TRIUMF

Precision Measurements for the Discovery of New Physics

The PIONNER and NA62 Experiments

Bob Velghe (he/him)*

TRIUMF Science Week
July 23, 2024

*bvelghe@triumf.ca

Outline

1. Precision Measurements?
2. Pions – PIONEER Experiment
3. Kaons – NA62 Experiment
4. Conclusion

CERN NA62 Experiment – Installation of the last STRAW detector in 2014 [CERN-PHOTO-201409-176-4]

Precision Measurements – An Historical Example

In ’58, “Theory of the Fermi Interaction” $\rightarrow$ Weak neutral currents are not allowed.

(Sudarshan, Marshak; Feynman, Gell-Mann)

In the ’60s, new unification models introduce a neutral boson (Z) making these transitions possible, but Z mass predicted to be $> 80\ \mathrm{GeV}$. **Out of reach!** (Salam and Ward, ’64; Weinberg, ’67)

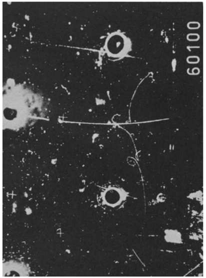
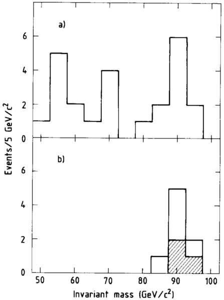


Fig. 1. Possible event of the type $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$.

After preselection:
24 e^+e^- pairs

$\bar{p}p \rightarrow Z^0 \rightarrow e^+e^-$

After all cuts:
8 e^+e^- pairs



In ’73, Gargamelle takes 375k ν and 360k $\overline{\nu}$ pictures, **one(!)** $\overline{\nu}_\mu e^- \rightarrow \overline{\nu}_\mu e^-$ **candidate.**
Finally, in ’83, UA1 and UA2 observe the **direct production** of Z bosons (CERN SPS).

[F.J Hasert et al, ’73], [UA2 Collaboration, ’83]

Precision Measurements – An Historical Example

In ’58, “Theory of the Fermi Interaction” $\rightarrow$ Weak neutral currents are not allowed.

(Sudarshan, Marshak; Feynman, Gell-Mann)

In the ’60s, new unification models introduce a neutral boson (Z) making these transitions possible, but Z mass predicted to be $> 80\ \mathrm{GeV}$. **Out of reach!** (Salam and Ward, ’64; Weinberg, ’67)

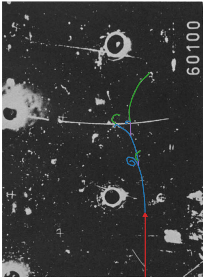
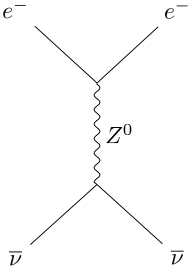


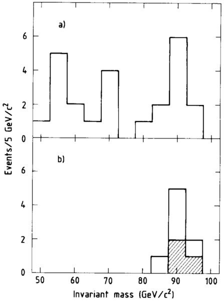
Fig. 1. Possible event of the type $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$.



After preselection:
24 e^+e^- pairs

$\bar{p}p \rightarrow Z^0 \rightarrow e^+e^-$

After all cuts:
8 e^+e^- pairs



In ’73, Gargamelle takes 375k ν and 360k $\overline{\nu}$ pictures, **one(!)** $\overline{\nu}_\mu e^- \rightarrow \overline{\nu}_\mu e^-$ **candidate.**
Finally, in ’83, UA1 and UA2 observe the **direct production** of Z bosons (CERN SPS).

[F.J Hasert et al, ’73], [UA2 Collaboration, ’83]

