The Search for Lepton-Number Violation Processes

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Outline:

A Brief Introduction:

- What we know about neutrinos
- Simplest extension beyond the SM:
  Dirac versus Majorana

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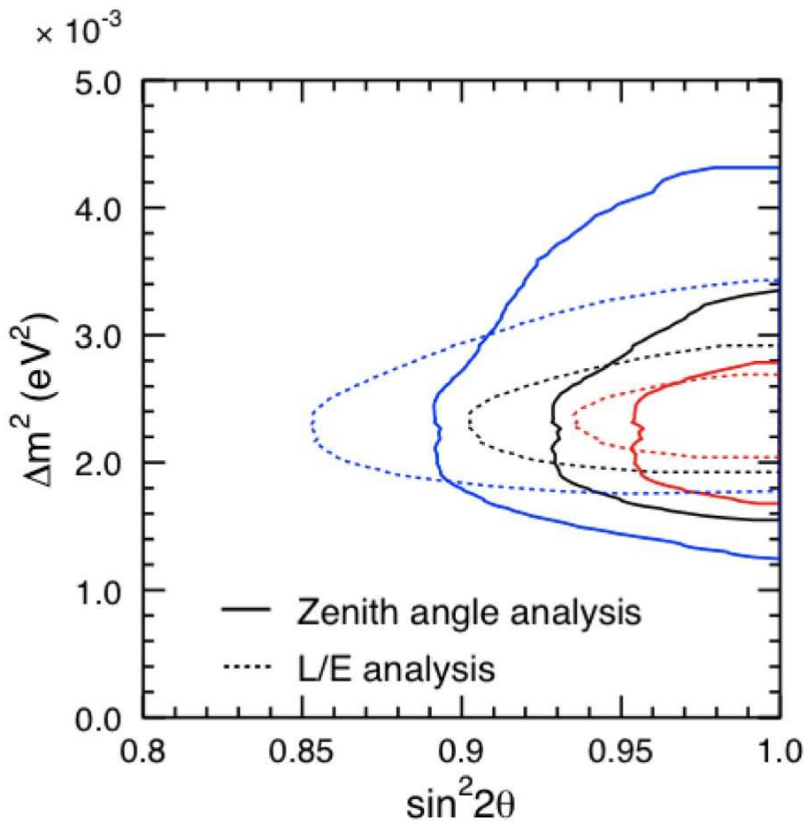
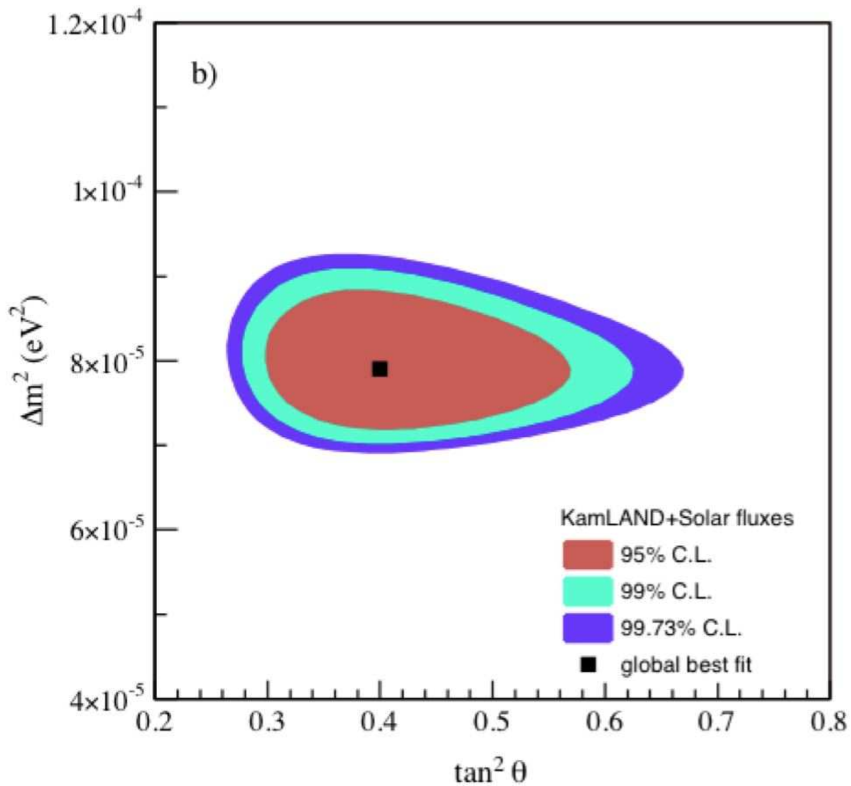
Summary

Neutrinos are massive

Now we know: *

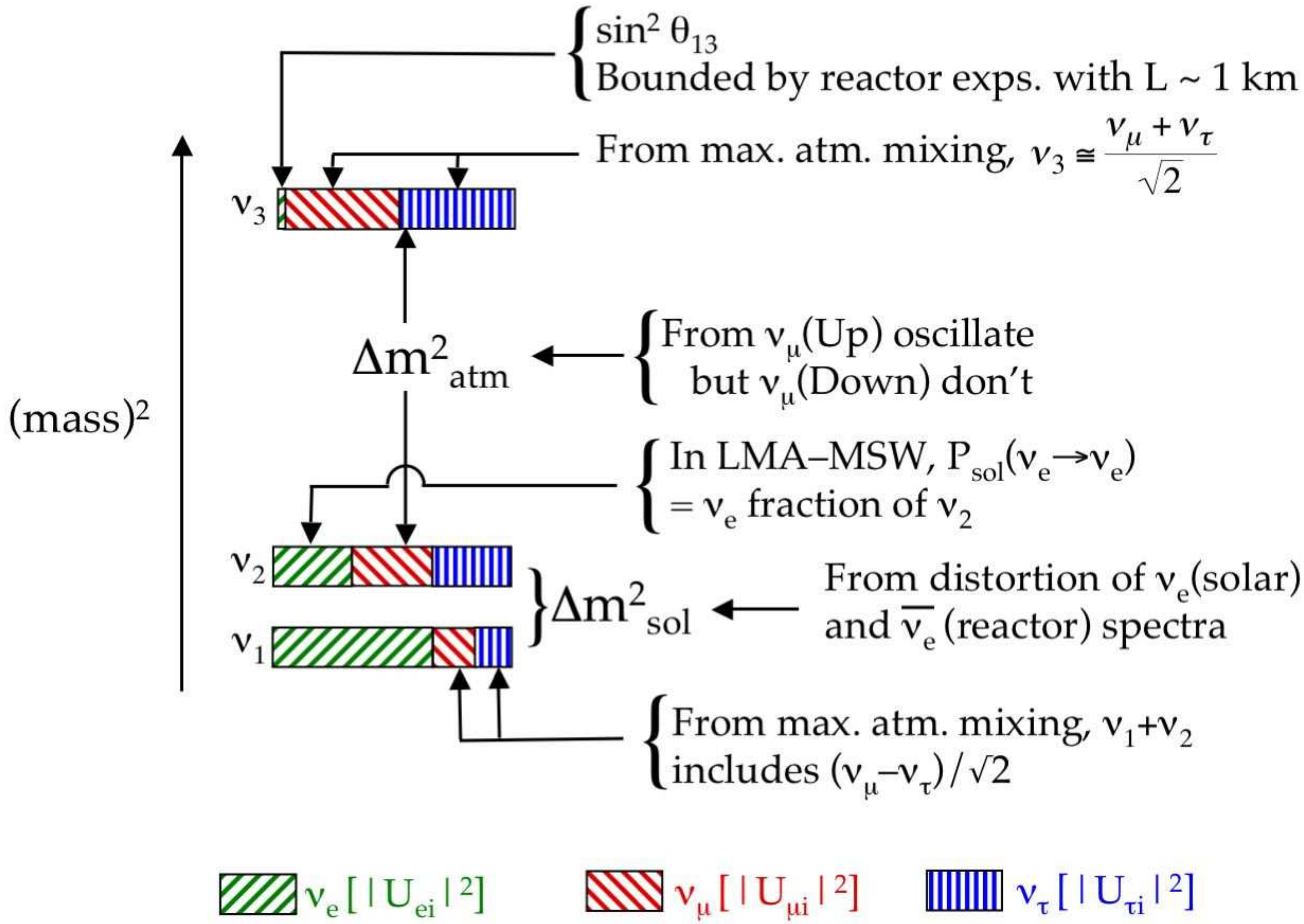




$$1.9 \times 10^{-3}\ \mathrm{eV}^2 < \ \Delta m^2_{atm} \ < 3.0 \times 10^{-3}\ \mathrm{eV}^2$$
$$7 \times 10^{-5}\ \mathrm{eV}^2 < \ \Delta m^2_{sol} \ < 9 \times 10^{-5}\ \mathrm{eV}^2.$$

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

The mass relation and flavor components:*



*B. Kayser

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- The absence of neutrinoless double-beta decay ($0\nu\beta\beta$)
  bound on Majorana mass: $\langle m_{ee} \rangle < 1$ eV.

Neutrinos masses: Dirac versus Majorana

Simplest extension of the SM:

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

Gauge-invariant Yukawa interactions

$$\begin{aligned} -\mathcal{L}_Y &= \sum_{a=1}^{3} \sum_{b=1}^{n} f^{\nu}_{ab} \, \overline{L_{aL}} \, \hat{H} N_{bR} + h.c. \\ &\Rightarrow \sum_{a=1}^{3} \sum_{b=1}^{n} \overline{\nu_{aL}} \, m^{\nu}_{ab} \, N_{bR} + h.c. \end{aligned}$$

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But, N_R's are “sterile” !

If there are Majorana mass terms:

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

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

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

All Majorana neutrinos:

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

$$N_{bR} = \sum_{m=1}^{3} X^*_{bm}\nu^c_{mR} + \sum_{m'=4}^{3+n} Y^*_{bm'}N_{m'R},$$

$$UU^\dagger + VV^\dagger = I, \quad XX^\dagger + YY^\dagger = I,$$

where U is the MNSP mixing matrix; and typically $V^\dagger V \sim m_\nu/m_N$.

The charged currents:

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

The neutral currents:

$$-\mathcal{L}_{NC} = \frac{g}{2\cos_W} Z_\mu \sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U_{\ell m}^* \, \overline{\nu_m} \gamma^\mu P_L \, \nu_\ell$$

$$+ \frac{g}{2\cos_W} Z_\mu \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V_{\ell m'}^* \, \overline{N_{m'}^c} \gamma^\mu P_L \, \nu_\ell$$

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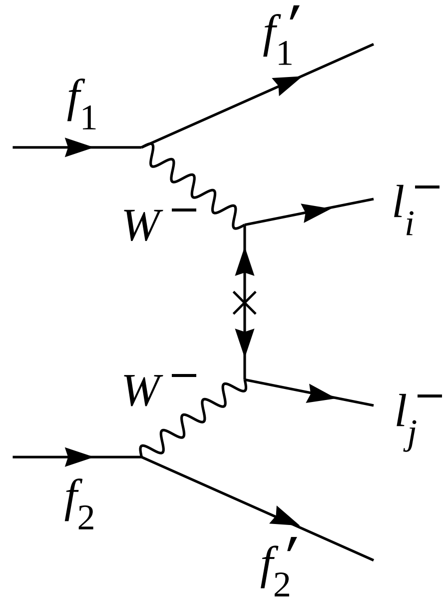
NC also off-diagonal once mass eigenstates involved.

While $U_{\ell m}$, Δm_ν are from oscillation experiments,
we consider $V_{\ell m}$, m_N free parameters.

$\Delta L = 2$ Processes

The fundamental diagram:



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

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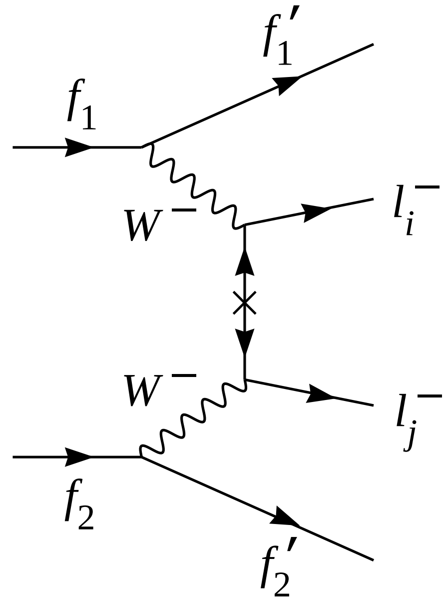

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The transition rates are proportional to

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

Three active light neutrinos:

Determination of the "effective neutrino mass"* $\langle m \rangle_{\ell_1 \ell_2}$

Trade input parameters:

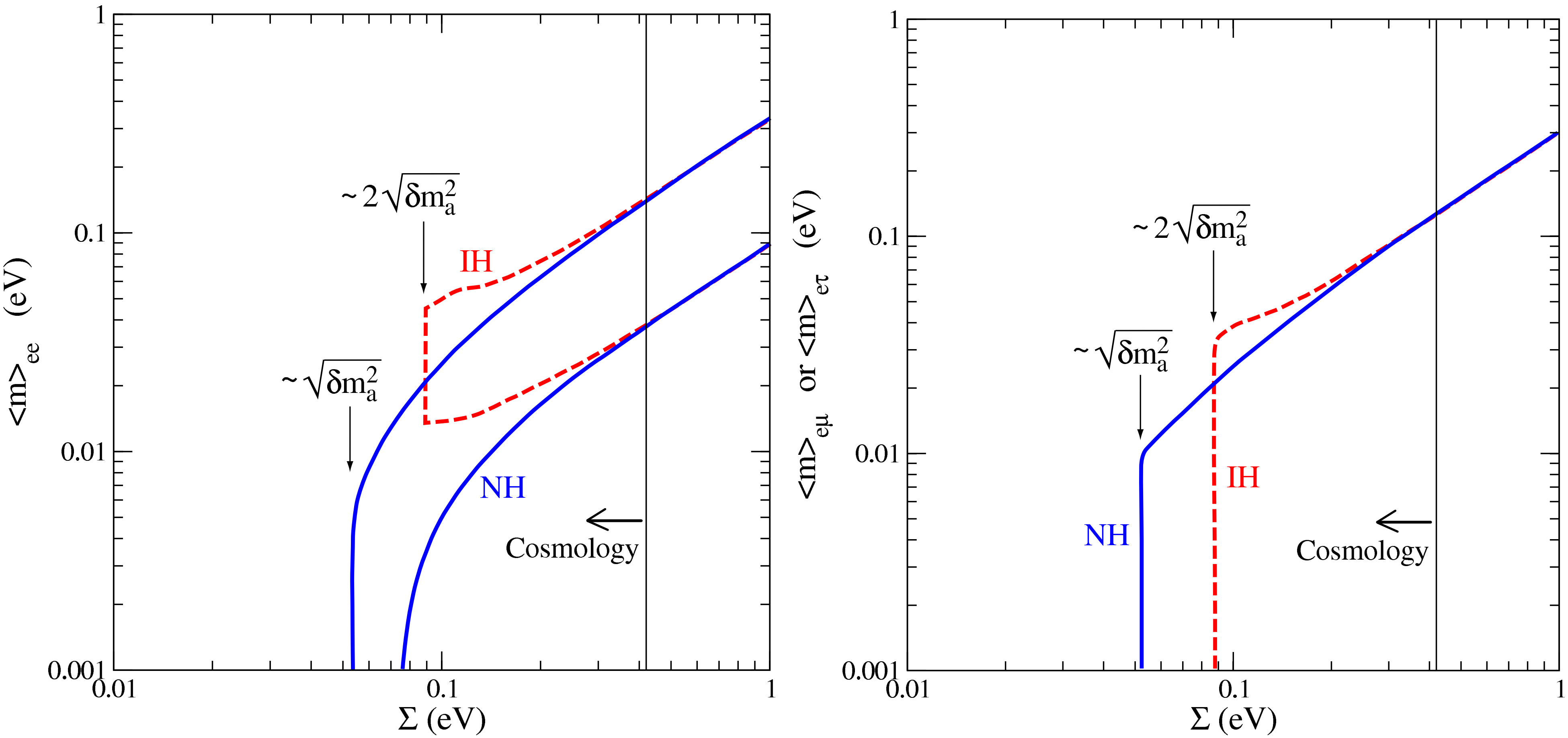
$$m_1,\ m_2,\ m_3 \Longrightarrow \delta m_s^2,\ \delta m_a^2,\ \Sigma = m_1 + m_2 + m_3.$$

Inputs to Monte Carlo sampling:

Parameter	Input
$\lvert \delta m_a^2 \rvert$	1.9×10^{-3} eV^2 – 3.0×10^{-3} eV^2
δm_s^2	90% CL δm_s^2 versus $\tan^2\theta_s$
θ_a	90% CL δm_a^2 versus $\sin^2 2\theta_a$
θ_s	90% CL δm_s^2 versus $\tan^2\theta_s$
θ_x	CHOOZ 90% CL exclusion
δ	0 to 2π
ϕ_2	0 to 2π
ϕ_3	0 to 2π

*A. Atre, V. Barger, T. Han, PRD (2005)

The allowed regions for $\langle m \rangle_{\ell_1 \ell_2}$: Upper bounds $\langle m \rangle_{ee}$ and $\langle m \rangle_{e\mu}$ ($\langle m \rangle_{e\tau}$) versus Σ (eV)



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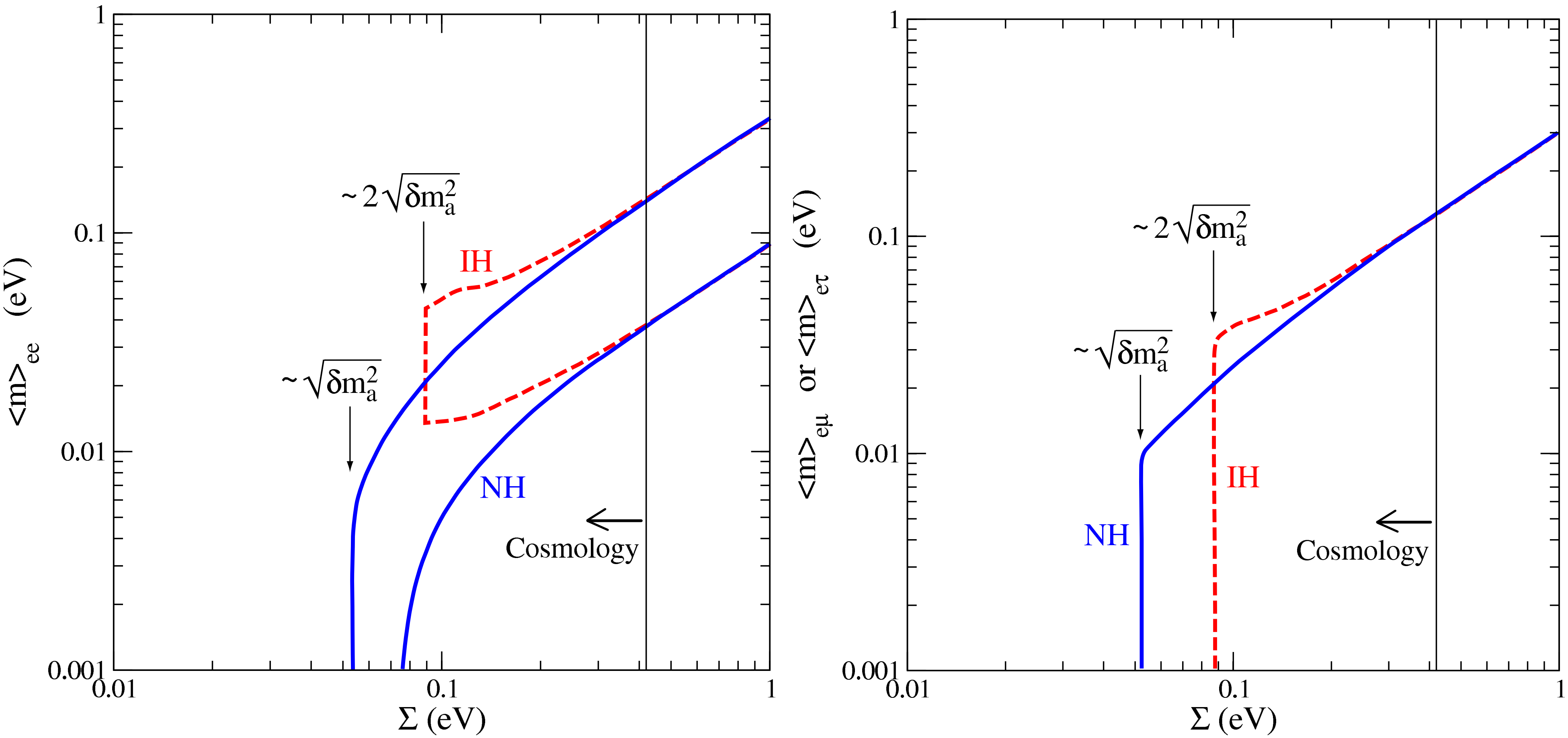
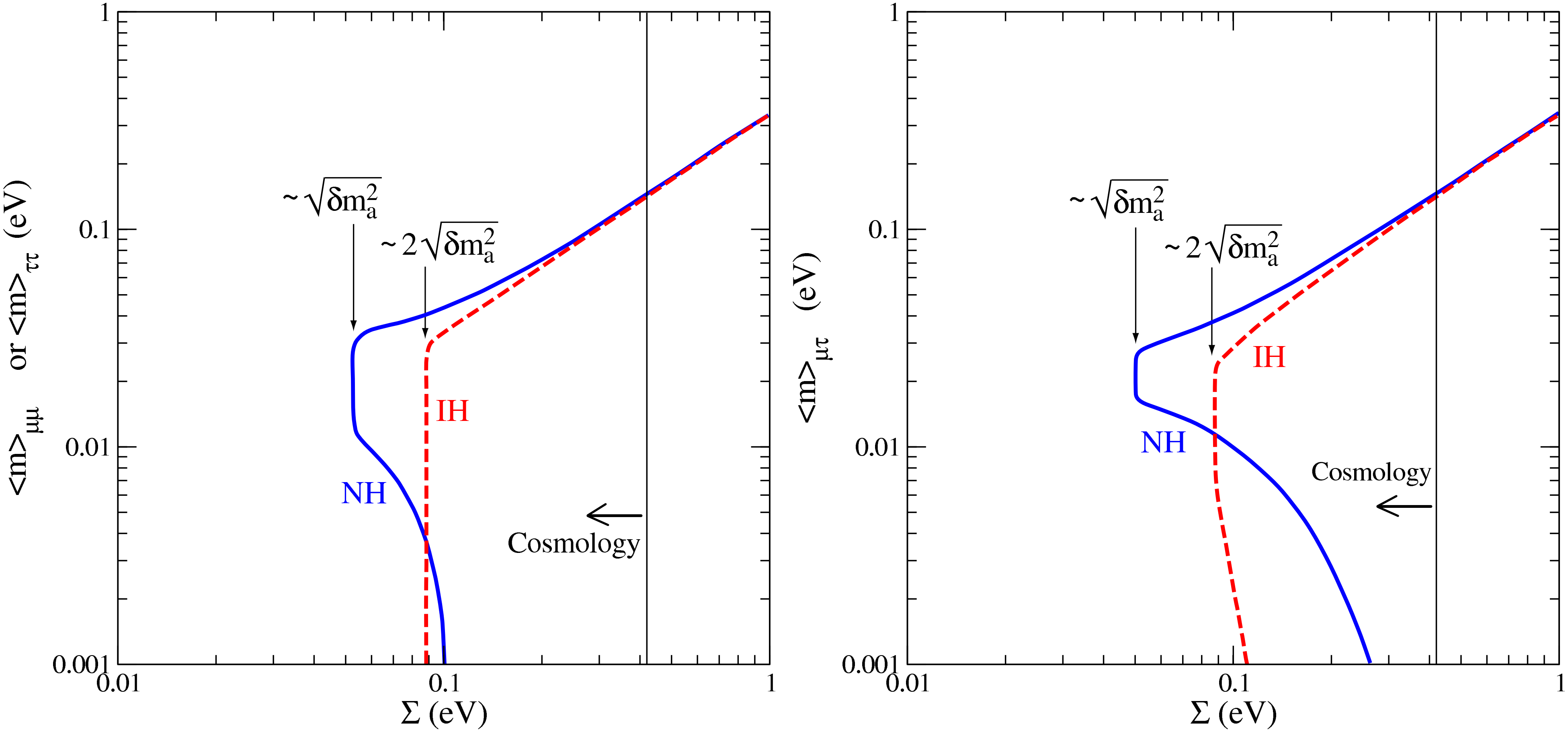
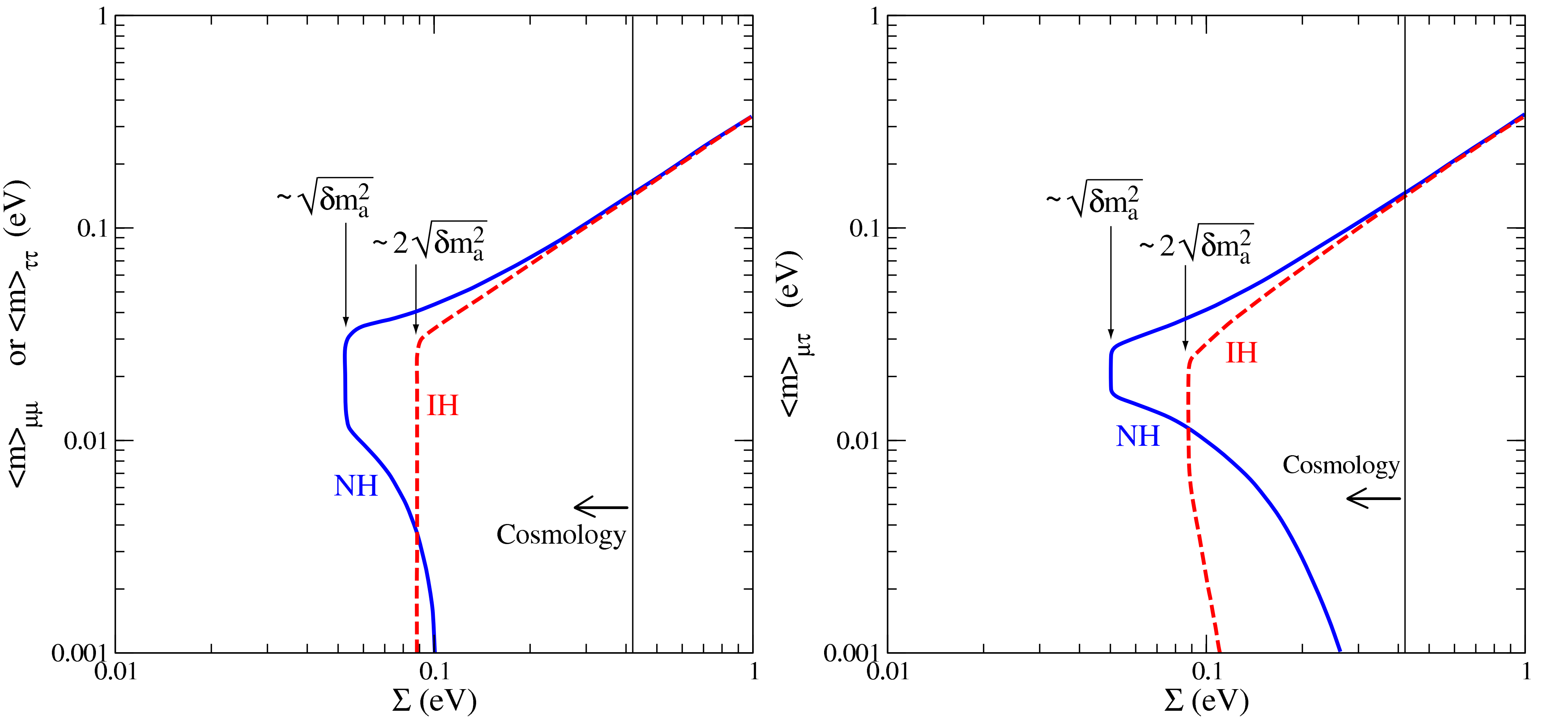


- Cosmo bound $\Sigma \leq 0.42$ eV leads to $\langle m \rangle_{\ell_1 \ell_2} < 0.14$ eV.

