Two portals to GeV sterile neutrinos: dipole vs mixing

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Motivations: mixing portal

Motivation

- ν's have masses
- The simplest (?) way to generate m_ν is to add sterile (RH) neutrinos: N_i
- How many? At least 2 (to generate solar and atmospheric mass differences)

minimal model on which we will focus

Motivation

two possibilities:

- Heavy N's ($M \gg M_{EW}$)
- Light N's ($M \lesssim M_{EW}$)

our focus (advantage: can be directly probed)

The νSM

$$\mathscr{L}_{\nu SM} = \mathscr{L}_{SM} + iN_i^{\dagger}\bar{\sigma}^{\mu}\partial_{\mu}N_i - \frac{1}{2}\mu_i N_i N_i - MN_1N_2 + h.c.$$

$$-Y_N^i(\tilde{H}^{\dagger}L)N_i$$

Dirac mass

Majorana masses

Yukawa interactions
(mixing)

The νSM

$$\mathscr{L}_{\nu SM} = \mathscr{L}_{SM} + iN_i^{\dagger}\bar{\sigma}^{\mu}\partial_{\mu}N_i - \frac{1}{2}\mu_i N_i N_i - MN_1N_2 + h.c.$$

$$-Y_N^i(\tilde{H}^{\dagger}L)N_i$$

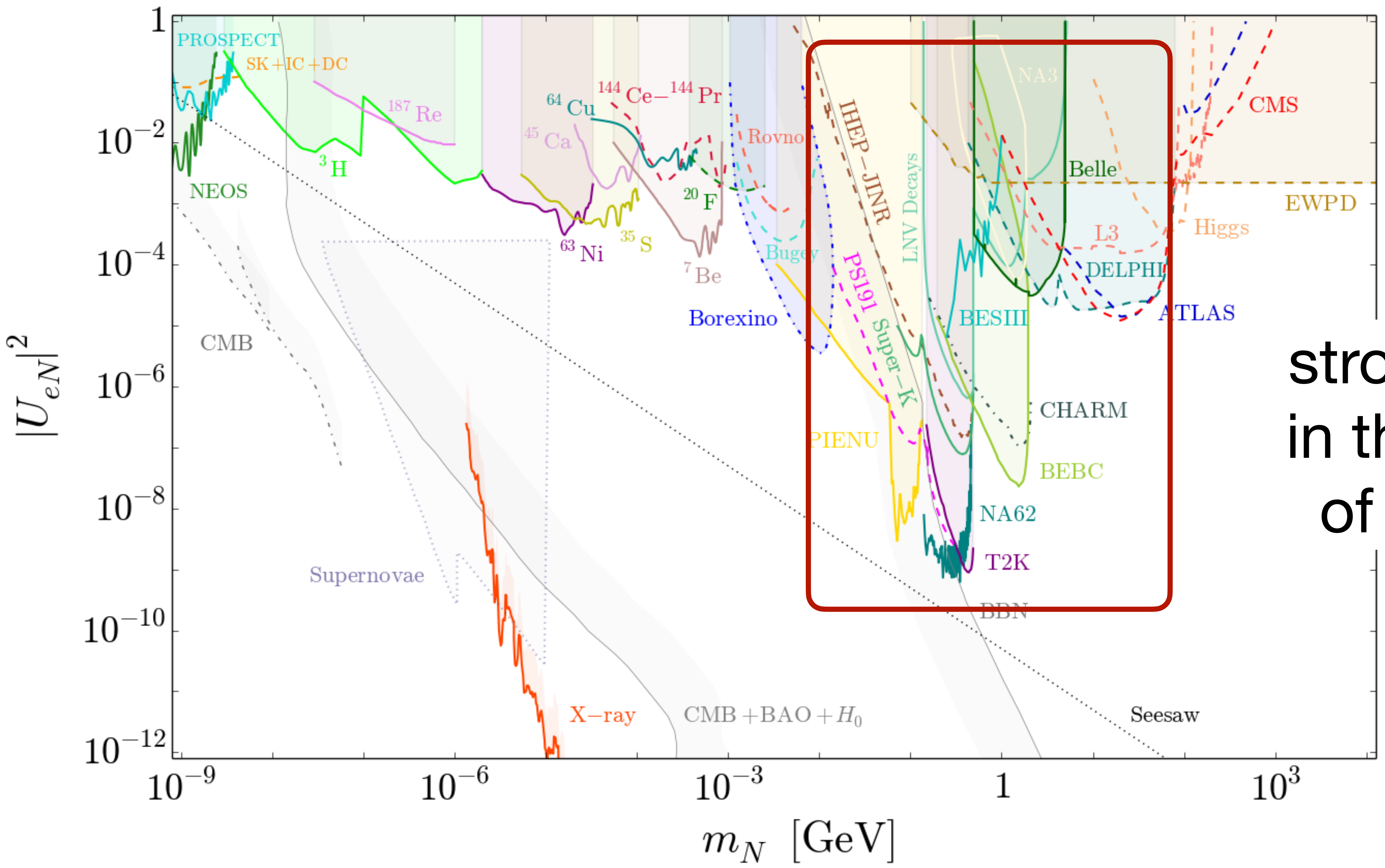
generates neutrino masses and mixings via seesaw

