Lepton Number Violation at Hadron Colliders

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type-i seesaw mechanism

extend standard model with sterile field N_1

$$\mathcal{L} \supset \begin{pmatrix} \overline{\vec{\nu}^c} & \overline{N_1^c} \end{pmatrix} \begin{pmatrix} \mathbf{0} & \vec{m}_D \\ \vec{m}_D & 0 \end{pmatrix} \begin{pmatrix} \vec{\nu} \\ N_1 \end{pmatrix}$$

type-i seesaw mechanism

extend standard model with **sterile** field N_1

$$\mathcal{L} \supset \begin{pmatrix} \overline{\vec{\nu}^c} & \overline{N_1^c} \end{pmatrix} \begin{pmatrix} \mathbf{0} & \vec{m}_D \\ \vec{m}_D & m_M \end{pmatrix} \begin{pmatrix} \vec{\nu} \\ N_1 \end{pmatrix}$$

ln-violating Majorana mass

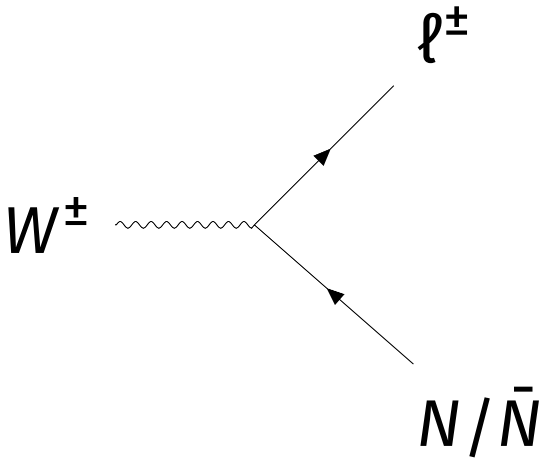
$$m_M \gg m_D$$

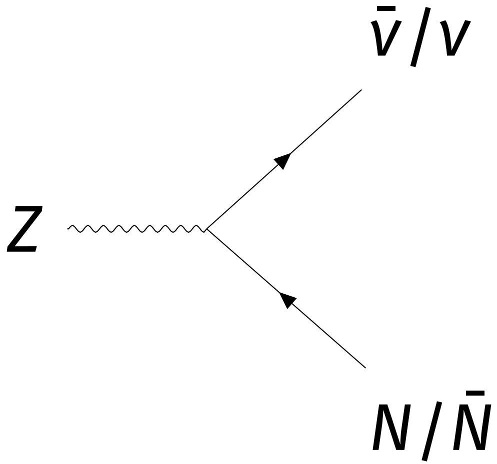
$$\downarrow$$

seesaw mechanism

$$m_{\text{light}} \approx m_M |\vec{\theta}|^2 \qquad m_{\text{heavy}} \approx m_M \qquad \vec{\theta} \equiv \frac{\vec{m}_D}{m_M}$$

type-i seesaw mechanism

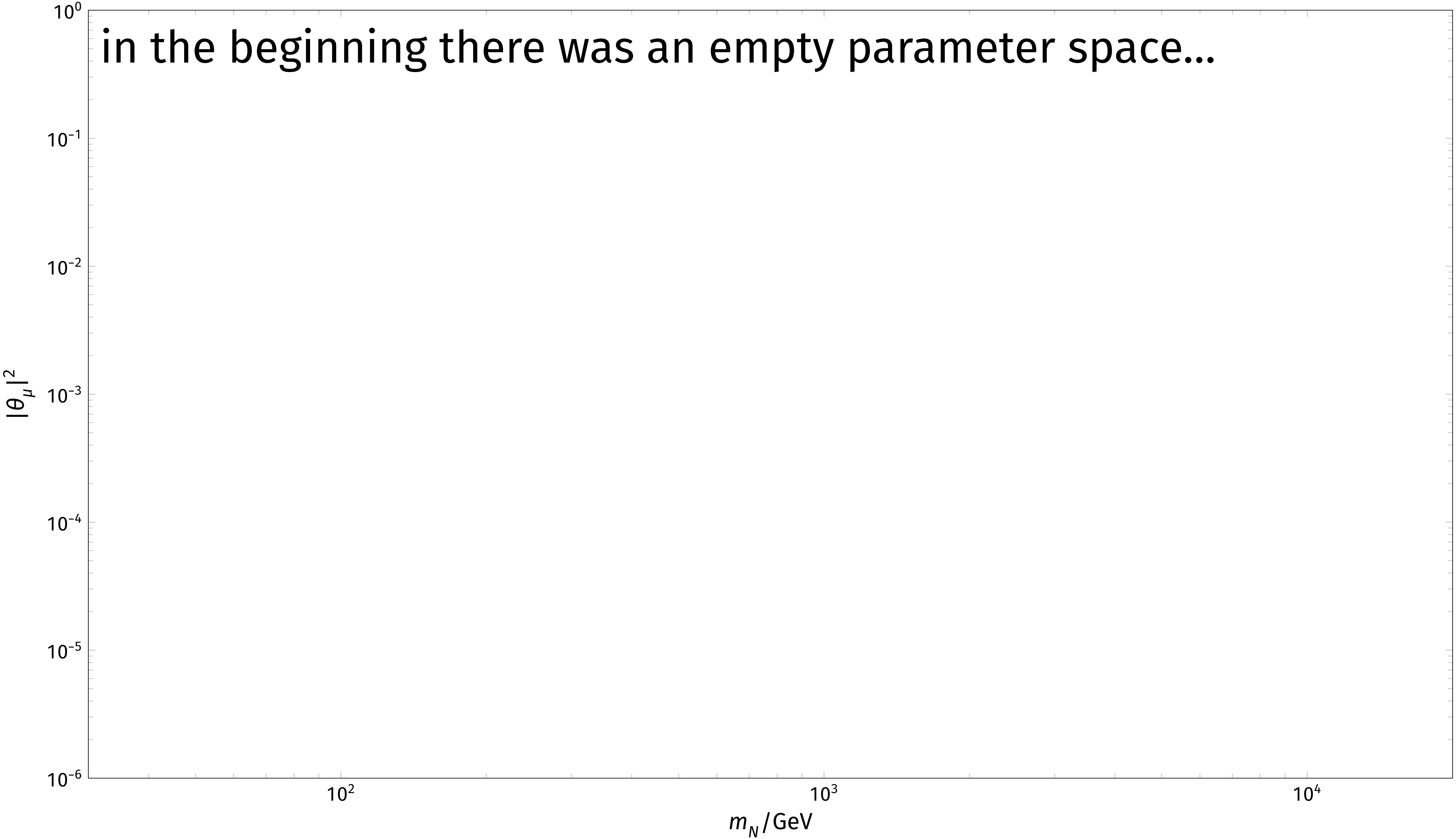


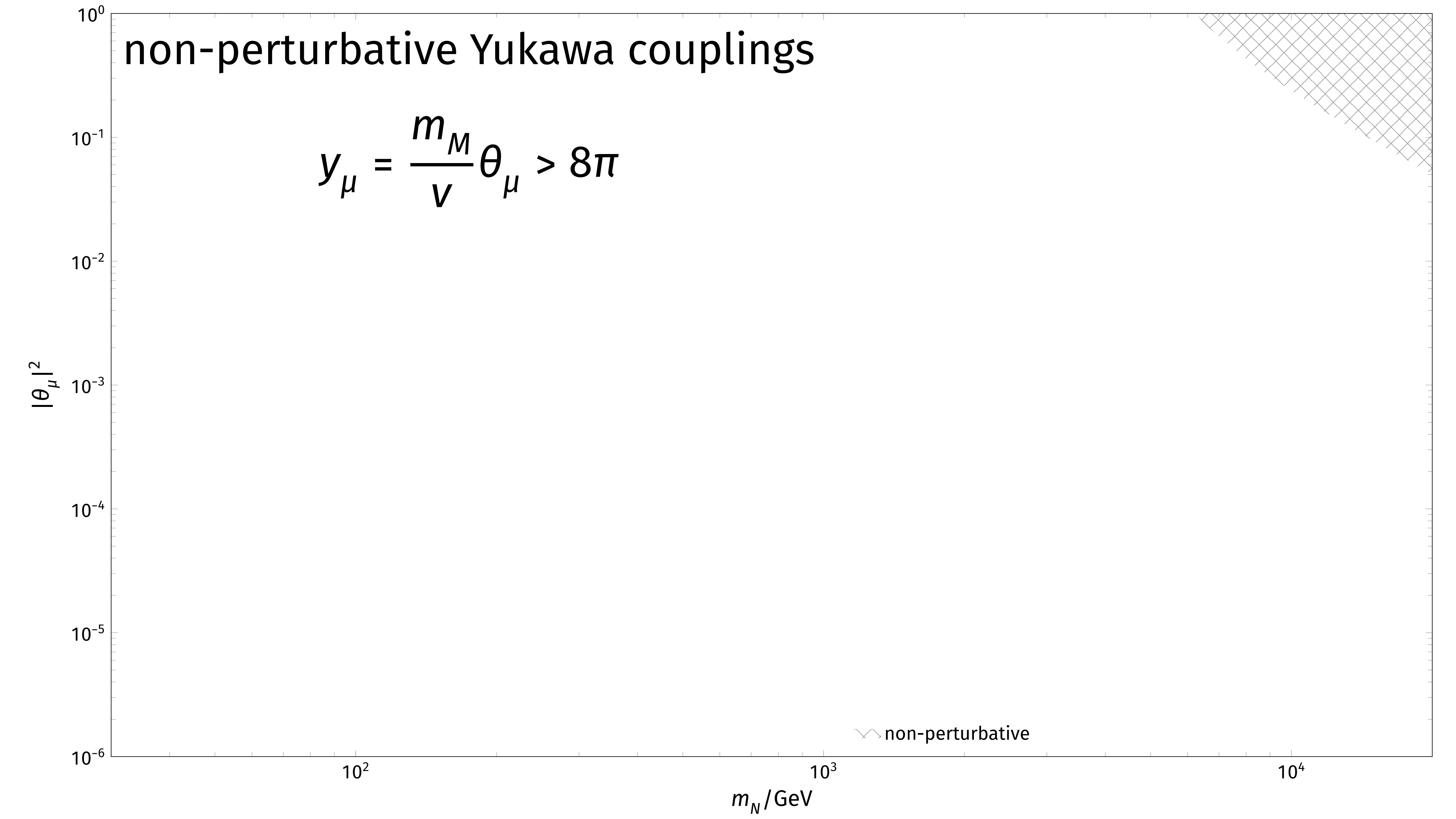


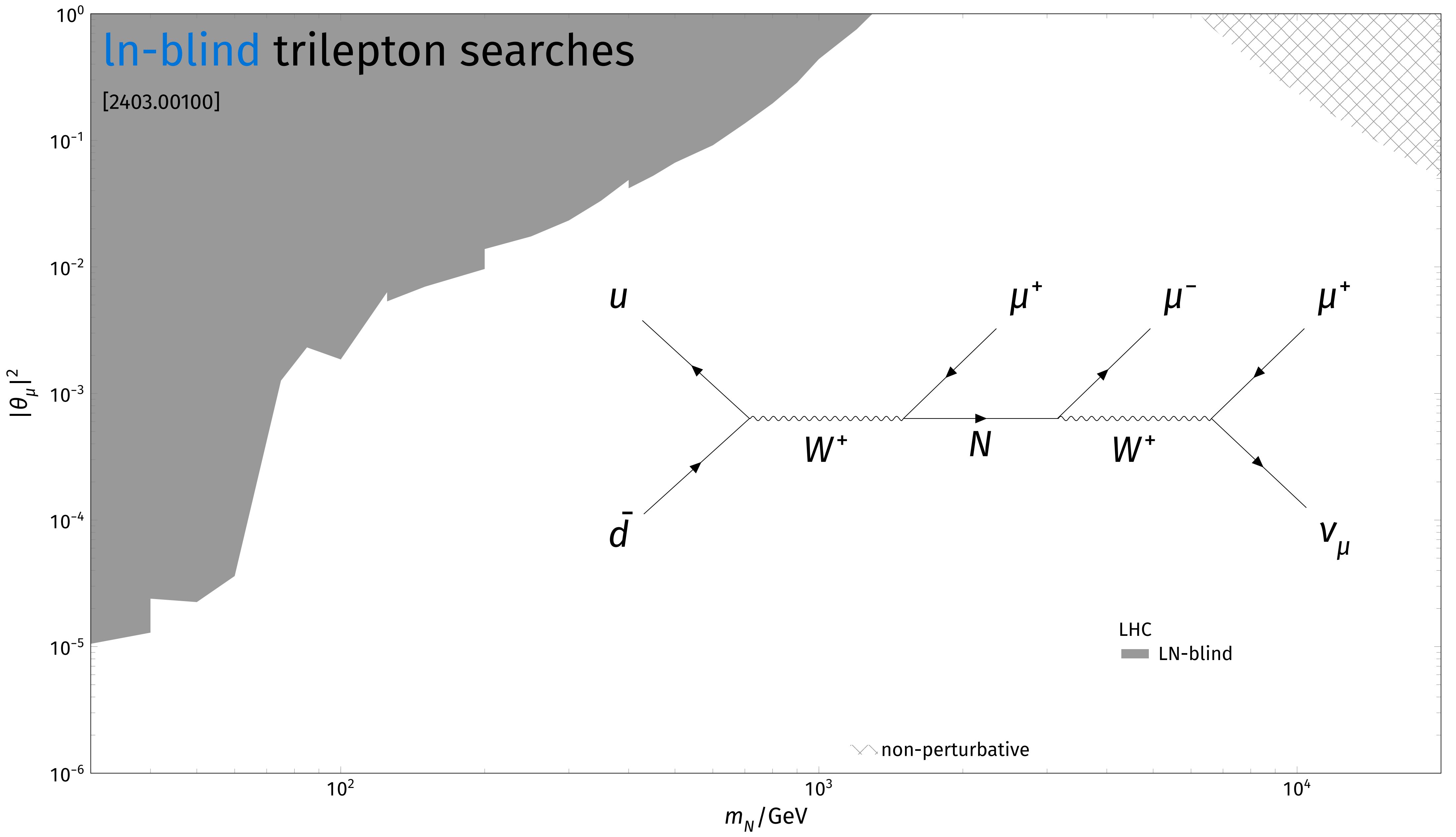
charged leptons
↓
can reconstruct ln

light neutrinos
↓
cannot reconstruct ln

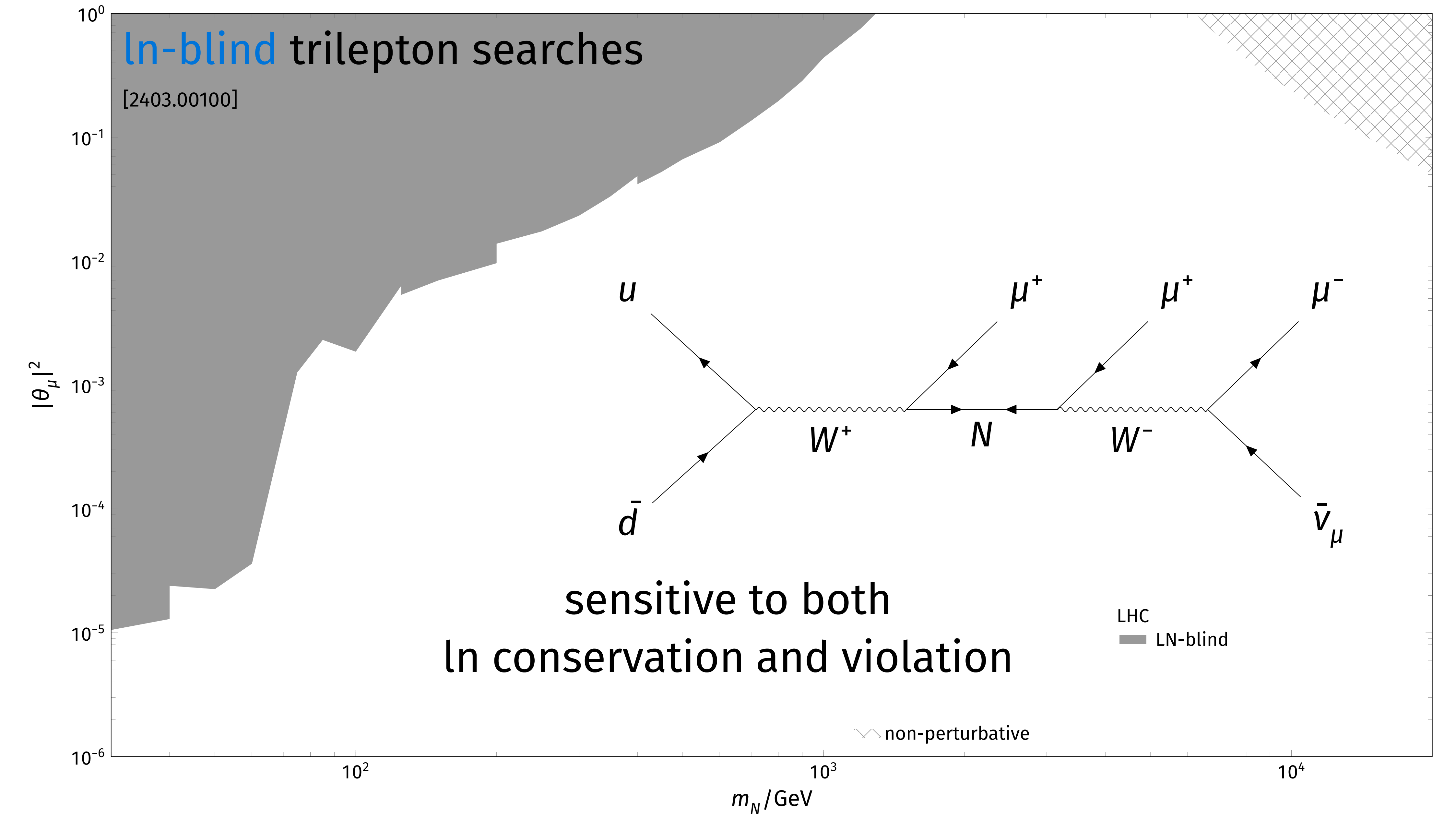
state of the art at the LHC

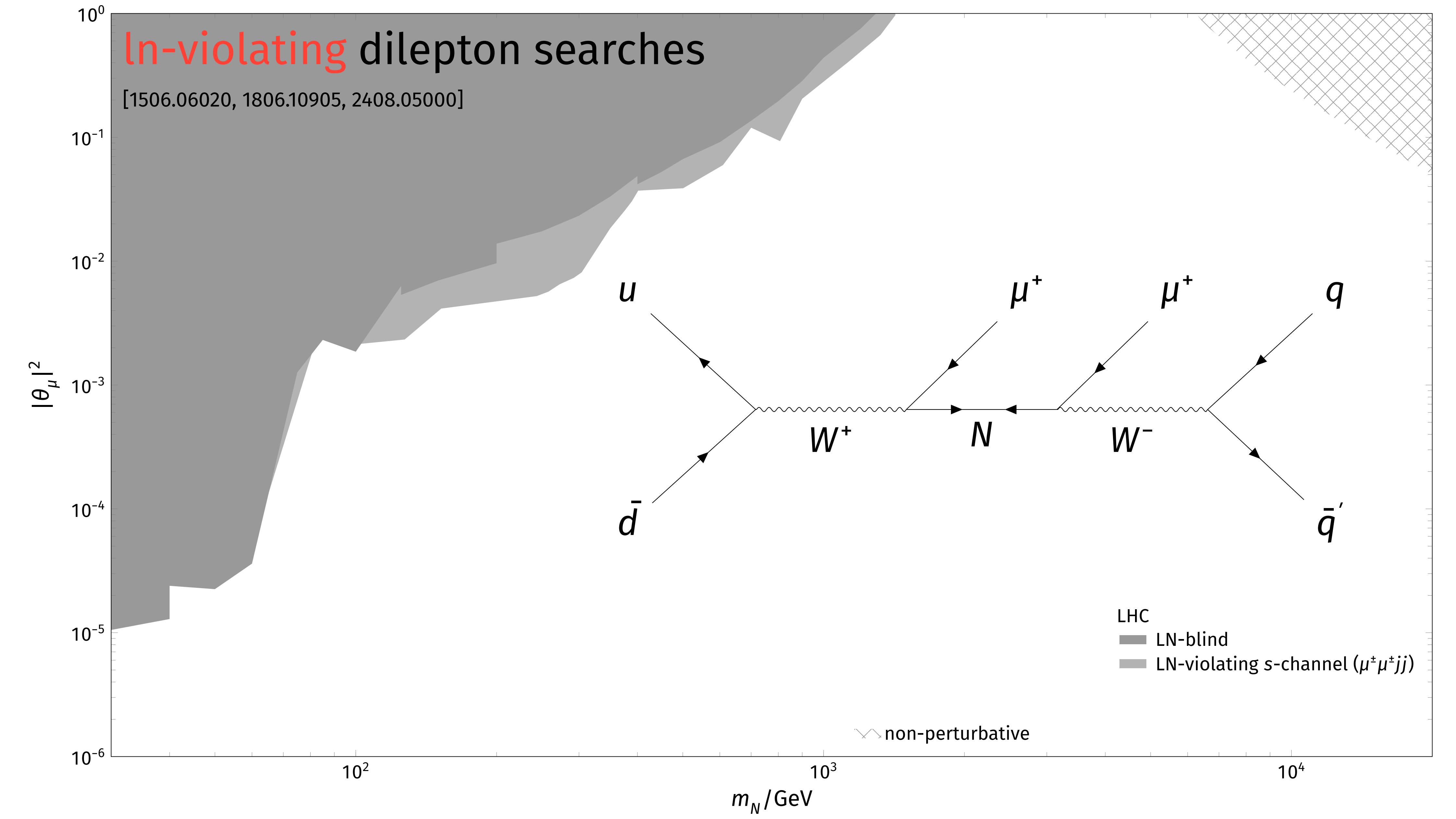

in the beginning there was an empty parameter space...
$|\theta_\mu|^2$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
m_N/GeV

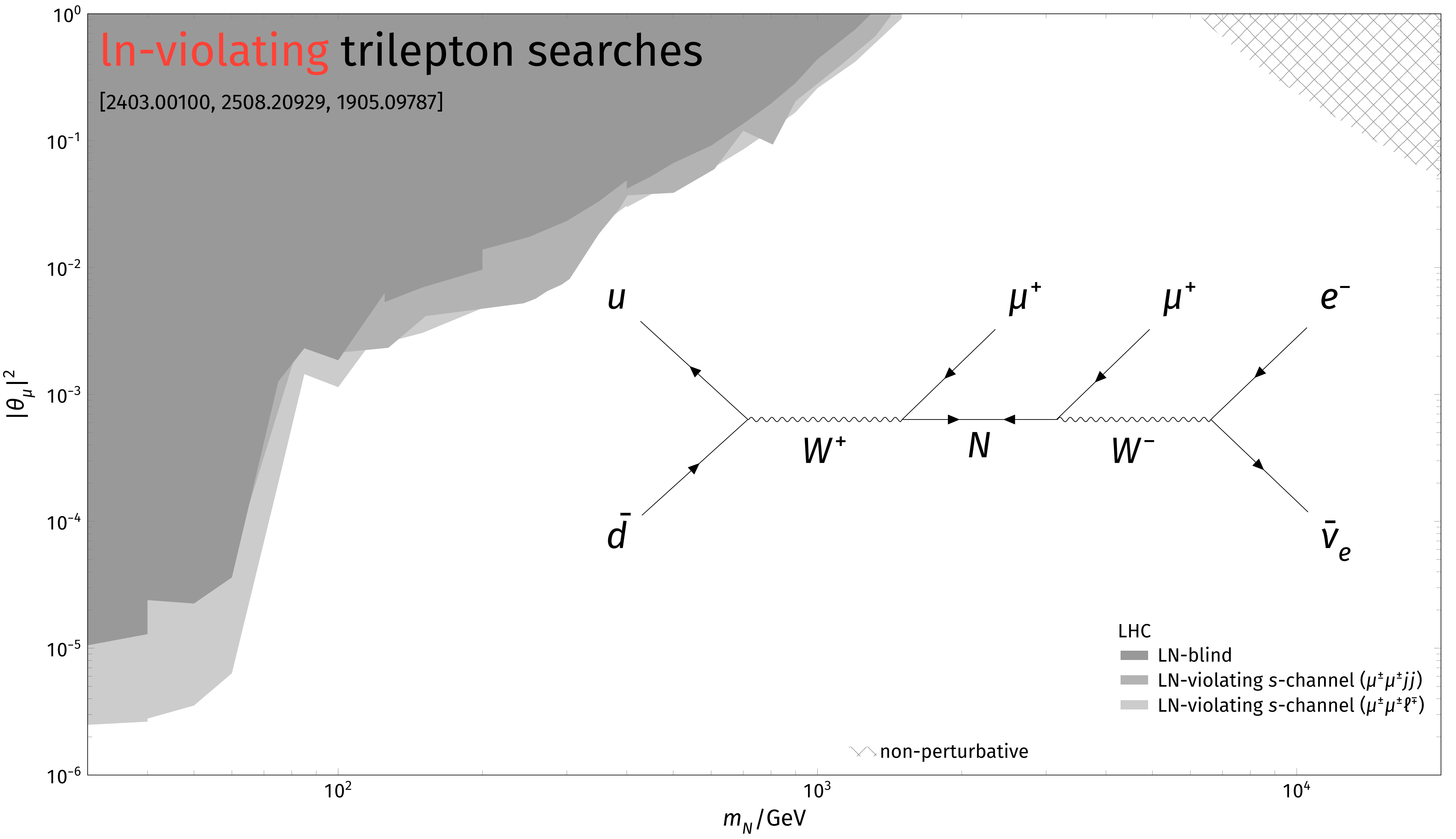

non-perturbative Yukawa couplings
$y_\mu = \frac{m_M}{v}\theta_\mu > 8\pi$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$|\theta_\mu|^2$
10^2
10^3
10^4
m_N/GeV
non-perturbative



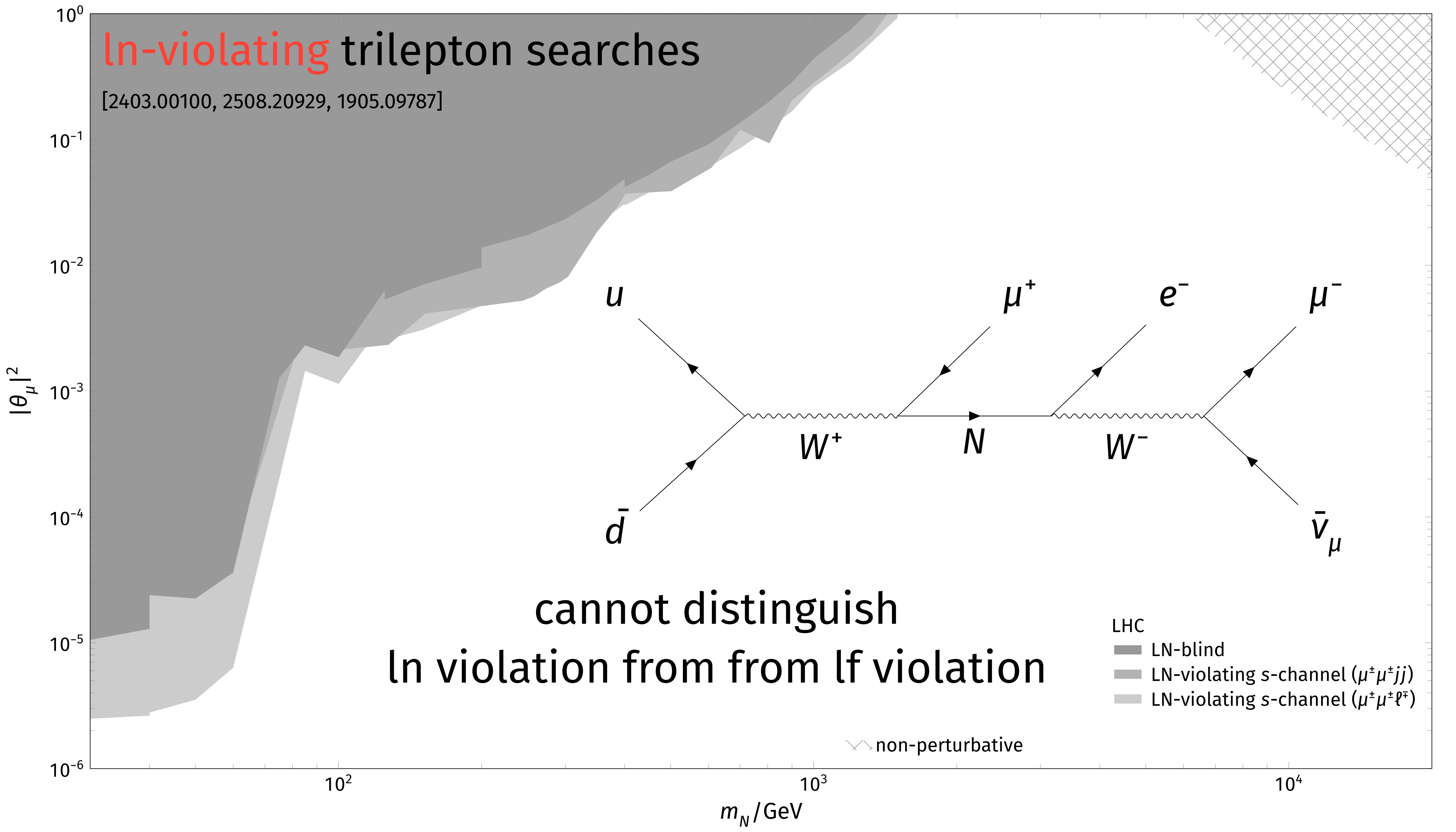
ln-blind trilepton searches
[2403.00100]
u
$\bar{d}$
W^+
N
W^+
μ^+
μ^-
μ^+
ν_μ
LHC
LN-blind
non-perturbative
$|\theta_\mu|^2$
m_N/GeV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4


ln-blind trilepton searches
[2403.00100]
sensitive to both
ln conservation and violation
LHC
LN-blind
non-perturbative
u
d̄
W⁺
N
W⁻
μ⁺
μ⁺
μ⁻
ν̄_μ
|θ_μ|²
m_N / GeV
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10²
10³
10⁴

