The search for $\tau \rightarrow l\,\gamma$ at Belle and Belle II

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Introduction: $\tau \rightarrow l\,\gamma$

- $\tau \rightarrow l\,\gamma$ is a prohibited decay in the SM for massless neutrinos
- extending the SM to include neutrino masses allows flavour mixing between generations → LFV can occur
- even so, LFV in the SM + massive neutrinos is suppressed and is unobservably small

$$B(\tau \rightarrow \mu\gamma)_{\mathrm{SM}} < 10^{-40}$$

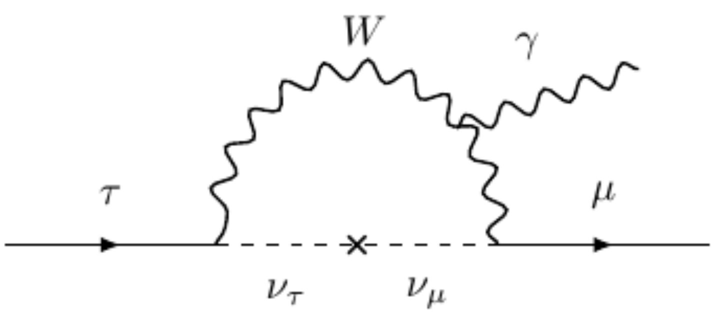

Figure 1: $\tau \rightarrow \mu\,\gamma$ via neutrino mixing

Introduction: $\tau \to l\, \gamma$

- unobservably small branching fraction for LFV processes allows New Physics (NP) to be probed without SM contamination
- these LFV modes are highly calculable!
- of the tau processes, $\tau \to l\, \gamma$ decays most sensitive
- why taus not muons? muons are easier to produce!
  - expected limit on branching fraction $\sim 10^{5-6}$ greater than $\mu \to e\, \gamma$ due to tau mass
  - if this NP is Higgs-like, then would be seen more strongly in tau-sector (taus couple more strongly than muons to the Higgs)

Other LFV

LFV Process	Present Bound	Future Sensitivity
$\mu \to e\gamma$	5.7×10^{-13} [1]	$\approx 6 \times 10^{-14}$ [2]
$\mu \to 3e$	1.0×10^{-12}[3]	$\approx 10^{-16}$ [4]
$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$	7.0×10^{-13} [5]	?
$\mu^- \mathrm{Ti} \to e^- \mathrm{Ti}$	4.3×10^{-12} [6]	?
$\mu^- \mathrm{Al} \to e^- \mathrm{Al}$	–	$\approx 10^{-16}$ [7, 8]
$\tau \to e\gamma$	3.3×10^{-8} [9]	$\sim 10^{-8} - 10^{-9}$ [10]
$\tau \to \mu\gamma$	4.4×10^{-8} [9]	$\sim 10^{-8} - 10^{-9}$ [10]
$\tau \to 3e$	2.7×10^{-8}[11]	$\sim 10^{-9} - 10^{-10}$ [10]
$\tau \to 3\mu$	2.1×10^{-8}[11]	$\sim 10^{-9} - 10^{-10}$ [10]

Table 1: Present and future experimental sensitivities for LFV processes (Paradisi, 2015)

Neutrino mixing

- lepton sector not fully understood (see: neutrino masses)
- many mechanisms which explain neutrino mixing introduce LFV!
- seesaw models, for example, can introduce new scalars which could couple with leptons to produce LFV

