PAUL SCHERRER INSTITUT

PSI

Thomas Prokscha :: Laboratory for Muon Spin Spectroscopy :: Paul Scherrer Institute

PSI muon beamlines update

BRIDGE2023 Workshop, PSI, October 18th – 20th 2023

Outline

1. **Muon facility overview**
2. **Permanent installation of a U- and Z-branch in μE1**
   - see poster of Cong Chen for details
3. **Muon beam properties of the low-energy muon facility (LEM)** at PSI
   - Reduced phase space degradation at new 1.7 μg/cm^2 carbon foil of «trigger detector» (TD)
   - Status μE4 upgrade
4. **Muons-On-REquest (MORE) in πM3 (GPS/FLAME instruments)**
5. **IMPACT/HIMB**
   - development of vertex reconstruction for μSR spectrometers, based on Si-pixel detectors

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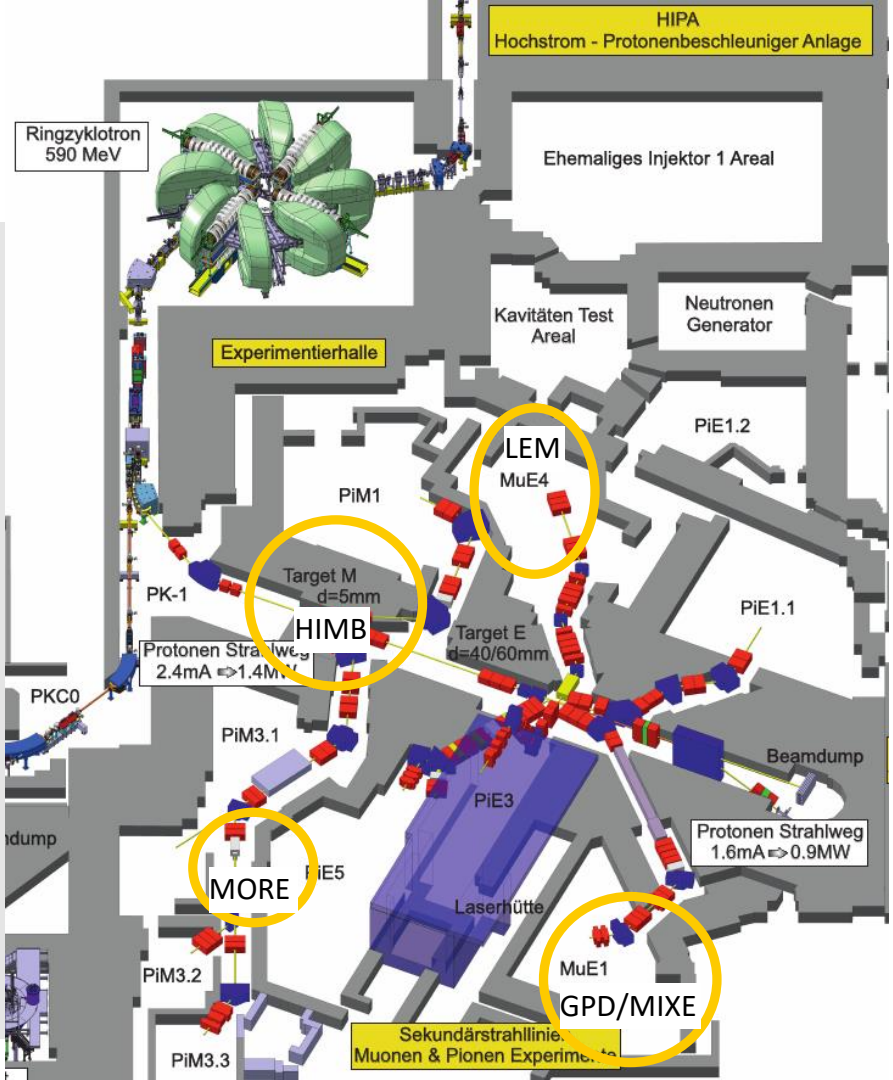
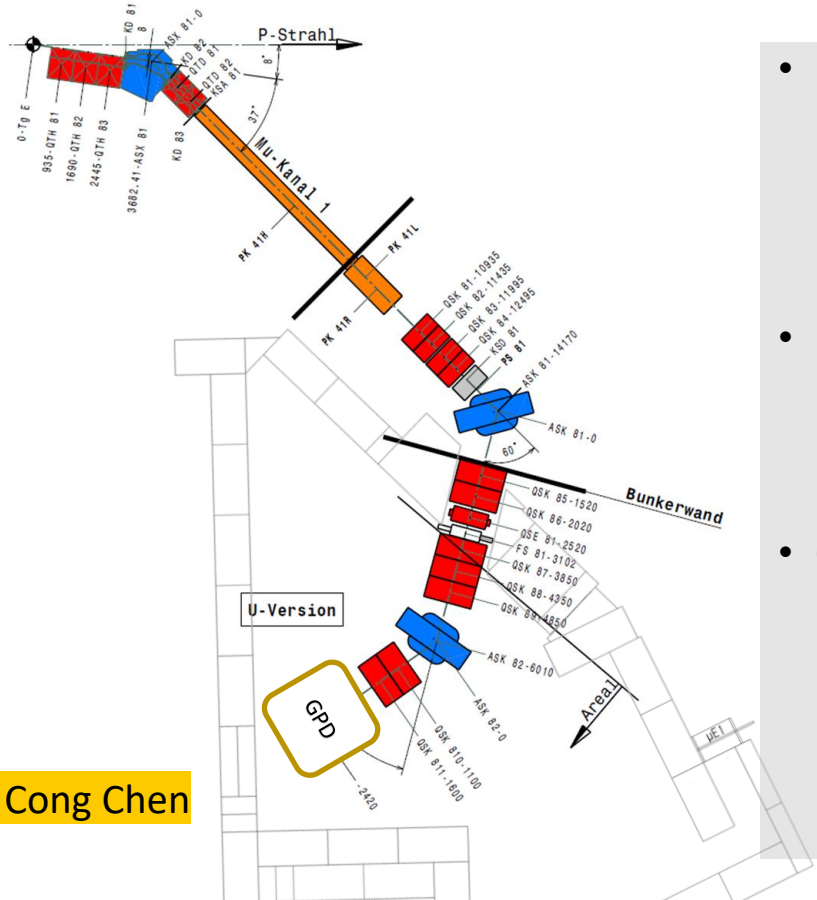
Experimental hall



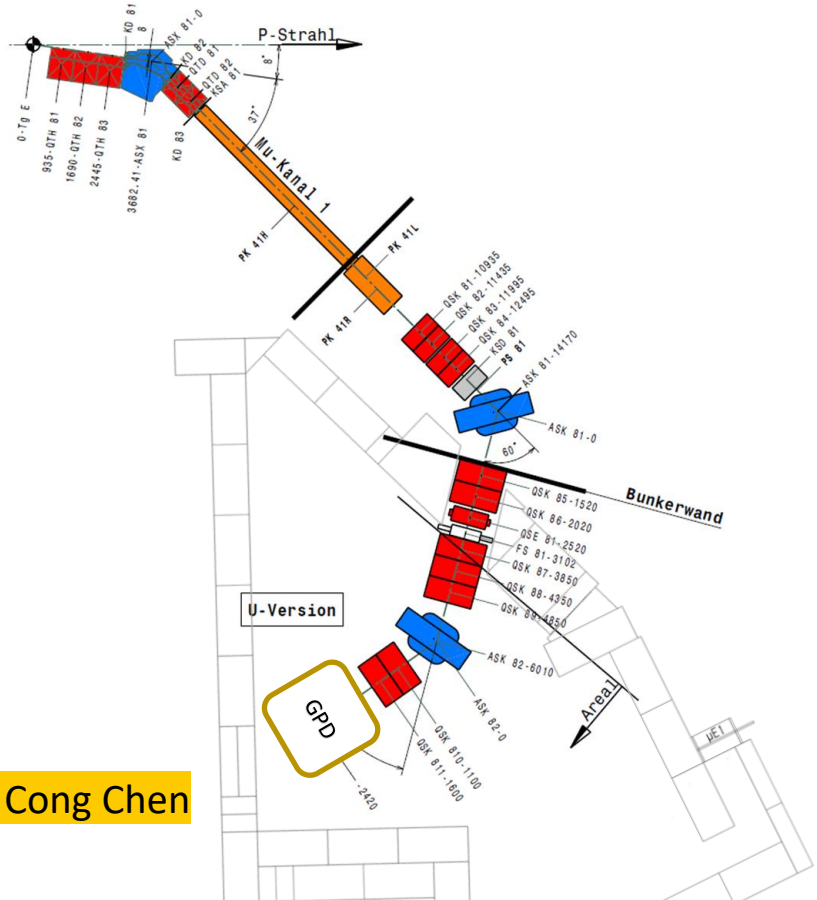
Current status of μE1, poster of Cong Chen

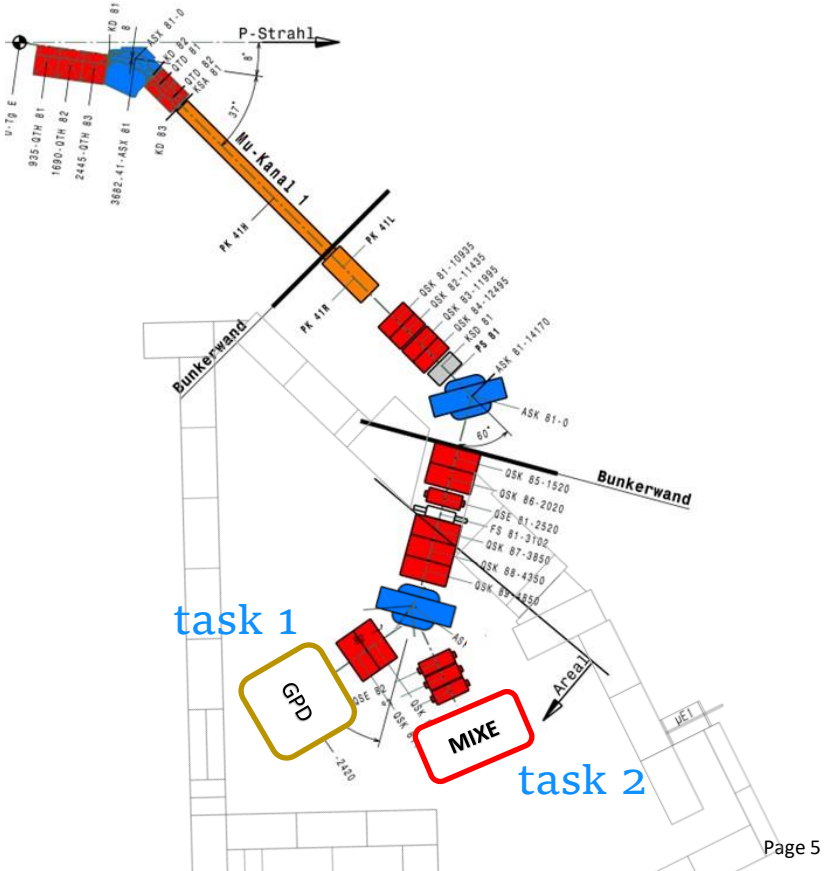


- Long Decay channel:
  - wide momentum range
    50 – 125 MeV/c
  - High flux > 10^7 μ-/s
- Extraction part:
  - 2 bending magnets and 12 quadrupoles
  - Allows for optimizing beam properties
- GPD (General Purpose Decay Channel Instrument),
  - Enough space for a new “Z-branch”
  - limited impact on the old application

