Testing Neutrino Physics at Colliders

(and other experiments)*

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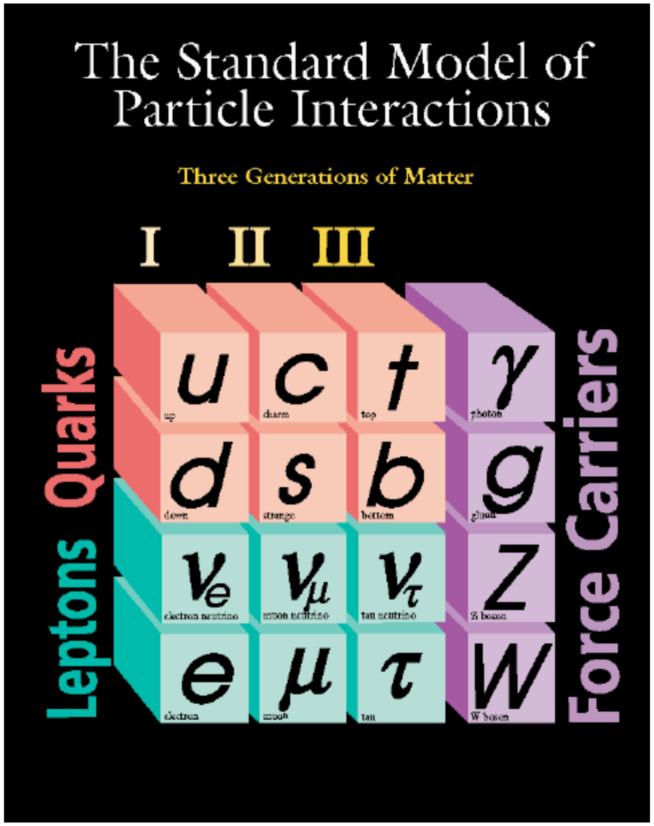
Fermilab

*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 *<1eV to 175 GeV*

Dark matter

Matter anti-matter asymmetry

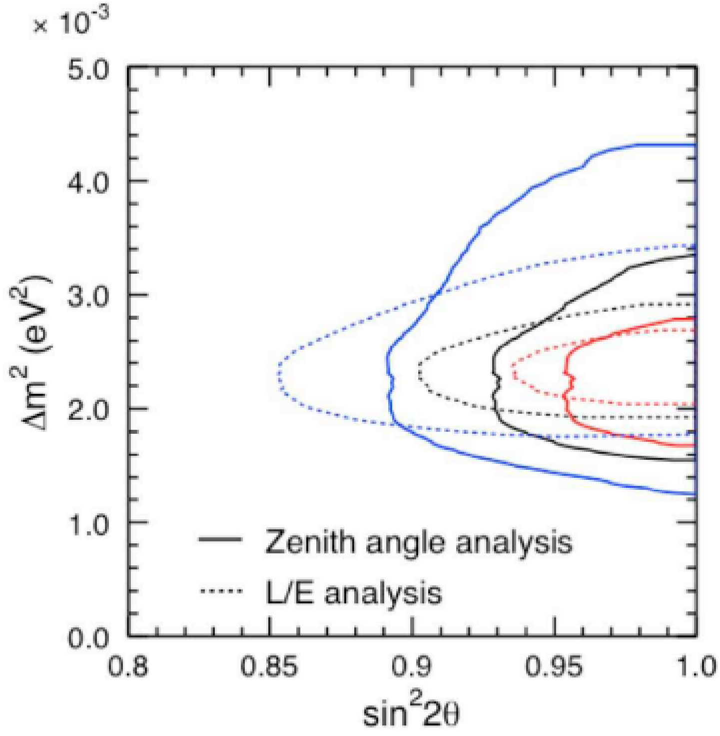
Dark energy ……

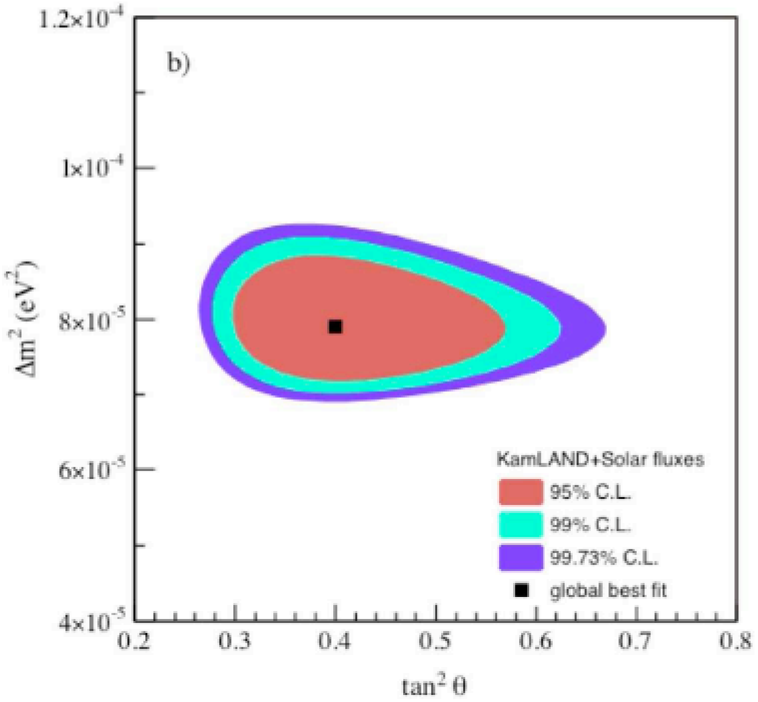
Collider Experiments (and others) will shed light on these questions

Outline

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

Neutrinos are massive

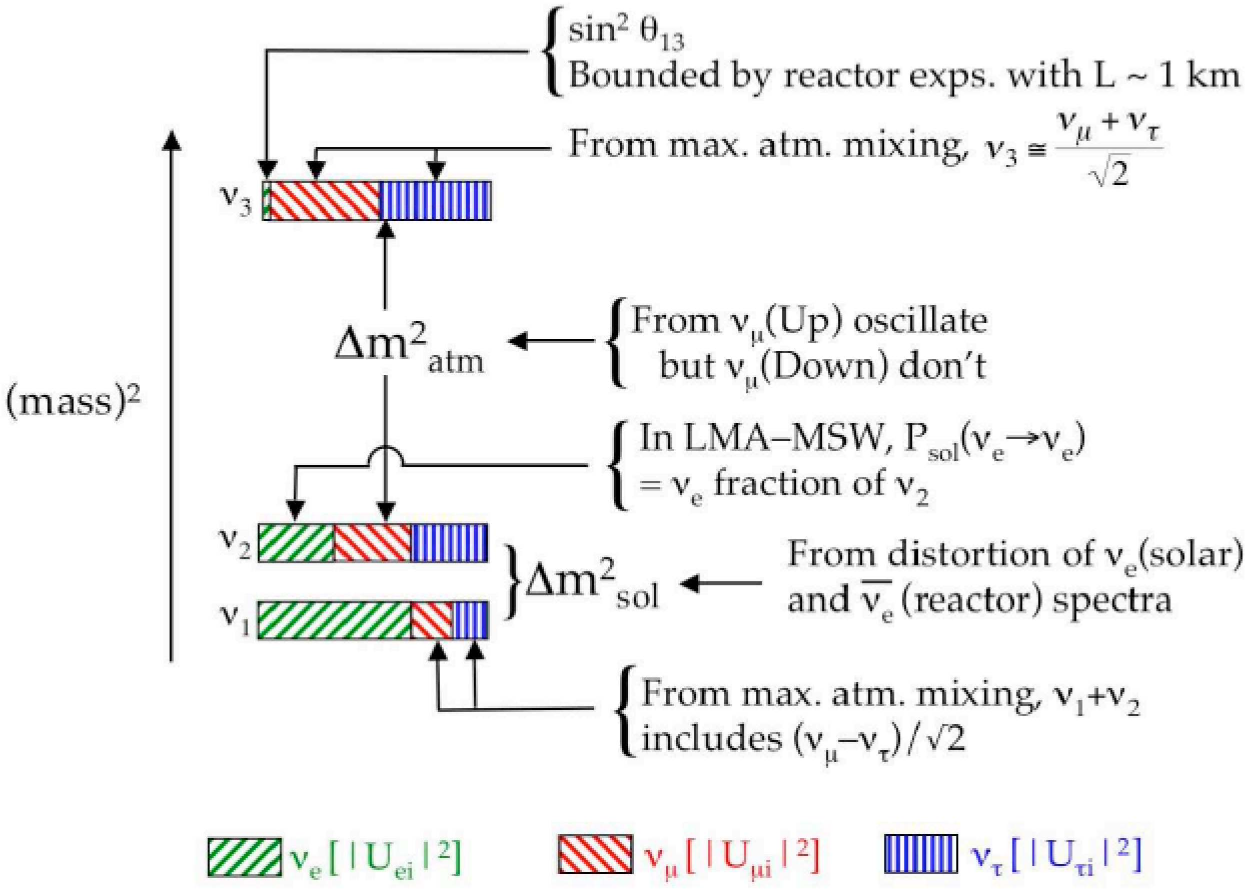




$$1.9 \times 10^{-3}\ \mathrm{eV}^2 < \quad \Delta m^2_{atm} \quad < 3.0 \times 10^{-3}\ \mathrm{eV}^2$$

$$7.4 \times 10^{-5}\ \mathrm{eV}^2 < \quad \Delta m^2_{sol} \quad < 8.6 \times 10^{-5}\ \mathrm{eV}^2.$$

The mass relation and flavor components:*



$\sin^2\theta_{13}$
Bounded by reactor exps. with L ~ 1 km

From max. atm. mixing, $\nu_3 \cong \frac{\nu_\mu + \nu_\tau}{\sqrt{2}}$

ν_3

Δm^2_{atm}

From ν_μ(Up) oscillate
but ν_μ(Down) don't

$(\text{mass})^2$

In LMA–MSW, $P_{sol}(\nu_e \rightarrow \nu_e)$
$= \nu_e$ fraction of ν_2

ν_2

ν_1

Δm^2_{sol}

From distortion of ν_e(solar)
and $\overline{\nu}_e$ (reactor) spectra

From max. atm. mixing, $\nu_1 + \nu_2$
includes $(\nu_\mu - \nu_\tau)/\sqrt{2}$

▨ $\nu_e\ [\,|U_{ei}|^2]$ ▨ $\nu_\mu\ [\,|U_{\mu i}|^2]$ ▥ $\nu_\tau\ [\,|U_{\tau i}|^2]$

* Kayser

We also know…….

- There are only three "active" light neutrinos
  $N_\nu = 2.984 \pm 0.008$, from Z pole at LEP-1.

- Direct lab bound: $m_\beta < 2.2$ eV
  from Tritium beta decay

- $\Sigma\, m\nu_i < 0.17 - 1$ eV
  from WMAP, SDSS (Lyα spectra), SNIa.

