# New limits on $W_R$ from meson decays


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FAPESP
FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

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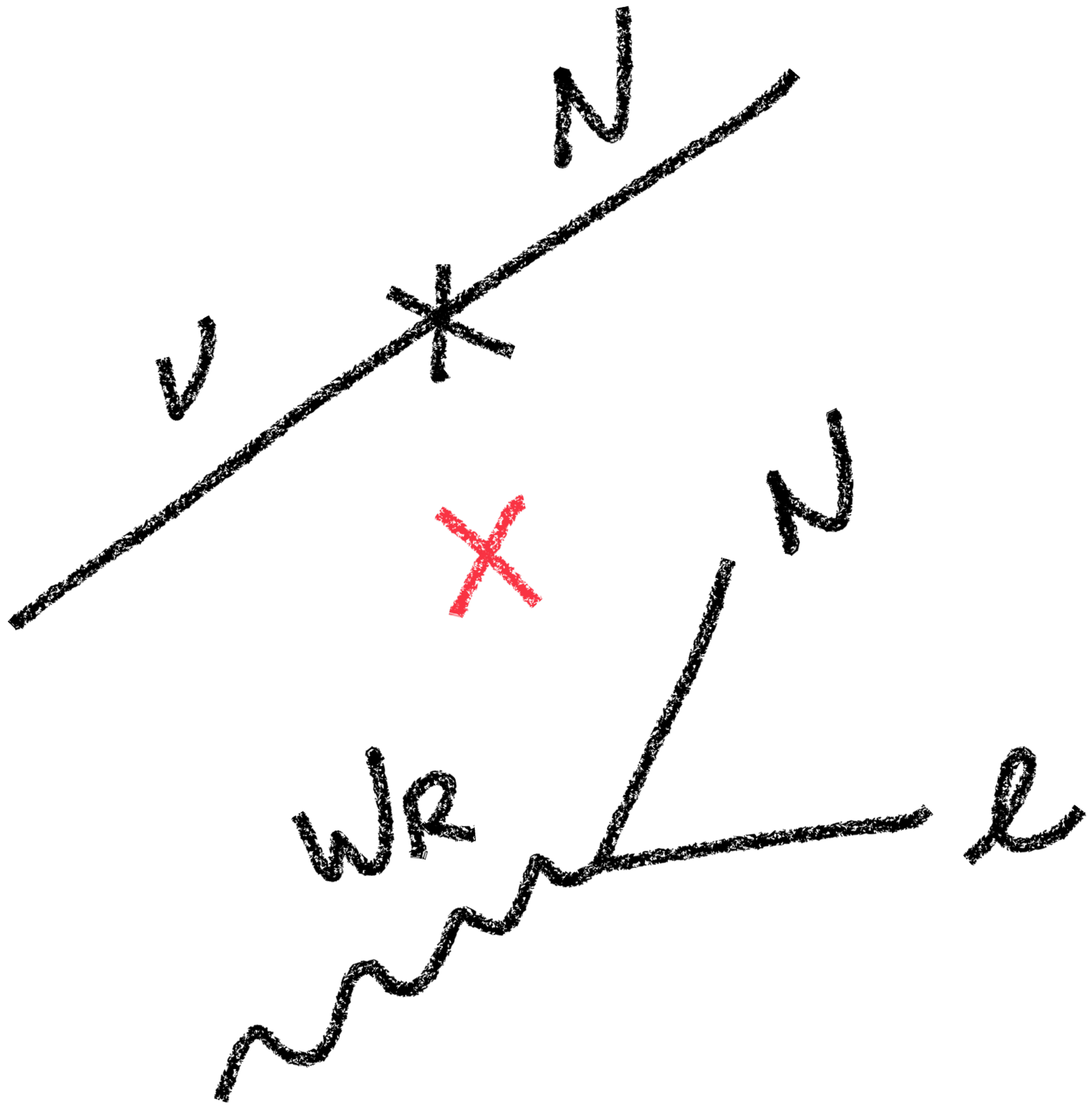
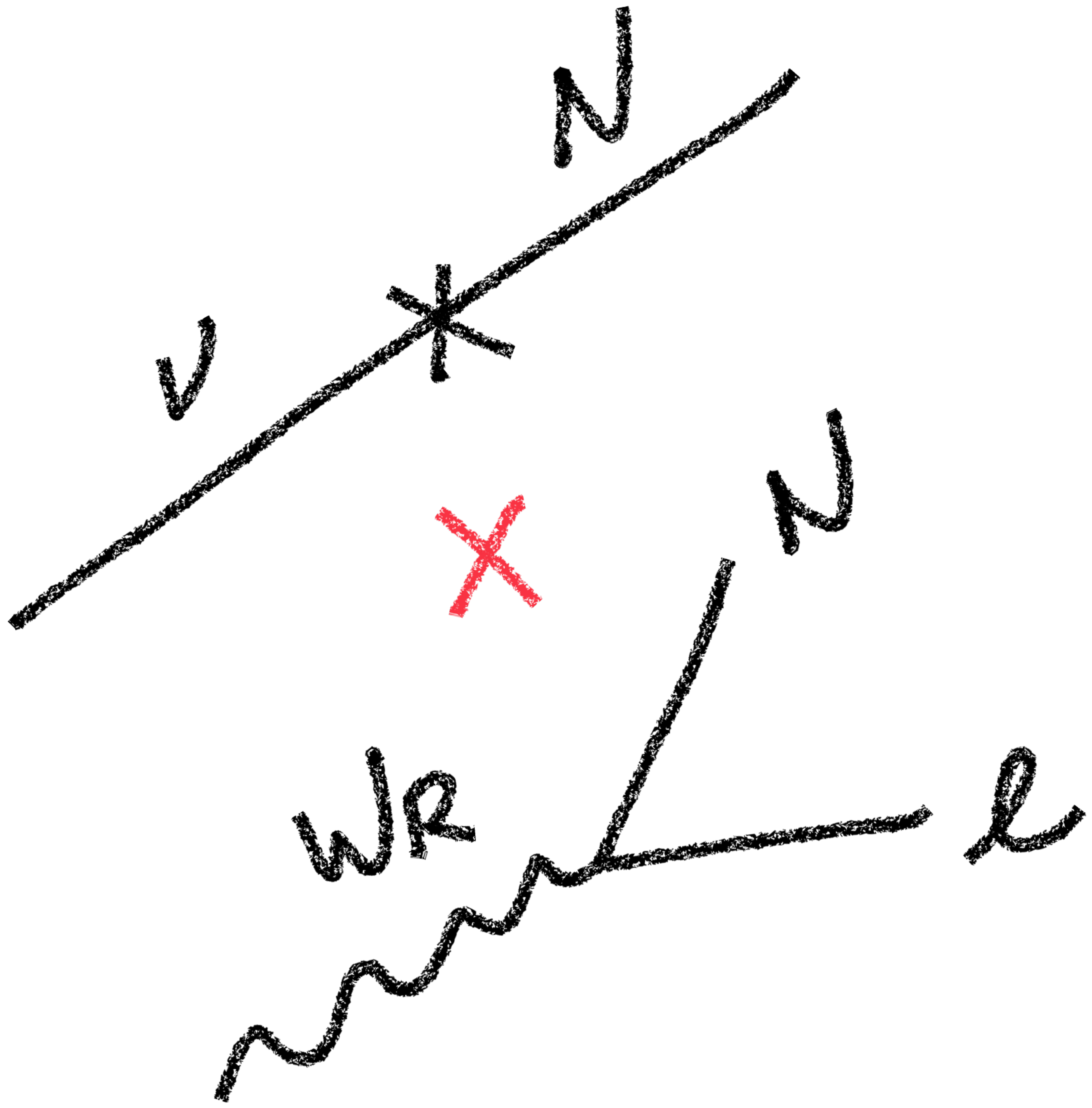
# Outline:

- Motivation
- From mixture to right handed currents
- HNL searches + reanalysis
- Results
- Conclusions



# Why RH currents?



# “V-A is the key”

- Weak interactions played a very important role to build the Standard Model (SM). Precisely, $\beta$-decays have:
  - Motivated a construction of a manifest parity-violating theory.
  - Hinted for new mediator scales.
- The status of the SM as a theory depends heavily on the V-A structure.
- That said, why is it parity violating?

S. Weinberg J. Phys. Conf. Ser. 196
C. S. Wu, E. Ambler, et al. Phys. Rev. 105, 1413
E. Fermi, Ric. Sc. 4, 491

# “Will V+A be the key?”

- The Left-Right Symmetric Model (LRSM) is one of the simplest and best motivated extensions of the SM. Based on

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

- Features:
  - Additional gauge bosons $W_R, Z_R$ - RH neutrinos are active under this sector!
  - Links parity violation of the SM to the breaking of the L-R symmetry.
  - Connects the point above to the generation of neutrino masses.

Pati and Salam, Phys. Rev. D 10, 275
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44
N. G. Deshpande, et. al, Phys. Rev. D 44
Senjanovic, arXiv:2011.01264

# Testing the RH scale: Portals for the RH neutrino

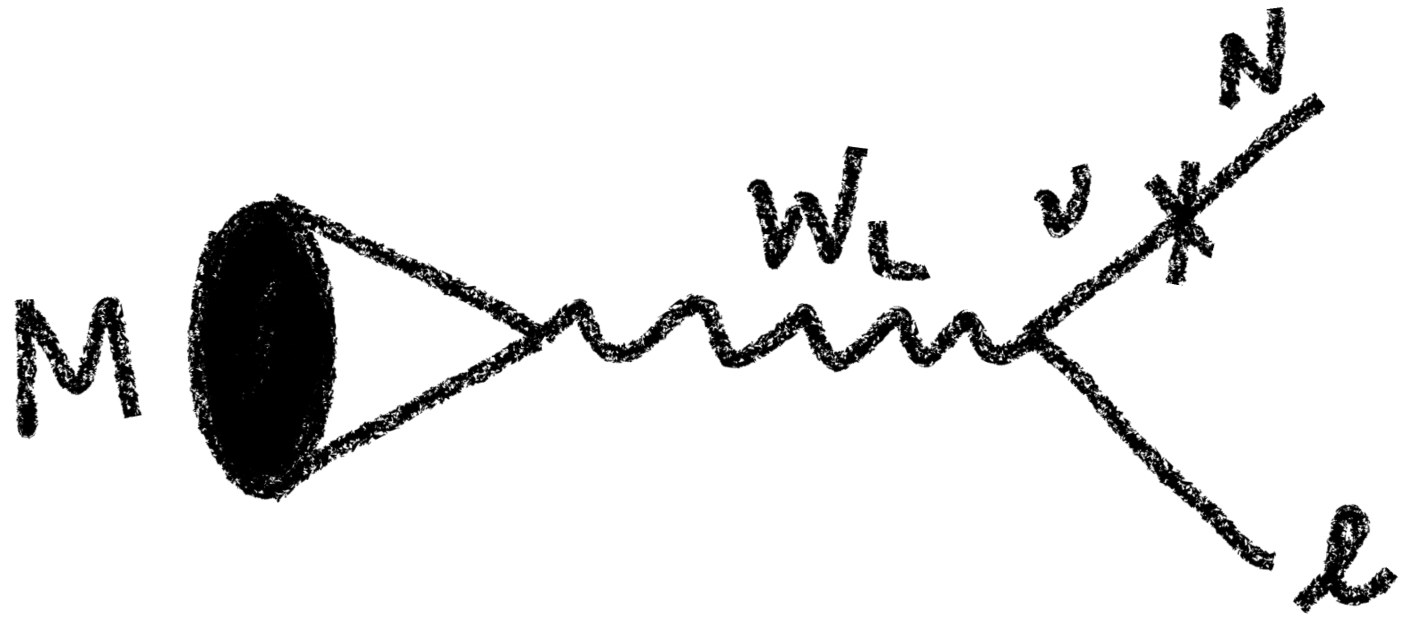
- The RH neutrino **is active** under the additional RH sector.

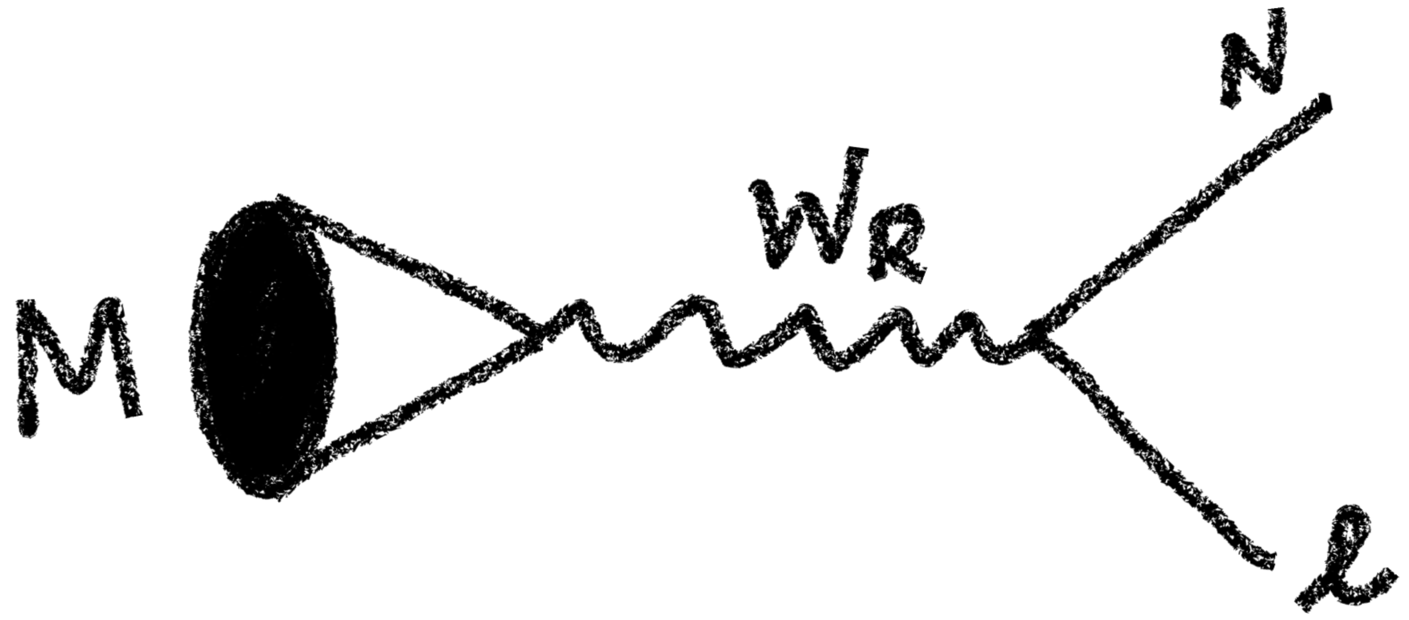
$$\mathscr{L}_R^{\mathrm{CC}} = -\frac{g_R}{\sqrt{2}}\left(\overline{N}U_{\mathrm{RR}}^{\dagger}\not{W}_R L_R + \overline{D}_R V_R^{\dagger}\not{W}_R U_R + \mathrm{h.c.}\right)$$

- This furnishes an **additional portal** that may compete with the production via mixture.

