Discovery of Light Sterile Neutrino ($M_N < M_W$) at the LHC

arXiv:1509.05981 (PRD (2015))

At IHEP, Beijing on Nov 20, 2015

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Outline

- 1. Introduction

- 2. Probing Majorana Neutrinos via
  (a) 0nuBB
  (b) K, D, Ds, B, Bc meson RARE decays
  (c) at the LHC

- 3. Discovery of Light Sterile Neutrino at LHC

- 4. Summary & Conclusions

1. Introduction

- Neutrinos are massless in the SM
  - No right-handed ν's ➔ Dirac mass term is not allowed.
  - Conserves the SU(2)_L gauge symmetry, and only contains the Higgs doublet (the SM accidently possesses (B - L) symmetry); ➔ Majorana mass term is forbidden.

- Why are physicists interested in neutrino mass ?

  ➔ Window to high energy physics beyond the SM!

- How exactly do we extend it?

➔ Without knowing if neutrinos are Dirac or Majorana, any attempts to extend the Standard Model are not successful.

- Effective Observability of Difference between Dirac and Majorana Nu is proportional to

$$\Delta(D-M) \propto m/E$$

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
- $\Sigma m_i \prec 1eV$ 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 [Nardi etal, PLB327,319]

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

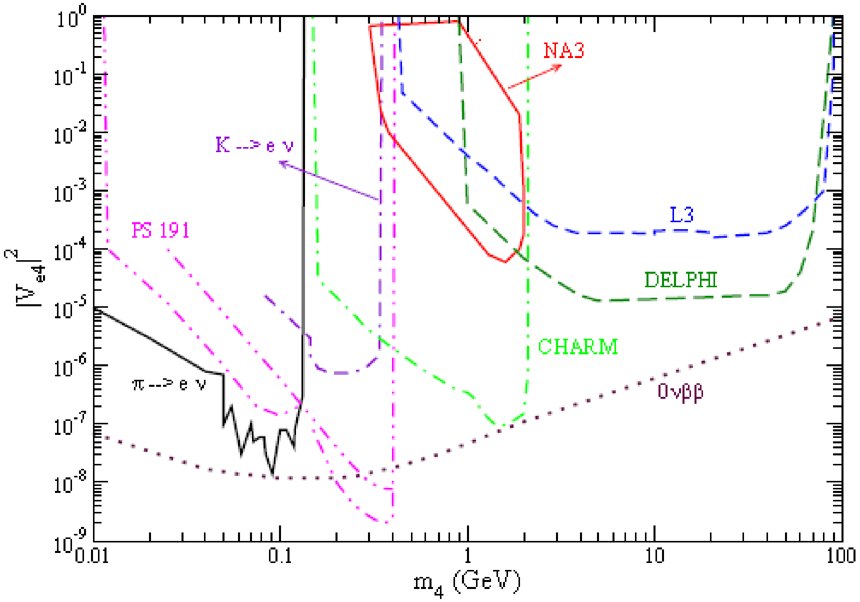
- M. Aoki *et al.* [PIENU Collaboration], Phys. Rev. D 84, 052002 (2011)

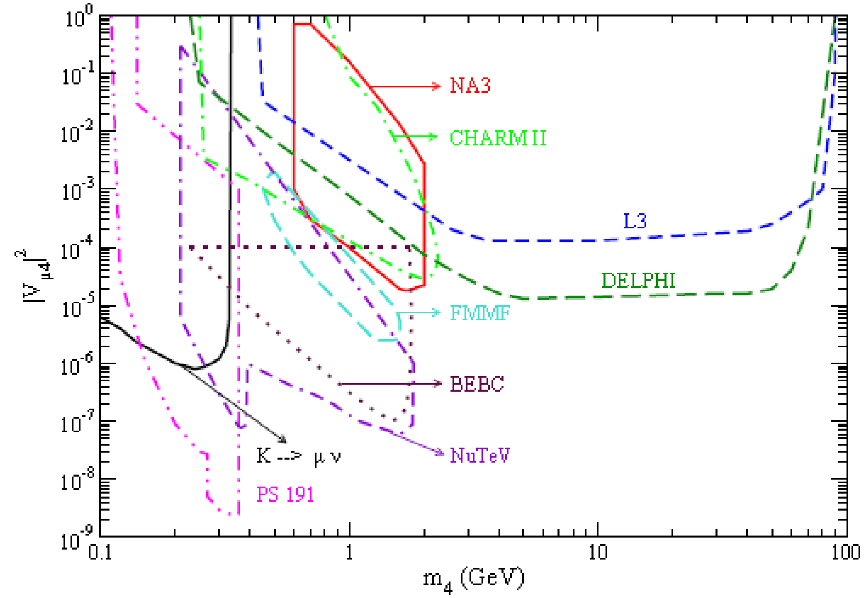
  current bound on the mixing element $|B_{eN}|^2 \lesssim 10^{-8}$

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

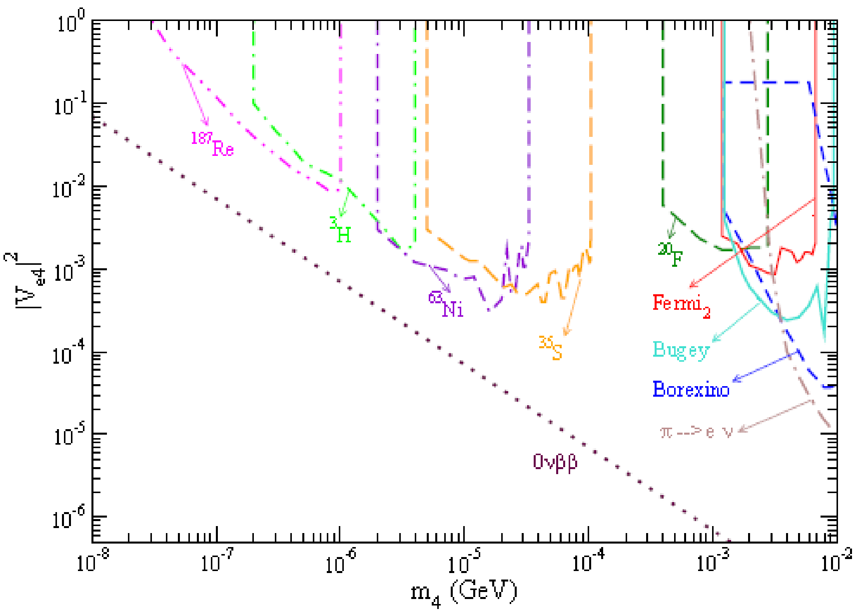
$$m_{\beta\beta} = \left|\sum_i m_i U_{ei}^2 + M_1\Theta_{e1}^2\right|, \quad |M_1\Theta_{e1}^2| = \frac{|M_{1e}^{D2}|}{M_1}. \qquad \Theta_{eN} = M^D / M_N$$

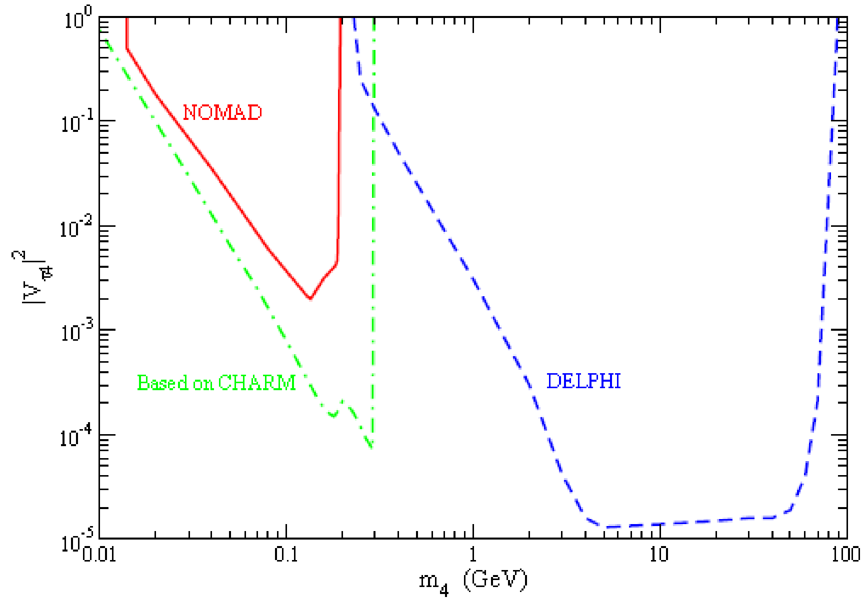
- We can assume any value of B_{lN}, which will be determined by experiments.