$\langle m \rangle_{\mu\mu}$ $(\langle m \rangle_{\tau\tau})$ and $\langle m \rangle_{\mu\tau}$ versus Σ (eV)



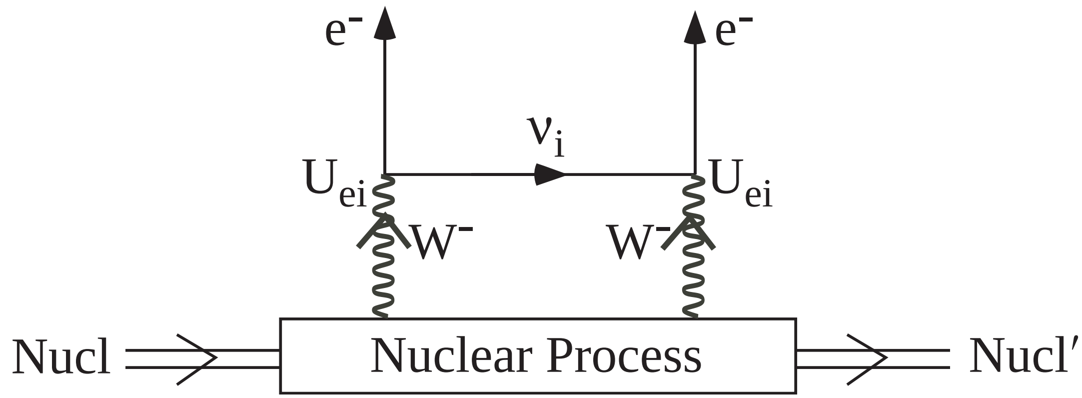
$\langle m \rangle_{\mu\mu}$ ($\langle m \rangle_{\tau\tau}$) and $\langle m \rangle_{\mu\tau}$ versus Σ (eV)



- For $m_\nu^{min} \gg \sqrt{\delta m_a^2}$, $\Sigma > 3 m_\nu^{min} \approx 3 \langle m \rangle_{\ell_1 \ell_2}$ (Degenerate masses).
- For $m_\nu^{min} \ll \sqrt{\delta m_a^2}$, $\Sigma > m_3 \approx \sqrt{\delta m_a^2}$ for NH,

  or $2 m_1 \approx 2 \sqrt{\delta m_a^2}$ for IH.

(a) $0\nu\beta\beta$ decay:*



*Elliott and Engel, J. Phys. (2004)

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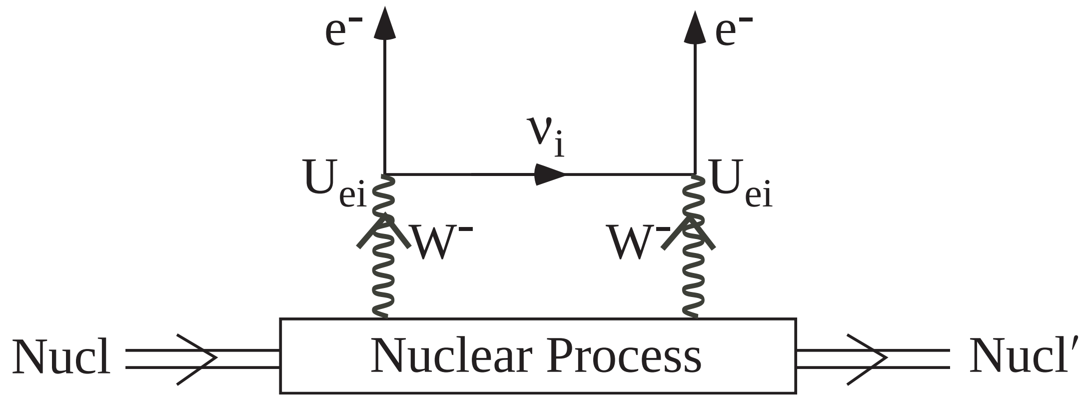

Isotope	Half-life (years)	$\langle m \rangle_{ee}$ (eV)	Year of published paper
^{76}Ge	$> 1.9 \times 10^{25}$	< 0.35	2001
^{76}Ge	$> 1.6 \times 10^{25}$	$< 0.33 - 1.35$	2002
^{76}Ge	$= 1.2 \times 10^{25}$	$= 0.44$	2004
^{100}Mo	$> 5.5 \times 10^{22}$	< 2.1	2001
^{116}Cd	$> 1.7 \times 10^{23}$	< 1.7	2003
^{130}Te	$> 5.5 \times 10^{23}$	$< 0.37 - 1.9$	2004
Cosmology	–	≤ 0.14	this paper†

- No surprise not to have seen $0\nu\beta\beta$.

*Elliott and Engel, J. Phys. (2004)

(b) $\mu^- - e^+$ conversion: *

$$B_{exp} = \frac{\Gamma(Ti + \mu^- \to e^+ + Ca_{gs})}{\Gamma(Ti + \mu^- \to \nu_\mu + Sc)} < 1.7 \times 10^{-12}$$

$$B \propto \kappa \left(\frac{\langle m \rangle_{e\mu}}{m_e}\right)^2 \Longrightarrow \langle m \rangle_{e\mu} \leq 17 \ (82) \ \text{MeV}.$$

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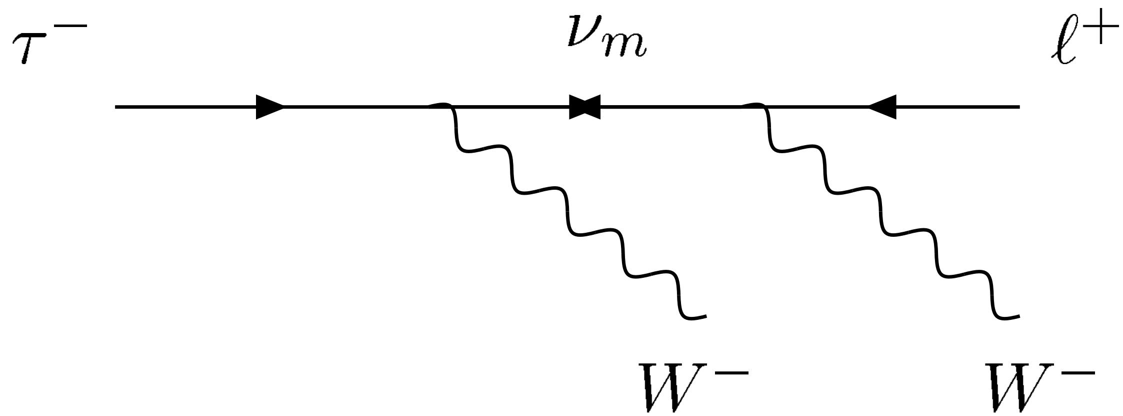
Note κ suffers from large nuclear matrix element uncertainties. †

*SINDRUM II (1998).

†K. Zuber (2000); P. Domin (2004).

(c) τ decays:*



*CLEO II.

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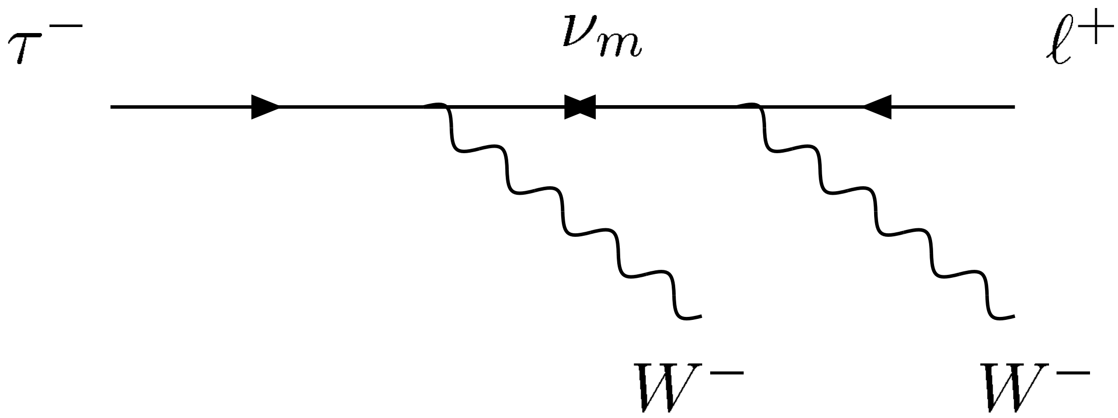
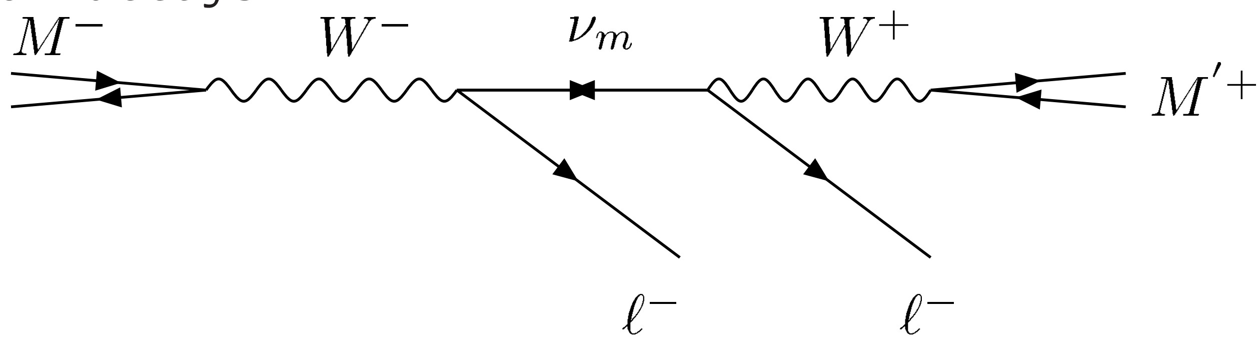


$$BR \approx 10^{-33} \, |V_{M_1}^{CKM} V_{M_2}^{CKM}|^2 \left(\frac{f_{M_1} \, f_{M_2}}{(100 \text{ MeV})^2} \right)^2 \left(\frac{1777 \text{ MeV}}{m_\tau} \right)^2 \left(\frac{\langle m \rangle_{\ell\tau}}{1 \text{ eV}} \right)^2 \Phi,$$

Decay mode	B_{exp}	$\langle m \rangle_{\ell\tau}$ (TeV)
$\tau^- \to e^+\pi^-\pi^-$	1.9×10^{-6}	12
$\tau^- \to e^+\pi^-K^-$	2.1×10^{-6}	46
$\tau^- \to e^+K^-K^-$	3.8×10^{-6}	730
$\tau^- \to \mu^+\pi^-\pi^-$	3.4×10^{-6}	20
$\tau^- \to \mu^+\pi^-K^-$	7.0×10^{-6}	100
$\tau^- \to \mu^+K^-K^-$	6.0×10^{-6}	1000

*CLEO II.

