LHC or fixed target experiments e.g. Dib et al 1712.08704 Tastet/Timiryasov 1912.05520

LNV at Lepton Colliders





Z-bosons are polarised due to P-violation of weak interaction:

$$g_R = 2\sin^2\theta_W \qquad g_L = (1 - 2\sin^2\theta_W) \qquad P_Z = \frac{(g_R^2 - g_L^2)}{(g_L^2 + g_R^2)} \simeq -0.15.$$

- Chiral nature of weak interaction correlates charge, spin, and momenta of observable final state particles to spin of initial Z-boson
- This correlation depends on whether HNLs are Dirac or Majorana

e.g. Blondel et al 2105.06576

Observables:

- **Forward-backward asymmetry of charged leptons**: vanishes in Majorana case, is proportional to Z-polarisation in Dirac case
- **Energy distribution of charged leptons**: Dirac N and anti-N are highly polarised, while Majorana H are only mildly polarised, leading to different charged lepton spectra

Constraining R_{ll} from HNL Lifetime

- HNL production cross section is same for Dirac and Majorana:

$$\mathrm{BR}(Z \to \nu N) = \frac{2}{3}|U_N|^2\,\mathrm{BR}(Z \to \text{invisible})\left(1 + \frac{{m_N}^2}{2{m_Z}^2}\right)\left(1 - \frac{{m_N}^2}{{m_Z}^2}\right)$$

- HNL decay length differs:
  Dirac: : $c_{dec} = 1/2$
  Majorana: $c_{dec} = 1$

$$\lambda_N = \frac{\beta\gamma}{\Gamma_N} \simeq \frac{1.6}{U^2 c_{\mathrm{dec}}}\left(\frac{M}{\mathrm{GeV}}\right)^{-6}\left(1 - (M/m_Z)^2\right)\ \mathrm{cm}.$$

- HNL mass extracted from full 4-momentum reconstruction or from time-of-flight

➢ **Extract U_a^2 from total # decays , c_{dec} from # decays between displacement l_0, l_1**

$$\sigma_N \sim U^2 c_{\mathrm{prod}} \sigma_\nu \qquad\qquad \Gamma_N \simeq c_{\mathrm{dec}} \frac{a}{96\pi^3} U^2 M^5 G_F^2$$

mass spectrum	c_{prod}	c_{dec}	R_{ll}	appearance
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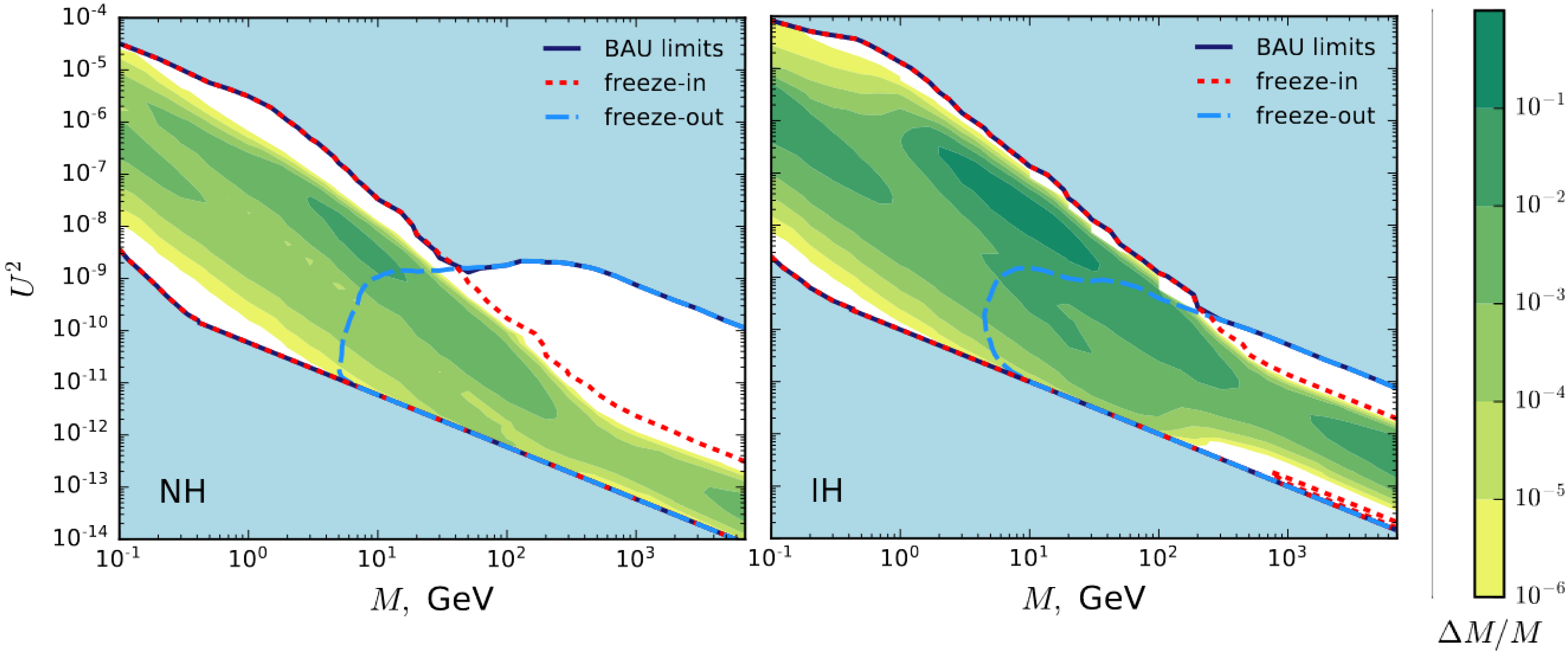
Cosmologyas a Guideline
[tells us a bit about everything]

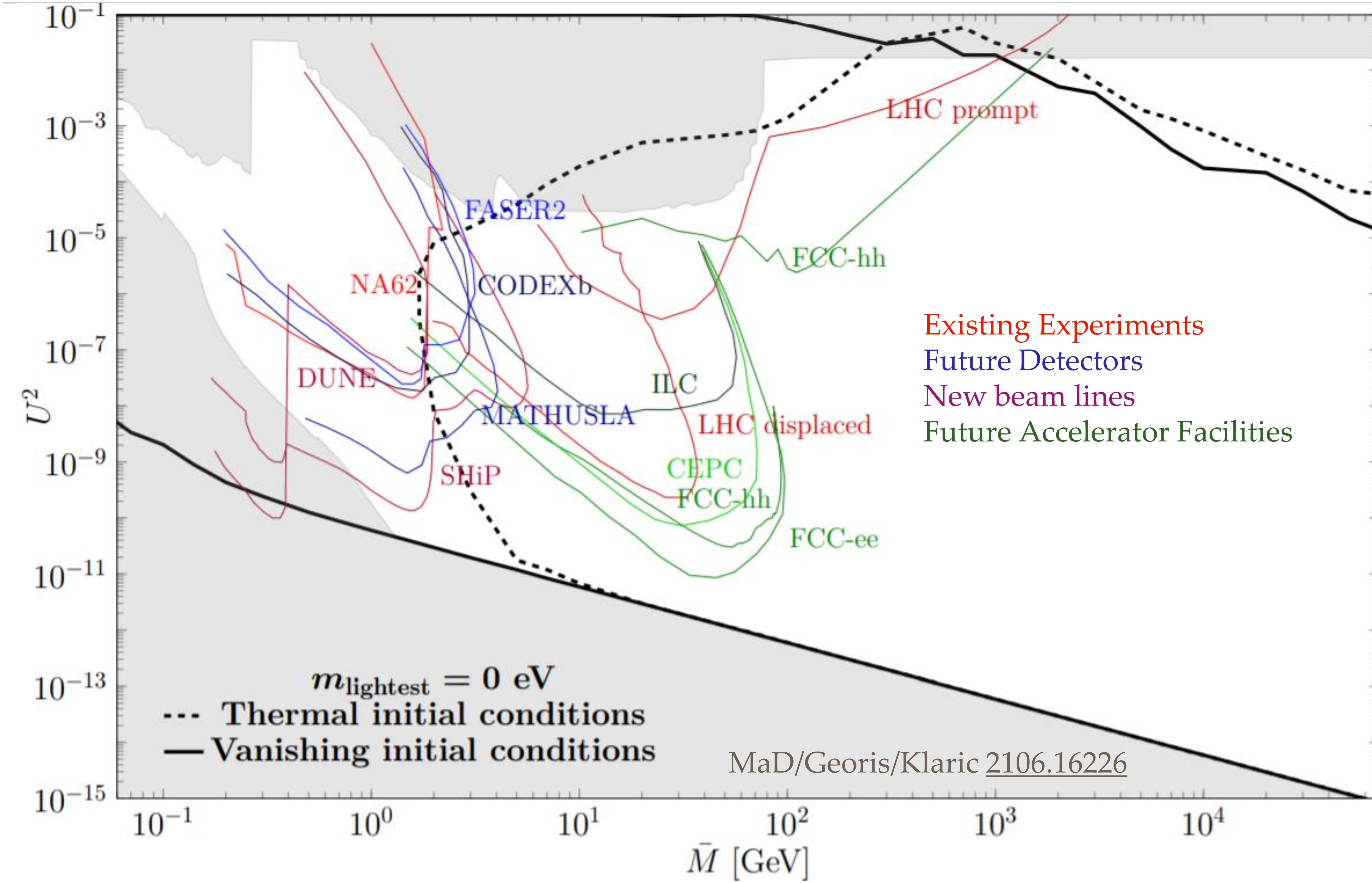
Leptogenesis with 2 HNLs



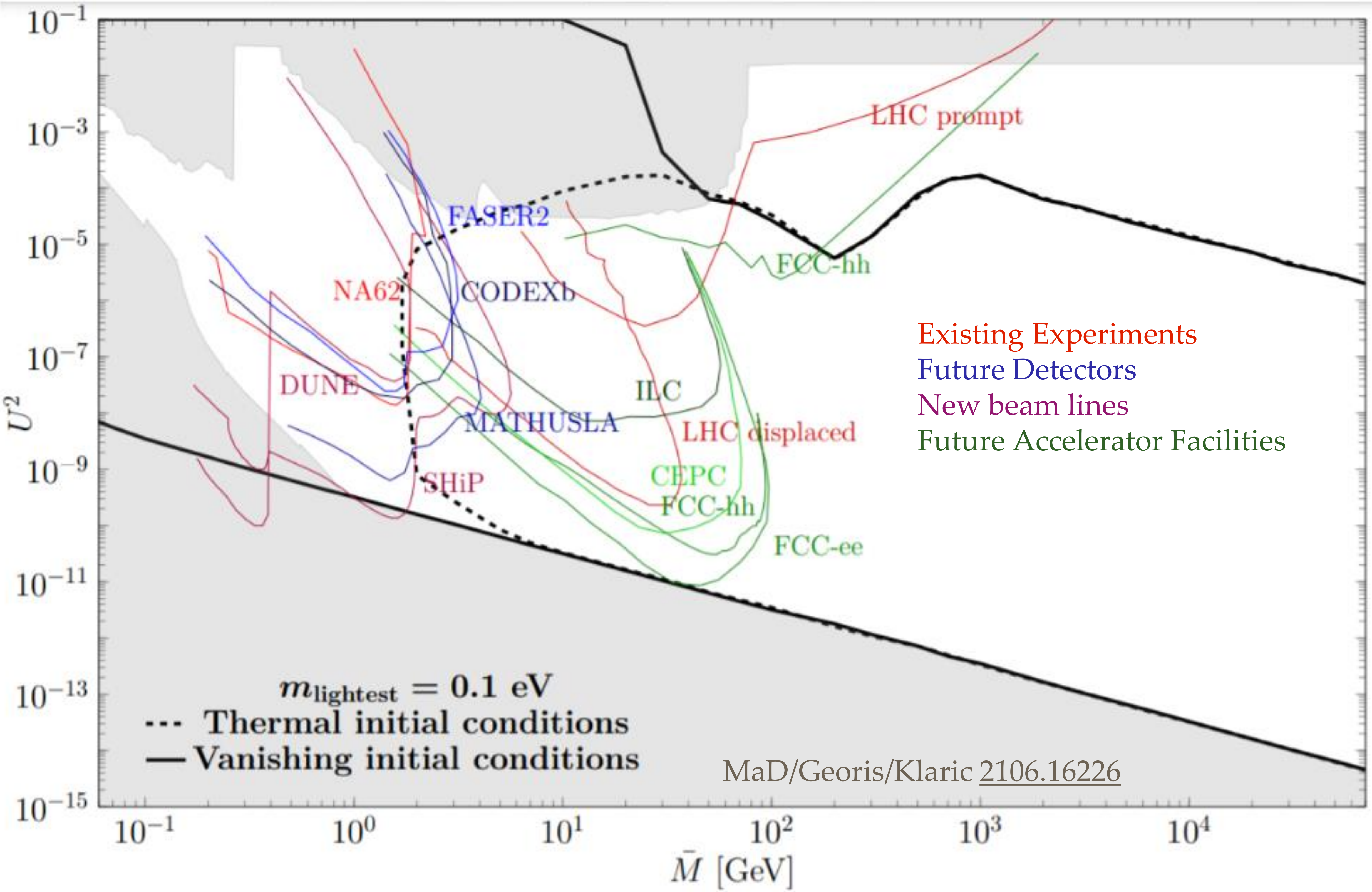
- Minimal # of HNL flavours consistent with ν-oscillations and leptogenesis is two
- This also effectively describes the seesaw mechanism and leptogenesis in the νMSM
- Leptogenesis requires mass degeneracy
- Leptogenesis region only accessible with LLP searches!

