Improved Search for Heavy Neutrinos and a Test of Lepton Universality in the Decay $\pi \to e\nu$

Precision Physics at High Intensities
CIPANP18

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for the PIENU collaboration

29 May 2018

Introduction

- Today's presentation will include two recently published results from the PiENu Experiment:

- Limits on heavy neutrinos coupling to electrons
  - A. Aguilar-Arevalo *et al.*, Phys. Rev. D **97**, 072012 (2018)
- Test of Lepton Universality in pion decay
  - A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. **115**, 071801 (2015)

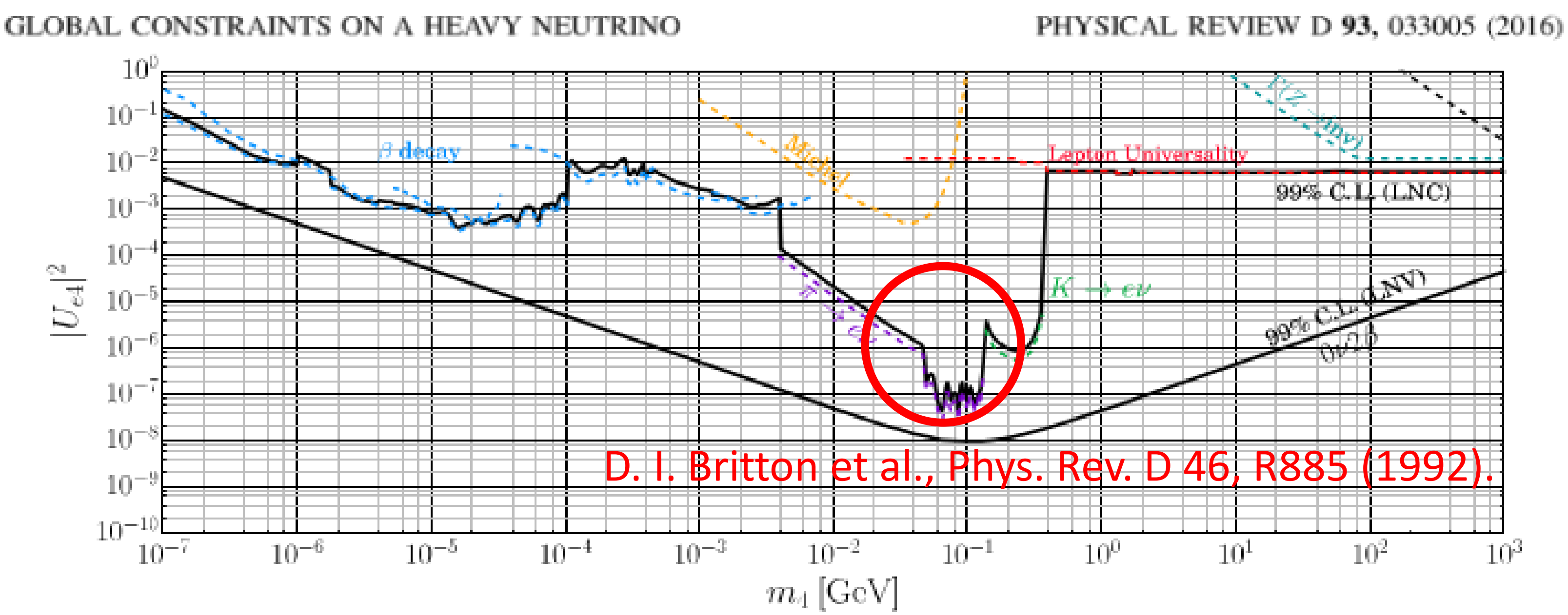
- Plus the status of the full analysis for the $\pi \rightarrow e\nu$ branching ratio

The PiENu Experiment and Heavy Neutrinos

PiENu stops pions to make a precise measurement of the rate for the rare decay $\pi \rightarrow e\nu$.

It is also sensitive to $\pi \rightarrow e\nu_h$ for $60 < M_\nu < 135$ MeV/c^2 and sets impressive limits on the coupling of a ν_h to the electron ($|U_{ei}|^2$)

A. de Gouvêa and A. Kobach



Importance of Heavy Neutrino Searches

Many extensions of the Standard Model include additional massive neutrinos.

The νMSM includes three sterile neutrinos, two of which may have masses in the range probed by meson decays.[1]

Other models (such as dark matter or thermalization) also have neutrino masses in the MeV/c^2 range.[2]

[1] A. Boyarsky, O. Ruchayskiy and M. Shaposhnikov, Ann.Rev. Nucl. Part. Sci. 59, 191 (2009).
[2] B. Bertoni, S. Ipek, D. McKeen, and A. Nelson, JHEP, 04, 170 (2015).
B. Batell, T. Han, D. McKeen, and B. Haghi, arXiv:1709.07001, (2015).
T. Appelquist, M. Piai, and R. Shrock, Phys. Rev. D 69, 015002 (2004).

The PiENu Experiment at TRIUMF

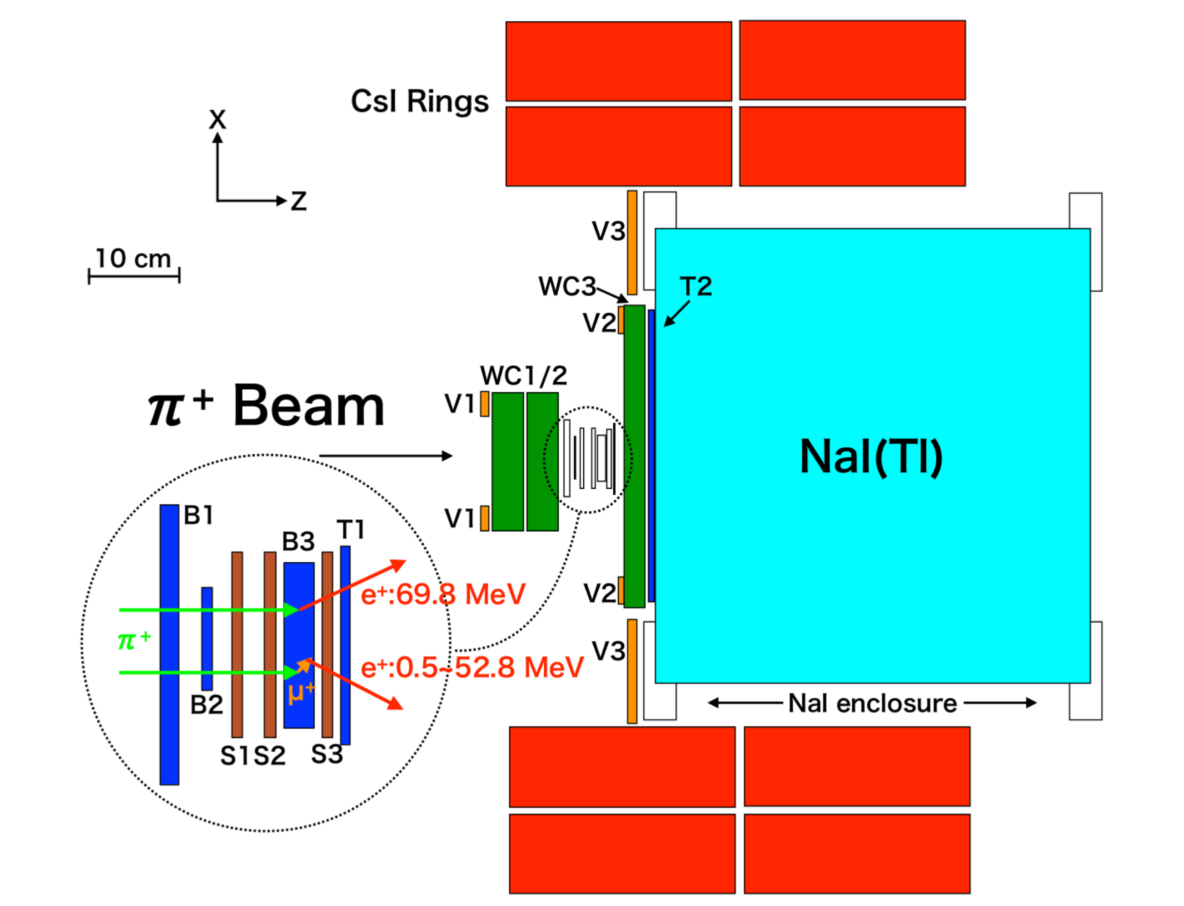
Beam:
60kHz pions @ 75 MeV/c
$\pi : \mu : e = 85 : 14 : 1$

