Pion Beta Decay with the PIONEER Apparatus

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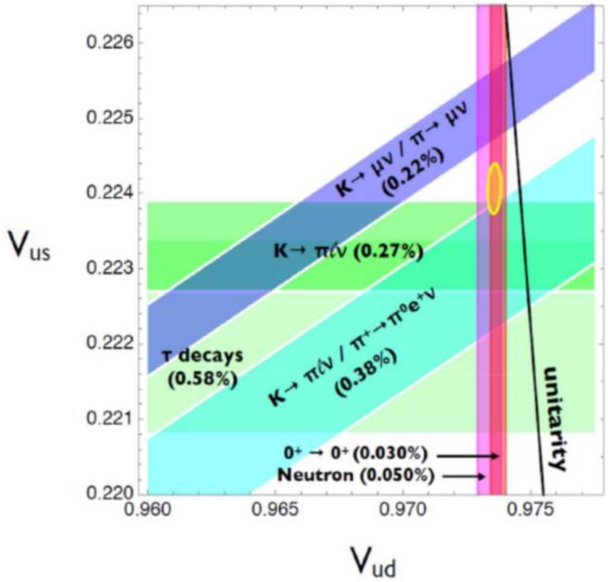
CKM Unitarity Tensions & Pion Beta Decay

- The first row of the CKM quark-mixing matrix has a 3σ tension with unitarity
- The pion beta decay branching ratio provides a theoretically clean determination of $|V_{ud}|$

Decay Mode	Branching Ratio
$\pi^+ \to \mu^+\nu_\mu$	$(99.98770 \pm 0.00004)\%$
$\pi^+ \to \mu^+\nu_\mu\gamma$	$(2.00 \pm 0.25) \times 10^{-4}$
$\pi^+ \to e^+\nu_e$	$(1.230 \pm 0.004) \times 10^{-4}$
$\pi^+ \to e^+\nu_e\gamma$	$(7.39 \pm 0.05) \times 10^{-7}$
$\pi^+ \to \pi^0 e^+\nu_e$	$(1.036 \pm 0.006) \times 10^{-8}$
$\pi^+ \to e^+\nu_e e^+ e^-$	$(3.2 \pm 0.5) \times 10^{-9}$



- The PiBeta experiment measured the branching ratio to ~0.6%

$$\frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\text{Total})} = 1.036 \pm 0.004(\text{stat}) \pm 0.004(\text{syst}) \pm 0.003(\pi \to e\nu) \times 10^{-8},$$

PIONEER Phase II aims for 3x PIONEER Phase III aims for 10x improvement in the precision of the pion beta decay branching ratio

