Neutrino Masses:
Synergies Between
The Energy & Intensity Frontiers

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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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The See-saw spirit: †

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

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The See-saw implies the "synergy"!

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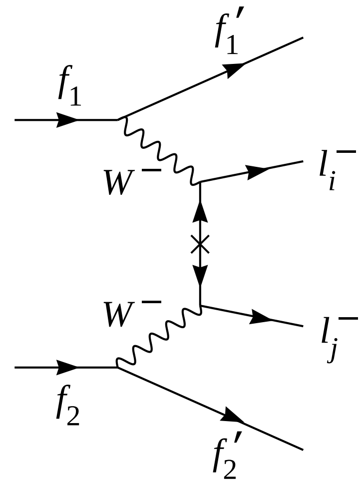

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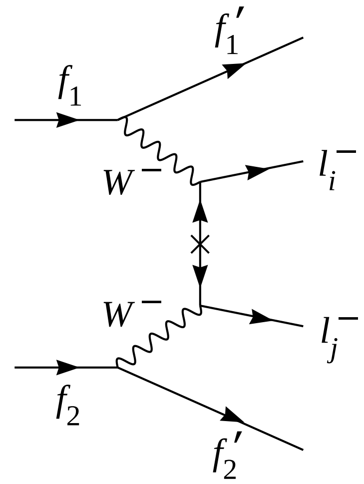

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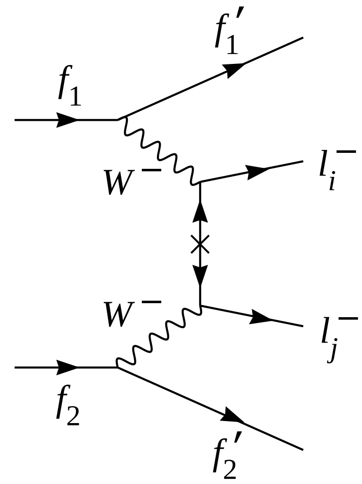

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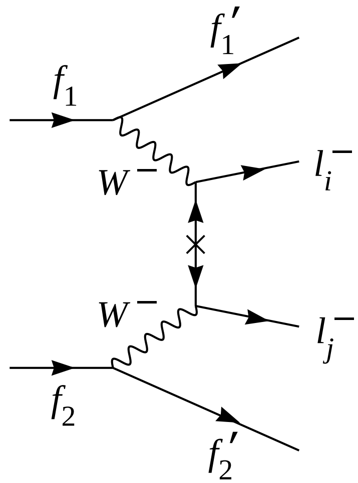

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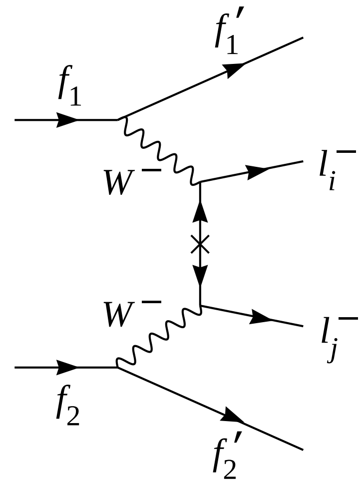

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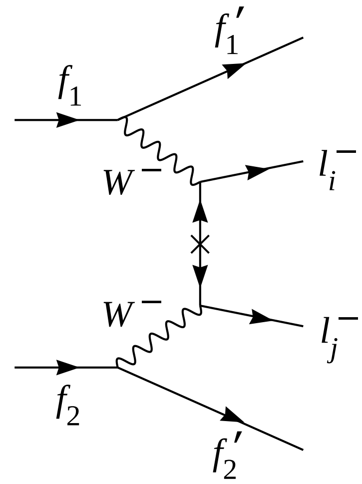

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Many theoretical models in SUSY, GUTs, SM extensions
(see talks by Mu-Chun Chen, Kayser, Pati, Babu, Mohapatra, Shafi ...)
We wiil stay in the minimal extension.

See-saw Models

Type I See-saw (with N_R):

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

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N_R's are "sterile"! No gauge interactions, only through mass mixing:

$$\sum_{a=1}^{3} \sum_{b=1}^{n} \overline{\nu_{aL}}\ m^{\nu}_{ab}\ N_{bR} + \sum_{b,b'=1}^{n\geq 2} \overline{N^c{}_{bL}}\ M_{bb'}\ N_{b'R} + h.c.$$

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

All Majorana neutrinos:

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

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

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

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

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$$+ \frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V^*_{\ell m'}\, \overline{N^c_{m'}} \gamma^\mu P_L \ell + h.c.$$

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

Still, it's possible for much lower see-saw scales[†], and sizable mixing[‡].

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All $U_{\ell m}$, Δm_ν are from oscillation experiments,
while taking $V_{\ell m}$, m_N free parameters
— in the hope, experimentally accessible.

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Type II see-saw (no N_R): *

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

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

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That leads to the Majorana mass:

$$M_{ij}\ \overline{\nu_i^c}\ \nu_j + h.c. \quad \text{where} \quad M_{ij} = Y_{ij}\langle\Phi\rangle = Y_{ij}v' \lesssim 1\ \text{eV},$$

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Very same gauge invariant/renormalizable term: †

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

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Main feature(s):

Doubly charged Higgs and their $\Delta L = 2$ decay.

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

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

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

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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.

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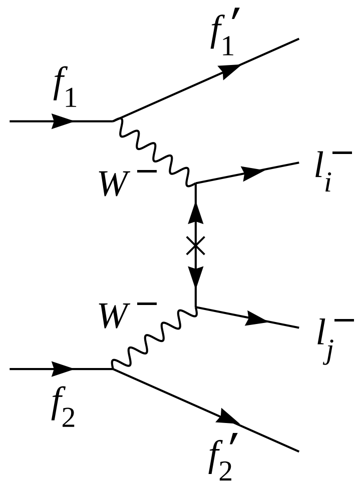
The Search for $\Delta L = 2$ Processes

(1). Neutrino-less double β Decay



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

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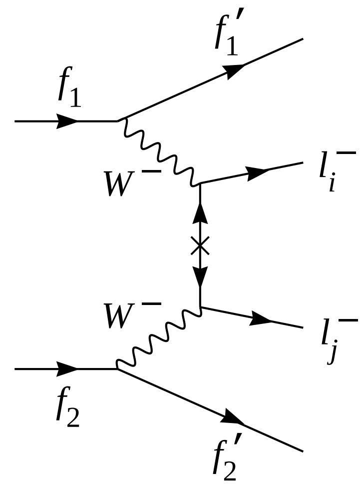

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The transition rates are proportional to

$$|\mathcal{M}|^2 \propto \begin{cases} \langle m \rangle_{ee}^2 = \left| \sum_{i=1}^{3} U_{ei} U_{ei} m_i \right|^2 & \text{for light } \nu \quad \Rightarrow \langle m \rangle_{ee} \sim \mathcal{O}(0.1 \text{ eV}) \\ \dfrac{\left| \sum_i^n V_{ei} V_{ei} \right|^2}{m_N^2} & \text{for heavy } N \ \Rightarrow |V_{eN}|^2 / m_N < 5 \times 10^{-8} \text{ GeV}^{-1} \end{cases}$$

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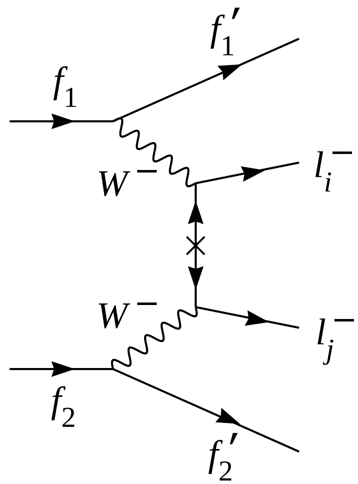

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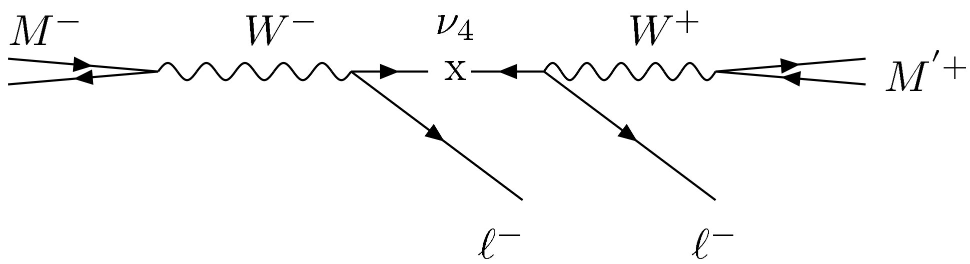
This afternoon session.

