PIENU: Searching for Dark Sectors in Pion Decay

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For the PIENU Collaboration

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Outline

- Pion decay.
- Experimental technique.
- The PIENU detector.
- Strategy of searching for dark sectors.
- Prospects for dark sectors.
- Summary.

$\pi^+ \to e^+\nu$ Branching Ratio

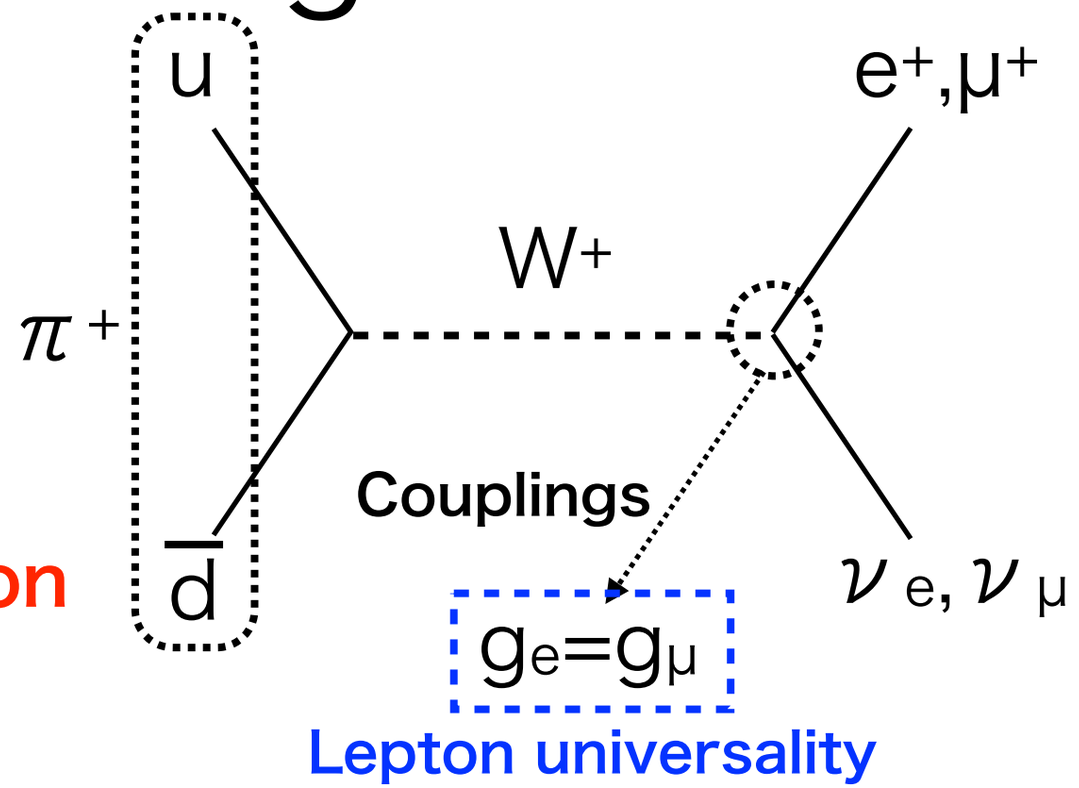
- $\pi^+ \to e^+\nu$ branching ratio in SM

$$R^{\pi}_{\mathrm{SM}} = \frac{\Gamma[\pi^+ \to e^+\nu(\gamma)]}{\Gamma[\pi^+ \to \mu^+\nu(\gamma)]}$$

$$= (1.2352 \pm 0.0002) \times 10^{-4}$$

$\pi^+ \to e^+\nu$ decay: **helicity suppression**

V.Cirigliano, I.Rosell, PRL 99 231801 (2007)



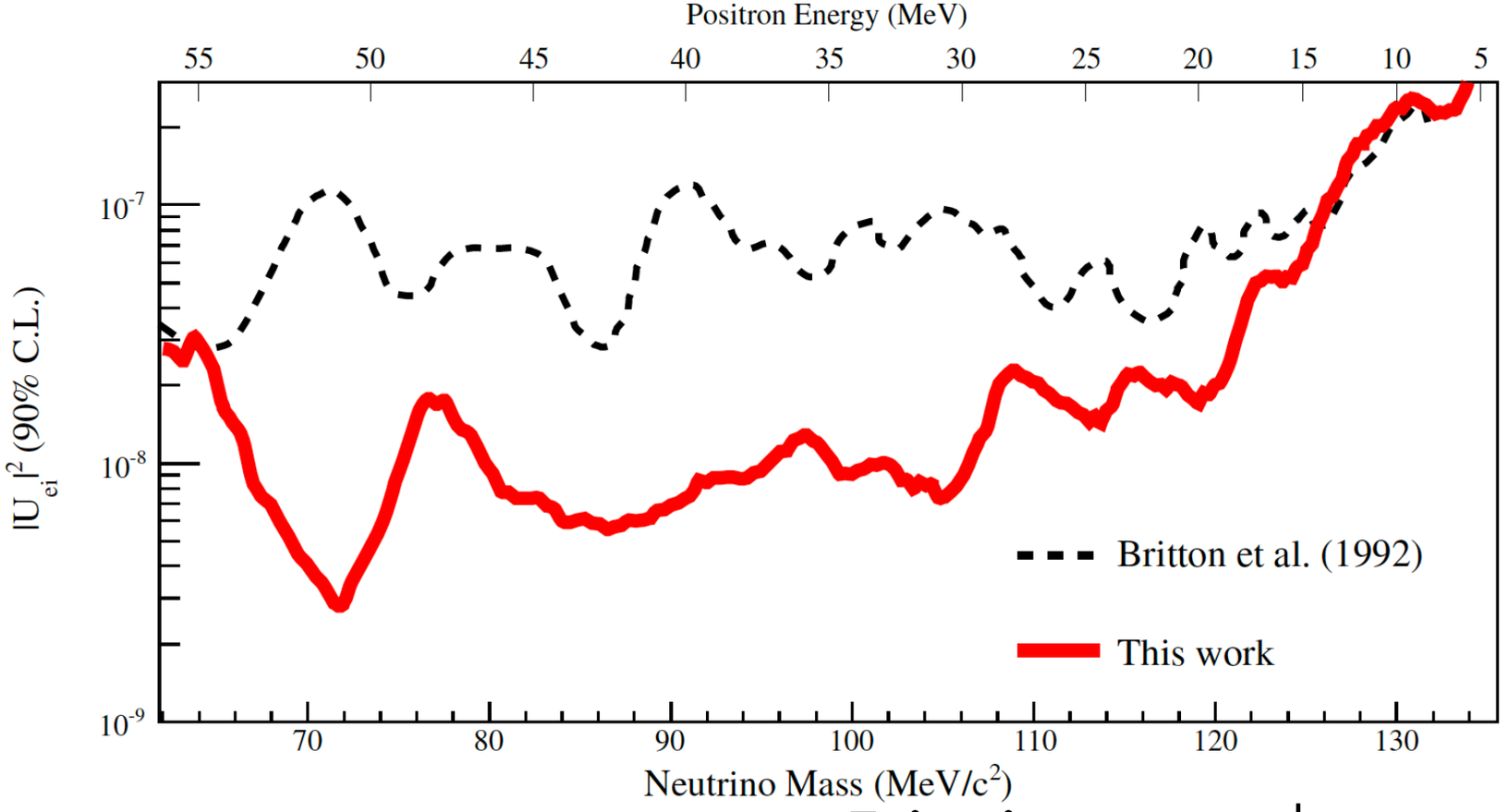
- **Lepton universality test**: R-parity violating SUSY, charged Higgs, Leptquarks, heavy neutrino couplings.
- Two experiments PIENU at TRIUMF and PEN at PSI aim to measure R^{π} with precision of <0.1%.
- Initial PIENU result (0.24% precision)

