Low Energy Particle Physics - Fundamental Interactions Group
of Prof. Dr. Anna Sótér

The PIONEER Experiment

Testing Lepton Flavour Universality in a Next-Generation Precision Pion Decay Experiment Located at PSI

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0 Motivation

Hints of Lepton Flavour Universality Violation

- Deviating branching ratios ($R(D^{(*)})$ with 3σ and $R(K^{(*)})$ with 4σ)

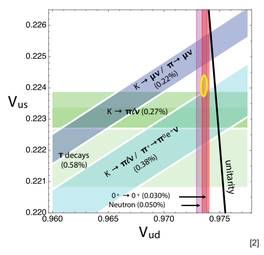
Measure branching ratio of π^+ (Phase I)

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

- Bridge gap between theoretical and experimental precision: improve precision by 15
- perhaps most precisely calculated weak interaction observable involving quarks
- New physics up to the PeV scale may be revealed

Cabibbo Angle Anomaly

- test CKM unitarity

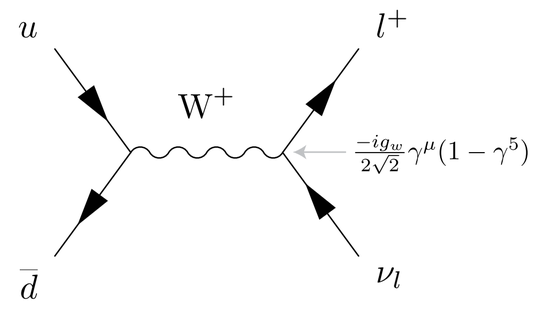


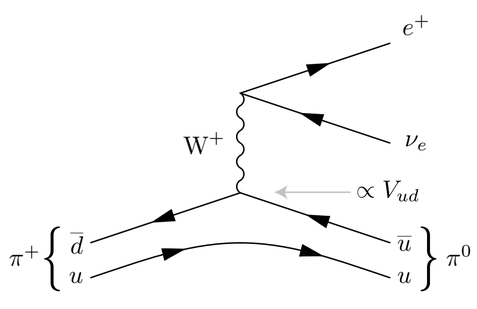
[2]

Study pion beta decay (Phase II/III)

