Heavy Neutral Leptons in Meson Decays

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June 26, 2026

Beyond the SM & Heavy Neutral Leptons

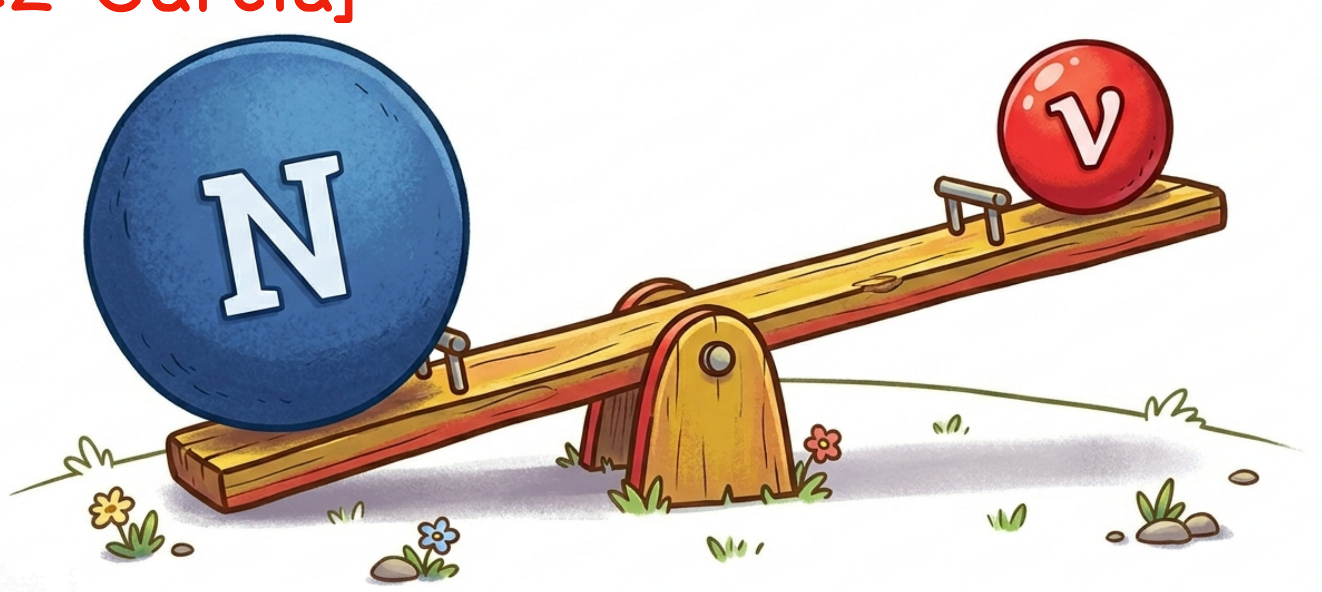
Common feature of BSM constructions: $SU(2)_L \times U(1)_Y$ singlet fermion fields N_R

Majorana mass is allowed

Rational for smallness of neutrino masses (seesaw Mechanism) [Talk K.S. Babu]

Need at least two to explains oscillation data [Talk M.C. Gonzalez-Garcia]

All values of M_N are technically natural



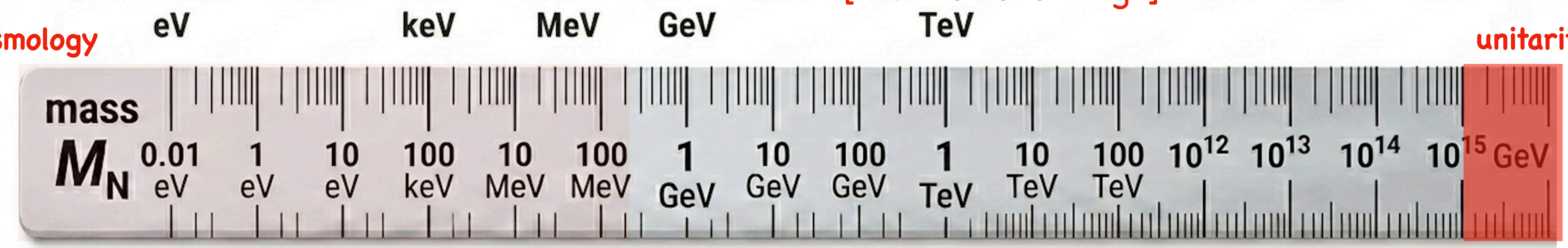
HNL

[Talk M. Hostert]

[Talk Tomoko Ariga]

cosmology

unitarity bound



[F. Maltoni, Niczyporuk, Willenbrock (2001)]

Beyond the SM & Heavy Neutral Leptons

Common feature of BSM constructions: $SU(2)_L \times U(1)_Y$ singlet fermion fields N_R

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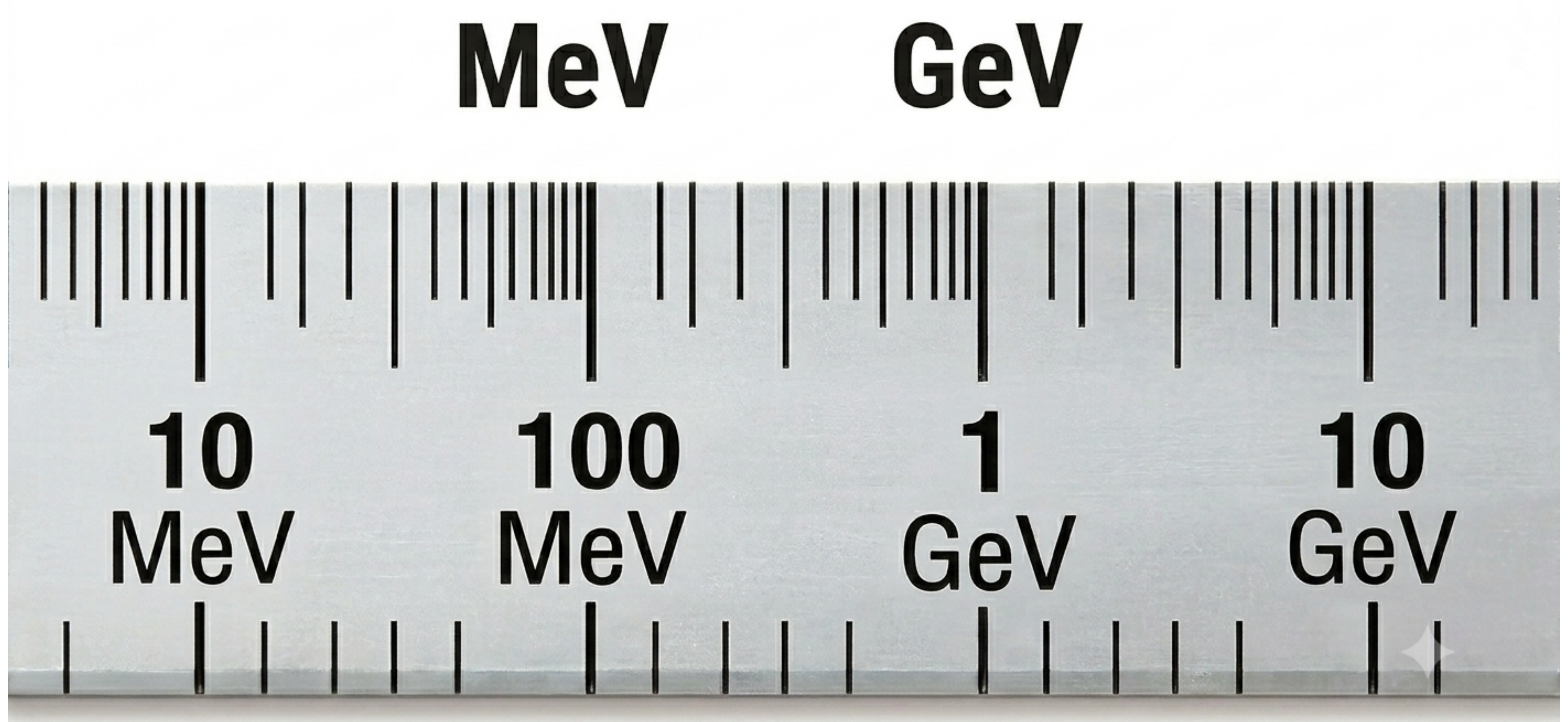
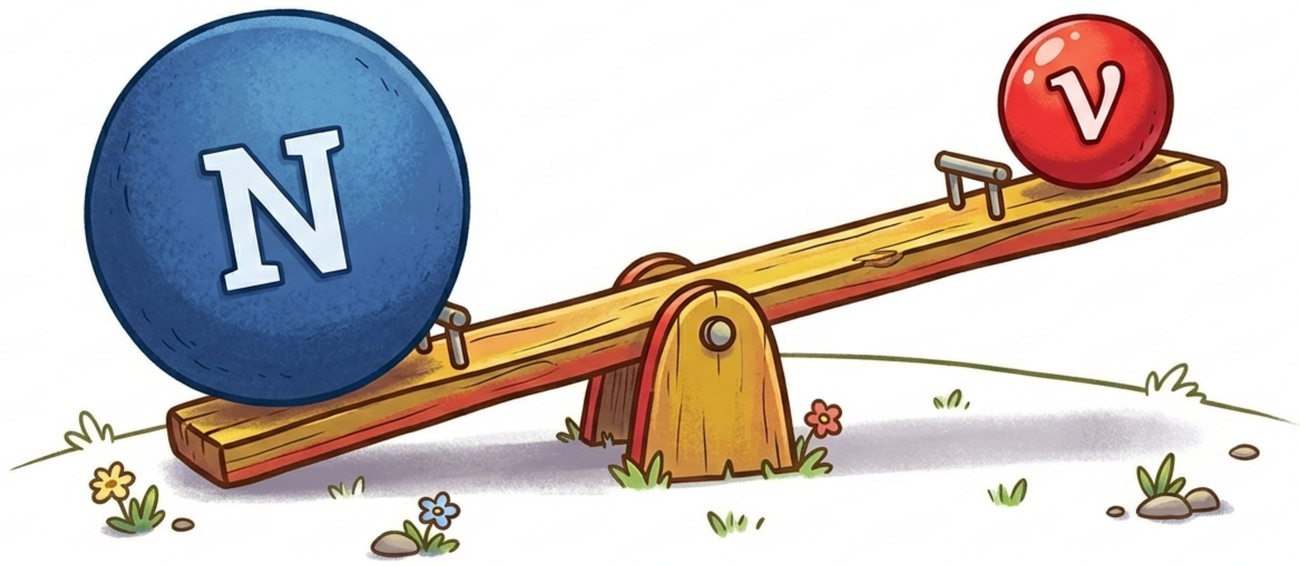
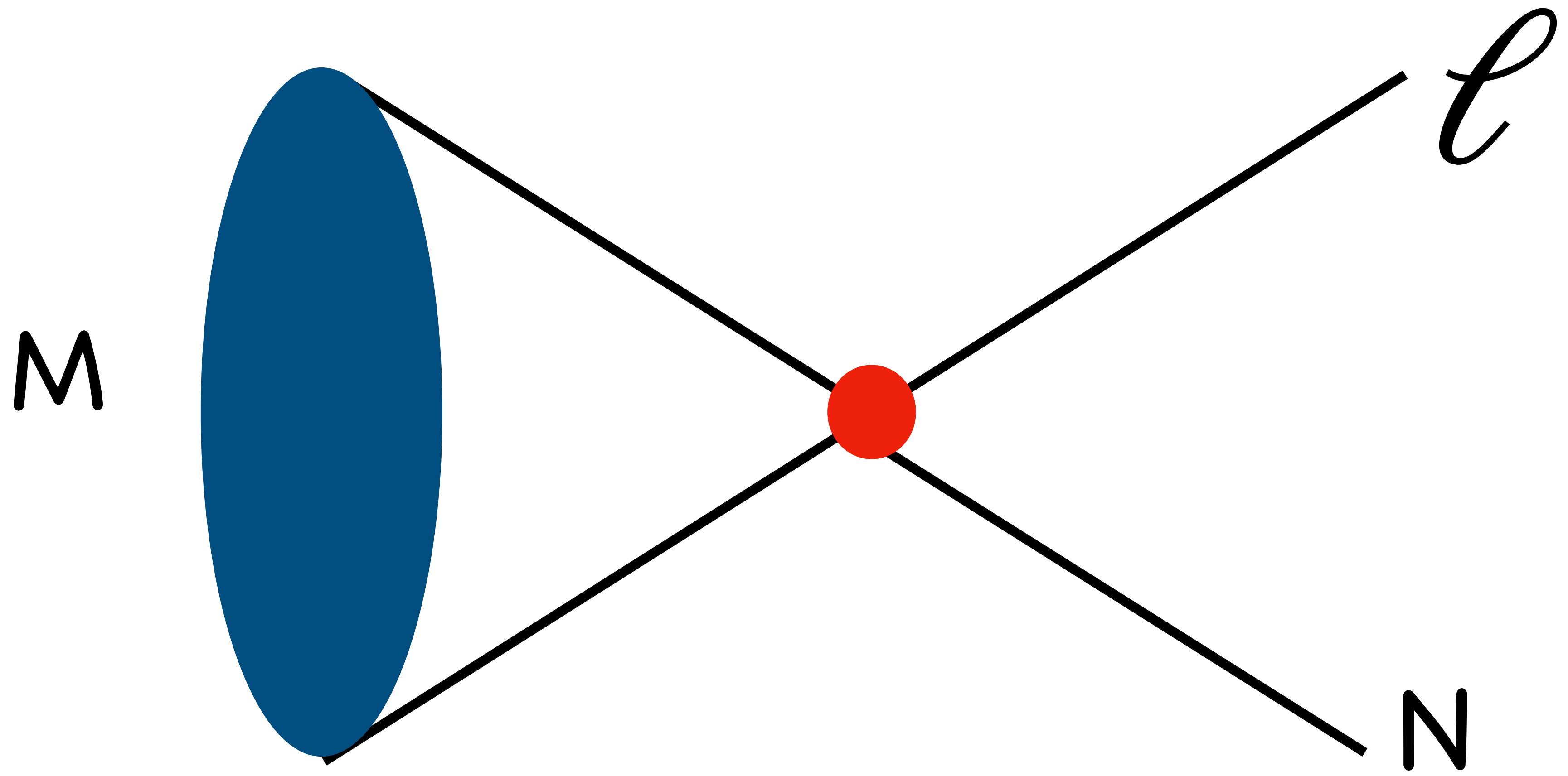
Focus of this talk





can be produced in high intensity accelerators by meson decays

Meson Decay Data



Production By Pseudo-Scalar Meson Leptonic Decays

$$M^\pm \to N + \ell^\pm \qquad \ell = e, \mu\ (\tau) \qquad M = \pi, K, D, B$$

Experiments differ by: energy and intensity of the beam, target material, meson(s) and decay modes selected, detector

