Advancement of the PSI muon facility

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Muon4Future 2025, 26th-30th May, Venezia (Italy)

Content and disclaim

- Status of the current particle physics facility with special emphasis on muons
  - Introduction to the dedicated talks at this workshop
  - muSR facility NOT covered here (please refer to Z. Salman and M. Heiss talks at this workshop)

- Special thanks to: A. Antognini, L. Caminada, B. Lauss, **K. Kirch**, A. Knecht, D. Ries, S. Ritt, P.Schmidt-Wellenburg, A. Soter

PSI particle physics vision

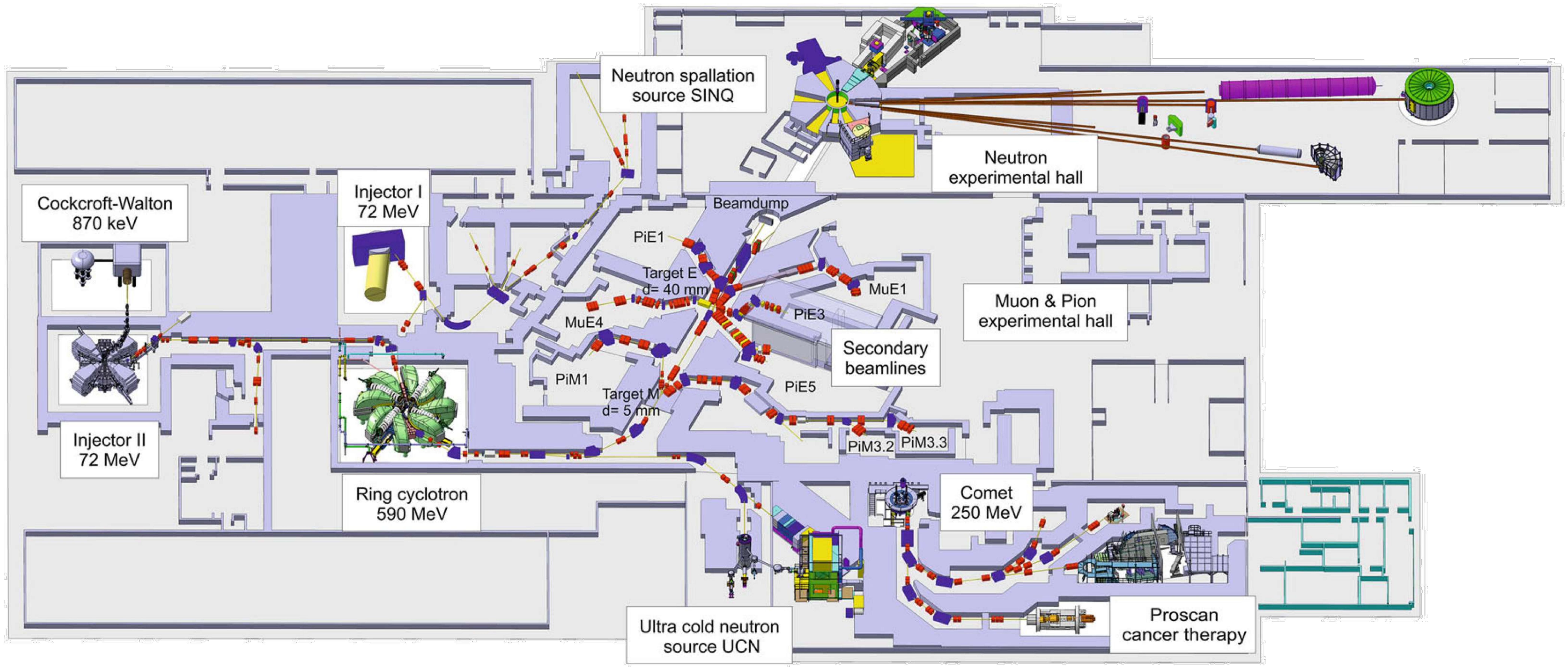
- Exploit and further develop the unique Swiss Infrastructure for Particle Physics at PSI
  - World-leading intensities of pion, muons and ultra-cold neutrons
- Facilitate and perform experiments at the low-energy, precision frontier with unique reach
- Realize HIMB 2025-28, re-arrange and improve experimental areas
  - Push beam intensities and beam quality
- Commission/operate & upgrade various beam lines
- Continue a focused program on improvements for beams, detectors, and theory
- **Everything is set for a leading particle physics program at PSI until 2045 and beyond**

Where we are


GERMANY
FRANCE
PSI
Schaffhausen
Lake Constance
Basel
Winterthur
Sankt Gallen
Zürich
LIECHTENSTEIN
AUSTRIA
Biel
Luzern
Kriens
BERN
Neuchâtel
Fribourg
Yverdon-les-Bains
Lausanne
Lac Léman
CERN
Genève (Geneva)
ITALY
Lugano
Lake Como
Lake Maggiore
ITALY
FRANCE
Milan

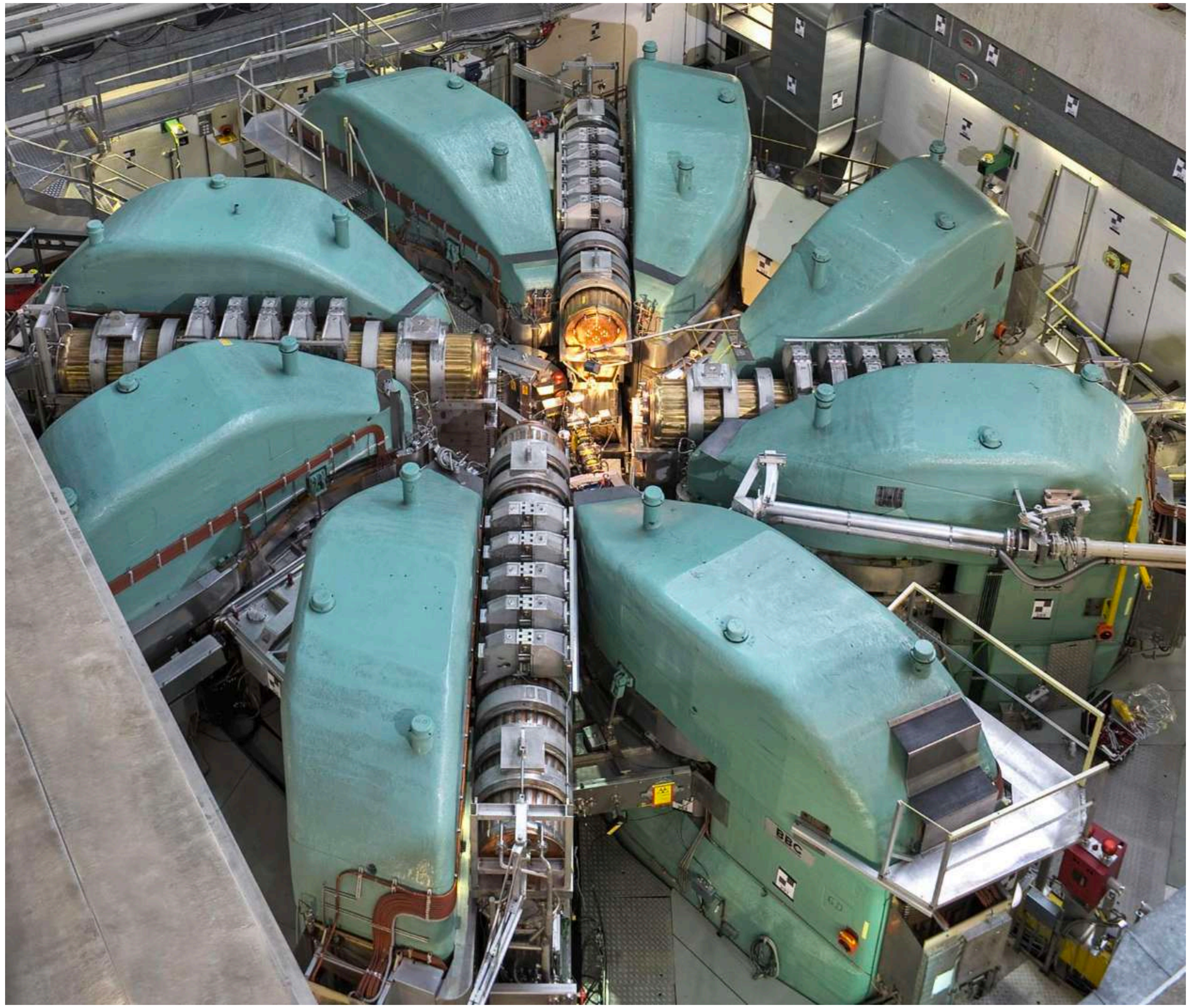
The PSI Facilities

The PSI High Intensity Proton Accelerator Facility (EH)

