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Heavy Neutral Leptons below the EW Scale

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ICISE - CBPF Workshop on New Physics with exotic and long lived particles

ICISE, Quy Nhon, Vietnam

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Heavy Neutral Leptons below the EW scale

Heavy Neutrinos were the cover story of February's issue of the German Physical Society's journal!

Physik Journal 18, Februar 2019, S. 28

Overview

The Low Scale Seesaw and the νMSM

Searches at Existing Facilities

Searches with Future Facilities

Connection to Cosmology

Complementarity and Full Testability

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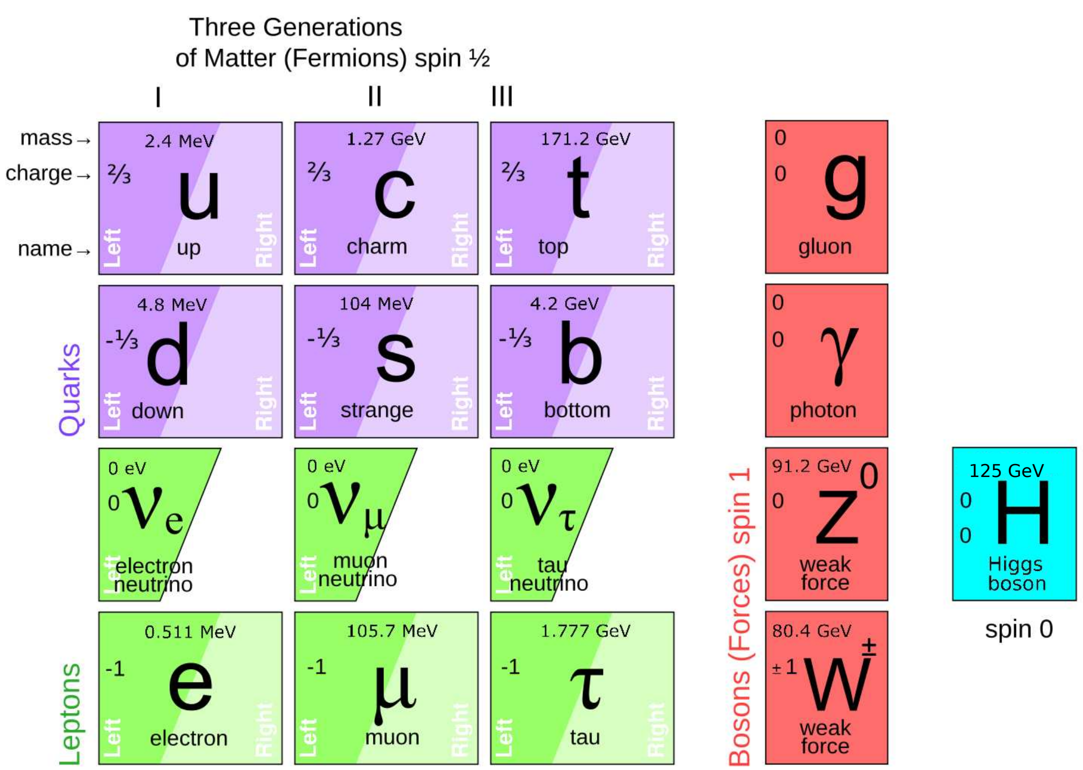
The Seesaw Mechanism (type I)

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L$$



$$\frac{1}{2}(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$

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

A minimal realisation: The νMSM

Shaposhnikov / Askaka 0505013

- **No sew scale.** Majorana mass is near the electroweak scale
- **No new gauge group.**
- **Same # families for RH and LH fermions.**
- **Yukawas similar to charged leptons.**
- **Approximately respect approximate B-L symmetry.** One RH neutrinos almost decouples, the other two form pseudo-Dirac spinor with gegenerate masses
- **Explain neutrino masses, DM, Baryogenesis.**

A minimal realisation: The νMSM

Effective theory for νMSM collider/fixed target phone:

Type I seesaw with two RH Neutrinos below EW scale

[observational constraints on DM candidate (cf. e.g. 1602.04816, 1807.07938) imply that it must have very feeble couplings]

Minimality makes the model fully testable!

cf. Hernandez et al 1606.06719, MaD et al 1609.09069

Can simultaneously explain Shaposhnikov / Askaka 0505013

- **Neutrio masses**
- **Leptogenesis**
- **Dark Matter**

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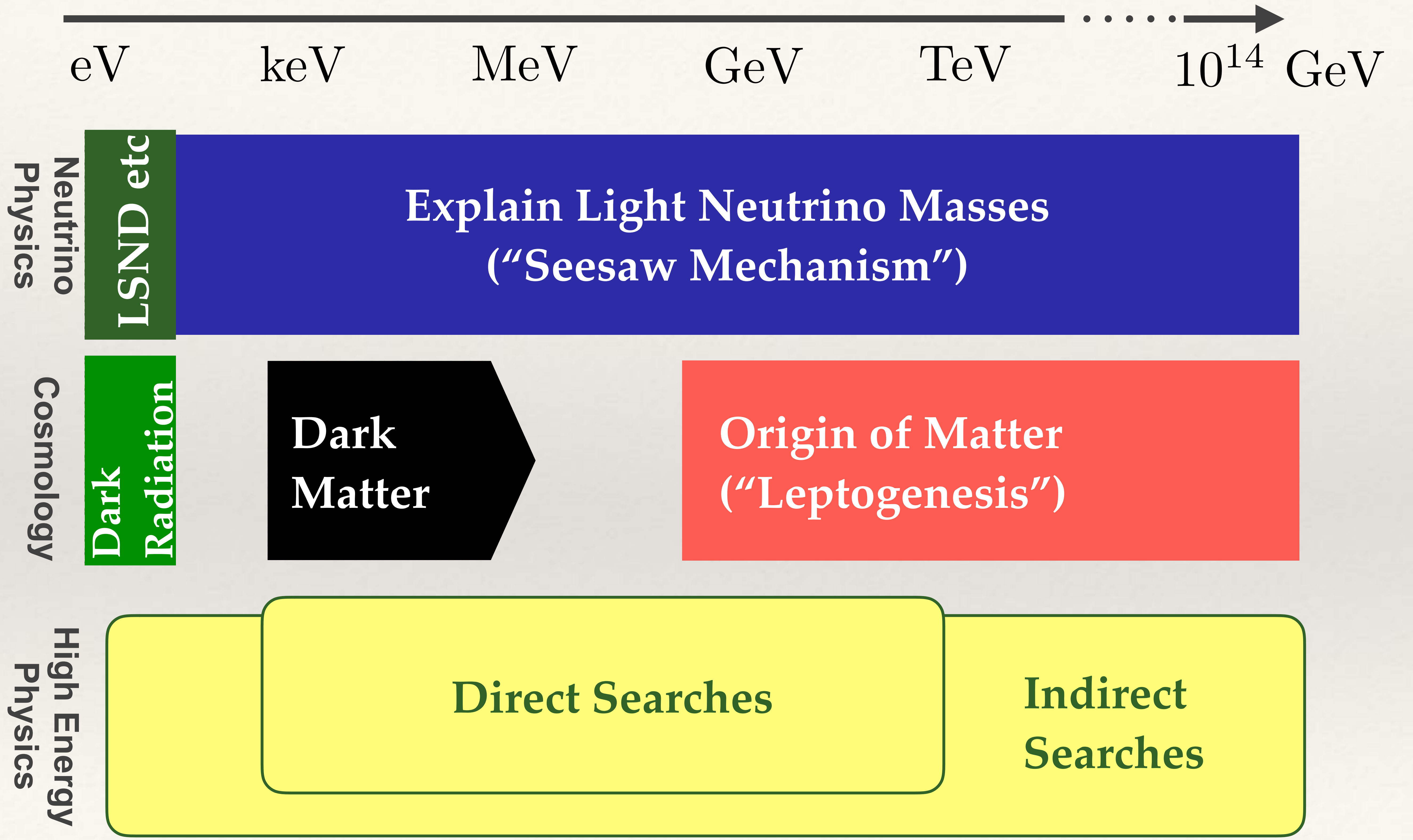
Right Handed Neutrino Mass Scale



