TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

The TRIUMF Particle Physics Local Program

A Selection: from TWIST & PIENU to UCN

Luca Doria
TRIUMF & JGU-Mainz
(luca@triumf.ca / doria@uni-mainz.de)

July 2018

Outline

- Muons & Pions
- Muon to Electron Conversion $\mu \to e\gamma$ $\mu \to eee$ $\mu N \to eN$
- The Muon Decay $\mu \to e\nu\bar{\nu}$
- The Pion Decay $\pi \to e\nu$ $\pi \to \mu\nu$
- The Future with Neutrons $n \to pe\nu$

Muons and Pions

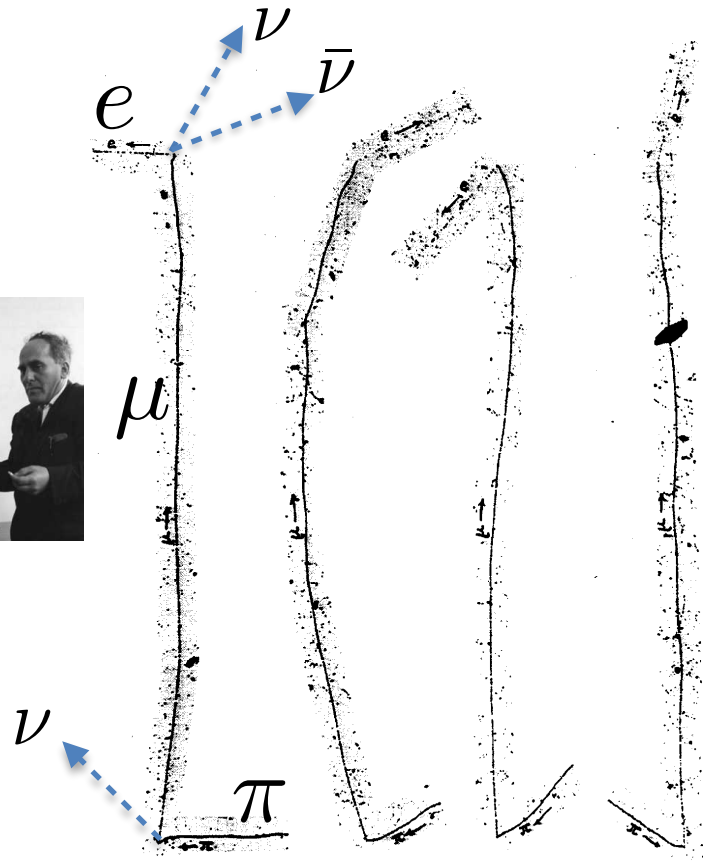
1935: H. Yukawa predicts a new particle

1936: Discovery of the Muon

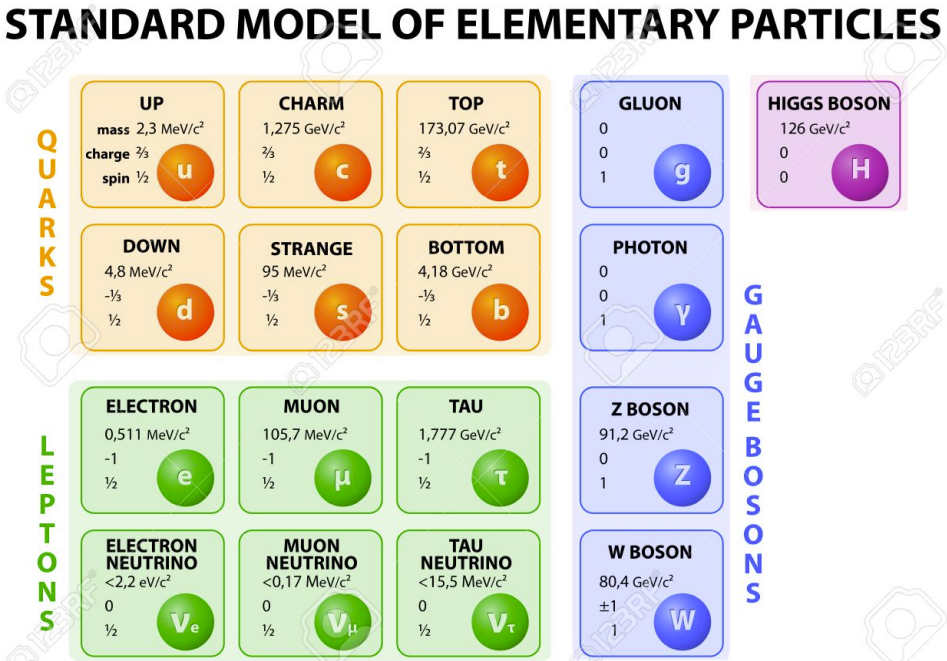
1947: C. Powell and collaborators discover the Pion
M.Lattes, H.Muirhead, G.Occhialini, C.Powell:
Nature, 159:694-697 (1947)

1949: H.Yukawa awarded the Nobel Prize.

1950: C. Powell awarded the Nobel Prize



Original tracks in Powell's Experiment


STANDARD MODEL OF ELEMENTARY PARTICLES
QUARKS
UP
mass 2,3 MeV/c²
charge ⅔
spin ½
u
CHARM
1,275 GeV/c²
⅔
½
c
TOP
173,07 GeV/c²
⅔
½
t
DOWN
4,8 MeV/c²
-⅓
½
d
STRANGE
95 MeV/c²
-⅓
½
s
BOTTOM
4,18 GeV/c²
-⅓
½
b
LEPTONS
ELECTRON
0,511 MeV/c²
-1
½
e
MUON
105,7 MeV/c²
-1
½
μ
TAU
1,777 GeV/c²
-1
½
τ
ELECTRON NEUTRINO
<2,2 eV/c²
0
½
νe
MUON NEUTRINO
<0,17 MeV/c²
0
½
νμ
TAU NEUTRINO
<15,5 MeV/c²
0
½
ντ
GAUGE BOSONS
GLUON
0
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1
g
PHOTON
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1
γ
Z BOSON
91,2 GeV/c²
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HIGGS BOSON
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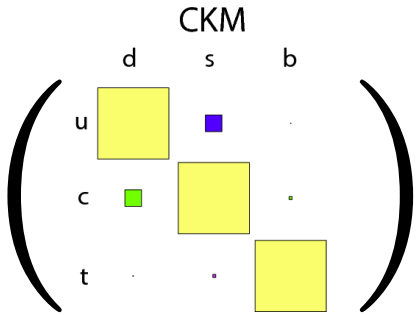
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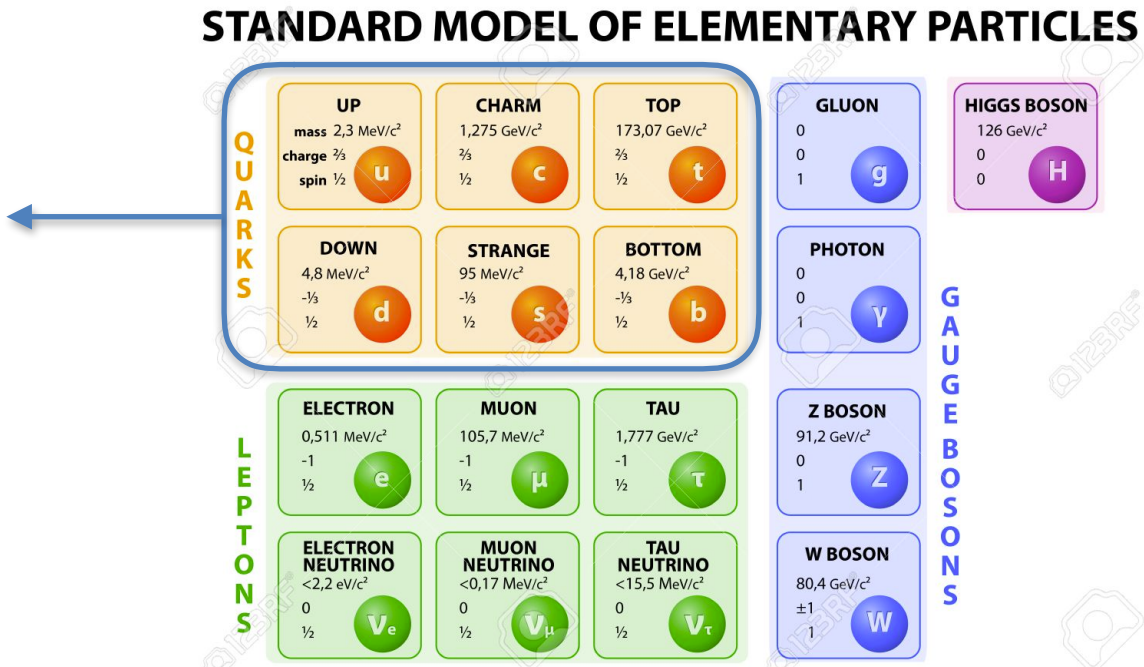
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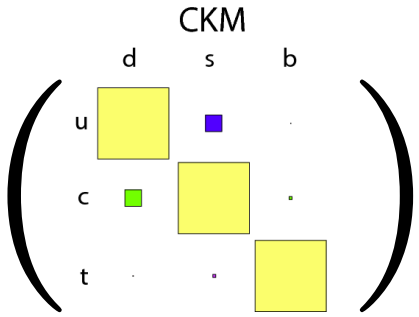
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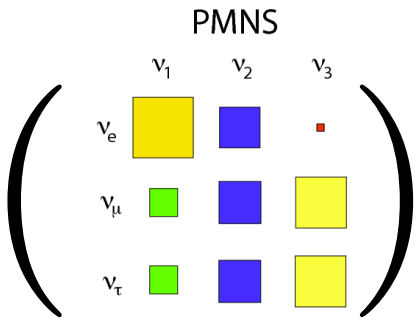
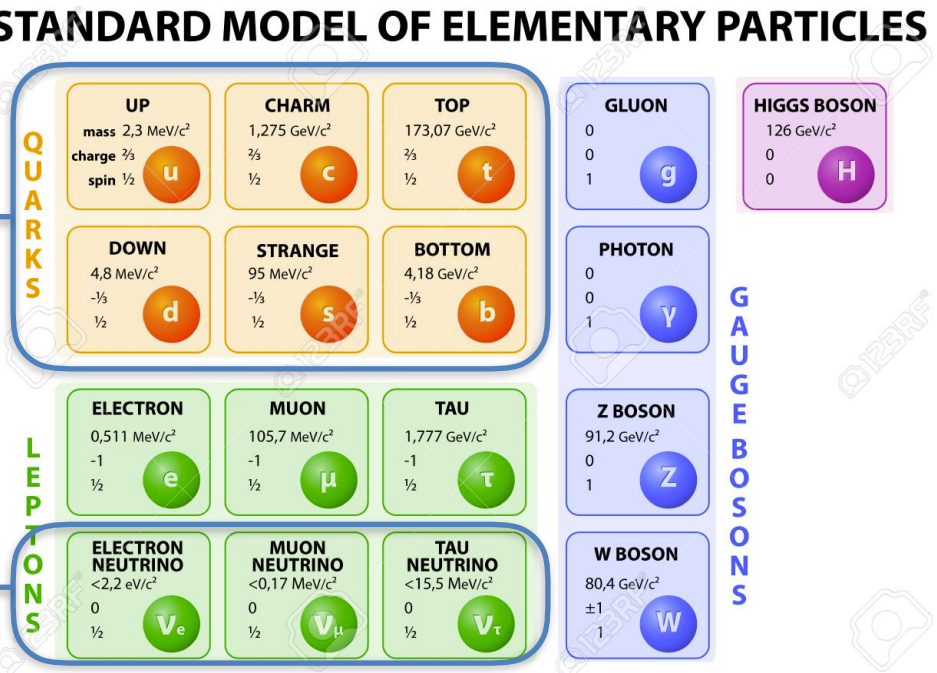