(d) Rare meson decays:*



*PDG

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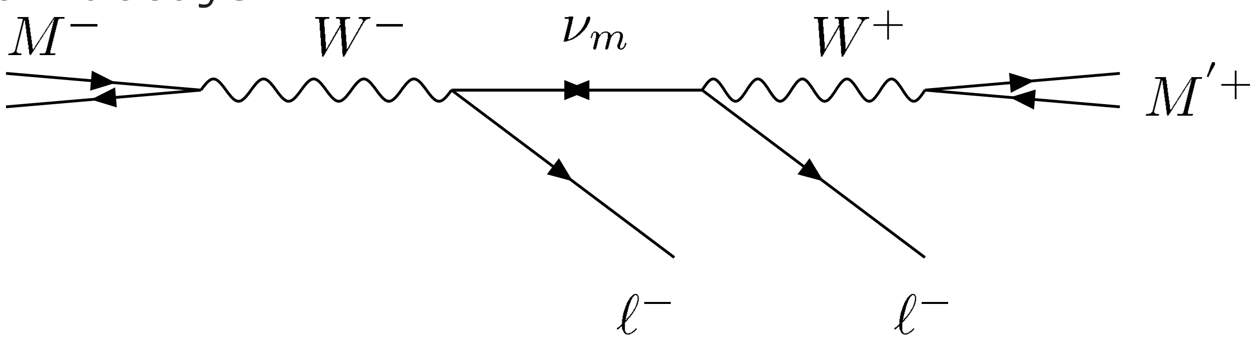

$$BR \approx 10^{-29}\ |V_{M_1}^{CKM} V_{M_2}^{CKM}|^2 \left(\frac{\tau_{M_1}}{1.0\times 10^{-8}\ s}\right) \left(\frac{f_{M_1}\ f_{M_2}}{(100\ \text{MeV})^2}\right)^2 \left(\frac{m_{M_1}}{1\ \text{GeV}}\right)^3 \left(\frac{\langle m\rangle_{\ell_1\ell_2}}{1\ \text{eV}}\right)^2 \Phi'$$

Decay mode	B_{exp}	$\langle m\rangle_{\ell_1\ell_2}$ (TeV)
$K^+ \to \pi^- e^+ e^+$	6.4×10^{-10}	0.11
$K^+ \to \pi^- \mu^+ \mu^+$	3.0×10^{-9}	0.48
$K^+ \to \pi^- e^+ \mu^+$	5.0×10^{-10}	0.09
$D^+ \to \pi^- e^+ e^+$	9.6×10^{-5}	320
$D^+ \to \pi^- \mu^+ \mu^+$	4.8×10^{-6}	76
$D^+ \to \pi^- e^+ \mu^+$	5.0×10^{-5}	170
$D_s^+ \to \pi^- e^+ e^+$	6.9×10^{-4}	200
$D_s^+ \to \pi^- \mu^+ \mu^+$	2.9×10^{-5}	42
$D_s^+ \to \pi^- e^+ \mu^+$	7.3×10^{-4}	150
$B^+ \to \pi^- e^+ e^+$	1.6×10^{-6}	420
$B^+ \to \pi^- \mu^+ \mu^+$	1.4×10^{-6}	400
$B^+ \to \pi^- e^+ \mu^+$	1.3×10^{-6}	270

*PDG

Summary of experimental bounds and cosmology limits on effective neutrino mass:

$\ell_1\ell_2$	Cosmo bounds on $\langle m \rangle_{\ell_1\ell_2}$	Exp bounds on $\langle m \rangle_{\ell_1\ell_2}$	Corresponding experiments
ee	0.14 eV	0.33 eV	$0\nu\beta\beta$
$e\mu$	0.14 eV	17 MeV (90 GeV)†	$\mu^- - e^+$ conversion
$e\tau$	0.14 eV	12 TeV	$\tau^- \to e^+\pi^-\pi^-$
$\mu\mu$	0.14 eV	480 GeV	$K^+ \to \pi^-\mu^+\mu^+$
$\mu\tau$	0.14 eV	19 TeV	$\tau^- \to \mu^+\pi^-\pi^-$
$\tau\tau$	0.14 eV	none	none

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$\mu\mu$	0.14 eV	480 GeV	$K^+ \to \pi^-\mu^+\mu^+$
$\mu\tau$	0.14 eV	19 TeV	$\tau^- \to \mu^+\pi^-\pi^-$
$\tau\tau$	0.14 eV	none	none

† The next conservative limit comes from $K^+ \to \pi^-\mu^+\mu^+$, which, unlike $\mu^- - e^+$ conversion, does not involve the large uncertainties from nuclear matrix element calculations.

One more (accessible) sterile neutrino:

The interactions are via mixing:

$$-\mathcal{L}_N = \frac{g}{\sqrt{2}} W_\mu^+ \sum_{\ell=e}^{\tau} V_{\ell 4}^* \; \overline{N_4^c} \gamma^\mu P_L \; \ell + h.c.$$

$$+ \frac{g}{2\cos_W} Z_\mu \sum_{\ell=e}^{\tau} V_{\ell 4}^* \; \overline{N_4^c} \gamma^\mu P_L \; \nu_\ell + h.c.$$

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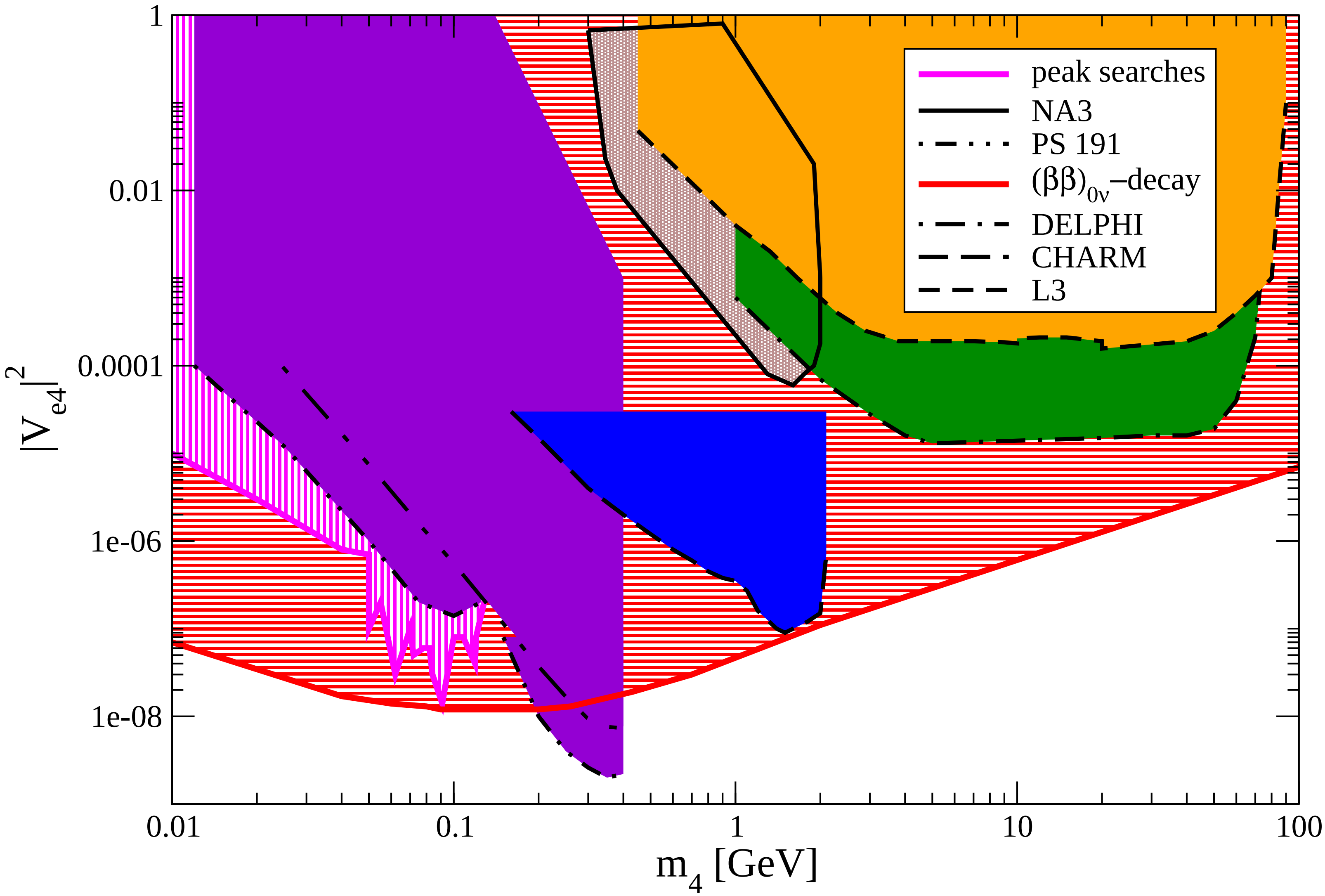
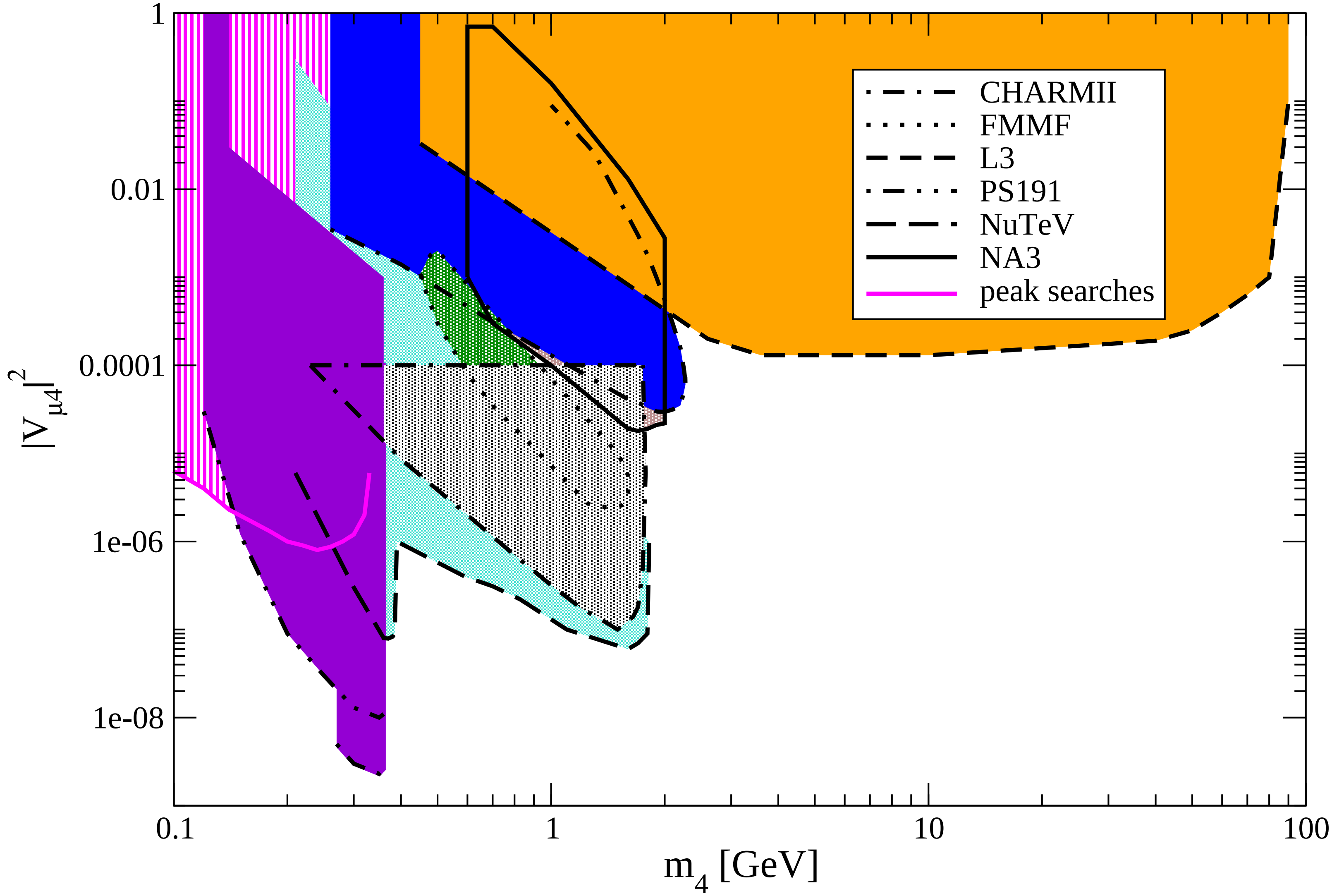
Direct experimental bounds on $V_{\ell 4}$ and m_4 compiled: †

†A. Atre, T. Han, S. Pascoli, B. Zhang to appear PRL.

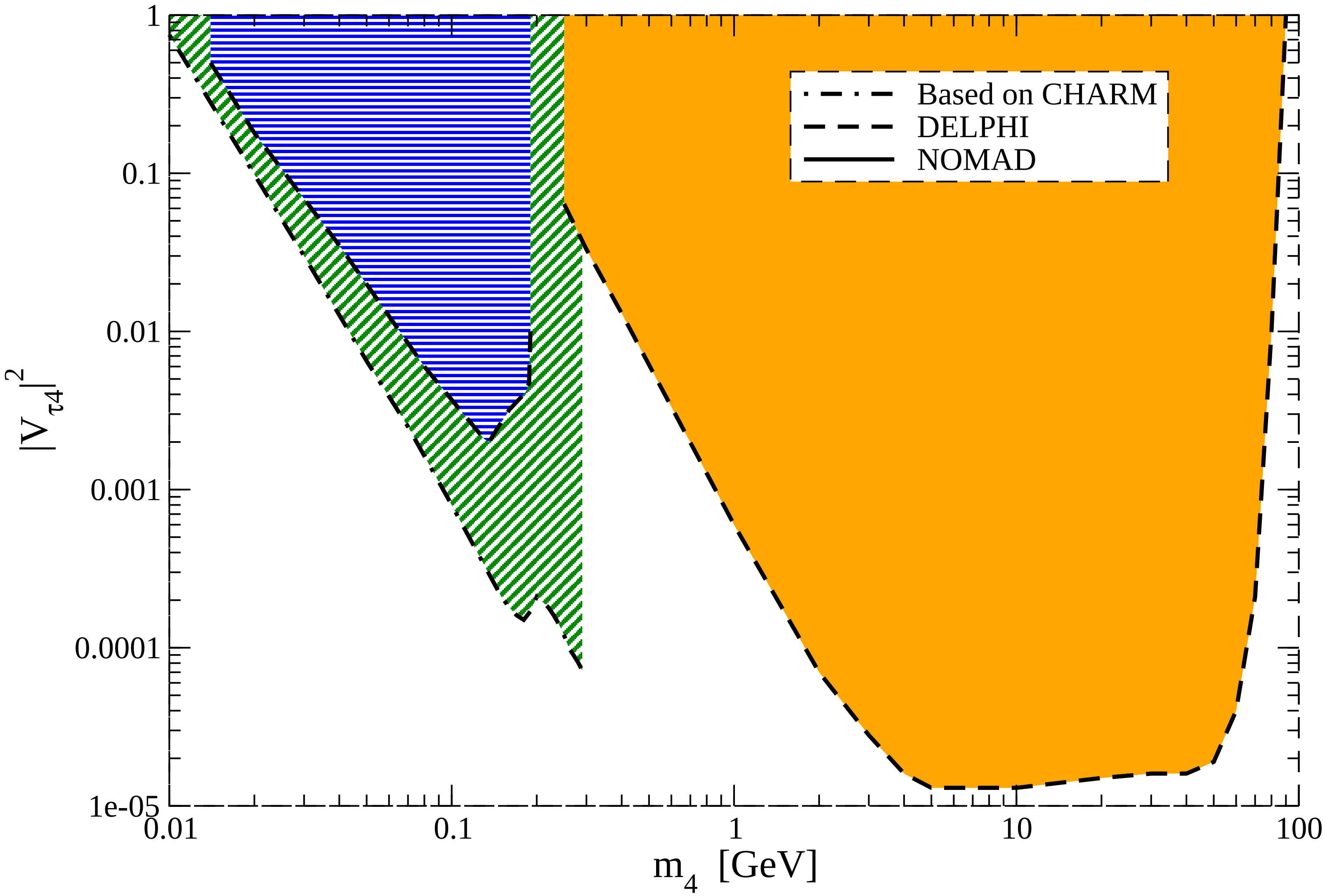


Most stringent bound from $0\nu\beta\beta$:

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

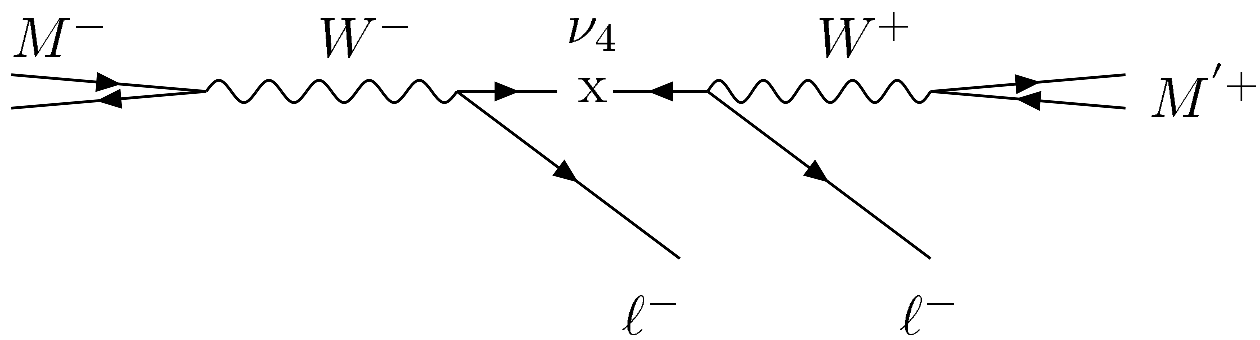


CHARMII
FMMF
L3
PS191
NuTeV
NA3
peak searches
1
0.01
0.0001
1e-06
1e-08
0.1
1
10
100
m_4 [GeV]
$|V_{\mu 4}|^2$



1
0.1
0.01
0.001
0.0001
1e-05
0.01
0.1
1
10
100
$|V_{\tau 4}|^2$
m_4 [GeV]
Based on CHARM
DELPHI
NOMAD

ν_4 production and decay:



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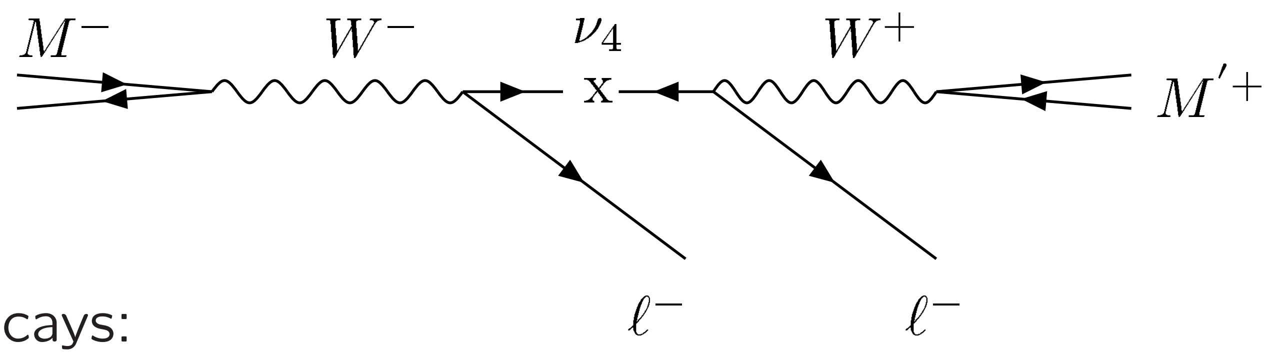

Two-body decays:

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

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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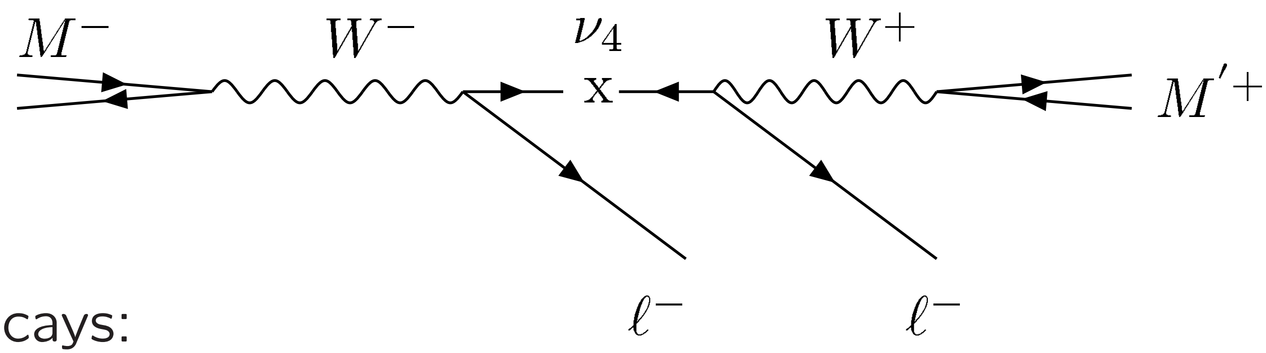

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Thus the total width

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

We calculate all the τ, K, D, B decays with $\Delta L = 2$ via a Majorana ν_4 and compare with the experimental bounds.*

We scan the parameters in the range:

$$10^{-10} < |V_{e4}|^2, \quad |V_{\mu 4}|^2, \quad |V_{\tau 4}|^2 < 0.2$$

and

$$m_4 > 140 \text{ MeV}, \quad m_e + m_\pi \text{ threshold;}$$

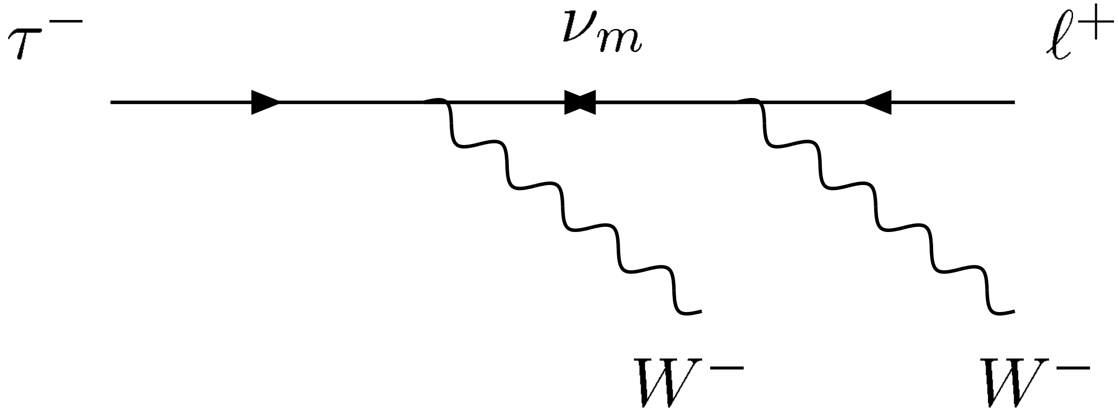
... ...

$$m_4 > 3.8 \text{ GeV}, \quad m_\tau + M_D \text{ threshold;}$$

$$m_4 \sim 5.2 \text{ GeV}, \quad M_B \text{ kinematics.}$$

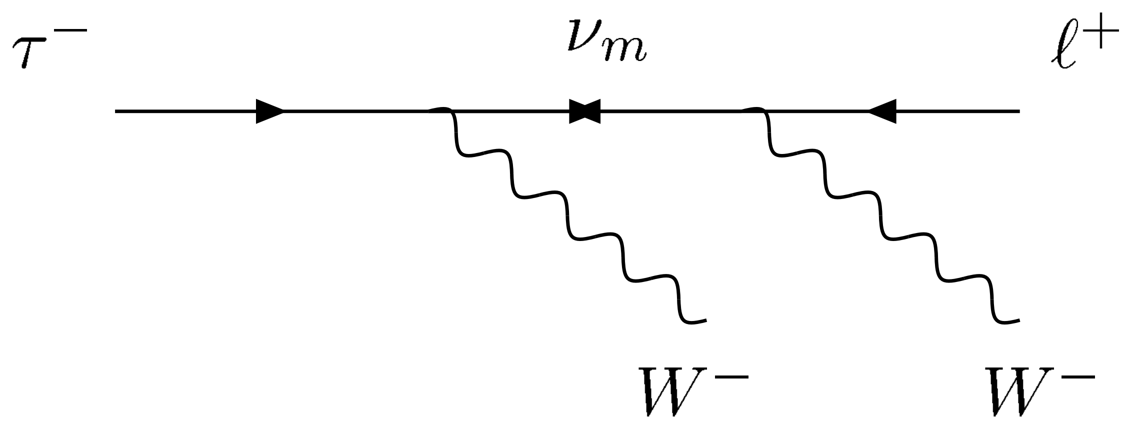
*PDG.

(a) τ decays:*



*Barbar, 2005.

(a) τ decays:*



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}

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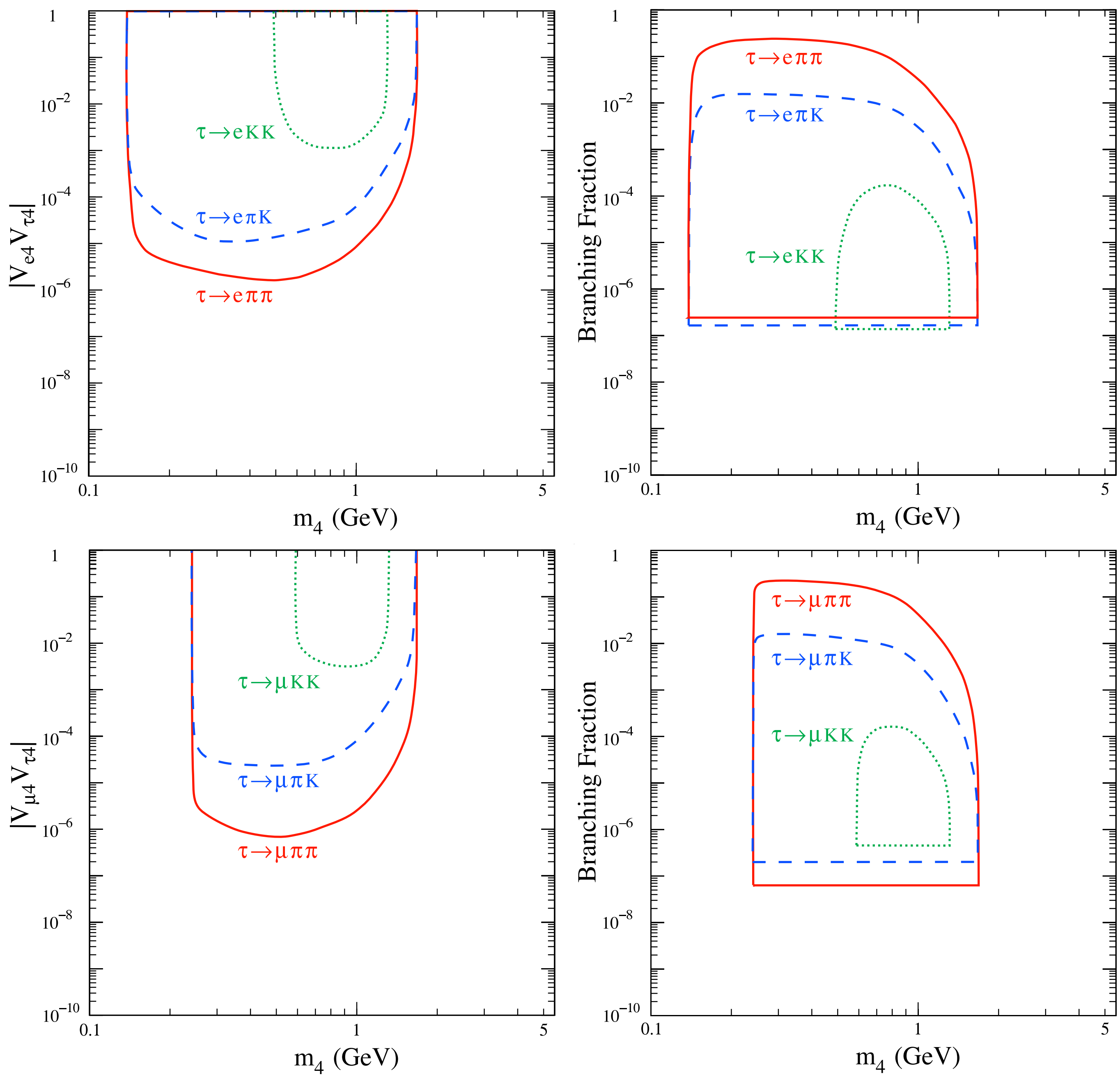
Sensitivity to $V_{\tau 4}$ in τ decays:



(b) Meson decays:*

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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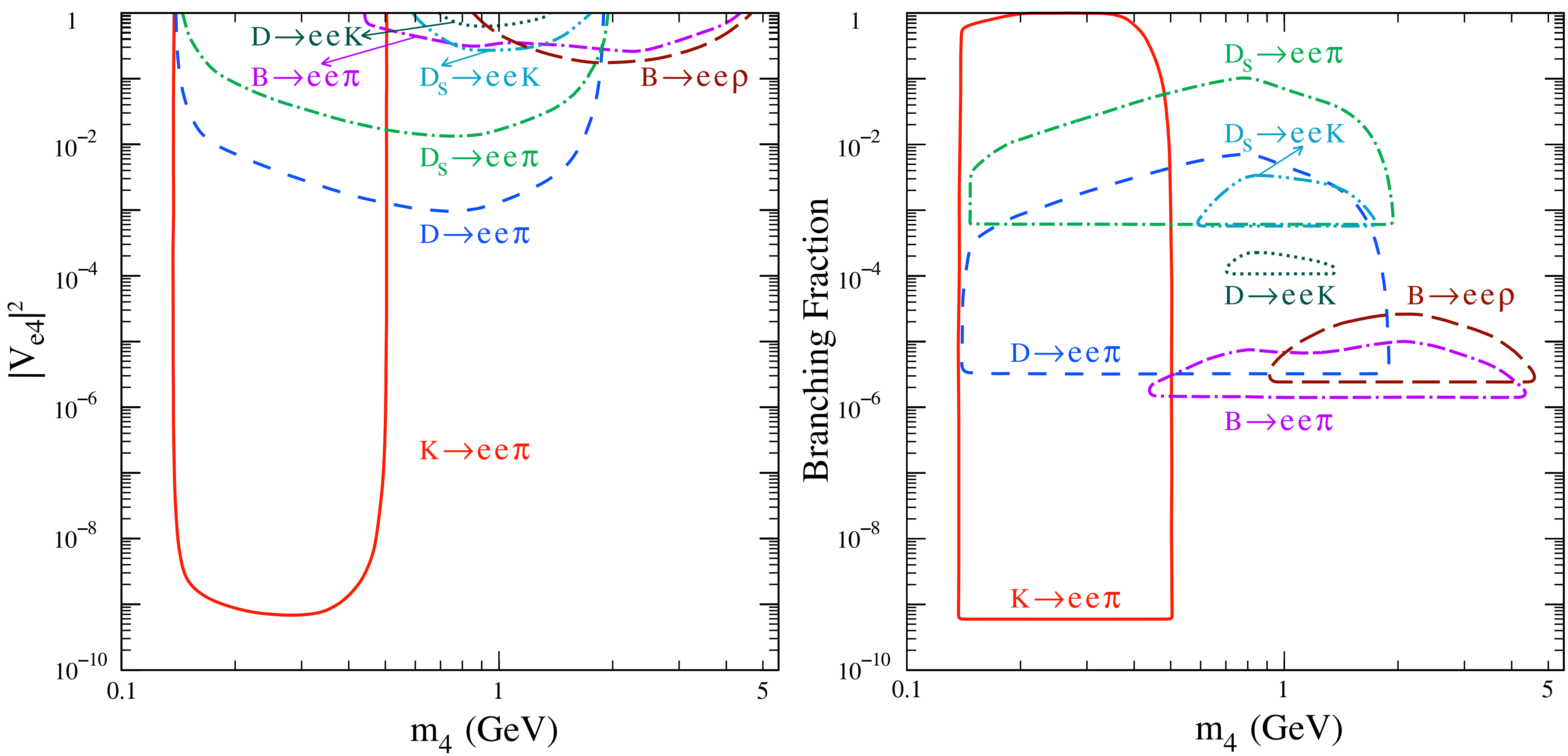

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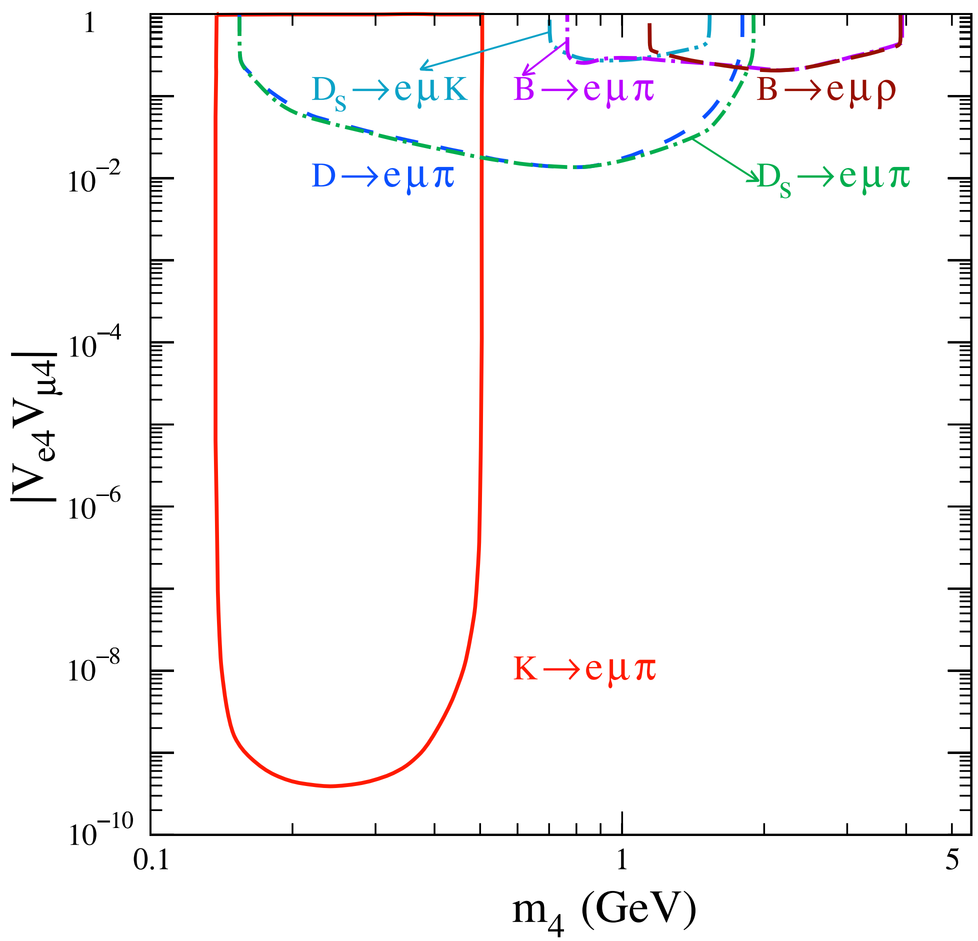
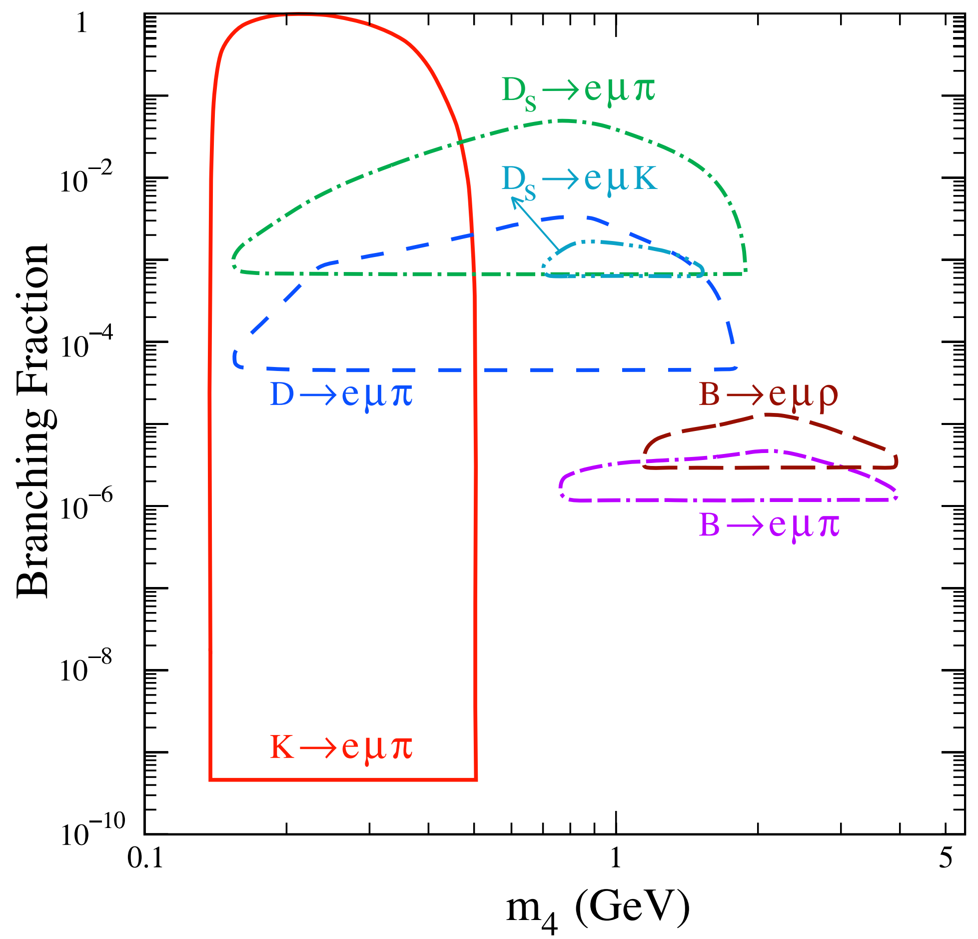
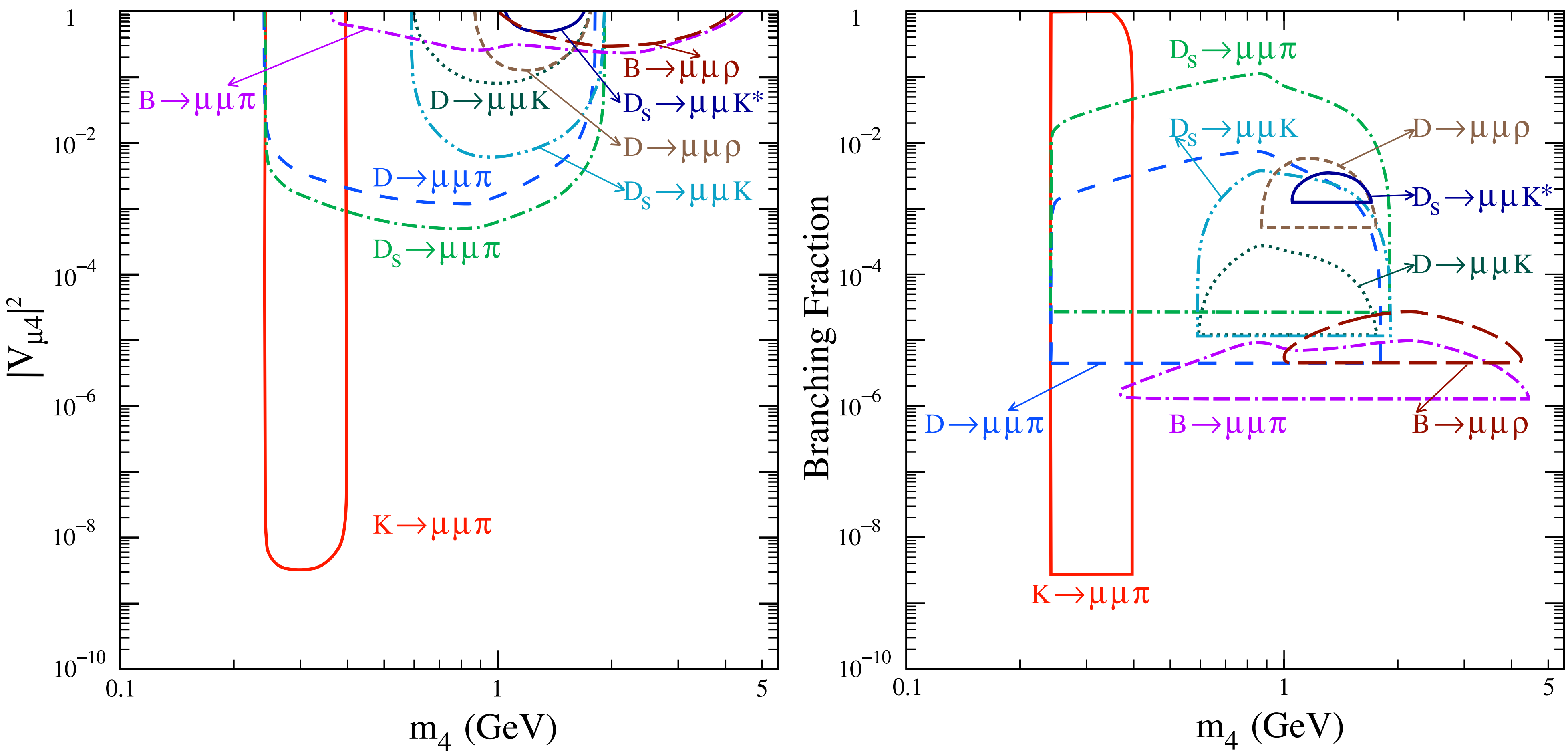
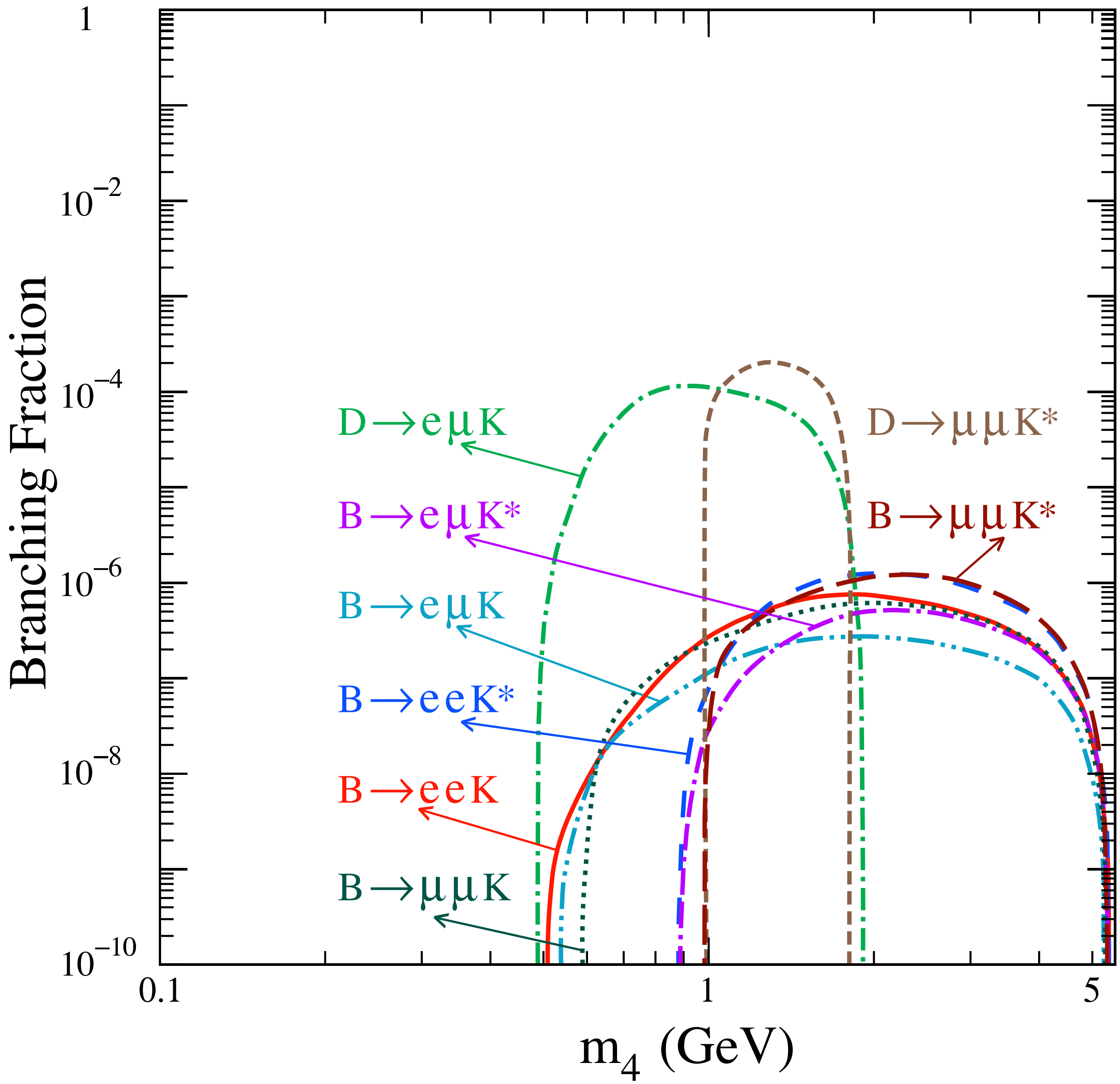




