Working Group Report
Theory

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Mu2e-II Snowmass21 Committee Meeting

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Theory working group conveners

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Doubled in size!!!

Comments, questions, and members welcome!

Theory input for Mu2e(-II)

1) Standard Model background
2) Desired signal: $\mu \to e$ conversion
3) Exotic signals

Theory input for Mu2e(-II)

1) Standard Model background

1) Decay-in-orbit in Al calculation sufficient?

$$\frac{m_\mu}{\Gamma_0}\frac{d\Gamma}{dE} \simeq 1.24(3)\times 10^{-4}\left(\frac{E_{max}-E}{m_\mu}\right)^{5.023}$$

[Szafron & Czarnecki '16]

2) Need similar precision for Ti?

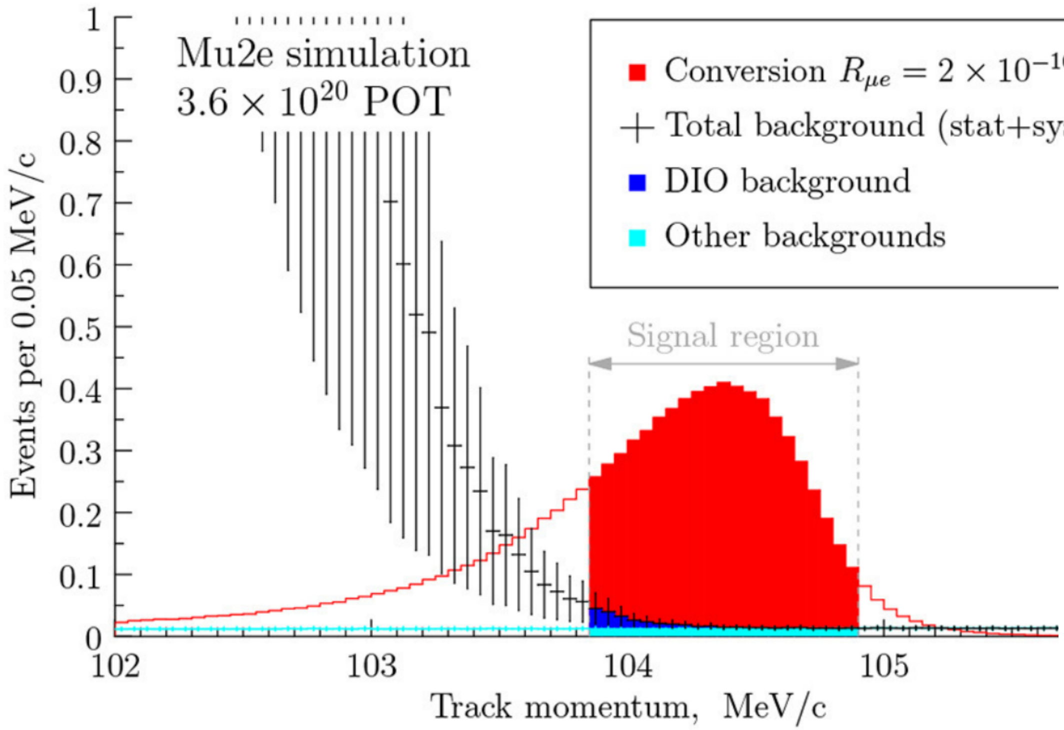


TABLE 1 | Backgrounds in Mu2e for the nominal 3.6×10^{20} protons-on-target.

Process	**Expected number**
Cosmic ray Muons	$0.209\pm0.02\pm0.06$
DIO	$0.144\pm0.03\pm0.11$
Antiprotons	$0.040\pm0.001\pm0.020$
RPC	$0.021\pm0.001\pm0.002$
Muon DIF	<0.003
Pion DIF	$0.001\pm<0.001$
Beam electrons	$2.1\pm1.0\times10^{-4}$
RMC	$0.000^{+0.004}_{-0.000}$
Total	0.41 ± 0.03

Theory input for Mu2e(-II)

1) Standard Model background

2) Desired signal: μ→e conversion

   1) Complementarity with MEG, Mu3e, COMET.

   2) Different targets probe (A,Z) and spin-structure.

