Testing charged lepton flavor universality with pions

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Flavor in the News!

3 unconfirmed anomalies that involve Muons

Possible connection to Lepton Flavor Universality

- Proton radius puzzle (6 σ)→***May be Solved?***

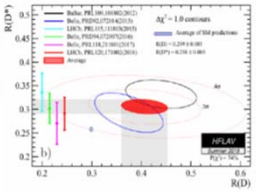
  μ-H atom result differs from e-H and e-scattering
- Muon g-2 (~3+ σ)

  Deviation from theory -- new physics?
- $B \to D^*\tau\,\nu / B \to D^*\mu\nu$, $B \to K^*\mu\,\mu$/ $B \to K^*ee$

  R($D^{(*)}$),R (K*): (3.8 σ, 2.6 σ*); O(10%) deviations from Universality?

  Quarks and leptons must both involved!

$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}l\bar{\nu}_l)} \text{ with } l = e, \mu$$



$$R(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$$

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} \Big/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\mu\mu))}{\mathcal{B}(B^+ \to K^+J/\psi(ee))}$$

$$R_K = 0.846\ ^{+0.060}_{-0.054}(\text{stat.})\ ^{+0.016}_{-0.014}(\text{syst.})$$

$\sim 2.5\,\sigma$ from SM.

LHCB 2019

τ / μ C.C. Universality Violation?

e / μ N.C. Universality Violation?

*Toledo at Moriond 2019

The Flavor Puzzle

Quarks

u	c	t
d	s	b

Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

- **Weak states mass states**
- **Quark, lepton flavors not conserved**

Unexplained observations (no theory of flavor):

Three ("identical") generations
Diverse mixing schemes – flavor changing interactions
Huge mass differences between and within the generations (mass hierarchy)
Universality of interactions
CP violation - where is the anti-matter in the universe?
Symmetry between lepton and quark sectors (GUT, scale?)

Leptons, Flavor Universality & Violation

Electron *Thompson, Townsand, Wilson 1896*

Muon *Nedermeyer, Anderson 1937*

Tau *Perl et al. 1974*

±40 yrs

Conserved Lepton Number ***Konopinski, Mahmoud*** *1953*

Separate lepton "numbers (flavors)" ***Pontecorvo*** *1959*

Lepton Flavor Universality ***Pontecorvo*** *1946*

Neutrino oscillations:

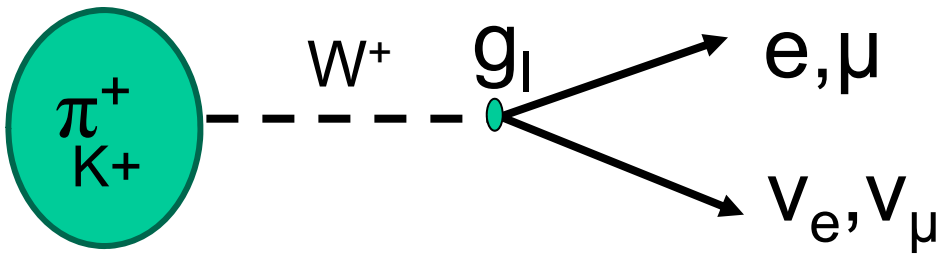
Pontecorvo *1957 → Davis, Kamioka, SNO, OPERA, MINOS… 1960-2001*

Lepton flavor is not conserved

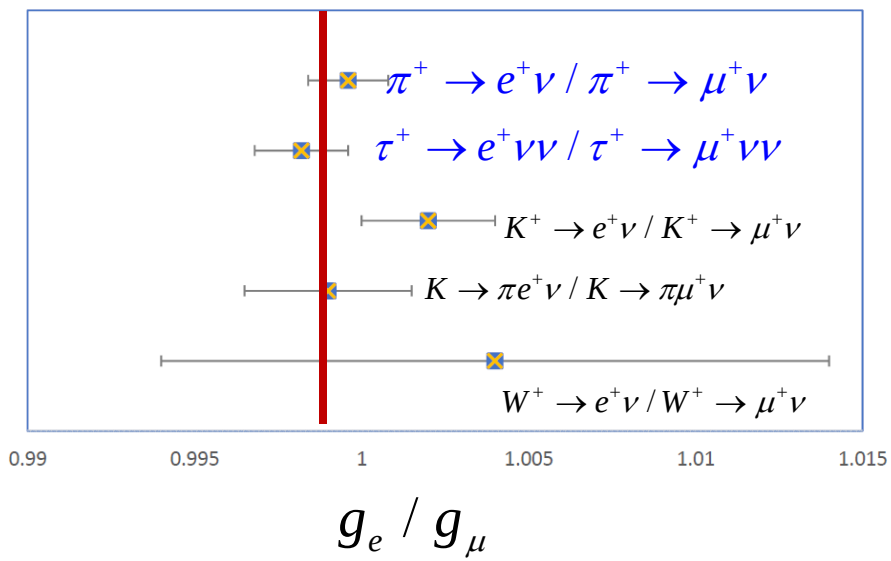
Neutrinos have (small) mass and mix

Charged Lepton Flavor Universality

Experiments compare expectations assuming $g_e = g_\mu = g_\tau$



Light meson/τau decay Precision: $O(10^{-3})$



But no real target for violation.

Other Universality Tests

<O(0.2%) effects

$\frac{\tau \to e\nu\nu}{\mu \to e\nu\nu}$ for τ-μ Universality and $\frac{\tau \to \mu\nu\nu}{\mu \to e\nu\nu}$ for τ-e Universality

$\frac{\tau \to \pi\nu}{\pi \to \mu\nu}$ for τ-μ Universality and $\frac{\tau \to \pi\nu}{\pi \to e\nu}$ for τ-e Universality

	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$
$\lvert g_\tau/g_\mu\rvert$	1.0011 (15)	0.9962 (27)	0.9858 (70)	1.034 (13)

	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to e}$
$\lvert g_\tau/g_e\rvert$	1.0030 (15)	1.031 (13)	1.0044 (60)

Pich 2013, DB 1992

How to interpret universality/non-universality observations?

Speculations :

- Sterile neutrinos
- New non-SM couplings?

  1000 TeV scale with couplings O(1)

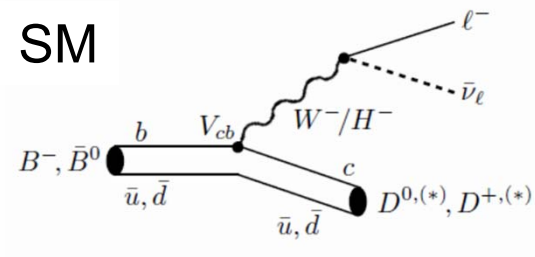
  Charged Higgs H^+

  Leptoquarks

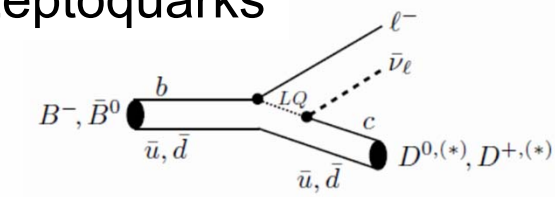
  New Z'

  Hidden sector ...

SM



Leptoquarks

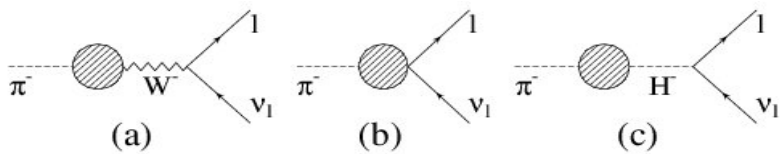


Could precise measurements of 1st, 2nd generation decays be used to distinguish between models explaining 3rd generation effects?

What are the connections with lepton flavor violation and lepton number violation?