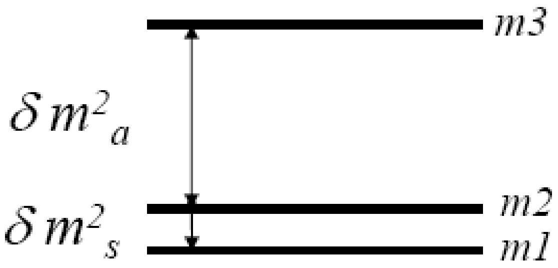
- The absence of neutrinoless double beta decay
  bound on Majorana mass $\langle m \rangle_{ee} < 1$ eV

- Absolute mass scale ?

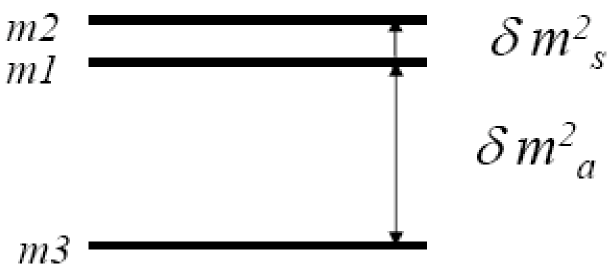
$$\Sigma = m_1 + m_2 + m_3$$

$$\begin{aligned} \delta m_a^2 &= m_3^2 - m_1^2 \\ \delta m_s^2 &= m_2^2 - m_1^2 \end{aligned}$$

- Hierarchy – inverted or normal?



Normal



Inverted

- Dirac or Majorana?

Neutrino Masses : Dirac vs Majorana

Simplest extension of the SM:

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

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

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

Then, the full neutrino mass terms read

$$\frac{1}{2}\left(\overline{\nu_L}\quad \overline{N^c{}_L}\right)\begin{pmatrix} 0_{3\times 3} & m^{\nu}_{3\times n} \\ m^{\nu T}_{n\times 3} & B_{n\times n} \end{pmatrix}\begin{pmatrix} \nu^c{}_R \\ N_R \end{pmatrix} + h.c.$$

The diagonalized masses read

$$-\mathcal{L}_m^\nu = \frac{1}{2}\left(\sum_{m=1}^{3} m_m^\nu\; \overline{\nu_{mL}}\; \nu^c_{mR} + \sum_{m'=4}^{3+n} M^N_{m'}\; \overline{N^c_{m'L}}\; N_{m'R}\right) + \text{h.c.}$$

Leads to Majorana neutrinos

$$\nu_{aL} = \sum_{m=1}^{3} U_{am}\nu_{mL} + \sum_{m'=4}^{3+n} V_{am'} N^c_{m'L}$$

$$m_\nu \approx \frac{D^2}{M}, \quad m_N \approx M,$$

$$N^c_{bL} = \sum_{m=1}^{3} X_{bm}\nu_{mL} + \sum_{m'=4}^{3+n} Y_{bm'} N^c_{m'L}$$

$$UU^\dagger \approx I\ (PMNS), \quad VV^\dagger \approx \frac{m_\nu}{m_N}.$$

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

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:

$$\mu H^T (i\sigma_2) \Phi^\dagger H + h.c.$$

predicts

$$v' = \mu \, \frac{v^2}{M_\phi^2},$$

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:[†]

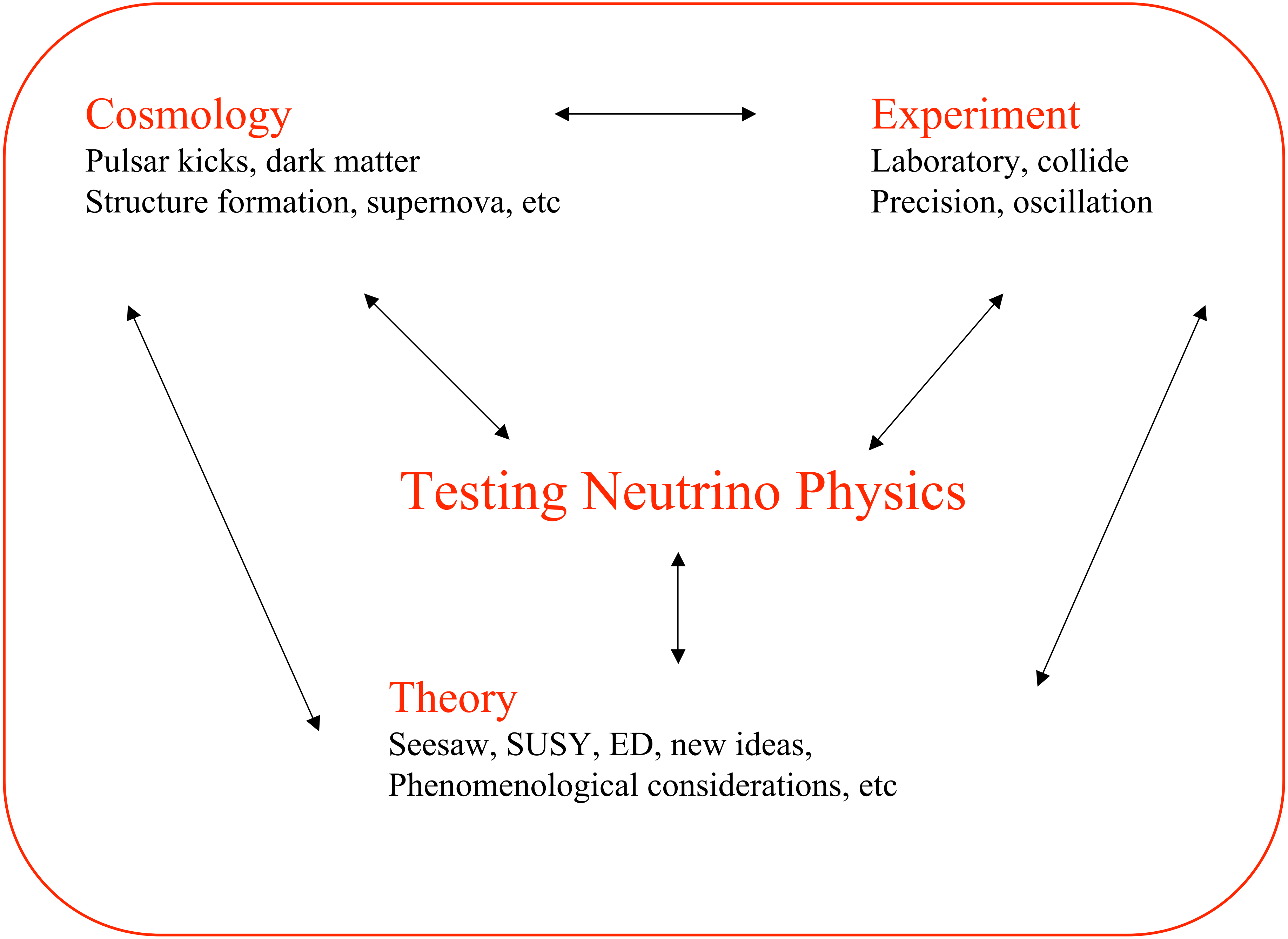
$$y_j \lesssim 10^{-6},$$

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

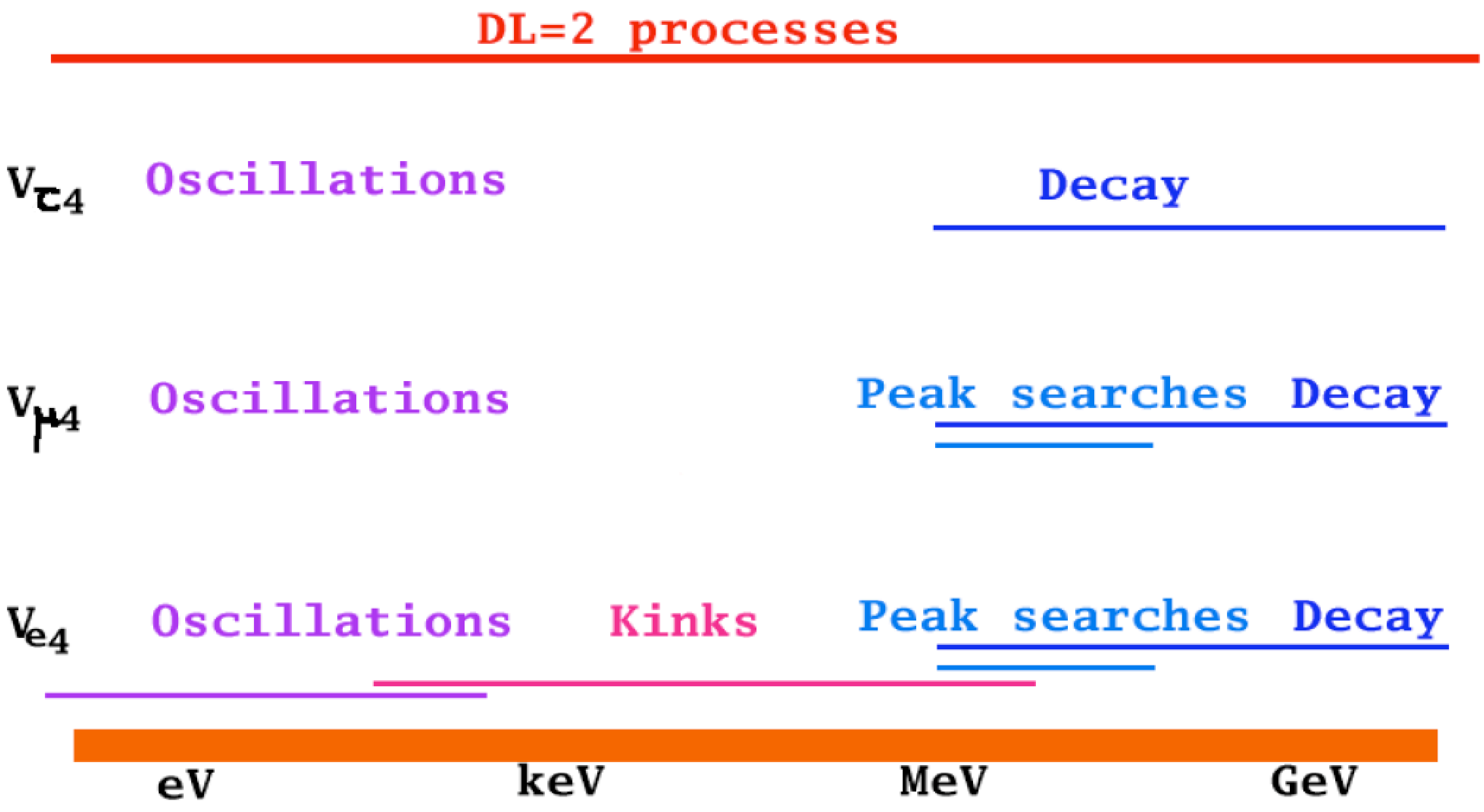
Theory
Seesaw, SUSY, ED, new ideas,
Phenomenological considerations, etc

**** The fine print ****

- non-oscillation experiments
- samples only
- reference omission – see fine print

