New limits on W_R from meson decays

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FAPESP
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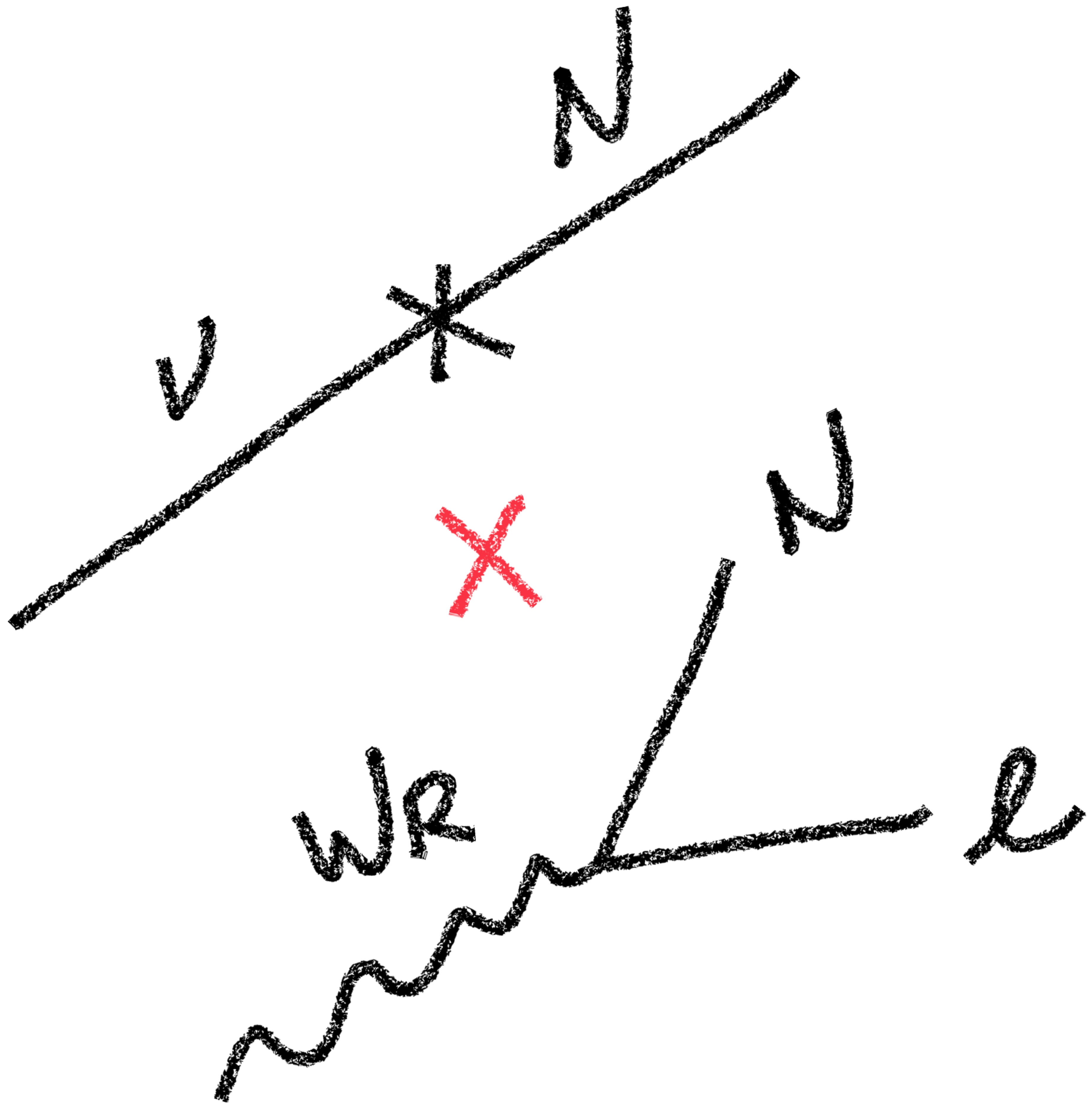
Why RH currents?



The road to the Standard Model

Weinberg, V-A is the key.
C. S. Wu, ReV. Mod. Phys. 36
Allan D. Franklin, Are there really neutrinos

The road to the Standard Model

Weak interactions played a key role in building the SM

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- **Becquerel & Rutherford: Radiation in three forms**

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- Becquerel & Rutherford: Radiation in three forms
- J. J. Thomson: Nature of cathode rays -> electrons
- Are β rays similar to cathode rays? Yes
- These experiments raised the question on the spectrum of beta rays, continuous or discrete?

Energy conservation under attack

"As regards the occurrence of transitions, which is the essential feature of the quantum theory, we abandon on the other hand any attempt at a causal connection between the transitions in distant atoms, and especially a direct application of the principles of energy and momentum so characteristic for the classical theories."

(Bohr, Kramers and Slater).

Energy conservation under attack

"It is impossible to believe that if science of the present time had not been saturated with the idea of conservation of energy, these complications would be avoided by saying that there is no exact conservation in such cases."

(Darwin, Sommerfeld)

"At present I have high hopes for solving the radiation problem, and that without light-quanta… One must renounce the energy principle in its present form."

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(A. Einstein)

***Three days later he wrote that it did not work..**

Energy conservation defense

“I should prefer to keep rigorous conservation of energy at all costs.”

(Dirac)

“I have hearded that you [Bohr] are on the warpath and wanting to upset the Conservation of Energy both microscopically and macroscopically. I will wait and see before expressing an opinion but I always feel there are more things in Heaven and Earth than are dreamt of in our philosophy.”

(Rutherford)

Energy conservation defense

“I must say that your paper has given me little satisfaction… I do not exactly mean that this is unpermissible but it is a risky business.. Let the stars radiate in piece”

(Pauli)

A desperate remedy (the neutrino)

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente

Enrico Fermi takes Pauli seriously

Propose an “effective field theory” of beta decays

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On theoretical grounds: S, T, V, A & P.

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Inspired by electromagnetism: only vector component

On theoretical grounds: S, T, V, A & P.

It took over 30 years for experiment and theory to agree on the correct form!

Weak decays are everywhere

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Pion and muon decays have similar strengths to the beta decays.

Is Fermi interaction universal?

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New venues to explore weak interactions!!

Bird’s eye view of the situation

Fun fact: Pions decay to electrons took a while to be probed experimentally. This led the community to favor pseudo scalar couplings

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Key ingredient is missing

Bird’s eye view of the situation

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If you do the math: there is no chiral suppression in this case and pions would decay preferentially to electrons!

Key ingredient is missing

“I do not believe that the Lord is a weak left-hander and I am willing to bet a very large sum that the experiments will give symmetric results.”

(Pauli)

Parity is not conserved

Lee, Yang gave up parity

Madame Wu

Evidence for parity violation

$$^{60}\mathrm{Co} \rightarrow ^{60}\mathrm{Ni}^* + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$$
$$\rightarrow e^- + \bar{\nu}_e + 2\gamma + ^{60}\mathrm{Ni}$$

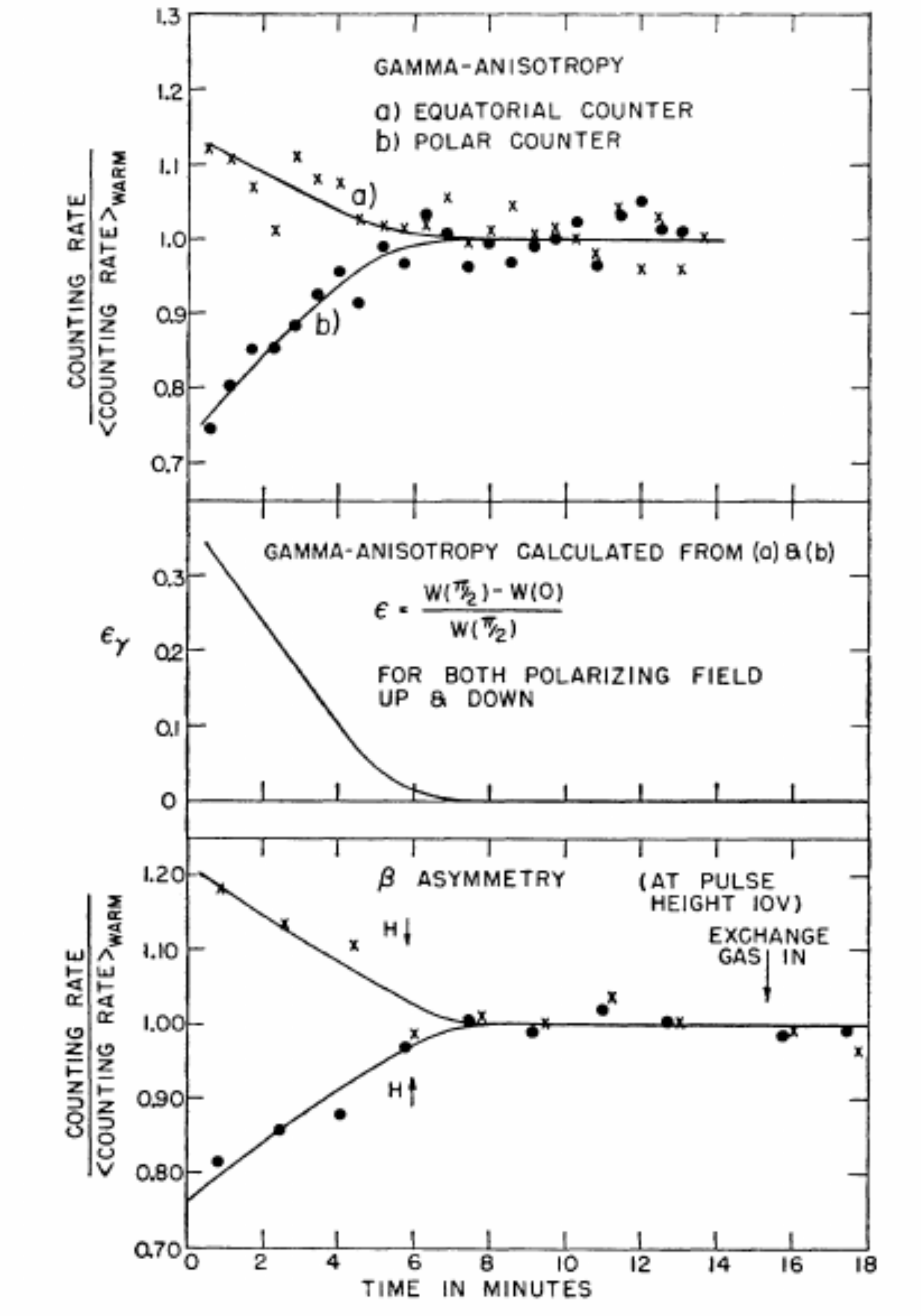
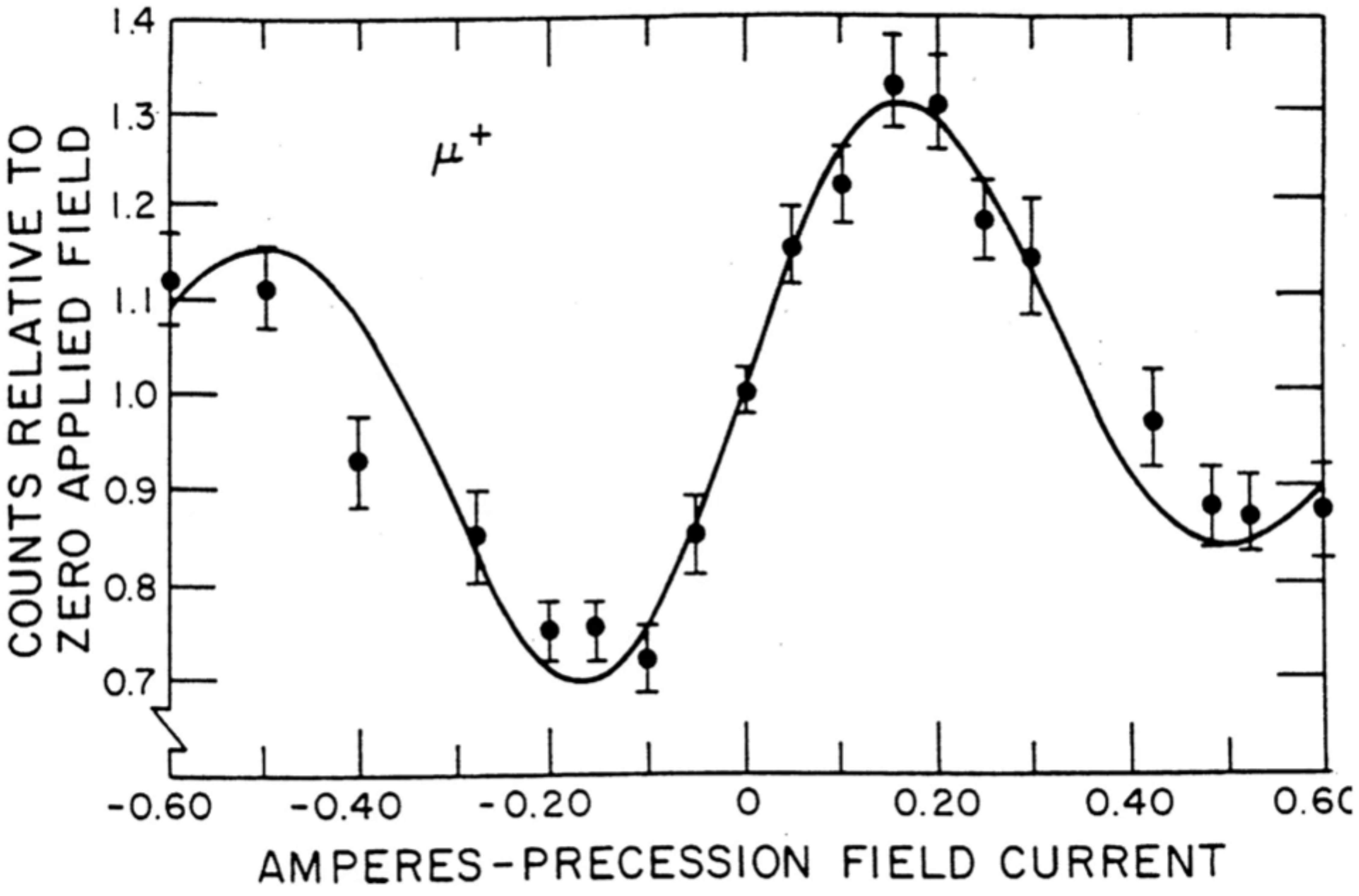


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.