Klaric/Shaposhnikov/Timiryasov 2103.16545

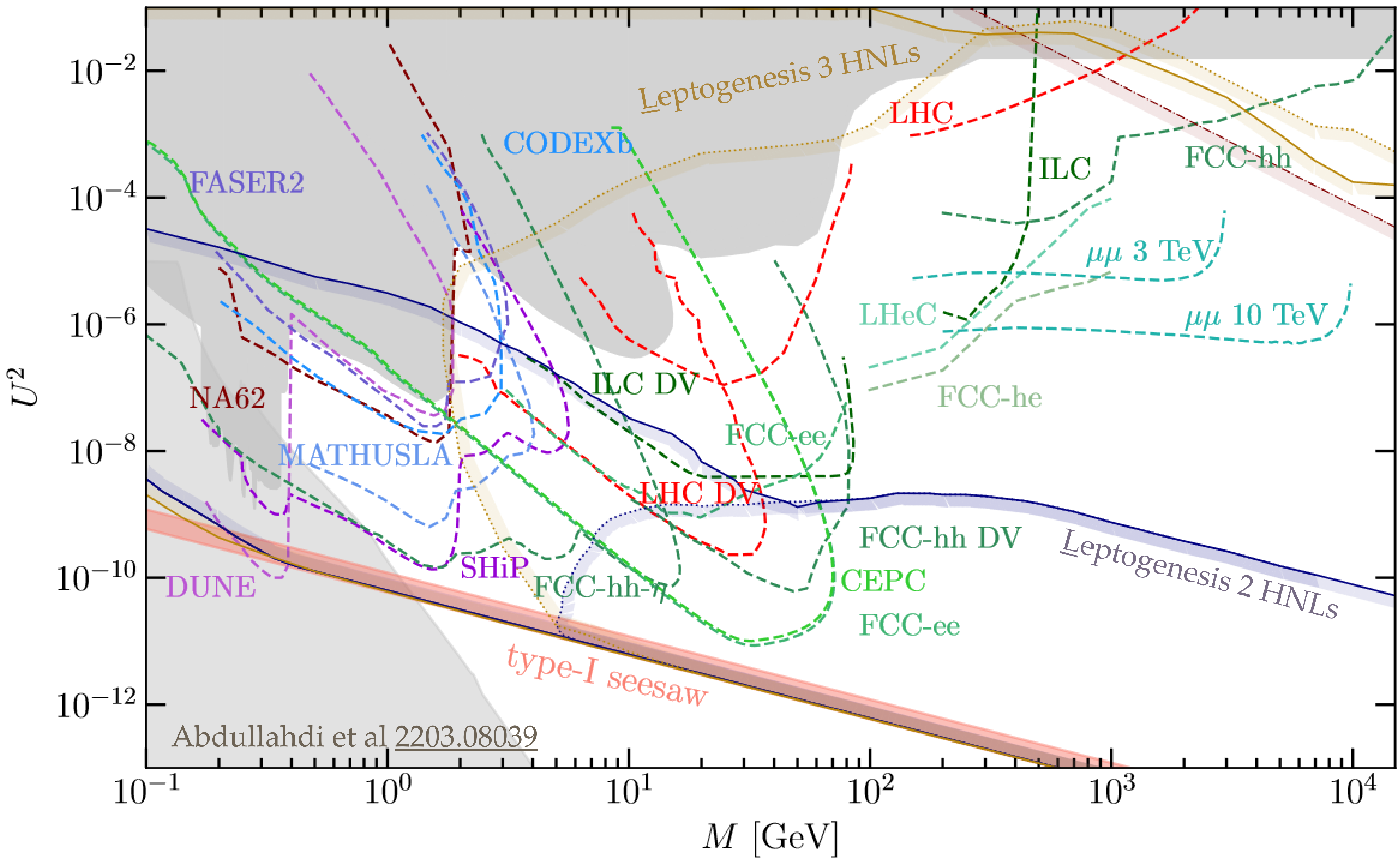
Leptogenesis with 3 HNLs



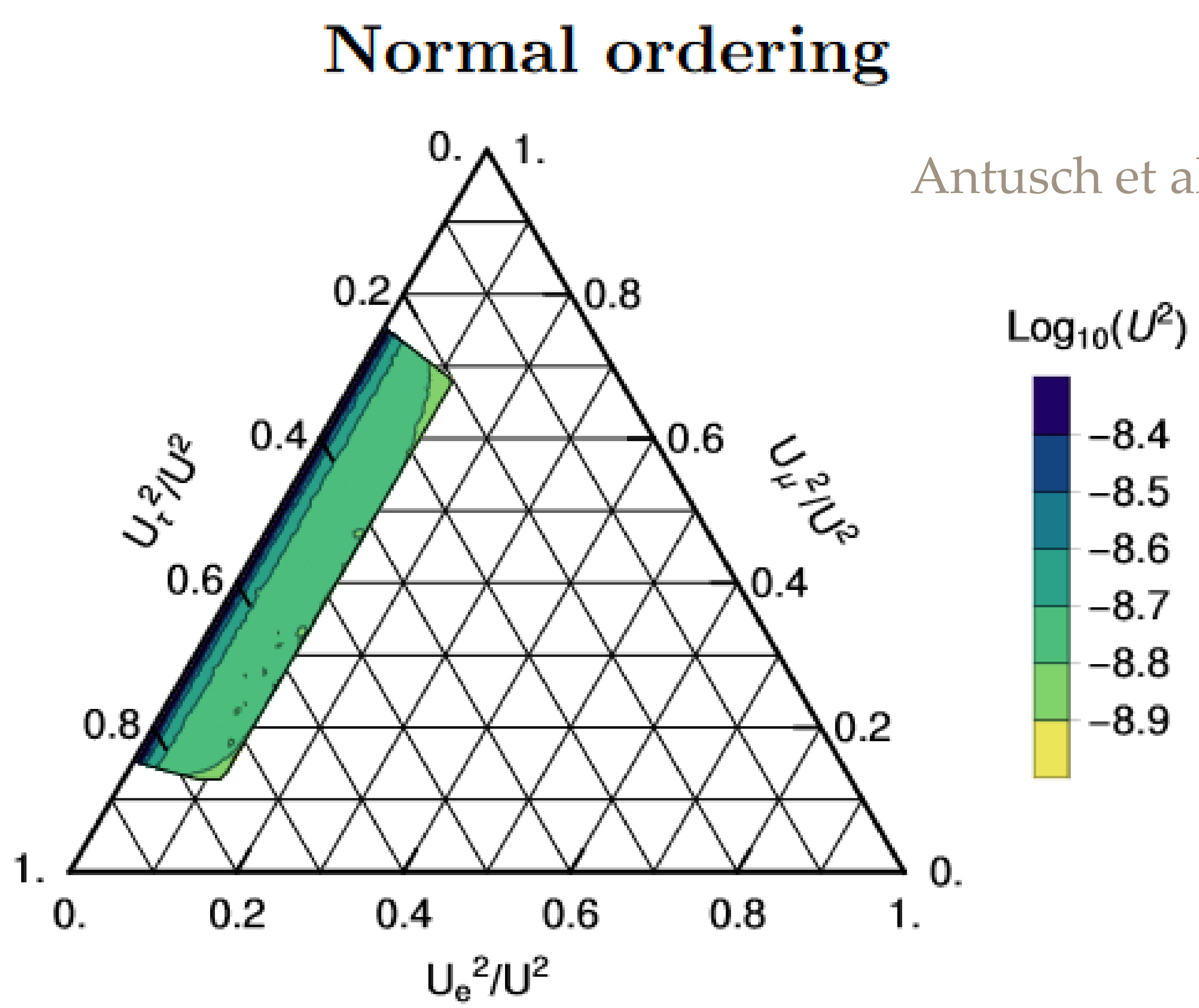
Impact of the lightest SM Neutrino



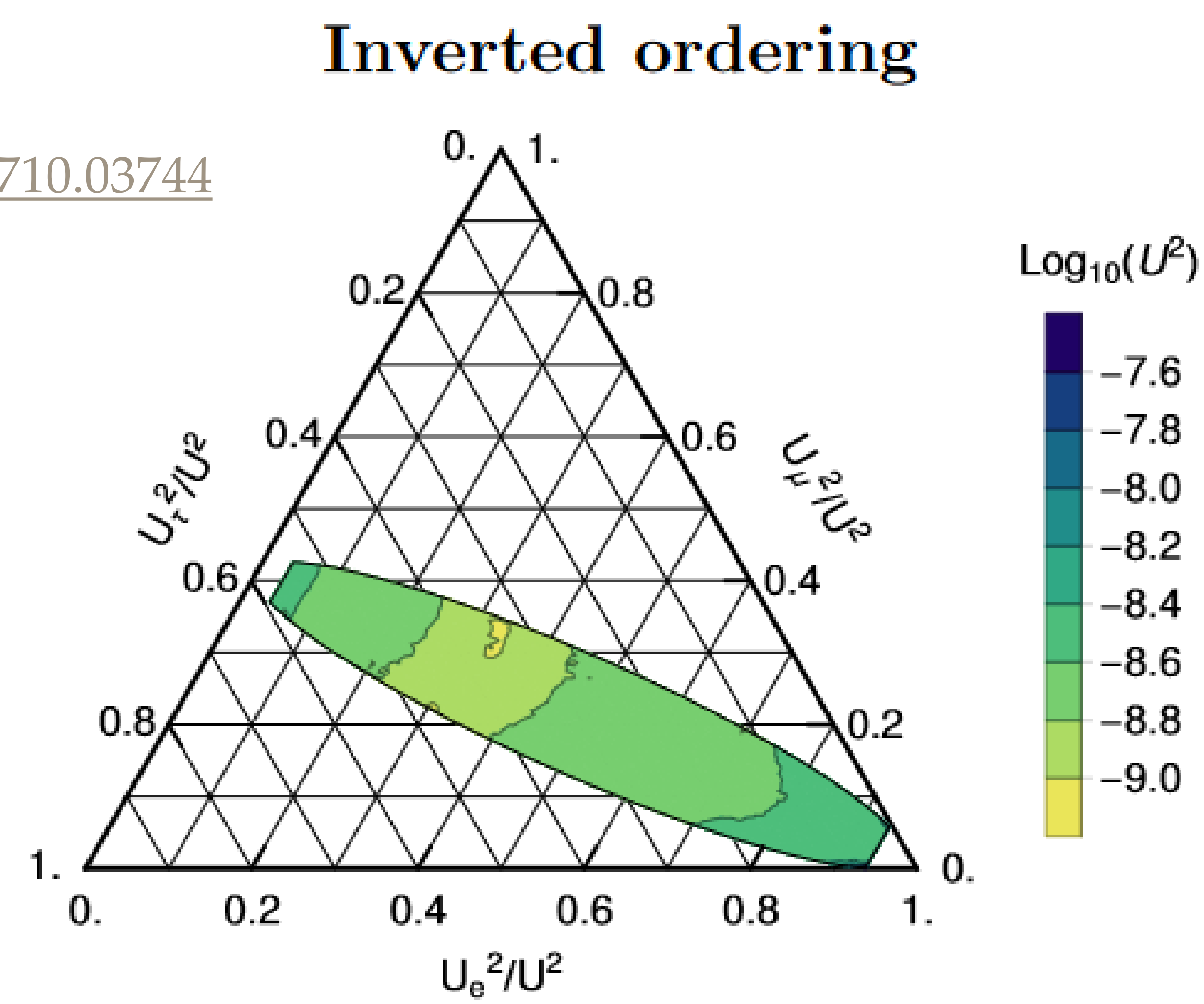
Leptogenesis: 2 vs 3 HNL Flavours



Leptogenesis Flavour Predictions



Antusch et al 1710.03744



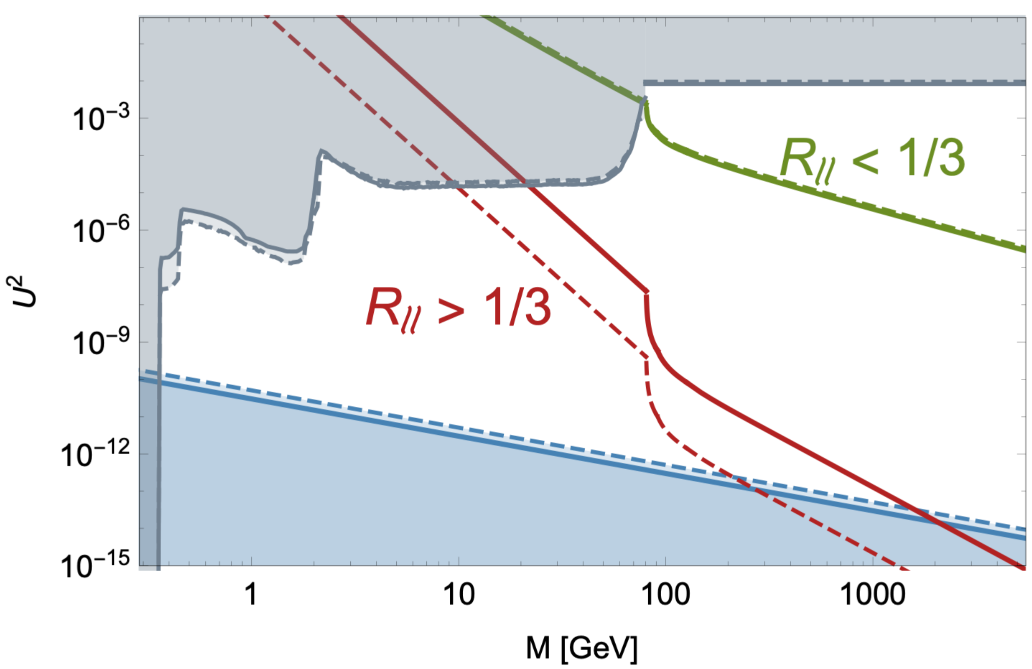
- Requirement for leptogenesis imposes additional constraints on branching ratios Antusch et al 1710.03744
- Recently confirmed and refined in Hernandez et al 2207.01651

How to measure ΔM?

ratio of LNV to LNC decays is sensitive to ΔM

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\text{phys}}}{2\Gamma_N^2 + \Delta M^2_{\text{phys}}}$$

Anamiati et al 1607.05641



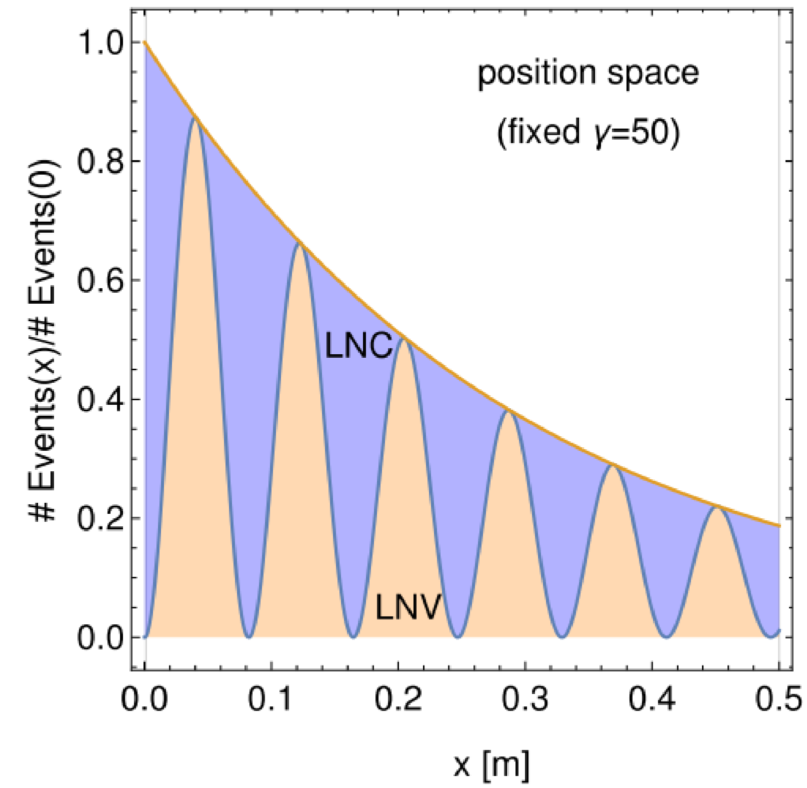
MaD/Klaric/Klose 1907.13034

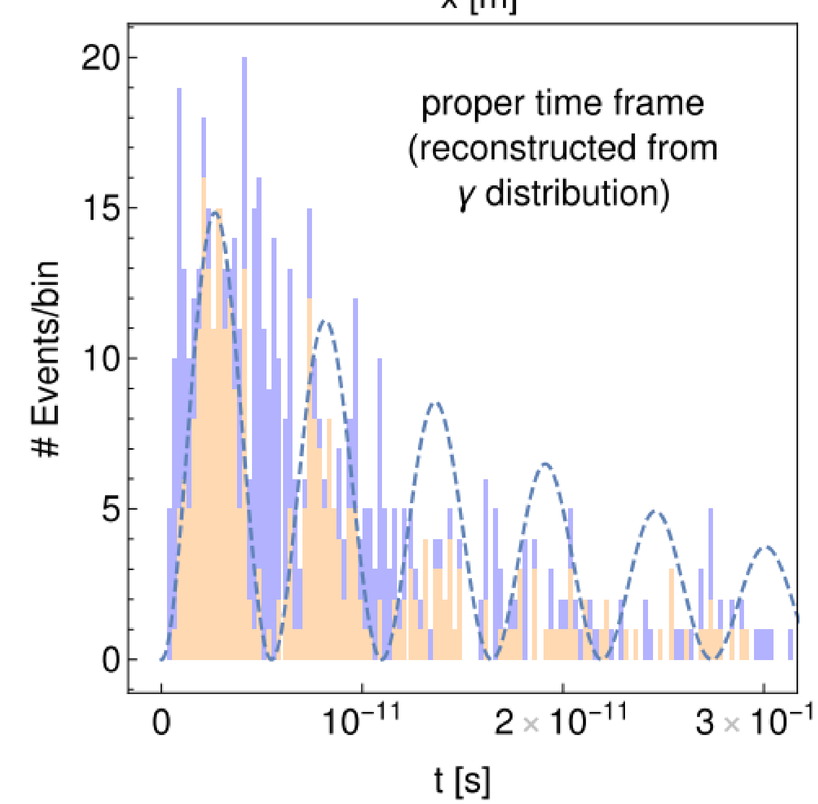
HNL oscillations may be resolved in LHC detectors

