Exotic Decay

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Outline

- Introduction and physics motivation of exotic decay search.
- Exotic decay searches in PIENU
  - $\pi^+ \to e^+\nu_H$
  - $\mu^+ \to e^+X_H$
- Prospects of exotic decay searches in PIONEER
- Summary.

Introduction and Physics Motivation

- In the SM,,,
  - neutrinos are massless particles.
  - lepton flavor conservation.

  ➡Due to the observation of neutrino oscillation (PRL 81, 1562 (1998)), neutrinos are massive and lepton flavor is not strictly conserved.

- Other problems in the SM,,,
  - Origin of neutrino masses.
  - Candidates of dark matter.
  - Explanation of baryogenesis.
  - Solution of strong CP problem.

  and so on...

Introduction and Physics Motivation

- To solve such problems and extend the SM, the existence of massive or massless weakly interacting neutral particles ($\nu_H, X, \cdots$) has been suggested.
  - Heavy neutrinos: JHEP 04 (2011) 011. PRD 97, 075016 (2018).
  - Axions (or axion like particles): PRD 101, 075002 (2020).
  - Familons: PRL 49, 1549 (1982).
  - Majorons: PLB 99, 411 (1981). PLB 98, 265 (1982).

  ➡ Pion and muon (and other mesons such as kaon) decays are potential sources of new particles.

Summary of Exotic Decay Searches in PIENU

Decay modes	Corresponding authors	Papers
$\pi^+ \to e^+\nu_H$	L. Doria	Phys. Rev. D 97, 072012 (2018)
$\pi^+ \to \mu^+\nu_H$	T. Numao and S. Ito	Phys. Lett. B 798 (2019) 134980
$\mu^+ \to e^+X_H$	D. A. Bryman and S. Ito	Phys. Rev. D 101, 052014 (2020)
$*\,\pi^+ \to \ell^+\nu_\ell\nu\bar{\nu}$	S. Ito	Phys. Rev. D 102, 012001 (2020)
$\pi^+ \to \ell^+\nu X$	S. Ito	Phys. Rev. D 103, 052006 (2021)

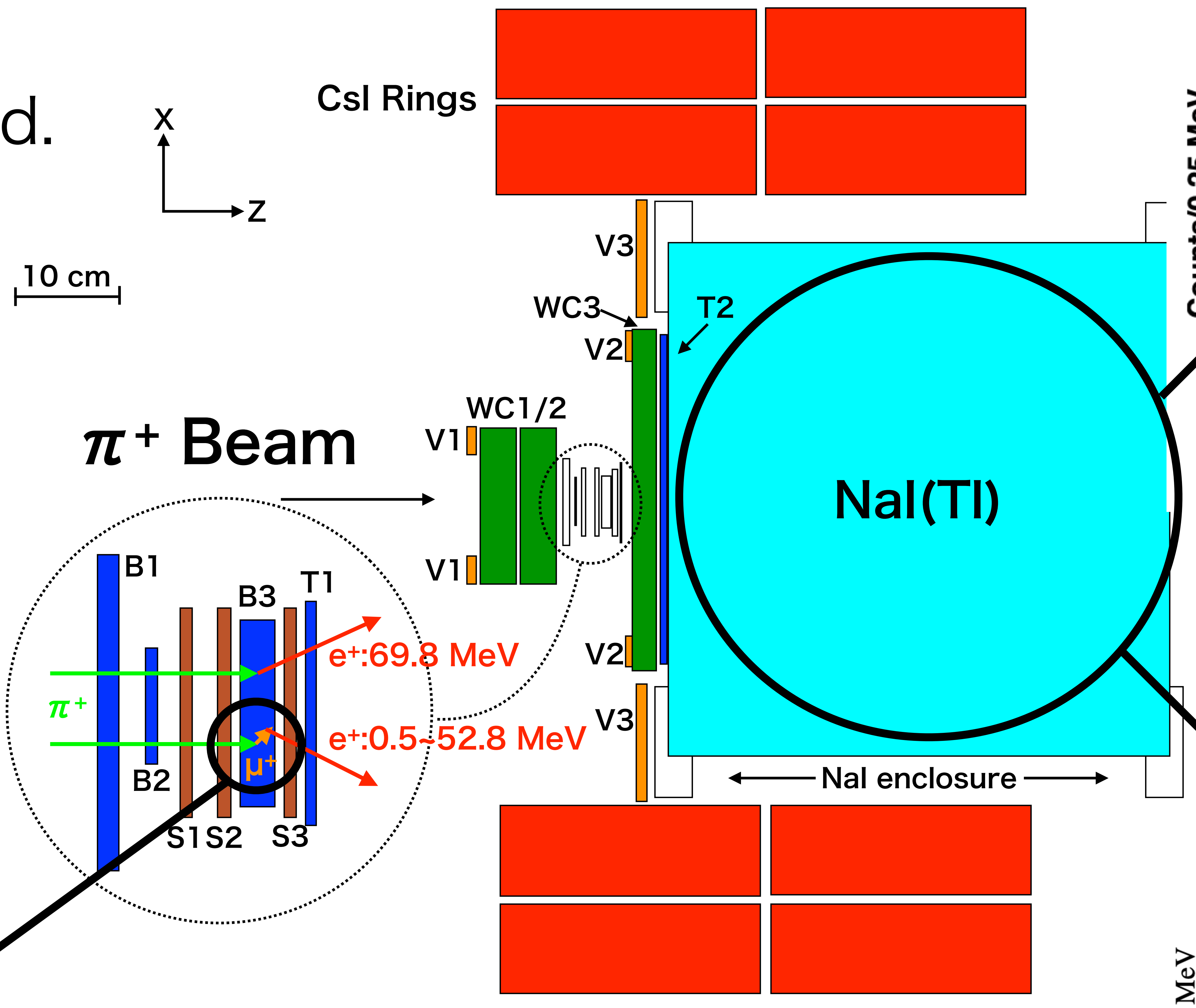
$(\ell = e,\, \mu)$

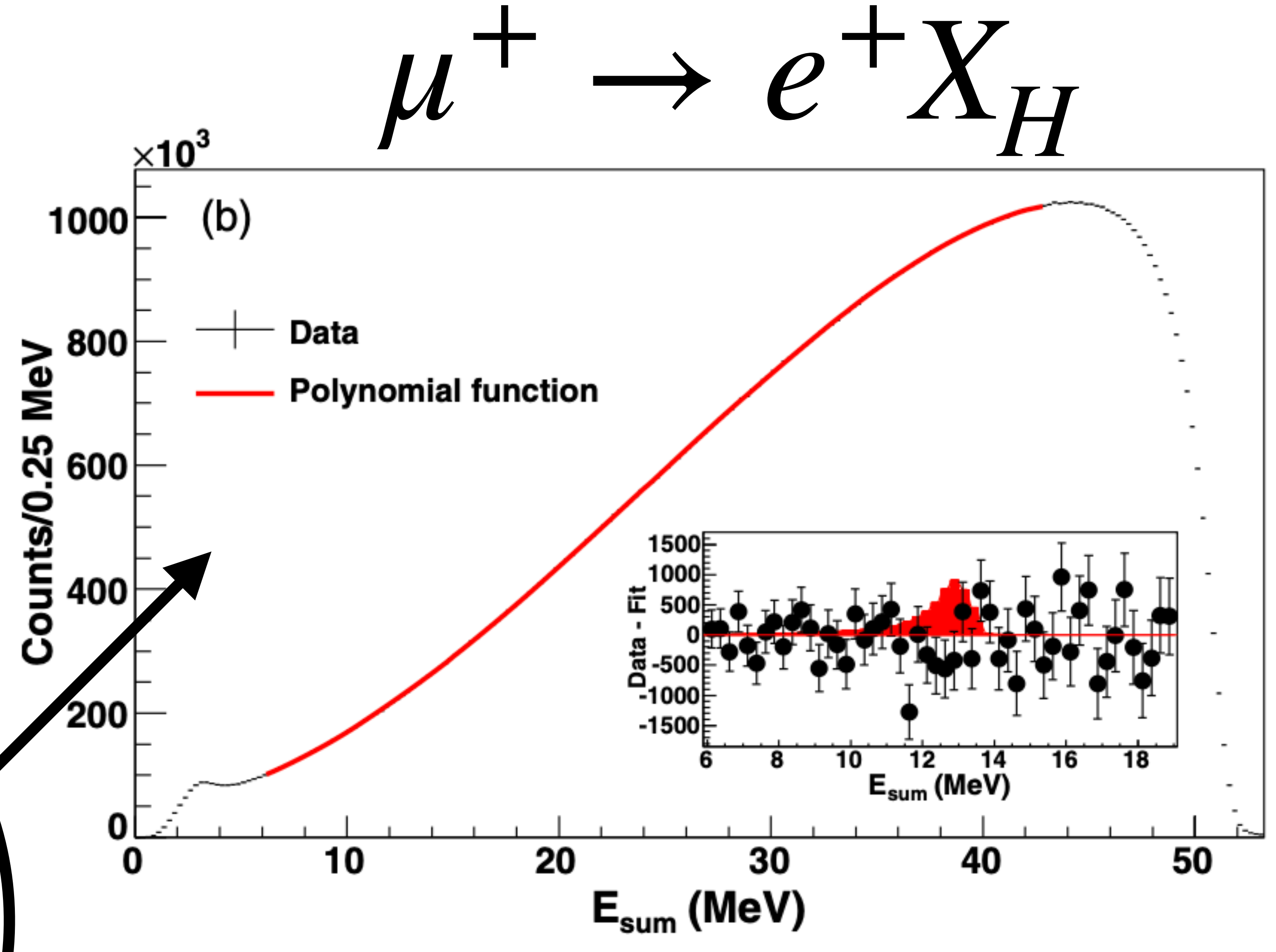
* Sensitive to new interactions such as $\nu - \nu$ interaction (PLB 32, 121 (1970))

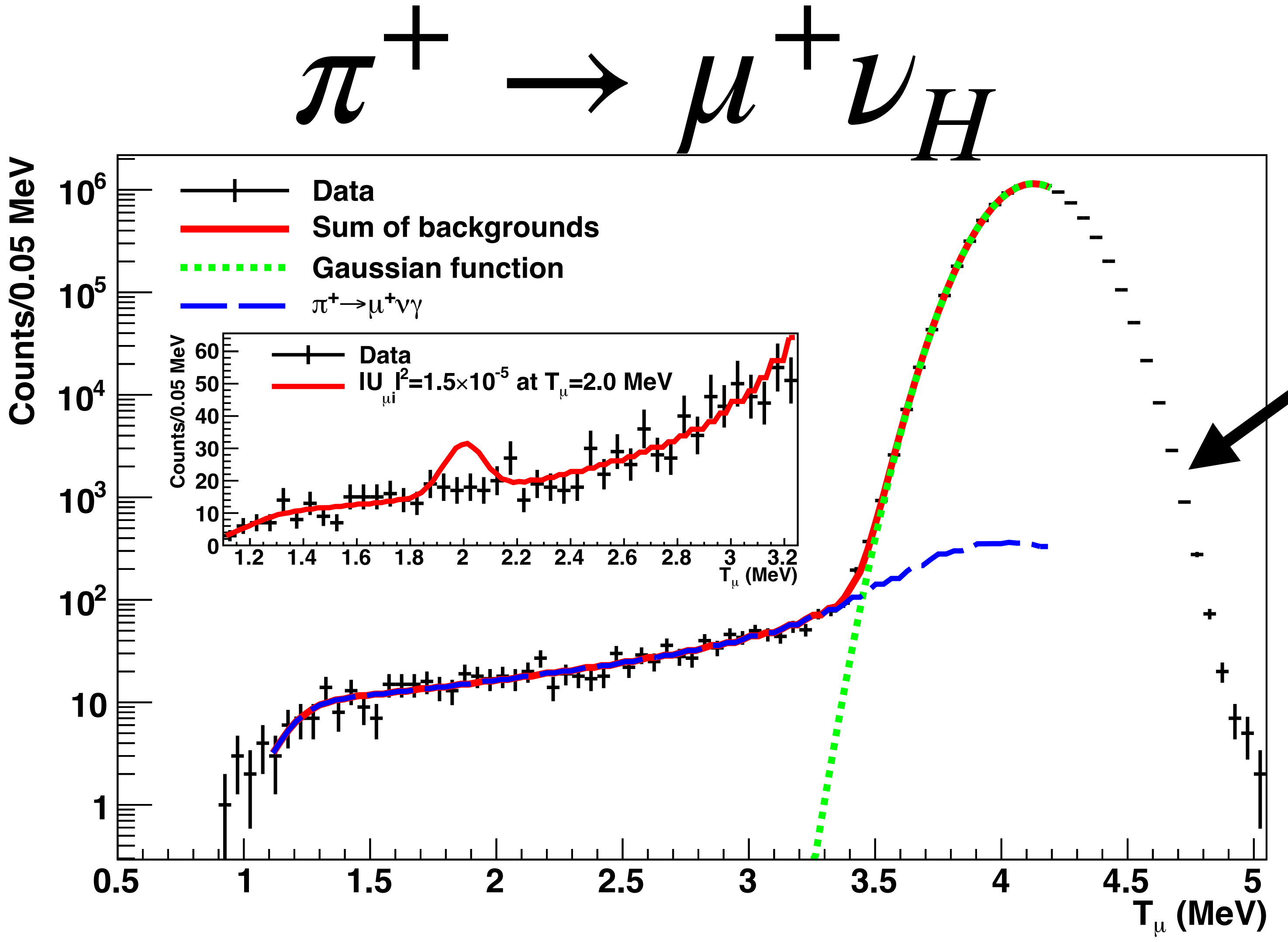
and 6-fermion interaction(Phys. Rev. 133, B130 (1964))

