Title: The Test of the Seesaw Mechanisms at the LHC

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Abstract: Observing lepton-number violating processes is a decisive step toward establishing the Majorana nature of the neutrino mass. We explore the prospects searching for Delta L = 2 processes and propose the tests for the three types of the Seesaw mechanisms. Potential signals at the LHC
are studied and correlations to the neutrino oscillation parameters are investigated.

The Test of "Seesaw" at the LHC

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PRELUDE

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- The EW symmetry breaking, Higgs-alike (Moriond)
- New symmetry principles: SUSY?
- New strong dynamics: TC/ETC-alike?
- Extended gauge sector and GUTs?
- Origin of the fermion flavors and CP-violation?
- Extended space-time, low-scale string/QG?
- ... ...

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"Burning" issues:

Physics (clearly) beyond the Standard Model:

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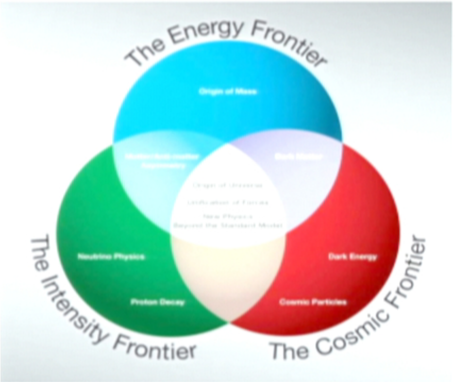

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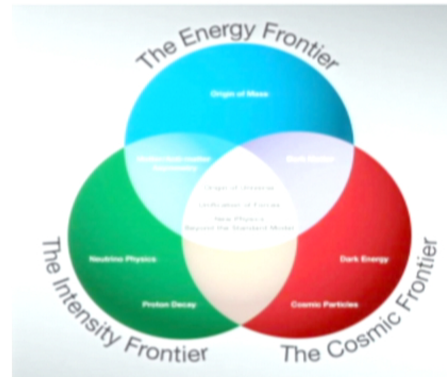

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Today, focus on neutrino issues.

Outline:

Introduction:

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- ν masses and the Seesaw schemes:

Type I, II, and III

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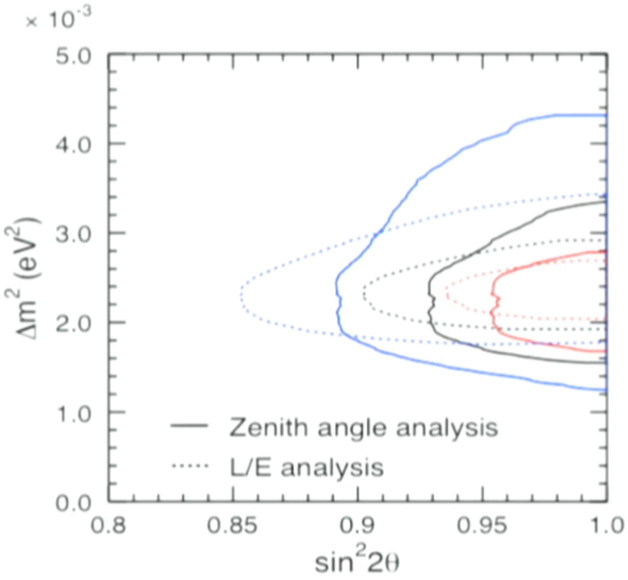
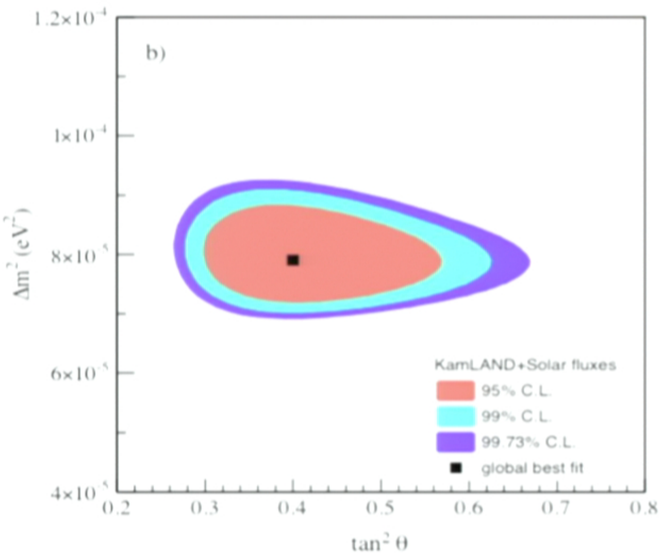
Neutrinos are massive

Now we know: *

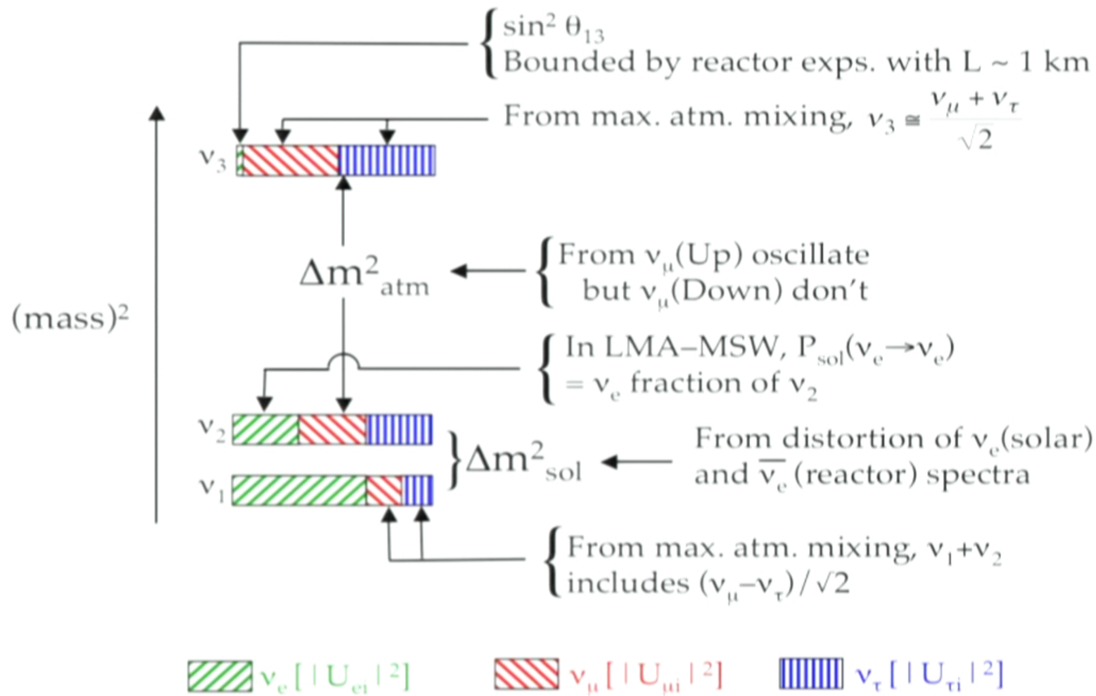




$$1.9 \times 10^{-3}\ \text{eV}^2 < \Delta m^2_{atm} < 3.0 \times 10^{-3}\ \text{eV}^2$$
$$7.4 \times 10^{-5}\ \text{eV}^2 < \Delta m^2_{sol} < 8.6 \times 10^{-5}\ \text{eV}^2.$$

*SuperK, SNO, CHOOZ, KamLAND, K2K, T2K ..., PDG

The mass relation and flavor components:*



*B. Kayser; and PDG.

