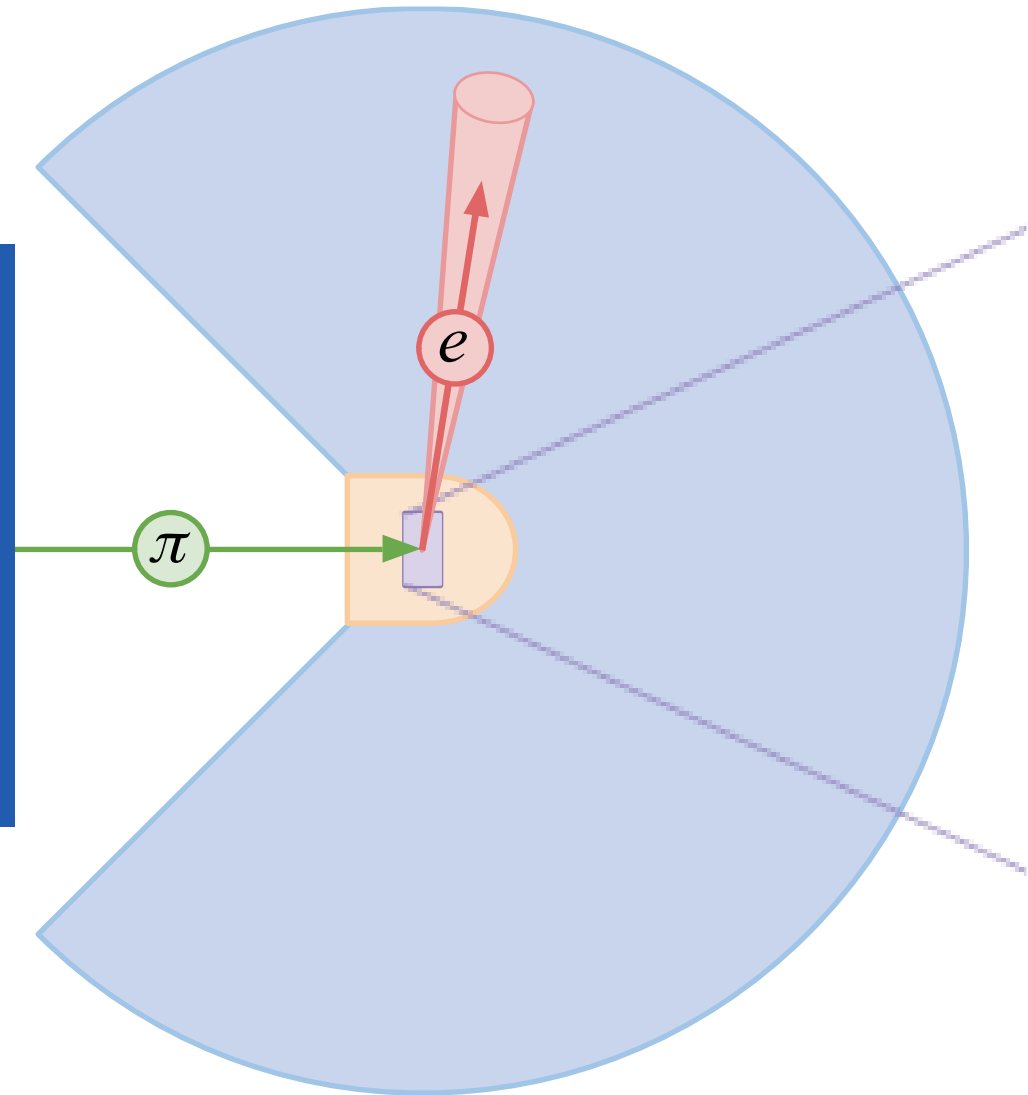


The PIONEER Experiment

ATTRACT workshop 2025
Kolja Frahm



Motivation of PIONEER

Standard Model of Elementary Particles

			three generations of matter (elementary fermions)			three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)	
			I	II	III	I	II	III		
QUARKS	mass		$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
	charge		$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	0	0
	spin		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
			u up	c charm	t top	$\bar{u}$ antiup	$\bar{c}$ anticharm	$\bar{t}$ antitop	g gluon	H higgs
			$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
			$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	0	
			$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
			d down	s strange	b bottom	$\bar{d}$ antidown	$\bar{s}$ antistrange	$\bar{b}$ antibottom	γ photon	
LEPTONS			$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
			-1	-1	-1	1	1	1	0	
			$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
			e electron	μ muon	τ tau	e^+ positron	$\bar{\mu}$ antimuon	$\bar{\tau}$ antitau	Z Z ⁰ boson	
			$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.360 \text{ GeV}/c^2$	$\approx 80.360 \text{ GeV}/c^2$
			0	0	0	0	0	0	1	-1
			$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	1
			ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	$\bar{\nu}_e$ electron antineutrino	$\bar{\nu}_\mu$ muon antineutrino	$\bar{\nu}_\tau$ tau antineutrino	W^+ W ⁺ boson	W^- W ⁻ boson

https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles_Anti.svg

Standard Model of Elementary Particles

three generations of matter (elementary fermions)						three generations of antimatter (elementary antifermions)						interactions / force carriers (elementary bosons)			
I		II		III		I		II		III					
mass $\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$					
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spin $\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0					
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$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	1							
$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0	0	1							
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QUARKS

LEPTONS

GAUGE BOSONS
VECTOR BOSONS

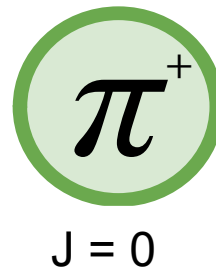
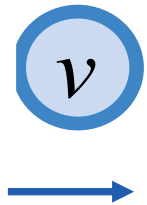
SCALAR BOSONS

https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles_Anti.svg

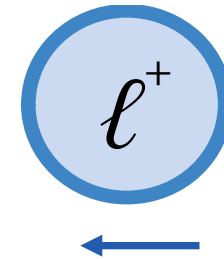
Pion decay

Textbook example of helicity suppression

LH relativistic neutrino



LH antilepton

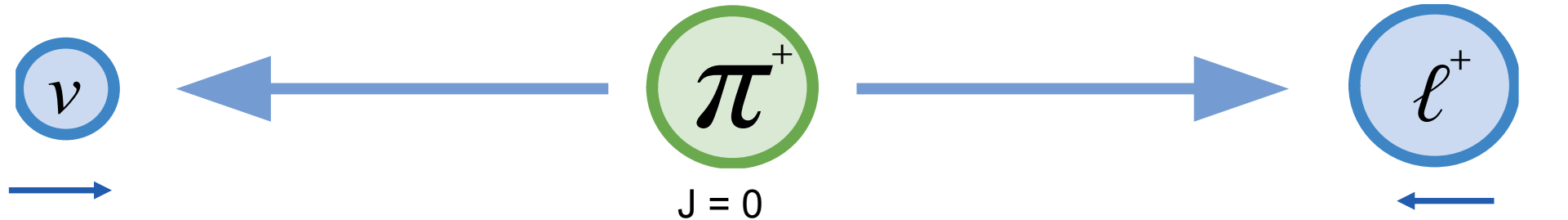


$$R_{e/\mu} = \frac{\Gamma(\pi^+ \rightarrow e^+ \nu_e(\gamma))}{\Gamma(\pi^+ \rightarrow \mu^+ \nu_\mu(\gamma))}$$