$$R^{\pi}_{\mathrm{exp}} = [1.2344 \pm 0.0023(\mathrm{stat}) \pm 0.0019(\mathrm{syst})] \times 10^{-4}$$

Phys. Rev. Lett. 115 071801, (2015)

Rare Decay Searches Using PIENU Data

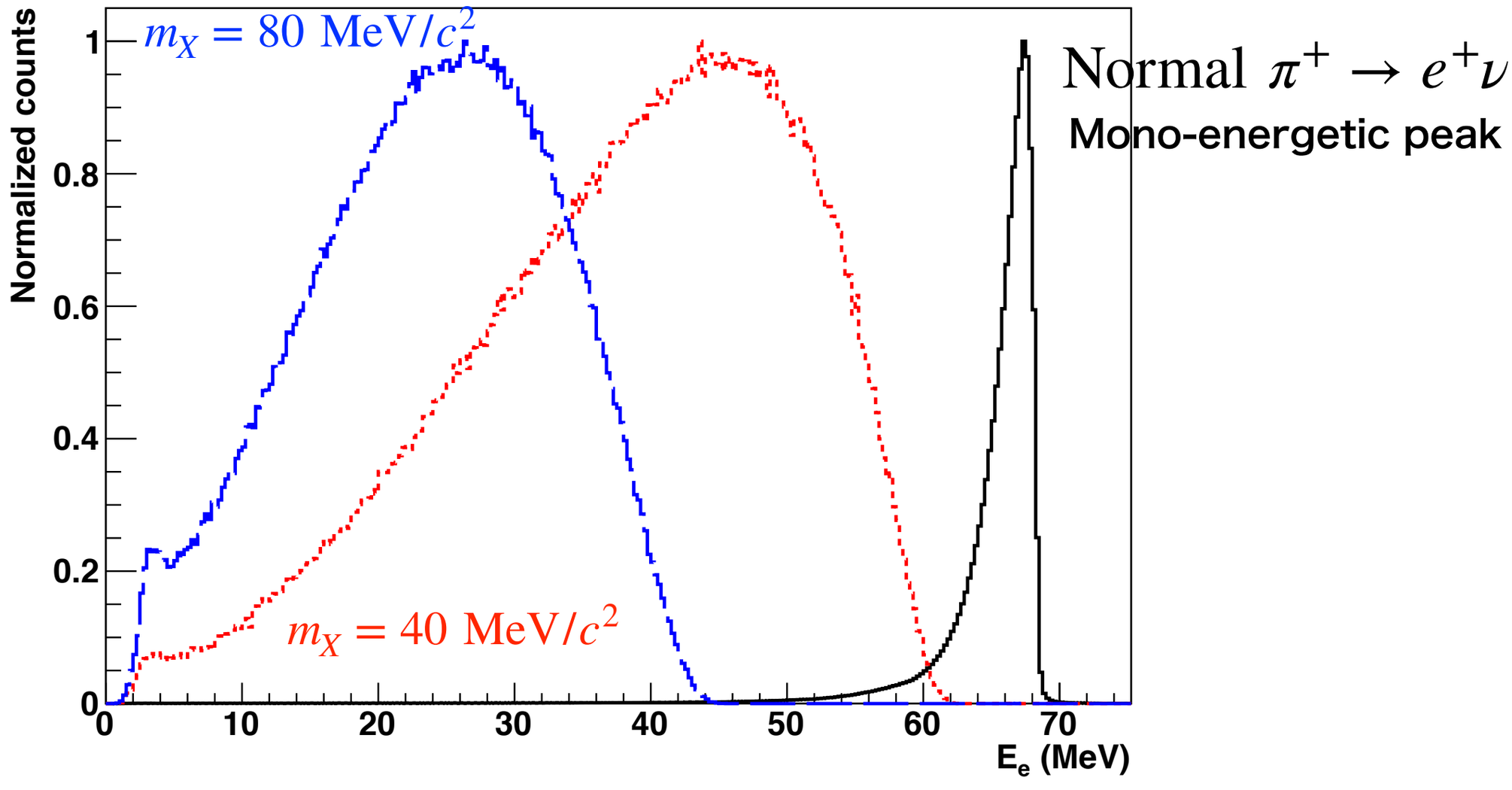
- Analysis of decay lepton (e, μ) energy spectrum is sensitive to search for exotic rare decays.
  - Massive neutrinos: Phys. Rev. D 97 072012 (2018)
    $\pi^+ \to e^+/\mu^+ \, \nu_H$ Phys. Lett. B 798 (2019) 134980
  - $\mu^+ \to e^+ X$ decay: Phys. Rev. D 101 052014 (2020)
  - $\pi^+ \to e^+/\mu^+ \, 3\nu$ decay: Phys. Rev. D 102 012001 (2020)