Slide by Cong Chen

Current status of μE1, poster of Cong Chen

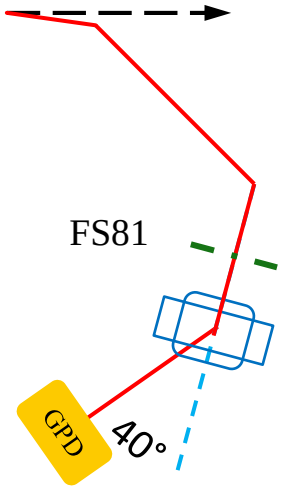


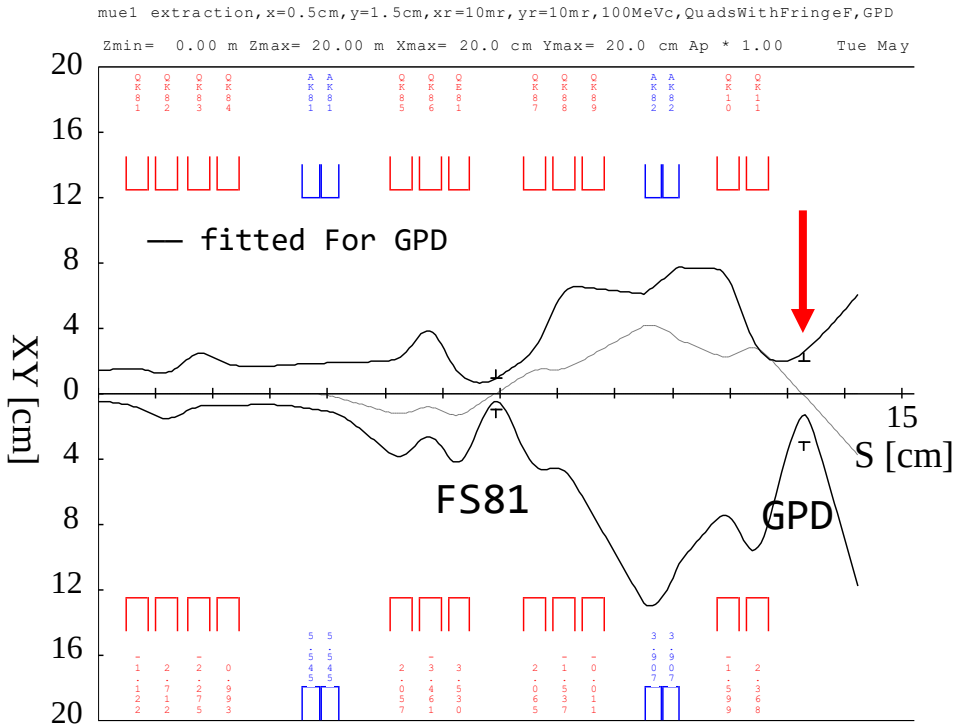


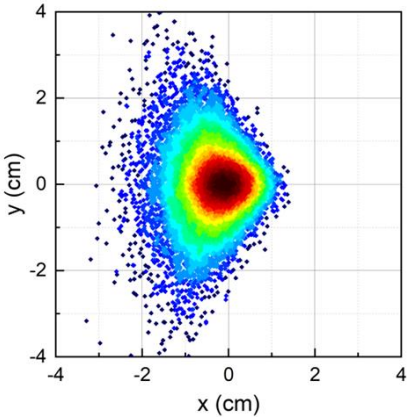
Slide by Cong Chen

Beam envelope calculation of μE1 with new layout

The fitted TRANSPORT beam optics and TURTLE simulation for the original GPD side with a rotated bending magnet
(2nd order calculation, Δp/p=3%)



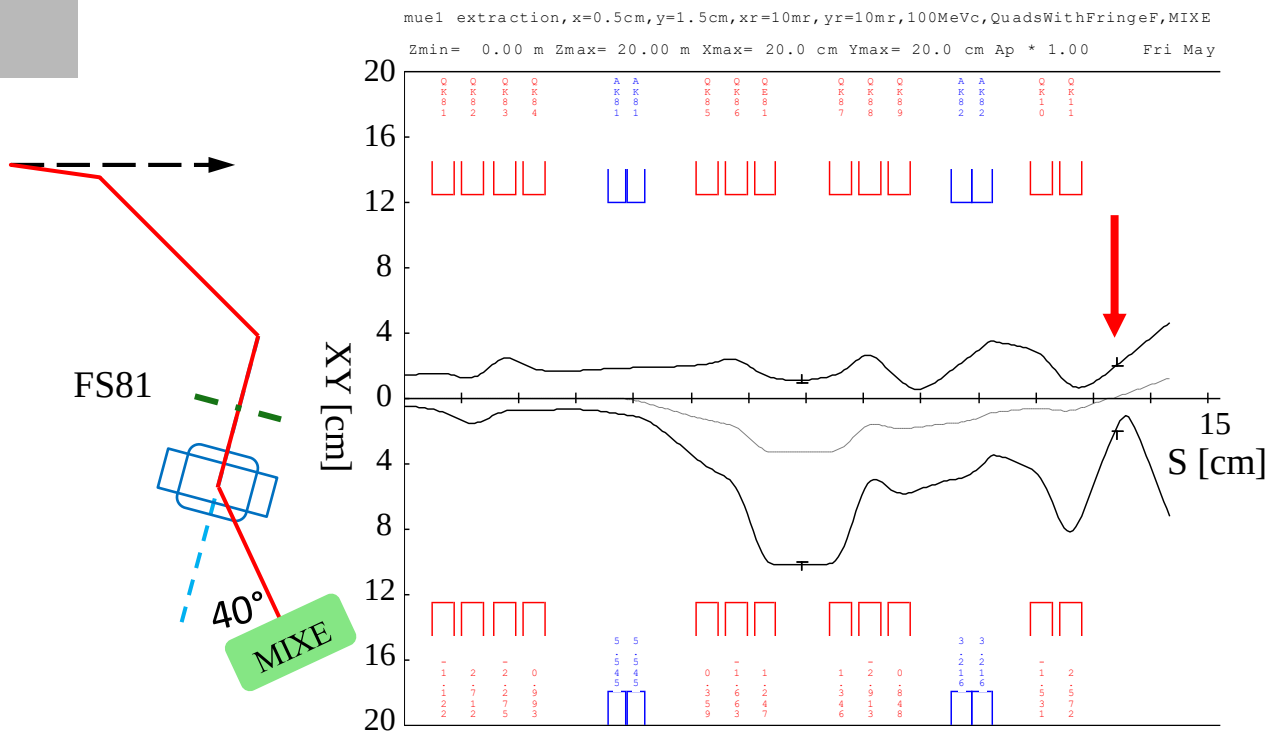




Slide by Cong Chen

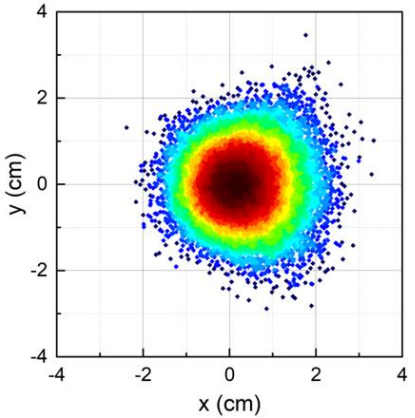
Beam envelope calculation of μE1 with new layout

For MIXE (rotated ASK82): Calculations of beam envelopes, 2nd order calculation, Δp/p=3%



