TRIUMF

Proposal Towards Measuring the Pion Lifetime

LOI S2307

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TRIUMF PP-EEC Meeting
May 2, 2024

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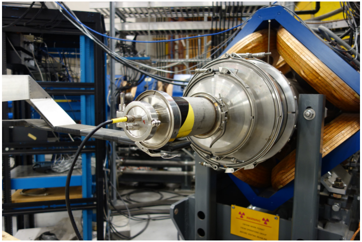
Presentation Outline

1. Pion Lifetime at TRIUMF – Overview
2. Progress Since Last PP-EEC Meeting
3. Request for 2024–2025

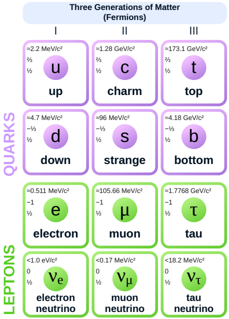


Physics Motivations – Lepton Universality

We observe three generations of fermions. The origin of this phenomenon is unknown.

Leptons couplings to the W bosons are presumed to be universal → $g_e^W = g_\mu^W = g_\tau^W$?

A broken symmetry (e.g. $g_e^W \neq g_\mu^W$) would be an unequivocal sign of new physics!



- The pion lifetime enters in the $R_{e/\mu}$ electron–muon universality test

$$R_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+\nu)}{\Gamma(\pi^+ \to \mu^+\nu)} \propto \left(\frac{g_e^W}{g_\mu^W}\right)^2 .$$

- The pion lifetime is not precisely calculated and depends on others physical constants (f_π, V_{ud}, ...).

Physics Motivations – Lepton Universality

$R_{e/\mu}$ has a rich experimental history at TRIUMF (PIENU '86, '94, '15)

$$R_{e/\mu}^{\mathrm{PDG}} = (1.2327 \pm 0.0023) \times 10^{-4} .$$

The uncertainty on the SM prediction ($g_e^W = g_\mu^W$) is only 0.012%

$$R_{e/\mu}^{\mathrm{SM}} = (1.23524 \pm 0.00015) \times 10^{-4} .$$

V. Cirigliano et al., Phys. Rev. Lett. **99** (2007) 231801, V. Cirigliano et al., JHEP **10** (2007) 005, W. J. Marciano et al., Phys. Rev. Lett. **71** (1993) 3629

New measurement of $R_{e/\mu}$ planned by the PIONEER collaboration, approved at PSI → Reduce the experimental uncertainty to 0.01%.

Impact of τ_π on the $R_{e/\mu}$ Error Budget

Base principle: count $\pi \to e$ and $\pi \to \mu \to e$ events; τ_π enters in the ratio

$$R_{e/\mu} = \frac{\lambda_\mu}{\boldsymbol{\lambda_\pi} - \lambda_\mu} \frac{\boldsymbol{N_{\pi e}}}{De^{\lambda_\mu t_s} - \boldsymbol{N_{\pi\mu e}}} \left(1 - e^{-(\boldsymbol{\lambda_\pi} - \lambda_\mu)t_s}\right)$$

E. Di Capua et al, Phys. Rev. **133** (1967) B1333

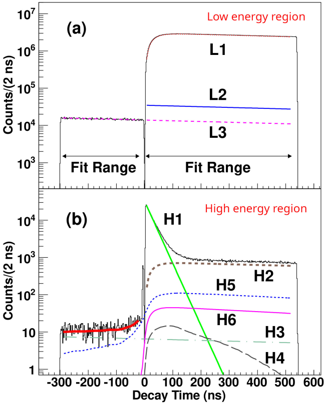
(Modern experiments are fitting a model to the time spectra.)

Impact on PIENU syst. uncertainty:
$\delta R = \pm 0.57 \times 10^{-8}$ ($\delta R/R = 0.005\%$)

In the PIONEER context, $\delta\tau_\pi/\tau_\pi$ becomes relevant

Error Source	PIENU 2015 %	PIONEER Estimate %
Statistics	0.19	0.007
Tail Correction	0.12	<0.01
t_0 Correction	0.05	<0.01
Muon DIF	0.05	0.005
Parameter Fitting	0.05	<0.01
Selection Cuts	0.04	<0.01
Acceptance Correction	0.03	0.003
Total Uncertainty	**0.24**	**$\leq$ 0.01**

[arXiv:2203.01981]



PIENU, Phys. Rev. Lett. **115** (2015) 071601

Pion Lifetime – Current Status

The PDG 2022 average is $\tau_\pi = 26.033 \pm 0.005$ ns ($\delta\tau/\tau = 0.02\%$)

$\pi^\pm$ MEAN LIFE

Measurements with an error $> 0.02 \times 10^{-8}$ s have been omitted.