$\pi^+ \to e^+\nu$ *LFU* Tests: Sensitivity to High Mass Scales

New Pseudoscalar interaction



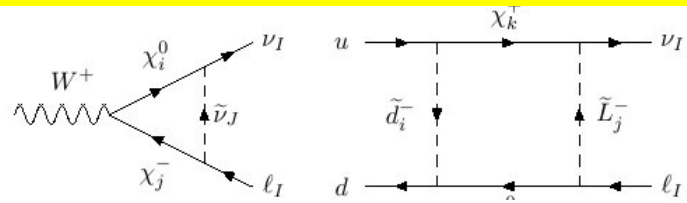
$$1 - \frac{R^{New}_{e/\mu}}{R^{SM}_{e/\mu}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda^2_{eP}} \frac{m_\pi^2}{m_e(m_d + m_u)}$$

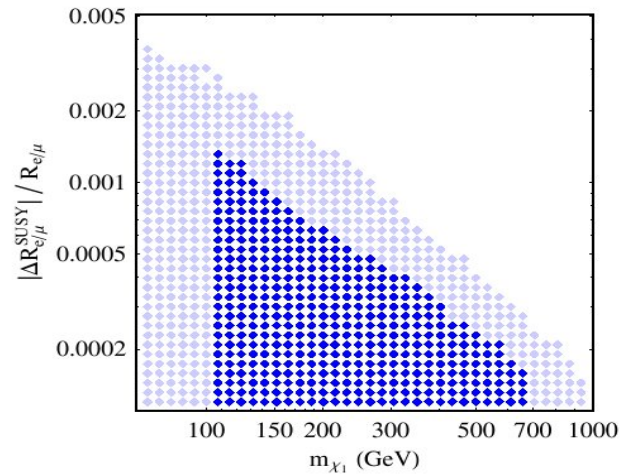
$$\sim \left(\frac{1TeV}{\Lambda_{eP}}\right)^2 \times 10^3$$

0.1 % measurement→Λ~1000 TeV

Assuming non-SM Higgs' couplings. Marciano…

R-parity violating SUSY





Lowest chargino mass

Ramsey-Musolf…

Others:

- **Leptoquarks**
- **Excited gauge bosons**
- **Compositeness**
- **SU(2)xSU(2)xSU(2)xU(1)**
- **Hidden sector ….**

$$\frac{\pi^+ \to e^+\nu(\gamma)}{\pi^+ \to \mu^+\nu(\gamma)}$$

W. Marciano → V. Cirigliano

$$R^{th}_{e/\mu} = (1.2353 \pm 0.0002)\, x10^{-4}$$

Possibly the most accurately calculated decay process involving hadrons. Structure-dependent radiation included (v. small).

PI E NU 2015

Current Result (PDG): $R^{\exp\pi}_{e/\mu} = 1.2327 \pm 0.0023 x10^{-4}$ (±0.19%)

Future: PIENU, PEN $\leq 0.1\%$

$$\frac{K^+ \to e^+\nu(\gamma)}{K^+ \to \mu^+\nu(\gamma)}$$

$$R^{th}_{K\to e/\mu} = (2.477 \pm 0.001)\, x10^{-5}$$

Finkemeier (1995)
Cirigliano, Rosell (2007)
Marciano et al. (2011) *

Structure-dependent radiation significant but not accounted for.

Current Result (PDG) NA62/KLOE: $R^{\exp K}_{e/\mu} = 2.488 \pm 0.009 x10^{-5}$ (±0.4%)

Future: NA62, TREK: 0.2%

PIENU Collaboration

A. Aguilar-Arevalo[1], M. Aoki[2], M. Blecher[3], D.I. Britton[4], D. vom Bruch[5,13], D.A. Bryman[5,6], S. Chen[7], J. Comfort[8], L. Doria[6,14], S. Cuen-Rochin[5,6], P. Gumplinger[6], A. Hussein[9,6], Y. Igarashi[10], S. Ito[2,11], S.H. Kettell[12], L. Kurchaninov[6], L. Littenberg[12], C. Malbrunot[5,15], R.E. Mischke[6], T. Numao[6], D. Protopopescu[4], A. Sher[6], T. Sullivan[5,16], D. Vavilov[6]

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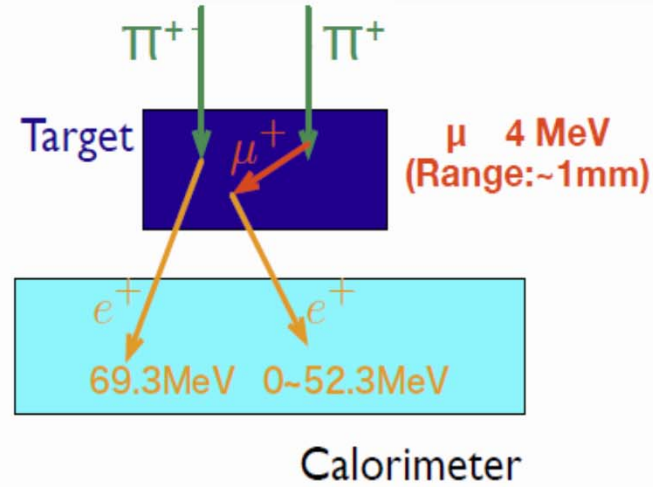
8. Arizona State University
9. University of Northern British Columbia
10. KEK
11. Okayama University
12. Brookhaven National Laboratory
13. LNHE, CNRS, Sorbonne and Paris Diderot Universities
14. Johannes Gutenberg University Mainz
15. CERN
16. Queen's University

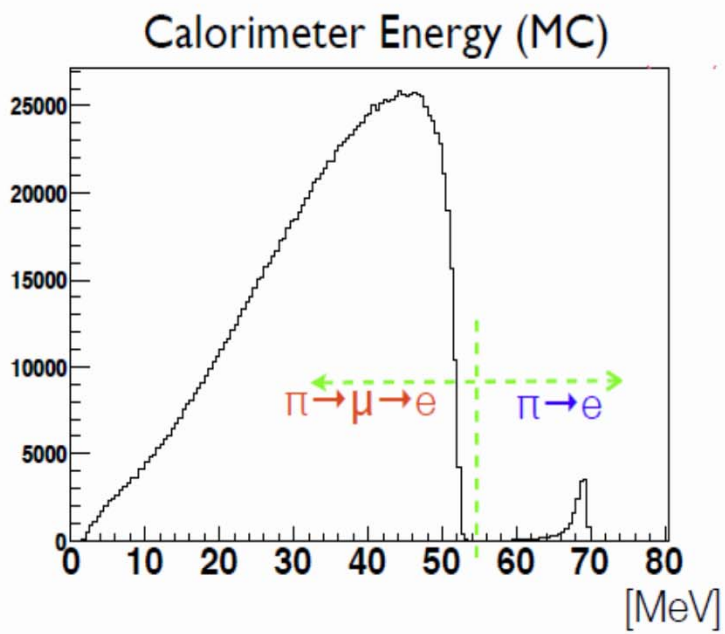
TRIUMF

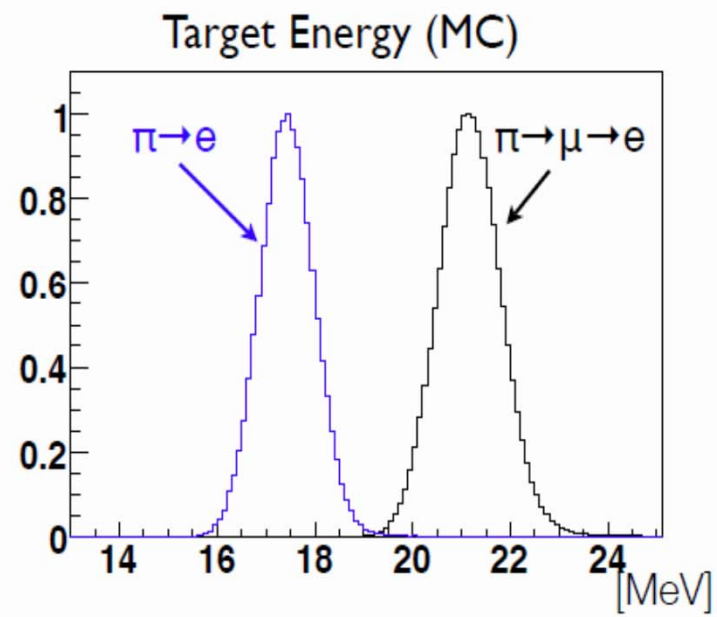
Canada, China, Japan, Mexico, UK, US

Exp. Method

- Pions stop in an active target.
- Out-going positrons are detected by a calorimeter.
- Tag decay modes by calorimeter energy.







