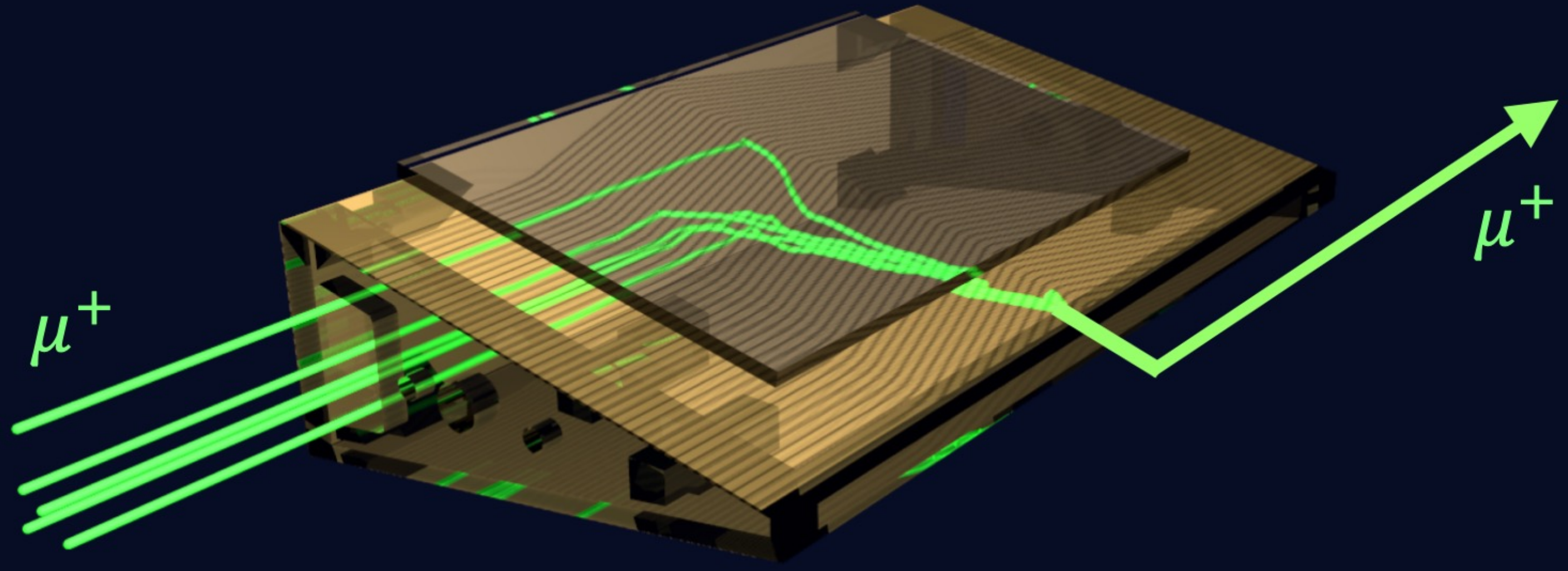


muCool: A novel low-energy muon beam for precision experiments

Giuseppe Lospalluto (ETH Zürich)

On the behalf of the muCool collaboration

CHIPP Winter School of Particle Physics

15–20 Jan 2023

Muon beamline at PSI

- High intensity positive muon beam (4.1 MeV) at the Paul Scherrer Institut (PSI)

$$p + p \rightarrow \pi^+ \ldots \rightarrow \mu^+ \ldots$$

(beam) (target)

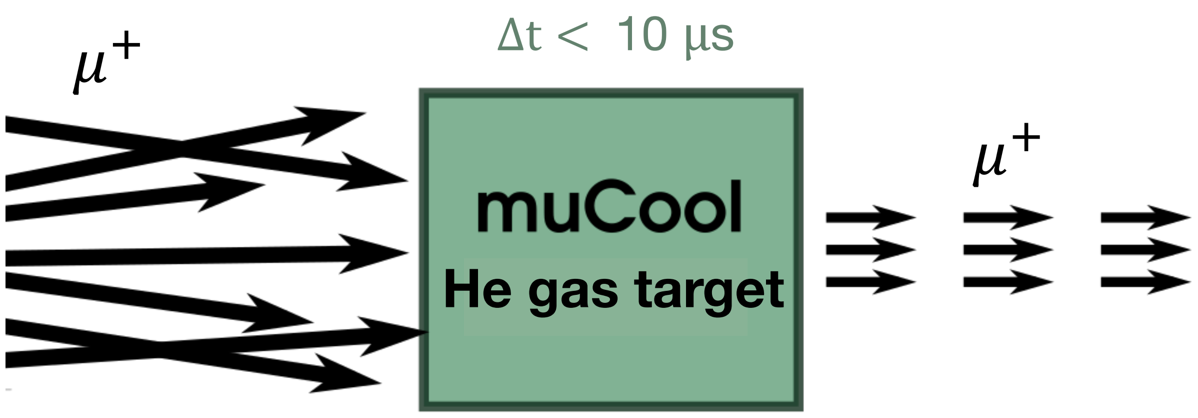
- What for?
  e.g. Rare muon decay searches ($\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^-e^+$)

High “rate”, poor “quality”

- How can we cool a muon beam? (τ_μ = 2.2 μs)

muCool : “fast” phase space compression

E ~ 4 MeV
cm-size
MeV-energy spread



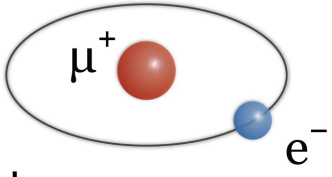
E ~ eV
sub mm-size

Re-acceleration

- Efficiency of $\sim 10^{-4}$
- Phase space improved by $> 10^8$

keV energies

- Muonium spectroscopy, muonium gravity experiments



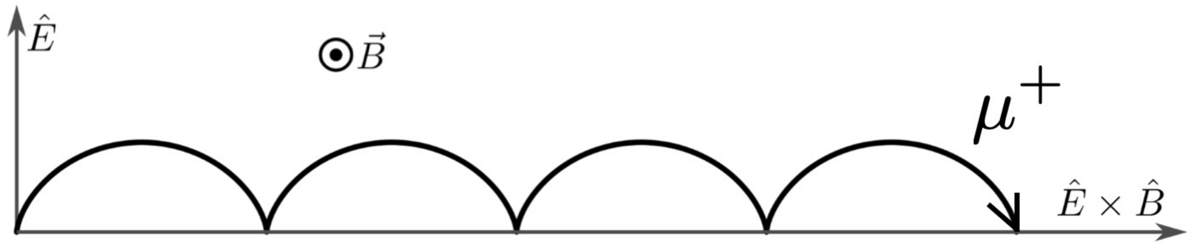
- Material Science (μSR)

