Issues in Observing Majorana Neutrinos (& B (pi,K,D) Meson Rare Decays)

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Contents

1 Introduction

Possible range of (Sterile) Nu mass

(a) From neutrino oscillation and WMAP:

- $|\Delta m_{12}^2| \approx 10^{-5} eV^2$ $\Delta m_{13}^2 \approx 10^{-3} eV^2$ from neutrino oscillation
- $\Sigma m_i \prec 1 eV$ from WMAP and Astrophysics
- $m_1 \approx O(10^{-5}) eV$ from nuMSM (a model)

(b) From dark matter searches:

$m_{N_1} \approx O(10) keV$ from nuMSM, warm DM, …

$m_N \approx O(1-10) GeV$ from DAMA, CDMS, XENON, …

$m_N \approx O(100-1000) GeV$ from SUSY, EDM, …

(C) From BAU and Inflation $m_N \leq 20 GeV$

(D) From usual see-saw $m_N \approx O(10^{12}) GeV$

(E) We can assume any value of m_N, which will be determined by experiments.

Possible bound of (Sterile) N mixing:

$$\nu_\ell = \sum_{j=1}^{3} B_{\ell\nu_j}\nu_j + B_{\ell N} N$$

➔ $B_{l\nu_j}$ = PMNS Mixing B_{lN} = Sterile N Mixing

- **Present bounds for heavy N, (m(N)>45 GeV) [Nardi etal, PLB327,319]**

$$\sum_N |U_{Ne}|^2 \equiv (s_L^{\nu_e})^2 \le 0.005\ , \qquad (s_L^{\nu_\mu})^2 \le 0.002\ , \quad (s_L^{\nu_\tau})^2 \le 0.010$$

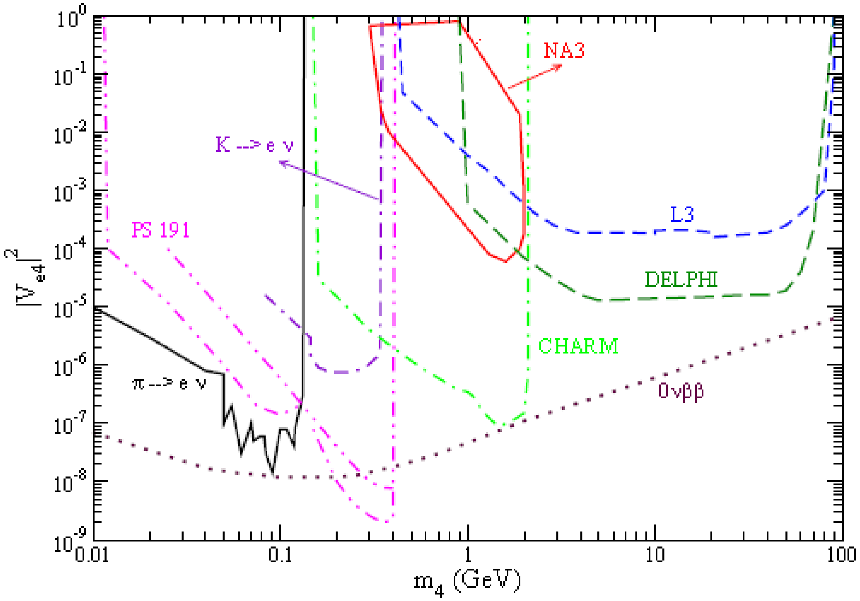
- M. Aoki *et al.* [PIENU Collaboration], Phys. Rev. D 84, 052002 (2011)

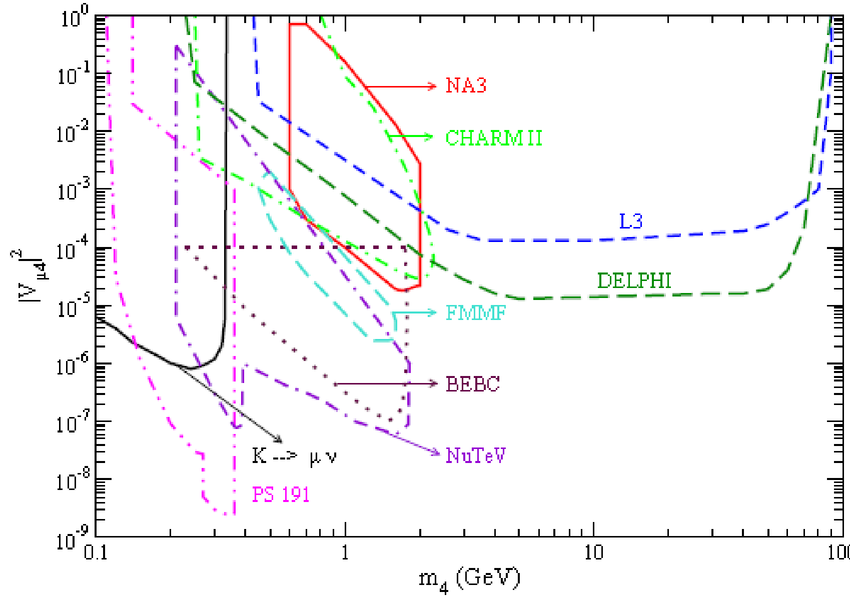
  current bound on the mixing element $|B_{eN}|^2 \lesssim 10^{-8}$

- In nuMSM, see-saw with (light RH sterile) N gives:

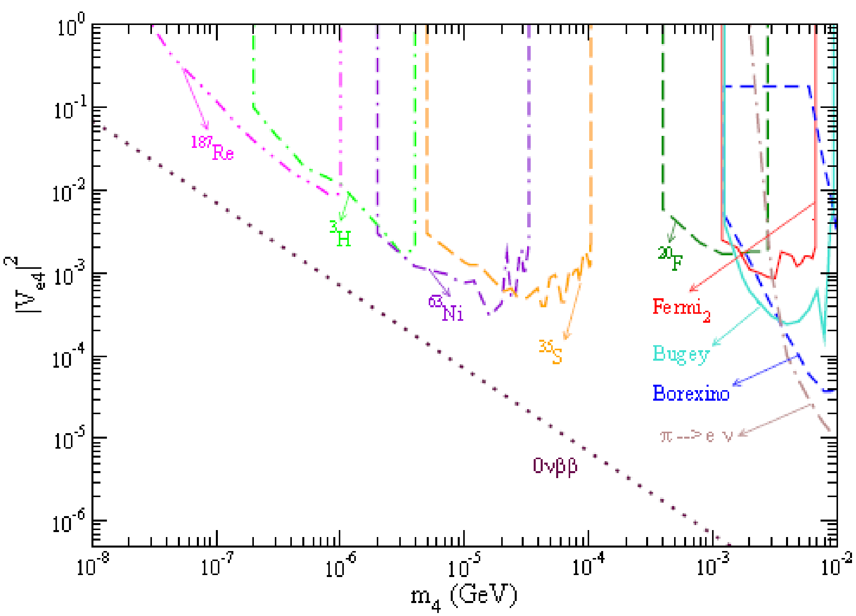
$$m_{\beta\beta} = \left| \sum_i m_i U_{ei}^2 + M_1 \Theta_{e1}^2 \right|, \quad |M_1 \Theta_{e1}^2| = \frac{|M_{1e}^{D2}|}{M_1}. \qquad \Theta_{eN} = M^D / M_N$$

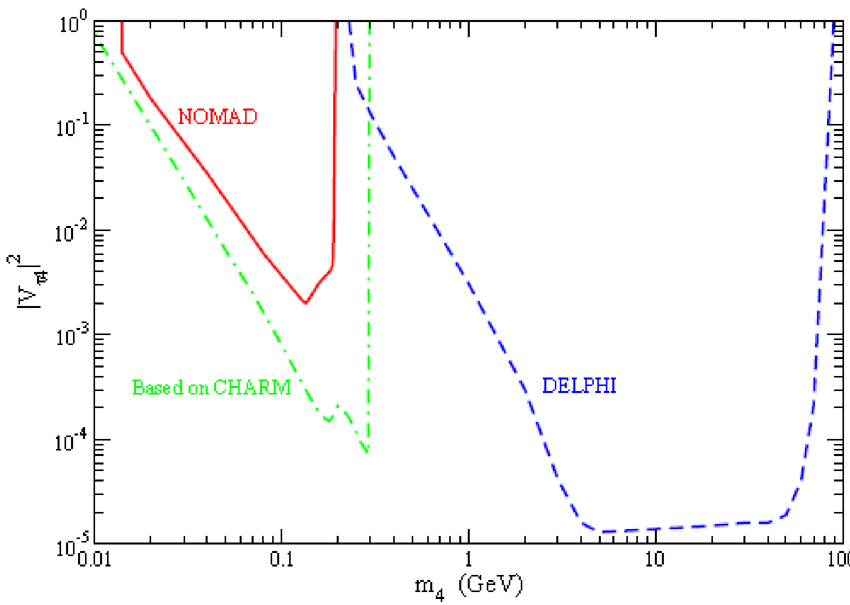
- We can assume any value of B_{lN}, which will be determined by experiments.





A. Atre et al, JHEP05(2009)030

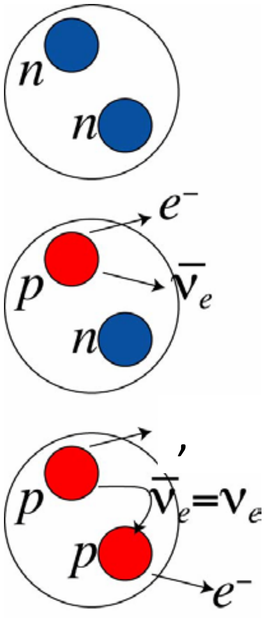


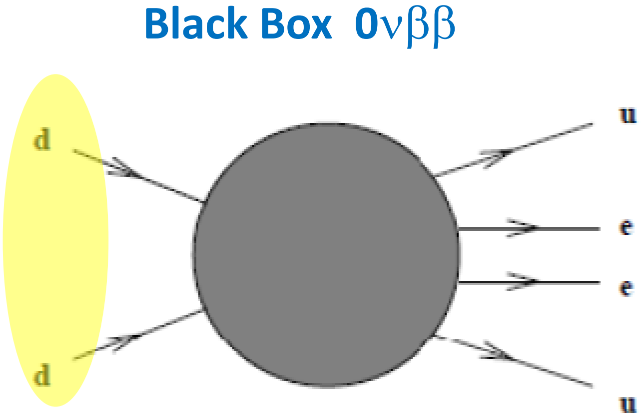


2. Probing Majorana neutrinos from $0\nu\beta\beta$

- Lepton number violation by 2 units $\Delta L = 2$ plays a crucial role to probe the Majorana nature of ν's,

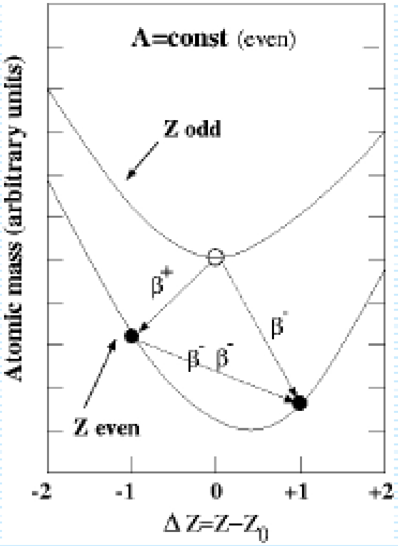
(a) The observation of $0\nu\beta\beta$

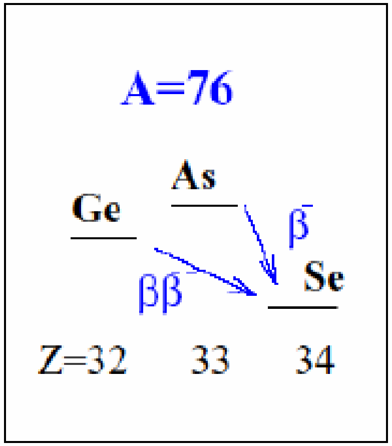


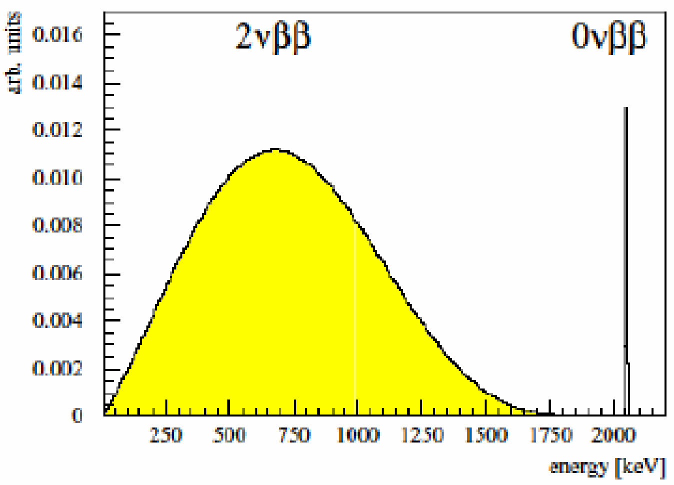


- Provides a promising lab. method for determining the absolute neutrino mass scale that is complementary to other measurement techniques

