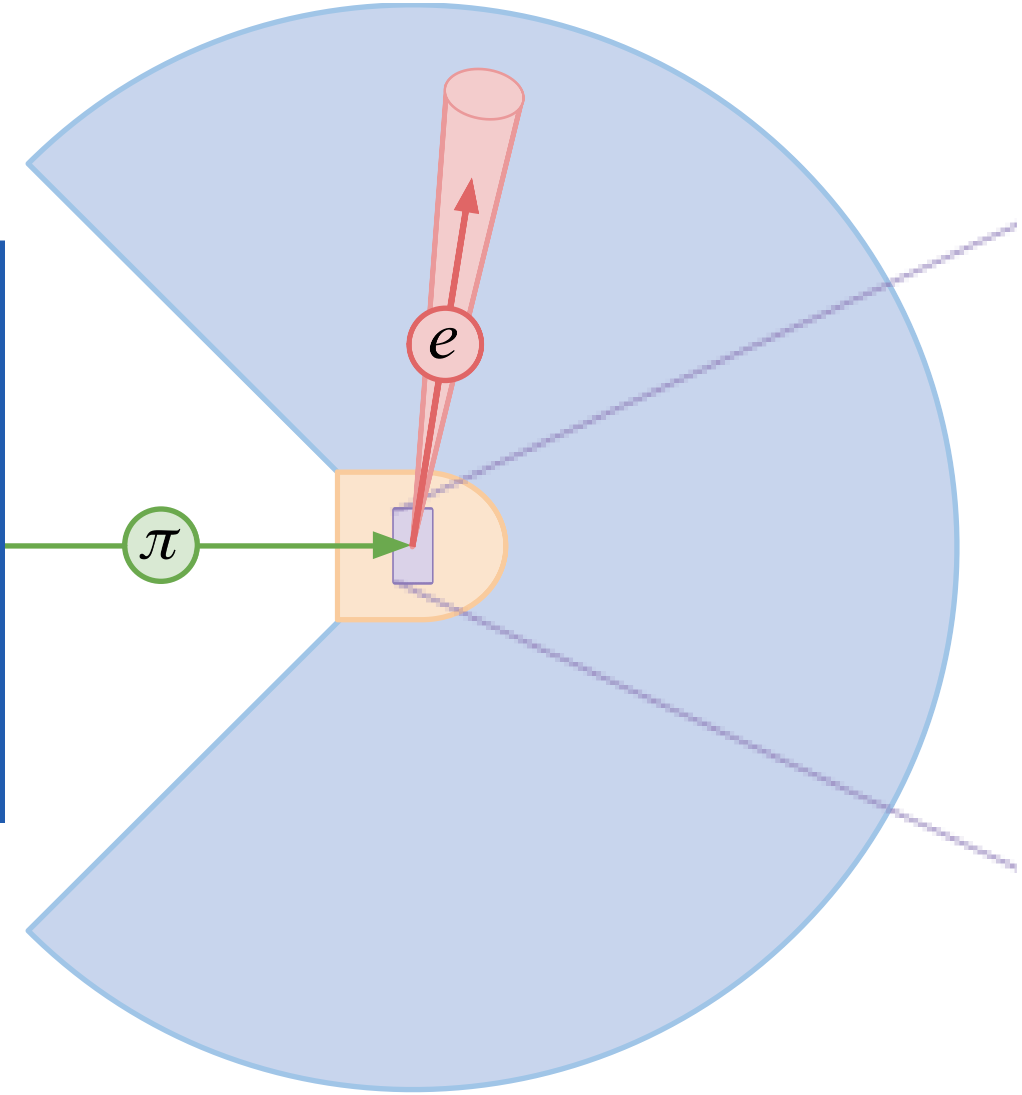
ETH zürich

The PIONEER Experiment

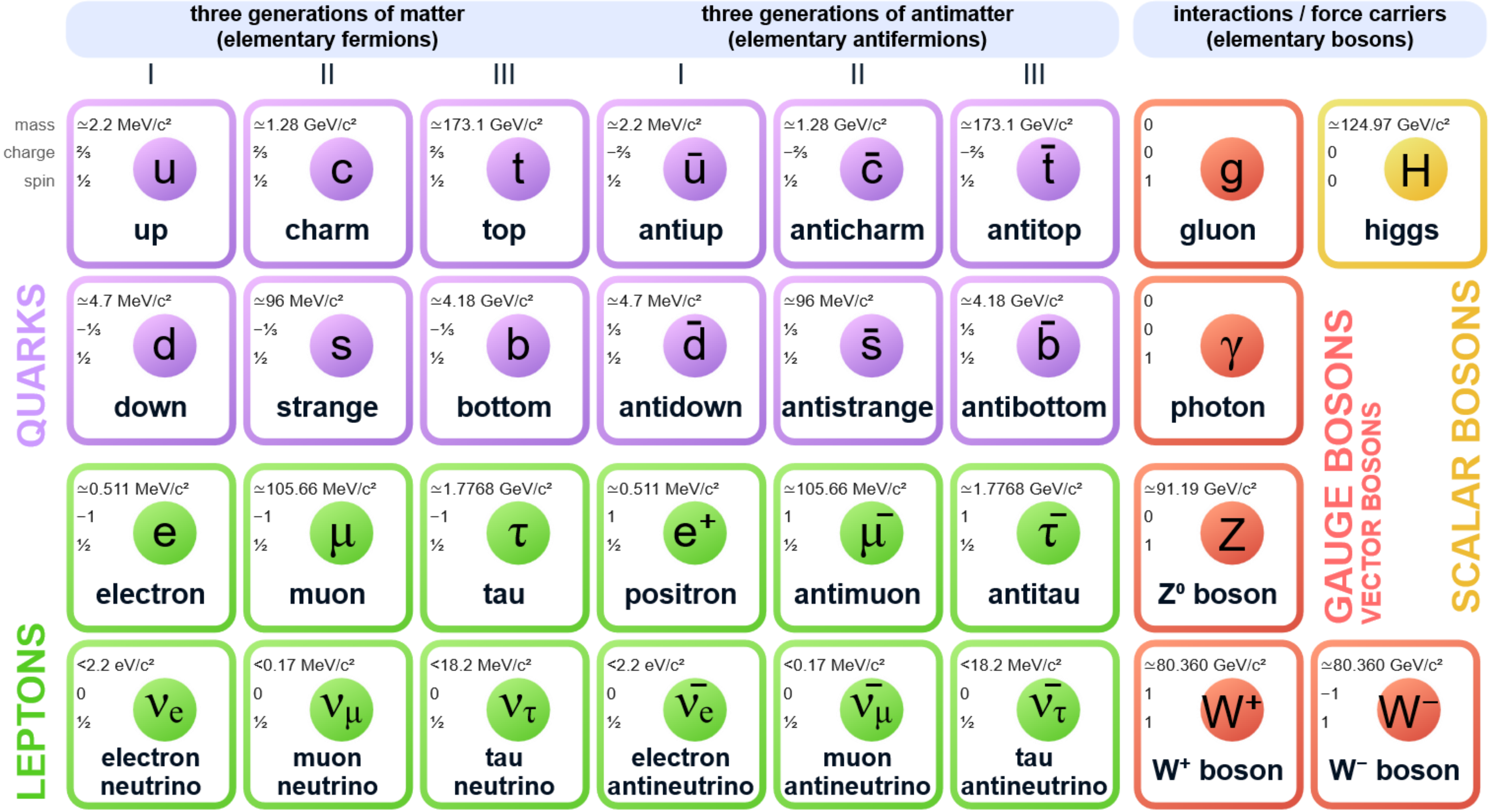
ATTRACT workshop 2025

Kolja Frahm



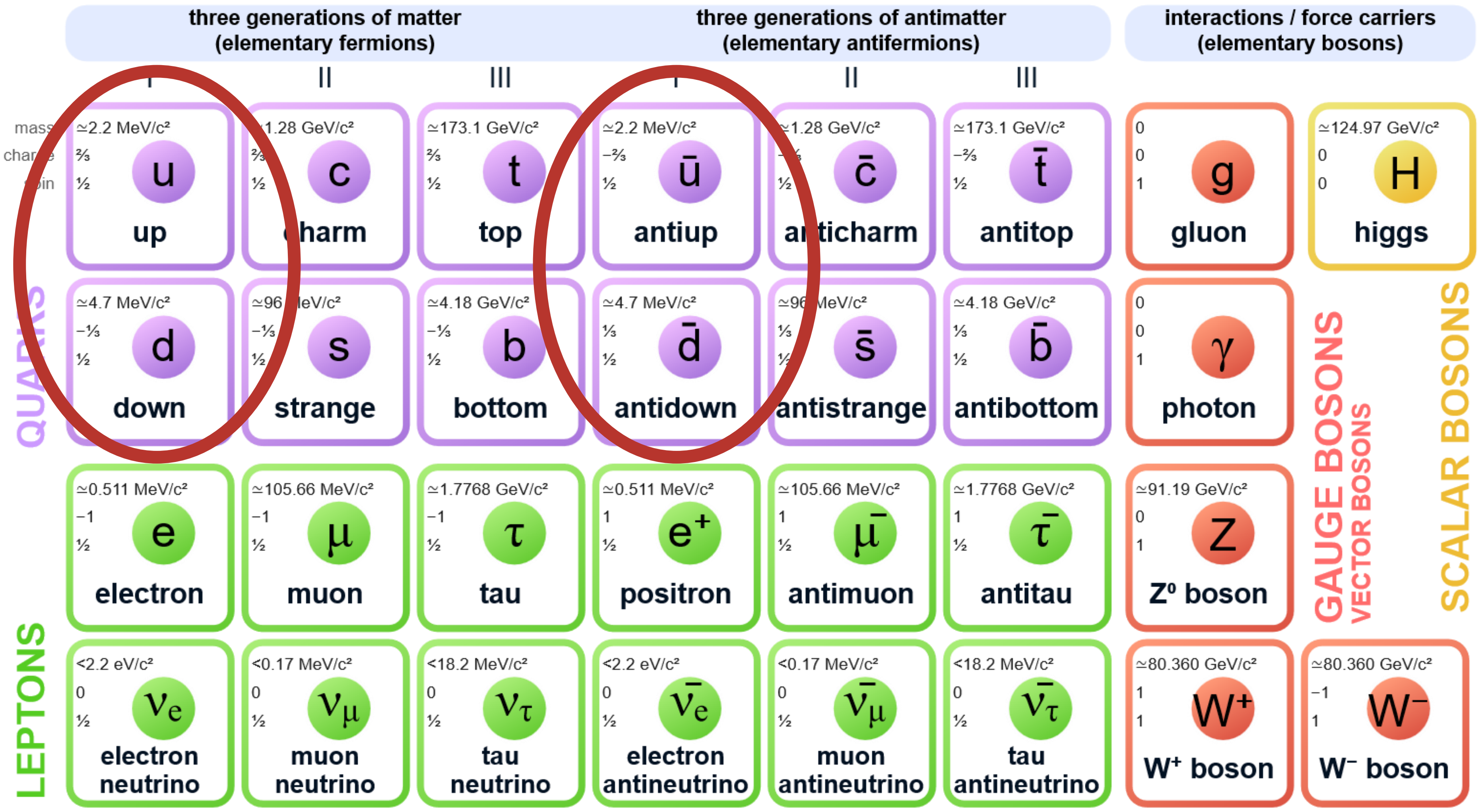
Motivation of PIONEER

Standard Model of Elementary Particles



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

Standard Model of Elementary Particles



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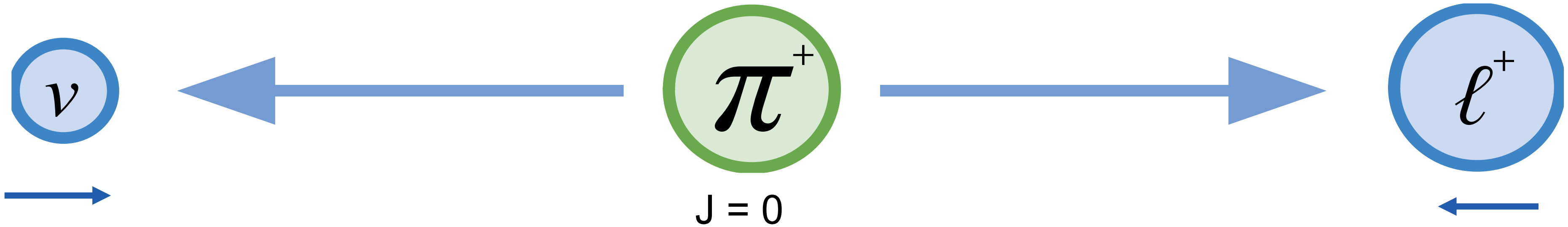
Pion decay

Textbook example of helicity suppression