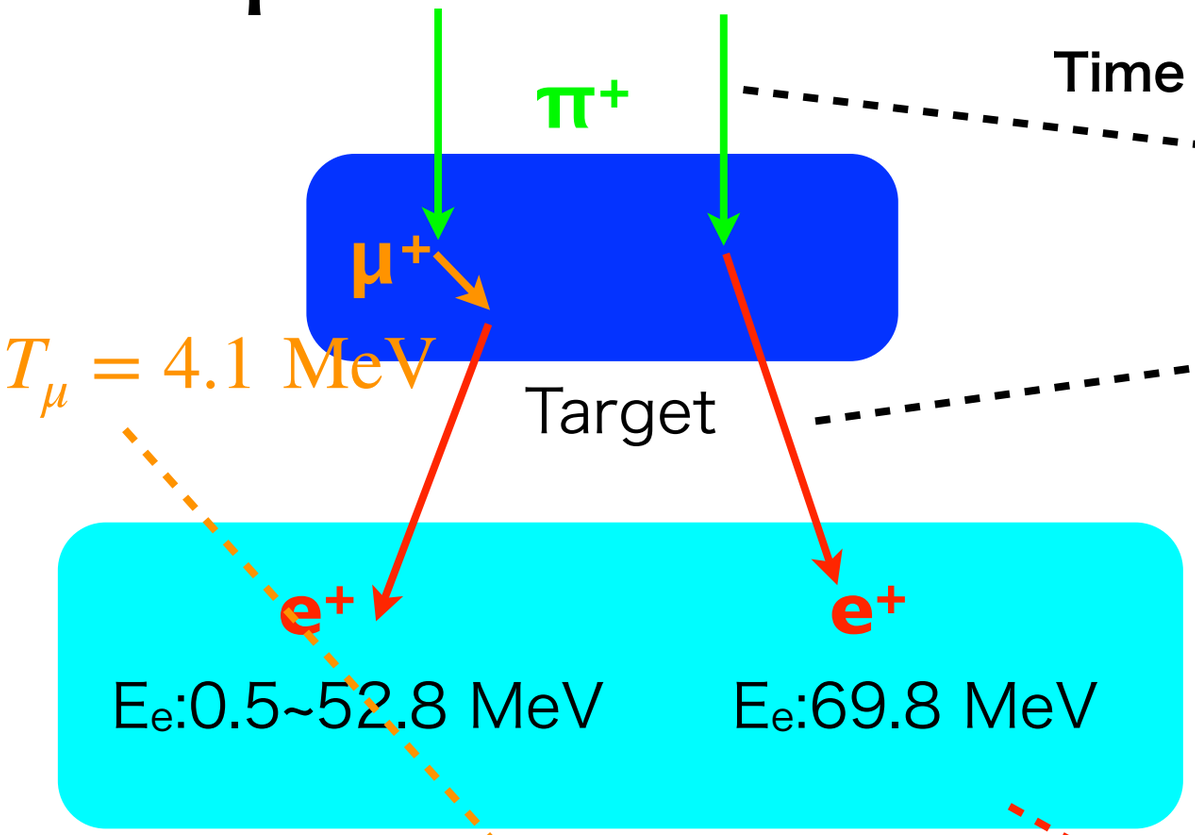
Limits on $\pi^+ \to e^+ \, \nu_H$ decay

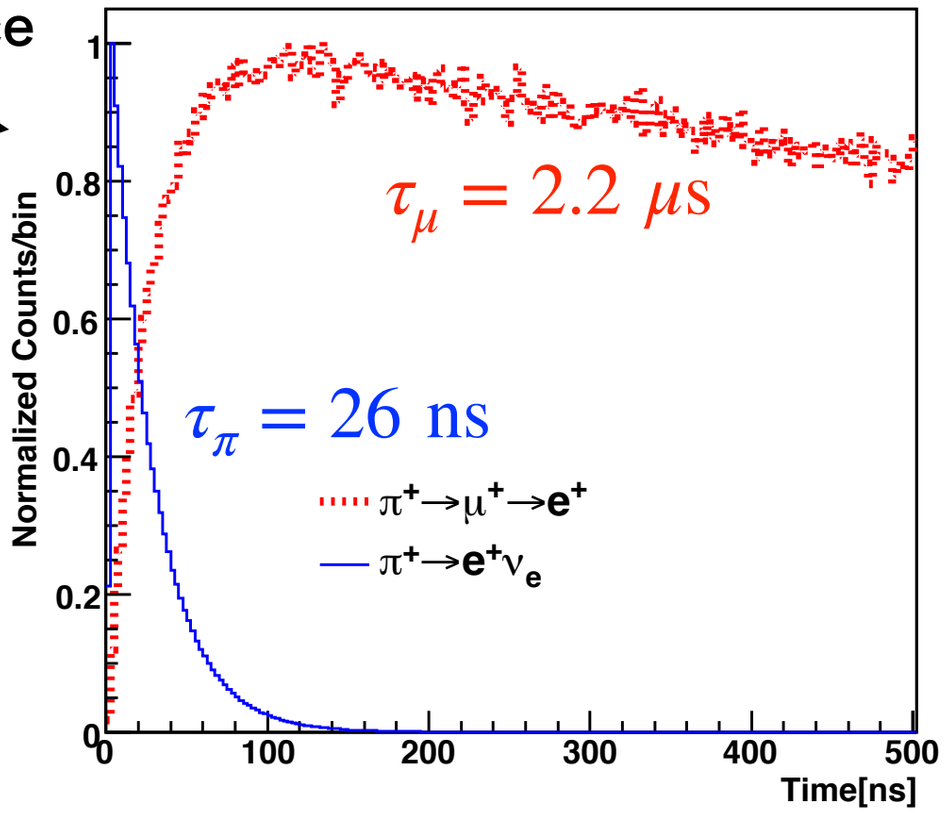
Dark Sectors Search Using PIENU Data

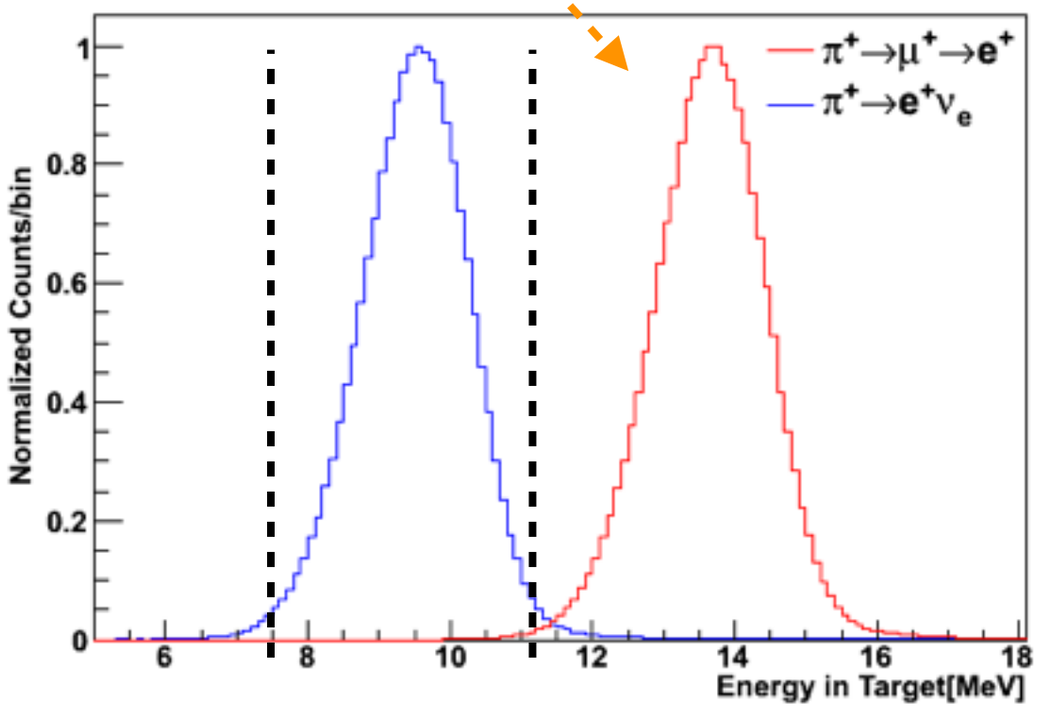
- Another exotic pion decay: $\pi^+ \to e^+ \nu X$ where X is
  - Axion like particles (Phys. Rev. D 101 075002 (2020))
  - Majoron-neutrino couplings (Phys. Lett. 99B 411 (1981))
  - Heavy neutrinos (Phys. Rev. D. 97 075016 (2018))