PMNS
ν1
ν2
ν3
νe
νμ
ντ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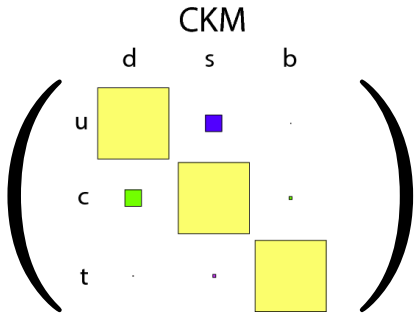
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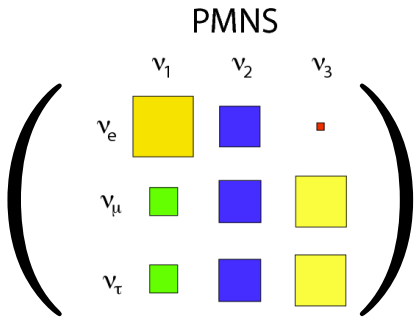
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νe
νμ
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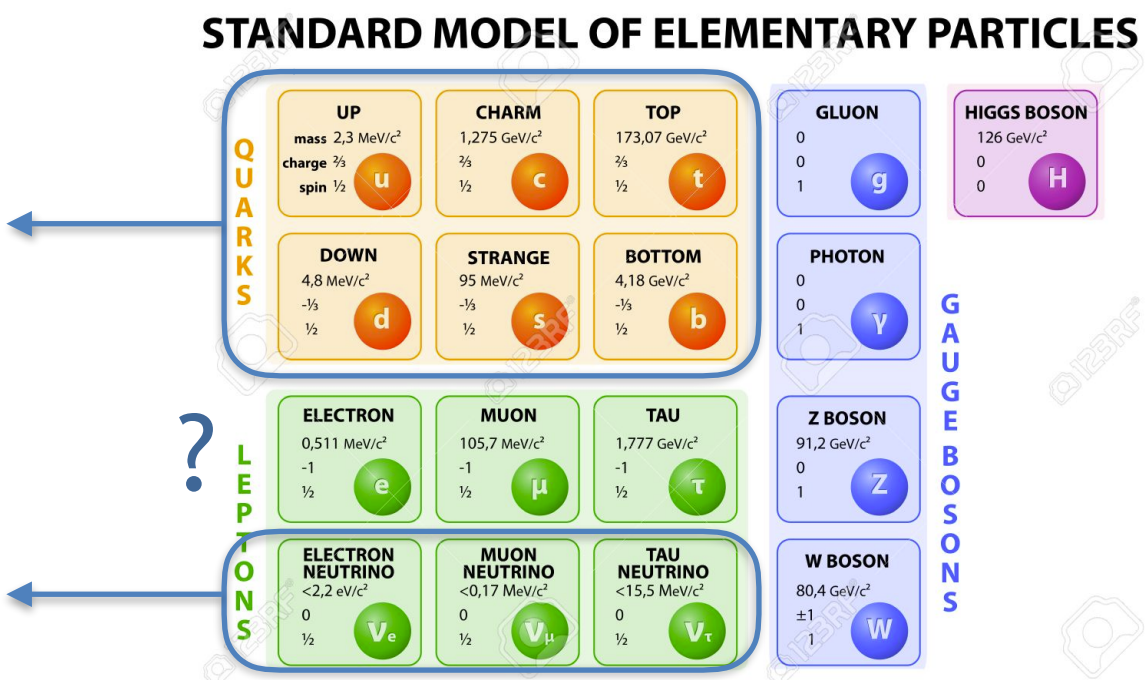
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HIGGS BOSON
126 GeV/c²
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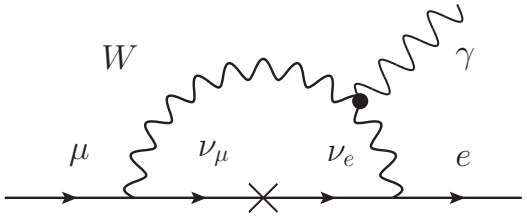
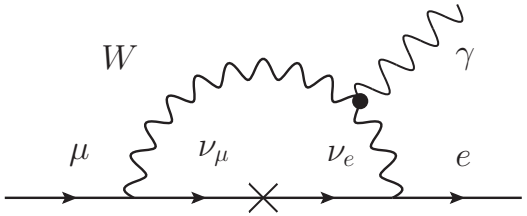
Standard Model



$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-55}$$

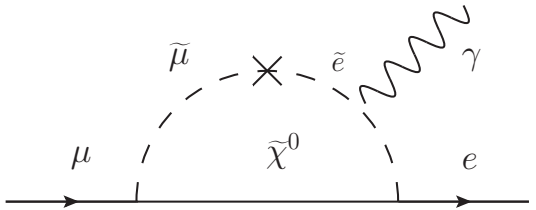
Lepton-flavour Violation (LFV)

Standard Model



$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-55}$$

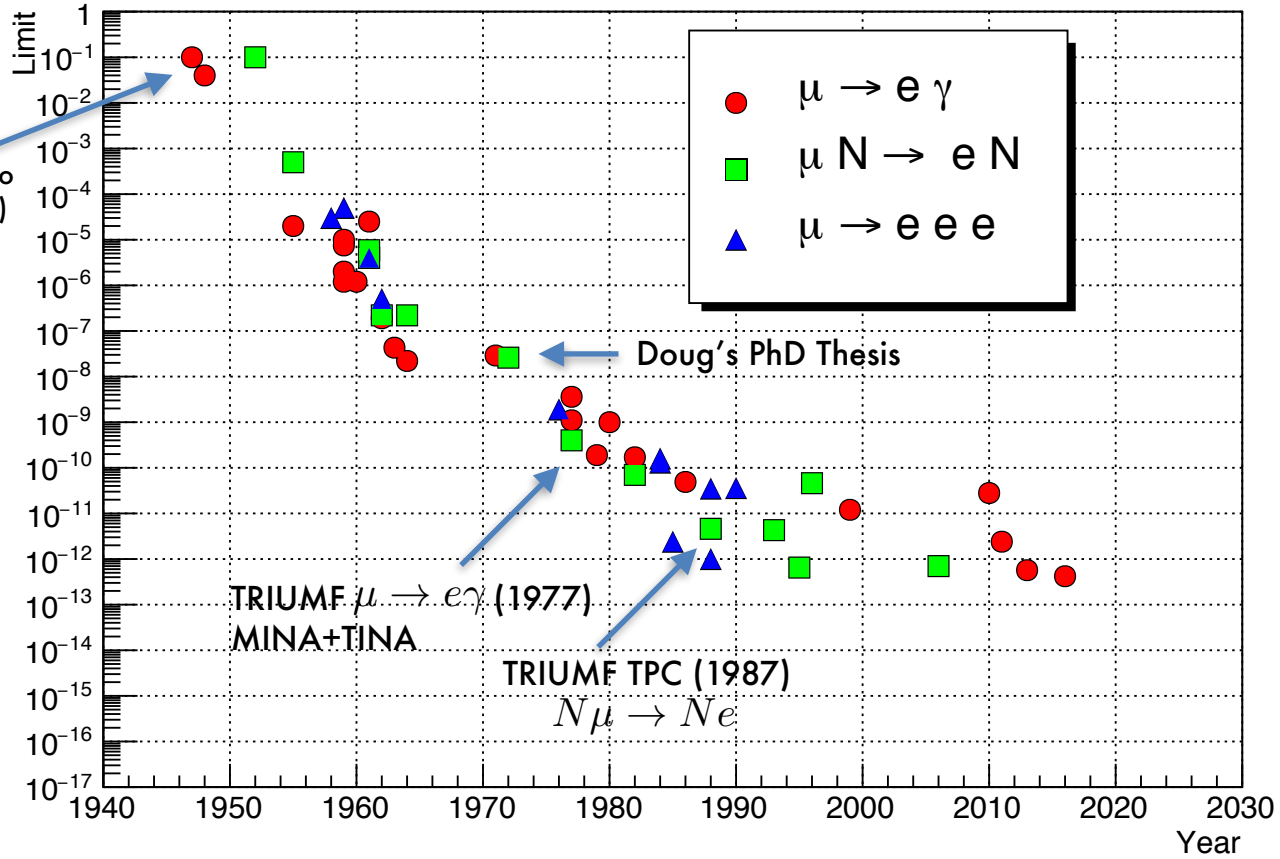
BSM (e.g. SUSY)