$$m_{\nu} \simeq -\frac{(Y_N^i v)^2}{M_i}$$

$$\theta \simeq -\frac{Y_N^i v}{M_i}$$

Current limits

See reviews https://www.hep.ucl.ac.uk/~pbolton/
2203.08039



strong limits in the region of interest

Current limits

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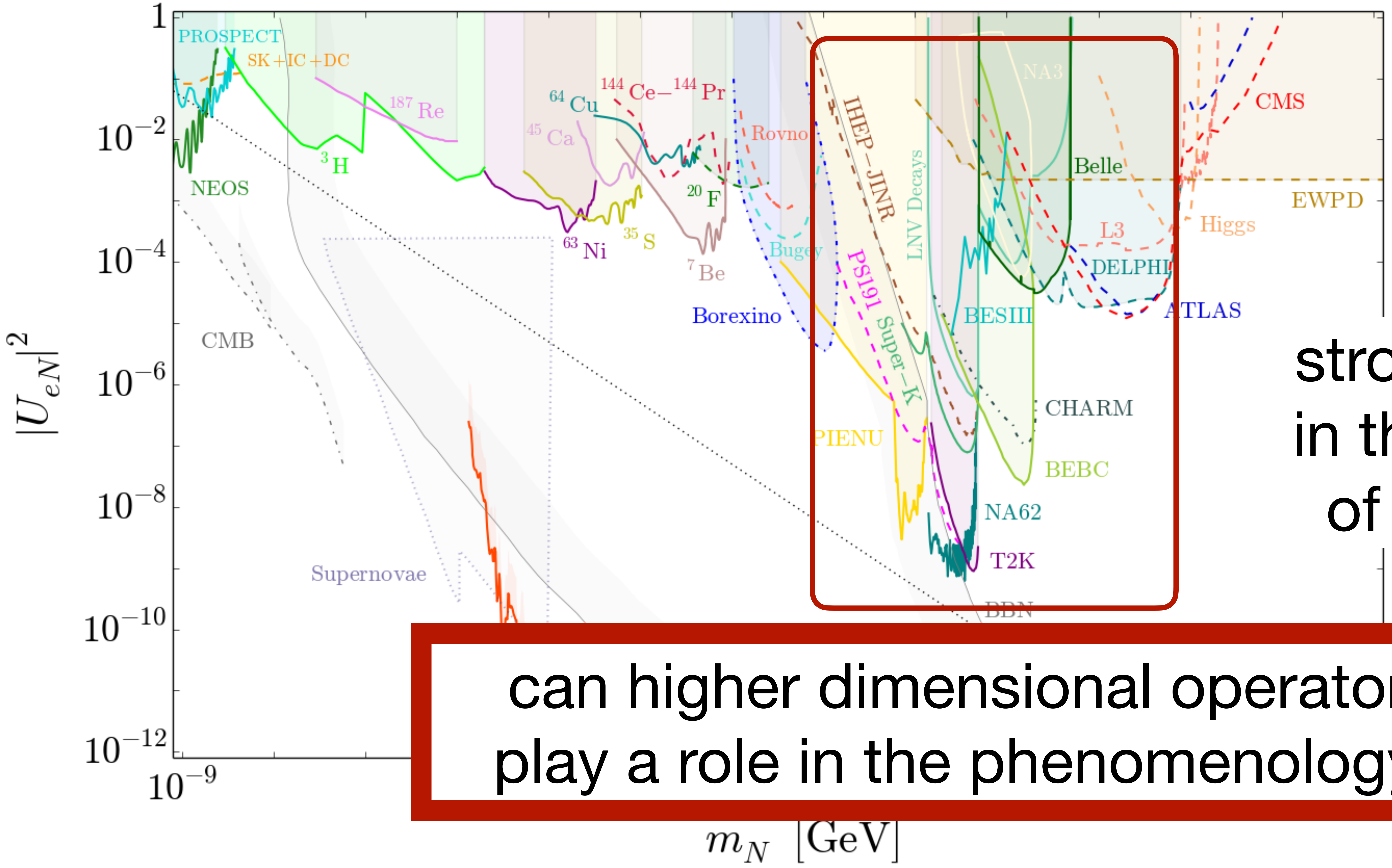
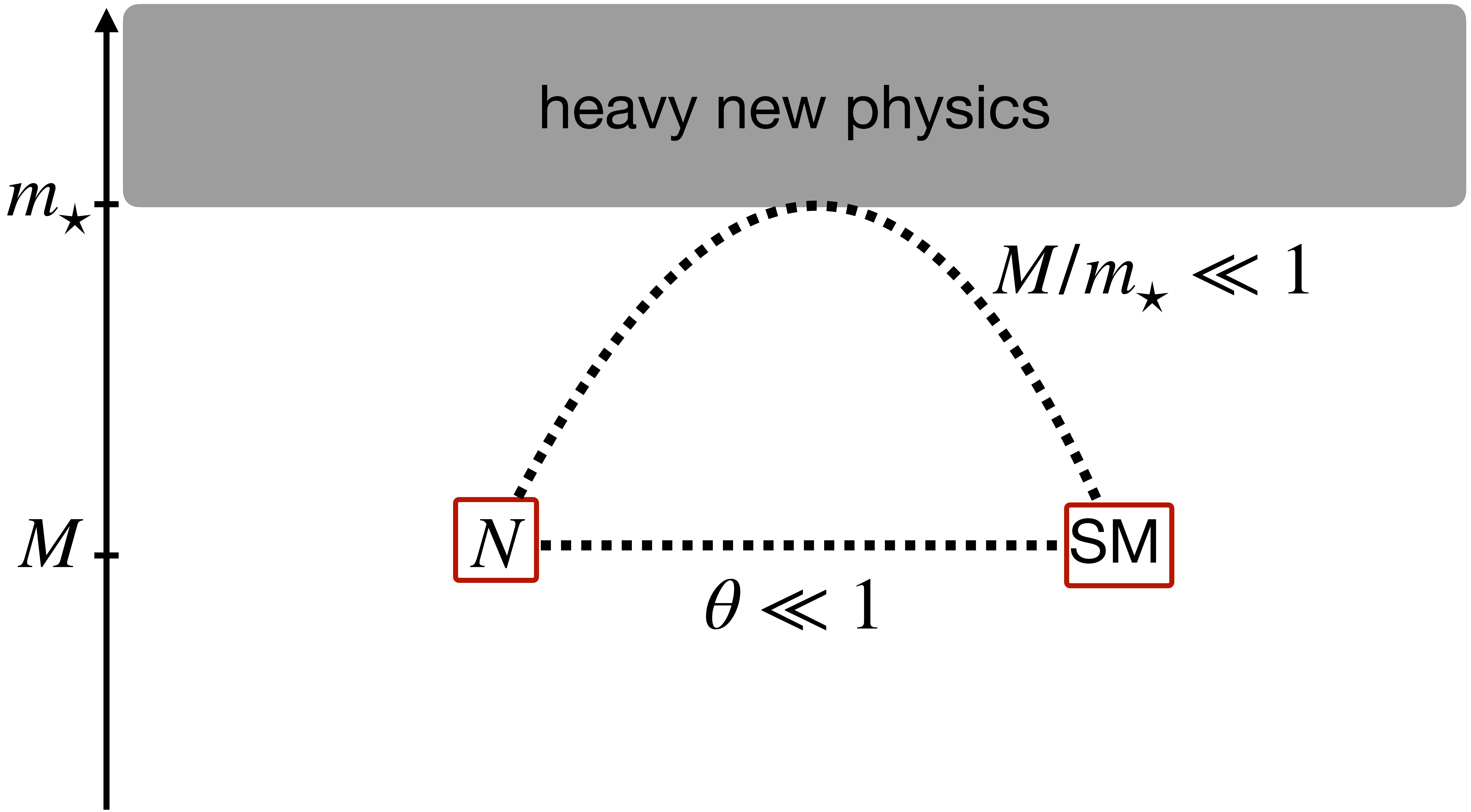


strong limits in the region of interest

can higher dimensional operators play a role in the phenomenology?



heavy new physics
$m_\star$
M
$M/m_\star \ll 1$
N
SM
$\theta \ll 1$

The dipole portal

Operators

At dimension 5:

- Weinberg operator $(LH)^2$ (de-correlates m_ν from N)
- $H^\dagger HNN$: Higgs physics + N mass
- $N\sigma^{\mu\nu}NB_{\mu\nu}$: dipole operator (may be important at low energy)

see
Aparici,Kim,Santamaria,Wudka'09

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The dipole

$$\mathscr{L}_{dipole} = d\, N_1 \sigma^{\mu\nu} N_2\, B_{\mu\nu} = \frac{d}{2} \vec{N}_a \sigma^{\mu\nu}\, \epsilon^{ab}\, \vec{N}_b\, B_{\mu\nu} \qquad \vec{N} = \begin{pmatrix} N_1 \\ N_2 \end{pmatrix}$$

power counting estimate:

$$d \sim \frac{g'\, g_\star^2}{16\pi^2\, m_\star}$$

how large can the dipole be?

The dipole

$$\vec{N} = \begin{pmatrix} N_1 \\ N_2 \end{pmatrix}$$

Symmetries give us a useful guidance:

$$\mathscr{L}_{kin} = i\vec{N}^\dagger \bar{\sigma}^\mu \partial_\mu \vec{N}$$

$$\vec{N} \to V_N \vec{N}$$
$$\vec{N} \to e^{i\alpha_N} \vec{N}$$

$$SU(2)_N \times U(1)_N$$

$$\mathscr{L}_{dipole} = \frac{d}{2} \vec{N}_a \sigma^{\mu\nu} \epsilon^{ab} \vec{N}_b B_{\mu\nu}$$

$$\vec{N} \to V_N \vec{N}$$
~~$\vec{N} \to e^{i\alpha_N} \vec{N}$~~

$$SU(2)_N$$

The dipole

Symmetries give us a useful guidance:

$$\mathscr{L}_{mass} = \mathscr{M}_{ij} N_i N_j \qquad \mathscr{M} \sim 3 \text{ of } SU(2)_N$$

$$\mathscr{M}_{ij} \in \mathbb{R} \longleftrightarrow U(1)'_N \subset SU(2)_N \quad \text{preserved}$$

$$\mathscr{M}_{ij} \in \mathbb{C} \longleftrightarrow SU(2)_N \quad \text{completely broken}$$

The dipole

when $U(1)'_N \subset SU(2)_N$ preserved

- can always assign $q(N_1) = 1 = -q(N_2)$
- $N_{1,2}$ combine in a Dirac pair (= 2 degenerate Majoranas)
- can be extended to $q(L) = -1 \quad \Rightarrow \quad U(1)'_N \simeq U(1)_L$

$$\Downarrow$$

$$m_\nu = 0$$

The dipole

when $U(1)'_N \subset SU(2)_N$ broken

- Lepton number broken
- $N_{1,2}$ are two non-degenerate Majorana fermions

The dipole

How large can the dipole be?