Most Relevant Experiments in the 50 MeV-few GeV mass range

- TINA(1992)/PIENU(2018) @ TRIUMF $10^5/10^7\ \pi^+ \to e^+ + N$ decay at rest

  $50 < m_N/\mathrm{MeV} < 130$

- CHARM(1986)/BEBC(1986) @ CERN $\sim 2 \times 10^{18}$ POT (each)

  $D^\pm \to \ell^\pm + N$ decays-in-flight $250 < m_N/\mathrm{MeV} < 2000$

- NuTeV (1999) @FNAL $\sim 3 \times 10^{18}$ POT

  $D^\pm, K^\pm \to \mu^\pm + N$ decays-in-flight $200 < m_N/\mathrm{MeV} < 2000$

Production By Pseudo-Scalar Meson Leptonic Decays

$M^\pm \to N + \ell^\pm \qquad \ell = e, \mu, (\tau) \qquad M = \pi, K, D, B$

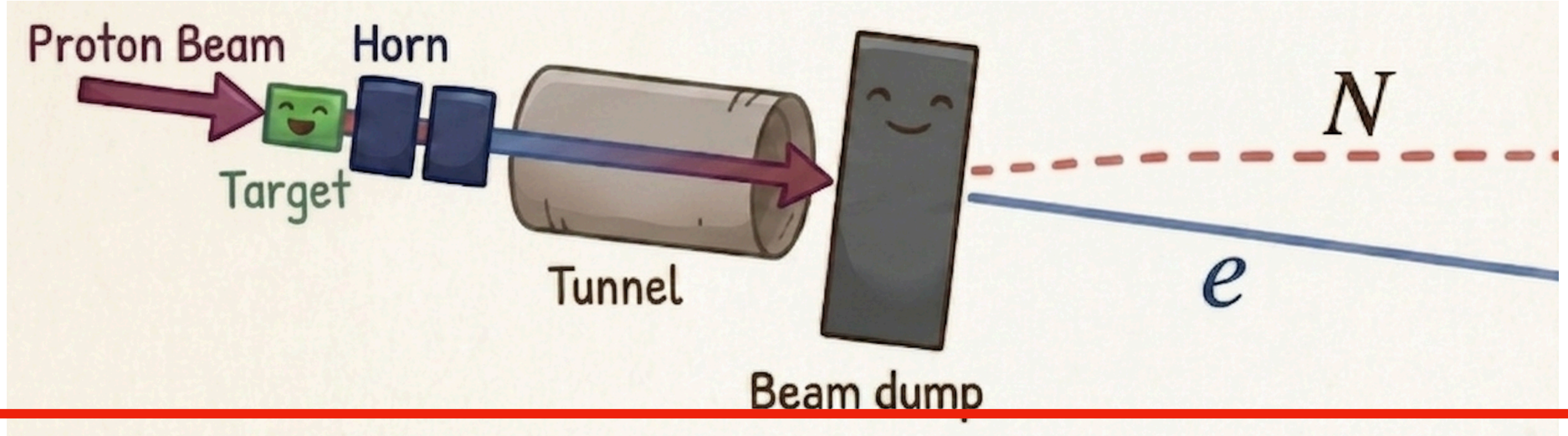
Experiments differ by: energy and intensity of the beam, target material, meson(s) and decay modes selected, detector

- E949 (2009) @ BNL $\sim 10^{12}$ stopped K^+

$180 < m_N/\text{MeV} \lesssim 300$

- T2K (2019) @ J-PARC $\sim 12.34\,(6.29) \times 10^{20}$ POT in neutrino (antineutrino) mode

$K^\pm \to \ell^\pm + N$ decays-in-flight $140 < m_N/\text{MeV} < 493$



Production By Pseudo-Scalar Meson Leptonic Decays

$M^\pm \to N + \ell^\pm \qquad \ell = e, \mu, (\tau) \qquad M = \pi, K, D, B$

Experiments differ by: energy and intensity of the beam, target material, meson(s) and decay modes selected, detector

- NA62 (2020) & (2025) @ CERN

  $\sim 10^{12}\, K^+$ decays in flight in fiducial volume

  $144 < m_N/\mathrm{MeV} < 462$

  $\sim 10^{12}\, \pi^+$ decays in flight in fiducial volume

  $95 < m_N/\mathrm{MeV} < 126$

- Belle (2007) @ KEK $\quad e^+e^- \to \Upsilon(4S) \qquad \sim 3\times 10^8\, B^+B^-$ events

  $B^+ \to N + \ell^+ \qquad B^0 \to K^{*0} + \mathrm{inv}$ **this is the only collider experiment**

How do they detect N ?

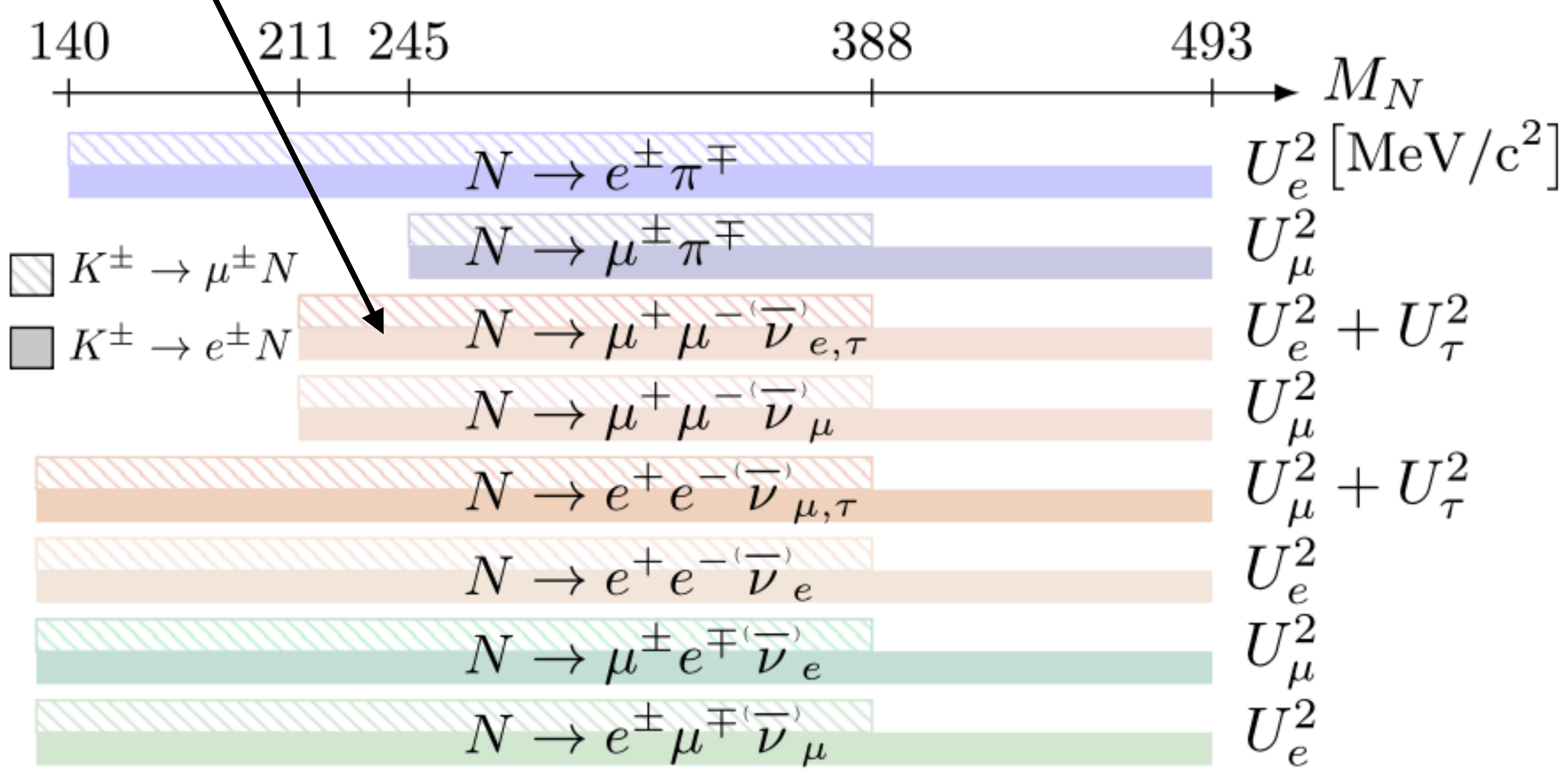
Visible Searches : CHARM(1986), BEBC(1985), NuTeV(1999) T2K(2019)

CHARM $D^{\pm} \to \ell^{\pm} + N$ only 3-body decay modes

BEBC 2 and 3-body decay modes

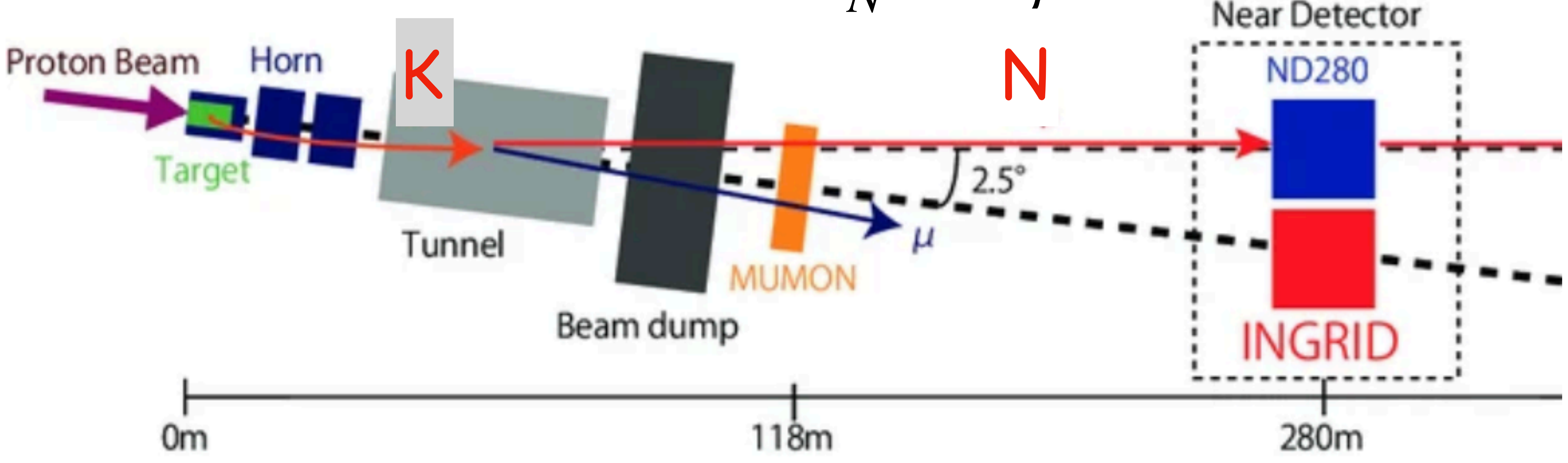
NuTeV 3-body with a final state μ

Decay modes @T2K/ND280



depends on the model

T2K $K^{\pm} \to \ell^{\pm} + N$ $\tau_N \gg 1 \mu s$



How do they detect N ?

Invisible Searches : TINA(1992), PIENU(2018), E949(2009), NA62(2020,2025)

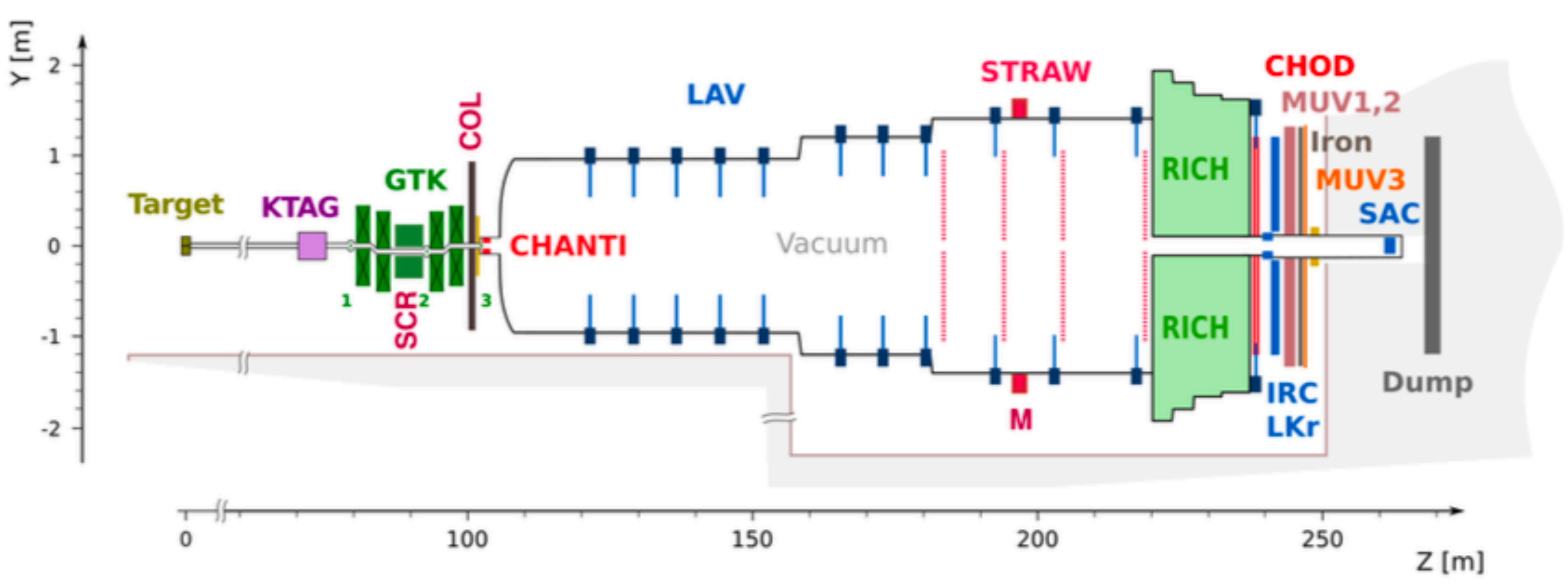
TINA/PIENU $\pi^+ \to N + e^+$ $E_{e^+} = 69.8 \text{ MeV}$