Detector: [1]
Acceptance: 20%
Plastic Scintillators
NaI(Tl) + CsI Calorimeter
Wire Chambers
Silicon Strips

Energy resolution:
2.2% FWHM @ 70MeV

Temperature Stabilization

Data taking:
2009-2012



[1] A. Aguilar-Arevalo et al., Nucl. Instrum. Methods Phys.Res., Sect. A 791, 38 (2015).

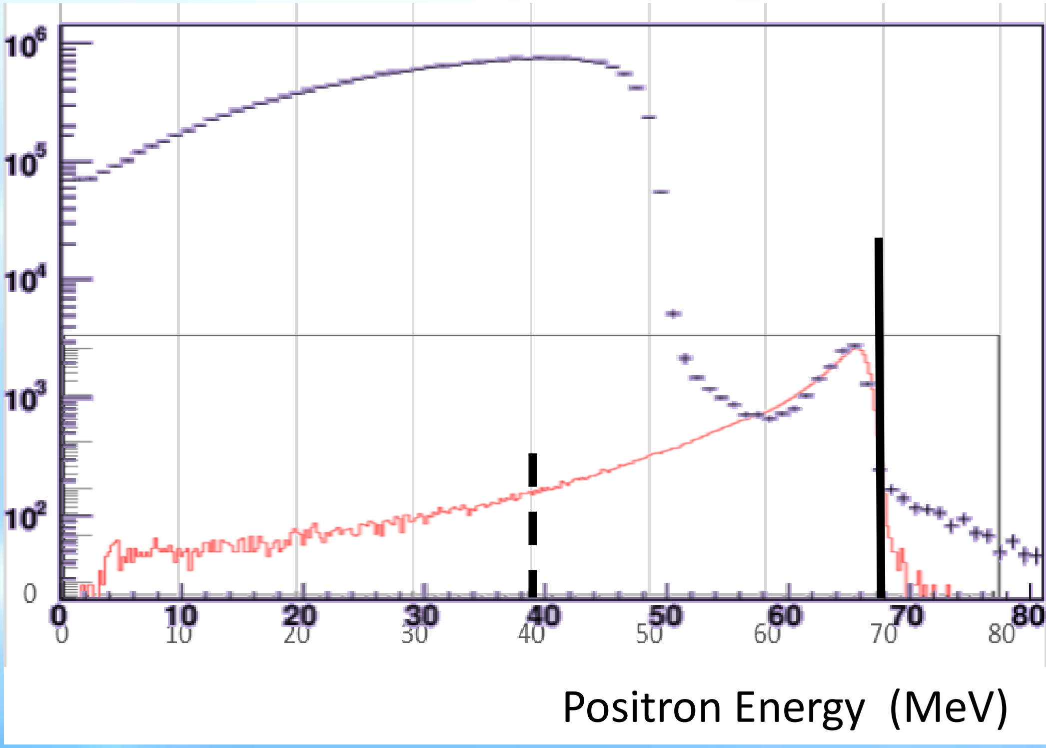
Ideal and observed spectra

two-body decay:
monoenergetic positron
$\pi \to e\nu$ $E_e = 69.8$ MeV

for $m_h = 90$ MeV/c^2
$\pi \to e\nu_h$ $E_e \approx 40$ MeV

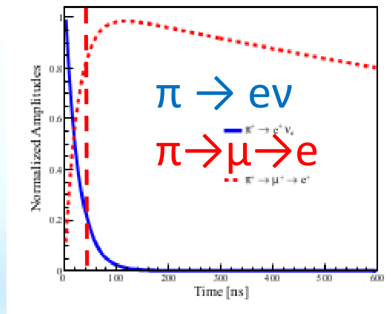
Simulation of spectrum including detector response

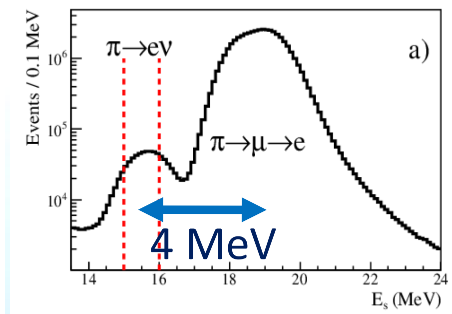
Add positrons from $\pi \to \mu \to e$ decay chain

