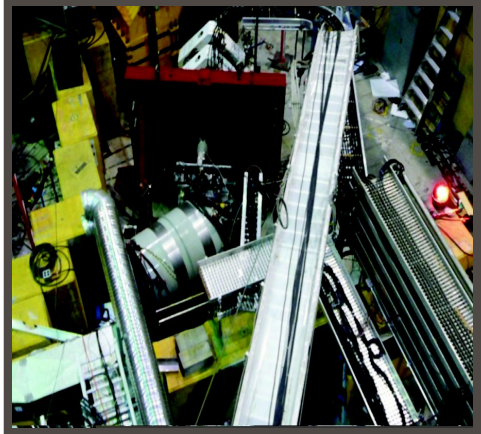
TRIUMF

Canada's national laboratory for particle and nuclear physics

Laboratoire national canadien pour la recherche en physique nucléaire

et en physique des particules



PIENU Experiment at TRIUMF:

A precision measurement of $\pi \to e\nu$ decay

Dima Vavilov
for the PIENU collaboration
BNL 2013

A. Aguilar-Arevalo[11], M. Aoki[4], M. Blecher[9], D.I. Britton[8], D. Bryman[6], D. vom Bruch[6], S. Chen[10], J. Comfort[1], M. Ding[10], L. Doria[5], P. Gumplinger[5], A. Hussein[7], Y. Igarashi[3], N. Ito[4], S. Ito[4], S. Kettell[2], Y. Kuno[4], L. Kurchaninov[5], L. Littenberg[2], C. Malbrunot[12], R. Mischke[5], T. Numao[5], A. Sardorfi[2], A. Sher[5], T. Sullivan[6], D. Vavilov[5], K. Yamada[4], Y. Yoshida[3]

1. Arizona State University
2. Brookhaven National Laboratory
3. KEK
4. Osaka University
5. TRIUMF
6. University of British Columbia
7. University of Northern British Columbia
8. University of Glasgow
9. Virginia Polytechnical Institute & State University
10. Tsinghua University
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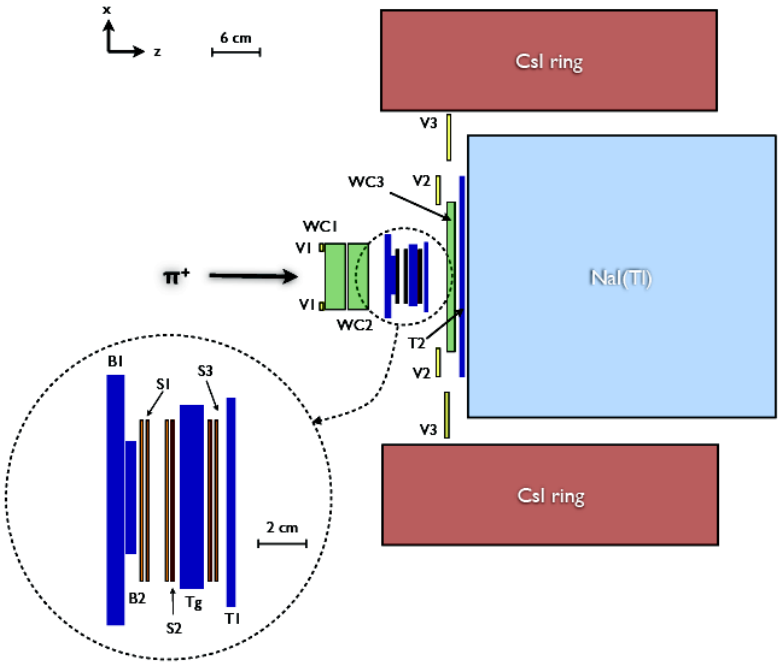
Outline

- Motivation
- Experiment
- Analysis
- Results
  - π → eν
  - Massive neutrino
- Conclusion

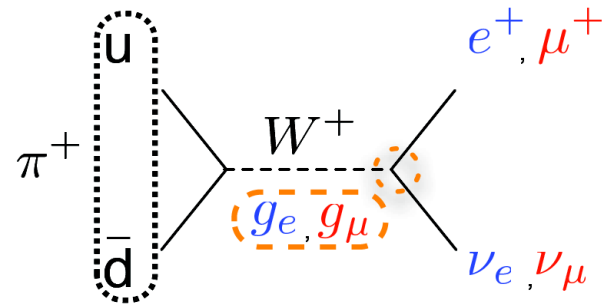


Motivation: Decays π+ → e+ν and π+ → μ+ν

Standard Model:

V.Cirigliano, I. Rossel, Phys. Rev. Lett. 99, 231801 (2007)
W.J.Marciano, A.Sirlin, Phys.Rev.Lett. 71, 3629-3632 (1993)

$$R^{SM}_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)} = 1.2352(1)\,x\,10^{-4}$$



$g_e = g_\mu$

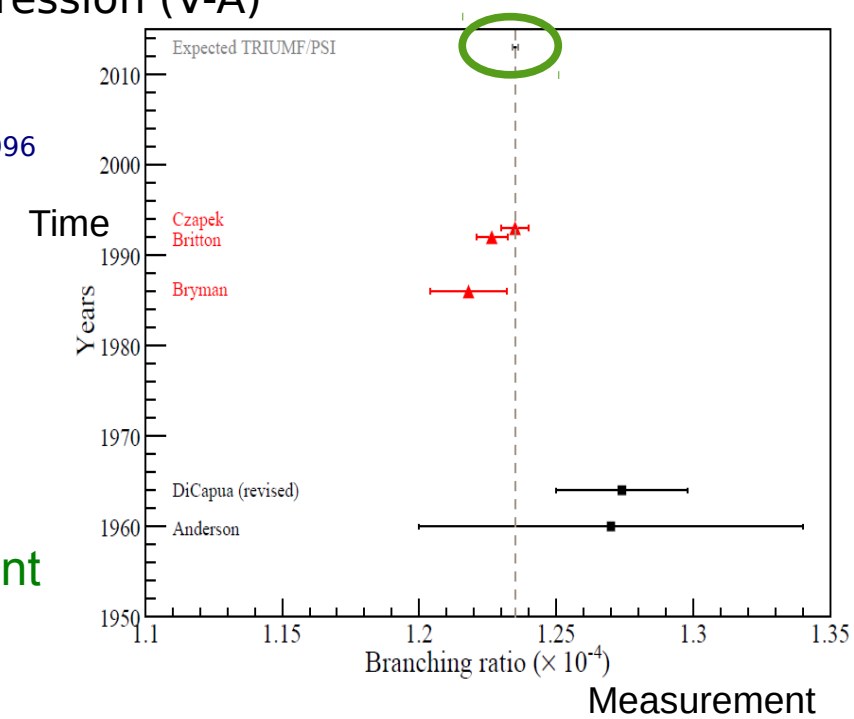
Calculated to extreme precision 0.01%

$\pi^+ \to \mu^+\nu$ is preferred due to helicity suppression (V-A)

Experimental result:

TRIUMF: D.A. Bryman, T. Numao, et al. Phys. Rev. D63:558-559,1996
PSI: G. Czapek et al. Phys. Rev. Lett. 70:17-20,1993

$$R^{exp}_{e/\mu} = 1.231(4)\,x\,10^{-4}$$



Large gap $O(10^2)$ in precision between Theory and Measurement

PIENU: aims at <0.1% in BR measurement

So does PEN experiment at PSI

Motivation

Beyond the Standard Model

- Non universality
- Pseudoscalar interaction: helicity suppression → very attractive effective mass reach

$$1-\frac{R_{e/\nu}^{New}}{R_{e/\nu}^{SM}} \sim \pm \frac{\sqrt{2}\pi}{G_\mu}\frac{1}{\Lambda_{eP}^2}\frac{m_\pi^2}{m_e(m_d+m_u)} \sim \left(\frac{1\,TeV}{\Lambda_{eP}}\right)^2 \times 10^3$$

0.1% BR → Λ_{eP}~1000 TeV

- Others:

Massive ν's
R.E. Schrock Rhys. Rev. D 24, 5 (1981)

Scalar couplings
B.A. Campbell, David W. Maybury Nucl. Phys. B, 709 419-439 (2005)

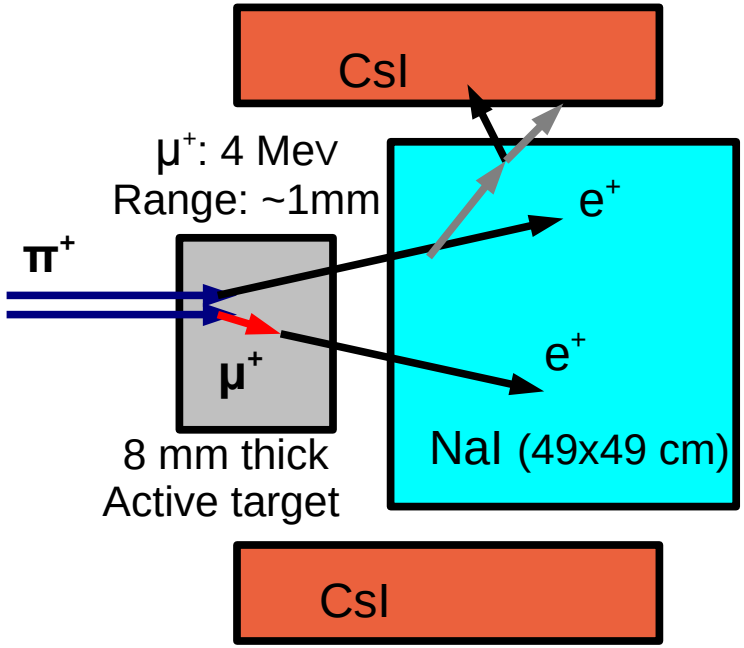
R-Parity violation SUSY
M.J. Ramsey-Musolf, S. Su, S. Tulin, Phys. Rev. D 76, 095017 (2007)

Decay mode	$(g_\mu/g_e)^2$
$\tau\to\mu$ / $\tau\to e$	1.0018 ± 0.0014
$\pi\to\mu$ / $\pi\to e$	1.0021 ± 0.0016
$K\to\mu$ / $K\to e$	0.996 ± 0.005
$K\to\pi\mu$ / $K\to\pi e$	1.002 ± 0.002
$W\to\mu$ / $W\to e$	0.997 ± 0.010

The pion decay branching ratio is **one of the most precise** tests of charged current lepton universality

