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 Sensitive Probe of New Physics

Aleksey Sher
for the PIENU collaboration
DPF 2013, Santa Cruz

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2. Brookhaven National Laboratory
3. KEK
4. Osaka University
5. TRIUMF
6. University of British Columbia
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10. Tsinghua University
11. Instituto de Ciencias Nucleares
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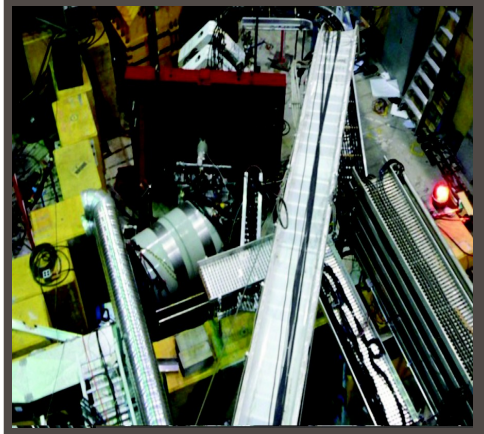


Outline

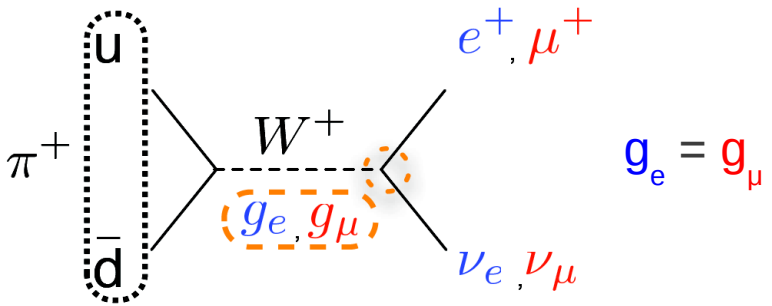
- Motivation
- Experiment
- Analysis
  - Lineshape
  - Massive neutrinos
  - $\pi^+ \rightarrow e^+\nu$
- Conclusion

Motivation: Decays $\pi^+ \to e^+\nu$ and $\pi^+ \to \mu^+\nu$

Standard Model:

V.Cirigliano, I. Rossel, Phys. Rev. Lett. 99, 231801 (2007)

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



Calculated to extreme precision 0.01%

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

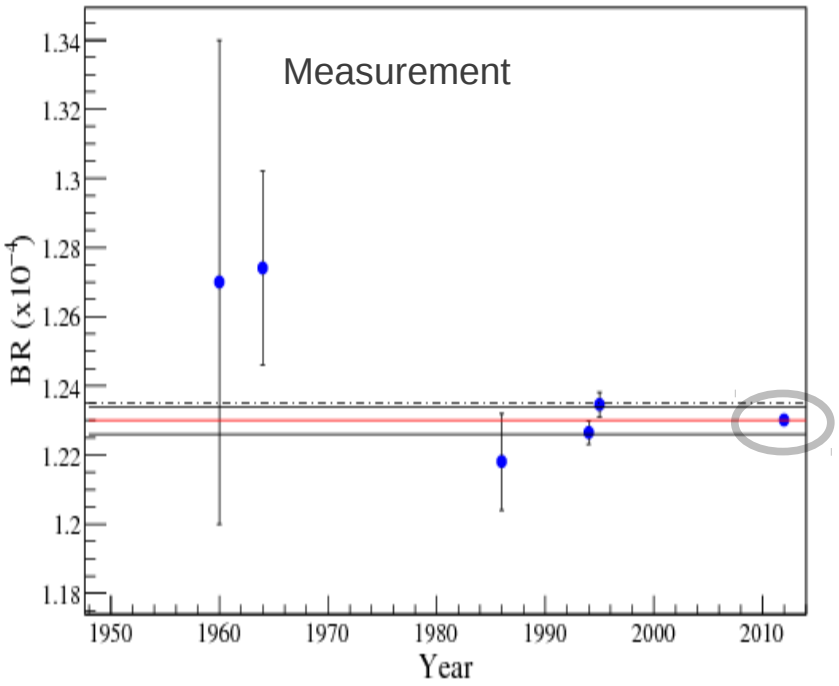
Experimental result:

TRIUMF: D. I. Britton et al., Phys. Rev. D 49, 28 (1994)
PSI: G. Czapek et al. Phys. Rev. Lett. 70:17-20,(1993)

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

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

PIENU: aims at <0.1% in BR measurement



Time

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 v'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)

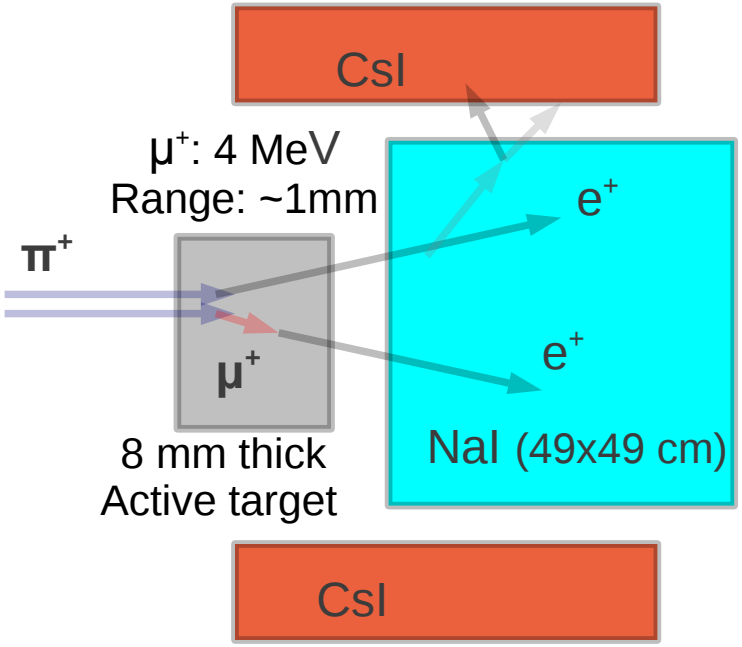
…..