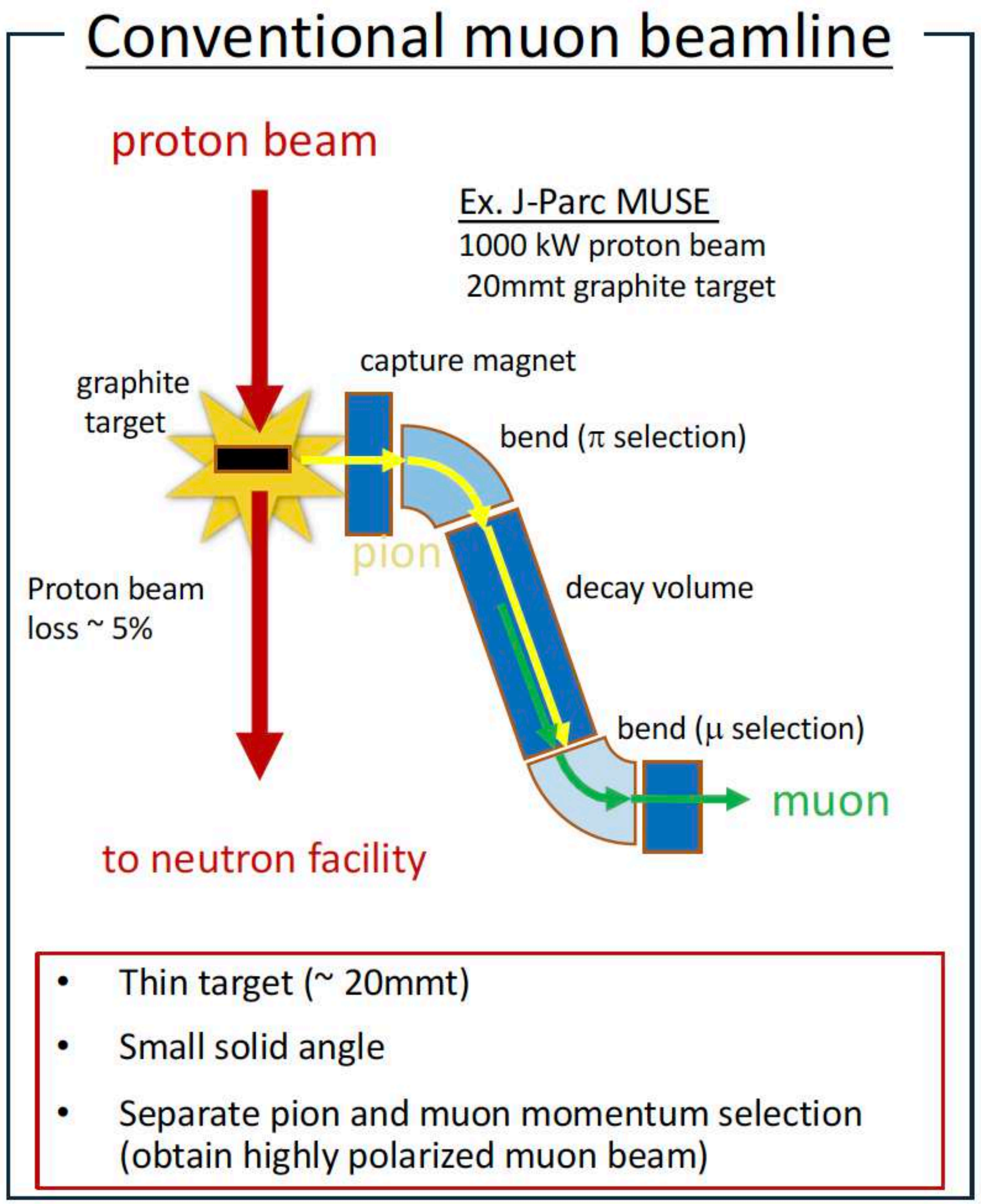


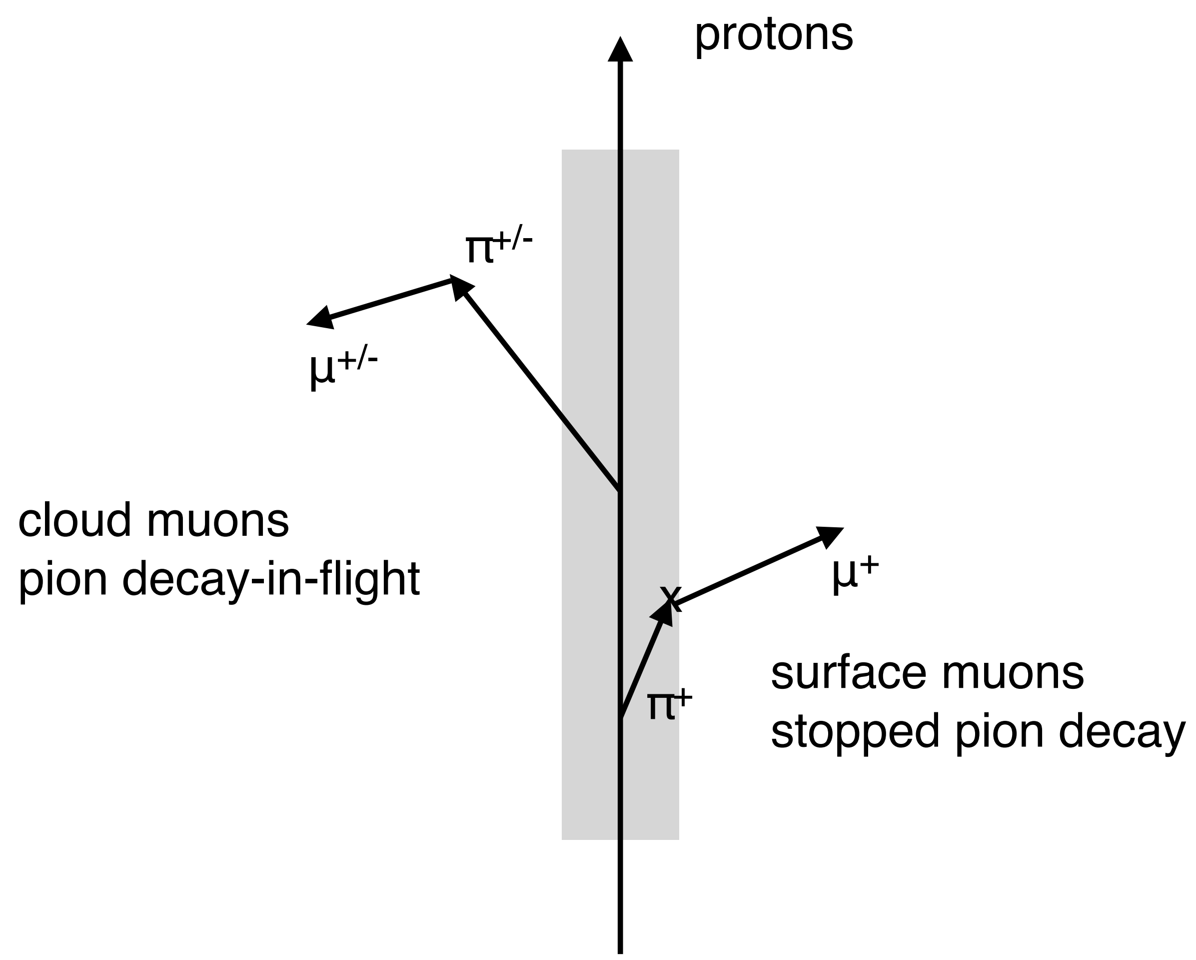
The PSI HIPA ring cyclotron

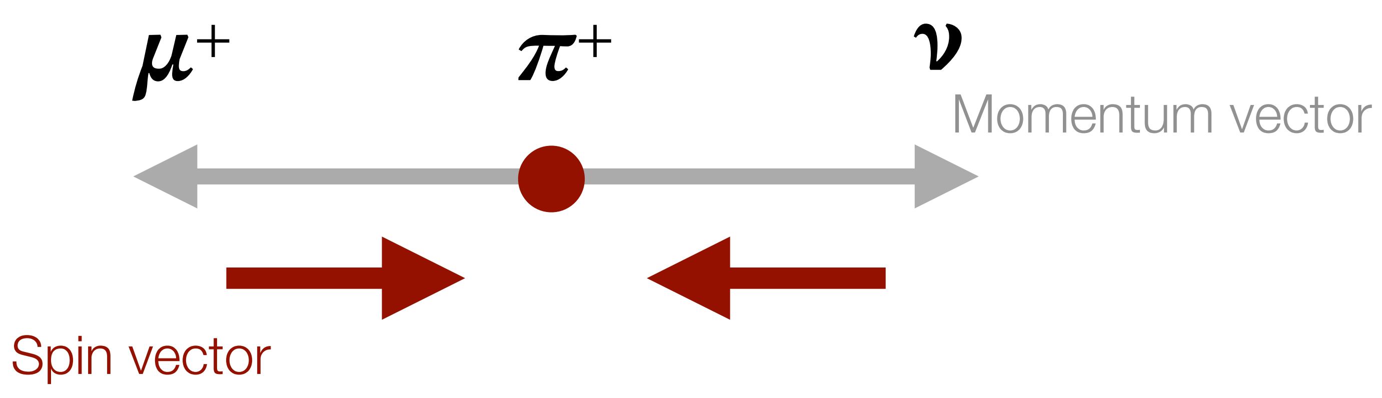
- at time of construction a new concept: separated sector ring cyclotron [H.Willax et al.]
- 8 magnets (280t, 1.6-2.1T),4 accelerating resonators (50MHz), 1 Flattop (150MHz), diam. 15m
- losses at extraction< 200W
- reducing losses by increasing RF voltage was main upgrade path [losses ~ (turn number)^3 W.Joho]
- 590MeV protons at 80%c
- 2.4mA x 590MeV=1.4MW



PSI’s muon beams



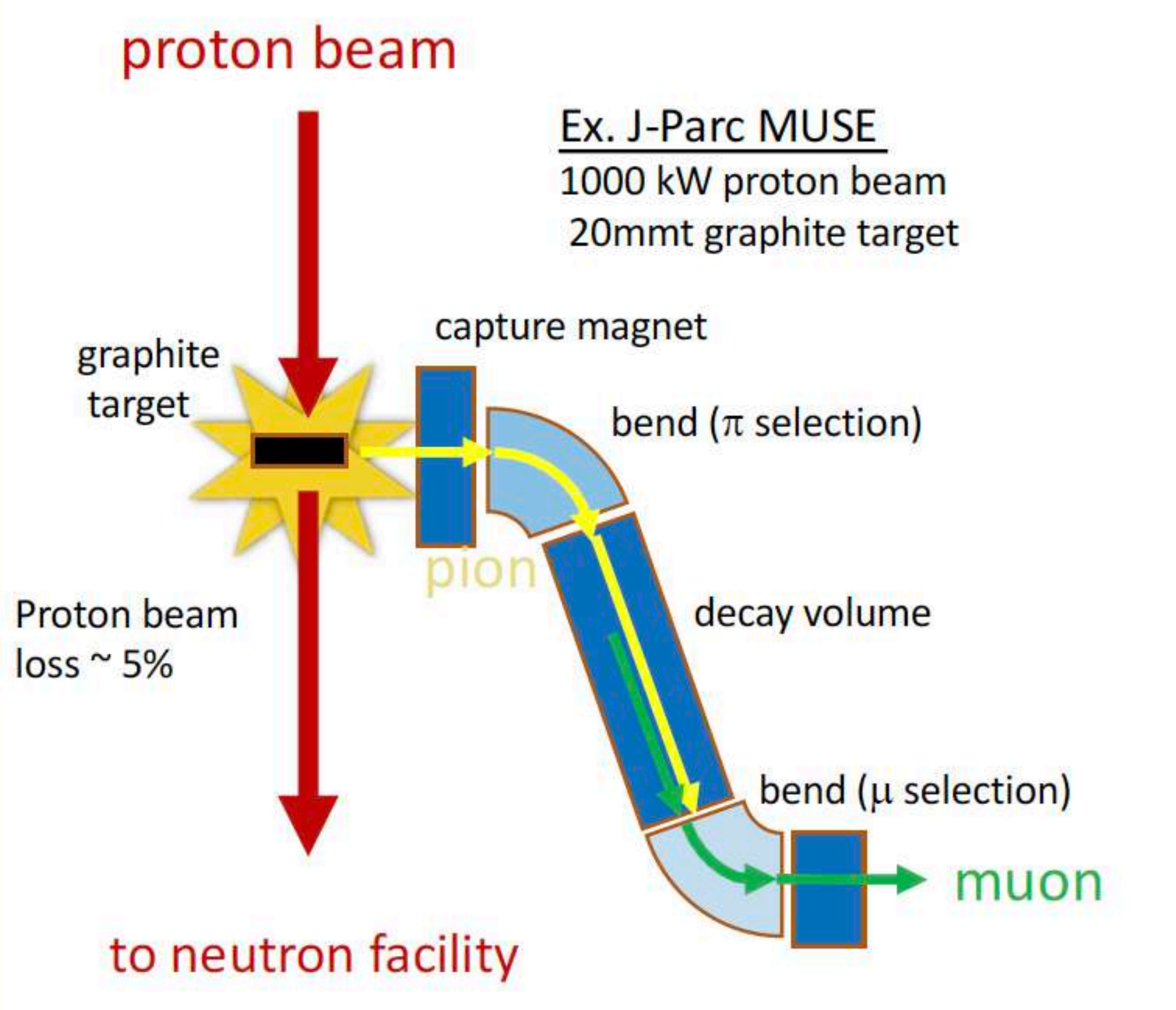




- Muon beams: **secondary** beam lines
- Low-energy muon beam lines typically tuned to surface-μ^+ at ~ 28 MeV/c
- **Note:** surface-μ —> polarised positively charged muons (spin antiparallel to the momentum)
- Contribution from cloud muons at similar momentum about 100x smaller
- Negative muons only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

PSI’s muon beams

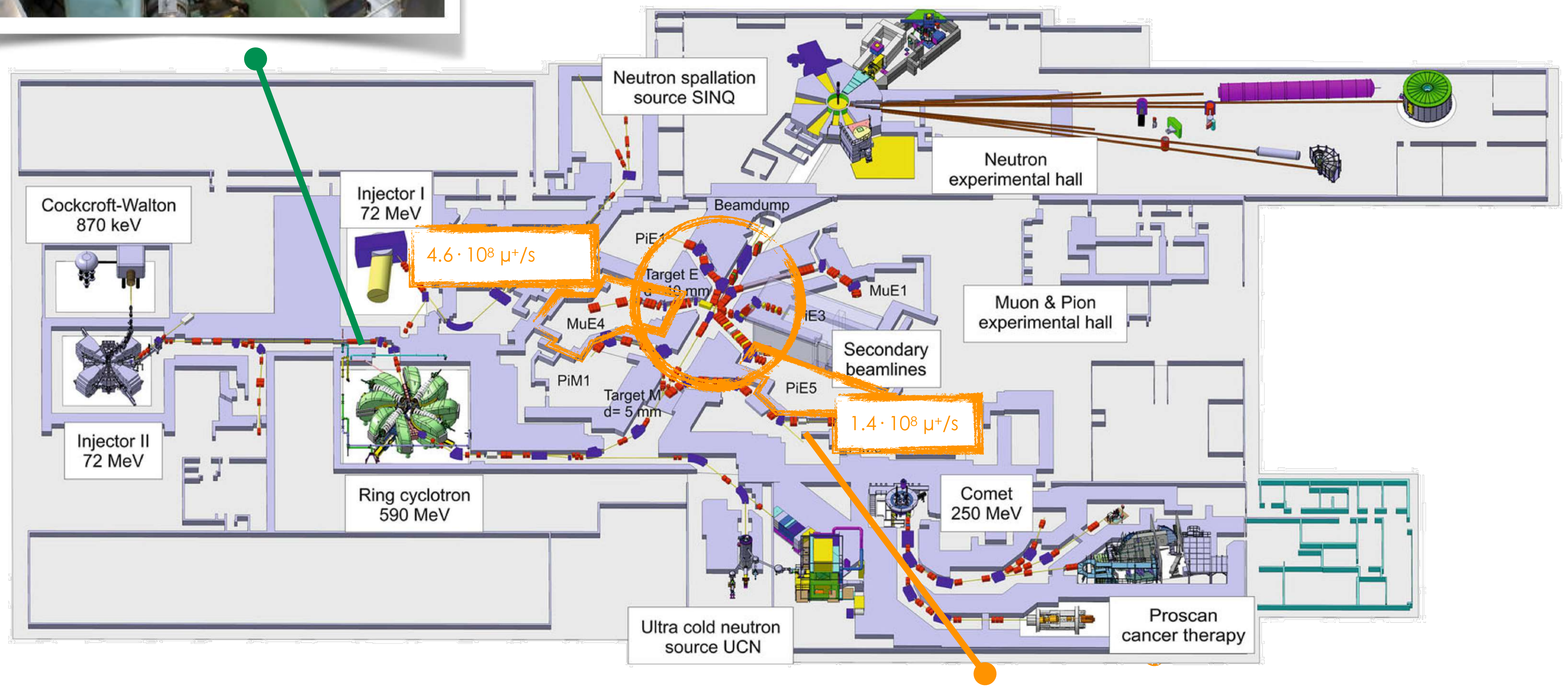
Conventional muon beamline



- Thin target (~ 20mmt)
- Small solid angle
- Separate pion and muon momentum selection (obtain highly polarized muon beam)

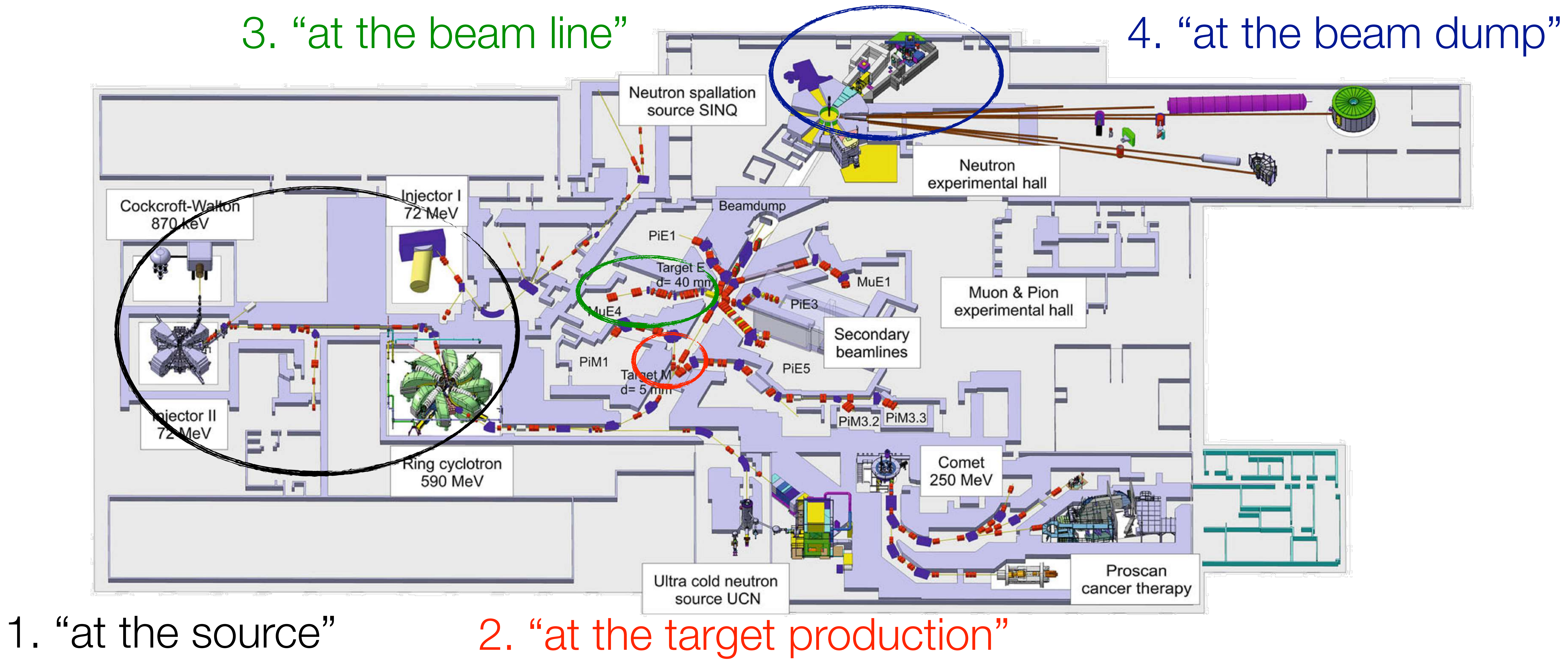
- PSI delivers the most intense continuous (DC) low momentum (surface) muon beam in the world up to few x 10^8 mu/s (28 MeV/c, polarised beam (**Intensity Frontiers**)