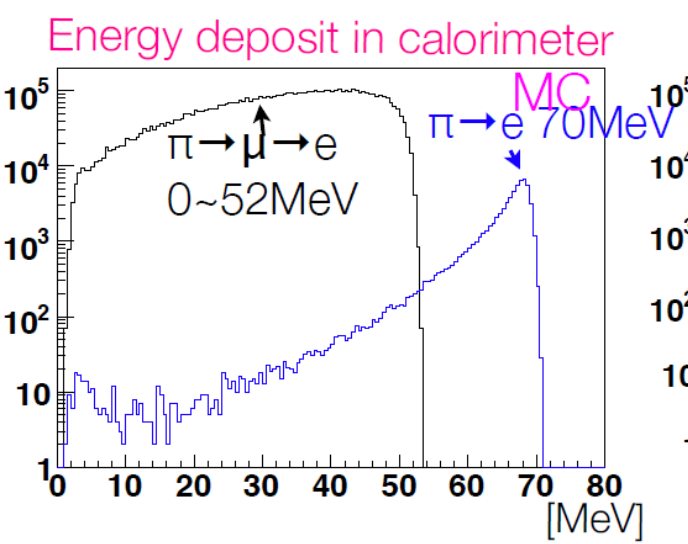
Agreement with SM → constraints for BSM
Disagreement with SM → New Physics

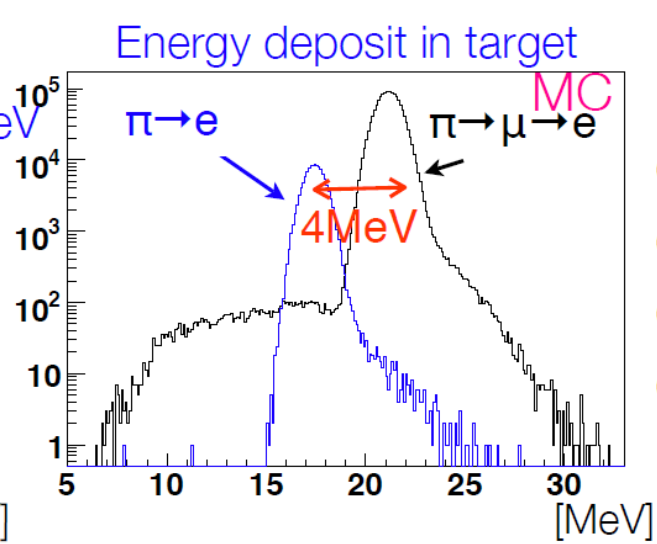
Experiment: Technique

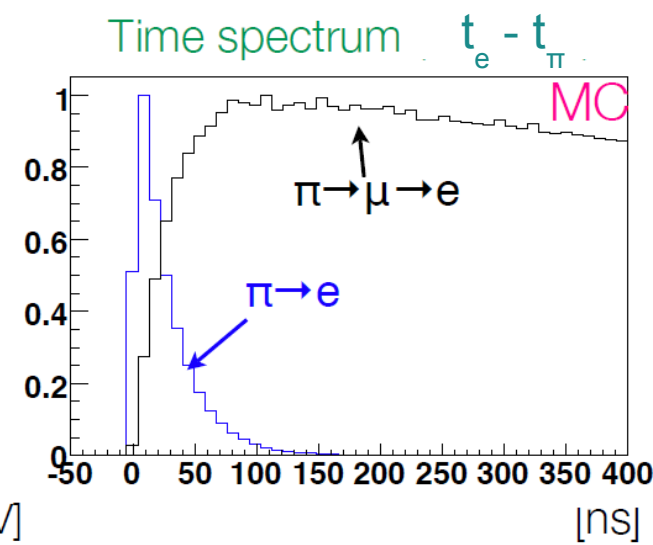


- Separated pion beam, pions stop in active target
- Simultaneous data collection
- Same final state
- Same acceptance

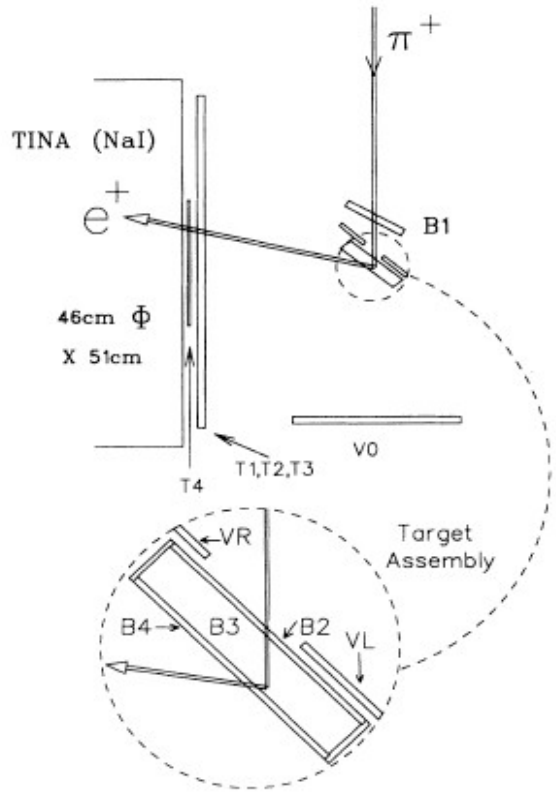
- **Discrimination of the decay mode**
  - Energy deposit in calorimeter
- **Estimation of raw branching ratio**
  - Simultaneous fitting of two time spectra pi-e and pi-mu-e (high and low energy region)
- **Important corrections:**
  Tail correction piDIF Acceptance

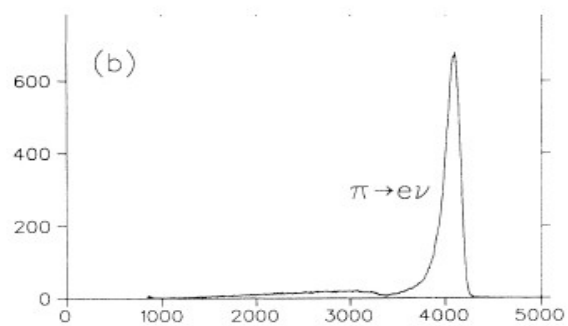






Experiment: Lessons from E248





E248:

- R = 1.2265±0.0034(stat)±0.0044(sys)x10^{-4}
- 10^5 π → ev were collected for a month
- Systematic and statistical errors of the same order

Main sources of uncertainties:

- Low energy tail
  - Large piDIF contribution
  - 20% events in tail region
- Small (2%) acceptance
  - Low statistics
  - Large acceptance correction

Experiment: PIENU Detector Concept

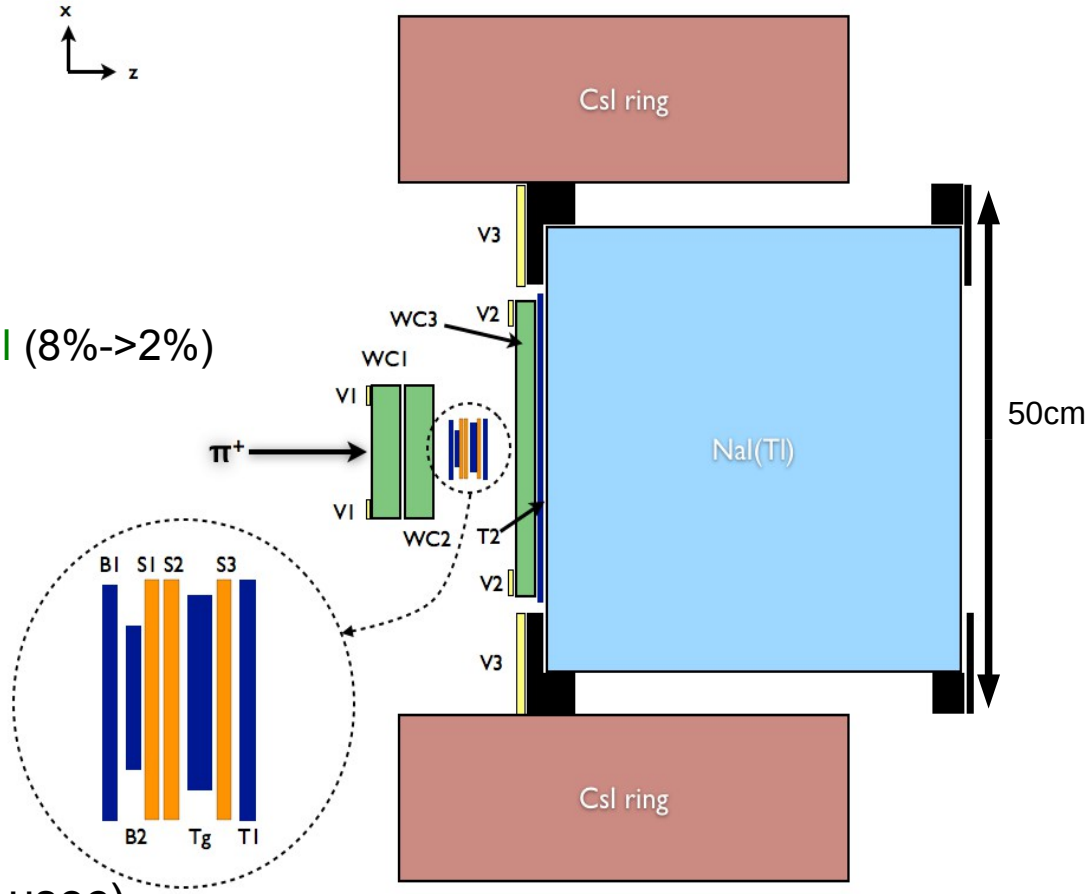
Large NaI crystal near target
- Large solid angle(25%)
- High resolution: ~1% σ at 70 MeV/c

CsI crystal array (annular)
- Extends NaI Calorimeter
- Reduces e+ low energy (<50 MeV) tail (8%->2%)

Si-strips + MWPC
- Tracking of particles upstream and downstream of the target
- Reduces π decays in flight

Fast readout digitizers
- 500MHz FADC for Scintillators (8 usec)
- 60MHz FADC for Crystals
- Pileup rejection and Pulse Shape Fit