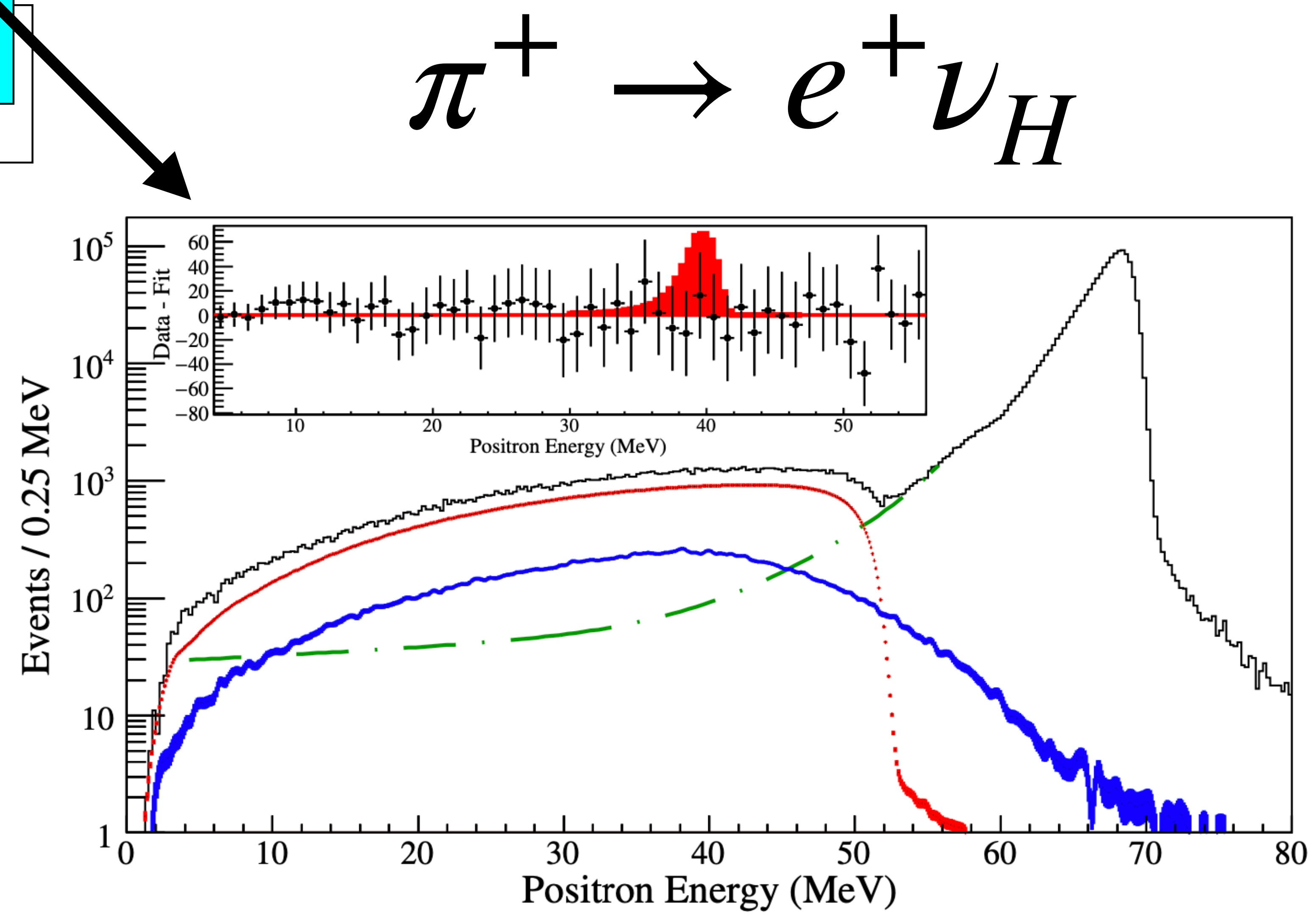
Strategy of Searches

1. Suppression of background.
2. Fit energy spectrum.
3. Search for signal shape.









Quick Theory of Massive Neutrinos

- Extension of the SM by adding massive neutrinos.

Neutrino Minimal Standard Model ($k = 3$)

JHEP 1104 11 (2011)

$$\begin{bmatrix} e \\ \nu_e \end{bmatrix} \begin{bmatrix} \mu \\ \nu_\mu \end{bmatrix} \begin{bmatrix} \tau \\ \nu_\tau \end{bmatrix} + \nu_{\chi_1},\ \nu_{\chi_2}, \cdots,\ \nu_{\chi_k}$$

- The relation between the weak eigenstates ν_ℓ and mass eigenstates ν_i with the mixing parameter $U_{\ell i}$ is

$$\nu_\ell = \sum_{i=1}^{3+k} U_{\ell i}\nu_i \qquad (\ell = e, \mu, \tau, \chi_1, \chi_2, \cdots, \chi_k)$$

- The contribution from massive neutrino to $\pi^+ \to e^+\nu_e$ decay is

$$R_{ei} = \frac{\Gamma(\pi^+ \to e^+\nu_i)}{\Gamma(\pi^+ \to e^+\nu_e)} = |U_{ei}|^2\rho_e$$

$$\rho_e = \frac{(\delta_e+\delta_i-(\delta_e-\delta_i)^2)\sqrt{1+\delta_e^2+\delta_i^2-2(\delta_e+\delta_i+\delta_e\delta_i)}}{\delta_e(1-\delta_i)^2},$$

$$\delta_e = \frac{m_e^2}{m_\pi^2},\ \delta_i = \frac{m_{\nu_i}^2}{m_\pi^2}$$

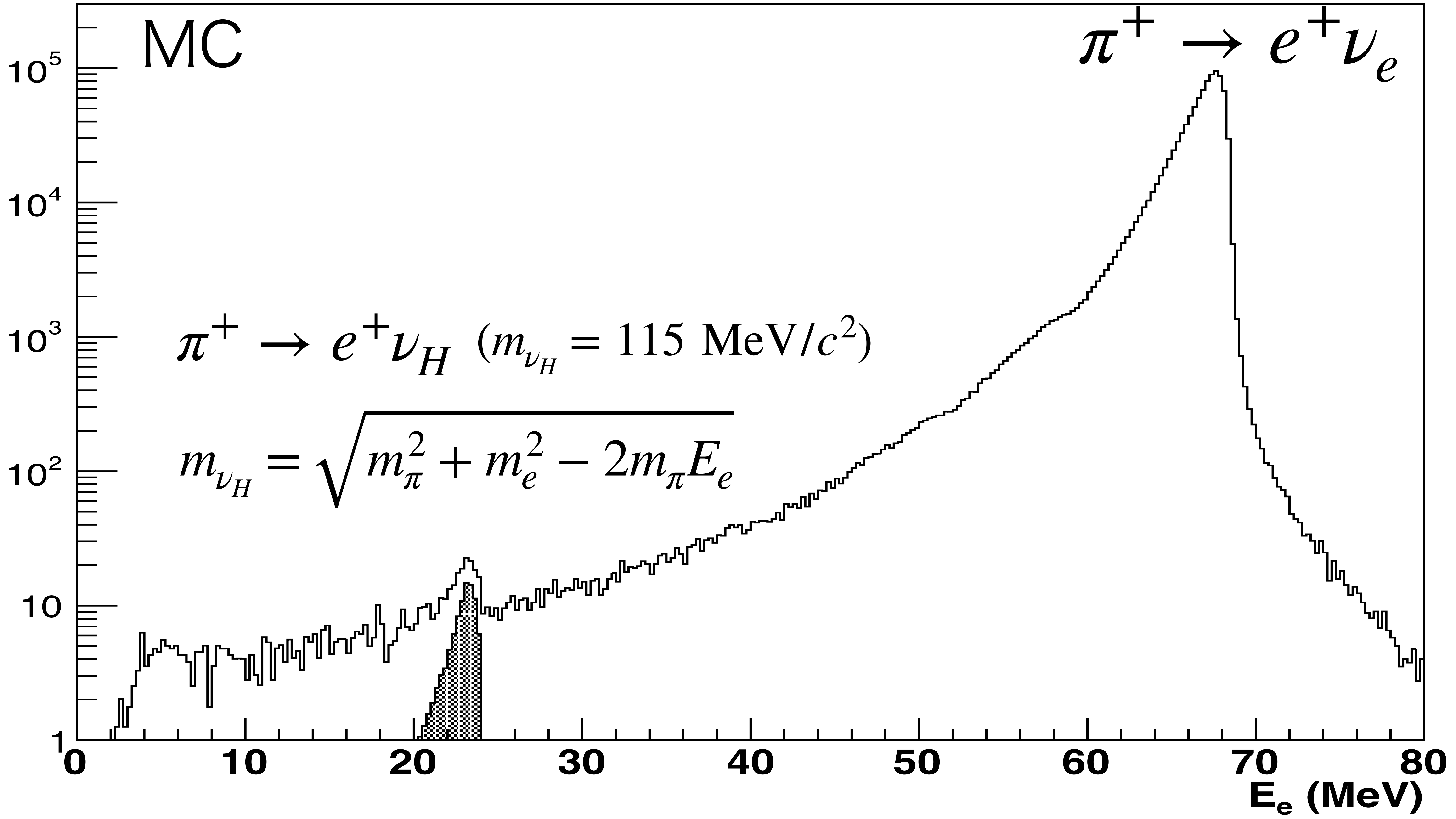
$\pi^+ \to e^+\nu_H$ (and other decays e.g. $\pi^+ \to \mu^+\nu_H$, $\mu^+ \to e^+X_H$)

- $\pi^+ \to e^+\nu_e : E_e = 69.8$ MeV
- $\pi^+ \to \mu^+\nu_\mu : T_\mu = 4.1$ MeV
- $\mu^+ \to e^+\nu\bar{\nu} : E_e = 0.5 \sim 52.8$ MeV

