How to simplify the reinterpretation of HNL searches

Jean-Loup Tastet <jean-loup.tastet@uam.es> · FIPs 2022 workshop · CERN · 2022-10-20

How to simplify the reinterpretation of ~~HNL~~ many FIP searches

→ see backup

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HNL crash course

Cf. this afternoon's talks for a more complete introduction

- New spin-1/2 SM singlet(s) $N_{1,2,\ldots}$.
- Yukawas (→ Dirac mass) + Majorana mass term: $M = \begin{pmatrix} 0 & vY^\dagger/\sqrt{2} \\ vY^*/\sqrt{2} & M_M \end{pmatrix}$
- Mixing between mass and flavour eigenstates: $\nu_\alpha \cong U^{\mathrm{PMNS}}_{\alpha i}\nu_i + \Theta_{\alpha I} N_I$.
- HNLs inherit weak interactions of neutrinos, suppressed by the mixing angle.
- 2+ HNLs may behave either as Dirac or Majorana fermions.
  They can even *oscillate*! → Jan's talk [1709.03797, 1912.05520, 2012.05763, and more...]
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TL;DR: HNLs are heavy Dirac/Majorana neutrinos with suppressed interactions!

Reporting experimental limits on HNLs

- Realistic models contain multiple HNLs

  ⟶ large parameter space

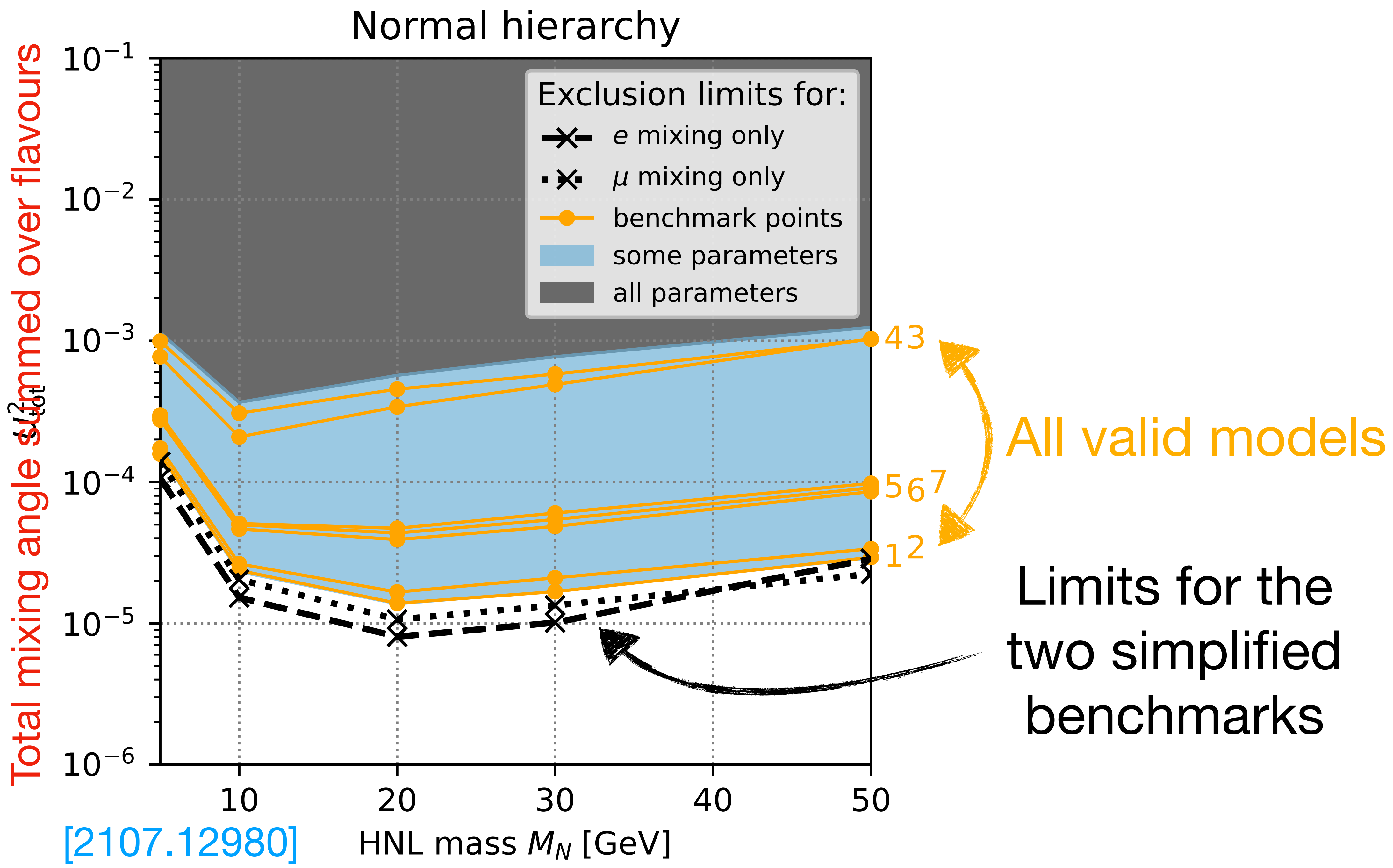
- To manage this complexity, experiments report limits under some simplifying assumptions, e.g.:
  "one Majorana HNL mixing with ν_e only"
  "one Majorana HNL mixing with ν_μ only"
  ...

- This can lead to under-coverage of the true parameter space!
  (but also to limits which are too conservative, especially when combined)

Example: ATLAS [see 2107.12980 & 2110.11907] → see backup

- Limits reported for 1 Majorana HNL mixing with only 1 flavour.
- Recasted to more realistic scenarios in a separate study.

⟶ The "simplified" limits don't accurately constrain more realistic models.



[2107.12980]

Previously in FIPs 2020

- New benchmarks proposed for HNLs to ensure that the parameter is adequately covered.

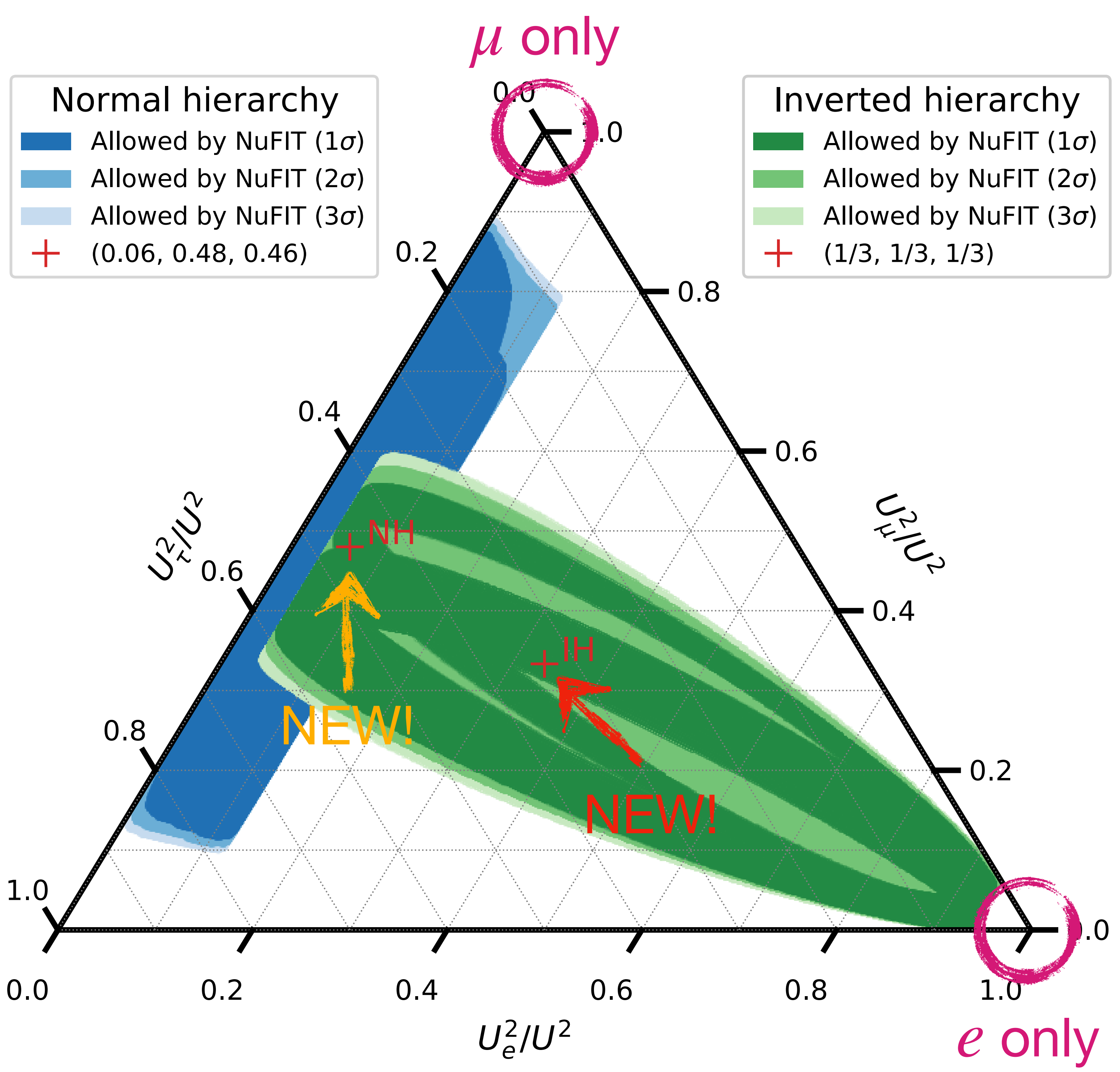
We advocate the use of the following two new benchmarks for the next round of experimental results:

- IH: $U_e^2 : U_\mu^2 : U_\tau^2 = 1/3 : 1/3 : 1/3$;
- NH: $U_e^2 : U_\mu^2 : U_\tau^2 = 0.06 : 0.48 : 0.46$

for both Dirac-like & Majorana-like

[2102.12143]

UPDATED! → Juraj's talk tomorrow and [2207.02742]



- Those benchmarks are consistent with the observed neutrino data within a low-scale type-I see-saw model with 2 HNLs.
(respectively for the normal (NH) and inverted (IH) hierarchy)

ATLAS delivered!

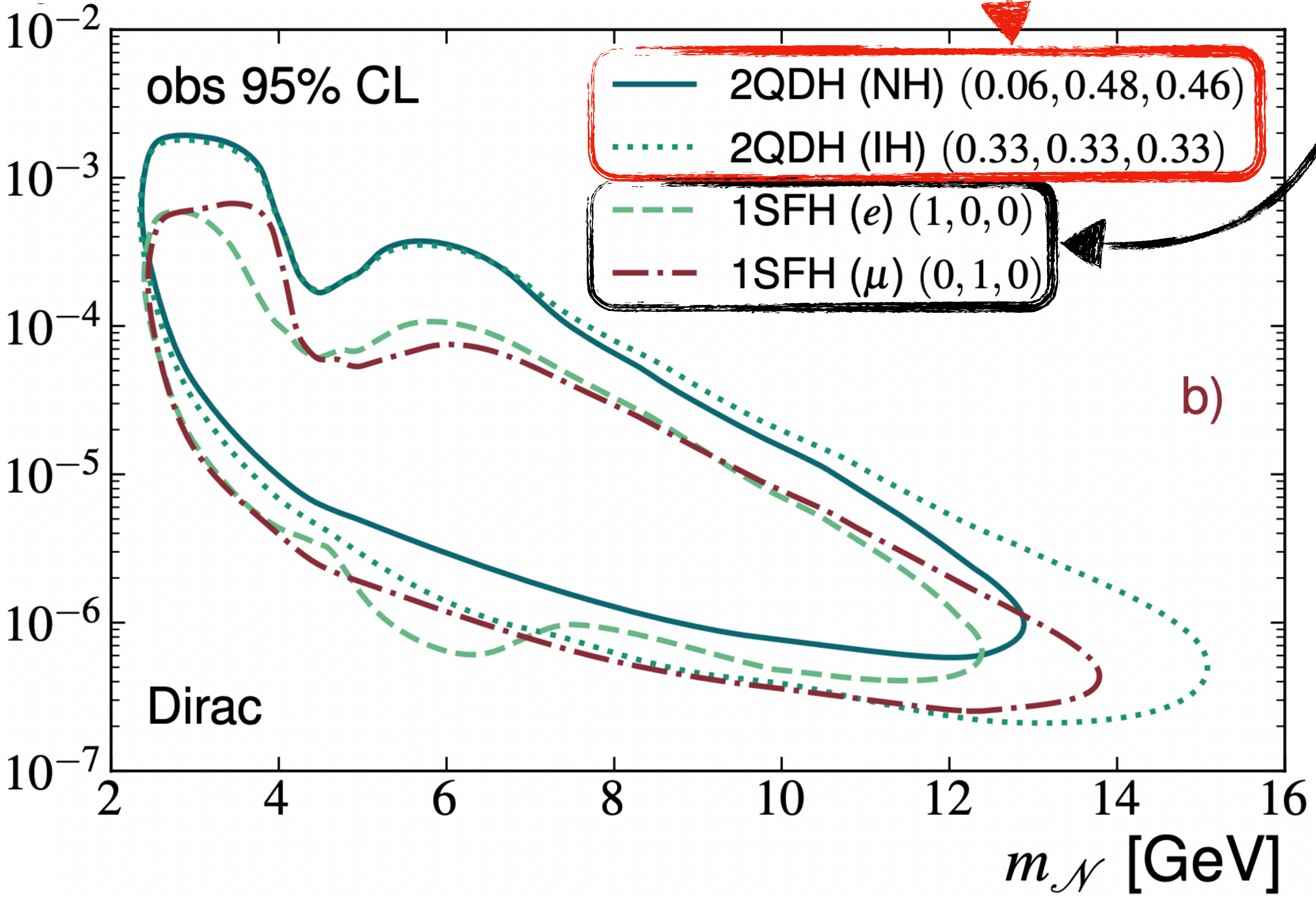
[ATLAS: 2204.11988 → PRL when affiliations are sorted out...]