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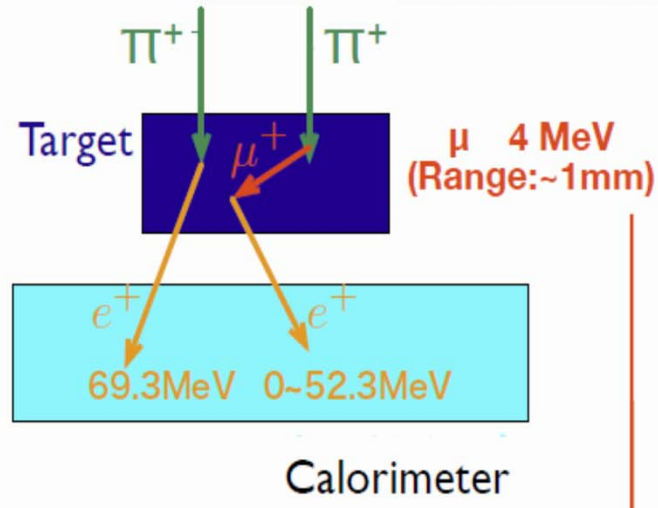
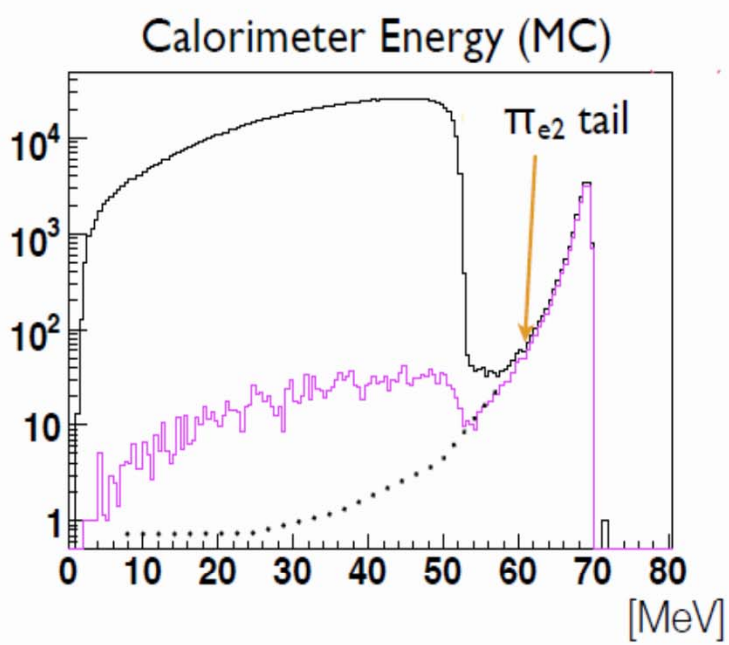
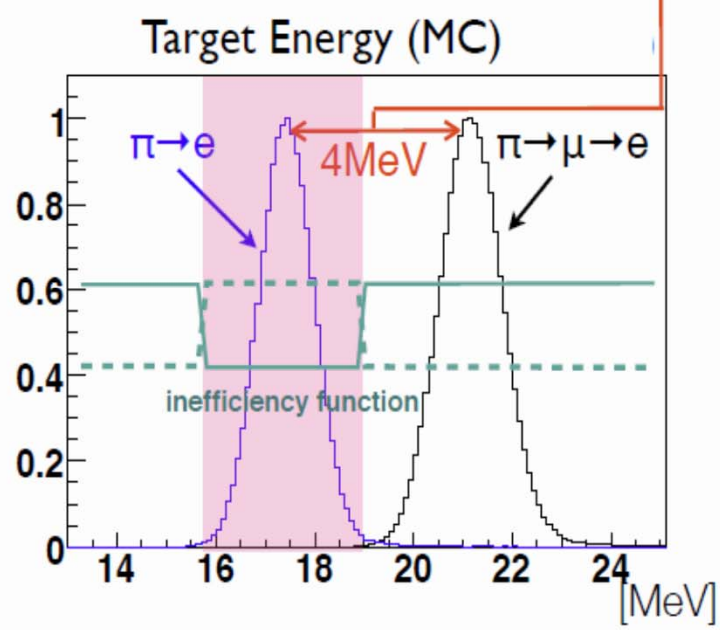




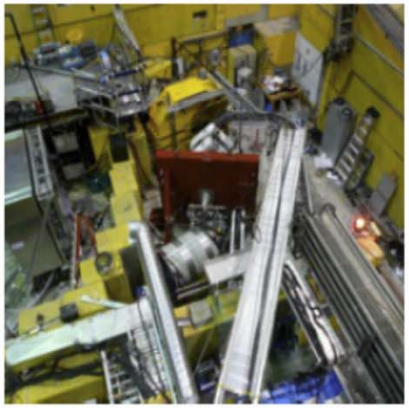


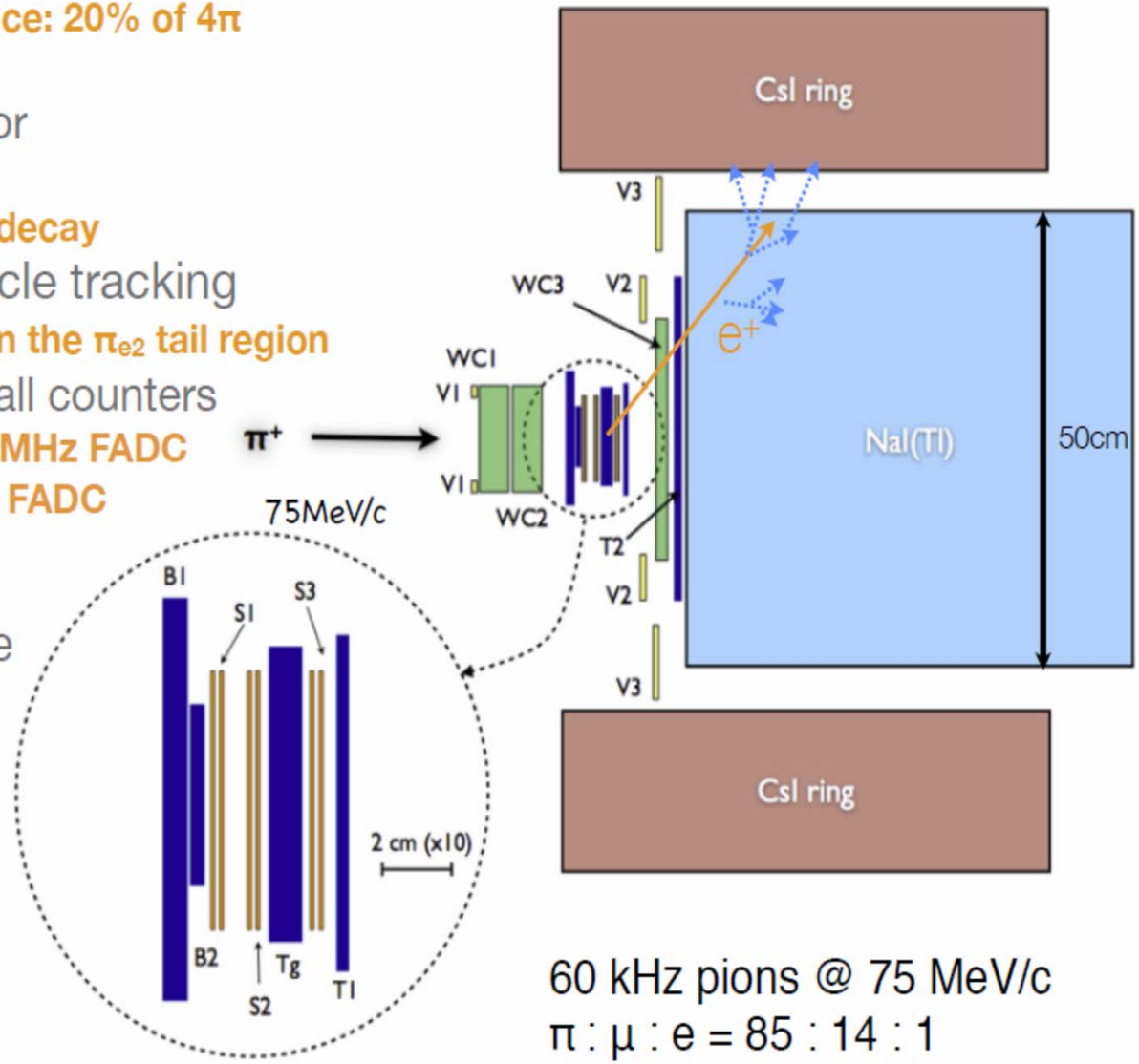
- Low-energy tail of π_{e2}: should be corrected.
- Use target energy to **"blind" the result:** hidden random target-energy-dependent inefficiency.

PIENU Detector

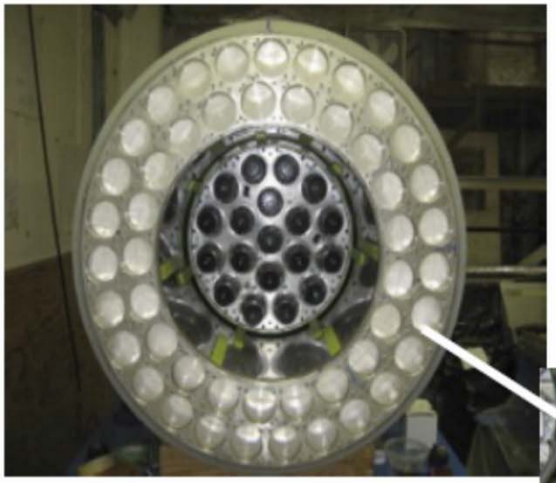
- Single crystal NaI(Tl) right behind the target
  - **Geometrical Acceptance: 20% of 4π**
  - **ΔE = 2.2%(FWHM)**
- CsI ring shower collector
  - **π_{e2} tail suppression**
  - **gamma from radiative decay**
- SSD and WC for particle tracking
  - **Identify π-DIF events in the π_{e2} tail region**
- Flash-ADC readout for all counters
  - **Plastic Scintillator: 500MHz FADC**
  - **NaI(Tl) and CsI: 60MHz FADC**
  - **Pile-up tagging**