Antusch et al 1709.03797

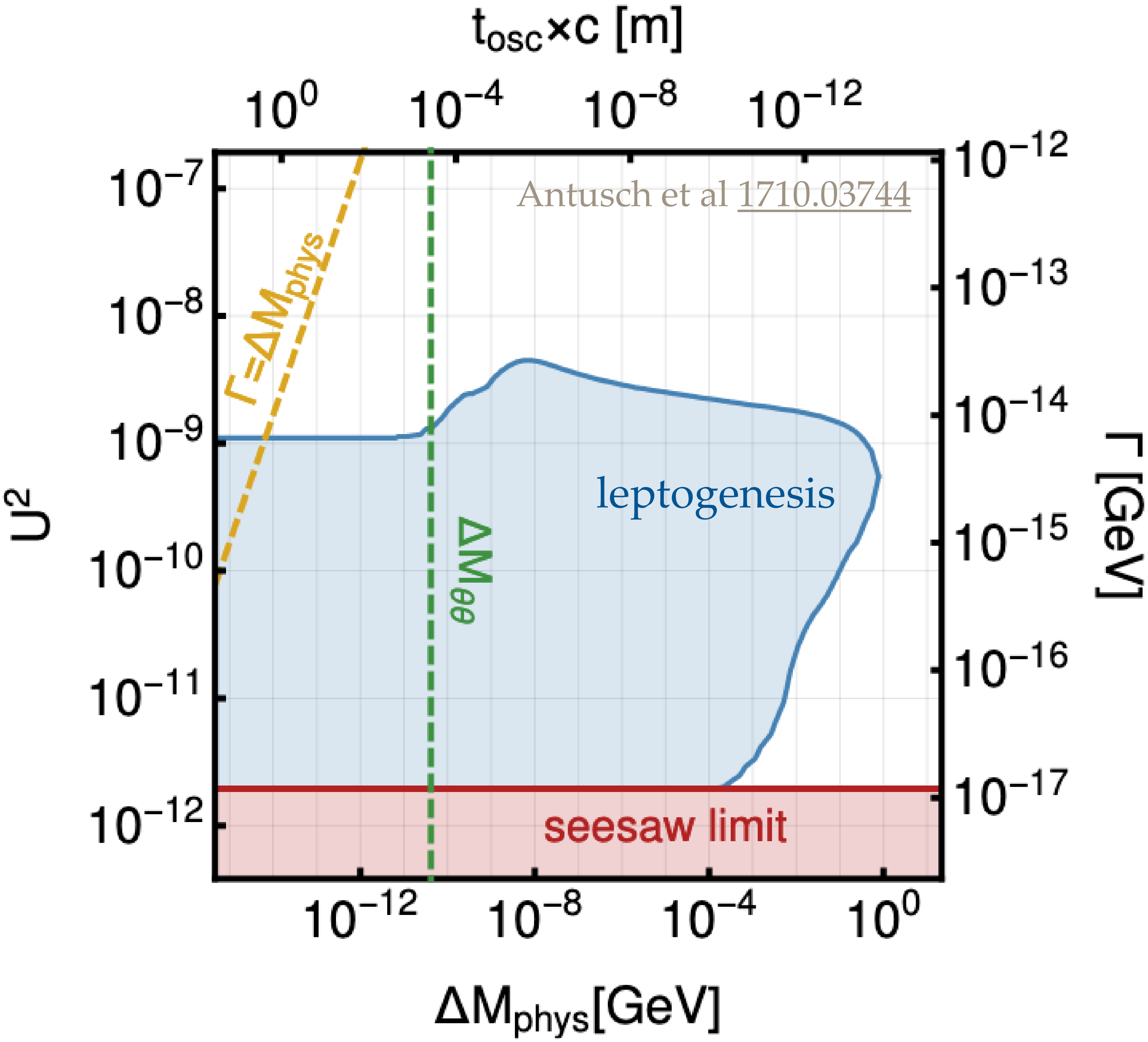
Measuring *Rll* as a function of displacement helps testing leptogenesis!

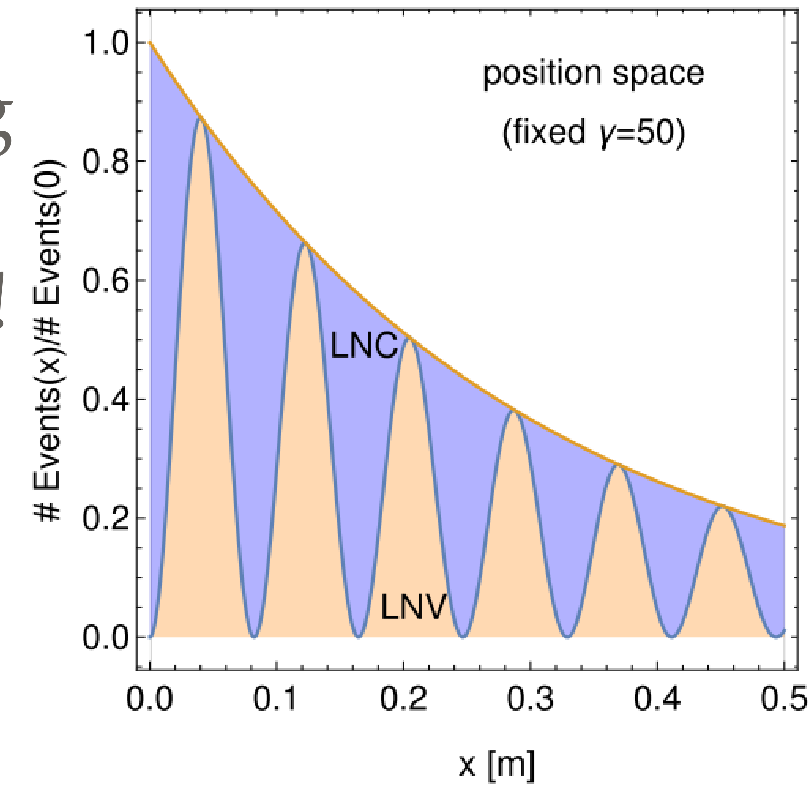
Antusch et al 1710.03744

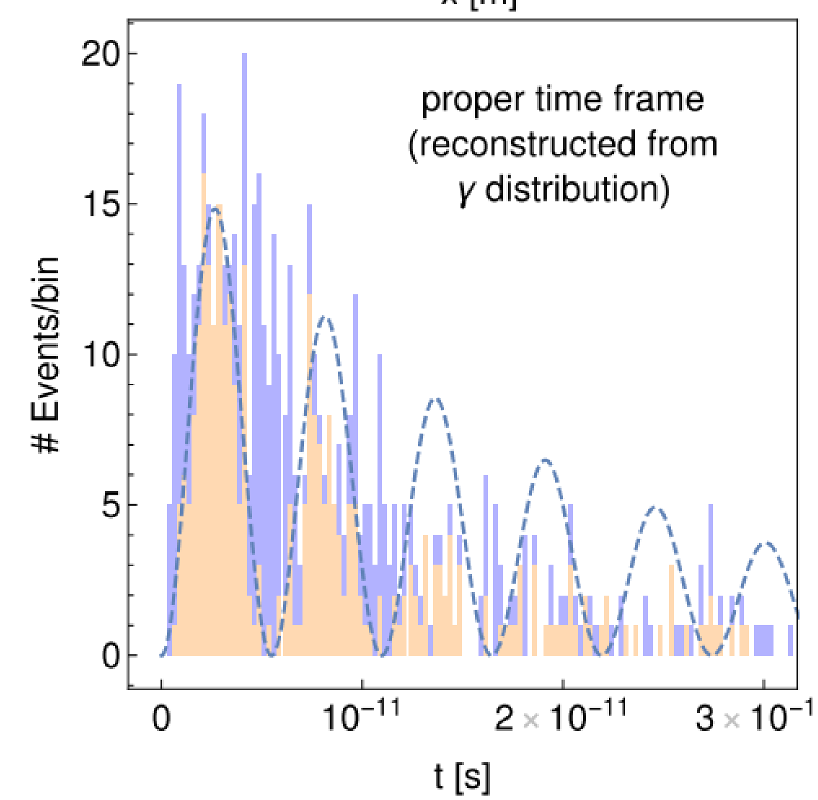




Testing Leptogenesis







Defining Benchmarks

Common phenomenological description: “Single HNL Model”

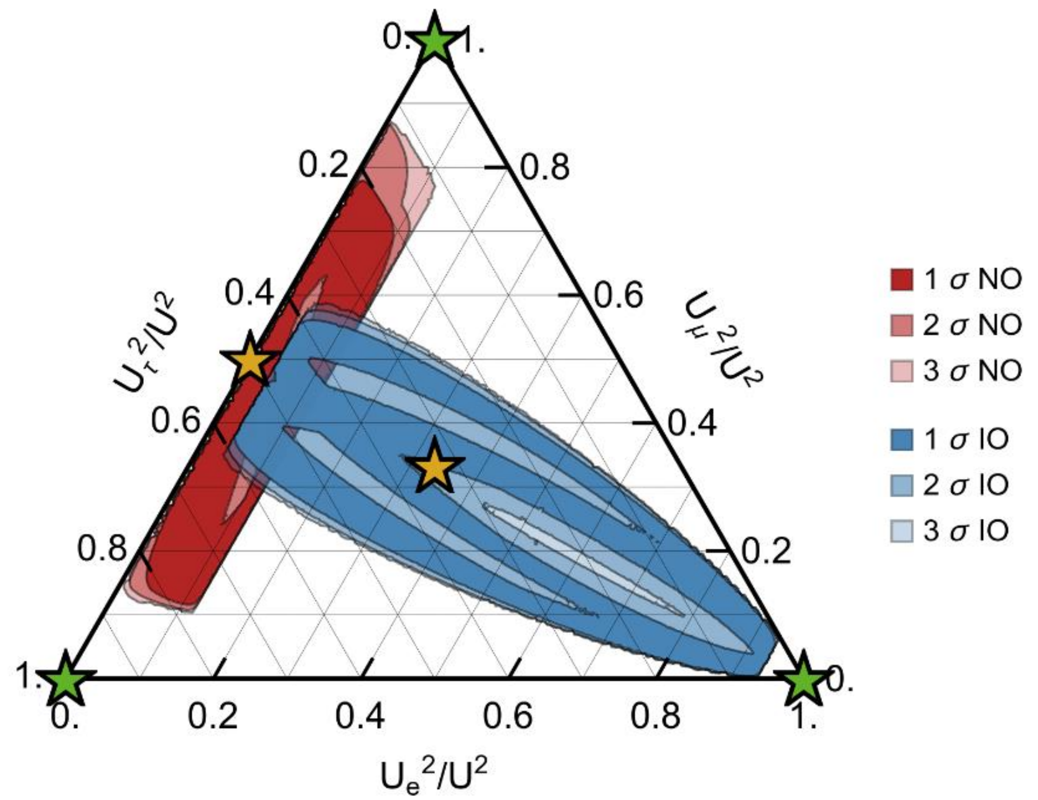
$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}\theta^*_\alpha\gamma^\mu e_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\overline{N}\theta^*_\alpha\gamma^\mu \nu_{L\alpha}Z_\mu - \frac{M}{v}\theta_\alpha h\overline{\nu_{L\alpha}}N + \text{h.c.}$$

- One flavour of HNLs N
- Couples to SM only through mixing θ_a with SM neutrinos, where a = e, μ, τ
- Model with five parameters : M, θ_e, θ_μ, θ_τ, and R_{ll}.
- **R_{ll} is ratio of lepton number violating (LNV) to lepton number conserving (LNC) N decays; R_{ll} = 1 for Majorana N and R_{ll} = 0 for Dirac N.**

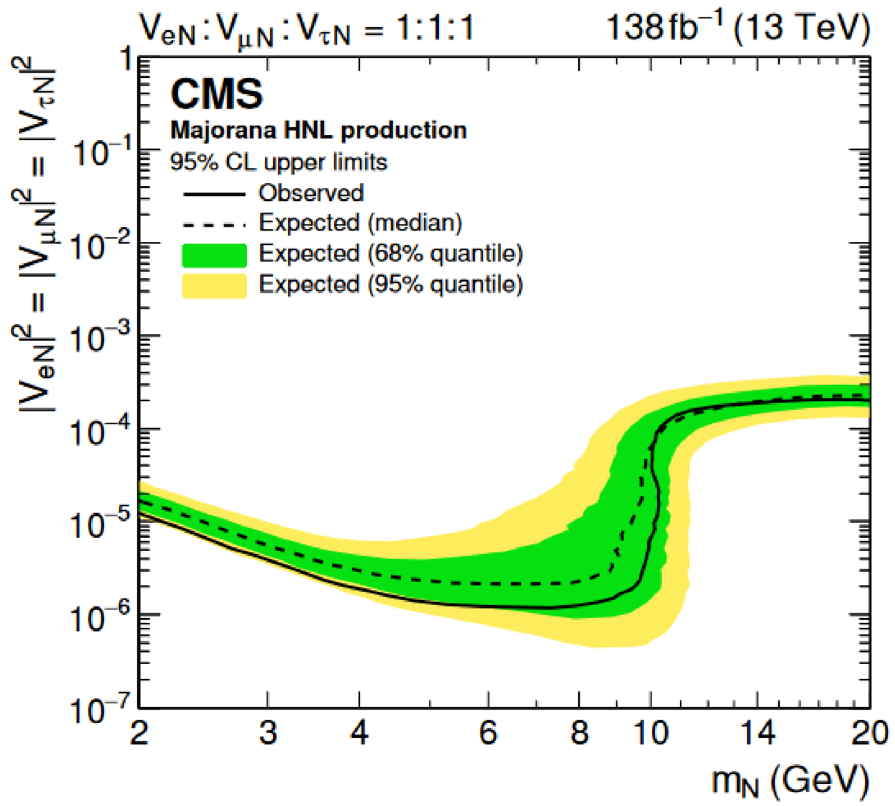
- can effectively describe some phenomenological aspects of realistic models with suitable choices of : M, θ_e, θ_μ, θ_τ, R_{ll}., with R_{ll} interpolating between 0 and 1.