- We will assume a **degenerate spectra** for N such that $U_{RR}$ drops out.

$$\Gamma(M \to lN) = (G_F^2 |U_{lN}|^2 + (G_F')^2) f(m_M, m_l, m_N)$$






Senjanovic and Tello, arXiv:1408.3835

# Can the RH current dominate production?

- The active-sterile mixture depends on the mass generation mechanism.
- Benchmark scenario: LR model with a bidoublet and two scalar triplets.
  - We have type I and II seesaw contributions. Neutrino masses and mixings given by:

$$m_\nu = \underbrace{M_L^\dagger}_{m_{II}} - \underbrace{M_D M_R^{-1} M_D^T}_{m_I} \qquad |U_{lN}|^2 \sim m_I m_R^{-1}$$


J. Barry and W. Rodejohann, arXiv:1303.6324.
P. S. Bhupal Dev, S. Goswami, and M. Mitra, arXiv:1405.1399.
G. Bambhaniya, P. S. B. Dev, S. Goswami, and M. Mitra, arXiv:1512.00440.
S. Goswami and K. N. Vishnudath, arXiv:2011.06314.
D. Borah and A. Dasgupta, arXiv:1606.00378.
V. Tello, M. Nemevsek, F. Nesti, G. Senjanovic, and F. Vissani, arXiv:1011.3522.
G. Li, M. Ramsey-Musolf, and J. C. Vasquez, arXiv:2009.01257.

# Can the RH current dominate production?

- Competing contributions:

$$G_F^2 |U_{lN}|^2 \times (G_F')^2$$

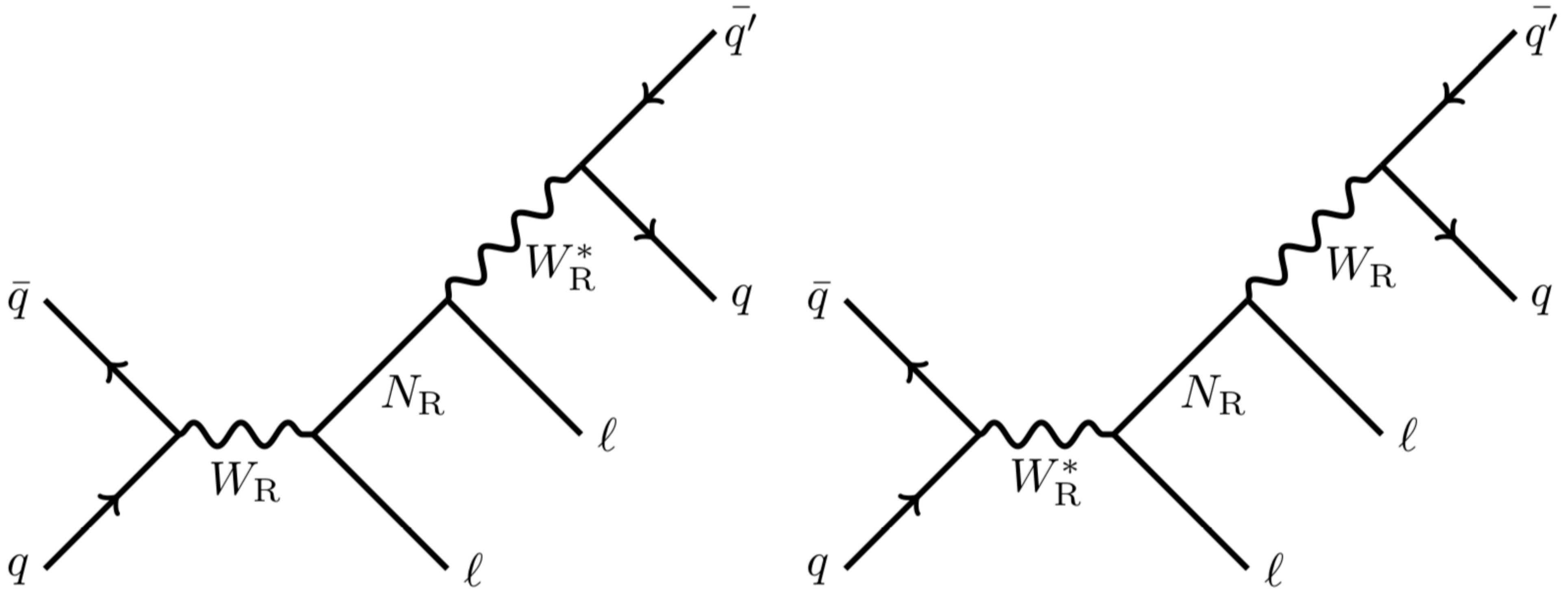
- For type I dominance we would have to satisfy:

$$m_\nu < 7 \times 10^{-2}\ \mathrm{eV} \left(\frac{\mathrm{m_N}}{1\ \mathrm{MeV}}\right)\left(\frac{5\ \mathrm{TeV}}{\mathrm{m_{W_R}}}\right)^4 \left(\frac{\mathrm{g_R}}{\mathrm{g_L}}\right)^4$$

- For type II mixing is always subdominant.

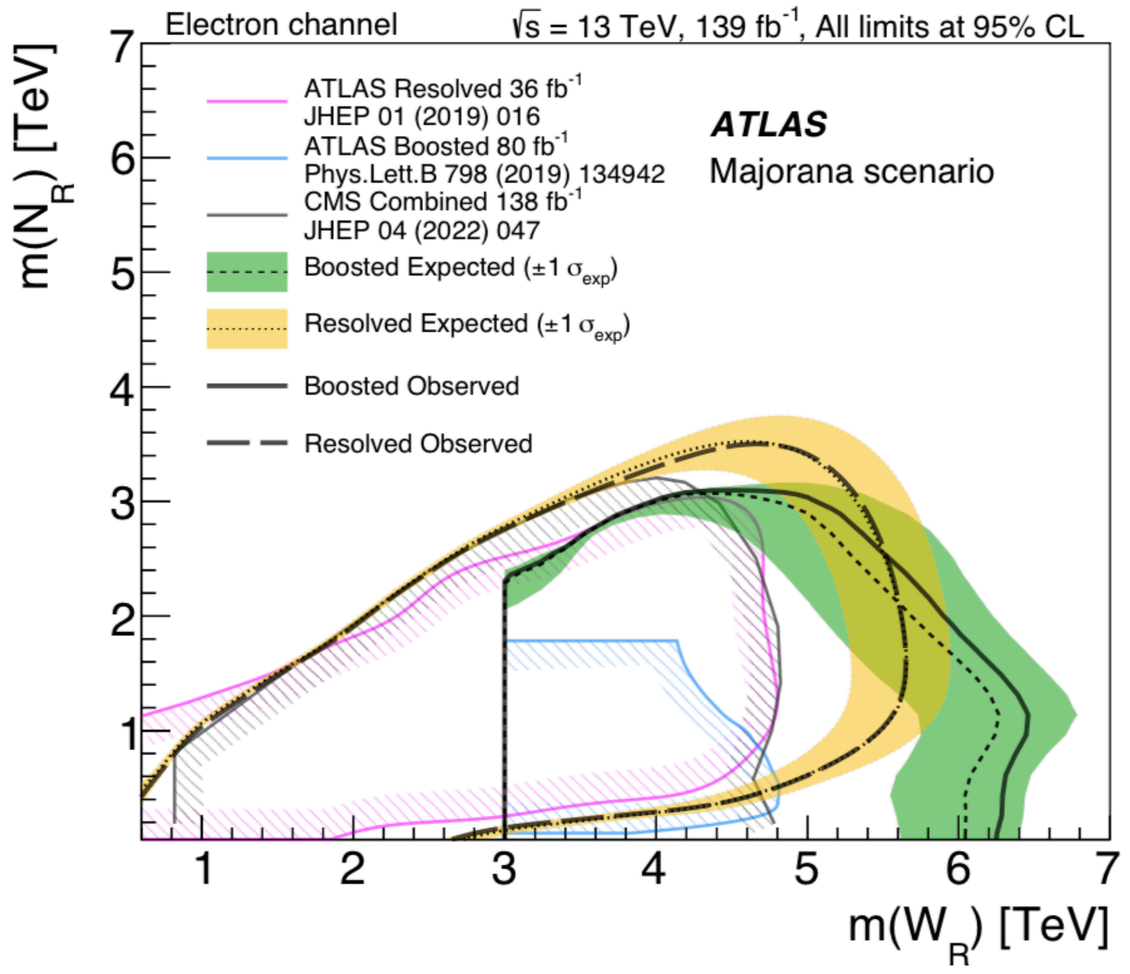
# Example: LHC constraints on $W_R$

- Searched for the Keung-Senjanovic process.

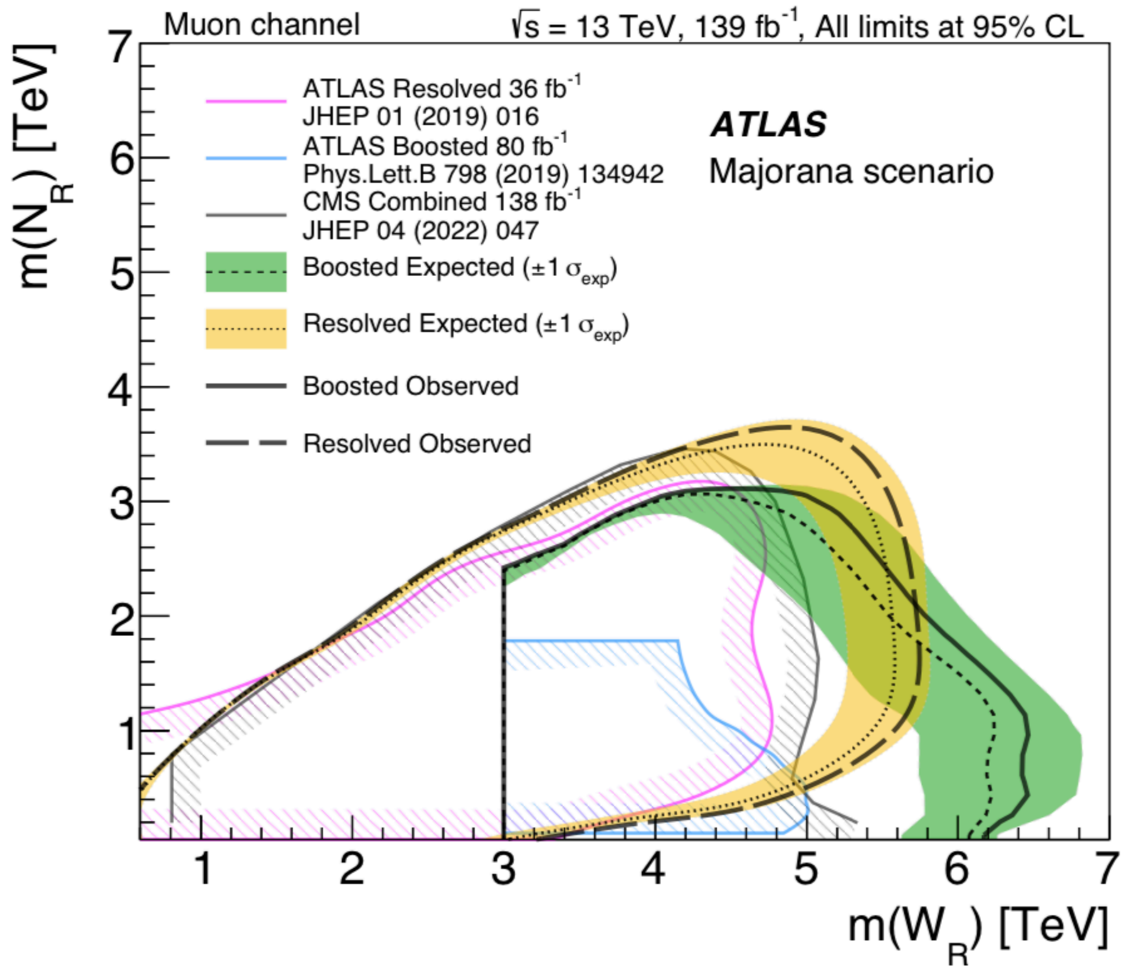



- Their bound extends up to $m_{W_R} > 6.4\ \mathrm{TeV}$, for HNLs in the GeV-TeV mass range.