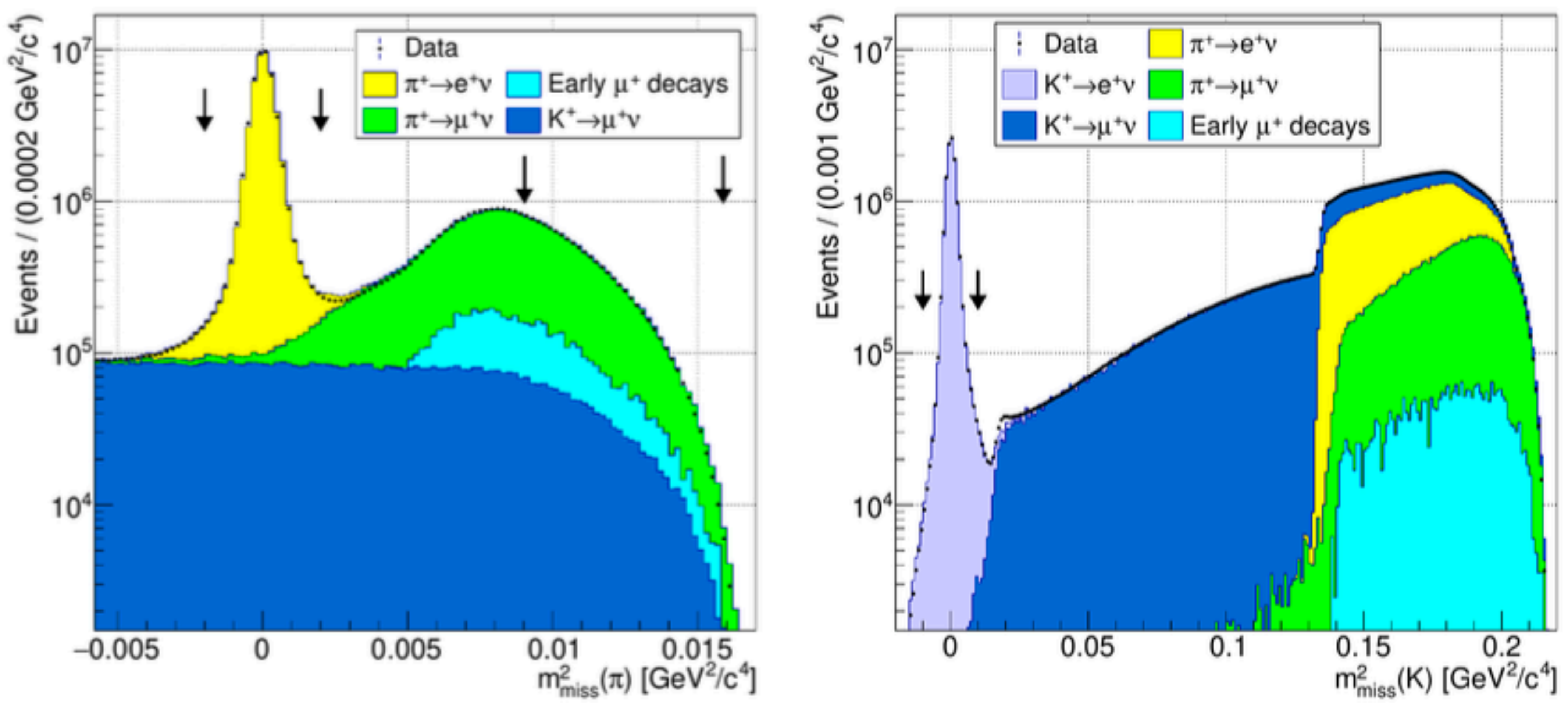
E949 $K^+ \to N + \mu^+$ $E_{\mu^+} = 258.2 \text{ MeV}$

NA62 $M^+ \to N + e^+$ $M = K, \pi$

Peak searches

[Shrock (1980, 1981)]





do the analysis for several HNL mass hypothesis

$$m^2_{\text{miss}} = (p_M - p_\ell)^2$$

How do they detect N ?

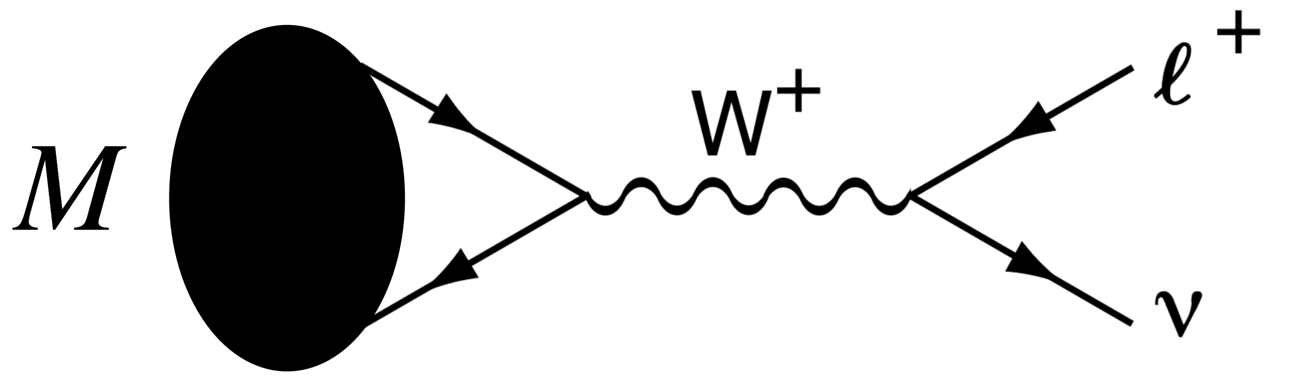
Charged Meson Decay Ratios

[Shrock (1980, 1981)]

[Bryman, Shrock (2019)]

$$R_{e/\mu}(M) = \frac{1 + R_{N/\nu_e}(M)}{1 + R_{N/\nu_\mu}} R^{\rm SM}_{e/\mu}(M)$$

$\ell = e, \mu \qquad M = \pi, K$



Universality Tests

$$R_{N/\nu_\ell}(M) \equiv \frac{\mathscr{B}(M \to \ell N)}{\mathscr{B}^{\rm SM}(M \to \ell \nu_\ell)} \qquad m_N \leq m_M - m_\ell$$

$$R^{\rm SM}_{e/\mu}(M) \equiv \frac{\mathscr{B}^{\rm SM}(M \to e\nu_e)}{\mathscr{B}^{\rm SM}(M \to \mu\nu_\mu)}$$

[PDG]

$$R^{\rm exp}_{e/\mu}(\pi) = (1.2327 \pm 0.0023) \times 10^{-4}$$

$$R^{\rm exp}_{e/\mu}(K) = (2.488 \pm 0.009) \times 10^{-5}$$

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

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

[Cirigliano, Rosell (2007)]

Scenario I: Flavor Mixing

HNL by Active-Sterile Mixing

Extend the SM particle content by a single HNL

$$\mathscr{L}_{\rm SM} + i\overline{N'}\partial\!\!\!/ N' - \left(\frac{M_N}{2} \overline{N'^c} N' + \sum_\ell Y_\ell \overline{L}_\ell \tilde{H} N' + \mathrm{h.c.} \right)$$

L_ℓ = SM lepton doublets

H = SM Higgs doublet

$\tilde{H} = i\tau^2 H \quad N^c = C\overline{N}^T$

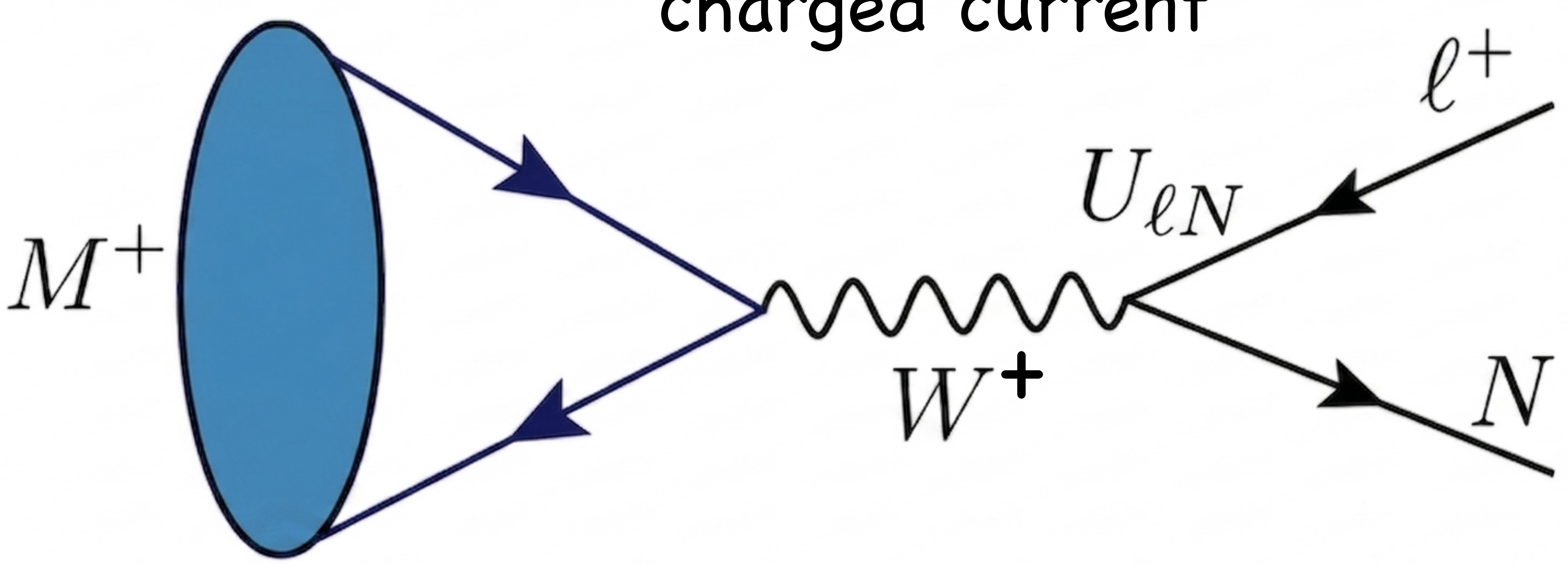
seesaw Lagrangian (d=4)

$\ell = e, \mu, \tau$

$$\nu_{\ell L} = \sum_{i=1}^{3} U_{\ell i} \nu_{iL} + U_{\ell N} N^c$$

flavor eigenstates

mass eigenstates



N takes part in any process SM neutrinos appear

R. Zukanovich Funchal

Best Active-Sterile Mixing Limits

[Fernández-Martínez, González-López, Hernández-García, Hostert and López-Pavón (2023) (updated)]

Scenario II: Minimal Left-Right Symmetric Model

HNL in the mLRSM

[Pati, Salam (1974)] [Mohapatra, Pati(1975)]
[Mohapatra, Senjanovic (1975),(1980),(1981)]

Minimal Left-Right Symmetric Model (mLRSM)

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

fermion doublets:

$$L_{\ell L} = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}_L \qquad L_{\ell R} = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}_R$$

$$Q_{\alpha L} = \begin{pmatrix} u_\alpha \\ d_\alpha \end{pmatrix}_L \qquad Q_{\alpha R} = \begin{pmatrix} u_\alpha \\ d_\alpha \end{pmatrix}_R$$

scalar sector:			vevs
	ϕ	bi-doublet	κ_1, κ_2
	$\Delta_{R,L}$	triplet	$\mathrm{v_R}, \mathrm{v_L}$

gauge sector:

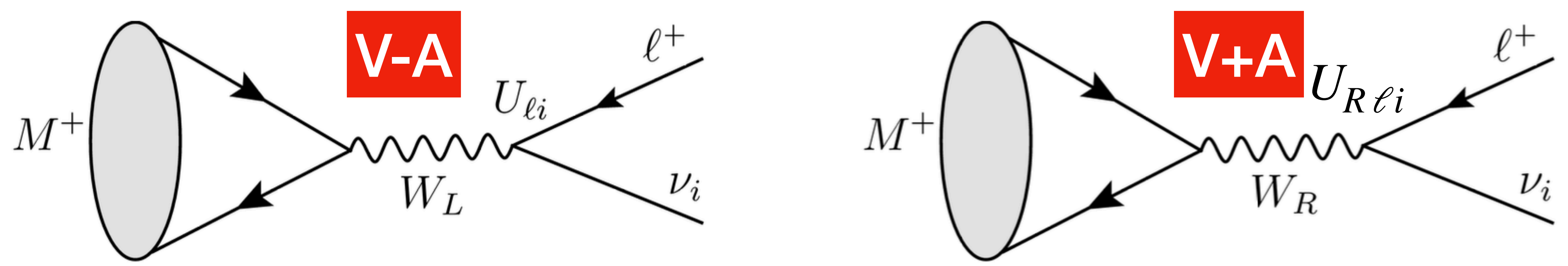
2 neutral bosons - Z_L, Z_R

2 charged bosons - $W_L^\pm, W_R^\pm$

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{\mathrm{v_R}} SU(2)_L \times U(1)_Y \xrightarrow{\mathrm{v_L}, \kappa_1, \kappa_2} U(1)_{\mathrm{em}} \qquad \mathrm{v_R^2} \gg \kappa_1^2 + \kappa_2^2 = \mathrm{v}^2 \gg \mathrm{v_L^2}$$