(2). N Resonance Production and Decay



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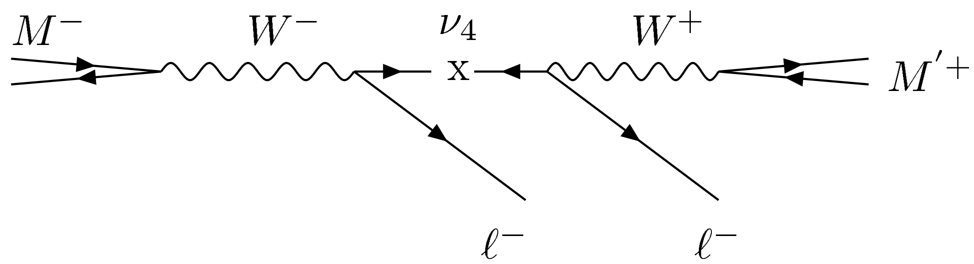

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We calculated† all the $\tau,\ K,\ D,\ B$ decays: $M^+ \to \ell_i^+ \ell_j^+ M^-$ via N and compare with the existing experimental bounds.*

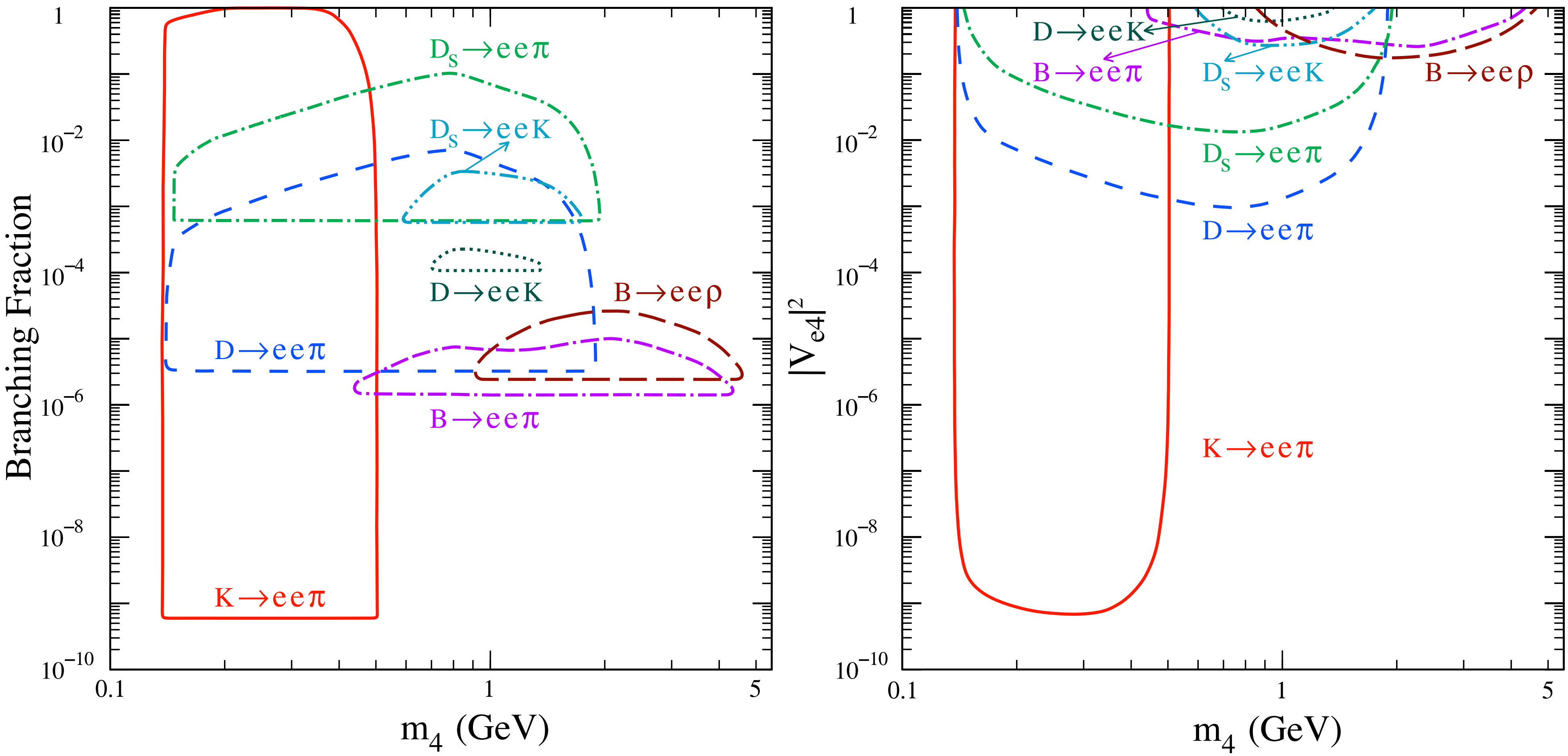
We scan the parameters in the range:

$$10^{-10} < |V_{e4}|^2,\quad |V_{\mu 4}|^2,\quad |V_{\tau 4}|^2 < 0.2$$
$$m_4 > 140 \text{ MeV},\quad m_e + m_\pi \text{ threshold;}$$
$$\dots\ \dots$$
$$m_4 > 3.8 \text{ GeV},\quad m_\tau + M_D \text{ threshold;}$$
$$m_4 \sim\ 5.2 \text{ GeV},\quad M_B \text{ kinematics.}$$

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

*PDG.

Sensitivity to V_{e4}:



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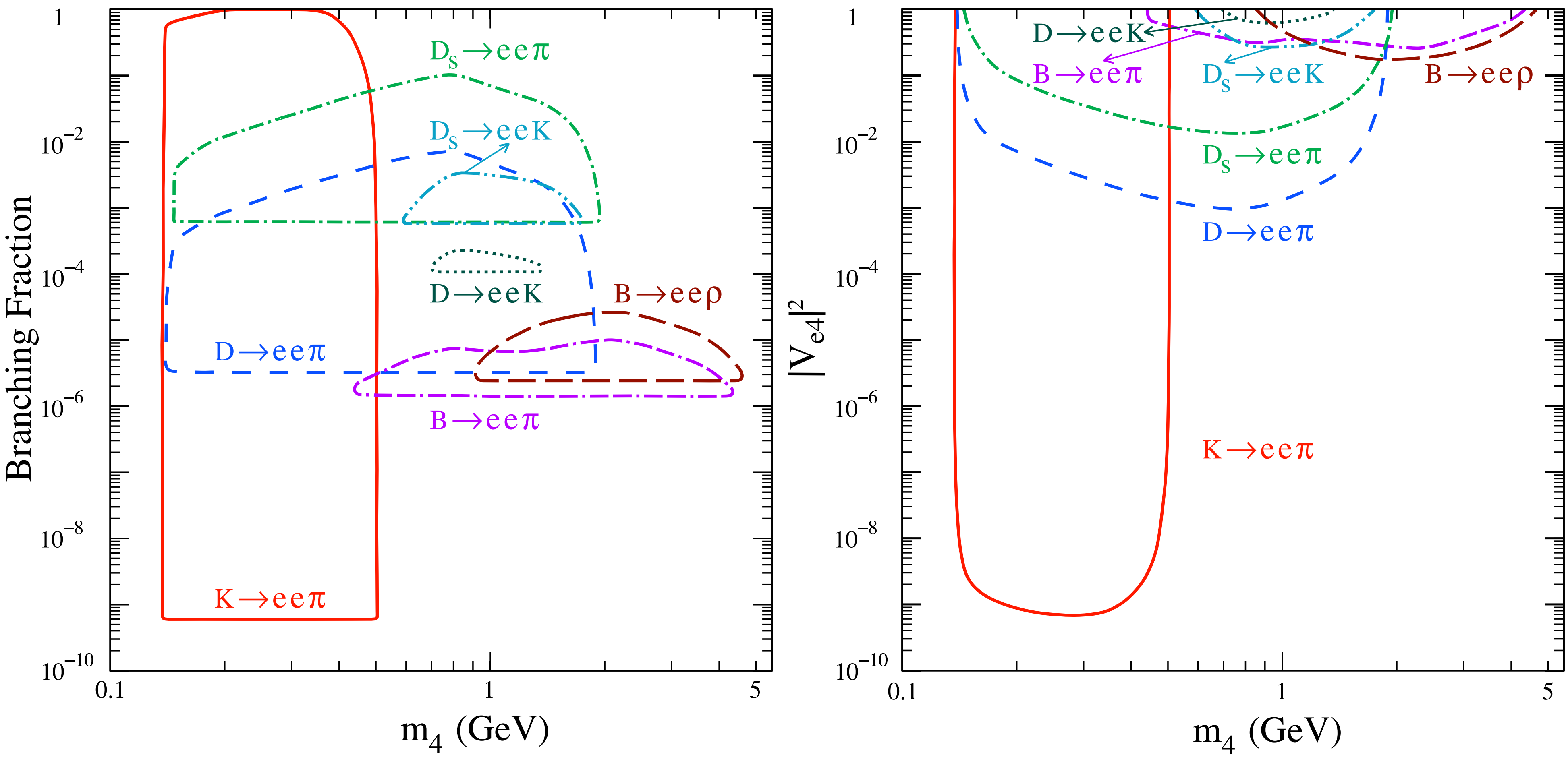
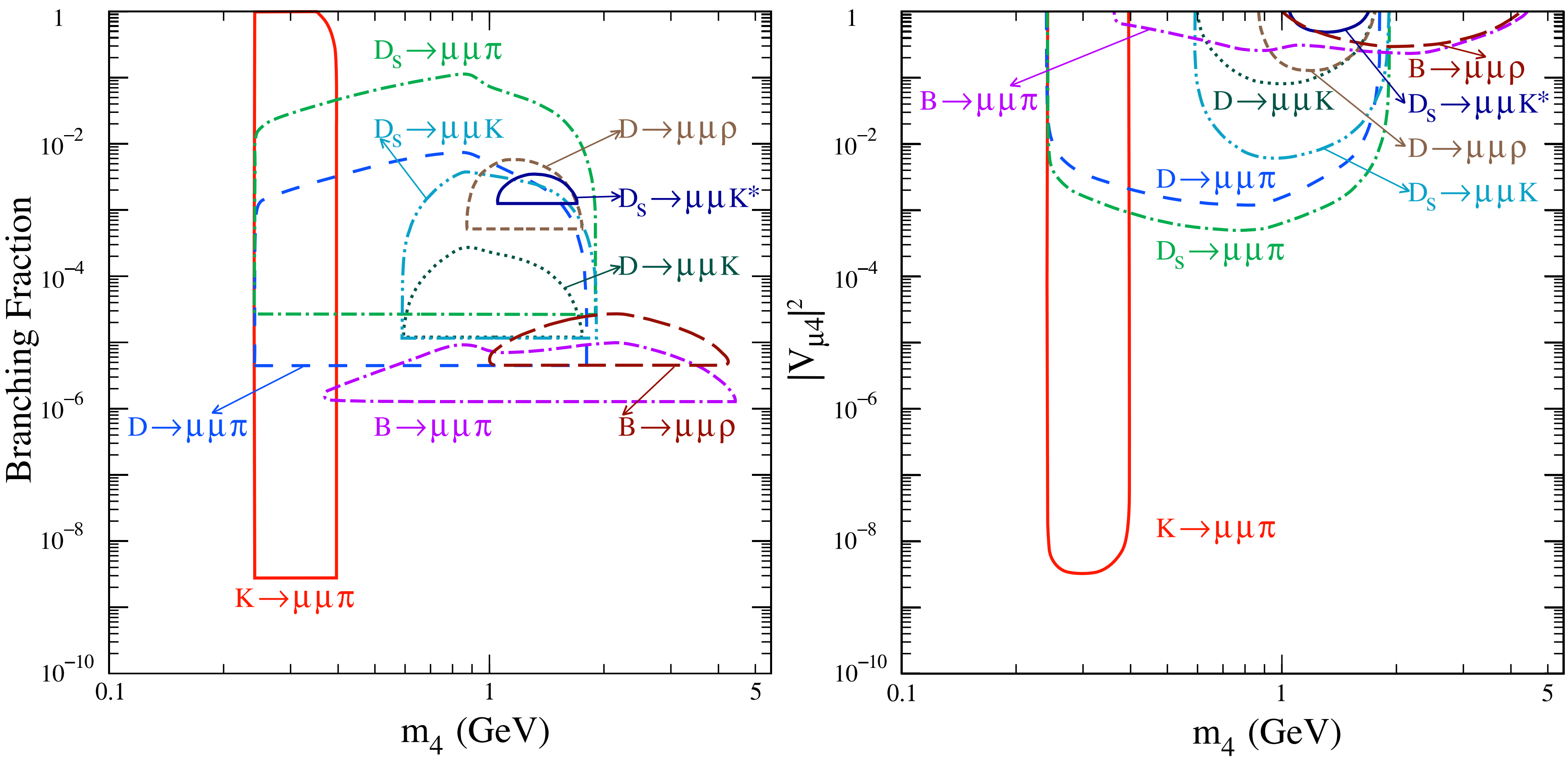


- Depending on the unkown parameter $|V_{\ell 4}|^2$,
  BR's can easily reach $10^{-6} - 10^{-2}$,
  N_4 may show up in any one of the channels !

Sensitivity to $V_{\mu 4}$:



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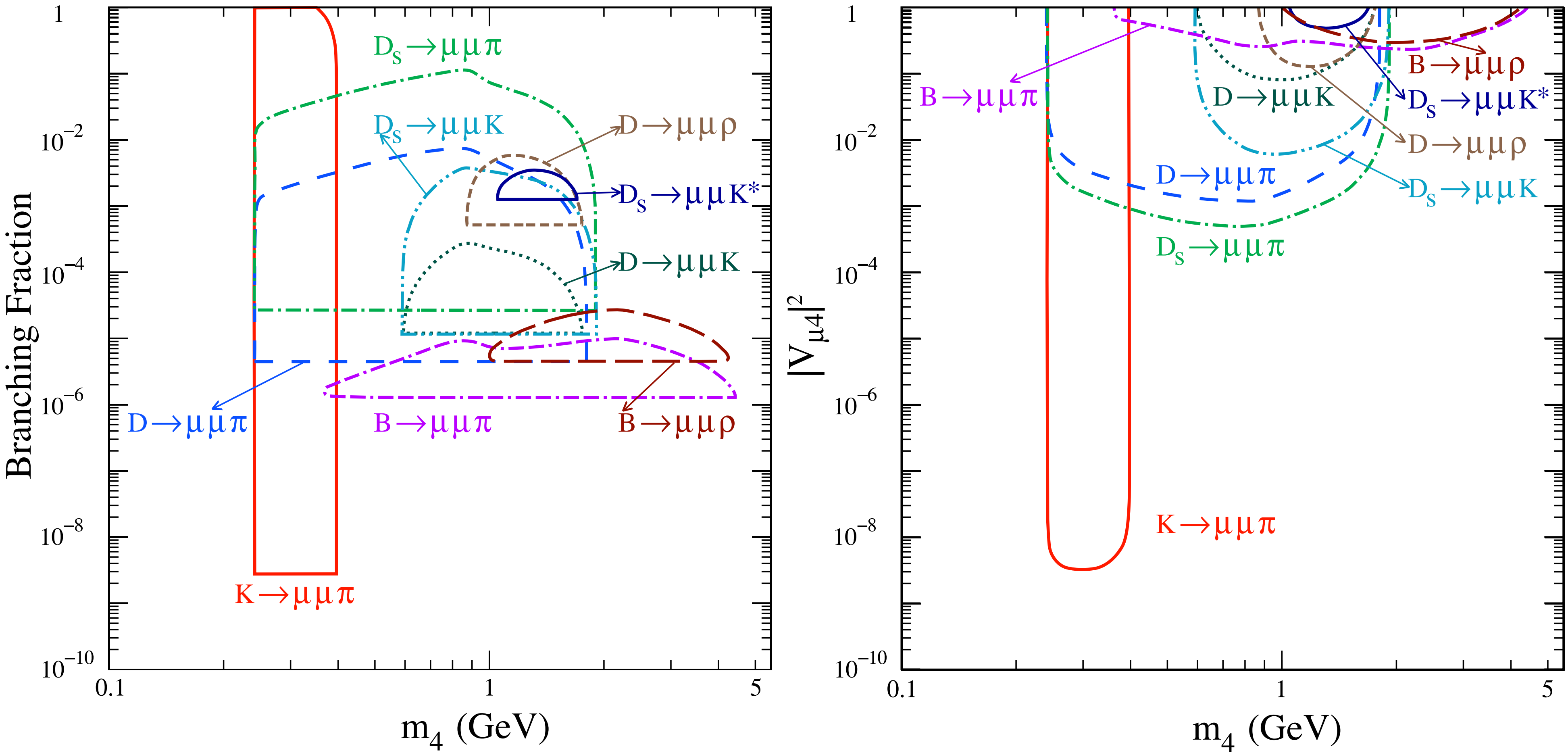
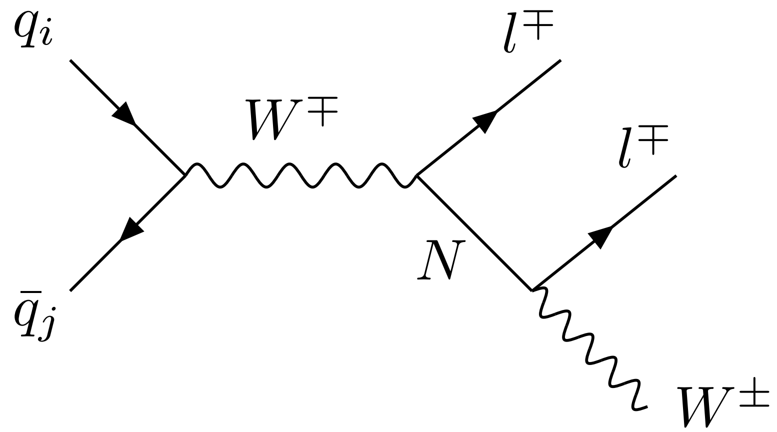