NA62 – Kaons Decaying in Flight

Proposed in 2005, running 2016–2025

~200 collaborators in ~30 institutes

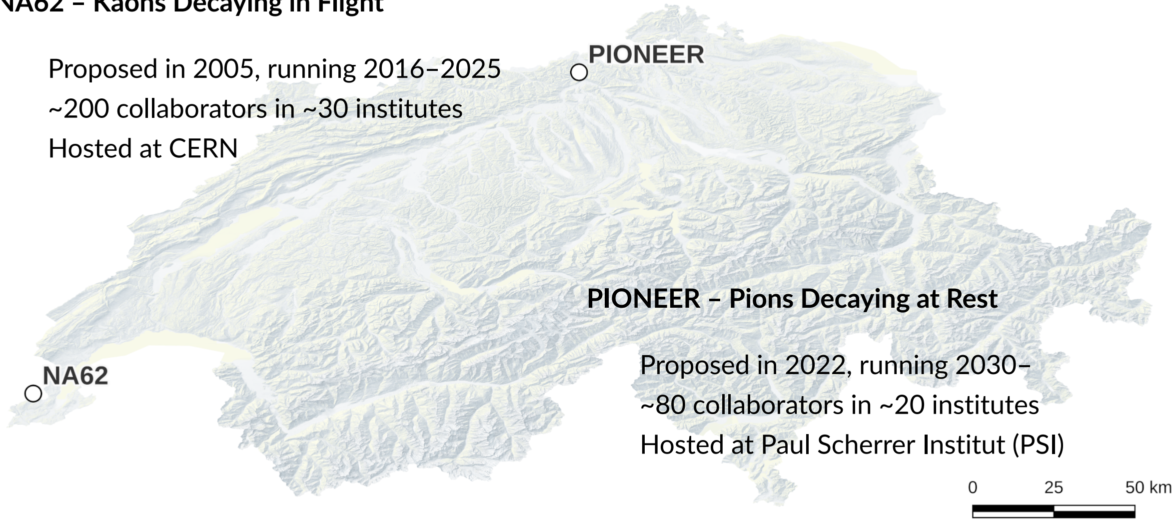
Hosted at CERN

PIONEER – Pions Decaying at Rest

Proposed in 2022, running 2030–

~80 collaborators in ~20 institutes

Hosted at Paul Scherrer Institut (PSI)

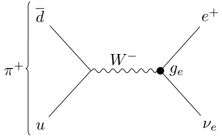


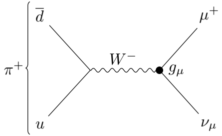
Map data from swisstopo

Phase I: Lepton Flavor Universality Test

$$R_{e/\mu} = \frac{\Gamma\left(\pi^+ \to e^+\nu(\gamma)\right)}{\Gamma\left(\pi^+ \to \mu^+\nu(\gamma)\right)}$$

Standard Model $\to$ All leptons couple to the $W^\pm$ bosons with the same strength ($g_e = g_\mu$)





If $g_e \neq g_\mu$, new physics!

Uncertainty on $R^{\mathrm{SM}}_{e/\mu}$ is 0.01%, a **factor** $15\times$ **lower** than the experimental value

$R_{e/\mu}$

- $1.23524(15) \times 10^{-4}$ (SM) [Phys. Rev. Lett. 71 (1993) 3629],[Phys. Rev. Lett. 99 (2007) 231801]
- $1.2327(23) \times 10^{-4}$ (World average, dominated by PIENU) [PDG 2022], [Phys. Rev. Lett. 115 (2015) 071801]

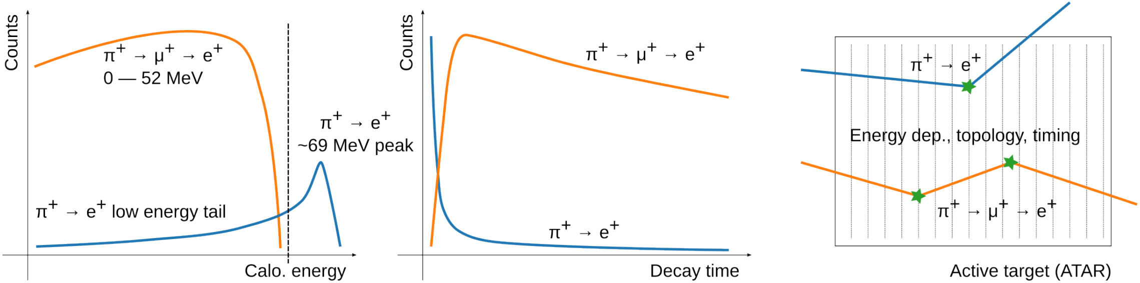
Measurement sensitive to NP up to $\mathcal{O}(1000)$ TeV in some scenarios [Annu. Rev. Nucl. Part. Sci. 61 (2011) 331]

Strong complementary program: CKM matrix unitarity (phase II), heavy neutral leptons, etc.