Search for heavy neutral leptons in decays of W bosons using a dilepton displaced vertex in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector

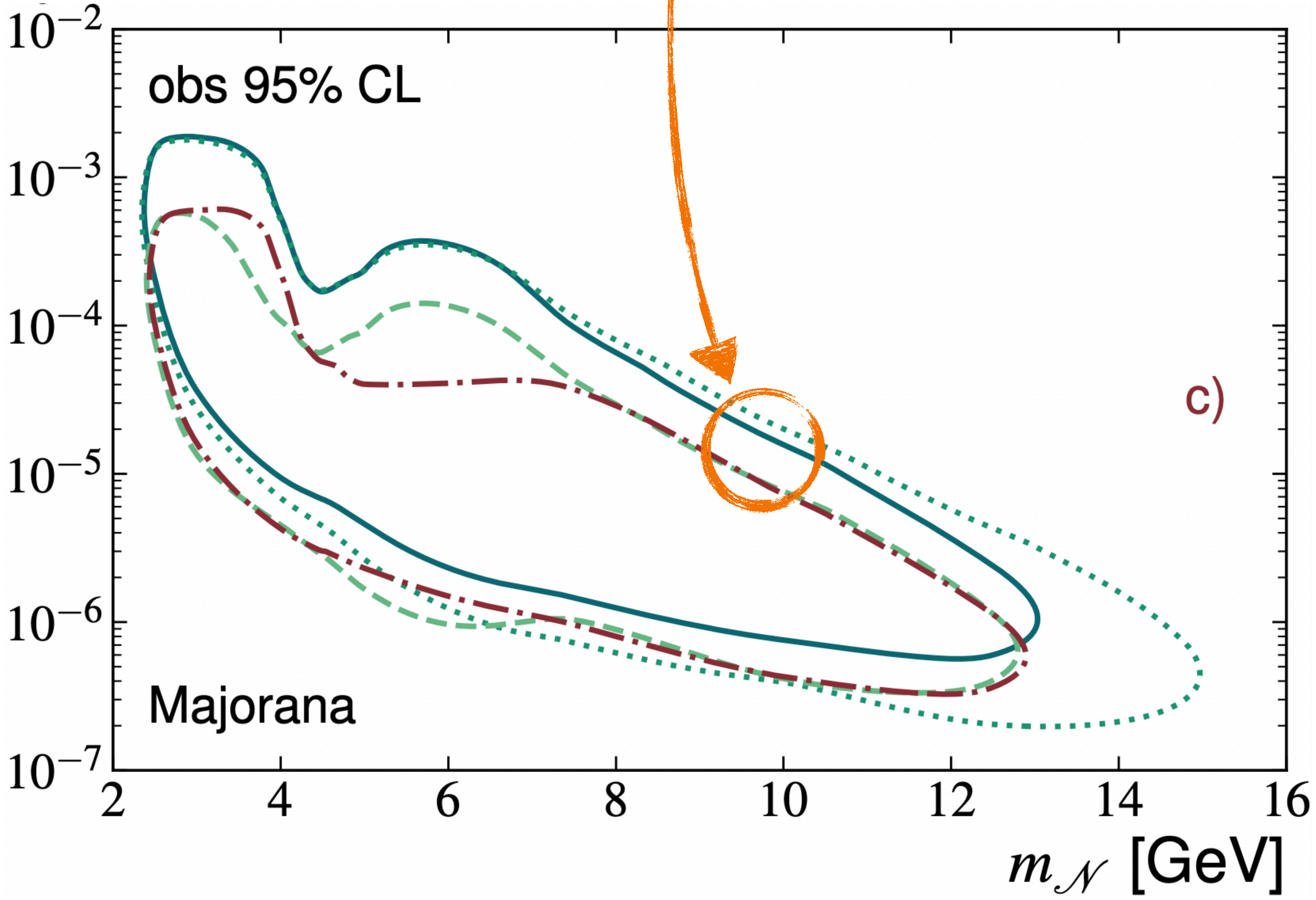
"1 Majorana HNL mixing with a single flavour"
is still there

New FIPs 2020 benchmarks!

Low variance between benchmarks → good coverage!



Majorana-like HNLs



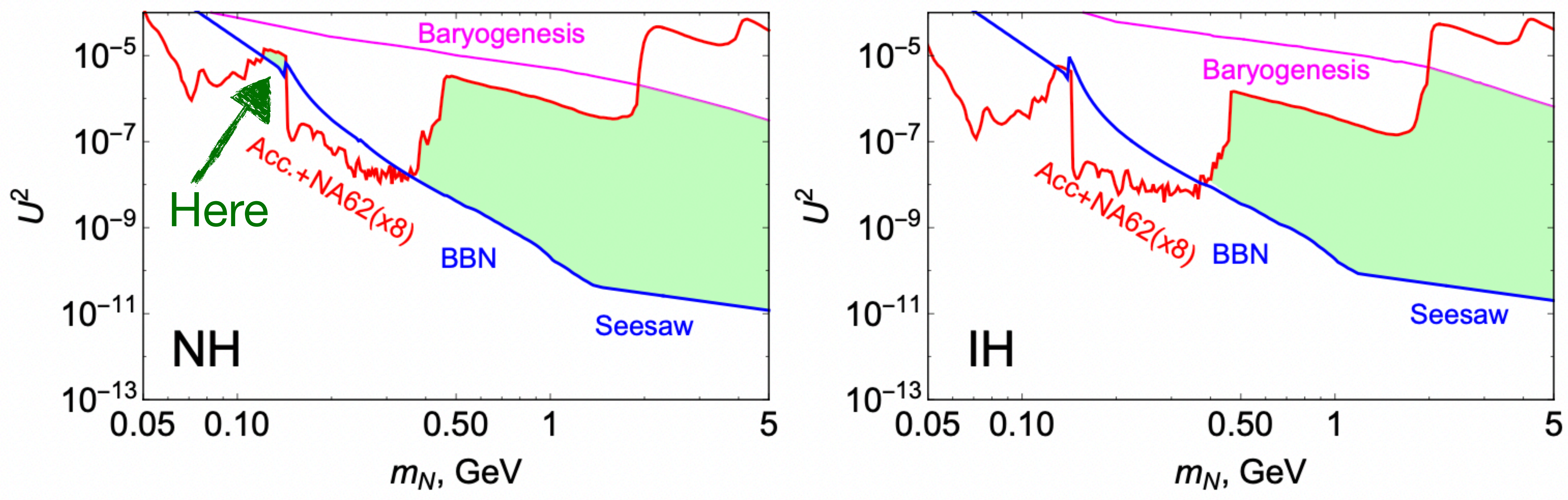
Dirac-like HNLs

Going beyond

Global parameter scans, Bayesian analyses, ...

- Sometimes it is necessary to precisely interpret the results for an arbitrary number of HNLs, choice of mixing angles $(\Theta_e, \Theta_\mu, \Theta_\tau)$, Dirac/Majorana nature...

Example: [2101.09255] by Bondarenko, Boyarsky, Klaric, Mikulenko, Ruchayskiy, Syvolap, Timiryasov. They combine constraints from neutrino oscillation data, accelerator searches, big bang nucleosynthesis and the requirement of successful baryogenesis, and find a low-mass region that isn't fully constrained yet:



- Beyond HNLs: do we need to define benchmarks for *all* FIPs?

3 required ingredients for an easy reinterpretation

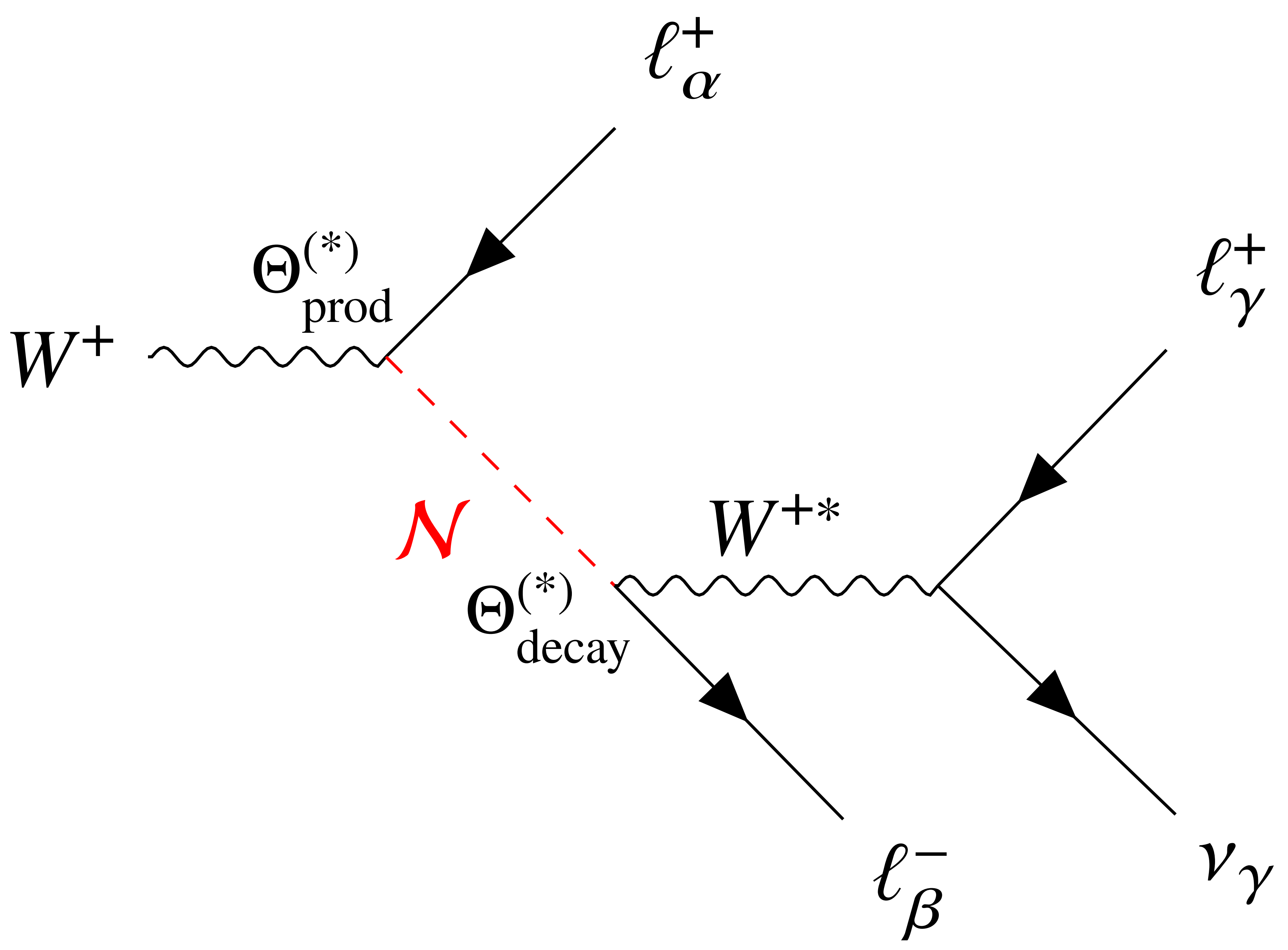
- The observed counts $n_b^{\rm obs}$ in each signal region and bin. ✔
- The expected signal, for arbitrary model parameters, in each signal region and bin, e.g.: $s_b(m_N, \Theta_e, \Theta_\mu, \Theta_\tau, \#\text{HNLs}, \{\text{Dirac} \,|\, \text{Majorana}\})$

  This talk → We'll use the scaling properties of the signal for that.
- The background model (unless the search is background-free).
  Either as 1) the full likelihood 2) a simplified likelihood or 3) the correlation matrix of the per-bin background counts.
  Cf. LHC Reinterpretation Forum guidelines [2003.07868]

Scaling properties of the signal

- Prior work: sensitivity matrix of SHiP to HNLs [1811.00930].
  See also [1807.10024] and more recently [2208.13882].

Example: HNLs



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  → narrow-width approximation

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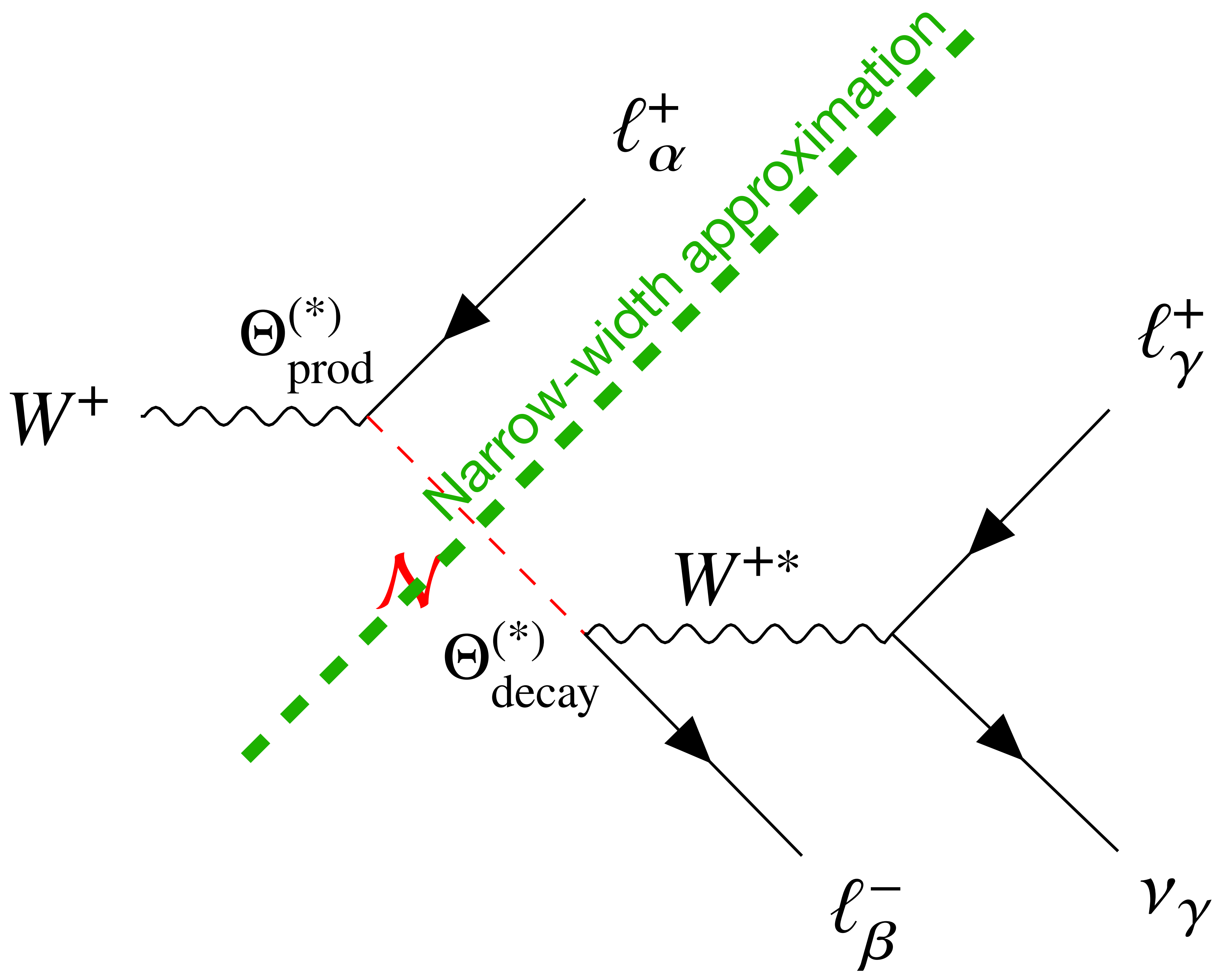

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- Cross-section for a given process:

$$\sigma_{\text{process}} = \sigma_{\text{prod}} \times \text{Br}_{\text{decay}}$$
$$\propto |\Theta_{\text{prod}}|^2 |\Theta_{\text{decay}}|^2 / \Gamma_{\text{total}}$$