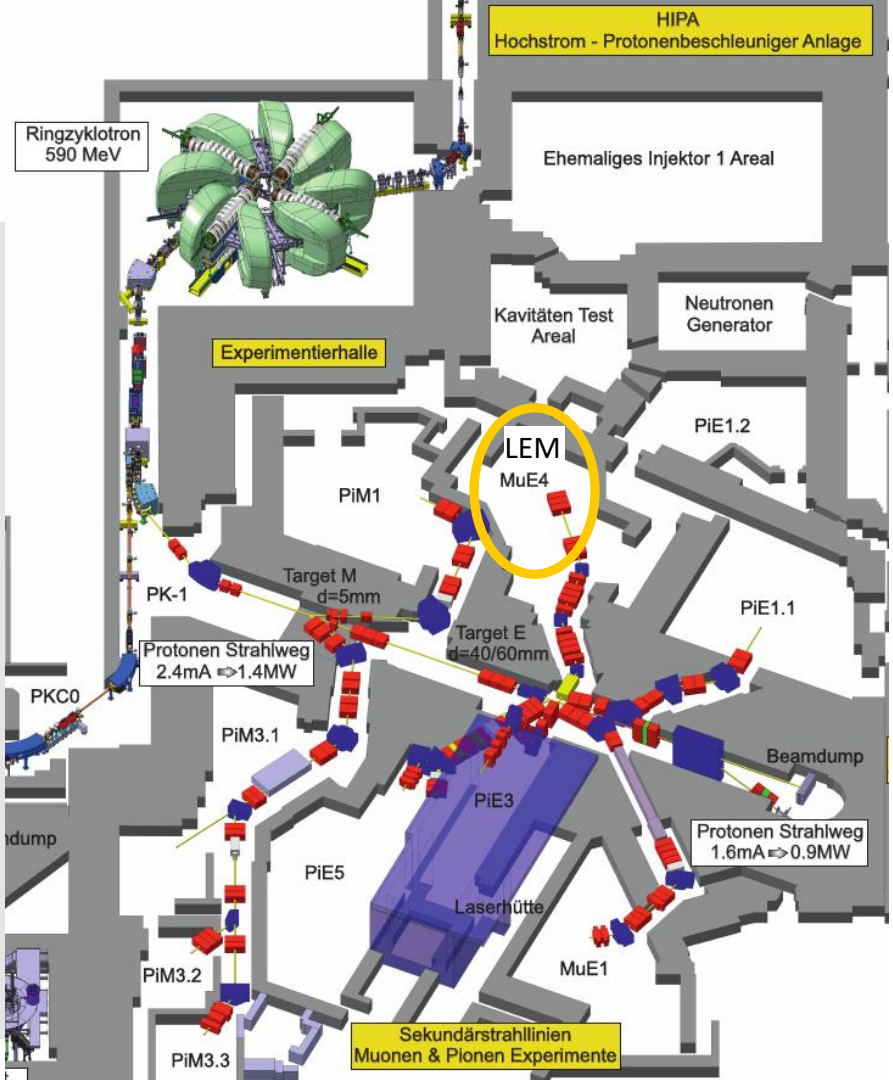
total opening of slit ~25 cm

big momentum dispersion ~4 cm



Slide by Cong Chen

Experimental hall



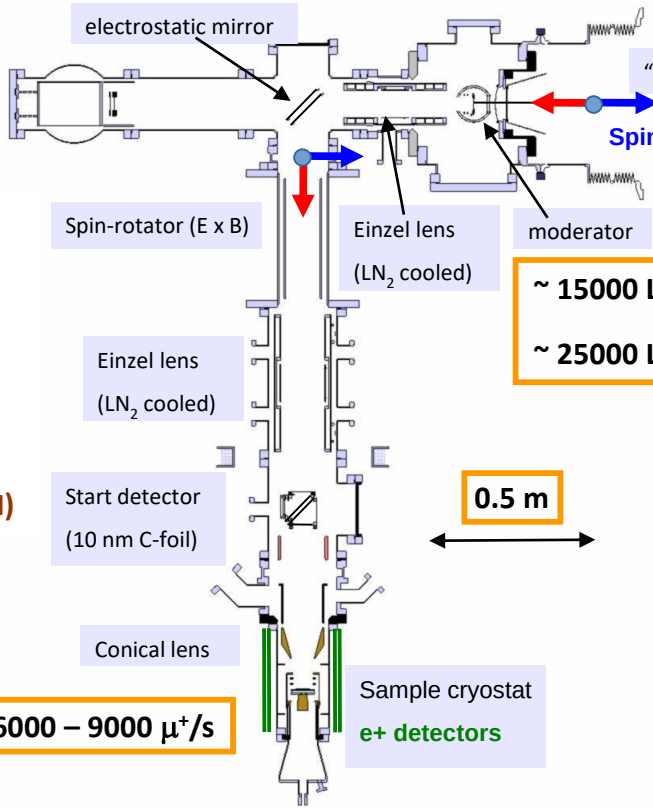
Low-energy (keV) μ^+ (LEM) facility at PSI

Rates are for 4-cm "slanted" target E and 2.0 mA proton current (2021)

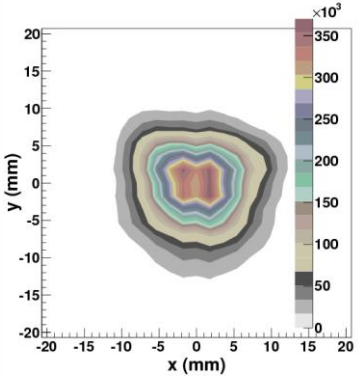
- UHV system, 10^{-10} mbar
- some parts LN_2 cooled

Polarized Low Energy Muon Beam

Energy:	1 – 30 keV
ΔE, Δt:	400 eV, 5 ns
Depth:	5 – 300 nm
Polarization	~100 %
Beam Spot:	12 mm (FWHM)



Beam spot at sample



Muon beam properties of LEM facility

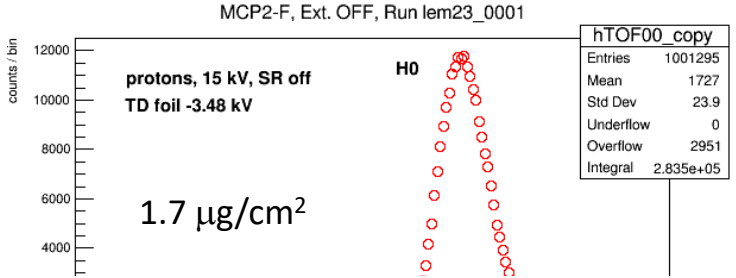
Slide from 2022 workshop

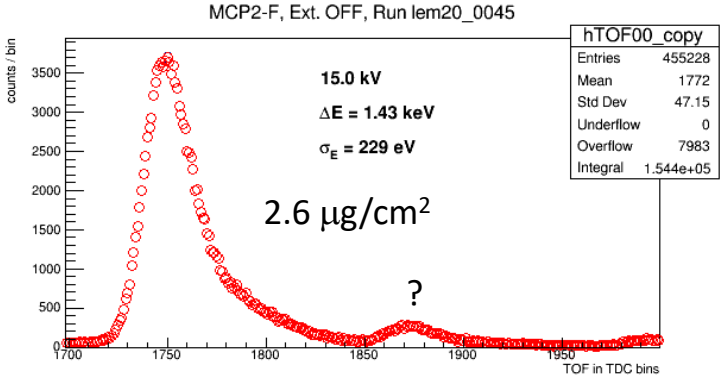
- **Problems**
  - Extraction at moderator with grids increases horizontal phase space
  - Interaction of beam with 10-nm carbon foil of TD:
    - Increase of transverse phase spaces: deteriorates beam spot
    - Increase of transverse phase spaces: reduces beam transmission
    - Energy loss distribution: deteriorates beam spot
    - Energy loss distribution: TOF distribution limits time resolution to 5 ns
    - Muonium formation: reduces polarization of the beam at sample

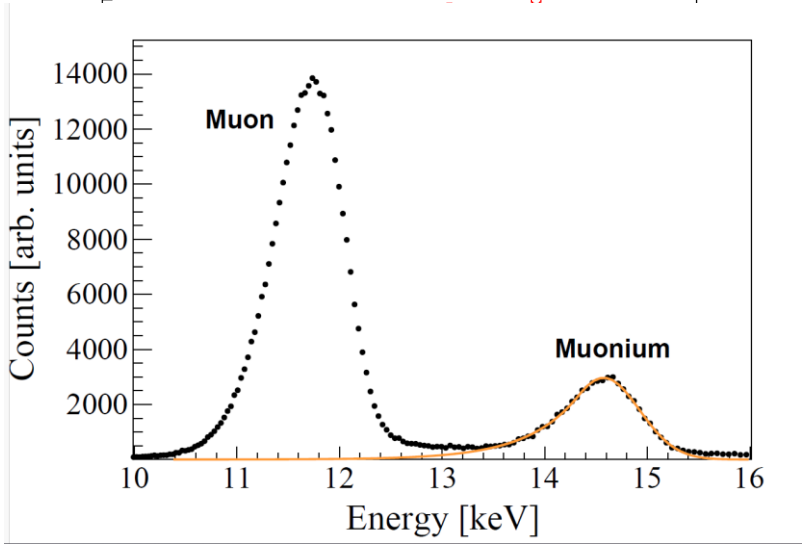
- **Improvements**
  - Change extraction to Soa lens type as in J-PARC USM facility (WIP)
  - 10 mm or 15 mm collimator at TD
    - Beam reduction of 50%, but beam spot much better: 5x5 mm^2 samples possible
    - Up to 5 samples can be mounted on one sample plate
  - Replace carbon foils by graphene foils: WIP, so far not successful; use 1.7 $\mu g/cm^2$ foil instead of 2.6 $\mu g/cm^2$ (acf-metals.com)
  - Upgrade of μE4 beam in 2026 (WIP)
    - replace last quadrupole triplett by special solenoid: 50% more surface muon on moderator target

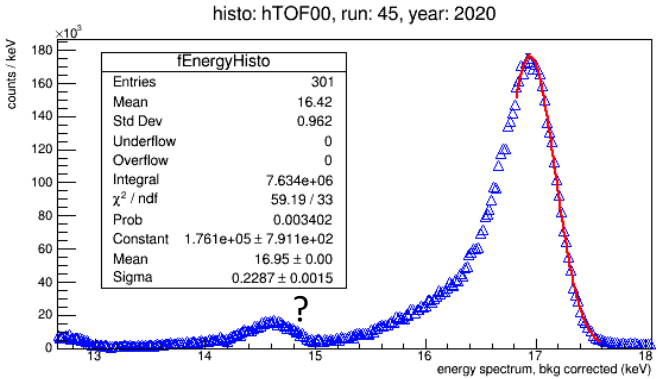
1.7 μg/cm² carbon foil in LEM TD.