MeV energies

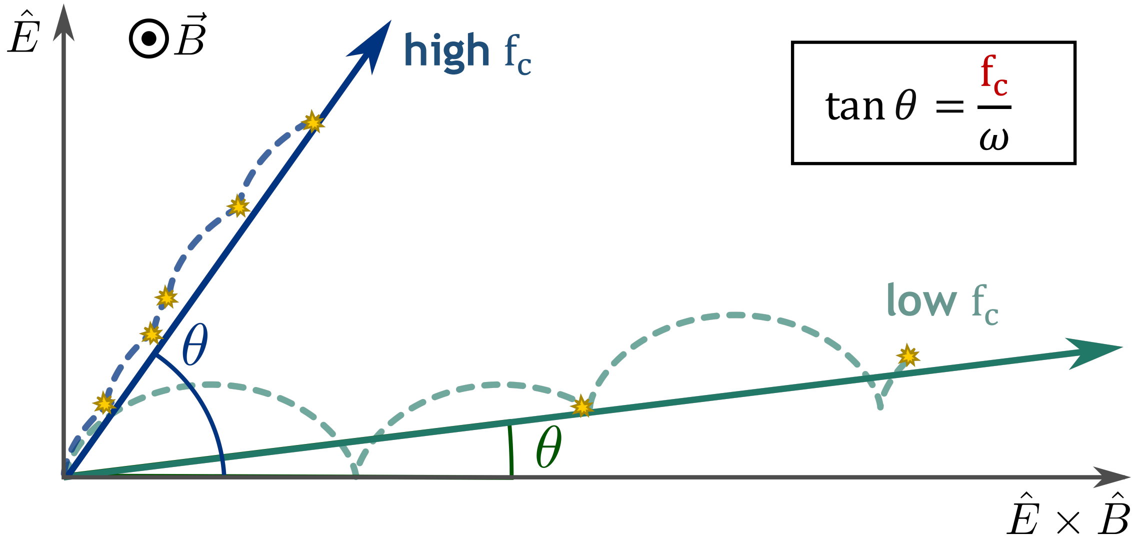
- Muon EDM with storage ring

D. Taqqu. *Phys. Rev. Lett.* 97.194801 **(2006)**

Muon drift in crossed E and B-fields



In vacuum

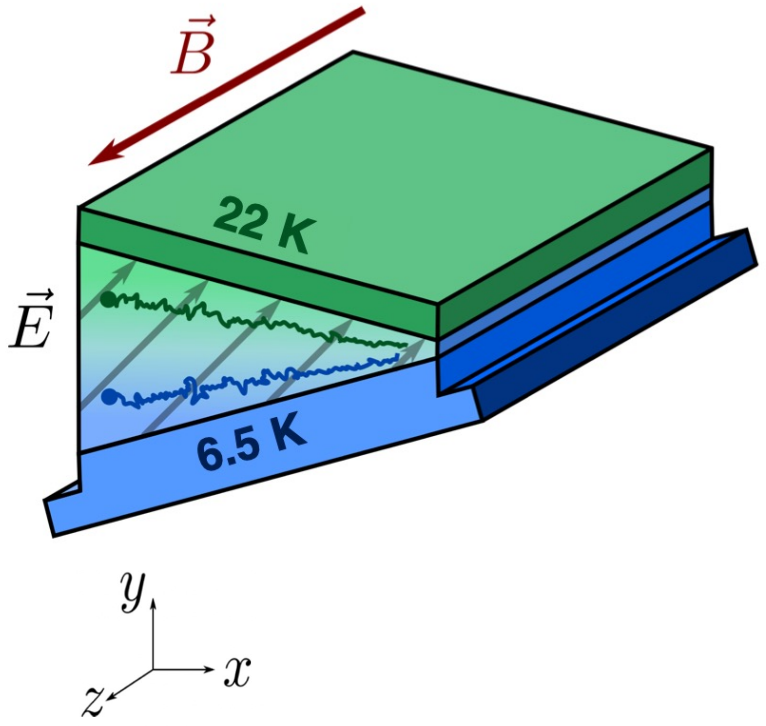


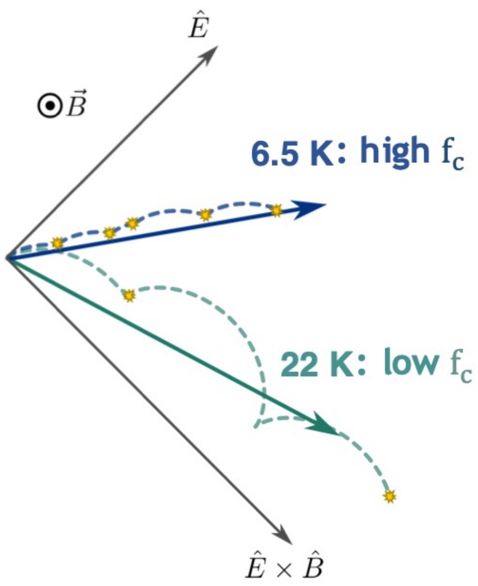
In gas

Collision with gas atoms at frequency f_c

muCool principle

Transverse Compression

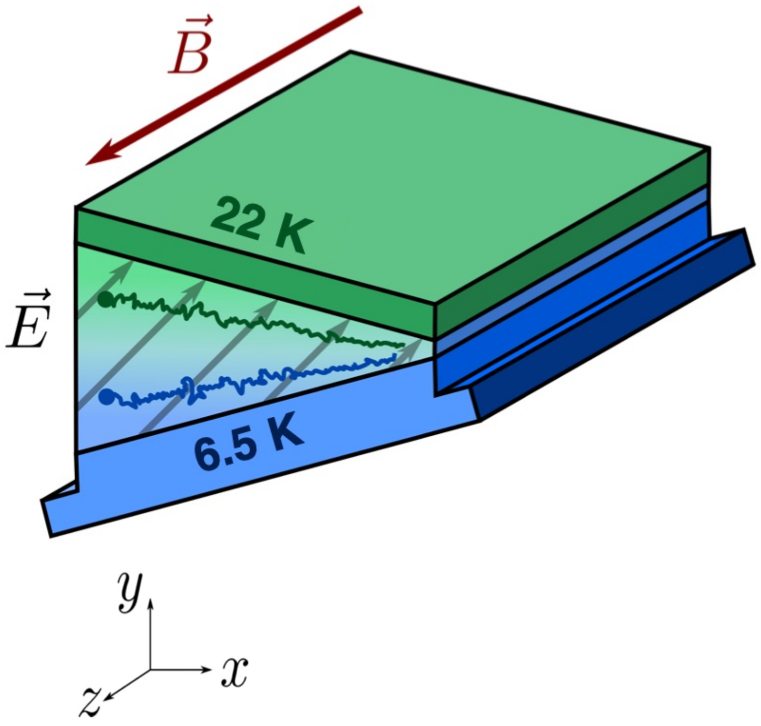




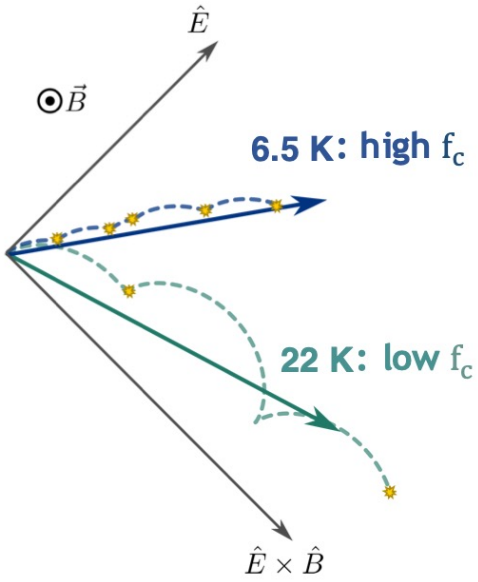
A. Antognini et al. *Phys. Rev. Lett.* 125.164802 **(2020)**

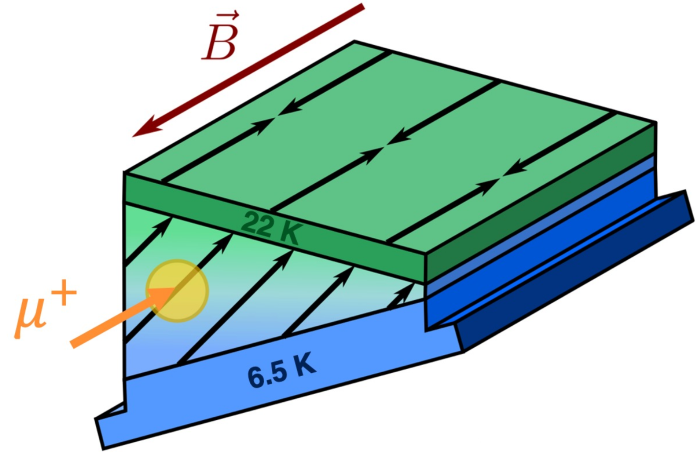
muCool principle

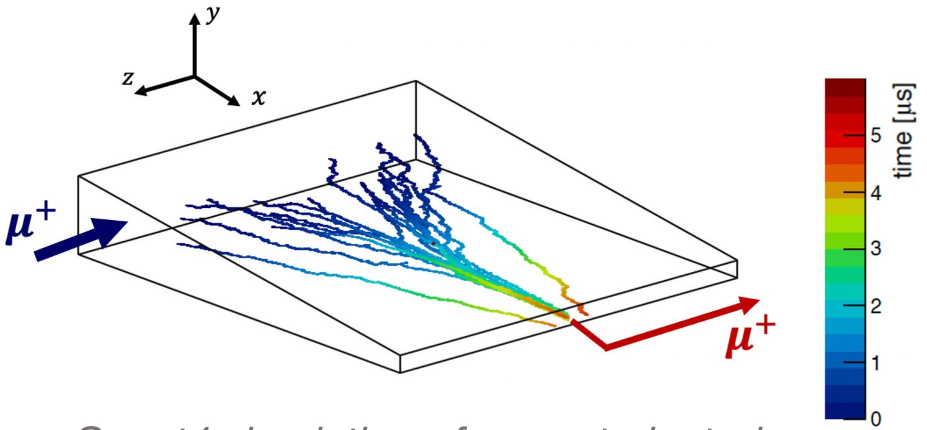
Transverse Compression **+** Longitudinal Compression **=** Mixed Compression