Double Beta Decay



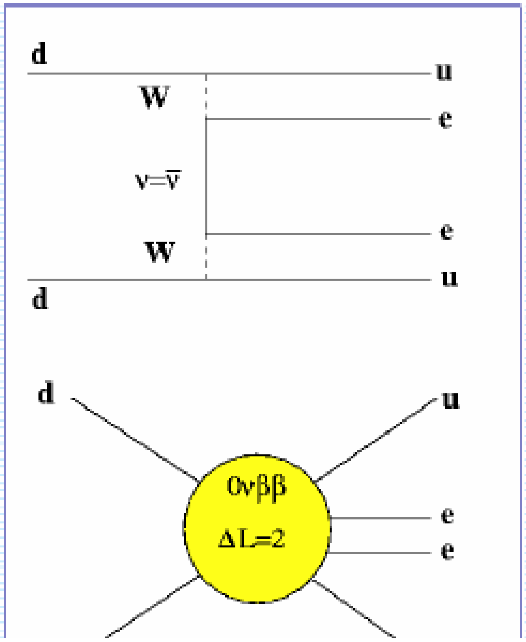




$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$$

$$(T^{2\nu}_{1/2})^{-1} = G^{2\nu}|M^{2\nu}_{GT}|^2$$

Observed for 10 isotopes: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo. ^{116}Cd. ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U, $T_{1/2} \approx 10^{18}$-10^{24} years



$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

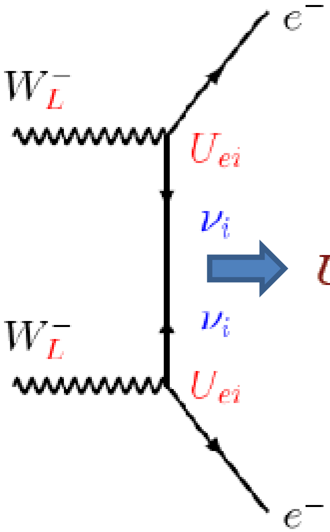
$$(T^{0\nu}_{1/2})^{-1} = \eta^{LNV}\ G^{0\nu}\ |M^{0\nu}|^2 \quad m_{\beta\beta} = \sum_i U^2_{ei} m_i$$

SM forbidden ,not observed yet: $T_{1/2}$ (^{76}Ge)>10^{25} years

- In the limit of small neutrino masses :

the half-life time, $T_{0\nu}^{1/2}$, of the 0νββ decay can be factorized as :

$$[T_{0\nu}^{1/2}]^{-1} = G^{0\nu}(E_0, Z)\,|M^{0\nu}|^2 |< m_{ee} >|^2$$



$$U_{ek}^2 \int \frac{d^4 p}{(2\pi)^4} \frac{m_{\nu_k} + \not{p}}{p^2 - m_{\nu_k}^2}$$

$|M^{0\nu}|^2$: Nuclear matrix element

$G^{0\nu}(E_0, Z)$: phase space factor

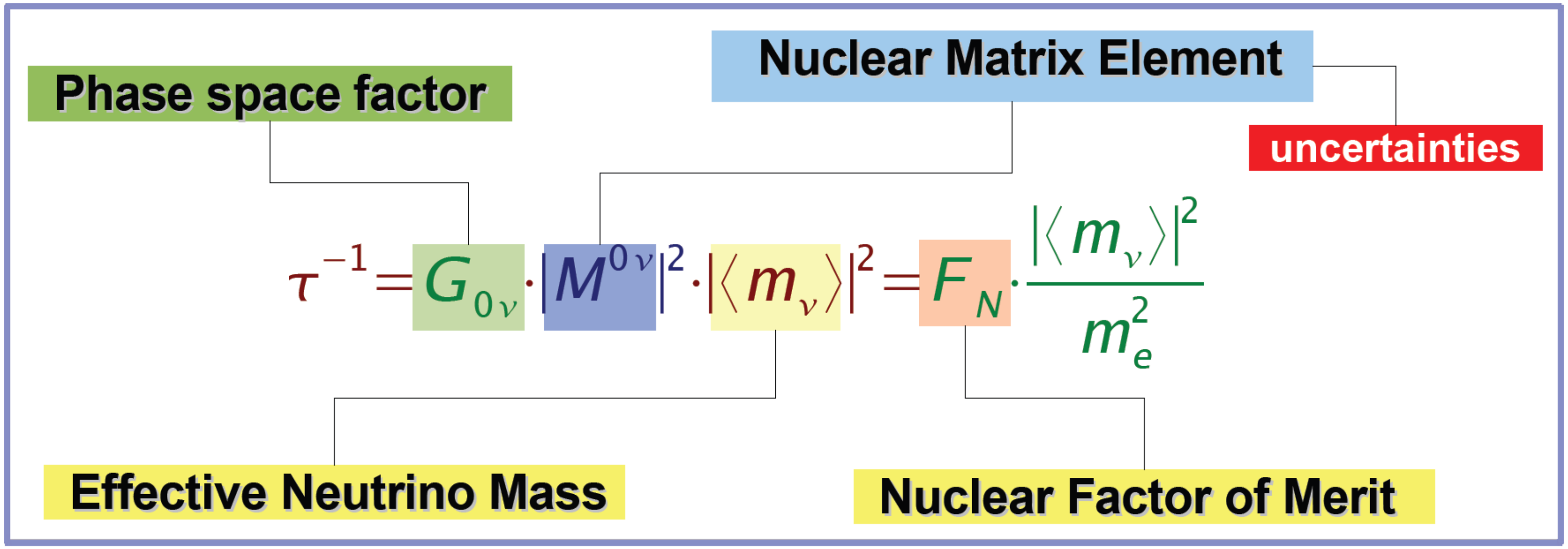
$< m_{ee} >$: effective neutrino mass (model independent)

$$< m_{ee} > = m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{i\alpha_{21}} + m_3 U_{e3}^2 e^{i\alpha_{31}}$$

➔ depends on neutrino mass hierarchy

Uncertainties

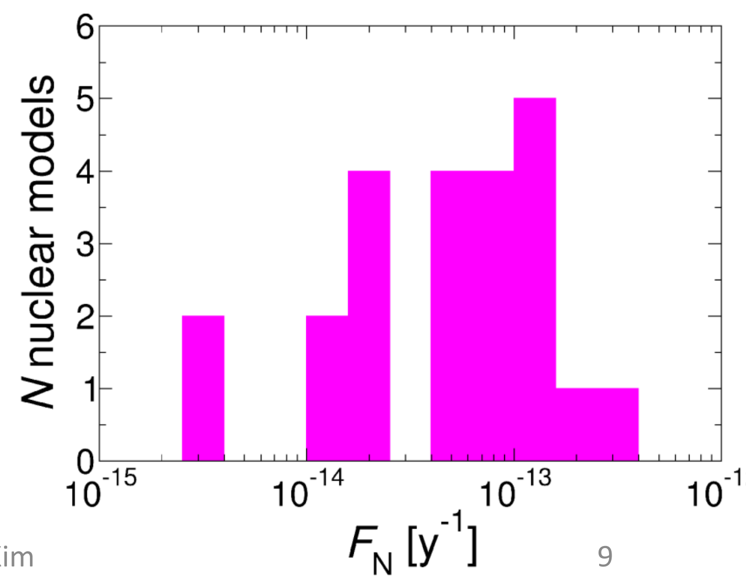
(O.Cremonesi, 05)



$$\tau^{-1} = G_{0\nu} \cdot |M^{0\nu}|^2 \cdot |\langle m_\nu \rangle|^2 = F_N \cdot \frac{|\langle m_\nu \rangle|^2}{m_e^2}$$

- Large uncertainties in NME

About factor of 100 in NME ➔
affect order 2-3 in $|< m_\nu >|$

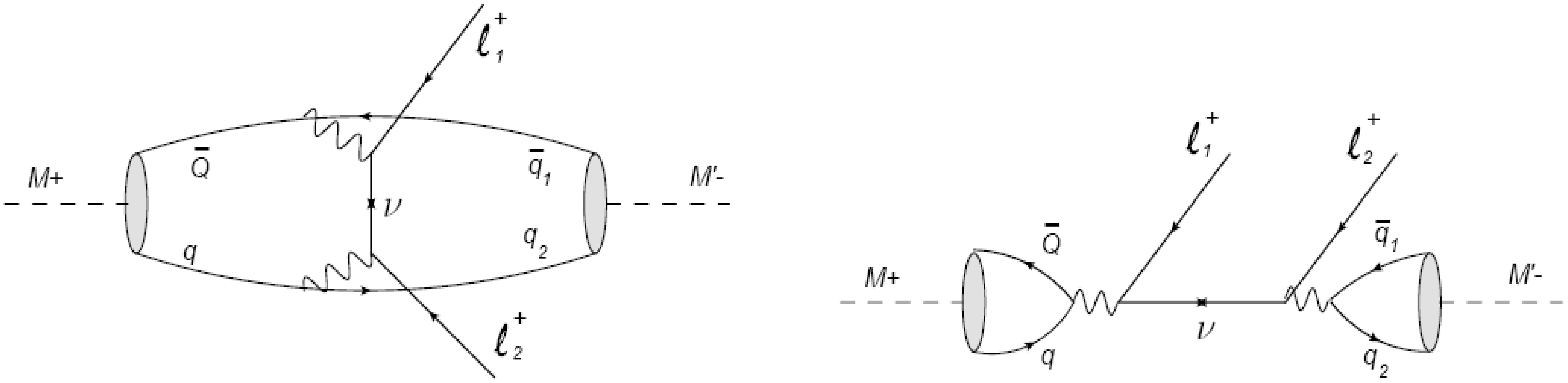


(b) Probe of Majorana neutrinos via rare decays of mesons

(G.Cvetic, C. Dib, S.Kang, C.S.Kim, arXiv:1005.4282 (PRD82,053010,2010))

$$\Delta L = 2 \quad \text{Processes} \; : \quad M^{+} \to M'^{-} l_1^{+} l_2^{+}$$

- Taking mesons in the initial and final state to be pseudoscalar (M : K, D, Ds, B, Bc / M'=pi, K, D,...)