Cross sectional schematic view of the PIENU detector

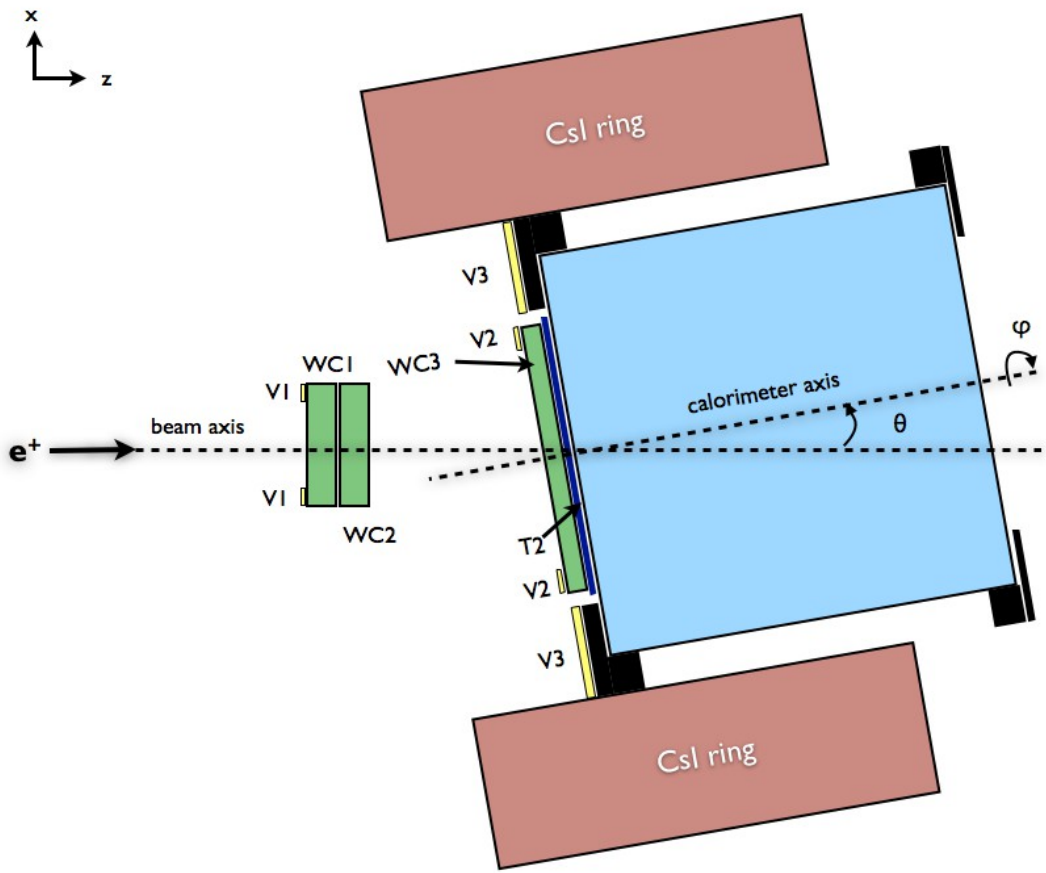


Experiment: Detector Concept

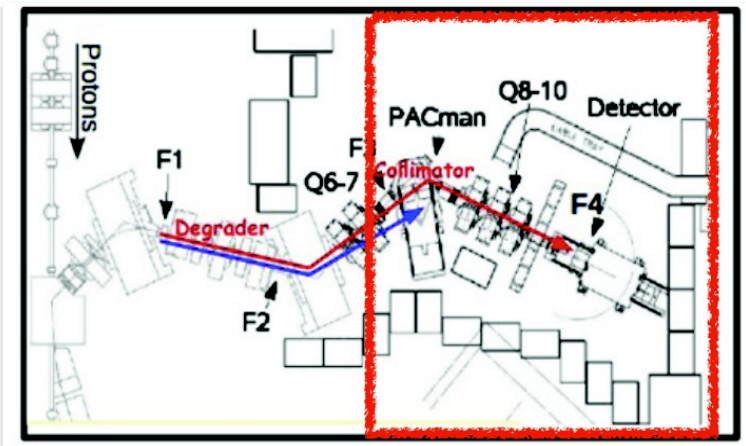
Cross sectional schematic view of the PIENU detector

Lineshape measurement ready

- The calorimeter part is mobile so can be exposed to the positron beam at different angles
- The Target assembly is removable
- Detailed measurement of the crystal response

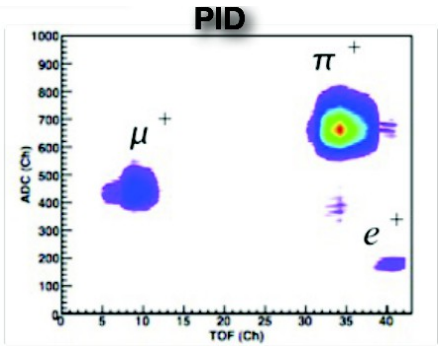


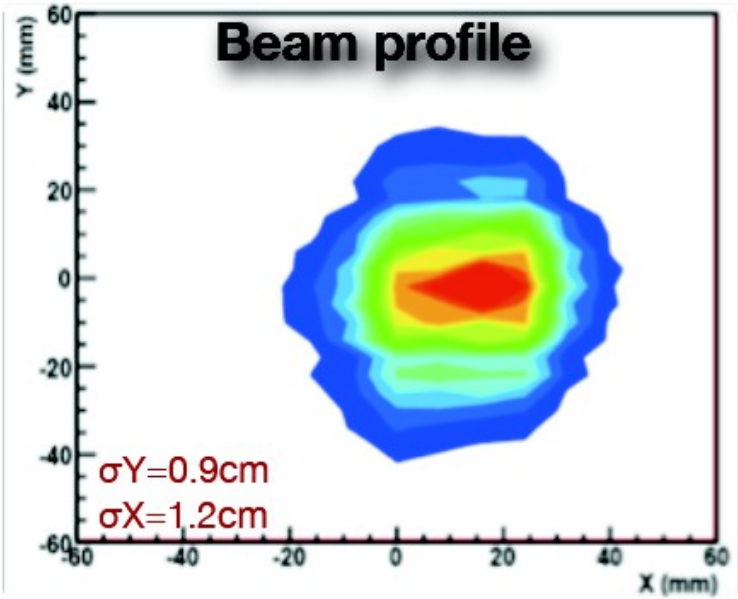
Experiment: Beamline

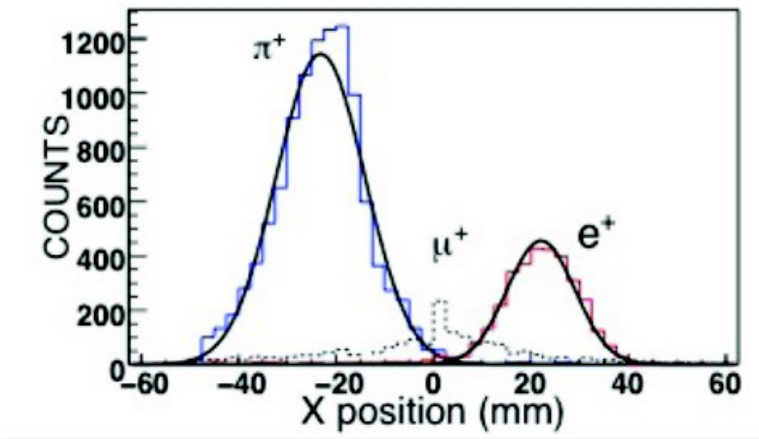


A. Aguilar-Arevalo et al. Nucl. Instr. and Methods A 609 (2009)

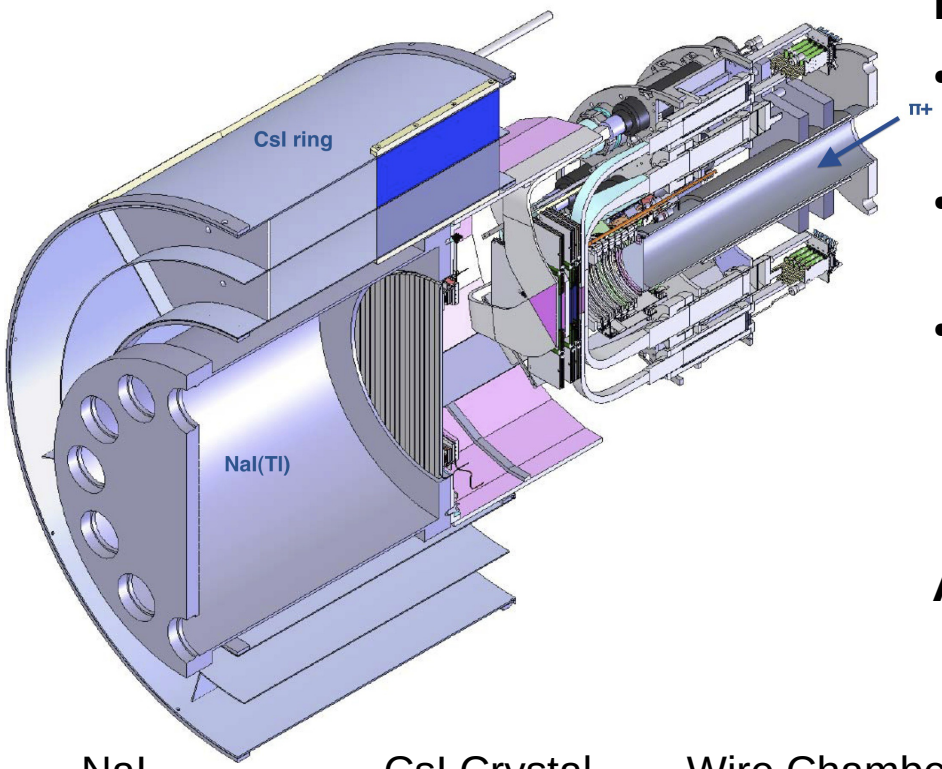
- **Beam positrons suppression**
  - Degrader after the first bending magnet
  - Collimator after the second one
  - Another magnet to avoid neutral particles produced in the collimator coming to the detector
- **Beam composition**
  - π (82%)
  - μ (14%)
  - e^+ (<2%)







Experiment: Realization



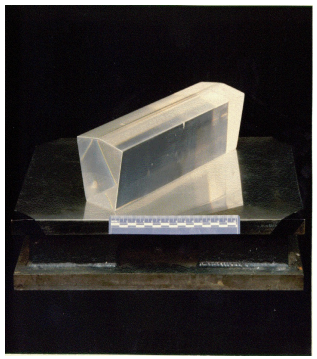
Mechanical Design and Realization

- NaI/CsI calorimeter needs to be mobile for response (lineshape) measurements
- Scintillator array modularity for test measurements
- Minimize scattering of the decay positrons and maximize acceptance