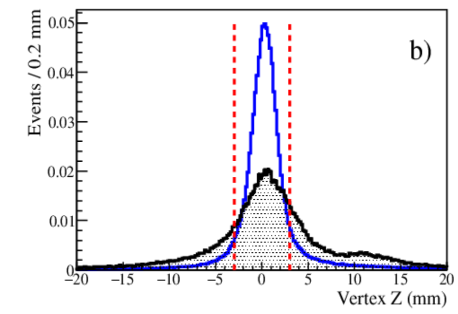


Suppressed spectrum

Suppress π→μ→e events with cuts



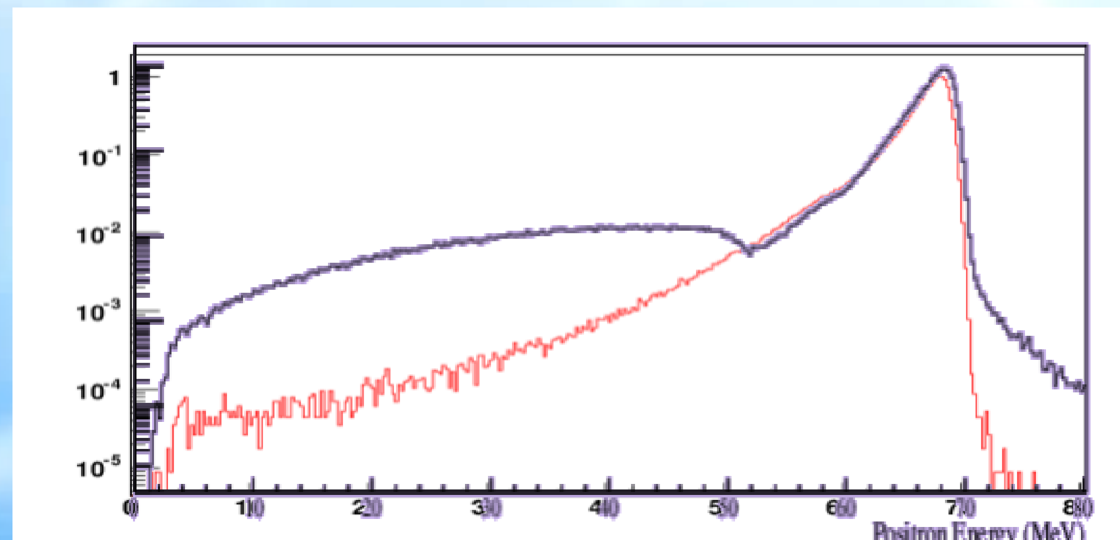




including timing (ns), target energy, and Z vertex

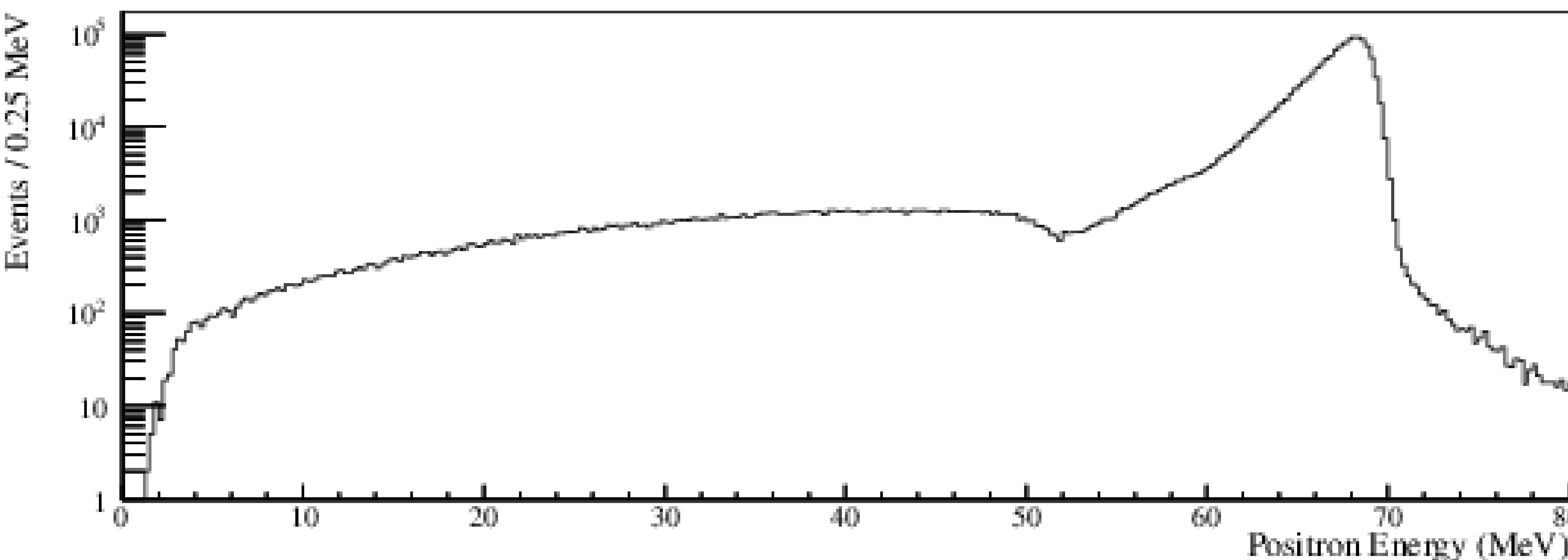
Simulation of spectrum including effects of detector

