Limits on Heavy Neutral Leptons and their Connection with Effective Operators

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SM Open Problems

zoom.us video

The SM is successful and predicts a wide variety of phenomena that has been tested experimentally to an incredible accuracy.

However, there are some open problems

Represent our best window for New Physics

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zoom.us video

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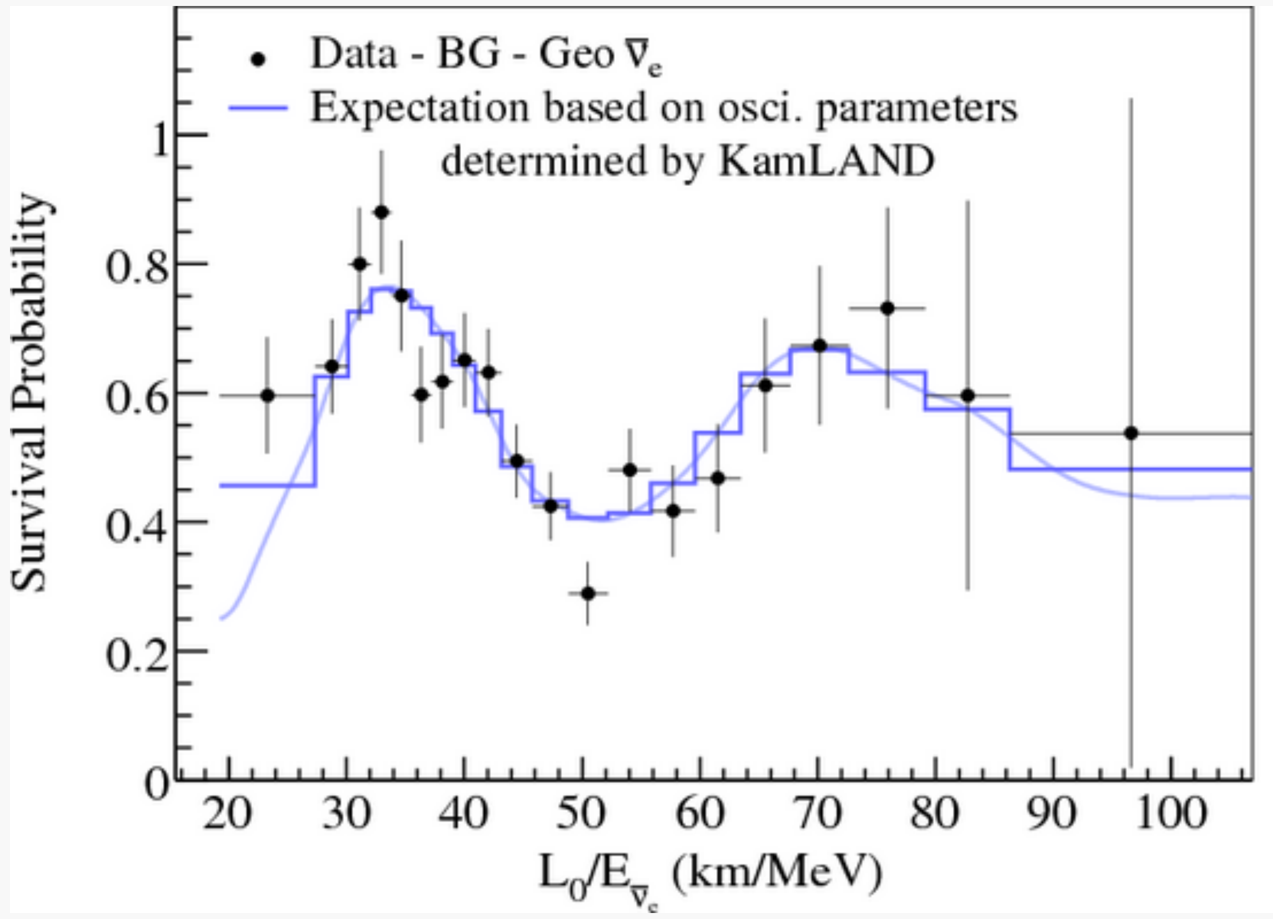
Represent our best window for New Physics

SM Open Problems

The discovery of neutrino oscillations points that



$\Rightarrow$ Neutrinos have (non-degenerate) masses

$\Rightarrow$ L_α violated

SM Open Problems

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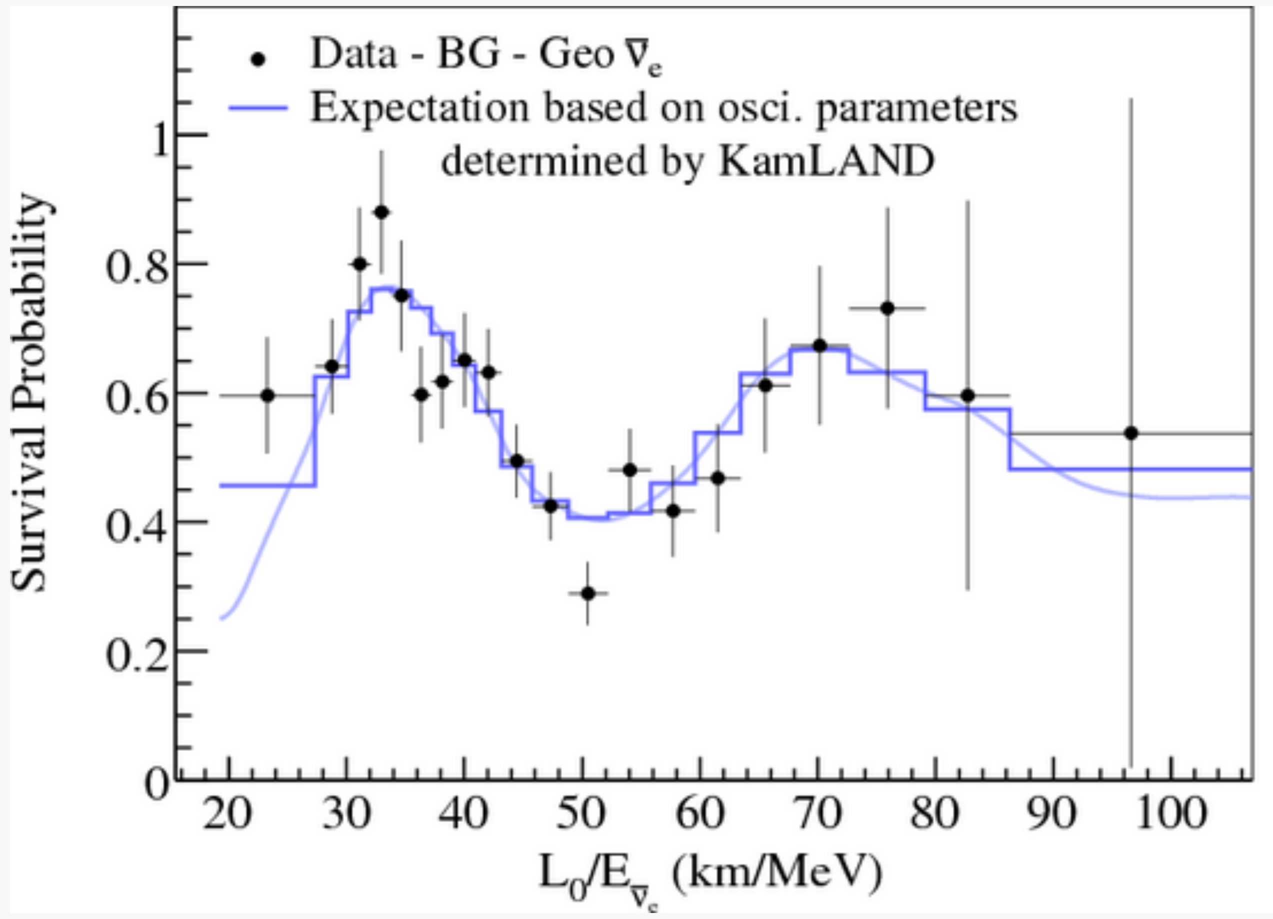

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They could hold the key to understanding some other SM open problems

– Dark matter candidate

SM Open Problems

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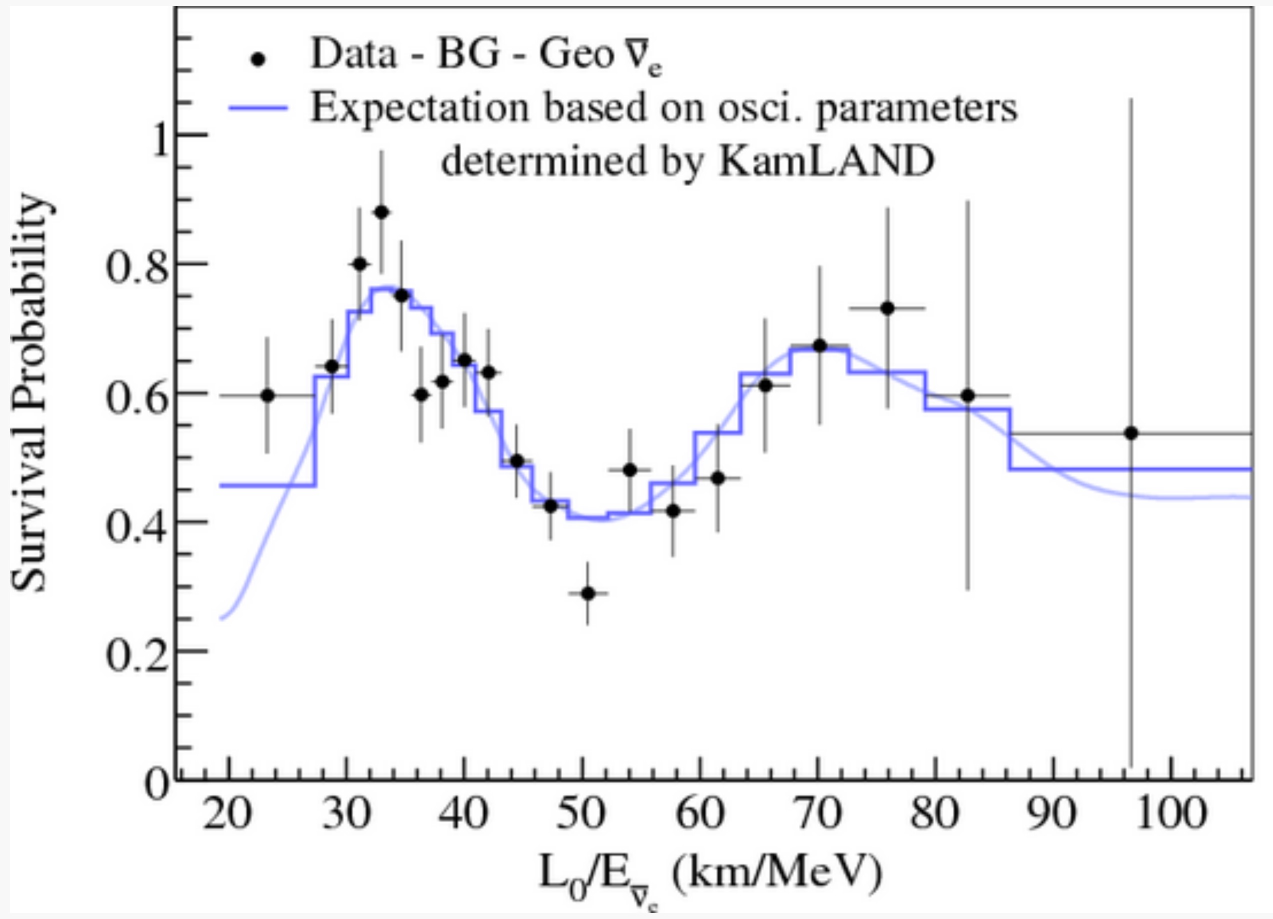

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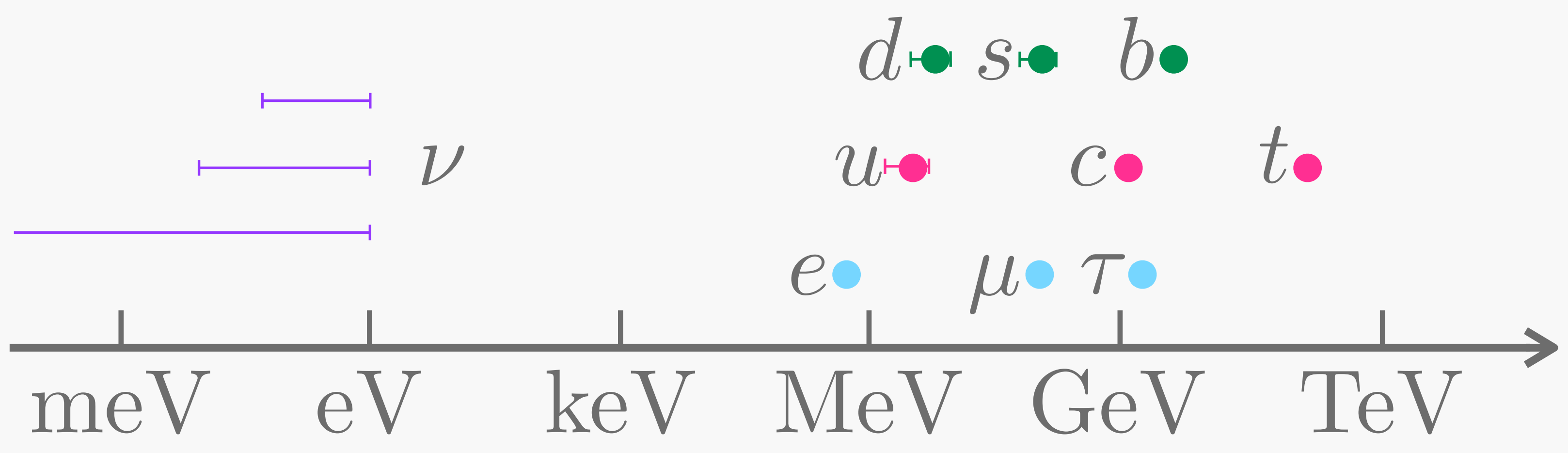

no SM explanation
for Yukawa ordering

SM Open Problems

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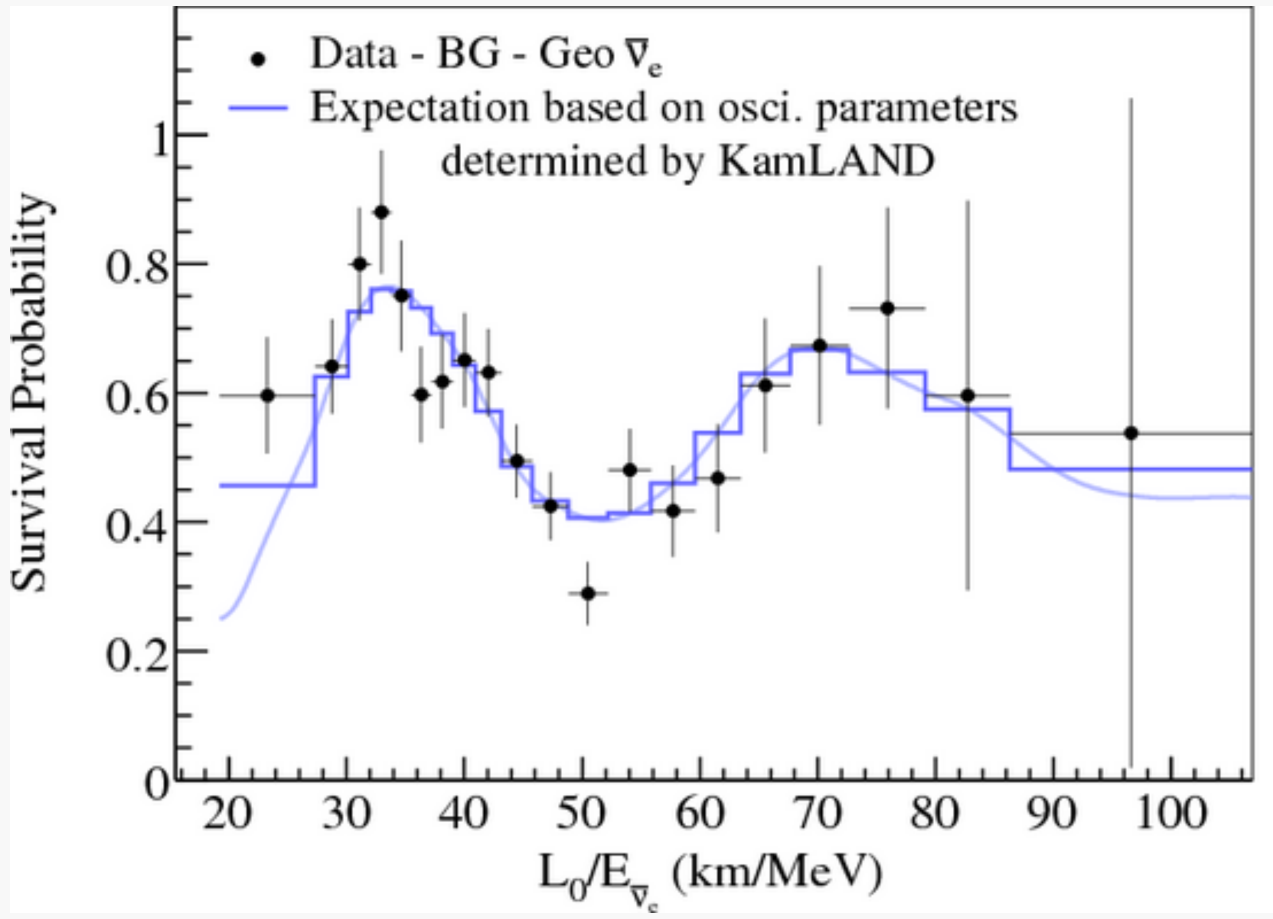

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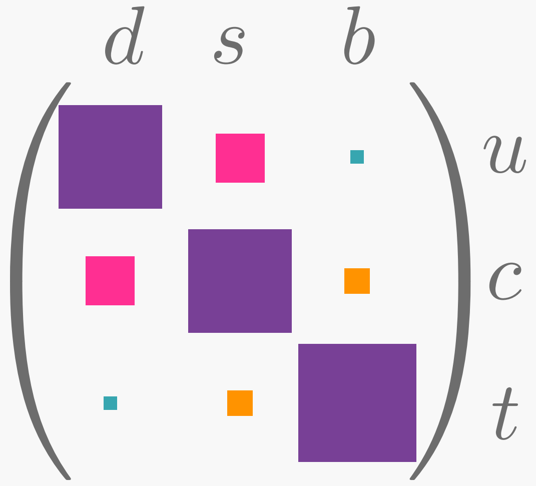
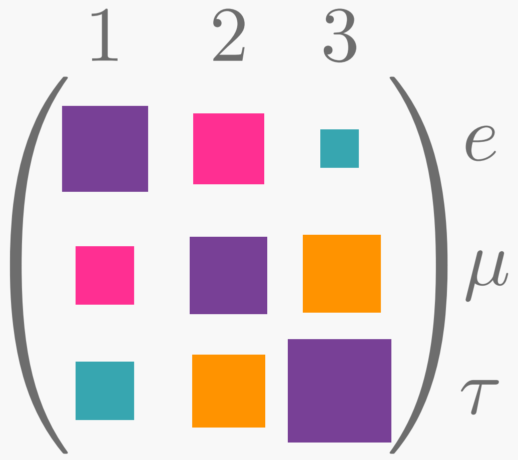
$V_{\mathrm{CKM}} =$ 

$U_{\mathrm{PMNS}} =$ 

dissimilar pattern of quark and lepton mixings

SM Open Problems

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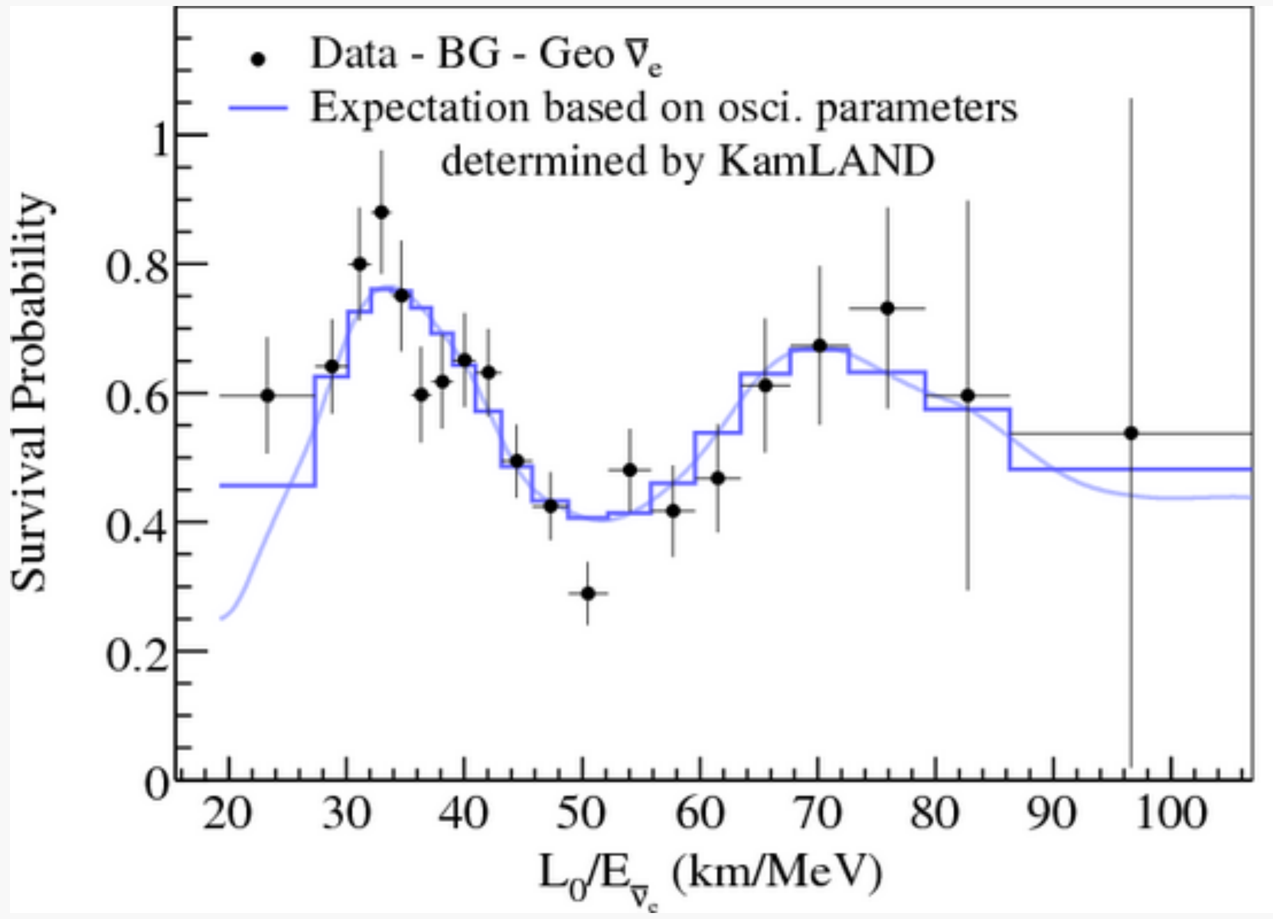
The discovery of neutrino oscillations points that



$\Rightarrow$ Neutrinos have (non-degenerate) masses

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They could hold the key to understanding some other SM open problems

– Dark matter candidate

– Flavor puzzle

– Matter-antimatter asymmetry of the Universe
  Baryogenesis through Leptogenesis

Neutrino Oscillation Parameters

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- The leptonic mixing matrix

If neutrinos are massive, it will be a misalignment between physical (mass) and flavor eigenstates

$$\boxed{\nu_\alpha} = (U_{\text{PMNS}})_{\alpha i} \boxed{\nu_i}$$

mass neutrino
(propagation)
$i = 1, 2, 3$

flavor neutrino
(production/detection)
$\alpha = e, \mu, \tau$

Neutrino Oscillation Parameters

zoom.us video

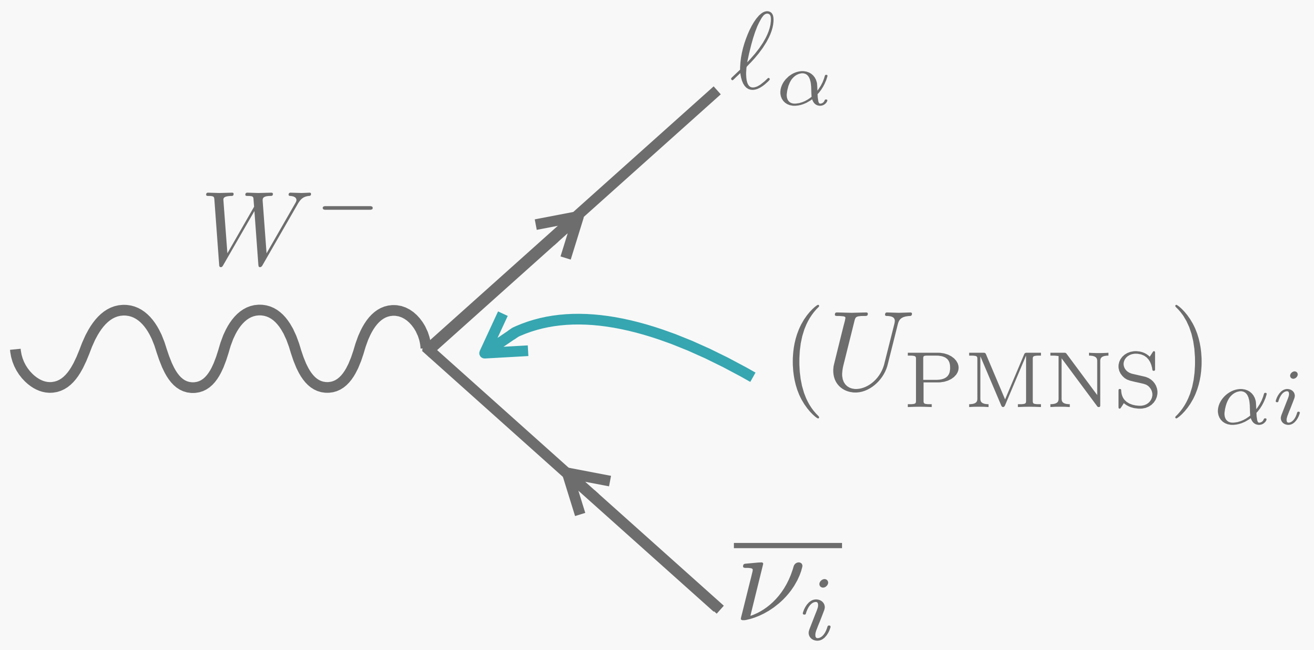
- The leptonic mixing matrix

  If neutrinos are massive, it will be a misalignment between physical (mass) and flavor eigenstates

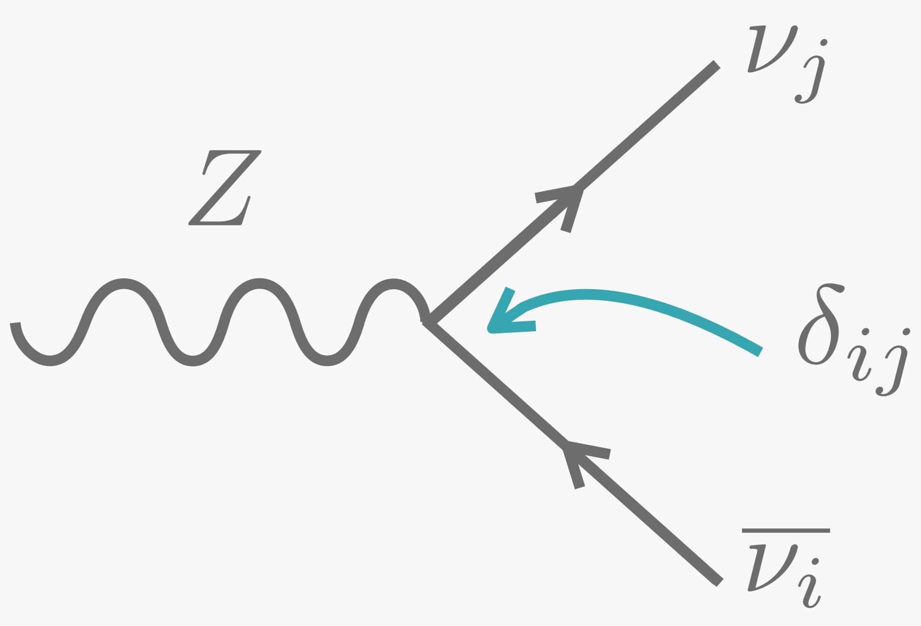
$$\nu_\alpha = (U_{\mathrm{PMNS}})_{\alpha i}\,\nu_i$$

  Pontecorvo–Maki–Nakagawa–Sakata (PMNS) mixing matrix

CC: $(U_{\mathrm{PMNS}})_{\alpha i}\nu_i\overline{\ell_\alpha}W^-$



NC: $\delta_{ij}\nu_i\overline{\nu_j}Z$



Neutrino Oscillation Parameters

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- The leptonic mixing matrix

  The $U_{\rm PMNS}$ an Unitary matrix, can be parametrized by

  – 3 angles: θ_{12}, θ_{23} & θ_{13}

  – CPV phases: δ, (α_1 & α_2 for Majorana ν)

$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & e^{-i\frac{\alpha_3}{2}} \end{pmatrix}$$

"atmospheric" angle
$\theta_{23} \simeq 45^{\rm o}$

"reactor" angle
$\theta_{13} \simeq 8.5^{\rm o}$
δ Dirac phase

"solar" angle
$\theta_{12} \simeq 33^{\rm o}$

Majorana phases do not participate in ν oscillations (only in $\cancel{L}$ processes)

L.-L. Chau and W.-Y. Keung, Phys. Rev. Lett. **53** (1984) 1802.

Neutrino Oscillation Parameters

zoom.us video

- Neutrino oscillation parameters

  Accesible parameters in neutrino oscillation experiments
  - PMNS parameters: θ_{12}, θ_{23}, θ_{13} & δ
  - Mass splittings: $\Delta m^2_{\rm sol}$ & $\Delta m^2_{\rm atm}$

Neutrino oscillation experiment	Leading dependence	Subleading dependence
Solar experiments [1]	θ_{12}	$\Delta m^2_{\rm sol}$ & θ_{13}
Reactor LBL [2]	$\Delta m^2_{\rm sol}$	θ_{12} & θ_{13}
Reactor MBL [3]	θ_{13}	$\lvert\Delta m^2_{\rm atm}\rvert$
Atmospheric experiments [4]	θ_{23}	$\Delta m^2_{\rm atm}$, θ_{13} & δ
Acc. LBL ν_μ & $\overline{\nu}_\mu$ disappearance [5]	$\lvert\Delta m^2_{\rm atm}\rvert$	θ_{23} & θ_{13}
Acc. LBL ν_e appearance [6]	θ_{13}	$\Delta m^2_{\rm atm}$, δ & θ_{23}

[1] SNO, Borexino, Gallex, SK
[2] KamLAND
[3] Daya Bay, Reno, Double-Chooz
[4] SK, MINOS, IceCUBE
[5,6] T2K, MINOS, NOνA

Neutrino Oscillation Parameters

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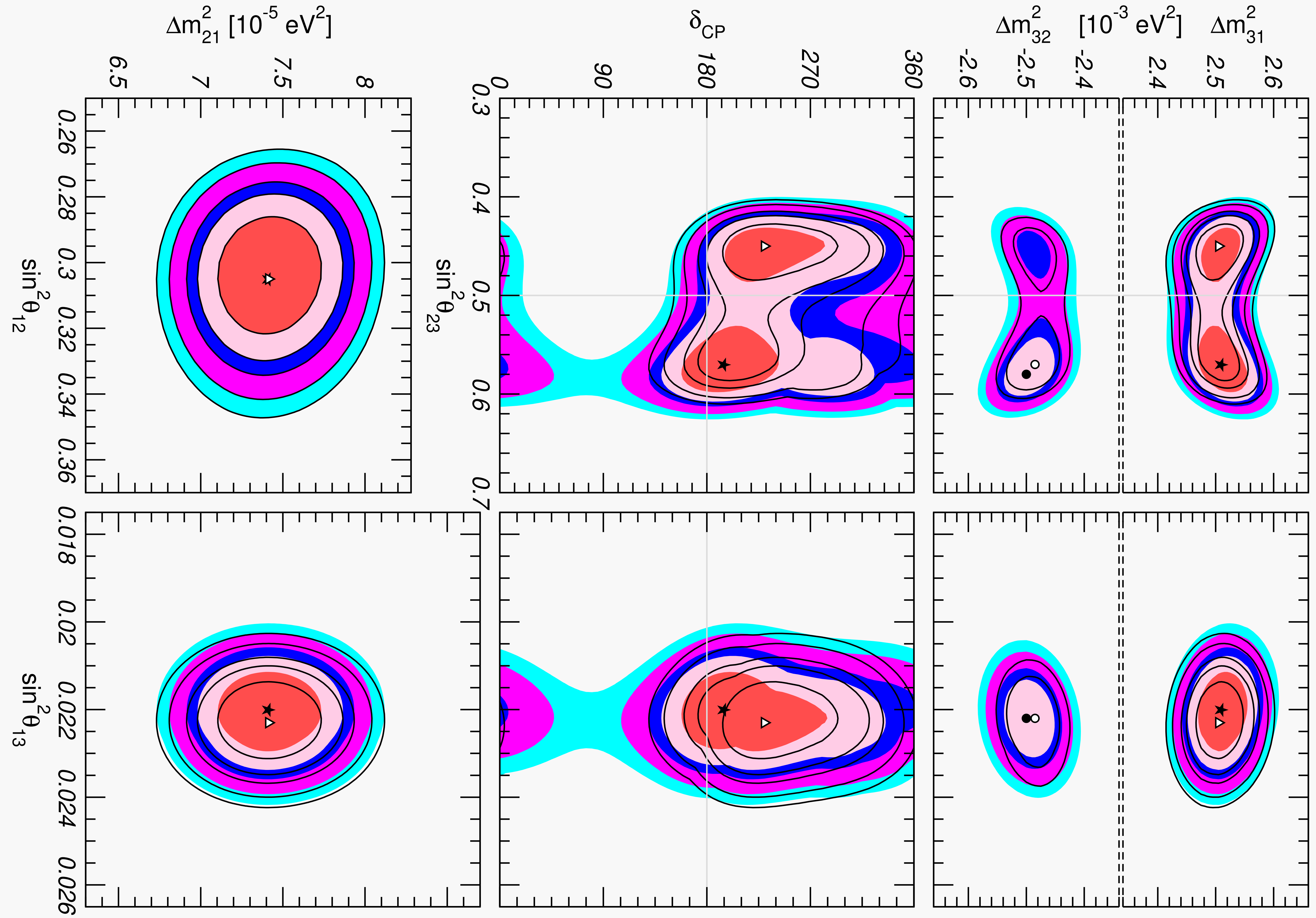
- Neutrino oscillation parameters

  Present values obtained through a global-fit to a complete set of ν oscillation experiments



NuFIT 5.2
www.nu-fit.org

Neutrino Oscillation Parameters

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- Neutrino oscillation parameters

The present best-fit values of the neutrino oscillation parameters are

$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.303^{+0.012}_{-0.011}$
$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.569^{+0.016}_{-0.021}$
$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02223^{+0.00058}_{-0.00058}$
$\delta_{\rm CP}\,[°]$	232^{+36}_{-26}	276^{+22}_{-29}
$\Delta m^2_{\rm sol}$	$7.41^{+0.21}_{-0.20}\cdot 10^{-5}{\rm eV}^2$	$7.41^{+0.21}_{-0.20}\cdot 10^{-5}{\rm eV}^2$
$\lvert\Delta m^2_{\rm atm}\rvert$	$2.507^{+0.026}_{-0.027}\cdot 10^{-3}{\rm eV}^2$	$-2.486^{+0.025}_{-0.028}\cdot 10^{-3}{\rm eV}^2$

NuFIT 5.2
www.nu-fit.org

However, there are still some unknown values

- δ (maximal?) $\Rightarrow$ $\cancel{CP}$?
- θ_{23} octant (maximal mixing?)
- $\Delta m^2_{\rm atm}$ sign

I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, A. Zhou. JHEP **09** (2020) 178

Neutrino Oscillation Parameters

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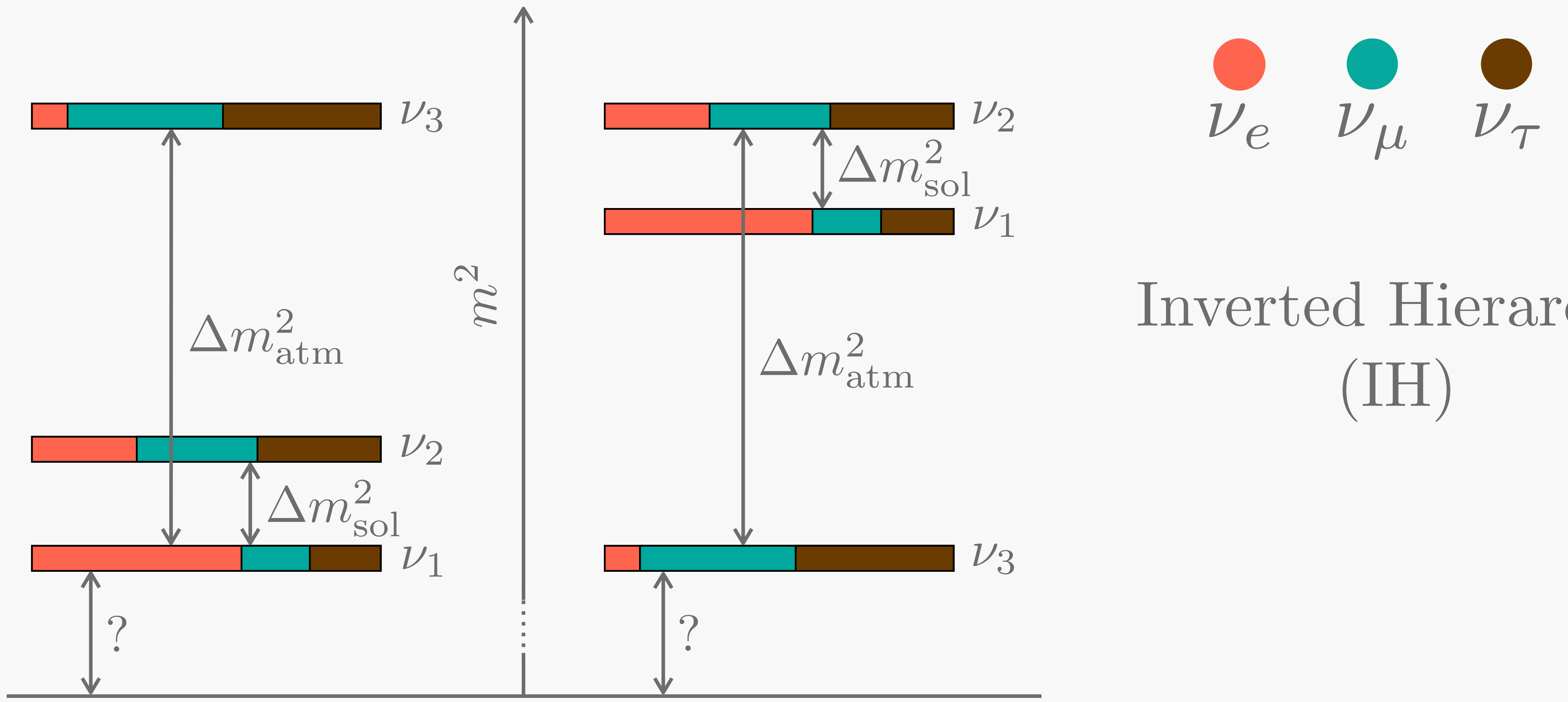
- Neutrino mass hierarchy and absolute scale

The sign of Δm^2_{atm} gives rise to

Normal Hierarchy
(NH)



Inverted Hierarchy
(IH)

Neutrino Oscillation Parameters

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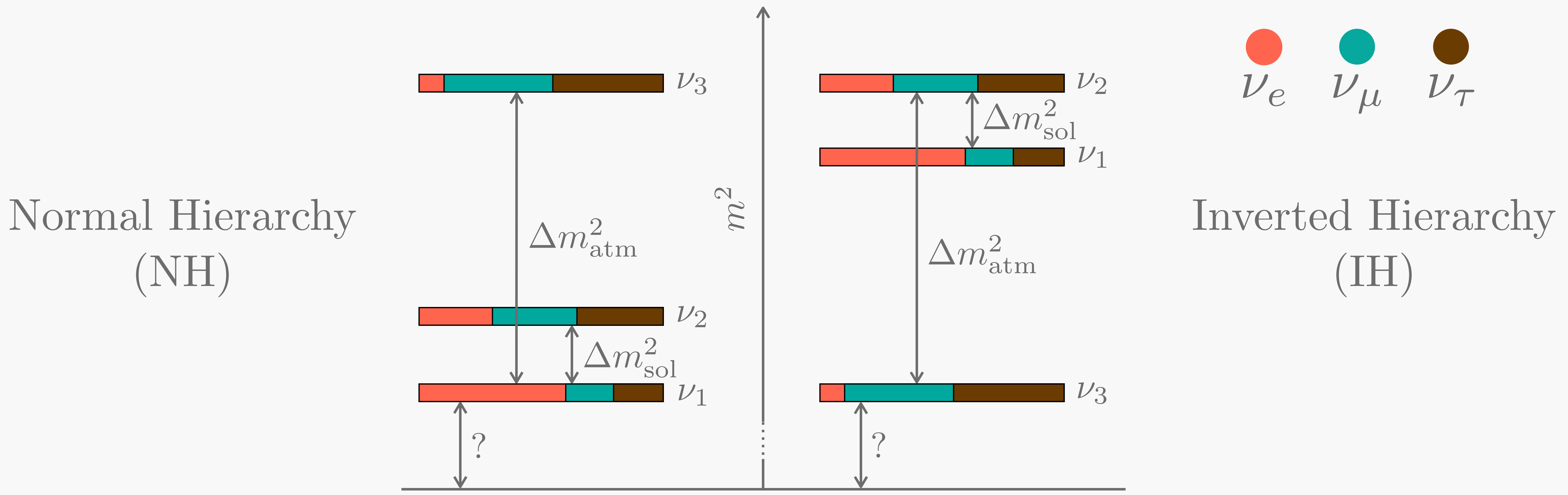

Direct bounds on the absolute neutrino mass scale

– Single β-decay

$$m^2_{\nu_\alpha} \equiv \sum_i |(U_{\text{PMNS}})_{\alpha i}|^2 m_i^2$$

$$m_{\nu_e} < 0.8 \text{ eV (90\%CL) (KATRIN)}$$

– Cosmology

$$\sum_i m_i < 0.12 \text{ eV (95\% CL) (Planck)}$$

Neutrino Masses in the SM

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- Dirac neutrino masses

All fermions get masses through the Yukawa interaction

$$\overline{\psi_L} y_\psi \phi \psi_R \xrightarrow[\text{EWSB}]{\text{after}} \boxed{y_\psi \frac{v_{\text{EW}}}{\sqrt{2}}} \overline{\psi_L} \psi_R$$

$$m_\psi \equiv y_\psi \frac{v_{\text{EW}}}{\sqrt{2}}$$

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For neutrinos

$$\overline{\nu_L} y_\nu \phi \nu_R \Rightarrow m_D = y_\nu \frac{v_{\text{EW}}}{\sqrt{2}}$$

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For neutrinos

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Not present in the SM

Neutrino Masses in the SM

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- Majorana neutrino masses

  Since neutrinos are the only neutral fermions

$$\hat{m}\overline{\nu_L^c}\nu_L$$

Neutrino Masses in the SM

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$$\hat{m}\overline{\nu_L^c}\nu_L \quad \text{but violates } \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

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  However, after EWSB, can be induced through Weinberg operator

$$\frac{1}{2} c^{d=5}_{\alpha\beta} \left(\overline{\ell_{\alpha}{}^c_L}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger \ell_{\beta L}\right) + \text{h.c.} \xrightarrow[\text{EWSB}]{\text{after}} \boxed{\frac{v_{\text{EW}}^2}{2} c^{d=5}} \overline{\nu_L^c}\nu_L$$

$$\hat{m} = -\frac{v_{\text{EW}}^2}{2} c^{d=5}$$

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$$\hat{m} = -\frac{v_{\text{EW}}^2}{2} c^{d=5}$$

$d = 5 \Rightarrow$ Is SM low energy remnant of higher energy theory?

Neutrino Masses in the SM

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And therefore, neutrinos are strictly massless in the SM.

The SM must be extended to account for neutrino oscillations.

Type-I Seesaw

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The simplest extension requires the addition of at least two heavy neutrinos which are singlets of the SM GG within the type-I seesaw. The so called HNLs

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \overline{N_{Ri}} i \partial\!\!\!/ N_{Ri} - \left(y_{i\alpha} \overline{L_\alpha} \tilde{H} N_{Ri} + \frac{M_N}{2} \overline{N^c_{Ri}} N_{Ri} \right) + \text{ h.c.}$$

P. Minkowski, Phys. Lett. **B67** (1977) 421.
T. Yanagida. Proceedings of the Workshop on the Baryon Number of the Universe.
M. Gell-Mann, P. Ramond, and R. Slansky, Print-80-0576 (CERN).
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44** (1980) 912.

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zoom.us video

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$$m_D = \frac{y v_{\rm EW}}{\sqrt{2}}$$

Dirac mass

Type-I Seesaw

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Majorana mass

New Physics scale

Type-I Seesaw

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The neutrino mass matrix diagonalized by U

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} \quad \Rightarrow \quad U^t \mathcal{M}_\nu U = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

with the Unitary matrix

$$U = \begin{array}{c} \\ \text{active} \\ \text{sterile} \end{array} \!\!\begin{array}{c} \begin{array}{cc} \text{light} & \text{heavy} \end{array} \\ \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix} \end{array}$$

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$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix} \quad N = \left(I - \frac{\Theta\Theta^\dagger}{2} \right) U_{\mathrm{PMNS}}$$

Type-I Seesaw

zoom.us video

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Type-I Seesaw

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Light neutrino masses given by

$$\hat{m} = m_D^t M_N^{-1} m_D = -U_{PMNS}^* m U_{PMNS}^\dagger$$

Active-heavy mixing given by

$$\Theta = m_D^\dagger M_N^{-1}$$

Type-I Seesaw

zoom.us video

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$$\underbrace{\boxed{\hat{m}}}_{\sim 0.1\mathrm{eV}} = m_D^t M_N^{-1} \underbrace{\boxed{m_D}}_{\substack{\sim \Lambda_{\mathrm{EW}} \\ (y \sim \mathcal{O}(1))}} \quad \Rightarrow \quad M_N \sim 10^{14}\mathrm{GeV} \quad \Rightarrow \quad \Theta \sim 10^{-12}$$

If smallenss of m_ν comes only from the suppression of M_N, active-heavy mixing will suppressed $\Rightarrow$ experimental verification extremelly challenging.

Low-scale Seesaw

zoom.us video

Alternatively, smallness of m_ν may naturally stem from an approximate L instead of a huge hierarchy of masses.

In particular

$$m_D = \frac{v_{\mathrm{EW}}}{\sqrt{2}} \begin{array}{cc} \begin{array}{r} \\ L = \end{array}\begin{array}{ccc} \nu_e & \nu_\mu & \nu_\tau \\ 1 & 1 & 1 \end{array} & \\ \begin{pmatrix} y_e & y_\mu & y_\tau \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & \begin{array}{cc} 1 & N_1 \\ -1 & N_2 \\ 0 & N_3 \end{array} \end{array} \qquad M_N = \begin{array}{cc} \begin{array}{r} \\ L = \end{array}\begin{array}{ccc} N_1 & N_2 & N_3 \\ 1 & -1 & 0 \end{array} & \\ \begin{pmatrix} 0 & M & 0 \\ M & 0 & 0 \\ 0 & 0 & M' \end{pmatrix} & \begin{array}{cc} 1 & N_1 \\ -1 & N_2 \\ 0 & N_3 \end{array} \end{array}$$

where N_i is an arbitrary number of extra heavy fields.

If L is exact:

- $\hat{m} = m_D^t M_N^{-1} m_D = 0$ (massless ν)
- $\theta_\alpha = \dfrac{y_\alpha v_{\mathrm{EW}}}{\sqrt{2}M} \neq 0$ (arbitrarily large)

R. Mohapatra and J. Valle, Phys.Rev. **D34**, 1642 (1986)
J. Bernabeu, A. Santamaria, J. Vidal, A. Mendez, and J. Valle, Phys. Lett. **B187**, 303 (1987)
G.C. Branco, W. Grimus, and L. Lavoura, Nucl. Phys. **B312**, 492 (1989)

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where N_i is an arbitrary number of extra heavy fields.