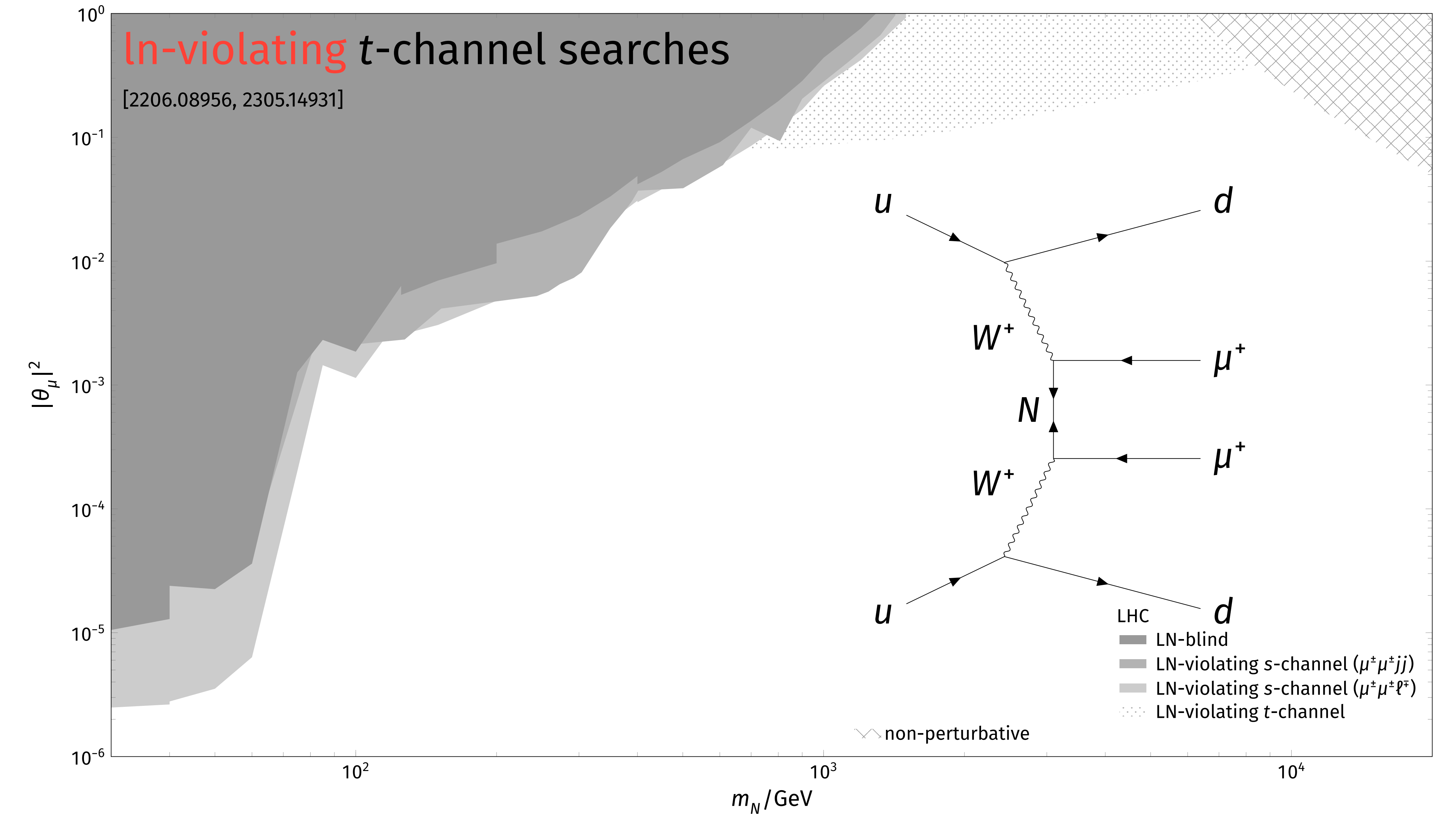

ln-violating dilepton searches
[1506.06020, 1806.10905, 2408.05000]
$|\theta_\mu|^2$
m_N/GeV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
u
$\bar{d}$
W^+
N
W^-
μ^+
μ^+
q
$\bar{q}'$
LHC
LN-blind
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
non-perturbative



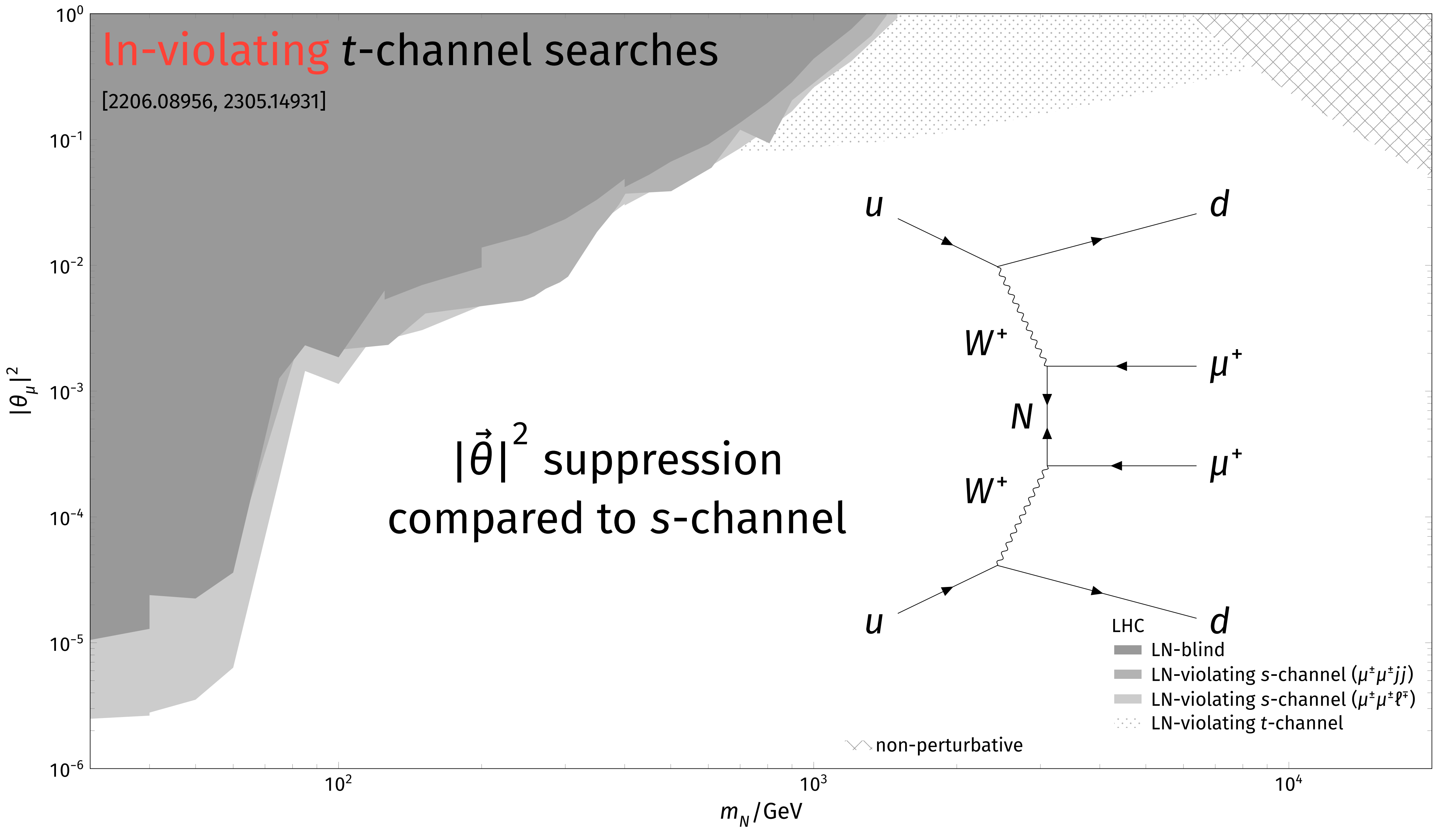
ln-violating trilepton searches
[2403.00100, 2508.20929, 1905.09787]
$|\theta_\mu|^2$
m_N/GeV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
u
$\bar{d}$
W^+
N
W^-
μ^+
μ^+
e^-
$\bar{\nu}_e$
LHC
LN-blind
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
LN-violating s-channel ($\mu^\pm\mu^\pm\ell^\mp$)
non-perturbative



ln-violating trilepton searches
[2403.00100, 2508.20929, 1905.09787]
u
d̄
W⁺
N
W⁻
μ⁺
e⁻
μ⁻
ν̄_μ
cannot distinguish
ln violation from from lf violation
LHC
LN-blind
LN-violating s-channel (μ±μ±jj)
LN-violating s-channel (μ±μ±ℓ∓)
non-perturbative
|θ_μ|²
m_N / GeV
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10²
10³
10⁴



ln-violating t-channel searches
[2206.08956, 2305.14931]
$|\theta_\mu|^2$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
m_N/GeV
u
d
W^+
μ^+
N
μ^+
W^+
u
d
LHC
LN-blind
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
LN-violating s-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating t-channel
non-perturbative



ln-violating t-channel searches
[2206.08956, 2305.14931]
$|\vec{\theta}|^2$ suppression
compared to s-channel
u
d
W^+
μ^+
N
μ^+
W^+
u
d
LHC
LN-blind
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
LN-violating s-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating t-channel
non-perturbative
$|\theta_\mu|^2$
m_N/GeV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4

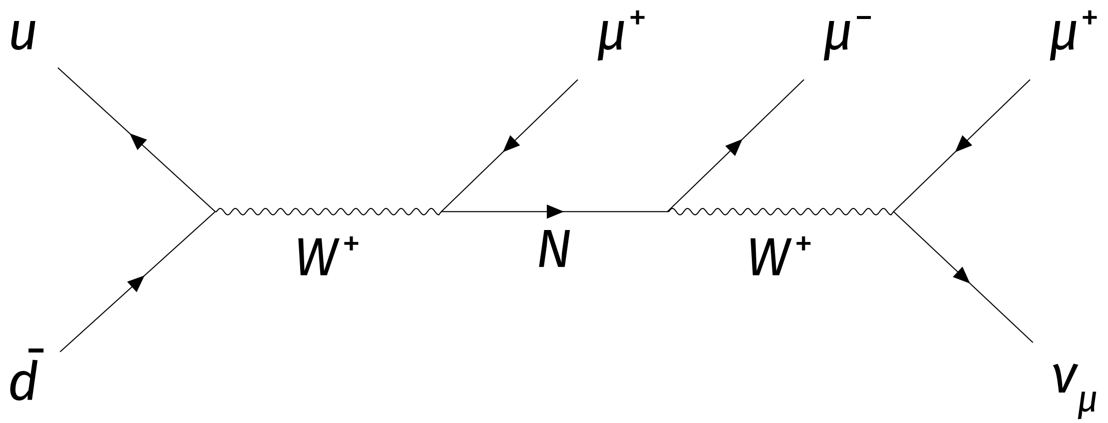
looking toward the future

FCC-*hh* and S*pp*C

prospects at future colliders

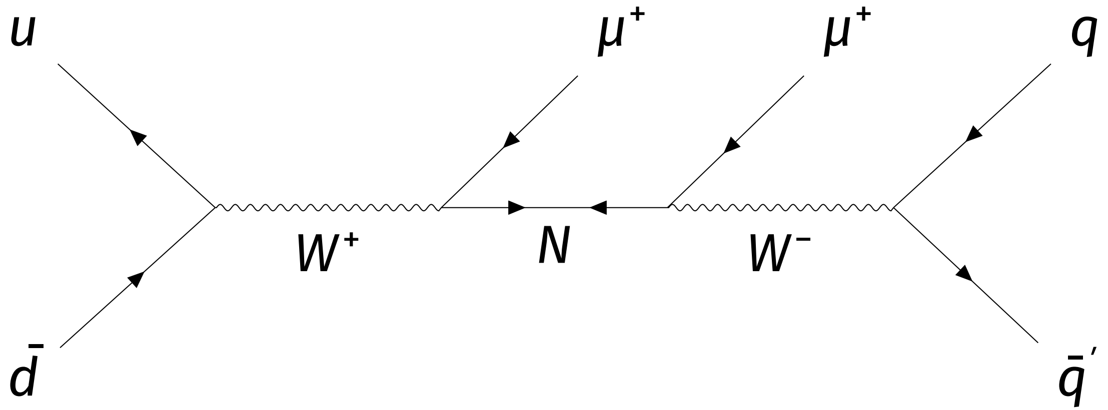
ln-blind

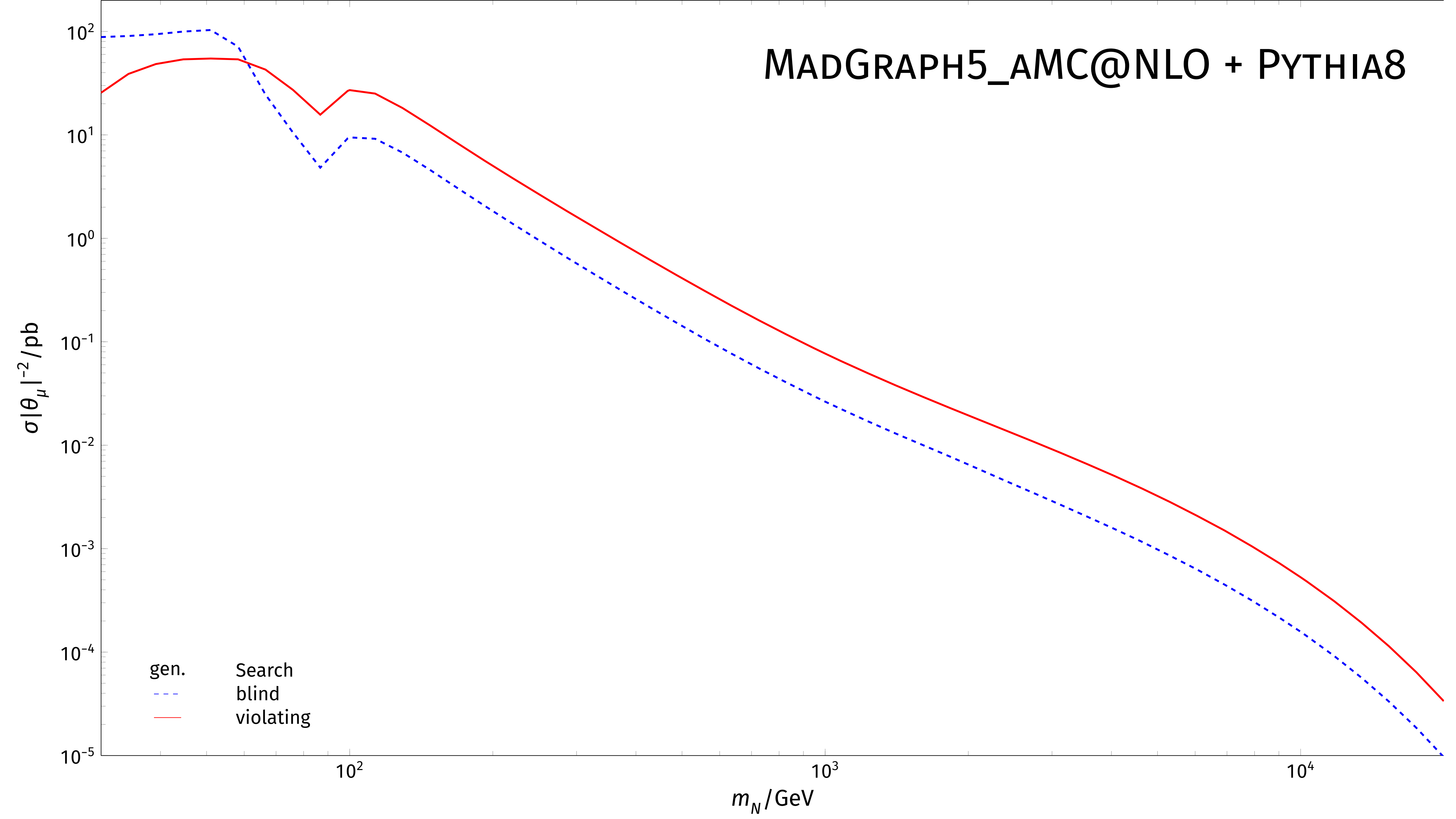
$\mu^+\mu^-\mu^+\nu_\mu$
$\mu^+\mu^-\mu^-\bar{\nu}_\mu$



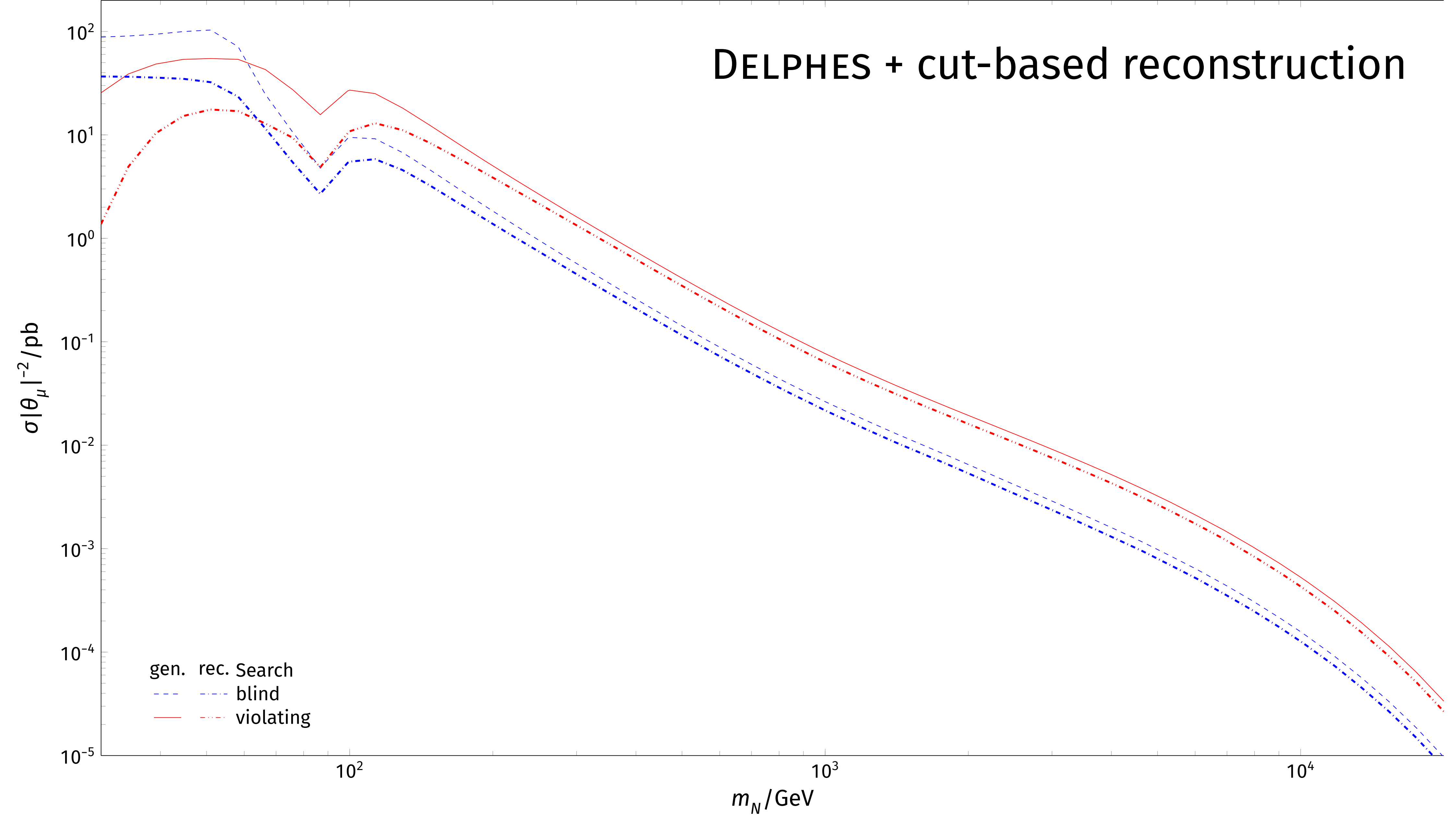
ln-violating

$\mu^+\mu^+jj$
$\mu^-\mu^-jj$

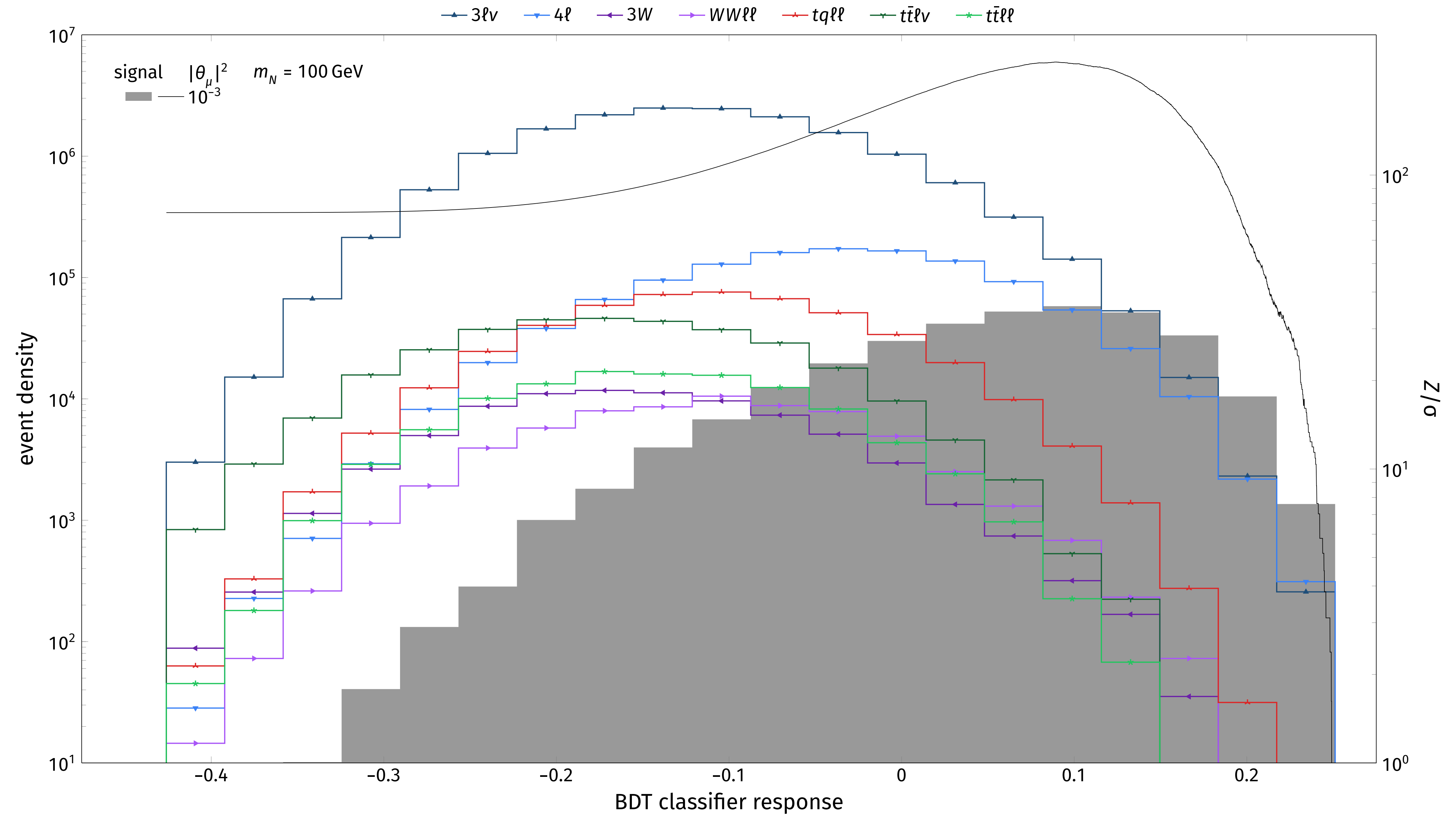




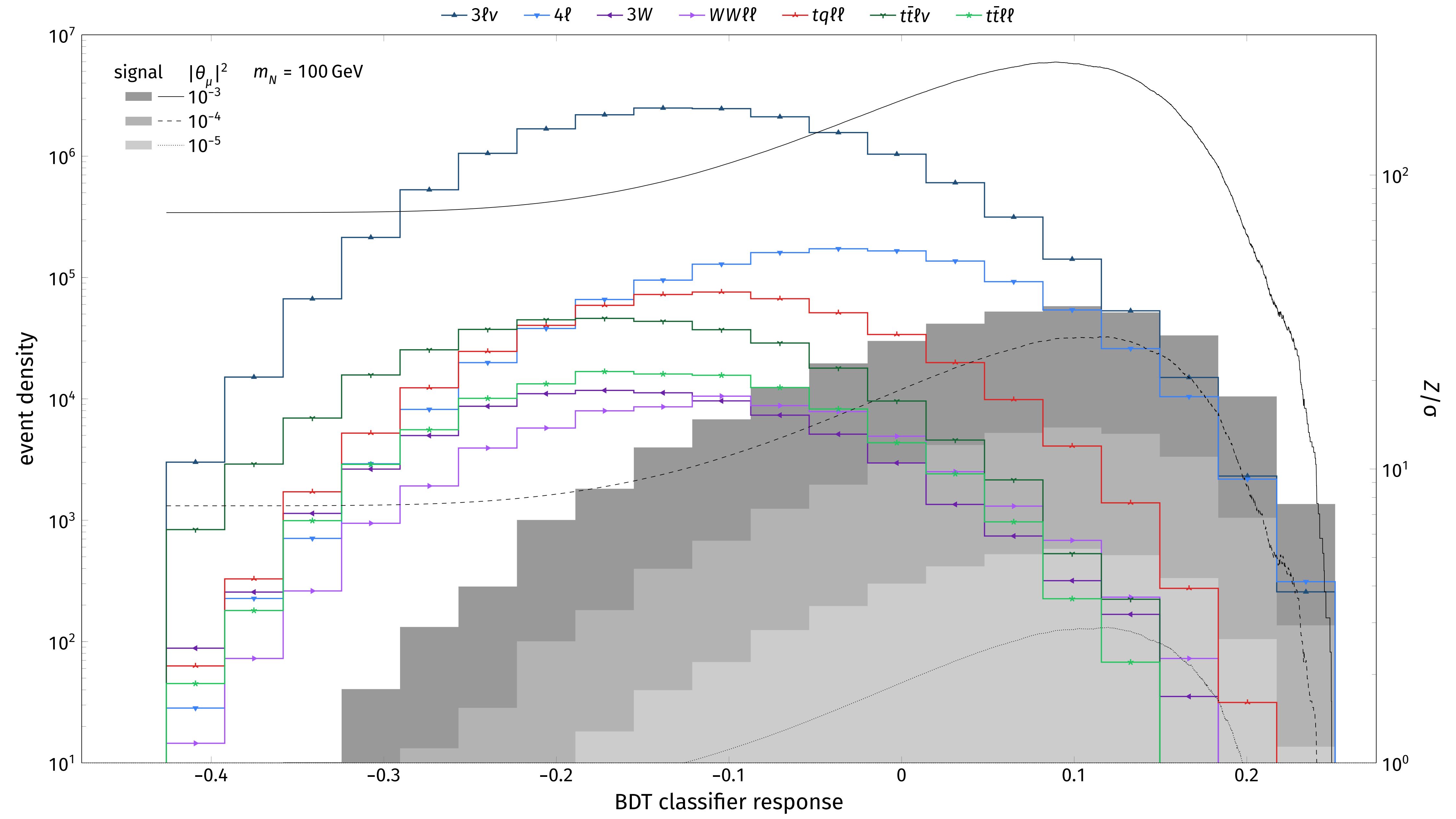
MadGraph5_aMC@NLO + Pythia8
$\sigma|\theta_\mu|^{-2}/\mathrm{pb}$
m_N/GeV
gen.
Search
blind
violating
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^2
10^3
10^4

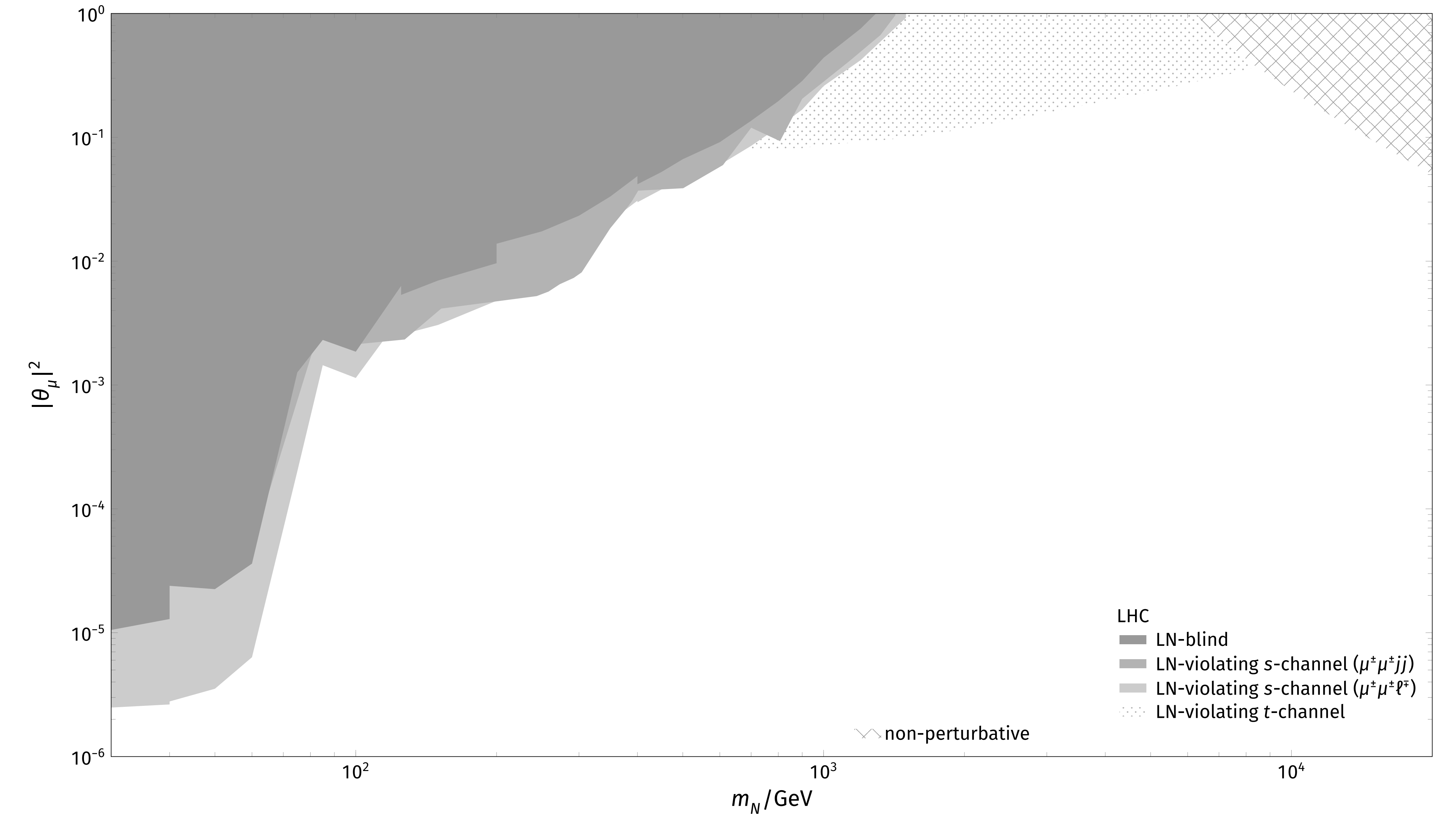


DELPHES + cut-based reconstruction
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$\sigma|\theta_\mu|^{-2}/\mathrm{pb}$
10^2
10^3
10^4
m_N/GeV
gen. rec. Search
blind
violating