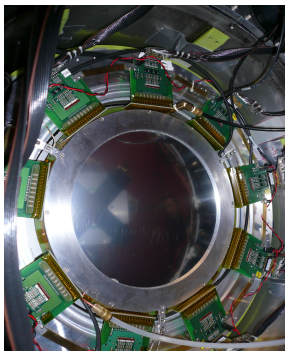
Assembled and commissioned in 05/2009

NaI

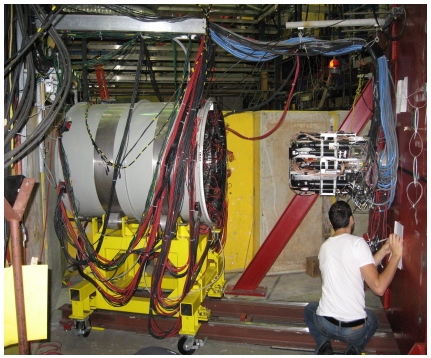
CsI Crystal



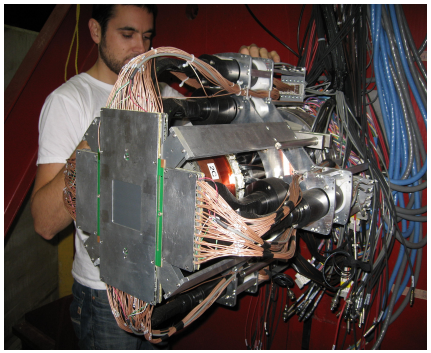
Wire Chamber



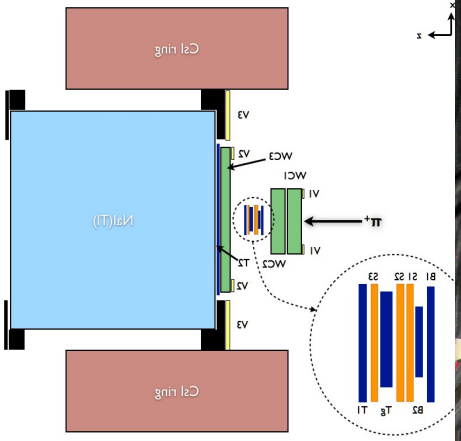
Detector

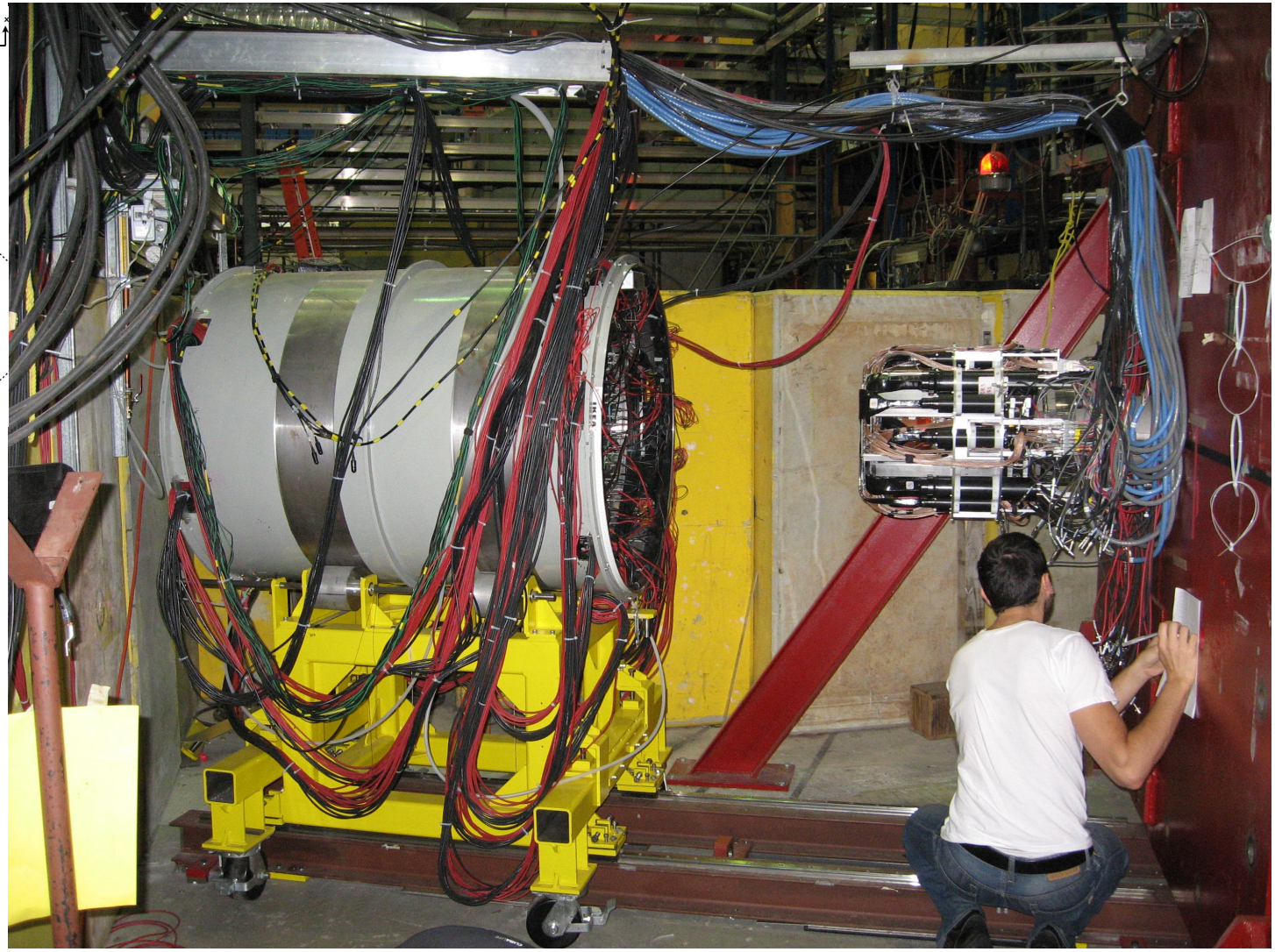


Scint + Si Strips

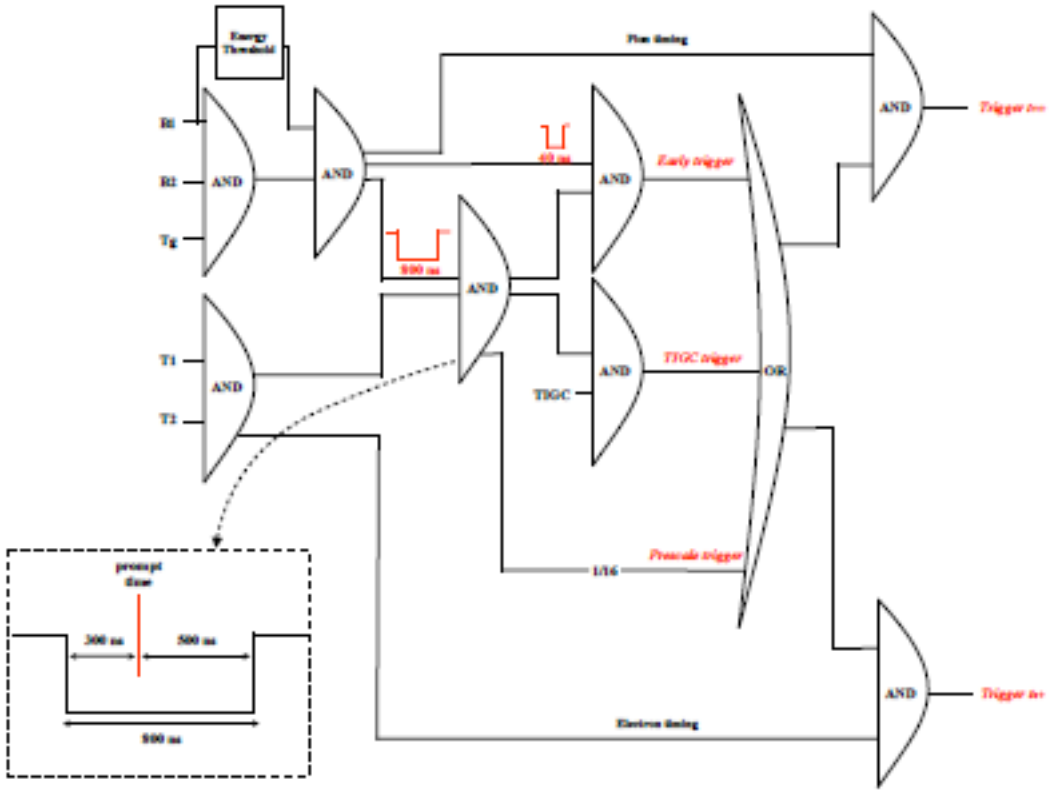


Experiment: Realization

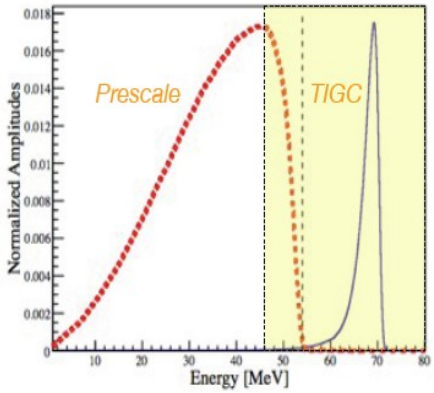


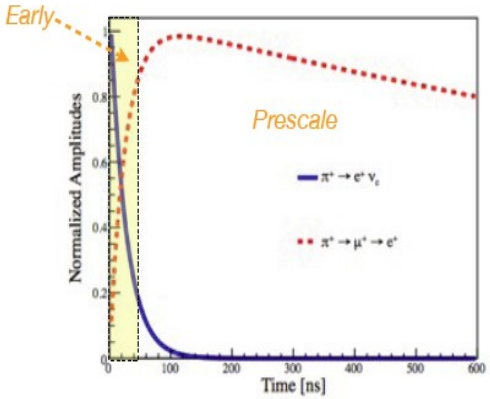


Experiment: Trigger



- NIM based logic
- Basic trigger (Prescale)
  - E_{inc} > thr
  - incoming/decay particles are in [-300,500]ns interval
  - Prescaled x16
- Early time: [4,40]ns
- TIGC (NaI+CsI>thr)
  - generated by a special VME module monitoring amplitudes in NaI/CsI channels