Decay mode	(g_μ/g_e)
$\tau\to\mu$ / $\tau\to e$	1.0018 ± 0.0014
$\pi\to\mu$ / $\pi\to e$	1.0021 ± 0.0016
$K\to\mu$ / $K\to e$	0.998 ± 0.004
$K\to\pi\mu$ / $K\to\pi e$	1.002 ± 0.002
$W\to\mu$ / $W\to e$	0.997 ± 0.010

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

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

Experiment: technique



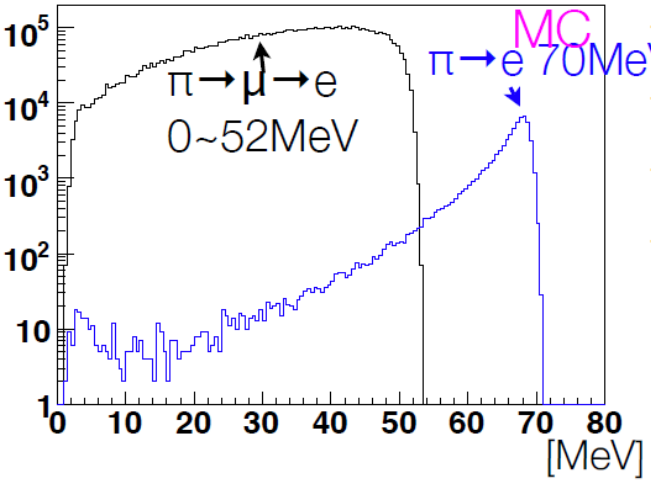
Stop pions in an active target
Measure decay e^+ energy and time

Discrimination of the decay mode
- Energy deposit in calorimeter
- Energy deposit in target

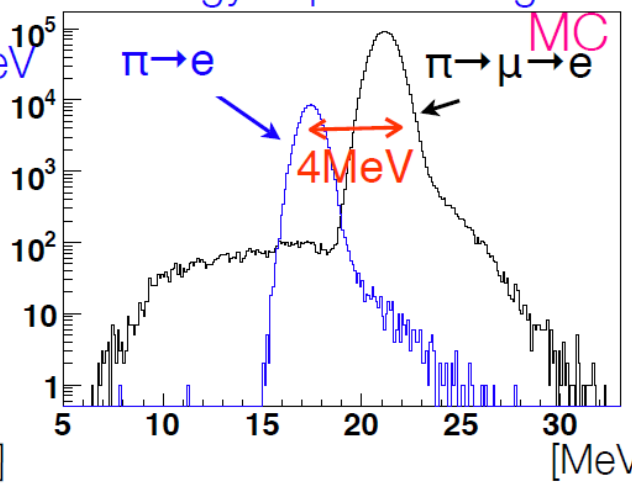
Estimation of raw branching ratio
- Simultaneous fitting of time spectra
  pi-e and pi-mu-e (high and low energy region)

Important:
Tail correction pi DIF Acceptance

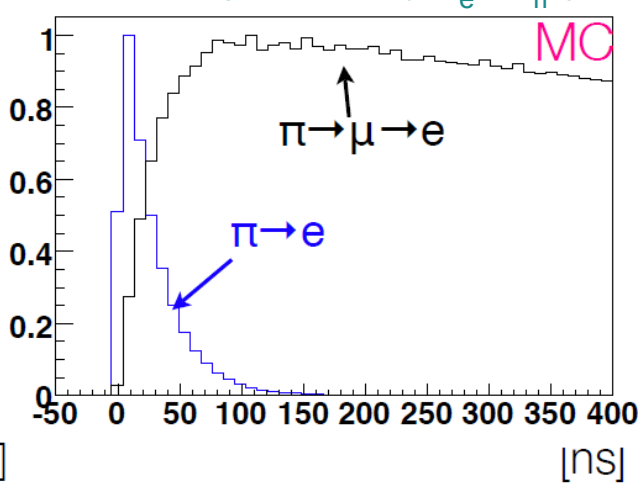
Energy deposit in calorimeter



Energy deposit in target



Time spectrum $t_e - t_\pi$



Experiment: detector concept

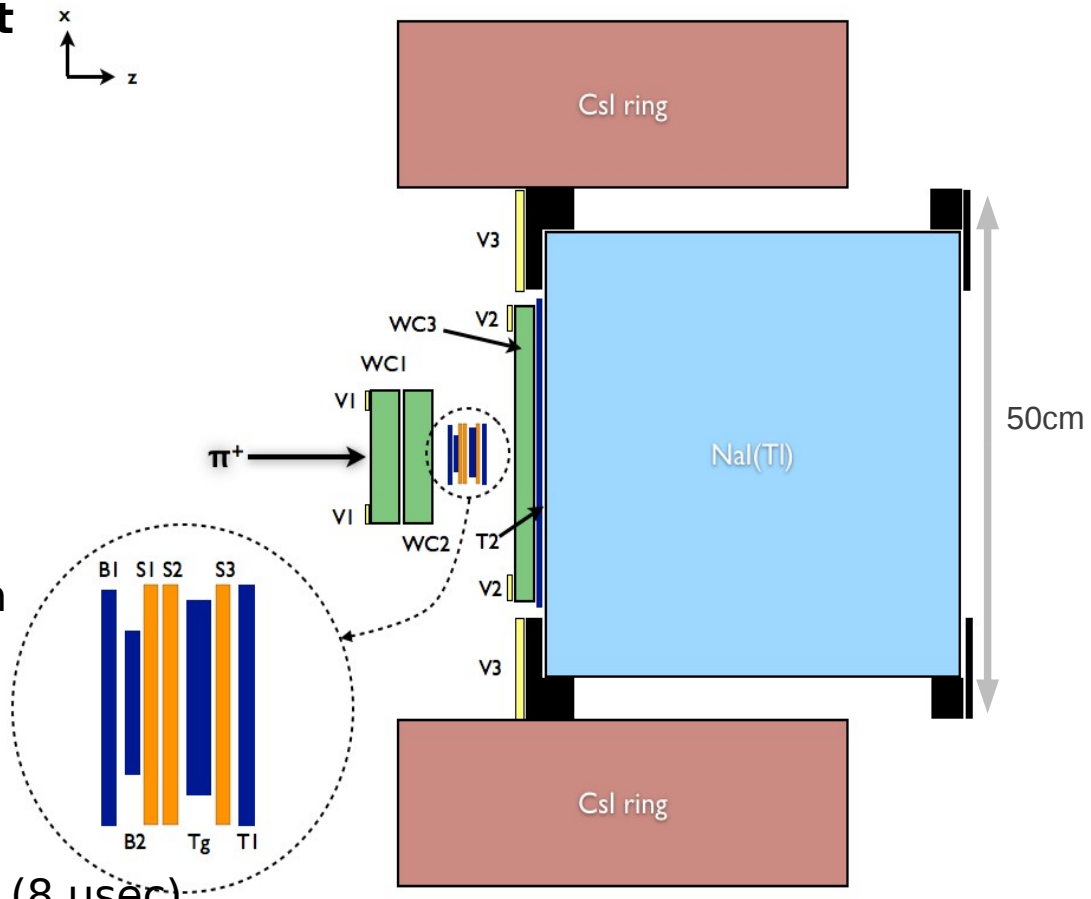
Large NaI crystal near target
- Large solid angle(25%)
- High resolution: ~1% σ at 70 MeV/c

CsI crystal array (annular)
- Reduces e+ low energy (<50 MeV) tail (8%->2%)
- Additional pile up rejection