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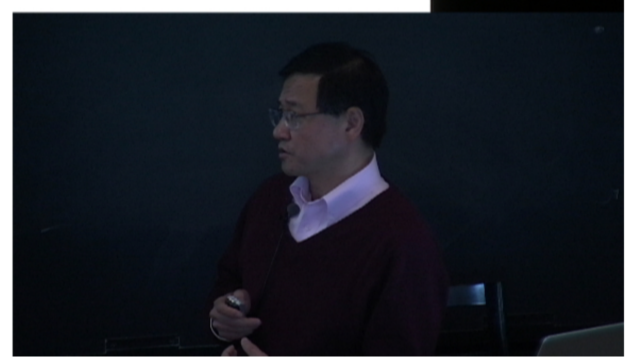
Yet to be determined:

Mass (hierarchical) pattern;
Dirac or Majorana;
θ_{13} and other phases (CPv)...



Neutrinos are massive

In the context of the Standard Model:

$$L_a = \begin{pmatrix} \nu_a \\ l_a \end{pmatrix}_L, \quad a = 1, 2, 3$$

The leading SM gauge invariant operator is at dim-5:*

$$\frac{1}{\Lambda} (y_\nu L H)(y_\nu L H) + h.c. \quad \Rightarrow \quad \frac{y_\nu^2 v^2}{\Lambda} \overline{\nu_L} \, \nu_R^c .$$

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Implication 1. Dim-5 operator indicates a new physics scale Λ

The See-saw spirit: †

If $m_\nu \sim 1$ eV, then $\Lambda \sim y_\nu^2$ (10^{14} GeV).

$$\Lambda \Rightarrow \begin{cases} 10^{14} \text{ GeV for } y_\nu \sim 1; \\ 100 \text{ GeV for } y_\nu \sim 10^{-6}. \end{cases}$$

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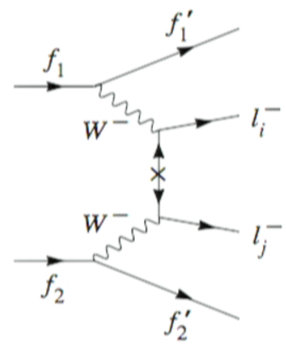

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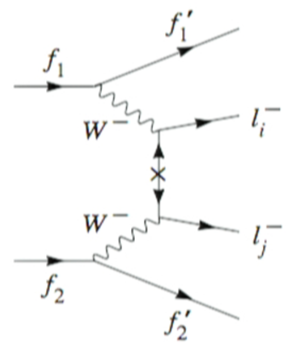

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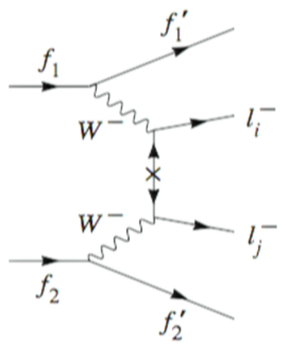

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Many theoretical models in SUSY, GUTs, SM extensions ...
We wiil stay in the minimal extension.

Neutrino masses: Dirac or Majorana

Simplest (renormalizible) extension of the SM:

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

Gauge-invariant Yukawa interactions:

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

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lead to three generations of Dirac neutrinos.

But, N_R's are "sterile" !

No gauge interactions to be imposed upon. So there you go ...

Type I Seesaw (with N_R): *

With the fermionic singlets N_R, one can have

$$\sum_{b,b'=1}^{n\geq 2} \overline{N^c{}_{bL}}\, M_{bb'}\, N_{b'R} + h.c.$$

then the full neutrino mass terms read

$$\begin{pmatrix} \overline{\nu_L} & \overline{N^c{}_L} \end{pmatrix} \begin{pmatrix} 0_{3\times 3} & D^{\nu}_{3\times n} \\ D^{\nu T}_{n\times 3} & M_{n\times n} \end{pmatrix} \begin{pmatrix} \nu^c{}_R \\ N_R \end{pmatrix}$$

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Majorana neutrinos:

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

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

$$m_\nu \approx \frac{D^2}{M}, \quad m_N \approx M, \quad UU^\dagger \approx I\ (PMNS), \quad VV^\dagger \approx \frac{m_\nu}{m_N}.$$

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If $D \sim y_\nu v,\ m_\nu \sim$1 eV, then $m_N \sim y_\nu^2$ (10^{14} GeV)

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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:

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

[†] 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)...

Type II Seesaw (no N_R): *

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

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

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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

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

leading to the Type II Seesaw. †

*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 (no N_R, but some other leptons): *

With a lepton triplet T $(Y = 0)$: $T^+ \; T^0 \; T^-$, add the terms:

$$-M_T(T^+T^- + T^0T^0/2) + y_T^i H^T i\sigma_2 T L_i + h.c.$$

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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.

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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. ...
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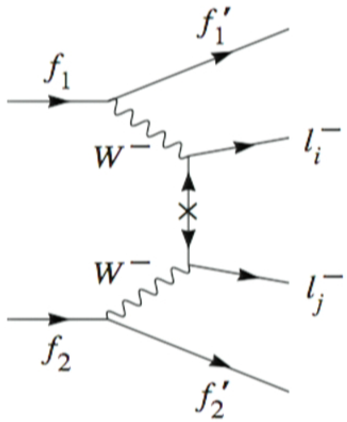
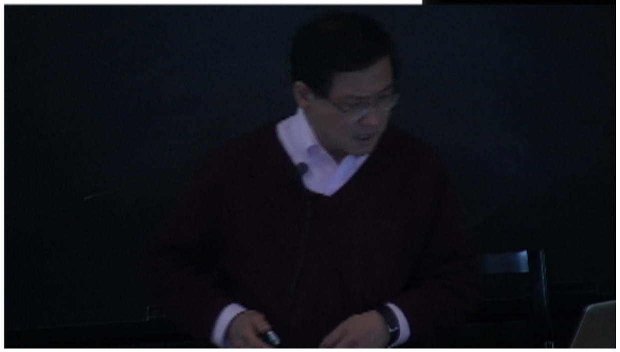
$\Delta L = 2$ Processes at Low Energies

The fundamental diagram:



$$U_{iN} \frac{\not{p} + m_N}{p^2 - m_N^2 + i\epsilon} U_{jN}.$$



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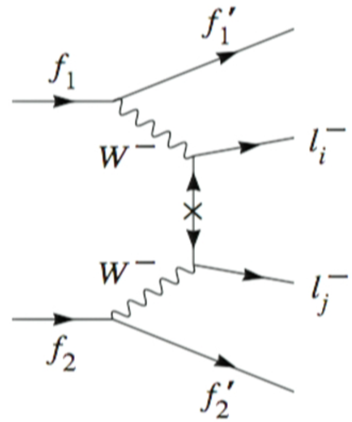

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The transition rates are proportional to

$$|\mathcal{M}|^2 \propto \begin{cases} \langle m \rangle^2_{\ell_1 \ell_2} = \left| \sum_{i=1}^{3} U_{\ell_1 i} U_{\ell_2 i} m_i \right|^2 & \text{for light } \nu; \\ \dfrac{\left| \sum_i^n V_{\ell_1 i} V_{\ell_2 i} \right|^2}{m_N^2} & \text{for heavy } N; \\ \dfrac{\Gamma(N \to i) \; \Gamma(N \to f)}{m_N \Gamma_N} & \text{for resonant N production.} \end{cases}$$