Experimental Technique in PIENU

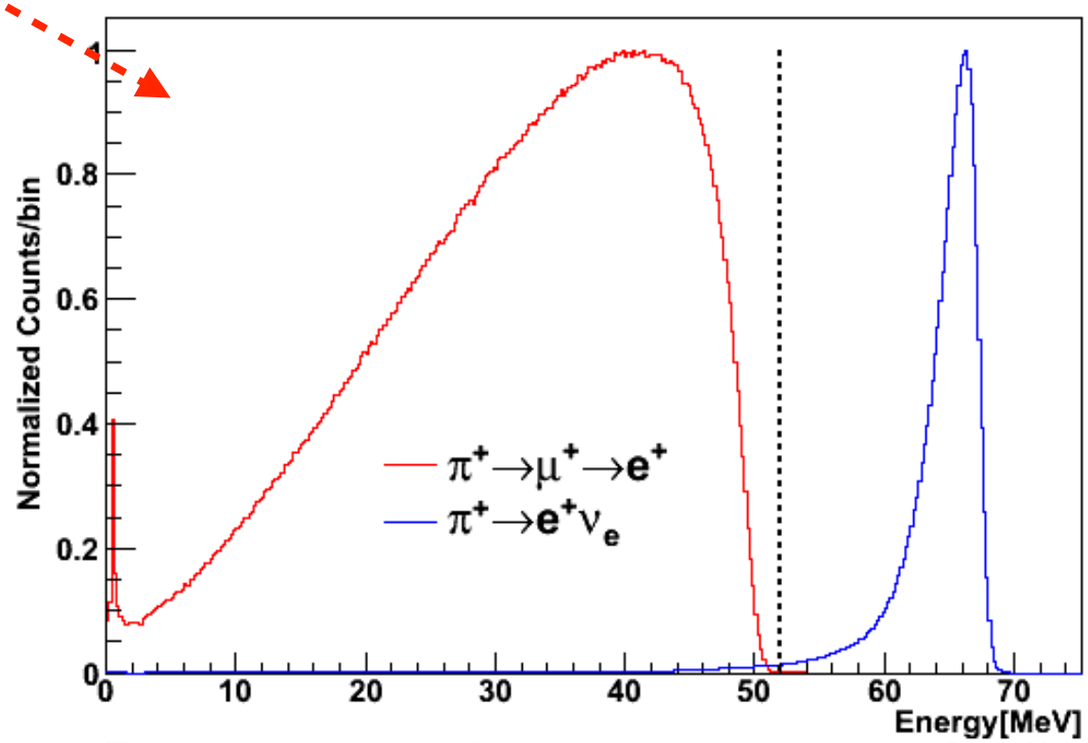






Energy in the target (MC)

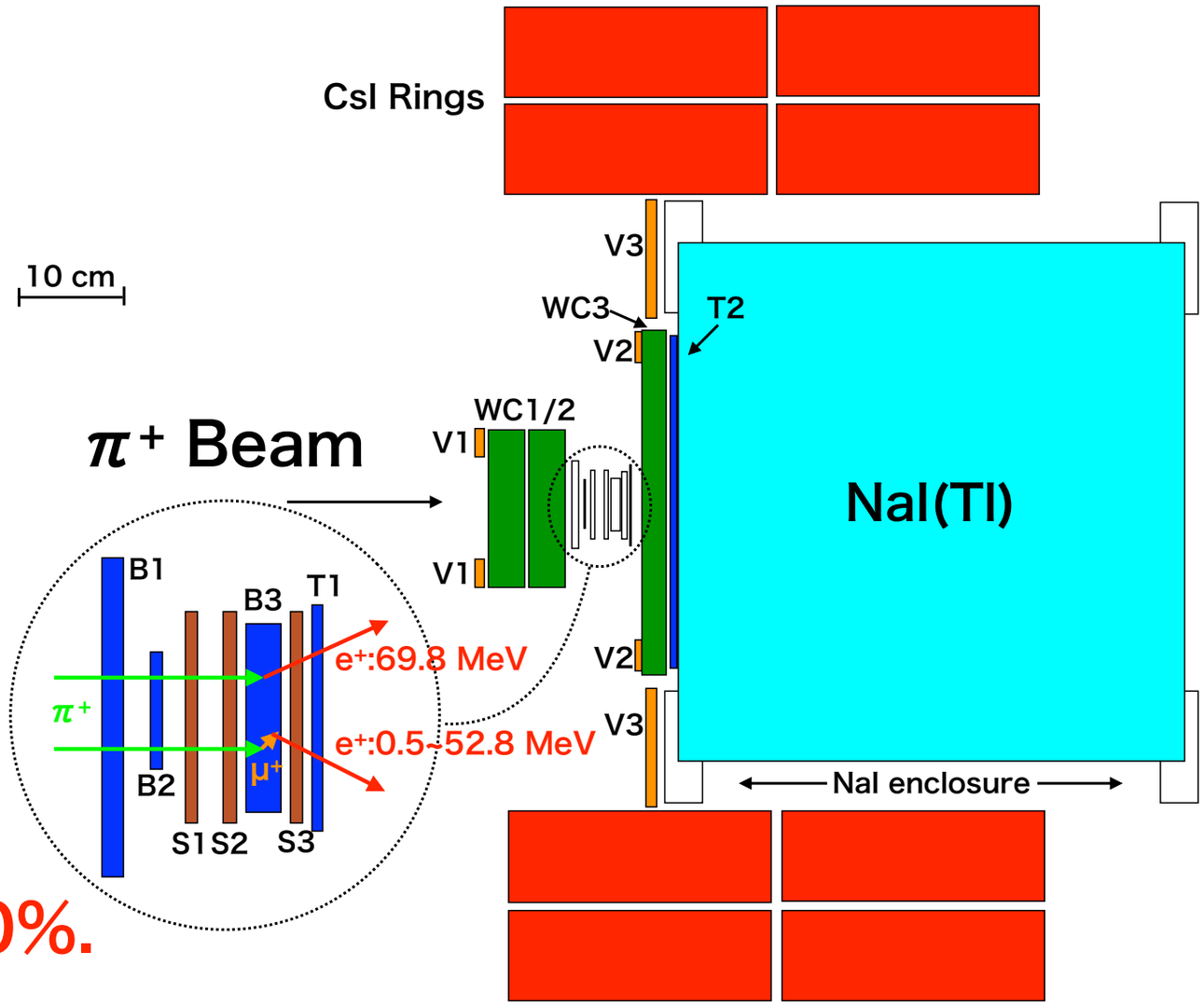
Ee in calorimeter



Decay positron energy (MC)

The PIENU Detector

- The PIENU detector
  - NaI(Tl):48 cm × 48 cm
  - CsI rings
  - WC:Wire chamber
  - S: Silicon strip
  - B1,B2,B3,T1,T2: Plastic scintillator



✓ Larger detector acceptance, **~20%.**

✓ NaI(Tl): better energy resolution.