$$m_{X_H} = \sqrt{m_\mu^2 + m_e^2 - 2m_\mu E_e}$$

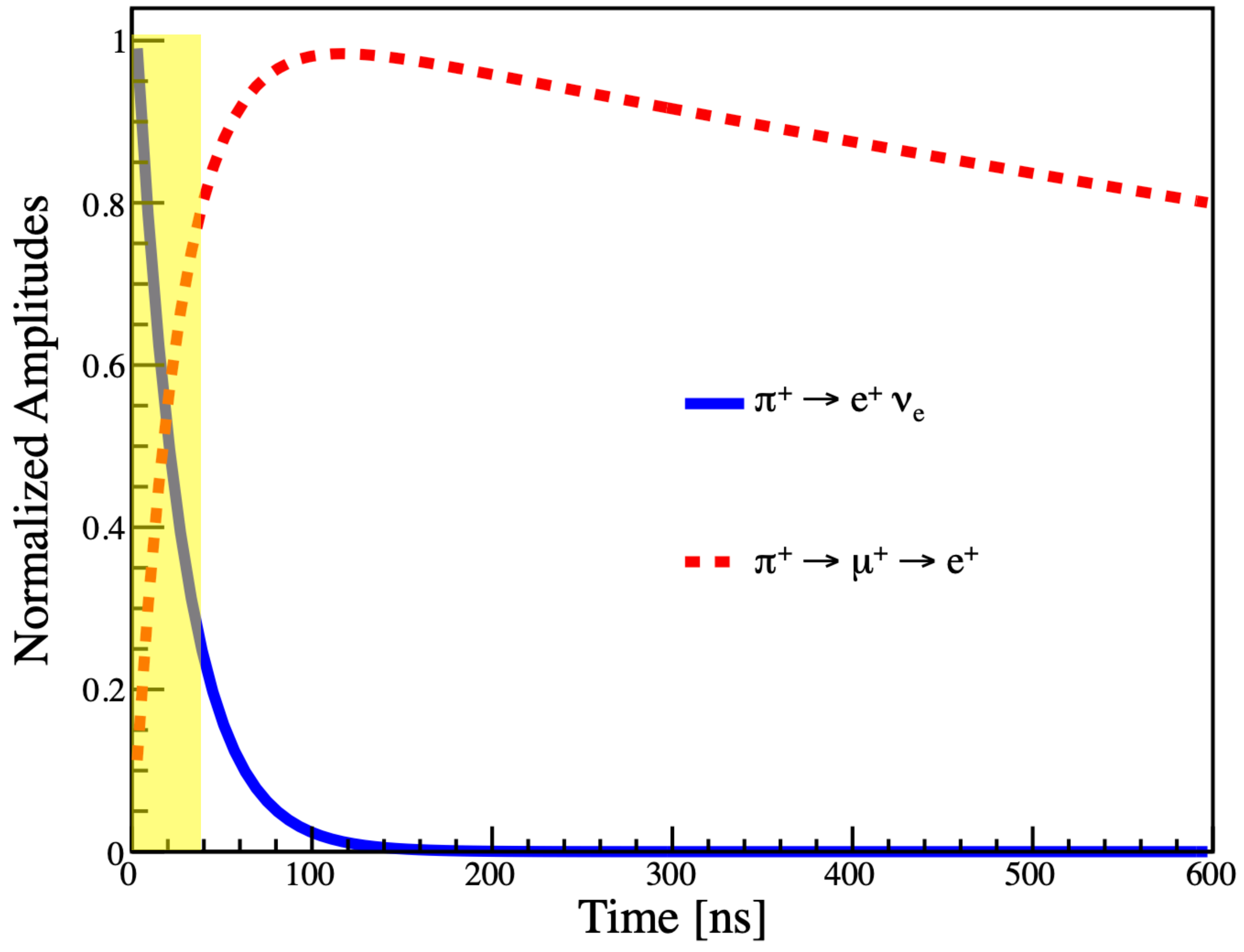
If there are exotic decays,,,

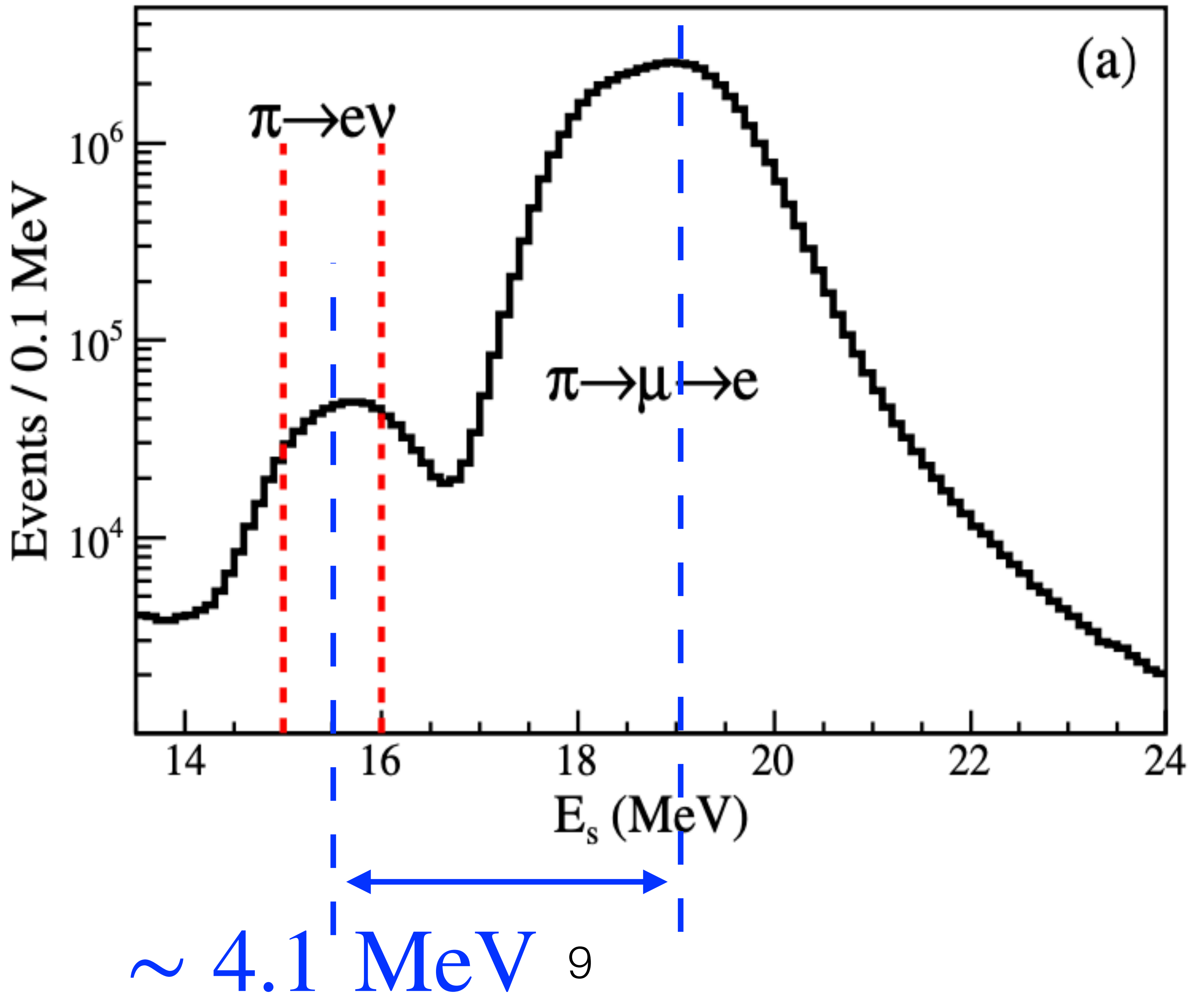
extra peaks would appear!!!

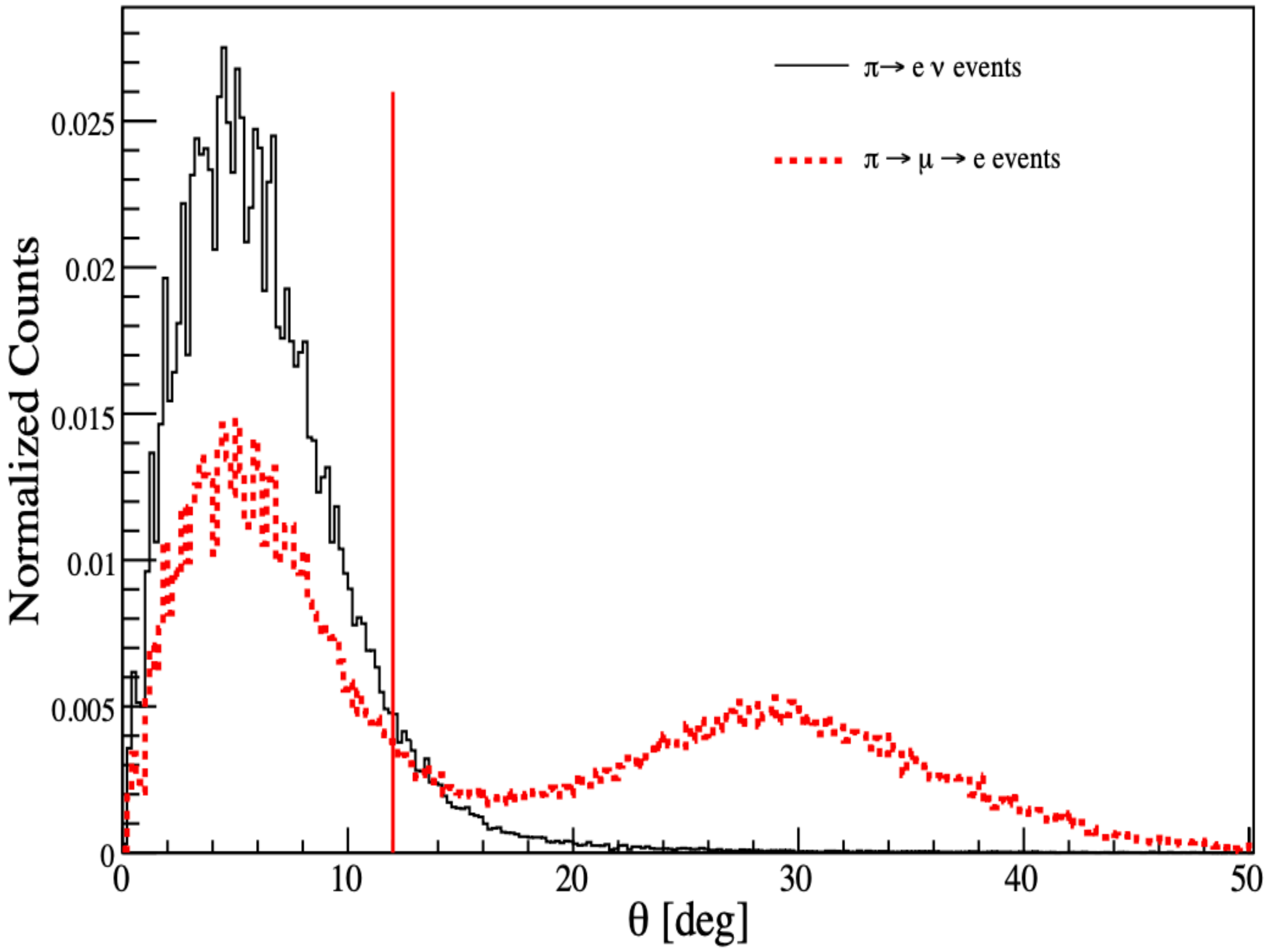


$\pi^+ \to e^+\nu_H$ (and $\pi^+ \to e^+\nu X$, $\pi^+ \to e^+\nu_e\nu\bar{\nu}$)

- Dominant $\pi^+ \to \mu^+ \to e^+$ (πDAR, πDIF, πDAR – μDIF) can be removed using
  - early time requirement: $\times \sim 1/100$
  - energy deposit in the target ($T_\mu = 4.1$ MeV): $\times \sim 1/1000$
  - tracking information called “kink angle” cut: $\times \sim 1/2$