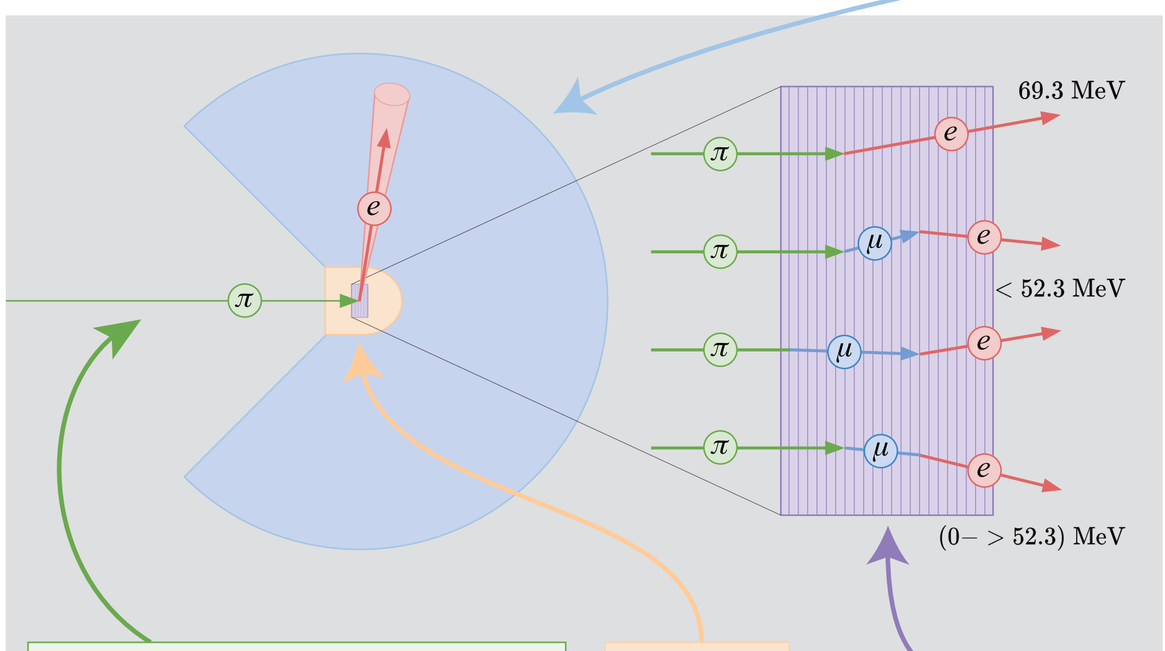
$\pi^+ \to \pi^0 e^+ \nu(\gamma)$

- Improve branching ratio by
  - a factor of three (Phase II)
  - order of magnitude (Phase III)
- theoretically cleanest extraction of $|V_{ud}|$ at 0.02% level
- comparable to deduction from superallowed beta decays
- lift 3σ tension of V_{ud}





1 Experimental Setup

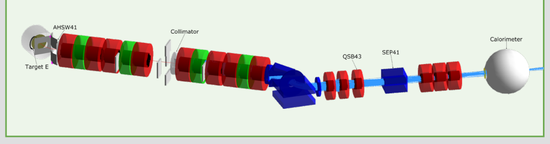


Pion Beam

Requirements:

Phase	p (MeV/c)	Δp/p (%)	ΔZ (mm)	ΔX x ΔY (mm²)	ΔX',ΔY'	R_π (10^6/s)
I	55-70	2	1	10x10	±10°	0.3
II,III	≈ 85	≤ 5	3	15x15	±10°	20

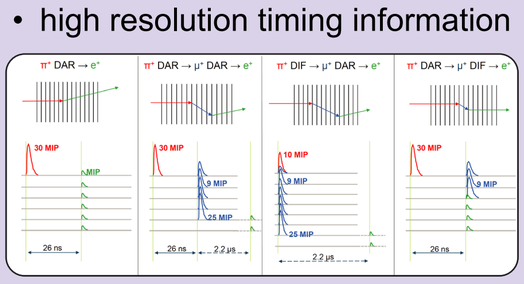
Planned to use the πE5 beamline at PSI High Intensity Proton Accelerator



Tracker

Highly segmented active target (**ATAR**)

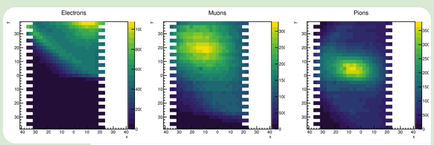
- defines pion stopping region
- high resolution timing information

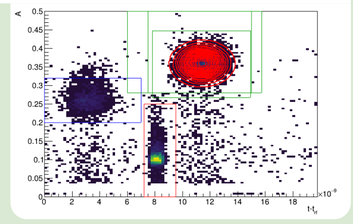


2 Momentum bite analysis of beam

Time of flight analysis

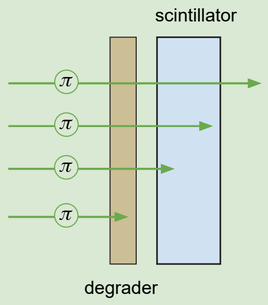
- Cut out pions in time-Energy-space
- calculate Δt and use it to get a rough estimate of Δp/p

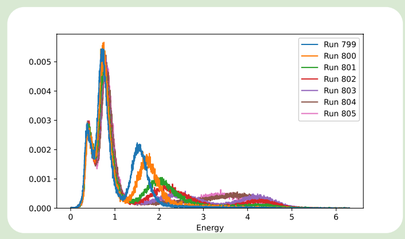




With degraders

- pion energy signal changes with different degraders
- use peak position to identify momentum bite
  - compare with simulation