Revisiting old experiments without parity

V-A emerges as the correct form!

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Universality of Fermi interactions led to the study of approximate and spontaneously broken symmetries

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Universality of Fermi interactions led to the study of approximate and spontaneously broken symmetries

Initial proposals fail (Goldstone Bosons) Higgs, Brout, Englert, Guralnik, Hagen and Kibble mechanism!

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Weak interacting (left handed) states are embedded in doublets

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Weak interacting (left handed) states are embedded in doublets

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The Higgs field is necessary to glue them together

That is where the predictivity of the SM emerges!

Neutrinos and minimality

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Enforce lepton number conservation

Add a Majorana mass term

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***Seesaw is theoretically appealing!**

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***Seesaw is theoretically appealing!**

The neutrino discovery guided us to complete the SM and its puzzles may guide us to go beyond it

“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

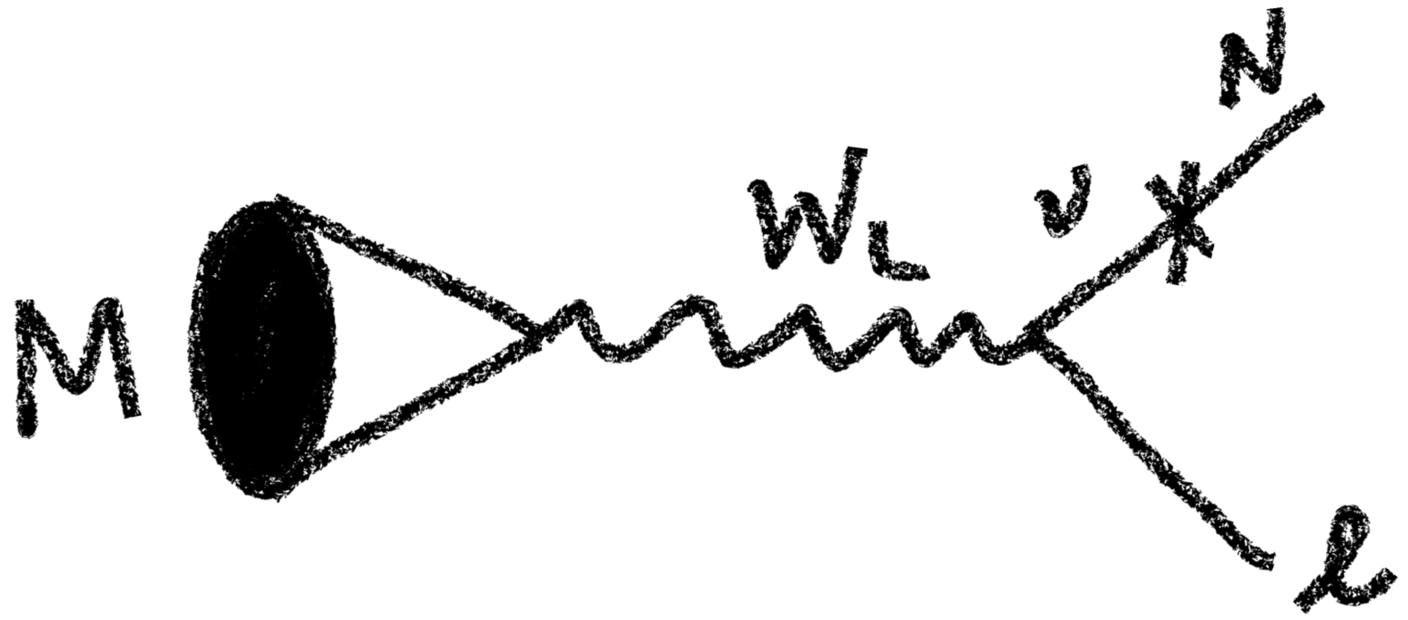
The RH neutrino is active under the additional RH sector.

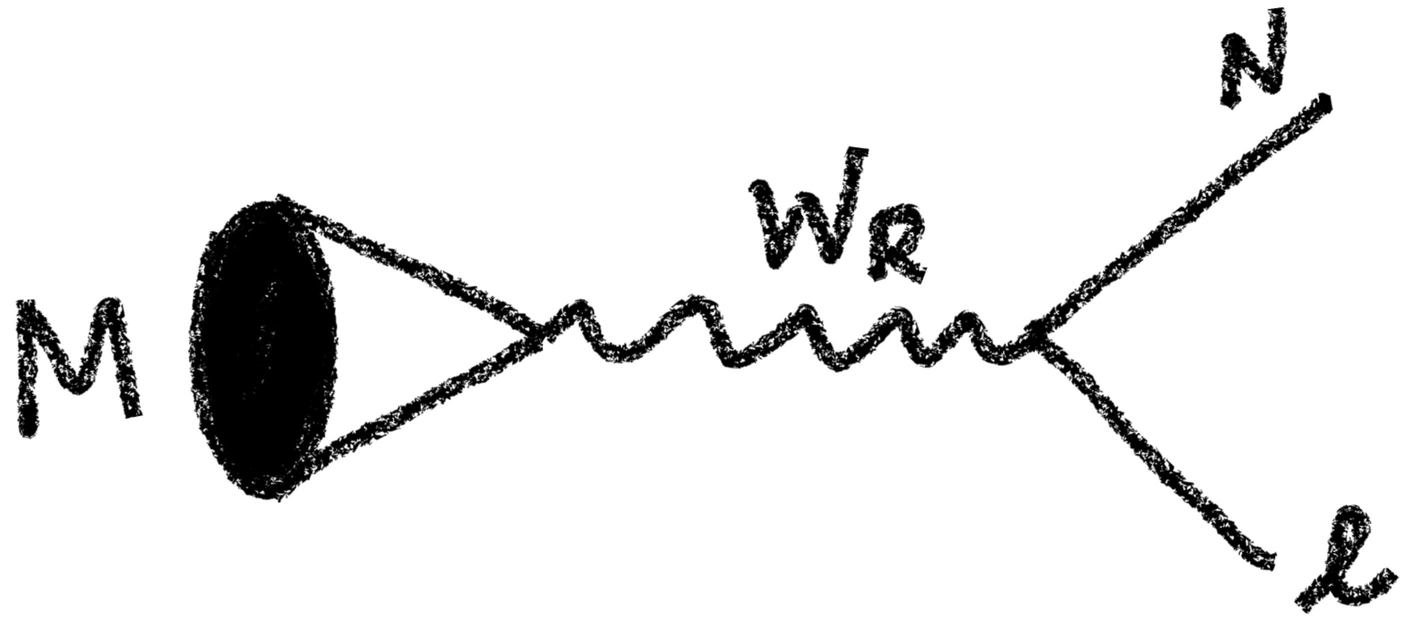
$$\mathscr{L}_R^{CC} = -\frac{g_R}{\sqrt{2}}\left(\overline{N}U_{\mathrm{RR}}^\dagger \not{W}_R L_R + \overline{D}_R V_R^\dagger \not{W}_R U_R + \mathrm{h.c.}\right)$$

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:

$$m_\nu = \underbrace{M_L^\dagger}_{m_{II}} - \underbrace{M_D M_R^{-1} M_D^T}_{m_I}$$

$$|U_{lN}|^2 \sim m_I m_R^{-1}$$

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:

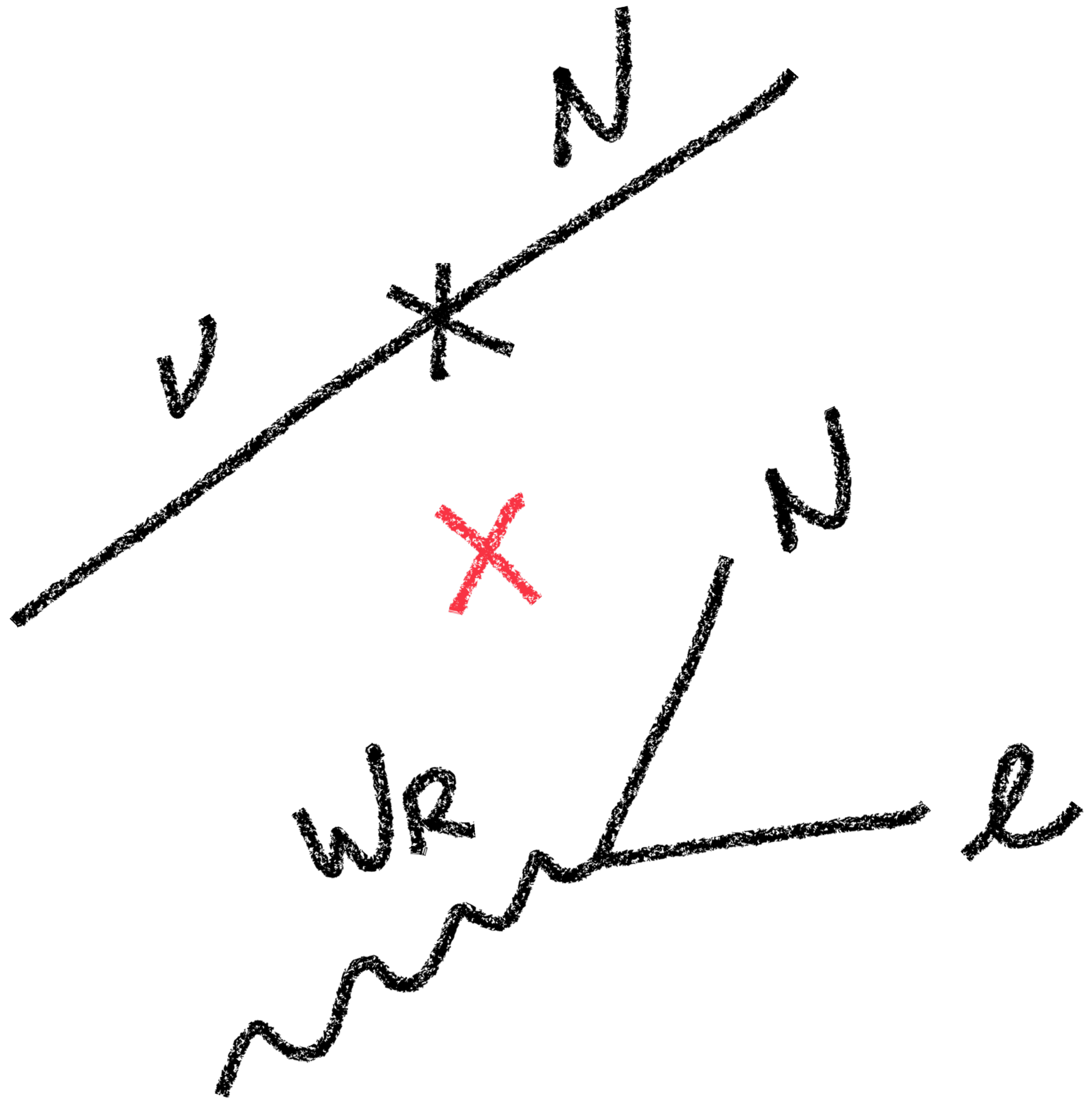
$$G_F^2 |U_{lN}|^2 \times (G_F')^2$$

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.