π→μ→ e decay chain Suppressed



Search for heavy neutrinos

Start with suppressed spectrum

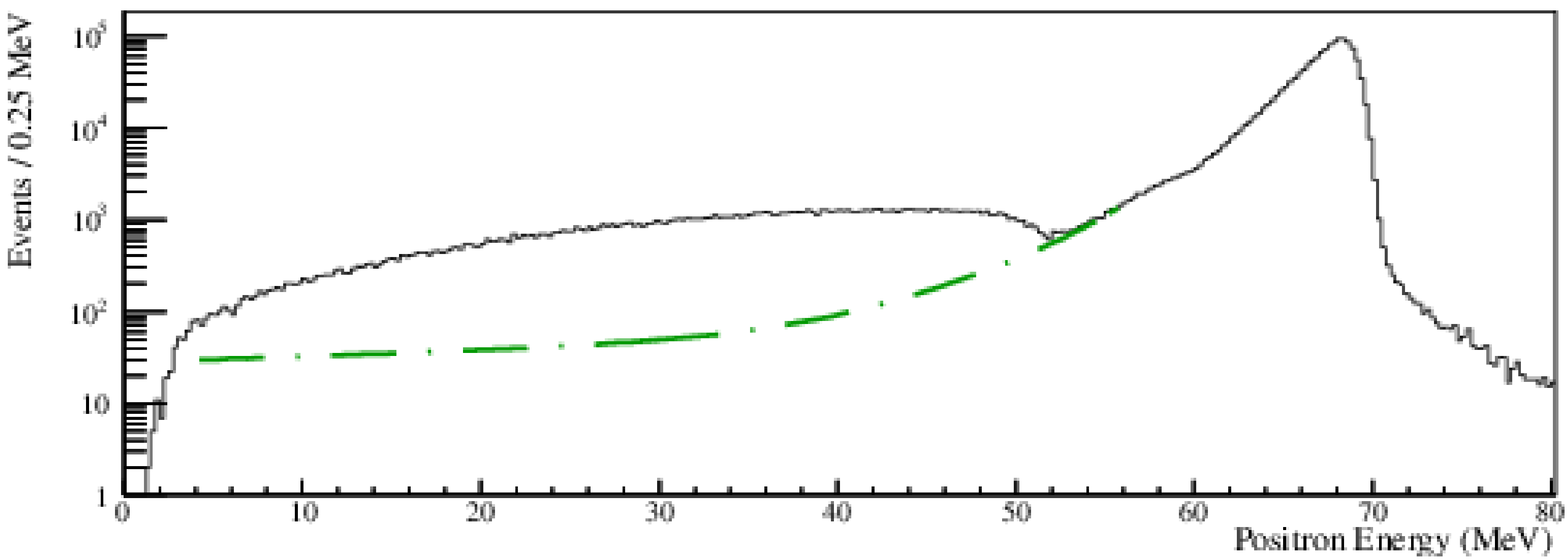


Search for heavy neutrinos

Start with suppressed spectrum

Fit known components prior to neutrino search

Extrapolation of $\pi \rightarrow e\nu$ tail from simulation



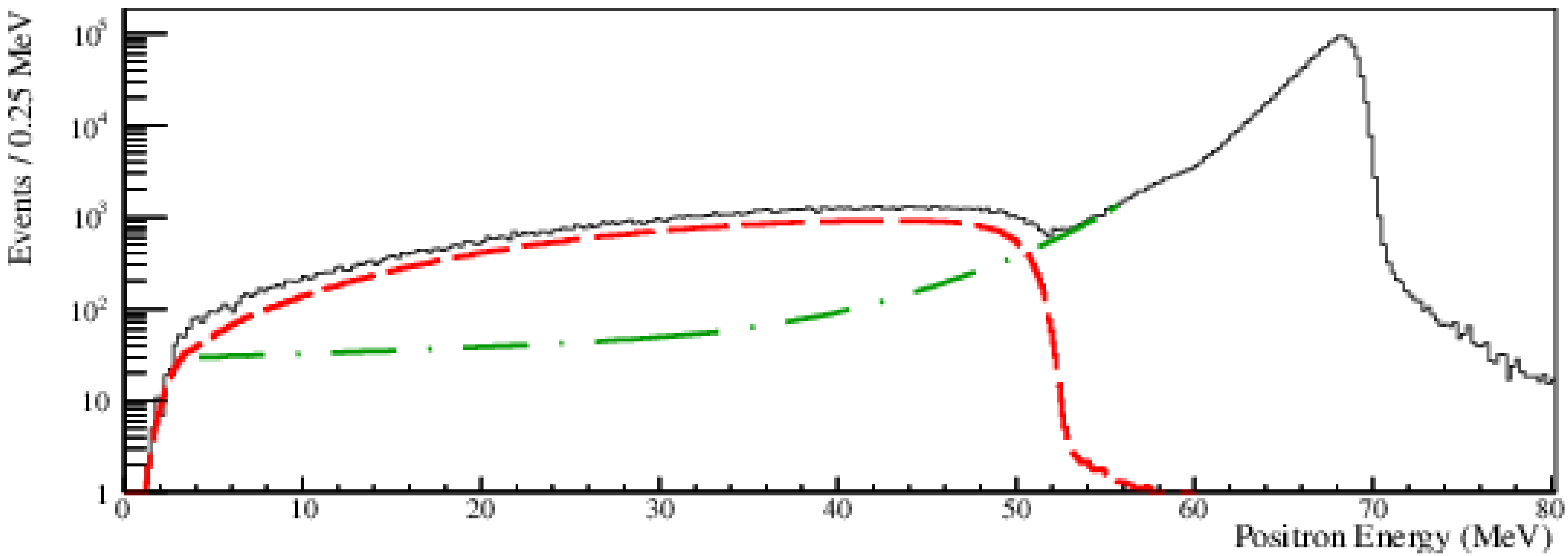
Search for heavy neutrinos

Start with suppressed spectrum

Fit known components prior to neutrino search

Extrapolation of $\pi \rightarrow e\nu$ tail from simulation

Include $\pi \rightarrow \mu \rightarrow e$ shape from late-time events



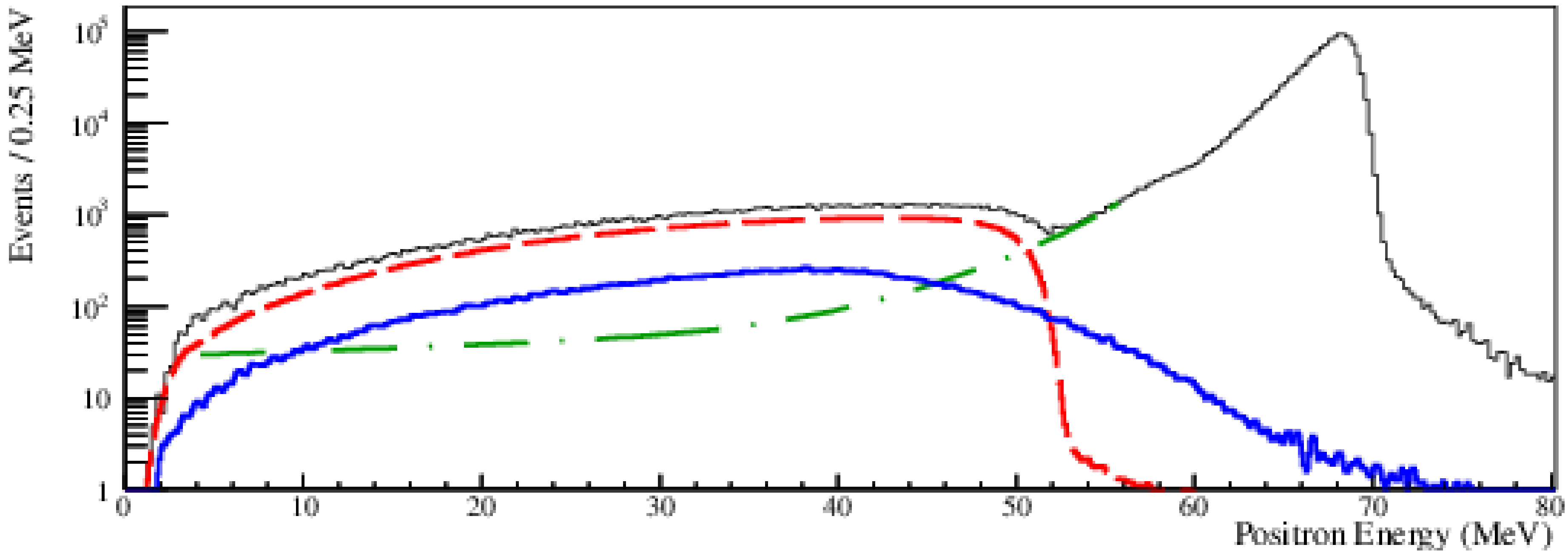
Search for heavy neutrinos

Fit known components prior to neutrino search

Extrapolation of $\pi \rightarrow e\nu$ tail from simulation

Include $\pi \rightarrow \mu \rightarrow e$ shape from late-time events

Add component for muon decay-in-flight