Right Handed Neutrino Mass Scale

nuclear decay spectra

TRISTAN, ECHO

fixed target experiments

SHiP
Search for Hidden Particles

NA62

b factories

LHCb

Belle II

proton colliders

electron colliders

FCC hh ee he

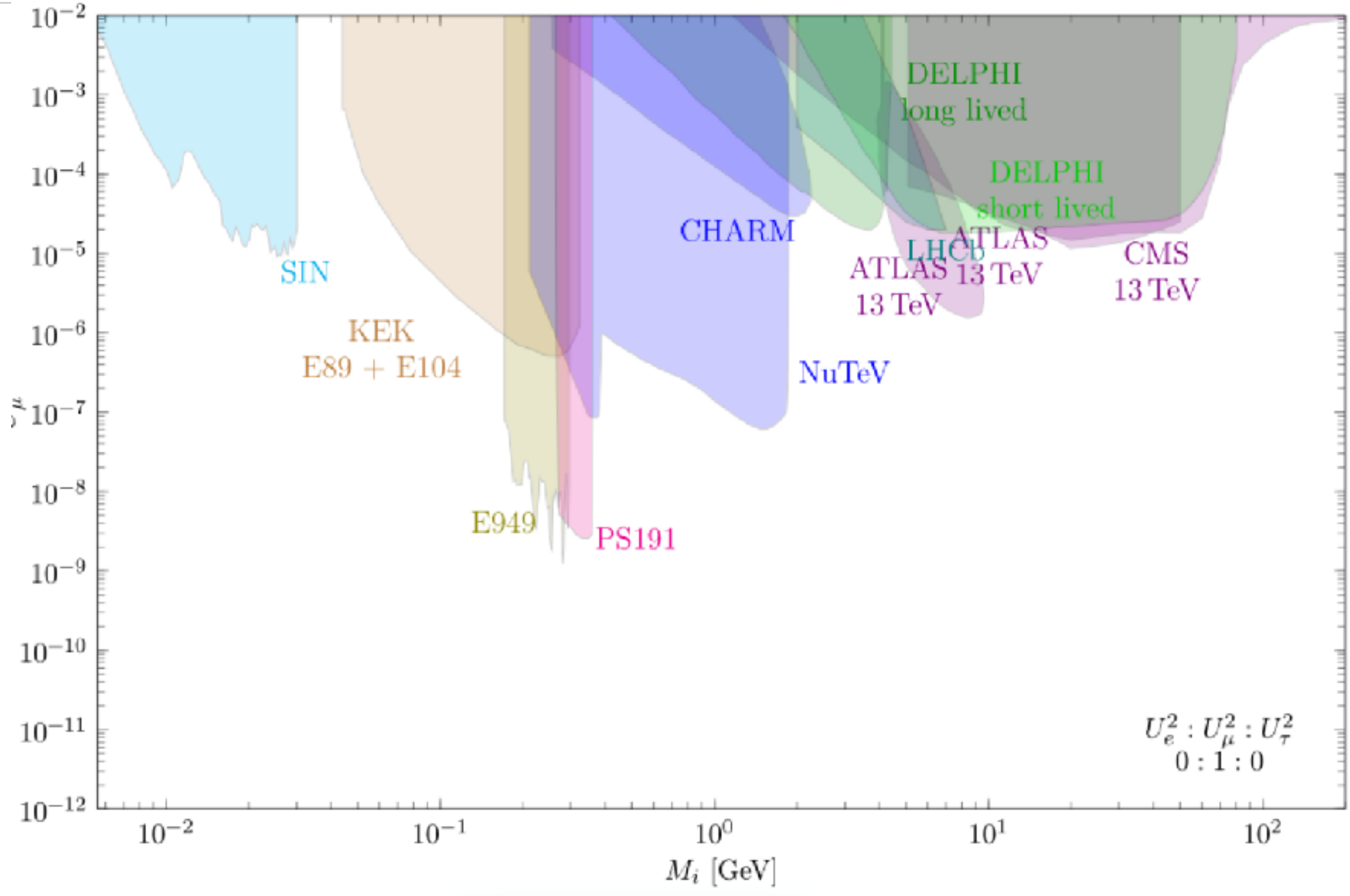
CEPC

ilc international linear collider

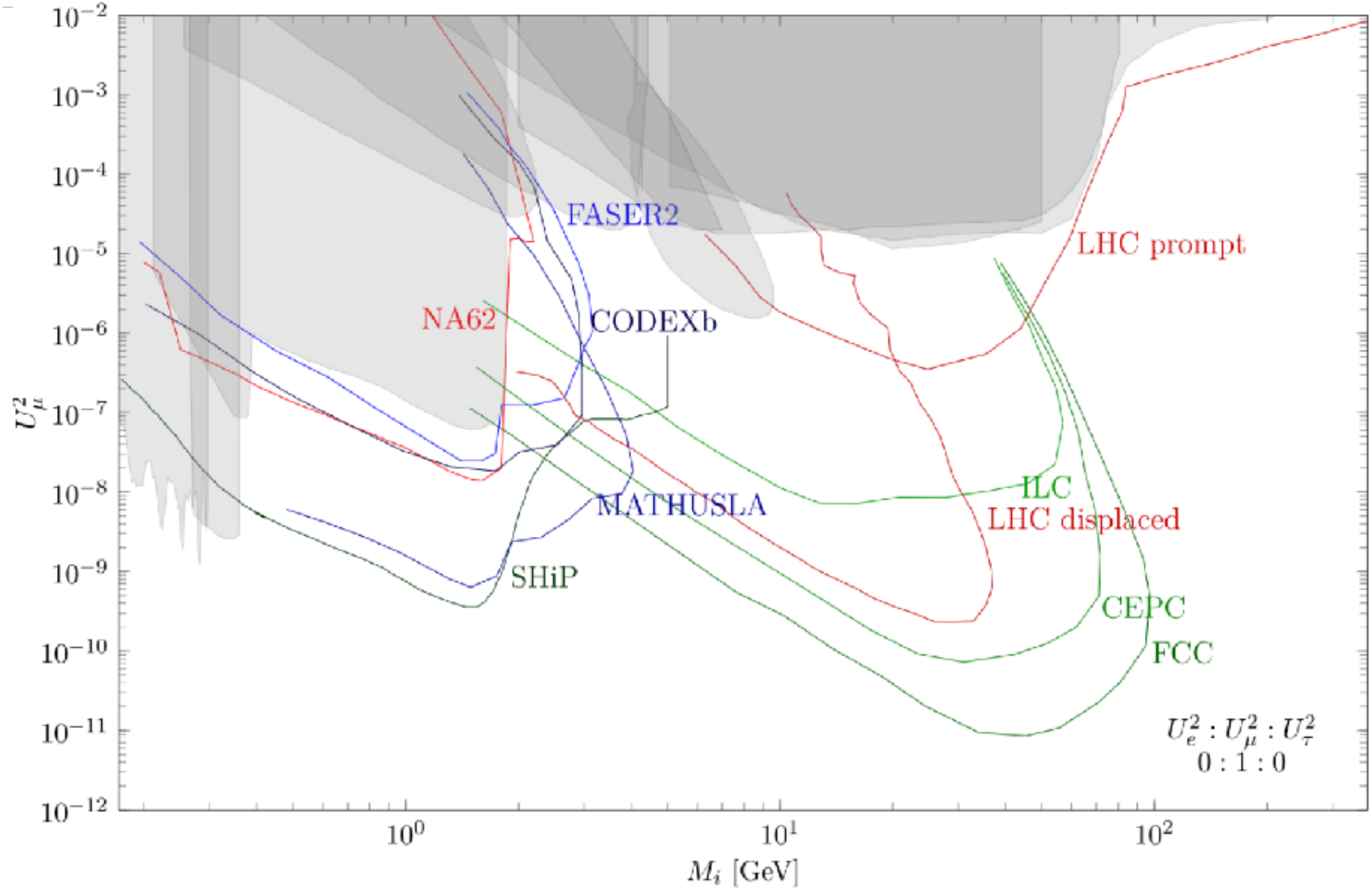
High Energy Physics

Direct Searches

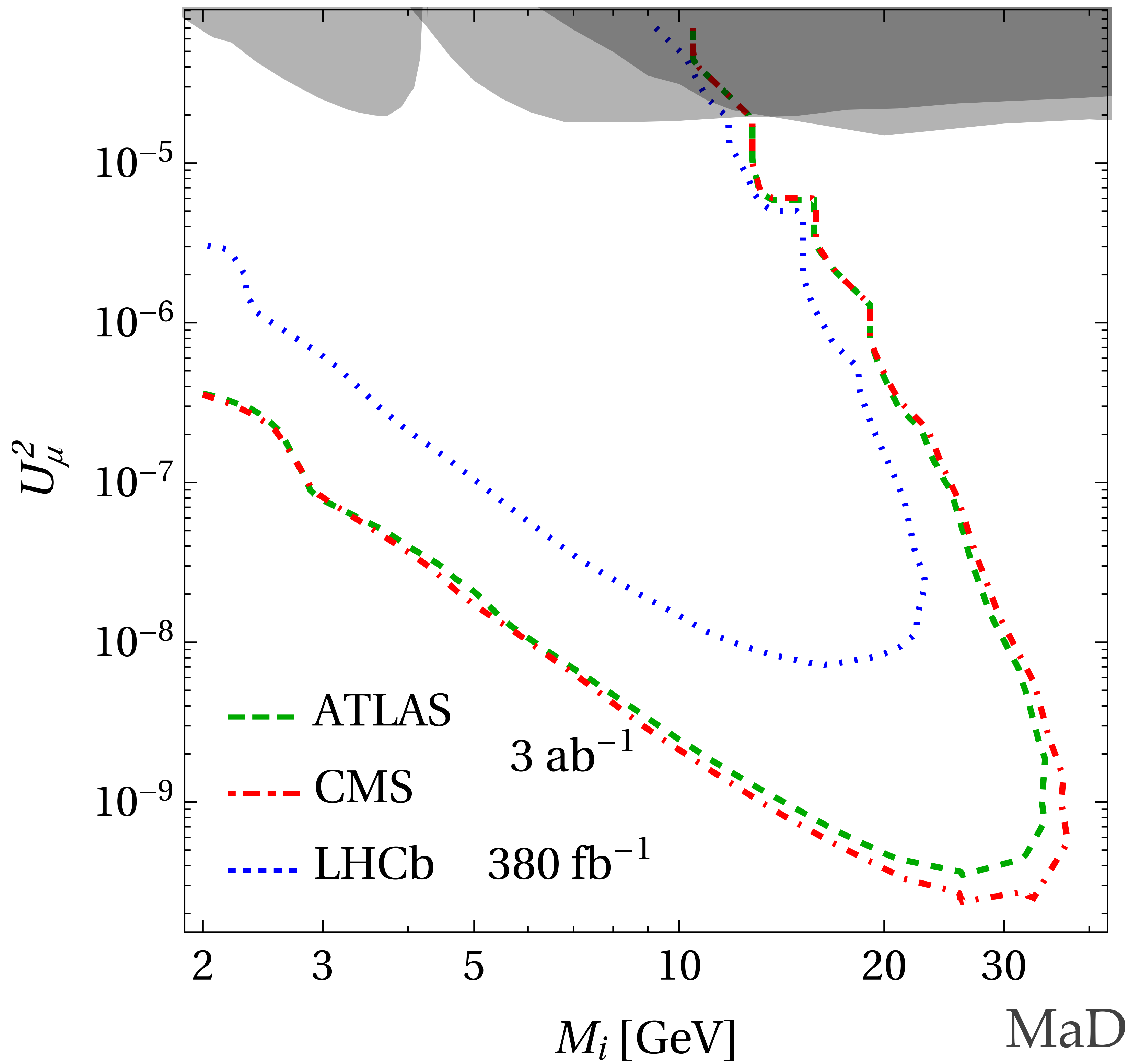
Current Direct Search Constraints



Future Searches

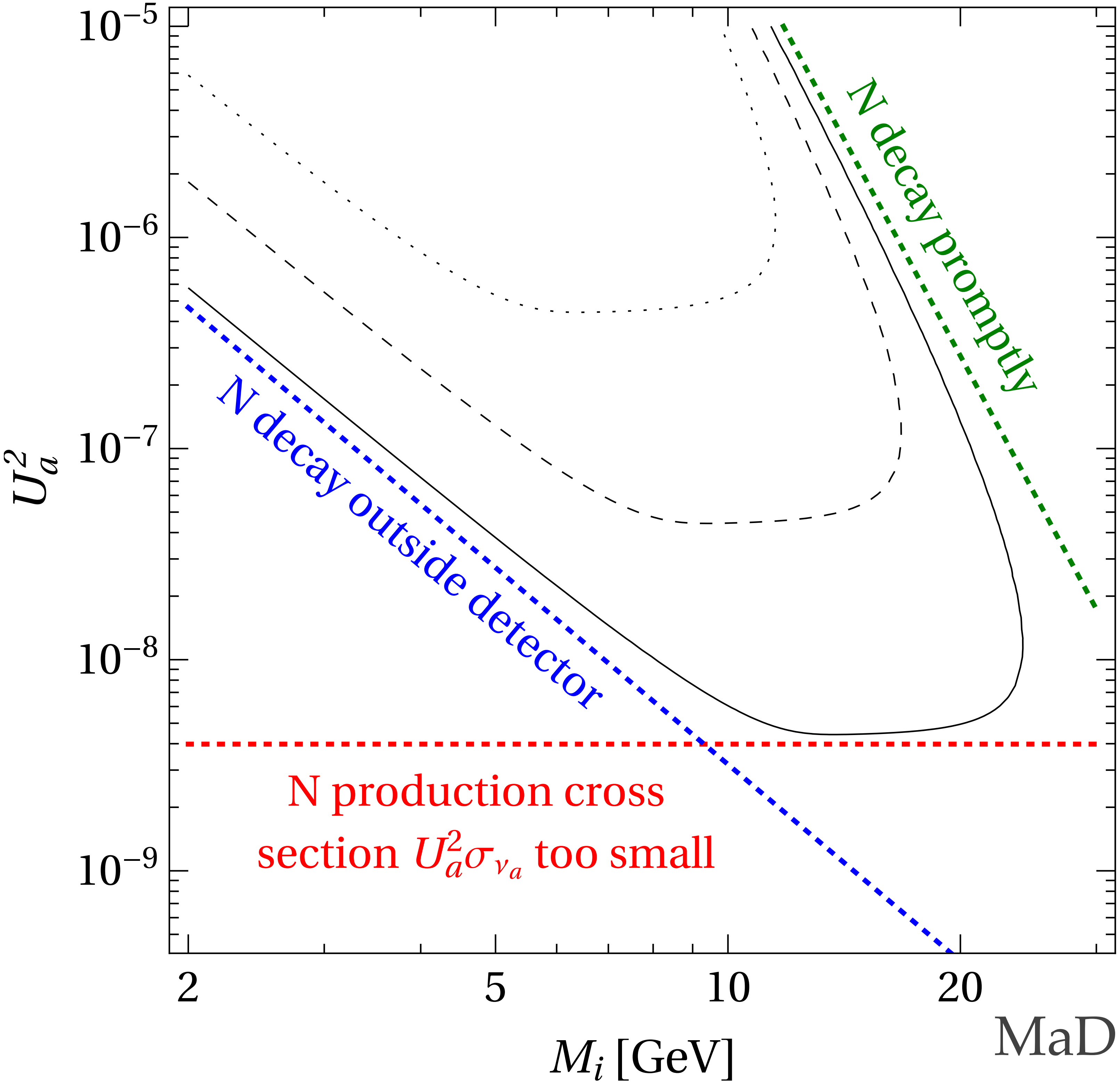


HL-LHC Displaced Vertex Search