Experiment: Trigger and rates

Other Triggers:

- Cosmic trigger (CsI calibration)
- Beam positron (Energy calibration)
- Xe lamp trigger (CsI gain monitoring system)

Typical rates

	Rate [Hz]
Pion stop in target	5×10^4
Physics Triggers	
Early trigger	160
TIGC trigger	170
Prescale trigger	240
Other Triggers	
Cosmics trigger	15
Beam Positron trigger	5
Xe lamp trigger	2
Total Trigger	600

Experiment: History

Year	Month	Events
2005	Dec.	Proposal approved by TRIUMF
2006		Detector design and test
2007		Detector construction and beam tests in M9
2008	May	Beam test in M13
2008	Oct.	M13 beam channel extension completed
2008	Oct.-Nov.	Test in M13 with most of the detectors
2009	May	PIENU detector completed
2009	May-Sep.	Run-I (1M)
2009	Oct.-Dec.	Run-II (0.5M)
2010	March	Temperature controlled enclosure completed
2010	Apr.-Sep.	Run-III (4M)
2010	Oct.-Dec.	Run-IV (2M)
2011	Aug.	Systematic studies with beam
2011	Sept-Oct.	Lineshape measurements
2011	Nov.	Run-V (2M)
2012	Jul.-Dec.	Run VI (4M)

December 2012 was the last month of data collection

13-14M $\pi \rightarrow e\nu$ were collected (before analysis cuts)

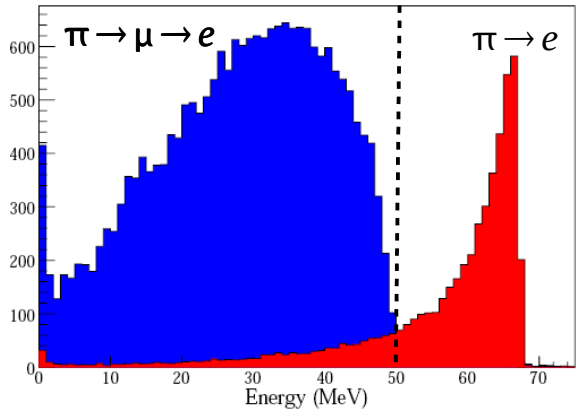
Analysis: Outline

- General Method
- Blind Analysis
- “Raw” branching ratio extraction
- Tail Correction
- Other corrections
  - Bhabha scattering
  - Muon decays-in-flight
  - Acceptance

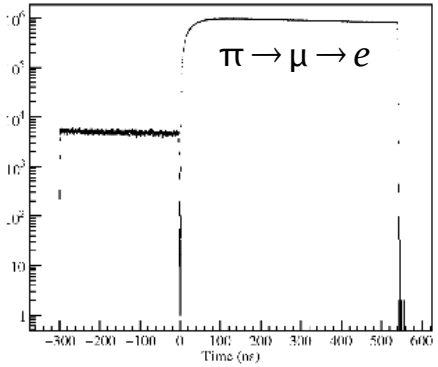
The results presented in the following are based on ~1/10 of the statistics collected and are PRELIMINARY

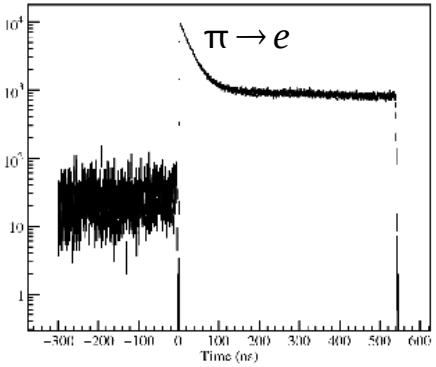
Analysis: Method

- Divide the Positron Energy Spectrum in 2 Regions



- Consider the Corresponding Time Spectra



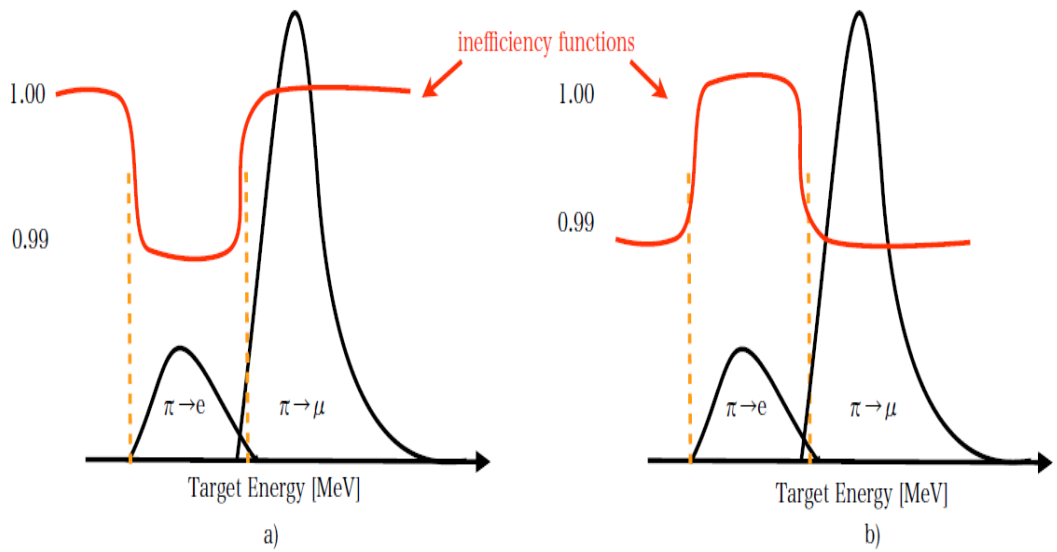


- Extract the BR by Fitting the Time Spectra Simultaneously
- Apply Corrections

Analysis: Data 2010

Before we start.....

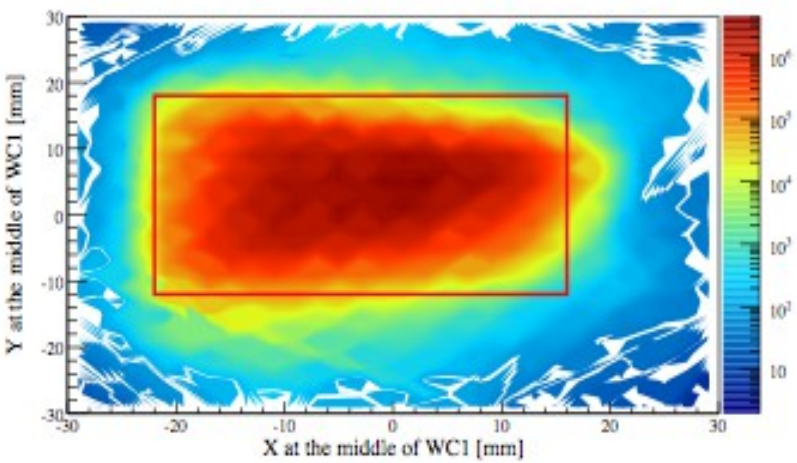
Data is blinded by altering the number (yield) of PIENU decays based on Target Energy

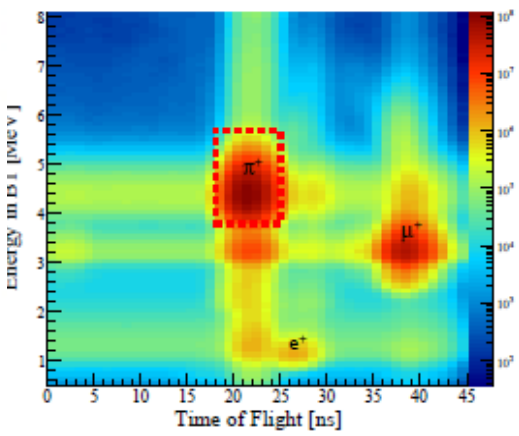


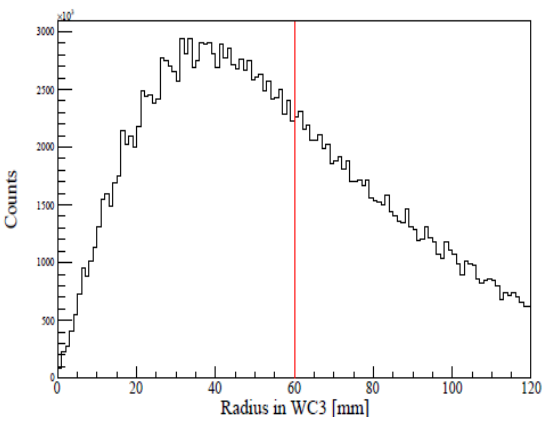
Analysis: Data 2010

Basic cuts:

- fiducial (beam profile in WC1,2)
- pion selection (dE/dX in B1, B2; TOF)
- pileup (no extra activity from -6.4us to the end of observation interval)
- acceptance

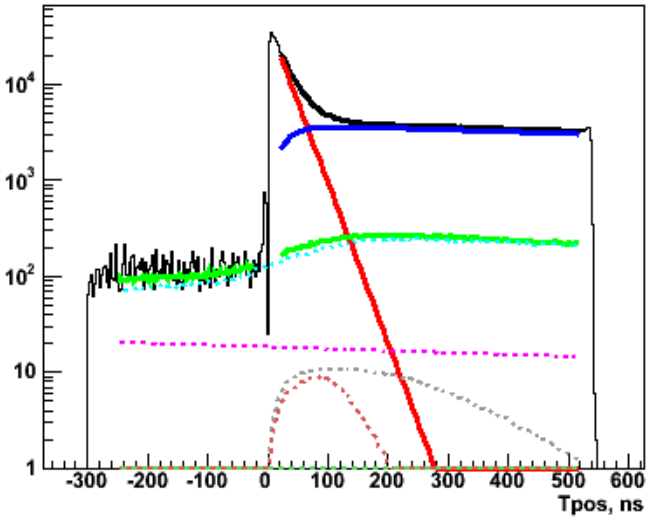


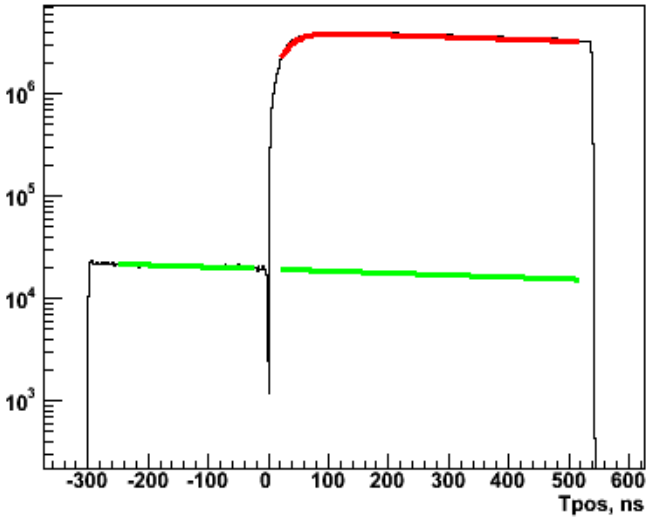




Analysis: Data 2010

- Simultaneous Fit of the Time Spectra:
  - Total χ^2/DoF = 1.1
  - t<0 region constrain backgrounds





