

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

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# Time Flies .....



あけましておめでとうございます  
この新しい年が素晴らしい一年になりますよう  
心よりお祈り申し上げます。  
平成七年 元旦



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茨城県つくば市松代5-524-203

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萩原 薫  
優美子  
悠佳



Merry Christmas and Happy Year 2000!  
あけまして  
おめでとうございます  
今年もよい年でありますように。  
2000年 元旦

How are you?

We liked your 〒305-0035 つくば市松代5-524-203

Kimuchi very much!

Please go very much

for your Kimuchi!

萩原 薫・優美子  
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# 1 Introduction

## Possible range of (Sterile) Nu mass

(a) From neutrino oscillation and WMAP:

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

(b) From dark matter searches:

- |                                       |                             |
|---------------------------------------|-----------------------------|
| $m_{N_1} \approx O(10) \text{ keV}$   | from nuMSM, warm DM, ...    |
| $m_N \approx O(1-10) \text{ GeV}$     | from DAMA, CDMS, XENON, ... |
| $m_N \approx O(100-1000) \text{ GeV}$ | from SUSY, EDM, ...         |

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

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

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

## Possible bound of (Sterile) N mixing:

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

→  $B_{\ell\nu_j}$  = PMNS Mixing       $B_{\ell N}$  = Sterile N Mixing

- Present bounds for heavy N, ( $m(N) > 45$  GeV) [Nardi et al, PLB327,319]

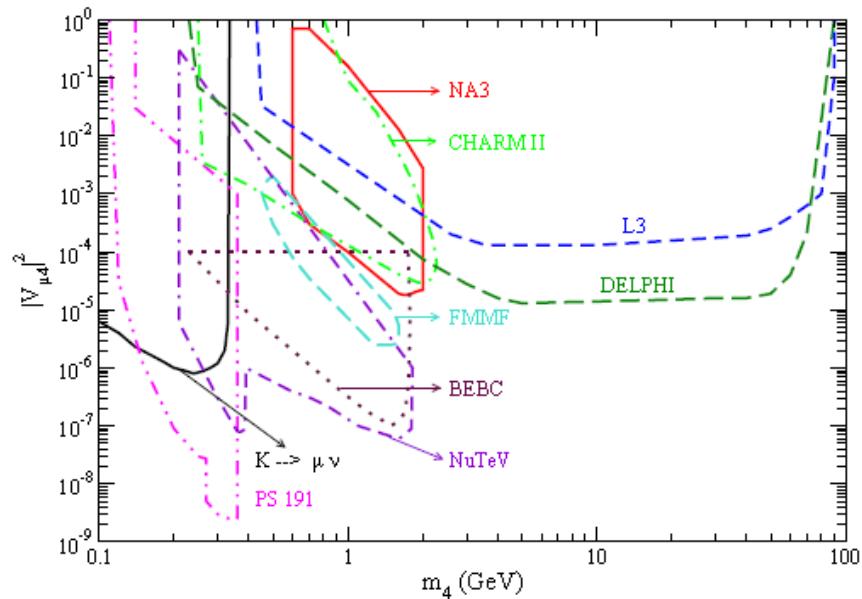
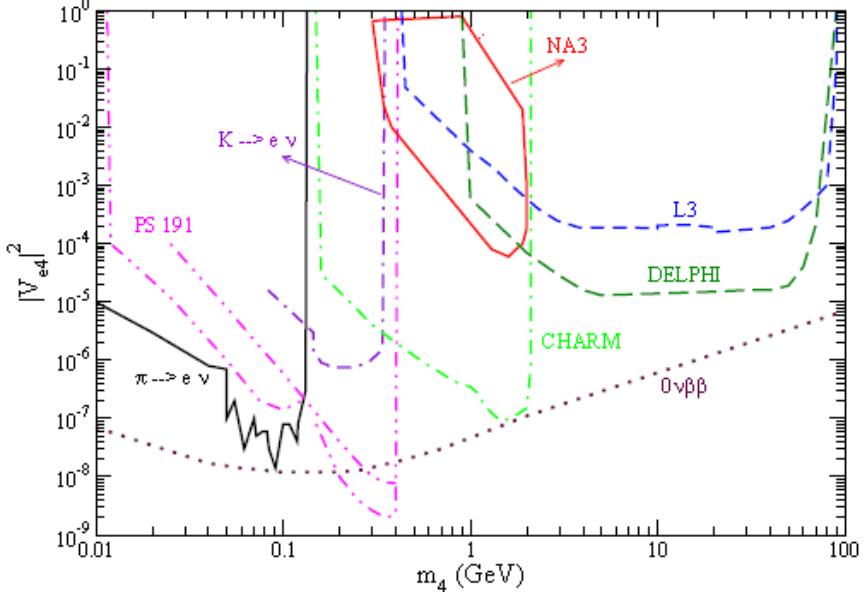
$$\sum_N |U_{Ne}|^2 \equiv (s_L^{\nu_e})^2 \leq 0.005 , \quad (s_L^{\nu_\mu})^2 \leq 0.002 , \quad (s_L^{\nu_\tau})^2 \leq 0.010$$

- M. Aoki et al. [PIENU Collaboration], Phys. Rev. D 84, 052002 (2011)  
current bound on the mixing element  $|B_{eN}|^2 \lesssim 10^{-8}$

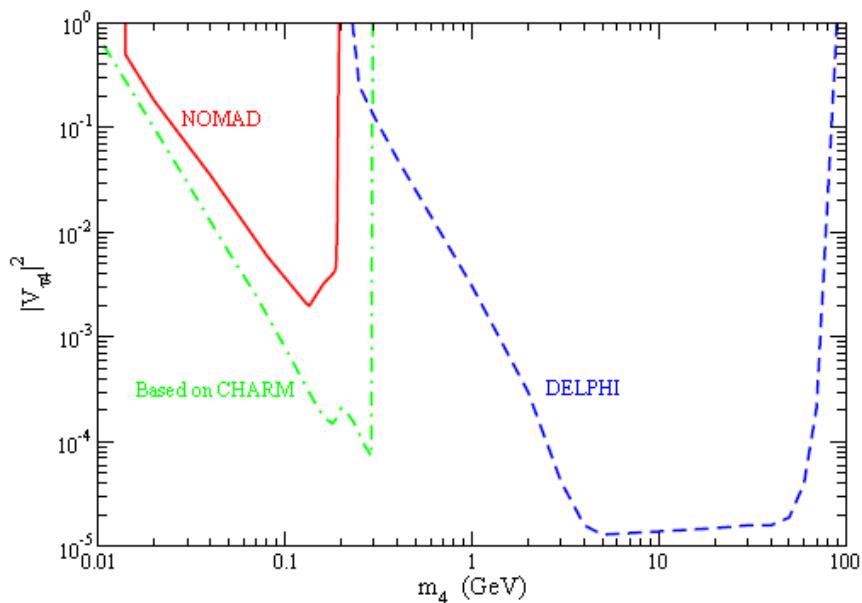
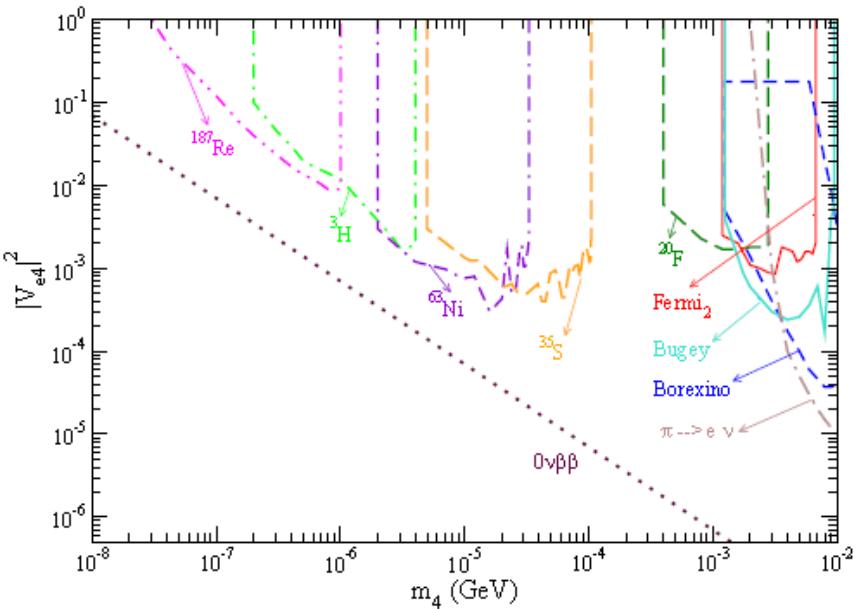
- In nuMSM, see-saw with (light RH sterile) N gives:

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

- We can assume any value of  $B_{\ell N}$ , which will be determined by experiments.