Mode	Branching ratio	C.L.
$e^- \bar{\nu}_e \nu_\mu$	$\approx 100\%$	
$e^- \bar{\nu}_e \nu_\mu \gamma$	$1.4 \pm 0.4\%$	
$e^- \bar{\nu}_e \nu_\mu e^+ e^-$	$3.4 \pm 0.4 \times 10^{-5}$	
$e^- \nu_e \bar{\nu}_\mu$	$< 1.2\%$	90%
$e^+ \gamma$	$< 5.7 \times 10^{-13}$	90%
$e^- e^+ e^-$	$< 1.0 \times 10^{-12}$	90%
$e^- 2\gamma$	$< 7.2 \times 10^{-11}$	90%

LFV History

E.P. Hincks, B. Pontecorvo
Phys. Rev. 73 257 (1948)



LFV History

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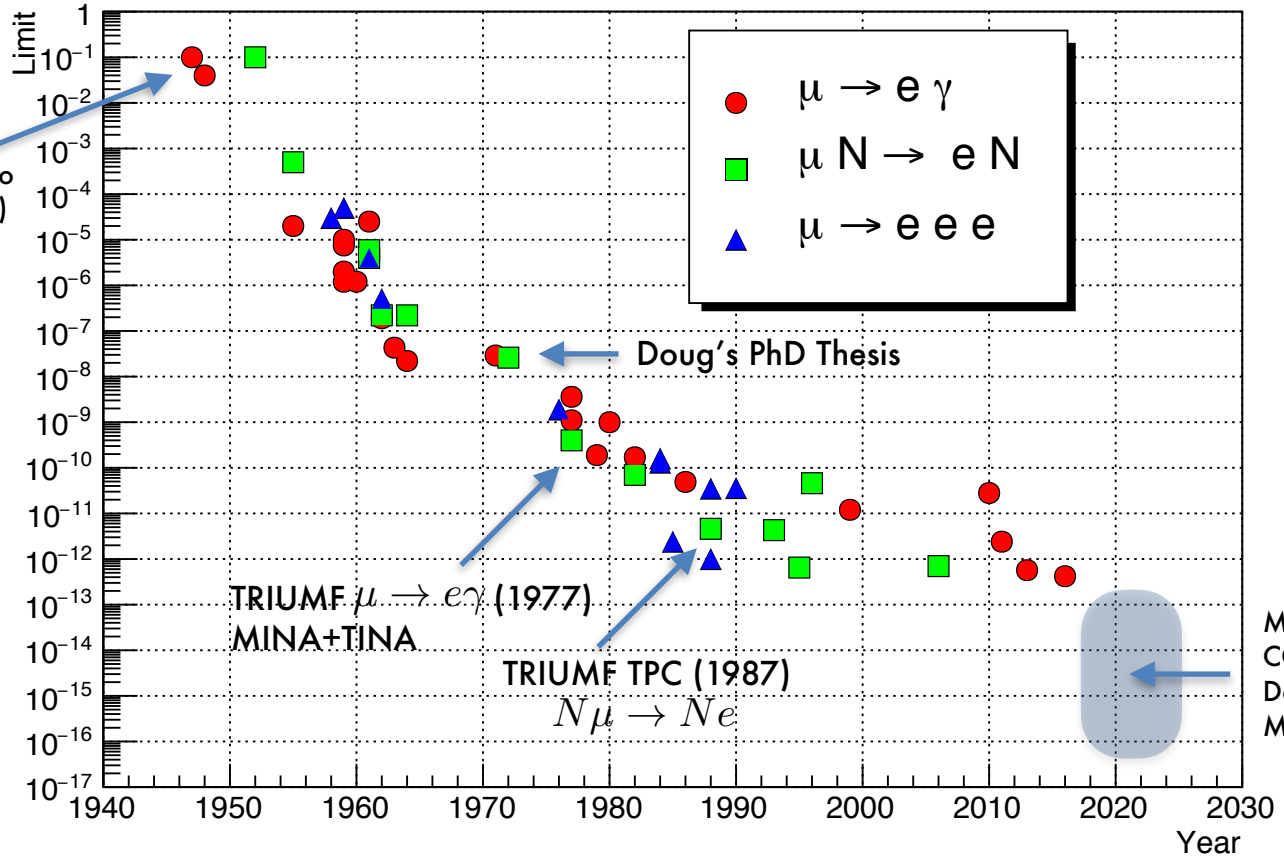
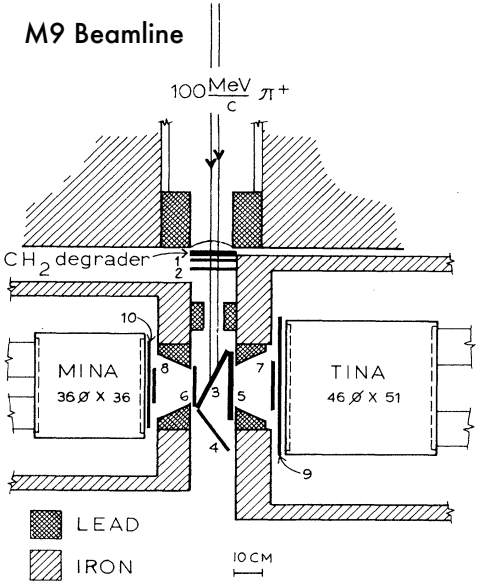


Mu2e @ FNAL (<10^{-16})
COMET@JPARC (<10^{-16})
DeeMee (<10^{-14})
Mu3e @ PSI (<10^{-16})



VOLUME 39, NUMBER 18 PHYSICAL REVIEW LETTERS 31 OCTOBER 1977

New Limit on the Decay $\mu^+ \to e^+\gamma$

P. Depommier, J.-P. Martin, J.-M. Poutissou, and R. Poutissou
Laboratoire de Physique Nucléaire, Université de Montréal, Montréal, Québec H3C 3J7, Canada

and

D. Berghofer, M. D. Hasinoff, D. F. Measday, and M. Salomon
Physics Department, University of British Columbia, Vancouver, British Columbia V6T 1W5, Canada

and

D. Bryman
TRIUMF, University of British Columbia, Vancouver, British Columbia V6T 1W5, Canada

and

M. Dixit and J. A. Macdonald
Physics Department–TRIUMF, University of Victoria, Victoria, British Columbia V8W 2Y2, Canada

and

G. I. Opat[a]
School of Physics, University of Melbourne, Parkville, Victoria 3052, Australia
(Received 16 August 1977)

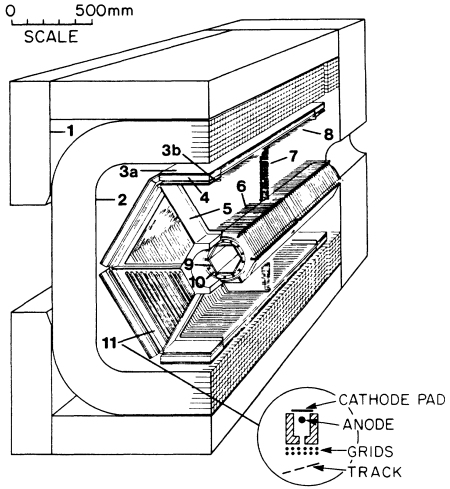
Using two large NaI detectors, a limit on the branching ratio for the $\mu^+ \to e^+\gamma$ decay has been found to be $R_{\mu e\gamma} = \Gamma(\mu^+ \to e^+\gamma)/\Gamma(\mu^+ \to e^+\nu_e\bar{\nu}_\mu) < 3.6\times10^{-9}$ at a 90% confidence level.

$\mu \to e\gamma$

$R_{\mu e\gamma} < 3.6\times10^{-9}$

Fast response from TRIUMF to rumours from SIN (now PSI) about LFV

M9 Beamline



$N\mu \rightarrow Ne$

PHYSICAL REVIEW D VOLUME 38, NUMBER 7 1 OCTOBER 1988

Search for muon-electron and muon-positron conversion

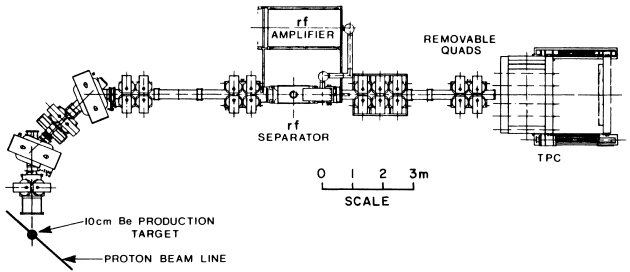
S. Ahmad,[a] G. Azuelos,[b] M. Blecher,[c] D. A. Bryman,[a] R. A. Burnham,[d] E. T. H. Clifford,[a] P. Depommier,[e] M. S. Dixit,[f] K. Gotow,[c] C. K. Hargrove,[f] M. Hasinoff,[d] M. Leitch,[a,*] J. A. Macdonald,[b] H. Mes,[f] I. Navon,[a] T. Numao,[b] J-M. Poutissou,[b] R. Poutissou,[e] P. Schlatter,[a,†] J. Spuller,[b] and J. Summhammer[a,‡]

[a]*TRIUMF and University of Victoria, Victoria, British Columbia, Canada V8W 2Y2*
[b]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3*
[c]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[d]*University of British Columbia, Vancouver, British Columbia, Canada V6T 2A6*
[e]*Université de Montréal, Montréal, Québec, Canada H3C 3J7*
[f]*National Research Council, Ottawa, Canada K1A 0R6*

(Received 3 May 1988)

Limits on the lepton-flavor-violating reactions $\mu^- + Z \rightarrow e^- + Z$ and $\mu^- + Z \rightarrow e^+ + (Z-2)$, muon-electron and muon-positron conversion, have been obtained from a search performed at TRIUMF using a time-projection chamber. Upper limits (90% C.L.) for the branching ratios compared to ordinary muon capture for a titanium target are $R_-(\mathrm{Ti}) = \Gamma(\mu^- \mathrm{Ti} \rightarrow e^- \mathrm{Ti}) / \Gamma(\mu^- \mathrm{Ti}\ \mathrm{capture}) < 4.6 \times 10^{-12}$ and $R_+(\mathrm{Ti}) = \Gamma(\mu^- \mathrm{Ti} \rightarrow e^+ \mathrm{Ca}^*) / \Gamma(\mu^- \mathrm{Ti}\ \mathrm{capture}) < 1.7 \times 10^{-10}$. A smaller data set obtained using a lead target yielded $R_-(\mathrm{Pb}) < 4.9 \times 10^{-10}$. The implications of these results for extensions of the standard model which allow lepton-flavor violation are discussed.