Pion decay

Textbook example of helicity suppression

LH relativistic neutrino



$$R_{e/\mu} = \frac{\Gamma(\pi^+ \rightarrow e^+ \nu_e(\gamma))}{\Gamma(\pi^+ \rightarrow \mu^+ \nu_\mu(\gamma))}$$

$$R_{e/\mu} = \left(\frac{m_e}{m_\mu}\right)^2 \cdot \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \cdot (1 + \text{EW corrections}) = 1.23524(15) \times 10^{-4}$$

Fully computed at NLO
 $O(10^{-4})$ uncertainties at NNLO

- perhaps most precisely calculated weak interaction observable involving quarks

Motivation of PIONEER (Phase I)

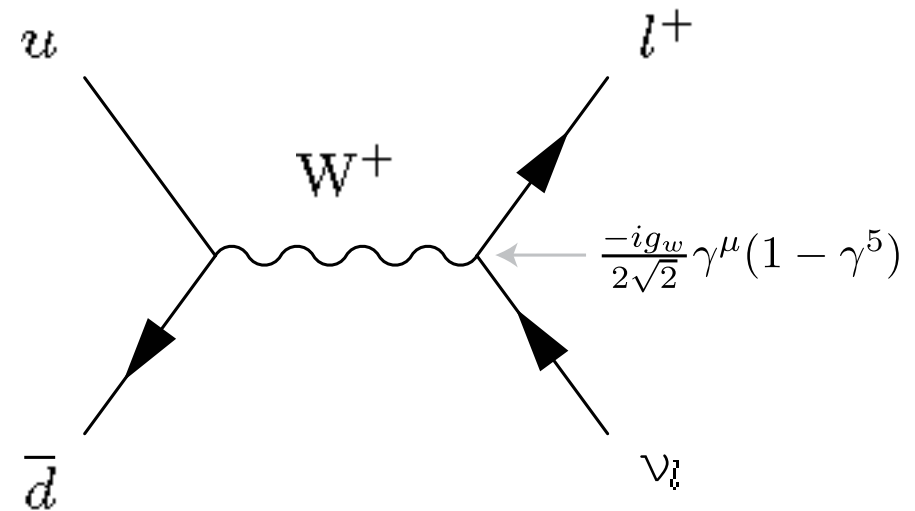
- Hints of Lepton Flavour Universality Violation
 - Deviating branching ratio $R(D^*)$ with 3σ
 - discrepancy in $(g - 2)_\mu$
 - forward-backward asym. of B-meson decays



Measure branching ratio of π^+

$$R_{e/\mu} = \frac{\Gamma(\pi^+ \rightarrow e^+ \nu_e(\gamma))}{\Gamma(\pi^+ \rightarrow \mu^+ \nu_\mu(\gamma))}$$

- $R_{e/\mu}(\text{exp.}) = 1.2327(23) \times 10^{-4}$
- $R_{e/\mu}(\text{SM}) = 1.23524(15) \times 10^{-4}$



Motivation of PIONEER (Phase I)

- Hints of Lepton Flavour Universality Violation
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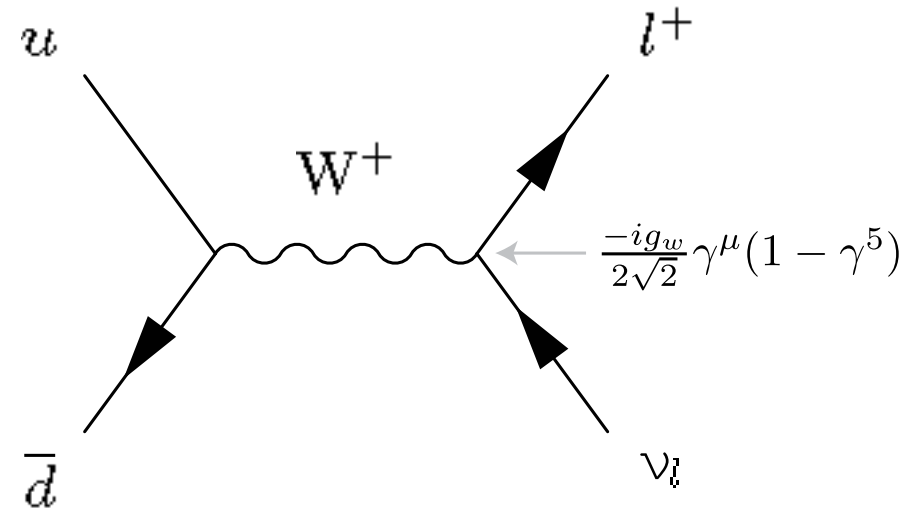
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- $R_{e/\mu}(\text{SM}) = 1.23524(15) \times 10^{-4}$

Goals:

- Bridge gap between theoretical and experimental precision: improve by 15
- Probe new physics models up to the PeV scale



Motivation of PIONEER (Phase II/III)

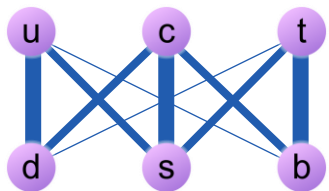
- Cabibbo Angle Anomaly



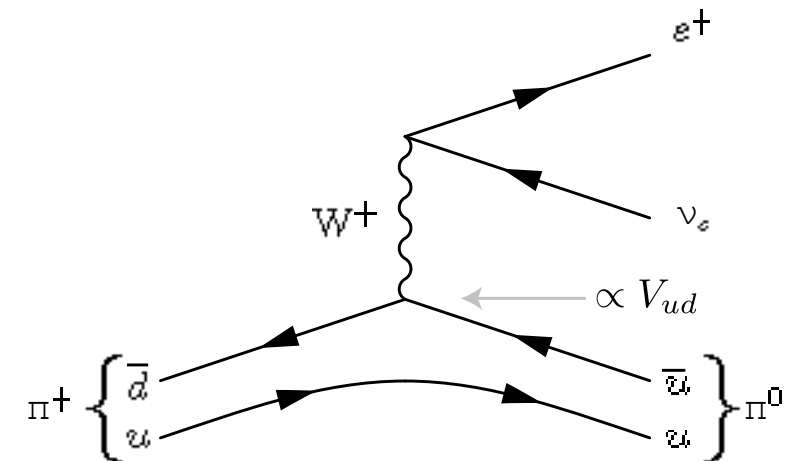
- **Study pion beta decay**

$$\pi^+ \rightarrow \pi^0 e^+ \nu_e (\gamma)$$

to test CKM unitarity



$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$



Motivation of PIONEER (Phase II/III)