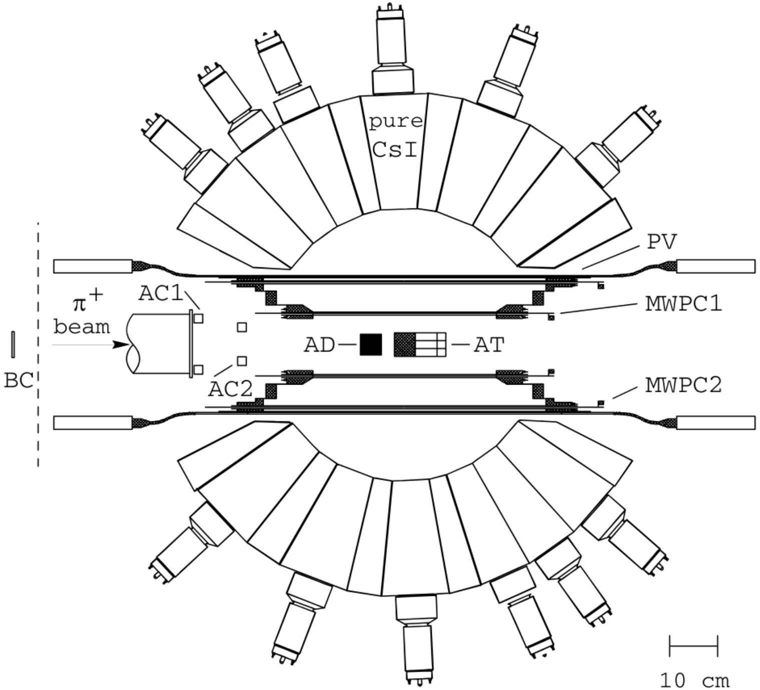
C. Pion Beta Decay

For the $\pi^+ \to \pi^0 e^+ \nu$ experiment the positive pion stop rate would have to be higher, $\geq 10^7$/s, possibly with a larger momentum bite $\frac{\Delta p}{p} \approx 3\%$ and likely using higher pion momentum. These beam conditions are compatible with the πE5 beam line. This would result in 7×10^5 $\pi^+ \to \pi^0 e^+ \nu$ events collected for 4 years of (5 months/yr) operation assuming similar efficiency factors as discussed for the $\pi \to e\nu$ measurement.[3] This would be sufficient to achieve the required statistical precision to improve the pion beta decay branching ratio measurement precision by a factor of 3 (Phase II). Systematic effects are expected to be reduced to the 0.06% level (10× lower than for the previous PiBeta experiment) due to the combined improvements to the calorimetry (principally, the time and energy resolutions) and the ATAR which may facilitate the observation of the positron in $\pi^+ \to \pi^0 e^+ \nu$ decay in coincidence with the π^0 detection.

Running at higher rates may be possible leading to a further precision improvement of 3 (Phase III) and will depend on the ability of the spectrometer to deal with higher rates of pile-up of accidental events. In this regard, we are studying the possibility to optically segmenting the LXe volume.

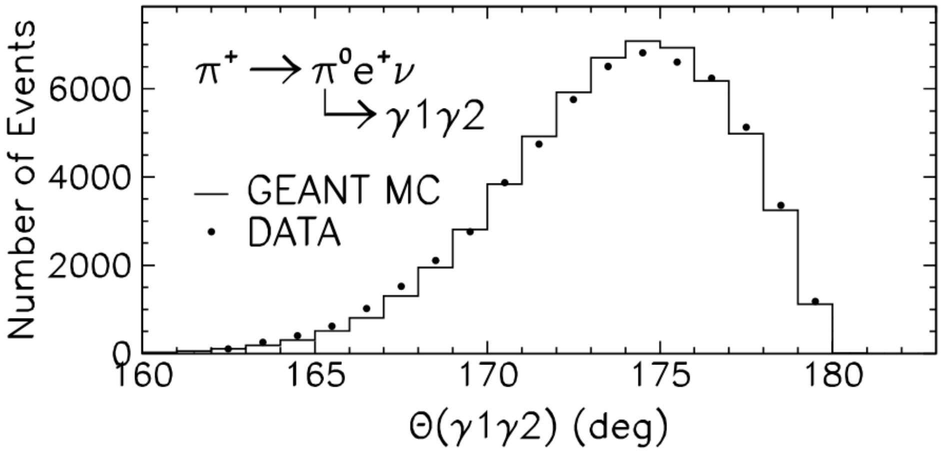
PiBeta Experiment - Design

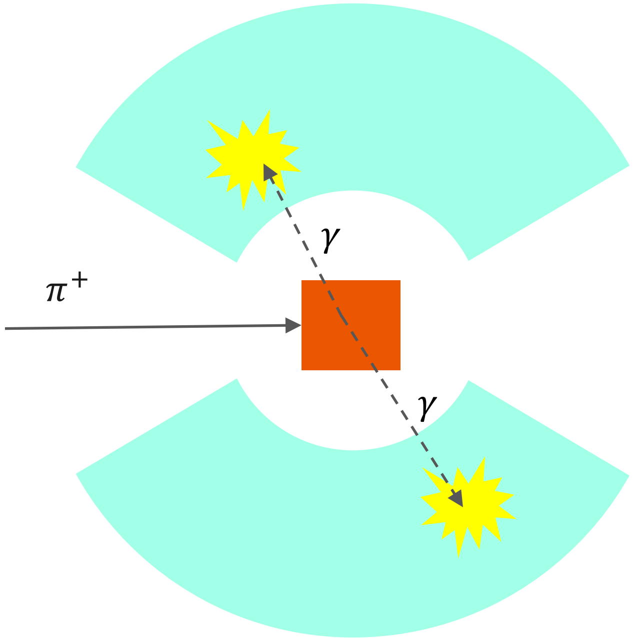
- PSI πE1 Beam Line at 110 MeV/c
- 10^6 pions/s stopped in active target
- Gamma and positron energy measured by CsI calorimeter
- Plastic Scintillator Hodoscope (PV) and Multi-Wire Proportional Chambers (MWPC) for tracking and particle identification