V+A Current Domination

if $\xi = \kappa_2/\kappa_1 \to 0$ then W_L & W_R do not mix



two charged current contributions

We consider

$$|U_{\ell N}|^2 \ll \left(\frac{G'_F}{G_F}\right)^2 \equiv \left(\frac{m_{W_L}\, g_R}{m_{W_R}\, g_L}\right)^4 \sim 7\times 10^{-8} \left(\frac{5\ \text{TeV}}{m_{W_R}}\right)^4 \left(\frac{g_R}{g_L}\right)^4$$

can recast limits as

active-sterile mixing domination $$\left(\frac{g_L}{m_{W_L}}\right)^4 |U_{\ell N}|^2 \to \left(\frac{g_R}{m_{W_R}}\right)^4$$ RH current domination

assuming N_1, N_2, N_3 are degenerate in mass

Limits on m_{W_R}

[G.F.S. Alves, C.S. Fong, L.P.S. Leal, RZF (2024) (updated)]

Limits on m_{W_R}

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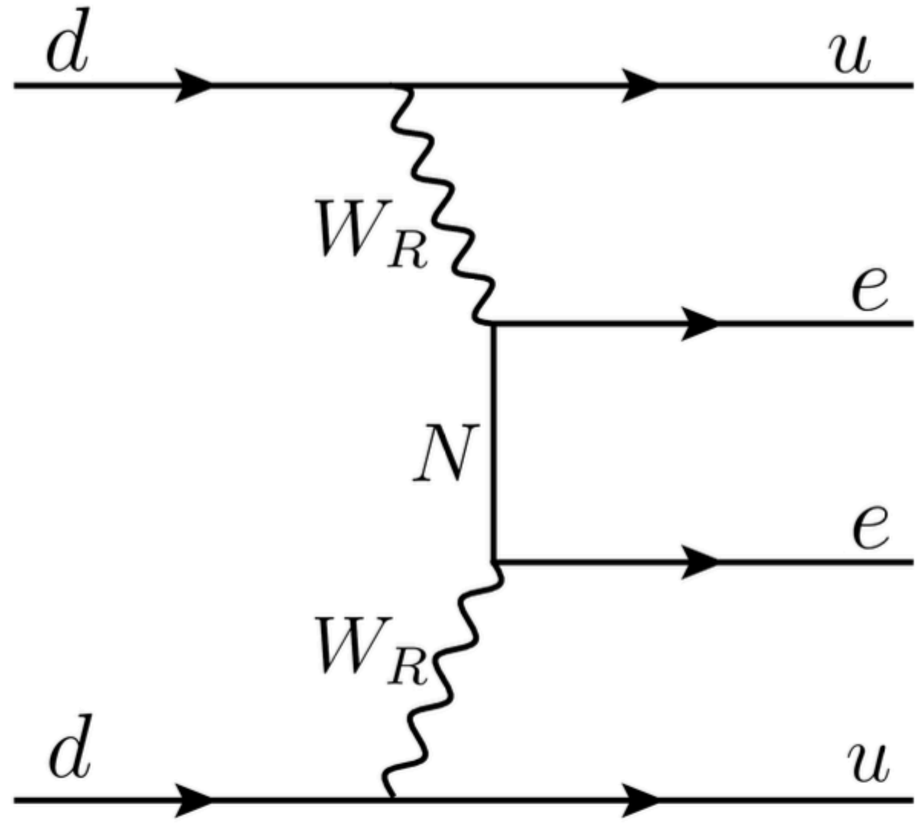
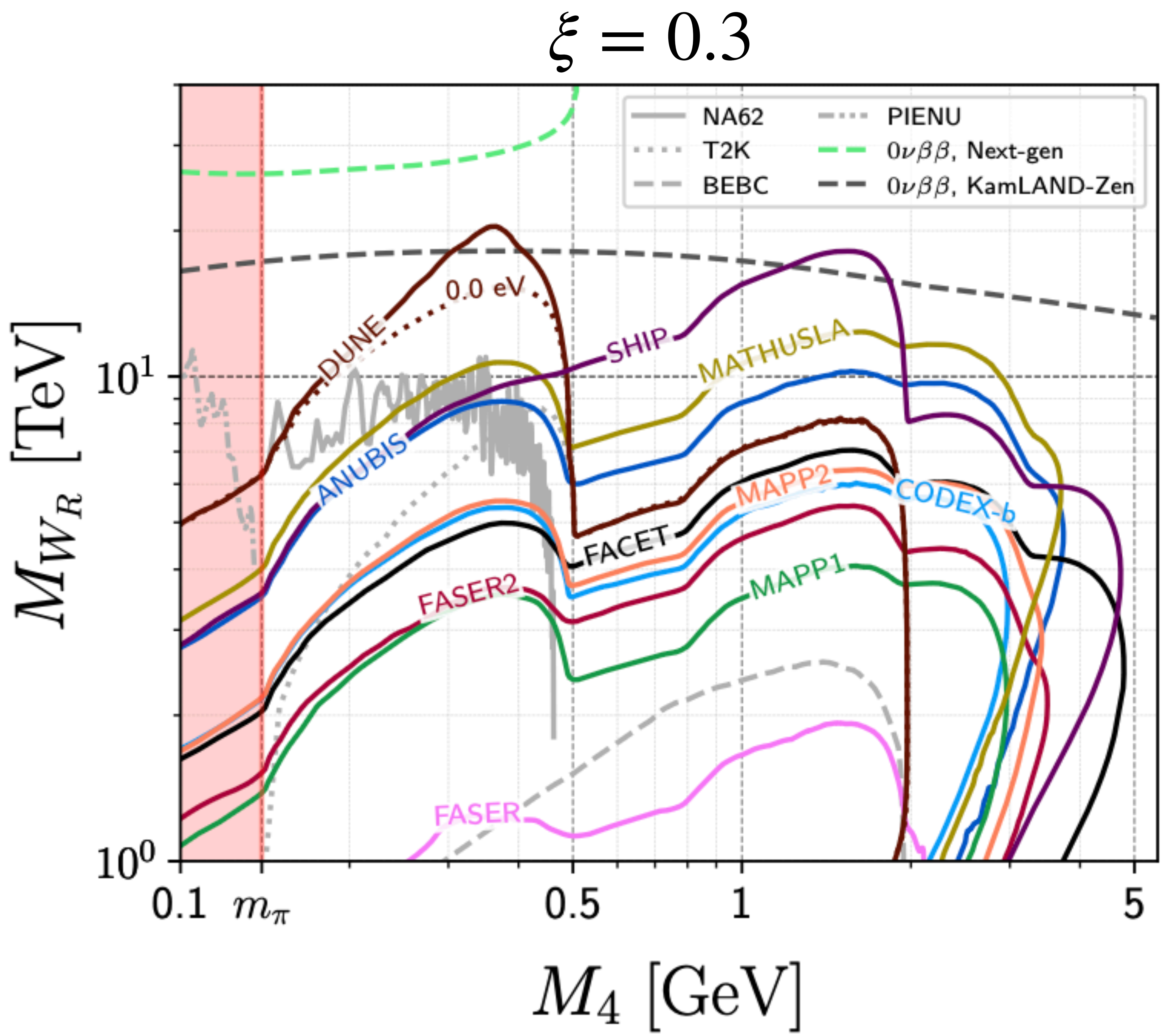
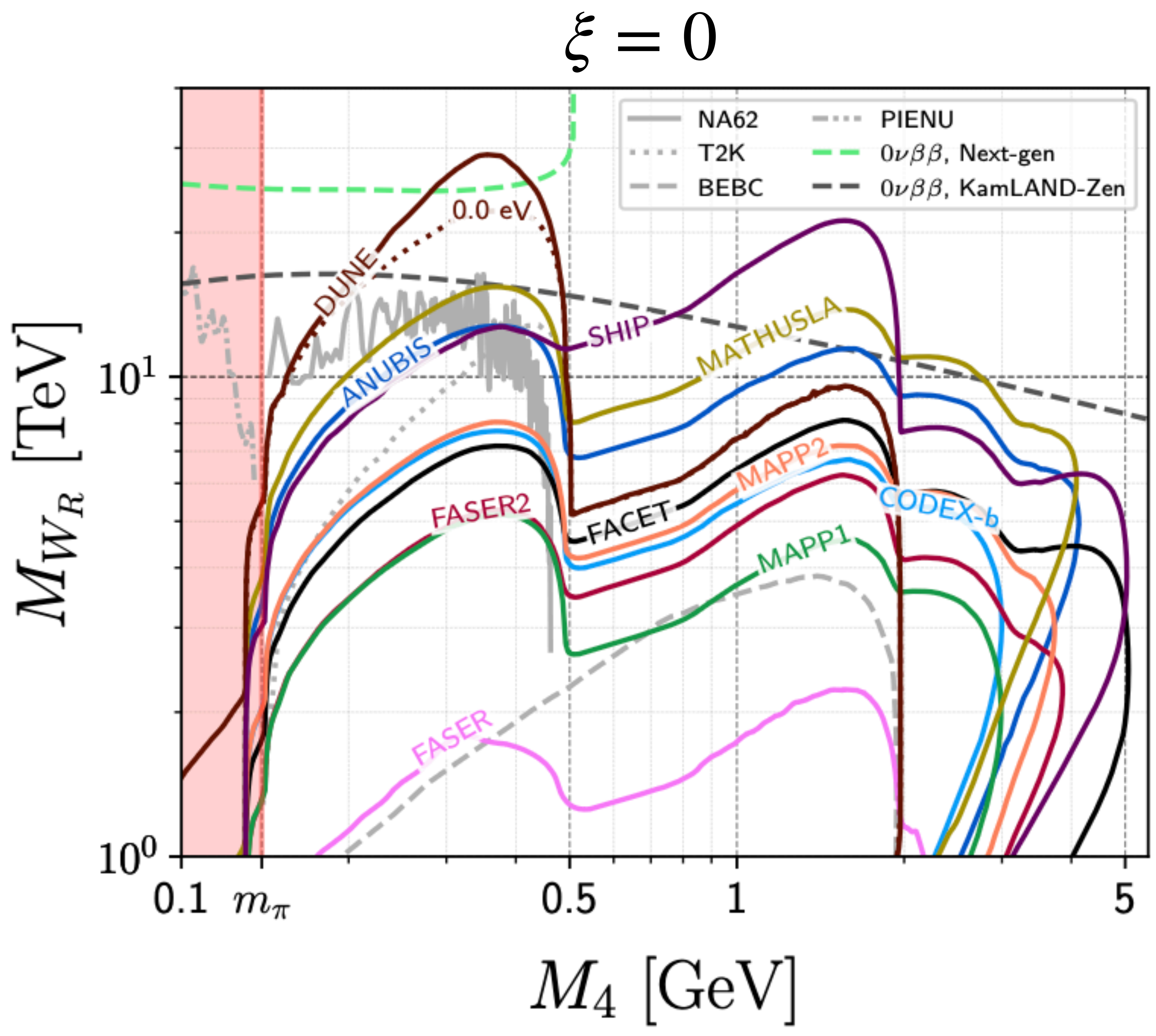
Limits on m_{W_R}



[G.F.S. Alves, C.S. Fong, L.P.S. Leal, RZF (2024) (updated)]

Case with $W_L - W_R$ mixing





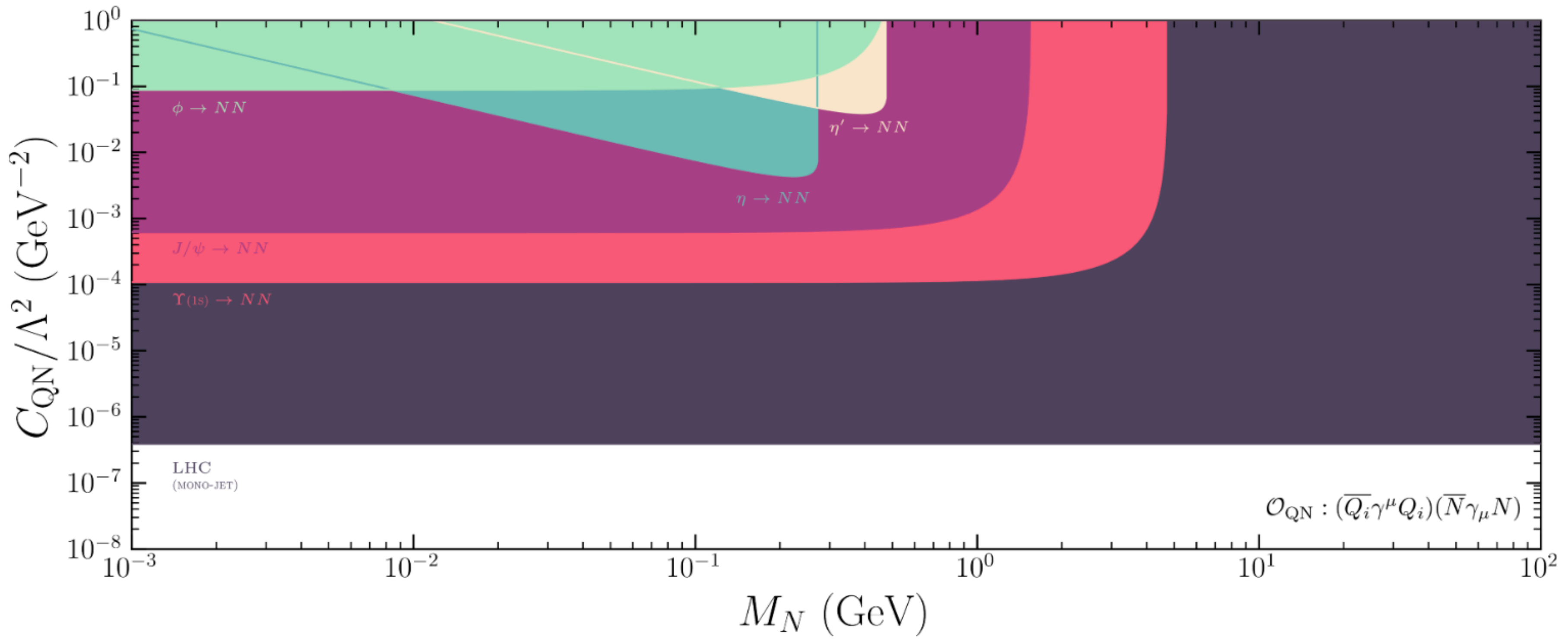
[J. Vries, H.K.Dreiner, J. Groot, J. Günter, Z.S. Wang (2025)]