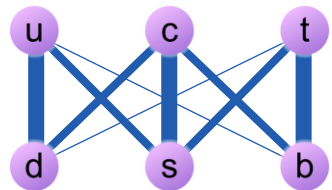
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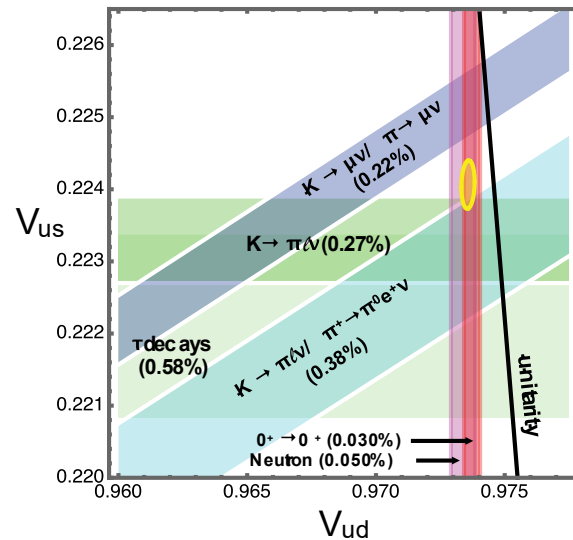
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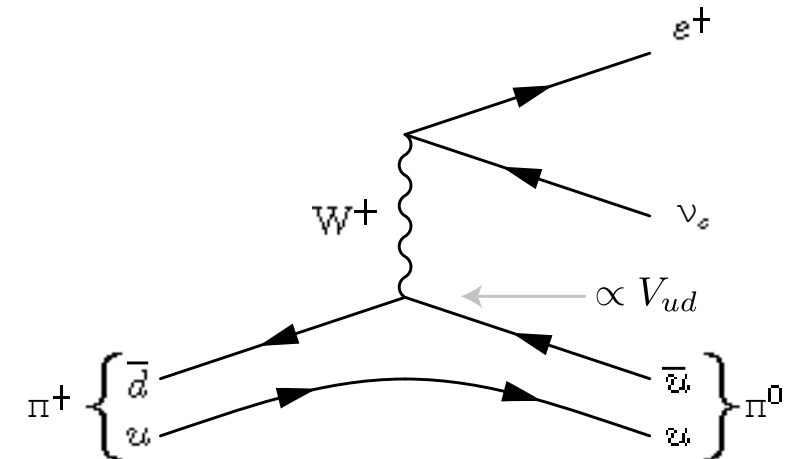
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D. Bryman et al. (2021) arXiv:2111.05338



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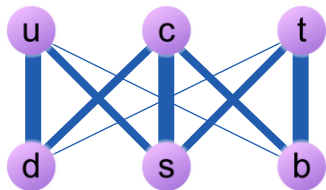
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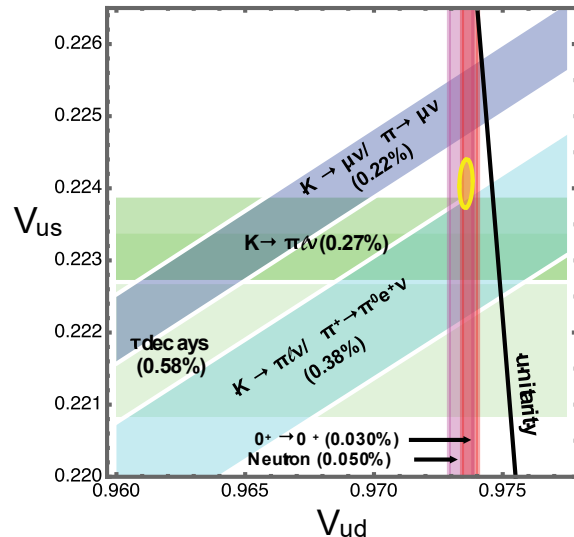
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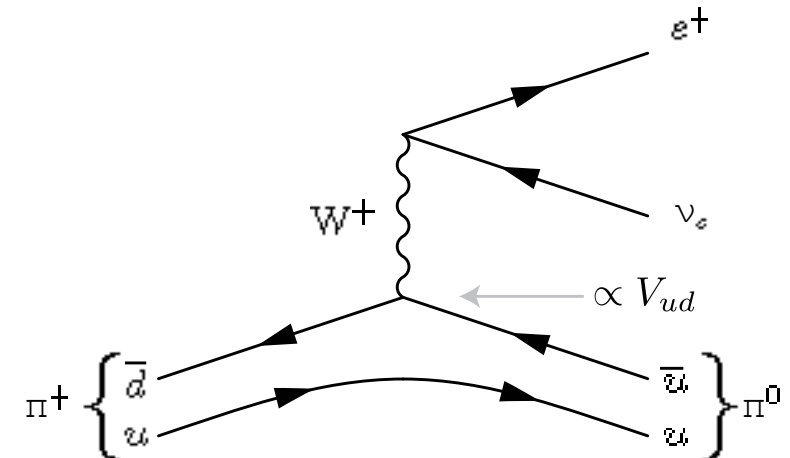
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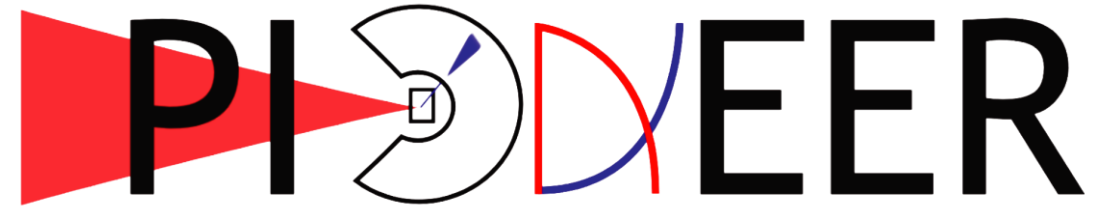
Goals:

- Improve precision of branching ratio by a factor of three (Phase II) and six (Phase III)
- theoretically clean extraction of $|V_{ud}|$ at 0.05% level
 - comparable to deduction from superallowed neutron decays
- lift 3σ tension of V_{ud}