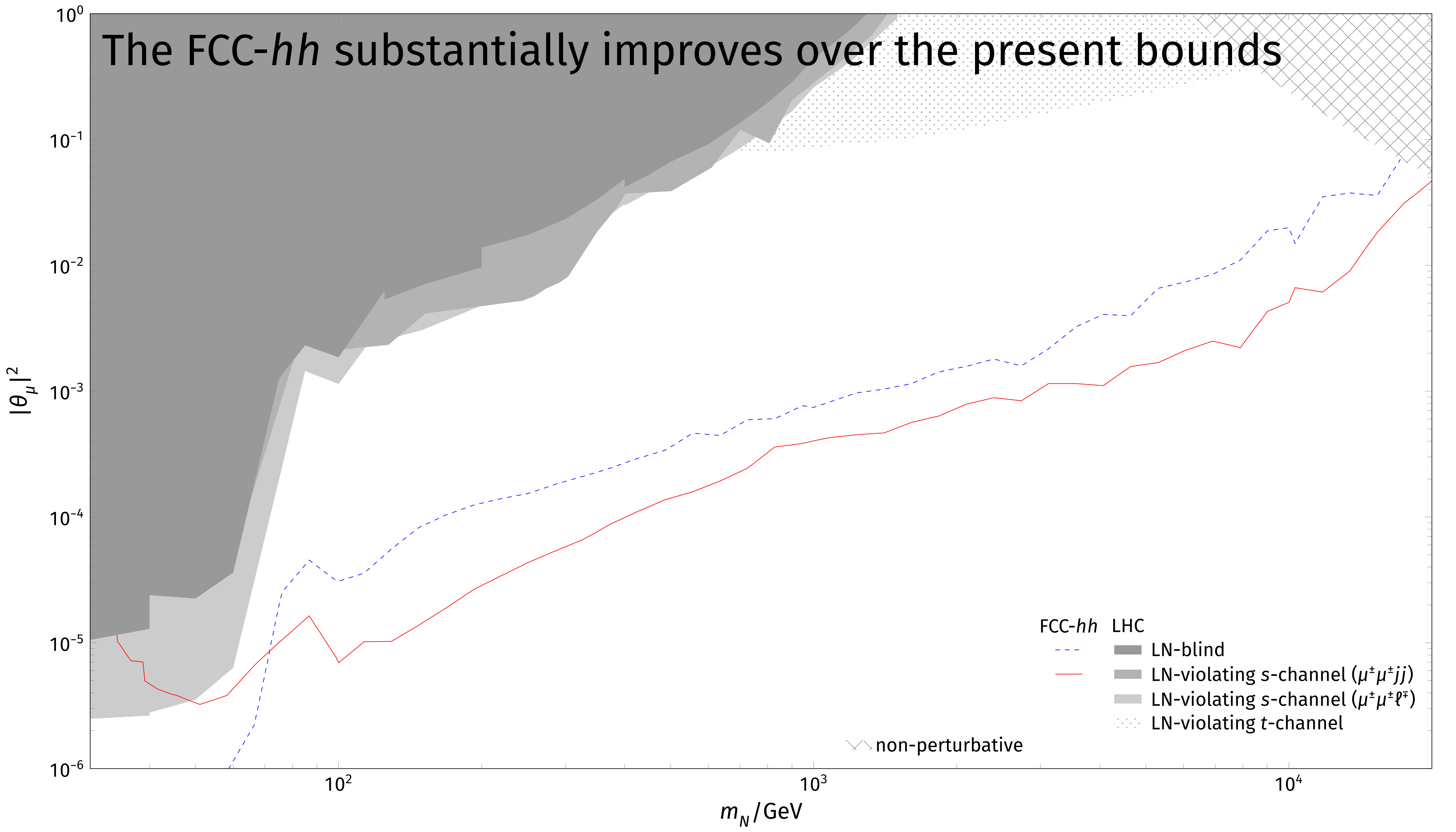


3ℓν
4ℓ
3W
WWℓℓ
tqℓℓ
tt̄ℓν
tt̄ℓℓ
signal
$|\theta_\mu|^2$
m_N = 100 GeV
10^{-3}
event density
Z/σ
BDT classifier response
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^0
10^1
10^2
−0.4
−0.3
−0.2
−0.1
0
0.1
0.2


3ℓν
4ℓ
3W
WWℓℓ
tqℓℓ
tt̄ℓν
tt̄ℓℓ
signal
|θ_μ|²
m_N = 100 GeV
10⁻³
10⁻⁴
10⁻⁵
event density
BDT classifier response
Z/σ
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
10²
10¹
10⁰
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2



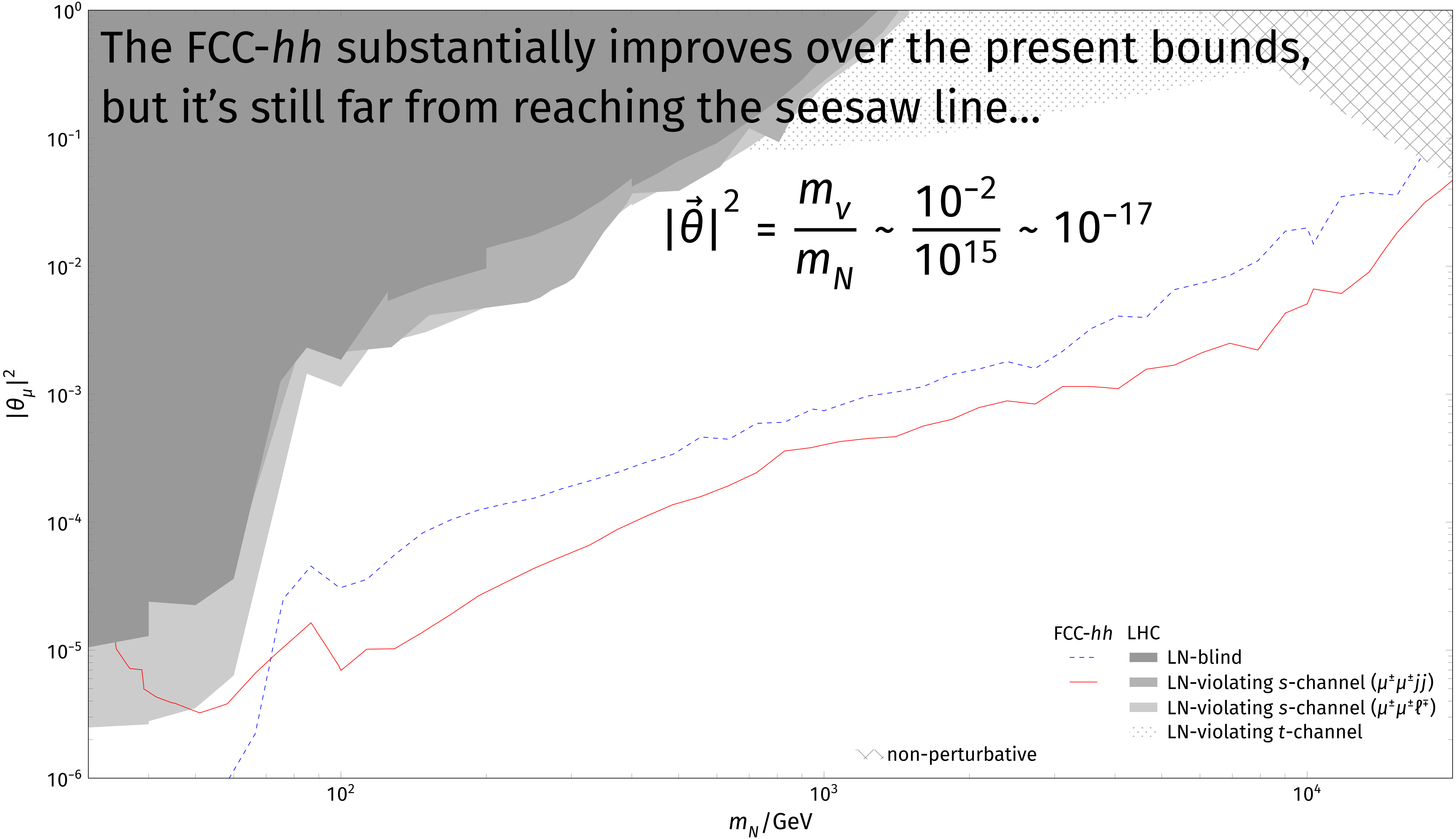
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$|\theta_\mu|^2$
10^2
10^3
10^4
m_N/GeV
LHC
LN-blind
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
LN-violating s-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating t-channel
non-perturbative



The FCC-hh substantially improves over the present bounds
$|\theta_\mu|^2$
m_N / GeV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
FCC-hh LHC
LN-blind
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
LN-violating s-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating t-channel
non-perturbative

The FCC-*hh* substantially improves over the present bounds, but it's still far from reaching the seesaw line...

$$|\vec{\theta}|^2 = \frac{m_\nu}{m_N} \sim \frac{10^{-2}}{10^{15}} \sim 10^{-17}$$

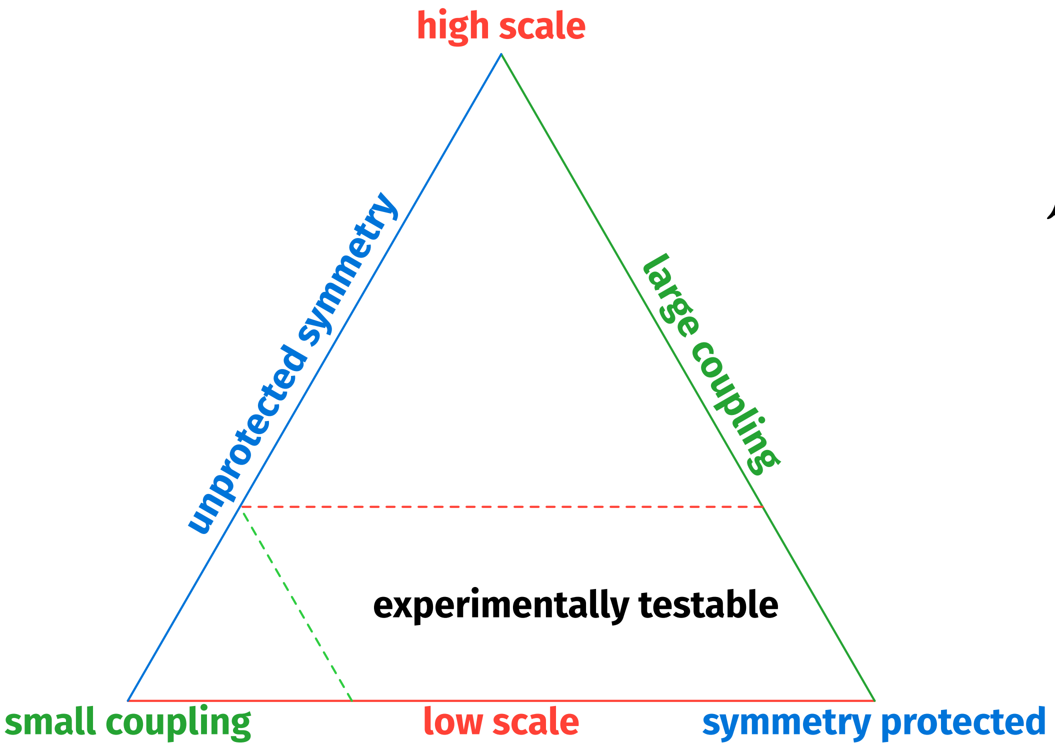


the naive seesaw is not collider-accessible

the naive seesaw is not collider-accessible

second hnl + symmetry

symmetry-protected seesaw



exact ln symmetry

$$\mathcal{L} \supset \begin{pmatrix} \overline{\vec{\nu}^c} & \overline{N_1^c} & \overline{N_2^c} \end{pmatrix} \begin{pmatrix} \mathbf{0} & \vec{m}_D & \vec{0} \\ \vec{m}_D^T & 0 & m_M \\ \vec{0}^T & m_M & 0 \end{pmatrix} \begin{pmatrix} \vec{\nu} \\ N_1 \\ N_2 \end{pmatrix}$$

$\downarrow$

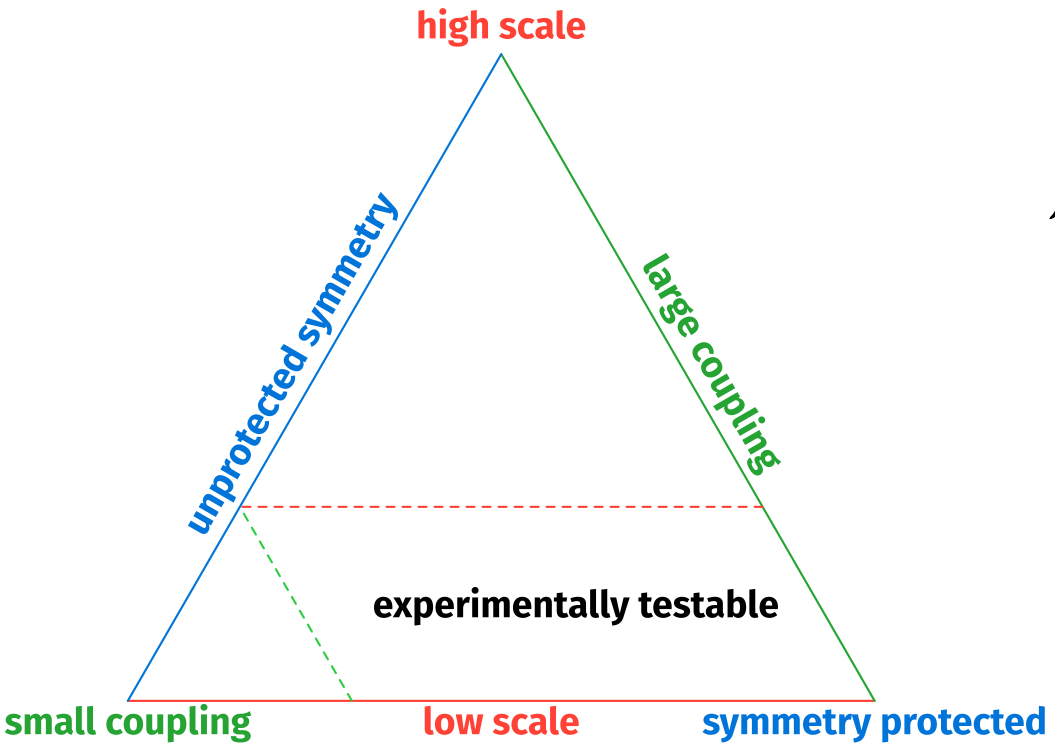
massless SM neutrinos

+

collider-accessible

Dirac hnl

symmetry-protected seesaw



approximate ln symmetry

$$\mathcal{L} \supset \begin{pmatrix} \overline{\vec{\nu}^c} & \overline{N_1^c} & \overline{N_2^c} \end{pmatrix} \begin{pmatrix} \mathbf{0} & \vec{m}_D & \vec{\mu}_D \\ \vec{m}_D^T & \mu'_M & m_M \\ \vec{\mu}_D^T & m_M & \mu_M \end{pmatrix} \begin{pmatrix} \vec{\nu} \\ N_1 \\ N_2 \end{pmatrix}$$

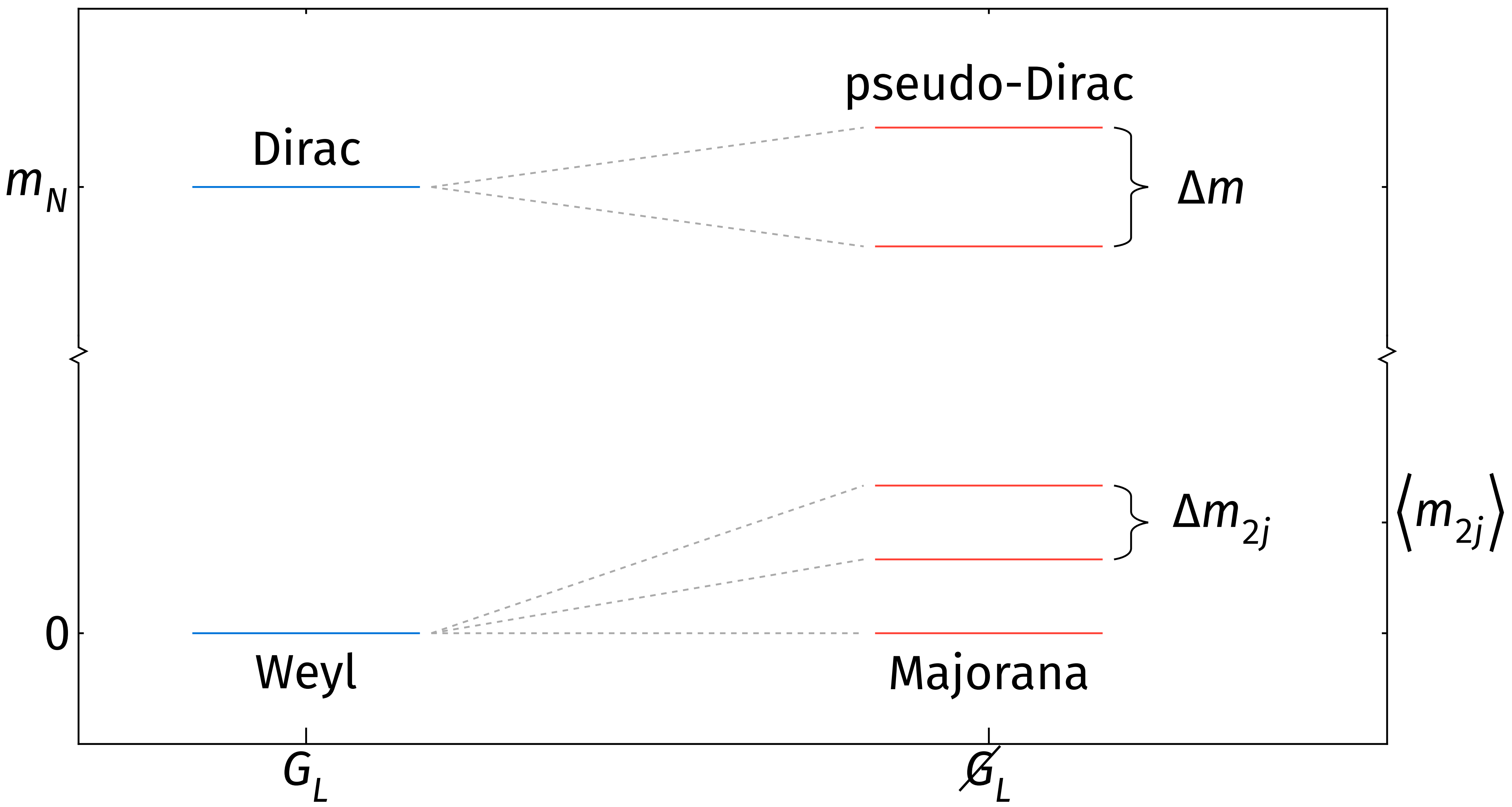
$\downarrow$

light SM neutrinos

+

collider-accessible

pseudo-Dirac hnl



pseudo-Dirac
Dirac
m_N
Δm
Δm_{2j}
$\langle m_{2j} \rangle$
0
Weyl
Majorana
G_L
$\cancel{G}_L$

what about ln violation?

what plane-wave qft tells us

regime:	symmetric	symmetry-protected	no symmetry protection
HNL:	Dirac	pseudo-Dirac	double-Majorana
LNV:		suppressed by $O(\Delta m/m)$	large
Δm:	0		$O(m)$

what plane-wave qft tells us

regime:	symmetric	symmetry-protected	no symmetry protection
HNL:	Dirac	pseudo-Dirac	double-Majorana
LNV:		suppressed by $O(\Delta m/m)$	large
Δm:	0		$O(m)$

not a complete picture!

heavy neutrino-antineutrino oscillations

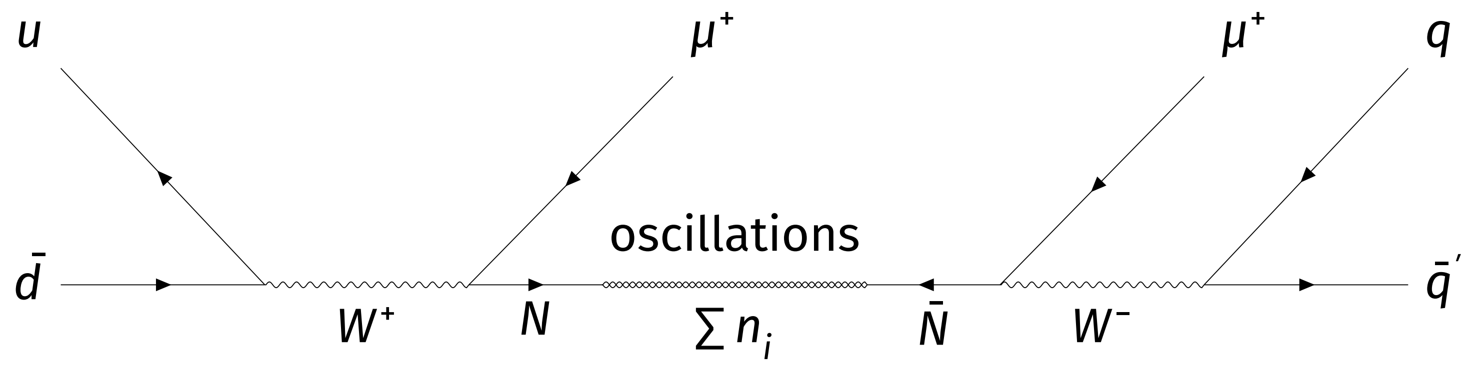
pseudo-Dirac pair contains two mass eigenstates

$$m_{4/5} = m_N \pm \frac{\Delta m}{2}$$

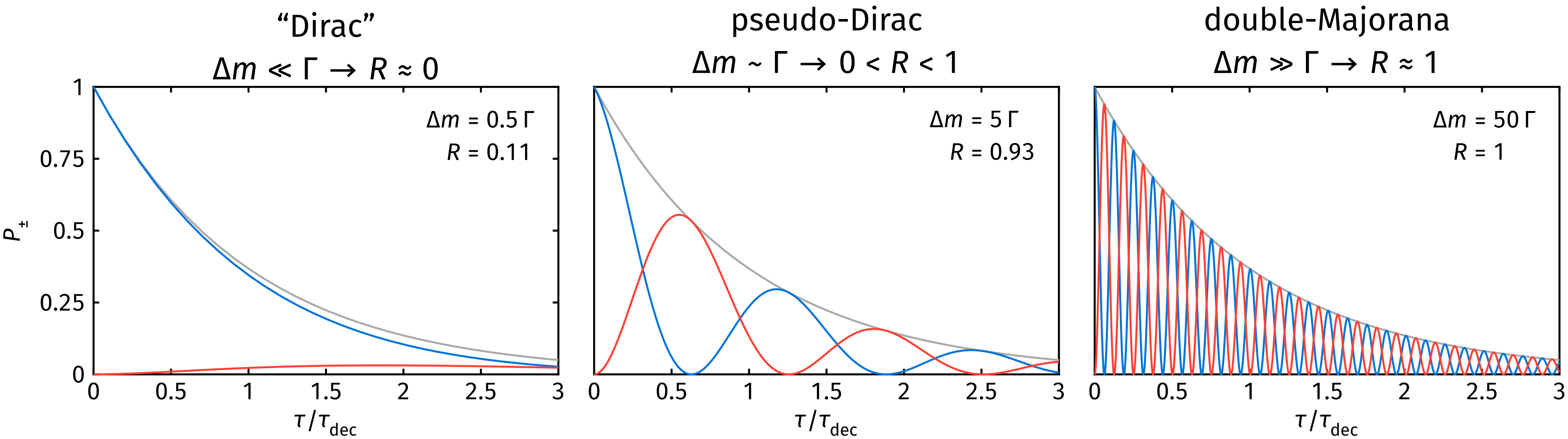
interference during resonant propagation

$\downarrow$

heavy neutrino-antineutrino oscillations



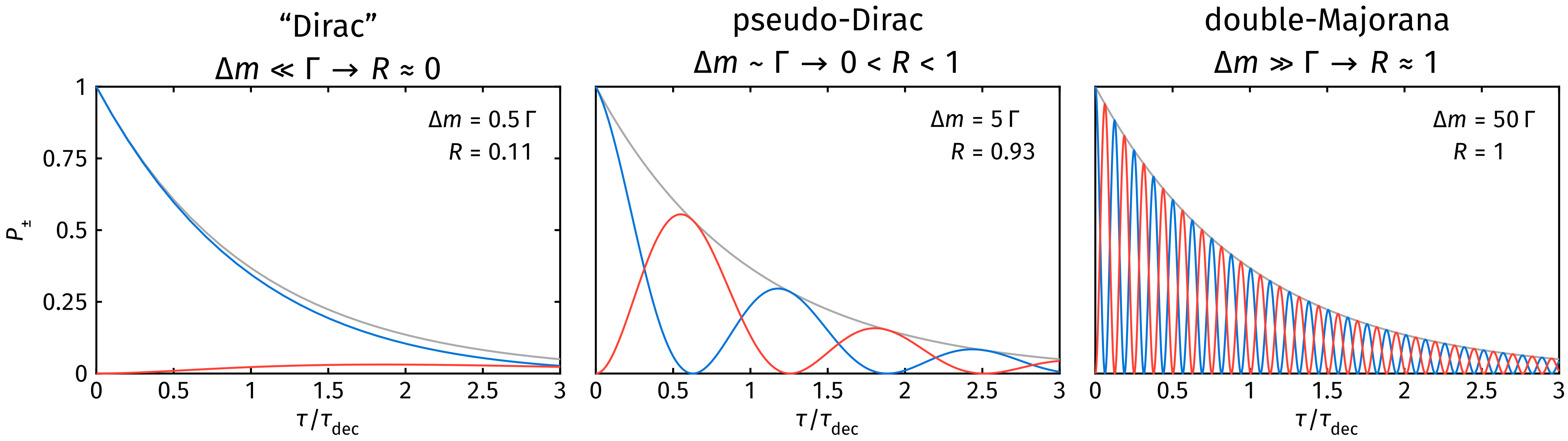
heavy neutrino-antineutrino oscillations



decaying oscillations

$$P^{\pm}(\tau) = P_{decay}(\tau) \times P^{\pm}_{osc}(\tau)$$

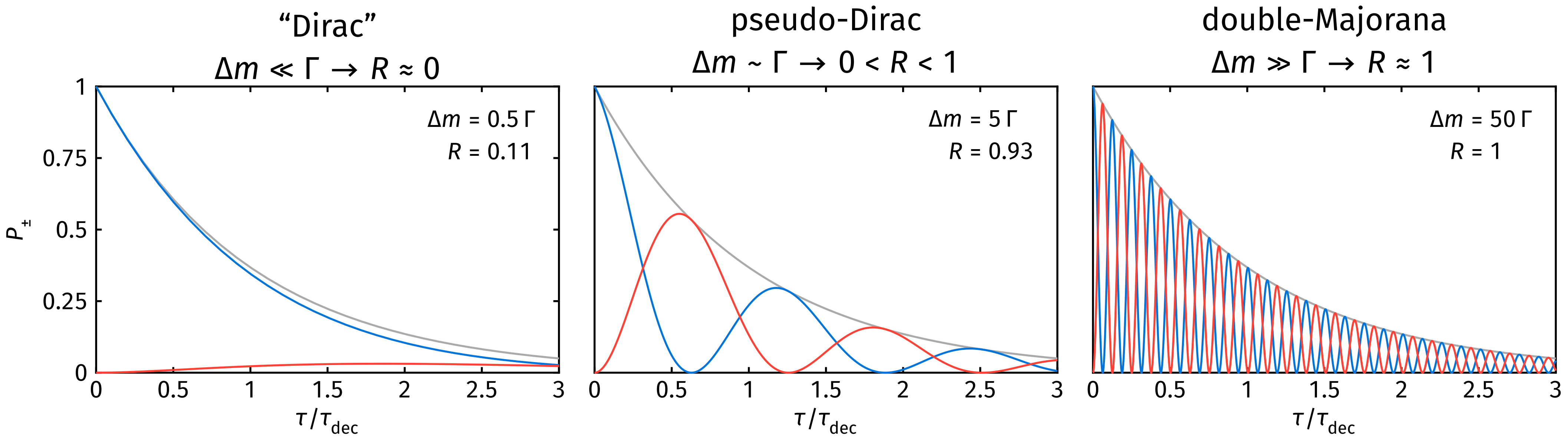
heavy neutrino-antineutrino oscillations



decaying oscillations

$$P_{\text{decay}}(\tau) = \Gamma e^{-\Gamma\tau} \qquad P^{\pm}_{\text{osc}}(\tau) = \frac{1 \pm \cos(\Delta m \tau)}{2}$$

heavy neutrino-antineutrino oscillations



time-integrated behaviour

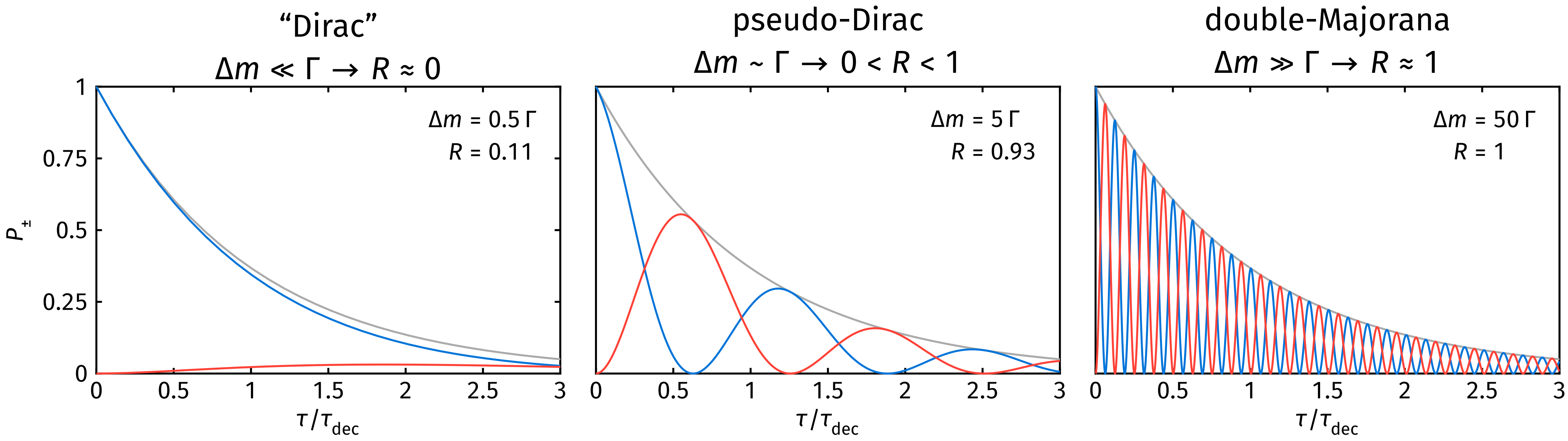
ln-conserving $\ell^\pm \ell^\mp$ events

$$N_{\text{OS}} = \sigma_{\text{OS}} \times \mathcal{L}_{\text{int}} \propto \int P^+(\tau)\,\mathrm{d}\tau$$