VALUE (10^{-8} s)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2.6033 ±0.0005 OUR AVERAGE	Error includes scale factor of 1.2.				
2.60361±0.00052	[1] KOPTEV	95	SPEC	+	Surface μ^+'s
2.60231±0.00050±0.00084	NUMAO	95	SPEC	+	Surface μ^+'s
2.609 ±0.008	DUNAITSEV	73	CNTR	+	
2.602 ±0.004	AYRES	71	CNTR	±	
2.604 ±0.005	NORDBERG	67	CNTR	+	
2.602 ±0.004	ECKHAUSE	65	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.640 ±0.008	[2] KINSEY	66	CNTR	+	

[1] KOPTEV 95 combines the statistical and systematic errors; the statistical error dominates.
[2] Systematic errors in the calibration of this experiment are discussed by NORDBERG 67.

TABLE I. Systematic uncertainties.

Sources	Uncertainties (ns)
Beam leakage,[a] slow π[a]	0.0083
Prompt positron background	0.0002
Flat positron background	0.0003
Pion background	0.0002
Extra muons	0.0001
Other pion sources	0.0001
Diffusion	0.0003
Total uncertainty	0.0084

[a] Included in the fit.

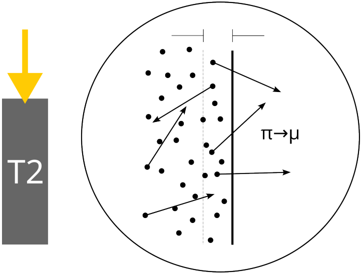
Phys. Rev. D **52** (1995) 4855

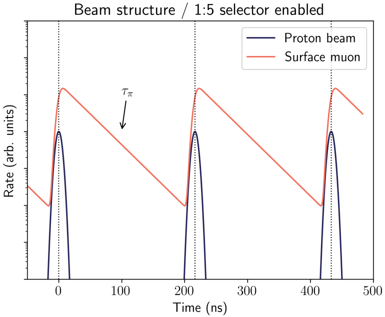
TRIUMF experiment: M. C. Fujiwara, T. Numao, A. J. Macdonald, G. M. Marshall, A. Olin, Phys. Rev. D **52** (1995) 4855

Our goal is to bring the pion lifetime uncertainty below 0.01%.

Measuring the Pion Lifetime at TRIUMF

We plan to measure the rate of surface muons emitted from the T2 target ($\pi^+ \to \mu^+ \nu$) in relation to the cyclotron's RF cycles.

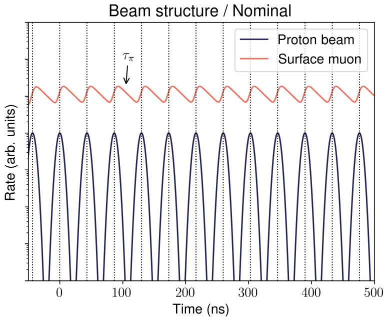


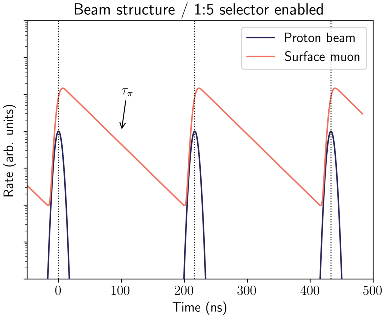


Beam line M20 selects a narrow momentum range near the surface muon peak ($P = 29.4$ MeV/c) and suppresses protons, pions and positrons.

The “1:5 Selector”

The 1:5 selector suppresses 4/5 bunches, lengthening the fit time window.