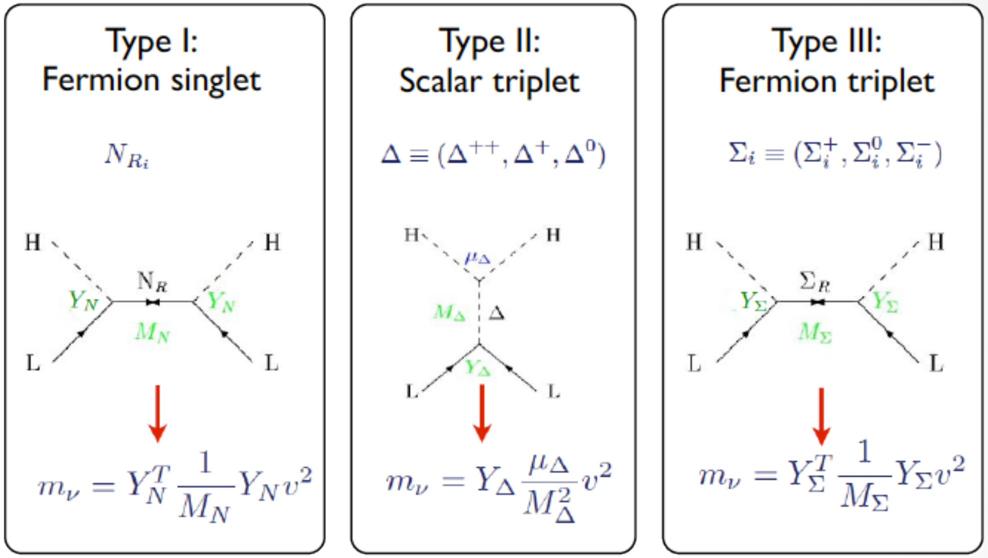

Figure 2: New particles introduced via seesaw models

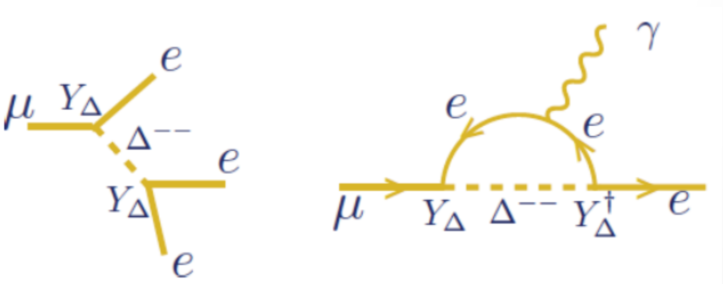

Figure 3: LFV in Type-II seesaw

h → τ μ excess

- CMS (2015) found 2.4σ excess in h → τ μ branching fraction

$$B(h \rightarrow \tau\mu) = (0.84^{+0.39}_{-0.37})\%$$

- ATLAS (2015) found 1.2σ excess

$$B(h \rightarrow \tau\mu) = (0.77 \pm 0.62)\%$$

- LFV can occur naturally in models with more than one Higgs doublet, e.g. Type-II 2HDM

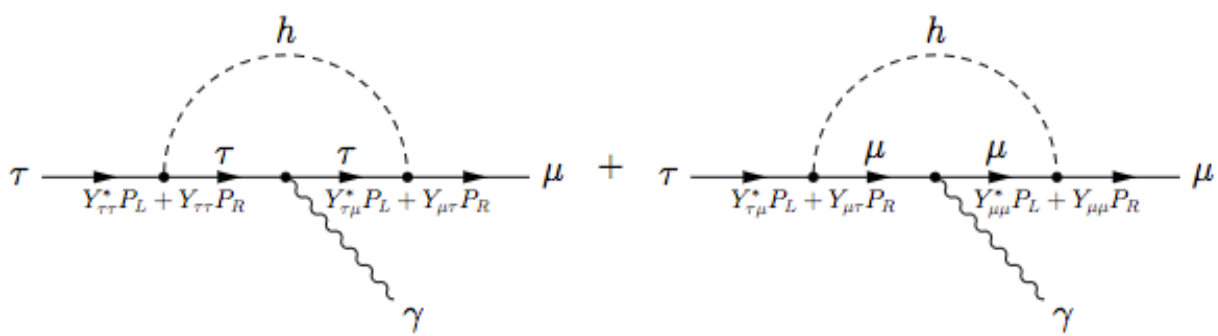

Figure 4: Diagrams contributing to τ → μ γ decay, mediated by a Higgs boson with flavour violating Yukawa couplings (*Harnick et al., 2012)*

