Current and Future beam lines developments at PSI and physics cases

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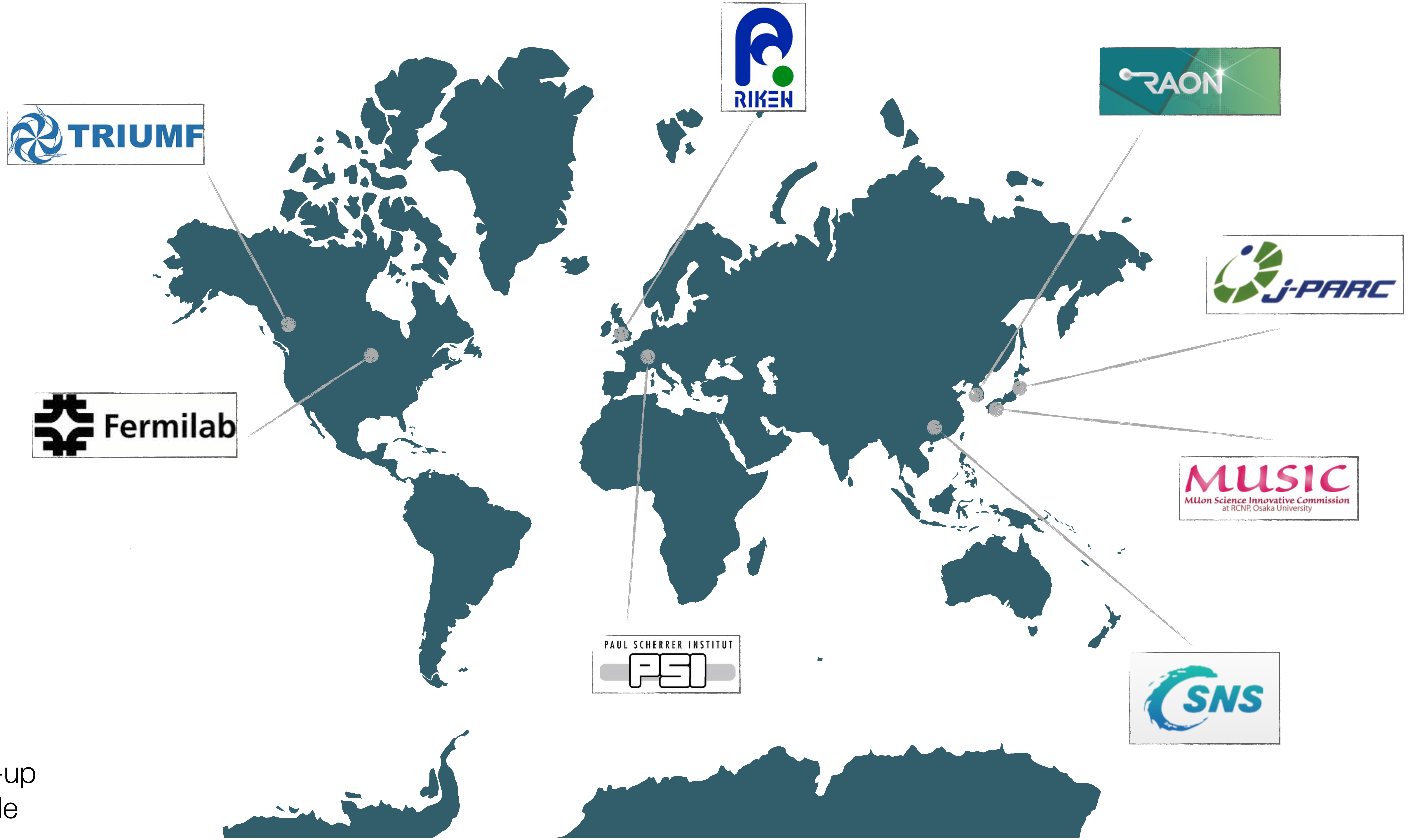
April 5th 2023
Workshop on Using Muons from Backscattered Photons on Targets for Various Studies at the EIC

Contents

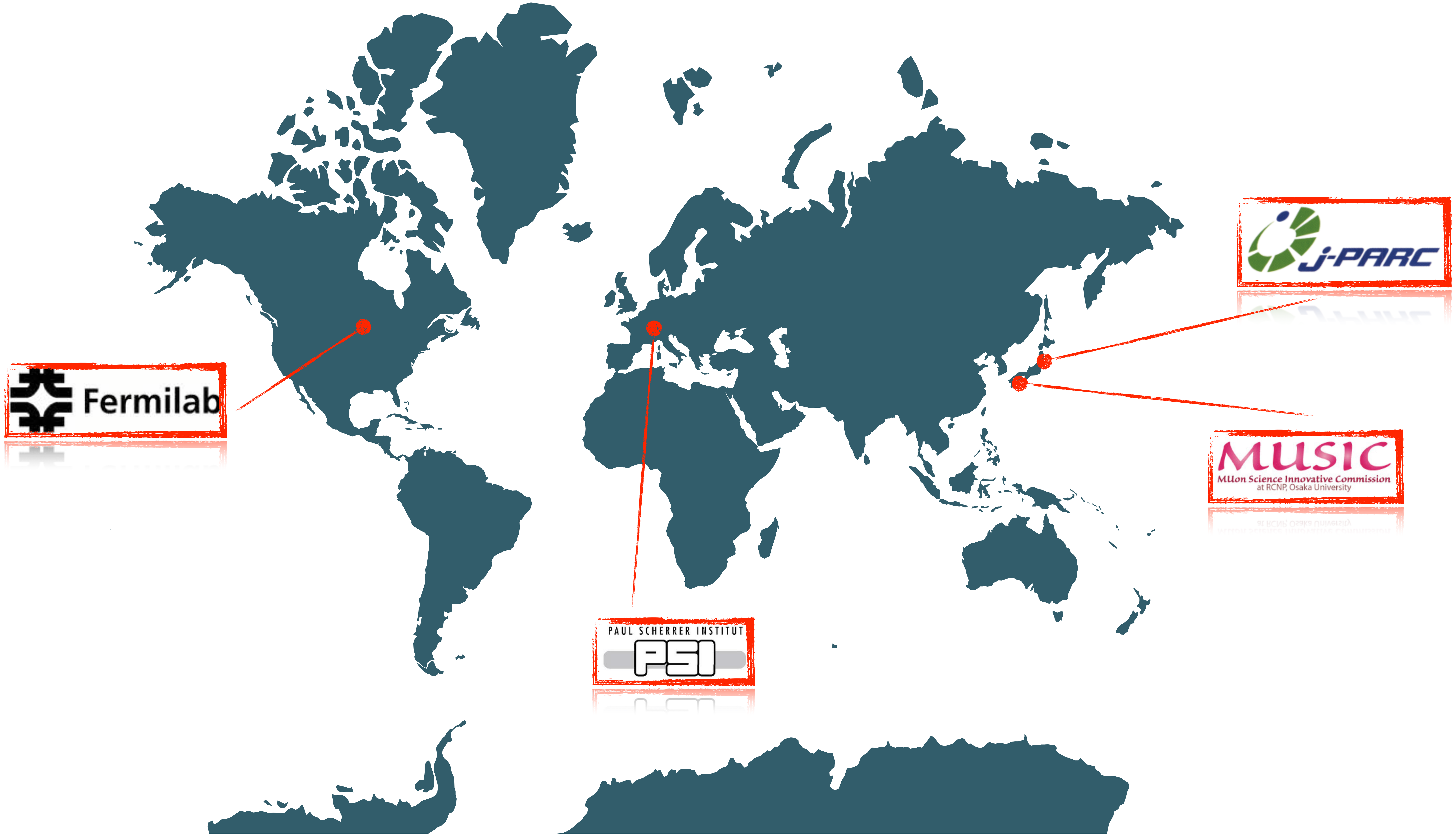
- PSI current beam lines
- PSI future beam line developments
  - HiMB status
  - muCool status
- Physics cases already associated to present/future muon beams
  - MEGII, Mu3e phase I/phase II
  - muEDM

Muon beams worldwide



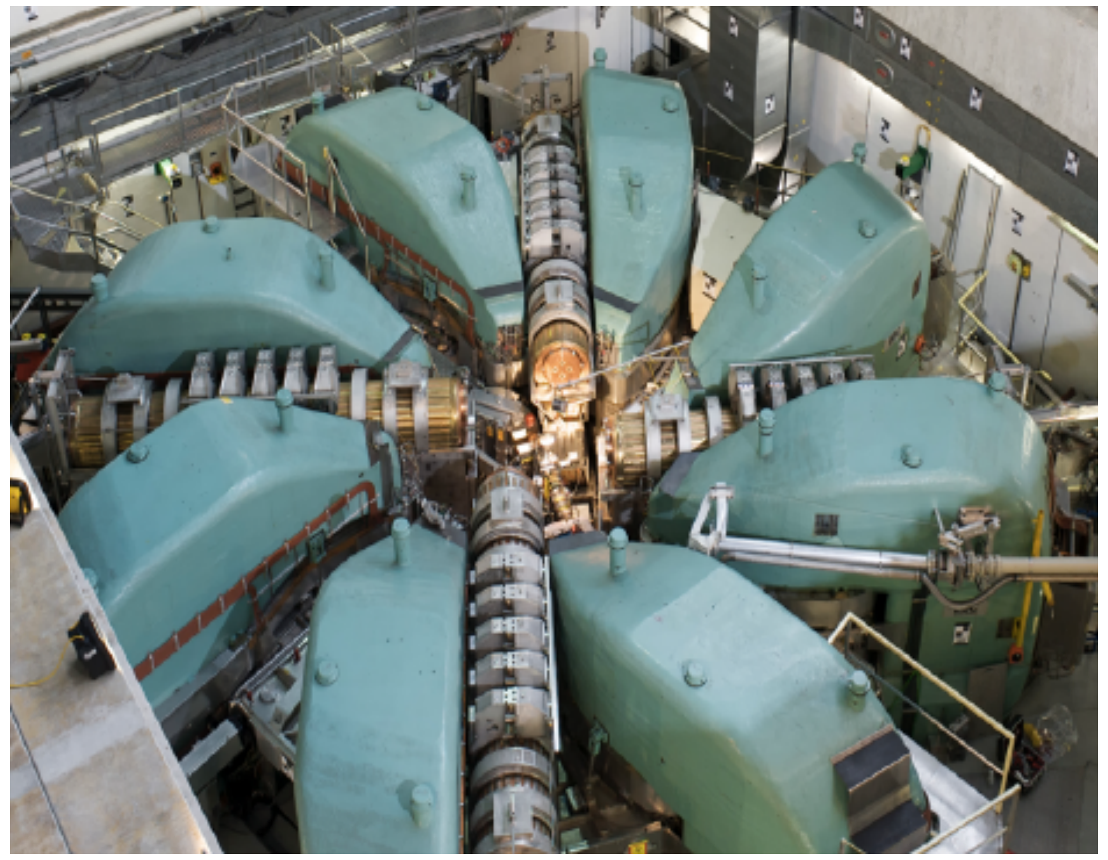
Note: See the back-up for a summary table

Muon beams worldwide associated to “present” experiments

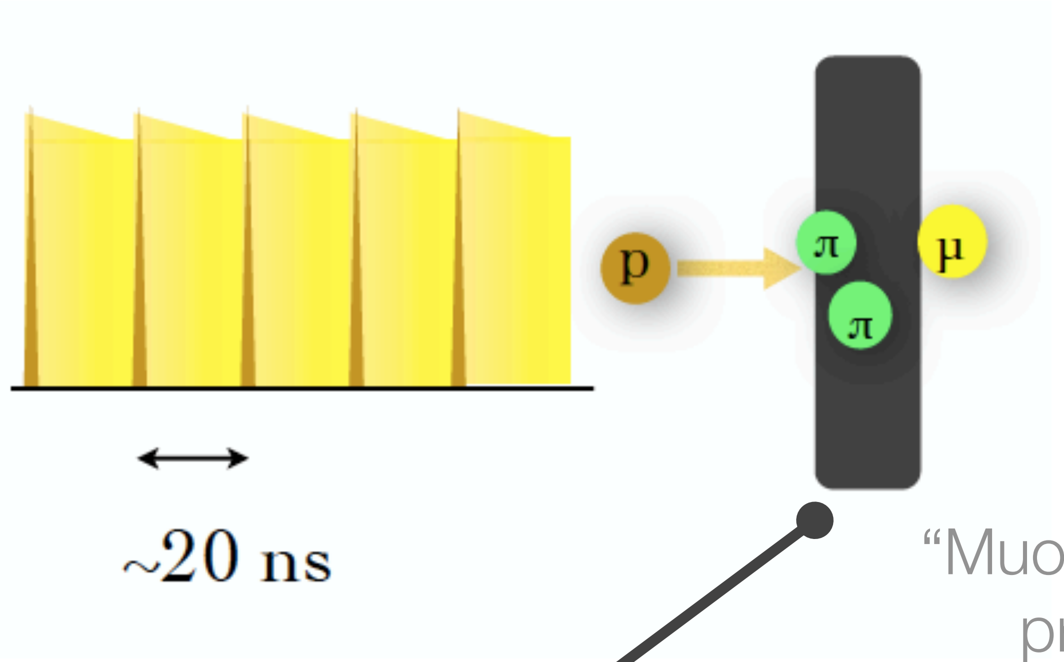


PSI’s muon beams

- PSI delivers the most intense continuous (DC) low momentum (surface) muon beam in the world up to few x 10^8 mu/s (28 MeV/c, polarised beam (**Intensity Frontiers**)

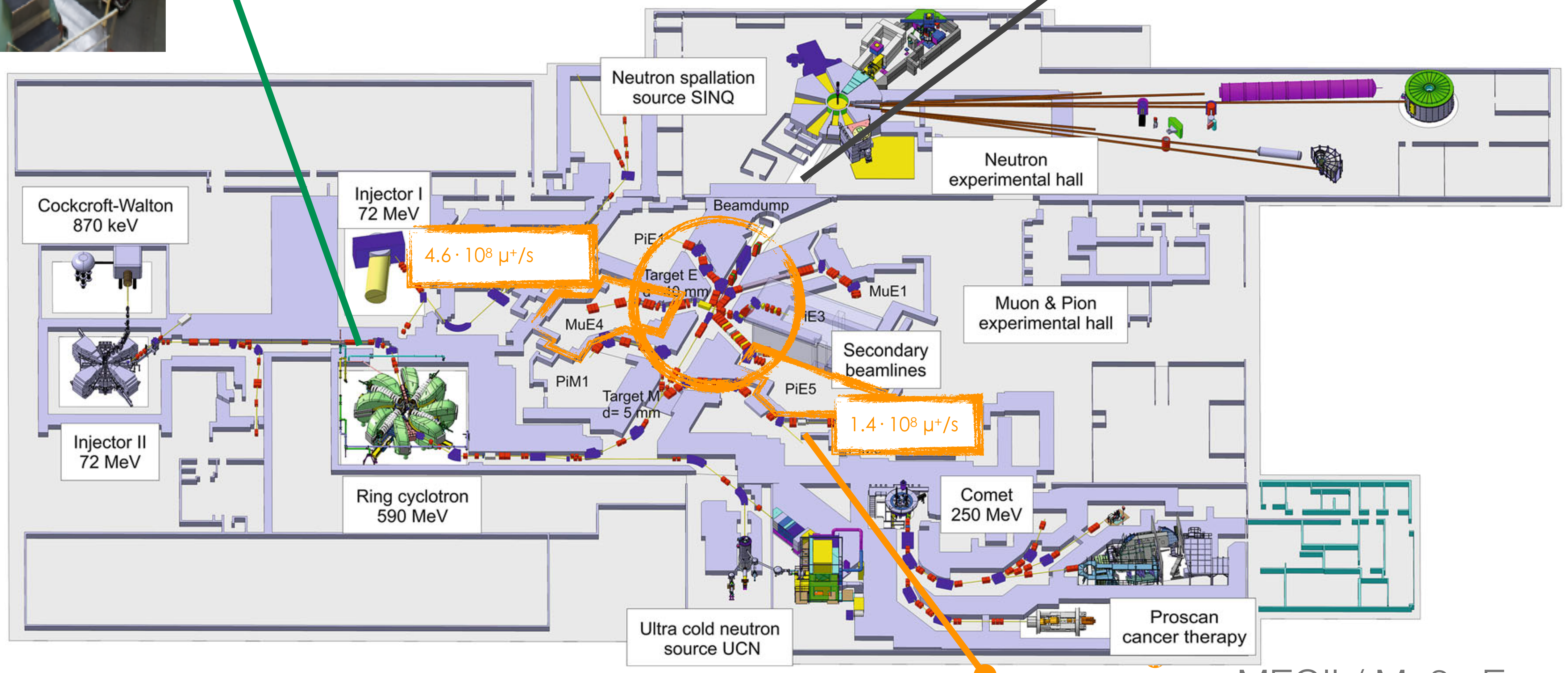


590 MeV proton
ring cyclotron
1.4 MW



Proton RF ~ 50 MHz
“DC” muon beam

“Muon” Target “E”
production

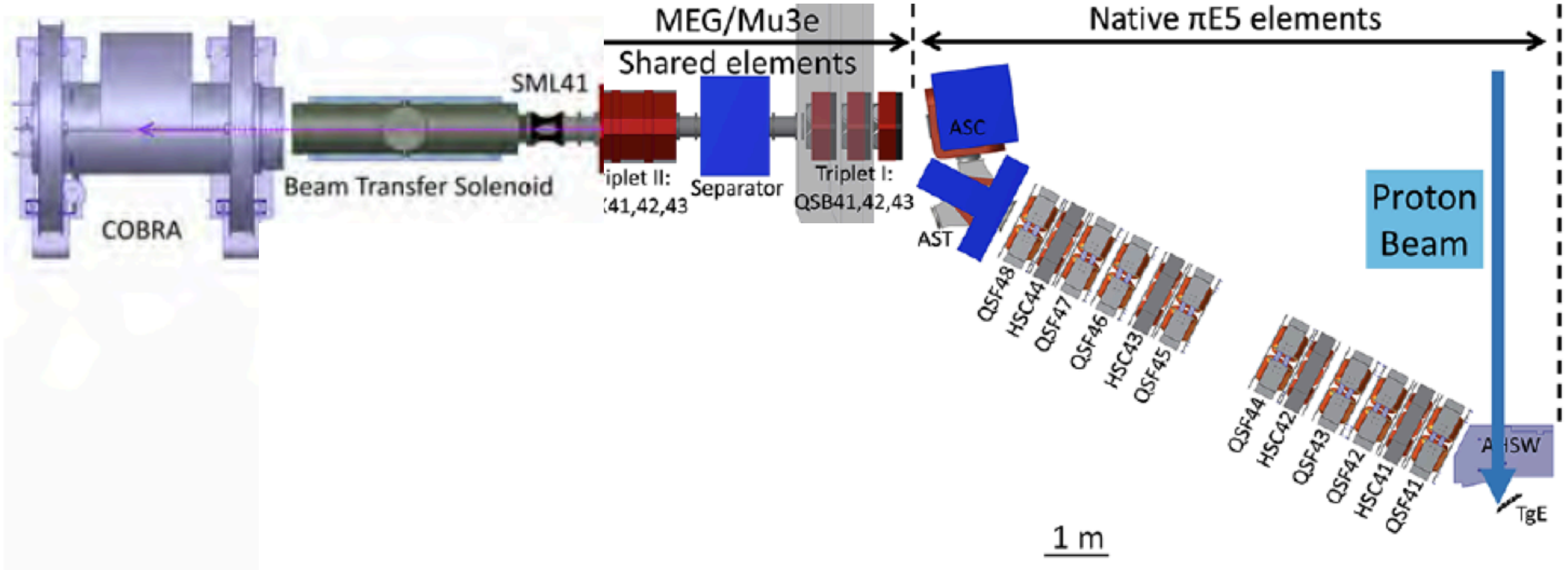


MEGII / Mu3e Experimental area

The MEGII and Mu3e beam lines

- MEGII and Mu3e (phase I) similar beam requirements:
  - **Intensity O(10^8 muon/s), low momentum p = 28 MeV/c**
  - **Small straggling and good identification of the decay region**
- MEG II beam settings released since 2019. More then 10^8 mu/s can be transport into Cobra (up to 1.6e8@2.2 mA during the 2022 beam time)
- A dedicated compact muon beam line (CMBL) sharing a large fraction of the native piE5&MEG elements will serve Mu3e
  - Proof-of-Principle: Delivered 8 x 10^7 muon/s during 2016 test beam (up to 1e8@2.4 mA during the 2022 beam time with the full assembled Mu3e beam line)

The MEGII



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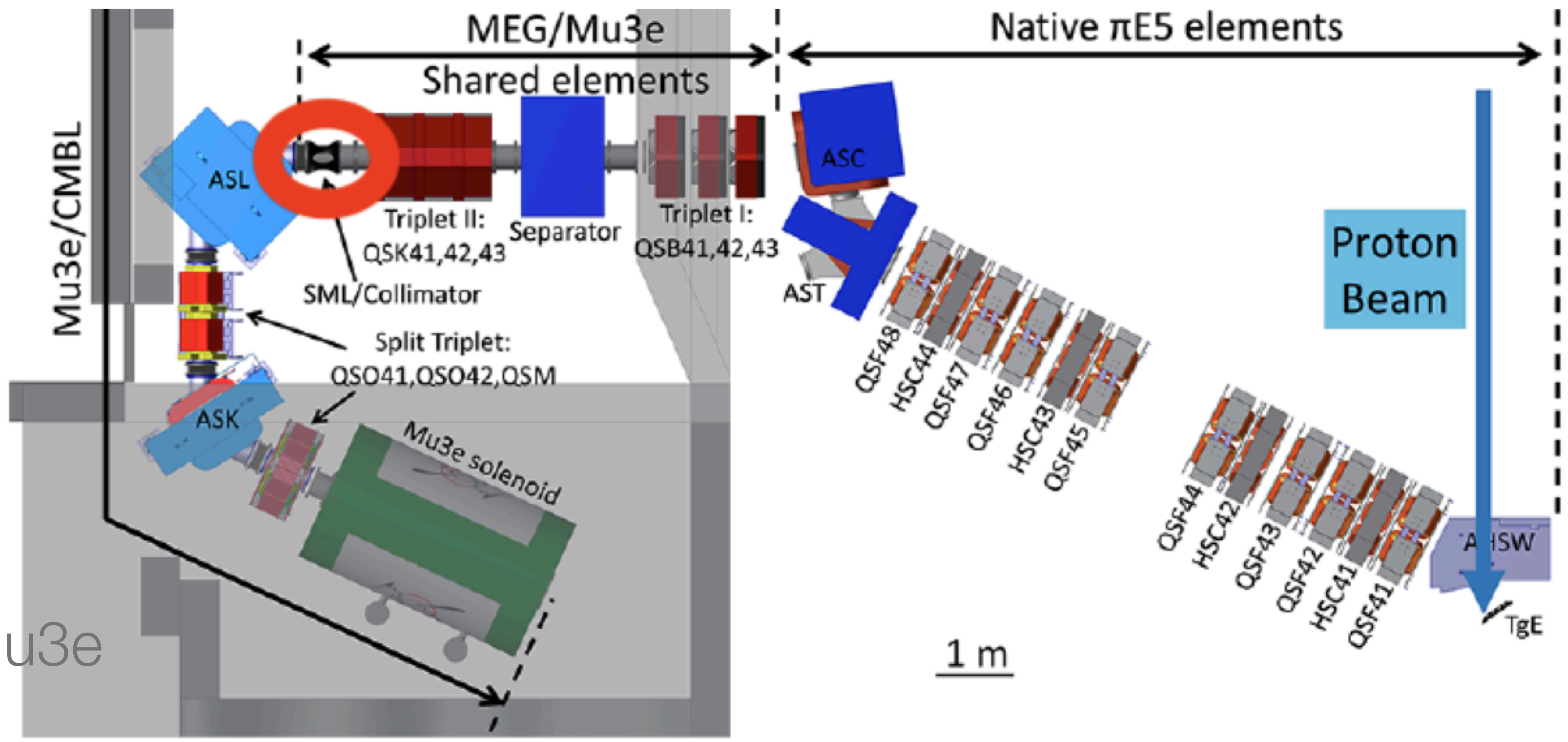
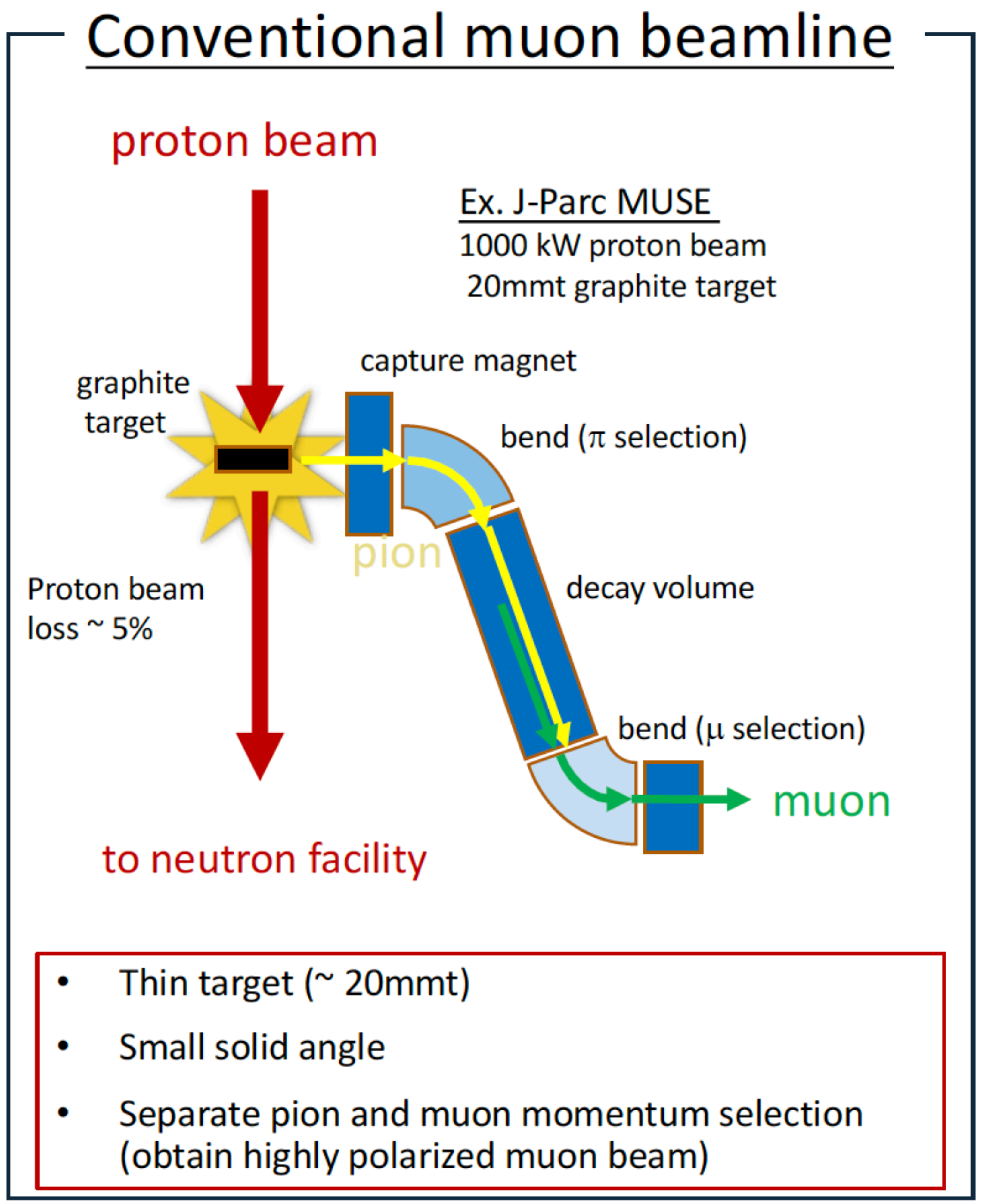
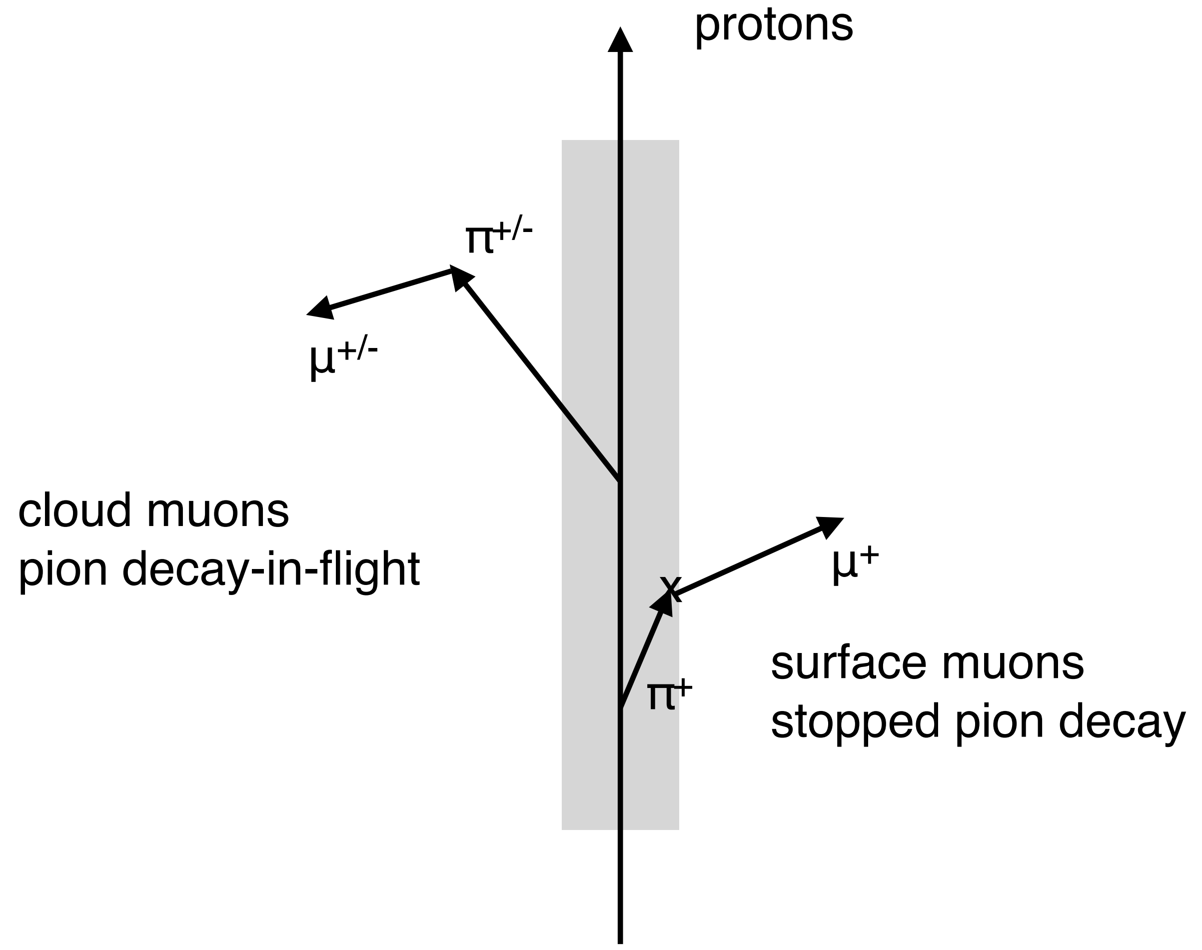
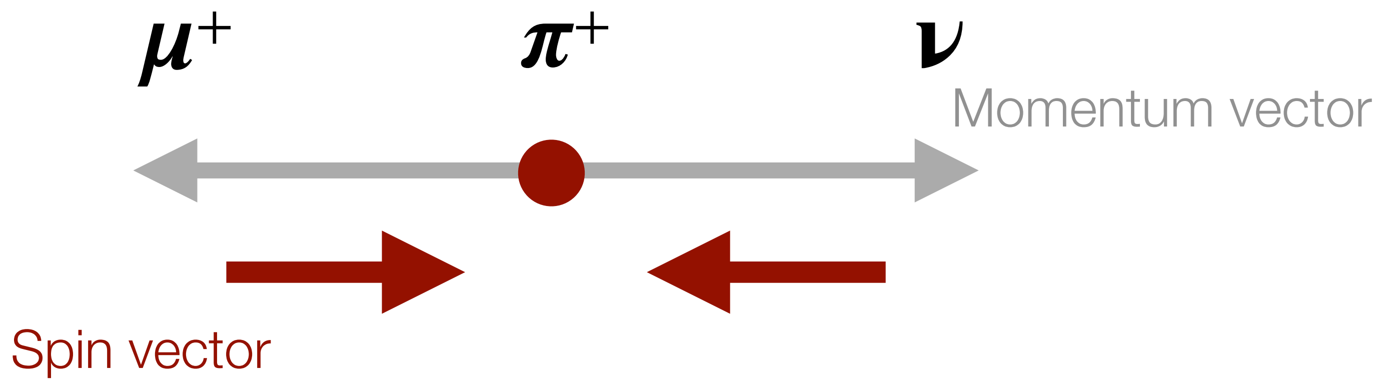


The Mu3e

PSI's muon beams







- Muon beams: **secondary** beam lines
- Low-energy muon beam lines typically tuned to surface-μ^+ at ~ 28 MeV/c
- **Note:** surface-μ —> polarised positively charged muons (spin antiparallel to the momentum)
- Contribution from cloud muons at similar momentum about 100x smaller
- Negative muons only available as cloud muons