Laboratory Constraints

The search for heavy Majorana neutrinos depends on mass



DL=2 processes

$\nu_{\tau 4}$ Oscillations Decay

$\nu_{\mu 4}$ Oscillations Peak searches Decay

ν_{e4} Oscillations Kinks Peak searches Decay

eV keV MeV GeV

Thanks to s.pascoli for graphic

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 ~ $|V_{\ell 4}|^2$

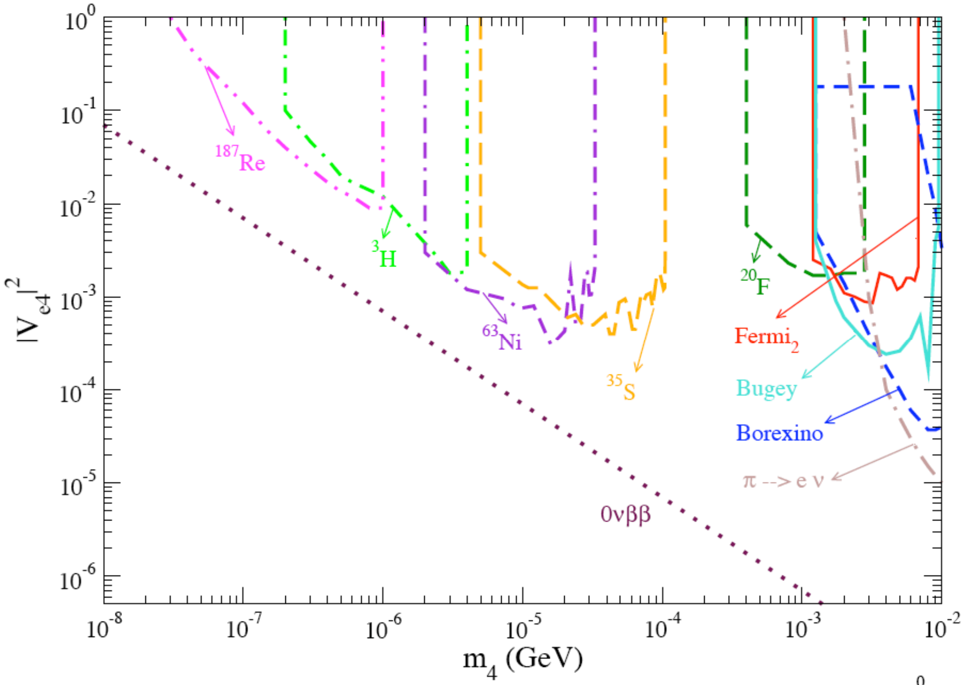
The heavy neutrinos decay ~$\Gamma_N(m_4, V_{l4})$

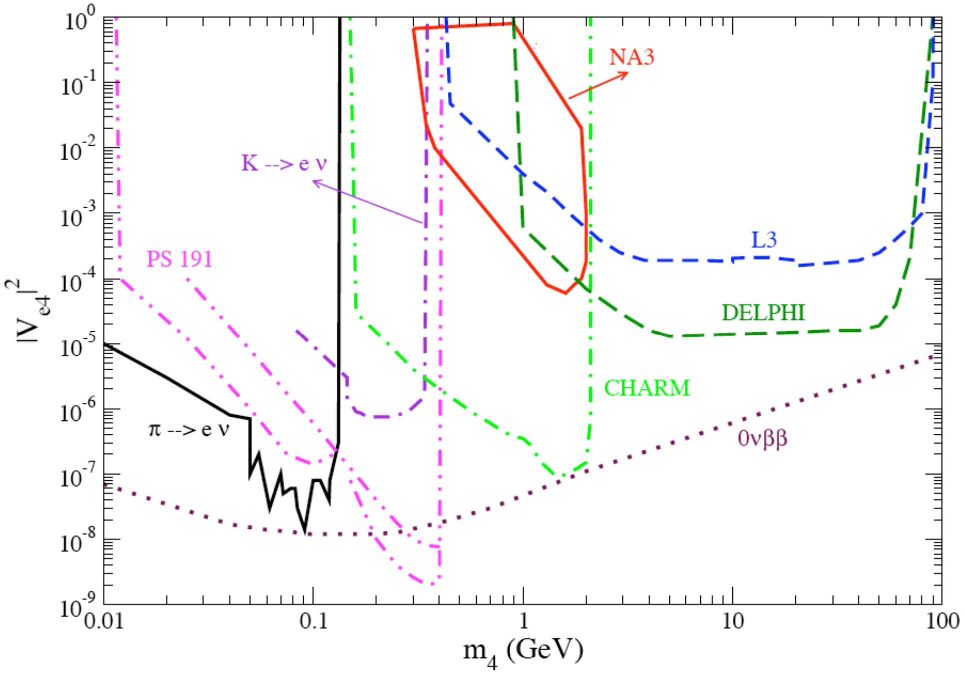
Look for SM decay products

Example: $N \to e^+e^-\nu, N \to \pi^0\nu$

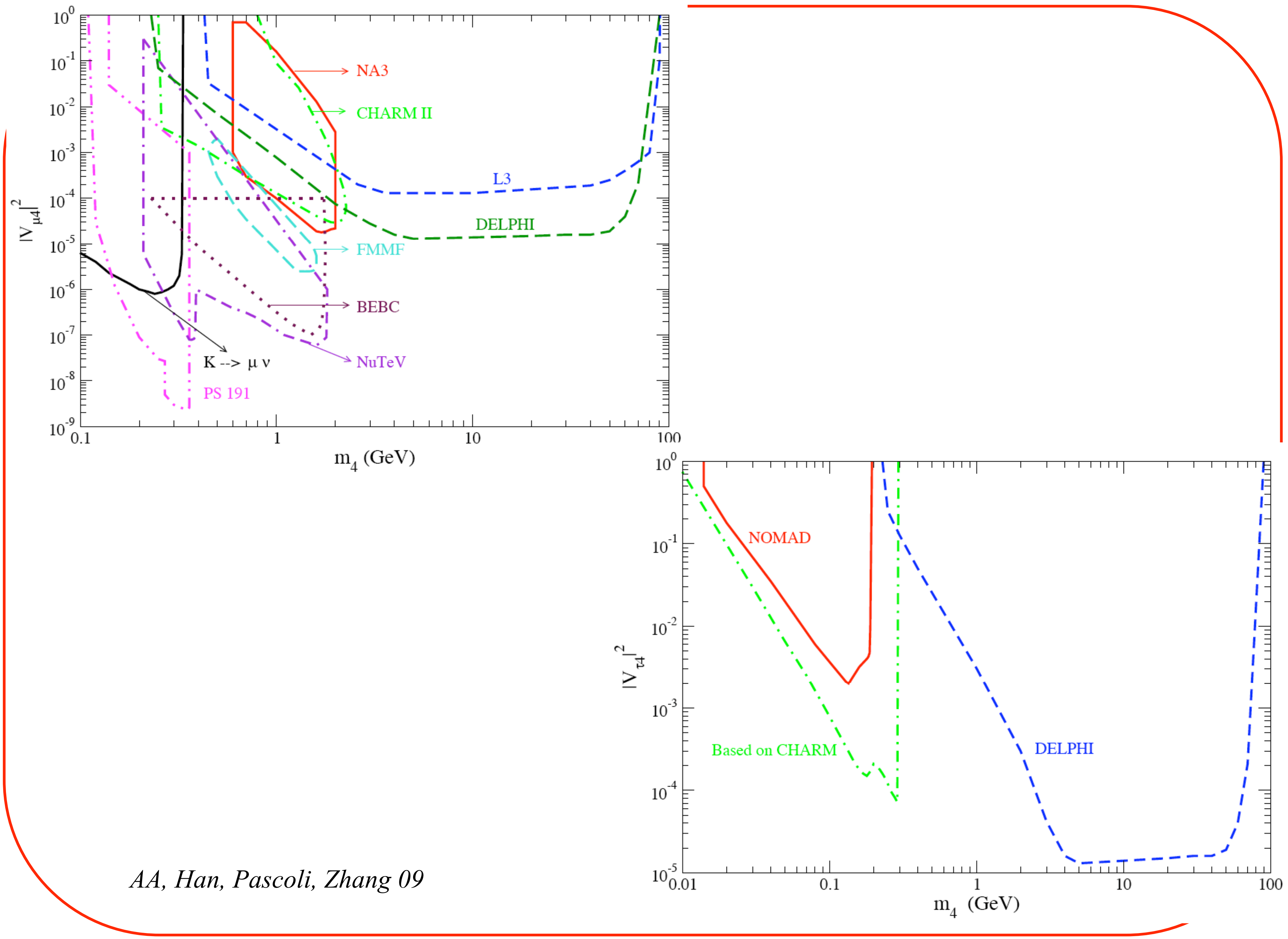
These bounds less reliable than peak searches. If non-SM decays exist the bounds can be weakened or evaded.

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





AA, Han, Pascoli, Zhang 09



AA, Han, Pascoli, Zhang 09

Other constraints

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

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

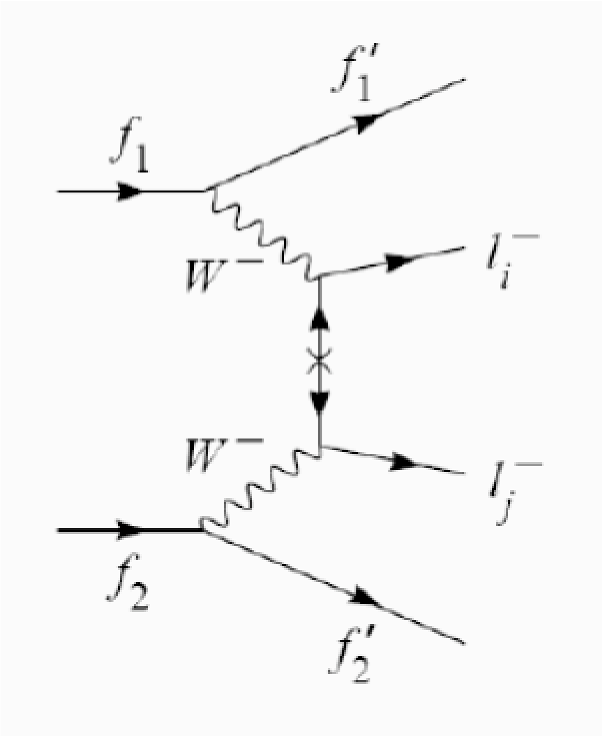
$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{8\pi}\left|\sum_{m'} V_{em'}V^*_{\mu m'}\; g\left(\frac{m^2_{N_{m'}}}{m^2_W}\right)\right|^2$$

$$\mathrm{Br}(\mu \to e\gamma) < 1.2 \times 10^{-11}$$

$$|V_{e4}V^*_{\mu 4}| < 0.015 \;\; (3.5 \times 10^{-4}) \;\; [1.2 \times 10^{-4}]$$

$$m_4 = 10 \text{ GeV} \;\; (100 \text{ GeV}) \;\; [1000 \text{ GeV}]$$

Searches for Majorana Neutrinos



generic diagram

The transition rates are proportional to:

- for light neutrino

$$\langle m\rangle^2_{\ell_1\ell_2} = |\sum_i U^{\ell\nu}_{\ell_1 i}U^{\ell\nu}_{\ell_2 i}m_i|^2$$

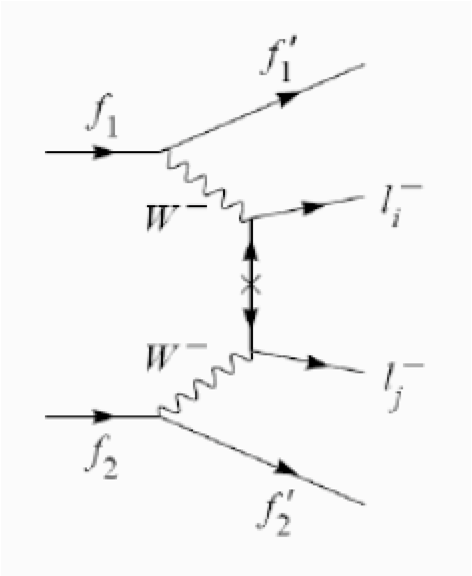
- for resonant neutrino production

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

- for heavy neutrino

$$\left\langle m^{-1}\right\rangle^2_{\ell_1\ell_2} = \left|\frac{\sum_i V^{\ell N}_{\ell_1 i}V^{\ell N}_{\ell_2 i}}{m_{N_i}}\right|^2$$

Three Light (active) Majorana Neutrinos



$$\propto \langle m \rangle^2_{\ell_1 \ell_2} = \left| \sum_i U^{\ell\nu}_{\ell_1 i} U^{\ell\nu}_{\ell_2 i} m_i \right|^2$$

We have six effective neutrino masses

$\langle m \rangle_{ee}$: 0νββ , rare meson decay

$\langle m \rangle_{e\mu}$: μ⁻ e⁺ conversion, rare meson decay

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

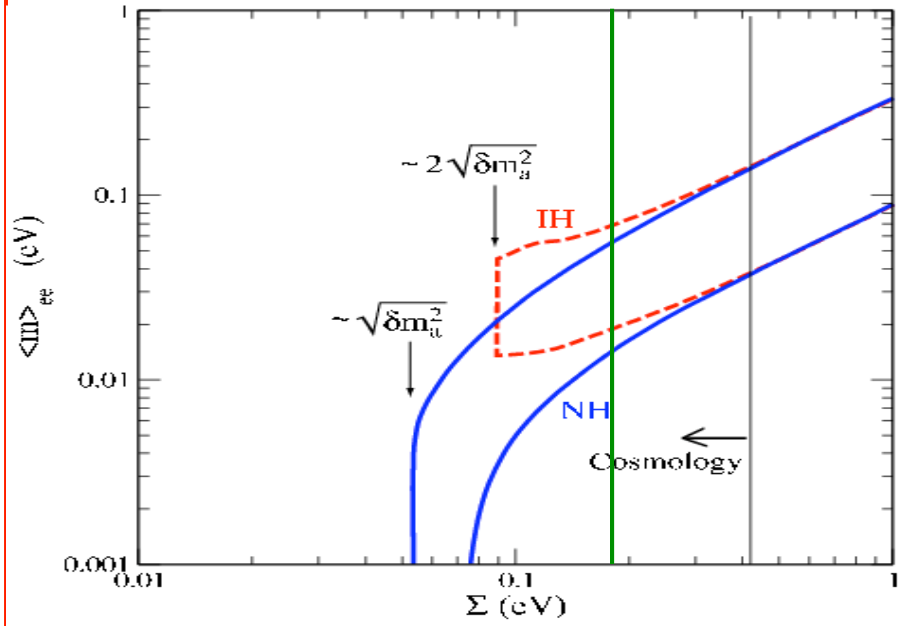
$\langle m \rangle_{e\tau}$: τ decay

$\langle m \rangle_{\mu\tau}$: τ decay

$\langle m \rangle_{\tau\tau}$: none

Cosmology bound :

$\Sigma \leq 0.42\ (0.17)^*$ eV leads to $\langle m \rangle_{\ell_1 \ell_2} \leq 0.14\ (0.06)$ eV

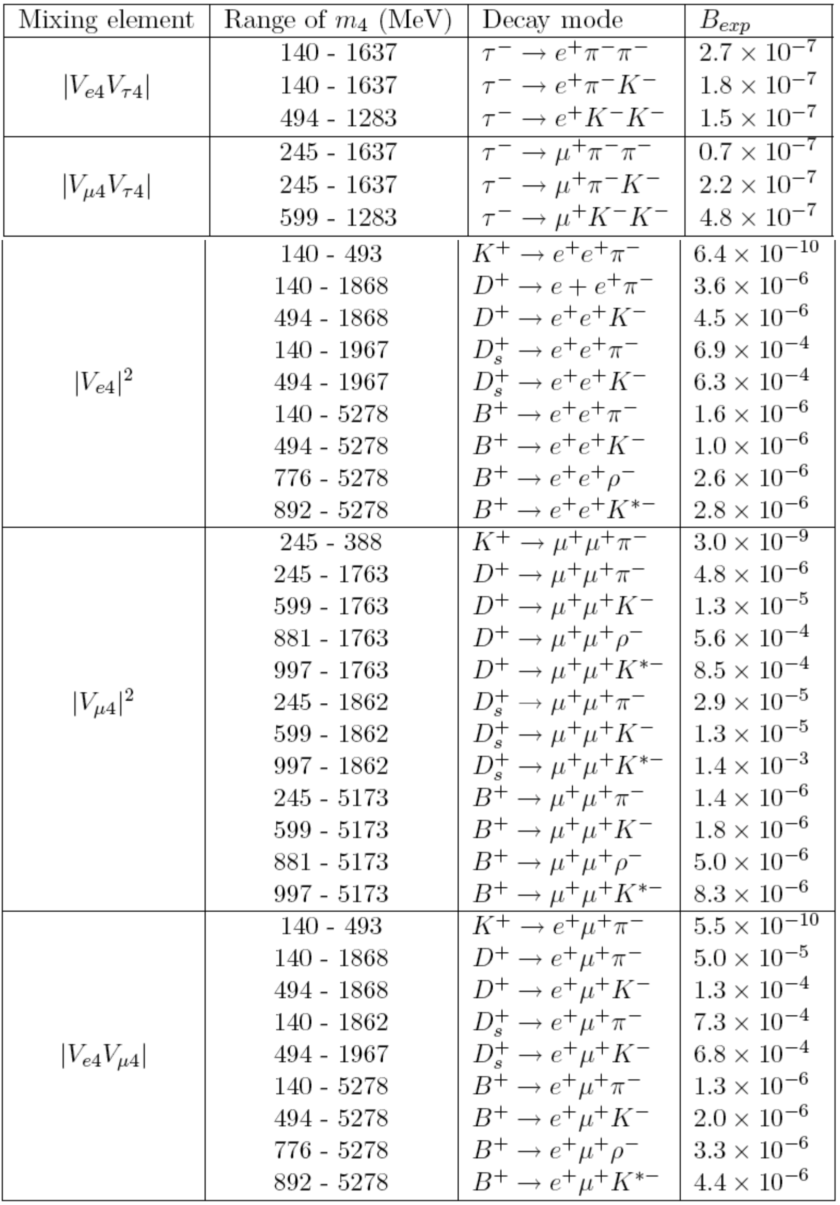


$\langle m \rangle_{\ell_1 \ell_2}$	Cosmo Bounds	Exp Bounds	Experiment
$\langle m \rangle_{ee}$	0.14 (0.06) eV	0.33 eV	$0\nu\beta\beta$
$\langle m \rangle_{e\mu}$	0.14 (0.06) eV	17 MeV*	$\mu^- - e^+$ conversion
$\langle m \rangle_{e\tau}$	0.14 (0.06) eV	12 TeV	$\tau^- \to e^+ \pi^- \pi^-$
$\langle m \rangle_{\mu\mu}$	0.14 (0.06) eV	480 GeV	$K^+ \to \pi^- \mu^+ \mu^+$
$\langle m \rangle_{\mu\tau}$	0.14 (0.06) eV	19 TeV	$\tau^- \to \mu^+ \pi^- \pi^-$
$\langle m \rangle_{\tau\tau}$	0.14 (0.06) eV	*none*	$B^- \to M^- \tau^+ \tau^+$

* 90 GeV from $K^+ \to \pi^- e^+ \mu^+$

- If $m^{\nu}_{\min} >> \sqrt{\delta m_a^2}$; $\Sigma > 3m^{\nu}_{\min} \approx 3\langle m \rangle_{\ell_1 \ell_2}$: Degenerate masses
- If $m^{\nu}_{\min} << \sqrt{\delta m_a^2}$; $\Sigma > m_3 \approx \sqrt{\delta m_a^2}$: Normal Hierarchy
- If $m^{\nu}_{\min} << \sqrt{\delta m_a^2}$; $\Sigma > 2m_1 \approx 2\sqrt{\delta m_a^2}$: Inverted Hierarchy