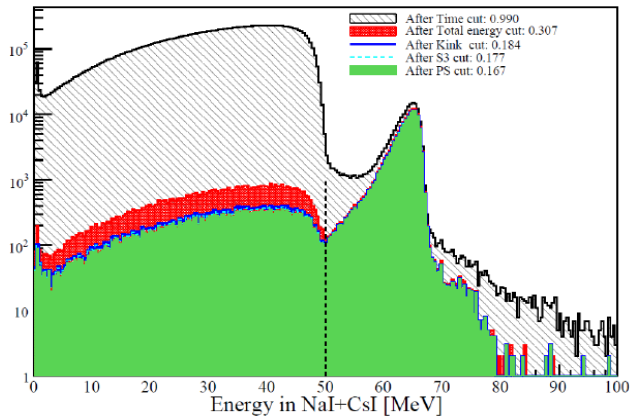
- Backgrounds
  - π→μ→e plus pileup
  - “old muon” plus NaI/CsI hit
  - “old muon” plus resolution
  - pion radiative decay

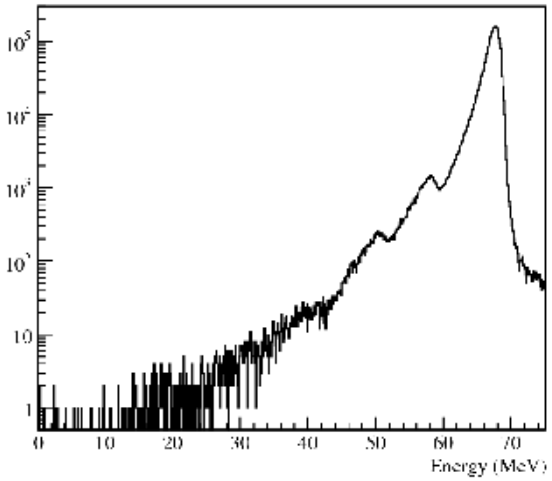
- Background
  - “old muon” decays

Analysis: Tail Correction

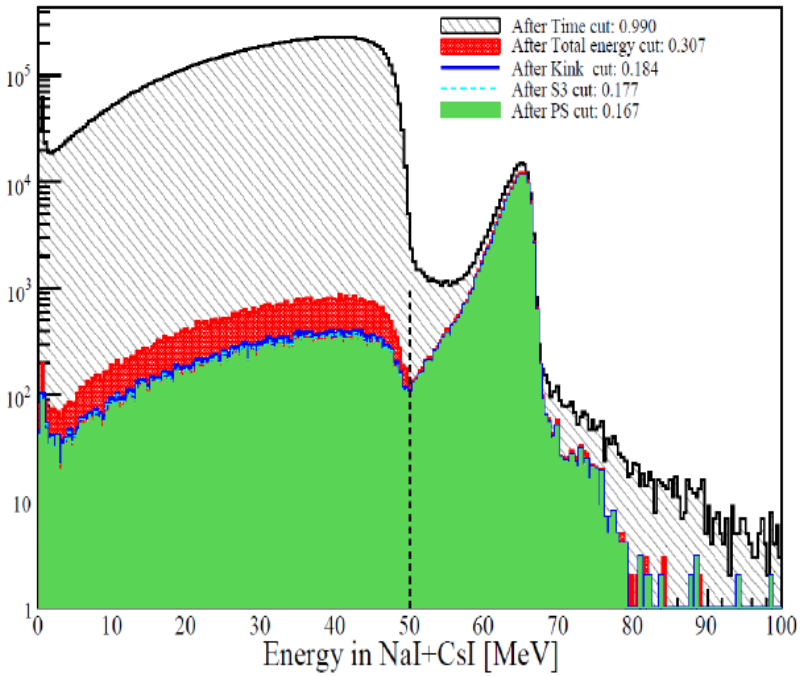
Low energy Tail correction

- Most significant correction (~2%)
- Two approaches are taken:
  - Lower limit value (direct observation using data with π→μ→e suppressed, i.e. Suppressed Spectrum)
  - Upper limit value (modelling based on special lineshape data when NaI/CsI is exposed to positron beam at different angles)



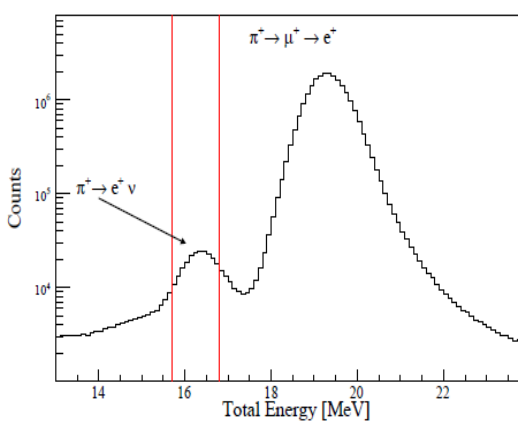


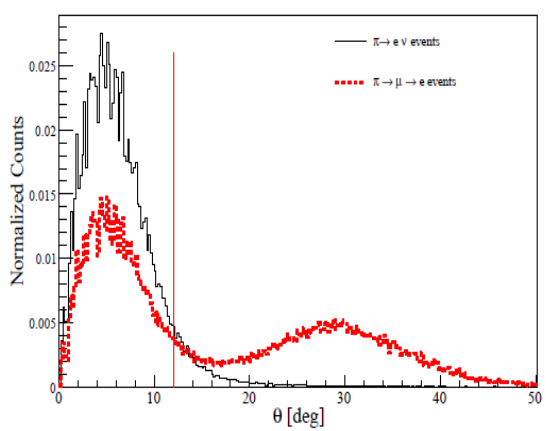
Analysis: Lower Limit

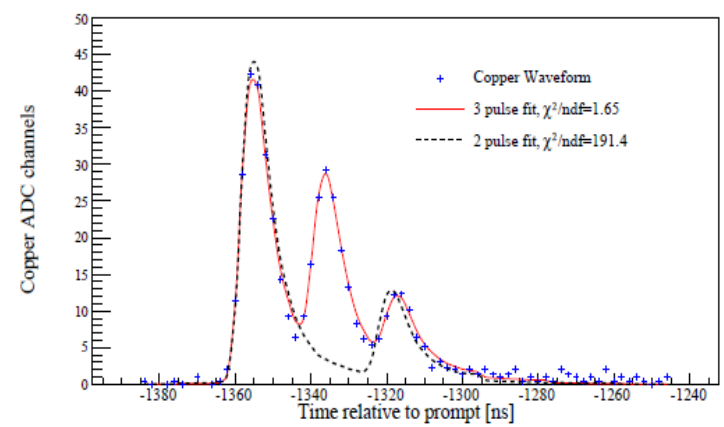


- Cuts applied to final energy spectrum to further suppress π→μ→e:

Cuts	Low energy fraction [%]	Signal efficiency [%]
Time	99.0	82.85
Total Energy *	30.7	76.80
Kink	18.4	93.14
S3 *	17.7	99.99
Pulse Shape *	16.7	99.46