- TRIUMF M13 beamline

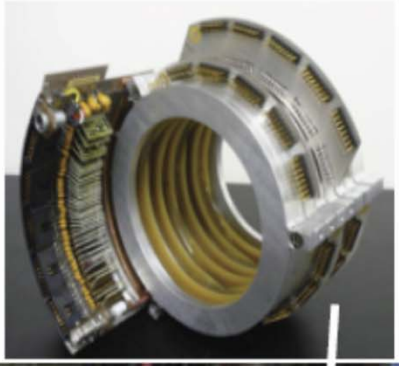




60 kHz pions @ 75 MeV/c
π : μ : e = 85 : 14 : 1

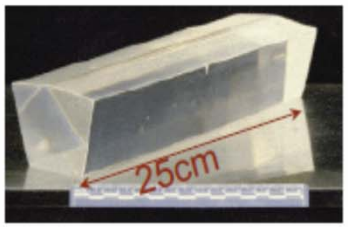


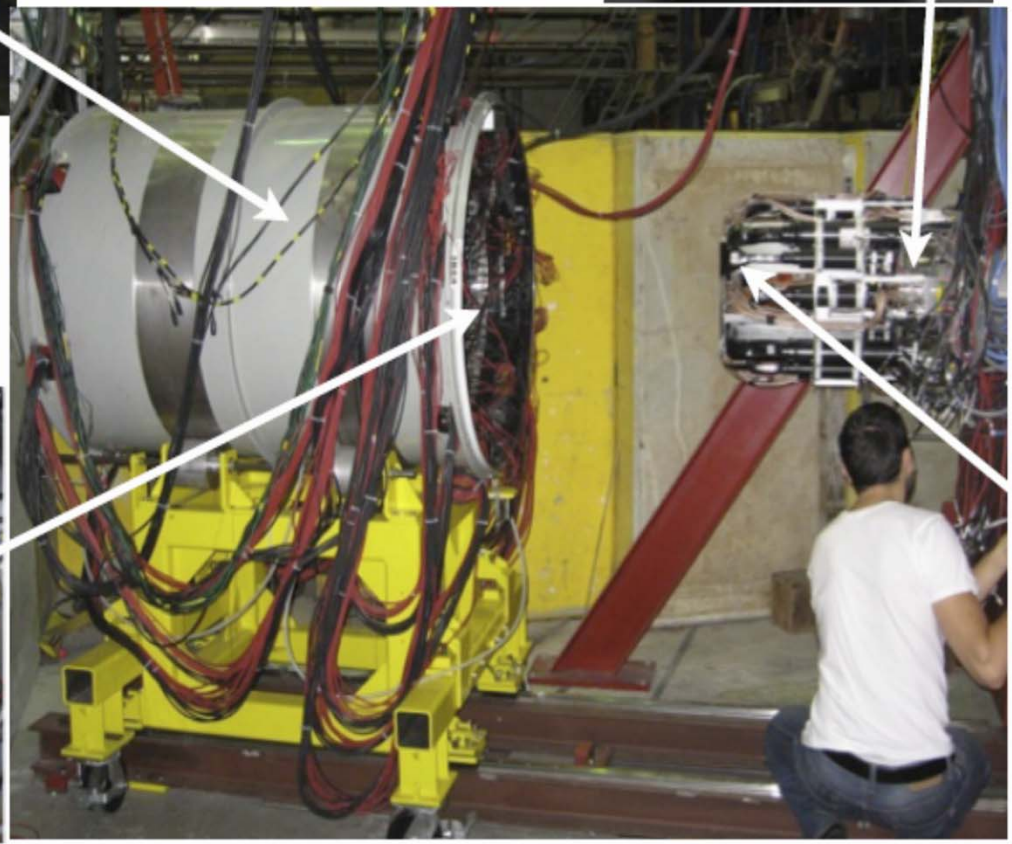
Monolithic NaI(Tl) crystal surrounded by 97 pure CsI crystals



Beam Wire Chamber

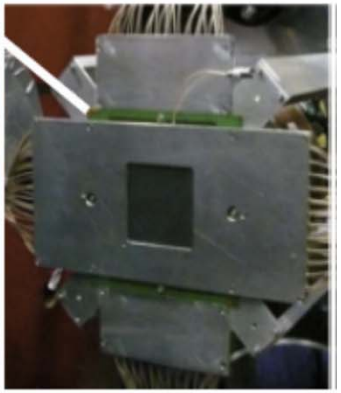
1 CsI crystal

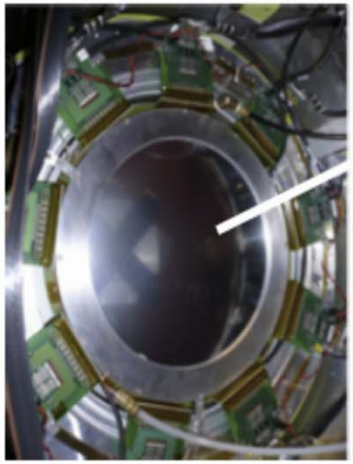




π^+

Silicon Trackers





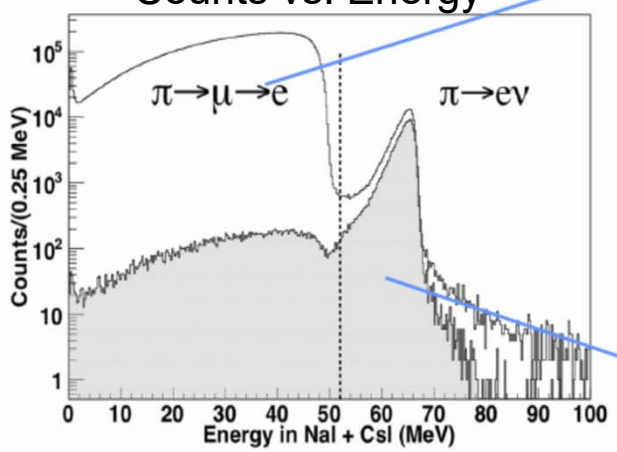
Acceptance Wire Chamber

PI E NU

2015 publication

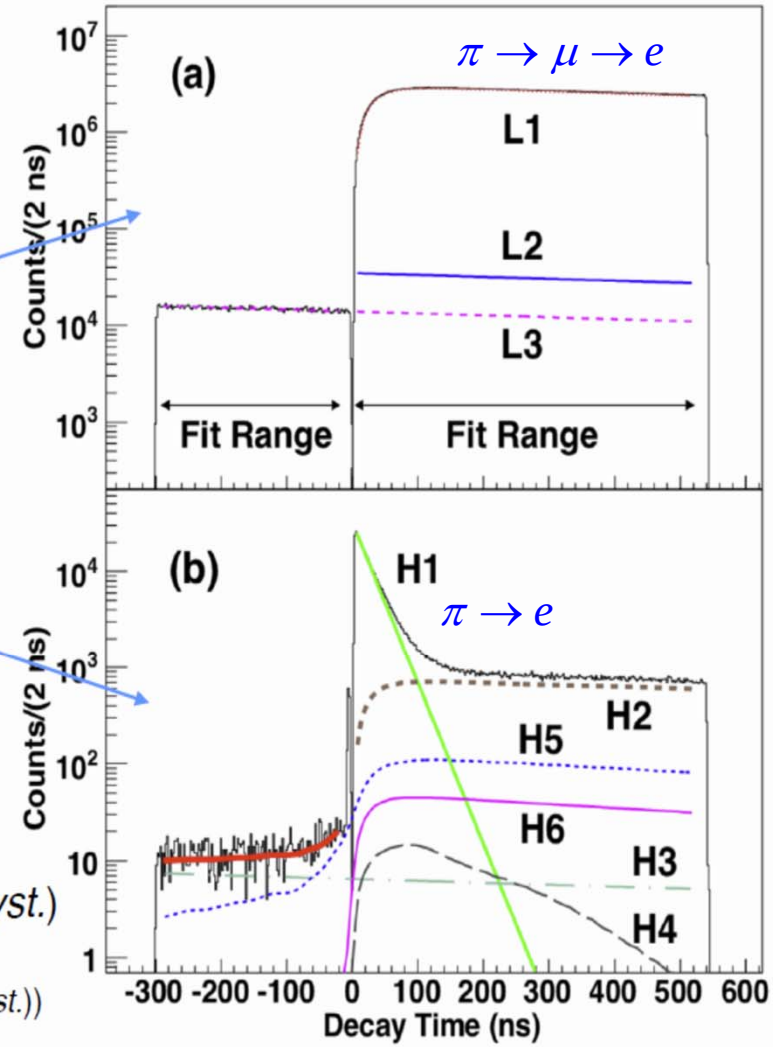
2010-data: 0.4 M $\pi^+ \rightarrow e^+ \nu$

Counts vs. Energy



Every spectra of positrons in the time region 5—35 ns.

