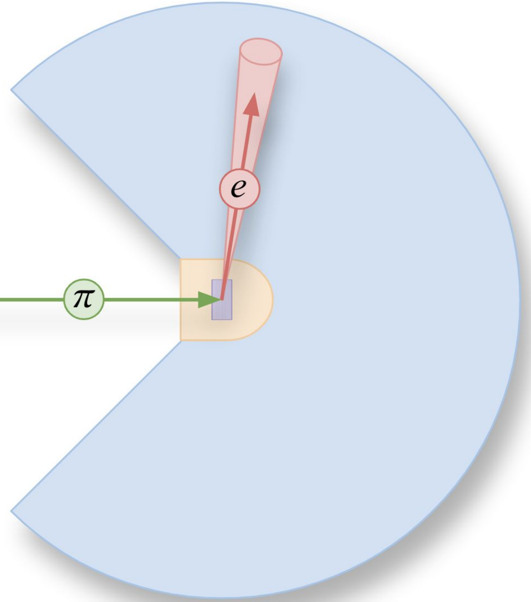
Beam tests for the PIONEER Experiment

A Next-Generation Rare Pion Decay Experiment Located at PSI



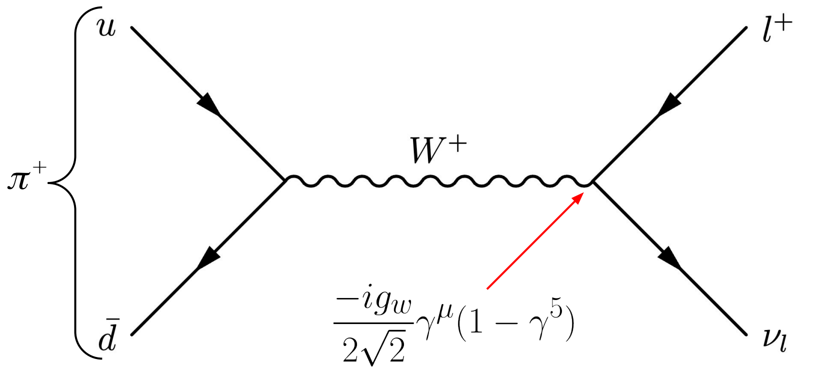
Beam Telescopes and Test Beams Workshop

Stefan Hochrein on behalf of the PIONEER collaboration

Edinburgh, 17.04.2024

Why study Pion decays?

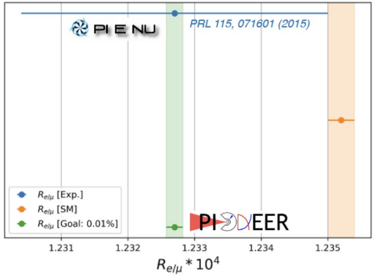
The charged Pion (here π+) decay:



Current situation:

- SM[1]: $R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = 1.23524(15) \times 10^{-4}$
- Exp.[2]: $R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = 1.2327(23) \times 10^{-4}$

Phase I measurement:



PIONEER goals:

- Improve sensitivity by a factor 15
- Directly test lepton flavour (e-μ) universality since $R_{e/\mu} \propto g_e/g_\mu$
- Probe SM extensions affecting $R_{e/\mu}$

Motivation:

- Hints for lepton flavour universality violation in $B \to D^{(*)}$ decays[3]
- Anomalous μ magnetic moment measurement[4]
- Observed forward-backward asymmetry in $B \to D^{(*)}$ decays to e/μ[5]

1 & 2: Altmannshofer, W., et al. arXiv preprint (2022) arXiv:2203.01981 [hep-ex].
1: V. Cirigliano and I. Rosell, Phys. Rev. Lett. 99, 231801 (2007), arXiv:0707.3439 [hep-ph].
2: A. Aguilar-Arevalo et al. (PIENU), Phys. Rev. Lett. 115, 071801 (2015), arXiv:1506.05845 [hep-ex]
3: R. Aaij et al. (LHCb), Phys. Rev. D 97, 072013 (2018), arXiv:1711.02505 [hep-ex].
4: D. P. Aguillard et al. (The Muon g−2 Collaboration) Phys. Rev. Lett. 131, 161802 (2023) arXiv:2308.06230 [hep-ex].
5: A. Carvunis, A. Crivellin, D. Guadagnoli, and S. Gangal, (2021), arXiv:2106.09610 [hep-ph].

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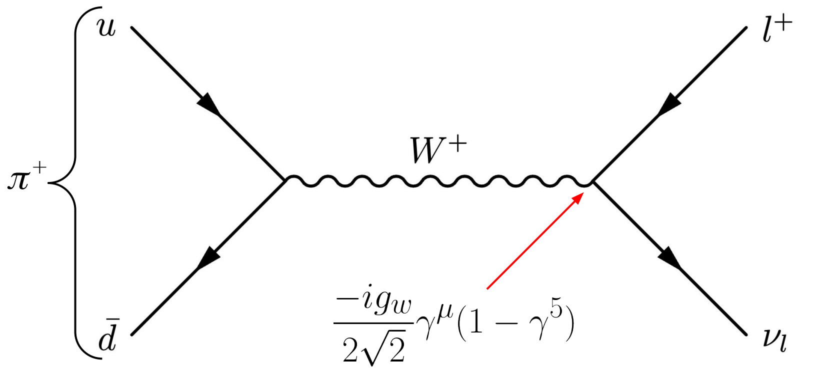

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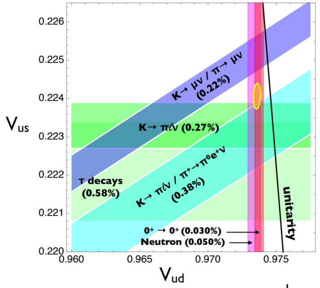
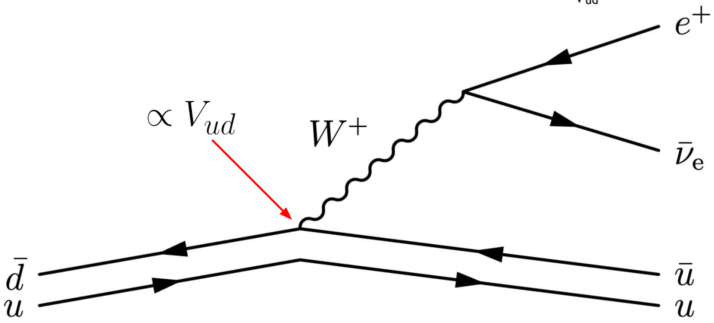
Phase II measurement:

PIONEER goals:

- Measure pion beta-decay for a direct measurement of V_{ud}:





Motivation:

- Hints for Cabibbo angle anomaly combining results of various experiments[3]

Experimental setup

PIONEER will need:

① High intensity, low momentum **pion beam**

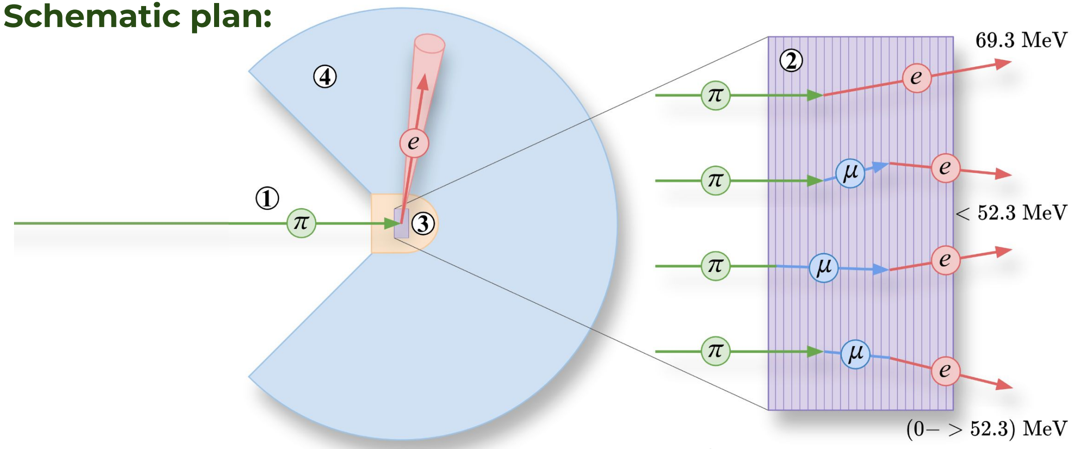
② Highly segmented **active target (ATAR)** with good energy and time resolution

③ **Tracker** to link ATAR and calorimeter signal

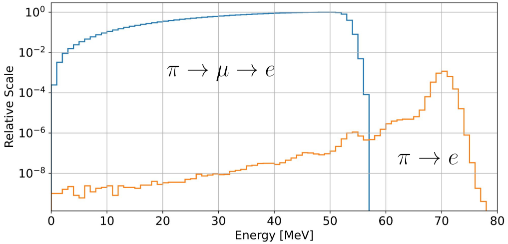
④ Fast **calorimeter** with excellent energy resolution, 25 radiation lengths deep and covering 3π sr solid angle

⑤ Entrance detectors, fast readout and electronics, DAQ,..