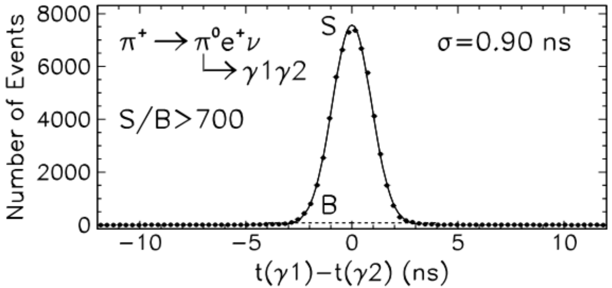


PiBeta Experiment - Method

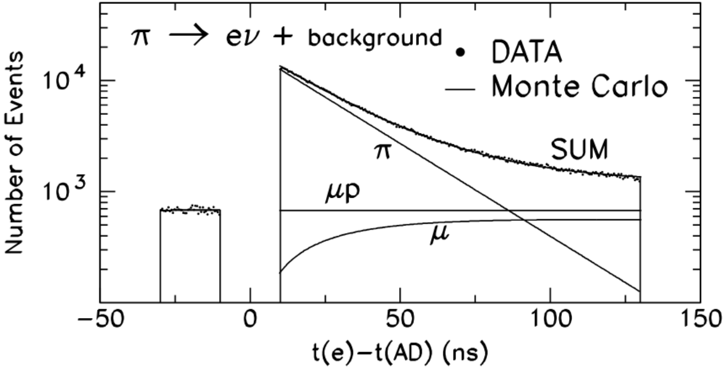
- π^0 decays quickly (~0.085 fs) to 2 gammas, observed in the calorimeter, nearly colinear
- Normalized to PIENU count (similar acceptance)