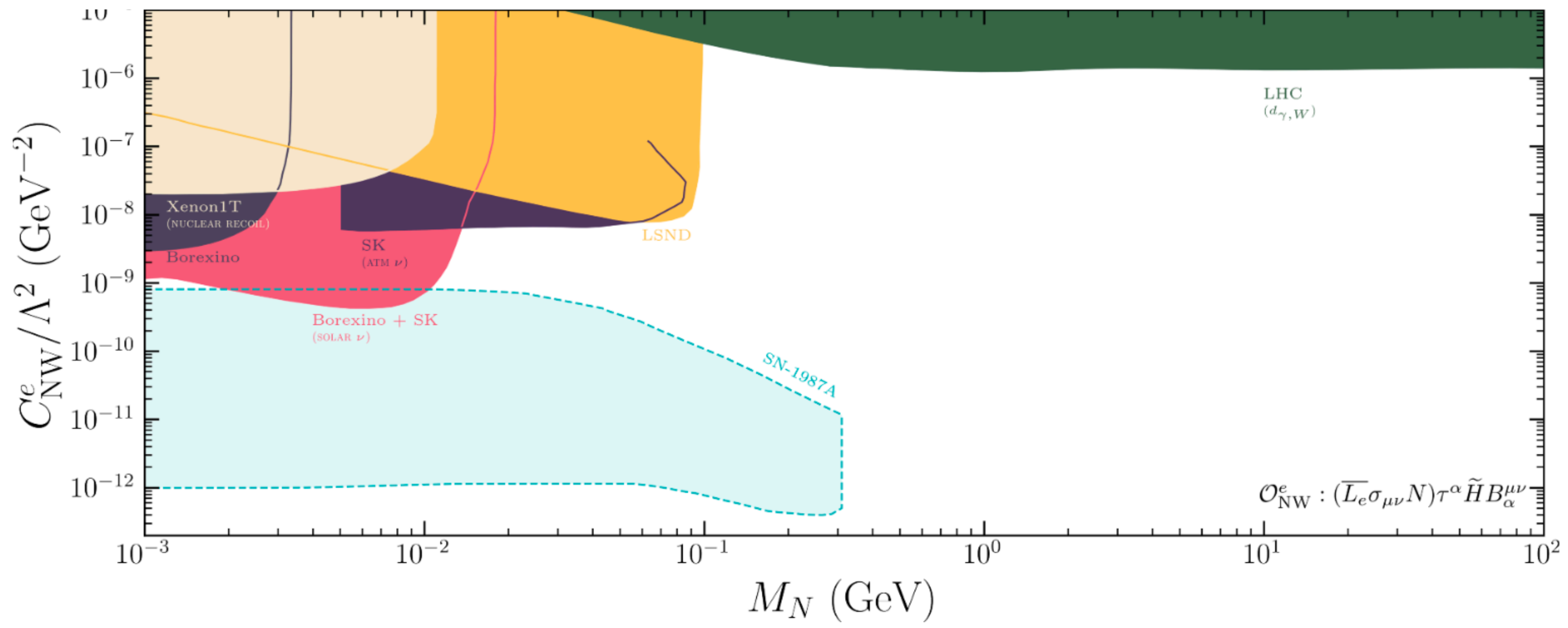
Scenario III: EFT Approach

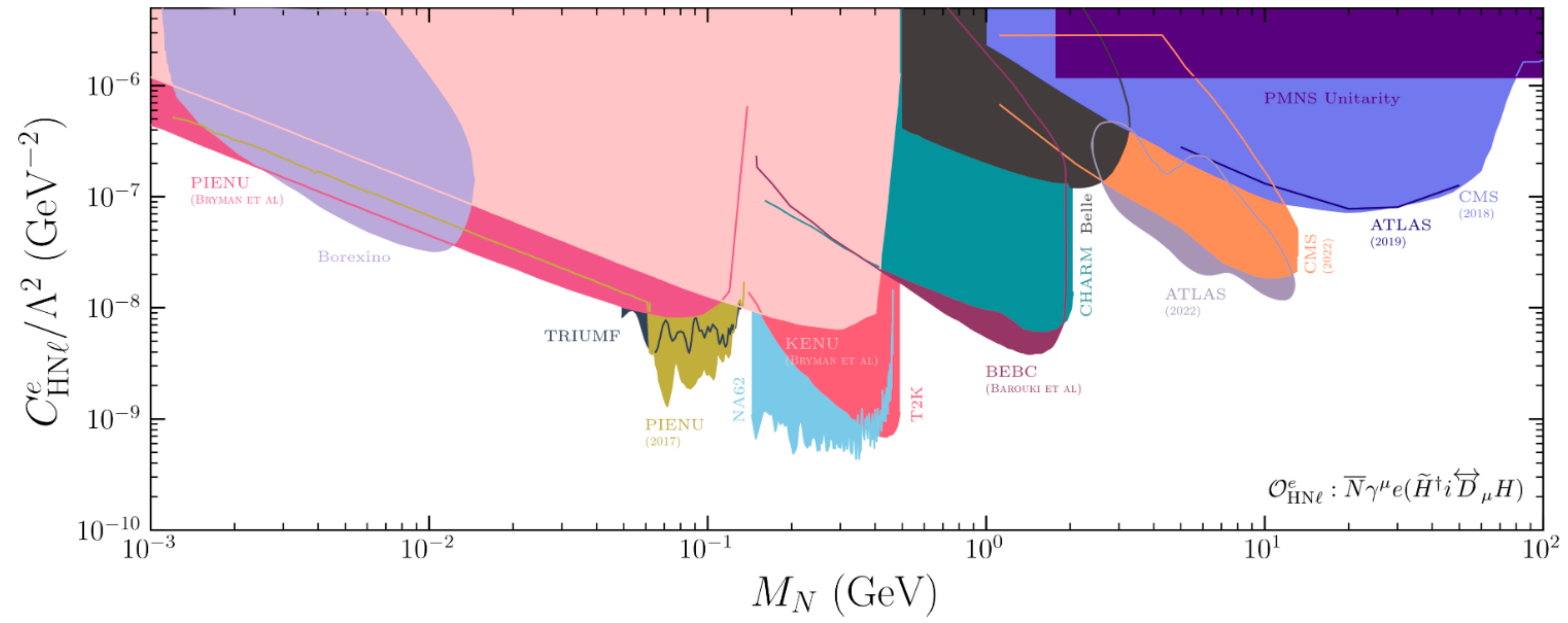
Limits on νSMEFT Operators

H-dressed mixing	$\mathcal{O}^{\alpha}_{\rm LNH}$	$\overline{L_\alpha}\widetilde{H}N(H^\dagger H)$	Standard mixing, invisible H decays.
Bosonic currents	$\mathcal{O}_{\rm HN}$	$\overline{N}\gamma^\mu N(H^\dagger i\overleftrightarrow{D}_\mu H)$	Invisible Z decays, monophoton searches, SN1987A.
	$\mathcal{O}^{\alpha}_{\rm HN\ell}$	$\overline{N}\gamma^\mu \ell_\alpha(\widetilde{H}^\dagger i\overleftrightarrow{D}_\mu H)$	Decay-in-flight and peak searches for e and μ. PMNS unitarity and peak searches for τ.
Moments	$\mathcal{O}^{\alpha}_{\rm NB}$	$\left(\overline{L_\alpha}\sigma_{\mu\nu}N\right)\widetilde{H}B^{\mu\nu}$	Neutrino upscattering, monophoton searches.
	$\mathcal{O}^{\alpha}_{\rm NW}$	$\left(\overline{L_\alpha}\sigma_{\mu\nu}N\right)\tau^a\widetilde{H}W^{\mu\nu}_a$	
4-fermion NC	$\mathcal{O}_{\rm ff}$	$(\overline{f}\gamma^\mu f)(\overline{N}\gamma_\mu N)$	Monophoton and monojet searches, SN1987A.
	$\mathcal{O}^{\alpha}_{\rm LN}$	$(\overline{L_\alpha}\gamma^\mu L_\alpha)(\overline{N}\gamma_\mu N)$	
	$\mathcal{O}_{\rm QN}$	$(\overline{Q_i}\gamma^\mu Q_i)(\overline{N}\gamma_\mu N)$	
4-fermion CC	$\mathcal{O}^{\alpha\beta}_{\rm LNL\ell}$	$(\overline{L_\alpha}N)\epsilon(\overline{L_\alpha}\ell_\beta)$	Monolepton searches, decay-in-flight and peak searches.
	$\mathcal{O}^{\alpha}_{\rm duN\ell}$	$\mathcal{Z}^{\rm duN\ell}_{ij}(\overline{d_i}\gamma^\mu u_j)(\overline{N}\gamma_\mu \ell_\alpha)$	
	$\mathcal{O}^{\alpha}_{\rm LNQd}$	$\mathcal{Z}^{\rm LNQd}_{ij}(\overline{L_\alpha}N)\epsilon(\overline{Q_i}d_j)$	
	$\mathcal{O}^{\alpha}_{\rm QuNL}$	$\mathcal{Z}^{\rm QuNL}_{ij}(\overline{Q_i}u_j)(\overline{N}L_\alpha)$	

[Fernández-Martínez, González-López, Hernández-García, Hostert and López-Pavón (2023)]







HNL in $B \to K^{(*)} + \text{inv}$ decays

Belle-II

$$\mathscr{B}(B^+ \to K^+ + \text{inv})^{\text{exp}} = (2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$$

$\sim 3\sigma$

SM prediction

$$\mathscr{B}(B^+ \to K^+ \nu\nu)^{\text{SM}} = (4.44 \pm 0.17_{\text{FF}} \pm 0.22_{\text{CKM}}) \times 10^{-6}$$

Belle

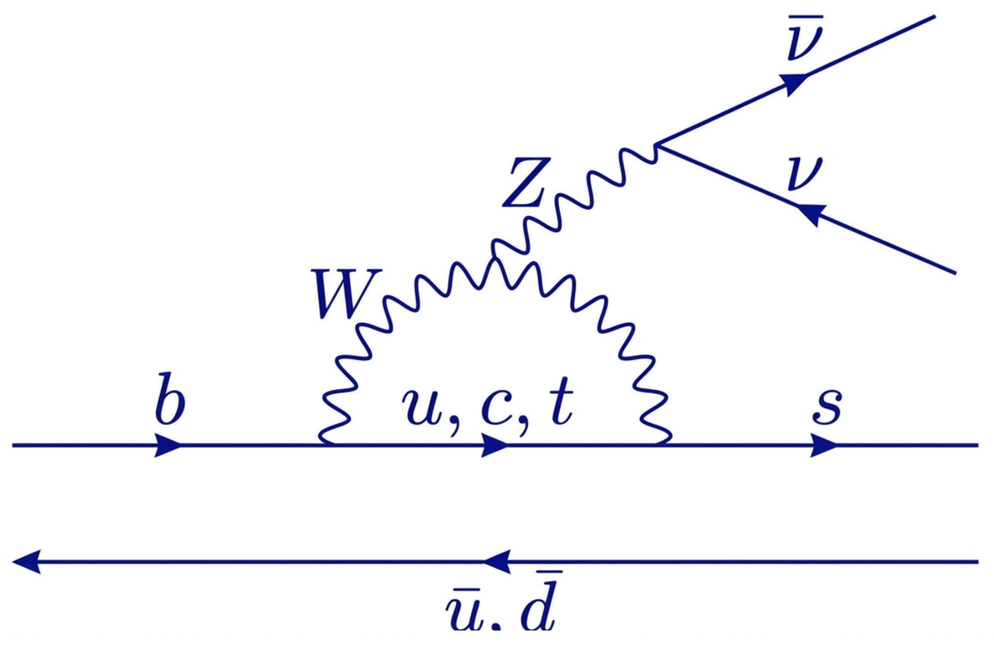
$$\mathscr{B}(B^0 \to K^{*0} + \text{inv})^{\text{exp}} < 2.7 \times 10^{-5} \ @\, 90\,\%\,\text{CL}$$

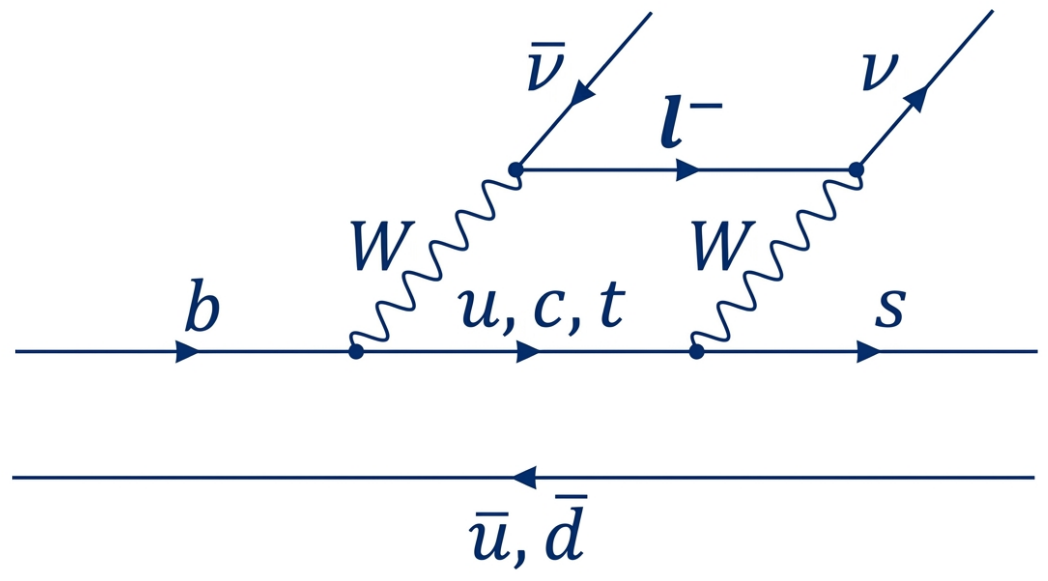
SM prediction

$$\mathscr{B}(B^0 \to K^{*0} + \nu\nu)^{\text{SM}} = (9.00 \pm 0.85_{\text{FF}} \pm 0.46_{\text{CKM}}) \times 10^{-6}$$

FCNC in the SM

$b \to s\nu\nu$





EFT Approach to $B \to K^{(*)} + \text{inv}$ decays

UV-model

Λ

νSMEFT

(SM dof + N)