- Not involve the uncertainties from nuclear matrix elements in 0βνν

Effective Hamiltonian:

$$H_{eff} = -\frac{G_F^2}{2}[C_t O_t^{\mu\nu} + C_s O_s^{\mu\nu}]L_{\mu\nu} \times \left[\frac{\not{p}_N + m_N}{p_N^2 - m_N^2 + i m_N \Gamma_N} \right]$$

$$O_t^{\mu\nu} = V_{q_2 q}^* V_{q_1 Q} J_{q_2 q}^{\mu} J_{q_1 Q}^{\nu}$$

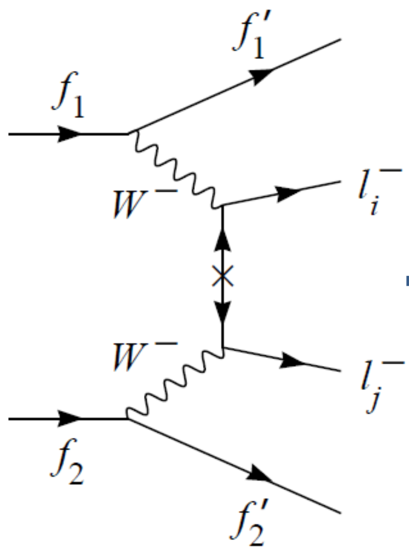
$$O_s^{\mu\nu} = V_{q_2 q_1}^* V_{q Q} J_{q_2 q_1}^{\mu} J_{q Q}^{\nu}$$

$$J_{qQ}^{\mu} = \overline{Q}\gamma^{\mu}(1-\gamma_5)q$$

$$L_{\mu\nu} = U_{i\ell}^* U_{i\ell} \lambda_N [\overline{u}_{\ell} \gamma_{\mu} \gamma_{\nu} (1-\gamma_5) v_{\ell}]$$

Decay Amplitude:

$$A(M^+ \to M'^- \ell_1^+ \ell_2^+) = < M'^- \ell_1^+ \ell_2^+ | H_{eff} | M^+ >$$

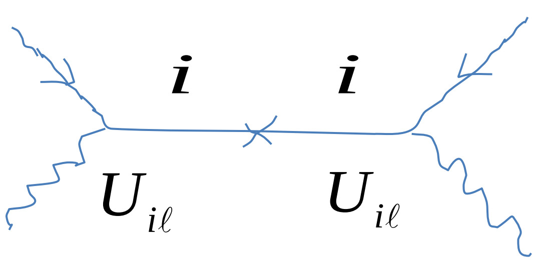


$$\longrightarrow U_{l_i N} \times \left[\frac{\not{p} + m_N}{p^2 - m_N^2 + i m_N \Gamma_N} \right] \times U_{l_j N}$$

- transition rates are proportional to

$$\longrightarrow \begin{cases} \langle m \rangle_{l_1 l_2}^2 = \left| \sum_{i=1}^{3} U_{l_1 i} U_{l_2 i} m_i \right|^2 & \text{for light } \nu \\ \left| \sum_{i=4}^{3+n} \frac{U_{l_1 i} U_{l_2 i}}{m_i} \right|^2 & \text{for heavy } \nu \\ \frac{\Gamma(N \to i)\Gamma(N \to f)}{m_N \Gamma_N} & \text{for resonant } \nu \text{ production} \end{cases} \longrightarrow C_t, C_s$$

For example, leptonic current :



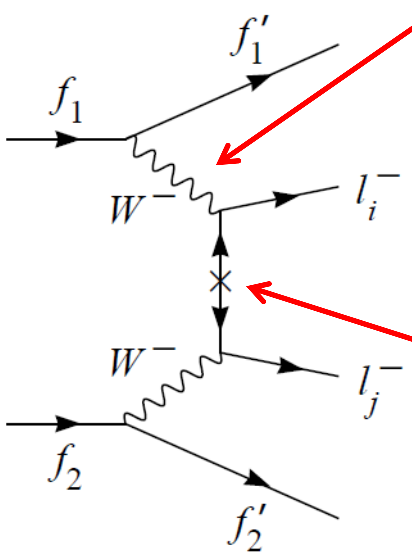
$$L_{\mu\nu} = (U_{i\ell} U_{i\ell}) \times \overline{\nu}_i \gamma_\mu \frac{(1-\gamma_5)}{2} \nu_\ell \times (---) \times \overline{\nu}_i \gamma_\nu \frac{(1-\gamma_5)}{2} \nu_\ell$$

$$= (U^*_{i\ell} U_{i\ell}) \times \overline{u}_\ell \gamma_\mu \frac{(1+\gamma_5)}{2} \nu_i \times (---) \times \overline{\nu}_i \gamma_\nu \frac{(1-\gamma_5)}{2} \nu_\ell$$

$$= \sum_i (U^*_{i\ell} U_{i\ell}) \times \overline{u}_\ell \gamma_\mu \frac{(1+\gamma_5)}{2} \left(\frac{\not{p}_{\nu_i} + m_{\nu_i}}{p^2_{\nu_i} - m^2_{\nu_i}} \right) \gamma_\nu \frac{(1-\gamma_5)}{2} \nu_\ell$$

$$= \left(\sum_i U^*_{i\ell} U_{i\ell} \frac{m_{\nu i}}{p^2_{\nu_i} - m^2_{\nu i}} \right) \times \overline{u}_\ell \gamma_\mu \gamma_\nu \frac{(1-\gamma_5)}{2} \nu_\ell$$

Model Independence of Effective Theory approach



This could be any gauge boson,
e.g. W, W', W_R

$$\Longrightarrow \begin{cases} V_{CKM} \to V' \\ U_{il} \to U' \\ G_F \to G_{NP} \end{cases}$$

This could be any Majorana particle,
e.g. $\nu, sterlie$ neutralino, heavy N,…

Propagator changed

$$\Longrightarrow C_{s,t} \to C'$$

(i) Light neutrino case $m_{\nu_i} << m_{M'}$

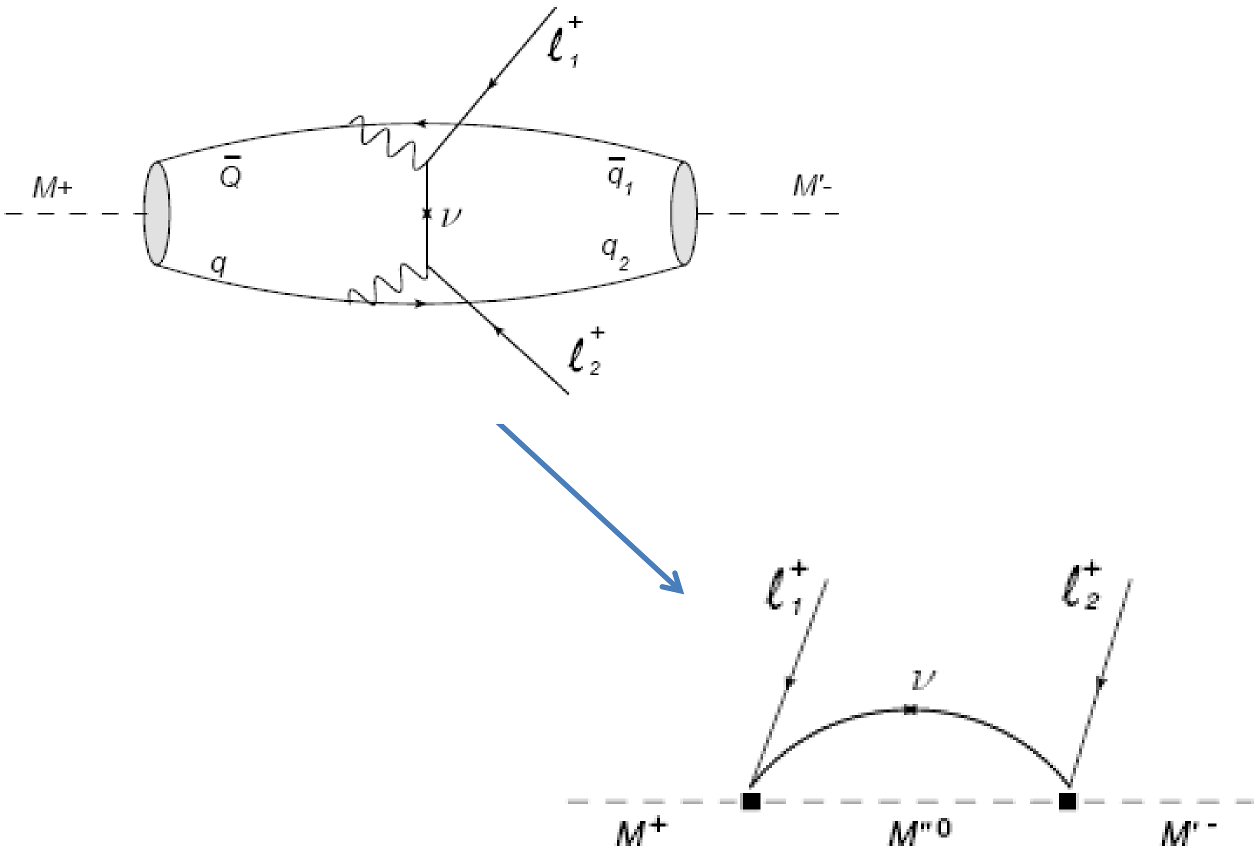


FIG. 2: The main diagram in an effective meson theory for $M^+ \to M'^- \ell^+ \ell^+$ (plus diagram with leptons exchanged if they are identical), mediated by Majorana neutrinos, when the neutrino is much lighter than the final meson. The amplitude is estimated considering the intermediate state on its mass shell.

(ii) Intermediate mass scale neutrino case $m_{M'^-} \le m_{\nu_i} \le m_{M^+}$

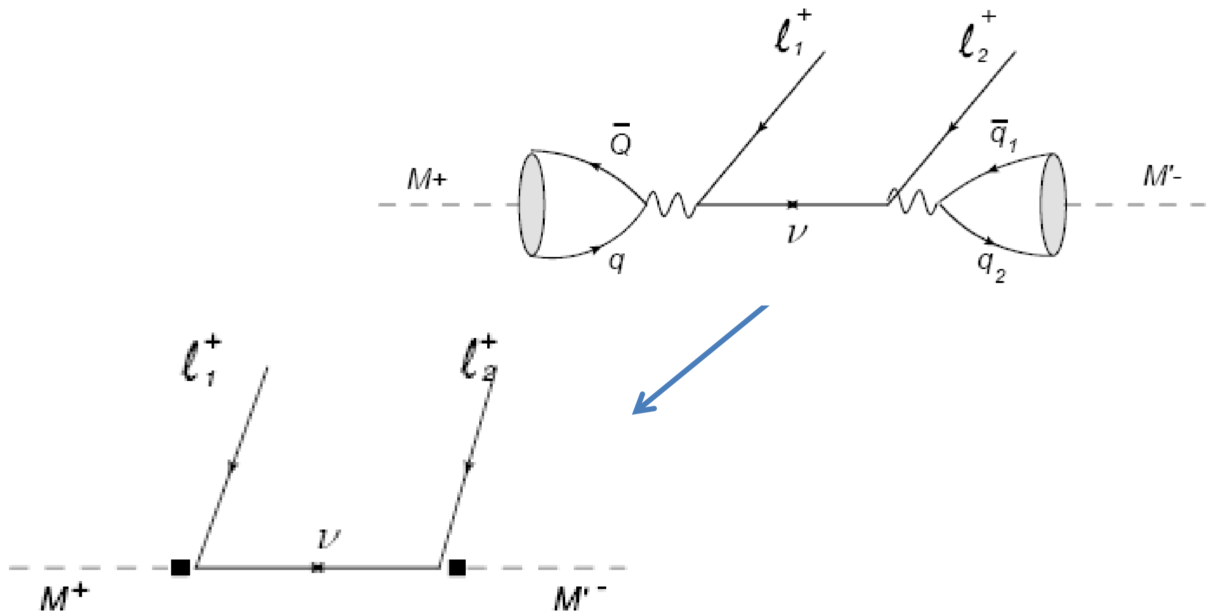


FIG. 3: The dominating diagram (plus diagram with leptons exchanged if they are identical) in an effective meson theory for$M^+ \to M'^- \ell^+ \ell^+$, mediated by Majorana neutrinos with mass in the range between $m_{M'}$ and m_M.