ln-violating $\ell^\pm \ell^\pm$ events

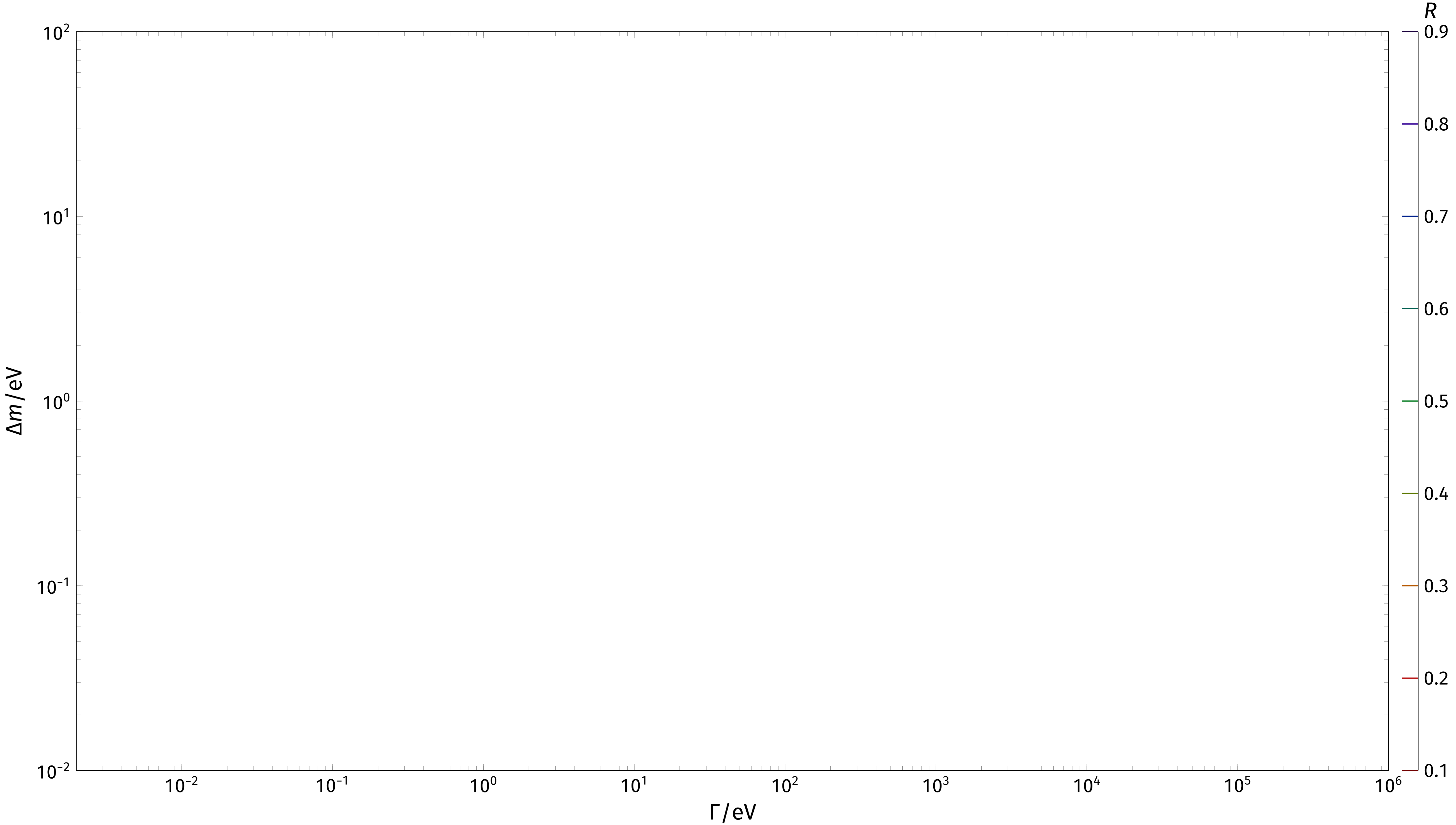
$$N_{\text{SS}} = \sigma_{\text{SS}} \times \mathcal{L}_{\text{int}} \propto \int P^-(\tau)\,\mathrm{d}\tau$$

heavy neutrino-antineutrino oscillations

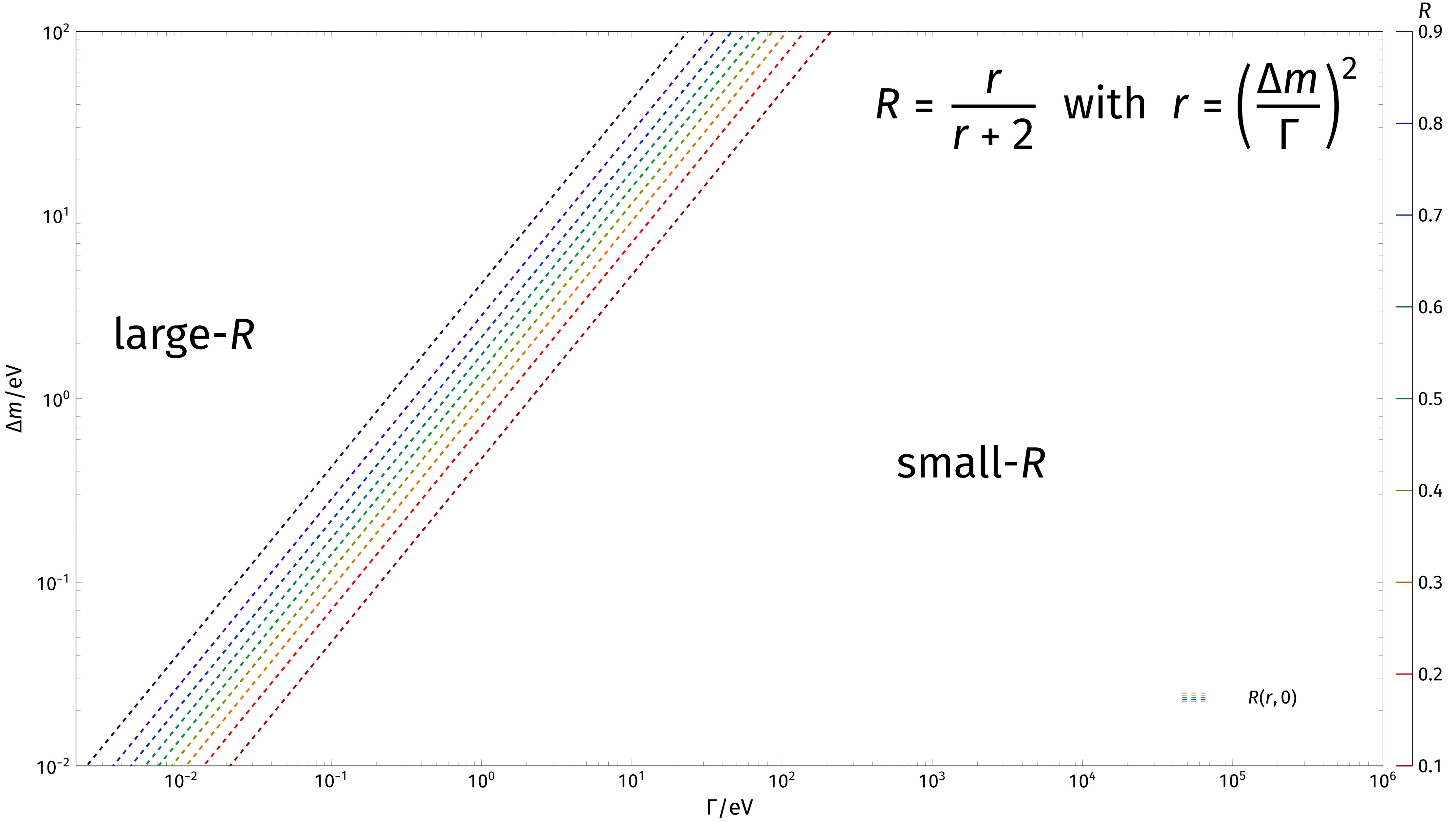


the decaying oscillations are governed by Δm and Γ

$$R \equiv \frac{N_{SS}}{N_{OS}} = \frac{r}{r+2} \to \begin{cases} \frac{r}{2} & \Delta m \ll \Gamma \\ 1 - \frac{2}{r} & \Delta m \gg \Gamma \end{cases} \qquad r \equiv \left(\frac{\Delta m}{\Gamma}\right)^2$$



$\Delta m/\mathrm{eV}$
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
Γ/eV
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
R
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1



$R = \frac{r}{r+2}$ with $r = \left(\frac{\Delta m}{\Gamma}\right)^2$
large-R
small-R
$R(r, 0)$
$\Delta m / \mathrm{eV}$
Γ / eV
R
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}

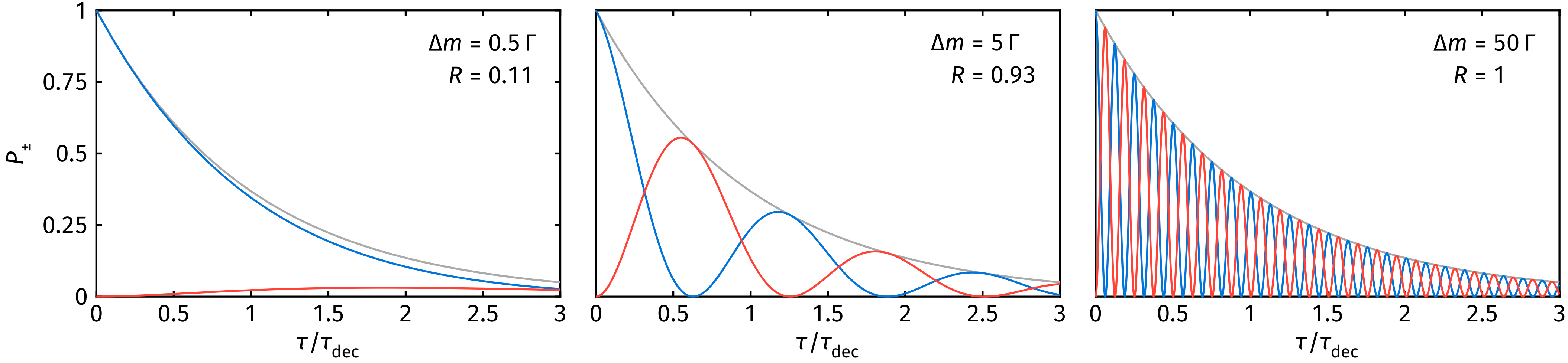
heavy neutrino-antineutrino oscillations

regime:	symmetric	symmetry-protected	no symmetry protection
HNL:	Dirac	pseudo-Dirac	double-Majorana
t-channel:		suppressed by $O(\Delta m/m)$	large at amplitude level

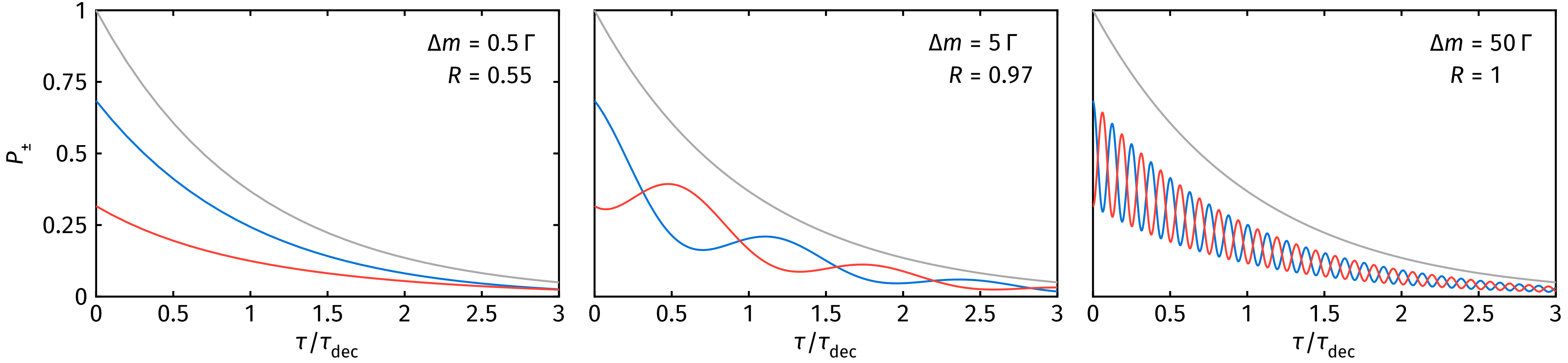
Δm: 0 — Γ — $O(m)$ →

s-channel:	small-R	large-R	large at amplitude level
	oscillation-enhanced		

heavy neutrino-antineutrino oscillations



heavy neutrino-antineutrino oscillations

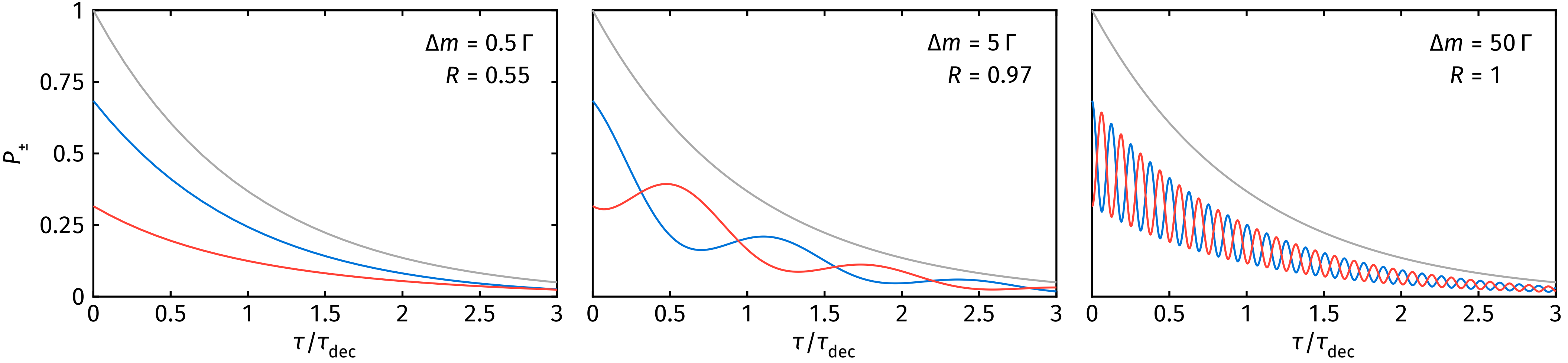


decoherence can damp quantum oscillations

$$P^{\pm}_{\mathrm{osc}}(\tau) = \frac{1 \pm e^{-\lambda}\cos(\Delta m \tau)}{2} \quad \text{where} \quad \lambda = \left(\frac{\Delta m}{\Delta m_\lambda}\right)^2$$

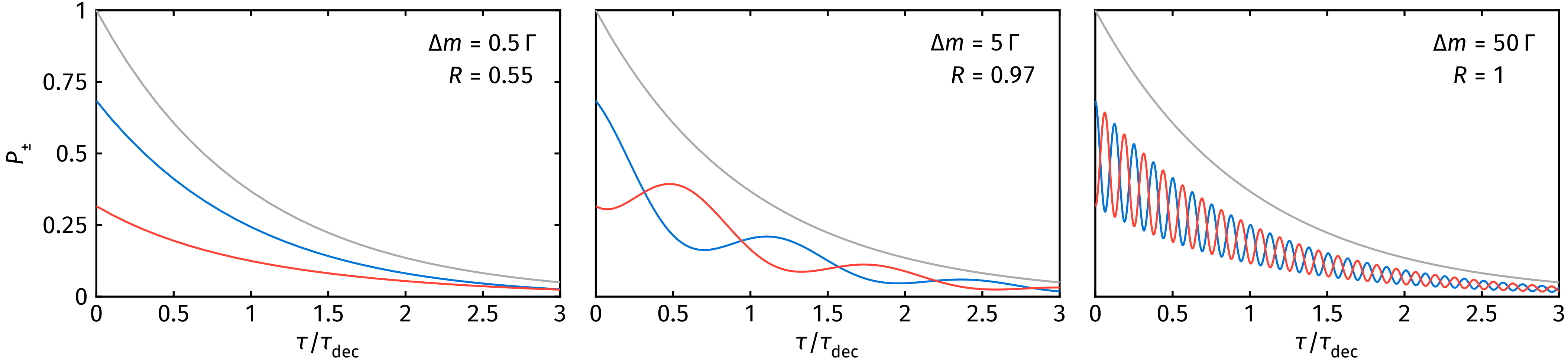
and $\Delta m_\lambda = \mathcal{O}(10\ \mathrm{eV})$

heavy neutrino-antineutrino oscillations



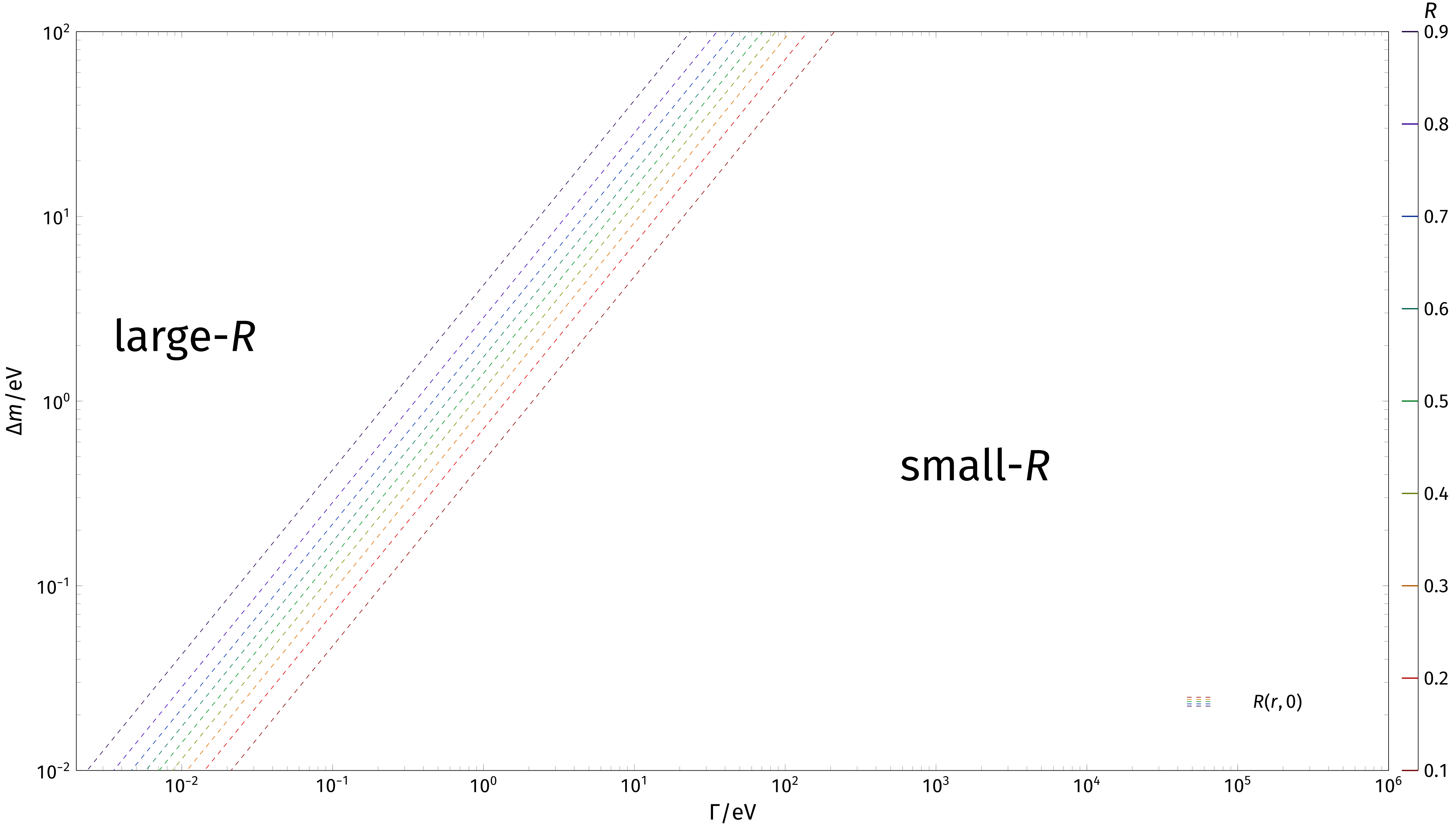
$$R(r,0) = \frac{r}{r+2} \qquad R(r,\lambda) = 1 - \frac{2}{1+(1+r)e^\lambda} \to \begin{cases} R(r,0) & \Delta m \ll \Delta m_\lambda \\ 1 & \Delta m \gg \Delta m_\lambda \end{cases}$$

heavy neutrino-antineutrino oscillations

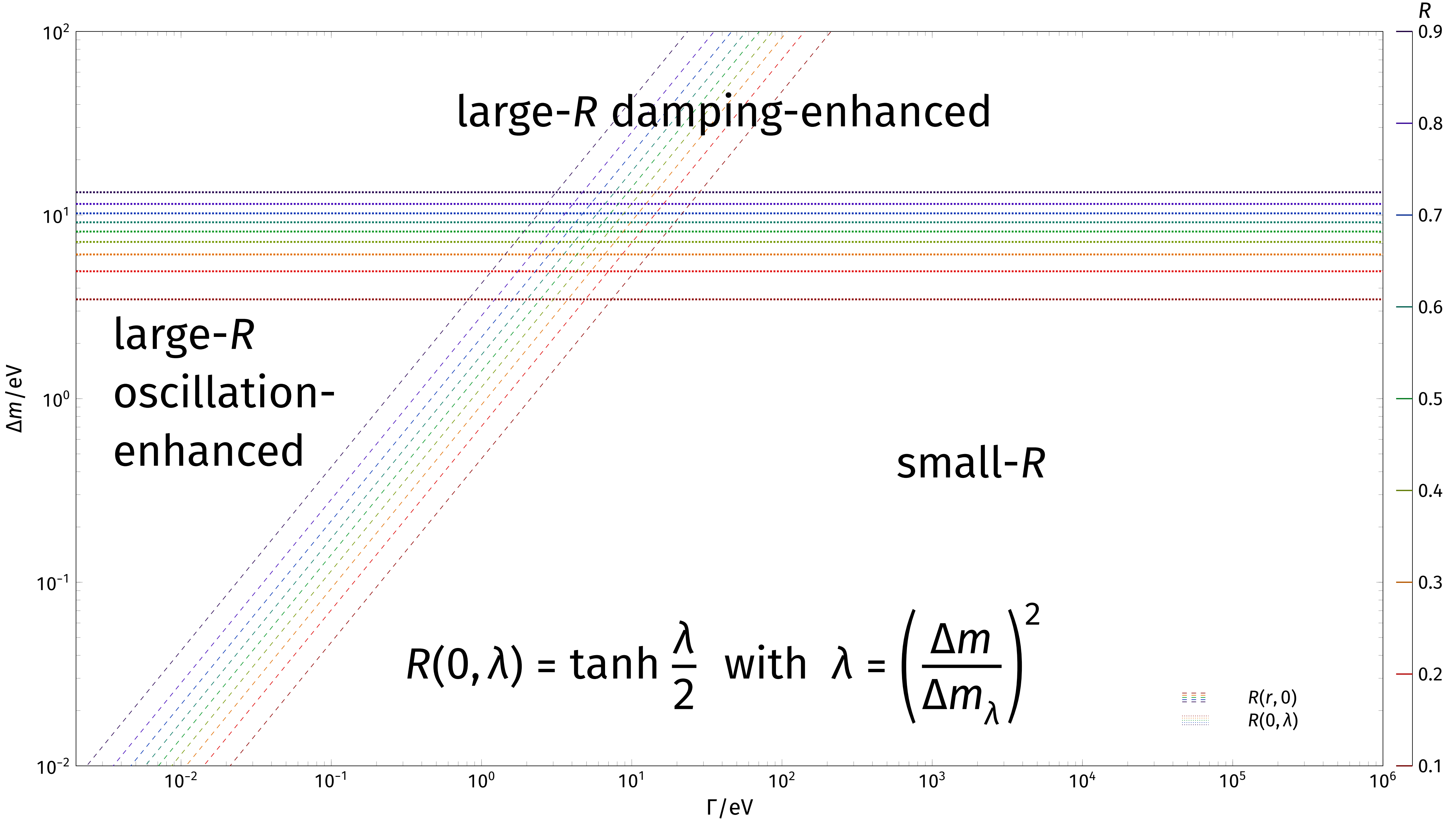


$$R(r,0) \to \begin{cases} \dfrac{r}{2} & \Delta m \ll \Gamma \\ 1 - \dfrac{2}{r} & \Delta m \gg \Gamma \end{cases} \qquad R(r,\lambda) \to \begin{cases} \tanh\dfrac{\lambda}{2} + \dfrac{r}{1+\cosh\lambda} & \Delta m \ll \Gamma \\ 1 \qquad\quad - \dfrac{2}{r} e^{-\lambda} & \Delta m \gg \Gamma \end{cases}$$

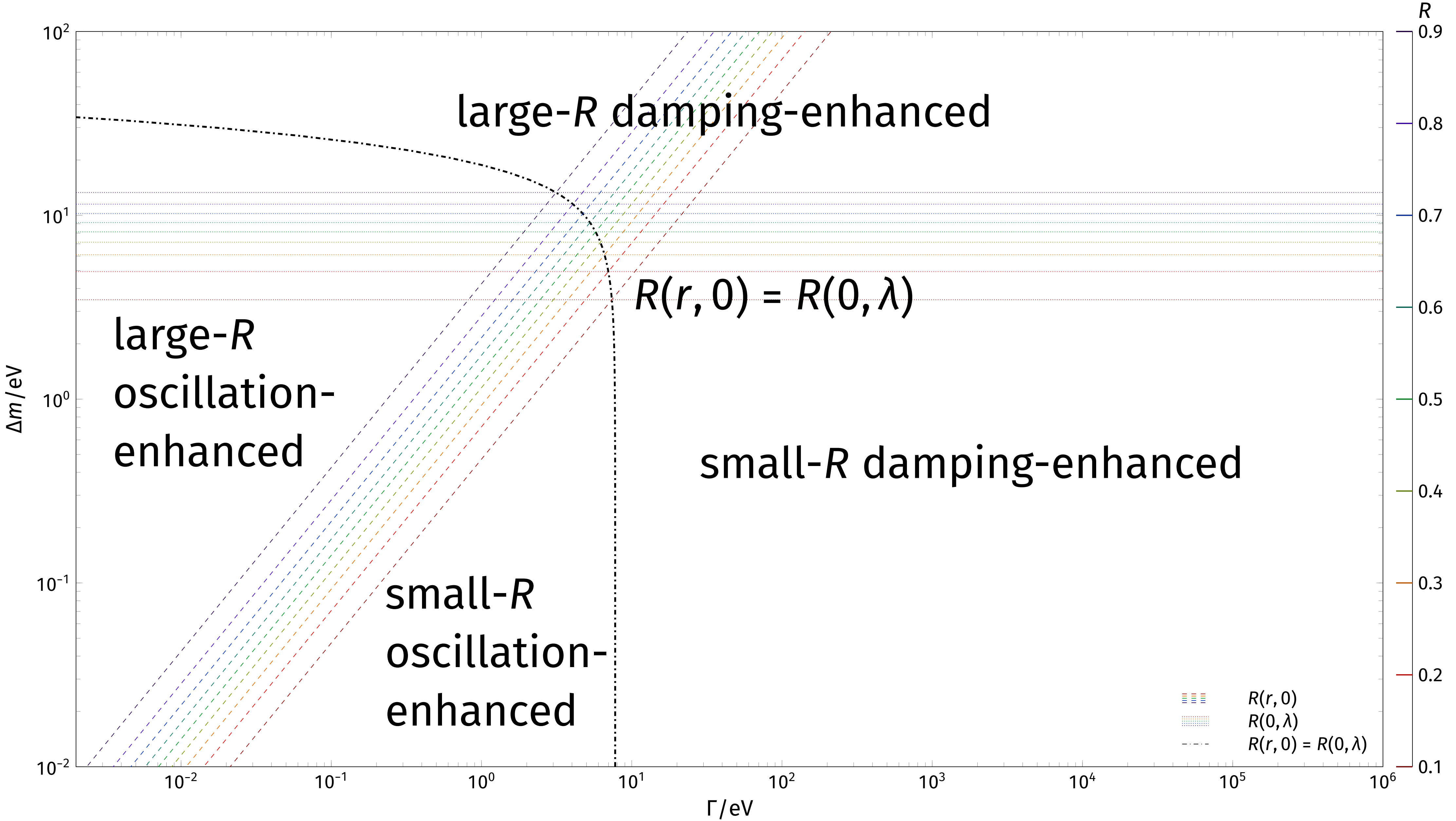
decoherence → ln violation floor at large Γ $\quad R(0,\lambda) = \tanh\dfrac{\lambda}{2}$



large-R
small-R
$R(r, 0)$
$\Delta m/\mathrm{eV}$
Γ/eV
R
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}



large-R damping-enhanced
large-R oscillation-enhanced
small-R
$R(0,\lambda) = \tanh\frac{\lambda}{2}$ with $\lambda = \left(\frac{\Delta m}{\Delta m_\lambda}\right)^2$
$R(r,0)$
$R(0,\lambda)$
$\Delta m/\mathrm{eV}$
Γ/eV
R
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9



large-R damping-enhanced
$R(r, 0) = R(0, \lambda)$
large-R oscillation-enhanced
small-R damping-enhanced
small-R oscillation-enhanced
$R(r, 0)$
$R(0, \lambda)$
$R(r, 0) = R(0, \lambda)$
Δm/eV
Γ/eV
R
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}

heavy neutrino-antineutrino oscillations

regime: symmetric symmetry-protected no symmetry protection

HNL: Dirac pseudo-Dirac double-Majorana

t-channel: suppressed by $O(\Delta m / m)$ large at amplitude level

Δm: 0 Γ Δm_λ $O(m)$

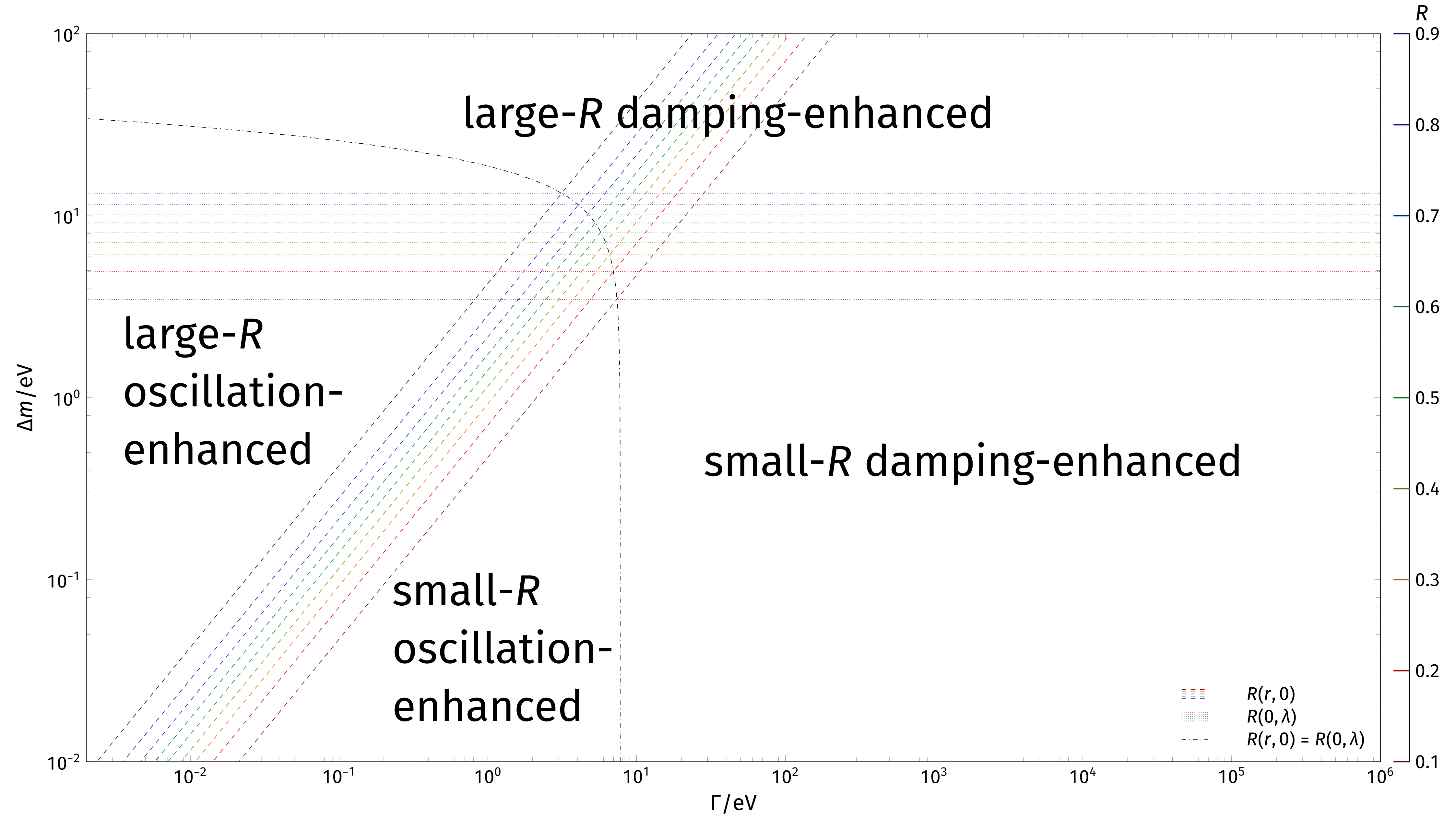
oscillation-dominated s-channel: small-R large-R damping-enhanced large at amplitude level