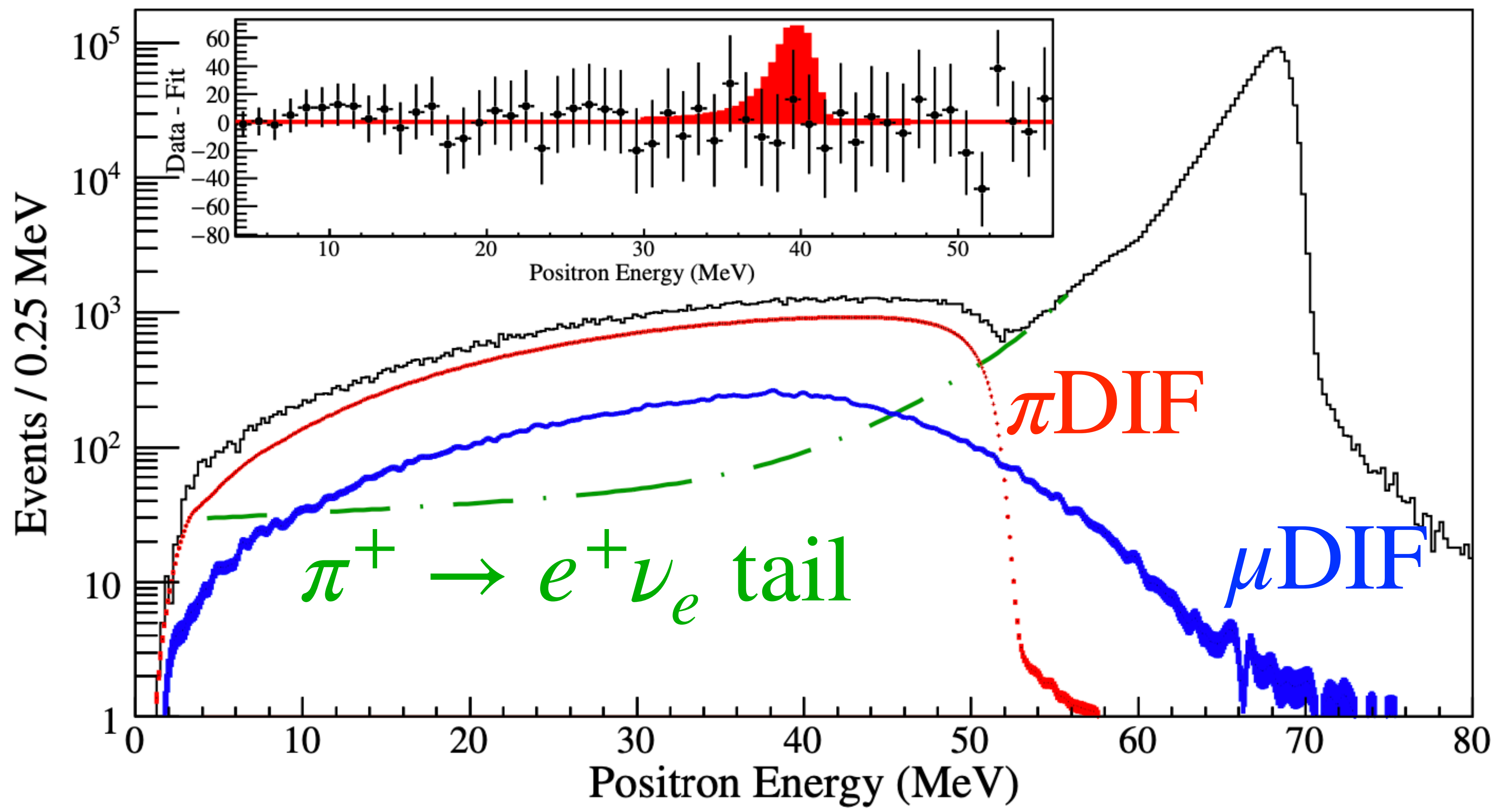


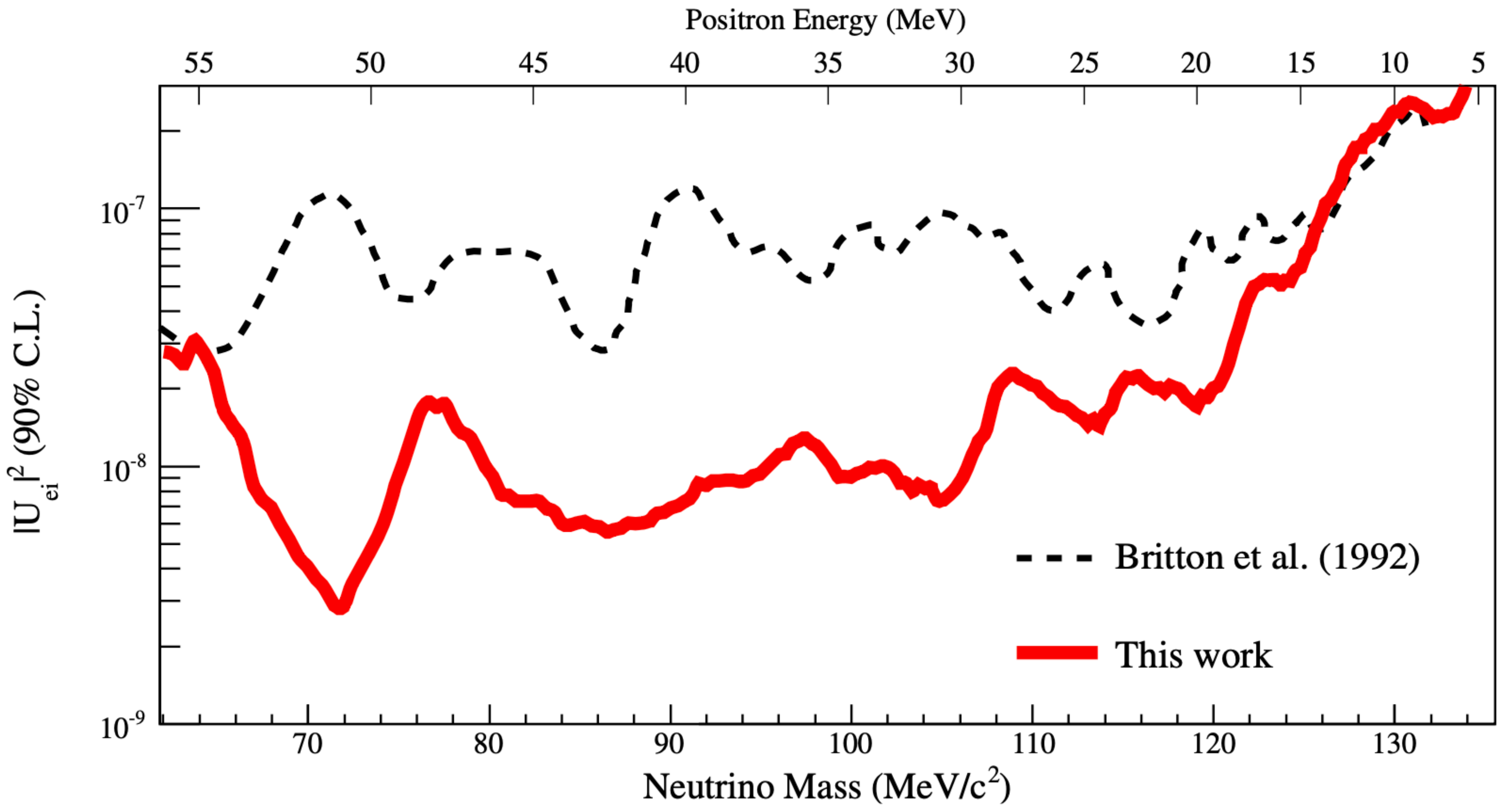


Results of $\pi^+ \to e^+\nu_H$

- Remaining backgrounds are πDIF, μDIF, and $\pi^+ \to e^+\nu_e$ tail.
  - Peak search with the range of $E_e = 4 \sim 56$ MeV ($m_{\nu_i} = 60 \sim 135$ MeV$/c^2$).
  - Set the 90% CL limits on $|U_{ei}|^2$ with $10^{-7} \sim 10^{-8}$.
- I'm revisiting higher mass region where photo nuclear bump appears.

Hypothetical signal at $E_e = 40$ MeV with $|U_{ei}|^2 = 1 \times 10^{-8}$





Quick Theory of $\mu^+ \to e^+ X_H$

Axions and Family Symmetry Breaking

Frank Wilczek
Institute for Theoretical Physics, University of California at Santa Barbara, Santa Barbara, California 93106

(Received 20 September 1982)

Possible advantages of replacing the Peccei-Quinn U(1) quasisymmetry by a group of genuine flavor symmetries are pointed out. Characteristic neutral Nambu-Goldstone bosons will arise, which might be observed in rare K or μ decays. The formulation of Lagrangians embodying these ideas is discussed schematically.

PACS numbers: 11.30.Qc, 12.35.Cn, 14.80.Gt

Phys. Rev. Lett. 49 549 (1982)

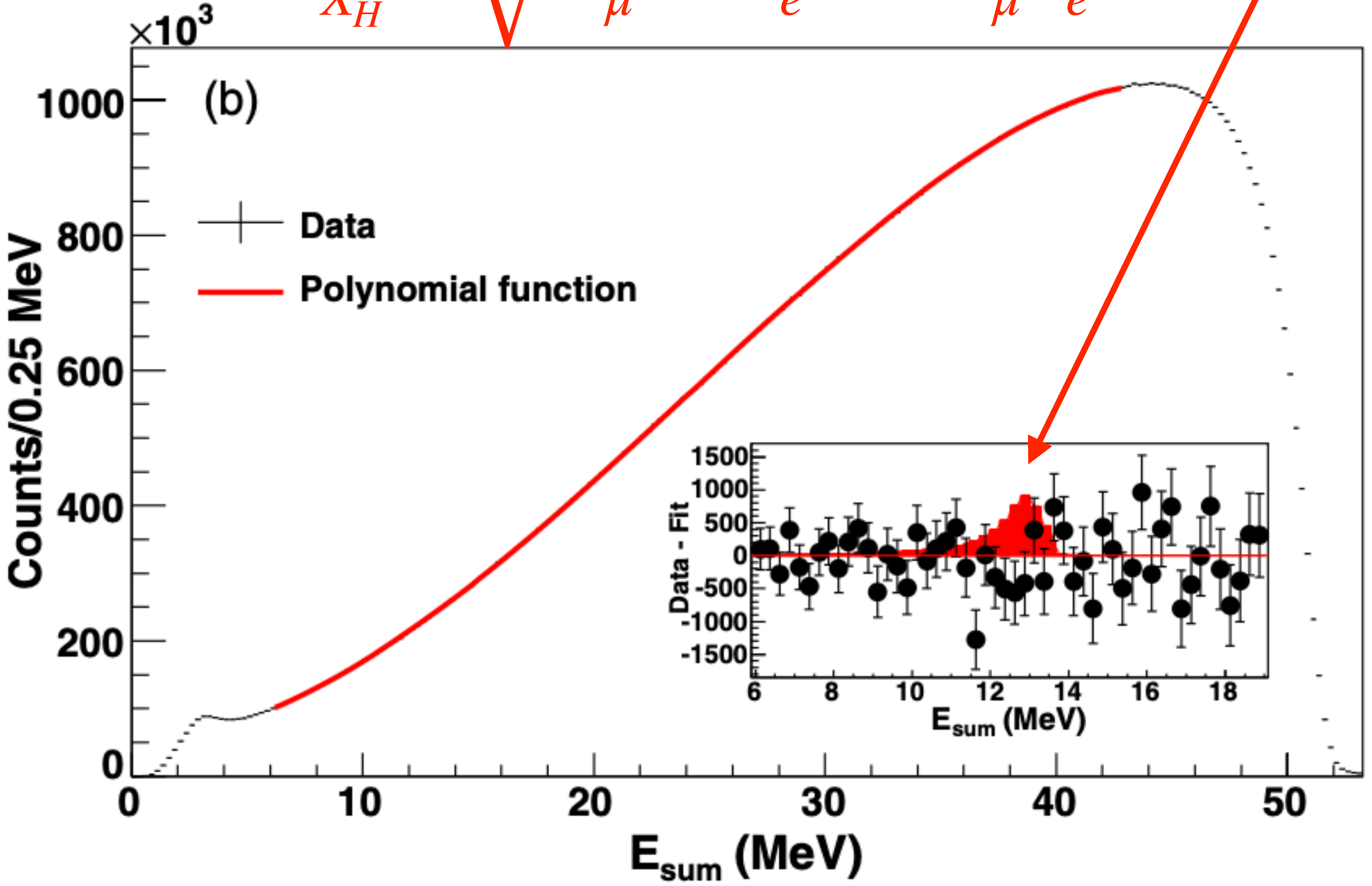
- Wilczek proposed neutral NG boson called “familon” will arise in the decays
  - $\mu^+ \to e^+ X$
  - $K^+ \to \pi^+ X$
- This was introduced to solve strong CP problem, baryon asymmetry, and this might be the hint for dark matter, and so on.

$\mu^+ \to e^+ X_H$

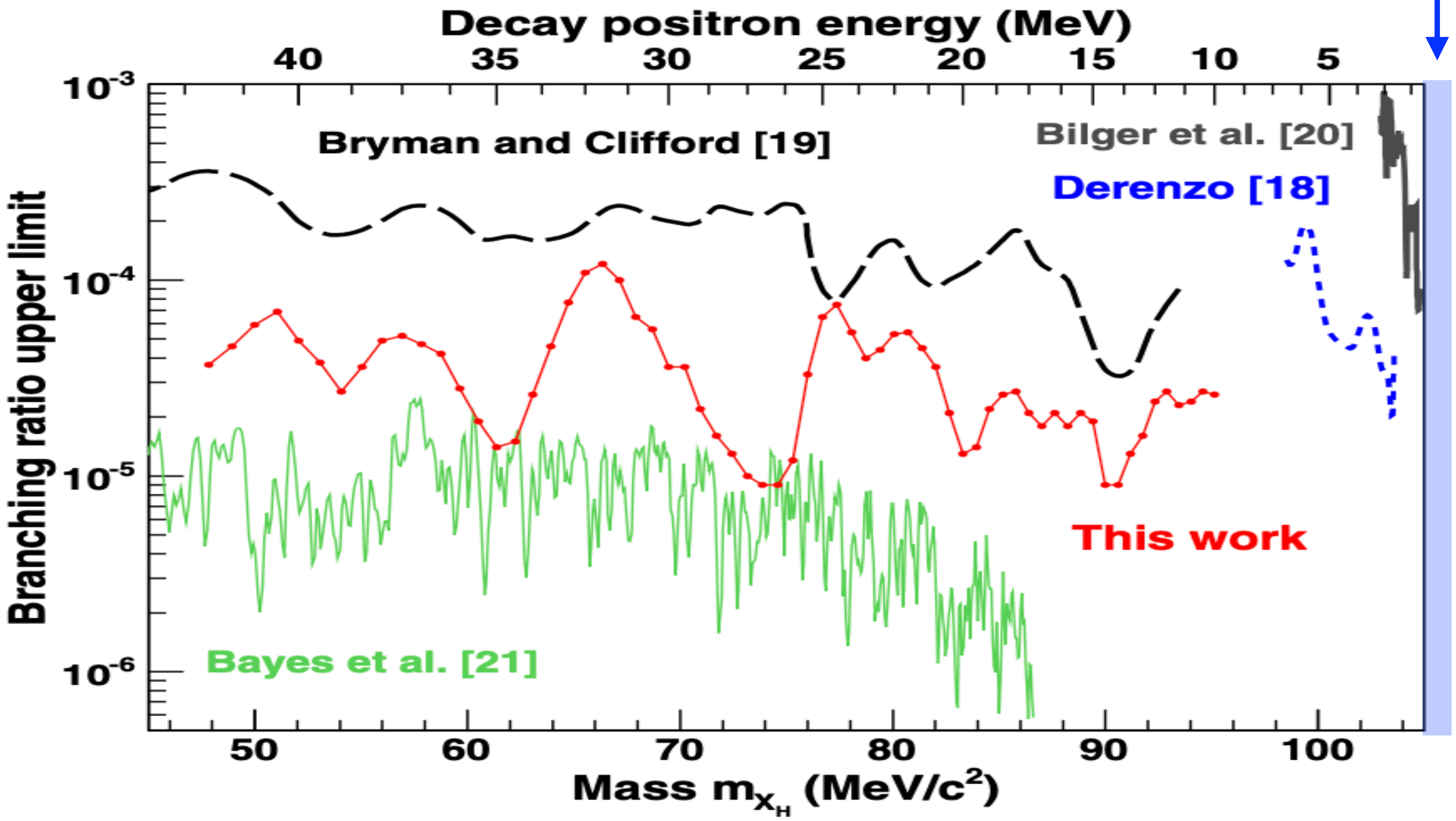
- Similar analysis method, but $\pi^+ \to \mu^+ \to e^+$ events were selected by a requirement of late decay time $t > 200$ ns.
- Michel spectrum was fitted to the smooth polynomial function and signal shape produced by MC.
- New limits were set on $R = \Gamma(\mu^+ \to e^+ X_H)/\Gamma(\mu^+ \to e^+ \nu\bar{\nu})$ with an order of 10^{-5}.