TOF from TD to sample position

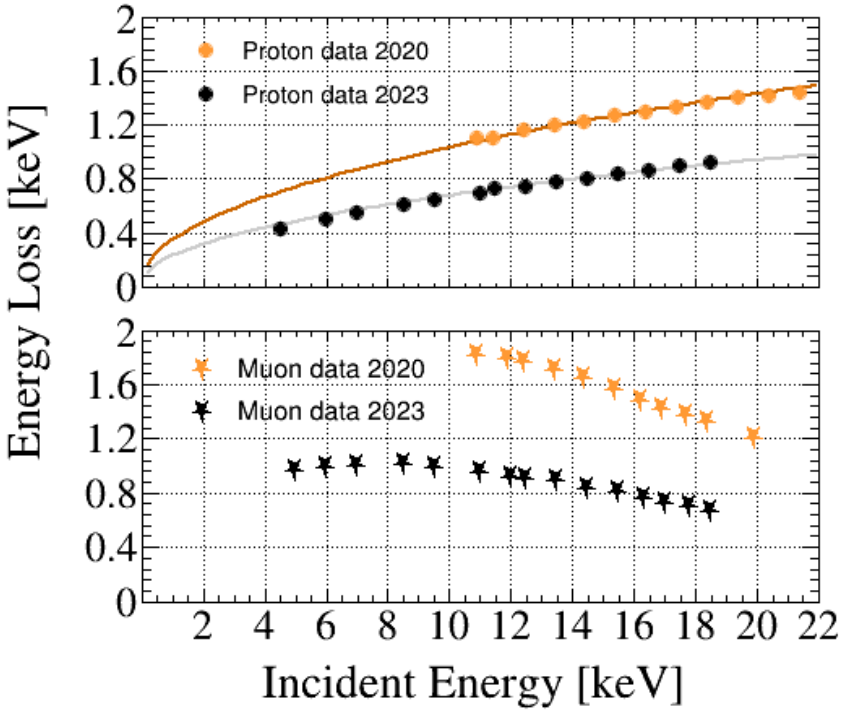


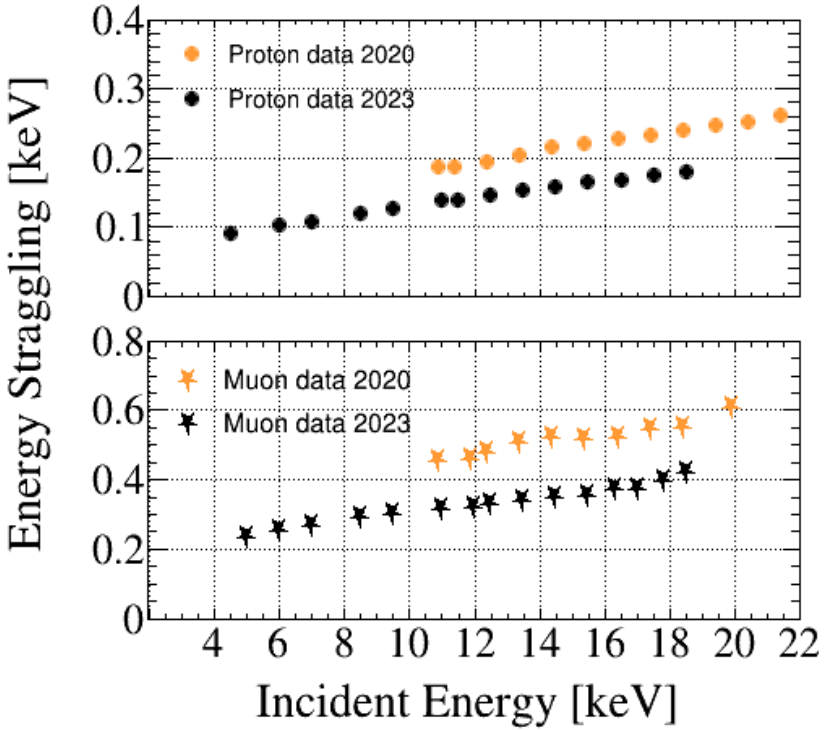






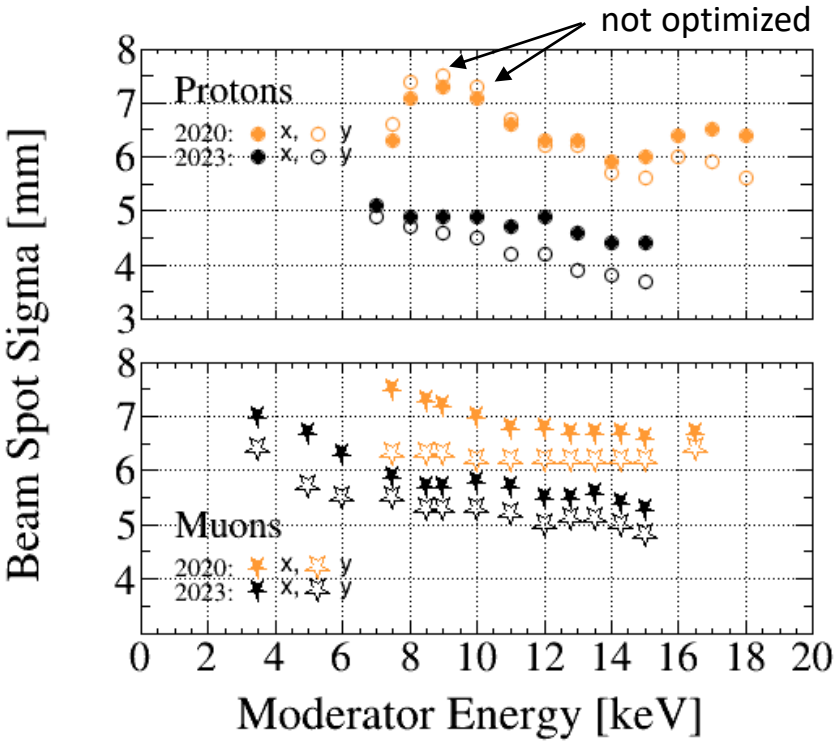
1.7 μg/cm² carbon foil (ACF) in LEM TD

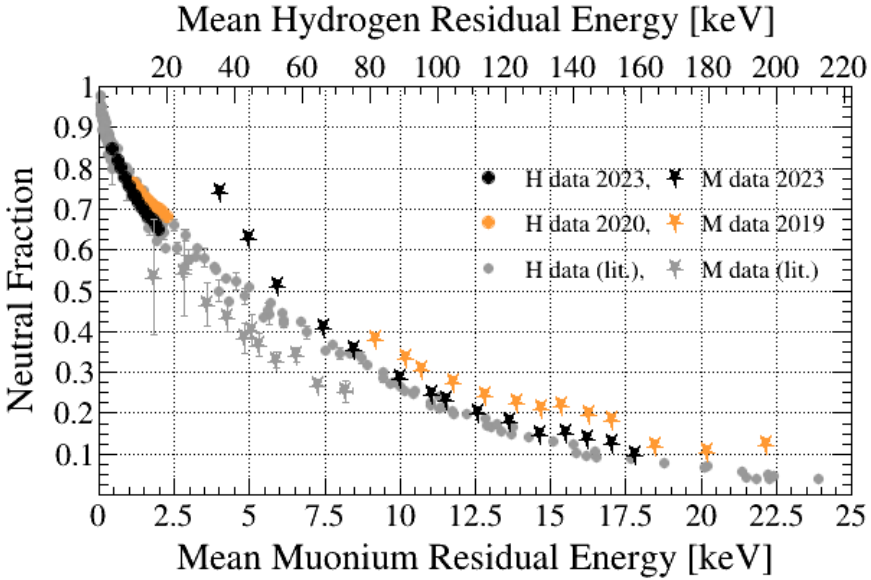




2020: 2.6 μg/cm²; 2023: 1.7 μg/cm²

1.7 μg/cm² carbon foil in LEM TD.





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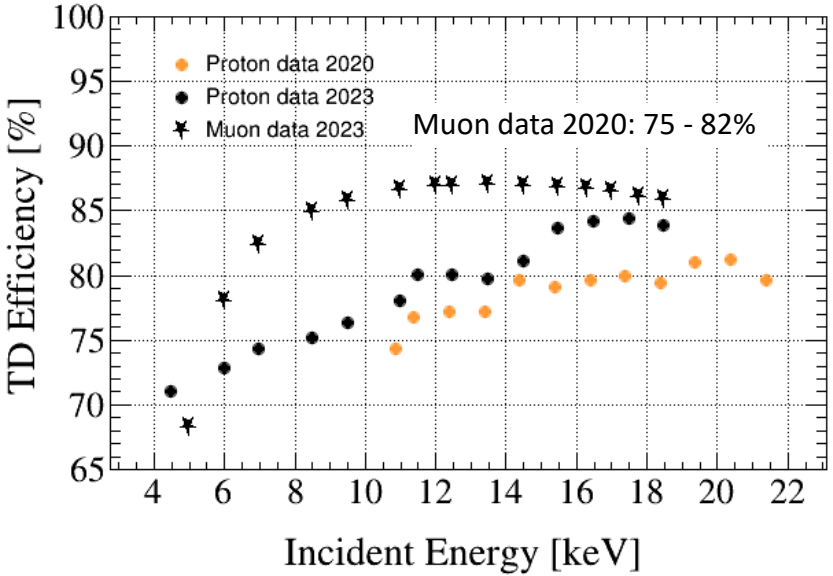
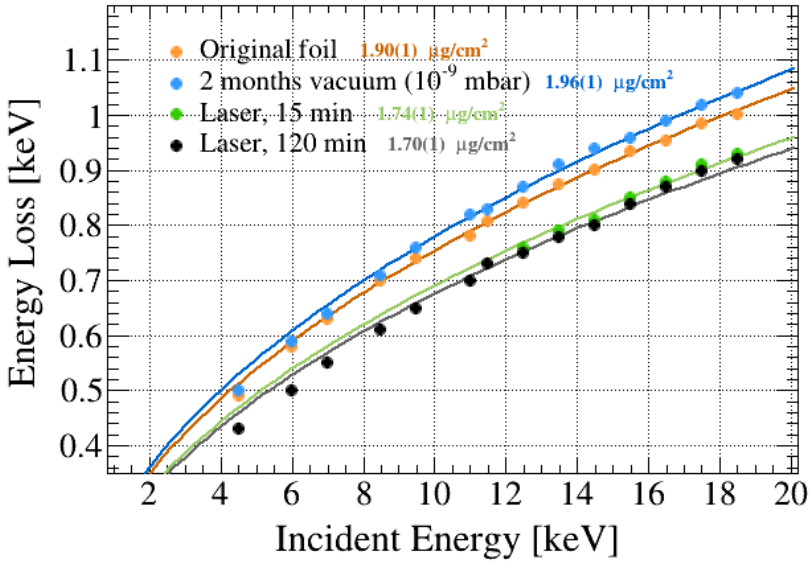
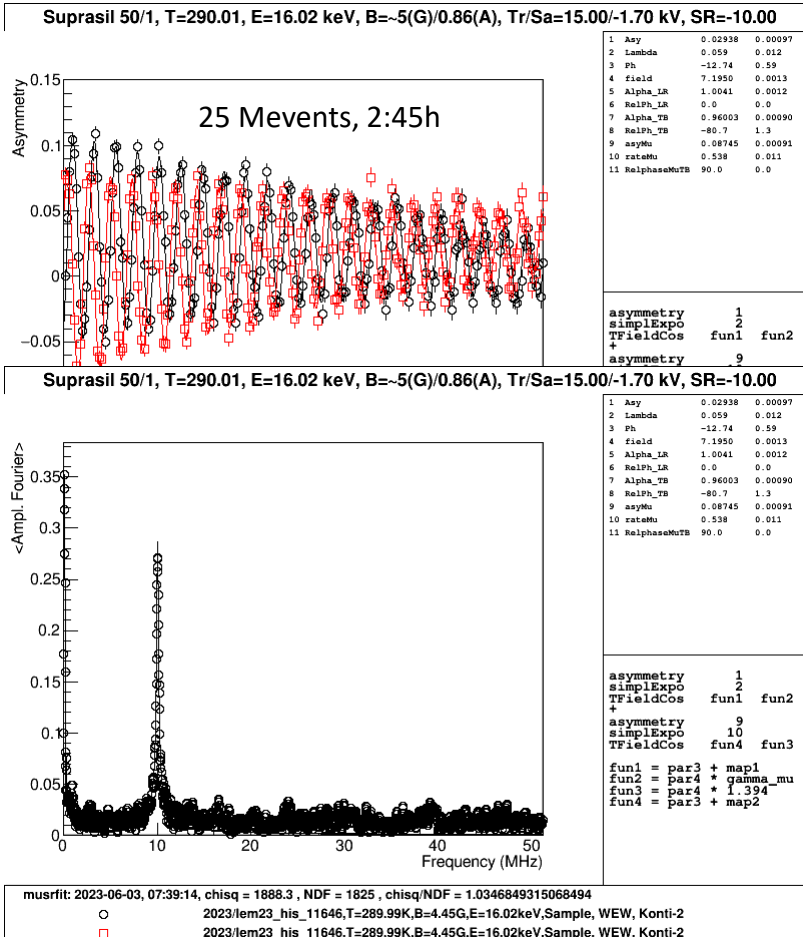
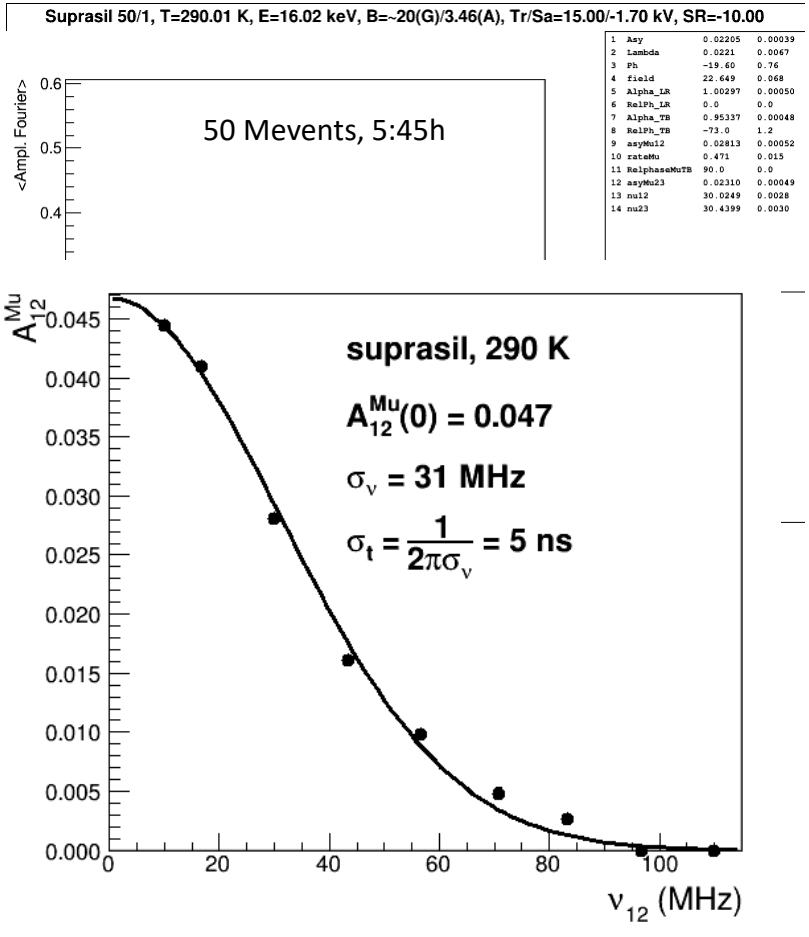