- Dipole can be as large as perturbativity allows

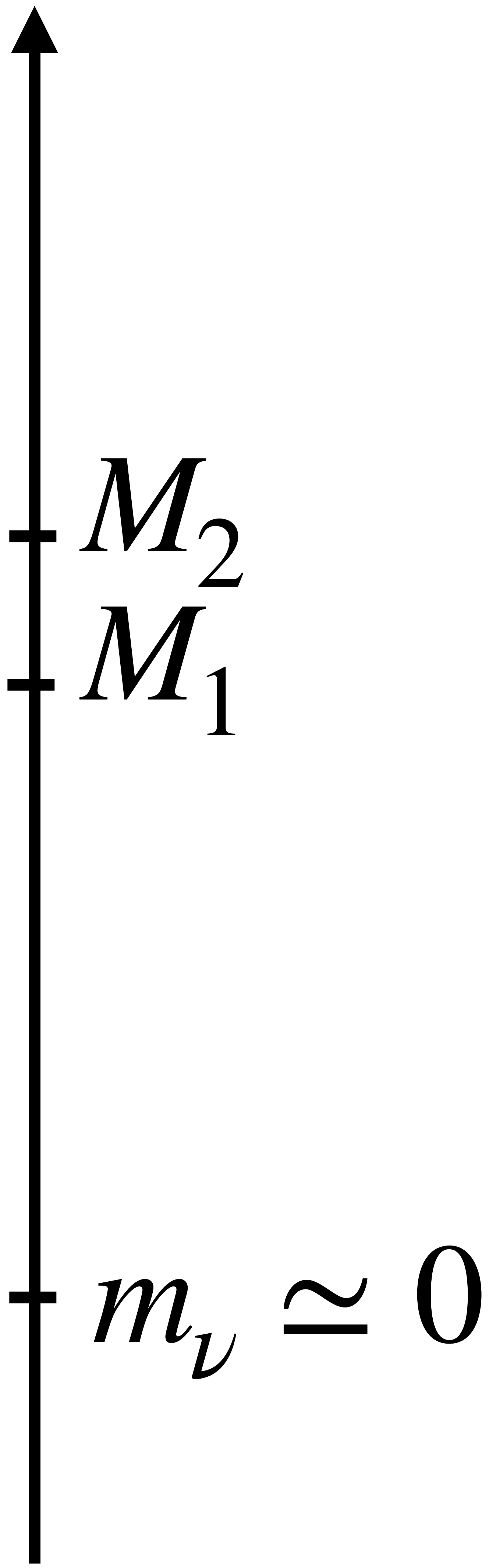
- $M_{1,2}$ small is technically natural

  (when $M_{1,2} = 0$ we recover $SU(2)_N$)

- $M_2 - M_1 \ll M_{1,2}$ also technically natural

  (when $M_1 = M_2$ we recover $U(1)'_N \simeq U(1)_L$)

Spectrum



$$\delta = \frac{M_2 - M_1}{M_2 + M_1}$$

useful quantity:
relative mass splitting

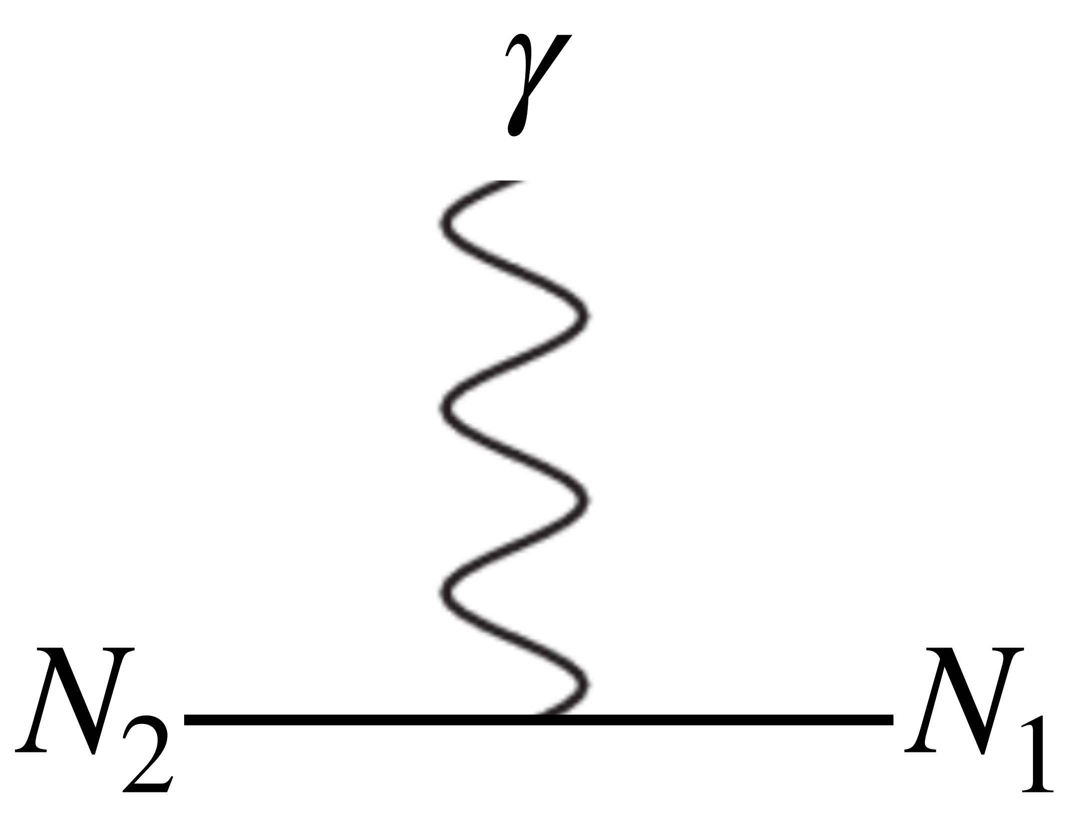
Phenomenology

Sketch of the physics

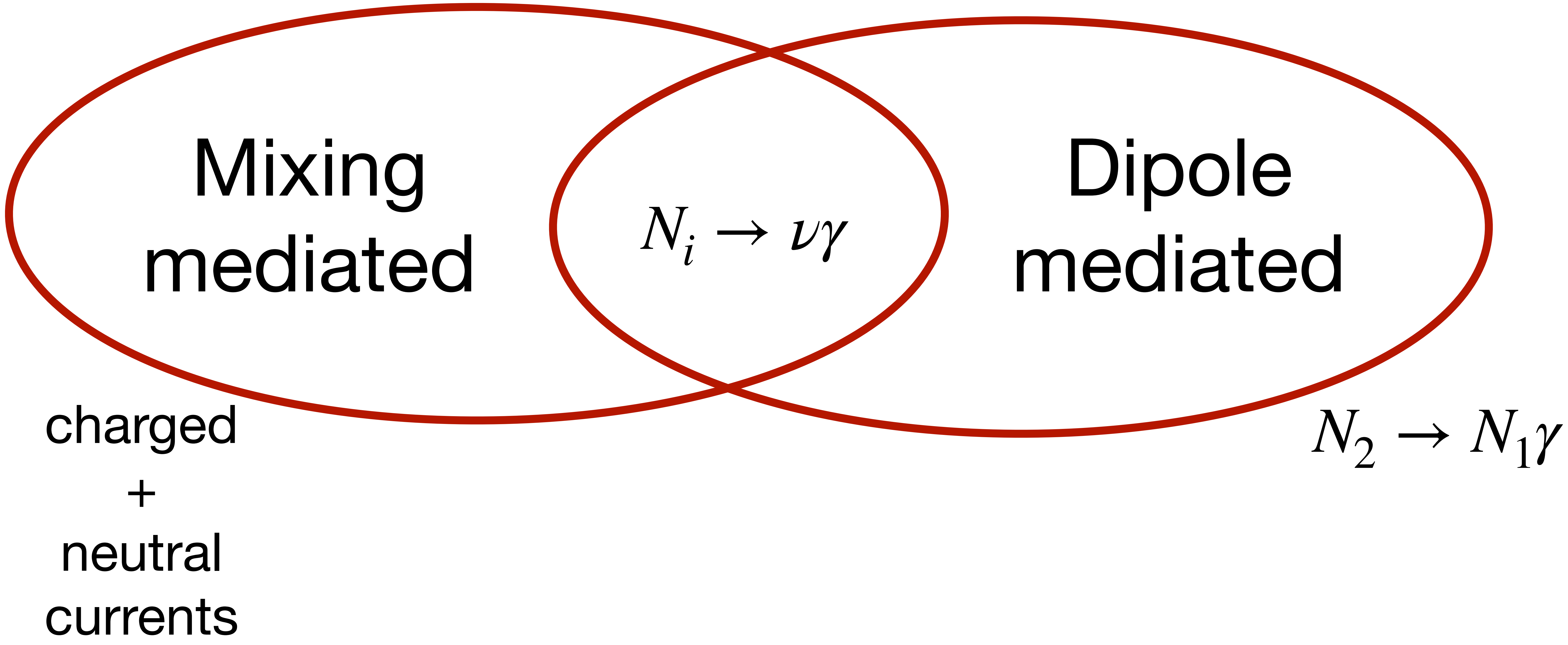
In addition to mixing-mediated charged and neutral currents