LH relativistic neutrino

LH antilepton

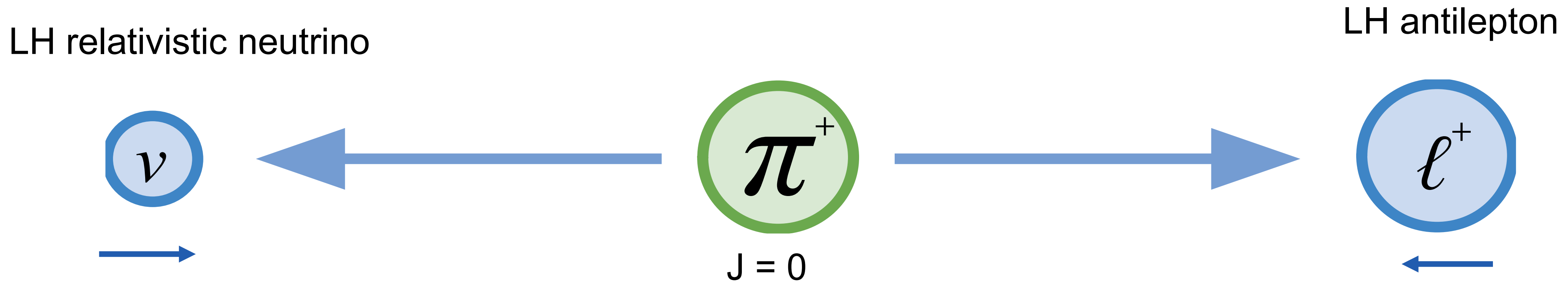


J = 0

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

Pion decay

Textbook example of helicity suppression



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

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

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

- perhaps most precisely calculated weak interaction observable involving quarks

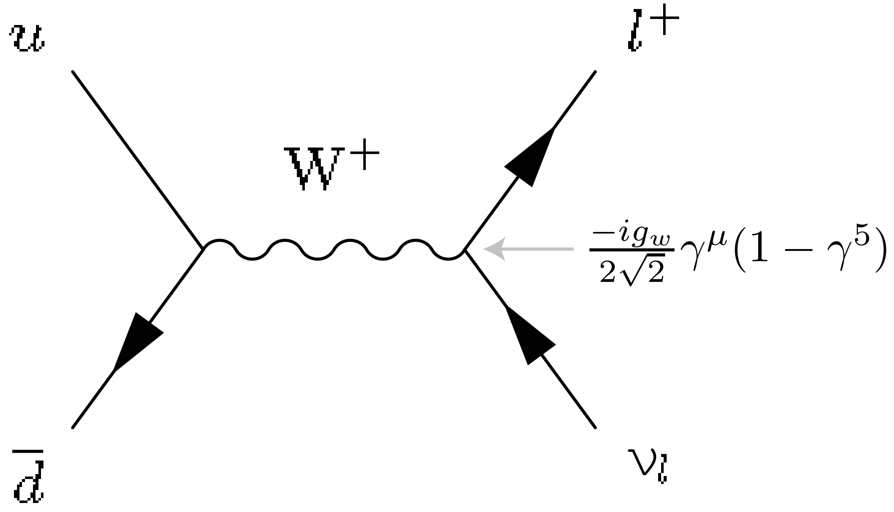
Motivation of PIONEER (Phase I)