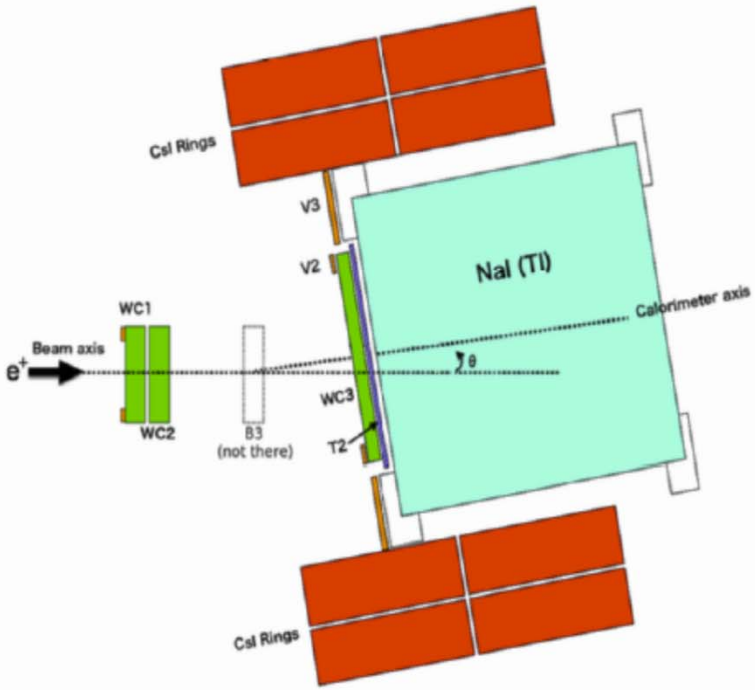
Counts vs. Time

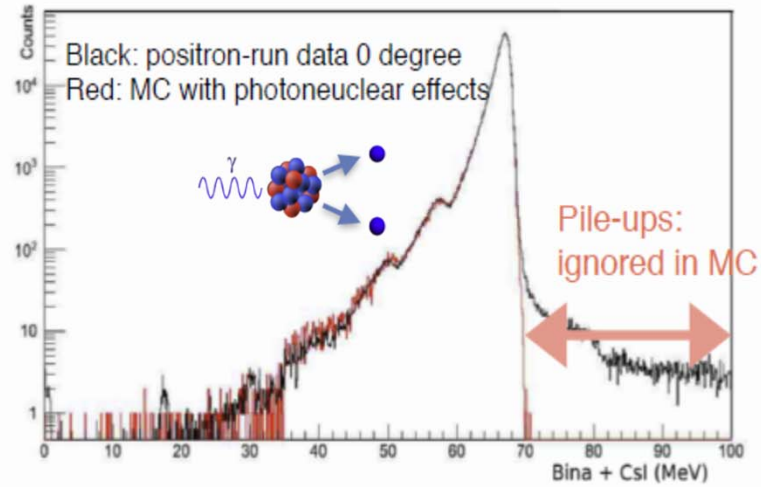


$R = 1.2344 \pm 0.0023(stat.) \pm 0.0019(syst.)$

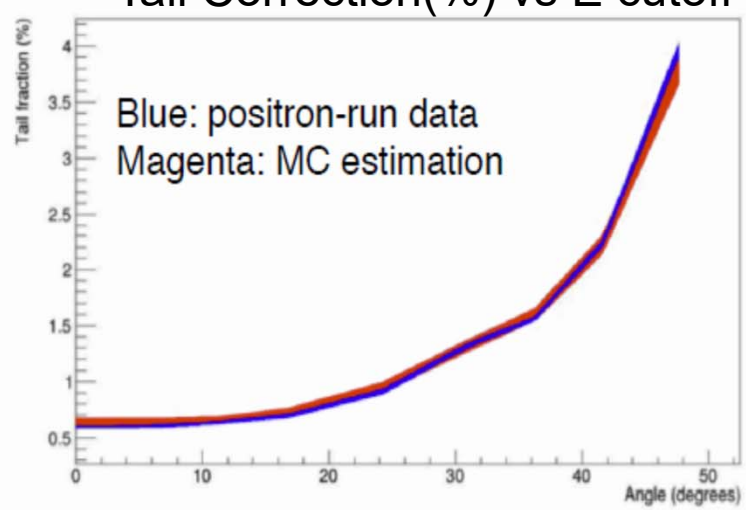
$(R_{@1992} = 1.2265 \pm 0.0034(stat.) \pm 0.0045(syst.))$

Tail Correction

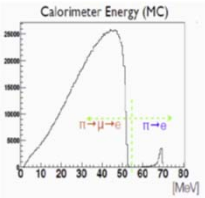




Tail Correction(%) vs E cutoff

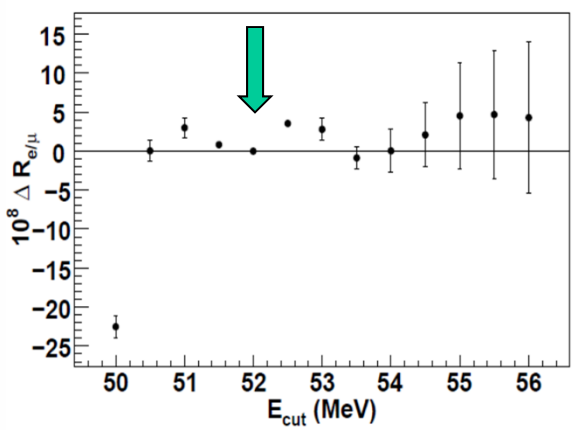


- Special positron runs to understand the behavior of low-energy tail.
- Perfect agreements between data and MC.
- Typical Tail-Correction factor is: $1.0261 \pm 0.0002(stat) \pm 0.0005(syst)$



PI E NU

$R_{e/\mu}^{\exp\pi}$ dependance on E_{cut}



PIENU Uncertainties

Error	PIENU 2010	PIENU goal
Statistical	0.19%	0.07%
Time Spectrum	0.04%	0.04%
Tail Correction	0.12%	0.06%
Others	0.07%	0.04%
Total	0.24%	< 0.1%

Current Result PIENU: $R_{e/\mu}^{\exp\pi} = 1.2344 \pm 0.0030 x 10^{-4}$: $\frac{g_e}{g_\mu} = 0.9996 \pm 0.0012$

Full Data Sample: 10^7 $\pi^+ \rightarrow e^+\nu$ Events

Precision Goal: $\pm 0.1\%$ (Coming Soon!)

"LFU Violation" Example: Massive Sterile Neutrinos e.g. $\pi^+ \to l^+ \nu_{e4}$

$$\nu_\ell = \sum_{i=1}^{3+n_s} U_{\ell i}\, \nu_i \ ,$$

- Extra peak in 2-body spectrum
- Effect on branching ratio

$R^{\pi}_{e/\mu} = \Gamma(\pi^+ \to e^+ \nu_e) / \Gamma(\pi^+ \to \mu^+ \nu_e)$

$$\bar{R}^{\pi}_{e/\mu} = \frac{R^{\pi\,\mathrm{exp}}_{e/\mu}}{R^{SM}_{e/\mu}} = \frac{(1-|U_{e4}|^2)+|U_{e4}|^2\ \bar{\rho}(m_e, m_{\nu 4})}{(1-|U_{\mu 4}|^2)+|U_{\mu 4}|^2\ \bar{\rho}(m_\mu, m_{\nu 4})} \sim (1-|U_{e4}|^2)+|U_{e4}|^2\ \bar{\rho}(m_e, m_{\nu 4})$$

$$|U_{\ell 4}|^2 < \frac{\bar{R}^{(M)}_{\ell/\ell'} - 1}{\bar{\rho}(\delta^{(M)}_\ell, \delta^{(M)}_{\nu_4}) - 1}$$

- Ratio of kinematic factors

$$\bar{\rho}(x,y) = \frac{\rho(x,y)}{\rho(x,0)} = \frac{\rho(x,y)}{x(1-x)^2}$$

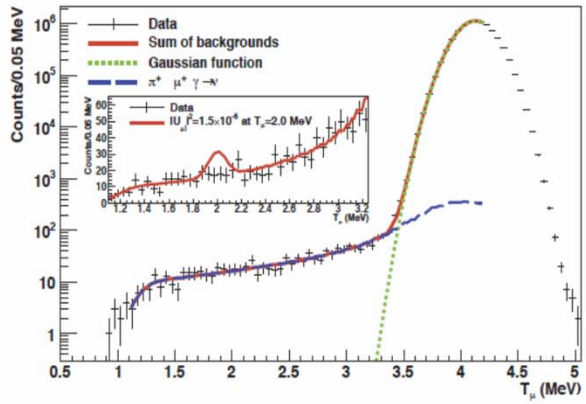
Decay	$(m_{\nu_4})_{\bar{\rho}_{max}}$	$\bar{\rho}_{max}$
$\pi^+ \to e^+\nu_4$	80.6	1.105×10^4
$K^+ \to e^+\nu_4$	285	1.38×10^5
$D^+ \to e^+\nu_4$	1.08×10^3	1.98×10^6
$D_s^+ \to e^+\nu_4$	1.14×10^3	2.20×10^6
$B^+ \to e^+\nu_4$	3.05×10^3	1.58×10^7
$\pi^+ \to \mu^+\nu_4$	3.46	1.00
$K^+ \to \mu^+\nu_4$	263	4.13
$D^+ \to \mu^+\nu_4$	1.07×10^3	47.3
$D_s^+ \to \mu^+\nu_4$	1.13×10^3	52.4
$B^+ \to \mu^+\nu_4$	3.05×10^3	371