If L is mildly broken by ϵ_i and μ_j:

- $\hat{m} = m_D^t M_N^{-1} m_D \neq 0$ $(m_\nu \sim \mathcal{O}(eV))$
- $\theta_\alpha \simeq \dfrac{y_\alpha v_{\rm EW}}{\sqrt{2} M} \neq 0$ (arbitrarily large)

R. Mohapatra and J. Valle, Phys.Rev. **D34**, 1642 (1986)
J. Bernabeu, A. Santamaria, J. Vidal, A. Mendez, and J. Valle, Phys. Lett. **B187**, 303 (1987)
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Low-scale Seesaw

zoom.us video

Minimal low-scale seesaw models + ν oscillation pattern

- 2 neutrino case

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & yv/\sqrt{2} & \epsilon y' v/\sqrt{2} \\ y^t v/\sqrt{2} & \mu' & M \\ \epsilon {y'}^t v/\sqrt{2} & M & \mu \end{pmatrix}$$

When solving

$$m_D^t M_N^{-1} m_D = -U^*_{\mathrm{PMNS}} m U^\dagger_{\mathrm{PMNS}}$$

strong correlations among the mixing elements

$$\theta_\alpha = \frac{\theta}{\sqrt{2}} \left(\sqrt{1+\rho}\, U^*_{\mathrm{PMNS}\alpha 3} + \sqrt{1-\rho}\, U^*_{\mathrm{PMNS}\alpha 2} \right) \quad \text{for NH}$$

$U_{\mathrm{PMNS}\alpha i} = g_{\alpha i}(\theta_{ij}, \delta_{\mathrm{CP}}, \alpha_2)$

$\rho = f(\Delta m^2_{ij})$

M. B. Gavela, T. Hambye, D. Hernandez, and P. Hernandez. JHEP **09** (2009) 038

Low-scale Seesaw

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strong correlations among the mixing elements

$$\theta_\alpha = \frac{\theta}{\sqrt{2}} \left(\sqrt{1+\rho}\, U^*_{\text{PMNS}\,\alpha 3} + \sqrt{1-\rho}\, U^*_{\text{PMNS}\,\alpha 2} \right) \quad \text{for NH}$$

$U_{\text{PMNS}\,\alpha i} = g_{\alpha i}(\theta_{ij}, \delta_{\text{CP}}, \alpha_2)$

$\rho = f(\Delta m^2_{ij})$

Flavor structure determined up to 3 free parameters

M. B. Gavela, T. Hambye, D. Hernandez, and P. Hernandez. JHEP **09** (2009) 038

Low-scale Seesaw

zoom.us video

Minimal low-scale seesaw models + ν oscillation pattern

- 2 neutrino case

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & yv/\sqrt{2} & \epsilon y' v/\sqrt{2} \\ y^t v/\sqrt{2} & \mu' & M \\ \epsilon {y'}^t v/\sqrt{2} & M & \mu \end{pmatrix}$$

When solving

$$m_D^t M_N^{-1} m_D = -U^*_{\text{PMNS}} m U^\dagger_{\text{PMNS}}$$

strong correlations among the mixing elements

$$\theta_\alpha = \frac{\theta}{\sqrt{2}} \left(\sqrt{1+\rho}\, U^*_{\text{PMNS}\,\alpha 3} + \sqrt{1-\rho}\, U^*_{\text{PMNS}\,\alpha 2} \right) \quad \text{for NH}$$

$U_{\text{PMNS}\,\alpha i} = g_{\alpha i}(\theta_{ij}, \delta_{\text{CP}}, \alpha_2)$

$\rho = f(\Delta m^2_{ij})$

Flavor structure determined up to 3 free parameters

Similar expression for IH. See back-up sildes

Low-scale Seesaw

Minimal low-scale seesaw models + ν oscillation pattern

- 3 neutrino case

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & yv/\sqrt{2} & \epsilon_1 y' v/\sqrt{2} & \epsilon_2 y'' v/\sqrt{2} \\ y^T v/\sqrt{2} & \mu_1 & M & \mu_3 \\ \epsilon_1 {y'}^t v/\sqrt{2} & M & \mu_2 & \mu_4 \\ \epsilon_2 {y''}^t v/\sqrt{2} & \mu_3 & \mu_4 & M' \end{pmatrix}$$

When solving

$$m_D^t M_N^{-1} m_D = -U^*_{\mathrm{PMNS}} m U^\dagger_{\mathrm{PMNS}}$$

correlations among the mixing elements

$$\theta_\tau = f\left(\theta_e, \theta_\mu, \delta_{\mathrm{CP}}, \alpha_1, \alpha_2, m_{1,3}\right)$$

Flavor structure determined up to 8 free parameters

E. Fernandez-Martinez, J. Hernandez-Garcia, J. Lopez-Pavon, and M. Lucente. JHEP **10** (2015) 130

Low-scale Seesaw

Most experiments provide sensitivity results assuming single flavor dominance

$$|U_{e4}|^2 : |U_{\mu 4}|^2 : |U_{\tau 4}|^2 = 1 : 0 : 0 \qquad (e\text{-dominance})$$

$$|U_{e4}|^2 : |U_{\mu 4}|^2 : |U_{\tau 4}|^2 = 0 : 1 : 0 \qquad (\mu\text{-dominance})$$

$$|U_{e4}|^2 : |U_{\mu 4}|^2 : |U_{\tau 4}|^2 = 0 : 0 : 1 \qquad (\tau\text{-dominance})$$

Low-scale Seesaw

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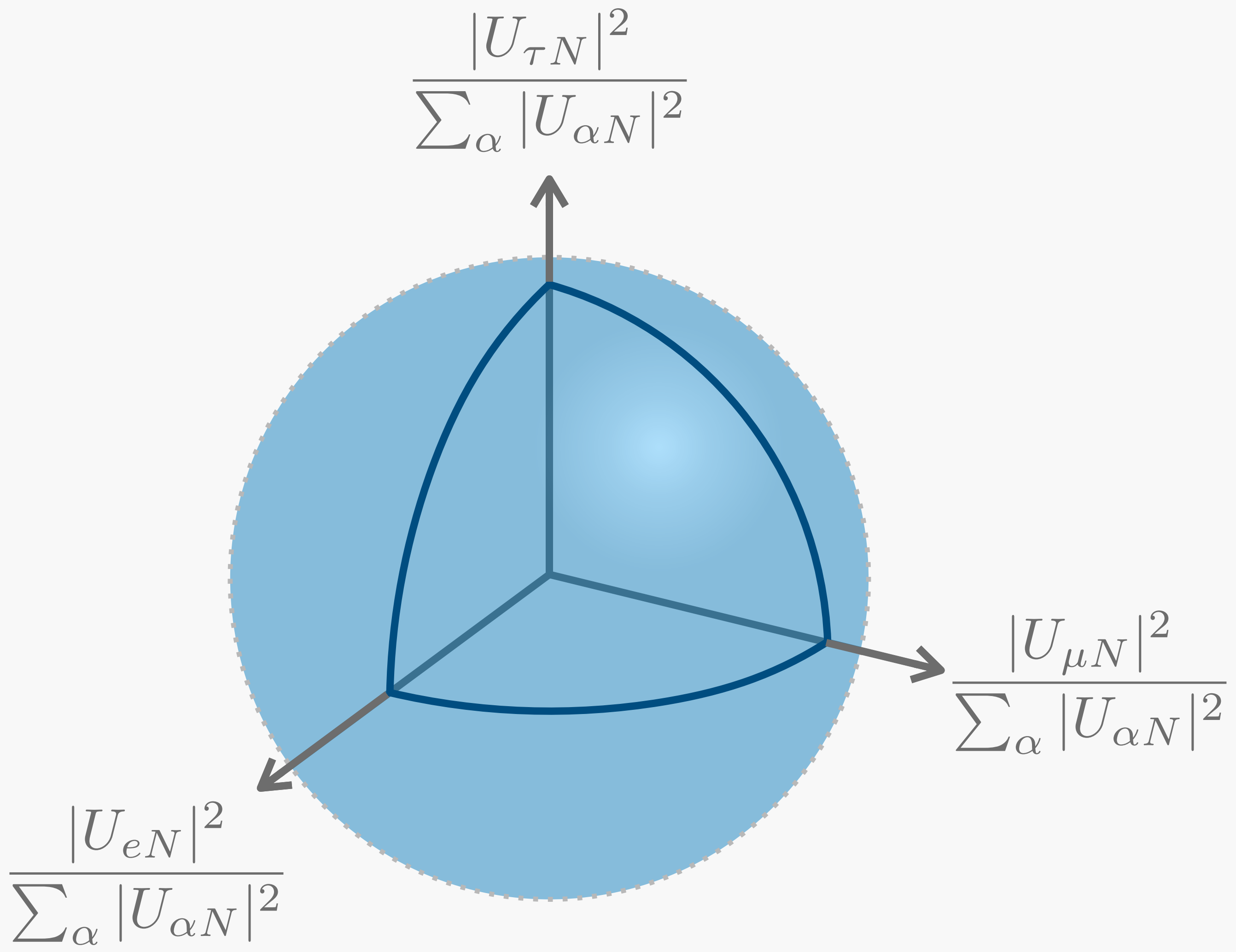
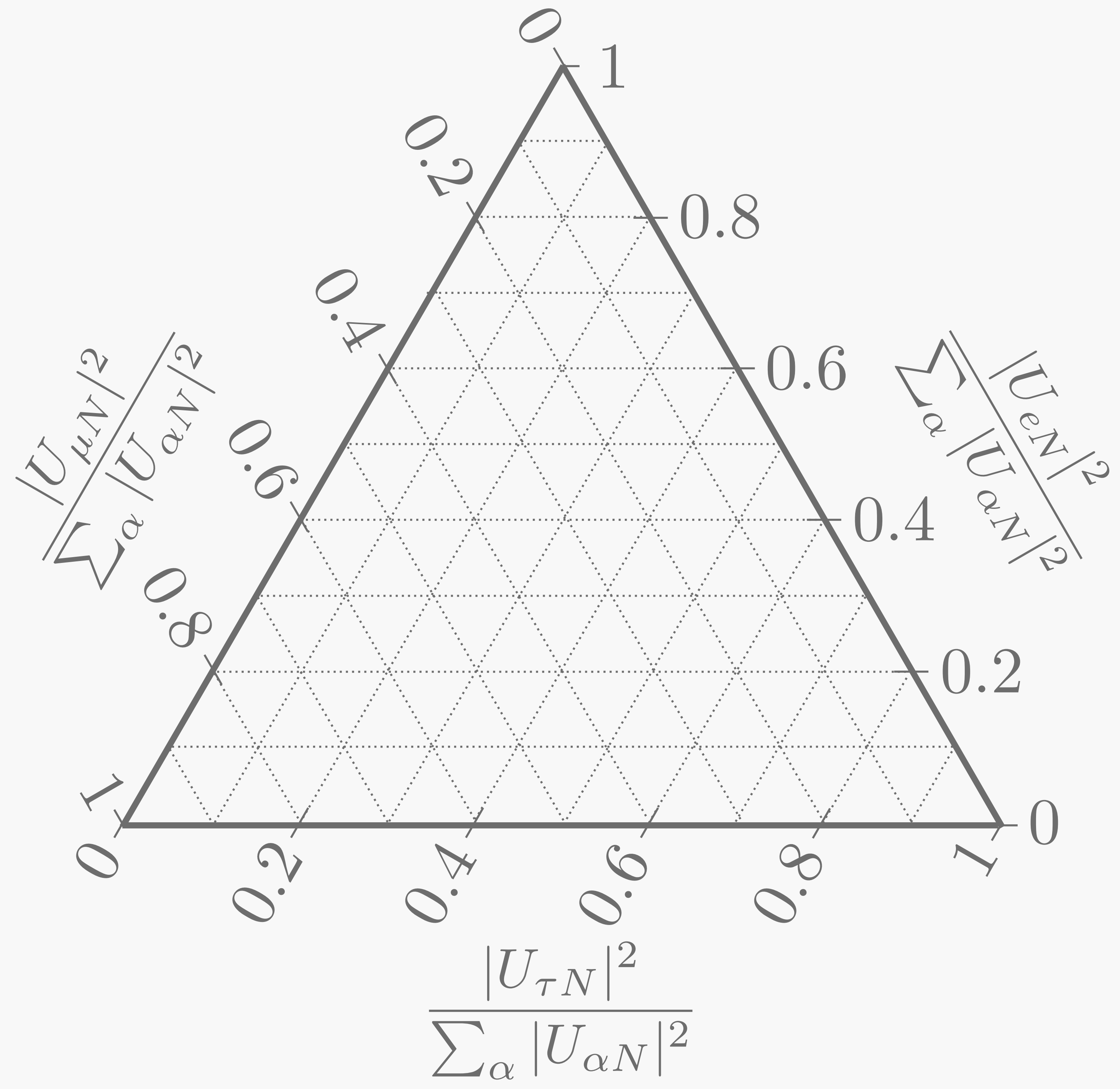
The normalized mixing matrix elements

$$\frac{|U_{\alpha N}|^2}{\sum_\alpha |U_{\alpha N}|^2} = \frac{|\theta_\alpha|^2}{\sum_\alpha |\theta_\alpha|^2} \in (0,1)$$



ternary plot



Low-scale Seesaw

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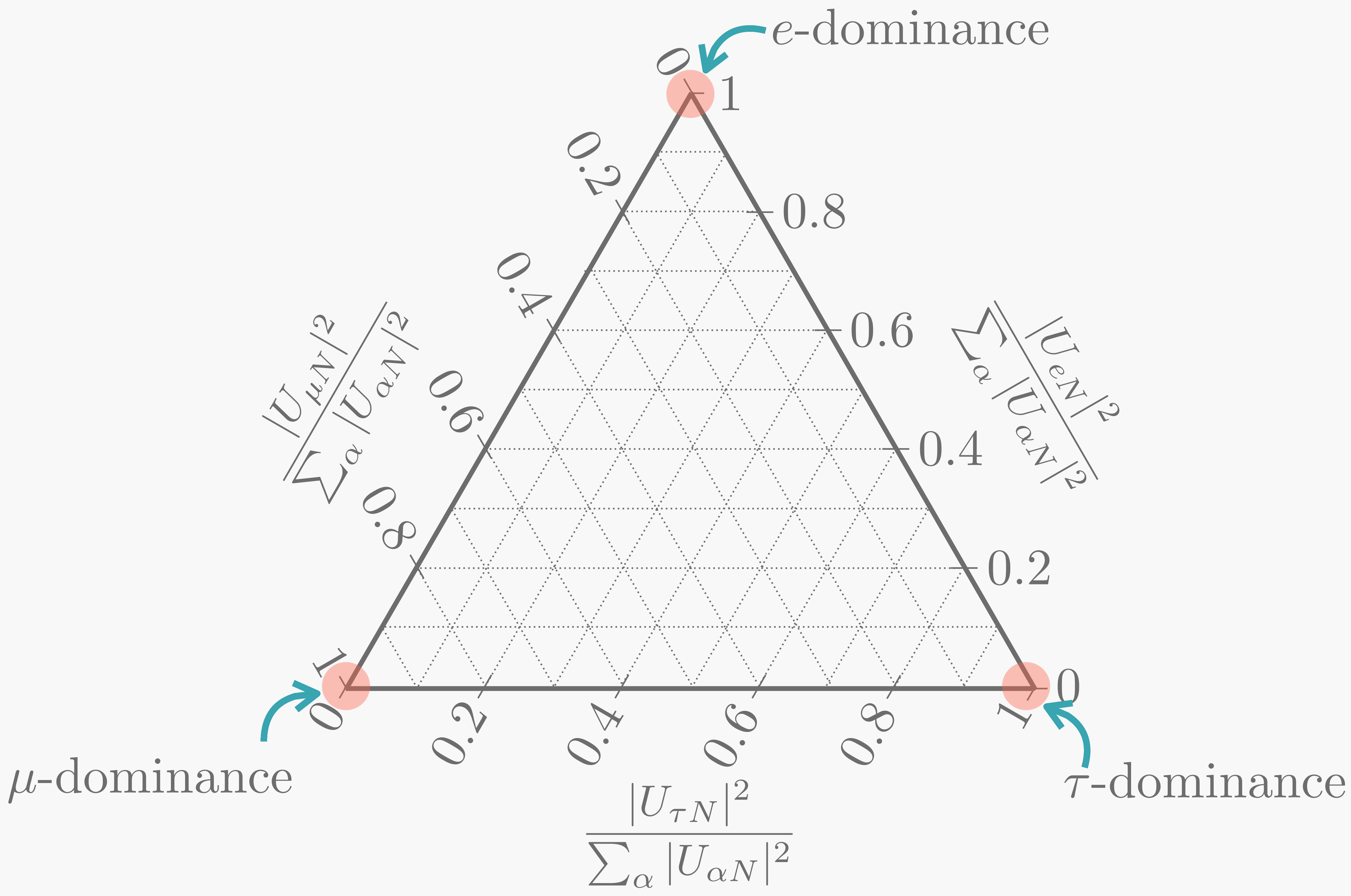

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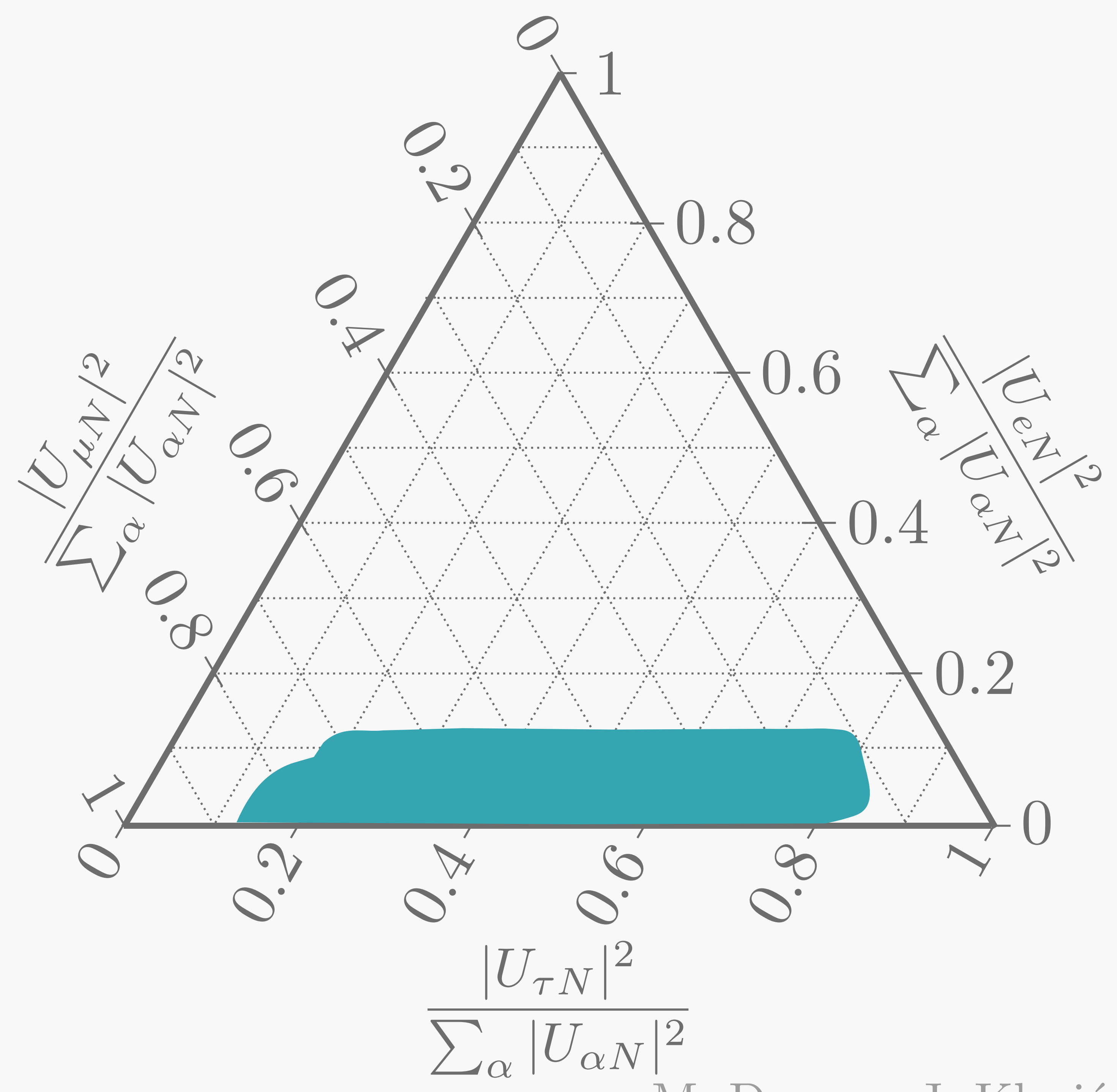
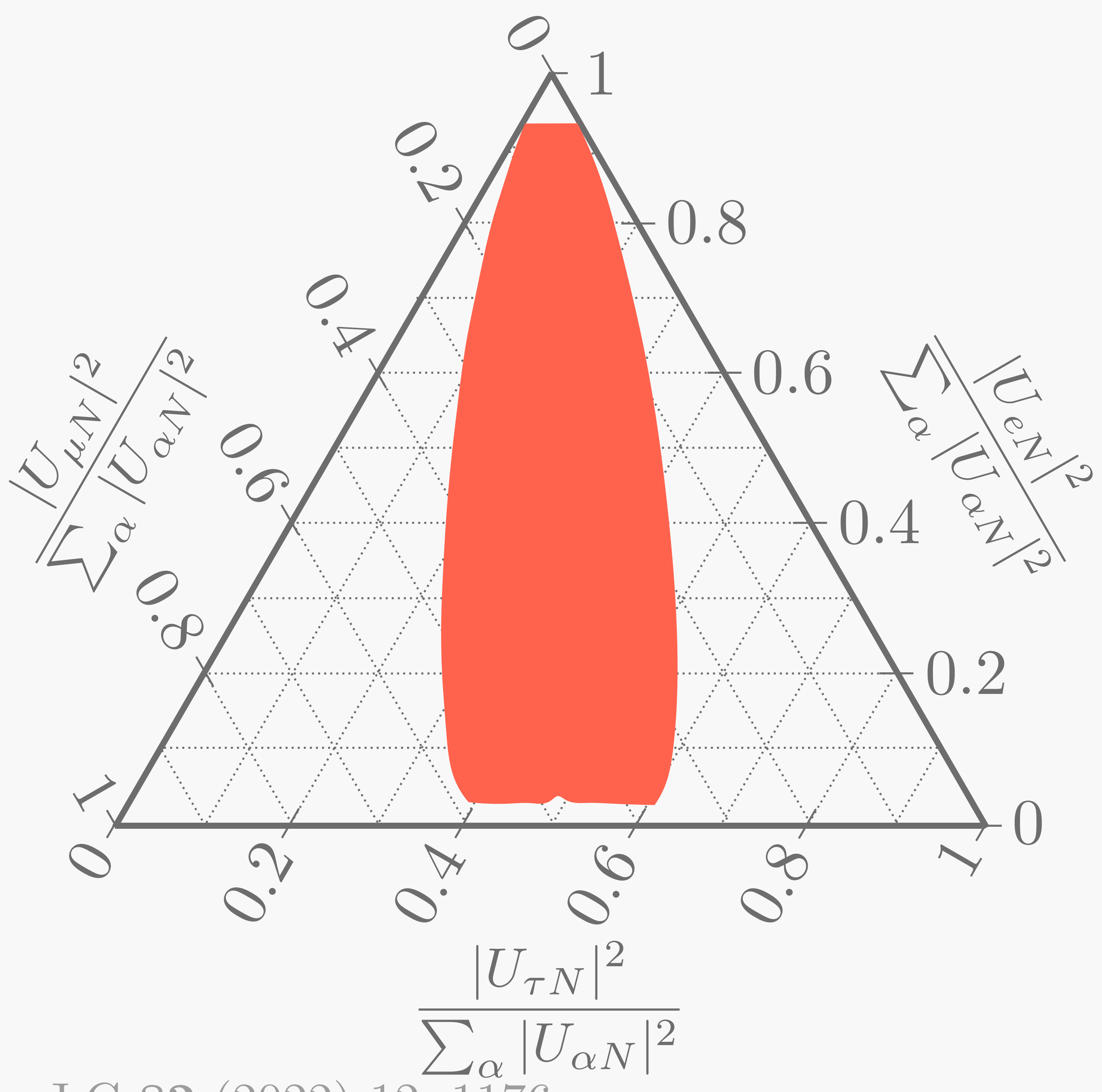
- NH : 2N



- IH : 2N



M. Drewes, J, Klarić, J. López-Pavón. Eur.Phys.J.C **82** (2022) 12, 1176

Low-scale Seesaw

zoom.us video

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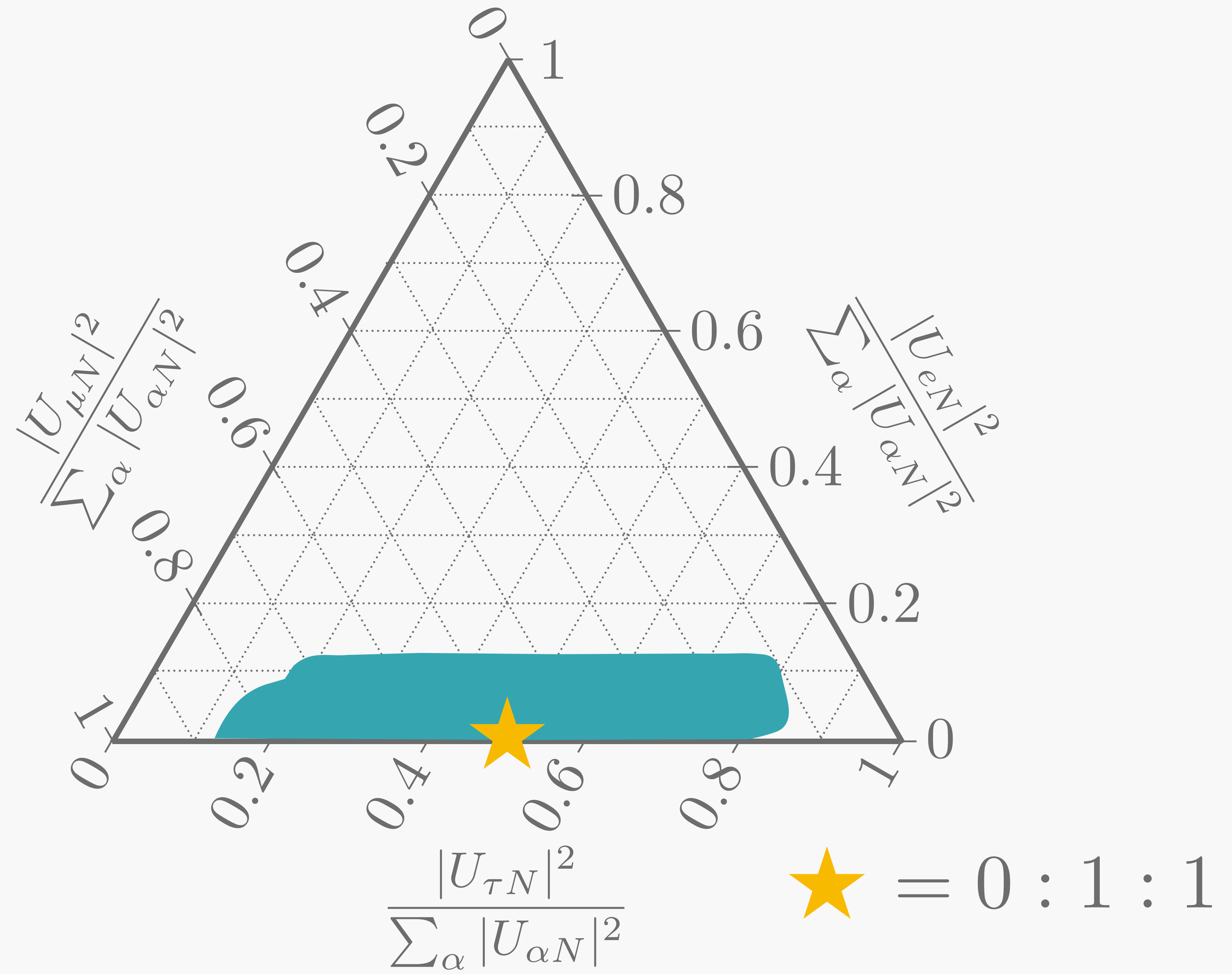

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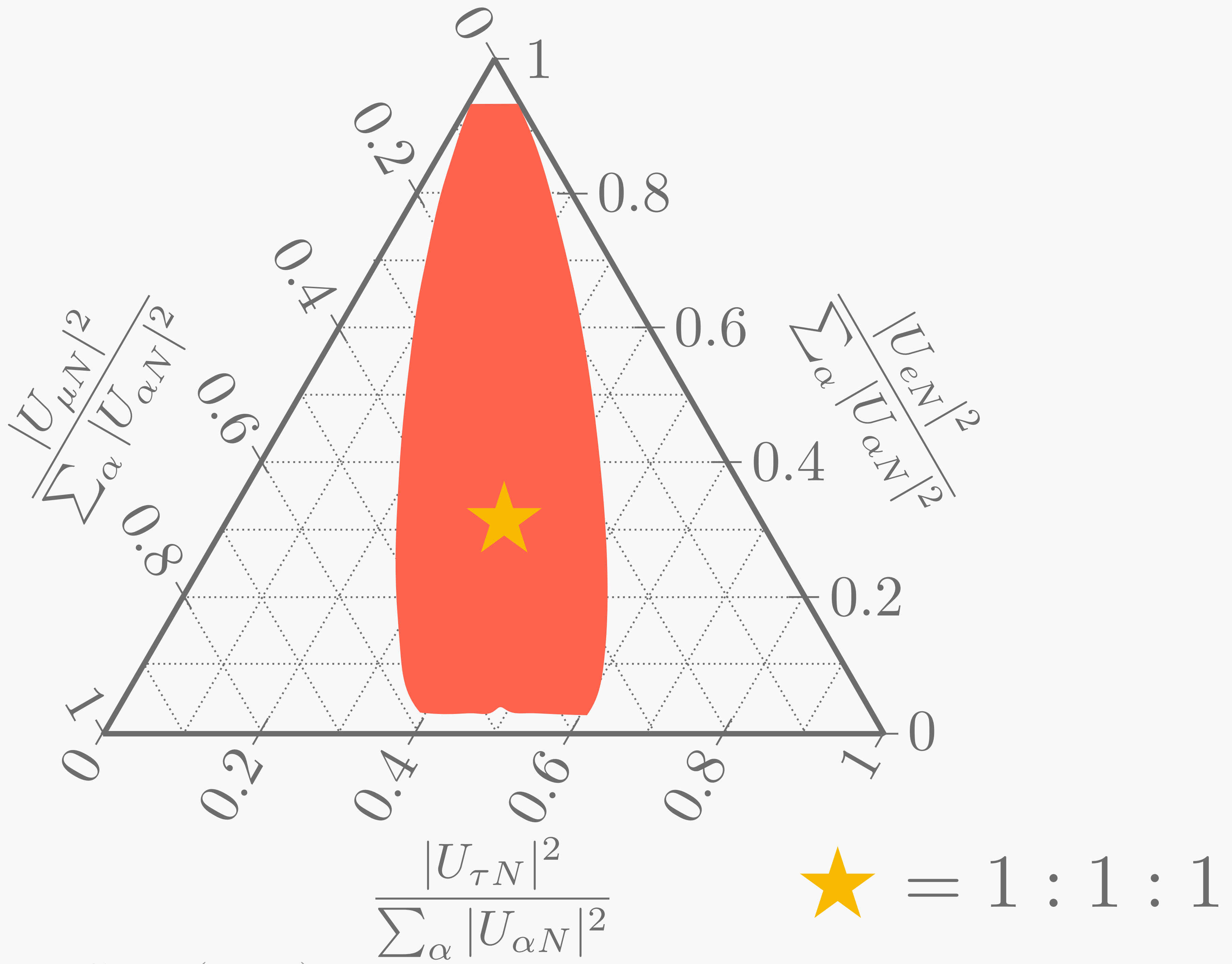

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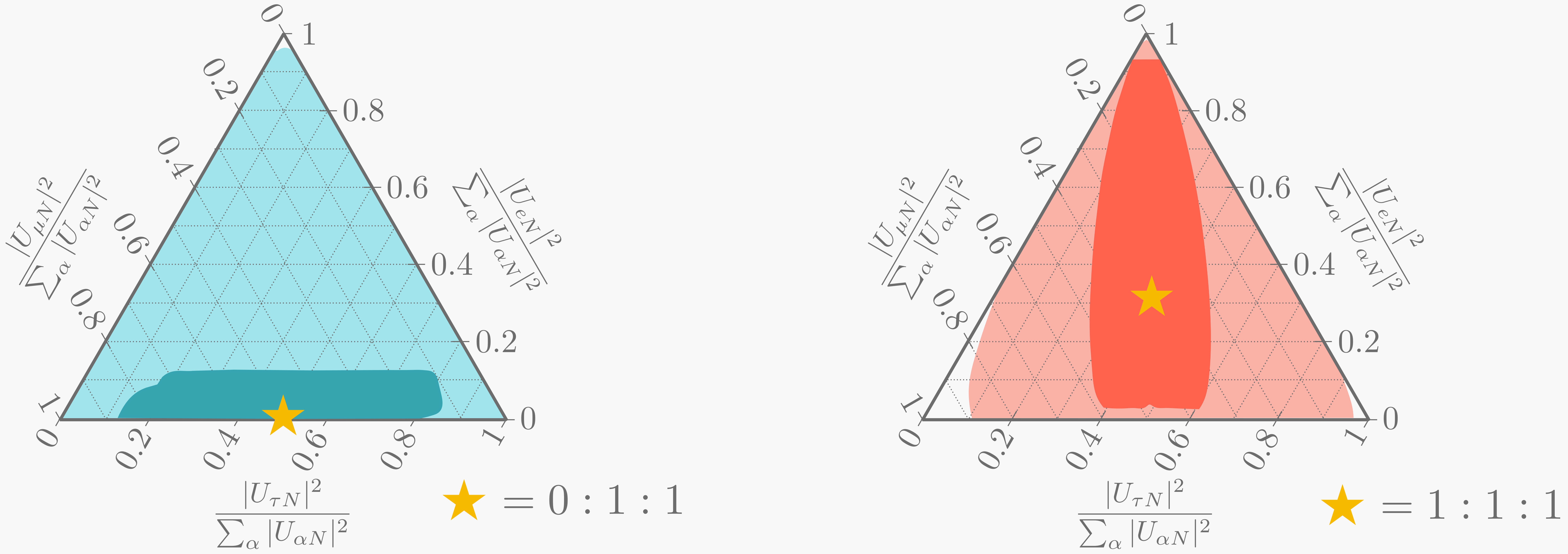
- IH : 2N ● 3N ●



M. Blennow, E. Fernandez-Martinez, JHG, J. Lopez-Pavon, X. Marcano, D. Naredo-Tuero, arXiv: 2306.01040

The Scale of New Physics

The flavor states

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i + \sum_{i=4}^{3+n} U_{\alpha i}N_i \equiv \sum_i U_{\alpha i}n_i$$

with U the unitary matrix that diagonalizes $\mathcal{M}$.

The Scale of New Physics

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with U the unitary matrix that diagonalizes $\mathcal{M}$.

If only one HNL is light enough to be produced in the experiment,

phenomenology described by 3 mixing elements $U_{\alpha N}$ + 1 mass M_N.

The Scale of New Physics

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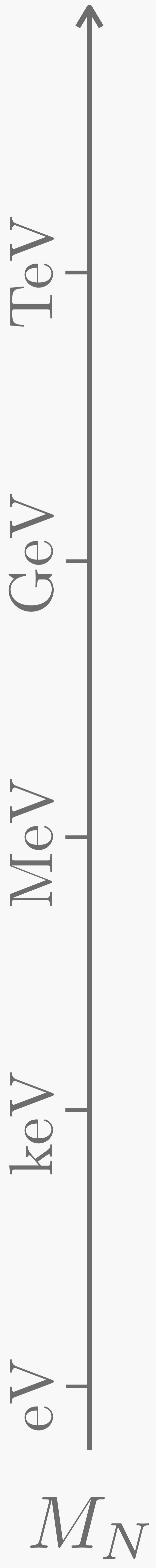
Depending on the range of M_N, very different phenomenology found



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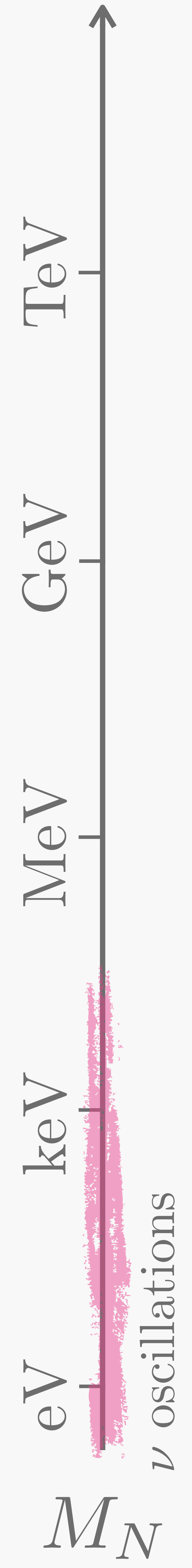
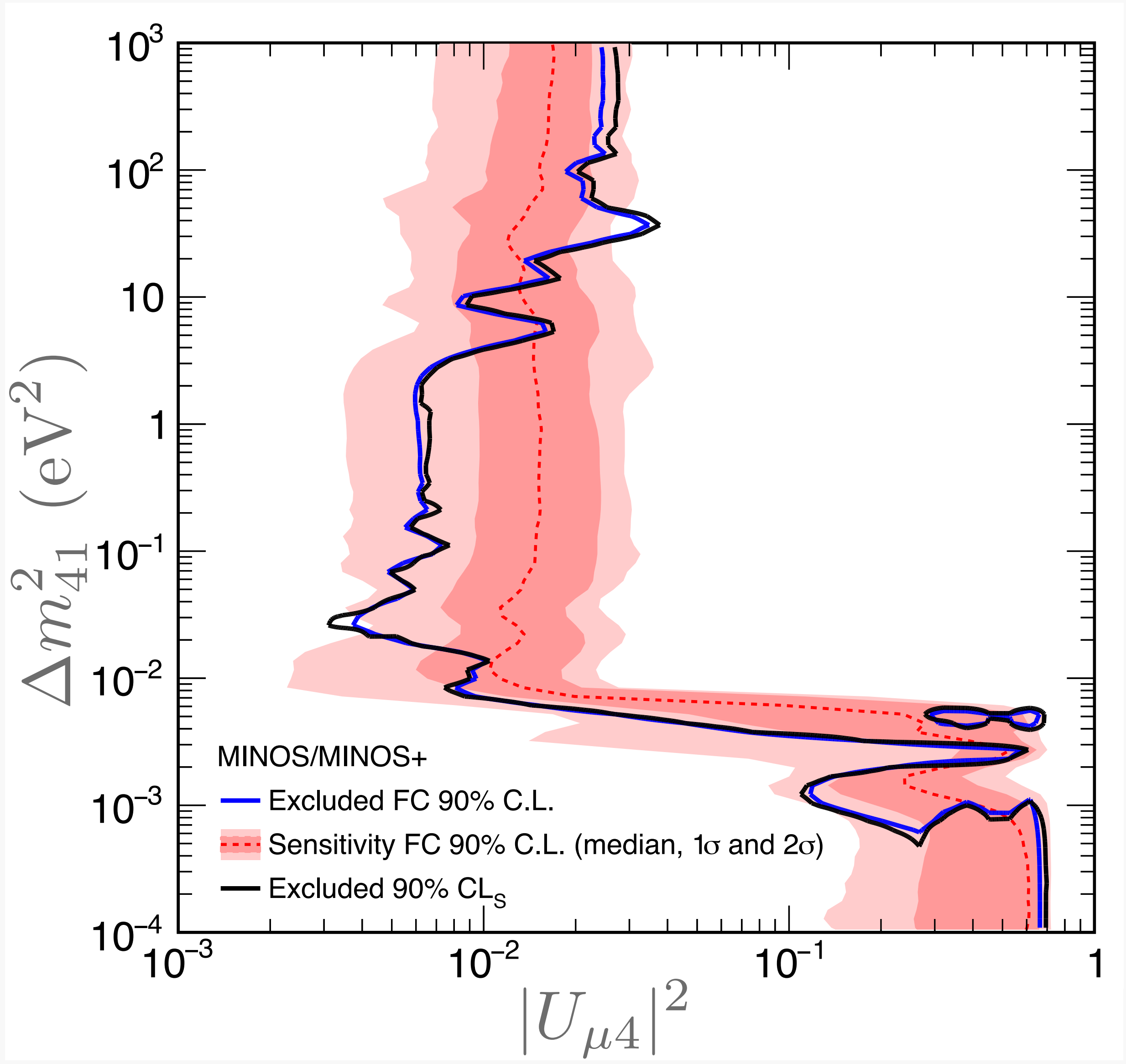


Depending on the range of M_N, very different phenomenology found

- ν oscillations

  If M_N light enough, HNLs would impact ν oscillations $\Rightarrow$ modification of predicted 3ν oscillation probabilities

  MINOS/MINOS+ ν_μ disappearance:



  – 3ν scenario:

$$P_{\mu\mu} \approx 1 - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

Phys. Rev. Lett. **125** (2020) 071801

The Scale of New Physics

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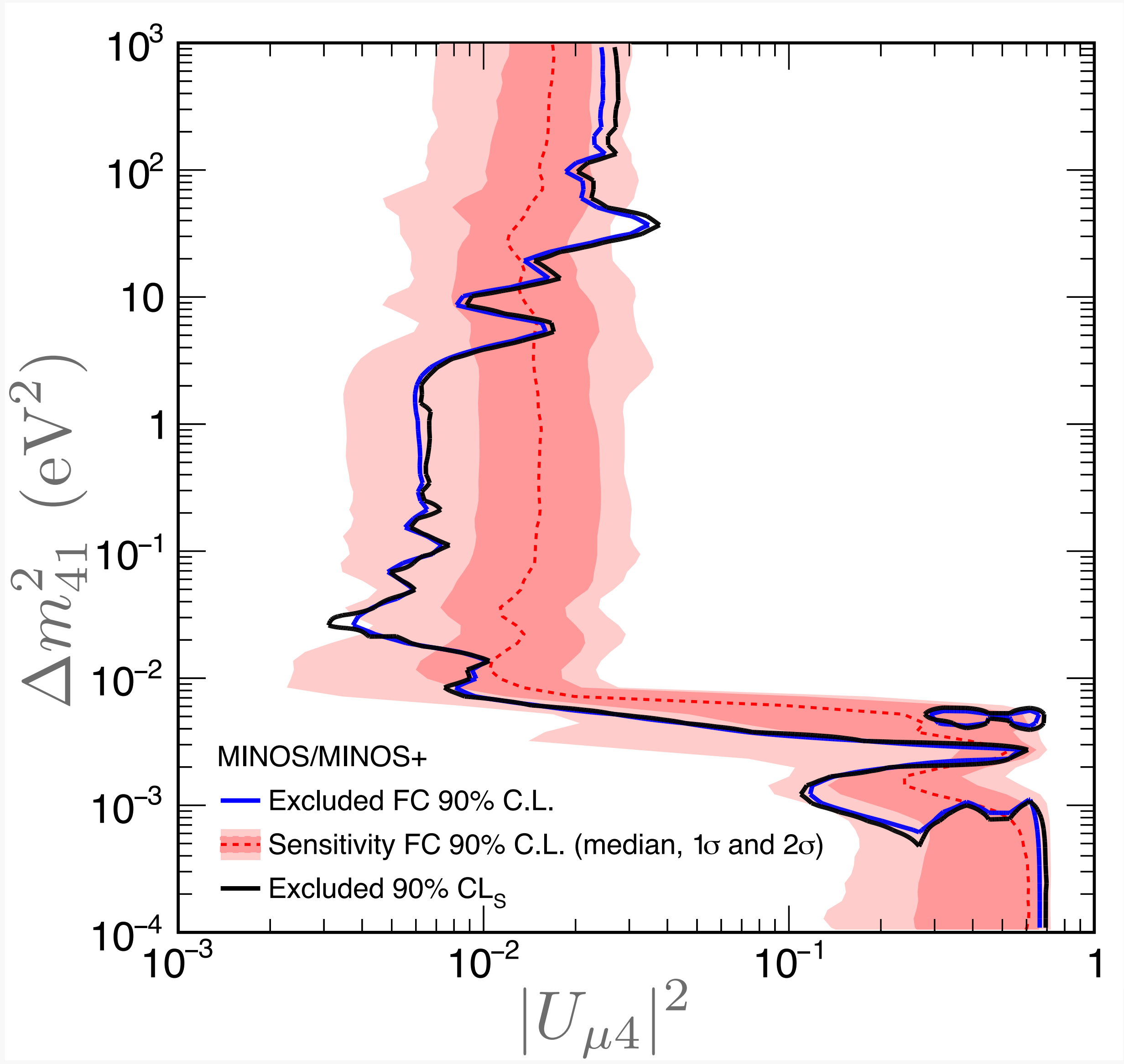

– 3ν scenario:

$$P_{\mu\mu} \approx 1 - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

– $(3+1)\nu$ scenario:

$$P_{\mu\mu} \approx 1 - \sin^2 2\theta_{24}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

Phys. Rev. Lett. **125** (2020) 071801

The Scale of New Physics

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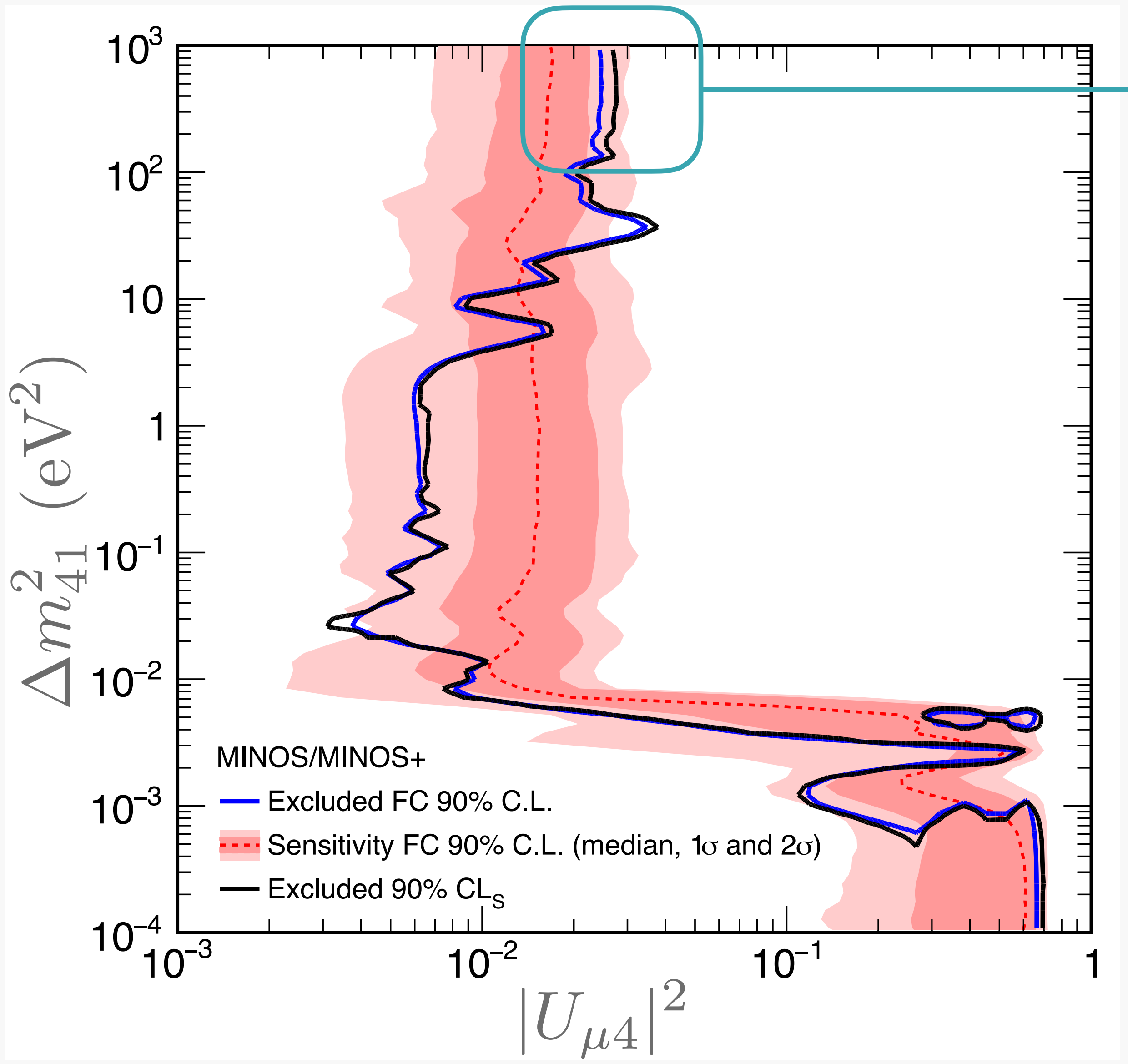

For $\Delta m^2 \gtrsim 100$ eV^2, oscillations are too fast to be resolved at the detector $\Rightarrow$ average-out regime