$f_c \propto$ gas density







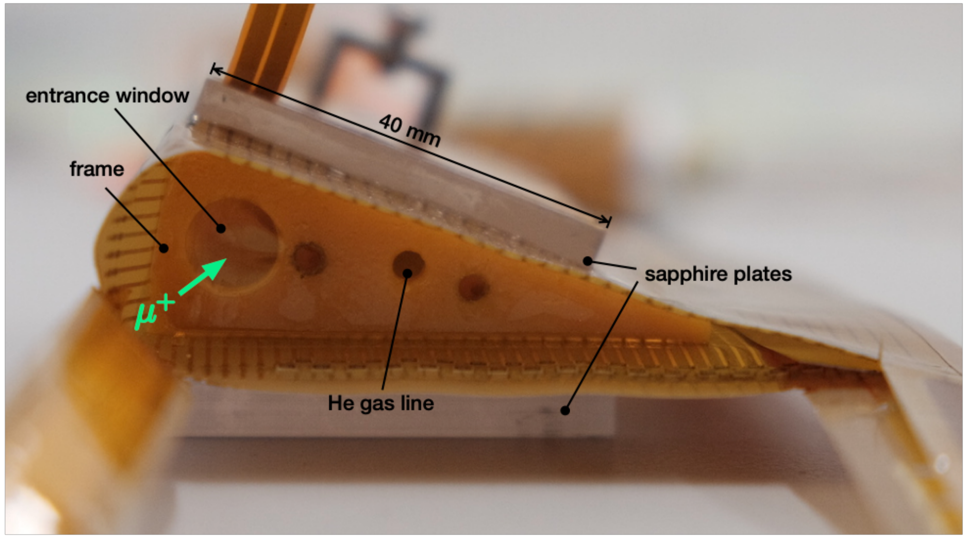
Geant4 simulation of muon trajectories

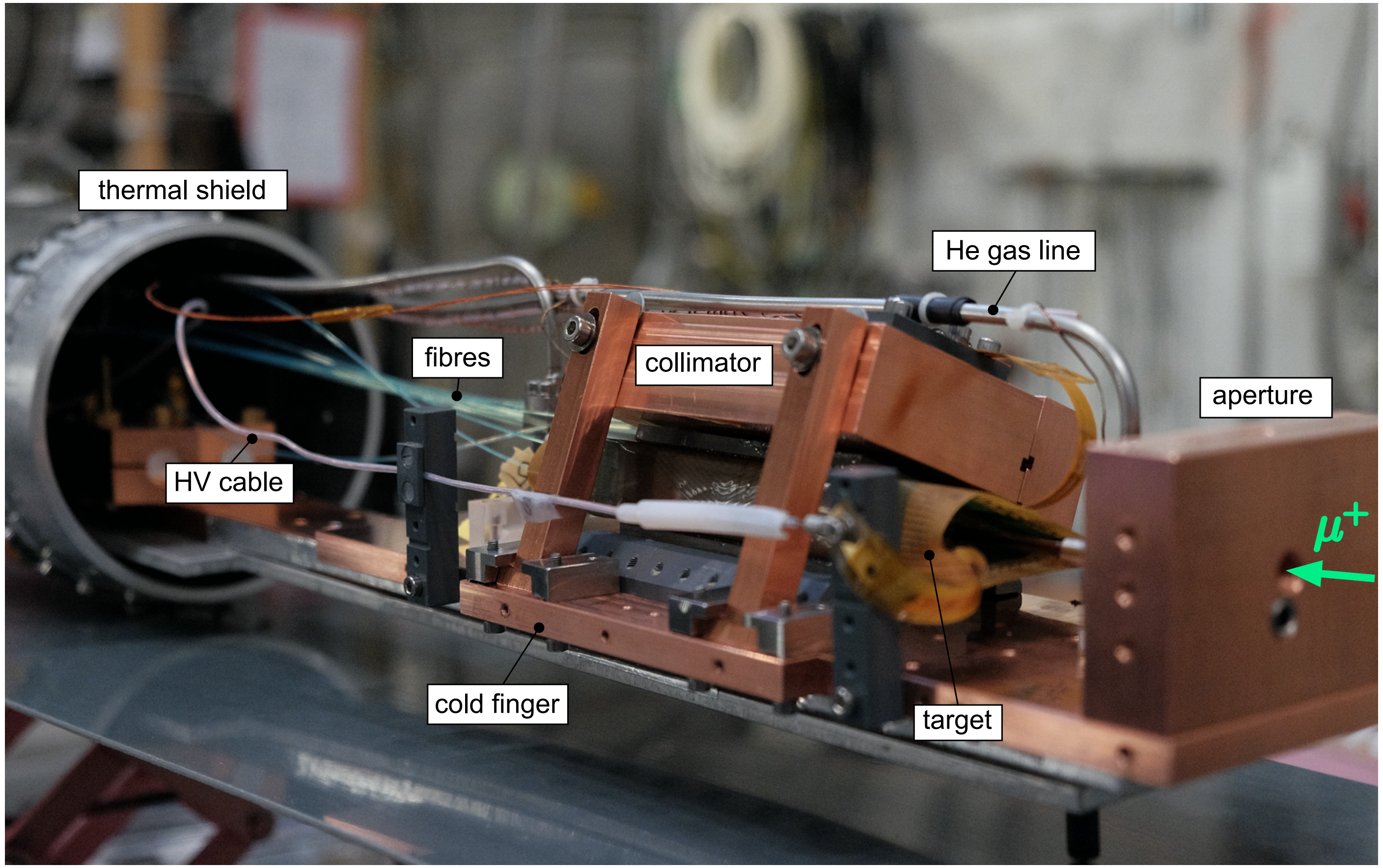
A. Antognini et al. *Phys. Rev. Lett.* 125.164802 **(2020)**

Experiment

muCool target realisation:

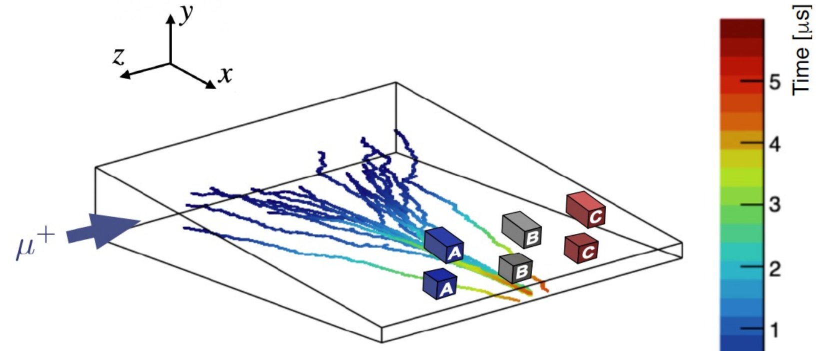
- Lined Kapton-foil → Electric field for mixed compression
- Sapphire plates → Vertical density gradient



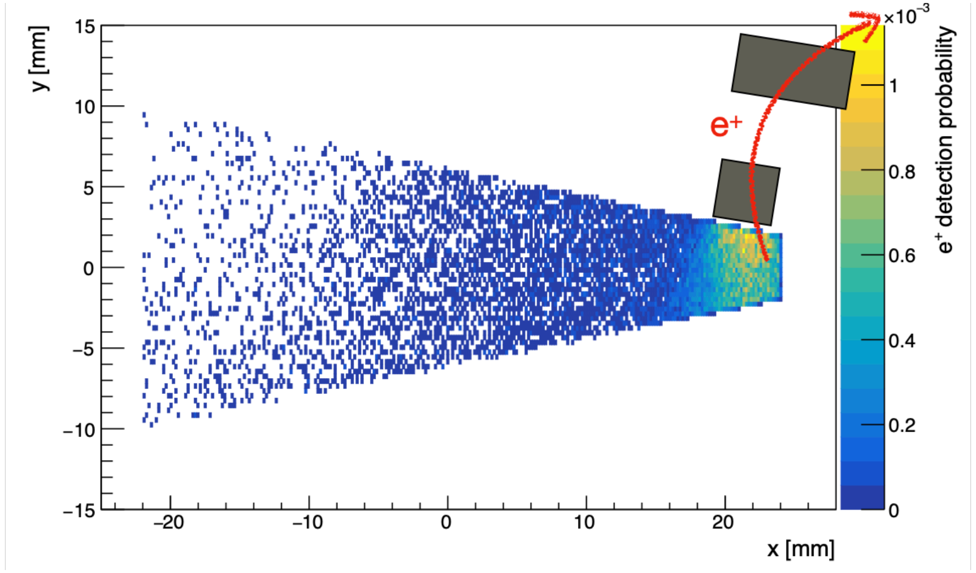


Test of mixed compression

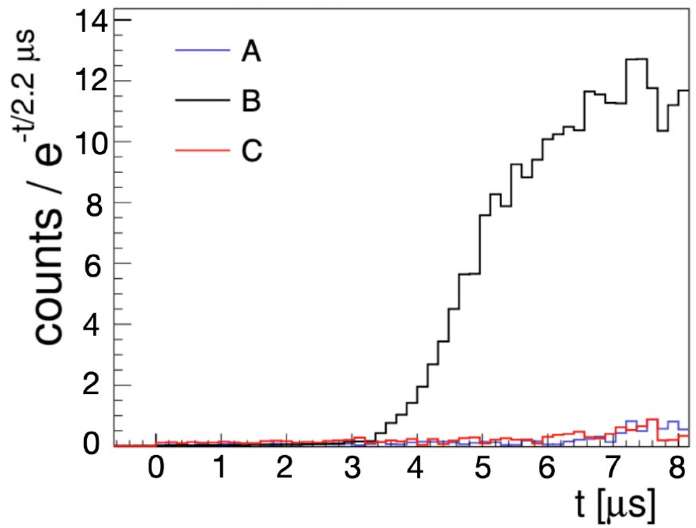
- PSI πE1 beamline (tuned to p ~15 MeV/c)
- "*Indirectly*" measure muon position by detecting decay positrons
- t = 0 given by entrance counter
- Large increase of counts: all muons reached target tip