Hypothetical signal at $m_{X_H} = 90\ \mathrm{MeV}/c^2$ with $R = 5 \times 10^{-5}$

$$m_{X_H} = \sqrt{m_\mu^2 + m_e^2 - 2m_\mu E_e}$$

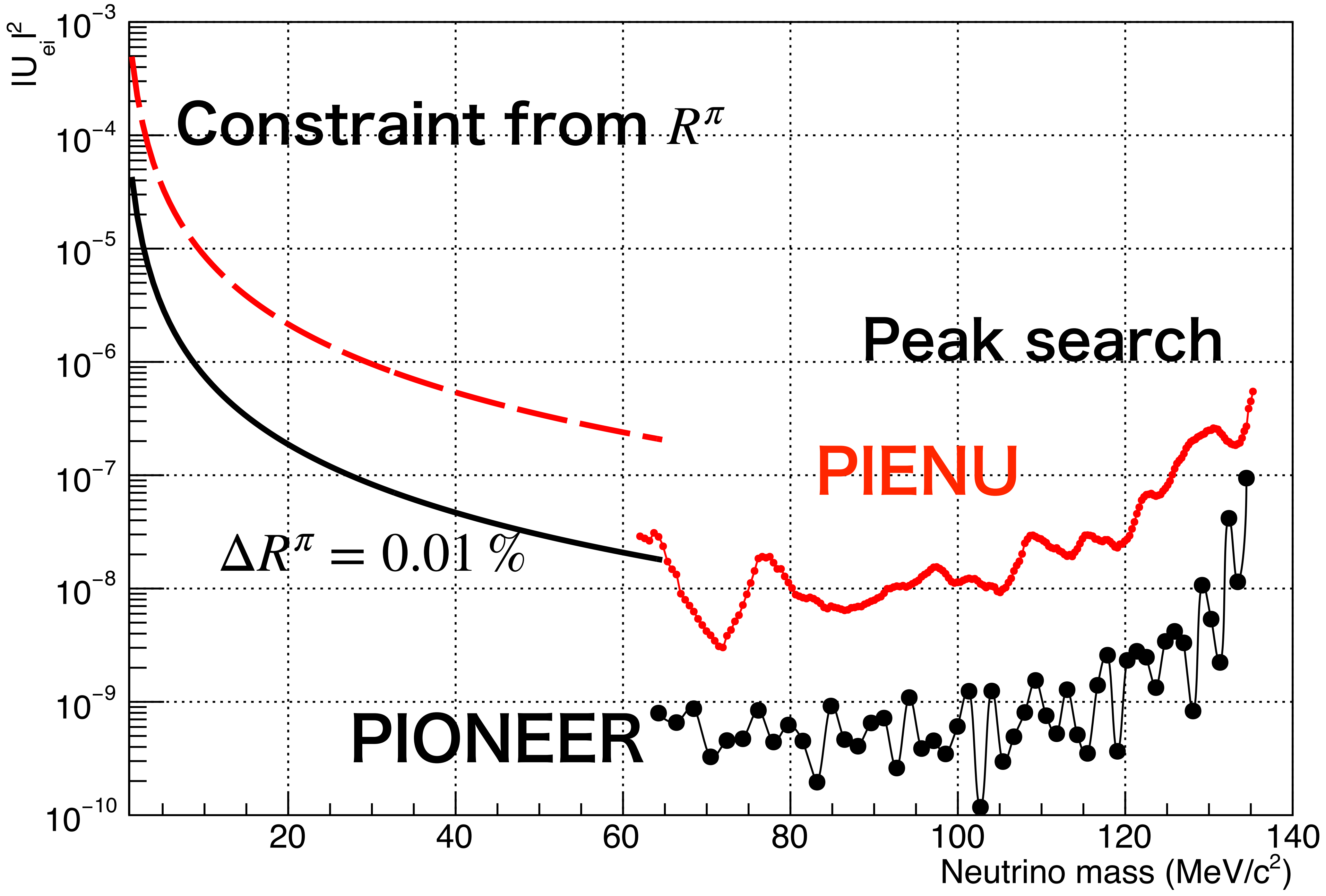


Another constraint in very light mass region by cosmological study (PRD 103, 52007 2021).



Prospects of Exotic Decay Searches in PIONEER

- To improve the sensitivity for exotic decay searches,
  - larger statistics: $\times 100$
  - higher background suppression: <1/10 for πDIF, less $\pi^+ \to e^+\nu_e$ tail
  - better energy resolution: $\times 2$?
- Toy MC study in $\pi^+ \to e^+\nu_H$
  - $\times 100$ larger statistics than PIENU
  - No πDIF event and 1% $\pi^+ \to e^+\nu_e$ tail.
  - the same energy resolution with PIENU

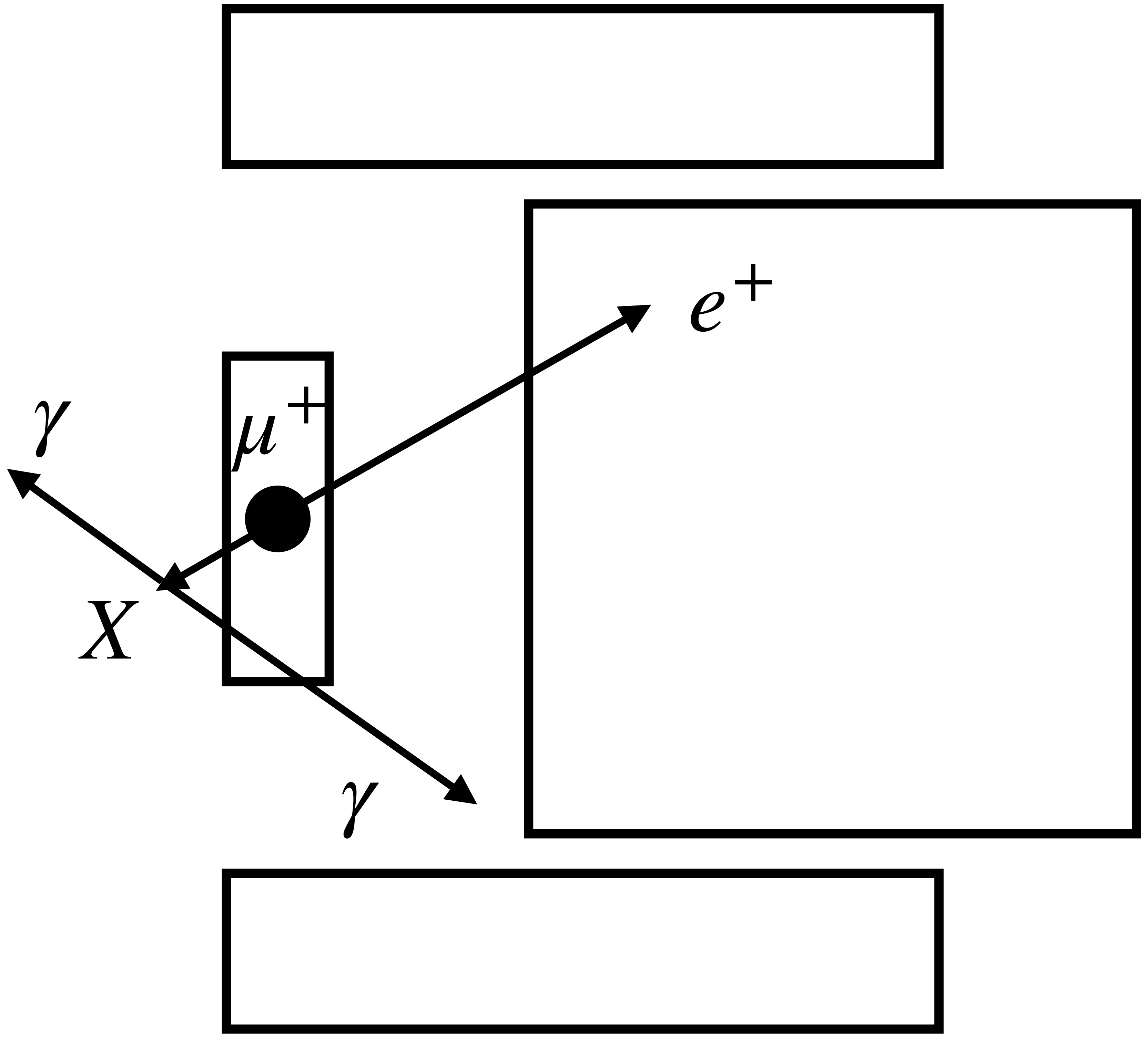


An order of magnitude of improvement is expected!!!

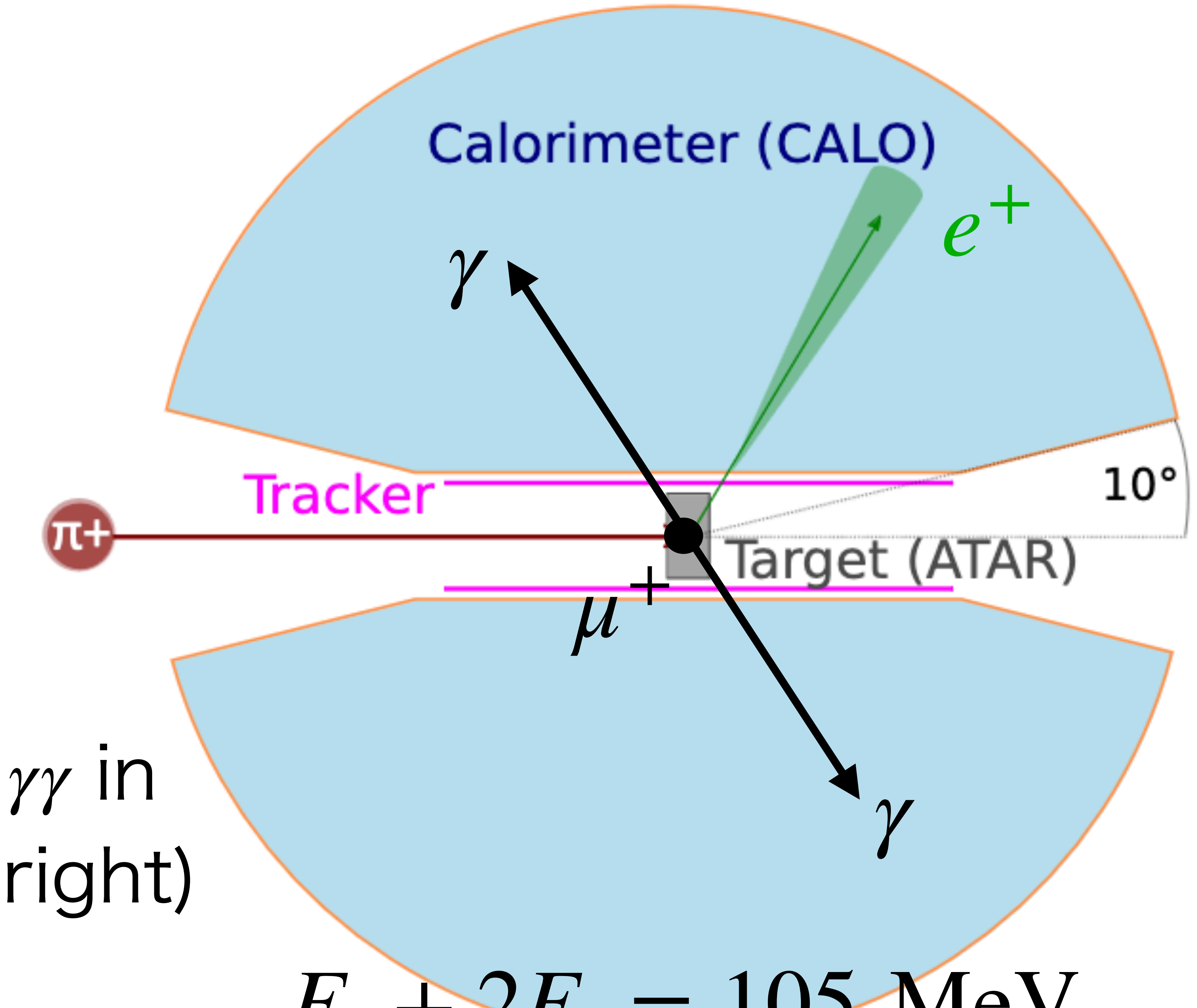
Also for other exotic decays!!!

