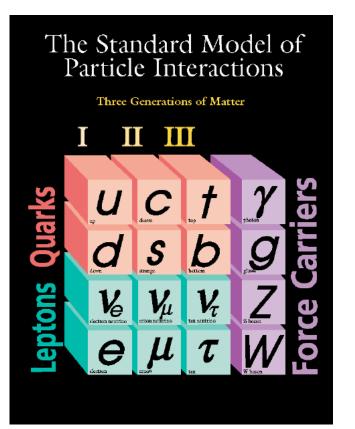
Testing Neutrino Physics at Colliders (and other experiments)*

Anupama Atre Fermilab

Based on **

- Standard Model of particle interactions is very successful
- Agrees remarkably well with experiments

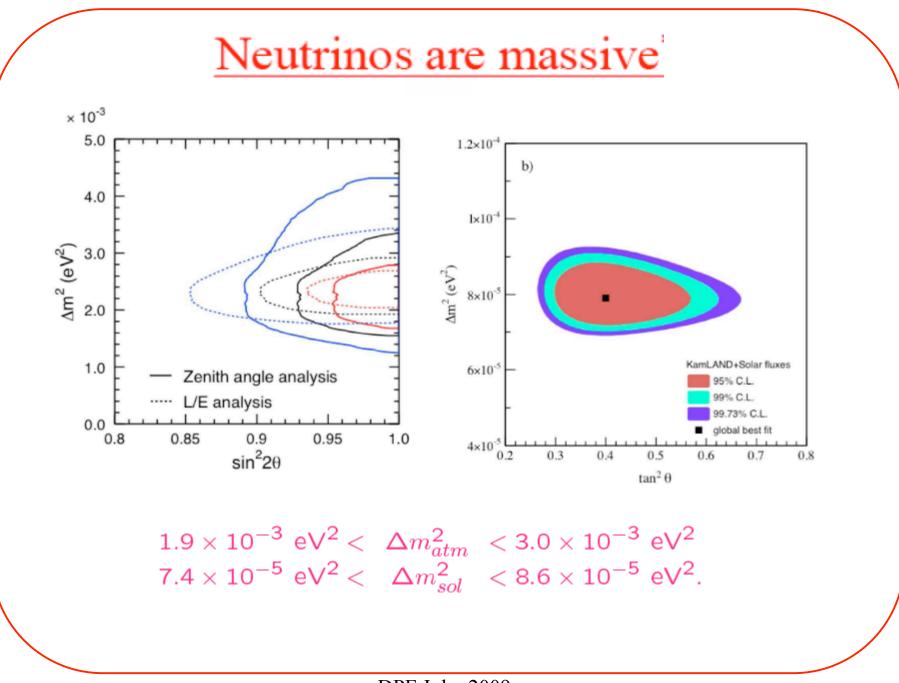


Effective theory - at least gravity at M_{Pl} Origin of mass of fundamental particles Hierarchy problem Neutrino mass - scale, inverted or normal, Dirac or Majorana? Fermion mass hierarchy <*leV to 175 GeV* Dark matter Matter anti-matter asymmetry Dark energy

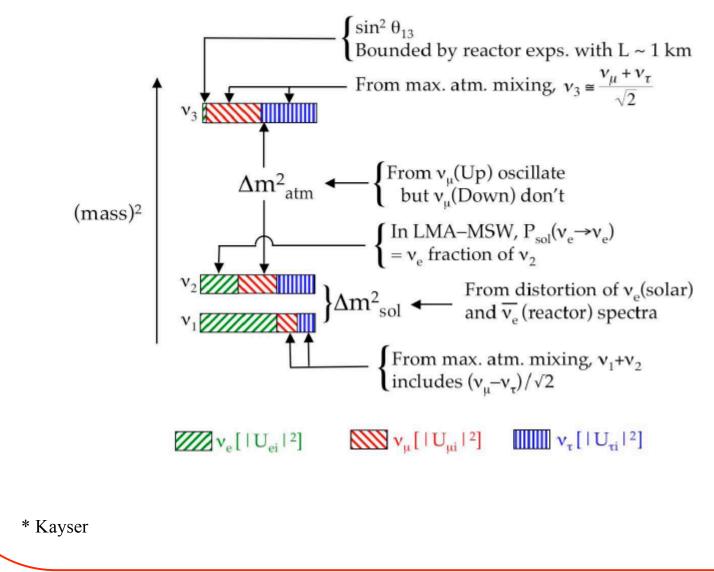
Collider Experiments (and others) will shed light on these questions

Outline

- Neutrinos what we know and don't know
- Motivation and survey
- Searches for neutrinos
 - Laboratory searches
 - Collider searches
 - Lepton number violating processes
- Summary

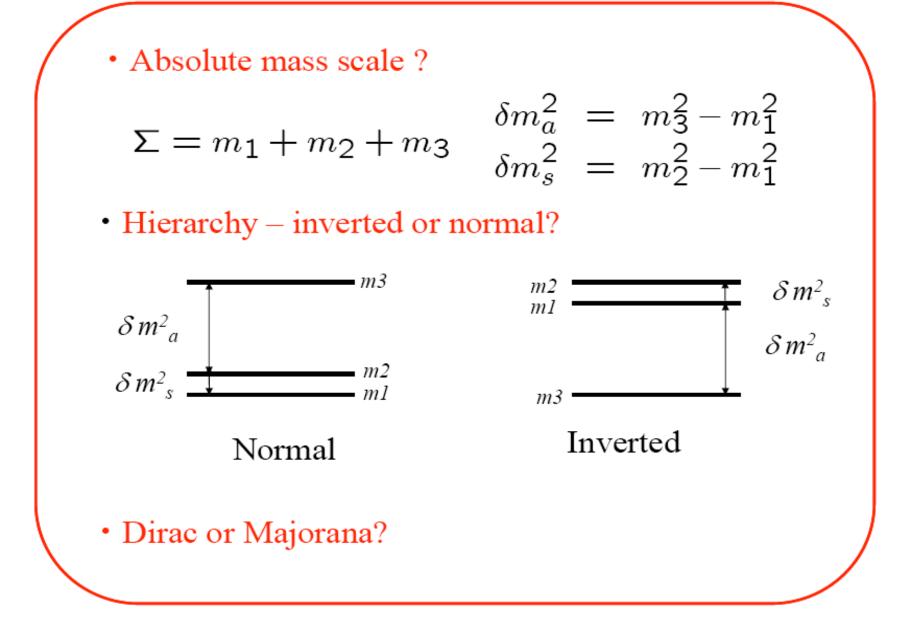


The mass relation and flavor components:*



We also know.....

- There are only three "active" light neutrinos $N_v = 2.984 \pm 0.008$, from Z pole at LEP-1.
- Direct lab bound: $m_{\beta} < 2.2 \text{ eV}$ from Tritium beta decay
- $\Sigma mv_i \le 0.17 1 \text{ eV}$ from WMAP, SDSS (Ly α spectra), SNIa.
- The absence of neutrinoless double beta decay bound on Majorana mass $<m>_{ee} < 1 \text{ eV}$



Neutrino Masses : Dirac vs Majorana

Simplest extension of the SM:

$$L_{aL} = \begin{pmatrix} V_a \\ l_a \end{pmatrix}_L, \quad a = 1, 2, 3; \qquad N_{bR}, \quad b = 1, 2, 3.$$

Gauge invariant Yukawa interactions

$$-\mathcal{L}_{Y} = \sum_{a=1}^{3} \sum_{b=1}^{n} f_{\nu}^{ab} \overline{L}_{aL} \hat{H} N_{bR} + h.c.$$
$$\Rightarrow \sum_{a=1}^{3} \sum_{b=1}^{n} \overline{\nu}_{aL} m_{ab}^{\nu} N_{bR} + h.c.$$

lead to Dirac neutrinos

Type I Seesaw

If there are Majorana mass terms

$$-\mathcal{L}_m^M = \frac{1}{2} \sum_{b,b'=1}^n \overline{N_{bL}^c} \ B_{bb'} \ N_{b'R} + \text{h.c.}$$

Then, the full neutrino mass terms read

$$\frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{N^c}_L \end{pmatrix} \begin{pmatrix} 0_{3\times3} & m^{\nu}_{3\times n} \\ m^{\nu T}_{n\times3} & B_{n\times n} \end{pmatrix} \begin{pmatrix} \nu^c_R \\ N_R \end{pmatrix} + h.c.$$

The diagonalized masses read

$$-\mathcal{L}_{m}^{\nu} = \frac{1}{2} \left(\sum_{m=1}^{3} m_{m}^{\nu} \,\overline{\nu_{mL}} \,\nu_{mR}^{c} + \sum_{m'=4}^{3+n} M_{m'}^{N} \,\overline{N_{m'L}^{c}} \,N_{m'R} \right) + \text{h.c.}$$

Leads to Majorana neutrinos

$$\nu_{aL} = \sum_{m=1}^{3} U_{am} \nu_{mL} + \sum_{m'=4}^{3+n} V_{am'} N_{m'L}^c \qquad \qquad m_{\nu} \approx \frac{D^2}{M}, \qquad m_N \approx M,$$
$$N_{bL}^c = \sum_{m=1}^{3} X_{bm} \nu_{mL} + \sum_{m'=4}^{3+n} Y_{bm'} N_{m'L}^c \qquad \qquad UU^{\dagger} \approx I \ (PMNS), \qquad VV^{\dagger} \approx \frac{m_{\nu}}{m_N}.$$

Minkowski (1977); Yanagita (1979); Gell-Mann, Ramond, Slansky (1979), S.L. Glashow (1980); Mohapatra, Senjanovic (1980) ...

DPF July, 2009

 m_N

Type II Seesaw

With a scalar triplet Φ (Y = 2): $\phi^{\pm\pm}, \phi^{\pm}, \phi^{0}$ (many representative models). Add a gauge invariant/renormalizable term:

 $Y_{ij}L_i^T C(i\sigma_2)\Phi L_j + h.c.$

That leads to the Majorana mass:

 $M_{ij}\nu_i^T C\nu_j + h.c.$

where

 $M_{ij} = Y_{ij} \langle \Phi \rangle = Y_{ij} v' \lesssim 1 \text{ eV},$

Very same gauge invariant/renormalizable term:

μH^T	$(i\sigma_2)\Phi^{\dagger}H + h.c.$
	$v' = \mu \ \frac{v^2}{M_\phi^2},$
	M_{ϕ}^{2}

predicts

Magg, Wetterich (1980); Lazarides, Shafi (1981); Mohapatra, Senjanovic (1981). ... In Little Higgs model: T.Han, H.Logan, B.Mukhopadhyaya, R.Srikanth (2005).

Type III Seesaw

With a lepton triplet T (Y = 0): $T^+ T^0 T^-$, add the terms: $-M_T(T^+T^- + T^0T^0/2) + y_T^i H^T i \sigma_2 T L_i + h.c.$

These lead to the Majorana mass: $M_{ij} \approx y_i y_j \frac{v^2}{2M_T}.$

Demand that $M_T \lesssim 1$ TeV, $M_{ij} \lesssim 1$ eV, Thus the Yukawa couplings:[†]

 $y_j \lesssim 10^{-6},$

making the mixing $T^{\pm,0} - \ell^{\pm}$ very weak.