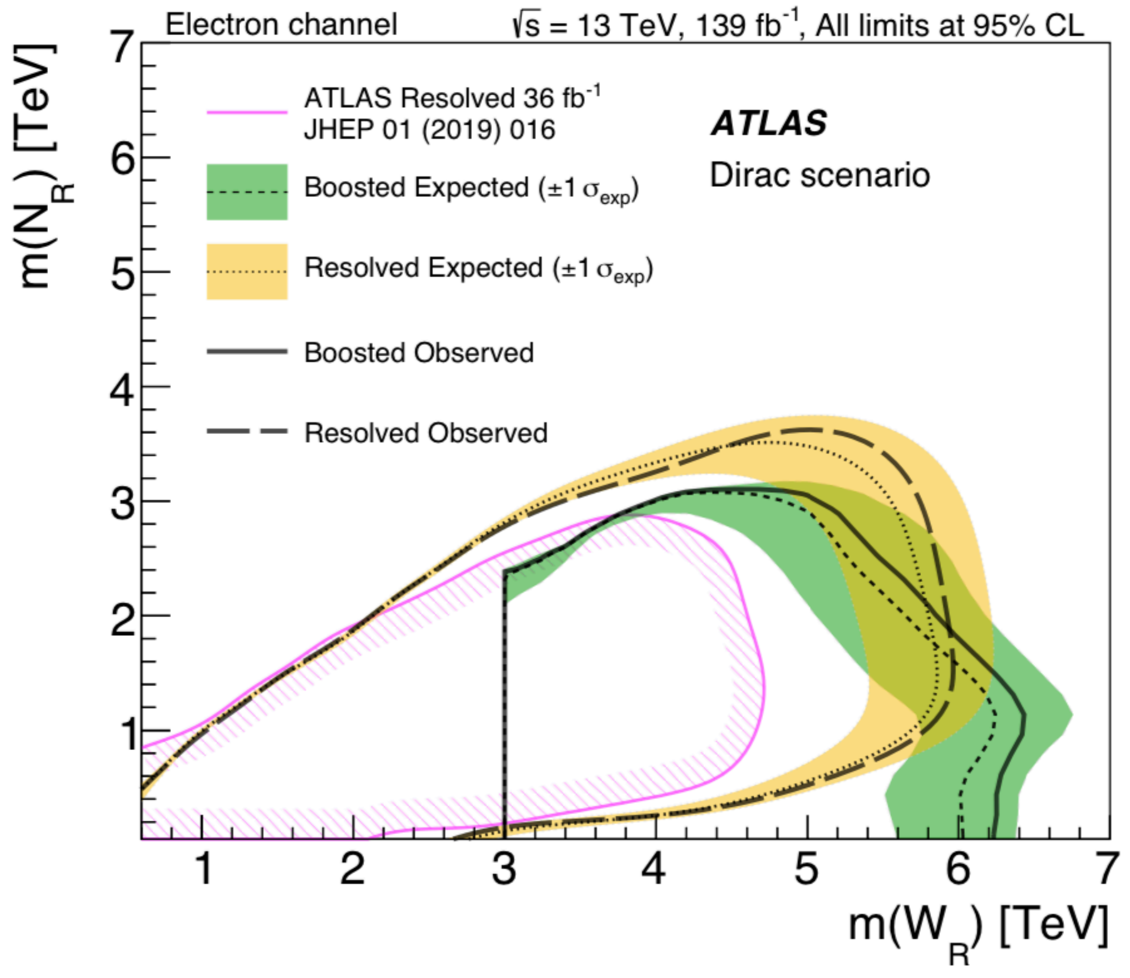
ATLAS, arxiv:2304.09553



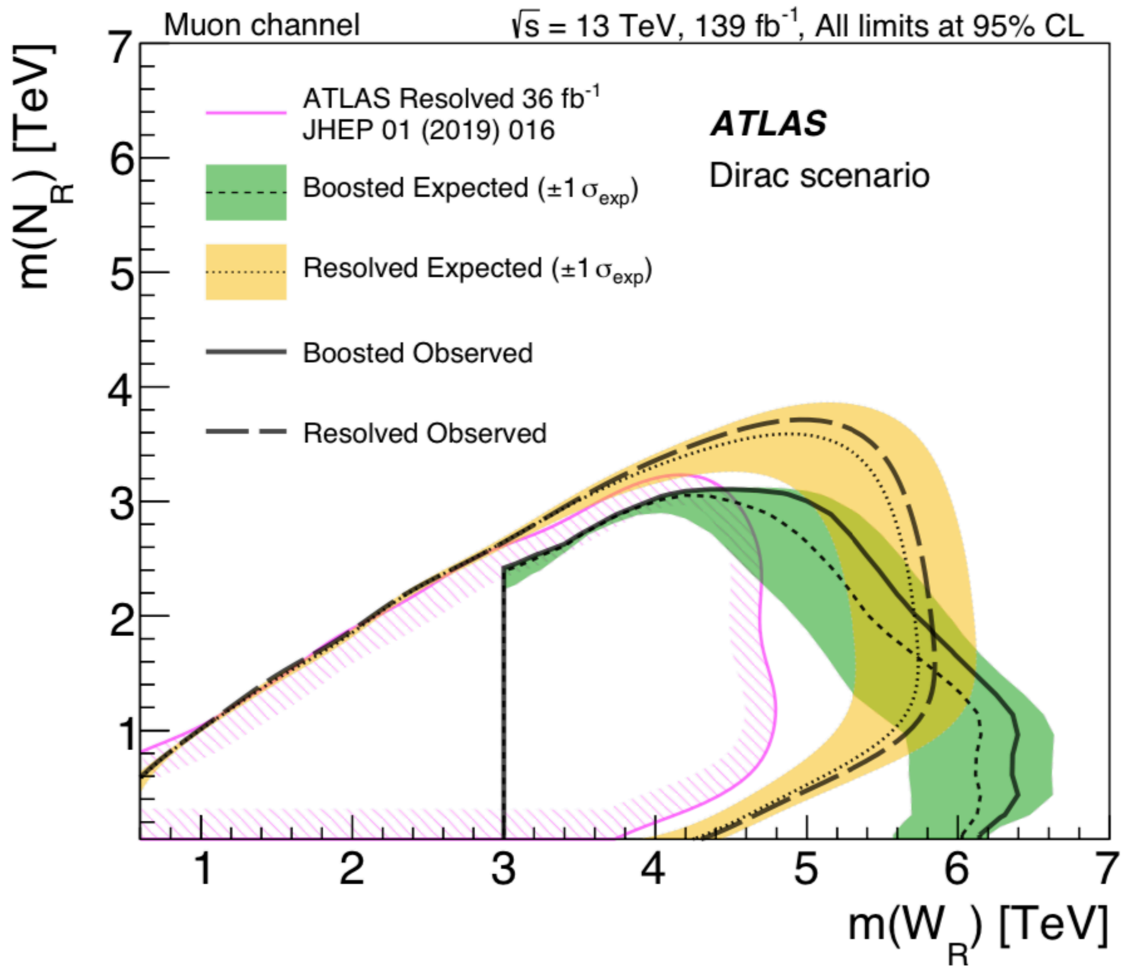
(a)



(b)

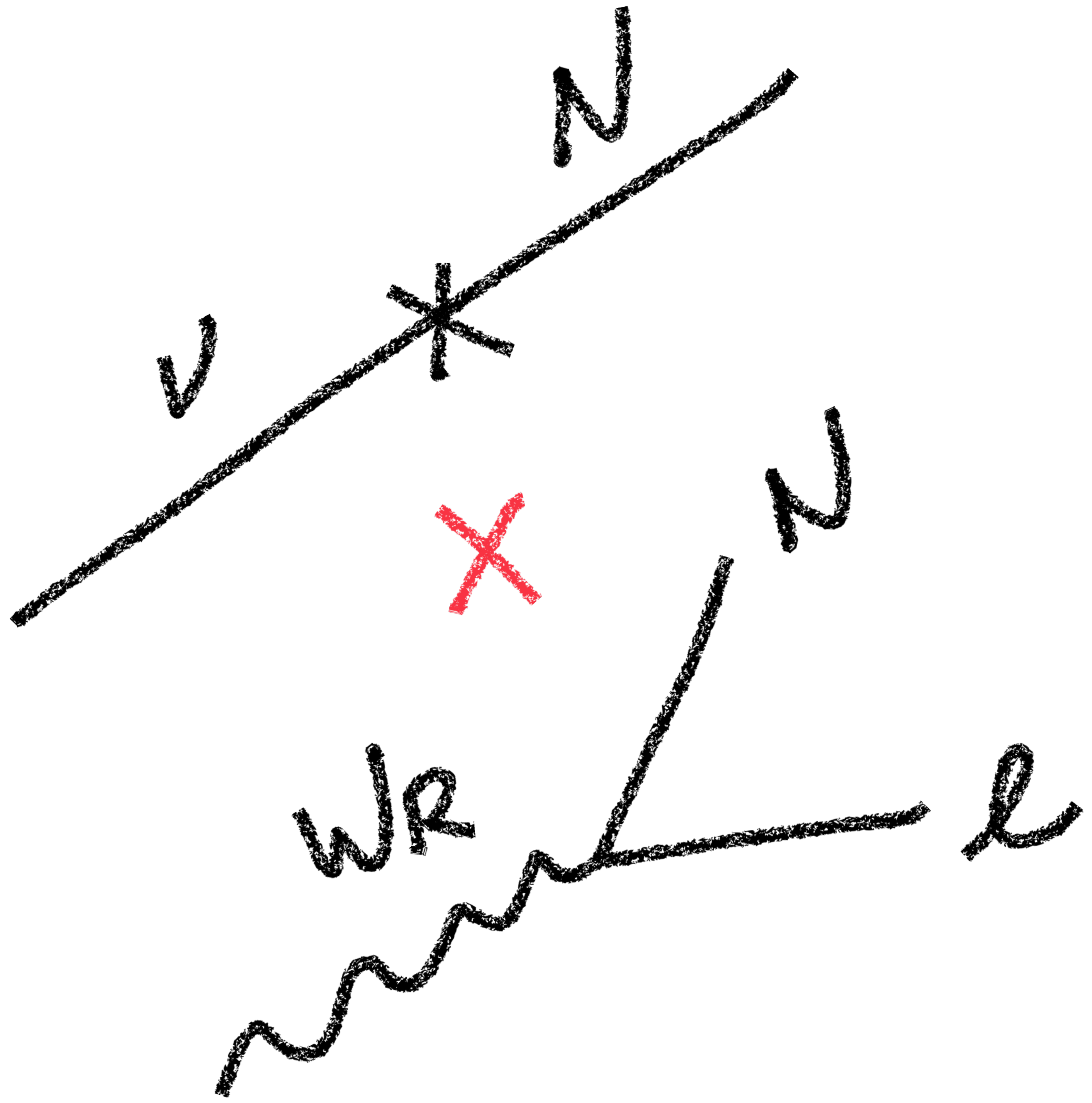


(c)



(d)

# Reanalysis of HNL searches

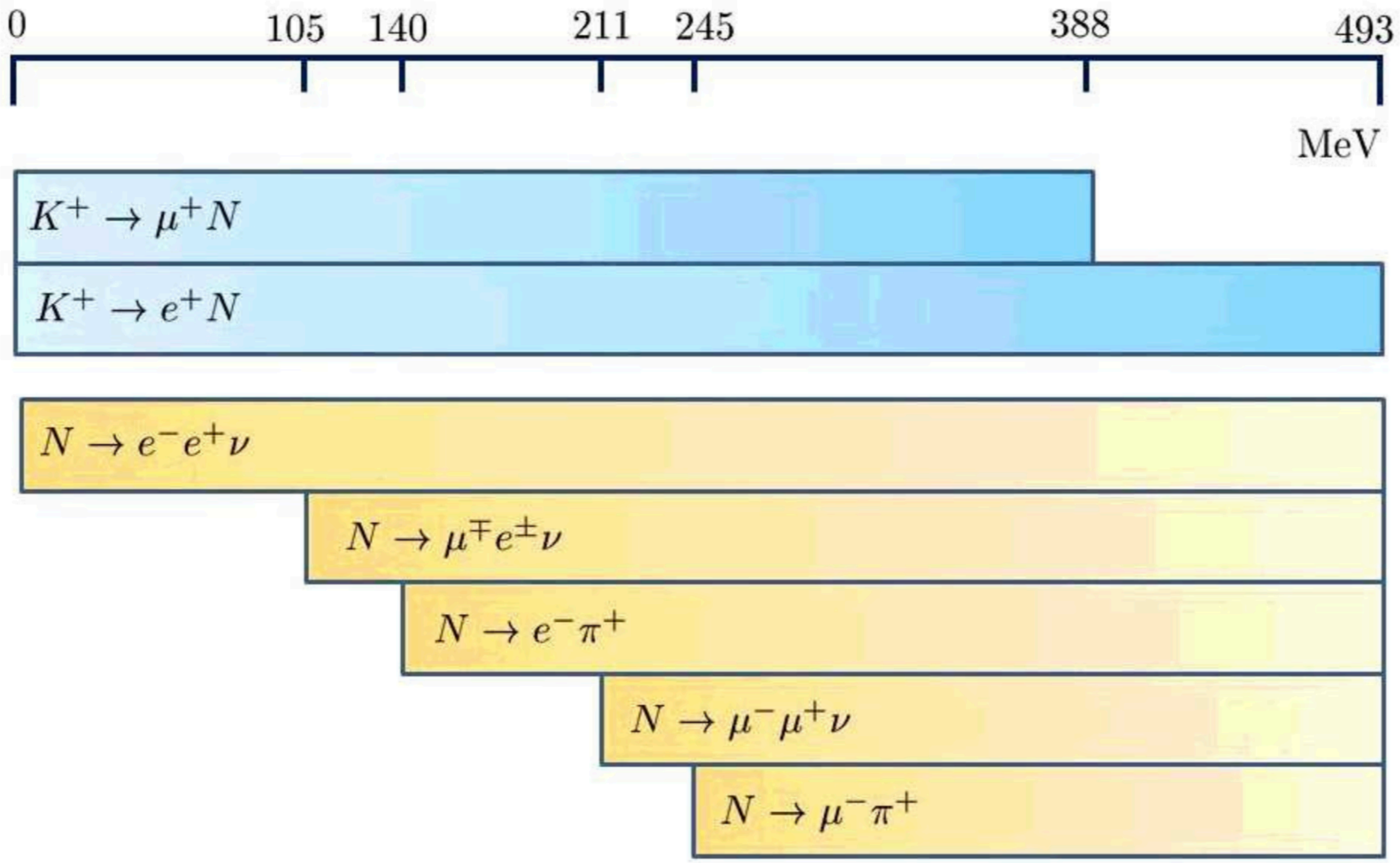


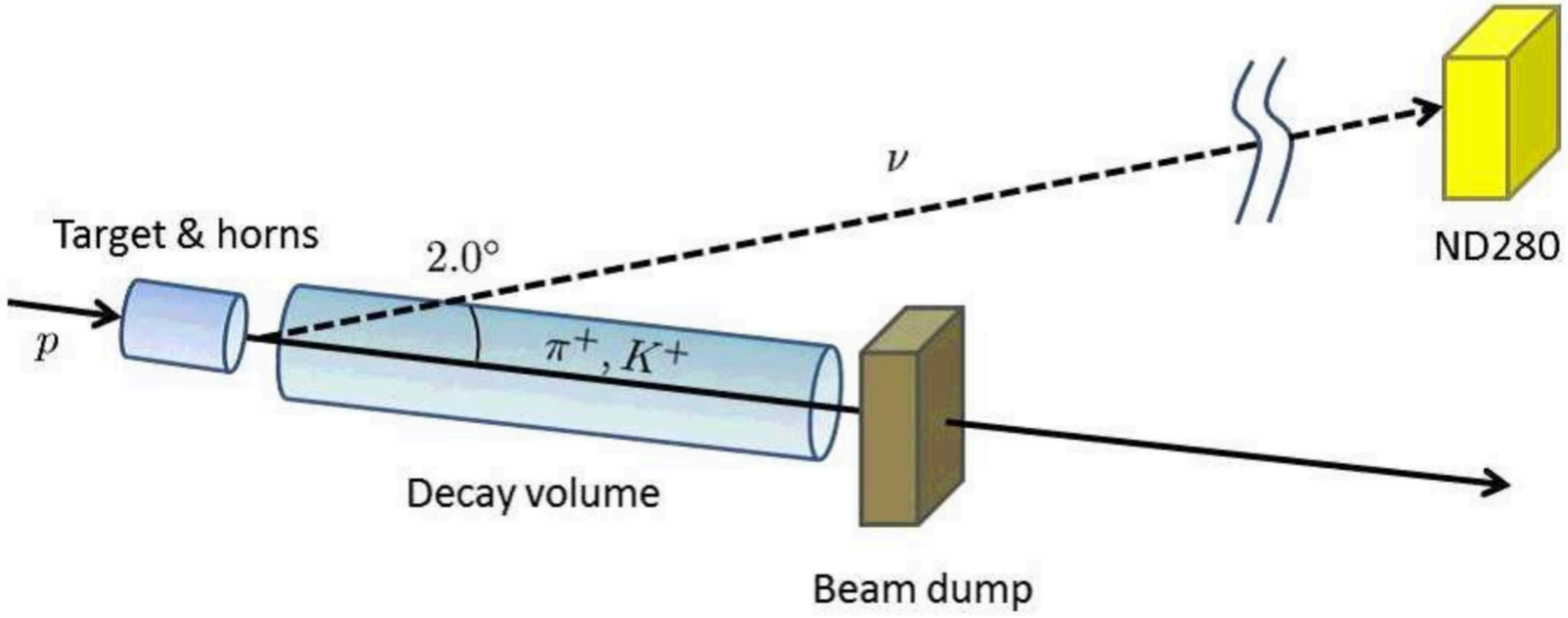
# HNL searches at the MeV scale

- Primary mode of production inherited from the light neutrino production mode. Types of searches:
  - **Visible searches**: Heavy neutrinos decay into visible particles.
  - **Invisibles searches**: Use energy distribution of the measured particles.
  - **Decay ratios**: Rate of meson decays change in the presence of a massive neutrino.