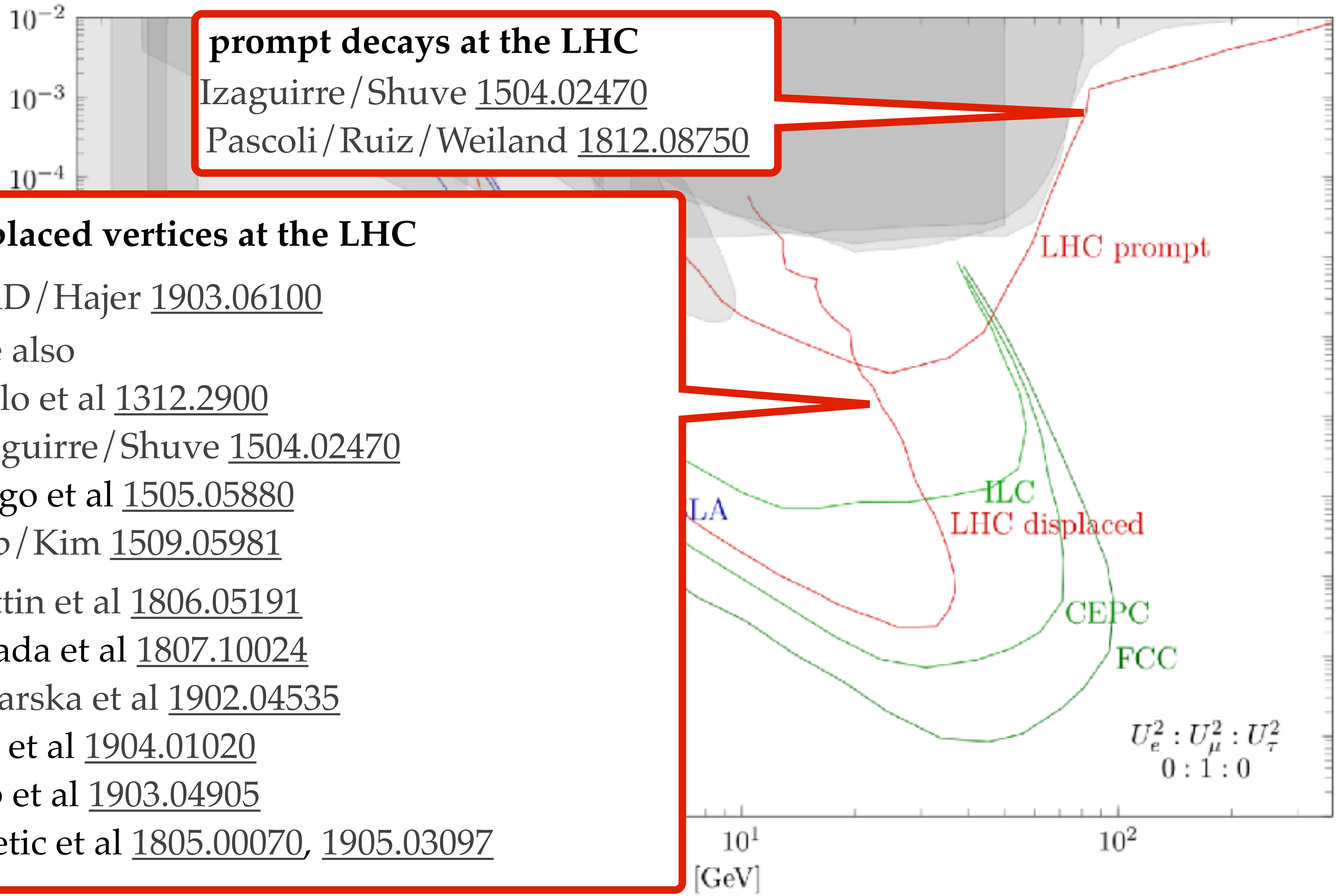
MaD / Hajer 1903.06100

Understanding the Sensitivity Region



MaD / Hajer 1903.06100

Future LHC Searches



prompt decays at the LHC

Izaguirre / Shuve 1504.02470

Pascoli / Ruiz / Weiland 1812.08750

displaced vertices at the LHC

MaD / Hajer 1903.06100

see also

Helo et al 1312.2900

Izaguirre / Shuve 1504.02470

Gago et al 1505.05880

Dib / Kim 1509.05981

Cottin et al 1806.05191

Abada et al 1807.10024

Boiarska et al 1902.04535

Liu et al 1904.01020

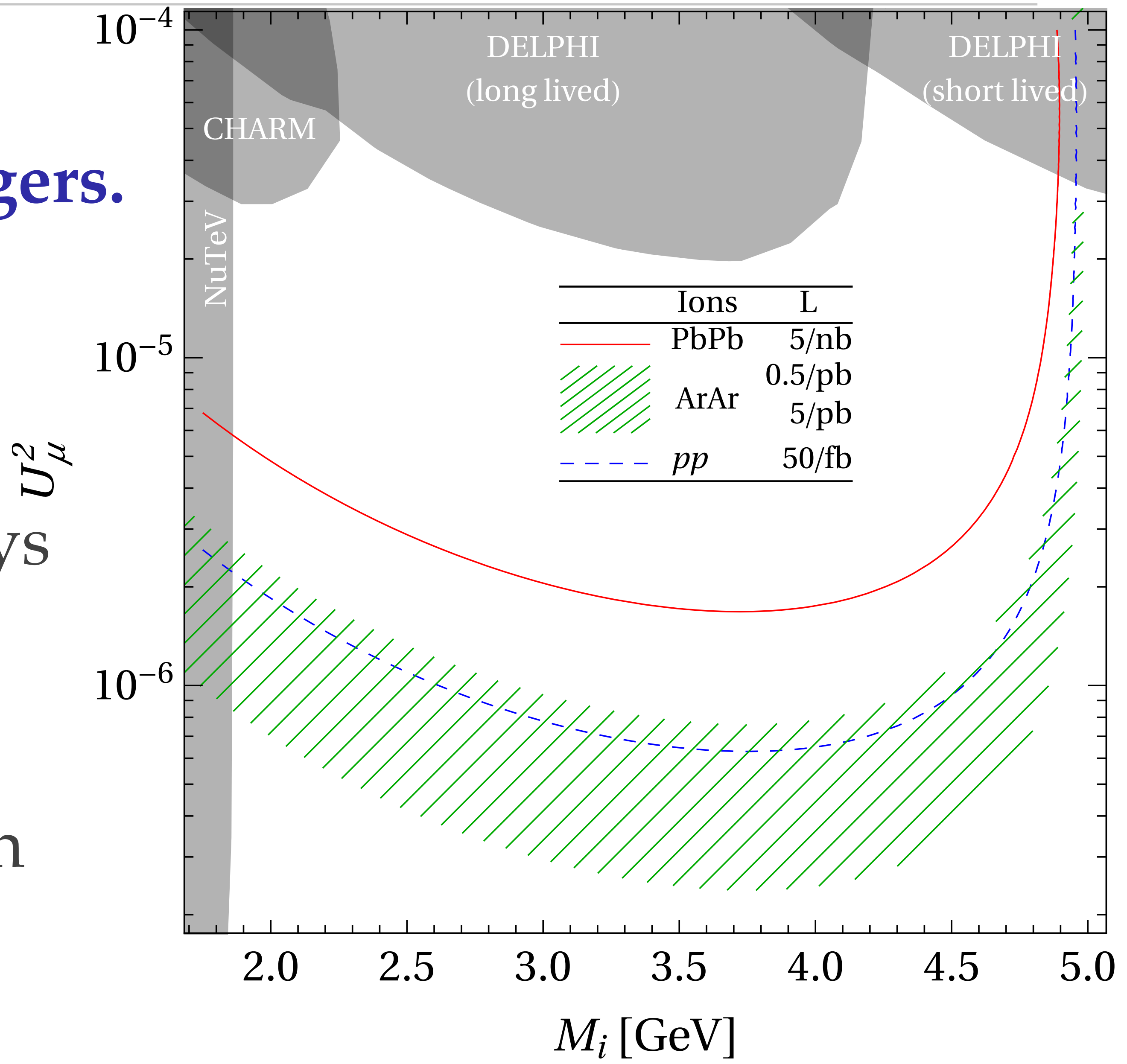
Dib et al 1903.04905