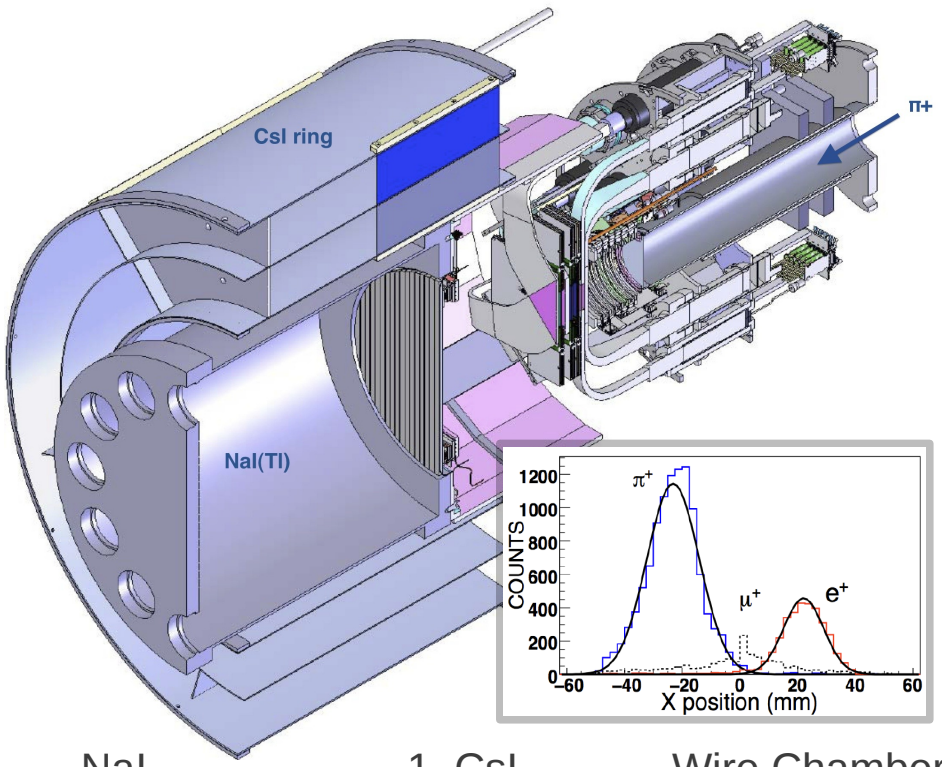
Si-strips + MWPC
- Tracking of particles upstream and downstream of the target
- Reduces π decays in flight

Fast readout modules
- 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: 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

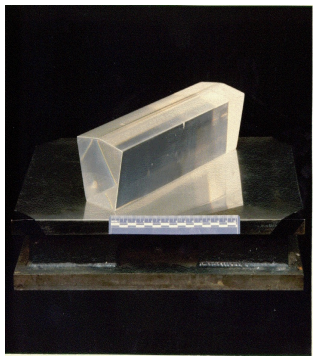
High purity π^+ beam at TRIUMF

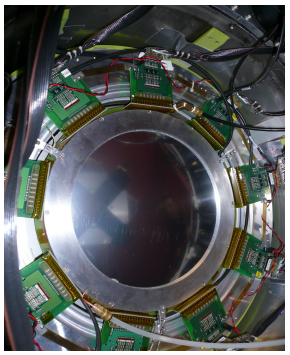
e^+ suppression (x100) by introduction of a Lucite degrader in the 75 MeV/c beamline, and a lead collimator at the focus of the third bending dipole (~10m after the production target)

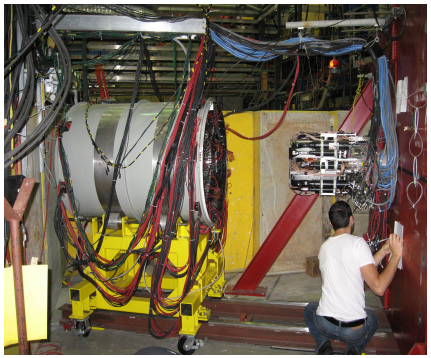
A. Aguilar-Arivalo et al. Nucl. Instr. and Methods A 609 (2009)

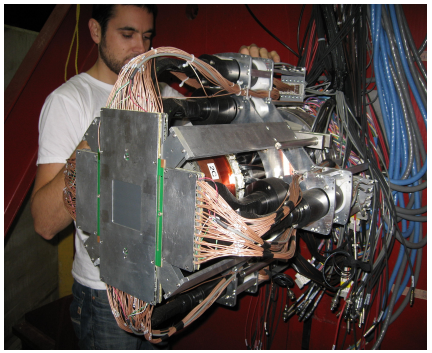
Assembled and commissioned in 05/2009

NaI | 1 CsI | Wire Chamber | Detector | Scint + Si Strips









Experiment: data taking

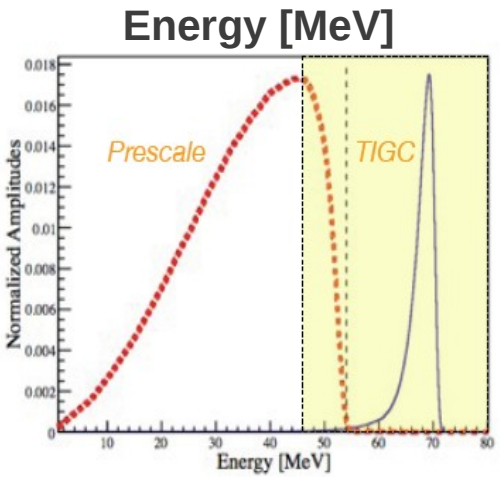
Beam:
50 Khz pion stops in the target

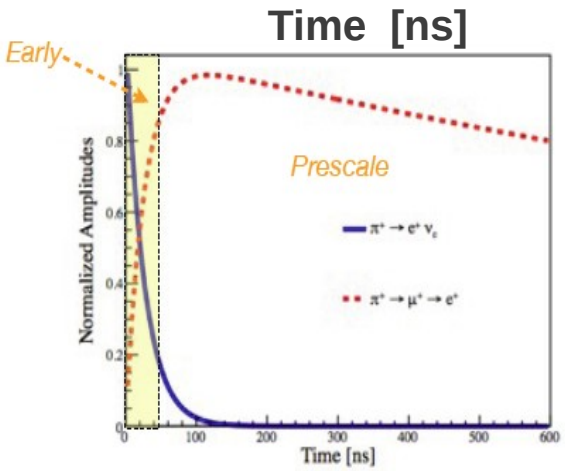
Triggers:
600 Hz during normal data taking

$\pi \rightarrow e\nu$
NaI + CsI > 46 MeV
OR
Early decay time (4-40ns)

