A. Flores-Tlalpa, G. López Castro, PR. arXiv: 1508.01822 [hep-ph]

$L \to l\, l'\, l'\, \nu_L\, \nu_l$ in the SM & beyond

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Mexico DF, Mexico

International Workshop on $e^+ e^-$ collisions from Phi to Psi 2015

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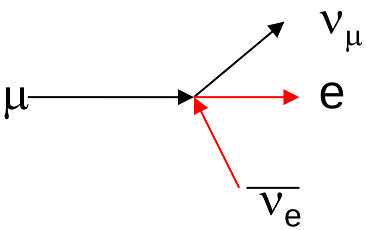
MOTIVATION



decay was essential in determining V-A structure of charged weak current

$$\overline{(e}\,\Gamma^n\,\nu_e)\overline{(\nu_\mu}\,\Gamma_n\,\mu) + \text{h.c.}$$

$$(I_4\,,\, i\gamma_5\,,\, \gamma^\mu\,,\, \gamma_5\gamma^\mu\,,\, \sigma^{\mu\nu})$$

S, P, V, A, T

$$\sigma_{\mu\nu} \equiv \frac{i}{2}\,[\gamma_\mu\,,\,\gamma_\nu]$$

Experimentally:

$$\mathcal{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}}\,[\bar{e}\gamma^\alpha(1-\gamma_5)\nu_e]\,[\bar{\nu}_\mu\gamma_\alpha(1-\gamma_5)\mu]$$

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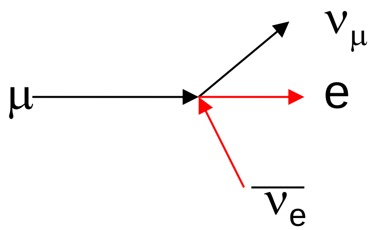

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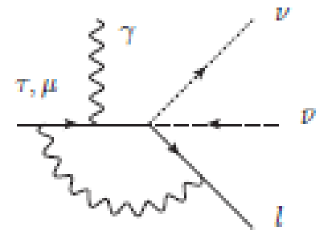
Precision tests of tiny departures from V-A through Michel (‘50) parameters

$$\frac{d\Gamma(\tau^\mp)}{d\Omega dx} = \frac{4G_F^2 M_\tau E_{\rm max}^4}{(2\pi)^4}\sqrt{x^2-x_0^2}\Bigg(x(1-x)+\frac{2}{9}\rho(4x^2-3x-x_0^2)+\eta x_0(1-x)$$

$$\mp\frac{1}{3}P_\tau cos\theta_\ell\xi\sqrt{x^2-x_0^2}\left[1-x+\frac{2}{3}\delta\left(4x-4+\sqrt{1-x_0^2}\right)\right]\Bigg),\;x=\frac{E_\ell}{E_{\rm max}},\;x_0=\frac{m_\ell}{E_{\rm max}}$$

In the SM: $\rho=\frac{3}{4}$, $\eta=0$, $\xi=1$, $\delta=\frac{3}{4}$

MOTIVATION

We have just heard about the interesting  (M. Fael's talk)

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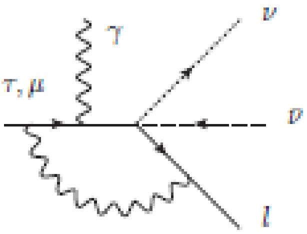
We have just heard about the interesting  (M. Fael's talk)

Motivations in our case (with $\gamma \to l' \, l'$) are quite similar:

As in the $L \to l \, \gamma \, \nu_L \, \nu_l$, information about **spin state of l** can be extracted for precise **tests of weak charged current** using Michel-like parameters analyses.

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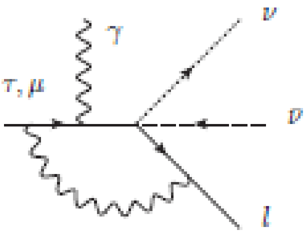
We have just heard about the interesting  (M. Fael's talk)

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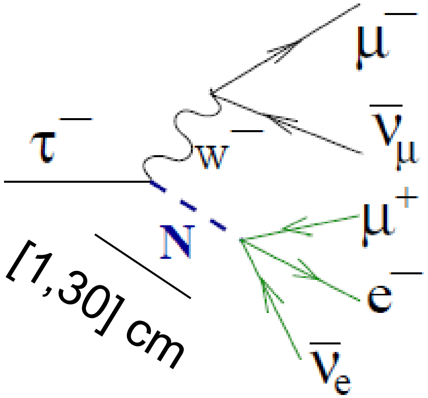
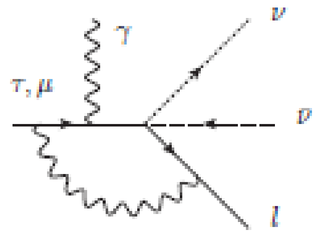
C. Dib *et al.*, Phys. Rev. D **85** (2012) 011301

$400\ \text{MeV} \lesssim m_N \lesssim 600\ \text{MeV},\ 1\times10^{-3} \lesssim |U_{\mu N}|^2 \lesssim 4\times10^{-3},\ \tau_N \lesssim 1\times10^{-9}\ \text{s}$



$\longrightarrow$ B=[2,8]x10^{-5}

MOTIVATION

We have just heard about the interesting  (M. Fael's talk)

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These decays represent the **hardest backgrounds for LFV $L \to l \, l' \, l'$** decays so they must be described accurately in the MC (Denis Epifanov, **Belle's TAUOLA**).

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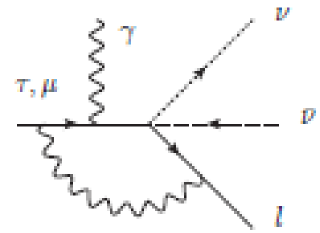
We have just heard about the interesting  (M. Fael's talk)

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Belle analyses need (1st) computation keeping daughter lepton mass dependence & general Michel-like framework for the polarized L case.

$$\tau^-(Q) \to \ell^-(p_1)\, \ell'^-(p_2)\, \ell'^+(p_3)\, \bar{\nu}_\ell(p_4)\, \nu_\tau(p_5)$$

SM description (unpolarized case)

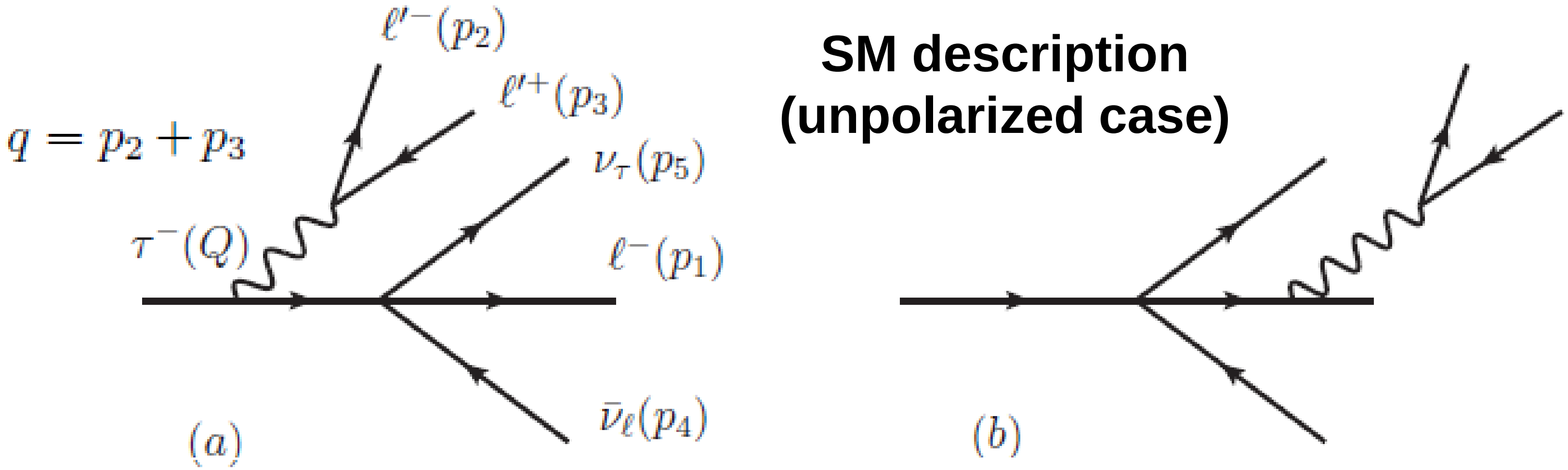

Figure 1. Feynman diagrams for five-lepton decays of taus. For identical leptons ($\ell' = \ell$) in the final state, two additional diagrams corresponding to the exchange $p_1 \leftrightarrow p_2$ should be considered.