      $\bar{\mu} e\, \bar{p} p,\ \bar{\mu} e\, \bar{n} n,\ \bar{\mu} e\, \bar{p} \gamma_5 p,\ \bar{\mu} e\, \bar{n} \gamma_5 n, \ldots$ [Cirigliano, Davidson, Kuno '17, ...]

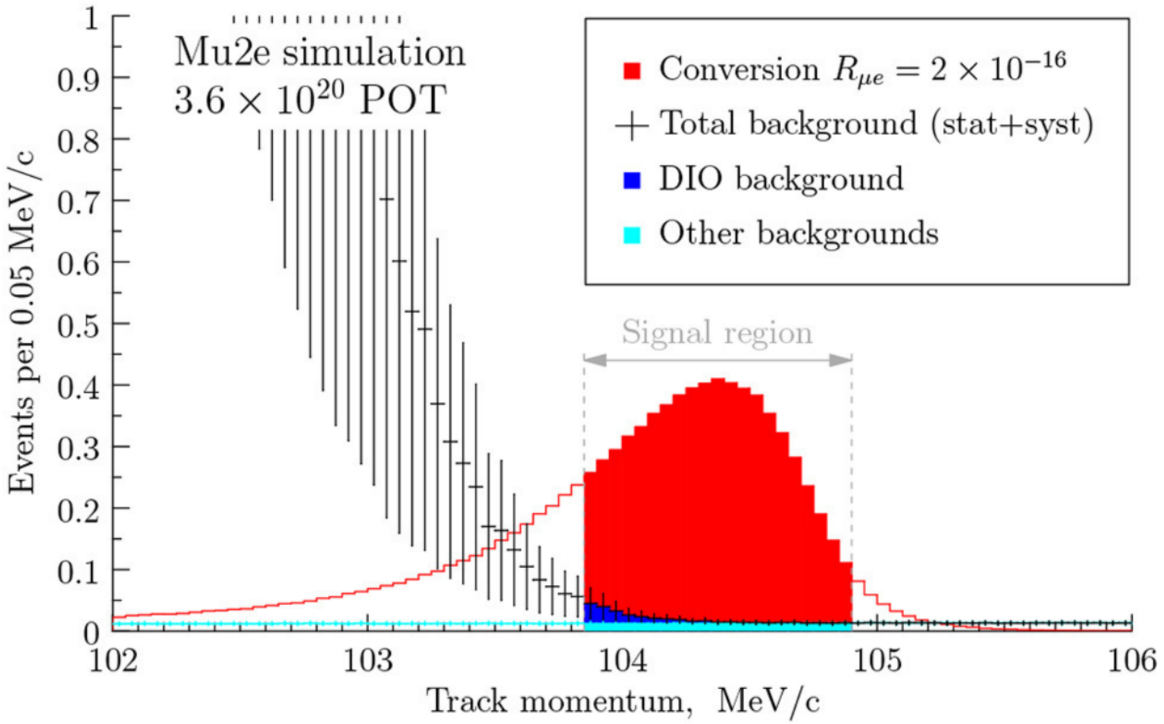
   3) Perfect world: measure e helicity. $\bar{\mu} P_L e\, \bar{p} p,\ \bar{\mu} P_R e\, \bar{p} p, \ldots$

3) Exotic signals

Theory input for Mu2e(-II)

1) Standard Model background
2) Desired signal: $\mu \to e$ conversion
3) Exotic signals
    1) $\mu \to e^+$ conversion.
    2) ΔB, ΔL, $\mu\mu \to ee$, …
    3) $\mu \to e\, X$.
    4) …

Mu2e region of interest

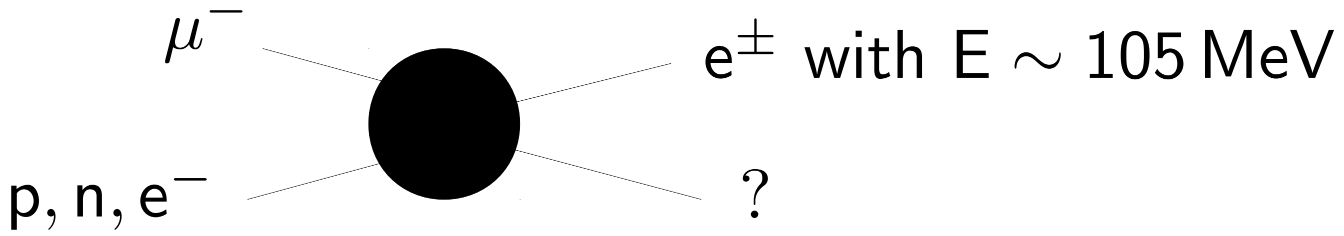


- Theorist's view:

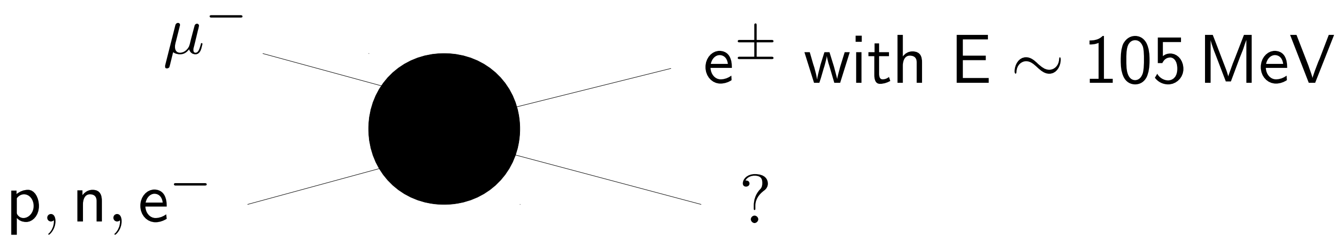
  Mu2e(-II) measures electrons around 105 MeV coming from muonic Al atom.

How does one get 105 MeV?

Combinatorics

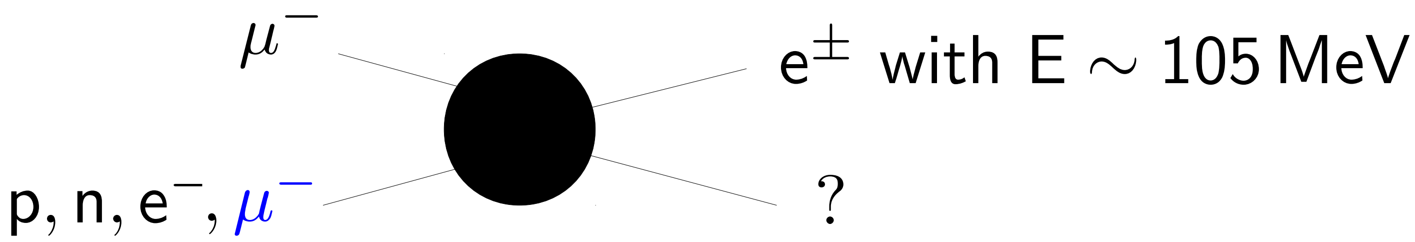


Combinatorics



- Obvious source: muon mass
  - $\mu p \to e p$, $\mu n \to e n$, $\mu e \to e e$. ← $E_e \sim m_\mu/2$ Possible in COMET-I?
    [Koike, Kuno, Sato, Yamanaka '10]
  - $\mu p p \to e^+ n n$. ← $\Delta L = 2, d \geq 9$

Combinatorics



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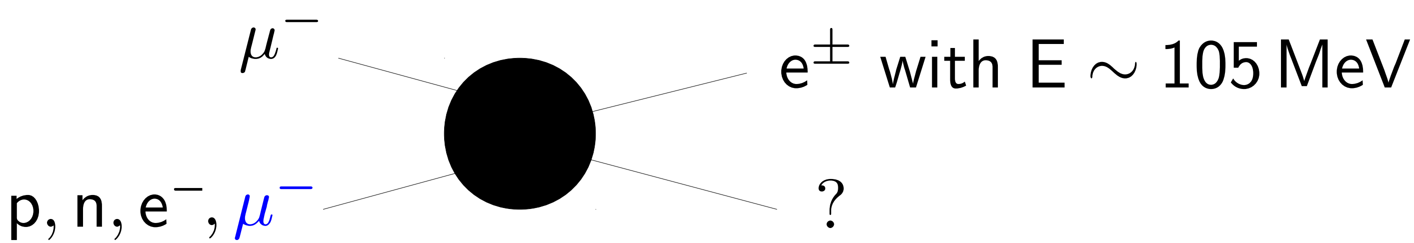
  - $\mu p p \to e^+ n n.$ ← $\Delta L = 2, d \geq 9$
  - $\mu\mu \to ee.$ ← $\Delta L_\mu = 2$ Probability for double muon capture? Competes with muonium-antimuonium conv.