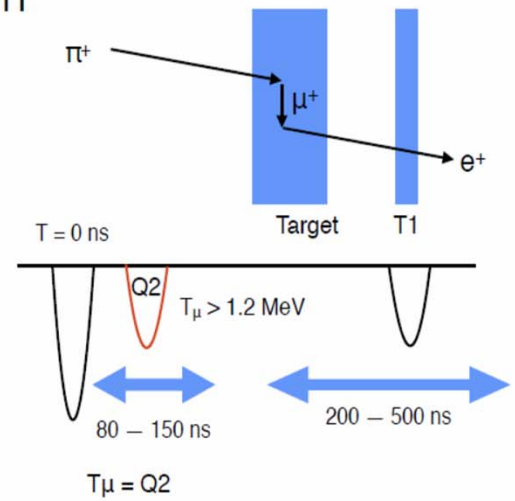
Large kinematic enhancements possible at larger mass due to absence of helicity suppression

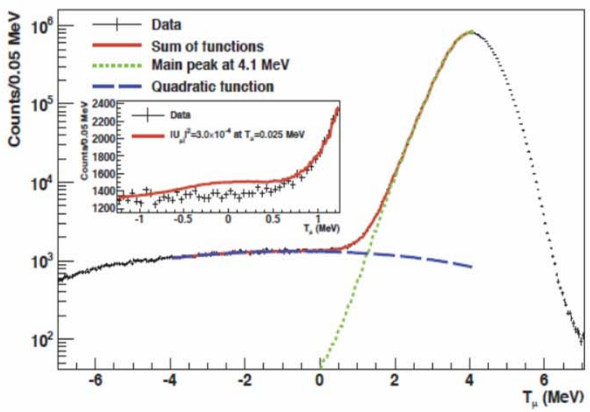
R. Shrock and D.B. 2019

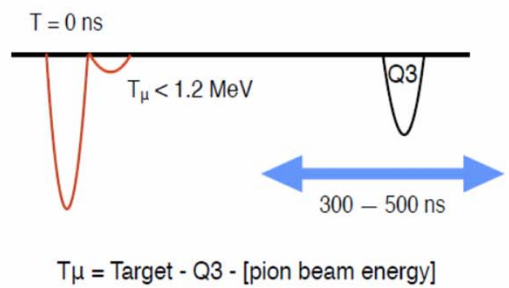
"LFU Violation" Example: Massive Sterile Neutrinos e.g. $\pi^+ \rightarrow \mu^+ \nu_{e4}$