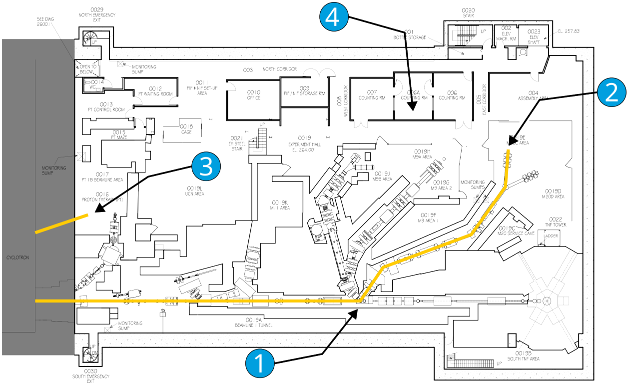




The beam extinction is the crux of the measurement. “Beam leakage” is the main source of systematic uncertainty, must be $< 10^{-5}$.

Innovation – Proposed Experiment Layout

Beam line 1A and 2C can run concurrently. We plan to have online monitoring for beam leakages.



1. Target T2 on beam line 1A,
2. Main detector setup on M20C,
3. Beam extinction monitor on 2C1,
4. Unified DAQ.

Status at the 2023 PP-EEC Meeting

LOI initially submitted to TRIUMF Particle Physics Experiments Evaluation Committee in April 2023.

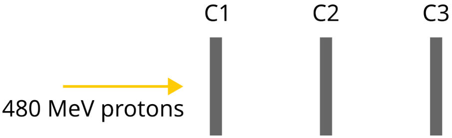
The operational status of 1:5 selector was unknown at the time of submission.

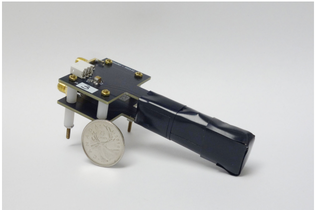
We wanted to answer two main questions:

- Can the beam leakage be mitigated/controlled?
- Is any of the μSR beam line suitable?

1:5 Selector and Beam Extinction

The 1:5 selector had not been used since (many) years → Two machine development (MD) shifts partially dedicated to the selector.

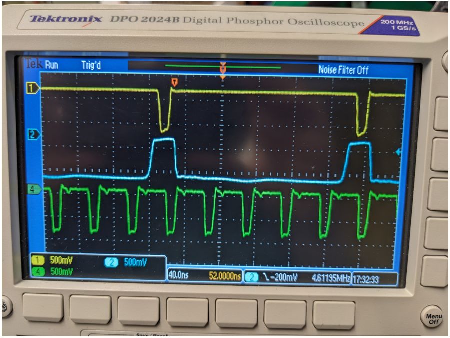




Three 1×1 cm^2 scintillation counters were installed in beam line 1B for the occasion. The source duty factor was about 3%. The extraction foil was adjusted for a rate of $\approx 7.7 \times 10^7$ p s^{-1} (very low intensity).

1:5 Selector and Beam Extinction in BL1B

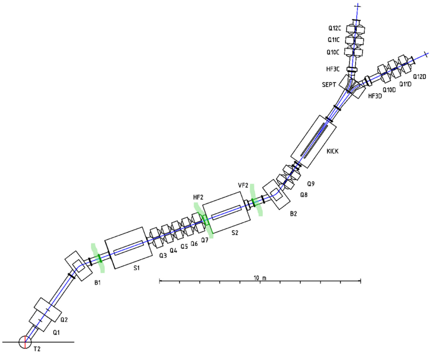
Two gates are defined, 13 ns (yellow) and 190 ns (cyan). Gates are open in response to the coincidence of the RF (green) and $C1 \times C2 \times C3$.



We counted $C1 \times C2 \times C3$ in both gates → The beam extinction $> 1.8 \times 10^6$ at 90% C.L. **Encouraging!** But conditions were not fully representative (MD, single user & low intensity).

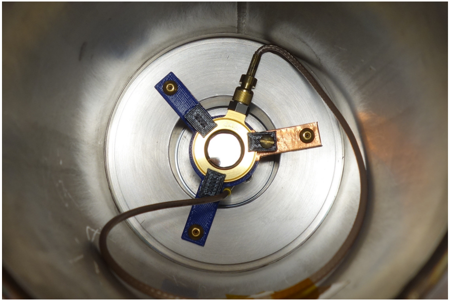
Beam Line M20

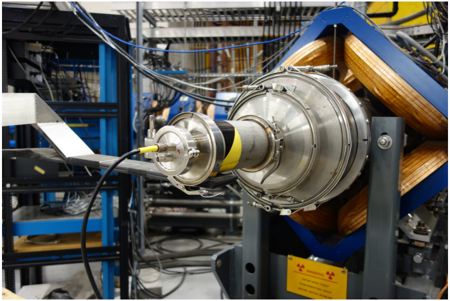
M20 is a 27 m long surface muon beam line, the beam rate goes up to 550k μ^+/s (open slits). Two DC separators reject the positrons.