$R_{e/\mu}$ Measurement – Basic Principles

Focus on **positrons** ($\pi^+ \to e^+\nu$) and ($\pi^+ \to \mu^+\nu \to e^+\nu\overline{\nu}$)

"Count and sort" the positrons emitted by the stopped pions $\to$ Many systematics cancel in $R_{e/\mu}$



Understanding the $\pi^+ \to e^+\nu$ low-energy tail is key! Positron energy measurement is imperfect: finite resolution, energy leakages, photonuclear interactions, ...

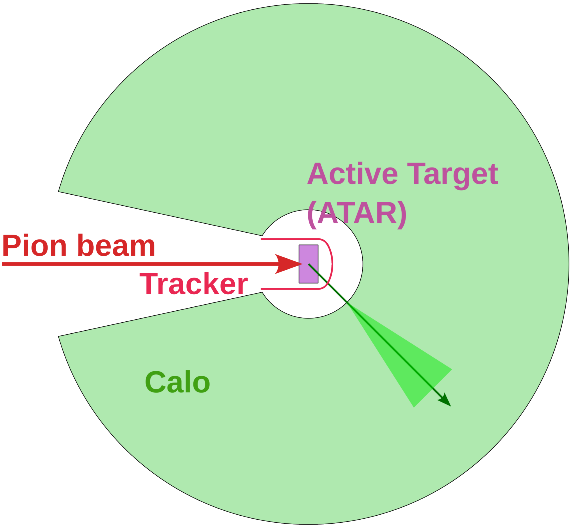
PIONEER – Beamline & Detector

Decays at rest!

High intensity pion beamline at PSI (πE5)
$55 < P < 70$ MeV/c

Key elements:

ATAR $\rightarrow$	Reconstruct decay topologies,
Tracker $\rightarrow$	Track positron pos. and time,
Calo $\rightarrow$	Measure the positron energy.

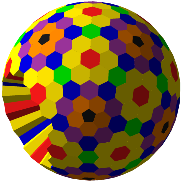


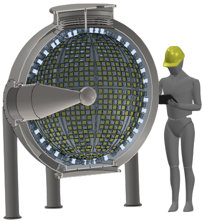
Proposal approved by PSI in 2022 arXiv:2203.01981, PSI website

PIONEER – LXe Calorimeter

Calorimeter: area of focus for the TRIUMF team. Part of the LXe R&D overlaps **with the nEXO R&D program and the LoLX experiment.**

Key qualities: Uniform response, able to contain e^+ showers ($\approx$20 X_0), $\Delta E/E < 2\%$, $\sigma_t < 200$ ps.





Liquid xenon (scintillation light) and LYSO crystals are being considered: Uniformity, energy resolution, pile-up suppression, etc. Both technologies are promising.

> A Monte Carlo simulation effort is ongoing and small-scale prototypes are being built.

See Jesus Corral contributions in the *Poster Session* on Wednesday!

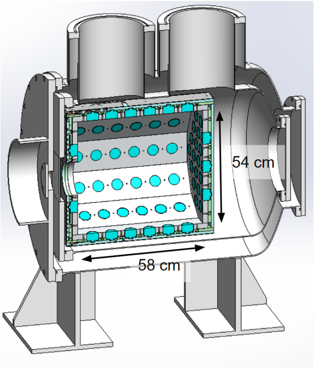
LXe Calorimeter – Prototype

Reuse the MEG large prototype cryostat with a newly developed inner structure. The setup will be tested with positrons ($20 < P < 100$ MeV/c).

A volume of $\approx$120L of LXe will be instrumented with UV sensitive photomultiplier tubes (PMT).

The main objectives are:

- Study the energy resolution,
- Validate the Monte Carlo simulations,
- Study the pile-up suppression,
- R&D for the calibration system.



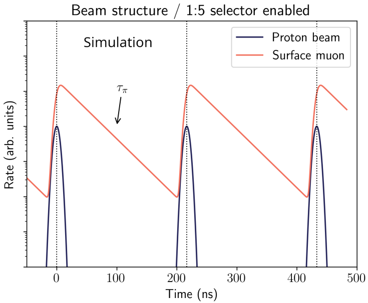
A LXe purity monitor is also currently being developed at TRIUMF (synergies with LoLX).