$$\mathscr{L}_{dipole} = \frac{d}{2} \overrightarrow{N}_a \sigma^{\mu\nu} \epsilon^{ab} \overrightarrow{N}_b B_{\mu\nu}$$

but $B_{\mu\nu} \supset F_{\mu\nu}$ and the photon is important at low energies



Sketch of the physics

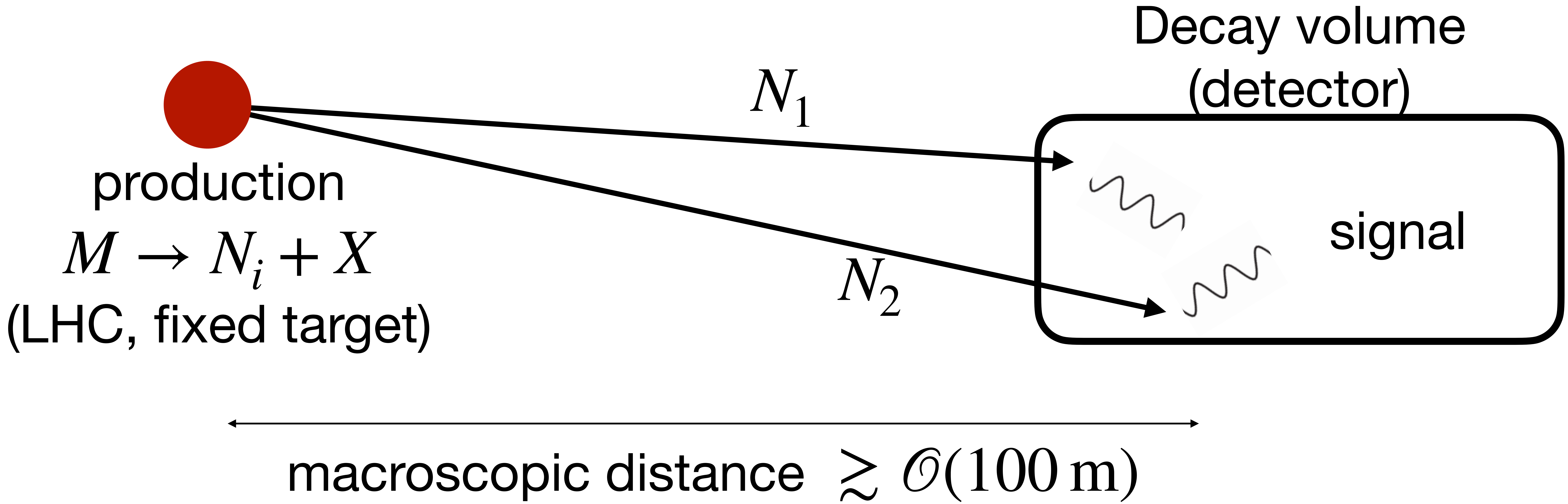


all amplitudes suppressed by $\theta \ll 1$, $dM \ll 1$ and/or δ