2020: 2.6 μg/cm²; 2023: 1.7 μg/cm²

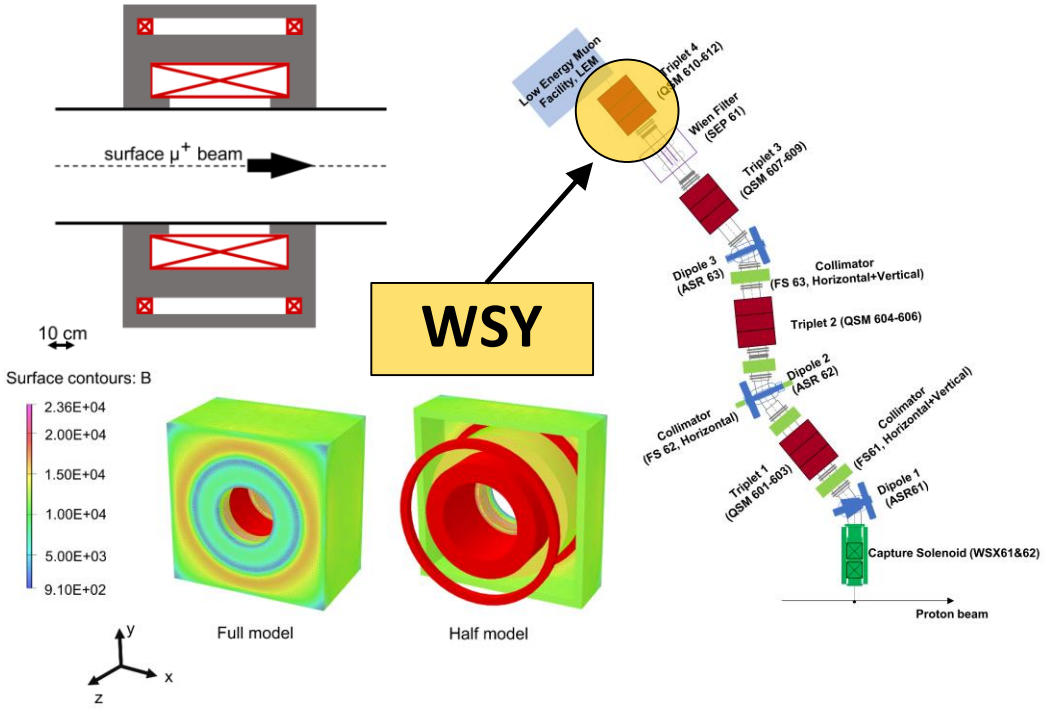
1.7 μg/cm² carbon foil, time resolution for LE-μSR

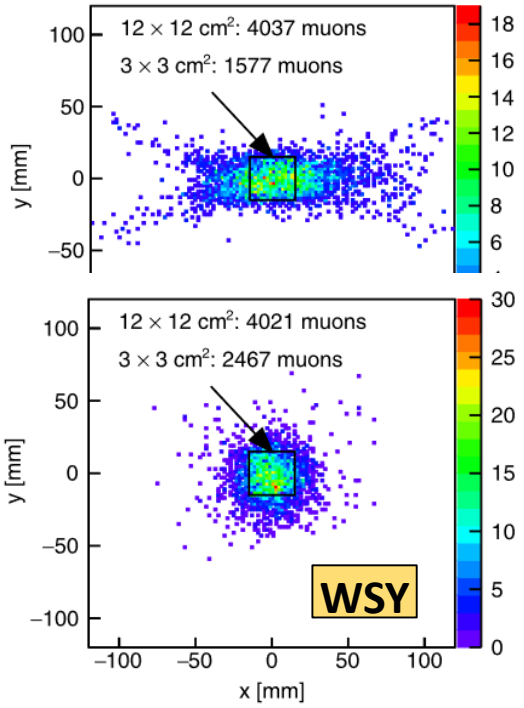




μE4 upgrade in 2026

- **Upgrade μE4 beamline to increase LEM rate by 50%:** smaller samples, higher external stimuli (illumination, electric fields), faster measurements, T_{min} = 100 mK (2.5 K now). Total costs: 250 kCHF.
- L. Zhou et al., Phys. Rev. AB 25, 051601 (2022), **minimum fringe fields in LEM**





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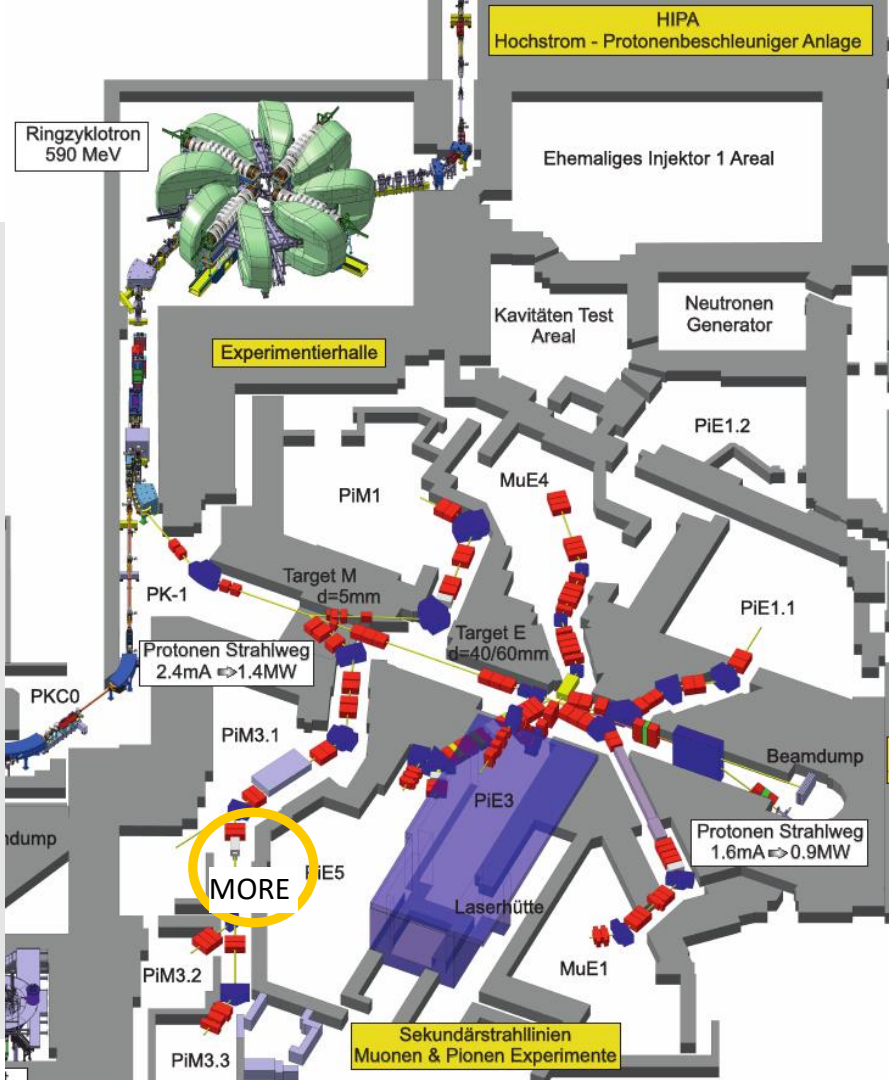
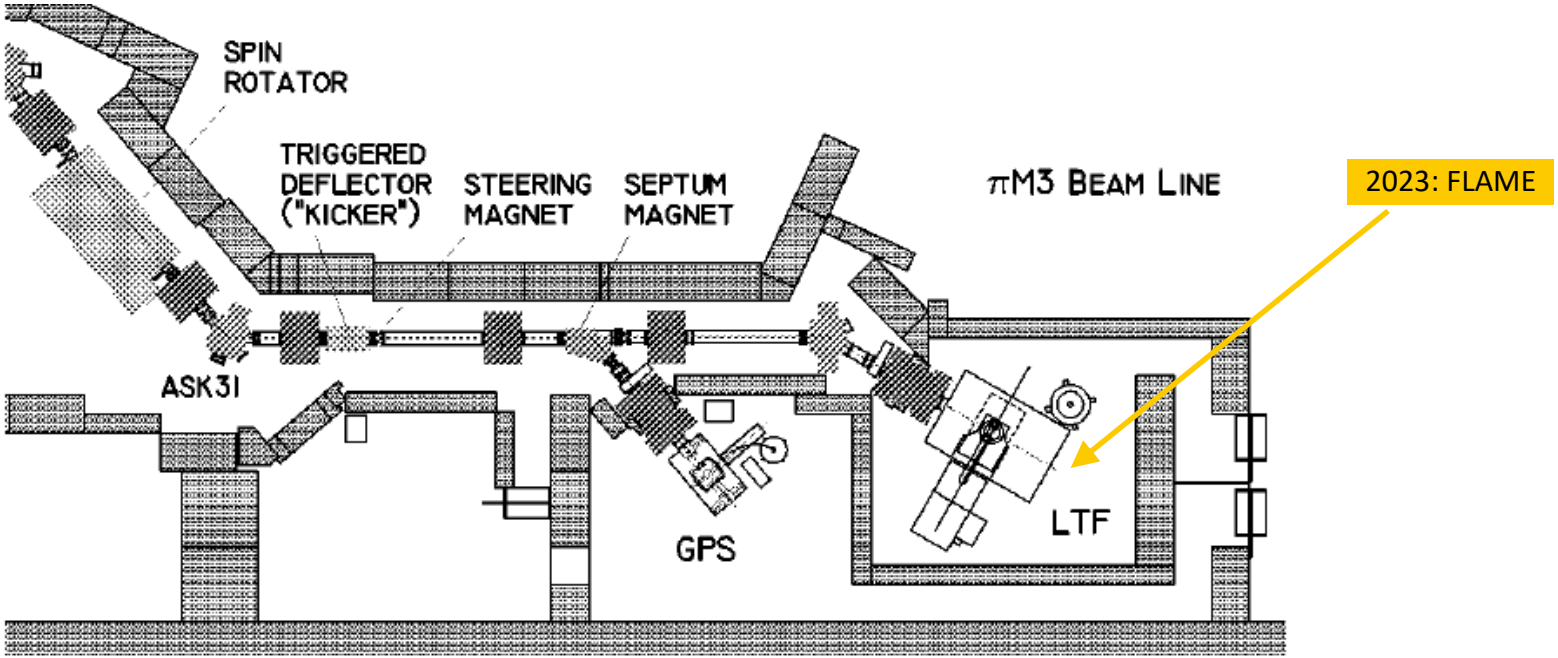
Experimental hall