$\pi^+ \rightarrow \mu^+ \nu_H$



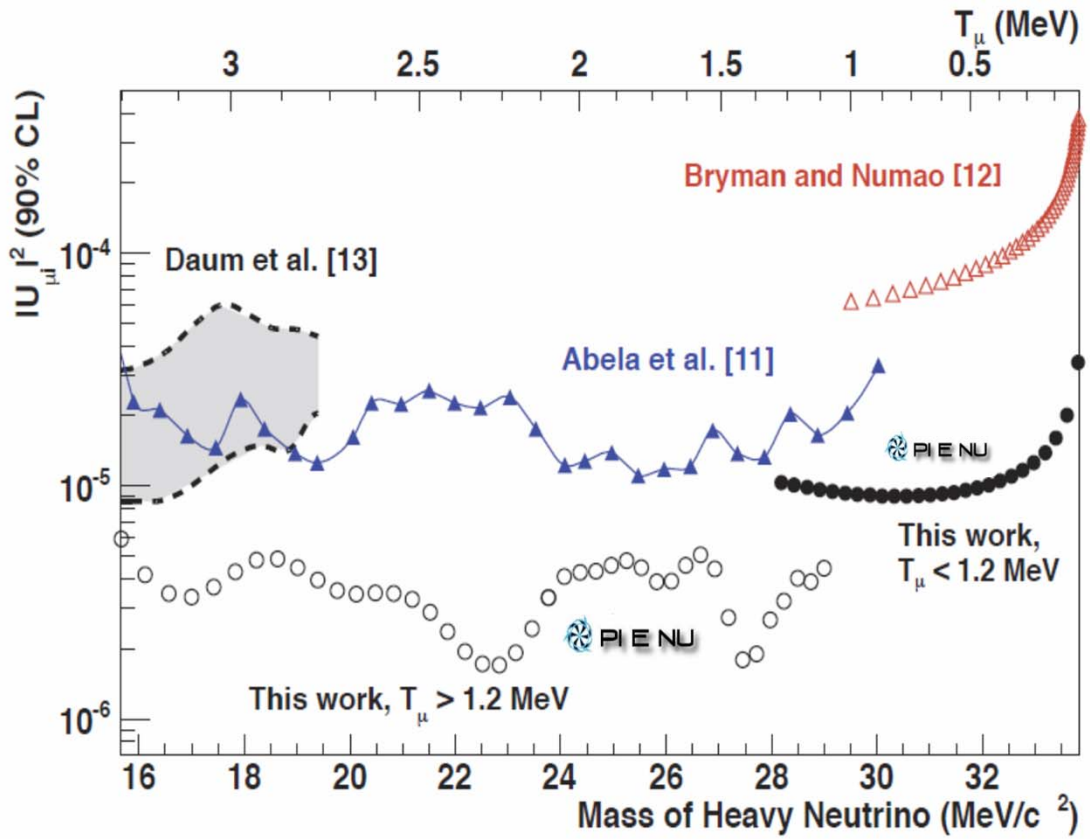






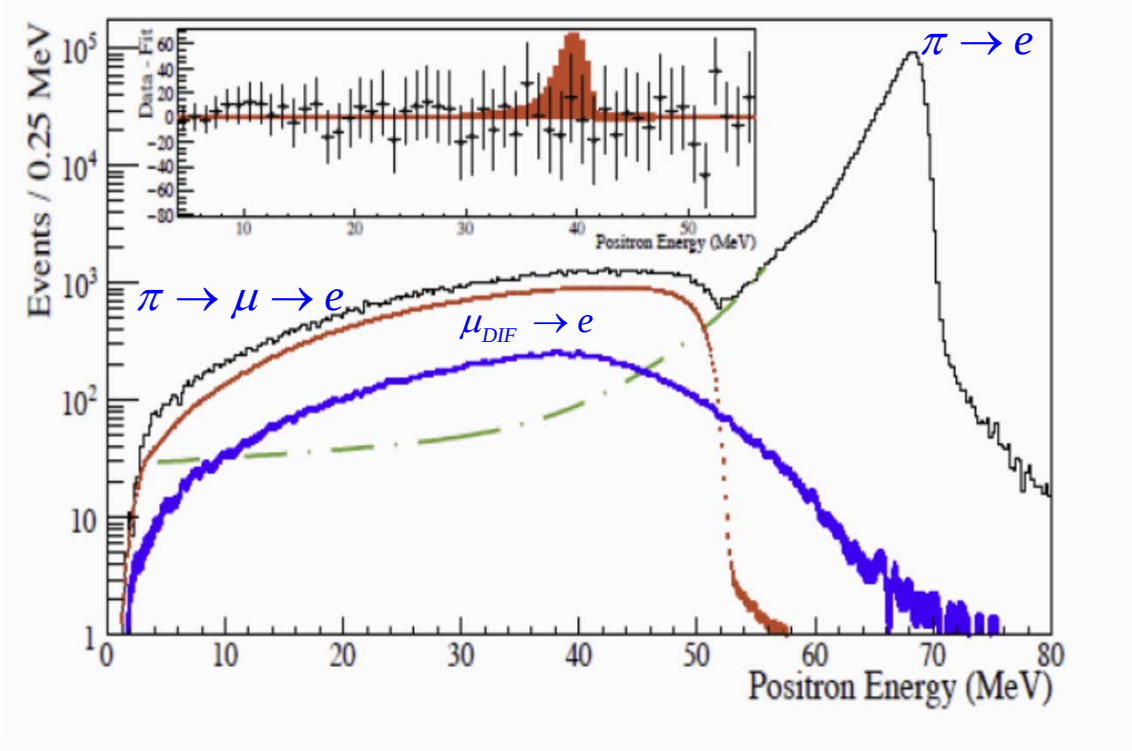
PI E NU 2019

$\left|U_{\mu 4}\right|^2$ vs $m_{\nu 4}$



arXiv:1904.03269, PLB submitted

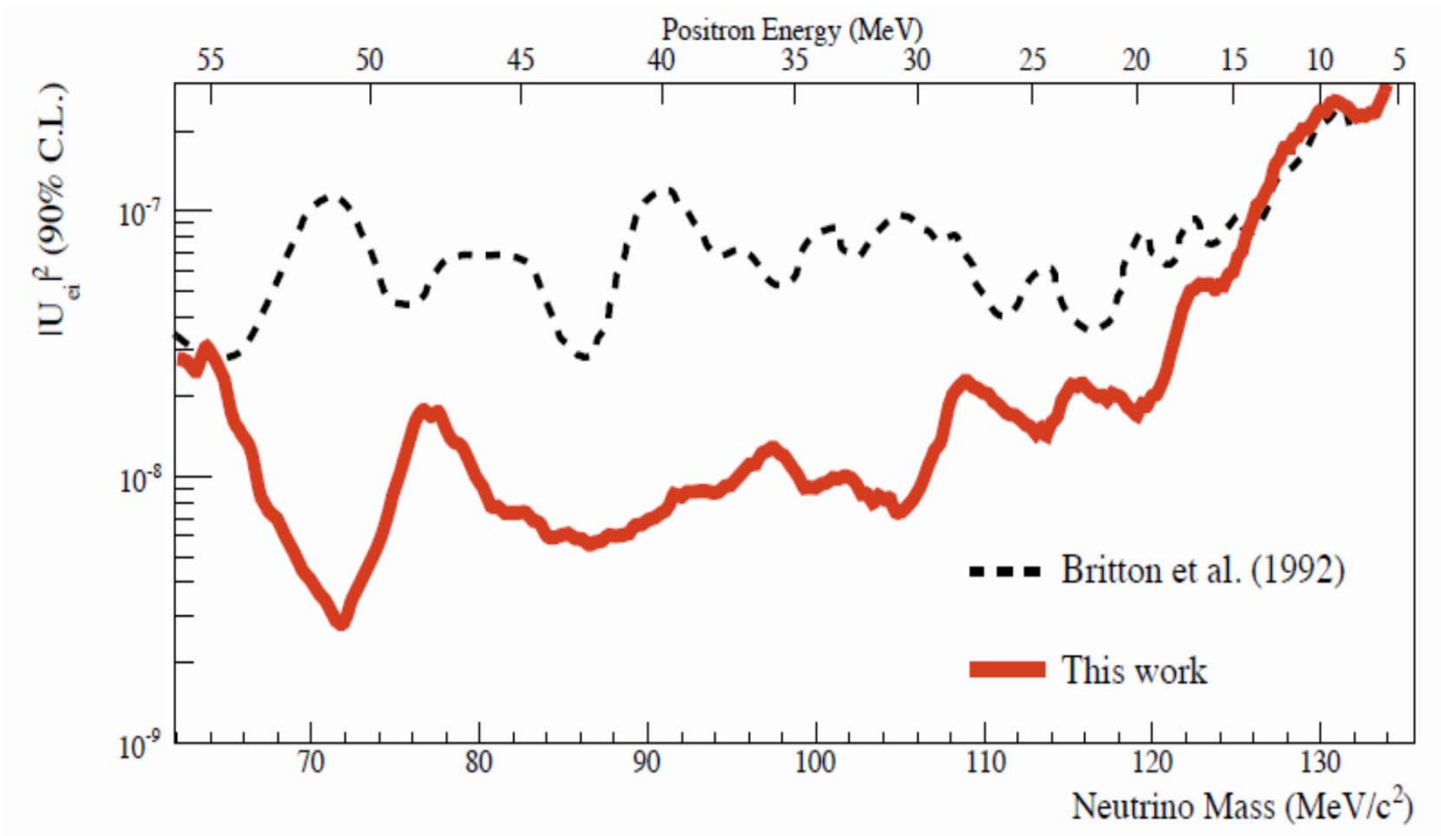
$\pi^+ \rightarrow e^+ \nu_{e4}$



A. Aguilar-Arevalo *et al.*
Phys. Rev. D **97**, 072012 (2018)

$|U_{e4}|^2$ vs $m_{\nu 4}$

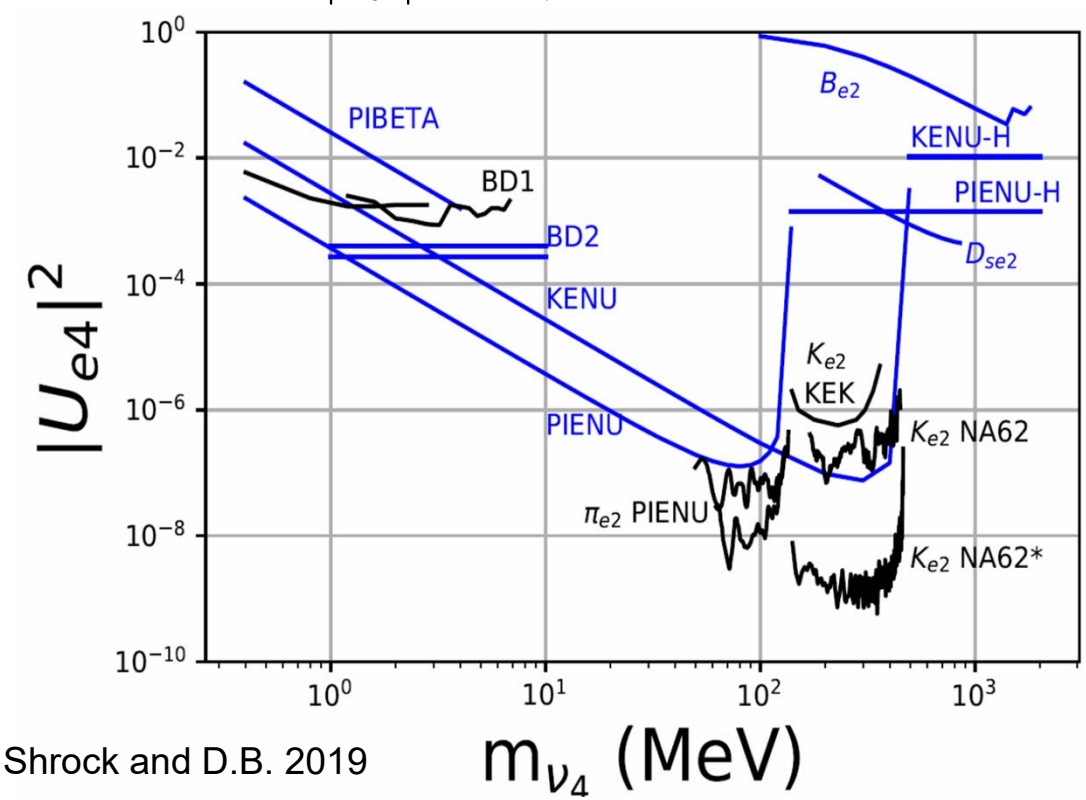
$\pi^+ \rightarrow e^+ \nu_{e4}$



"LFU Violation" due to Massive Sterile Neutrinos e.g. $\pi^+ \rightarrow e^+ \nu_{e4}$

$$\frac{R_{e/\mu}^{\exp \pi}}{R_{e/\mu}^{SM}} = \frac{(1-|U_{e4}|^2)+|U_{e4}|^2\ \bar{\rho}(m_e, m_{\nu 4})}{(1-|U_{\mu 4}|^2)+|U_{\mu 4}|^2\ \bar{\rho}(m_\mu, m_{\nu 4})} \sim (1-|U_{e4}|^2)+|U_{e4}|^2\ \bar{\rho}(m_e, m_{\nu 4})$$