How the beam intensity can be increased…

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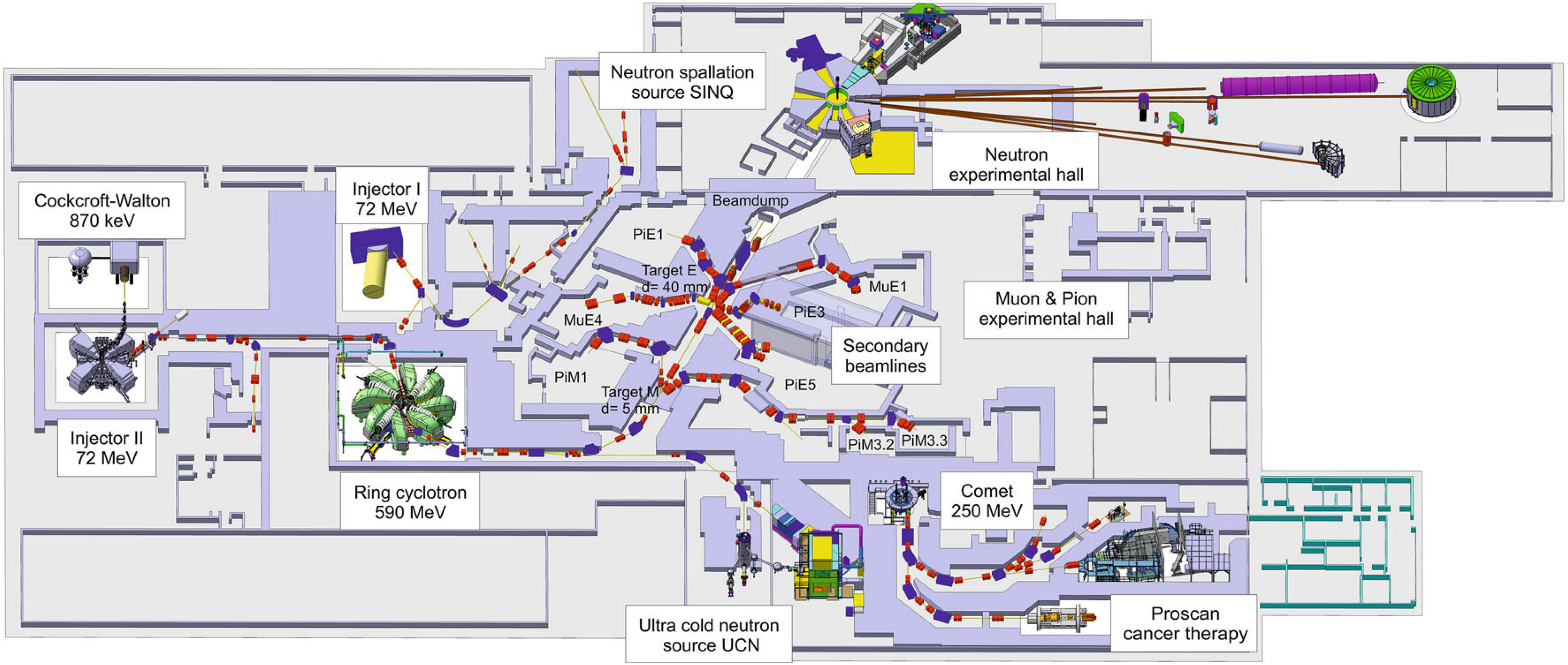
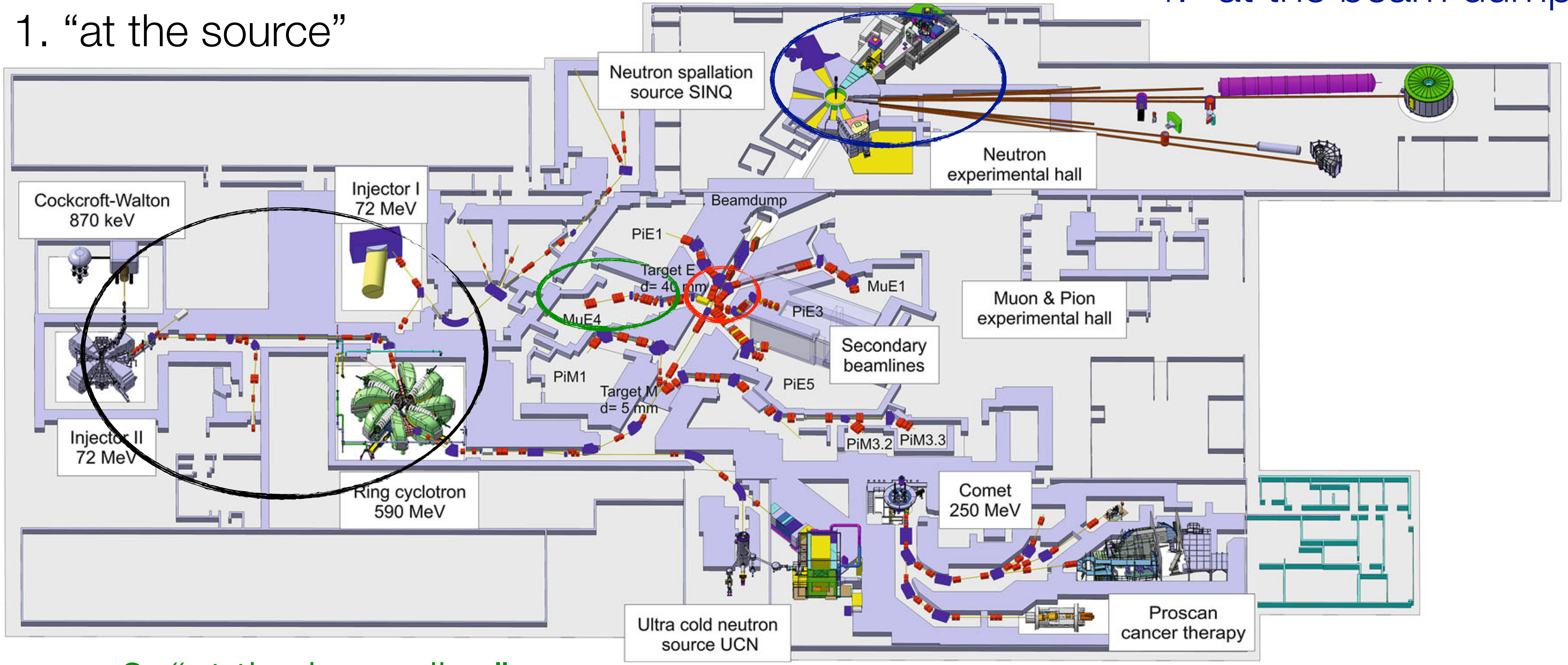


How the beam intensity can be increased…

2. “at the target production”

4. “at the beam dump”

1. “at the source”



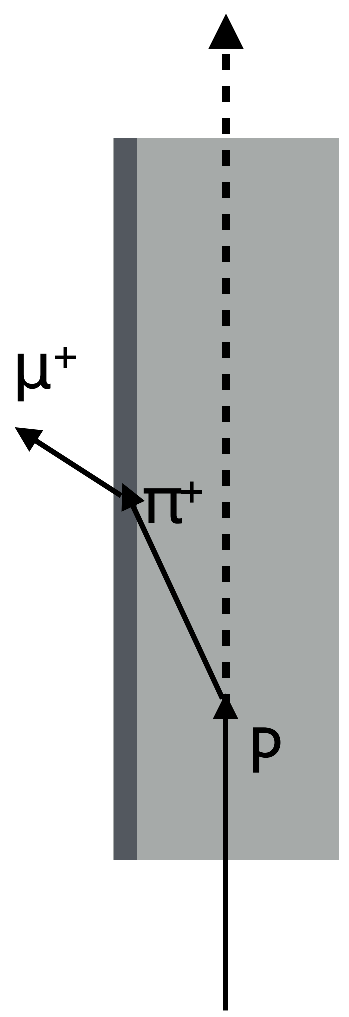
3. “at the beam line”

How the beam intensity can be increased…

Always looking for —> Relative “simple”, “easy”, “fast” and “cheap” solutions

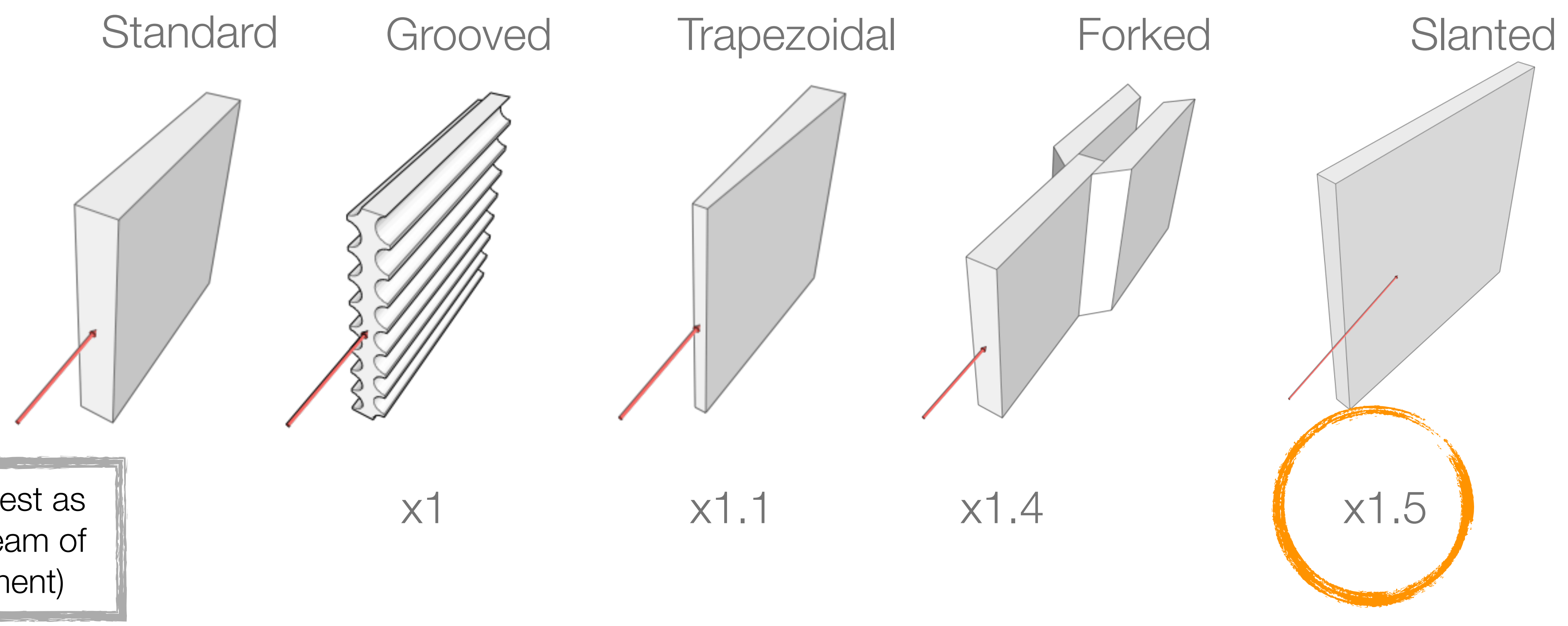
At the target:

- Optimised Target: Alternative materials or different geometry
  - Search for high pion yield materials -> higher muon yield
  - Either increasing the surface volume (surface area times acceptance depth) or the pion stop density near the surface



$$
\begin{aligned}
\text{relative } \mu^{+} \text{yield} \;&\propto\; \pi^{+} \text{stop density} \cdot \mu^{+} \text{Range} \cdot \text{length} \\
&\propto n \cdot \sigma_{\pi^{+}} \cdot SP_{\pi^{+}} \cdot \frac{1}{SP_{\mu^{+}}} \cdot \frac{\rho_C (6/12)_C}{\rho_x (Z/A)_x} \\
&\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z} \\
&\propto \frac{1}{Z^{2/3}}
\end{aligned}
$$

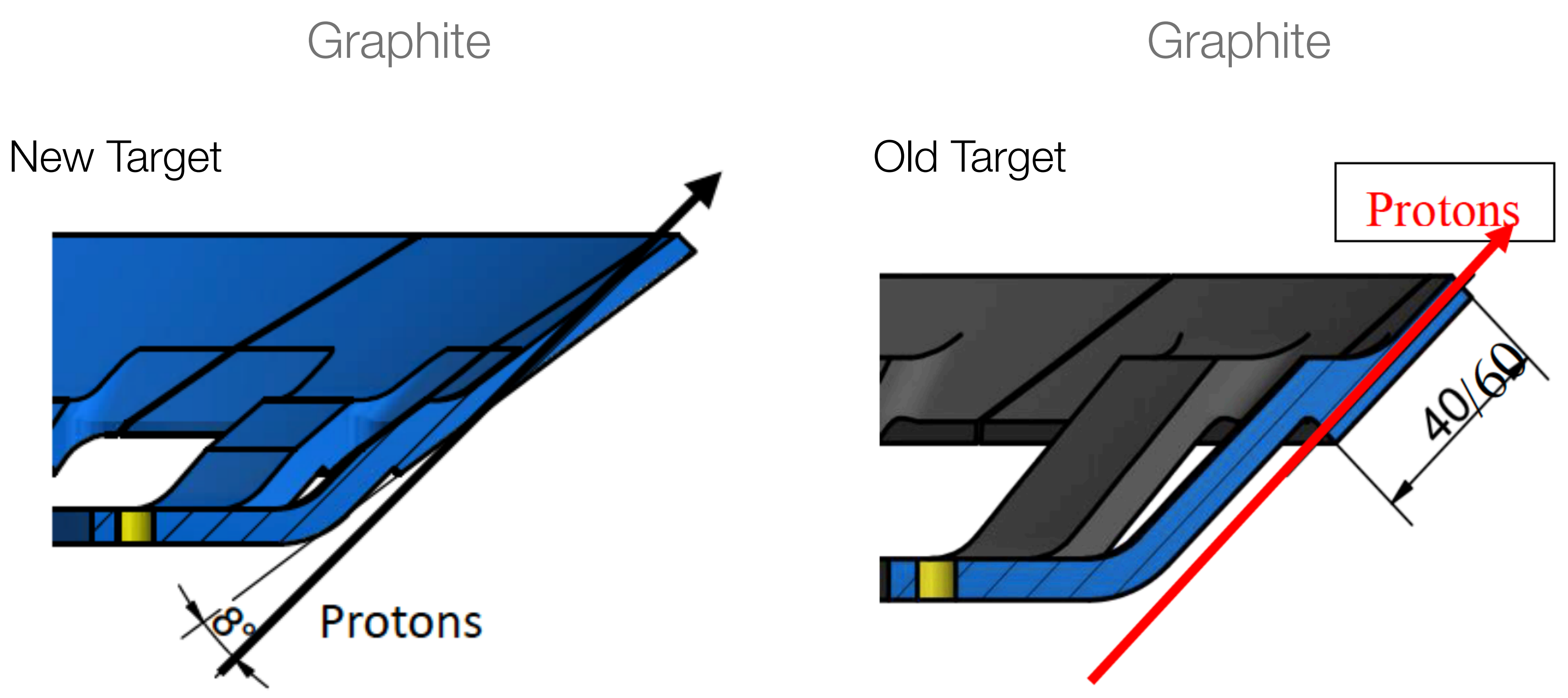
- Several materials have pion yields > 2x Carbon
- Relative muon yield favours low-Z materials, but difficult to construct as a target
- B_4C and Be_2C show 10-15% gain

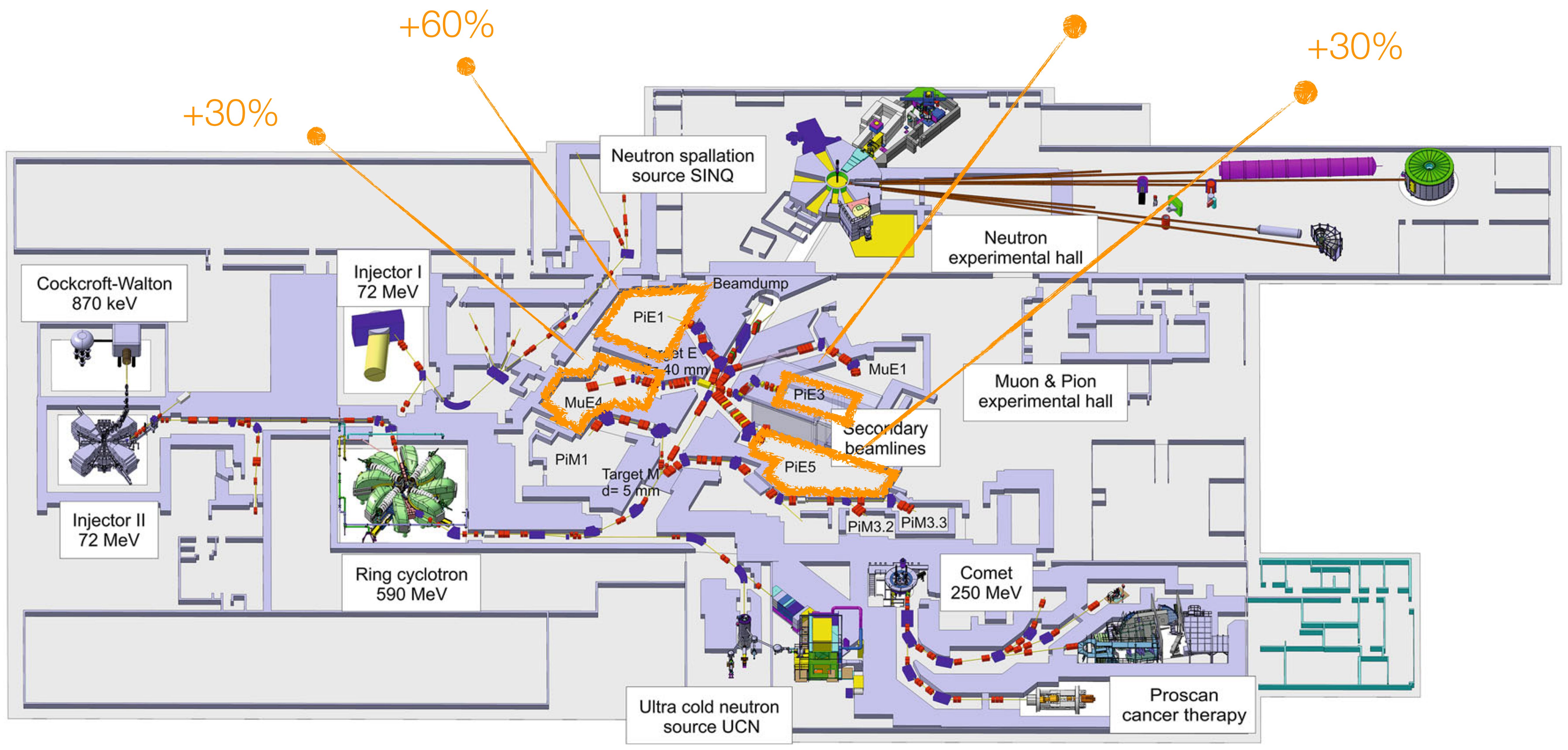


note: Each geometry was required to preserve, as best as possible, the proton beam characteristics down-stream of the target station (spallation neutron source requirement)

Slanted target: Prototype test

- Impact of the optimised target:
  - Put into perspective the target optimisation only, corresponding to **50%** of muon beam intensity gain, would corresponds to effectively raising the proton beam power at PSI by **650 kW**, equivalent to a beam power of almost **2 MW** without the additional complications such ad increased energy and radiation deposition into the target and its surroundings

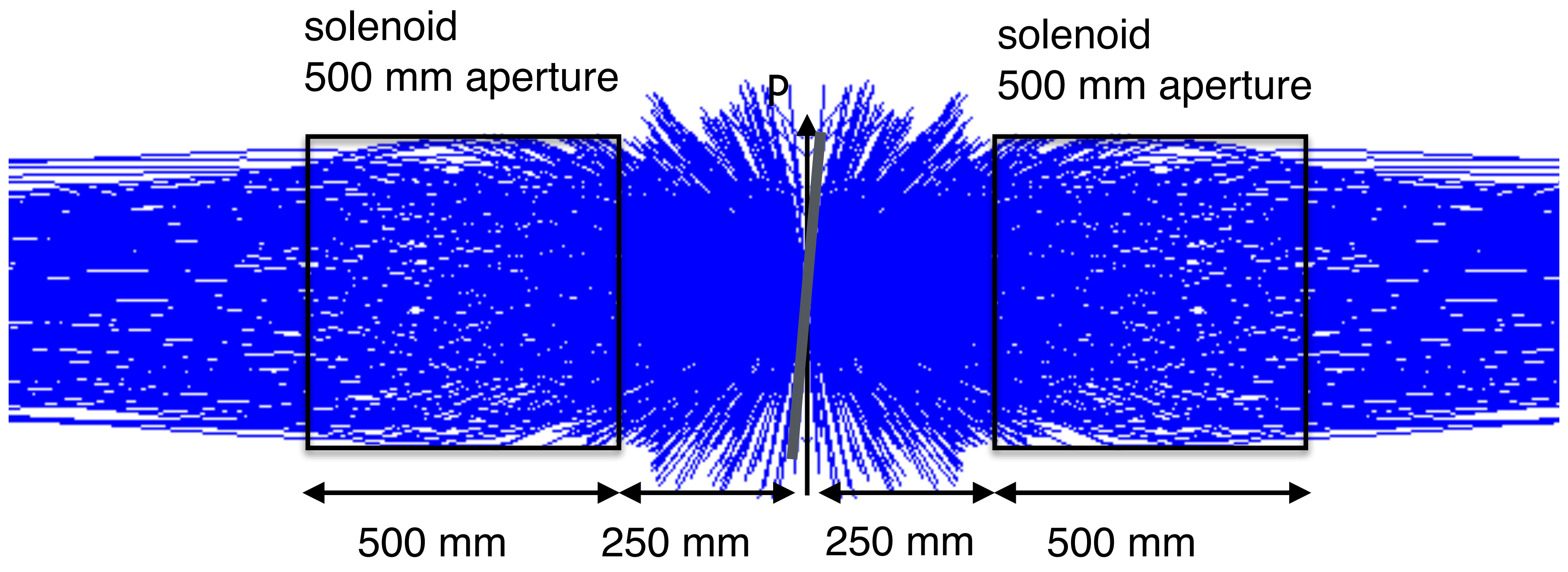




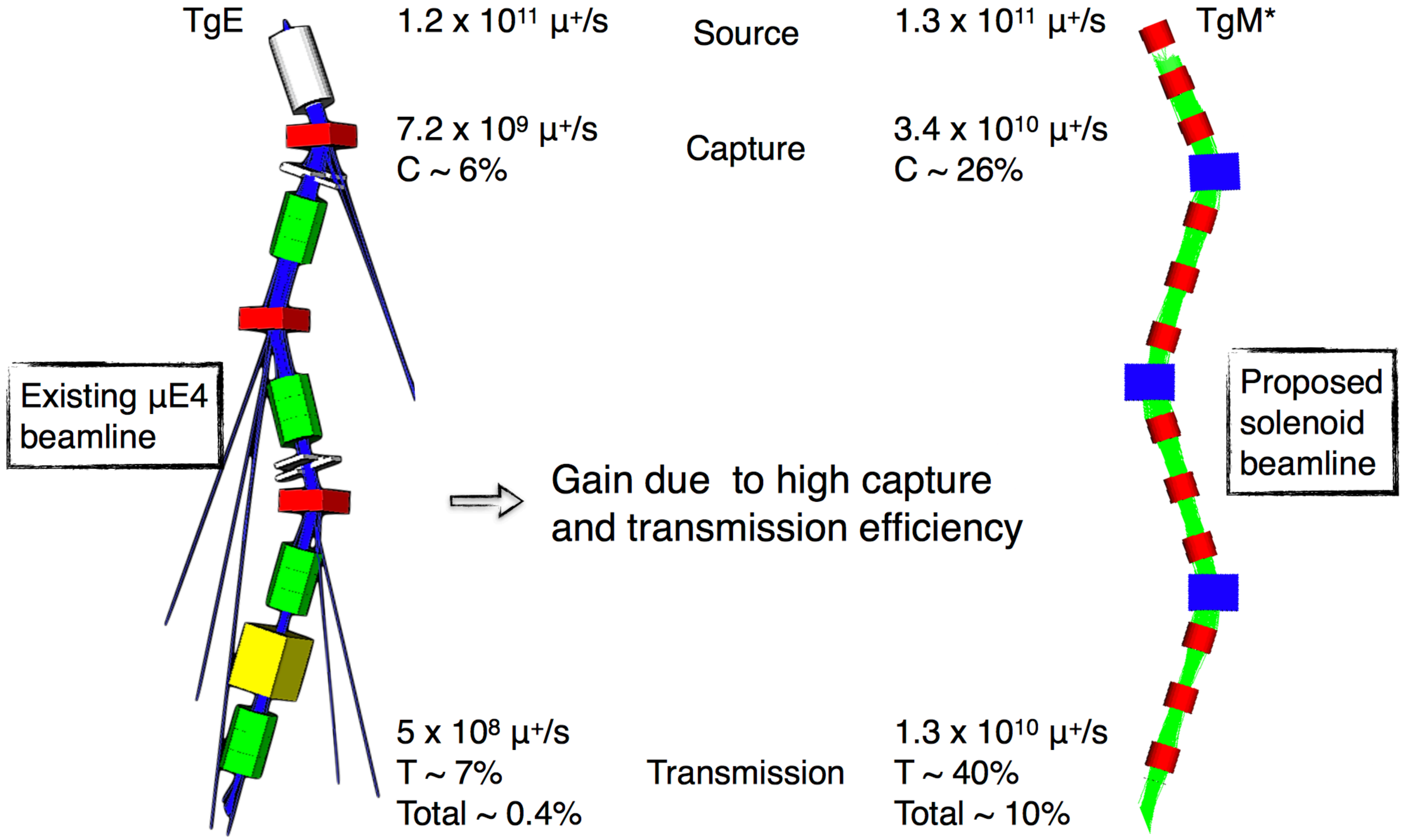
At the beam line

- Optimised the beam line: increased capture and transmission

- Two normal-conducting, radiation-hard solenoids close to target to capture surface muons
  - Central field of solenoids ~0.35 T
  - Field at target ~0.1 T



- A quasi "pure" solenoidal beam line to increase the transmission



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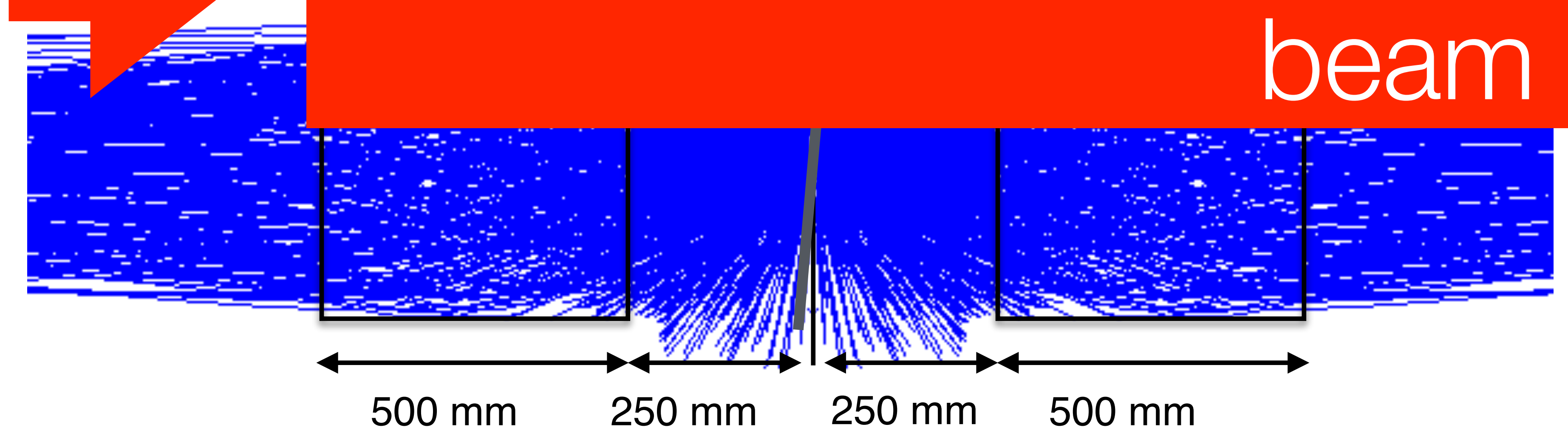

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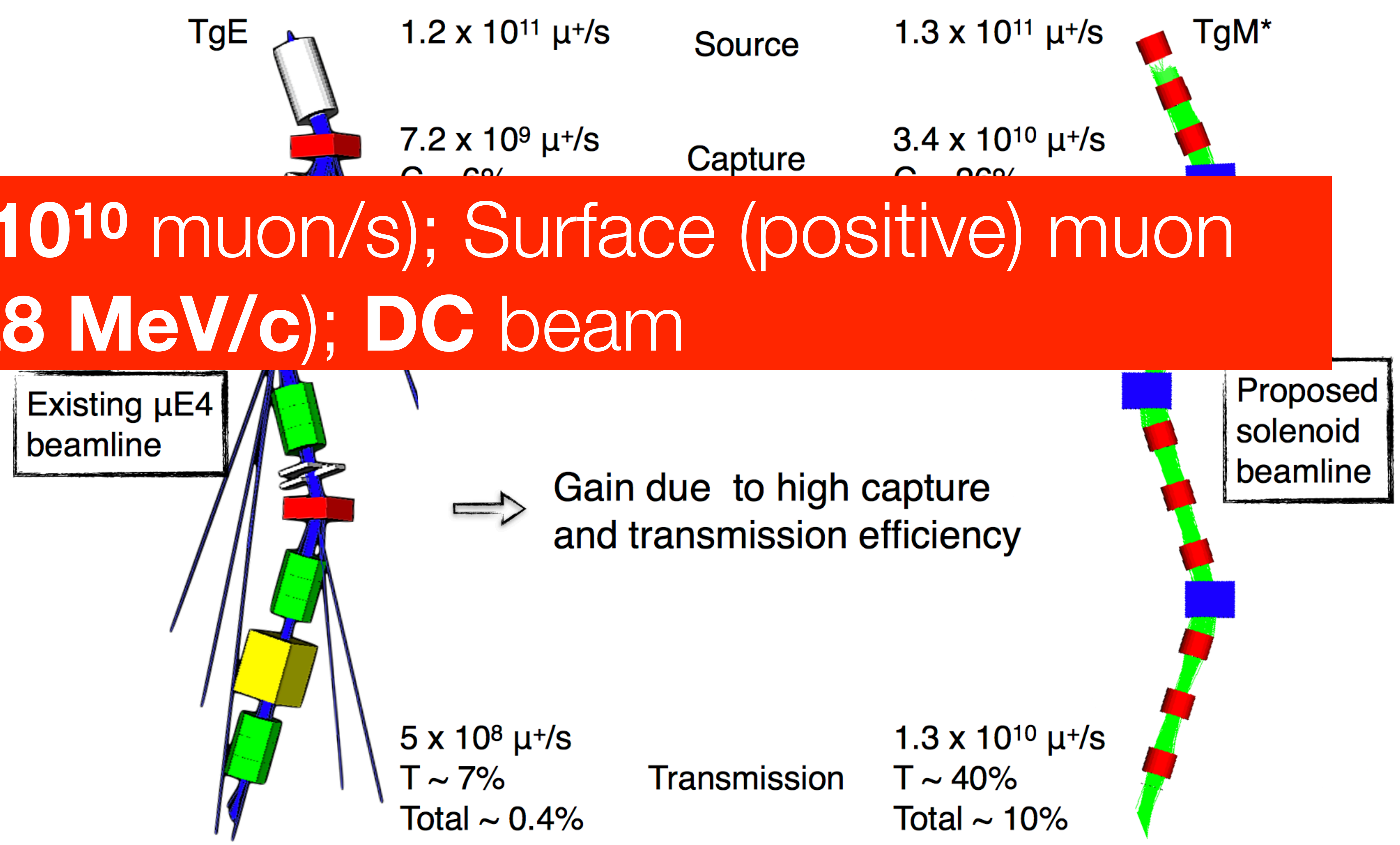


HIMB project at PSI. Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC beam**

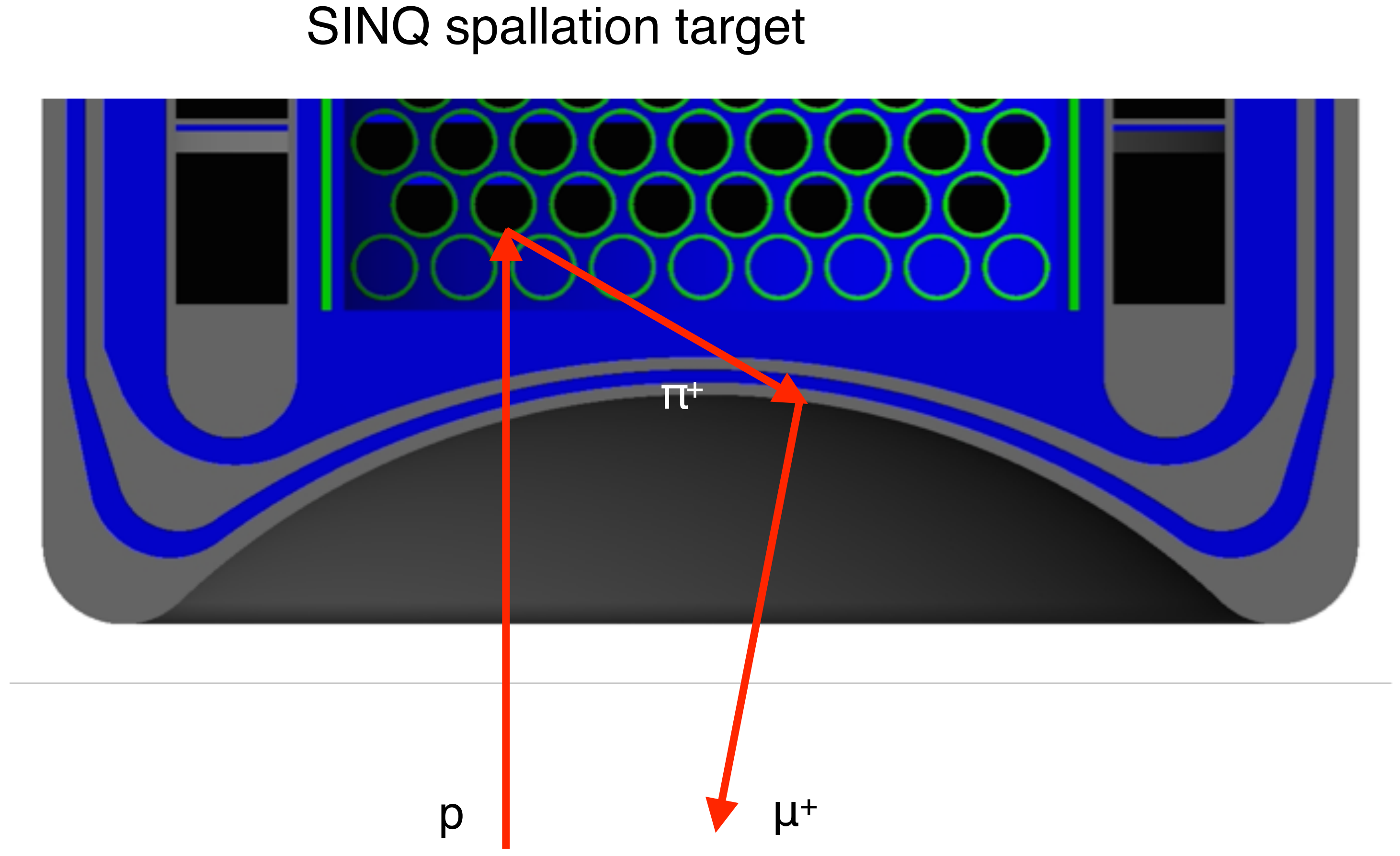
A quick departure: The HiMB project at the beam dump