$$L^\mu = \bar{u}(p_2)\gamma^\mu v(p_3)$$

$$\mathcal{M}_{SM} = \frac{ie^2 G_F}{\sqrt{2}\, q^2} (\mathcal{M}_1 + \mathcal{M}_2)^\mu L_\mu \,, \qquad (\ell' \neq \ell)$$

$$q^\mu L_\mu = 0$$

$$\mathcal{M}_1^\mu = \bar{u}(p_5)\gamma_\alpha(1-\gamma_5)\left(\frac{i}{\not{Q} - \not{q} - M}\right)\gamma^\mu u(Q) \cdot \bar{u}(p_1)\gamma^\alpha(1-\gamma_5)v(p_4)\,,$$

$$\mathcal{M}_2^\mu = \bar{u}(p_5)\gamma^\alpha(1-\gamma_5)u(Q) \cdot \bar{u}(p_1)\gamma^\mu \left(\frac{i}{\not{p}_1 + \not{q} - m_1}\right)\gamma_\alpha(1-\gamma_5)v(p_4)\,,$$

$$\tau^-(Q) \to \ell^-(p_1)\, \ell'^-(p_2)\, \ell'^+(p_3)\, \bar\nu_\ell(p_4)\, \nu_\tau(p_5)$$

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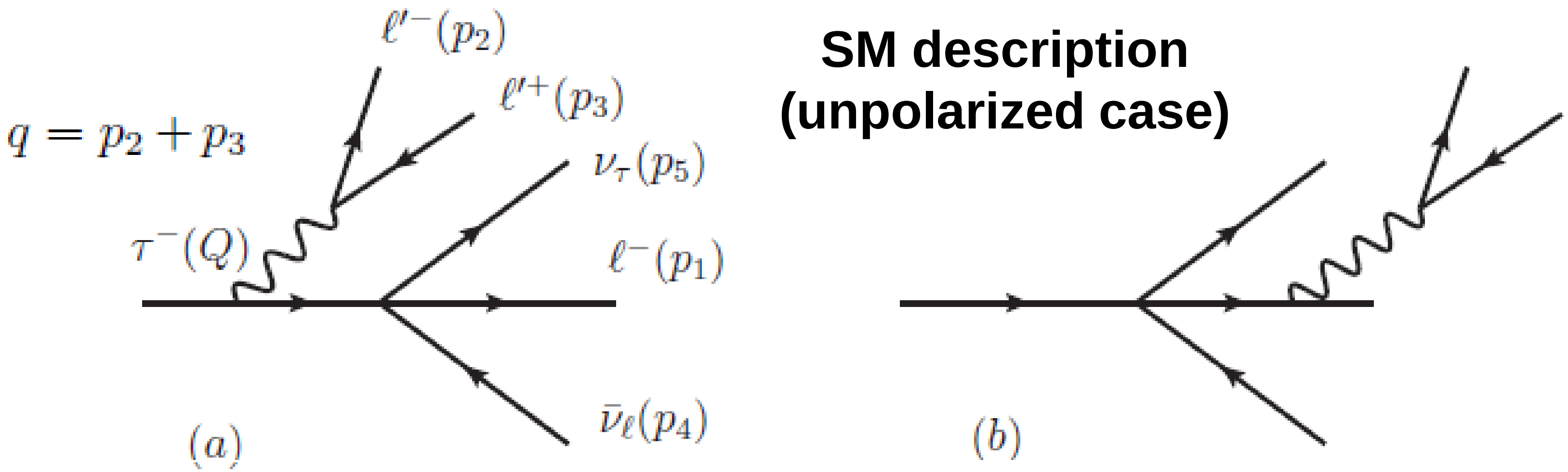

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$$q^\mu L_\mu = 0$$

$$\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2 - \underbrace{(\mathcal{M}_3 + \mathcal{M}_4)}_{p_1 \leftrightarrow p_2},$$

We perform the first computation keeping l, l' masses

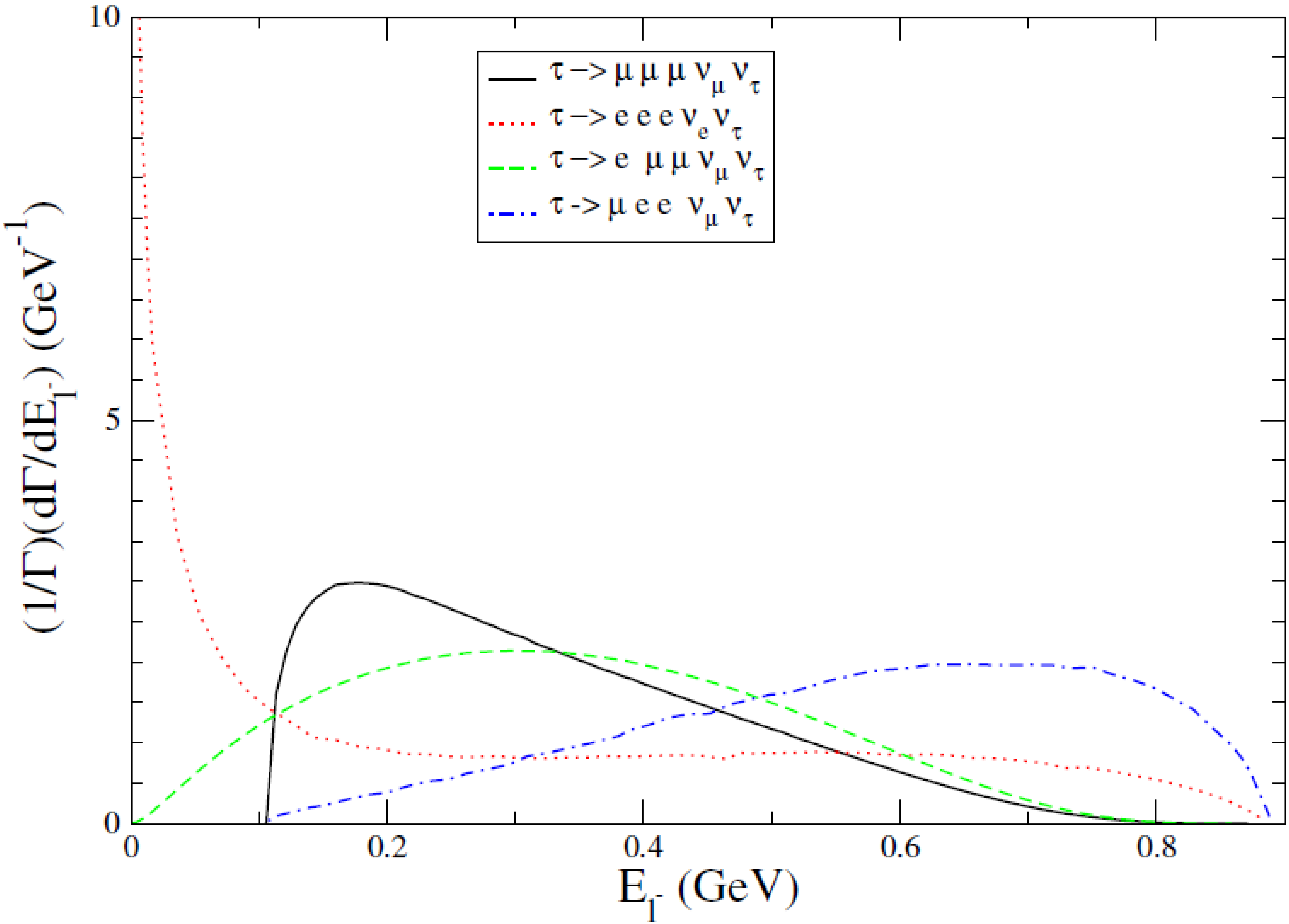
Channel	Ref. [17]	Ref. [18]	This work	PDG [24]
$\mathrm{BR}(\tau^- \to e^- e^+ e^- \bar{\nu}_e \nu_\tau)\times 10^5$	4.15 ± 0.06	4.457 ± 0.006	4.21 ± 0.01	2.8 ± 1.5
$\mathrm{BR}(\tau^- \to e^- \mu^+ \mu^- \bar{\nu}_e \nu_\tau)\times 10^7$	1.257 ± 0.003	1.347 ± 0.002	1.247 ± 0.001	-
$\mathrm{BR}(\tau^- \to \mu^- e^+ e^- \bar{\nu}_\mu \nu_\tau)\times 10^5$	1.97 ± 0.02	2.089 ± 0.003	1.984 ± 0.004	< 3.6
$\mathrm{BR}(\tau^- \to \mu^- \mu^+ \mu^- \bar{\nu}_\mu \nu_\tau)\times 10^7$	1.190 ± 0.002	1.276 ± 0.004	1.183 ± 0.001	-
$\mathrm{BR}(\mu^- \to e^- e^+ e^- \bar{\nu}_e \nu_\mu)\times 10^5$	3.60 ± 0.02	3.605 ± 0.005	3.597 ± 0.002	3.4 ± 0.4