oscillation-enhanced

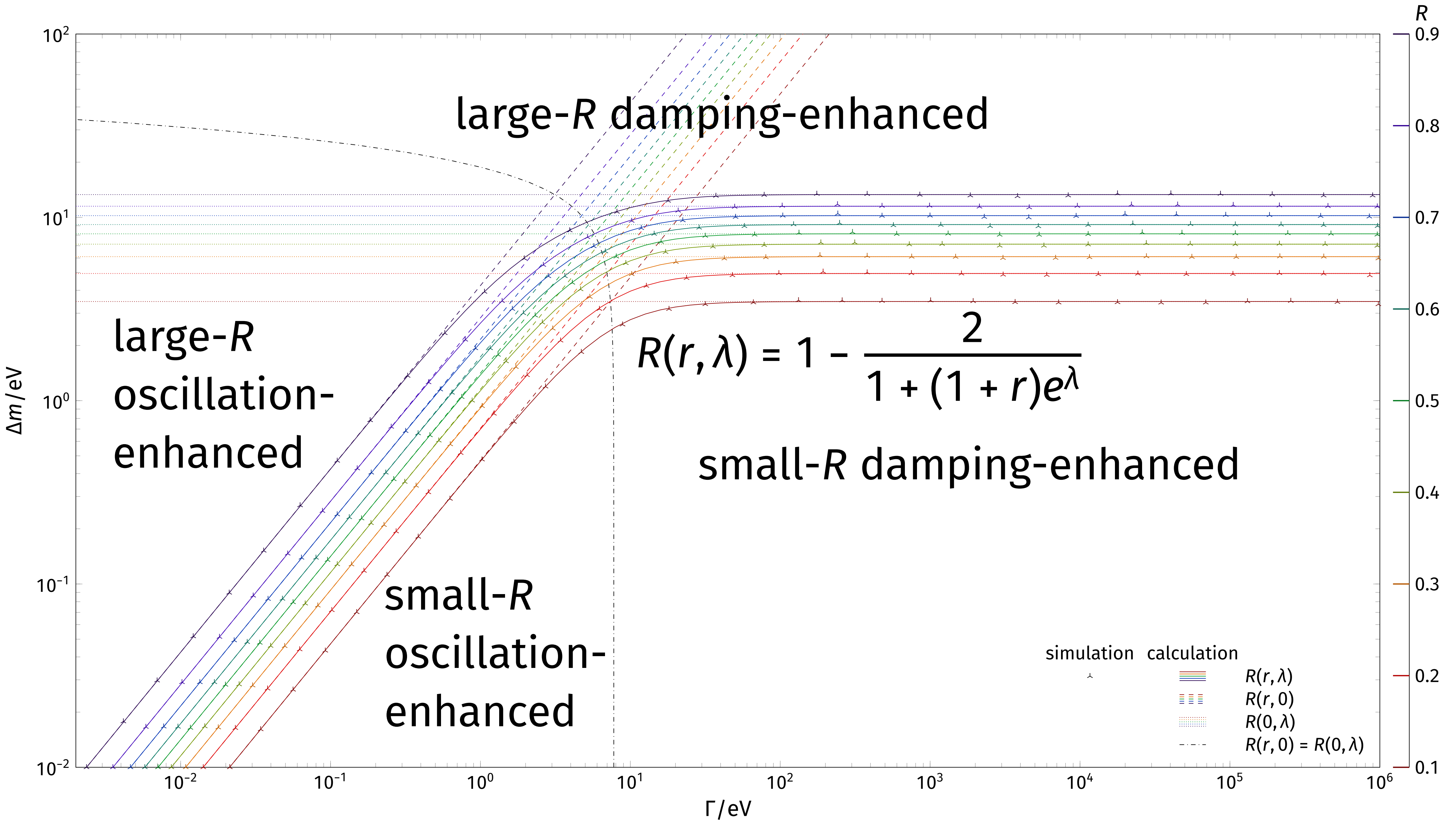
heavy neutrino-antineutrino oscillations

	0 – Γ	Γ – Δm_λ	Δm_λ – $O(m)$	$> O(m)$
regime:	symmetric	symmetry-protected	symmetry-protected	no symmetry protection
HNL:	Dirac	pseudo-Dirac	pseudo-Dirac	double-Majorana
t-channel:	suppressed by $O(\Delta m/m)$	suppressed by $O(\Delta m/m)$	suppressed by $O(\Delta m/m)$	large at amplitude level
oscillation-dominated s-channel:	small-R, oscillation-enhanced	large-R, oscillation-enhanced	damping-enhanced	large at amplitude level
damping-dominated s-channel:	small-R, damping-enhanced	small-R, damping-enhanced	large-R, damping-enhanced	large at amplitude level

Δm: 0 — Γ — Δm_λ — $O(m)$ →



large-R damping-enhanced
large-R oscillation-enhanced
small-R damping-enhanced
small-R oscillation-enhanced
$\Delta m/\mathrm{eV}$
Γ/eV
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
R
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
$R(r,0)$
$R(0,\lambda)$
$R(r,0) = R(0,\lambda)$



large-R damping-enhanced
large-R oscillation-enhanced
small-R oscillation-enhanced
small-R damping-enhanced
$R(r,\lambda) = 1 - \frac{2}{1+(1+r)e^{\lambda}}$
simulation
calculation
$R(r,\lambda)$
$R(r,0)$
$R(0,\lambda)$
$R(r,0) = R(0,\lambda)$
$\Delta m/\mathrm{eV}$
Γ/eV
R

back to colliders!

sensitivity to pseudo-Dirac hnls

collider-accessible = symmetry-protected

↓

pseudo-Dirac hnls

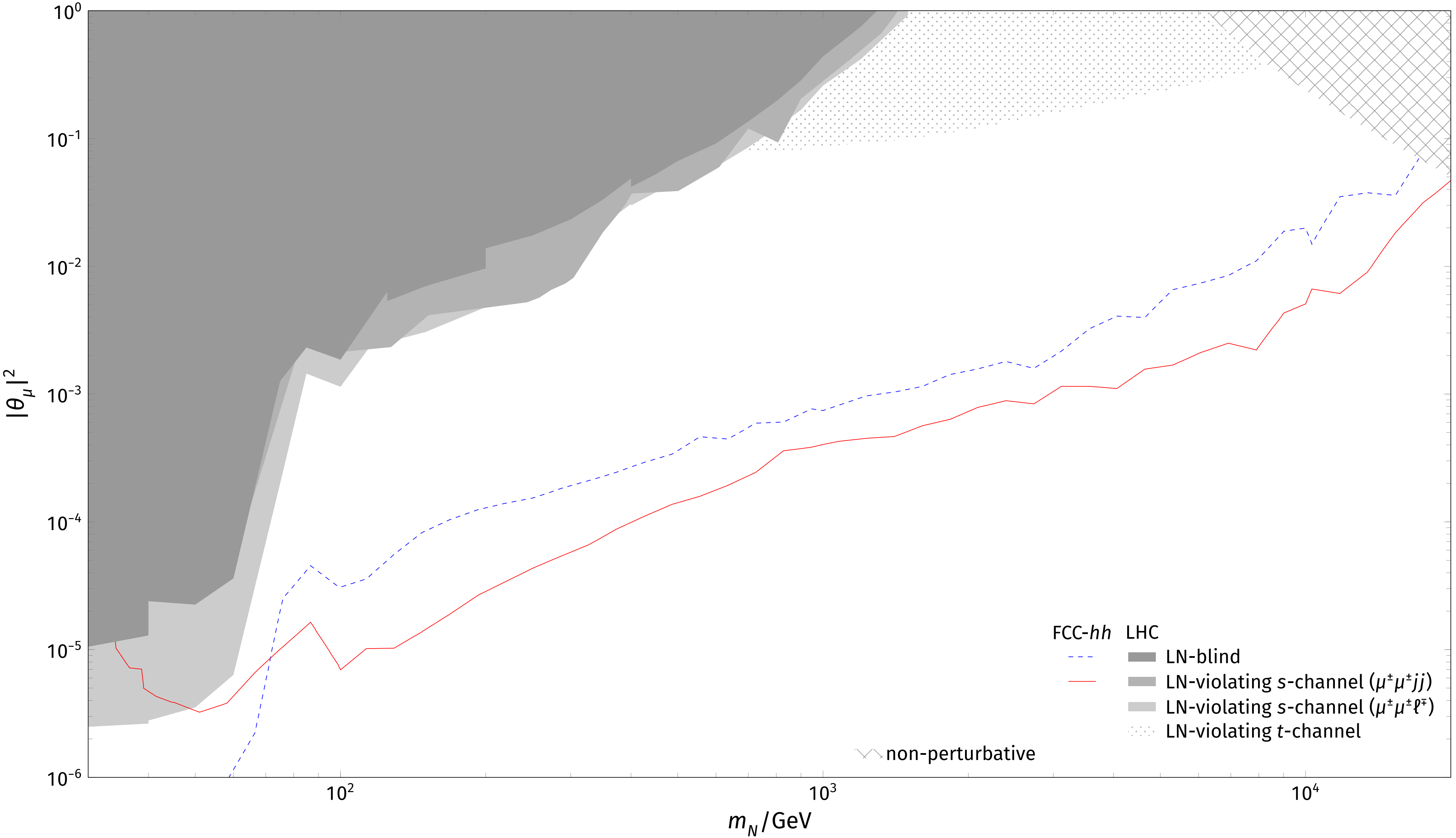
↓

damped oscillations

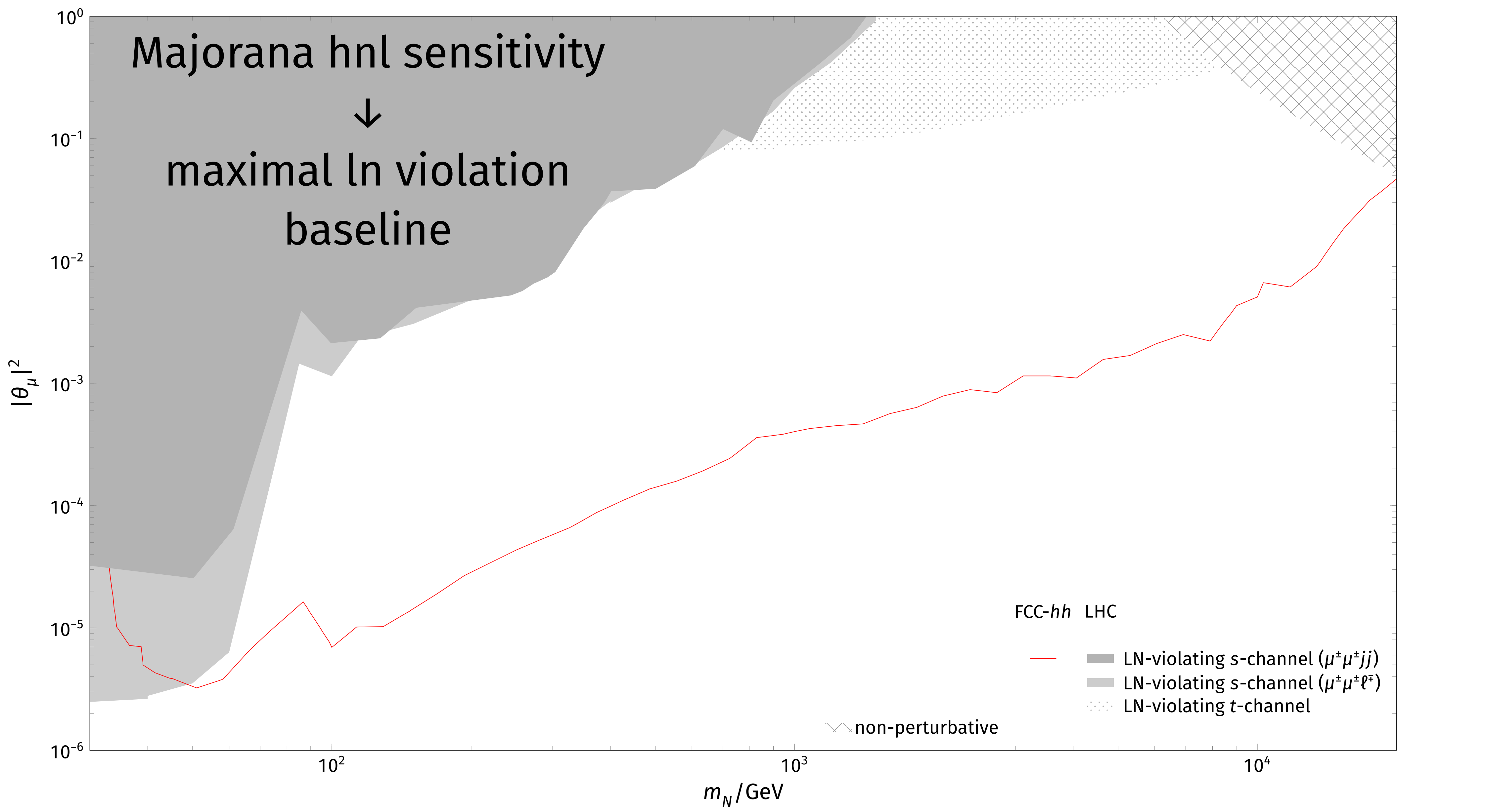
↓

ln violation interpolates between Dirac and Majorana limits

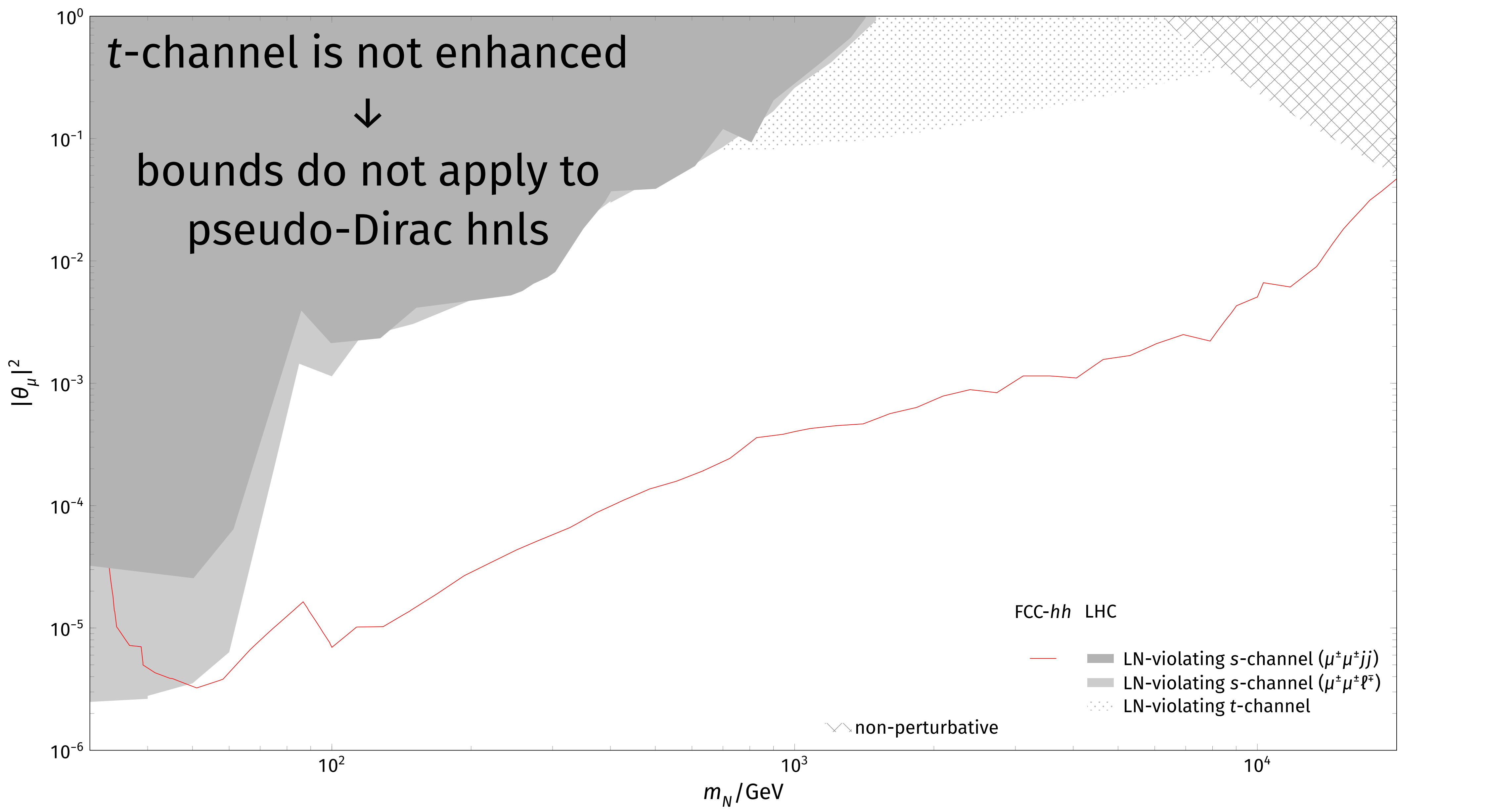
$$\zeta_{\text{os}/\text{ss}}(R) \equiv \frac{\sigma(R)}{\sigma(R=1)} = 1 \pm \frac{1}{1+r} e^{-\lambda} \to \begin{cases} 1 \pm e^{-\lambda} & \Delta m \ll \Gamma \\ 1 & \Delta m \gg \Gamma \end{cases}$$



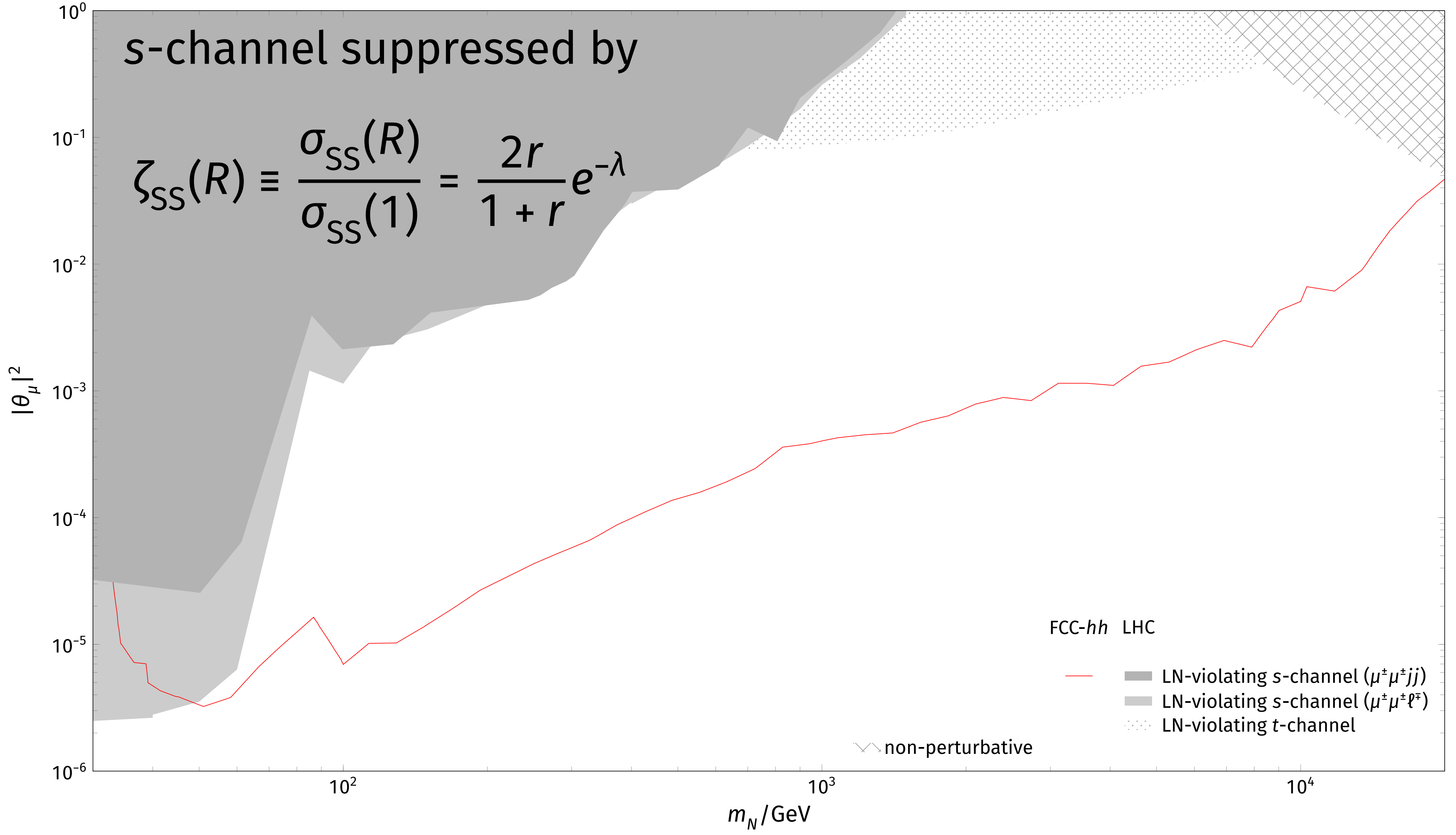
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$|\theta_\mu|^2$
10^{2}
10^{3}
10^{4}
m_N/GeV
FCC-*hh* LHC
LN-blind
LN-violating *s*-channel ($\mu^\pm\mu^\pm jj$)
LN-violating *s*-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating *t*-channel
non-perturbative



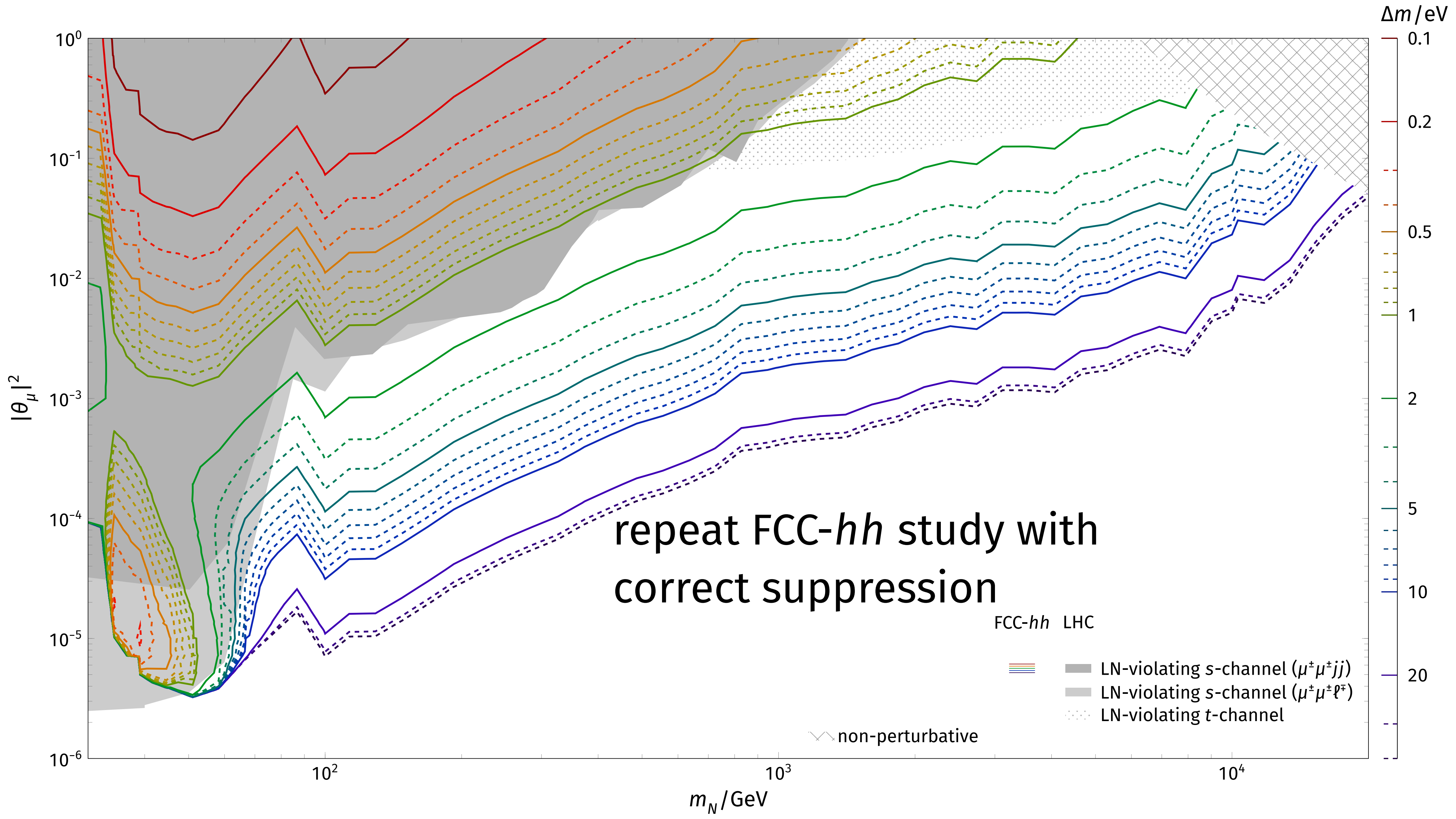
Majorana hnl sensitivity
↓
maximal ln violation
baseline
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$|\theta_\mu|^2$
10^2
10^3
10^4
m_N/GeV
FCC-hh LHC
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
LN-violating s-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating t-channel
non-perturbative



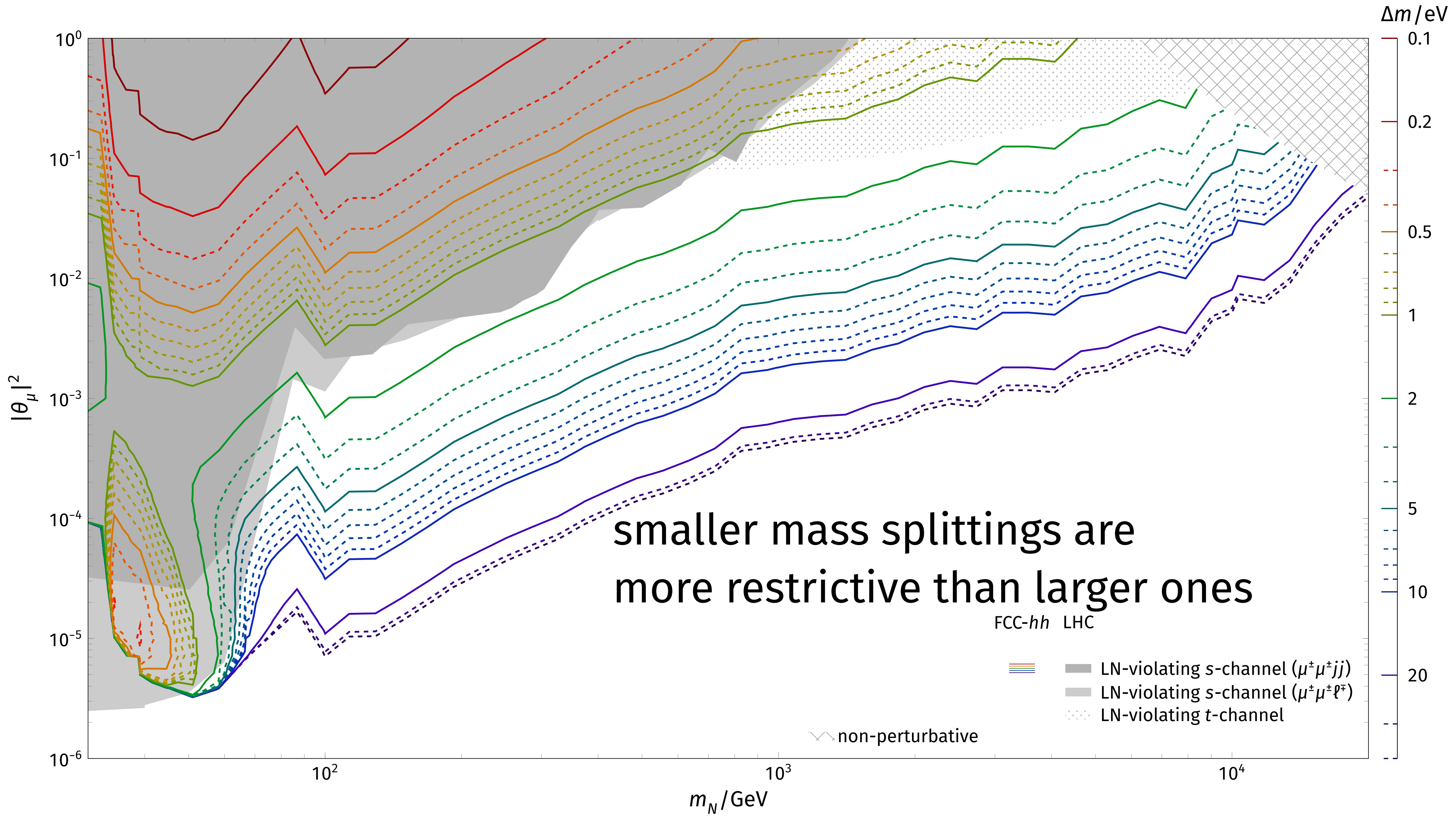
t-channel is not enhanced
↓
bounds do not apply to
pseudo-Dirac hnls
$|\theta_\mu|^2$
m_N/GeV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
FCC-hh LHC
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
LN-violating s-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating t-channel
non-perturbative