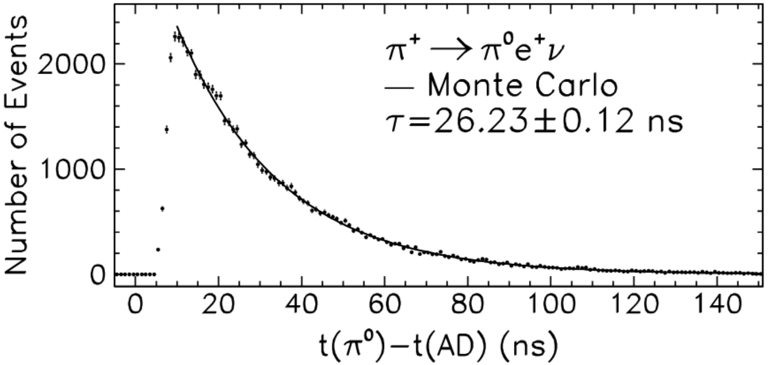




PiBeta Experiment - Timing



PIENU (π) and Michel (μ) timing histogram

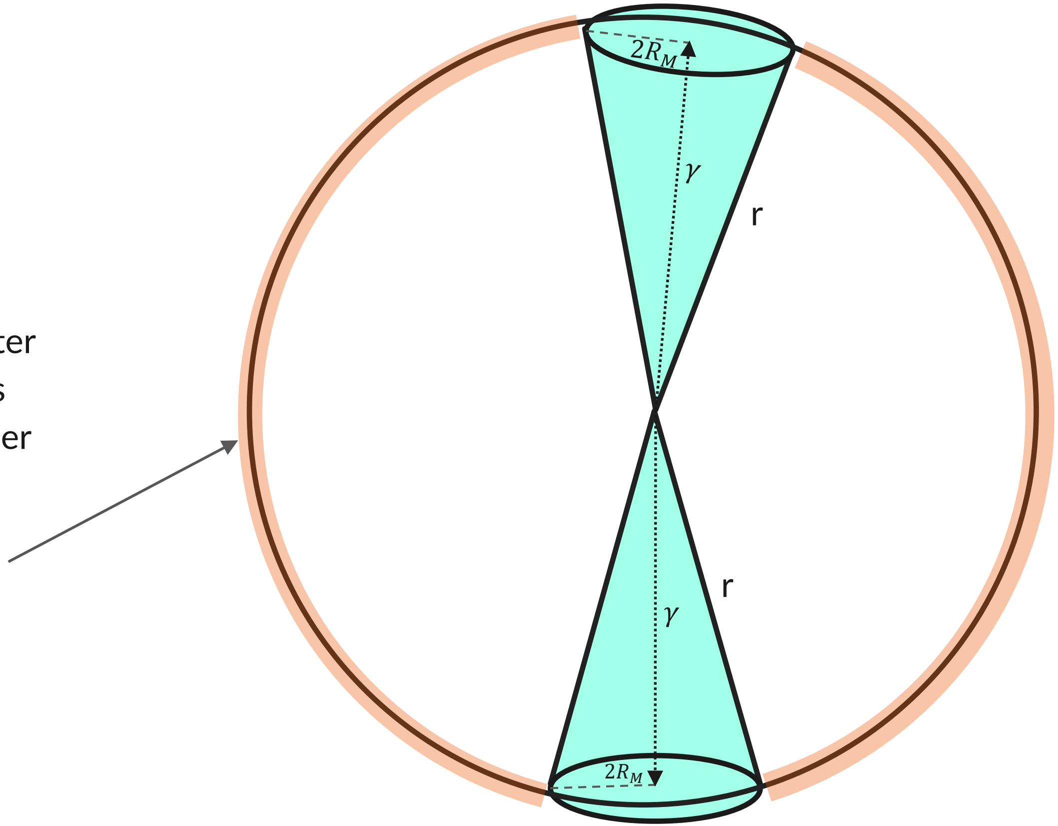


Pion Beta Decay timing histogram

PIENU and Pion Beta decays have similar time distributions

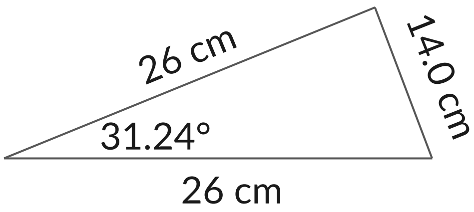
Angular Resolution & Pileup Suppression

- 95% of energy is contained in two Molière radii
- Angular resolution of the calorimeter is dependent on the Molière radius (R_M) of the calorimeter and the inner radius of the calorimeter (r)
- The remaining surface area can be used for pileup suppression



Calorimeter Comparison

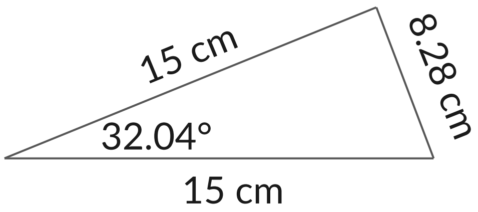
PiBeta Calorimeter



26 cm inner radius
3.5 cm Molière Radius (CsI)

Energy of 2γ in 3.6%
of the Calorimeter

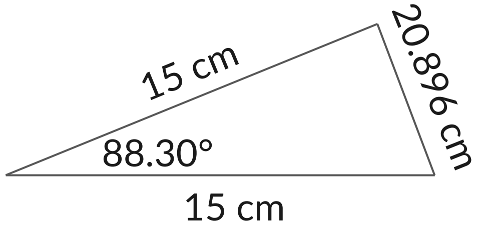
PIONEER Calorimeter (LYSO)



15 cm inner radius
2.07 cm Molière Radius (LYSO)

Energy of 2γ in 3.8%
of the Calorimeter

PIONEER Calorimeter
(Segmented LXe)



15 cm inner radius
5.224 cm Molière Radius (LXe)

Energy of 2γ in 24.3%
of the Calorimeter

PiBeta Uncertainty Summary

TABLE I. Summary of the main sources of uncertainty $\Delta R_{\pi\beta}$ in the extraction of the $\pi\beta$ branching ratio, given in % (see text for discussion).