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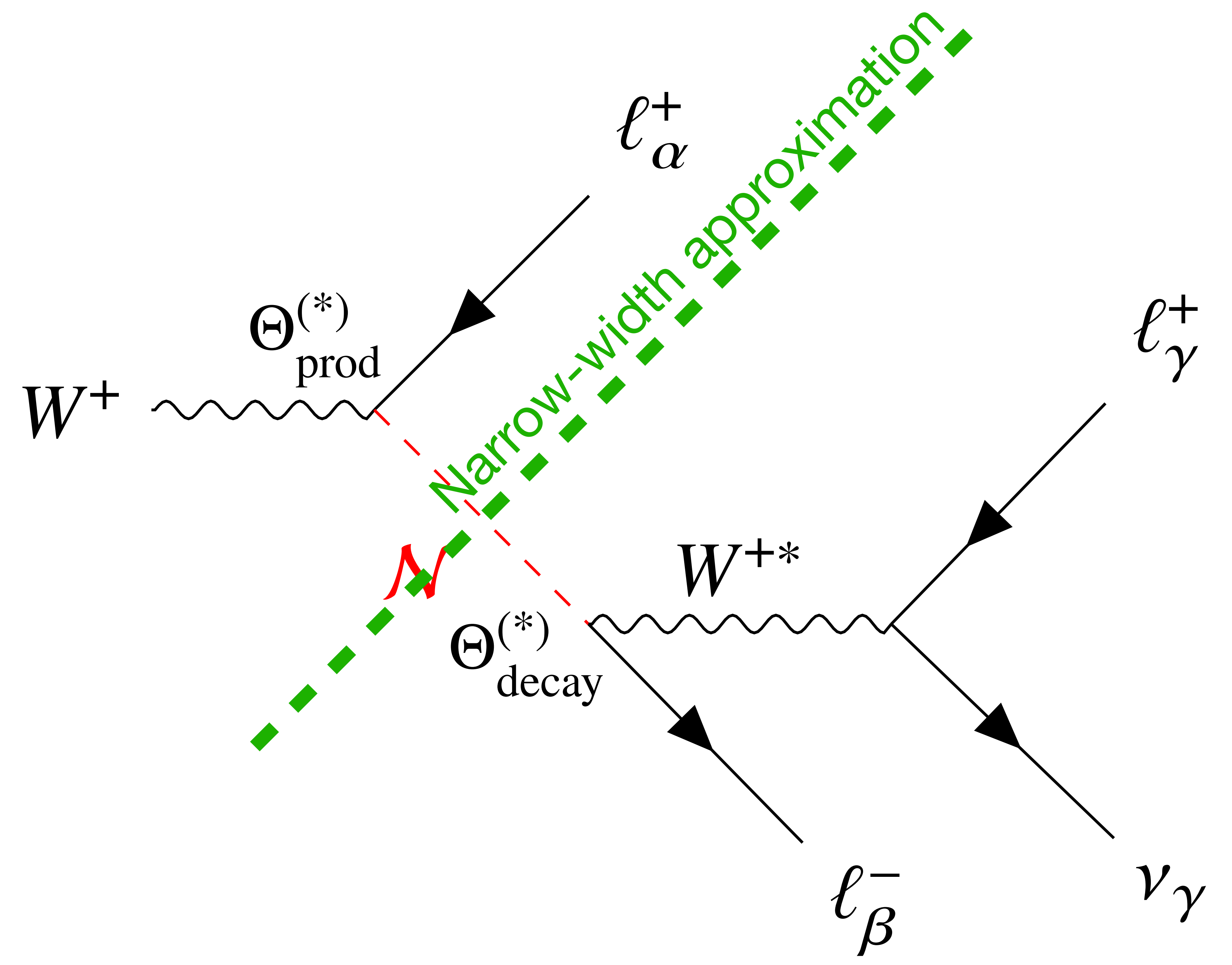

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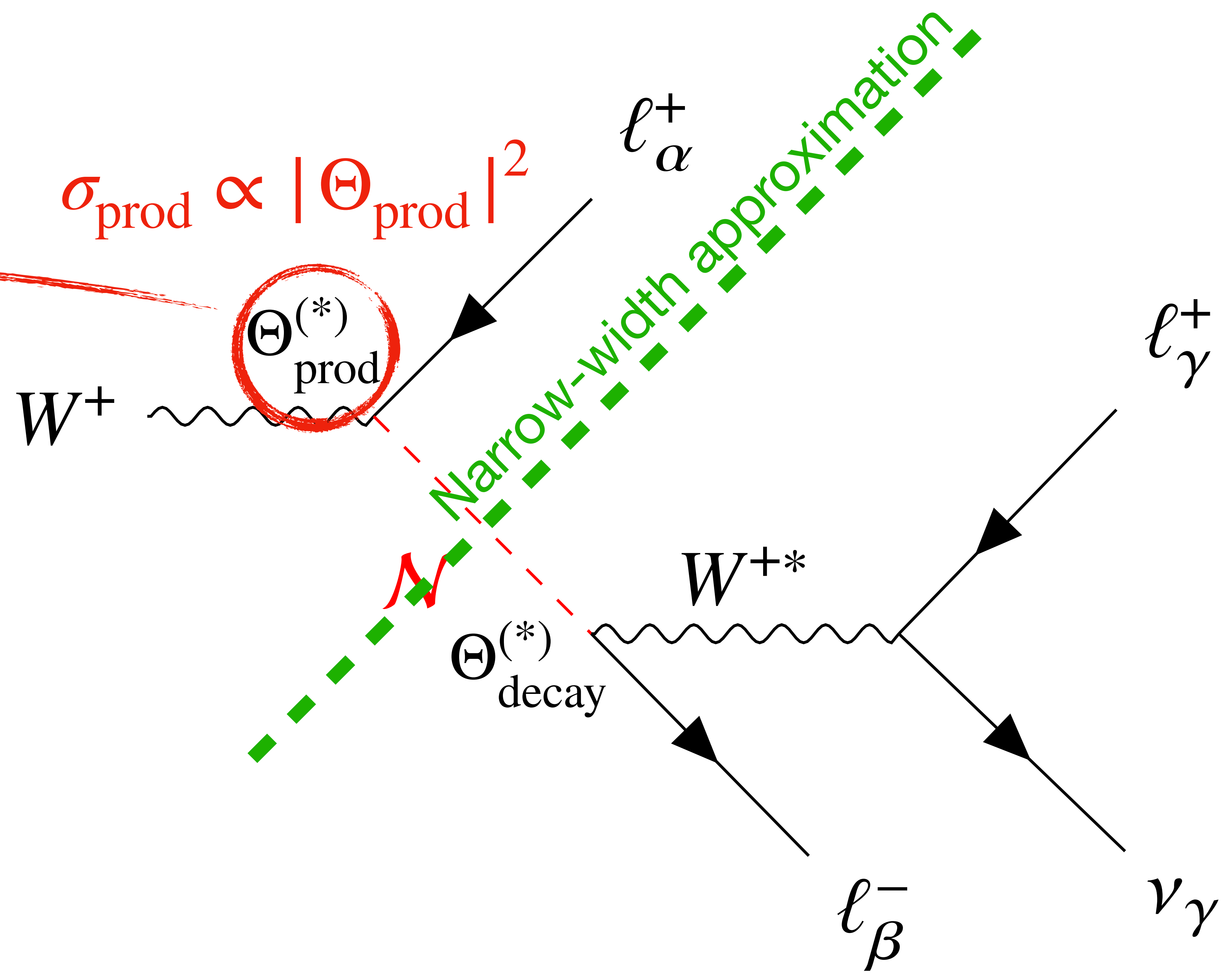

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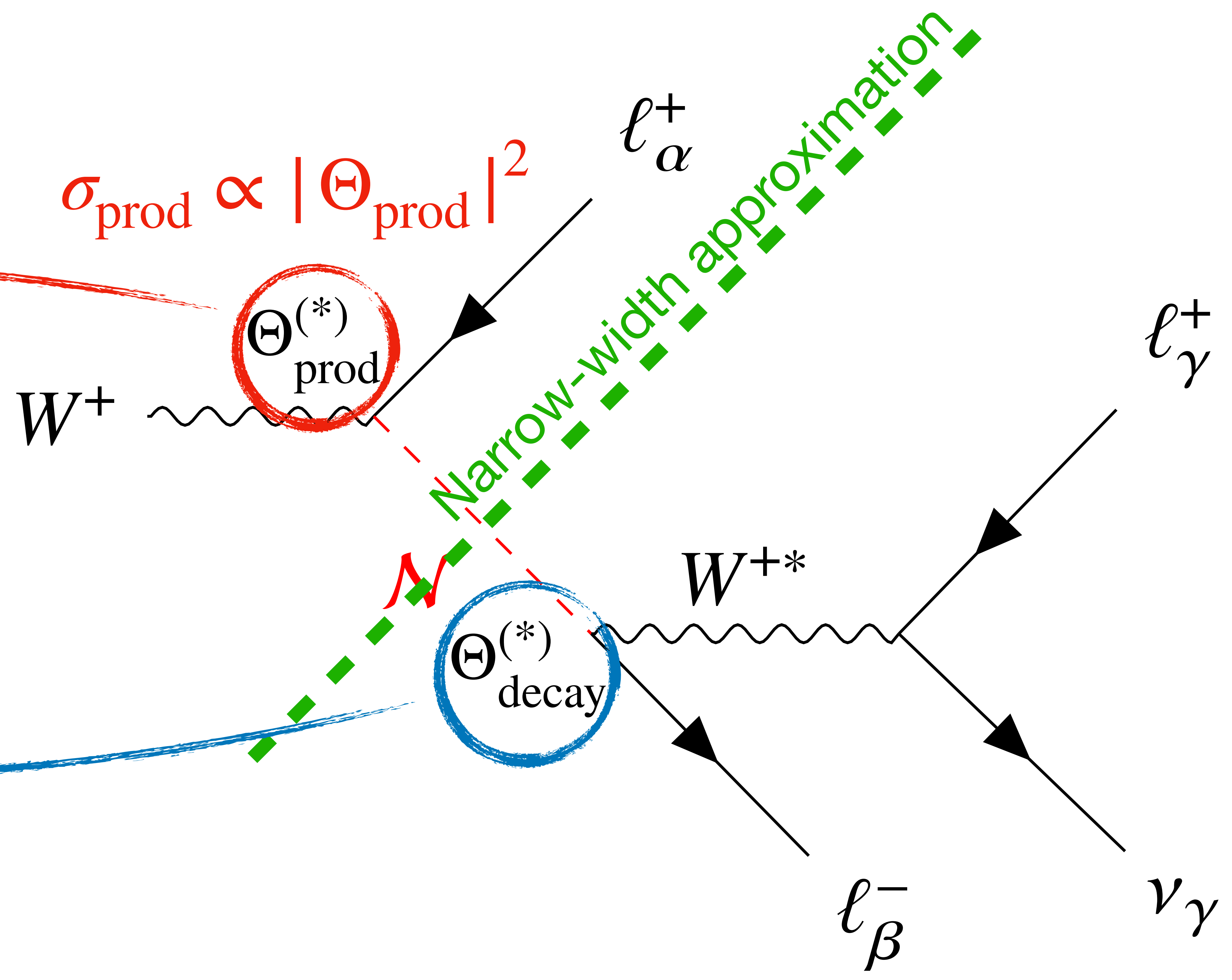

$$\text{Br}_{\text{decay}} = \frac{\Gamma_{\text{decay}}}{\Gamma_{\text{total}}} \propto \frac{|\Theta_{\text{decay}}|^2}{\Gamma_{\text{total}}}$$

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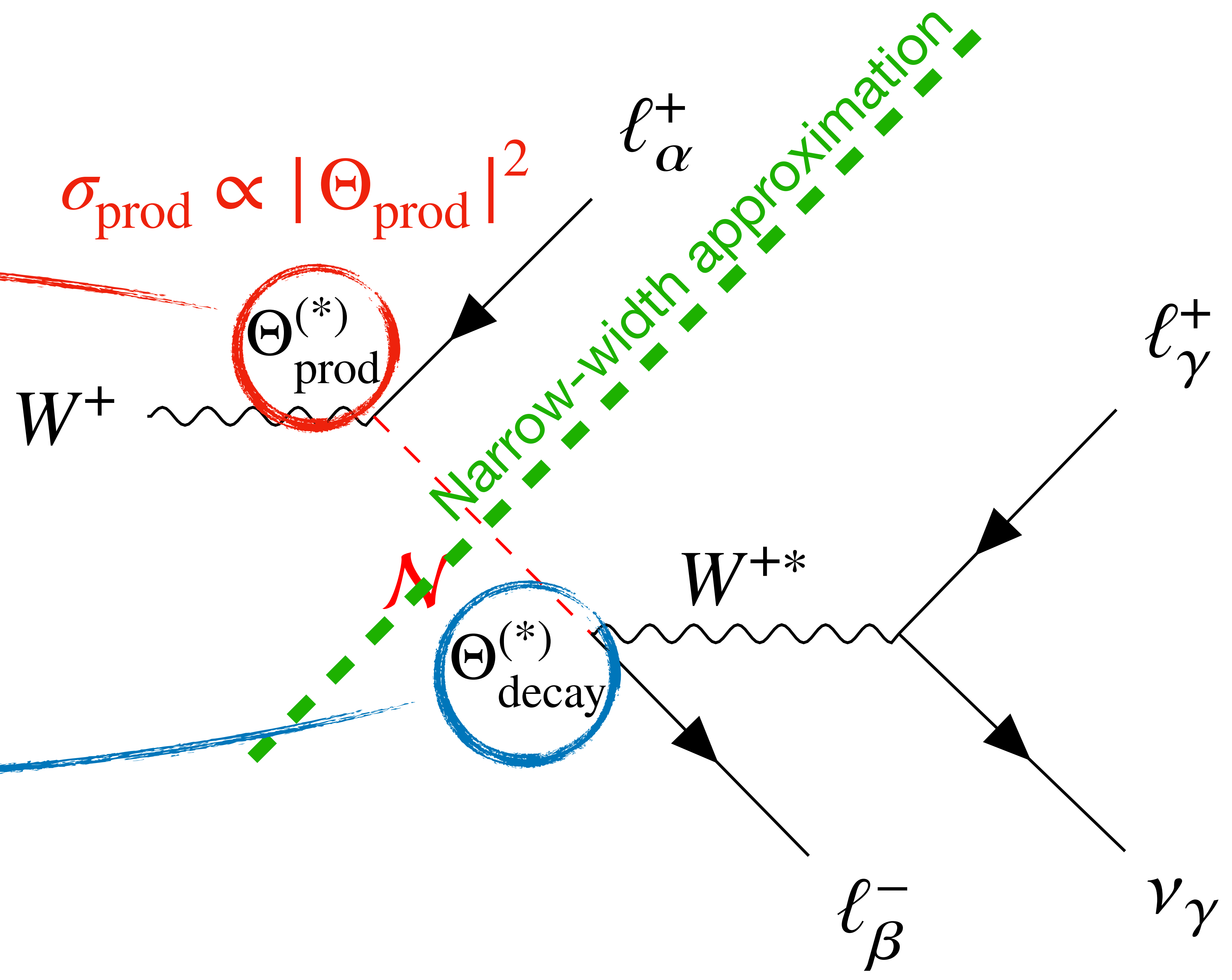
- The total width Γ_{total} is the sum of partial widths for processes mediated by e, μ and τ mixings:

$$\Gamma_{\text{total}}(M_N, \Theta_e, \Theta_\mu, \Theta_\tau) = \sum_{\alpha=e,\mu,\tau} |\Theta_\alpha|^2 \hat{\Gamma}_\alpha(M_N)$$

Example: HNLs

$$\sigma_{\text{prod}} \propto |\Theta_{\text{prod}}|^2$$



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Extrapolating the expected signal (for HNLs)

See [2107.12980, section 3.2]

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- Summing over processes, we obtain the expected number of signal events **in bin *b***:

$$s_b(M_N, \tau_N, \Theta_e, \Theta_\mu, \Theta_\tau) = \frac{\sum_{\alpha,\beta} |\Theta_\alpha|^2 \Sigma_b^{\alpha\beta}(M_N, \tau_N) |\Theta_\beta|^2}{\sum_\gamma |\Theta_\gamma|^2 \hat{\Gamma}^\gamma(M_N)} = \frac{(\mathbf{\Theta^2})^{\mathrm{T}} \Sigma_b(M_N, \tau_N) \mathbf{\Theta^2}}{\mathbf{\Theta^2} \cdot \mathbf{\Gamma}(M_N)}$$

$\hat{\Gamma}^\alpha$ = sum of the partial widths mediated by flavour α, computed for a *unit mixing angle* $\Theta_\rho = \delta_{\rho\alpha}$.