Phys. Rev. Lett. **125** (2020) 071801

The Scale of New Physics

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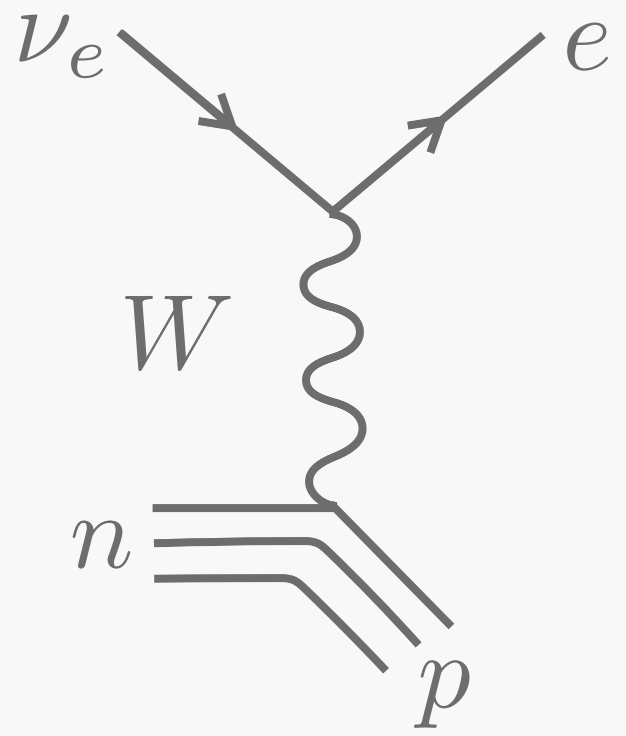
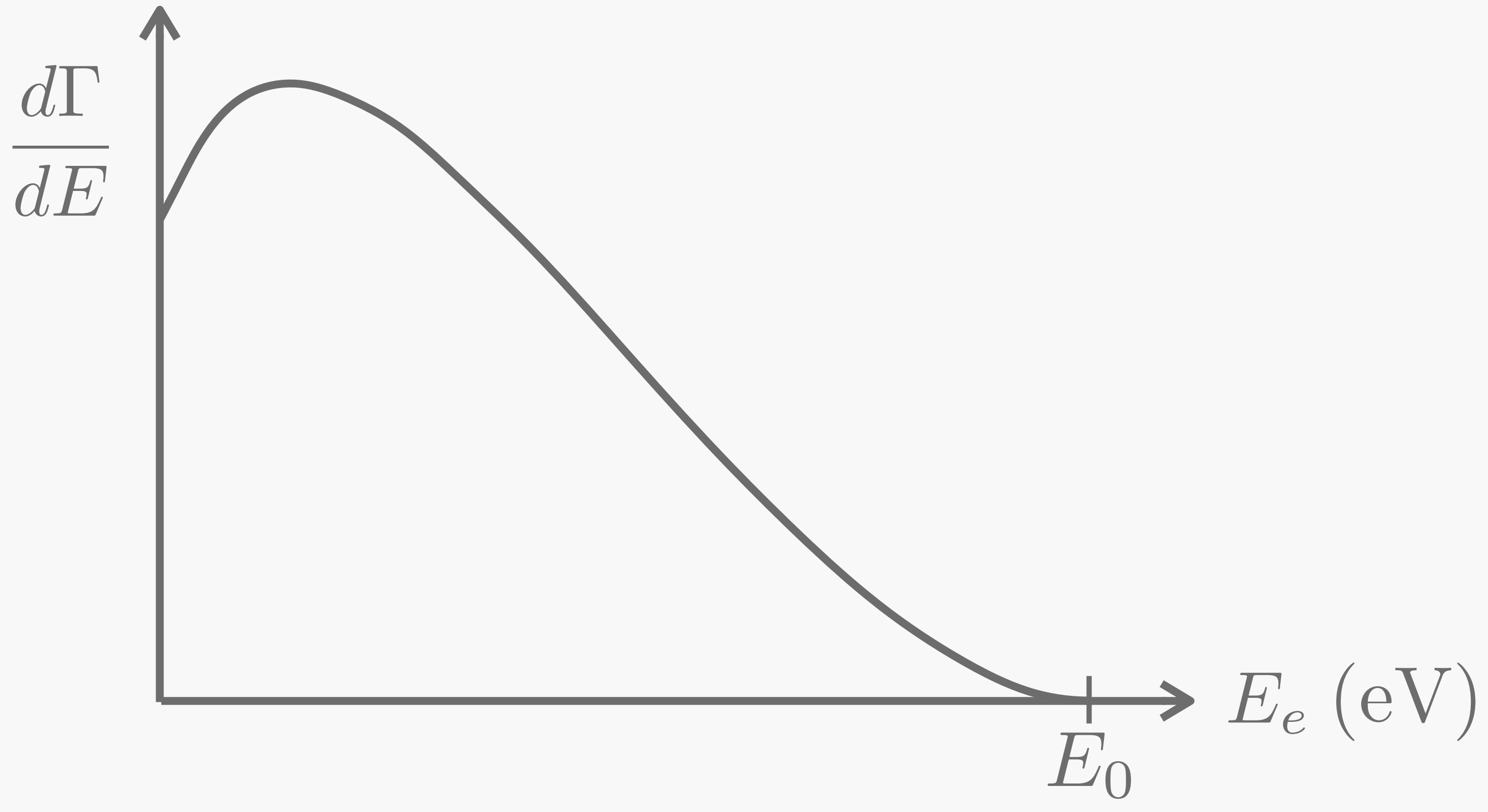
Depending on the range of M_N, very different phenomenology found

- Kinks in β-decay searches

  If no HNL, the effective mass of light neutrinos probed by looking at the β-decay spectrum close to E_0





The Scale of New Physics

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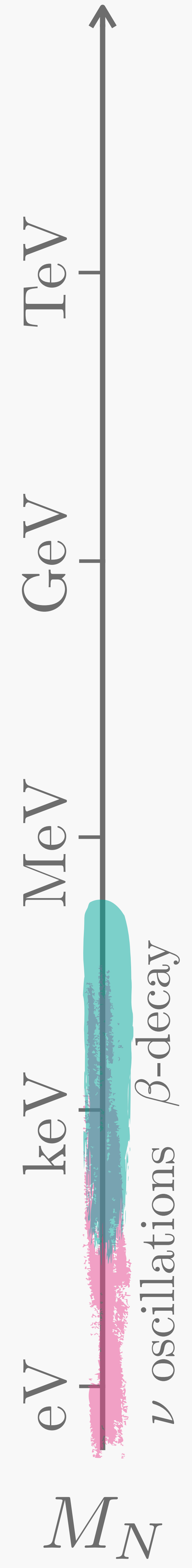

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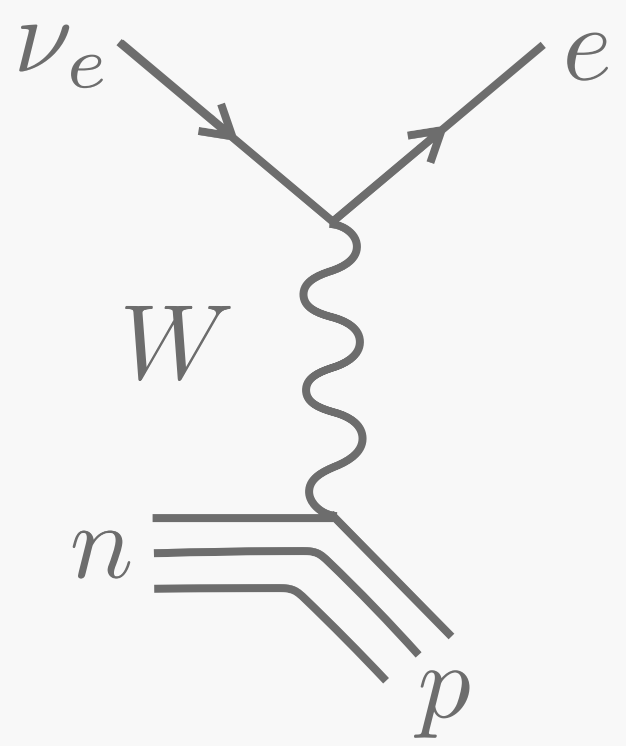

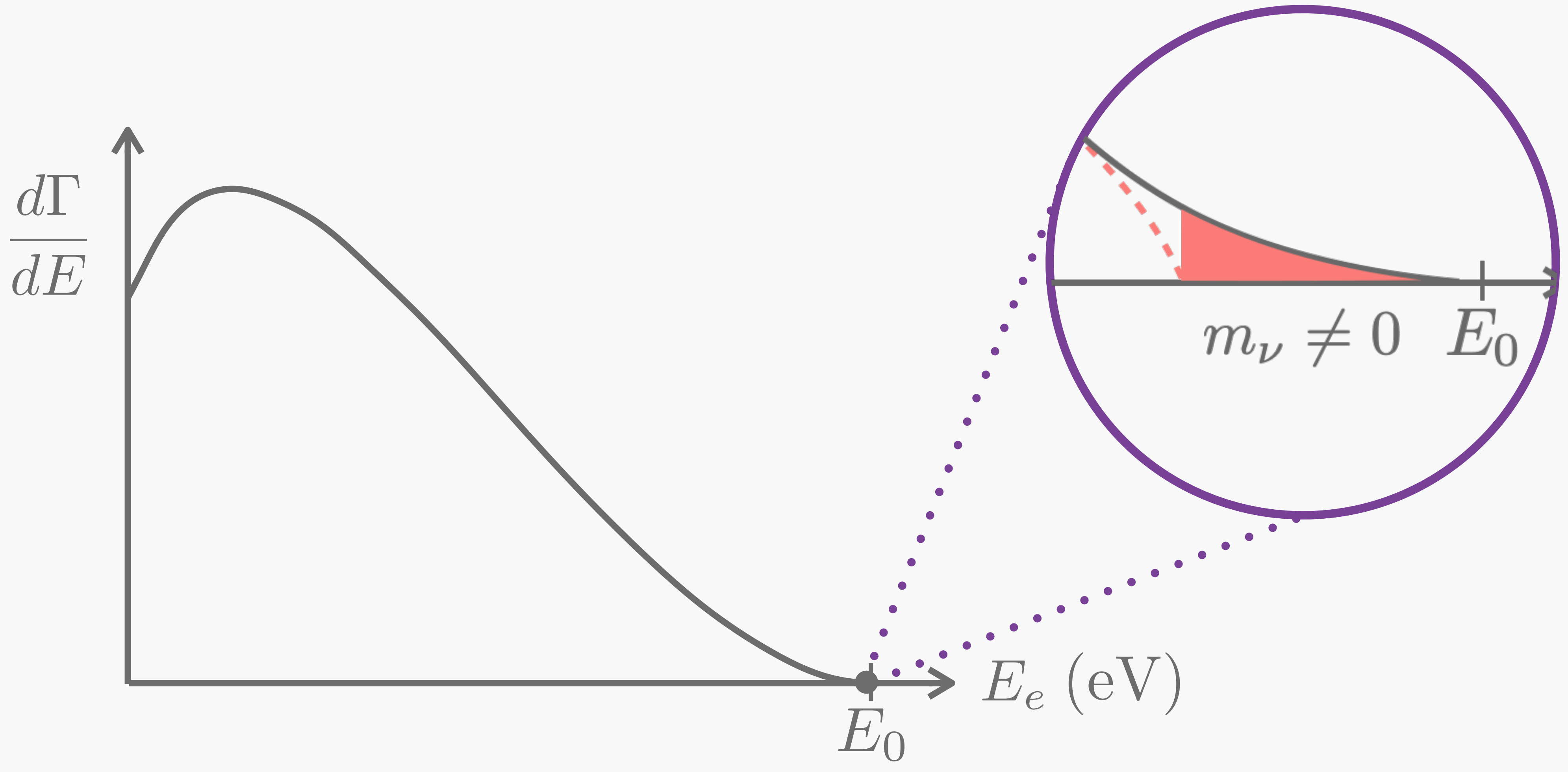

$$\frac{d\Gamma}{dE} = \frac{d\Gamma}{dE}(m_\beta^2) \quad \Rightarrow \quad m_\beta^2 = \sum_i |\,(U_{\mathrm{PMNS}})_{ei}\,|^2 m_i^2$$

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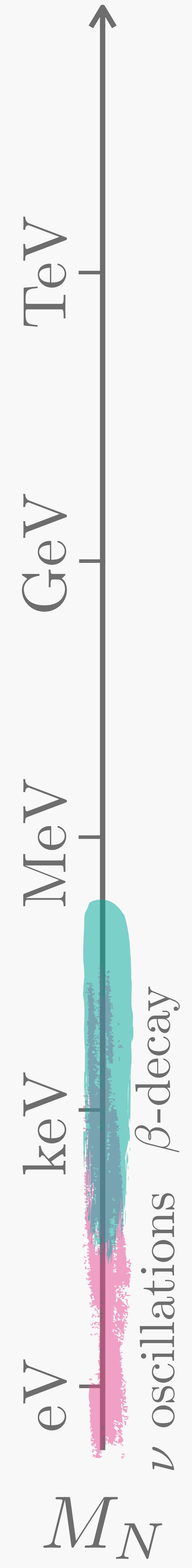
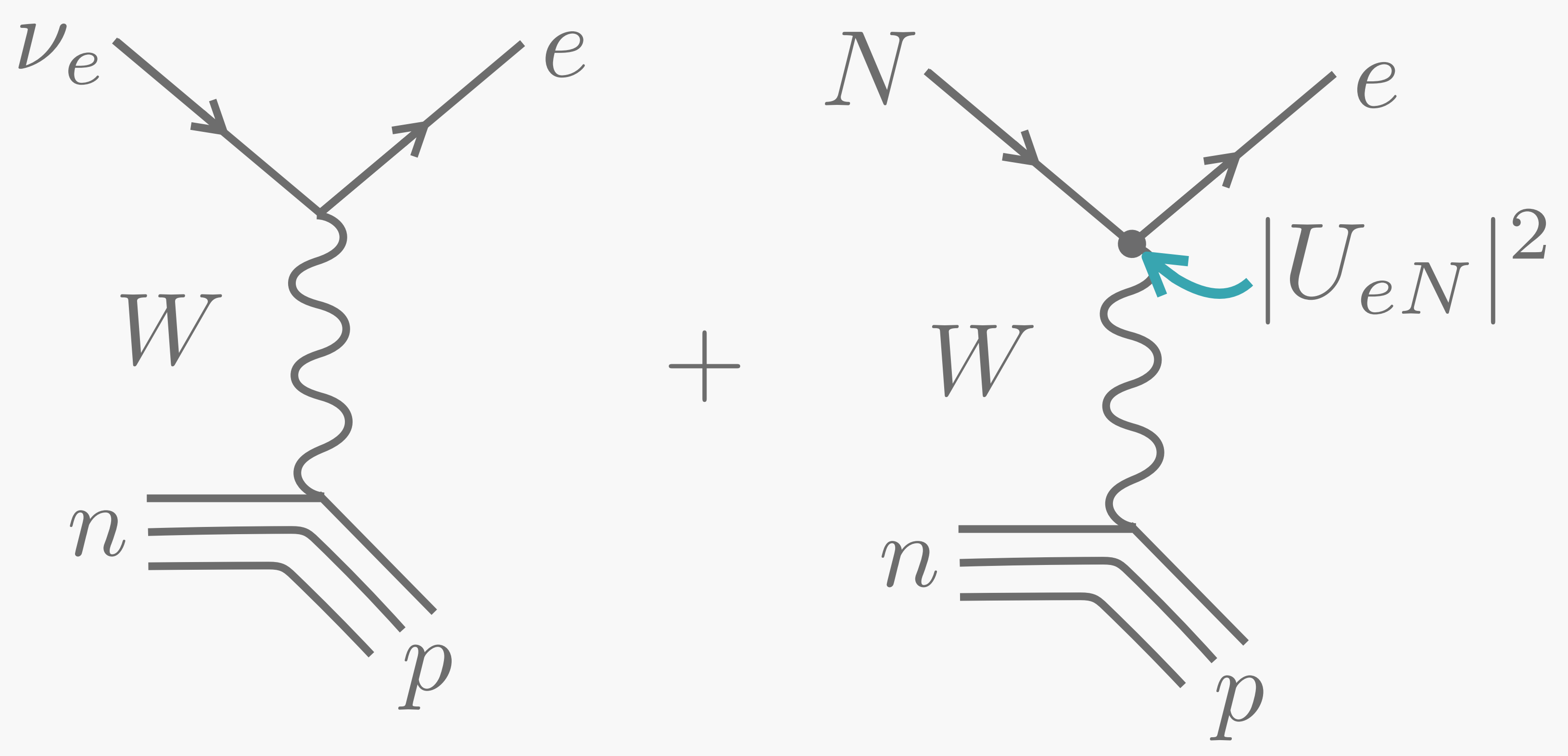
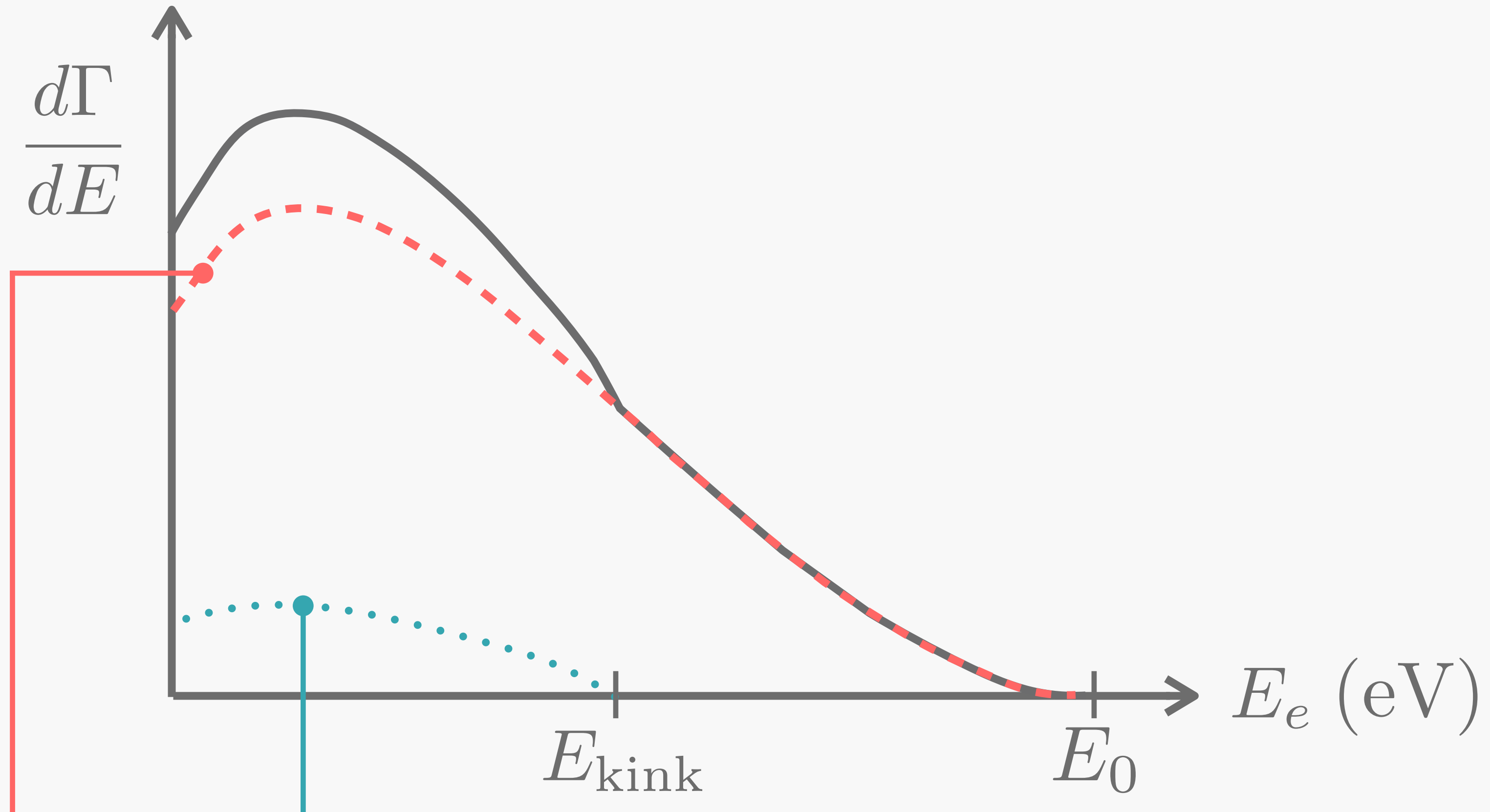


Depending on the range of M_N, very different phenomenology found

- Kinks in β-decay searches

  HNLs could modify the spectrum of nuclear β-decays if $M_N < E_0$
  $\Rightarrow$ it could produce a kink at $E_{\text{kink}} = E_0 - M_N$





$$\frac{d\Gamma}{dE} = \boxed{\left(1 - |U_{eN}|^2\right) \frac{d\Gamma}{dE}(m_\beta^2)} + \boxed{|U_{eN}|^2 \frac{d\Gamma}{dE}(M_N^2)}$$

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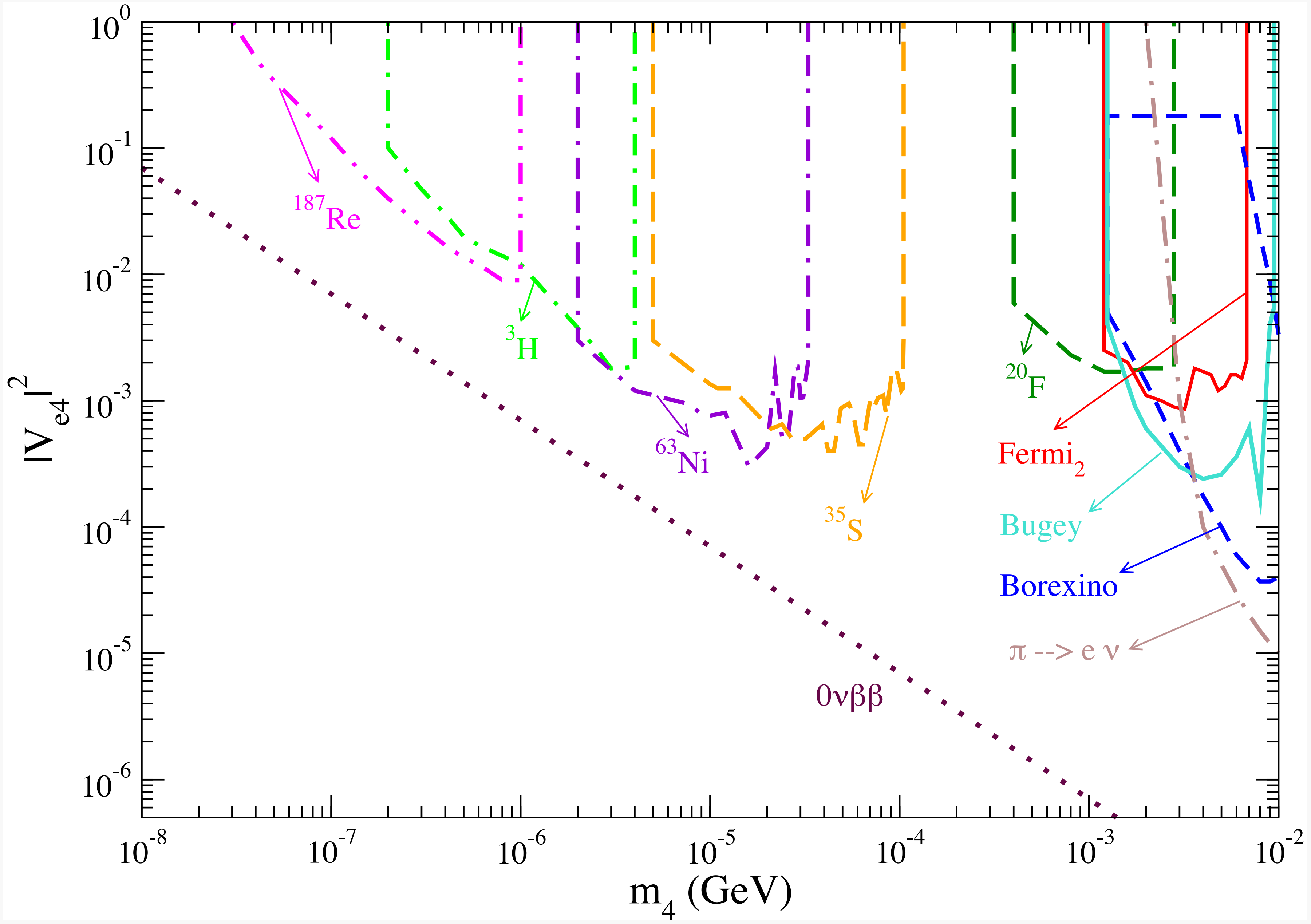

A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP **05** 2009 030

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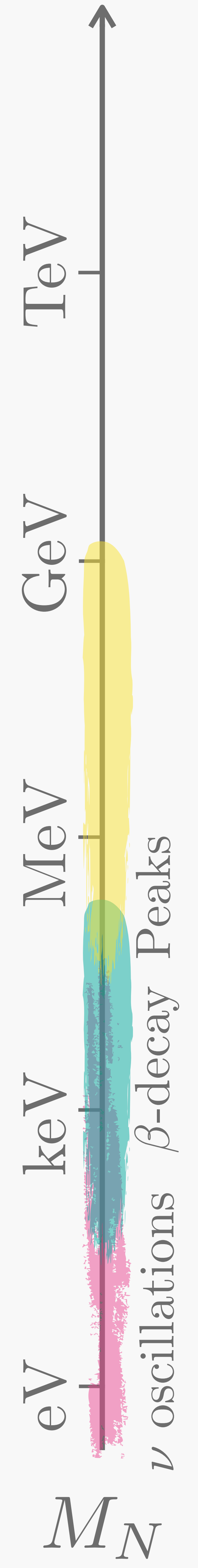
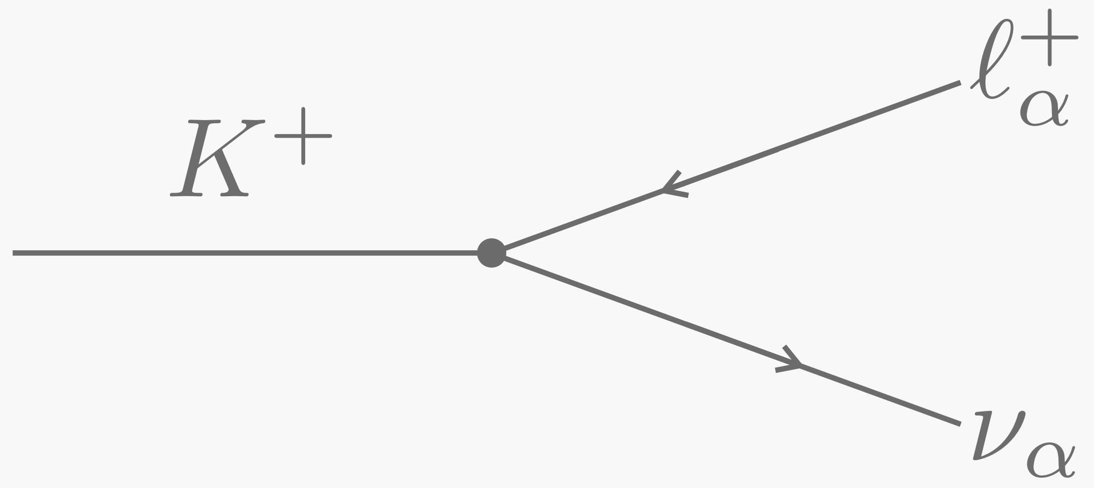


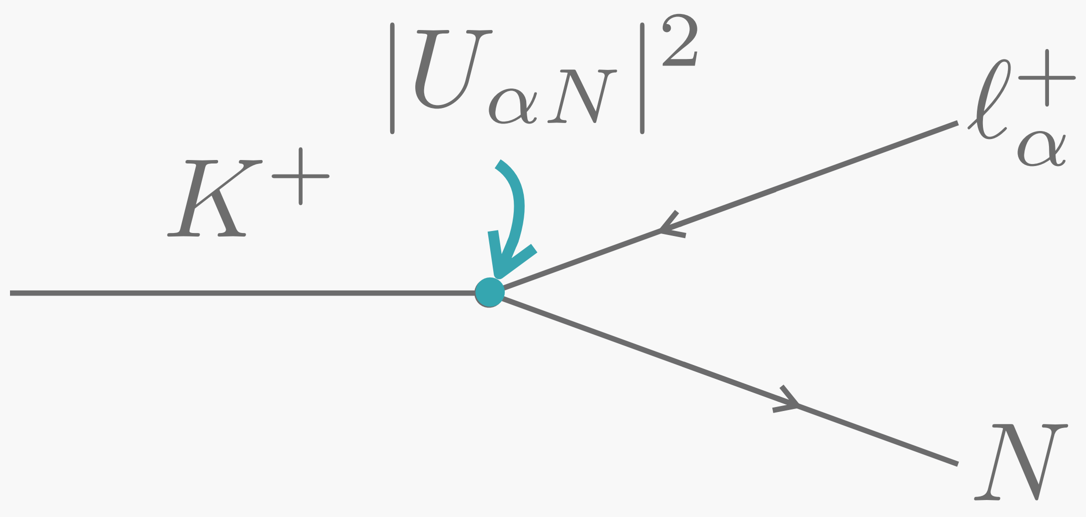
Depending on the range of M_N, very different phenomenology found

- Peak searches in meson decays

HNLs could modify the energy spectrum of pseudoscalar 2-body decay



monochromatic energy spectrum



extra peaks in energy spectrum

$$\frac{N(K^+ \to \ell_\alpha N)}{N(K^+ \to \ell_\alpha \nu_\alpha)} = |U_{\alpha N}|^2 f(m_K, m_\ell, E_\ell, m_N)$$

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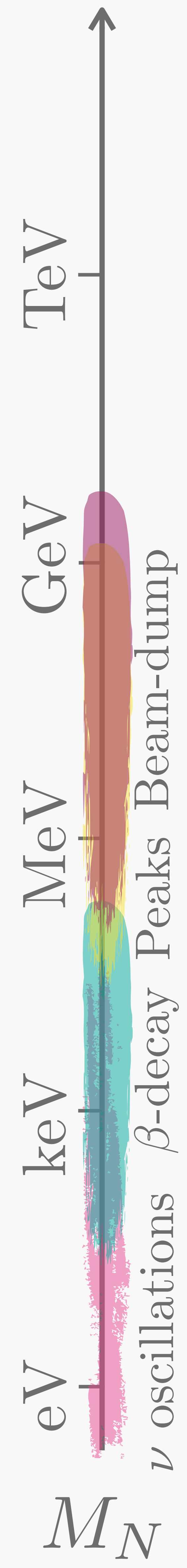
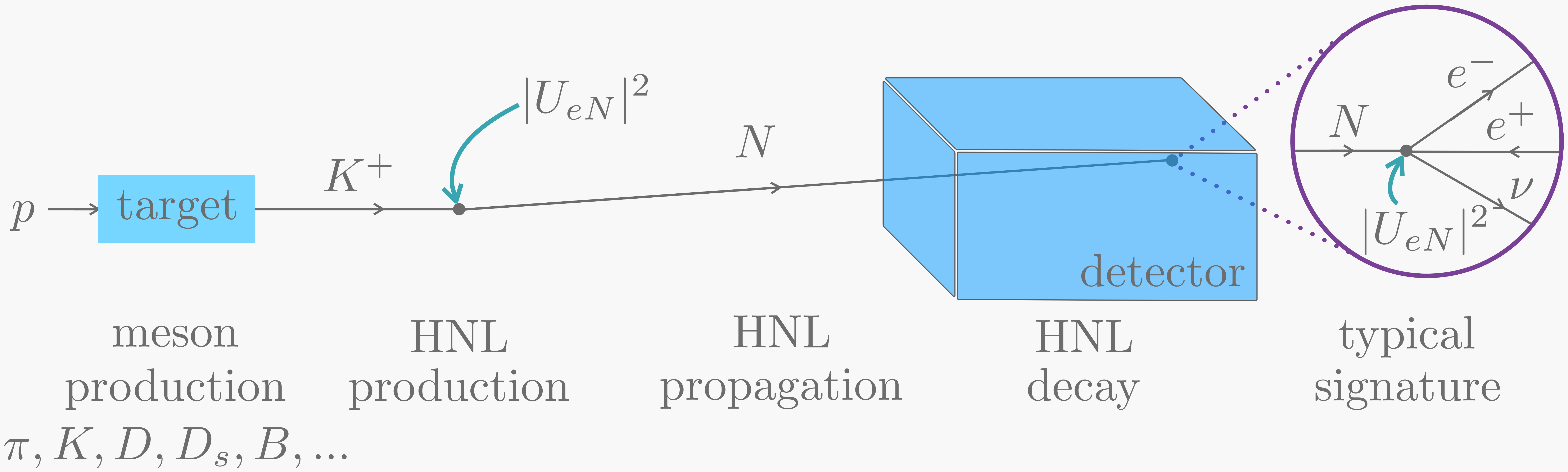


Depending on the range of M_N, very different phenomenology found

- Beam-dump experiments

  Decay in-flight of HNLs produced in meson decays



For a given M_N, the number of decay events inside detector $\propto |U_{\alpha N}|^4$

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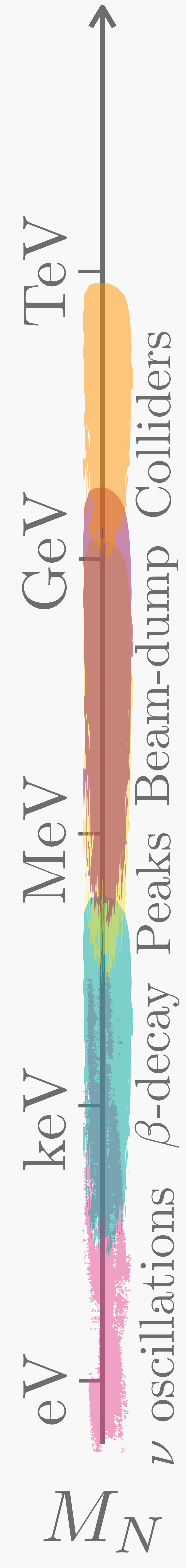
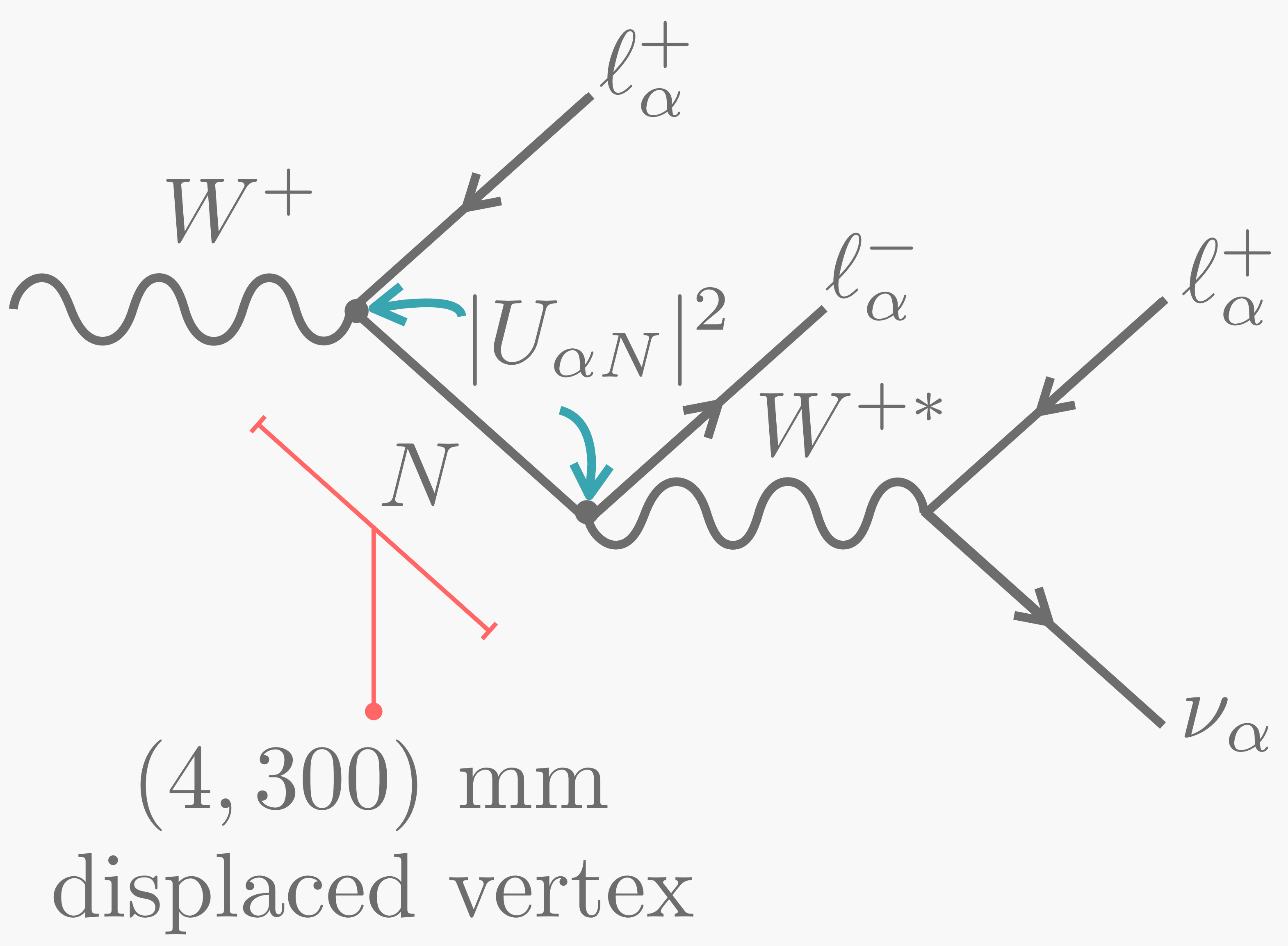


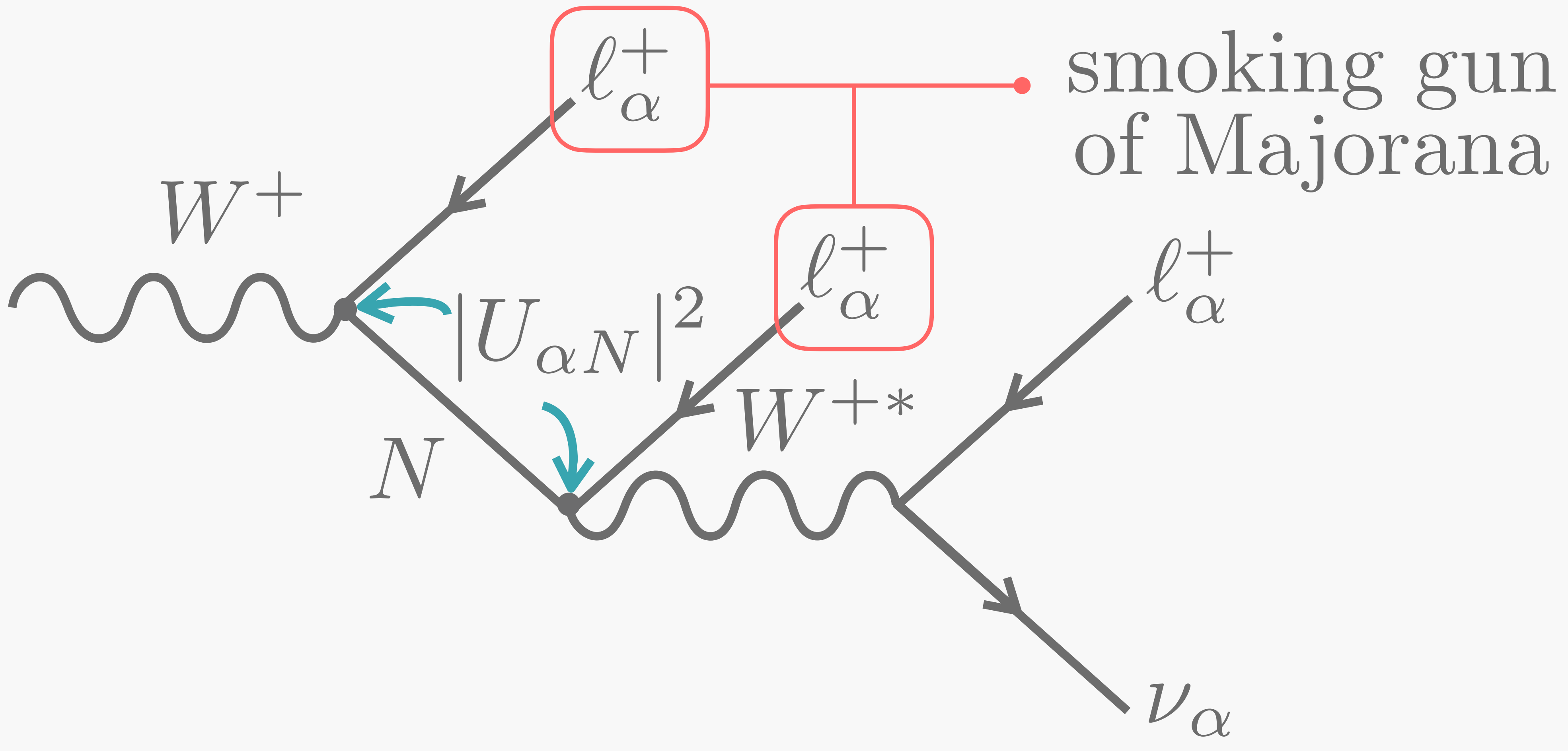
Depending on the range of M_N, very different phenomenology found

- Collider searches

  HNLs produced via W or Z interactions, and decaying back to SM $\Rightarrow$ producing displaced vertices or same sign lepton pairs (if Majorana)



$\Delta L = 0$



$\Delta L = 2$

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Depending on the range of M_N, very different phenomenology found

- Non-Unitarity of PMNS

  When $M_N > \Lambda_{\text{EW}}$, HNLs no longer produced in the experiment.
  However, they would induce deviations on EW and flavor observables through the non-Unitarity of U_{PMNS}

$$N \equiv (I - \eta) U_{\text{PMNS}}$$

$$\eta \equiv \frac{\Theta\Theta^\dagger}{2}$$

THE SCALE OF NEW PHYSICS

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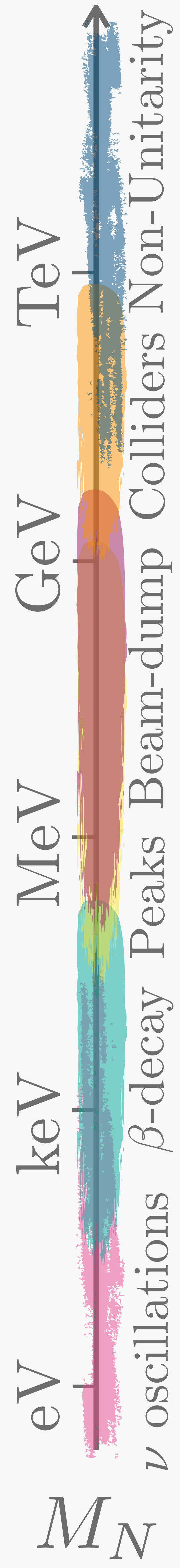

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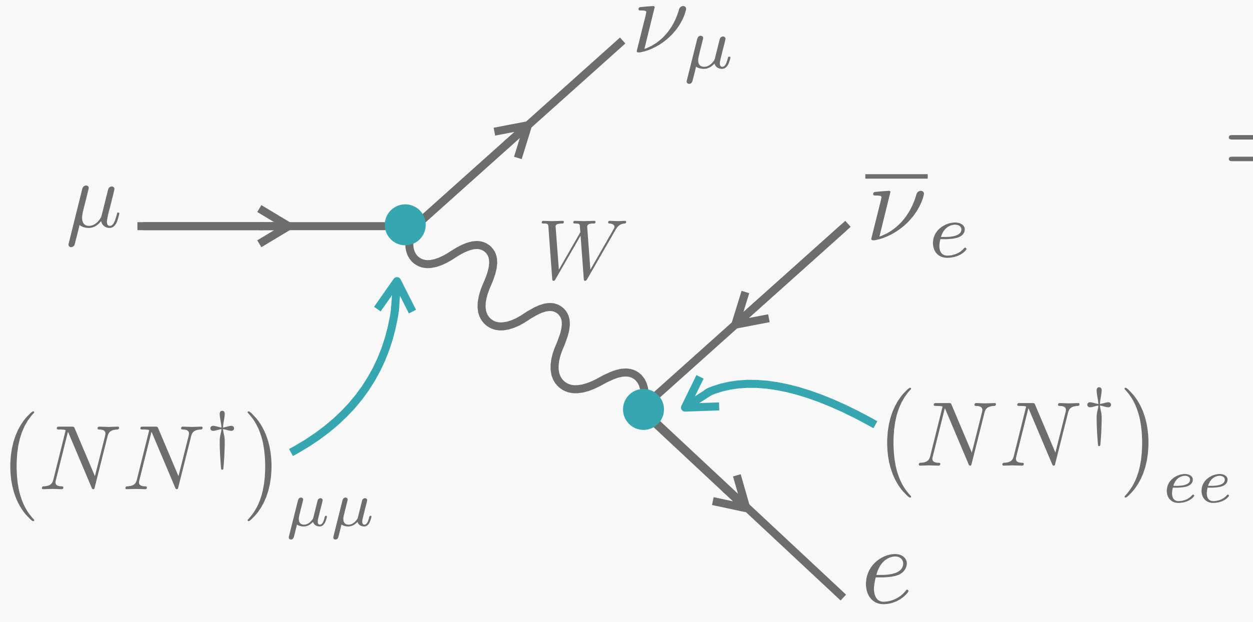
$$N \equiv (I - \eta) U_{\rm PMNS}$$

G_F measured in μ decay



$$\Rightarrow \quad G_F^2(1 - 2\eta_{ee} - 2\eta_{\mu\mu}) = G_\mu^2 \quad \Rightarrow$$

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2} G_F s_{\rm W}^2 (1 - \Delta r)} = \frac{\pi\alpha(1 + \eta_{ee} + \eta_{\mu\mu})}{\sqrt{2} G_\mu s_{\rm W}^2 (1 - \Delta r)}$$

Kinematic measurements of M_W constrain η

M. Blennow, E. Fernandez-Martinez, JHG, J. Lopez-Pavon, X. Marcano, D. Naredo-Tuero, arXiv: 2306.01040

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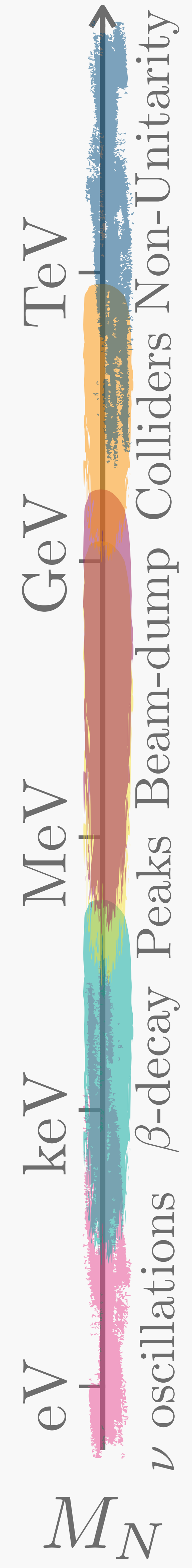
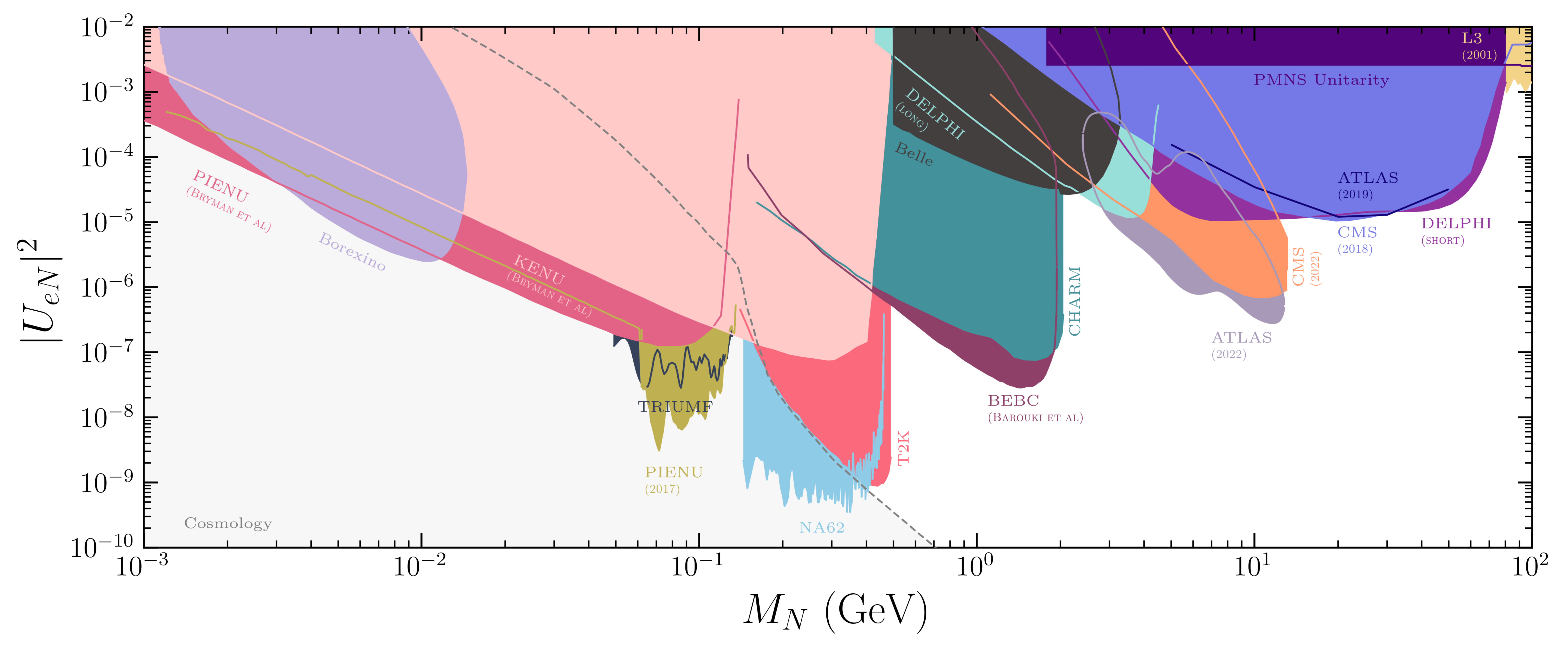