$\mu_{\rm EW}$

μ scale

$$\mathscr{L}_{\nu\rm SMEFT} = \mathscr{L}_{\rm SMEFT} + \mathscr{L}_N + \sum_{d\geq 5} \frac{1}{\Lambda^{d-4}} \sum_I \mathscr{C}_I^d \mathscr{O}_I^d$$

$$\mathscr{L}_N = \overline{N} i \partial\!\!\!/ N - \left(\frac{m_N}{2} \overline{N^c} N + (y_N)_{\alpha N} \overline{L_\alpha} \tilde{H} N + \text{h.c.} \right)$$

[del Aguila+ (2009), Aparici+ (2009), Bhattacharya and Wudka (2016), Liao and Ma (2017), Li+ (2021) - νSMEFT basis up to d=9]

EFT Approach to $B \to K^{(*)} + \text{inv}$ decays

UV-model

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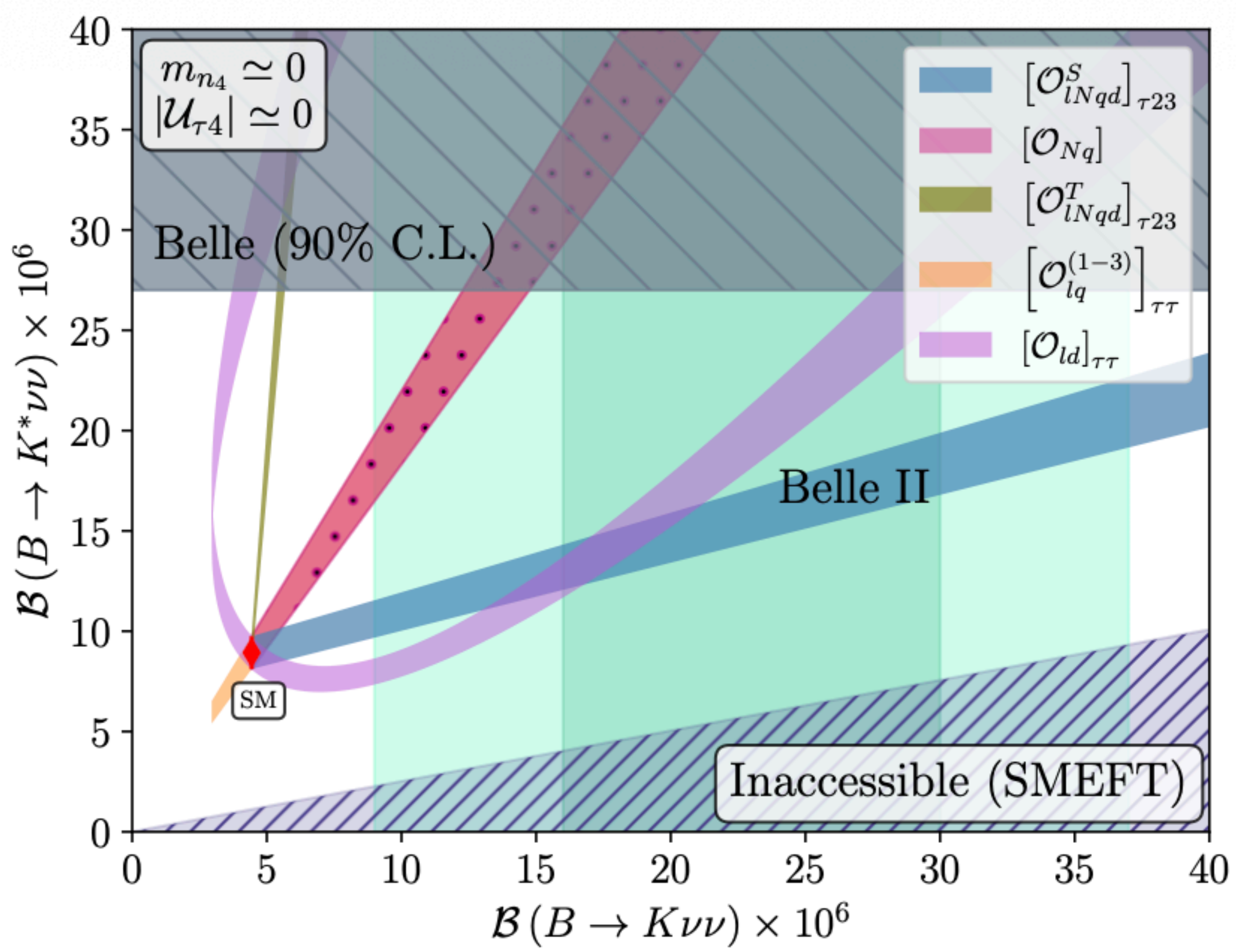


Ψ^4 - d=6 operators

$$\mathcal{O}_{LNQd} = (\bar{L}N)\epsilon(\bar{Q}d_R)$$

$$\mathcal{O}_{NQ} = (\bar{N}\gamma^\mu N)(\bar{Q}\gamma_\mu Q)$$

$$\mathcal{O}^T_{LNQd} = (\bar{L}\sigma_{\mu\nu}N)\epsilon(\bar{Q}\sigma^{\mu\nu}d_R)$$

[Felkl, Giri, Mohanta and Schmidt (2024), Leal and Rosauro-Alcaraz (2024)]]

EFT Approach to $B \to K^{(*)} + \text{inv}$ decays

UV-model

Λ

νSMEFT

(SM dof + N)

μ_{EW}

μ scale

$$\underset{\alpha Nij}{\mathscr{C}_{LNQd}}(\Lambda) = \mathscr{C}_{\text{UV}}(\Lambda)$$

$\psi^4 : (\bar{L}R)(\bar{L}R)$ (d=6)

$\underset{\alpha Nij}{\mathscr{O}_{LNQd}} \equiv (\bar{L}_\alpha N)\epsilon(\bar{Q}_i d_{Rj})$ (flavor basis)

$$L_\ell = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}_L$$

$$Q_i = \begin{pmatrix} V^\dagger u_i \\ d_i \end{pmatrix}_L$$

EFT Approach to $B \to K^{(*)} + \text{inv}$ decays

UV-model

Λ $\mathscr{C}_{\substack{LNQd \\ \alpha Nij}}(\Lambda)$

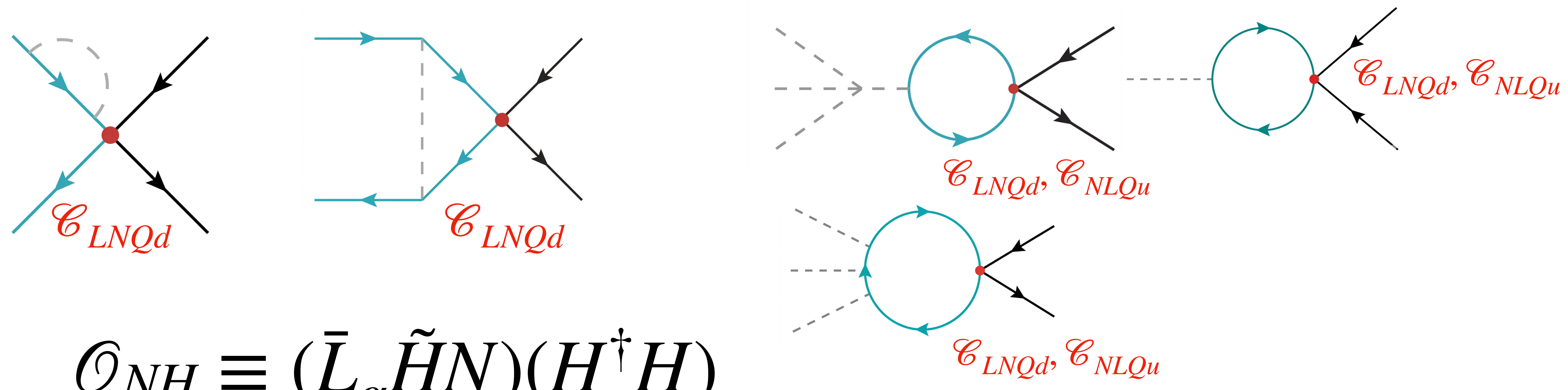
RGE

νSMEFT

(SM dof + N)

Operator mixing @ 1 loop

$\mu_{\rm EW}$ $\mathscr{C}_{\substack{LNQd \\ \alpha Nkj}}(\mu_{\rm EW}), \mathscr{C}_{\substack{NLQu \\ N\alpha kl}}(\mu_{\rm EW}), \mathscr{C}_{\substack{NH \\ \alpha N}}(\mu_{\rm EW}), y_N(\mu_{\rm EW})$



μ scale

$\mathcal{O}_{\substack{NLQu \\ N\alpha Q_k u_l}} \equiv (\bar{N}L_\alpha)(\bar{Q}_k u_{Rl})$ $\quad \mathcal{O}_{\substack{NH \\ \alpha N}} \equiv (\bar{L}_\alpha \tilde{H} N)(H^\dagger H)$

[Ardu and Marcano (2024), Jenkins+ (2013)]

EFT Approach to $B \to K^{(*)} + \text{inv}$ decays

UV-model

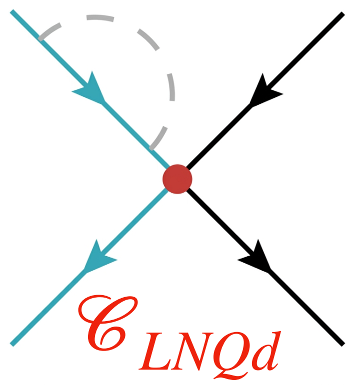
Λ .... $\mathscr{C}_{\substack{LNQd \\ \alpha Nij}}(\Lambda)$

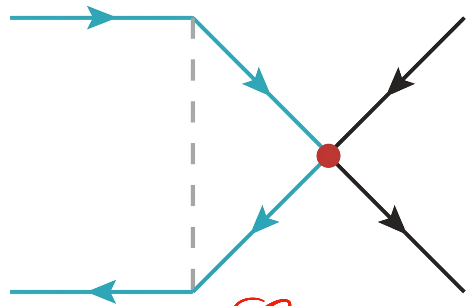
RGE

νSMEFT

(SM dof + N)

$\mu_{\rm EW}$ .... $\mathscr{C}_{\substack{LNQd \\ \alpha Nkj}}(\mu_{\rm EW}), \mathscr{C}_{\substack{NLQu \\ N\alpha kl}}(\mu_{\rm EW}), \mathscr{C}_{\substack{NH \\ \alpha N}}(\mu_{\rm EW}), y_N(\mu_{\rm EW})$

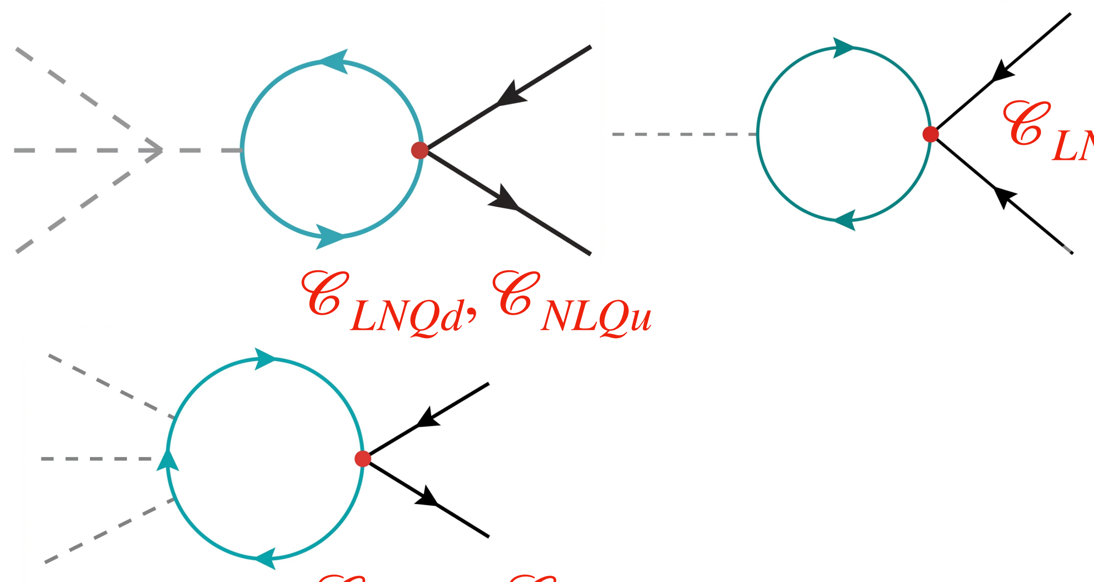




$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_N \end{pmatrix}$$

Contribute to Dirac Neutrino Mass

$$m_D \equiv m_D^0 + \delta m_D$$



μ scale

$\mathscr{O}_{\substack{NLQu \\ N\alpha Q_k u_l}} \equiv (\bar{N}L_\alpha)(\bar{Q}_k u_{Rl})$ $\quad \mathscr{O}_{\substack{NH \\ \alpha N}} \equiv (\bar{L}_\alpha \tilde{H} N)(H^\dagger H)$

[Ardu and Marcano (2024), Jenkins+ (2013)]

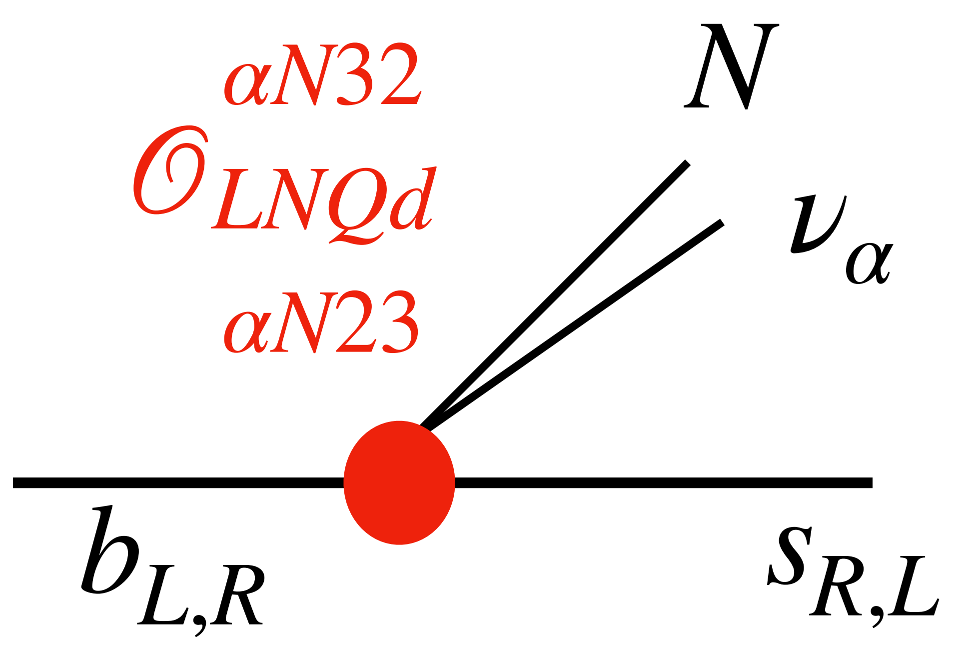
EFT Approach to $B \to K^{(*)} + \text{inv}$ decays

μ scale

- UV-model
- Λ ....
- νSMEFT (SM dof + N)
- μ_{EW} ....
- νLEFT
- m_b ....