Signal matrix $\Sigma_b^{\alpha\beta}(M_N, \tau_N)$ function of "normalised" cross-sections and efficiencies $\varepsilon_{P,b}(M_N, \tau_N)$.

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→ see backup

- Only non-trivial thing that we need from experiments = signal efficiencies $\varepsilon_{P,b}(M_N, \tau_N)$ for each pair of process *P* and bin *b*. Split by process what experiments already have!

- Typically computed on a $M_N \times \tau_N$ grid. Interpolate efficiencies in τ_N to compute $\Sigma_b^{\alpha\beta}(M_N, \tau_N)$ at the physical lifetime $\Gamma_{\mathrm{total}}^{-1}(M_N, \Theta_e, \Theta_\mu, \Theta_\tau)$.

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→ see backup

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= signal efficiencies ε
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Efficiencies treated as a black box:
Works even for complicated efficiencies!
(MVA, neural networks, etc...)

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Interpolate efficiencies in τ_N to compute $\Sigma_b^{\alpha\beta}(M_N, \tau_N)$ at the physical lifetime $\Gamma_{\mathrm{total}}^{-1}(M_N, \Theta_e, \Theta_\mu, \Theta_\tau)$.

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Conclusion

- The new benchmarks adopted at FIPs 2020 for HNLs have been successfully used to ensure that the latest ATLAS search has good parameter space coverage.
- There exist valid use cases that require going beyond benchmarks.
  (+ selecting/standardising good benchmarks *takes time*)
- If experiments release 1) fine-grained efficiencies (per bin, per process) and 2) a reasonably accurate background model, then one can leverage the scaling properties common to many FIP signatures to interpret their results for *arbitrary parameters* within the model of interest.

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EoI: I want to propose writing a short paper (or chapter in the FIPs report) describing precisely and step by step what experiments need to report.

Backup slides

EoI

- The endorsement of new, non-minimal benchmark points in the FIPs 2020 Workshop Report gave them the legitimacy needed to be adopted by at least one major experiment 🎉
- Throughout the years, there have been a number of efforts by theorists to reinterpret and/or combine the results of *direct* searches for HNLs.
  Non-exhaustive list: 1112.3319, 1807.10024, 2101.09255, 2107.12980, 2208.13882, ...
- This talk has discussed a way to make this task far easier, more accurate, and applicable to some other FIPs. To use it in practice, we need experiments to report some additional data.
- Having a precise, step-by-step guide describing what exactly is needed and how to compute it would make it more likely that experiments will *actually* release such data.
- If ***you*** are interested in repeating the success of the FIPs 2020 workshop and collaborate with me on a whitepaper aimed at experiments, don't hesitate to contact me!

Generalising

- Let $\varepsilon_1, \ldots, \varepsilon_{N_\varepsilon}$ be the (small) couplings involved in the SM ↔ FIP interactions.
  (for complex couplings both ε and ε^* should be included)

- A diagram involving an on-shell FIP will generically separate into production, propagation and decay parts, contributing a factor $\propto \varepsilon_{i_\text{prod}} \varepsilon_{i_\text{decay}} / \left(p_\text{FIP}^2 - m^2 + im\Gamma_\text{total}(m, \{\varepsilon_i\})\right)$ with small Γ_total.

- After 1) summing diagrams 2) reordering the sum 3) squaring the amplitude and using the NWA 4) taking the experimental efficiencies into account and 5) integrating over phase space, then repeating steps (1,2,3,5) for the total width, we obtain for the **expected signal in bin *b***:

$$s_b = \frac{\Sigma_b^{(ij)(kl)}(m,\tau)\varepsilon_i^*\varepsilon_j^*\varepsilon_k\varepsilon_l}{\Gamma^{ij}(m)\varepsilon_i^*\varepsilon_j}$$

(with implied Einstein summation)

- This expression may appear daunting at first, but it is actually usable in practice!
  (thanks to the sparsity and symmetry properties of the tensors $\Sigma_b^{(ij)(kl)}$ and Γ^{ij}, as we saw for HNLs)

Properties of Σ, Γ and simplifications

- The tensors have symmetry properties and will often be sparse.
  $\rightarrow$ Only a restricted number of elements will need to be computed.

- Γ^{ij} is hermitian.
  $\Sigma_b^{(ij)(kl)}$ is hermitian under $(ij) \leftrightarrow (kl)$ and symmetric under $i \leftrightarrow j$ and $k \leftrightarrow l$.

- If all couplings are **real**, Γ^{ij} is symmetric and $\Sigma_b^{(ij)(kl)} \equiv \Sigma_b^{ijkl}$ completely symmetric.

- If all the diagrams contributing to a given process **involve the same couplings**, then Γ^{ij} is diagonal and $\Sigma_b^{(ij)(kl)}$ diagonal in i, k and j, l (applies to HNLs!)

- For a dense $\Sigma_b^{(ij)(kl)}$, the efficiencies will need to be reported for interference terms too.

Note on the τ dependence of Σ

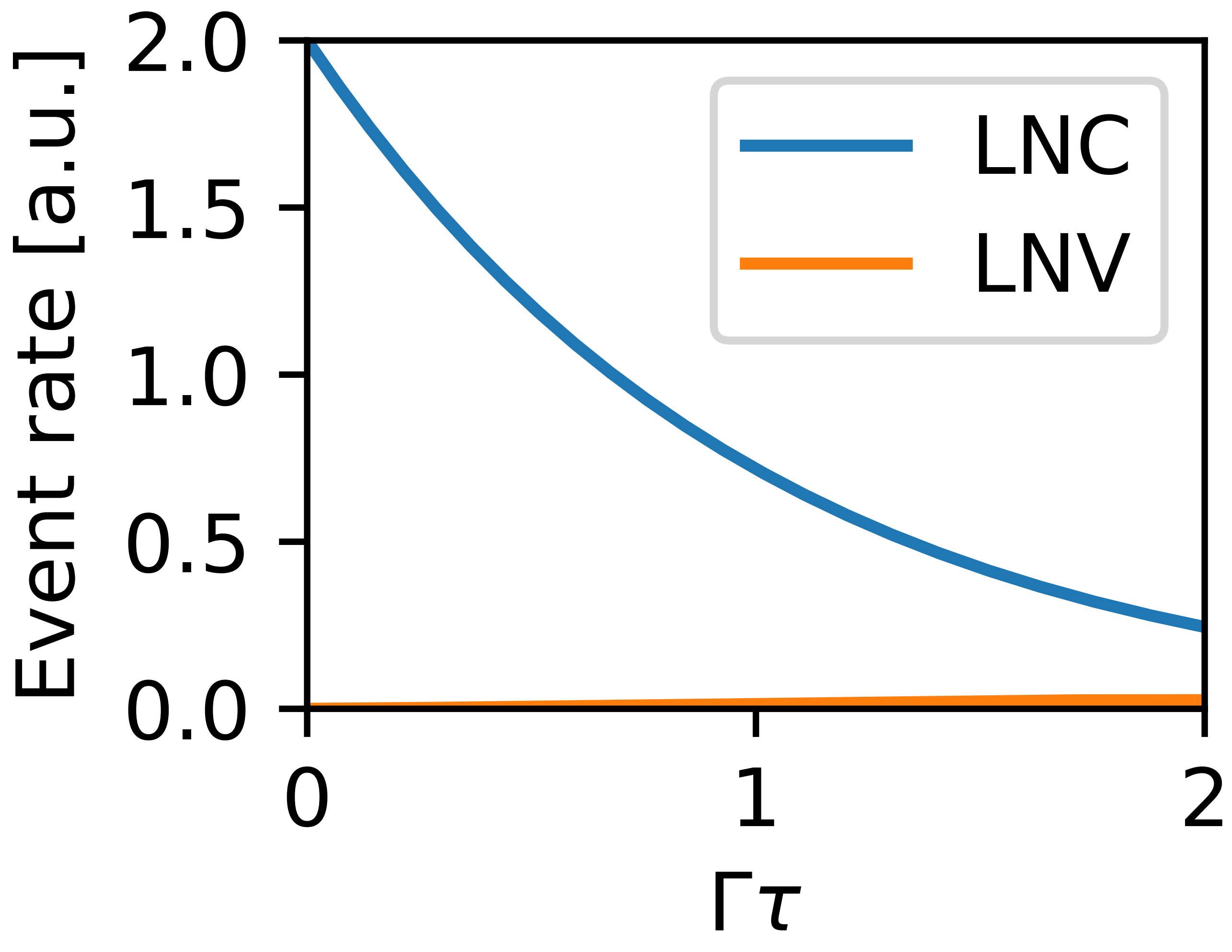
- $\Sigma(m, \tau)$ depends of the lifetime τ through the experimental signal efficiencies.
- For a promptly-decaying FIP, τ doesn't matter: $\Sigma(m, \tau) \equiv \Sigma(m)$.
- For a very long-lived FIP ($\gamma\tau \gg L_{\rm exp}$), the efficiency goes as $\propto \tau^{-1}$.
  In this case $\Sigma(m, \tau) \cong \Sigma_0(m) \times (\tau_0/\tau)$ and the $1/\tau$ cancels the $1/\Gamma_{\rm total}$, leading to the "ε^4" scaling that is typical of long-lived particles:

$$s_b = \tau \times \Sigma_b^{(ij)(kl)}(m, \tau)\varepsilon_i^* \varepsilon_j^* \varepsilon_k \varepsilon_l \cong \left(\tau_0 \Sigma_{0,b}^{(ij)(kl)}(m)\right) \varepsilon_i^* \varepsilon_j^* \varepsilon_k \varepsilon_l$$

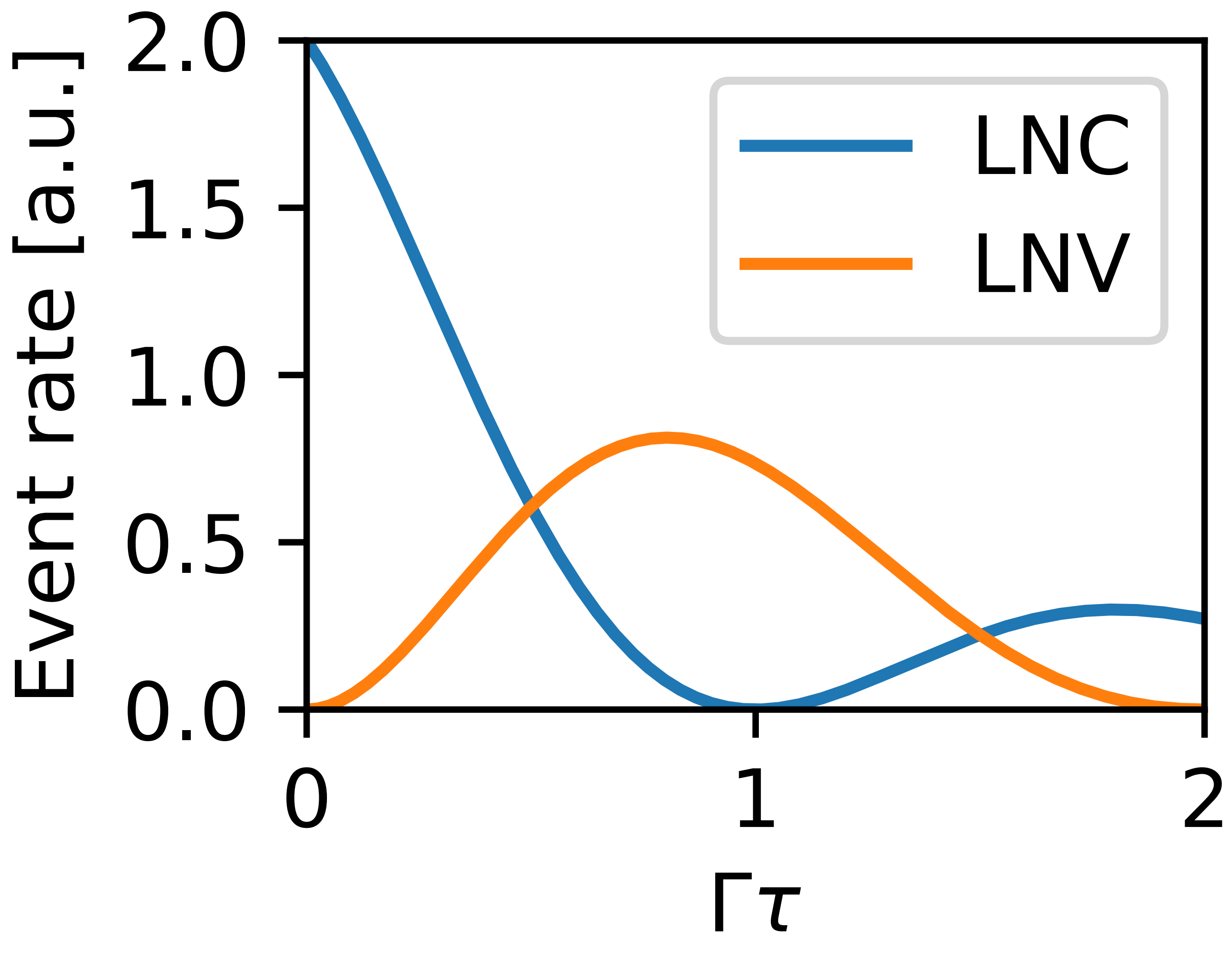
Coherent HNL oscillations

- If $\delta M = M_2 - M_1$ is small enough → coherent oscillations of frequency $\delta M / 2\pi$.
  (in their rest frame of the HNL: the phase is $\delta M \times$ proper time)
  [Antusch, Cazzato, Fischer: 1709.03797], [Beuthe: hep-ph/0109119], [Tastet: master thesis], [Antusch, Rosskopp: 2012.05763]
  NEW TODAY! [Antusch, Hajer, Rosskopp: 2210.10738]
- **Three** regimes of interest, depending on how δM^{-1} compares with the proper time scale $\Gamma^{-1} = \min(\Gamma_N^{-1}, L_{\text{exp}}/\gamma)$ probed by the experiment.