- 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^+

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

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



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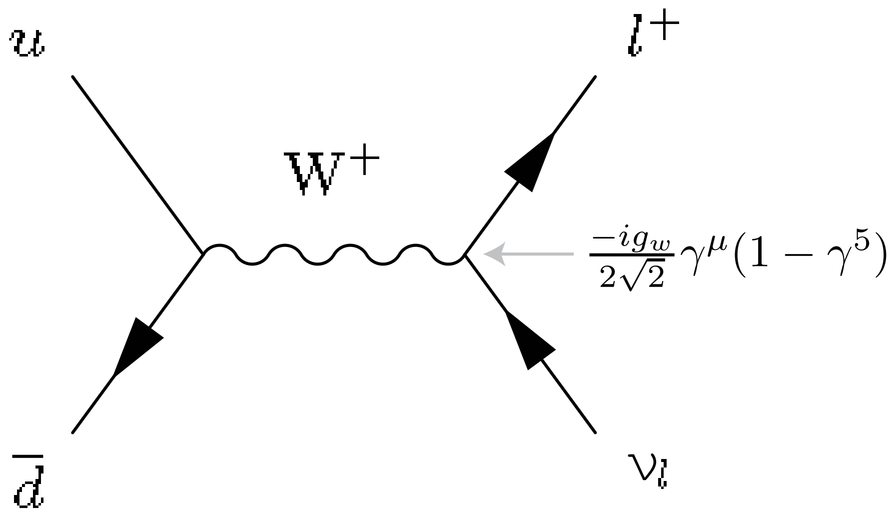
Goals:

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



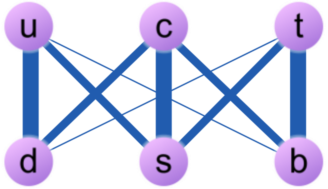
Motivation of PIONEER (Phase II/III)

- Cabibbo Angle Anomaly

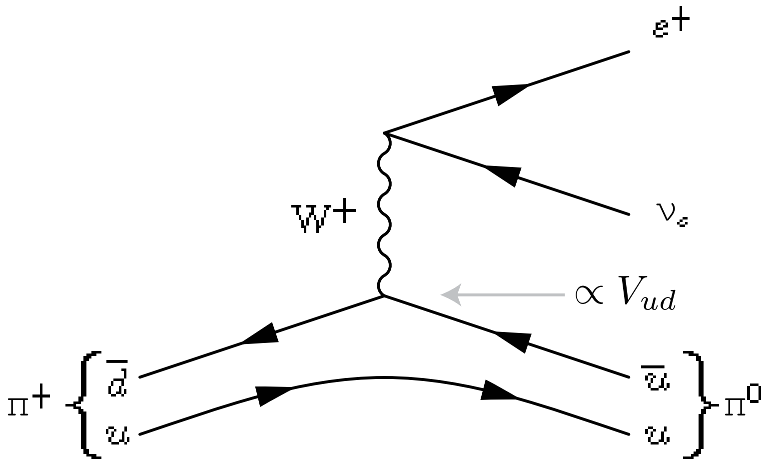
- **Study pion beta decay**

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

to test CKM unitarity



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



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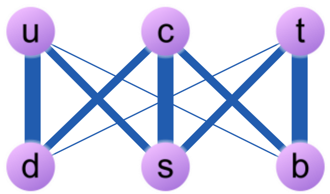

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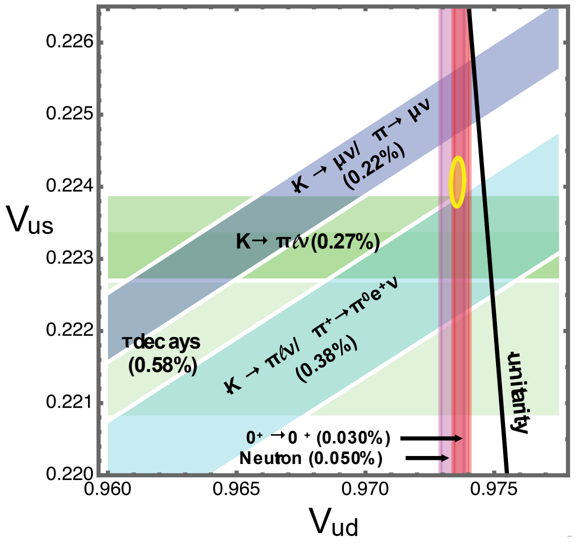
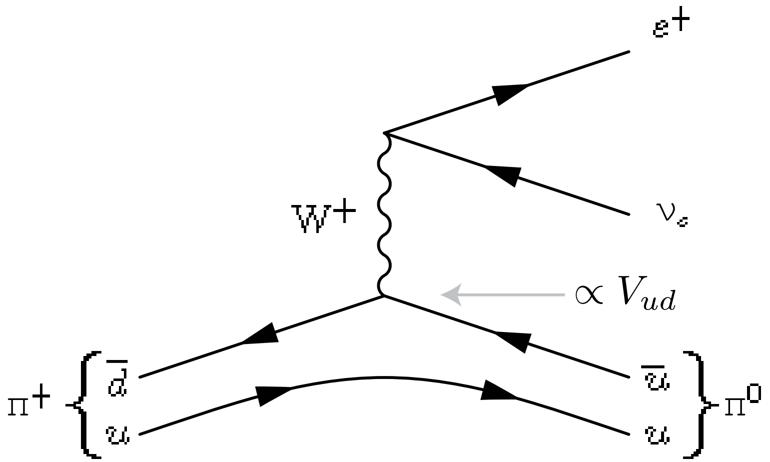


D. Bryman et al. (2021) arXiv:2111.05338



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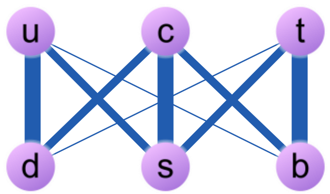

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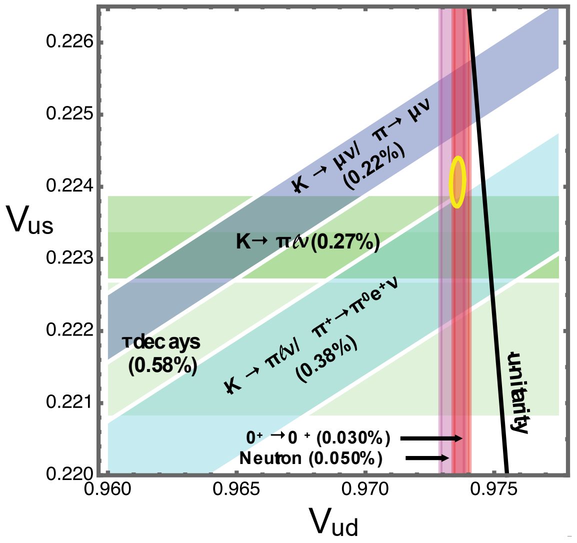