- Other processes to look for:

$$D^+,\ B^+ \to \ell^+ \ell^+ K^*,$$
$$B^+ \to \tau^+ e^+ M^-,\ \tau^+ \mu^+ M^-,\ \tau^+ \tau^+ M^-.$$

(3). Collider searches for Majorana N

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



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

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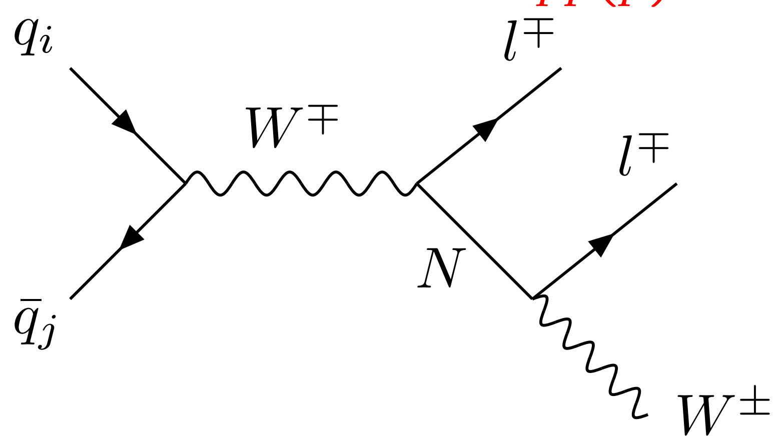

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Factorize out the mixing couplings: †

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

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

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†T. Han and B. Zhang, hep-ph/0604064, PRL (2006).

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;
- $m(jj) = M_W,\ m(jj\mu) = m_N$.

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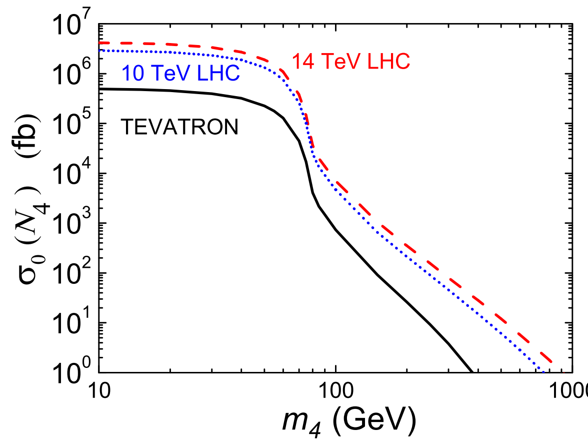

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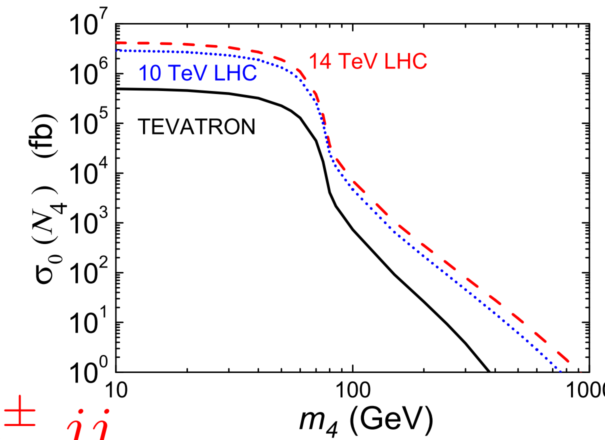

A very clean channel:

- like-sign di-muons plus two jets;
- no missing energies;
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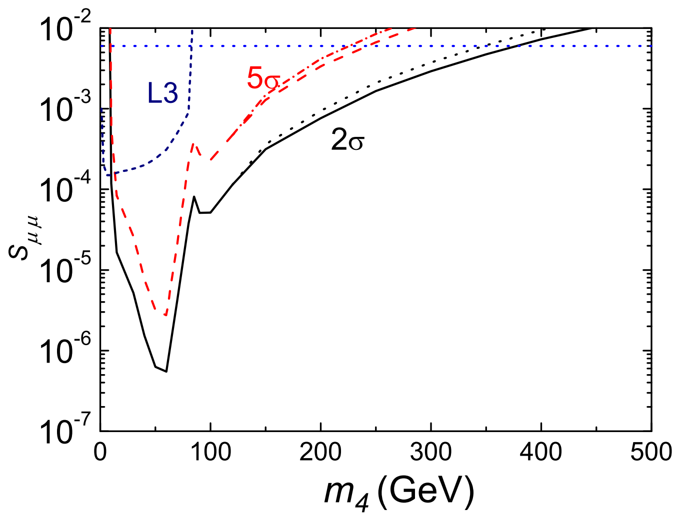
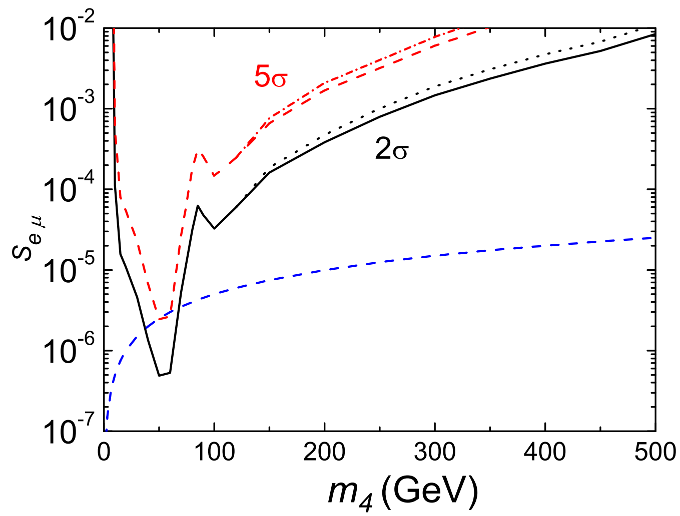
At the LHC:† $\mu^\pm\mu^\pm\ jj$ and $\mu^\pm e^\pm\ jj$