Reanalysis of HNL searches



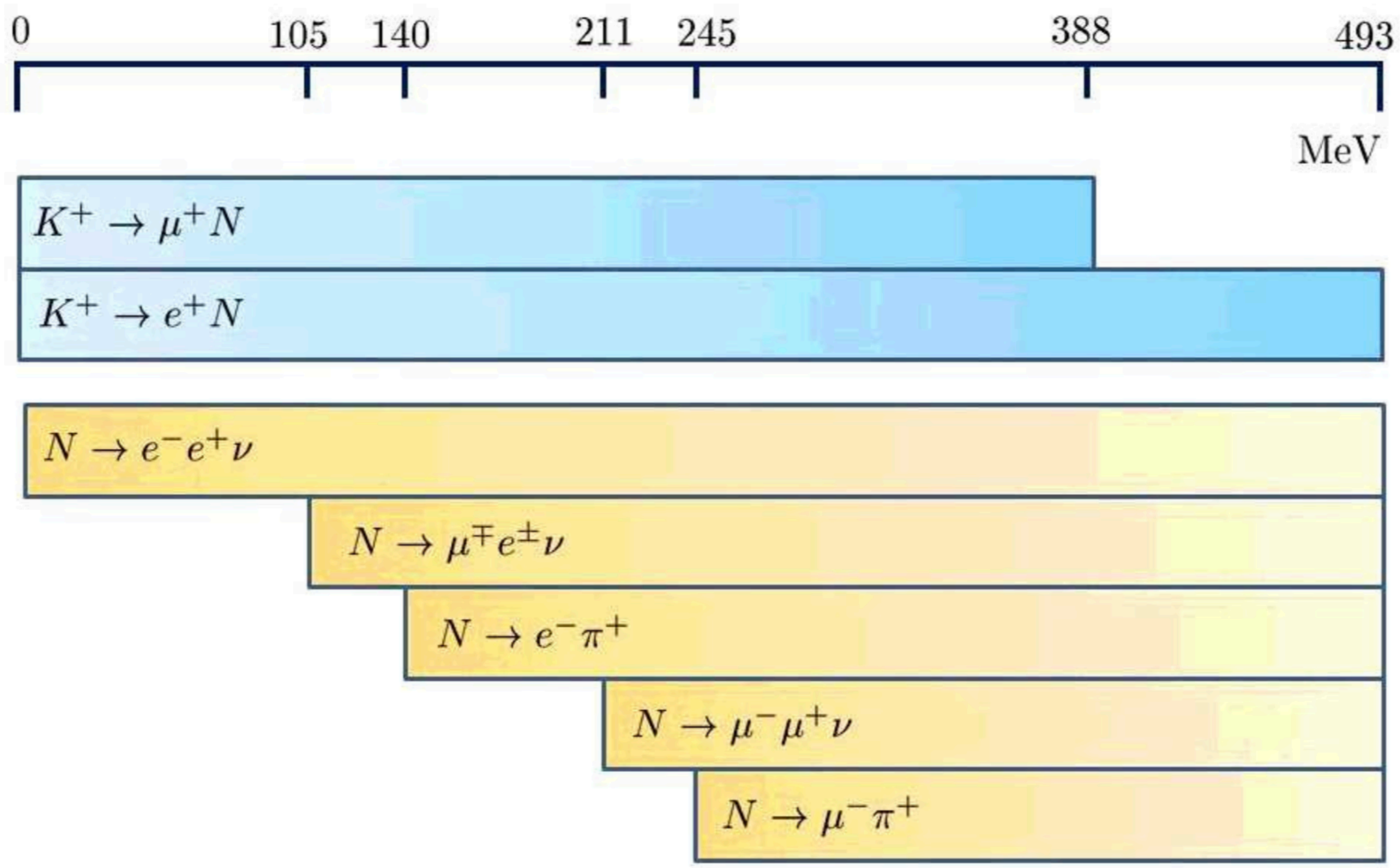
HNL searches at the MeV scale

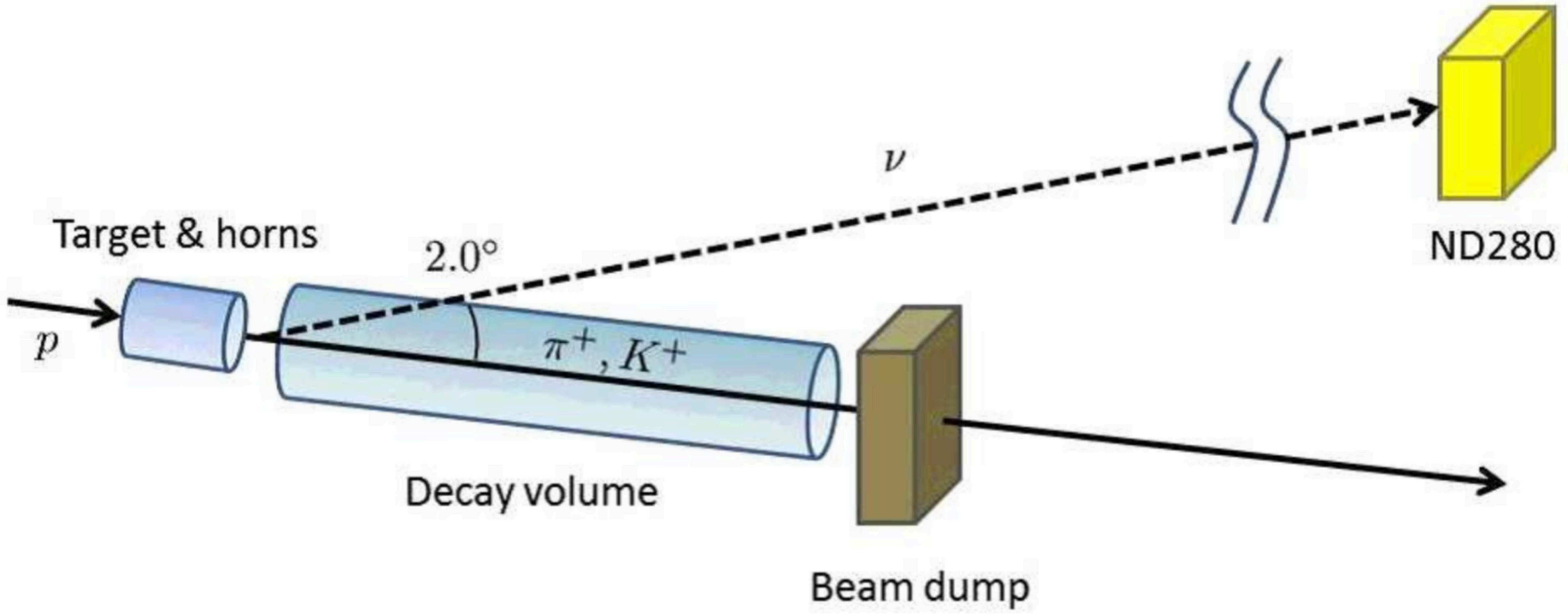
- **Primary mode of production inherited from the light neutrino production mode. Types of searches:**
  - **Visible searches: Heavy neutrinos decay into visible particles.**
  - **Invisibles searches: Use energy distribution of the measured particles.**
  - **Decay ratios: Rate of meson decays change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

Visible searches

Look for visible decays of heavy neutral leptons.

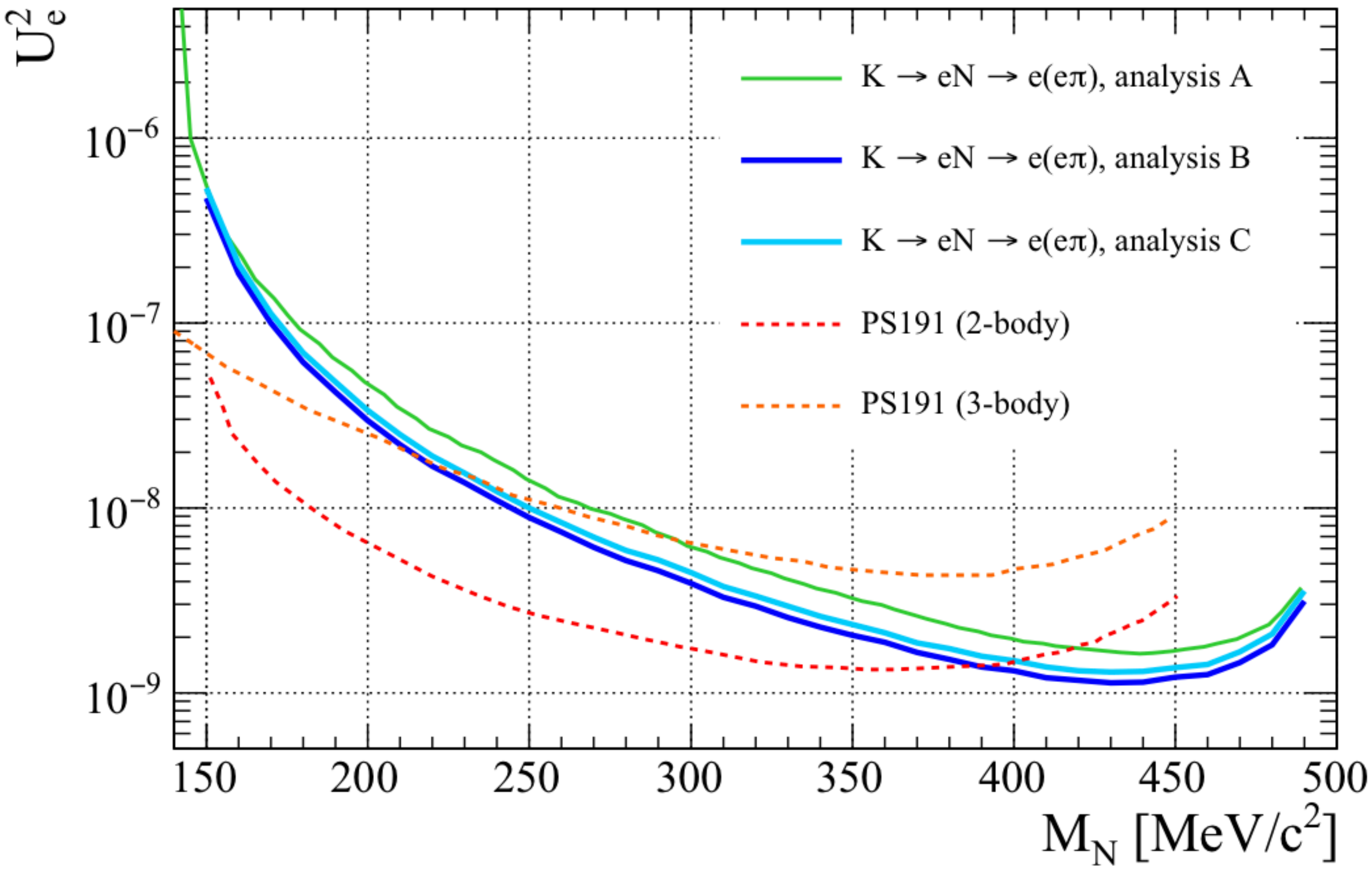
Example: T2K ND280.





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

T2K ND280 search

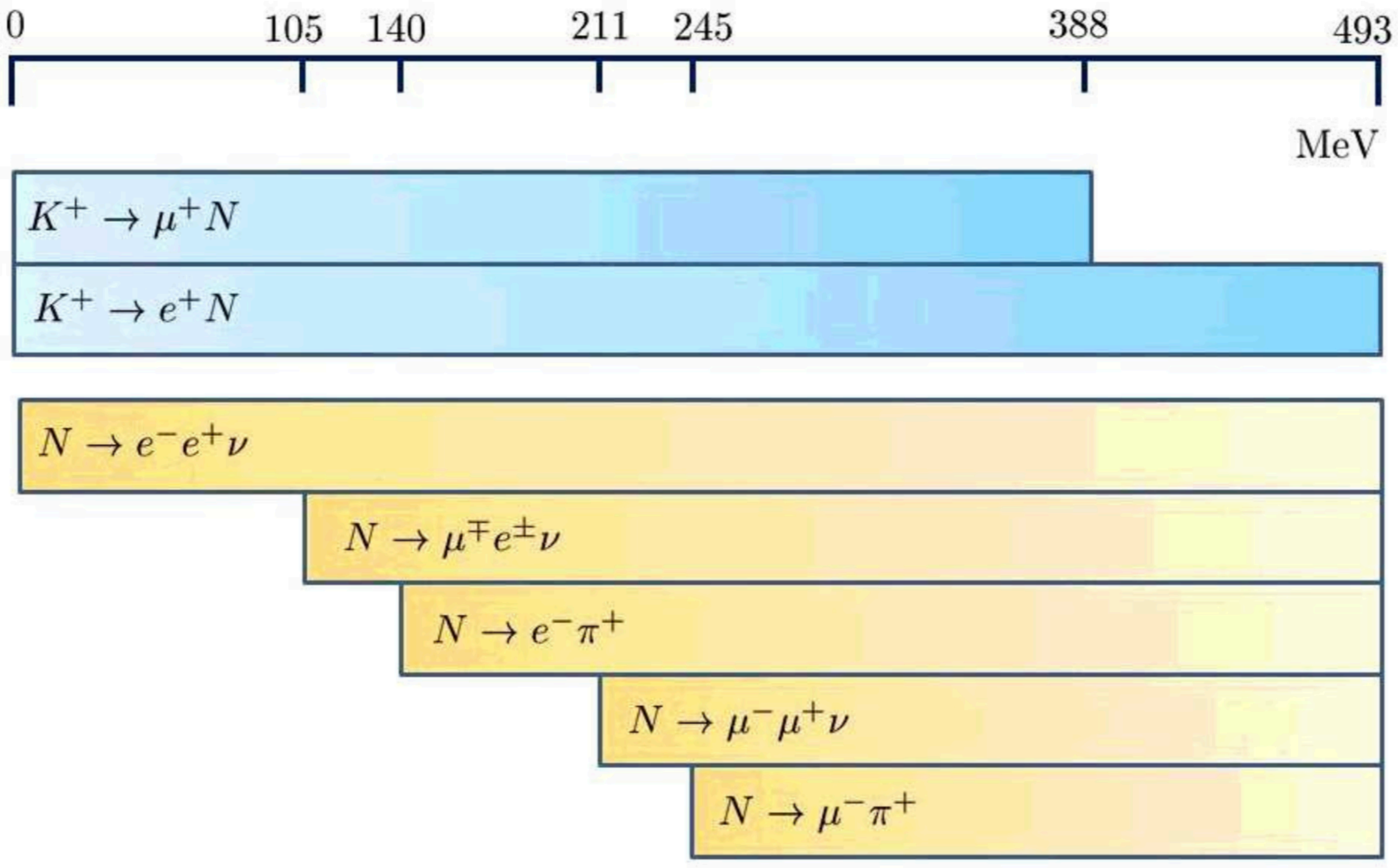


Abe et. al, arXiv:1902.07598

Reanalysis for RH current dominance

To Do:

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



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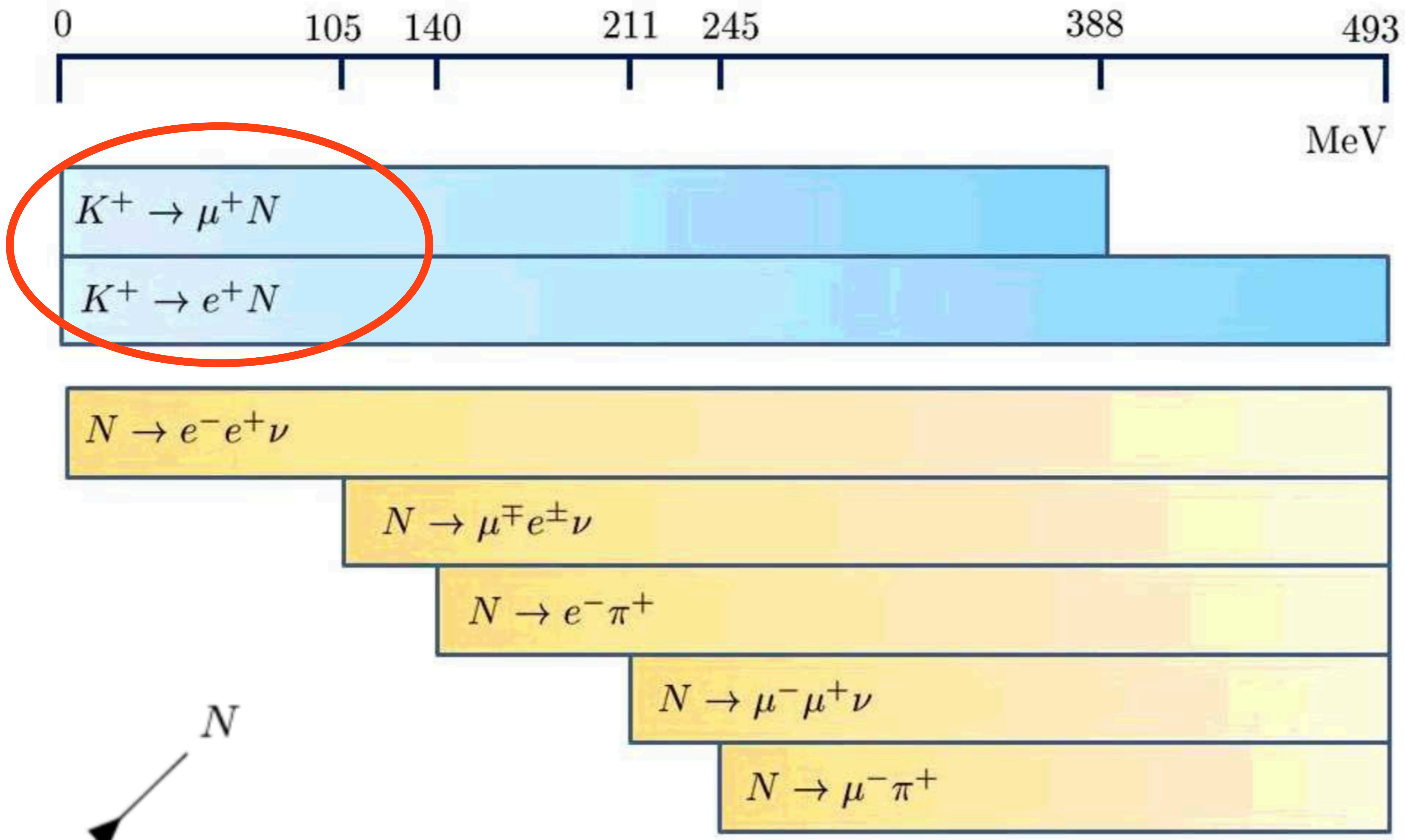

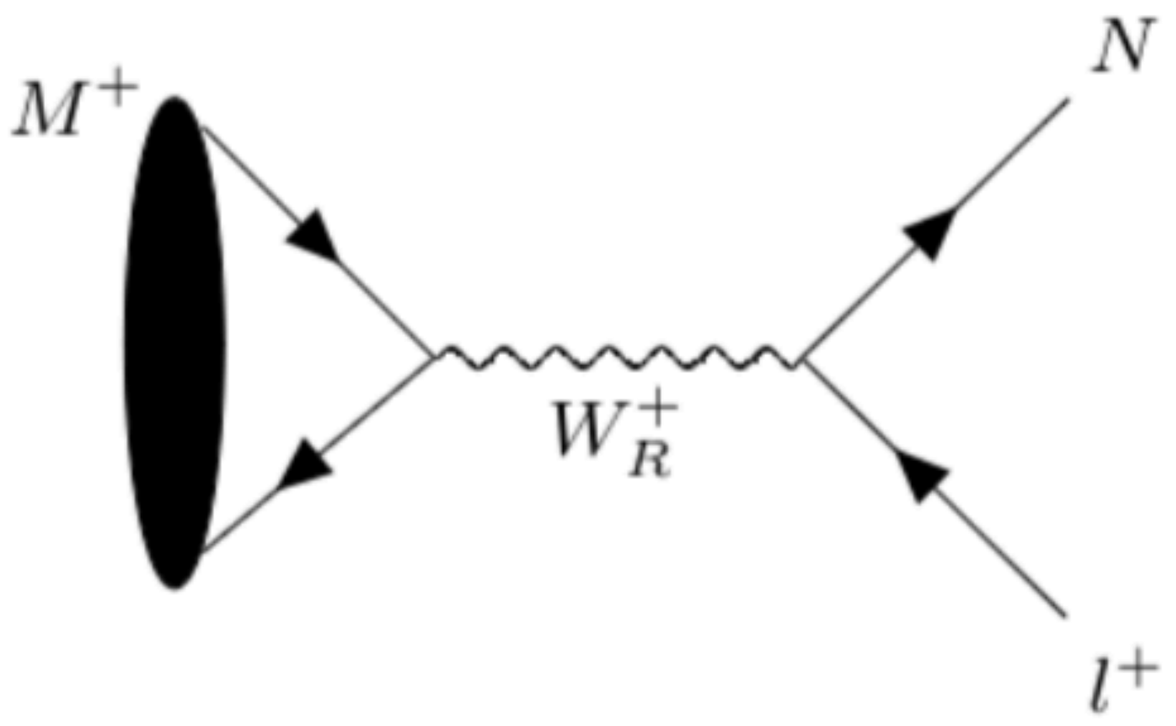

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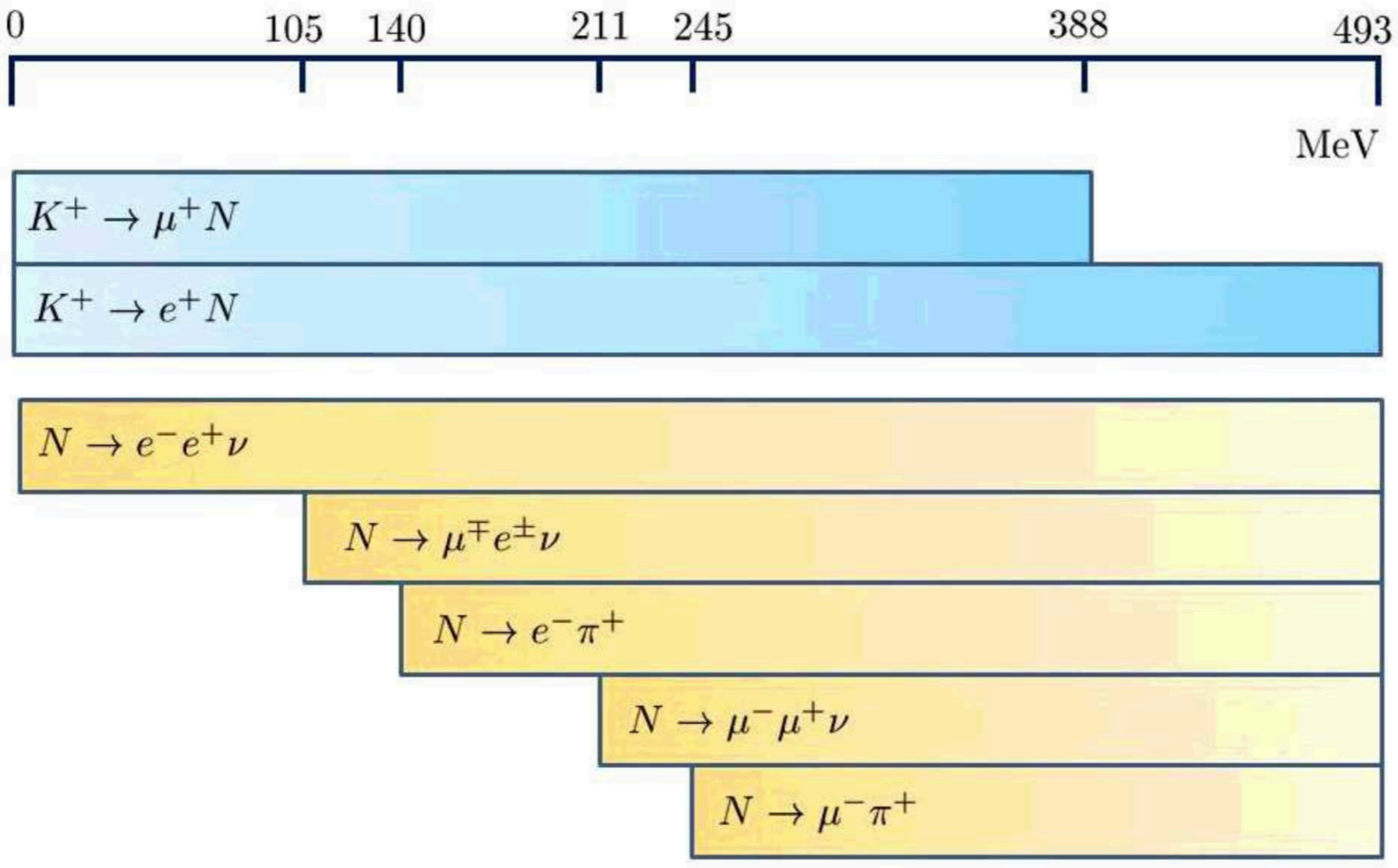


Abe et. al, arXiv:1902.07598
Asaka et. al., arXiv:1212.1062

Analytical approach to the T2K SM neutrino flux

- Input: Parametrization for the kaon spectra.

$$\phi_K(p_K)$$

- Define the light neutrino source term:

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

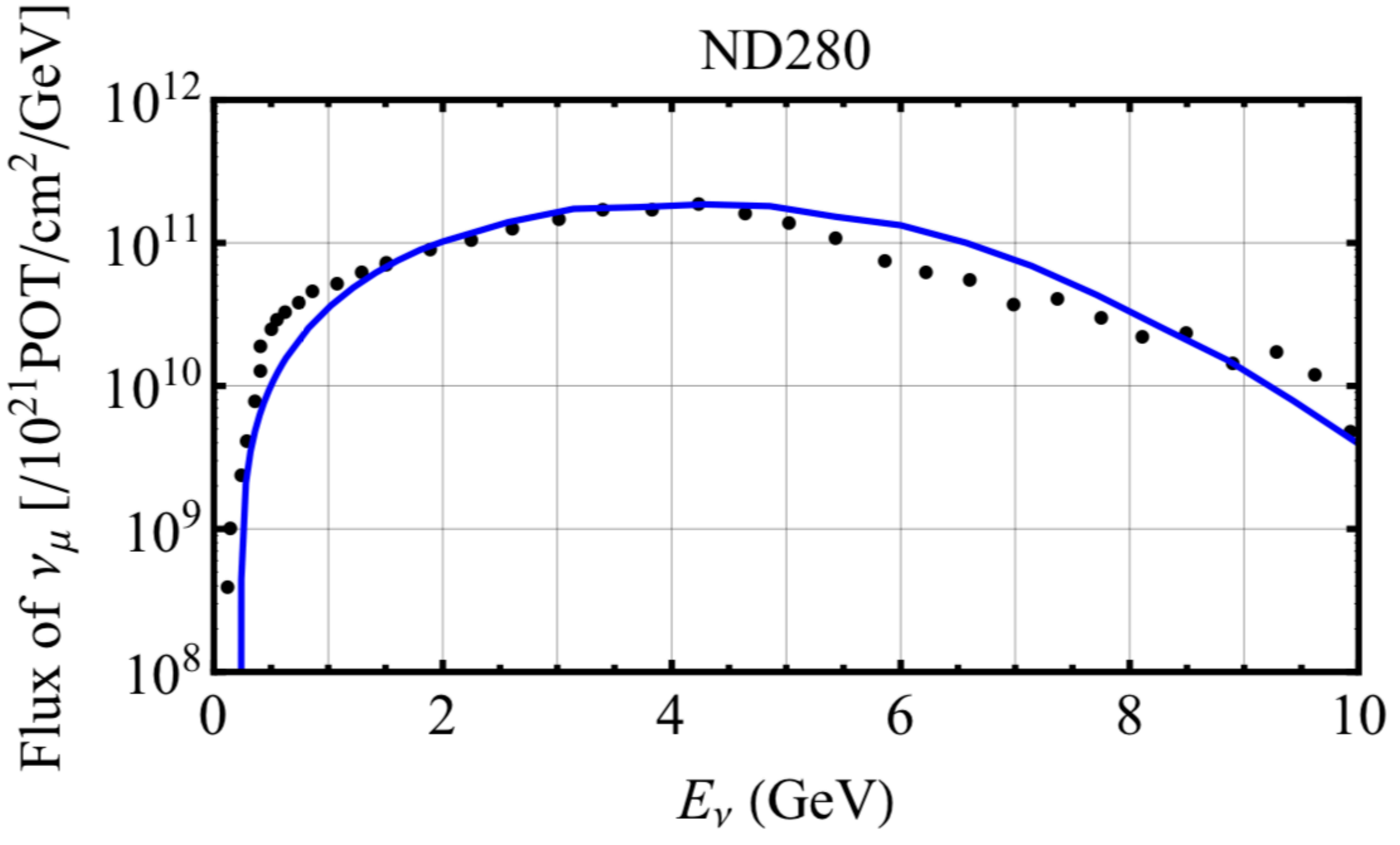
Asaka et. al., arXiv:1212.1062

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.