Main features:

 T^0 a Majorana neutrino; Decay via mixing (Yukawa couplings); $T\overline{T}$ Pair production via EW gauge interactions.

```
Foot, Lew, He, Joshi (1989); G. Senjanovic et al. ...
Bajc, Nemevsek, Senjanovic (2007)
```

Cosmology

Pulsar kicks, dark matter Structure formation, supernova, etc

Experiment

Laboratory, collide Precision, oscillation

Testing Neutrino Physics

Theory

Seesaw, SUSY, ED, new ideas, Phenomenological considerations, etc

For earlier comprehensive discussions of neutrino physics see e.g., Massive Neutrinos in Physics and Astrophysics by R. N. Mohapatra and P. B. Pal (World Scientific 2004); Physics of Neutrinos and Applications to all stronghungers and a Van Stronghunger Verlag 2003. For result of the stron [hep-ph]; R. N. Mohapatra and A. Y. Smirnov, Ann. Rev. Nucl. Part. Sci. 56 (2006) 569: A. Strumia and F. Vissani, arXiv:hep-ph/0606054. P. Minkowski, Phys. Lett. B67, 421 (1977); T. Yanagida, in Proc. of the Workshop on Grand Unified Theory and Baryon Number of the Universe, KEK, Japan, 1979; M. Gell-Mann, P. Ramond and R. Slansky in Sanibel Symposium, February 1979, CALT-68-709 [retroprint arXiv:hep-ph/9809459], and in Supergravity, eds. D. Freedman et al. (North Holland, Amsterdam, 1979): S. L. Glashow in Quarks and Leptons, Cargese, eds. M. Levy et al. (Plenum, 1980, New York), p. 707; R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44, 912 (1980). J. C. Pati and A. Salam Phys. Rev. D10, 275 (1974); R. N. Mohapatra and J. C. Pati, Phys. Rev. D11, 566, 2558 (1975); G. Senianovic and B. N. Mohanatra, Phys. Rev. D12, 1502 (1975); J. A. Harvey, F. Ramond and D. B. Reiss, Nucl. Phys. B199, 223 (1982); S. Dimopoulos, L. J. Hall and S. Raby, Phys. Rev. Lett. 68, 1984 (1992); L. J. Hall and S. Raby, Phys. Rev. D51, 6524 (1995 [arXiv:hep-ph/9501298], I. Dorsner and P. Fileviez Pérez, Nucl. Phys. B 723 (2005) 53 [arXiv:hep-ph/0504276]; see also: I. Dorsner, P. Fileviez Pérez and R. Gonzalez Felipe, Nucl. Phys. B 747 (2006) 312 [arXiv:hep-ph/0512068]; P. Fileviez Pérez, AIP Conf. Proc 903 (2006) 385 [arXiv:hep-ph/0606279]; I. Dorsner, P. Fileviez Pérez and G. Rodrigo, Phys. Rev. D 75 (2007) 125007 [arXiv:hep-ph/0607208]. A. Zee, Phys. Lett. B93, 389 (1980) [Erratum - ibid. B95, 461 (1980)]; Phys. Lett B161, 141 (1985). E. Ma and U. Sarkar Phys. Rev. Lett. 80, 5716 (1998) [arXiv:hep-ph/9802445]; E. Ma and G. Rajasekarar Phys. Rev. D64, 113012 (2001) [arXiv:hep-ph/0106291]; E. Ma. Mod. Phys. Lett. A17, 289 (2002) [arXiv:hep-ph/0201225]; K. S. Babu, E. Ma and J. W. Valle, Phys. Lett. B552, 207 (2003) [arXiv:hep-ph/0206292]; E. Ma. Mod. Phys. Lett. A17, 2361 (2002) rXiv:hep-ph/0211393]. C. S. Aulakh and R. N. Mohapatra, Phys. Lett. B119, 136 (1982); L. J. Hall and M. Suzuki, Nucl. Phys. B231, 419 (1984); G. G. Ross and J. W. F. Valle, Phys. Lett. B151, 375 (1985); J. Ellis, G. Gelmini, C. Jarlskog, G. G. Ross and J. W. F. Valle. Phys. Lett. B150, 142 (1985); S. Dawson, Nucl. Phys. B261, 297 (1985); M. Drees, S. Pakvasa, X. Tata and T. ter, Vekhuis, Phys. Rev. D57, R5335 (1998) [arXiv:hep-ph/9712392]; E. J. Chun, S. K. Kang, C. W. Kim and U. W. Lee, Nucl. Phy B544, 89 (1999) [arXiv:hep-ph/9807327]; V. Barger, T. Han, S. Hessech and D. Marfatia, Phys. Lett. B538, 346 (2002) [arXiv:hep-ph/0108261]; for a recent review see Barbieri et al., Phys. Rept. 420, 1 (2005) [arXiv:hep-ph/0406039]; V. Barger, P. F. Perez and S. Spinner, arXiv:0812.3661 [hep-ph]. N. Arkani-Hamed, S. Dimopoulos, G. Dvali and J. March-Russell, Phys. Rev. D65, 024032 (2002) [arXiv:hep-ph/9811448]; . Grossman and M. Neubert, Phys. Lett. B 474, 361 (2000) [arXiv:hep-ph/9912408]; K. R. Dienes and I. Sarcevic, Phys. Lett. B500, 133 (2001) [arXiv:hep-/0008144] S. J. Huber and Q. Shafl, Phys. Lett. B 544, 295 (2002) [arXiv:hep-p205327]; M. C. Chen and H. B. Yu, arXiv:0804.2503 [hep-ph]: G. Perez and L. Randall arXiv:0805.4652 [hep-ph]. W. Konetschny and W. Kummer, Phys. Lett. B 70 (1977) For earlier comprehensive discussions of neutrino physics see e.g., Massive Neutrinos in Physics and Astrophysics by R. N. Mohapatra and P. B. Pal (World Scientific 2004); Physics of Neutrinos and Applications to Astrophysics by M. Fukugita and T. Yanagida (Springer-Verlag 2003), For recent reviews, see e.g., V. Barger, D. Marfatia, and K. Whismant, Int. J. Mod. Phys. E12, 569 (2003); B. Kayser, p. 145 in Phys. Lett. B802, 1 (2004); M. C. Gonzier-Carcin and M. Maltoni, arXiv:10704.1800 [hep-ph]; R. N. Mohapatra and A. Y. Smirnov, Ann. Rev. Nucl. Part. Sci. 56 (2006) 565 A. Strumia and F. Vissani, arXiv:hep-ph/0606054, P. Minkowski, Phys. Lett. B67, 421 (1977); T. Yanagida, in Proc. of the Workshop on Grand Unified Theory and Baryon Number of the Universe, KEK, Japan, 1979; M. Gell-Mann, P. Ramond and R. Slansky in Sanibel Symposium, February 1979, CALT-68-709 [retroprint arXiv:hep-ph/9809459], and in eramenity eds. D. Freedman et al. (North Holland, Amsterdam, 1979); S. L. Glashow in Quarks and Leptons, Cargese, eds. M. Levy et al. (Plenum, 1980, New York), p. 707; R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44, 912 (1980), J. C. Pati and A. Salam Phys. Rev. D10, 275 (1974); R. N. Mohapatra and J. C. Pati, Phys. Rev. D11, 566, 255 (1975); G. Senianovic and R. N. Mohapatra, Phys. Rev. D12, 1502 (1975), J. A. Harvey, P. Ramond and D. B. Reiss, Nucl. Phys. B199, 223 (1982); S. Dimopoulos, L. J. Hall and S. Raby, Phys. Rev. Lett. 68, 1984 (1992); L. J. Hall and S. Raby, Phys. Rev. D51, 6524 (1995) [arXiv:hep-ph/9501298]. I. Dorsner and P. Fileviez Pérez, Nucl. Phys. B 723 (2005) 53 [arXiv:hep-ph/0504276]; see also: I. Dorsner, P. Fileviez Pérez and R. Gonzalez Felipe, Nucl. Phys. B 747 (2006) 312 [arXiv:hep-ph/0512068]; P. Fileviez Pérez, AIP Conf. Proc. 903 (2006) 385 [arXiv:hep-ph/0606279]; I. Dorsner, P. Fileviez Pérez and G. Rodrigo, Phys. Rev. D 75 (2007) 125007 [arXiv:hep-ph/0607208]. A. Zee, Phys. Lett. B93, 389 (1980) [Erratum - ibid, B95, 461 (1980)]; Phys. Lett B161, 141 (1985), E. Ma and U. Sarkar Phys. Rev. Lett. 80, 5716 (1998) [arXiv:hep-ph/9802445]; E. Ma and G. Rajasekarar Phys. Rev. D64, 113012 (2001) [arXiv:hep-ph/0106291]; E. Ma, Mod. Phys. Lett. A17, 289 (2002) [arXiv:hep-ph/0201225]; K. S. Babu, E. Ma and J. W. Valle, Phys. Lett. B552, 207 (2003) [arXiv:hep-ph/0206292]; E. Ma. Mod. Phys. Lett. A17, 2361 (2002) hep-ph/0211393]. C. S. Aulakh and R. N. Mohapatra, Phys. Lett. B119, 136 (1982); L. J. Hall and M. Suzuki, Nucl. Phys. B231, 419 (1984); G. G. Ross and J. W. F. Valle, Phys. Lett. B151, 375 (1985); J. Ellis, G. Gelmini, C. Jarlskog, G. G. Ross and J. W. F. Valle, Phys. Lett. B150, 142 (1985); S. Dawson, Nucl. Phys. B261, 297 (1985); M. Drees, S. Pakvasa, X. Tata and T. ter. Veldhuis, Phys. Rev. D57, R5335 (199 arXiv:hev-ph/9712392]; E. J. Chun, S. K. Kang, C. W. Kim and U. W. Lee, Nucl. Phys. B544, 89 (1999) [arXiv:hep-ph/9807327]; V. Barger, T. Han, S. Hesselbach and D. Marfatia, Phys. Lett. B538, 346 (2002) [arXiv:hep-ph/0108261]; for a recent review see R. Barbieri et al., Phys. Rept. 420, 1 (2005) [arXiv:hep-ph/0406039]; V. Barger, P. F. Perez and S. Spinner, arXiv: 0812, 3661 [her-ph], N. Arkani-Hamed, S. Dimopoulos, G. Dvali and J. March-Russell, Phys. Rev. D65, 024032 (2002) [arXiv:hep-ph/9811448]; Y. Grossman and M. Neubert, Phys. Lett. B 474, 361 (2000) [arXiv:hep-ph/9912408]; K. R. Dienes and I. Sarcevic, Phys. Lett. B500, 133 (2001) [arXiv:hep-ph/0008144]; S. J. Huber and O. Shafi, Phys. Lett. B 544, 295 (2002) [arXiv:hep-ph/0205327]: M. C. Chen and H. B. Yu, arXiv:0804.2503 [hep-ph]: G. Perez and L. Randall

arXiv:0805.4652 [hep-ph]. W. Konetschny and W. Kummer, Phys. Lett. B 70 (1977)

Phys. Rev. D 22 (1980) 2860; G. Lazarides, O. Shafi and C. Wetterich, Nucl. Phys. B 181 R. Pittau, JHEP 0710, 047 (2007) [arXiv:hep-ph/0703261]. W. Clarida, T. Yetkin, Prigs. Rev. D 22 (1980) 2800; G. Larandes, Q. Shañ and C. Weiterich, Nucl. Phys. B 181 (1981) 258; R. Nohaparra and G. Syshenović, Phys. Rev. D 23 (1981) 254; R. Not. Phys. Rev. D 25 (1991) 254; R. Not. Phys. Rev. D 250; Rev. Phys. Rev. D 250;

Phys. Rev. Lett. 43 (1979) 1566. K. S. Babu and C. N. Leung, Nucl. Phys. B610, 667 (2001) 029 (2007) [arXiv: p-ph/0612216]; B. Bajc, M. Nemevsek and G. Senjanović, Phys. Rev. [arXiv:hep-ph/0106054]. W. H. Furry, Phys. Rev. 56, 1184 (1939); for early reviews see, Primakoff and Rosen, Rep. Prog. Phys. 22, 121 (1959); Ann. Rev. Nucl. Part. Sci. 31, 145 (1981). M. Doi, T. Kotani and E. Takasugi, Prog. Theor. Phys. Suppl. 83, 1 (1985). For recent review see eg. S. R. Elliott and J. Engel, J. Physics. G30 R183 (2004)

(1995) [arXiv:hep-ph/9503456]; A. Bakowac and A. Pilaftsis, Nucl. Phys. B437, 491 (1995) 201801 (2003) [arXiv:hep-ph/0301108]; ibidem, Phys. Lett. B 548, 204 (2002) arXiv:hep-ph/9403398]; A. Ilakovac, Phys. Rev. D54, 5653 (1996) arXiv:hep-ph/9608218]; V. Gribanov, S. Kovalenko and I. Schmidt, Nucl. Phys. B 607, 355 Conf. Proc. 721 (A.I.P., New York, 2004), p. 261; T. Appelquist, M. Piai and R. Shrock, (2001) [arXiv:hep-ph/0102155]. A. Atre, V. Barger and T. Han, Phys. Rev. D71, 113014 (2005) [arXiv:hep-ph/0502163]. J. N. Ng and A. N. Kamal, Phys. Rev. D 18, 3412 (1978); eve and A. F. Pacheco, Phys. Rev. D 30, 1488 (1984); C. Dib. I Abad I G Est V. Gribanov, S. Kovalenko and I. Schmidt, Phys. Lett. B 493, 82 (2000) (1992); C. Barbero, G. Lopez Castro and A. Mariano, Phys. Lett. B566, 98 (2003) arXiv:nucl-th/0212083].C. S. Lim, E. Takasugi and M. Yoshimura, Prog. Theor. Phys. 113, 1367 (2005), [arXiv:hep-ph/0411139]. SINDRUM II Collaboration, J. Kaulard et al., Phys. Lett. B422, 334 (1998); K. Zuber, arXiv:hep-ph/0008080; P. Domin, A. Faessler, S Kovalenko and F. Simkovic, Phys. Rev. C70, 065501 (2004) [arXiv:nucl-th/0409033]. J. H. Missimer, R. N. Mohapatra and N. C. Mukhopadhyay, Phys. Rev. D50, 2067 (1994); F. Simkovic, A. Faessler, S. Kovalenko and P. Domin, Phys. Rev. D66, 033005 (2002) arXiv:hep-ph/01122711; E. Takasugi, Nucl. Instrum. Meth. A503, 252 (2003); M. Aoki, Meth. A503, 258 (2003). T. G. Rizzo, Phys. Lett. B116, 23 (1982); C. A Heusch and P. Minkowski, Nucl. Phys. B416, 3 (1994), M. Dittmar, A. Santamaria,