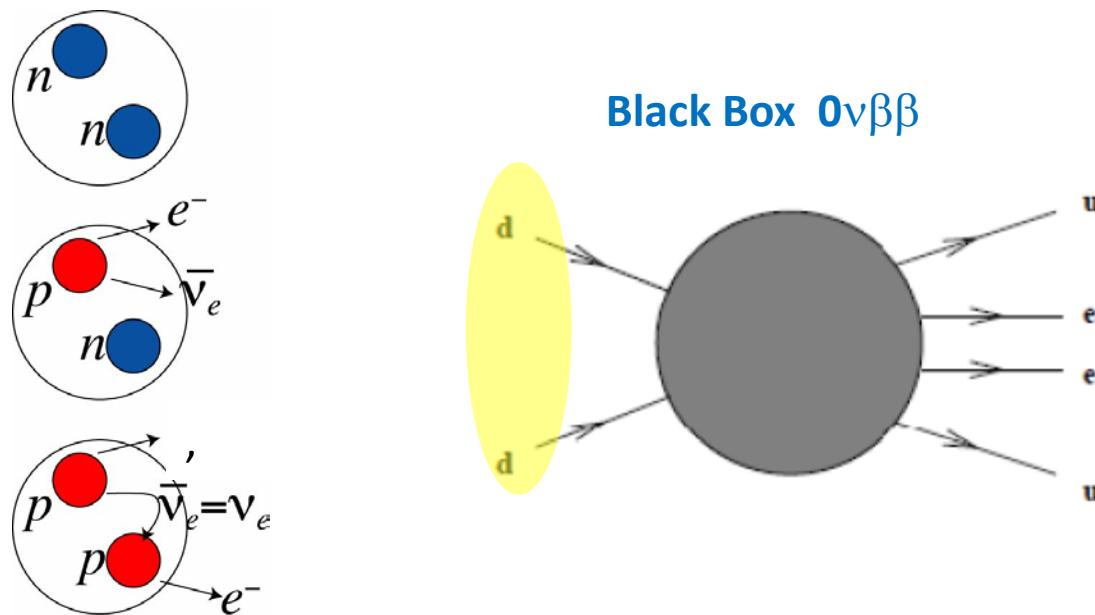
A. Atre et al, JHEP05(2009)030



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

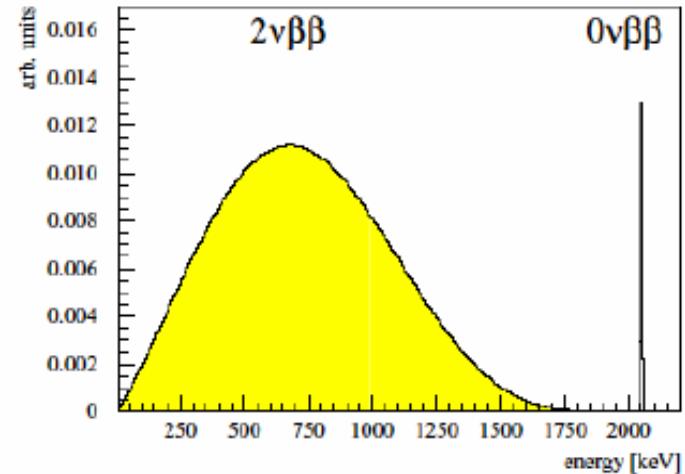
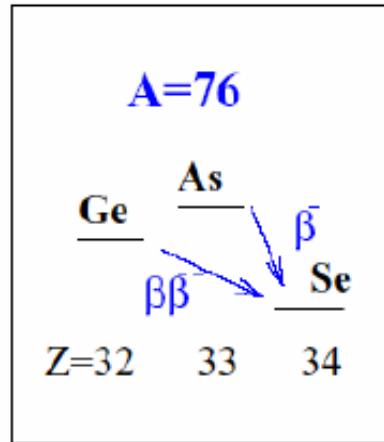
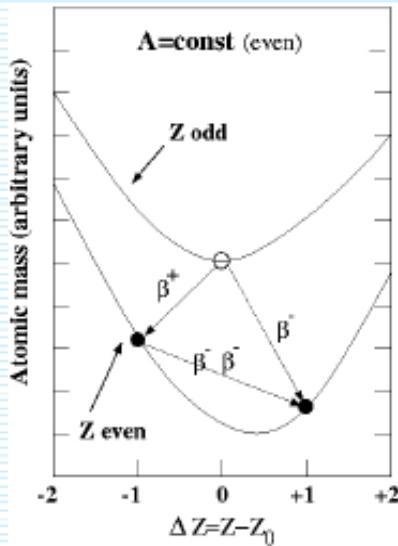
- Lepton number violation by 2 units  $\Delta L = 2$  plays a crucial role to probe the **Majorana** nature of  $\nu$ 's,

### (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



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

$$(T_{1/2}^{2\nu})^{-1} = G^{2\nu} |M_{GT}^{2\nu}|^2$$

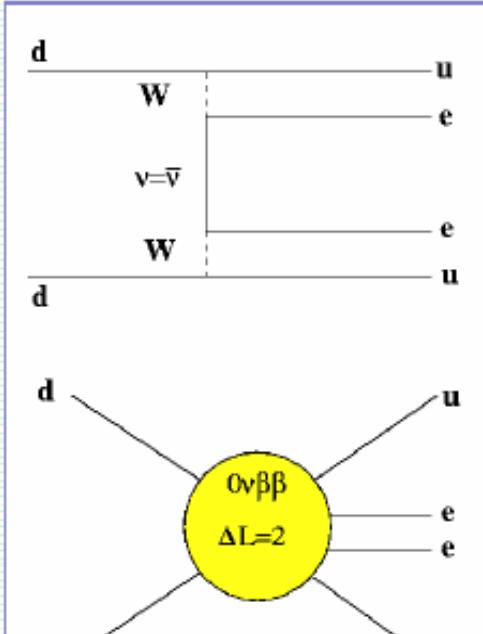
Observed for 10 isotopes:  $^{48}\text{Ca}$ ,  $^{76}\text{Ge}$ ,  $^{82}\text{Se}$ ,  $^{96}\text{Zr}$ ,  $^{100}\text{Mo}$ .

$^{116}\text{Cd}$ ,  $^{128}\text{Te}$ ,  $^{130}\text{Te}$ ,  $^{150}\text{Nd}$ ,  $^{238}\text{U}$ ,  $T_{1/2} \approx 10^{18}\text{-}10^{24}$  years

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

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

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



- In the limit of small neutrino masses :

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

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

U\_{ei} → U\_{ek}  $\int \frac{d^4 p}{(2\pi)^4} \frac{m_{\nu_k} + p}{p^2 - m_{\nu_k}^2}$

W\_L^-  
W\_L^-

U\_{ei}  
→  
U\_{ek}

U\_{ei}  
U\_{ei}

e-  
e-

e-  
e-

ν\_i  
ν\_i

U\_{ek}  $\int \frac{d^4 p}{(2\pi)^4} \frac{m_{\nu_k} + p}{p^2 - m_{\nu_k}^2}$

U\_{ei}  
U\_{ei}

W\_L^-  
W\_L^-

e-  
e-

U\_{ei}  
U\_{ei}

e-  
e-

W\_L^-  
W\_L^-

e-  
e-

U\_{ei}  
U\_{ei}

e-  
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# Uncertainties

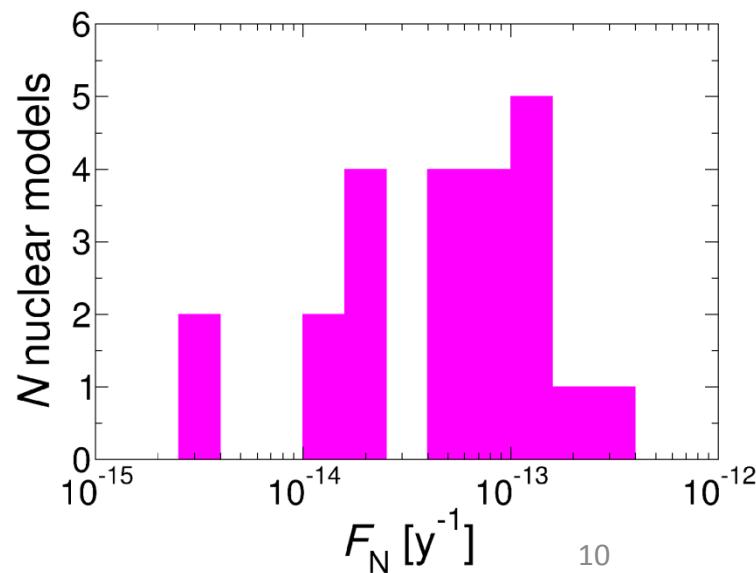
(O.Cremonesi, 05)

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

## Effective Neutrino Mass

## Nuclear Factor of Merit

- Large uncertainties in NME

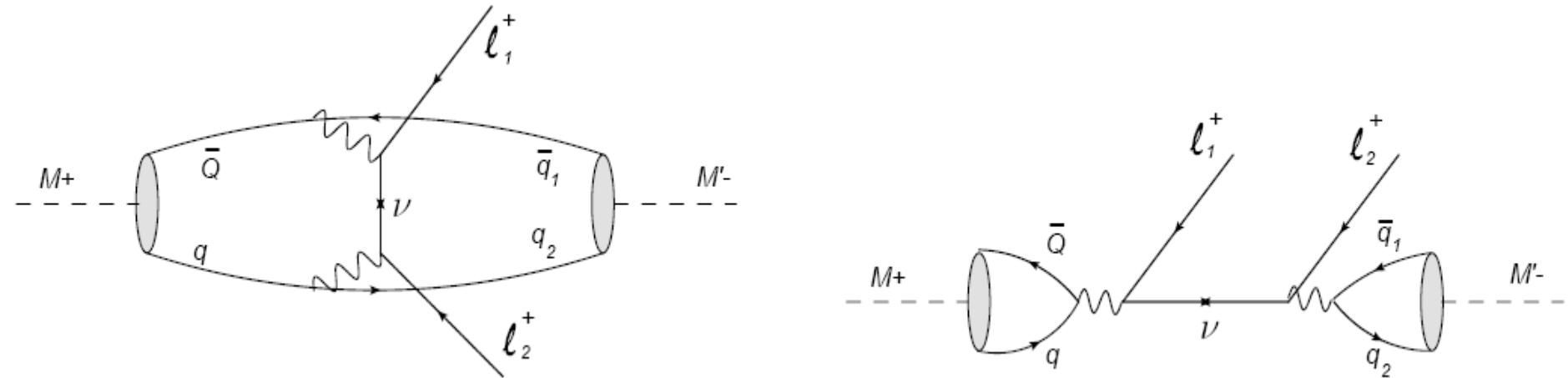


## (b) Probe of Majorana neutrinos via rare decays of mesons

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

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

- Taking mesons in the initial and final state to be pseudoscalar ( $M : K, D, D_s, B, B_c / M' = \pi, K, D, \dots$ )



- Not involve the uncertainties from nuclear matrix elements in  $0\beta\nu\nu$

## Effective Hamiltonian:

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

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

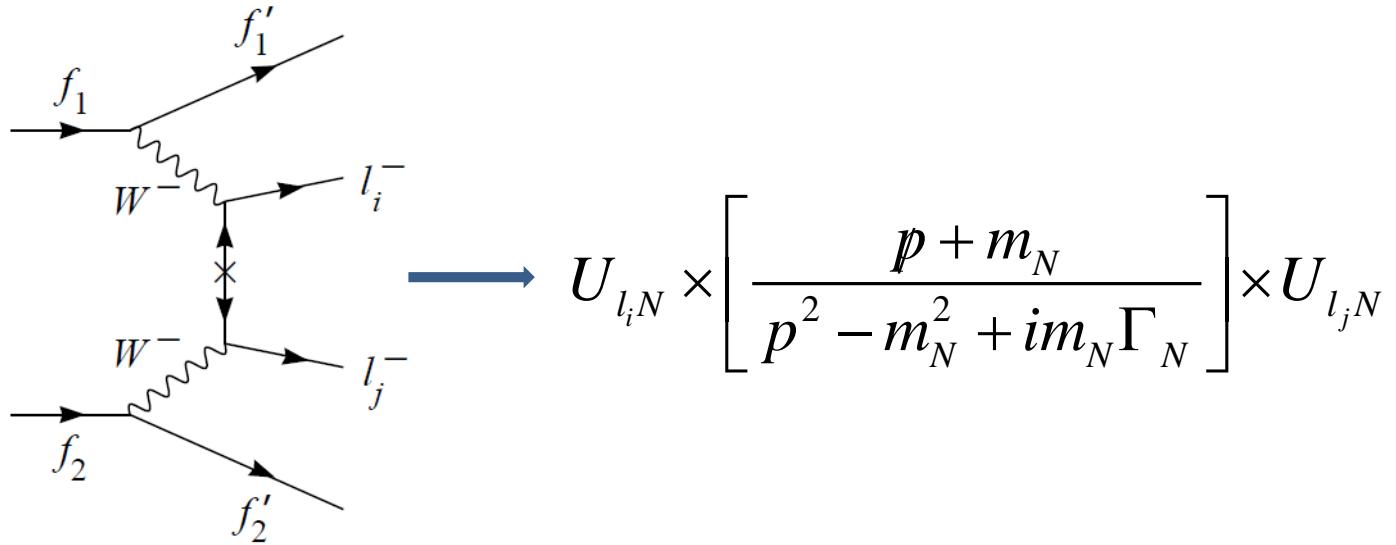
$$O_s^{\mu\nu} = V_{q_2 q_1}^* V_{q Q} J_{q_2 q_1}^\mu J_{q Q}^\nu$$