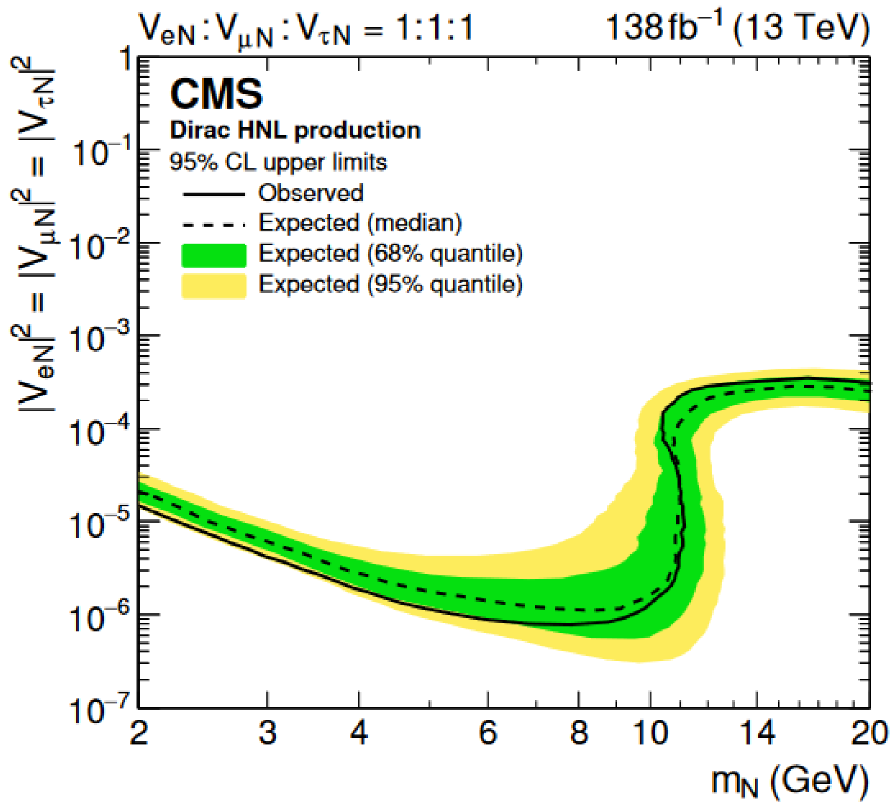
- We propose 5 benchmarks for the θ_e, θ_μ, θ_τ with R_{ll} = 0 or 1 each to map the space of possibilities….

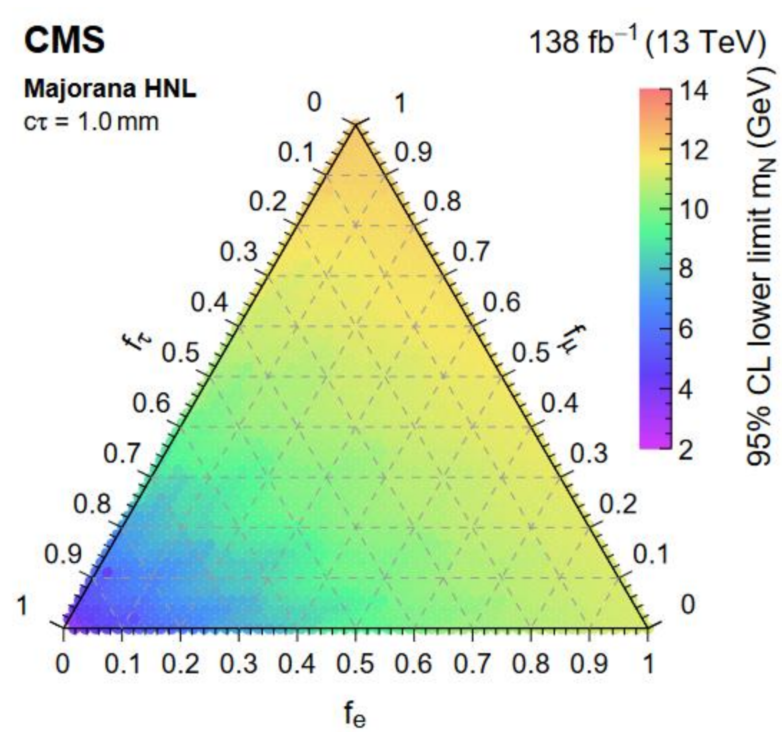
MaD/Klaric/Lopez-Pavon 2207.02742

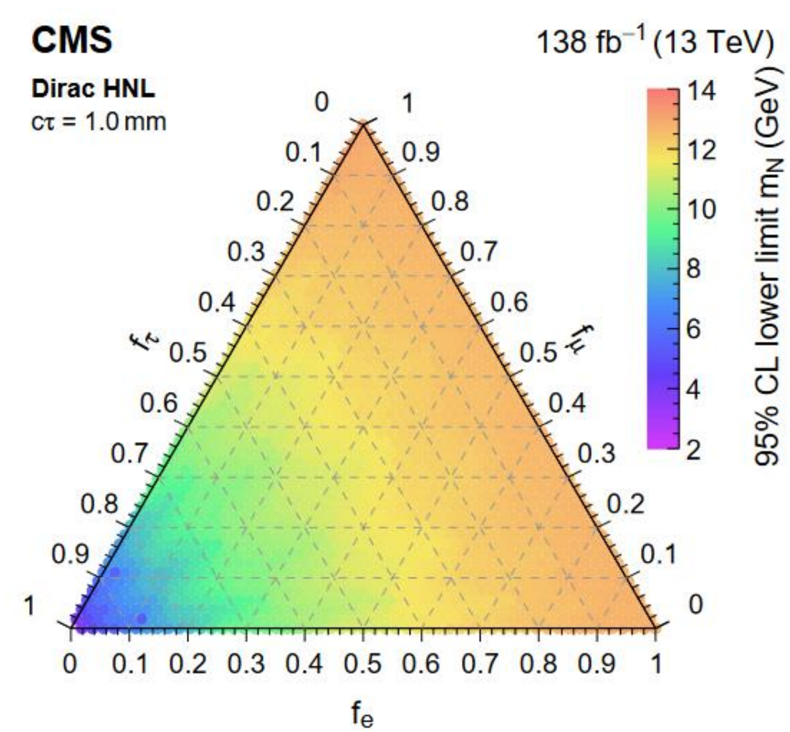


But maybe I am preaching to the choir…









CMS 2312.07484

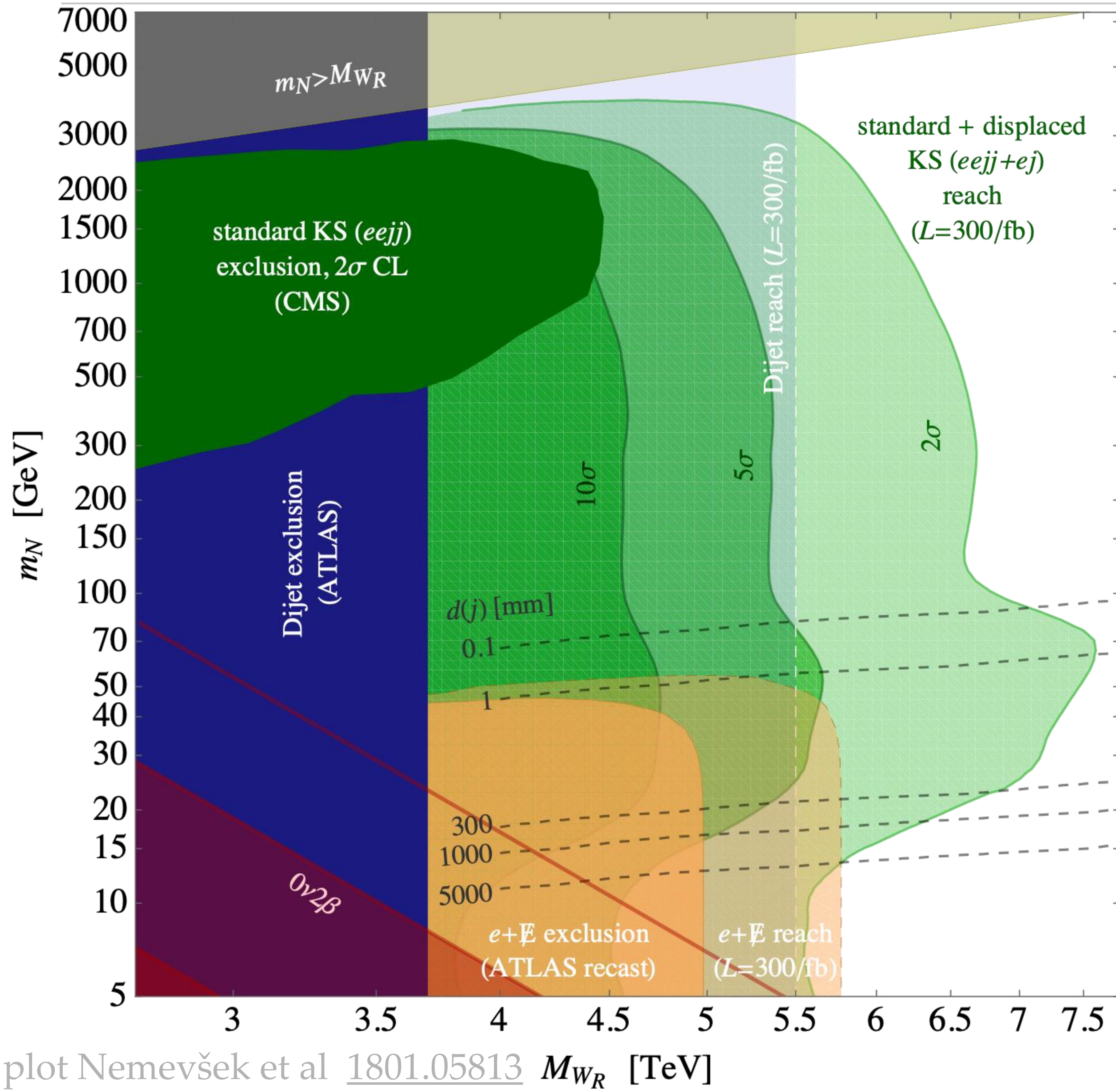
Summary

- Heavy neutrinos with-collider accessible masses and couplings can simultaneously explain the light neutrino masses and origin of matter
- Can be realised in natural and UV complete models below the TeV scale.
- LLP searches can still explore orders of magnitude of uncharted terrain, and can potentially see thousands of events at the LHC
- Minimal scenarios are highly testable in case of a HNL discovery (νMSM, testable models with discrete symmetries discussed here, …)
- This can be used to define benchmark scenarios to enable fair comparisons between existing exclusion bounds and discovery proposals of future experiments and searches.

Backup Slides

Non-minimal models

LNV in the LRSM at the LHC

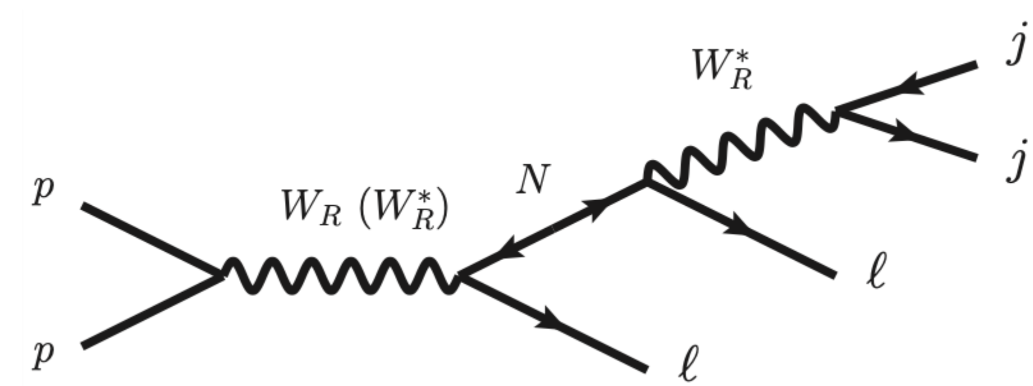


plot Nemevšek et al 1801.05813

- example: L-R symmetric models

  Pati, Salam, Mohapatra, Senjanovic

- HNLs can be long-lived and violate LNV in their decay

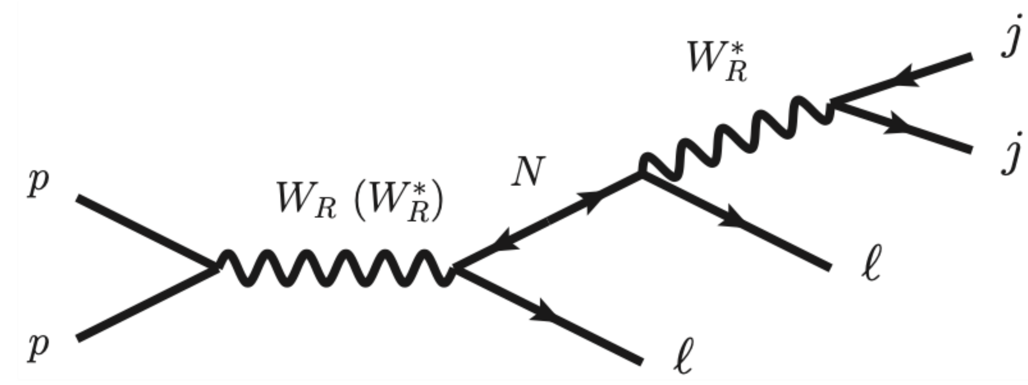


Keung/Senjanovic 83

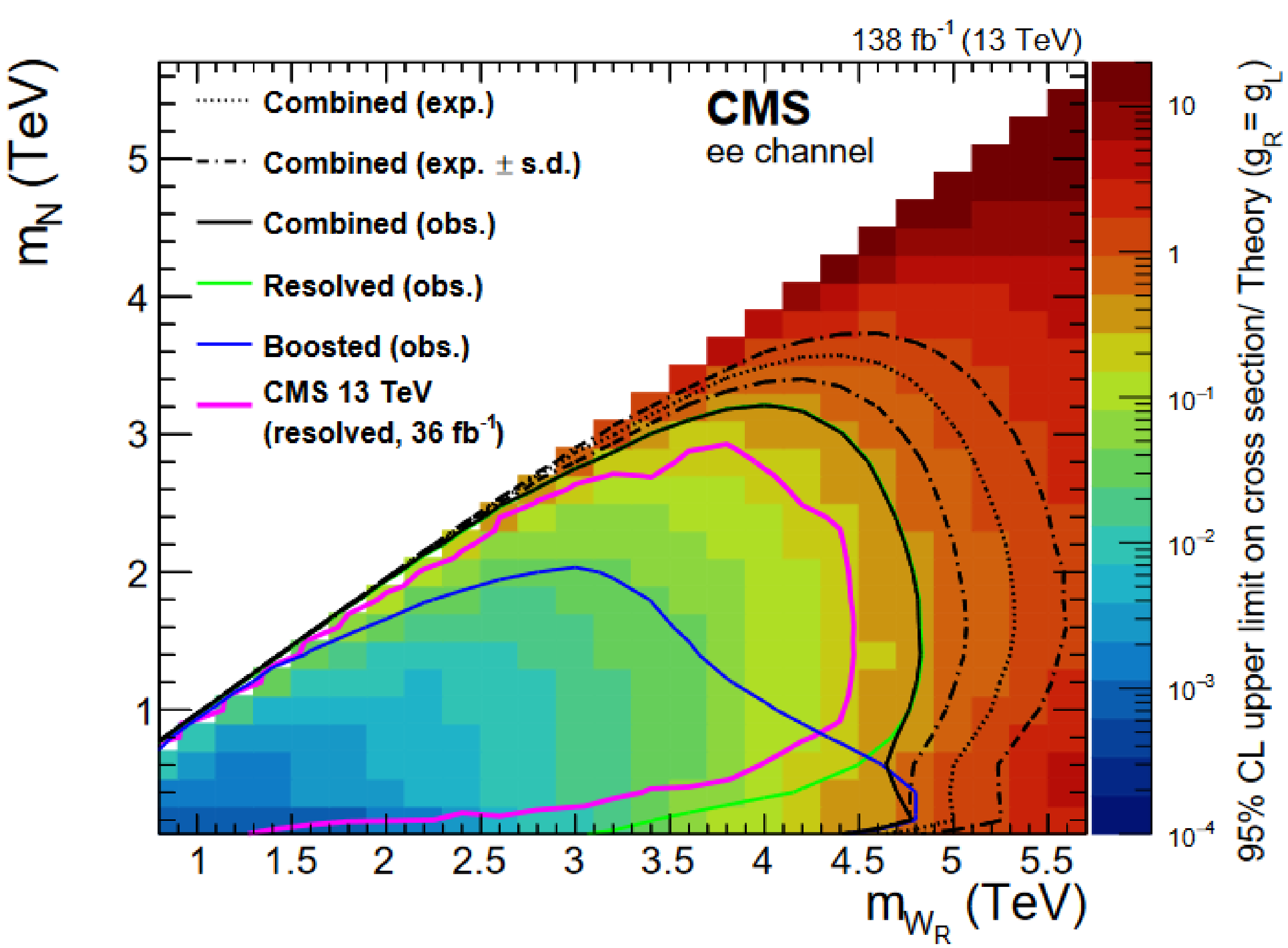
- But: This process is not directly connected to neutrino masses