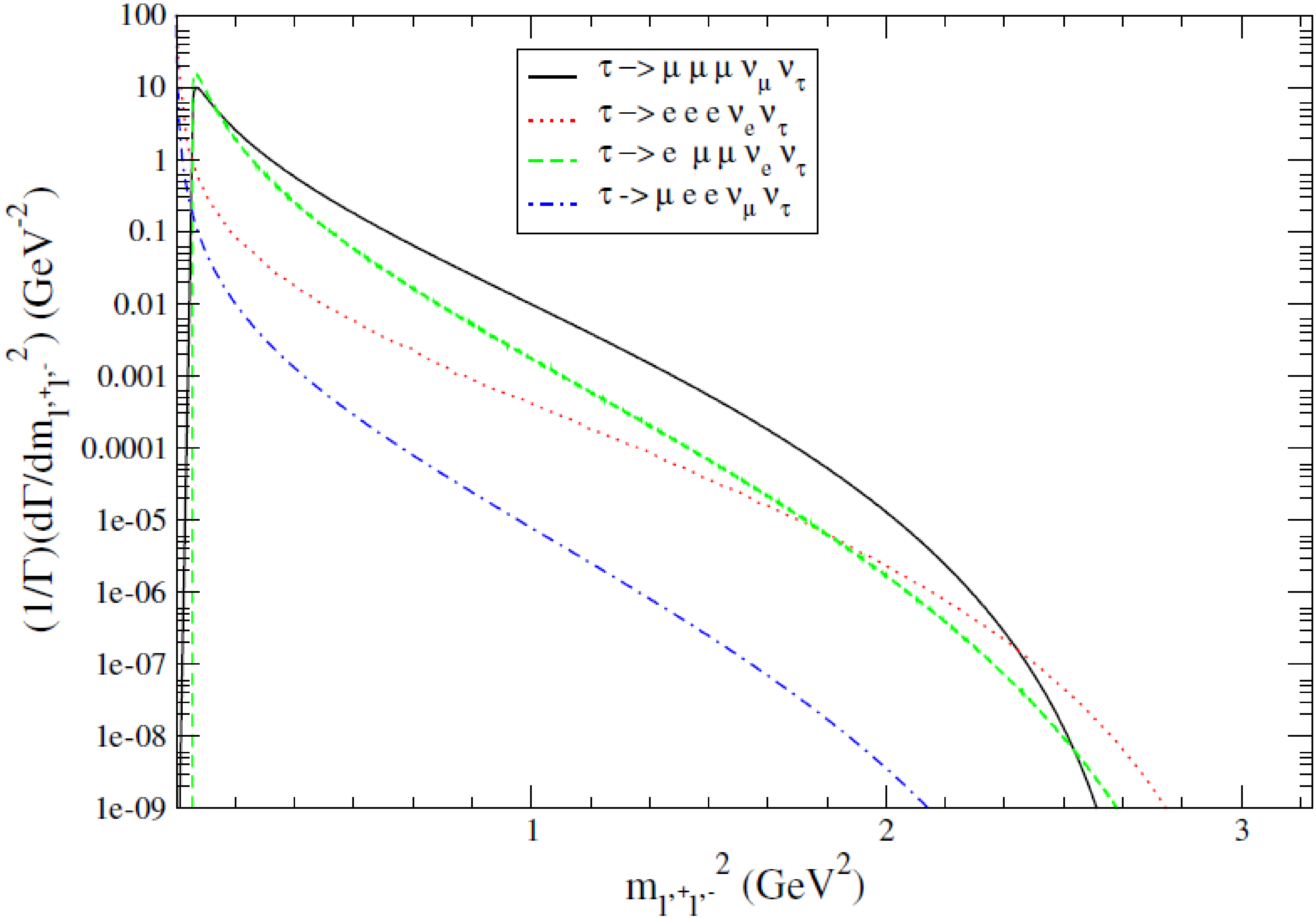
Table 1. Branching ratios for the five-body decays of τ and μ leptons. Some of the previous calculations are shown, for comparison, in the second and third columns. Experimental data are scarce, with large error bars but still consistent with the SM predictions.

1777.8 ± 1.8 MeV $\quad$ 1776.82 ± 0.16 MeV

$(2.91 \pm 0.14) \cdot 10^{-13}$ s $\quad$ $(2.903 \pm 0.005) \cdot 10^{-13}$ s

Small differences with Dicus & Vega understood in terms of slightly different inputs [17]


τ -> μ μ μ ν_μ ν_τ
τ -> e e e ν_e ν_τ
τ -> e μ μ ν_μ ν_τ
τ -> μ e e ν_μ ν_τ
(1/Γ)(dΓ/dE_l-) (GeV^-1)
E_l- (GeV)
10
5
0
0.2
0.4
0.6
0.8


τ –> μ μ μ ν_μ ν_τ
τ –> e e e ν_e ν_τ
τ –> e μ μ ν_e ν_τ
τ -> μ e e ν_μ ν_τ
$(1/\Gamma)(d\Gamma/dm_{l'^+l'^-}^2)$ (GeV^{-2})
100
10
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
1
2
3
$m_{l'^+l'^-}^2$ (GeV^2)

τ polarization

$$(\not{Q} + M) \to \frac{1}{2}(\not{Q} + M)(1 + \gamma_5 \not{s})$$

$Q \cdot s = 0$ and $s^2 = -1.$

$s = (0, \vec{s})$

$$x_i = 2E_i/M \;\; (i = 1, 2, 3) \qquad \frac{d\Gamma_5}{dx_1 d\Omega_1 dx_2 d\Omega_2 dx_3 d\Omega_3} = \frac{M^2 |\vec{p}_1||\vec{p}_2||\vec{p}_3|}{3 \cdot 2^{21} \pi^{10}} \mathcal{T}^s_{\alpha\beta} I^{\alpha\beta}(P)$$

$$\mathcal{T}^s_{\alpha\beta} I^{\alpha\beta}(P) = e^4 G_F^2 \left[F \; - \; L \, \vec{p}_1 \cdot \vec{s} \; - \; G_1 \, \vec{p}_2 \cdot \vec{s} \; - \; G_2 \, \vec{p}_3 \cdot \vec{s} \right]$$

$$\mathcal{T}^s_{\alpha\beta} I^{\alpha\beta}(P) \; = \; e^4 G_F^2 \left[T_{11} + T_{22} + T_{1221} + T_{33} + T_{44} - T_{1331} - T_{1441} - T_{2332} - T_{2442} + T_{3443} \right]$$

$$F \; = \; F_{11} + F_{22} + F_{1221} + F_{33} + F_{44} - F_{1331} - F_{1441} - F_{2332} - F_{2442} + F_{3443}$$

(analogously for L, G_1 & G_2)

Inclusion of **our results** (SM & EFT) for (un)polarized τ **in TAUOLA-Belle** is needed to fight the background and search for signals in different analyses (D. Epifanov).

Effective field theory analysis

(Michel '50, Bouchiat & Michel '57, Fetscher et. al. '86, …)

$$\mathcal{L} = -\frac{4G_{\ell\ell'}}{\sqrt{2}} \sum_{i,\lambda,\rho} g^i_{\lambda\rho} \left[\overline{\ell'_\lambda} \Gamma^i (\nu_{\ell'})_\xi\right] \left[\overline{(\nu_\ell)_\kappa} \Gamma_i \ell_\rho\right]$$

$$i = S,\, V,\, T;\ \Gamma^S = I,\ \Gamma^V = \gamma^\mu,\ \Gamma^T = \sigma^{\mu\nu}/\sqrt{2}$$