Depending on the range of M_N, very different phenomenology found



https://github.com/mhostert/Heavy-Neutrino-Limits

E. Fernandez-Martinez, M. Gonzalez-Lopez, JHG, M. Hostert, J. Lopez-Pavon. JHEP **09** 2023 001

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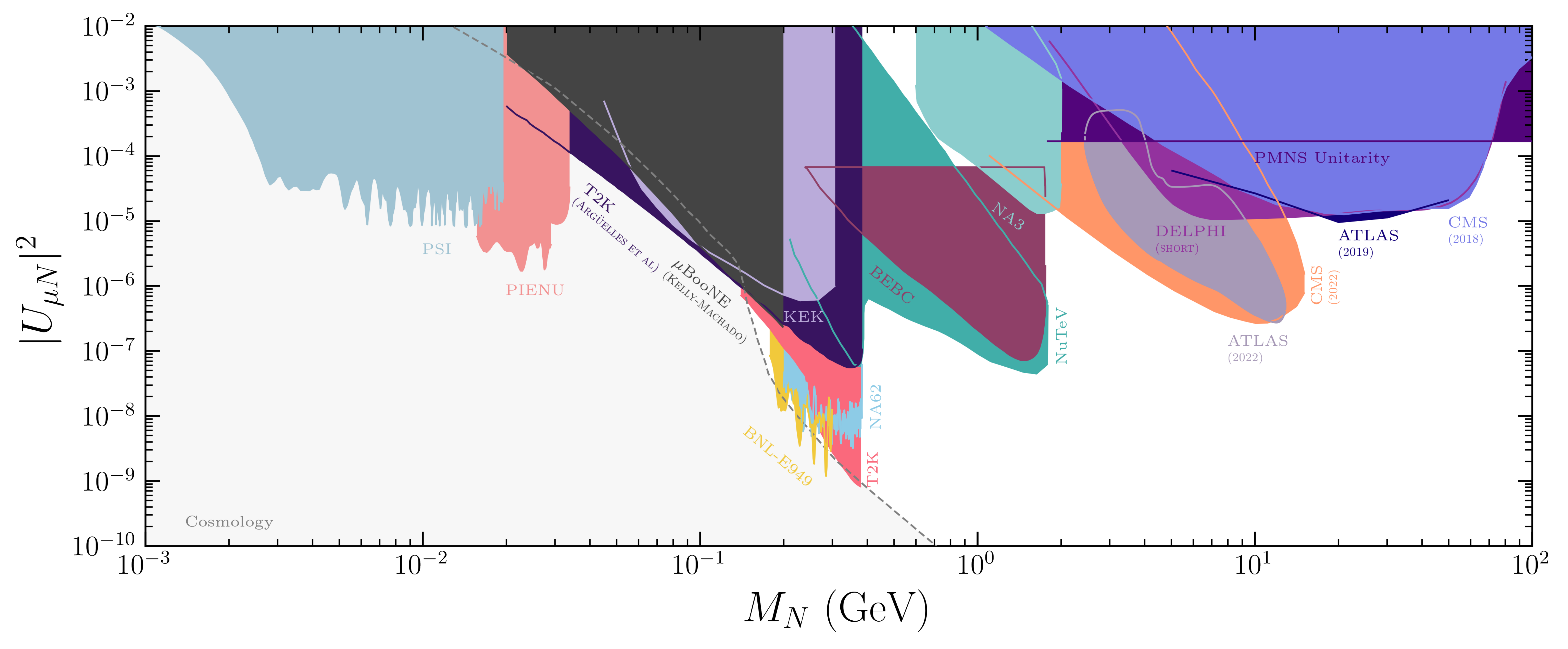

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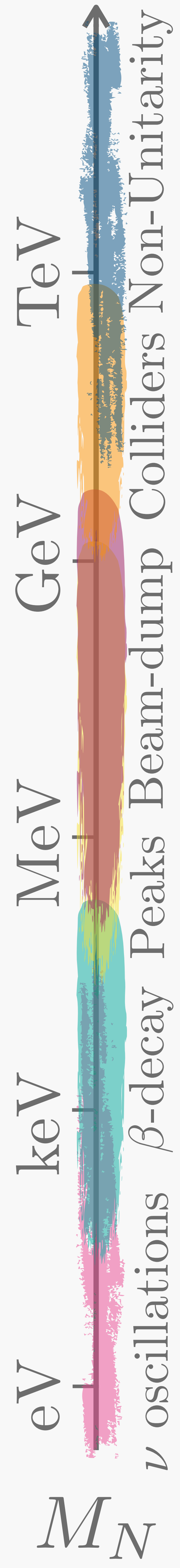

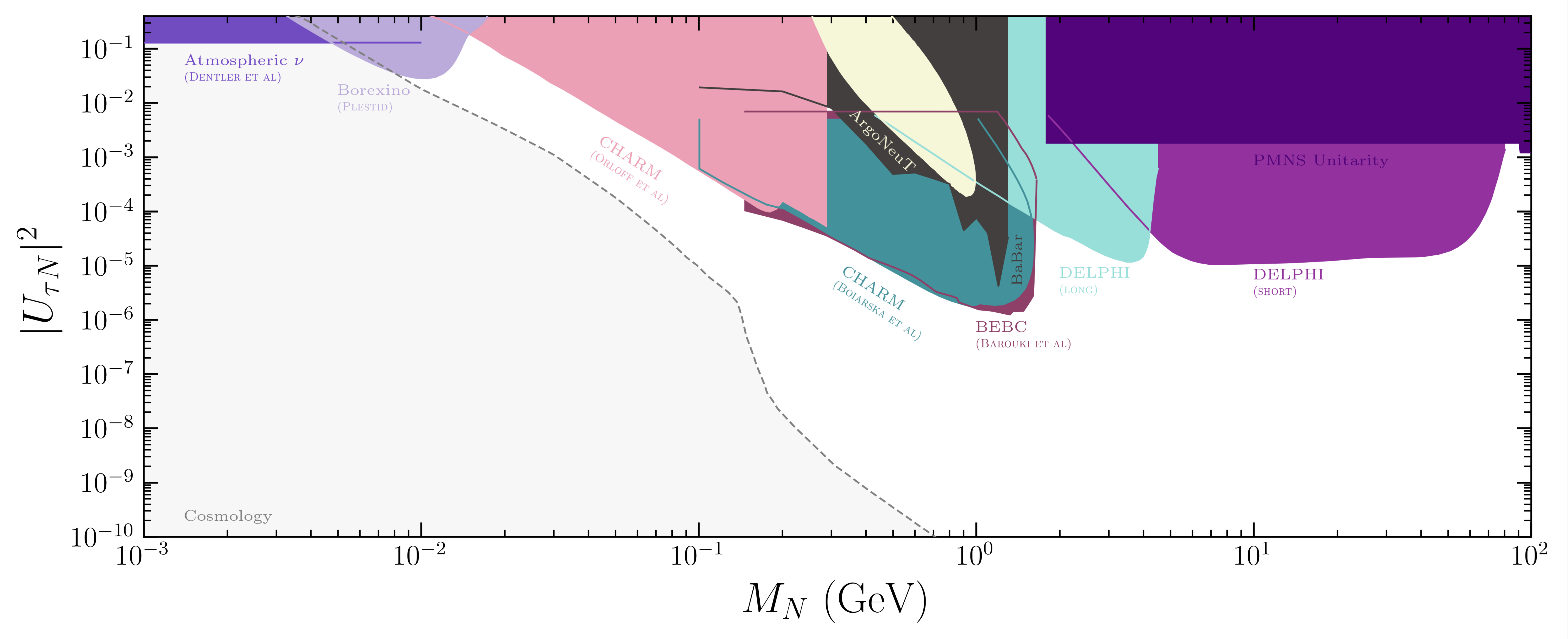

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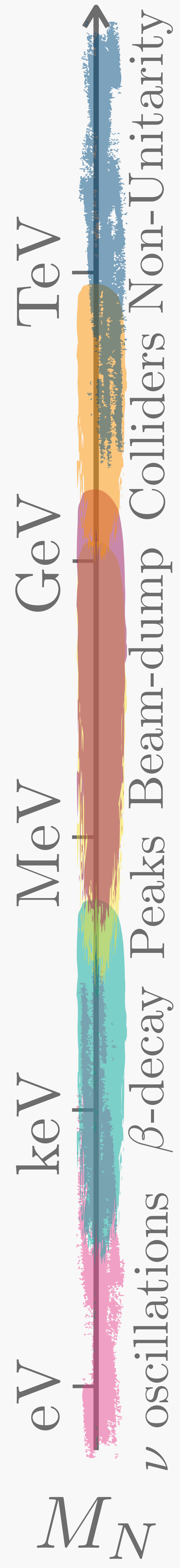

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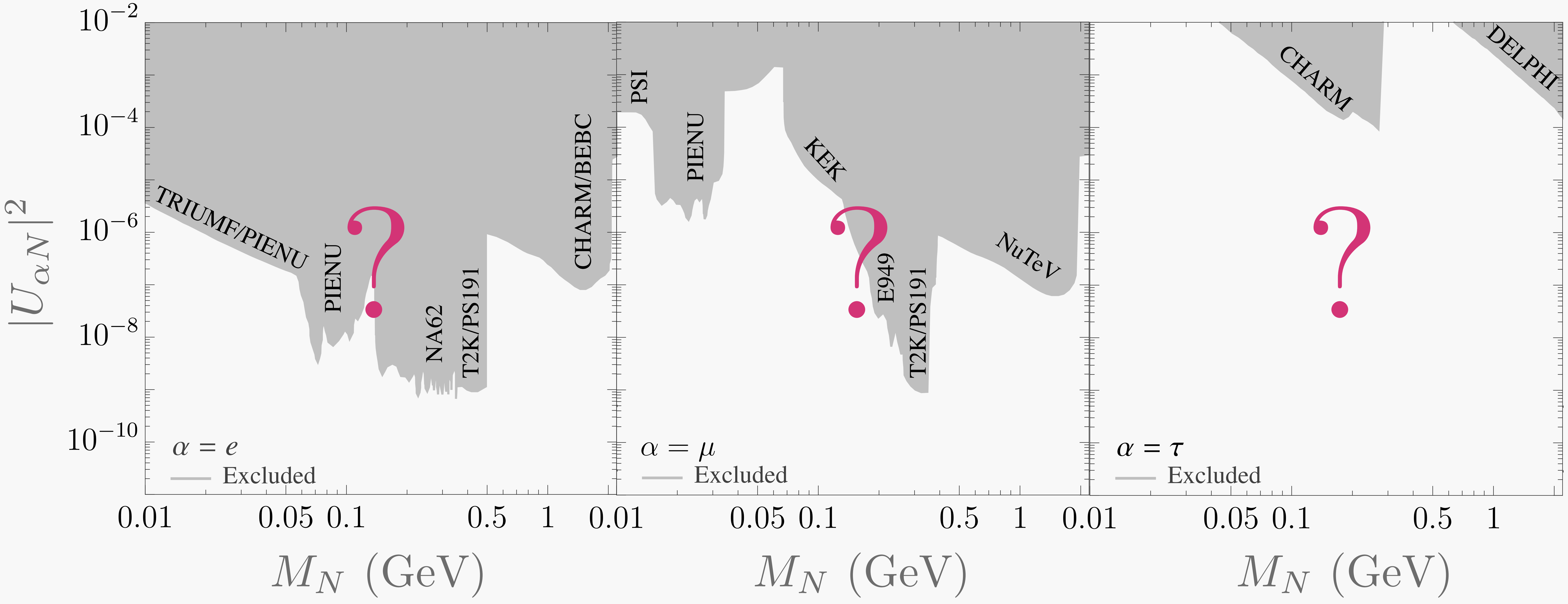

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GeV-scale HNL at DUNE

The DUNE Experiment and ND

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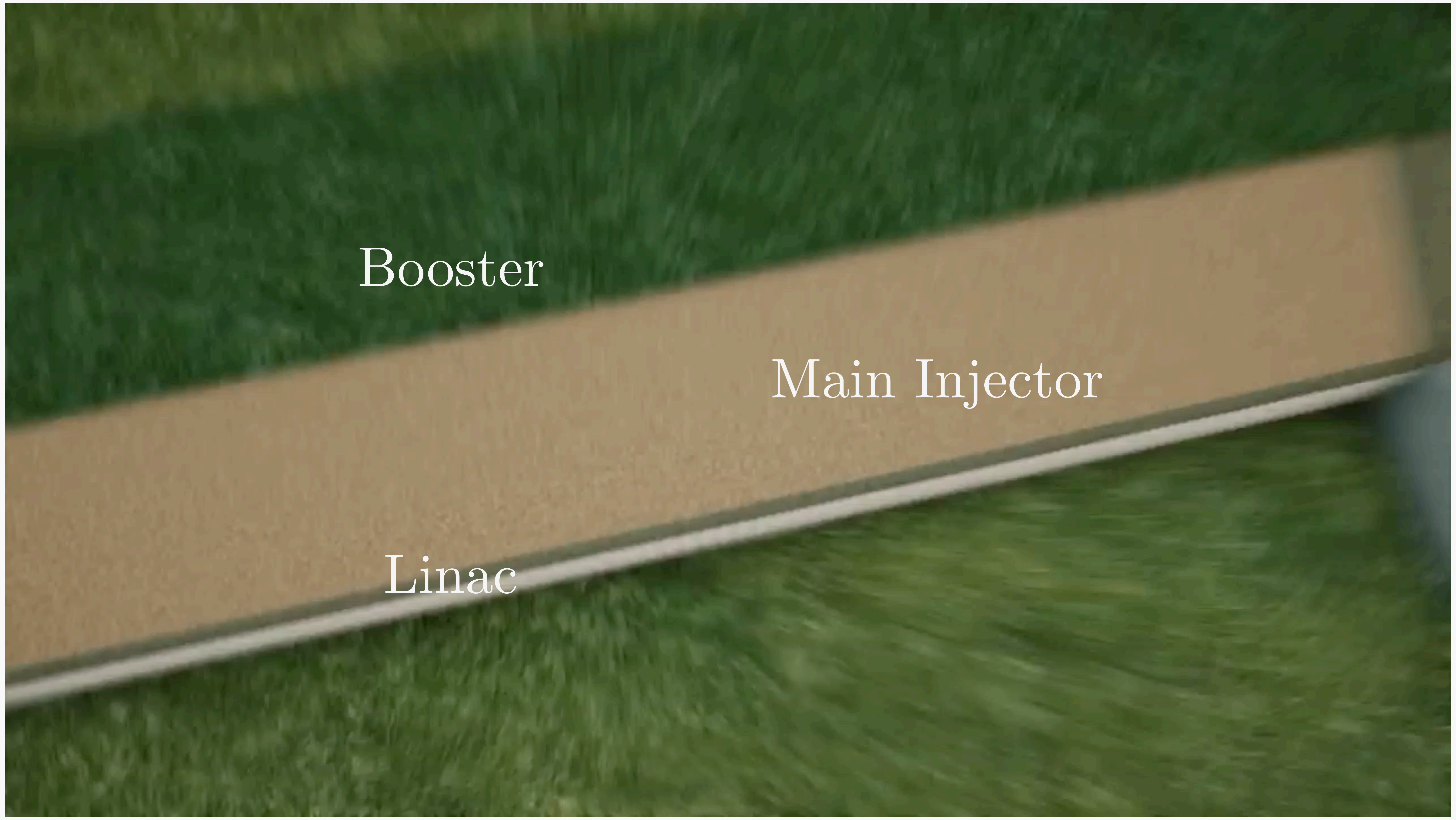
New generation of neutrino oscillation experiments at Fermilab

The DUNE Experiment and ND

zoom.us video



Beam configuration & luminosity : – 120 GeV protons – $1.1 \cdot 10^{21}$ PoT/year

The DUNE Experiment and ND

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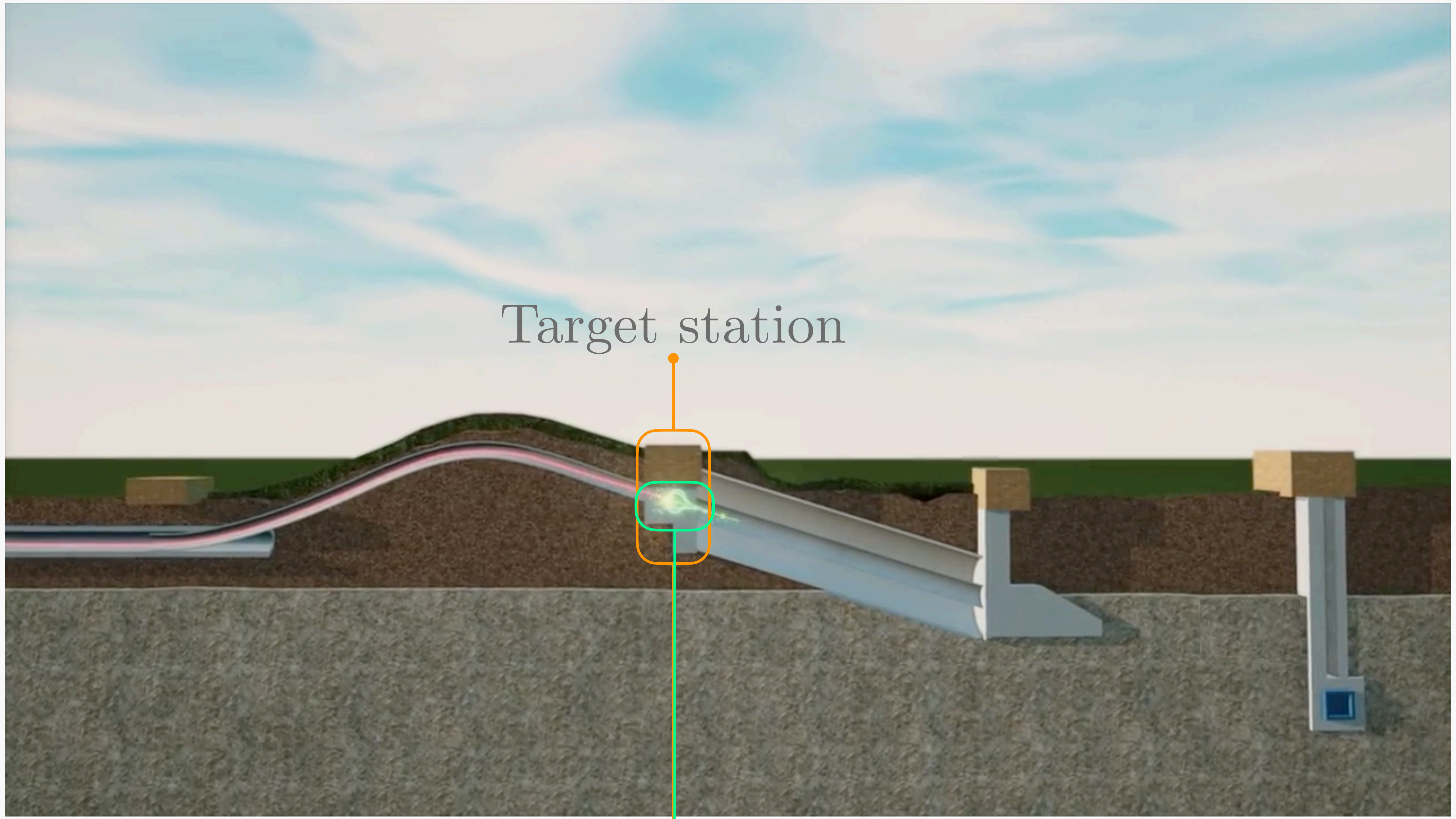
120 GeV protons

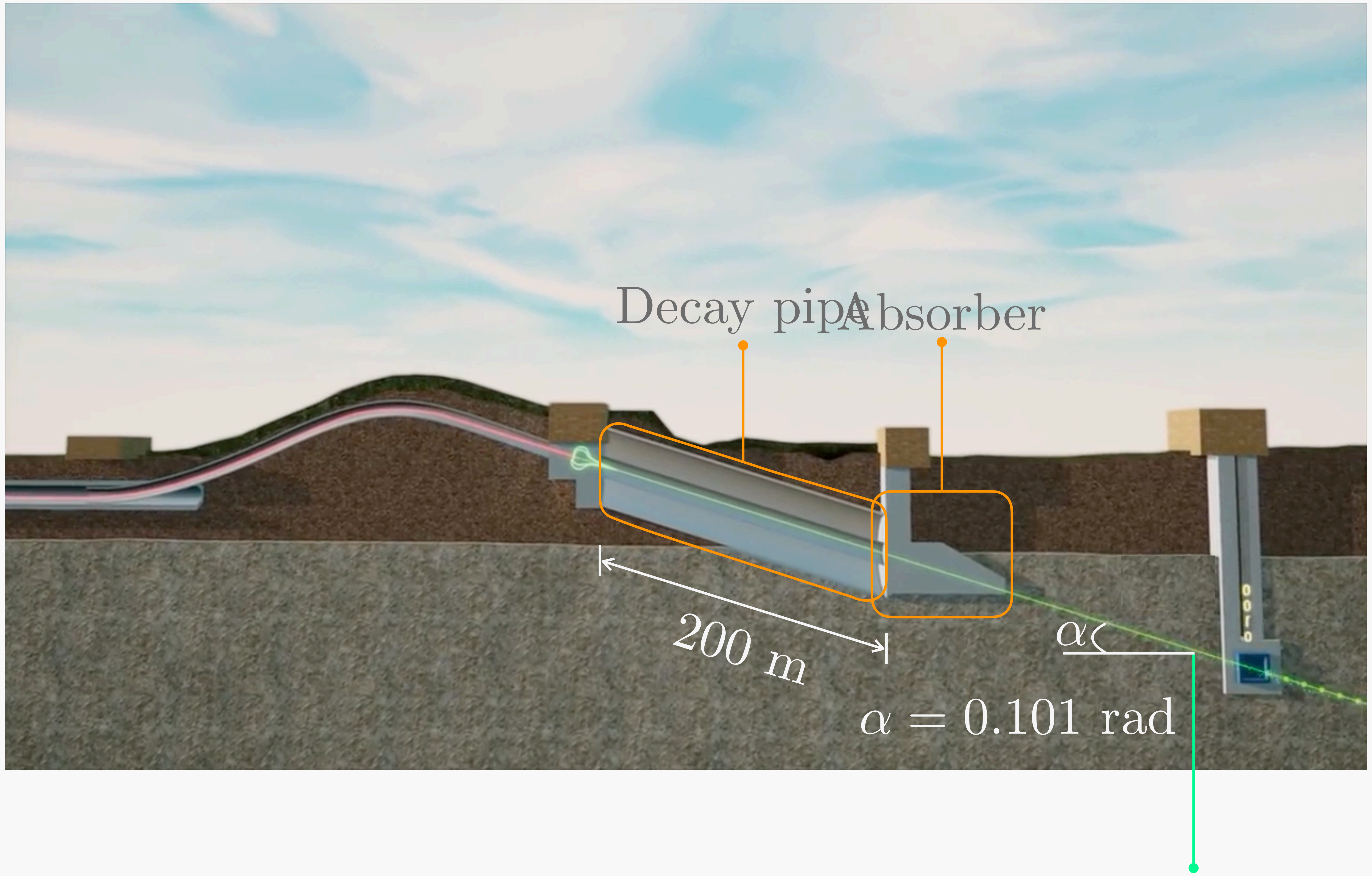


Meson production: $\pi^\pm$, $K^\pm$, $D^\pm$ & $D_s^\pm$

1.5m long target + 3 focussing horns

The DUNE Experiment and ND

zoom.us video



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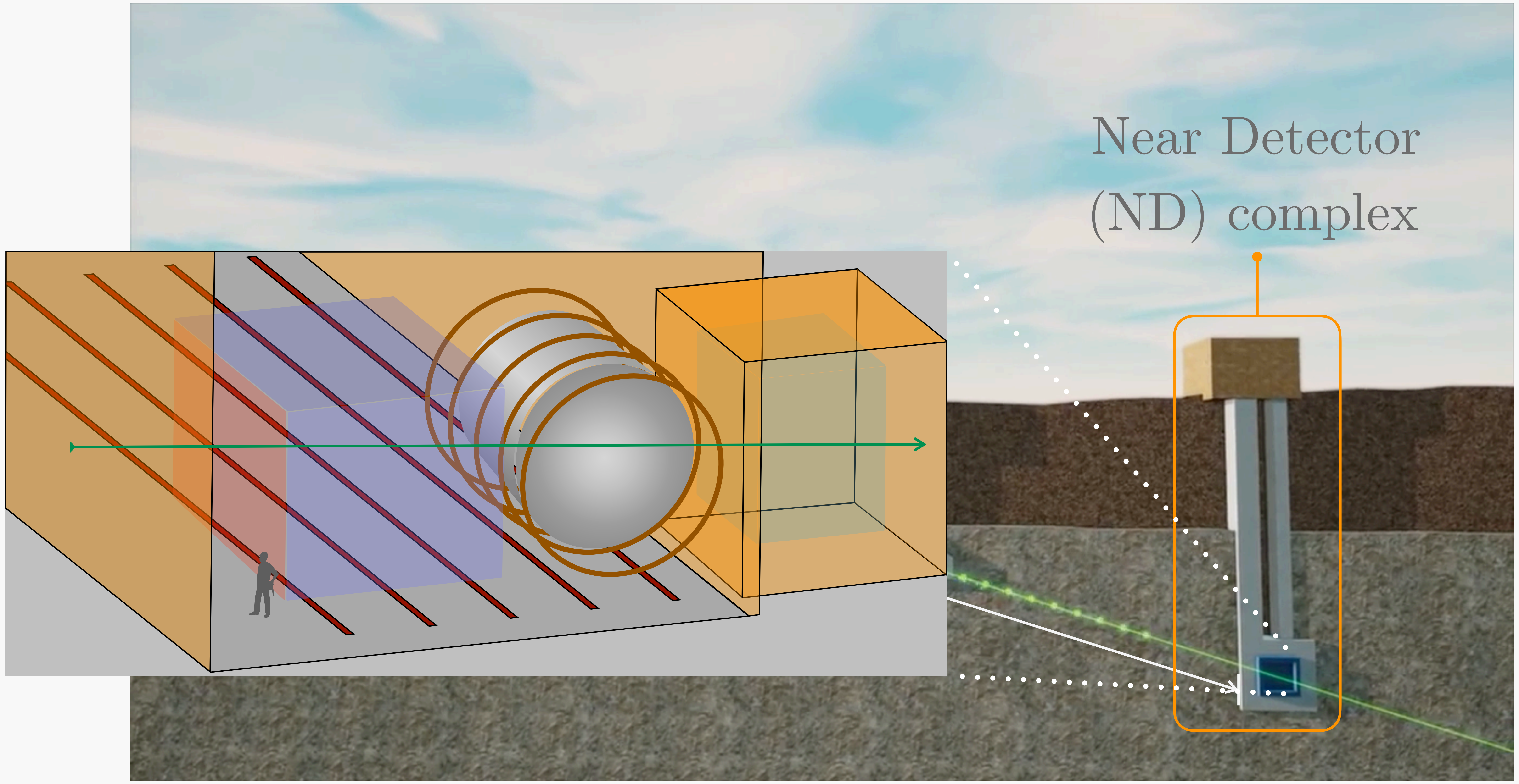
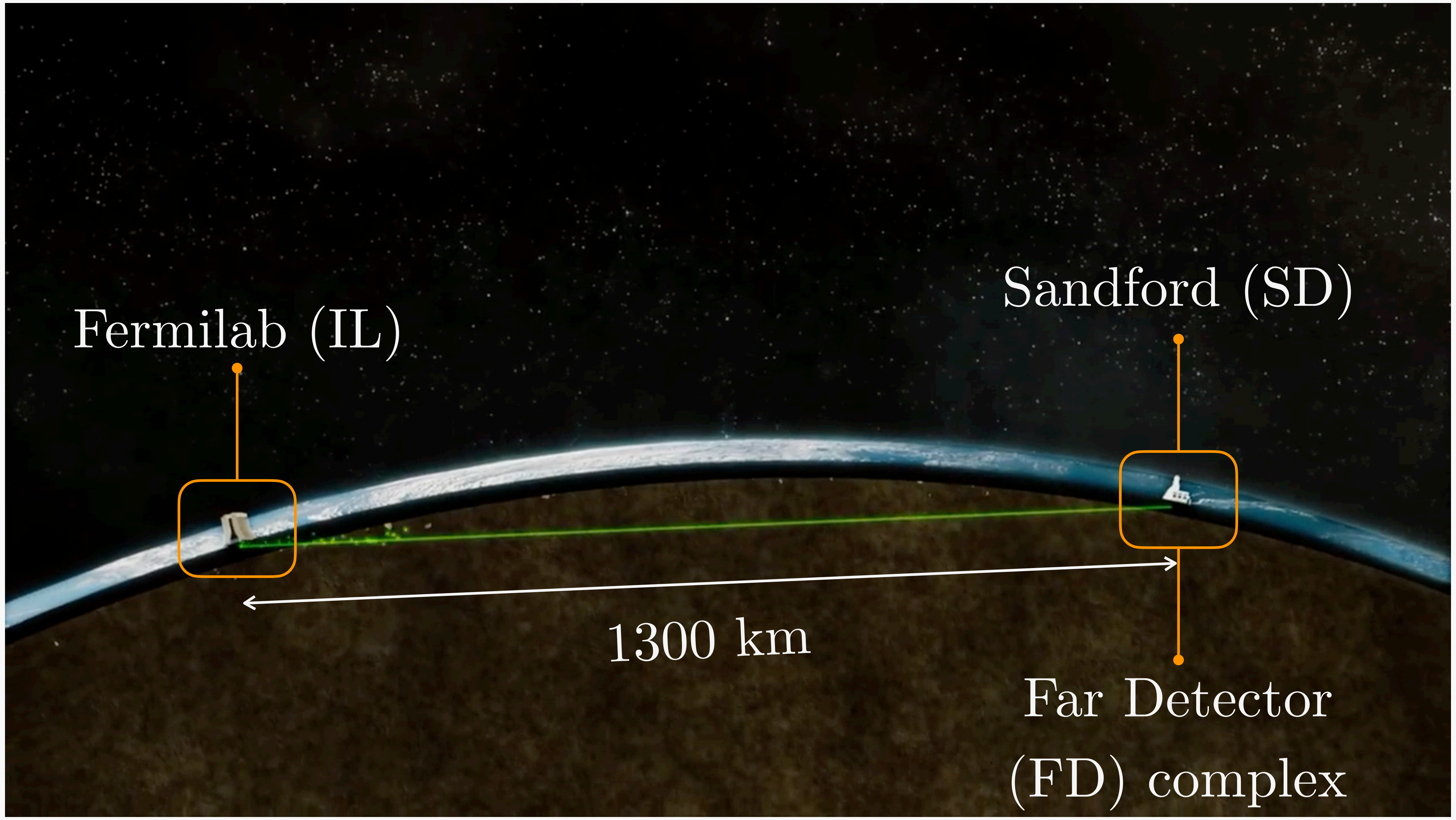


The DUNE Experiment and ND

zoom.us video



DUNE FD: 68 ktons LArTPC 1.5 km underground

The Light Neutrino Approximation

zoom.us video

Some present results based on

$$\frac{d\phi_N^{\pm}}{dE}(E_N) \approx \sum_{Q,\alpha} \mathcal{K}^{\pm}_{Q,\alpha} \frac{d\phi_{Q\to\nu_\alpha}}{dE}(E_N - M_N)$$

I. Krasnov, Phys. Rev. D **100** (2019) 075023
P. Ballett, T. Boschi, S. Pascoli, JHEP **03** (2020) 111

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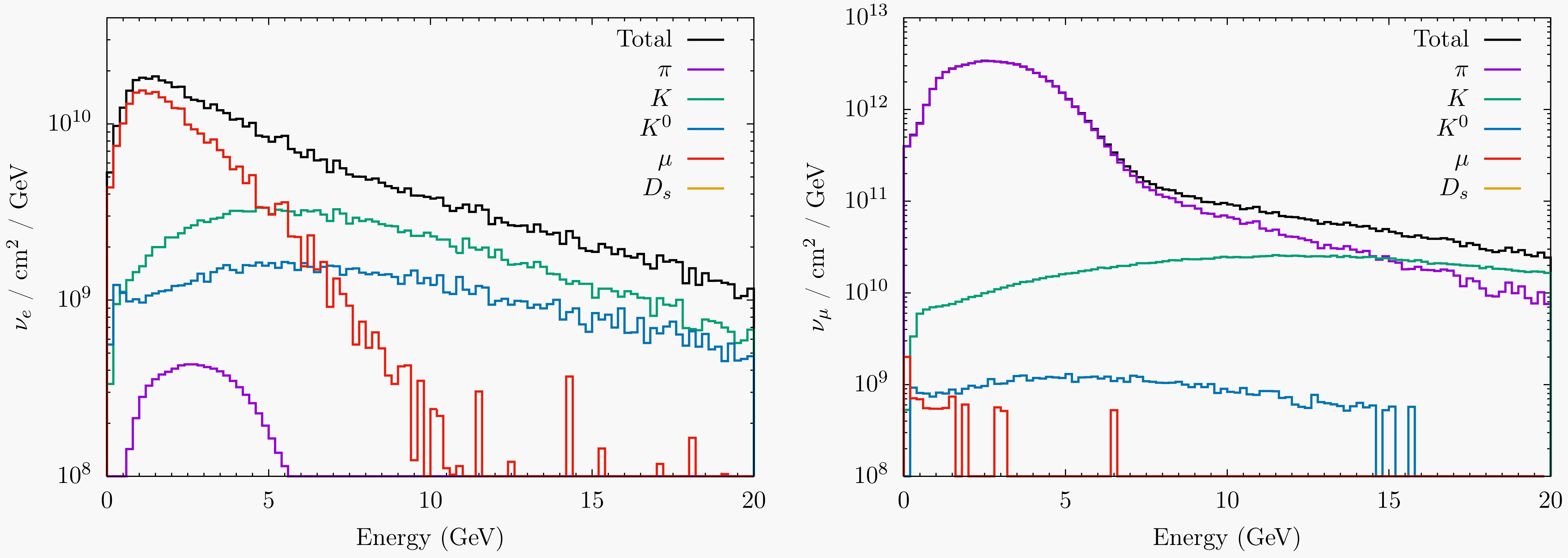
By using the official prediction of light neutrino flux at DUNE ND



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But re-scaled by a kinematic factor

$$\mathcal{K}^{\pm}_{Q,\alpha} = \frac{\Gamma\left(Q \to N + X\right)}{\Gamma\left(Q \to \nu_\alpha + X\right)}$$

Ratio of BRs to account for the different phase space.

It does not depend on the energy E_N, only on M_N and $|U_{\alpha N}|^2$.

I. Krasnov, Phys. Rev. D **100** (2019) 075023
P. Ballett, T. Boschi, S. Pascoli, JHEP **03** (2020) 111

The Light Neutrino Approximation

zoom.us video

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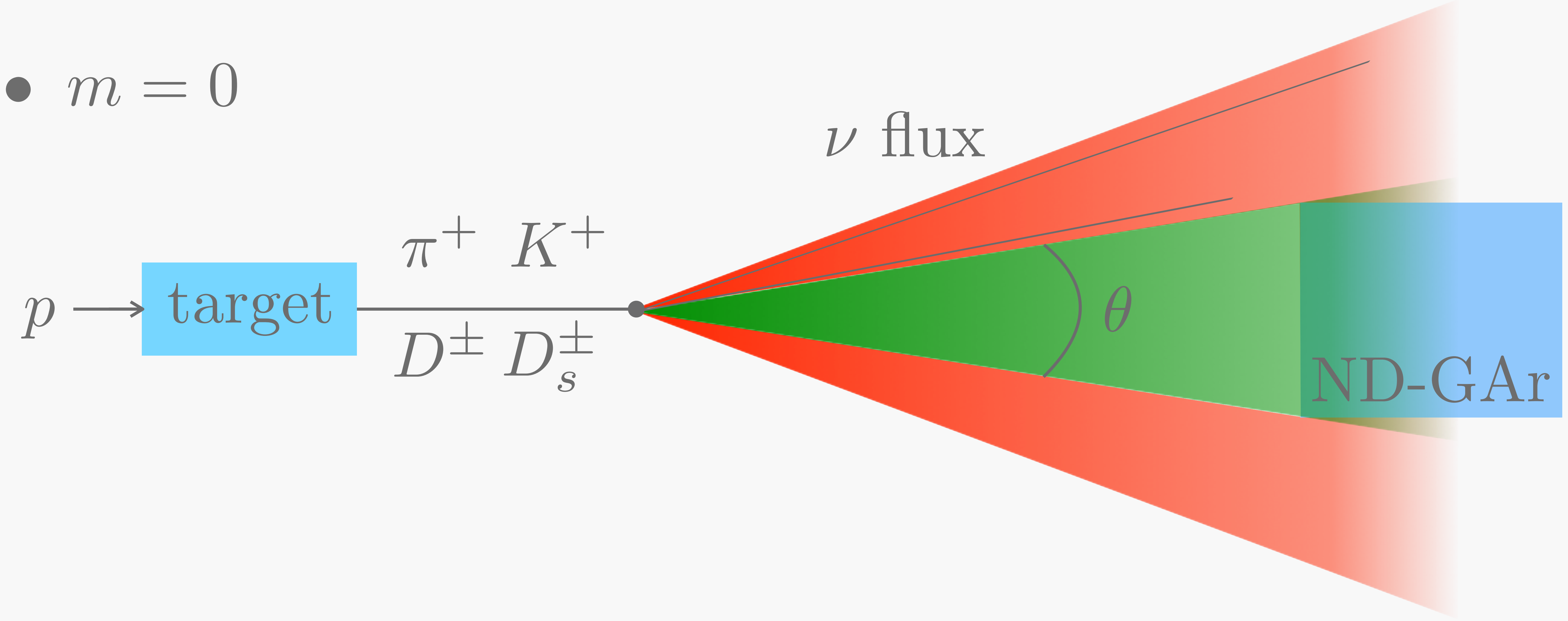
However, deviations of the energy and angular distributions for the HNL with respect to the massless case are expected.

- $m = 0$



θ in the lab frame $\Rightarrow$ acceptance of detector

The Light Neutrino Approximation

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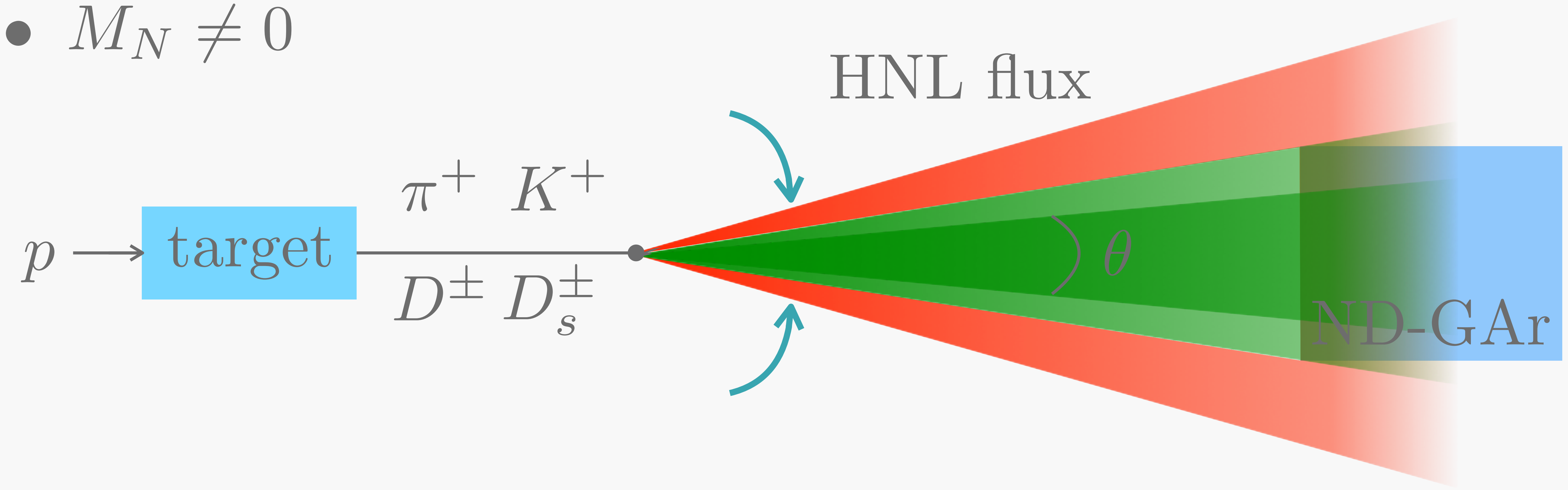
$$\frac{d\phi_N^{\pm}}{dE}(E_N) \approx \sum_{Q,\alpha} \mathcal{K}^{\pm}_{Q,\alpha} \frac{d\phi_{Q\to\nu_\alpha}}{dE}(E_N - M_N)$$

However, deviations of the energy and angular distributions for the HNL with respect to the massless case are expected.

- $M_N \neq 0$



θ in the lab frame $\Rightarrow$ acceptance of detector

The heavier the HNL, the larger the boost $\Rightarrow$ better acceptance

The Light Neutrino Approximation

zoom.us video

Some present results based on

$$\frac{d\phi_N^\pm}{dE}(E_N) \approx \sum_{Q,\alpha} \mathcal{K}^\pm_{Q,\alpha} \frac{d\phi_{Q\to\nu_\alpha}}{dE}(E_N - M_N)$$

Furthermore, many significant discrepancies found in the couplings between mesons and HNL affecting $\mathcal{K}^\pm_{Q,\alpha}$ $\Rightarrow$ effective theory describing interactions mesons and HNL reviewed.

R. E. Shrock , Phys. Rev. D **24** 1981 1232
D. Gorbunov and M. Shaposhnikov, JHEP **10** 2007 015
A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP **05** 2009 030
P. Ballett, T. Boschi, S. Pascoli, JHEP **03** (2020) 111
K. Bondarenko, A. Boyarsky, D. Gorbunov and O. Ruchayskiy, JHEP **11** 2018 032
J. C. Helo, S. Kovalenko and I. Schmidt, Nucl. Phys. B **853** 2011 80

Effective Mesons and HNL Interacti

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The leptonic part of the electroweak Lagrangian

$$
\begin{aligned}
\mathcal{L}^{\ell}_{\mathrm{EW}} &= \frac{g}{\sqrt{2}} W^{+}_{\mu} U^{*}_{\alpha i} \bar{n}_i \gamma^{\mu} P_L \ell_\alpha + \\
&+ \frac{g}{4c_w} Z_\mu \left(\boxed{C_{ij}} \bar{n}_i \gamma^{\mu} P_L n_j + \bar{\ell}_\alpha \gamma^{\mu} \left[2s_w^2 P_R - (1 - 2s_w^2) P_L \right] \ell_\alpha \right) + \mathrm{h.c.}
\end{aligned}
$$

$$C_{ij} \equiv U^{*}_{\alpha i} U_{\alpha j}$$

Effective Mesons and HNL Interacti

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\end{aligned}$$

$$C_{ij} \equiv U^{*}_{\alpha i} U_{\alpha j}$$

HNL can also interact with quarks through CC and NC interactions.

$$\mathcal{L}^{q}_{\mathrm{EW}} = \frac{g}{\sqrt{2}} W^{+\mu} j_{W,\mu} + \frac{g}{4c_w} Z^{\mu} j_{Z,\mu} + \mathrm{h.c.}.$$

with

$$j_{W,\mu} = j^{V}_{W,\mu} + j^{A}_{W,\mu} = \frac{1}{2} V_{qq'} \bar{q} \gamma_\mu q' - \frac{1}{2} V_{qq'} \bar{q} \gamma_\mu \gamma_5 q'.$$

$$j_{Z,\mu} = j^{V}_{Z,\mu} + j^{A}_{Z,\mu} = \bar{q}(T_3 - 2Q s_w^2) \gamma_\mu q - \bar{q} \gamma_\mu \gamma_5 T_3 q.$$

Effective Mesons and HNL Interacti

zoom.us video

Definition of the pseudoscalar (P) and vector (V) meson decay constants

$$\langle 0 | j^A_{a,\mu} | P_b \rangle = i\delta_{ab} \frac{f_P}{\sqrt{2}} p_\mu \qquad \text{and} \qquad \langle 0 | j^V_{a,\mu} | V_b \rangle = \delta_{ab} \frac{f_V}{\sqrt{2}} \epsilon_\mu$$

with p_μ the momentum of P and ϵ_μ the polarization of V and

Effective Mesons and HNL Interacti

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$$j^A_{a,\mu} = \bar{q} \lambda_a \gamma_\mu \gamma_5 q \qquad \text{and} \qquad j^V_{a,\mu} = \bar{q} \lambda_a \gamma_\mu q$$

the axial and vector currents.

Effective Mesons and HNL Interacti

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the axial and vector currents.

The set $\{\lambda_a\}$ corresponds to linear combinations of the 8 Gell-Mann matrices.

Effective Mesons and HNL Interacti

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- Pseudoscalar mesons
  - Neutral mesons: π^0, η, η'

    The quark content of neutral P corresponds to linear combinations of the diagonal generators λ_0, λ_3 and λ_8

$$\boxed{j^A_{3,\mu} = \frac{1}{2}\left[\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d\right]} \longrightarrow \pi^0$$

$$\left.\begin{aligned} j^A_{8,\mu} &= \frac{1}{2\sqrt{3}}\left[\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d - 2\bar{s}\gamma_\mu\gamma_5 s\right] \\ j^A_{0,\mu} &= \frac{1}{\sqrt{6}}\left[\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d + \bar{s}\gamma_\mu\gamma_5 s\right] \end{aligned}\right\} \longrightarrow \eta \text{ and } \eta'$$

The Z axial current as a linear combination of the neutral axial currents

$$j^A_{Z,\mu} = -\frac{1}{2}\left(\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d - \bar{s}\gamma_\mu\gamma_5 s\right) = -\left(j^A_{3,\mu} + \frac{1}{\sqrt{3}}j^A_{8,\mu} - \frac{1}{\sqrt{6}}j^A_{0,\mu}\right)$$

Effective Mesons and HNL Interacti

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- Pseudoscalar mesons
  - Neutral mesons: π^0, η, η'

    At low energies (integrating out the Z), the amplitude for $\pi^0 \to n_i n_j$

$$i\mathcal{M}_{\pi^0 n_i \bar{n}_j} = \frac{ig^2}{4c_w^2 M_Z^2} C_{ij} \bar{u}_i \gamma^\mu P_L v_j \langle 0 | j^A_{Z,\mu} | \pi^0 \rangle = G_F C_{ij} f_\pi \bar{u}_i \gamma^\mu P_L v_j p_\mu$$

Effective Mesons and HNL Interacti

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In configuration space, the effective operator that leads to this amplitude

$$\mathcal{O}_{\pi^0 n_i \bar{n}_j} = \frac{1}{2} G_F C_{ij} f_\pi \partial_\mu (\bar{n}_i \gamma^\mu P_L n_j) \pi^0 + \text{h.c.}$$

Effective Mesons and HNL Interacti

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If all particles are on-shell, applying Dirac's equation

$$\boxed{\mathcal{O}_{\pi^0 n_i \bar{n}_j} = \frac{i}{2} G_F C_{ij} f_\pi \bar{n}_i (m_i P_L - m_j P_R) n_j \pi^0 + \text{h.c.}}$$

Effective Mesons and HNL Interacti

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The coupling to heavy states dominate the interaction $\Rightarrow$ chiral enhancement

Effective Mesons and HNL Interacti

- Pseudoscalar mesons
  - Neutral mesons: π^0, η, η'

    Similarly, $\mathcal{O}_{\eta_0 n_i \overline{n}_j}$ and $\mathcal{O}_{\eta_8 n_i \overline{n}_j}$ are obtained.