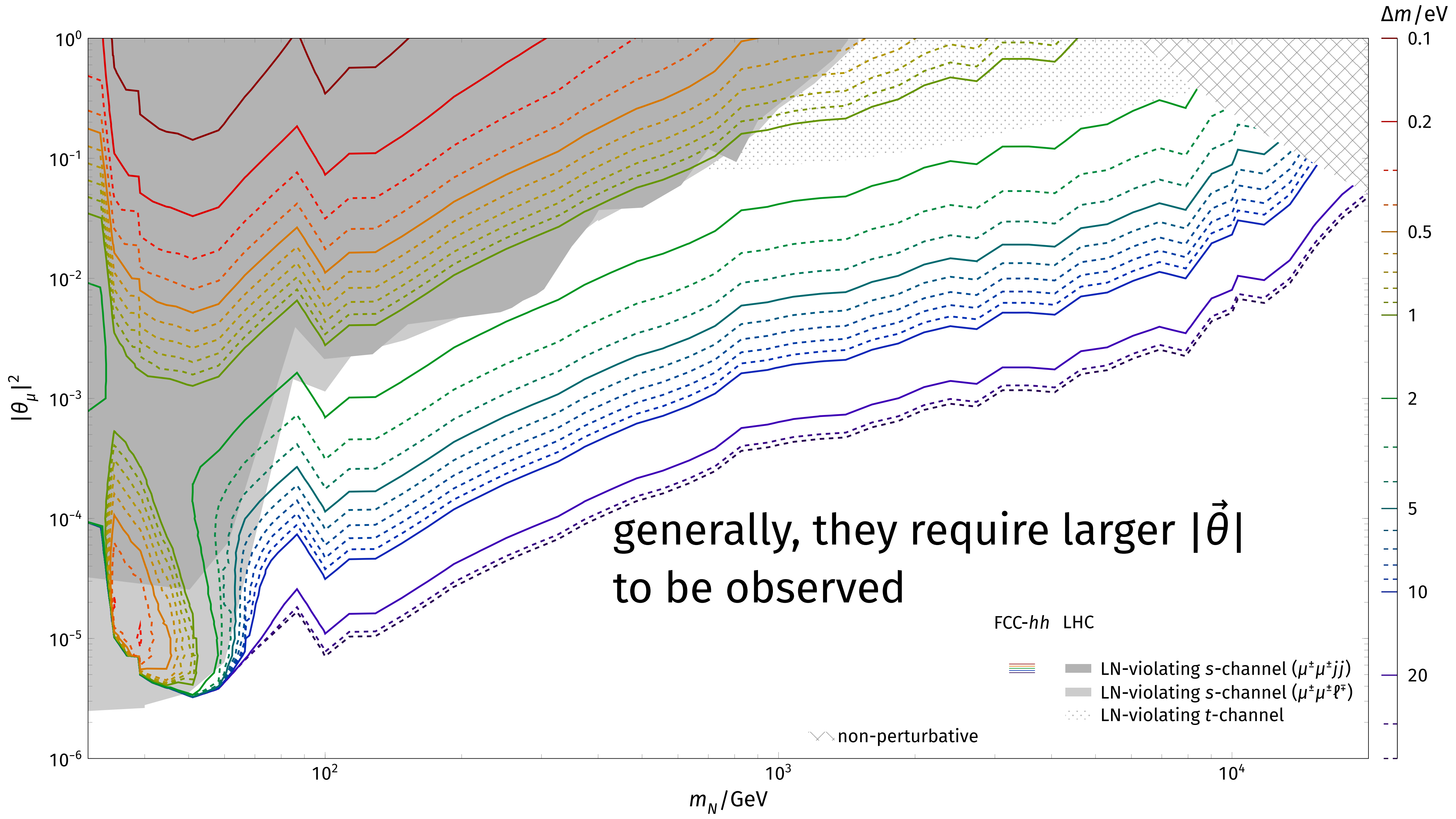
s-channel suppressed by
$\zeta_{SS}(R) \equiv \frac{\sigma_{SS}(R)}{\sigma_{SS}(1)} = \frac{2r}{1+r} e^{-\lambda}$
$|\theta_\mu|^2$
m_N/GeV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
FCC-hh LHC
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
LN-violating s-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating t-channel
non-perturbative



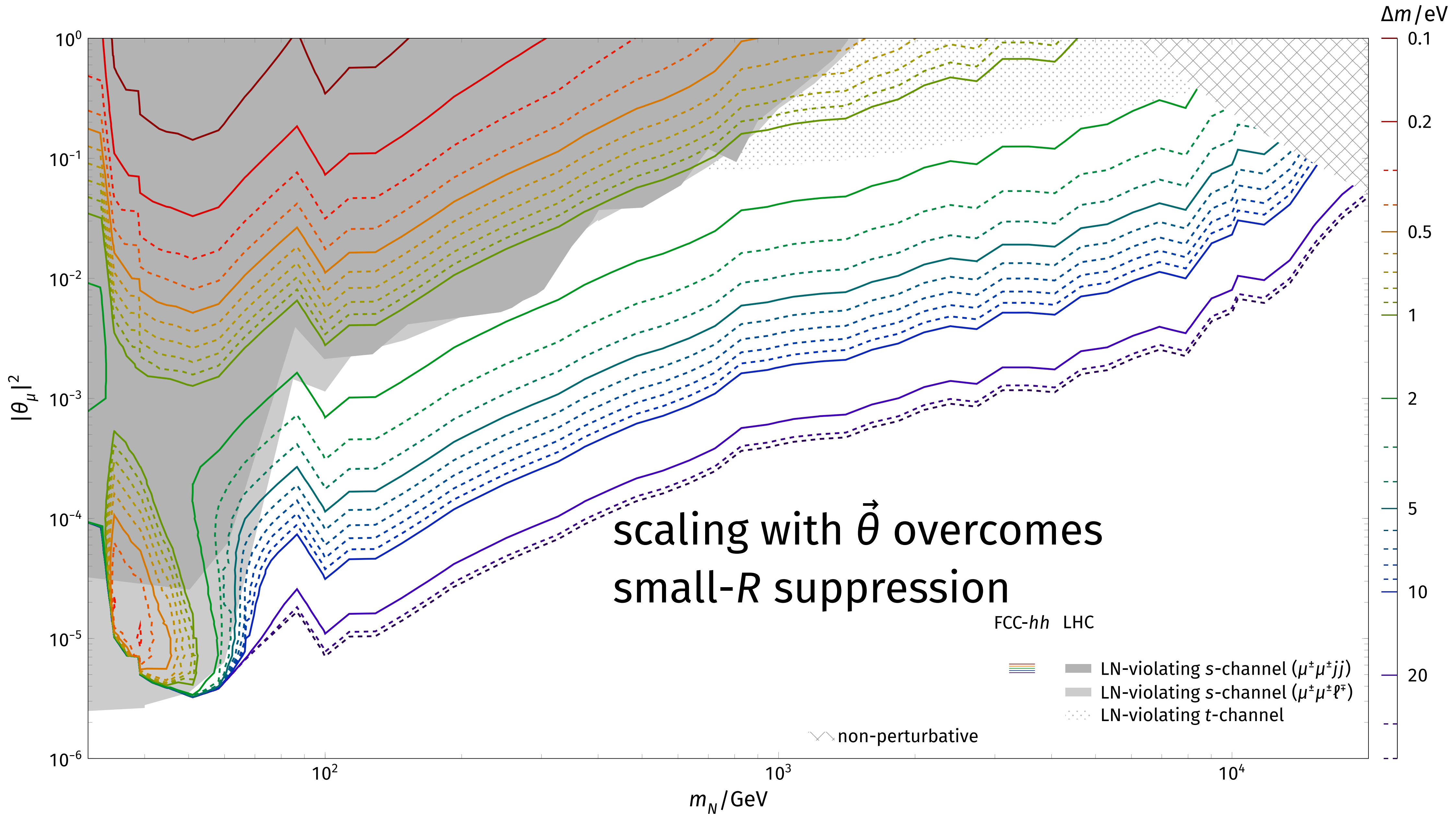
repeat FCC-*hh* study with correct suppression
$|\theta_\mu|^2$
m_N/GeV
Δm/eV
0.1
0.2
0.5
1
2
5
10
20
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
FCC-*hh* LHC
LN-violating *s*-channel ($\mu^\pm\mu^\pm jj$)
LN-violating *s*-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating *t*-channel
non-perturbative



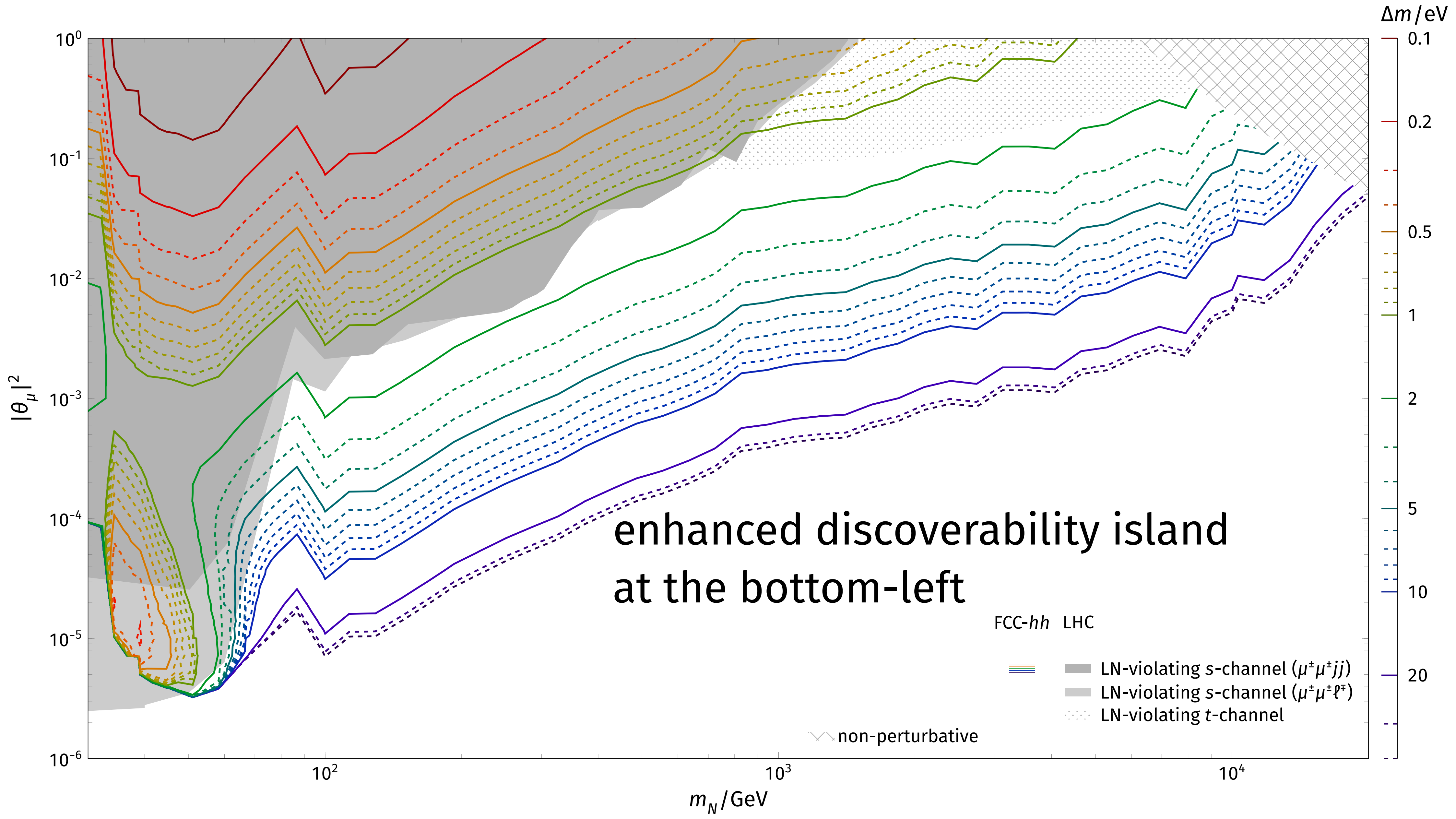
smaller mass splittings are
more restrictive than larger ones
$|\theta_\mu|^2$
m_N/GeV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
Δm/eV
0.1
0.2
0.5
1
2
5
10
20
FCC-hh LHC
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
LN-violating s-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating t-channel
non-perturbative



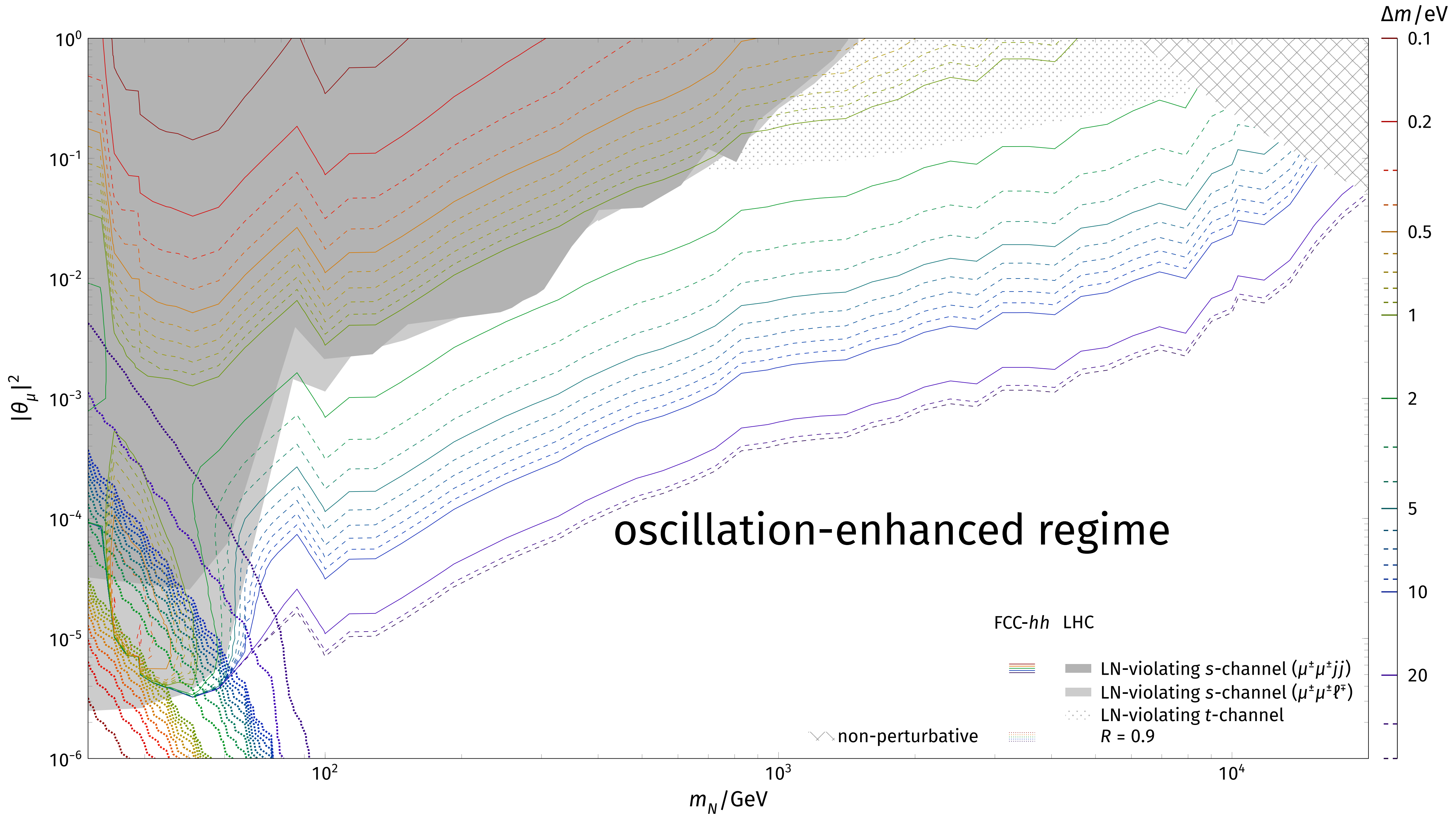
generally, they require larger $|\vec{\theta}|$ to be observed
$|\theta_\mu|^2$
m_N/GeV
Δm/eV
0.1
0.2
0.5
1
2
5
10
20
FCC-*hh* LHC
LN-violating *s*-channel ($\mu^\pm\mu^\pm jj$)
LN-violating *s*-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating *t*-channel
non-perturbative



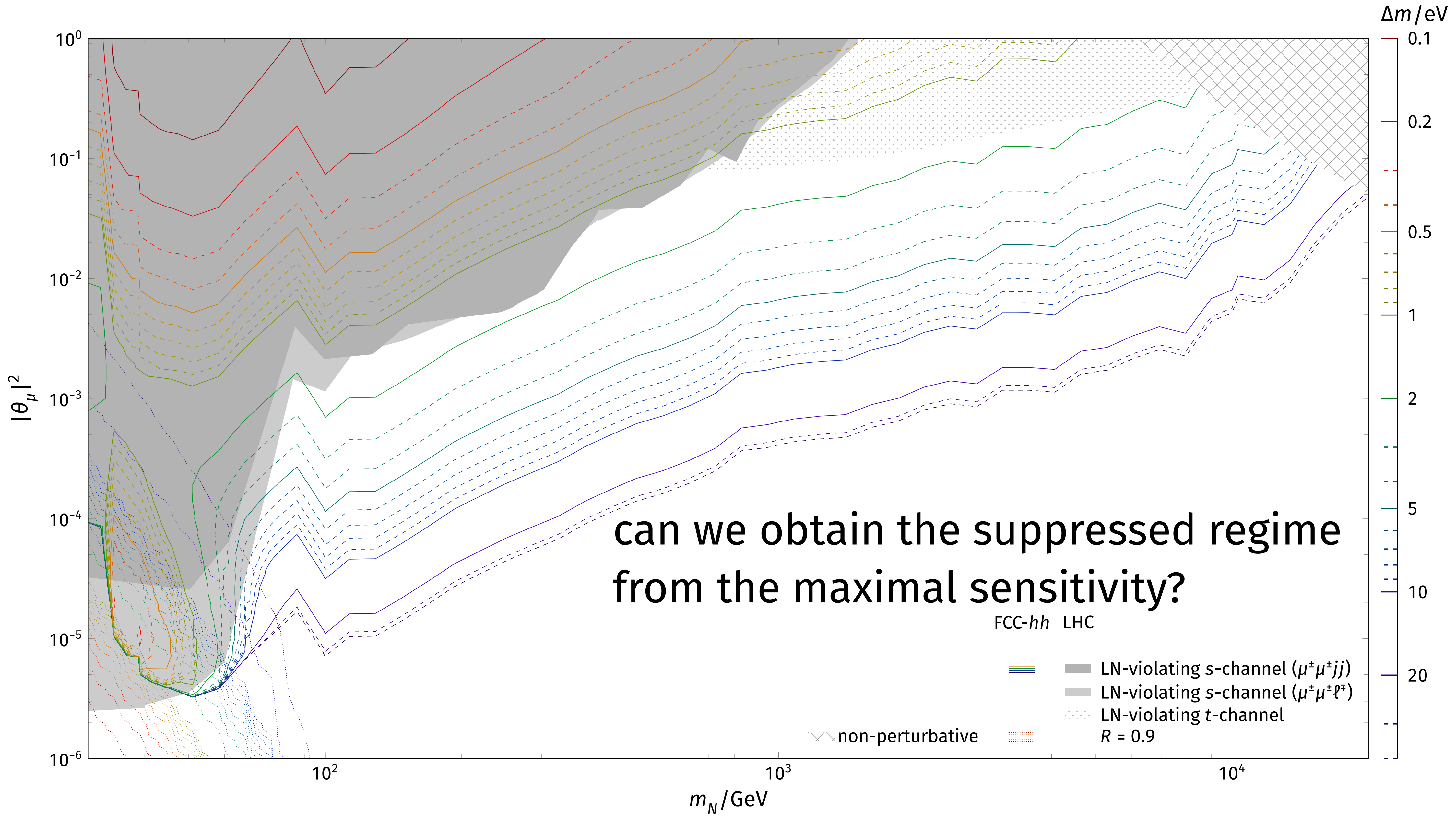
Δm/eV
0.1
0.2
0.5
1
2
5
10
20
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$|\theta_\mu|^2$
10^2
10^3
10^4
m_N/GeV
scaling with $\vec{\theta}$ overcomes small-R suppression
FCC-hh LHC
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
LN-violating s-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating t-channel
non-perturbative



Δm / eV
0.1
0.2
0.5
1
2
5
10
20
$|\theta_\mu|^2$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
m_N / GeV
enhanced discoverability island
at the bottom-left
FCC-hh LHC
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
LN-violating s-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating t-channel
non-perturbative



Δm / eV
0.1
0.2
0.5
1
2
5
10
20
$|\theta_\mu|^2$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
m_N / GeV
oscillation-enhanced regime
FCC-hh LHC
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
LN-violating s-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating t-channel
non-perturbative
R = 0.9



can we obtain the suppressed regime from the maximal sensitivity?

reinterpreting existing bounds

exclusion of ln-violation

$$Z \approx \frac{s(m_N, \vec{\theta}, R)}{\sqrt{b}} > 2\sigma \to \vec{\theta}(m_N, R)$$

typically, we are provided with

$$\vec{\theta}_0(m_N) \equiv \vec{\theta}(m_N, R = 1)$$

reinterpreting existing bounds

exclusion of ln-violation

$$Z \approx \frac{s(m_N, \vec{\theta}, R)}{\sqrt{b}} > 2\sigma \to \vec{\theta}(m_N, R)$$

typically, we are provided with

$$\vec{\theta}_0(m_N) \equiv \vec{\theta}(m_N, R = 1)$$

solve for $\vec{\theta}$

$$s(m_N, \vec{\theta}, R) = s(m_N, \vec{\theta}_0, 1)$$

$$\zeta_{SS(R)} = \frac{s(m_N, \vec{\theta}, R)}{s(m_N, \vec{\theta}, 1)} = \frac{2r}{1+r} e^{-\lambda}$$

reinterpreting existing bounds

exclusion of ln-violation

$$Z \approx \frac{s(m_N, \vec{\theta}, R)}{\sqrt{b}} > 2\sigma \rightarrow \vec{\theta}(m_N, R)$$

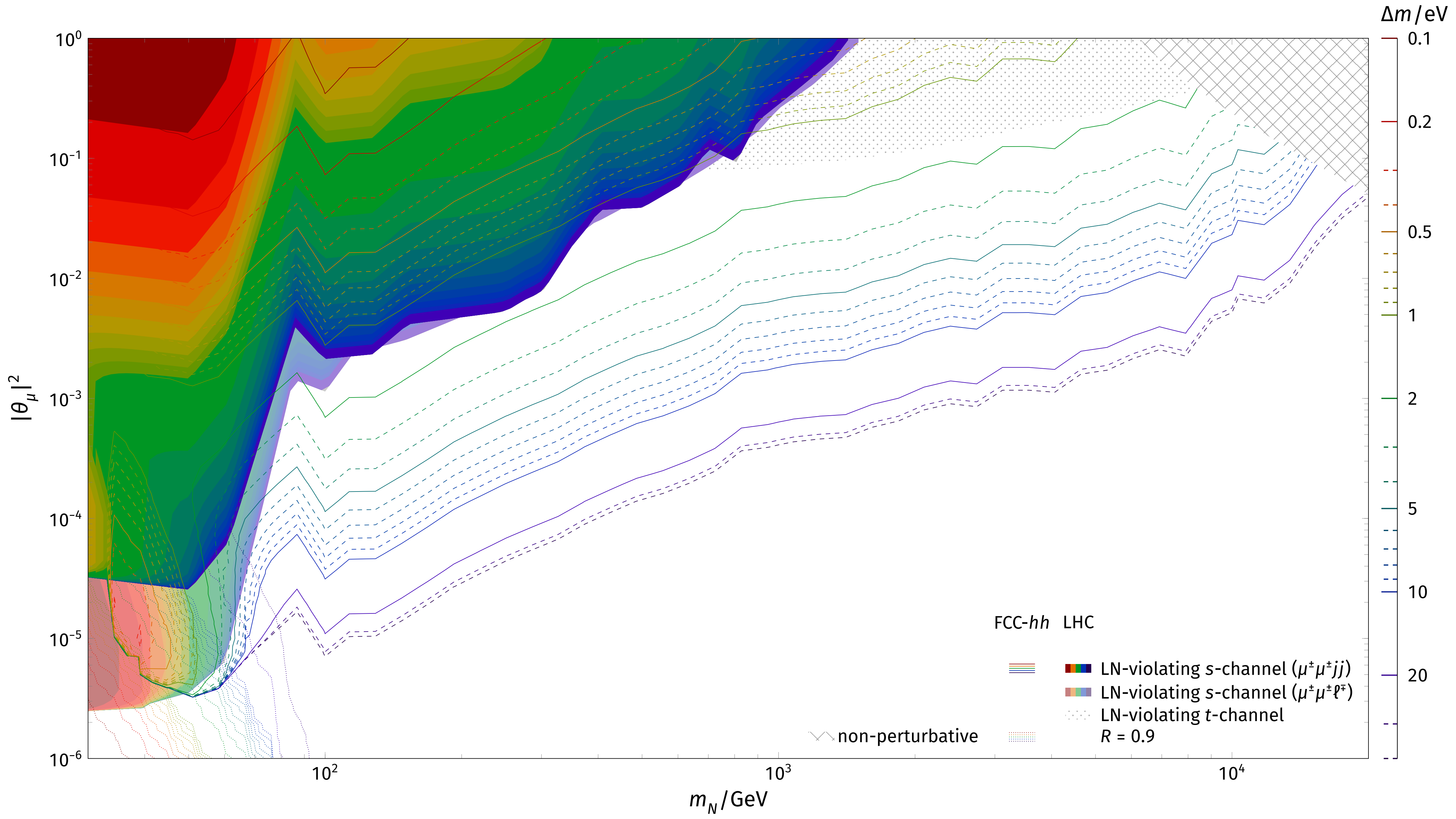
typically, we are provided with

$$\vec{\theta}_0(m_N) \equiv \vec{\theta}(m_N, R = 1)$$

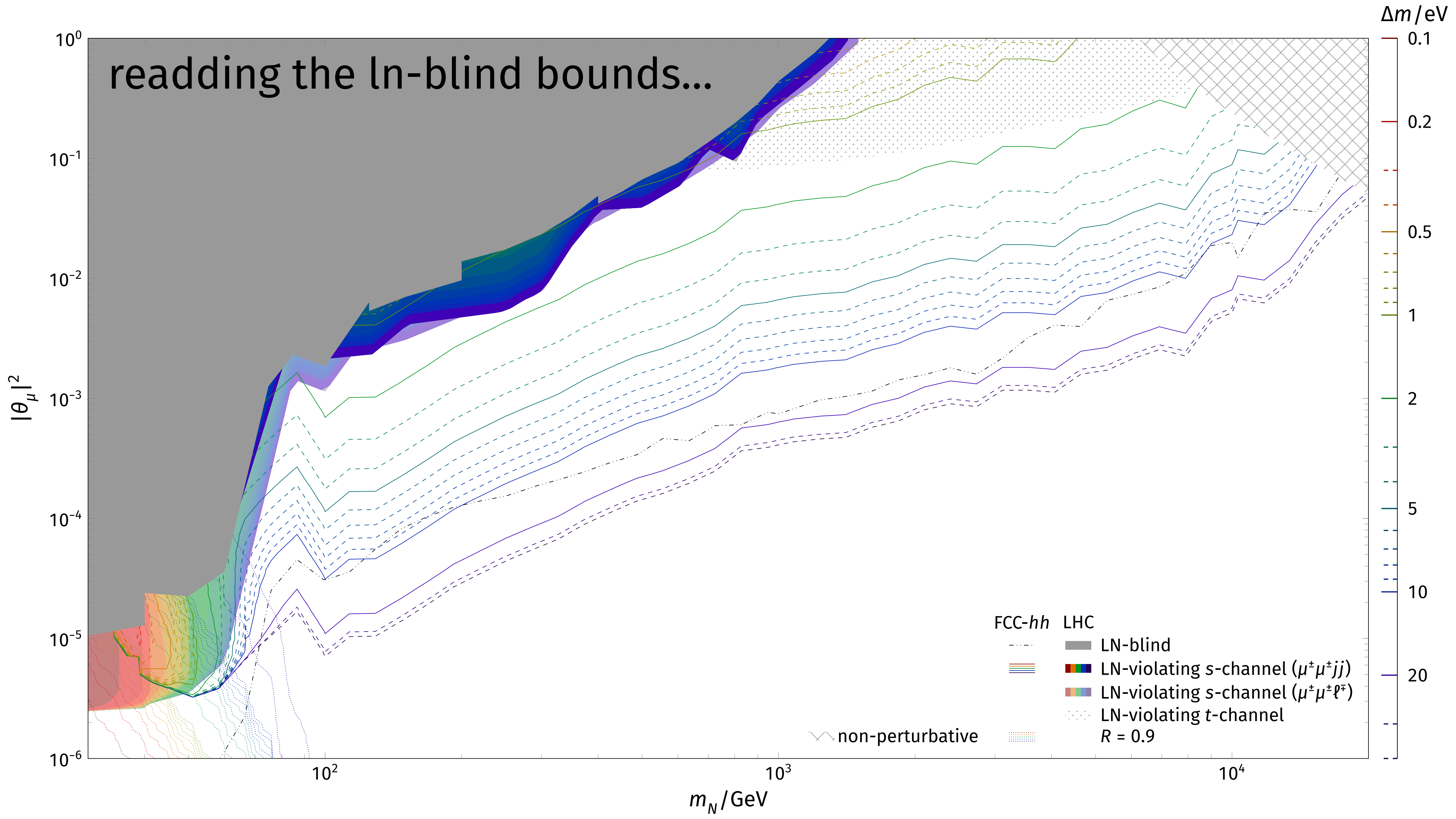
solve for $\vec{\theta}$

$$s(m_N, \vec{\theta}, R) = s(m_N, \vec{\theta}_0, 1) \qquad \zeta_{SS(R)} = \frac{s(m_N, \vec{\theta}, R)}{s(m_N, \vec{\theta}, 1)} = \frac{2r}{1+r} e^{-\lambda}$$