M. C. Gonzalez-Garcia and J. W. F. Valle, Nucl. PhyseB 522, 12 1990). M. Flanz, and C. Soundarez-Gardana and A. W. F. Vang Yudo, Fullowin and Y. H. 1999). In: Events in the operation of the state of

(1983); D. Dicus, D. Karatas, and P. Roy, Phys. Rev. D44, 2033 (1991); A. Datta, Guchait, and A. Pilaftsis, Phys. Rev. D50, 3195 (1994) [arXiv:hep-ph/931125] F. M. L. Almeida, Y. A. Coutinho, I. A. M. Simoes and M. A. B. Vale, Phys. Lett. D62, F. M. L. Amonta, T. A. Coutinhord, A. M. Simess and M. A. B. Vale, Phys. Rev. D62, 175044 (2020). Express periods of 1-8 Aparally, M. Cangeni, C. Chargania Iand, X. Y. Singaron, Phys. Rev. D 5, 00 100 (2000) arXiv: a tobar-physical bit (2010). F. G. gry anti 97, 211 (4): 906 arx: a tobar physical bit (2010). Sublets, size, e.g., F. del. 2016, J. A. Agalhar-Sarwoff, and R. Pittan, J. Phys. Conf. Jer. Phys. Rev. D 22 (1980) 2960; G. Lararidos, Q. Shafi and C. Weterich, Nucl. Phys. B 181 (1981) 269: P. M. Mohareter, and J. Sarkowich Phys. Rev. D 29 (1980) 2980; B. 1841

[1981] 287; R. N. Mohapatra and G. Senjanović, Phys. Rev. D 23 (1981) 165; R. Foot, H. Lew, X. S. He and G. C. Joshi, Z. Phys. C 44 (1989) 441; E. Ma, Phys. Rev. Lett. 81

arXiv:0705.3589 [hep-ph]; P. Fileviez Perez, arXiv:0809.1202 [hep-ph]. S. Wei arXiv:hep-ph/0106054]. W. H. Furry, Phys. Rev. 56, 1184 (1939); for early reviews Primakoff and Rosen, Rep. Prog. Phys. 22, 121 (1959); Ann. Rev. Nucl. Part. Sci. 31, 145 (1981). M. Doi, T. Kotani and E. Takasugi, Prog. Theor. Phys. Suppl. 83, 1 (1985). For recent review see eg. S. R. Elliott and J. Engel, J. Physics. G30 R183 (2004) arTiv:hep-ph/04050781 A. Bakwar, B. A. Kniehl and A. Pilaftsis, Phys. Rev. D52, 3993 113001 (2005) [arTiv:hep-ph/0506107]. T. Appelouist and R. Shrock, Phys. Rev. Lett. 90. 95) [arXiv:hep-ph/9503456]; A. Ilakovac and A. Pilaftsis, Nucl. Phys. B437, 491 (1995) arXiv:hep-ph/9403398]; A. Ilakovac, Phys. Rev. D54, 5653 (1996) arXiv:hep-ph/9606226]; V. Gibanov, S. Kovalenko and I. Schmidt, Nucl. Phys. B 607, 355 Conf. Proc, 721 (A.I.P., New York, 2004), p. 261; T. Appelquist, M. Piai and R. Shrock, (2001) [arXiv:hen-ph/0102155]. A. Atre, V. Barrer and T. Han, Phys. Rev. D'71, 113014 rXiv:hep-ph/0502163]. J. N. Ng and A. N. Kamal, Phys. Rev. D 18, 3412 (1978); J. Abad, J. G. Esteve and A. F. Pacheco, Phys. Rev. D 30, 1488 (1984); C. Dib, V. Gribanov, S. Kovalenko and I. Schmidt, Phys. Lett. B 493, 82 (2000) [arXiv:hep-ph/0006277]. A. Ali, A. V. Borisov and N. B. Zamorin, Eur. Phys. J. C21, 123 (2001) [arXiv:hep-ph/0104123]. L. S. Littenberg and R. E. Shrock, Phys. Rev. D46, R892 1992); C. Barbero, G. Lopez Castro and A. Mariano, Phys. Lett. B566, 98 (2003 arXiv:nucl-th/0212083]. C. S. Lim, E. Takasugi and M. Yoshimura, Prog. Theor. Phys. 113, 1367 (2005), [arXiv:hep-ph/0411139]. SINDRUM II Collaboration, J. Kaulard et al., Phys. Lett. B422, 334 (1998); K. Zuber, arXiv:hep-ph/0008080; P. Domin, A. Faessler, S. Kovalenko and F. Simkovic, Phys. Rev. C70, 065501 (2004) [arXiv:nucl-th/0409033]. J. H. Missimer, R. N. Mohapatra and N. C. Mukhopadhyay, Phys. Rev. D50, 2067 (1994); F.

Simkovic, A. Faessler, S. Kovalenko and P. Domin, Phys. Rev. D66, 033005 (2002) [arXiv:hep-ph/0112271]; E. Takasugi, Nucl. Instrum. Meth. A503, 252 (2003); M. Aoki, Nucl. Instrum. Meth. A503, 258 (2003). T. G. Rizzo, Phys. Lett. B116, 23 (1982); C. A. sch and P. Minkowski, Nucl. Phys. B416, 3 (1994). M. Dittmar, A. Sant M. C. Gonzalez-Garcia and J. W. F. Valle, Nucl. Phys. B 332, 1 (1990). M. Flanz, W Rodejohann and K. Zuber, Phys. Lett. B473, 324 (2000), Errutum - ibid. B480, 418 (2000) [arXiv:hep-ph/9911298], M. Flanz, W. Rodeiohann and K. Zuber, Eur. Phys. J. C16, 453 (2000) [arXiv:hep-ph/9907203]; W. Rodejohann and K. Zuber, Phys. Rev. D63, 054031 (2001) [arXiv:hep-ph/0011050]. W.-Y. Keung and G. Senjanovic, Phys. Rev. Lett. 50, 1427 (1983); D. Dicus, D. Karatas, and P. Roy, Phys. Rev. D44, 2033 (1991); A. Datta, M. Guchait, and A. Pilaftsis, Phys. Rev. D50, 3195 (1994) [arXiv:hep-ph/9311257] F. M. L. Almeida, Y. A. Coutinho, J. A. M. Simoes and M. A. B. Vale, Phys. Rev. D62, D75004 (2000) [arXiv:hep-ph/0008201]; O. Panella, M. Cannoni, C. Carimalo, and Y. N. Srivastava, Phys. Rev. D65, 035005 (2002) [arXiv:hep-ph/0107308]. T. Han and B. Zhang, Phys. Rev. Lett. 97, 171804 (2006) [arXiv:hep-ph/0604064]. For a comparison for different colliders, see e.e., F. del Aguila, J. A. Aguilar-Saavedra and R. Pittau, J. Phys. Conf. Ser.

133; J. Schechter and J. W. F. Valle, Phys. Rev. D 22 (1980) 2227; T. P. Cheng and L. F. Li, 53, 506 (2006) [arXiv:hep-ph/0606198]. F. del Aguila, J. A. Aguilar-Saavedra and R. Pittau, JHEP 0710, 047 (2007) [arXiv:hep-ph/0103203;
 R. Vidal, W. Wu, Tao Han, H. Fi, and E. Yazgan, CMS Note 2008/054 (Dec. 2008)
 R. Vidal, W. Wu, Tao Han, H. Fi, and E. Yazgan, CMS Note 2008/054 (Dec. 2008)

D 76. 055011 (200 arXiv:hep-ph/0703080]. A. de Gouvea, J. Jenkins and N. Vasudevan, Phys. Rev. D 75, 013003 (2007) [arXiv:hep-ph/0608147]; A. de Gouw arXiv:0706.1732 [hep-ph], A. Pilaftsis and T. E. J. Underwood, Nucl. Phys. B 692, 303 (2004) [arXiv:hep-ph/0309342]; A. Pilaftsis and T. E. J. Underwood, Phys. Rev. D 72, arXiv:hep-ph/0405078]. A. Ilakovac, B. A. Kniehl and A. Pilaftsis, Phys. Rev. D52, 3993 113001 (2005) [arXiv:hep-ph/0506107]. T. Appelquist and R. Shrock. Phys. Rev. Lett. 90. [arXiv:hep-ph/0204141]; ibidem, in Neutrino Factories and Superbeams, NuFact03, A.I.P. Phys. Rev. D 69, 015002 (2004) [arXiv:hep-ph/0308061]; T. Appelquist, N. D. Christensen M. Piai and R. Shrock, Phys. Rev. D 70, 093010 (2004) [arXiv:hep-ph/0409035].

K. R. S. Balaji, A. Perez-Lorenzana and A. Y. Smirnov, Phys. Lett. B 509, 111 (2001) rXiv:hep-ph/0101005]; A. Y. Smirnov and R. Zukanovich Funchal, Phys. Rev. D 74, M. Viel, J. Lescourgues, M. G. Haehnelt, S. Matarrese and A. Biotto, Phys. Rev. Lett. 97, 071301 (2006) [arXiv:astro-ph/0605706]. G. M. Fuller, A. Kusenko and K. Petraki arXiv:0806.4273[astro-ph]. S. Dodelson and L. M. Widrow, Phys. Rev. Lett. 72, 17 (1994) [arXiv:hep-ph/9303287]; X. D. Shi and G. M. Fuller, Phys. Rev. Lett. 82 [arXiv:astro-ph/9810076], 2832 (1999); A. D. Dolgow and S. H. Hansen, Astropart, Phys.

16, 339 (2002). K. Abazajian, G. M. Fuller and M. Patel, Phys. Rev. D 64, 023501 (2001) [arXiv:astro-ph/0101524]. G. Gelmini, S. Palomares-Ruiz and S. Pascoli. Phys. Rev. Lett. 93, 081302 (2004) [arXiv:astro-ph/0403323]. A. D. Dolgov, Phys. Rept. 370, 333 (2002) [arXiv:hep-ph/0202122], A. Kusenko and G. Serre, Phys. Lett. B396, 197 (1997) [arXiv:hep-ph/9701311]; G. M. Fuller, A. Kusenko, I. Mociolu and S. Pascoli, Phys. Rev. D68, 103002 (2003) [arXiv:astro-ph/0307267]; for preview, see A. Kusenko

Ref. D89, 100002 (2000) JEXAY is a support of the proceeding in the constraint of the support of the proceeding of th (2006) [arXiv:astro-ph/0603368]; A. Boyarsky, A. Neronov, O. Ruchayskiy,

M. Shaposhnikov and I. Tkachev, Phys. Rev. Lett. 97, 261302 (2006) [arXiv: astro-ph/0603660]. C. Boehm, Y. Farzan, T. Hambye, S. Palomares-Ruiz and

S. Pascoli, arXiv:hep-ph/0612228. T. Asaka, S. Blanchet and M. Shaposhnikov, Phys. Lett. B 631, 151 (2005) [arXiv:hep-ph/0503065]; T. Asaka and M. Shaposhnikov, Phys. Lett. B 620, 17 (2005) [arXiv:bep-ph/0505013]; T. Asaka, M. Laine and M. Shaposhnikov, JHEF 53, 505 (2005) [arXiv:bep-ph/0505136]; T. Gei Aguna, J. A. Agunar-baavedra and R. Pittau, JHEP 0710, 047 (2007) [arLiv:hep-ph/0703261]. W. Clarida, T. Yetkin,

R. Vidal, W. Wu, Tao Han, H. Pi, and E. Yazgan, CMS Note 2008/054 (Dec. 2008) unpublished. S. Bar-Shalom, N. G. Deshpande, G. Eilam, J. Jiang and A. Soni, Pf 5. ket B145 342 200 h 5 Fr hep-ph/0608309[c.4, S'AB, K Mar, g ark: 061 266 D 4mo 1. B4 Shabar 4. Sha 'Phi Rev. (776,083004 007) [147] Sha-yi 0 10 14 B5 Shabar 6. Ellan, T. Jan Jao, San Ja Shay 77,