A. Atre et al, JHEP05(2009)030

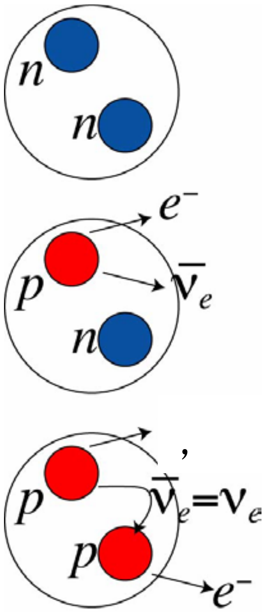


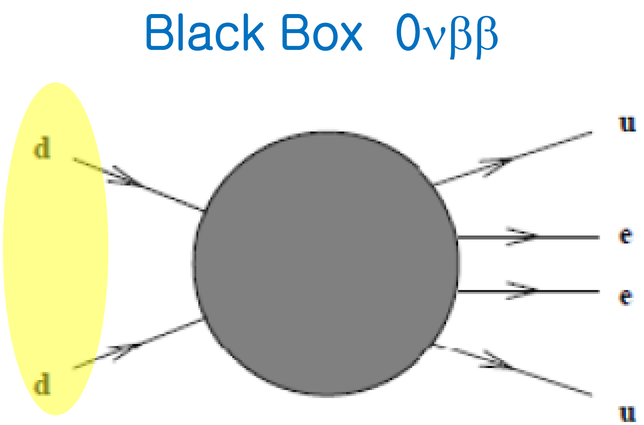


2. Probing Majorana neutrinos

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

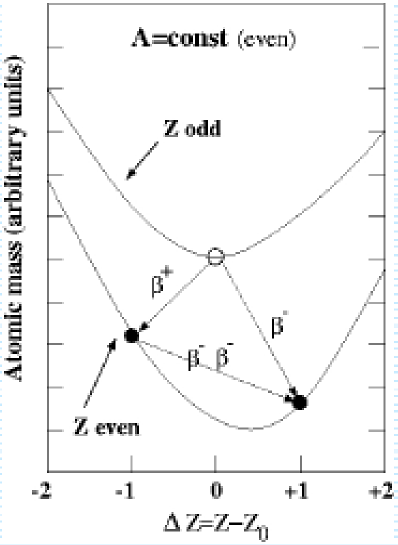
(a) The observation of $0\nu\beta\beta$

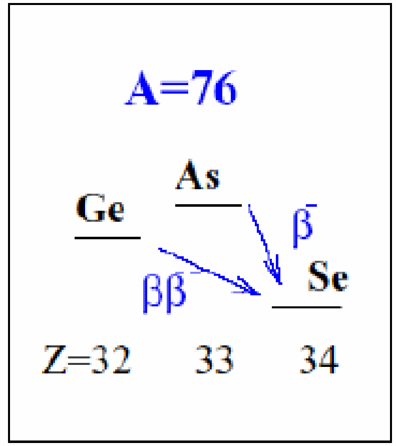


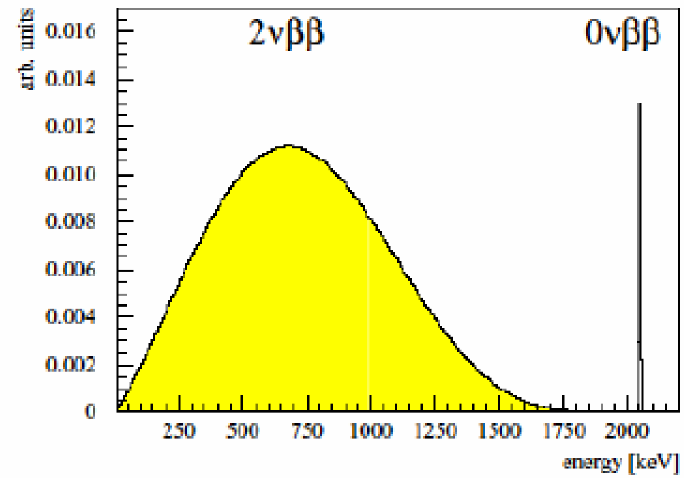


- Provides a promising lab. method for determining the absolute neutrino mass scale that is complementary to other measurement techniques

Double Beta Decay







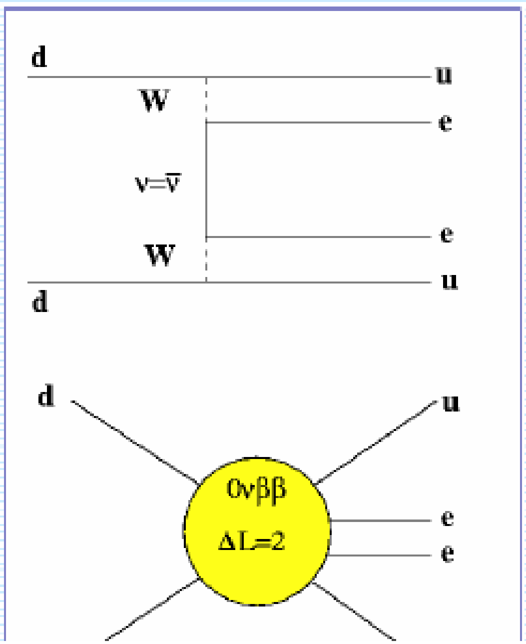
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$$

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

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

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

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

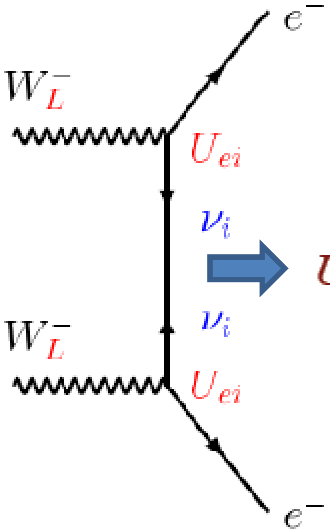


SM forbidden ,not observed yet: $T_{1/2}$ (^{76}Ge)>10^{25} years

- In the limit of small neutrino masses :

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

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



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

: Nuclear matrix element

: phase space factor

: 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)