$\pi \rightarrow \mu \rightarrow e$
Prescale: x16

Auxiliary: Cosmic, e+, Xe lamp

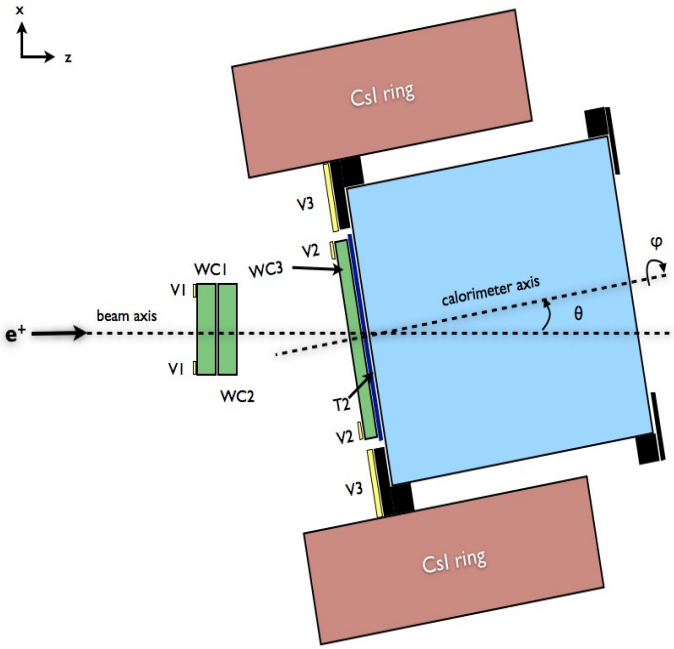




Inspection interval is -300 to +500 ns

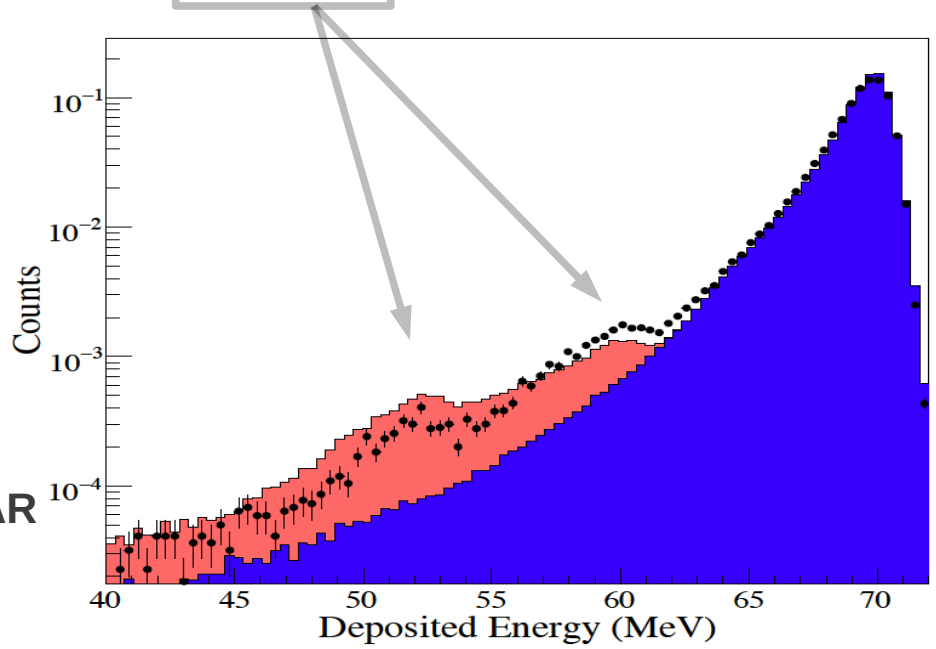
Information recorded by 500 MHz digitizers for all plastic scintillators in the range of (-6 μs;+2μs) around π^+ time.

Analysis: NaI lineshape



NaI+CsI array response function measurement using beam e^+

Additional structures are seen at low incident angles



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

Peaks are consistent with neutrons escaping

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

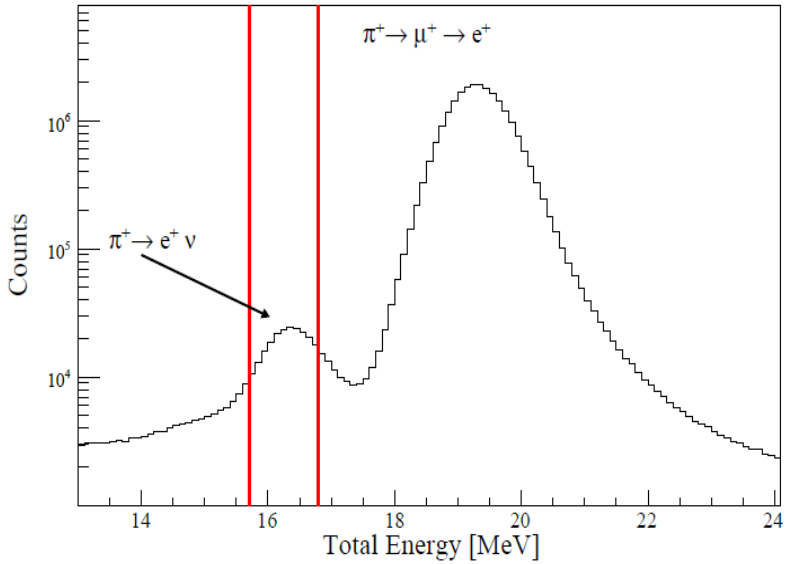
This effect isn't properly modeled in G4 and influences the amount of low energy tail

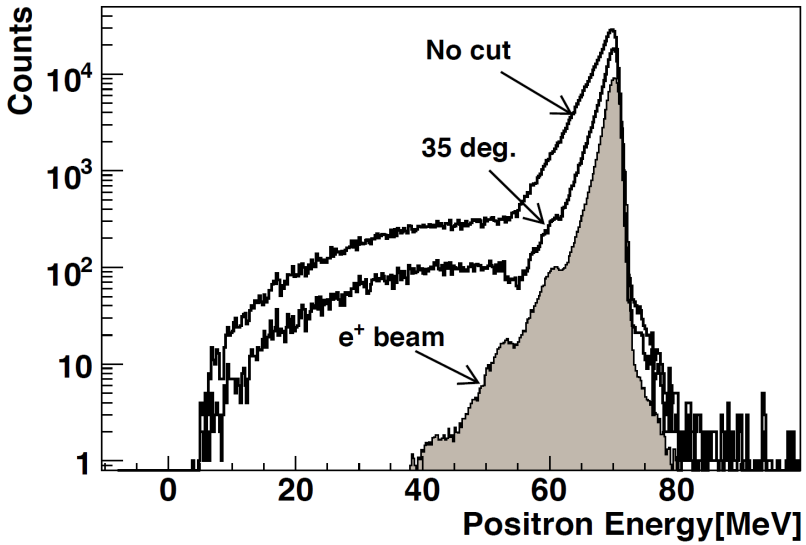
MC without Hadronic interactions
MC with Hadronic interactions
Data (closed circles with error bars)