115019 (2008) [arXiv: 0803.2835 [hep-ph]]. I. Dorsner and P. Fileviez Perez, JHEP 0706 Phys. Rev. Lett. 43 (1979) 1566. K. S. Babu and C. N. Leung, Nucl. Phys. B619, 667 (2001) 029 (2007) [arXiv:hep-ph/0612216]; B. Bajc, M. Nemevsek and G. Senjanović, Phys. Rev. D 76, 055011 (2007) [arXiv:hep-ph/0703080]. A. de Gouvea, J. Jenkins and

N. Vasudevan, Phys. Rev. D 75, 013003 (2007) [arXiv:hep-ph/0608147]; A. de Gouvea arXiv:0706.1732 [hep-ph]. A. Pilaftsis and T. E. J. Underwood, Nucl. Phys. B 692, 303 (2004) [arXiv:hep-ph/0309342]; A. Pilaftsis and T. E. J. Underwood, Phys. Rev. D 72, 201801 (2003) [arXiv:hep-ph/0301108]; ibidem, Phys. Lett. B 548, 204 (2002) [arXiv:hep-ph/0204141]; ibidem, in Neutrino Factories and Superbeams, NuFact03, A.I.P. Phys. Rev. D 69, 015002 (2004) [arXiv:hep-ph/0308061]; T. Appelouist, N. D. Christenser M. Piai and R. Shrock, Phys. Rev. D 70, 093010 (2004) [arXiv:hep-ph/0409035] K. R. S. Balaji, A. Perez-Lorenzana and A. Y. Smirnov, Phys. Lett. B 509, 111 (2001)

arXiv:hep-ph/0101005]; A. Y. Smirnov and R. Zukanovich Funchal, Phys. Rev. D 74, 013001 (2006) [arXiv:hep-ph/0603009]. M. Viel, J. Lesgourgues, M. G. Haehnelt, S. Matarrese and A. Riotto, Phys. Rev. D 71, 063534 (2005) [arXiv:astro-ph/0501562] M. Viel, J. Lesgourgues, M. G. Haehnelt, S. Matarrese and A. Riotto, Phys. Rev. Lett. 97, 071301 (2006) [arXiv:astro-ph/0605706]. G. M. Fuller, A. Kusenko and K. Petraki arLiv:0806.4273[astro-ph]. S. Dodelson and L. M. Widrow, Phys. Rev. Lett. 72, 17 (1994) [arXiv:hep-ph/9303287]; X. D. Shi and G. M. Fuller, Phys. Rev. Lett. 82

[arXiv:astro-ph/9810076], 2832 (1999); A. D. Dolgov and S. H. Hansen, Astropart, Phys 16, 339 (2002), K. Abazajian, G. M. Fuller and M. Patel, Phys. Rev. D 64, 023501 (2001) arXiv:astro-ph/0101524], G. Gelmini, S. Palomares-Ruiz and S. Pascoli,

Phys. Rev. Lett. 93, 081302 (2004) [arXiv:astro-ph/0403323]. A. D. Dolgov, Phys. Rept 370, 333 (2002) [arXiv:hep-ph/0202122], A. Kusenko and G. Serre, Phys. Lett. B396, 197 (1997) [arXiv:hep-ph/9701311]; G. M. Fuller, A. Kusenko, I. Mocioiu and S. Pascoli, Phys Rev, D68, 103002 (2003) [arXiv:astro-ph/0307267]; for a review, see A. Kusenko Int. J. Mod. Phys. D13, 2065 (2004) [arXiv:astro-ph/0409521]. S. H. Hansen and Z. Haiman, Astrophys. J. 600, 26 (2004) [arXiv:astro-ph/0305126]; P. L. Biermann and A. Kusenko, Phys. Rev. Lett. 96, 091301 (2006) [arXiv: astro-ph/0601004]. K. Abazajian. M. Fuller and W. H. Tucker, Astrophys. J. 562, 593 (2001) [arXiv:astro-ph/0106002]. A. Boyarsky, A. Neronov, O. Ruchavskiy and M. Shanoshnikov, Phys. Rev. D 74, 103506 (2006) [arXiv:astro-ph/0603368]; A. Boyarsky, A. Neronov, O. Ruchayskiy,

M. Shaposhnikov and I. Tkachev, Phys. Rev. Lett. 97, 261302 (2006) [arXiv:astro-ph/0603680]. C. Boehm, Y. Farzan, T. Hambye, S. Pakomares-Ruiz and S. Pascoli, arXiv:hep-ph/0612228. T. Asaka, S. Blanchet and M. Shaposhnikov, Phys. Lett.

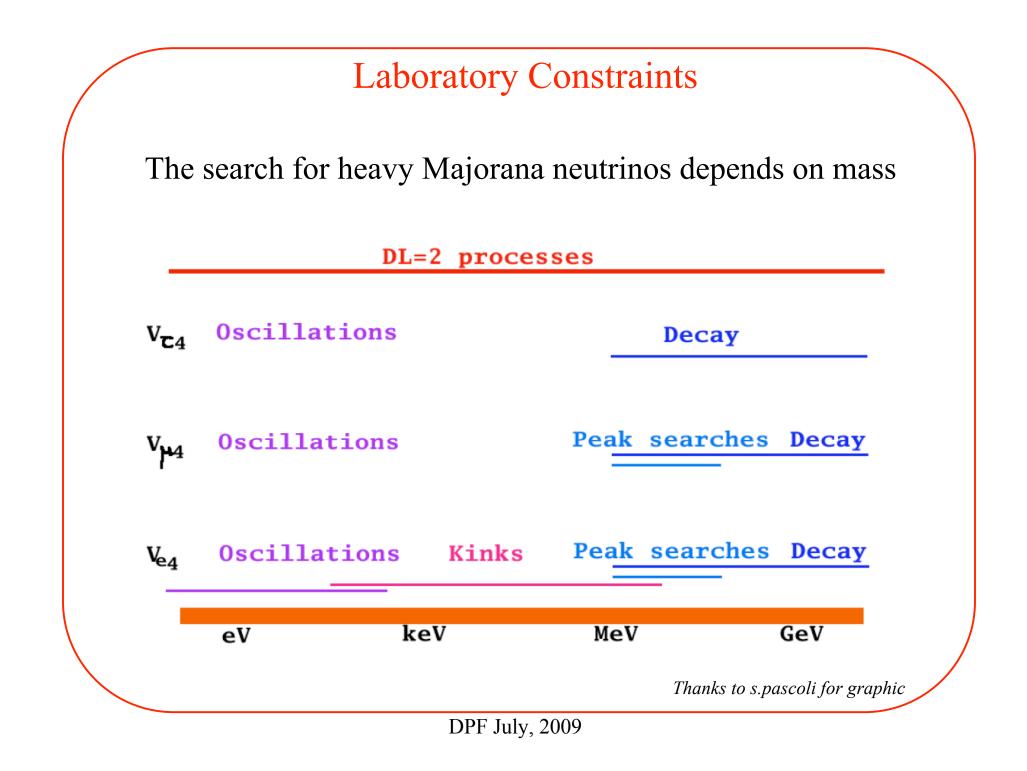
B 631, 151 (2005) [arXiv:hep-ph/0503065]; T. Asaka and M. Shaposhnikov, Phys. Lett. B 620, 17 (2005) [arXiv:hep-ph/0505013]; T. Asaka and M. Shaposhnikov, JHEP

0701, 091 (2007) [arXiv:hep-ph/0612182]. T. Asaka, M. Shaposhnikov and A. Kusenko, 9105, 151 (2007) REAV (1997) provided provided provided and an examination of a common physical term (Social Science) and a science of the S. Pascoli, JCAP 0810, 029 (2008) [arXiv:0803.2735 [astro-ph]], W. Chao, Z. G. Si. Z. Z. Xing and S. Zhou, Phys. Lett. B 666, 451 (2008) [arXiv:0804.1265 [hep-ph]]. F. E. Wietfeldt and E. B. Norman, Phys. Rept. 273, 149 (1996). B. Armbruster et a KARMEN Collaboration], Phys. Lett. B 348, 19 (1995). M. Daum et al., Phys. Rev. Lett. 85, 1815 (2000) [arXiv:hep-ex/0008014], M. Cirelli, G. Marandella, A. Strumia and F. Vissani, Nucl. Phys. B 708, 215 (2005) [arXiv:hep-ph/0403158]. A. A. Aguilar-Arevalo et al. [The MiniBooNE Collaboration], arXiv:0704.1500 [hep-ex]. M. Maltoni and Schwetz, arXiv: 0705.0107 [hep-ph]. R. E. Shrock, Phys. Lett. B 96, 159 (1980) Z. Chacko, L. J. Hall, S. J. Oliver and M. Perelstein, Phys. Rev. Lett. 94, 111801 (2005) [arXiv:hep-ph/0405067]; S. Palomares-Ruiz, S. Pascoli and T. Schwetz, JHEP 0509, 048 (2005) [arXiv:hep-ph/0505216], D. Errede et al., Phys. Rev. D 37, 577 (1988); D. Decamp al. [ALEPH Collaboration], Phys. Lett. B 236, 511 (1990); P. Burchat et al., Phys. Rev. D 41, 3542 (1990); B. Adeva et al. IL3 Collaboration], Phys. Lett. B 251, 321 (1990); P. Achard et al. L3 Collaboration], Phys. Lett. B 517, 67 (2001) [arXiv:hep-ex/0107014], E. Nardi, E. Roulet and D. Tommasini, Phys. Lett. B 327, 319 (1994) [arXiv:hen-ph/9402224]; E. Nardi, E. Roulet, and D. Tommasini, Phys. Lett. B 344, 225 (1995)

[arXiv:hep-ph/9409310], S. Bergmann and A. Kagan, Nucl. Phys. B 538, 368 (1999) arXiv:hep-ph/9803305]. F. del Aguila, J. de Blas and M. Perez-Victoria, Phys. Rev. D 78 (2008) 013010 [arXiv:0803.4008 [hep-ph]]. E. Ma and A. Pramudita, Phys. Rev. D 24, 1410 (1981). P. Langacker and D. London, Phys. Rev. D 38, 907 (1988). D. Tommasini, G. Barenboim, J. Bernabeu and C. Jarlskog, Nucl. Phys. B 444, 451 (1995) [arXiv:hep-ph/9503228]. M. Galeazzi, F. Fontanelli, F. Gatti and S. Vitale, Phys. Rev. Lett. 86, 1978 (2001), K. H. Hiddemann, H. Daniel and O. Schwentker, J. Phys. G 21, 639 (1995). E. Holzschuh, W. Kundig, L. Palermo, H. Stussi and P. Wenk, Phys. Lett. B 451, 247 (1999), E. Holzschuh, L. Palermo, H. Stussi and P. Wenk, Phys. Lett. B 482, 1 (2000) J. Deutsch, M. Lebrun and R. Prieels, Nucl. Phys. A 518, 149 (1990). H. O. Back et al., JETP Lett. 78, 261 (2003) [Pisma Zh. Eksp. Teor. Fiz. 78, 707 (2003)]. C. Hagner Altmann, F. von Feilitzsch, L. Oberauer, Y. Declais and E. Kajfasz, Phys. Rev. D 52 (4095) D. I. Britton et al. Phys. Rev. Lett. 68, 3000 (1992); D. I. Britton et al. Phys.