590 MeV proton
ring cyclotron
1.4 MW



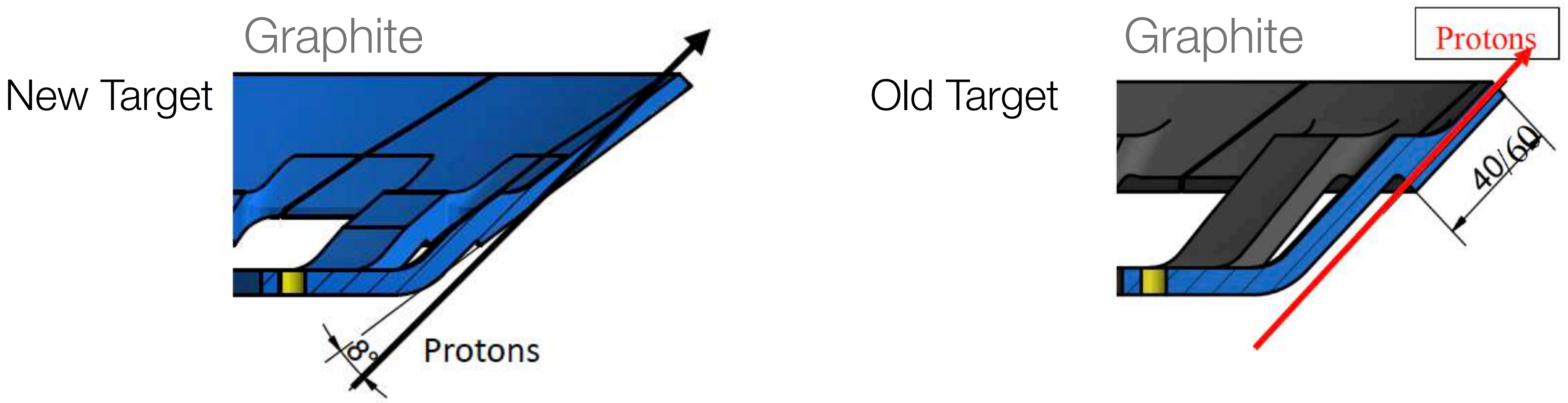
MEGII / Mu3e Experimental area

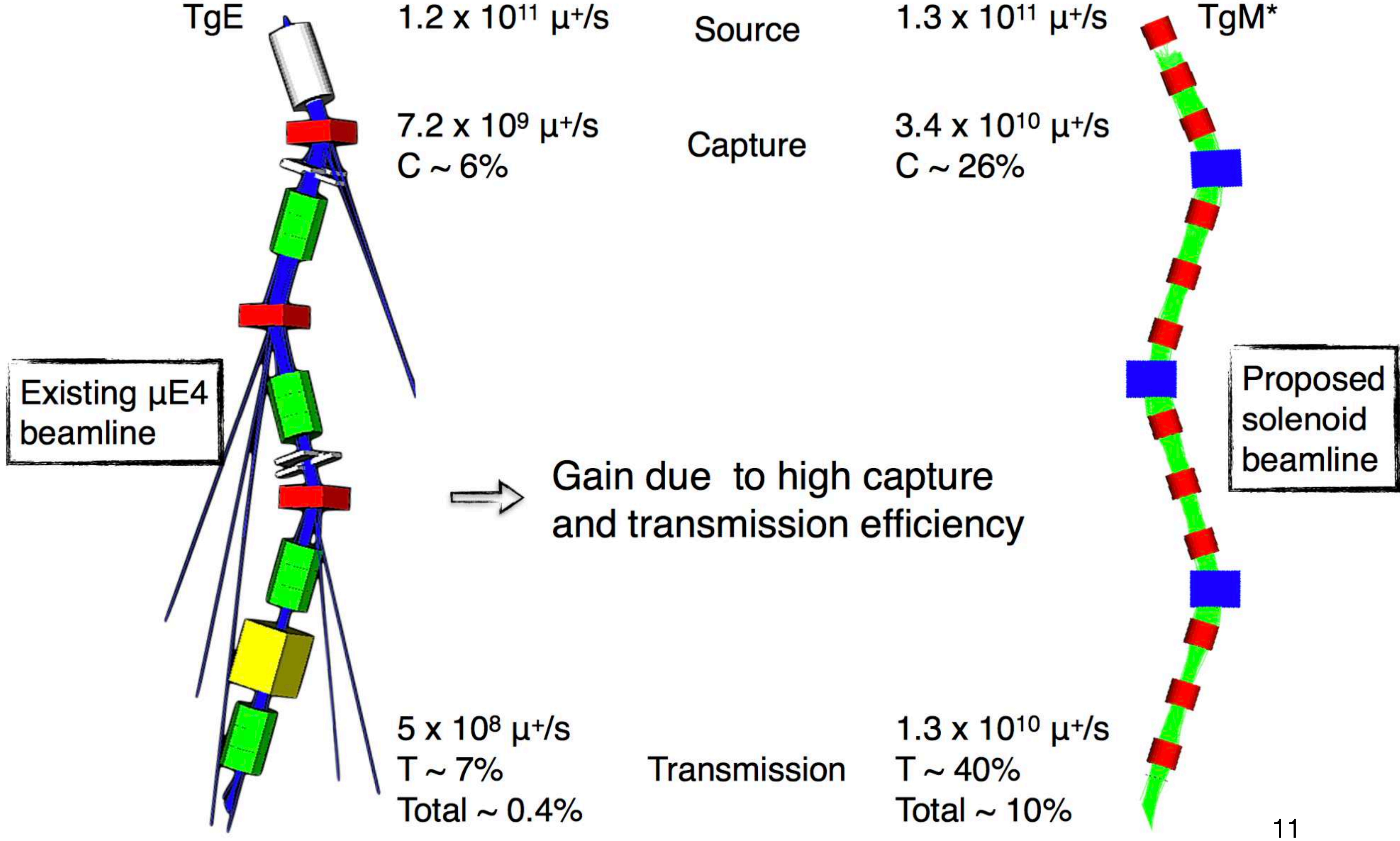
How the beam intensity can be increased…

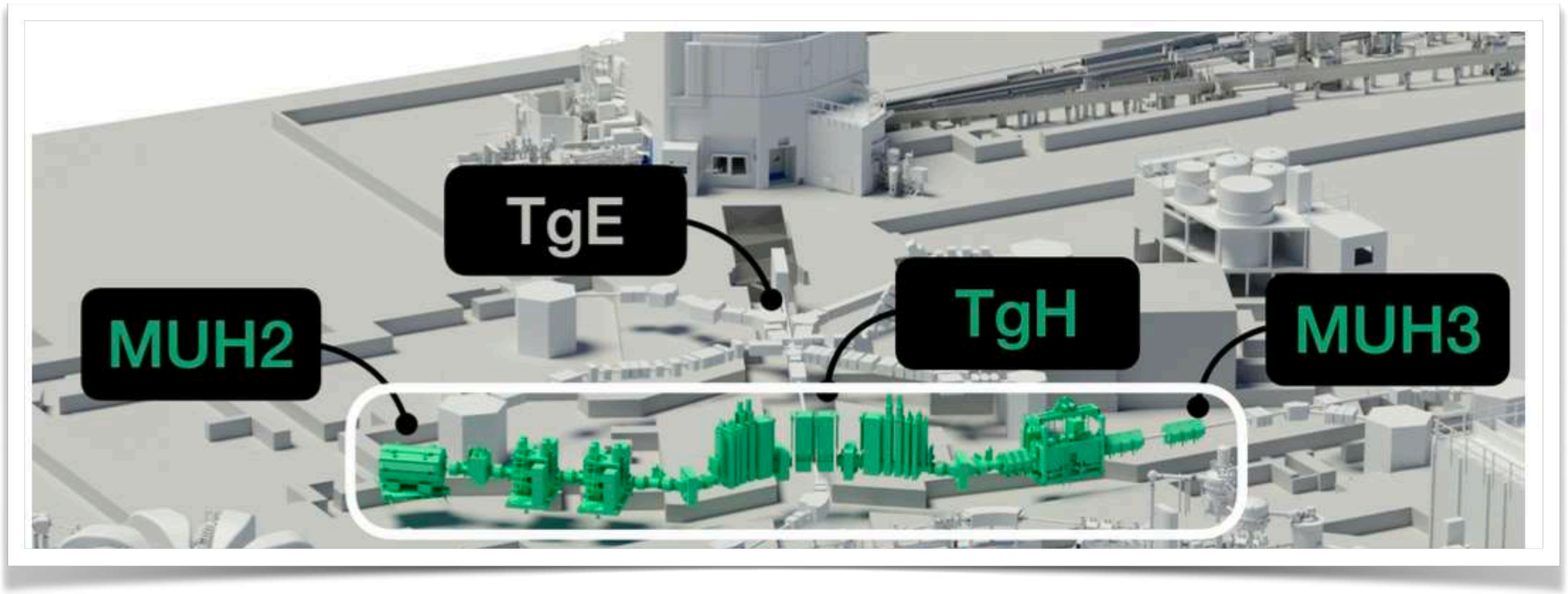


The HiMB (High Intensity Muon Beam) project at PSI

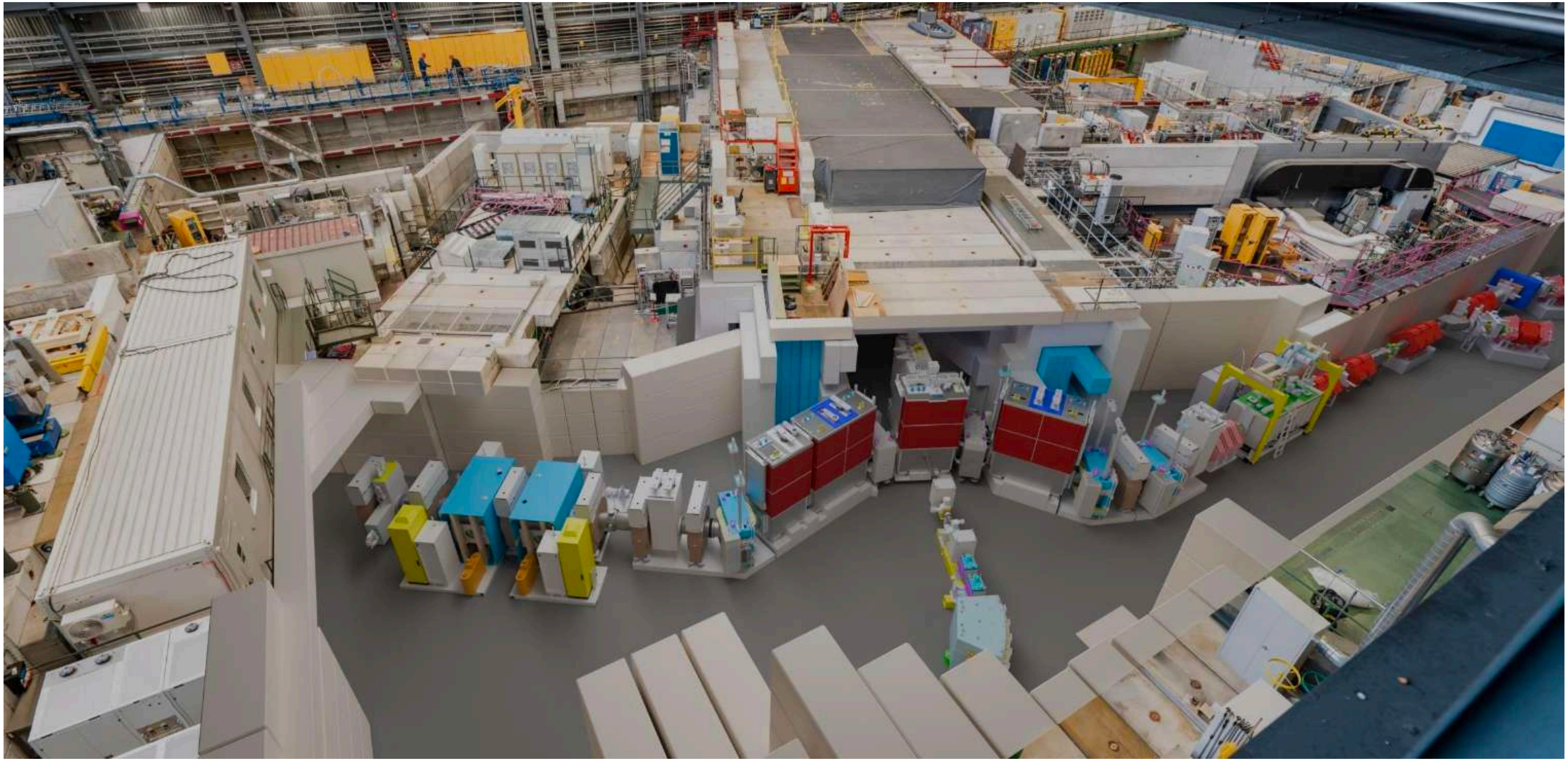
- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
  - Target: alternate materials (B_4C and Be_2C show 10-15% gain) and/or geometry (up to 60% of gain: Graphite **Slanted target**)
  - Beam line: high capture efficiency and large phase space acceptance transport channel
- Slanted target test successfully done and installed as "default" target since 2020
    - **Increase surface muon rates (30-60% increase depending of the beamline)**
    - **Increase safety margin for "missing" target with the proton beam**
- PSI Long shut-down: **2027-8. HiMB from end of 2028**







HiMB landscape…



Eagers not only for more muons…

- Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world's **highest** beam **intensities**, proper (DC or pulsed) **time structure, w/o polarization,** optimal **phase space**