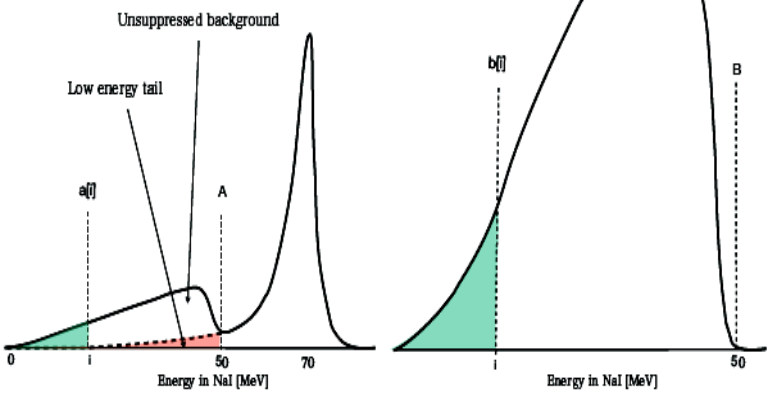






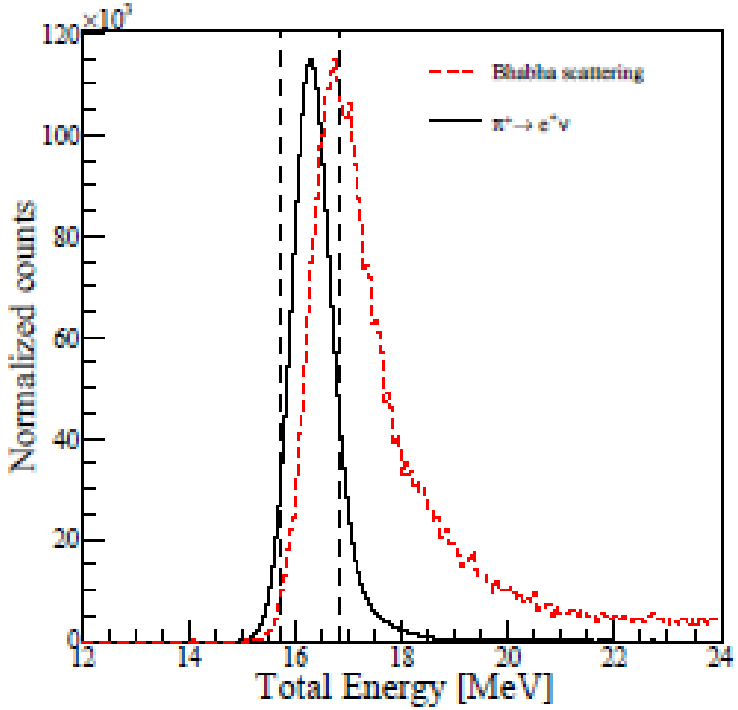
Analysis: Lower Limit

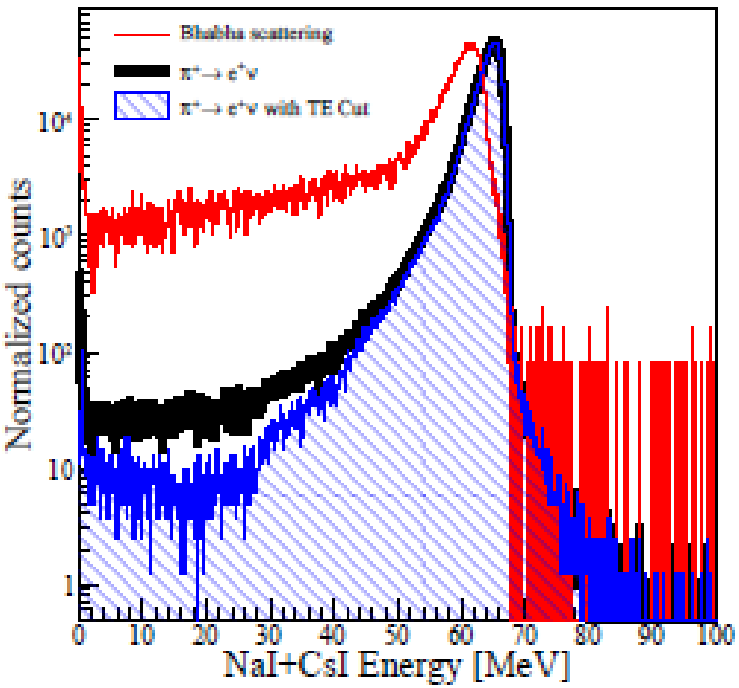
$$Ll[i] = A - a[i]\frac{B}{b[i]}$$



- Tail can be estimated if background shape is known
- Background events: piDIF, muDIF
- piDIF shape obtained from data (late decays)
- muDIF is MC
- Target total energy cut removes a fraction of Bhabha scattering events, this is accounted for later when final tail correction value is calculated

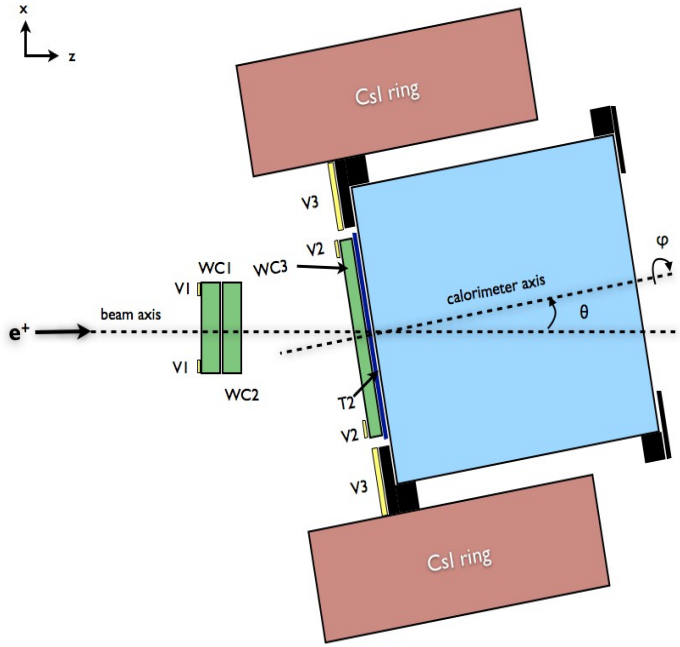
Analysis: Bhabha Correction

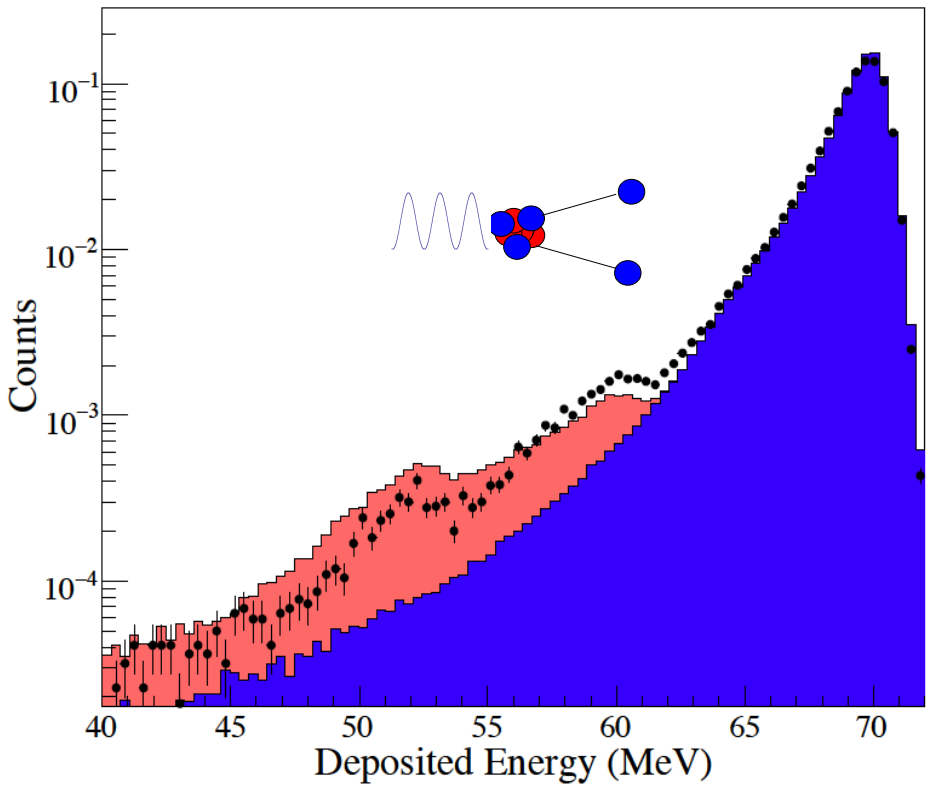




- MC based
- +0.70% to tail fraction

Analysis: Upper Limit





First observation of the **PHOTO-NUCLEAR** peaks in NaI crystal response to monochromatic positron beam

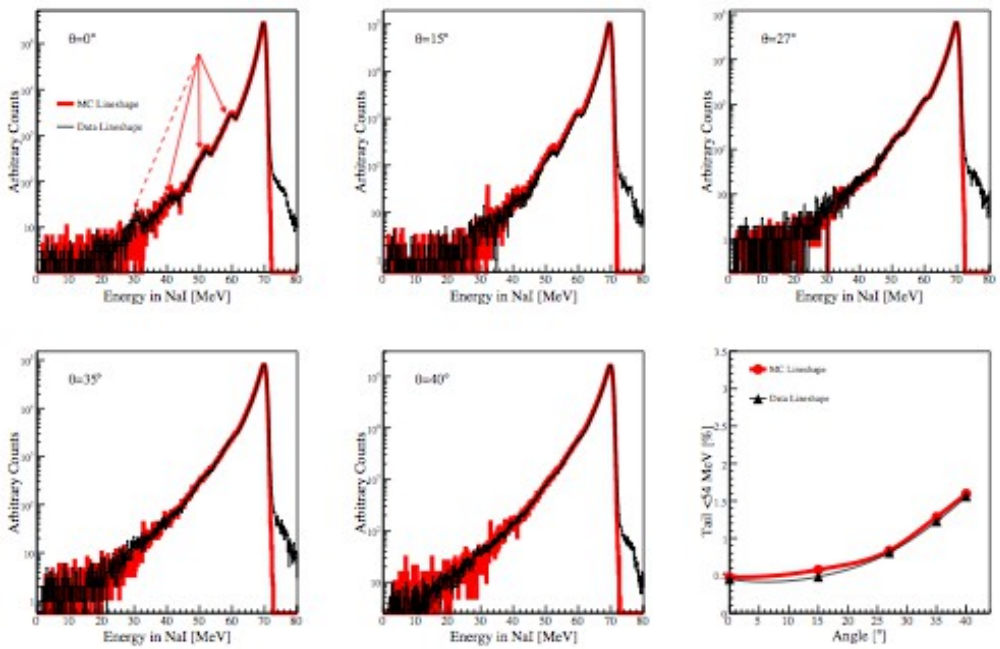
Peaks are consistent with neutrons escaping

A. Aguilar-Arevalo et al. Nucl. Instr. and Methods A (2010)

This effect isn`t properly modeled in G4 and influences the amount of low energy tail

MC without hadronic interactions
MC with hadronic interactions
Data (closed circles with error bars)

Analysis: Upper Limit



- NaI/CsI was exposed to a monochromatic 70MeV positron beam at different angles
- Energy spectra were used to tune MC (no Hadronic interactions) to reproduce the main peak
- The difference between the number of tail events in MC and data for each angle was parametrized
- Tail value is calculated as MC tail plus photo-nuclear correction based on parametrization of difference above

Because positron beam has finite momentum bite and possibly tails in momentum distribution this method overestimates the amount of tail events(Upper Limit)

Analysis: Tail Correction Summary

- Lower limit 0.87±0.12%
  with Bhabha correction 1.57±0.12%(stat.+syst.)
- Upper limit 1.7±0.1%(syst.)

- Procedures are not finalized yet but we seem to be able to control systematics at desired level

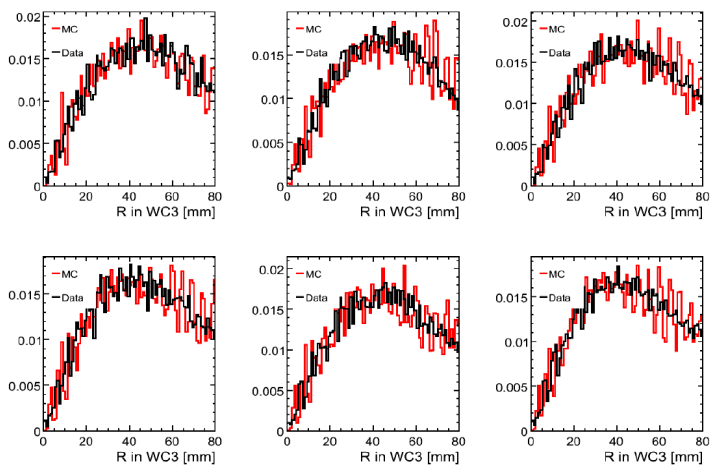
Analysis: Acceptance Correction

Acceptance Correction is small, but has to rely on the MC

Various systematic effects are estimated. Deviations are within statistical uncertainty.