46, 885 (1992). P. Benes, A. Faessler, F. Simkovic and S. Kovalenko, Phys. Rev. D 1 (2005) [arXiv:hep-ph/0501295]. D. Berghofer et al., Proc. Intern. Conf. on eutrino Physics and Astrophysics (Mau), Hawaii, 1981), 67 (1981), eds. R. J. Cence, E. Ma and A. Roberts, Vol. II (University of Hawaii, Honolulu, HI, 1981); T. Yamazaki, Proc. 22nd Intern. Conf. on High-energy physics (Leipzig, 1984), 262 (1984), eds. A. Meyer and E. Wieczorek, Vol. I (Akademie der Wiessenachaften der DDR, Leipzig, 1984). G. Bernardi et al., Phys. Lett. B 203, 332 (1988). J. Badier et al. [NA3 Collaboration], Z. Phys. C 31, 21 (1986), F. Berzsma et al. [CHARM Collaboration], Phys. Lett. B 166, 473 (1986), P. Abreu et al. [DELPHI Collaboration], Z. Phys. C 74, 57 (1997) [Erratum-ibid. C 75, 580 (1997)]. O. Adriani et al. [L3 Collaboration], Phys. Lett. B 295, 371 (1992). G. Bélanger, F. Phys. Lett. B 638, 401 (2006) [arXiv:hep-ph/0602150]. F. L. Bezrukov and

M. Shaposhnikov, Phys. Rev. D 75, 053005 (2007) [arXiv:hep-ph/0611352]; D. Gorbunov and M. Shaposhnikov, JHEP 0710, 015 (2007) [arXiv: 0705.1729 [hep-ph]], A. Y. Smirnov [KARMEN Collaboration], Phys. Lett. B 348, 19 (1995). M. Daum et al., Phys. Rev. Lett. 85, 1815 (2000) [arXiv:hep-ex/0008014], M. Cirelli, G. Marandella, A. Strumia and F. Vissani, Nucl. Phys. B 708, 215 (2005) [arXiv:hep-ph/0403158]. A. A. Aguilar-Arevald et al. [The MiniBooNE Collaboration], arXiv:0704.1500 [hep-ex]. M. Maltoni and T. Schwetz, arXiv:0705.0107 [hep-ph]. R. E. Shrock, Phys. Lett. B 96, 159 (1980). Z. Chacko, L. J. Hall, S. J. Oliver and M. Perelstein, Phys. Rev. Lett. 94, 111801 (2005) [arXiv:hep-ph/0405067]; S. Palomares-Ruiz, S. Pascoli and T. Schwetz, JHEP 0509, 048 (2005) [arXiv:hep-ph/0505216]. D. Errede et al., Phys. Rev. D 37, 577 (1988); D. Decamp et al [ALEPH Collaboration] Phys. Lett. B 236, 511 (1990); P. Burchat et al. Phys. Rev. D. 41, 3542 (1990); B. Adeva et al. [L3 Collaboration], Phys. Lett. B 251, 321 (1990); P. Achard et al. L.S. Collaboration], Phys. Lett. B 517, 67 (2001) [arXiv:hep-ex/0107014], E. Nardi, E. Roulet and D. Tommasini, Phys. Lett. B 327, 319 (1994) [arXiv:hep-ph/9402224]; E. Nardi, E. Roulet, and D. Tommasini, Phys. Lett. B 344, 225 (1995) arXiv:hep-ph/9409310]. S. Bergmann and A. Kagan, Nucl. Phys. B 538, 368 (1999) arXiv:hep-ph/9803305]. F. del Aguila, J. de Blas and M. Perez-Victoria, Phys. Rev. D 78 (2008) 013010 [arXiv:0803.4008 [hep-ph]]. E. Ma and A. Pramudita, Phys. Rev. D 24, 1410 (1981). P. Langacker and D. London, Phys. Rev. D 38, 907 (1988). D. Tommasini, G. Barenboim, J. Bernaben and C. Jarlskor, Nucl. Phys. B 444, 451 (1995) [arXiv:hep-ph/9503228]. M. Galeazzi, F. Fontanelli, F. Gatti and S. Vitale, Phys. Rev Lett. 86, 1978 (2001), K. H. Hiddemann, H. Daniel and O. Schwentker, J. Phys. G 21, 639 1995). E. Holzschuh, W. Kundig, L. Palermo, H. Stussi and P. Wenk, Phys. Lett. B 451, 247 (1999), E. Holzschuh, L. Palermo, H. Stussi and P. Wenk, Phys. Lett. B 482, 1 (2000) J. Deutsch, M. Lebrun and R. Prieels, Nucl. Phys. A 518, 149 (1990), H. O. Back et al. JETP Lett. 78, 261 (2003) [Pisma Zh. Eksp. Teor. Fiz. 78, 707 (2003)]. C. Hagner, M. Altmann, F. von Feilitzsch, L. Oberauer, Y. Declais and E. Kaifasz, Phys. Rev. D 52. 1343 (1995). D. I. Britton et al., Phys. Rev. Lett. 68, 3000 (1992); D. I. Britton et al., Phys. Rev. D 46, 885 (1992), P. Benes, A. Faessler, F. Simkovic and S. Kozalenko, Phys. Rev. D 71, 077901 (2005) [arXiv:hep-ph/0501295]. D. Berghofer et al., Proc. Inte Neutrino Physics and Astrophysics (Mau), Hawali, 1981), 67 (1981), eds. R. J. Cence, E. Ma and A. Roberts, Vol. II (University of Hawaii, Honolulu, HI, 1981); T. Yamazaki, Proc. 22nd Intern. Conf. on High-energy physics (Leipzig, 1984), 262 (1984), eds. A. Meyer and E. Wieczorek, Vol. I (Akademie der Wiessenachsften der DDR, Leipzig, 1984). G. Bernardi et al., Phys. Lett. B 203, 332 (1988). J. Badier et al. [NA3 Collaboration], Z. Phys. C 31, 21 (1986). F. Bergsma et al. [CHARM Collaboration], Phys. Lett. B 166, 473 (1986). P. Abreu et al. [DELPHI Collaboration], Z. Phys. C 74, 57 (1997) [Erratum-ibid. C 75, 580 (1997)]. O. Adriani et al. [L3 Collaboration], Phys. Lett. B 295, 371 (1992). G. Bélanger, F.



Laboratory Constraints

Beta decay:

Searches for kinks in electron beta decay spectra

$$E_e = \frac{M_i^2 + m_e^2 - (M_f + m_4)^2}{2M_i}$$

Sensitive for masses of 10 eV to 1 MeV Sensitive to mixing with electron neutrino

Peak Searches:

If heavy neutrino mixes with light ones it would modify the spectrum of leptons in meson decays For example, in pion and kaon decays a peak would appear

$$E_{\ell} = \frac{m_M^2 + m_{\ell}^2 - m_4^2}{2m_M}$$

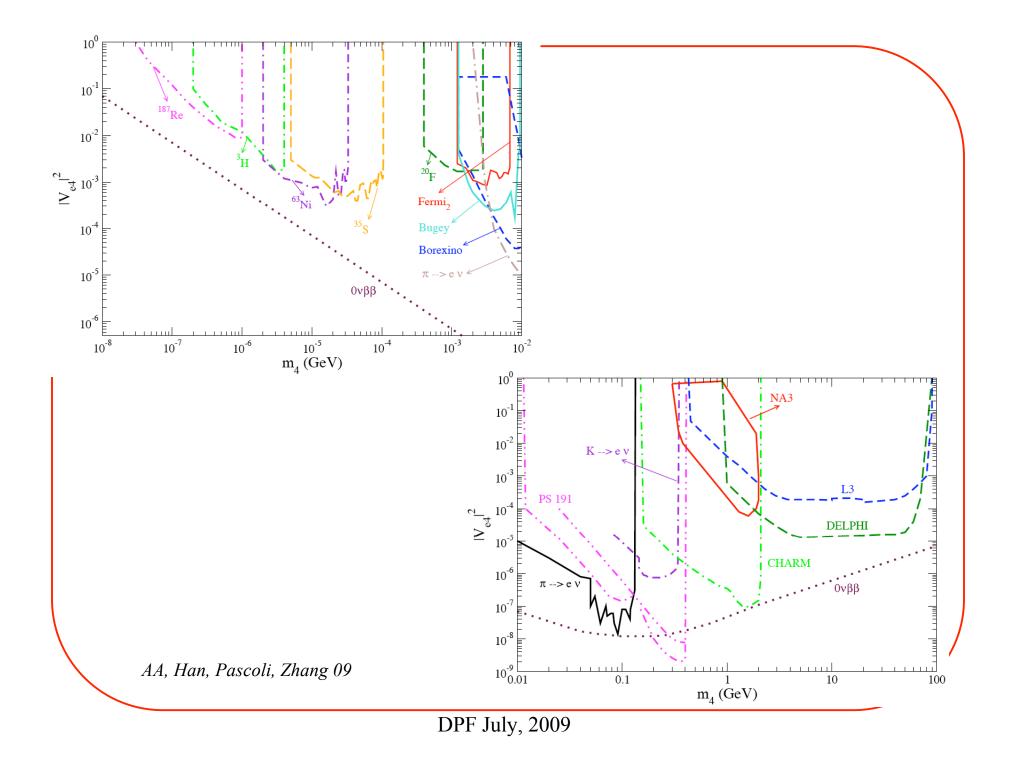
Laboratory Constraints

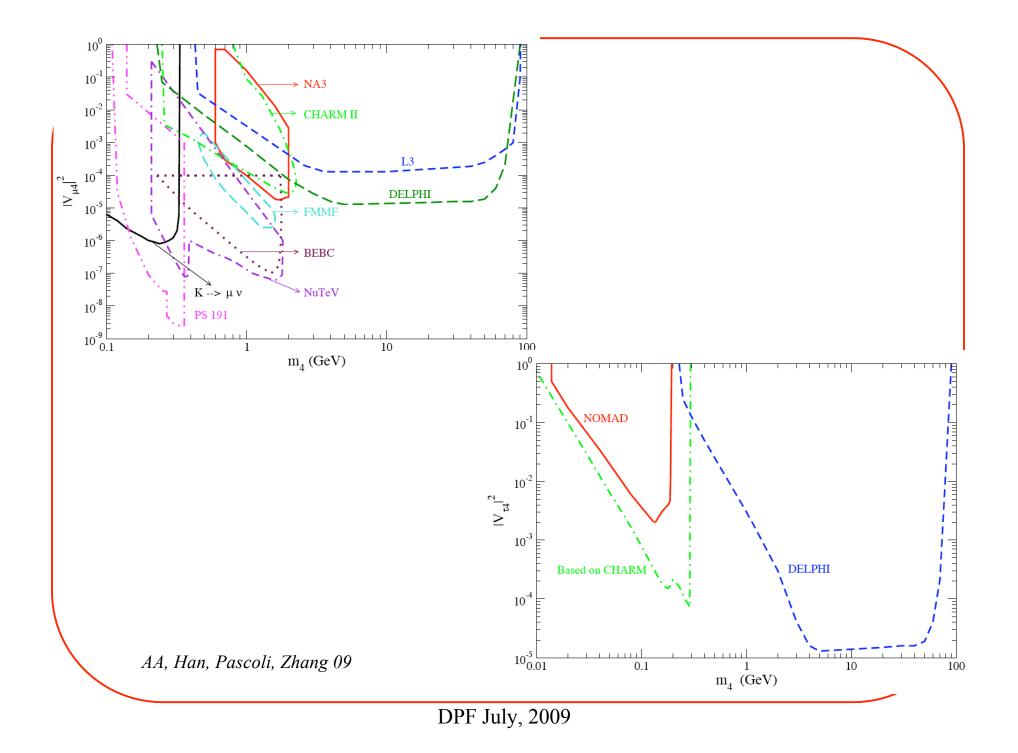
Decays

Heavy neutrino that mix with active ones are produced in colliders, beams, etc ~ $|V_{\ell 4}|^2$. The heavy neutrinos decay ~ $\Gamma_N(m_4, V_{l4})$ Look for SM decay products Example: $N \to e^+e^-\nu$, $N \to \pi^0\nu$

These bounds less reliable than peak searches. If non-SM decays exist the bounds can be weakened or evaded.