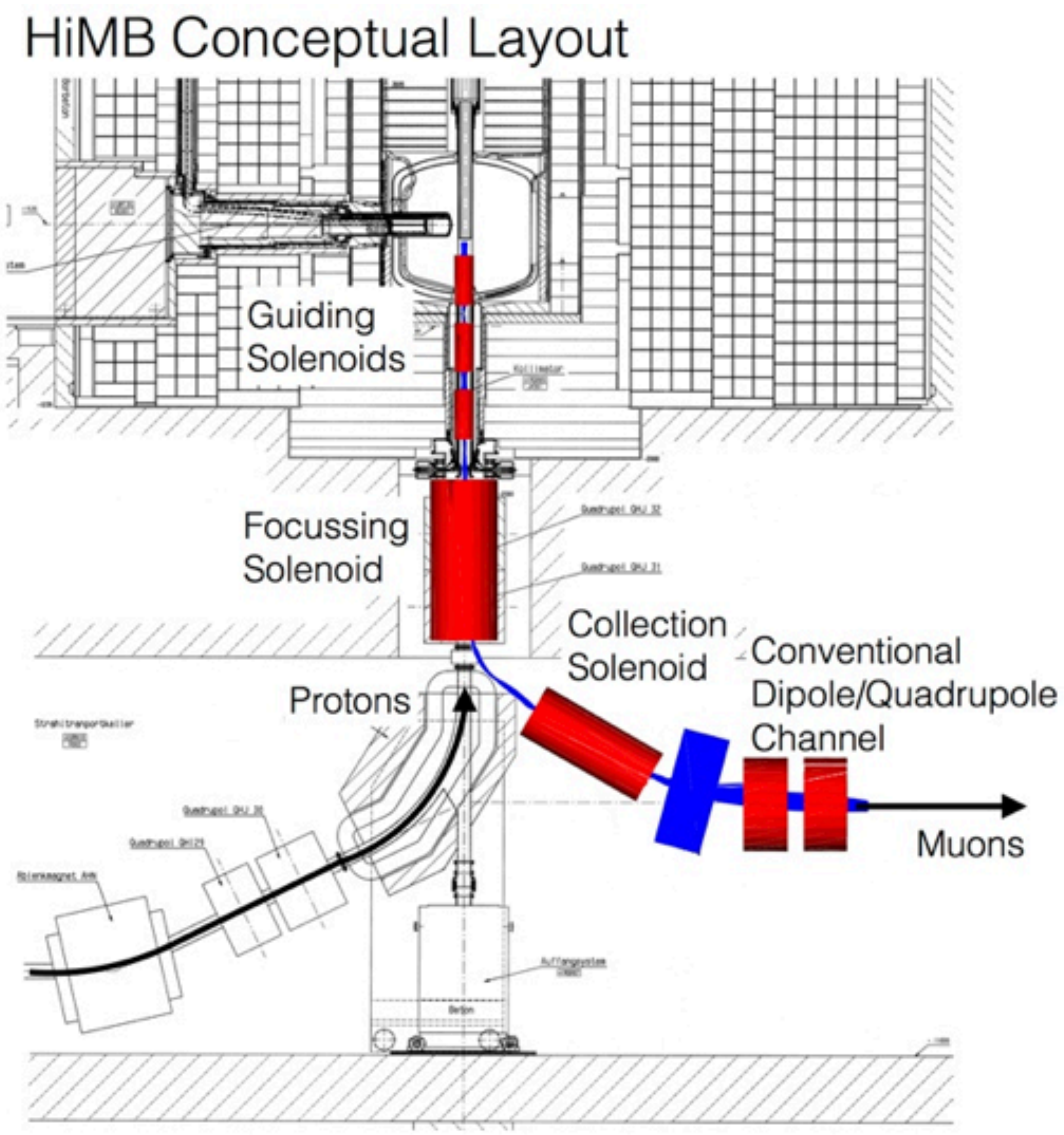
- Source simulation (below safety window):
  9 x 10¹⁰ surface-μ⁺/s @ 1.7 mA I_p
- Profit from stopping of full beam
- Residual proton beam (~1 MW) dumped on SINQ

- Replace existing quadrupoles with solenoids:
  - Preserve proton beam footprint
  - Capture backward travelling surface muons
- Extract muons in Dipole fringe field
- Backward travelling pions stopped in beam window

- Capturing turned out to be difficult :
  - Large phase space (divergence & 'source' extent)
  - Capture solenoid aperture needed to be increased, but constrained by moderator tank
- High radiation level close to target

- Due these constraints and after several iterations with different capturing elements:
  - **Not enough captures muons to make an high intensity beam**
  - **Alternative solution: HiMB @ EH**

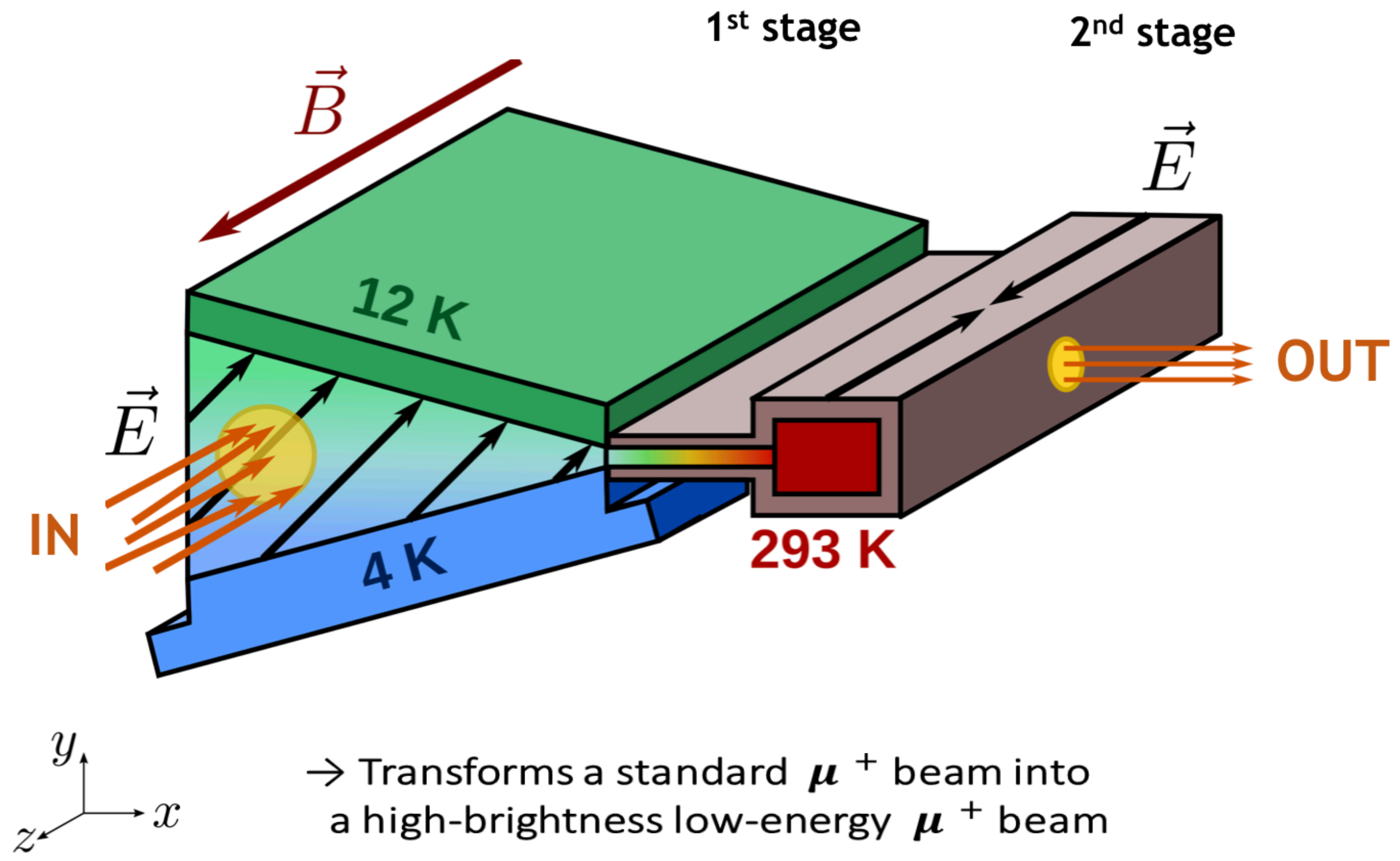




The muCool project at PSI

- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor **10^{10}** with an efficiency of O(**10^{-4}**)

Standard/secondary μ^+ beam
- σ = 10 mm
- E = 4 MeV
- Continuous

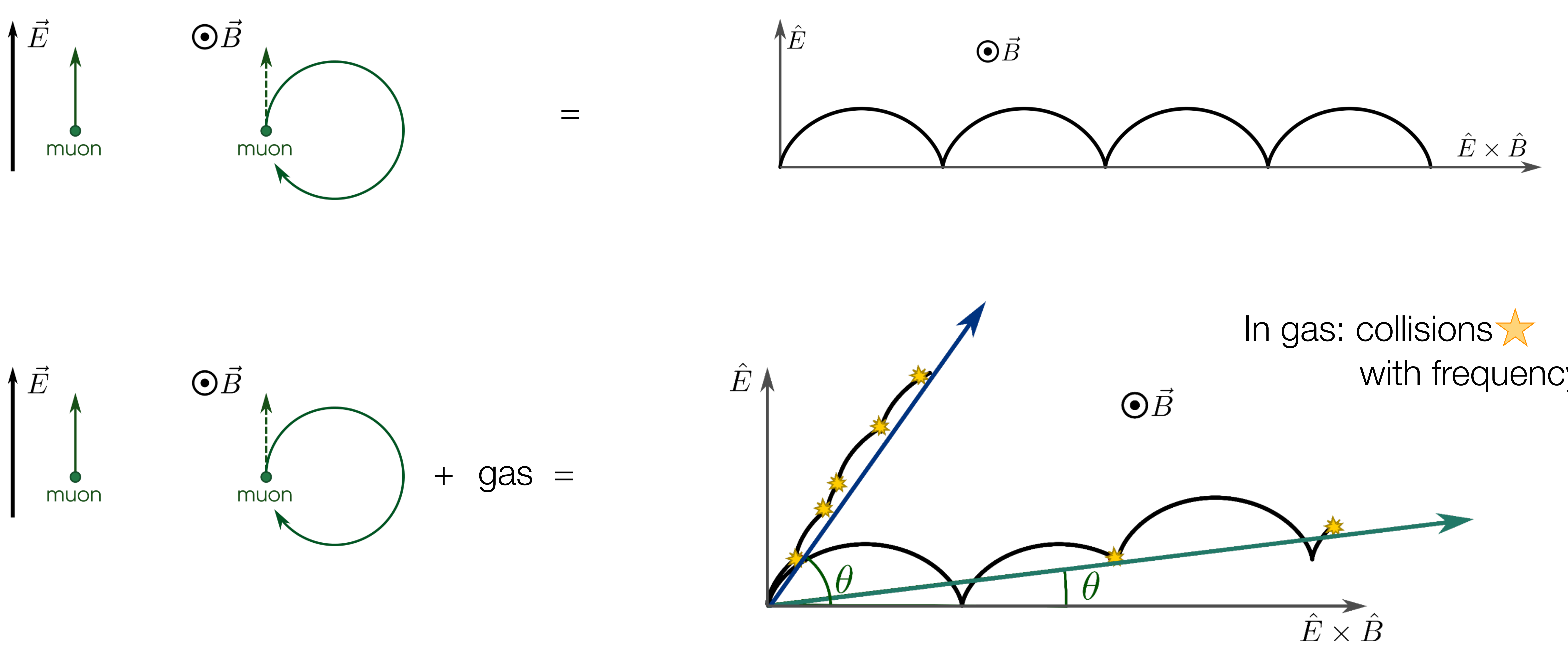


muCool/tertiary μ^+ beam
- σ < 1mm
- E < eV
- Tagged

→ Transforms a standard μ^+ beam into a high-brightness low-energy μ^+ beam

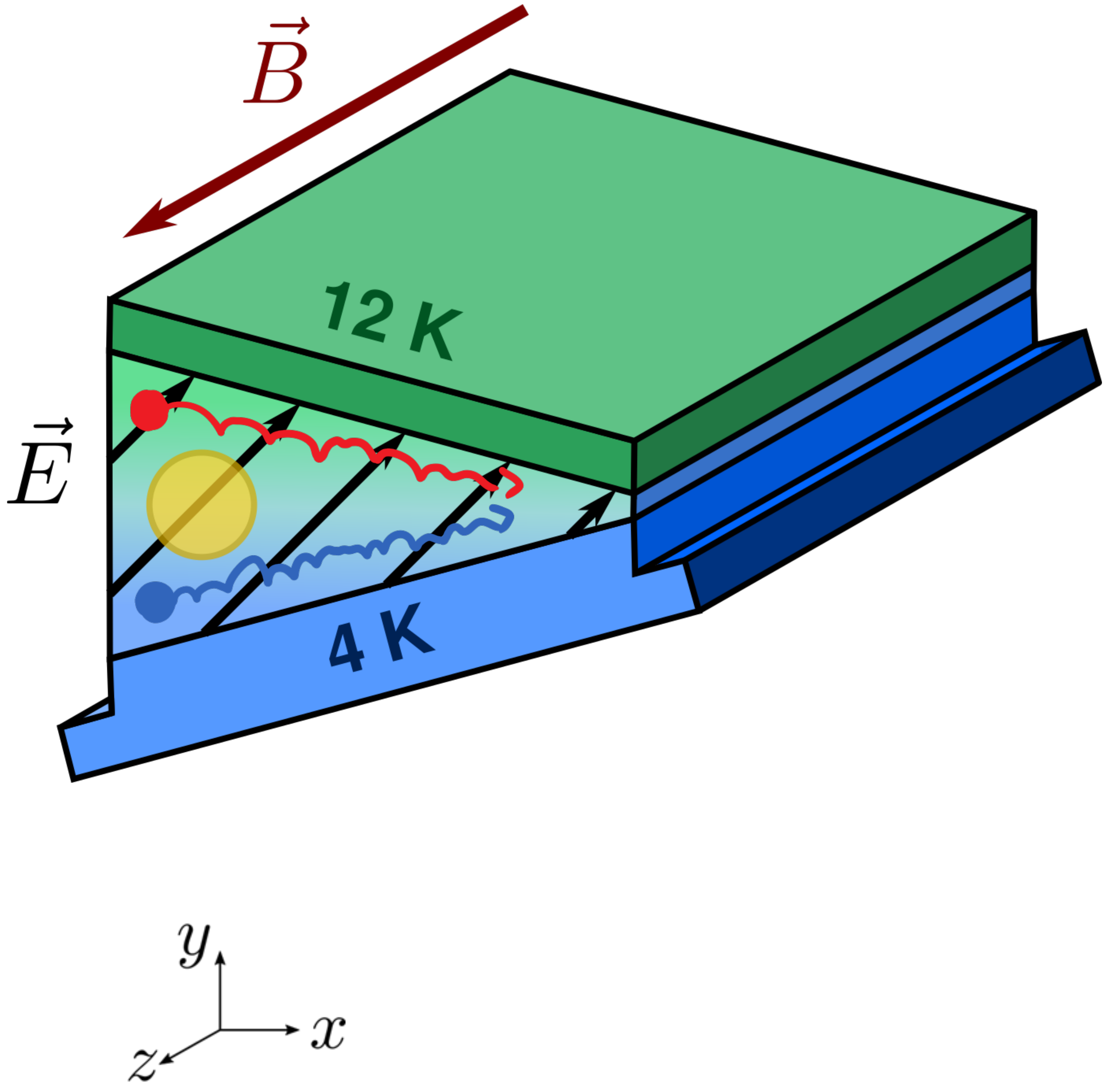
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

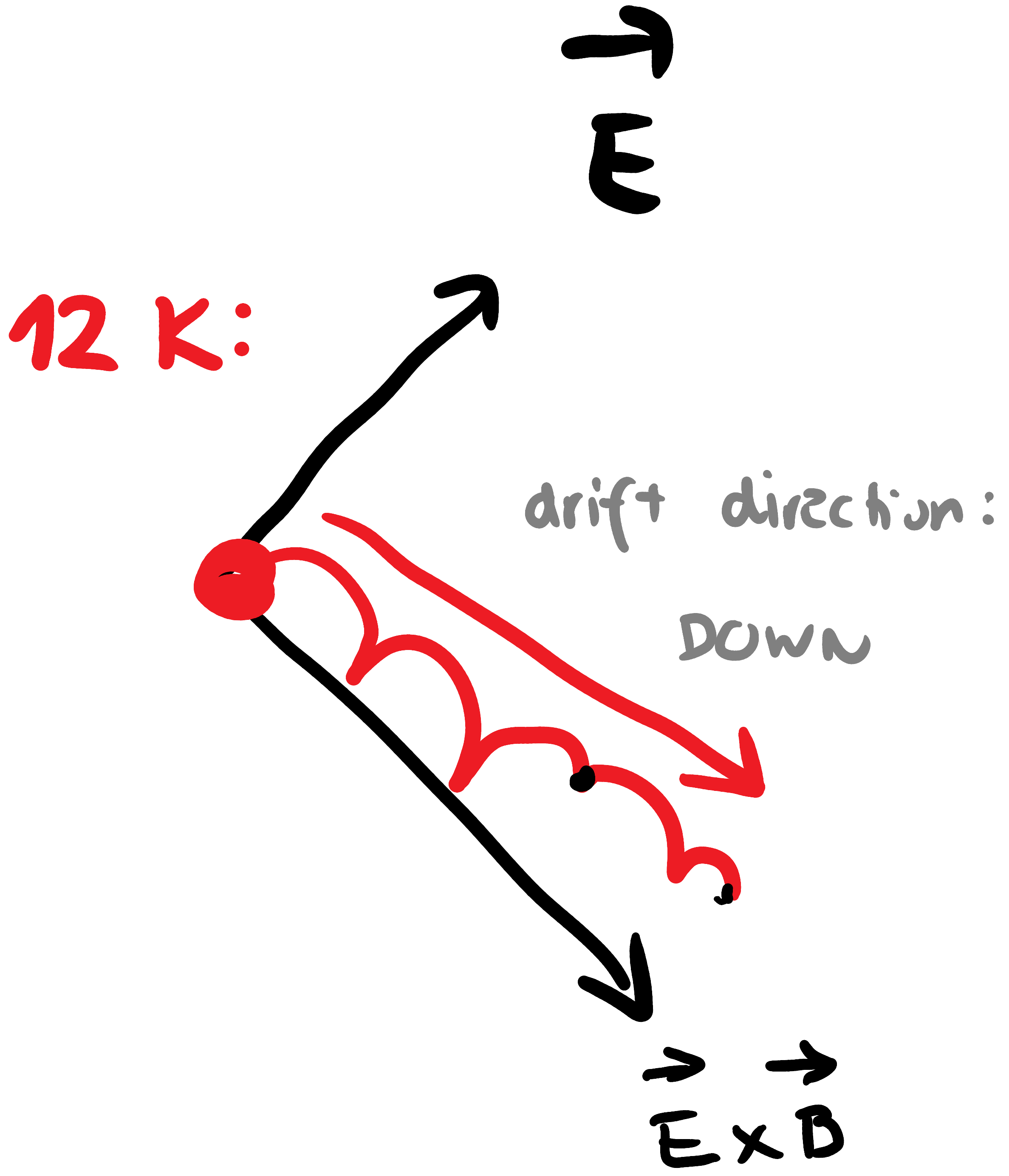
Trajectories in E and B field

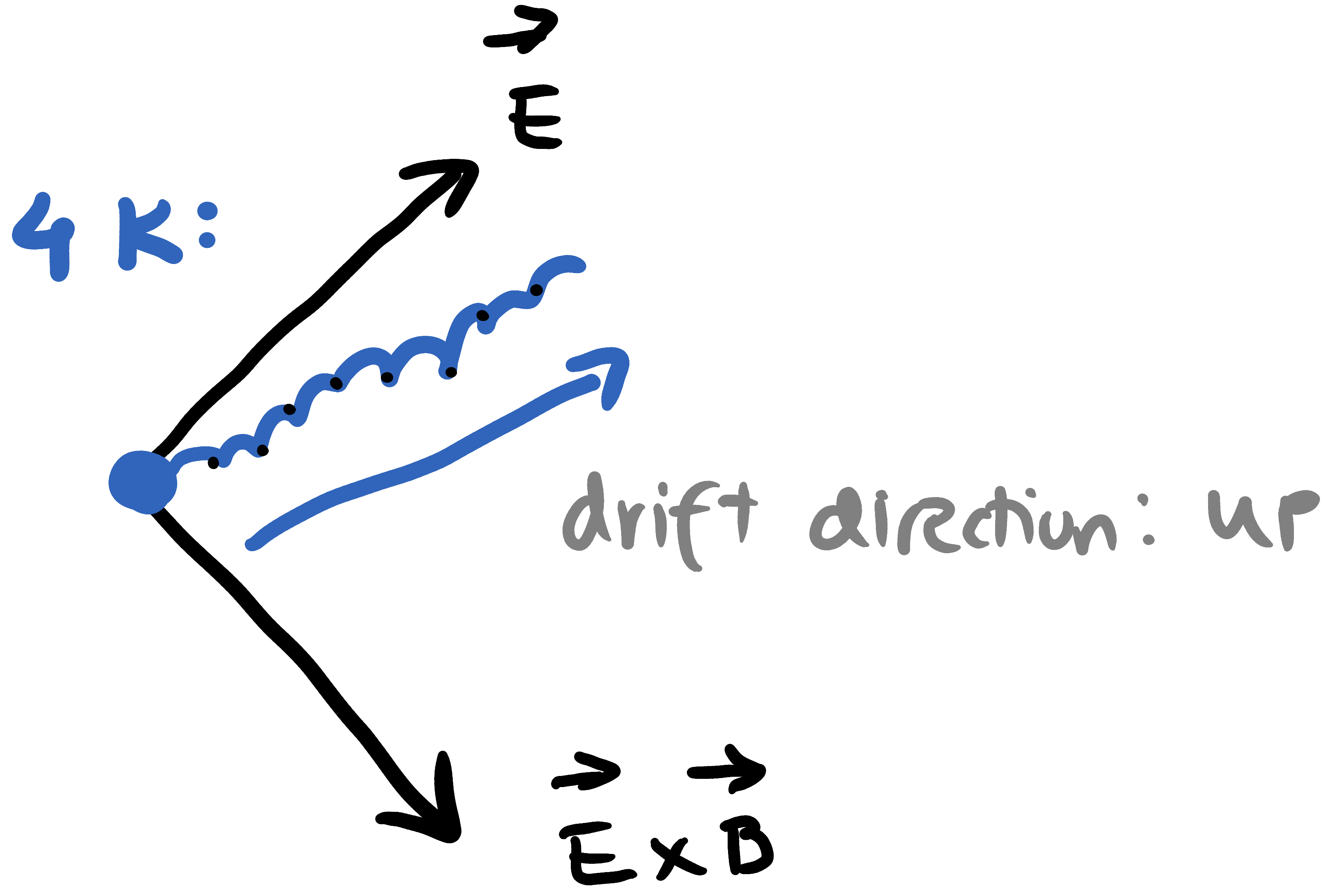


In gas: collisions ☆ with frequency f_{col}

Working principle: 1st Stage

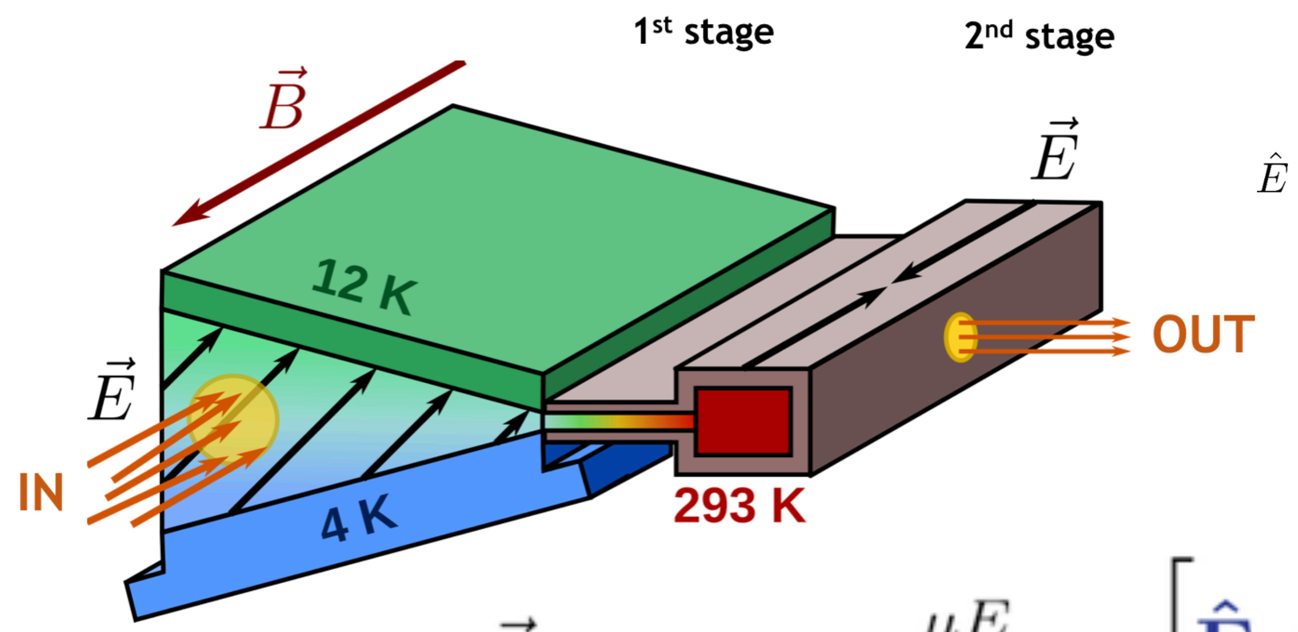


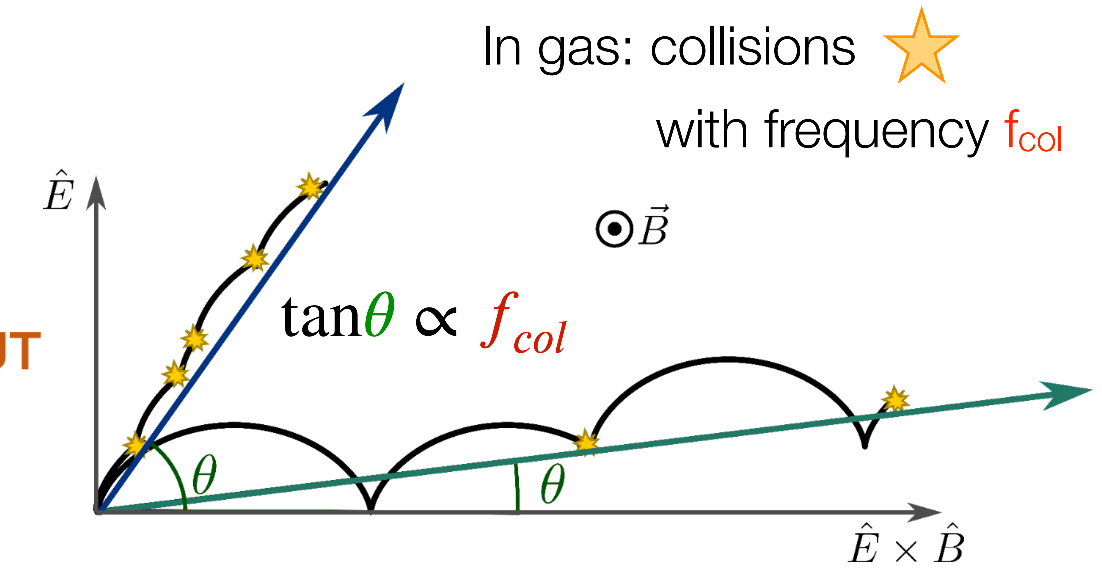




Summary: The muCool project at PSI

- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor **10^{10}** with an efficiency of O(**10^{-4}**)
- Longitudinal and transverse compression (1st stage + 2nd stage): experimentally proved
- **Next Step**: Extraction into vacuum
- Current activity: abundant MC simulations in order to define the detailed experimental setup for the beam extraction in vacuum and eventually the beam re-acceleration





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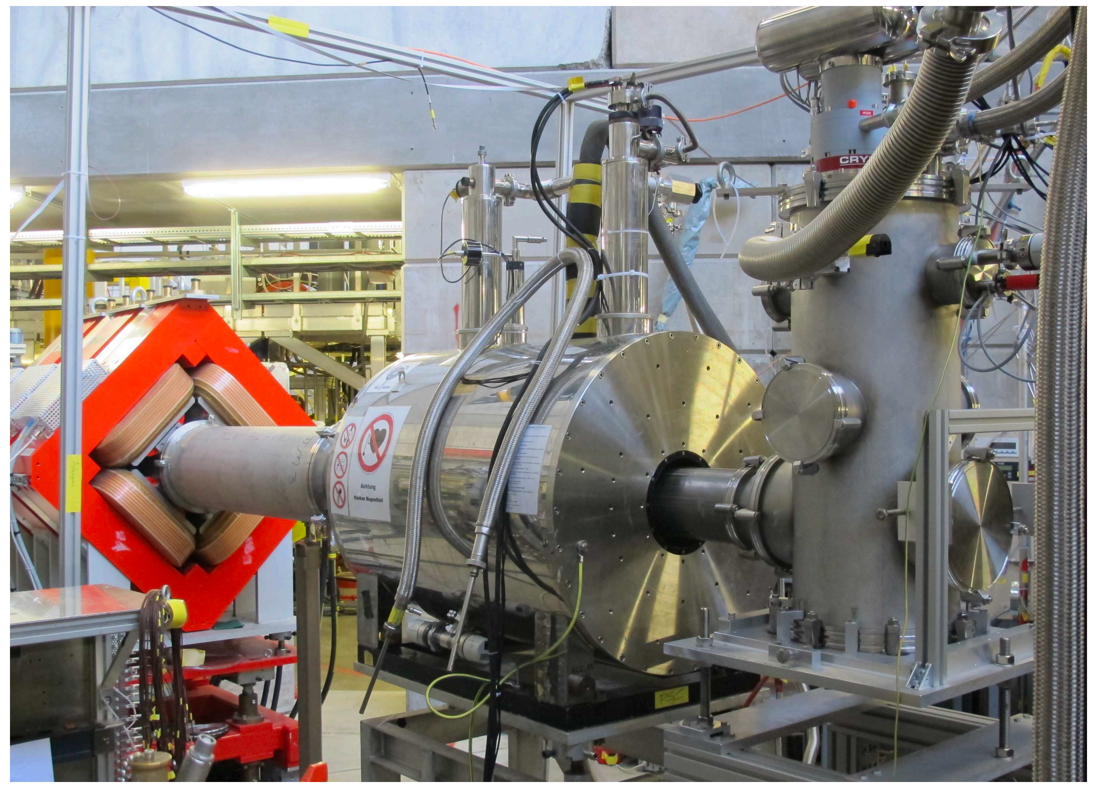
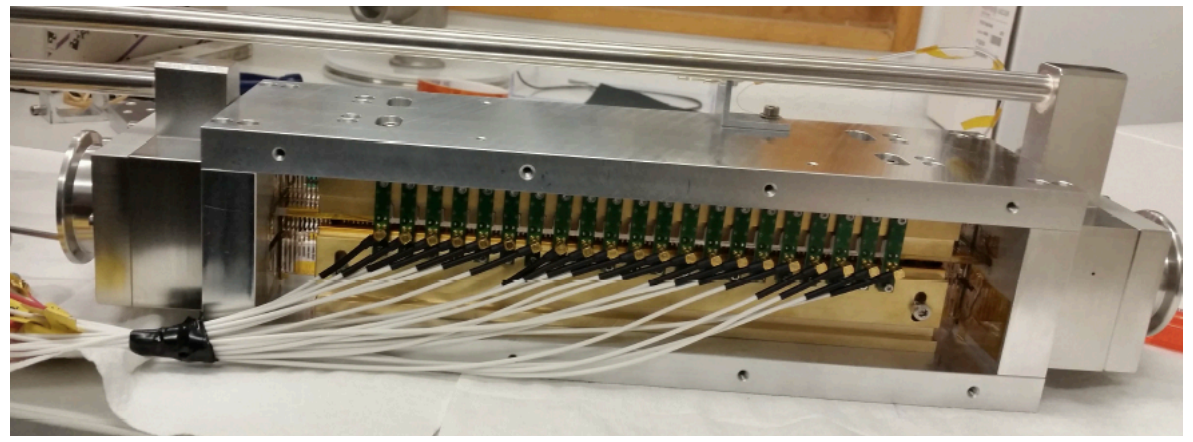
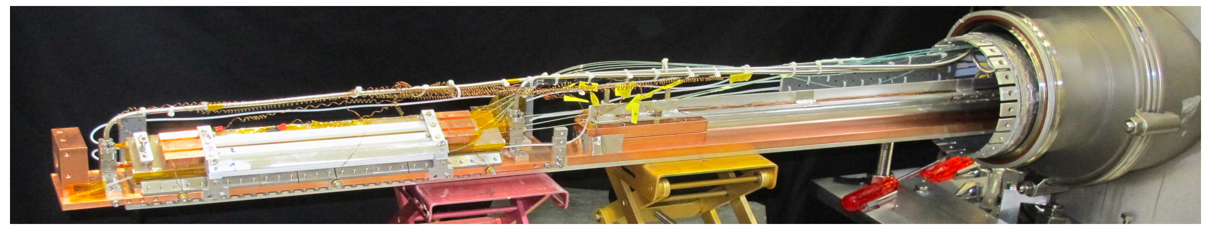
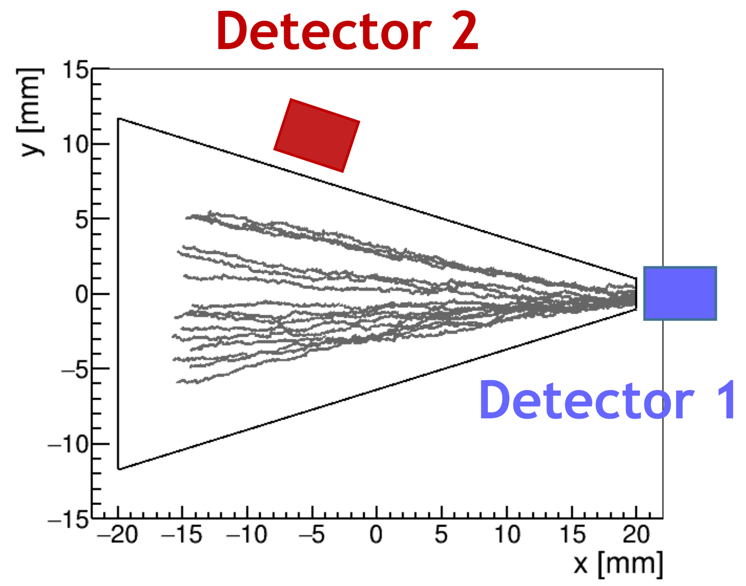
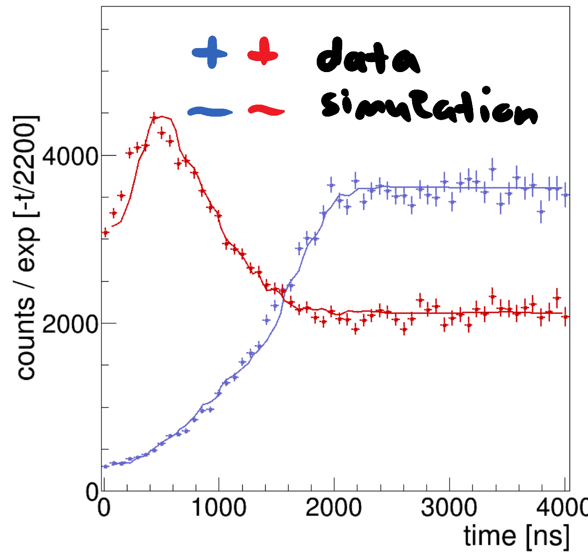