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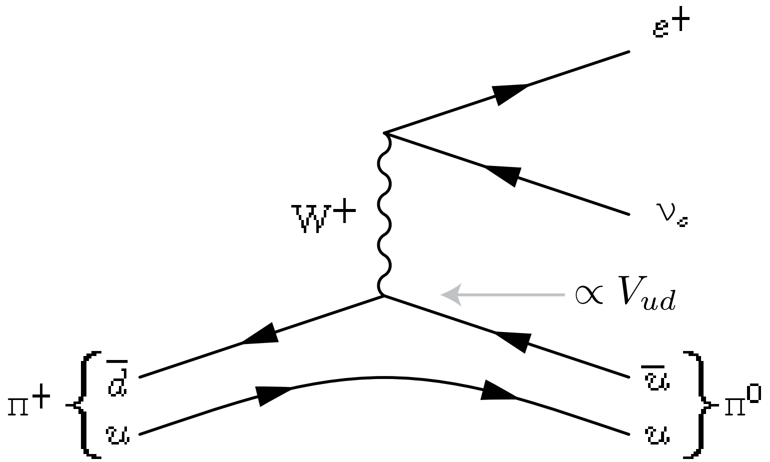
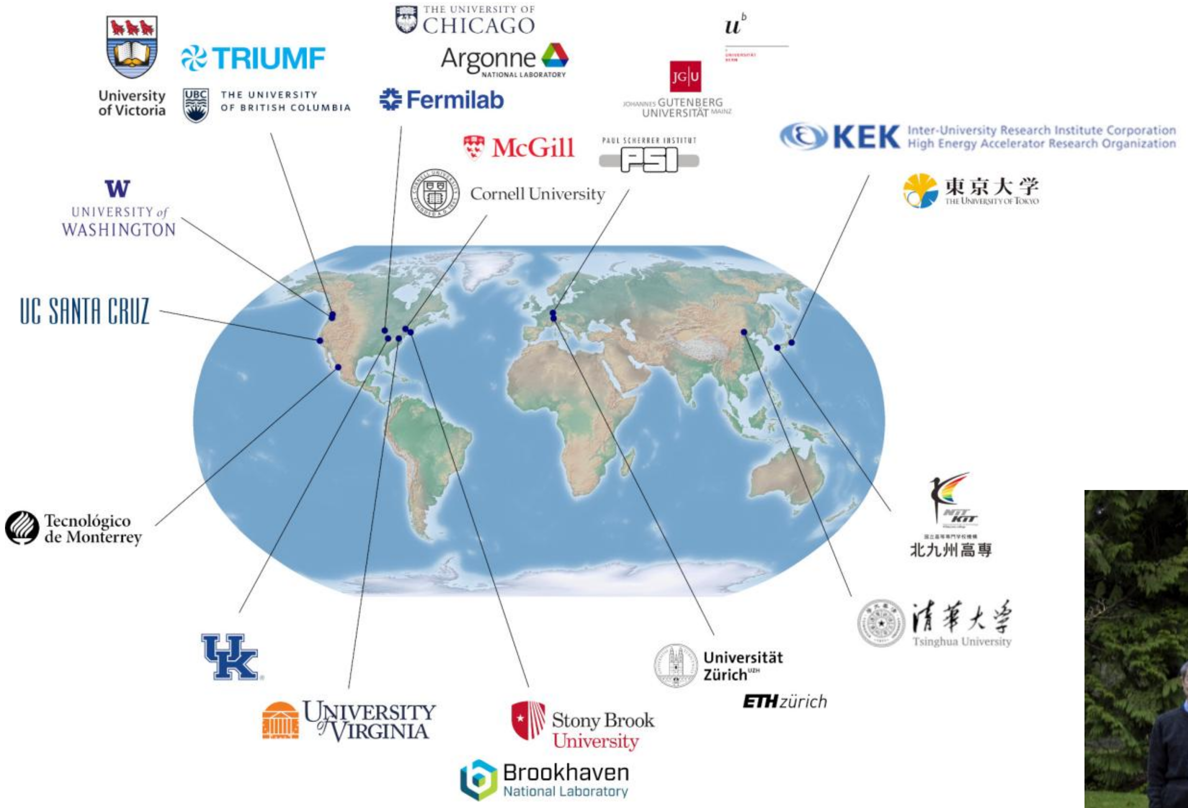
Goals:

- 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}



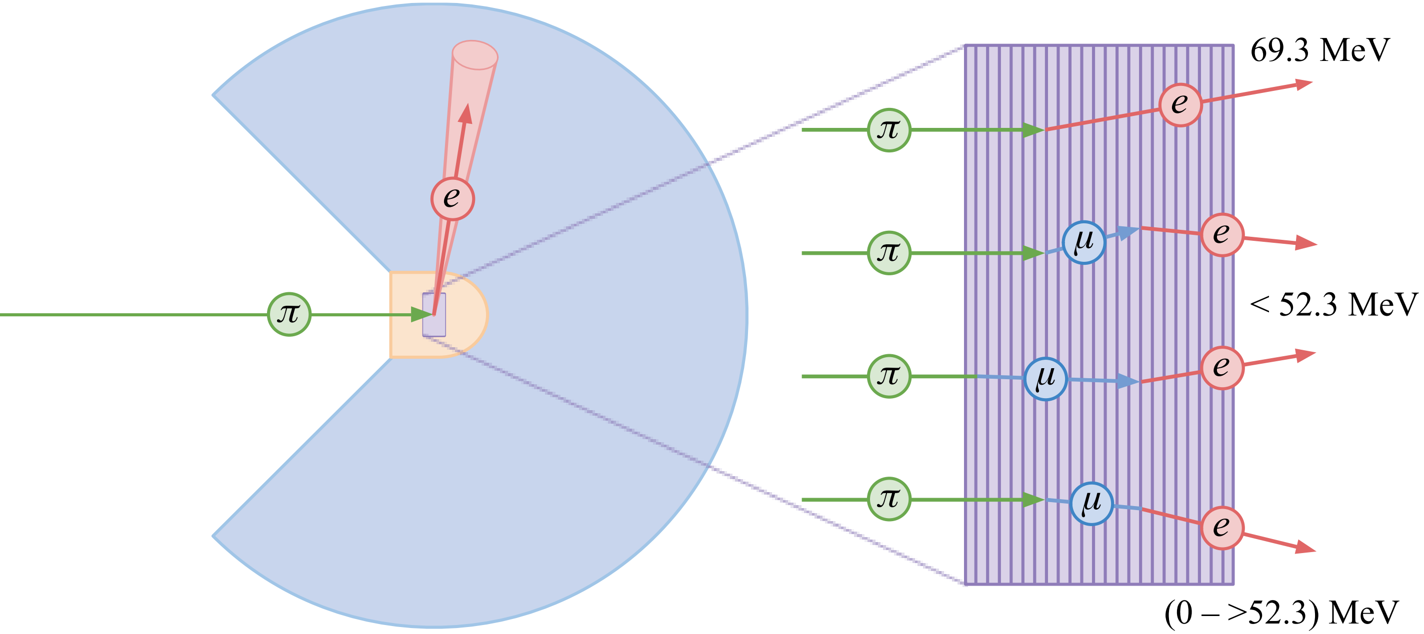
The PIONEER Experiment

The PIONEER Collaboration



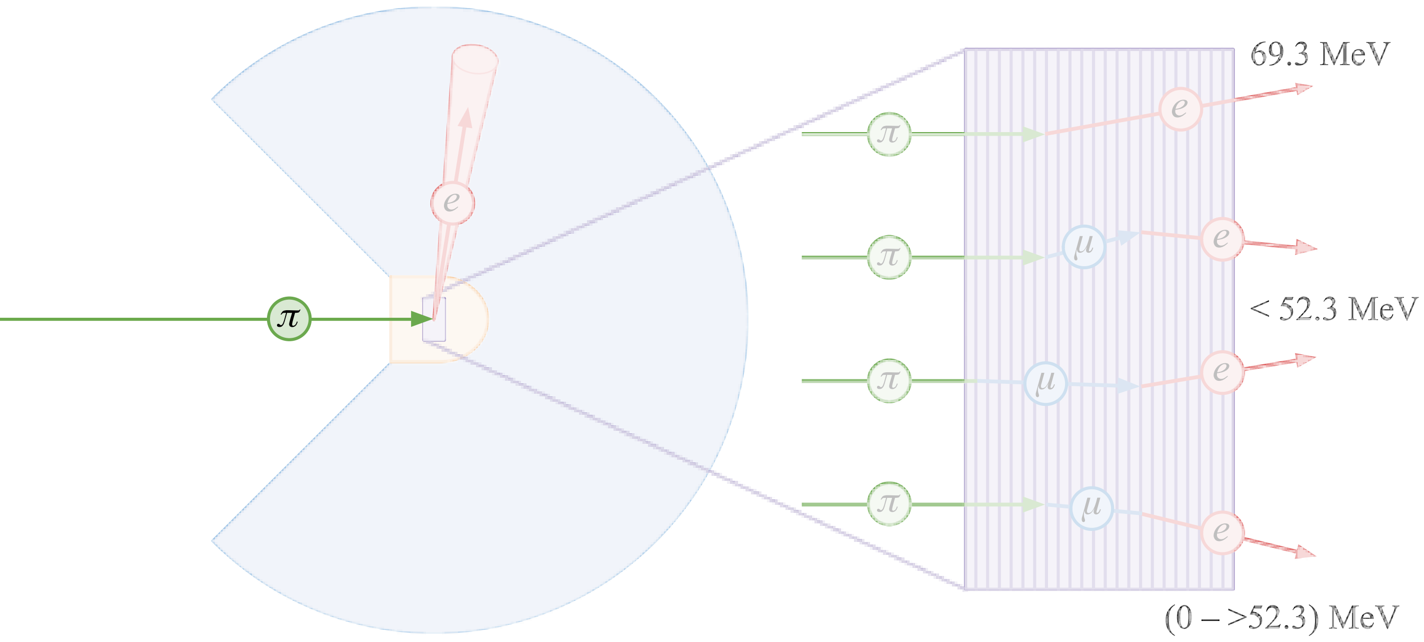
https://pioneer.triumf.ca/Collaboration/

Experimental Setup



Schematic made by Stefan Hochrein

Experimental Setup



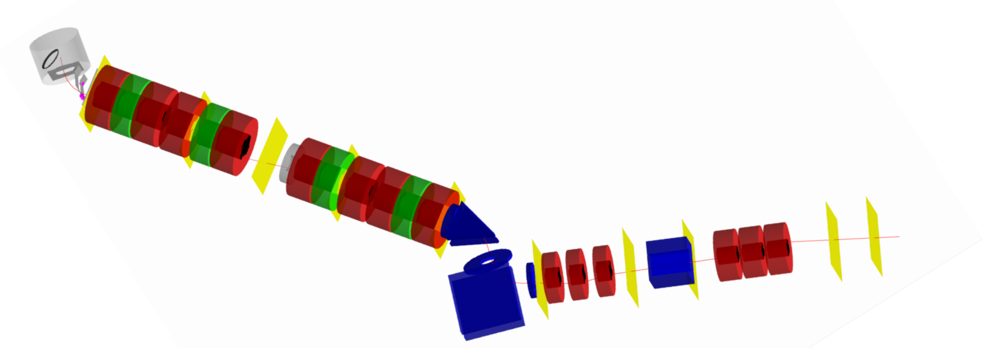
Pion Beam

- Requirements:

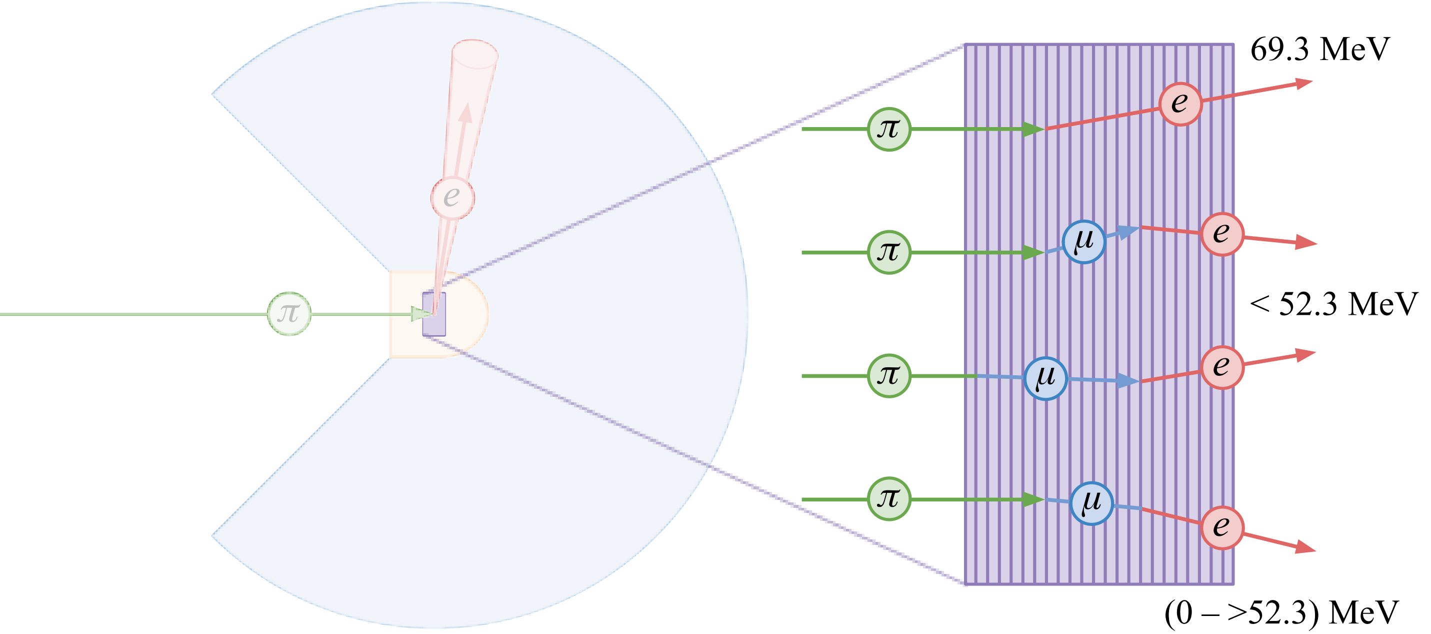
Phase	p (MeV/c)	Δp/p (%)	ΔZ (mm)	ΔX x ΔY (mm²)	ΔX',ΔY'	R_π (10^6/s)
I	55-70	2	1	10x10	±10°	0.3
II,III	≈ 85	≤ 5	3	15x15	±10°	20