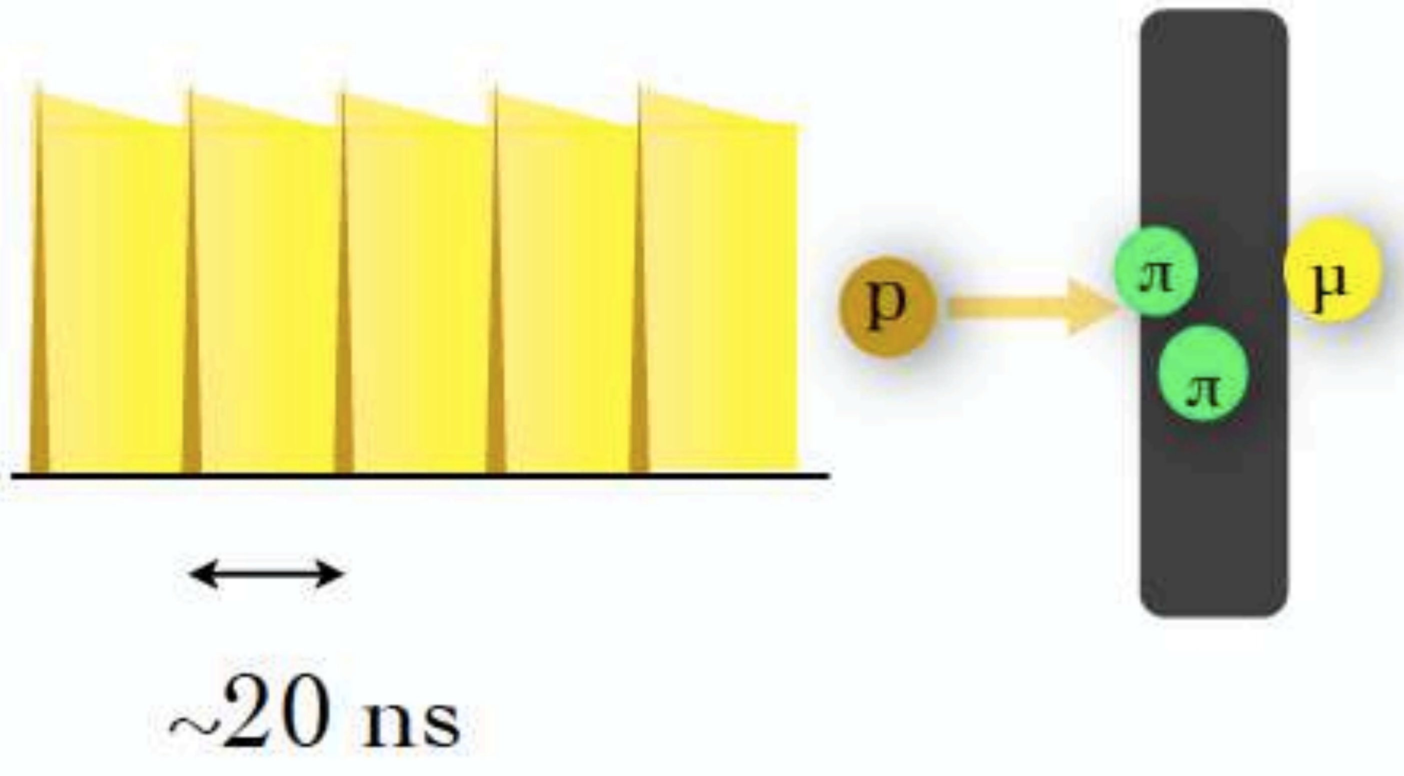
$I_{beam} \sim 10^8 - 10^{10}$ μ/s

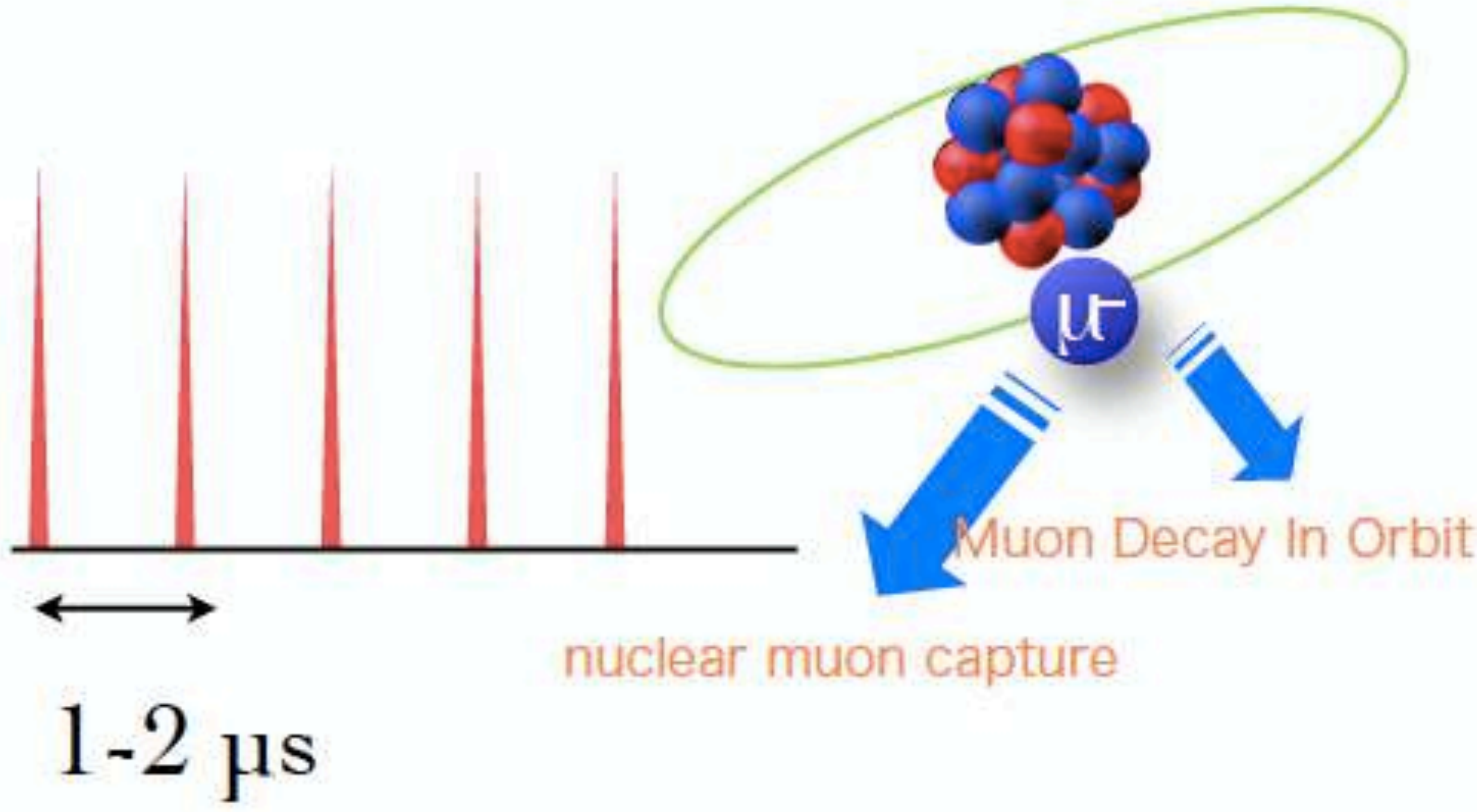
DC or Pulsed?

$I_{beam} \sim 10^{11}$ μ/s

- DC beam for coincidence experiments
  - $\mu \rightarrow e \gamma$, $\mu \rightarrow e\ e\ e$
- Pulse beam for non-coincidence experiments
  - μ-e conversion

@ PSI

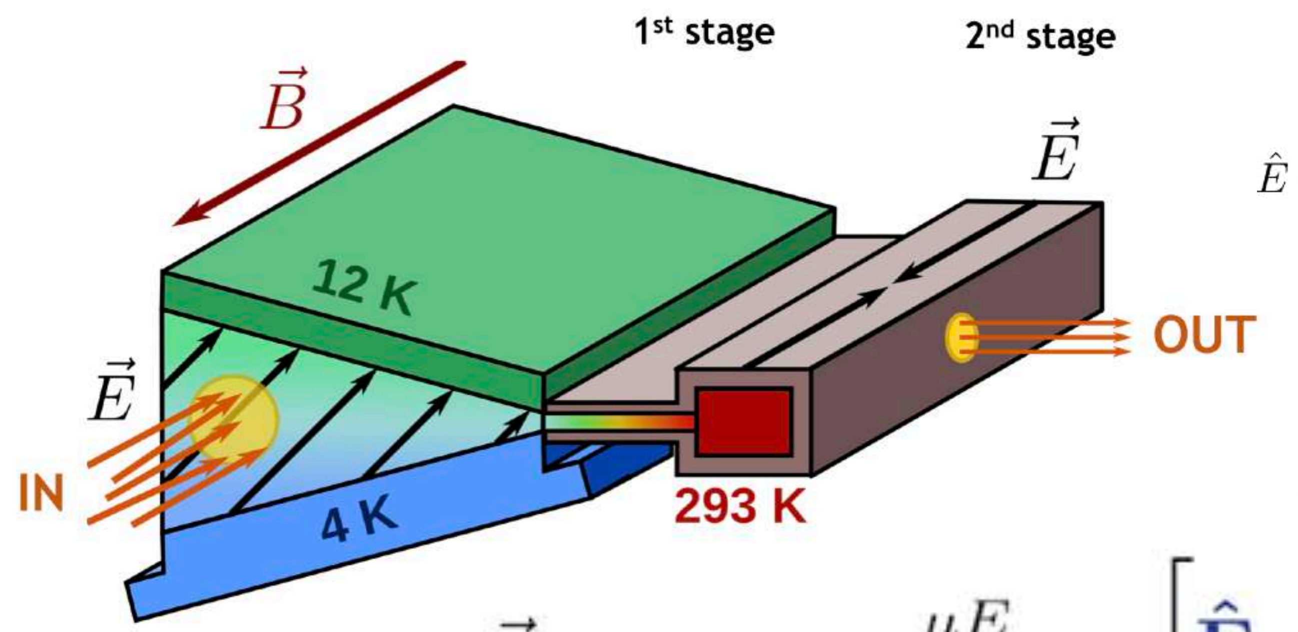


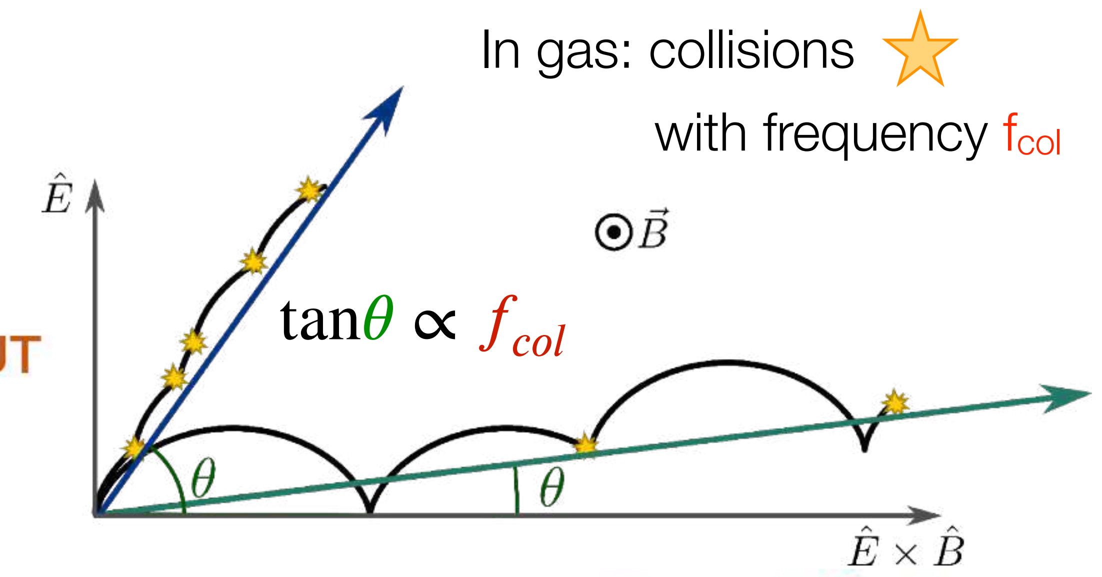


@ JPARC, FERMILAB

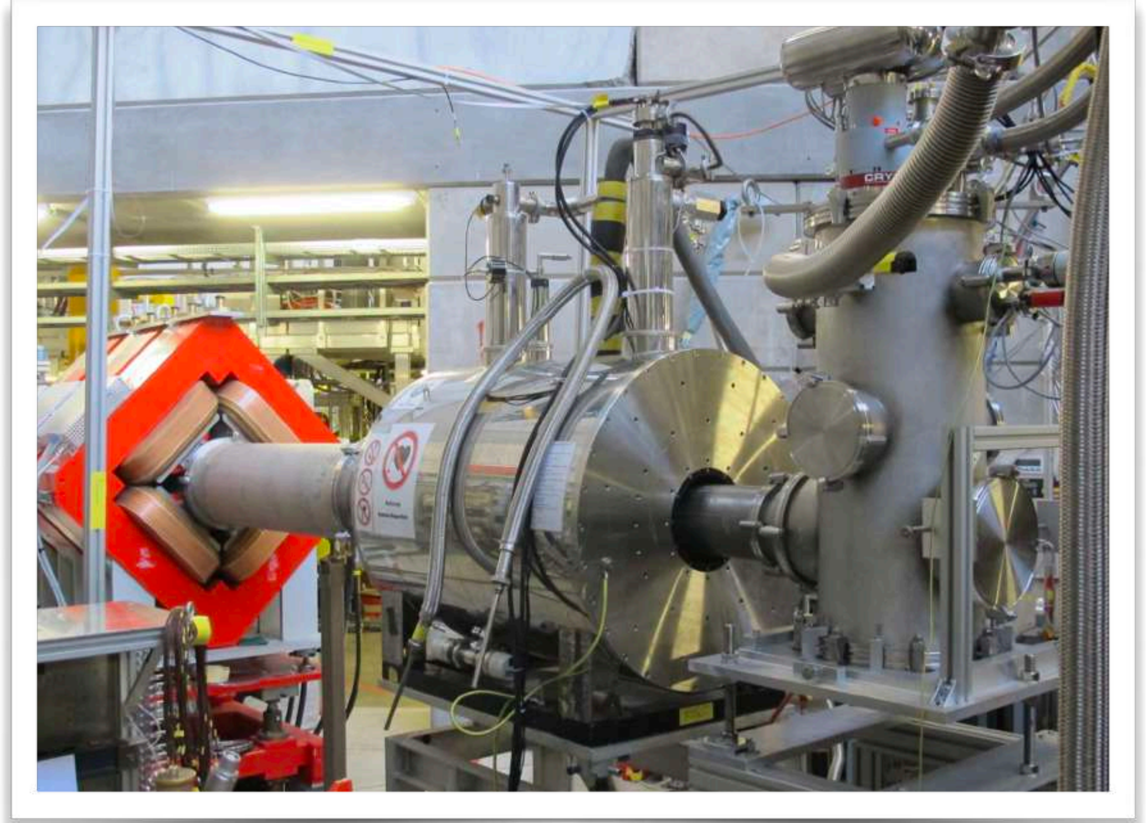
The muCool project at PSI

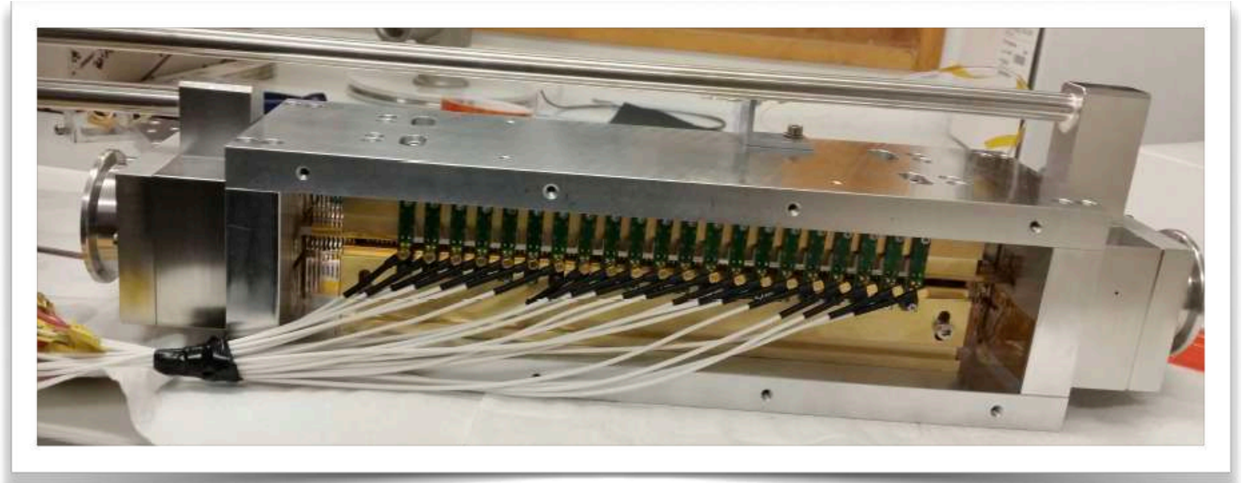
- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor **10^{10}** with an efficiency of **10^{-4}**
- Longitudinal and transverse compression (1st stage + 2nd stage): experimentally proved
- **Next Step**: Extraction into vacuum