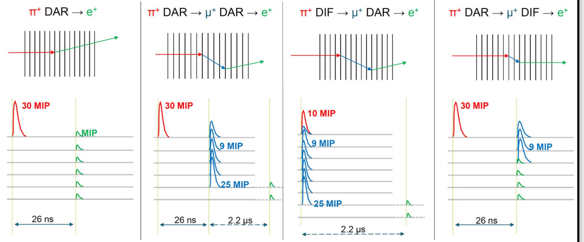
Schematic plan:



Calorimeter signal[1]:



ATAR signal[2,3]:



1: Altmannshofer, W., et al. arXiv preprint (2022) arXiv:2203.01981 [hep-ex].
2: Mazza, S. Instruments, 2021, 5. no. 4: 40. arXiv:2111.05375 [physics.ins-det]
3: Mazza, S. et al. Proceedings of Science, 2023 V 420. https://doi.org/10.22323/1.420.0015

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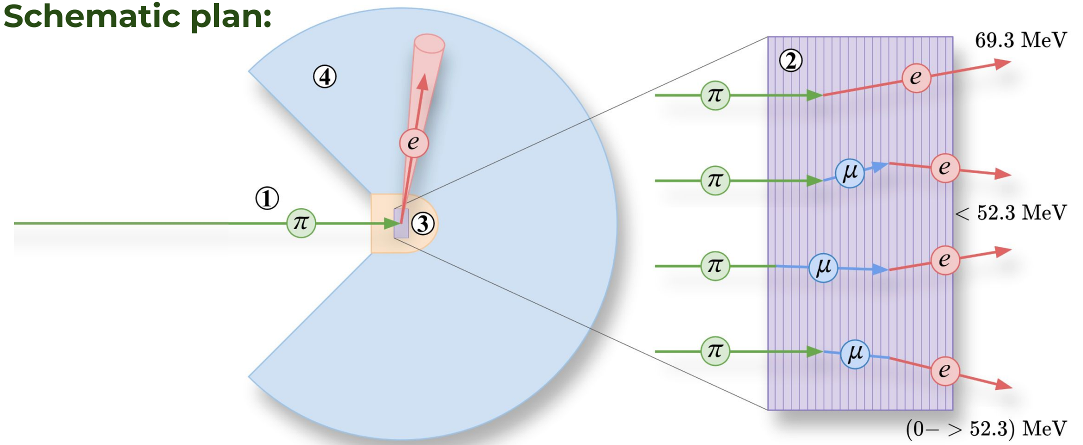

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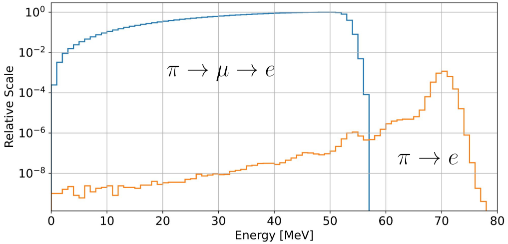
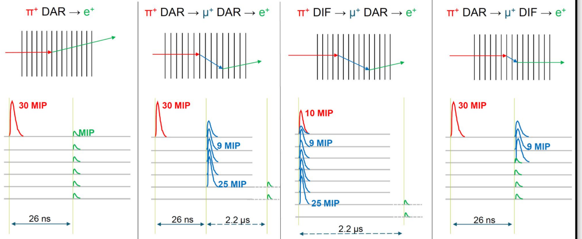


ATAR signal[2,3]:



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The pion beam

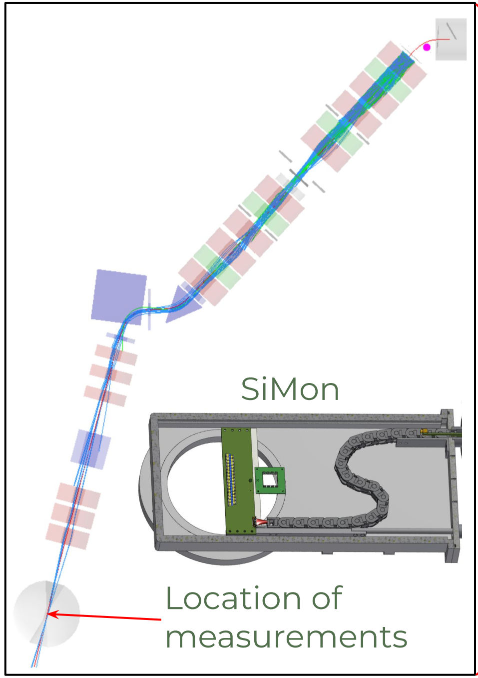
Test beam 2022 at PSI:

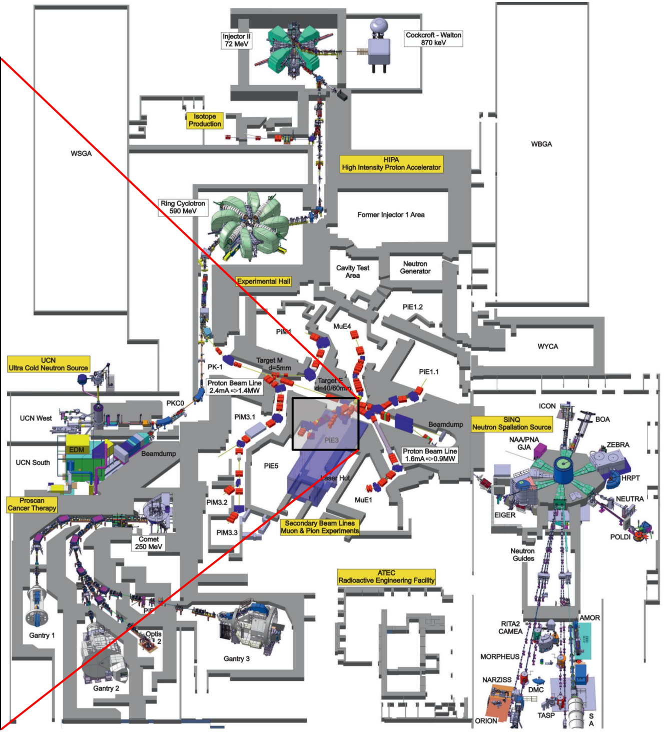
- Measure important parameters of the beam
- Use results as simulation input for design studies

Key parameters:

- Pion rate
- Momentum bite
- Beam contamination
- Spot size in beam focus
- Beam emittance

PiE5 beamline at PSI:





The pion beam

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- Measure important parameters of the beam
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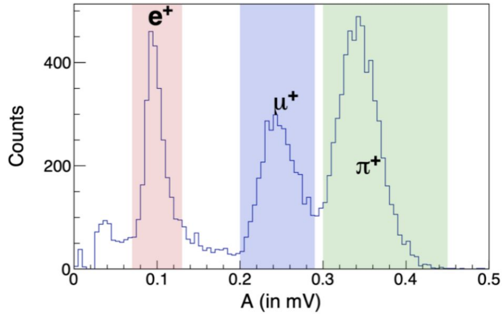
Key parameters:

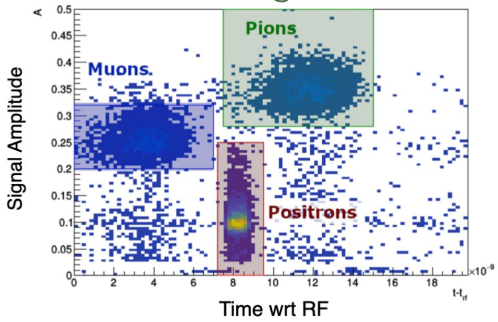
- Pion rate R_π = 633 kHz (~300 kHz in target area)
- Momentum bite $\Delta p/p < 2\%$
- Particle contamination 32% muons, 25% positrons
- Spot size in beam focus σ_x = 23 mm, σ_y = 10 mm
- Beam emittance

Results:

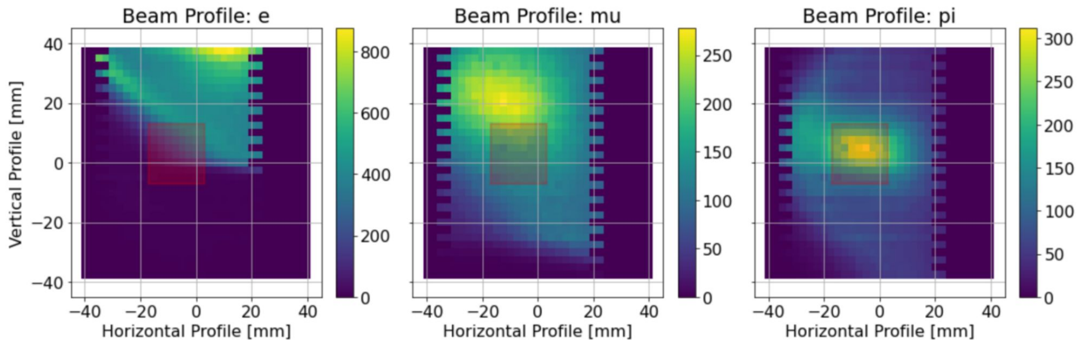
Energy



Timing



Position



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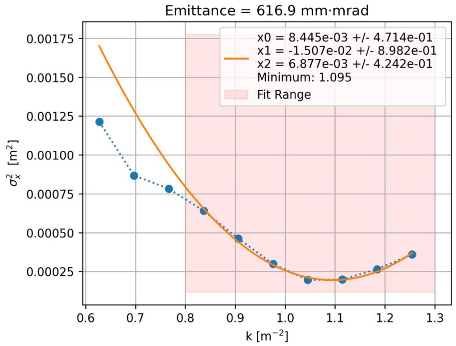
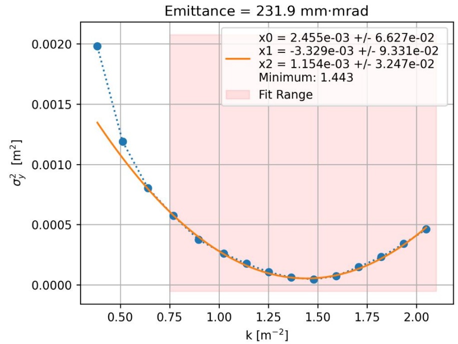
- Spot size in beam focus σ_x = 23 mm, σ_y = 10 mm
- Beam emittance $\varepsilon_{x/y}$ = 617/232 mm mrad

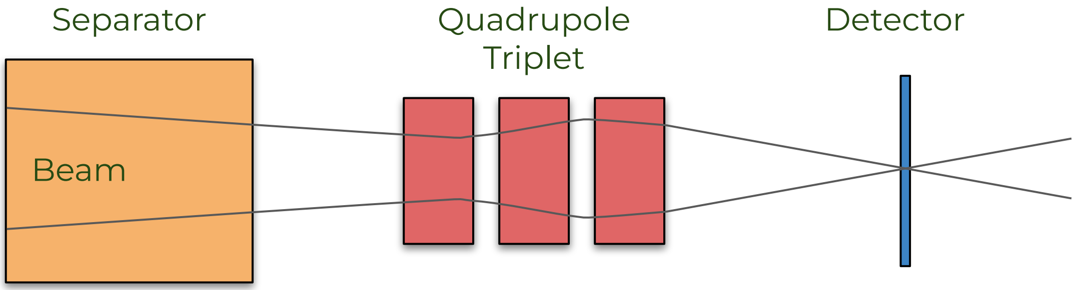
Results:

X-Measurement



Y-Measurement





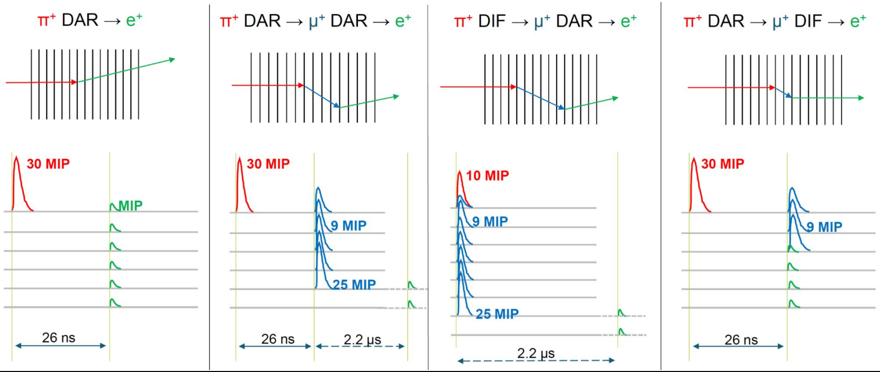
The ATAR

Test beam 2023 at CENPA:

- Characterization of AC-LGAD prototypes
- Measurement of angular dependent gain

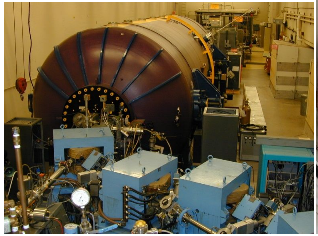
Key parameters[1,2]:

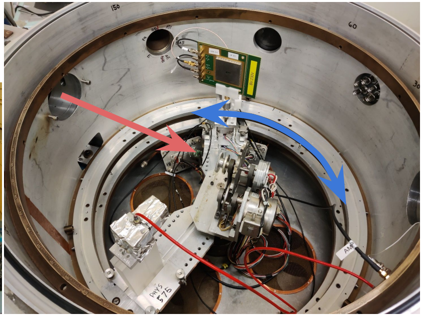
- High granularity, minimal blind/ dead regions
- Fast timing
- Good energy resolution over large dynamic range

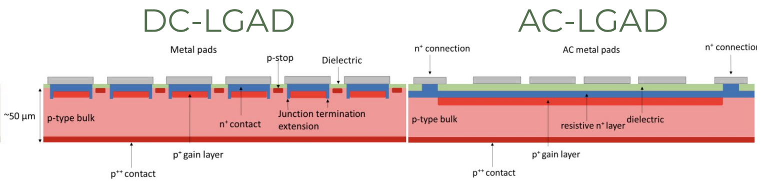


Setup:

Low energy proton beam at CENPA







AC-LGADs have:

- Less dead area
- Intrinsic charge sharing

1: Mazza, S. Instruments, 2021, 5. no. 4: 40. arXiv:2111.05375 [physics.ins-det]
2: Mazza, S. et al. Proceedings of Science, 2023 V 420. https://doi.org/10.22323/1.420.0015
3:Ott, J.13th Hiroshima Symposium, https://indico.cern.ch/event/1184921/contributions/5574780/

The calorimeter

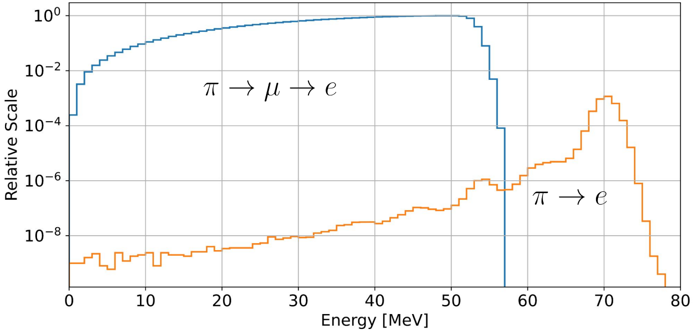
Test beam 2023 at PSI:

- Explore possibility of a LYSO calorimeter

Key parameters:

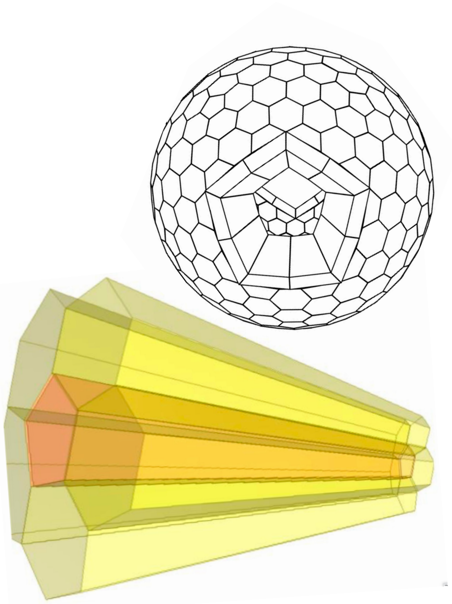
- Excellent energy resolution
- Fast detector response

Simulated energy spectrum[1]

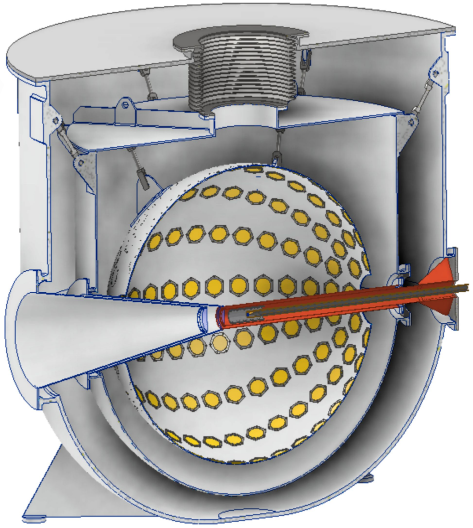


Possible calorimeter choices[1]:

LYSO crystals



Liquid Xenon (LXe)



1: Altmannshofer, W., et al. arXiv preprint (2022) arXiv:2203.01981 [hep-ex].

LYSO beamtime

Goals:

Measure:

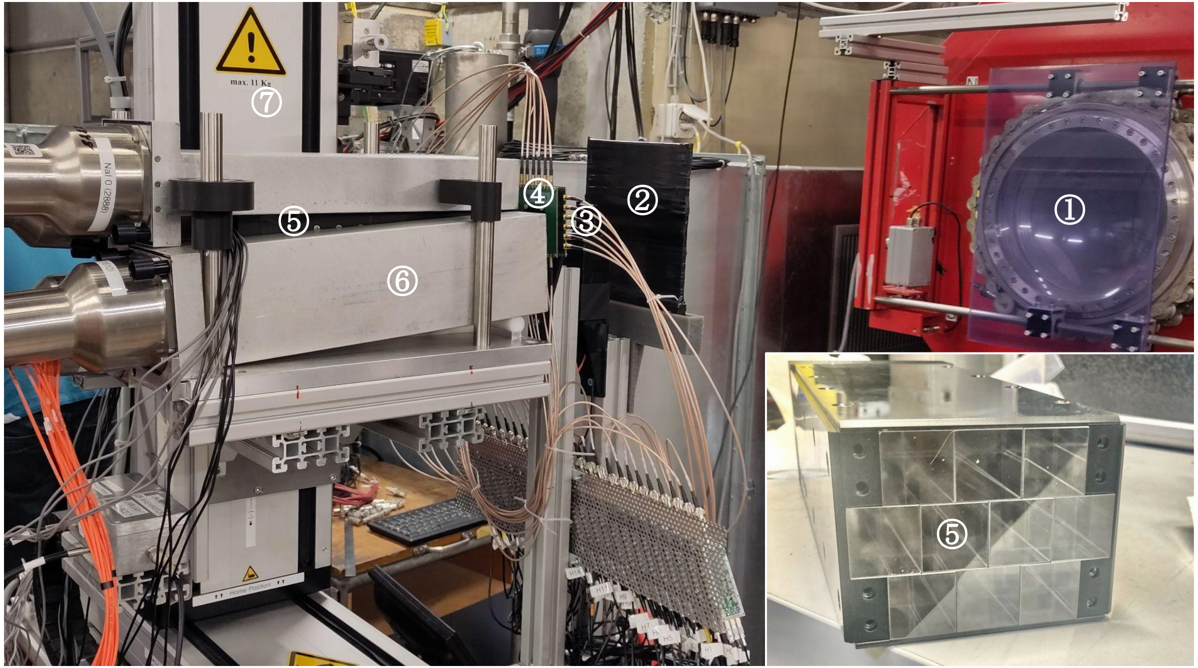
- Energy resolution
- Uniformity
- Albedo

of an array of LYSO crystals

Setup:

① Positron beam exit
② Veto detector
③ Entrance detector T0
④ Beam hodoscope
⑤ LYSO array
⑥ NaI detectors
⑦ XY-table

Setup at PSI PiM1 beamline:

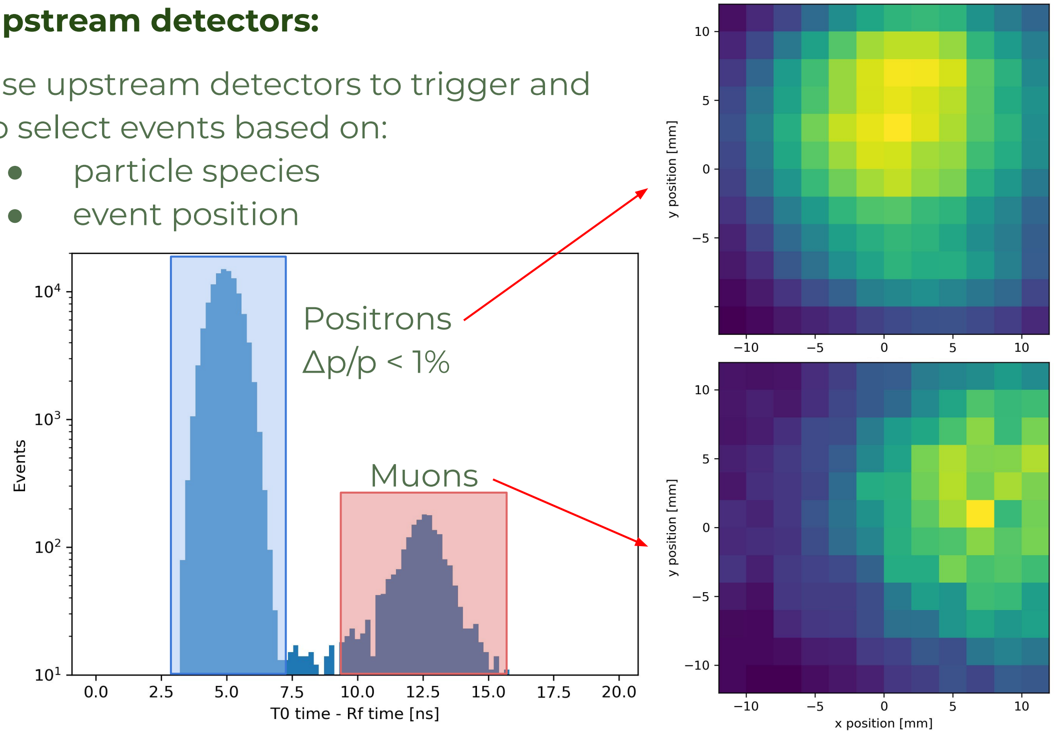


LYSO beamtime analysis - work in progress

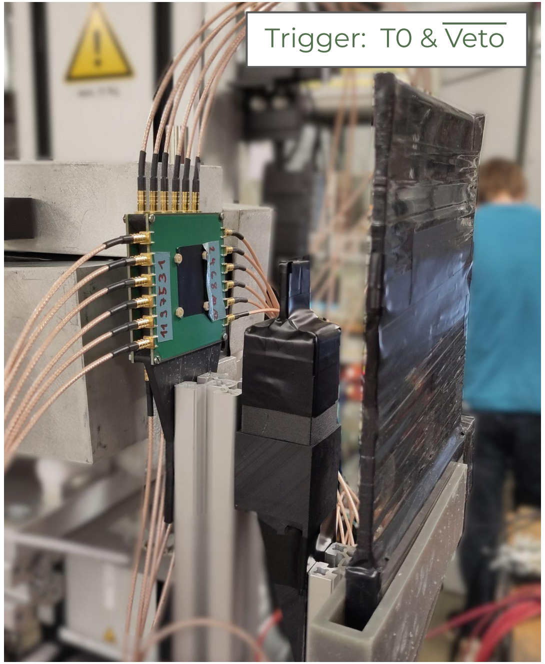
Upstream detectors:

Use upstream detectors to trigger and to select events based on:

- particle species
- event position



Setup:

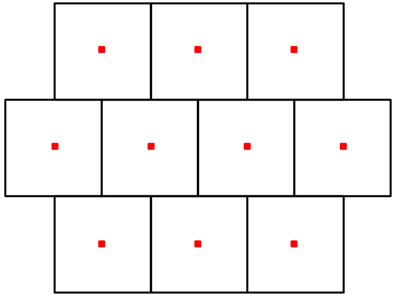


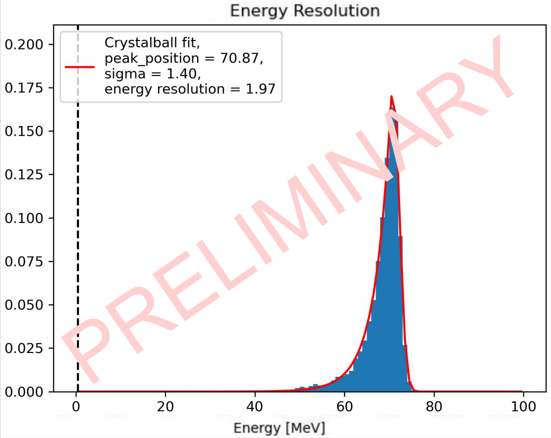
LYSO beamtime analysis - work in progress

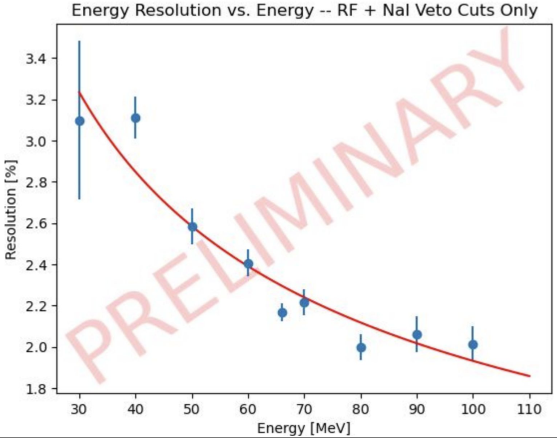
Energy resolution:

Strategy:

- Select events/ apply cuts
- Apply calibration
- Add up contributions of all crystals
- Fit energy distribution

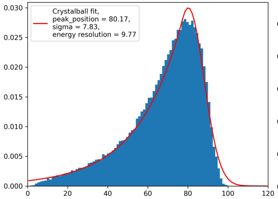




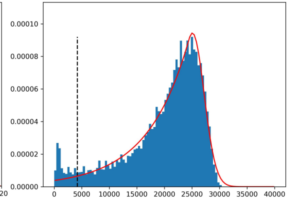


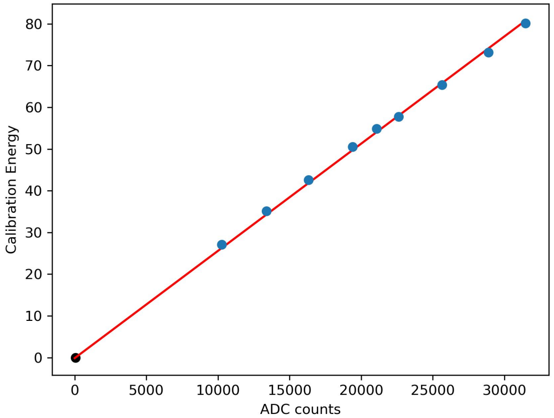
Calibration:

Simulation



Data

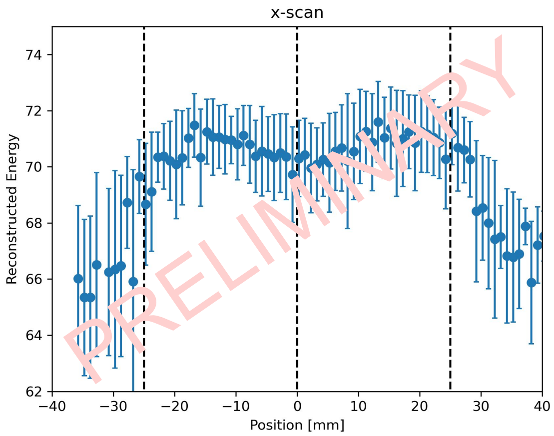


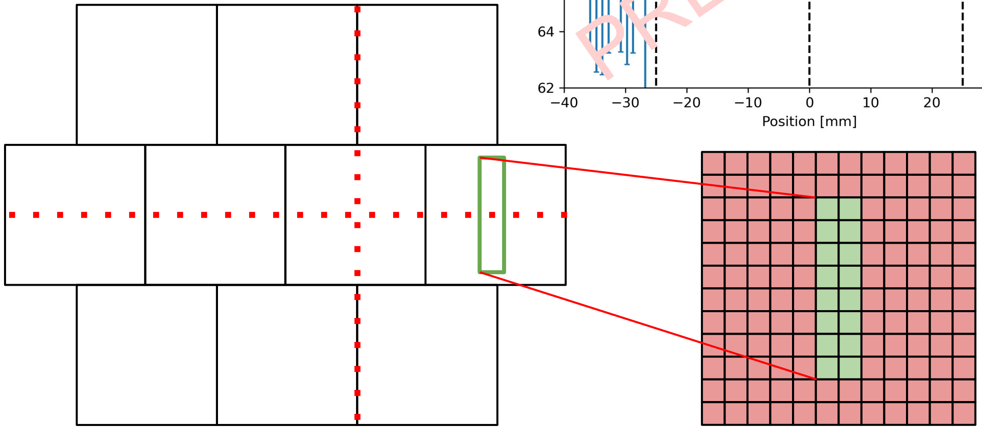


LYSO beamtime analysis - work in progress

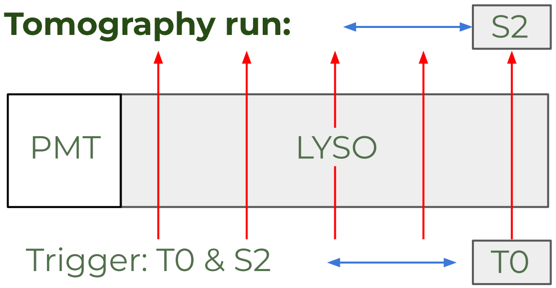
Uniformity:

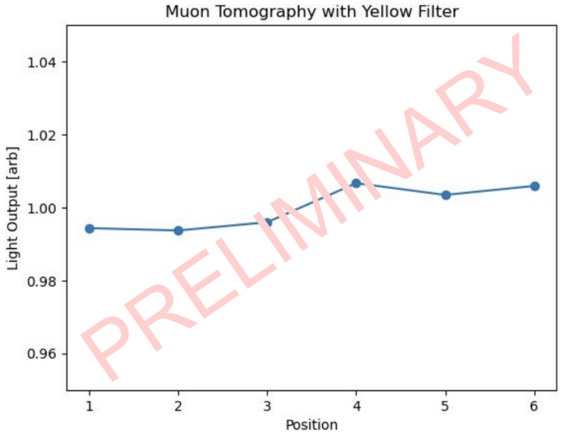
- Scan the crystal array along each axis
- Check uniformity of detector response





Tomography run:





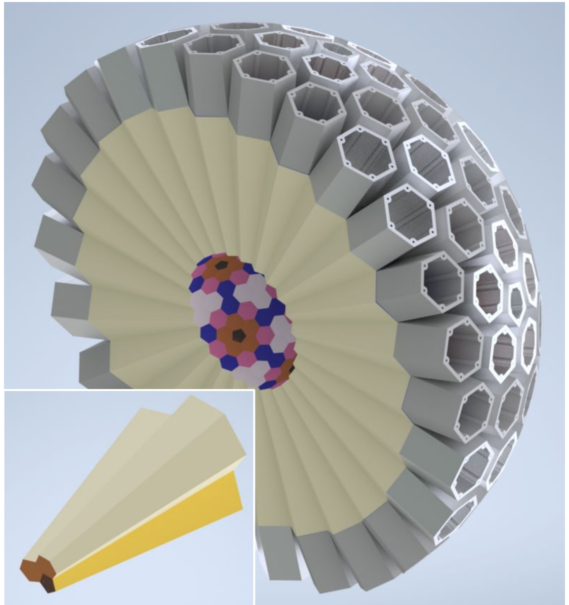
Outlook

Planned test beams:

- Test tapered LYSO crystal array
- Remeasure PiE5 beam as upstream as possible
- Test liquid xenon calorimeter prototype
- More LGAD /ATAR prototype tests upcomming
- Large prototype beam test