From μ decay

$$1 = \frac{1}{4}\sum_{\lambda,\rho} |g^S_{\lambda\rho}|^2 + \sum_{\lambda,\rho} |g^V_{\lambda\rho}|^2 + 3\left(|g^T_{RL}|^2 + |g^T_{LR}|^2\right)$$

$$|g^V_{LL}| = 1$$

$$\begin{aligned}
\mathcal{L} = & -\frac{G_{\ell\ell'}}{\sqrt{2}} \{ g^S_{LL} \left[\bar{\ell}'(1+\gamma_5)\nu_{\ell'}\right] \left[\bar{\nu}_\ell(1-\gamma_5)\ell\right] + g^S_{RL} \left[\bar{\ell}'(1-\gamma_5)\nu_{\ell'}\right] \left[\bar{\nu}_\ell(1-\gamma_5)\ell\right] \\
& + g^S_{LR} \left[\bar{\ell}'(1+\gamma_5)\nu_{\ell'}\right] \left[\bar{\nu}_\ell(1+\gamma_5)\ell\right] + \underline{g^S_{RR} \left[\bar{\ell}'(1-\gamma_5)\nu_{\ell'}\right] \left[\bar{\nu}_\ell(1+\gamma_5)\ell\right]} \\
& + \underline{g^V_{LL} \left[\bar{\ell}'\gamma^\mu(1-\gamma_5)\nu_{\ell'}\right] \left[\bar{\nu}_\ell\gamma_\mu(1-\gamma_5)\ell\right]} + g^V_{RL} \left[\bar{\ell}'\gamma^\mu(1+\gamma_5)\nu_{\ell'}\right] \left[\bar{\nu}_\ell\gamma_\mu(1-\gamma_5)\ell\right] \\
& + g^V_{LR} \left[\bar{\ell}'\gamma^\mu(1-\gamma_5)\nu_{\ell'}\right] \left[\bar{\nu}_\ell\gamma_\mu(1+\gamma_5)\ell\right] + g^V_{RR} \left[\bar{\ell}'\gamma^\mu(1+\gamma_5)\nu_{\ell'}\right] \left[\bar{\nu}_\ell\gamma_\mu(1+\gamma_5)\ell\right] \\
& + \frac{g^T_{LR}}{2} \left[\bar{\ell}'\sigma^{\mu\nu}(1+\gamma_5)\nu_{\ell'}\right] \left[\bar{\nu}_\ell\sigma_{\mu\nu}(1+\gamma_5)\ell\right] + \frac{g^T_{RL}}{2} \left[\bar{\ell}'\sigma^{\mu\nu}(1-\gamma_5)\nu_{\ell'}\right] \left[\bar{\nu}_\ell\sigma_{\mu\nu}(1-\gamma_5)\ell\right] \}
\end{aligned}$$

——— Non-vanishing for massless (left-handed) neutrinos

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$$\mathcal{T}^s_{\alpha\beta} I^{\alpha\beta}(P) = e^4 |G_{\ell\ell'}|^2 \Big[F - L\,\vec{\mathrm{p}}_1 \cdot \vec{\mathrm{s}} - G_1\,\vec{\mathrm{p}}_2 \cdot \vec{\mathrm{s}} - G_2\,\vec{\mathrm{p}}_3 \cdot \vec{\mathrm{s}} + H_1 \vec{\mathrm{s}} \cdot (\vec{\mathrm{p}}_1 \times \vec{\mathrm{p}}_2) + H_2 \vec{\mathrm{s}} \cdot (\vec{\mathrm{p}}_2 \times \vec{\mathrm{p}}_3) + H_3 \vec{\mathrm{s}} \cdot (\vec{\mathrm{p}}_1 \times \vec{\mathrm{p}}_3)\Big]$$

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$$g_{\rho\sigma}\epsilon_{\alpha\beta\mu\nu} + g_{\rho\alpha}\epsilon_{\beta\mu\nu\sigma} + g_{\rho\beta}\epsilon_{\mu\nu\sigma\alpha} + g_{\rho\mu}\epsilon_{\nu\sigma\alpha\beta} + g_{\rho\nu}\epsilon_{\sigma\alpha\beta\mu} = 0$$

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$$+ H_1 \vec{s}\cdot(\vec{p}_1\times\vec{p}_2) + H_2\vec{s}\cdot(\vec{p}_2\times\vec{p}_3) + H_3\vec{s}\cdot(\vec{p}_1\times\vec{p}_3)\Big]$$

$$g_{\rho\sigma}\epsilon_{\alpha\beta\mu\nu} + g_{\rho\alpha}\epsilon_{\beta\mu\nu\sigma} + g_{\rho\beta}\epsilon_{\mu\nu\sigma\alpha} + g_{\rho\mu}\epsilon_{\nu\sigma\alpha\beta} + g_{\rho\nu}\epsilon_{\sigma\alpha\beta\mu} = 0$$

$$\mathcal{L} = \sum_{i,j} g_{Z'} \overline{\psi}_i \gamma^\mu (v_{ij} - a_{ij}\gamma_5)\psi_j Z'_\mu + \text{h.c.}$$

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$$+H_1\vec{\mathrm{s}}\cdot(\vec{\mathrm{p}}_1\times\vec{\mathrm{p}}_2) + H_2\vec{\mathrm{s}}\cdot(\vec{\mathrm{p}}_2\times\vec{\mathrm{p}}_3) + H_3\vec{\mathrm{s}}\cdot(\vec{\mathrm{p}}_1\times\vec{\mathrm{p}}_3)\Big]$$

T-violation is not suppressed in L → l l’ l’, so its measurement signals LFV

(Okada et. al. ’00, ’01)

LFV τ decays

(Celis, Cirigliano and Passemar '14)

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

The next-to-leading-order (NLO) effective Lagrangian of the SM with a dynamically broken EW symmetry takes the form

$$\mathcal{L} = \mathcal{L}_{LO} + \sum_i c_i \frac{v^{6-d_i}}{\Lambda^2} \mathcal{O}_i$$

LFV $\tau-\mu$ transitions $\quad \mathcal{L}_{eff} = \mathcal{L}_{eff}^{(D)} + \mathcal{L}_{eff}^{(\ell q)} + \mathcal{L}_{eff}^{(G)} + \mathcal{L}_{eff}^{(4\ell)} + \cdots$

$$\mathcal{L}_{eff}^{(D)} = -\frac{m_\tau}{\Lambda^2}\left\{ (\mathrm{C_{DR}}\,\bar\mu\,\sigma^{\rho\nu}\,P_L\,\tau + \mathrm{C_{DL}}\,\bar\mu\,\sigma^{\rho\nu}\,P_R\,\tau)\,F_{\rho\nu} + \mathrm{h.c.}\right\}$$

$$\begin{aligned}\mathcal{L}_{eff}^{(4\ell)} = -\frac{1}{\Lambda^2}\Big\{ & \mathrm{C_{SLL}}\,(\bar\mu\,P_L\,\tau)\,(\bar\mu\,P_L\,\mu) + \mathrm{C_{SRR}}\,(\bar\mu\,P_R\,\tau)\,(\bar\mu\,P_R\,\mu) \\ & + \mathrm{C_{VLL}}\,(\bar\mu\gamma^\mu\,P_L\,\tau)\,(\bar\mu\,\gamma_\mu\,P_L\,\mu) + \mathrm{C_{VRR}}\,(\bar\mu\,\gamma^\mu\,P_R\,\tau)\,(\bar\mu\,\gamma_\mu\,P_R\,\mu) \\ & + \mathrm{C_{VLR}}\,(\bar\mu\,\gamma^\mu\,P_L\,\tau)\,(\bar\mu\,\gamma_\mu\,P_R\,\mu) + \mathrm{C_{VRL}}\,(\bar\mu\,\gamma^\mu P_R\,\tau)\,(\bar\mu\,\gamma_\mu\,P_L\,\mu) + \mathrm{h.c.}\Big\}\end{aligned}$$

LFV τ decays

- Vector Model: $C_{VLR} = C_{VRL} = 0.3$ with all other couplings vanishing.
- Scalar Model: $C_{SLL} = C_{SRR} = 1$ with all other couplings vanishing.
- Dipole Model: $C_{DL} = C_{DR} = 0.1$ with all other couplings vanishing.