$$R_-(\mathrm{Pb}) = \frac{\Gamma(\mu^- + \mathrm{Pb} \rightarrow e^- + \mathrm{Pb})}{\Gamma(\mu^-\ \mathrm{Pb\ capture})} < 3.9 \left[f_c \sum_i (f_s N_{\mathrm{LT}} A)_i \right]^{-1} = 4.9 \times 10^{-10}$$

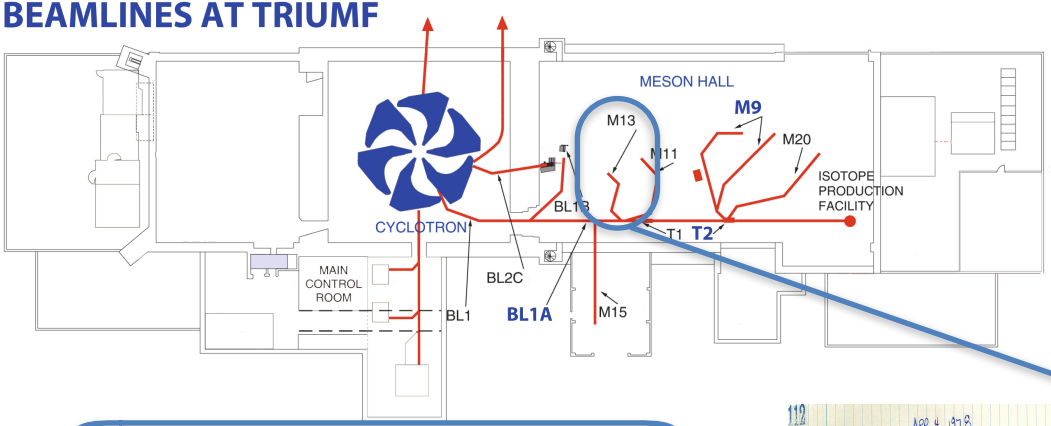


Electron-muon conversion experiment with TPC. Believed to be the first experiment ever collecting data with a TPC (newly invented by D.R. Nygren)!

Experiments at the M13 Beamline

The M13 Beamline

BEAMLINES AT TRIUMF



COMMISSIONING OF A NEW LOW ENERGY π-μ CHANNEL AT TRIUMF

Nucl. Instr. Meth. 179-1, 95-103 (1981)

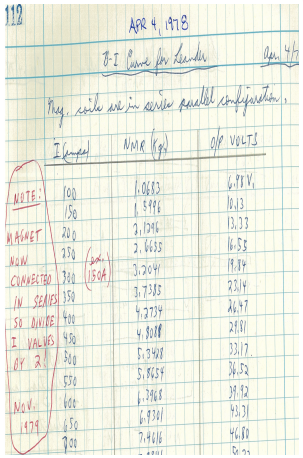
C.J. Oram, J.B. Warren and G.M. Marshall

Physics Department, University of British Columbia
Vancouver, B.C., Canada V6T 2A6

J. Doornbos

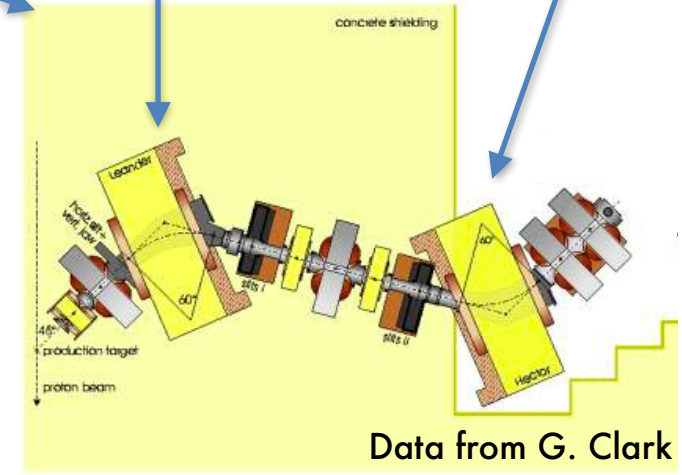
TRIUMF, Vancouver, B.C., Canada V6T 2A3

- Survey grid was same as used for flip coils.
- TTY output is in "Dipole Meas. RB. #3"
- IBM output is in "DIPOLES 1977"



"Leander"
LRL Berkeley
0.64 T
300A max
1.3x2.5x1.3m
22 tons
Gap: 7.65''
45deg bend

"Hector"
LRL Berkely
0.74 T
350A max
1.2x2.4x1.1m
17.2 tons
Gap: 7.65''
45deg bend



Data from G. Clark

TWIST

The Muon Decay

Louis Michel
(1923-1999)

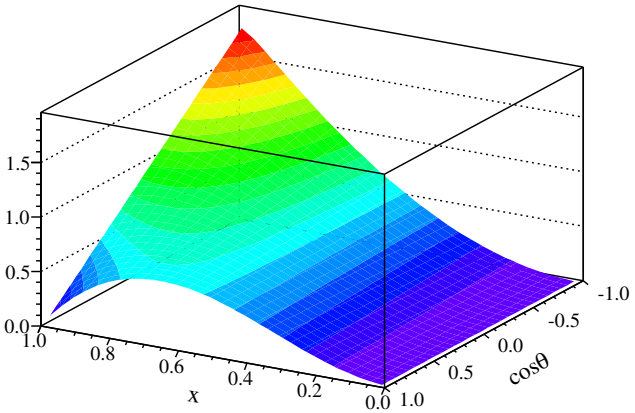
The Michel Decay

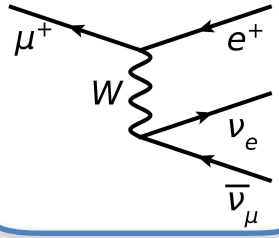
$$\frac{d^2\Gamma}{dx\, d\cos\theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2} \cdot \{\mathcal{F}_{IS}(x, \rho, \eta) + \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x, \xi, \delta)\} + R.C.$$

$$\mathcal{F}_{IS}(x, \rho, \eta) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0 (1-x)$$

$$\mathcal{F}_{AS}(x, \xi, \delta) = \frac{1}{3}\sqrt{x^2 - x_0^2}\left[\xi\{1-x\} + \frac{2}{3}\xi\delta\left\{4x - 3 + \left(\sqrt{1-x_0^2} - 1\right)\right\}\right]$$

$$W_{\mu e} = \frac{m_\mu^2 + m_e^2}{2m_\mu},\ x = \frac{E_e}{W_{\mu e}},\ x_0 = \frac{m_e}{W_{\mu e}}.$$





Standard Model Prediction

$$\rho = \frac{3}{4}, \qquad \eta = 0, \qquad \xi = 1, \qquad \delta = \frac{3}{4}$$

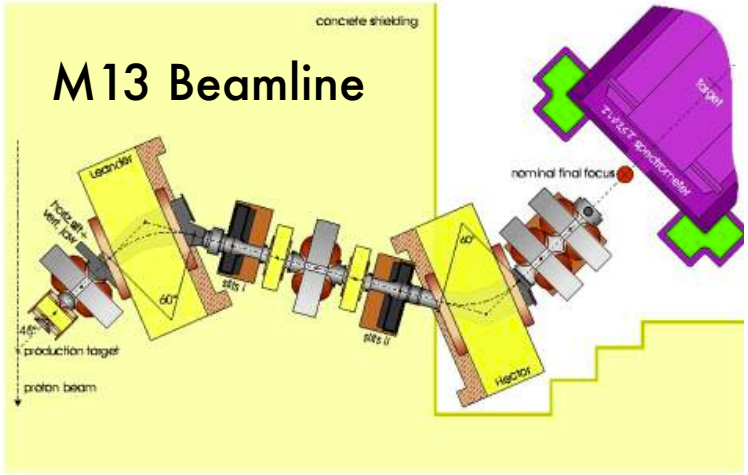
$$P_\mu^\pi \xi = 1$$

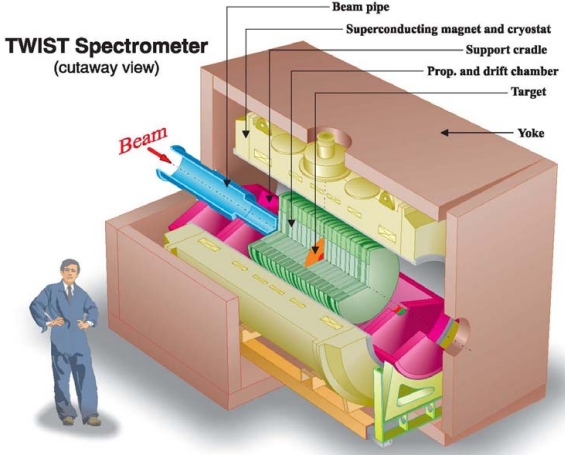
L. Michel, Proc. Phys. Soc. A63:514 (1950).
C. Bouchiat, L. Michel, Phys. Rev. 106(1):170-172 (1957).
T. Kinoshita, A. Sirlin, Phys. Rev. 107(2)593-599 (1957).
T. Kinoshita, A. Sirlin, Phys. Rev. 108(3)844-850 (1957).

TWIST (E614)

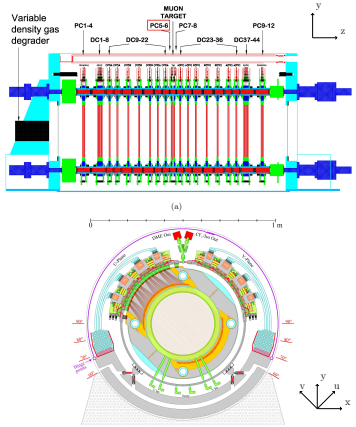
TRIUMF Weak Interaction Symmetry Test

A high precision measurement of the decay distribution of polarized muons.