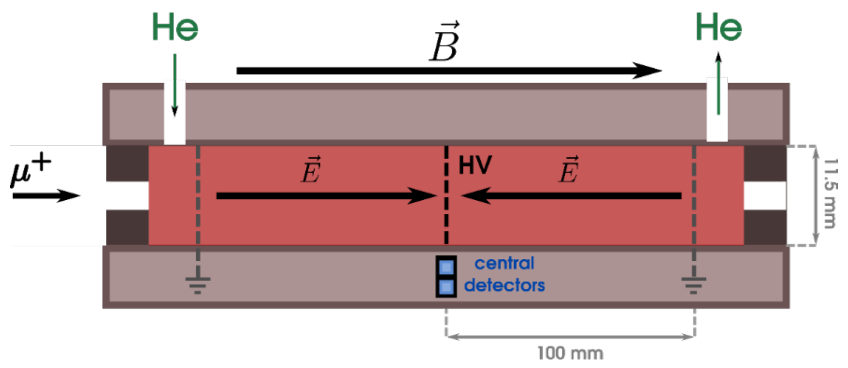


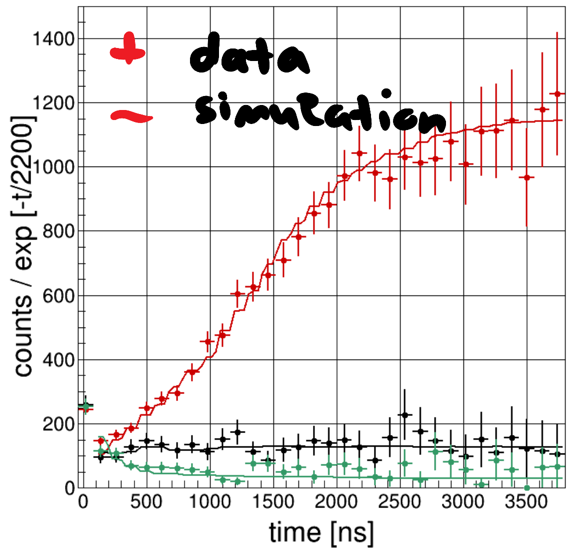
Transverse Compression



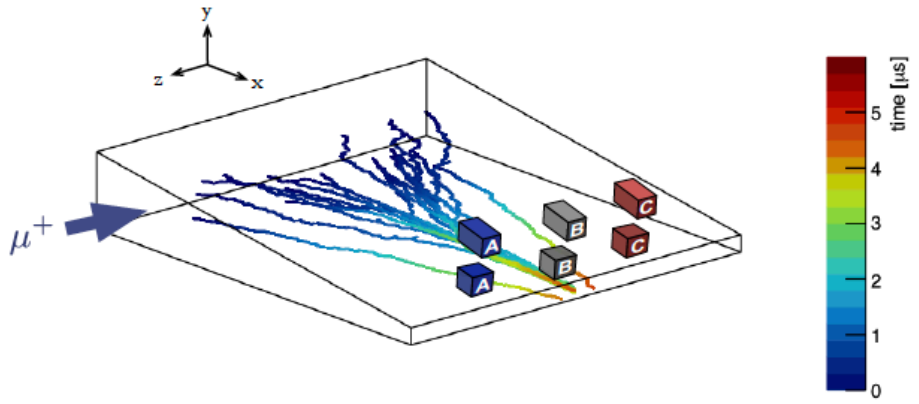


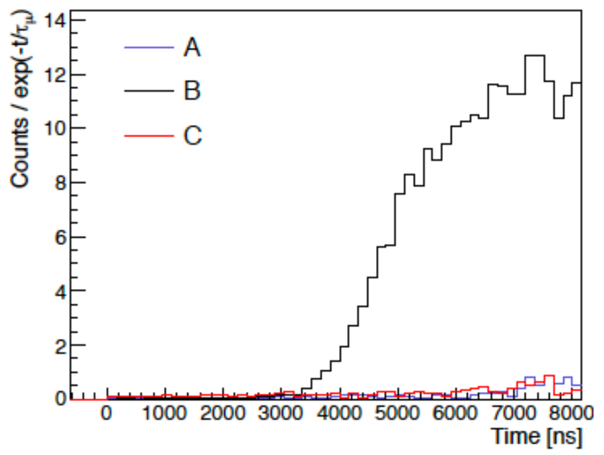
Longitudinal Compression





Longitudinal+ Transverse Compression

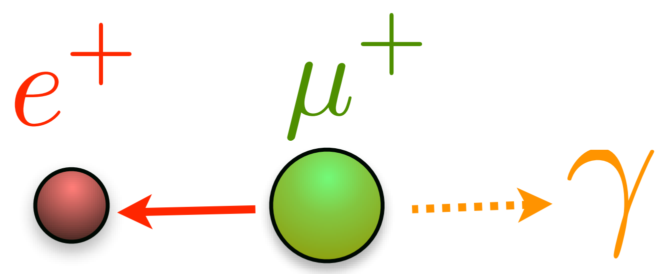




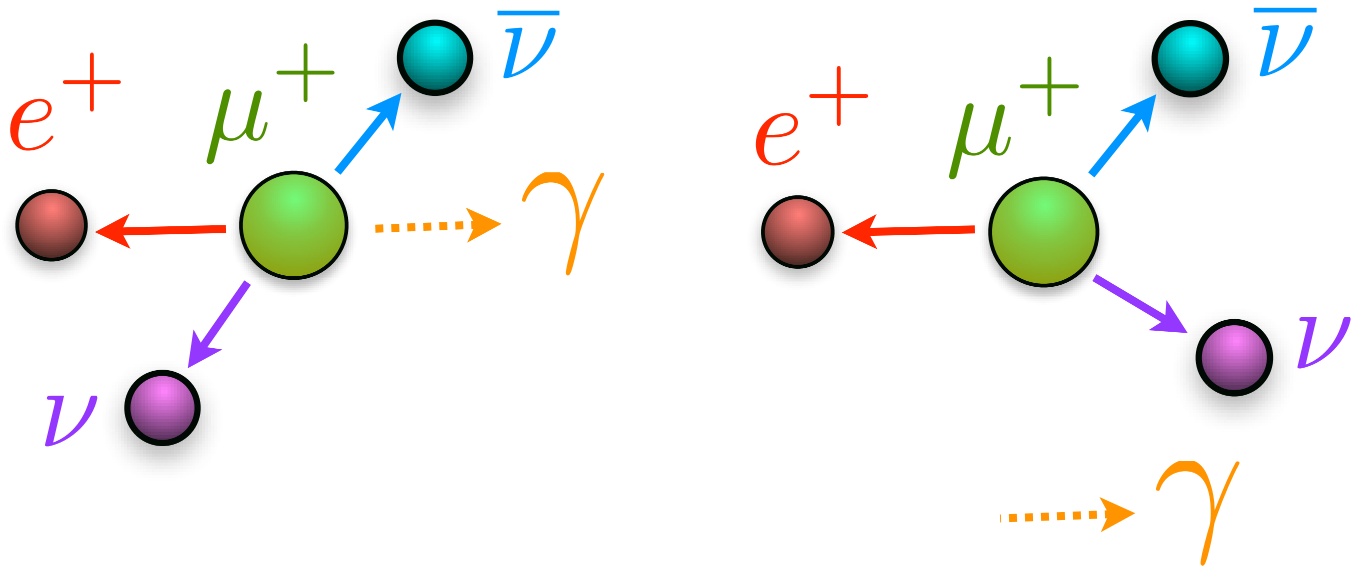
The MEGII experiment at PSI

- Best upper limit on the BR ($\mu^+ \rightarrow e^+ \gamma$) set by the MEG experiment (**$4.2\ 10^{-13}$** @90% C.L.)
- Searching for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~ **$6\ 10^{-14}$**
- Five observables **(E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg})** to identify $\mu^+ \rightarrow e^+ \gamma$ events

Signature



Backgrounds



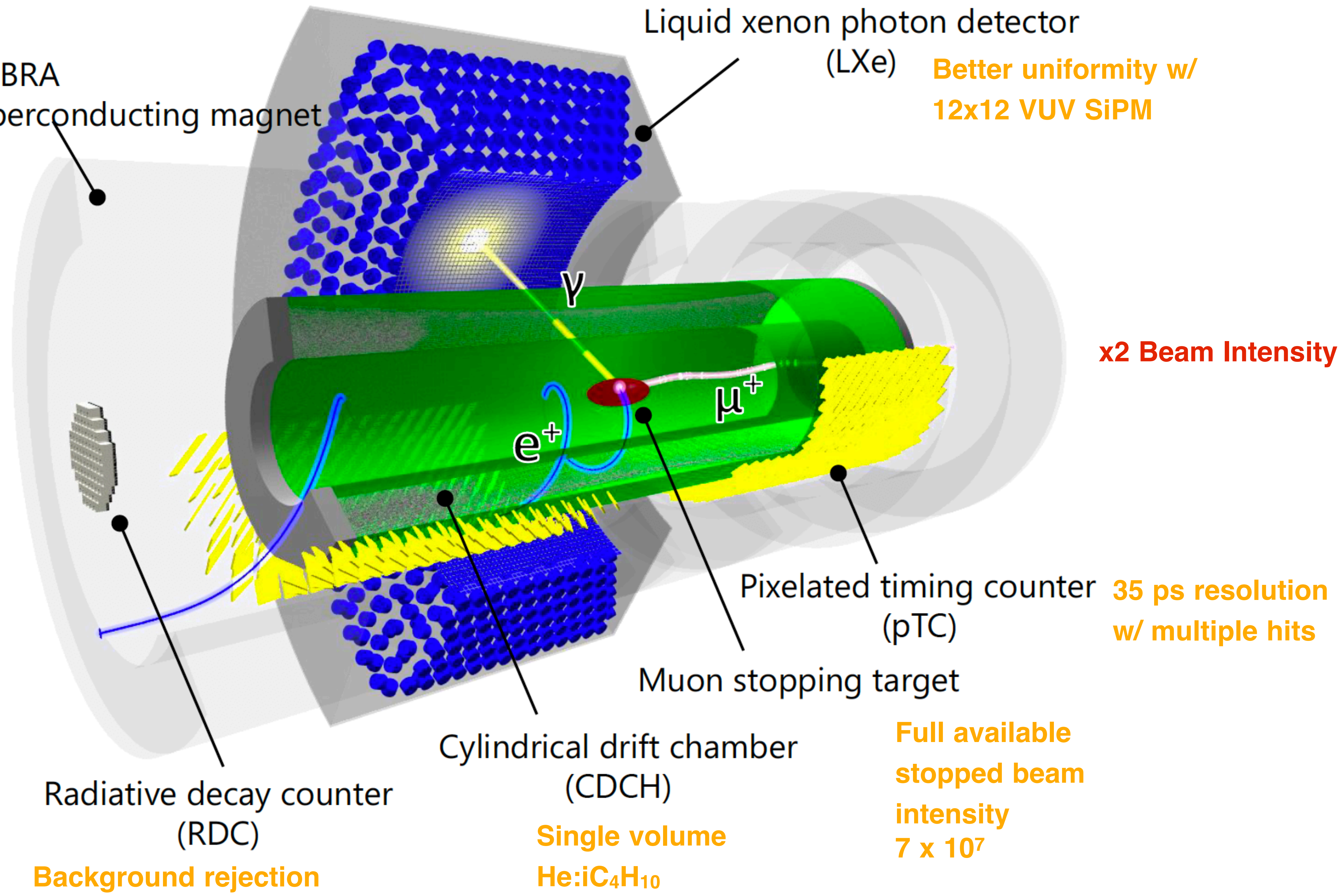
New electronics:
WaveDAQ

~9000 channels at 5GSPS

x2 Resolution everywhere

Updated and new Calibration methods

Quasi mono-chromatic positron beam

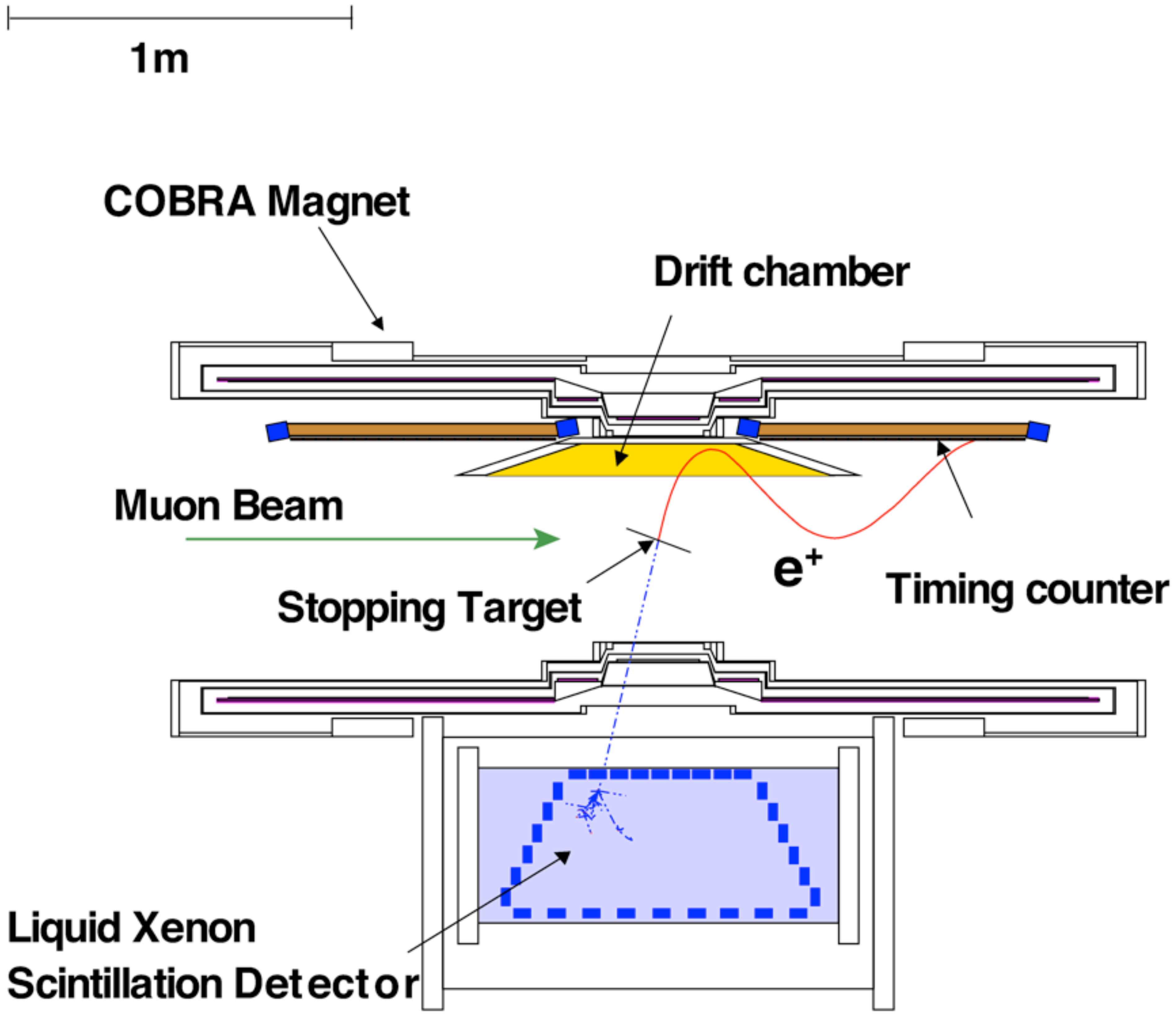


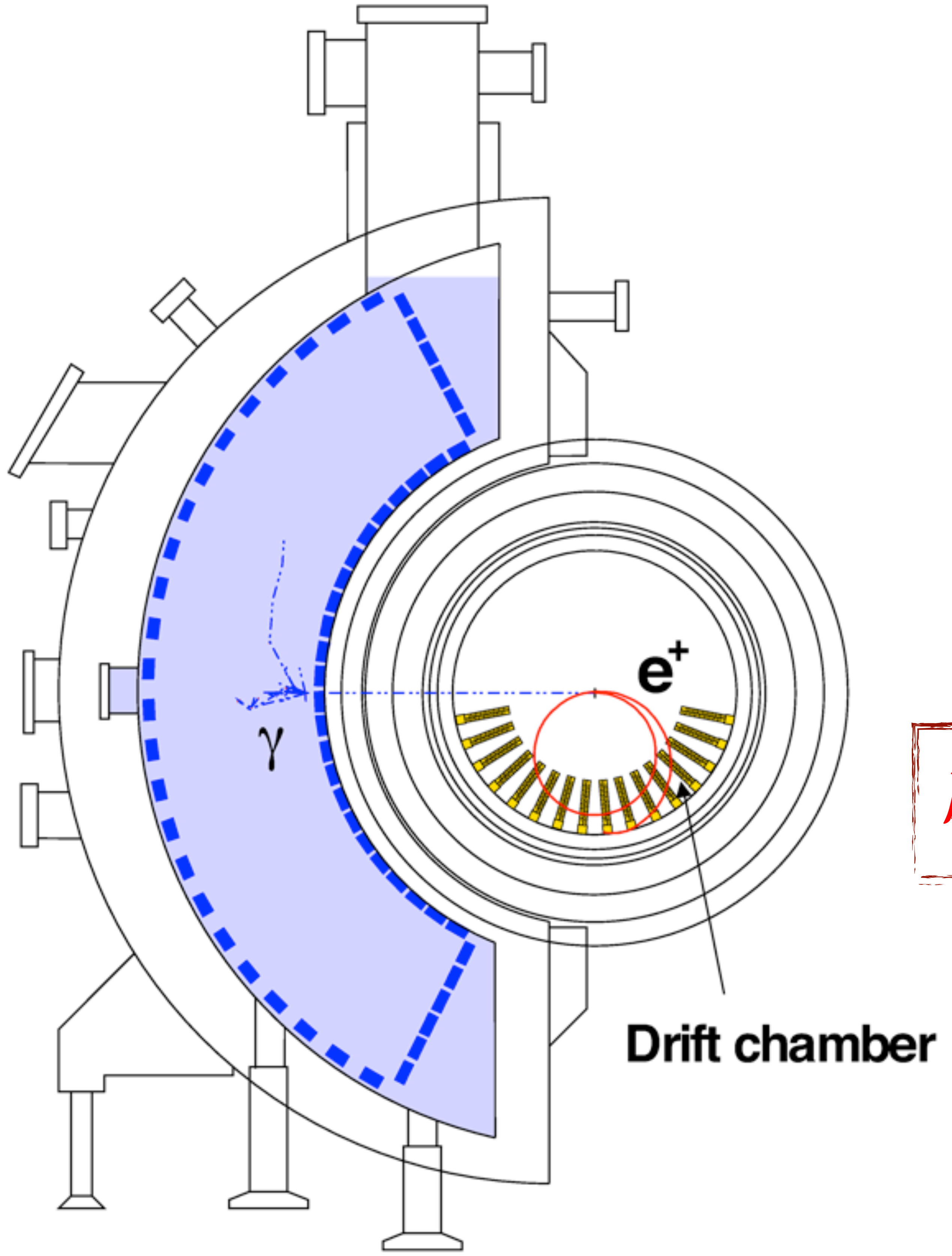
A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C73 (2013) 2365

A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C76 (2016) no. 8, 434

A step back: The MEG experiment

- The MEG experiment aims to search for $\mu^+ \to e^+ \gamma$ with a sensitivity of ~10^{-13} (previous upper limit $BR(\mu^+ \to e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \to e\gamma$ events



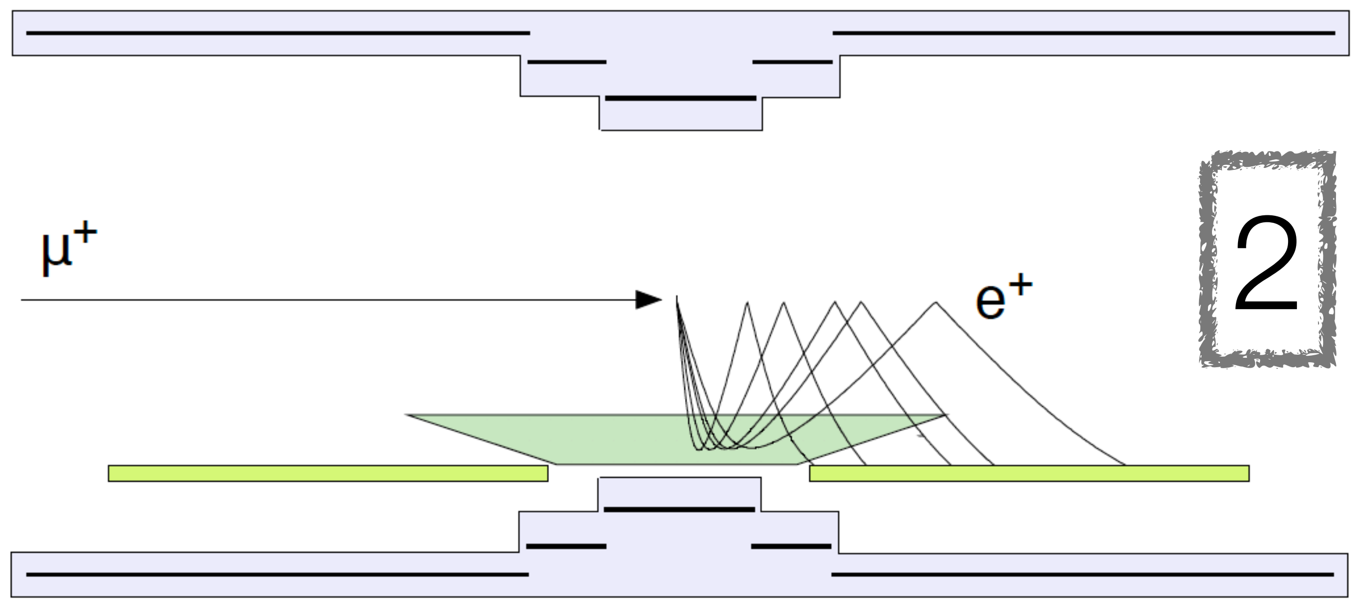


Full data sample:
2009-2013
Best fitted branching ratio
at 90% C.L.:

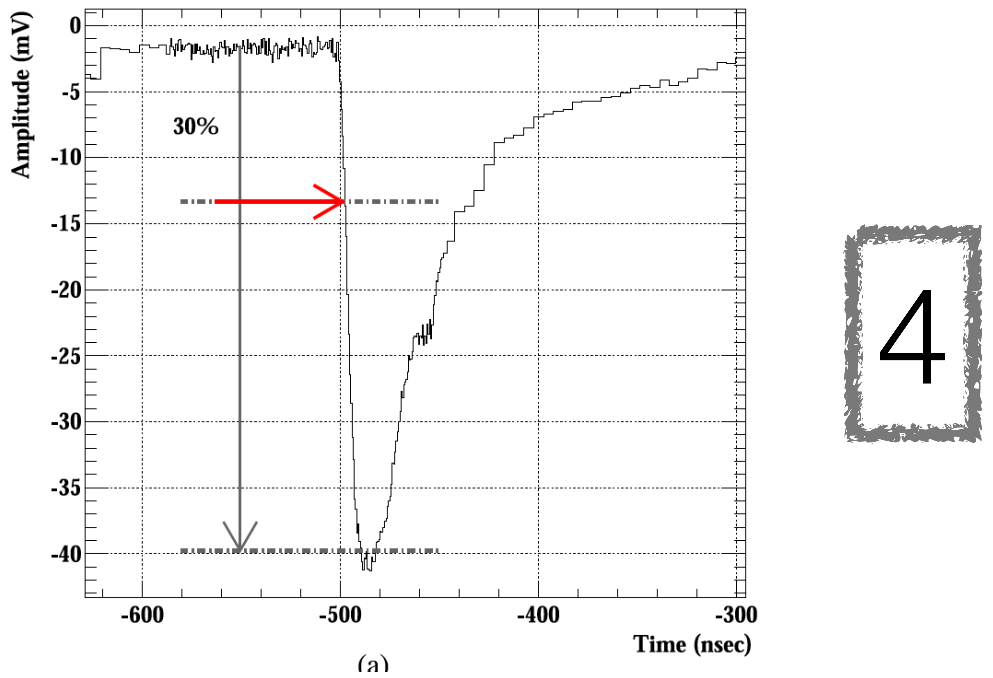
$$\boxed{\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}}$$

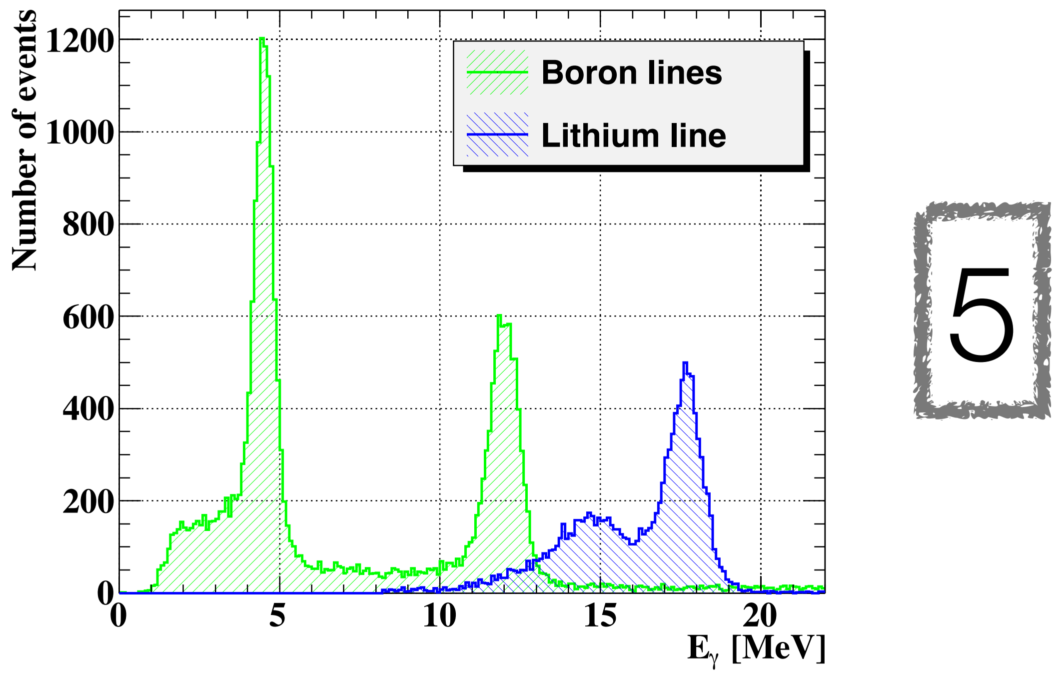
MEG: The key elements

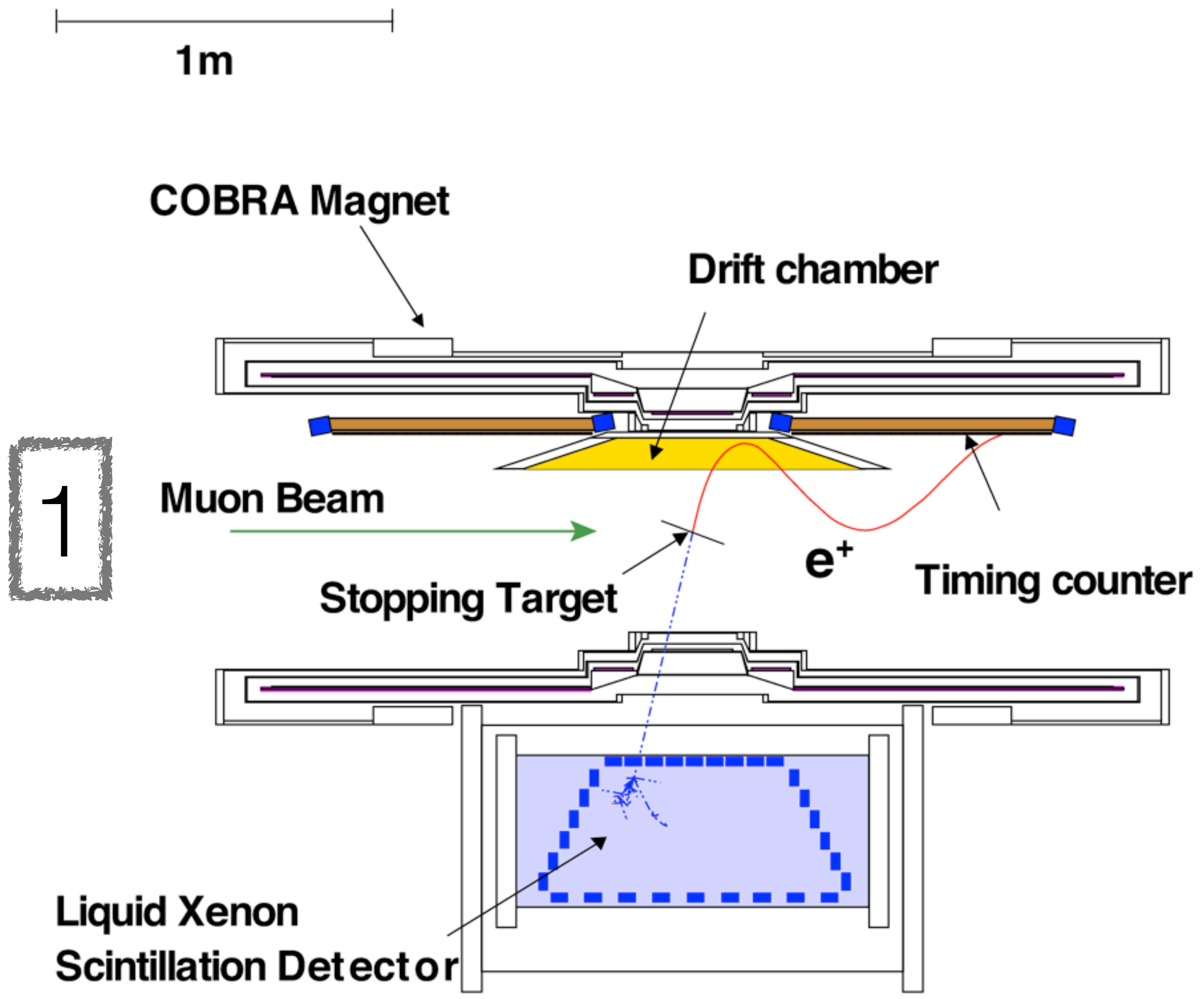
1. The world's intense low momentum muon beam stopped in a thin and slanted target
2. The gradient field e+-spectrometer
3. The innovative Liquid Xenon calorimeter
4. The full waveform based DAQ (digitization up to 1.6 GSample/s)
5. Complementary calibration and monitoring methods

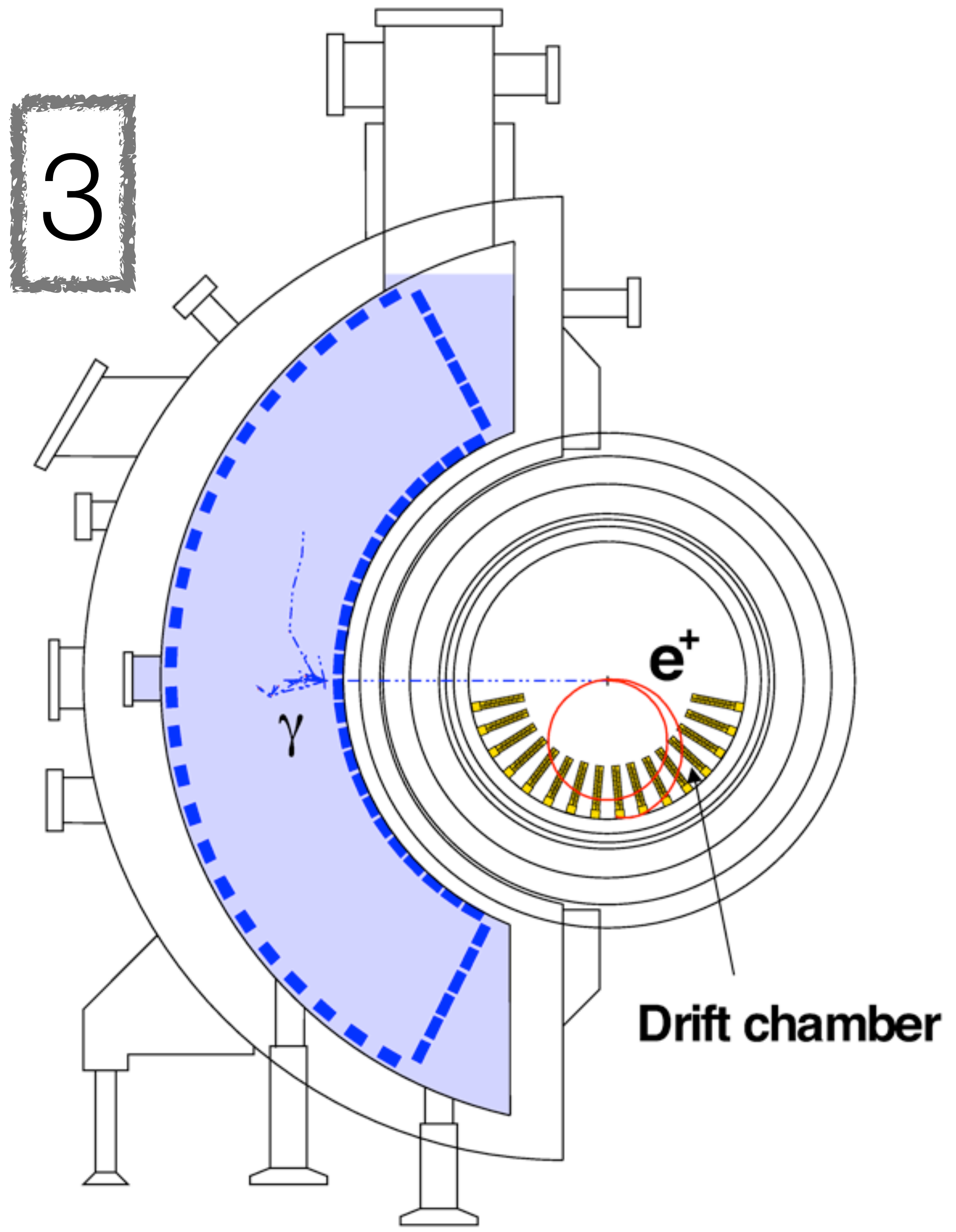


a) Constant projected bending radius for positrons with equal momentum.