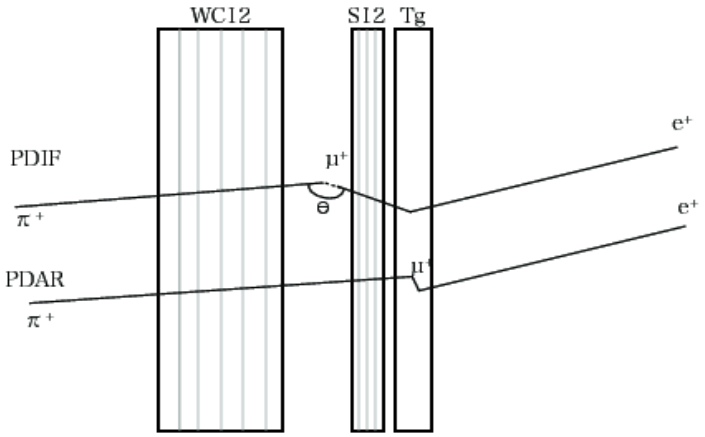
Analysis: Massive neutrinos in $\pi^+ \rightarrow e^+\nu$

A heavy sterile neutrino will appear as an extra peak in the $\pi^+ \rightarrow e^+\nu$ energy spectrum.
$\pi^+ \rightarrow \mu^+ \rightarrow e^+$ background is the problem

- timing (2-33 ns)
  τ= 26ns and 2.2 μs for π^+ and μ^+
- Energy deposit in beam + Target counters
- kink in the incoming particle trajectory
  π^+ decays in flight
- acceptance improves peak resolution



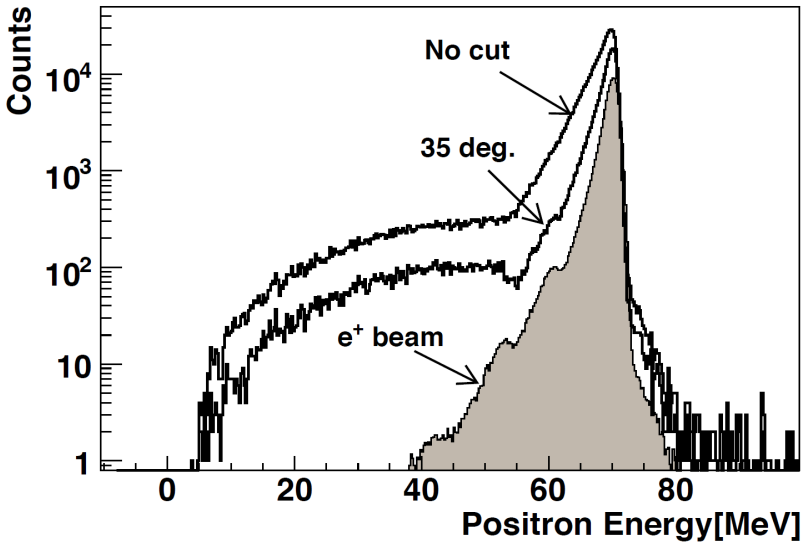




Pion **D**ecays **I**n **F**light (PDIF) diagram

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

Suppressed spectrum

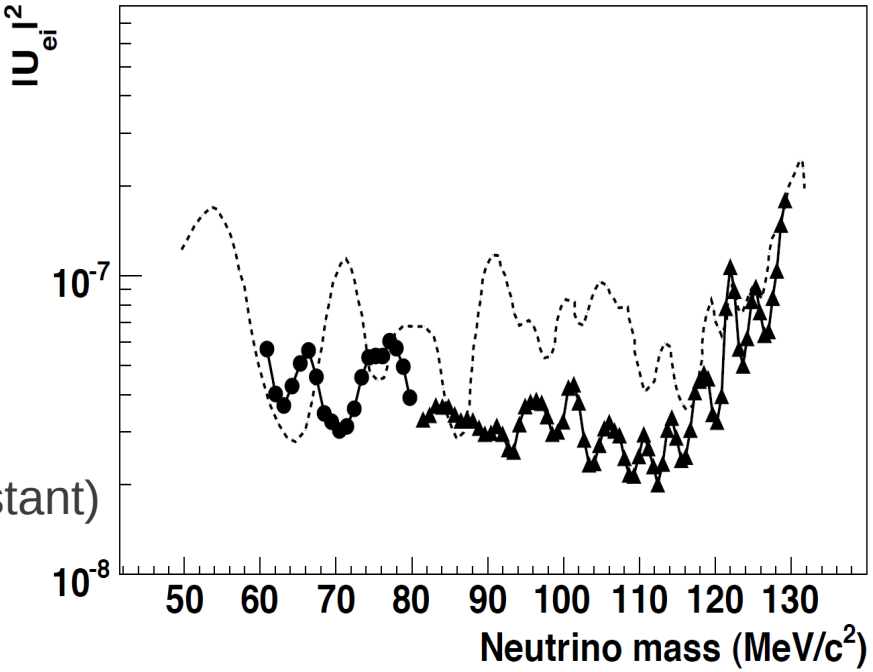


Heavy ν

Kinematic factor

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

Conventional ν



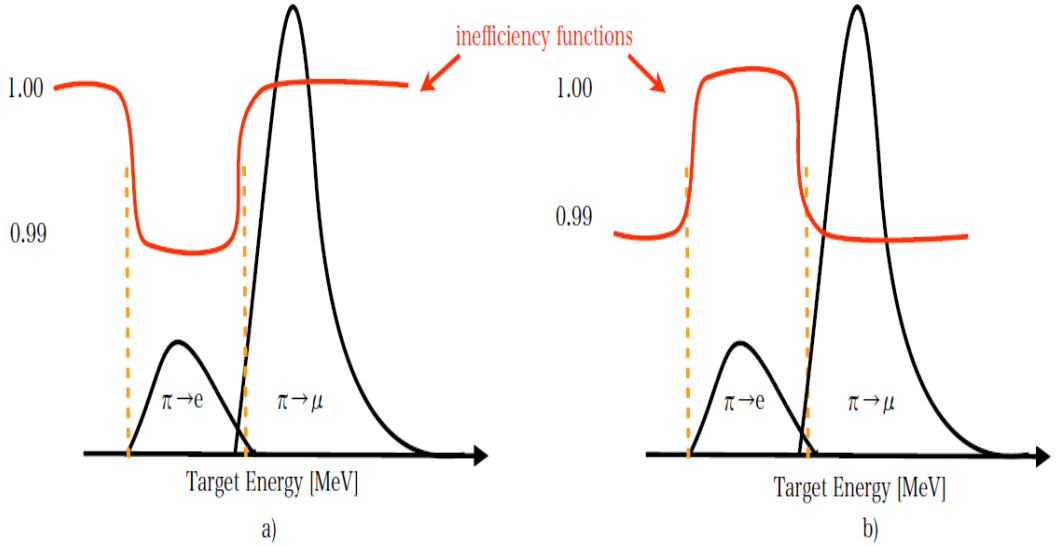
Spectrum is fitted with:
- PDIF
- MDIF
- Smooth background (exponent + constant)
- Heavy neutrino peak

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

Analysis: PIENU 2010 data

Before we start.....