Phase space factor

Nuclear Matrix Element

uncertainties

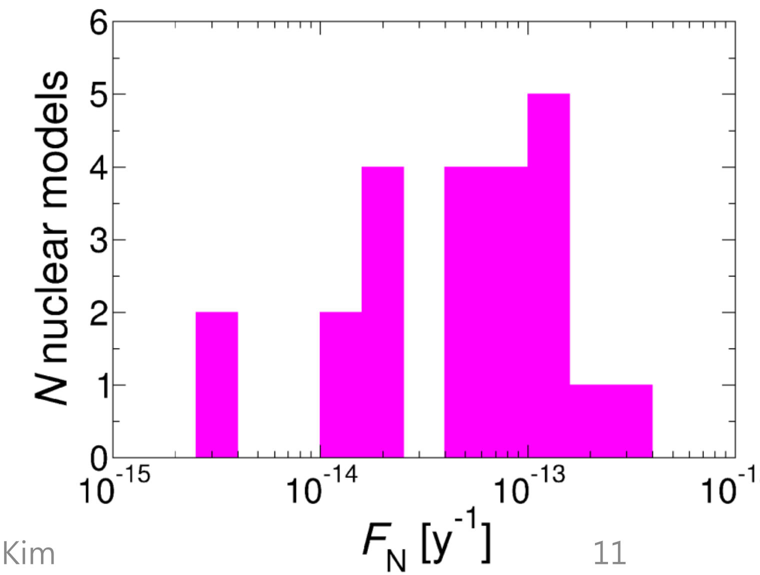
$$\tau^{-1} = G_{0\nu} \cdot |M^{0\nu}|^2 \cdot |\langle m_\nu \rangle|^2 = F_N \cdot \frac{|\langle m_\nu \rangle|^2}{m_e^2}$$

Effective Neutrino Mass

Nuclear Factor of Merit

- Large uncertianties in NME

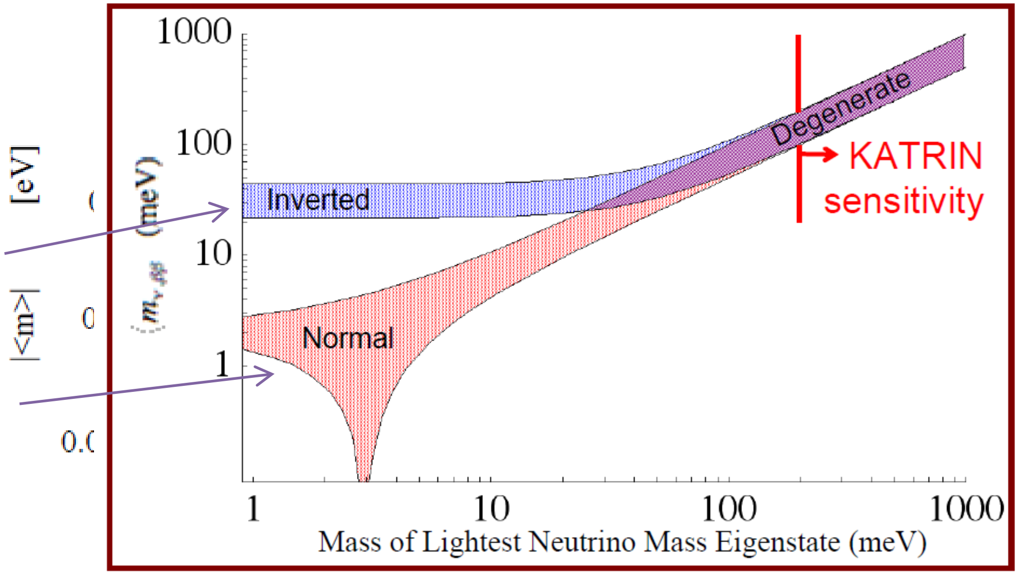
About factor of 100 in NME ➔ affect order 2-3 in $|< m_\nu >|$



- Estimate by using the best fit values of parameters including uncertainties in Majorana phases

Long Baseline

Normal hierarchy is NOT TESTABLE



Bornschein, *Nucl. Phys. A* **752** (2005) 14c-23c.

➢ Best present bound :

$$< m_\nu > \leq 0.35 - 0.50 \text{ eV}$$

$$^{76}Ge \rightarrow {}^{76}Se + e^- + e^-$$ Heidelberg-Moscow

^{76}Ge Half-life $T_{1/2} > 1.2 \times 10^{25}\, ys$

consistent with cosmological bound

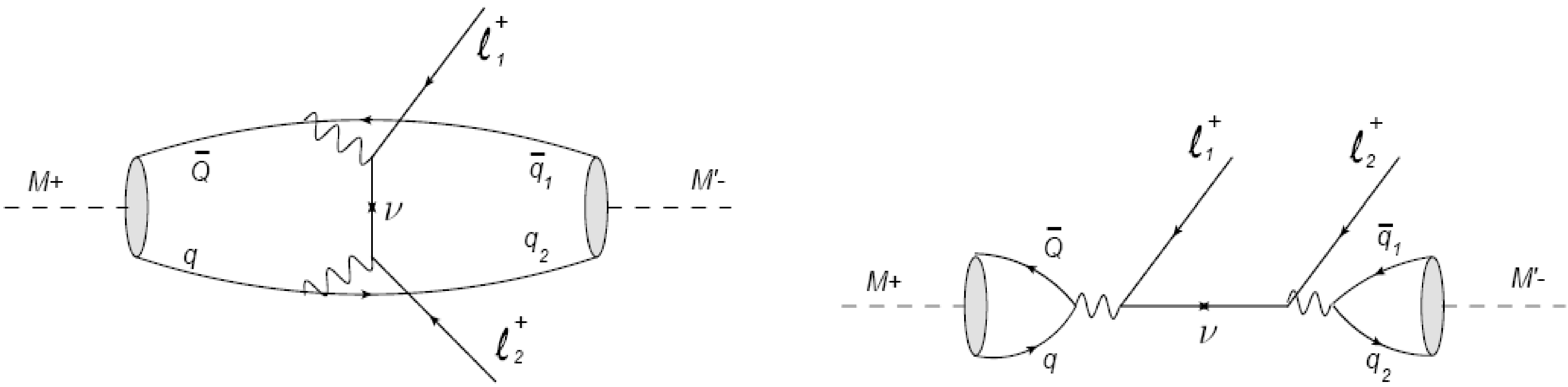
$$\sum m_{\nu_i} \leq 2.0 \text{ eV}$$

(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))

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

- 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 $0\beta\nu\nu$

Effective Hamiltonian:

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

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

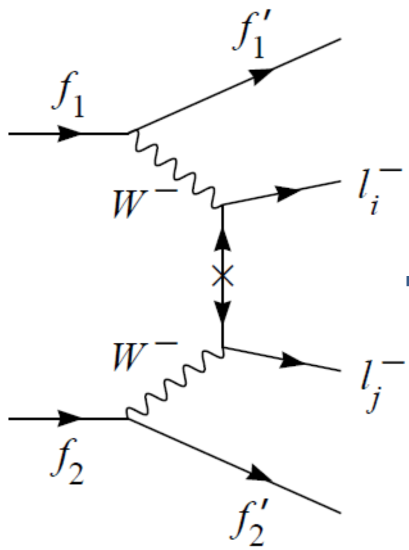
$$O_s^{\mu\nu} = V_{q_2 q_1}^* V_{qQ} J_{q_2 q_1}^{\mu} J_{qQ}^{\nu}$$

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

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

Decay Amplitude:

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

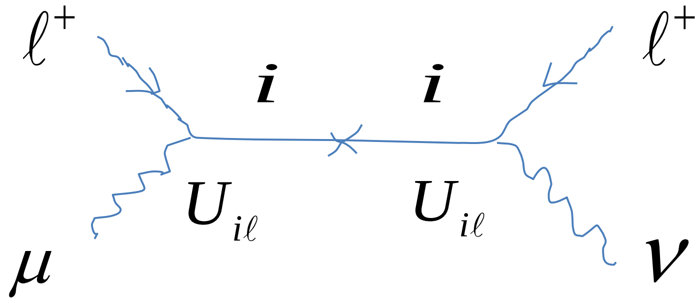


$$\longrightarrow U_{l_i N} \times \left[\frac{\not{p} + m_N}{p^2 - m_N^2 + i m_N \Gamma_N} \right] \times U_{l_j N}$$

- 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 :



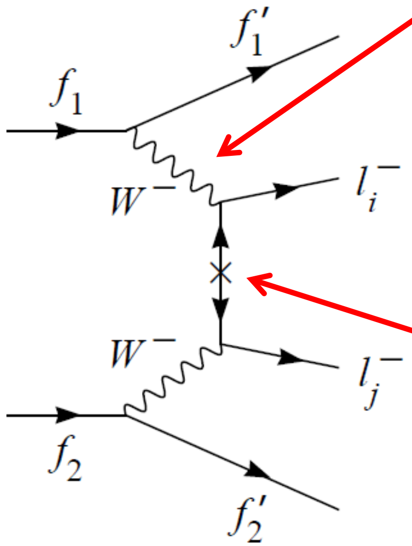
$$L_{\mu\nu} = (U_{i\ell}U_{i\ell}) \times \overline{\nu_i}\gamma_\mu \frac{(1-\gamma_5)}{2}\nu_\ell \times (---) \times \bar{\nu}_i\gamma_\nu \frac{(1-\gamma_5)}{2}\nu_\ell$$

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

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

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

Model Independence of Effective Theory approach



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

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

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

Propagator changed

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

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

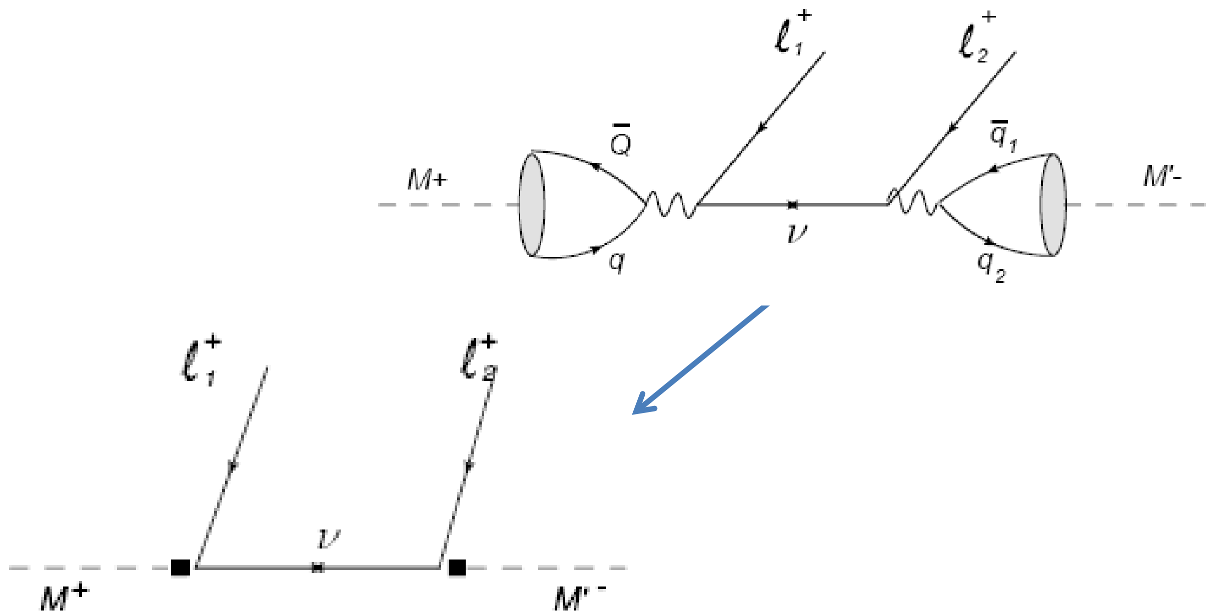


FIG. 3: The dominating diagram (plus diagram with leptons exchanged if they are identical) in an effective meson theory for$M^+ \to M'^- \ell^+ \ell^+$, mediated by Majorana neutrinos with mass in the range between $m_{M'}$ and m_M.

- 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:

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

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

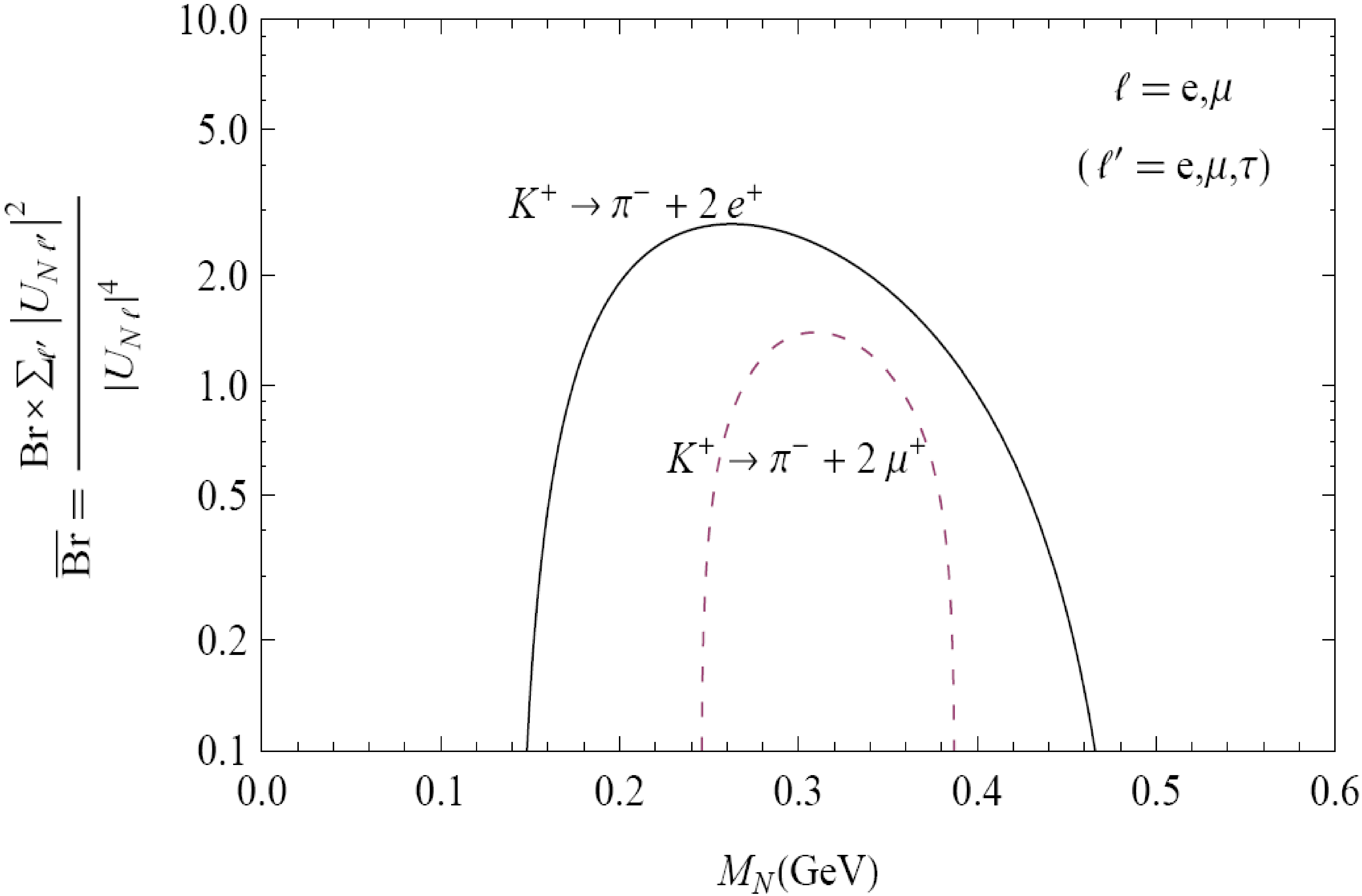
$$|\tilde{\mathcal{M}}|^2 = 32\, m_N^2\, \left\{ (m_N^2 - m_\ell^2)^2 (l_1 \cdot l_2) + m_\ell^2 \left((m_N^2 - m_\ell^2)^2 - m_M^2 m_{M'}^2 \right) \right\}$$