- dominant contribution to the process is from the “s-type” diagram because the neutrino propagator is kinematically entirely on-shell

Effective amplitude at meson level:

$$\mathcal{M} = \frac{G_F^2}{2} U_{N\ell}^{*2}\, V_{qQ}^* V_{q_2 q_1}^* f_M f_{M'} \; \frac{\tilde{M}}{(p_N^2 - m_N^2) + i m_N \Gamma_N}$$

$$\tilde{\mathcal{M}} = \lambda_N \; \bar{u}_{\bar{\ell}}(l_1)\, \not{p}_M (1+\gamma_5)\, (\not{p}_N + m_N)\, \not{p}_{M'} (1-\gamma_5) v(l_2)$$

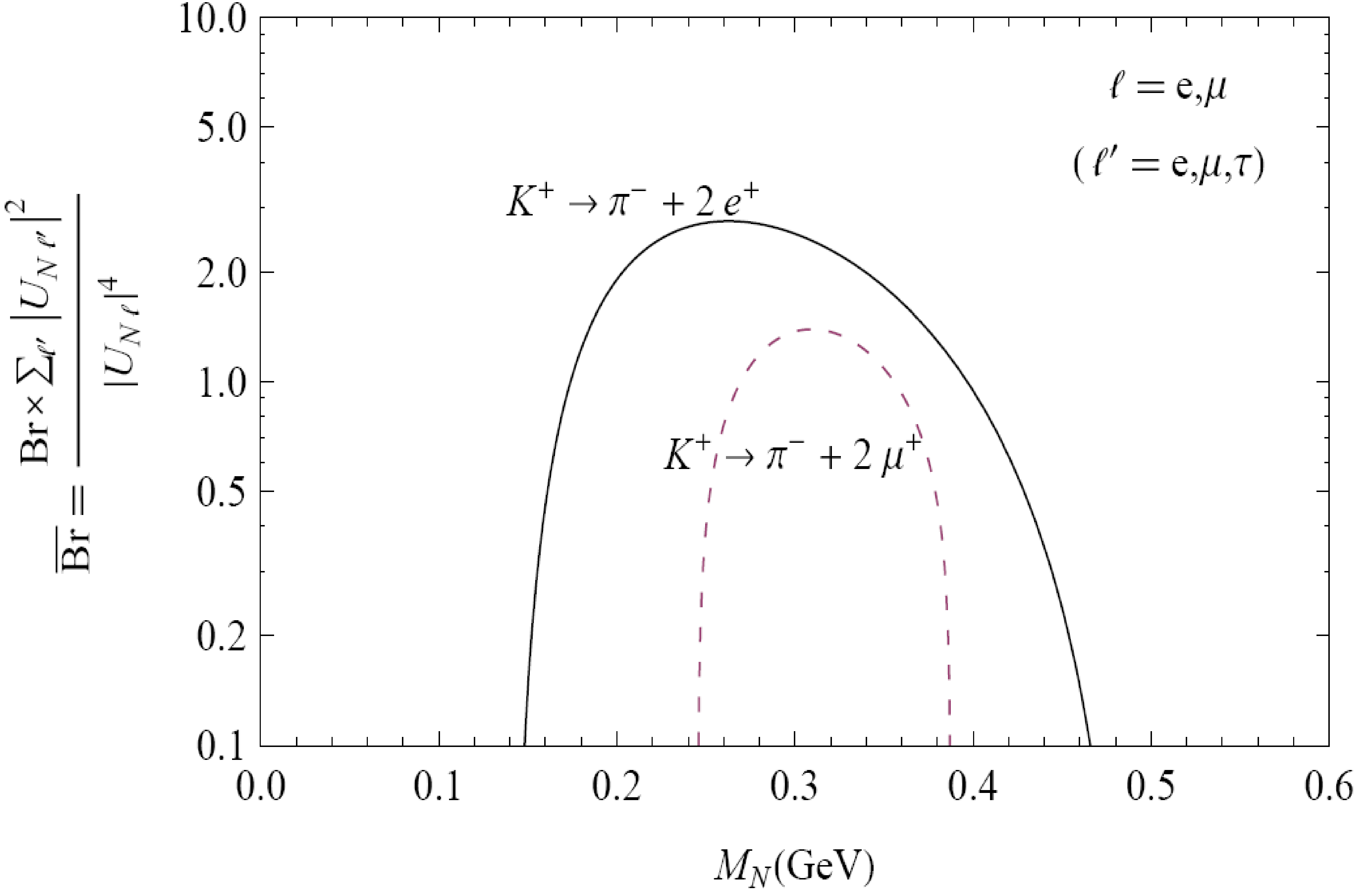
$$|\tilde{\mathcal{M}}|^2 = 32\, m_N^2 \left\{ (m_N^2 - m_\ell^2)^2 (l_1 \cdot l_2) + m_\ell^2 \left((m_N^2 - m_\ell^2)^2 - m_M^2 m_{M'}^2 \right) \right\}$$

$$\frac{1}{(p_N^2 - m_N^2)^2 + m_N^2 \Gamma_N^2} \to \frac{\pi}{m_N \Gamma_N} \delta(p_N^2 - m_N^2). \qquad \Gamma_N \approx 2 \sum_{\ell'} |U_{N\ell'}|^2 \left(\frac{m_N}{m_\tau} \right)^5 \times \Gamma_\tau$$

$$\int d\mathrm{ps}_3 = \int \frac{dp_N^2}{2\pi} \int d\mathrm{ps}_{(M \to l_1 N)} \int d\mathrm{ps}_{(N \to l_2 M')}$$

If we neglect charged lepton masses;

$$\Gamma(M \to M' \ell^+ \ell^+) \approx \frac{1}{128\pi^2} G_F^4 f_M^2 f_{M'}^2 |V_{qQ} V_{q_2 q_1}|^2 \frac{|U_{N\ell}|^4}{\sum_{\ell'} |U_{N\ell'}|^2} \frac{m_M m_\tau^5}{2\Gamma_\tau} \left(1 - \frac{m_{M'}^2}{m_N^2}\right)^2 \left(1 - \frac{m_N^2}{m_M^2}\right)^2.$$



Br for $K^+ \to \pi^- \ell^+ \ell^+ (\ell = e, \mu)$ as function of mN, with lepton mixings divided out

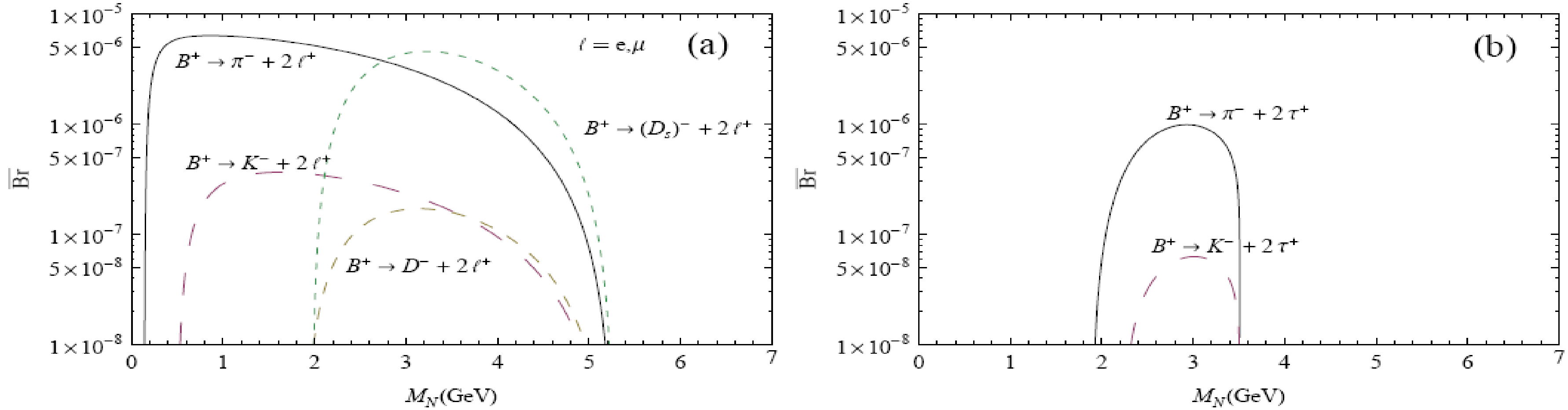


FIG. 6: Branching ratios for $B^+ \to M'^- \ell^+ \ell^+$ as functions of the neutrino mass m_N, with the lepton mixing factor divided out as in Fig. 4. The produced pseudoscalars are $M' = \pi, K, D, D_s$. (a) The case of leptons with negligible mass ($\ell = e, \mu$); (b) the case $\ell = \tau$ (here $M' = D, D_s$ are kinematically forbidden).

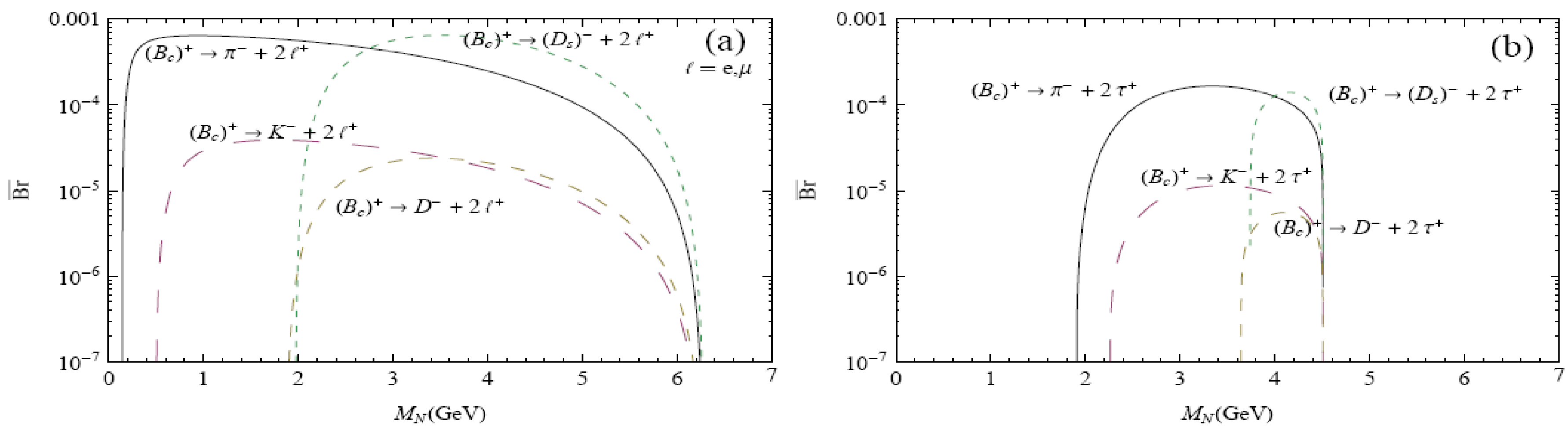


FIG. 7: Branching ratios for $B_c \to M'^- \ell^+ \ell^+$ as functions of the neutrino mass m_N, with the lepton mixing factor divided out as in Fig. 4. The produced pseudoscalars are $M' = \pi, K, D, D_s$. (a) The case of leptons with negligible mass ($\ell = e, \mu$); (b) the case $\ell = \tau$.