The PIONEER Experiment

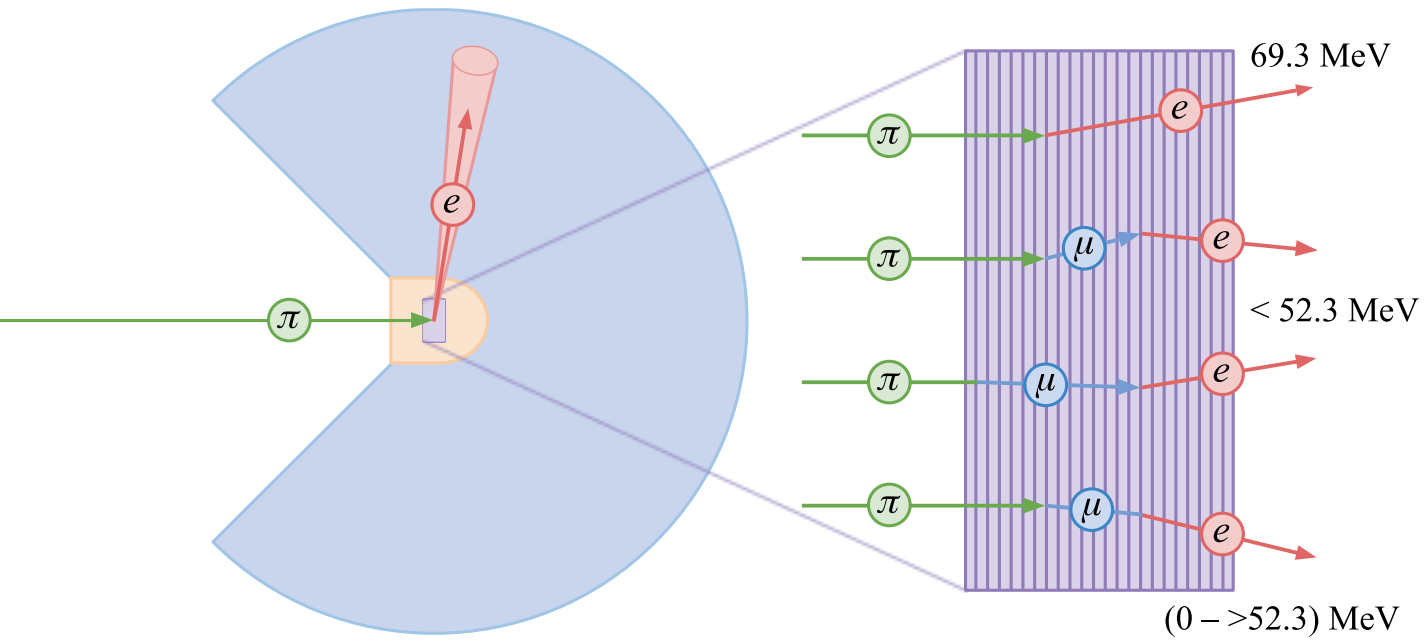
The PIONEER Collaboration



<https://pioneer.triumf.ca/Collaboration/>

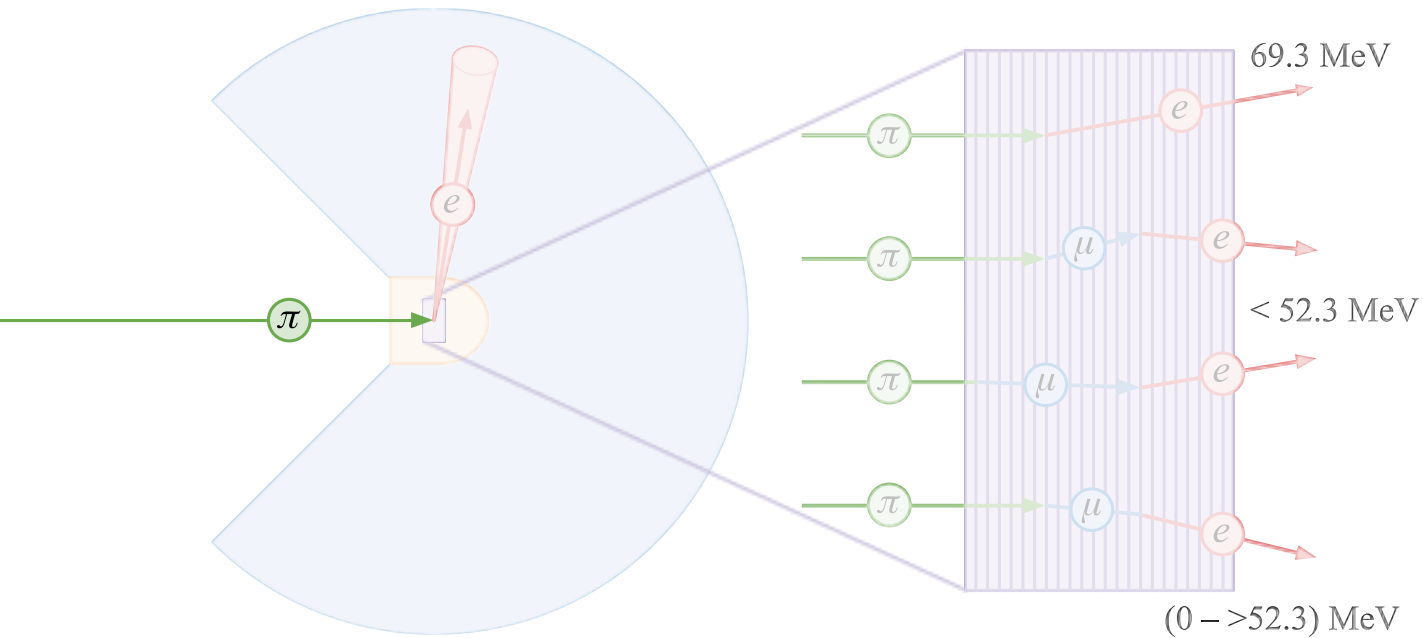


Experimental Setup



Schematic made by Stefan Hochrein

Experimental Setup

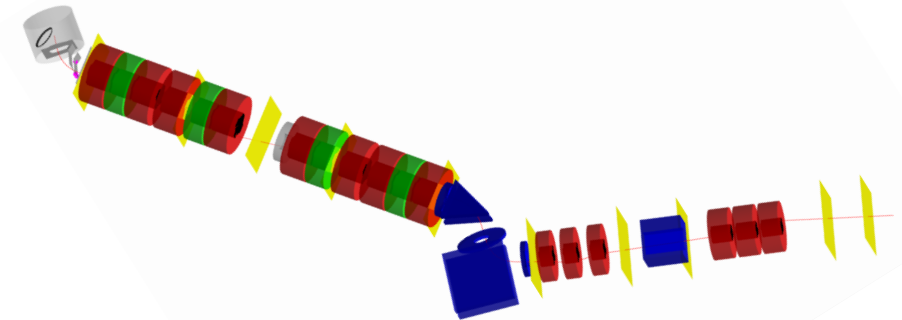


Pion Beam

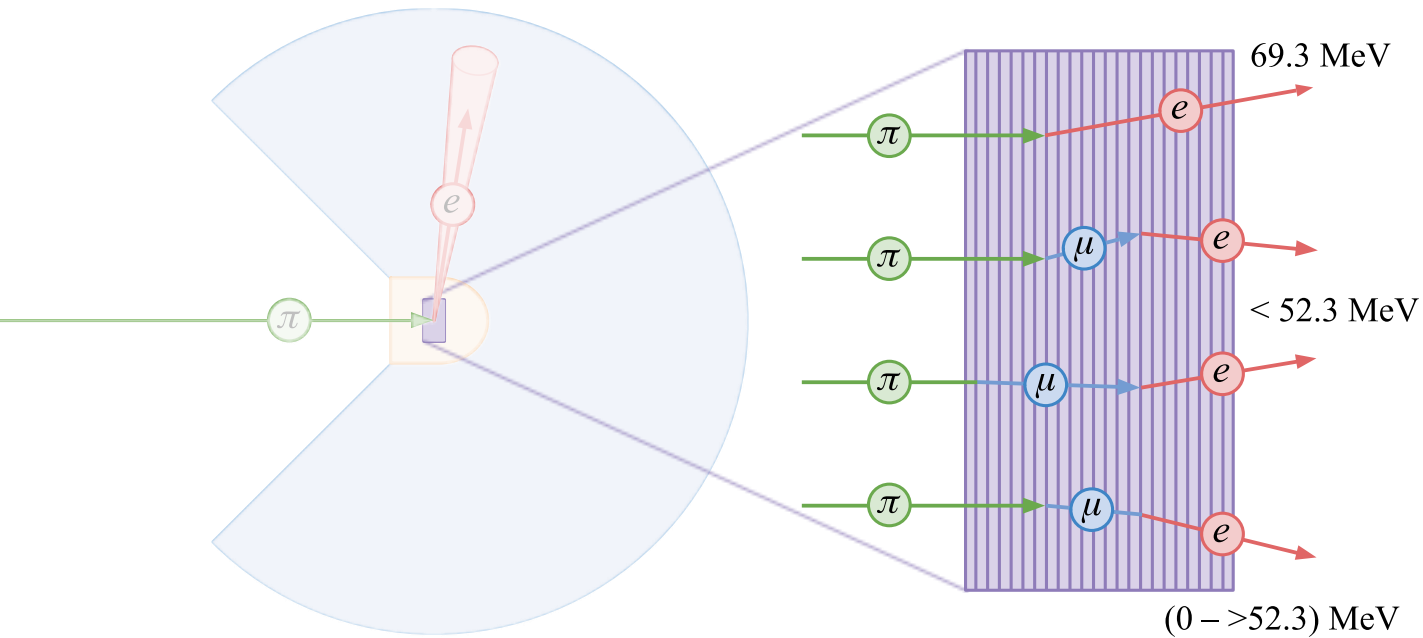
- Requirements:

Phase	p (MeV/c)	$\Delta p/p$ (%)	ΔZ (mm)	$\Delta X \times \Delta Y$ (mm ²)	$\Delta X', \Delta Y'$	R_{τ} (10 ⁶ /s)
I	55-70	2	1	10x10	$\pm 10^\circ$	0.3
II,III	≈ 85	≤ 5	3	15x15	$\pm 10^\circ$	20

- High intensity, low momentum
- Planned to use the π E5 beamline at PSI High Intensity Proton Accelerator

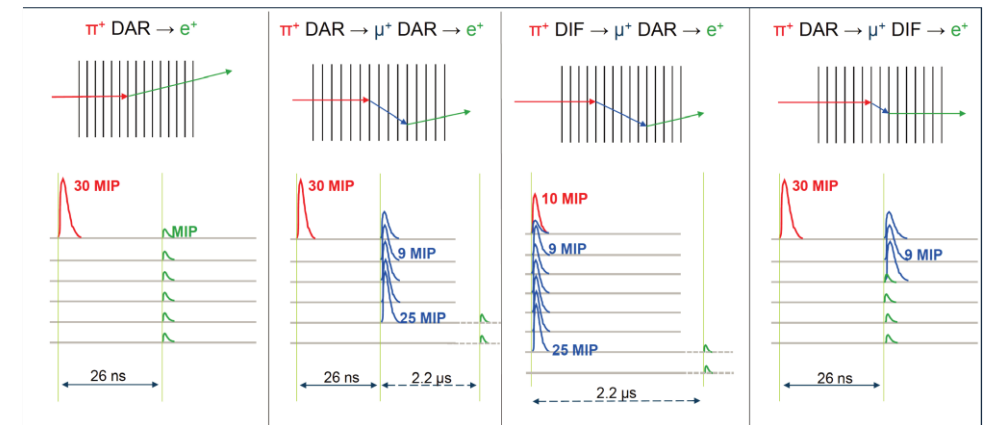


Experimental Setup



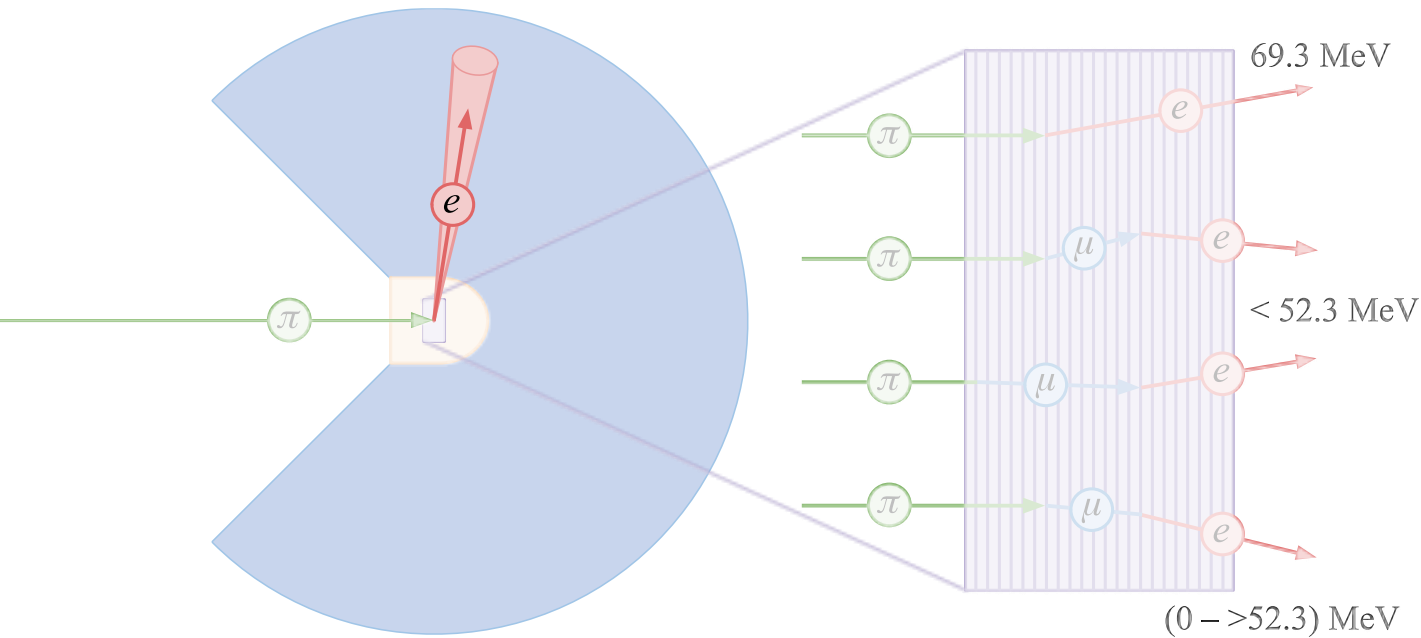
ATAR (Highly segmented active target)