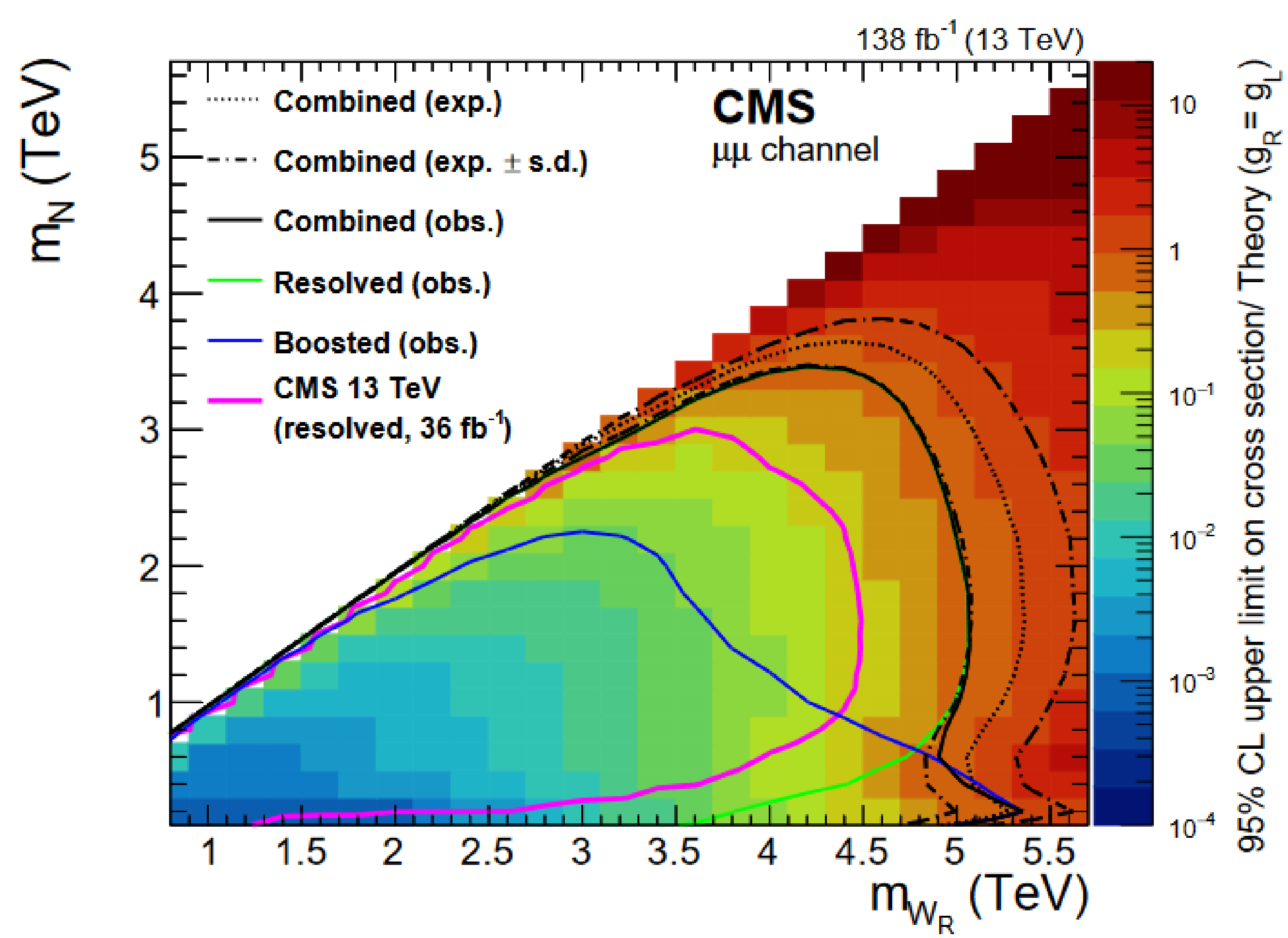
W_R interactions in LRSM

- New gauge interactions facilitate collider searches…
- …but current LHC bounds are strong
- W_R mass bound > 4 TeV makes detection at FCC-ee difficult



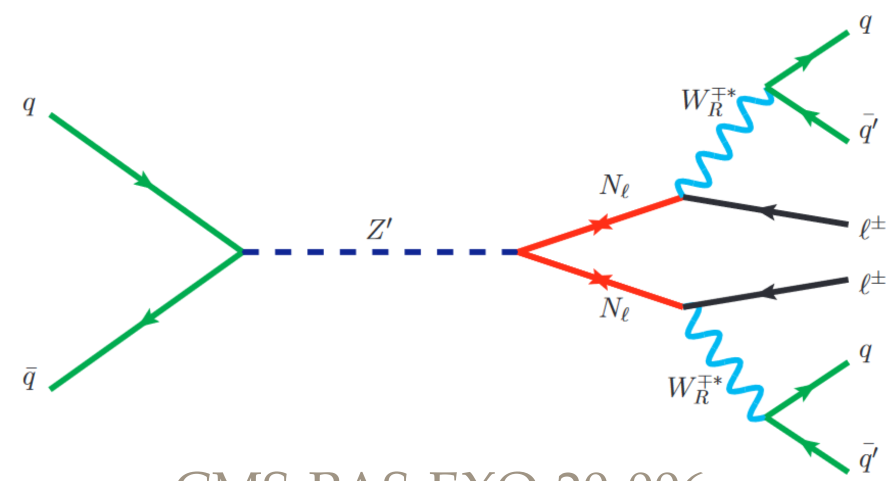
CMS 2112.03949



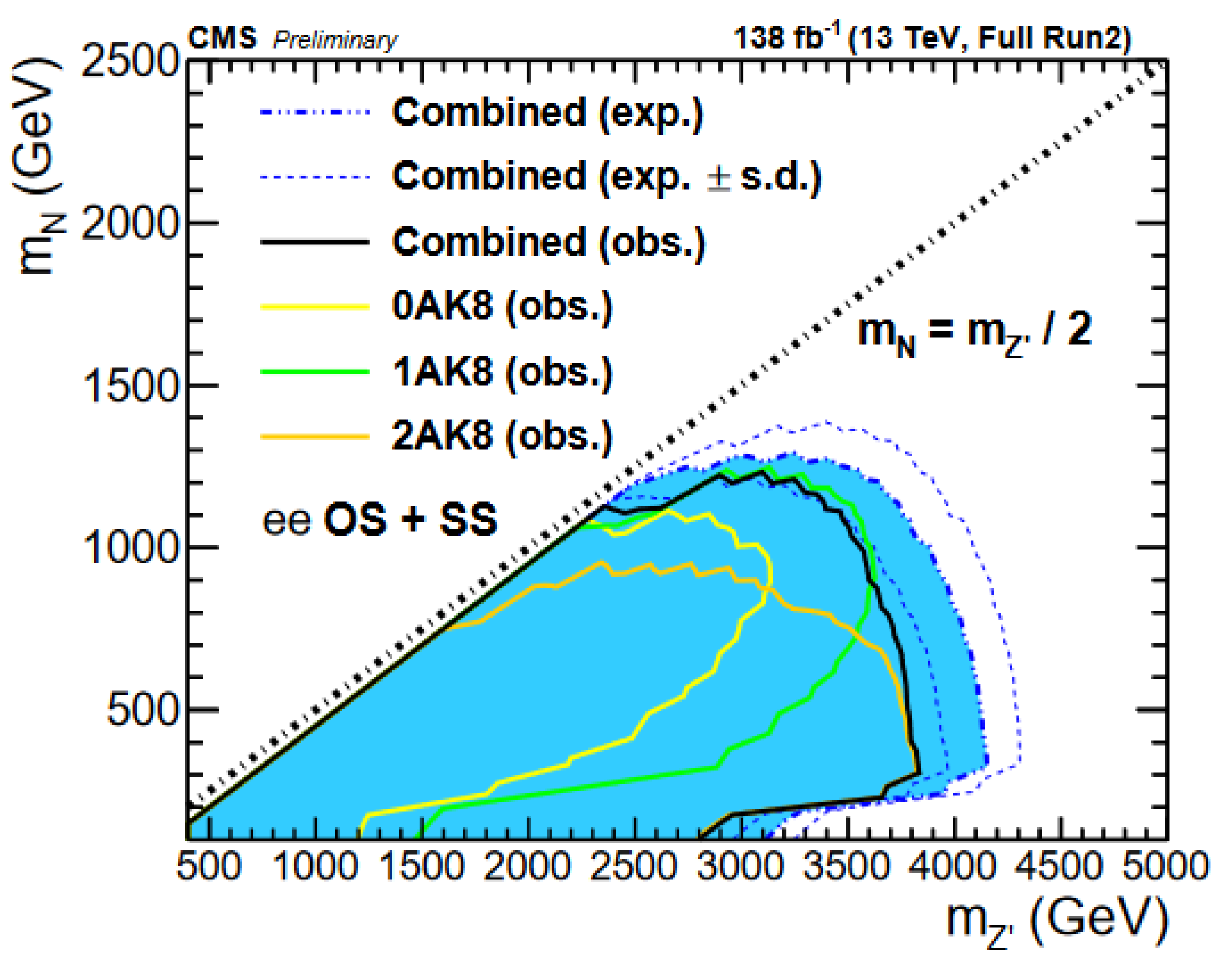


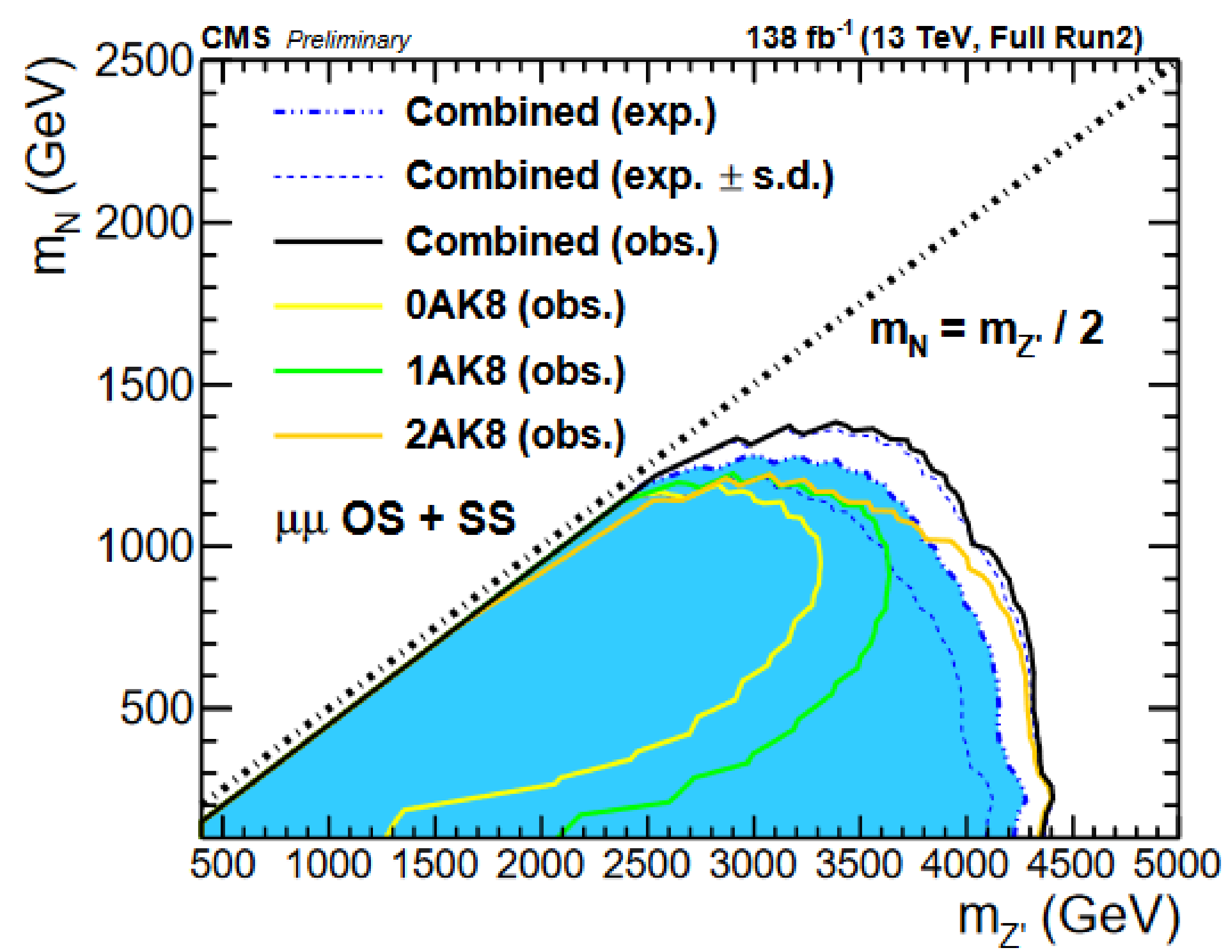
Z’ interactions in LRSM

- New gauge interactions facilitate collider searches…
- …but current LHC bounds are strong
- Z' mass bound > 4 TeV makes detection at FCC-ee difficult