  – High intensity, low momentum

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

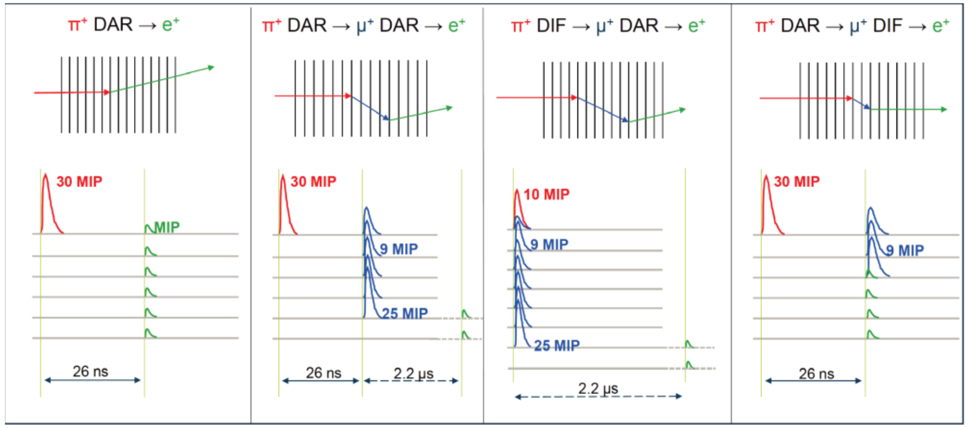


Experimental Setup



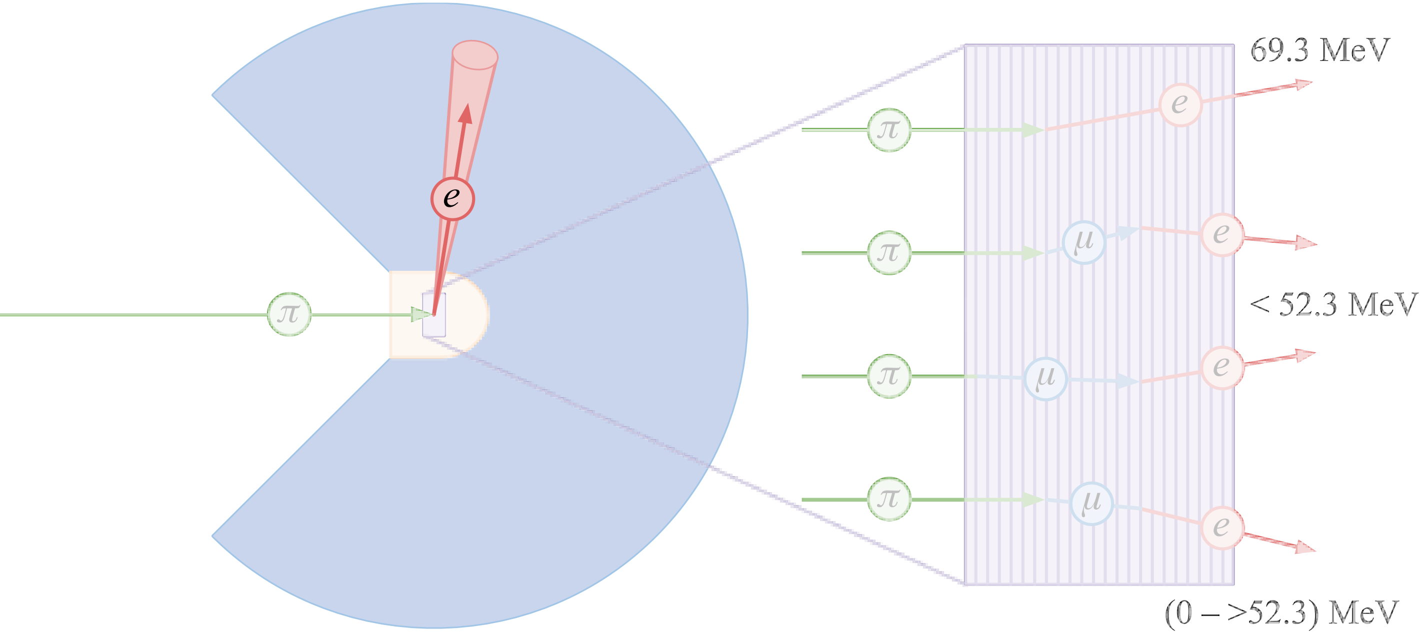
ATAR (Highly segmented active target)

- defines pion stopping region
- high resolution timing information



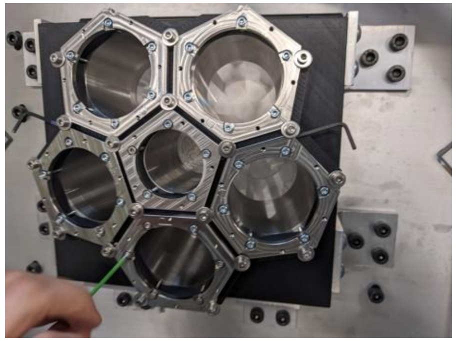
Mazza, S. et al. Proceedings of Science, 2023 V 420. https://doi.org/10.22323/1.420.0015