Additional Decay Modes

- In the PIENU, the detector acceptance was limited (~20%).
- All neutral particles X analyzed in PIENU were assumed to be long lifetime.
  - If X is very short lifetime and decays $X \to \gamma\gamma$, one γ is missed.
- For PIONEER, 2γ could be detected due to larger acceptance.



Schematic of $\mu^+ \to e^+X, X \to \gamma\gamma$ in PIENU (left) and PIONEER (right)



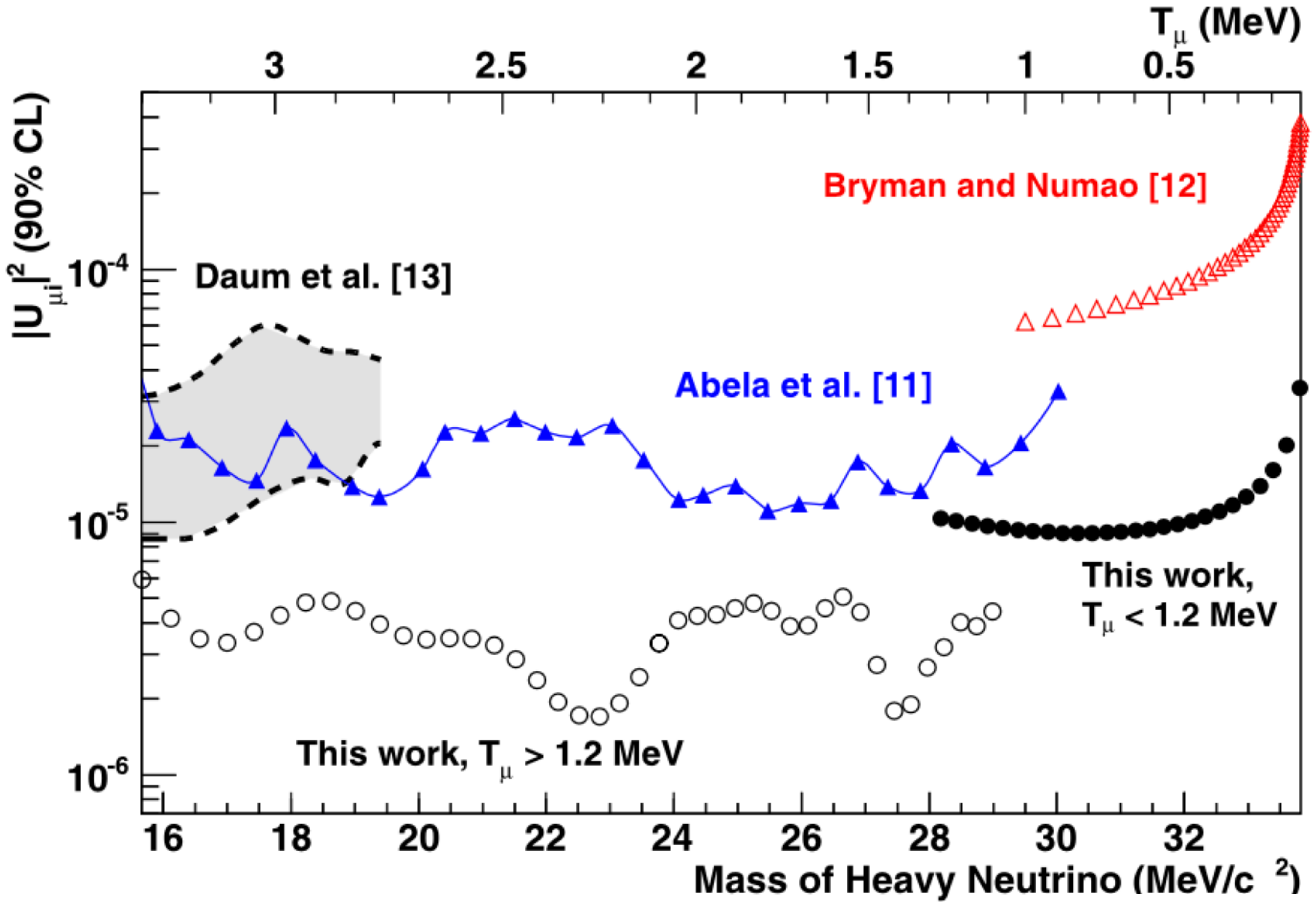
$E_e + 2E_\gamma = 105$ MeV

Summary

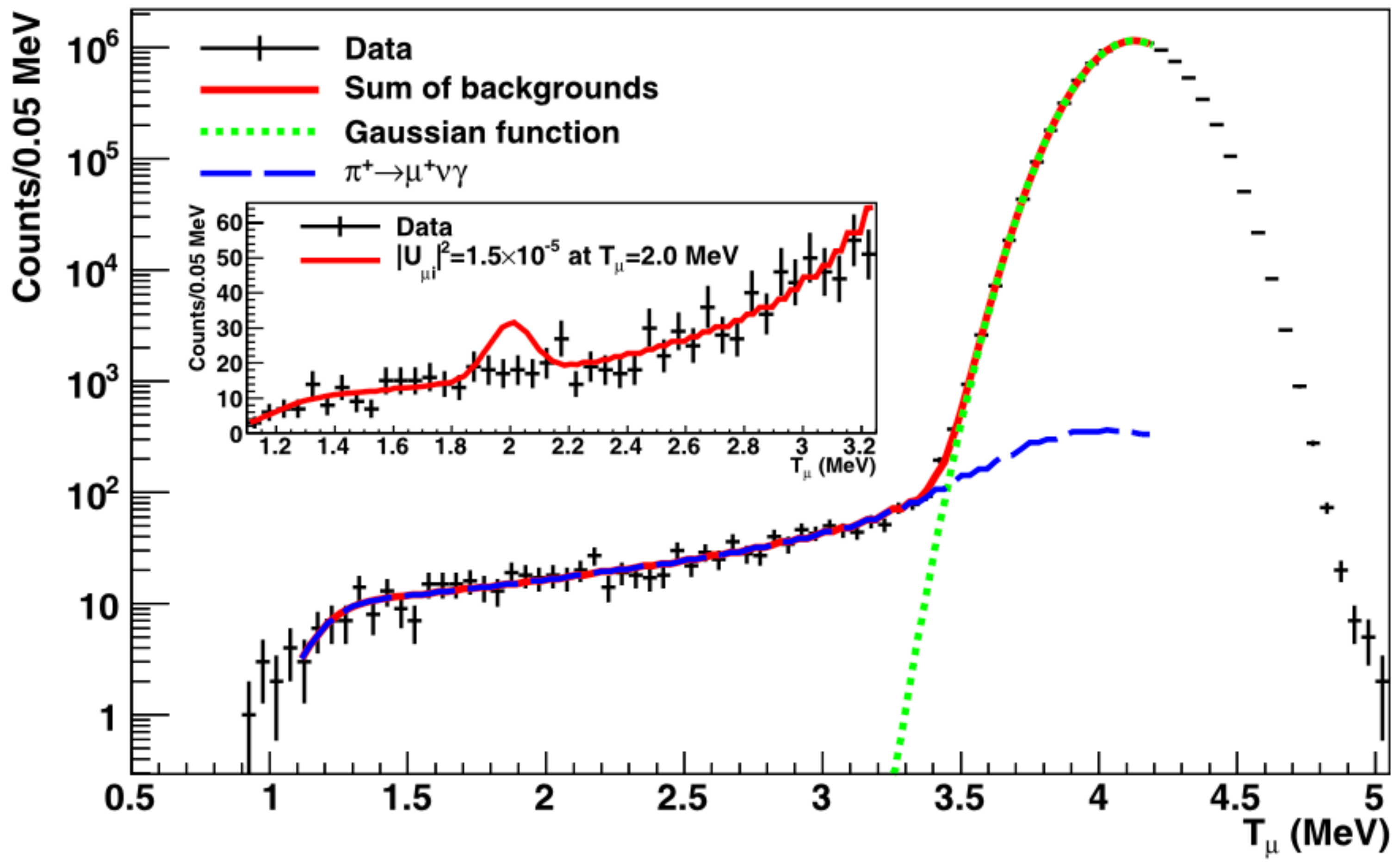
- Exotic decay searches may reveal the problem of the SM.
- PIENU and PIONEER have capability to search for the decays involving new particles.
- PIENU has achieved many searched with high sensitivity.
- PIONEER is expected to improve the sensitivity by an order of magnitude.
- New decay modes can also be search for.

Back Up

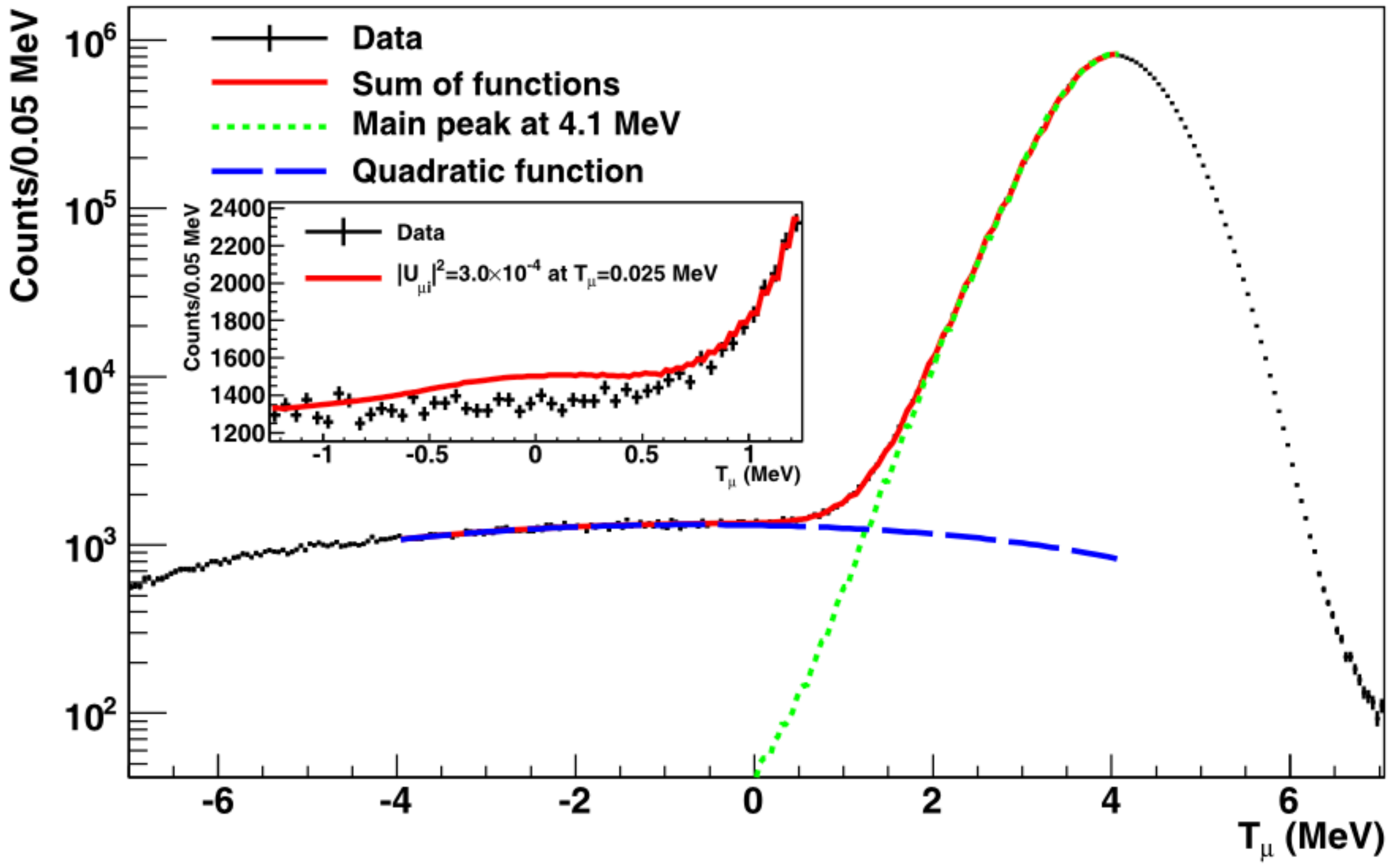
$\pi^+ \to \mu^+ \nu_H$



T_μ (MeV)
3
2.5
2
1.5
1
0.5
|U_μi|² (90% CL)
Bryman and Numao [12]
Daum et al. [13]
Abela et al. [11]
This work, T_μ < 1.2 MeV
This work, T_μ > 1.2 MeV
Mass of Heavy Neutrino (MeV/c²)