Scintillator detectors at target tip



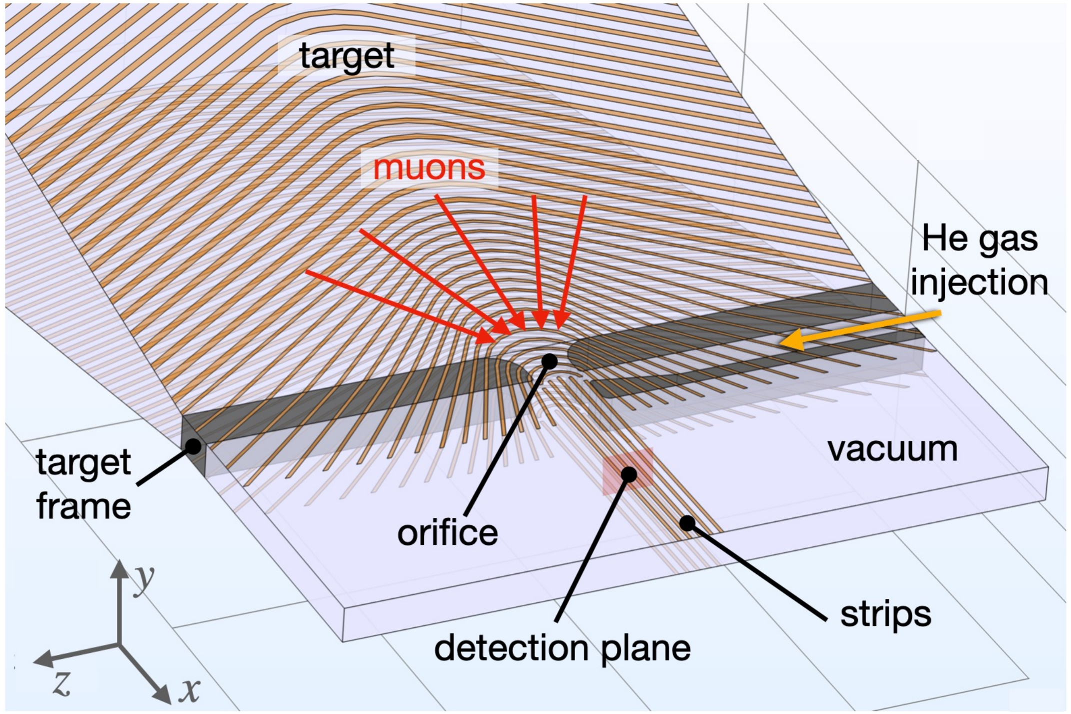
Detection simulation

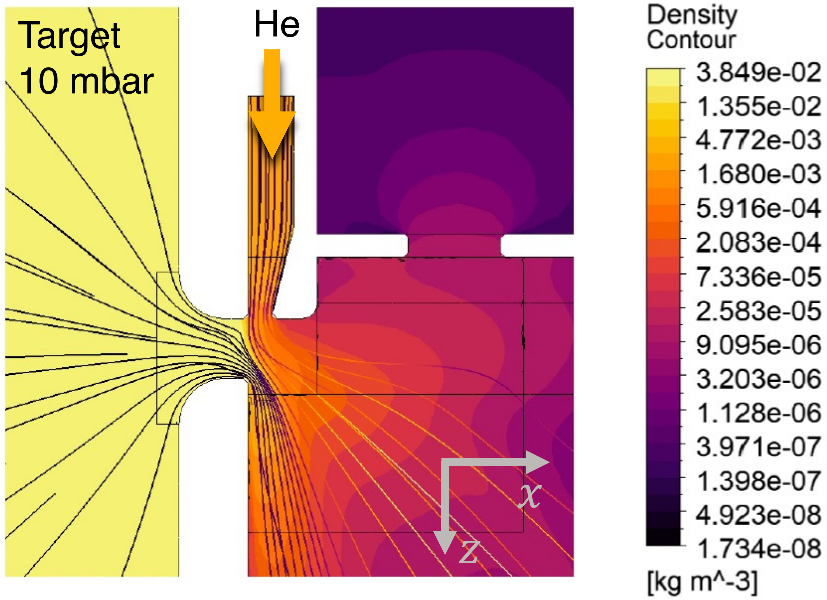


Measured time spectra (2019 beamtime)

Muon extraction from gas target into vacuum

- Make a hole (1x1.3 mm^2) at the tip of the target
- Extend electrode lines from the target terminating with pairs of parallel strips.
- Inject He at the orifice acting as a "gas barrier"





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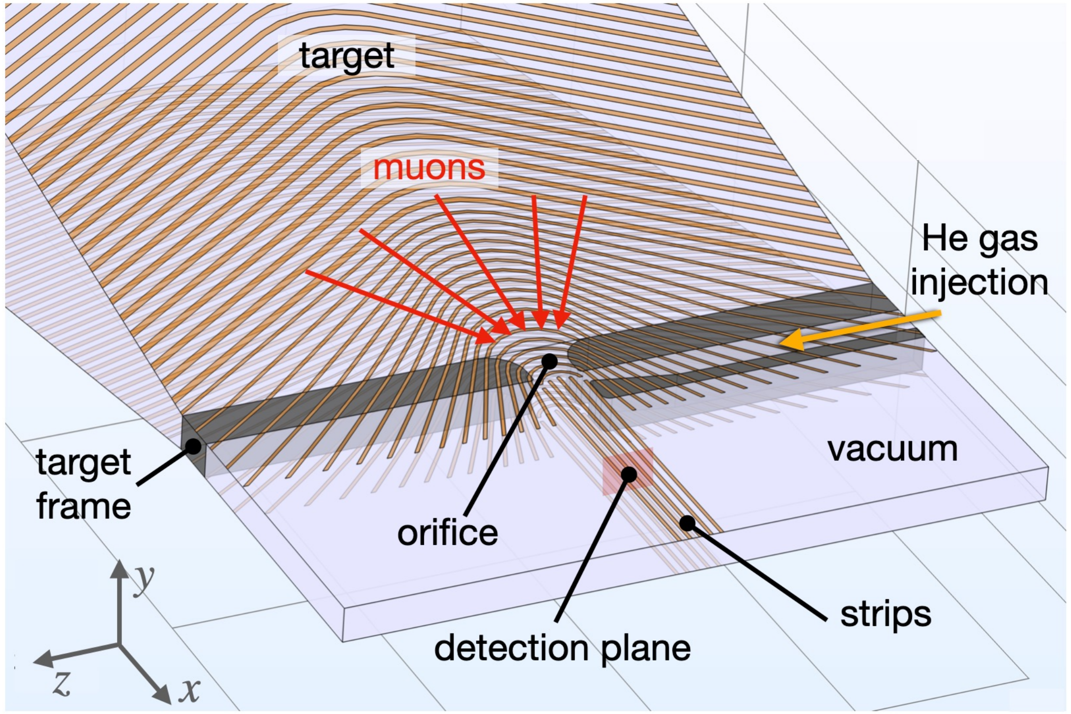

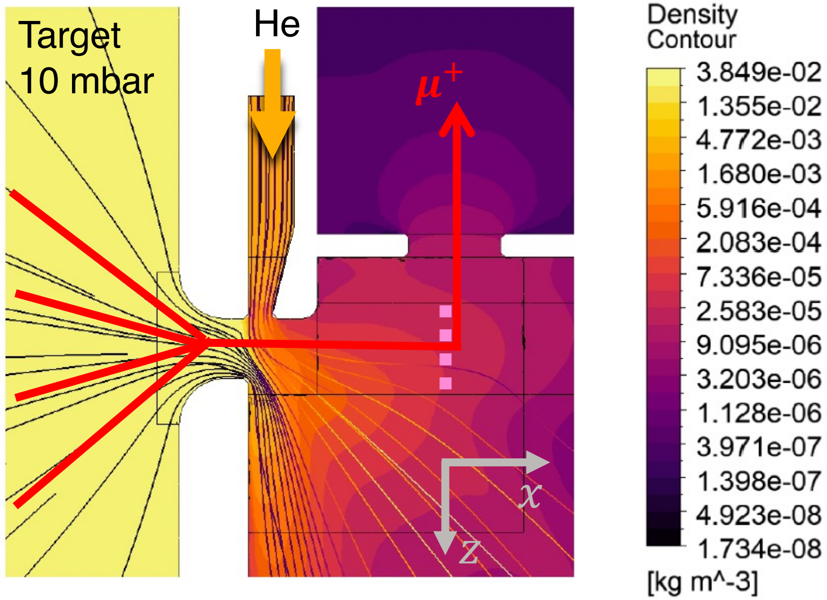

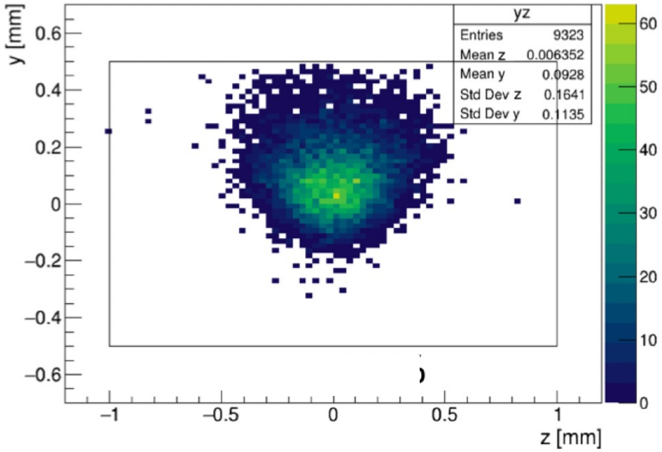

Beam profile (zy) at detection plane

~ 90 % transmission without muon decay

Summary

- We propose a “fast” phase space compression scheme for $\mu+$ beam for future low energy experiments
- This is achieved with complex E-fields and B-field in combination with a He gas density gradient
- **Mixed compression stage successfully tested!**
- Performed simulations of muon extraction into vacuum and re-acceleration: experimental tests begin now