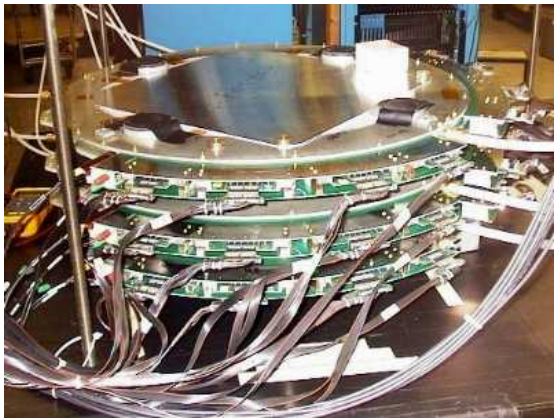
Nucl. Instr. and Meth. A548 (2005) 306-335



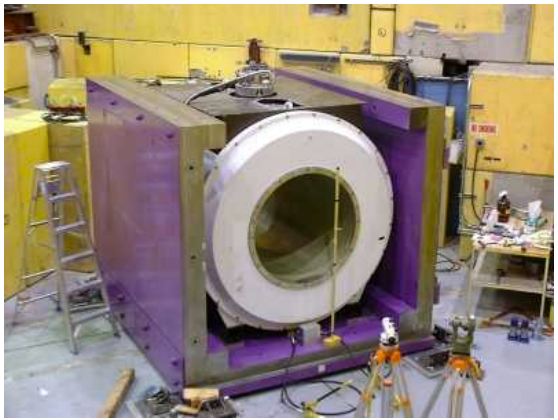
The TWIST Detector

Support Cradle

Planar Wire Chambers (44 DC + 12 PC)

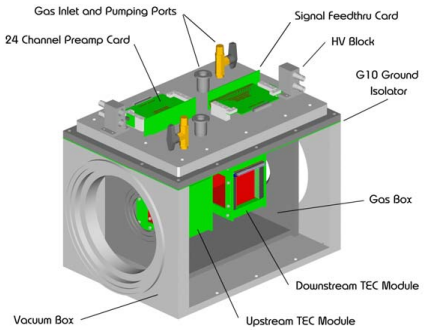


MRI Magnet (2T)



G. Sheffer (1952-2016)

Time Expansion Chambers



DETECTOR

2T field (0.5g precision)
44 Drift Chambers + 12 Prop. Chambers
2 TECs for beam monitoring
Al / Ag muon stopping foil + var. density gas degrader

ANALYSIS

10^{10} muon decays in 14 datasets analyzed.
Strategy: Compare well tested MC to data –> extract mu decay parameters
BLIND ANALYSIS (MC used hidden parameters with encryption key)

Blind Analysis

(First) Attempt to retrieve the CD with blind-analysis keys.

Blind Analysis

(First) Attempt to retrieve the CD with blind-analysis keys.

..ehm..

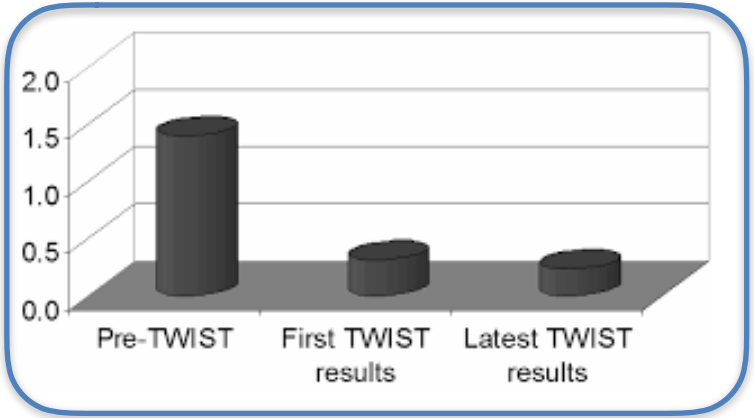
Blind Analysis

(First) Attempt to retrieve the CD with blind-analysis keys.

..ehm..

...found!

The TWIST Collaboration



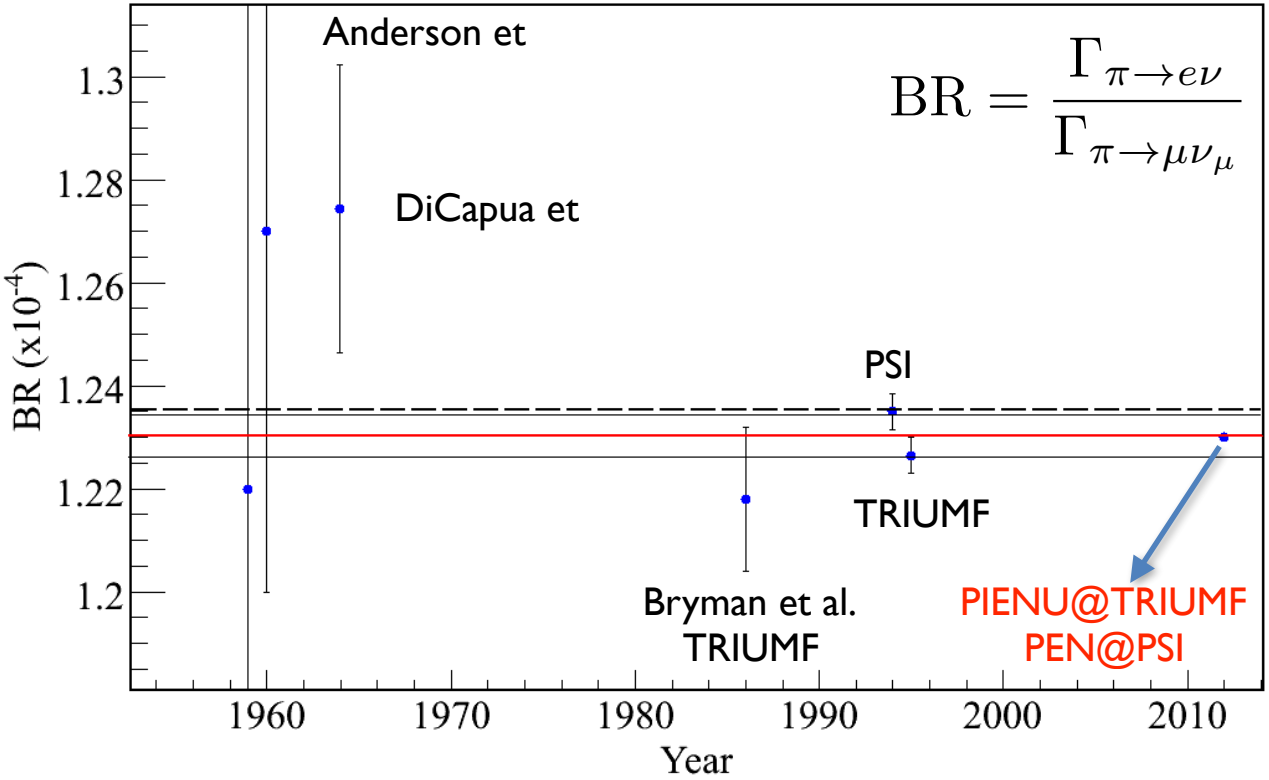
PDG 2003

ρ	0.7518 ± 0.0026
δ	0.7486 ± 0.0038
$P_\mu \xi$	1.0027 ± 0.0085
$P_\mu \xi \delta / \rho$	0.99787 ± 0.00082

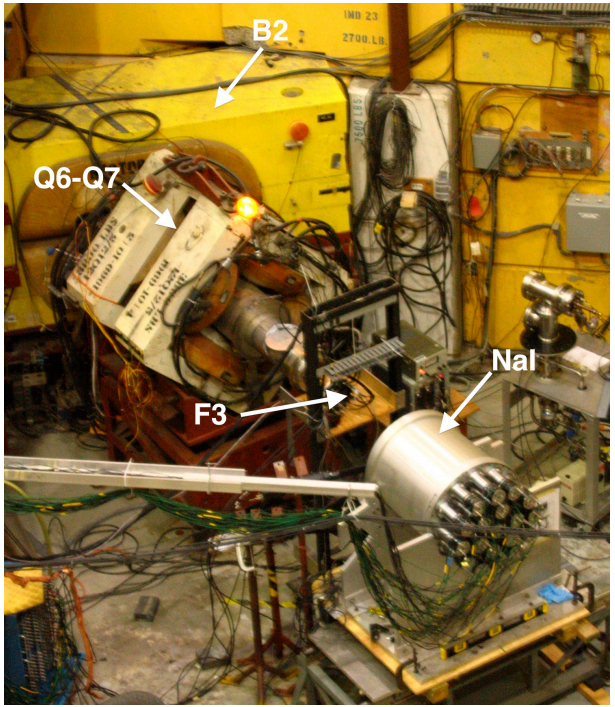
TWIST (final results)

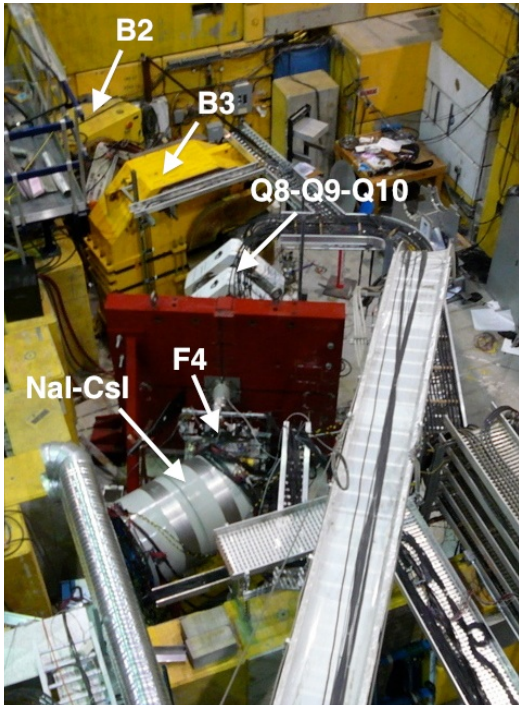
ρ	$0.74997 \pm 0.00012(\text{st.}) \pm 0.00023(\text{sys.})$
δ	$0.75049 \pm 0.00021(\text{st.}) \pm 0.00027(\text{sys.})$
$P_\mu^\pi \xi$	$1.00084 \pm 0.00029(\text{st.})^{+0.00165}_{-0.00063}(\text{sys.})$
$P_\mu^\pi \xi \delta / \rho$	$1.00179 \pm^{+0.00156}_{-0.00063}$