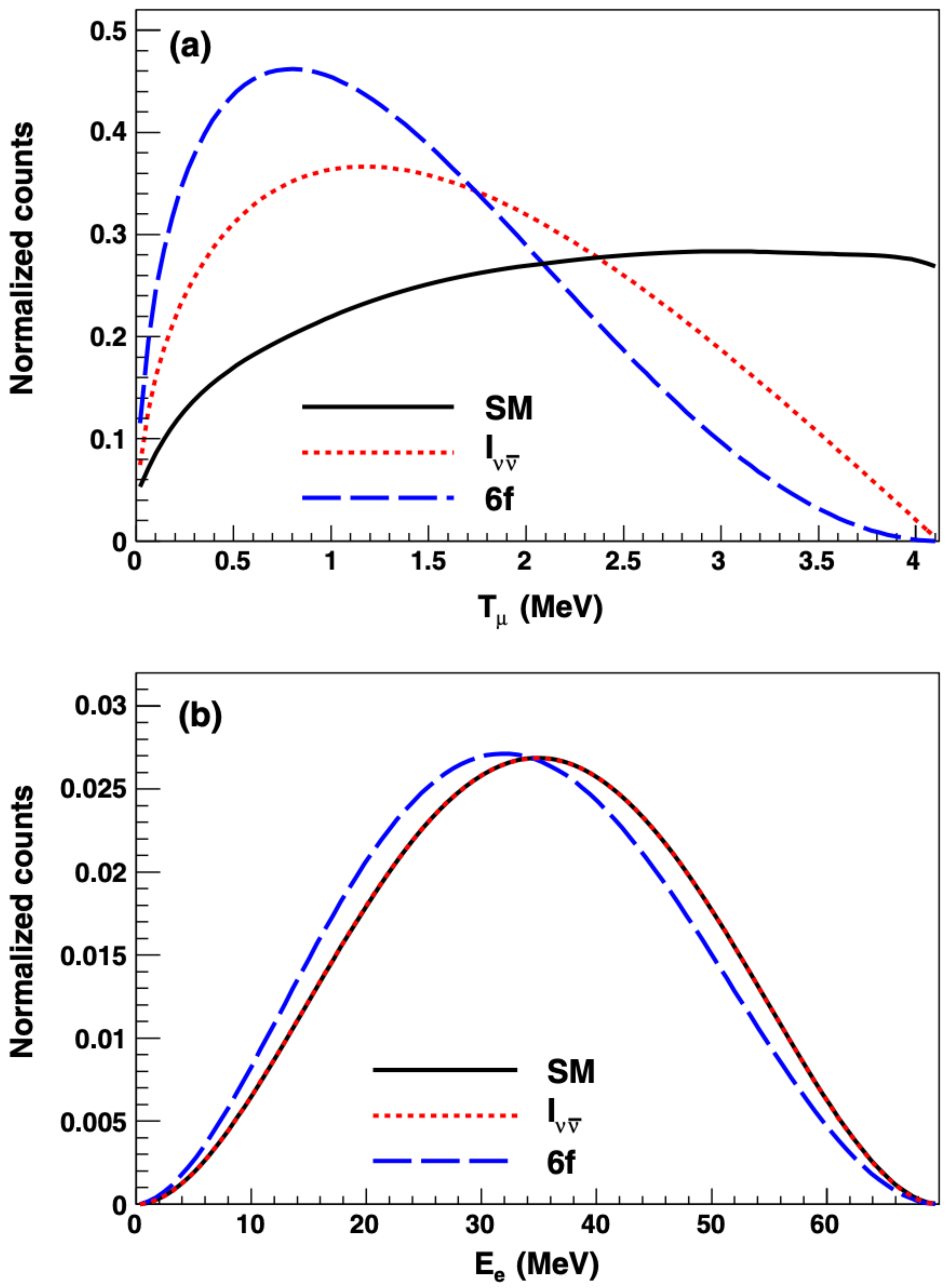
Data
Sum of backgrounds
Gaussian function
π⁺→μ⁺νγ
Data
|U_μi|²=1.5×10⁻⁵ at T_μ=2.0 MeV
Counts/0.05 MeV
T_μ (MeV)



Data
Sum of functions
Main peak at 4.1 MeV
Quadratic function
Data
|U_μi|²=3.0×10⁻⁴ at T_μ=0.025 MeV
Counts/0.05 MeV
T_μ (MeV)

$\pi^+ \to \ell^+ \nu_\ell \nu \bar{\nu}$

- In the SM, the BRs are
  - $BR(\pi^+ \to \mu^+ \nu_\mu \nu \bar{\nu}) \approx 10^{-20}$
  - $BR(\pi^+ \to e^+ \nu_e \nu \bar{\nu}) \approx 10^{-18}$



$\pi^+ \to e^+\nu_e\nu\bar{\nu}$

- Similar analysis with $\pi^+ \to e^+\nu_H$, but cuts were optimized.

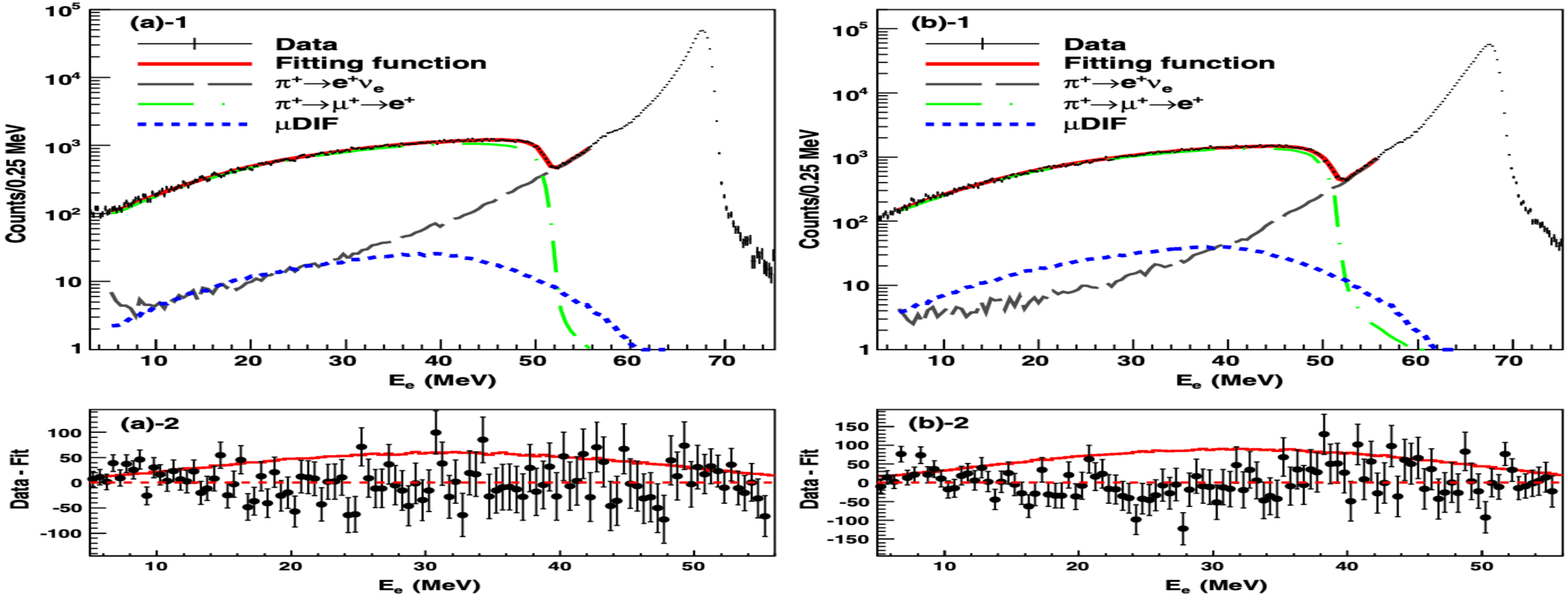


FIG. 5. Top: The E_e spectra of $\pi^+ \to e^+\nu_e$ decay after $\pi^+ \to \mu^+ \to e^+$ suppression cuts from data taken before (a) and after (b) 1 November 2010. The black crosses with the statistical uncertainties show the data. Background components illustrated by the dashed and dotted green line, dashed gray line, dotted blue line, and solid red line represent $\pi^+ \to \mu^+ \to e^+$ decays, low-energy $\pi^+ \to e^+\nu_e$ tail, μDIF events, and the sum of those three components, respectively (see text). Bottom: The residual plots (rebinned for visual clarity) shown by the black circles with the statistical error bars and hypothetical neutrino-neutrino interaction ($I_{\nu\bar{\nu}}$) signals (solid red curves) with the branching ratio $B^{\pi e3\nu}_{I_{\nu\bar{\nu}}} = 1.0 \times 10^{-6}$ for data taken before (a) and after (b) 2 November 2010. The dashed horizontal red lines represent the residual of 0.

$\pi^+ \to \mu^+ \nu_\mu \nu \bar{\nu}$

- The same analysis method with $\pi^+ \to \mu^+ \nu_H$.

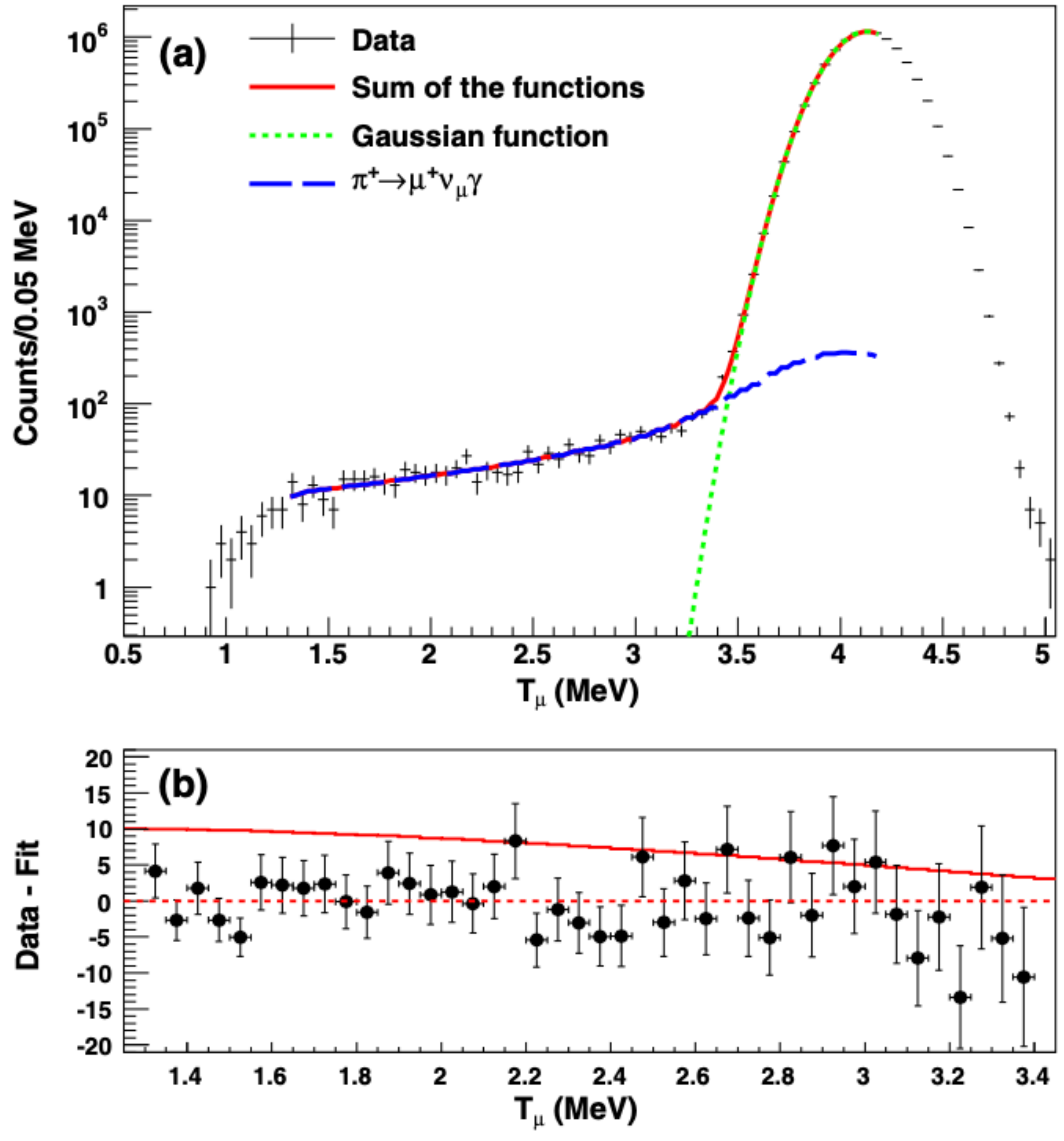
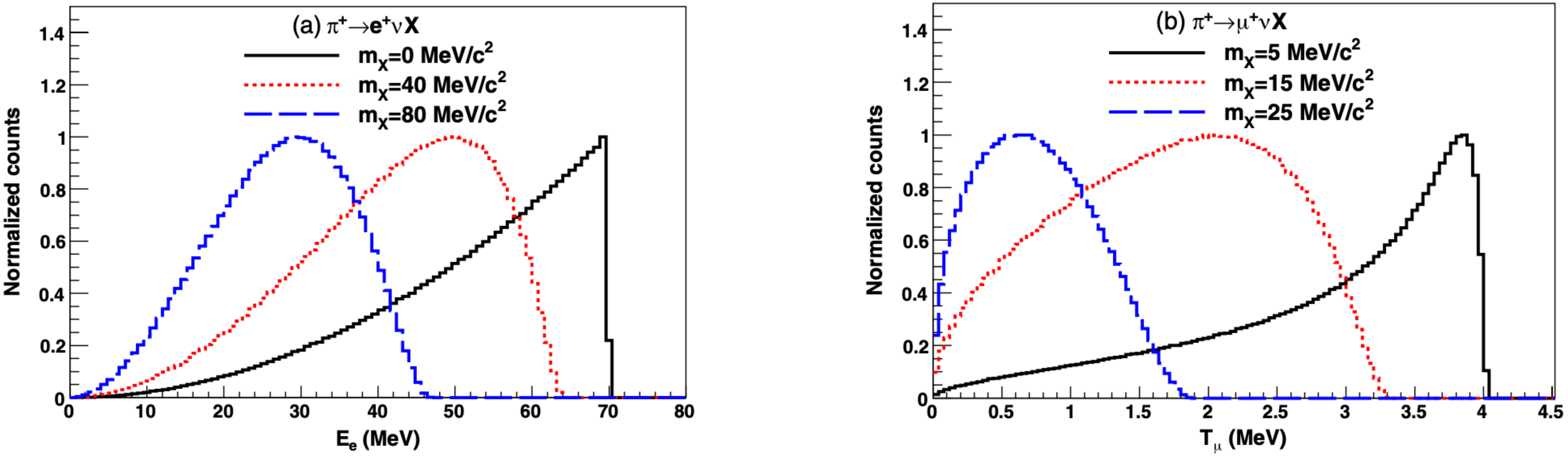