Summary

- We propose a “fast” phase space compression scheme for μ+ beam for future low energy experiments
- This is achieved with complex E-fields and B-field in combination with a He gas density gradient
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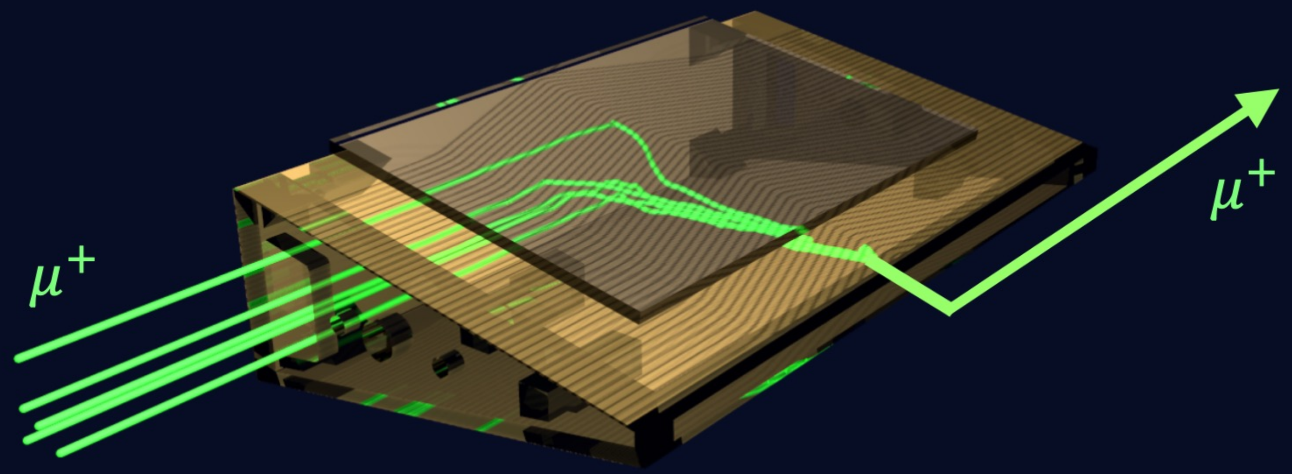
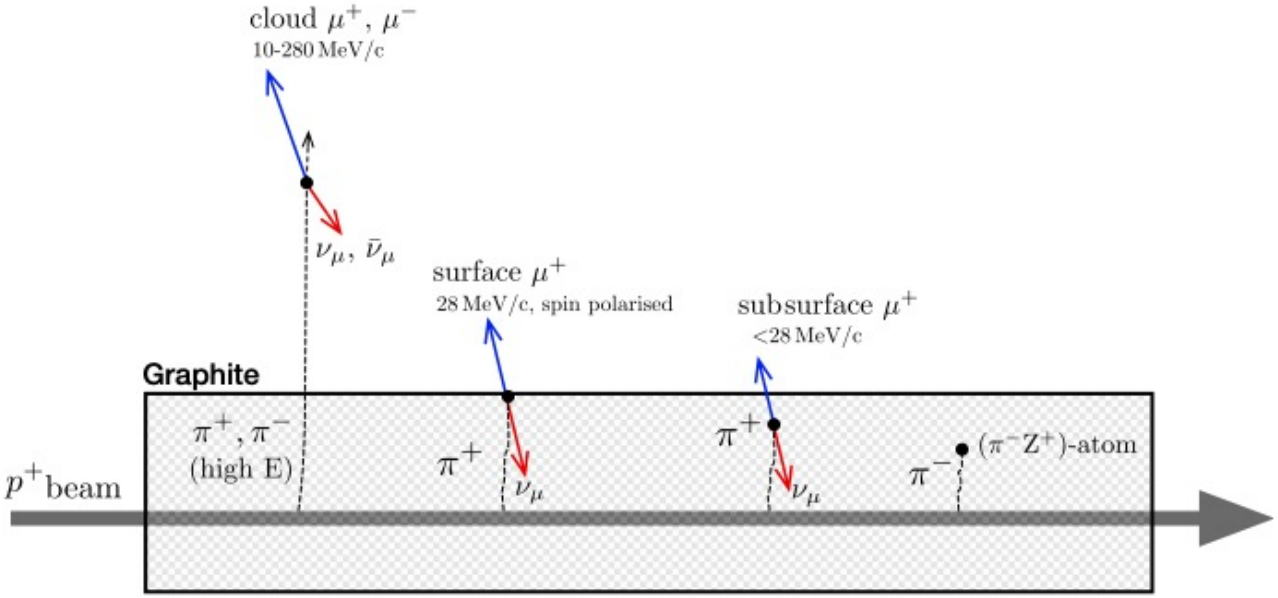
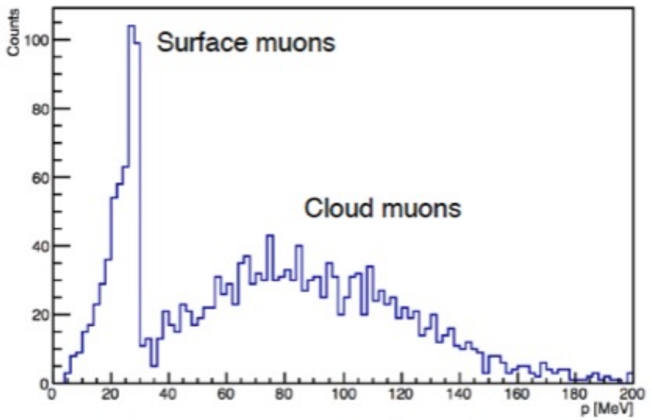


Thank you!

EXTRA SLIDES

Muon production

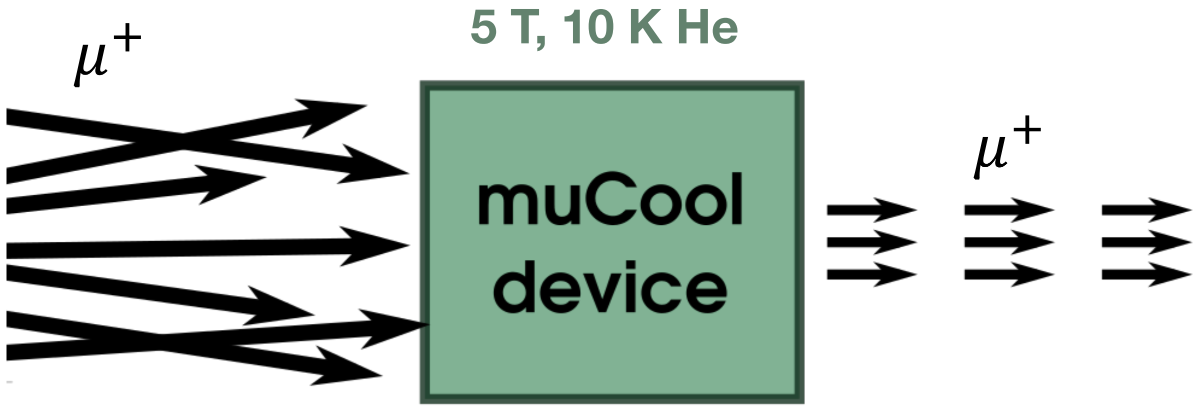




muCool : a phase space compressor

”Fast” compression scheme (within 10 μs)

E: 4 MeV
ΔE (FWHM): 800 keV
Diameter: 70 mm
Divergence: 200 mrad
cw beam



E: 10 keV
ΔE: 100 eV
Diameter: 10 mm
Divergence: 2 mrad

$$\sigma_x \sigma_{\theta_x} = 1910 \text{ mm mrad}$$

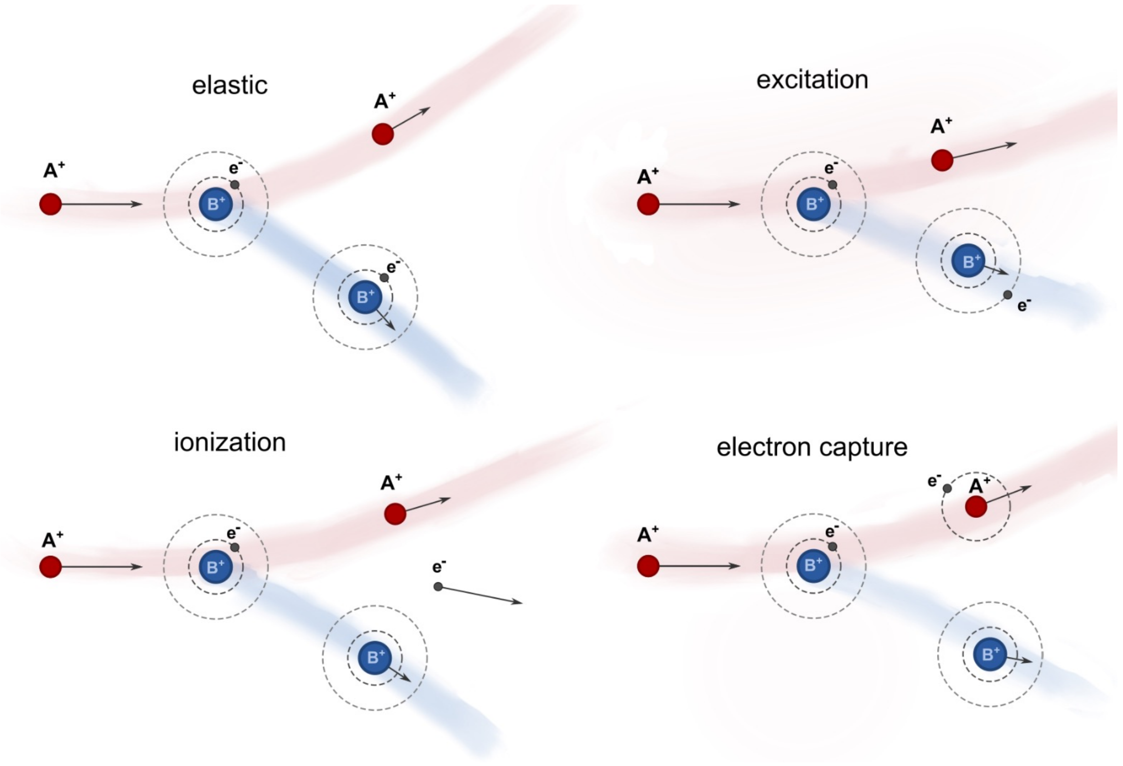
12.6% momentum bite.