$\mathcal{O}_{\substack{LNQd \\ \alpha N32}}$

$\mathcal{O}_{\substack{LNQd \\ \alpha N23}}$



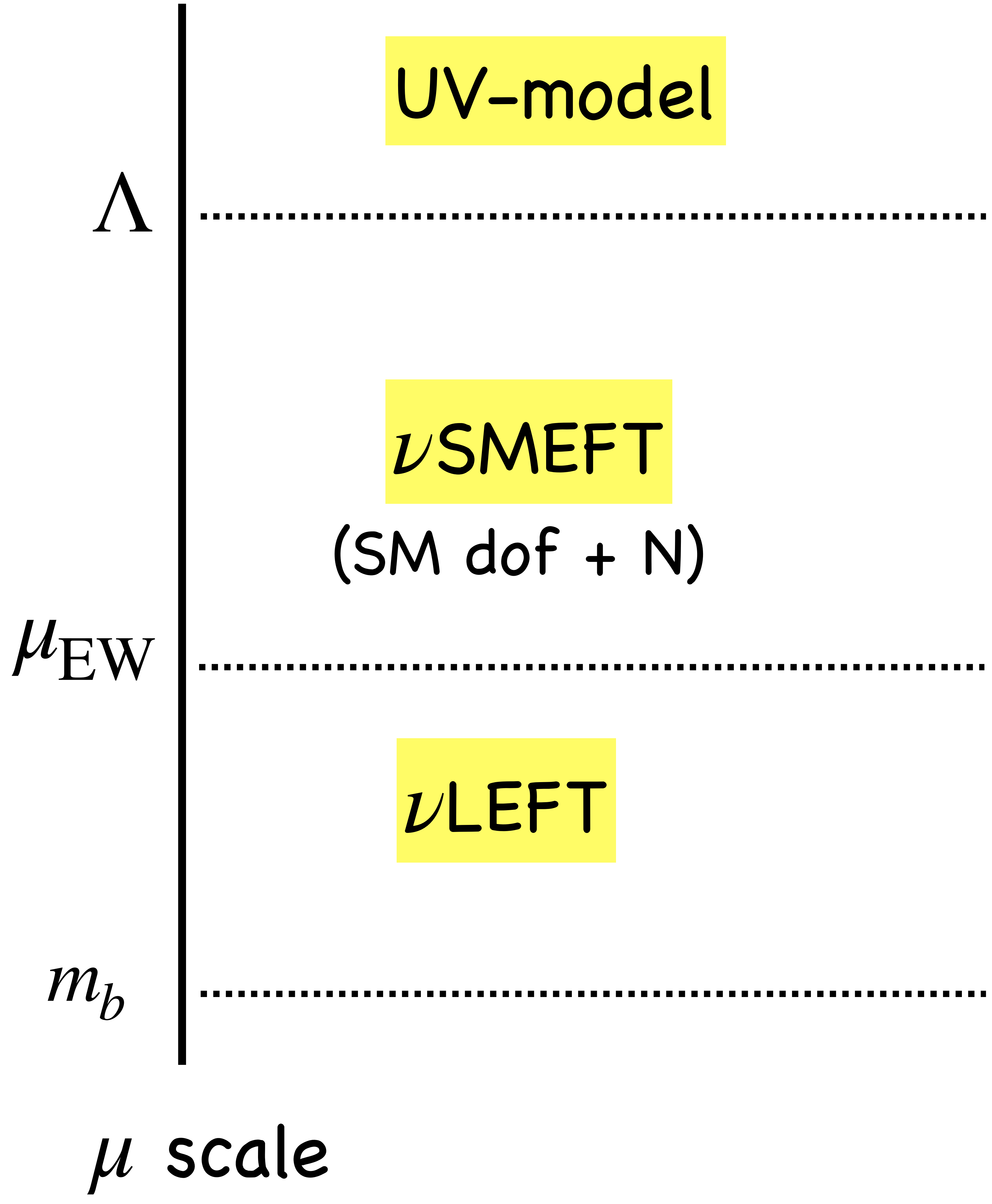
$$C^{S_{\text{NC}}}_{ijN\alpha}(\mu_{\text{EW}}) = \frac{v^2}{\Lambda^2}\mathscr{C}_{\substack{LNQd \\ \alpha Nji}}(\mu_{\text{EW}})$$

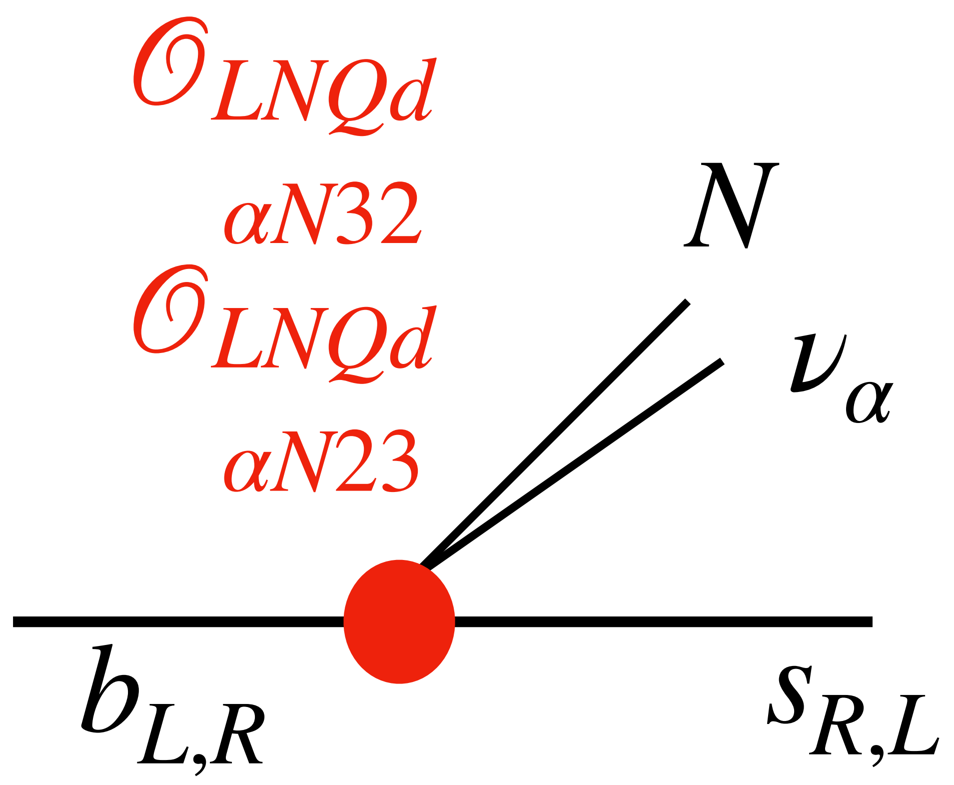
$$O^{S_{\text{NC}}}_{ijN\alpha} = (\bar{d}_{Ri}\, d_{Lj})(\bar{N}\,\nu_{\alpha L})$$

FCNC

$$\mathscr{L}_{\nu\text{LEFT}} \supset \frac{1}{v^2}\sum_{I=S,V,T} C^I O^I$$

EFT Approach to $B \to K^{(*)} + \text{inv}$ decays

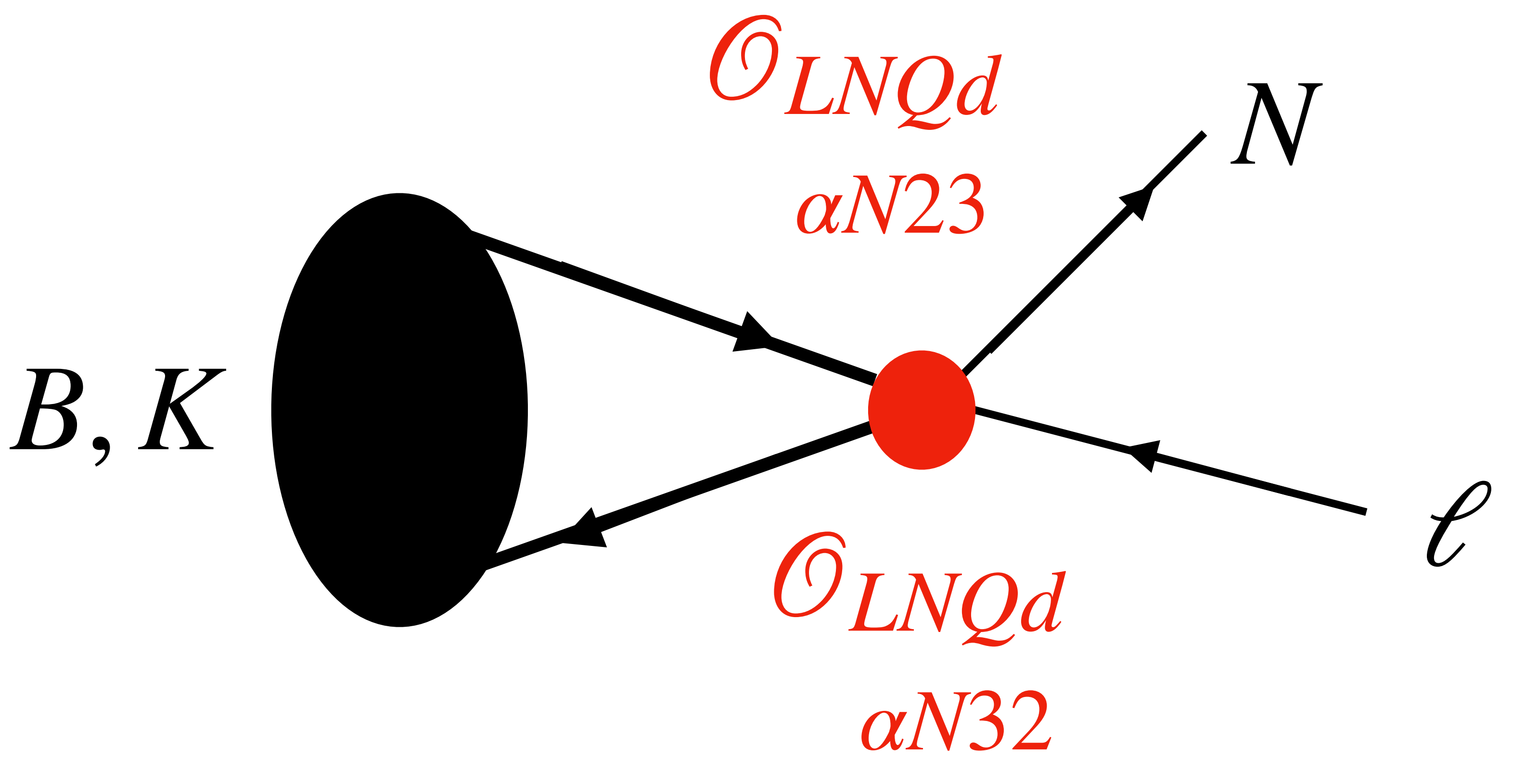




$$C^{S_{\text{NC}}}_{ijN\alpha}(\mu_{\text{EW}}) = \frac{v^2}{\Lambda^2}\mathscr{C}_{\substack{LNQd \\ \alpha Nji}}(\mu_{\text{EW}})$$

$$O^{S_{\text{NC}}}_{ijN\alpha} = (\bar{d}_{Ri}\, d_{Lj})(\bar{N}\,\nu_{\alpha L})$$