MC validation effort focusing on
- Bhabha scattering
- Multiple scattering
- Annihilation in flight

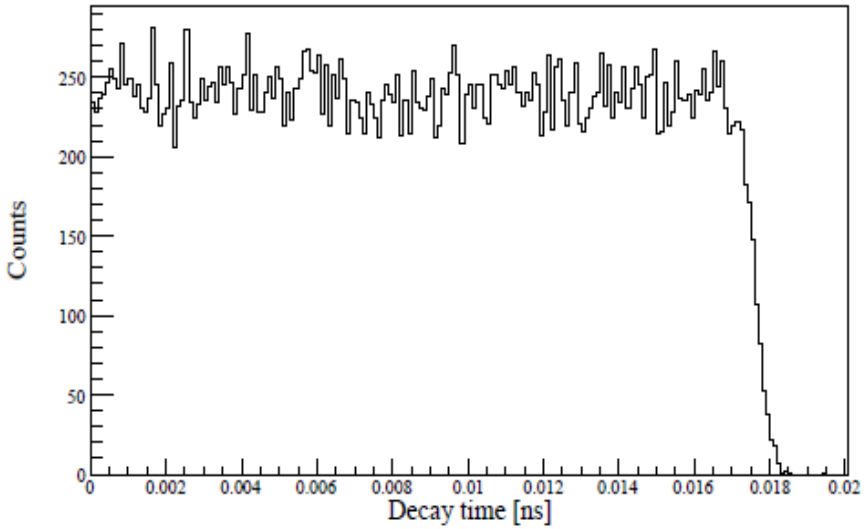
Is underway...

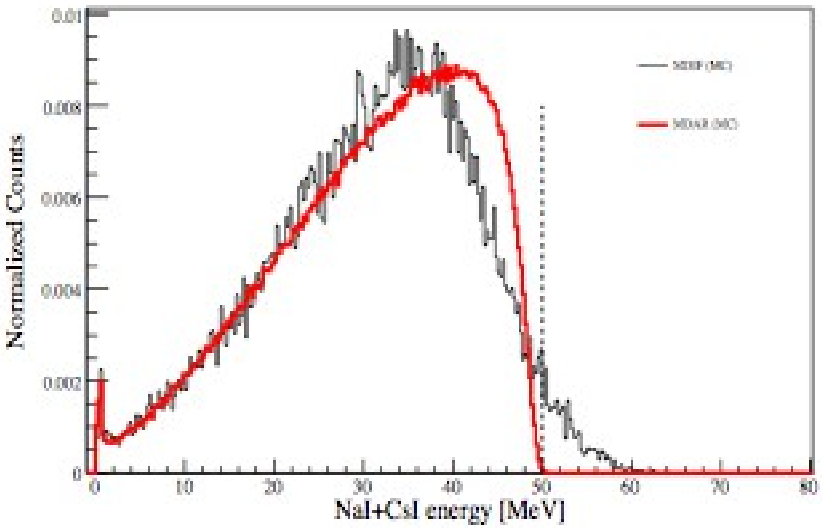


R at WC3 for various π^+ momenta

Case	Description	Ratio of acceptances at R=60 mm
π stop in Tg	[mm]	
I.a)	z = 0.08 (nominal)	0.9994
I.b)	z =+1	0.9997
I.c)	z =-1	0.9993
I.d)	σ=1%	0.9996
Displacement	[mm]	
II.a)	z WC3 =+2	1.0000
II.b)	z WC3 =-2	0.9999
II.c)	z S3 =+0.2	0.9995
II.d)	z S3 =-0.2	0.9992
III.a)	x WC3 =+0.2	0.9988
III.b)	x WC3 =-0.2	0.9996
III.c)	y WC3 =+0.2	0.9997
III.d)	y WC3 =-0.2	0.9997
III.e)	x S3 =+0.02	0.9996
III.f)	x S3 =-0.02	0.9998
III.g)	y S3 =+0.02	1.0002
III.h)	y S3 =-0.02	0.9999

Analysis: muDIF Correction





- Positrons from muDIF can have energy above Michel end point, their time distribution is the same as for $\pi \rightarrow e\nu$
- They are indistinguishable from $\pi \rightarrow e\nu$
- MC based correction is applied
- 0.9976±0.0002 in value

Analysis: Other Systematics

Other Systematics:

- Energy dependence of t_0
- Tracking detector inefficiencies and acceptance
- WC3 inefficiency
- S3 inefficiency
- Multiple hits in WC3

Found to be negligible

Analysis: Correction Summary/Results

Process	Correction	Uncertainty stat.	Uncertainty syst.
"Raw" Branching ratio ($\times 10^{-4}$)	[redacted]	0.003	0.0010
t_0 energy dependence	$\times 0.9993$	/	0.0007
Muon Decay in Flight	$\times 0.9976$	/	0.0002
Low energy tail	$\times 1.0173$	/	0.0010
Acceptance correction	$\times 0.9998$	/	0.0006
Total Correction	$\times 1.0139$	/	0.0014
Total Branching Ratio	[redacted]	0.003	0.0020

PRELIMINARY

$$R^{exp}_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)} = ([redacted] \pm 0.003\ (stat.) \pm 0.002\ (syst.))\ x\ 10^{-4}$$

Analysis is in progress. Further possible improvements:

- looser pileup cuts (increase statistics; 40% is removed by it)
- better acceptance optimization
- better technique to extract tail and acceptance corrections

Analysis: Massive neutrinos in $\pi^+ \rightarrow e^+\nu$

Suppressed spectrum

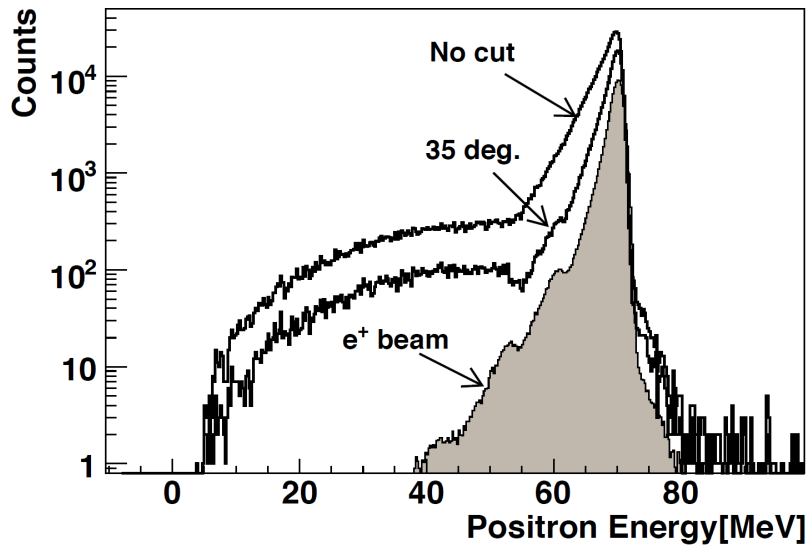
Massive ν_i will appear as additional peak in the $\pi \rightarrow e^+\nu$ energy spectrum

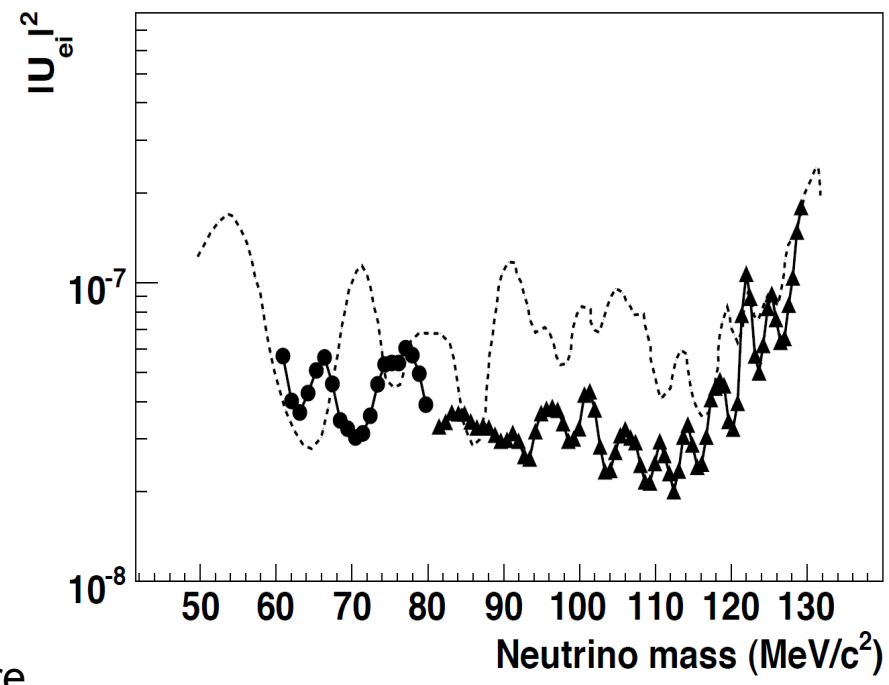
Heavy ν

Kinematic factor

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

Conventional ν





no extra peaks due to ν_i found, and limits are obtained:

Further improvement is possible with more statistics and better understanding of the lineshape

M. Aoki et al. Phys. Rev. D 84, 052002 (2011)

Summary

- All the correction estimation results are preliminary and the “raw” branching ratio blind analysis correction is not revealed yet!
- PiENu experiment at TRIUMF finished collecting data Analysis is under way
- Systematics is under control, factor of 10 more statistics available
- Results are coming out

A. Aguilar-Arevalo et al. Nucl. Instr. and Methods A 609 (2009)

A. Aguilar-Arevalo et al. Nucl. Instr. and Methods A (2010)

M. Aoki et al. Phys. Rev. D 84, 052002 (2011)

- We are moving toward achieving the goal of <0.1% accuracy on $R_{e/\mu}^{\exp} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)}$ measurement

EOP

Thank you!