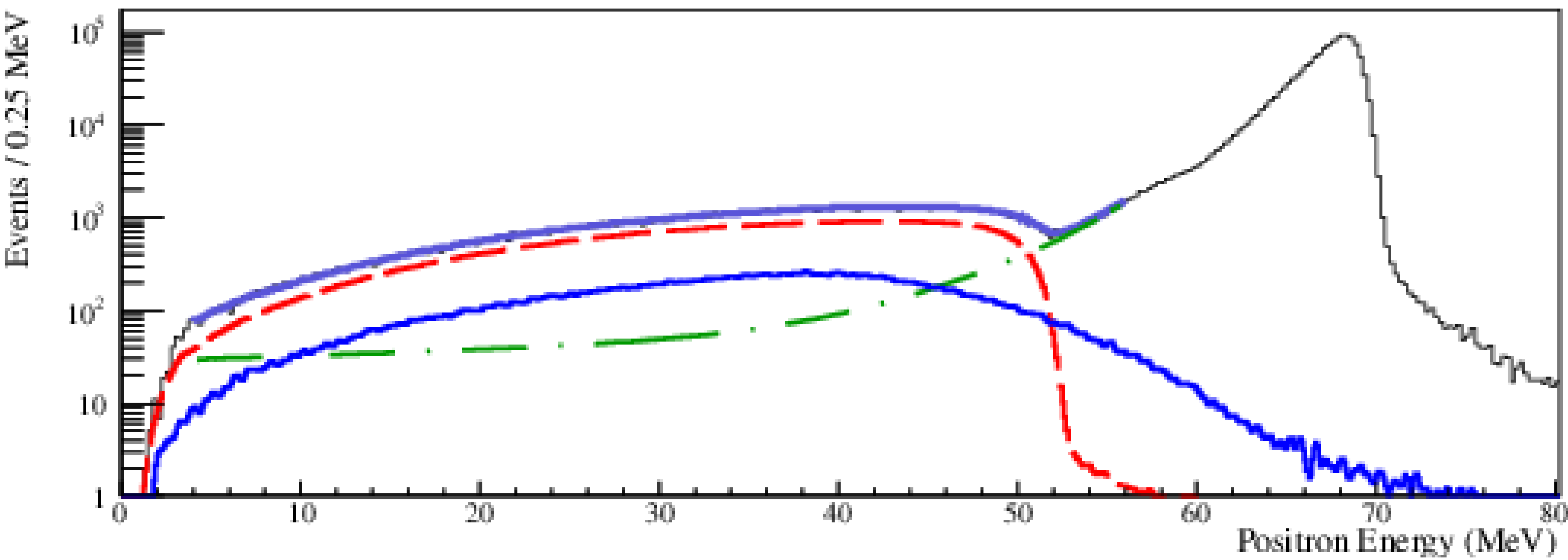
Search for heavy neutrinos

Extrapolation of π → eν tail from simulation

Include π→μ→ e shape from late-time events

Add component for muon decay-in-flight

Background fit over 4 – 56 MeV



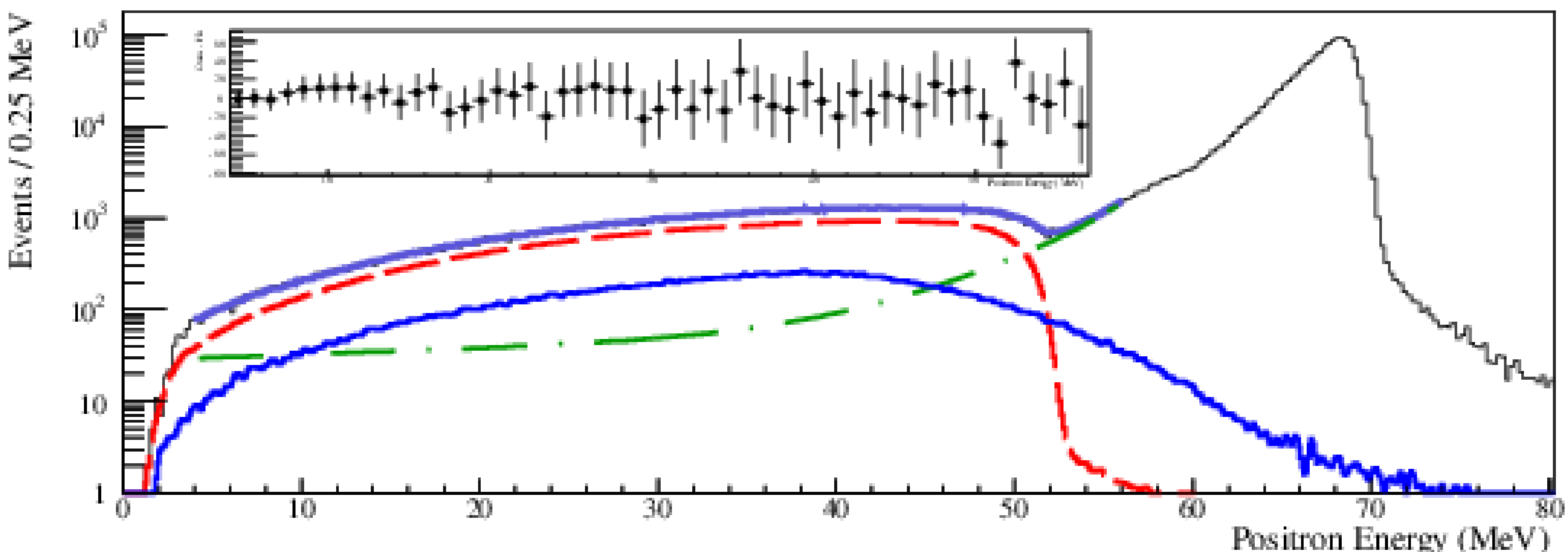
Search for heavy neutrinos

Include π→μ→ e shape from late-time events

Add component for muon decay-in-flight

Background fit over 4 – 56 MeV

Residuals from background fit shown in insert

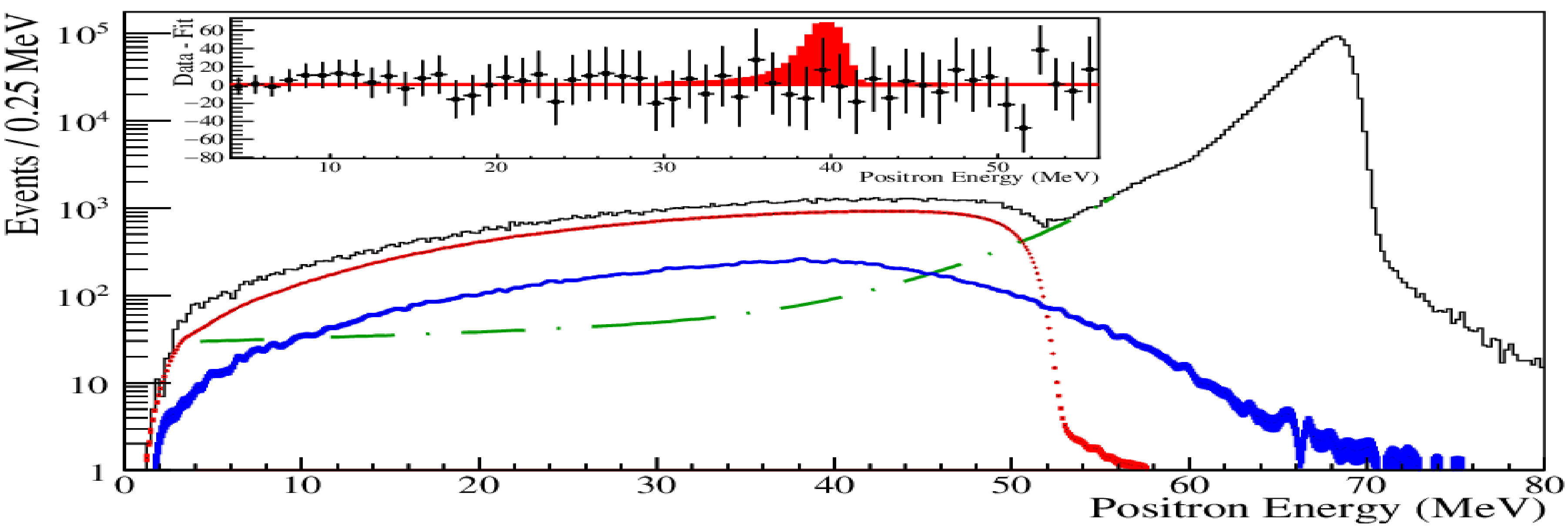


Search for heavy neutrinos

Step signal shape for candidate $\pi \rightarrow e\nu_h$ decay across positron energy spectrum

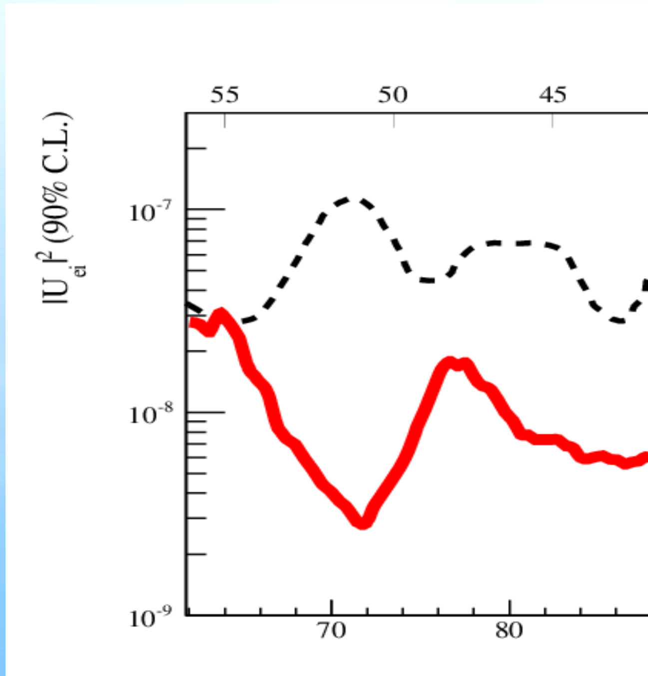
Sample test signal for $\pi \rightarrow e\nu_h$ at 40 MeV shown

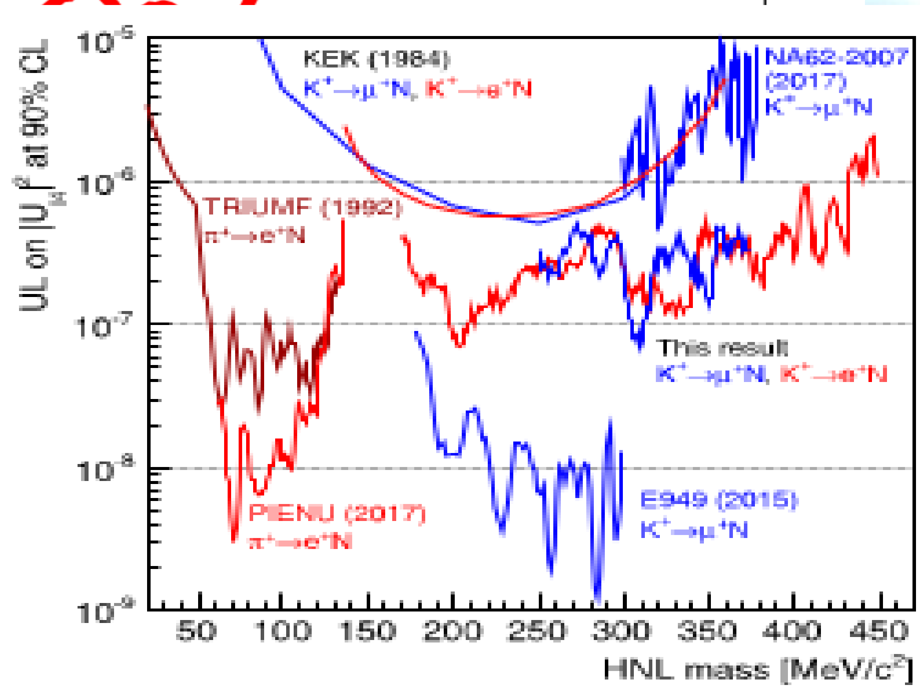
Shape of test signal at each energy follows detector response