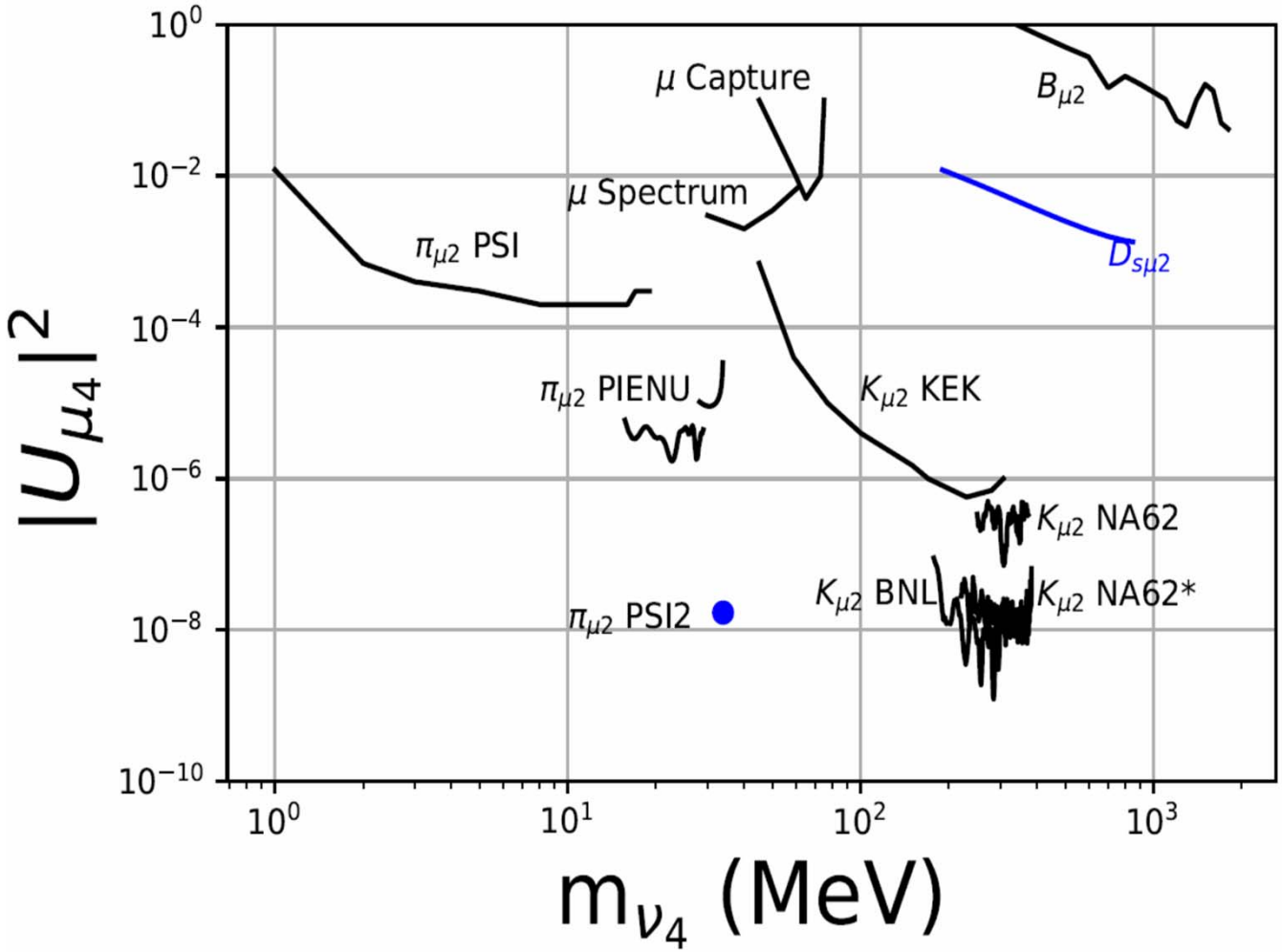
$|U_{e4}|^2$ vs $m_{\nu 4}$ (MeV - GeV)



R. Shrock and D.B. 2019

Sterile neutrinos could range in mass from eV to GUT scale; constraints from oscillations, cosmology, HEP…. Possible correlation with LFV, LNV….

$\left|U_{\mu 4}\right|^2$ vs $m_{\nu 4}$ (MeV - GeV)



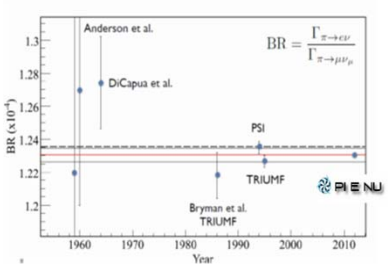
R. Shrock and D.B. 2019

How to improve experimental precision by another order of magnitude to match theory?

$$R^{th}_{e/\mu} = (1.2353 \pm 0.0002)\, x10^{-4}$$ *±0.016%*

10 x more precise than experiments!

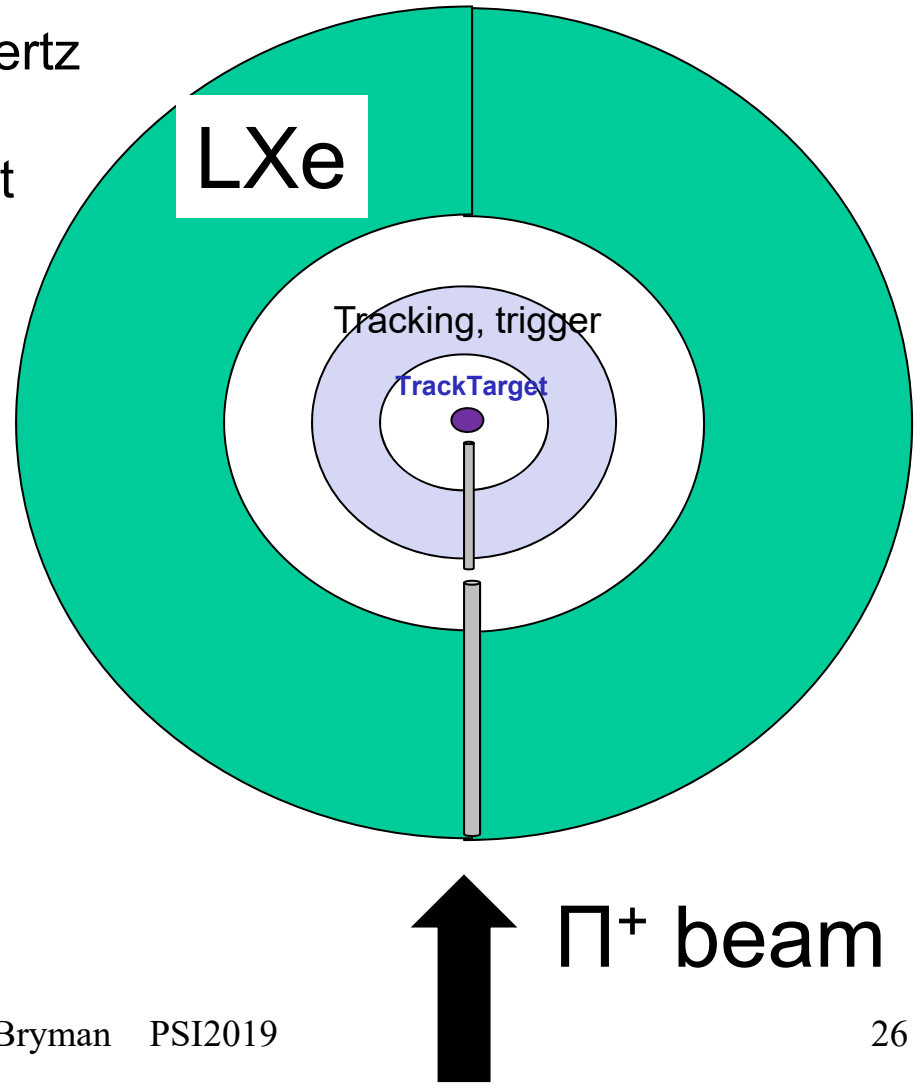
$\pi^+ \rightarrow e^+\nu$ Experiments -- stopped pions



- CERN (1958) 6 events
- Chicago (1960) – *magnetic spectrometer*
  - 1st precise measurement ±6%
- Columbia (1964) *NaI(Tl) crystal*; ± 2%
- TRIUMF (1986, 1992, 2015 → **PIENU**) → *NaI(Tl)/CsI crystals*
  - ± 0.24% →0.1%? 10^7 events
- PSI (1994, → **PEN**) BGO → CsI crystals >10^7 events
  - ± 0.4% → <0.1%?
- ***Future Experiment: LXe Calorimeter?***
  - ± 0.1% → <0.01%?

New $\pi^+ \rightarrow e^+\nu$ Experiment with LXe?

- Π^+ Beam: 75±0.3 MeV/c 10^5 Hertz
- Tracking target – SciFi, SiPMs
- LXe calorimeter – SiPM readout
  - 40 X_0
  - Δt~50 ps, ΔE~1%
- Sensitivity, Precision:
  - 10^8 events
  - ±0.015% in 1 Yr.



Conclusions: Tests of Lepton Flavor Universality with Pions (and other particles)

- **Rare μ, π and K decays have unique and important roles to play in the search for new physics involving exotic effects like *Flavor Universality and Lepton Flavor Violation* --- especially sensitivity to very high mass scales.**

- **New π/K/B results expected soon from PIENU, PEN, NA62, and LHCb BESSIII, BELLE-II**

- **Important connections with searches for sterile neutrinos, high mass scale physics and L(F/N)V tests (0νββ, $K \rightarrow \pi\, \mu^+\mu^+$, $K \rightarrow \pi\, e^+ e^+$, $\mu \rightarrow e\gamma$, $\mu^- Z \rightarrow e^- Z$, $\mu^- Z \rightarrow e^+ (Z-2)$, $\mu \rightarrow 3e$, muonium-antimuonium…)**