- defines pion stopping region
- high resolution timing information



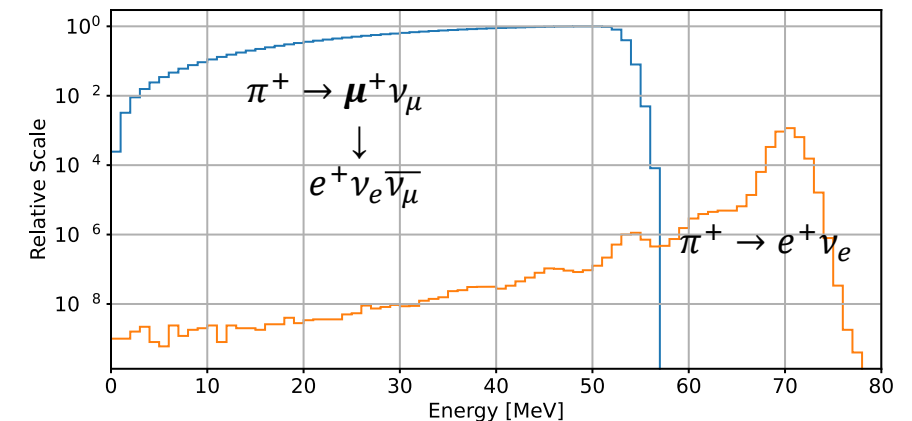
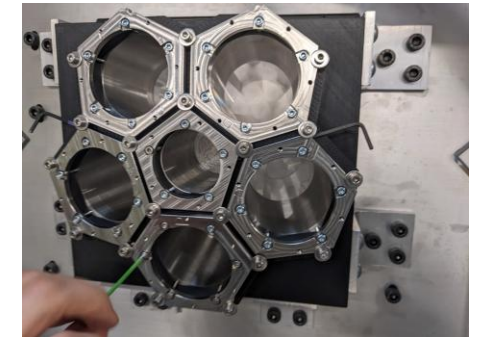
Mazza, S. et al. Proceedings of Science, 2023 V 420. <https://doi.org/10.22323/1.420.0015>

Experimental Setup



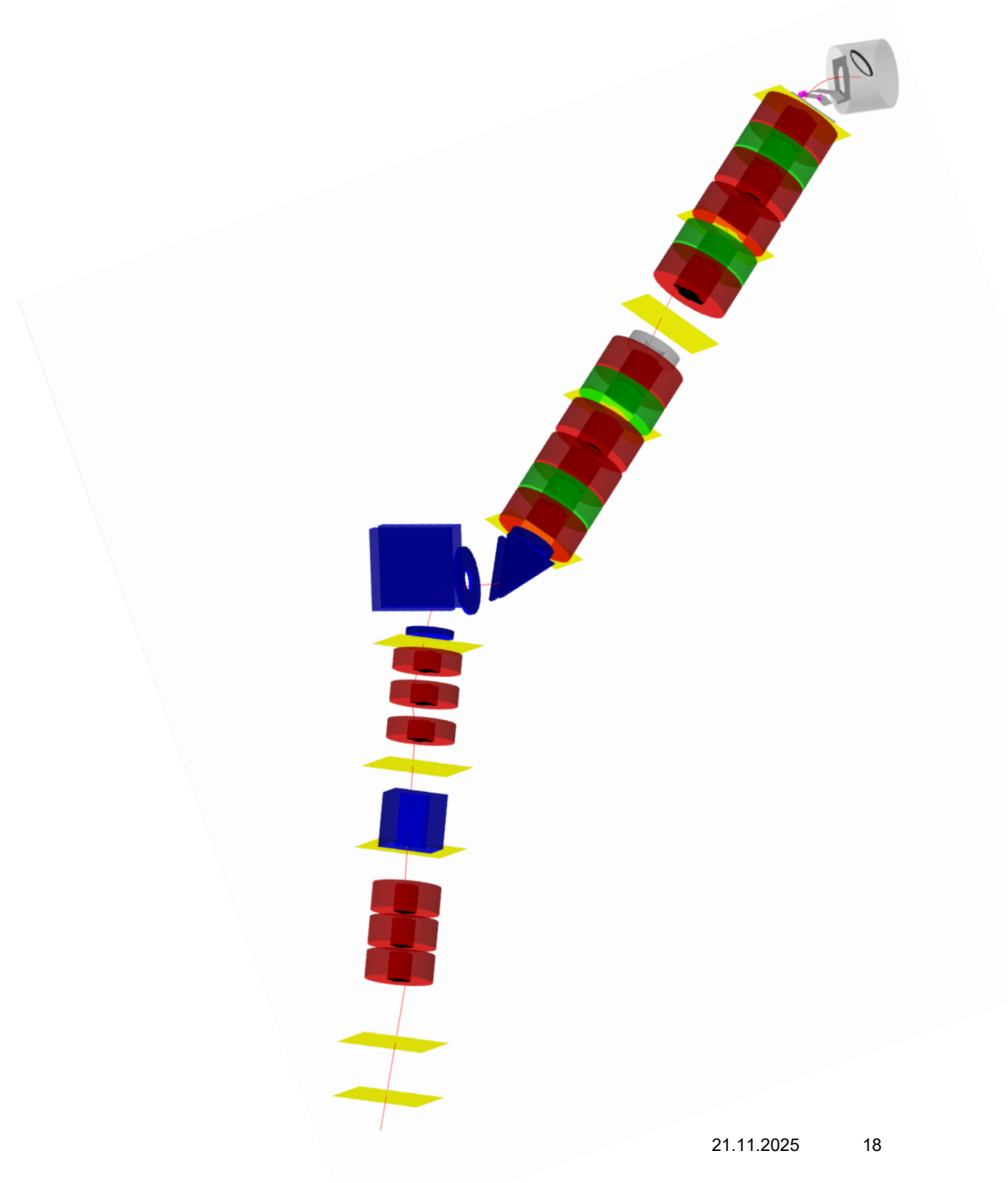
Calorimeter

- 25 radiation length 3π sr sphere surrounding the ATAR
- Energy resolution $\leq 2\%$
- LXe and LYSO crystals in consideration
- LYSO Test beam 2025 completed successfully