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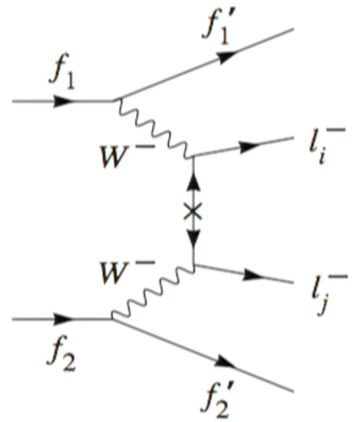

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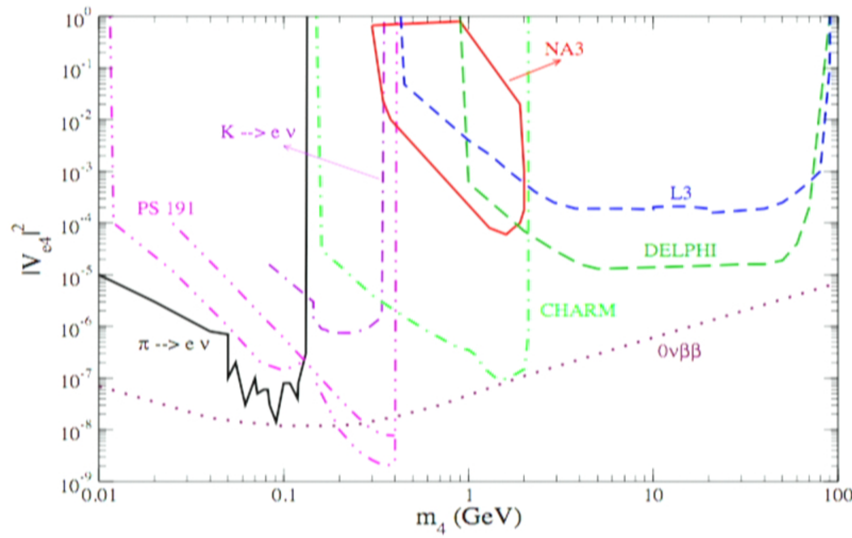
One more (accessible) sterile neutrino:

Direct experimental bounds on $V_{\ell 4}$ and m_4 compiled: †

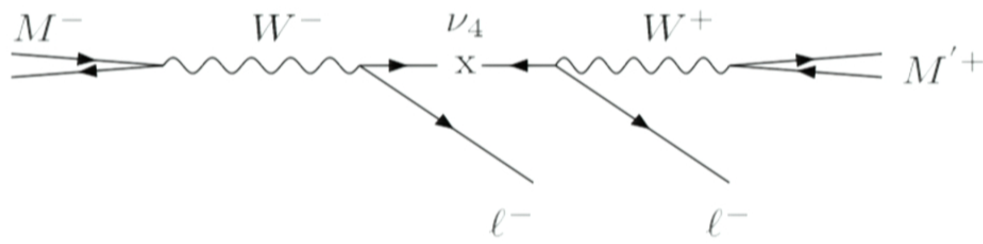


Most stringent bound from $0\nu\beta\beta$:

$$\sim \sum_N \frac{|V_{eN}|^2}{m_N} < 5 \times 10^{-8}\ \mathrm{GeV}^{-1}.$$

†A. Atre, T. Han, S. Pascoli, B. Zhang, arXiv:0901:3589.

ν_4 production and decay:



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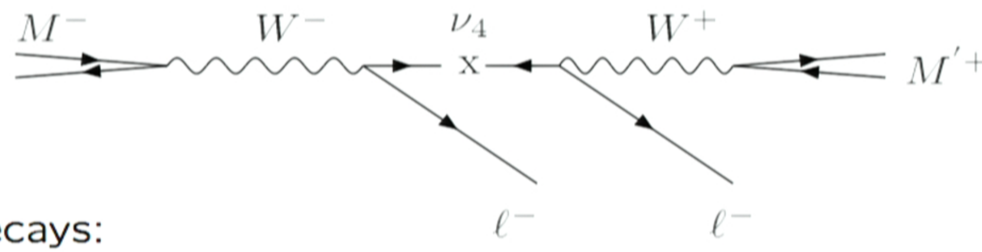
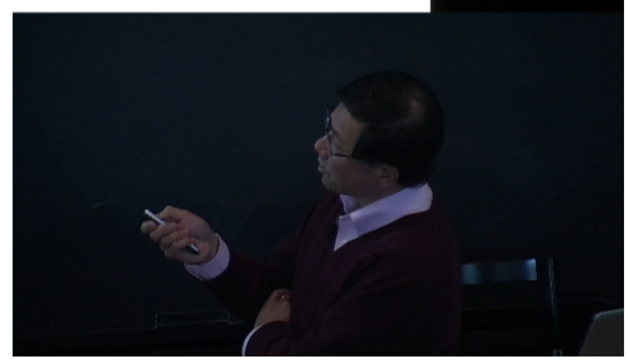


Two-body decays:

$$\begin{aligned} \nu_4 &\to \ell^- M^+ \\ &\to \nu_\ell M^0. \end{aligned}$$

Three-body decays:

$$\begin{aligned} \nu_4 &\to \nu_\ell \ell_i^- \ell_j^+ \quad (CC + NC) \\ &\to \nu_\ell \nu_i \nu_j \quad (NC). \end{aligned}$$



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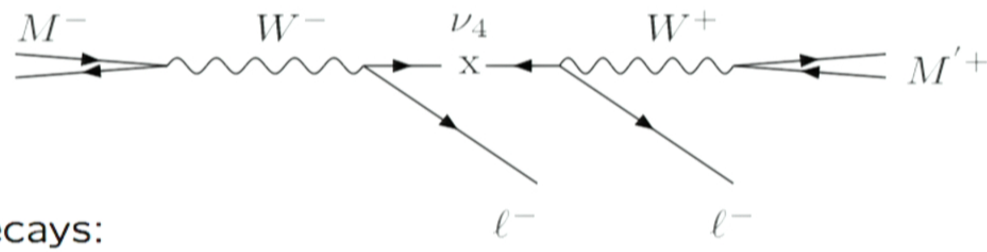

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Thus the total width

$$\Gamma_4 \approx \frac{G_F^2 f_M^2 m_4^3}{16\pi} \sum_\ell |V_{\ell 4}|^2 \quad \Rightarrow \quad c\tau_0 \approx \frac{10^{-3}\ \mathrm{m}}{\sum_\ell |V_{\ell 4}|^2} \left(\frac{\mathrm{GeV}}{m_4}\right)^3 \left(\frac{200\ \mathrm{MeV}}{f_M}\right)^2$$

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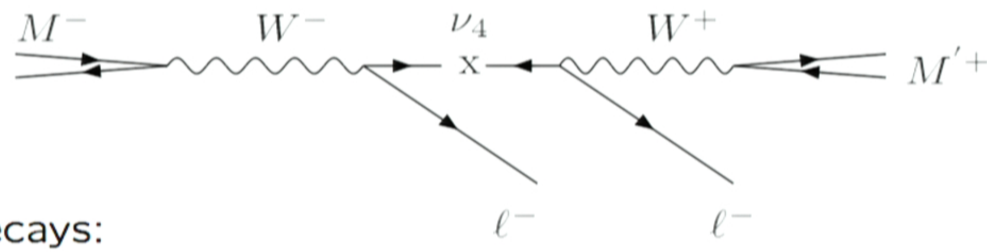