Uncertainty type	Quantity	Value	$\Delta R_{\pi\beta}$ (%)	Approximate Phase II Goals
External	$R^{\mathrm{exp}}_{\pi e2}$	1.230×10^{-4}	0.33	0.01
	$R^{\mathrm{exp}}_{\pi^0 \to \gamma\gamma}$	0.9880	0.03	0.02
	π^+ lifetime	26.033 ns	0.02	0.01
Combined external			0.33	0.02
Internal	$N^{\mathrm{tot}}_{\pi e2}$ (syst)	6.779×10^{8}	0.19	0.05
	$A^{\mathrm{HT}}_{\pi\beta}/A^{\mathrm{HT}}_{\pi e2}$	0.9432	0.12	0.05
	$r_{\pi \mathrm{G}} = f^{\pi\beta}_{\pi \mathrm{G}}/f^{\pi e2}_{\pi \mathrm{G}}$	1.130	0.26	0.10
	$N^{\mathrm{accid}}_{\pi\beta}$	0	<0.1	0.08
	f_{CPP} correction	0.9951	0.10	0.05
	f_{ph} correction	0.9980	0.10	0.03
Combined internal			0.38	0.16
Statistical	$N_{\pi\beta}$	64 047	0.395	0.13
			Total: 0.63	0.21

PiBeta Statistical Uncertainty ($N_{\pi\beta}$)

- 0.395% Uncertainty in PiBeta Experiment
- Phase II would need to run at a 10x higher rate (10^7 pions/s) for 3 years to improve statistical uncertainty by a factor of 3 ($6.25 \times 10^5\ \pi\beta$ events)
- Phase III would need to run at a $6 \times 10^7\ \mathrm{pions/s}$ for 5 years to improve statistical uncertainty by a factor of 10 ($6.25 \times 10^6\ \pi\beta$ events)

More Investigation Needed

II: $1.036 \times 10^{-8}\ \pi\beta\ events\ /\ pion\ \times 0.2\ [Acceptance\ \&\ Timing\ Cuts] \times 10^7\ \frac{pions}{sec} \times 10^7\ running\ sec/year = 2.07 \times 10^5\ \pi\beta\ events\ /\ \mathrm{year}$

$$\left(6.25 \times 10^5\ \pi\beta\ events\right) \times \left(2.07 \times 10^5\ \pi\beta\ events\ /\ \mathrm{year}\right)^{-1} = 3\ years$$

III: $(6.25 \times 10^6\ \pi\beta\ events) \times (1.036 \times 10^{-8}\ \pi\beta\ events\ /\ pion)^{-1} \times 5\ [Acceptance\ \&\ Timing\ Cuts] \times (5\ years)^{-1} \times (10^7\ running\ sec/year)^{-1} = 6 \times 10^7\ pions/sec$

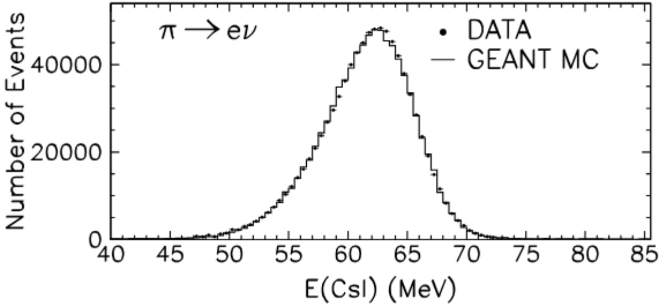
$\pi^+ \rightarrow e^+\nu$ Branching Ratio ($R_{\pi e2}^{exp}$)

- 0.33% Uncertainty in PiBeta Experiment
- PIENU experiment improved to 0.24%
- Phase I plans to improve to 0.01%

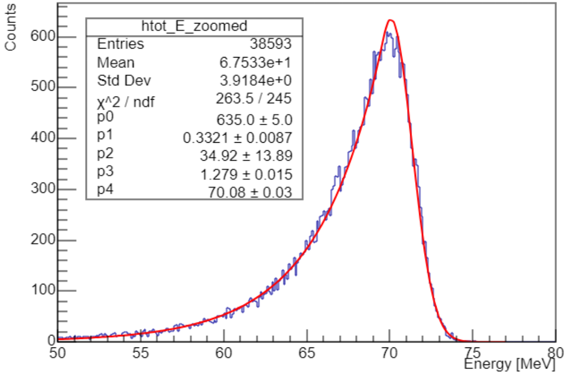
$\pi^+ \rightarrow e^+\nu$ Count ($N_{\pi e2}^{tot}$) (Systematic)