$\Rightarrow$ **$N_{1,2}$ expected to be LONG LIVED**

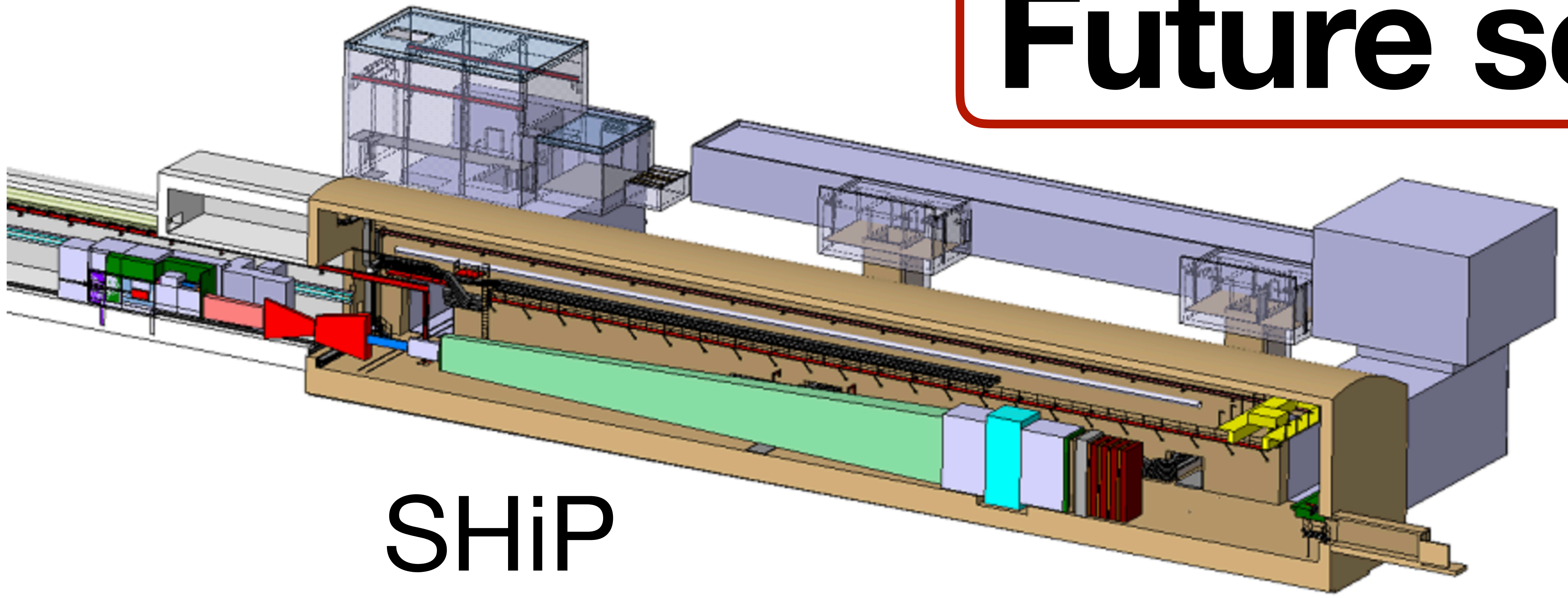
Sketch of the physics

INTENSITY (LONG-LIVED) FRONTIER

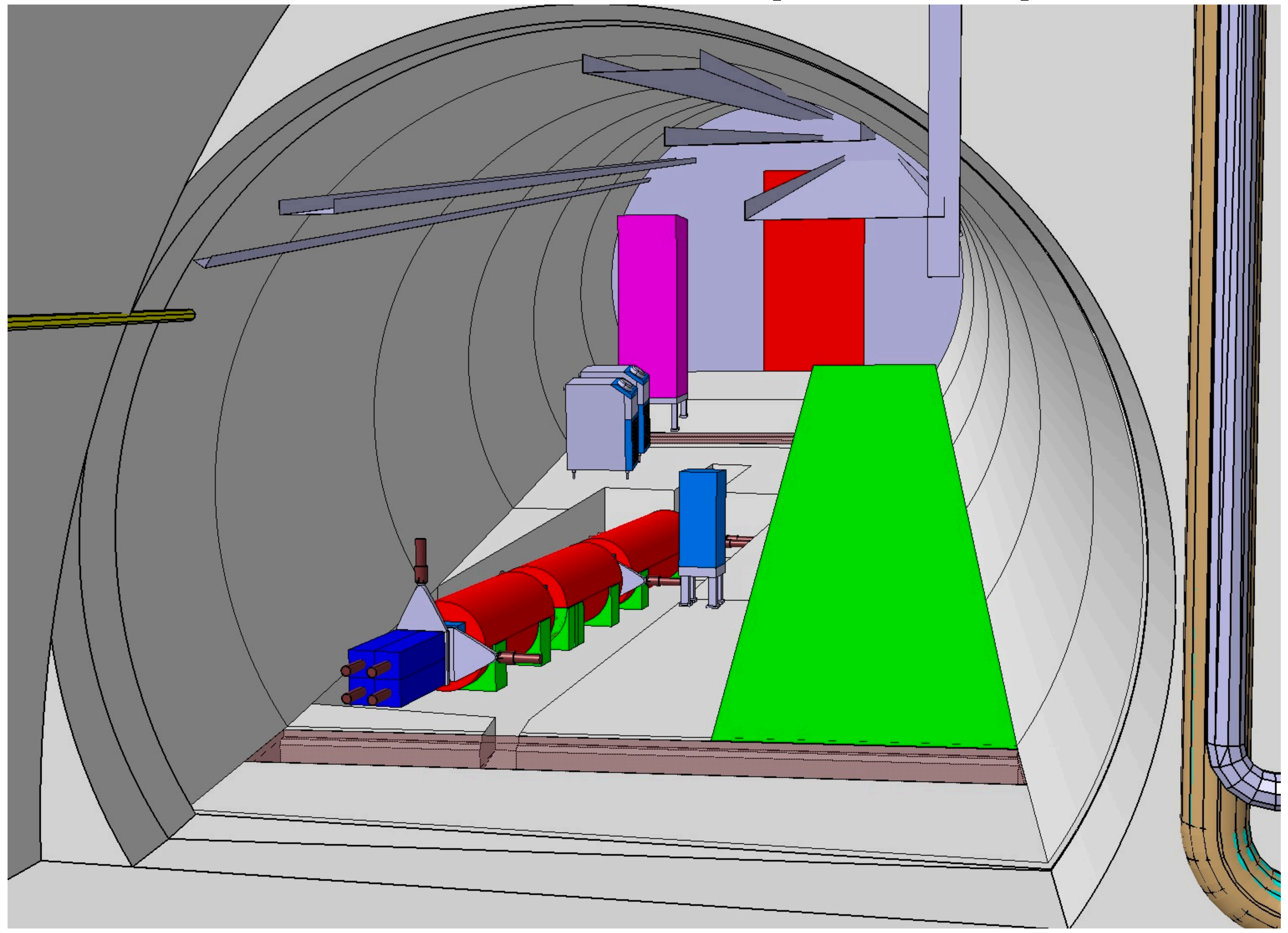


Future sensitivities

FASER
(LHC)



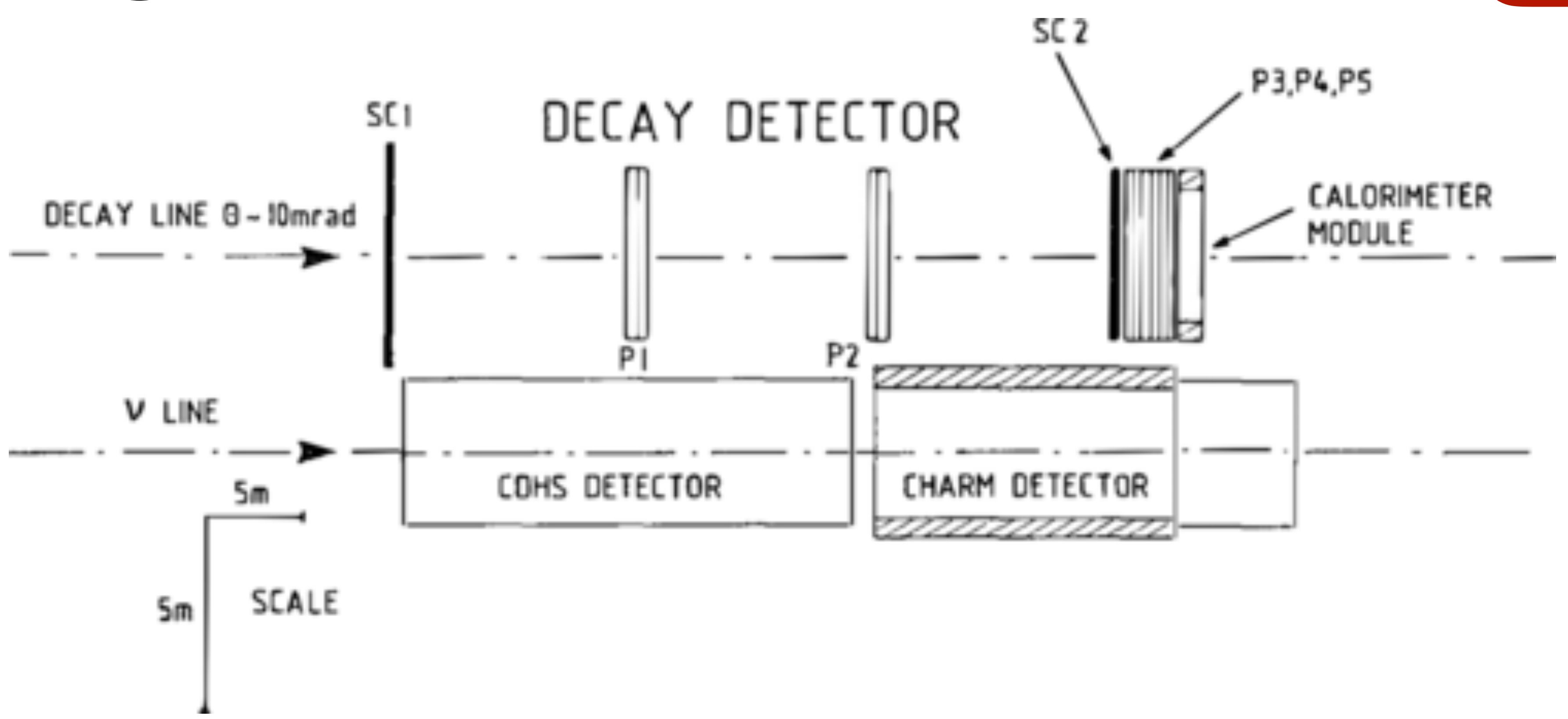
SHiP
(400 GeV)



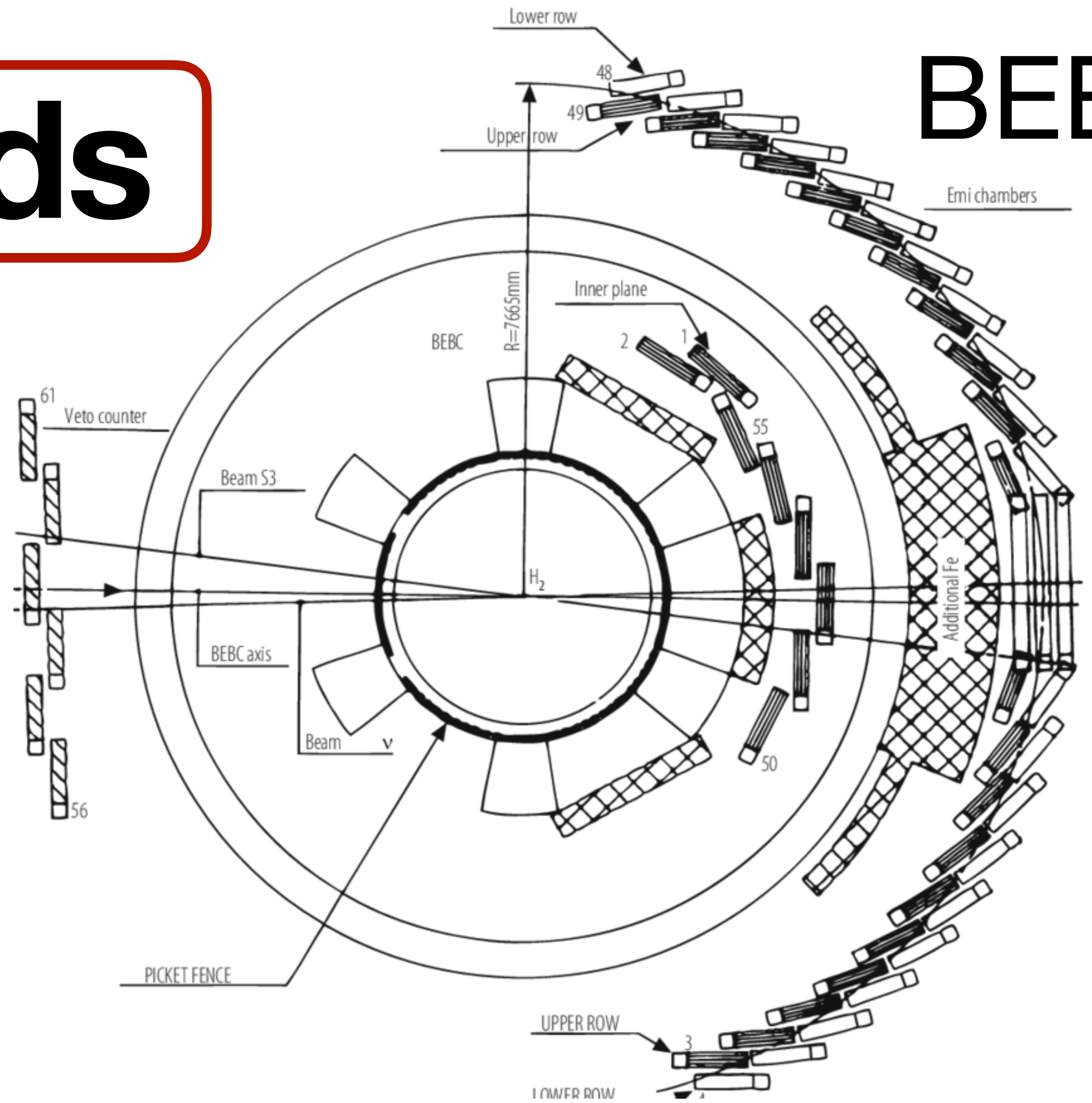
NA62 - beam dump
(400 GeV)