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

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

## Decay Amplitude:

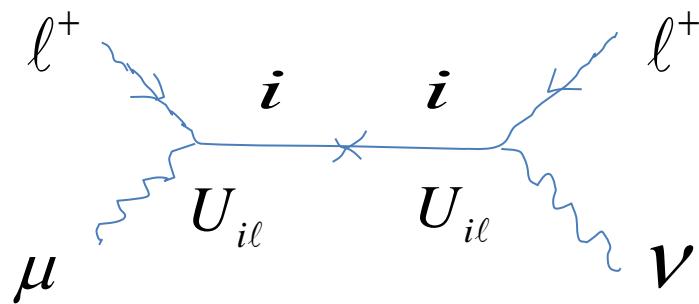
$$A(M^+ \rightarrow M'^- \ell_1^+ \ell_2^+) = \langle M'^- \ell_1^+ \ell_2^+ | H_{eff} | M^+ \rangle$$



- transition rates are proportional to

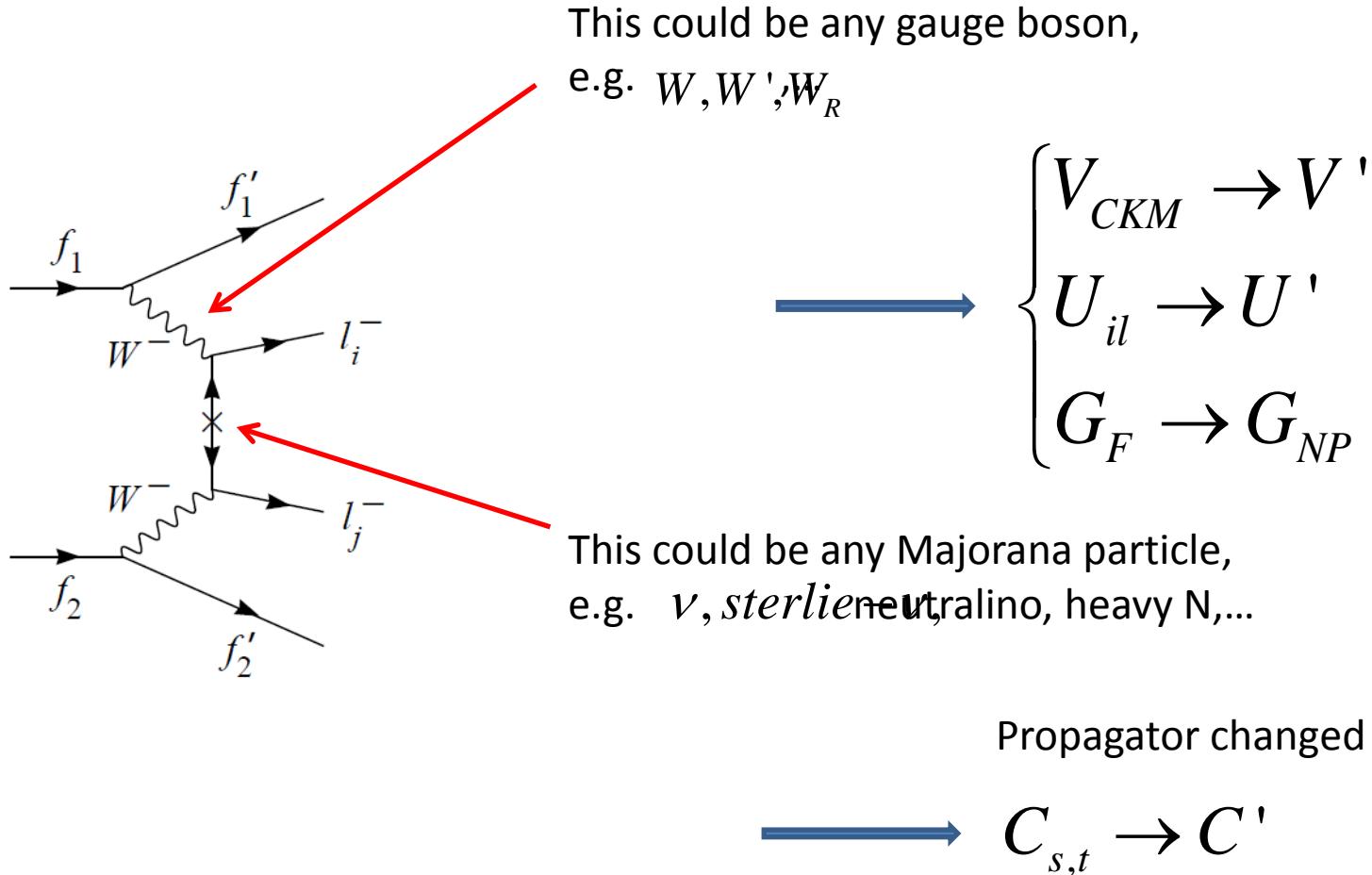
$$\begin{aligned}
 & \left\{ \begin{array}{l} \langle m \rangle_{l_1 l_2}^2 = \left| \sum_{i=1}^3 U_{l_1 i} U_{l_2 i} m_i \right|^2 \quad \text{for light } \nu \\ \left| \sum_{i=4}^{3+n} \frac{U_{l_1 i} U_{l_2 i}}{m_i} \right|^2 \quad \text{for heavy } \nu \\ \frac{\Gamma(N \rightarrow i) \Gamma(N \rightarrow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

For example, leptonic current :



$$\begin{aligned}
 L_{\mu\nu} &= (U_{i\ell} U_{i\ell}) \times \bar{\nu}_i \gamma_\mu \frac{(1 - \gamma_5)}{2} v_\ell \times (\text{---}) \times \bar{\nu}_i \gamma_\nu \frac{(1 - \gamma_5)}{2} v_\ell \\
 &= (U_{i\ell}^* U_{i\ell}) \times \bar{u}_\ell \gamma_\mu \frac{(1 + \gamma_5)}{2} v_i \times (\text{---}) \times \bar{\nu}_i \gamma_\nu \frac{(1 - \gamma_5)}{2} v_\ell \\
 &= \sum_i (U_{i\ell}^* U_{i\ell}) \times \bar{u}_\ell \gamma_\mu \frac{(1 + \gamma_5)}{2} \left( \frac{\cancel{p}_{\nu_i} + m_{\nu_i}}{\cancel{p}_{\nu_i}^2 - m_{\nu_i}^2} \right) \gamma_\nu \frac{(1 - \gamma_5)}{2} v_\ell \\
 &= \left( \sum_i U_{i\ell}^* U_{i\ell} \frac{m_{\nu_i}}{\cancel{p}_{\nu_i}^2 - m_{\nu_i}^2} \right) \times \bar{u}_\ell \gamma_\mu \gamma_\nu \frac{(1 - \gamma_5)}{2} v_\ell
 \end{aligned}$$

## Model Independence of Effective Theory approach



(i) Light neutrino case

$$m_{\nu_i} \ll m_{M'}$$

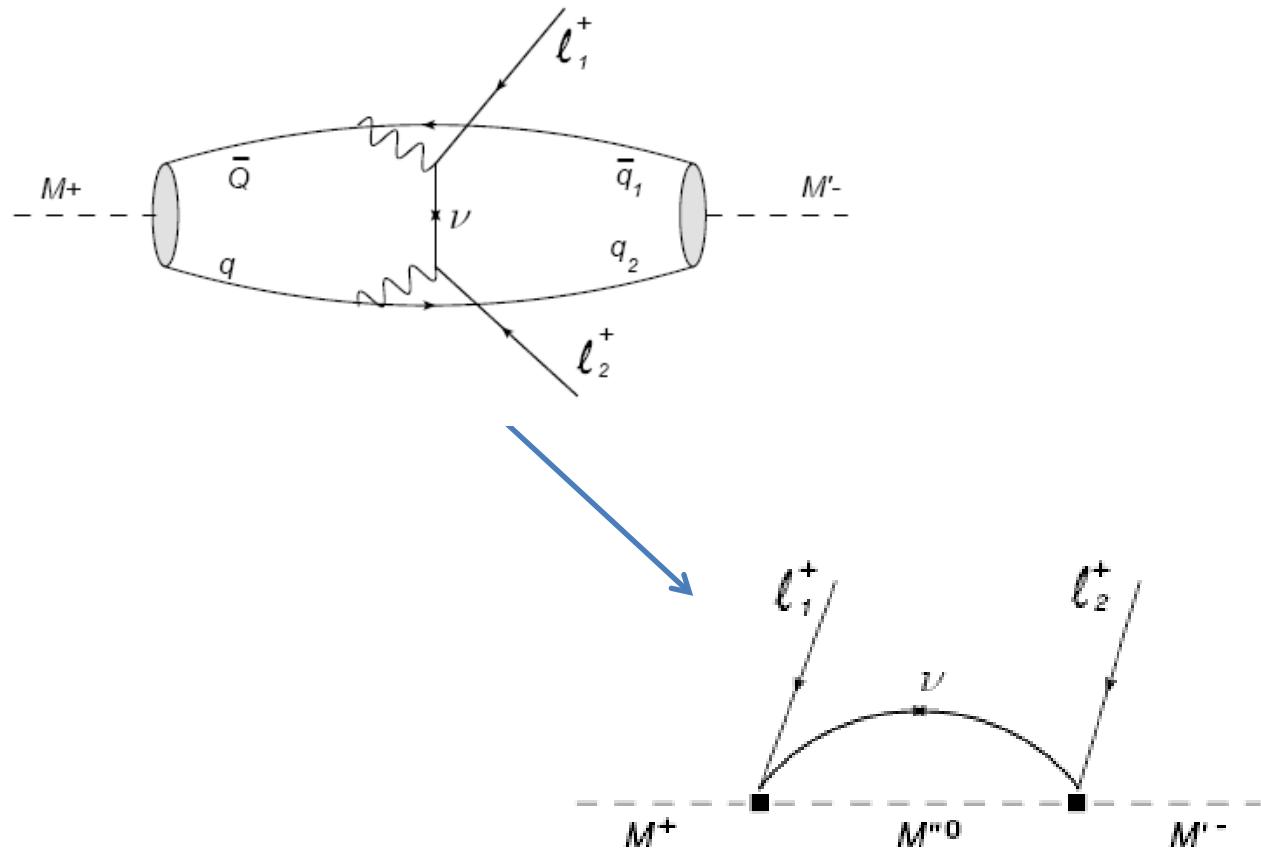


FIG. 2: The main diagram in an effective meson theory for  $M^+ \rightarrow M'^- \ell^+ \ell^+$  (plus diagram with leptons exchanged if they are identical), mediated by Majorana neutrinos, when the neutrino is much lighter than the final meson. The amplitude is estimated considering the intermediate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