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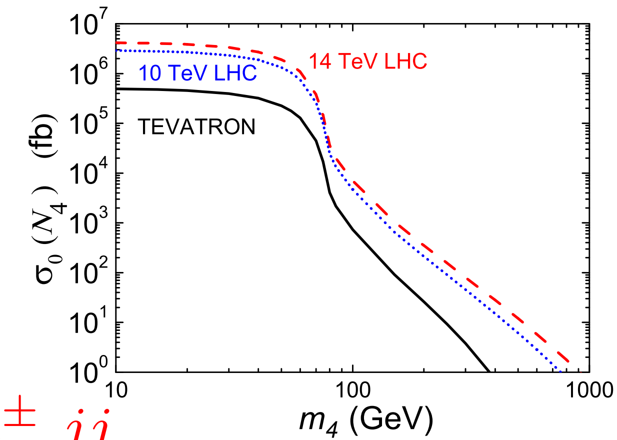

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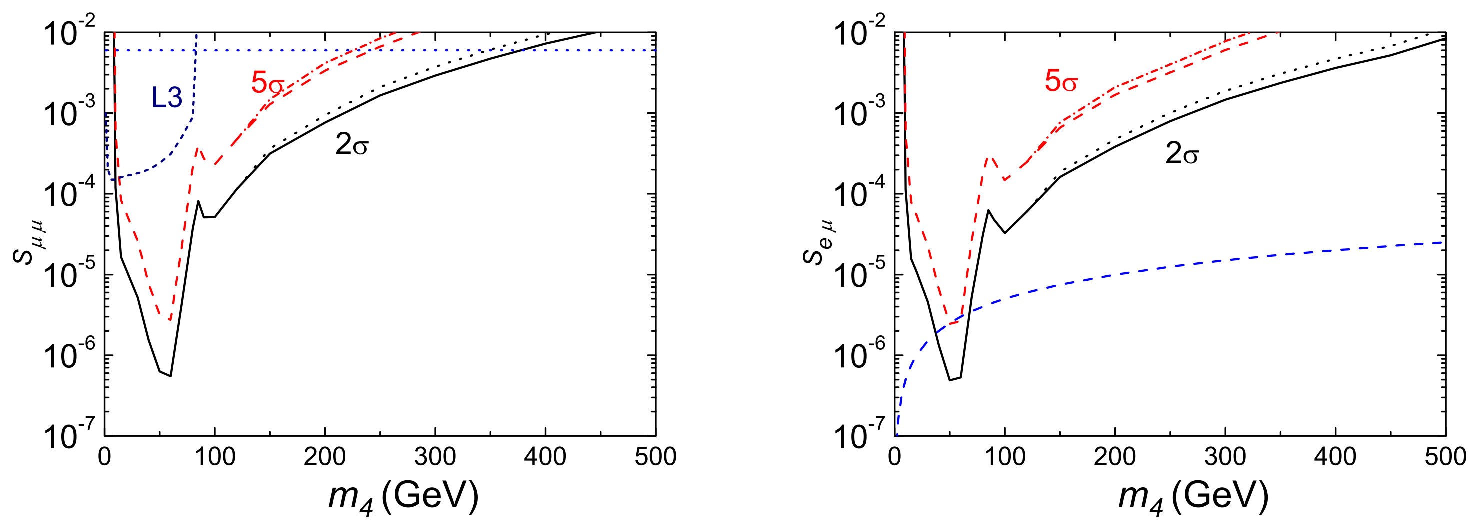


Sensitivity reach:

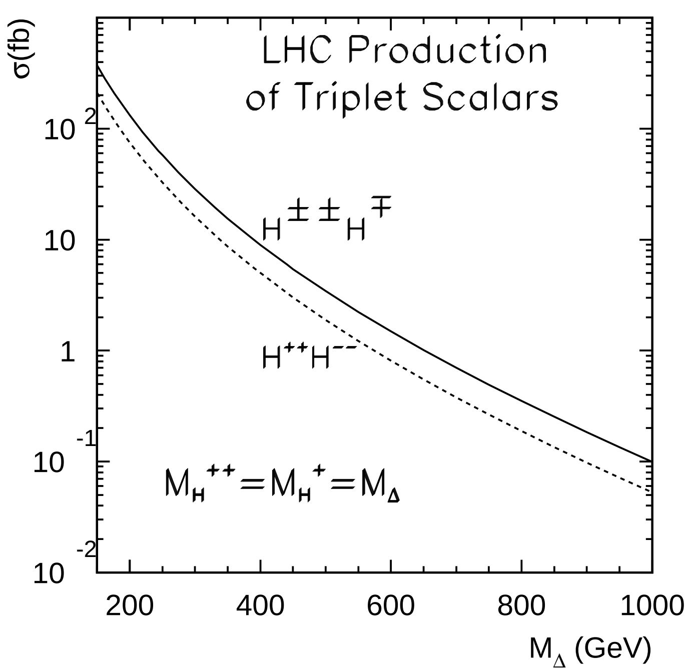
$\mu\mu$ mode: $V^2_{\mu\mu} \sim 5 \times 10^{-7},\ or\ m_4 \sim 400$ GeV.

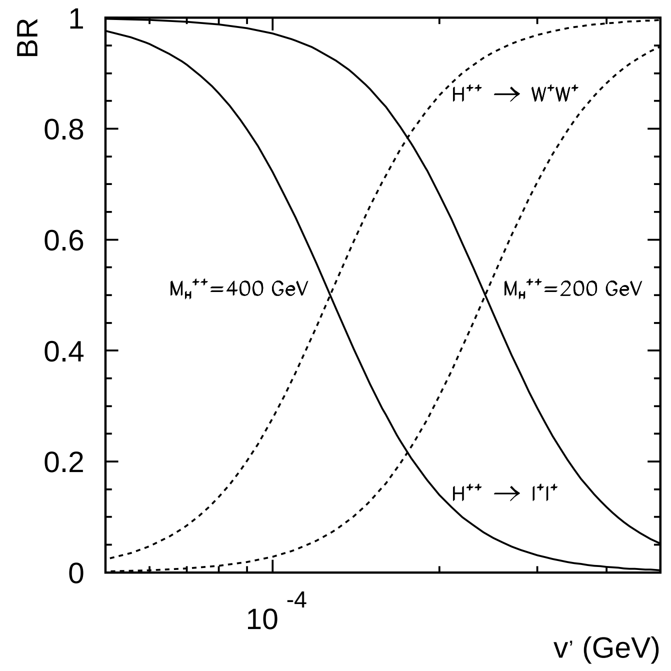
$e\mu$ mode: $V^2_{e\mu}$ below $0\nu\beta\beta$ bound at $m_4 \sim M_W$.

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

(4). Type II See-saw at the LHC

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





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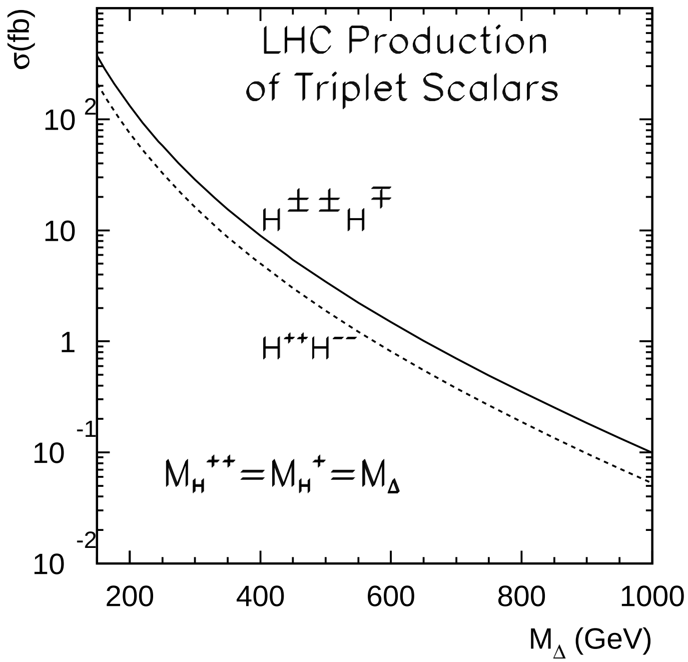