Data is blinded by altering the number (yield) of PIENU decays



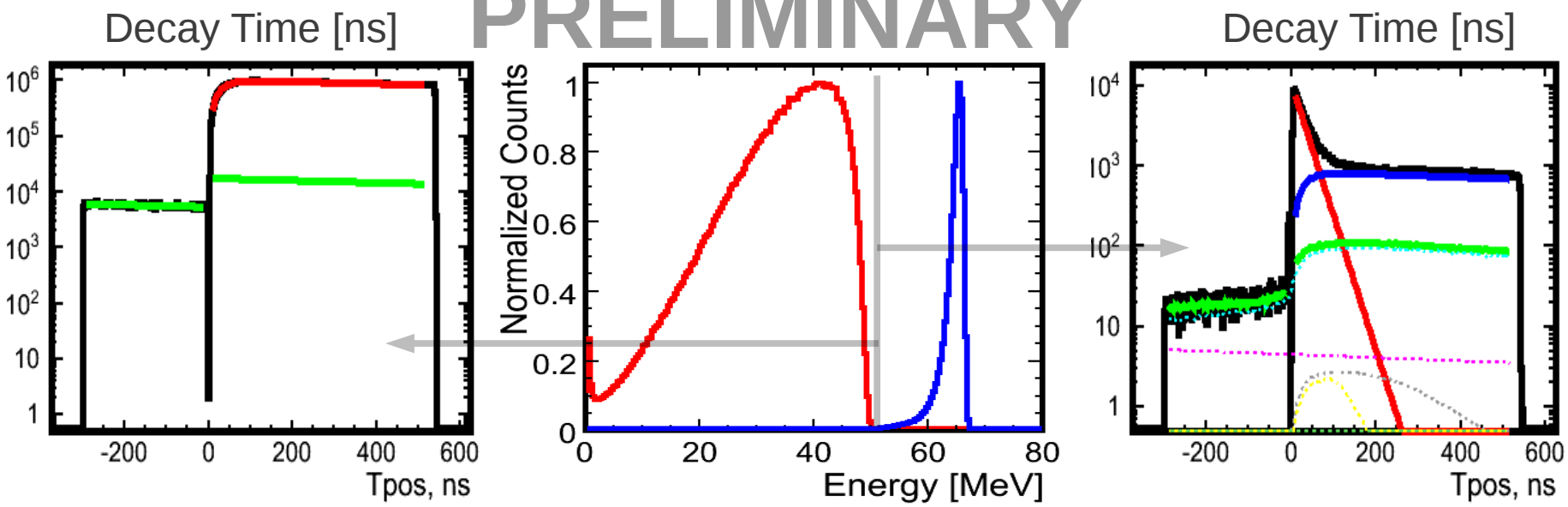
Very basic selection after calibration is done and waveforms are fitted

- π^+ using dE/dx, TOF
- Pileup cuts
- Fiducial cuts

Analysis: PIENU 2010 data

Br is extracted from the Time Spectrum fit of low and high Energy region

PRELIMINARY



- Fit is simultaneous (-290ns:530ns)
- Backgrounds are included
- Common χ^2 is minimized

Br^{blind} still to be corrected for:
- low energy tail
- Energy dependent Acceptance
- Muon Decay In Flight correction

Reduced χ^2 =1.07

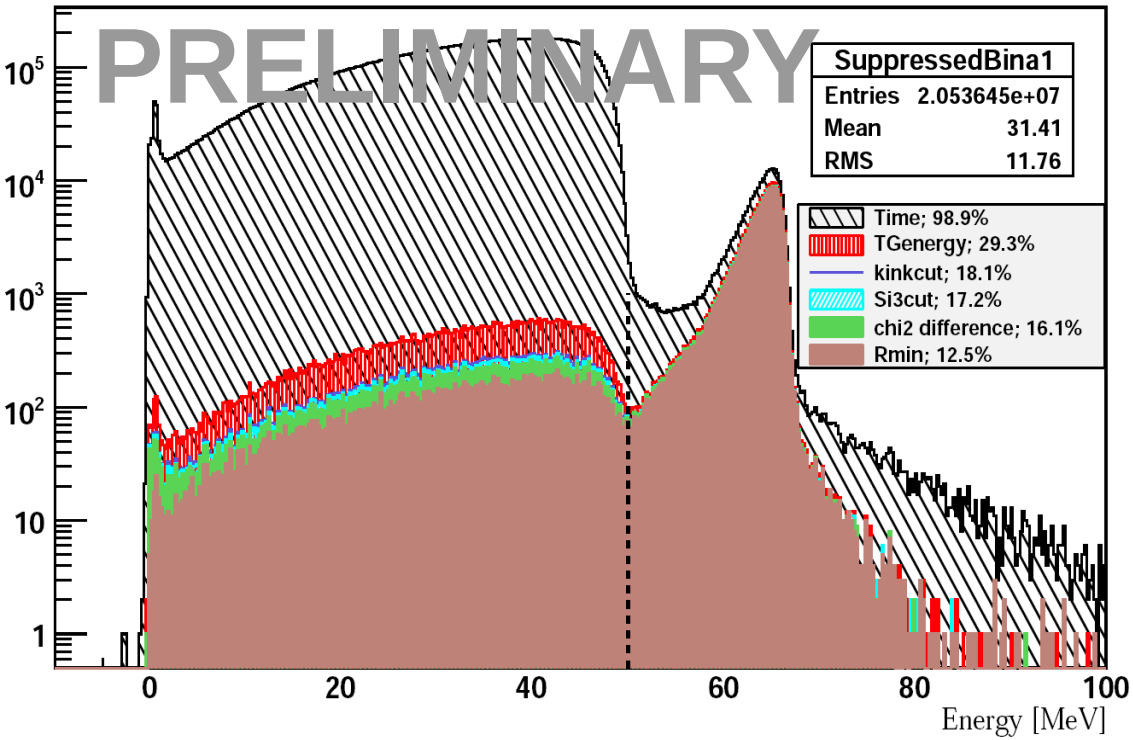
Br^{blind} = 1.2XXX(23) x 10^{-4}

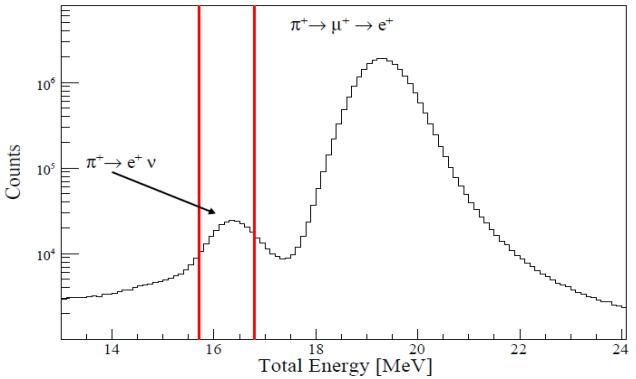
Systematic effects of the fit are being finalized