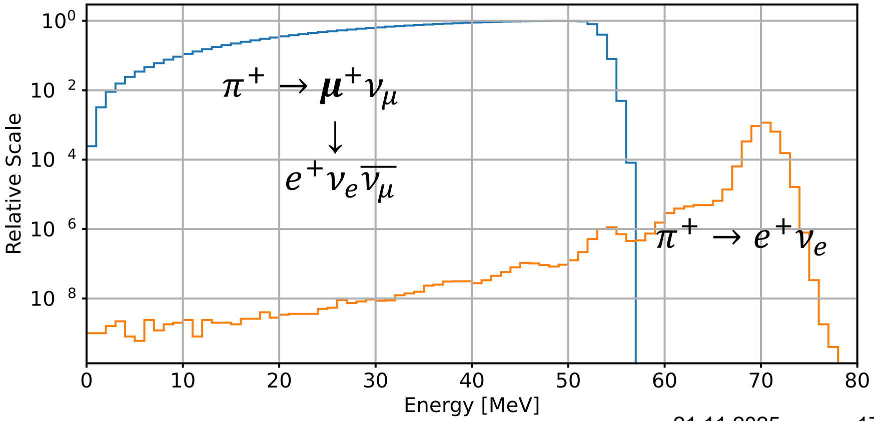
Experimental Setup



Calorimeter

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

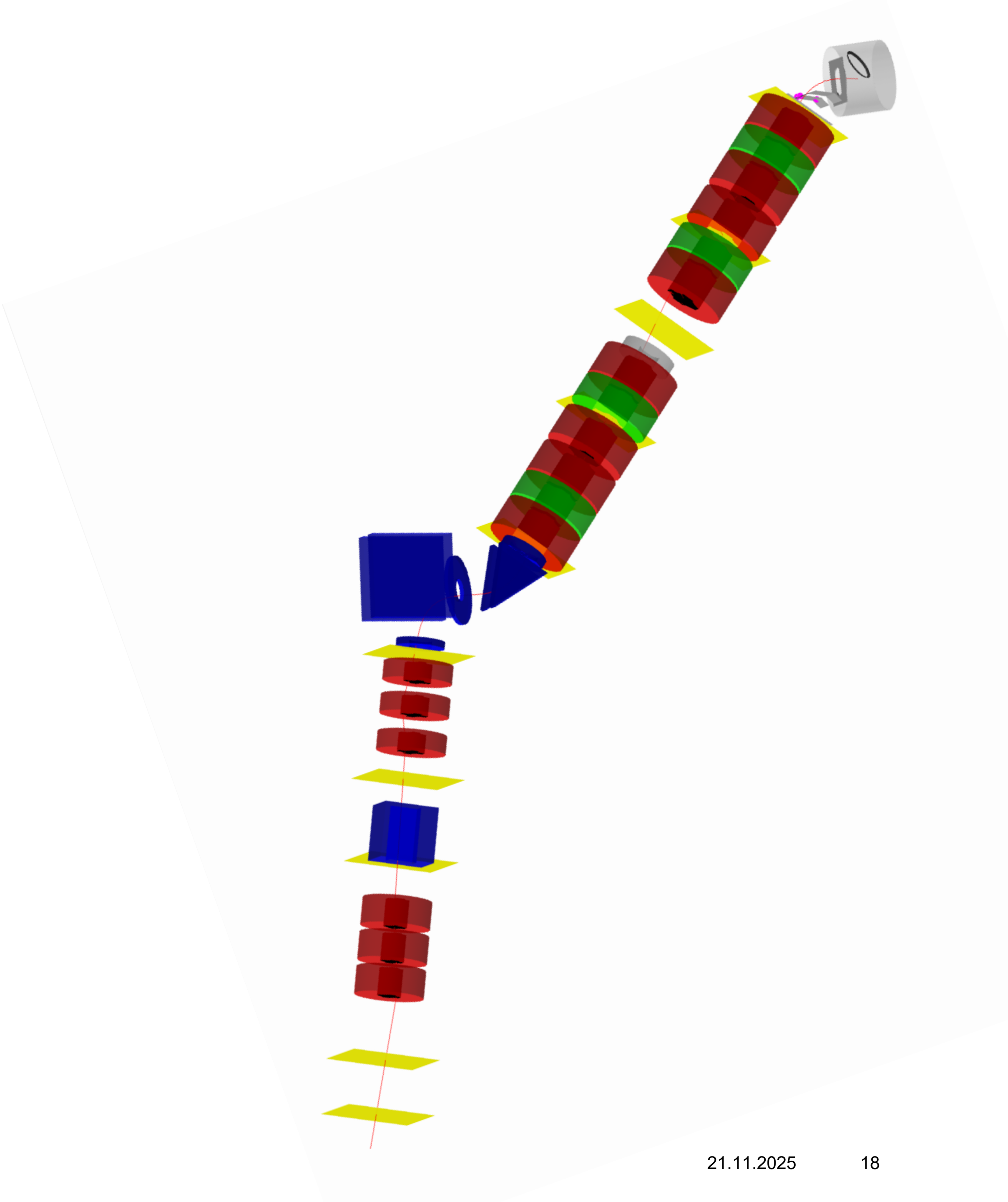




W. Altmannshofer et al (2022) arXiv:2203.01981

Beam optimisation

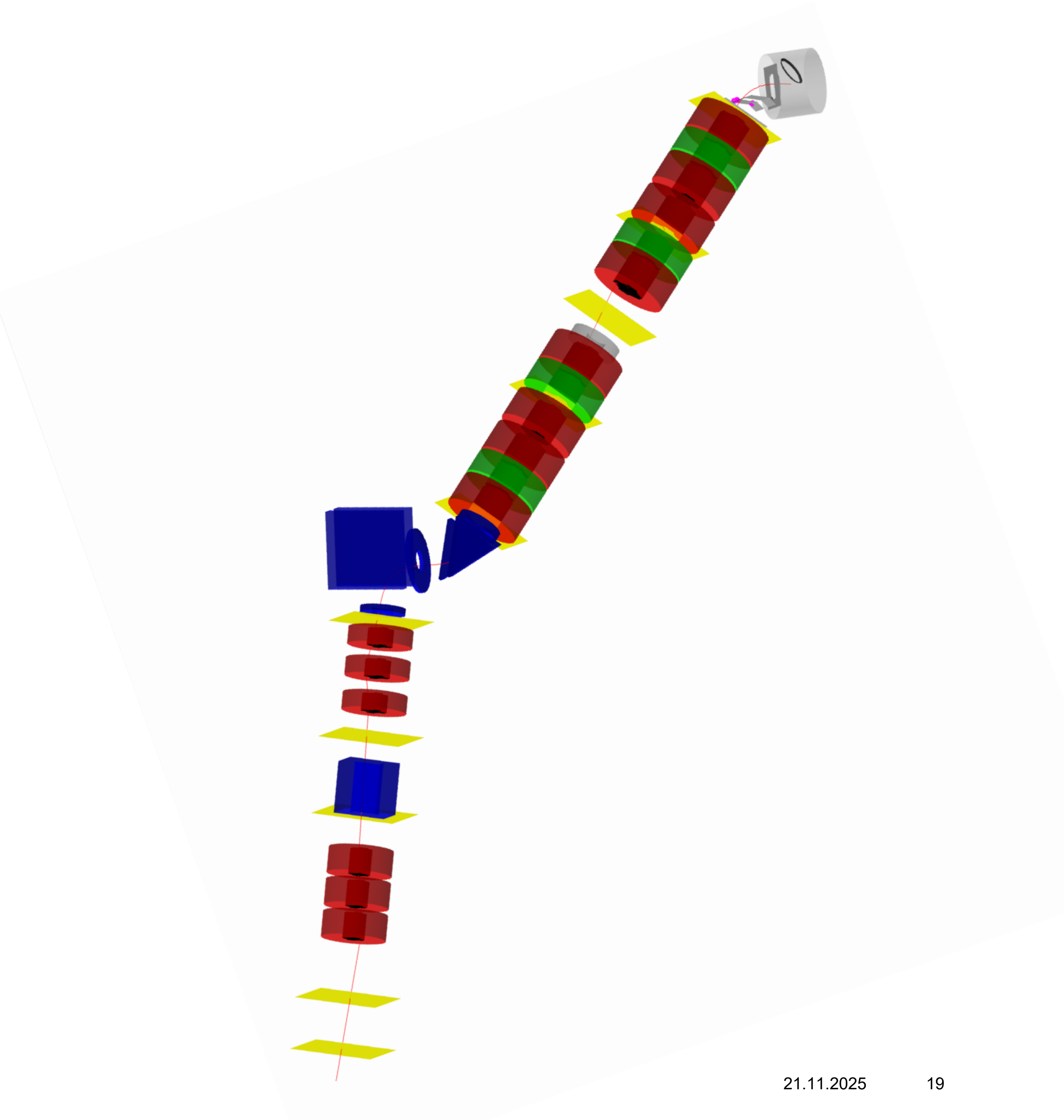
- Find best parameters
- Trying out alignment of beam with simulation
- Test alignment with a test beam next year