# Visible searches

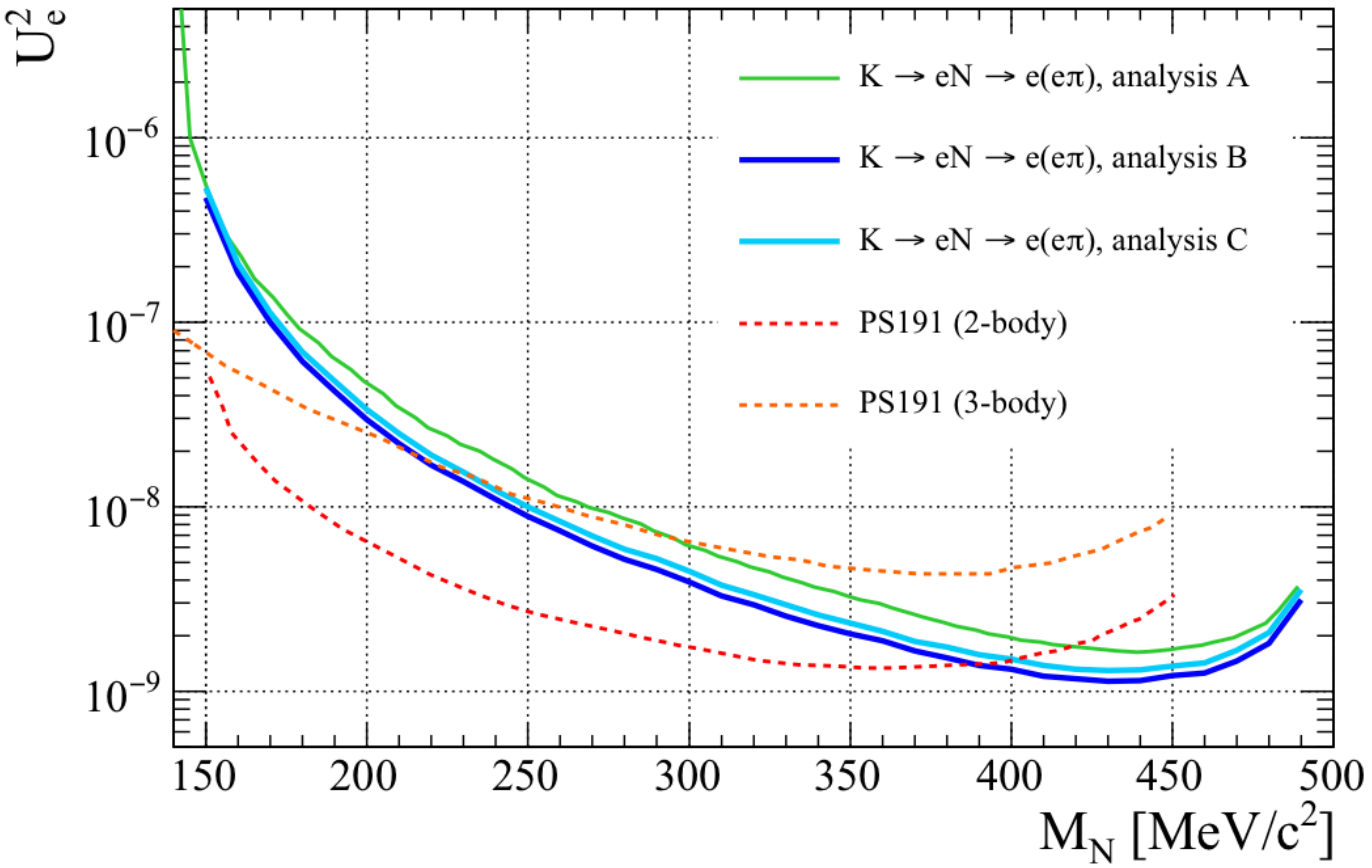
- Look for visible decays of heavy neutral leptons.
- Example: T2K ND280.




Abe et. al, arXiv:1902.07598
Asaka et. al., arXiv:1212.1062

# T2K ND280 search

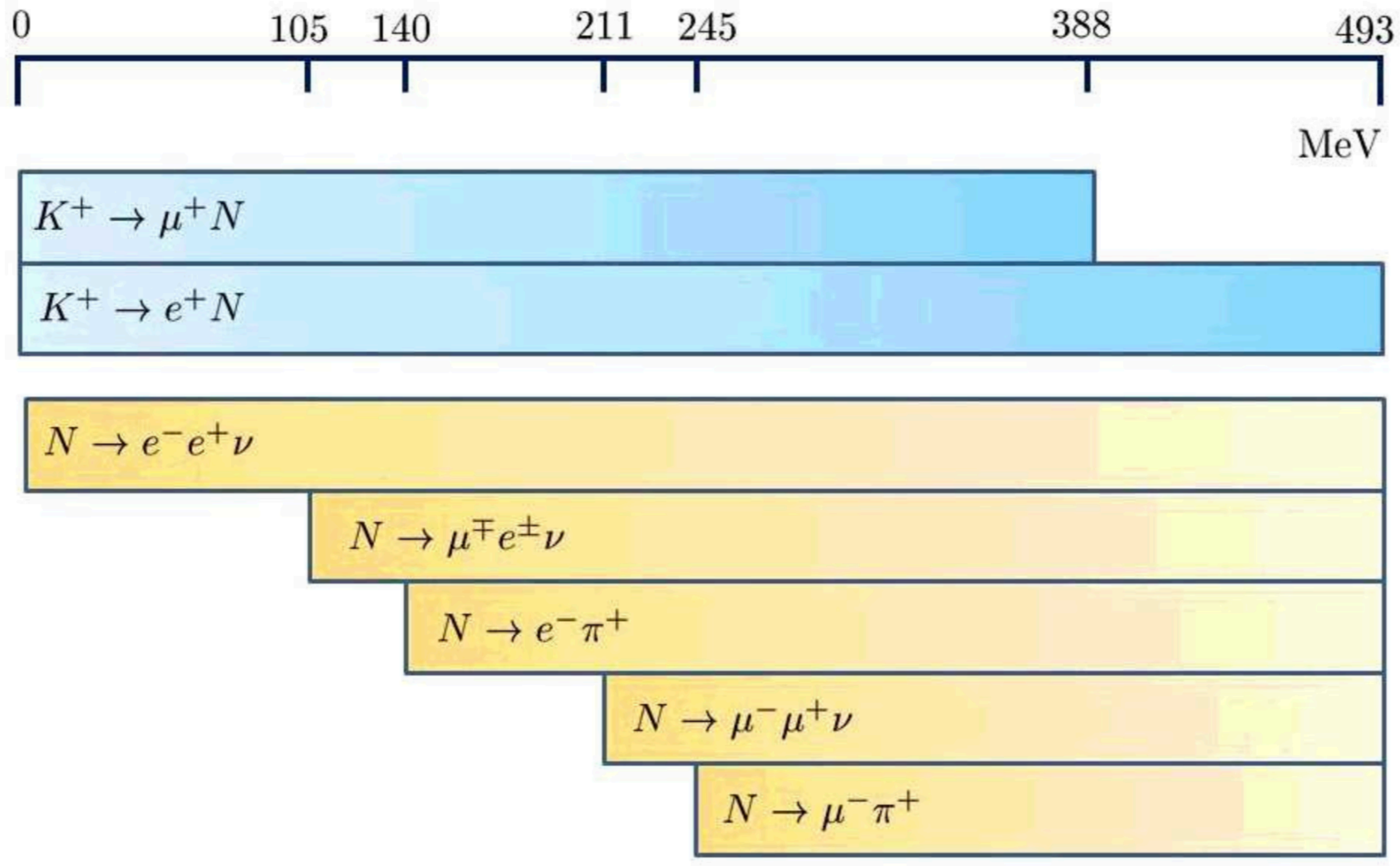



Abe et. al, arXiv:1902.07598

# Reanalysis for RH current dominance

**To Do:**

- ☐ Are all production channels available?
- ☐ Phase space and kinematics implemented accordingly?
- ☐ Detection channels available?




Abe et. al, arXiv:1902.07598
Asaka et. al., arXiv:1212.1062

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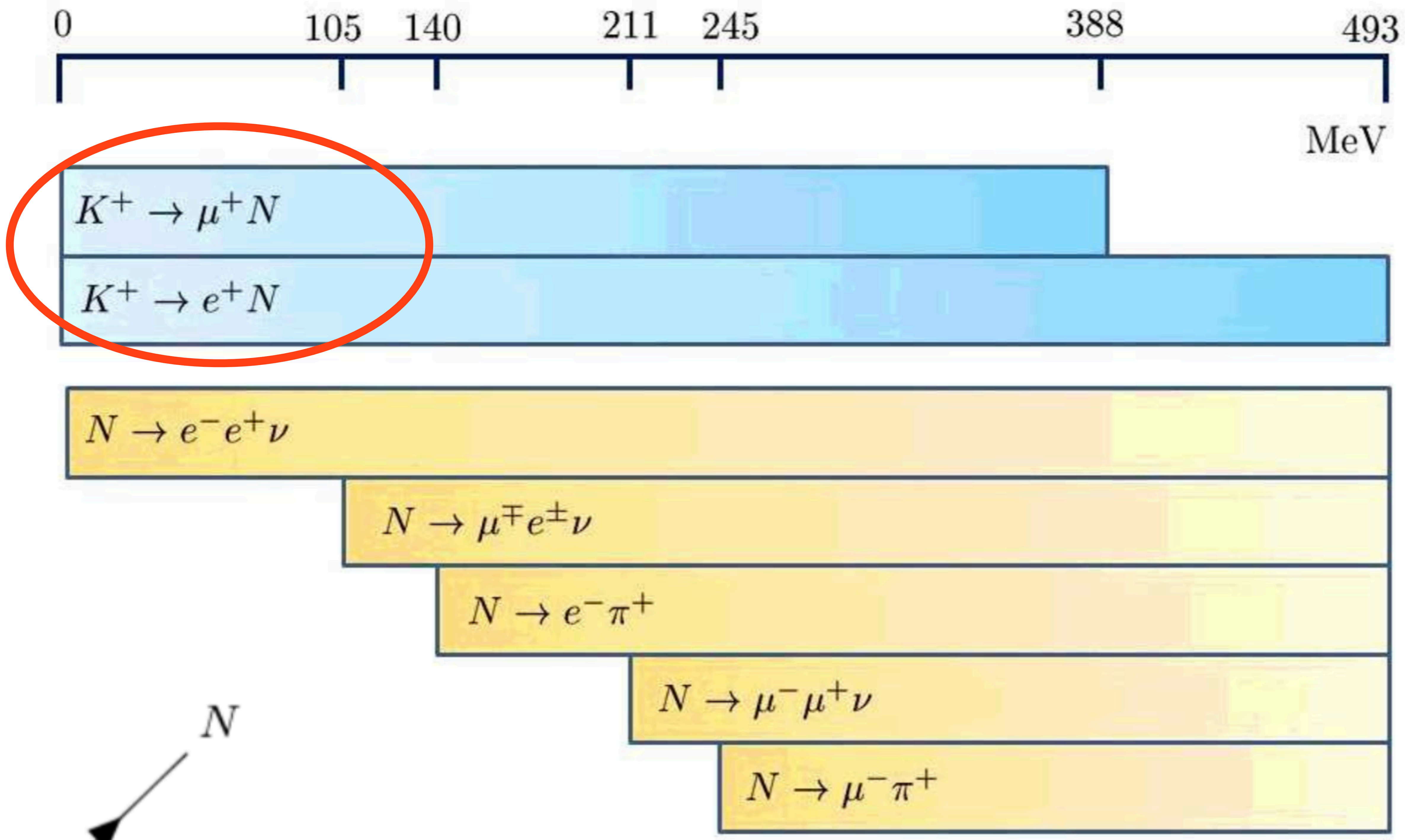


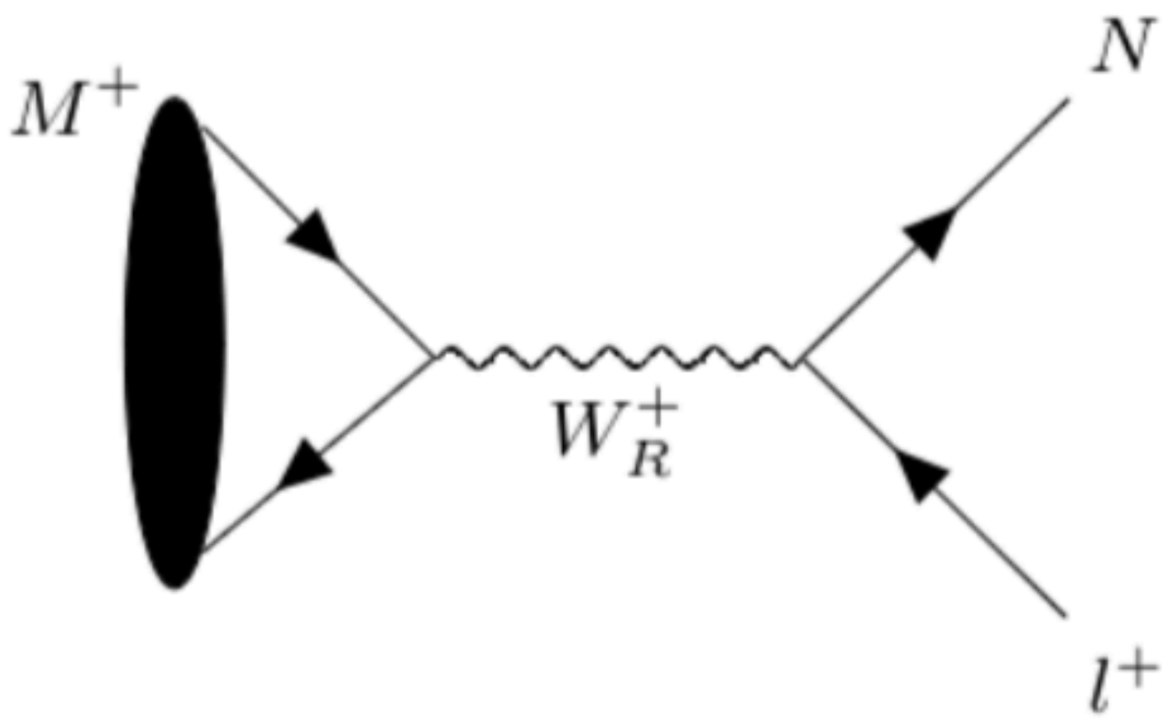


Abe et. al, arXiv:1902.07598
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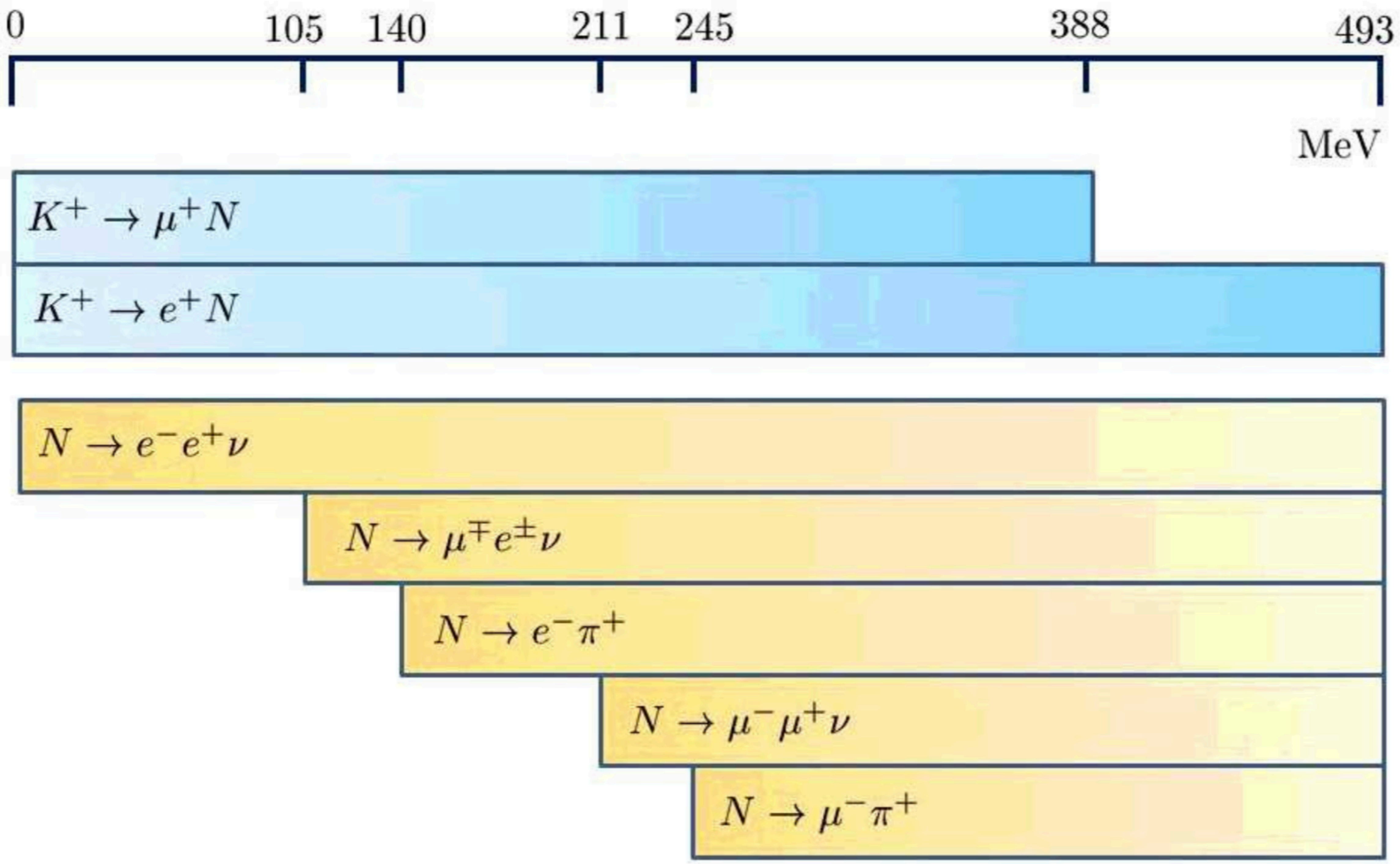