➡ **2.3%** at 70 MeV (FWHW).

✓ CsI rings: **shower leakage detection.**

✓ S1~S3, WC1~3: pion & positron tracking.

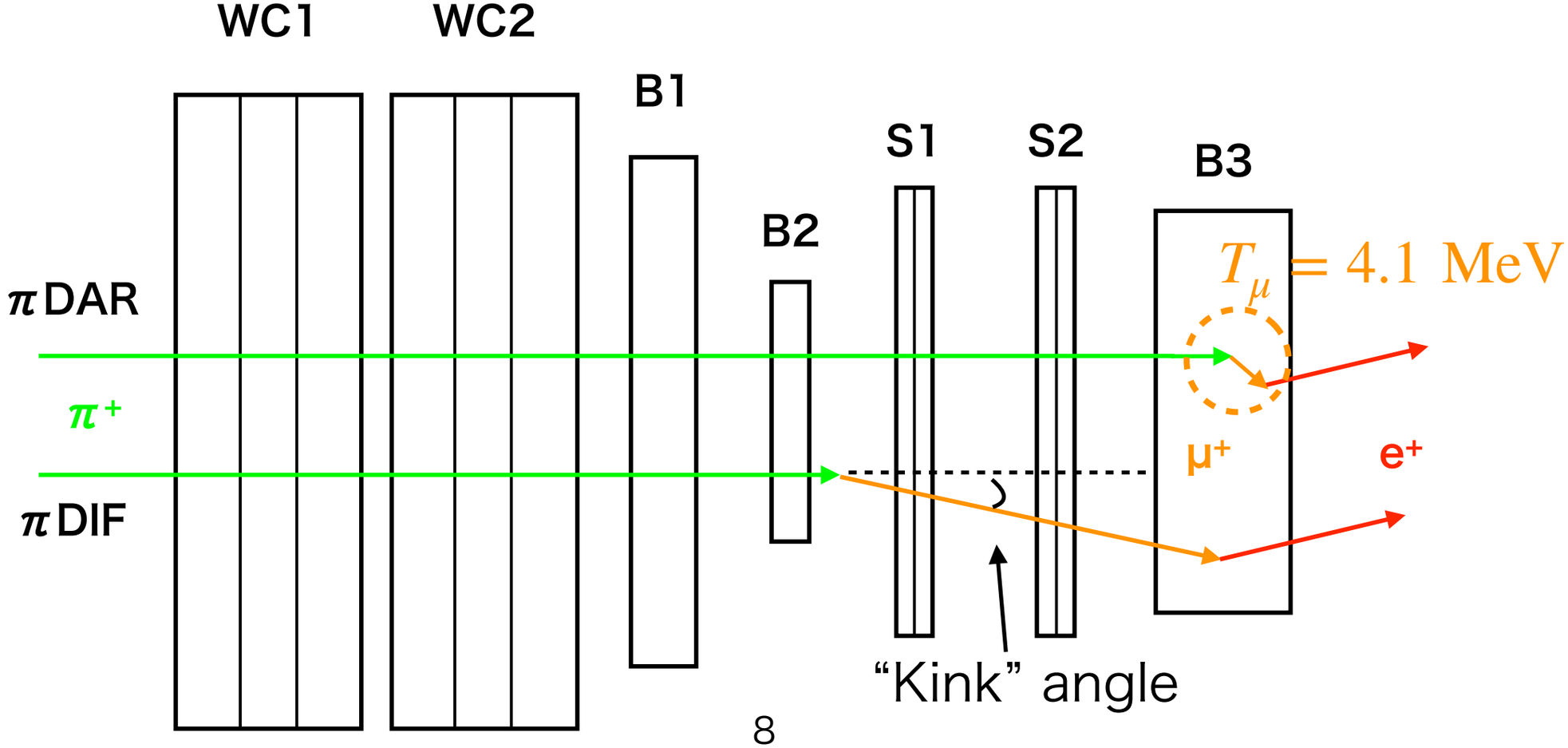
✓ Fast waveform digitizers (500 MHz).

Nucl. Instrum. Methods., A 791 38-46 (2015)

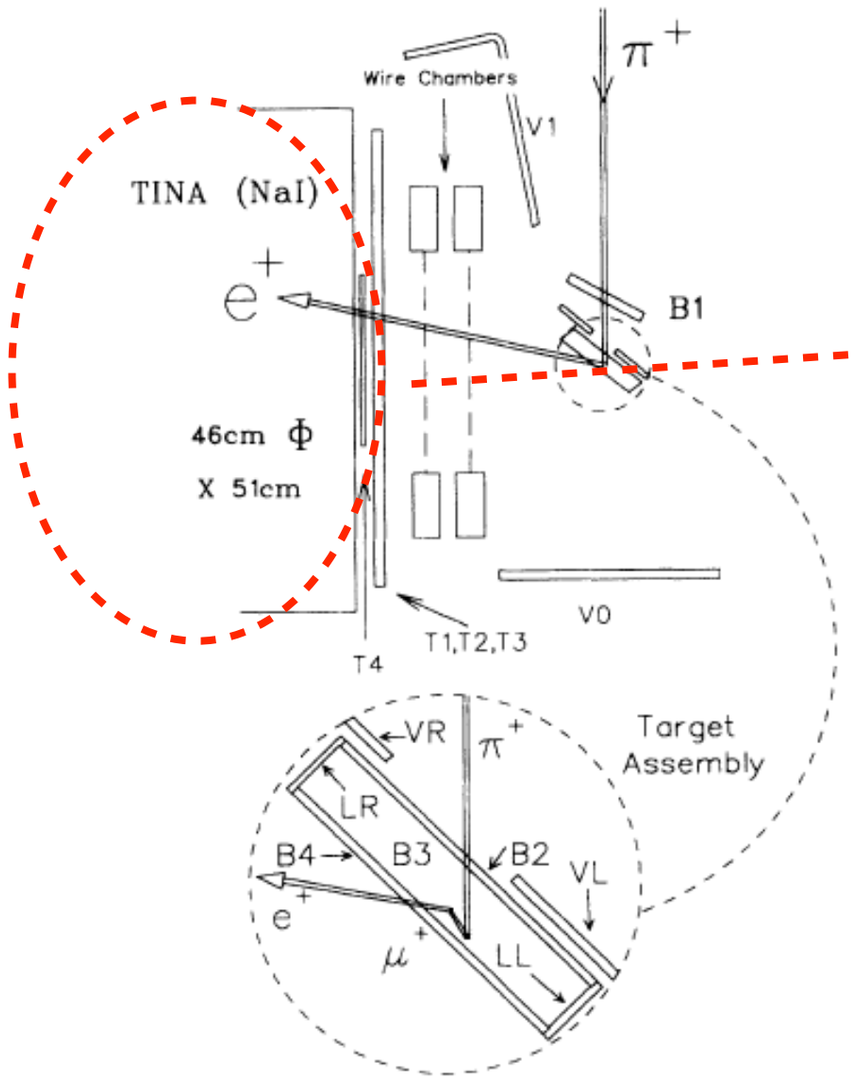
$\pi^+ \to \mu^+ \to e^+$ Suppression Techniques