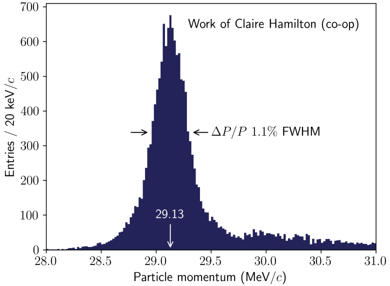
See William Chow and Pierce Comerford contributions in the *Student Competition* session later today!

Measuring the Pion Lifetime at TRIUMF

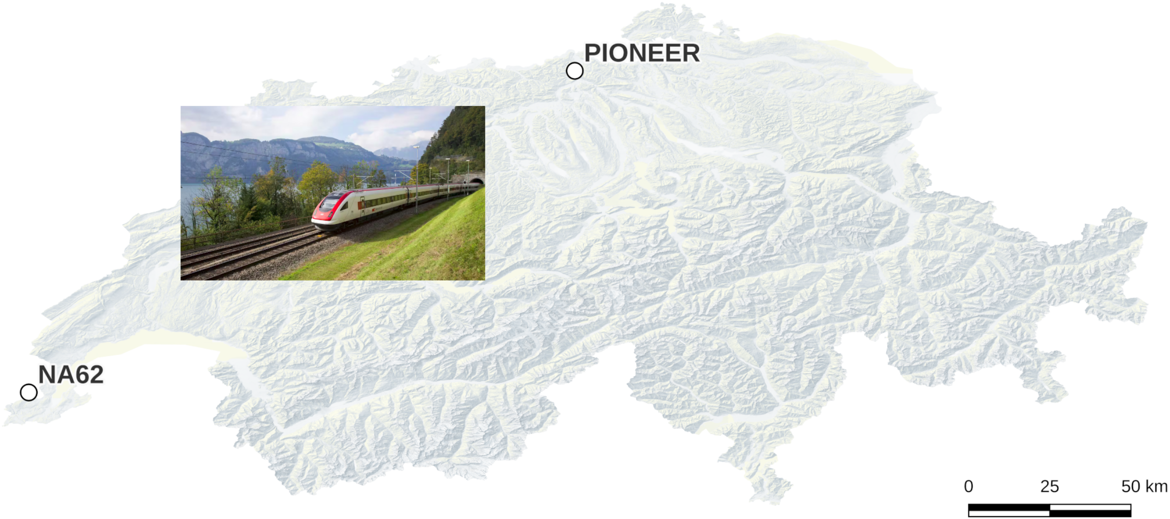
The pion lifetime enters as an external parameter in the extraction of $R_{e/\mu}$ from the data.

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





Measurement of the M20 beamline characteristics in 2023. Accelerator and CMMS groups involved. LOI presented to the PP-EEC in 2024, endorsed for test shifts on M20 and 2C1.

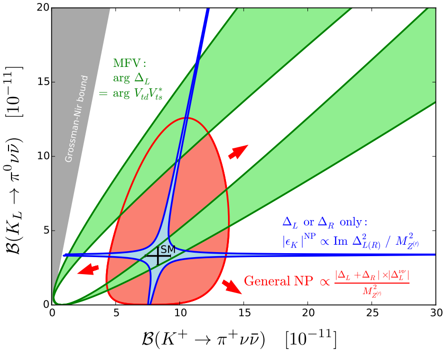


Map data from swisstopo, train photo from SSB

CERN SPS NA62 Experiment – Kaon Decay-in-Flight

$K^+ \to \pi^+ \nu \bar{\nu}$ probes the Standard Model up to energy scales out of reach for direct production. Measurable deviations are predicted for many New Physics scenarios, e.g.