Abe et. al, arXiv:1902.07598
Asaka et. al., arXiv:1212.1062

# Analytical approach to the T2K SM neutrino flux

- Input: Parametrization for the Kaon spectra.

$$\phi_K(p_K)$$

- Define the light neutrino source term:

$$S_\nu(E_\nu, \theta, \phi, l) = \int_0^\infty dp_K \phi_K(p_K) e^{-\frac{l}{\Lambda}} \left(\frac{m_K}{p_K}\right) \frac{d^3\Gamma_{K\to\nu_\mu\mu}}{dE_\nu d\cos\theta d\phi}$$

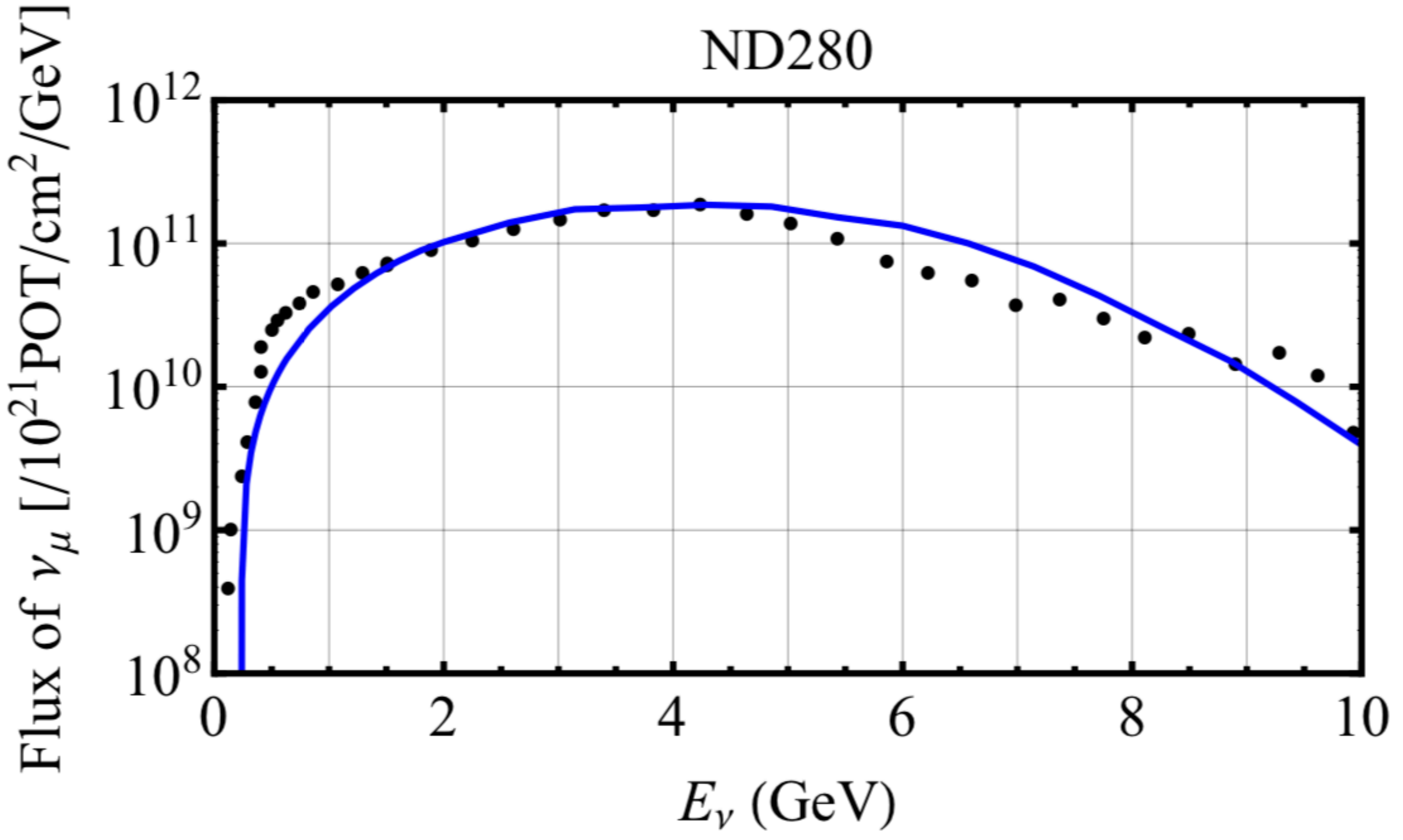
Asaka et. al., arXiv:1212.1062

# Analytical approach to the T2K SM neutrino flux

- Light neutrino Flux:

$$\phi_\nu(E_\nu) = \int_0^{L_B} dl \int_{-1}^{1} d\cos\theta \int_0^{2\pi} d\phi \frac{1}{A} S_\nu(E_\nu, \theta, \phi, l) P(\theta, \phi)$$

- Fit the Kaon spectra using the experimental simulation.



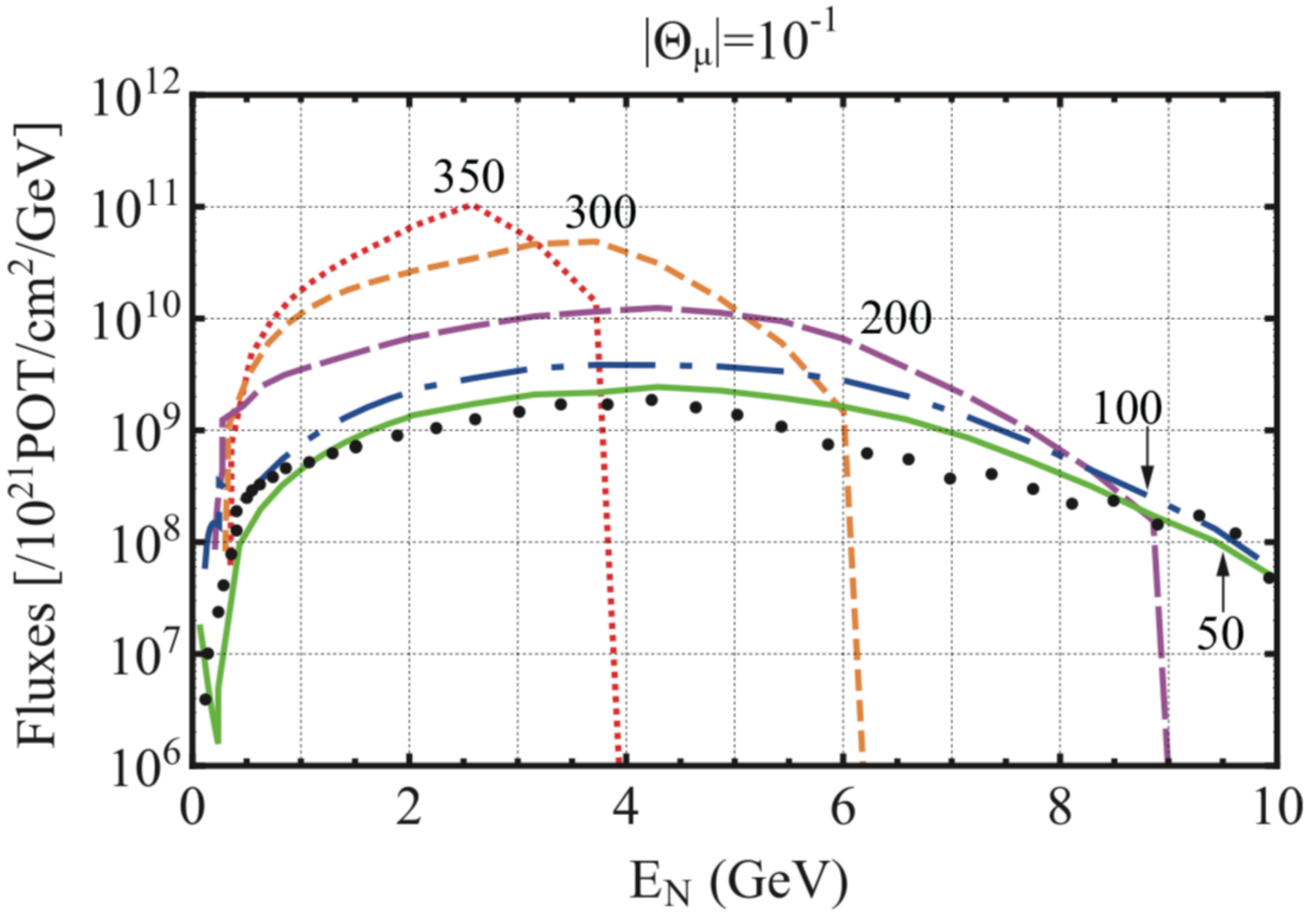

Asaka et. al., arXiv:1212.1062

# Analytical approach to the T2K SM neutrino flux

- In possession of the Kaon spectra we can define the heavy neutrino source term:

$$S_N(E_N, \theta, \phi, l) = \int_0^\infty dp_K \phi_K(p_K) e^{-\frac{l}{\Lambda}} \left(\frac{m_K}{p_K}\right) \frac{d^3\Gamma_{K\to N\mu}}{dE_N d\cos\theta d\phi}$$

- Get the HNL flux similarly to the light neutrino flux.




- Number of events:

$$N_{\text{evts}} = A \int_{M_N}^\infty dE_N \left(\frac{1}{\lambda_N}\right) \int_{x_0}^{x_1} dx \phi_N(E_N) e^{-\frac{x}{\Lambda_N}}$$

Asaka et. al., arXiv:1212.1062

# Reanalysis for RH current dominance

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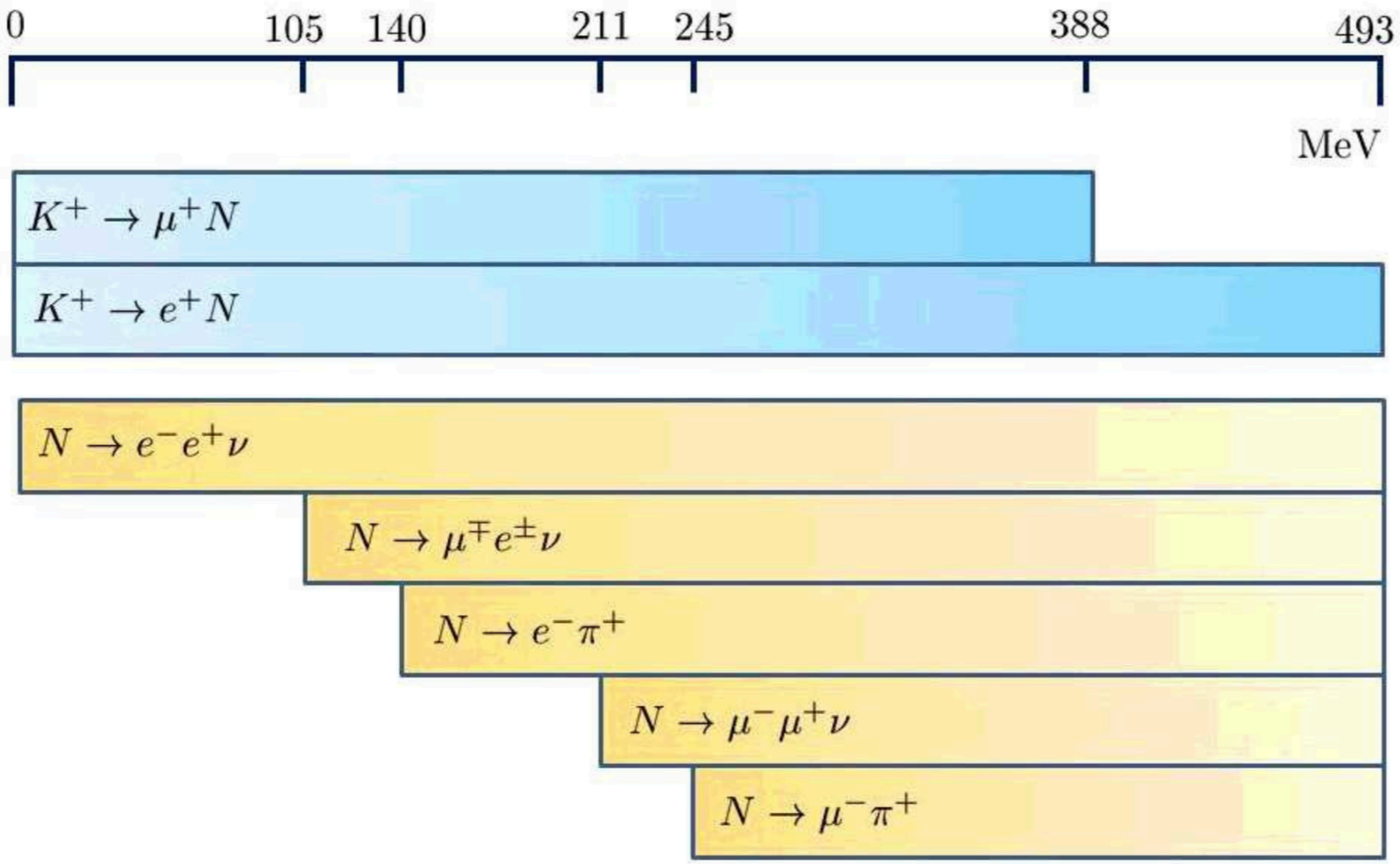