Present and future neutrino facilities can improve on these bounds due to large neutrino flux





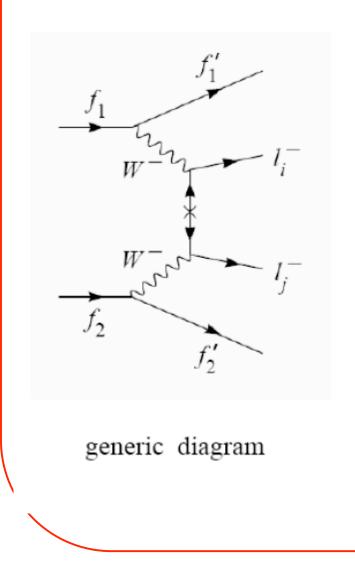
Other constraints

Precision electroweak tests $\sim 10^{-3}$ Fermi constant measured in muon decays, lepton universality, invisible Z decay width, etc

Lepton Flavor Violation, muon-electron conversion, mu to 3e

$$Br(\mu \to e\gamma) = \frac{3\alpha}{8\pi} \left| \sum_{m'} V_{em'} V_{\mu m'}^* g\left(\frac{m_{N_{m'}}^2}{m_W^2}\right) \right|^2$$
$$Br(\mu \to e\gamma) < 1.2 \times 10^{-11}$$
$$|V_{e4} V_{\mu 4}^*| < 0.015 \ (3.5 \times 10^{-4}) \ [1.2 \times 10^{-4}]$$
$$m_4 = 10 \ \text{GeV} \ (100 \ \text{GeV}) \ [1000 \ \text{GeV}]$$

Searches for Majorana Neutrinos



The transition rates are proportional to:

• for light neutrino

$$\langle m \rangle_{\ell_1 \ell_2}^2 = |\sum_i U_{\ell_1 i}^{\ell \nu} U_{\ell_2 i}^{\ell \nu} m_i|^2$$

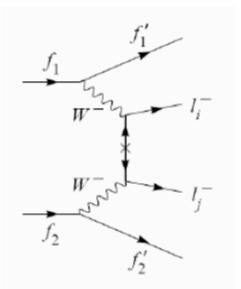
• for resonant neutrino production

$$\propto \frac{|V_{\ell_1 4}^{\ell N} V_{\ell_2 4}^{\ell N}|^2}{\Gamma_{\nu_4} m_4}$$

• for heavy neutrino

$$\left\langle m^{-1} \right\rangle_{\ell_1 \ell_2}^2 = \mid \frac{\sum_i V_{\ell_1 i}^{\ell N} V_{\ell_2 i}^{\ell N}}{m_{N_i}} \mid^2$$





$$\propto \langle m \rangle_{\ell_1 \ell_2}^2 = |\sum_i U_{\ell_1 i}^{\ell \nu} U_{\ell_2 i}^{\ell \nu} m_i|^2$$

We have six effective neutrino masses

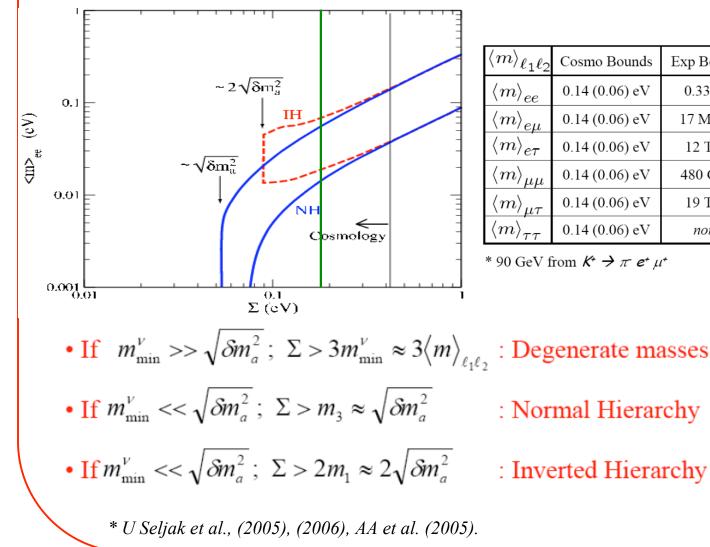
 $\langle m
angle_{ee}$: $0 \nu \beta \beta$, rare meson decay $\langle m
angle_{e au}$: au decay

 $\langle m \rangle_{e\mu}$: $\mu^- e^+$ conversion, rare meson decay $\langle m \rangle_{\mu\tau}$: τ decay

 $\langle m \rangle_{\mu\mu}$: μ - e+ conversion, rare meson decay $\langle m \rangle_{\tau\tau}$: none

<u>Cosmology bound :</u>

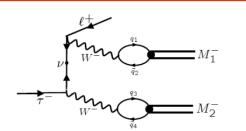
 $\Sigma \le 0.42 \ (0.17)^* \text{ eV} \text{ leads to } \langle m \rangle_{\ell,\ell_2} \le 0.14 \ (0.06) \text{ eV}$



$\langle m \rangle_{\ell_1 \ell_2}$	Cosmo Bounds	Exp Bounds	Experiment
$\langle m \rangle_{ee}$	0.14 (0.06) eV	0.33 eV	Ονββ
$\langle m angle_{e\mu}$	0.14 (0.06) eV	17 MeV*	μ^{-} - e ⁺ conversion
$\langle m \rangle_{e\tau}$	0.14 (0.06) eV	12 TeV	$\tau^{-} \rightarrow e^{+} \pi^{-} \pi^{-}$
$\langle m angle_{\mu\mu}$	0.14 (0.06) eV	480 GeV	$K^+ \rightarrow \pi^- \mu^+ \mu^+$
$\langle m angle_{\mu au}$	0.14 (0.06) eV	19 TeV	$\tau^{-} ightarrow \mu^{+} \pi^{-} \pi^{-}$
$\langle m \rangle_{\tau \tau}$	0.14 (0.06) eV	none	$B^{\scriptscriptstyle -} \to \mathrm{M}^{\scriptscriptstyle -} \: \tau^{\scriptscriptstyle +} \: \tau^{\scriptscriptstyle +}$

* 90 GeV from $k^* \rightarrow \pi^- e^* \mu^*$

Mixing element	Range of m_4 (MeV)	Decay mode	B_{exp}
	140 - 1637	$\tau^- \rightarrow e^+ \pi^- \pi^-$	2.7×10
$ V_{e4}V_{\tau 4} $	140 - 1637	$\tau^- \rightarrow e^+ \pi^- K^-$	1.8×10
	494 - 1283	$\tau^- \rightarrow e^+ K^- K^-$	1.5×10
	245 - 1637	$\tau^- \to \mu^+ \pi^- \pi^-$	0.7×10
$ V_{\mu4}V_{\tau4} $	245 - 1637	$\tau^- \to \mu^+ \pi^- K^-$	2.2×10
	599 - 1283	$\tau^- \to \mu^+ K^- K^-$	4.8×10
	140 - 493	$K^+ \rightarrow e^+ e^+ \pi^-$	6.4×10^{-10}
	140 - 1868	$D^+ \rightarrow e + e^+ \pi^-$	3.6×10^{-1}
	494 - 1868	$D^+ \rightarrow e^+ e^+ K^-$	4.5×10^{-1}
	140 - 1967	$D_s^+ \rightarrow e^+ e^+ \pi^-$	6.9×10^{-5}
$ V_{e4} ^2$	494 - 1967	$D_s^+ \rightarrow e^+ e^+ K^-$	6.3×10^{-5}
	140 - 5278	$B^+ \rightarrow e^+ e^+ \pi^-$	1.6×10^{-1}
	494 - 5278	$B^+ \rightarrow e^+ e^+ K^-$	1.0×10^{-1}
	776 - 5278	$B^+ \rightarrow e^+ e^+ \rho^-$	2.6×10^{-1}
	892 - 5278	$B^+ \rightarrow e^+ e^+ K^{*-}$	2.8×10^{-1}
	245 - 388	$K^+ \rightarrow \mu^+ \mu^+ \pi^-$	3.0×10^{-1}
	245 - 1763	$D^+ \rightarrow \mu^+ \mu^+ \pi^-$	4.8×10^{-1}
	599 - 1763	$D^+ \to \mu^+ \mu^+ K^-$	1.3×10^{-5}
	881 - 1763	$D^+ \rightarrow \mu^+ \mu^+ \rho^-$	5.6×10^{-5}
	997 - 1763	$D^+ \to \mu^+ \mu^+ K^{*-}$	8.5×10^{-5}
$ V_{\mu 4} ^2$	245 - 1862	$D_s^+ ightarrow \mu^+ \mu^+ \pi^-$	2.9×10^{-5}
	599 - 1862	$D_s^+ \to \mu^+ \mu^+ K^-$	1.3×10^{-5}
	997 - 1862	$D_s^+ \to \mu^+ \mu^+ K^{*-}$	1.4×10^{-1}
	245 - 5173	$B^+ \to \mu^+ \mu^+ \pi^-$	1.4×10^{-1}
	599 - 5173	$B^+ \to \mu^+ \mu^+ K^-$	1.8×10^{-5}
	881 - 5173	$B^+ \to \mu^+ \mu^+ \rho^-$	5.0×10^{-5}
	997 - 5173	$B^+ \to \mu^+ \mu^+ K^{*-}$	8.3×10^{-5}
	140 - 493	$K^+ \rightarrow e^+ \mu^+ \pi^-$	5.5×10^{-5}
	140 - 1868	$D^+ \rightarrow e^+ \mu^+ \pi^-$	5.0×10^{-5}
	494 - 1868	$D^+ \rightarrow e^+ \mu^+ K^-$	1.3×10^{-1}
	140 - 1862	$D_s^+ \to e^+ \mu^+ \pi^-$	7.3×10^{-1}
$ V_{e4}V_{\mu4} $	494 - 1967	$D_s^+ \to e^+ \mu^+ K^-$	6.8×10^{-5}
	140 - 5278	$B^+ \rightarrow e^+ \mu^+ \pi^-$	1.3×10^{-1}
	494 - 5278	$B^+ \to e^+ \mu^+ K^-$	2.0×10^{-1}
	776 - 5278	$B^+ \to e^+ \mu^+ \rho^-$	3.3×10^{-1}
	892 - 5278	$B^+ \to e^+ \mu^+ K^{*-}$	4.4×10^{-1}

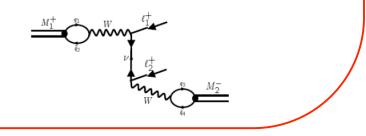


Rare decays of tau and mesons Mass ~ 100 MeV - 5 GeV Real particle, propagates before decaying May exit the detector before decaying

 $P = 1 - \exp(-L_{\exp}\Gamma_N)$

Limits weakened to

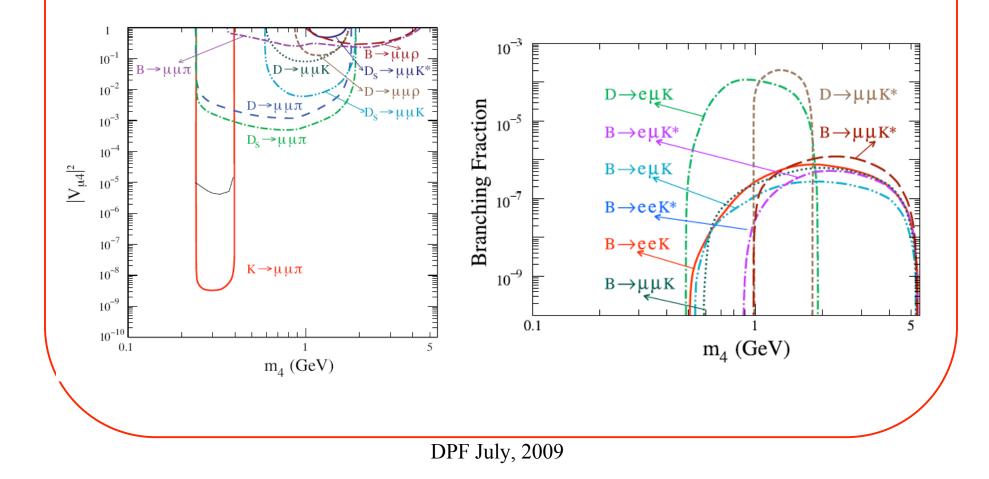
 $|V_{e4}V_{\tau4}| (= |V_{e4}|^2) = \sqrt{|V_{e4}|_{\infty}^2/(L_{\exp}\Gamma_{N0})},$



Lepton Number Violating Meson Decays $M_1^+ \rightarrow \ell_1^+ \ell_2^+ M_2^-$

The branching ratios can be approximated as

$$\begin{split} & \text{Br}(K) \sim |V_{M_1}^{CKM} V_{M_2}^{CKM}|^2 \ |V_{\ell_1 4} V_{\ell_2 4}|, \\ & \text{Br}(D, \ B) \sim 10^{-4} \ |V_{M_1}^{CKM} V_{M_2}^{CKM}|^2 \ |V_{\ell_1 4} V_{\ell_2 4}|, \\ & \text{Br}(D_s) \sim 10^{-5} \ |V_{M_1}^{CKM} V_{M_2}^{CKM}|^2 \ |V_{\ell_1 4} V_{\ell_2 4}|. \end{split}$$



Collider Searches of Heavy Neutrinos

• It was proposed :1

 $e^-e^- \rightarrow W^-W^-,$

but the $0\nu\beta\beta$ constraint on $|V_{e4}|^4\!/m_4^{-2}$ makes it impossible