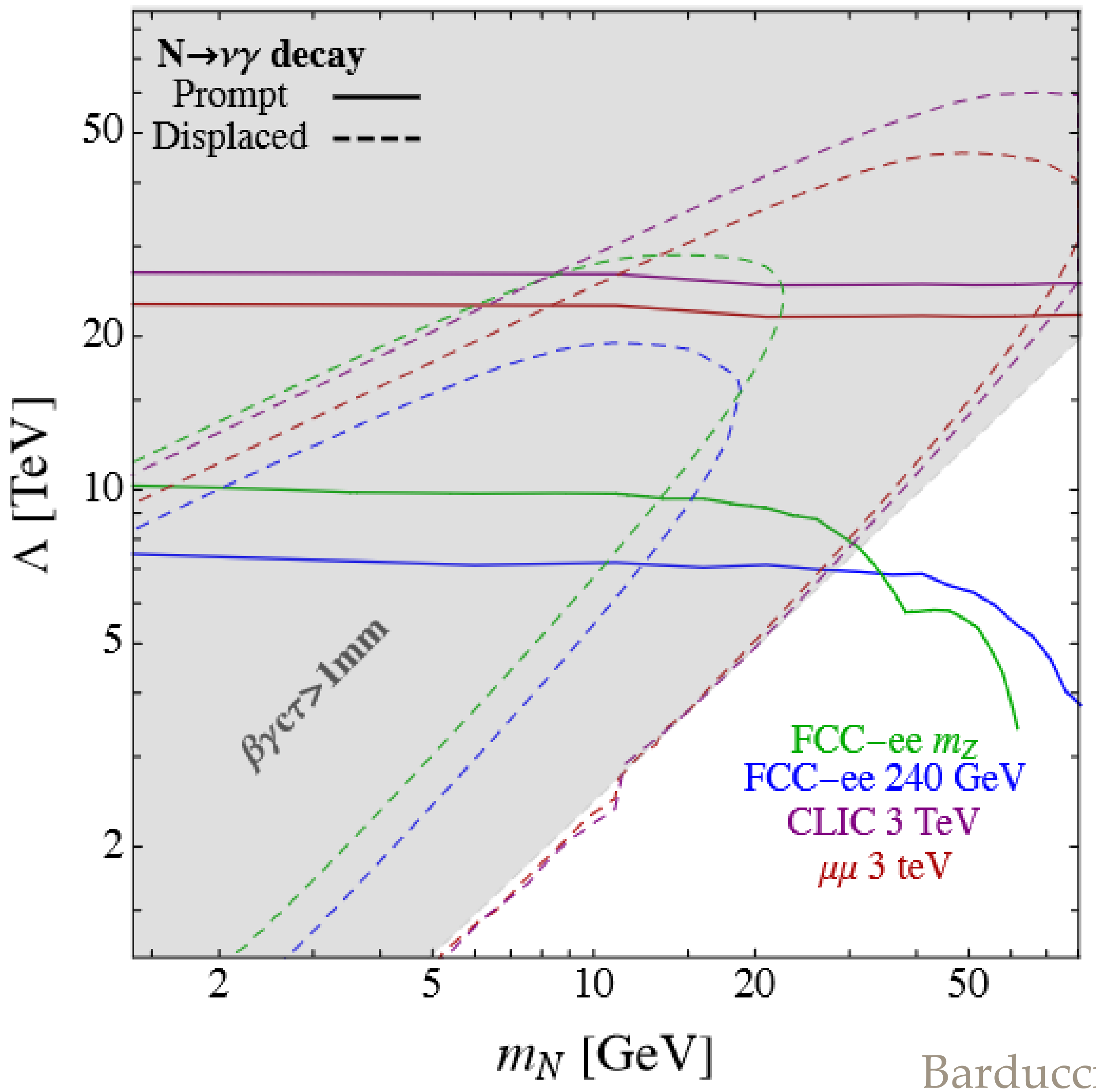
CMS-PAS-EXO-20-006

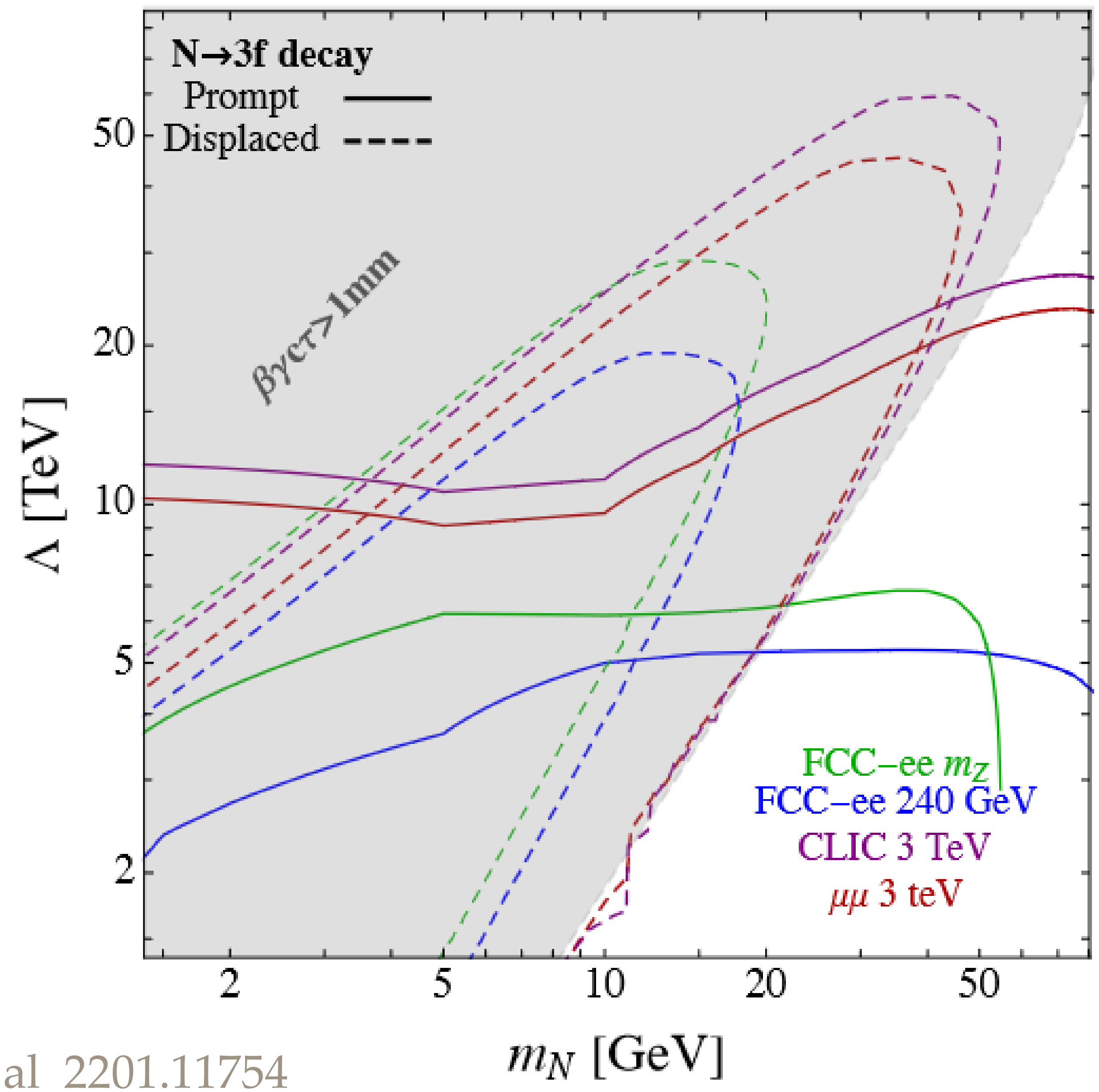




HNLs with EFT at FCC-ee

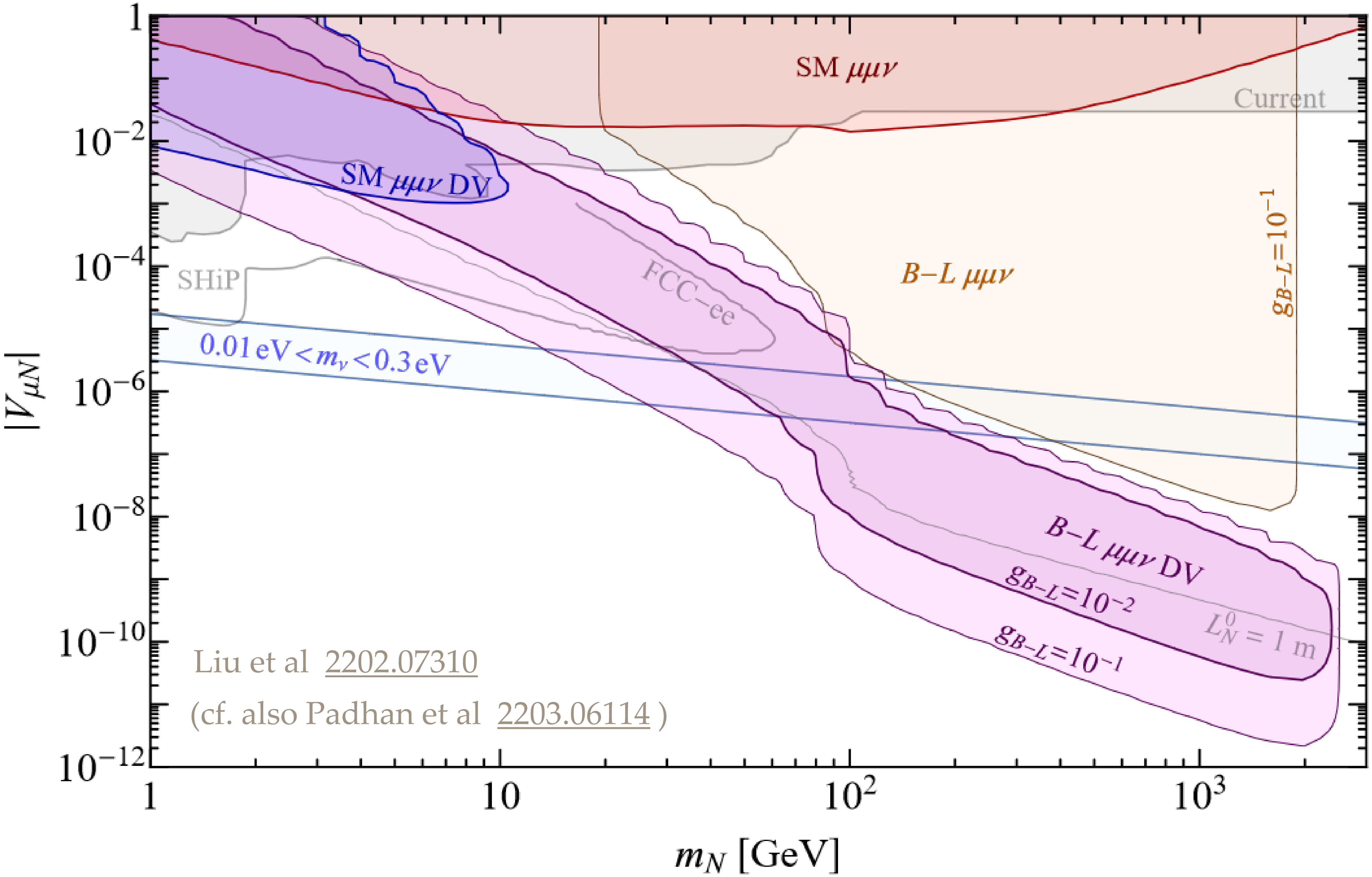
- FCC-ee can still probe larger masses in EFT framework





Barducci et al 2201.11754

Z’ interactions at FCC-hh



Complementarity and Testability

Parameter Spaces

$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}} \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$

Casas/Ibarra 01

2 Heavy Neutrinos (νMSM)
+ 2 RHN masses
+ 1 *complex* ($\times 2$) angle
+ **2 light neutrino masses**
+ **3 PMNS angles**
+ 1 CP phase δ
+ 1 Majorana phase α
11 (6 free) parameters

3 Heavy Neutrinos
+ 3 RHN masses
+ 3 *complex* ($\times 2$) angles
+ **$2 + 1$ light neutrino masses**
+ **3 PMNS angles**
+ 1 CP phase δ
+ 2 Majorana phases $\alpha_{1,2}$
18 (13 free) parameters

Full Testability?

Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}}\, \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$

Casas/Ibarra 01

Dirac phase δ
Majorana phase α

lightest ν mass

complex angle(s) ω

HNL-masses

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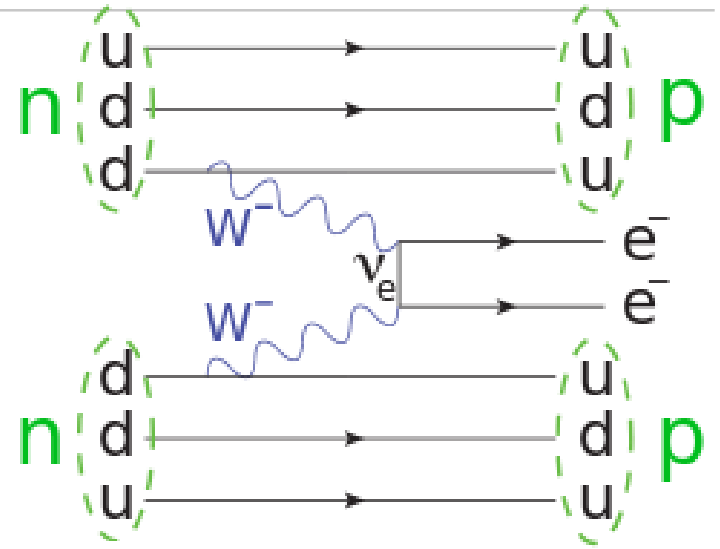
11 (6 free) parameters

Heavy neutrinos in 0νββ Decay

- Heavy mass states also contribute to $m_{\beta\beta}$



$$m_{\beta\beta} = \left| \sum_i (U_\nu)^2_{ei} m_i + \sum_I \Theta^2_{eI} M_I f_A(M_I) \right|$$

$$= \left| [1 - f_A(\bar{M})] m^\nu_{\beta\beta} + \sum_I M_I \Theta^2_{eI} [f_A(M_I) - f_A(\bar{M})] \right|$$

suppression of standard contribution

new contribution from RH neutrinos

Bezrukov 0505247 , Blennow et al 1005.3240 , Lopez Pavon et al 1209.5342, MaD/Eijima 1606.06221, Hernandez et al 1606.06719, Asaka et al 1606.06686, Abada et al 1810.12463

Heavy neutrinos in 0νββ Decay

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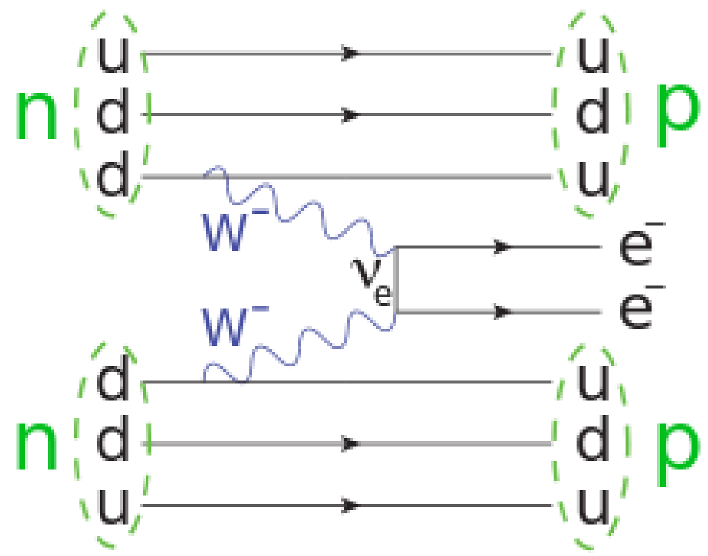
$$m_{\beta\beta} = \left| \sum_i (U_\nu)^2_{ei} m_i + \sum_I \Theta^2_{eI} M_I f_A(M_I) \right|$$



- Example: Minimal model with 2 RH neutrinos

new contribution from RH neutrinos is sensitive to Reω

$$m_{\beta\beta} \simeq \Big| [1 - f_A(\bar{M})] m^\nu_{\beta\beta} + f_A^2(\bar{M}) \frac{\bar{M}^2}{\langle p^2 \rangle} \frac{\Delta M}{\bar{M}} |\Delta m_{\rm atm}| \sin^2\theta_{13} e^{2{\rm Im}\omega} e^{-2i({\rm Re}\omega+\delta)} \Big|$$

suppression of standard contribtion

Bezrukov 0505247 , Blennow et al 1005.3240 , Lopez Pavon et al 1209.5342, MaD/Eijima 1606.06221, Hernandez et al 1606.06719, Asaka et al 1606.06686, Abada et al 1810.12463

Full Testability!