Abe et. al, arXiv:1902.07598
Asaka et. al., arXiv:1212.1062

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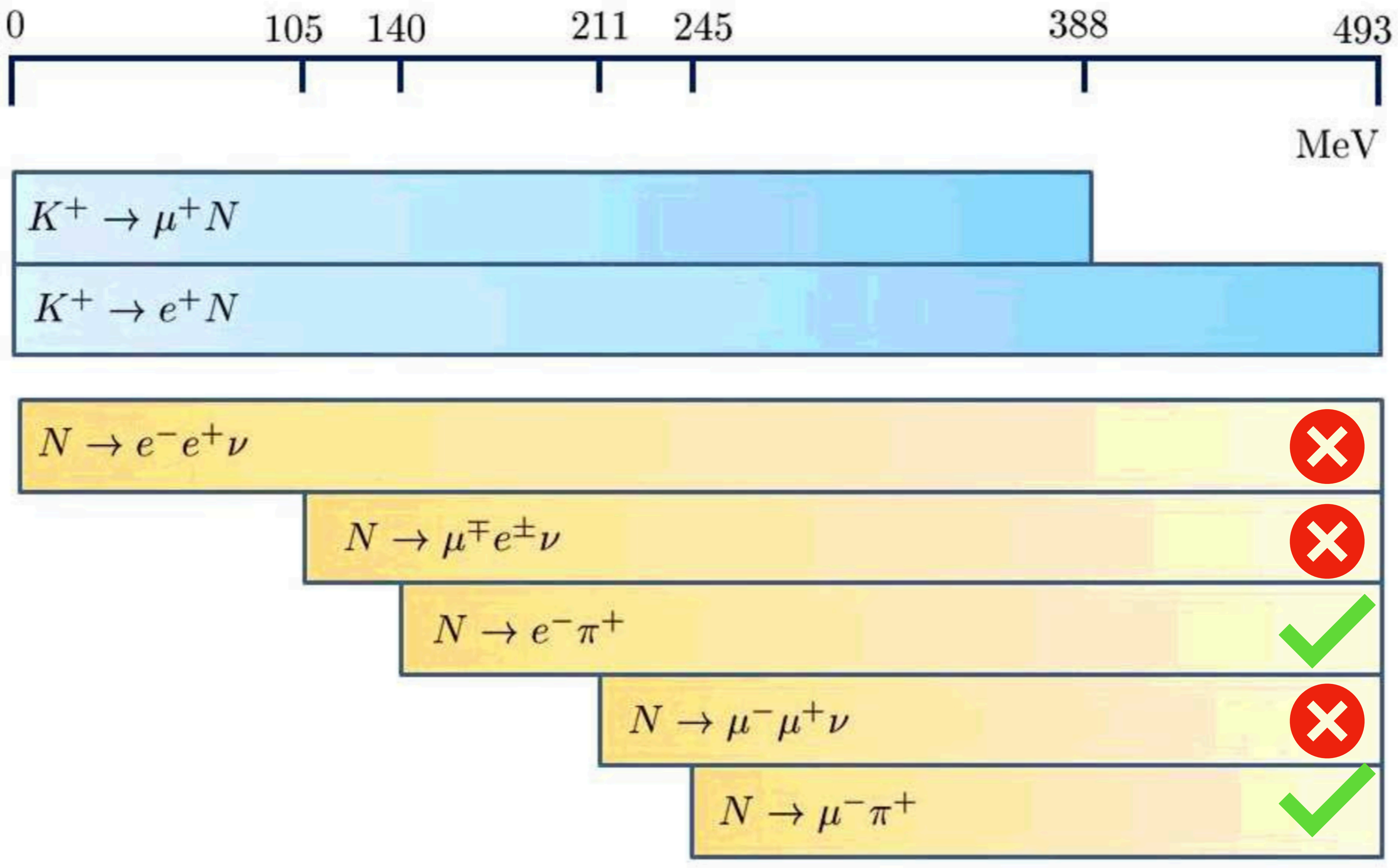
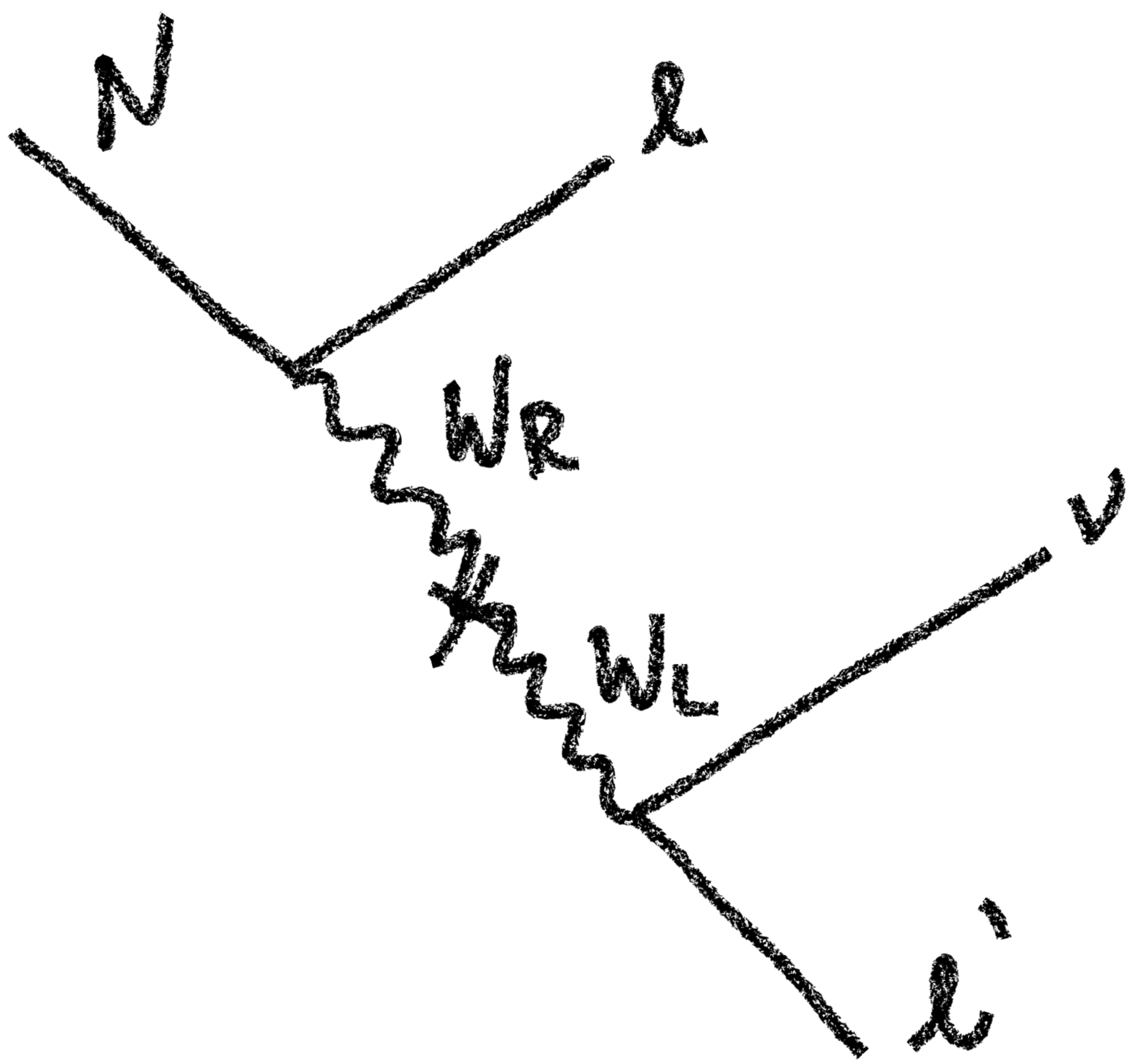
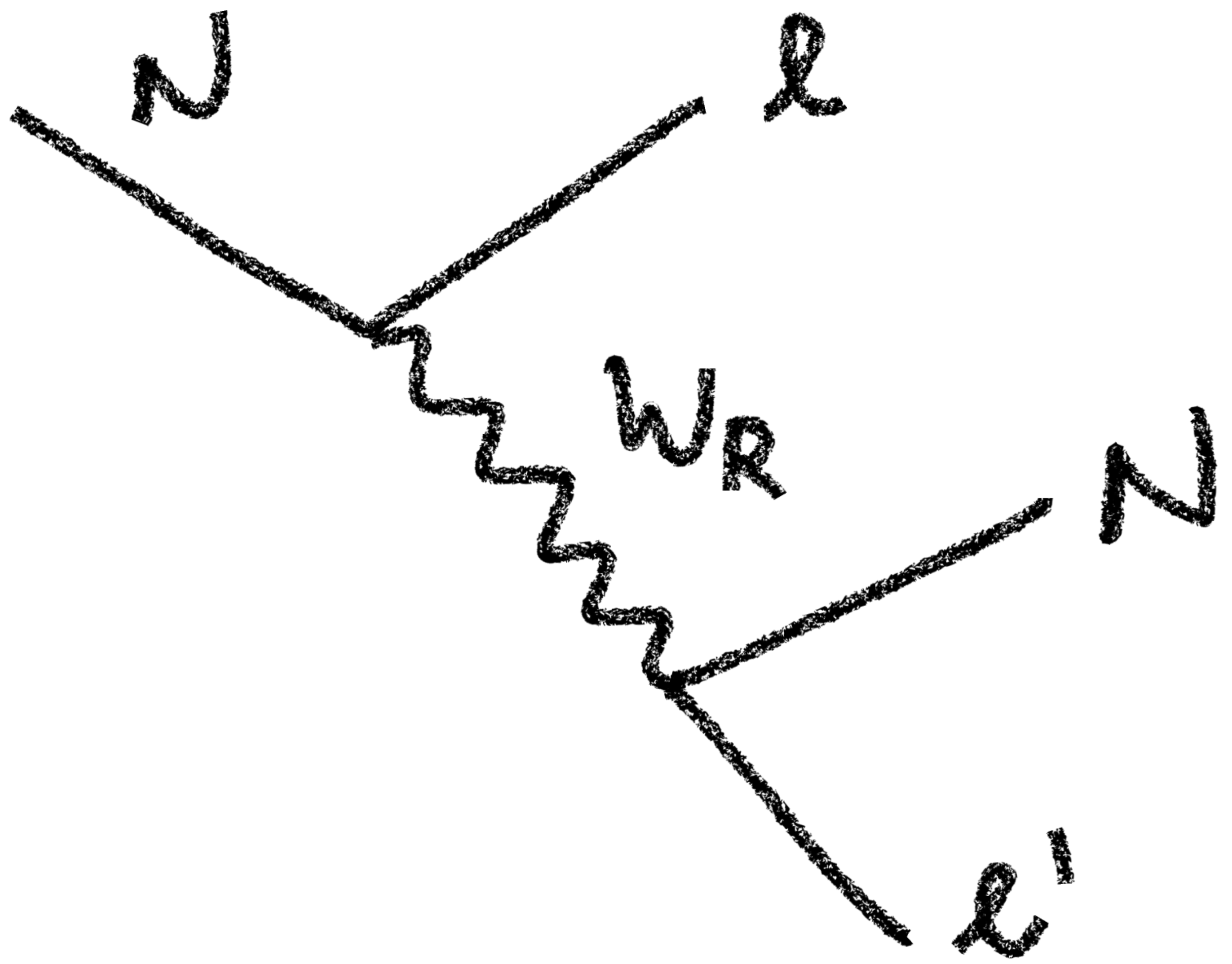



Abe et. al, arXiv:1902.07598
Asaka et. al., arXiv:1212.1062

# Reanalysis for RH current dominance

- Similar analysis for BEBC.
- Unfortunately we can't use CHARM for charged current production as they have only considered three body final states.




Grassler et al., Nucl. Phys. B 273
Cooper-Sarkar et al., Phys. Lett. B 160
Bergsma et al., Phys. Lett. B 166

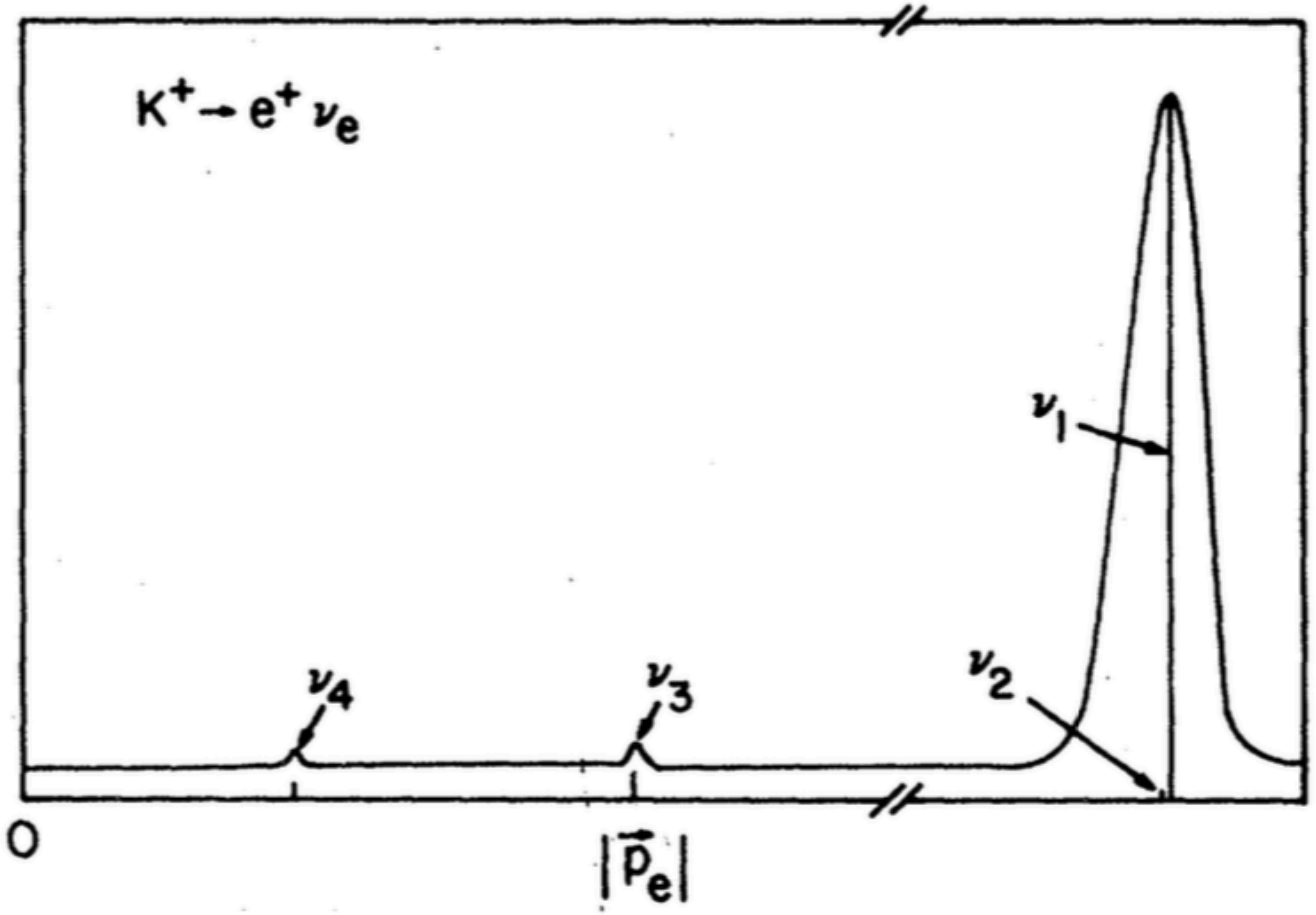
# Invisible searches

- Emission of massive neutrinos manifest itself indirectly through peaks in the energy spectrum.
- The idea is to compare the experimental ratio with the SM calculation:

$$B(M^+ \to e^+ N) = B^{\mathrm{SM}}(M^+ \to e^+ \nu_e) \rho_e^{MN} |U_{lN}|^2$$

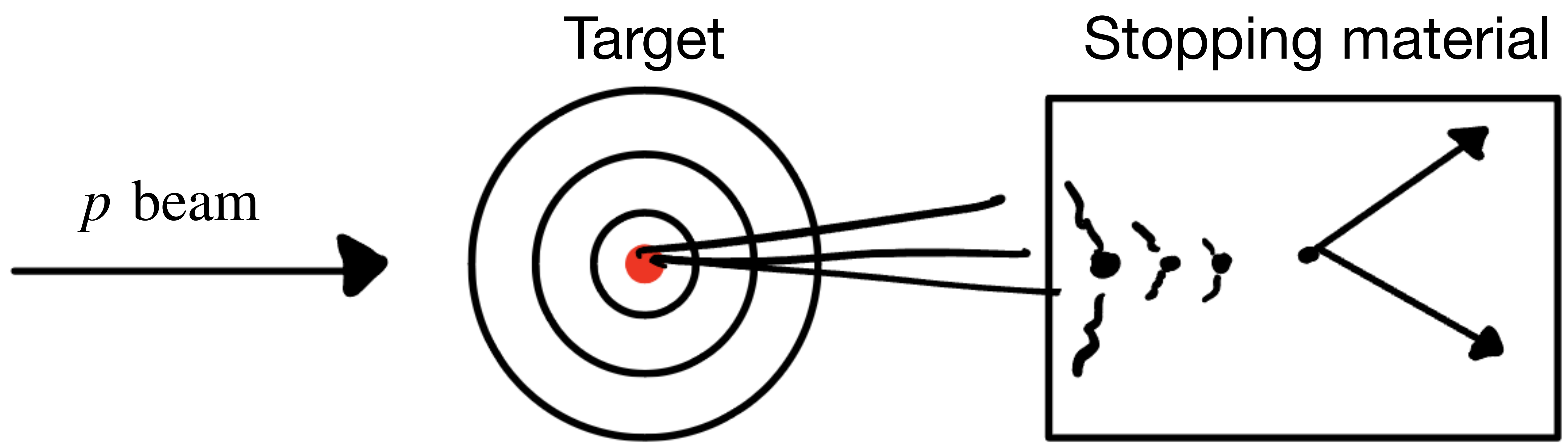
$$\downarrow$$

$$B(M^+ \to e^+ N) = B^{\mathrm{SM}}(M^+ \to e^+ \nu_e) \rho_e^{MN} \left( \frac{G_F'}{G_F} \right)^2$$