We want the time-of-flight spread to be < 5 ns. M20's momentum bite was not precisely known (depends on slits positions) → We measured it.

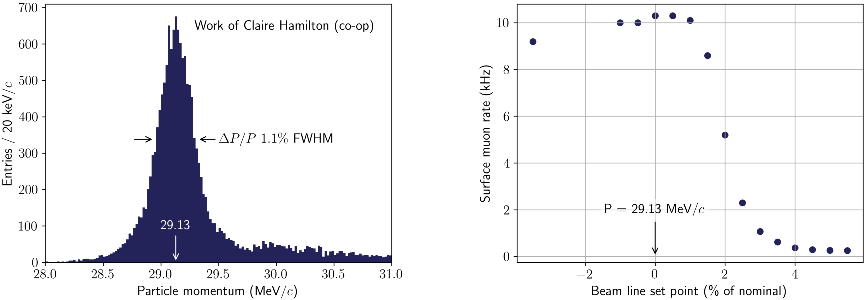
Beam Line M20





The silicon sensor thickness is about 1 mm (fully active), enough to stop 29.9 MeV/c muons. Waveforms were digitized and analyzed offline.

The setup was calibrated with a electroplated composite α source.



Again, those are **very encouraging** results! A momentum bite of 1.1% (FWHM), while keeping the rate around 10 kHz, can be obtained.

2024 – 2025 Timeline & Beamtime Request

Before moving to the full proposal, we would like to:

1. Verify the beam extinction on beam line 2C, while concurrently measuring the surface muon beam on beam line M20C,
2. Measure the cloud muon component of the beam.

We have access to waveform digitizers developed for the Muon $g-2$ Fermilab experiment. Up to 50 channels, 12-bit resolution, 800 MHz sampling rate → Unified DAQ.

Activity	Requested	1:5 Selector	2C1	M20C
Commissioning	3 shifts	No	Yes	Yes
Beam studies	5 shifts	Yes	Yes	Yes

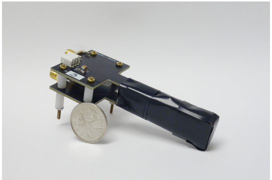
If those studies are conclusive, we are confident the pion lifetime measurement can be improved at TRIUMF.

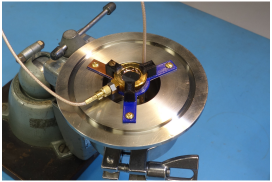
2024 – 2025 Experimental Setup

We have requested access to 1:5 selector 4.6 MHz driving signal. It will considerably simplify the NIM logic associated to the Beam Extinction Monitor.

The current plan is to

1. Complete the Beam Extincting Monitor. It is based on existing scintillation counters and is well advanced,
2. Reuse last year silicon detector to monitor the surface muons in beam line M20C,
3. Setup a central DAQ system build around the $g-2$ digitizers and MIDAS.





The PIONEER experiment will push the e–μ universality test sensitivity in the next few years.

Reducing the pion lifetime uncertainty is important to fully realize PIONEER physics potential.

Our initial feasibility studies are very encouraging,

- Measurements on beam line 1B indicate that a beam extinction level $> 2 \times 10^6$ can be achieved,
- With a $\Delta P/P$ of 1.1% (FWHM) and low positron contamination, the beam line M20C characteristics are ideal for measuring the pion lifetime.

We would like to study the beam extinction on BL2C, while extracting protons on BL1A, before moving to the full proposal.

> The prospects for an improved pion lifetime measurement at TRIUMF are very encouraging!

Acknowledgment

A special thanks to

- Barry Davids for loaning the silicon detector,
- Adam Garnsworthy for loaning the charge preamp.