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$$\Gamma_4 \approx \frac{G_F^2 f_M^2 m_4^3}{16\pi} \sum_\ell |V_{\ell 4}|^2 \quad \Rightarrow \quad c\tau_0 \approx \frac{10^{-3}\ \mathrm{m}}{\sum_\ell |V_{\ell 4}|^2} \left(\frac{\mathrm{GeV}}{m_4}\right)^3 \left(\frac{200\ \mathrm{MeV}}{f_M}\right)^2$$

Meson decay inputs:*

Mixing element	range of m_4(MeV)	decay mode	B_{exp}
$\|V_{e4}\|^2$	140 - 493	$K^+ \to e^+ e^+ \pi^-$	6.4×10^{-10}
	140 - 1868	$D^+ \to e + e^+ \pi^-$	9.6×10^{-5}
	494 - 1868	$D^+ \to e^+ e^+ K^-$	1.2×10^{-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}
$\|V_{\mu 4}\|^2$	245 - 388	$K^+ \to \mu^+ \mu^+ \pi^-$	3.0×10^{-9}
	245 - 1763	$D^+ \to \mu^+ \mu^+ \pi^-$	4.8×10^{-6}
	599 - 1862	$D_s^+ \to \mu^+ \mu^+ K^-$	1.3×10^{-5}
	245 - 5173	$B^+ \to \mu^+ \mu^+ \pi^-$	1.4×10^{-6}
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$\|V_{e4} V_{\mu 4}\|$	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}
	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}
$\|V_{e4} V_{\tau 4}\|$	140 - 1637	$\tau^- \to e^+ \pi^- \pi^-$	1.9×10^{-6}
	494 - 1283	$\tau^- \to e^+ K^- K^-$	3.8×10^{-6}
$\|V_{\mu 4} V_{\tau 4}\|$	245 - 1637	$\tau^- \to \mu^+ \pi^- \pi^-$	1.9×10^{-6}
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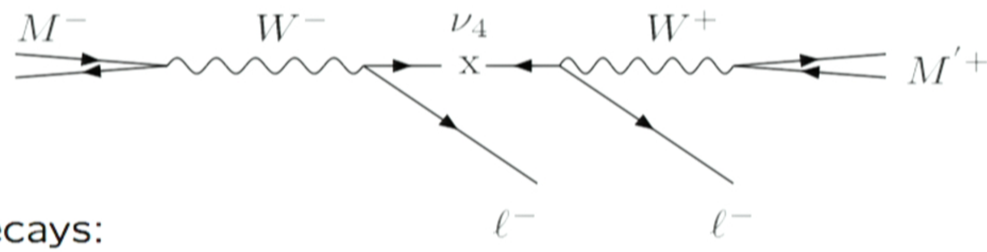
*BaBar, 2005.

ν_4 production and decay:



Two-body decays:

$$\begin{aligned}\nu_4 &\to \ell^- M^+ \\ &\to \nu_\ell M^0.\end{aligned}$$

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Remarks:

- We emphasize the search for the genuine $\Delta L = 2$ processes.

- Depending on the unkown parameter $|V_{\ell 4}|^2$,
  BR's can easily reach $10^{-6} - 10^{-2}$,
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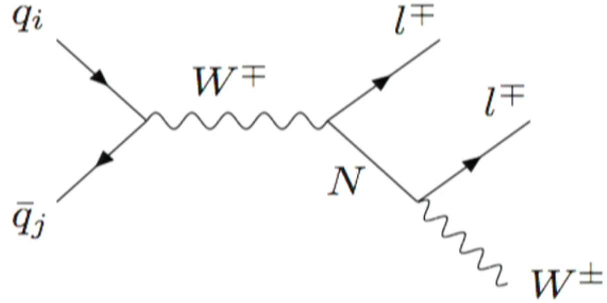
Collider searches for Majorana neutrinos

At hadron colliders: ‡ $pp(\bar{p}) \to \ell^\pm \ell^\pm jjX$



$$\sigma(pp \to \mu^\pm \mu^\pm W^\mp) \approx \sigma(pp \to \mu^\pm N) Br(N \to \mu^\pm W^\mp) \equiv \frac{V_{\mu N}^2}{\sum_l \left|V^{\ell N}\right|^2} V_{\mu N}^2 \, \sigma_0.$$

‡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).

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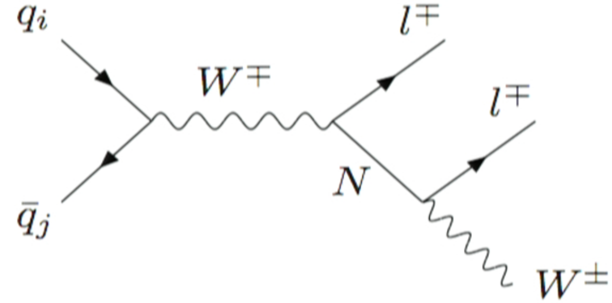

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Factorize out the mixing couplings: †

$$\sigma(pp \to \mu^\pm \mu^\pm W^\mp) \equiv S_{\mu\mu} \ \sigma_0,$$

$$S_{\mu\mu} = \frac{V_{\mu N}^4}{\sum_l |V_{\ell N}|^2} \approx \frac{V_{\mu N}^2}{1 + V_{\tau N}^2 / V_{\mu N}^2}.$$

This is verified for $\sigma_0(m_N < 3 \text{ TeV}) \Rightarrow$ narrow-width approximation valid.

‡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).

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

A very clean channel:

- like-sign di-muons plus two jets;
- no missing energies;
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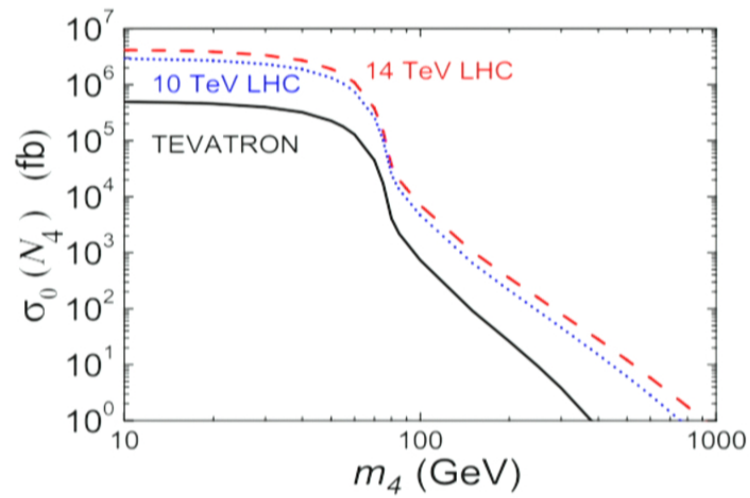
Bare cross sections (scaled down by $S_{\mu\mu}$.)