Shrock Phys. Rev. D 24

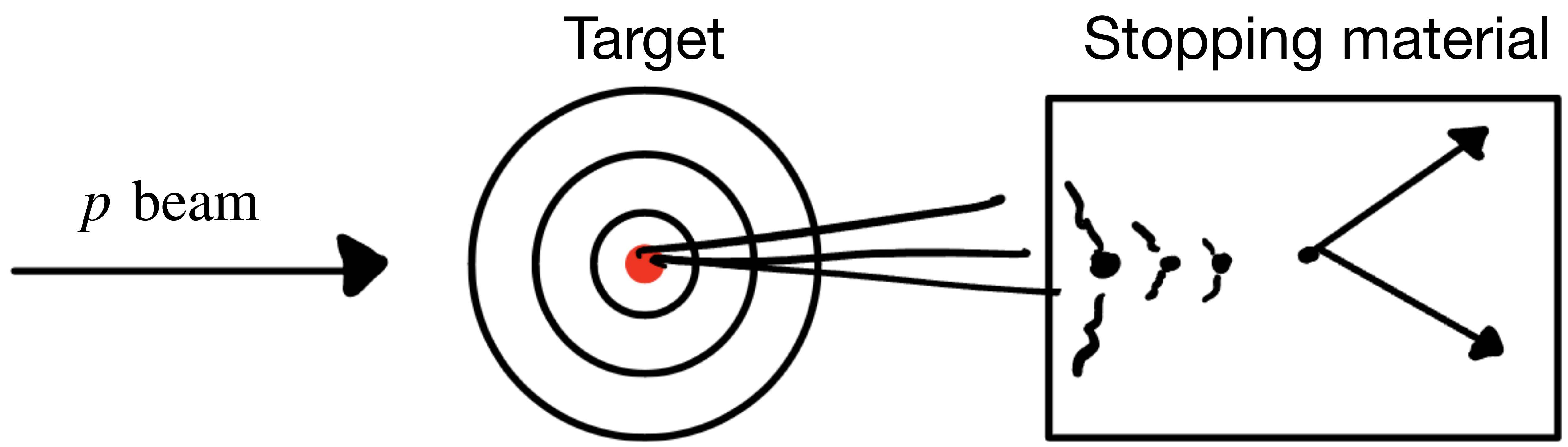
# Bird's eye view of the experiment




For $\pi \to e^+\nu_e$ with SM neutrinos:

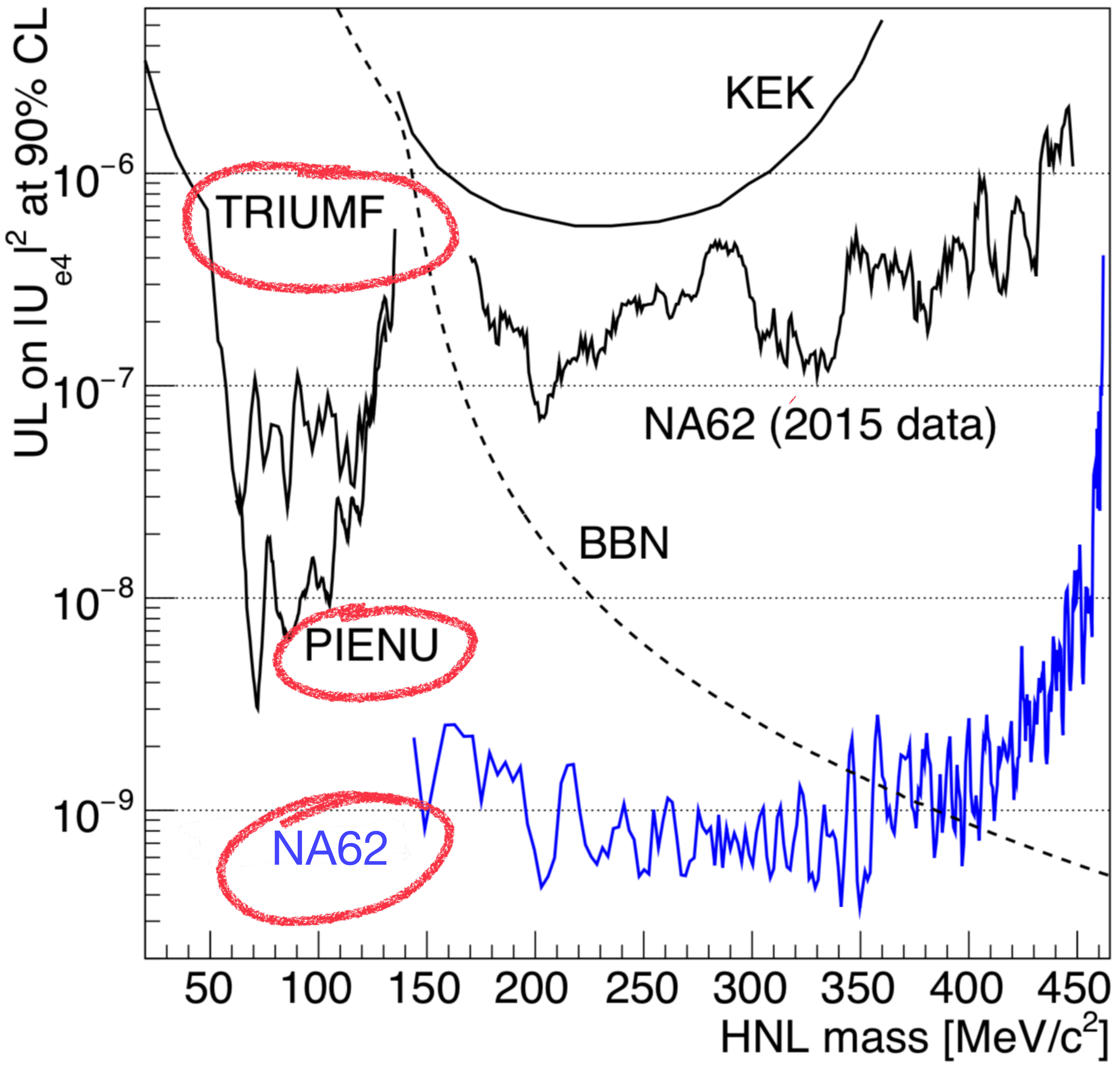
$$E_e = \frac{m_\pi^2 + m_e^2 - m_\nu^2}{2m_\pi} \sim 69.8 \text{ MeV}$$

# Bird's eye view of the experiment




- Decay in flight can also be studied.
- Main background comes from $\pi \to \nu_\mu \mu$, followed by $\mu \to e \nu_e \nu_\mu$ decays.

# Nice idea nice constraints




NA62 collaboration, arXiv:2005.09575
PiENu, arXiv:1505.02737
Britton et al., Phys. Rev. D 46

# Meson Decay Ratios

- The decay $\pi \to e\nu$ is helicity suppressed but $\pi \to eN$ is not!
- The idea is to compare the theoretical prediction and experimental value for the ratio:

$$R_{e/\mu}^{\mathrm{SM}} = \frac{B(M \to e\nu_e)}{B(M \to \mu\nu_\mu)}$$

- Heavy neutral lepton emission would impact the value!

$$R_{e/\mu} = \frac{1 + R_{N/\nu_e}}{1 + R_{N/\nu_\mu}} R_{e/\mu}^{\mathrm{SM}} \qquad R_{N/\nu_\alpha} = \frac{B(M \to l_\alpha N)}{B(M \to l_\alpha \nu_\alpha)}$$

# Meson Decay Ratios

- We considered the PDG experimental values:

$$R_{e/\mu}^{PDG}(\pi) = (1.2327 \pm 0.0023) \times 10^{-4}$$

$$R_{e/\mu}^{PDG}(K) = (2.488 \pm 0.009) \times 10^{-5}$$

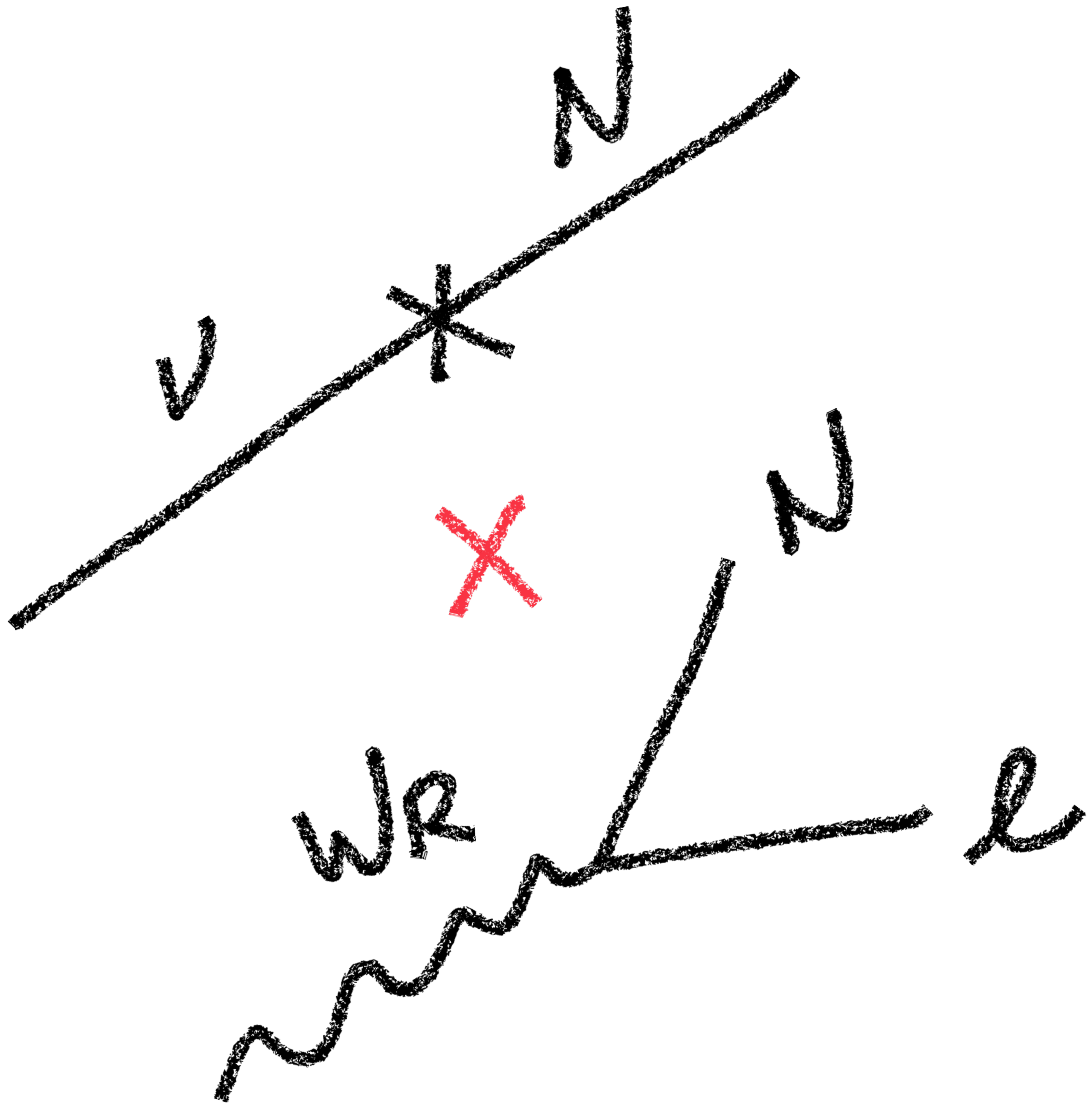
- For the theoretical input we used the SM prediction:

$$R_{e/\mu}^{SM}(\pi) = (1.2352 \pm 0.0001) \times 10^{-4}$$

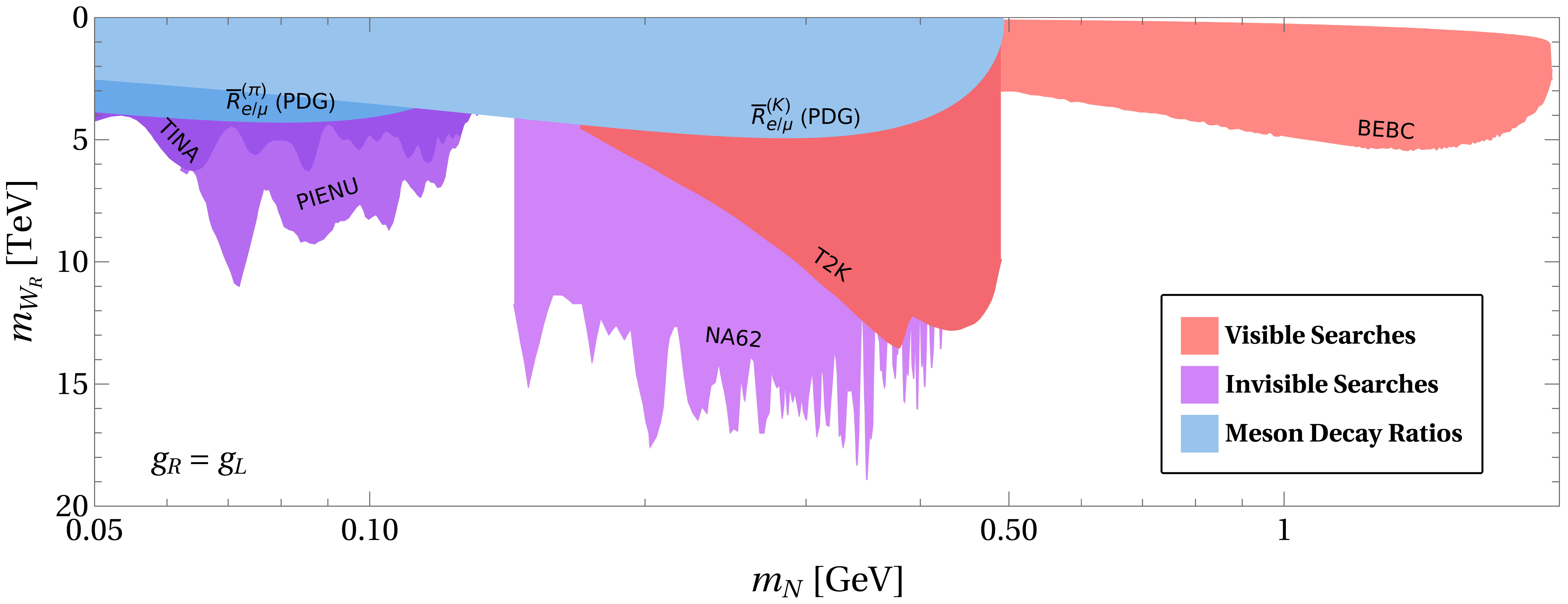
$$R_{e/\mu}^{SM}(K) = (2.477 \pm 0.001) \times 10^{-5}$$

Cirigliano and Rosell, Phys. Rev. Lett. 99.
Marciano and Sirlin, Phys. Rev. Lett. 71.