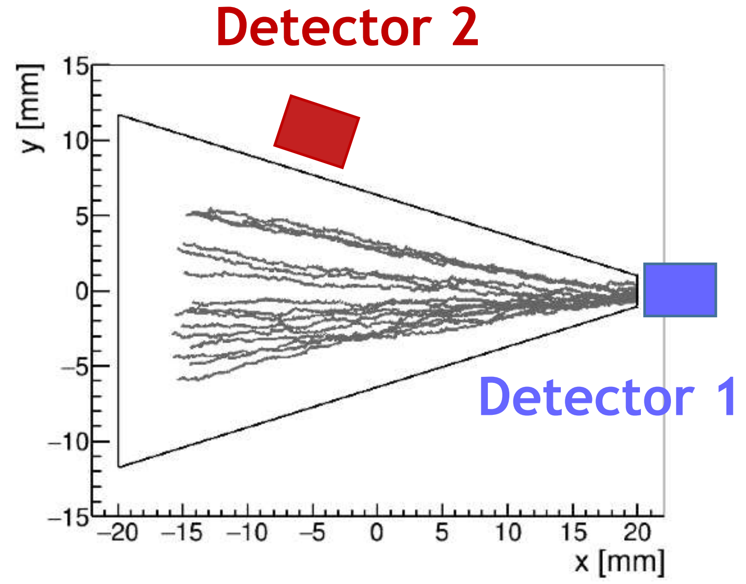


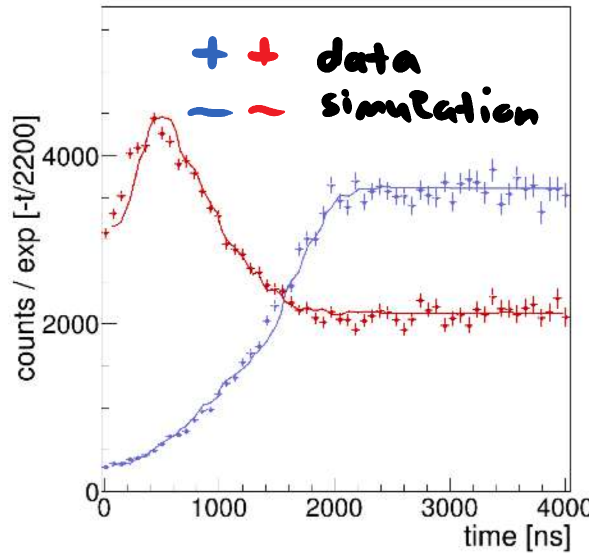
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$



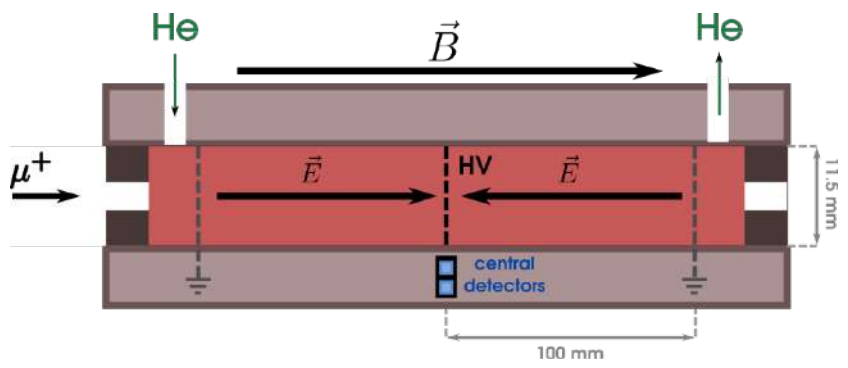


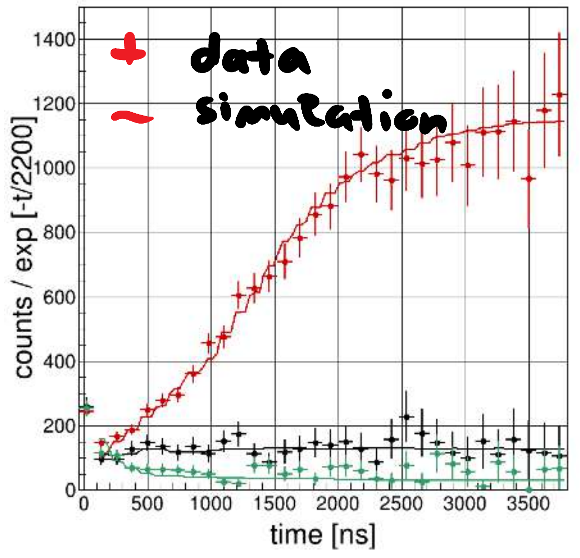
Transverse Compression



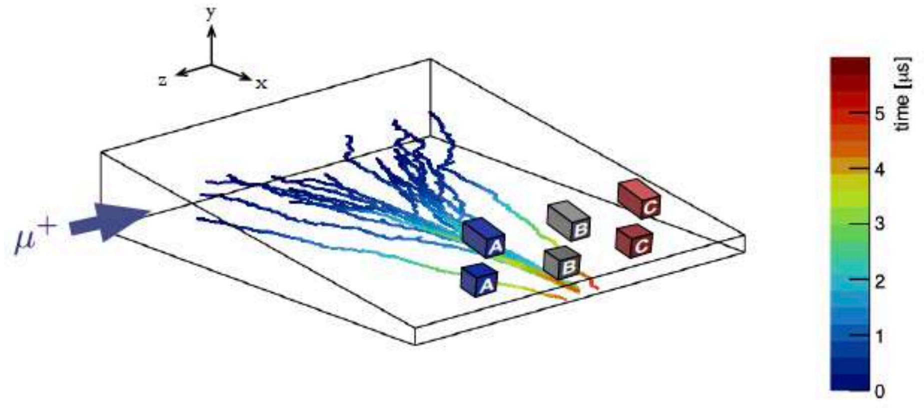


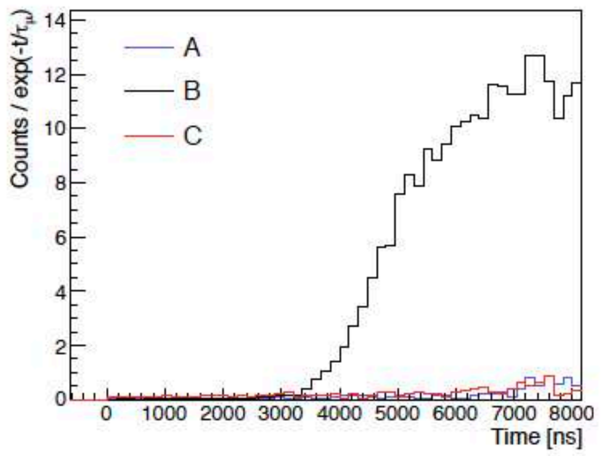
Longitudinal Compression





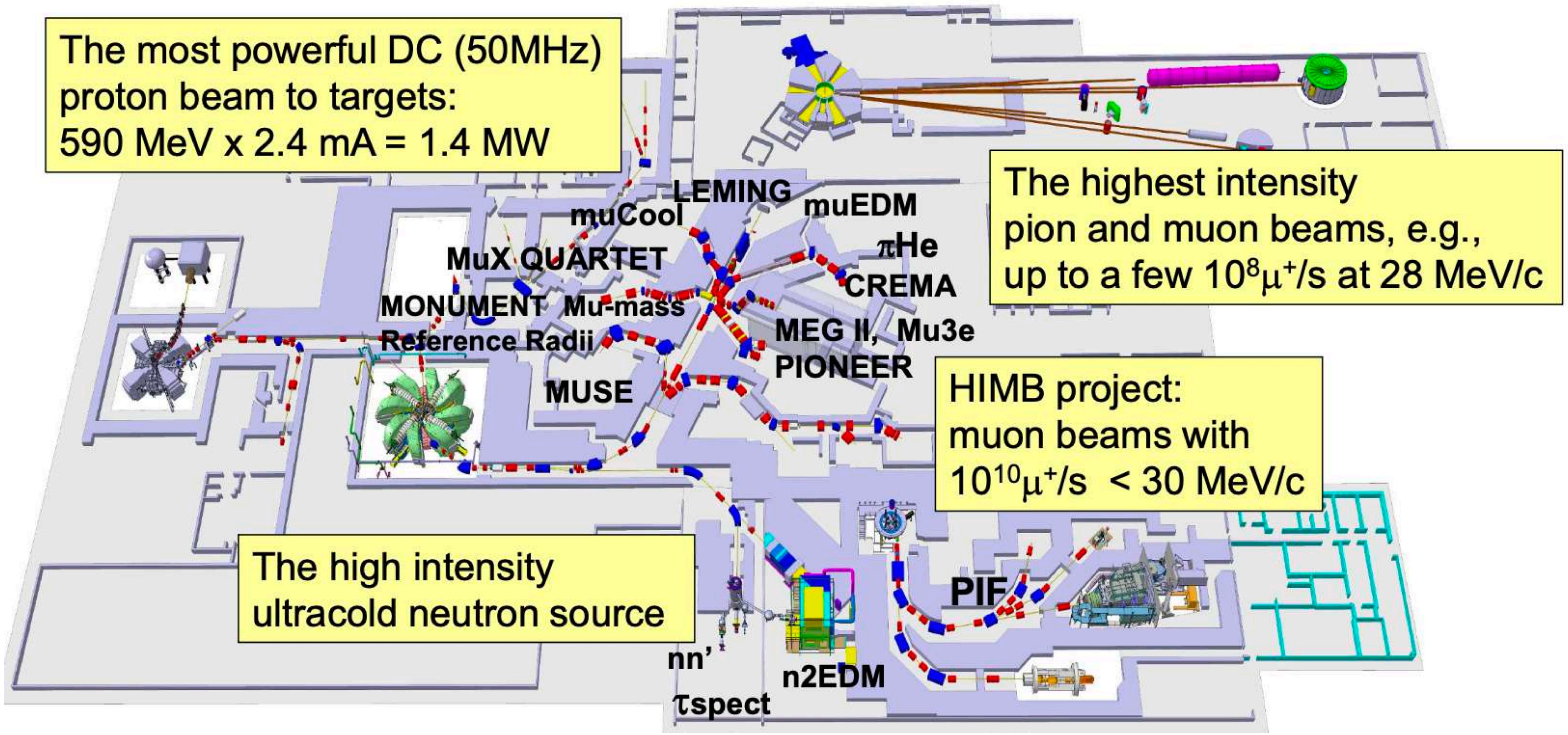
Longitudinal+ Transverse Compression





The intensity frontier at PSI: Pions, muons and UCN

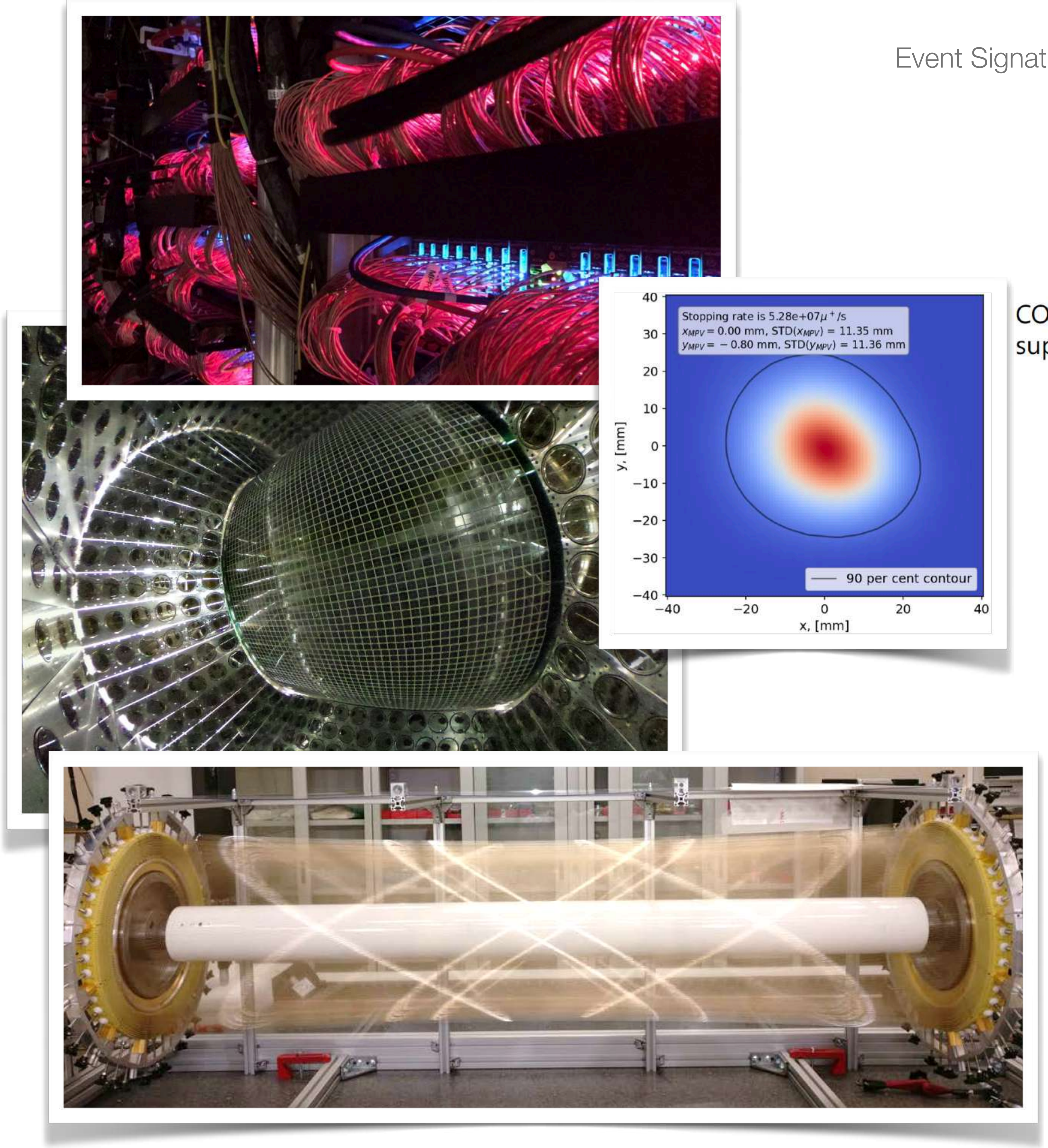
- Precision experiments with the lightest unstable particles of their kind



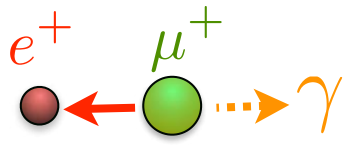
See recent Particle Physics at PSI, https://scipost.org/SciPostPhysProc.5.001