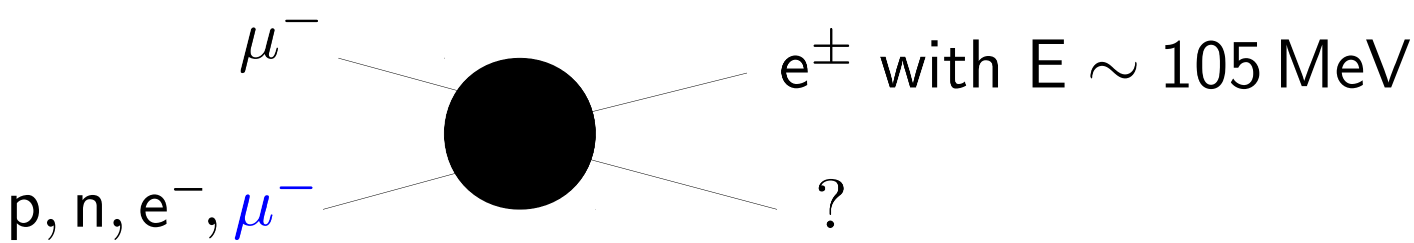
$E_e \sim m_\mu,$ but tails in both directions!

Combinatorics



- Obvious source: muon mass
  - $\mu p \to ep, \mu n \to en, \mu e \to ee.$ ← $E_e \sim m_\mu/2$ Possible in COMET-I?
    [Koike, Kuno, Sato, Yamanaka '10]
  - $\mu pp \to e^+ nn.$ ← $\Delta L = 2, d \geq 9$
  - $\mu\mu \to ee.$ ← $\Delta L_\mu = 2$ Probability for double muon capture? Competes with muonium-antimuonium conv.
- Overkill: nucleon mass (ΔB = 1)
  - $\mu^- p \to \mu^- e^+, \mu^- p \to e^- e^+, \ldots$ ← Always gives nucleon decay, e.g. $p \to \mu^+ \mu^- e^+$.