# Results



# Constraints on a RH current



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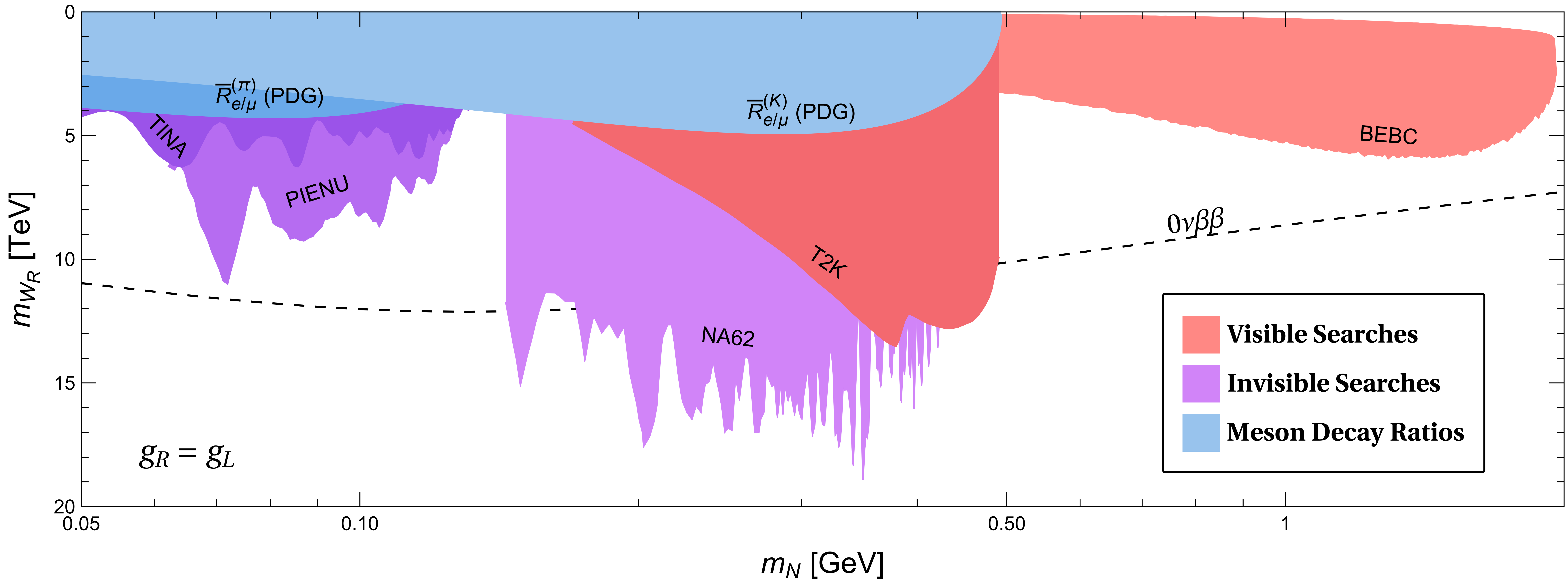
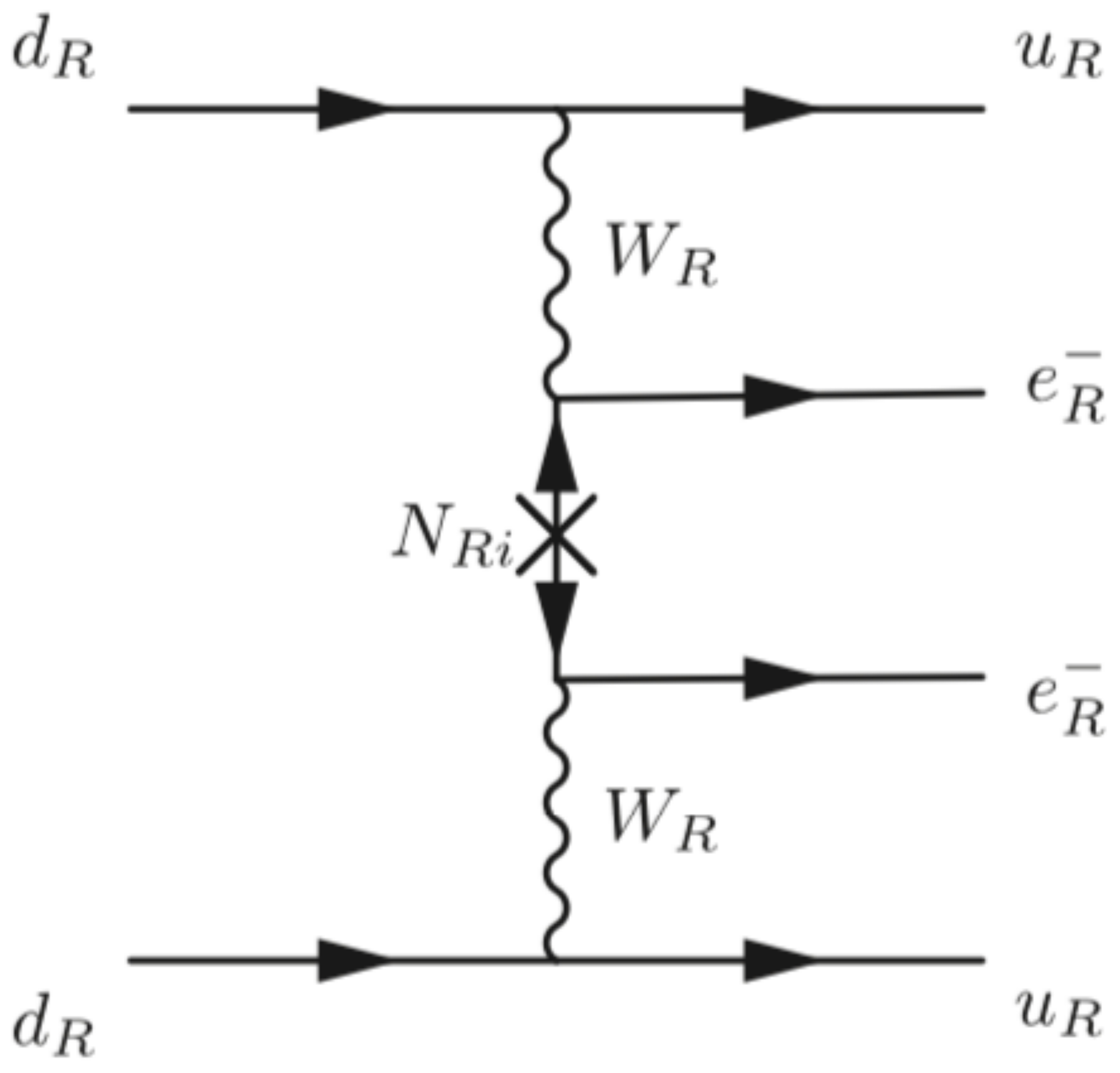
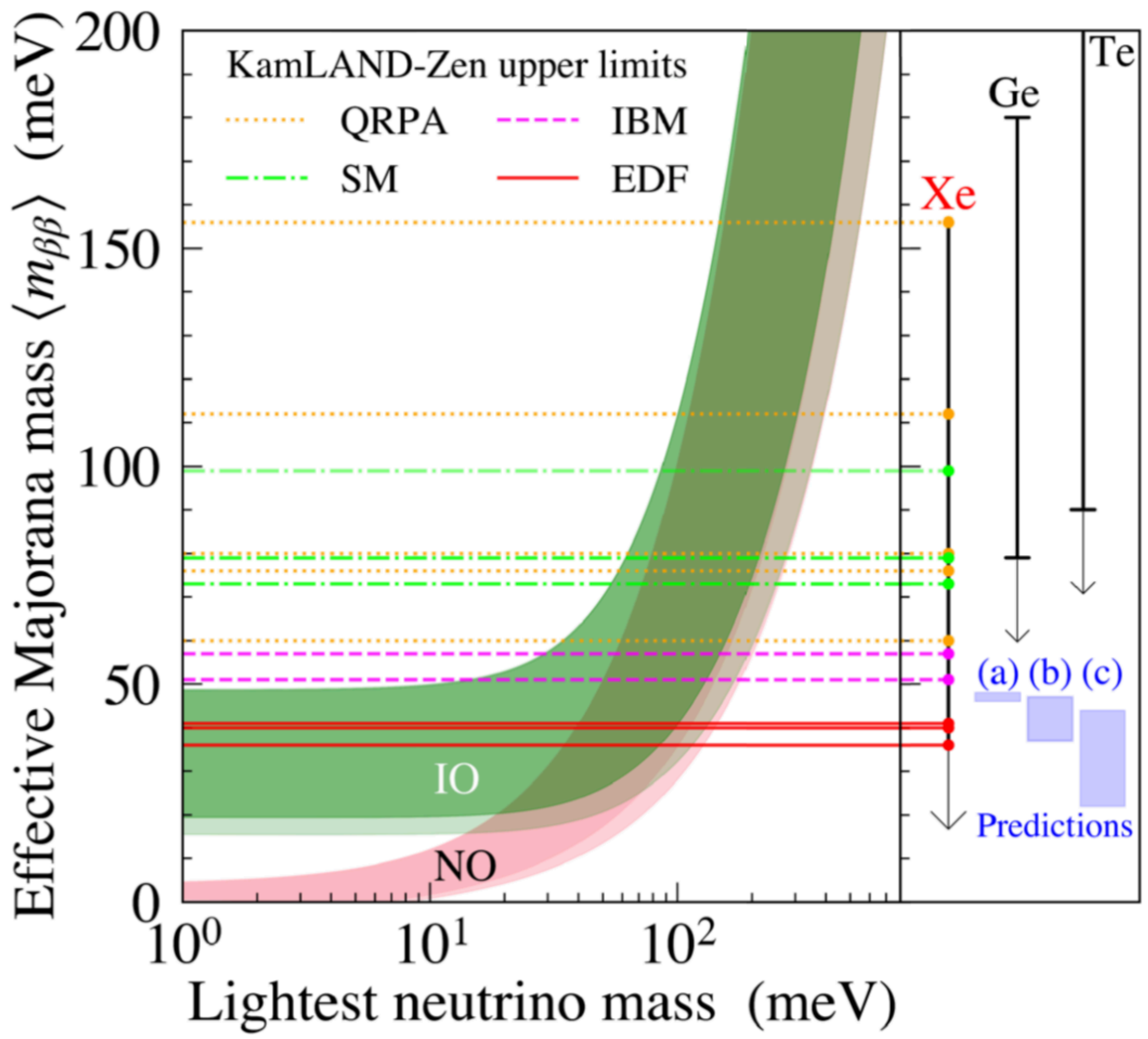


# Comment on $0\nu\beta\beta$ contribution

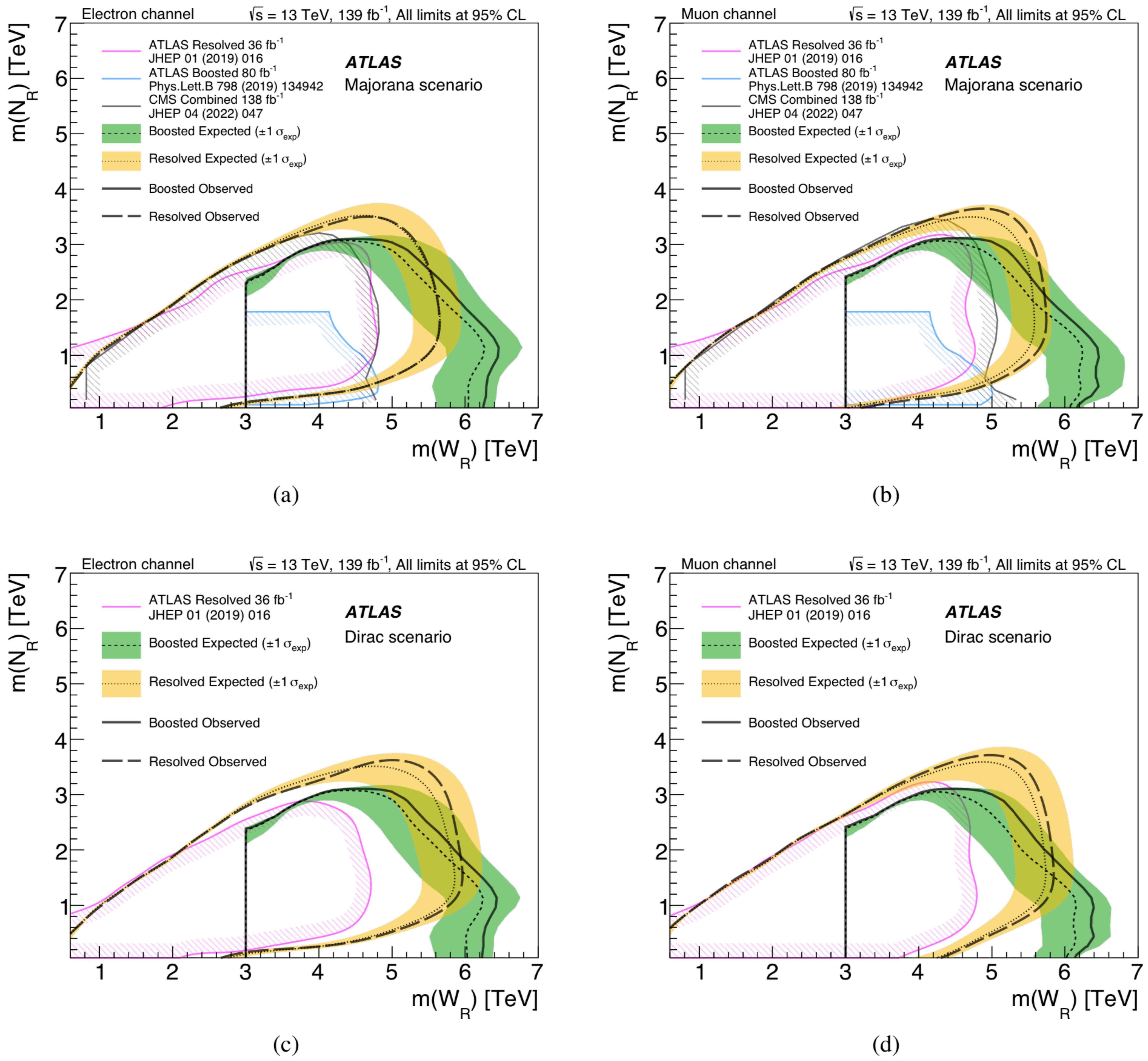



KamLAND-Zen, arXiv:2203.02139

# Revisiting the LHC bound:

- LHC: Best bounds on $m_{W_R}$, for HNL in the GeV-TeV mass range.
- Loose sensitivity for smaller masses.
- Their bound extends up to $m_{W_R} > 6.4$ TeV.
- Neutrino experiments kick in for lighter HNL's!




ATLAS, arxiv:2304.09553

# Conclusions

- We have used low energy pseudoscalar mesons leptonic decays to constrain the mass of a right hand gauge boson.
- Our bounds cover the mass range $50 \leq m_N/MeV \leq 1900$ and are complementary to the LHC bounds on $m_{W_R}$ for lighter neutral leptons.
- Different portals can be studied in this framework!
- Experiments such as ICARUS, MicroBooNE, SBND, DUNE, Belle II, SuperKEKB and HIKE can constrain even more this scenario in the future.