PIENU

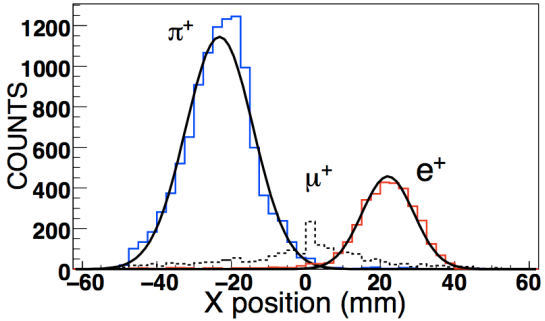

Anderson et
DiCapua et
PSI
TRIUMF
Bryman et al.
TRIUMF
PIENU@TRIUMF
PEN@PSI
$\mathrm{BR} = \frac{\Gamma_{\pi\to e\nu}}{\Gamma_{\pi\to\mu\nu_\mu}}$
BR (x10^{-4})
1.3
1.28
1.26
1.24
1.22
1.2
1960
1970
1980
1990
2000
2010
Year

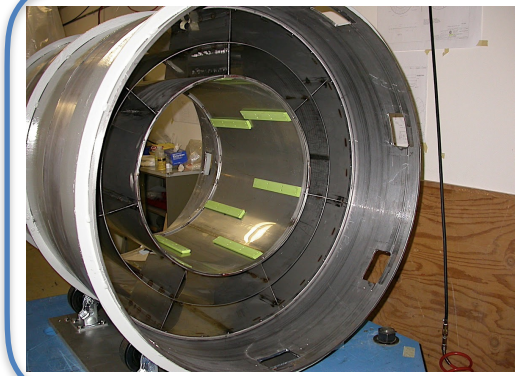
M13 & PIENU





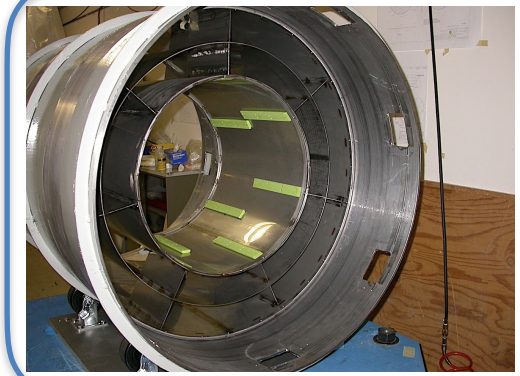
- 3-Dipoles Beamline
- 10 Quadrupoles
- Separation:
  - Energy-loss
  - Collimator
- Positron Contamination <1%
- dp/p ~ 1.5% FWHM





NaI+CsI Steel Frame

NaI Crystal “BiNa”



NaI+CsI Steel Frame

NaI Crystal "BiNa"