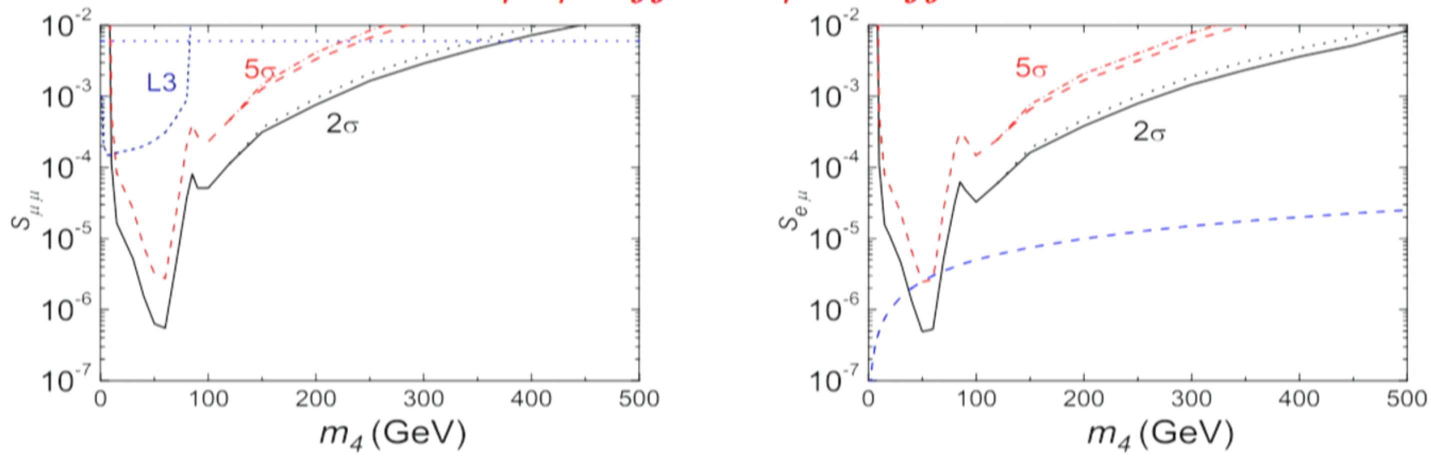


At the LHC:[†]

Main backgrounds:

- $t\bar{t} \to W^+ b, W^- \bar{b} \to b\mu^+,\ jj\ \bar{c}\ \mu^+ + E_T^{miss}$
- $pp \to W^\pm W^\pm\ jj;$
- $pp \to W^\pm W^\pm\ W^\mp.$

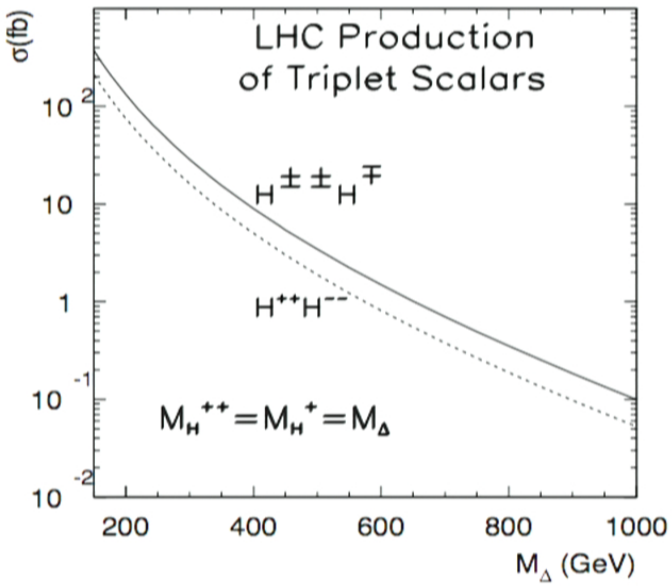
$\mu^\pm\mu^\pm\ jj$ and $\mu^\pm e^\pm\ jj$



[†] A. Atre, T. Han, S. Pascoli, B. Zhang, arXiv.0901.3589.

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

$H^{++}H^{--}$ production at hadron colliders: †



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

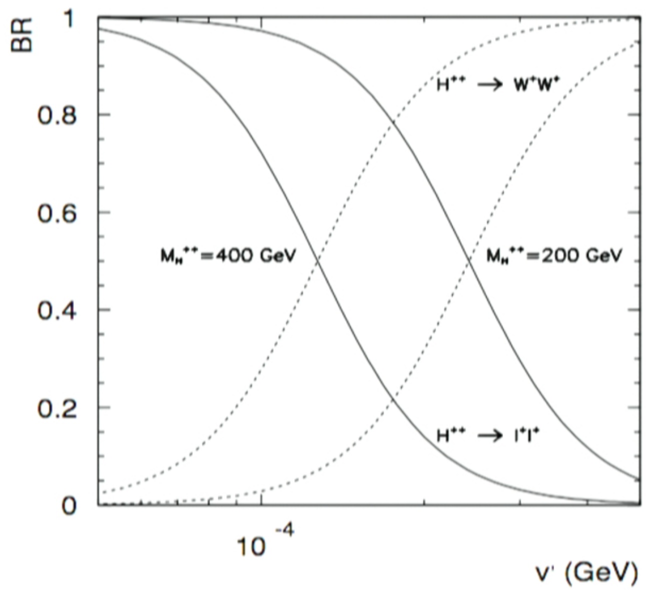
†Revisit, T.Han, B.Mukhopadhyaya, Z.Si, K.Wang, arXiv:0706.0441.

Unique decays:

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

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

with $Y_{ll}v' \approx m_\nu\ (eV) \Rightarrow v' \approx 2 \times 10^{-4}$ GeV the division.



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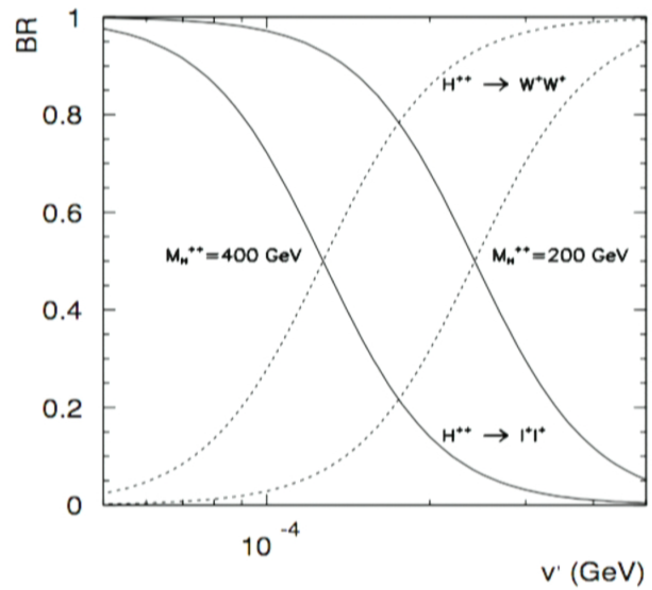
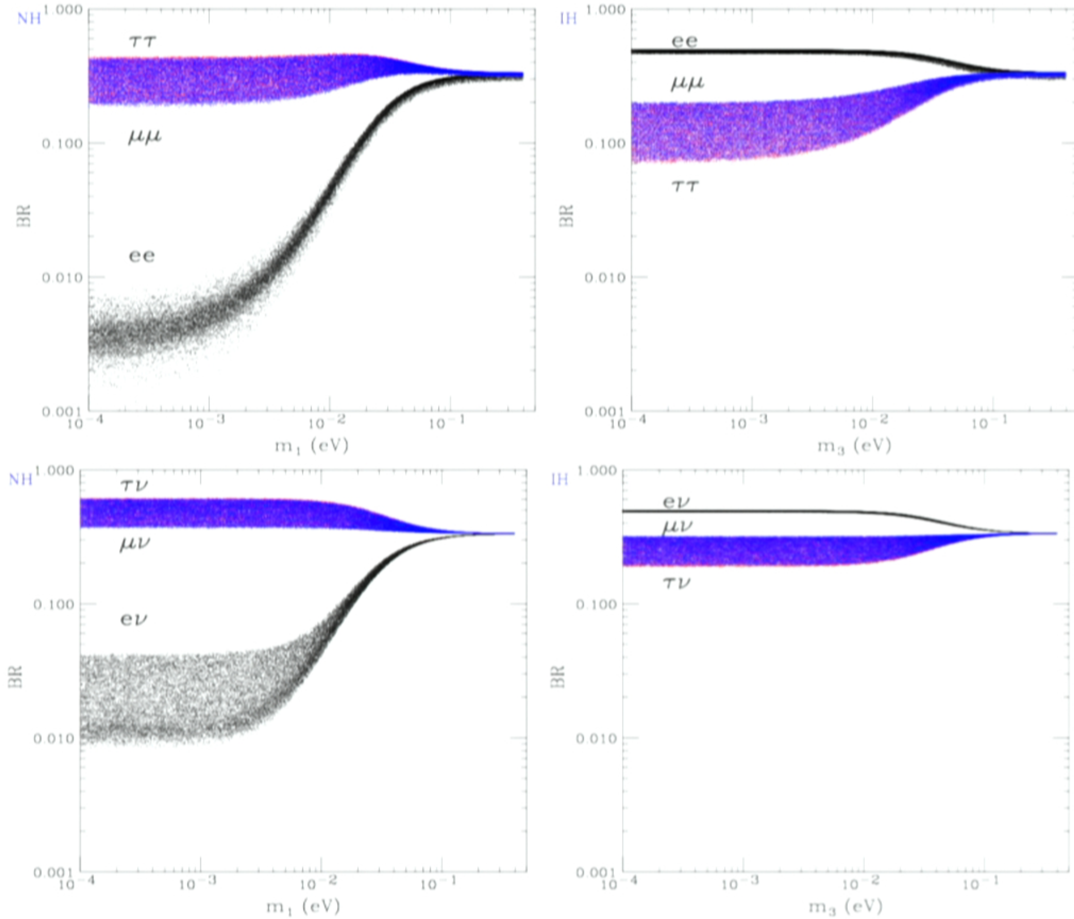