• At HERA :2

 $e^{\pm}p \to \nu \ell^{\pm} \ell^{\pm} X,$

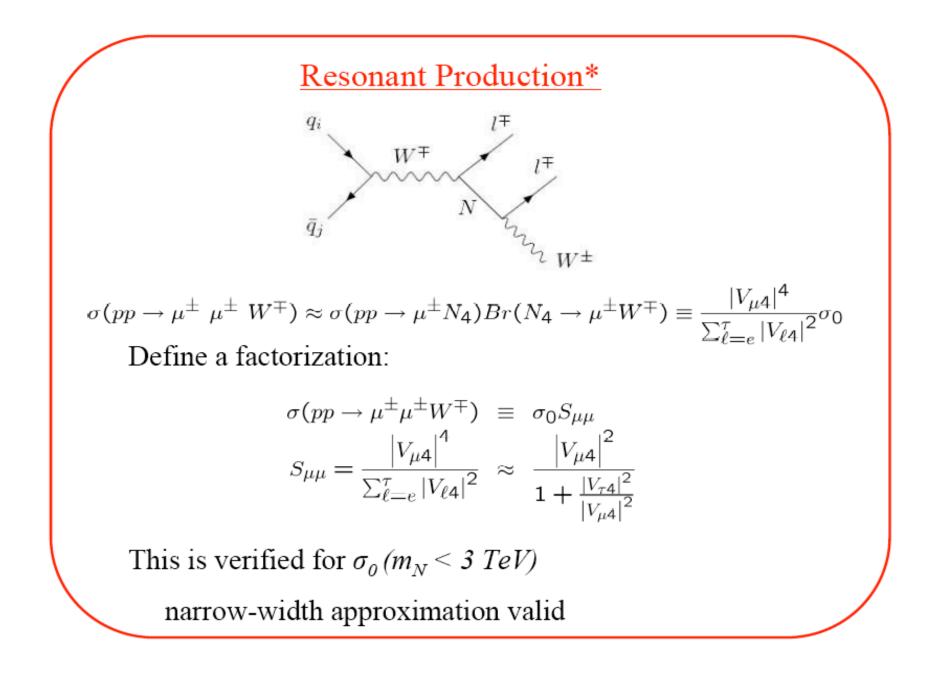
but leads to too weak a signal

• At hadron colliders :3

 $pp(\bar{p}) \to \ell^{\pm} \ell^{\pm} j j X,$

Rizzo (1982), Heusch (1994) 2. Rodejohann, Zuber (2000)
 Almeida et al. (2000), Ali et al. (2001)

*Keung, Senjanovic (1983); Dicus et al. (1991); A. Datta, M. Guchait, A. Pilaftsis (1993); ATLAS TDR (1999); F. Almeida et al. (2000); F. del Aguila et al. (2007).
[†]T. Han and B. Zhang, hep-ph/0604064, PRL (2006).



Phenomenological considerations

The Seesaw spirit:

If $D \sim y_{\nu}v$, $m_{\nu} \sim 1 \text{ eV}$, then $m_N \sim y_{\nu}^2$ (10¹⁴ GeV) $\Rightarrow \begin{cases} 10^{14} \text{ GeV for } y_{\nu} \sim 1; \\ 100 \text{ GeV for } y_{\nu} \sim 10^{-6}. \end{cases}$

 $U_{\ell m}^2 \sim V_{PMNS}^2 \approx \mathcal{O}(1); \ V_{\ell m}^2 \approx m_{\nu}/m_N.$

Still, it's possible for much lower Seesaw scales[†], and sizable mixing[‡]

All $U_{\ell m}$, Δm_{ν} are from oscillation experiments. But, we consider $V_{\ell m}$, m_N free parameters — hopefully, experimentally accessible.

The charged currents:

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} W^{+}_{\mu} \sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U^{*}_{\ell m} \,\overline{\nu_{m}} \gamma^{\mu} P_{L} \ell + h.c. \\ + \frac{g}{\sqrt{2}} W^{+}_{\mu} \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V^{*}_{\ell m'} \,\overline{N^{c}_{m'}} \gamma^{\mu} P_{L} \ell + h.c.$$

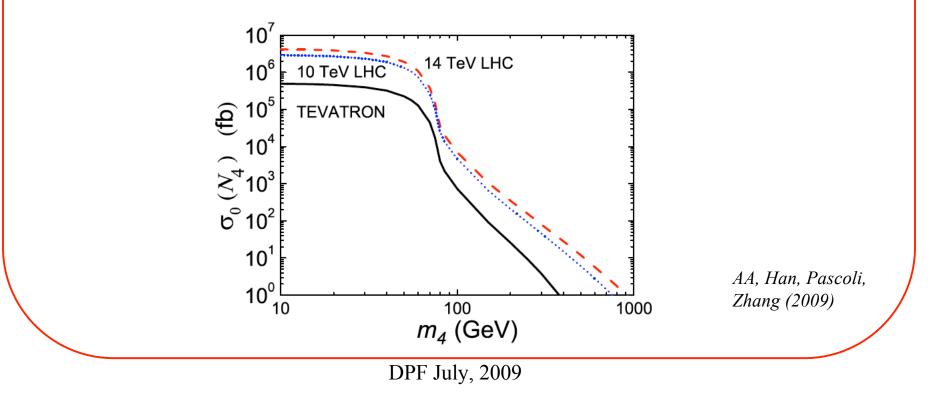
[†]Andrè de Gouvea (2005); Andrè de Gouvea, Jenkins, Vasudevan (2006); ... [‡]M.C. Gonzalez-Garcia, J.W.F. Valle (1989); Z.Z.Xing et al (2008)... Consider $p\overline{p}(pp) \rightarrow \mu^{\pm} \ \mu^{\pm} \ W^{\mp} \rightarrow \mu^{\pm} \mu^{\pm} jj$

A very clean channel :

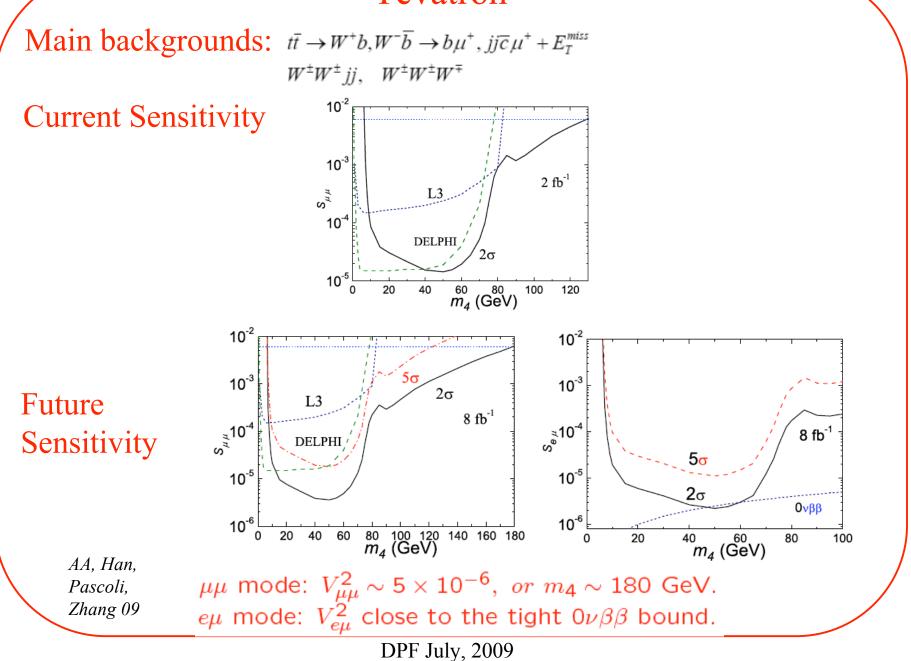
- · like-sign di-muons plus two jets
- no missing energies

•
$$m(jj) = M_W, m(jj\mu) = m_N$$

Bare cross sections (scaled by Sµµ)



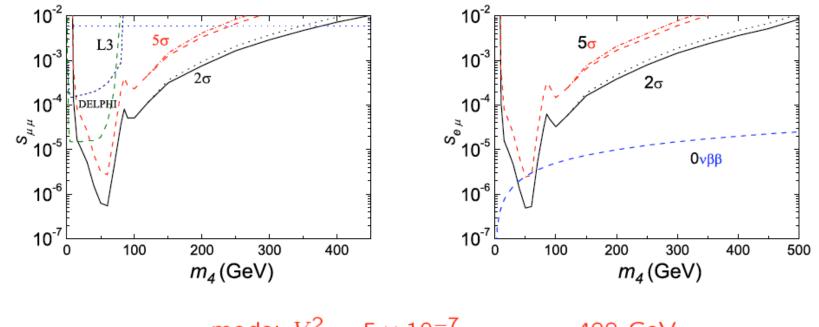
Tevatron



LHC

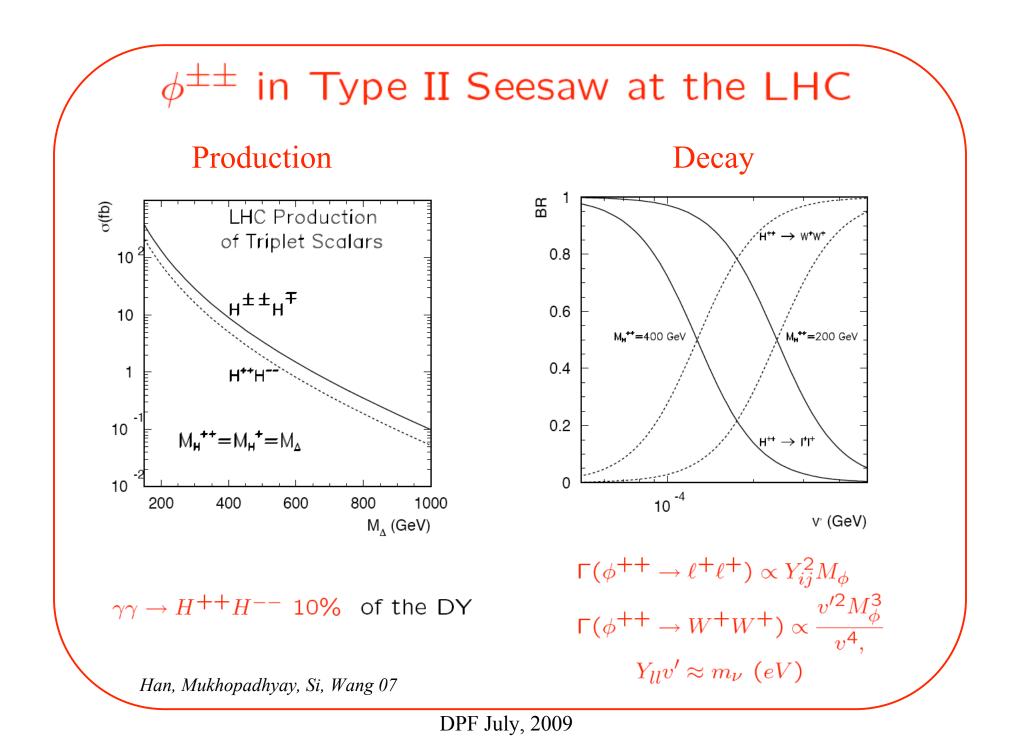
Main backgrounds: $t\bar{t} \rightarrow W^+b, W^-\bar{b} \rightarrow b\mu^+, jj\bar{c}\mu^+ + E_T^{miss}$ $W^{\pm}W^{\pm}jj, W^{\pm}W^{\mp}W^{\mp}$