Cvetic et al 1805.00070, 1905.03097

A Heavy Metal Path to New Physics

In heavy ion runs: use very low triggers. Allows to search for low p_T events!

- HNLs with masses below 5 GeV can be produced in B meson decays
- Searches at CMS and ATLAS are difficult because of the low transverse momentum (more than 99% of them have below 25 GeV)
- Low triggers in heavy ion runs allow to collect this data



MaD / Giammanco / Hajer / Lucente 1905.09828

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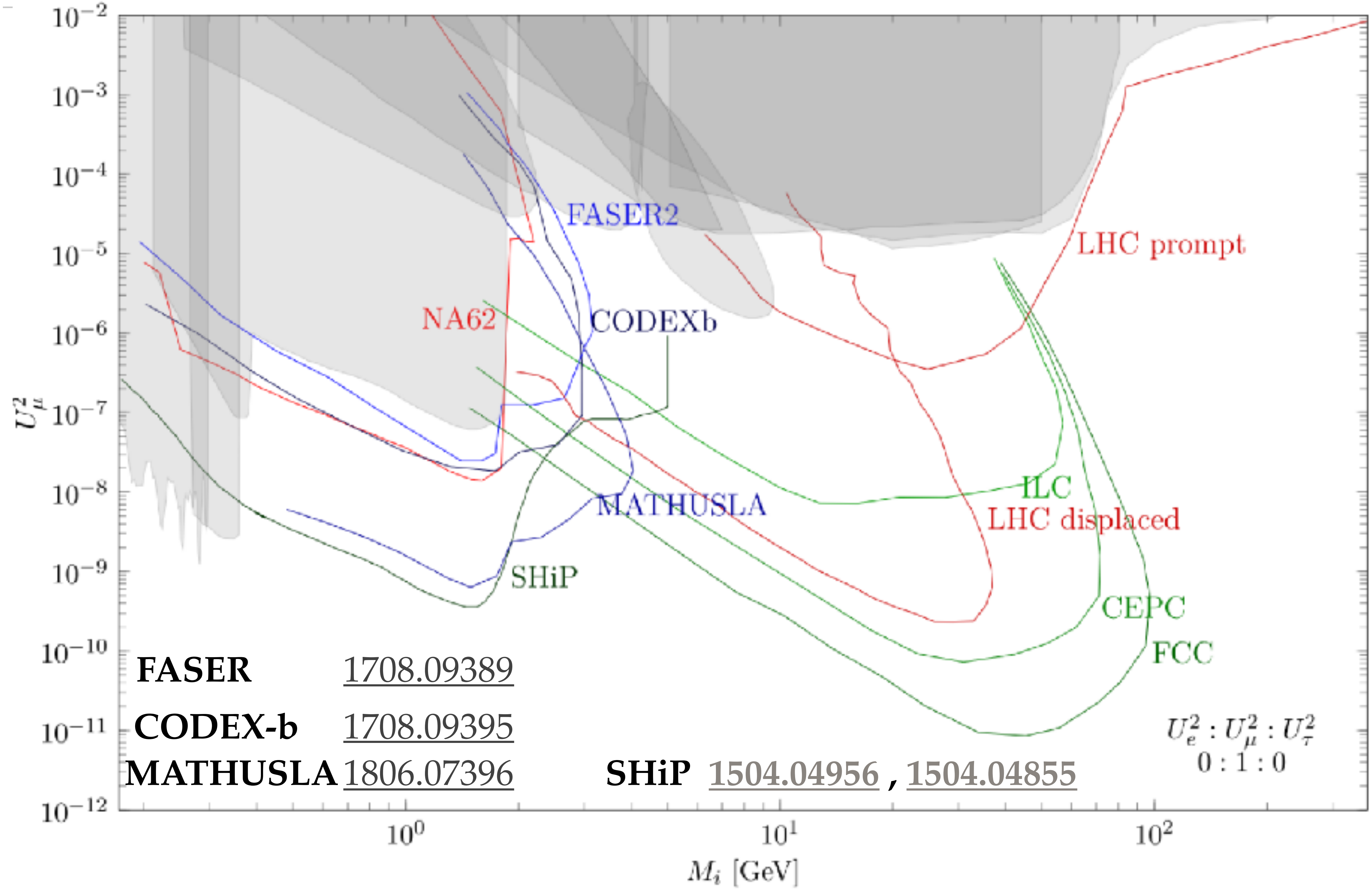
Future Detectors