## (ii) Intermediate mass scale neutrino case

$$m_{M'^-} \leq m_{\nu_i} \leq m_{M^+}$$

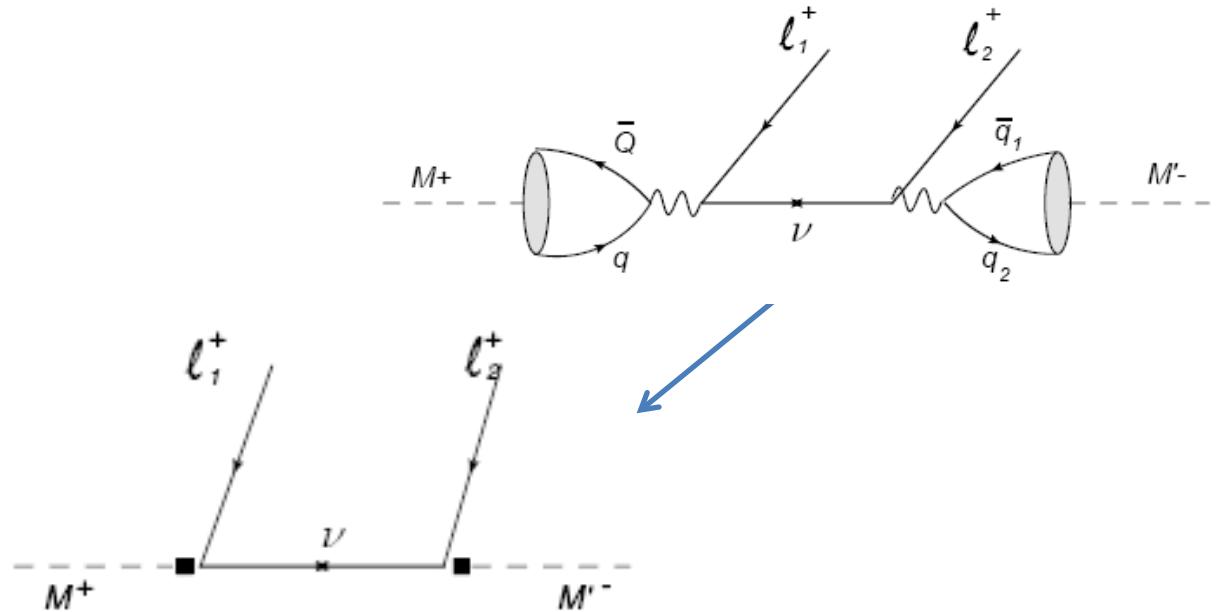


FIG. 3: The dominating diagram (plus diagram with leptons exchanged if they are identical) in an effective meson theory for  $M^+ \rightarrow M^- \ell^+ \ell^+$ , mediated by Majorana neutrinos with mass in the range between  $m_{M'}$  and  $m_M$ .

- 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:

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

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

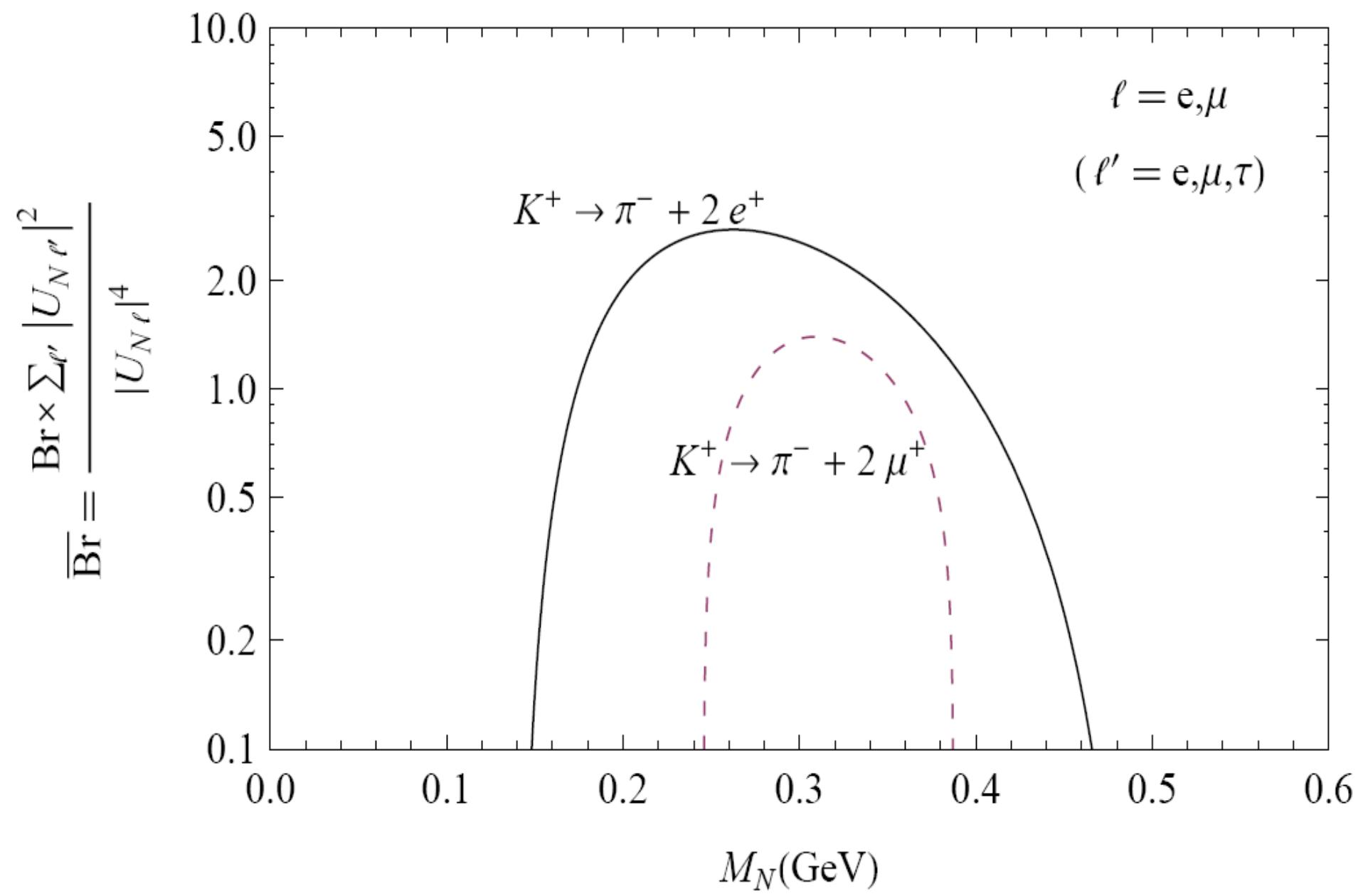
$$|\tilde{\mathcal{M}}|^2 = 32 m_N^2 \left\{ (m_N^2 - m_\ell^2)^2 (l_1 \cdot l_2) + m_\ell^2 ((m_N^2 - m_\ell^2)^2 - m_M^2 m_{M'}^2) \right\}$$

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

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

If we neglect charged lepton masses;

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



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

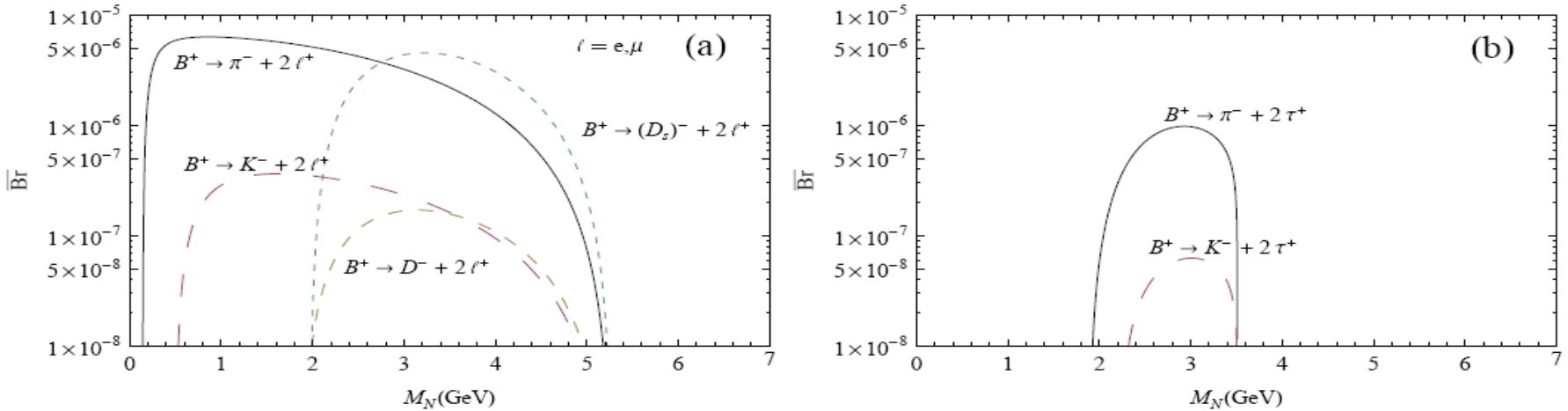


FIG. 6: Branching ratios for  $B^+ \rightarrow M'^- \ell^+ \ell^+$  as functions of the neutrino mass  $m_N$ , with the lepton mixing factor divided out as in Fig. 4. The produced pseudoscalars are  $M' = \pi, K, D, D_s$ . (a) The case of leptons with negligible mass ( $\ell = e, \mu$ ); (b) the case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