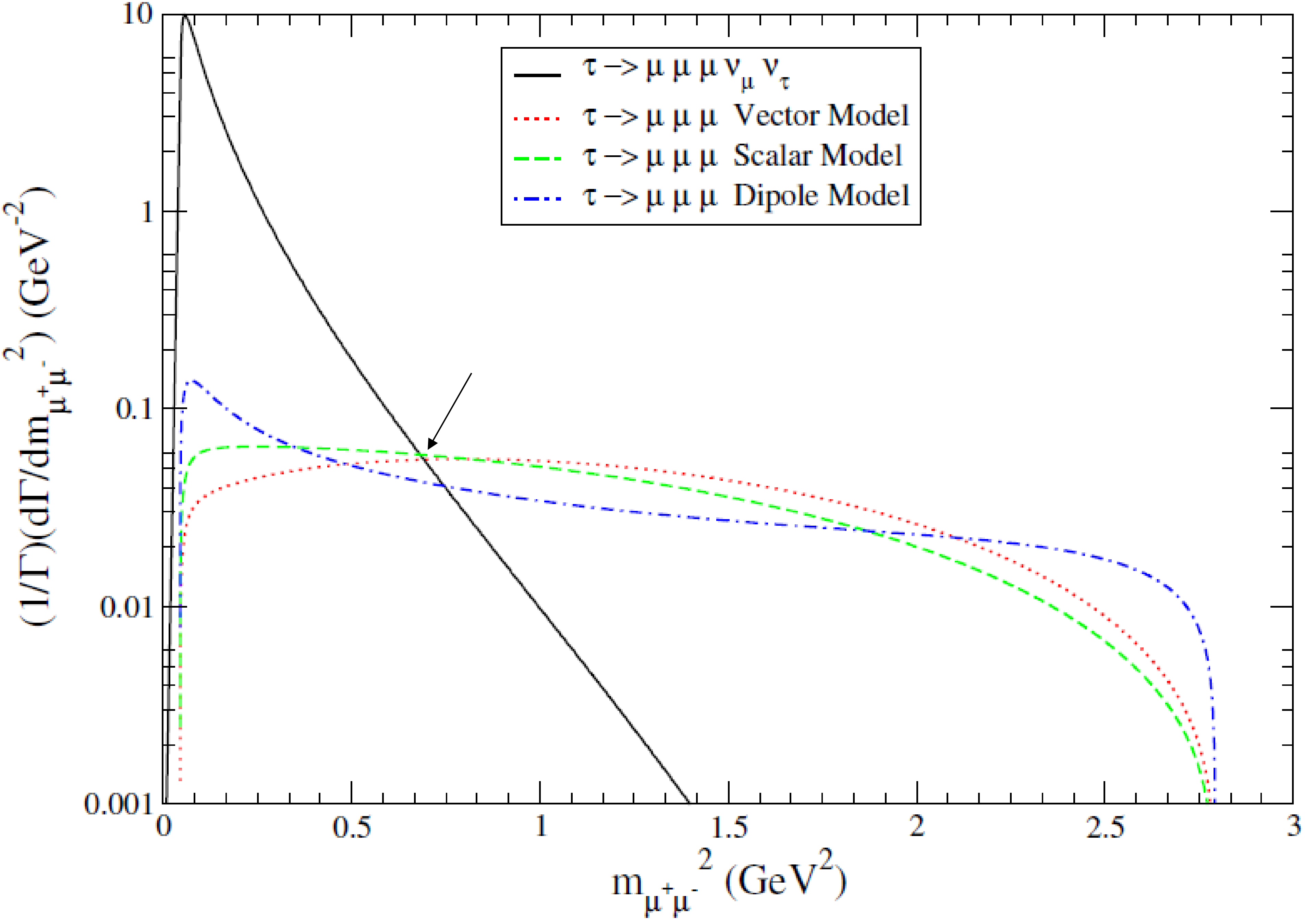
$\Lambda = 1$ TeV

(According to Celis, Cirigliano and Passemar '14)

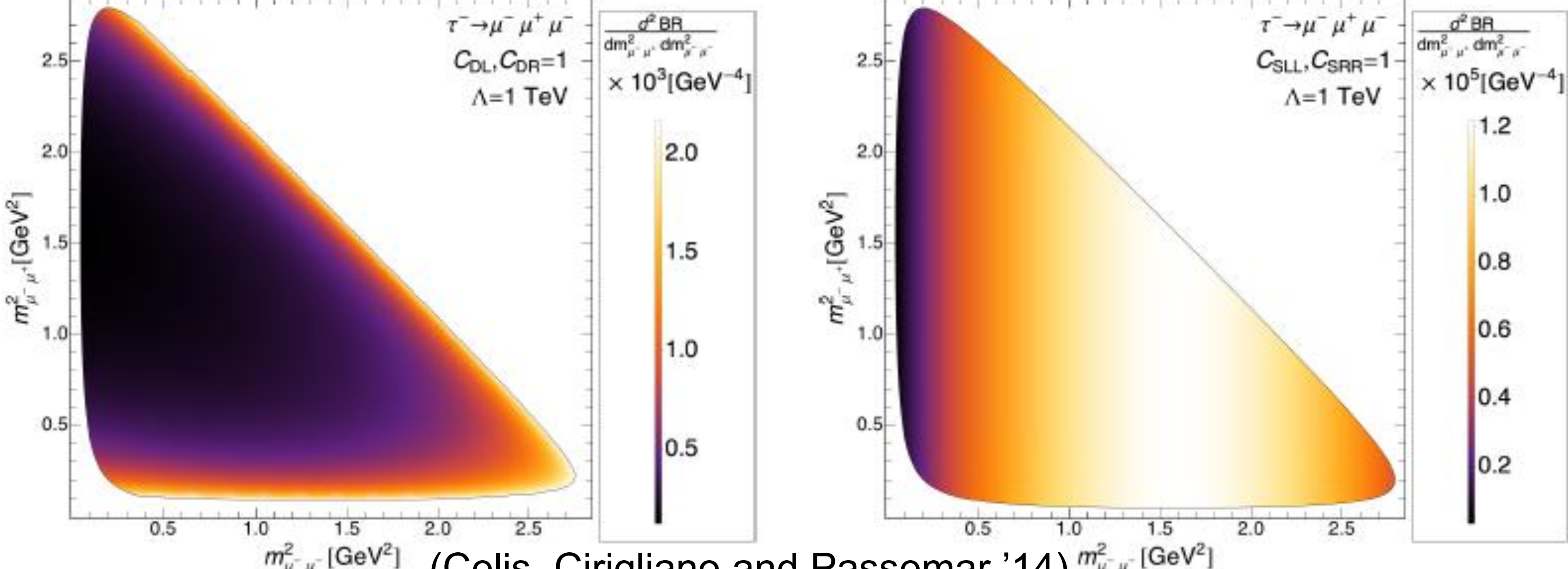
Channel	Current upper limit (UL) [24, 44]	S/B (UL)	Expected UL [45]
$\mathrm{BR}(\tau^- \to e^- e^+ e^-)$	$1.4 \cdot 10^{-8}$	$\sim 3 \cdot 10^{-4}$	$\sim 10^{-9}$
$\mathrm{BR}(\tau^- \to e^- \mu^+ \mu^-)$	$1.6 \cdot 10^{-8}$	~ 0.1	$\sim 10^{-9}$
$\mathrm{BR}(\tau^- \to \mu^- e^+ e^-)$	$1.1 \cdot 10^{-8}$	$\sim 6 \cdot 10^{-4}$	$\sim 10^{-9}$
$\mathrm{BR}(\tau^- \to \mu^- \mu^+ \mu^-)$	$1.2 \cdot 10^{-8}$	~ 0.1	$\sim 10^{-9}$
$\mathrm{BR}(\mu^- \to e^- e^+ e^-)$	$1.0 \cdot 10^{-12}$	$\sim 3 \cdot 10^{-8}$	$\sim 10^{-16}$

Table 2. Current and expected signal to background ratios in LFV $L^- \to \ell^- \ell'^+ \ell'^-$ searches. The expected UL is also shown for reference.

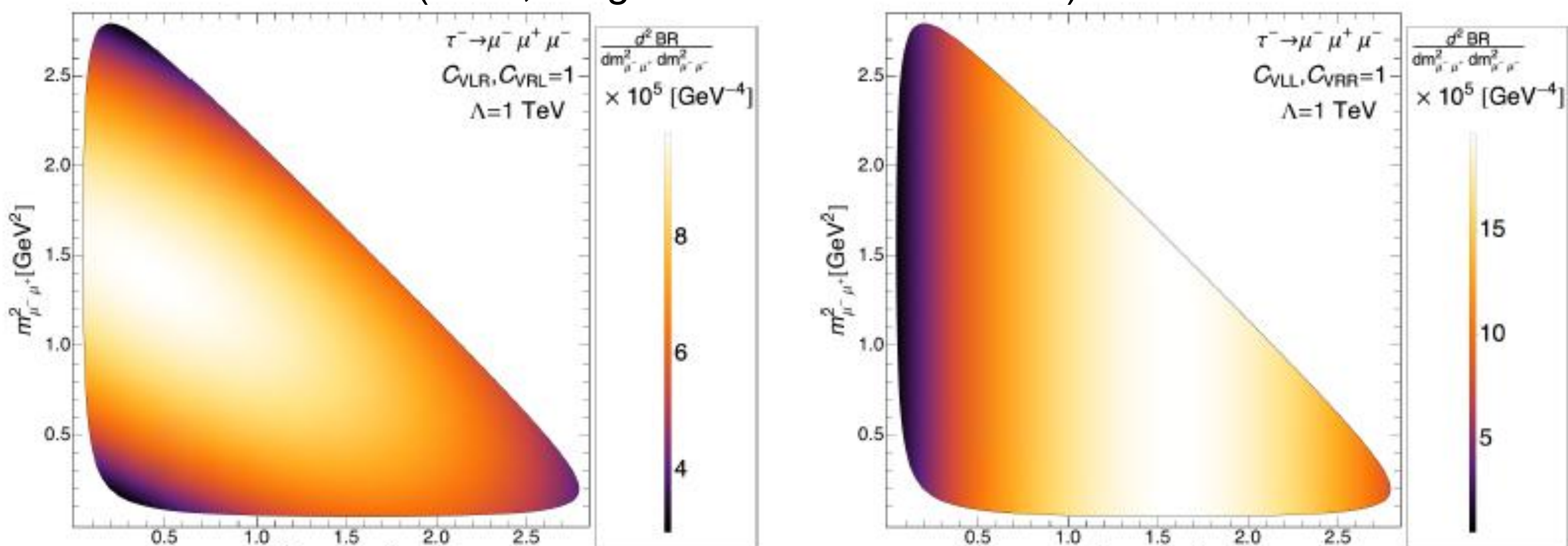
HFAG Report 12/14 for τ's and PDG for μ's