    Unlike π^0, η and η' are not interaction eigenstates. With the change of basis

$$\begin{pmatrix} f_{\eta,8} & f_{\eta,0} \\ f_{\eta',8} & f_{\eta',0} \end{pmatrix} = \begin{pmatrix} f_8 \cos\theta_8 & -f_0 \sin\theta_0 \\ f_8 \sin\theta_8 & f_0 \cos\theta_0 \end{pmatrix} \Rightarrow \begin{aligned} j^A_{\eta,\mu} &= \cos\theta_8 j^A_{8,\mu} - \sin\theta_0 j^A_{0,\mu} \\ j^A_{\eta',\mu} &= \sin\theta_8 j^A_{8,\mu} + \cos\theta_0 j^A_{0,\mu} \end{aligned}$$

R. Escribano, S. Gonzalez-Solis, P. Masjuan and P. Sanchez-Puertas, Phys. Rev. D **94** 2016 054033

Effective Mesons and HNL Interacti

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- Pseudoscalar mesons
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the operators in the mass basis

$$\boxed{\begin{aligned} \mathcal{O}_{\eta n_i \bar{n}_j} &= \frac{i}{2} G_F C_{ij} \left[\frac{\cos\theta_8 f_8}{\sqrt{3}} + \frac{\sin\theta_0 f_0}{\sqrt{6}} \right] \bar{n}_i \left(m_i P_L - m_j P_R \right) n_j \eta + \text{h.c.} \\ \mathcal{O}_{\eta' n_i \bar{n}_j} &= \frac{i}{2} G_F C_{ij} \left[\frac{\sin\theta_8 f_8}{\sqrt{3}} - \frac{\cos\theta_0 f_0}{\sqrt{6}} \right] \bar{n}_i \left(m_i P_L - m_j P_R \right) n_j \eta' + \text{h.c.} \end{aligned}}$$

Effective Mesons and HNL Interacti

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- Pseudoscalar mesons
  - Charged mesons: $\pi^\pm, K^\pm, D^\pm, D_s^\pm$

    The combinations of generators that reproduce quark content of $\pi^\pm$ and $K^\pm$

$$
\begin{aligned}
j^A_{\pi^\pm,\mu} &= \frac{1}{\sqrt{2}}\bar{q}\gamma_\mu\gamma_5(\lambda_1 \mp i\lambda_2)q \\
j^A_{K^\pm,\mu} &= \frac{1}{\sqrt{2}}\bar{q}\gamma_\mu\gamma_5(\lambda_4 \mp i\lambda_5)q
\end{aligned}
\quad \Rightarrow \quad j^A_{W,\mu} = -\frac{1}{\sqrt{2}}\left(V_{ud}\, j^A_{\pi^-,\mu} + V_{us}\, j^A_{K^-,\mu}\right)
$$

Effective Mesons and HNL Interacti

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At low energies (integrating out the W), the amplitude for $\pi^- \to \ell_\alpha^- \overline{n}_i$

$$i\mathcal{M}_{\pi\ell_\alpha\bar{n}_i} = \frac{ig^2}{2M_W^2}U_{\alpha i}\bar{u}_\alpha\gamma^\mu P_L v_i\langle 0|j^A_{W,\mu}|\pi^-\rangle = \sqrt{2}G_F U_{\alpha i}V_{ud}f_\pi\bar{u}_\alpha\gamma^\mu P_L v_i p_\mu$$

Following the same procedure used to derive the effective vertex $\pi^0 \to n_i\overline{n}_j$

$$\boxed{\mathcal{O}_{\pi\ell_\alpha\bar{n}_i} = i\sqrt{2}G_F U_{\alpha i}V_{ud}f_\pi\bar{\ell}_\alpha(m_\alpha P_L - m_i P_R)n_i\pi^- + \text{h.c.}}$$

Effective Mesons and HNL Interacti

- Pseudoscalar mesons
  - Charged mesons: $\pi^\pm, K^\pm, D^\pm, D_s^\pm$

    Repeating the procedure for $K^\pm$, and generalizing for $D^\pm$ and $D_s^\pm$

$$\boxed{\begin{aligned}
\mathcal{O}_{K\ell_\alpha \bar{n}_i} &= i\sqrt{2} G_F U_{\alpha i} V_{us} f_K \bar{\ell}_\alpha (m_\alpha P_L - m_i P_R) n_i K^- + \text{h.c.} \\[2ex]
\mathcal{O}_{D\ell_\alpha \bar{n}_i} &= i\sqrt{2} G_F U_{\alpha i} V_{cd} f_D \bar{\ell}_\alpha \left(m_\alpha P_L - m_i P_R\right) n_i D^- + \text{h.c.} \\[2ex]
\mathcal{O}_{D_s\ell_\alpha \bar{n}_i} &= i\sqrt{2} G_F U_{\alpha i} V_{cs} f_{D_s} \bar{\ell}_\alpha (m_\alpha P_L - m_i P_R) n_i D_s^- + \text{h.c.}
\end{aligned}}$$

Effective Mesons and HNL Interacti

- Vector mesons
  - Neutral mesons: ρ^0, ω, ϕ

$$\mathcal{O}_{\rho^0 n_i \bar{n}_j} = -\frac{1}{2} G_F C_{ij} \left(1 - 2s_w^2\right) f_\rho \rho^0_\mu \left(\bar{n}_i \gamma^\mu P_L n_j\right) + \text{h.c.}$$

$$\mathcal{O}_{\omega n_i \bar{n}_j} = \frac{1}{2} G_F C_{ij} \frac{2}{3} s_w^2 f_\omega \omega_\mu \left(\bar{n}_i \gamma^\mu P_L n_j\right) + \text{h.c.}$$

$$\mathcal{O}_{\phi n_i \bar{n}_j} = \frac{1}{2} G_F C_{ij} \sqrt{2} \left(\frac{1}{2} - \frac{2}{3} s_w^2\right) f_\phi \phi_\mu \left(\bar{n}_i \gamma^\mu P_L n_j\right) + \text{h.c.}$$

  - Charged mesons: $\rho^\pm, K^{*,\pm}$

$$\mathcal{O}_{\rho \ell_\alpha \bar{n}_i} = -\sqrt{2} G_F U_{\alpha i} V_{ud} f_\rho \rho^-_\mu \left(\bar{\ell}_\alpha \gamma^\mu P_L n_i\right) + \text{h.c.}$$

$$\mathcal{O}_{K^* \ell_\alpha \bar{n}_i} = -\sqrt{2} G_F U_{\alpha i} V_{us} f_{K^*} K^{*,-}_\mu \left(\bar{\ell}_\alpha \gamma^\mu P_L n_i\right) + \text{h.c.}$$

Effective Mesons and HNL Interacti

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- Semileptonic decays

  After integrating out the W boson, the amplitude for the $P \to D\bar{n}\ell$ decay

$$i\mathcal{M}_{PD\ell_\alpha \bar{n}_i} = \frac{ig^2}{2M_W^2} U_{\alpha i} \bar{u}_\alpha \gamma^\mu P_L v_i \langle D | j^V_{W,\mu} | P \rangle$$

  The hadronic matrix element expressed in terms of 2 form factors f_+ & f_-

$$\langle D | j^V_{W,\mu} | P \rangle = \frac{1}{2} V_{qq'} \left(p_\mu f_+(q^2) + q_\mu f_-(q^2) \right)$$

$p_\mu \equiv p_\mu^D + p_\mu^P$, while $q_\mu \equiv p_\mu^D - p_\mu^P$ is 4-momentum transfer between them.

Effective Mesons and HNL Interacti

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$$i\mathcal{M}_{PD\ell_\alpha\bar{n}_i} = i\sqrt{2} G_F V_{qq'} U_{\alpha i} \bar{u}_\alpha \gamma^\mu P_L v_i \left[2p^D_\mu f_+(q^2) + p^{n\ell}_\mu \left(f_+(q^2) - f_-(q^2) \right) \right]$$

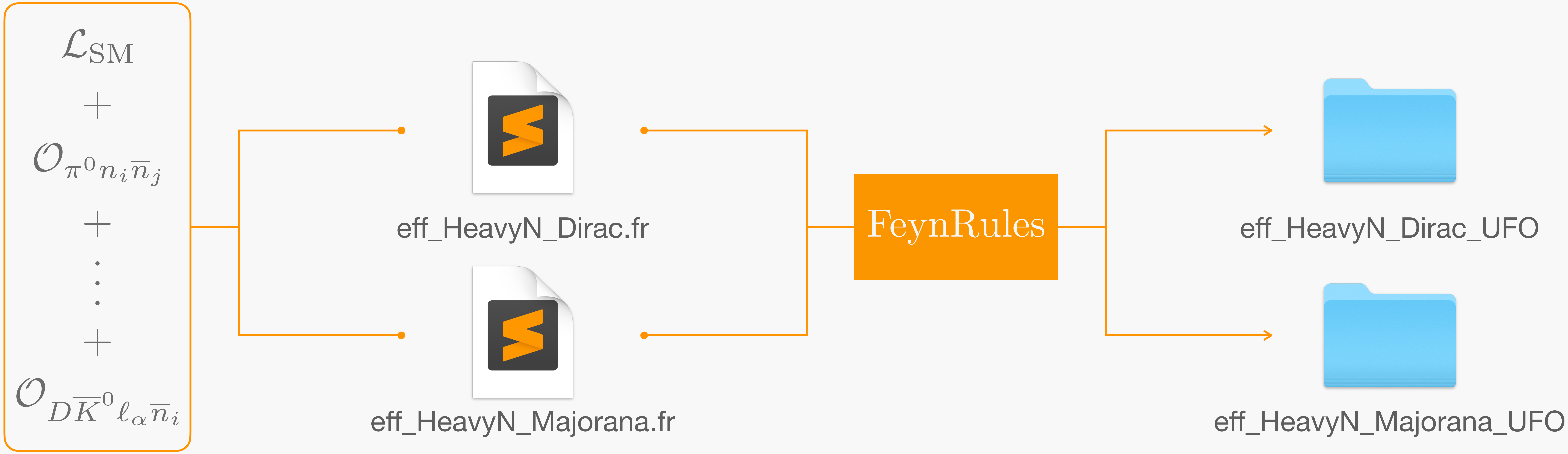
  The effective operator in configuration space after applying Dirac's equation

$$\boxed{\begin{aligned} \mathcal{O}_{PD\ell_\alpha\bar{n}_i} \quad = \quad & \sqrt{2} G_F V_{qq'} U_{\alpha i} \bar{\ell}_\alpha \left[\left(f_+(q^2) - f_-(q^2) \right) \left(m_\alpha P_L - m_i P_R \right) \phi_D \right. \\ & \left. -2i f_+(q^2) \left(\partial_\mu \phi_D \right) \gamma^\mu P_L \right] n_i \phi_P^\dagger + \text{h.c.} \end{aligned}}$$

HNL Flux Simulation

zoom.us video

The effective operators describing interactions between light mesons $(\pi, K, \eta, \rho, \omega, \dots)$ and one HNL that mixes with SM ν implemented in FeynRules model files*.



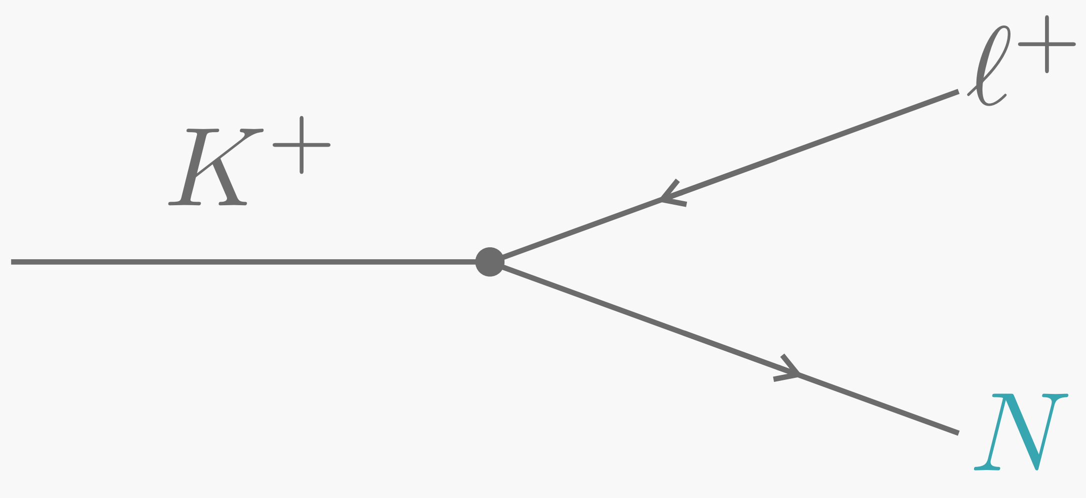
*publicly available (see ancillary files of arXiv: 2007.03701)

HNL Flux Simulation

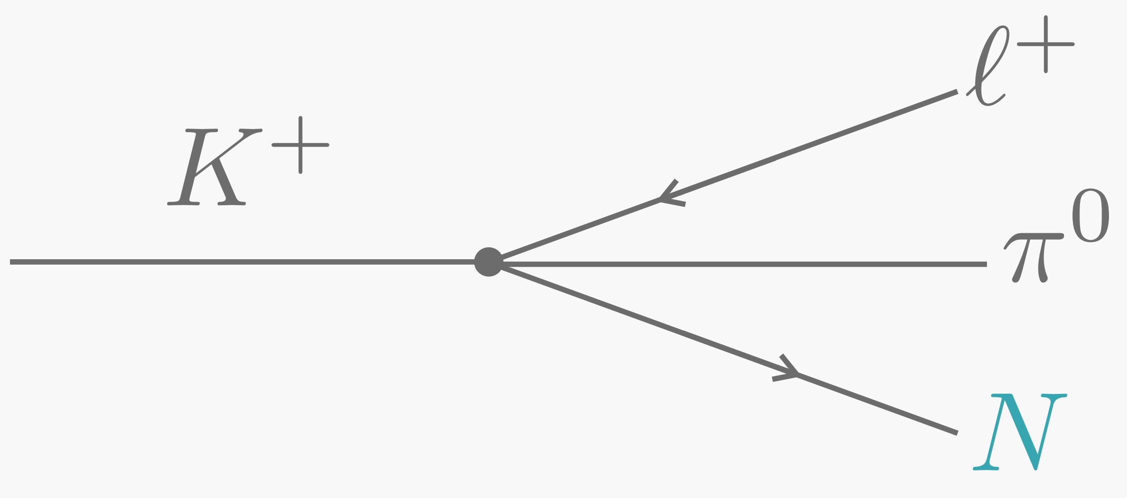
zoom.us video

Interfacing UFO with event generator such as MadGraph5 (MG) to simulate

- HNL production: $|U_{\alpha 4}|^2$



2-body leptonic decays



3-body semileptonic decays

```
mg5_aMC>
    import model effective_HeavyN_Dirac_UFO
    generate k+ > n1 lepton QED <= 2
    add process k+ > n1 lepton meson QED <= 2
    launch
    set MN4 0.05
    set thetae 0.001
    set thetamu 0
    set thetatau 0
    set nevents 100000
```

2-body + 3-body meson decays

M_4

$|U_{\alpha 4}|^2$

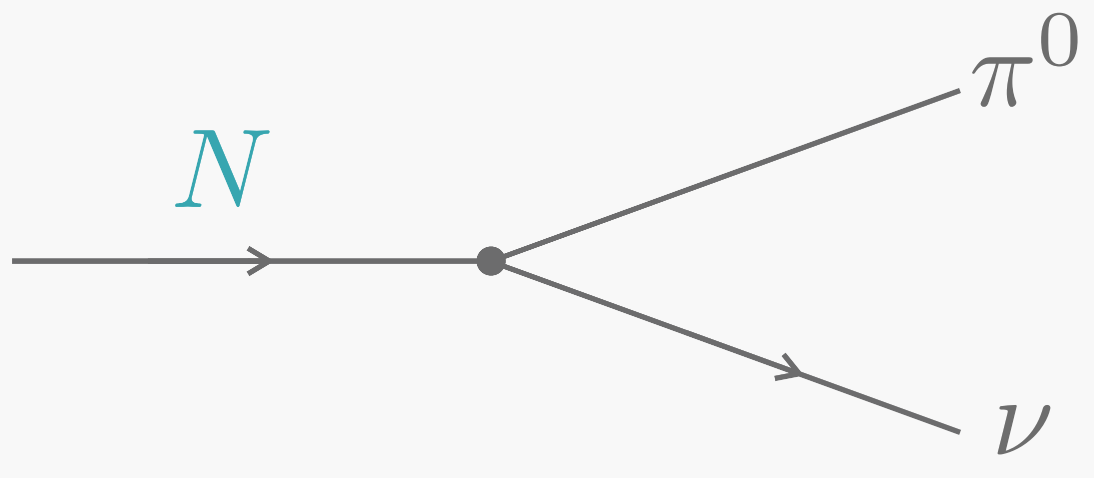
\# of events

HNL Flux Simulation

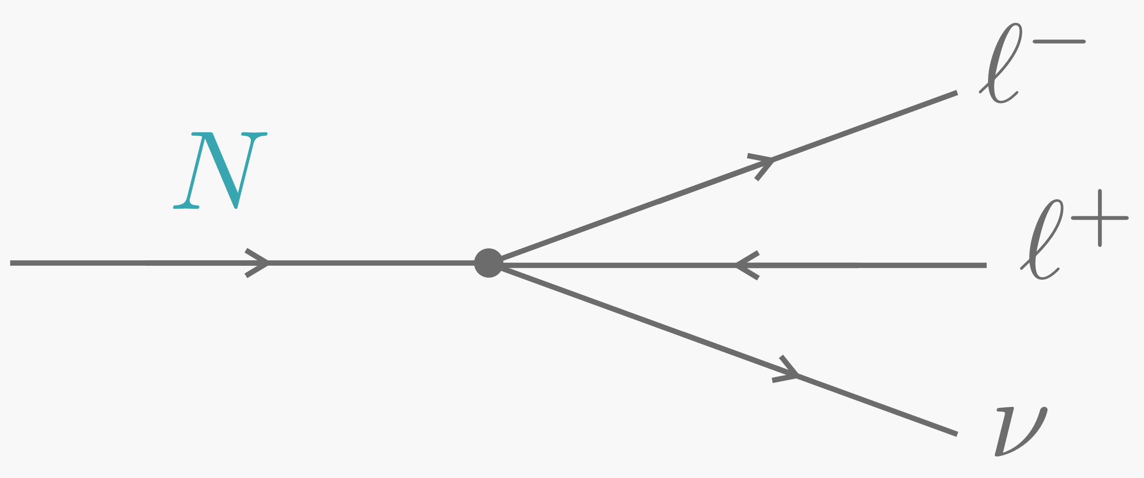
zoom.us video

Interfacing UFO with event generator such as MadGraph5 (MG) to simulate

- HNL decay: $|U_{\alpha 4}|^2$



2-body decays



3-body decays

```
mg5_aMC>
    import model effective_HeavyN_Dirac_UFO
    generate n1 > meson lepton QED <= 2
    add process n1 > lepton lepton lepton QED <= 2
    launch
    set MN4 0.05
    set thetae 0.001
    set thetamu 0
    set thetatau 0
    set nevents 100000
```

2-body + 3-body HNL decays

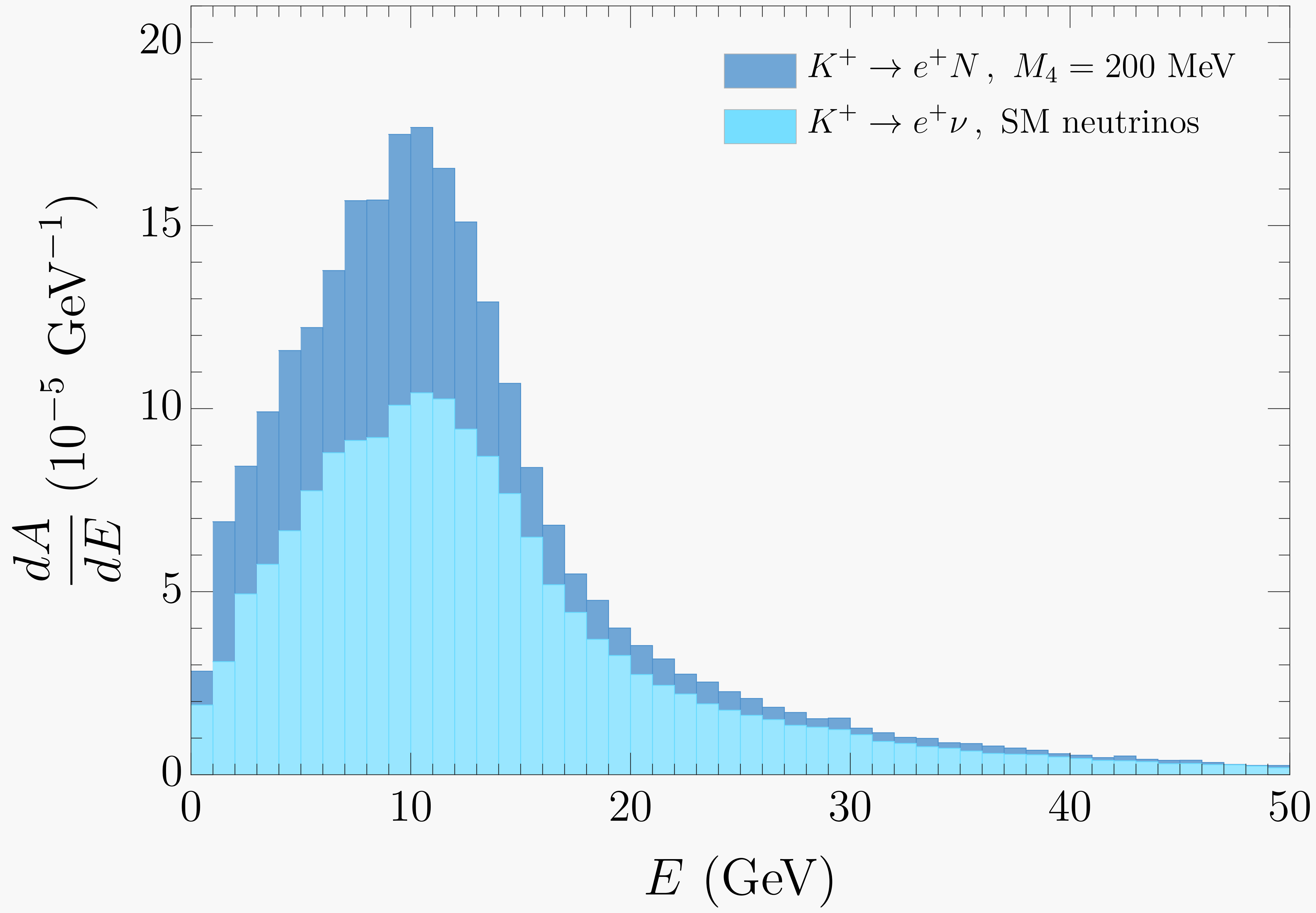
M_4

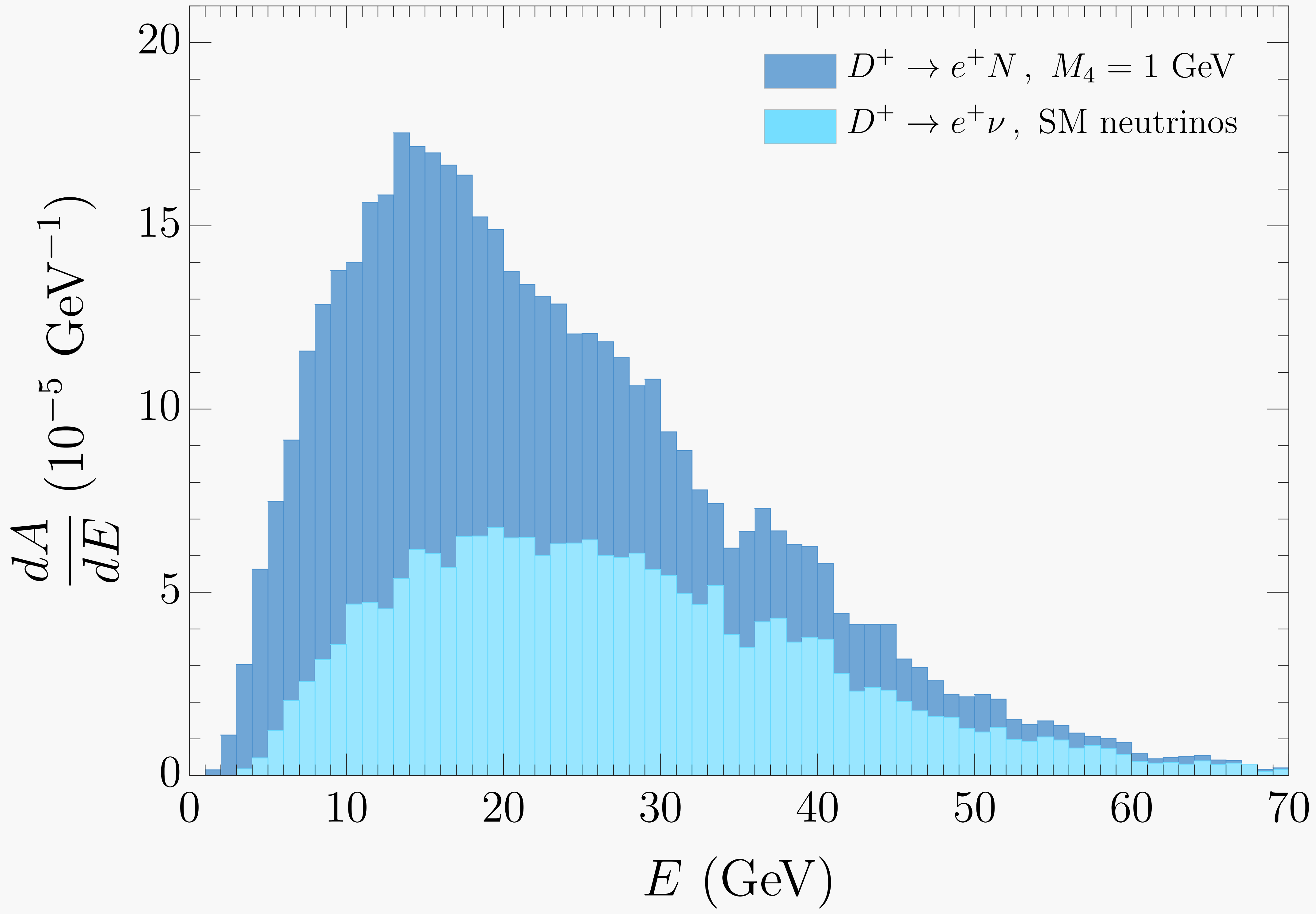
$|U_{\alpha 4}|^2$

# of events

The Boost Effect

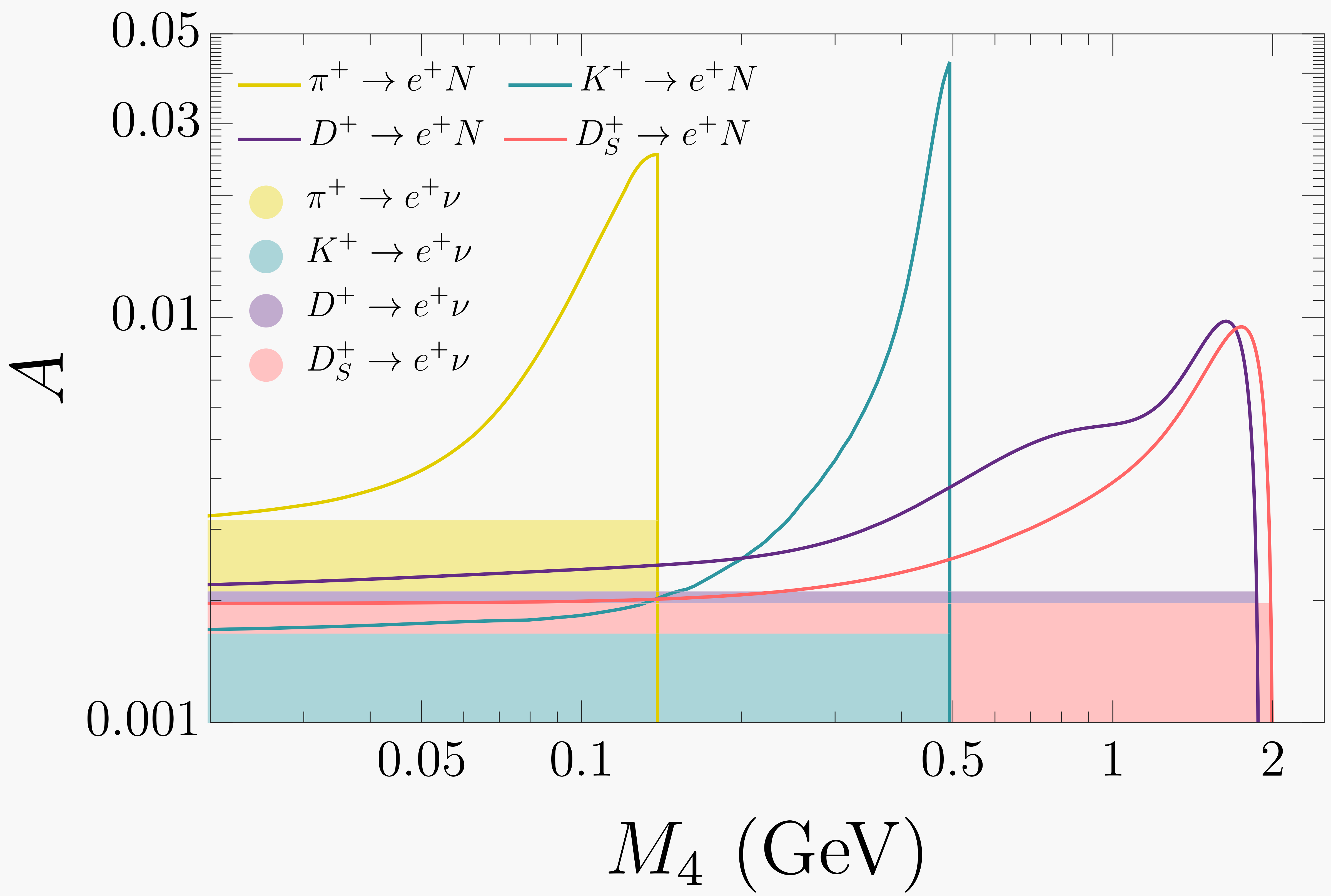
Particles with low velocities experience a stronger boost $\Rightarrow$ detector aceptance favored to heavy neutrinos





The Boost Effect

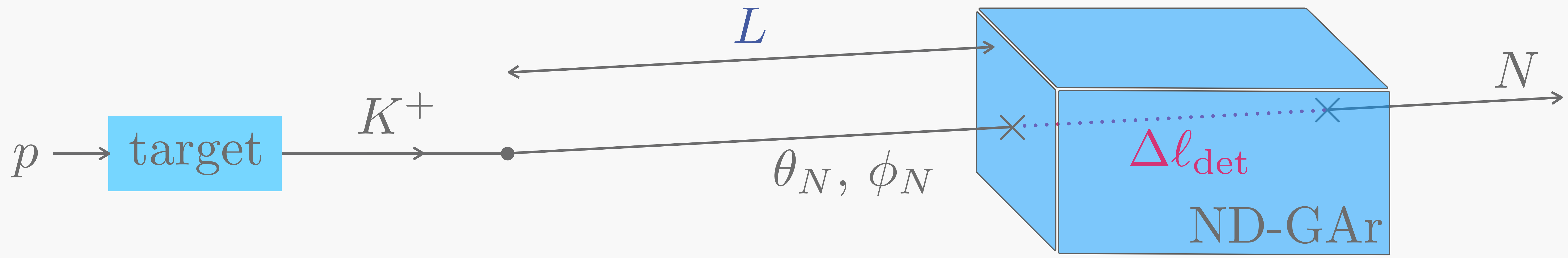
Relevant effect close to kinematic thresholds of HNL production



DUNE ND Sensitivity

zoom.us video

For each HNL decay event



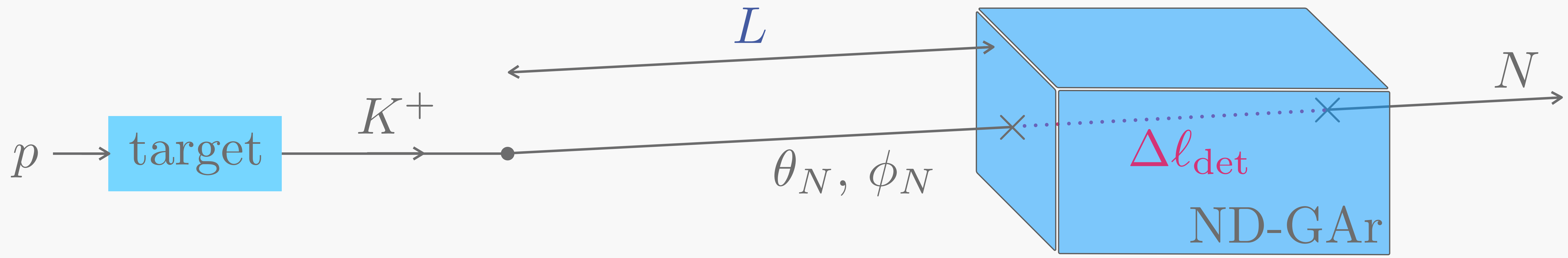
Probability of the HNL decaying inside the detector

$$P(E_N) = e^{-\frac{\Gamma L}{\gamma\beta}} \left(1 - e^{-\frac{\Gamma \Delta\ell_{\text{det}}}{\gamma\beta}}\right)$$

DUNE ND Sensitivity

zoom.us video

For each HNL decay event



Probability of the HNL decaying inside the detector

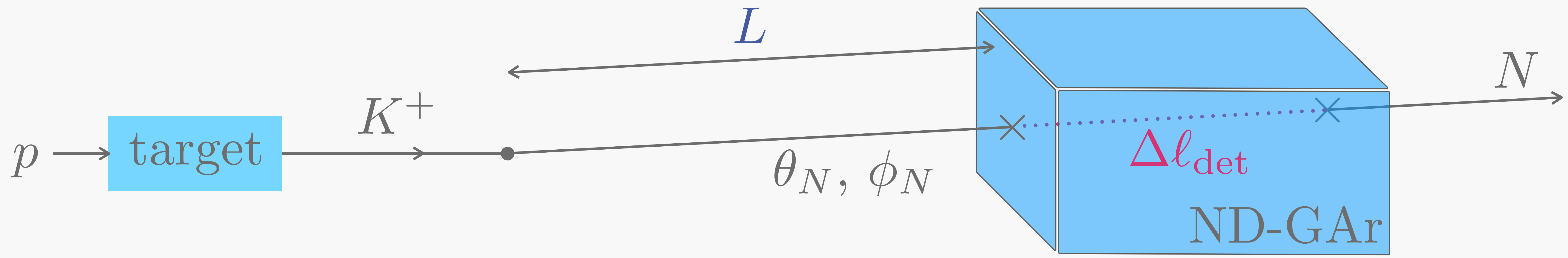
$$P(E_N) = e^{-\frac{\Gamma L}{\gamma\beta}}\left(1 - e^{-\frac{\Gamma\Delta\ell_{\text{det}}}{\gamma\beta}}\right)$$

and the total number of expected HNL decays into a given decay channel c

$$N_c(\text{ND}) = \text{BR}_c \times \int dE_N P(E_N)\frac{d\phi_N}{dE_N}$$

DUNE ND Sensitivity

For each HNL decay event



Probability of the HNL decaying inside the detector

$$P(E_N) = e^{-\frac{\Gamma L}{\gamma\beta}}\left(1 - e^{-\frac{\Gamma\Delta\ell_{\rm det}}{\gamma\beta}}\right)$$

and the total number of expected HNL decays into a given decay channel c

$$N_c(\mathrm{ND}) = \mathrm{BR}_c \times \int dE_N P(E_N)\frac{d\phi_N}{dE_N} \leq 2.44 \Rightarrow$$

90% CL sensitivity (no BG and under hypothesis of no observed events).

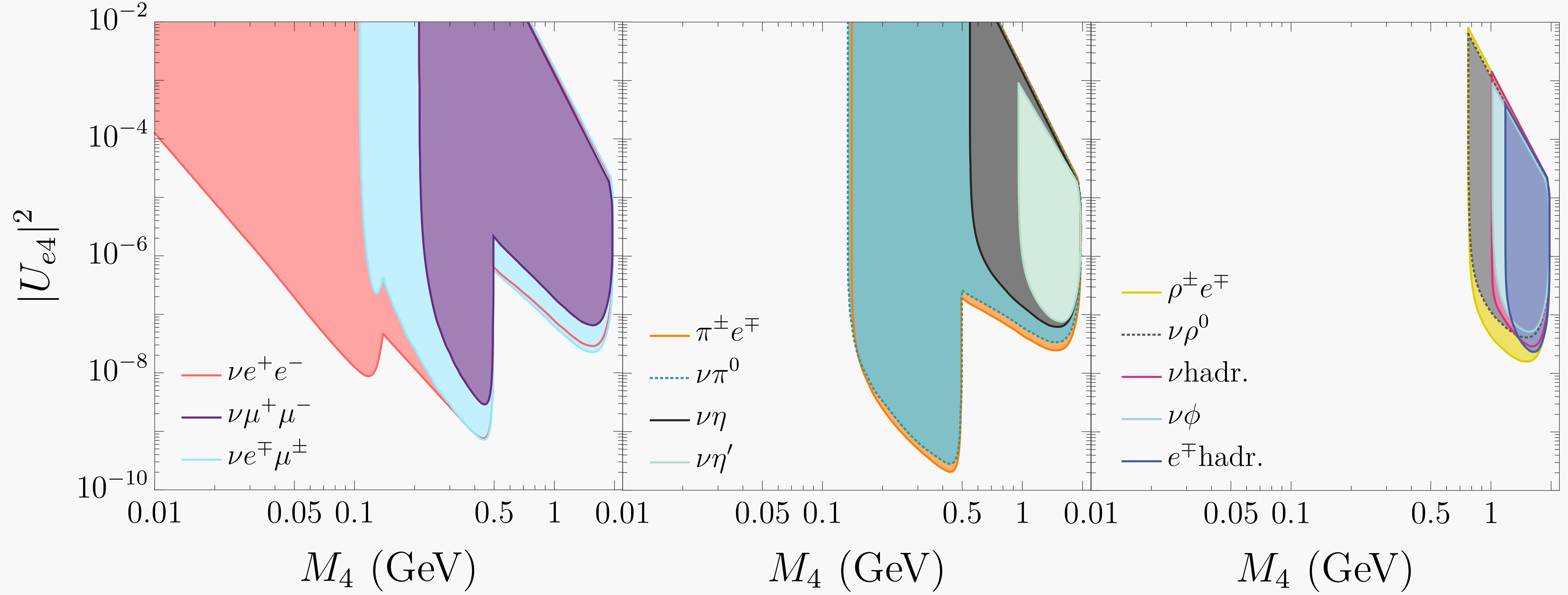
Signal efficiency of 20% assumed for fully background rejection.

T2K collaboration, K. Abe et al., Phys. Rev. D **100** 2019 052006

DUNE ND Sensitivity

zoom.us video

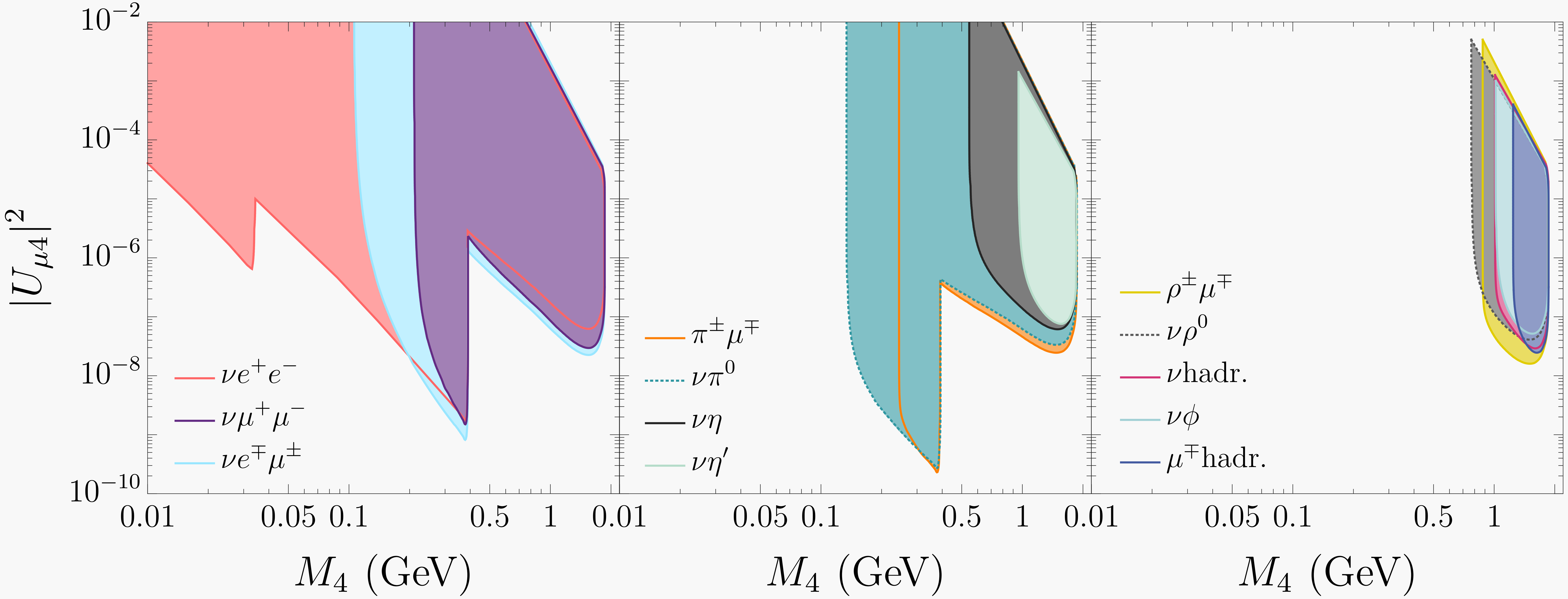
- Sensitivity plots: $|U_{e4}|^2$



Expected DUNE sensitivity at 90% CL for $7.7 \cdot 10^{21}$ PoT collected.

DUNE ND Sensitivity

- Sensitivity plots: $|U_{\mu 4}|^2$

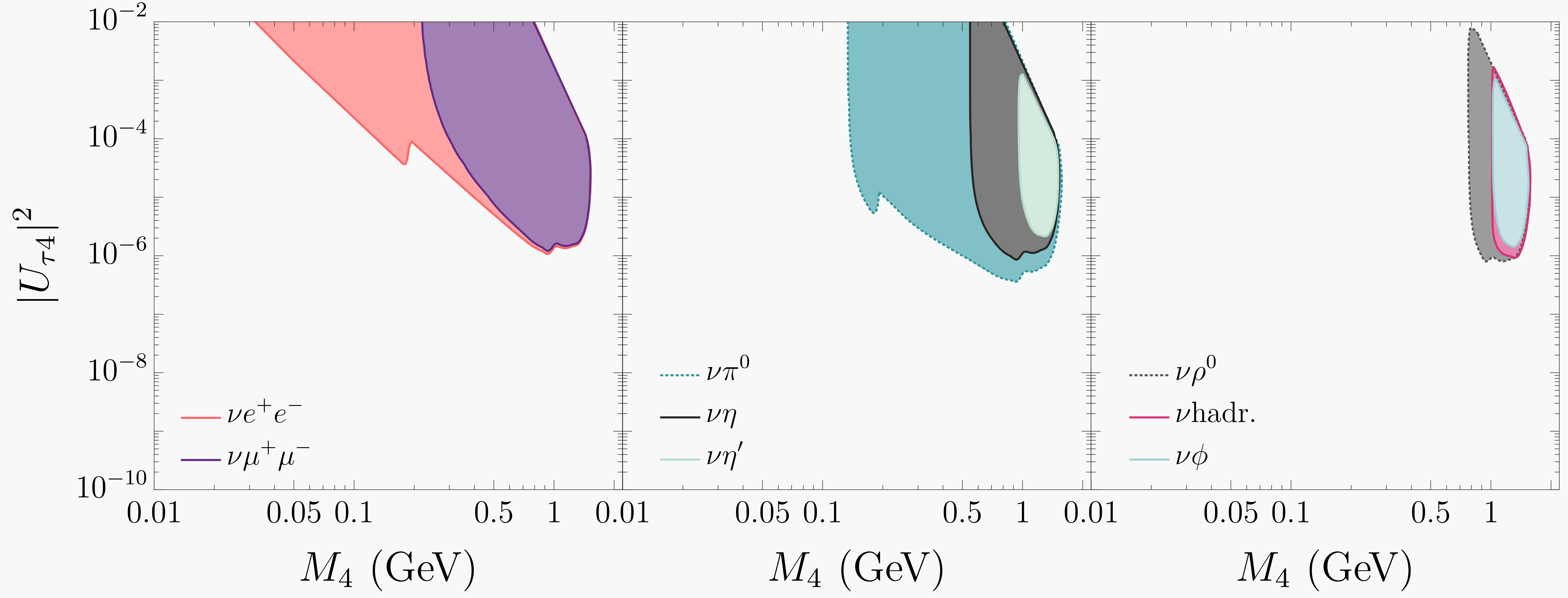


Expected DUNE sensitivity at 90% CL for $7.7 \cdot 10^{21}$ PoT collected.

DUNE ND Sensitivity

zoom.us video

- Sensitivity plots: $|U_{\tau 4}|^2$

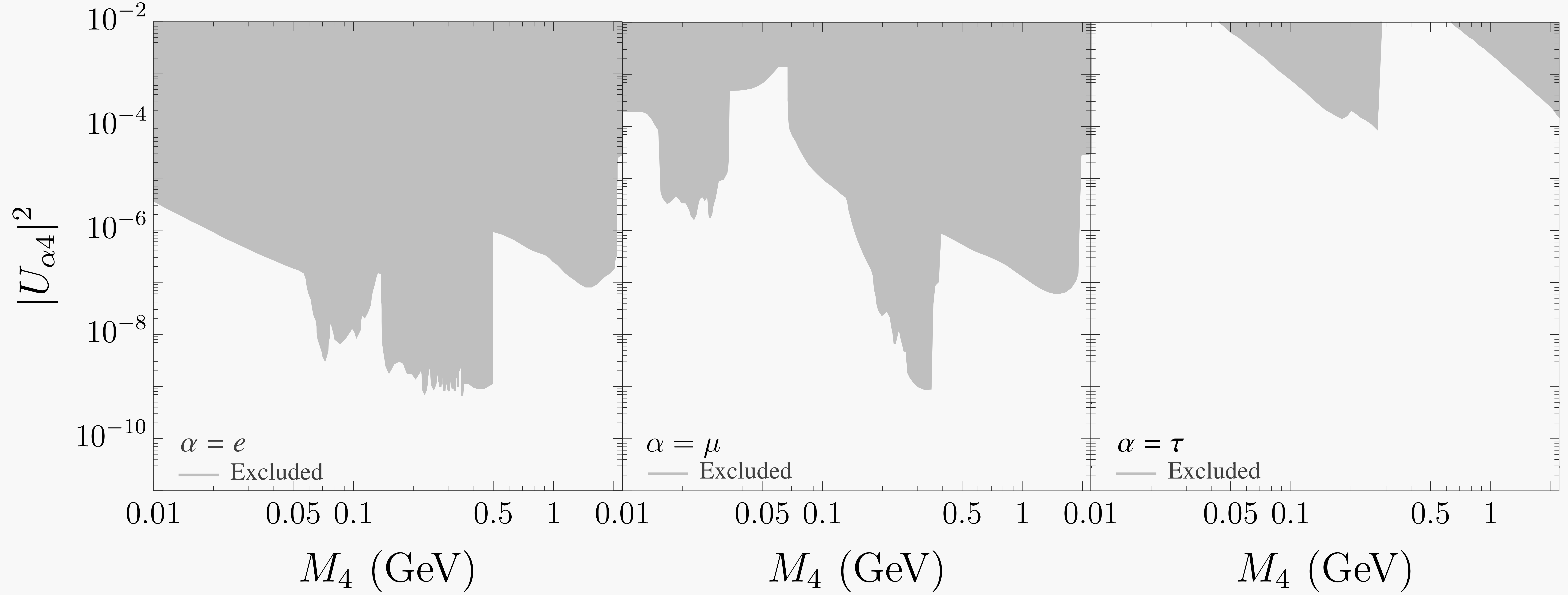


Expected DUNE sensitivity at 90% CL for $7.7 \cdot 10^{21}$ PoT collected.