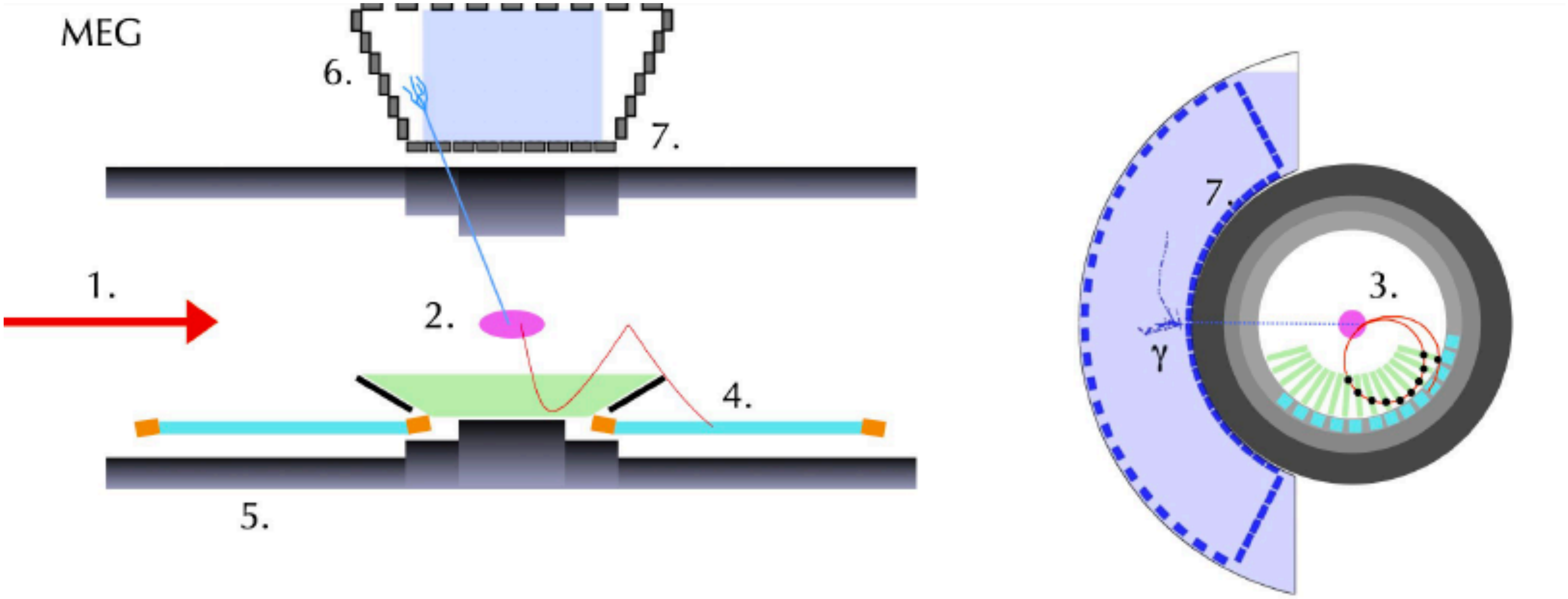








The MEG experiment vs the MEGII experiment



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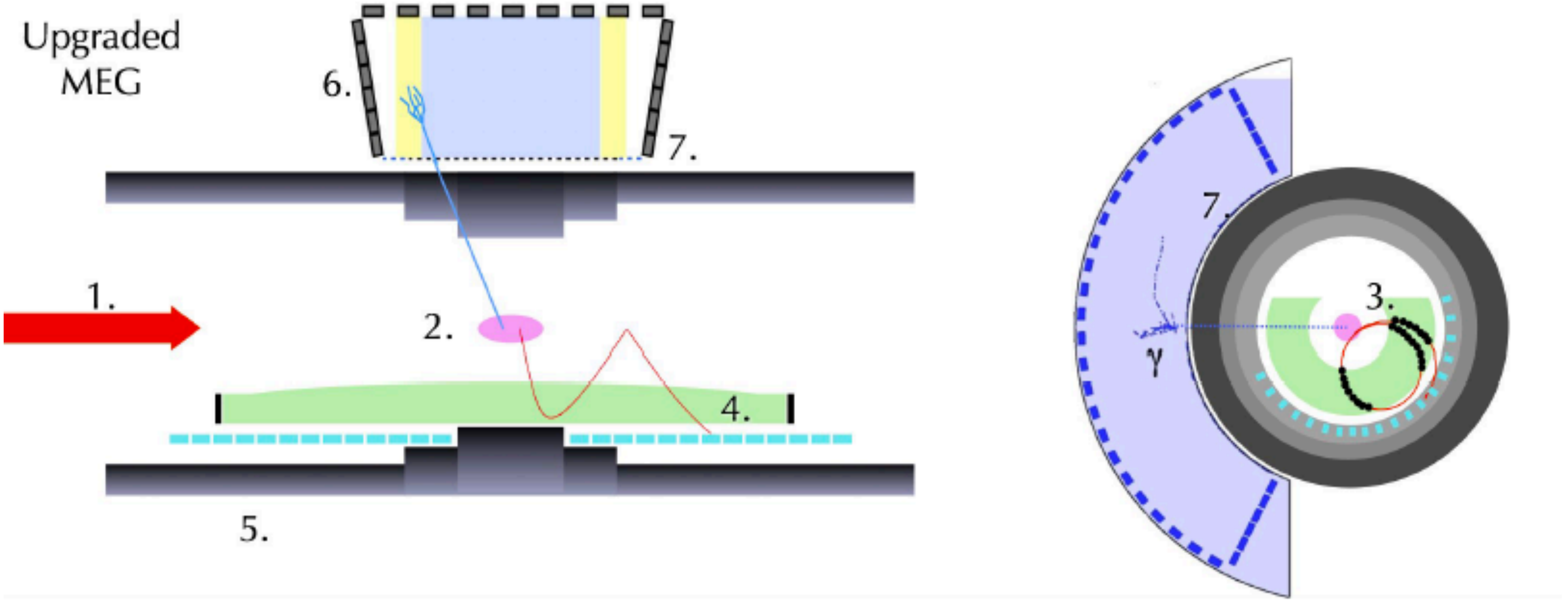
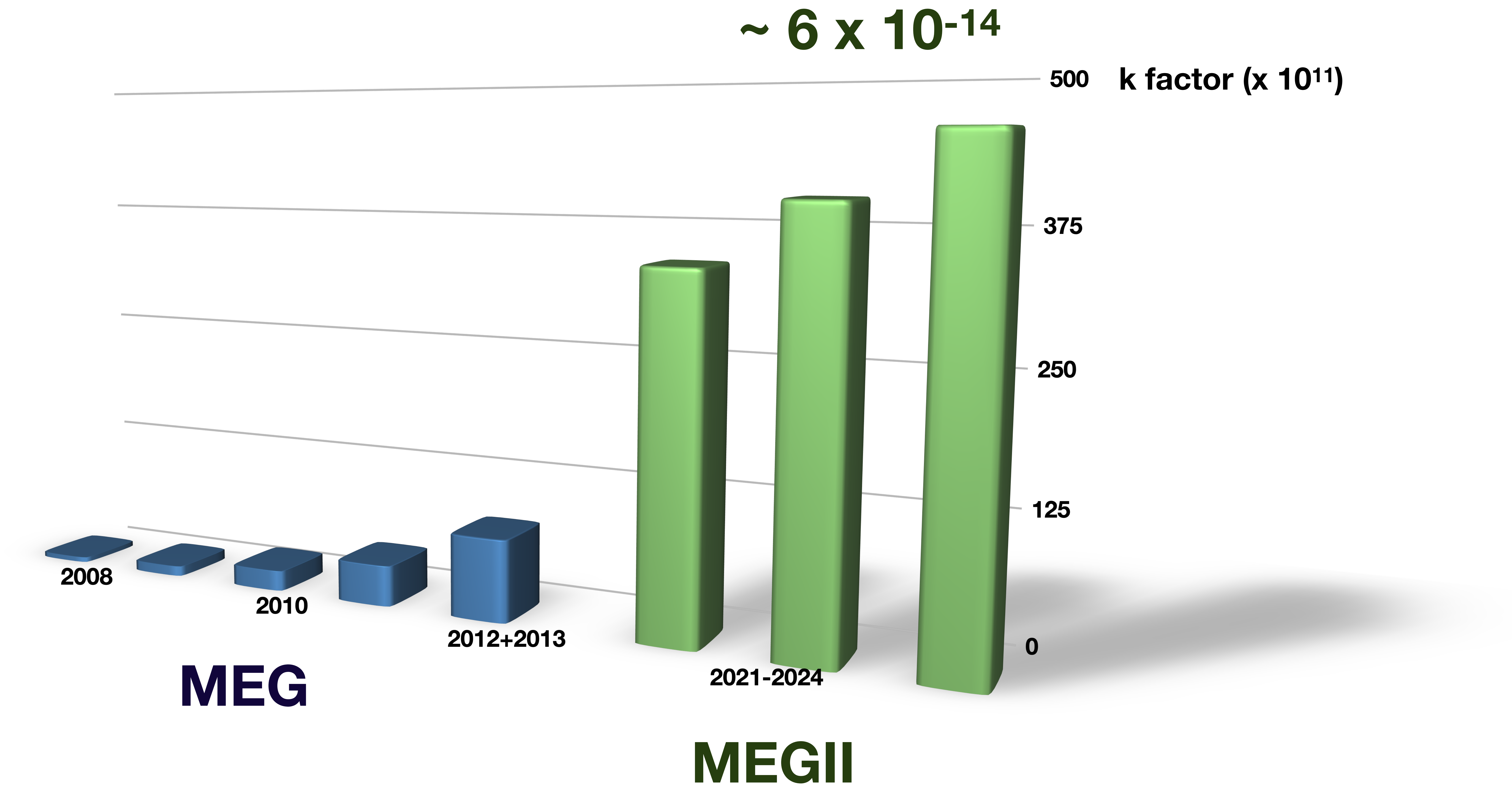


Where we will be



Latest news and currents status

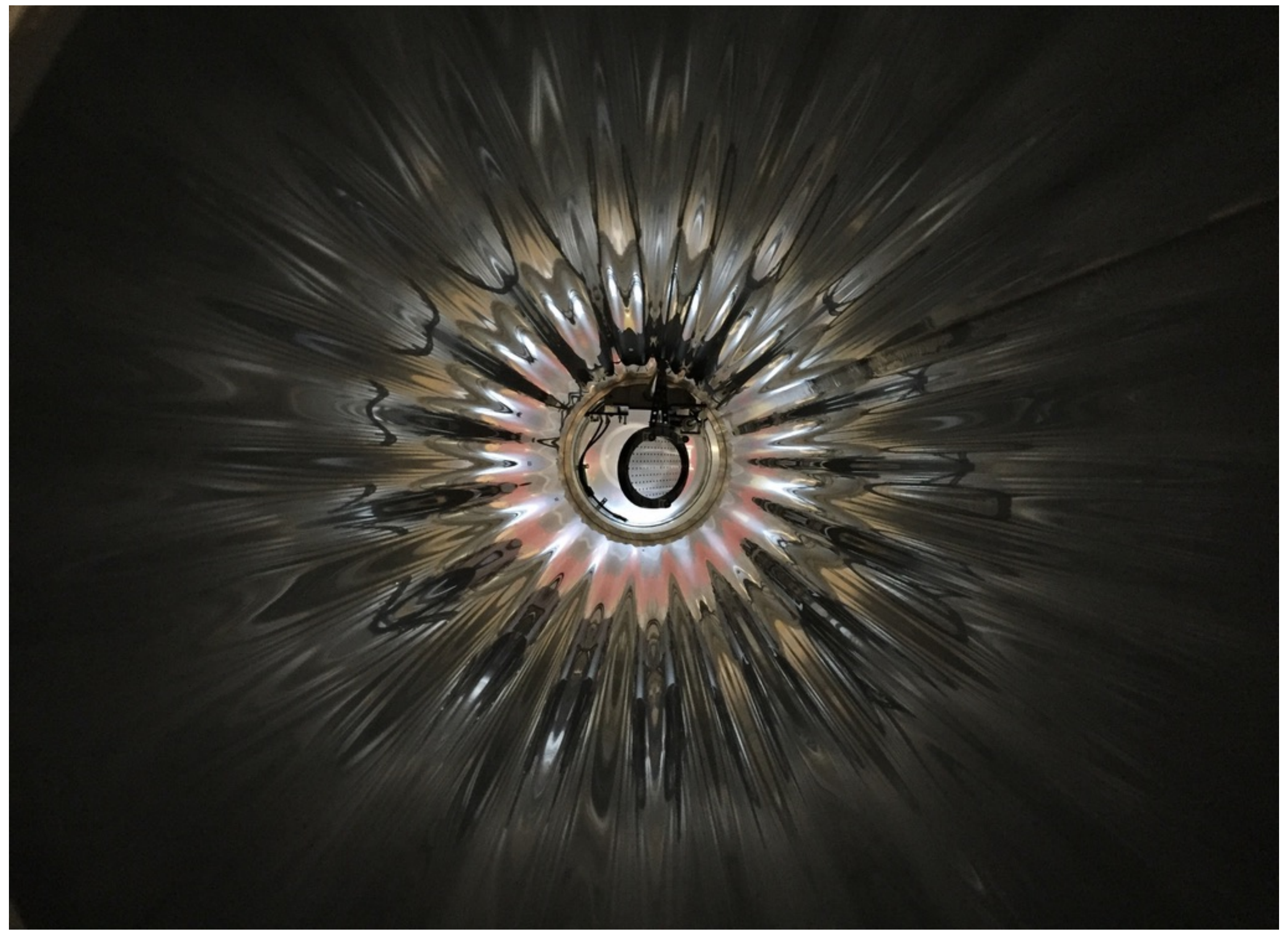
Key points:

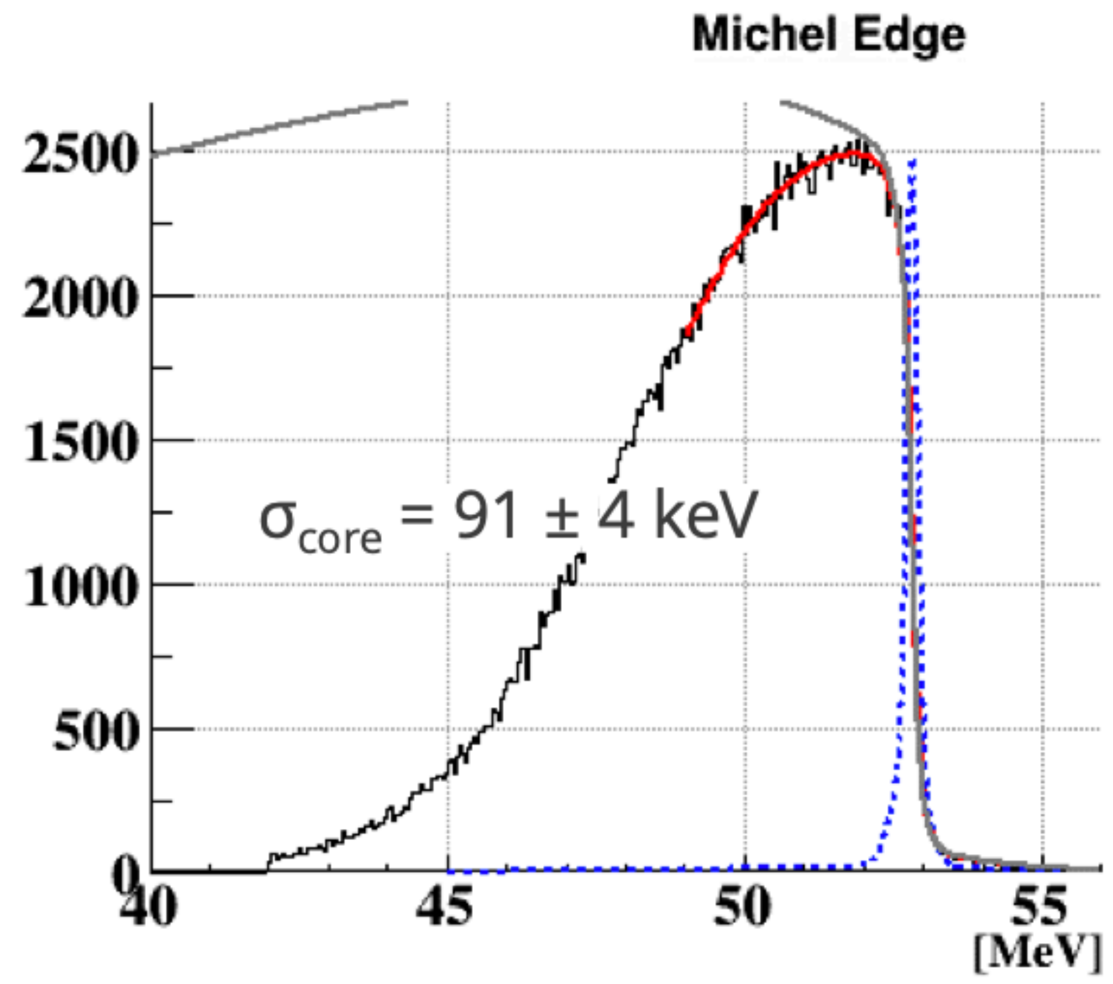
- **Run2021 very successful**
- Electronics fully installed and tested with all sub-detectors and calibration tools
- All calibration and physics trigger configurations released
- Assessed performances of each sub-detectors in the final MEG II conditions
- Collected data at different beam intensities
- Dedicated RMD at reduced beam intensity as proof-of-principle of the experiment quality
- **Physics run started at the end of September 2021**
- …with the COVID19 outbreak ongoing

Outlook:

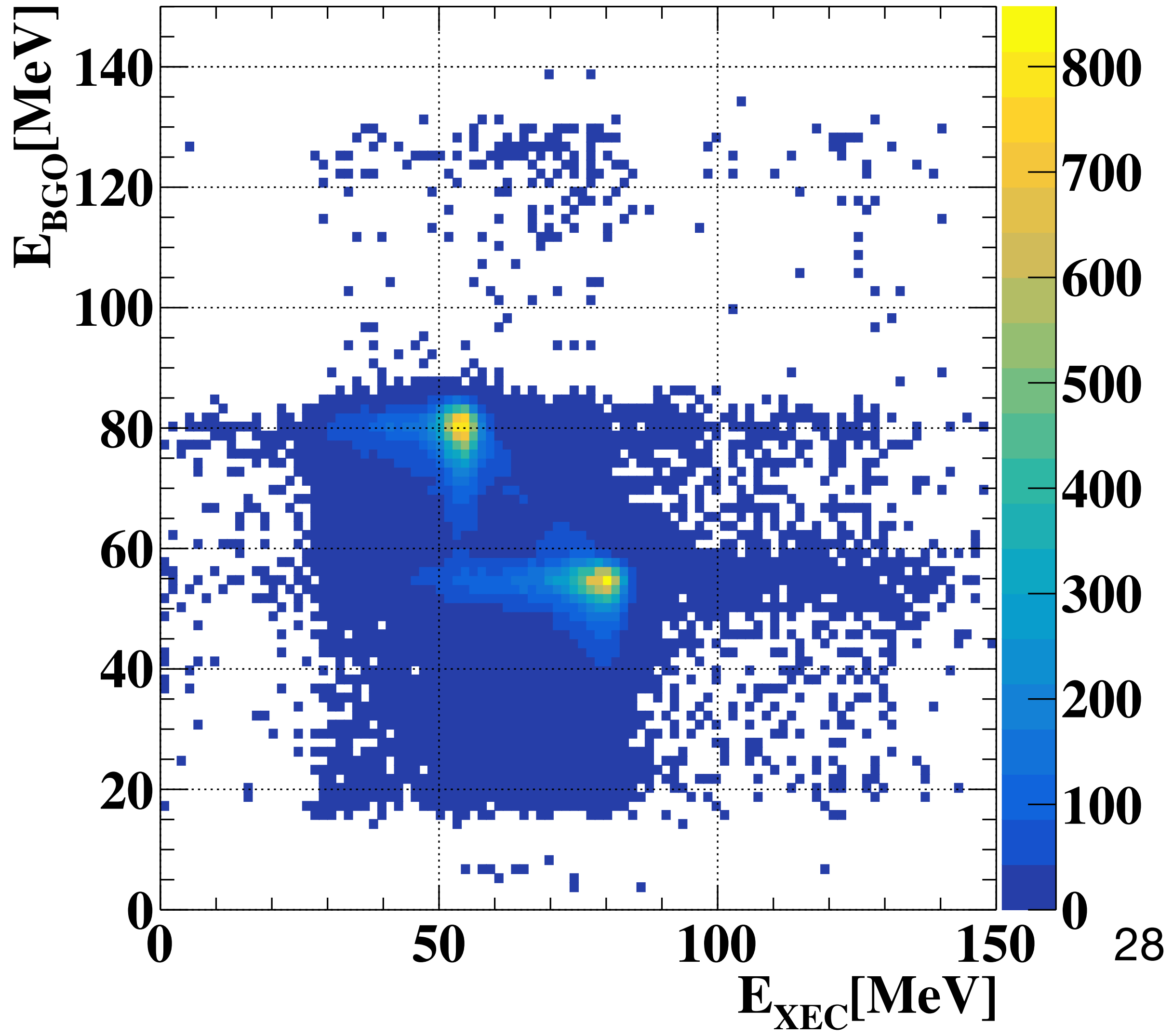
- **MEGII beam time 2022 started on June 7th**
- The run with muons has been completed on Nov 17th
- MEG sensitivity expected to be **surpassed by the Run 2022 and actually fully addressed it**
- **MEG 2022 the MOST efficient physics run compared to all the others (including MEG) physics run!!!**
- **Calibration of the detectors with pion beam currently ongoing**

MEGII **fully** installed!



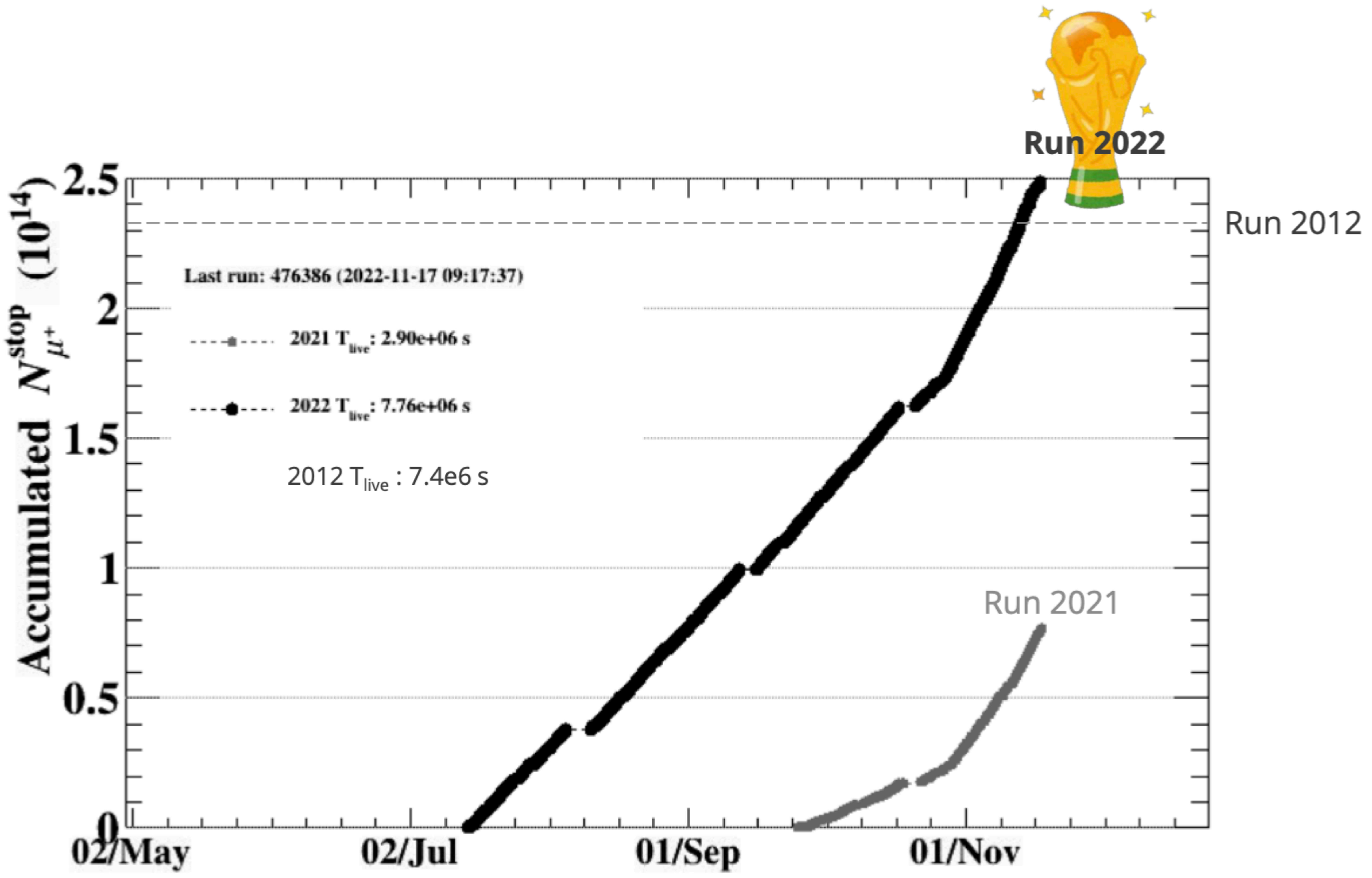


Data from the **first** Physics Run2021



MEGII: A very successful physics run 2022…

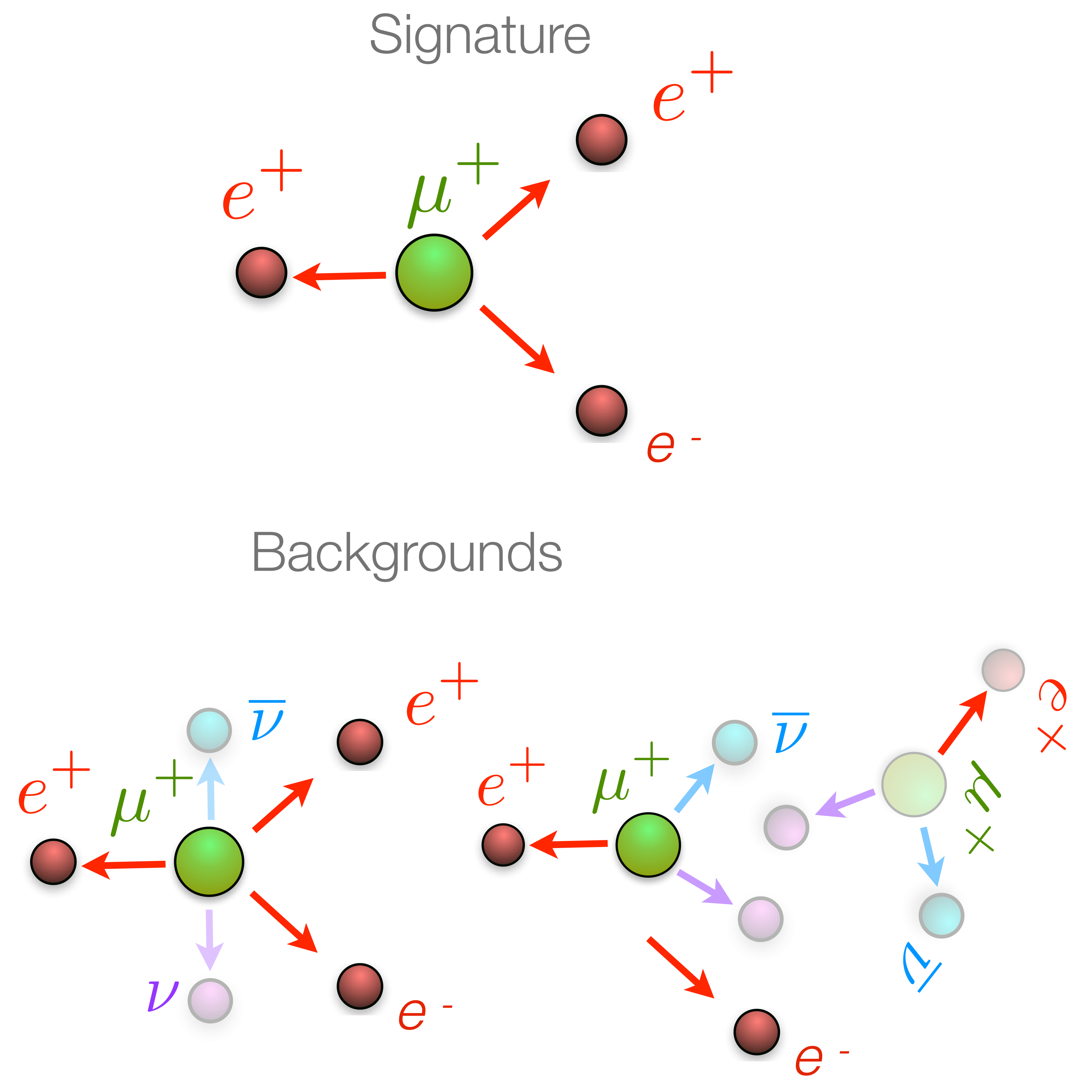
- A large amount of data already collected
- Intense work on the analysis to be ready with all the algorithms for the mu e gamma search
- Data taking will continue the next years to achieve the final sensitivity

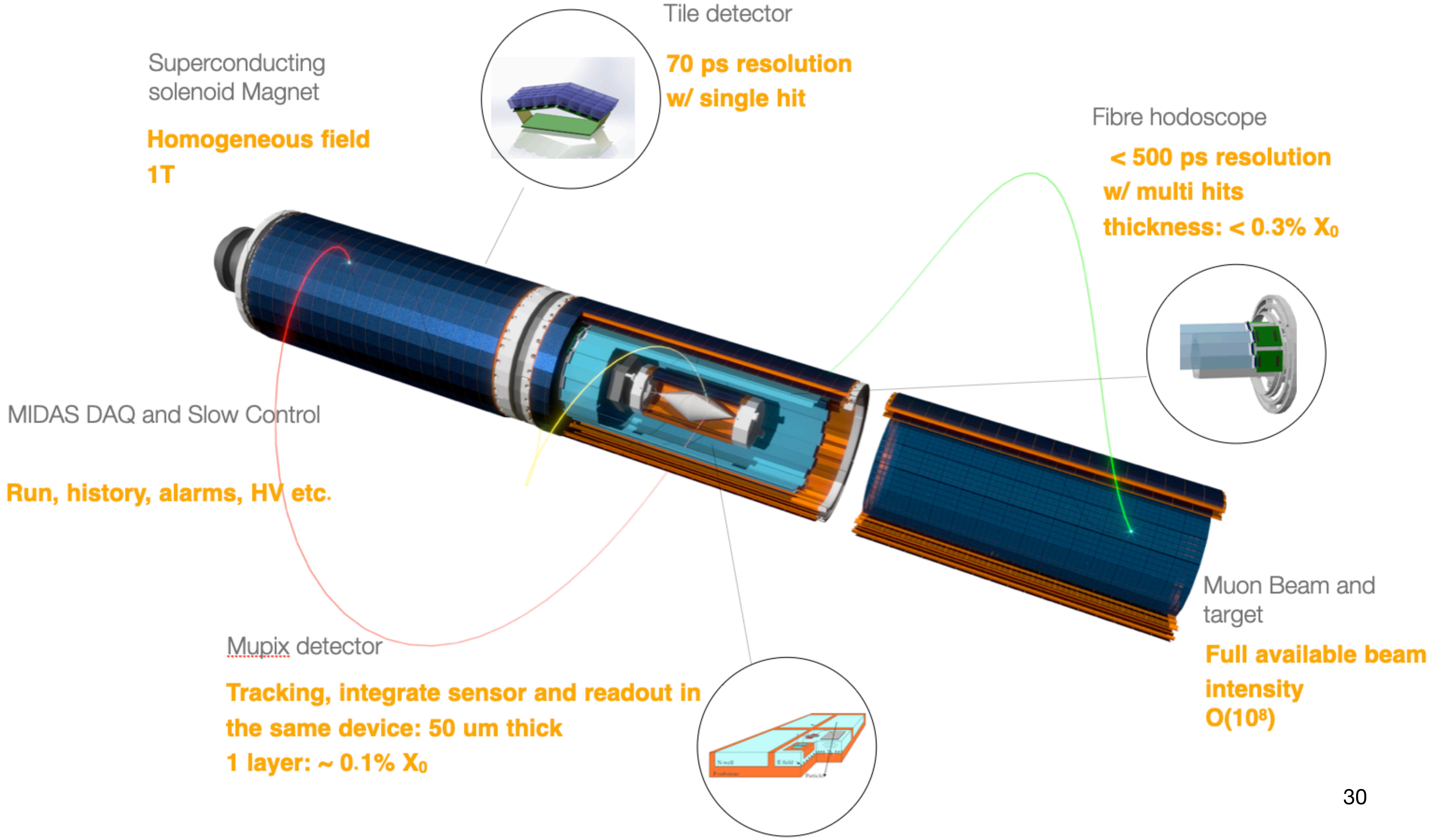


Longest run we ever achieved,
×3 statistics of 2021

The Mu3e experiment at PSI

- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of $\sim 10^{-15}$ (Phase I) up to down $\sim 10^{-16}$ (Phase II). Previous upper limit $BR(\mu^+ \rightarrow e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by SINDRUM experiment)
- Observables (E_e, t_e, vertex) to characterize $\mu \rightarrow eee$ events