- *Z' models* [A. J. Buras, F. De Fazio, J. Girrbach, 13'] [A. J. Buras, D. Buttazzo, R. Knegjens, 15'] [J. Aebischer, A. J. Buras, J. Kumar, 20']
- *Extra dimensions* [M. Blanke et al, 09']
- *Leptoquark models* [C. Bobeth, A. J. Buras, 18'] [S. Fajfer, N. Košnik, L. Vale Silva, 18']
- *Littlest Higgs models* [M. Blanke et al, 16']
- *Lepton Flavour Violation models* [M. Bordone et al, 17']

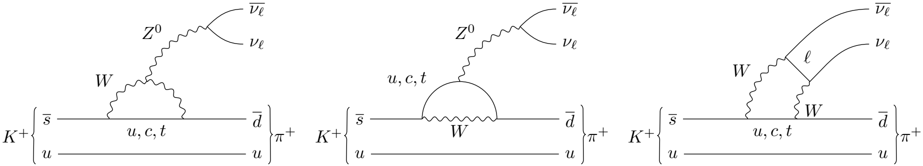


[A. J. Buras et al, '15]

Strong complementary program: Dark photons, heavy neutral leptons, LNV/LFV decays, etc.

$K^+ \to \pi^+ \nu\overline{\nu}$ – Standard Model & Previous Measurements

Flavor Changing Neutral Current; the decay is extremely suppressed: $s \to d \sim \frac{m_t^2}{m_W^2} \left|V_{ts}^\star V_{td}\right|$



Theoretical uncertainties well controlled: QCD and electroweak corrections; hadronic matrix element related to $K^+ \to \pi^0 e^+ \nu_e$. [F. Mescia, C. Smith, '07] [J. Brod, M. Gorbahn, '08] [J. Brod, M. Gorbahn, E. Stamou, '11]

> SM branching ratio: $\mathcal{B}_{\rm SM}\left(K^+ \to \pi^+ \nu\overline{\nu}\right) = (8.60 \pm 0.42) \times 10^{-11}$ [A. J. Buras, '23]

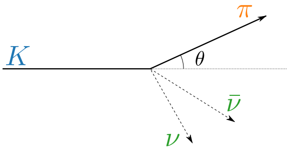
Before NA62, BNL E787 & E949 (2008) $\to \mathcal{B}\left(K^+ \to \pi^+ \nu\overline{\nu}\right) = 17.3^{+11.5}_{-10.5} \times 10^{-11}$ [E949 Collaboration]

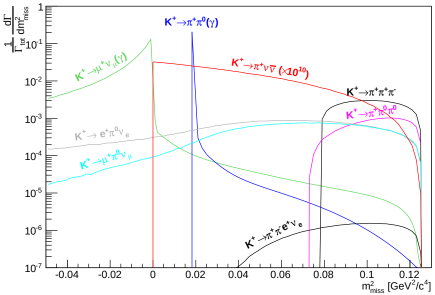
NA62 – $K^+ \to \pi^+ \nu\overline{\nu}$ – Decay-in-Flight

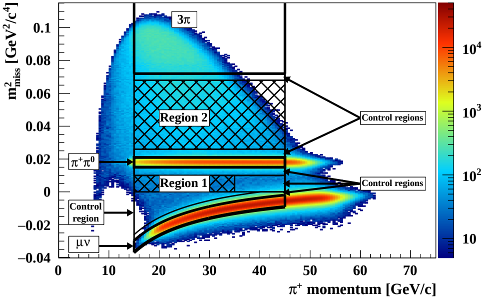
Signal: K^+ associated to a π^+ and missing energy (ν)

- Identification of K and π,
- Multi-track event rejection,
- Vetoes for γ and μ, rejection $> \mathcal{O}\left(10^7\right)$,
- $\mathcal{O}\left(100\ \mathrm{ps}\right)$ timing for K - π matching,
- Excellent kinematic reconstruction $\to m^2_{\mathrm{miss.}} = \left(P_{K^+} - P_{\pi^+}\right)^2$.

$$\mathcal{B}\left(K^+ \to \pi^+\nu\overline{\nu}\right) \sim 10^{-10}$$

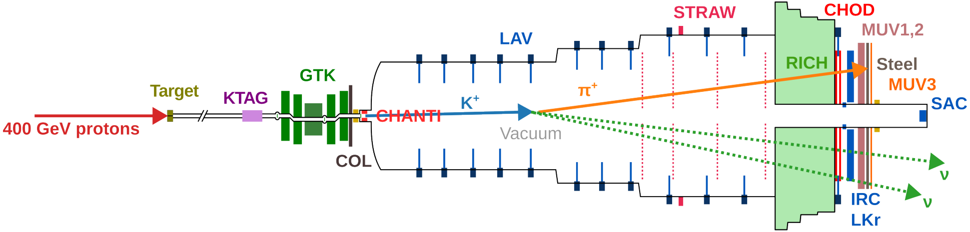






Decays in flight!