* *U Seljak et al., (2005), (2006), AA et al. (2005).*



Mixing element	Range of m_4 (MeV)	Decay mode	B_{exp}
$\lvert V_{e4}V_{\tau 4}\rvert$	140 - 1637	$\tau^- \to e^+\pi^-\pi^-$	2.7×10^{-7}
	140 - 1637	$\tau^- \to e^+\pi^-K^-$	1.8×10^{-7}
	494 - 1283	$\tau^- \to e^+K^-K^-$	1.5×10^{-7}
$\lvert V_{\mu 4}V_{\tau 4}\rvert$	245 - 1637	$\tau^- \to \mu^+\pi^-\pi^-$	0.7×10^{-7}
	245 - 1637	$\tau^- \to \mu^+\pi^-K^-$	2.2×10^{-7}
	599 - 1283	$\tau^- \to \mu^+K^-K^-$	4.8×10^{-7}
$\lvert V_{e4}\rvert^2$	140 - 493	$K^+ \to e^+e^+\pi^-$	6.4×10^{-10}
	140 - 1868	$D^+ \to e + e^+\pi^-$	3.6×10^{-6}
	494 - 1868	$D^+ \to e^+e^+K^-$	4.5×10^{-6}
	140 - 1967	$D_s^+ \to e^+e^+\pi^-$	6.9×10^{-4}
	494 - 1967	$D_s^+ \to e^+e^+K^-$	6.3×10^{-4}
	140 - 5278	$B^+ \to e^+e^+\pi^-$	1.6×10^{-6}
	494 - 5278	$B^+ \to e^+e^+K^-$	1.0×10^{-6}
	776 - 5278	$B^+ \to e^+e^+\rho^-$	2.6×10^{-6}
	892 - 5278	$B^+ \to e^+e^+K^{*-}$	2.8×10^{-6}
$\lvert V_{\mu 4}\rvert^2$	245 - 388	$K^+ \to \mu^+\mu^+\pi^-$	3.0×10^{-9}
	245 - 1763	$D^+ \to \mu^+\mu^+\pi^-$	4.8×10^{-6}
	599 - 1763	$D^+ \to \mu^+\mu^+K^-$	1.3×10^{-5}
	881 - 1763	$D^+ \to \mu^+\mu^+\rho^-$	5.6×10^{-4}
	997 - 1763	$D^+ \to \mu^+\mu^+K^{*-}$	8.5×10^{-4}
	245 - 1862	$D_s^+ \to \mu^+\mu^+\pi^-$	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^{-3}
	245 - 5173	$B^+ \to \mu^+\mu^+\pi^-$	1.4×10^{-6}
	599 - 5173	$B^+ \to \mu^+\mu^+K^-$	1.8×10^{-6}
	881 - 5173	$B^+ \to \mu^+\mu^+\rho^-$	5.0×10^{-6}
	997 - 5173	$B^+ \to \mu^+\mu^+K^{*-}$	8.3×10^{-6}
$\lvert V_{e4}V_{\mu 4}\rvert$	140 - 493	$K^+ \to e^+\mu^+\pi^-$	5.5×10^{-10}
	140 - 1868	$D^+ \to e^+\mu^+\pi^-$	5.0×10^{-5}
	494 - 1868	$D^+ \to e^+\mu^+K^-$	1.3×10^{-4}
	140 - 1862	$D_s^+ \to e^+\mu^+\pi^-$	7.3×10^{-4}
	494 - 1967	$D_s^+ \to e^+\mu^+K^-$	6.8×10^{-4}
	140 - 5278	$B^+ \to e^+\mu^+\pi^-$	1.3×10^{-6}
	494 - 5278	$B^+ \to e^+\mu^+K^-$	2.0×10^{-6}
	776 - 5278	$B^+ \to e^+\mu^+\rho^-$	3.3×10^{-6}
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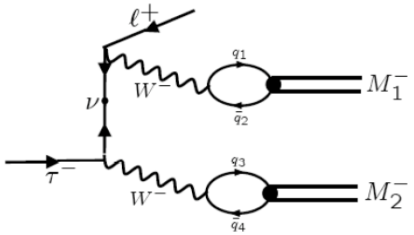


Rare decays of tau and mesons

Mass ~ 100 MeV - 5 GeV

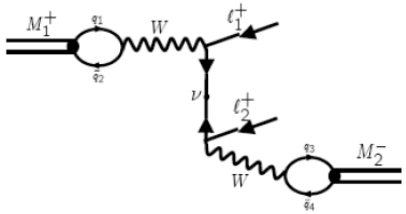
Real particle, propagates before decaying

May exit the detector before decaying

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

Limits weakened to

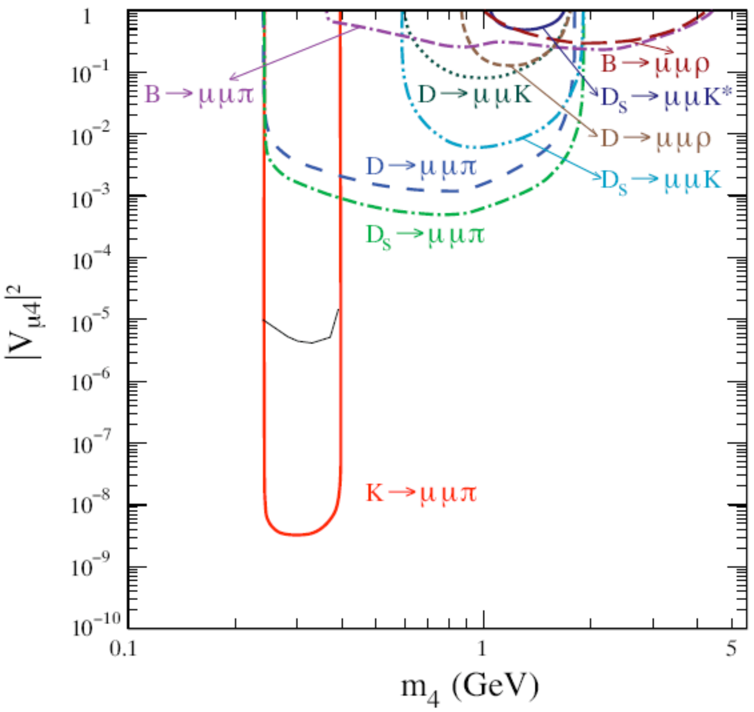
$$|V_{e4}V_{\tau 4}|(= |V_{e4}|^2) = \sqrt{|V_{e4}|^2_\infty/(L_{\rm exp}\Gamma_{N0})},$$

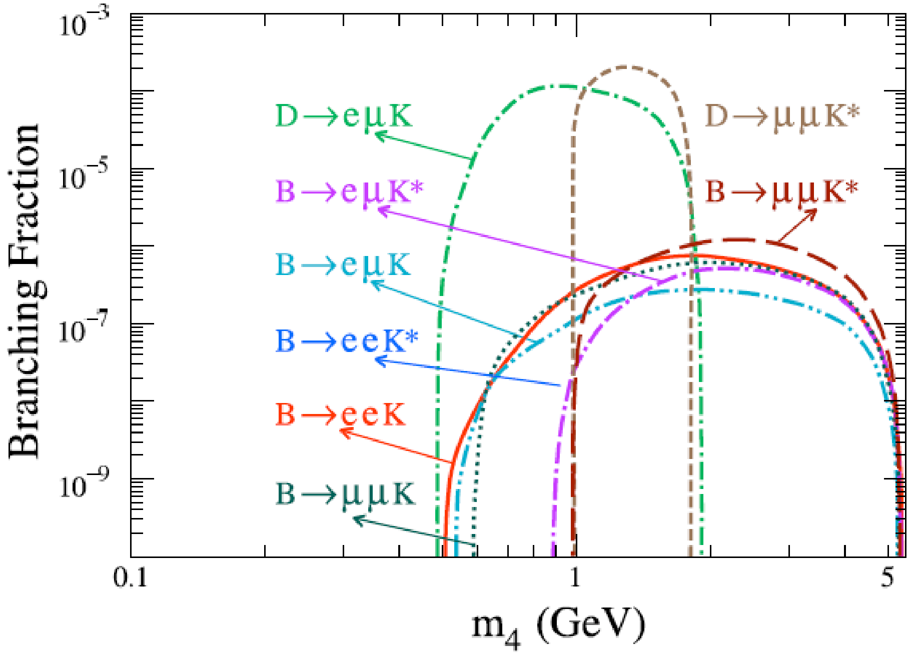


Lepton Number Violating Meson Decays $M_1^+ \to \ell_1^+ \ell_2^+ M_2^-$

The branching ratios can be approximated as

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





Collider Searches of Heavy Neutrinos

- It was proposed :[1]

$$e^- e^- \to W^- W^-,$$

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]

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

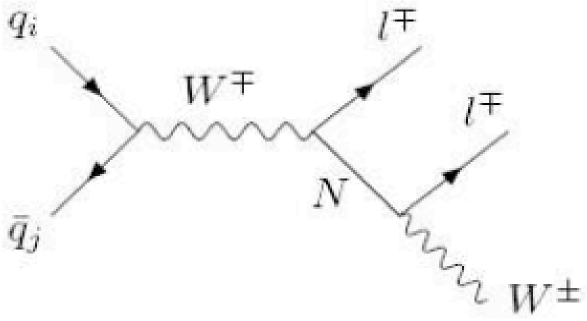
1. Rizzo (1982), Heusch (1994) 2. Rodejohann, Zuber (2000)

3. 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).

Resonant Production*



$$\sigma(pp \to \mu^{\pm}\ \mu^{\pm}\ W^{\mp}) \approx \sigma(pp \to \mu^{\pm} N_4) Br(N_4 \to \mu^{\pm} W^{\mp}) \equiv \frac{|V_{\mu 4}|^4}{\sum_{\ell=e}^{\tau} |V_{\ell 4}|^2} \sigma_0$$

Define a factorization:

$$\begin{aligned} \sigma(pp \to \mu^{\pm}\mu^{\pm}W^{\mp}) &\equiv \sigma_0 S_{\mu\mu} \\ S_{\mu\mu} = \frac{\left|V_{\mu 4}\right|^4}{\sum_{\ell=e}^{\tau} |V_{\ell 4}|^2} &\approx \frac{\left|V_{\mu 4}\right|^2}{1 + \frac{|V_{\tau 4}|^2}{|V_{\mu 4}|^2}} \end{aligned}$$

This is verified for $\sigma_0\ (m_N < 3\ TeV)$

narrow-width approximation valid

Phenomenological considerations

The Seesaw spirit:

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

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

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

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

The charged currents:

$$\begin{aligned} -\mathcal{L}_{CC} &= \frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U^*_{\ell m}\ \overline{\nu_m} \gamma^\mu P_L \ell + h.c. \\ &+ \frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V^*_{\ell m'}\ \overline{N^c_{m'}} \gamma^\mu P_L \ell + h.c. \end{aligned}$$

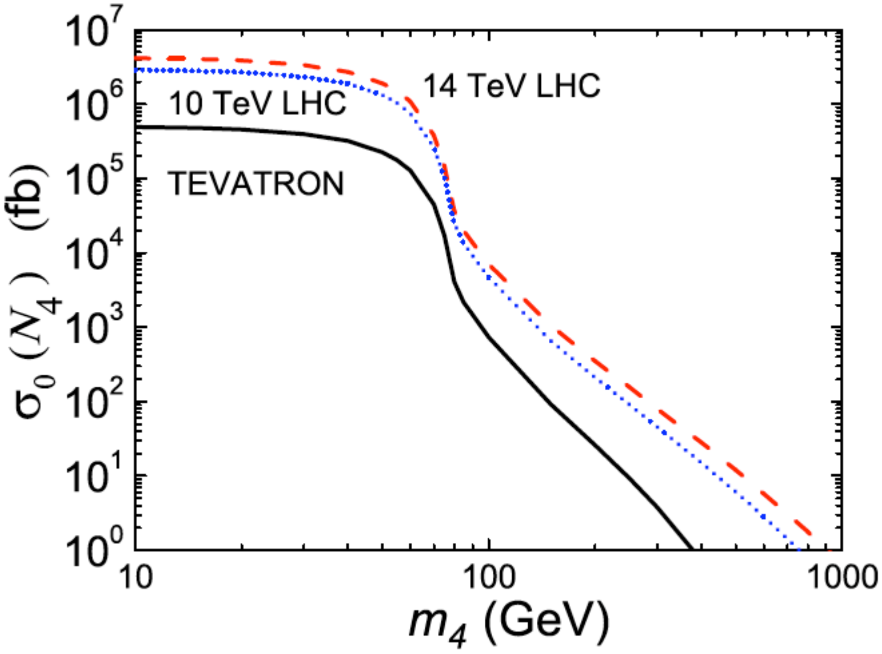
[†] Andrè de Gouvea (2005); Andrè de Gouvea, Jenkins, Vasudevan (2006); ...
[‡] M.C. Gonzalez-Garcia, J.W.F. Valle (1989); Z.Z.Xing et al (2008)...