FCNC

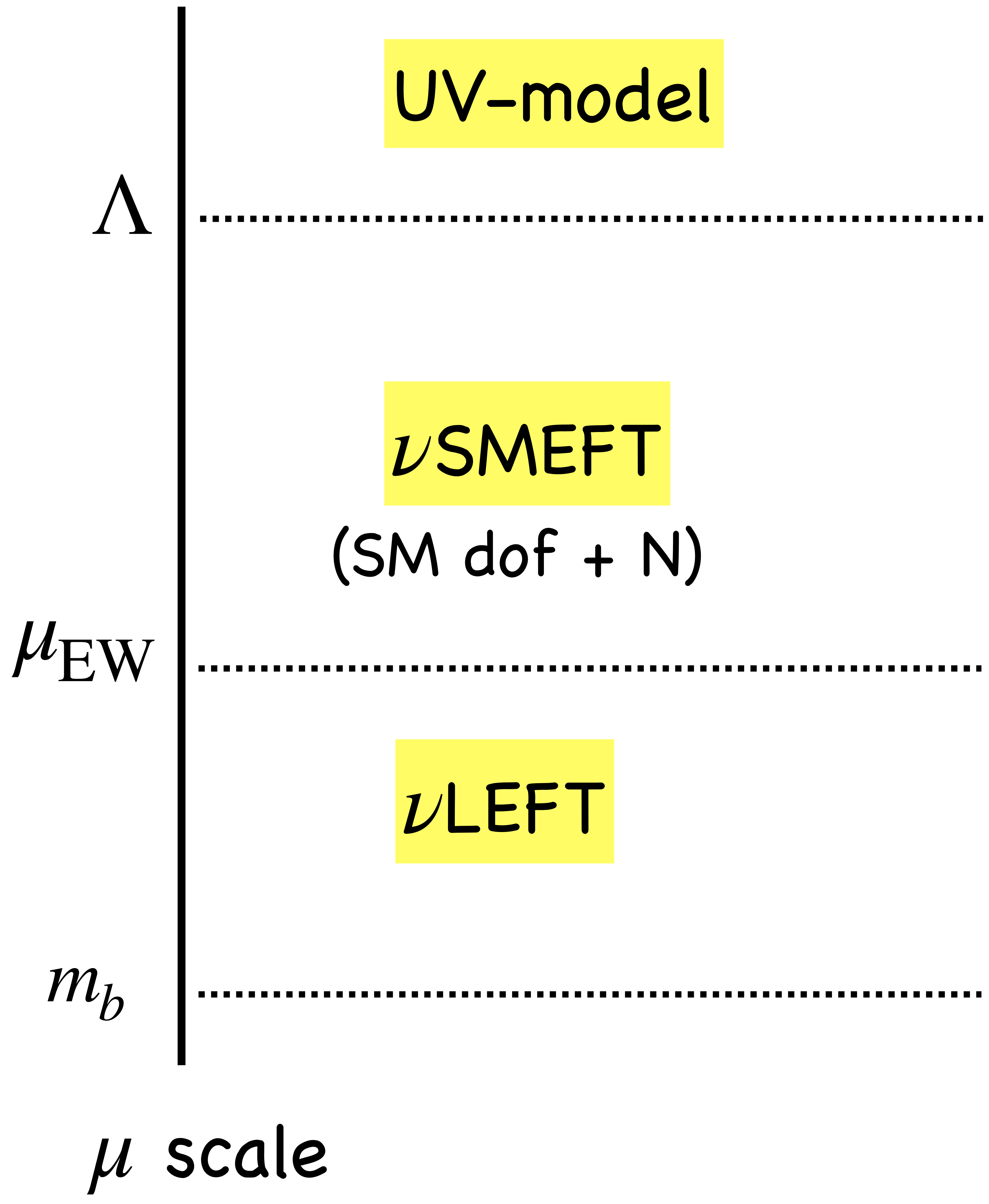


$$C^{S_{\text{CC}}}_{ij\ell N}(\mu_{\text{EW}}) = -\frac{v^2}{\Lambda^2}\sum_k V_{ik}\mathscr{C}_{\substack{LNQd \\ \ell Nkj}}(\mu_{\text{EW}})$$

$$O^{S_{\text{CC}}}_{ij\ell N} = (\bar{u}_{Li}\, d_{Rj})(\overline{\ell_L}\, N)$$

CC

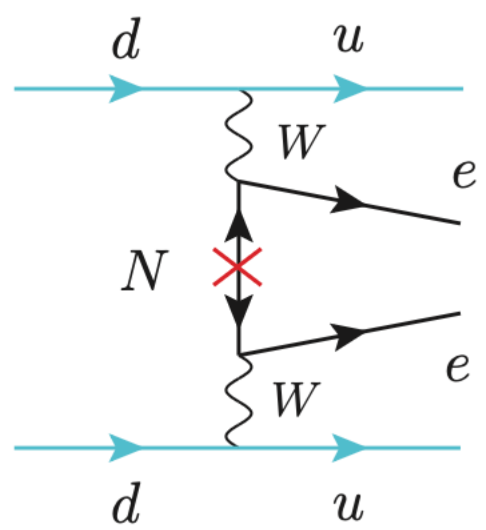
EFT Approach to $B \to K^{(*)} + \text{inv}$ decays



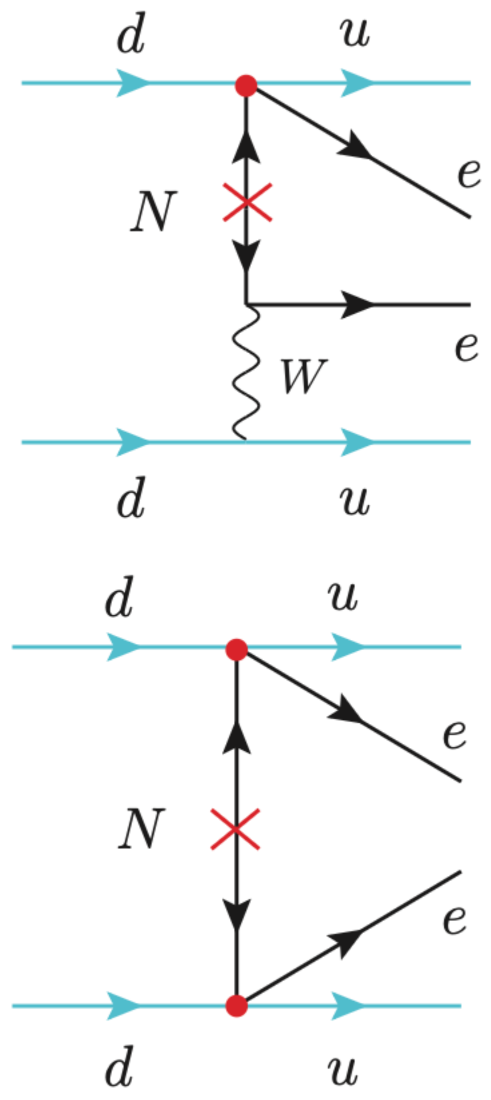
$$C^{S_{\rm NC}}_{ijN\alpha}(\mu_{\rm EW}) = \frac{v^2}{\Lambda^2}\mathscr{C}_{\substack{LNQd\\ \alpha Nji}}(\mu_{\rm EW}) \qquad C^{S_{\rm CC}}_{ij\alpha N}(\mu_{\rm EW}) = -\frac{v^2}{\Lambda^2}\sum_k V_{ik}\mathscr{C}_{\substack{LNQd\\ \alpha Nkj}}(\mu_{\rm EW})$$

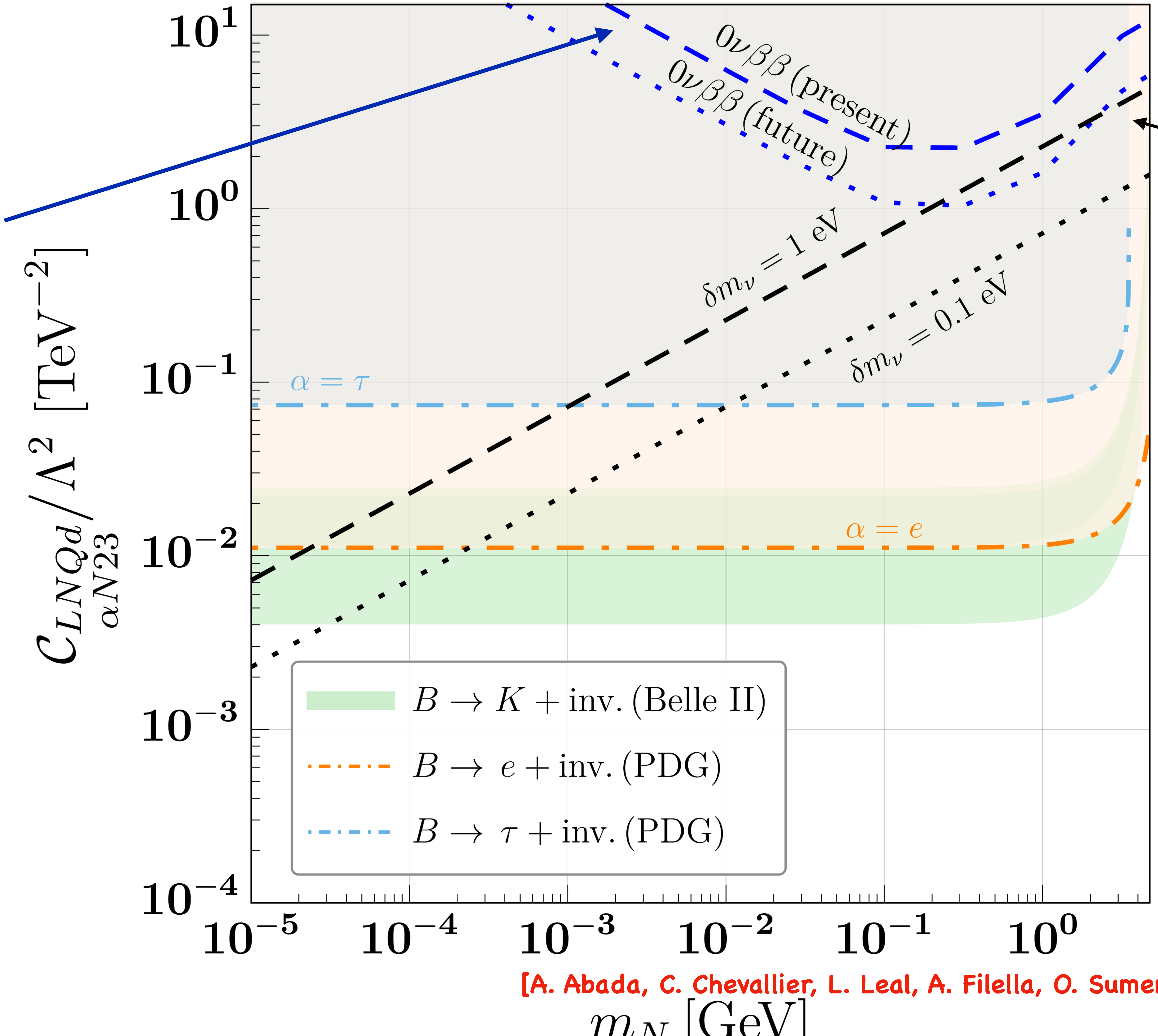
RGE ↓   RGE ↓

$$C^{S_{\rm NC}}_{ijN\alpha}(m_b) \qquad C^{S_{\rm CC}}_{ij\alpha N}(m_b)$$



d=6 contact interactions





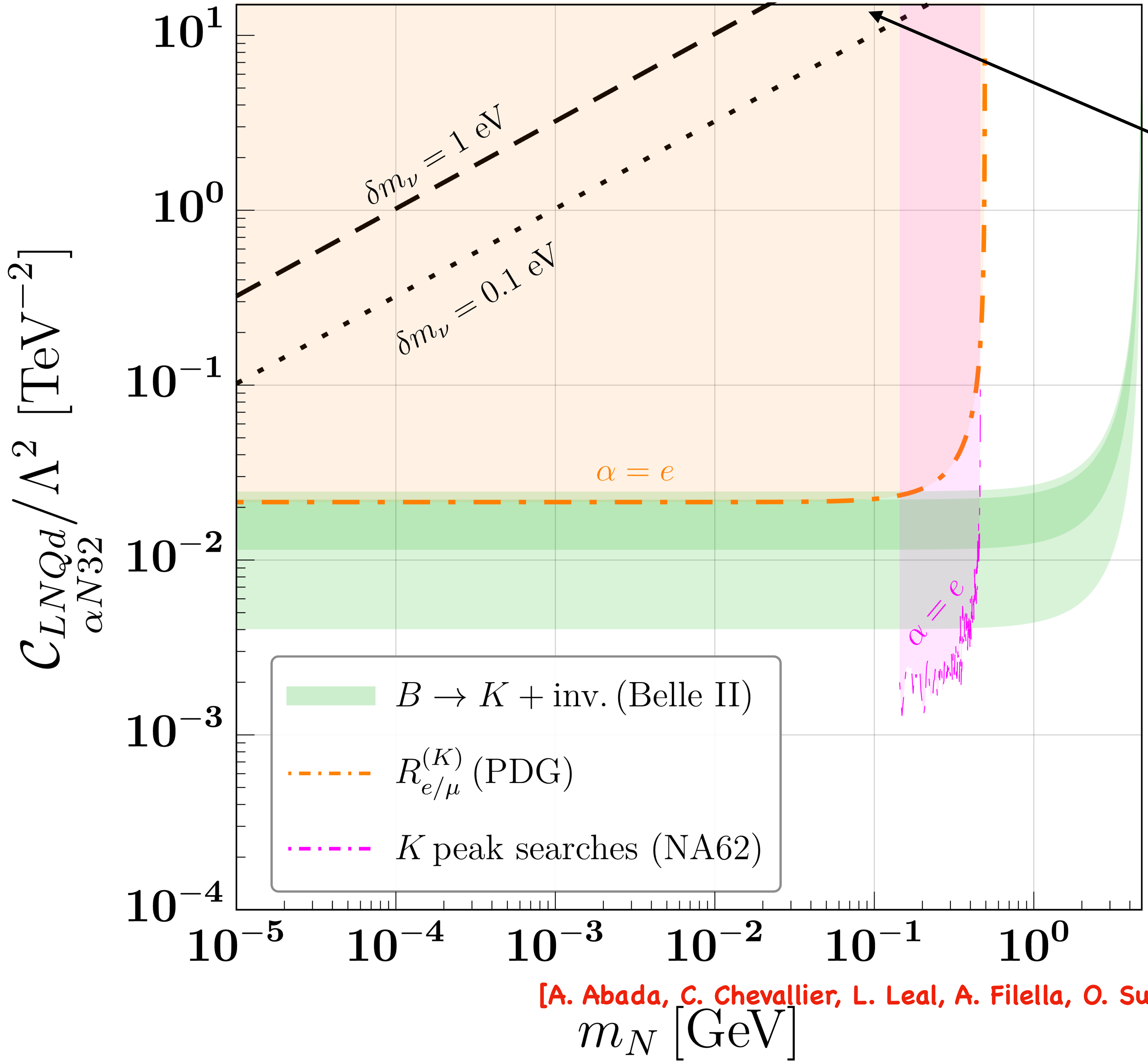
no fine-tuning

$$\delta m_\nu = \frac{(\delta m_D)^2}{m_N}$$

RGE contribution must be small

@ $\Lambda = 1$ TeV

[A. Abada, C. Chevallier, L. Leal, A. Filella, O. Sumensari, RZF arXiv:2607.XXXXX]



no fine-tuning

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RGE contribution must be small

@ $\Lambda = 1$ TeV

[A. Abada, C. Chevallier, L. Leal, A. Filella, O. Sumensari, RZF arXiv:2607.XXXXX]

Conclusions

- Pseudo-scalar meson decays experiments continue to improve limits on HNL mixing to SM neutrinos (in particular for $\mathrm{MeV} \lesssim \mathrm{m_N} \lesssim \mathrm{GeV}$)

- These limits can be used to bound M_{W_R} in the Minimal LRSM

- These limits can be also used to bound νSMEFT operator Wilson coefficients in particular scenarios

- By using the EFT approach we have shown that HNL can produce sizable effects for $B^+ \to K^+ + \mathrm{inv}$ in consistency with the current Belle-II result, neutrinoless double beta decay and current meson decay data