Muons-On-REquest (MORE) in πM3

- **Fast HV-kicker broken in 2015**
- New fast kicker design finished in 2022, commissioning planned for 2024
- MORE combines the advantages of continuous (high time resolution) and pulsed beams (low background)



R. Abela et al., Hyp. Int. 120/121, 575 (1999)

Muons-On-REquest (MORE) in πM3

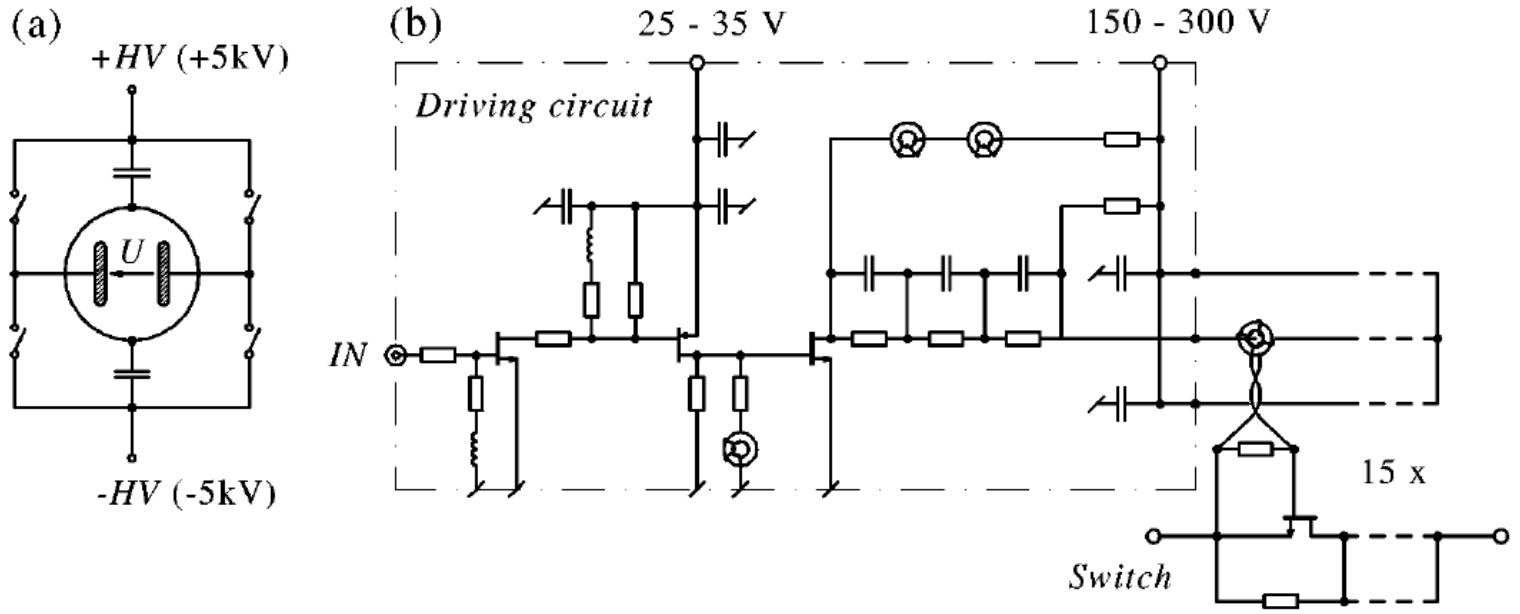


Figure 2. (a) Schematic circuit of the fast-switching deflector ("kicker") for muons on request. Power per switch ⩽600 VA, repetition rate ⩽40 kHz, voltage $|U| \leqslant 10$ kV between electrodes, switching time: <25 ns (10–90%). (b) Driving circuit for one switch. Delay between trigger signal input and high-voltage output ∼40 ns.

R. Abela et al., Hyp. Int. 120/121, 575 (1999)

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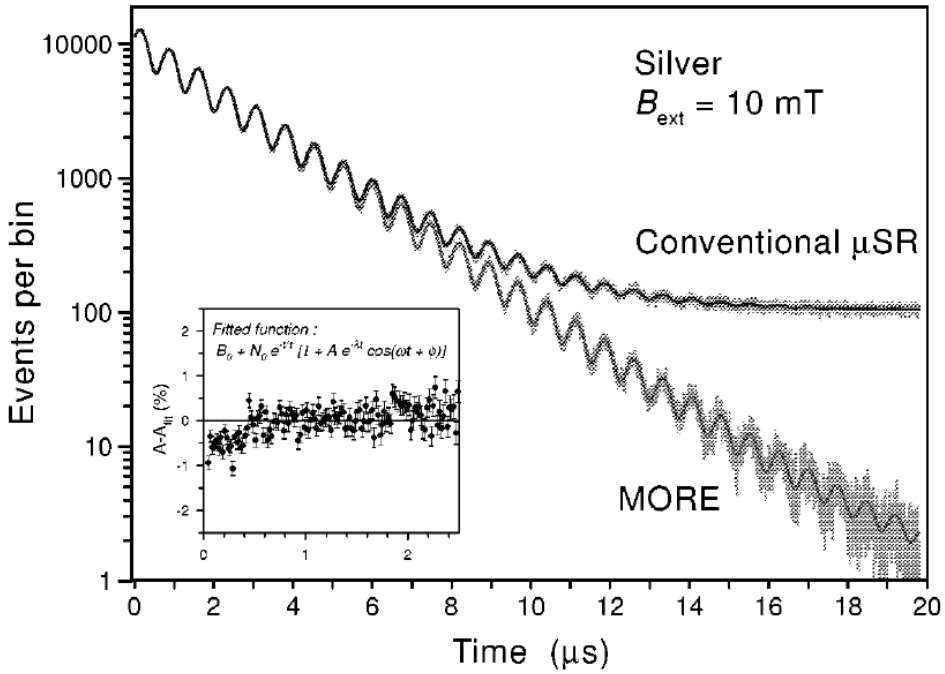

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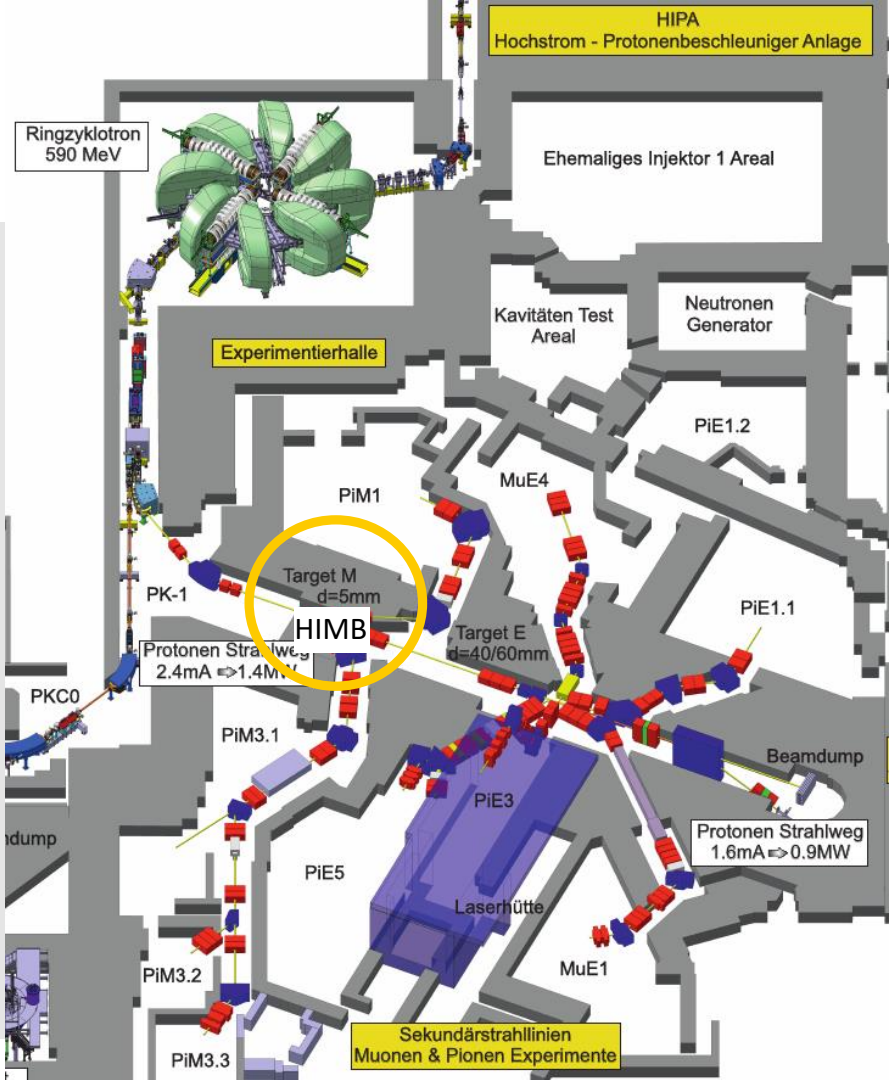


IMPACT – a major upgrade proposal for HIPA

Current limitations of μSR at PSI:

- Maximum rate 40k muons/s
- Sample area > 4x4 mm^2
- Thickness > ~200 μm, < 200 nm

Vertex Reconstruction

- Novel small samples
- Multi samples in parallel
- >10x faster measurements
- 10x higher pressure/strain

High Rate

- Extend muon range to 200 nm – 200 μm ("sub-surface muons")
- 10x more low energy muons for thin-film and device applications (< 200 nm)
- Elemental analysis tomography (mm sized objects)