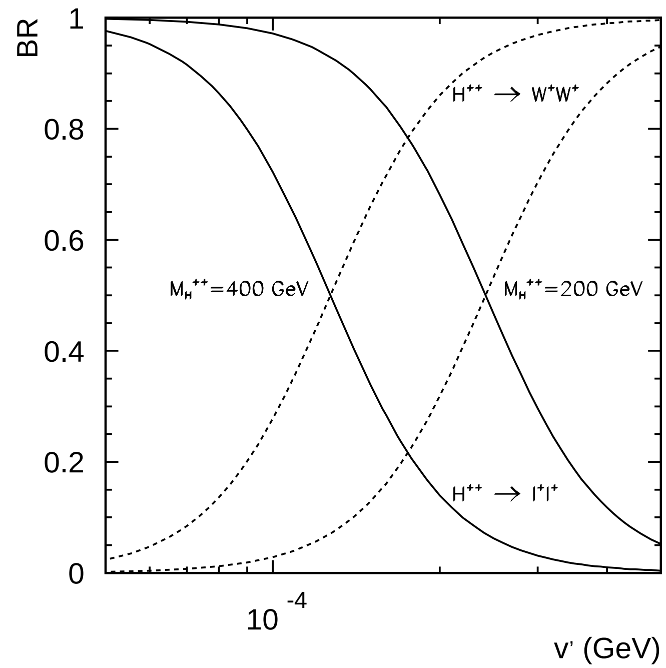

Unique decays:

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

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

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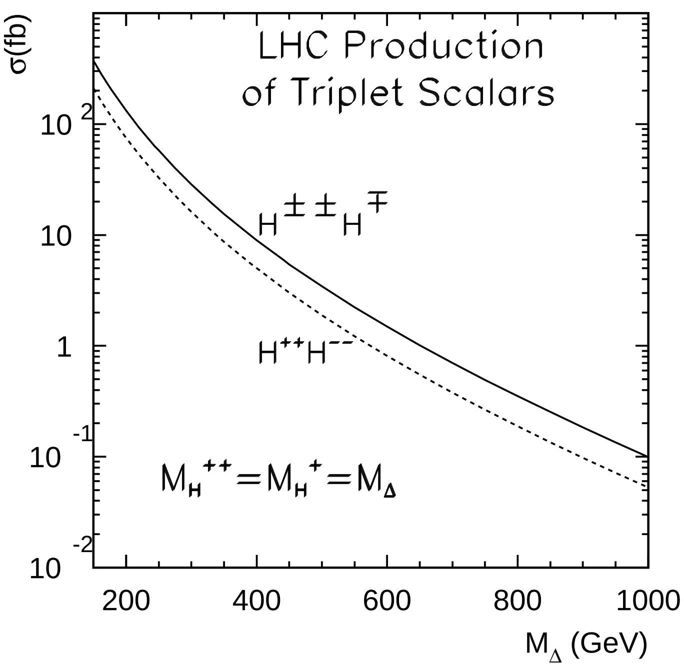

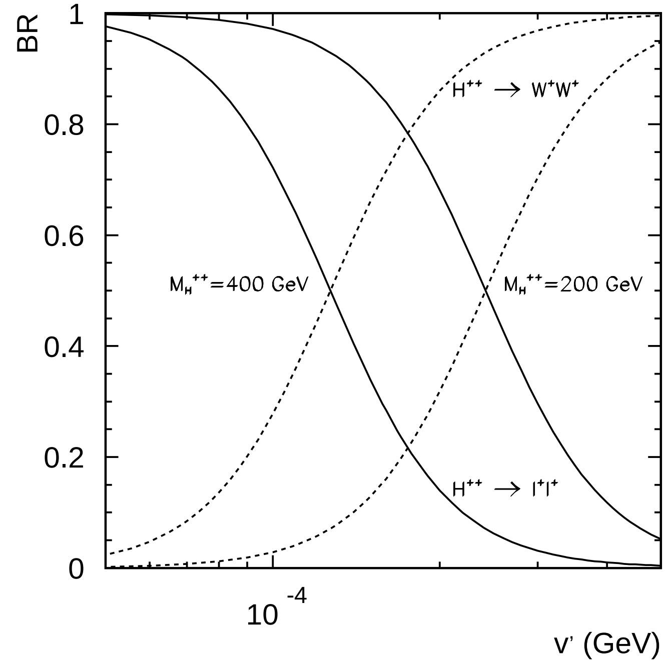

Unique decays:

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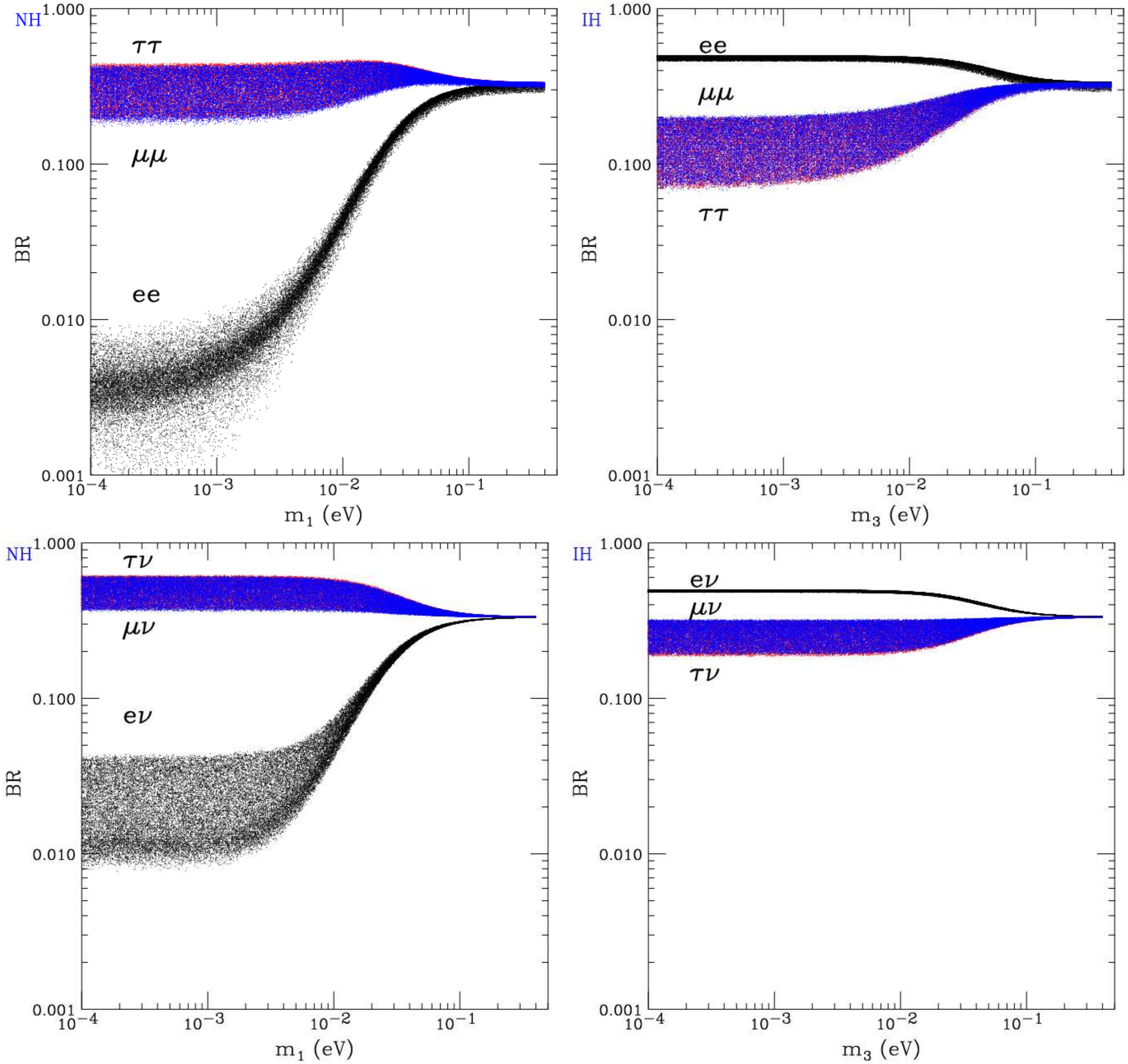
Will concentrate on the leptonic modes. †

† Pavel Fileviez Perez, Tao Han, Gui-Yu Huang, Tong Li, Kai Wang, arXiv:0803.3450 [hep-ph]