Combinatorics



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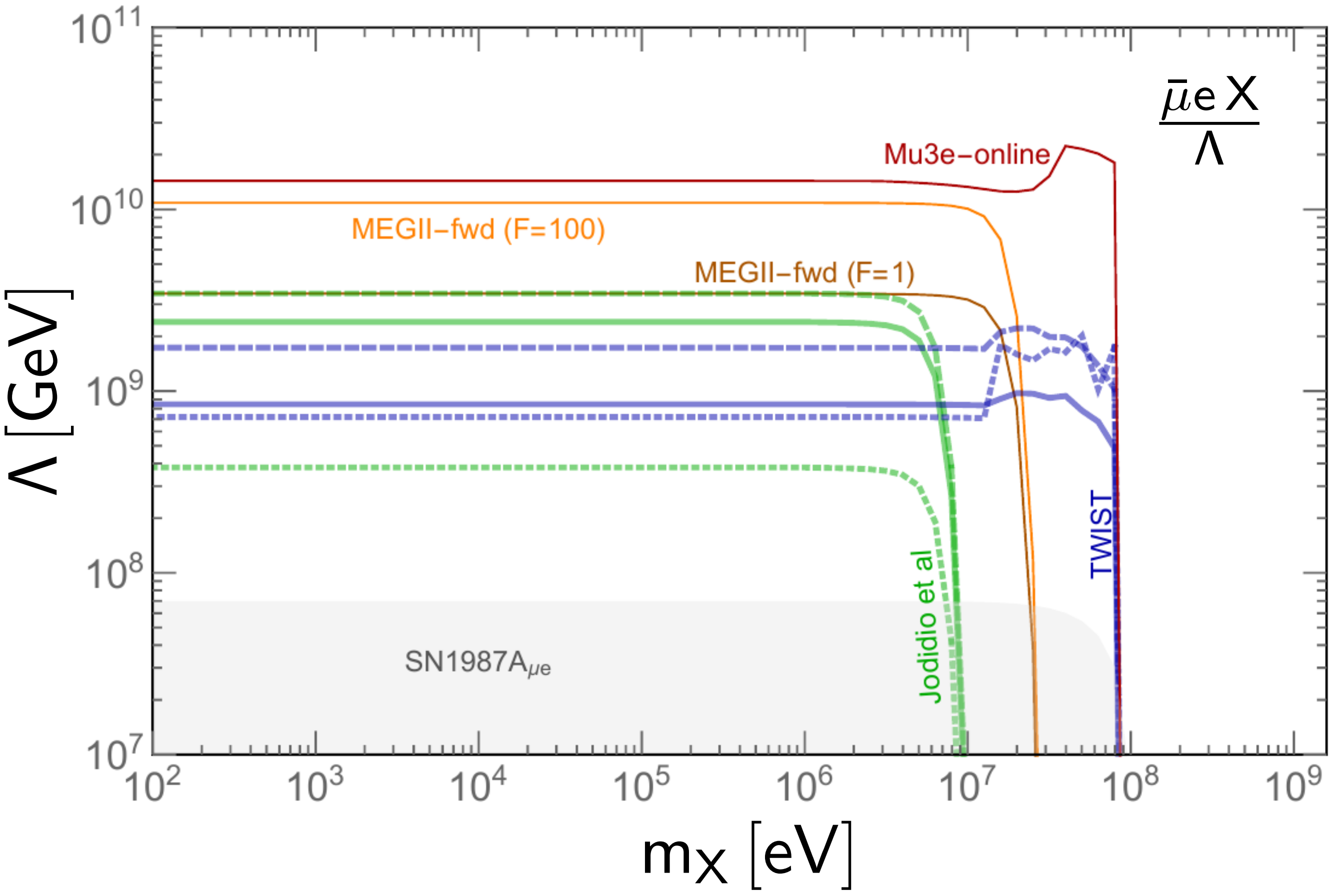
- Overkill: nucleon mass (ΔB = 1)
  - $\mu^- p \to \mu^- e^+, \mu^- p \to e^- e^+, \ldots$ ← Always gives nucleon decay, e.g. $p \to \mu^+ \mu^- e^+$.
- μ mass + nuclear recoil
  - every μ decay, e.g. SM, $\mu \to 3e$, $\mu \to e\gamma$, $\mu \to eX$, …

$\mu \to e\, X$

- New light boson X, e.g. Majoron, axion, Z'.
- $\mathrm{BR}(\mu \to eX) \lesssim 10^{-5}$–$10^{-6}$ [Jodidio++ '86; TWIST '15]
- Motivated by XENON1T anomaly?