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

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

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

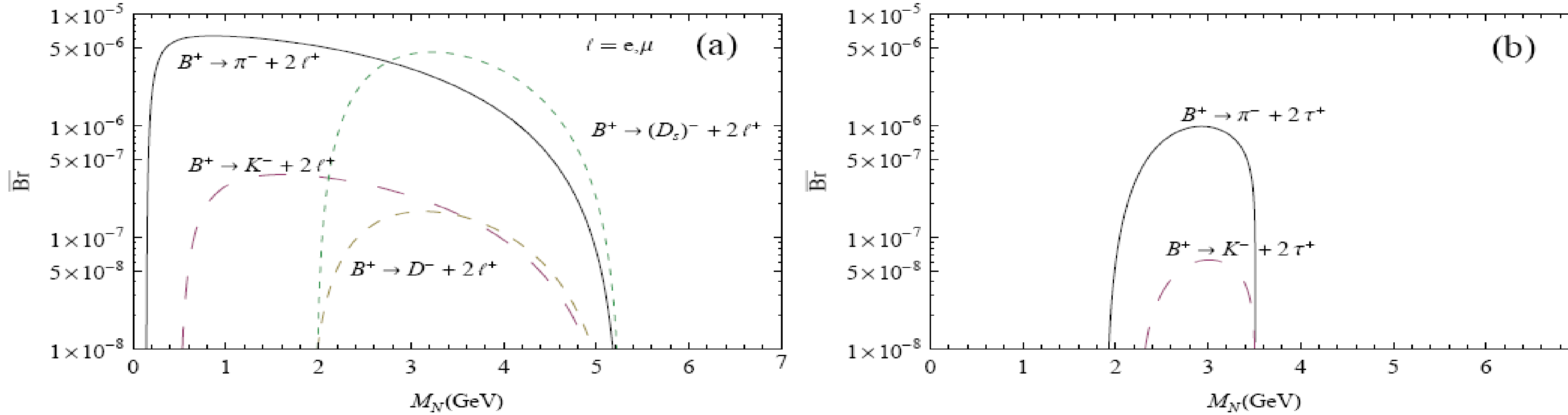


FIG. 6: Branching ratios for $B^+ \to M'^- \ell^+ \ell^+$ as functions of the neutrino mass m_N, with the lepton mixing factor divided out as in Fig. 4. The produced pseudoscalars are $M' = \pi, K, D, D_s$. (a) The case of leptons with negligible mass ($\ell = e, \mu$); (b) the case $\ell = \tau$ (here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

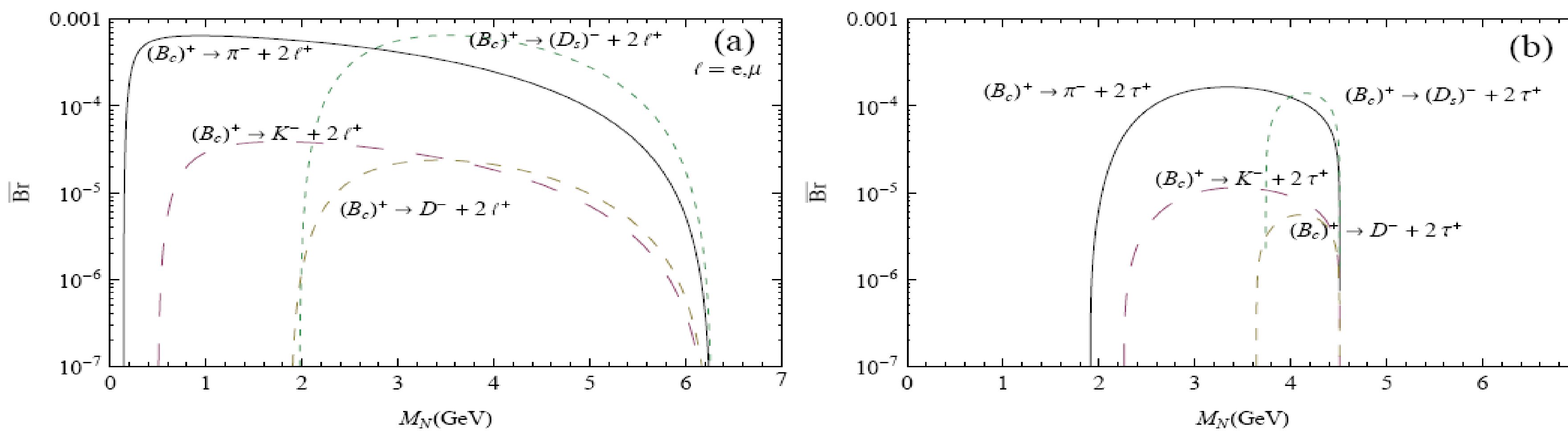


FIG. 7: Branching ratios for $B_c \to M'^- \ell^+ \ell^+$ as functions of the neutrino mass m_N, with the lepton mixing factor divided out as in Fig. 4. The produced pseudoscalars are $M' = \pi, K, D, D_s$. (a) The case of leptons with negligible mass ($\ell = e, \mu$); (b) the case $\ell = \tau$.

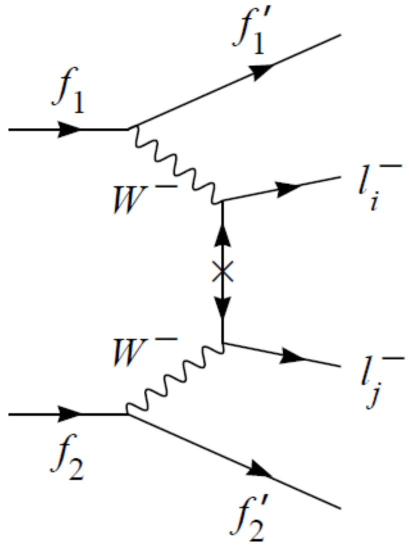
(c) Probing Majorana Neutrinos at LHC

- 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

Basic process we consider



$$\Longrightarrow \quad U_{l_i N}\,\frac{\not{p} + m_N}{p^2 - m_N^2 + i\varepsilon}\,U_{l_j N}$$