Sensitivity to $V_{\mu 4}$:



Predictions for unexplored channels:



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- Depending on the unkown parameter $|V_{\ell 4}|^2$,
  BR's can easily reach $10^{-6} - 10^{-2}$,
  ν_4 showing up in any one of the channels !

- Other processes to look for:

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

Collider searches for heavier N:

- It was proposed:*

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

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

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- At hadron colliders: ‡

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

We study this carefully ... §

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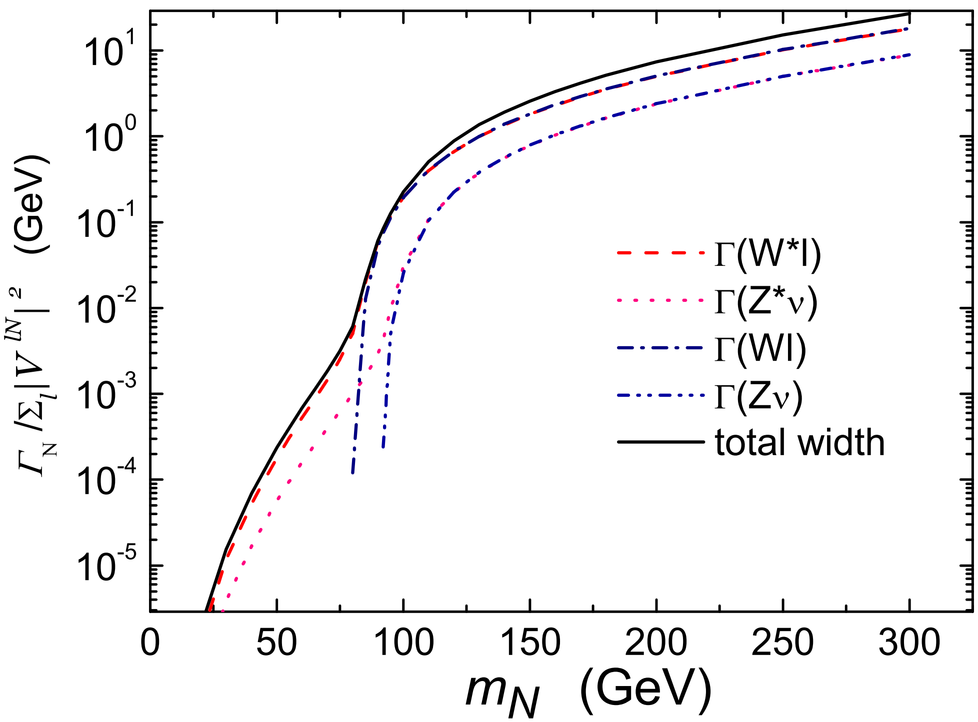
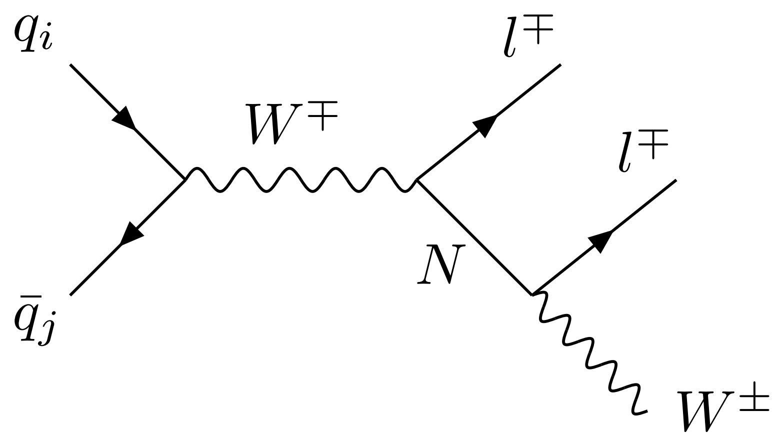
‡ATLAS TDR (1999); F. Almeida et al. (2000); A. Ali, A.V. Borisov et al. (2001).

§T. Han, B. Zhang, hep-ph/0604064.

$$\Gamma_N \approx \begin{cases} \sum_\ell |V_{\ell N}|^2 \; G_F m_N^3/10 & \text{for} \quad m_N \gg m_W, \\ \sum_\ell |V_{\ell N}|^2 \; G_F^2 m_N^5/10^3 & \text{for} \quad m_N \ll m_W. \end{cases}$$



(a) Resonant production: *



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

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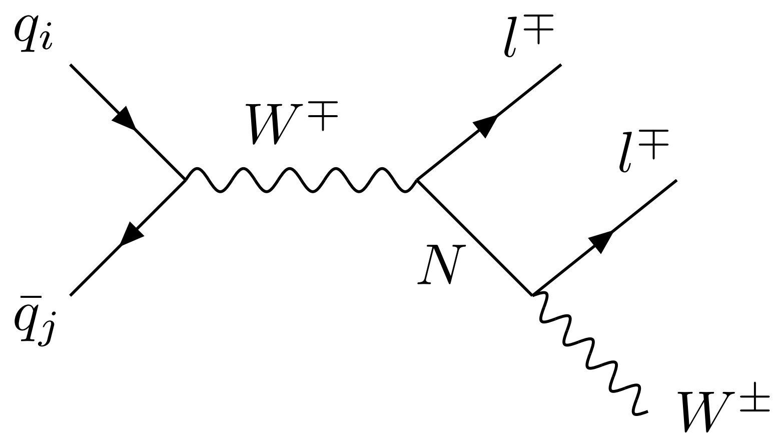

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So, define a factorization:

$$\sigma(pp \to \mu^{\pm}\mu^{\pm}W^{\mp}) \equiv S_{\mu\mu} \ \sigma_0,$$
$$S_{\mu\mu} = \frac{V_{\mu N}^4}{\sum_l |V_{\ell N}|^2} \approx \frac{V_{\mu N}^2}{1 + V_{\tau N}^2/V_{\mu N}^2}.$$

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

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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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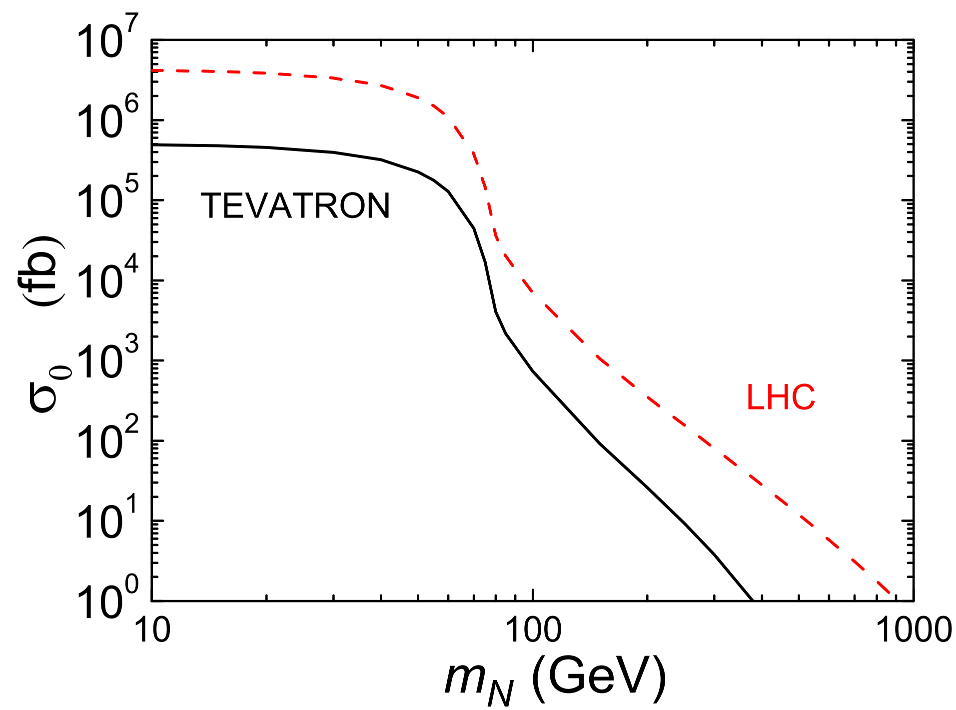
Bare cross sections (scaled down by $S_{\mu\mu}$.)



At the Tevatron: (1 fb^{-1})

Main backgrounds:

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

Judicious cuts:

$p_T(\mu) > 5$ GeV, $|\eta(\mu)| < 2$;

$p_T(j) > 5$ GeV, $|\eta(j)| < 3$;

$\Delta R_{ij} > 0.5$, $\not{E}_T < 20$ GeV,

$m(jj)$ or $m(jj\mu\mu) = M_W \pm 20$ GeV.