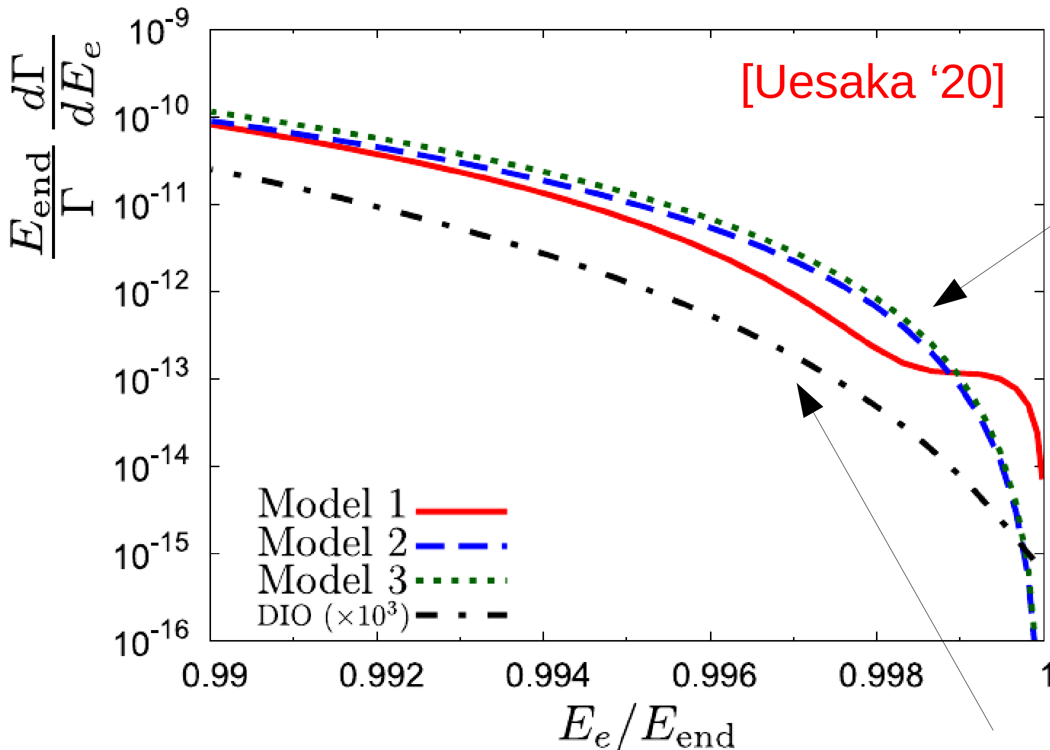


[Calibbi, Redigolo, Ziegler, Zupan '20]

μ → e X in Mu2e(-II)

- μ → e X in bound muon produces tail up to E_e ~ 105 MeV.
- Different tail shape!

[Tormo, Bryman, Czarnecki, Dowling '11]



$\mu \to eX: \; (E_{end} - E)^3$

$SM: \; (E_{end} - E)^5$

- Fit background shape to reveal exotic contribution?
- Measure *entire* spectrum in future experiment?
- Strong suppression from tail, still competitive?

Summary

- Questions for theorists:
  - Viable models for $\mu \to e^+$?
  - $\mu^-\mu^- \to e^-e^-$ vs. $\mu^+e^- \to \mu^-e^+$.
- Questions for experimentalists:
  - Do you need more precise DIO calculation?
  - Is a spectral fit to DIO tail planned?
  - How probable is double muon capture?
- Dreams:
  - Measure the entire electron spectrum.
  - Measure electron helicity.

Have we missed anything?

Backup

Present best limits				
Process	BR Limit	Decay constant	Bound (GeV)	Experiment
Star cooling	–	F^A_{ee}	4.6×10^9	WDs [44]
	–	$F^A_{\mu\mu}$	1.6×10^6	SN1987A$_{\mu\mu}$ [45]
	4×10^{-3}	$F_{\mu e}$	1.4×10^8	SN1987A$_{\mu e}$ (Sec. 6.1)
$\mu \to e\,a$	$2.6 \times 10^{-6*}$	$F_{\mu e}$ (V or A)	4.8×10^9	Jodidio at al. [9]
$\mu \to e\,a$	$2.5 \times 10^{-6*}$	$F_{\mu e}$ ($V+A$)	4.9×10^9	Jodidio et al. [9]
$\mu \to e\,a$	$5.8 \times 10^{-5*}$	$F_{\mu e}$ ($V-A$)	1.0×10^9	TWIST [10]
$\mu \to e\,a\,\gamma$	$1.1 \times 10^{-9*}$	$F_{\mu e}$	$5.1 \times 10^{8\#}$	Crystal Box [46]
$\tau \to e\,a$	$2.7 \times 10^{-3**}$	$F_{\tau e}$	4.3×10^6	ARGUS [43]
$\tau \to \mu\,a$	$4.5 \times 10^{-3**}$	$F_{\tau\mu}$	3.3×10^6	ARGUS [43]

Expected future sensitivities				
Process	BR Sens.	Decay constant	Sens. (GeV)	Experiment
$\mu \to e\,a$	$1.3 \times 10^{-6*}$	$F_{\mu e}$ (V or A)	6.8×10^9	MEGII-fwd*
$\mu \to e\,a$	$1.3 \times 10^{-7*}$	$F_{\mu e}$ (V or A)	2.1×10^{10}	MEGII-fwd**
$\mu \to e\,a$	$7.3 \times 10^{-8*}$	$F_{\mu e}$ (V or A)	2.9×10^{10}	Mu3e [42]
$\tau \to e\,a$	$8.4 \times 10^{-6**}$	$F_{\tau e}$	7.7×10^7	Belle II
$\tau \to \mu\,a$	$1.6 \times 10^{-5**}$	$F_{\tau\mu}$	5.6×10^7	Belle II

[Calibbi, Redigolo, Ziegler, Zupan ‘20]