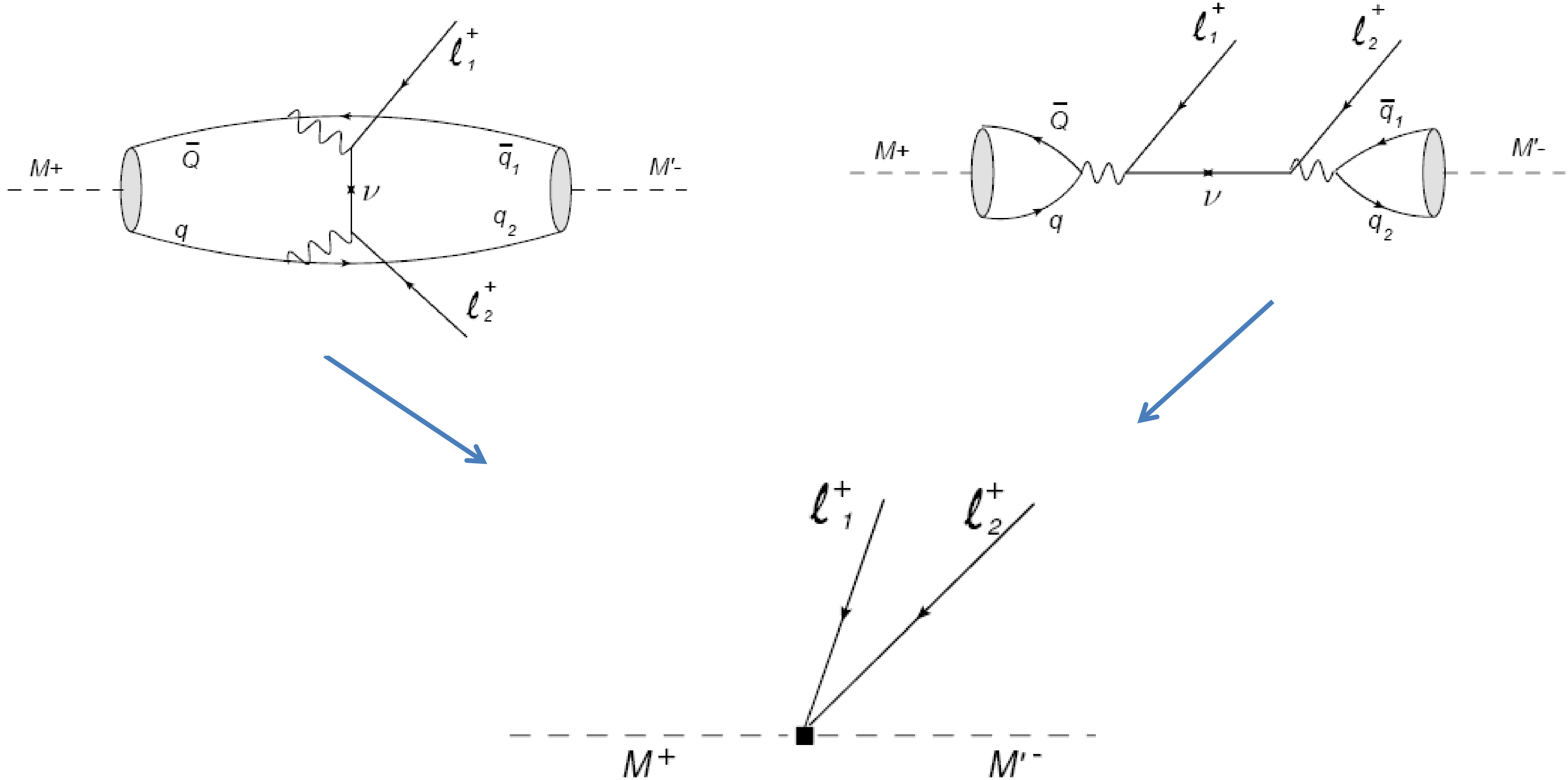
decay	$\mathcal{C}$	m_N at maximum	$Br <$
$K^+ \to \pi^- \ell^+ \ell^+$	2.8	0.26 GeV	$2.8 \cdot 10^{-6}$
$D^+ \to \pi^- \ell^+ \ell^+$	$4.5 \cdot 10^{-3}$	0.51 GeV	$4.5 \cdot 10^{-10}$
$D^+ \to K^- \ell^+ \ell^+$	$1.4 \cdot 10^{-4}$	0.96 GeV	$1.4 \cdot 10^{-11}$
$D_s^+ \to \pi^- \ell^+ \ell^+$	$6.9 \cdot 10^{-2}$	0.53 GeV	$6.9 \cdot 10^{-9}$
$D_s^+ \to K^- \ell^+ \ell^+$	$2.2 \cdot 10^{-3}$	0.99 GeV	$2.2 \cdot 10^{-10}$
$D_s^+ \to D^- \ell^+ \ell^+$	$8.5 \cdot 10^{-8}$	1.92 GeV	$8.5 \cdot 10^{-15}$
$B^+ \to \pi^- \ell^+ \ell^+$	$6.3 \cdot 10^{-6}$	0.86 GeV	$6.3 \cdot 10^{-13}$
$B^+ \to K^- \ell^+ \ell^+$	$3.6 \cdot 10^{-7}$	1.61 GeV	$3.6 \cdot 10^{-14}$
$B^+ \to D^- \ell^+ \ell^+$	$1.7 \cdot 10^{-7}$	3.14 GeV	$1.7 \cdot 10^{-14}$
$B^+ \to D_s^- \ell^+ \ell^+$	$4.5 \cdot 10^{-6}$	3.23 GeV	$4.5 \cdot 10^{-13}$
$B_c^+ \to \pi^- \ell^+ \ell^+$	$6.4 \cdot 10^{-4}$	0.94 GeV	$6.4 \cdot 10^{-11}$
$B_c^+ \to K^- \ell^+ \ell^+$	$3.9 \cdot 10^{-5}$	1.76 GeV	$3.9 \cdot 10^{-12}$
$B_c^+ \to D^- \ell^+ \ell^+$	$2.4 \cdot 10^{-5}$	3.43 GeV	$2.4 \cdot 10^{-12}$
$B_c^+ \to D_s^- \ell^+ \ell^+$	$6.5 \cdot 10^{-4}$	3.52 GeV	$6.5 \cdot 10^{-11}$
$B_c^+ \to B^- \ell^+ \ell^+$	$1.6 \cdot 10^{-11}$	5.76 GeV	$1.6 \cdot 10^{-18}$

$$\mathrm{Br}_{\mathrm{max}}(M^+ \to M'^- \ell^+ \ell^+) = \mathcal{C} \times \frac{|U_{N\ell}|^2}{\sum_{\ell'} |U_{N\ell'}|^2}$$

the last column, the expected upper bound on the branching ratios, provided $|U_{N\ell}|^2 \sim 10^{-6}$ or 10^{-7}, for $m_N \sim 0.1$ GeV or ~ 1 GeV, respectively.

(iii) Heavy neutrino case $m_{\nu_i} >> m_{M^+}$

- In this case, both contributions of “s-type” and “t-type” diagrams are rather comparable.



- neutrino propagators reduce to $-1/(m_N)^2$

(c) Probing Majorana Neutrinos at LHC

- In accelerator-based experiments, neutrinos in the final state are undetectable by the detectors, leading to the "missing energy".

So it is desirable to look for charged leptons in the final state.

- It is hard to avoid the TeV-scale physics to contribute to flavor-changing effects in general whatever it is,
  - SUSY, extra dimensions, TeV seesaw, technicolor, Higgsless, little Higgs

Testability at the LHC

- Two necessary conditions to test at the LHC:
  - -- Masses of heavy Majorana ν's must be less than TeV
  - -- Light-heavy neutrino mixing (i.e., M_D/M_R) must be large enough.

$$\Delta(D-M) \propto m/E \Rightarrow m \approx O(100GeV - 1TeV)$$

- LHC signatures of heavy Majorana ν's are essentially decoupled from masses and mixing parameters of light Majorana ν's.

- Non-unitarity of the light neutrino flavor mixing matrix might lead to observable effects.

- Nontrivial limits on heavy Majorana neutrinos can be derived at the LHC, if the SM backgrounds are small for a specific final state.

$\Delta L = 2$ like-sign dilepton events

$$pp \to W^{\pm}W^{\pm} \to \mu^{\pm}\mu^{\pm}jj \text{ and } pp \to W^{\pm} \to \mu^{\pm}N \to \mu^{\pm}\mu^{\pm}jj$$

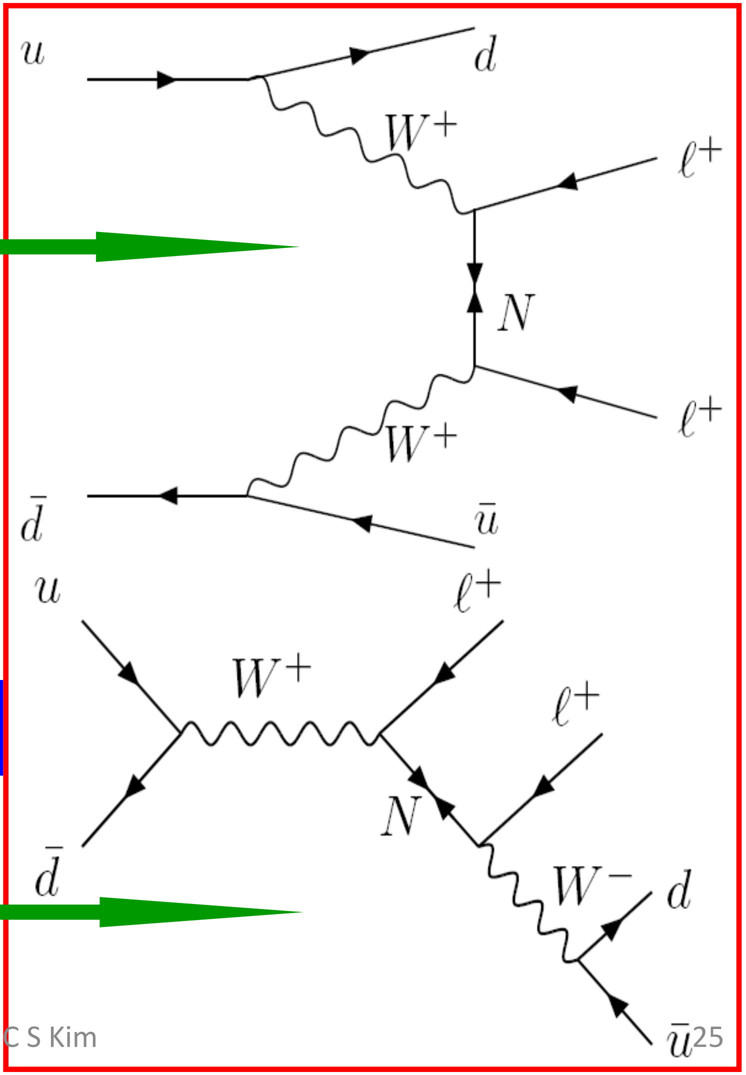
Collider Signature

Lepton number violation: like-sign dilepton events at hadron colliders, such as Tevatron (~2 TeV) and LHC (~14 TeV).

collider analogue to 0νββ decay

dominant channel

N can be produced on resonance

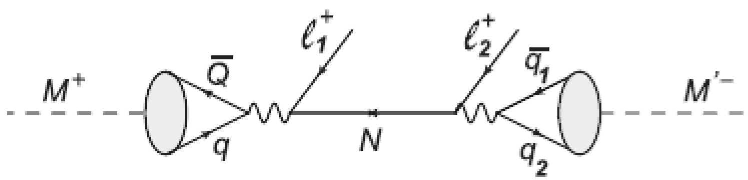


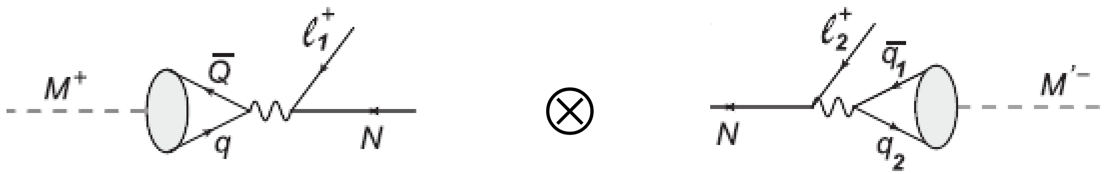
3. Issues on Displacement of Vertices

CSK et al PHYSICAL REVIEW D 89, 077301 (2014)

Gronau et al, PRD29(1984)2539

- **When** $m(\pi) \le m(N) \le m(B)$ **in** $B^+ \to l^+ N(\to l^+ \pi^-)$ **:**
  a) N is on mass-shell
  b) Two charged leptons at displaced vertices
  c) Possibly 2ndary vertex fall outside of detector

- 

= 

- $$\Gamma(M^+ \to \ell^+ \ell^+ M'^-) = \Gamma(M^+ \to \ell^+ N) \cdot \mathrm{Br}(N \to \ell^+ M'^-)$$

Atre et al, JHEP05,035

CSK et al PHYSICAL REVIEW D 89, 093012 (2014)

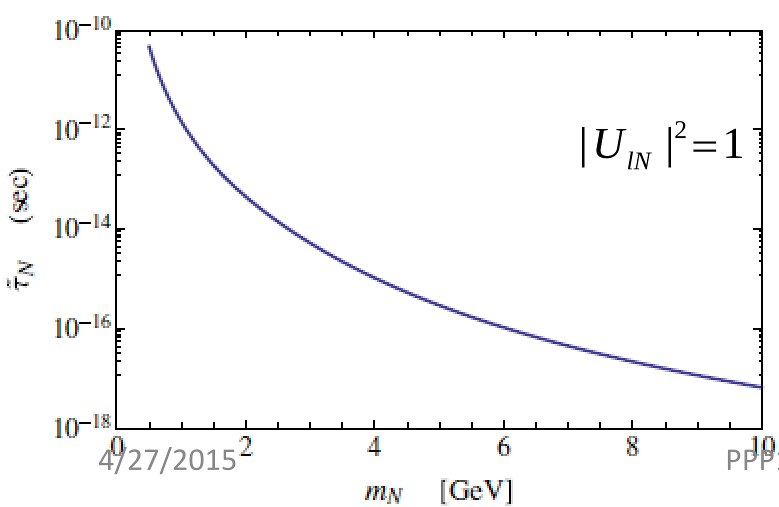
Life time of N, τ_N

- Present bound

TABLE I. Present upper bounds for the squares $|B_{\ell N}|^2$ of the heavy-light mixing matrix elements, for various specific values of M_N.