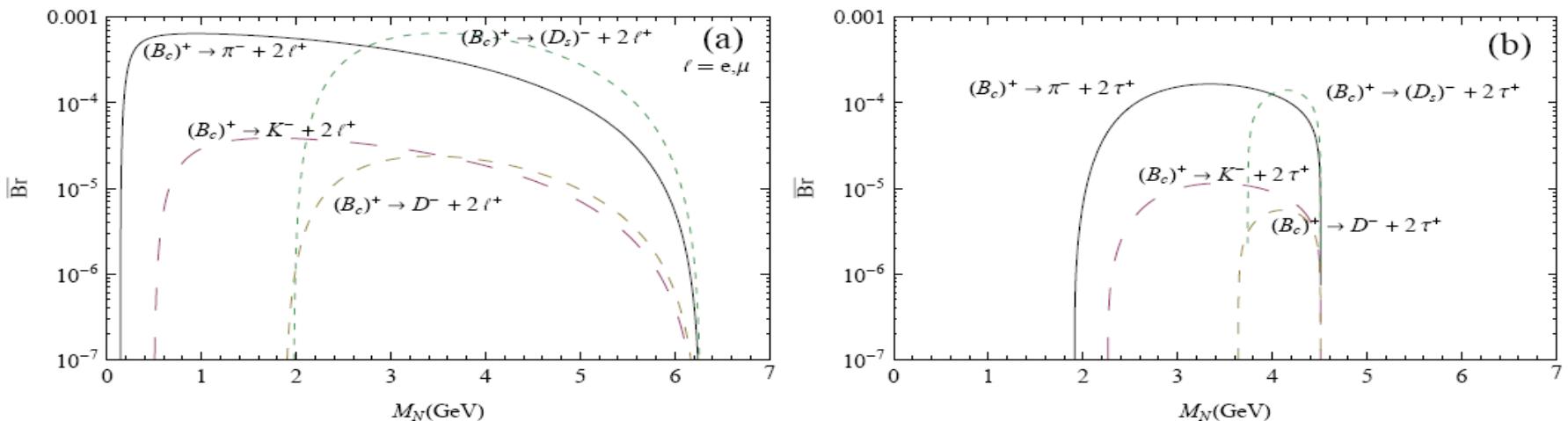


FIG. 7: Branching ratios for  $B_c^+ \rightarrow M'^- \ell^+ \ell^+$  as functions of the neutrino mass  $m_N$ , with the lepton mixing factor divided out as in Fig. 4. The produced pseudoscalars are  $M' = \pi, K, D, D_s$ . (a) The case of leptons with negligible mass ( $\ell = e, \mu$ ); (b) the case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

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

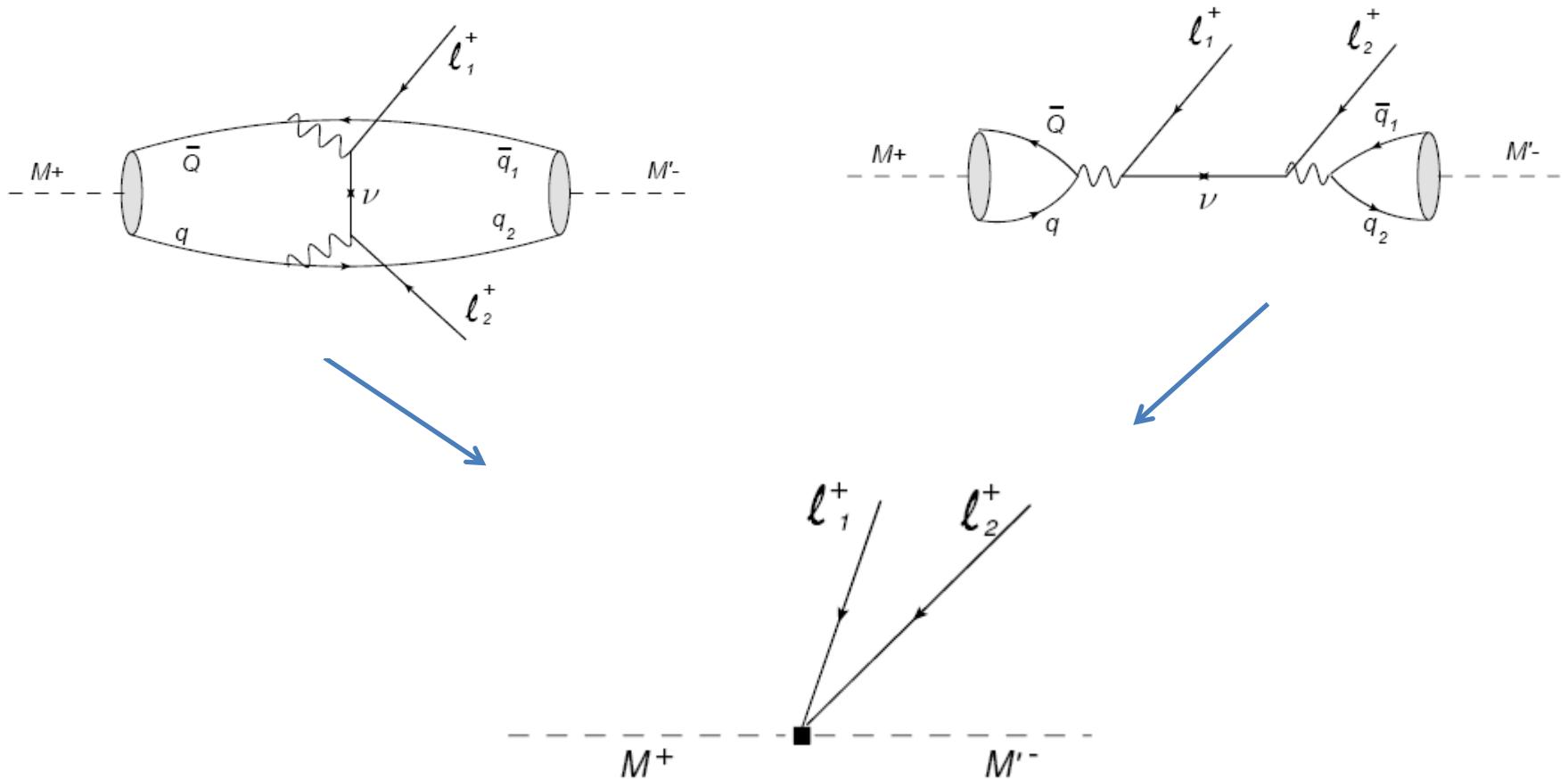
$$\text{Br}_{\max}(M^+ \rightarrow M'^- \ell^+ \ell^+) = \mathcal{C} \times \frac{|U_{N\ell}|^2}{\sum_{\ell'} |U_{N\ell'}|^2}$$

the last column, the expected upper bound on the branching ratios, provided  $|U_{N\ell}|^2 \sim 10^{-6}$  or  $10^{-7}$ , for  
 3/23/2015 KAERU Conf. C S Kim page 21  
 $m_N \sim 0.1$  GeV or  $\sim 1$  GeV, respectively.

### (iii) Heavy neutrino case

$$m_{\nu_i} \gg m_{M^+}$$

- 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  $\nu$ '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  $\nu$ 's are essentially decoupled from masses and mixing parameters of light Majorana  $\nu$ '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

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

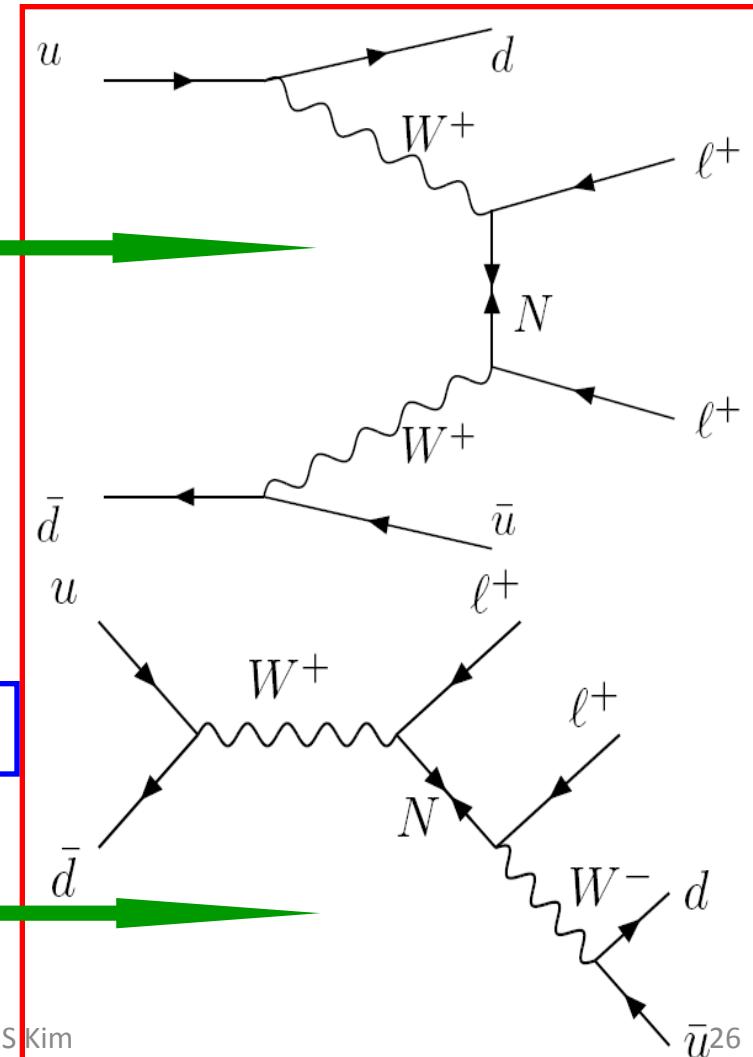
# Collider Signature

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

collider analogue to  $0\nu\beta\beta$  decay

dominant channel

$N$  can be produced on resonance

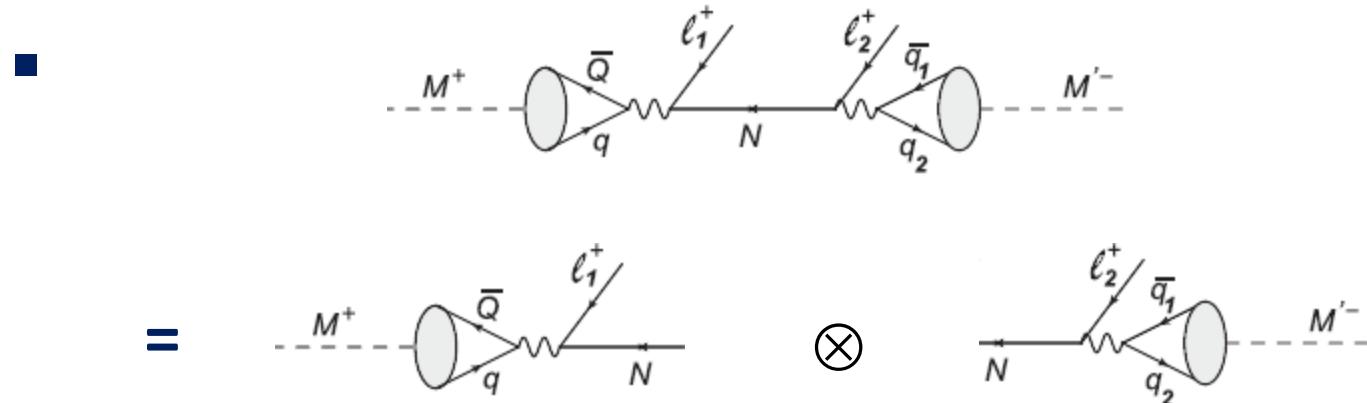


# 3. Issues on Displacement of Vertices

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

Gronau et al, PRD29(1984)2539

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



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

# Life time of N, $\tau_N$

- 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]	$ B_{eN} ^2$	$ B_{\mu N} ^2$	$ B_{\tau N} ^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	$(3.5 \pm 0.5) \times 10^{-7}$	$(1.5 \pm 0.5) \times 10^{-5}$	$(1.5 \pm 0.5) \times 10^{-5}$