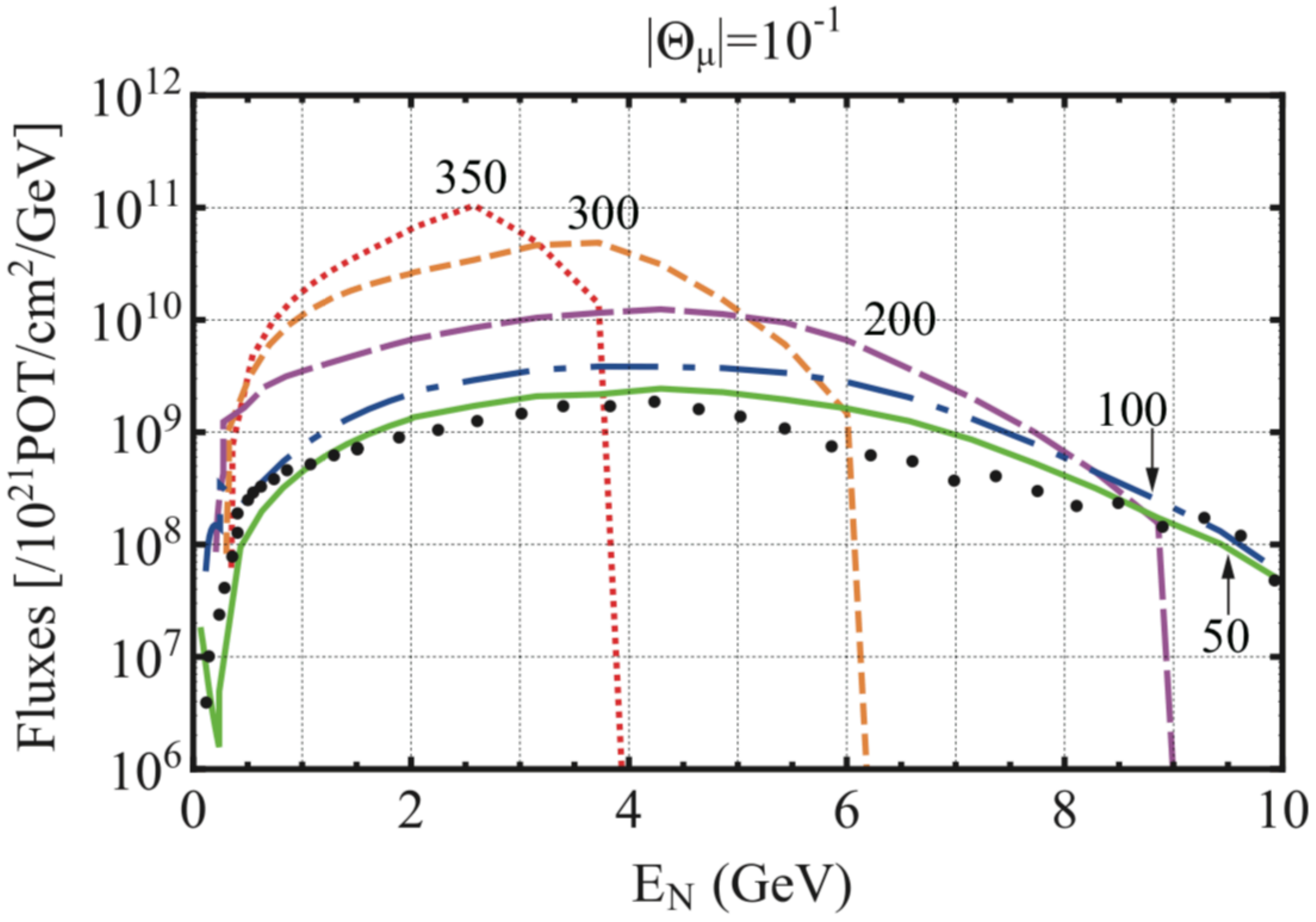
Asaka et. al., arXiv:1212.1062

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

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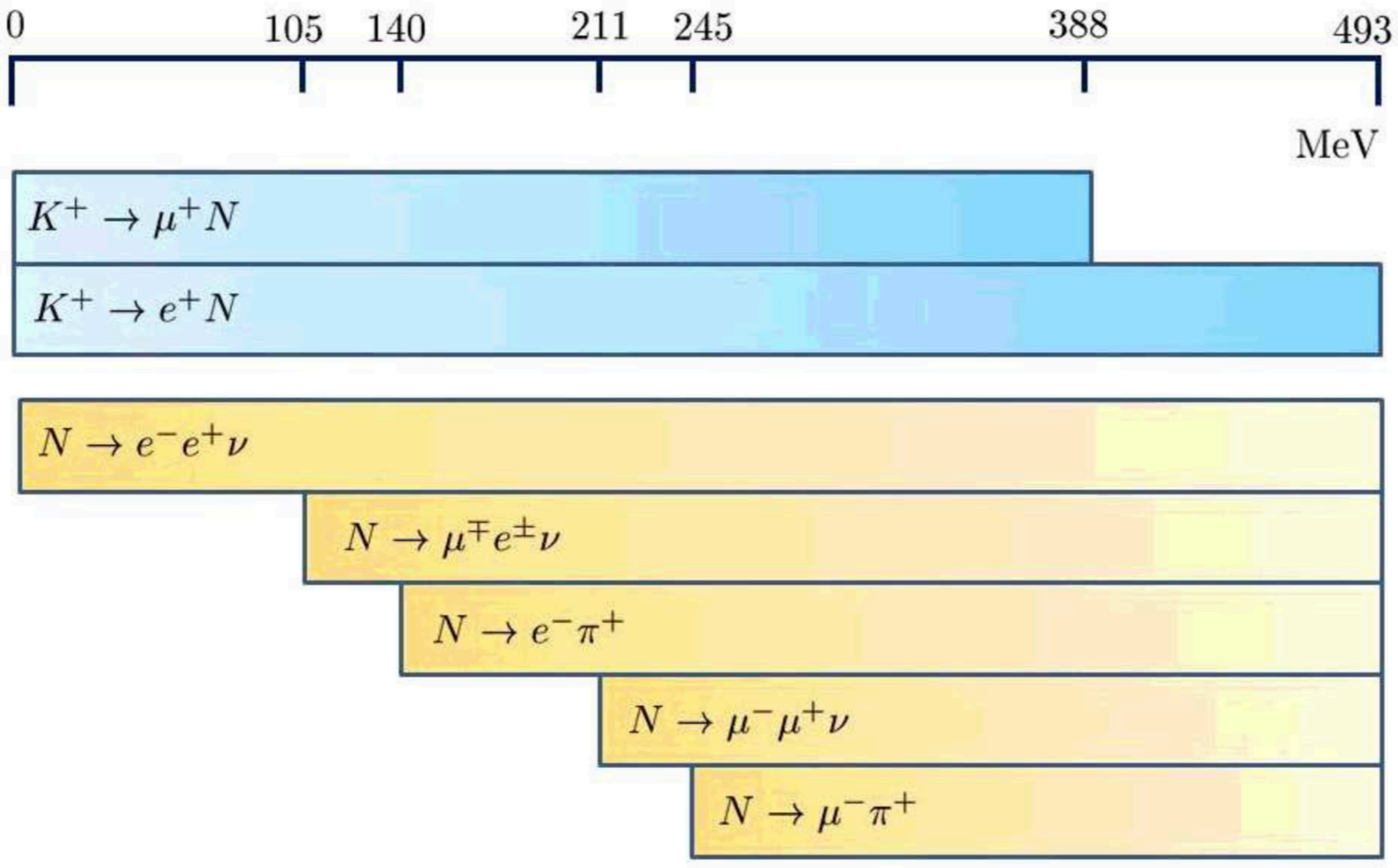

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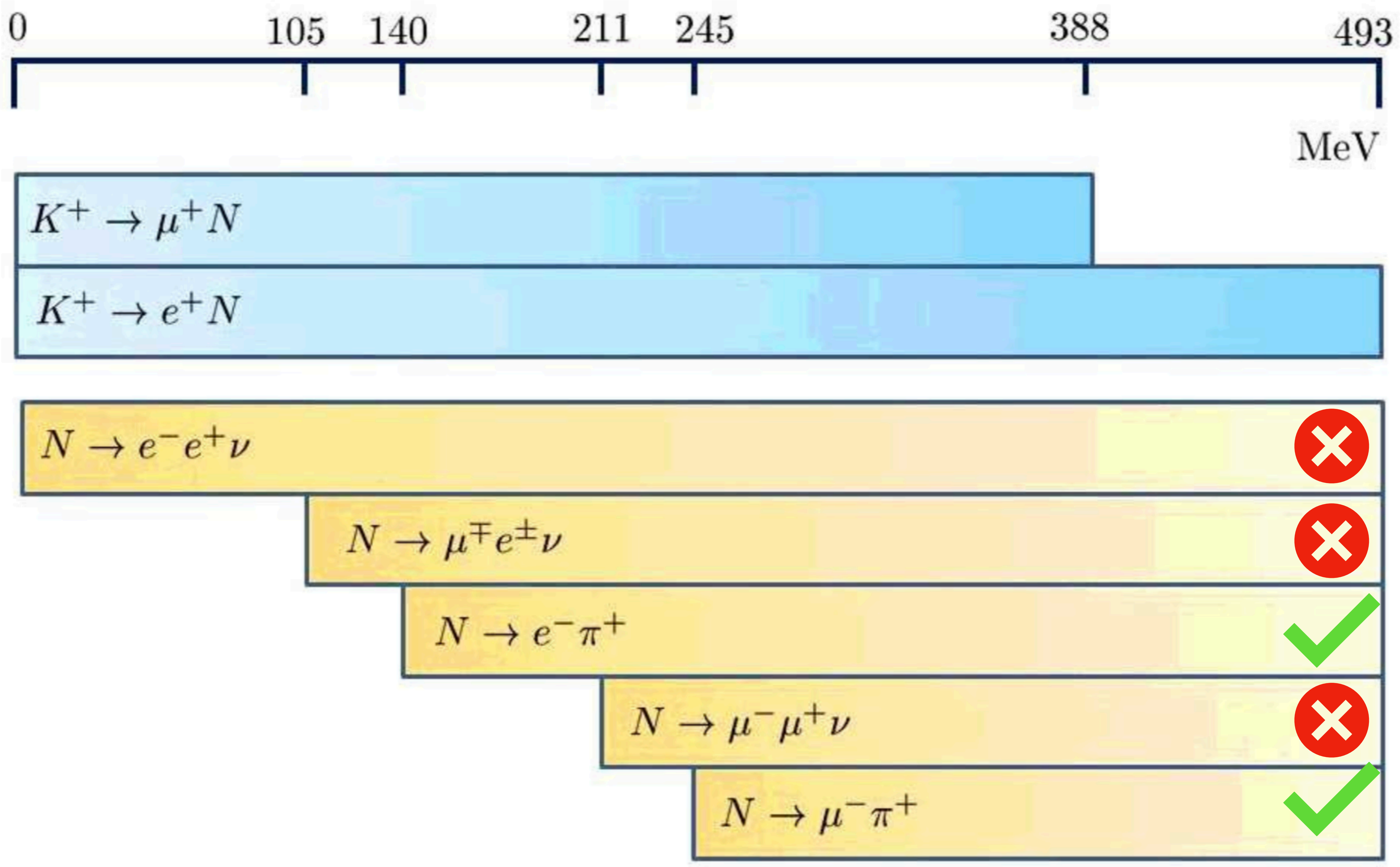
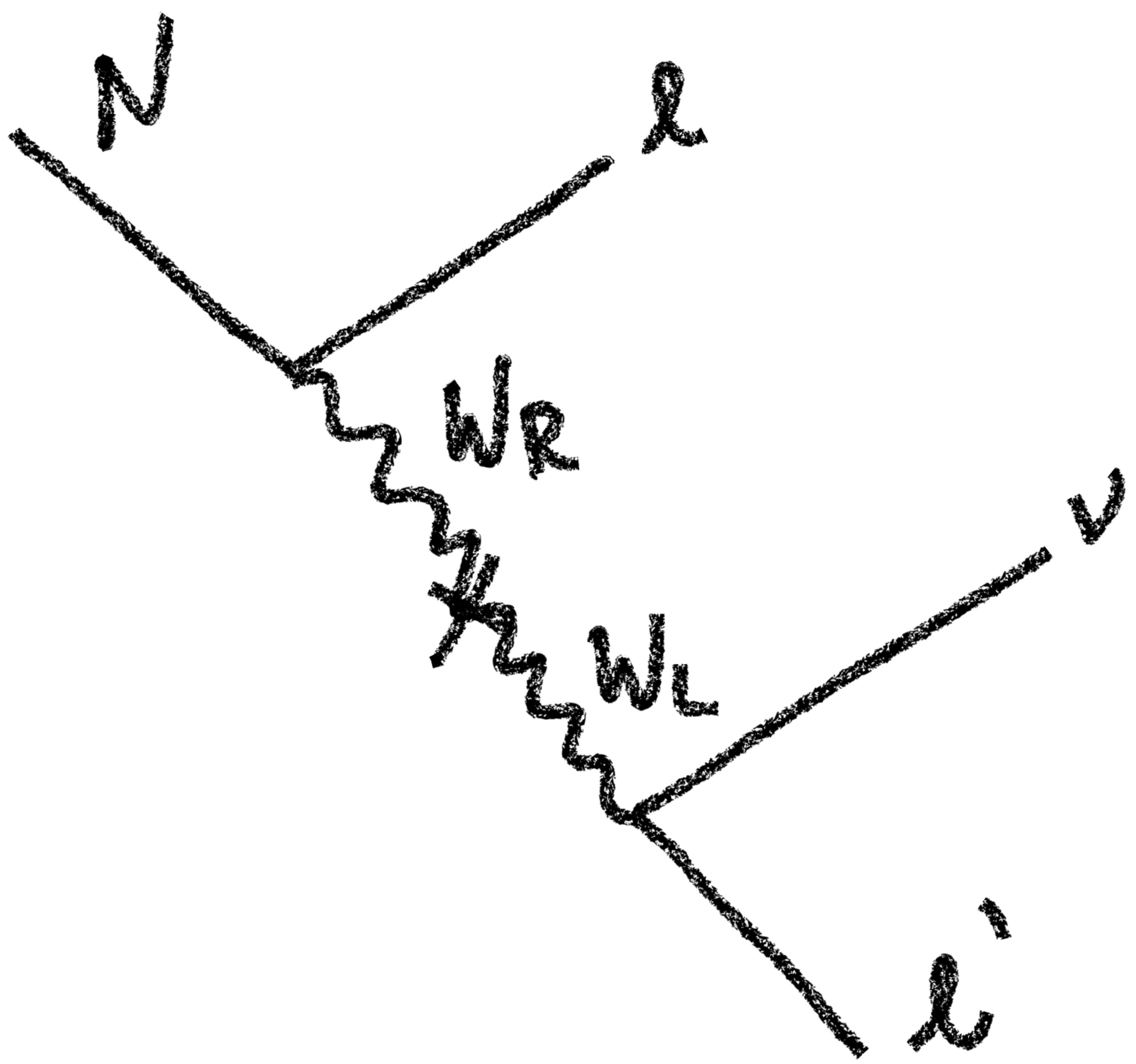
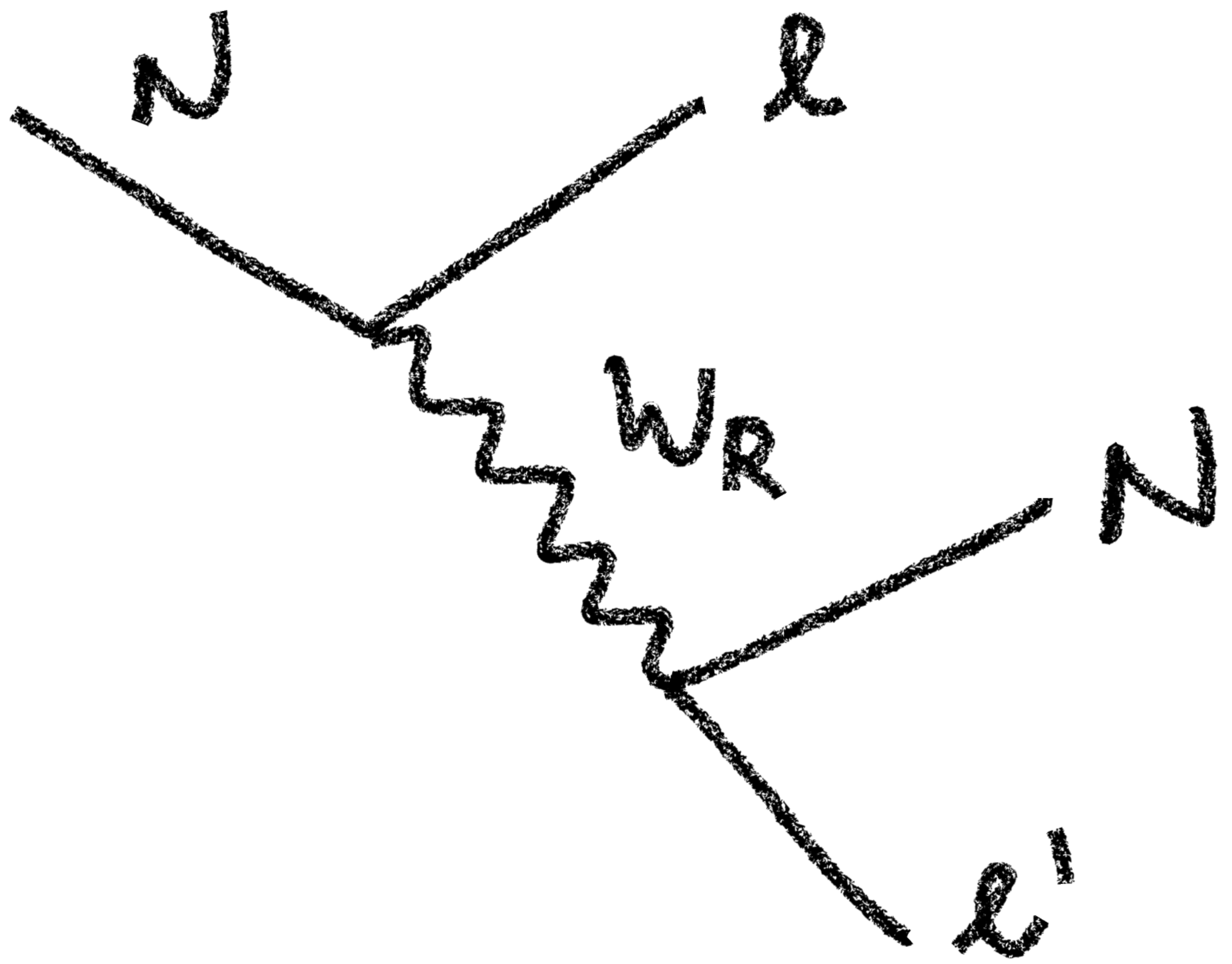