Consider $p\bar{p}(pp) \to \mu^{\pm}\ \mu^{\pm}\ W^{\mp} \to \mu^{\pm}\mu^{\pm}jj$

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 $S\mu\mu$)



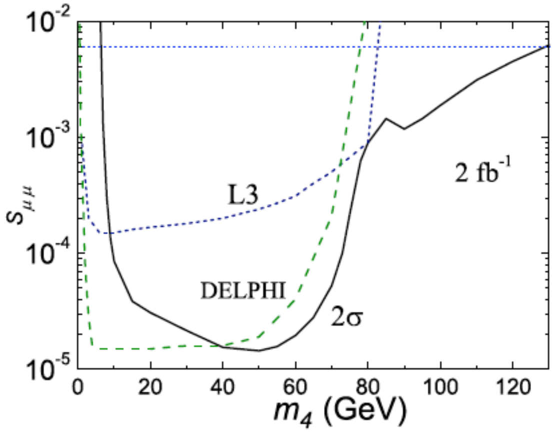
AA, Han, Pascoli, Zhang (2009)

Tevatron

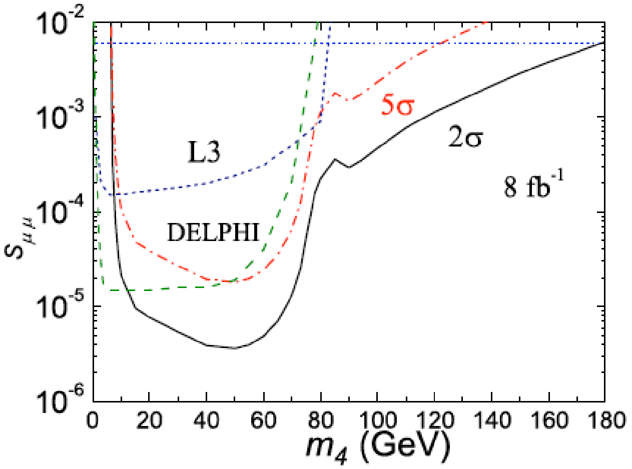
Main backgrounds: $t\bar{t} \to W^+ b, W^- \bar{b} \to b\mu^+, jj\bar{c}\mu^+ + E_T^{miss}$

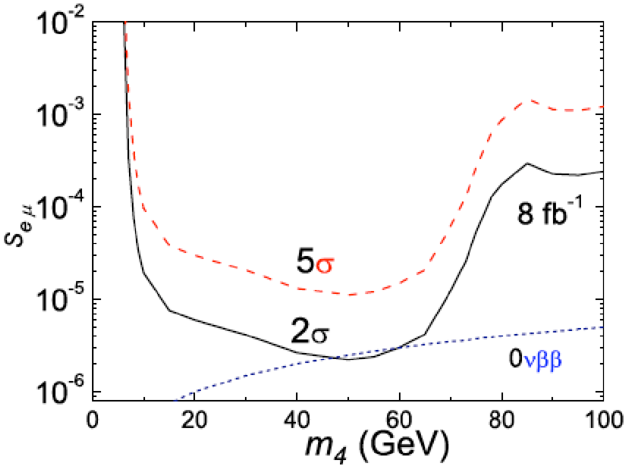
$W^\pm W^\pm jj, \quad W^\pm W^\pm W^\mp$

Current Sensitivity



Future Sensitivity





AA, Han,
Pascoli,
Zhang 09

$\mu\mu$ mode: $V^2_{\mu\mu} \sim 5 \times 10^{-6}$, *or* $m_4 \sim 180$ GeV.

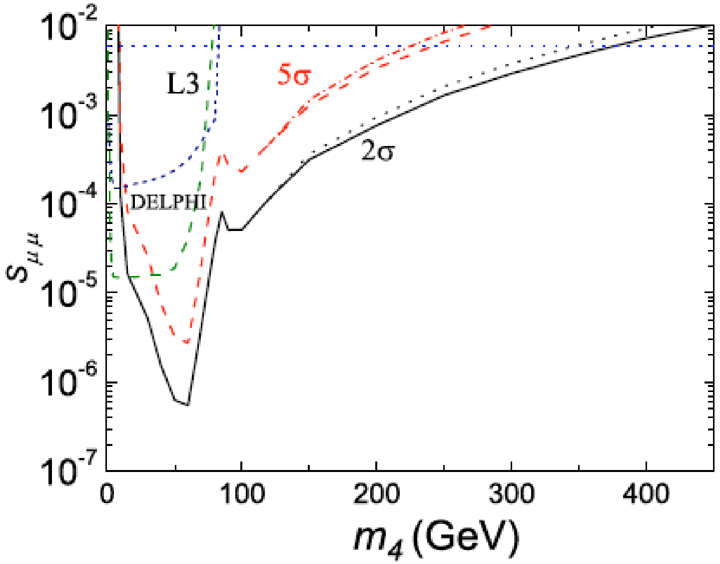
$e\mu$ mode: $V^2_{e\mu}$ close to the tight $0\nu\beta\beta$ bound.

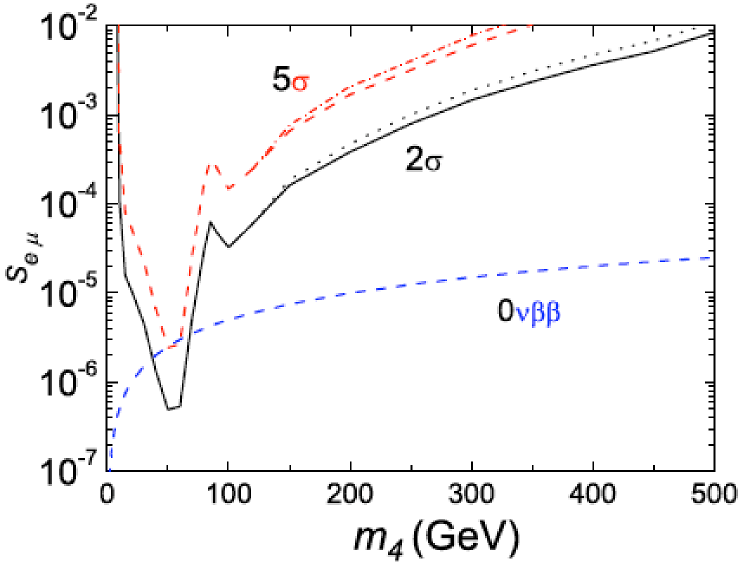
LHC

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

$W^\pm W^\pm jj, \quad W^\pm W^\pm W^\mp$

Sensitivity





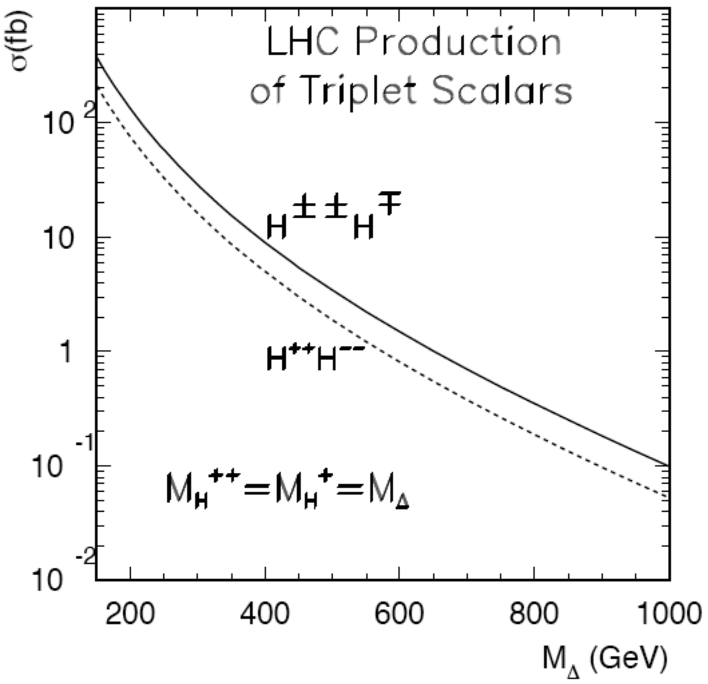
$\mu\mu$ mode: $V_{\mu\mu}^2 \sim 5 \times 10^{-7}$, *or* $m_4 \sim 400$ GeV.

$e\mu$ 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.