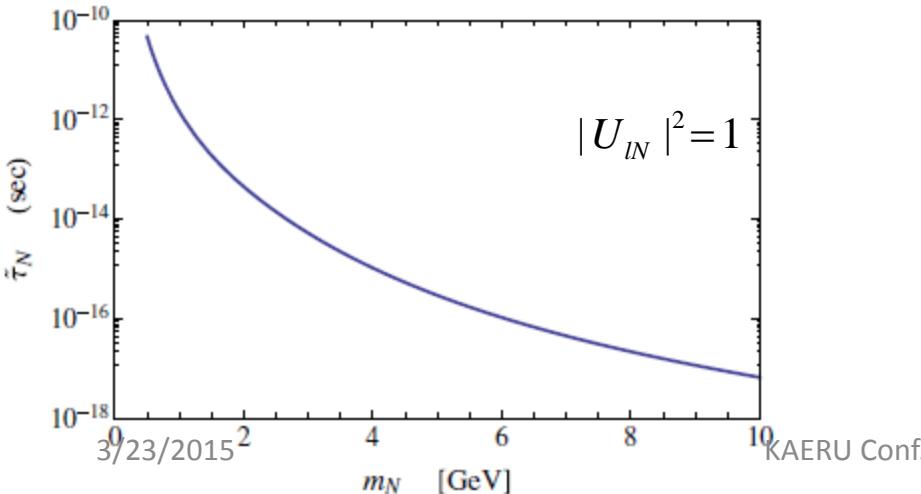
$$\tau_N = 1/\Gamma_N(\text{total}) \propto 1/[m_N^5 |U_{LN}|^2]$$

$$\text{For } m_\pi \leq m_N \leq m_B , \quad |U_{LN}|^2 \leq 10^{-7}$$

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

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

→ Need consider vertex displacement

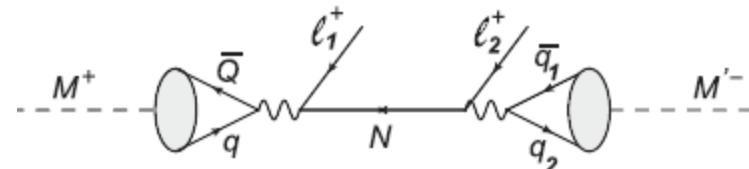


# Correct Branching Ratios

- 1 Theoretical BR w/ unlimited detectability

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

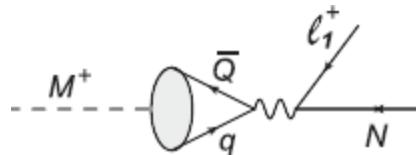
$$Br(M^+ \rightarrow l^+ l^+ M'^-)_{th} = Br(M^+ \rightarrow l^+ N) \cdot Br(N \rightarrow l^+ M'^-)$$



- 2 However, experimentally observed BR

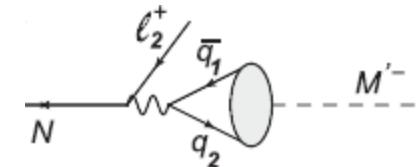
$$Br(M^+ \rightarrow l^+ l^+ M'^-)_{ex} = Br(M^+ \rightarrow l^+ N) \cdot P_N \cdot Br(N \rightarrow l^+ M'^-)$$

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

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

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

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

- Ex) CERN LHC,  $m(N) \sim 100\text{-}1000$  GeV,  $P_N \sim 1$

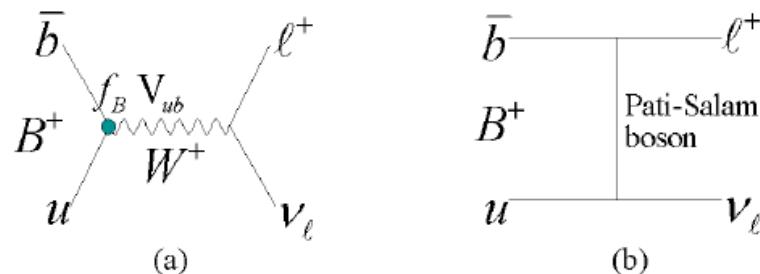
$$Br(B^+ \rightarrow e^+ e^+ D^-)_{th} \simeq Br(B^+ \rightarrow e^+ e^+ D^-)_{ex}$$

→ Huge implication to the present bounds on  
 $B_{lN}(V_{l4}, U_{Nl})$

# 4. Issues on $\Gamma(B^+ \rightarrow \tau^+\nu)$ VS. $\Gamma(B^+ \rightarrow \tau^+ N)$

What Belle/BaBar had done:

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



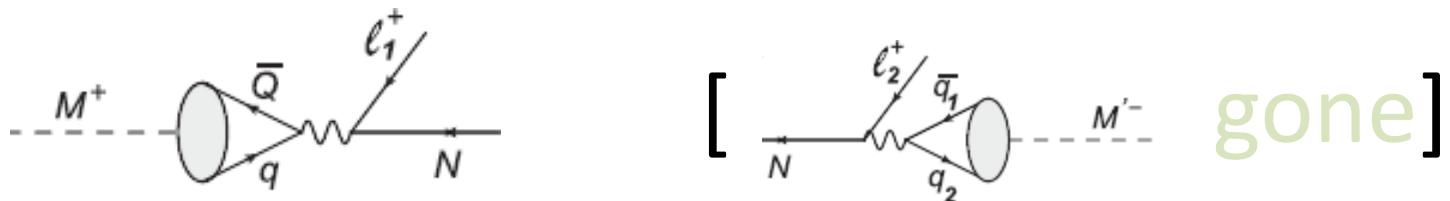
$$\Gamma(B^+ \rightarrow \ell^+\nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \quad \leftarrow \text{Need recalculate this}$$

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

PRL 97, 251802 (2006)

# Need to consider:

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



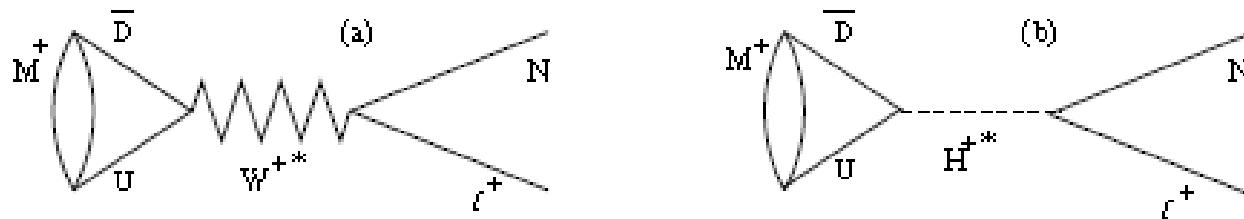
- When you see  $B^+ \rightarrow \tau^+ + \text{miss}(E, \vec{P})$ ,  
is the event  $B^+ \rightarrow \tau^+ \nu$  or  $B^+ \rightarrow \tau^+ N$  ?  
(where  $N =$  massive sterile (Dirac or Majorana) particle)  
∴ tau decay involves neutrinos, so  $m(\nu)$  cannot be constrained.

$$M(\nu) = 0$$

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

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

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



$$M(N) \neq 0$$

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

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

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

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

# Need new numerical analysis (possibly 4 cases)

- 1 Within SM,  $M(\nu) = 0$   $\rightarrow \Gamma_{\text{SM}}(B^+ \rightarrow \nu_\tau \tau^+)$
- 2 With new physics (eg. 2HDM) with  $M(\nu) = 0$   
 $\rightarrow \Gamma_{\text{2HDM(II)}}(B^+ \rightarrow \nu_\tau \tau^+)$
- 3 Within SM with sterile N,  $M(N) \neq 0$   
 $\rightarrow \Gamma_{\text{SM}}(B^+ \rightarrow \nu_\tau \tau^+) + \Gamma_{\text{SM}}(B^+ \rightarrow N \tau^+)$
- 4 With new physics (eg. 2HDM) with  $M(N) \neq 0$   
 $\rightarrow \Gamma_{\text{2HDM(II)}}(B^+ \rightarrow \nu_\tau \tau^+) + \Gamma_{\text{2HDM(II)}}(B^+ \rightarrow N \tau^+)$

$\text{Br}(B^+ \rightarrow \tau^+ + \text{missing})_{\text{exp}} = (\text{PDG average}) = (1.14 \pm 0.27) \times 10^{-4}$

$\text{Br}(\dots)_{\text{SM}} = (\text{CKMfitter}) = (0.758 \pm 0.080) \times 10^{-4}$

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  $\bar{L}_N^{-1}$  (for  $\gamma_N = 2$ ).

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

From DELPHI, ZPC74(1997)57

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

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

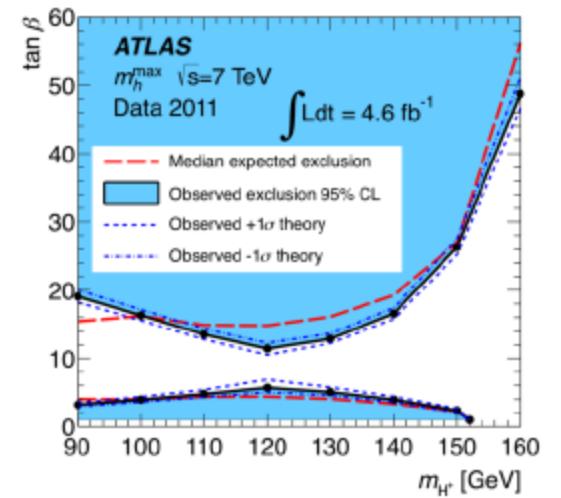
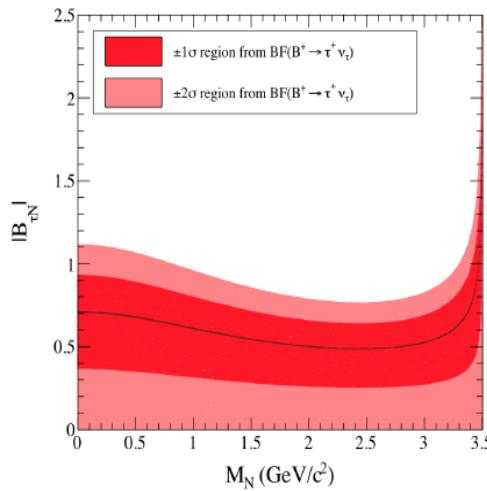


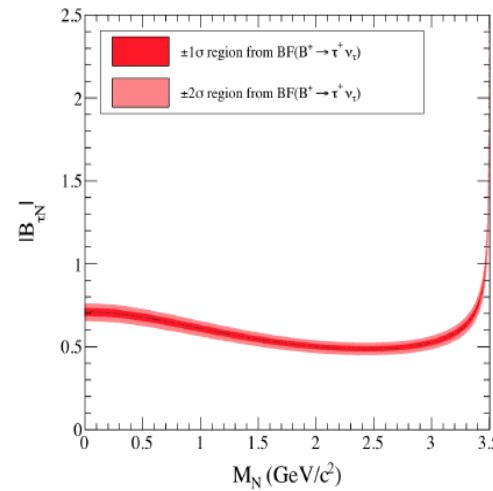
Figure 2: Combined 95% CL exclusion limits on  $\tan\beta$  as a function of  $m_{H^+}$  in the context of the MSSM  $m_h^{\max}$  scenario [6].