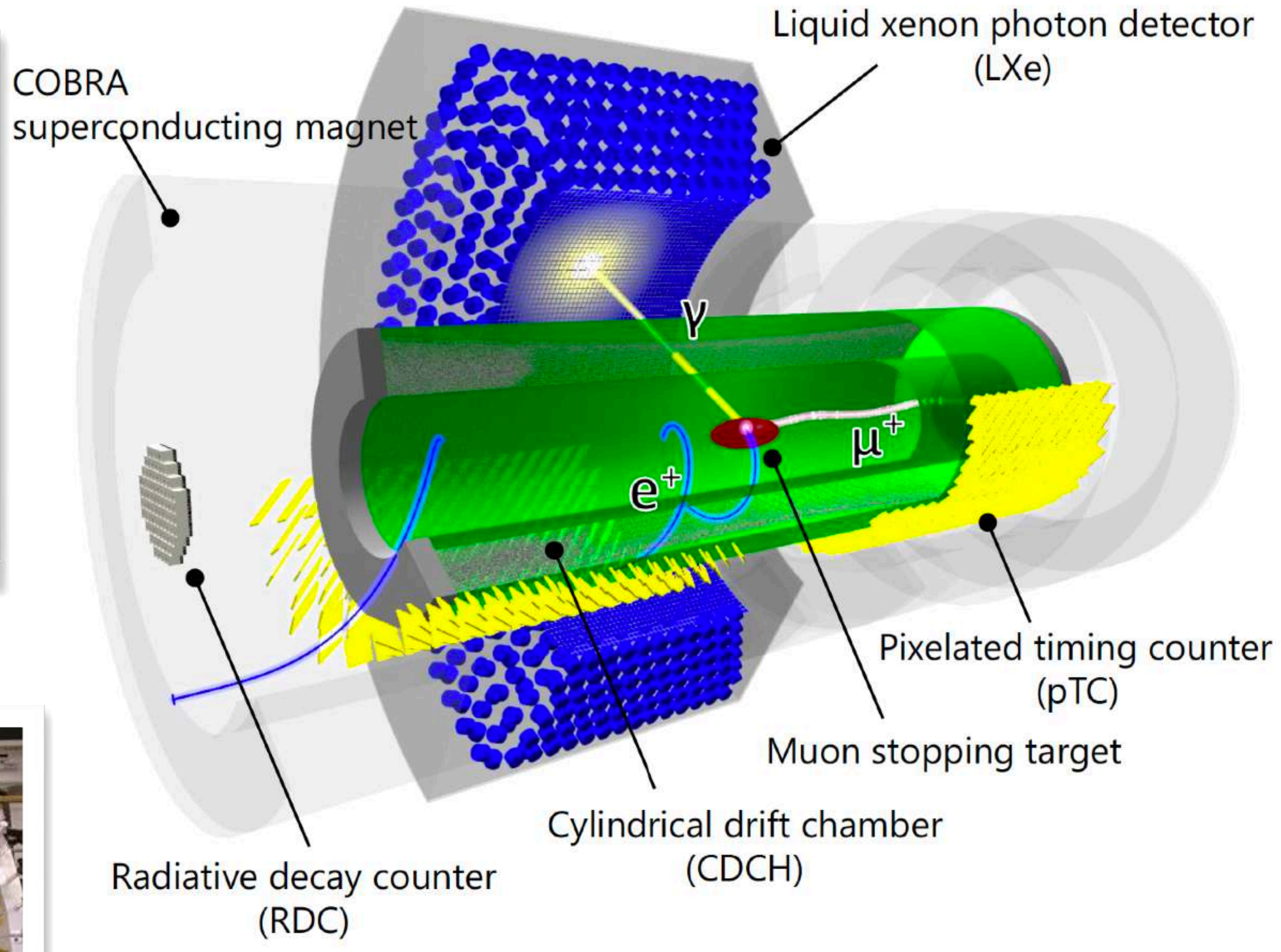
cLFV with the MEGII experiment

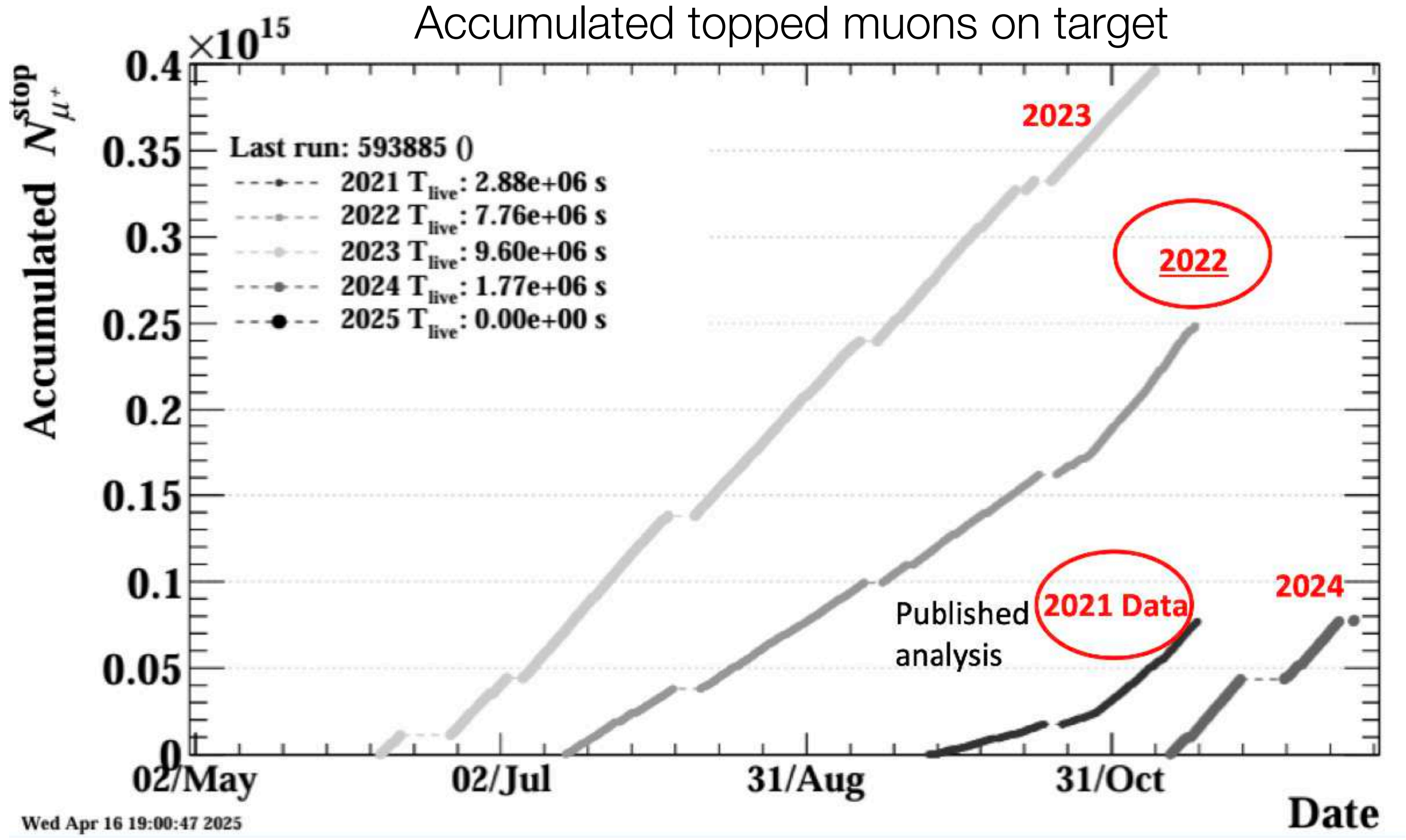
- The MEGII experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~6 x 10^{-14}. It started data taking in 2021 and is expected to run until 2026 (~ O(10) better than MEGI)
- A new Physics Result has recently been released based on the data 2021+2022 setting a new Upper Limit on the Branching ratio of the **$\mu^+ \rightarrow e^+ \gamma$: 1.5 x 10^{-13} (@90% CL.)**



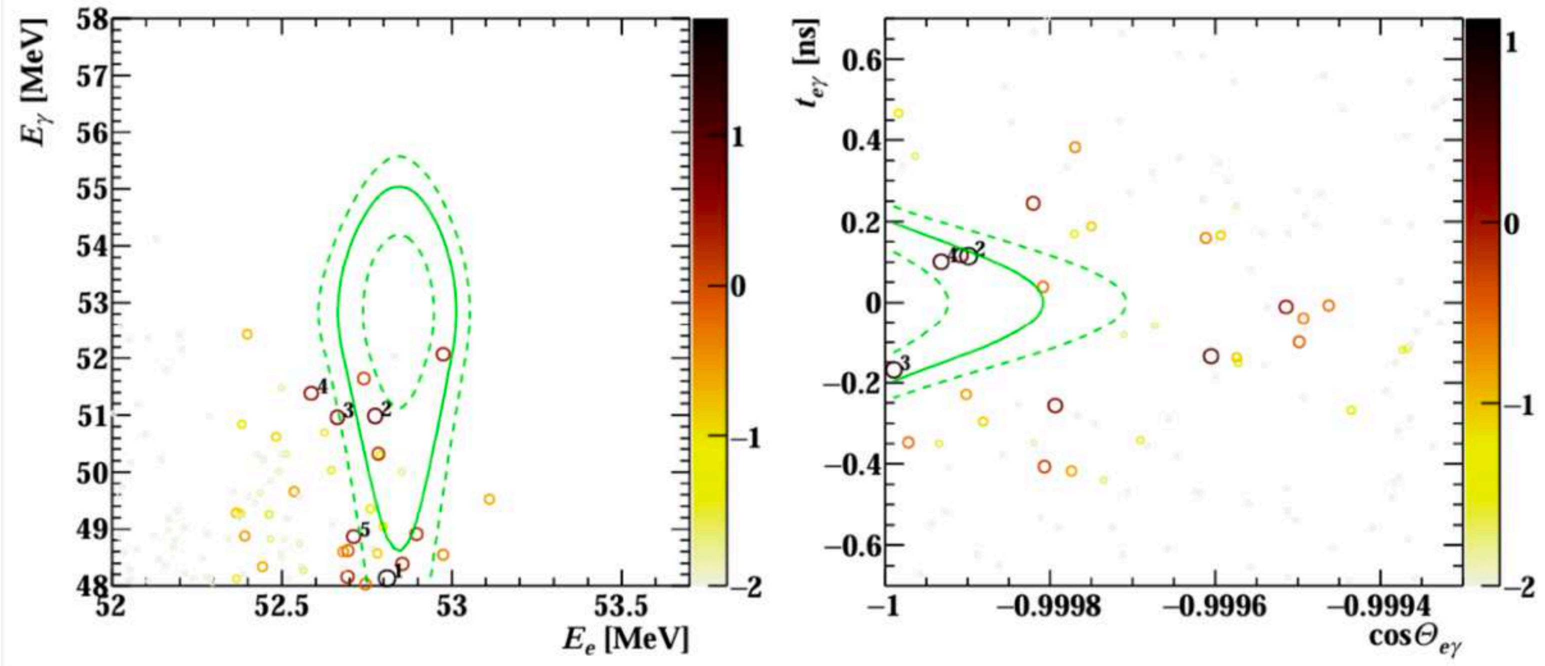
Event Signature from stopped muons in the target







Data 2021+2022: Opening the signal region

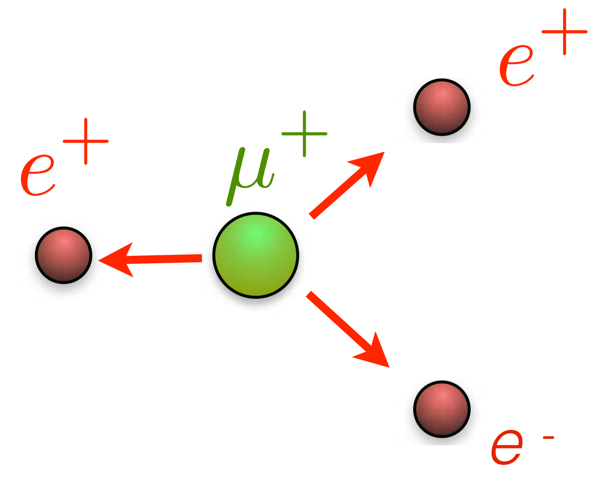


MEGII 2021+2022 result (NEW):
Upper Limit (90% CL) on **BR = 1.5 x 10^{-13}**

cLFV with the Mu3e experiment

- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of ~10^{-15} (Phase I) up to down ~10^{-16} (Phase II)
- Previous upper limit BR($\mu^+ \rightarrow e^+ e^+ e^-$) ≤ 1 x 10^{-12} @90 C.L. by SINDRUM experiment)