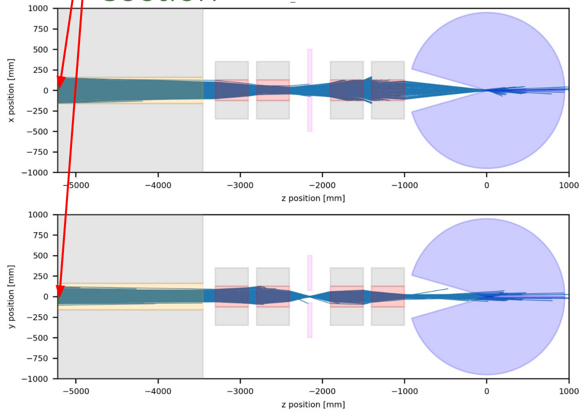
Tapered LYSO array:

- Test section a LYSO calo



PiE5 beamline:

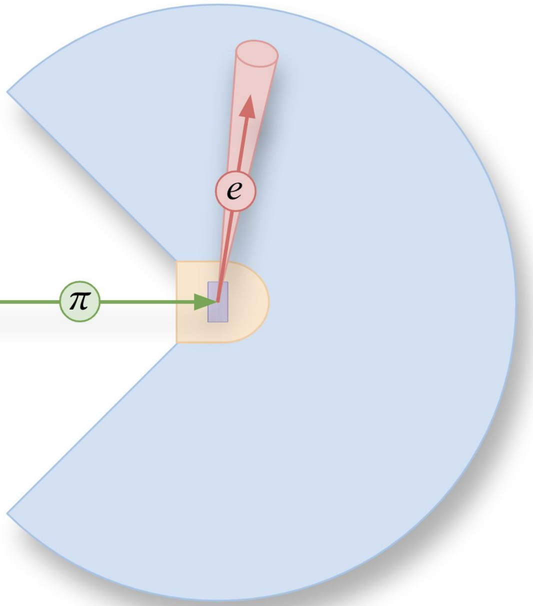
- Measure full phase space (momentum & position)
- Measure as upstream as possible to explore possible improvements on last beam section



Thank you!

The PIONEER collaboration: Over 80 collaborators from 24 institutions

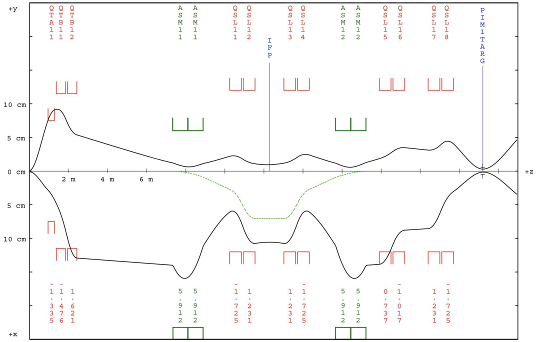
Backup slides



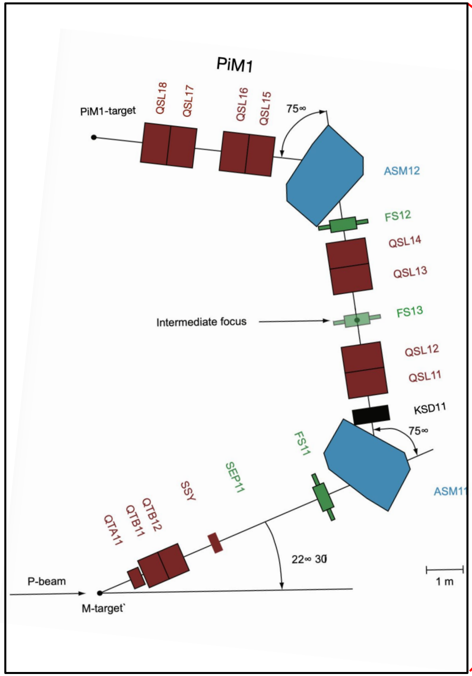
PiM1 beamline

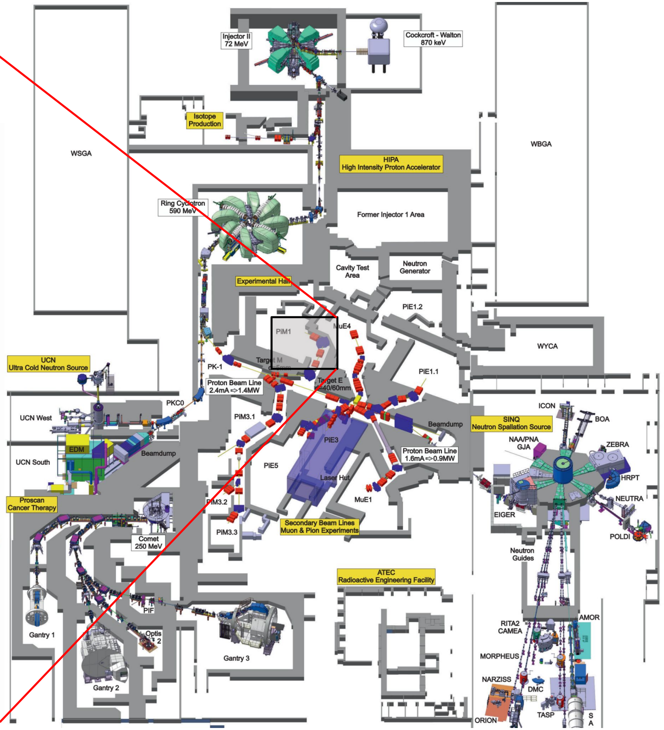
Beam properties:

Property	Value
Total path length	23.12 m
Momentum range	100 – 500 MeV/c
Solid angle	6 msr
Momentum acceptance (FWHM)	±1.5%
Momentum resolution	0.1%
Dispersion at the IFP	7 cm/%
Spot size on target (FWHM)	15 mm horizontal by 10 mm vertical
Angular divergence on target (FWHM)	35 mrad horizontal by 75 mrad vertical



PiM1 beamline at PSI:





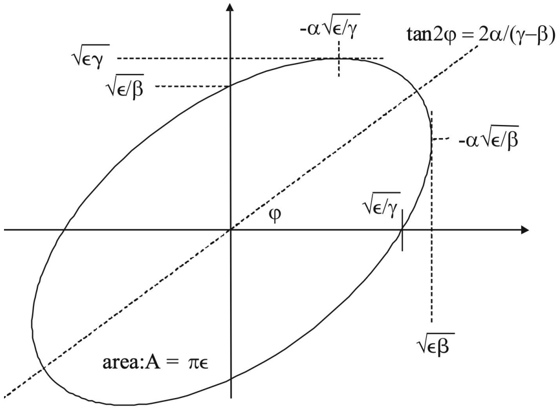
Cline, E., et al. "Characterization of muon and electron beams in the Paul Scherrer Institute PiM1 channel for the MUSE experiment." Physical Review C 105.5 (2022): 055201.

Beam Transport with a Quadrupole

Define sigma Matrix:

$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

$$\sigma_{11} = \langle x_i^2 \rangle = \epsilon\beta,$$
$$\sigma_{22} = \langle x_i'^2 \rangle = \epsilon\gamma,$$
$$\sigma_{12} = \langle x_i x_i' \rangle = -\epsilon\alpha.$$



Sigma Matrix changes as:

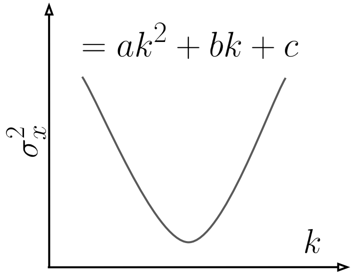
$$\boldsymbol{\sigma}_1 = \mathcal{M}\boldsymbol{\sigma}_0\mathcal{M}^T \qquad \mathcal{M} = \begin{pmatrix} 1-d/f & d \\ -1/f & 1 \end{pmatrix} = \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$$

Free beam transport → $\begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}$; Focus → $\begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$

Sigma at new position:

$$\sigma_{1,11}(k) = \left(d^2\ell_q^2\sigma_{0,11}\right)k^2 + \left(-2d\,\ell_q\sigma_{0,11} - 2d^2\ell_q\sigma_{0,12}\right)k + \left(\sigma_{0,11} + 2d\,\sigma_{0,12} + d^2\sigma_{0,22}\right)$$

$$\sigma_{0,11} = \frac{a}{d^2\ell_q^2} \qquad \sigma_{0,12} = \frac{-b - 2d\ell_q\sigma_{0,11}}{2d^2\ell_q} \qquad \sigma_{0,22} = \frac{c - \sigma_{0,11} - 2d\sigma_{0,12}}{d^2}$$

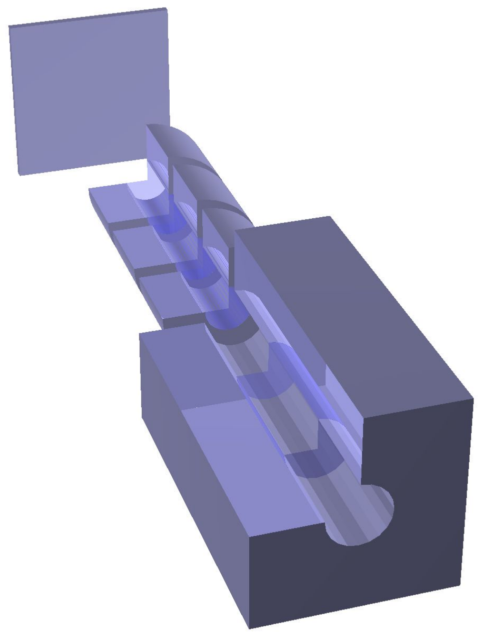


Emittance: $\sigma_{11}\,\sigma_{22} - \sigma_{12}^2 = \epsilon^2$

Implementation of upstream beam elements

Multiple upstream elements of beamline have been implemented:

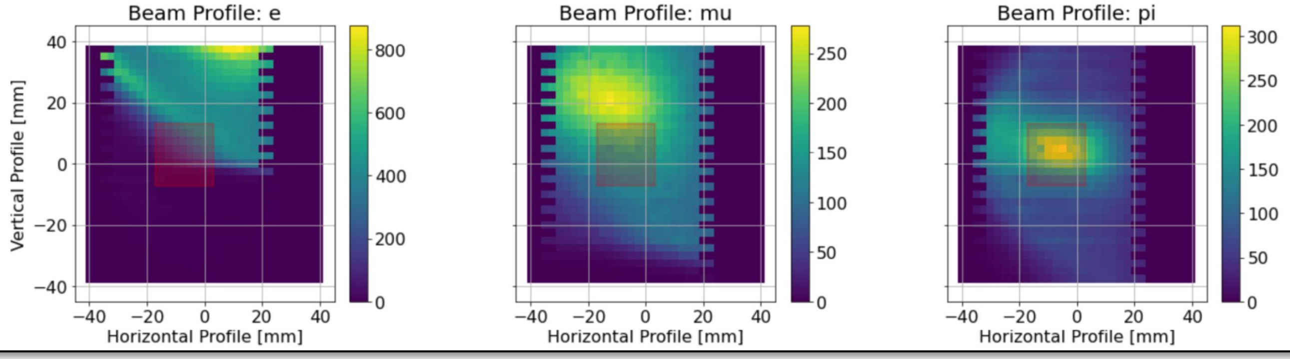
- **Quadrupole magnets**
  - Based on geometry of QSK 41 - 43 triplet
  - Quadrupole field strength can be set in json file
  - Field can be scaled in macro file
- **Dipole magnets**
  - Dipole field strength can be set in json file
  - Field can be scaled in macro file
- **Separator**
  - Based on geometry of SEP 41
  - Strength of electric and magnetic field can be set in json file
- **Collimator**
  - Thickness and opening in x & y can be set in json file
- **Ghost planes**
  - Record the particles that fly through



Comparison with last beam time results

Measurement:

- **Rate: 633 kH / 46 % in ATAR Box**
- Mean X = 0.3 mm
- Mean Y = 0.2 mm
- Sig X = 23 mm
- Sig Y = 10.1 mm



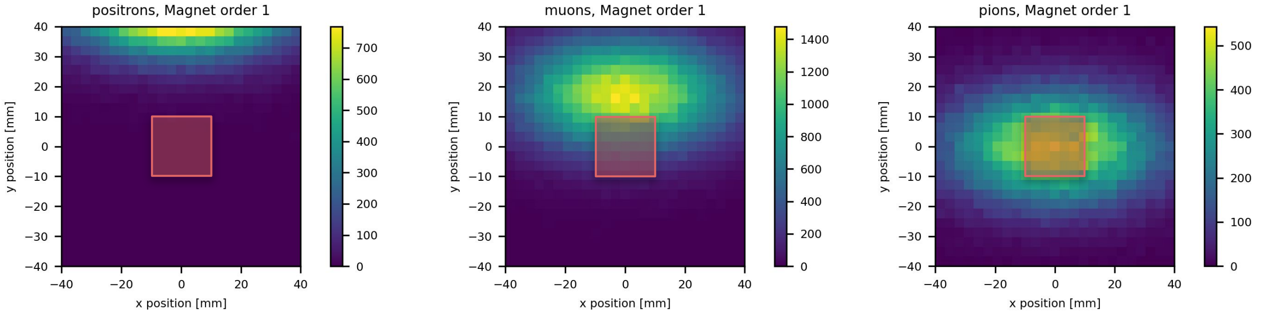
Simulation:

Pions:

- Mean X = 0.0 mm
- Mean Y = 0.0 mm
- Sig X = 26.76 mm
- Sig Y = 13.1 mm

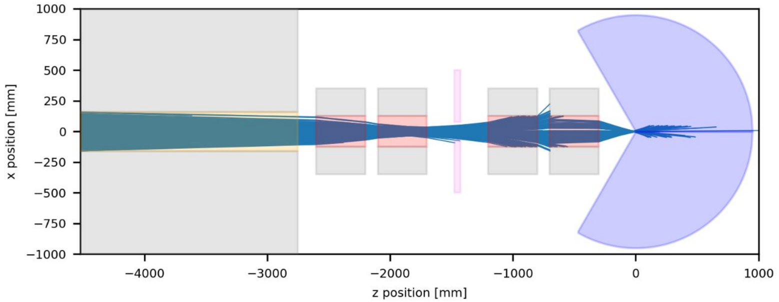
Muons:

- Mean Y = 17.4 mm



Full final beam section simulation - pure pion beam

Short beamline setup:



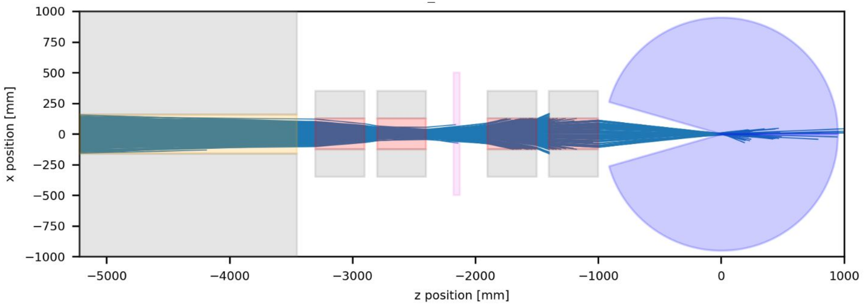
Arriving pions:

- **6.9 %** of simulated pions stop in ATAR
- **~ 372 kHz** estimated from beamtime rates

Backgrounds, per stopped pion:

- **0.03 pion** in Calo
- **0.33 muon** in Calo
- **0.013 muon** in ATAR

Long beamline setup:



Arriving pions:

- **4.1 %** of simulated pions stop in ATAR
- **~ 219 kHz** estimated from beamtime rates

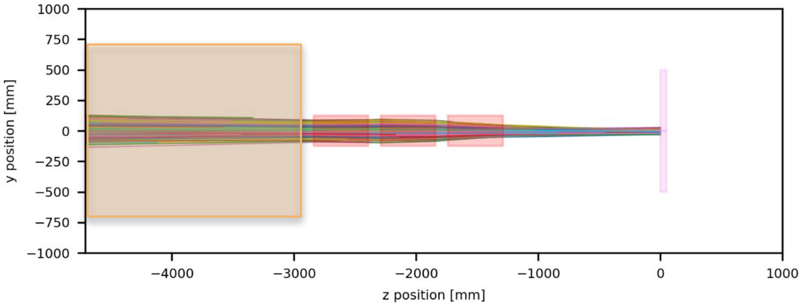
Backgrounds, per stopped pion:

- **0.09 pion** in Calo
- **1.05 muon** in Calo
- **0.014 muon** in ATAR

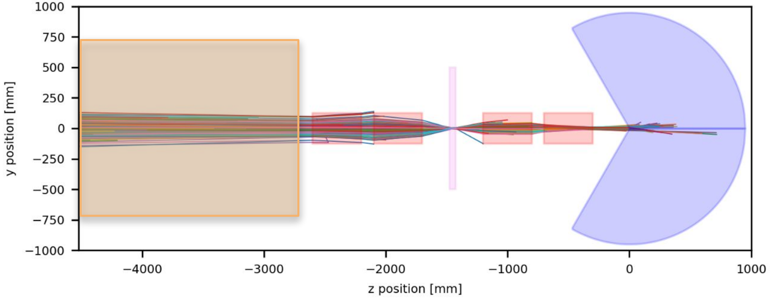
Short vs long focus

Example of scaling with measured rate:

Beamtime setup:



Short beamline setup:



Counts: Pions on SiMON: 268’437 / 1’000’000 → Pions in ATAR: 69’425 / 1’000’000

Corresponds to ↕ Corresponds to ↕

Rates: Measured: 1’375 kHz → Calculated: 372 kHz

Full final beam section simulation - pure pion beam

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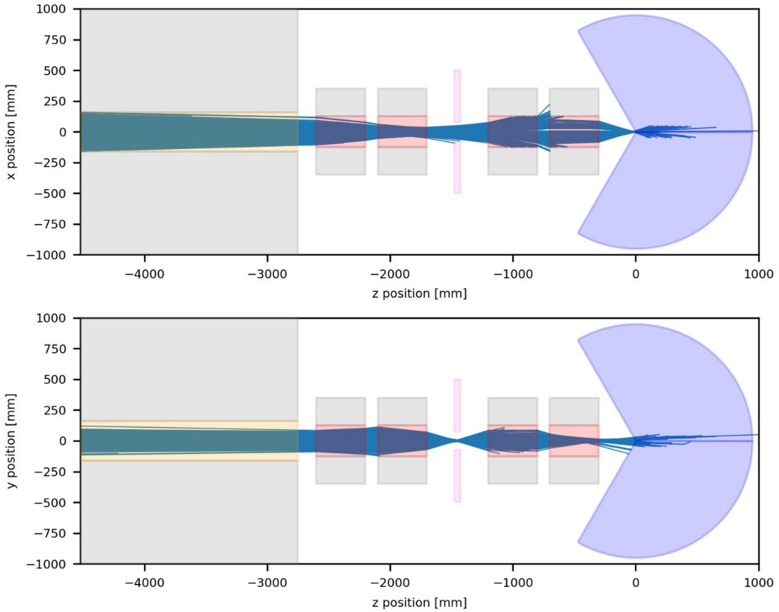

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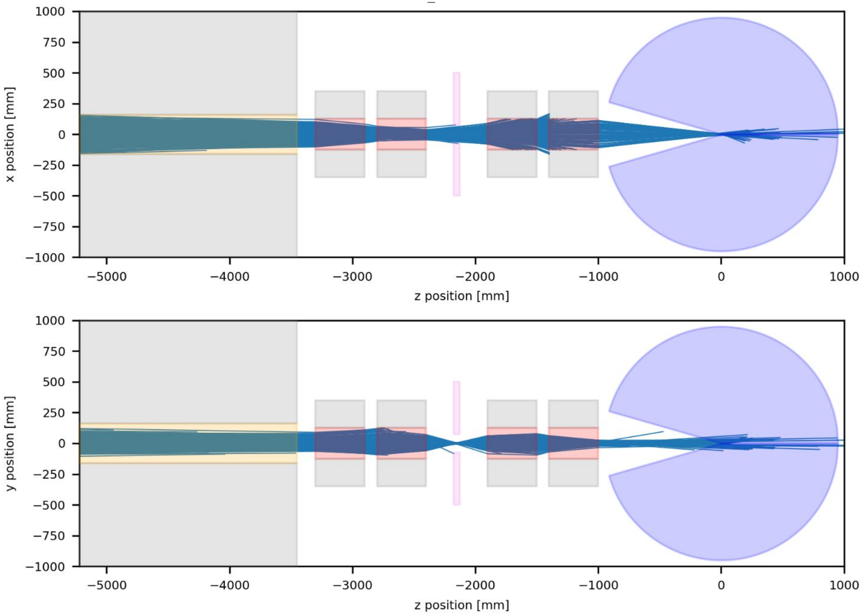