$$\sigma_x \sigma_{\theta_x} \approx 20 \text{ mm mrad}$$

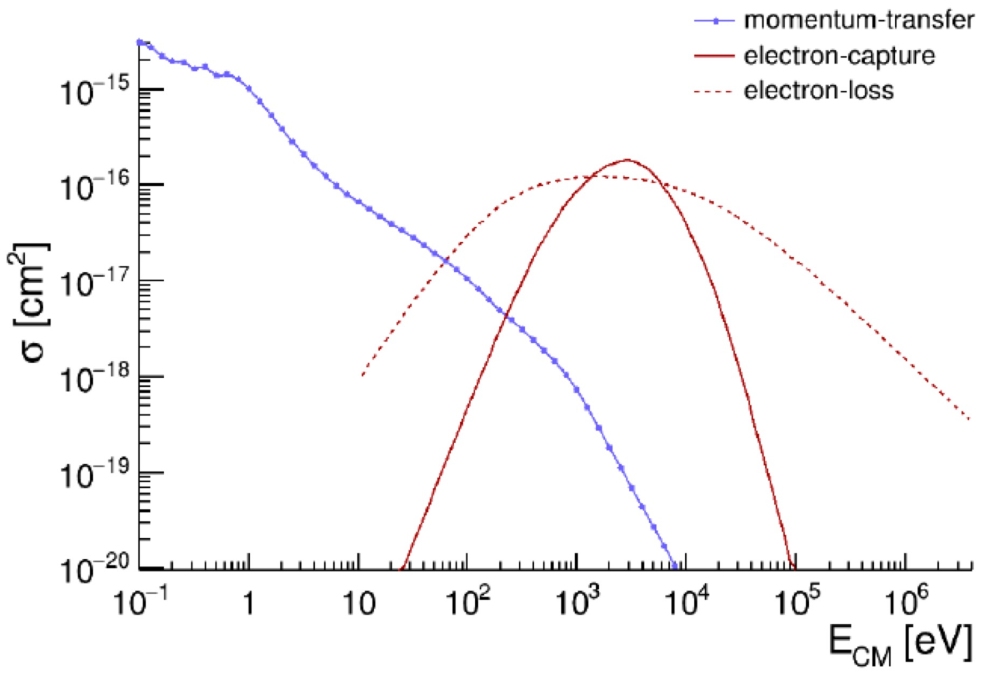
- Efficiency of 10^{-4} - 10^{-5}
- Phase space improved by 10^{9} - 10^{8}

D. Taqqu. *Phys. Rev. Lett.* 97.194801 **(2006)**

Muon-helium collisions

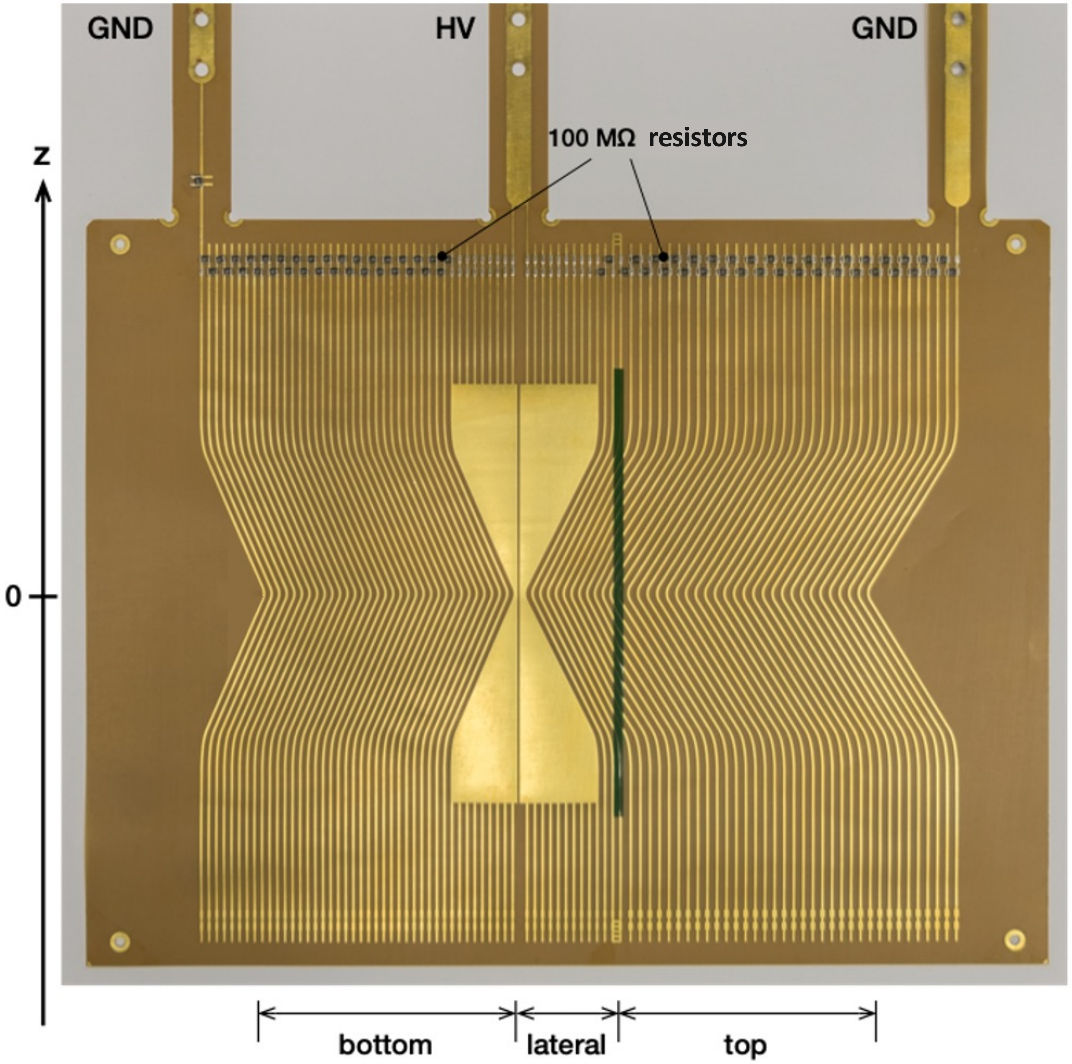


- ➢ collision type depends on muon energy
- ➢ consequences of the collisions: *energy loss, direction change*



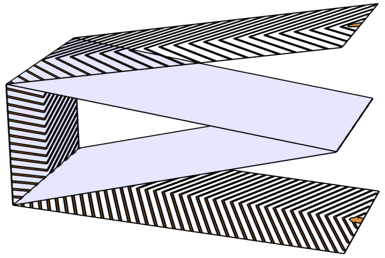
Target realisation

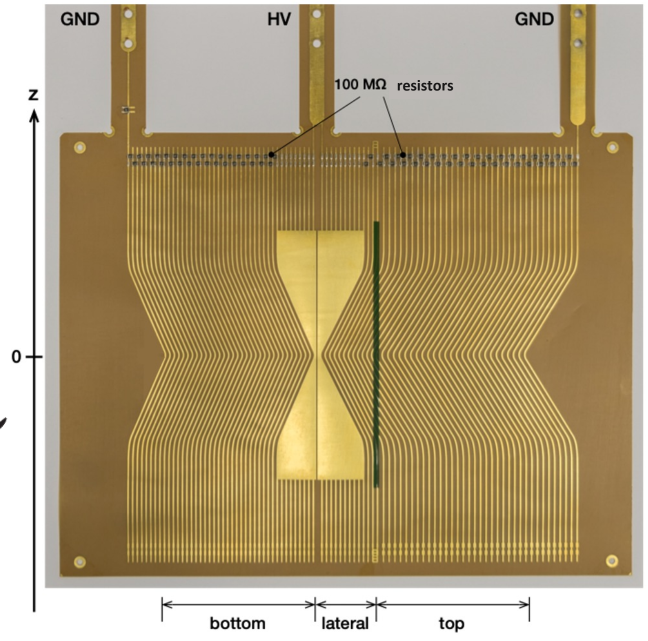
- Lined Kapton-foil: Electric field for mixed compression