$L \to l\, l'\, l'\, \nu_L\, \nu_l$

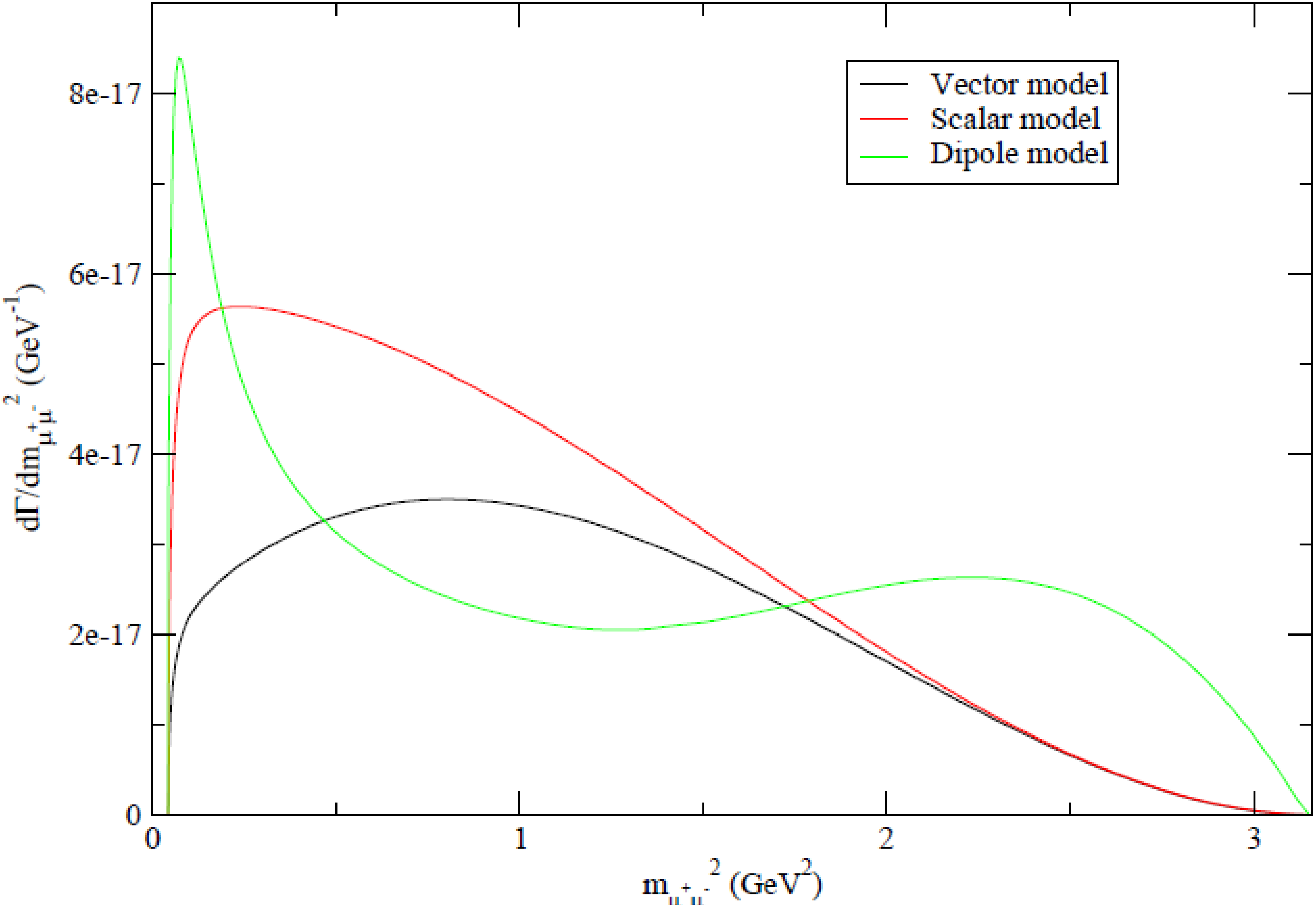


(Celis, Cirigliano and Passemar '14)