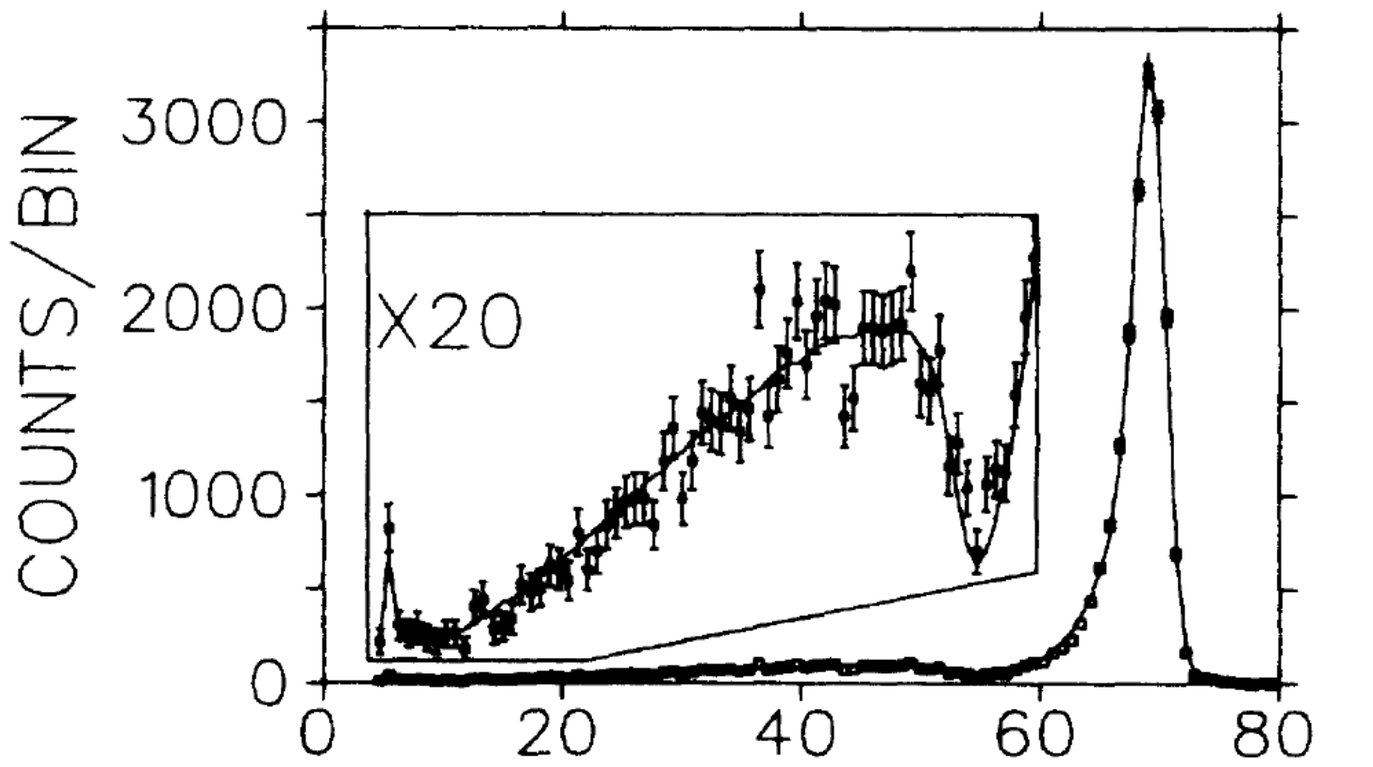
- To search for $\pi^+ \to e^+\nu X$ decay, dominant $\pi^+ \to \mu^+ \to e^+$ background should be suppressed by
  - exploiting shorter pion lifetime than muon
  - target energy due to the presence of muon (T_μ=4.1 MeV)
  - "kink" angle cut to reject π-decay-in-flight (πDIF)

  ➡ $\pi^+ \to \mu^+ \to e^+$ suppression factor ~10^5.



Previous Experiment at TRIUMF





after $\pi \to \mu \to e$ suppression cuts

- Previous experiment at TRIUMF in 1980's
  Phys. Rev. D 37 1131 (1988)
  - $\sim 1.8 \times 10^4$ $\pi \to e\nu$ events
  - Small detector acceptance (~2%)
  - No pion tracking detector: no π DIF rejection.

$$BR = \frac{\Gamma(\pi \to e\nu X)}{\Gamma(\pi \to \mu\nu)} \lesssim 4 \times 10^{-6}$$

in mass range m_X=0~125 MeV/c2.