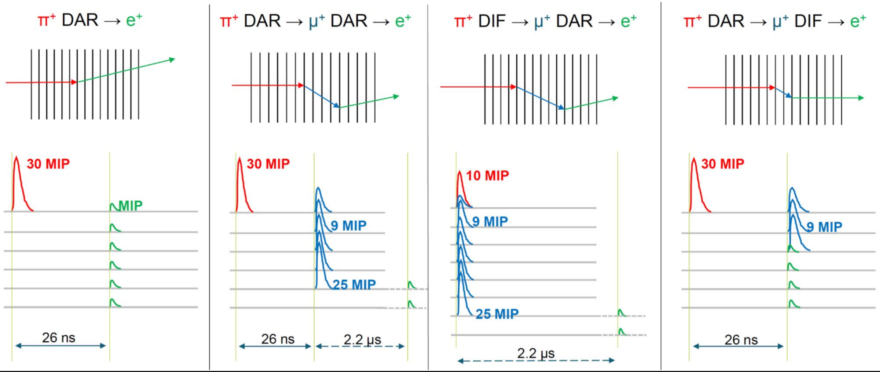
The ATAR

Test beam 2023 at CENPA:

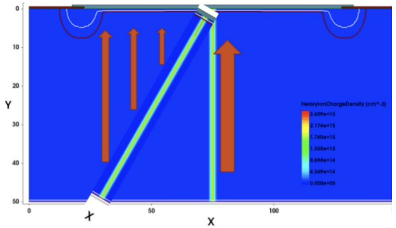
- Testing gain suppression as a function of angle in low gain avalanche detectors (AC-LGADs)

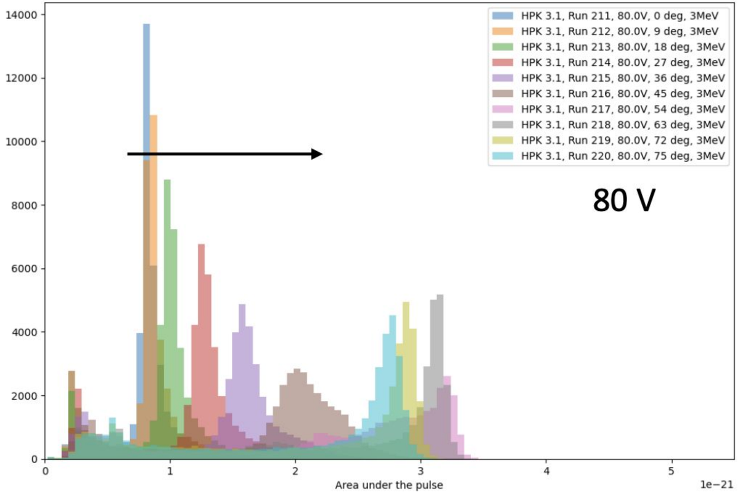
Key parameters[1,2]:

- High granularity, minimal blind/ dead regions
- Fast timing
- Good energy resolution over large dynamic range



Results:





1: Mazza, S. Instruments, 2021, 5. no. 4: 40. arXiv:2111.05375 [physics.ins-det]
2: Mazza, S. et al. Proceedings of Science, 2023 V 420. https://doi.org/10.22323/1.420.0015

3:Ott, J.13th Hiroshima Symposium, https://indico.cern.ch/event/1184921/contributions/5574780/

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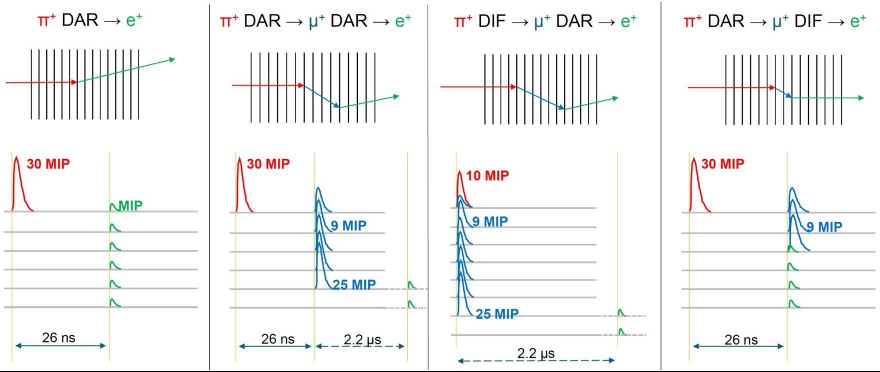

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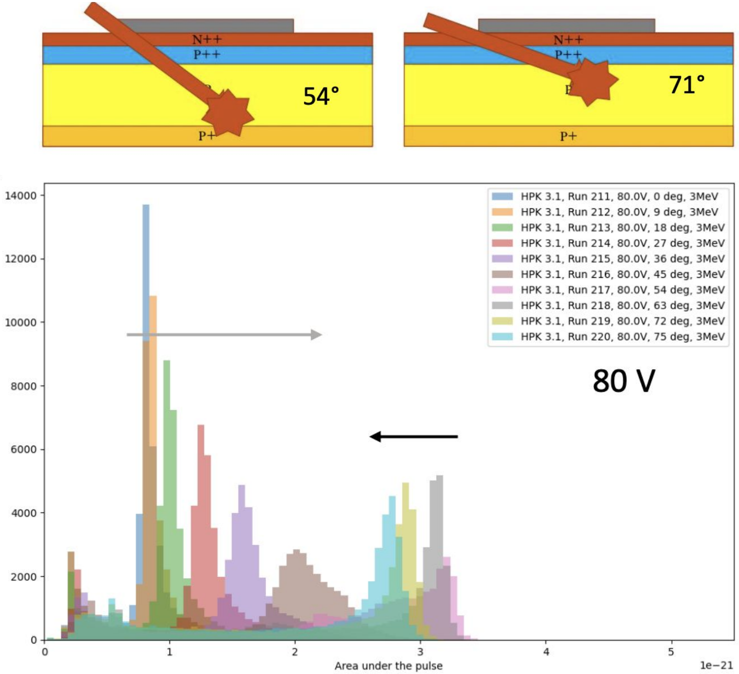

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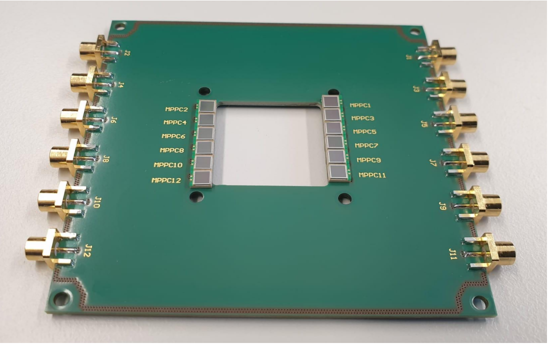
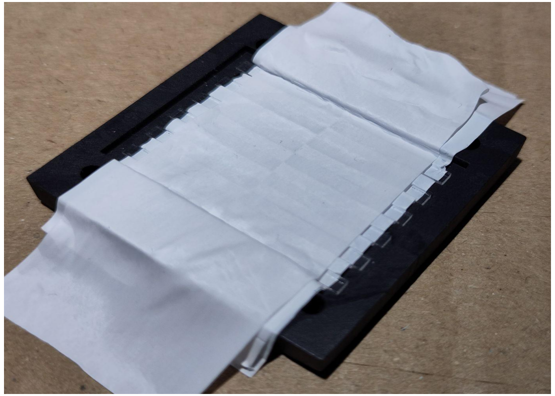
Entrance detectors for LYSO beamtime

Hodoscope:
- 24 x 24 mm^2 total area
- 2 layers of BC 404 bars with 12 channels
- Each channel
  - 2 mm wide
  - 1mm thick
- Read out by 24 SiPMs on alternating sides

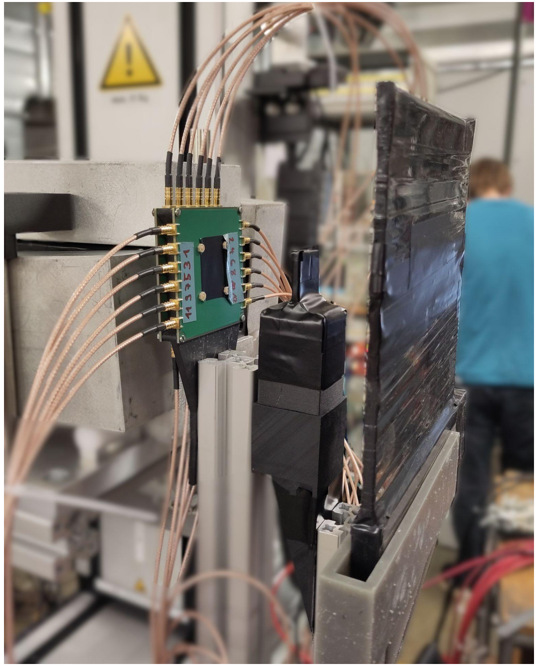
Entrance detector:
- 25 x 25 mm^2 total area
- 1 piece of BC 404 with 1mm thickness
- Read out by a PMT

Veto detector:
- 22 mm diameter hole





Setup:



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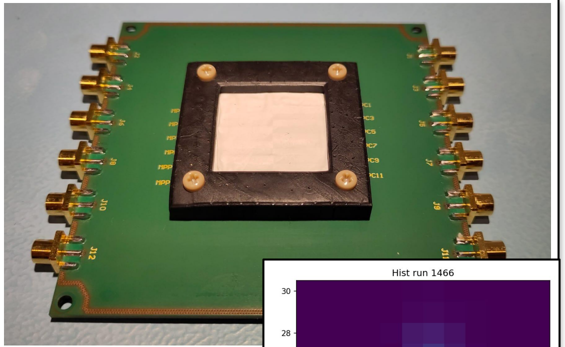