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

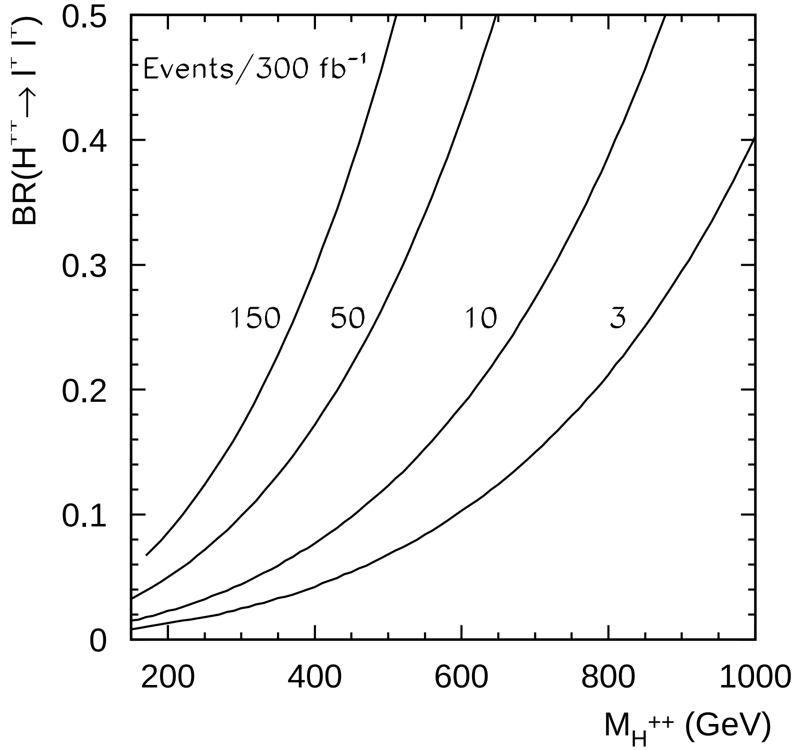


Summarize the discovery modes:

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($H^{+} \to \tau^+\bar{\nu}$) $\approx 1/3$

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.

†Pavel Fileviez Perez, Tao Han, Gui-Yu Huang, Tong Li, Kai Wang, arXiv:0803.3450 [hep-ph]

(5). Type III See-saw at the LHC: T^0, $T^\pm$

Lepton flavor combination determines the ν mass pattern: †

$$m_\nu^{ij} \sim -v^2 \frac{y_T^i y_T^j}{M_T}, \quad BR(T^{\pm,0} \to W^\pm \ell,\ Z\ell) \sim y_T^2 \sim V_{PMNS}^2 \, \frac{M_T m_\nu}{v^2}.$$

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

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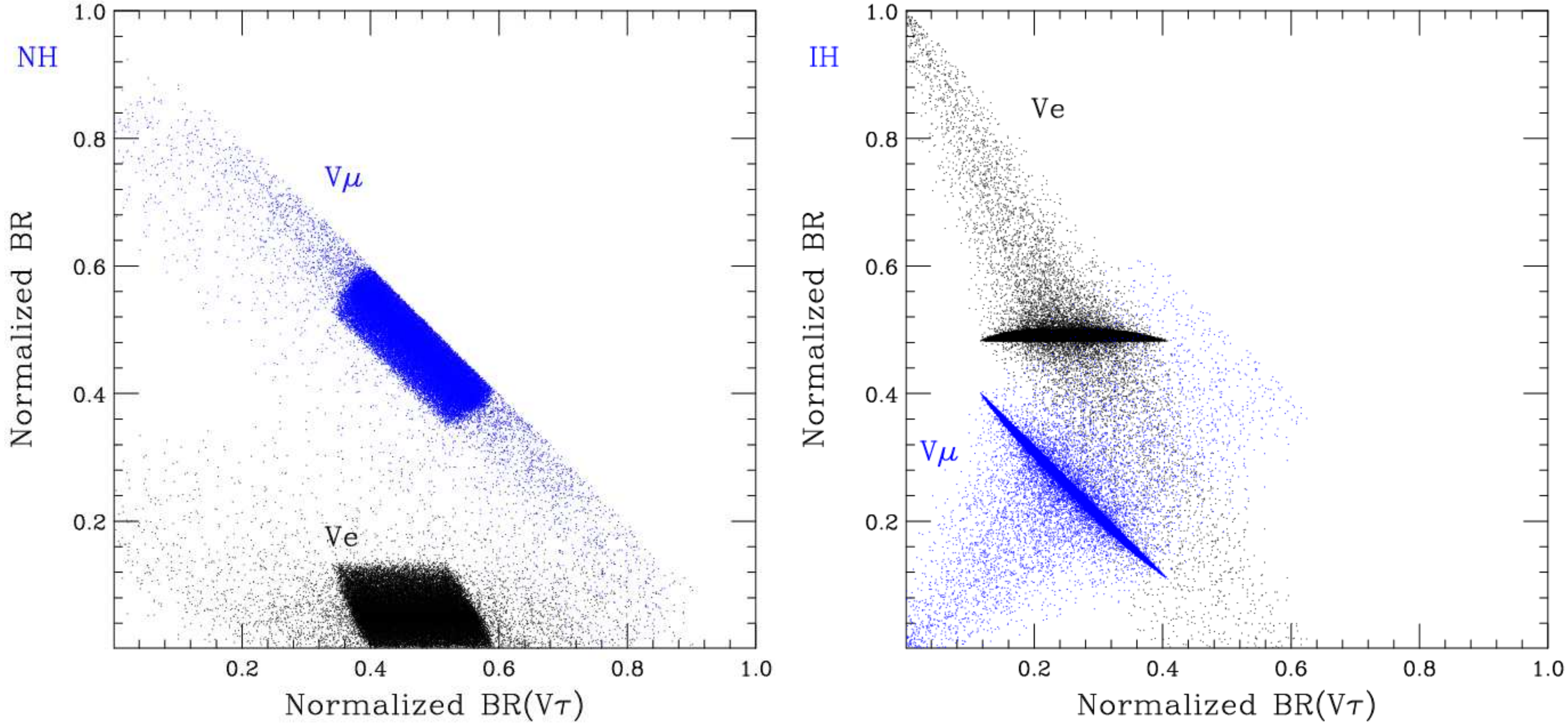

Lepton flavors correlate with the ν mass pattern.

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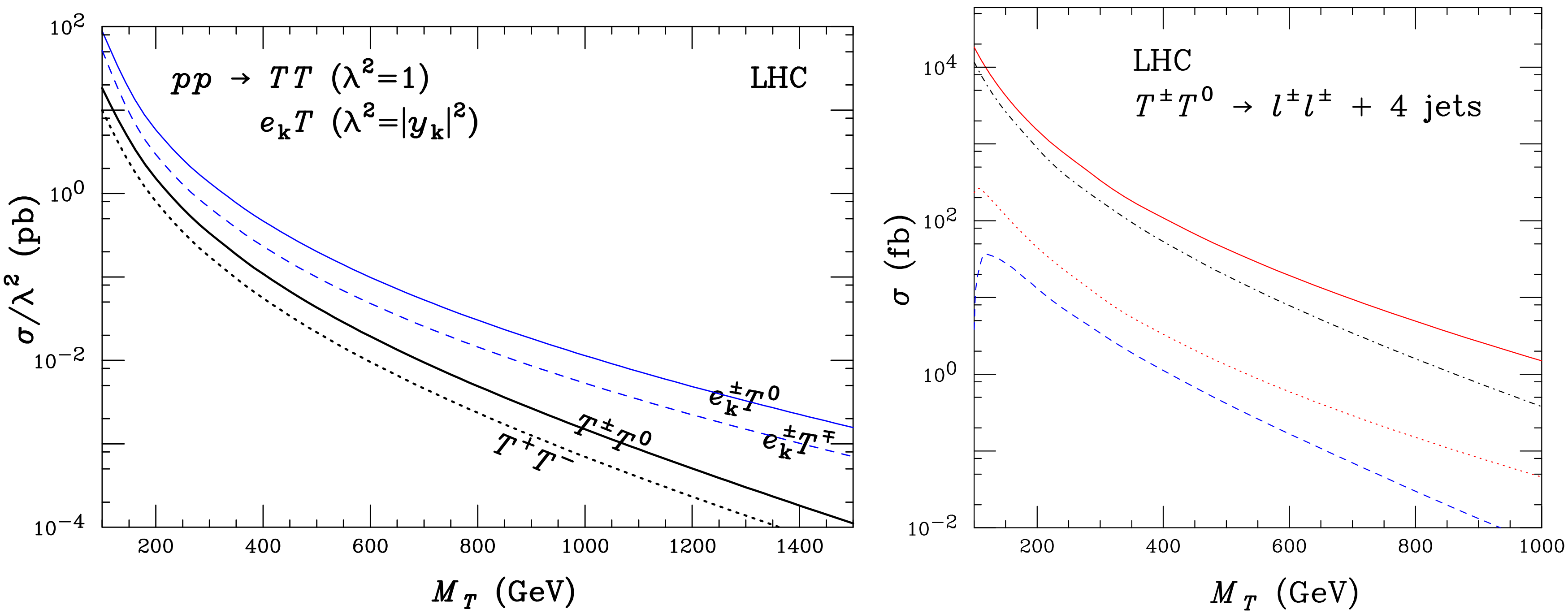
Production rates at the Tevatron/LHC: †