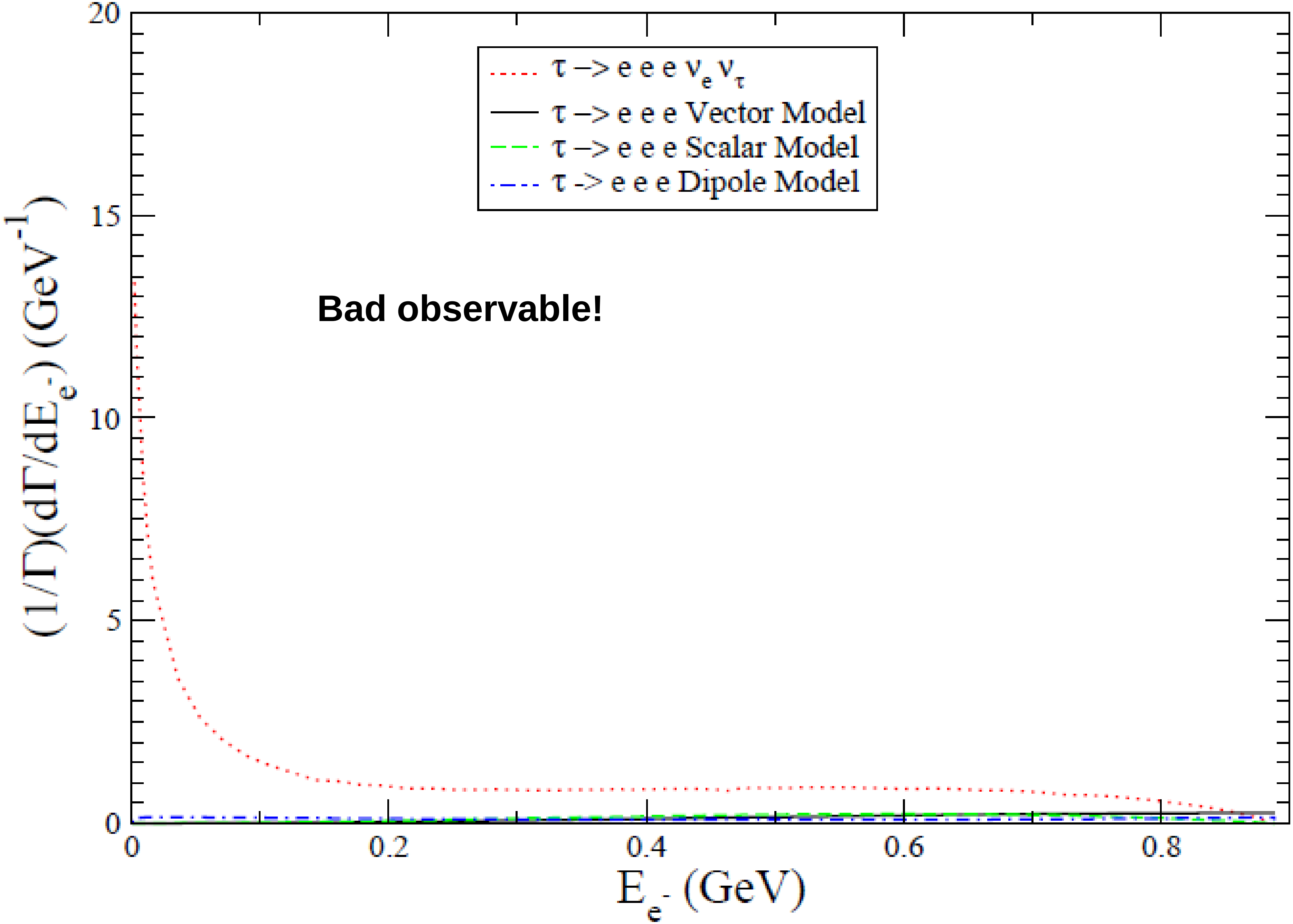


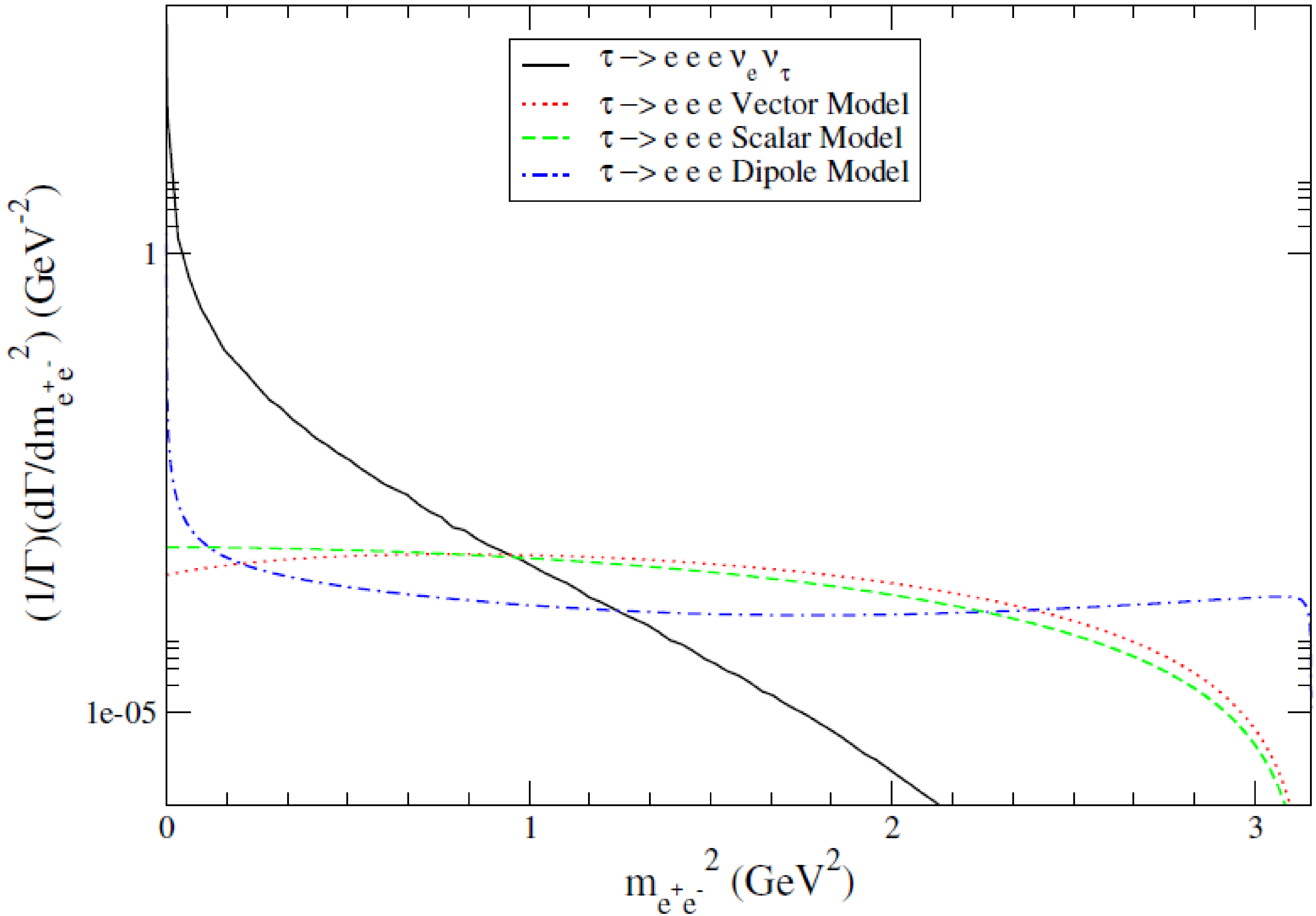
$L \to l\, l'\, l'\, \nu_L\, \nu_l$

τ -> e μμ

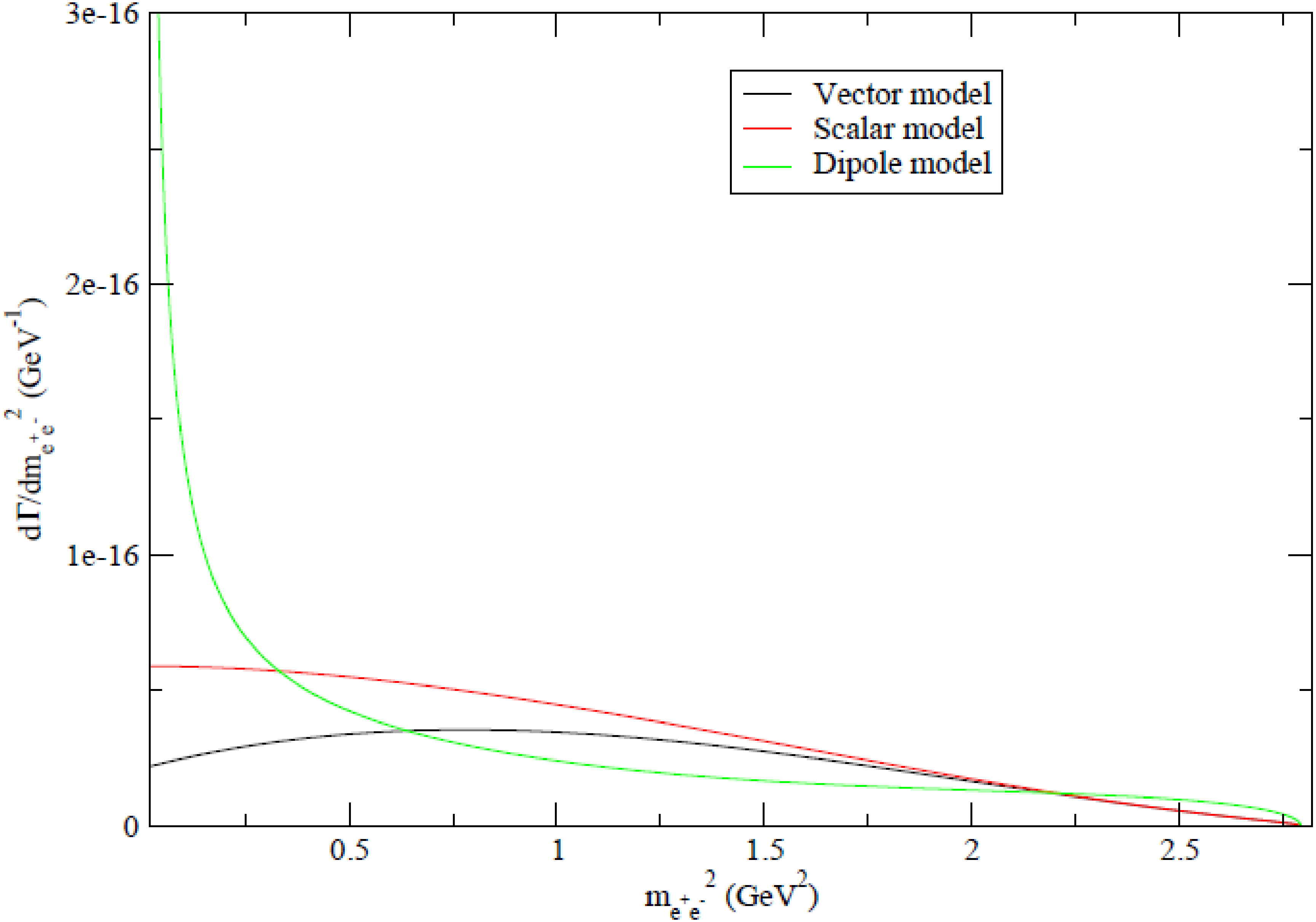


Vector model
Scalar model
Dipole model
8e-17
6e-17
4e-17
2e-17
0
0
1
2
3
dΓ/dm$_{\mu^+\mu^-}^2$ (GeV^{-1})
m$_{\mu^+\mu^-}^2$ (GeV^2)