Other bounds

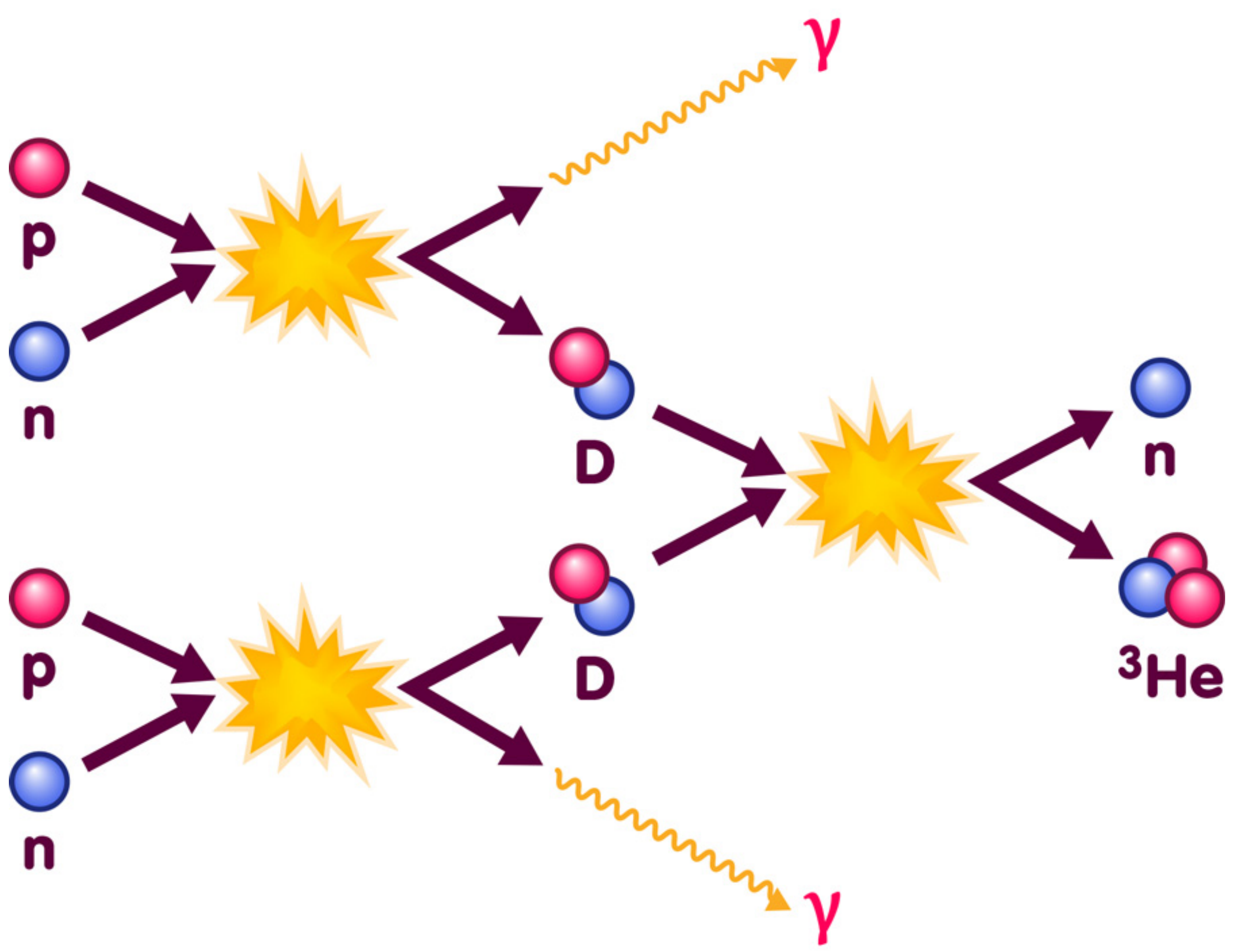
CHARM II



BEBC

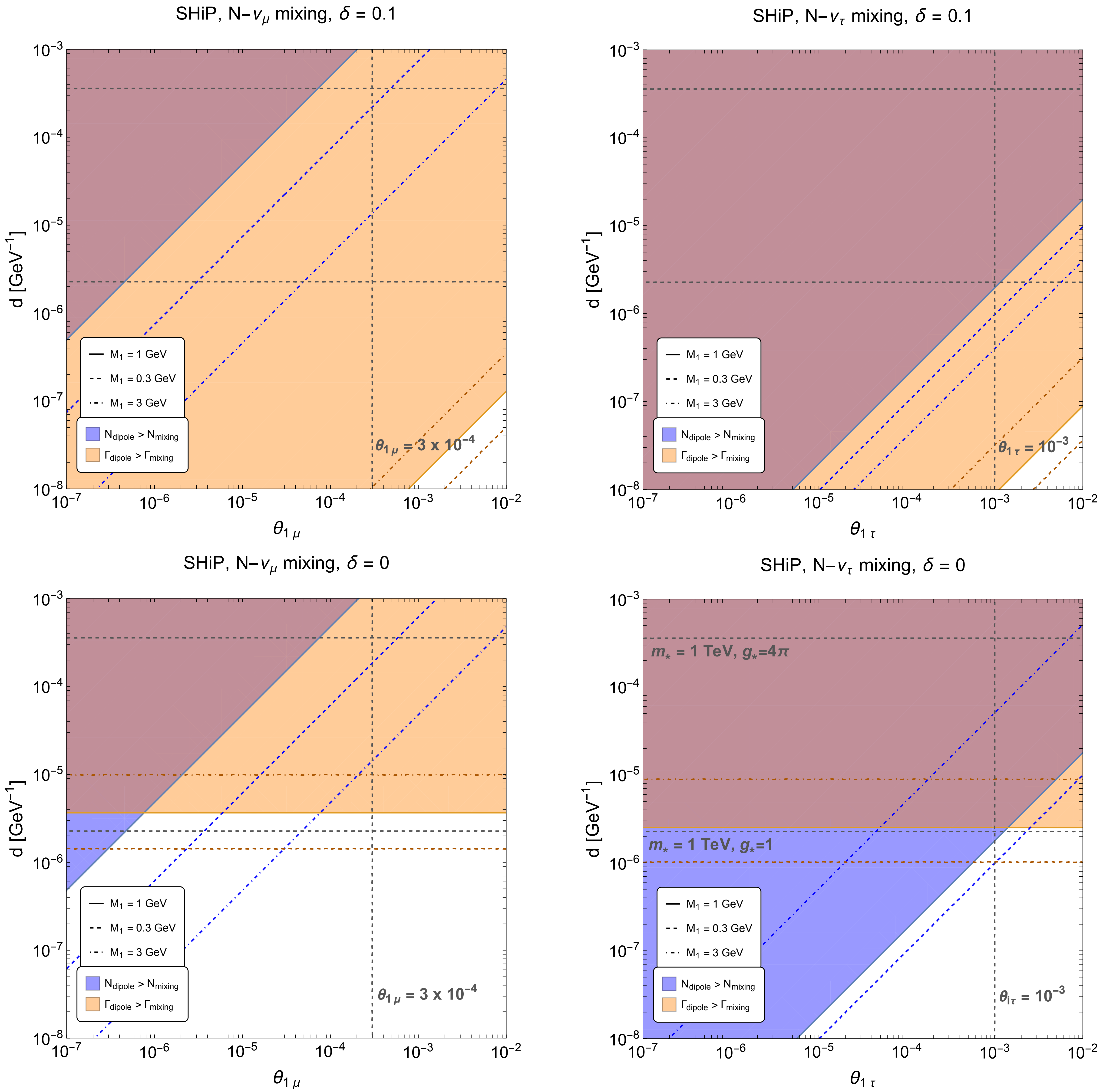


supernova explosion



BBN

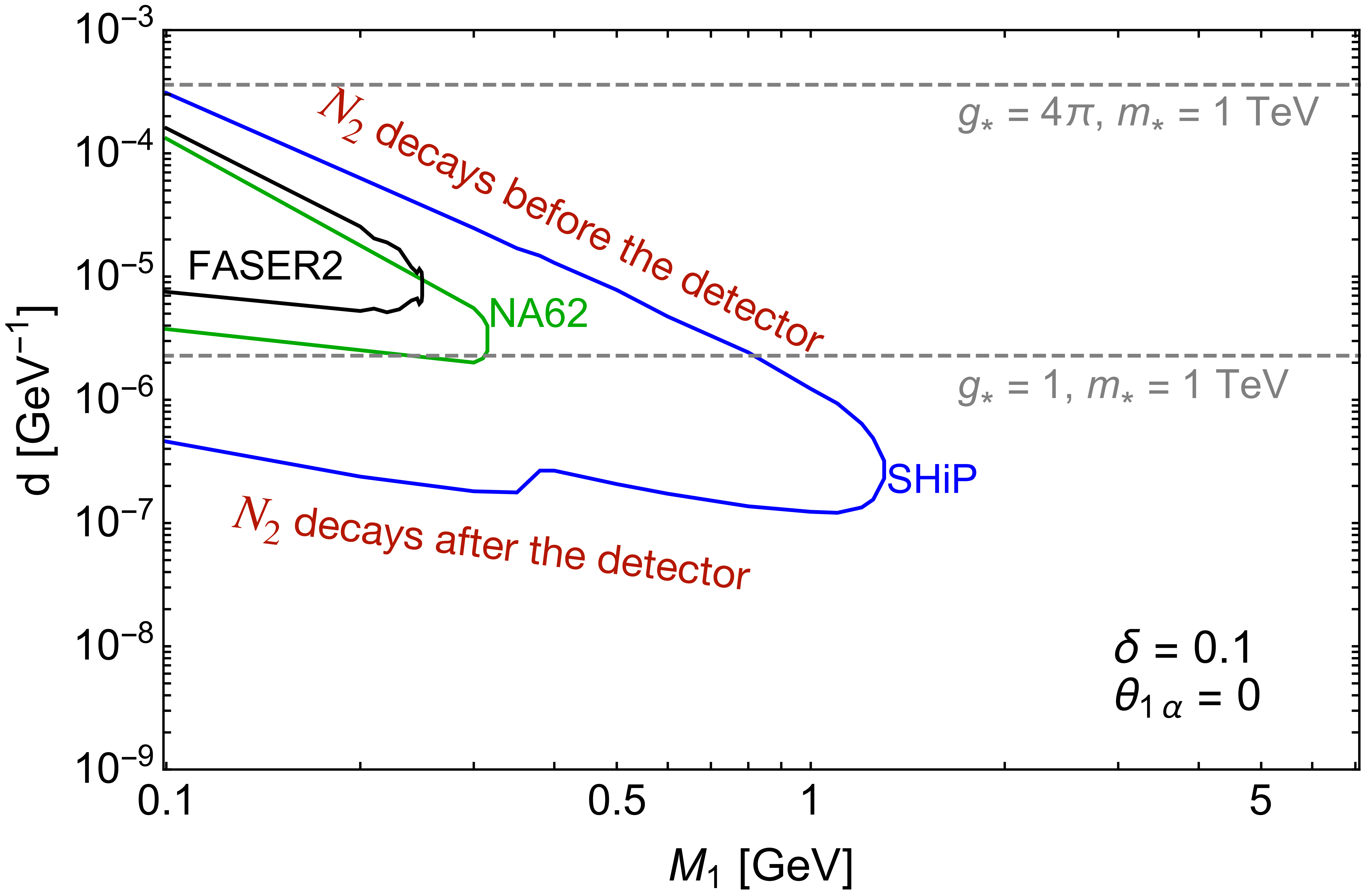
θ vs d



mixing or dipole dominance in production/decays depends crucially on parameters/flavour