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light neutrino mixing angles

light neutrino mass splittings

$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}}\,\mathcal{R}\sqrt{M^{\mathrm{diag}}}$$

Casas/Ibarra 01

Dirac phase δ
Majorana phase α

lightest ν mass

complex angle(s) ω

HNL-masses

2 Heavy Neutrinos (νMSM)

+ 2 RHN masses
+ 1 *complex* ($\times 2$) angle
+ **2 light neutrino masses**
+ **3 PMNS angles**
+ 1 CP phase δ
+ 1 Majorana phase α

11 (6 free) parameters

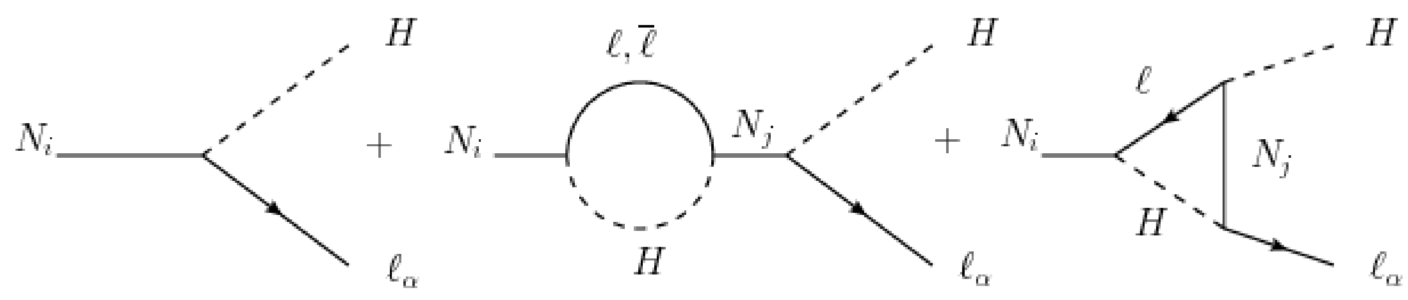
- In the minimal model (νMSM-like) all parameters can in principle be constrained by experiment
  Hernandez et al 1606.06719 MaD et al 1609.09069
- This makes it a UV complete and testable model of neutrino masses and baryogenesis (and possibly a third HNL is DM)
- It is also a poster child example of cross frontier research

Leptogenesis

Leptogenesis as the Origin of Matter

Basic idea Fukugita/Yanagida 86

- N are around in the early universe
- N interactions are CP violating
- N may preferably decay into matter

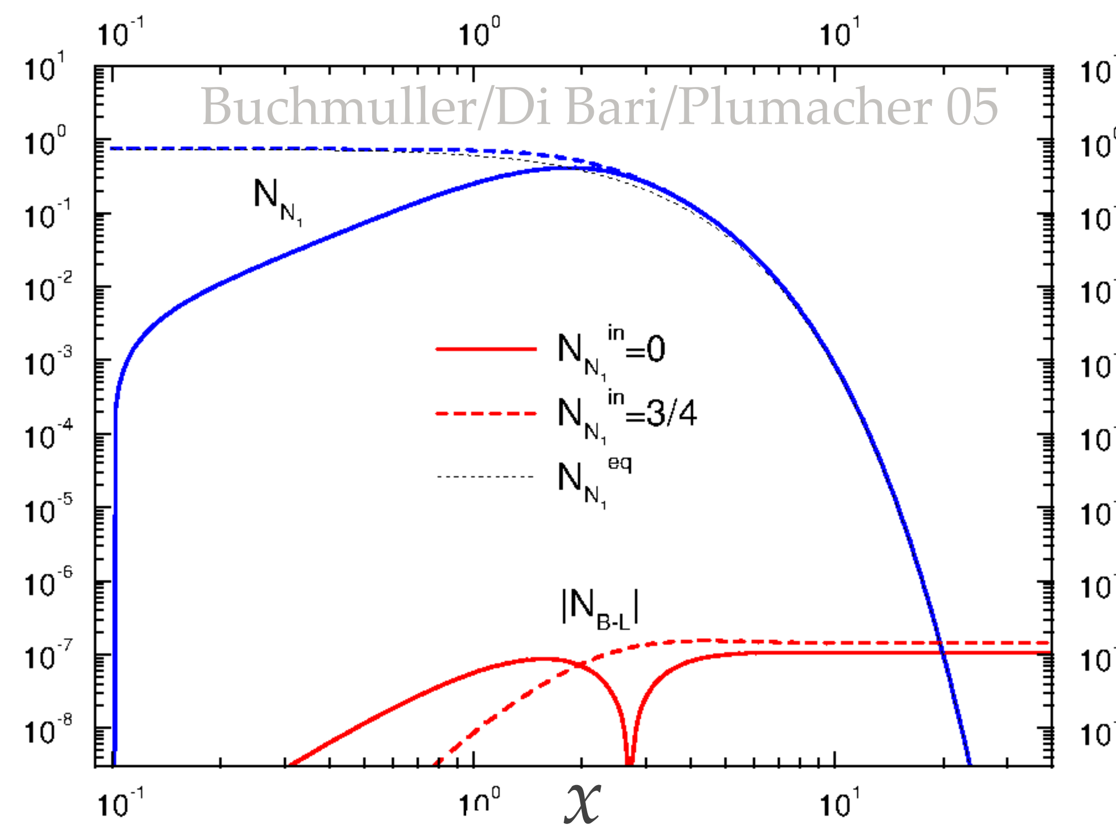


Quantitative description

- Conventionally described by semi-classical Boltzmann equations

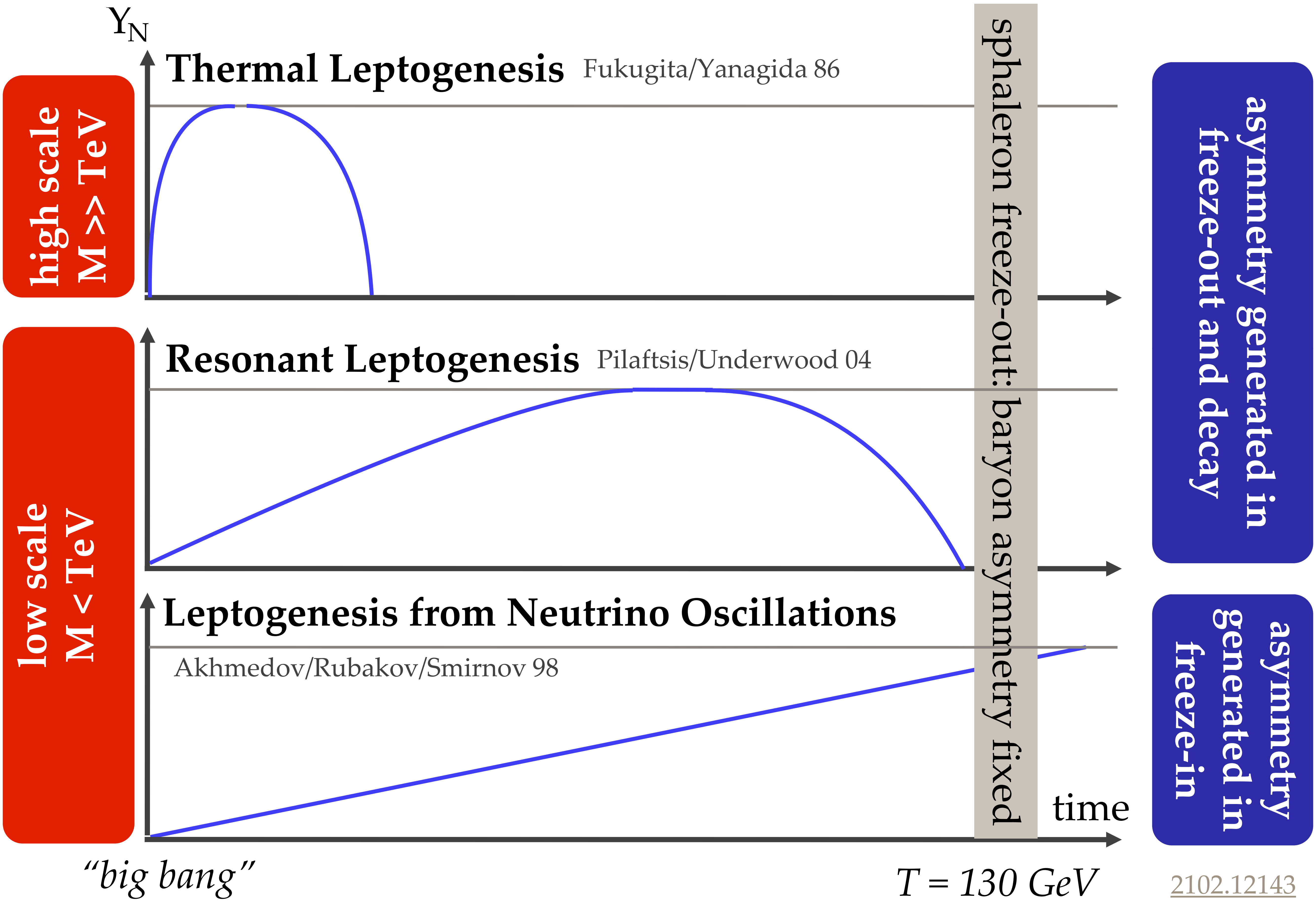
$$xH\frac{d\mathrm{Y}_N}{dx} = -\Gamma_N(\mathrm{Y}_N - \mathrm{Y}_N^{\mathrm{eq}}) \qquad x = M/T$$

$$xH\frac{d\mathrm{Y}_{\mathrm{B-L}}}{dx} = \epsilon\Gamma_N(\mathrm{Y}_N - \mathrm{Y}_N^{\mathrm{eq}}) - c_W\Gamma_N\mathrm{Y}_{\mathrm{B-L}}$$



- But: asymmetry arises from quantum interference in the plasma
- Low scale leptogenesis: asymmetry generated at M < T, flavour effects are crucial, thermal and quantum corrections can be large
  ⇒ derive quantum kinetic equations from first principles

recall $m_\nu = -v^2 F M_M^{-1} F^T = -m_D M_M^{-1} m_D^T = -\theta M_M \theta^T$



2102.12143

Quantitative Description

- Need to track three SM chemical potentials
- Track coherences for heavy neutrinos ("density matrix equations")

$$i\frac{dn_{\Delta_\alpha}}{dt} = -2i\frac{\mu_\alpha}{T}\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}[\Gamma_\alpha]f_N(1-f_N) + i\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}[\tilde{\Gamma}_\alpha\,(\delta\bar{\rho}_N-\delta\rho_N)]\,,$$

$$i\frac{d\delta\rho_N}{dt} = -i\frac{d\rho_N^{eq}}{dt} + [H_N,\rho_N] - \frac{i}{2}\{\Gamma,\delta\rho_N\} - \frac{i}{2}\sum_\alpha\tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N(1-f_N)\right],$$

$$i\frac{d\delta\bar{\rho}_N}{dt} = -i\frac{d\rho_N^{eq}}{dt} - [H_N,\bar{\rho}_N] - \frac{i}{2}\{\Gamma,\delta\bar{\rho}_N\} + \frac{i}{2}\sum_\alpha\tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N(1-f_N)\right].$$

SM chemical potentials

Heavy neutrino density matrix

Heavy neutrino effective Hamiltonian

LNC rate ~ *F^2 T*

LNV rate ~ *$(M/T)^2$ F^2 T*

Leptogenesis with 2 HNL Flavours

Two HNL flavours

- Mass basis at $T=0$ is the one where M is diagonal
- B-L limit: ν_{Rs} and ν_{Rw} define "interaction basis"
- $T >> M$: thermal masses dominate, interaction basis is mass basis

Approx. conserved for $M << T$

spinors	$\widetilde{L}$-charge
$P_+N_i, \quad \bar{N}_iP_+$	$+1$
$P_-N_i, \quad \bar{N}_iP_-$	-1

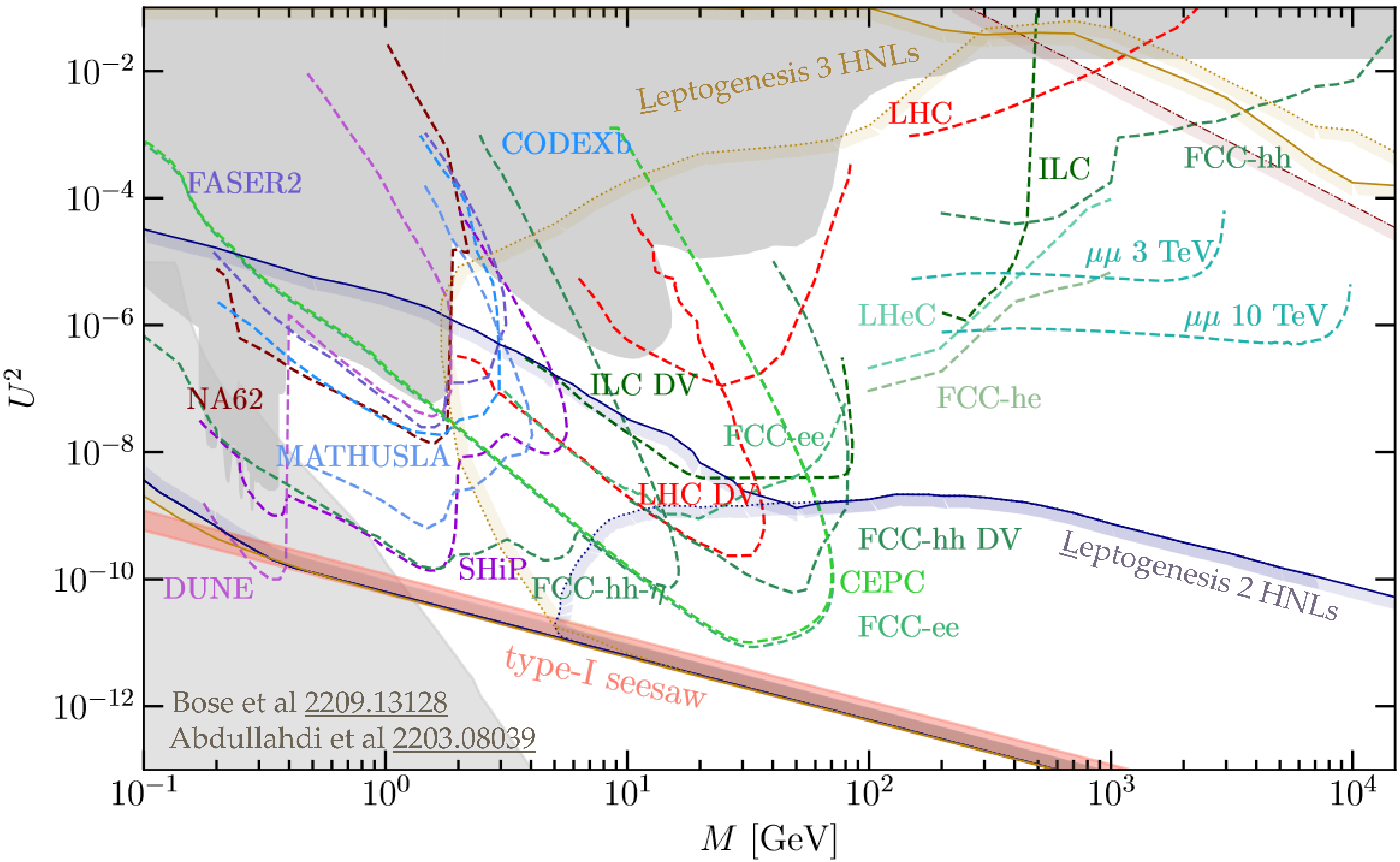
$$F = \begin{pmatrix} F_e(1+\epsilon_e) & \mathrm{i}F_e(1-\epsilon_e) \\ F_\mu(1+\epsilon_\mu) & \mathrm{i}F_\mu(1-\epsilon_\mu) \\ F_\tau(1+\epsilon_\tau) & \mathrm{i}F_\tau(1-\epsilon_\tau) \end{pmatrix}$$