Event Signature from stopped muons in the target

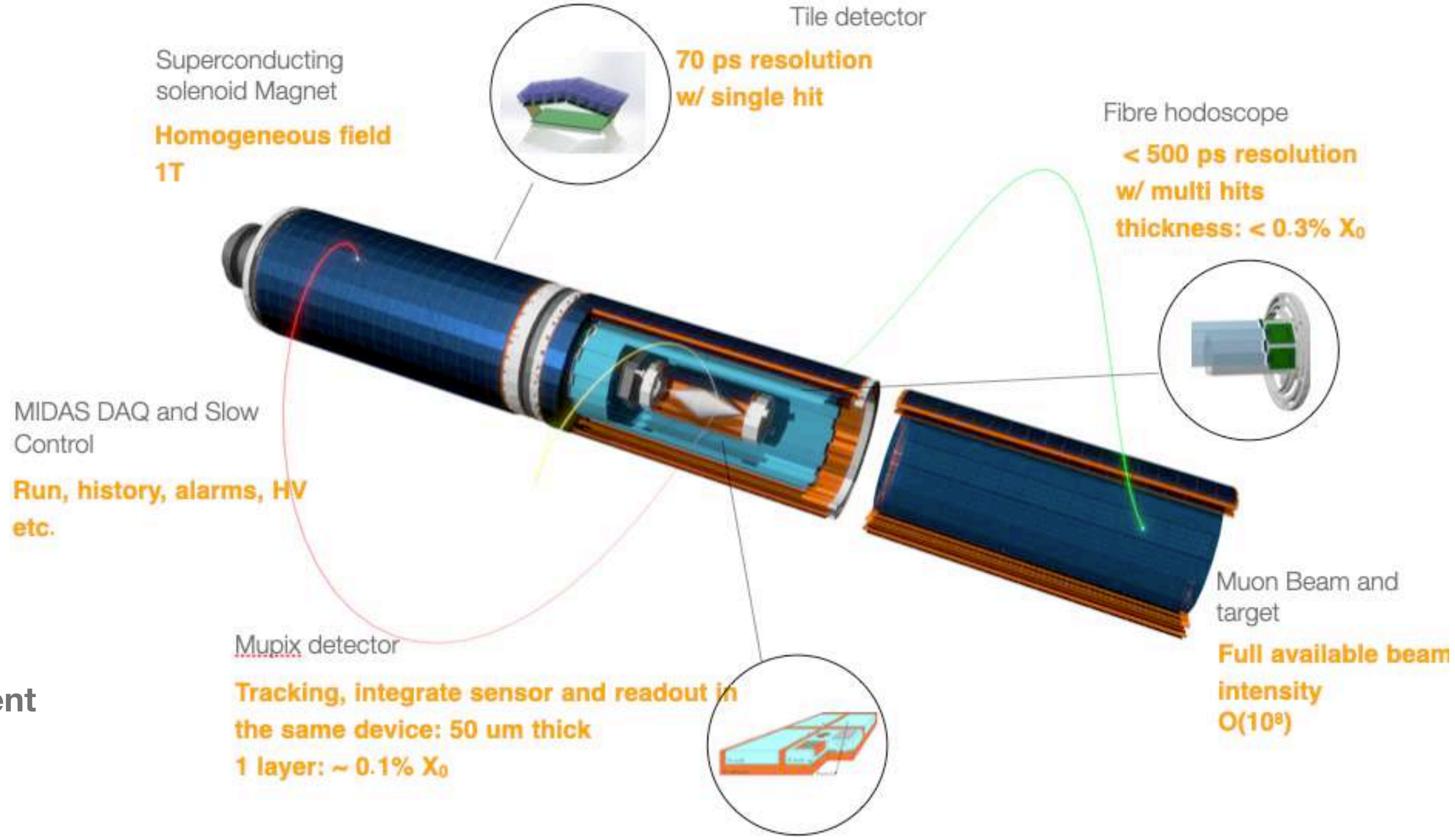


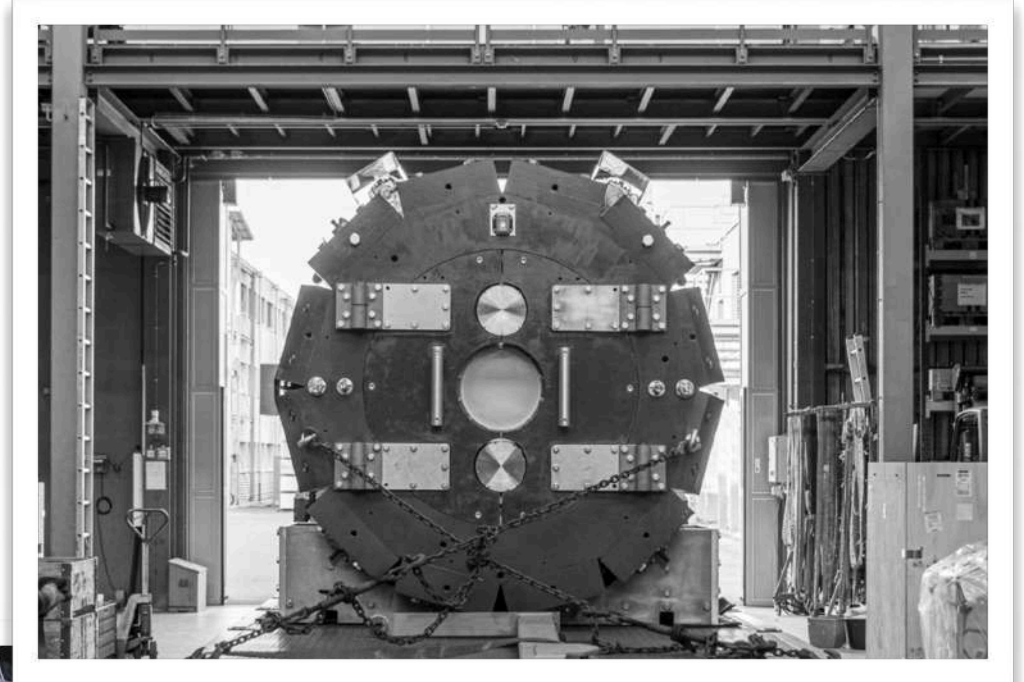
- Detector concept validated during the Integration run 2021
- Full beam line commissioned with fine tuning in 2023 [new record of transported muons]
  - **1.02e^8 mu/s @2.4 mA** (Mu3e magnet)

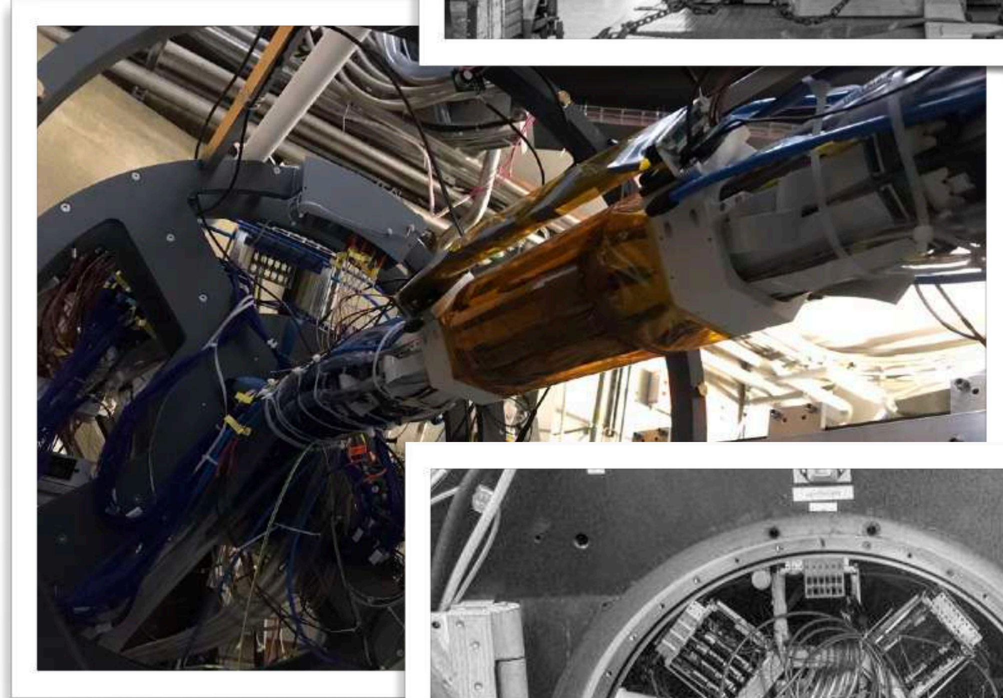
Time line phase I (exploiting current beam-line intensity)

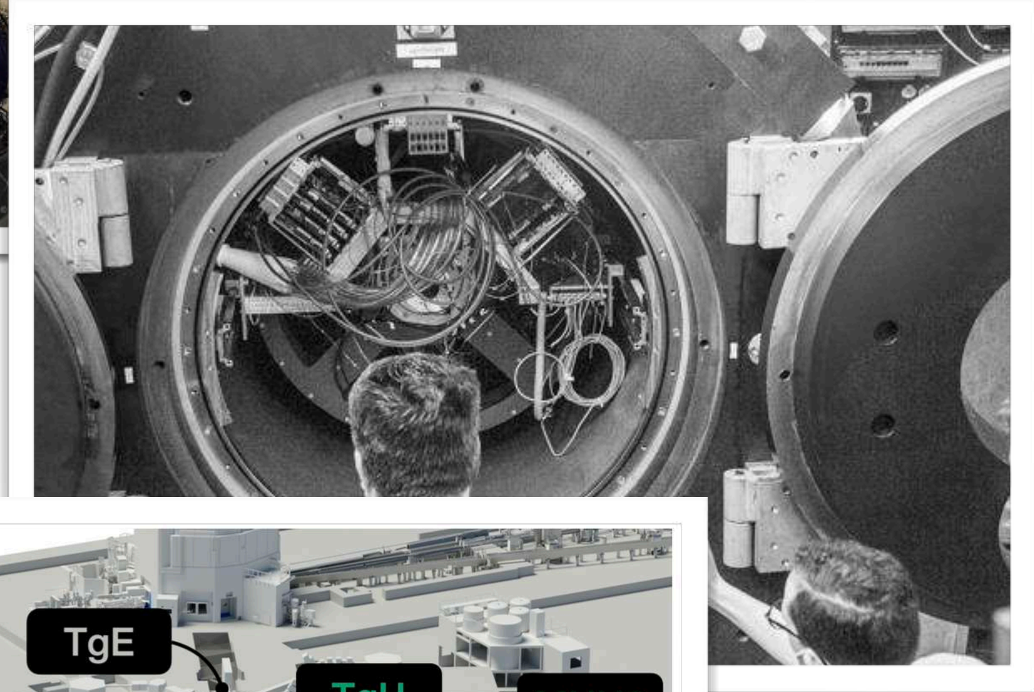
- Engineering run: 2025
- First physics run: 2026

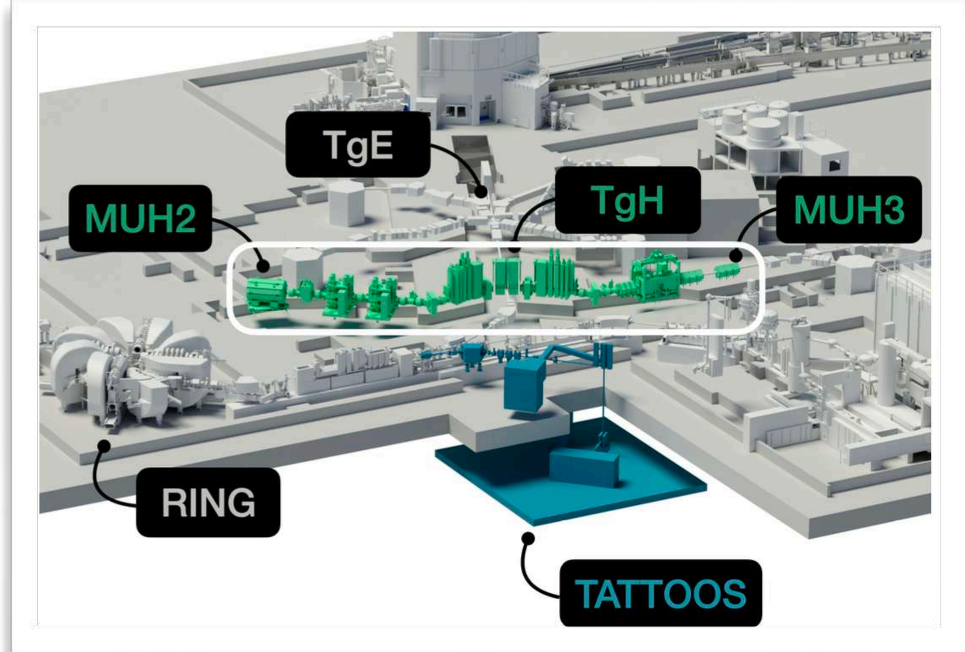
Phase II: It requires 10^9 mu/s —> **HiMB**