Analysis: tail correction

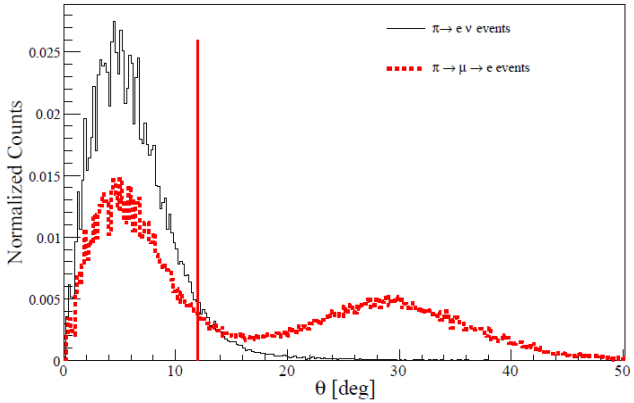
Tail Correction: amount of $\pi \rightarrow e\nu$ events missing from the high energy region

Suppressed spectrum: $\pi \rightarrow e\nu$ energy spectrum with $\pi \rightarrow \mu \rightarrow e$ background highly suppressed is used to produce a lower limit on the tail correction





Total Energy recorded in the Target and upstream detectors



Angle of the 'kink' in the reconstructed track, entering the Target

$\pi \rightarrow \mu \rightarrow e$ is suppressed by a factor of ~10^5

Lower limit Tail fraction: $T^{\text{Lower Limit}} = (1.13 \pm 0.07(\text{stat}) \pm 0.1(\text{syst}))\%$

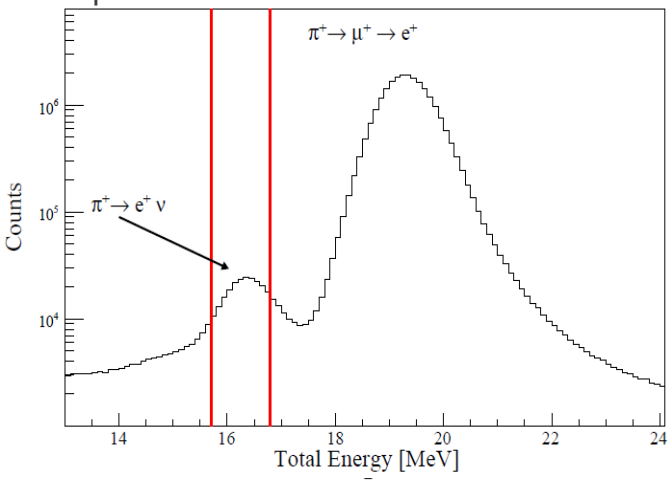
Analysis: tail correction

TG cut Correction: amount of $\pi \rightarrow e\nu$ tail events missing from the suppressed spectrum due to the Total Energy cut.

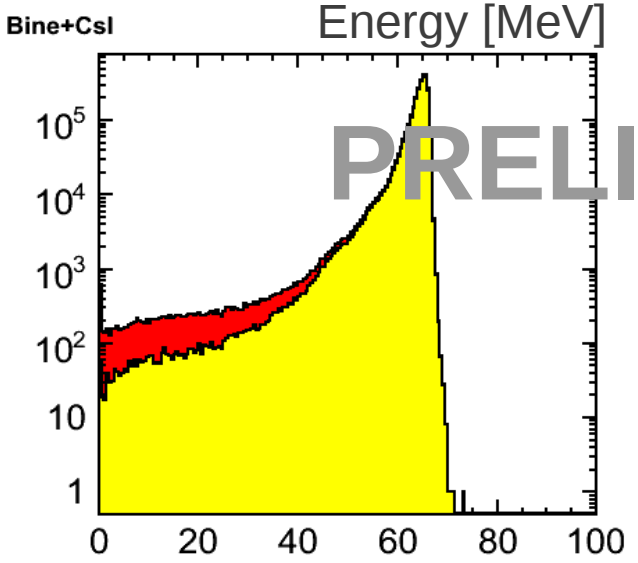
Majority of higher Total energy $\pi \rightarrow e\nu$ decays are events with Bhabha scattering in the target

$T^{Bhabha} = (0.960 \pm 0.006(stat) \pm 0.1(syst))\%$

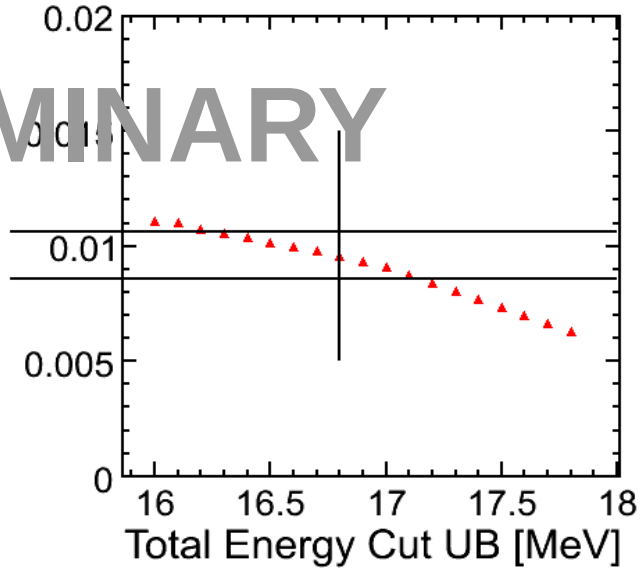
Total Energy recorded in the Target and upstream detectors



Red – without the Total Energy cut
Yellow – with the Total Energy cut



PRELIMINARY



$T^{Lower\ Limit} = (2.09 \pm 0.07(stat) \pm 0.14(syst))\%$

Analysis: tail correction

- Upper limit on the tail correction is estimated using lineshape measurement (data)

- 10 different entrance angle measurements performed using a 70 MeV/c e^+ beam

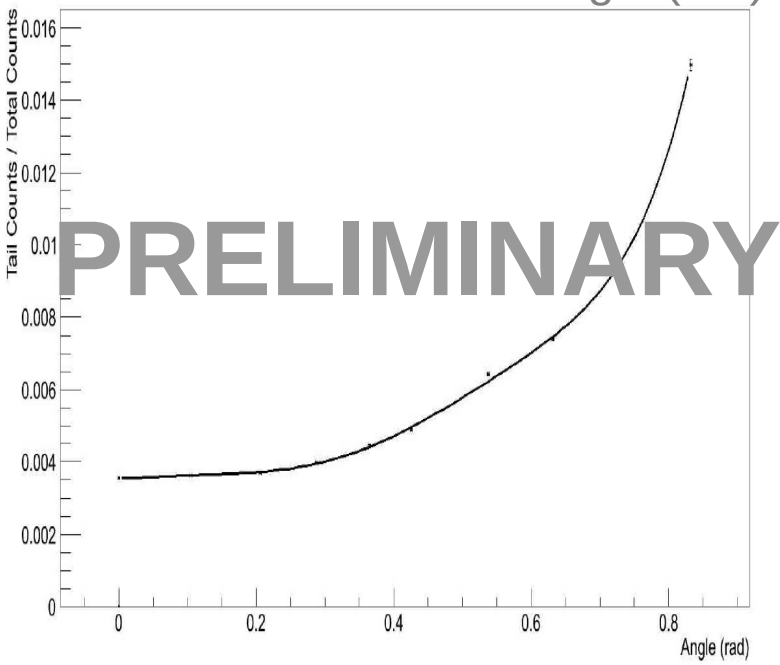
Tail is measured with positron beam, but has to be related to $\pi^+ \rightarrow e^+\nu$ tail.