FIG. 4. (a) The T_μ spectra of $\pi^+ \to \mu^+ \nu_\mu$ decay. The black crosses with the statistical uncertainties show the data. The dotted green line, dashed blue line, and solid red line represent the Gaussian distribution at 4.1 MeV, $\pi^+ \to \mu^+ \nu_\mu \gamma$ decay, and the sum of those two functions, respectively. (b) Residual plot shown by the black circles with the statistical error bars for the signal region $T_\mu = 1.3$–3.4 MeV. The solid red curve represents the hypothetical neutrino-neutrino interaction ($I_{\nu\bar{\nu}}$) signal with the branching ratio $B^{\pi\mu3\nu}_{I_{\nu\bar{\nu}}} = 6.0 \times 10^{-5}$. The dashed horizontal red line indicates the residual of 0.

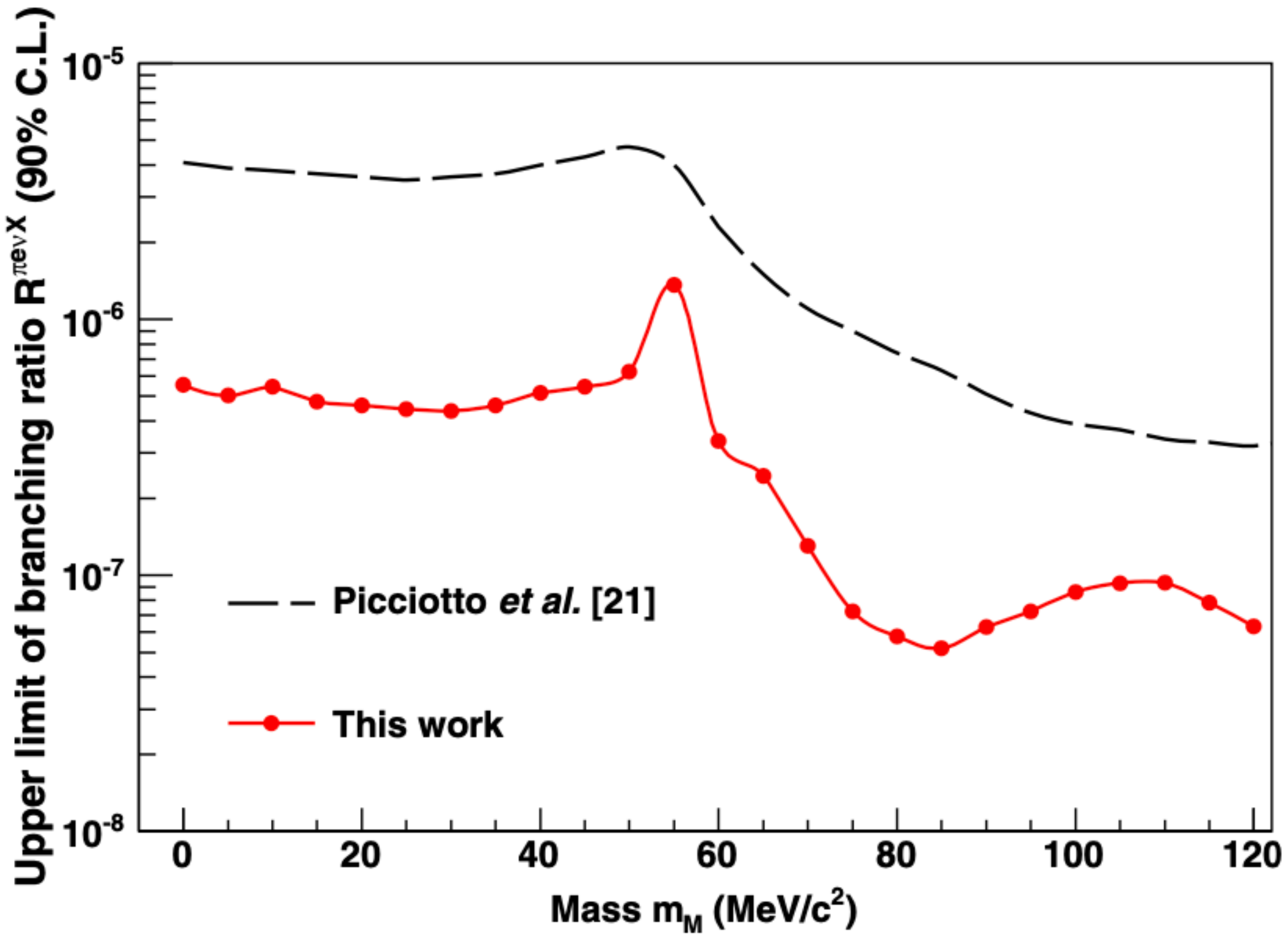
$\pi^+ \to \ell^+ \nu X$

- Similar analysis with heavy neutrino searches, but the signal spectra are continuous.

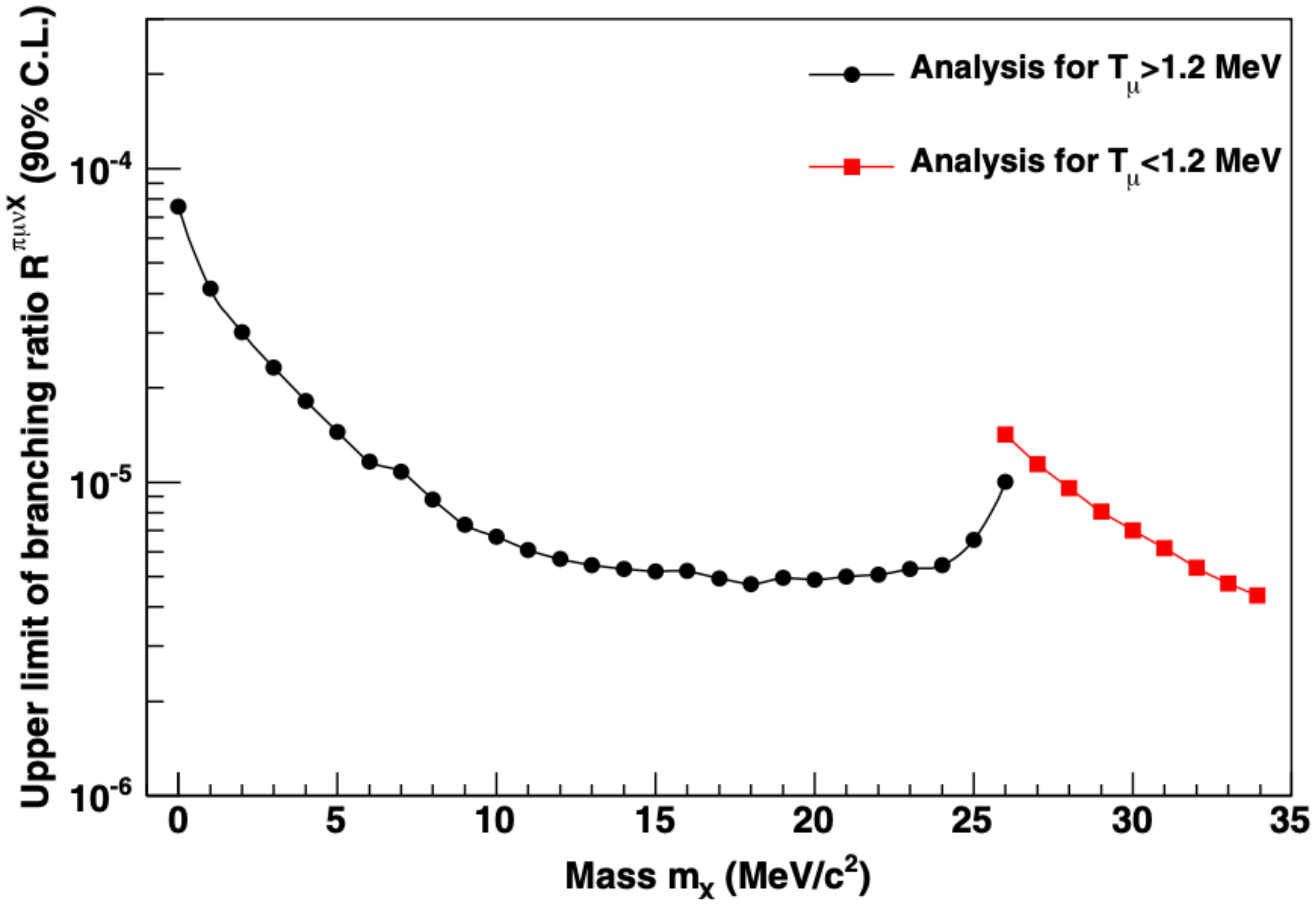


$\pi^+ \to \ell^+ \nu X$

- The same analysis method with $\pi^+ \to \ell^+ \nu_\ell \nu \bar{\nu}$.



$\pi^+ \to e^+ \nu X$



$\pi^+ \to \mu^+ \nu X$

Constraint on the Majoron Model: $\pi^+ \to e^+\nu X$

- Majoron model can also be constrained using R^π.
- The predicted R^π including the massless Majoron X_0 and a light neutral Higgs $H'(\lesssim 1\ \mathrm{MeV}/c^2)$ can be written as (PRD 25, 907 (1982))

$$\frac{\Gamma(\pi \to eL^0)/\Gamma(\pi \to \mu L^0)}{\Gamma(\pi \to e\nu_e)/\Gamma(\pi \to \mu\nu_\mu)} = 1 + 157.5g^2.$$

L^0 : Final state $\nu, \nu X_0, \nu H'$ g : Majoron-neutrino coupling constant

- Averaged experimental branching ratio: $R^\pi_{\mathrm{exp}} = (1.2327 \pm 0.0023) \times 10^{-4}$

$$\frac{R^\pi_{\mathrm{exp}}}{R^\pi_{\mathrm{SM}}} < 1.0014 \Rightarrow g^2 < 9 \times 10^{-6}$$

- If 0.01% precision of R^π is assumed, then $g^2 \approx 1 \times 10^{-6}$.