$\phi^{\pm\pm}$ in Type II Seesaw at the LHC

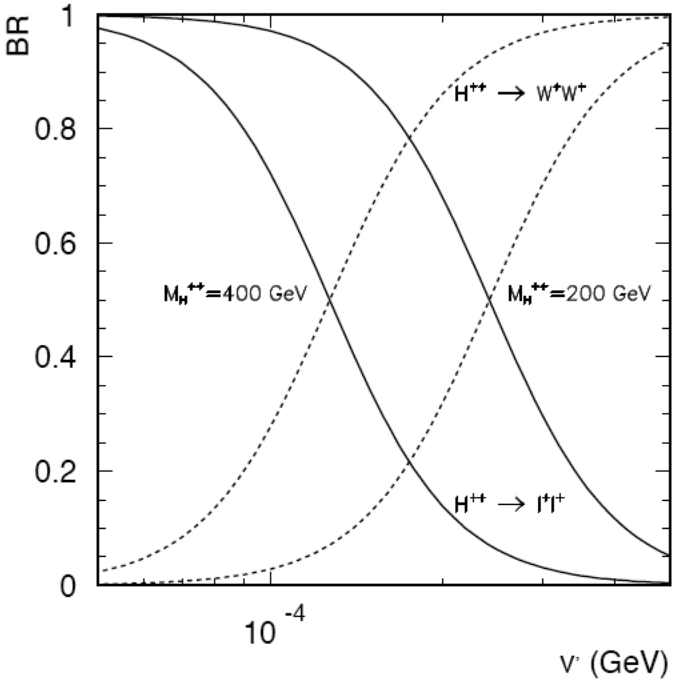
Production



$\gamma\gamma \to H^{++}H^{--}$ 10% of the DY

Han, Mukhopadhyay, Si, Wang 07

Decay

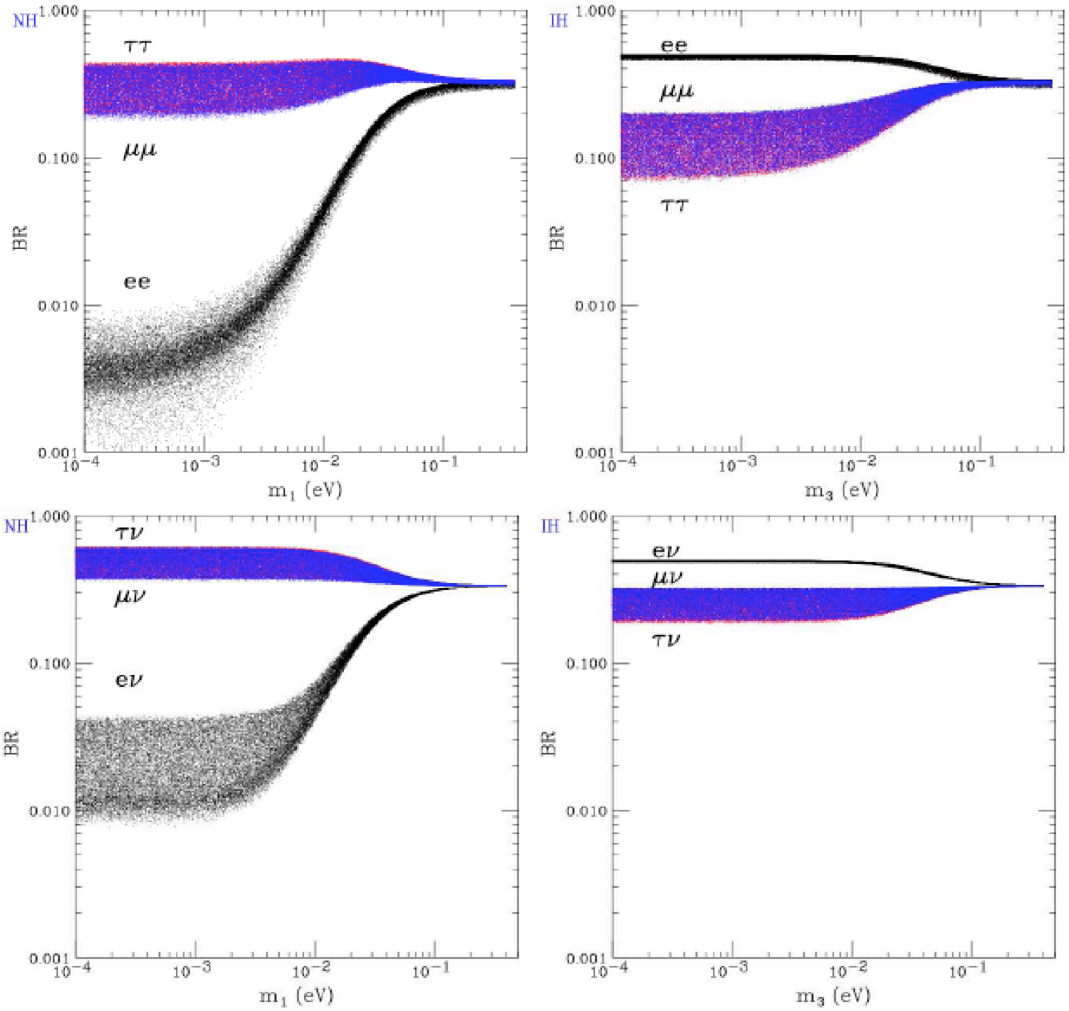


$$\Gamma(\phi^{++} \to \ell^+\ell^+) \propto Y_{ij}^2 M_\phi$$

$$\Gamma(\phi^{++} \to W^+W^+) \propto \frac{v'^2 M_\phi^3}{v^4},$$

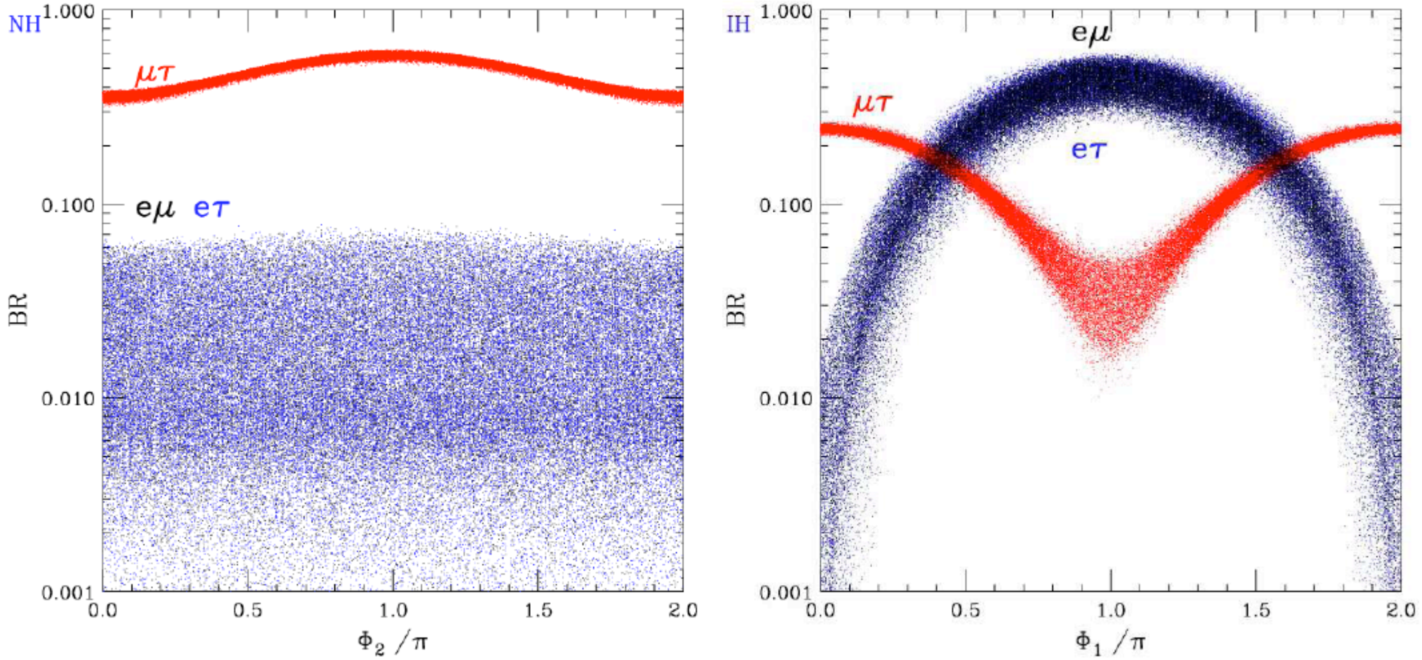
$$Y_{ll}v' \approx m_\nu\ (eV)$$

$H^{\pm\pm}, H^{\pm}$ decays predicted by the light neutrino spectrum:



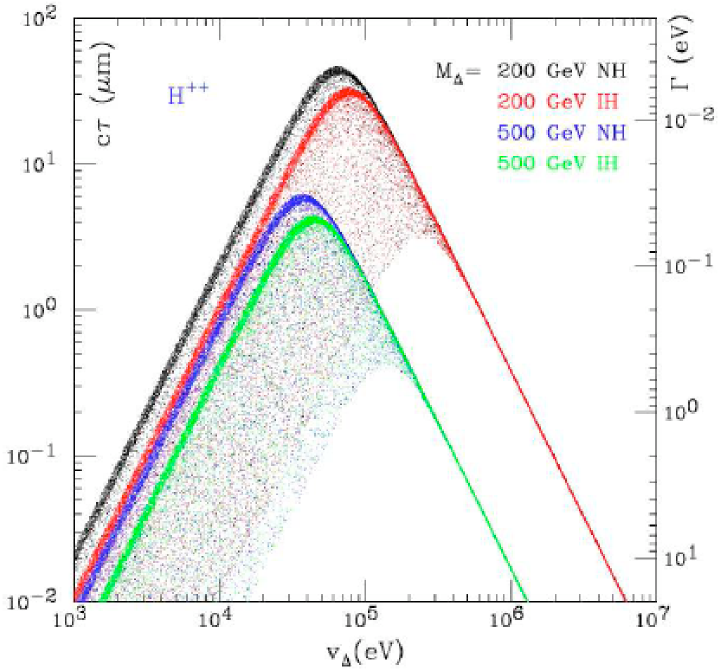
Perez, Han, Si, Wang, Huang, Li 08

Dependence on the Majorana phases: $H^{\pm\pm}$ decay

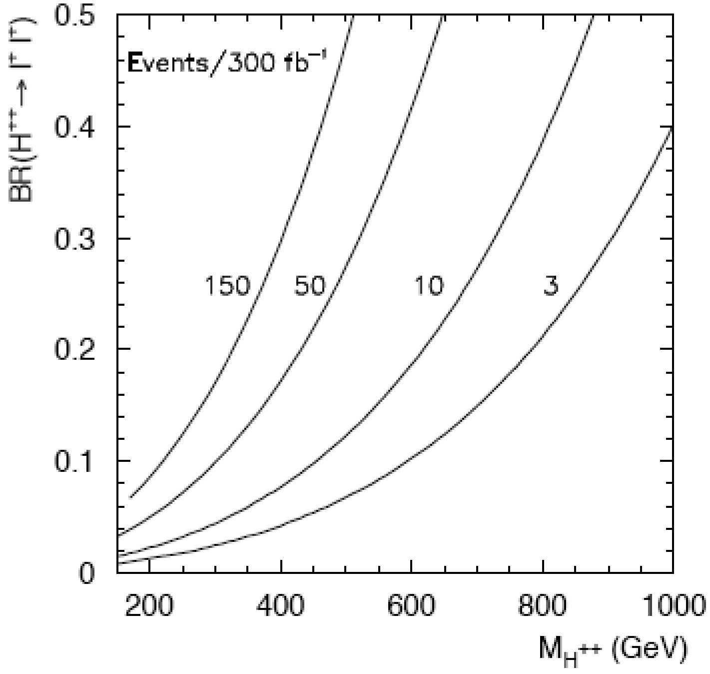


Spectrum	Relations
Normal Hierarchy $(\Delta m^2_{31} > 0)$	$\mathrm{BR}(H^{++} \to \tau^+\tau^+)$, $\mathrm{BR}(H^{++} \to \mu^+\mu^+) \gg \mathrm{BR}(H^{++} \to e^+e^+)$ $\mathrm{BR}(H^{++} \to \mu^+\tau^+) \gg \mathrm{BR}(H^{++} \to e^+\mu^+)$, $\mathrm{BR}(H^{++} \to e^+\tau^+)$ $\mathrm{BR}(H^{+} \to \tau^+\bar{\nu})$, $\mathrm{BR}(H^{+} \to \mu^+\bar{\nu}) \gg \mathrm{BR}(H^{+} \to e^+\bar{\nu})$
Inverted Hierarchy $(\Delta m^2_{31} < 0)$	$\mathrm{BR}(H^{++} \to e^+e^+) > \mathrm{BR}(H^{++} \to \mu^+\mu^+)$, $\mathrm{BR}(H^{++} \to \tau^+\tau^+)$ $\mathrm{BR}(H^{++} \to \mu^+\tau^+) \gg \mathrm{BR}(H^{++} \to e^+\tau^+)$, $\mathrm{BR}(H^{++} \to e^+\mu^+)$ $\mathrm{BR}(H^{+} \to e^+\bar{\nu}) > \mathrm{BR}(H^{+} \to \mu^+\bar{\nu})$, $\mathrm{BR}(H^{+} \to \tau^+\bar{\nu})$
Quasi-Degenerate $(m_1, m_2, m_3 > \lvert\Delta m_{31}\rvert)$	$\mathrm{BR}(H^{++} \to e^+e^+) \sim \mathrm{BR}(H^{++} \to \mu^+\mu^+) \sim \mathrm{BR}(H^{++} \to \tau^+\tau^+) \approx 30\%$ $\mathrm{BR}(H^{+} \to e^+\bar{\nu}) \sim \mathrm{BR}(H^{+} \to \mu^+\bar{\nu}) \sim \mathrm{BR}(H^{+} \to \tau^+\bar{\nu}) \approx 30\%$

Sensitivity to $H^{++}H^{--} \to \ell^+\ell^+,\ \ell^-\ell^-$ Mode



Nearly background-free.