- transition rates are proportional to

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

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

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

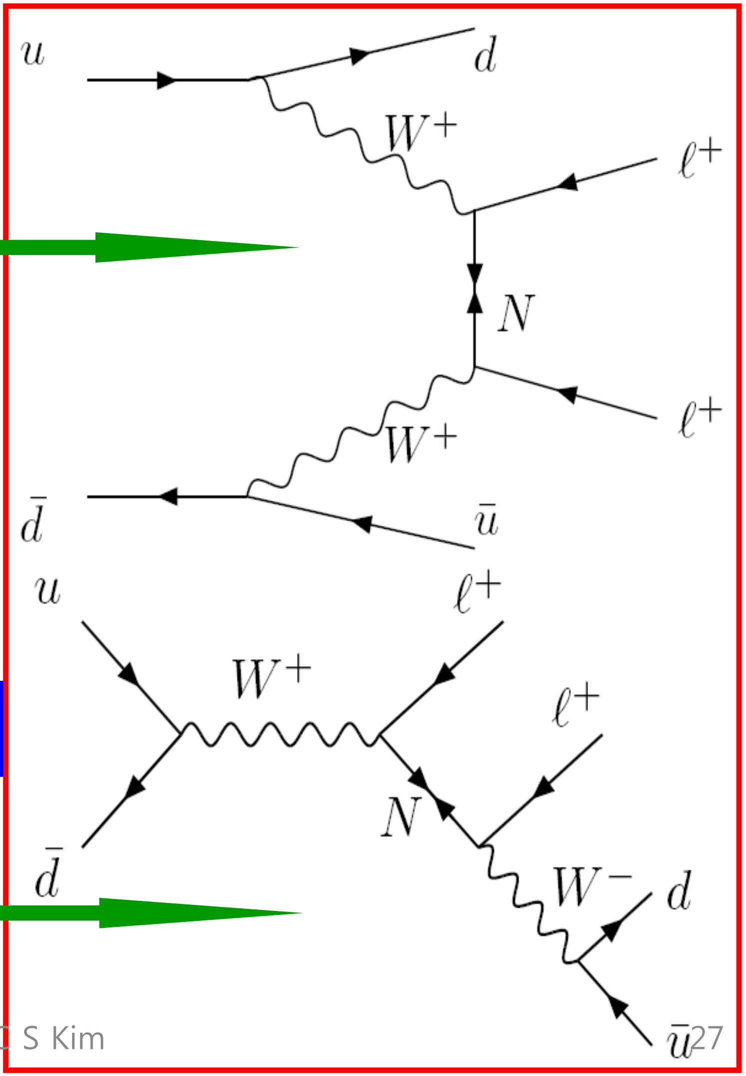
Collider Signature

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

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

dominant channel

N can be produced on resonance



Some Results

- Cross sections are generally smaller for larger masses of heavy Majorana neutrinos. [Han, Zhang (hep-ph/0904064)]
- Signal & background cross sections (in fb) as a function of the heavy Majorana neutrino mass (in GeV) :

[Del Aguila *et al* (hep-ph/0906198)]

*Background could be much larger by soft–piling up !!

	Tevatron		LHC	
m_N	$\mu^\pm\mu^\pm jj$ signal	$W^\pm W^\pm W^\mp$ background	$\mu^\pm\mu^\pm jj$ signal	$W^\pm W^\pm W^\mp$ background
100	0.40	0.0001	2.0	0.0012
200	0.071	0.0004	0.48	0.0044
300	0.014	0.0001	0.16	0.0023
400	0.0032	0.00005	0.068	0.0012
500	0.0008	0.00001	0.034	0.0007

3. Discovery of light sterile N at LHC

C Dib, CS Kim, arXiv:1509.05981 (PRD(2015))

- In previous works for LHC, $m_N \geq m_W$ covered.
  - Is a way to cover $m_N \leq m_W$?
  - Cosmology & astrophysics motivate strongly $m_N \approx 0.1 \leftrightarrow 50$ GeV.
  - How about on-shell W leptonic decays? $W^+ \to l^+ l^+ \mu^- \overline{\nu}_\mu$

- Possible problems
  - Large radiative decays, $W^+ \to \mu^+ \nu_\mu + \gamma^* (\to e^+ e^-)$

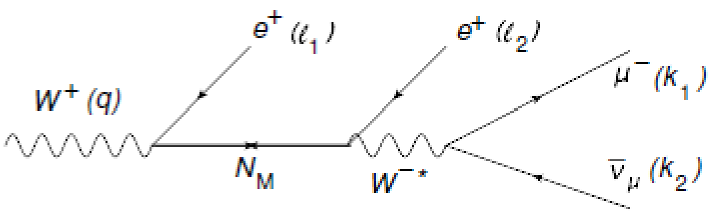
    ⟹ we choose μ^- from W+ decay (no radiative bg)
  - Final neutrino flavor not observed

    ⟹ $W^+ \to e^+ e^+ \mu^- \overline{\nu_\mu}$ or $W^+ \to e^+ e^+ \mu^- \nu_e$

    ⟹ LNV (Majorana N) or LNC-LFV (Maj./Dirac N)

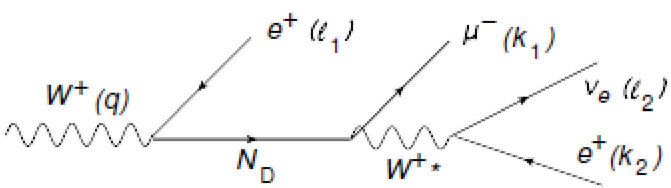
$$W^+ \to e^+ e^+ \mu^- \overline{\nu_\mu} \quad \textbf{VS} \quad W^+ \to e^+ e^+ \mu^- \nu_e$$

- two competing processes (for $m_\mu \le m_N \le m_W$) :



$$W^+ \to e^+ N(\to e^+ \mu^- \overline{\nu_\mu})$$

⟹ LNV (only Majorana neutrino N)



$$W^+ \to e^+ N(\to \mu^- e^+ \nu_e)$$

⟹ LNC but LFV (Majorana or Dirac neutrino N)

** We cannot indentify the final neutrino flavor, $\overline{\nu_\mu}$ or ν_e

Comments:

1. Same processes $W^+ \to e^+ e^+ \mu^- \overline{\nu_\mu}$, $W^+ \to \mu^+ \mu^+ e^- \overline{\nu_e}$,

   and their C.C. (as long as no + − for the same flavor)

2. Comparison of $W^+ \to l^+ l^+ l^- \nu$ vs. $W^+ \to l^+ l^+ jj$

- need well isolated energetic 2 jets (same for $pp \to l^+ l^+ jj$)

  (otherwise large background from WW, instead of WWW)

- → m(N) > ~ m(W) for W -> l l j j

  → m(N) < m(W) for W -> l l l nu

3. arXiv:1504.02470 considered only $W^+ \to e^+ e^+ \mu^- \overline{\nu_\mu}$,

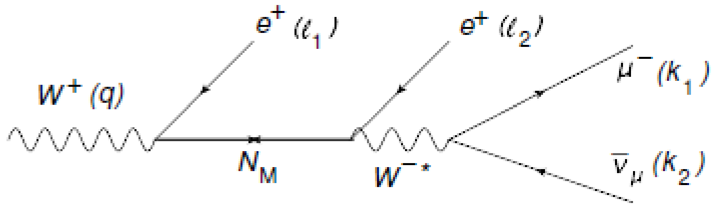
   not $W^+ \to e^+ e^+ \mu^- \nu_e$ (flavor of final nu unidentifiable)

4. Reconstruction of on-shell W at LHC (hadronic colliders)

   $W^+ \to l^+ l^+ l^- \nu$ or $W^+ \to l^+ \nu$ for m(nu)~0

   reconstructible event-by-event by using p(l) and m_T.