Secondary beam: 75 GeV/$c \pm 1\%$, K^+, π^+ and p (6:70:23), 750 MHz at nominal intensity.



KTAG →	Kaon tagging ($\sigma_t = 70$ ps),	CHOD →	Event multiplicity,
GTK →	Beam tracker (0.5 X_0/station),	LKr, MUV1, MUV2 →	Particle ID,
CHANTI →	Charged particles veto,	LAV, IRC, LKr, SAC →	Photon vetos,
STRAW →	Downstream tracker,	MUV3 →	Muon vetos,
RICH →	Particle ID ($\sigma_t = 70$ ps),	MUV0, HASC →	Off-acceptance vetos.

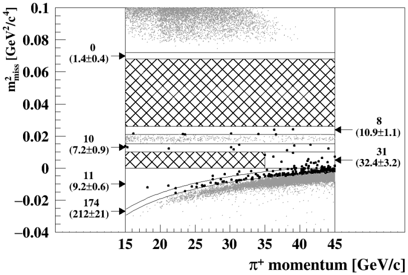
Note: 2018 data set is divided into two subsets: S1 (20%) w/o COL and S2 (80%) w/ COL. For details about the detector, see [NA62 collaboration, 17'].

The CERN NA62 Experiment in 2021 [CERN-PHOTO-202104-059-8]

After unblinding the Run I data, we found 20 $K^+ \to \pi^+\nu\overline{\nu}$ candidates, consistent with the expectations.

$$\mathcal{B}\left(K^+ \to \pi^+\nu\overline{\nu}\right) = \left(10.6^{+4.0}_{-3.4}\Big|_{\text{stat.}} \pm 0.9_{\text{syst.}}\right) \times 10^{-11} \text{ at } 68\% \text{ CL}$$

in agreement with the SM value: $(8.60 \pm 0.42) \times 10^{-11}$ [NA62 Collaboration, 21' (JHEP 06(2021)093)]



Expected signal	$10.01 \pm 0.42_{\text{syst.}} \pm 1.19_{\text{ext.}}$
Expected background	$7.03^{+1.05}_{-0.82}$
Observed candidates	20

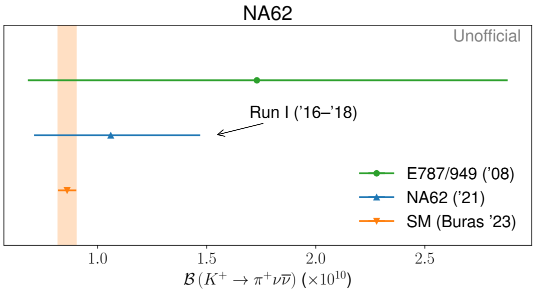
Rich complementary program: searches for dark photons, heavy neutral leptons, beam dump mode, etc. → Click to see all the NA62 papers

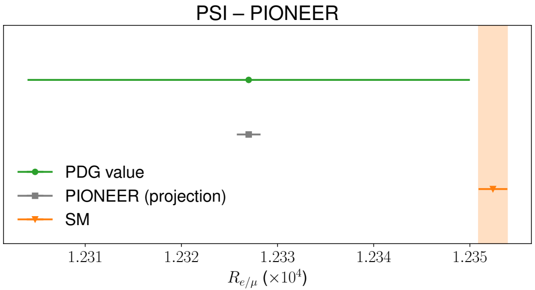
Conclusion and Future Prospects

The group expertise with precision pion and kaon physics is going back to PIENU and the BNL E787/E949 experiments, and is continuing with PIONEER and NA62.

We are making important contributions to NA62's instrumentation and data analysis, including machine learning tools (w/ W. Fedorko).

We have a leading role in the PIONEER experiment design, with a focus on LXe calorimeter R&D efforts.