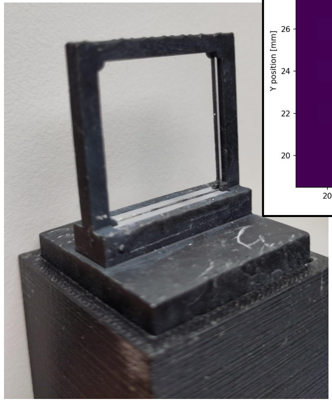

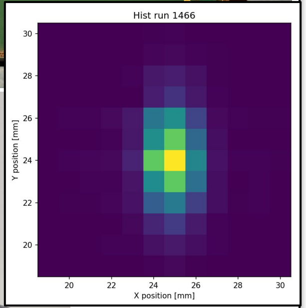

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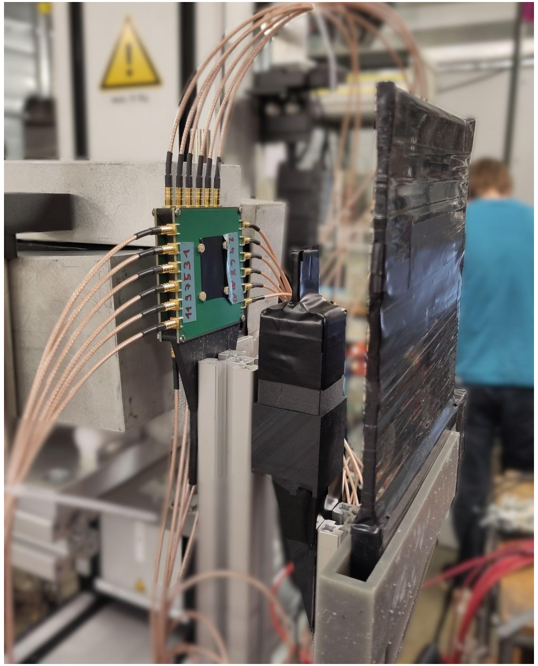
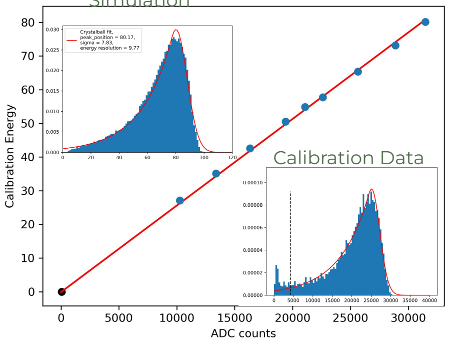


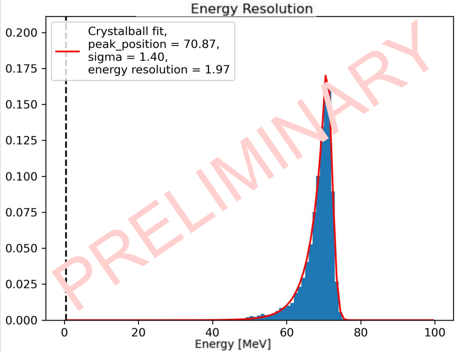
LYSO beamtime analysis - work in progress

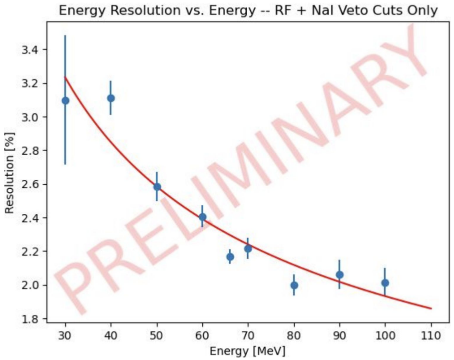
Energy resolution:

Strategy:
- Select events
- Apply calibration
- Add up contributions of all crystals
- Fit energy distribution

Calibration:

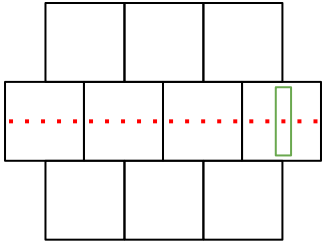


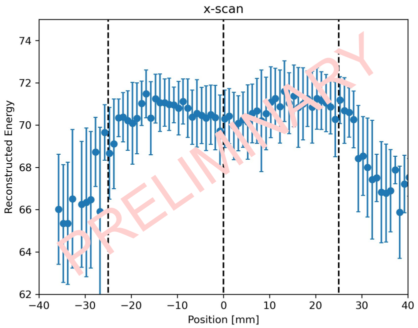




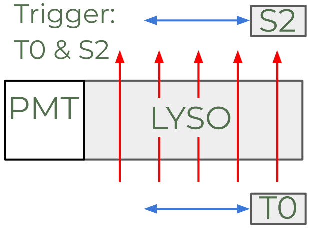
Uniformity:

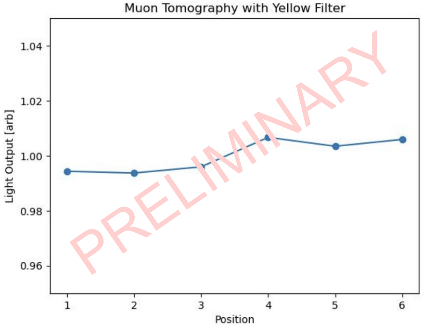
X-scan:





Tomography run:

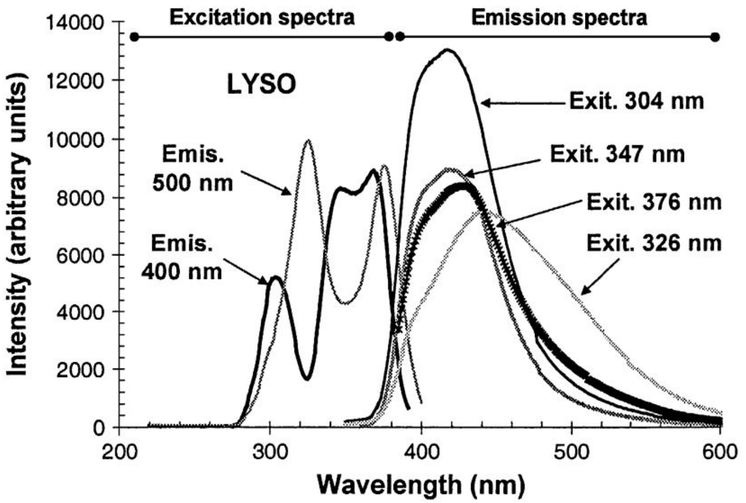




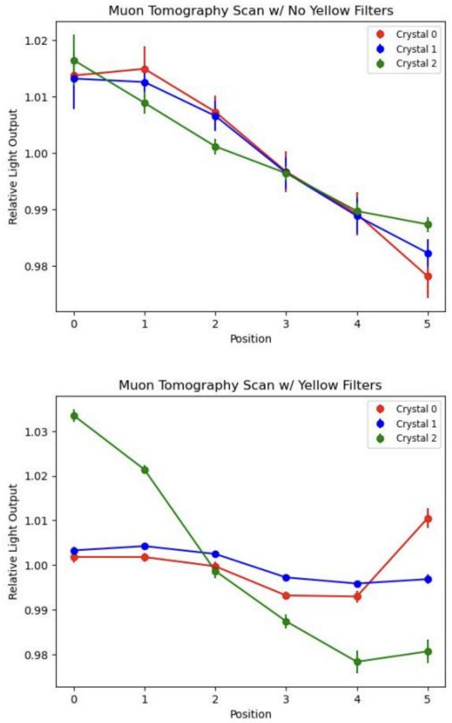
Muon tomography run

Idea:

- Test uniformity along the crystals
- Shoot 220 MeV beam sideways into the crystal (MIP like behaviour)
- Use yellow filters



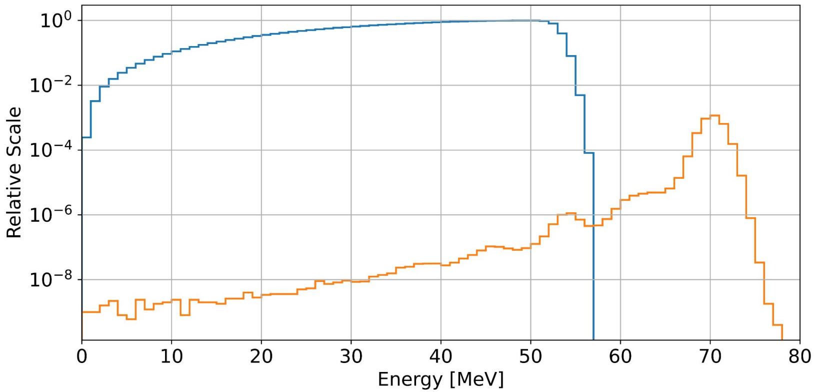
Result:



Albedo measurement

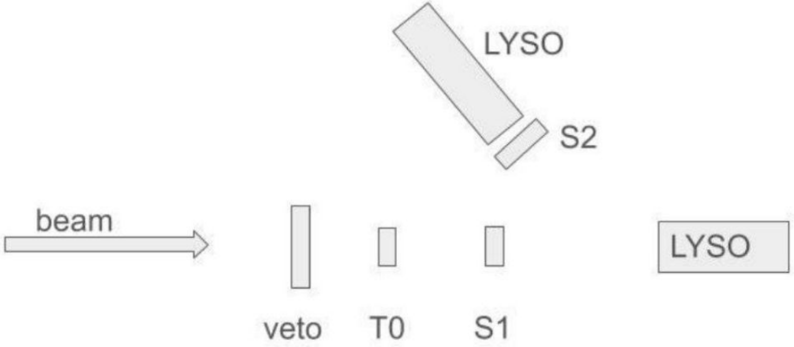
Reason for the measurement:

- Different Geant4 physics lists have a huge difference in albedo of LYSO
- Albedo could contribute significantly to the tail fraction (⅓ in the worse case)



Setup:

- Measure particles multiple scattering on the surface and not depositing the full energy in the crystal
- Trigger on T0 & S2 & not Veto



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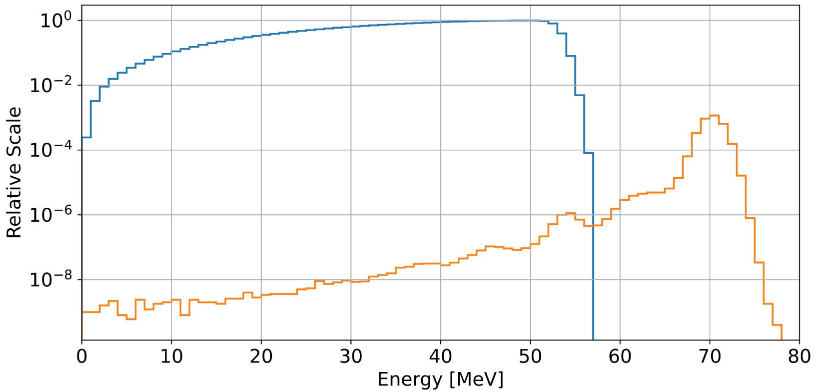

Result:

Albedo measured but not quantified