LNV, Pure Majorana, Process: $W^+ \to e^+ e^+ \mu^- \bar{\nu}_\mu$



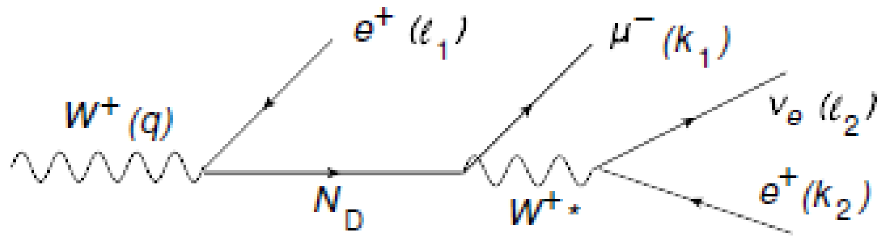
$$|\overline{\mathcal{M}}|^2 = 256\frac{\sqrt{2}}{3} G_F^3 M_W^2 |U_{Ne}|^4 \, \frac{1}{(k_N^2 - m_N^2)^2 + m_N^2 \Gamma_N^2} \, m_N^2 (k_2 \cdot \ell_2) \Big\{ (k_1 \cdot \ell_1) + \frac{2}{M_W^2} (q \cdot k_1)(q \cdot \ell_1) \Big\}$$

$$\Gamma(W^+ \to e^+ e^+ \mu^- \bar{\nu}_\mu) = \frac{G_F^3 M_W^3}{12\sqrt{2}\,\pi^4} \frac{|U_{Ne}|^4 m_N}{\Gamma_N} \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 + \frac{m_N^2}{2M_W^2}\right) \int_0^{m_N/2} dE_{k_1} \left(m_N E_{k_1}^2 - 2E_{k_1}^3\right)$$

$$Br(W^+ \to e^+ e^+ \mu^- \bar{\nu}_\mu) = \frac{1}{12 \times 96\pi} \left(\frac{G_F}{\sqrt{2}} \frac{M_W^3}{\Gamma_W}\right) \left(|U_{Ne}|^4 \frac{G_F^2 m_N^5}{\pi^3 \Gamma_N}\right) \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 + \frac{m_N^2}{2M_W^2}\right)$$

$$\approx 4.8 \times 10^{-3} \frac{|U_{Ne}|^4}{\sum_{\ell=e,\mu,\tau} |U_{N\ell}|^2} \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 + \frac{m_N^2}{2M_W^2}\right).$$

LNC but LFV, Pure Dirac, Process: $W^+ \to e^+ e^+ \mu^- \nu_e$



$$|\overline{\mathcal{M}}|^2 = 256\frac{\sqrt{2}}{3}G_F^3 M_W^2 |U_{Ne}U_{N\mu}|^2 \times \frac{1}{(k_N^2 - m_N^2)^2 + m_N^2\Gamma_N^2}$$
$$\times (k_1\cdot\ell_2)\left\{2(k\cdot k_2)\left[(k\cdot\ell_1) + \frac{2}{M_W^2}(q\cdot k)(q\cdot\ell_1)\right] - m_N^2\left[(k_2\cdot\ell_1) + \frac{2}{M_W^2}(q\cdot k_2)(q\cdot\ell_1)\right]\right\}$$

$$\Gamma(W^+ \to e^+e^+\mu^-\nu_e) = \frac{G_F^3 M_W^3}{12\sqrt{2}\pi^4}|U_{Ne}U_{N\mu}|^2\frac{m_N}{\Gamma_N}\left(1 - \frac{m_N^2}{M_W^2}\right)^2\left(1 + \frac{m_N^2}{2M_W^2}\right)\int_0^{m_N/2} dE_{k_1}\left(\frac{m_N}{2}E_{k_1}^2 - \frac{2}{3}E_{k_1}^3\right)$$

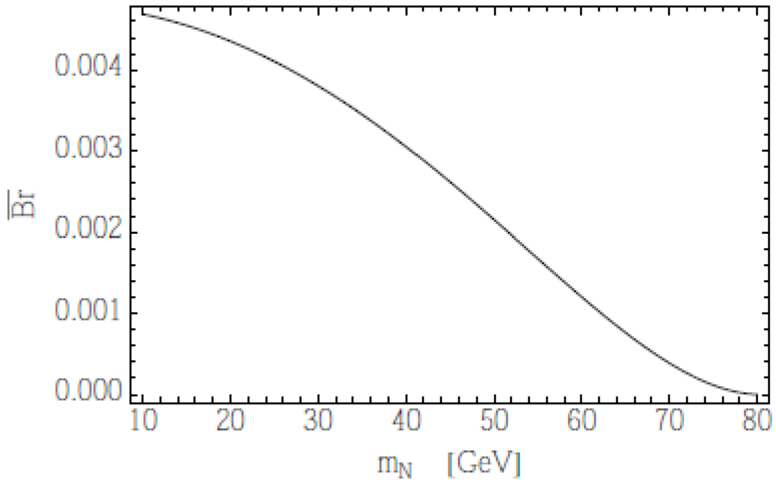
$$Br(W^+ \to e^+e^+\mu^-\nu_e) = \frac{1}{12\times 96\pi}\left(\frac{G_F}{\sqrt{2}}\frac{M_W^3}{\Gamma_W}\right)\left(|U_{Ne}U_{N\mu}|^2\frac{G_F^2\, m_N^5}{\pi^3\Gamma_N}\right)\left(1 - \frac{m_N^2}{M_W^2}\right)^2\left(1 + \frac{m_N^2}{2M_W^2}\right)$$

$$\approx 4.8\times 10^{-3}\;\frac{|U_{Ne}|^2|U_{N\mu}|^2}{\sum_{\ell=e,\mu,\tau}|U_{N\ell}|^2}\left(1 - \frac{m_N^2}{M_W^2}\right)^2\left(1 + \frac{m_N^2}{2M_W^2}\right).$$

Numerical studies and discussions

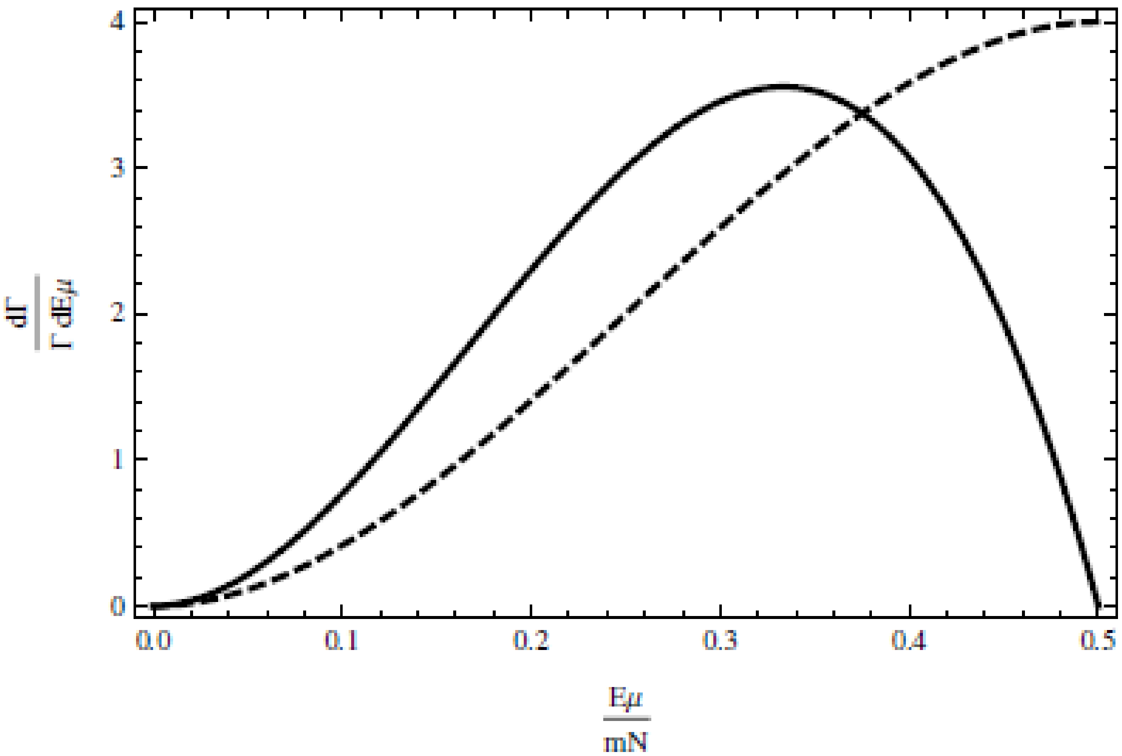
(A) branching ratios:

reduced BR for $W^+ \to e^+ e^+ \mu^- \nu$



$Br = \overline{Br} \times |U_{Ne}|^4 / (\sum_\ell |U_{N\ell}|^2)$ and $Br = \overline{Br} \times |U_{Ne} U_{N\mu}|^2 / (\sum_\ell |U_{N\ell}|^2)$, respectively.

(B) Spectrum analysis to separate Majorana from Dirac neutrino:



Normalized muon energy spectrum, $(1/\Gamma)d\Gamma/dE_\mu$

$$\left(\frac{1}{\Gamma_{LNV}+\Gamma_{LNC}}\right)\frac{d\Gamma}{d\varepsilon_\mu} = \frac{1}{|U_{Ne}|^2+|U_{N\mu}|^2}\left\{|U_{Ne}|^2\left(\varepsilon_\mu^2-2\varepsilon_\mu^3\right)+|U_{N\mu}|^2\left(\frac{1}{2}\varepsilon_\mu^2-\frac{2}{3}\varepsilon_\mu^3\right)\right\}$$

where $\varepsilon_\mu = E_\mu/m_N$ is the normalised muon energy in the N rest frame.

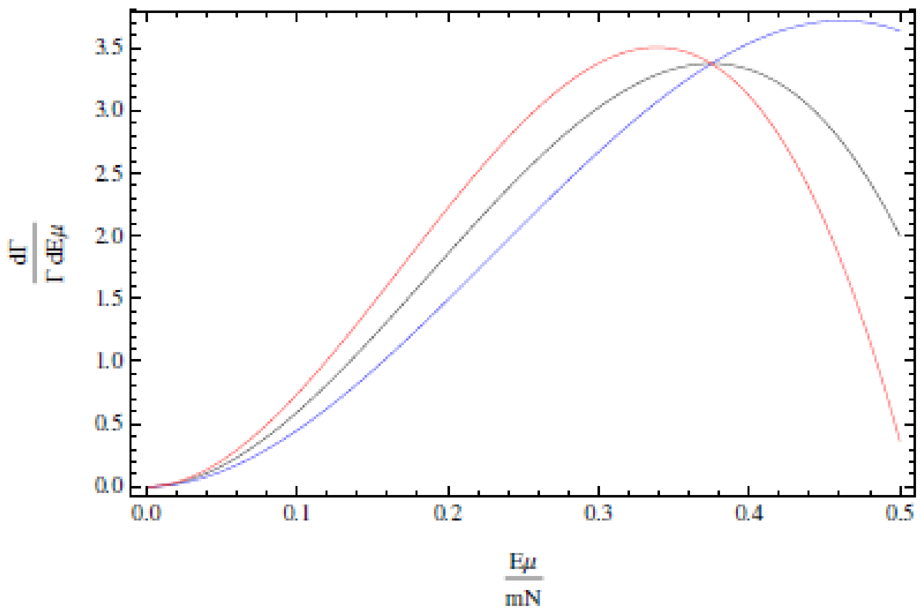


Figure 5. Normalized muon energy spectrum for the signal + background $d\Gamma/dE_\mu(W^+ \to e^+e^+\mu^-\bar{\nu}_\mu) + d\Gamma/dE_\mu(W^+ \to e^+e^+\mu^-\nu_e)$, normalised by the sum of the two rates. The two rates are proportional to $|U_{Ne}|^2$ and $|U_{N\mu}|^2$, respectively. The curves correspond to $|U_{Ne}|^2/|U_{N\mu}|^2 = 10^{-1}, 1$, and 10 (blue, black and red lines, respectively).

4. Summary and Conclusions

- Knowing that neutrinos are Dirac or Majorana is THE MOST important to go beyond the SM.

- We have discussed a new way to probe Majorana neutrinos with much less uncertainty for mass ranges of $m_\mu \le m_N \le m_W$, from the rare leptonic decay of on-shell $W^+ \to e^+ e^+ \mu^- \nu$

- We investigated Br(W^+ → e^+ e^+ mu^- nu) as well as the energy spectrum of the decays to separate the Majorana neutrino from Dirac one.

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Particles & Fields

SYNOPSIS: LHC Data Might Reveal Nature of Neutrinos

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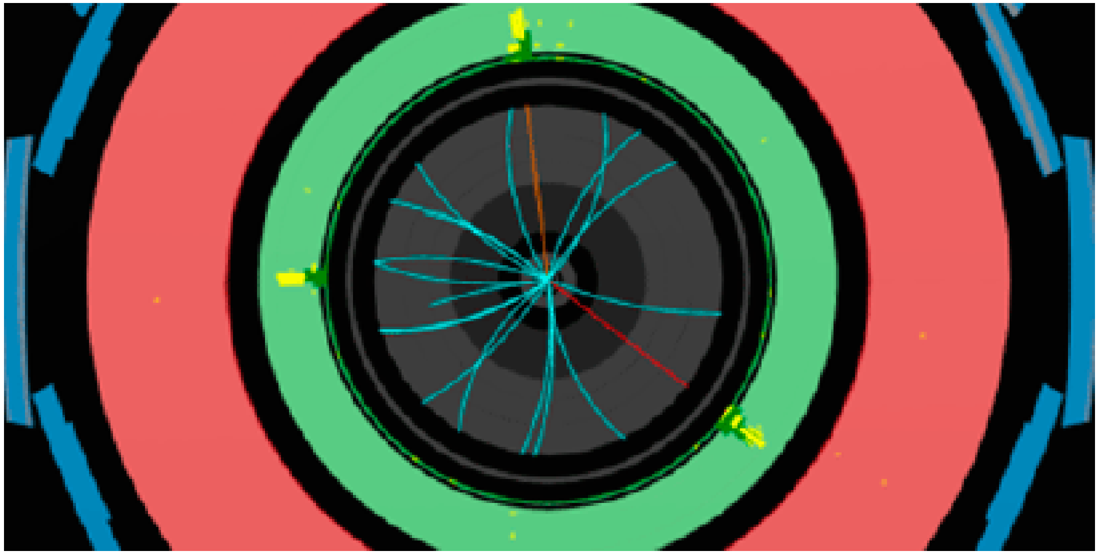

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