M_N[GeV]	$\lvert B_{eN}\rvert^2$	$\lvert B_{\mu N}\rvert^2$	$\lvert B_{\tau N}\rvert^2$
0.1	$(1.5 \pm 0.5) \times 10^{-8}$	$(6.0 \pm 0.5) \times 10^{-6}$	$(8.0 \pm 0.5) \times 10^{-4}$
0.3	$(2.5 \pm 0.5) \times 10^{-9}$	$(3.0 \pm 0.5) \times 10^{-9}$	$(1.5 \pm 0.5) \times 10^{-1}$
0.5	$(2.0 \pm 0.5) \times 10^{-8}$	$(6.5 \pm 0.5) \times 10^{-7}$	$(2.5 \pm 0.5) \times 10^{-2}$
0.7	$(3.5 \pm 0.5) \times 10^{-8}$	$(2.5 \pm 0.5) \times 10^{-7}$	$(9.0 \pm 0.5) \times 10^{-3}$
1.0	$(4.5 \pm 0.5) \times 10^{-8}$	$(1.5 \pm 0.5) \times 10^{-7}$	$(3.0 \pm 0.5) \times 10^{-3}$
2.0	$(1.0 \pm 0.5) \times 10^{-7}$	$(2.5 \pm 0.5) \times 10^{-5}$	$(3.0 \pm 0.5) \times 10^{-4}$
3.0	$(1.5 \pm 0.5) \times 10^{-7}$	$(2.5 \pm 0.5) \times 10^{-5}$	$(4.5 \pm 0.5) \times 10^{-5}$
4.0	$(2.5 \pm 0.5) \times 10^{-7}$	$(1.5 \pm 0.5) \times 10^{-5}$	$(1.5 \pm 0.5) \times 10^{-5}$
5.0	$(3.0 \pm 0.5) \times 10^{-7}$	$(1.5 \pm 0.5) \times 10^{-5}$	$(1.5 \pm 0.5) \times 10^{-5}$
6.0	$(3.5 \pm 0.5) \times 10^{-7}$	$(1.5 \pm 0.5) \times 10^{-5}$	$(1.5 \pm 0.5) \times 10^{-5}$

$$\tau_N = 1/\Gamma_N(total) \propto 1/[m_N^5 \, |U_{lN}|^2]$$



For $m_\pi \le m_N \le m_B$, $|U_{lN}|^2 \le 10^{-7}$

Therefore, for $m_N = 2GeV$ $\tau_N \sim 10^{-6}$ sec

→ $L_N = \gamma_N \beta_N \tau_N c \approx \tau_N c \sim 100m$

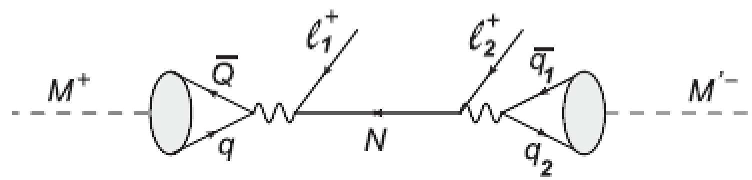
➔ Need consider vertex displacement

Correct Branching Ratios

- 1 Theoretical BR w/ unlimited detectability

$$\Gamma(M^+ \to l^+ l^+ M'^-)_{th} = \Gamma(M^+ \to l^+ N) \bullet Br(N \to l^+ M'^-)$$

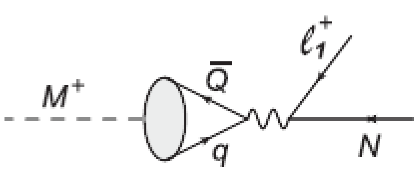
$$Br(M^+ \to l^+ l^+ M'^-)_{th} = Br(M^+ \to l^+ N) \bullet Br(N \to l^+ M'^-)$$



- 2 However, experimentally observed BR

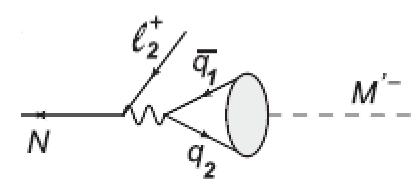
$$Br(M^+ \to l^+ l^+ M'^-)_{ex} = Br(M^+ \to l^+ N) \bullet P_N \bullet Br(N \to l^+ M'^-)$$

where probability for N to decay inside detector (size L_D)



$$P_N = 1 - \exp(-L_D / L_N) \sim L_D / L_N$$

$$L_N = \gamma_N \beta_N \tau_N$$



- 3 Therefore, the correct (theoretical) BR is

$$Br(M^+ \to l^+ l^+ M^{'-})_{th} = Br(M^+ \to l^+ l^+ M^{'-})_{ex} / P_N \sim Br(M^+ \to l^+ l^+ M^{'-})_{ex} \times [L_N / L_D]$$

- Ex) KEKB (3.5 on 8 GeV), $\gamma_N \sim 2, \tau_N \sim 10^{-7}\,\mathrm{sec} \to L_N \sim 100m$

$$Br(B^+ \to e^+ e^+ D^-)_{th} = Br(B^+ \to e^+ e^+ D^-)_{ex} \times [100m] / L_D$$

- Ex) CERN LHC, m(N)~ 100-1000 GeV, P_N ~1

$$Br(B^+ \to e^+ e^+ D^-)_{th} \simeq Br(B^+ \to e^+ e^+ D^-)_{ex}$$

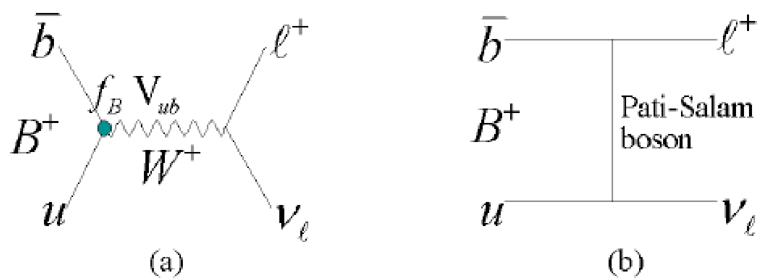
➔ Huge implication to the present bounds on

$$B_{lN}(V_{l4}, U_{Nl})$$

4. Issues on $\Gamma(B^+ \to \tau^+ \nu)$ vs. $\Gamma(B^+ \to \tau^+ N)$

What Belle/BaBar had done:

$B^+ \to \tau^+ \nu_\tau$ the basics

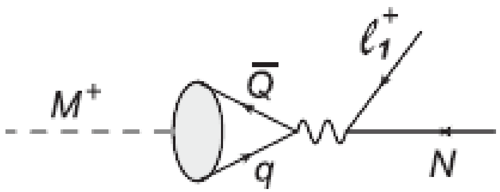


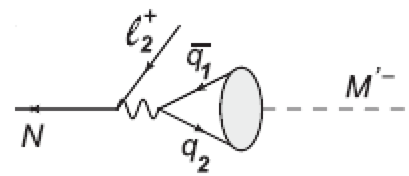
$$\Gamma(B^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2$$ ←Need recalculate this

- very clean place to measure f_B (or V_{ub}?) and/or search for new physics (e.g. H^+, LQ)
- but, helicity-suppressed: $\Gamma(B^+ \to e^+ \nu_e) \ll \Gamma(B^+ \to \mu^+ \nu_\mu) \ll \Gamma(B^+ \to \tau^+ \nu_\tau)$
- First evidence for $B^+ \to \tau^+ \nu_\tau$ by Belle using hadronic tagging ("Full reconstruction") PRL 97, 251802 (2006)

Need to consider:

- Due to long lifetime of N, (and small P_N)



[

gone]

- When you see $B^+ \to \tau^+ + miss(E, \vec{P})$,
  is the event $B^+ \to \tau^+ \nu$ or $B^+ \to \tau^+ N$?
  (where $N =$ massive sterile (Dirac or Majorana) particle)

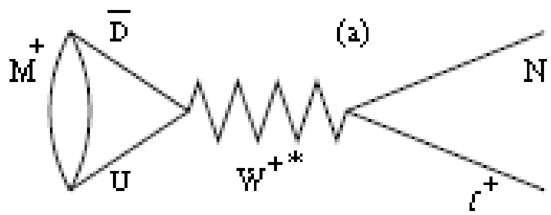
∴ tau decay involves neutrinos, so m(nu) cannot be constrained.

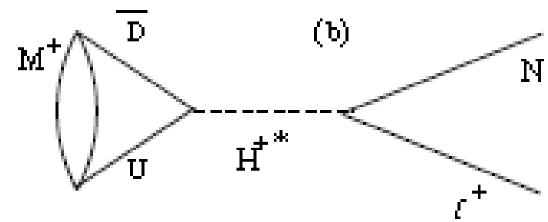
$$M(\nu) = 0$$

$$\Gamma_{\rm SM}(B^+ \to \nu_\tau \tau^+) = \frac{1}{8\pi} G_F^2 f_B^2 |V_{ub}|^2 \left(1 - \frac{M_\tau^2}{M_B^2}\right)^2 M_B M_\tau^2 \approx 4.69 \times 10^{-17}\ {\rm GeV}$$

$$\Gamma_{\rm 2HDM(II)}(B^+ \to \nu_\tau \tau^+) = \frac{1}{8\pi} G_F^2 f_B^2 |V_{ub}|^2 \left(1 - \frac{M_\tau^2}{M_B^2}\right)^2 M_B M_\tau^2 r_H^2 = r_H^2 \Gamma_{\rm SM}(B^+ \to \tau^+ \nu_\tau)$$

$$r_H = -1 + \frac{M_B^2}{M_H^2} \tan^2\beta$$





$$M(N) \neq 0$$

$$\begin{aligned}\Gamma_{\rm SM}(B^+ \to N\tau^+) &= \frac{1}{8\pi} G_F^2 f_B^2 |V_{ub}|^2 |B_{\tau N}|^2 \lambda^{1/2}\left(1, \frac{M_N^2}{M_B^2}, \frac{M_\tau^2}{M_B^2}\right) \\ &\times \frac{1}{M_B}\left[(M_\tau^2 + M_N^2)(M_B^2 - M_N^2 - M_\tau^2) + 4M_N^2 M_\tau^2\right], \\ \Gamma_{\rm 2HDM(II)}(B^+ \to N\tau^+) &= \frac{1}{8\pi} G_F^2 f_B^2 |V_{ub}|^2 |B_{\tau N}|^2 \lambda^{1/2}\left(1, \frac{M_N^2}{M_B^2}, \frac{M_\tau^2}{M_B^2}\right) \\ &\times \frac{1}{M_B}\left[(M_\tau^2 r_H^2 + M_N^2 l_H^2)(M_B^2 - M_N^2 - M_\tau^2) - 4 r_H l_H M_N^2 M_\tau^2\right]\end{aligned}$$

$$r_H = -1 + \frac{M_B^2}{M_H^2} \tan^2\beta$$

$$l_H = 1 + \frac{M_B^2}{M_H^2}$$

Need new numerical analysis (possibly 4 cases)

- 1 Within SM, $M(\nu) = 0$ → $\Gamma_{\mathrm{SM}}(B^+ \to \nu_\tau \tau^+)$
- 2 With new physics (eg. 2HDM) with $M(\nu) = 0$

  → $\Gamma_{\mathrm{2HDM(II)}}(B^+ \to \nu_\tau \tau^+)$
- 3 Within SM with sterile N, $M(N) \neq 0$

  → $\Gamma_{\mathrm{SM}}(B^+ \to \nu_\tau \tau^+)$ + $\Gamma_{\mathrm{SM}}(B^+ \to N \tau^+)$
- 4 With new physics (eg. 2HDM) with $M(N) \neq 0$

  → $\Gamma_{\mathrm{2HDM(II)}}(B^+ \to \nu_\tau \tau^+)$ + $\Gamma_{\mathrm{2HDM(II)}}(B^+ \to N \tau^+)$

Br(B^+ → tau^+ + missing)_exp= (PDG average)= (1.14+-0.27) X 10^-4
Br(…)_SM= (CKMfitter)= (0.758 +- 0.080) X 10^-4

All parameter values from CKMfitter

TABLE I: Presently known upper bound estimates for $|B_{\ell N}|^2$ ($\ell = e, \mu, \tau$) for $M_N \approx 1$, 3 GeV; and the inverse canonical decay width $\overline{L}^{-1}$ (for $\gamma_N = 2$).