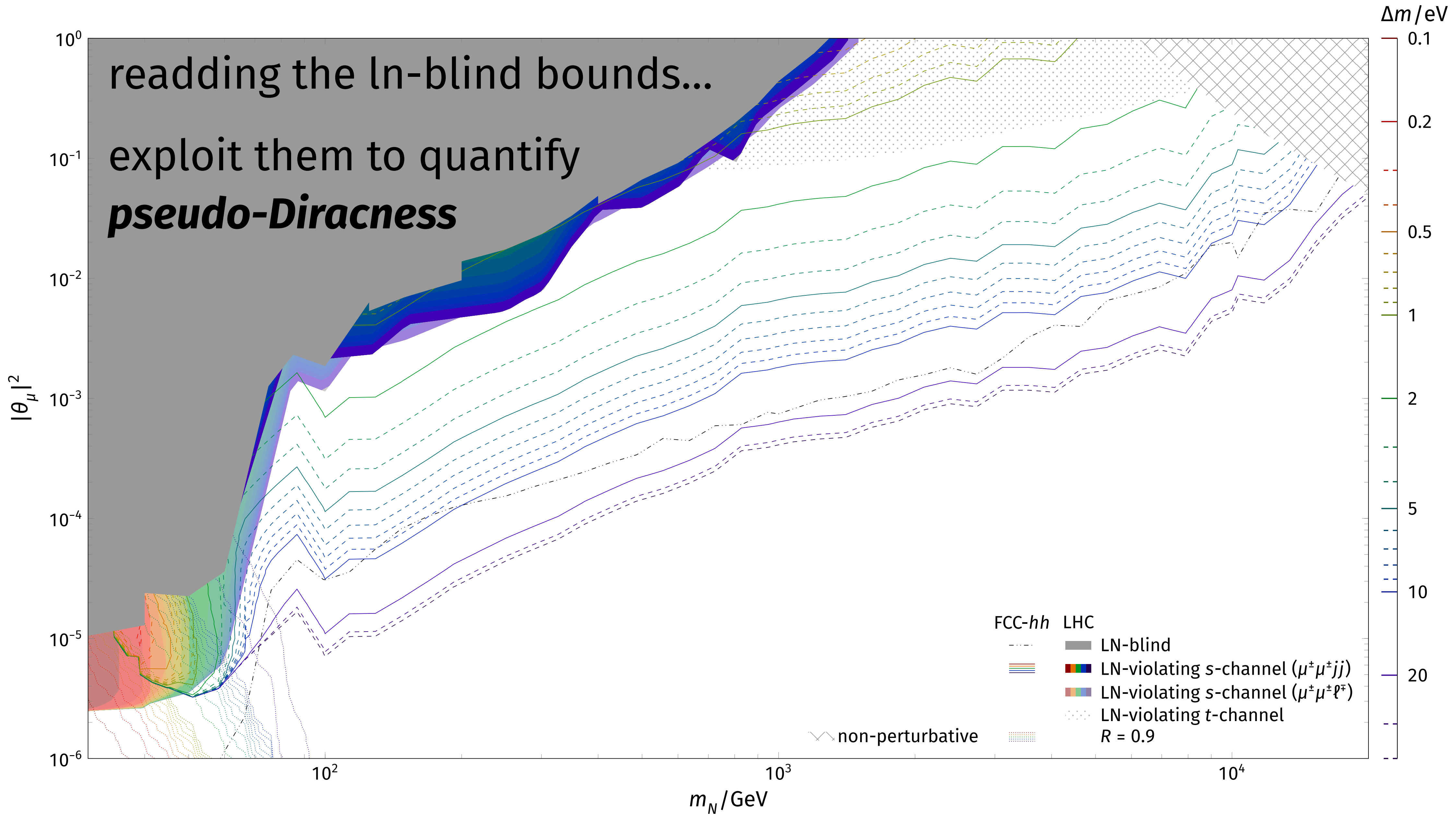
$$\left.\begin{array}{rl} \text{small-coupling} & |\vec{\theta}|^2 \ll 1 \\ \text{damping-enhanced} & \Gamma \gtrsim \Delta m_\lambda \end{array}\right\} \rightarrow |\vec{\theta}|^2 = \frac{|\vec{\theta}_0|^2}{1 - e^{-\lambda}}$$

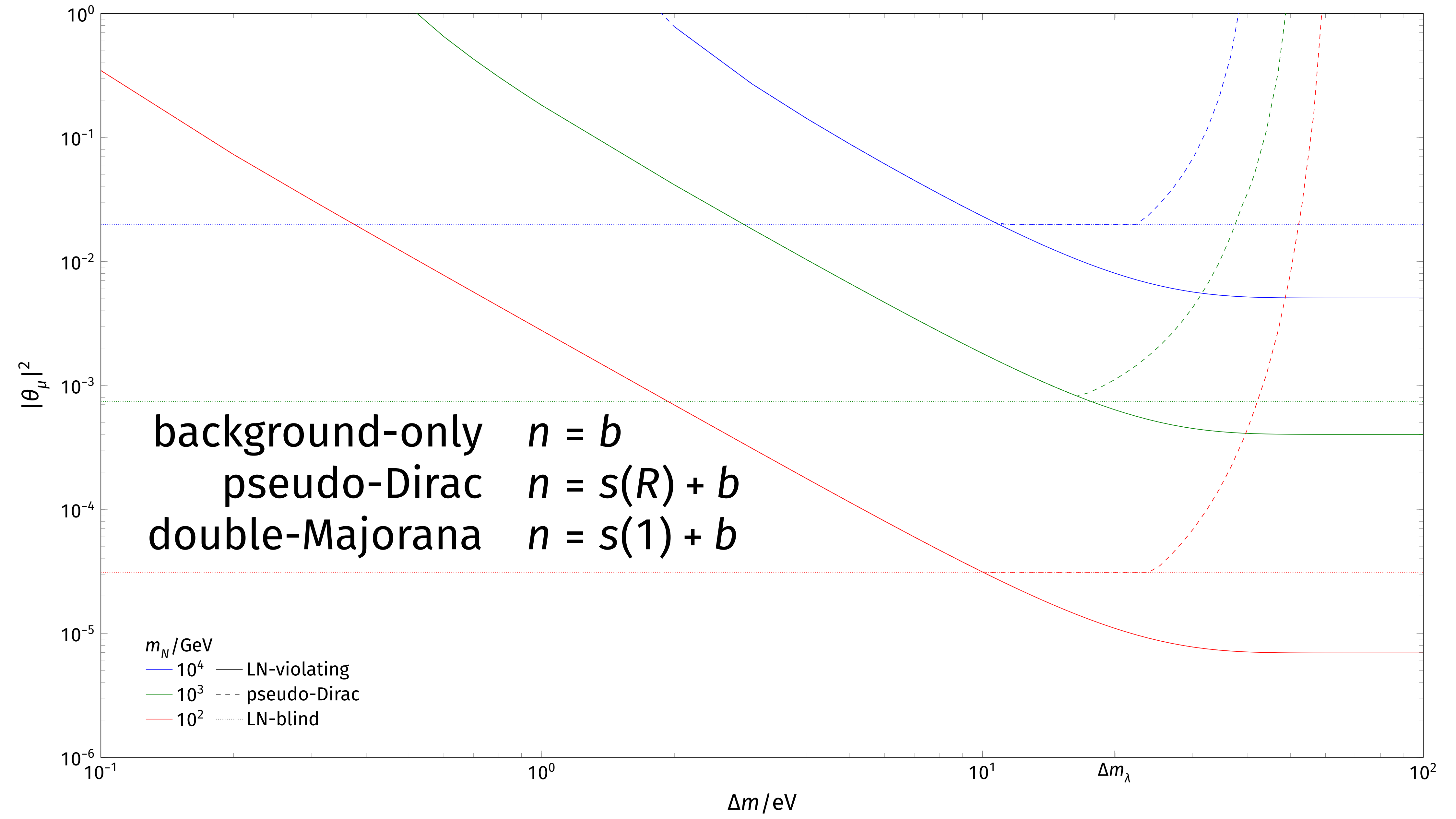


Δm / eV
0.1
0.2
0.5
1
2
5
10
20
$|\theta_\mu|^2$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
m_N / GeV
FCC-*hh* LHC
LN-violating *s*-channel ($\mu^\pm\mu^\pm jj$)
LN-violating *s*-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating *t*-channel
non-perturbative
$R = 0.9$

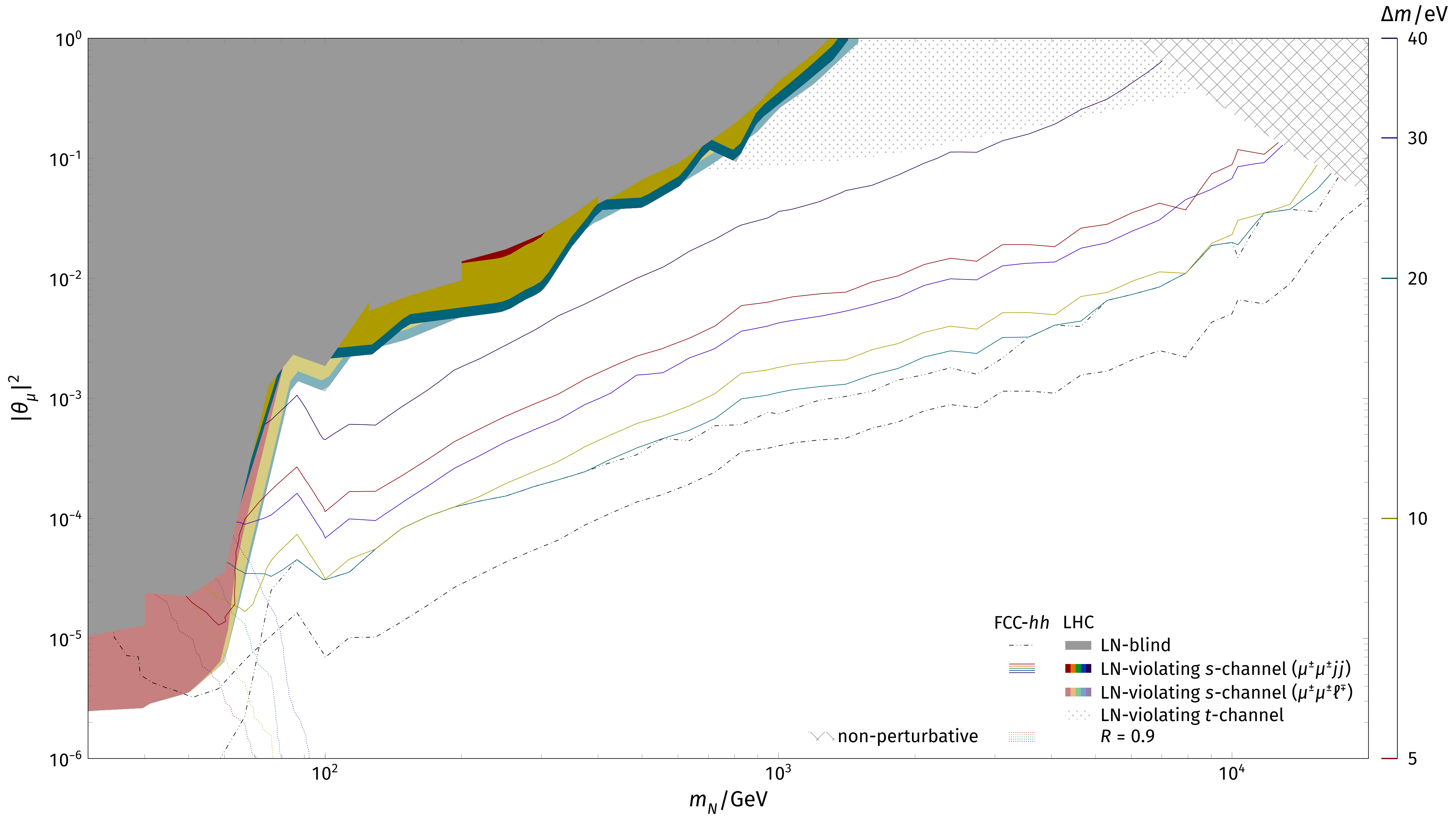


readding the ln-blind bounds...
$|\theta_\mu|^2$
m_N/GeV
Δm/eV
0.1
0.2
0.5
1
2
5
10
20
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
FCC-*hh*
LHC
LN-blind
LN-violating *s*-channel ($\mu^\pm\mu^\pm jj$)
LN-violating *s*-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating *t*-channel
non-perturbative
R = 0.9


readding the ln-blind bounds...
exploit them to quantify
pseudo-Diracness
$|\theta_\mu|^2$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
m_N/GeV
10^2
10^3
10^4
Δm/eV
0.1
0.2
0.5
1
2
5
10
20
FCC-*hh*
LHC
LN-blind
LN-violating *s*-channel ($\mu^\pm\mu^\pm jj$)
LN-violating *s*-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating *t*-channel
R = 0.9
non-perturbative

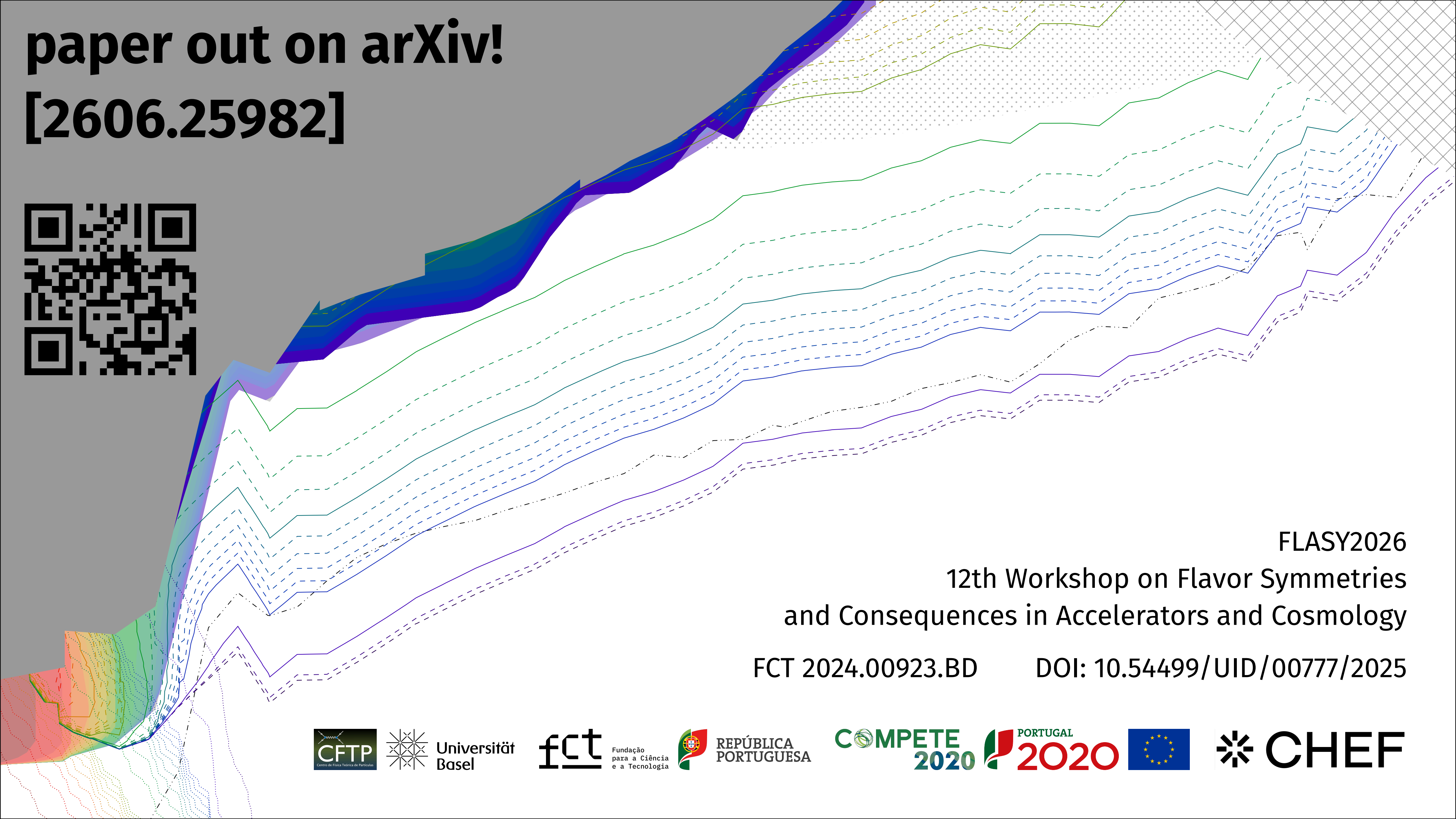


$|\theta_\mu|^2$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-1}
10^0
10^1
Δm_λ
10^2
$\Delta m\,/\,\mathrm{eV}$
background-only $n = b$
pseudo-Dirac $n = s(R) + b$
double-Majorana $n = s(1) + b$
$m_N\,/\,\mathrm{GeV}$
10^4 LN-violating
10^3 pseudo-Dirac
10^2 LN-blind



$\Delta m/\mathrm{eV}$
40
30
20
10
5
$|\theta_\mu|^2$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
m_N/GeV
FCC-*hh* LHC
LN-blind
LN-violating *s*-channel ($\mu^\pm\mu^\pm jj$)
LN-violating *s*-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating *t*-channel
$R = 0.9$
non-perturbative

paper out on arXiv!
[2606.25982]



FLASY2026
12th Workshop on Flavor Symmetries
and Consequences in Accelerators and Cosmology

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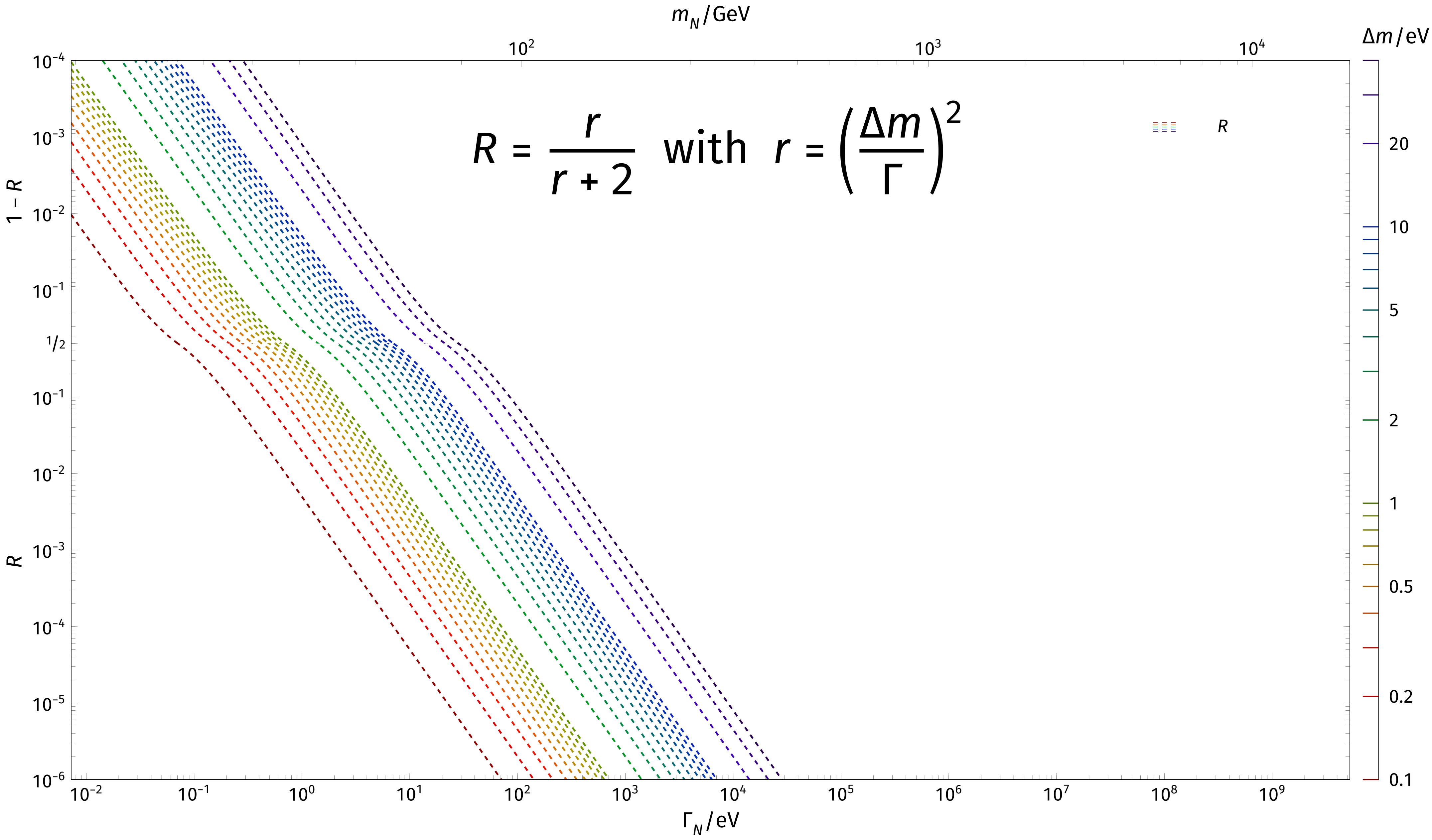
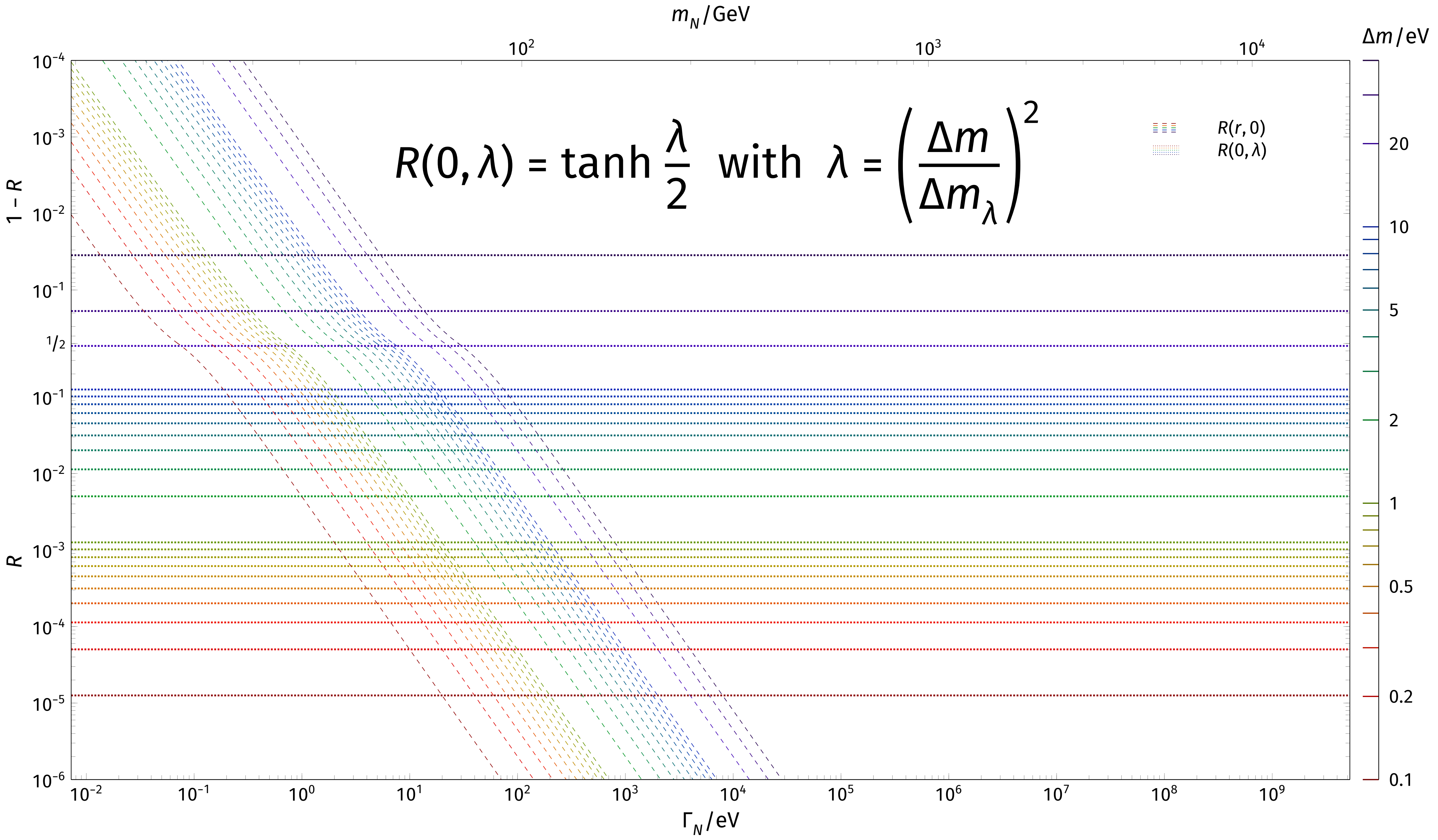
CFTP Universität Basel fct Fundação para a Ciência e a Tecnologia REPÚBLICA PORTUGUESA COMPETE 2020 PORTUGAL 2020 CHEF

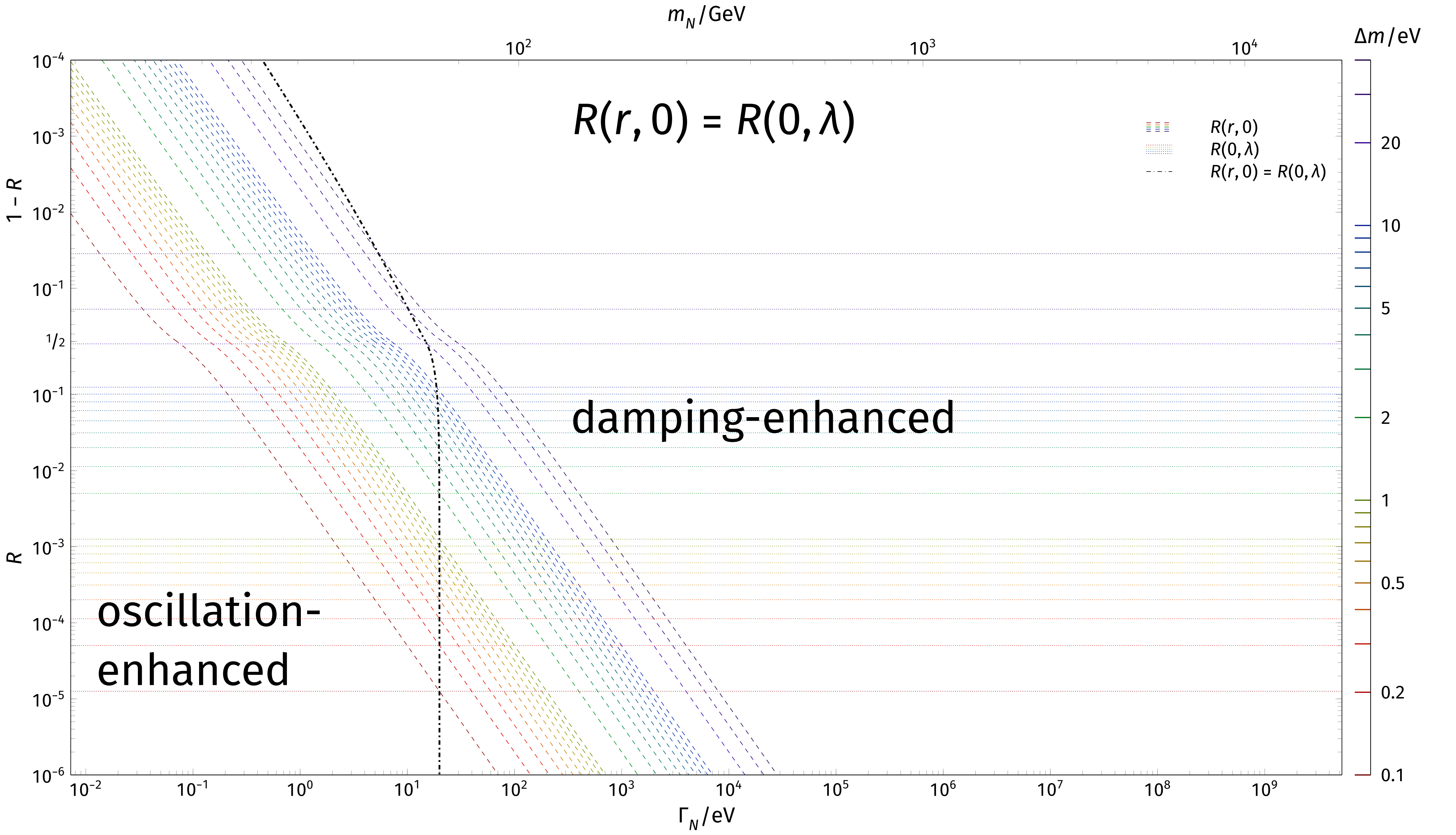
Appendix



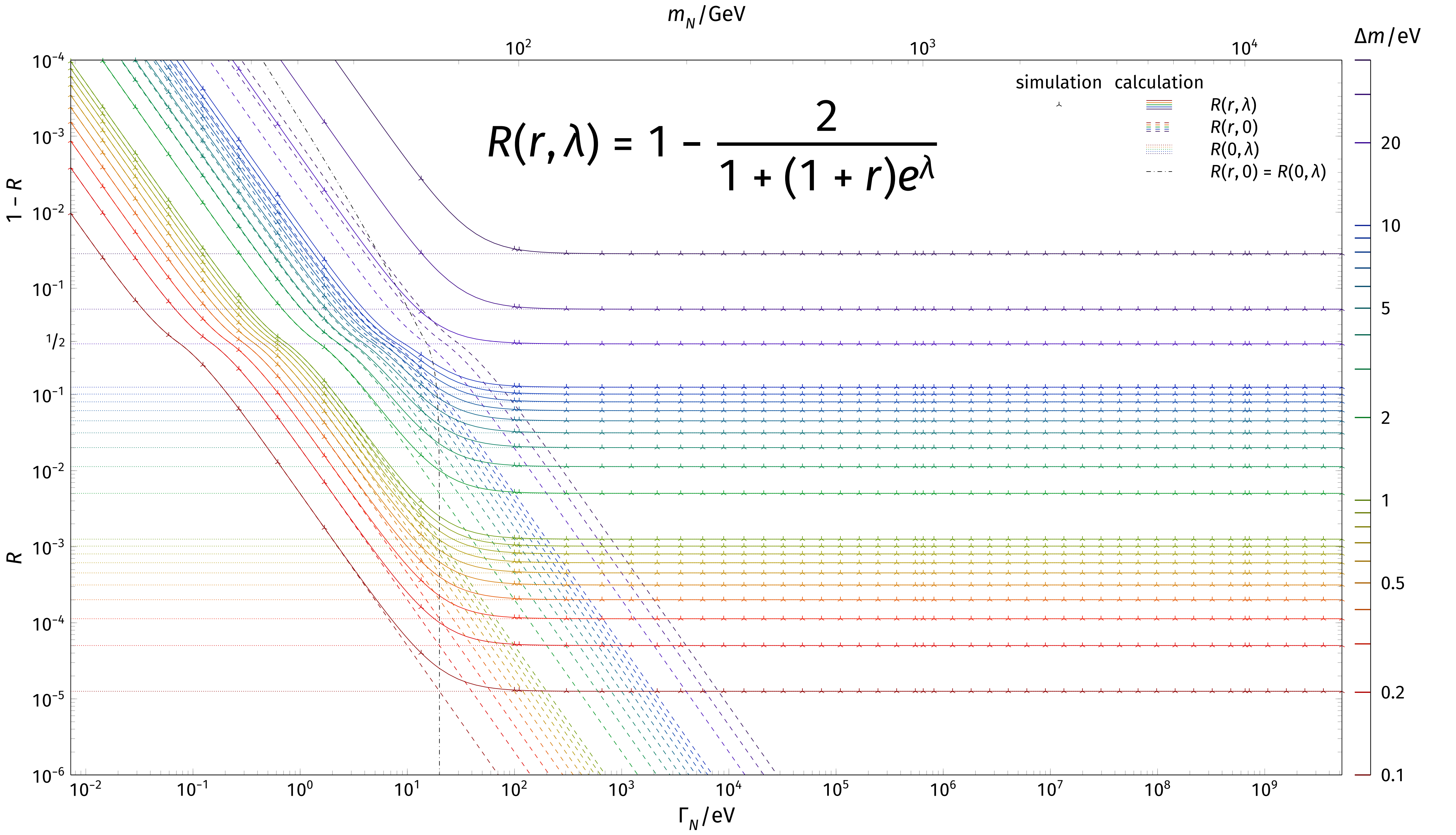
m_N/GeV
10^2
10^3
10^4
Δm/eV
$R = \frac{r}{r+2}$ with $r = \left(\frac{\Delta m}{\Gamma}\right)^2$
R
$1 - R$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$1/2$
R
10^{-6}
10^{-5}
20
10
5
2
1
0.5
0.2
0.1
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
Γ_N/eV



m_N/GeV
10^2
10^3
10^4
Δm/eV
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$1 - R$
$1/2$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
R
$R(0,\lambda) = \tanh\frac{\lambda}{2}$ with $\lambda = \left(\frac{\Delta m}{\Delta m_\lambda}\right)^2$
$R(r,0)$
$R(0,\lambda)$
20
10
5
2
1
0.5
0.2
0.1
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
Γ_N/eV