"mass basis"

$$F \sim \begin{pmatrix} F_e & F_e\epsilon_e \\ F_\mu & F_\mu\epsilon_\mu \\ F_\tau & F_\tau\epsilon_\tau \end{pmatrix}$$

"interaction basis"

Leptogenesis: 2 vs 3 HNL Flavours



Leptogenesis: 2 vs 3 HNL Flavours

Two HNL flavours

- Mass basis at T=0 is the one where M is diagonal
- B-L limit: ν_{Rs} and ν_{Rw} define "interaction basis"
- $T >> M$: thermal masses dominate, interaction basis is mass basis

Approx. conserved for $M << T$

spinors	$\widetilde{L}$-charge
$P_+ N_i, \quad \bar{N}_i P_+$	$+1$
$P_- N_i, \quad \bar{N}_i P_-$	-1

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & \mathrm{i}F_e(1-\epsilon_e) \\ F_\mu(1+\epsilon_\mu) & \mathrm{i}F_\mu(1-\epsilon_\mu) \\ F_\tau(1+\epsilon_\tau) & \mathrm{i}F_\tau(1-\epsilon_\tau) \end{pmatrix}$$

"mass basis"

$$F \sim \begin{pmatrix} F_e & F_e\epsilon_e \\ F_\mu & F_\mu\epsilon_\mu \\ F_\tau & F_\tau\epsilon_\tau \end{pmatrix}$$

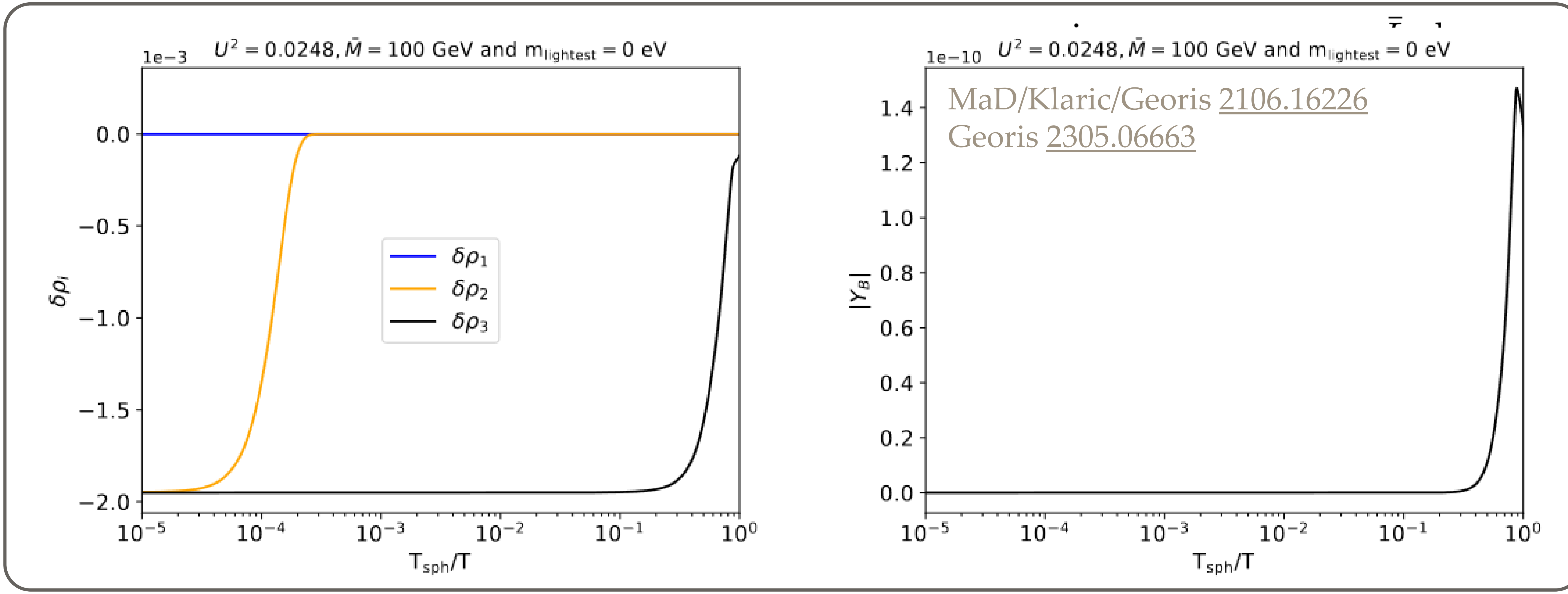
"interaction basis"

Three HNL flavours

- Third state ν_{R3} is free of constraints that relates ν_{Rs} and ν_{Rw}
- It can maintain deviation from equilibrium even when LNV rates come into equilibrium
- void washout even for large couplings of pseudo-Dirac pair
- No need for hierarchy in SM flavour couplings to prevent washout!

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix},$$

Maverick Heavy Neutrino



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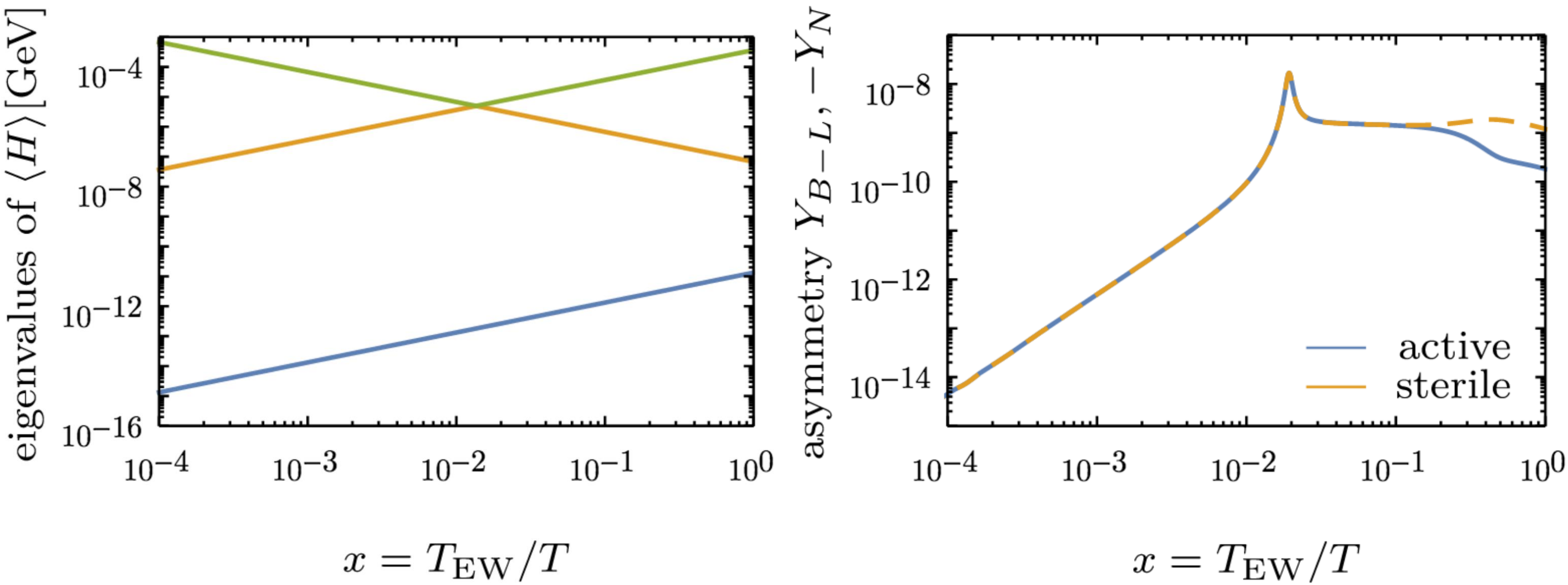
Dynamical Generation of Resonance

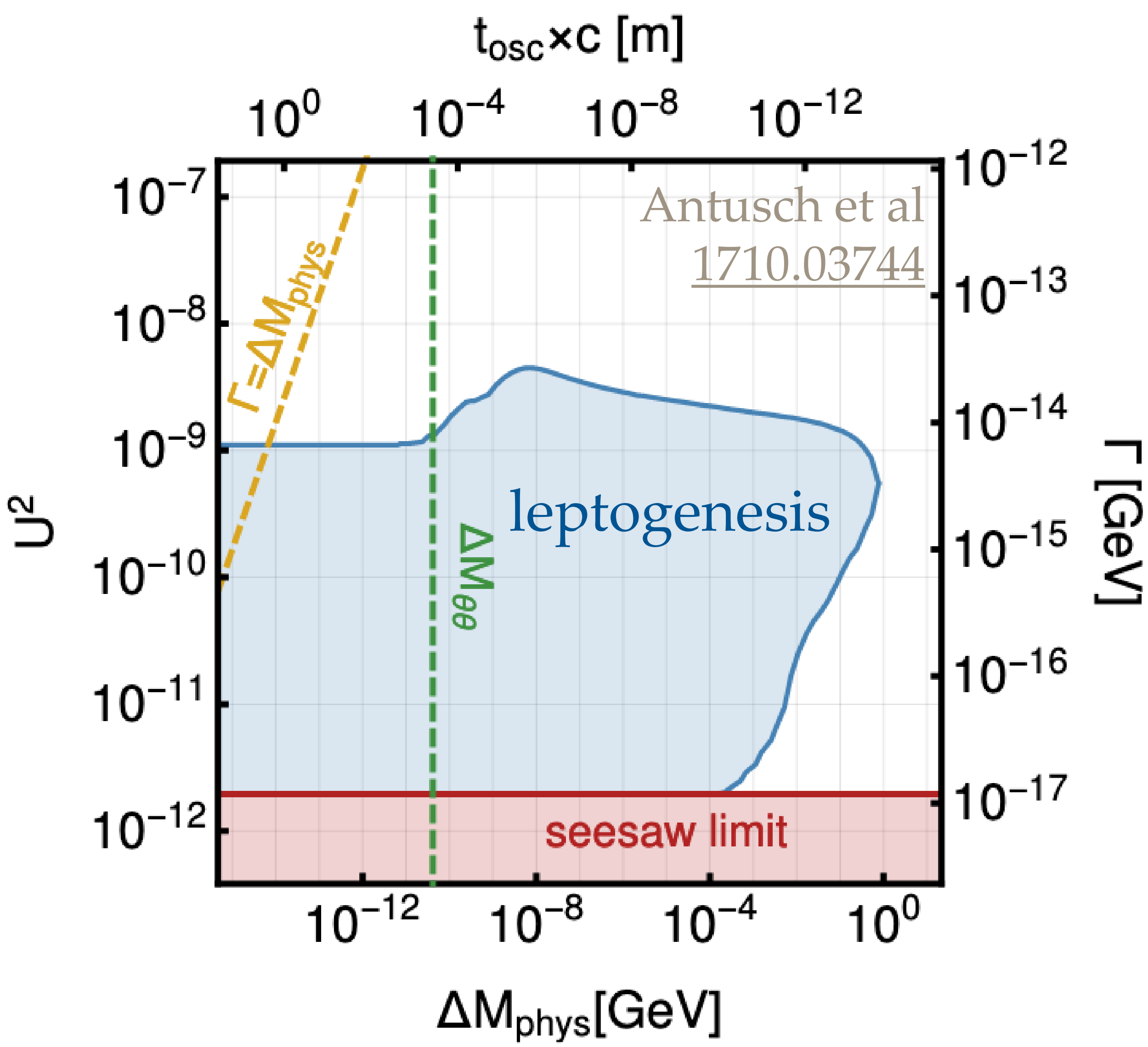


Abada et al 1810.12463

- level crossing between the quasiparticle dispersion relations in the plasma (“thermal masses”) can dynamically generate a resonance
- Strong enhancement of the asymmetry with only moderate degeneracy in the vacuum masses

Leptogenesis with Exactly Degenerate Majorana Masses: 2HNLs

- Leptogenesis is feasible even if Majorana mass in Lagrangian is a unit matrix



- Different contributions to thermal masses lead to misalignment between "mass basis" and "interaction basis"

$$H_N^{\rm vac} = \frac{\pi^2}{18\zeta(3)}\frac{a_{\rm R}}{T_{\rm ref}^3}\left({\rm Re}[M^\dagger M] + ih{\rm Im}[M^\dagger M]\right) ,$$

$$H_N^{\rm th} = \frac{a_{\rm R}}{T_{\rm ref}}\left(\mathfrak{h}_+^{\rm th}\Upsilon_{+h} + \mathfrak{h}_-^{\rm th}\Upsilon_{-h}\right) + \mathfrak{h}^{\rm EV}\frac{a_{\rm R}}{T_{\rm ref}}{\rm Re}[Y^* Y^t] ,$$

$$\Gamma_N = \frac{a_{\rm R}}{T_{\rm ref}}\left(\gamma_+\Upsilon_{+h} + \gamma_-\Upsilon_{-h}\right) ,$$

$$\tilde{\Gamma}_N^a = h\frac{a_{\rm R}}{T_{\rm ref}}\left(\tilde{\gamma}_+\Upsilon_{+h}^a - \tilde{\gamma}_-\Upsilon_{-h}^a\right) ,$$

- Effect is only seen when using density matrix and including thermal corrections!

- Similar mechanism enables HNL oscillations in detector and observable LNV,

$$M_N = M_M + \frac{1}{2}(\theta^\dagger\theta M_M + M_M^T\theta^T\theta^*)$$

MaD/Klaric/Klose 1907.13034

Flavour Invariants

- Density matrix equation

$$i\frac{dn_{\Delta_\alpha}}{dt} = -2i\frac{\mu_\alpha}{T}\int \frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}\left[\Gamma_\alpha\right] f_N\left(1-f_N\right) \quad + i\int \frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}\left[\tilde{\Gamma}_\alpha\left(\bar{\rho}_N - \rho_N\right)\right],$$

$$i\,\frac{d\rho_N}{dt} = \left[H_N, \rho_N\right] - \frac{i}{2}\left\{\Gamma, \rho_N - \rho_N^{eq}\right\} \quad - \frac{i}{2}\sum_\alpha \tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T} f_N\left(1-f_N\right)\right],$$

$$i\,\frac{d\bar{\rho}_N}{dt} = -\left[H_N, \bar{\rho}_N\right] - \frac{i}{2}\left\{\Gamma, \bar{\rho}_N - \rho_N^{eq}\right\} \quad + \frac{i}{2}\sum_\alpha \tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T} f_N\left(1-f_N\right)\right].$$

- Small Yukawas: solve perturbatively

$$\mathrm{Tr}\left[\tilde{\Gamma}_\alpha(\bar{\rho}_N - \rho_N)\right] \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\left[H_N, \Gamma\right]\right)$$

- Find CPV combinations

$$C_{\mathrm{LFV},\alpha} = i\,\mathrm{Tr}\left(\left[\hat{M}_R^2, \hat{Y}_D^\dagger \hat{Y}_D\right]\hat{Y}_D^\dagger P_\alpha \hat{Y}_D\right), \qquad \text{LFV source}$$

$$C_{\mathrm{LNV},\alpha} = i\,\mathrm{Tr}\left(\left[\hat{M}_R^2, \hat{Y}_D^\dagger \hat{Y}_D\right]\hat{Y}_D^T P_\alpha \hat{Y}_D^*\right), \qquad \text{LNV source}$$

$$C_{\mathrm{DEG},\alpha} = i\,\mathrm{Tr}\left(\left[\hat{Y}_D^T \hat{Y}_D^*, \hat{Y}_D^\dagger \hat{Y}_D\right]\hat{Y}_D^T P_\alpha \hat{Y}_D^*\right), \qquad \text{mass-degenerate source}$$

Antusch et al 1710.03744 MaD/Georis/HagedornKlaric 2203.08538