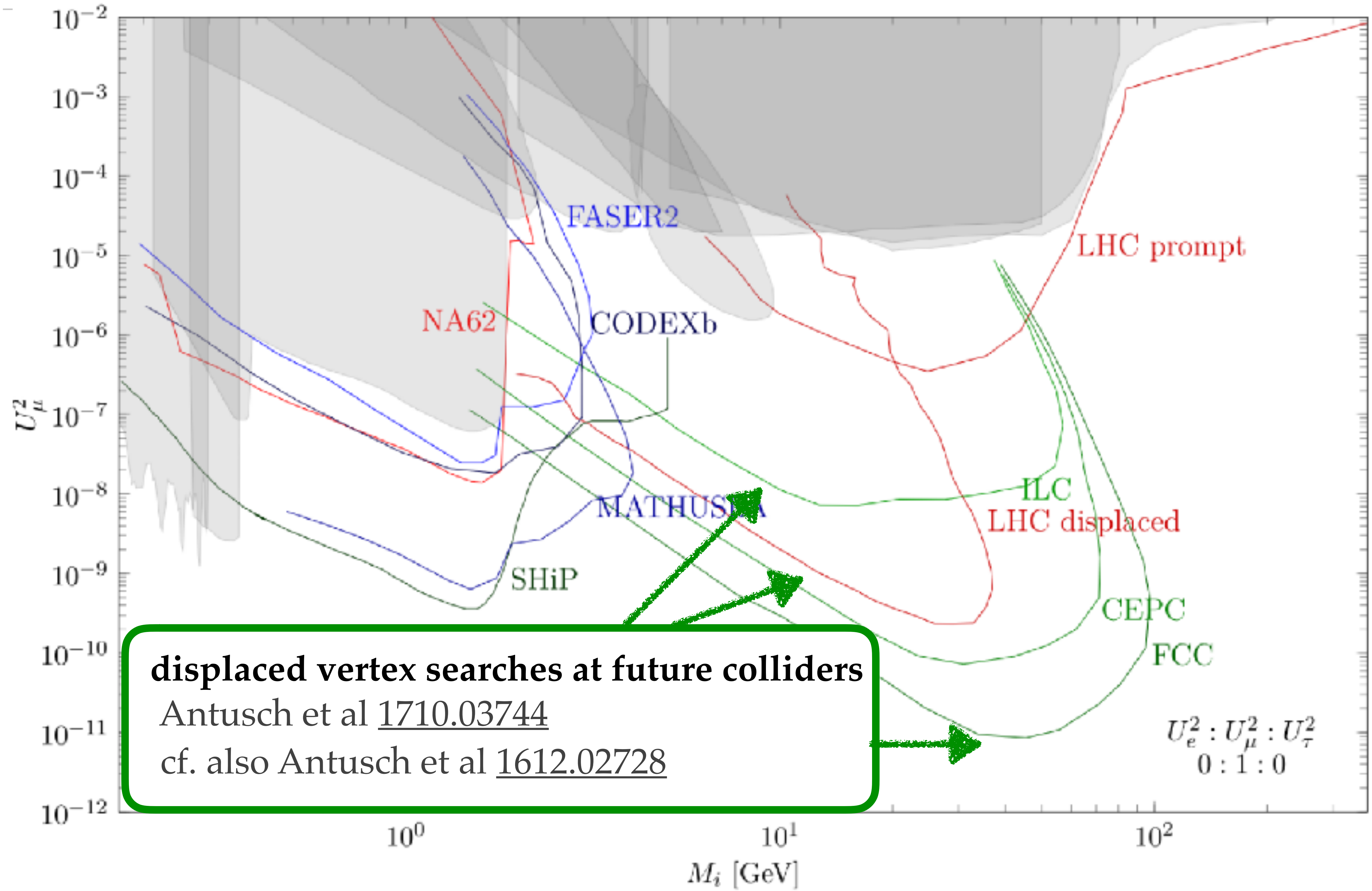
FASER 1708.09389

CODEX-b 1708.09395

MATHUSLA 1806.07396

SHiP 1504.04956 , 1504.04855

Future Colliders

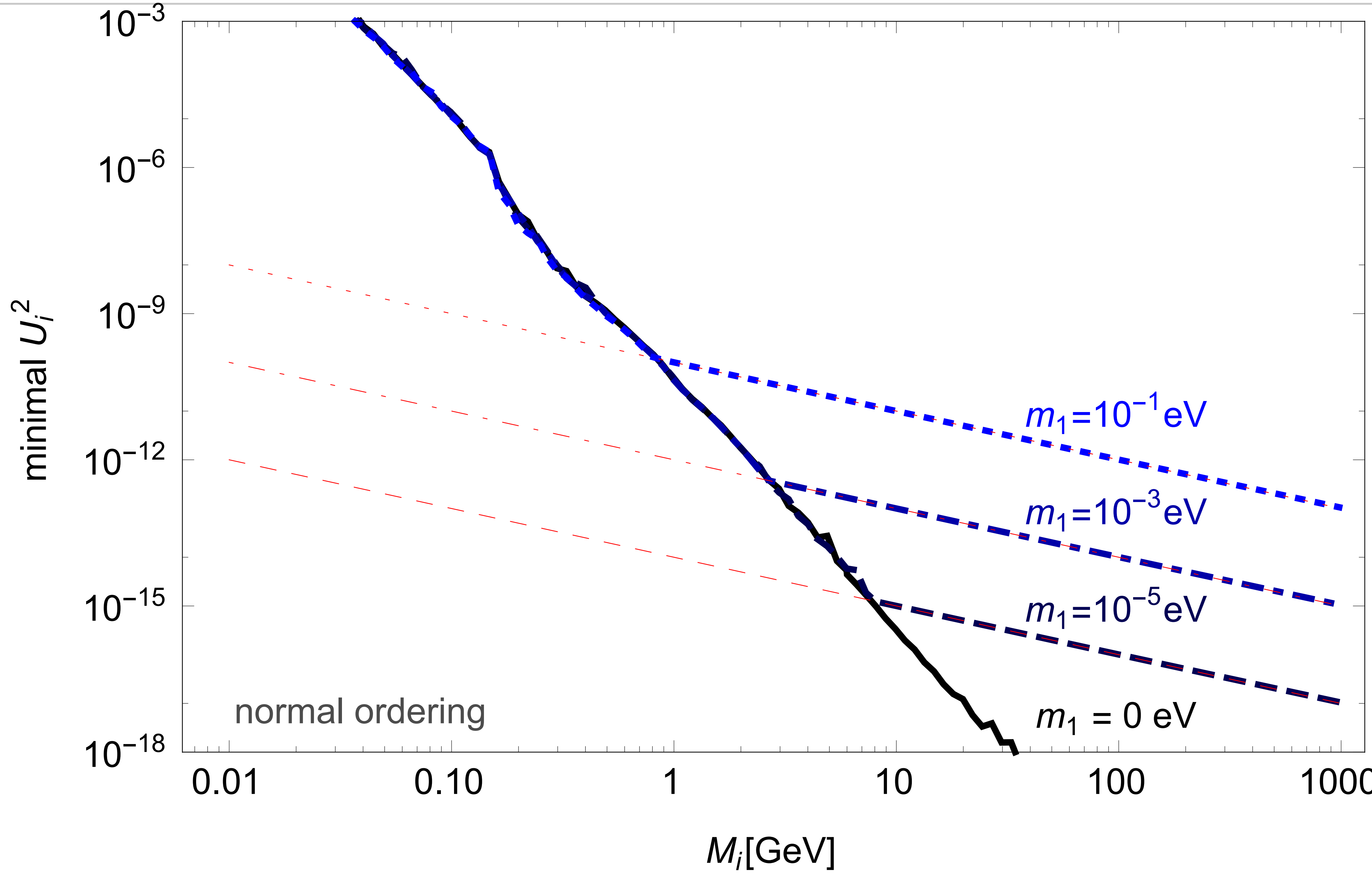


displaced vertex searches at future colliders

Antusch et al 1710.03744

cf. also Antusch et al 1612.02728

A lower limit?