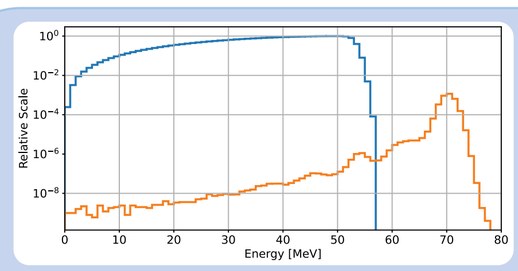




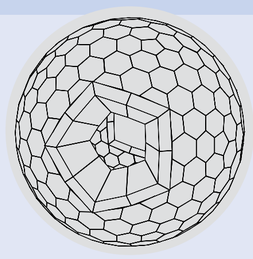
Signal amplitude in Scintillator

3 Calorimeter

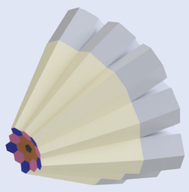
- 25 radiation length 3π sr sphere surrounding the ATAR
- Energy resolution ≤ 2%
- LXe and LYSO crystals in consideration

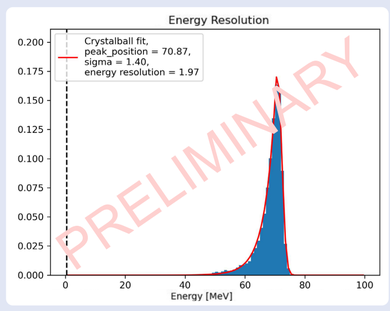


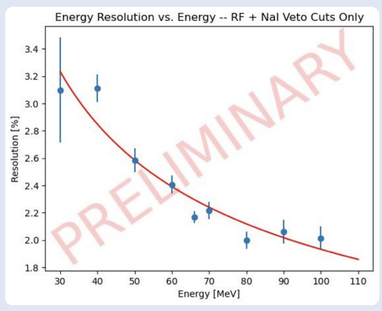
LYSO Test Setup (2023 Beamtime): Measuring the Energy resolution of LYSO crystals

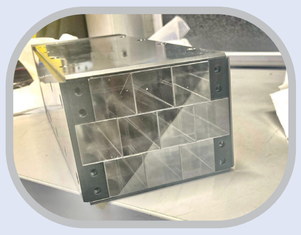


1. Calibration of single crystals
2. Apply cuts on events
3. Add contribution of all crystals together
4. Fit peak and calculate energy resolution



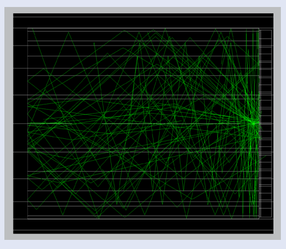


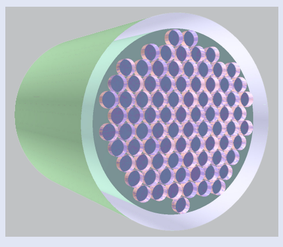


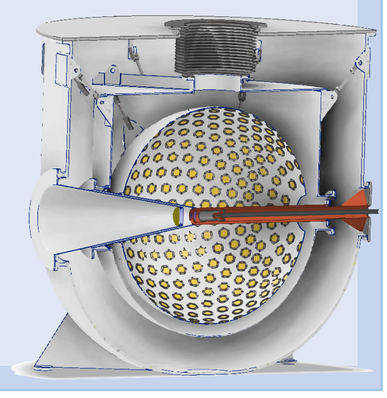


LXe Test Setup

- Optical Simulations with optical photons from Geant4
- Using simplified „Prototype“ geometry, PMTs placed on one end
- test different surface materials







References

[1] PIONEER Collaboration · W. Altmannshofer et al. *PIONEER: Studies of Rare Pion Decays* arXiv:2203.01981 (2022)
[2] Douglas Bryman et al. *Testing Lepton Flavor Universality with Pion, Kaon, Tau, and Beta Decays* arXiv:2111.05338 (2021)
[3] PIONEER Collaboration · S. M. Mazza. *An LGAD-based full active target for the PIONEER experiment* arXiv:2111.05375 (2022)
[4] Muon g-2 Collaboration · D. P. Aguillard, et al. *Measurement of the positive muon anomalous magnetic moment to 0.20 ppm* PhysRevLett:131.161802 (2023)