DUNE ND Sensitivity

zoom.us video

Present experiments + DUNE ND expected sensitivity

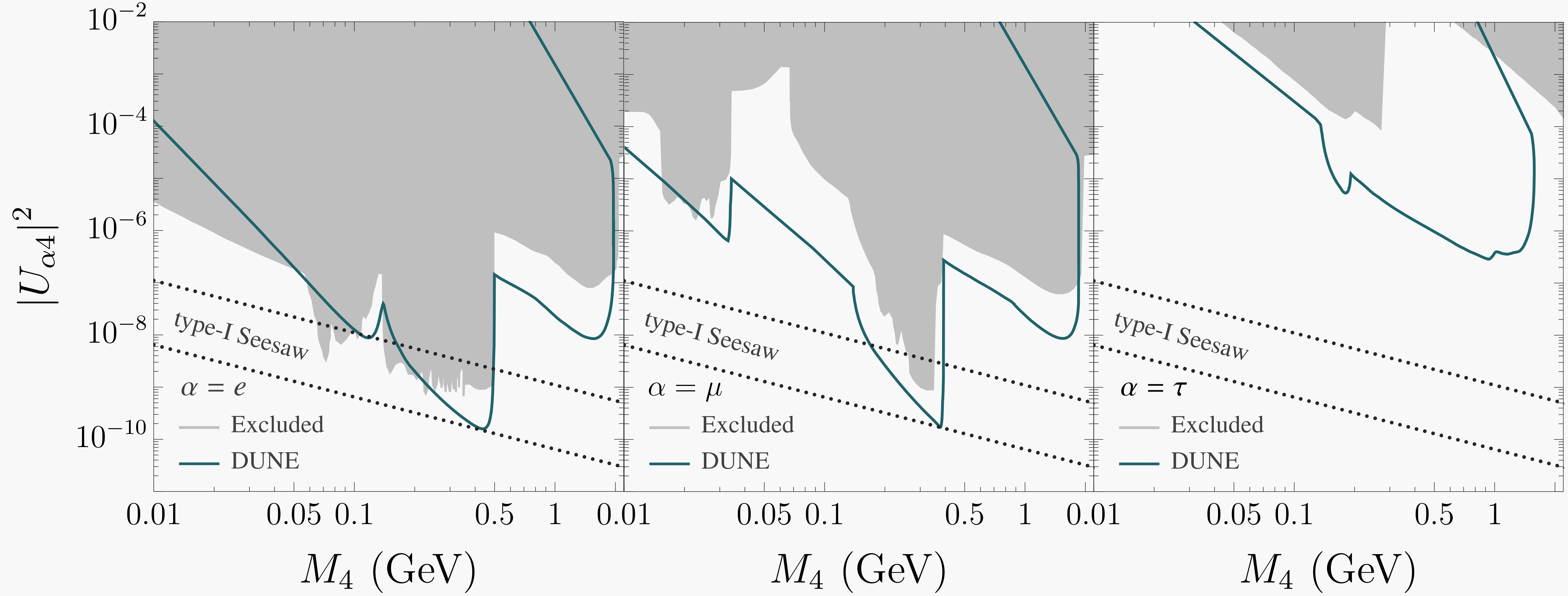


Expected DUNE sensitivity at 90% CL for $7.7 \cdot 10^{21}$ PoT collected.

DUNE ND Sensitivity

zoom.us video

Present experiments + DUNE ND expected sensitivity



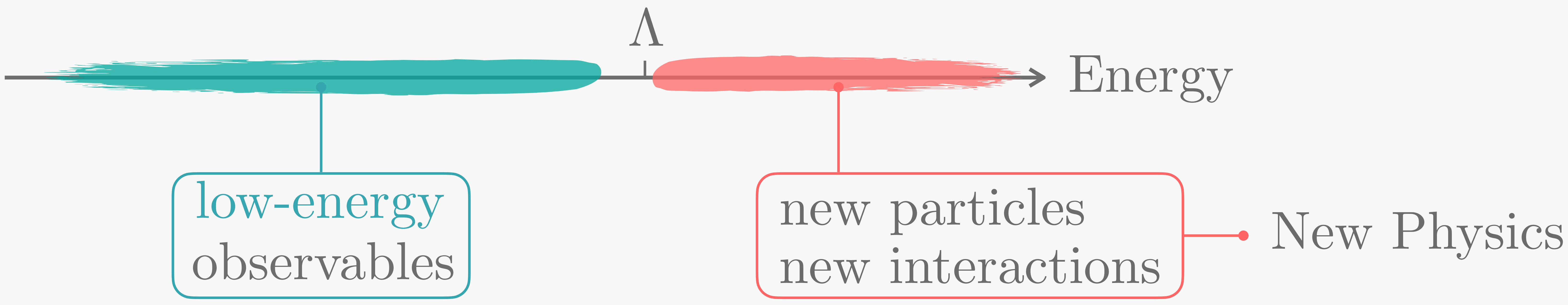
Expected DUNE sensitivity at 90% CL for $7.7 \cdot 10^{21}$ PoT collected.

zoom.us video

Effective Portals to HNL

SM Effective Field Theory

zoom.us video



The Standard Model Effective Field Theory (SMEFT) parametrize the effects of New Physics on low-energy observables

SM Effective Field Theory

zoom.us video

The SMEFT consist on a tower of higher dimensional operators

$$\mathcal{L} = \underbrace{\boxed{\mathcal{L}_{d=4}}}_{\mathcal{L}_{\text{SM}}} + \underbrace{\boxed{\mathcal{L}_{d=5}}}_{\text{Weinberg operator}} + \mathcal{L}_{d=6} + \dots$$

where, at given dimension n

$$\mathcal{L}_{d=n} = \sum_i \mathcal{O}_i = \frac{1}{\Lambda^{n-4}} \sum_i C_i \boxed{\widetilde{\mathcal{O}}_i}$$

BSM encoded in effective operators

– non-renormalizable

– build from SM fields $\Rightarrow$
  respect fundamental symmetries

SM Effective Field Theory

zoom.us video

The SMEFT consist on a tower of higher dimensional operators

$$\mathcal{L} = \underbrace{\boxed{\mathcal{L}_{d=4}}}_{\mathcal{L}_{\text{SM}}} + \underbrace{\boxed{\mathcal{L}_{d=5}}}_{\text{Weinberg operator}} + \mathcal{L}_{d=6} + \ldots$$

where, at given dimension n

$$\mathcal{L}_{d=n} = \sum_i \mathcal{O}_i = \boxed{\frac{1}{\Lambda^{n-4}}} \sum_i C_i \widetilde{\mathcal{O}_i}$$

suppressed by scale
of New Physics

SM Effective Field Theory

zoom.us video

The SMEFT consist on a tower of higher dimensional operators

$$\mathcal{L} = \underbrace{\boxed{\mathcal{L}_{d=4}}}_{\mathcal{L}_{\mathrm{SM}}} + \underbrace{\boxed{\mathcal{L}_{d=5}}}_{\text{Weinberg operator}} + \mathcal{L}_{d=6} + \ldots$$

where, at given dimension n

$$\mathcal{L}_{d=n} = \sum_i \mathcal{O}_i = \frac{1}{\Lambda^{n-4}} \sum_i \boxed{C_i} \widetilde{\mathcal{O}_i}$$

Wilson coefficients: dimensionless parameters controlling respective coupling strength

SM Effective Field Theory

zoom.us video

The SMEFT consist on a tower of higher dimensional operators

$$\mathcal{L} = \underbrace{\boxed{\mathcal{L}_{d=4}}}_{\mathcal{L}_{\mathrm{SM}}} + \underbrace{\boxed{\mathcal{L}_{d=5}}}_{\text{Weinberg operator}} + \mathcal{L}_{d=6} + \ldots$$

where, at given dimension n

$$\mathcal{L}_{d=n} = \sum_i \mathcal{O}_i = \frac{1}{\Lambda^{n-4}} \sum_i C_i \widetilde{\mathcal{O}_i}$$

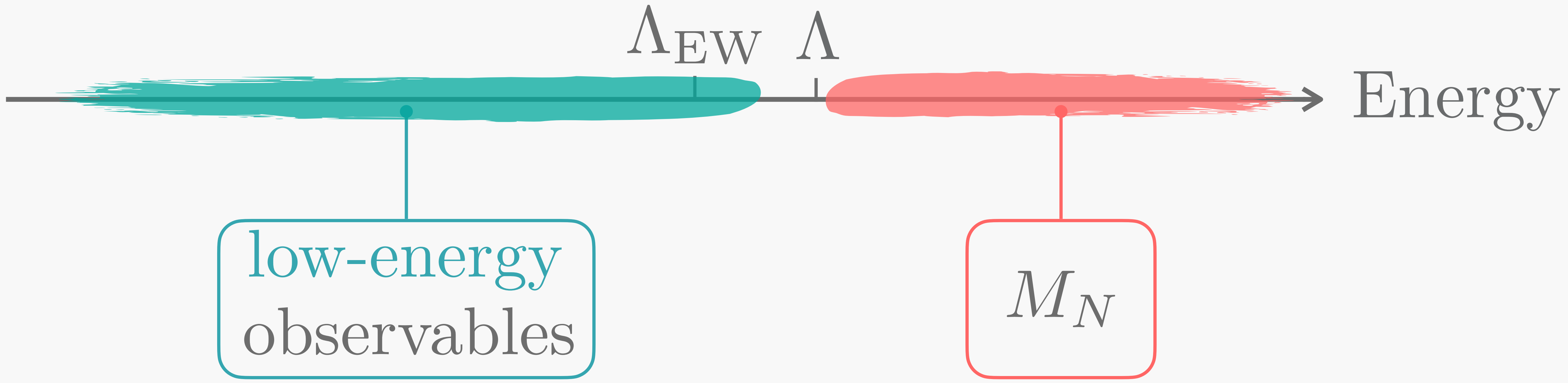
The higher the dimension n, the greater the number $\mathcal{O}_i$

But smaller the effects in low-energy observables, as suppressed by larger powers of Λ

Bounds on ν-SMEFT

zoom.us video

HNL + SMEFT = ?



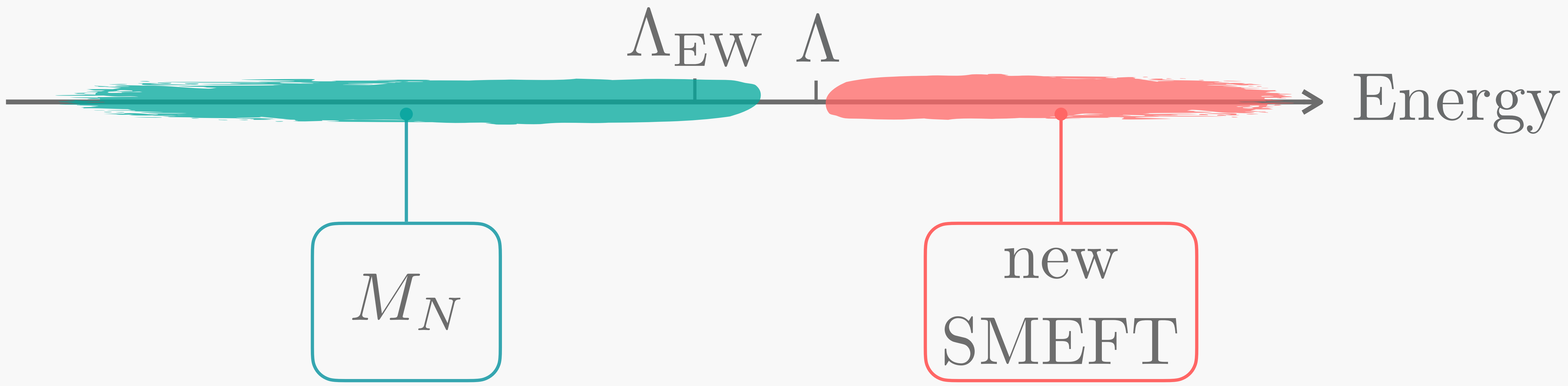
If $M_N > \Lambda \Rightarrow$ their effects described by effective operators of SMEFT

- $d = 5$: neutrino masses via Weinberg operator
- $d = 6$: non-Unitarity of U_{PMNS}

Bounds on ν-SMEFT

zoom.us video

HNL + SMEFT = ?



If $M_N < \Lambda \Rightarrow$ HNLs added as fundamental building blocks of the theory $\Rightarrow$ the new SMEFT contains new operators involving N and SM particles $\Rightarrow$

ν-SMEFT

Bounds on ν-SMEFT

zoom.us video

The only two new operators at $d = 5$

- HNL dipole moment

$$\mathcal{O}_{\text{dipole}}^{d=5} = \frac{C_{\text{dipole}}^{d=5}}{\Lambda} \overline{N^c} \sigma_{\mu\nu} N B^{\mu\nu}$$

After EWSB generates dipole moments among the HNLs

D. Barducci, E. Bertuzzo, M. Taoso, C. Toni. JHEP **03** (2023) 239
A. Aparici, K. Kim, A. Santamaria, J. Wudka. Phys.Rev.D **80** (2009) 013010

Bounds on ν-SMEFT

zoom.us video

The only two new operators at $d = 5$

- HNL dipole moment

$$\mathcal{O}^{d=5}_{\text{dipole}} = \frac{C^{d=5}_{\text{dipole}}}{\Lambda} \overline{N^c} \sigma_{\mu\nu} N B^{\mu\nu}$$

After EWSB generates dipole moments among the HNLs

Since we consider just one, it vanishes

Bounds on ν-SMEFT

zoom.us video

The only two new operators at $d = 5$

- Higgs-dressed mass

$$\mathcal{O}^{d=5}_{\text{Higgs}} = \frac{C^{d=5}_{\text{Higgs}}}{\Lambda} \overline{N^c} N |H|^2$$

D. Barducci, E. Bertuzzo. JHEP **06** (2022) 077
D. Barducci, E. Bertuzzo, A. Caputo, P. Hernandez. JHEP **06** (2020) 185
D. Barducci, E. Bertuzzo, A. Caputo, P. Hernandez, B. Mele.JHEP **03** (2031) 117
A. Caputo, P. Hernandez, J. Lopez-Pavon, J. Salvado. JHEP **06** (2017) 112
M. L. Graesser. arXiv: 0705.2190

Bounds on ν-SMEFT

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The only two new operators at $d = 5$

- Higgs-dressed mass

$$\mathcal{O}^{d=5}_{\text{Higgs}} = \frac{C^{d=5}_{\text{Higgs}}}{\Lambda}\overline{N^c}N|H|^2$$

After EWSB generates

– Contribution to Majorana mass

$$M_M = \frac{C^{d=5}_{\text{Higgs}}v^2}{2\Lambda}$$

Bounds on ν-SMEFT

The only two new operators at $d = 5$

- Higgs-dressed mass

$$\mathcal{O}^{d=5}_{\text{Higgs}} = \frac{C^{d=5}_{\text{Higgs}}}{\Lambda} \overline{N^c} N |H|^2$$

After EWSB generates

- Contribution to Majorana mass
- Invisible Higgs decay $h \to NN$

Higgs signal strength μ

$$i \to h \to f$$

$$\boxed{\mu_i \equiv \frac{\sigma_i}{(\sigma_i)_{\text{SM}}}} \qquad \boxed{\mu^f \equiv \frac{\mathcal{B}^f}{(\mathcal{B}^f)_{\text{SM}}}}$$

Bounds on ν-SMEFT

zoom.us video

The only two new operators at $d = 5$

- Higgs-dressed mass

$$\mathcal{O}^{d=5}_{\text{Higgs}} = \frac{C^{d=5}_{\text{Higgs}}}{\Lambda} \overline{N^c} N |H|^2$$

After EWSB generates

- Contribution to Majorana mass
- Invisible Higgs decay $h \to NN$

Higgs signal strength μ

ATLAS and CMS measure precise values of $\mu^{\gamma\gamma}$ and $\mu^{WW} \Rightarrow \mu \geq 0.94$ (95%CL)

$$\boxed{\frac{C^{d=5}_{\text{Higgs}}}{\Lambda} < 3 \times 10^{-5}\ \text{GeV}^{-1} \quad \text{for} \quad M_N < 40\ \text{GeV}}$$

Bounds on ν-SMEFT

zoom.us video

The base of $d = 6$ effective operators

- Higgs-dressed mixing

$\widetilde{\mathcal{O}}^{\alpha}_{\rm LNH}: \ \overline{L_\alpha}\widetilde{H}N(H^\dagger H)$

- Bosonic currents

$\widetilde{\mathcal{O}}_{\rm HN}: \ \overline{N}\gamma^\mu N(H^\dagger i\overleftrightarrow{D}_\mu H)$

$\widetilde{\mathcal{O}}^{\alpha}_{\rm HN\ell}: \ \overline{N}\gamma^\mu \ell_\alpha(\widetilde{H}^\dagger i\overleftrightarrow{D}_\mu H)$

- Tensor currents

$\widetilde{\mathcal{O}}^{\alpha}_{\rm NB}: \ \left(\overline{L_\alpha}\sigma_{\mu\nu}N\right)\widetilde{H}B^{\mu\nu}$

$\widetilde{\mathcal{O}}^{\alpha}_{\rm NW}: \ \left(\overline{L_\alpha}\sigma_{\mu\nu}N\right)\tau^a\widetilde{H}W^{\mu\nu}_a$

- 4-fermion

Neutral $\supset \widetilde{\mathcal{O}}^{\alpha}_{\rm LN}: \ (\overline{L_\alpha}\gamma^\mu L_\alpha)(\overline{N}\gamma_\mu N)$

Charged $\supset \widetilde{\mathcal{O}}^{\alpha}_{\rm duN\ell}: \ \mathcal{Z}^{\rm duN\ell}_{ij}(\overline{d_i}\gamma^\mu u_j)(\overline{N}\gamma_\mu \ell_\alpha)$

Y. Liao, X.-D. Ma. Phys.Rev.D **96** (2017) 1, 015012
F. del Aguila, S. Bar-Shalom, A. Soni, J. Wudka.Phys.Lett.B **670** (2009) 399-402

Bounds on ν-SMEFT

zoom.us video

The base of $d = 6$ effective operators

- Higgs-dressed mixing

  $\widetilde{\mathcal{O}}^{\alpha}_{\rm LNH}: \ \overline{L_\alpha}\widetilde{H}N(H^\dagger H)$

- Tensor currents

  $\widetilde{\mathcal{O}}^{\alpha}_{\rm NB}: \ \left(\overline{L_\alpha}\sigma_{\mu\nu}N\right)\widetilde{H}B^{\mu\nu}$

  $\widetilde{\mathcal{O}}^{\alpha}_{\rm NW}: \ \left(\overline{L_\alpha}\sigma_{\mu\nu}N\right)\tau^a\widetilde{H}W^{\mu\nu}_a$

- Bosonic currents

  $\widetilde{\mathcal{O}}_{\rm HN}: \ \overline{N}\gamma^\mu N(H^\dagger i\overleftrightarrow{D}_\mu H)$

  $\widetilde{\mathcal{O}}^{\alpha}_{\rm HN\ell}: \ \overline{N}\gamma^\mu \ell_\alpha(\widetilde{H}^\dagger i\overleftrightarrow{D}_\mu H)$

- 4-fermion

  Neutral $\supset \widetilde{\mathcal{O}}^{\alpha}_{\rm LN}: \ (\overline{L_\alpha}\gamma^\mu L_\alpha)(\overline{N}\gamma_\mu N)$

  Charged $\supset \widetilde{\mathcal{O}}^{\alpha}_{\rm duN\ell}: \ \mathcal{Z}^{\rm duN\ell}_{ij}(\overline{d_i}\gamma^\mu u_j)(\overline{N}\gamma_\mu \ell_\alpha)$

In the following, I assume one HNL with negligible $|U_{\alpha N}|$, and study the bounds on C_i/Λ^2 of each operator, assuming one operator at a time

Bounds on ν-SMEFT

zoom.us video

- Higgs-dressed mixing

$$\mathcal{O}^{\alpha}_{\rm LNH} = \frac{C^{\alpha}_{\rm LNH}}{\Lambda^2}(H^\dagger H)\overline{L_\alpha}\widetilde{H}N$$

Bounds on ν-SMEFT

zoom.us video

- Higgs-dressed mixing

$$\mathcal{O}^{\alpha}_{\rm LNH} = \frac{C^{\alpha}_{\rm LNH}}{\Lambda^2}(H^\dagger H)\overline{L_\alpha}\widetilde{H}N$$

After EWSB:

– Contribution to mixing

$$U_{\alpha N} = \left(\frac{C^{\alpha}_{\rm LNH}}{\Lambda^2}\right)\frac{v^3}{2\sqrt{2}M_N}$$

Mapping between $U_{\alpha N}$ and $C^{\alpha}_{\rm LNH}$

Bounds on ν-SMEFT

zoom.us video

- Higgs-dressed mixing

$$\mathcal{O}^{\alpha}_{\mathrm{LNH}} = \frac{C^{\alpha}_{\mathrm{LNH}}}{\Lambda^2}(H^\dagger H)\overline{L_\alpha}\widetilde{H}N$$

After EWSB:

– Contribution to mixing

– Contribution to m_ν

$$m_\nu = \left(\frac{C^{\alpha}_{\mathrm{LNH}}}{\Lambda^2}\right)^2 \frac{v^6}{8M_N}$$

More than one HNL needed to explain ν masses $\Rightarrow$ possible cancellations

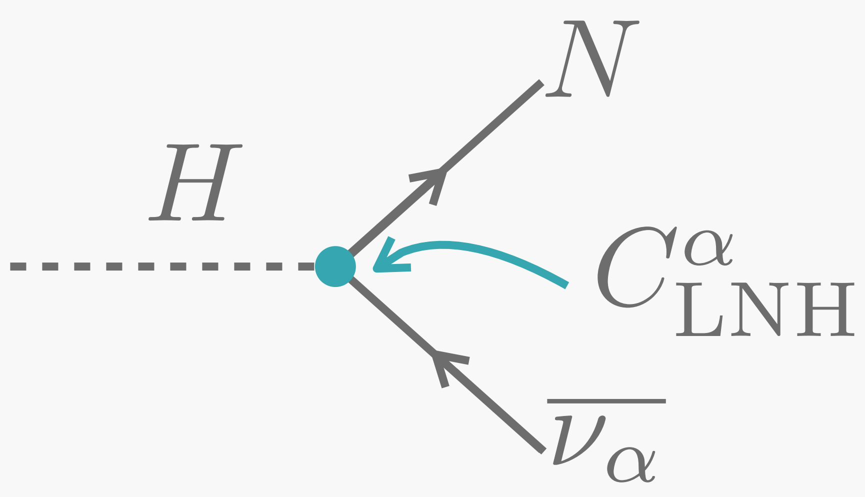
Bounds on ν-SMEFT

- Higgs-dressed mixing

$$\mathcal{O}^{\alpha}_{\rm LNH} = \frac{C^{\alpha}_{\rm LNH}}{\Lambda^2}(H^\dagger H)\overline{L_\alpha}\widetilde{H} N$$

After EWSB:

- Contribution to mixing
- Contribution to m_ν
- Invisible Higgs decay

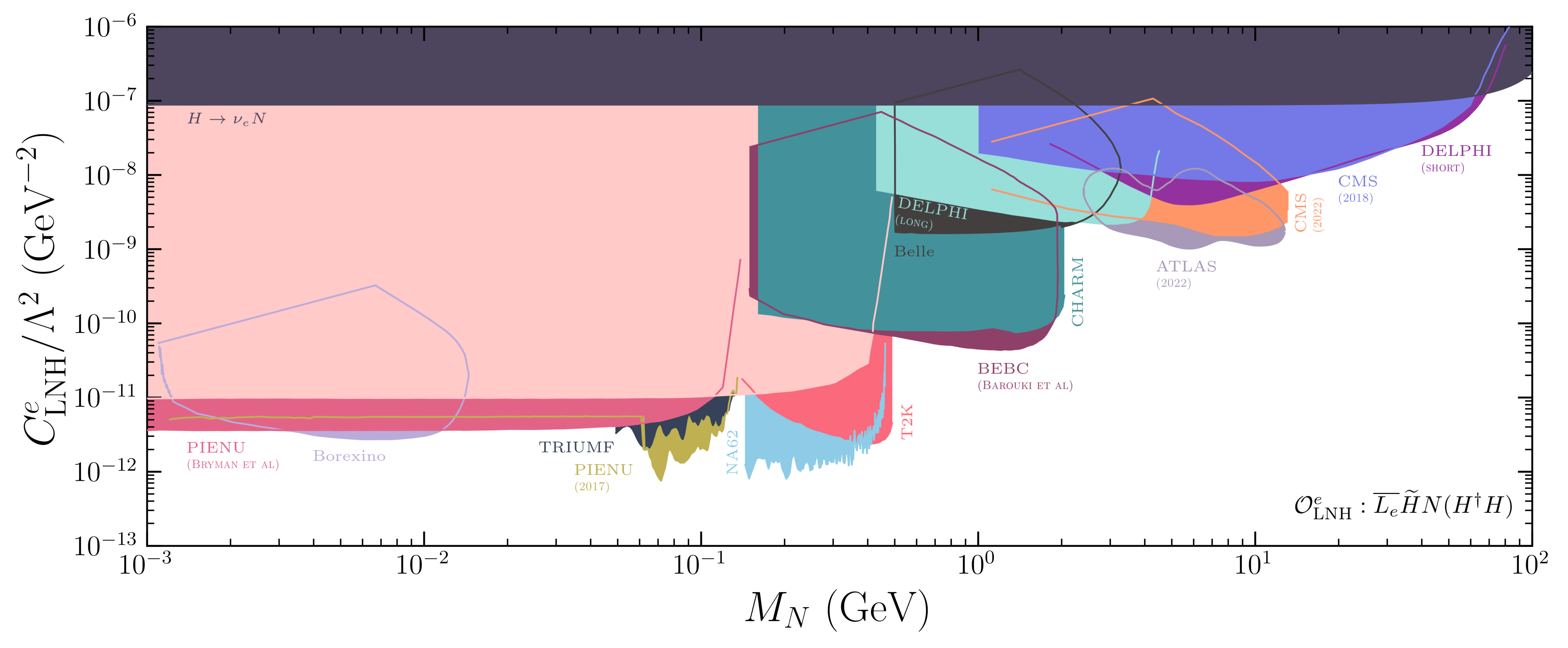


Higgs signal strength yields to $\mathcal{B}\left(h \to N\overline{\nu_\alpha}\right) < 0.06$ (95%CL) $\Rightarrow$ bound on $C^{\alpha}_{\rm LNH}/\Lambda^2$

BOUNDS ON ν-SMEFT

zoom.us video

- Higgs-dressed mixing



Equivalent bounds on $C^\mu_{\mathrm{LNH}}/\Lambda^2$ and $C^\tau_{\mathrm{LNH}}/\Lambda^2$. See back-up slides

Bounds on ν-SMEFT

zoom.us video

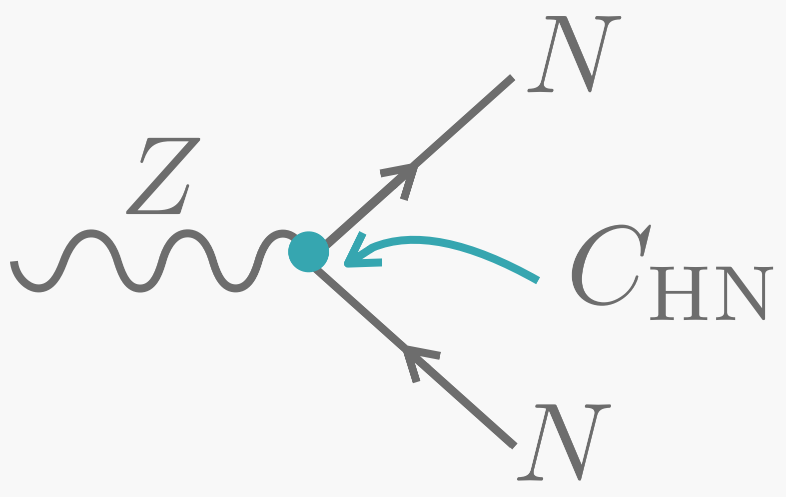
- Bosonic currents: neutral

$$\mathcal{O}_{\rm HN} = \frac{C_{\rm HN}}{\Lambda^2}\overline{N}\gamma^\mu N(H^\dagger i\overleftrightarrow{D}_\mu H)$$

Bounds on ν-SMEFT

- Bosonic currents: neutral

$$\mathcal{O}_{\mathrm{HN}} = \frac{C_{\mathrm{HN}}}{\Lambda^2}\overline{N}\gamma^\mu N(H^\dagger i\overleftrightarrow{D}_\mu H) \xrightarrow[\text{EWSB}]{\text{after}} \left(\frac{C_{\mathrm{HN}}}{\Lambda^2}\frac{gv^2}{2c_{\mathrm{W}}}\right)\overline{N}\gamma^\mu N Z_\mu$$

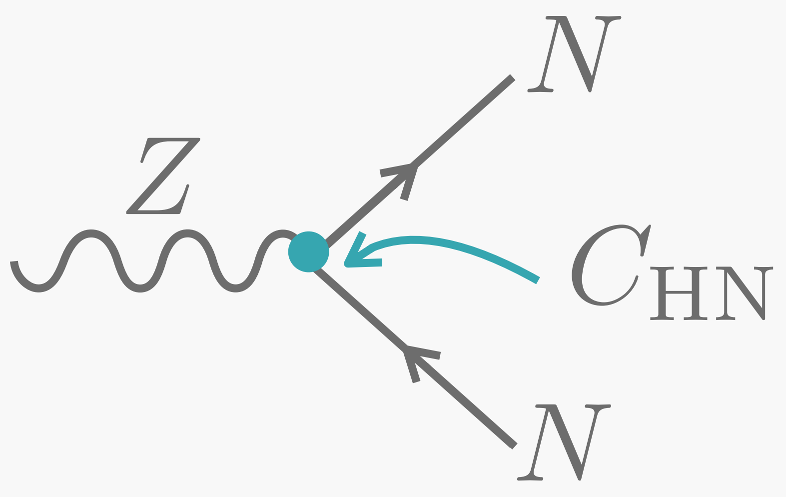


Bounds on ν-SMEFT

zoom.us video

- Bosonic currents: neutral

$$\mathcal{O}_{\mathrm{HN}} = \frac{C_{\mathrm{HN}}}{\Lambda^2}\overline{N}\gamma^\mu N(H^\dagger i\overleftrightarrow{D}_\mu H) \xrightarrow[\text{EWSB}]{\text{after}} \left(\frac{C_{\mathrm{HN}}}{\Lambda^2}\frac{gv^2}{2c_{\mathrm{W}}}\right)\overline{N}\gamma^\mu N Z_\mu$$



The following bounds can be recasted

  - Neutral meson decays

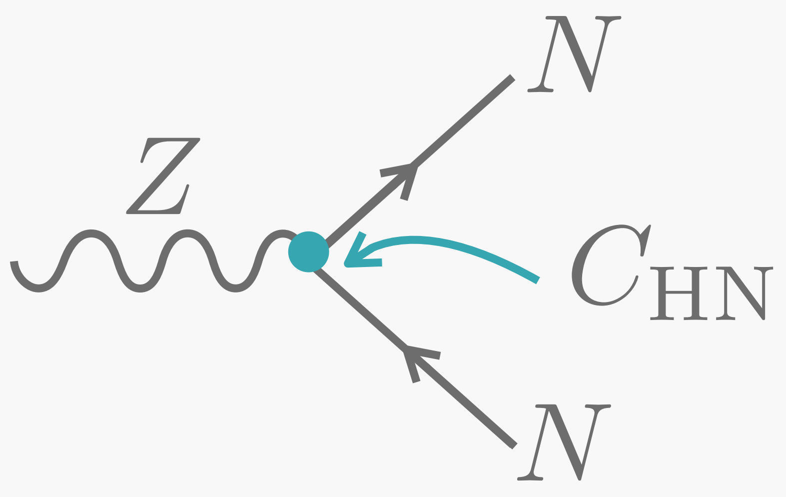
    Neutral pseudoscalar and vector meson decays suppressed in SM $\Rightarrow$ bounds on invisible decay of π^0 (NA62) and $\Upsilon(1s)$ (BaBar) constrain C_{NH}

Bounds on ν-SMEFT

zoom.us video

- Bosonic currents: neutral

$$\mathcal{O}_{\mathrm{HN}} = \frac{C_{\mathrm{HN}}}{\Lambda^2}\overline{N}\gamma^\mu N(H^\dagger i \overleftrightarrow{D}_\mu H) \xrightarrow[\text{EWSB}]{\text{after}} \left(\frac{C_{\mathrm{HN}}}{\Lambda^2}\frac{g v^2}{2c_{\mathrm{W}}}\right)\overline{N}\gamma^\mu N Z_\mu$$



The following bounds can be recasted

– Neutral meson decays

– Monophoton searches at colliders

DM searches by LEP via $ee \to \psi\psi\gamma$ in the context of EFT

$$\left|\frac{C_{\mathrm{HN}}}{\Lambda^2}\right|^2 = \left|\frac{C_{\mathrm{vec}}}{\Lambda^2}\right|^2 \frac{\sigma_{\mathrm{vec}}(ee \to \psi\psi\gamma)}{\sigma_{\mathrm{HN}}(ee \to NN\gamma)}$$

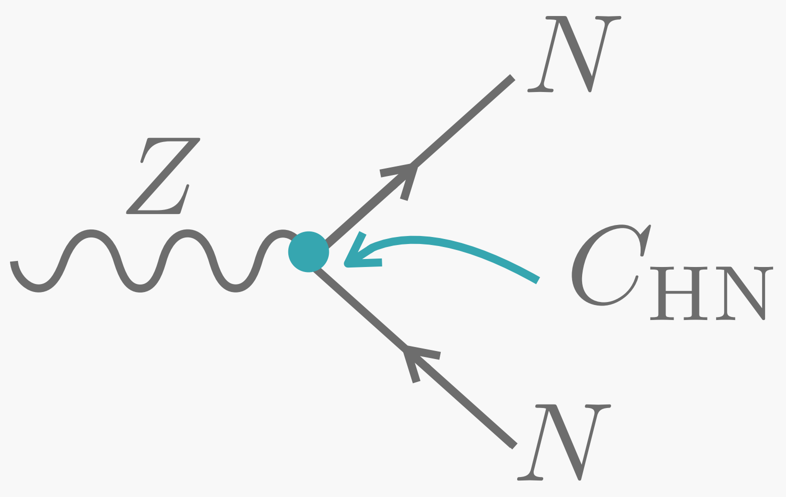
P. J. Fox, R. Harnik, J. Kopp, Y. Tsai. Phys.Rev.D **84** (2011) 014028

Bounds on ν-SMEFT

zoom.us video

- Bosonic currents: neutral

$$\mathcal{O}_{\mathrm{HN}} = \frac{C_{\mathrm{HN}}}{\Lambda^2} \overline{N}\gamma^\mu N (H^\dagger i \overleftrightarrow{D}_\mu H) \xrightarrow[\text{EWSB}]{\text{after}} \left(\frac{C_{\mathrm{HN}}}{\Lambda^2} \frac{g v^2}{2 c_{\mathrm{W}}} \right) \overline{N}\gamma^\mu N Z_\mu$$



The following bounds can be recasted

- Neutral meson decays
- Monophoton searches at colliders
- Supernova cooling

  ν dominant cooling mechanism of core-collapse SN

  HNL with large mixing would be trapped, keeping the energy $\Rightarrow$ lower limit

  HNL with small mixing would extract energy from the SM $\Rightarrow$ upper limit

  Depending on M_N, $\gamma\gamma \to \pi^0 \to NN \Rightarrow$ faster cooling $\Rightarrow$ upper limit

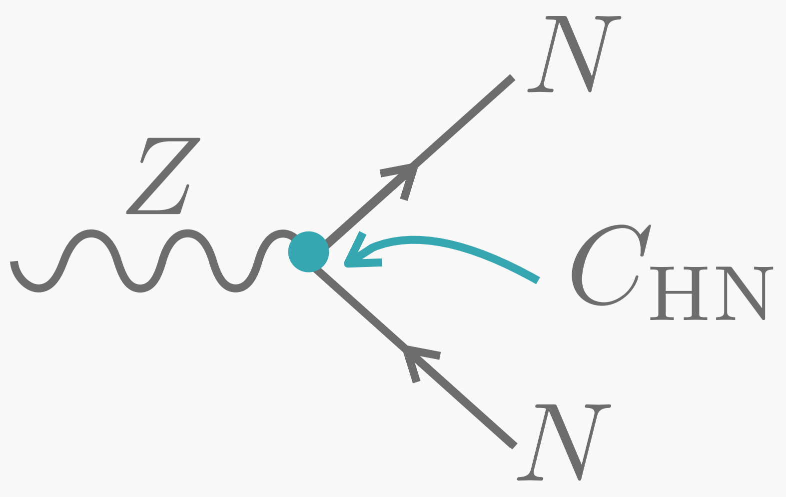
A.A. Natale. Phys.Lett.B **258** (1991) 227-230

W. DeRocco, P. W. Graham, D. Kasen, G. Marques-Tavares, S. Rajendran. Phys.Rev.D **100** (2019) 7, 075018

Bounds on ν-SMEFT

- Bosonic currents: neutral

$$\mathcal{O}_{\mathrm{HN}} = \frac{C_{\mathrm{HN}}}{\Lambda^2} \overline{N} \gamma^\mu N (H^\dagger i \overleftrightarrow{D}_\mu H) \xrightarrow[\text{EWSB}]{\text{after}} \left(\frac{C_{\mathrm{HN}}}{\Lambda^2} \frac{g v^2}{2 c_{\mathrm{W}}} \right) \overline{N} \gamma^\mu N Z_\mu$$



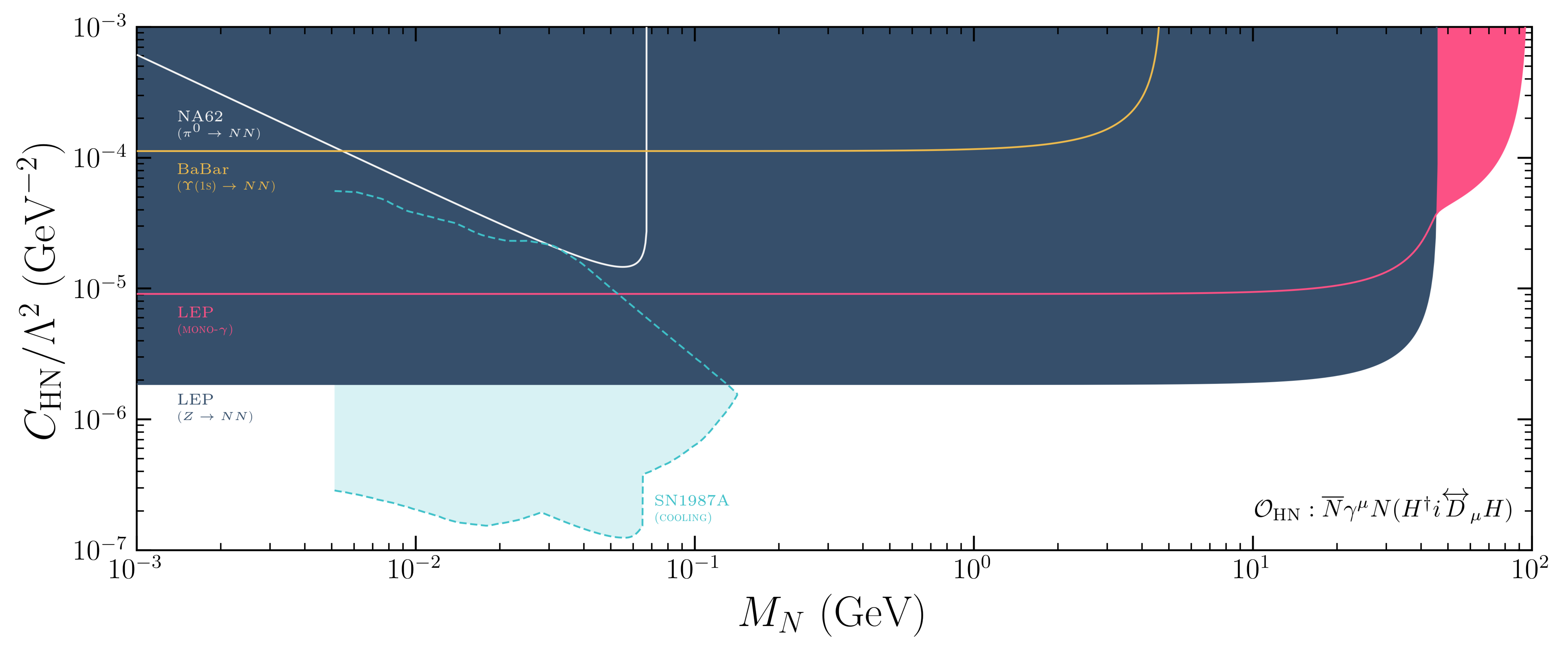
The following bounds can be recasted

- Neutral meson decays
- Monophoton searches at colliders
- Supernova cooling
- Invisible decay of the Z

Additional contribution to Z_{inv}, measured with high accuracy at LEP

Bounds on ν-SMEFT

- Bosonic currents: neutral



Bounds on ν-SMEFT

zoom.us video

- Bosonic currents: charged

$$\mathcal{O}^{\alpha}_{\mathrm{HN}\ell} = \frac{C^{\alpha}_{\mathrm{HN}\ell}}{\Lambda^2}\overline{N}\gamma^{\mu}\ell_{\alpha}(\widetilde{H}^{\dagger}i\overleftrightarrow{D}_{\mu}H)$$

Bounds on ν-SMEFT

- Bosonic currents: charged

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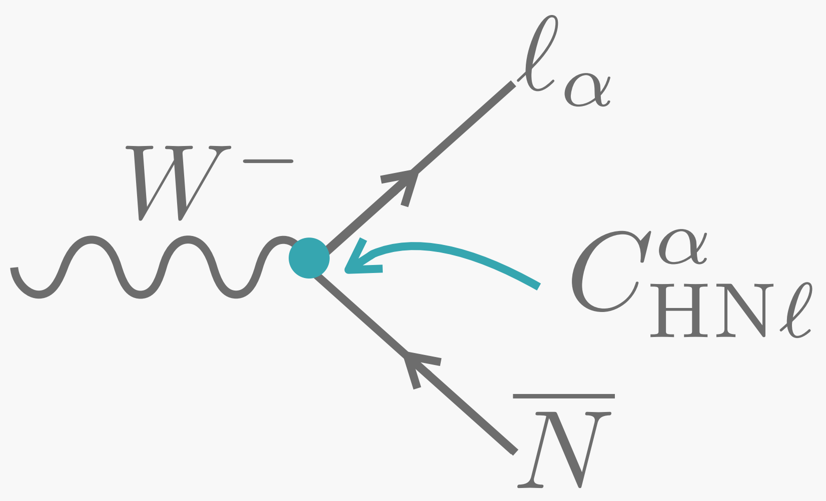

$$U^{\mathrm{CC}}_{\alpha N} \equiv \frac{C^{\alpha}_{\mathrm{HN}\ell}v^2}{\sqrt{2}\Lambda^2}$$

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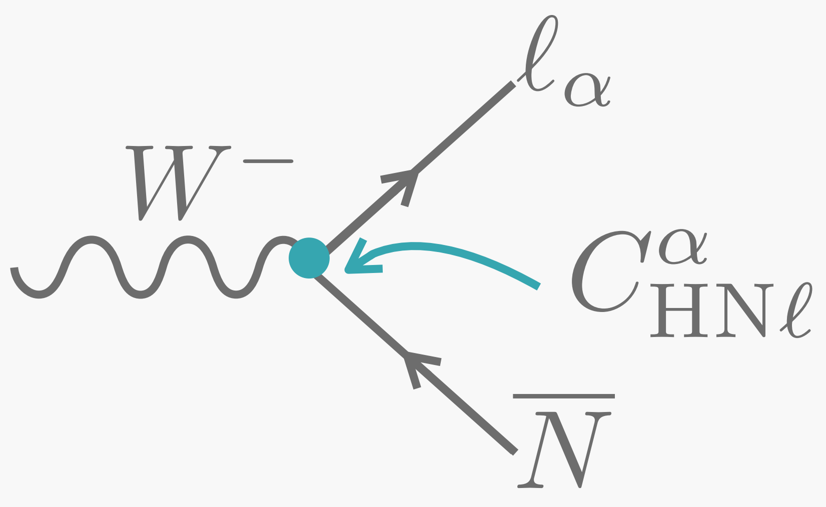

$$U^{\mathrm{CC}}_{\alpha N} \equiv \frac{C^{\alpha}_{\mathrm{HN}\ell}v^2}{\sqrt{2}\Lambda^2}$$

Bounds on $U_{\alpha N}$ can be re-scaled:

- Bounds from peak searches $\Rightarrow$ HNL searches via CC meson decay

$$N_{\mathrm{ev}} = \hat{\Gamma}_{\mathrm{mix}}|U_{\alpha N}|^2 = \hat{\Gamma}_{\mathrm{eff}}|U^{\mathrm{CC}}_{\alpha N}|^2 \Rightarrow \left|\frac{C^{\alpha}_{\mathrm{HN}\ell}}{\Lambda^2}\right|^2 = \frac{2}{v^4}|U_{\alpha N}|^2$$

Bounds on ν-SMEFT

zoom.us video

- Bosonic currents: charged

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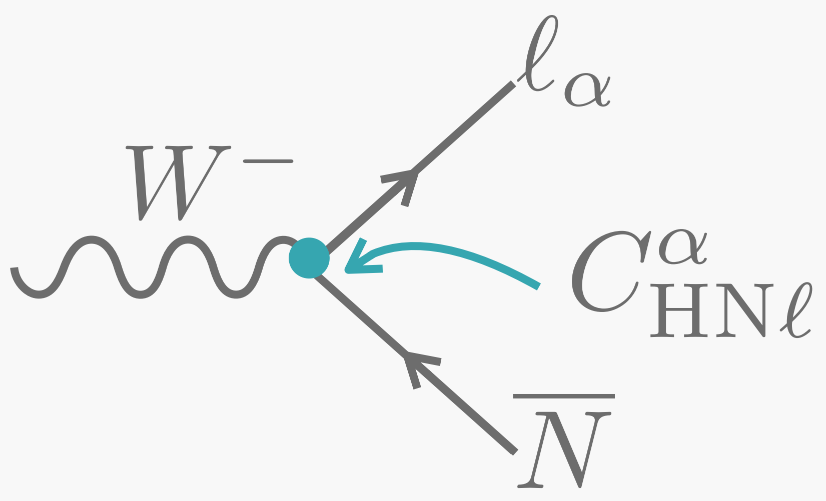

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- Bounds from beam-dump $\Rightarrow$ HNL searches via CC (+ NC ?) decays in flight

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Bounds on ν-SMEFT

zoom.us video

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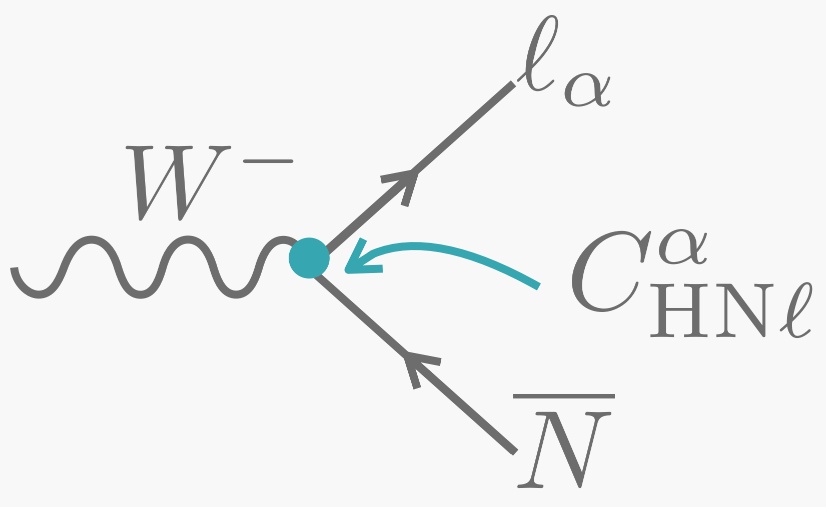

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Bounds on ν-SMEFT

zoom.us video

- Bosonic currents: charged

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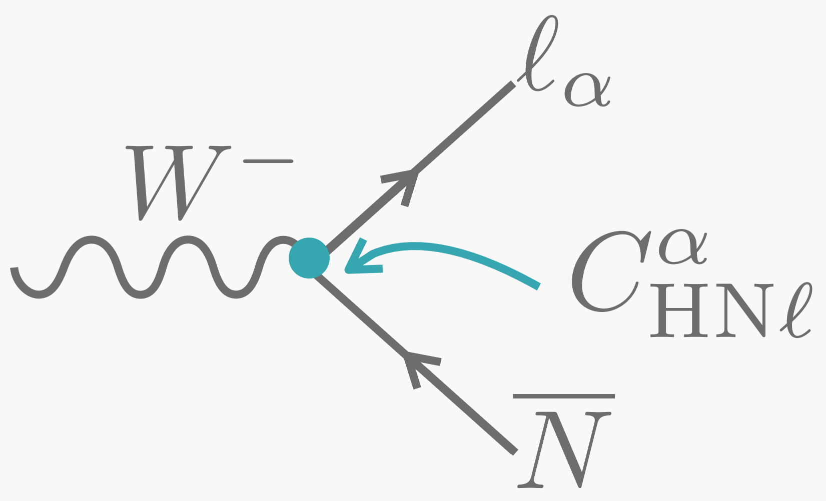

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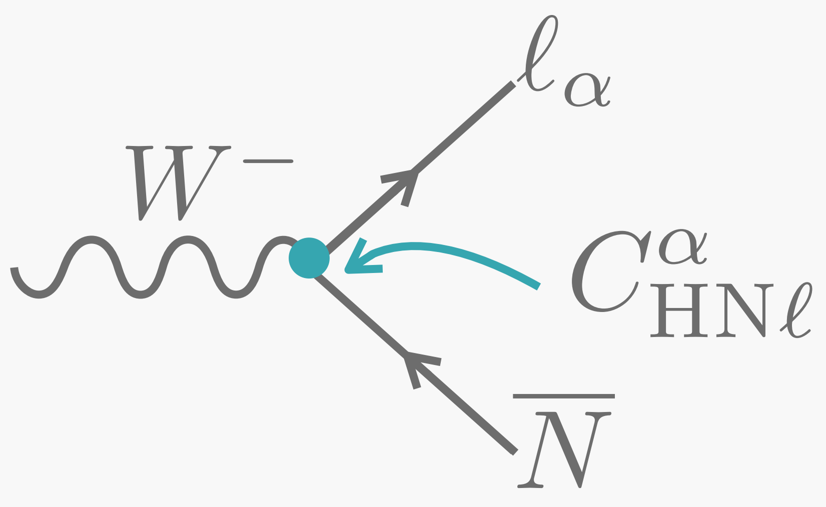
- Bounds from colliders $\Rightarrow$ HNL searches via W decays
  + HNL searches via Z decays $\Rightarrow$ do not apply
  + HNL searches via W decays $\Rightarrow$ same procedure as beam-dumps

Bounds on ν-SMEFT

- Bosonic currents: charged

$$\mathcal{O}^{\alpha}_{\mathrm{HN}\ell} = \frac{C^{\alpha}_{\mathrm{HN}\ell}}{\Lambda^2}\overline{N}\gamma^{\mu}\ell_{\alpha}(\widetilde{H}^{\dagger} i \overleftrightarrow{D}_{\mu} H) \xrightarrow[\text{EWSB}]{\text{after}} \left(\frac{C^{\alpha}_{\mathrm{HN}\ell}}{\Lambda^2}\frac{g v^2}{2}\right)\overline{N}\gamma^{\mu}\ell_{\alpha}W^{-}_{\mu} + \text{h.c.}$$



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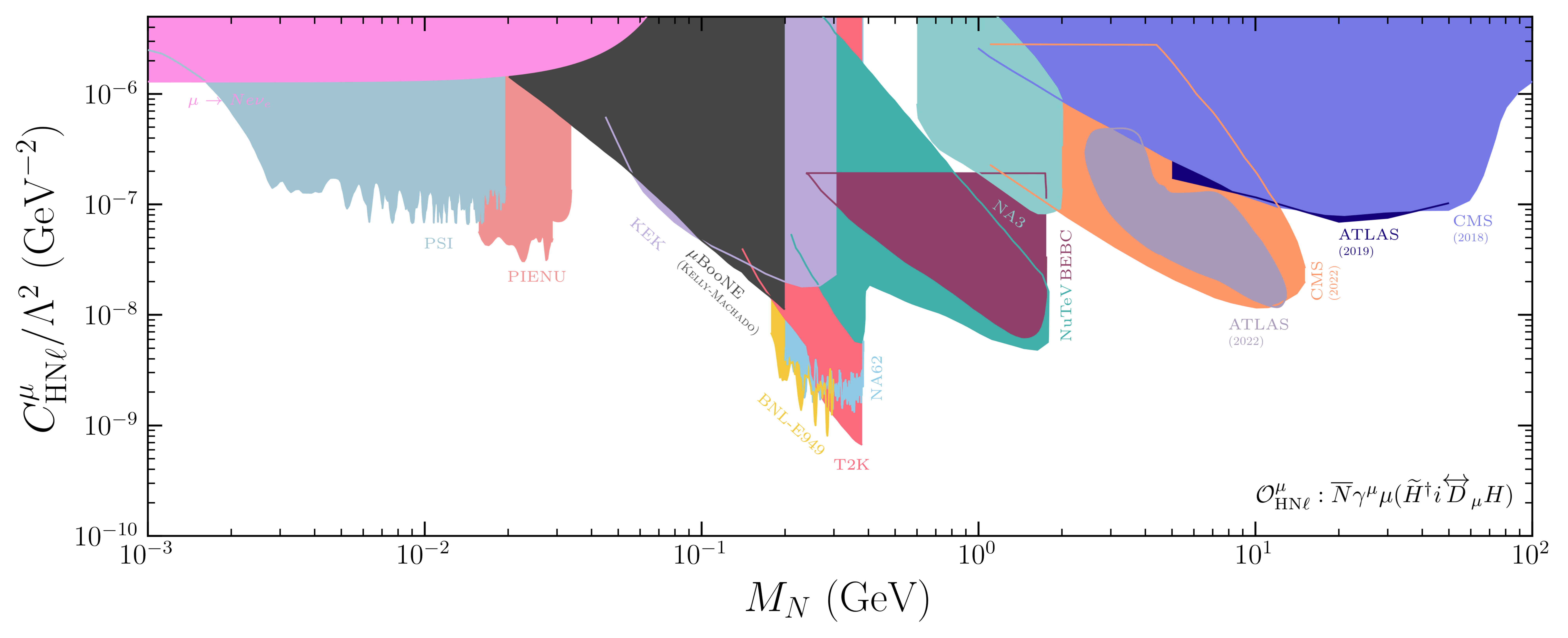
- Bounds from colliders $\Rightarrow$ HNL searches via W decays
- Bounds from CC lepton decays $\ell_{\alpha} \to \ell_{\beta}\nu_{\beta}N$

Bounds on ν-SMEFT

zoom.us video

- Bosonic currents: charged



Equivalent bounds on $C^{e}_{\mathrm{HN}\ell}/\Lambda^2$ and $C^{\tau}_{\mathrm{HN}\ell}/\Lambda^2$. See back-up slides

Summary

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Neutrino masses are one of the most promising open windows for NP.