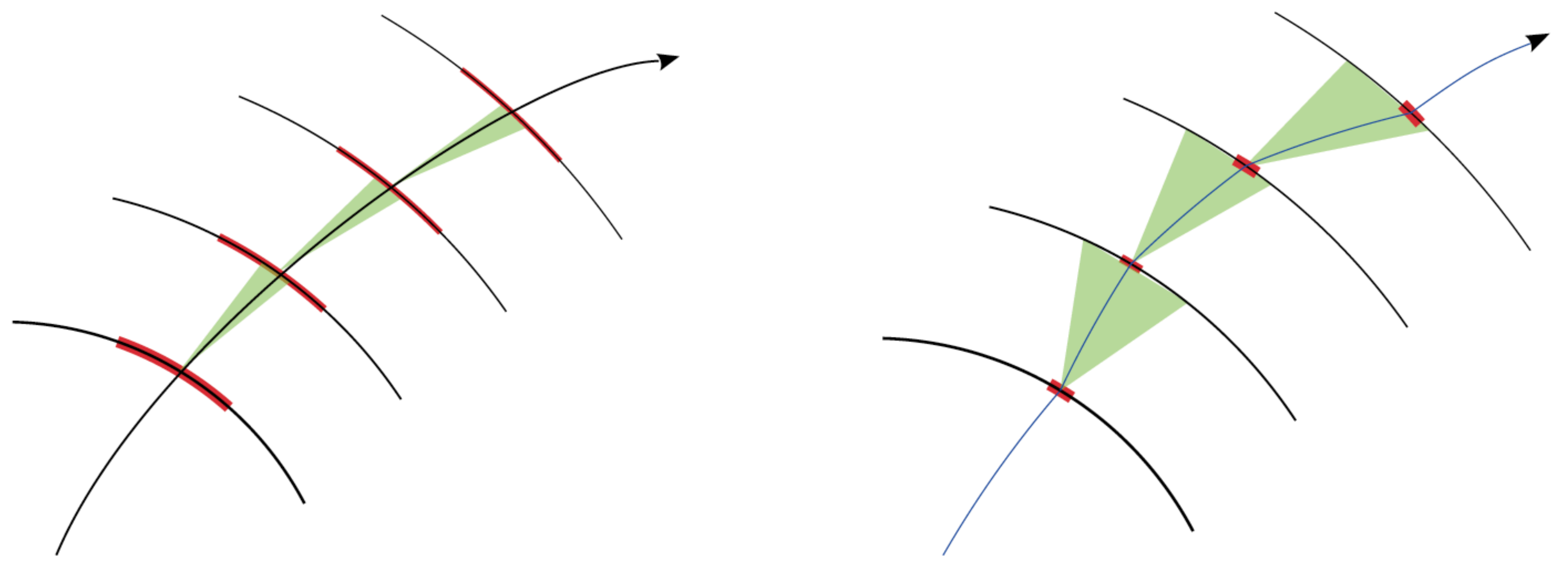




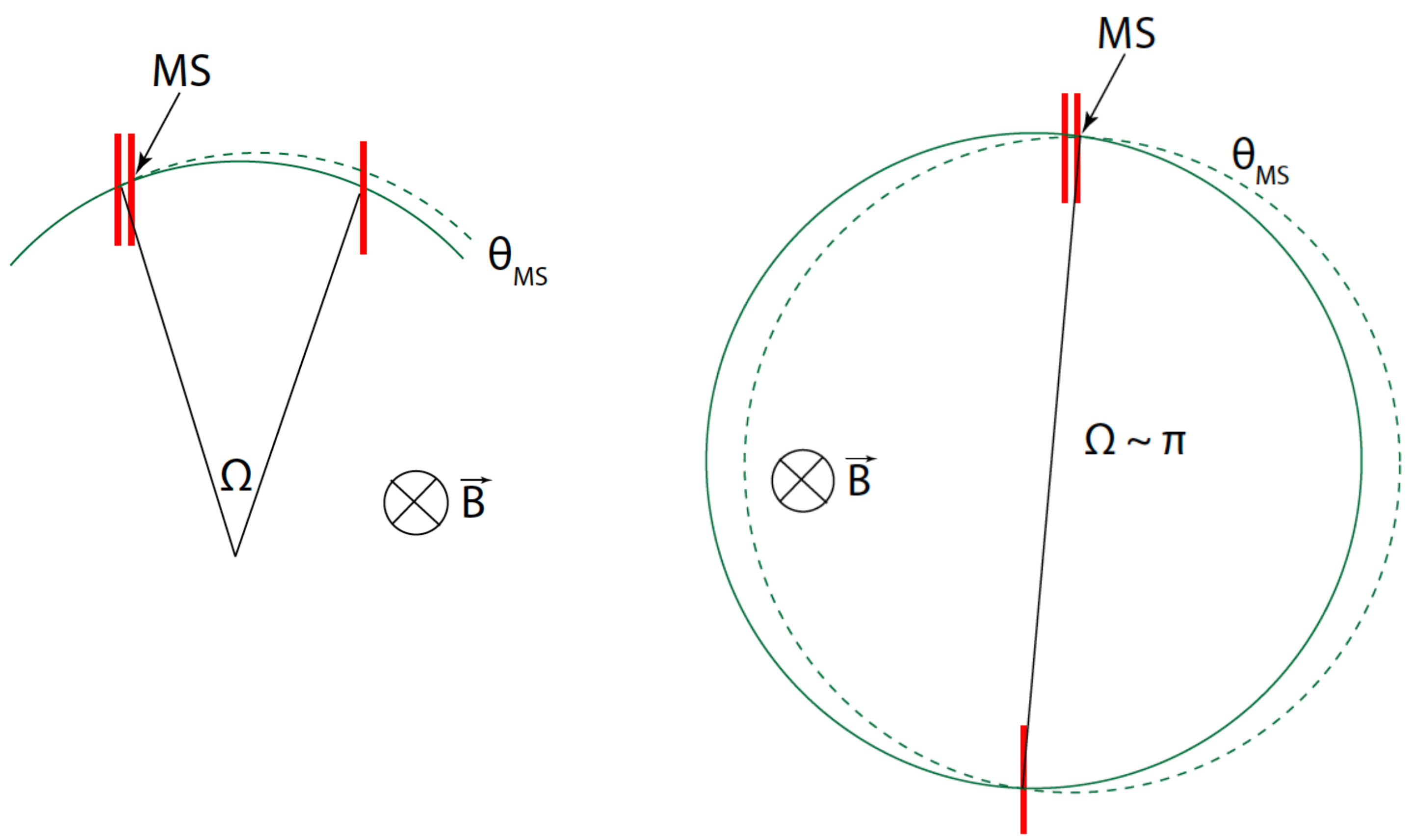
The pixel tracker: The principle

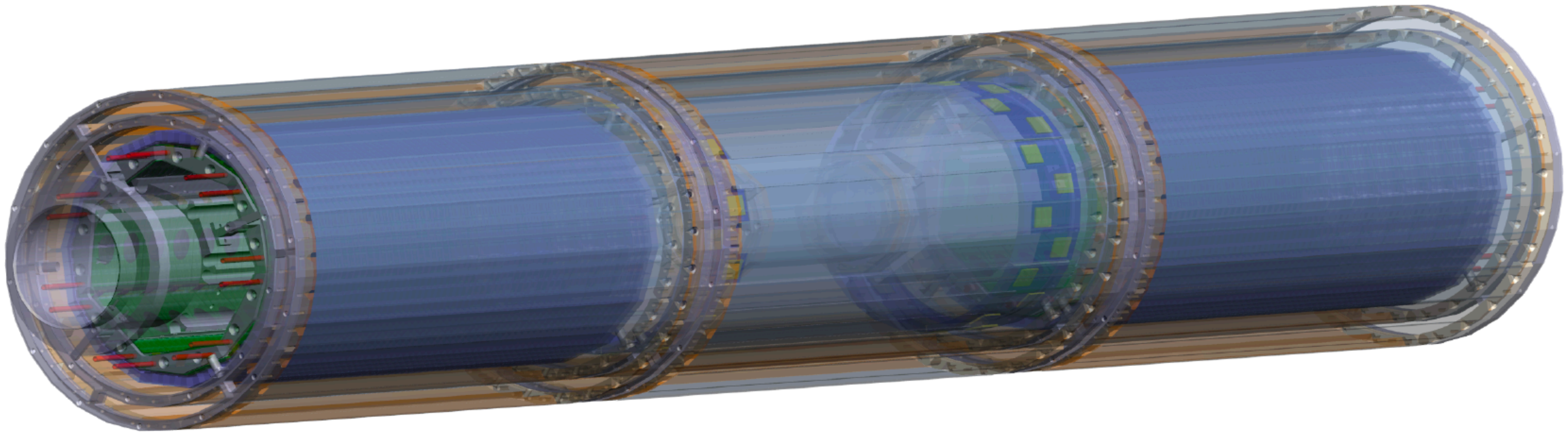
- Central tracker: Four layers; Re-curl tracker: Two layers
- Minimum material budget: Tracking in the scattering dominated regime

Tracking in the spacial and scattering dominated regime



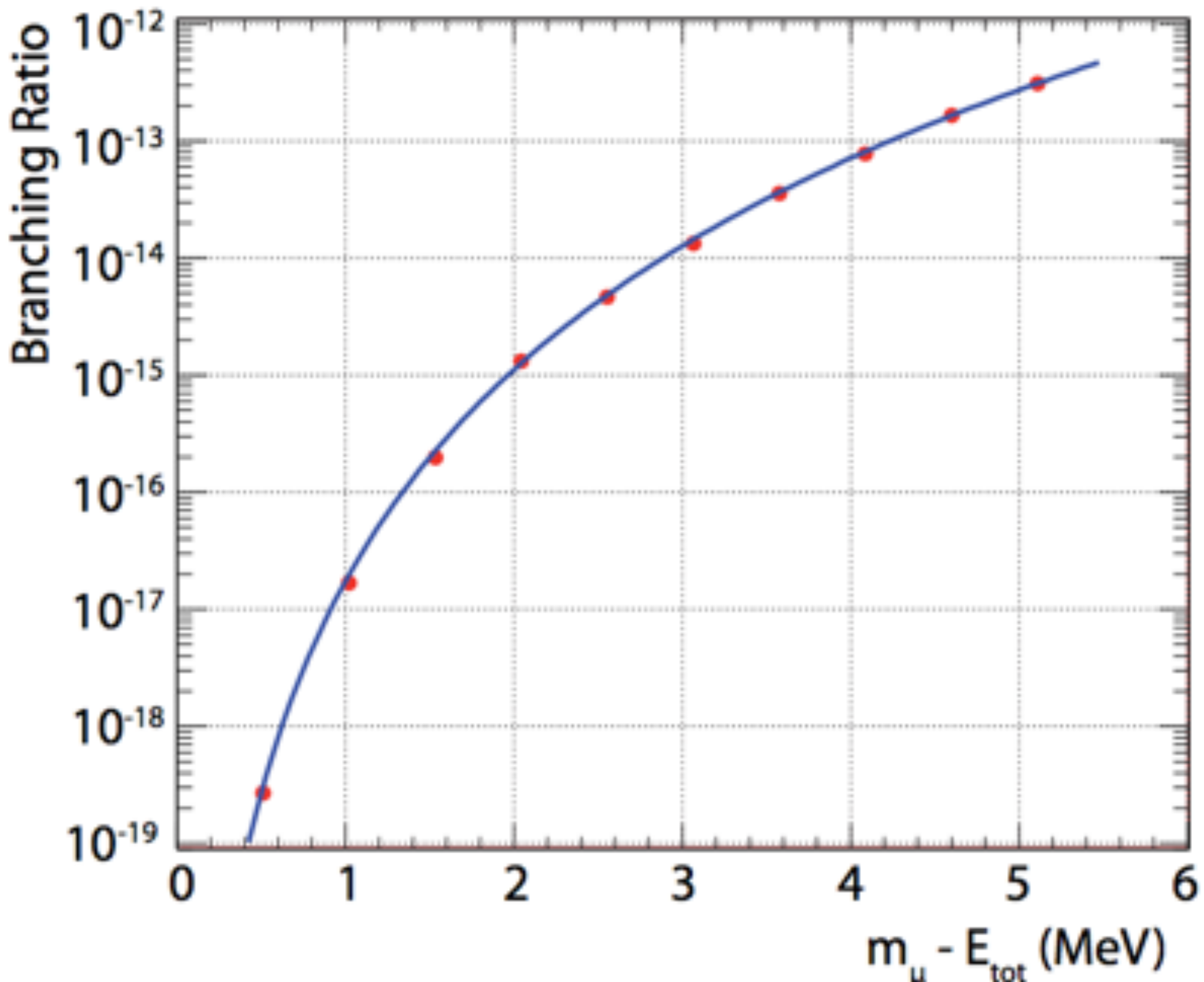
Momentum with re-curlers

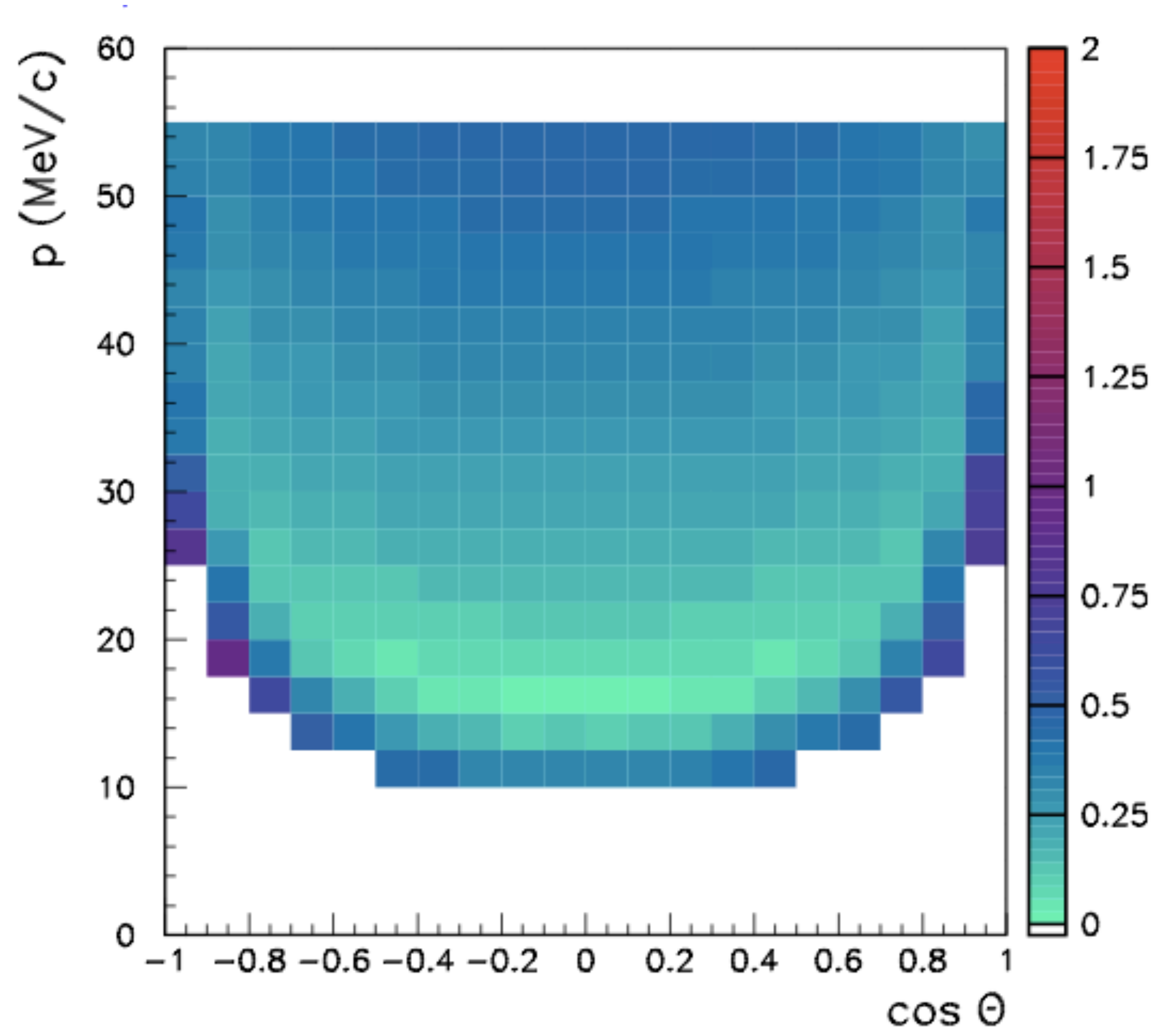




The pixel tracker: The performances

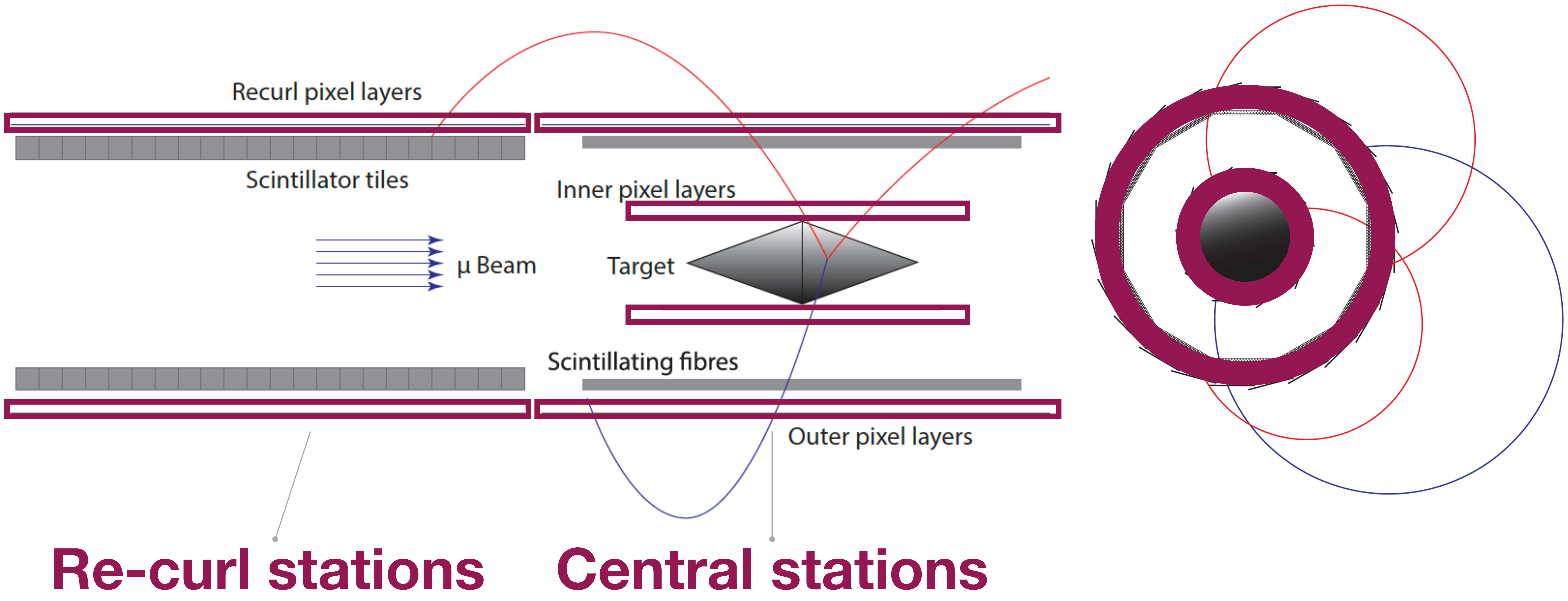
- Momentum resolution: < 0.5 MeV/c over a large phase space
- Geometrical acceptance: ~ 70%
- X/X_0 per layer: ~ 0.011%
- Vertex resolution: < 200 μm





The pixel tracker: Overview

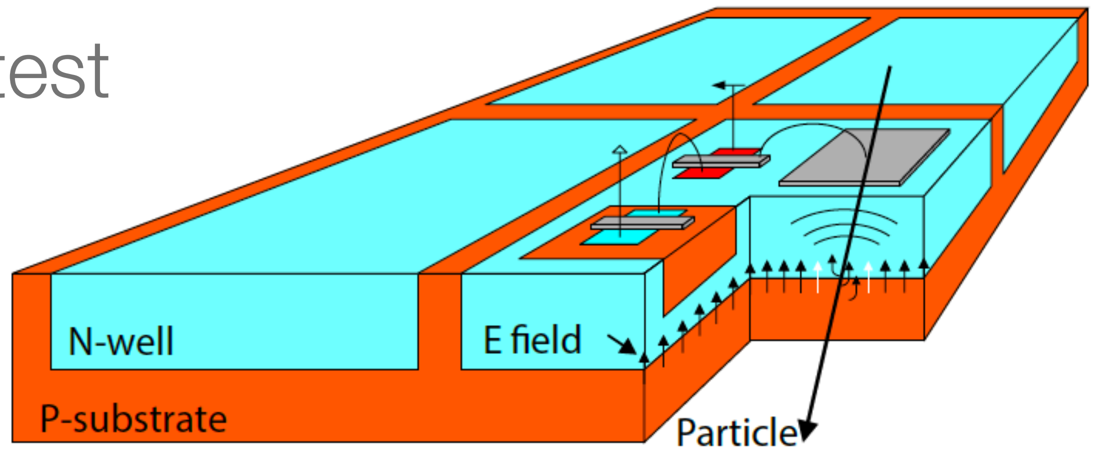
- Central tracker: Four layers; Re-curl tracker: Two layers
- Minimum material budget: Tracking in the scattering dominated regime
- Momentum resolution: < 0.5 MeV/c over a large phase space; Geometrical acceptance: ~ 70%; X/X_0 per layer: ~ 0.011%



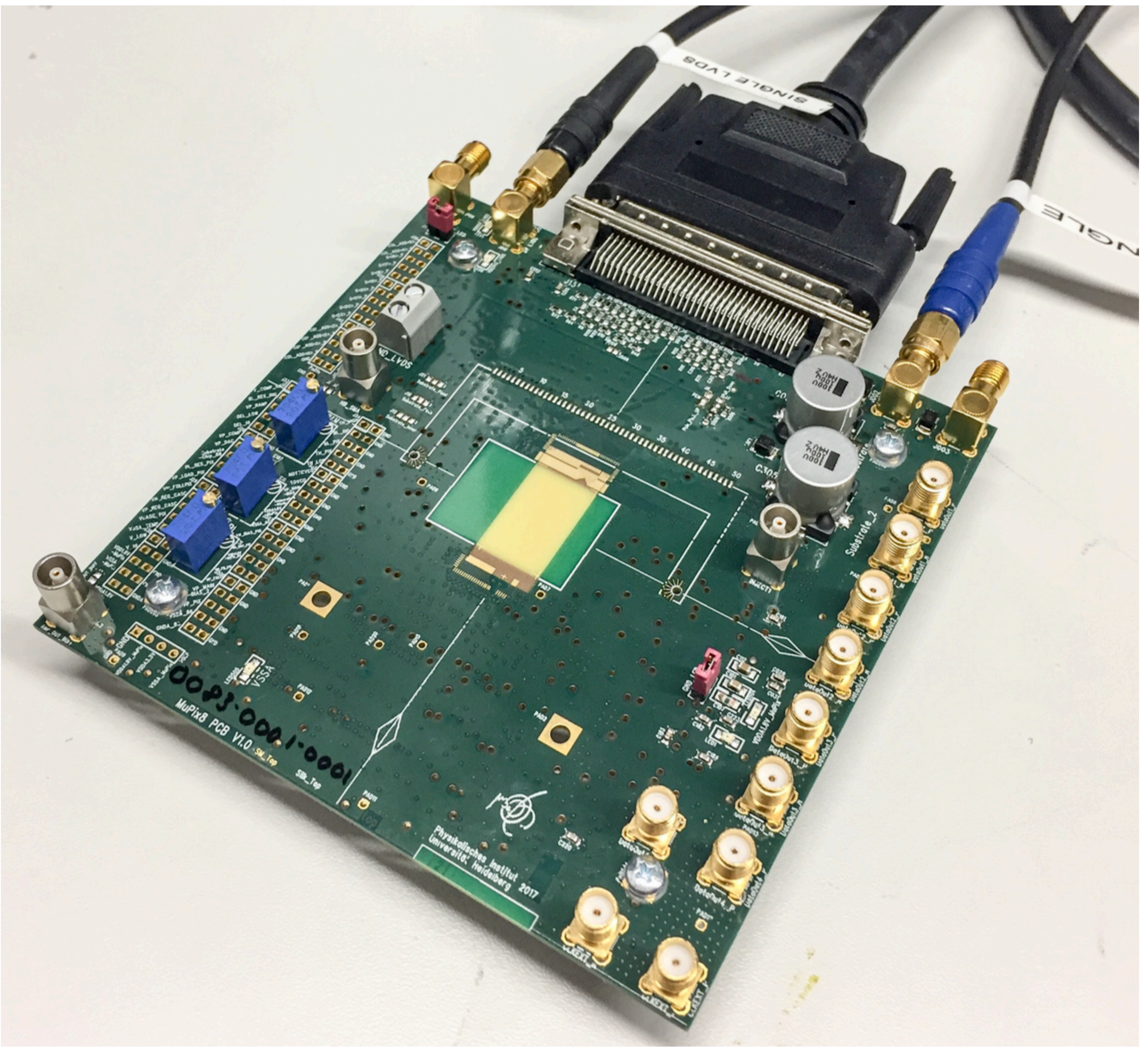
The pixel tracker: The MuPix detector

- Based on HV- MAP: Pixel dimension: 80 x 80 μm^2 , Thickness: 50 μm , Time resolution: < 20 ns, Active area chip: 20 x 20 mm^2 , Efficiency: > 99 %, Power consumption : < 350 mW/cm^2
- MuPix 7: The first small-scale prototype which includes all Mu3e functionalities
- MuPix 8, the first large area prototype: from O(10) mm^2 to 160 mm^2 : Ready and extensively tested!
- MuPix 9, small test chip for: Slow Control, voltage regulators and other test circuits. 2019 year test beam campaign
- MuPix 10, towards the final version: 380 mm^2

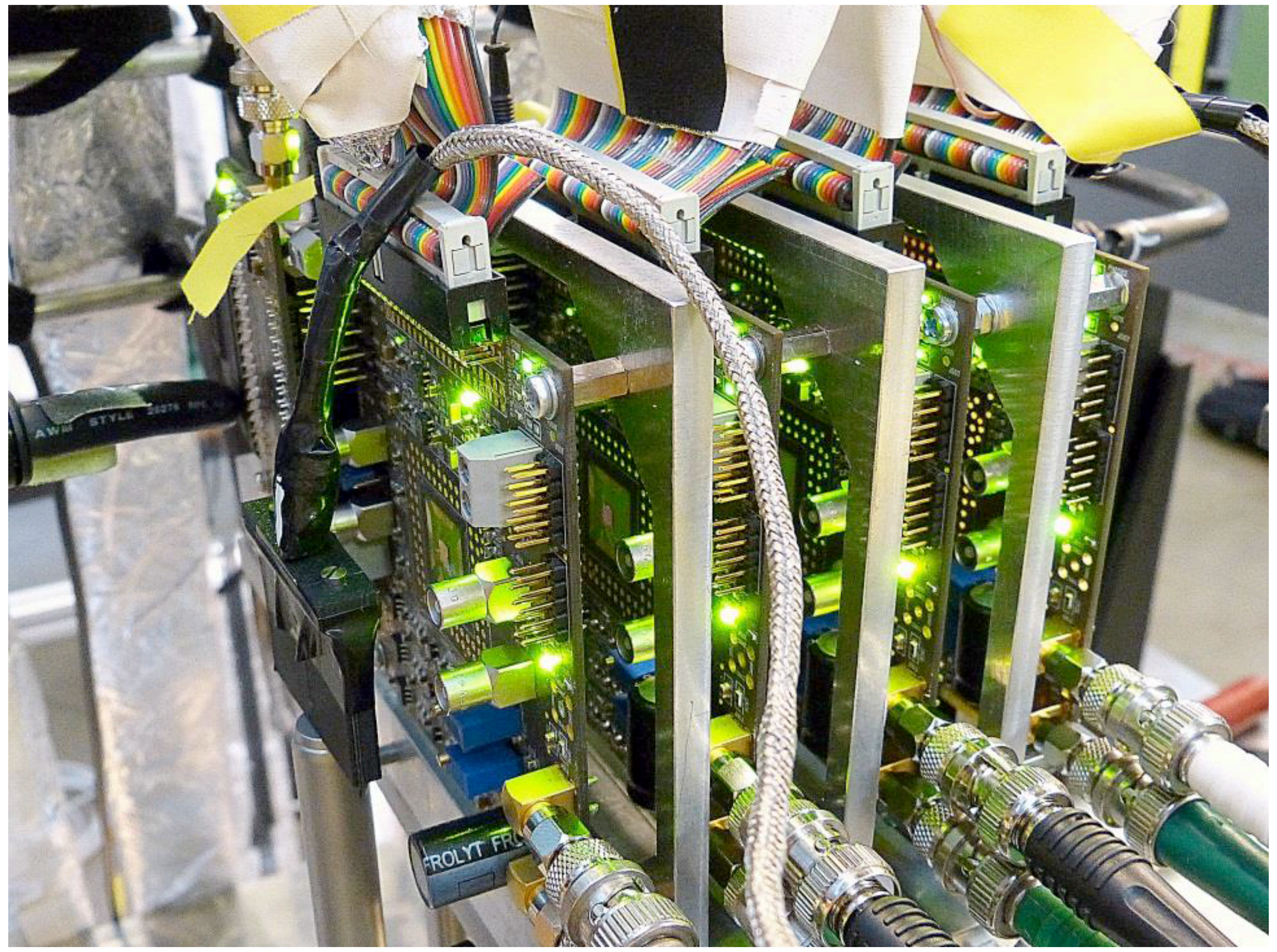
Ivan Peric, Nucl.Instrum.Meth. A582 (2007) 876-885



MuPix8



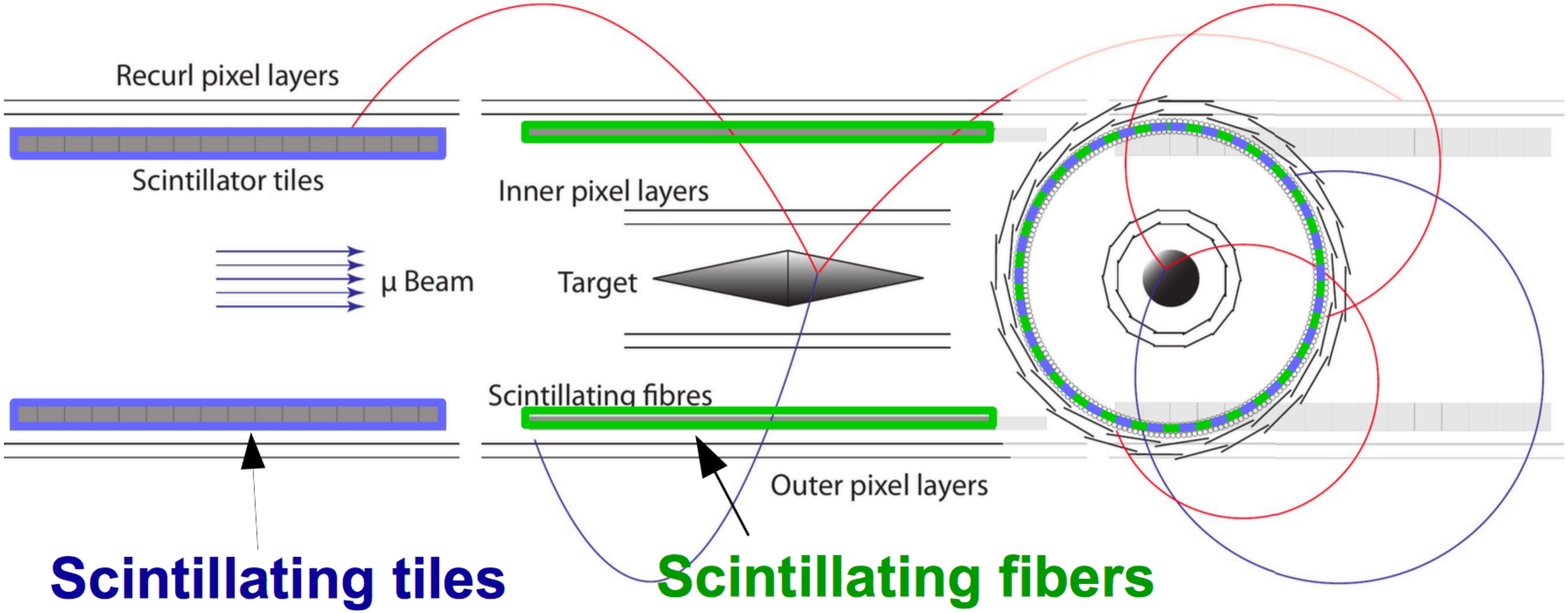
Mupix 7 telescope



Prototype	Active Area [mm^2]
MuPix1	1.77
MuPix2	1.77
MuPix3	9.42
MuPix4	9.42
MuPix6	10.55
MuPix7	10.55

The timing detectors: Fibers and tiles

- Precise timing measurement: Critical to reduce the accidental BGs
  - Scintillating fibers (SciFi) O(1 ns), full detection efficiency (>99%)
  - Scintillating tiles O(100 ps), full detection efficiency (>99%)