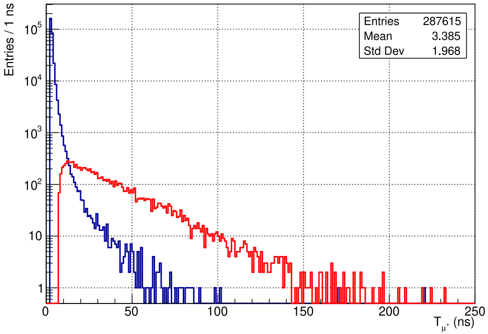
Also, thank you to

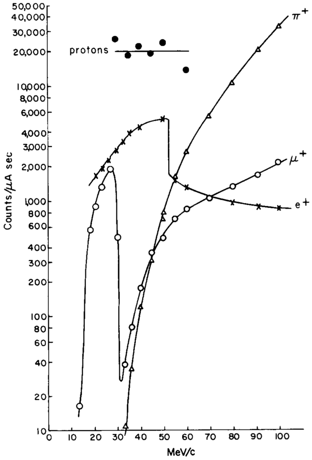
Alec Stokton, Anthony Ip, Derek Orth, Keven Langton, Leonid Kurchaninov,
Lige Zhang, Nicolas Massacret, Marco Marchetto, Mike Wicken,
Rick Baartman, Rick Maharaj, …

Many people have given us a leg up!


MESON HALL
TRIUMF
520 MeV Cyclotron
520 Million Electron Volts Cyclotron
TRIUMF
M9

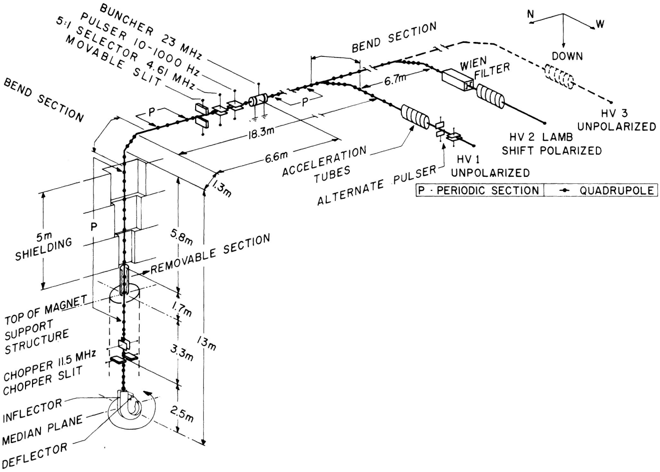
Cloud Muons





NIM 179 (1981) 95

1:5 Selector



J. Beveridge et al., IEEE Trans. Nucl. Sci. **NS-22** (1975) 1707

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C. B.-Champagne is a PIF & NIF expert, G. Morris is a TRIUMF's μSR beam lines expert, and T. Numao led the past TRIUMF measurement.

Charged Pion Decay – Formulae

At first order, the $\pi^+ \to \ell^+\nu$ decay rate can be written as:

$$\Gamma\left(\pi^+ \to \ell^+\nu\right) = \frac{G_F^2\left|V_{ud}\right|^2 f_\pi^2}{4\pi} m_\pi m_\ell^2 \left(1 - \frac{m_\ell^2}{m_\pi^2}\right)^2 ,$$

where, G_F is the Fermi constant; V_{ud} is the CKM matrix element; and f_π^2 is the pion form factor.

See e.g. V. Cirigliano et al., JHEP **10** (2007) 00

The $\pi^+ \to \pi^0 e^+\nu$ decay rate can be written as:

$$\Gamma\left(\pi^+ \to \pi^0 e^+\nu\right) = \frac{G_F^2\left|V_{ud}\right|^2}{30\pi^3}\left(1 - \frac{\Delta}{2m_{\pi^+}}\right)^3 \Delta^5 f(\varepsilon, \Delta)(1+\delta) ,$$

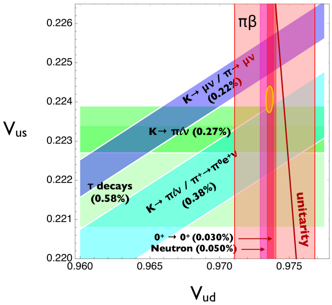
where $\Delta = m_{\pi^+} - m_{\pi^0}$; $\varepsilon = m_e^2/\Delta$; and δ encodes the radiative corrections. See A. Sirlin, 1978, for the form of f.

A. Sirlin, Rev. Mod. Phys **50** (1978) 573

Charged Pion Lifetime & V_{ud}

The tension in the CKM matrix first-row unitarity relation could be connected to a violation of the lepton flavor universality.