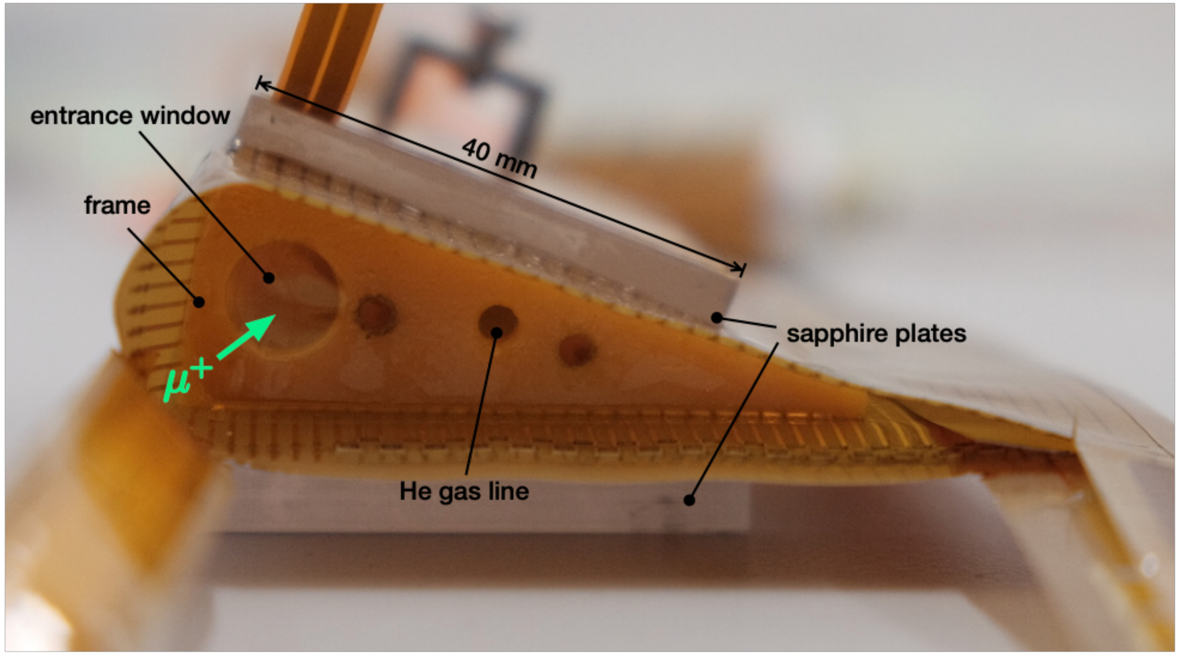


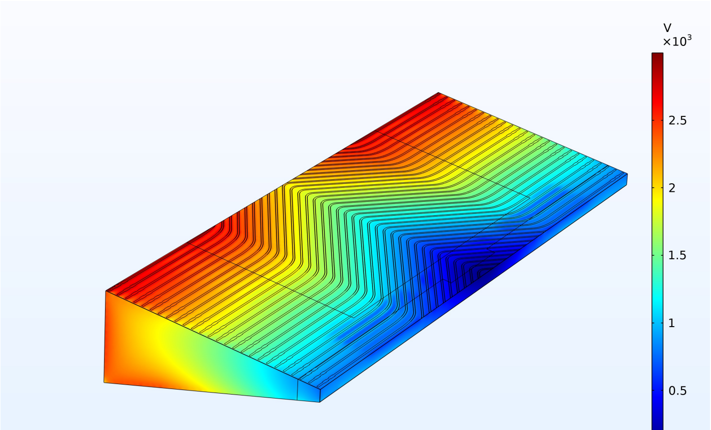
Target realisation

- Lined Kapton-foil: Electric field for mixed compression
- Sapphire plates: Vertical density gradient