h → τ μ excess

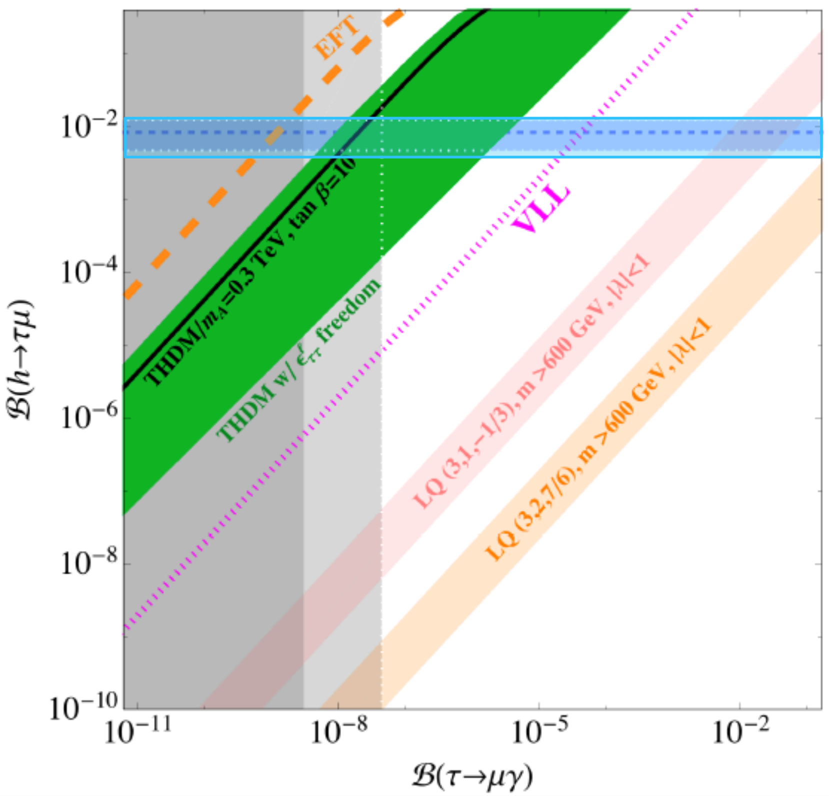

Figure 5: B(h → τ μ) against B(τ → μ γ), with various ranges predicted by NP models (*Dorsner et al.*, 2015)

horizontal lines are CMS 1σ bands on B(h → τ μ) (at 90% CL)

vertical lines are (right) current upper limit B(τ → μ γ) and (left) Belle II expected sensitivity

under this model we would expect to find a signature in Belle II (!!)

Models predicting $\tau \rightarrow l \gamma$

model	$Br(\tau \rightarrow \mu\gamma)$
mSUGRA + seesaw	10^{-7}
SUSY + SO(10)	10^{-8}
SM + seesaw	10^{-9}
Non-Universal Z'	10^{-9}
SUSY + Higgs	10^{-10}

Table 2: Upper limits of branching fractions of $\tau \rightarrow \mu \gamma$, predicted by models of new physics beyond the SM (various sources)

- many NP models predict LFV to occur
- present and future bounds on LFV processes can reduce available phase space; determining branching fractions can rule out certain models

LFV Process	Present Bound	Future Sensitivity
$\tau \rightarrow e\gamma$	3.3×10^{-8} [9]	$\sim 10^{-8} - 10^{-9}$ [10]
$\tau \rightarrow \mu\gamma$	4.4×10^{-8} [9]	$\sim 10^{-8} - 10^{-9}$ [10]