[arXiv:2111.05338]



The CKM matrix element V_{ud} can be cleanly extracted from the pion beta decay branching ratio $\mathcal{B}$:

$$\Gamma\left(\pi^+ \to \pi^0 e^+ \nu\right) = \frac{\mathcal{B}\left(\pi^+ \to \pi^0 e^+ \nu\right)}{\tau_\pi} \propto |V_{ud}|^2 \ .$$

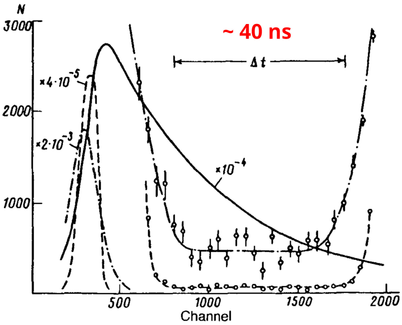
The experimental $\mathcal{B}$, $(1.036 \pm 0.006) \times 10^{-8}$, is not competitive (red strip).

D. Počanić et al., Phys. Rev. Lett. **93** (2004) 181803

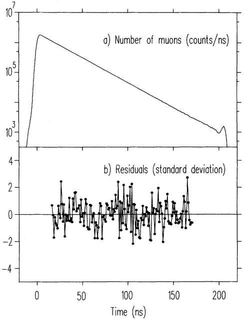
In a second phase, PIONEER plans to improve $\mathcal{B}\left(\pi^+ \to \pi^0 e^+ \nu\right)$. A new π^+ lifetime measurement is needed to achieve the best precision on V_{ud}.

Previous Measurements

Two “recent” experiments (1995): Koptev et al. and Numao et al., both used momentum-analyzed surface-muons. [‡]



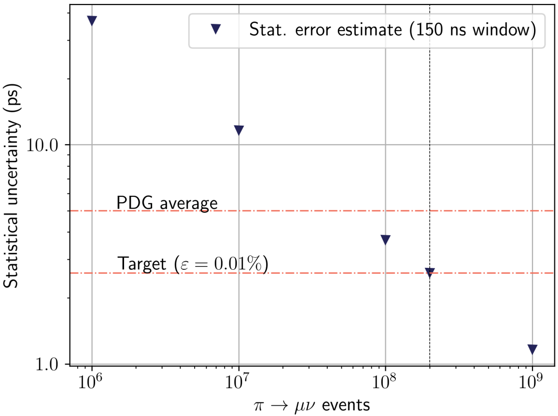
Koptev et al., statistics limited.
$\tau_\pi^+ = 26.0361 \pm 0.0052$



Numao et al., **150 ns** examination window, systematics limited.
$\tau_\pi^+ = 26.0231 \pm 0.0050 \pm 0.0084$

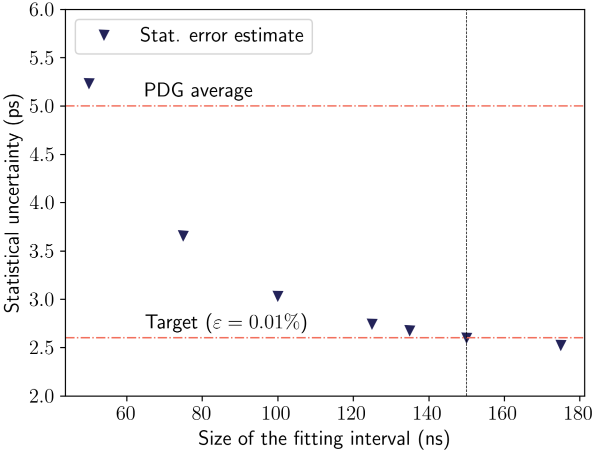
[‡] Older experiments examined the $\pi^+ \to \mu^+$ or $\pi^+ \to \mu^+ \to e^+$ (stopped pions) sequence, or the $\pi^\pm$ attenuation along a decay volume, see PDG for details.