lower limits from neutrino data+BBN

strongly depend on #RHN and mass of the lightest neutrino MaD 1904.11959

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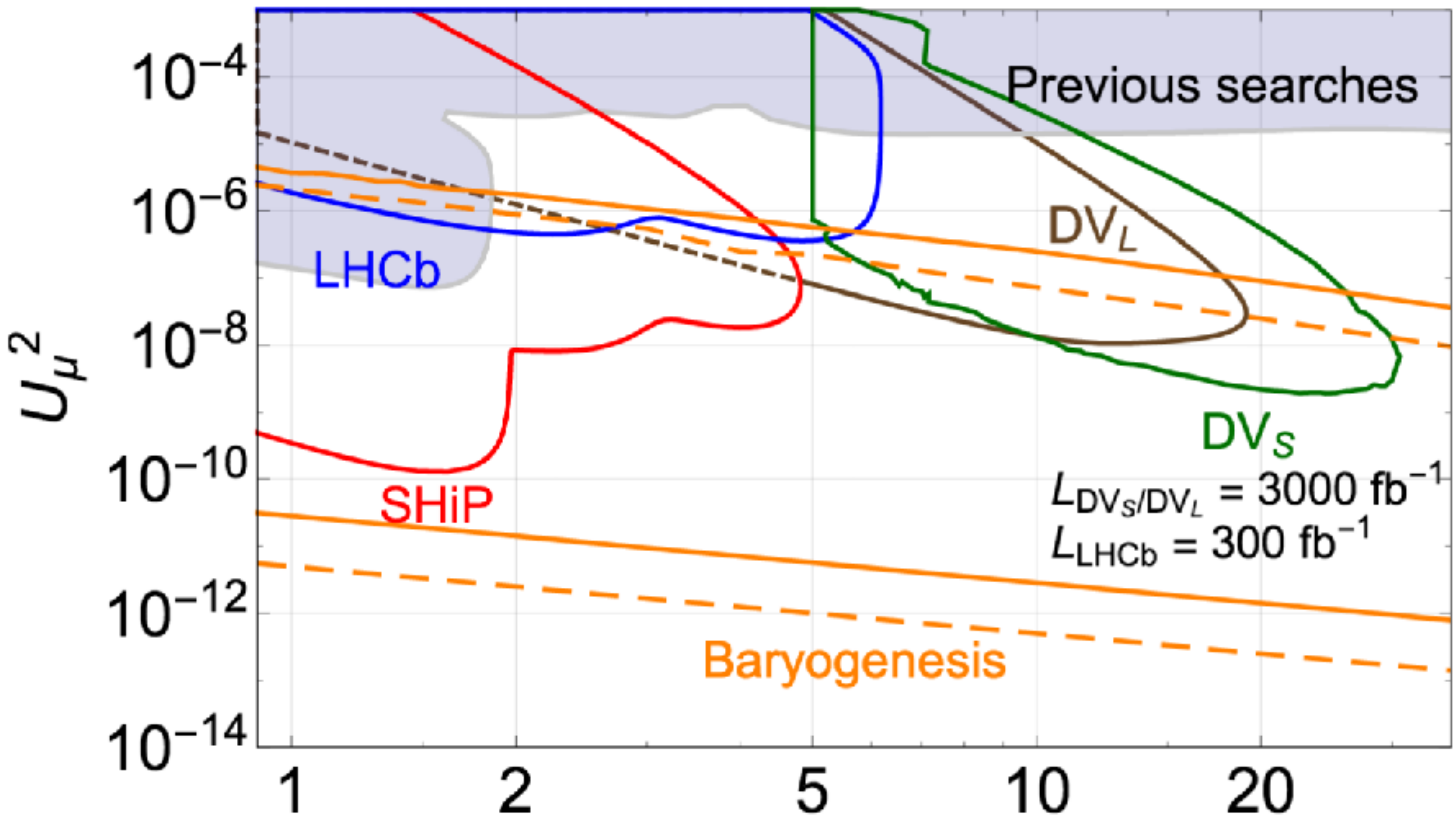
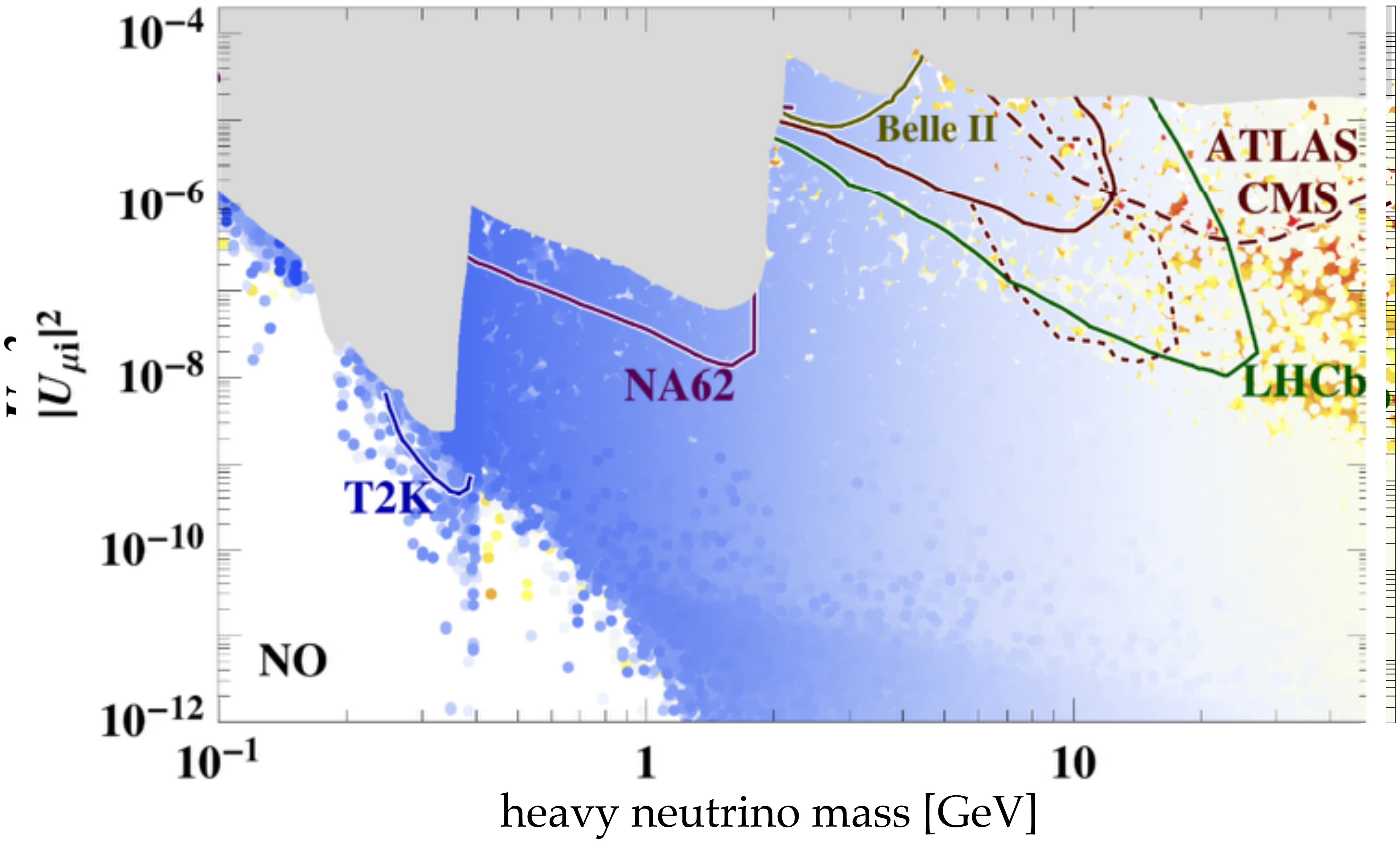
Leptogenesis in the νMSM



Plot from Boiarska et al 1902.04535 , leptogenesis computation used on Eijima et al 1808.10833

Low Scale Leptogenesis at the LHC



plot from
Abada et al 1810.12463

Parameter space grows in all directions!

- **colourful points:**
  leptogenesis + neutrino masses with three heavy neutrinos
- **colour code measures the degree of fine tuning**

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Full Testability of the νMSM

Effective theory for νMSM collider/fixed target phone:

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[observational constraints on DM candidate (cf. e.g. 1602.04816, 1807.07938) imply that it must have very feeble couplings]

Minimality makes the model fully testable!

cf. Hernandez et al 1606.06719, MaD et al 1609.09069

$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}} \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$ Casas/Ibarra 01

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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 (almost) vanishes

complex angle ω

N-mass M and splitting ΔM

Full Testability of the νMSM

Effective theory for νMSM collider/fixed target phone:

Type I seesaw with two RH Neutrinos below EW scale

Unknown parameters:

M, Δ*M*, Reω, Imω, δ, α

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 (almost) vanishes

complex angle ω

N-mass *M* and splitting Δ*M*

Full Testability of the νMSM

heavy neutrino masses

size of N_1 and N_2 couplings relative to each other

overall N_i coupling strength

DUNE, NOvA, ...

Unknown parameters:

M, ΔM, Reω, Imω, δ, α

N_i flavour mixing pattern

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 (almost) vanishes

complex angle ω

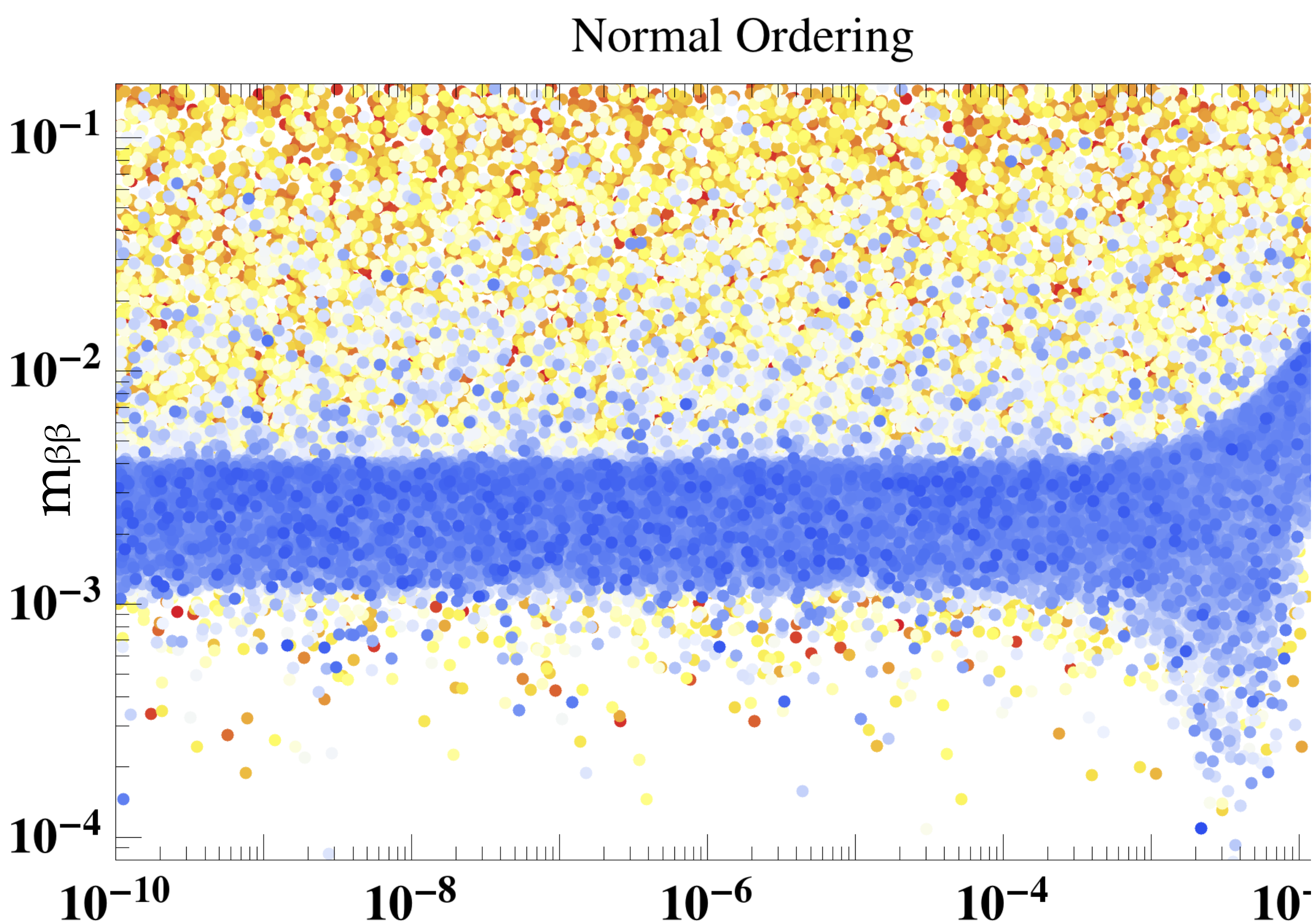
N-mass M and splitting ΔM

The 0νββ Connection

Heavy neutrino exchange can dominate 0νββ…

…even in the leptogenesis region

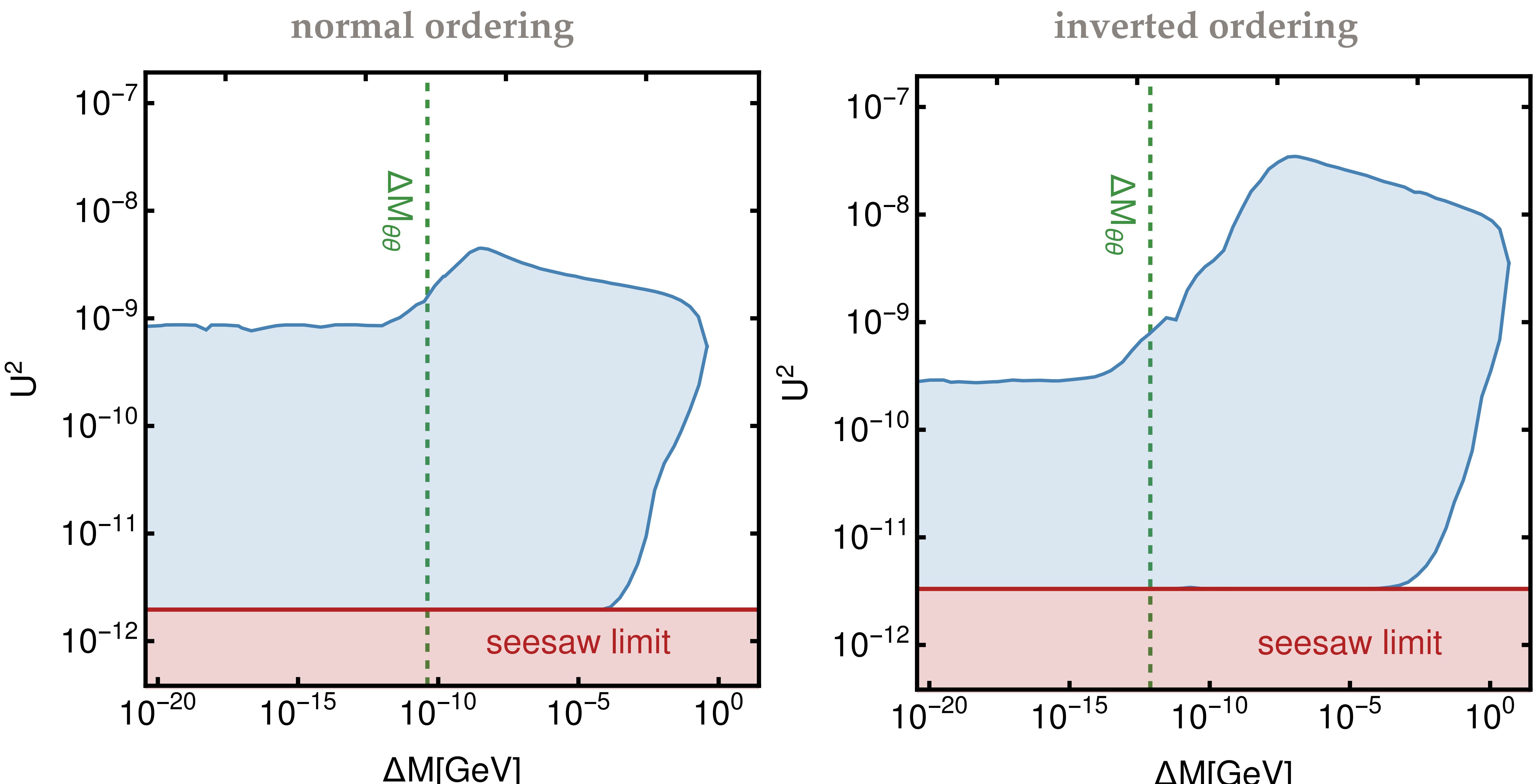
⇒ additional probe of Reω !



Abada et al 1810.12463

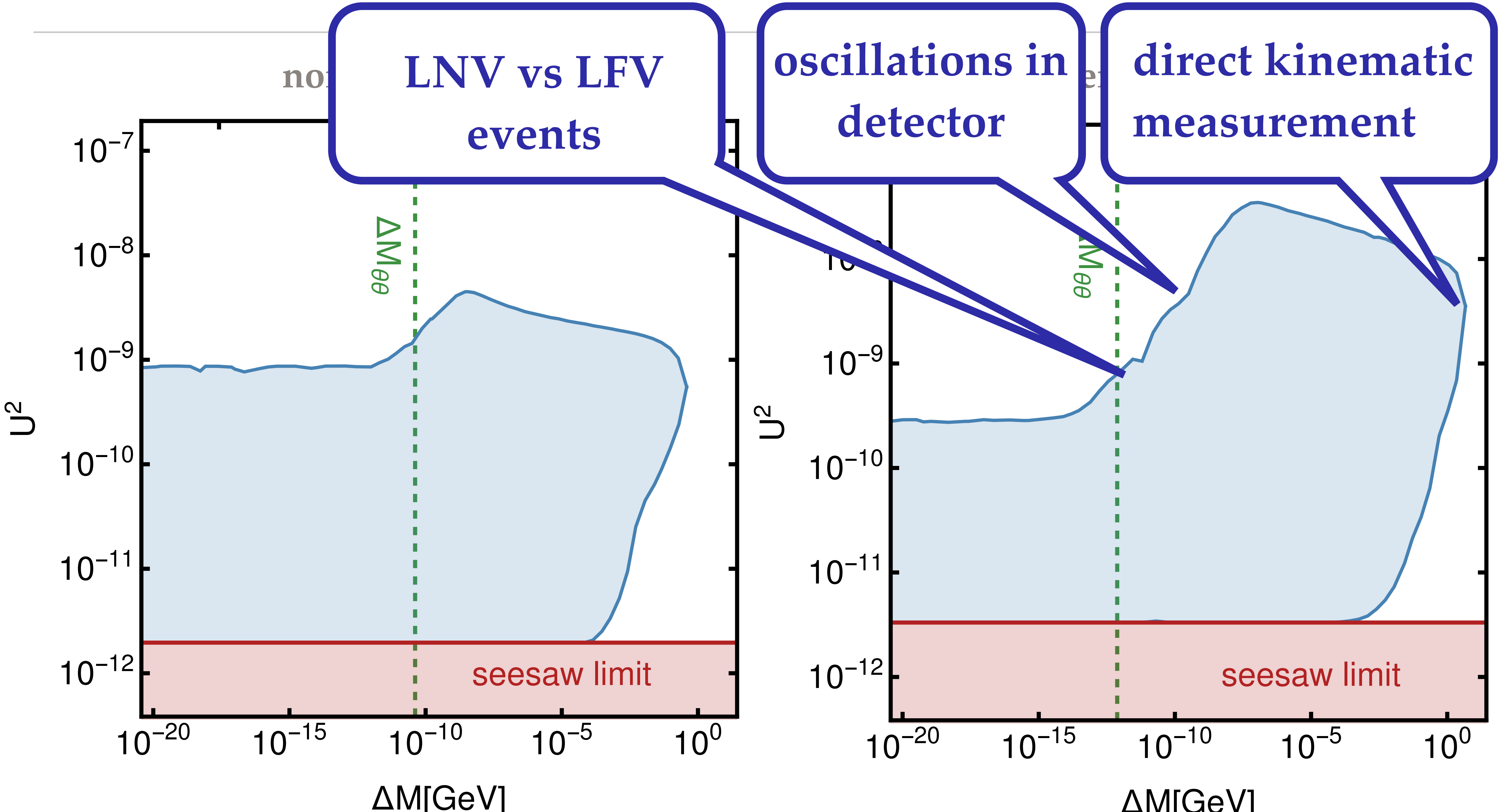
Bezrukov 0505247
Blennow et al 1005.3240
Lopez Pavon et al 1209.5342
MaD / Eijima 1606.06221,
Hernandez et al 1606.06719,
Asaka et al 1606.06686
Abada et al 1810.12463

Leptogenesis and Heavy Neutrino Mass Splitting



plot from Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744
cf. also Boyanovsky 14, Cvetic/Kim/Kogerler/Saa 15,
Anamiati/Nardi/Hirsch 16, Dib/Kim/Wang 17, Cvetic/Das/Saa 18