$H^{\pm\pm}, H^{\pm}$ decays predicted by the light neutrino spectrum:



Summarize the discovery modes:

Spectrum	Relations
Normal Hierarchy ($\Delta m^2_{31} > 0$)	BR($H^{++} \to \tau^+\tau^+$), BR($H^{++} \to \mu^+\mu^+$) $\gg$ BR($H^{++} \to e^+e^+$) BR($H^{++} \to \mu^+\tau^+$) $\gg$ BR($H^{++} \to e^+\mu^+$), BR($H^{++} \to e^+\tau^+$) BR($H^+ \to \tau^+\bar{\nu}$), BR($H^+ \to \mu^+\bar{\nu}$) $\gg$ BR($H^+ \to e^+\bar{\nu}$)
Inverted Hierarchy ($\Delta m^2_{31} < 0$)	BR($H^{++} \to e^+e^+$) $>$ BR($H^{++} \to \mu^+\mu^+$), BR($H^{++} \to \tau^+\tau^+$) BR($H^{++} \to \mu^+\tau^+$) $\gg$ BR($H^{++} \to e^+\tau^+$), BR($H^{++} \to e^+\mu^+$) BR($H^+ \to e^+\bar{\nu}$) $>$ BR($H^+ \to \mu^+\bar{\nu}$), BR($H^+ \to \tau^+\bar{\nu}$)
Quasi-Degenerate ($m_1, m_2, m_3 > \|\Delta m_{31}\|$)	BR($H^{++} \to e^+e^+$) $\sim$ BR($H^{++} \to \mu^+\mu^+$) $\sim$ BR($H^{++} \to \tau^+\tau^+$) $\approx 1/3$ BR($H^+ \to e^+\bar{\nu}$) $\sim$BR($H^+ \to \mu^+\bar{\nu}$) $\sim$BR($H^+ \to \tau^+\bar{\nu}$) $\approx 1/3$

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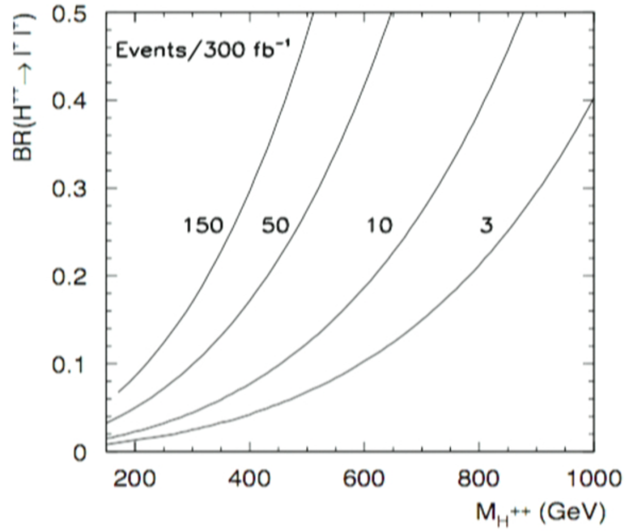
Sensitivity to $H^{++}H^{--} \to \ell^+\ell^+,\ \ell^-\ell^-$ Mode: †

Nearly background-free.



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.

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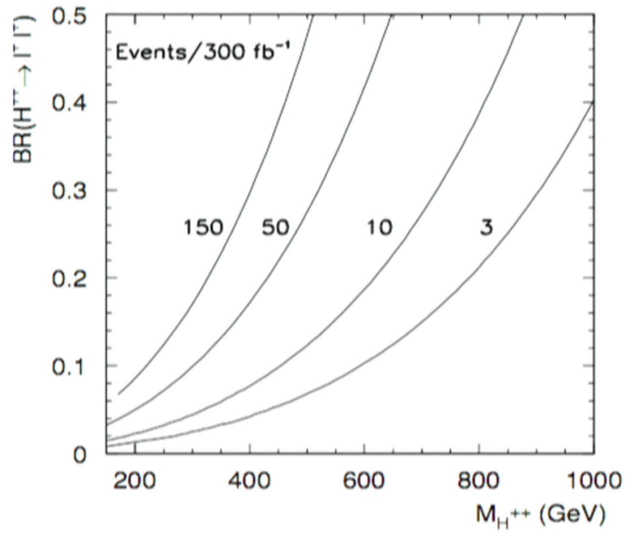

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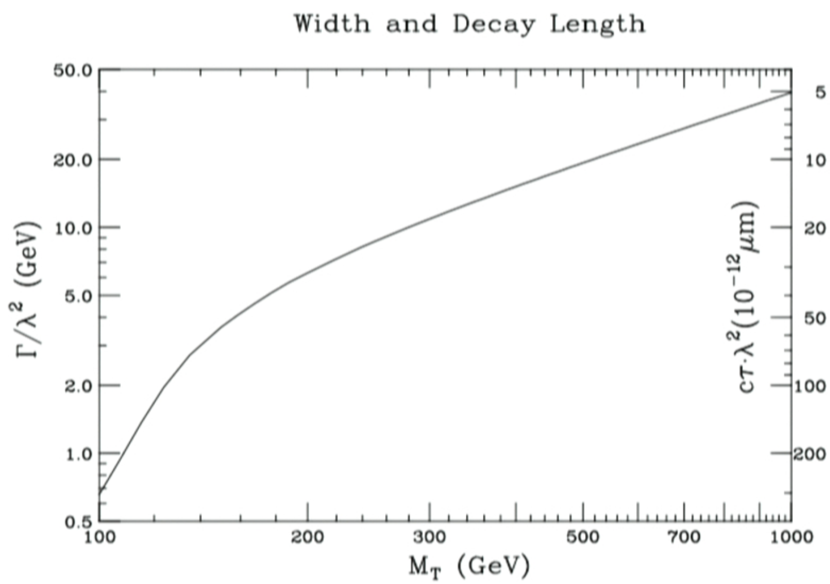
T^0, $T^\pm$ in Type III Seesaw at the LHC