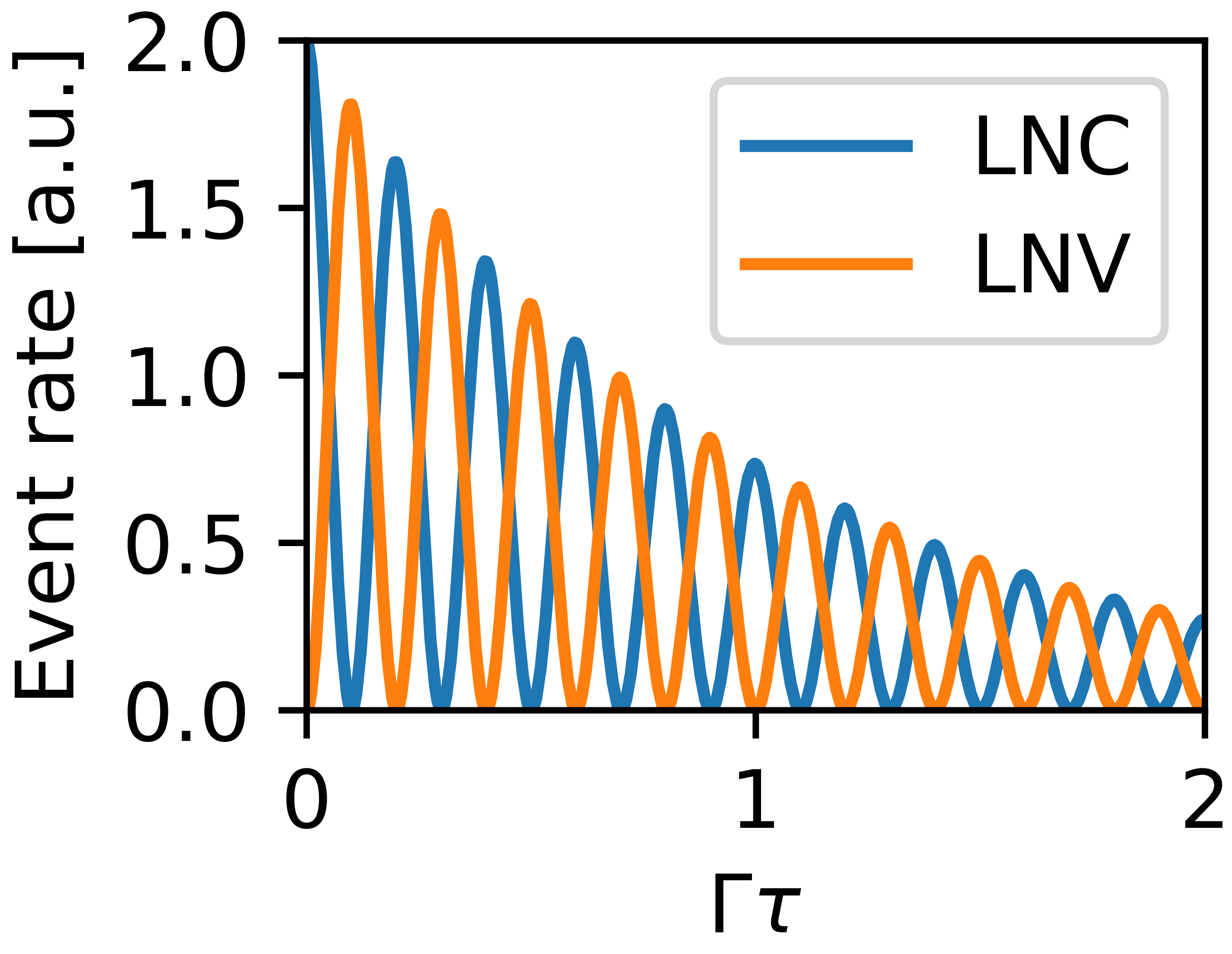
$\delta M \ll \Gamma$: Dirac-like



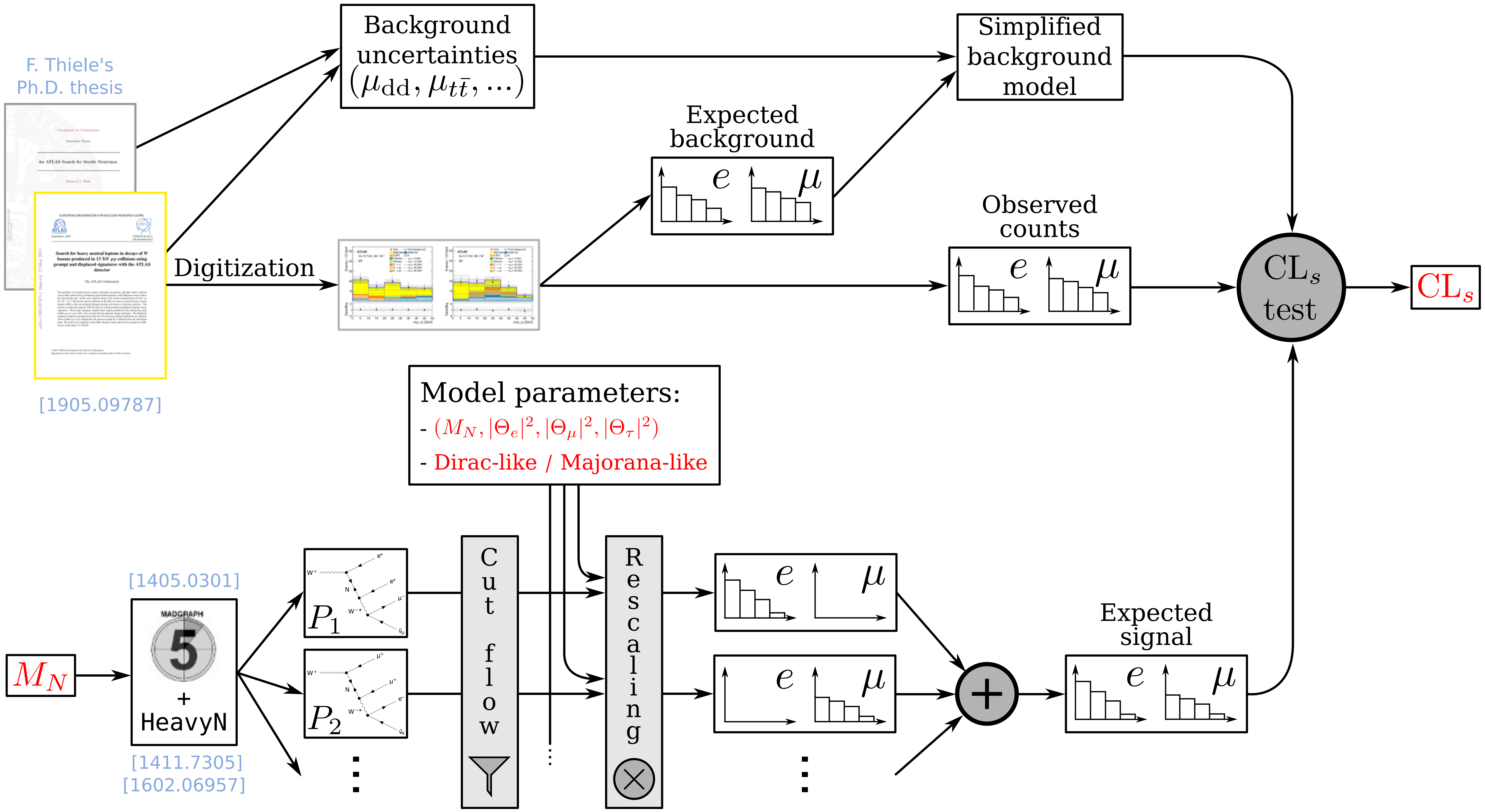
$\delta M \sim \pi\Gamma$: resolvable osc.



$\delta M \gg \Gamma$: Majorana-like



Reinterpretation of the prompt ATLAS search

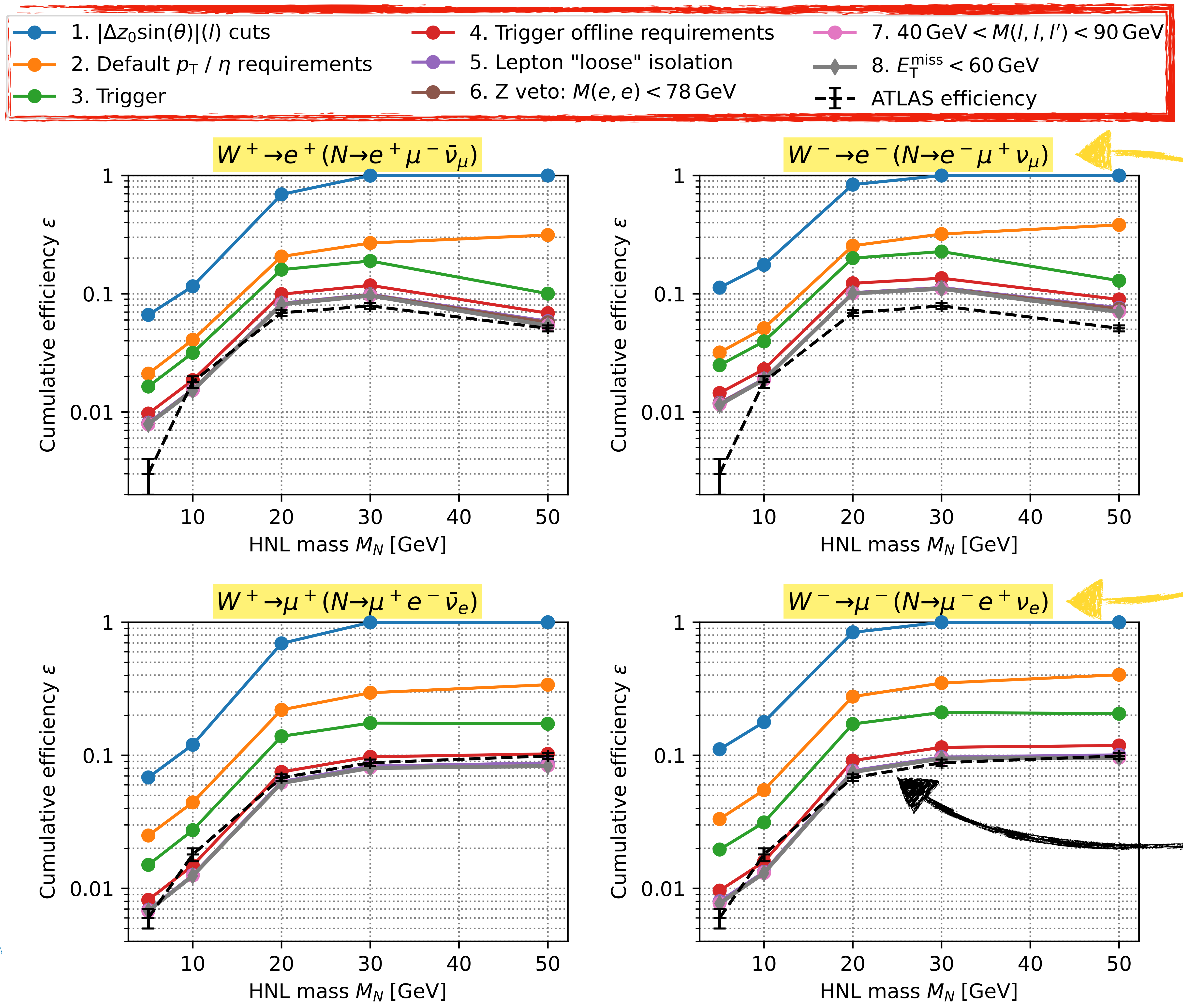


ATLAS prompt search: cutflow

	Muon channel	Electron channel
No OSSF	exactly $\mu^{\pm}\mu^{\pm}e^{\mp}$ signature	exactly $e^{\pm}e^{\pm}\mu^{\mp}$ signature
"Minimal" detector cuts	$p_{\mathrm{T}}(\mu) > 4\,\mathrm{GeV}$ $p_{\mathrm{T}}(e) > 7\,\mathrm{GeV}$ (2015), $4.5\,\mathrm{GeV}$ (2016)	
"Softest" available triggers	leading muon $p_{\mathrm{T}} > 23\,\mathrm{GeV}$ subleading muon $p_{\mathrm{T}} > 14\,\mathrm{GeV}$	leading electron $p_{\mathrm{T}} > 27\,\mathrm{GeV}$ subleading electron $p_{\mathrm{T}} > 10\,\mathrm{GeV}$
Avoid Z pole in e channel		$m(e,e) < 78\,\mathrm{GeV}$
Further cuts with almost no effect on signal	$40 < m(\ell,\ell,\ell') < 90\,\mathrm{GeV}$ b-jet veto $E_{\mathrm{T}}^{\mathrm{miss}} < 60\,\mathrm{GeV}$	

Signal efficiency validation

Cuts applied in order



Cumulative efficiencies = efficiencies with the *k* first cuts applied

Processes

Black line = reported by ATLAS

Extrapolating the expected signal

- The expected signal **in bin *b***, as a function of model parameters, is:

$$s_b(M_N, \tau_N, \Theta_e, \Theta_\mu, \Theta_\tau) = \frac{\sum_{\alpha,\beta} |\Theta_\alpha|^2 \Sigma_{b,\alpha\beta}(M_N, \tau_N) |\Theta_\beta|^2}{\sum_\gamma |\Theta_\gamma|^2 \hat{\Gamma}_\gamma(M_N)}$$

  with the signal matrix $\Sigma_{b,\alpha\beta}(M_N, \tau_N) = L_{\text{int}} \times \sum_P \varepsilon_{P,b}(M_N, \tau_N) \times \frac{c_P}{c_\Gamma} \times \hat{\sigma}_P(M_N, \tau_N) \times \Gamma_{\text{ref}}$

  where the sum runs over processes *P* mediated by flavours α at production and β at decay, and $\hat{\sigma}_P$ is the cross-section computed for **unit mixing angles** and assuming the (small) reference width Γ_{ref}, and with $\hat{\Gamma}_\gamma$ the sum of the partial widths mediated by flavour γ, computed for a **unit mixing angle**.

- The efficiencies $\varepsilon_P(M_N, \tau_N)$ are typically computed on a $M_N \times \tau_N$ grid.
  To compute $\Sigma_{b,\alpha\beta}(M_N, \tau_N)$ at the physical lifetime $\Gamma_{\text{total}}^{-1}(M_N, \Theta_e, \Theta_\mu, \Theta_\tau)$, the efficiencies should be interpolated in τ_N between the nearest grid points.

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$$s_b(M_N, \tau_N, \Theta_e, \Theta_\mu, \Theta_\tau) = \frac{\sum_{\alpha,\beta} |\Theta_\alpha|^2 \Sigma_{b,\alpha\beta}(M_N, \tau_N) |\Theta_\beta|^2}{\sum_\gamma |\Theta_\gamma|^2 \hat{\Gamma}_\gamma(M_N)}$$

Multipliers for Dirac/Majorana

with the signal matrix $\Sigma_{b,\alpha\beta}(M_N, \tau_N) = L_{\text{int}} \times \sum_P \varepsilon_{P,b}(M_N, \tau_N) \times \frac{c_P}{c_\Gamma} \times \hat{\sigma}_P(M_N, \tau_N) \times \Gamma_{\text{ref}}$

where the sum runs over processes *P* mediated by flavours α at production and β at decay, and $\hat{\sigma}_P$ is the cross-section computed for **unit mixing angles** and assuming the (small) reference width Γ_{ref}, and with Γ_γ the sum of the partial widths mediated by flavour γ, computed for a **unit mixing angle**.

- The efficiencies $\varepsilon_P(M_N, \tau_N)$ are typically computed on a $M_N \times \tau_N$ grid.
To compute $\Sigma_{b,\alpha\beta}(M_N, \tau_N)$ at the physical lifetime $\Gamma_{\text{total}}^{-1}(M_N, \Theta_e, \Theta_\mu, \Theta_\tau)$, the efficiencies should be interpolated in τ_N between the nearest grid points.