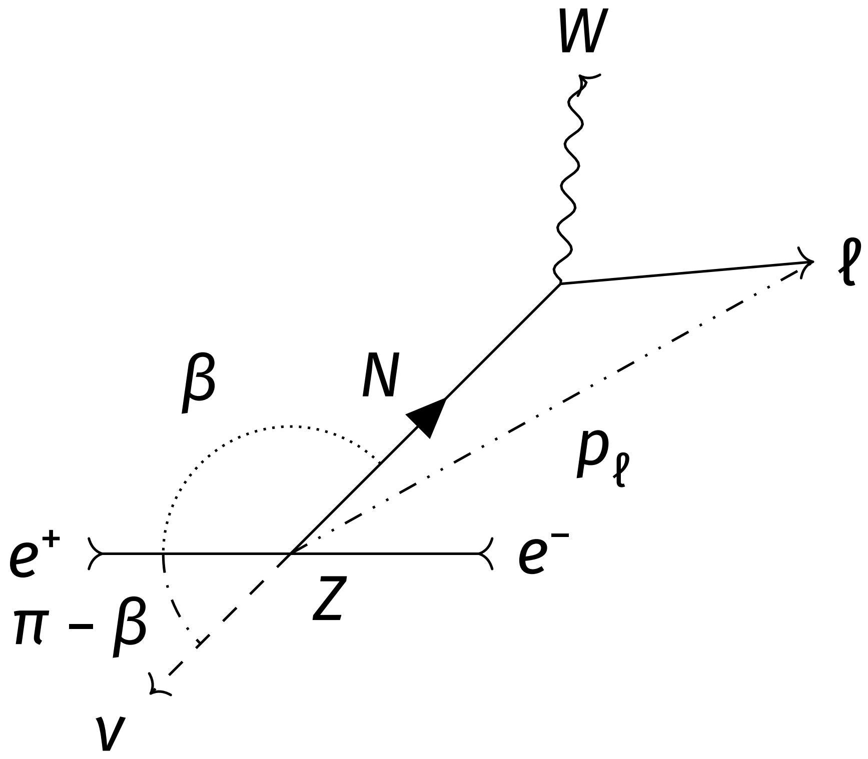
m_N / GeV
10^2
10^3
10^4
Δm / eV
$R(r, 0) = R(0, \lambda)$
$R(r, 0)$
$R(0, \lambda)$
$R(r, 0) = R(0, \lambda)$
$1 - R$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$1/2$
R
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
damping-enhanced
oscillation-enhanced
20
10
5
2
1
0.5
0.2
0.1
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9}
Γ_N / eV



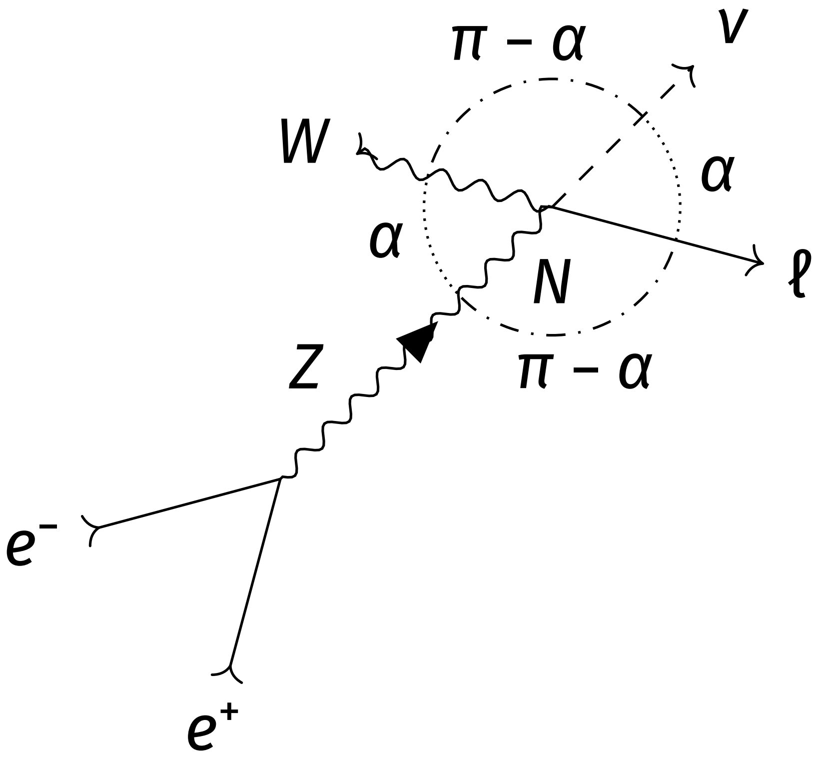
m_N / GeV
Δm / eV
simulation
calculation
$R(r,\lambda)$
$R(r,0)$
$R(0,\lambda)$
$R(r,0) = R(0,\lambda)$
$R(r,\lambda) = 1 - \frac{2}{1 + (1 + r)e^{\lambda}}$
$1 - R$
R
Γ_N / eV

oscillations in kinematic observables

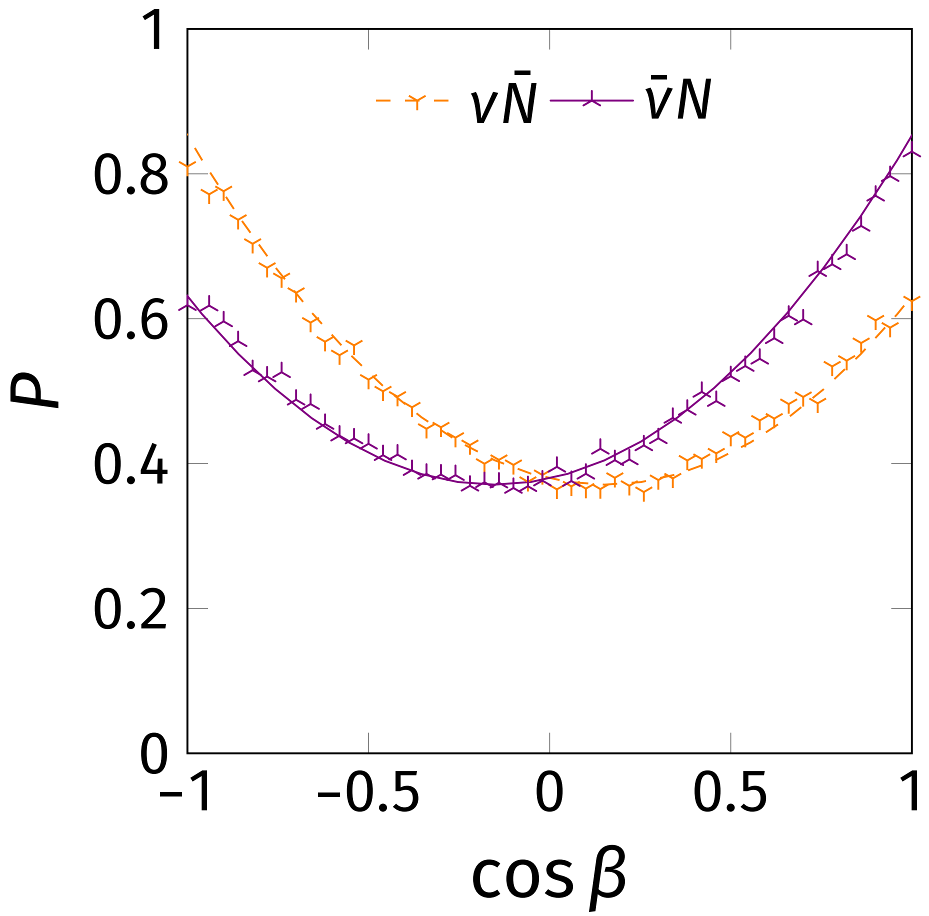
forward-backward asymmetry (lab frame)

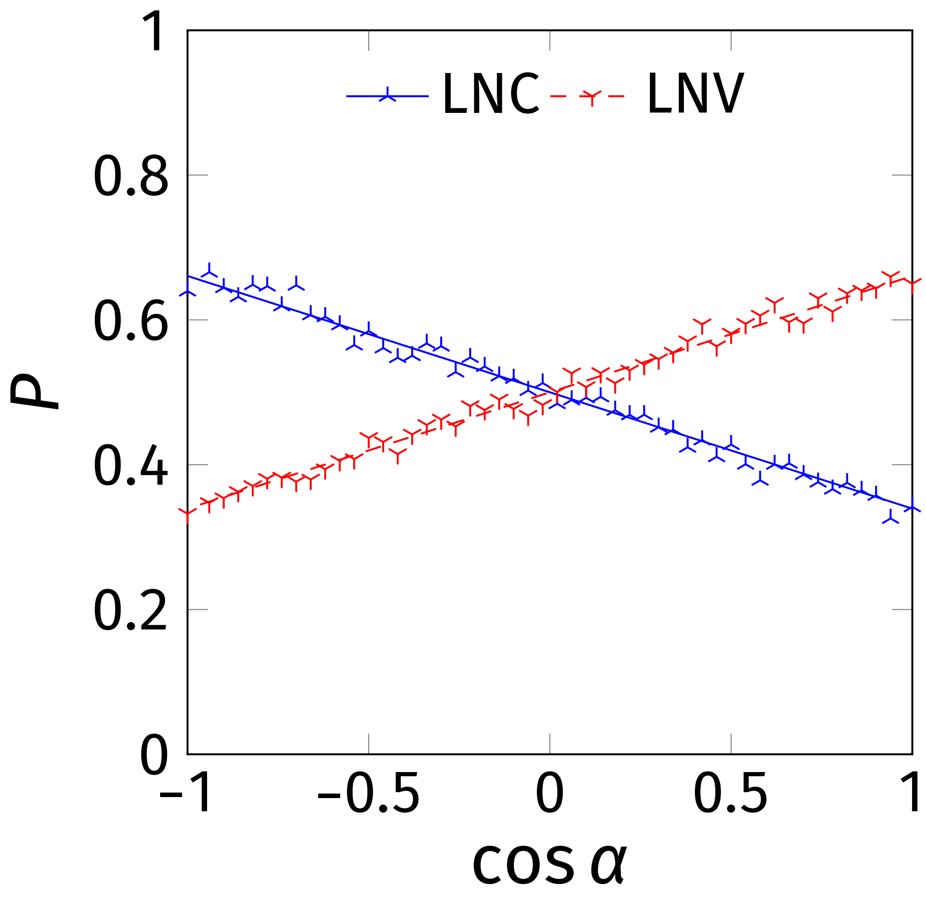


opening angle asymmetry (hnl frame)

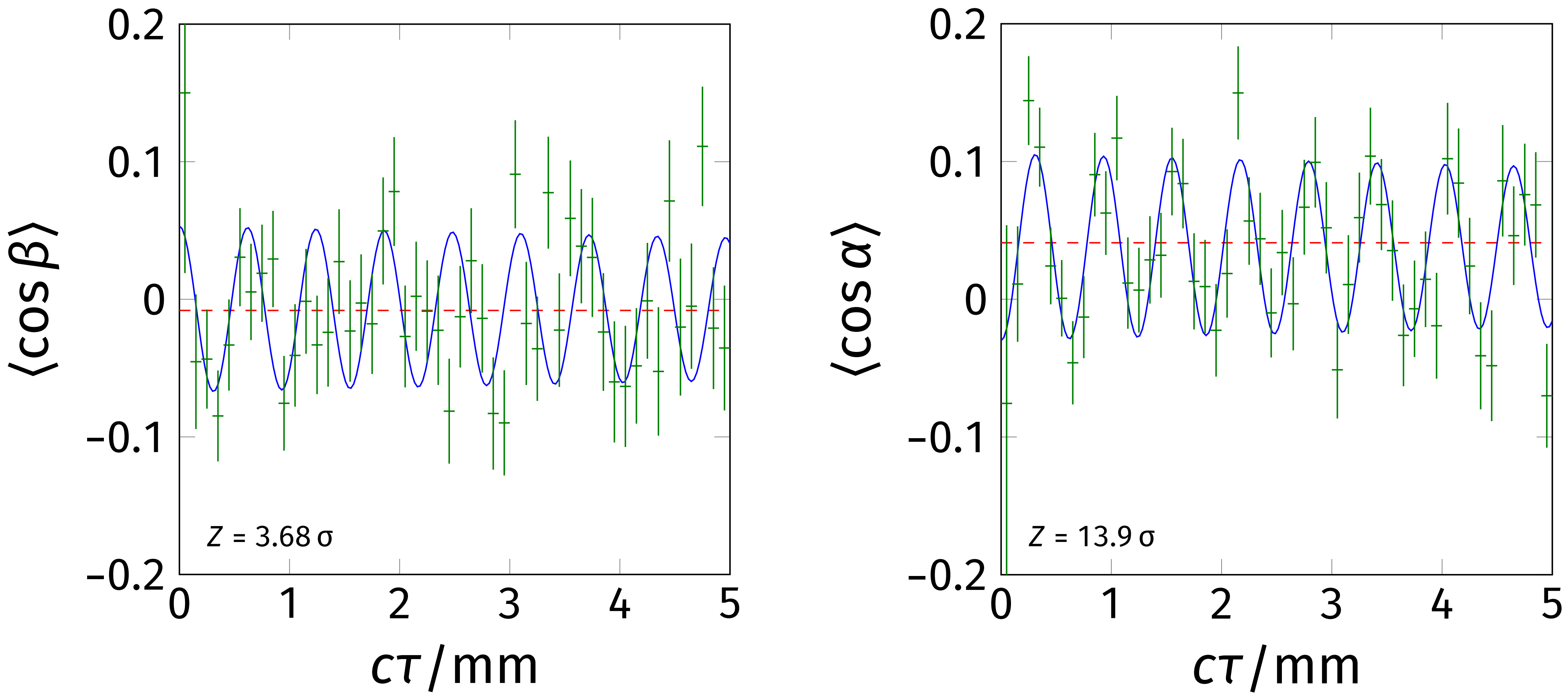


oscillations in kinematic observables





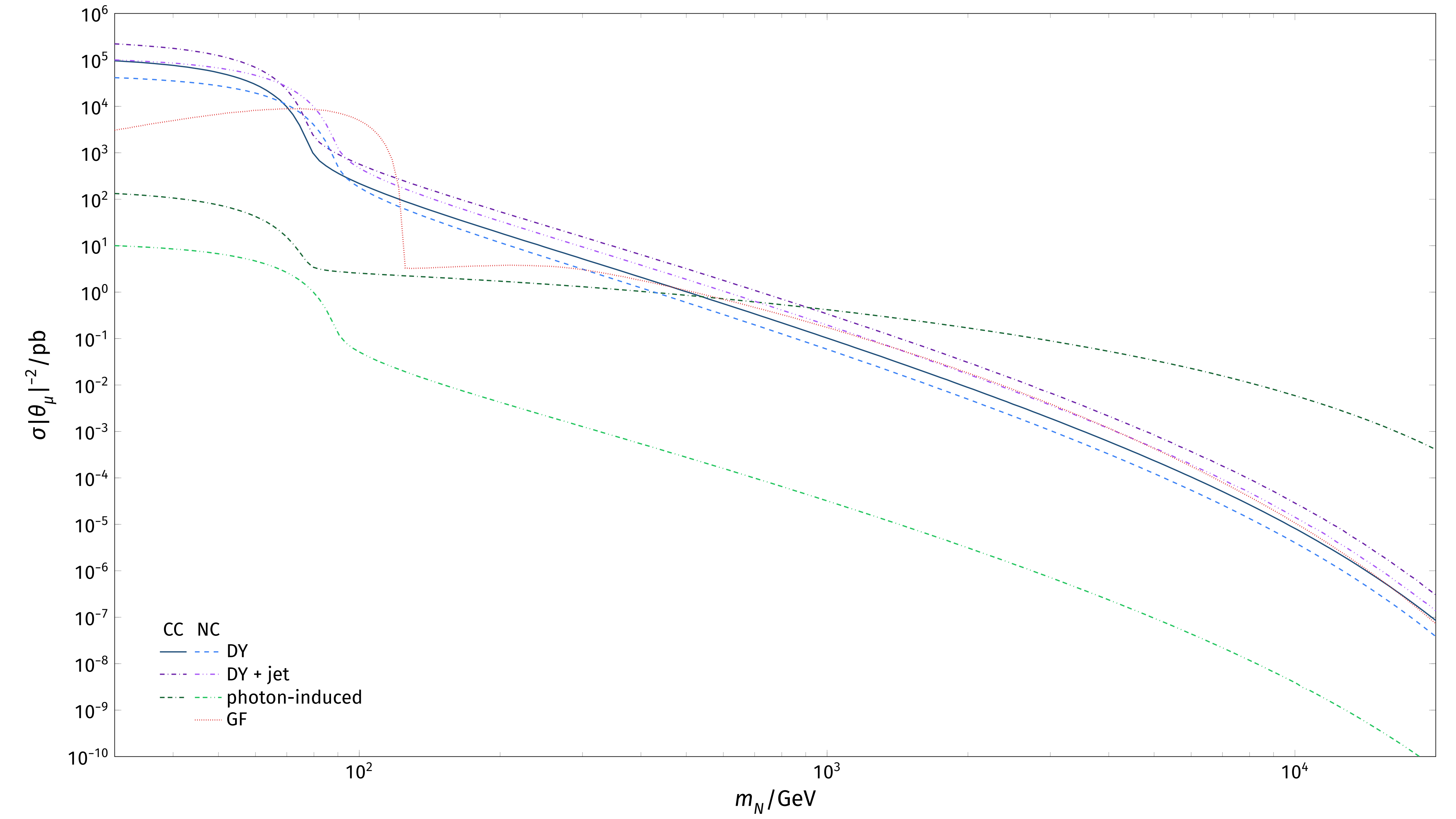
oscillations in kinematic observables



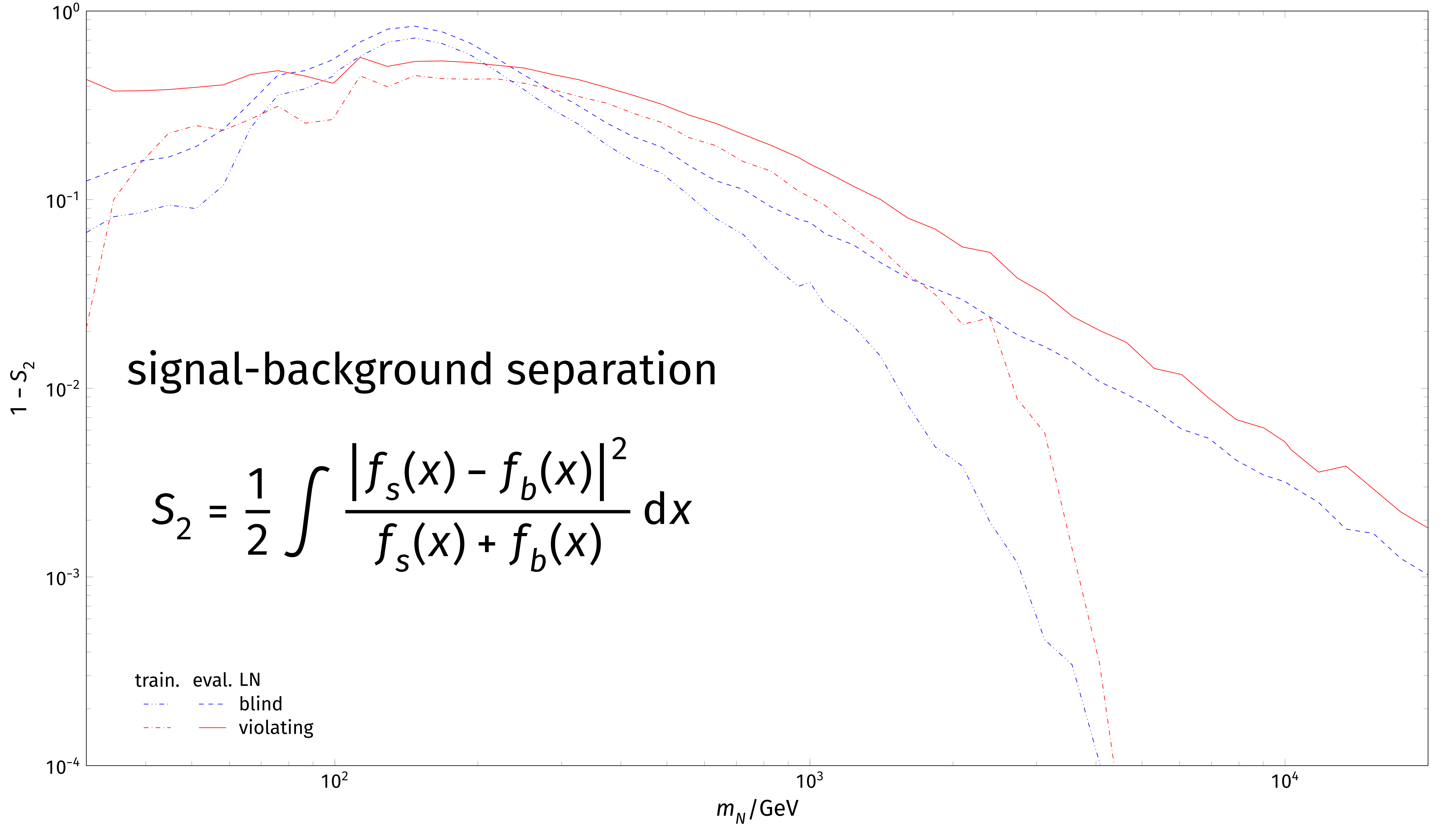
oscillations in kinematic observables

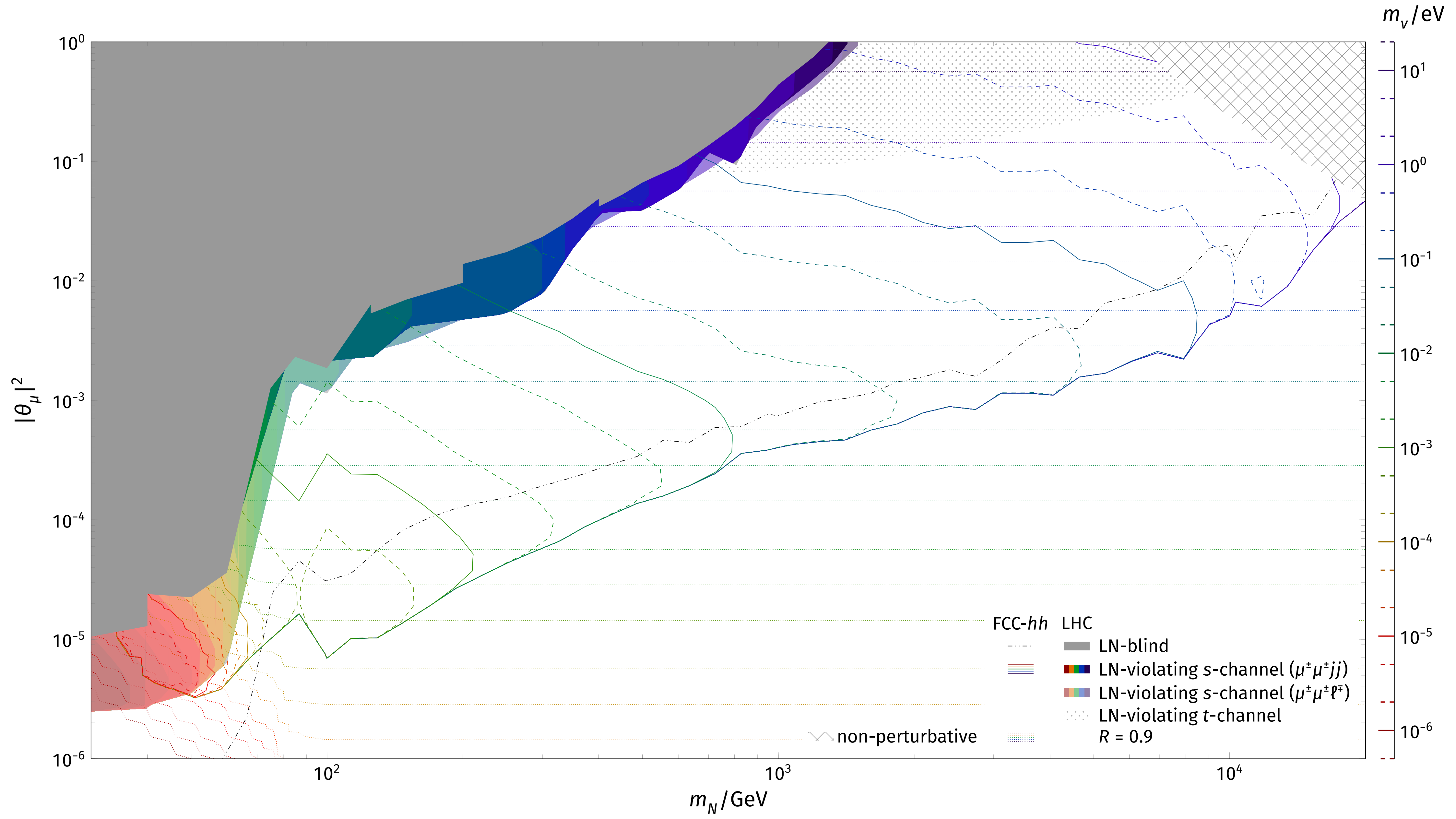
[2308.07297]

[2408.01389]

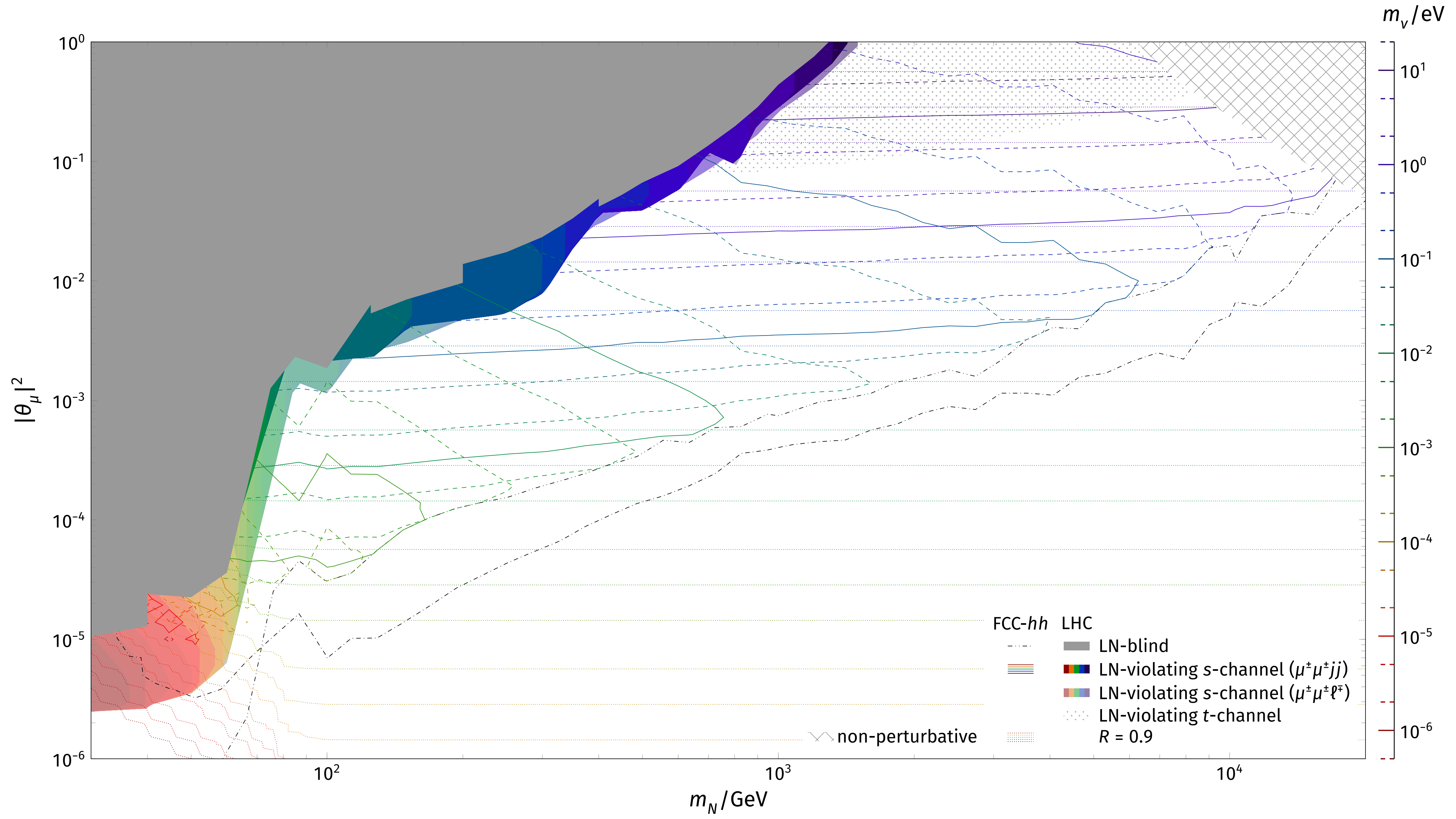


10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$\sigma|\theta_\mu|^{-2}/\mathrm{pb}$
10^{2}
10^{3}
10^{4}
m_N/GeV
CC NC
DY
DY + jet
photon-induced
GF


signal-background separation
$$S_2 = \frac{1}{2} \int \frac{\left| f_s(x) - f_b(x) \right|^2}{f_s(x) + f_b(x)} \, \mathrm{d}x$$
$1 - S_2$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^2
10^3
10^4
m_N / GeV
train. eval. LN
blind
violating



$|\theta_\mu|^2$
m_N/GeV
m_ν/eV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
FCC-*hh* LHC
LN-blind
LN-violating *s*-channel ($\mu^\pm\mu^\pm jj$)
LN-violating *s*-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating *t*-channel
non-perturbative
R = 0.9



m_ν/eV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$|\theta_\mu|^2$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
m_N/GeV
FCC-hh
LHC
LN-blind
LN-violating s-channel ($\mu^\pm\mu^\pm jj$)
LN-violating s-channel ($\mu^\pm\mu^\pm\ell^\mp$)
LN-violating t-channel
non-perturbative
R = 0.9