Sample Size and Statistical Uncertainties



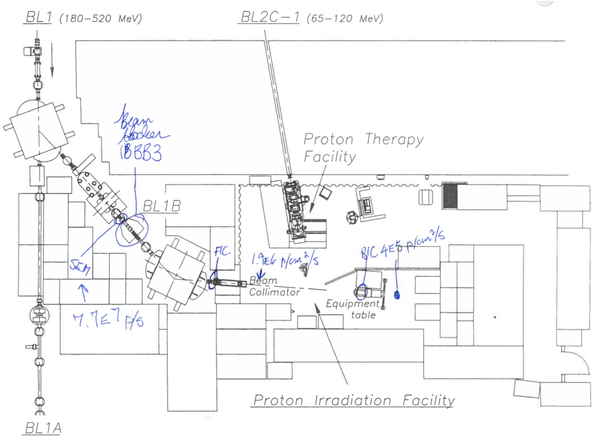
We need to collect a minimum of 2×10^8 $\pi^+ \to \mu^+\nu$ events.

Statistical Uncertainty – Fitting Interval

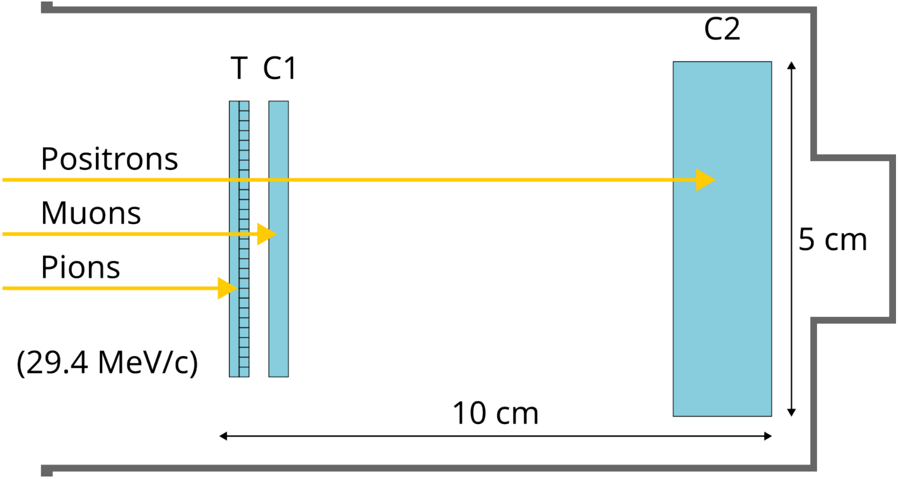


Estimate based on 2×10^8 $\pi^+ \to \mu^+\nu$ events.

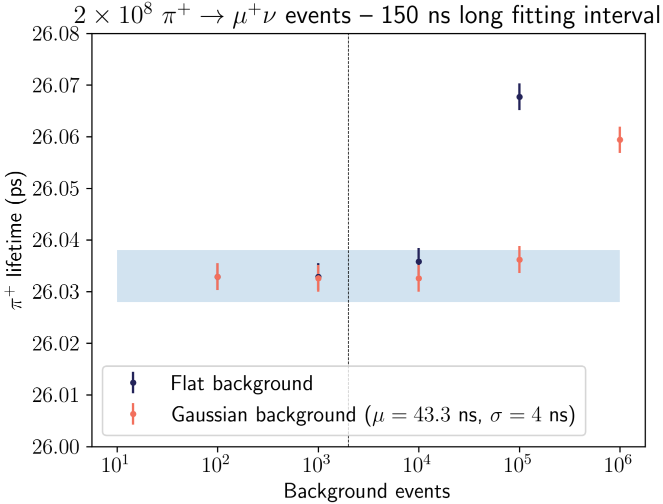
PIF & NIF – Sept. 12, 2024 – Fluence



Main Detector – Conceptual Design



Systematic Uncertainties – Overview



→ Keep the contamination fraction of the μ^+ sample below 10^{-5}.

Systematic Uncertainty – Positrons

The positron background has two components:

- Prompt, $\pi^0 \to \gamma(\gamma \to e^+e^-)$ → Discard the first 15 ns after the proton burst,
- Flat, $\mu^+ \to e^+\nu\bar{\nu}$ ($\tau_\mu \gg \tau_\pi$) → Negligible (stopping rate in counters & dE/dx cut).

Positrons in the beam are further suppressed by the DC separators.

Systematic Uncertainty – Time of Flight

Keep the surface-μ arrival time dispersion < 5 ns.

- $\delta P/P$ 1.1% (FWHM) → 1.4 ns,
- G4beamline simulation (includes path variations) → 1.7 ns.