Extrapolating the expected signal

- The expected signal **in bin *b***, as a function of model parameters, is:

Only non-trivial part that we need from experiments = signal efficiencies for each pair of process *P* and bin *b*

$$s_b(M_N, \tau_N, \Theta_e, \Theta_\mu, \Theta_\tau) = \frac{\sum_{\alpha,\beta} |\Theta_\alpha|^2 \Sigma_{b,\alpha\beta}(M_N, \tau_N) |\Theta_\beta|^2}{\sum_\gamma |\Theta_\gamma|^2 \hat{\Gamma}_\gamma(M_N)}$$

Multipliers for Dirac/Majorana

with the signal matrix $\Sigma_{b,\alpha\beta}(M_N, \tau_N) = L_{\text{int}} \times \sum_P \varepsilon_{P,b}(M_N, \tau_N) \times \frac{c_P}{c_\Gamma} \times \hat{\sigma}_P(M_N, \tau_N) \times \Gamma_{\text{ref}}$

where the sum runs over processes *P* mediated by flavours α at production and β at decay, and $\hat{\sigma}_P$ is the cross-section computed for **unit mixing angles** and assuming the (small) reference width Γ_{ref}, and with Γ_γ the sum of the partial widths mediated by flavour γ, computed for a **unit mixing angle.**

- The efficiencies $\varepsilon_P(M_N, \tau_N)$ are typically computed on a $M_N \times \tau_N$ grid.
  To compute $\Sigma_{b,\alpha\beta}(M_N, \tau_N)$ at the physical lifetime $\Gamma^{-1}_{\text{total}}(M_N, \Theta_e, \Theta_\mu, \Theta_\tau)$, the efficiencies should be interpolated in τ_N between the nearest grid points.

Quasi-Dirac HNLs

(Note that "2 Dirac-like HNLs" = "1 Dirac HNL" up to a rescaling of Θ by $\sqrt{2}$)

Nature	$c_P,\ P \in \mathrm{LNC}$	$c_P,\ P \in \mathrm{LNV}$	$c_\Gamma = \Gamma_N/\Gamma_{\mathrm{Maj.}}$
One Majorana HNL (reference)	**1**	**1**	**1**
One Dirac HNL	1	0	1/2
Quasi-Dirac pair: **Majorana-like**	2	2	1
Quasi-Dirac pair: **Dirac-like**	4	0	1

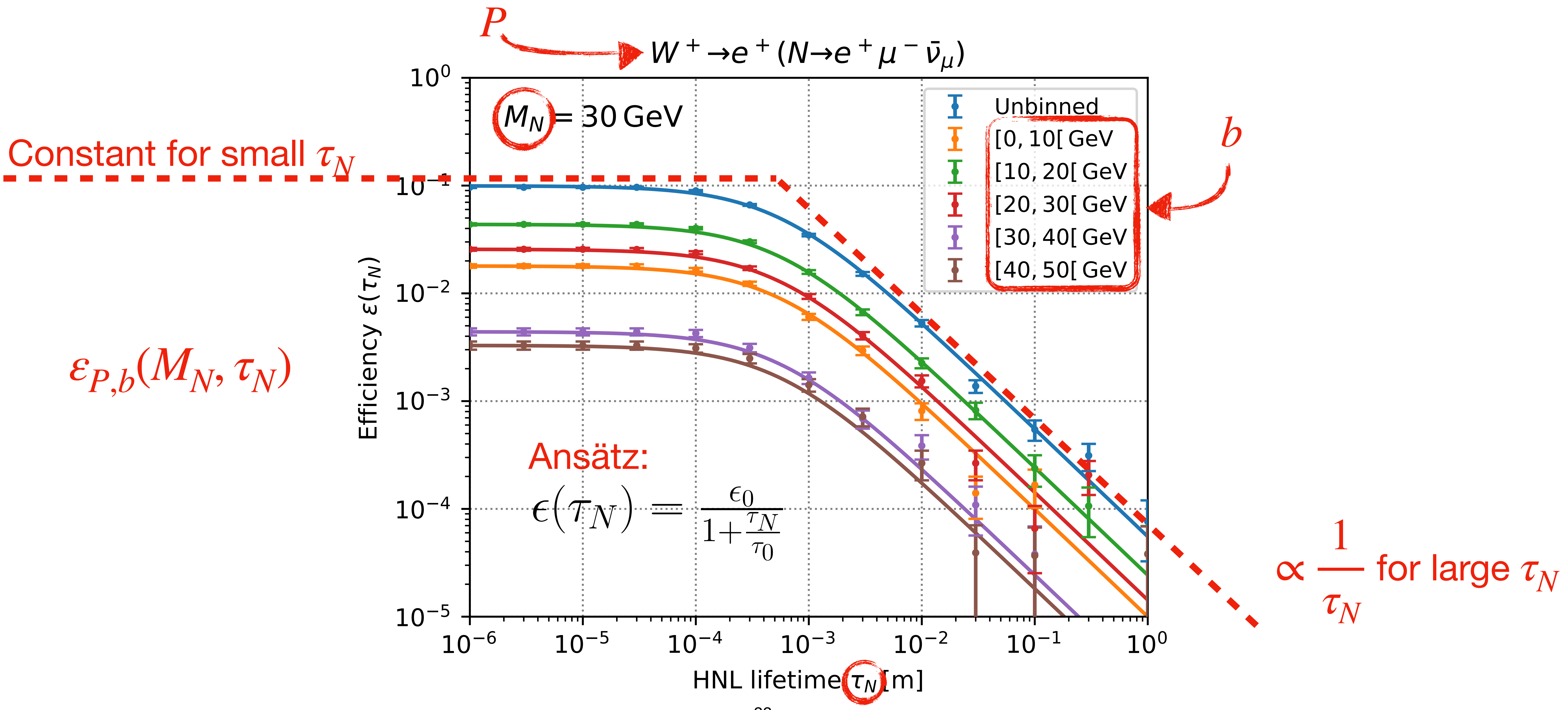
- If HNLs are quasi-Dirac, it is enough to compute the cross-sections and width for one Majorana HNL, as long as we correct the cross-sections and total width with the following multiplicative factors:

$$s_b = L_{\mathrm{int}} \times \sum_P \varepsilon_{P,b}(M_N, \tau_N) \times c_P \times \sigma_P(M_N, \Theta_e, \Theta_\mu, \Theta_\tau)$$

$$\Gamma_{\mathrm{total}}(M_N, \Theta_e, \Theta_\mu, \Theta_\tau) = c_\Gamma |\Theta_\alpha|^2 \hat{\Gamma}_\alpha(M_N)$$

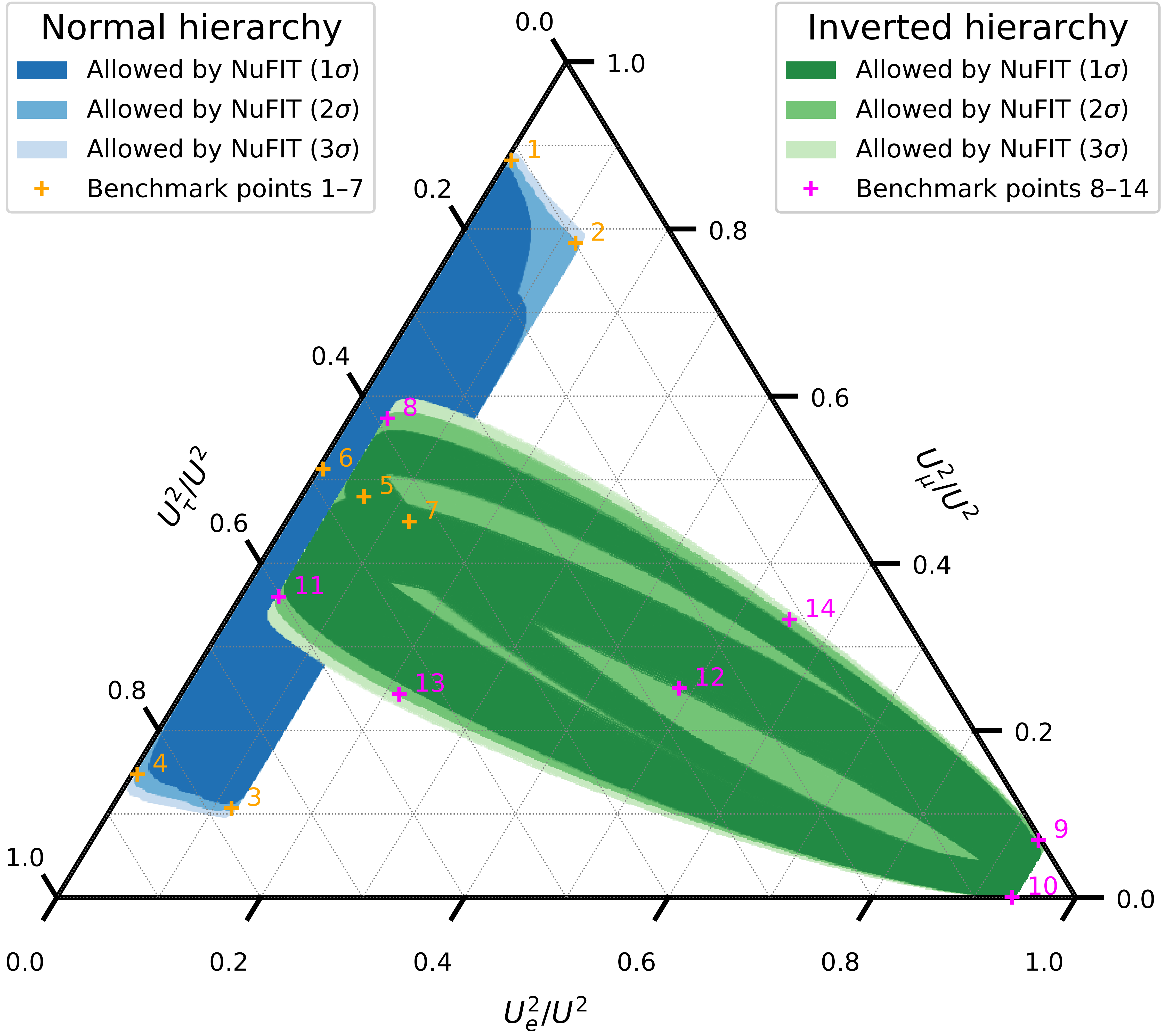
Interpolation of efficiencies

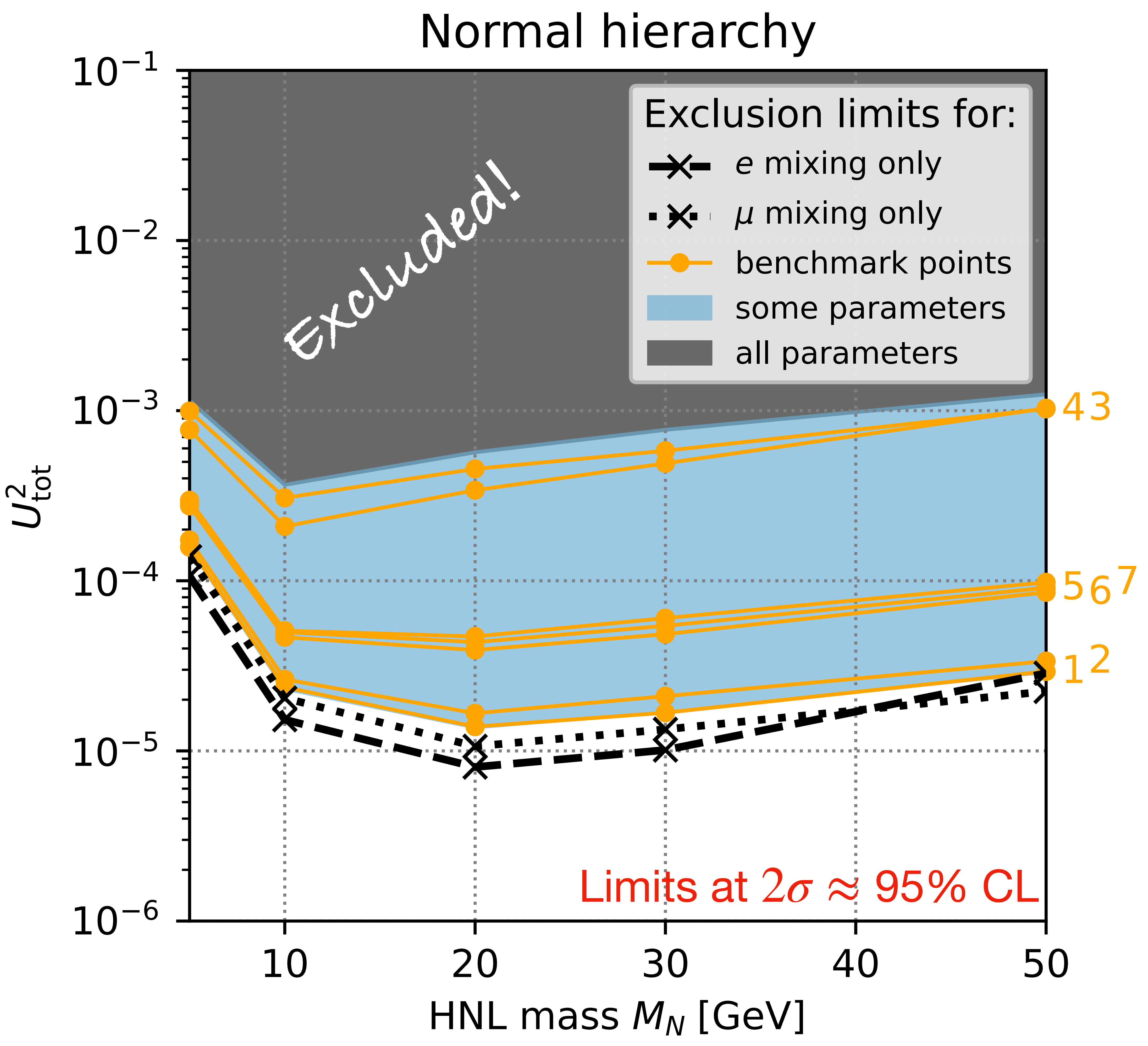
Example from the reinterpretation of the prompt search



Reinterpretation of limits [Tastet, Ruchayskiy, Timiryasov: 2107.12980]