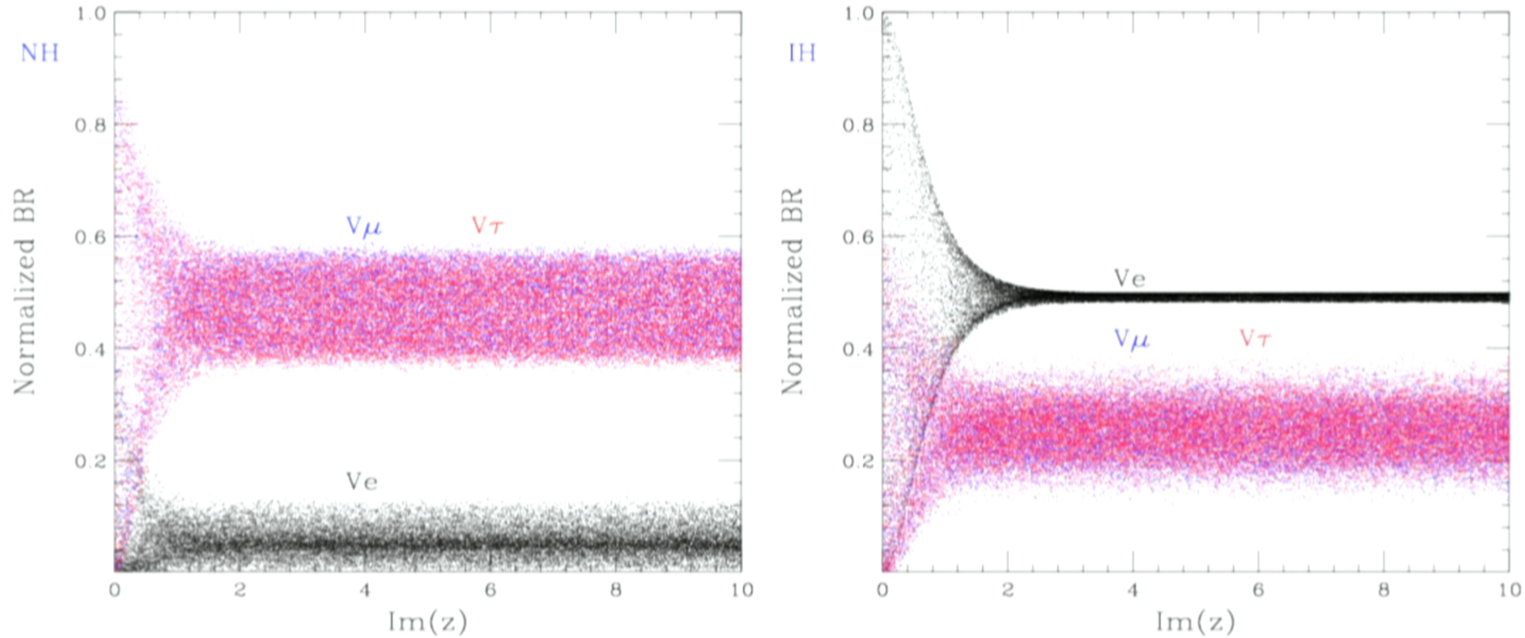
Consider their decay length:

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



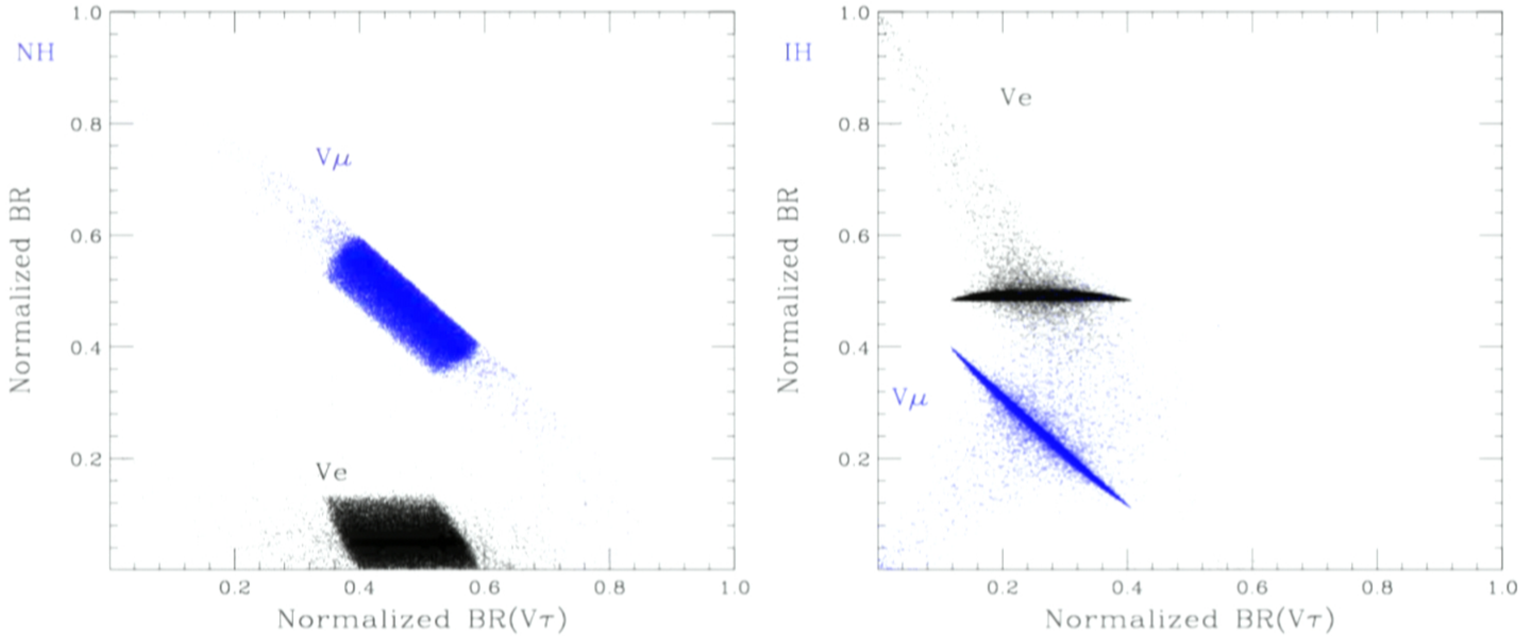
Lepton flavor combination determines the ν mass pattern: †

$$m_\nu^{ij} \sim -v^2 \frac{y_T^i y_T^j}{M_T}, \qquad BR \sim y_T^2 \sim V_{MNS}^2 \frac{M_T m_\nu}{v^2} \; (\sin z, \; \cos z).$$