M_N [GeV]	$\lvert B_{eN}\rvert^2$	$\lvert B_{\mu N}\rvert^2$	$\lvert B_{\tau N}\rvert^2$	$\overline{L}_N^{-1} [m^{-1}]$
≈ 1.0	10^{-7}	10^{-7}	10^{-2}	115.
≈ 3.0	10^{-6}	10^{-4}	10^{-4}	$2.81 \cdot 10^4$

|B_tauN| from DELPHI, ZPC74(1997)57

$$BR\,(Z^0 \to \nu_m \overline{\nu}) = BR\,(Z^0 \to \nu\overline{\nu})\,|U|^2\,\left(1 - \frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right)^2 \times \left(1 + \frac{1}{2}\frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right),$$

Recent LHC (ATLAS, CMS) Results for charged Higgs boson NPB(Proc.Suppl.) 253(2014)171

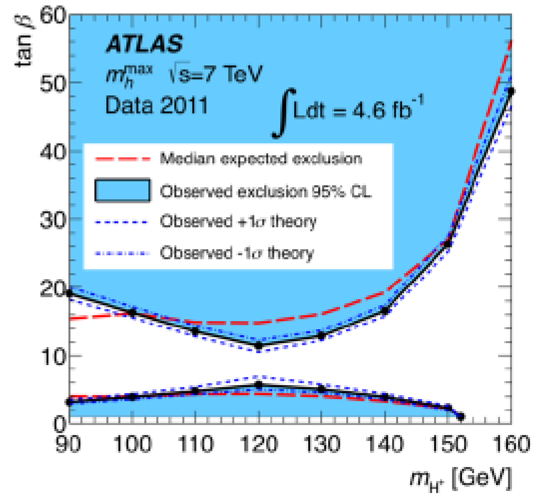
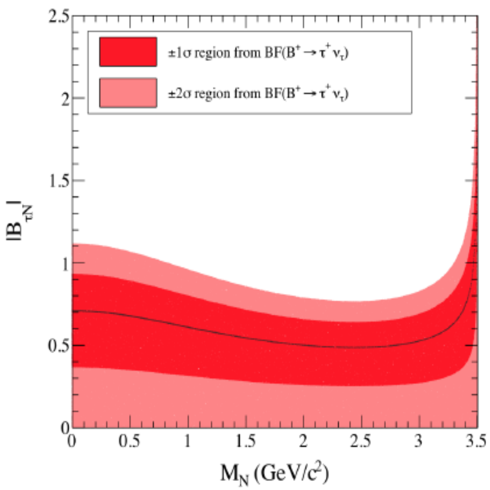


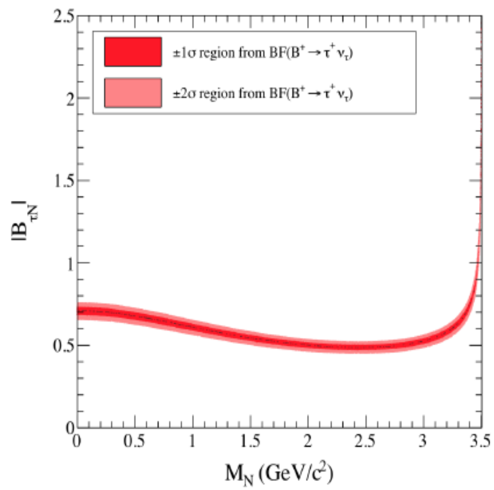
Figure 2: Combined 95% CL exclusion limits on tanβ as a function of m_{H^+} in the context of the MSSM m_h^{max} scenario [6].

Numerical analysis

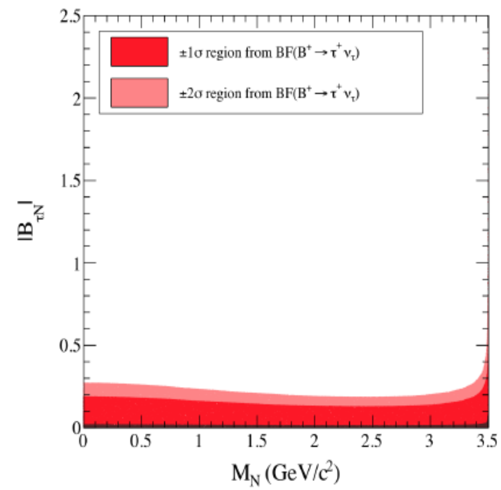
no charged Higgs



central value ⇒ PDG2014
uncertainty ⇒ from PDG2014
compared to "SM" (CKMfitter)

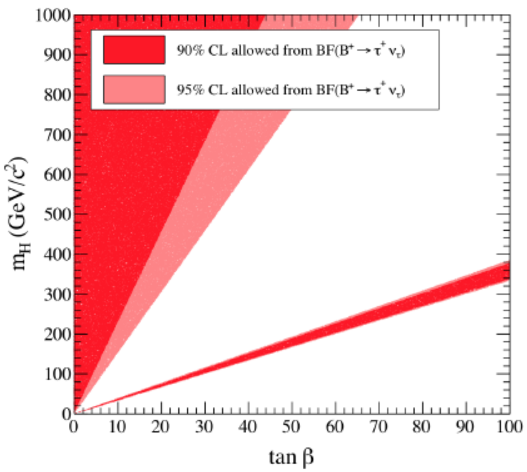


central value ⇒ PDG2014
uncertainty ⇒ (PDG2014)$\times$0.1
compared to "SM" (CKMfitter)

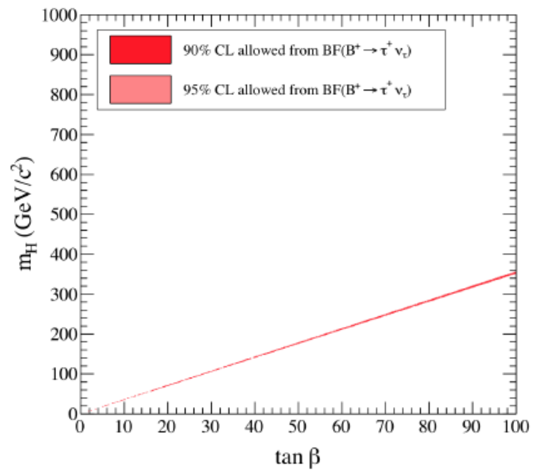


central value ⇒ CKMfitter
uncertainty ⇒ (PDG2014)$\times$0.1
compared to "SM" (CKMfitter)

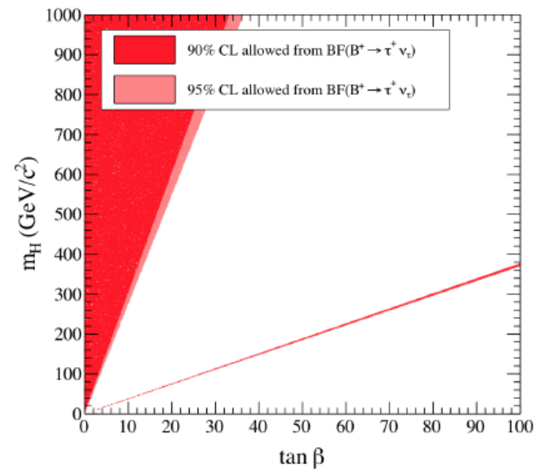
no heavy neutral (N)



central value ⇒ PDG2014
uncertainty ⇒ from PDG2014
compared to "SM" (CKMfitter)

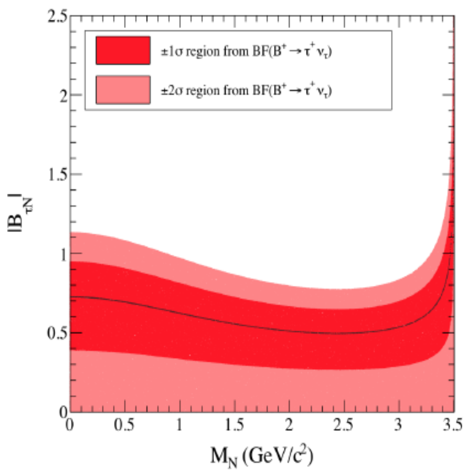


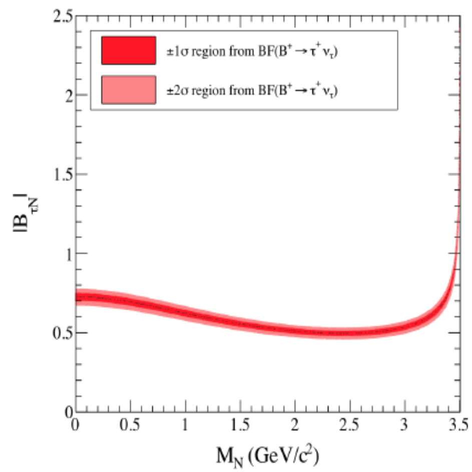
central value ⇒ PDG2014
uncertainty ⇒ (PDG2014) $\times$ 0.1
compared to "SM" (CKMfitter)

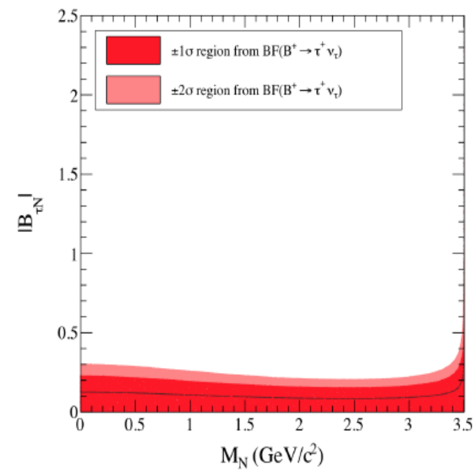


central value ⇒ CKMfitter
uncertainty ⇒ (PDG2014) $\times$ 0.1
compared to "SM" (CKMfitter)

$\tan\beta = 5.0$, $m_H = 300$, **“allowed”**







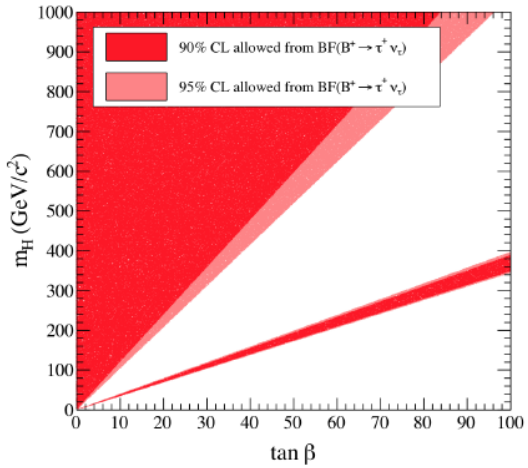
central value ⇒ PDG2014
uncertainty ⇒ from PDG2014
compared to “SM” (CKMfitter)

central value ⇒ PDG2014
uncertainty ⇒ (PDG2014)×0.1
compared to “SM” (CKMfitter)

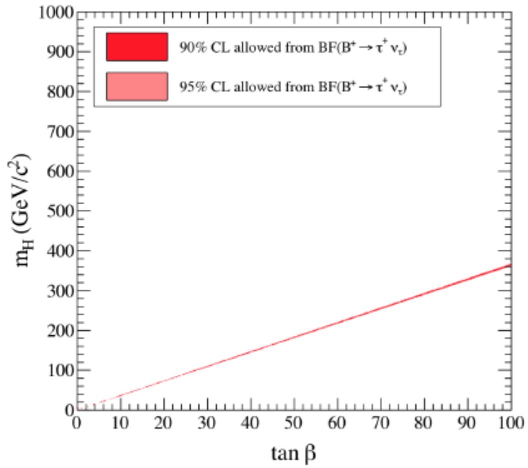
central value ⇒ CKMfitter
uncertainty ⇒ (PDG2014)×0.1
compared to “SM” (CKMfitter)