The timing detectors: Fibers and tiles

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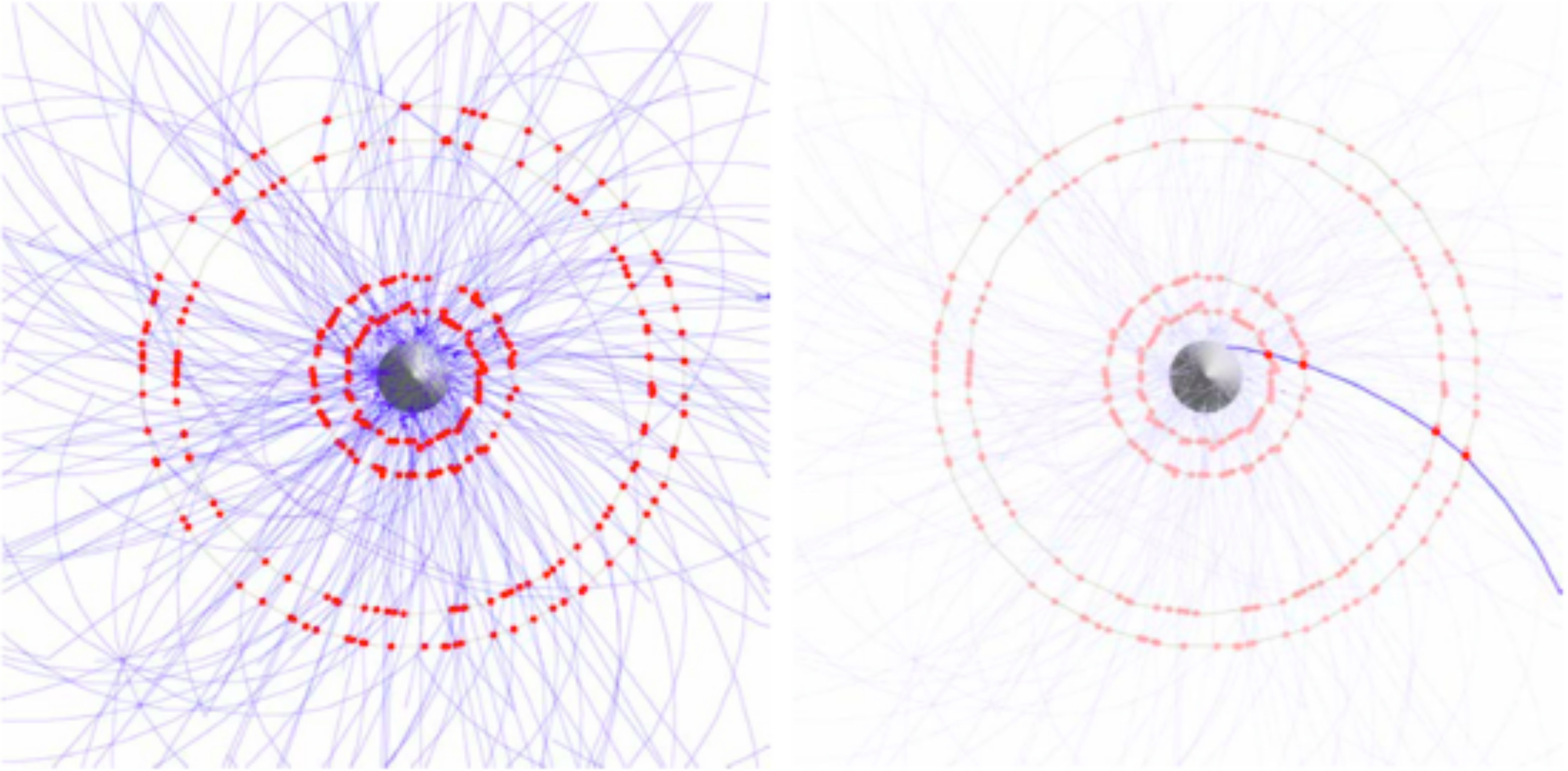
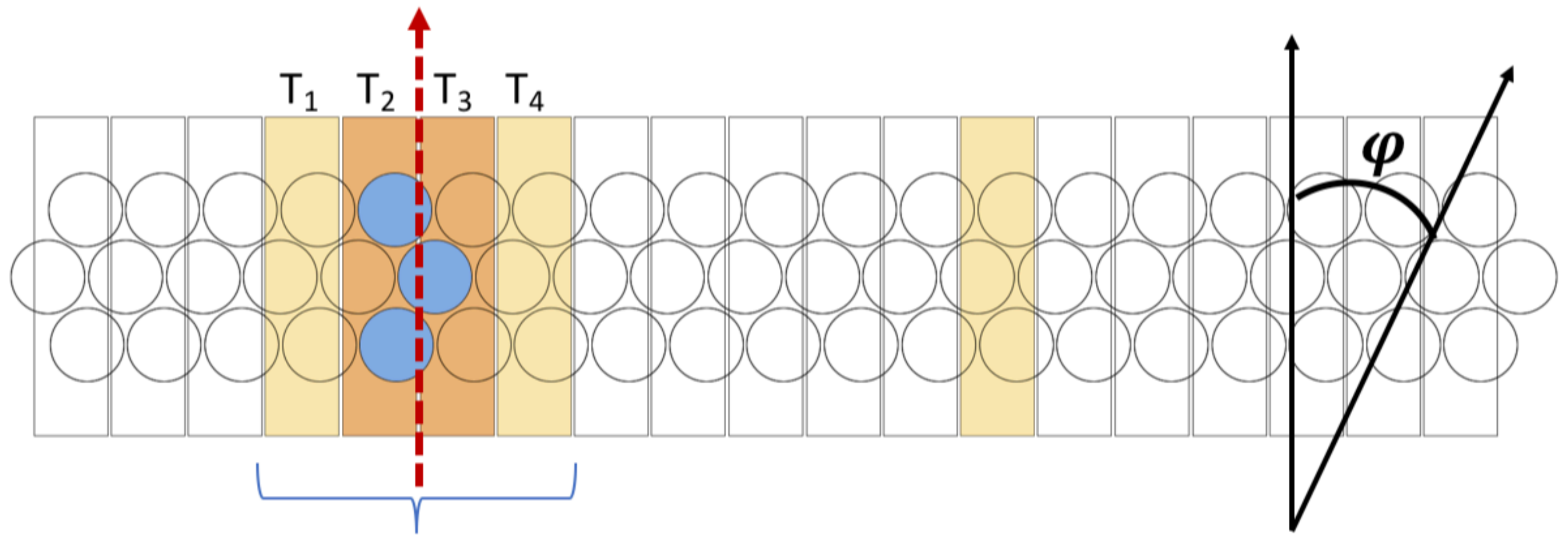


Pixels: O(50 ns)

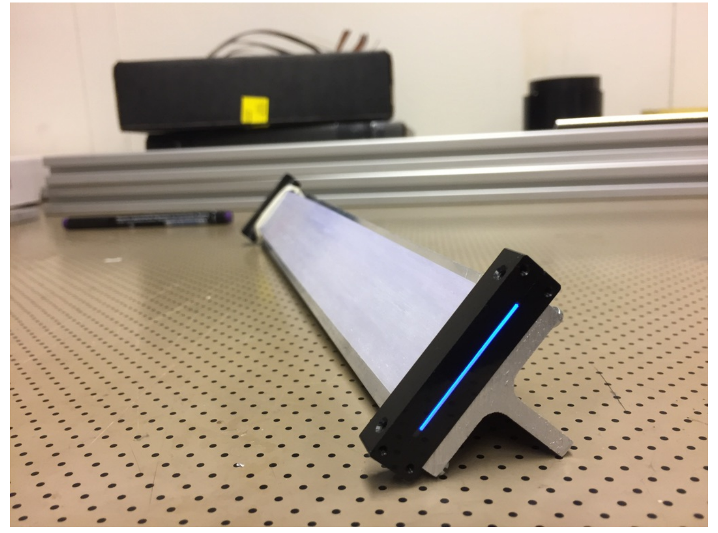
Scintillating fibres O(1 ns); Scintillating tiles O(100 ps)

SciFi prototypes: Results

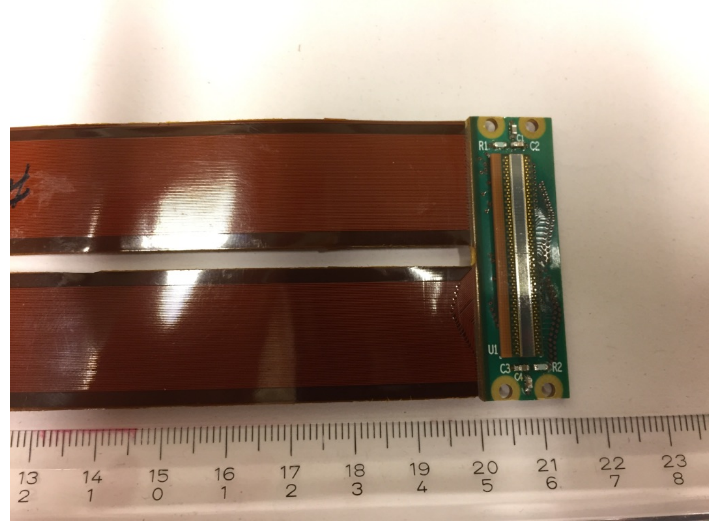
- Studied a variety of fibres (SCSF 78 MJ, clear; SCSF 78 MJ, with 20% TiO2; NOL 11, clear; NOL 11, with 20% TiO2; SCSF 81 MJ, with 20% TiO2; BCF12 clear; BCF12, with 100 nm Al deposit)
- Confirmed full detection efficiency (> 96 % @ 0.5 thr in Nphe) and timing performances for multi-layer configurations (square and round fibres) with several prototypes: individual and array readout with standalone and prototyping (STiC) DAQ

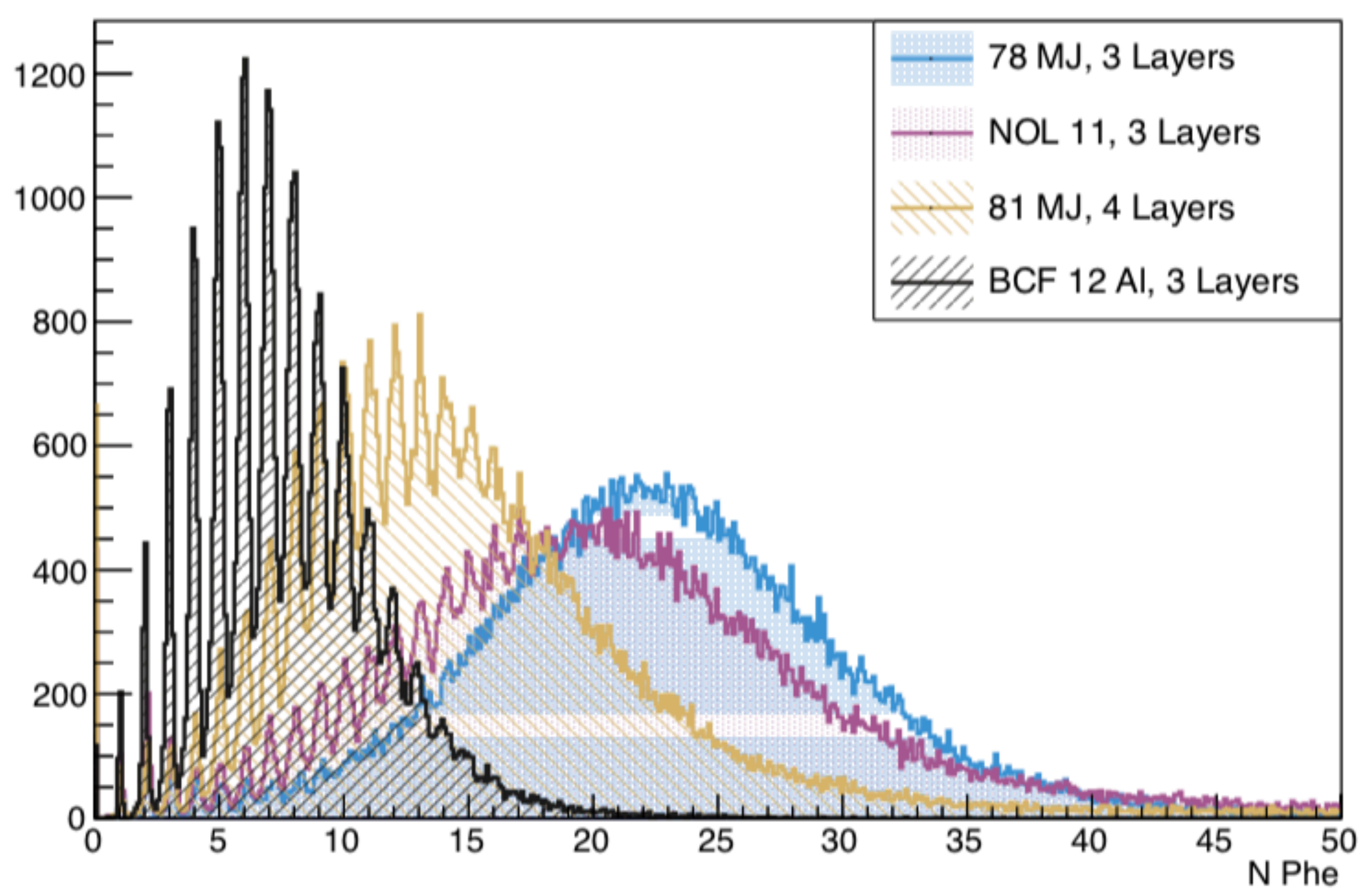


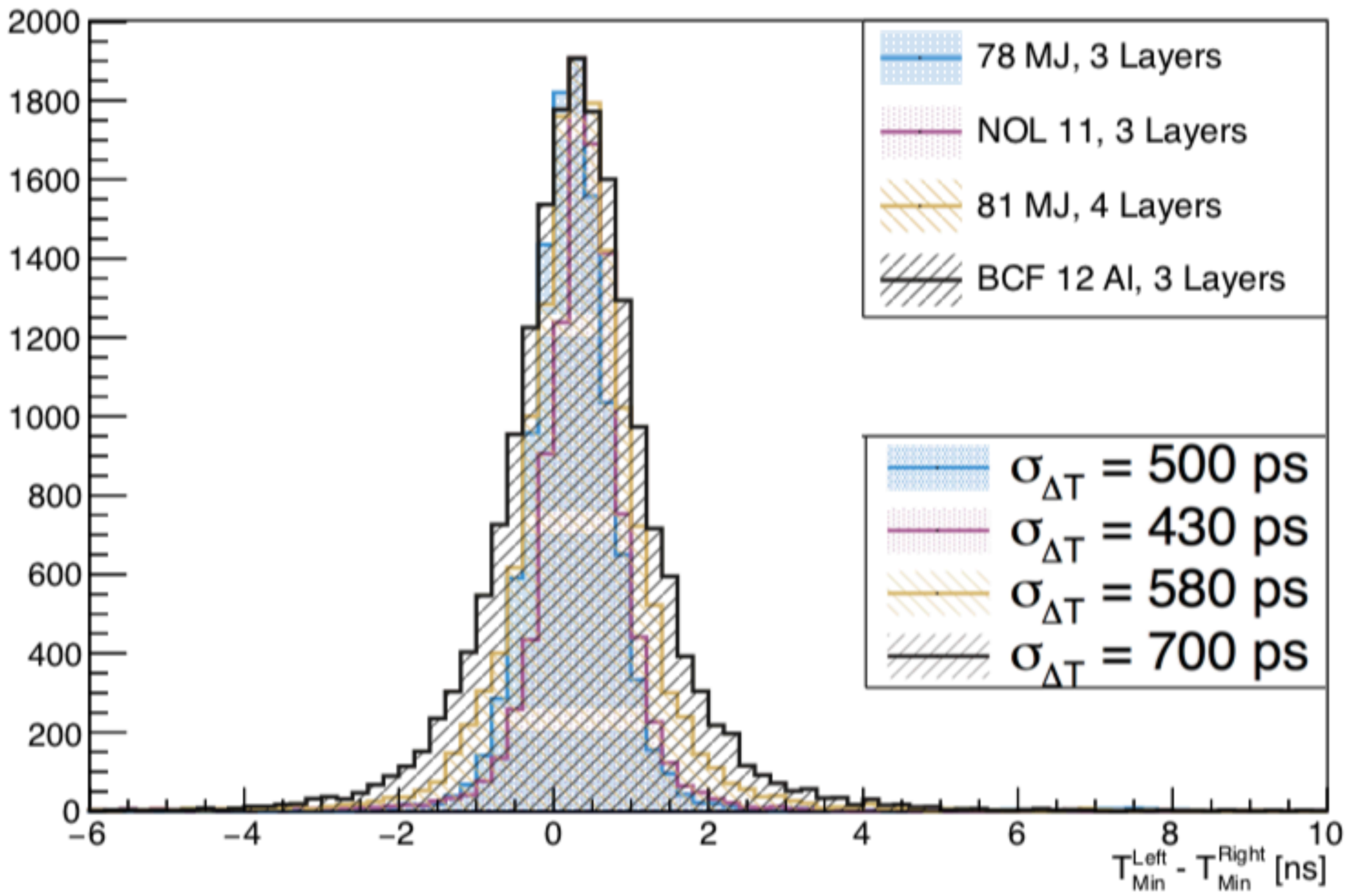
Fibre ribbons:



SiPM Array:
Hamamatsu S13552-HQR

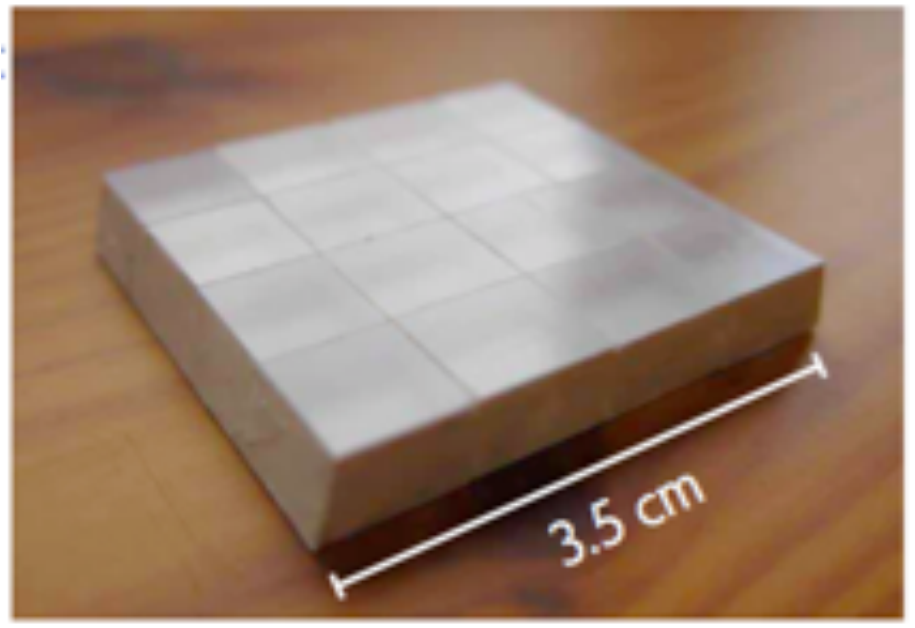


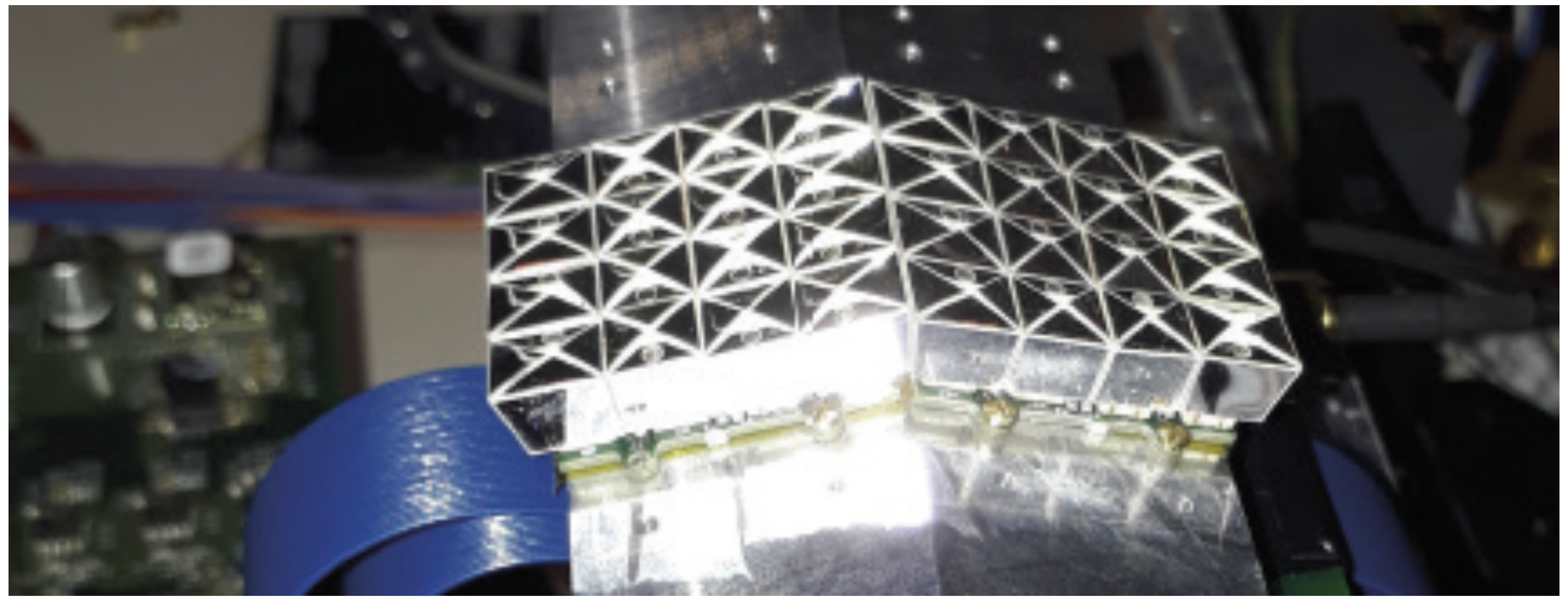


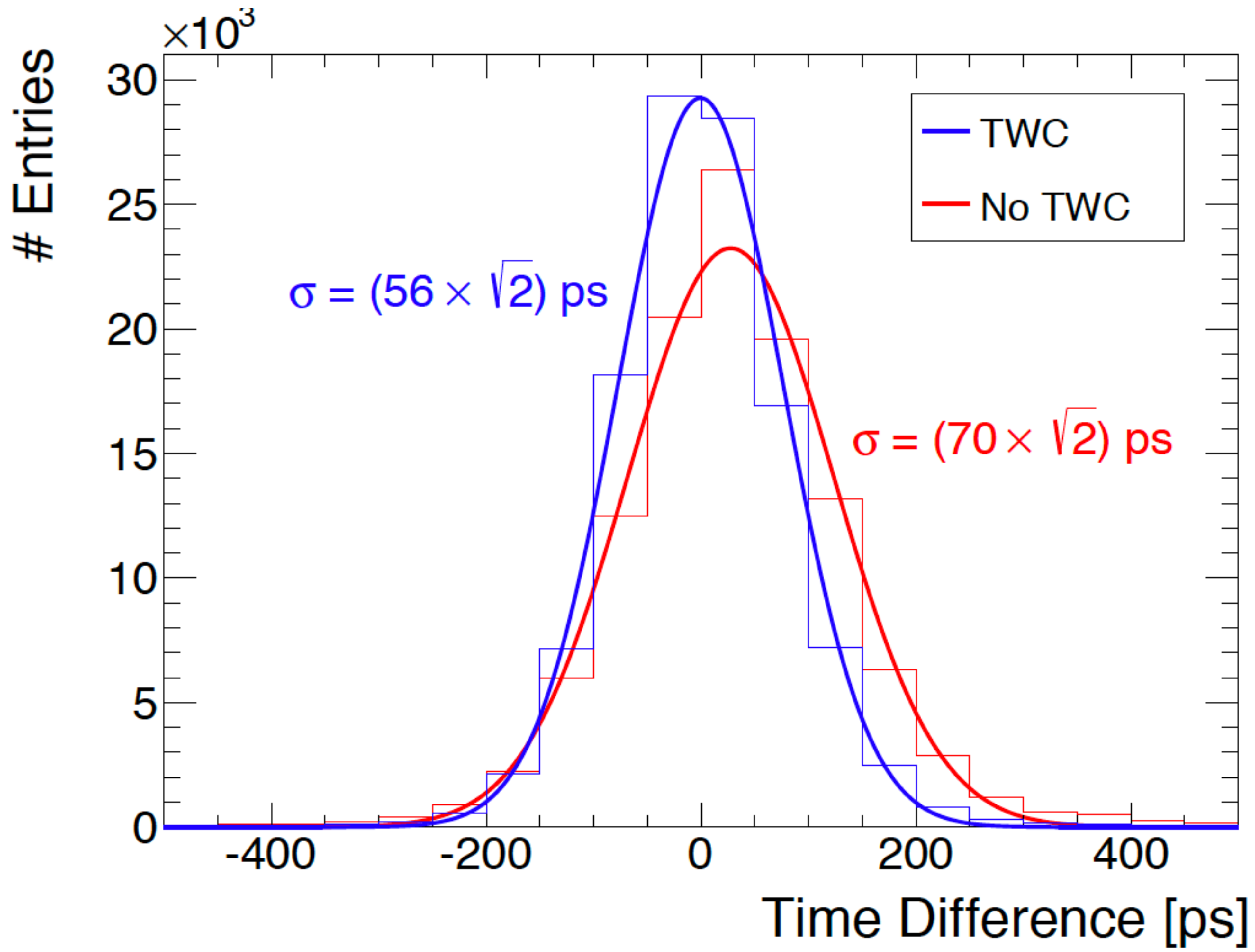


Tile Prototype: Results

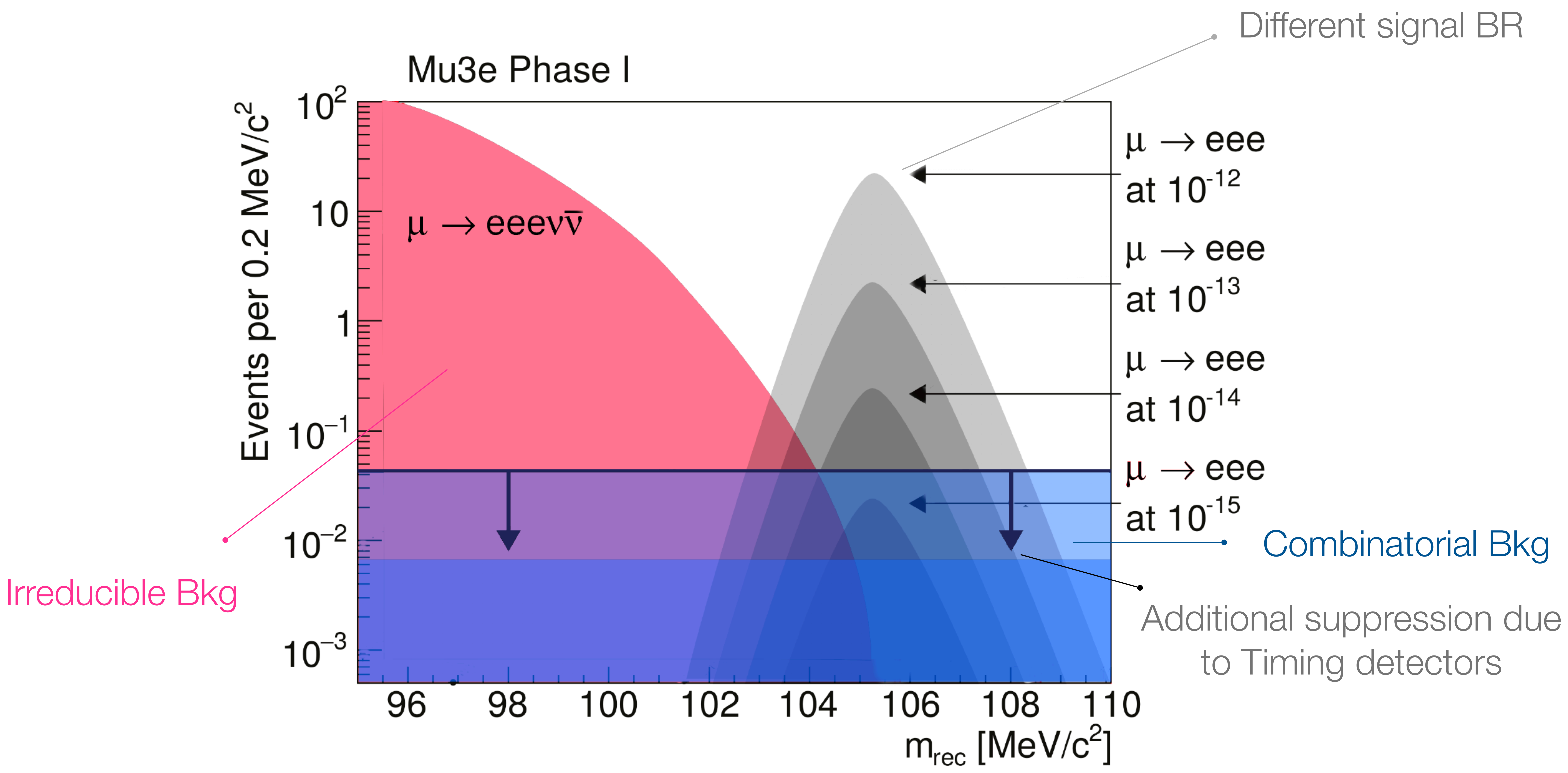
- Mu3e requirements fulfilled: Full detection efficiency (> 99 %) and timing resolution O (60) ps
- 4 x 4 channel BC408
- 7. 5 x 8. 5 x 5. 0 mm^3
- Hamamatsu S10362-33-050C (3 x 3 mm^2)
- readout with STiC2







Mu3e Phase I sensitivity



Latest news and currents status

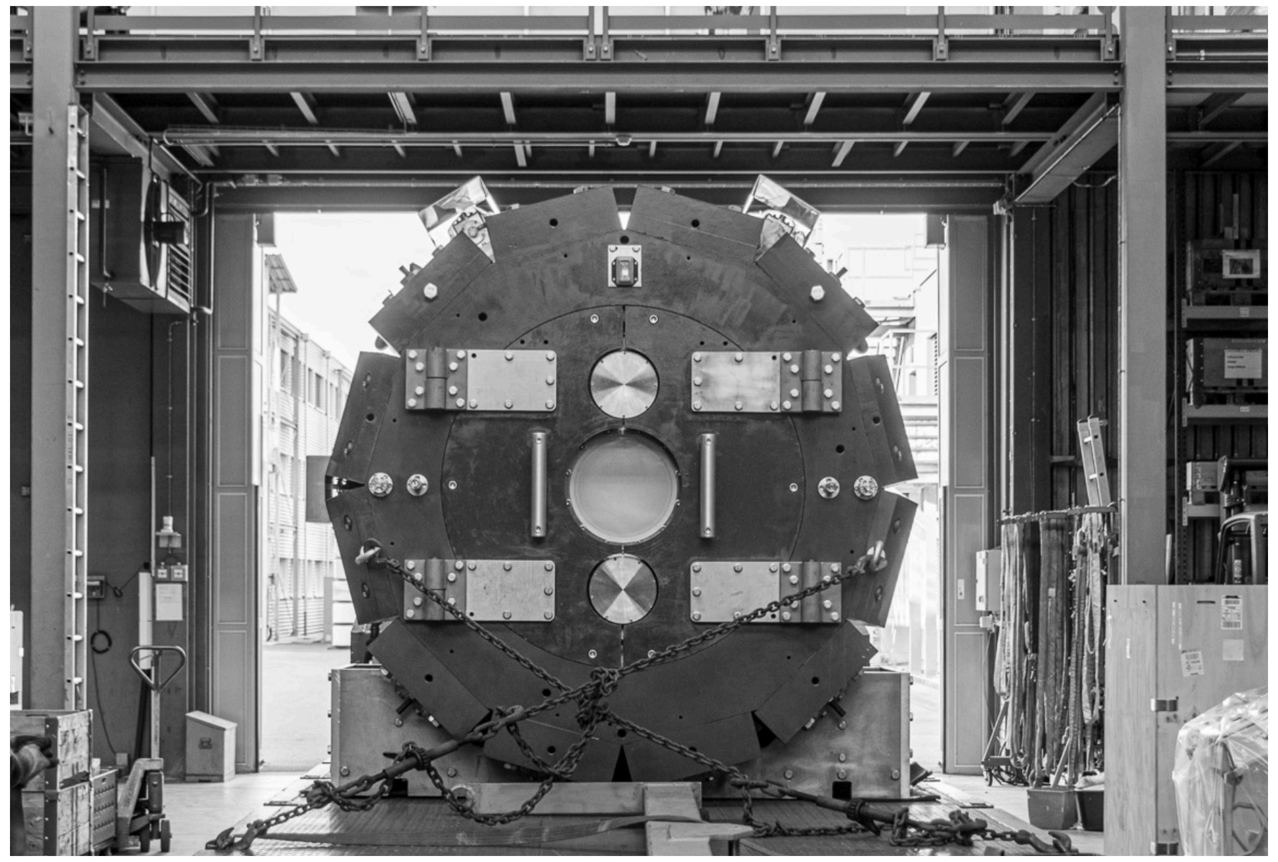
Key points:

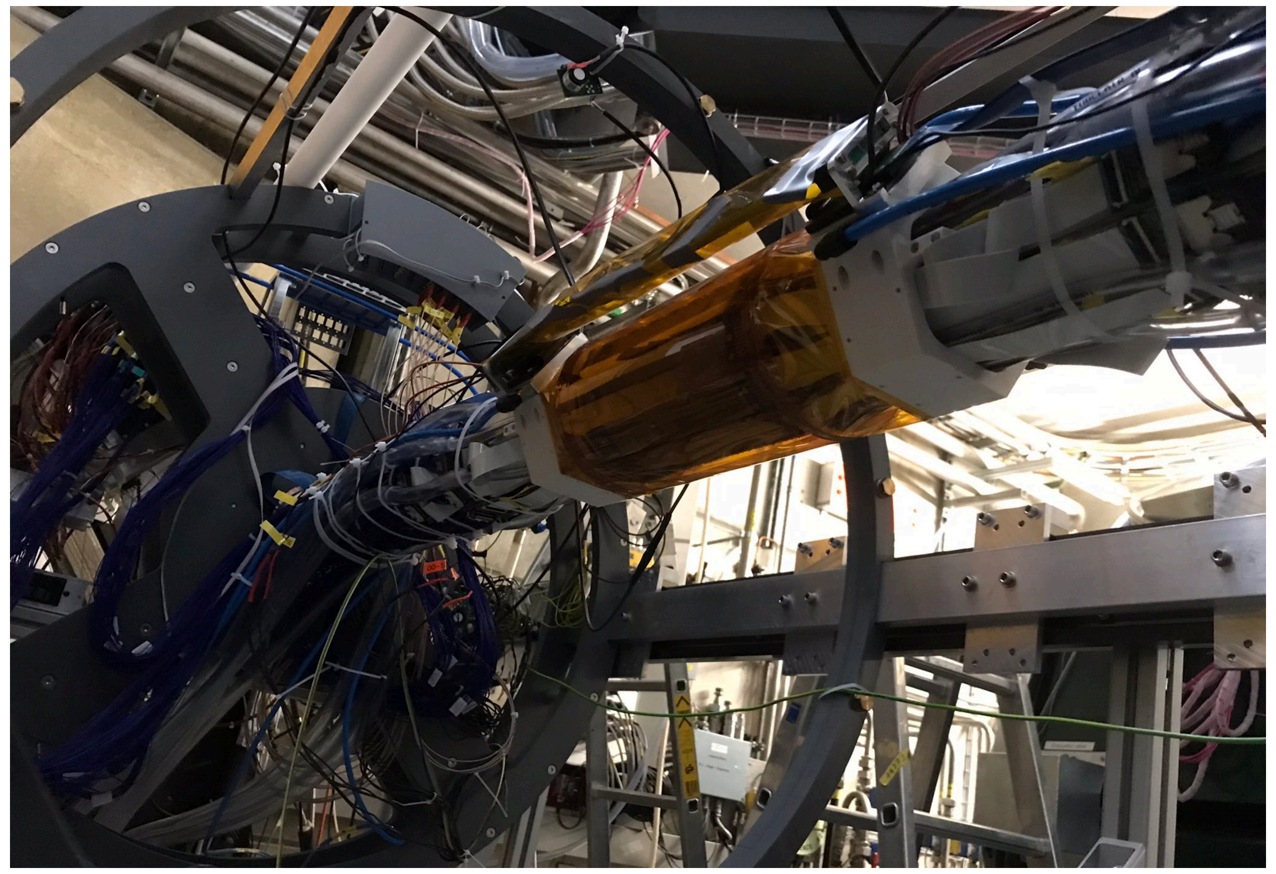
- **First integration Run 2021**
- Inner MuPix layer
- SciFi ribbons
- Sub-detector services

- **Full beam line commissioning 2022**
- Very successful: TDR promised values **matched!**
  - **2.49e10⁸ mu/s @2.4 mA** (at the collimator): The highest beam rate in pie5 at the collimator
  - **1.02e10⁸ mu/s @2.4 mA** (Mu3e magnet): Several beam configurations studied, some of them connected with possible Mu3e magnetic field intensity optimisation

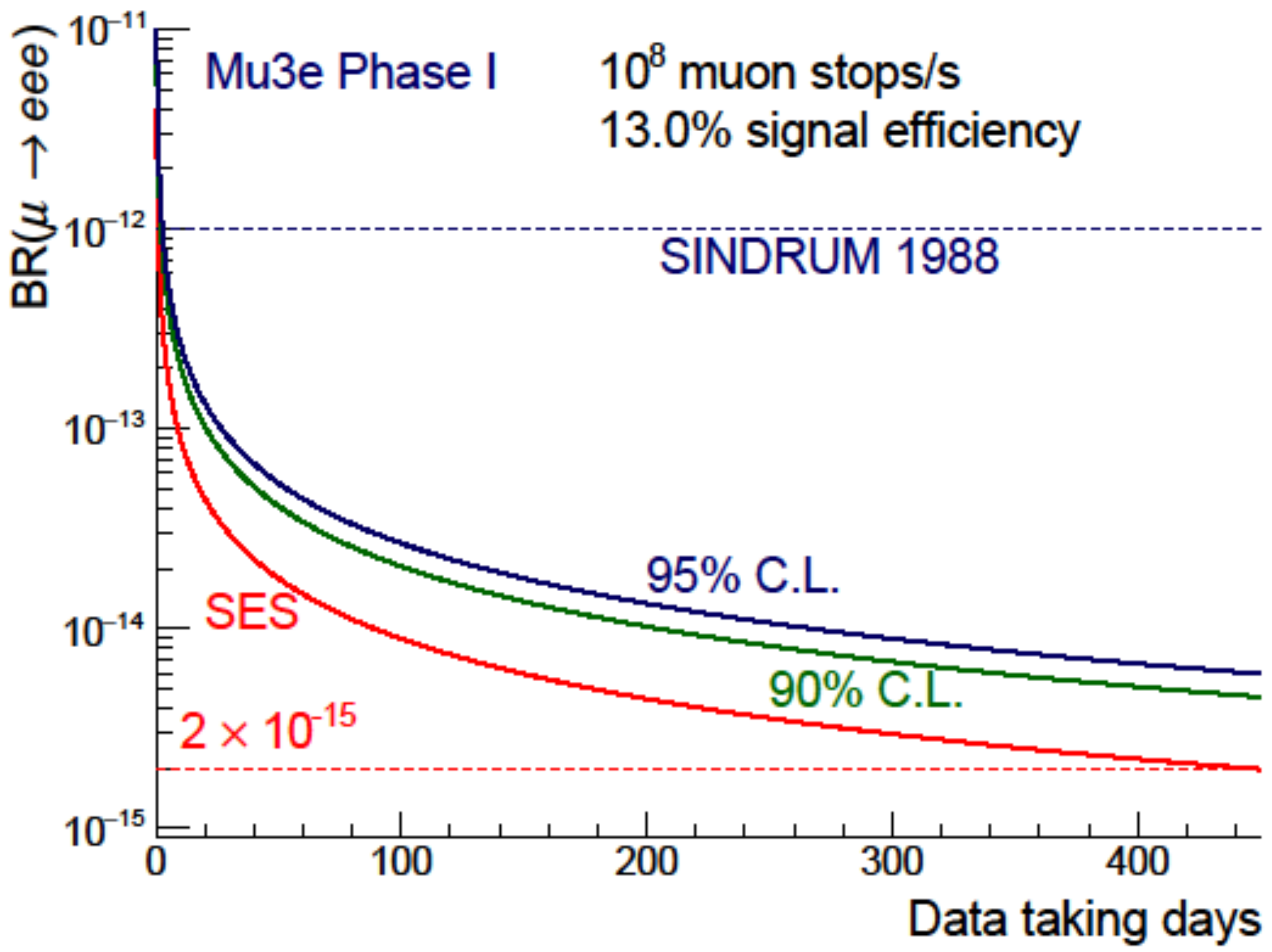
Outlook:

- Cosmic Ray Run ongoing outside the experimental area with all sub-detector services
- MuPix mass production: ongoing
- Complete integration run: 2023
- Engineering run: 2024
- First physics run: 2025

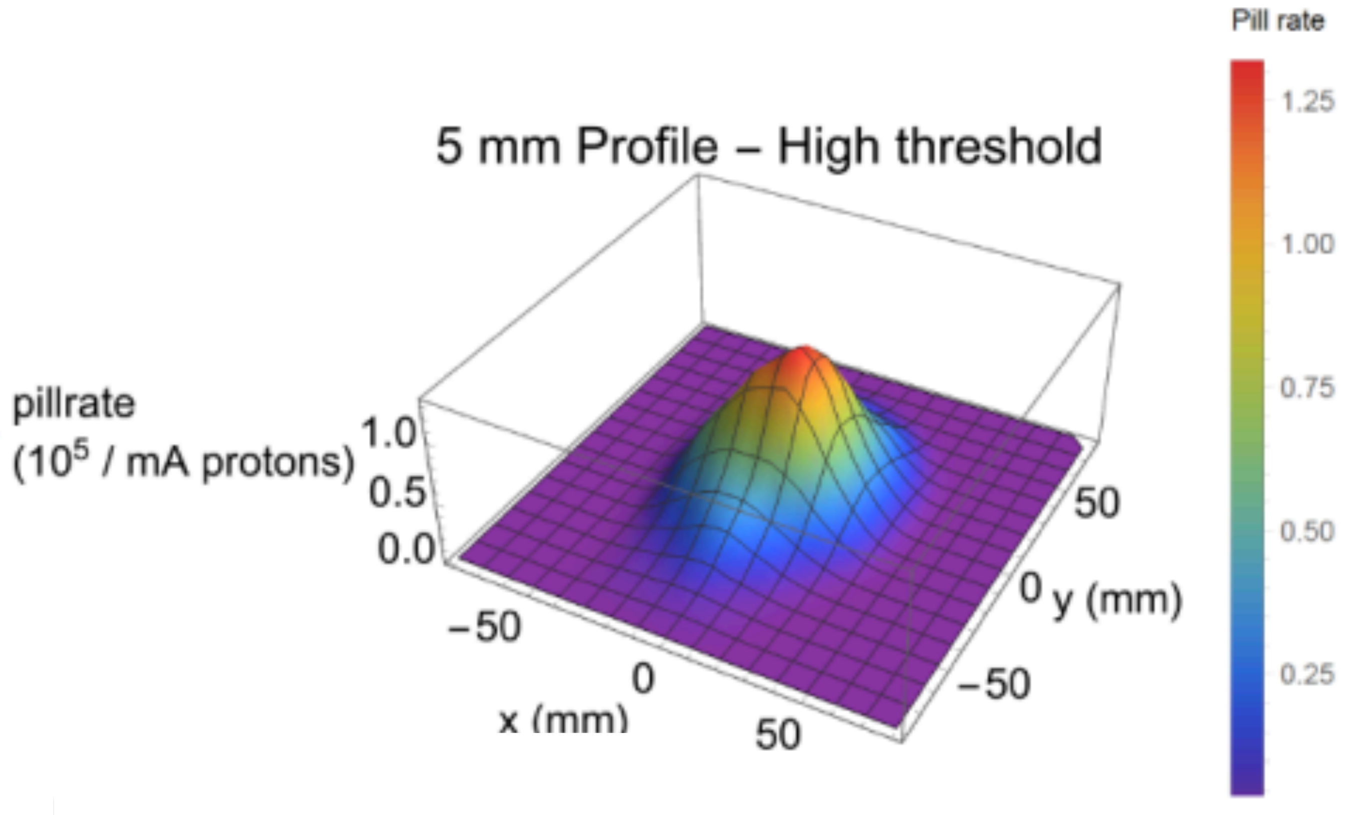




Full analysis performed on Simulated data

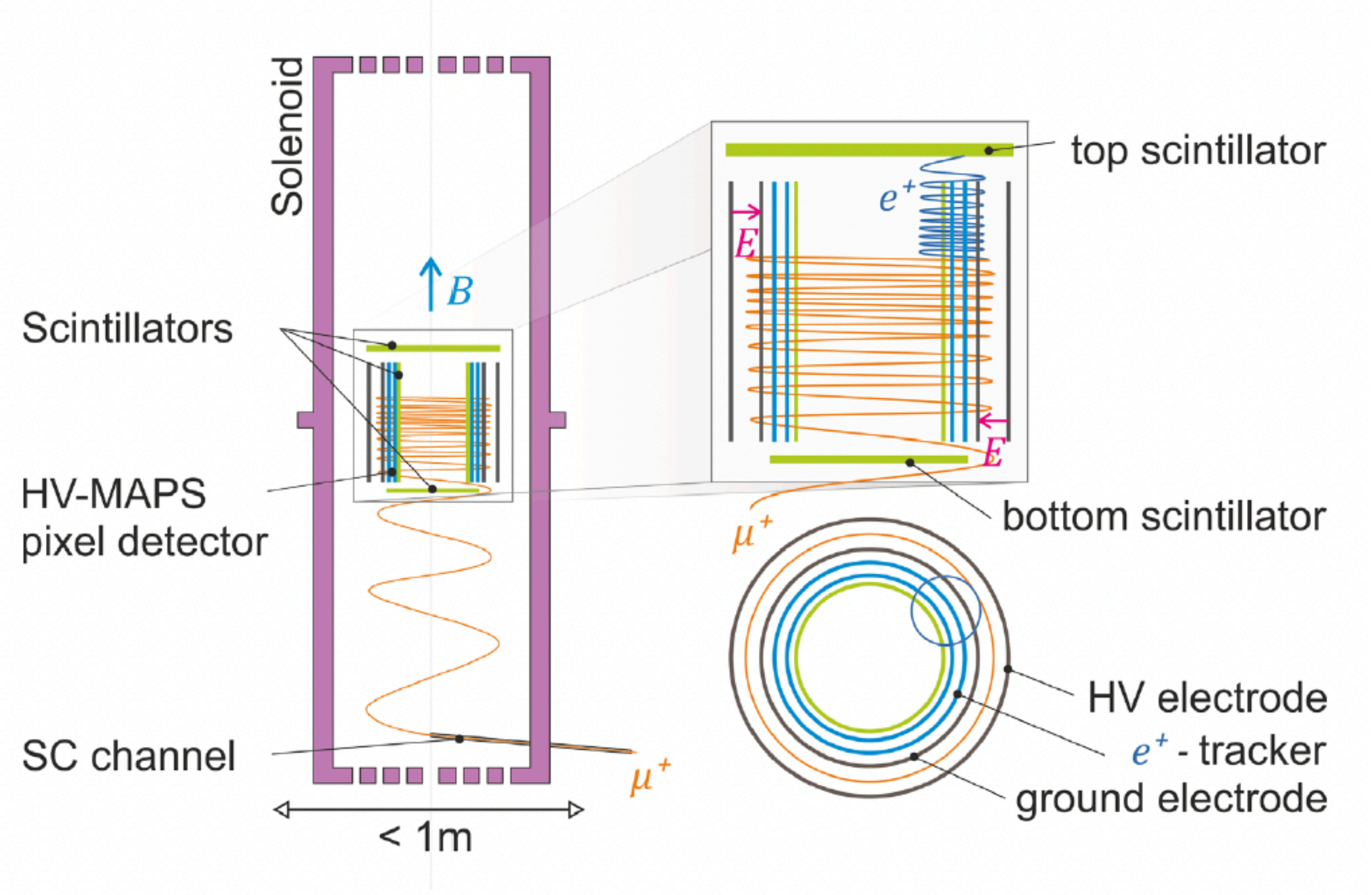


Beam commissioning **2022**



2.49e10⁸ mu/s @2.4 mA

muEDM final at PSI: Frozen spin and longitudinal injection



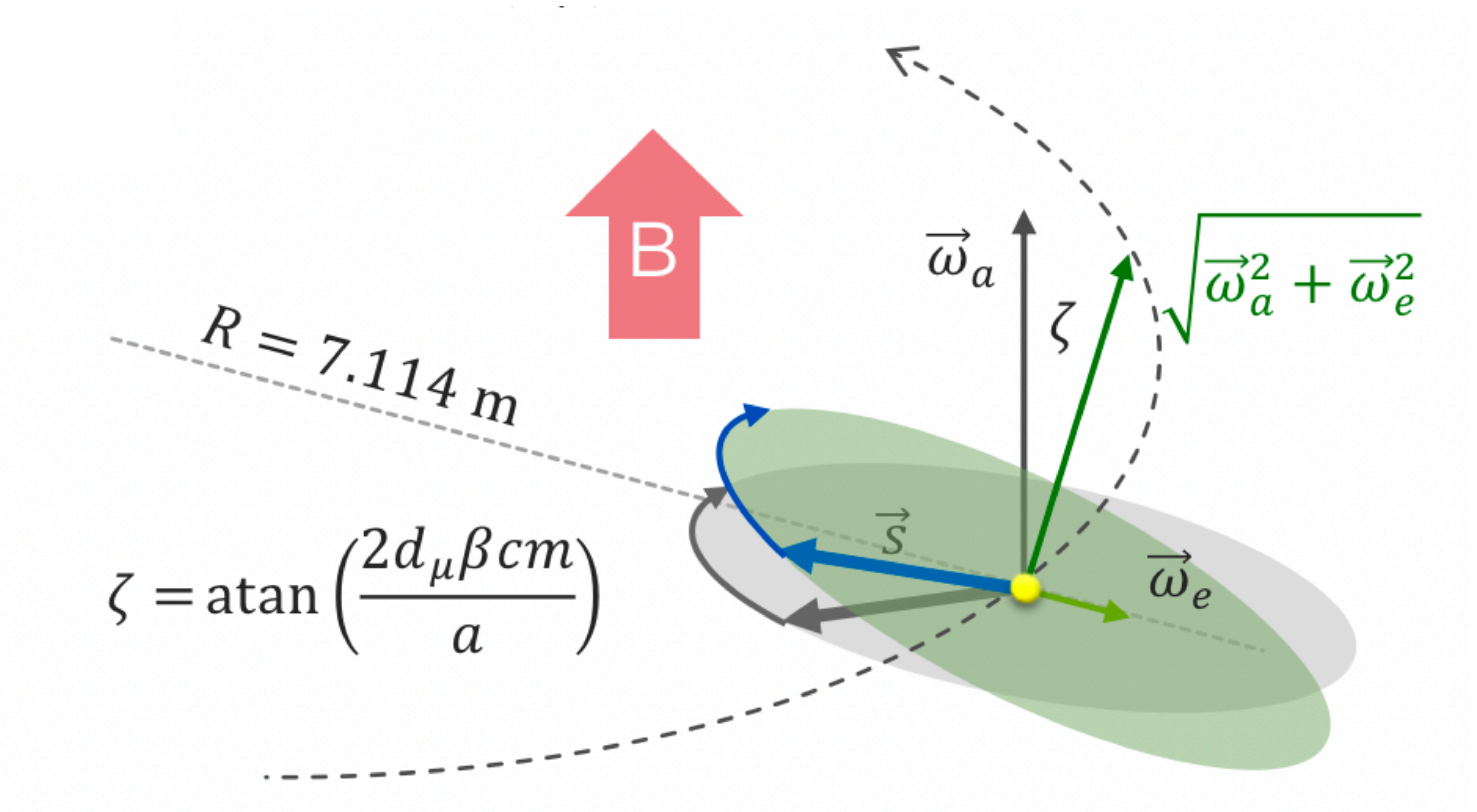
p=125 MeV/c [muE1]

- μ^+ from Pion–decay → high polarization $p \approx 95\%$
- Injection through superconducting channel
- Fast scintillator triggers pulse
- Magnetic pulse stops longitudinal motion of μ^+
- Weakly focusing field for storage
- Thin electrodes provide electric field for frozen spin
- Pixelated detectors for e^+– tracking

EDM search: From the “frequency” approach…

$$\vec{\omega} = \underbrace{\frac{q}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]}_{\omega_a} + \underbrace{\frac{q}{m}\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)}_{\omega_e}$$

- i.e. FNAL: The decay positrons are recorded using calorimeters and straw tube trackers inside the storage ring
- The sensitivity to a muon EDM is limited by the resolution of the vertical amplitude, proportional to ζ, of the oscillation in the tilted precession plane
- i.e. J-PARC: even if the technique is different the sensitivity to an EDM is limited by the resolution of the vertical amplitude



…to the frozen-spin technique

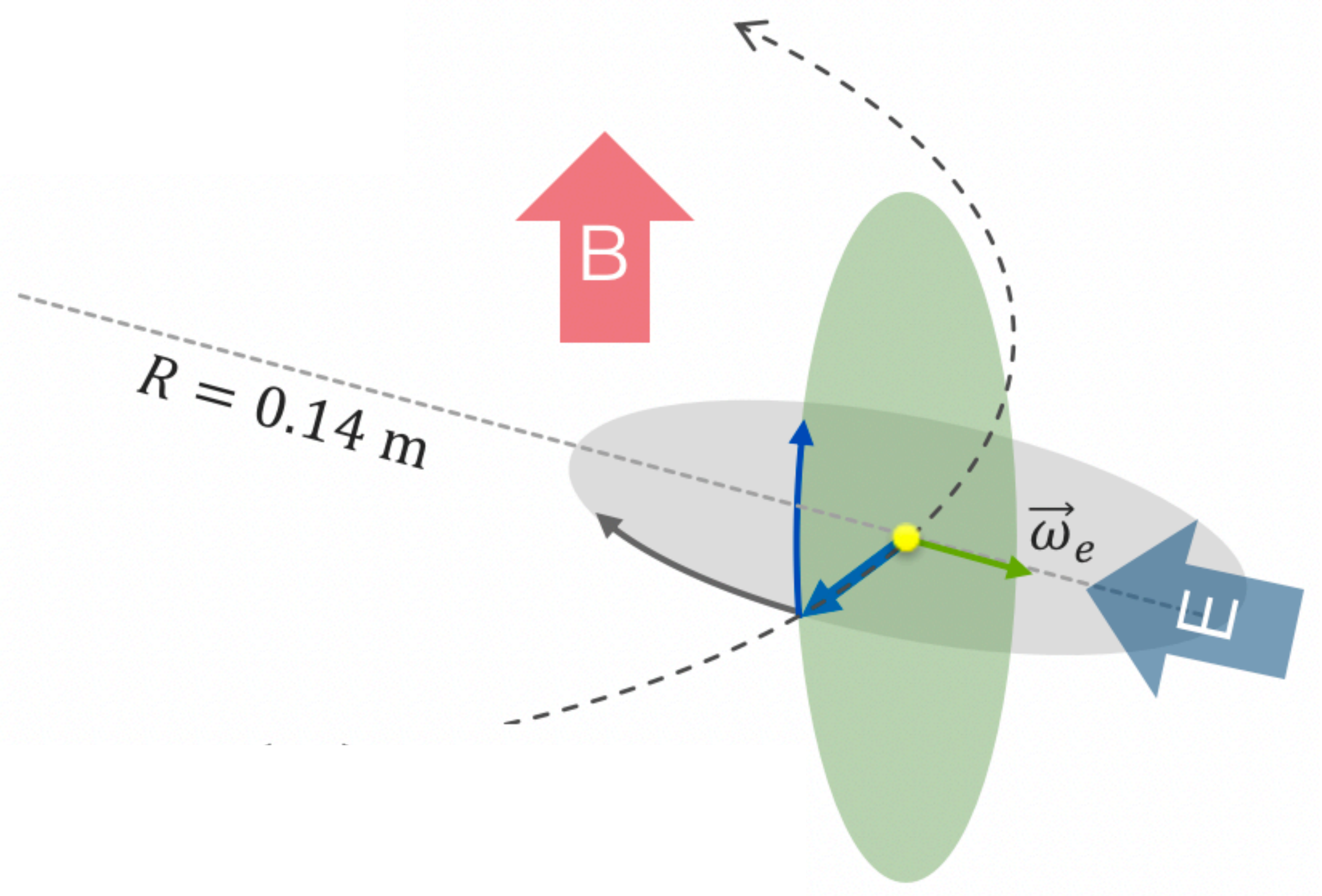
$$\vec{\omega} = \frac{q}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{q}{m}\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)$$

ω_a ω_e

- The frozen-spin technique uses an Electric field perpendicular to the moving particle and magnetic field, fulfilling the condition:

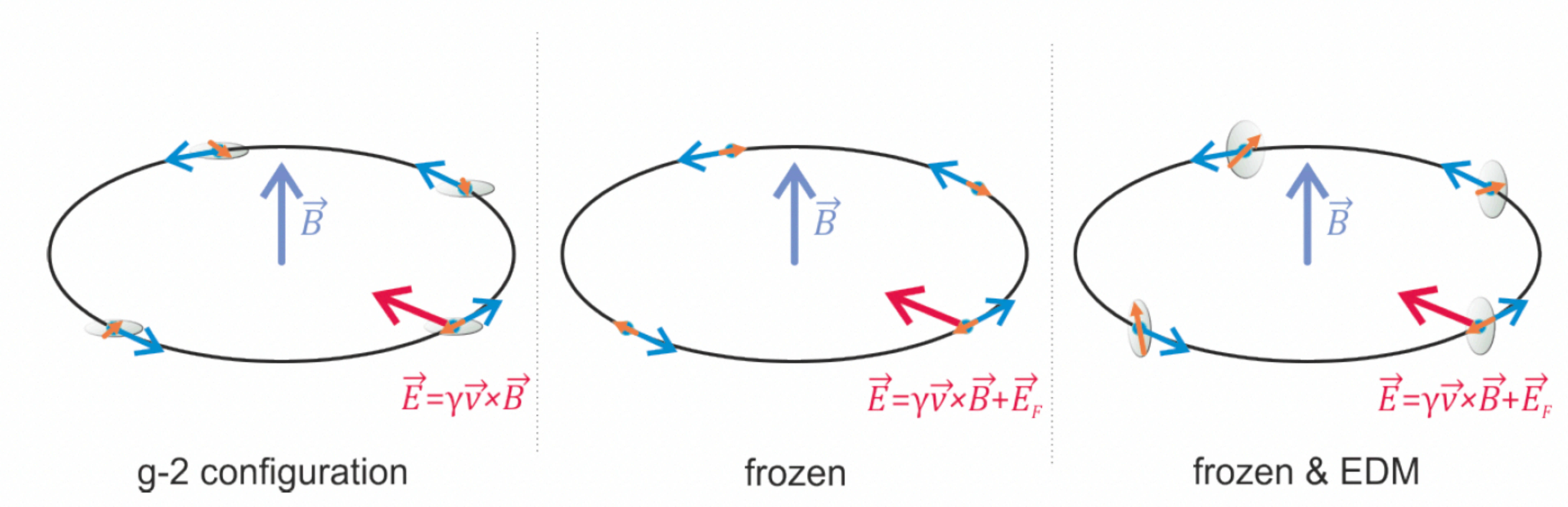
$$a\vec{B} = \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}_f}{c}$$

- Without EDM, $\omega = 0$, the spin follows the momentum vector as for an ideal Dirac spin-1/2 particle, while with an EDM it will result in a precession of the spin with $\omega_e \parallel E$
- The sensitivity to a muon EDM is given by the asymmetry up/down of the positron from the muon decay



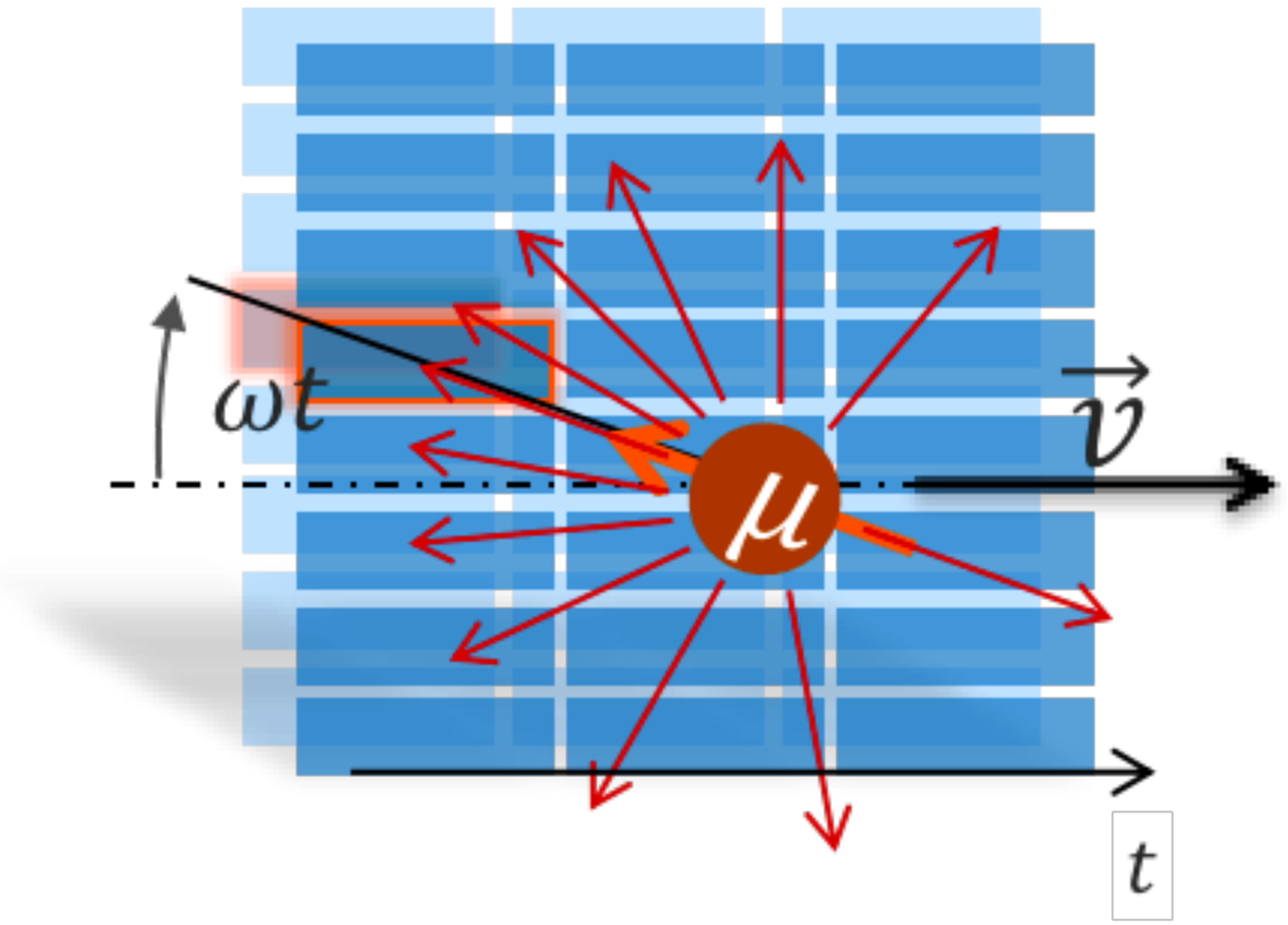
EDM: From the “frequency” approach to the frozen-spin technique

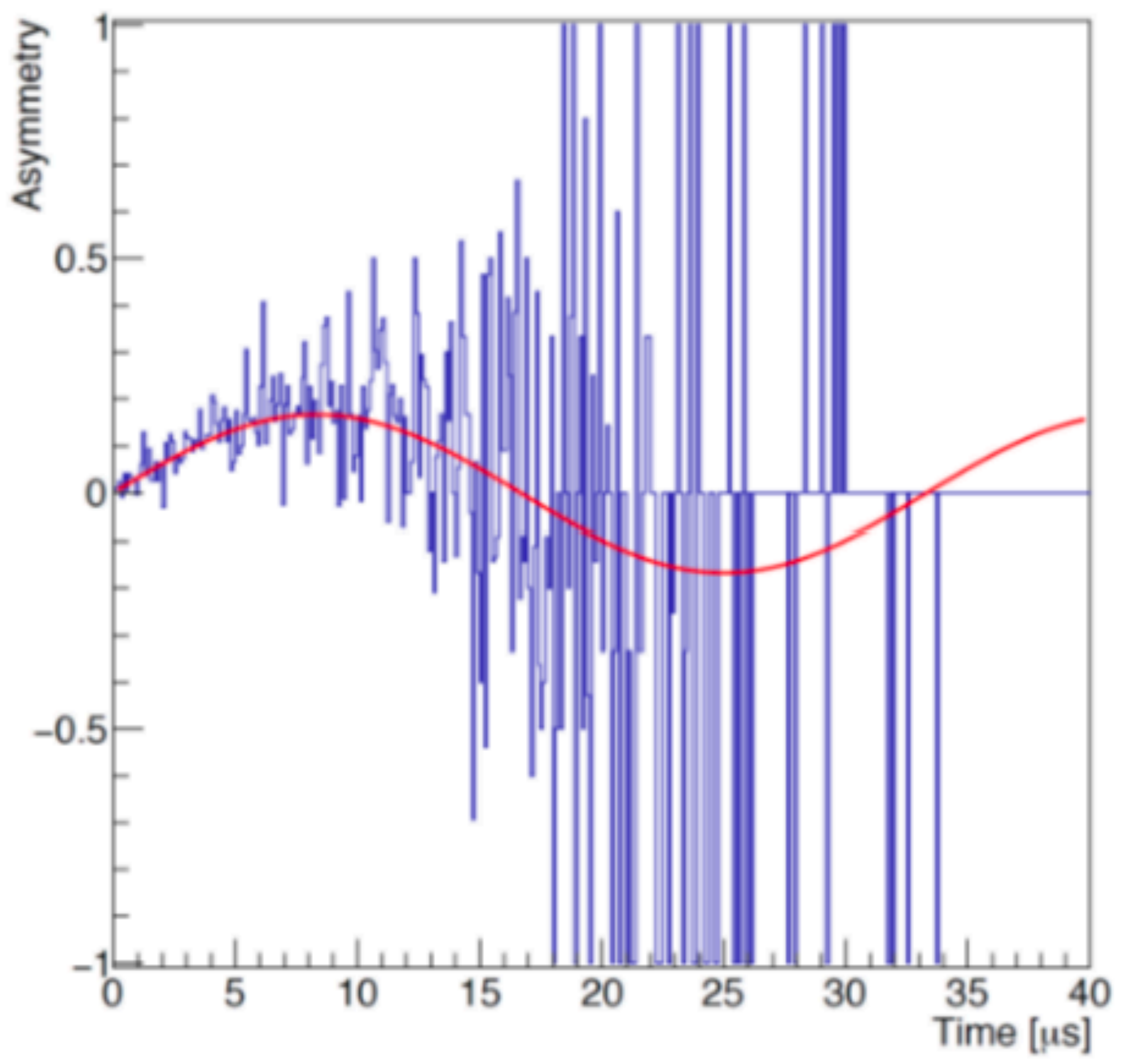
- Putting everything together, here a summary:



The muEDM at PSI: The general experimental idea

- The sensitivity to a muon EDM is given by the asymmetry up/down of the positron from the muon decay. Positrons are emitted predominantly along the muon spin direction





$$A(t) = \frac{N_\uparrow(t) - N_\downarrow(t)}{N_\uparrow(t) + N_\downarrow(t)} = \alpha p \sin\left(\frac{2d_\mu}{\hbar} t\right) \approx \alpha p \frac{2d_\mu}{\hbar} t$$

The slope gives the sensitivity of the measurement:

$$\sigma(d_\mu) = \frac{\hbar \gamma^2 a_\mu}{2pE_f\sqrt{N}\,\gamma\tau_\mu\,\alpha}$$

p := initial polarization
E_f := Electric field in lab
$\sqrt{N}$:= number of positrons
τ_μ := lifetime of muon
α := mean decay asymmetry

Outlook

- Next generation on muon based experiments require higher muon rates
  - New opportunities for future muon (particle physics) based experiments
  - New opportunities for μSR experiments

- Different experiments demand for a variety of beam characteristics:
  - DC vs pulsed
  - Momentum depends on applications: stopped beams require low momenta
  - Phase space

- Beam with different characteristics are/will be available worldwide

- PSI is working, and will continue to do it, to keep muon based researchers at the frontier