- 0.19% Uncertainty in PiBeta Experiment
- Uncertainty primarily from extracting the PIENU tail from Michel events - PiBeta used Monte Carlo estimates
- PIONEER should have a better understanding of the tail fraction from Phase I – the fraction will change if the target is changed for phase II
- The PIONEER ATAR will be able to distinguish PIENU events from Michel events
- PIONEER's increased calorimeter depth will greatly decrease the tail size compared to PiBeta (20 RL vs 12 RL)
- The calorimeter's improved energy resolution (~2% versus ~5%) should also improve this precision

More Investigation Needed



Energy Resolution 70 MeV -- 1.82%

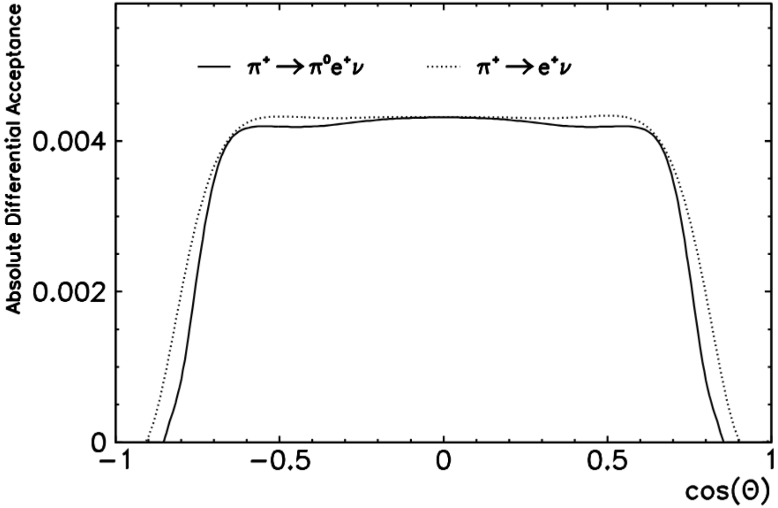


(LYSO)

Acceptance Ratio ($A_{\pi\beta}^{HT}/A_{\pi e2}^{HT}$)

- 0.12% Uncertainty in PiBeta Experiment
- Acceptance uncertainty dominated by uncertainty in pion stop distribution
- PiBeta backtracked charged particles from their trackers to the target to determine the pion stop distribution (50 micron uncertainty)
- The PIONEER ATAR and tracker should be able to improve this precision
- Also includes uncertainty from PiBeta track identification and radiative decay correction

More Investigation Needed



Gate Fraction Ratio ($r_{\pi G} = f_{\pi G}^{\pi\beta} / f_{\pi G}^{\pi e2}$)

- 0.26% Uncertainty in PiBeta Experiment
- This is the probability the decay occurs in some data collection window
- The uncertainty is primarily from determining window opening
  - PiBeta triggered on the beam and the calorimeter and used a 10 ns hardware veto
  - Some delay is needed to remove charge exchange events
  - Thus, the gate opening time needed to be determined from experimental data
  - This method includes more $\pi\beta$ events, maximizing useful statistics
- Since PIONEER will be running at a higher rate, we may be able to open the window later (with software), lowering this uncertainty, without significantly impacting statistical uncertainty

More Investigation Needed

Other Uncertainties

Tracker Pileup Correction (f_{CPP})

- 0.10% Uncertainty in PiBeta Experiment
- Can we have a better tracker than PiBeta?

Photonuclear Correction (f_{ph})

- 0.10% Uncertainty in PiBeta Experiment
- Probability PiBeta photon converts to electron-positron pair
- Calculated using GEANT3 and ‘conservatively assigned a 50% uncertainty’

More Investigation Needed

We will use our simulation this summer to better understand how to perform a Pion Beta Decay measurement using our apparatus and analyze if/how we can make significant improvements over the PiBeta experiment's precision

References

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