Abe et. al, arXiv:1902.07598
Asaka et. al., arXiv:1212.1062

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

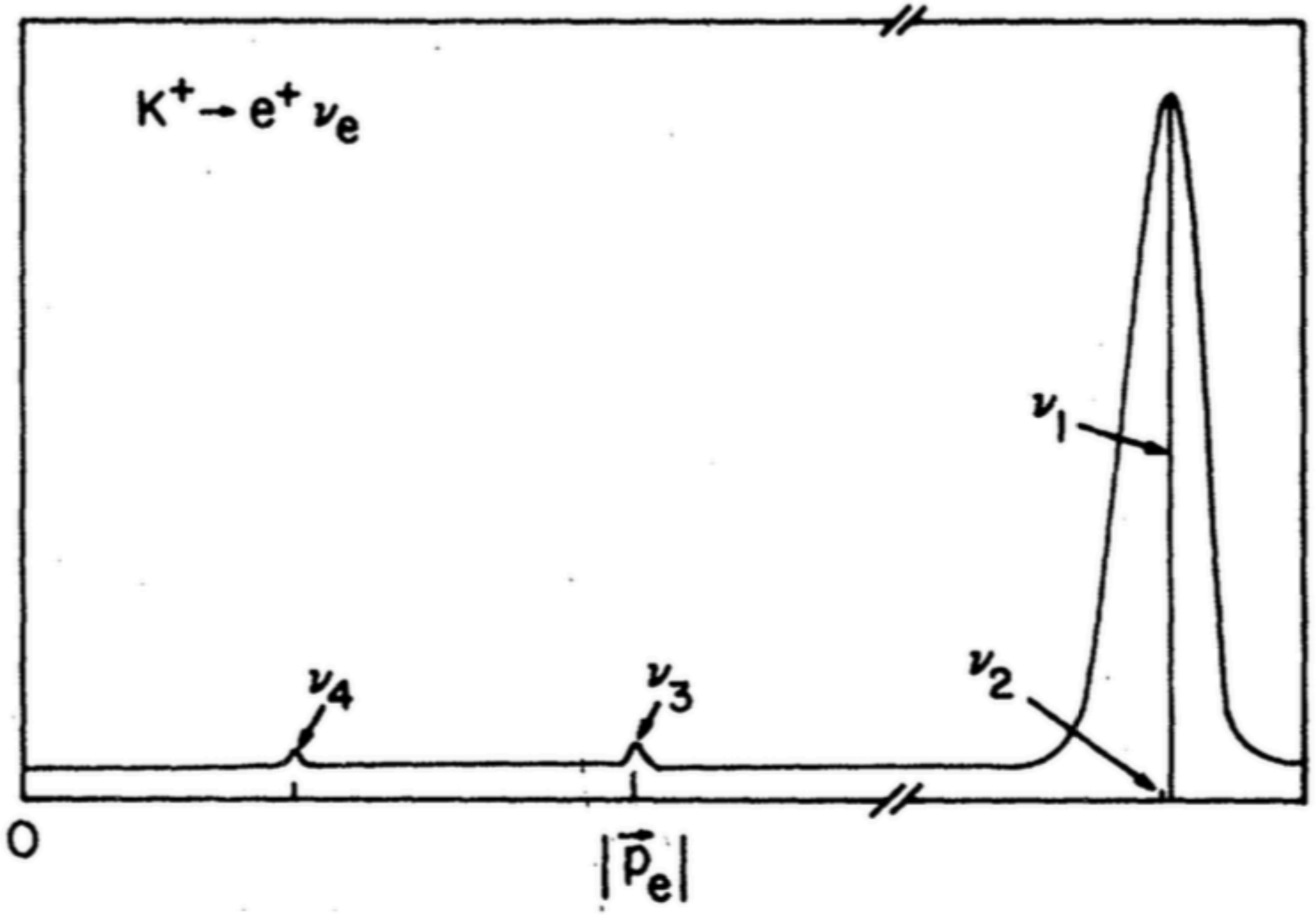
- Emission of massive neutrinos manifest itself indirectly through peaks in the energy spectrum.
- The idea is to compare the experimental ratio with the SM calculation:

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

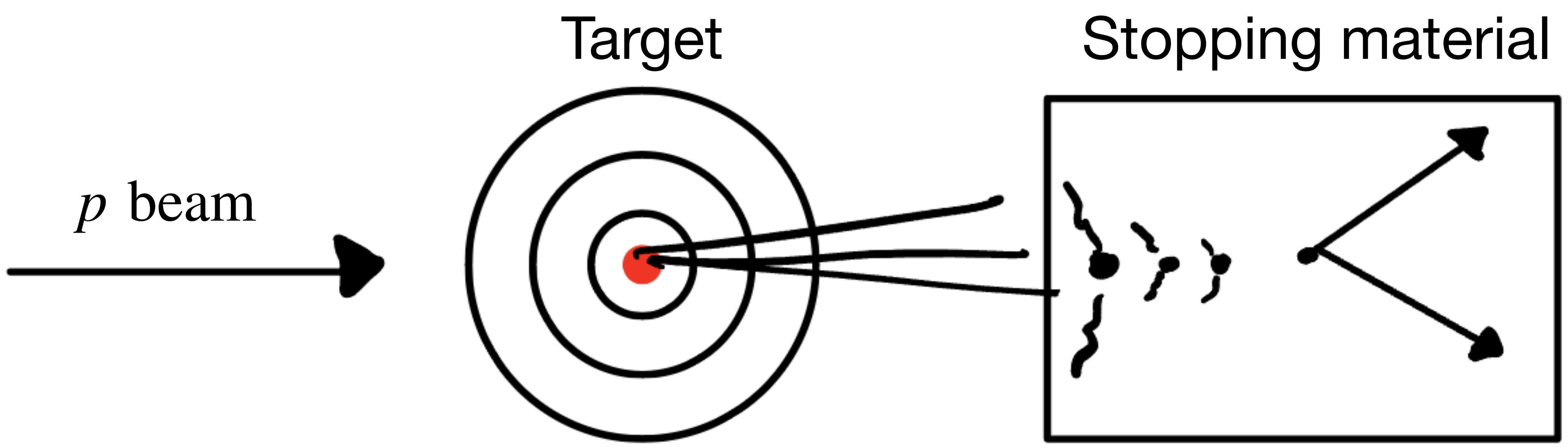
$$\downarrow$$

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

Shrock Phys. Rev. D 24



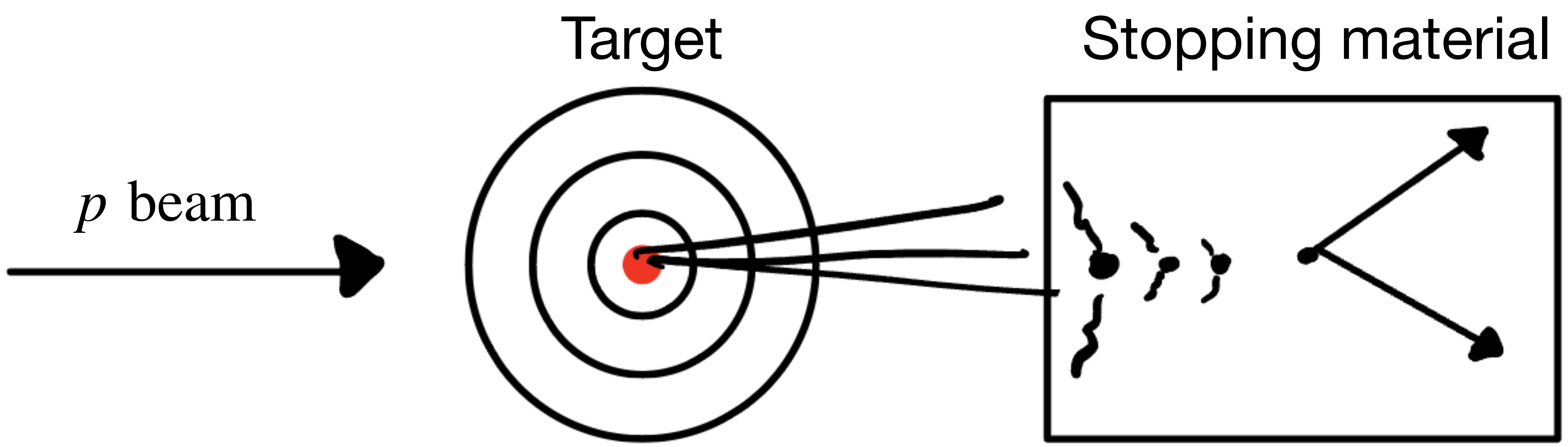
Bird's eye view of the experiment



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

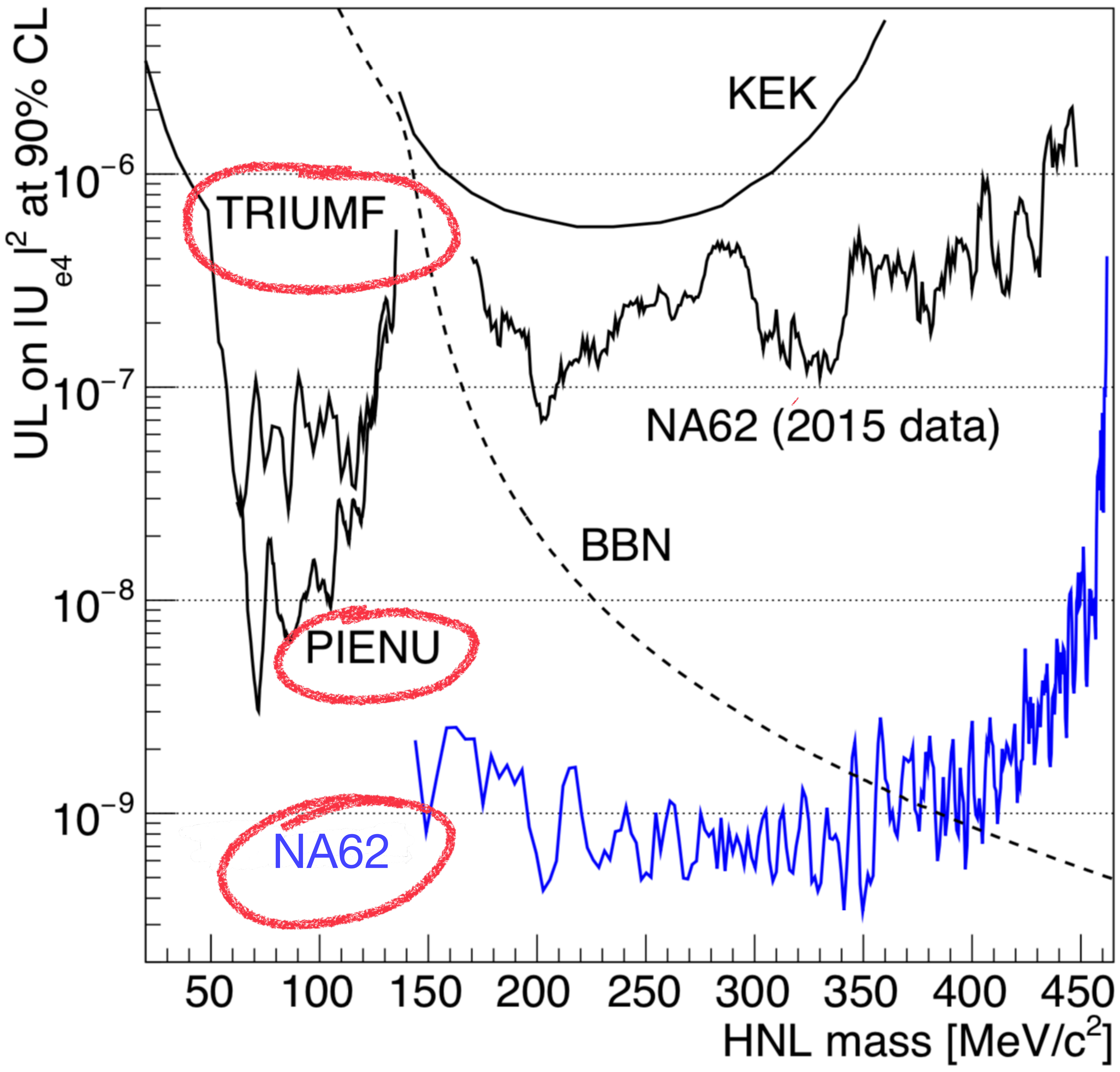
$$E_e = \frac{m_\pi^2 + m_e^2 - m_\nu^2}{2m_\pi} \sim 69.8 \text{ MeV}$$

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:

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

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

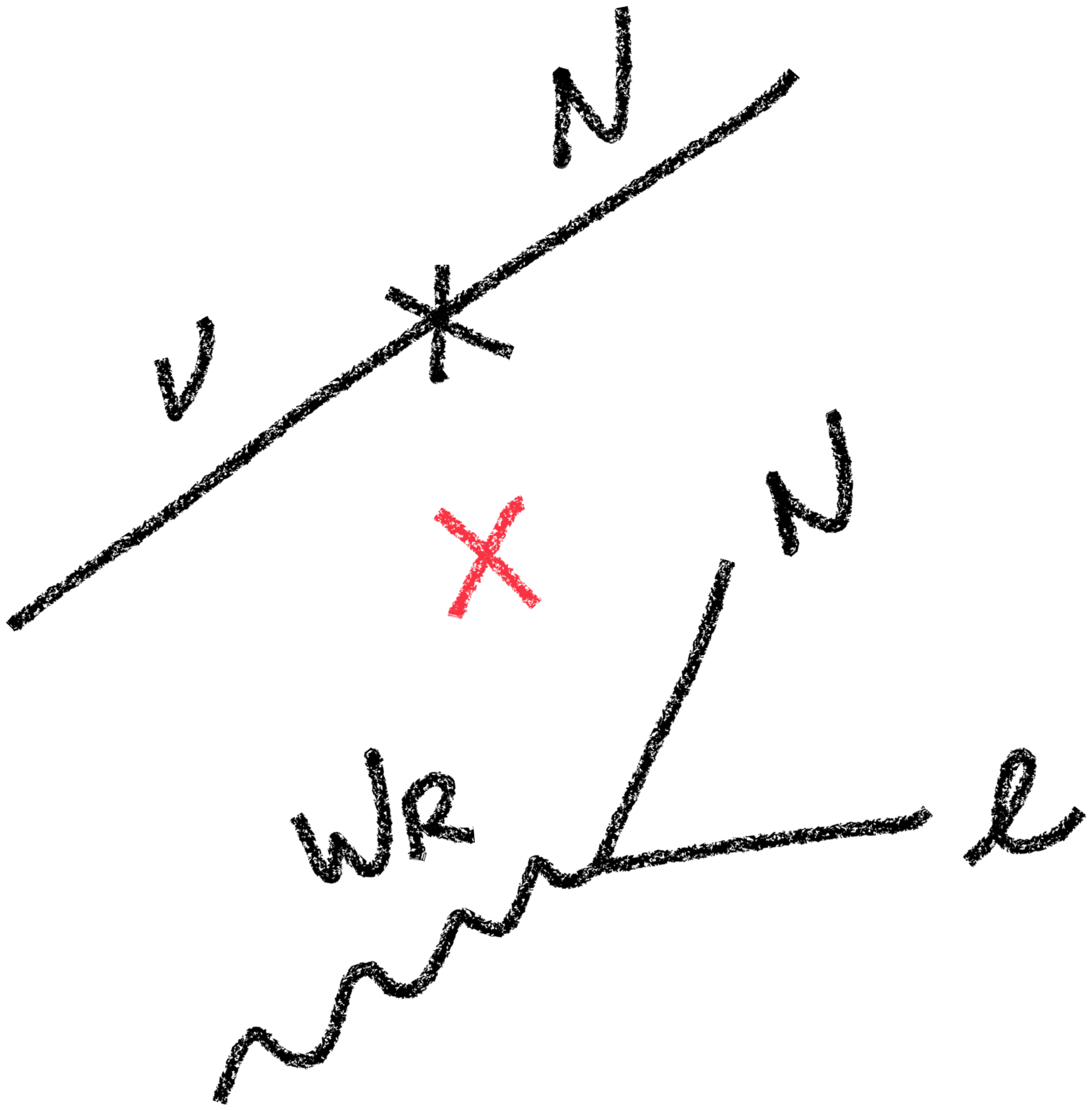
- For the theoretical input we used the SM prediction:

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

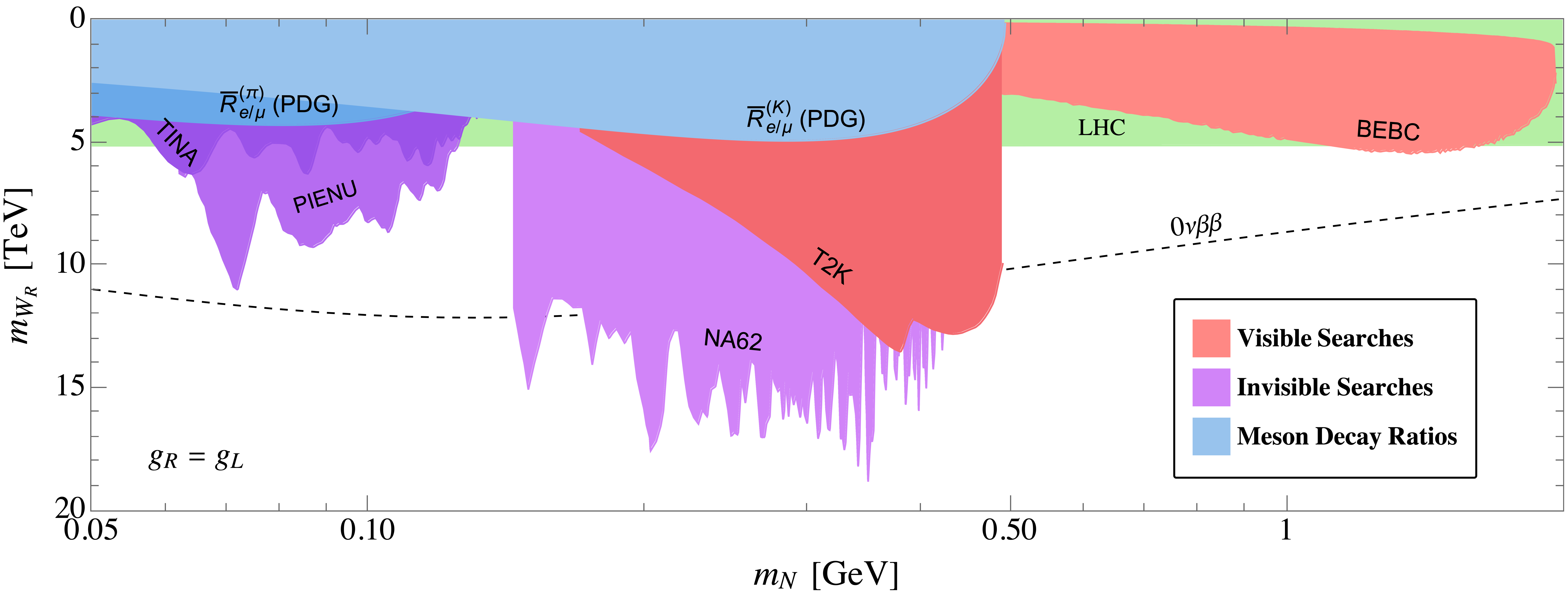
$$R_{e/\mu}^{SM}(K) = (2.477 \pm 0.001) \times 10^{-5}$$