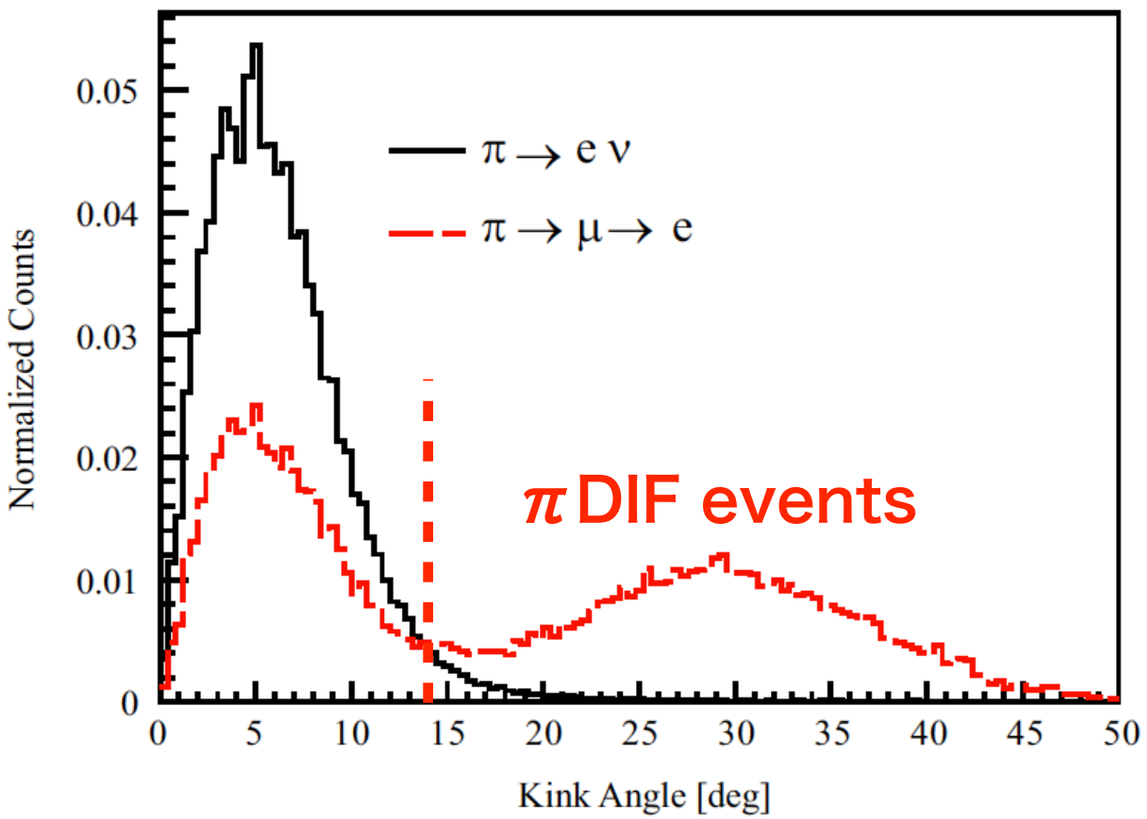
Prospects of Dark Sector in PIENU

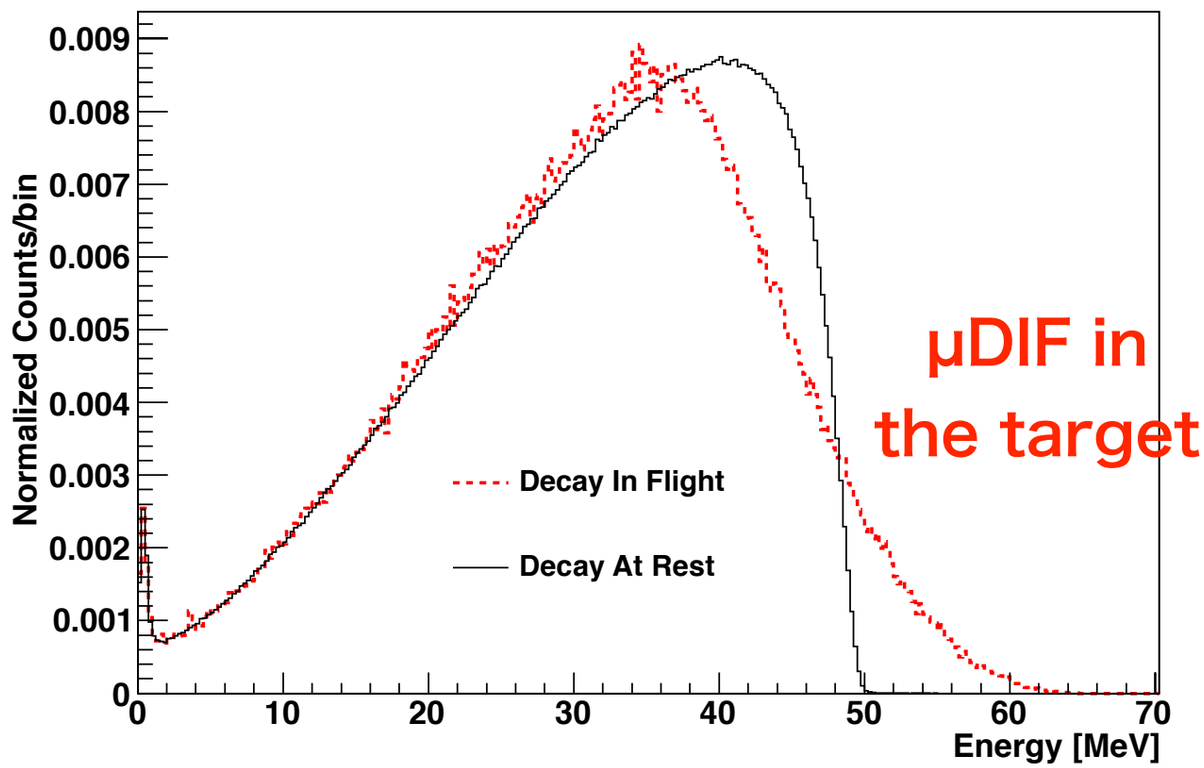
- Improvements in PIENU
  - larger detector acceptance (~20%)

    ➡ an order of magnitude larger statistics.
  - “kink” angle cut using WCs/Silicon strips

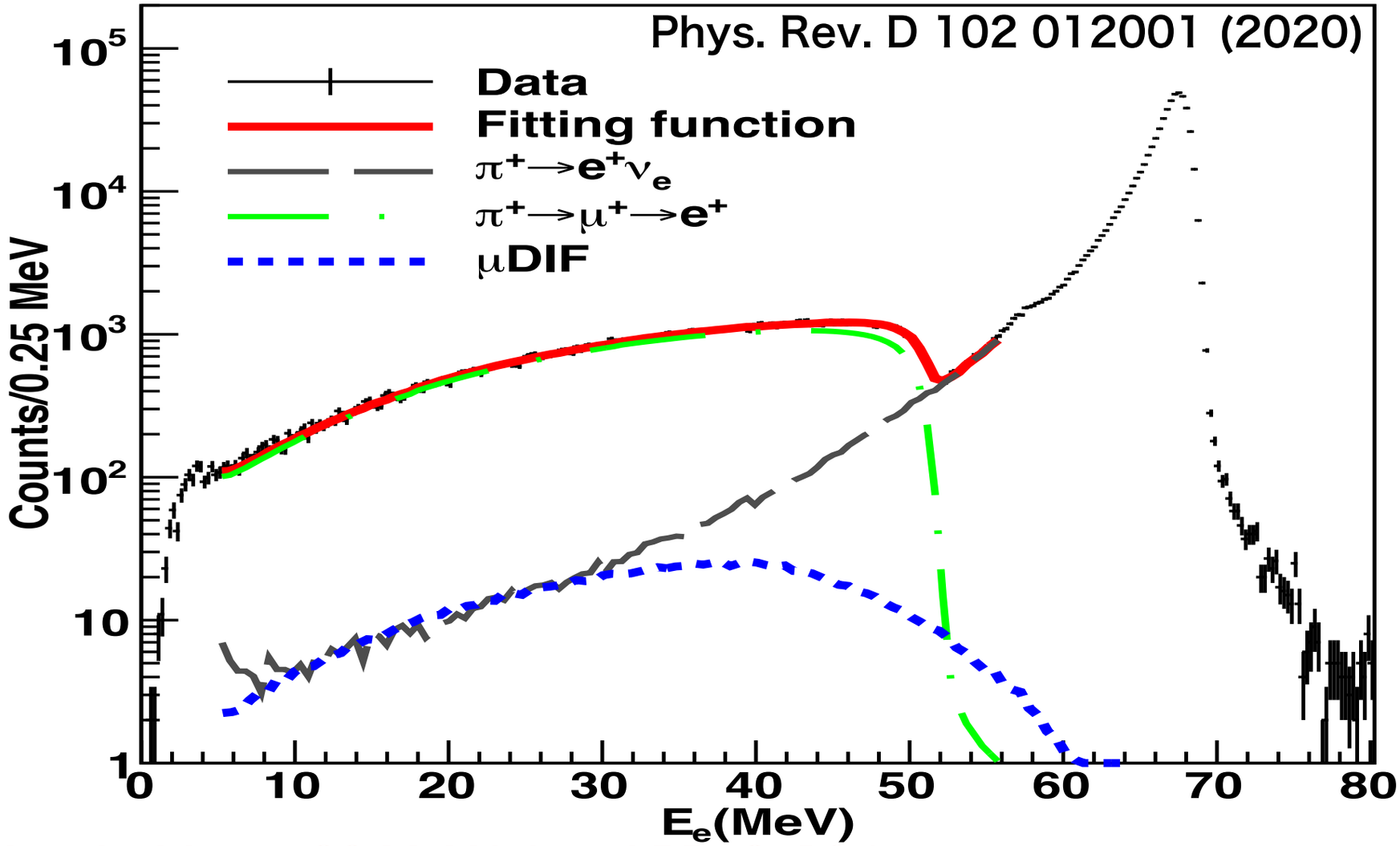
    ➡ half of πDIF events.
  - More precise estimates of background: μDIF events.
  - Better understanding of low energy $\pi \to e\nu$ tail.