C. Lim

PIENU

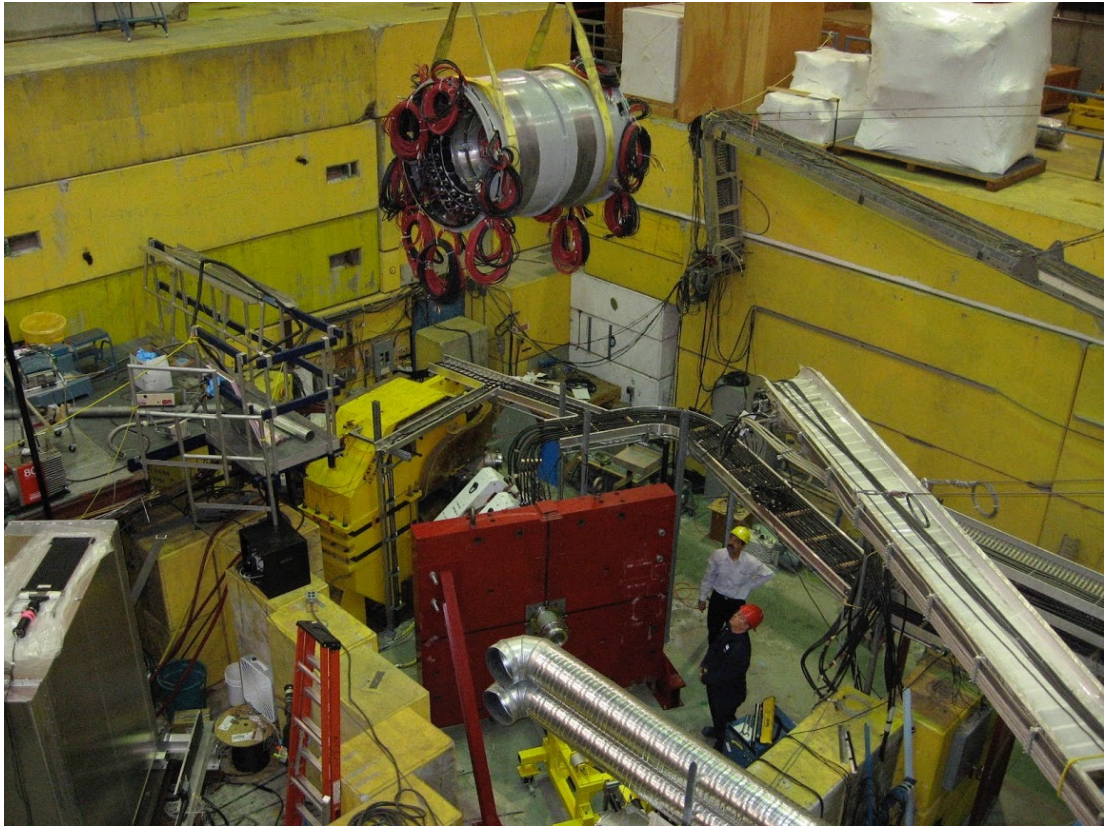
T. Numao

PIENU

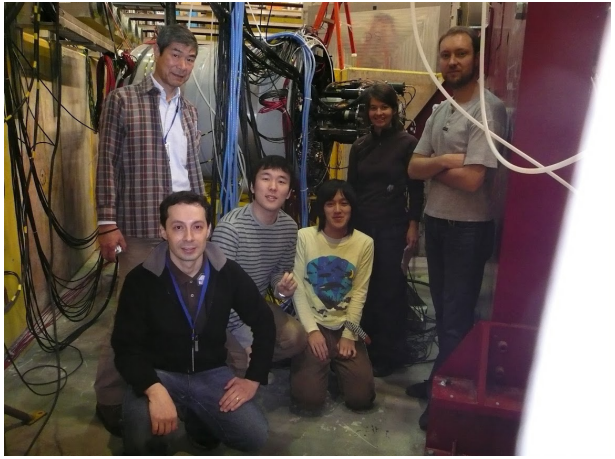
T. Numao

D. A. Bryman

PIENU

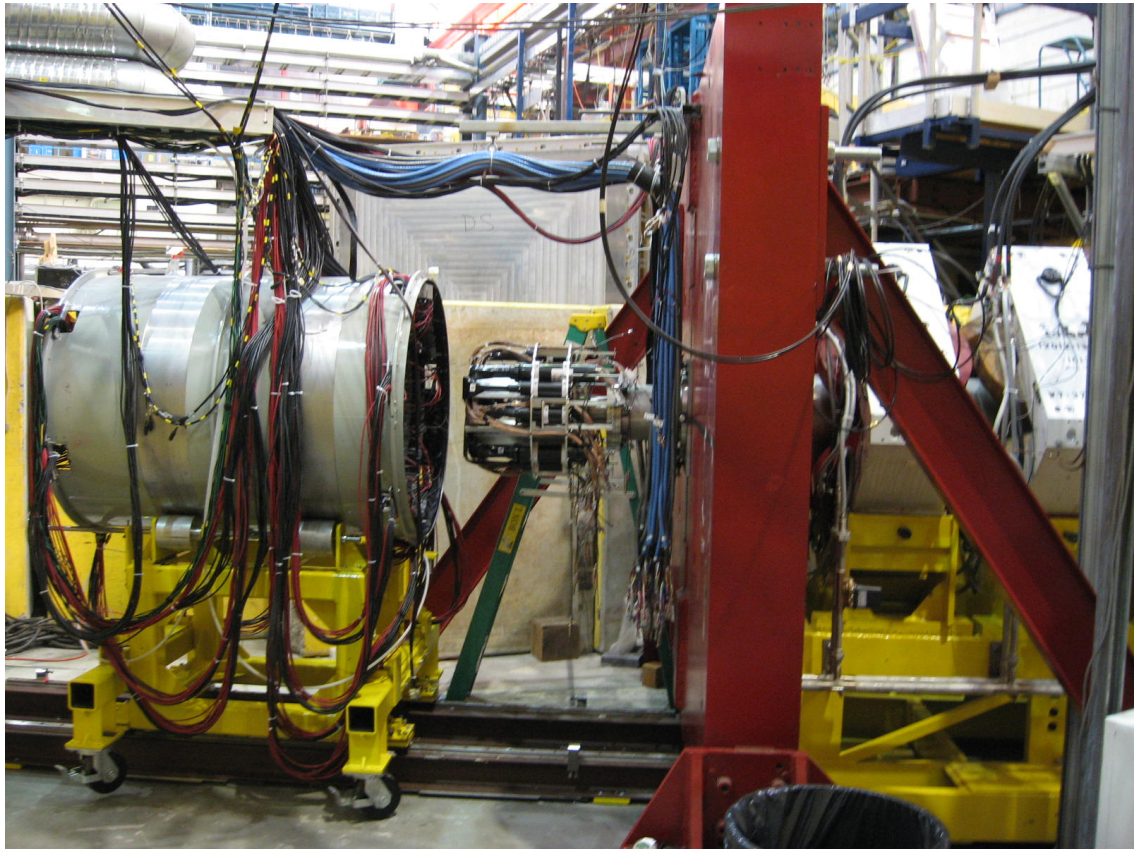


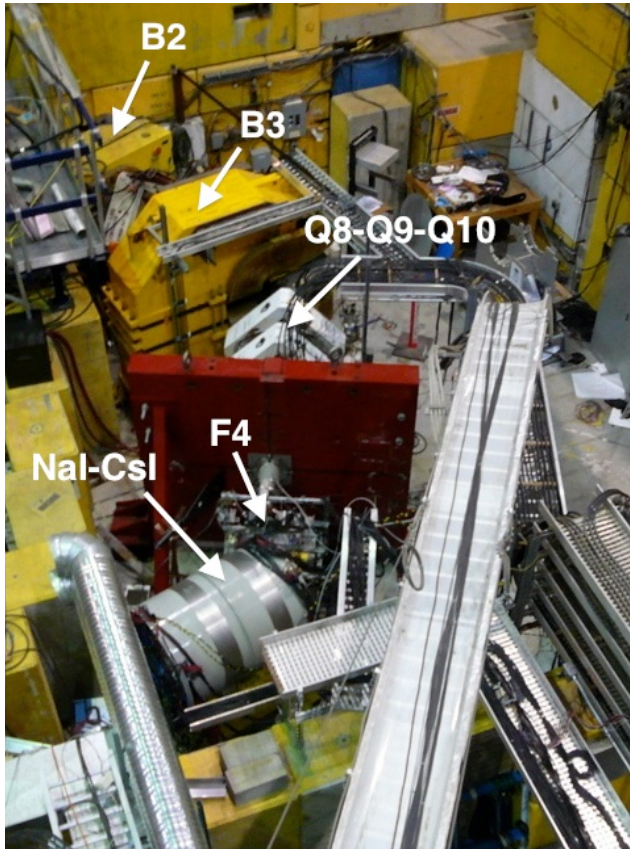




N. Khan

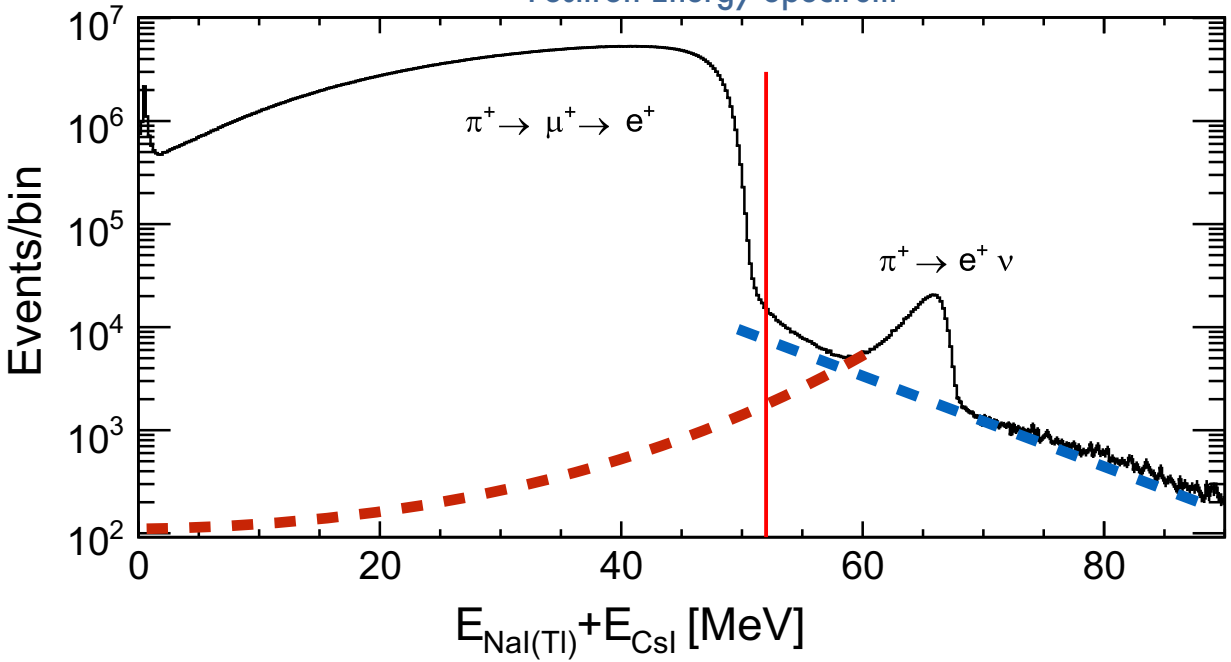
PIENU



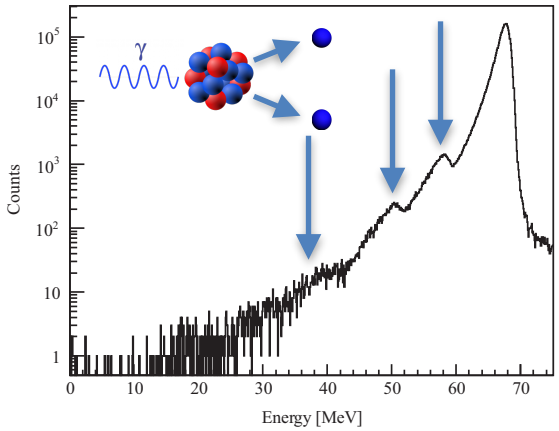


Energy Spectrum

Positron Energy Spectrum



Calorimeter Response to a Positron Beam



- Pileup
- Low Energy Tail

A. Aguilar-Arevalo et al. Phys. Rev. Lett. 115, 071801

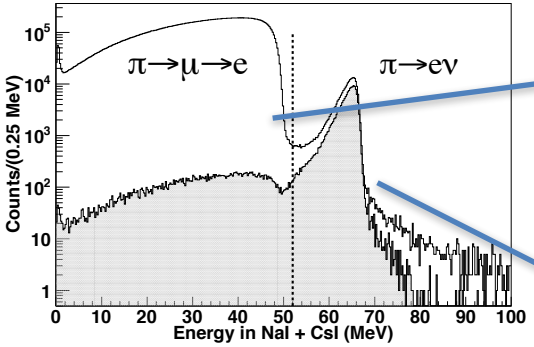
Improved measurement of the $\pi \to e\nu$ branching ratio

A.Aguilar-Arevalo[1], M. Aoki[2], M. Blecher[3], D.I. Britton[4], D.A. Bryman[5], D. vom Bruch[5], S. Chen[6], J. Comfort[7], M. Ding[6], L. Doria[8], S. Cuen-Rochin[5], P. Gumplinger[8], A. Hussein[9], Y. Igarashi[a], S. Ito[2], S.H. Kettell[b], L. Kurchaninov[8], L.S. Littenberg[b], C. Malbrunot[5,*], R.E. Mischke[8], T. Numao[8], D. Protopopescu[4], A. Sher[8], T. Sullivan[5], D. Vavilov[8], K. Yamada[2]
(PIENU Collaboration)

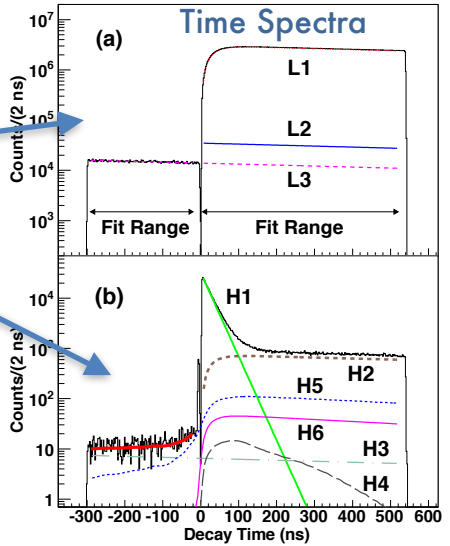
	Values	Uncertainties	
		Stat	*Syst*
$R^{Raw}_{e/\mu}$ (10^{-4})	1.1972	0.0022	0.0005
π,μ lifetimes			0.0001
Other parameters			0.0003
Excluded components			0.0005
Corrections			
Acceptance	0.9991		0.0003
Low-energy tail	1.0316		0.0012
Other	1.0004		0.0008
$R^{Exp}_{e/\mu}$ (10^{-4})	1.2344	0.0023	0.0019