March 18, 2015 2

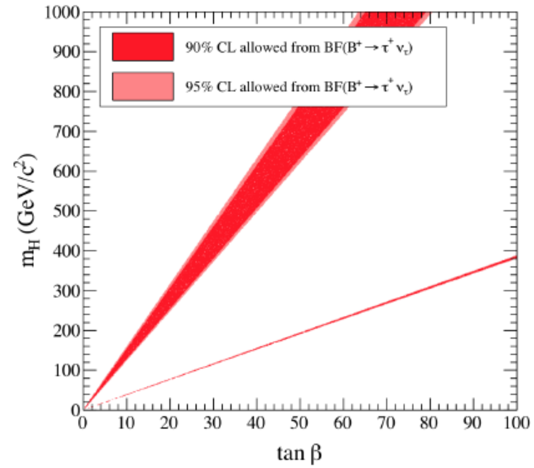
$$m_N = 1, \quad B_{\tau N} = 0.5$$



central value ⇒ PDG2014
uncertainty ⇒ from PDG2014
compared to "SM" (CKMfitter)



central value ⇒ PDG2014
uncertainty ⇒ (PDG2014)×0.1
compared to "SM" (CKMfitter)



central value ⇒ CKMfitter
uncertainty ⇒ (PDG2014)×0.1
compared to "SM" (CKMfitter)

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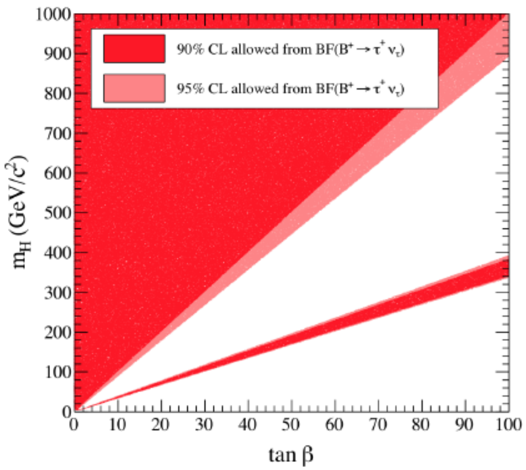
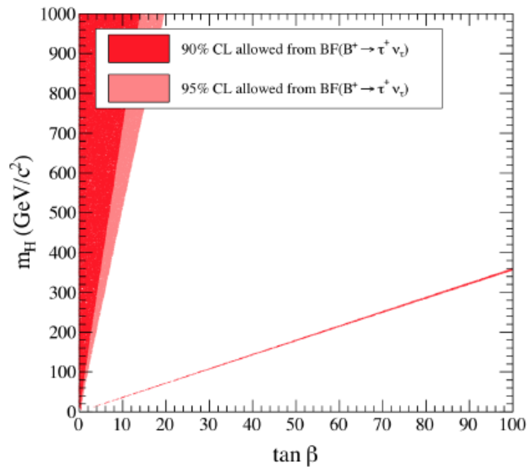
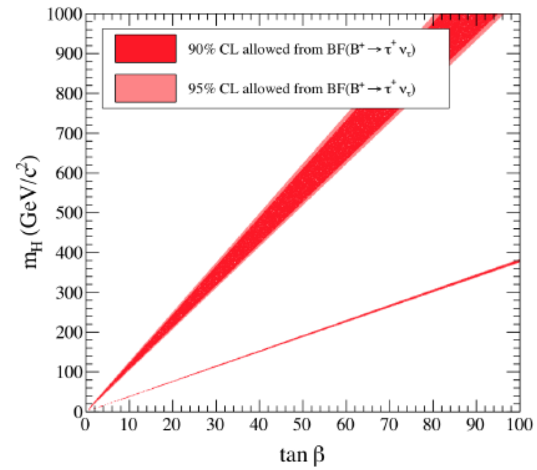
$m_N = 3, \quad B_{\tau N} = 0.5$







central value ⇒ PDG2014
uncertainty ⇒ from PDG2014
compared to "SM" (CKMfitter)

central value ⇒ PDG2014
uncertainty ⇒ (PDG2014)×0.1
compared to "SM" (CKMfitter)

central value ⇒ CKMfitter
uncertainty ⇒ (PDG2014)×0.1
compared to "SM" (CKMfitter)

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** When $P_N = 1 - \exp(-L_D / L_N)$ =1 :

- 1 When P_N becomes 1 (ie N decays within the detector due to some unknown reason), WHAT WOULD HAPPEN?
- 2 $B^+ \to \tau^+ N$ and $N \to e^+ \pi^-$ (Majorana N) OR

  $N \to e^- \pi^+$ (Majorana N or Dirac N)
- 3 Therefore,

  for N_M $B^+ \to \tau^+ e^+ \pi^-$ or $B^+ \to \tau^+ e^- \pi^+$

  for N_D $B^+ \to \tau^+ e^- \pi^+$
- 4 Numerical analysis in going on.

CSK et al JHEP02(2015)108
CSK et al PHYSICAL REVIEW D 89, 093012 (2014)

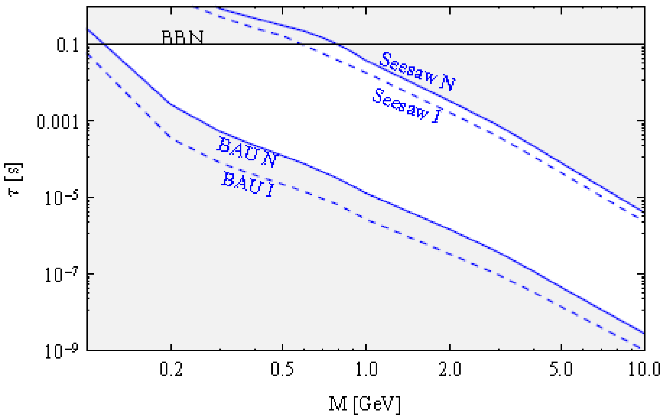
5. Issues of CP Violation in $\Delta_L = 2$ decays

- CERN-SPSC-2013-024 (arXiv:1310.1762 [hep-ex]) :
  CERN SPS Proposal to search Heavy Neutral Leptons
  through CPV in $\Delta_L = 2$ at a new fixed target exp.

- Theoretical background: nuMSM model
  [T. Asala etal, PLB631,151; M. Shaposhnikov, PLB639,414, …]

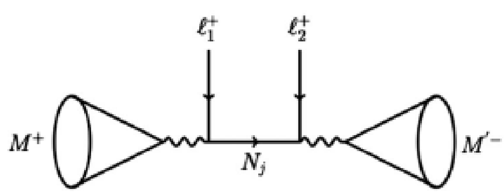
➔ $N_1 \sim 100keV, 100MeV < N_2 \simeq N_3 < 5GeV$

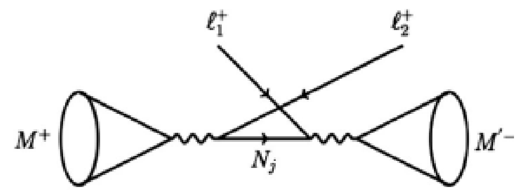
- Experimental bounds for HNLs



CP Violation in $M^{+} \to M'^{-} l_1^{+} l_2^{+}$ decays

- CPV in $\Delta L = 2 \quad \text{Processes} : \quad M^{+} \to M'^{-} l_1^{+} l_2^{+}$





$$A_{CP} = \frac{\Gamma(K^+ \to \pi^- \ell^+ \ell^+) - \Gamma(K^- \to \pi^+ \ell^- \ell^-)}{\Gamma(K^+ \to \pi^- \ell^+ \ell^+) + \Gamma(K^- \to \pi^+ \ell^- \ell^-)}.$$

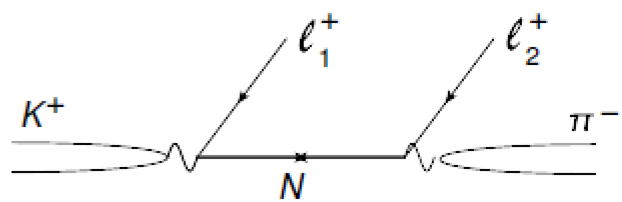


Figure 1. Diagram of the dominating amplitude for the lepton number violating decay $K^+ \to \pi^- \ell^+ \ell^+$ mediated by a Majorana neutrino N with mass in the range between m_π and m_K.

$$\mathcal{M}_{N_i} = -G_F^2 f_\pi f_K \; V_{ud}^* V_{us}^* \; \frac{\lambda_i \, U_{N_i \ell}^2 \, m_{N_i}}{p_N^2 - m_{N_i}^2 + i m_{N_i} \Gamma_{N_i}} \bar{u}(l_2) \not{p} \not{k} \, (1 - \gamma_5) v(l_1),$$

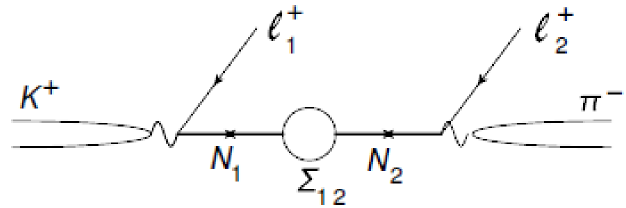
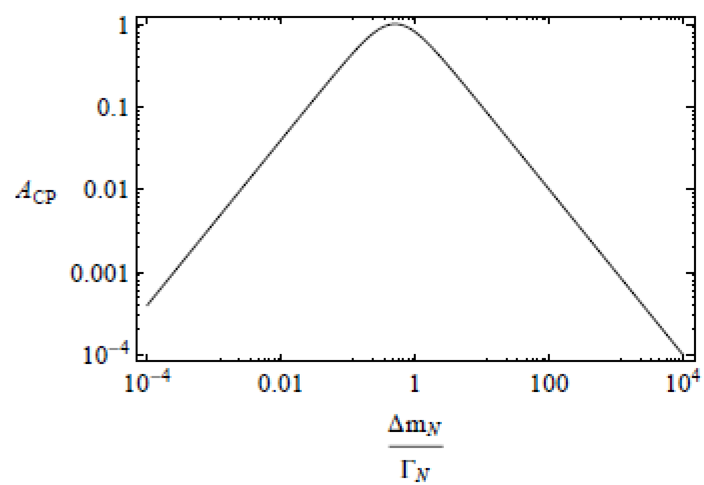


Figure 2. Non-diagonal contribution of the absorptive part of the 2-neutrino propagator to the amplitude for the lepton number violating decay $K^+ \to \pi^- \ell^+ \ell^+$.

$$\mathcal{M}_{12} + \mathcal{M}_{21} = iG_F^2 f_\pi f_K \, V_{ud}^* V_{us}^* \, (\lambda_1 + \lambda_2) \, U_{N_1\ell} U_{N_2\ell} \frac{\Gamma_{12}}{\Delta m^2} \times \left(\frac{m_{N_2}^2}{p_N^2 - m_{N_2}^2 + i\epsilon} - \frac{m_{N_1}^2}{p_N^2 - m_{N_1}^2 + i\epsilon} \right) \bar{u}(l_2) \, \not{p} \, \not{k} \, (1 - \gamma_5) v(l_1),$$

As a crude estimate, we can assume that the lepton mixing elements are comparable (albeit small), $|U_{N_1\ell}| \sim |U_{N_2\ell}|$, and also the decay rates, $\Gamma_{N_1} \sim \Gamma_{N_2}$. Then the asymmetry simplifies to:

$$\hat{A}_{CP} \sim 2 m_N \Gamma_N \frac{\Delta m_N^2}{(\Delta m_N^2)^2 + m_N^2 \Gamma_N^2}.$$



6 Conclusion

- 1
- 2
- 3

Thanks Hai-Yang, but Time Flies …….

Sep 21, 2007

May 31, 2013