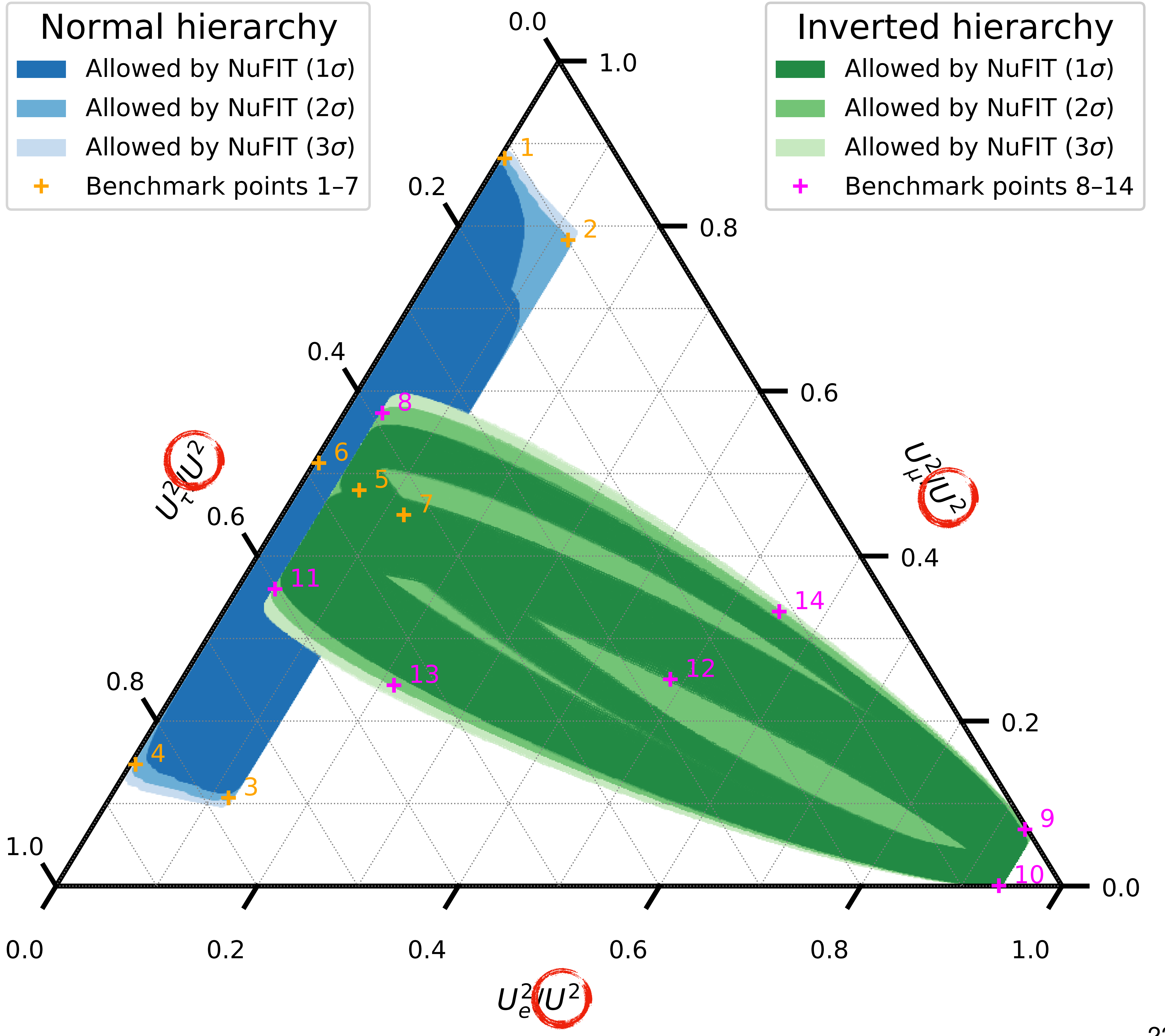
How to read the results

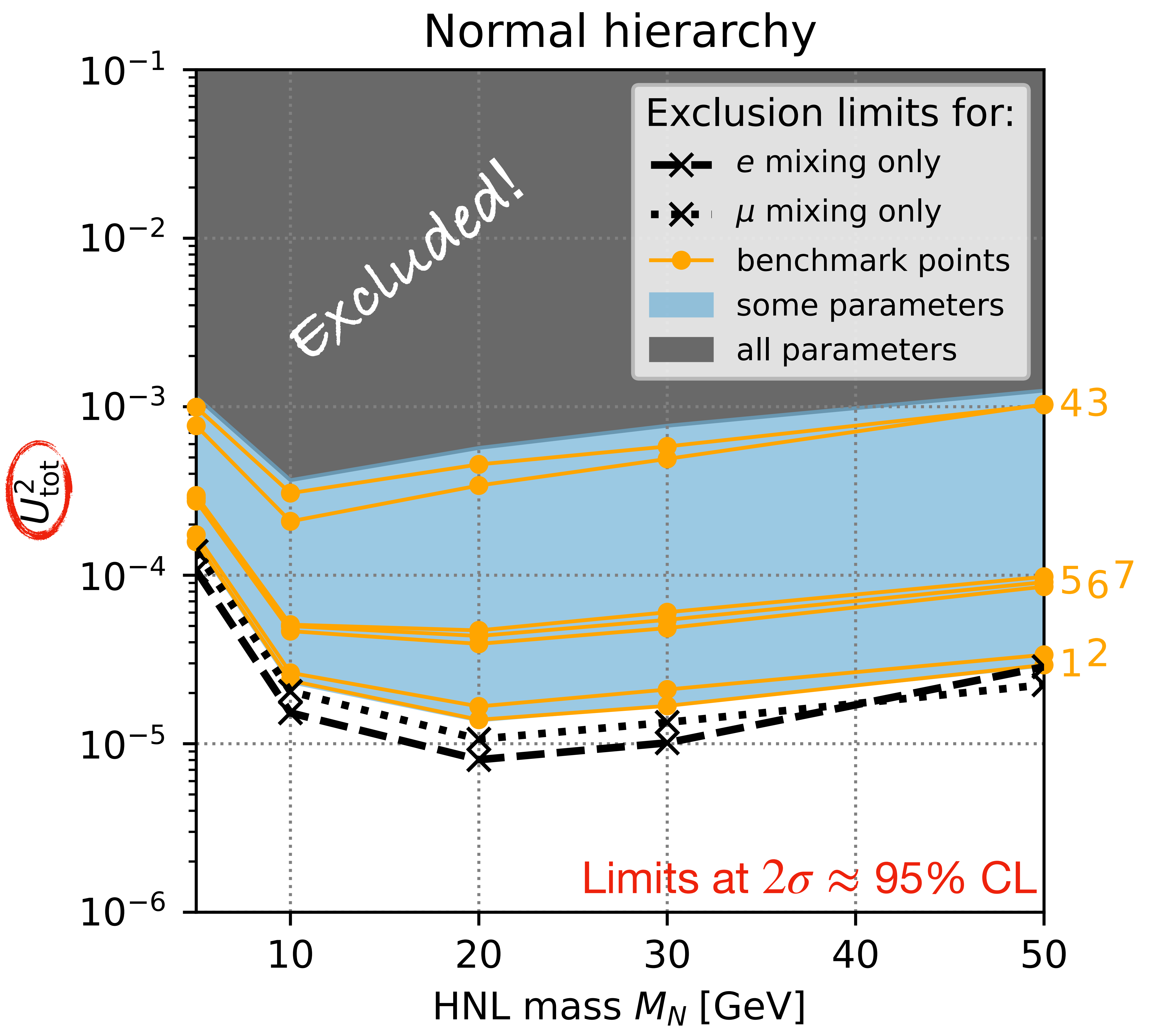




Reinterpretation of limits [Tastet, Ruchayskiy, Timiryasov: 2107.12980]

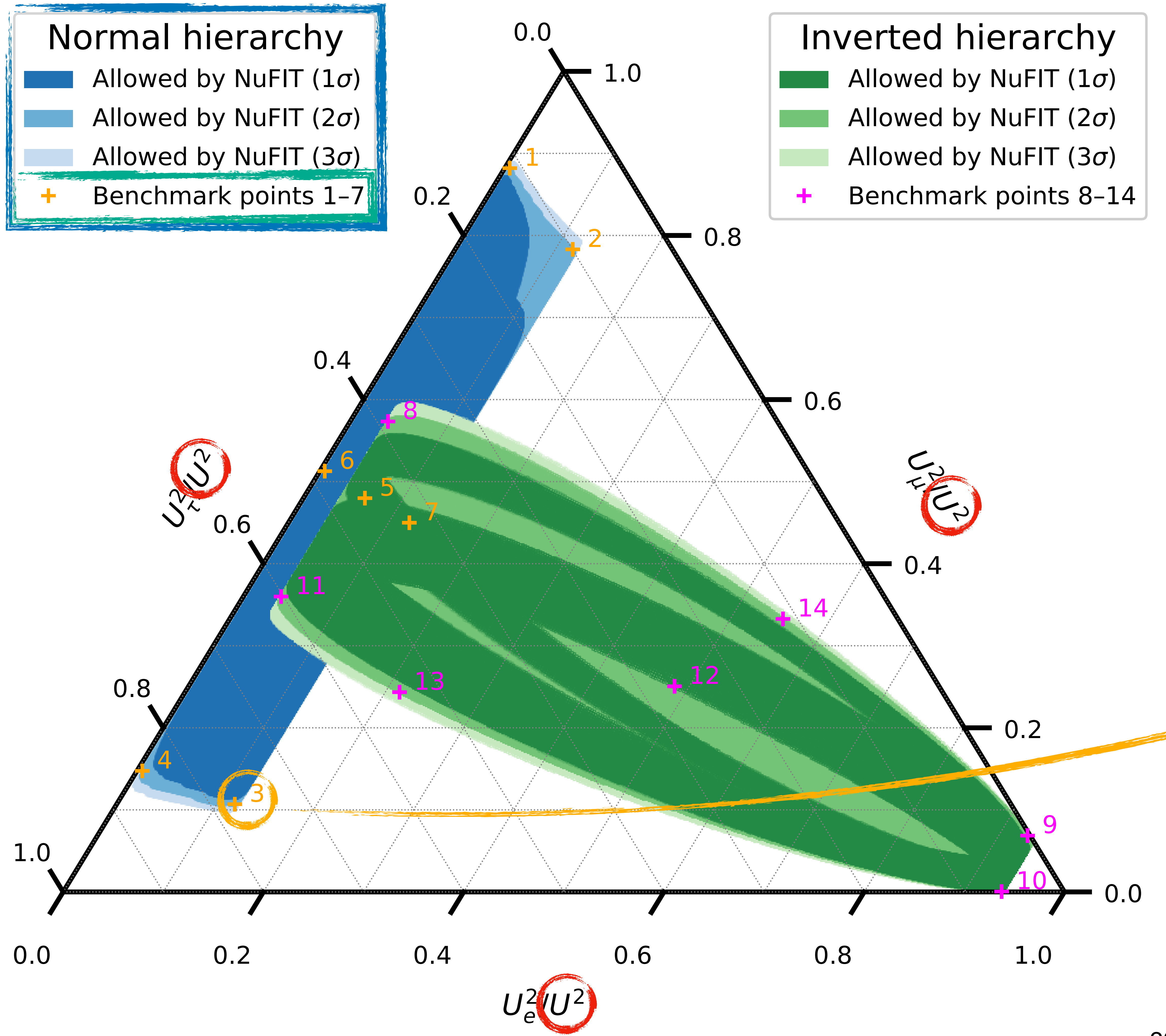
How to read the results → Decompose 4d parameter space into 2d + 2d

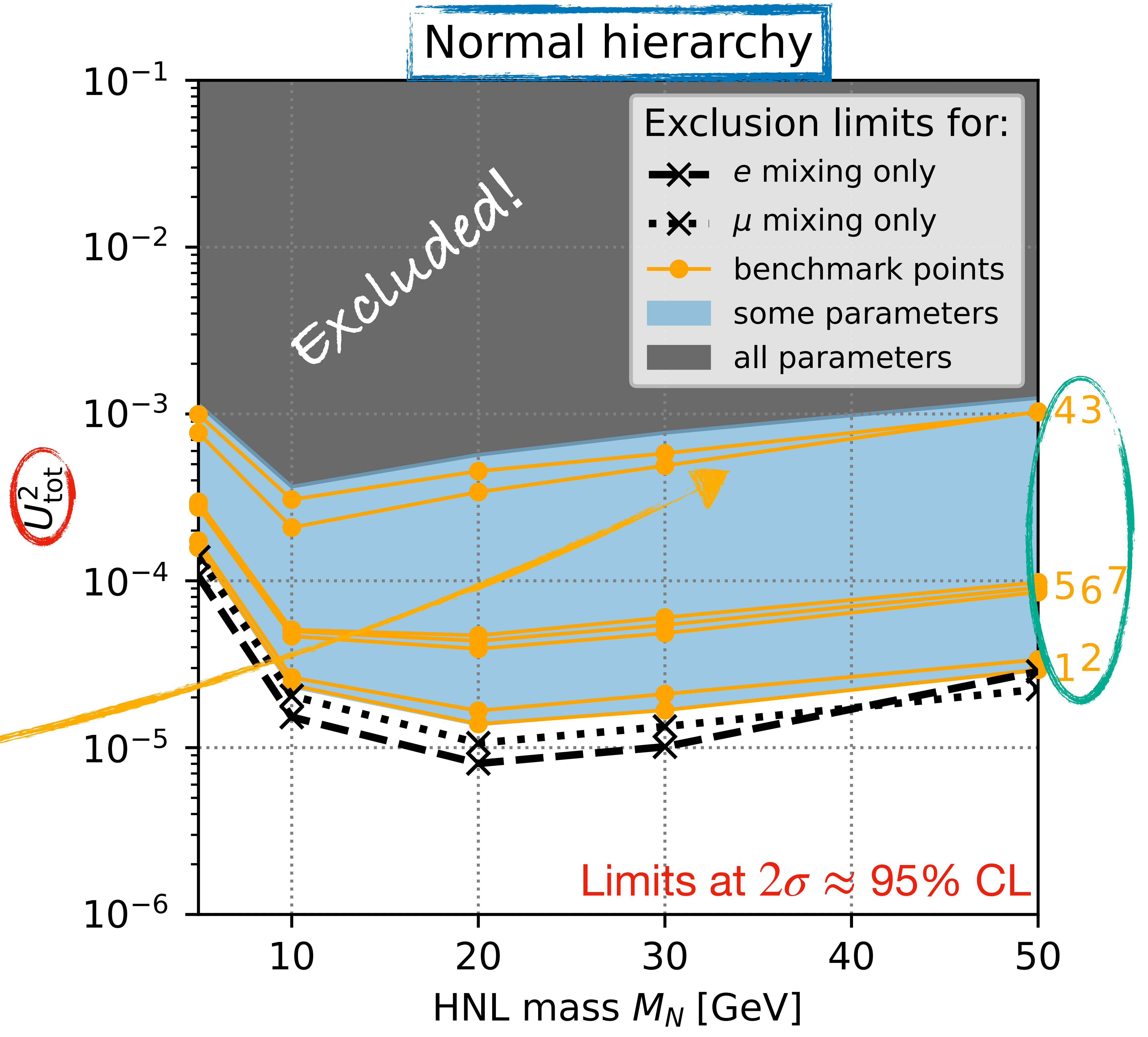




Reinterpretation of limits [Tastet, Ruchayskiy, Timiryasov: 2107.12980]