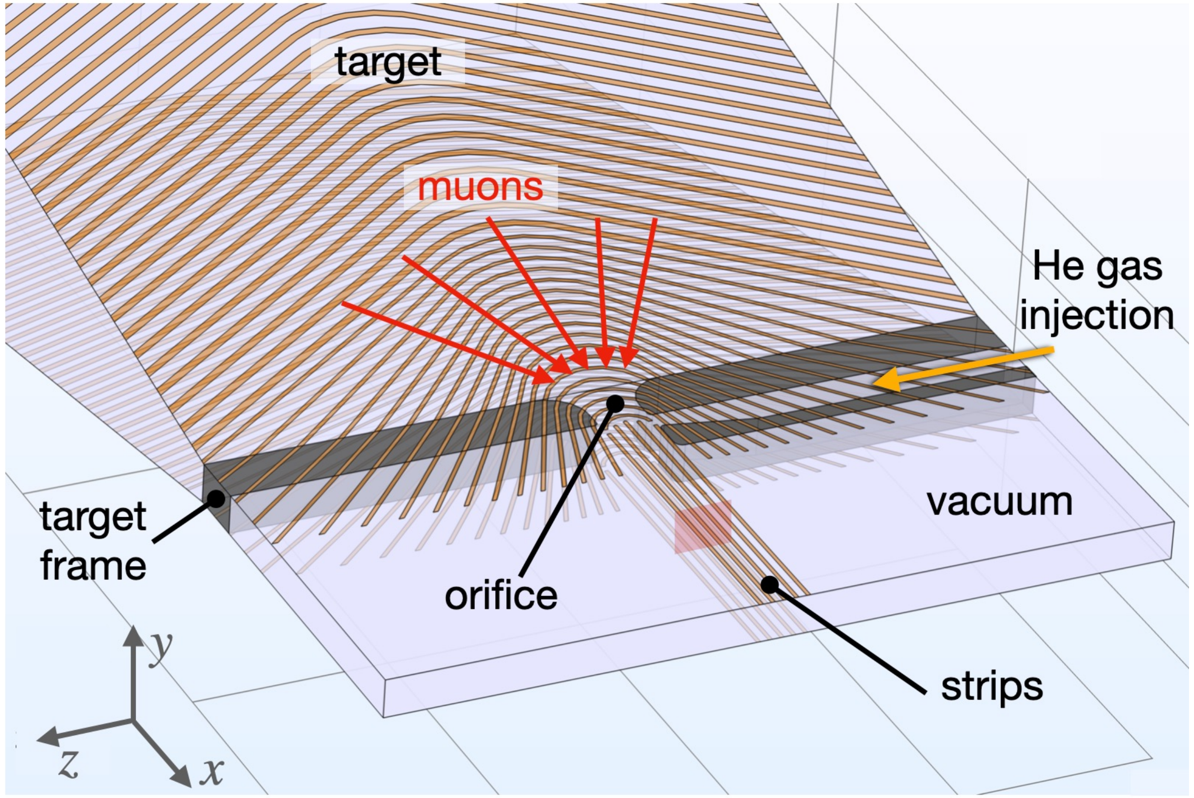


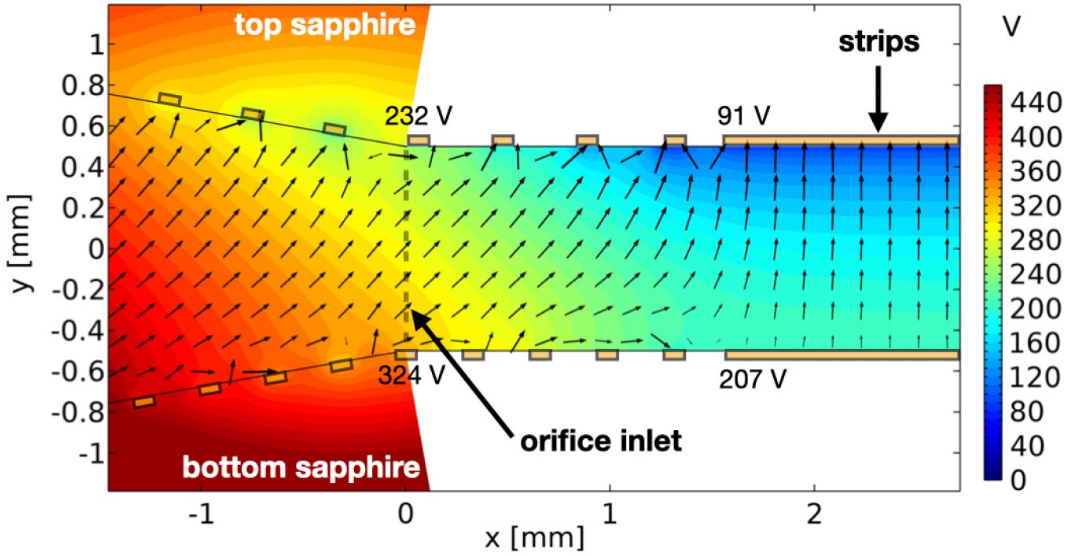


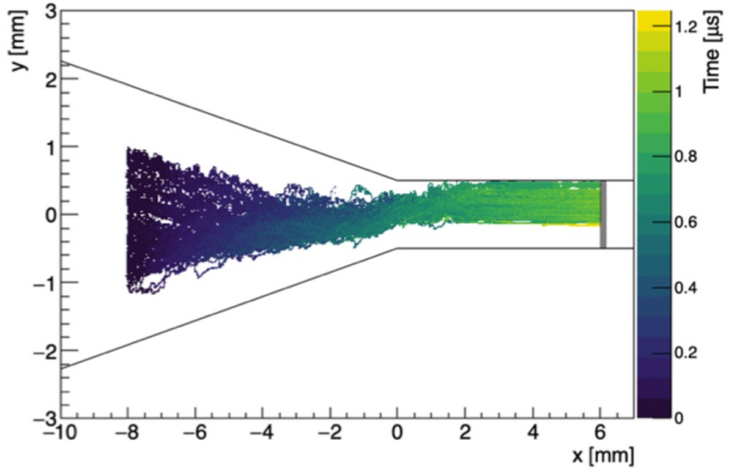


Electric potential simulation

Extraction: xy plane

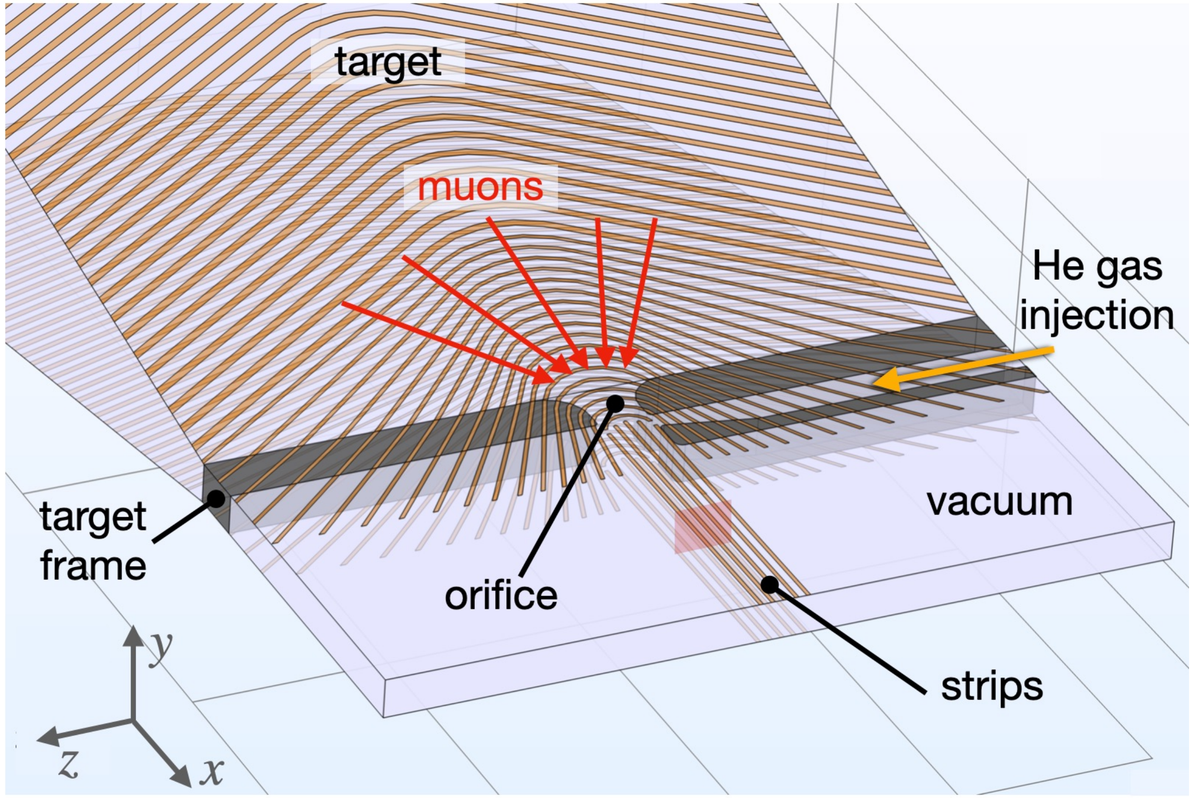


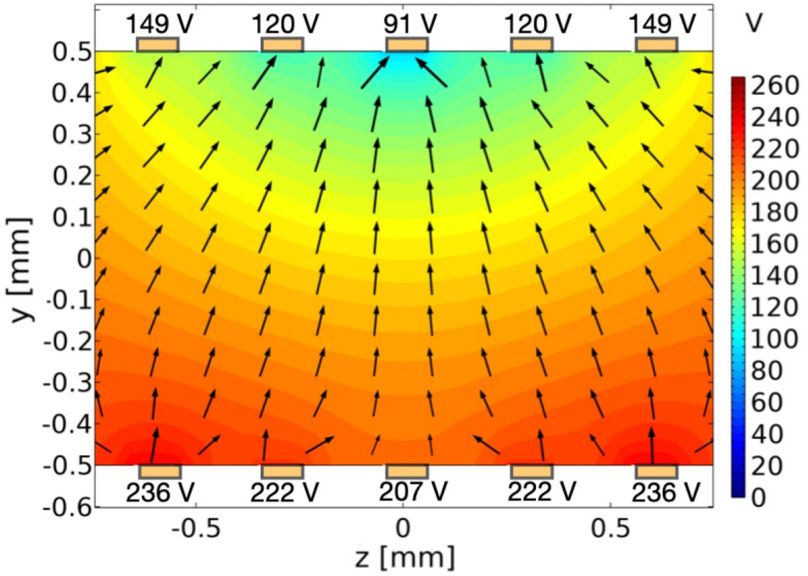


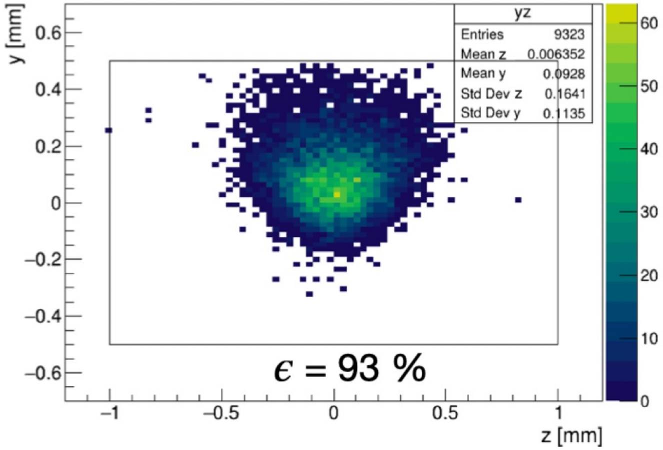


Position the parallel strips at x point where density drops sufficiently, i.e. drift angle in $\vec{E} \times \vec{B}$ tends to 0

Extraction: zy plane







Position the parallel strips at x point where density drops sufficiently, i.e. drift angle in $\vec{E} \times \vec{B}$ *tends to 0*

Preliminary conclusions

Baseline Efficiency	Possible Improvements	Description
$5.6 \cdot 10^{-1}$		Coupling to the 5 T solenoid with 60 mm coil diameter
$4.8 \cdot 10^{-1}$	$\times 2$	Impinging on the target entrance-face
$4.1 \cdot 10^{-3}$	$\times 1.6$	Stopping probability in active region of the target
$8 \cdot 10^{-2}$	$\times 1.5$	Compression towards the orifice (within 5 μs)
$4 \cdot 10^{-1}$	$\times 1.3$	Extraction from the orifice
$7 \cdot 10^{-1}$		Drift from orifice to re-acceleration region (in ~ 0.5 μs)
$8 \cdot 10^{-1}$		Re-acceleration and transport to the iron grid
$7 \cdot 10^{-1}$		Transmission through the iron grid terminating the B-field
$1.4 \cdot 10^{-5}$	$\times 6$	Total baseline compression efficiency (and possible improvement)

HIMB rate: $10^{10}\ \mu/s$

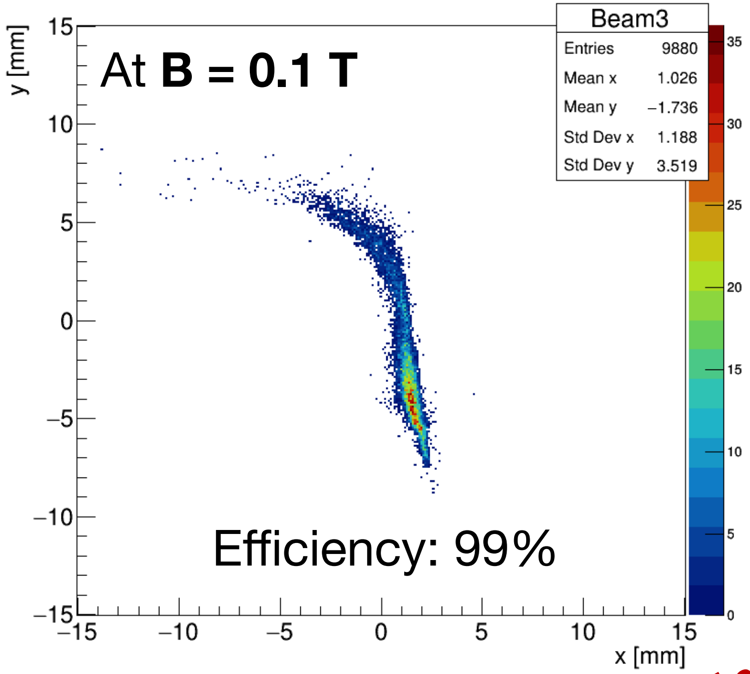
- ☑ Material science: distribute the muCool beam to several μSR setups at 40 kHz each
- ☑ Efficient Mu production: Mu-spectroscopy and Mu-gravity
- ☑ Re-accelerate to higher energies: e.g. 60 MeV for storage-ring-like experiments as μEDM or g-2

Next steps

① Muon extraction from gas target into vacuum

② **Re-acceleration to 10 keV**

③ Extraction from 5T solenoid



Preliminary

$\sigma_x \approx$ 1 mm
$\Delta E \approx$ 20 eV