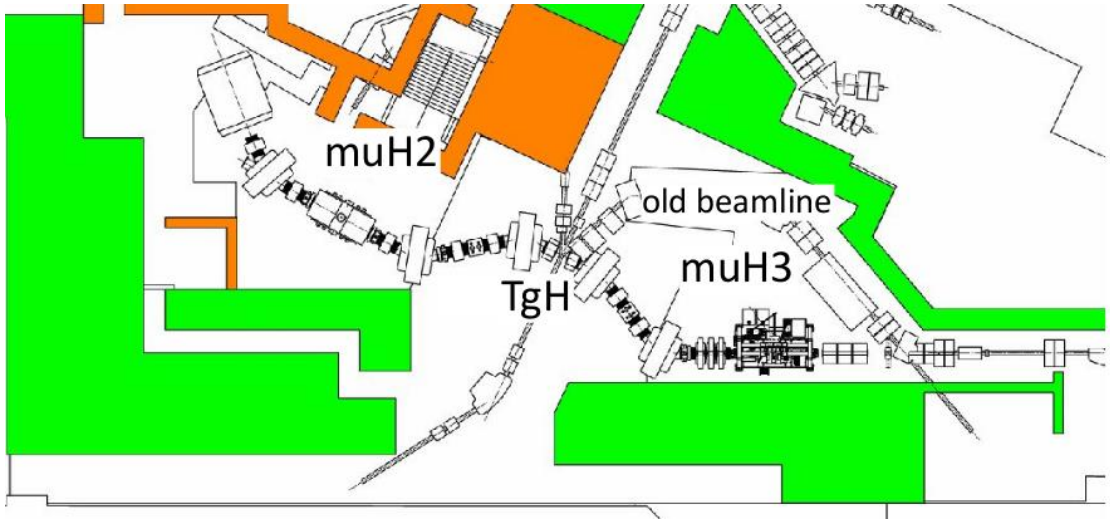
Pulsed beam

- Pump-probe measurements
- Multiple stations in parallel
- Semi-integral measurements

Science case: https://arxiv.org/abs/2111.05788

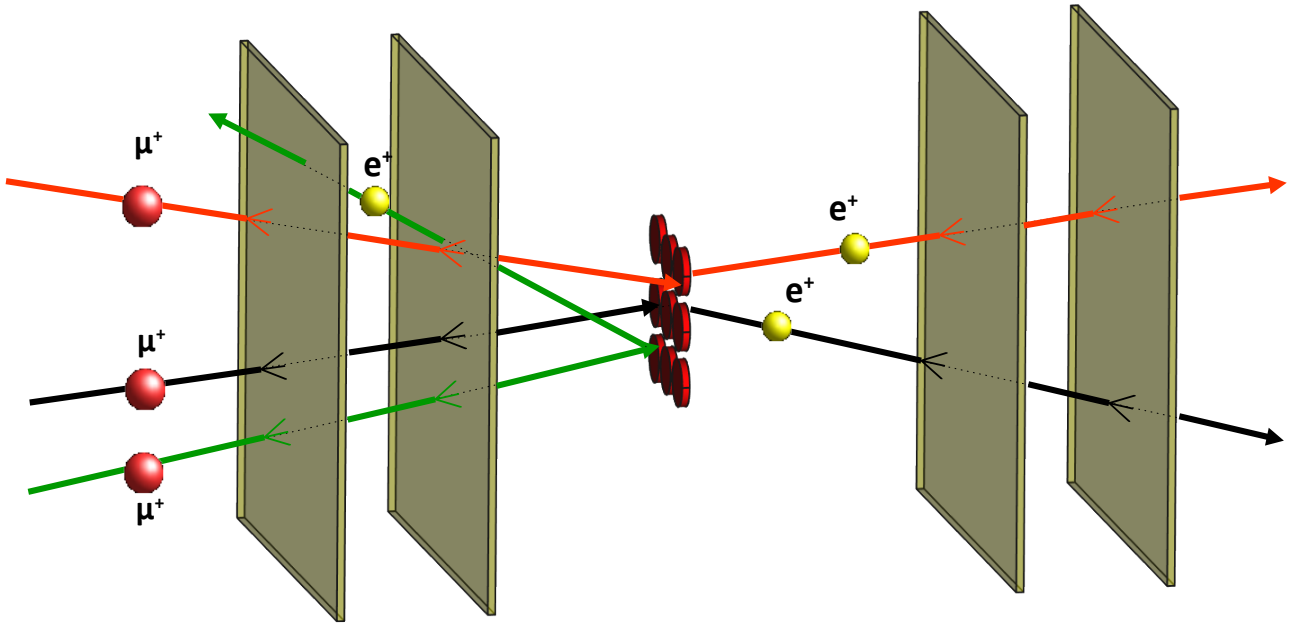
IMPACT – a major upgrade proposal for HIPA

- Vertex reconstruction with ≤1 mm resolution to fully exploit the >20 times higher beam intensities made available by HIMB (**in collaboration with U Heidelberg, U Mainz, LTP and U Zurich**).
- **A «game changer» for μSR! (HIMB Science Case: https://arxiv.org/abs/2111.05788)**



10^8 μ^+/s → **GPS + FLAME**

Vertex reconstruction using Si pixel detectors



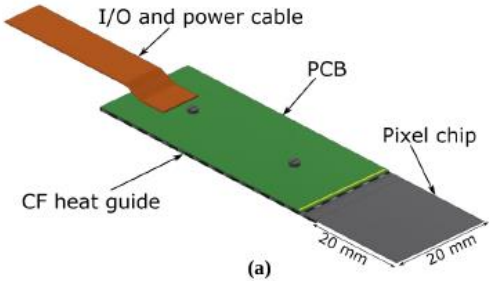
Vertex reconstruction using Si pixel detectors

Benefits of pixel detectors at continuous muon beams:

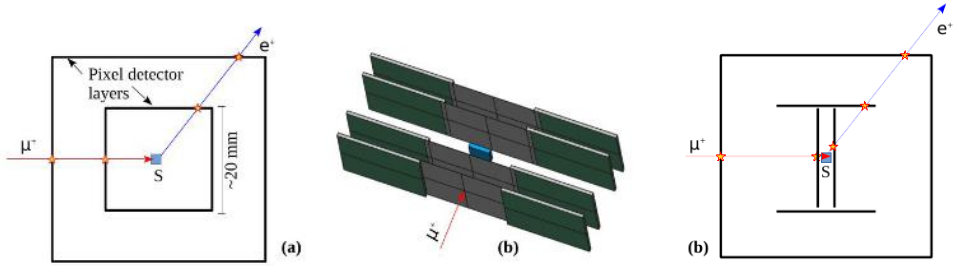
- overcome rate limitation, increase rate by > 1 order of magnitude
- overcome sample size limitation: < 1x1 mm^2 instead of > 4x4 mm^2, measurement of multiple samples simultaneously, 10 – 100 times faster experiments
- reduction of uncorrelated background by tagging and tracking μ's

Prototype from Mu3e experiment, U Mainz, U Heidelberg, LTP

SNSF project approved in 3/2023: Zaher Salman
In collaboration with U Zurich and LTP, Lea Caminada

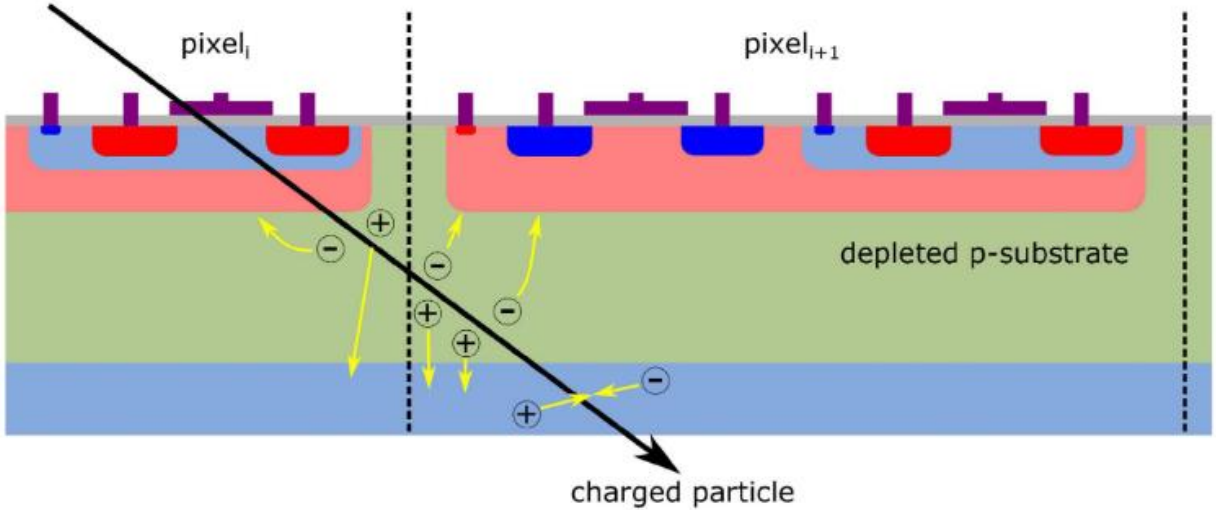


Schematic for a μSR spectrometer using thin Si pixel sensors



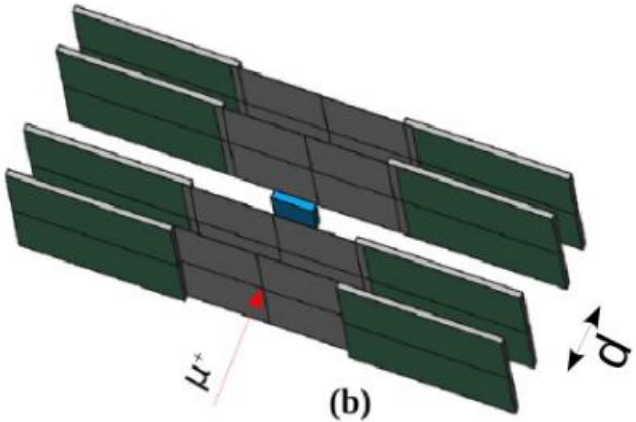
MuPix11

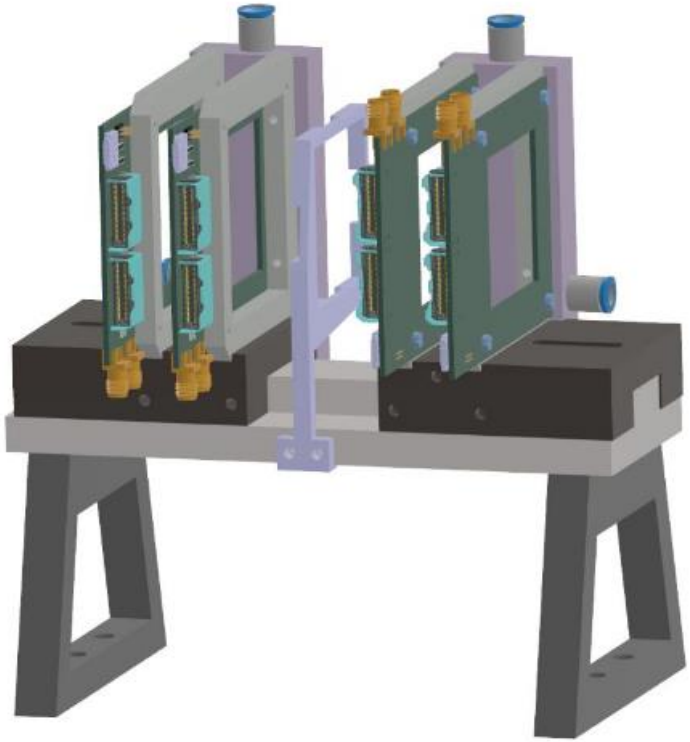
- HV-MAPS (high-voltage monolithic active pixel sensor)
  - 180 nm HV-CMOS process
  - digital readout fully integrated
  - charges in silicon collected fast via drift