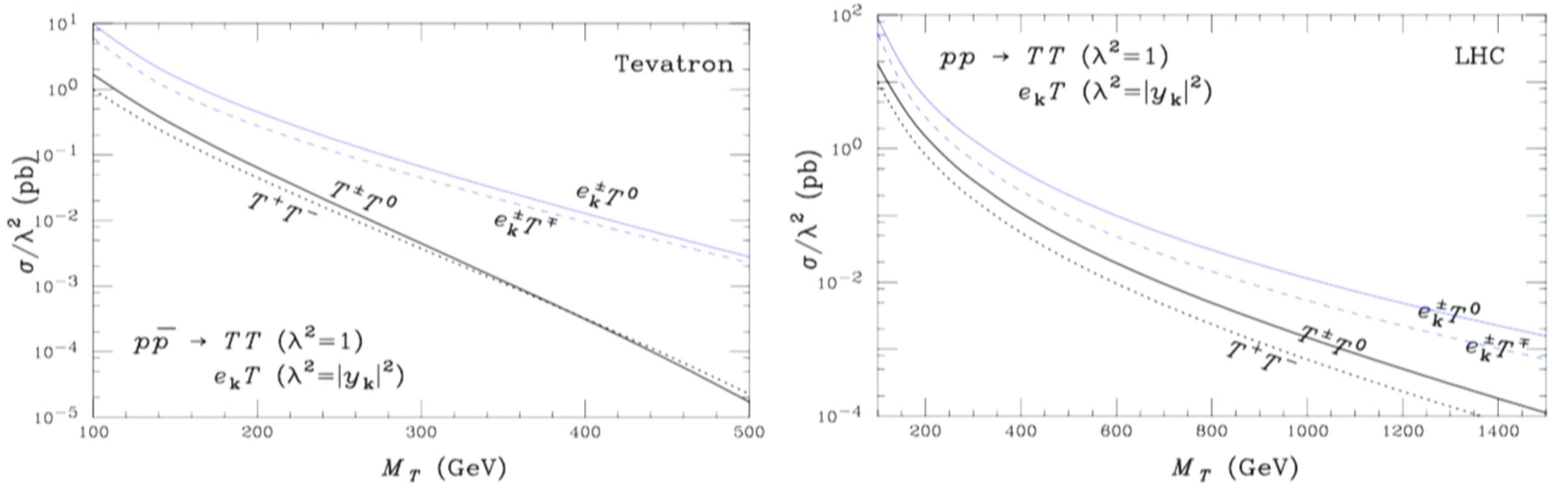


†Abdesslam Arhrib, Borut Bajc, Dilip Kumar Ghosh, Tao Han, Gui-Yu Huang, Ivica Puljak, Goran Sejanovic, arXiv:0904.2390.

Lepton flavor correlations for the ν mass pattern:



Production rates at the Tevatron/LHC: †



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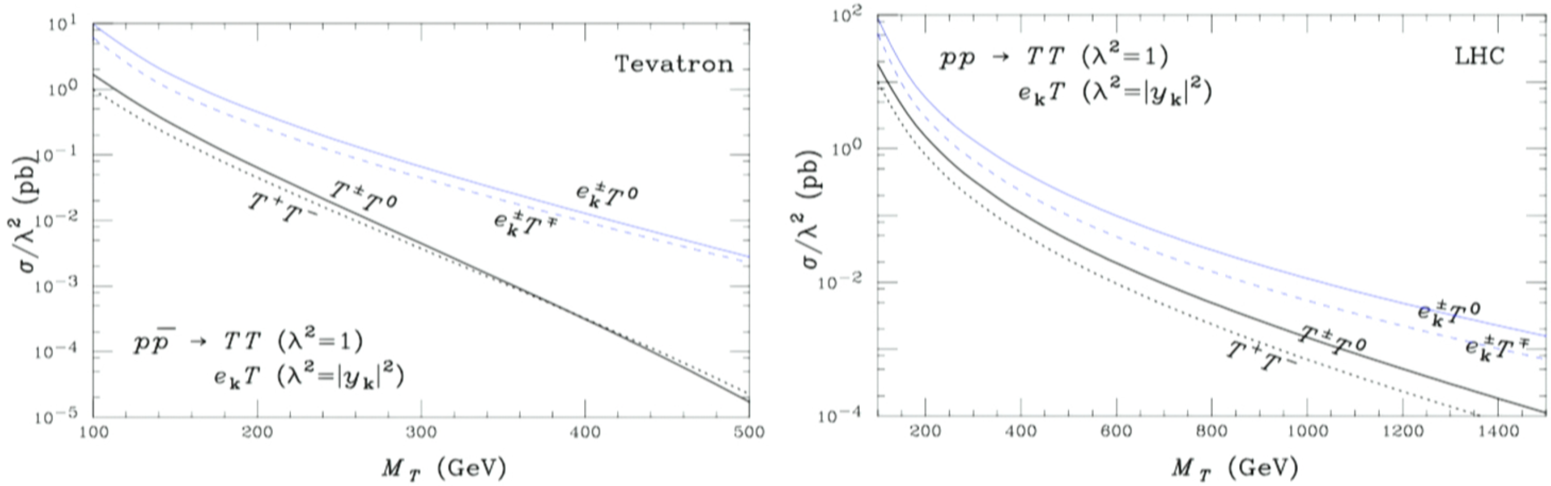


- Single production $T^\pm \ell^\mp$, $T^0 \ell^\pm$:

Kinematically favored, but highly suppressed by mixing.

- Pair production with gauge couplings.

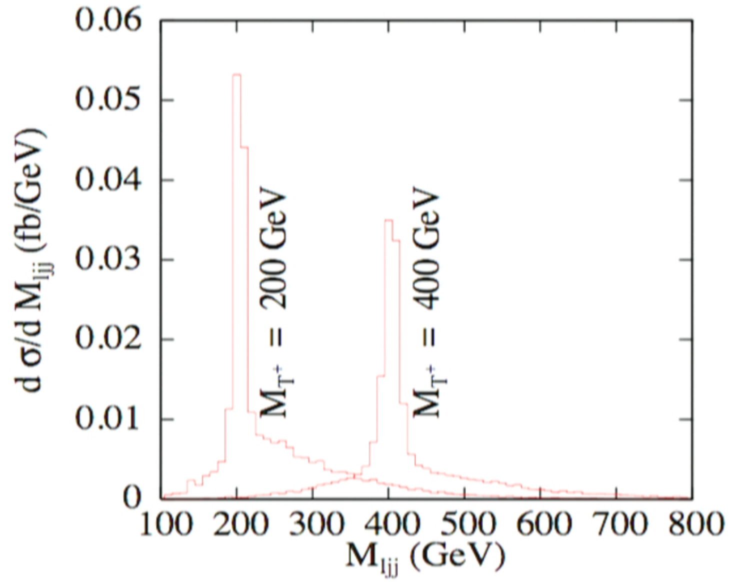
Example: $T^\pm + T^0 \to \ell^+ Z(h) + \ell^+ W^- \to \ell^+ jj(b\bar{b}) + \ell^+ jj.$

Low backgrounds.

†Similar earlier work: Franceschini, Hambye, Strumia, arXiv:0805.1613.

Reconstruct mass bump: $M(\ell jj)$

Sensitivity reach: $\mathcal{O}$(200/800 GeV) at the Tevatron/LHC.



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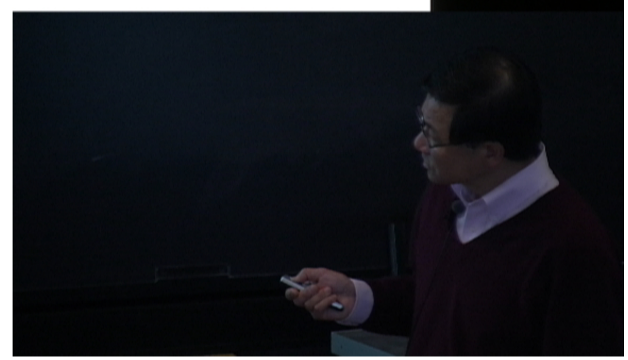

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IF lucky, hadron colliders may serve
as the discovery machine for Majorana nature of ν's.