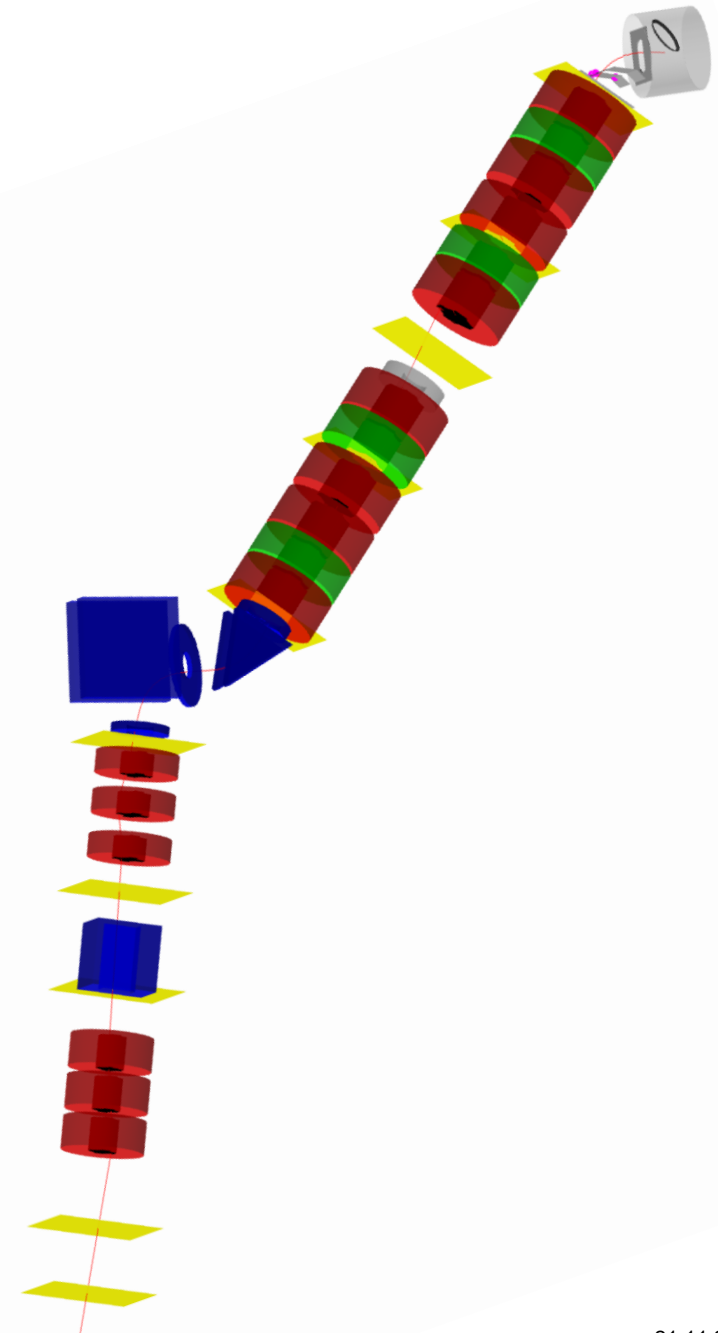
Beam optimisation

- Find best parameters
- Trying out alignment of beam with simulation
- Test alignment with a test beam next year



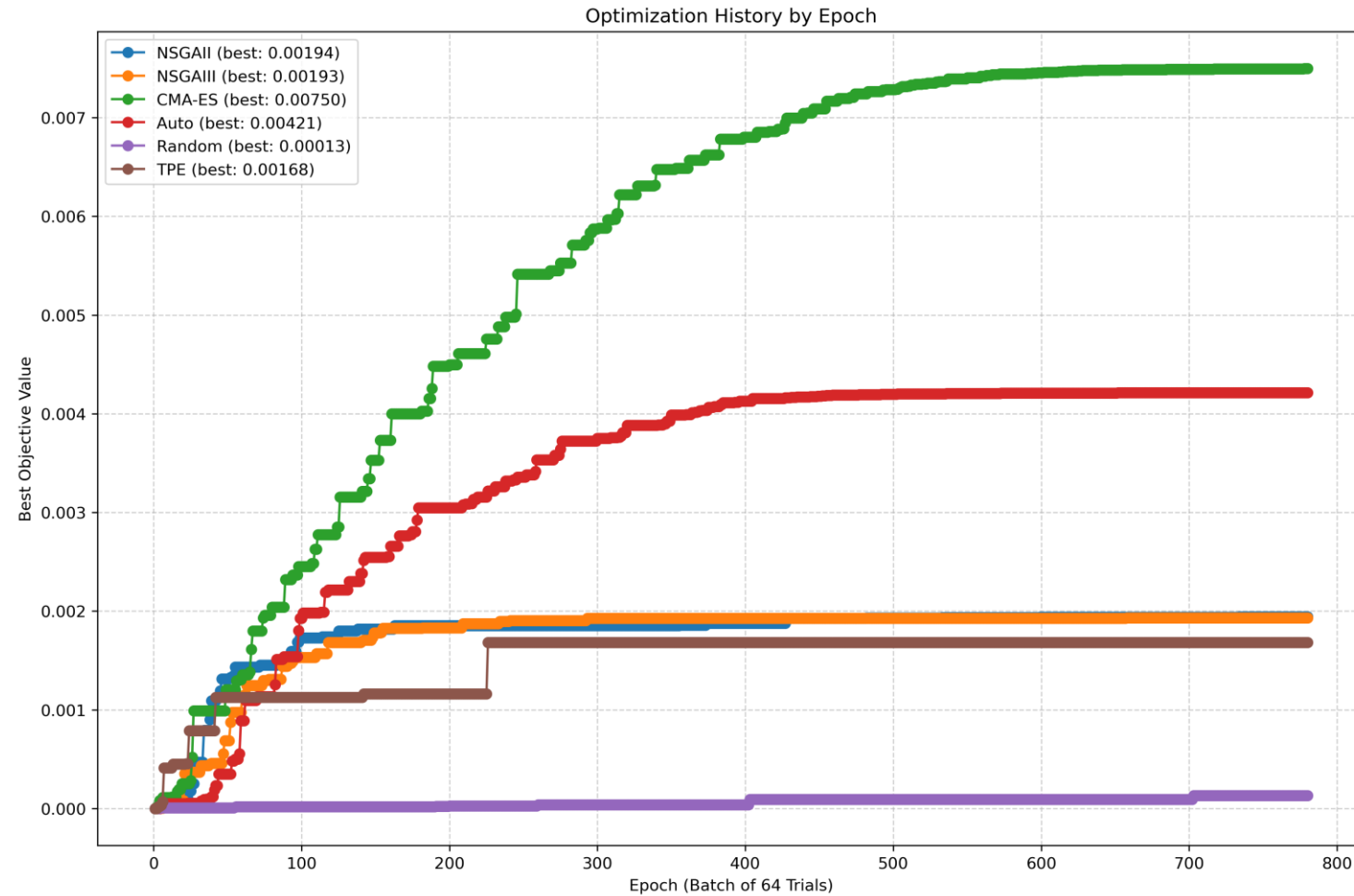
Beam optimisation Setup

- 20 parameters to optimise
 - 14 quadrupoles (red), 4 sextupoles (green), 2 dipoles (blue)
- Place detectors (yellow) in the beamline to investigate phase space
- Optimise intensity and focus
- Use different Samplers
 - Random/Grid search
 - Bayesian optimization (GP/TPE)
 - Evolution strategies (Genetic algorithms (NSGA), CMA-ES)