Backup Slides

NA62 – Single Event Sensitivity (SES)

$K^+ \to \pi^+\pi^0$ from the control trigger chain are used for normalization.

$$\mathrm{SES} = \frac{\mathcal{B}\left(K^+ \to \pi^+\pi^0\right) \cdot A_{\pi\pi}}{D \cdot N_{\pi\pi} \cdot A_{\pi\nu\bar{\nu}} \cdot \epsilon_{\mathrm{RV}} \cdot \epsilon_{\mathrm{trig.}}^{\mathrm{PNN}}} \propto \frac{1}{N_K \cdot \epsilon_{\pi\nu\nu}} .$$

		Subset S1 (w/o COL)	Subset S2 (w/ COL)
CTRL Trig. downscale	D	400	400
	$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
Acceptance (MC)	$A_{\pi\pi} \times 10^2$	7.62 ± 0.77	11.77 ± 1.18
Acceptance (MC)	$A_{\pi\nu\bar{\nu}} \times 10^2$	3.95 ± 0.40	6.37 ± 0.64
Trig. efficiency	$\epsilon_{\mathrm{trig}}^{\mathrm{PNN}}$	0.89 ± 0.05	0.89 ± 0.05
Random veto	ϵ_{RV}	0.66 ± 0.01	0.66 ± 0.01
	$SES \times 10^{10}$	0.54 ± 0.04	0.14 ± 0.01
	$N_{\pi\nu\bar{\nu}}^{\mathrm{exp}}$	$1.56 \pm 0.10 \pm 0.19_{\mathrm{ext}}$	$6.02 \pm 0.39 \pm 0.72_{\mathrm{ext}}$

ϵ_{RV} encodes the random vetos caused by accidental activity in the detector.

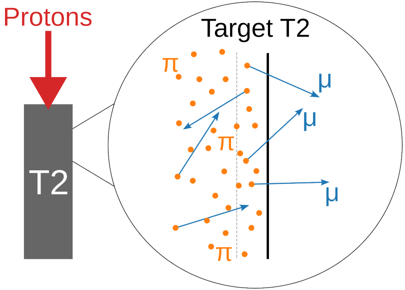
NA62 – $K^+ \to \pi^+ \nu\bar{\nu}$ – Run I Background Analysis

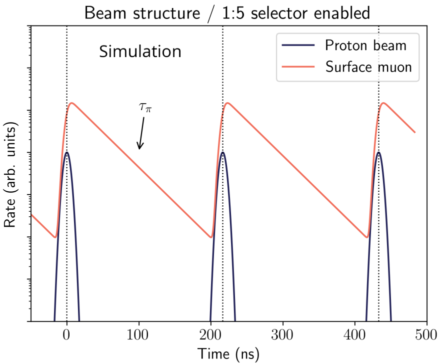
Background	Expected (S1, w/o COL)	Expected (S2, w/ COL)
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^- e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

[NA62 Collaboration, 21']

Measuring the Pion Lifetime at TRIUMF

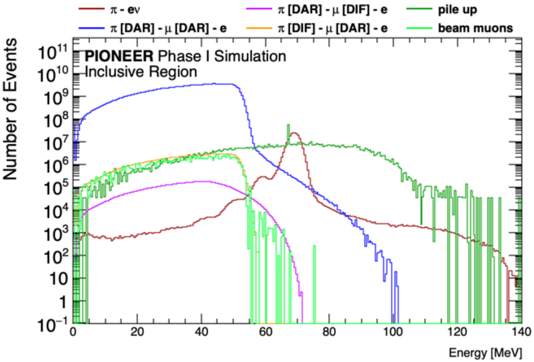
We plan to measure the rate of surface muons emitted from the T2 target ($\pi^+ \rightarrow \mu^+\nu$) in relation to the cyclotron's RF cycles.

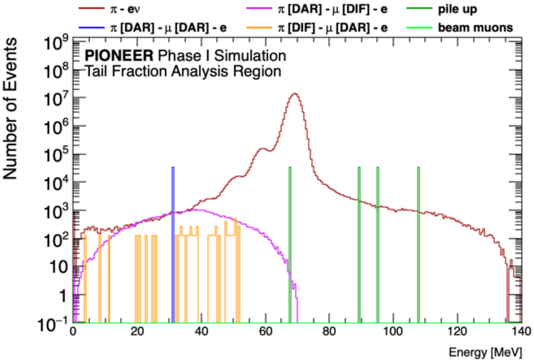




Beam line M20 selects a narrow momentum range near the surface muon peak ($P = 29.4$ MeV/c) and suppresses protons, pions and positrons.