Search for heavy neutrinos: Result

$$\frac{1}{Acc(E_{e^+})} \frac{N(\pi \to e\nu_i)_{UL}}{N(\pi \to e\nu)} = |U_{ei}|^2_{UL} \rho_e(E_{e^+})$$





NA62 Collaboration,
Phys. Lett. **B** 778, 137 (2018)

Precise prediction for the π → eν decay rate

Pion Decay Rate: $$\Gamma_{\pi\to l\nu_l} = G^2 \frac{m_\pi f_\pi^2 m_l^2}{8\pi}\left(1-\frac{m_l^2}{m_\pi^2}\right)^2$$

Branching Ratio (assuming **LEPTON UNIVERSALITY**):

$$R_0 = \frac{\Gamma_{\pi\to e\nu_e}}{\Gamma_{\pi\to\mu\nu_\mu}} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2-m_e^2}{m_\pi^2-m_\mu^2}\right)^2 = 1.28336(2)\times 10^{-4}$$

With Radiative and Structure Corrections:

$$R = R_0 \times \left[1+\frac{\alpha}{\pi}\left\{F(\frac{m_e}{m_\pi}) - F(\frac{m_\mu}{m_\pi}) + \frac{m_\mu^2}{m_\rho^2}\left(c_2 \ln\frac{m_\rho^2}{m_\mu^2}+c_3\right) + c_4\frac{m_\pi^6}{m_e^2 m_\rho^4}\right\} + c_5\left(\frac{\alpha}{\pi}\ln\frac{m_\mu}{m_e}\right)^2 + ..\right]$$

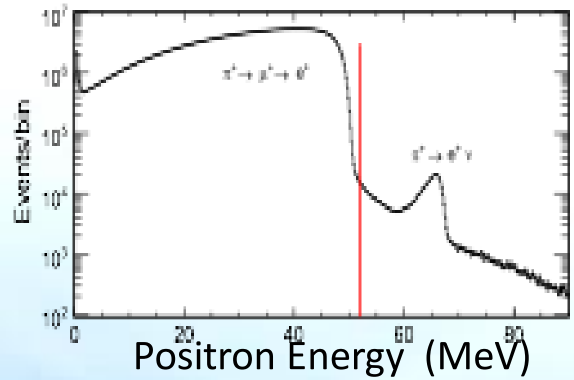
S. Berman: Phys.Rev.Lett. 1(12), 468 (1958)
T. Kinoshita: Phys.Rev.Lett. 2(11), 477 (1959)
T. Goldman, W.Wilson: Phys.Rev.D 14(9), 2428 (1976)
W. Marciano, A. Sirlin: Phys.Rev.Lett. 36(24), 1425 (1976)
M. Terent'ev: Yad. Fiz. 18(870) (1973)
V.Cirigliano, I.Rosell: Phys.Rev.Lett. 99(23), 231801 (2007)

$$R_{e/\mu}^{exp} = \frac{\Gamma(\pi^+\to e^+\nu(\gamma))}{\Gamma(\pi^+\to\mu^+\nu(\gamma))}$$

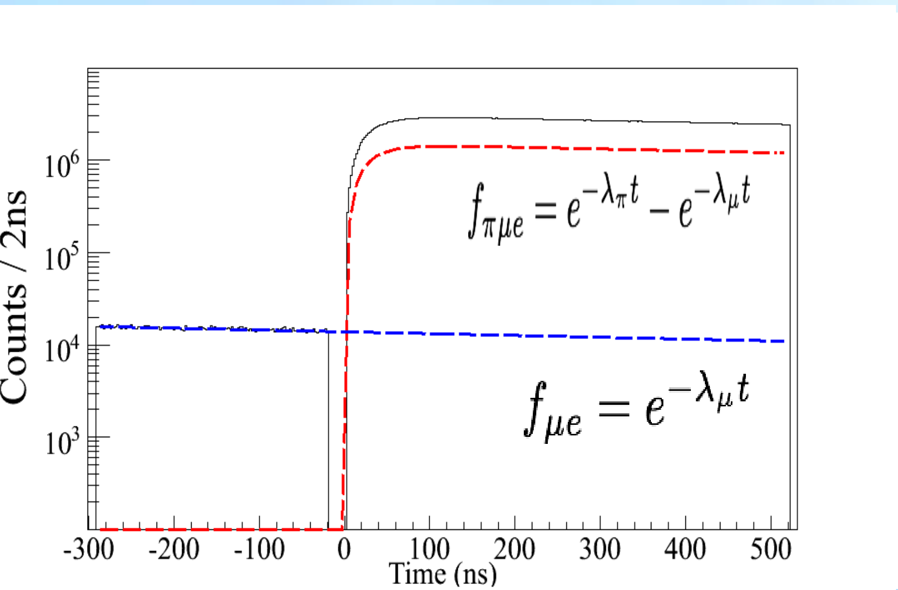
$$R_{e/\mu}^{Th}\ (10^{-4}) = 1.2352(2)$$

Analysis: π → eν decay

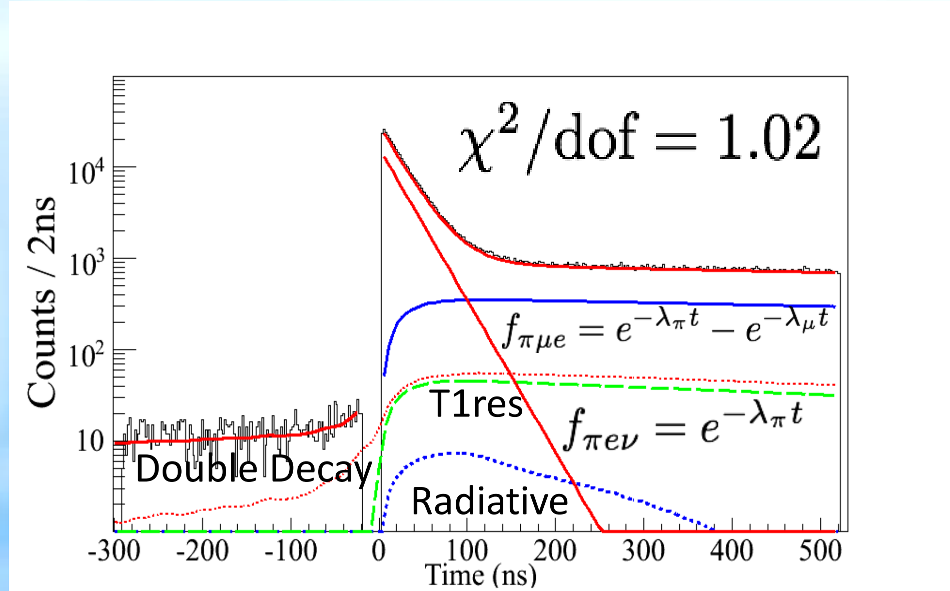
E<52MeV



E>52MeV



Low Energy time (ns)