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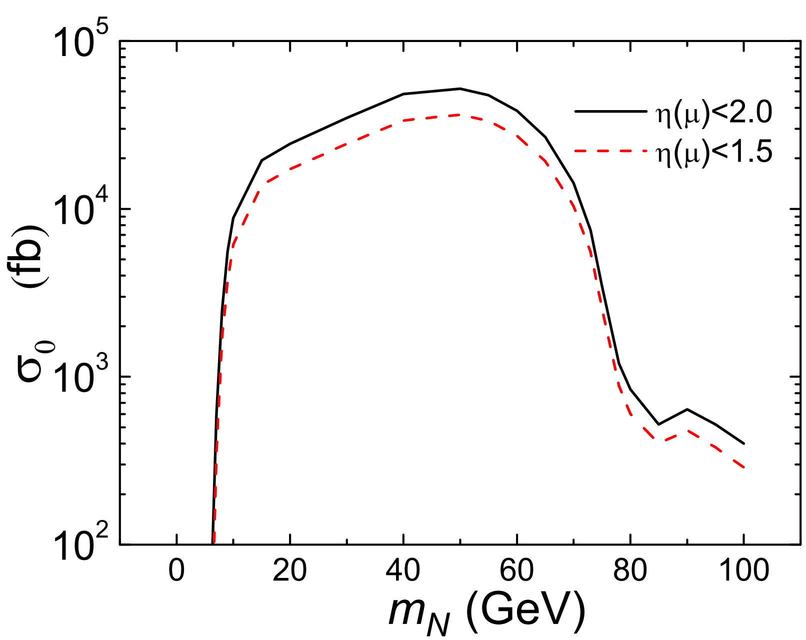

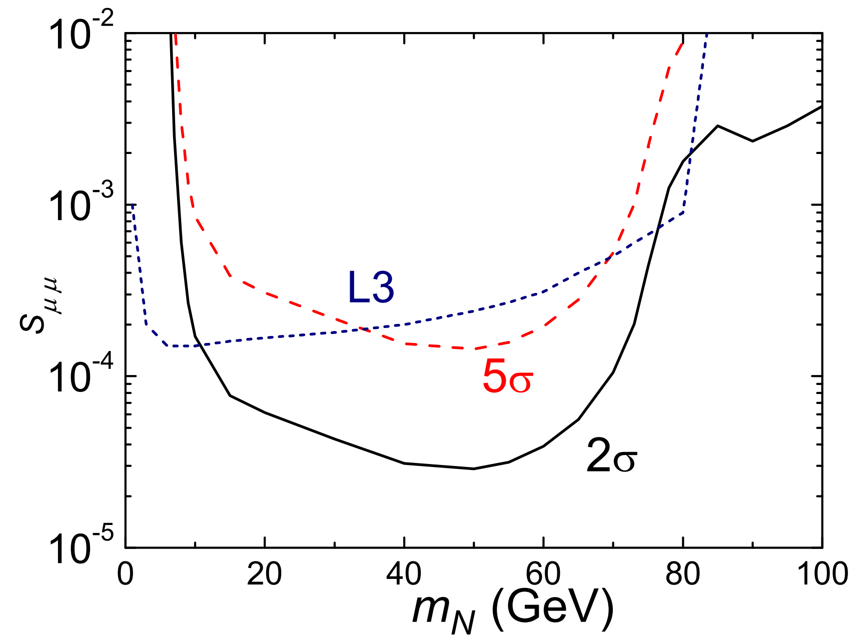

At the LHC:

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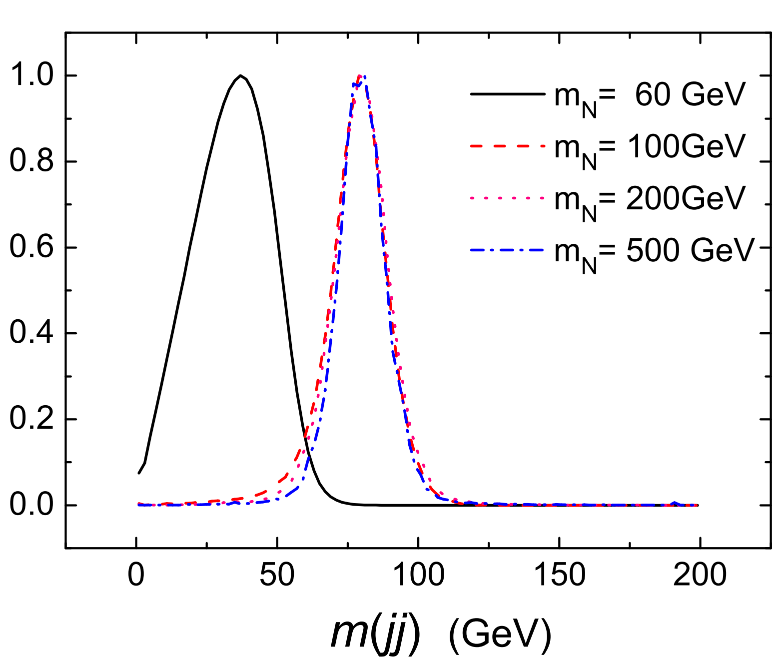
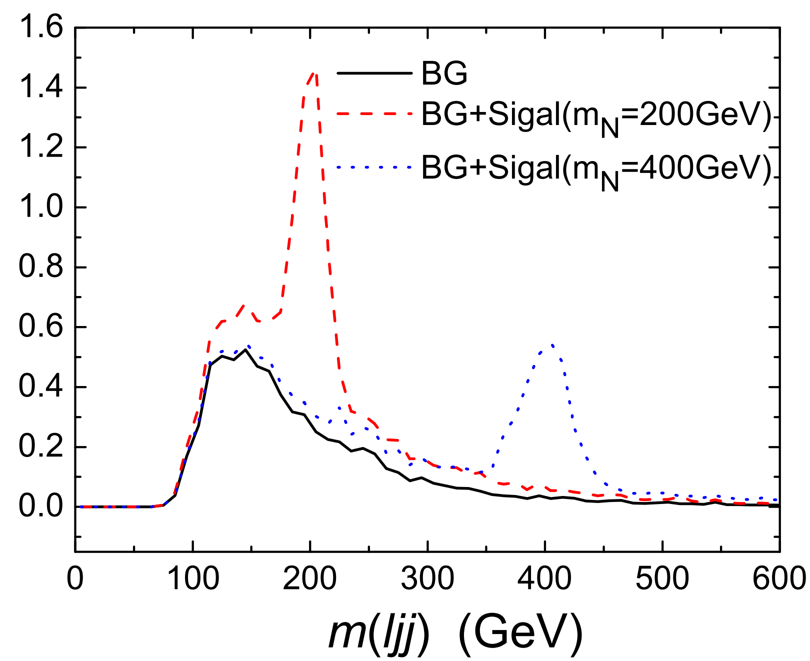
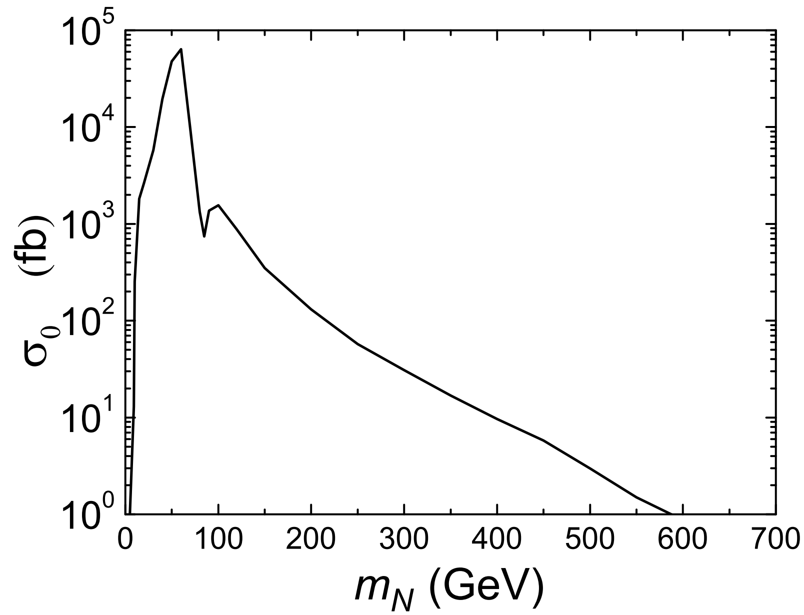
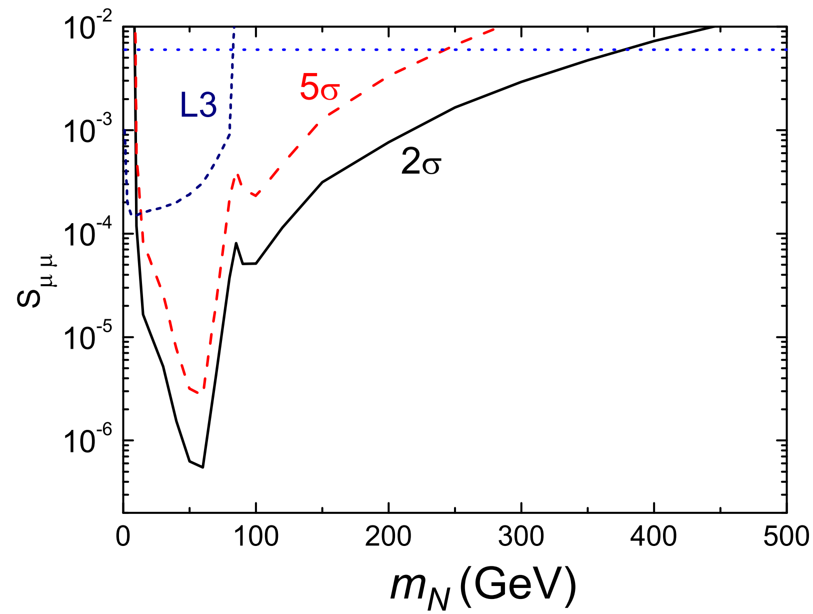


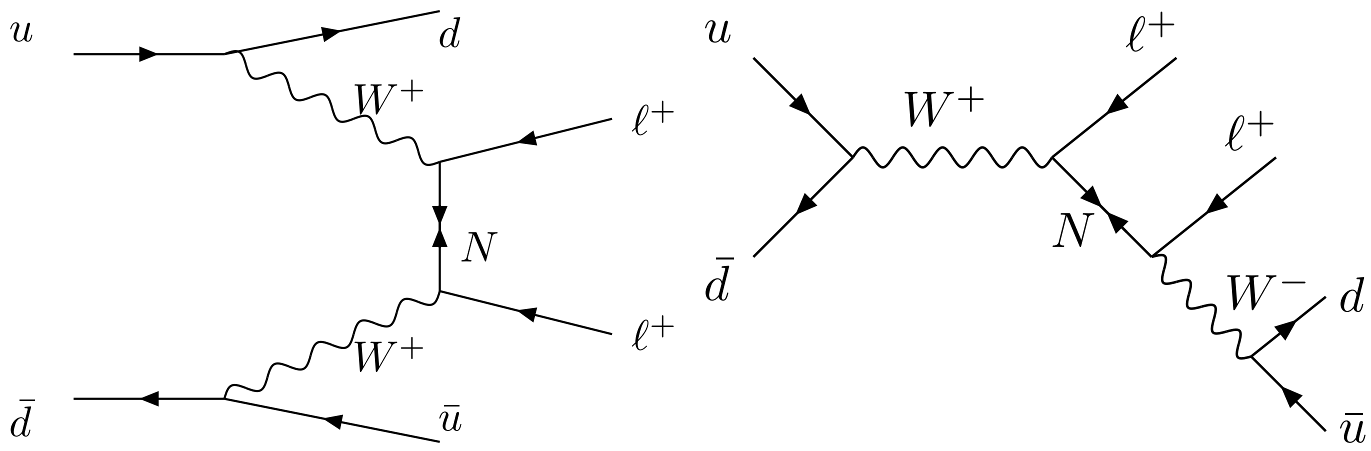


At the LHC with 100 fb^{-1}





A note on WW fusion process:



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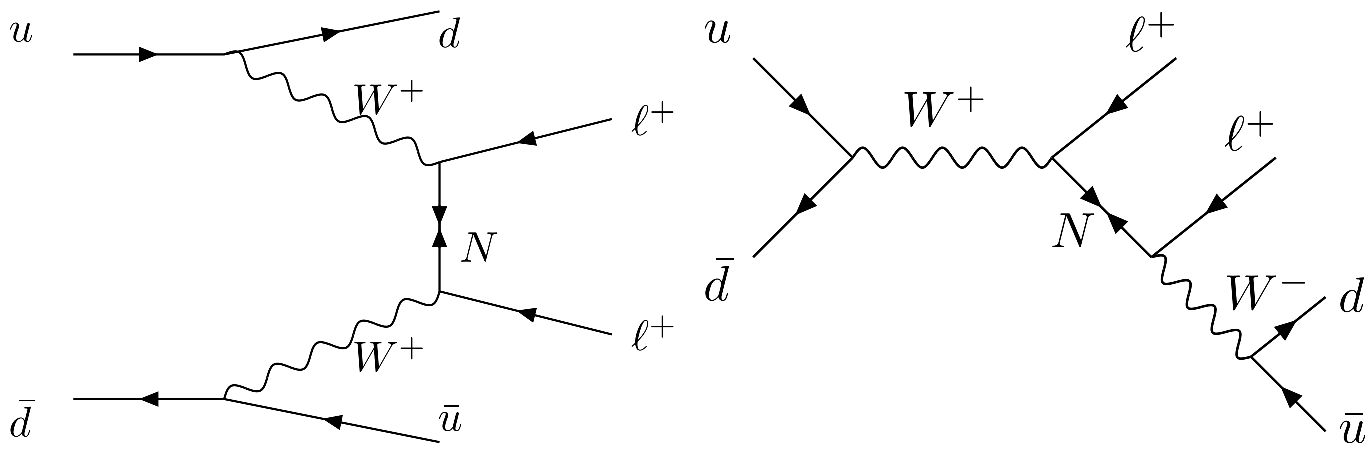

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Without a resonant enhancement,
WW fusion contribution is very limited:

- Down by $|V_{\mu N}|^2$;
- No resonant structure anymore $m(jj\mu) = m_N^2$.

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IF lucky, hadron colliders may serve
as the discovery machine for N!