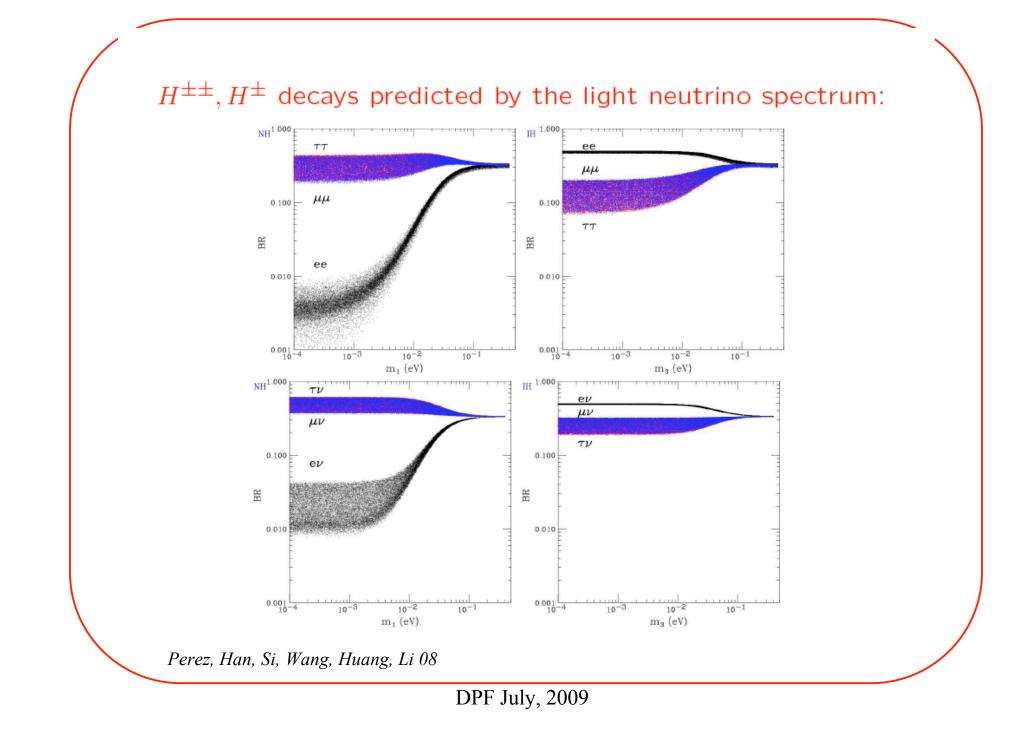
Sensitivity

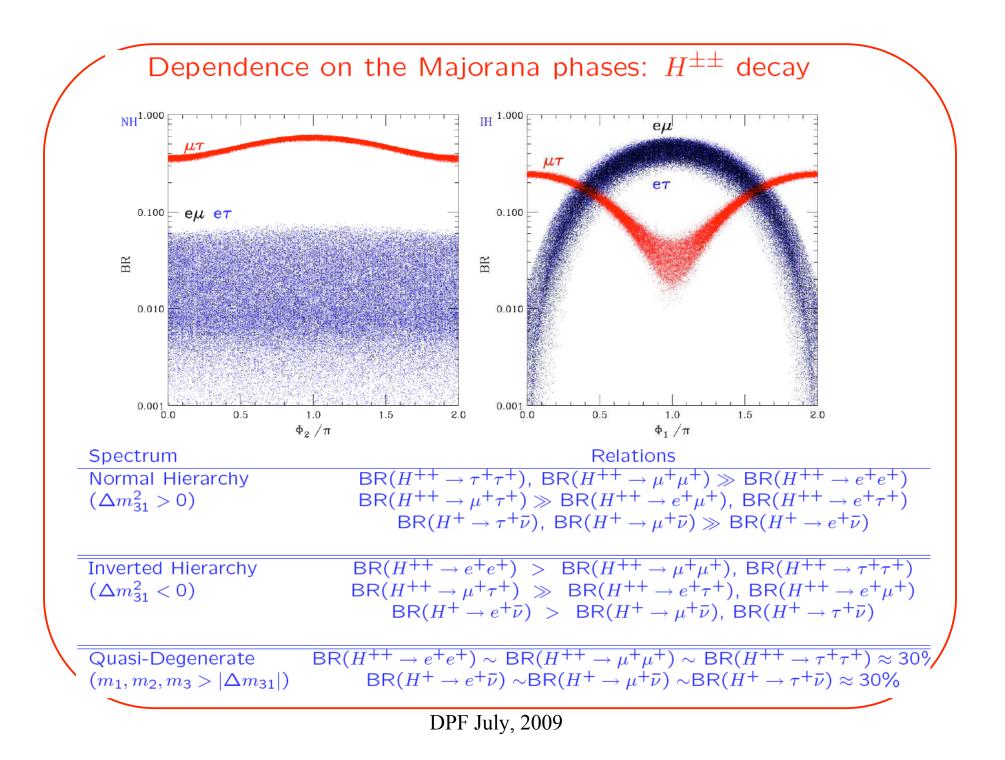


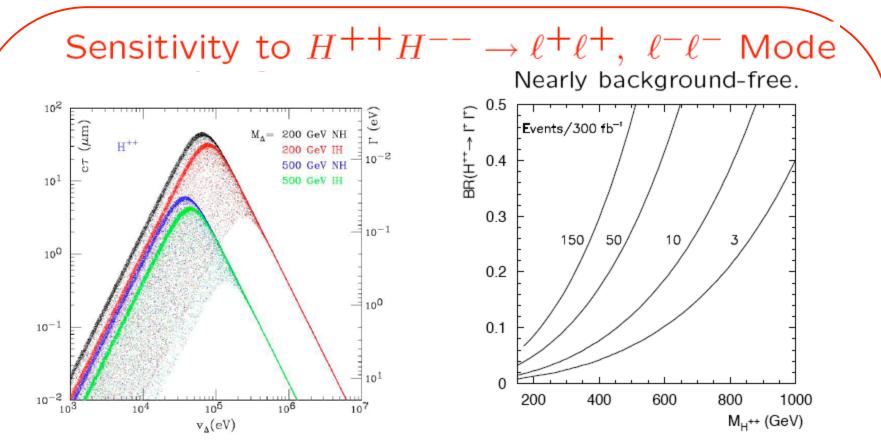
 $\mu\mu$ mode: $V_{\mu\mu}^2 \sim 5 \times 10^{-7}$, or $m_4 \sim 400$ GeV. $e\mu$ mode: $V_{e\mu}^2$ below $0\nu\beta\beta$ bound at $m_4 \sim M_W$.

AA, Han, Pascoli, Zhang 09, A-Saavedra et al.



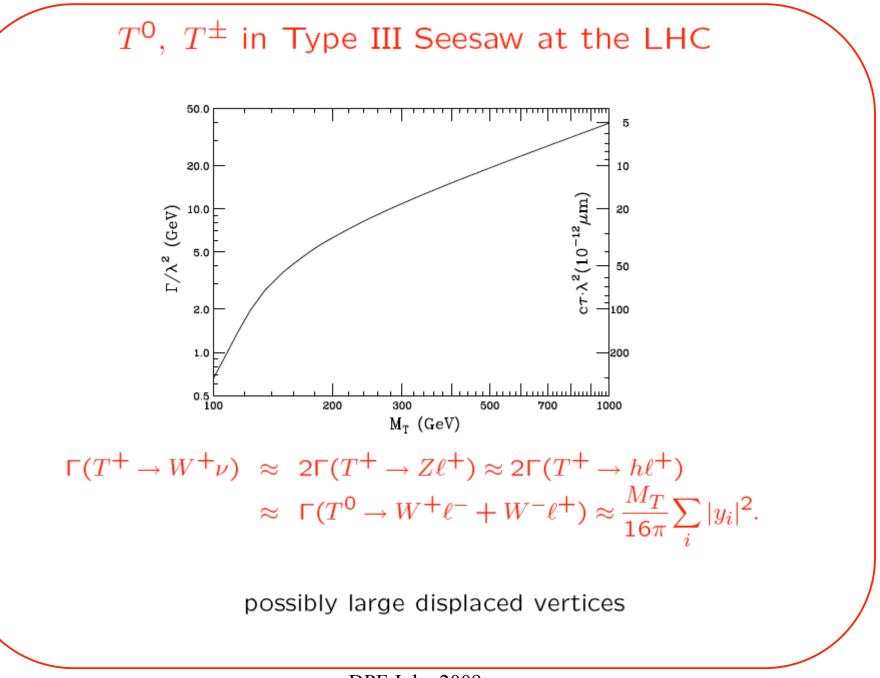


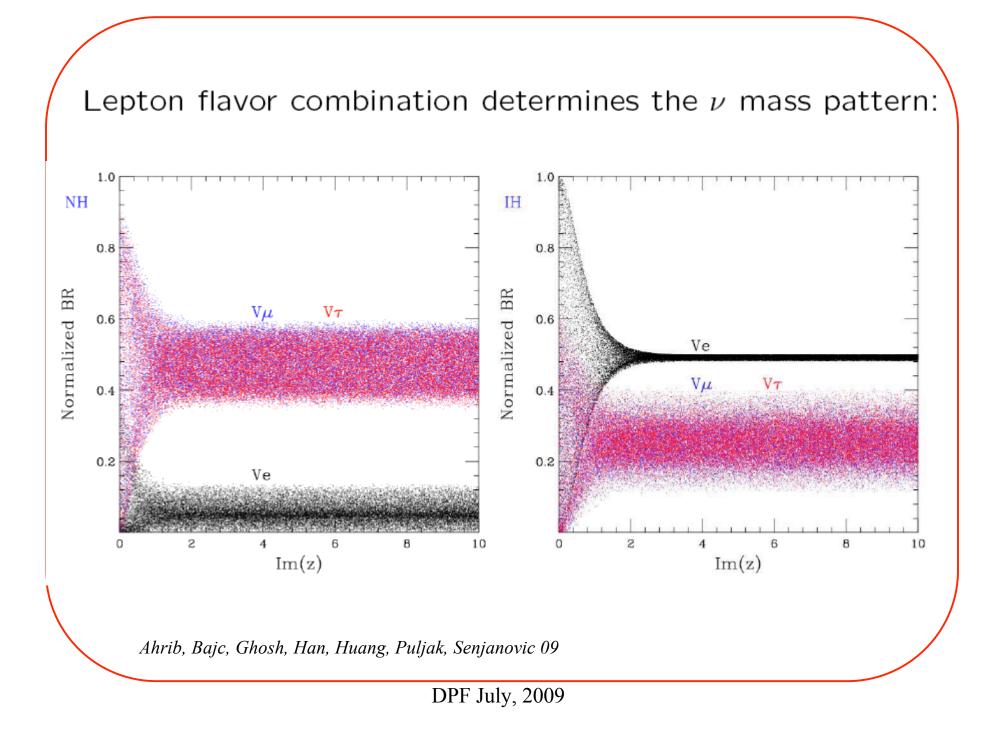


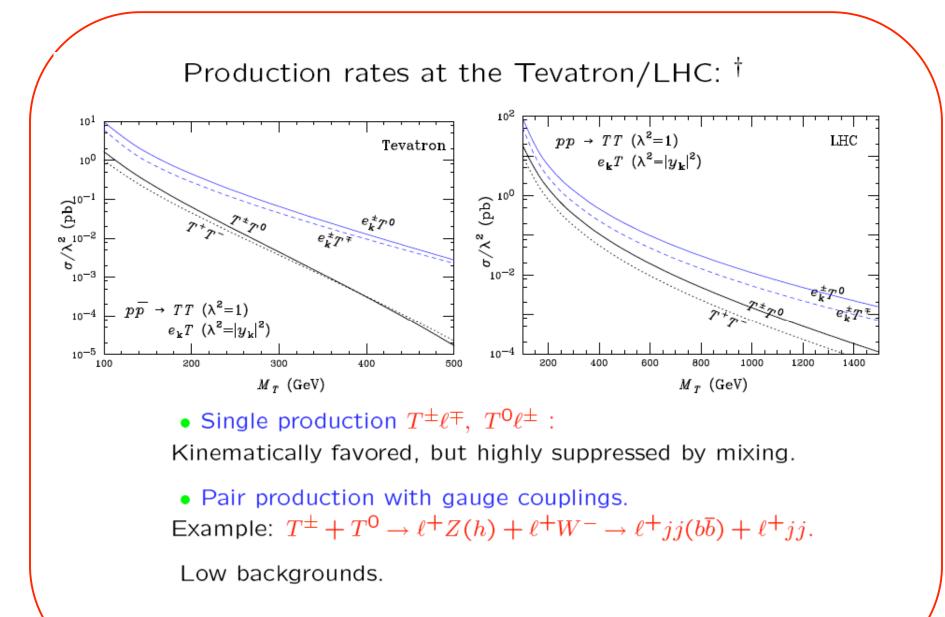


 $H^{\pm\pm}$, H^{\pm} decay promptly: $H^{++} \rightarrow \ell^+ \ell^+$, W^+W^+ complementary. May reach 20 – 40 μ m, leading to displaced vertices.

With 300 fb⁻¹ integrated luminosity, a coverage upto $M_{H^{++}} \sim 1$ TeV even with $BR \sim 40 - 50\%$. Possible measurements on BR's.







Thanks to T.Han

Summary

- Important to test the Dirac or Majorana nature of neutrinos Need lepton number violating processes
- For light neutrinos, neutrinoless double beta decay may be the only hope if $m_{\nu} \sim \sqrt{\Delta m_a^2} \sim 0.05 \text{ eV}$
- For a heavy neutrino, sensitivity at Tevatron 10 GeV < m_4 < 100 GeV, $10^{-4} < |V_{\mu4}|^2 < 10^{-2}$; LHC 10 GeV < m_4 < 400 GeV, $10^{-6} < |V_{\mu4}|^2 < 10^{-2}$;
- For scalar triplets (Type II seesaw)
 LHC reach M_φ ~ 600 − 1000 GeV (ℓ[±]ℓ[±] or W[±]W[±])
 Distinguish normal/inverted hierarchy, Probe Majorana phases
- For lepton triplets(Type III seesaw)
 - LHC reach $M_T \sim 800 \text{ GeV}$

Probe normal/inverted hierarchy

Many places to look, many things to discover - exciting times!!