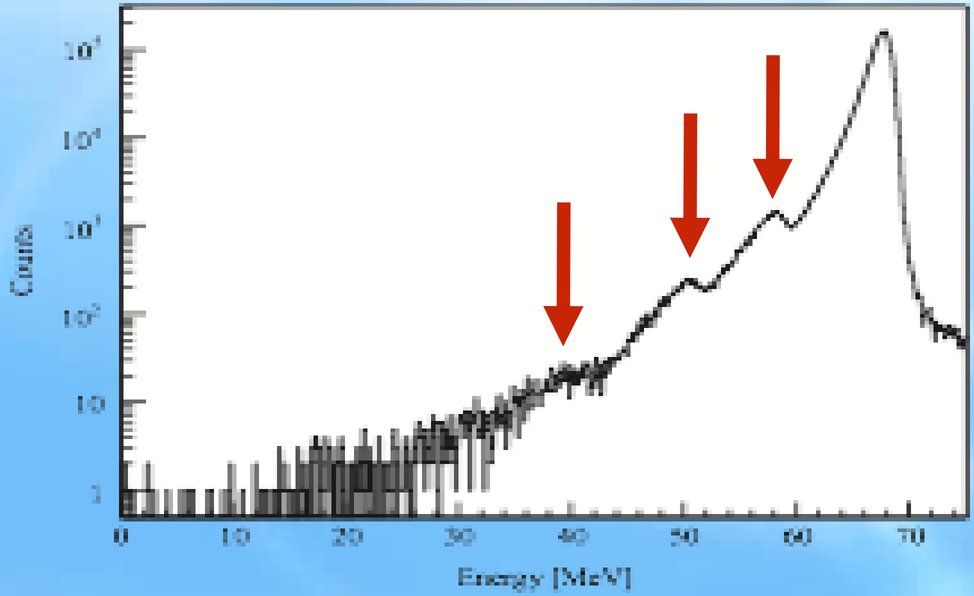


High Energy time (ns)

Simultaneous fit of both time spectra with all components

Low Energy Tail (LET)

- Largest correction
- From data: MC does not reproduce hadronic reactions (photonuclear with neutron escape)[1]
- Positron beam (0°)



Combine LET estimate from positron beam with estimate from suppressed spectrum

Estimated LET: (3.06 +/- 0.10) %

[1] A. Aguilar-Arevalo et al., Nucl. Instrum. Methods Phys. Res., Sect. A 621, 188 (2010).

Initial Result: π → eν decay

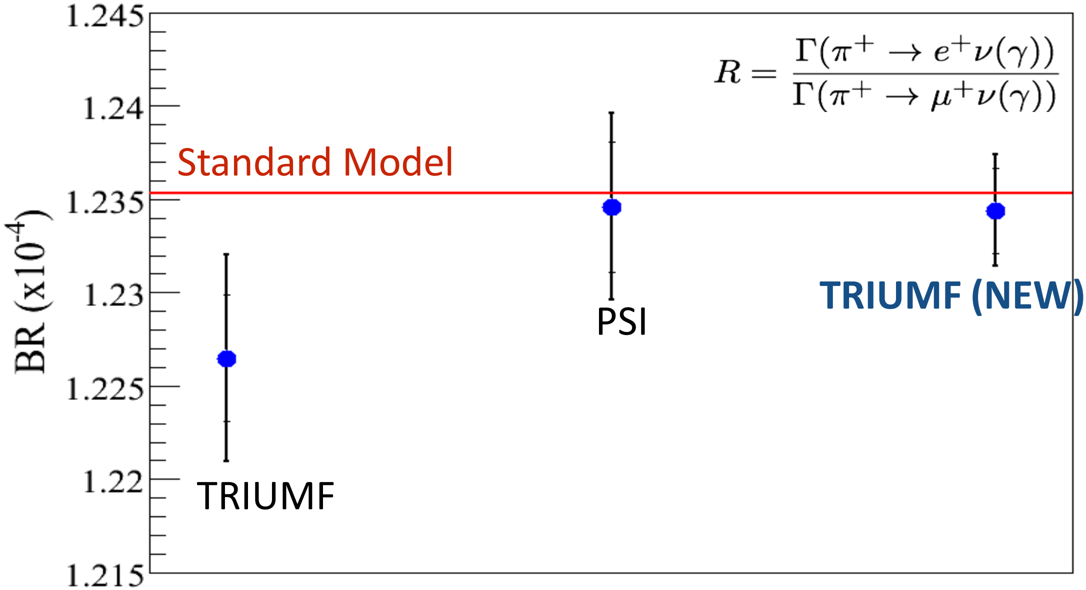
Based on one month

(~12% of data)

Result blinded until:

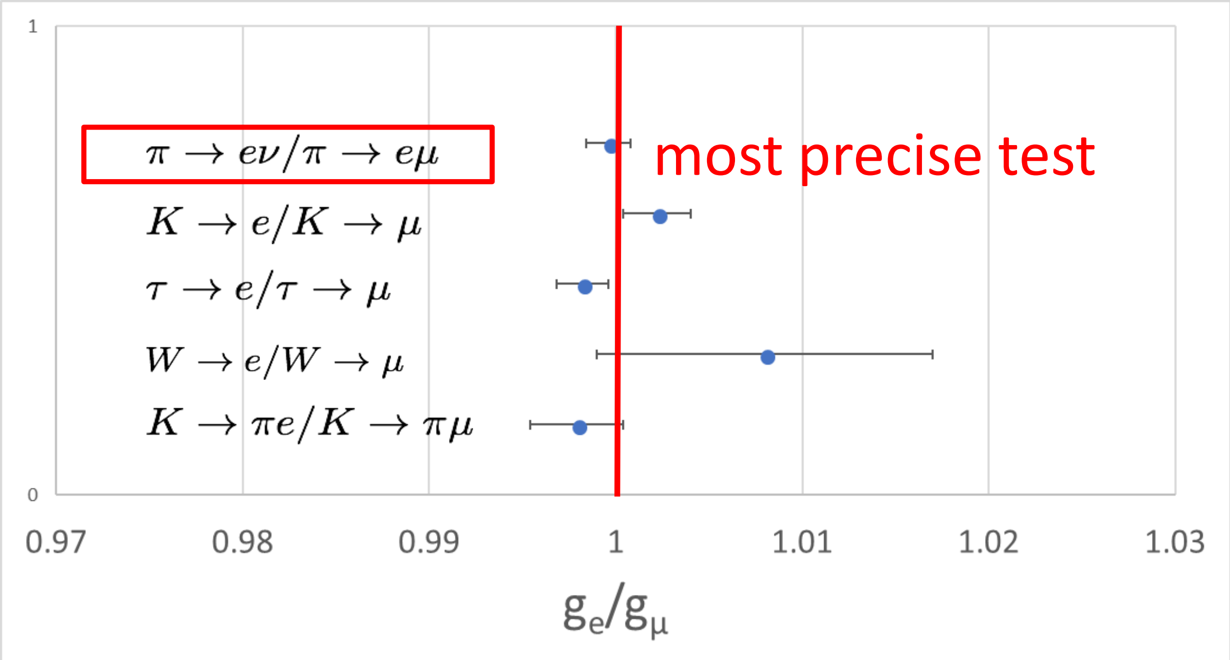
- all cuts finalized
- stability checks OK
- syst. uncertainties set

	Values	Uncertainties	
		Stat	Syst
$R^{raw}_{e/\mu}$ (10^{-4})	1.1972	0.0022	0.0005
π,μ lifetimes			0.0001
Other parameters			0.0003
Excluded components			0.0005
Corrections			
Acceptance	0.9991		0.0003
Low-energy tail	1.0316		0.0012
Other	1.0004		0.0008
$R^{exp}_{e/\mu}$ (10^{-4})	1.2344	0.0023	0.0019