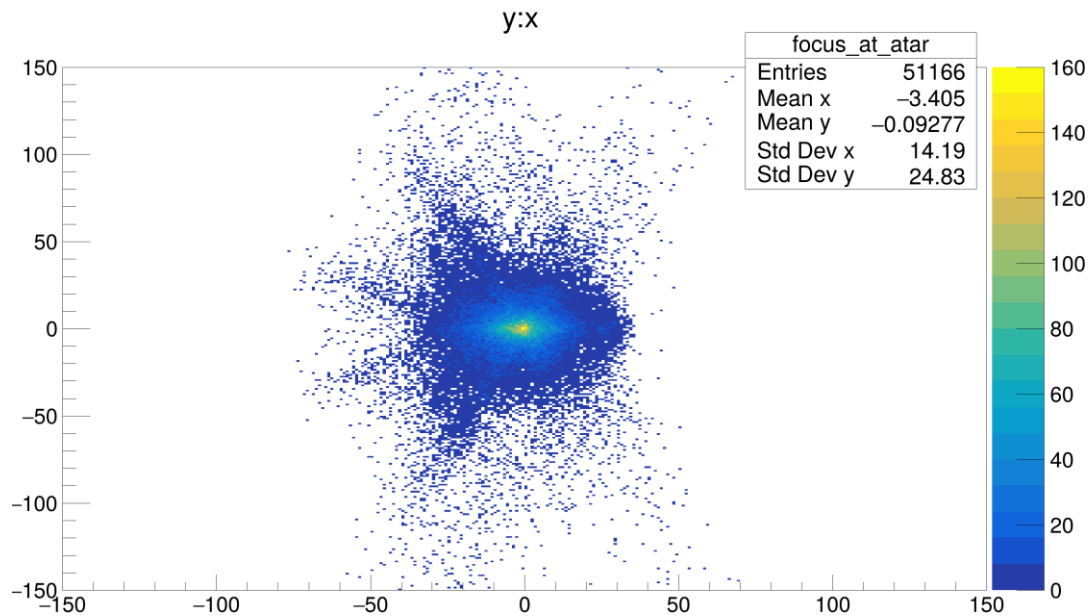
Beam optimisation

Convergence (Parallel simulations in large search space)

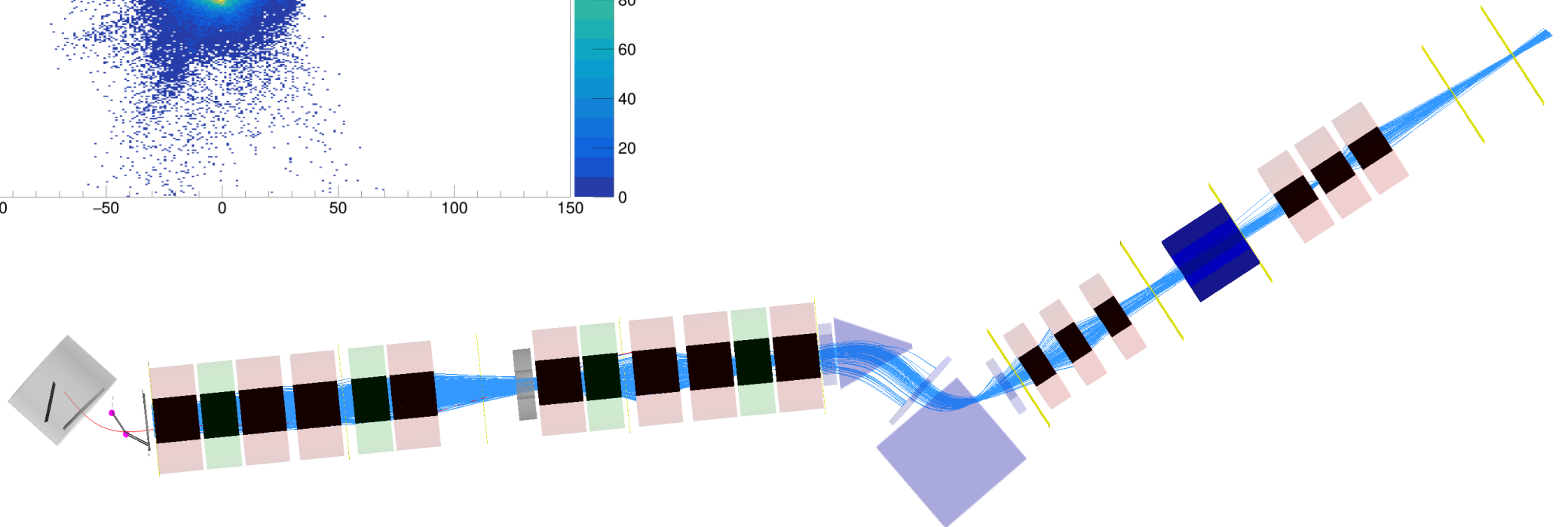
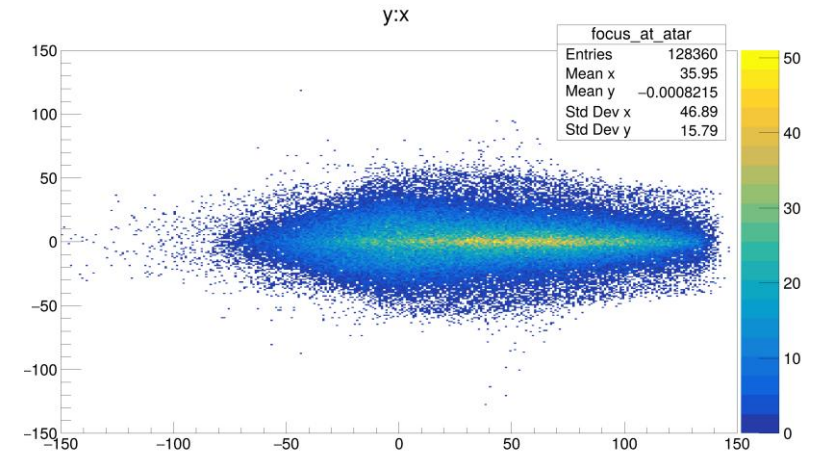


Intensity and focus tune

Phase space best tune at ATAR



For comparison: Phase space of old tune at ATAR



Thank you!