Sensitivity will be improved by an order of magnitude!!

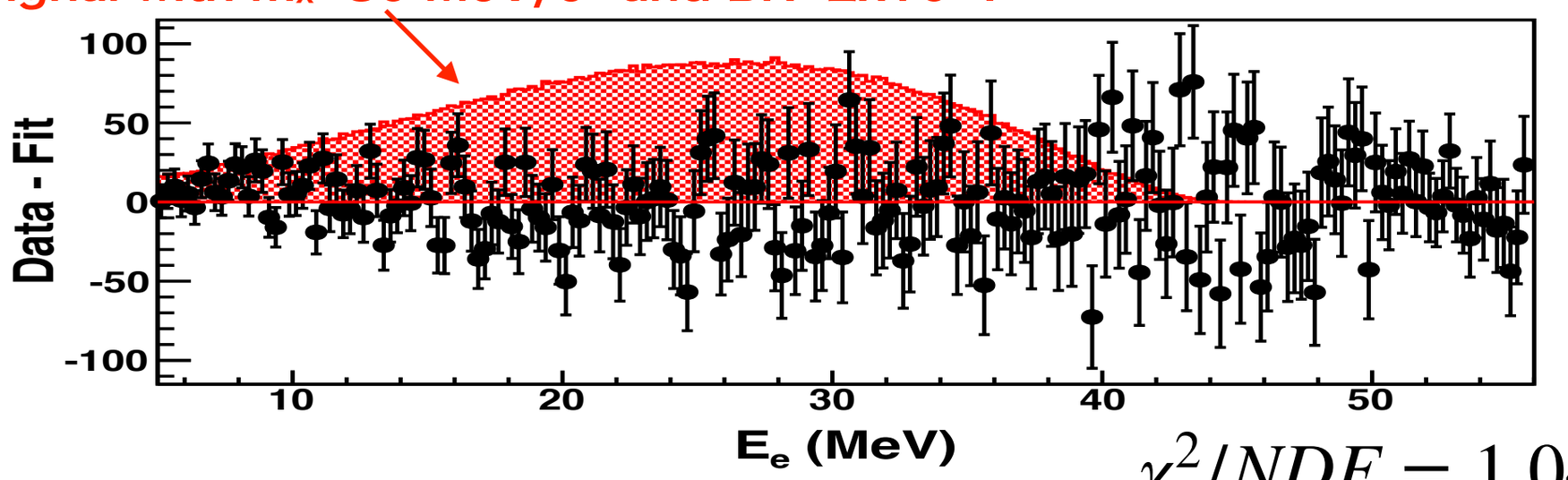




Prospects of Dark Sector in PIENU



Hypothetical signal with m_X=80 MeV/c^2 and BR=2x10^{-6}.



$\chi^2/NDF = 1.04$

Another Constraint on Majoron-Neutrino Couplings

- A Nambu-Goldstone bosons called **"Majoron"** arises in gauge models: spontaneously broken global B-L symmetry.
  ➡Gelmini and Roncadelli, Phys. Lett. 99B 411 (1981)
- Barger, Keung, and Pakvasa extended Majoron model to leptonic pion decay (Phys. Rev. D 25 907 (1982)).
- In the presence of massless Majoron M, the expected pion branching ratio is slightly higher,

$$R' = \frac{\Gamma(\pi \to eL^0)/\Gamma(\pi \to \mu L^0)}{\Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)} = 1 + 157.5 g_M^2$$

L^0 : final states including ν, νM, and $\nu\chi$ (very light neutral Higgs (keV))

g_M : Majoron – neutrino coupling constant

Another Constraint on Majoron-Neutrino Couplings

- Initial PIENU result for pion branching ratio

$$R^{\pi}_{\mathrm{exp}} = [1.2344 \pm 0.0023(\mathrm{stat}) \pm 0.0019(\mathrm{syst})] \times 10^{-4}$$

- Upper limit on the branching ratio (90% C.L.)

$$R' = \frac{R^{\pi}_{\mathrm{exp}}}{R^{\pi}_{\mathrm{SM}}} < 1.0033 \qquad R' = \frac{\Gamma(\pi \to eL^0)/\Gamma(\pi \to \mu L^0)}{\Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)} = 1 + 157.5 g_M^2$$

Hyperfine Interact. 238 (2017) 1, 1

- The limit on Majoron-neutrino coupling constant (90% C.L.)

Previous result : $g_M^2 < 3 \times 10^{-5}$, PIENU : $g_M^2 < 2.1 \times 10^{-5}$

Phys. Rev. D 49 28 (1994)

- Assuming 0.1% precision for Rπ, the limit on the coupling constant will be improved to $g_M^2 < \sim 1 \times 10^{-5}$

Summary

- The PIENU experiment was performed at TRIUMF to measure $\pi^+ \to e^+\nu$ branching ratio <0.1%.
- The PIENU data is very sensitive to new physics such as heavy neutrinos, exotic muon decay, $\pi^+ \to l^+ 3\nu$, and so on.
- Prospects to search for dark sectors $\pi^+ \to e^+\nu X$ in PIENU
  - An order of magnitude of improvement.
  - Constraint on several models: e.g. Majoron model
- Results of dark sector searches and $\pi^+ \to e^+\nu$ branching ratio with full statistics are coming soon.

Thank you for your attention!!