see also
Barducci,B,Taoso,Toni ’22
Barducci,B,Taoso,Ternes,Toni ‘24

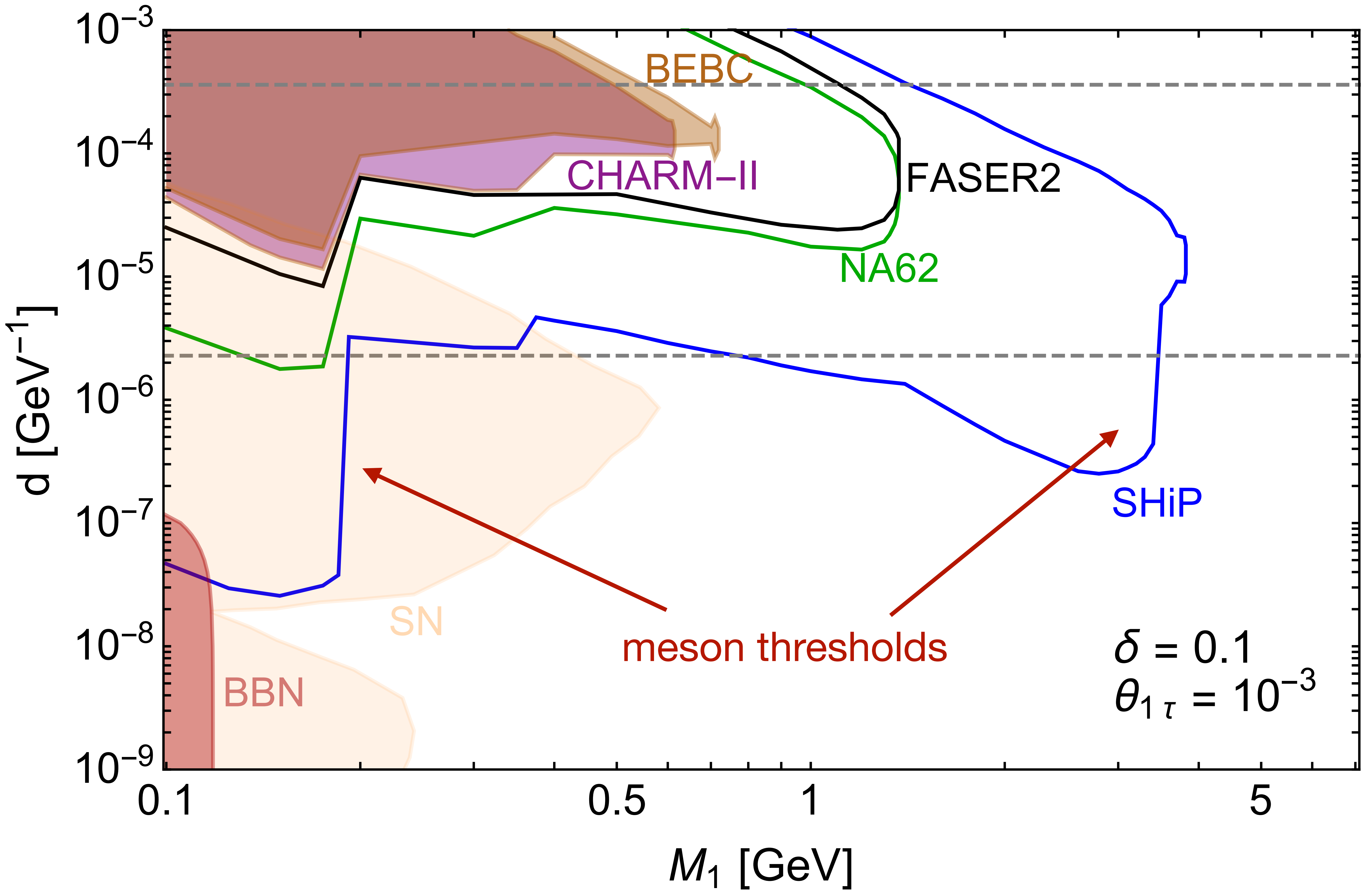
Sensitivities



- No mixing
- only $N_2 \to N_1\gamma$ active
- 95% C.L. curves

turning on mixing?