# Numerical analysis

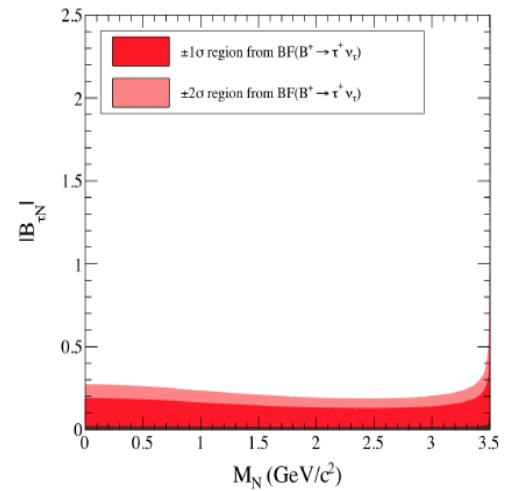
no charged Higgs



central value  $\Rightarrow$  PDG2014  
uncertainty  $\Rightarrow$  from PDG2014  
compared to “SM” (CKMfitter)

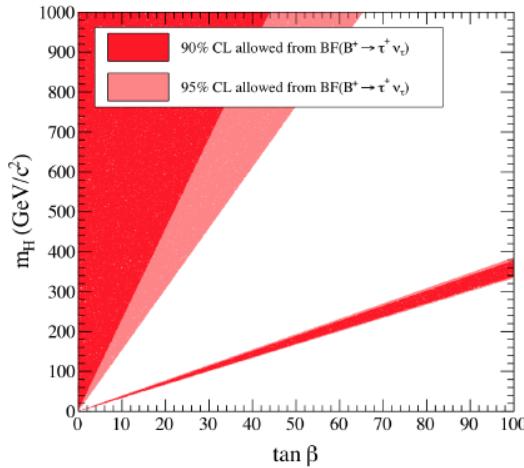


central value  $\Rightarrow$  PDG2014  
uncertainty  $\Rightarrow$  (PDG2014)  $\times 0.1$   
compared to “SM” (CKMfitter)

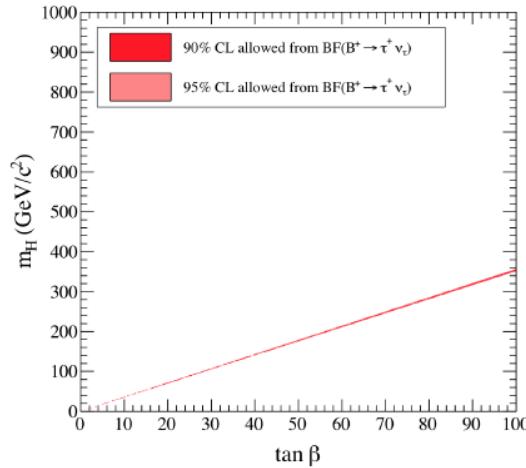


central value  $\Rightarrow$  CKMfitter  
uncertainty  $\Rightarrow$  (PDG2014)  $\times 0.1$   
compared to “SM” (CKMfitter)

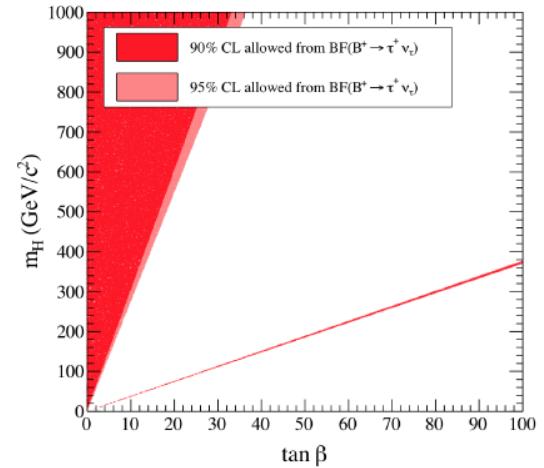
## no heavy neutral ( $N$ )



central value  $\Rightarrow$  PDG2014  
 uncertainty  $\Rightarrow$  from PDG2014  
 compared to “SM” (CKMfitter)

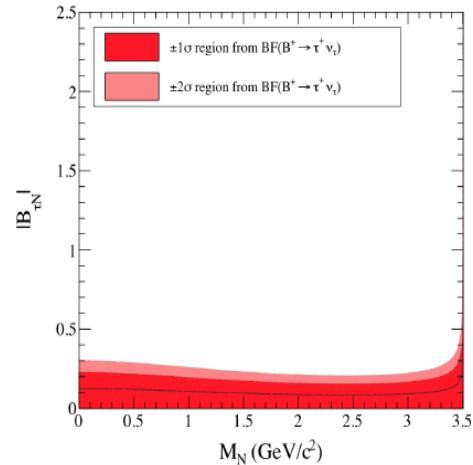
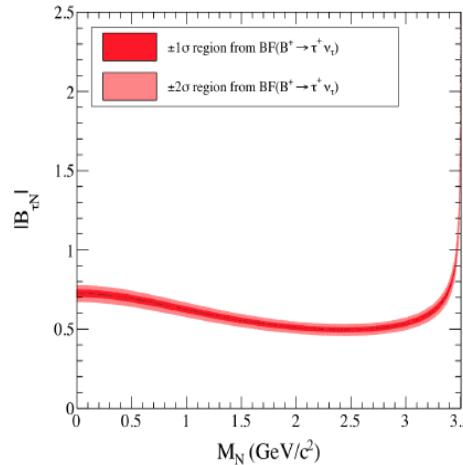
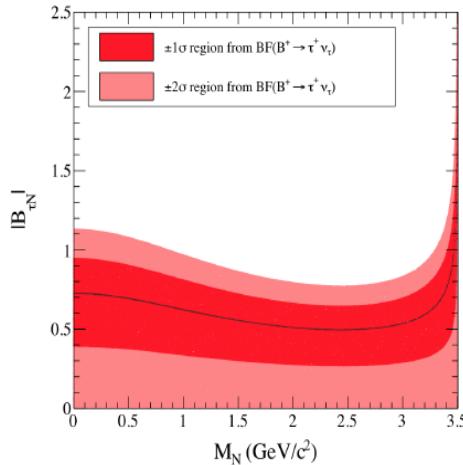


central value  $\Rightarrow$  PDG2014  
 uncertainty  $\Rightarrow$  (PDG2014)  $\times 0.1$   
 compared to “SM” (CKMfitter)

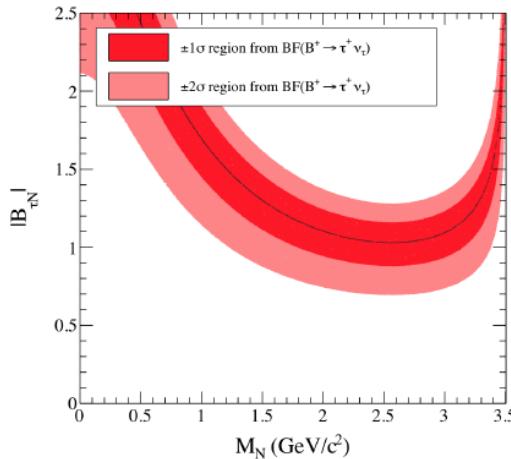


central value  $\Rightarrow$  CKMfitter  
 uncertainty  $\Rightarrow$  (PDG2014)  $\times 0.1$   
 compared to “SM” (CKMfitter)

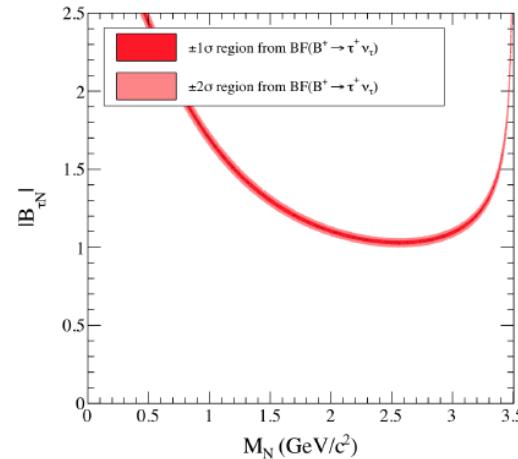
$$\tan \beta = 5.0, m_H = 300, \text{“allowed”}$$



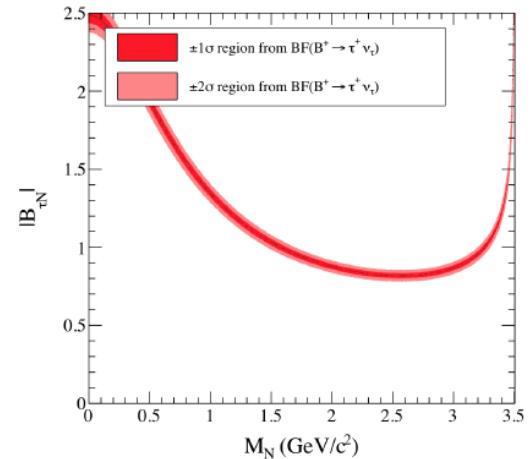
$\tan \beta = 30.0, m_H = 200$ , “forbidden”



central value  $\Rightarrow$  PDG2014  
 uncertainty  $\Rightarrow$  from PDG2014  
 compared to “SM” (CKMfitter)

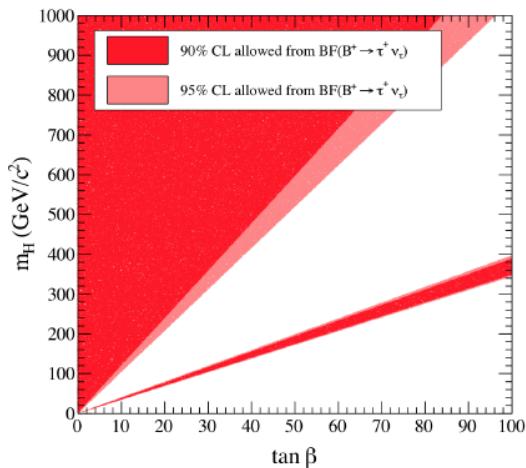


central value  $\Rightarrow$  PDG2014  
 uncertainty  $\Rightarrow$  (PDG2014)  $\times 0.1$   
 compared to “SM” (CKMfitter)