Depending on HNL mass range, very different bounds on $|U_{\alpha N}|^2$ apply.

The expected sensitivity to HNLs of DUNE ND has been simulated by using a FeynRules model file describing HNL interactions with mesons.
The DUNE ND could test large part of the HNL parameter space.

Effective operators can be very useful to describe NP involving HNLs.
Present laboratory searches constrain $d = 6$ Wilson coefficients of ν-SMEFT.

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Thanks

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DE CIENCIA, INNOVACIÓN
Y UNIVERSIDADES

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Plan de Recuperación,
Transformación y
Resiliencia

AGENCIA
ESTATAL DE
INVESTIGACIÓN

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Back-Up

Effective Mesons and HNL Interactions

- Vector mesons
  - Neutral mesons: ρ^0, ω, ϕ

$$
\begin{aligned}
j^V_{3,\mu} &= \frac{1}{2}\left[\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d\right] \\
j^V_{8,\mu} &= \frac{1}{2\sqrt{3}}\left[\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d - 2\bar{s}\gamma_\mu s\right] \\
j^V_{0,\mu} &= \frac{1}{\sqrt{6}}\left[\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d + \bar{s}\gamma_\mu s\right]
\end{aligned}
\quad \Rightarrow \quad
\begin{aligned}
j^V_{\rho^0,\mu} &= j^V_{3,\mu} \\
j^V_{\omega,\mu} &= \sqrt{\frac{1}{3}} j^V_{8,\mu} + \sqrt{\frac{2}{3}} j^V_{0,\mu} \\
j^V_{\phi,\mu} &= -\sqrt{\frac{2}{3}} j^V_{8,\mu} + \sqrt{\frac{1}{3}} j^V_{0,\mu}
\end{aligned}
$$

The vector component of the Z current

$$
j^V_{Z,\mu} = \left(1 - 2s_w^2\right) j^V_{\rho^0,\mu} - \frac{2}{3}s_w^2 j^V_{\omega,\mu} - \sqrt{2}\left(\frac{1}{2} - \frac{2}{3}s_w^2\right) j^V_{\phi,\mu}
$$

Effective Mesons and HNL Interactions

- Vector mesons
  - Neutral mesons: ρ^0, ω, ϕ

    The effective operators in configuration space

$$\boxed{\begin{aligned}
\mathcal{O}_{\rho^0 n_i \bar{n}_j} &= -\frac{1}{2} G_F C_{ij} \left(1 - 2s_w^2\right) f_\rho \rho^0_\mu \left(\bar{n}_i \gamma^\mu P_L n_j\right) + \text{h.c.} \\
\mathcal{O}_{\omega n_i \bar{n}_j} &= \frac{1}{2} G_F C_{ij} \frac{2}{3} s_w^2 f_\omega \omega_\mu \left(\bar{n}_i \gamma^\mu P_L n_j\right) + \text{h.c.} \\
\mathcal{O}_{\phi n_i \bar{n}_j} &= \frac{1}{2} G_F C_{ij} \sqrt{2} \left(\frac{1}{2} - \frac{2}{3} s_w^2\right) f_\phi \phi_\mu \left(\bar{n}_i \gamma^\mu P_L n_j\right) + \text{h.c.}
\end{aligned}}$$

Effective Mesons and HNL Interactions

- Vector mesons
  - Charged mesons: $\rho^{\pm}, K^{*,\pm}$

The charged vector meson, and the vector component of the W currents

$$j^V_{\rho^\pm,\mu} = \frac{1}{\sqrt{2}}\bar{q}\gamma_\mu(\lambda_1 \mp i\lambda_2)q$$
$$j^V_{K^{*,\pm},\mu} = \frac{1}{\sqrt{2}}\bar{q}\gamma_\mu(\lambda_4 \mp i\lambda_5)q$$

$$\Rightarrow \qquad j^V_{W,\mu} = \frac{1}{\sqrt{2}}\left(V_{ud}\, j^V_{\rho^-,\mu} + V_{us}\, j^V_{K^{*,-},\mu}\right)$$

The effective operators of the charged vector mesons in configuration space

$$\boxed{\begin{aligned} \mathcal{O}_{\rho\ell_\alpha\bar{n}_i} &= -\sqrt{2}G_F U_{\alpha i} V_{ud} f_\rho \rho^-_\mu \left(\bar{\ell}_\alpha \gamma^\mu P_L n_i\right) + \text{h.c.} \\ \mathcal{O}_{K^*\ell_\alpha\bar{n}_i} &= -\sqrt{2}G_F U_{\alpha i} V_{us} f_{K^*} K^{*,-}_\mu (\bar{\ell}_\alpha \gamma^\mu P_L n_i) + \text{h.c.} \end{aligned}}$$

Determining Meson Decay Constants

- Pseudoscalar mesons
  - π, K, D and D_s decay constants precisely measured

$$\boxed{f_\pi = 0.130 \text{ GeV} \quad f_K = 0.156 \text{ GeV} \quad f_D = 0.212 \text{ GeV} \quad f_{D_s} = 0.249 \text{ GeV}}$$

Particle Data Group, M. Tanabashi et al., Phys. Rev. D **98** 2018 030001

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  - η and η' are not interaction eigenstates $\Rightarrow$ effective constants are employed

$$\begin{aligned} f_\eta &: \quad \left(\frac{\cos\theta_8 f_8}{\sqrt{3}} + \frac{\sin\theta_0 f_0}{\sqrt{6}}\right) \\ f_{\eta'} &: \quad \left(\frac{\sin\theta_8 f_8}{\sqrt{3}} - \frac{\cos\theta_0 f_0}{\sqrt{6}}\right) \end{aligned}$$

with

f_0	0.148 GeV	θ_0	-6.9°
f_8	0.165 GeV	θ_8	-21.2°

R. Escribano, S. Gonzalez-Solis, P. Masjuan and P. Sanchez-Puertas, Phys. Rev. D **94** 2016 054033

Determining Meson Decay Constants

- Vector mesons

  V resonances wide & unstable under QCD $\Rightarrow f_V$ not easily defined

  - Neutral mesons: ρ^0, ω, ϕ

    Compute Γ for decay mediated by EW interaction precisely measured and compare the result to the experimental values from PDG.

    $V \to e^+e^-$ has been precisely measured and is dominated by γ exchange.

    Decompose the EM current as a linear combination of the meson currents

$$j^V_{\mathrm{EM},\mu} = ieQ\bar{q}\gamma_\mu q = ie\left(j^V_{\rho,\mu} + \frac{1}{3}j^V_{\omega,\mu} - \frac{\sqrt{2}}{3}j^V_{\phi,\mu}\right)$$

Determining Meson Decay Constants

- Vector mesons

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    The width for the vector meson decays into e^+e^- pairs mediated by a photon

$$\Gamma(\rho \to e^+e^-) = \frac{2\pi}{3}\frac{\alpha^2 f_\rho^2}{m_\rho^3}$$

$$\Gamma(\omega \to e^+e^-) = \frac{2\pi}{27}\frac{\alpha^2 f_\omega^2}{m_\omega^3} \quad \Rightarrow$$

$$\Gamma(\phi \to e^+e^-) = \frac{4\pi}{27}\frac{\alpha^2 f_\phi^2}{m_\phi^3}$$

$$\boxed{\begin{aligned} f_\rho &= 0.171\ \mathrm{GeV}^2 \\ f_\omega &= 0.155\ \mathrm{GeV}^2 \\ f_\phi &= 0.232\ \mathrm{GeV}^2 \end{aligned}}$$

Particle Data Group, M. Tanabashi et al., Phys. Rev. D **98** 2018 030001

Determining Meson Decay Constants

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  - Charged mesons: $\rho^{\pm}, K^{*,\pm}$

    $\rho^{\pm}$ isospin breaking corrections should be negligible $\Rightarrow \boxed{f_{\rho^{\pm}} \approx f_{\rho^0}}$

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    $\rho^{\pm}$ isospin breaking corrections should be negligible $\Rightarrow \boxed{f_{\rho^{\pm}} \approx f_{\rho^0}}$

    Combining EW measurements of the $\tau \to \rho\nu_\tau$ and $\tau \to K^*\nu_\tau$

$$\frac{f_{K^*}}{f_\rho} = 1.042 \quad \Rightarrow \quad \boxed{f_{K^*} = 0.178 \text{ GeV}^2}$$

P. Maris and P. C. Tandy, Phys. Rev. C **60** 1999 055214

Determining Meson Decay Constants

Determining the meson decay constants and semileptonic decay form factors

Most of the paranetrizations for the hadronic form factors are given in the literature in terms of f_+ and f_0

$$f_0(q^2) = f_+(q^2) + \frac{q^2}{M_D^2 - M_P^2} f_-(q^2)$$

Linear parametrization for K → πnl

$$f_{+,0}^{K\pi}(q^2) = f_+^{K\pi}(0)\left(1 + \lambda_{+,0}^{K\pi}\frac{q^2}{M_{\pi^+}^2}\right)$$

PD	$f_+^{\mathrm{PD}}(0)$	λ_+^{PD}	λ_0^{PD}
$K^\pm\pi^0$	0.9749	0.0297	0.0195
$K^0\pi^\pm$		0.0282	0.0138

We have numerically checked with MadGraph5 that our implementation of the semileptonic decays reaches an agreement of at least a 95% with the measured branching ratios for the SM decay channels K → πνl and D → Kνl

Determining Meson Decay Constants

Determining the meson decay constants and semileptonic decay form factors

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$$f_0(q^2) = f_+(q^2) + \frac{q^2}{M_D^2 - M_P^2} f_-(q^2)$$

Pole parametrization for D → Knl

$$f_+^{DK}(q^2) = \frac{f_+^{DK}(0) + c_+^{DK}(z - z_0)\left(1 + \frac{z + z_0}{2}\right)}{1 - \frac{q^2}{M_{D_s^*}^2}}$$

$$f_0^{DK}(q^2) = f_+^{DK}(0) + c_0^{DK}(z - z_0)\left(1 + \frac{z + z_0}{2}\right)$$

$f_+^{DK}(0)$	c_+^{DK}	c_0^{DK}
0.7647	-0.066	-2.084

$$z = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

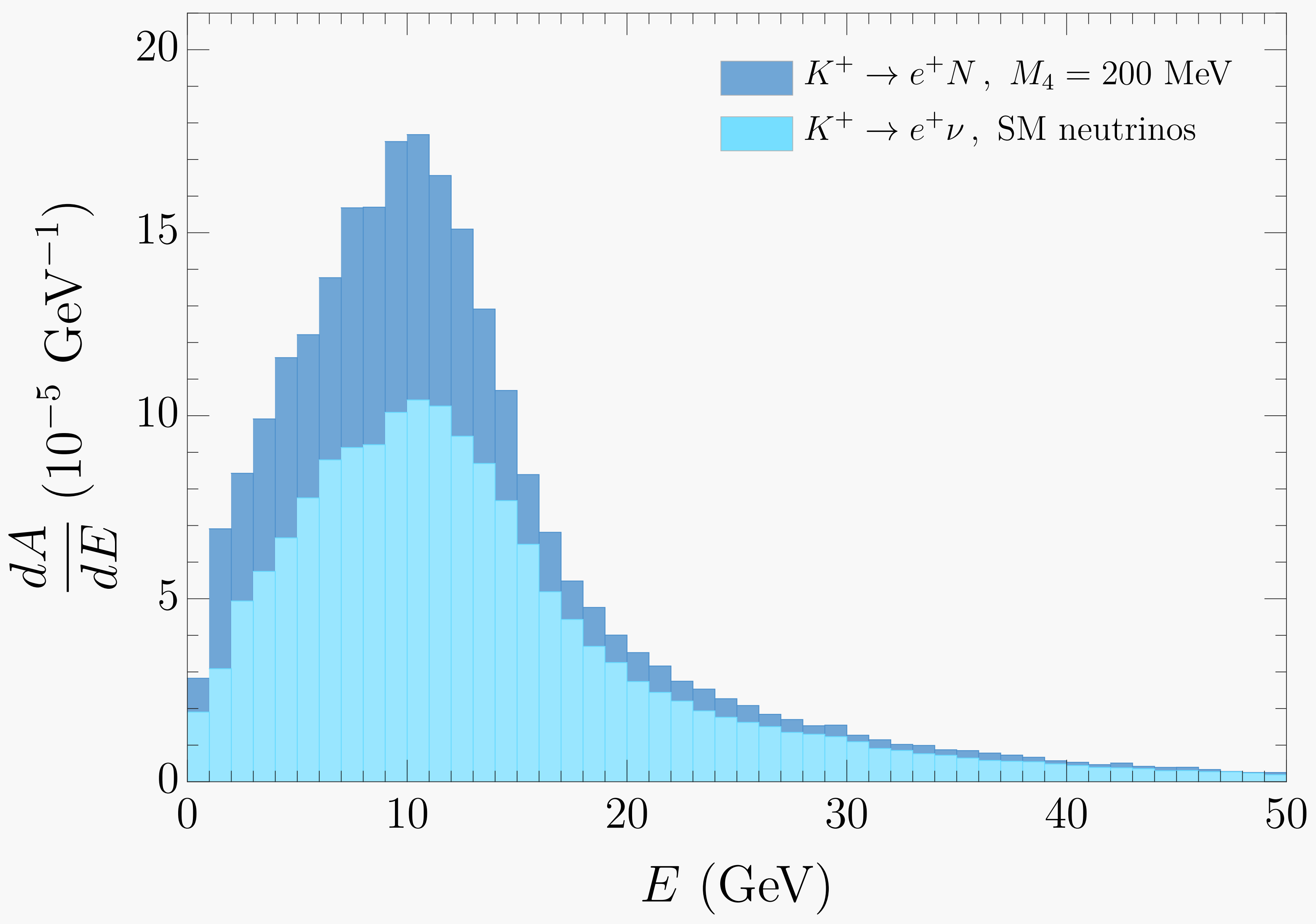
$$z_0 \equiv z(q^2 = 0)$$

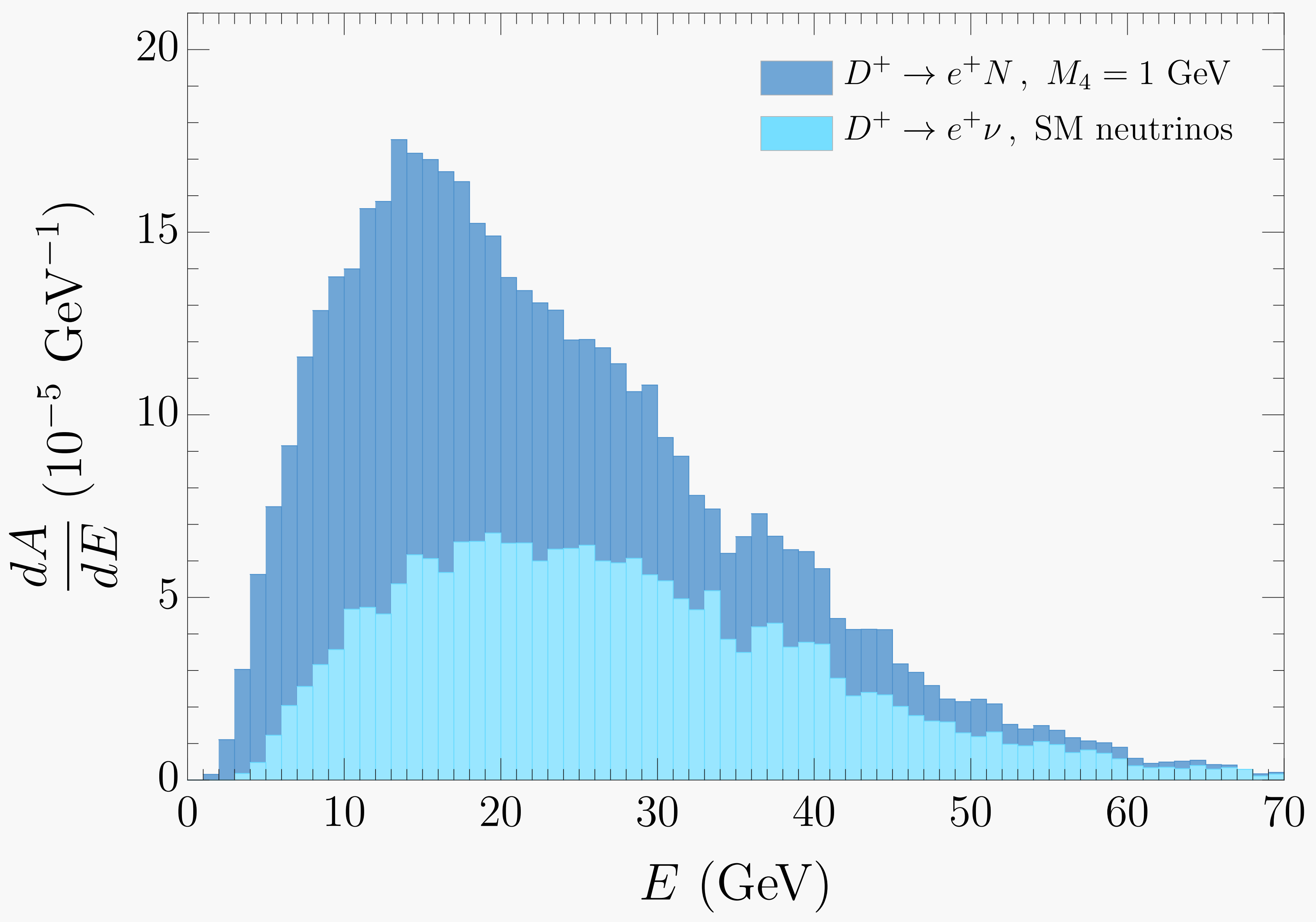
$$t_0 = (M_D + M_P)\left(\sqrt{M_D} - \sqrt{M_P}\right)^2$$

$$t_+ = (M_D + M_P)^2$$

We have numerically checked with MadGraph5 that our implementation of the semileptonic decays reaches an agreement of at least a 95% with the measured branching ratios for the SM decay channels K → πνl and D → Kνl

The Boost Effect





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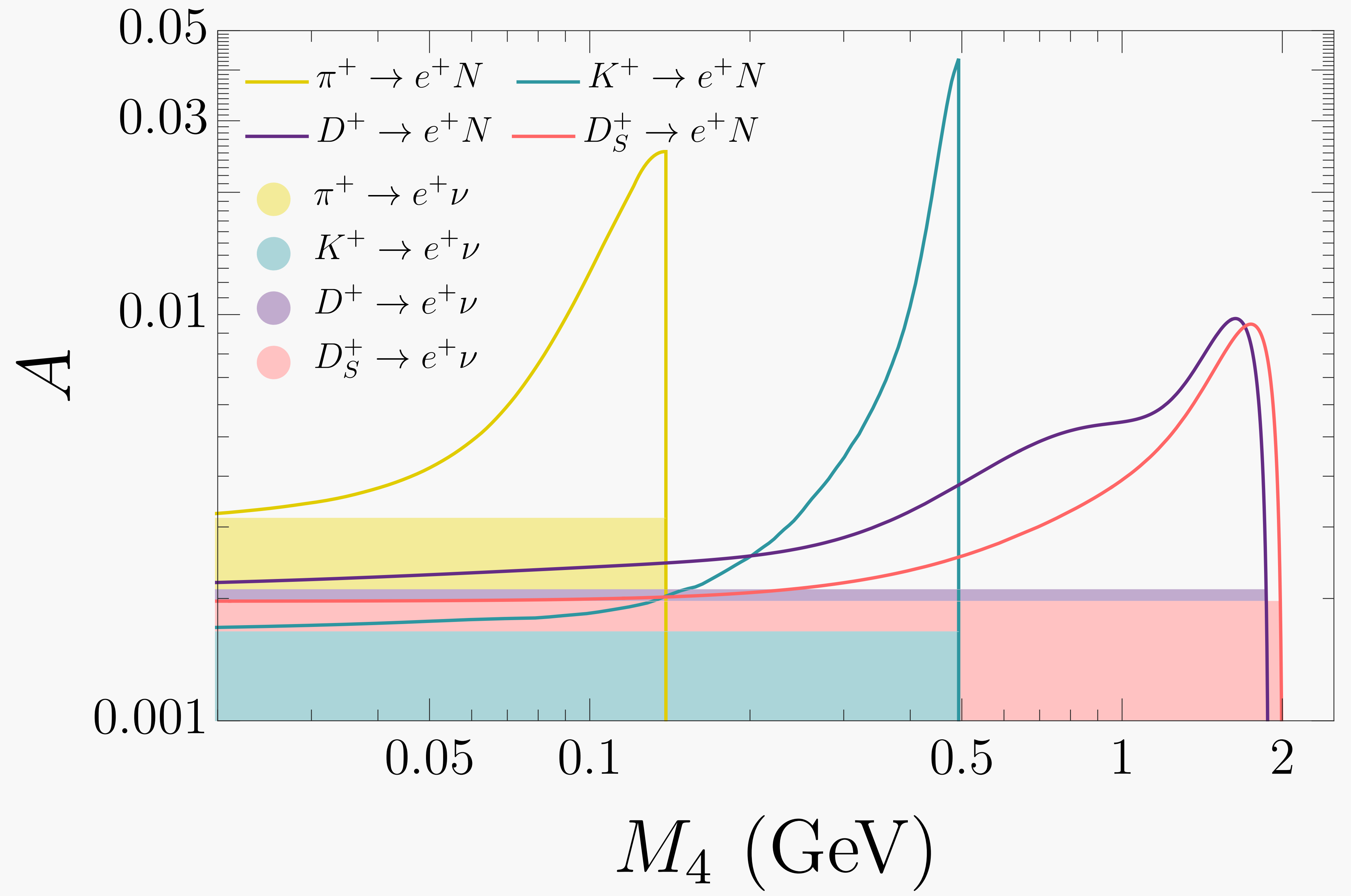

HNL Flux Simulation

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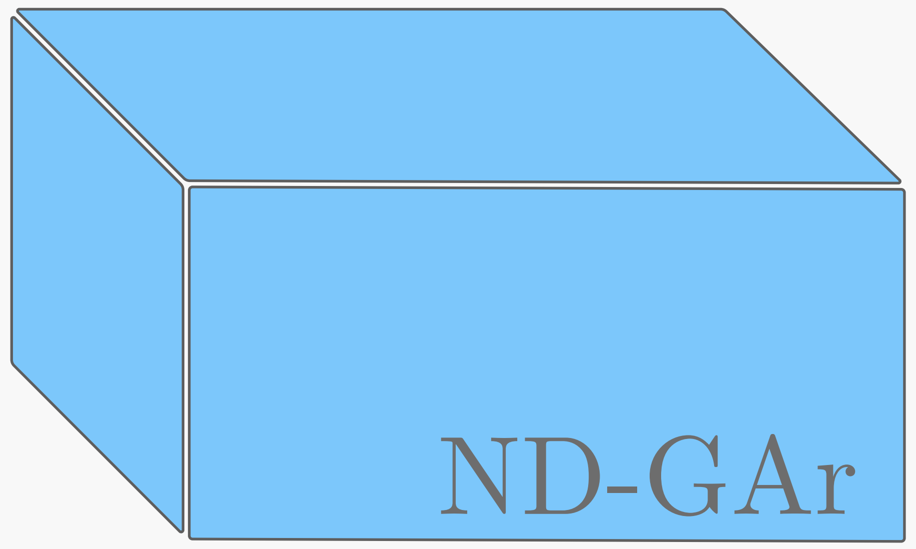
$p \longrightarrow$ target $\xrightarrow[D^{\pm} \quad D_s^{\pm}]{\pi^{\pm} \quad K^{\pm}}$



1) Fluxes of mesons produced in the target

– $\pi^{\pm}$ and $K^{\pm}$ from the oficial DUNE TDR n-tuples*

– $D^{\pm}$, $D_s^{\pm}$ and $\tau^{\pm}$ simulated with Pythia8 + GEANT4

	π	K	τ	D	D_s
P^+/PoT	6.3	0.54	$2.1 \cdot 10^{-7}$	$1.2 \cdot 10^{-5}$	$3.3 \cdot 10^{-6}$
P^-/PoT	5.7	0.24	$3.0 \cdot 10^{-7}$	$1.9 \cdot 10^{-5}$	$4.6 \cdot 10^{-6}$

*most up to date optimized 3-horn design (1.5m target) by L. Fields et al.

HNL Flux Simulation

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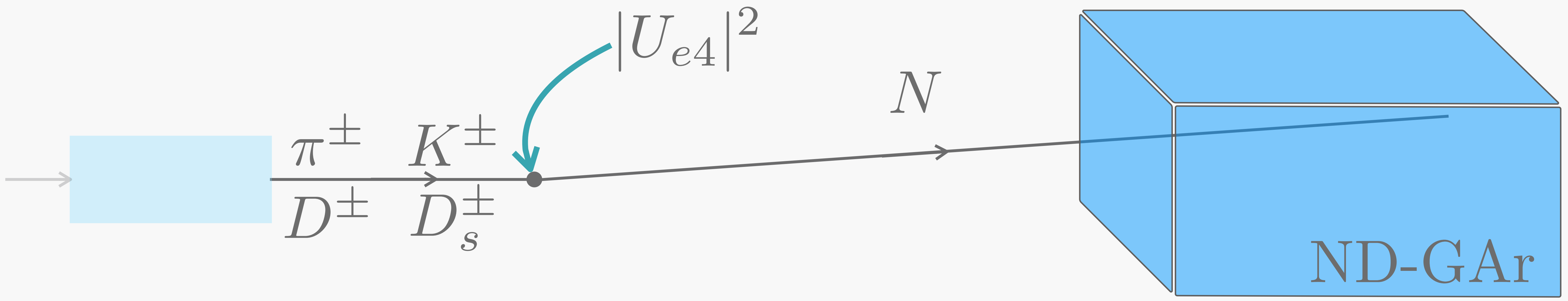


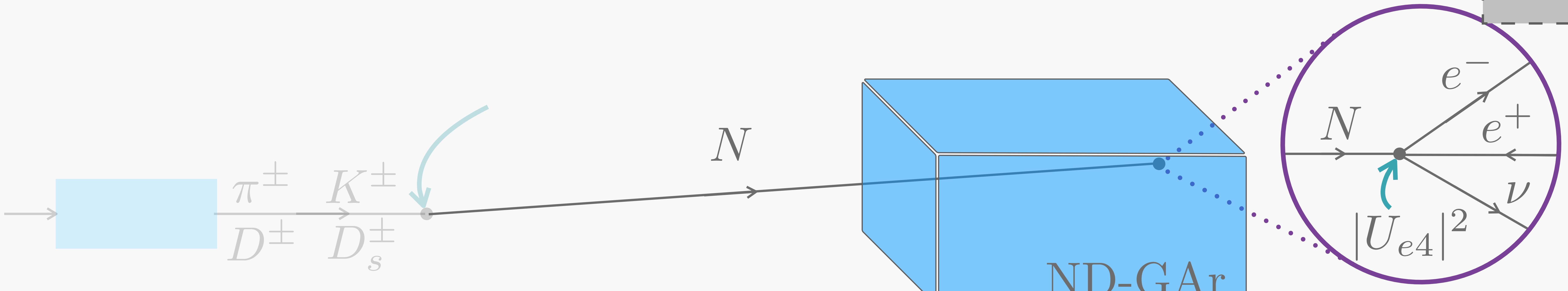
2) MadGraph events of HNL production via meson decays

Parent	**2-body decay**	**3-body decay**
$\pi^+ \to$	$e^+ N_4$	—
	$\mu^+ N_4$	
$K^+ \to$	$e^+ N_4$	$\pi^0 e^+ N_4$
	$\mu^+ N_4$	$\pi^0 \mu^+ N_4$
$\tau^- \to$	$\pi^- N_4$	$e^- \overline{\nu} N_4$
	$\rho^- N_4$	$\mu^- \overline{\nu} N_4$

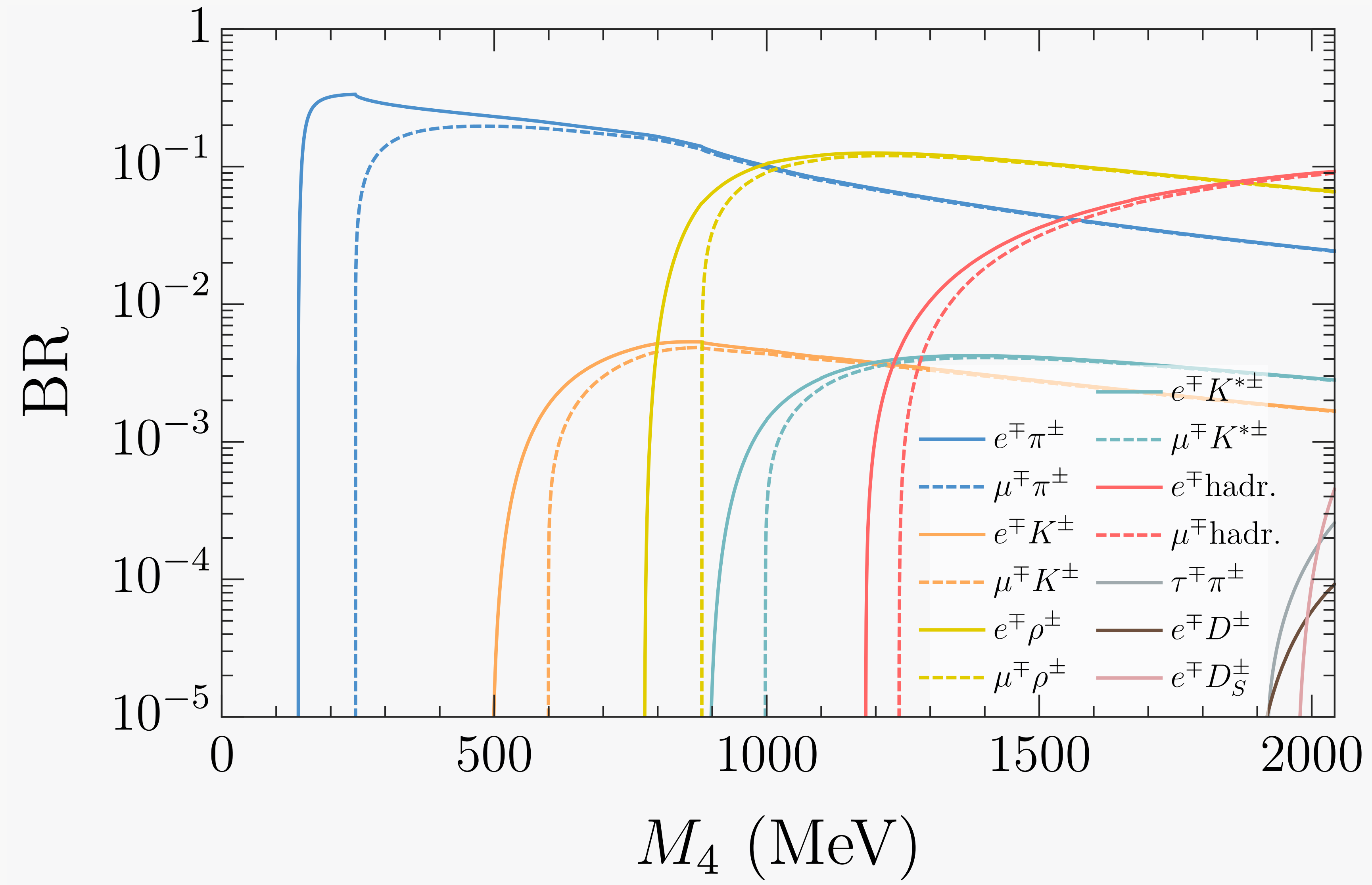
Parent	**2-body decay**	**3-body decay**
$D^+ \to$	$e^+ N_4$	$e^+ \overline{K^0} N_4$
	$\mu^+ N_4$	$\mu^+ \overline{K^0} N_4$
	$\tau^+ N_4$	
$D_s^+ \to$	$e^+ N_4$	—
	$\mu^+ N_4$	
	$\tau^+ N_4$	

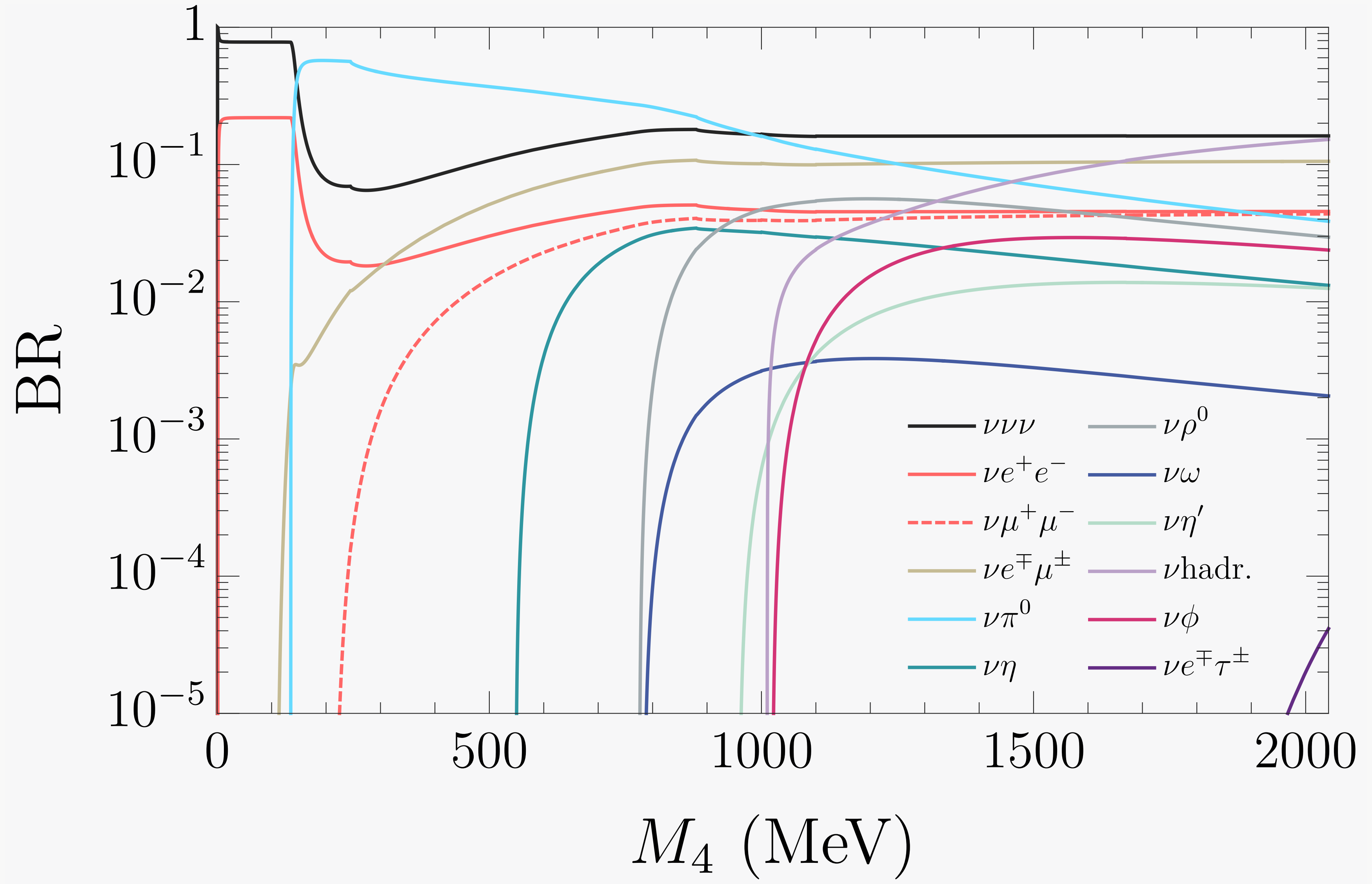
HNL Flux Simulation

zoom.us video



3) MadGraph events of HNL decays into SM particles





HNL Flux Simulation

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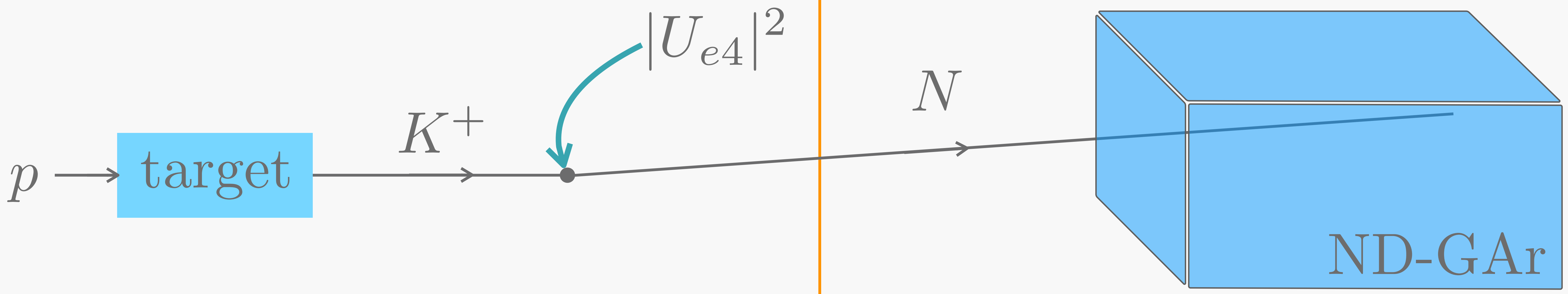
Example: DUNE ND sensitivity to HNL from K^+ decays

Step 1: HNL production



1) K^+ fluxes
2) MG events of HNL production from K^+

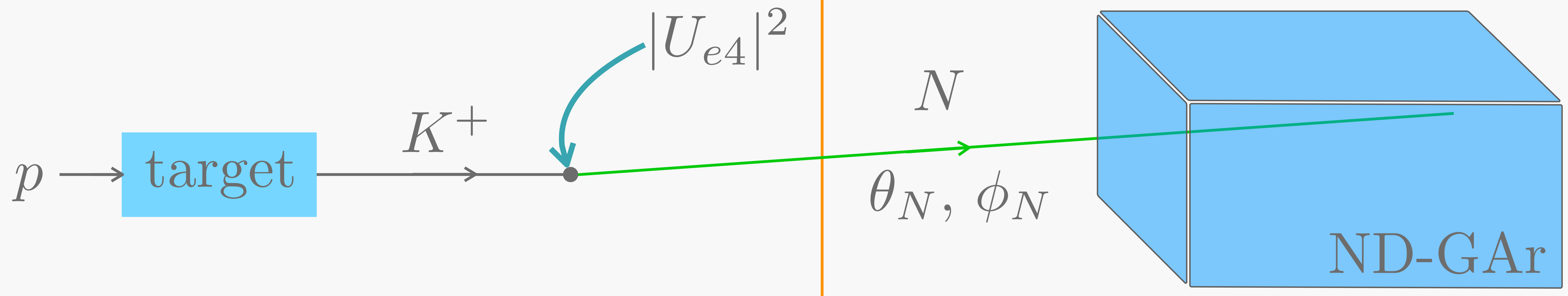
HNL fluxes pointing ND

Each MG event matched to one K^+ in the histogram and boosted to the lab frame (LF).

HNL Flux Simulation

Example: DUNE ND sensitivity to HNL from K^+ decays

Step 1: HNL production



1) K^+ fluxes
2) MG events of HNL production from K^+

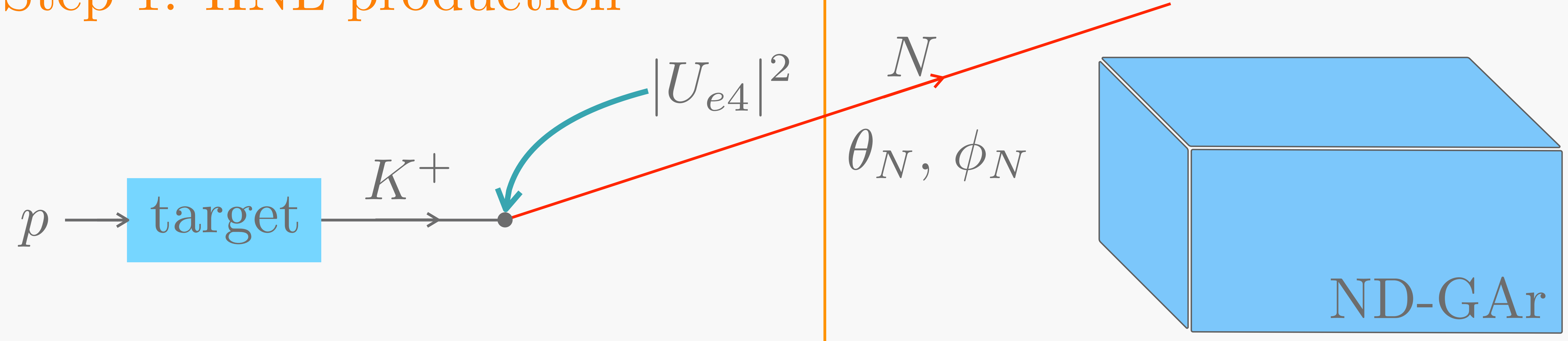
→ HNL fluxes pointing ND

Each MG event matched to one K^+ in the histogram and boosted to the lab frame (LF). If HNL pointing the DUNE ND, is storaged.

HNL Flux Simulation

Example: DUNE ND sensitivity to HNL from K^+ decays

Step 1: HNL production



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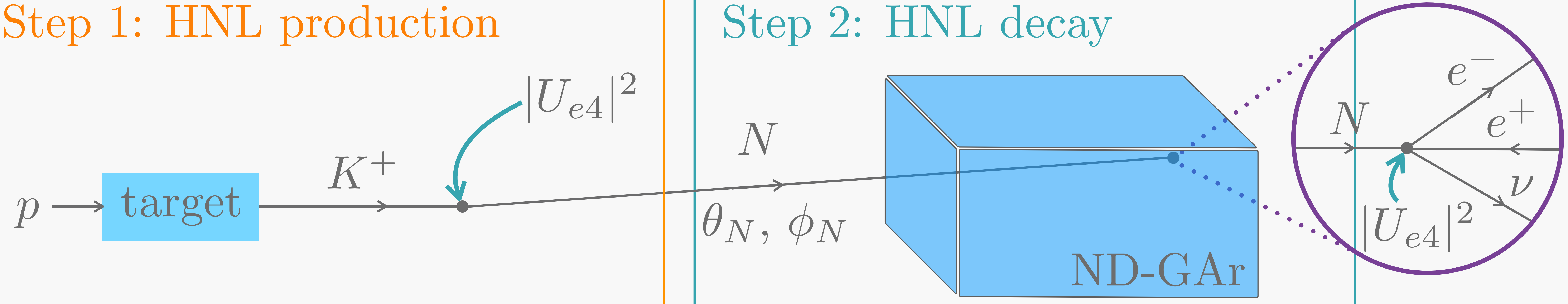
HNL Flux Simulation

Example: DUNE ND sensitivity to HNL from K^+ decays

Step 1: HNL production

Step 2: HNL decay



1) K^+ fluxes
2) MG events of HNL production from K^+

HNL fluxes pointing ND
3) MG events of HNL decay into SM

HNL + decay products inside ND

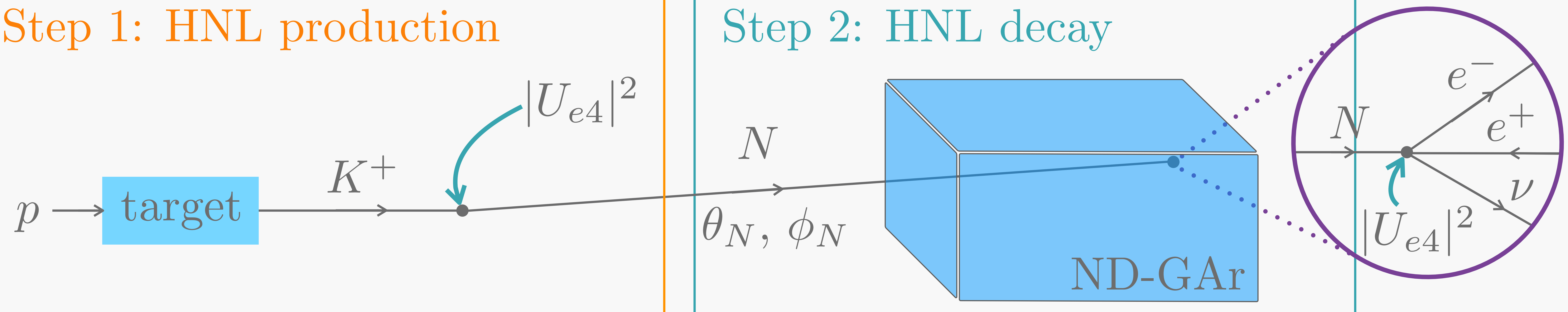
Each MG event matched to one HNL in the histogram and boosted to LF.