Key backgrounds

$$\boxed{\mathcal{B}(\tau \to \mu\nu\nu) = 17.41\%}$$

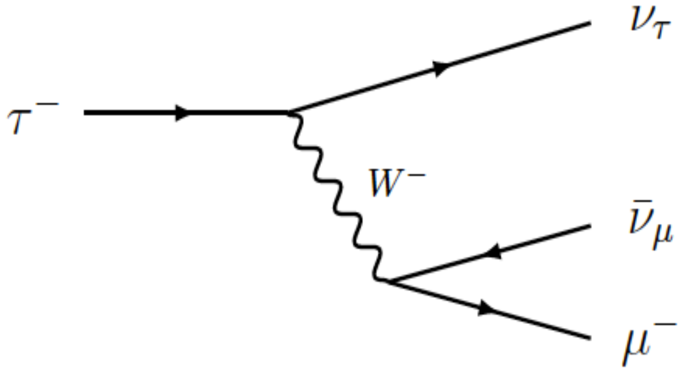

Figure 6: τ → μ ν ν diagram

$$\boxed{\mathcal{B}(\tau \to \pi\nu) = 10.83\%}$$

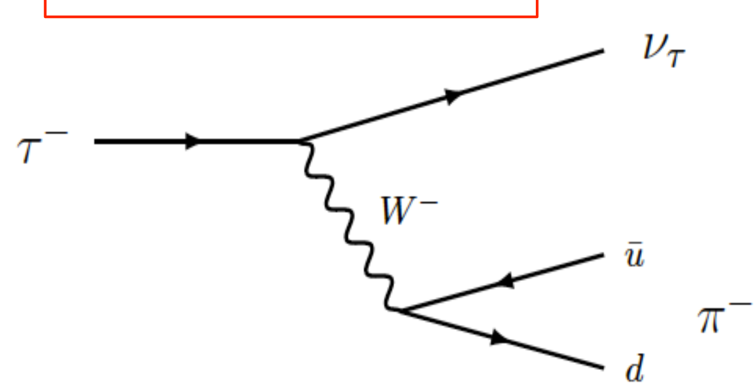

Figure 7: τ → π ν diagram

$$\boxed{\sigma(e^+e^- \to \mu^+\mu^-\gamma) = 0.242\,\mathrm{nb}}$$

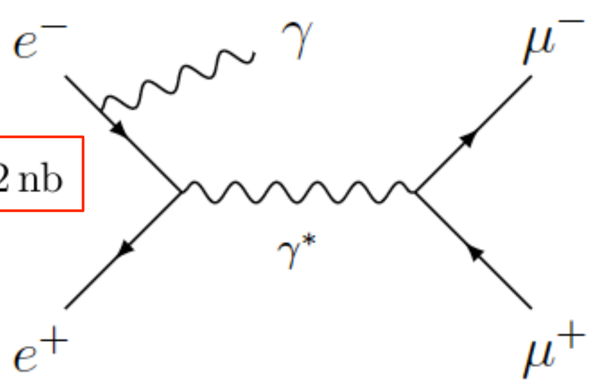

Figure 8: e e → μ μ γ diagram

Belle & Belle II

$$\sigma(e^+e^- \to \tau^+\tau^-) = 0.919\,\mathrm{nb}$$

$$\mathcal{L} = N\sigma$$

- Belle – 1000 fb^{-1} of data (full run data)
  - $e^+ e^- \to \tau^+ \tau^- \sim 900 \times 10^6$ tau-pairs
  - $\tau \to \mu \nu \nu \sim 150 \times 10^6$ events
  - $\tau \to \pi \nu \sim 100 \times 10^6$ events
  - $e\, e \to \mu \mu \gamma \sim 250 \times 10^6$ events

× 50 more expected total luminosity at Belle II compared to Belle

- Belle II – 50 ab^{-1} (predicted luminosity)
  - $e^+ e^- \to \tau^+ \tau^- \sim 450 \times 10^8$ tau-pairs
  - $\tau \to \mu \nu \nu \sim 75 \times 10^8$ events
  - $\tau \to \pi \nu \sim 50 \times 10^8$ events
  - $e\, e \to \mu \mu \gamma \sim 125 \times 10^8$ events

at my current BG efficiency (10^{-4} %): ~10,000 background events

$e\, e \to \mu \mu \gamma$ background not yet studied in my analysis

Current searches

Belle (2007), 535 fb^{-1} :

$$B(\tau \to \mu\gamma) < 4.5\times10^{-8}$$

$$B(\tau \to e\gamma) < 1.2\times10^{-7}$$

Babar (2010), 515.5 fb^{-1} :

$$B(\tau \to \mu\gamma) < 4.4\times10^{-8}$$

$$B(\tau \to e\gamma) < 3.3\times10^{-8}$$

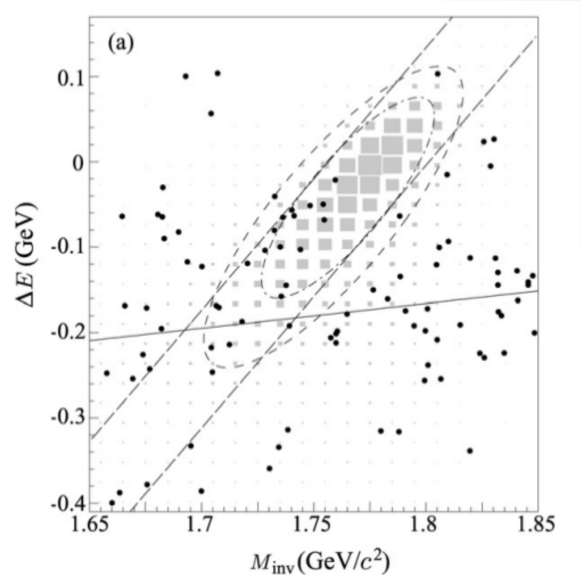

Figure 9: M_{inv} - ΔE distribution in the search for $\tau\to\mu\gamma$ at Belle (*Hayasaka,* 2008)