Lepton Universality Summary

$$\frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} = \frac{g_e^2}{g_\mu^2} R^{th}_{e/\mu} \qquad \frac{g_e}{g_\mu} = 0.9996 \pm 0.0012$$



Complementary to tests with heavy quarks

The ensemble of B decay results appear to violate lepton universality [1]

[1] See recent summary in CERN Courier, **58**, 23 (2018)

In this conference: G. Onderwater, A. Datta, O. Witzel, …

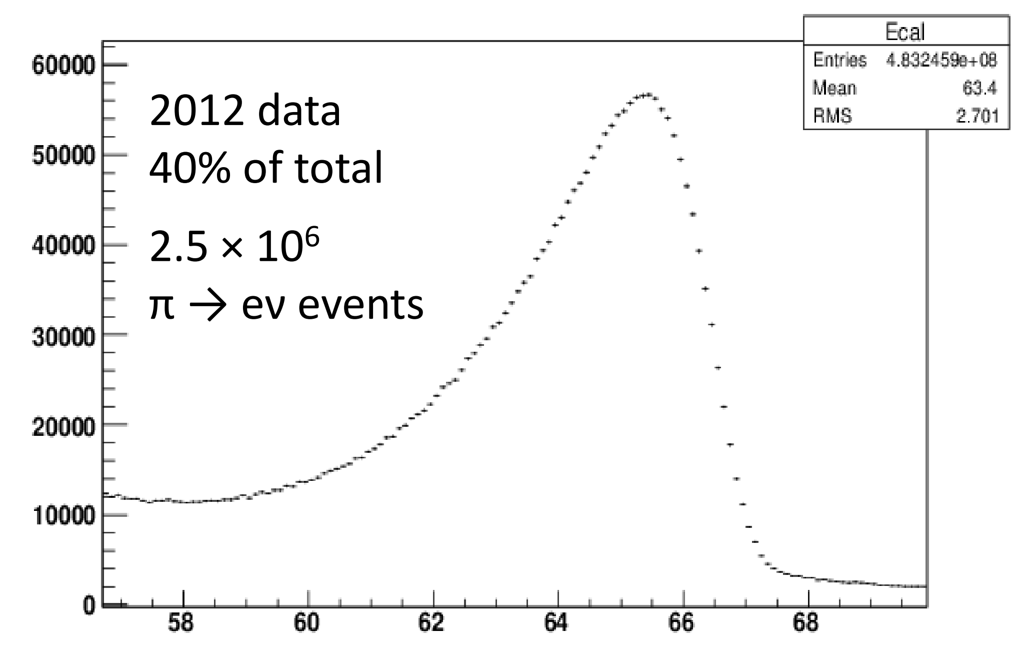
Status of full analysis for $R_{e/\mu}^{exp}$

All data have been processed
- ~8 times more data than for 2015 result
- 10^7 $\pi \rightarrow e\nu$ events

Value of branching ratio is blinded

Final review of cuts underway

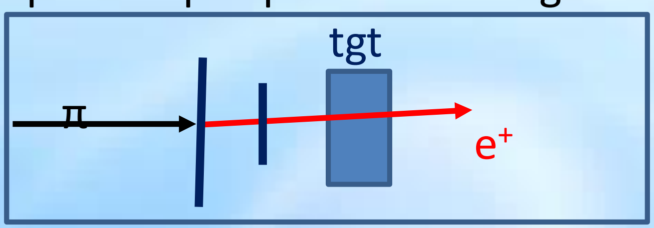
Statistical uncertainty
- <0.1% in $R_{e/\mu}^{exp}$ dependent on cut for solid angle acceptance



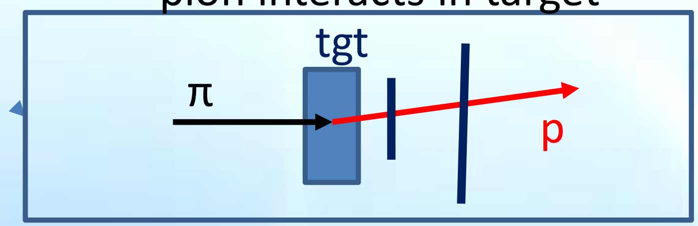
Status of full analysis for $R_{e/\mu}^{exp}$

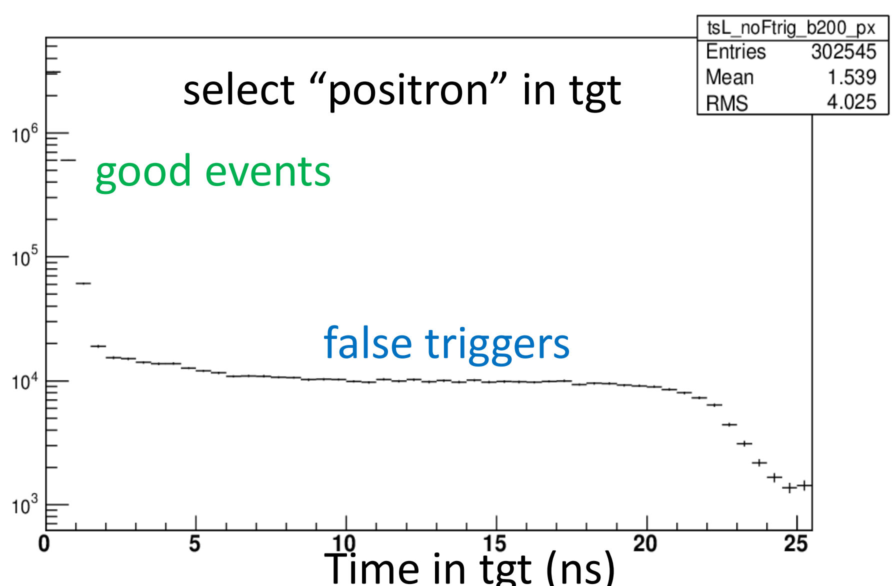
- Systematic uncertainties under evaluation
  - approx. equal to statistical uncertainty
  - two examples of improved study of backgrounds

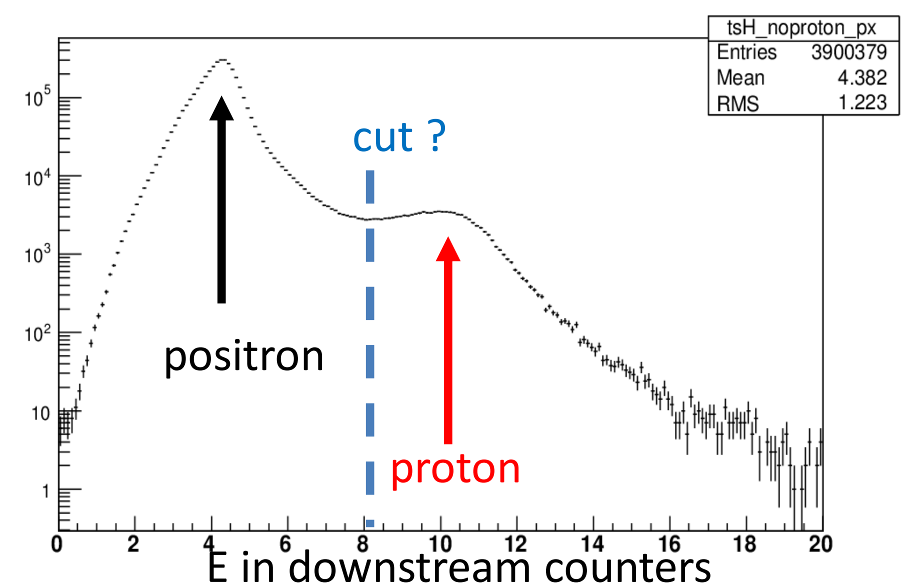
pion stops upstream of target



pion interacts in target







Thank You
on behalf of the
PiENu Collaboration

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Extra slides

Energy dependent acceptance

- Correction for heavy neutrino limits