Leptogenesis and Heavy Neutrino Mass Splitting



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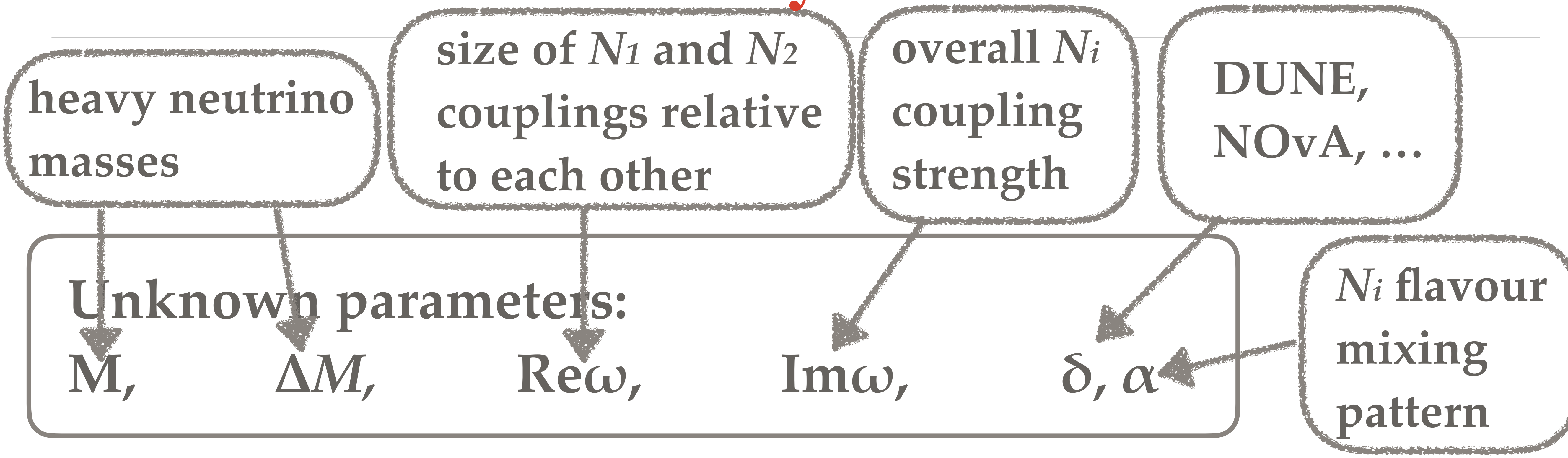
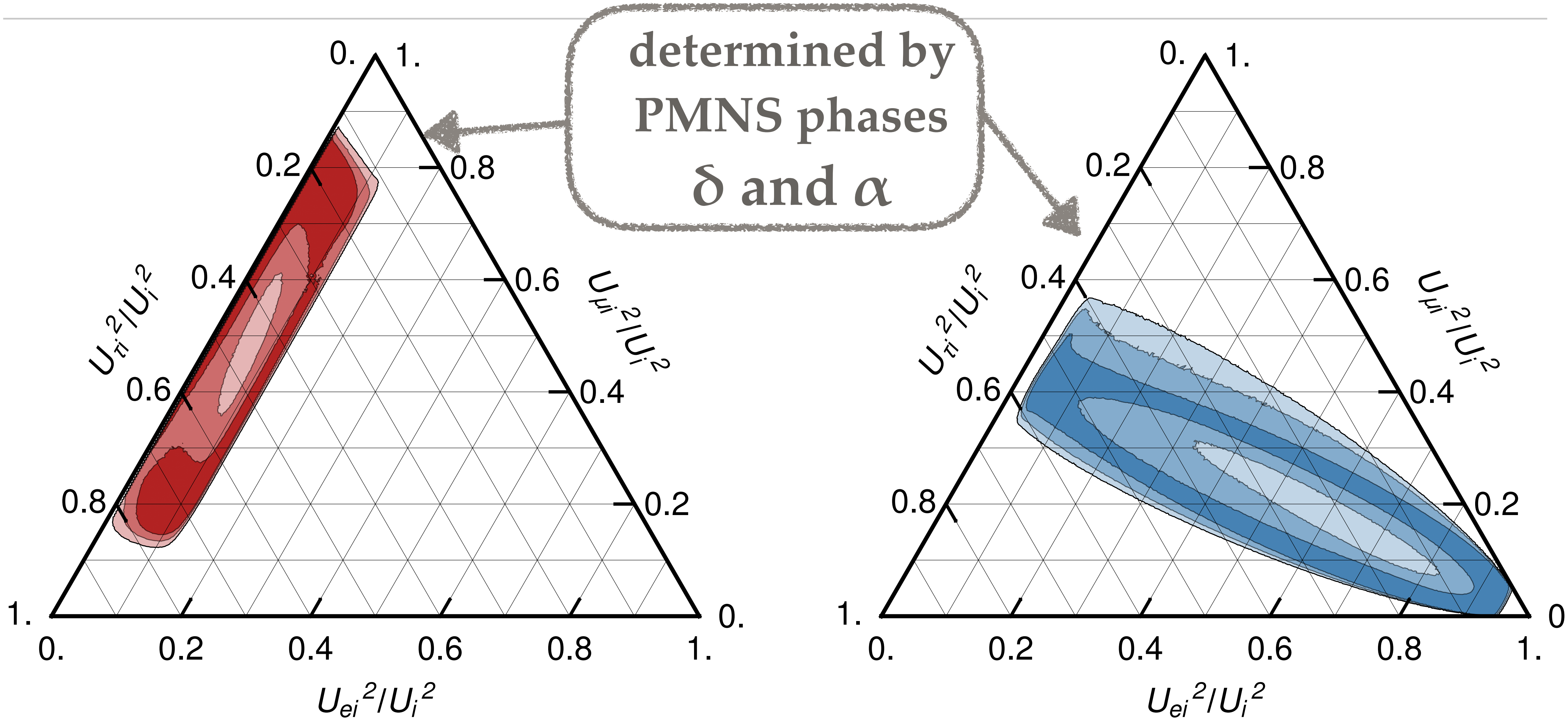
Full Testability of the νMSM



- In principle all parameters can be measured
  ⇒ fully testable model of neutrino masses and baryogenesis
- This requires a combination of collider / fixed target experiment data and ν-osc. data (and possibly $0\nu\beta\beta$)
  ⇒ poster child example for synergy between collider and long baseline programs! cf. Hernandez et al 1606.06719, MaD et al 1609.09069

Current Status: Constraints from ν-oscillation Data



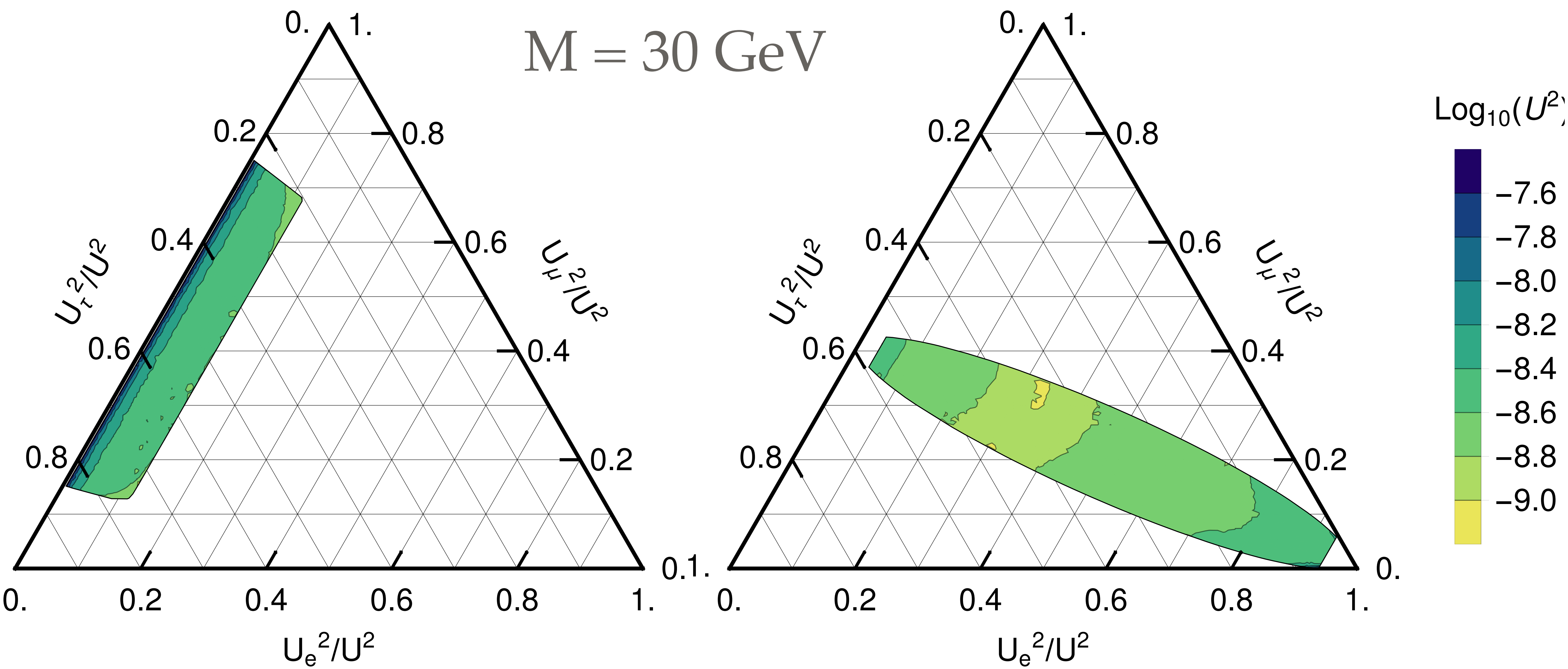
normal neutrino mass ordering | **inverted neutrino mass ordering**

coloured areas: consistent with ν-oscillation data at 1σ, 2σ and 3σ

from MaD / Hajer / Klaric / Lafranchi [1801.04207]()

Current Status:
Constraints from Leptogenesis

M = 30 GeV



normal neutrino mass ordering **inverted neutrino mass ordering**

plots from Antusch / Cazzato / MaD / Fischer / Garbrecht / Gueter / Klaric 1710.03744

Summary

- Heavy neutrinos with masses below the electroweak scale can simultaneously generate the **light neutrinos masses** (seesaw mechanism) and **baryon asymmetry of the universe** (leptogenesis)… and possibly even the **Dark Matter**.

- Depending on their mass, they can be **searched for at the LHC** or at **fixed target experiments**.

- Measurements of their couplings to all flavours could, together with data from neutrino oscillation experiments, potentially allow to constrain all model parameters.
  $\Rightarrow$ **A fully testable model of baryogenesis and neutrino masses (and Dark Matter)!**