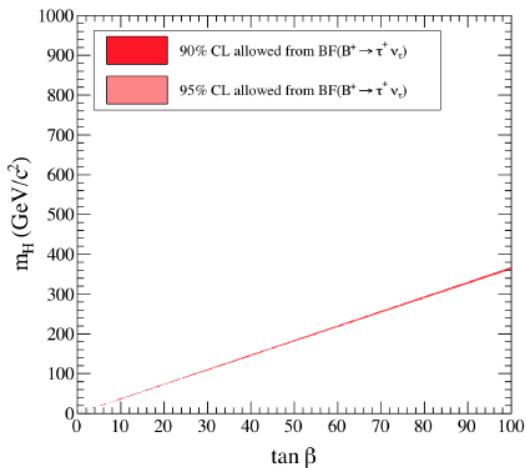


central value  $\Rightarrow$  CKMfitter  
 uncertainty  $\Rightarrow$  (PDG2014)  $\times 0.1$   
 compared to “SM” (CKMfitter)

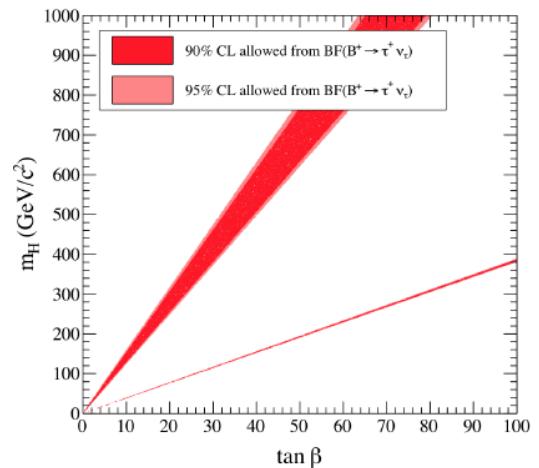
$$m_N = 1, \quad B_{\tau N} = 0.5$$



central value  $\Rightarrow$  PDG2014  
 uncertainty  $\Rightarrow$  from PDG2014  
 compared to “SM” (CKMfitter)

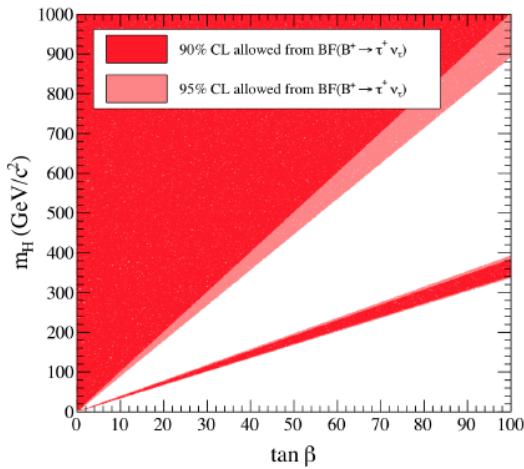


central value  $\Rightarrow$  PDG2014  
 uncertainty  $\Rightarrow$  (PDG2014)  $\times 0.1$   
 compared to “SM” (CKMfitter)

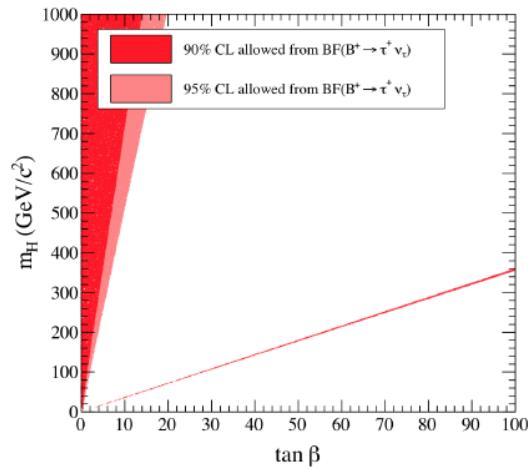


central value  $\Rightarrow$  CKMfitter  
 uncertainty  $\Rightarrow$  (PDG2014)  $\times 0.1$   
 compared to “SM” (CKMfitter)

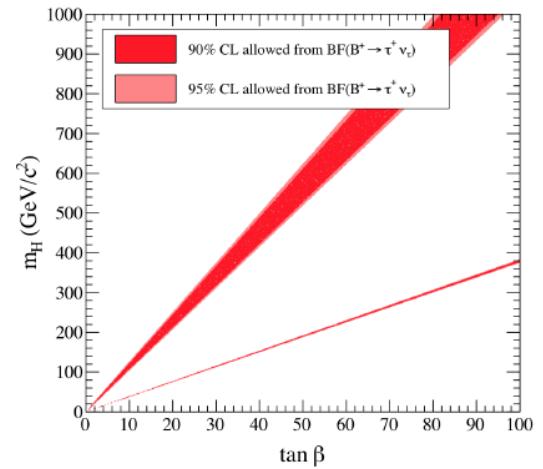
$$m_N = 3, \quad B_{\tau N} = 0.5$$



central value  $\Rightarrow$  PDG2014  
uncertainty  $\Rightarrow$  from PDG2014  
compared to “SM” (CKMfitter)



central value  $\Rightarrow$  PDG2014  
uncertainty  $\Rightarrow$  (PDG2014)  $\times 0.1$   
compared to “SM” (CKMfitter)



central value  $\Rightarrow$  CKMfitter  
uncertainty  $\Rightarrow$  (PDG2014)  $\times 0.1$   
compared to “SM” (CKMfitter)

March 18, 2015

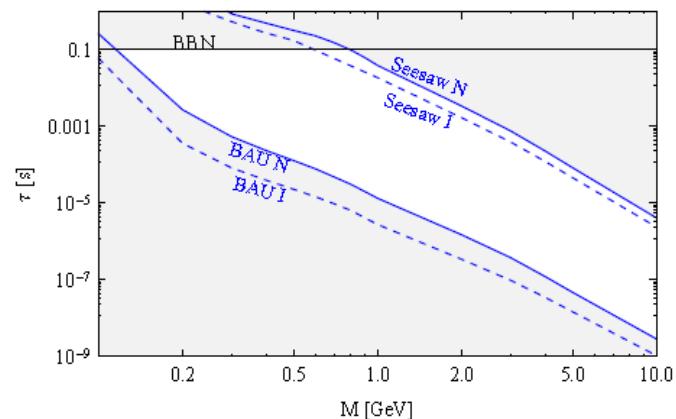
6

\*\* 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  $B^+ \rightarrow \tau^+ N$  and  $N \rightarrow e^+ \pi^-$  (Majorana N) OR  
 $N \rightarrow e^- \pi^+$  (Majorana N or Dirac N)
- 3 Therefore,  
for N\_M  $B^+ \rightarrow \tau^+ e^+ \pi^-$  or  $B^+ \rightarrow \tau^+ e^- \pi^+$   
for N\_D  $B^+ \rightarrow \tau^+ e^- \pi^+$
- 4 Numerical analysis is going on.

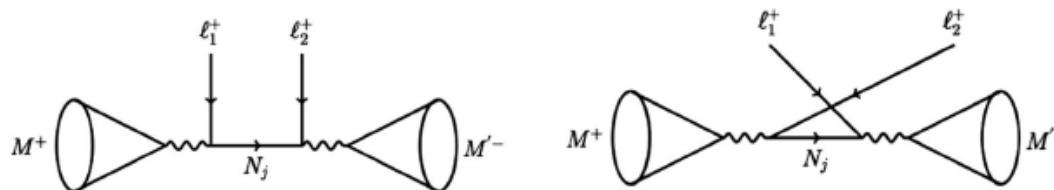
## 5. Issues of CP Violation in $\Delta_L = 2$ decays

- 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 et al, PLB631,151; M. Shaposhnikov, PLB639,414, ...]  
 $\rightarrow N_1 \sim 100\text{keV}, 100\text{MeV} < N_2 \simeq N_3 < 5\text{GeV}$
- Experimental bounds for HNLs

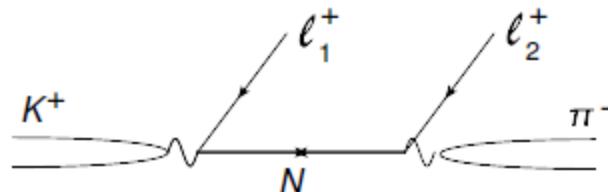


# CP Violation in $M^+ \rightarrow M'^- l_1^+ l_2^+$ decays

- CPV in  $\Delta L = 2$  Processes :  $M^+ \rightarrow M'^- l_1^+ l_2^+$

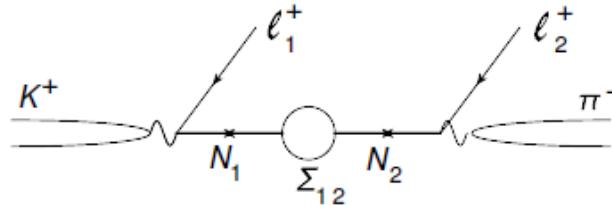


$$A_{CP} = \frac{\Gamma(K^+ \rightarrow \pi^- \ell^+ \ell^+) - \Gamma(K^- \rightarrow \pi^+ \ell^- \ell^-)}{\Gamma(K^+ \rightarrow \pi^- \ell^+ \ell^+) + \Gamma(K^- \rightarrow \pi^+ \ell^- \ell^-)}.$$



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

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

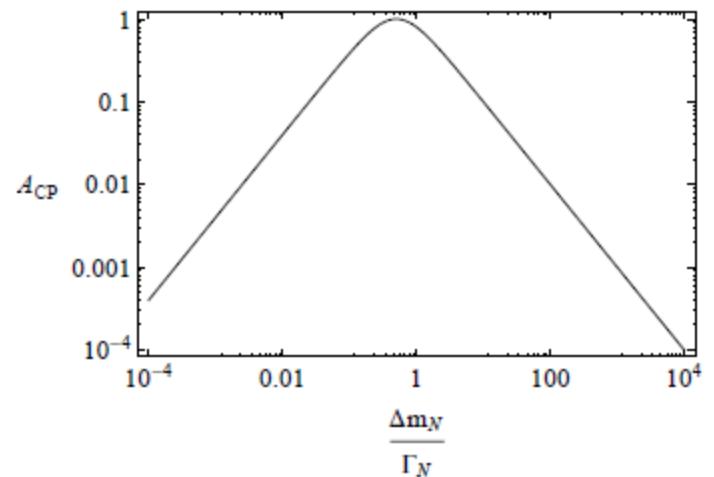


**Figure 2.** Non-diagonal contribution of the absorptive part of the 2-neutrino propagator to the amplitude for the lepton number violating decay  $K^+ \rightarrow \pi^- \ell^+ \ell^+$ .

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

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:

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



# 6 Conclusion

- 1
- 2
- 3

# Work with K. Hagiwara

## 1) Supersymmetry parameter analysis: SPA convention and project

Published in **Eur.Phys.J. C46 (2006) 43-60**

[Cited by 315 records](#)

## 2) Particle physics experiments at JLC

KEK-REPORT-2001-11

[Cited by 417 records](#)

## 3) A Novel approach to confront electroweak data and theory

Published in **Z.Phys. C64 (1994) 559-620**

[Cited by 178 records](#)

## 4) Weak boson production by charm quarks

Published in **Phys.Rev. D41 (1990) 1471-1475**

[Cited by 6 records](#)

# Thanks, KAORU !!!