2023 prototype

- 4x ultra-thin detection ladders
- 50 µm thin silicon chip on Kapton foil
- variable distance between inner layers

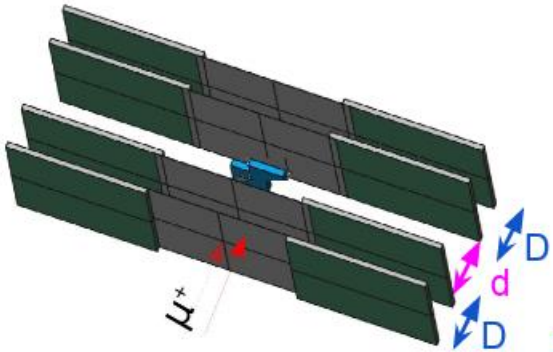




Simulations (musrSim/Geant4)

Spatial resolution

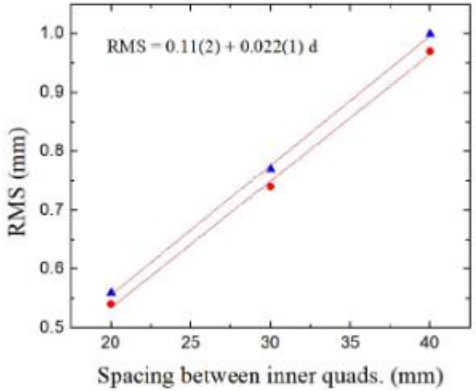
- distance between layers



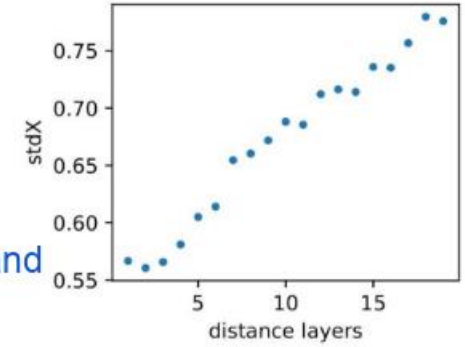
Props to Zaher Salman & Marius Köppel

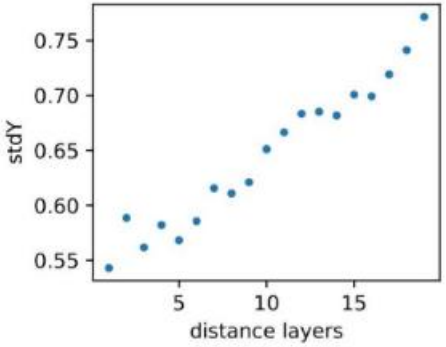
Distance d:
between inner layers

d/2 = sample to pixel distance



Distance D:
between outer and inner layers





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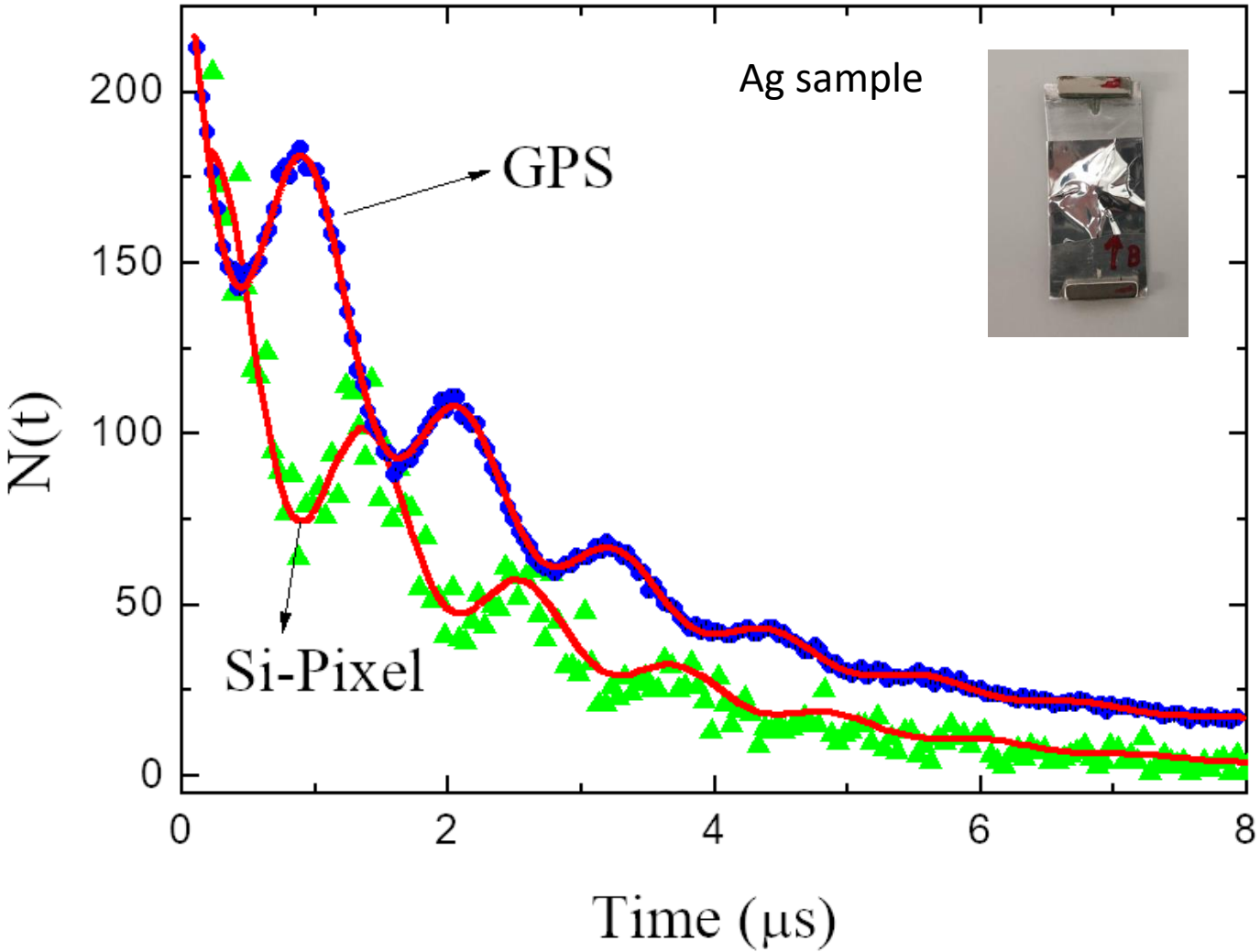
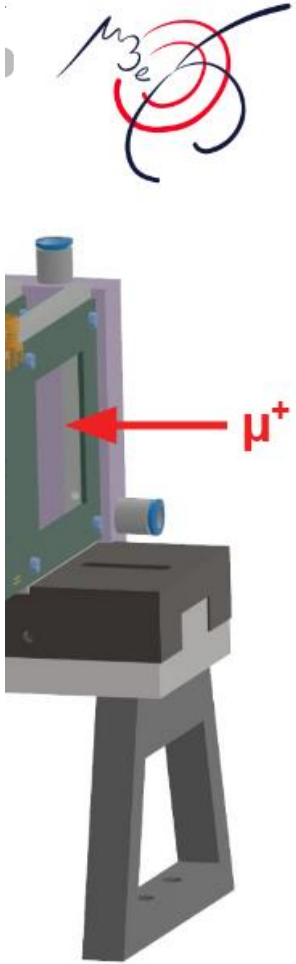




μSR pixel team

External:

- Marius Köppel (Mainz)
  - PhD student in the Mu3e group
  - Firm- and software, simulations, data taking and analysis
- Lukas Mandok (Heidelberg)
  - Master student
  - PCB design, data taking and analysis
- Thomas Rudzki (Heidelberg @PSI)
  - Postdoc in the Mu3e group
  - Module construction, data taking and analysis
- Heiko Augustin (Heidelberg)
  - Postdoc in the Mu3e group
  - Sensor development and characterisation

PSI:

- Zaher Salman
  - Research scientist, LEM group
  - Conceptual design, simulations, data taking and analysis
- Thomas Prokscha
  - LMU head
- Hubertus Luetkens
  - Bulk μSR head
  - muon beam setup
- Lea Caminada
  - LTP high energy group leader
- Hans-Christian Kästli
  - senior scientist
  - development ultra-fast pixel detectors
- Tilman Rohe
  - senior scientist

Wir schaffen Wissen – heute für morgen

Thank you for your attention!

Thank you Cong Chen and Thomas Rudzki for providing slides!

Pileup at continuous muon beams

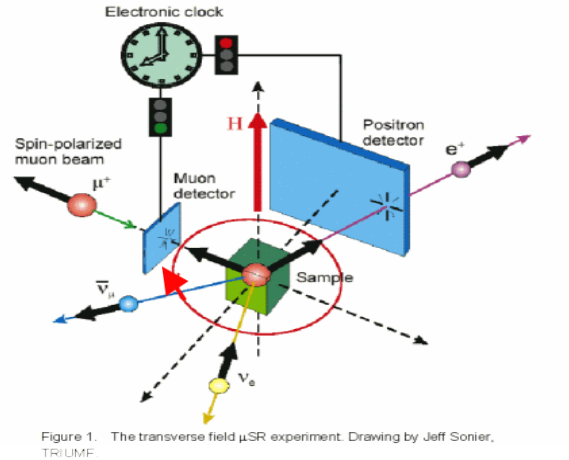
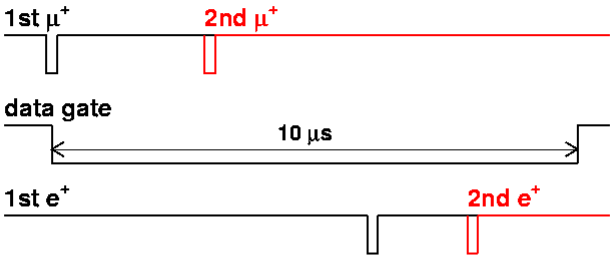


Figure 1. The transverse field μSR experiment. Drawing by Jeff Sonier, TRIUMF



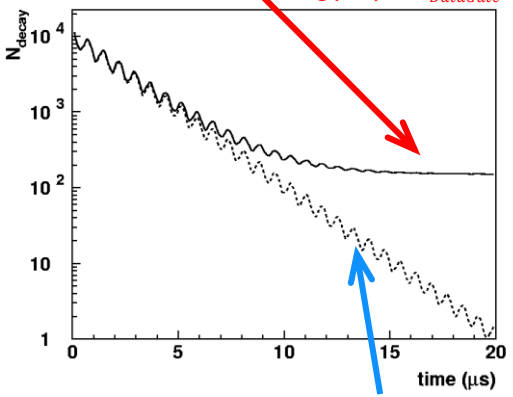
1st μ^+: there was no other μ^+ for at least 10μs in the past

Good Event = (data gate) • (1st e^+) • (no 2nd μ^+) • (no 2nd e^+)

$R_{acc} = R_\mu \times \exp(-2\Delta t\, R_\mu)$, $\Delta t = 10$ μs

background due to uncorrelated detector hits

$\mathrm{bkg(bin)} \cong N_{DataGate} * tbin * R_{e+}$



Low background at a pulsed beam