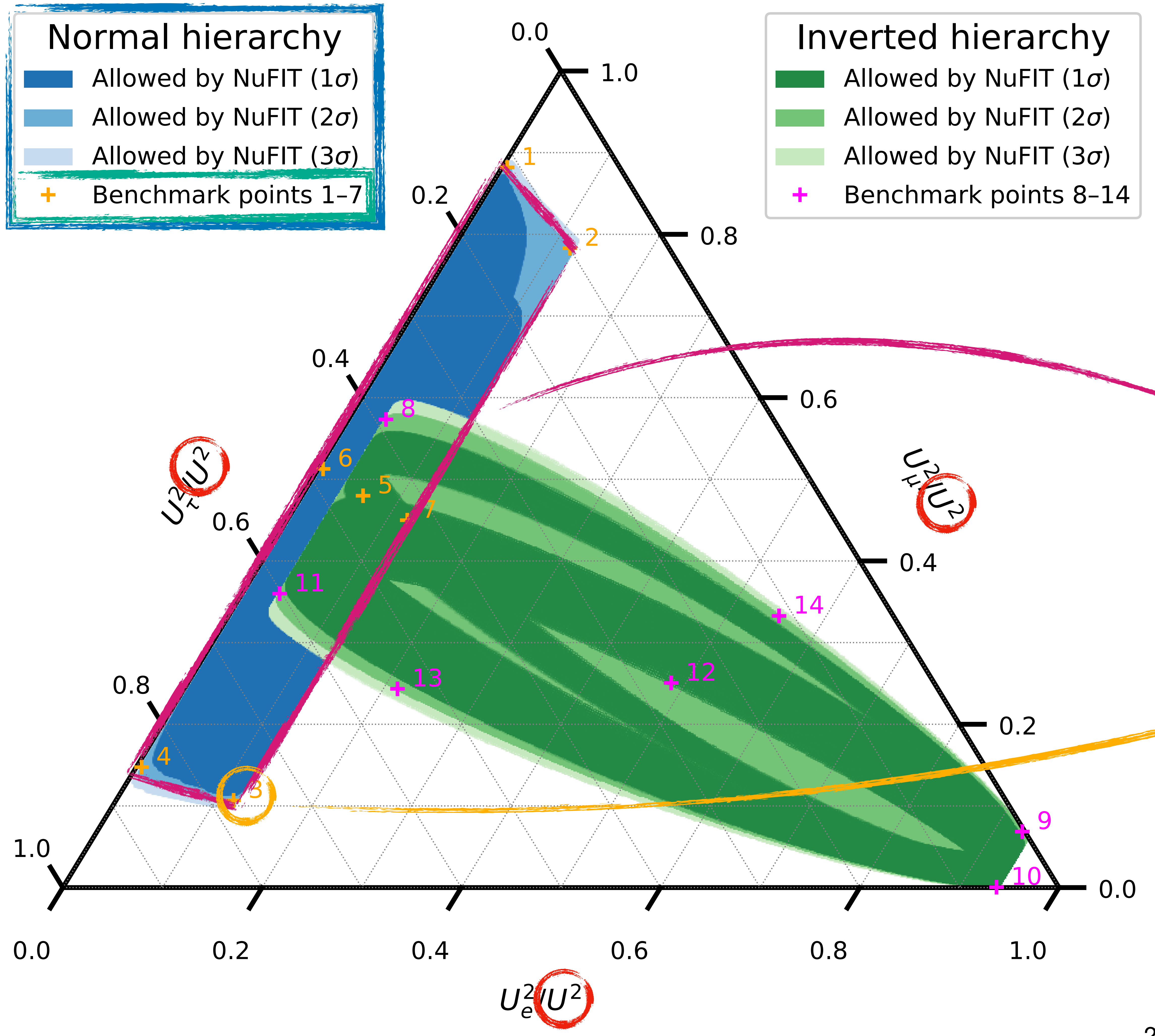
How to read the results → Decompose 4d parameter space into 2d + 2d

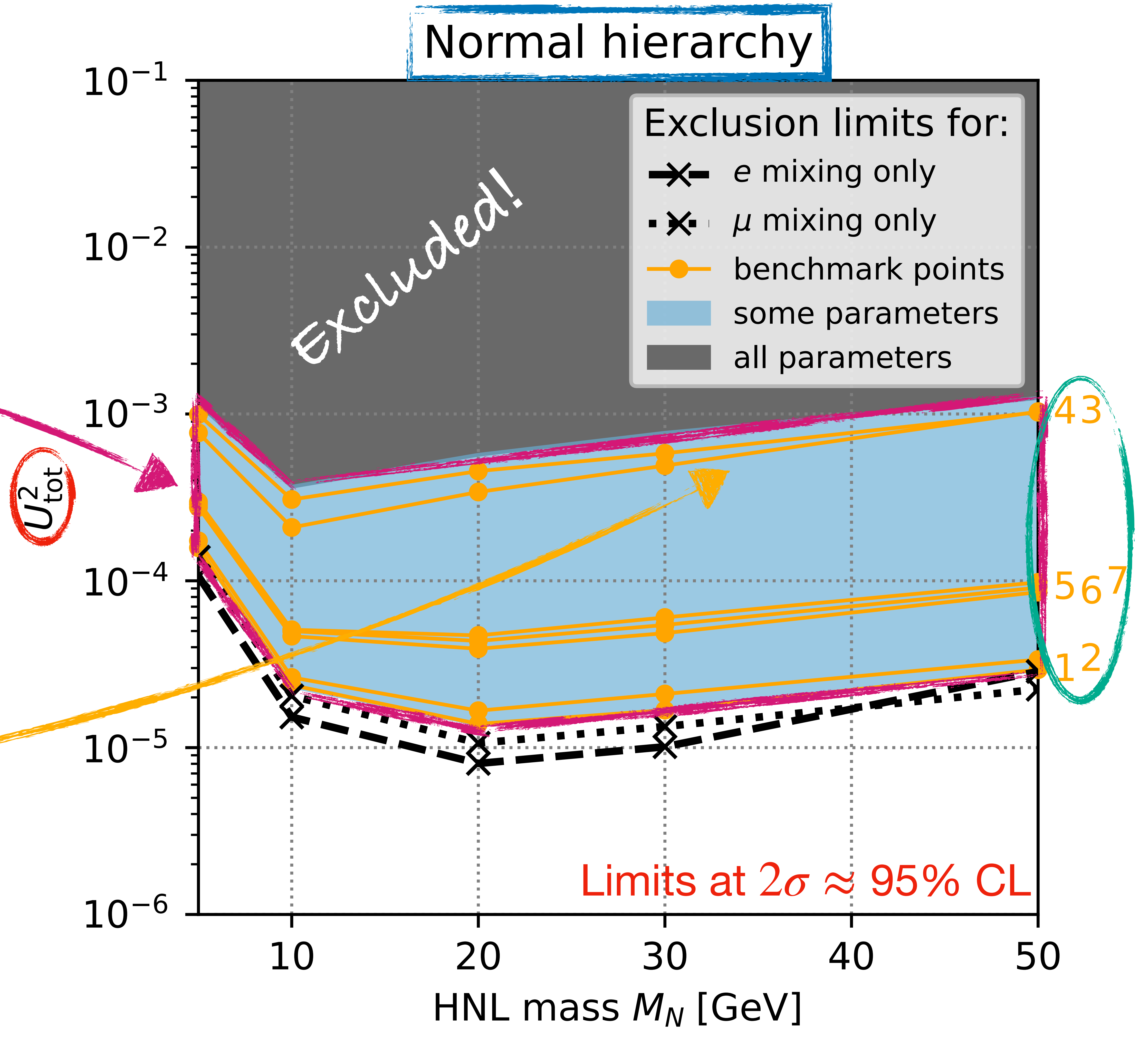




Reinterpretation of limits [Tastet, Ruchayskiy, Timiryasov: 2107.12980]

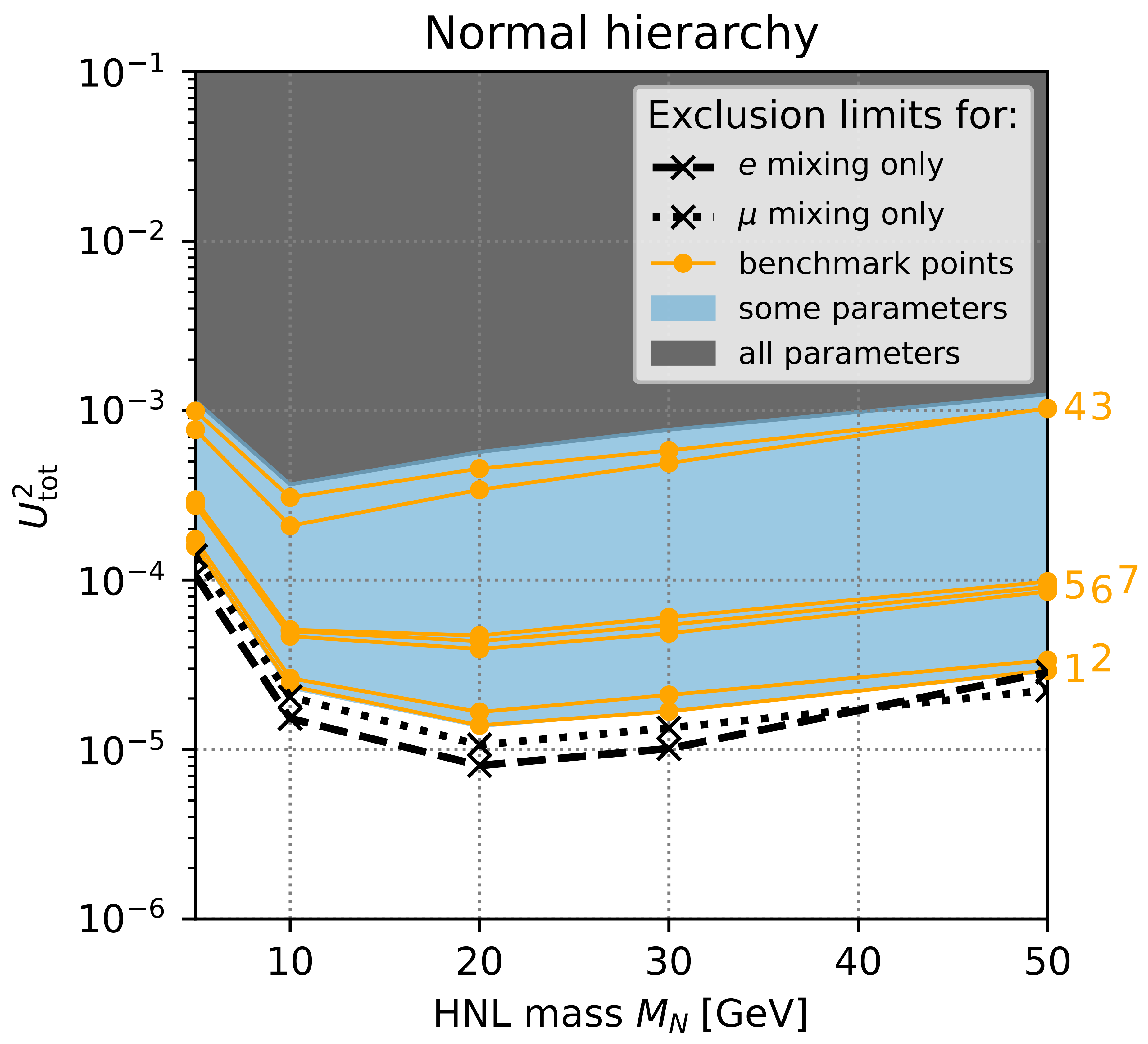
How to read the results → Decompose 4d parameter space into 2d + 2d





Reinterpretation of limits [Tastet, Ruchayskiy, Timiryasov: 2107.12980]

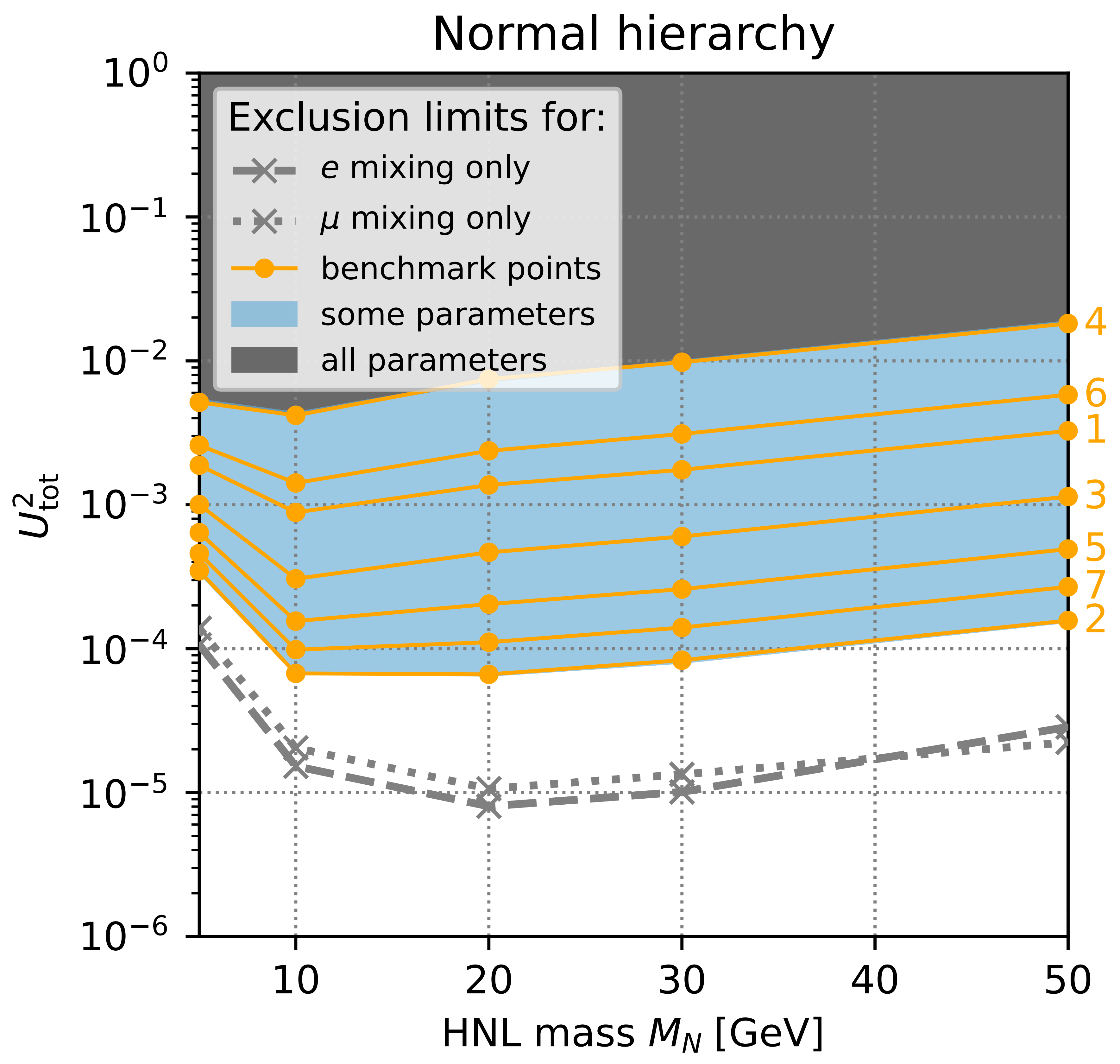
Majorana-like HNLs



- Recast limits almost always weaker than single-flavour (up to 1 order of magnitude)
- Weakest limits ↔ largest τ mixing
  Smaller BR in signal channels
  Many HNLs produced with taus
  → Search for τ's to close the blind spots!
- Similar results for the inverted hierarchy

Reinterpretation of limits [Tastet, Ruchayskiy, Timiryasov: 2107.12980]

Dirac-like HNLs



- Previously: no sensitivity for single-flavour
- Limits weaker by up to 3 orders of magnitude vs. original benchmarks (weakest limits when a mixing is suppressed)
- There exist allowed models 3 orders of magnitude above the reported limit
- Increased variance between benchmarks → weaker marginalised limit