PIONEER Phase I – $R_{e/\mu}$



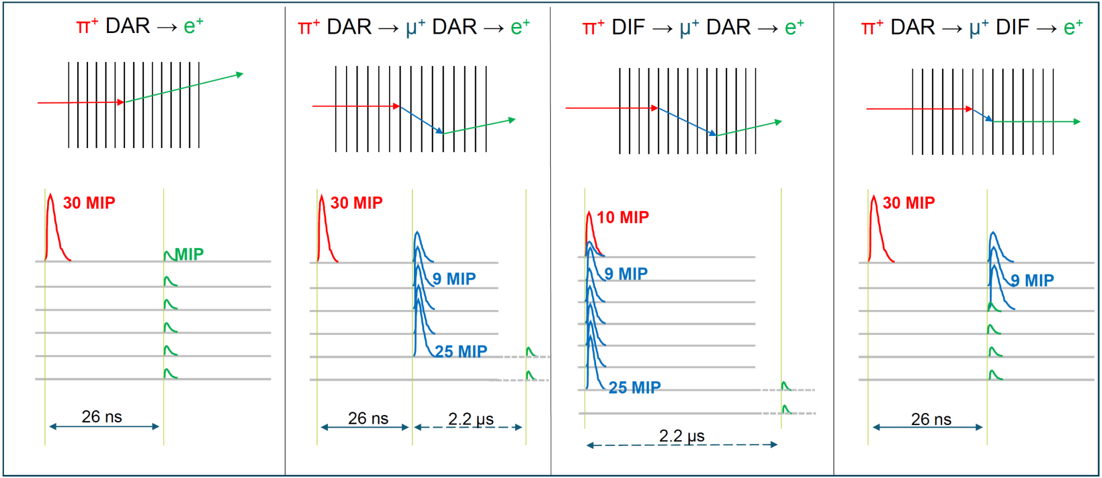


Plots from Q. Buat

Active Target – $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ Tagging

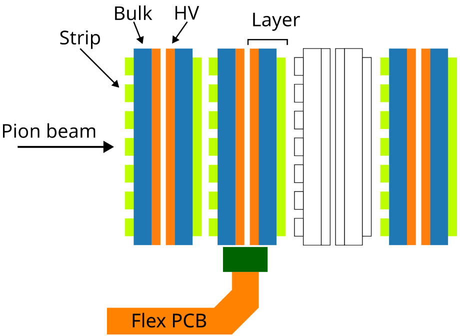
Identify (and suppress) $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ events → Reveals the tail such that it can be corrected for.

❑ Topology ❑ Calorimetry ❑ Timing



Baseline design is $\approx 50\times$ alternating silicon strips planes (120 μm thick).

- Low Gain Avalanche Detectors (LGAD), silicon with a thin gain layer,
- 100 strips, 2 cm length, with 200 μm pitch (2×2 cm^2 area),
- Sensors are packed in stack of 2 with facing HV side and rotated by 90°.



Strips are wire-bonded to a flex PCB, signals are routed to fast analog amplifiers ($d < 5$ cm), digitizers installed outside of the main detector volume.

PIONEER – Pion Beta Decay & CKM

$\Gamma\left(\pi^+ \to \pi^0 e^+ \nu(\gamma)\right) = 1.036(6) \times 10^{-8}$ (PIBETA @ PSI) [Phys. Rev. Lett. 93 (2004) 181803]

$$\Gamma_{\pi\beta} = \frac{G_\mu^2 \left|V_{ud}\right|^2 m_{\pi^+}^5}{64\pi^3} \left|f_+^\pi(0)\right|^2 (1 - RC_\pi)\, I_\pi$$

[Phys. Rev. D 101 (2020) 091301(R)]

$\lvert V_{ud}\rvert$	0.97373(31)	(Superallowed β decays) [Phys. Rev. C 102 (2020) 045501]
	$0.9740(28)_{\mathrm{exp}}(1)_{\mathrm{th}}$	$(R_{\pi\beta})$ [Phys. Rev. Lett. 124 (2020) 192002]

The V_{ud} extraction from $R_{\pi\beta}$ is theoretically clean but not yet competitive with the superallowed β decays (long term goal).

But, $3\times$ improvement in $\delta R_{\pi\beta} \to \delta 0.2\%$ on $V_{us}/V_{ud} \to$ Competitive ! (Phase II)