Correction to the MC (due crystal response) is extracted from the DATA/MC comparisons And MC is used to simulate the PIENU tail.

Various systematic effects due to uncertainties in the following parameters:

Beam angle:	+0.003/-0.002%
Center of rotation:	+0.005/-0.004%
Beam momentum spread:	no effect
Beam spatial spread:	+0.009%/-0.007%
T2 Calibration (selection cuts):	+/- 0.001%

Measured tail fraction vs Angle (rad)



Total Tail also includes: Bhabha events contribution and Radiative $\pi^+ \rightarrow e^+\nu\gamma$ decays.
With their respective systematic uncertainties: $T^{UpperLimit} = (2.25 \pm 0.057(syst))\ \%$

Analysis: tail correction

PRELIMINARY

$T^{UpperLimit} = (2.25 \pm 0.057(syst))\ \%$

$T^{Lower\ Limit} = (2.09 \pm 0.07(stat) \pm 0.14(syst))\ \%$

Combining upper and lower limits yields:

PIENU Low Energy Tail Fraction:

$T = (2.17 \pm 0.07(stat) \pm 0.1(syst))\%$

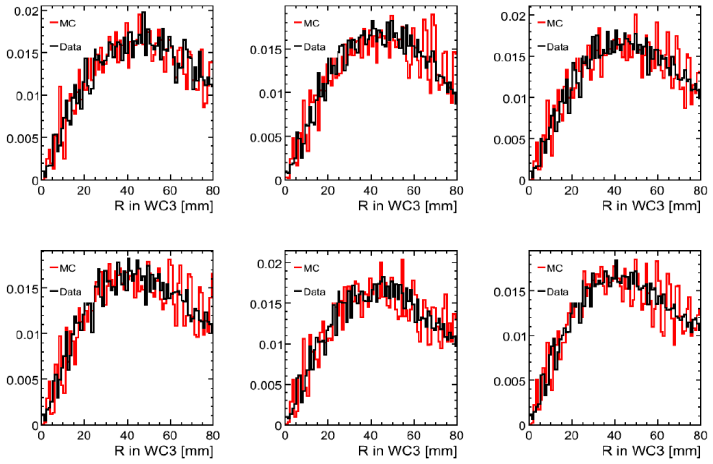
Analysis: acceptance correction

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

Various systematic effects are estimated. Deviations are within statistical uncertainty (0.0004)

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: summary

2010 Data Analysis is being finalized

- Systematics for Tail Correction are ~ 0.1%

- Finalization of the Fit systematic effects up to 0.1% level is in progress

- All cut parameters to vary as a final check:

  - Energy separation Threshold
  - Acceptance Definition (Reconstructed R coordinate in the WC3 middle plane)
  - .....

DATA Quality assessment of the 2009,2011, and 2012 data is in progress.

Conclusion

- Experiment finished taking data in 2012 and is dismantled
- PIENU aims to measure Br($\pi \rightarrow e\nu + \pi \rightarrow e\nu\gamma$) to 0.1% level
- "Blind" Analysis of the PIENU data is underway
- Results are coming out

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

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

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

- Complemented by PEN, a PSI-based experiment

(analysis is also in progress)

Stay tuned.....

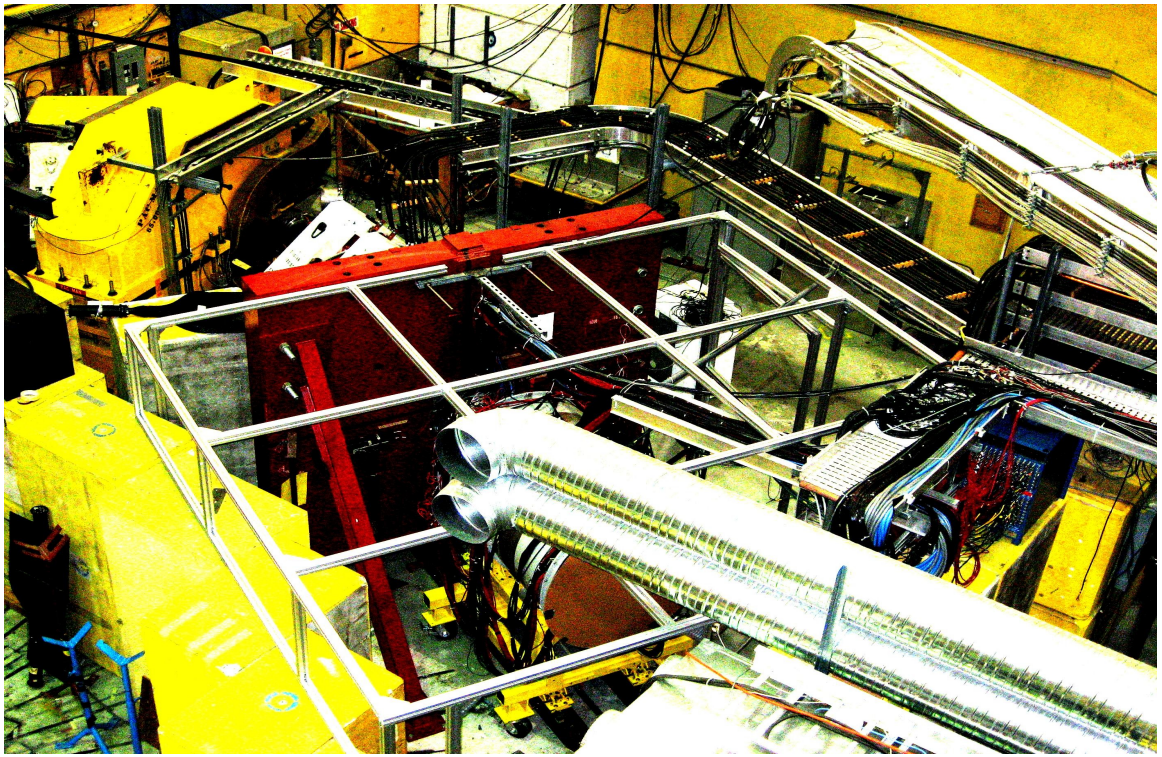
TRIUMF

Canada's national laboratory for particle and nuclear physics

Laboratoire national canadien pour la recherche en physique nucléaire

et en physique des particules

On behalf of the PIENU collaboration:



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