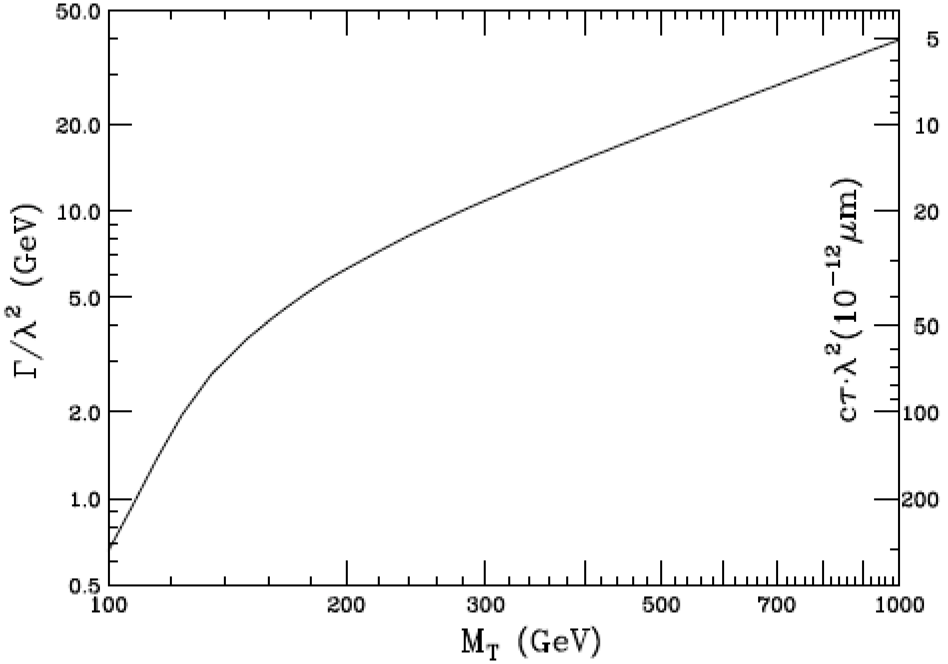


$H^{\pm\pm}$, $H^{\pm}$ decay promptly: $H^{++} \to \ell^+\ell^+$, W^+W^+ complementary.
May reach 20 – 40 μm, leading to displaced vertices.

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.

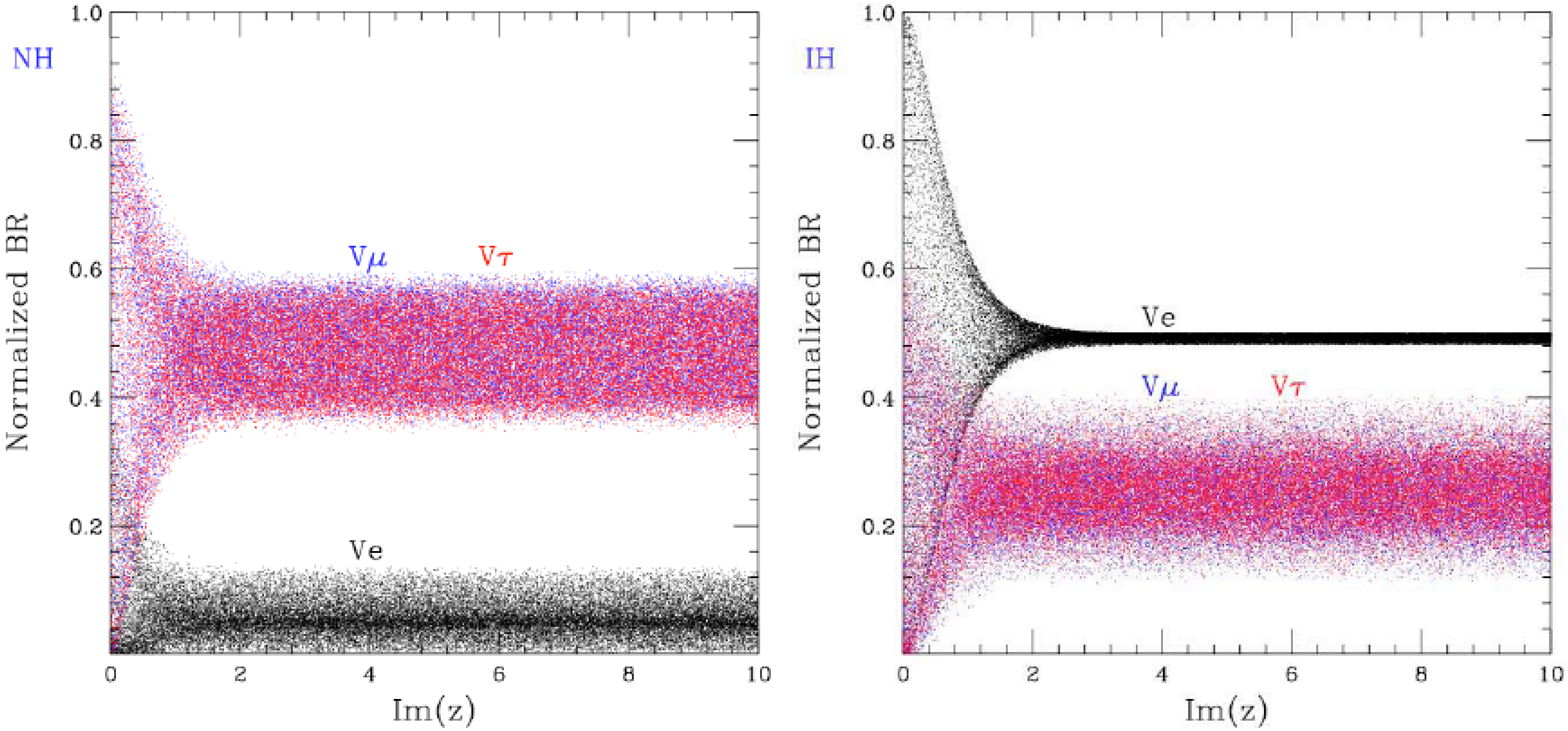
T^0, $T^\pm$ in Type III Seesaw at the LHC



$$\begin{aligned}\Gamma(T^+ \to W^+\nu) &\approx 2\Gamma(T^+ \to Z\ell^+) \approx 2\Gamma(T^+ \to h\ell^+)\\ &\approx \Gamma(T^0 \to W^+\ell^- + W^-\ell^+) \approx \frac{M_T}{16\pi}\sum_i |y_i|^2.\end{aligned}$$

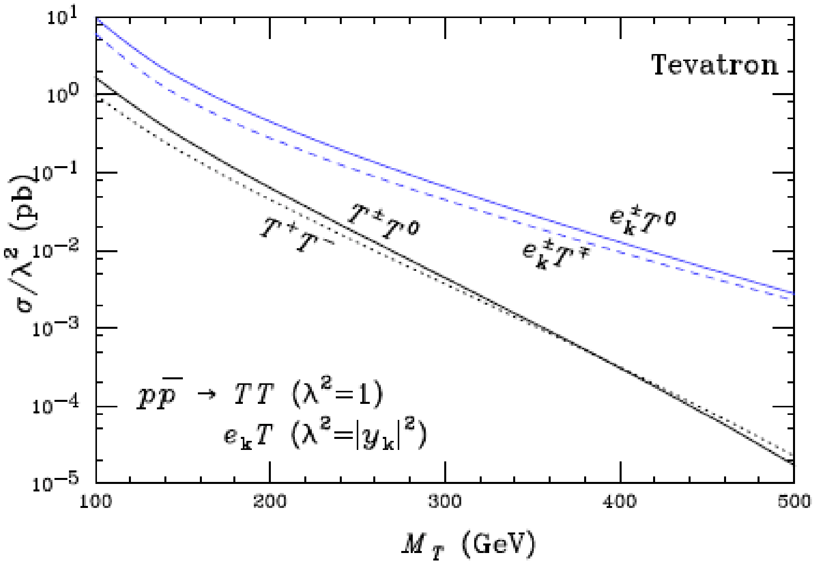
possibly large displaced vertices

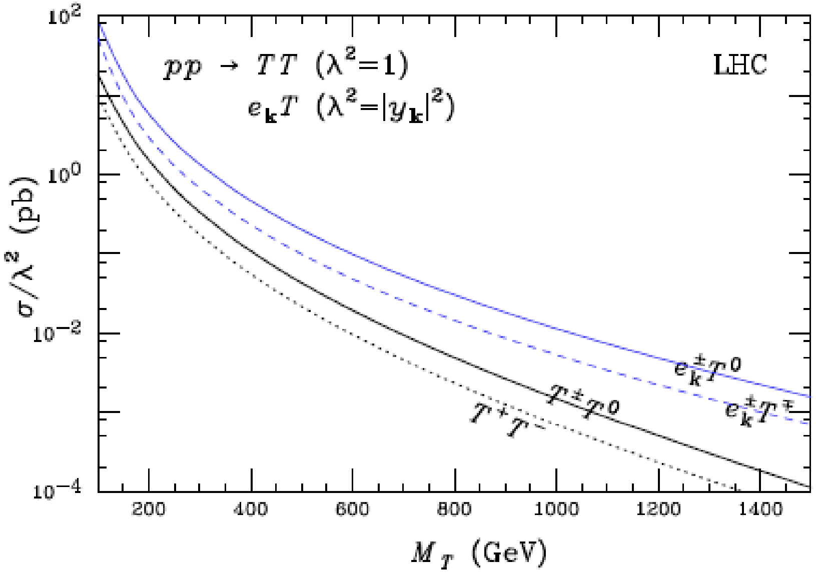
Lepton flavor combination determines the ν mass pattern:



Ahrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanovic 09

Production rates at the Tevatron/LHC: †





- Single production $T^{\pm}\ell^{\mp}$, $T^0\ell^{\pm}$:

Kinematically favored, but highly suppressed by mixing.

- Pair production with gauge couplings.

Example: $T^{\pm} + T^0 \to \ell^+ Z(h) + \ell^+ W^- \to \ell^+ jj(b\bar{b}) + \ell^+ jj.$

Low backgrounds.

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 $10 \text{ GeV} < m_4 < 100 \text{ GeV}, \ 10^{-4} < |V_{\mu 4}|^2 < 10^{-2}$

  LHC $10 \text{ GeV} < m_4 < 400 \text{ GeV}, \ 10^{-6} < |V_{\mu 4}|^2 < 10^{-2}$
- For scalar triplets (Type II seesaw)

  LHC reach $M_\phi \sim 600 - 1000 \text{ GeV } (\ell^\pm \ell^\pm \ or \ W^\pm W^\pm)$

  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!!