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

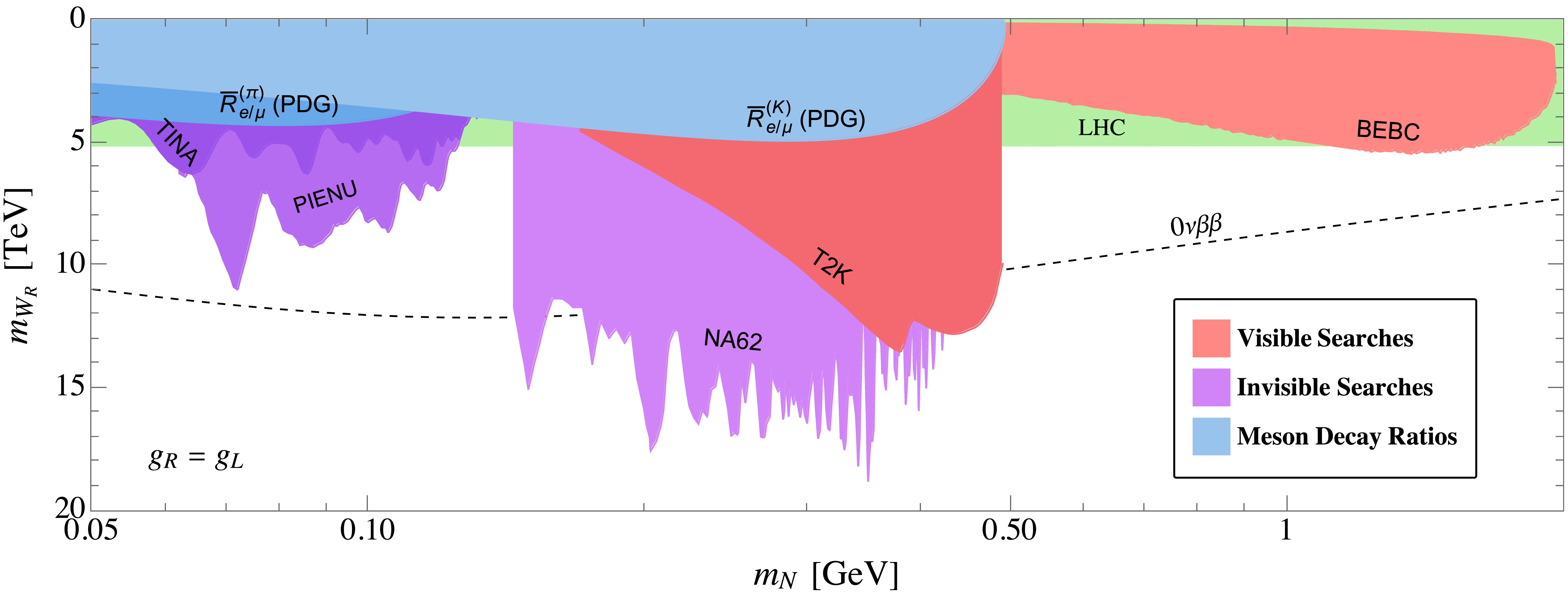
Results



Constraints on a RH current



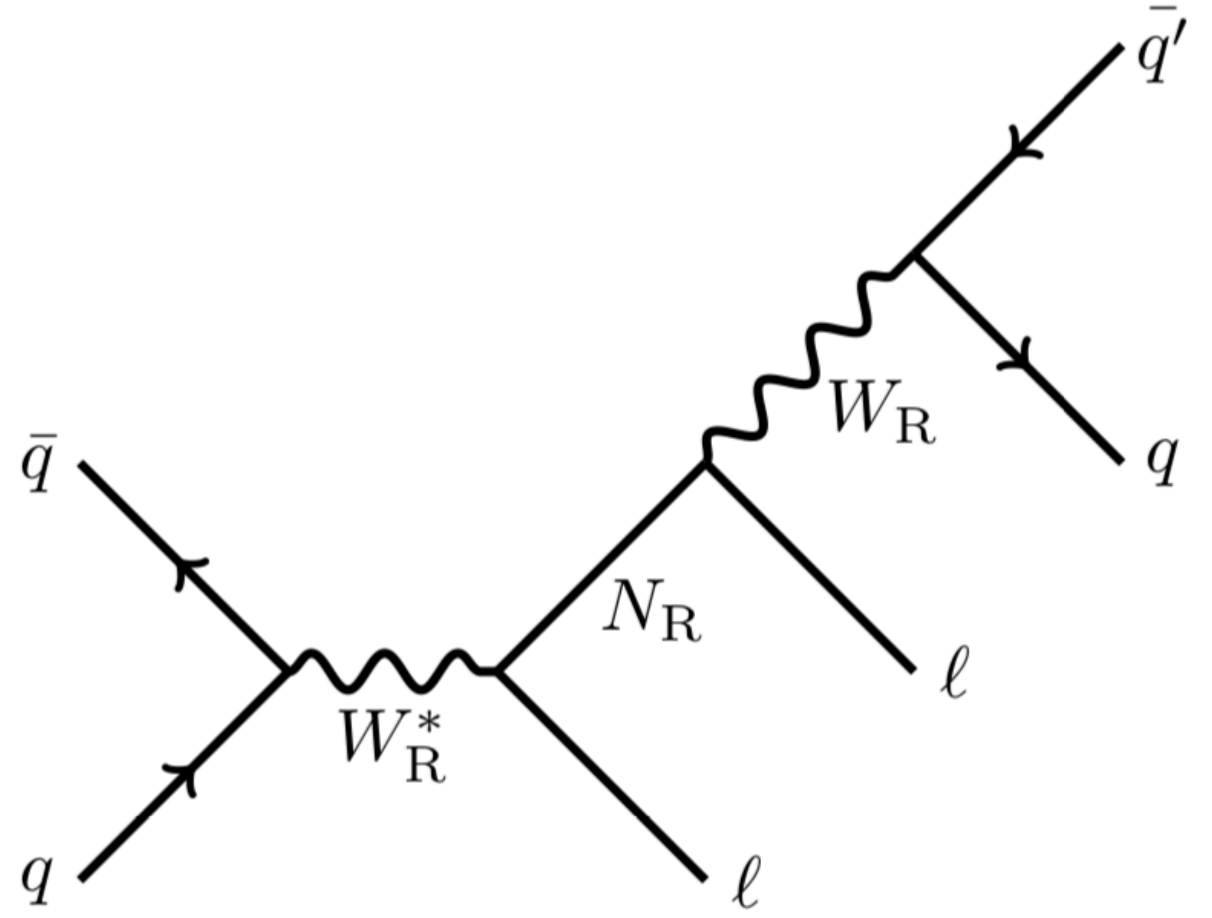
Constraints on a RH current

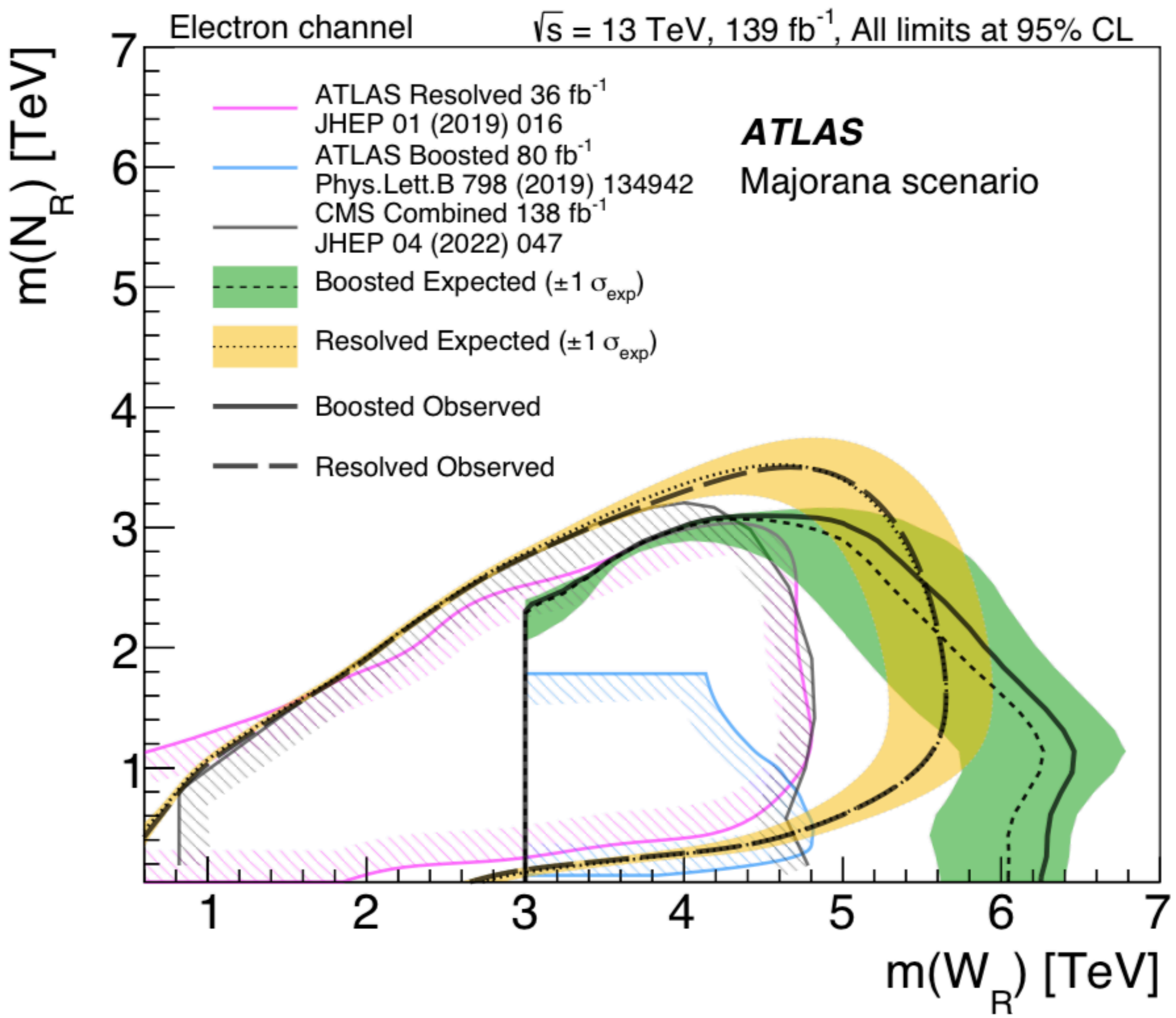


> 4000	95	3 ALVES	2024	RVUE	K and π decays

The LHC bound for heavier HNLs

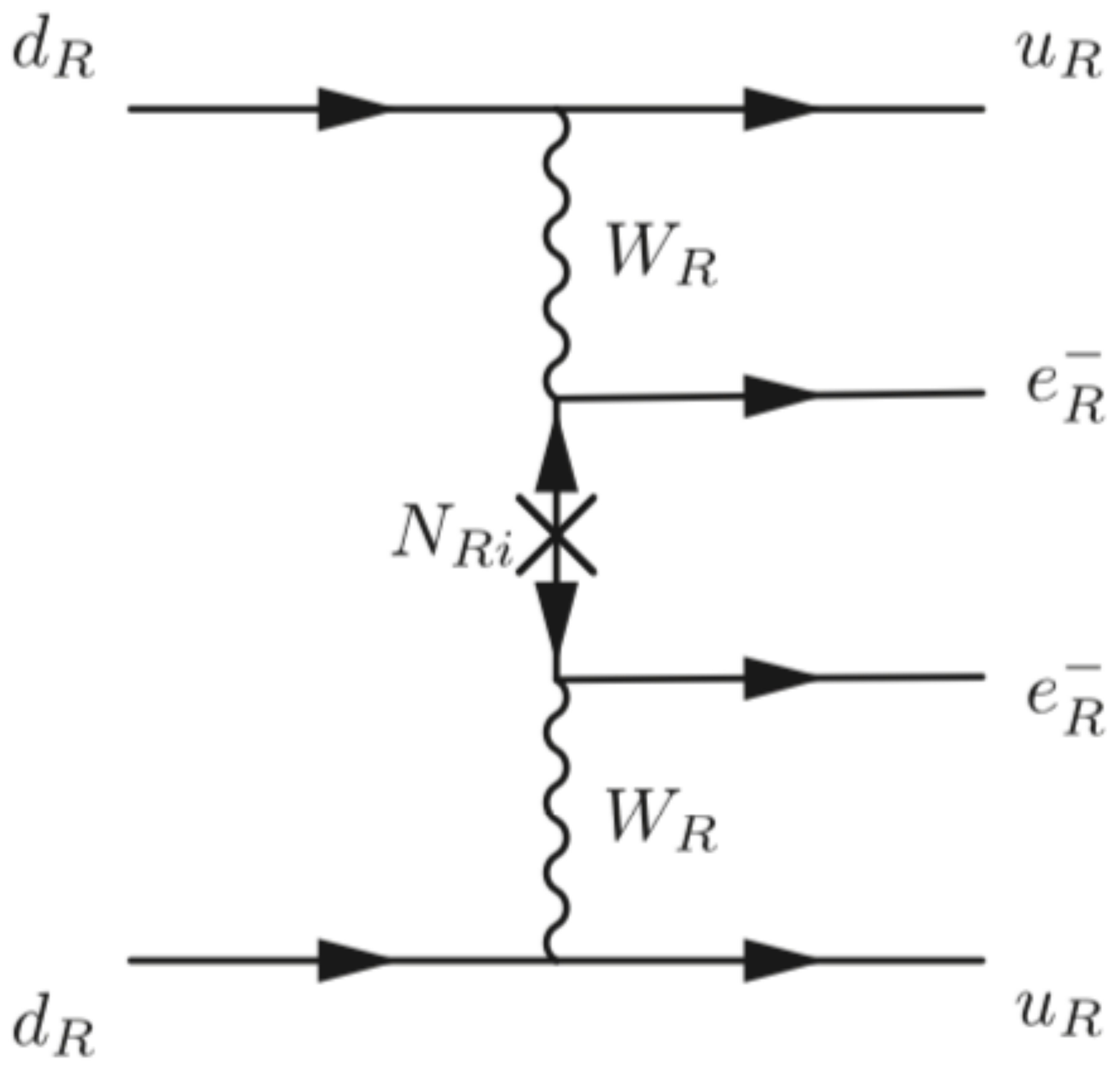
- LHC: Best bounds on m_{W_R}, for HNL in the GeV-TeV mass range.
- Their bound extends up to $m_{W_R} > 6.4$ TeV.

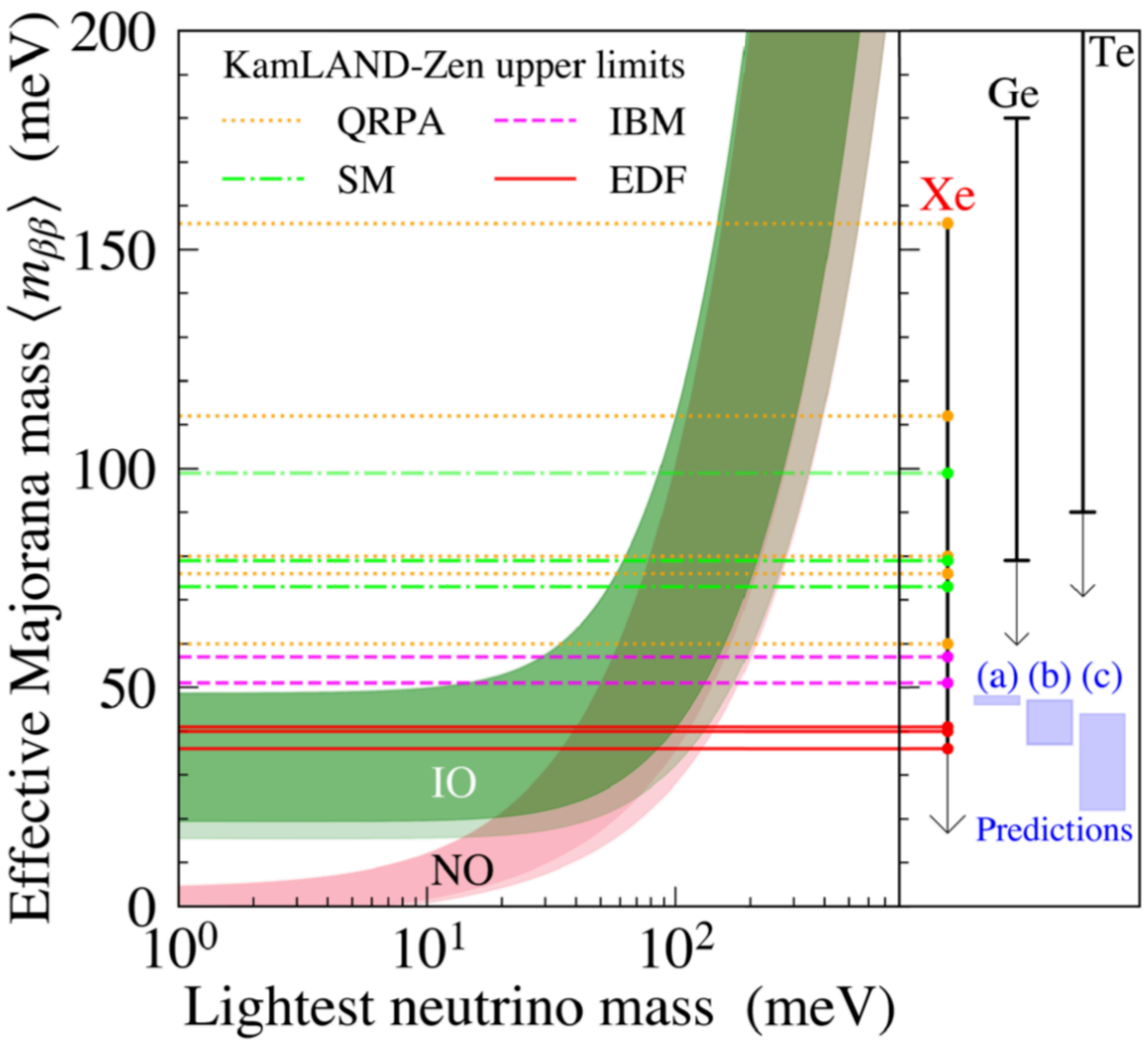




ATLAS, arxiv:2304.09553

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





KamLAND-Zen, arXiv:2203.02139

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.