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

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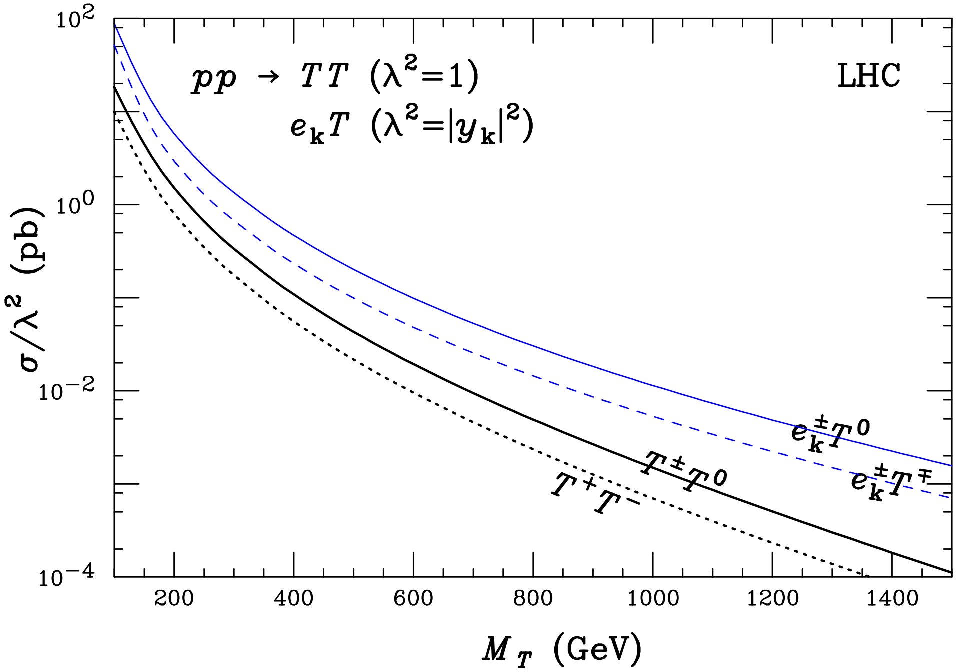

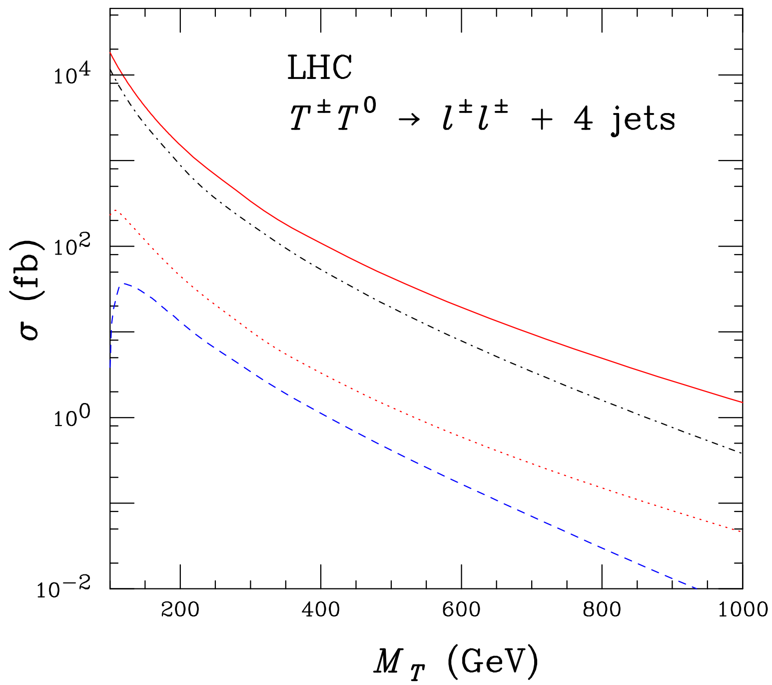

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Example: $T^\pm + T^0 \to \ell^+ Z(h) + \ell^+ W^- \to \ell^+ jj(b\bar{b}) + \ell^+ jj.$

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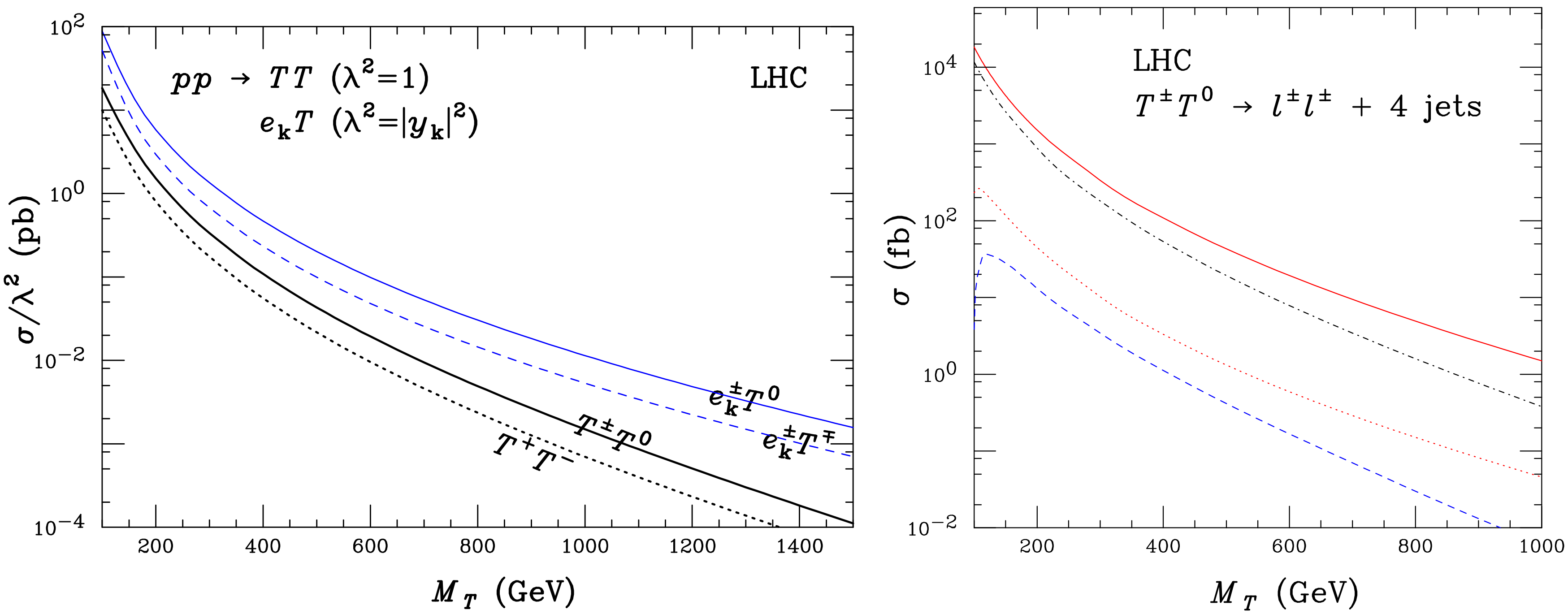

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The See-saw models for m_ν may be the best playground

for synergies between the intensity and energy frontiers.
(connecting to the cosmo frontier as well.)