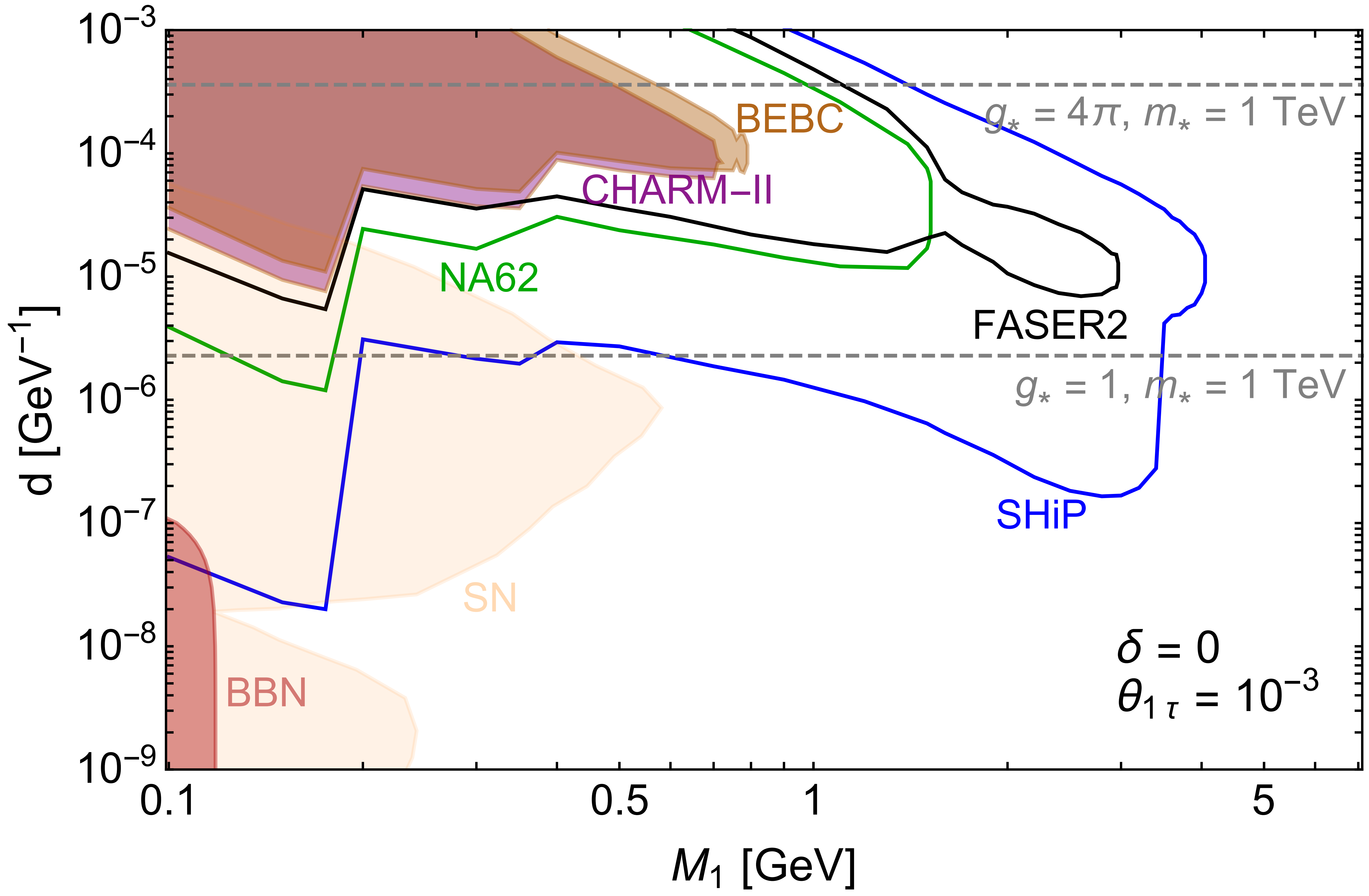
Sensitivities



- mixing with τ
- $N_2 \to N_1\gamma, N_i \to \nu_\tau\gamma$
- 95% C.L. curves
- mixing dominates production

changing δ?

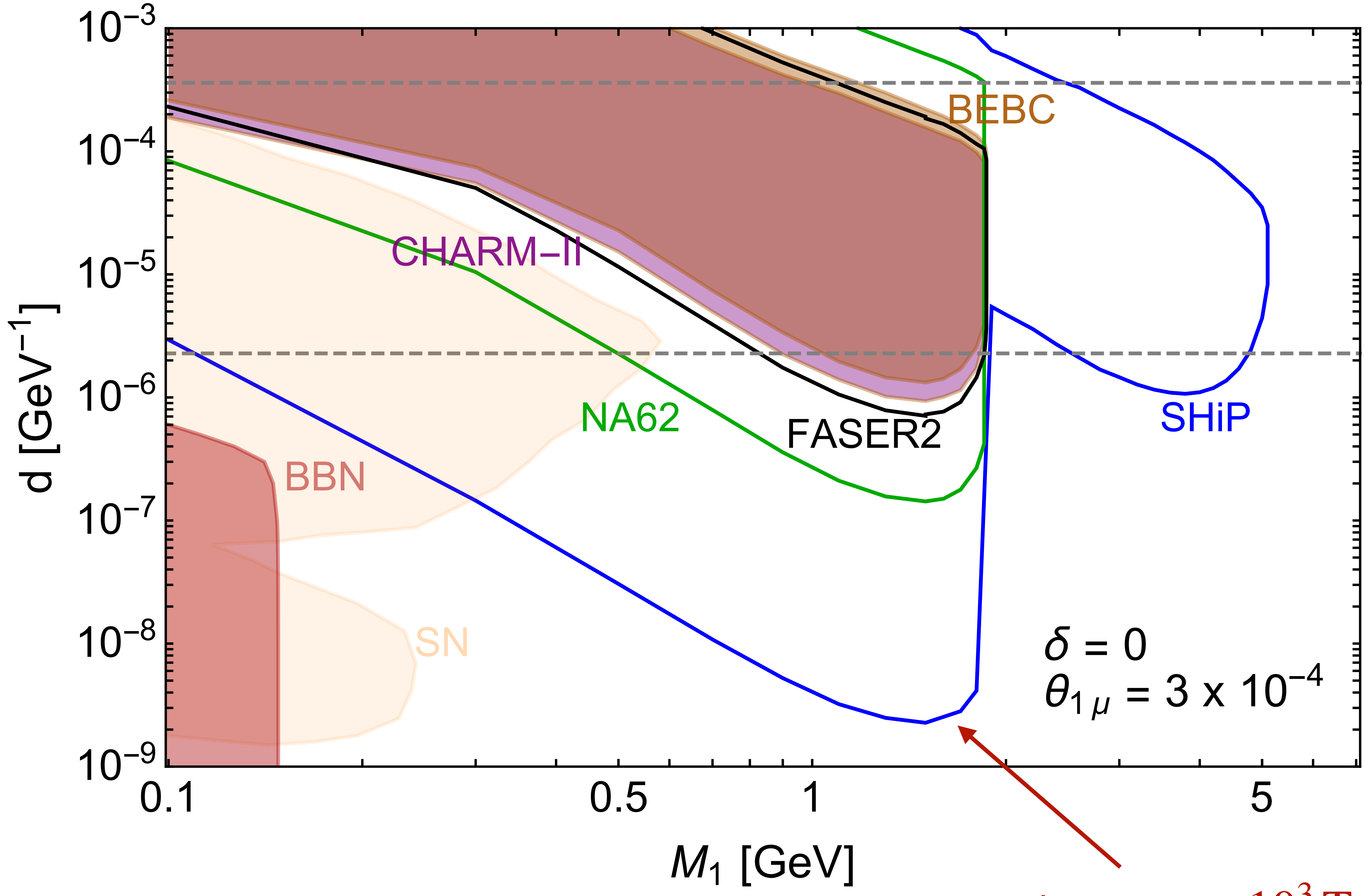
Sensitivities



- mixing with τ
- $N_2 \to N_1\gamma, N_i \to \nu_\tau\gamma$
- 95% C.L. curves
- mixing dominates production

changing flavour?

Sensitivities



corresponds to $m_\star \simeq 10^3\,\mathrm{TeV}$ ($10^6\,\mathrm{TeV}$) in weakly (strongly) coupled theories

- mixing with μ
- $N_2 \to N_1\gamma$, $N_i \to \nu_\tau\gamma$
- 95% C.L. curves
- mixing dominates production

Takeaway messages

Takeaway messages

- Interplay between dipole & mixing highly non-trivial:

  strong correlation between flavour and reach

- Future intensity frontier experiments will probe unconstrained regions of parameter space

- SHiP will mark a jump in sensitivity:

  up to 10^3 TeV (10^6 TeV) in weakly (strongly) coupled theories

Takeaway messages

- Bonus: when $\theta_{i\alpha} = 0$, N_1 is a DM candidate