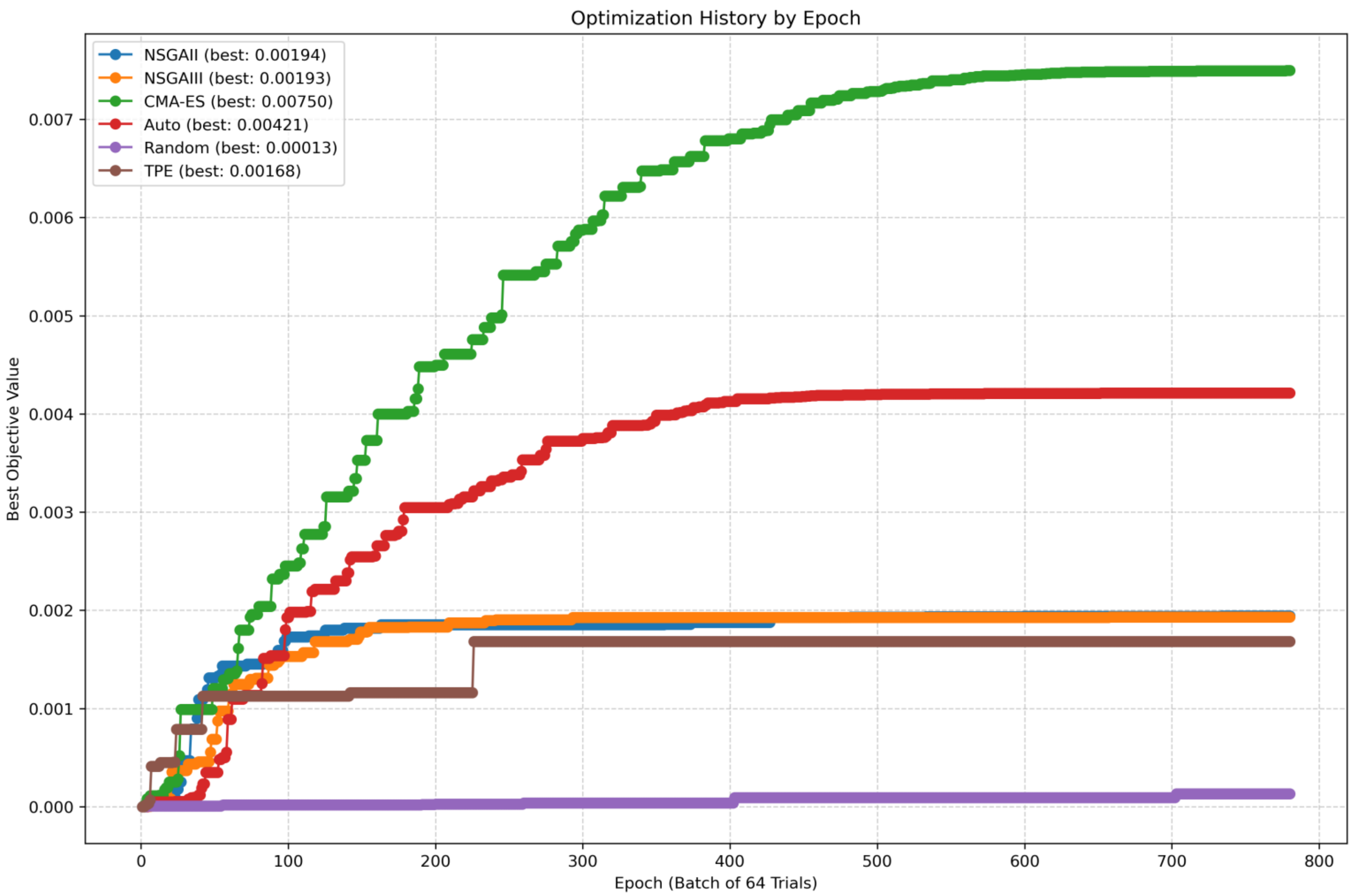
Beam optimisation
Setup

- 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)

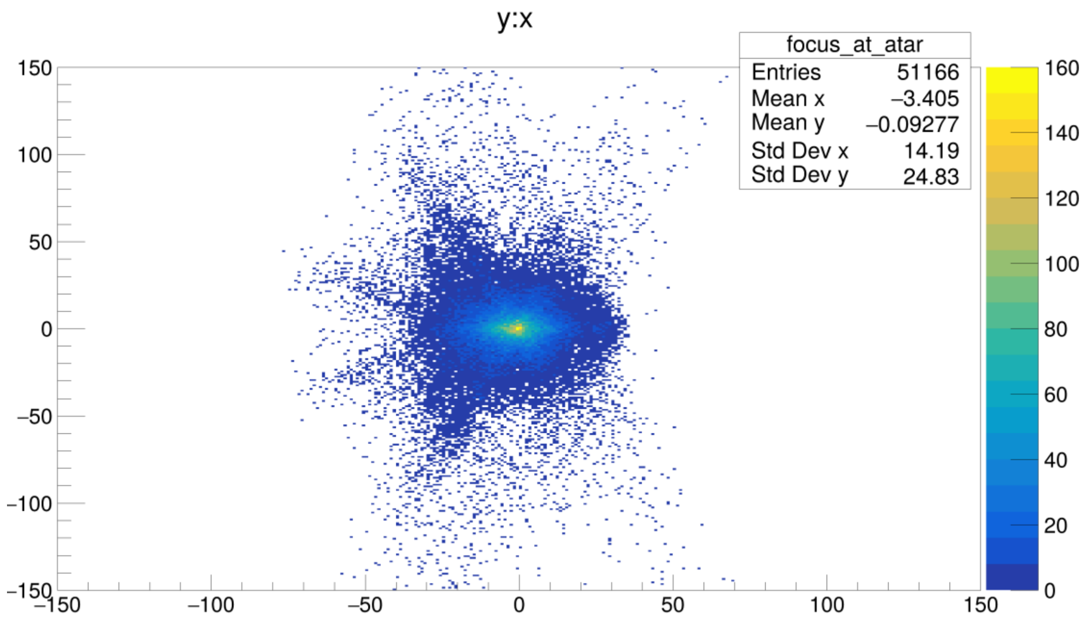


Beam optimisation
Convergence (Parallel simulations in large search space)

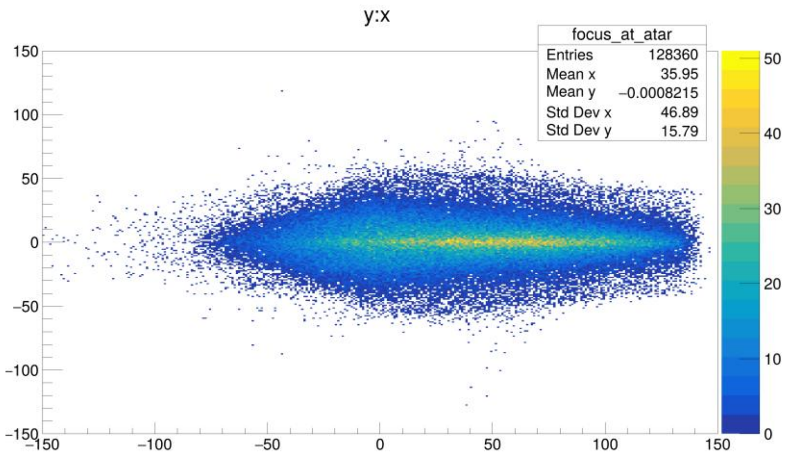


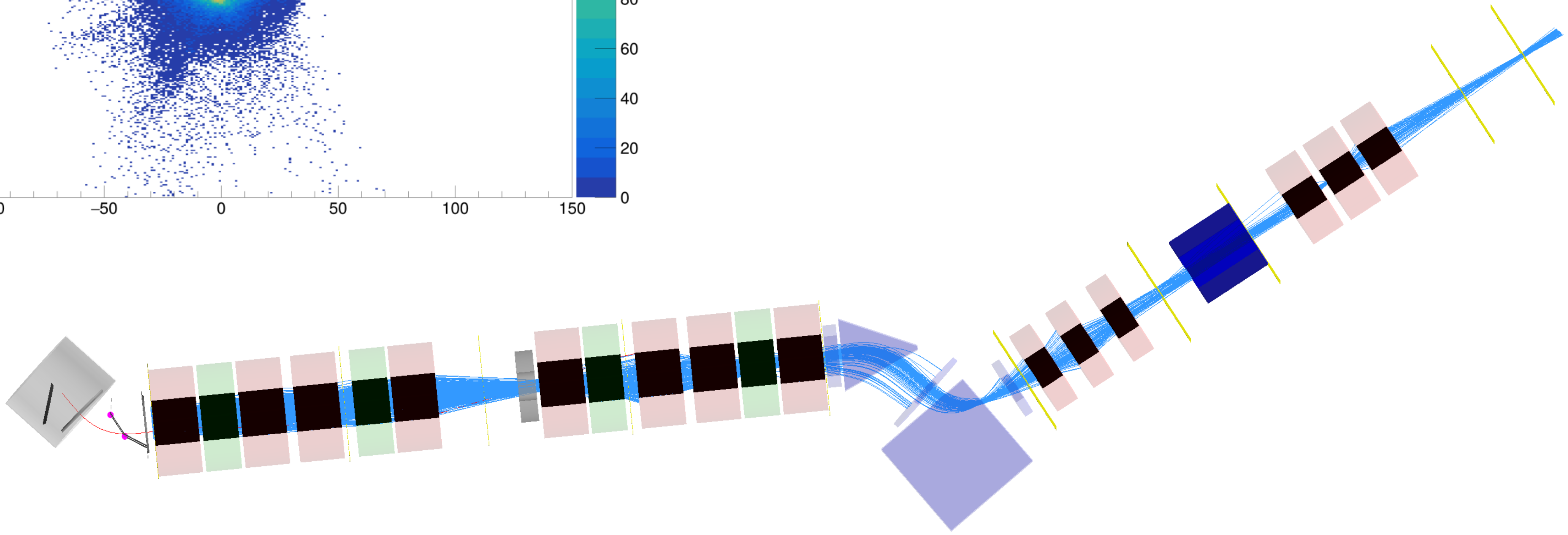
Intensity and focus tune

Phase space best tune
at ATAR



For comparison: Phase space of old tune at ATAR





Thank you!