HNL Flux Simulation

Example: DUNE ND sensitivity to HNL from K^+ decays

Step 1: HNL production

Step 2: HNL decay



1) K^+ fluxes
2) MG events of HNL production from K^+

→ HNL fluxes pointing ND

3) MG events of HNL decay into SM

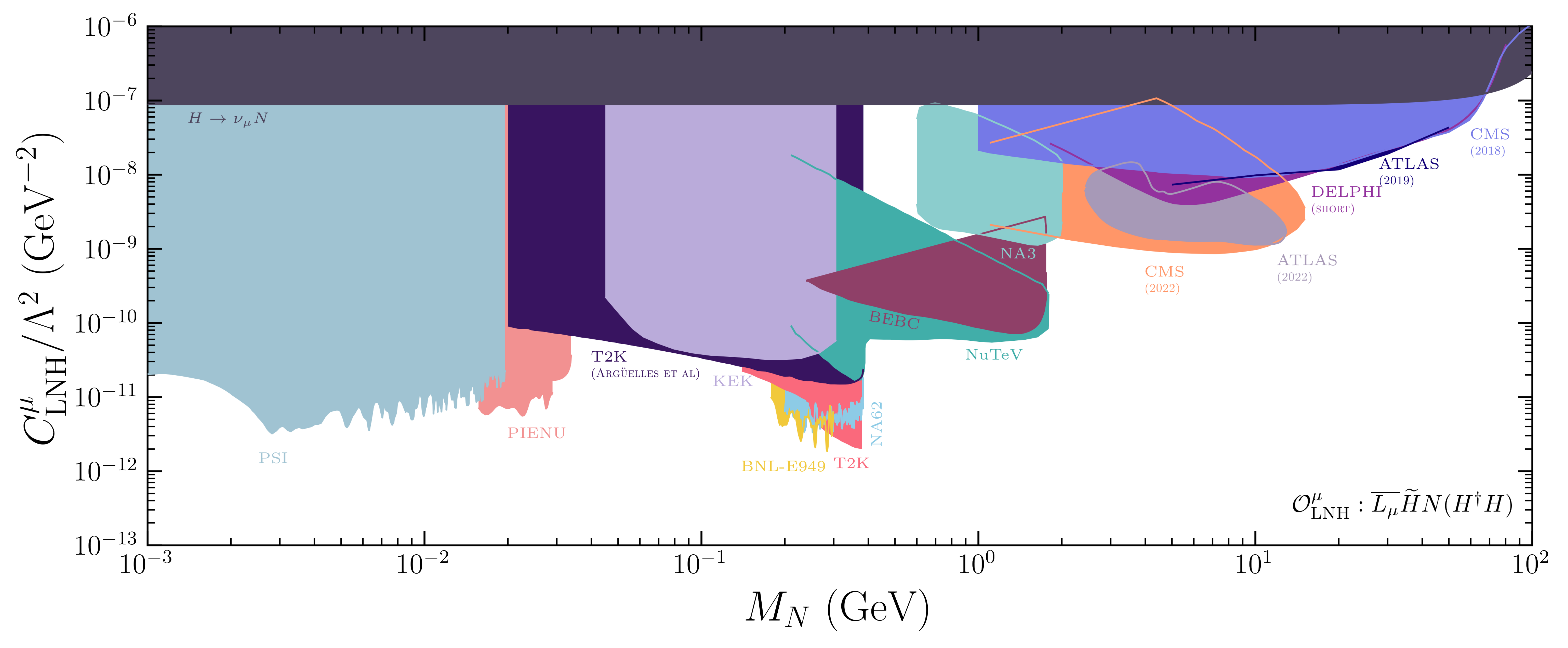
→ HNL + decay products inside ND

Each MG event matched to one HNL in the histogram and boosted to LF.

Repeat Step 1 and 2 for all the mesons assuming different M_4 and $|U_{\alpha 4}|^2$.

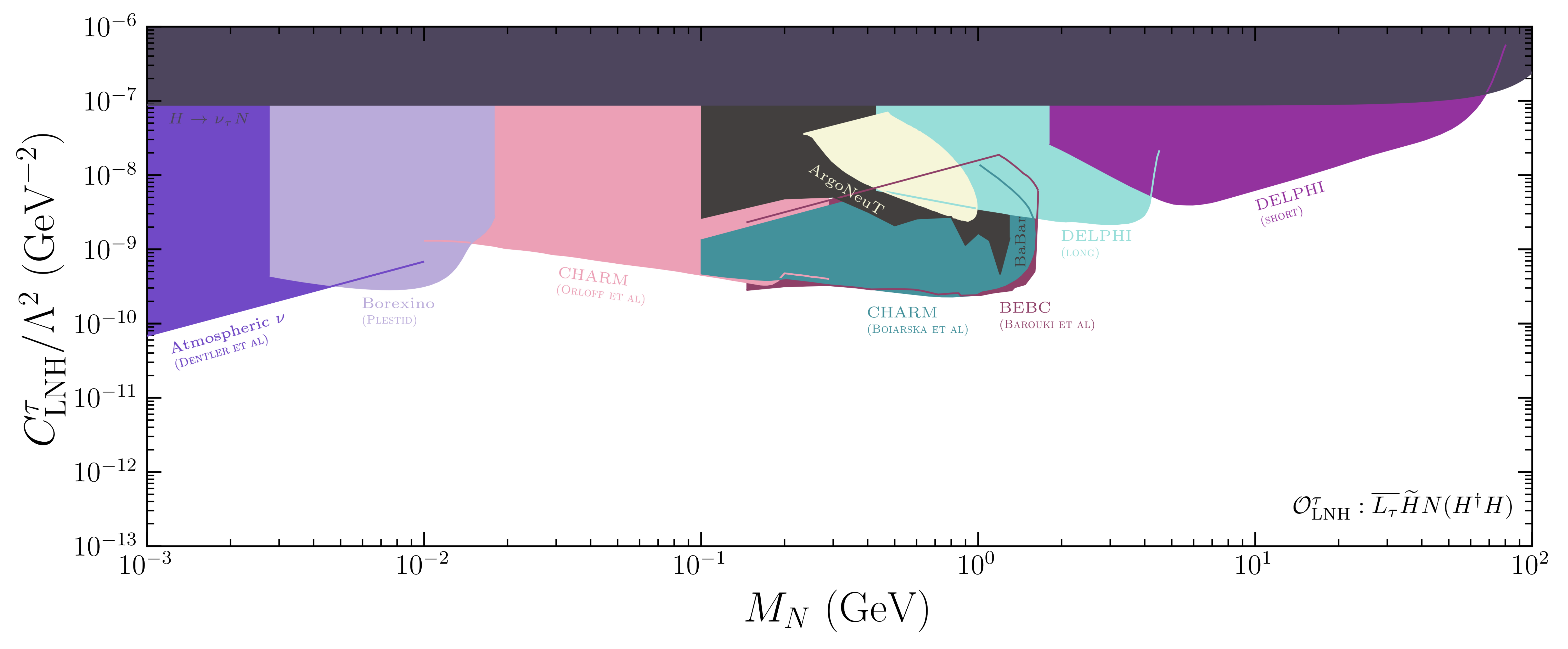
Bounds on ν-SMEFT

- Higgs-dressed mixing



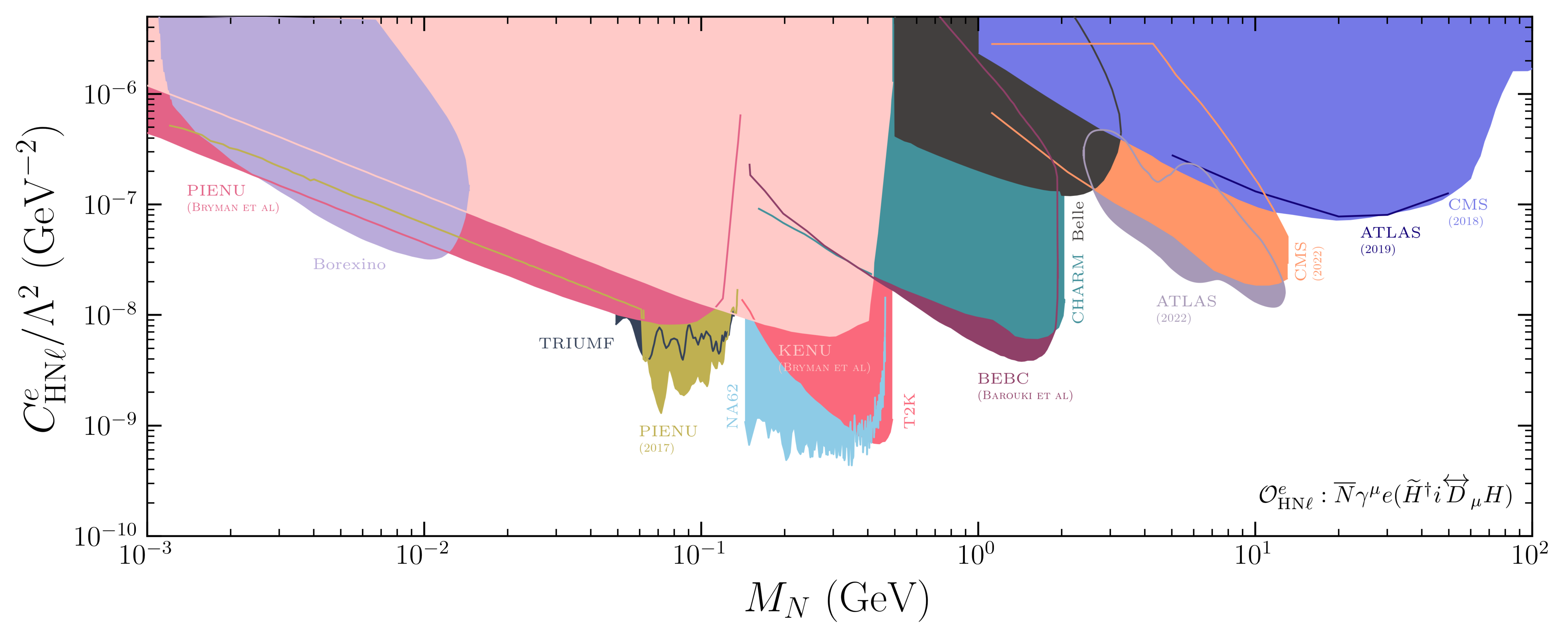
Bounds on ν-SMEFT

- Higgs-dressed mixing



Bounds on ν-SMEFT

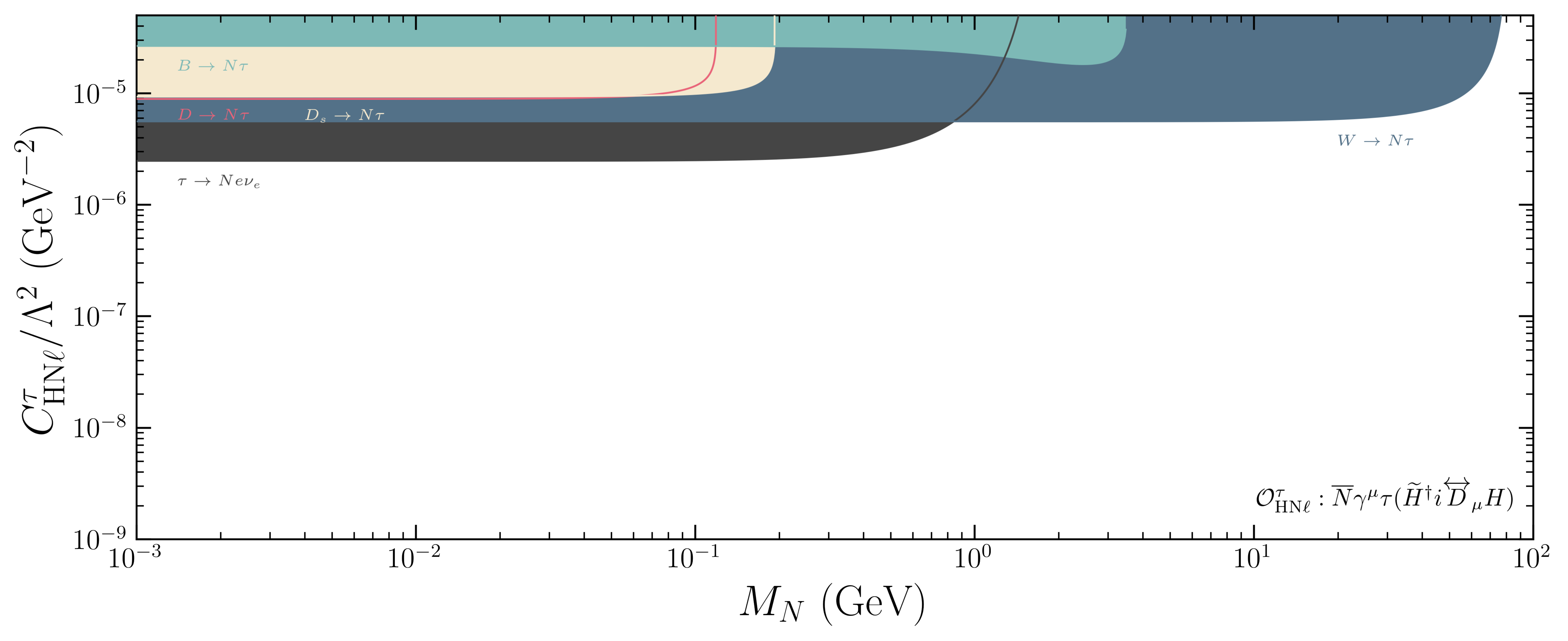
- Bosonic currents: charged



Equivalent bounds on $C^e_{\mathrm{HN}\ell}/\Lambda^2$ and $C^\tau_{\mathrm{HN}\ell}/\Lambda^2$. See back-up slides

Bounds on ν-SMEFT

- Bosonic currents: charged

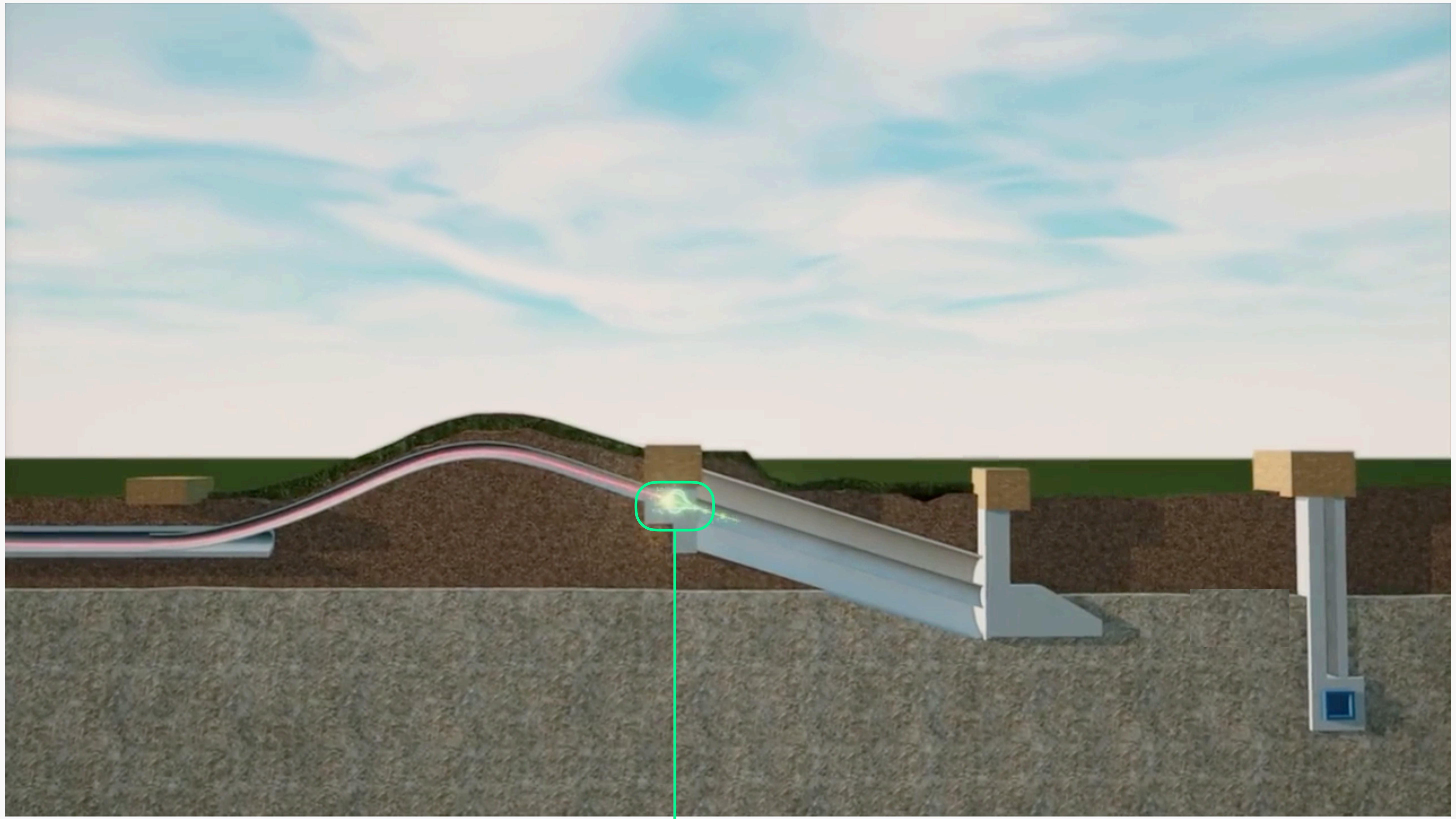


Introduction to HNL

zoom.us video

120 GeV

protons



Meson production: $\pi^{\pm}$, $K^{\pm}$, $D^{\pm}$ & $D_s^{\pm}$

Introduction to HNL

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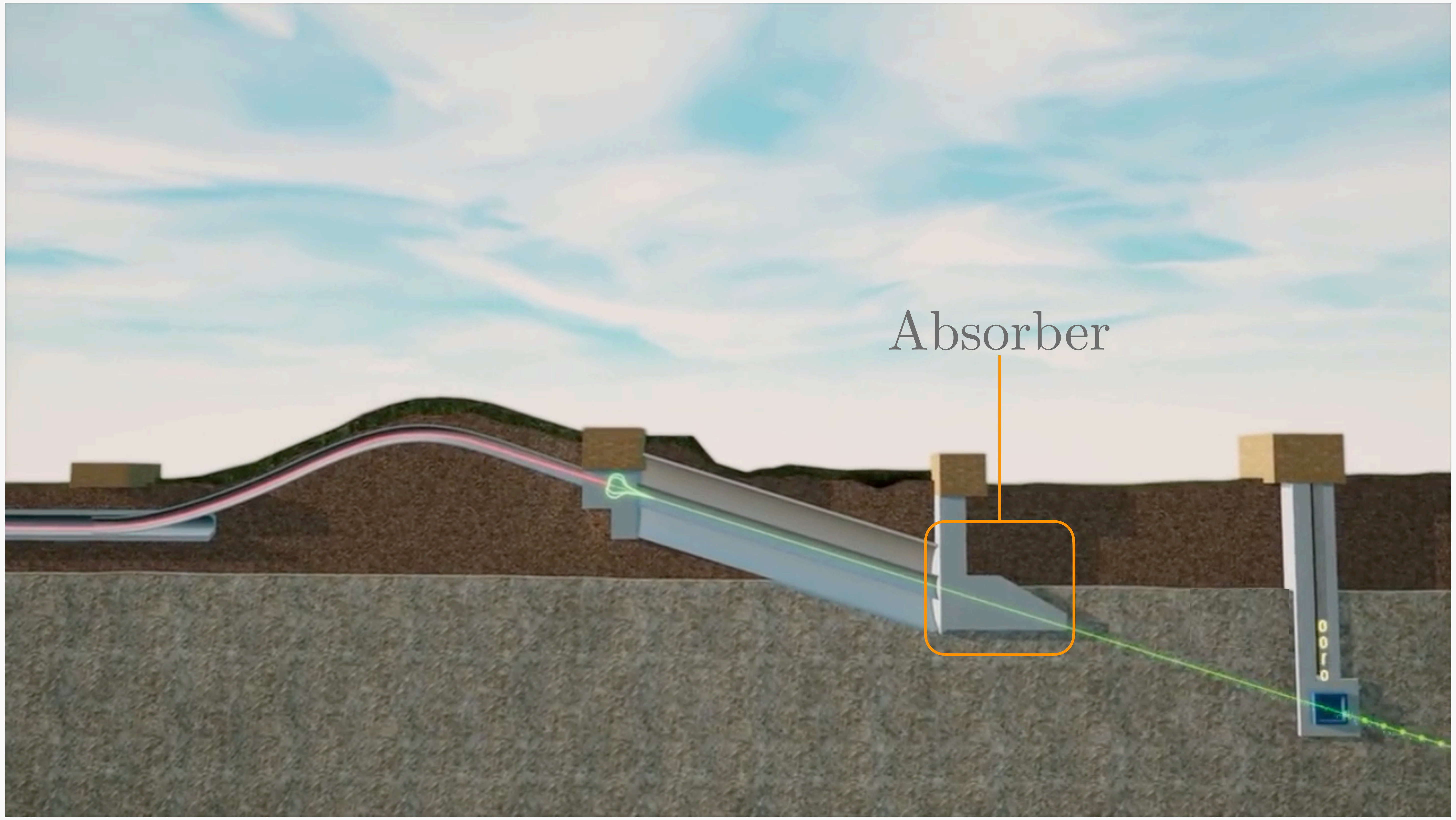

Introduction to HNL

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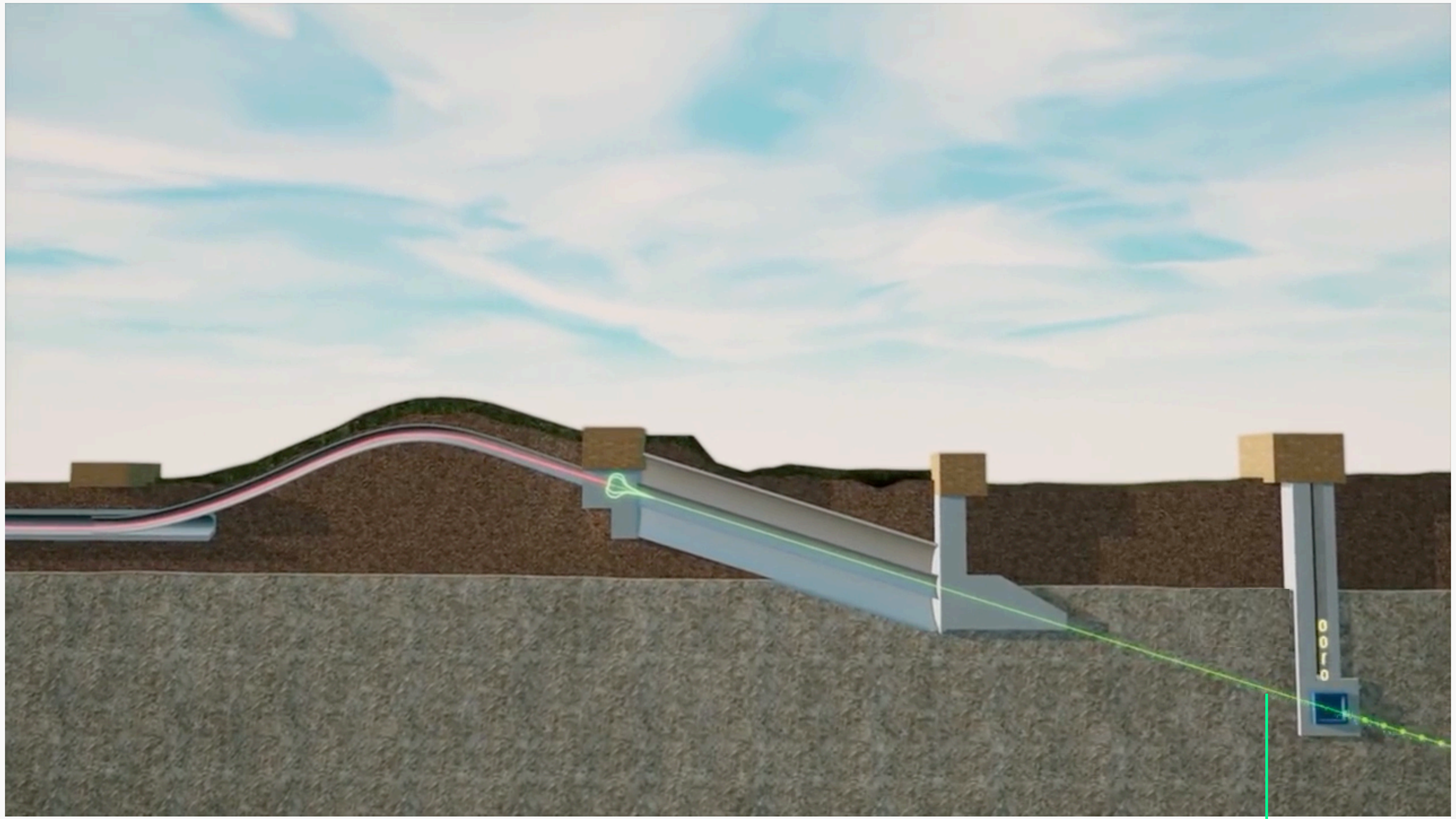

$\nu/\overline{\nu}$ beam

Introduction to HNL

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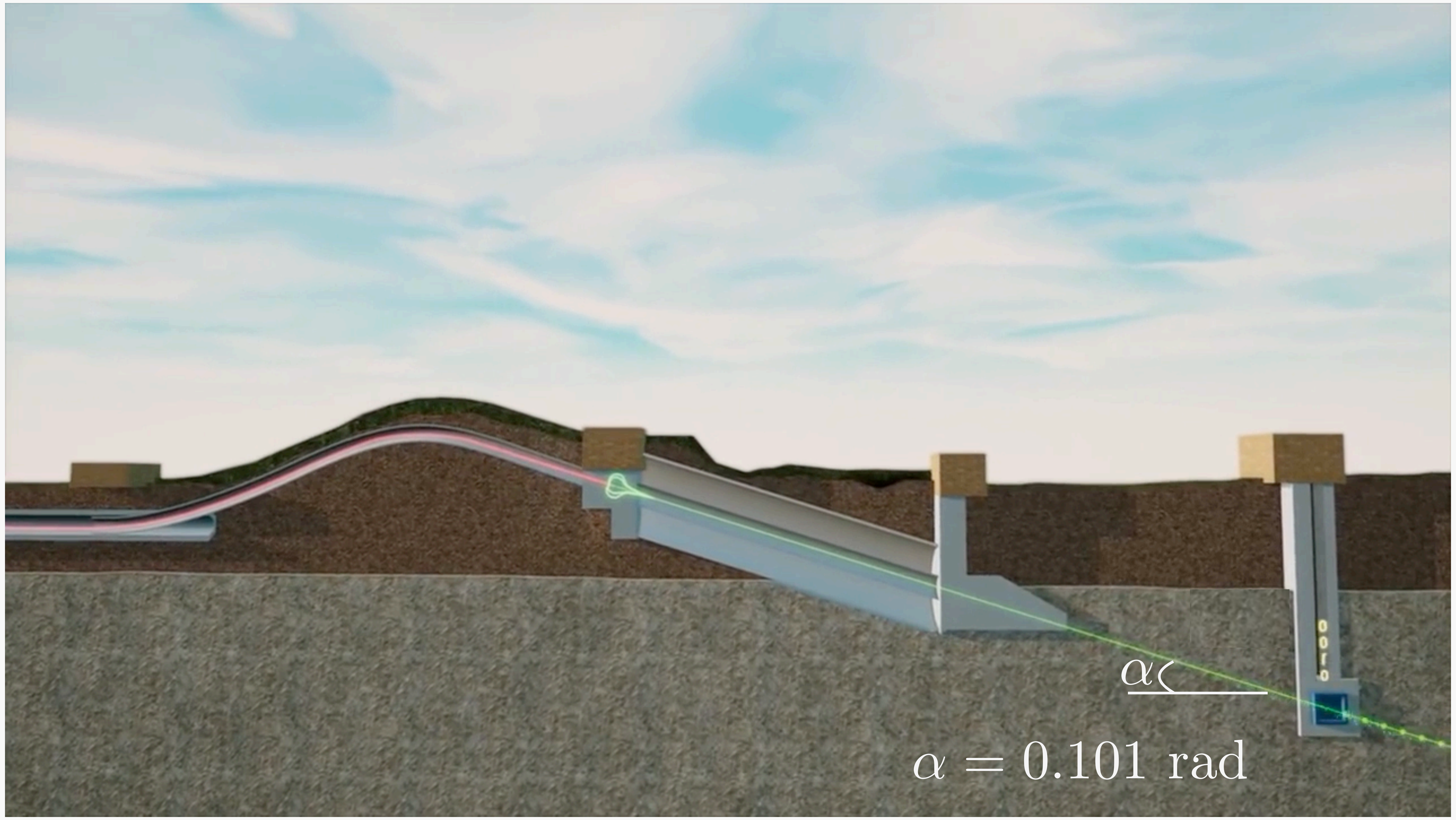
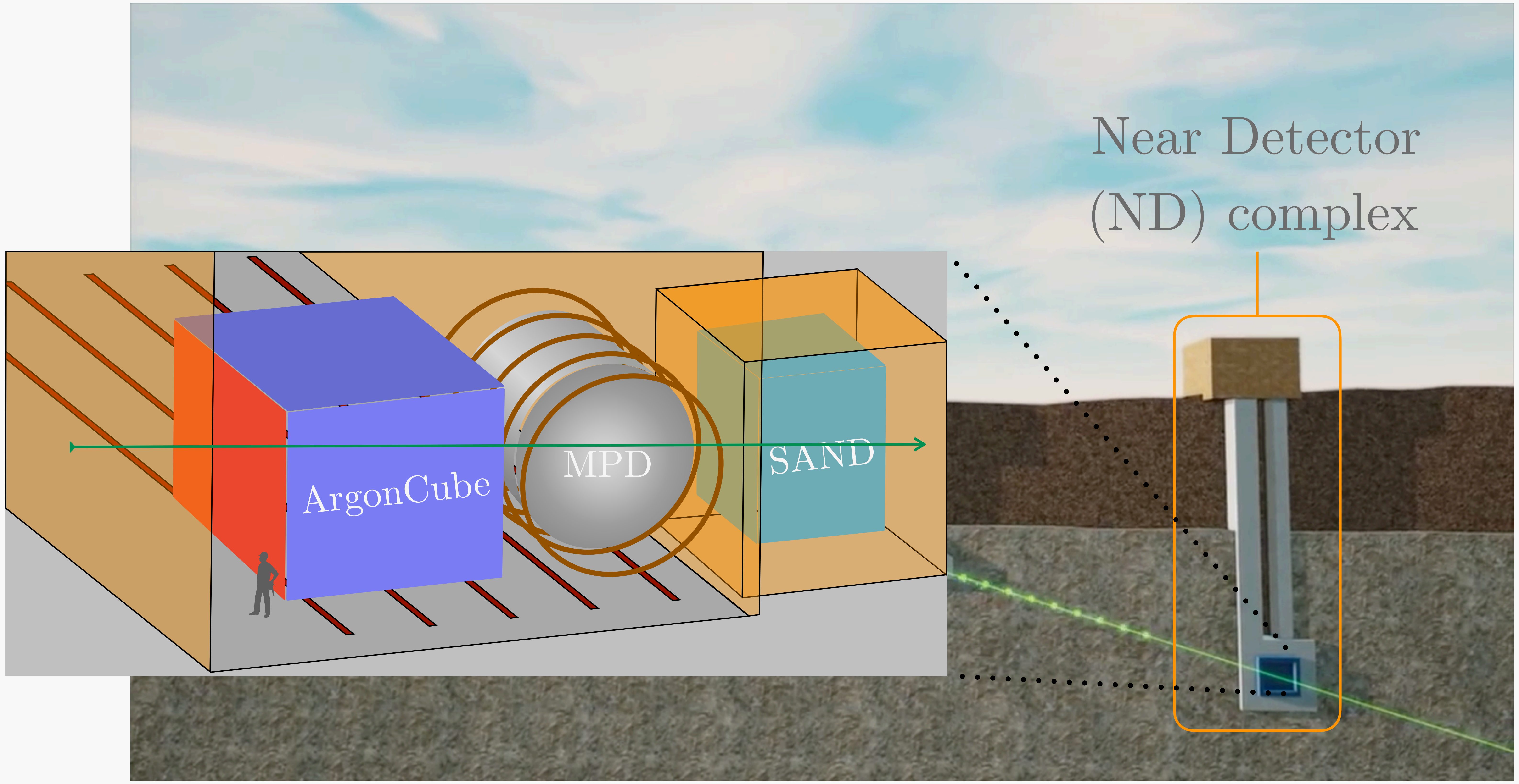


Introduction to HNL

zoom.us video



– ArgonCube: LArTPC rectangle of $(7, 3, 5)$ m
– MPD: HPgTPC + ECAL in a 0.5 T magnetic field cylinder of $(5, 5)$ m
– SAND: on-axis beam monitor

Introduction to HNL

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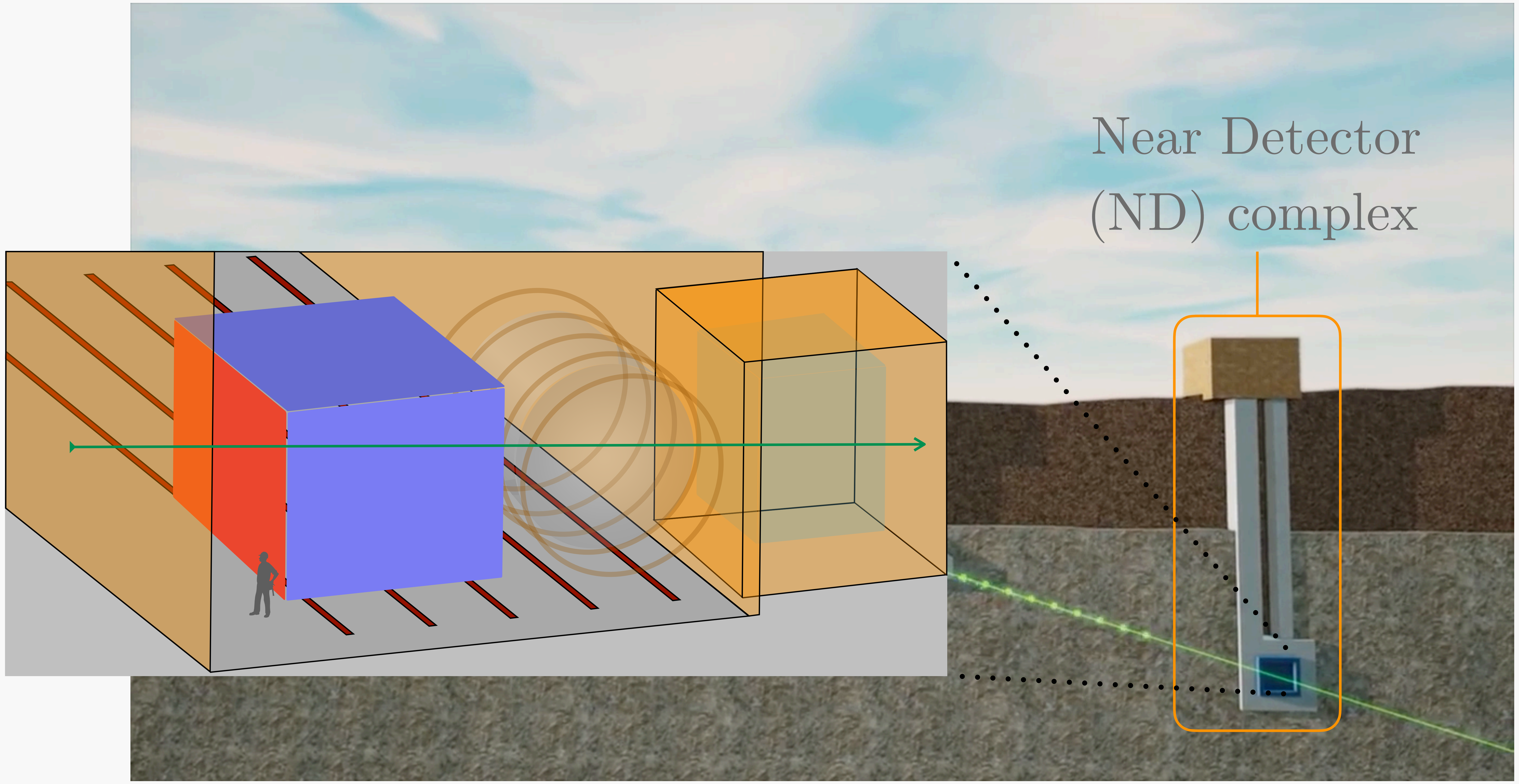
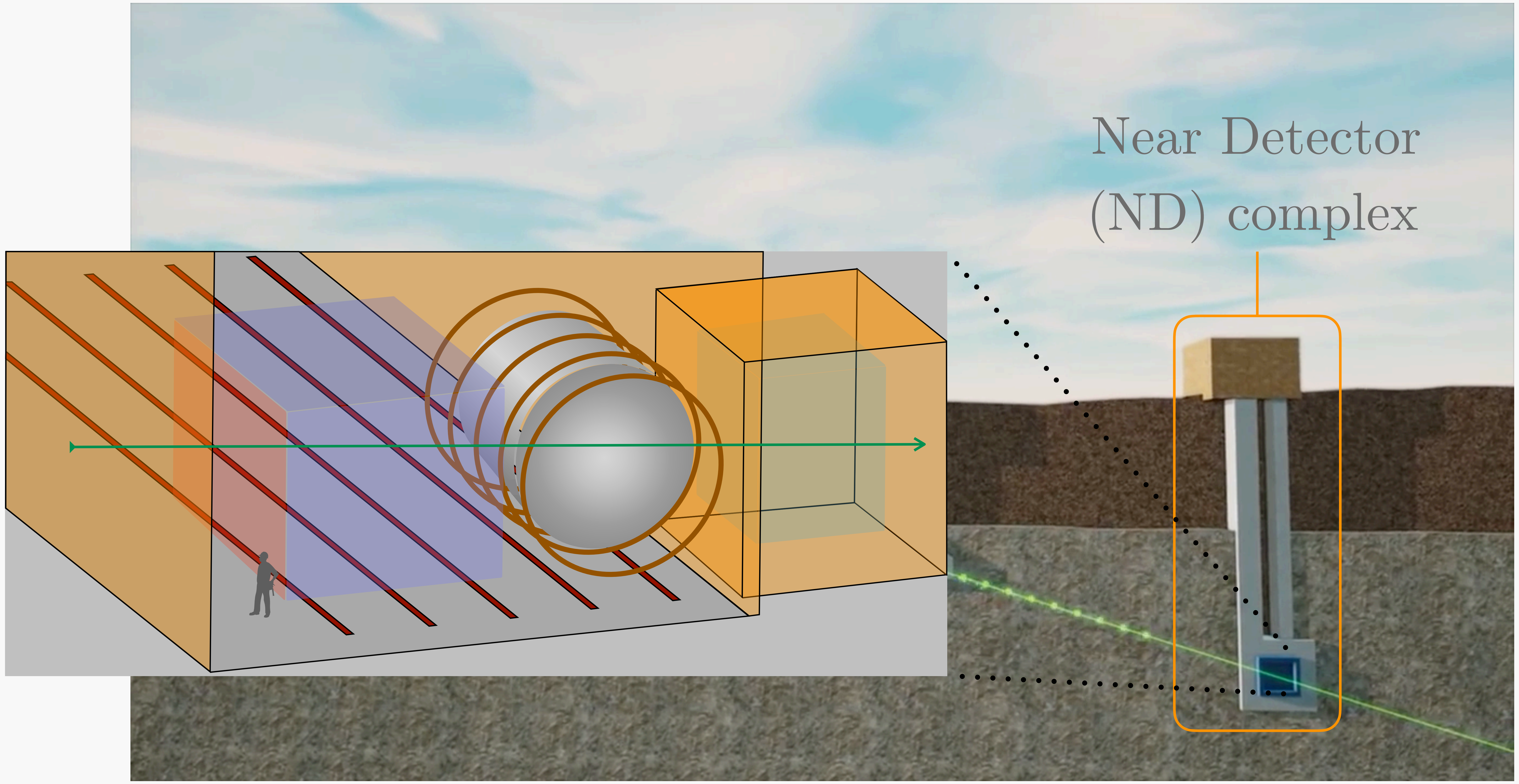


ArgonCube: LArTPC rectangle of $(7, 3, 5)$ m

Introduction to HNL

zoom.us video



MPD: HPgTPC + ECAL in a 0.5 T magnetic field cylinder of $(5, 5)$ m

Introduction to HNL

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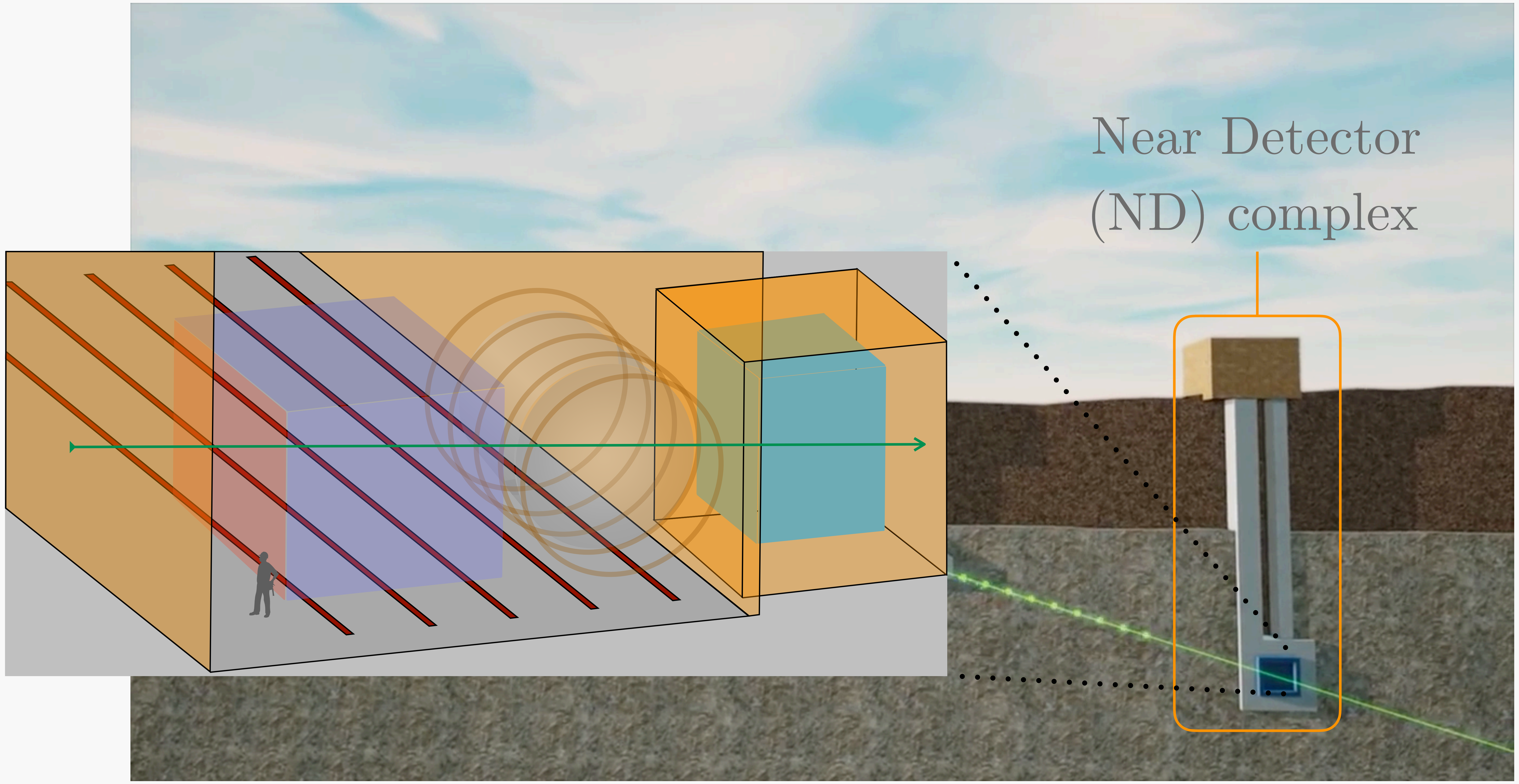
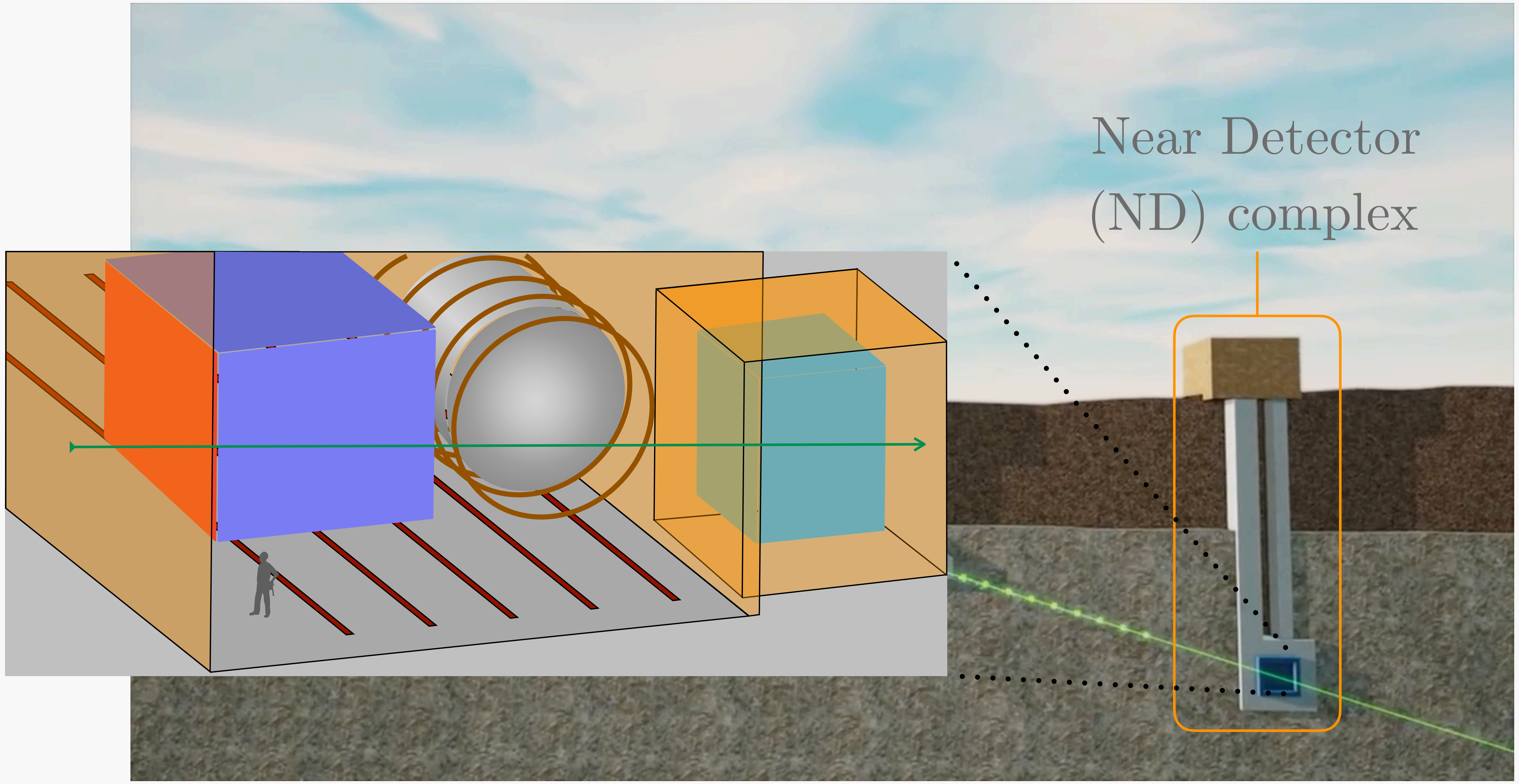


SAND: on-axis beam flux monitor

Introduction to HNL

zoom.us video



Off-axis measurements with ArgonCube + MPD $\Rightarrow$ (DUNE-PRISM)