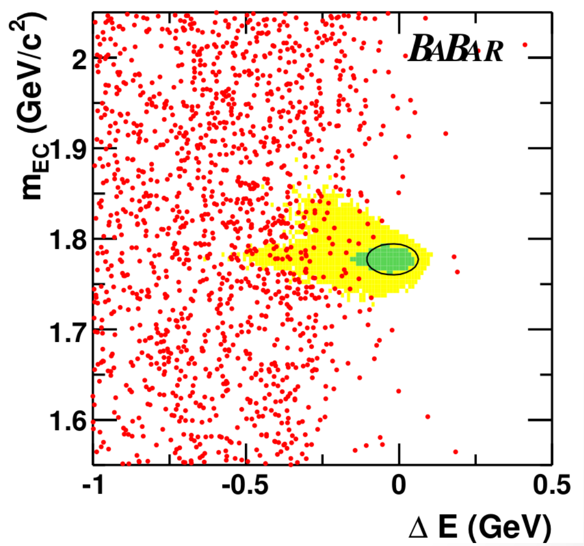

Figure 10: M_{bc} - ΔE distribution in the search for $\tau\to\mu\gamma$ at Babar (*Babar Collaboration,* 2010)

Future searches

Belle II, 5 ab^{-1}:

$$B(\tau \to \mu\gamma) < 1.5 \times 10^{-8}$$
$$B(\tau \to e\gamma) < 3.9 \times 10^{-8}$$

Belle II, 50 ab^{-1}:

$$B(\tau \to \mu\gamma) < 4.7 \times 10^{-9}$$
$$B(\tau \to e\gamma) < 1.2 \times 10^{-8}$$

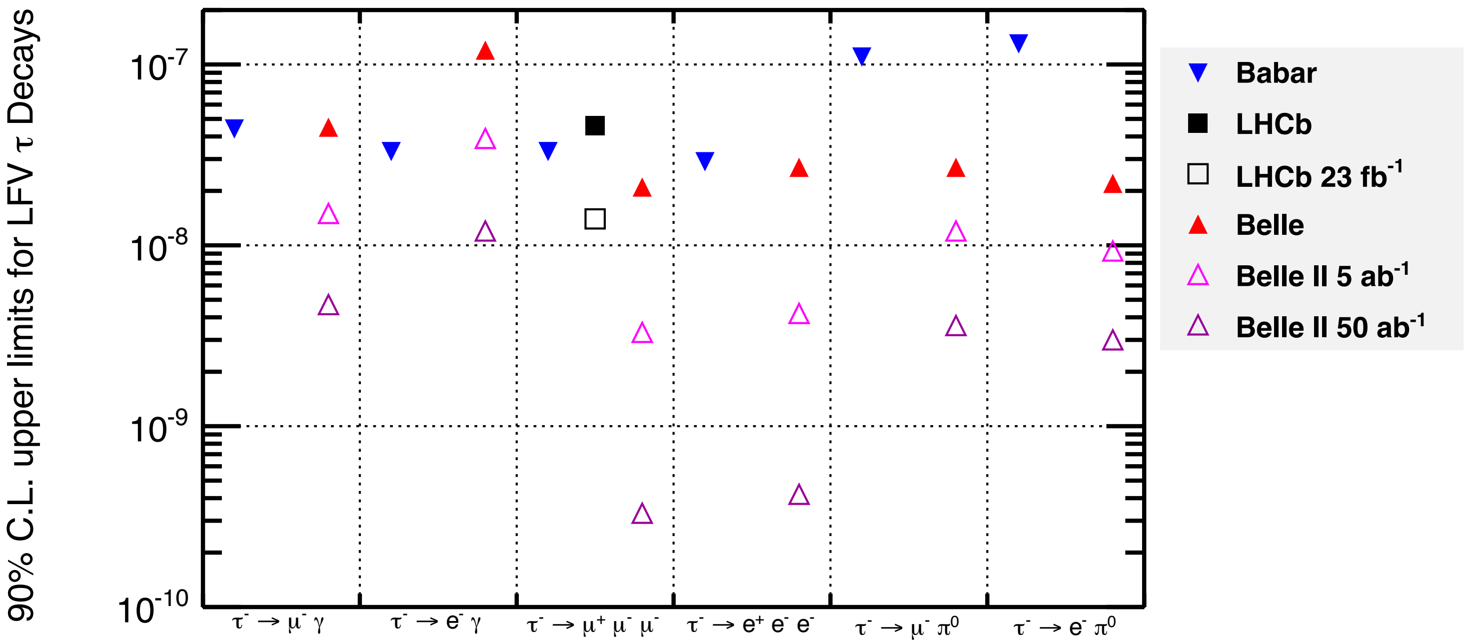

Figure 11: Current and future sensitivities on tau LFV branching fractions (*Urquijo*, 2016)