$$g_e/g_\mu = 0.9996 \pm 0.0012$$

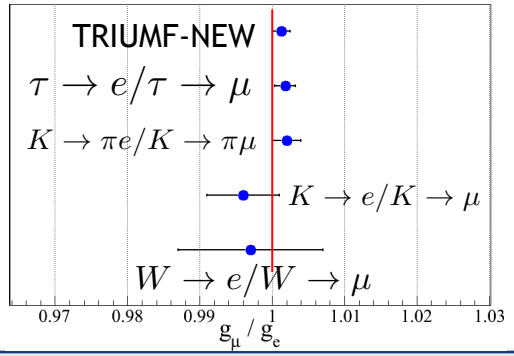
Energy Spectrum

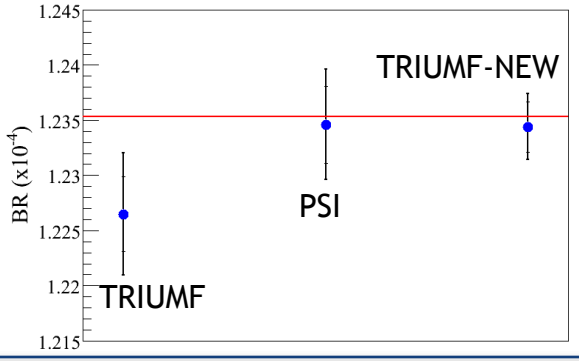


Time Spectra



Best test of e/mu Universality





Results

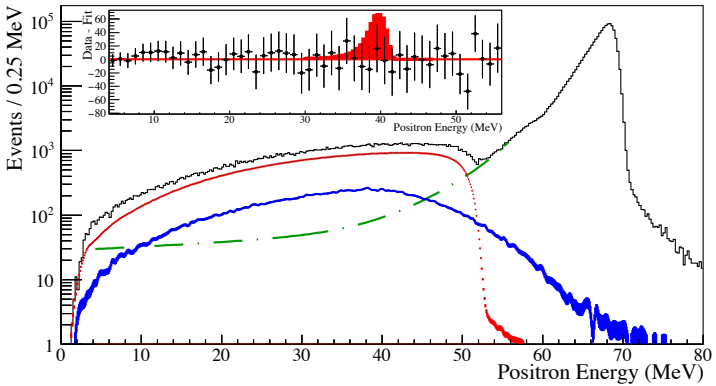
EDITORS' SUGGESTION

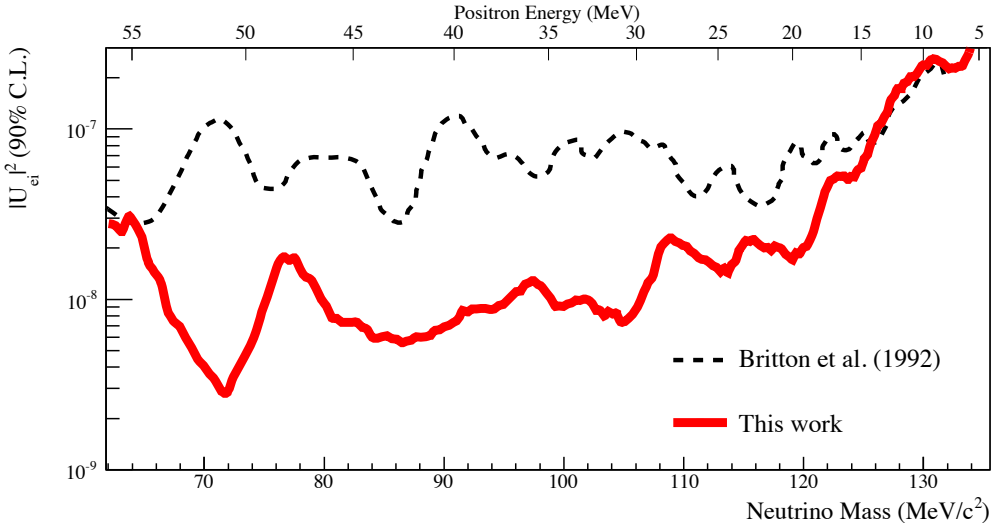
Improved search for heavy neutrinos in the decay $\pi \to e\nu$

As established conclusively in recent years, standard model neutrinos have mass. Additional heavy neutrino states, such as sterile neutrinos, are required in many models of neutrino masses. PIENU, via a novel use of the positron decay mode of the pion, has set new limits on these massive states.

A. Aguilar-Arevalo *et al.*

Phys. Rev. D **97**, 072012 (2018)





- Best limit in the ~100 MeV/c^2 mass range
- Relevant for dark matter / cosmology models
- Matches neutrino less beta decay limits
- No assumption on neutrino nature (Dirac/Majorana)

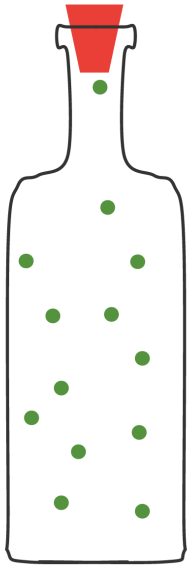
Ultra-Cold Neutrons

Ultra-Cold Neutrons

E_{UCN} < 300 neV ~ 3.5mK
UCNs undergo total reflection —>
—> Storable by common materials

<u>Can be used for the study of :</u>

- exotic interactions
- axions, dark matter
- quantized states in g potential
- …



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Can be used for the study of :

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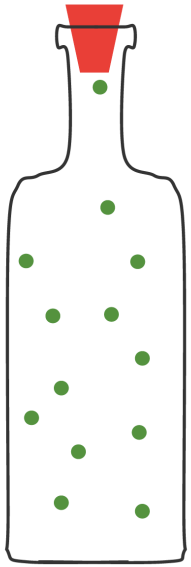
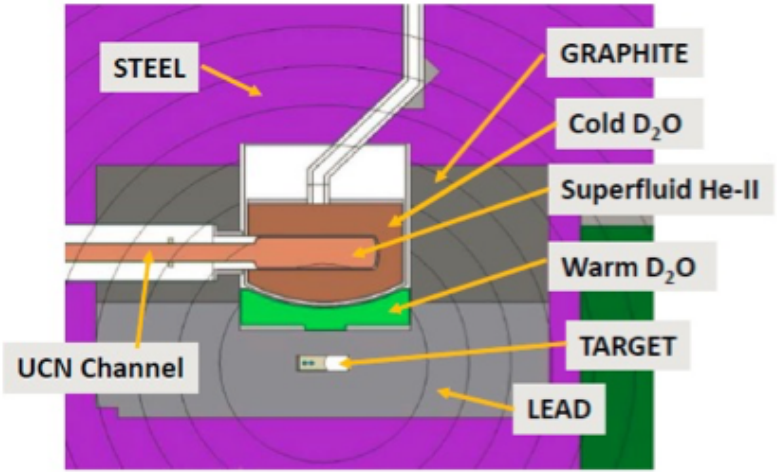
- …

Aim:
Operate the world's strongest intensity UCN source.

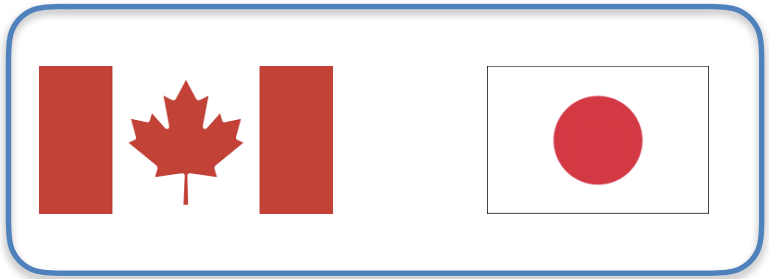
Technique:
Spallation target + superfluid LHe converter



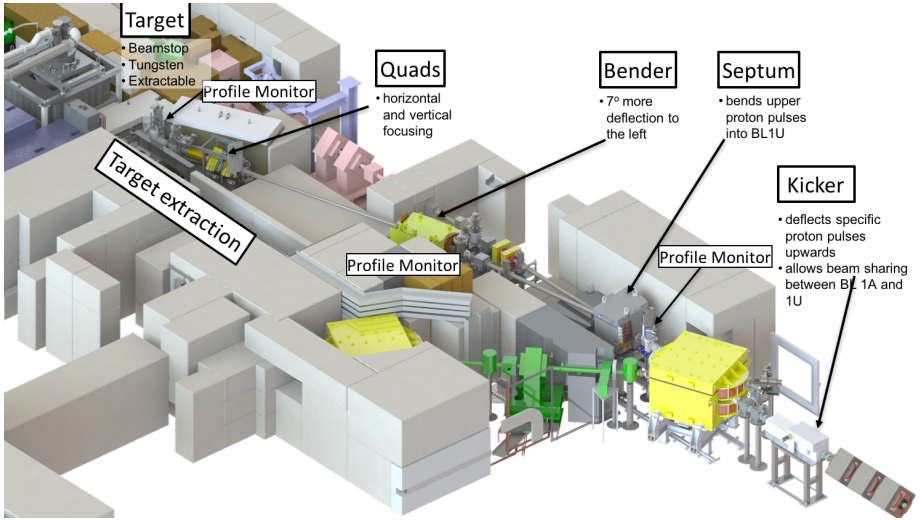


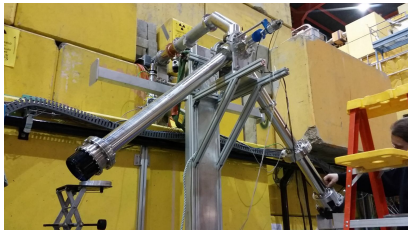
The TUCAN Collaboration (TRIUMF Ultra-Cold Advanced Neutron)

KEK	T. Adachi, S. Jeong, S. Kawasaki, Y. Makida, K. Mishima, T. Okamura, Y. Watanabe
RCNP Osaka	K. Hatanaka, I. Tanihata, E.Pierre (E.P. also TRIUMF)
U Nagoya	M. Kitaguchi, H. Shimizu
UBC	E. Altiere, D. Jones, K. Madison, E. Miller, T. Momose, T. Hayamizu
U Winnipeg	C. Bidinosti, B. Jamieson, R. Mammei (also TRIUMF), J.Martin
U Manitoba	T. Andalib, J. Birchall, M. Gericke, M. Lang, J. Mammei, S.Page, L. Rebenitsch, S. Hansen-Romu, S. Ahmed
TRIUMF	C. Davis, B. Franke, K. Katsika, T. Kikawa, A. Konaka (also UVic and Osaka U), F. Kuchler, L.Lee (also U. Manitoba), R. Picker (also SFU), W.Ramsay, W.vanOers (also U. Manitoba), T. Lindner (also UW)
UNBC	E. Korkmaz
SFU	J. Sonier

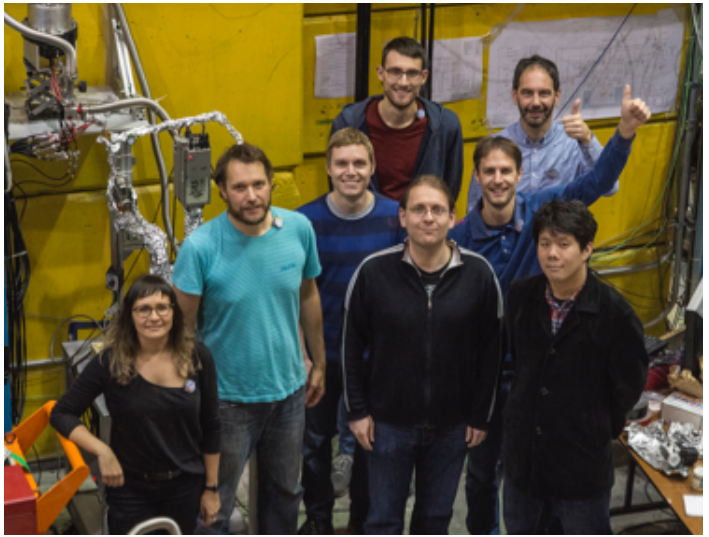


UCNs at TRIUMF





First UCNs produced in Canada



Nov. 13th 2017

Conclusion

- Successful local particle physics program at TRIUMF
- Unique experiments with clear impact on our knowledge of the SM
- Testing of fundamental symmetries of the Standard Model:
  - Lepton Flavour
  - Properties of the weak interactions
  - Search for Physics beyond the SM
  - Forerunners in precision physics: a relevant topic today.

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Happy 50th birthday TRIUMF!
I wish You many more decades of success!

TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

Thank you!
Merci!

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