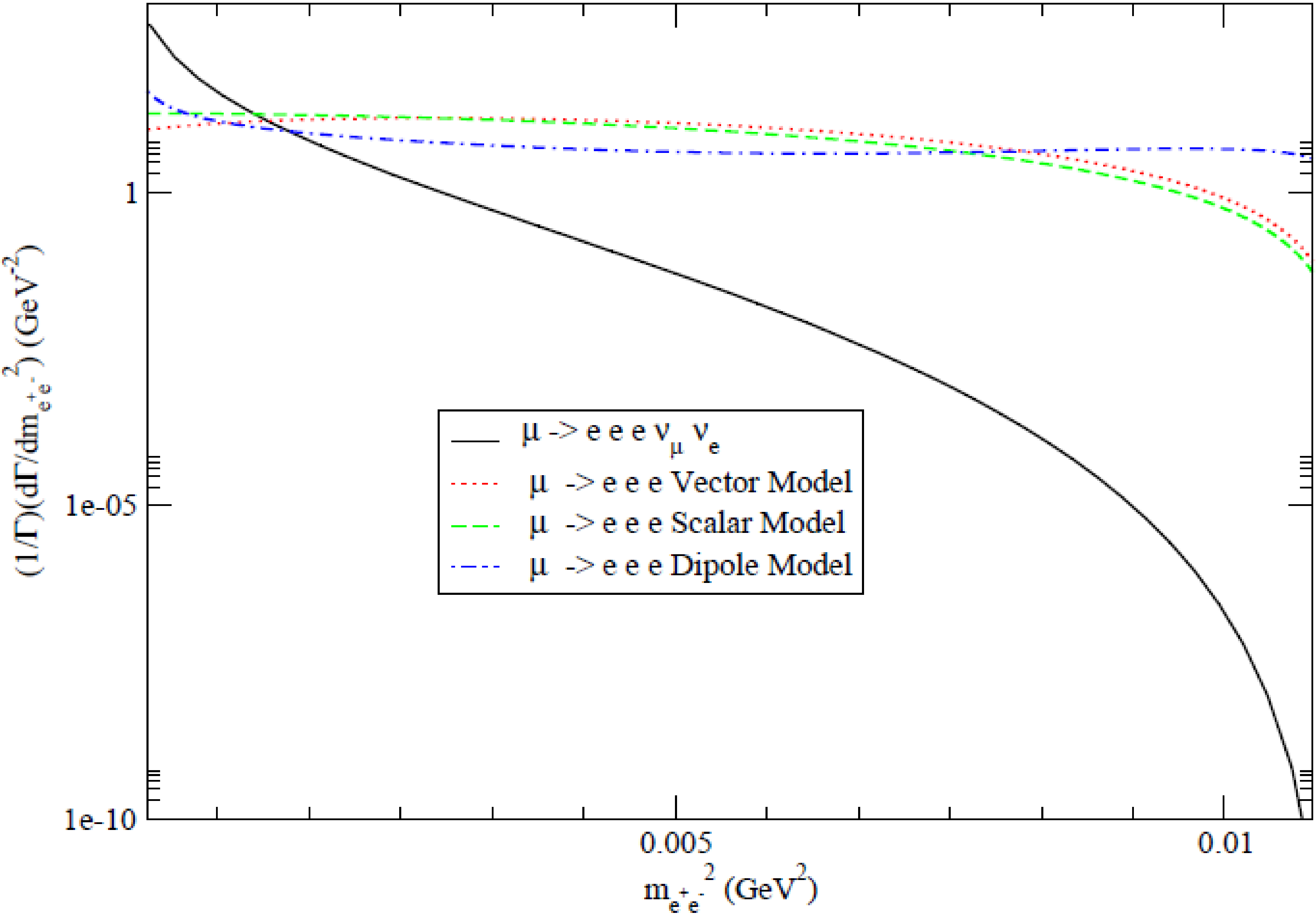

τ -> e e e ν_e ν_τ
τ -> e e e Vector Model
τ -> e e e Scalar Model
τ -> e e e Dipole Model
Bad observable!
(1/Γ)(dΓ/dE$_{e^-}$) (GeV^{-1})
E_{e^-} (GeV)
0
5
10
15
20
0.2
0.4
0.6
0.8


τ −> e e e ν_e ν_τ
τ −> e e e Vector Model
τ −> e e e Scalar Model
τ −> e e e Dipole Model
1
1e-05
0
1
2
3
$m_{e^+e^-}^2$ (GeV^2)
(1/Γ)(dΓ/d$m_{e^+e^-}^2$) (GeV^{-2})

τ -> μee

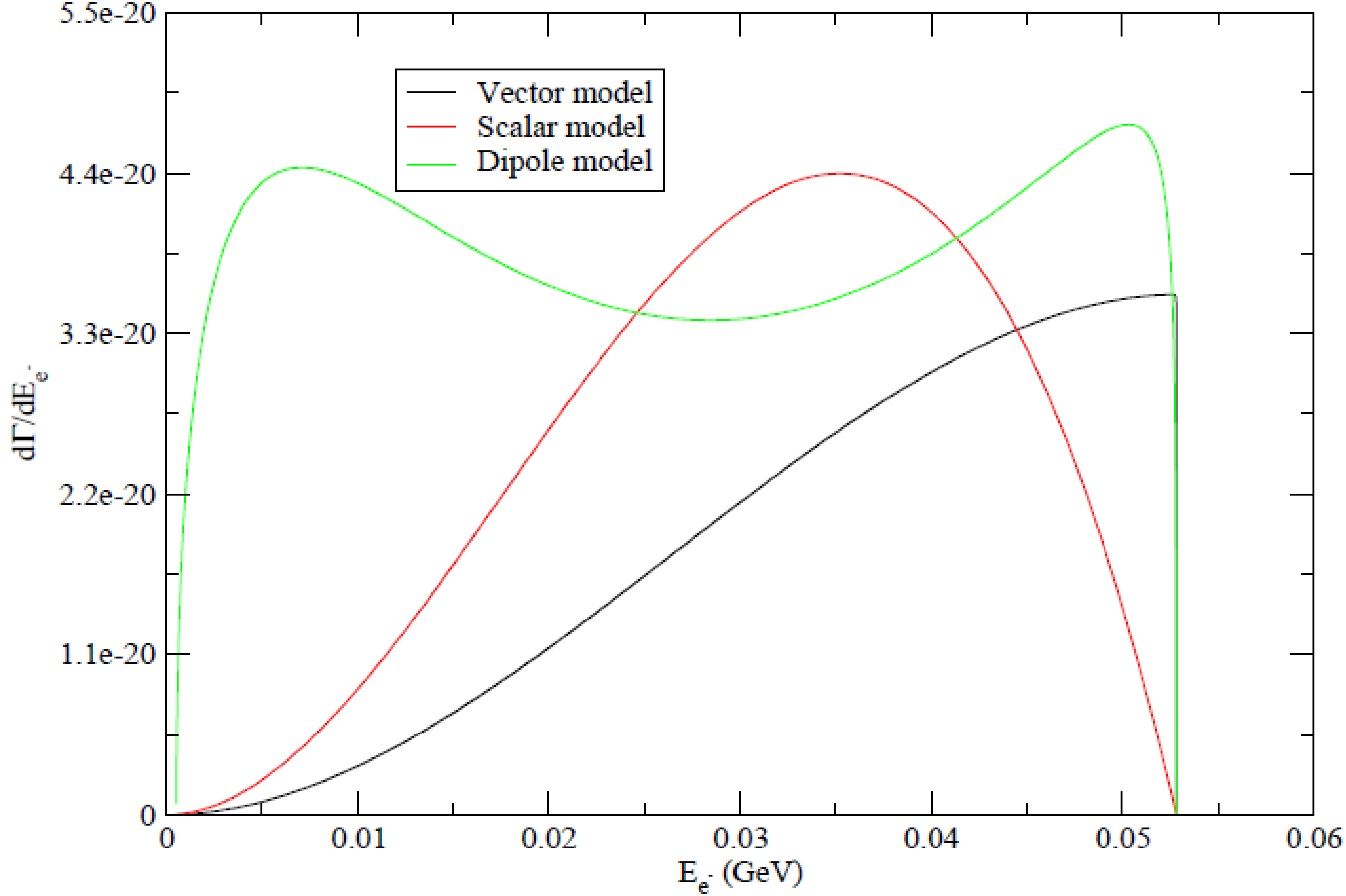


Vector model
Scalar model
Dipole model
3e-16
2e-16
1e-16
0
0.5
1
1.5
2
2.5
$d\Gamma/dm_{e^+e^-}^2$ (GeV^{-1})
$m_{e^+e^-}^2$ (GeV^2)



μ -> e e e ν_μ ν_e
μ -> e e e Vector Model
μ -> e e e Scalar Model
μ -> e e e Dipole Model
1
1e-05
1e-10
0.005
0.01
(1/Γ)(dΓ/dm_{e+e-}^2) (GeV^-2)
m_{e+e-}^2 (GeV^2)

μ -> eee



Vector model
Scalar model
Dipole model
5.5e-20
4.4e-20
3.3e-20
2.2e-20
1.1e-20
0
0.01
0.02
0.03
0.04
0.05
0.06
$d\Gamma/dE_{e^-}$
E_{e^-} (GeV)

CONCLUSIONS

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- **This renders possible a precise analysis of the V-A structure using Belle(-II)[coll. with Denis Epifanov]/PEN data.**

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- **This renders possible a precise analysis of the V-A structure using Belle(-II)[coll. with Denis Epifanov]/PEN data.**

- **We have considered in detail the background these (SM) processes constitute in LFV $L \to 3l$ searches: efficient cuts & CPV**