My search

- approx 1.5 million signal ($\tau \rightarrow \mu\ \gamma$) MC events produced
- approx 3,500 million generic (tau-pair) MC events produced by the Belle II Collaboration
- 24 selection criteria added (based on previous Belle search)
- cuts made to suppress various backgrounds

- production and analysis being performed in `basf2`
  - currently optimising selection criteria for Belle II MC
  - analysis should be ready for Belle II first data
  - plan to optimise selection criteria for Belle MC also, to run over complete Belle dataset

My search

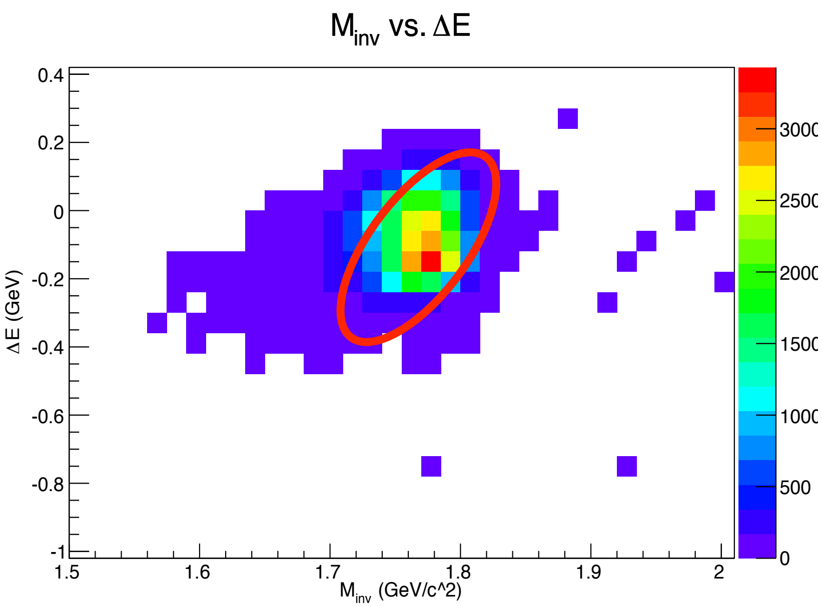

Figure 12: M_{inv} - ΔE distribution for signal MC ($\tau \rightarrow \mu\ \gamma$) after selection cuts (59,265 events out of 1,632,596)

Efficiency: $\sim 3.6\%$

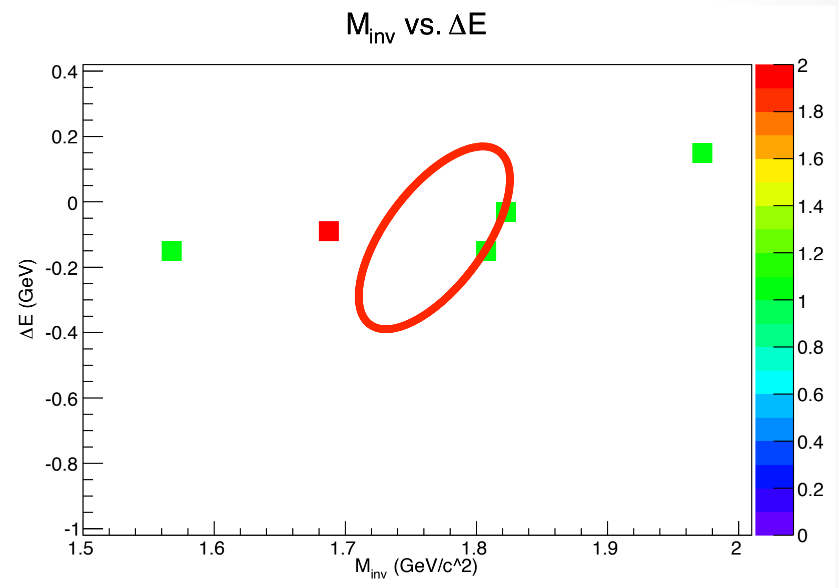

Figure 13: M_{inv} - ΔE distribution for background MC after selection cuts (6 events out of 5,938,869)

Efficiency: $\sim 10^{-4}\ \%$

Conclusion

- LFV is an exciting place to search for new physics
- lepton sector is not fully understood
- negligible SM background means an observation would be an unambiguous signature of NP
- analysis framework is being set up for Belle II data analyses (can be run over Belle and Belle II data)

Conclusion

Thank you for your attention!

Questions?