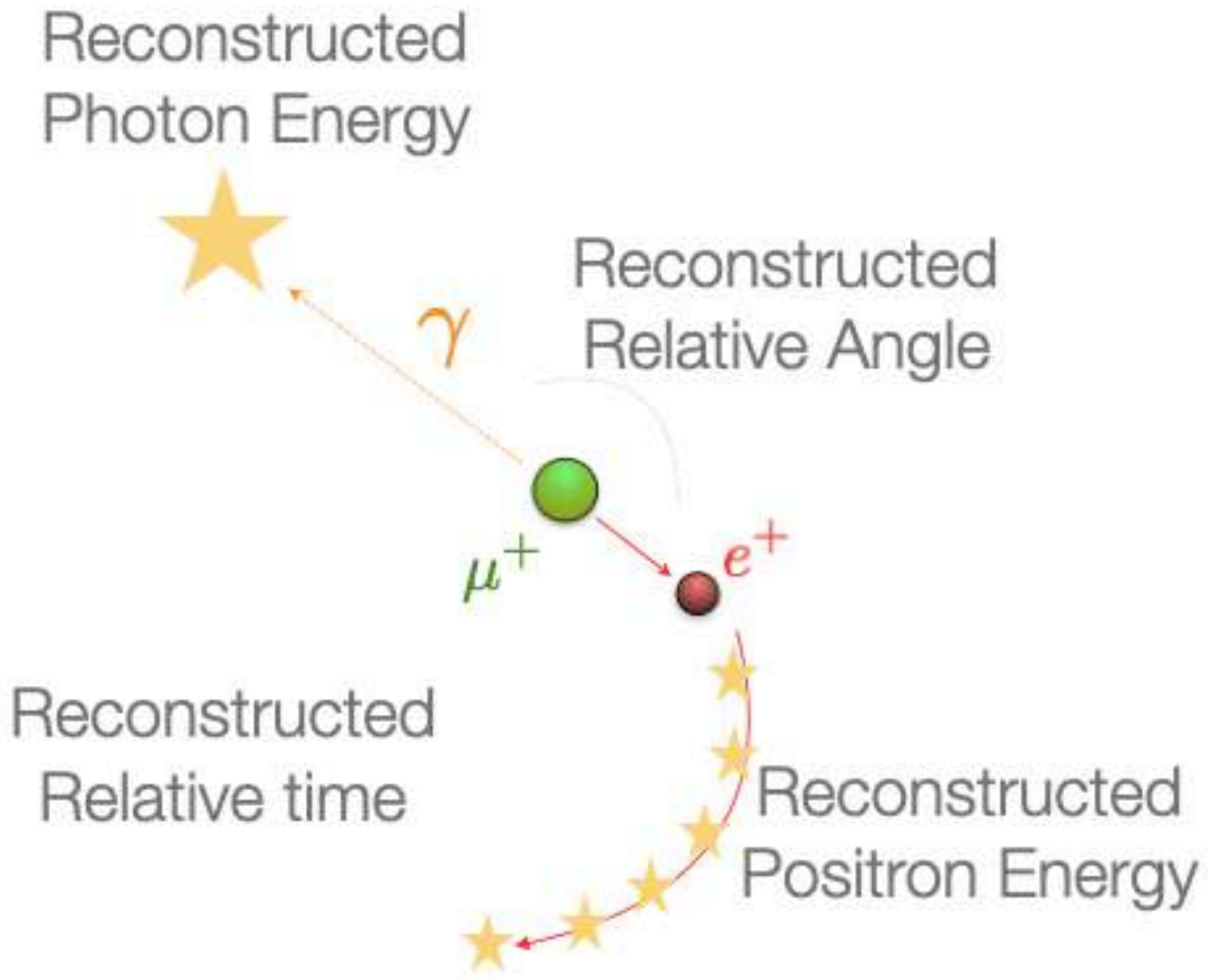


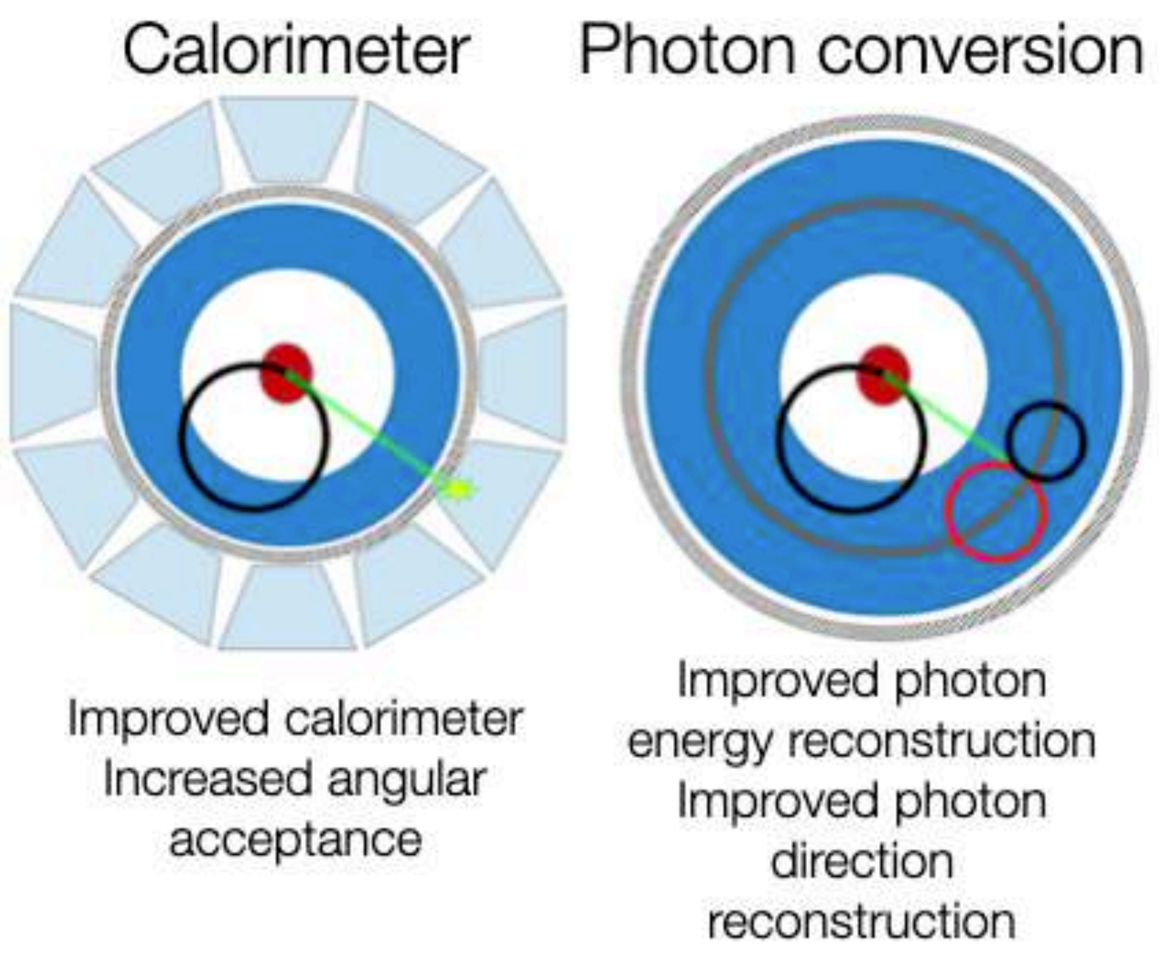




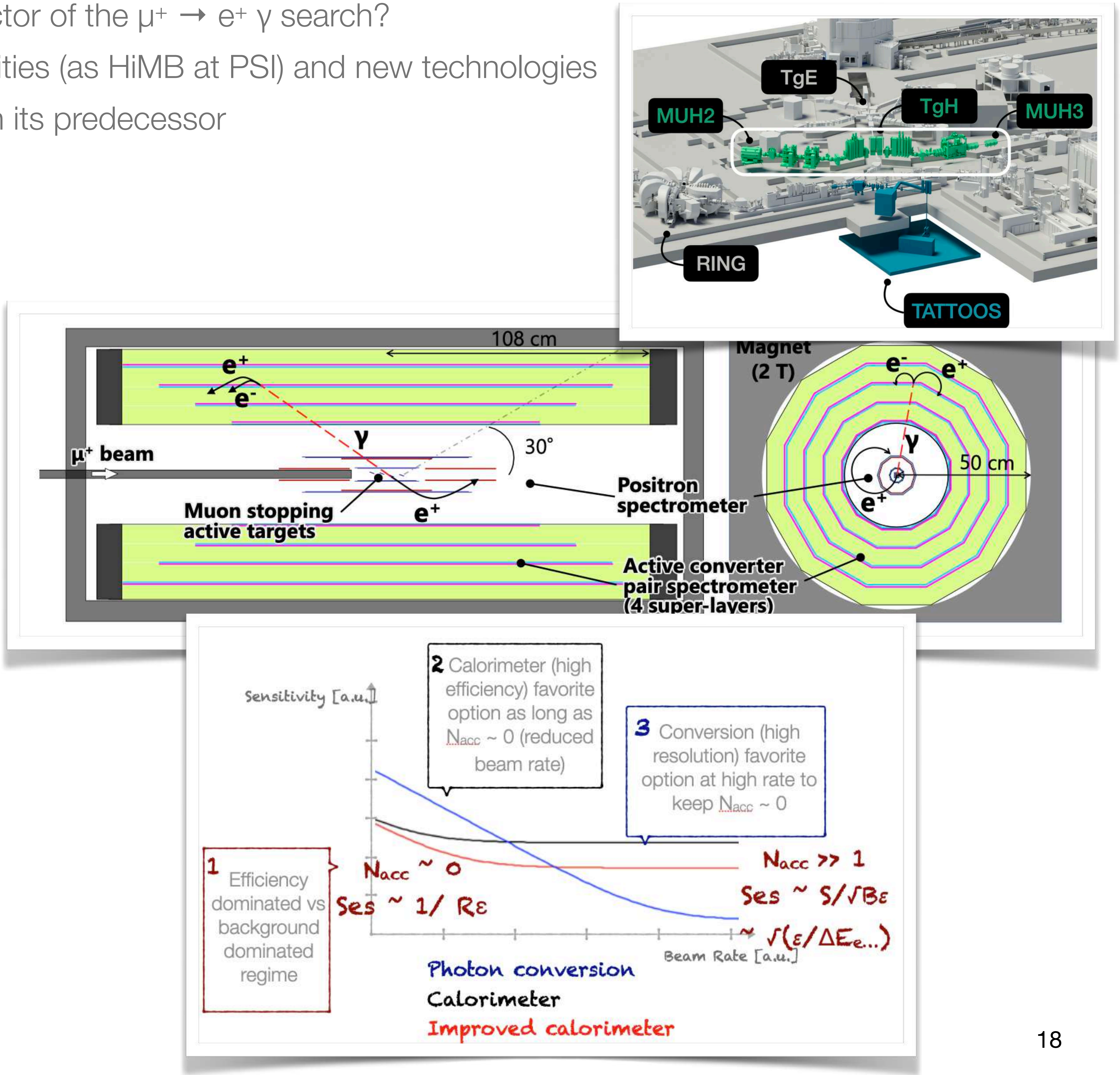
Future cLFV searches: A community is growing up

- How the $\mu^+ \to e^+ \gamma$ sensitivity can be improved? Or…which are the current limiting factor of the $\mu^+ \to e^+ \gamma$ search?
- A community is growing up with the aim of exploiting the new upcoming beam intensities (as HiMB at PSI) and new technologies for future $\mu^+ \to e^+ \gamma$ searches aiming at least at one further order of magnitude better than its predecessor



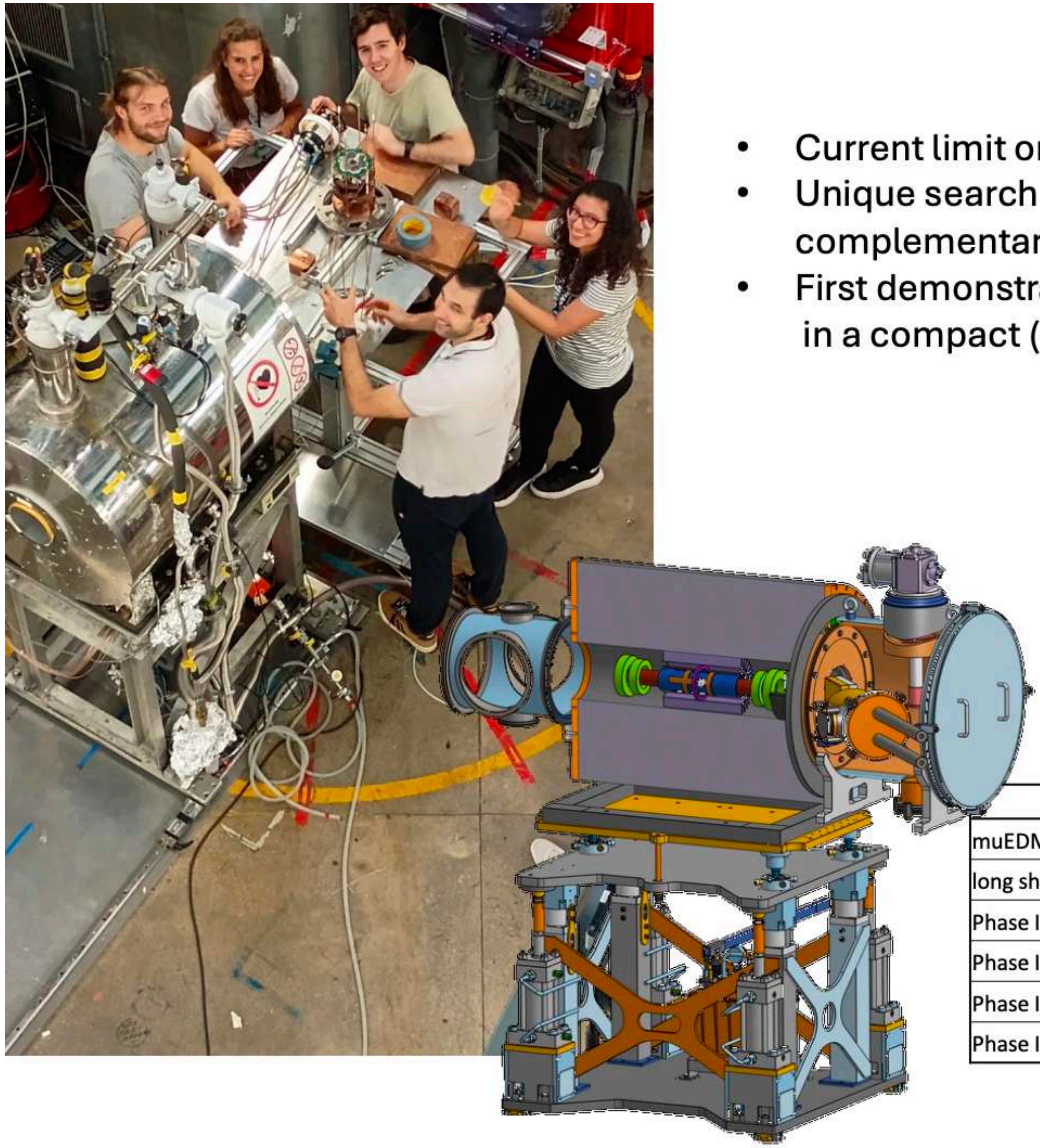


Vertex decay reconstruction



L. Morvaj’s talk

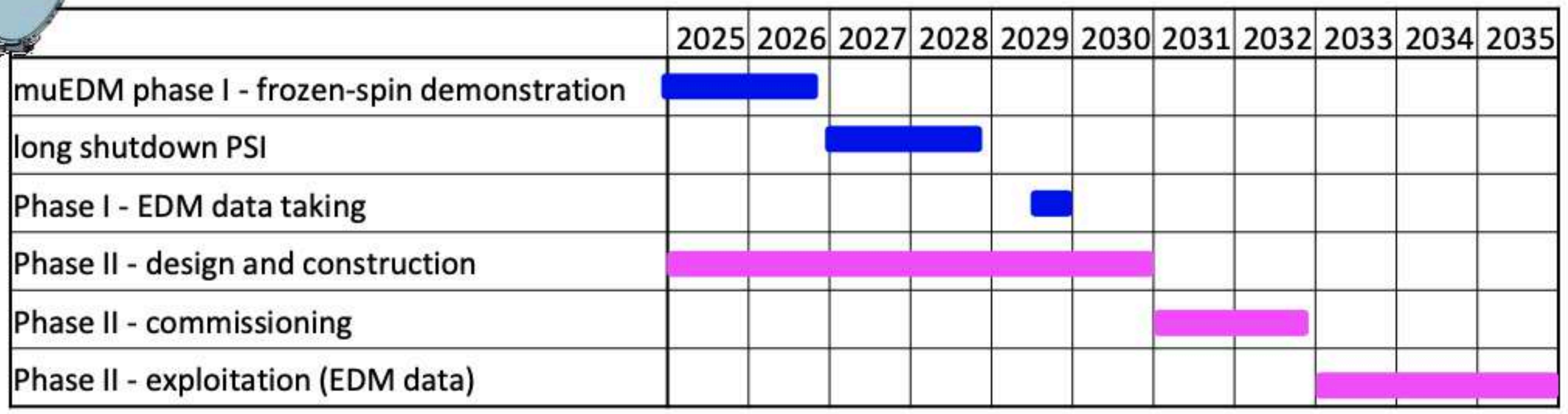
The muEDM experiment at PSI



- Current limit on muon EDM: $1.8 \times 10^{-19} e\mathrm{cm}^{**}$
- Unique search for an **electric dipole moment** of a **bare lepton** complementary to other EDM searches.
- First demonstration of the **frozen-spin technique** in a compact ($\sim$ 6 cm – diameter) storage trap.

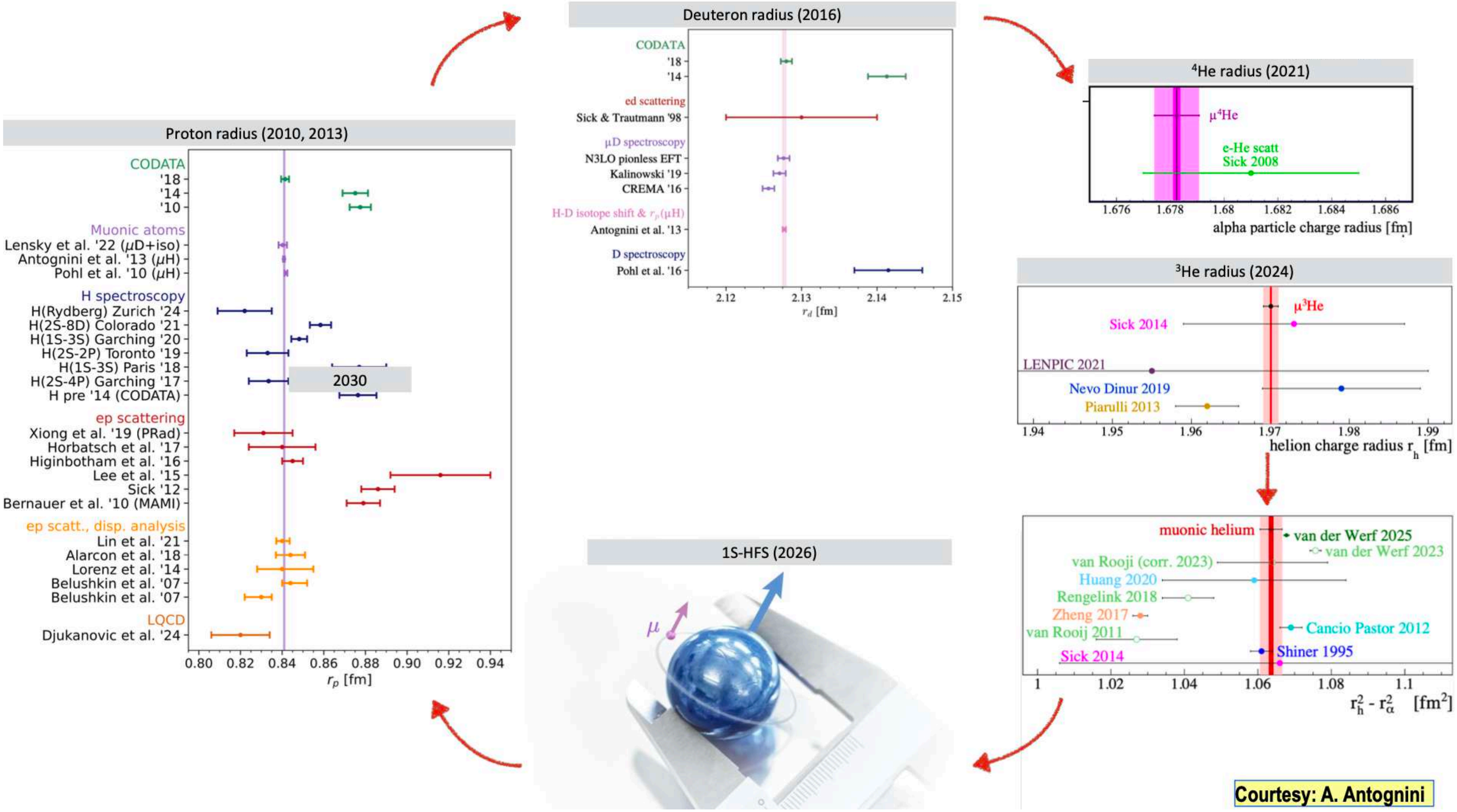
Phase I: Demonstration of techniques an methods using a surface muon beam with $p = 28\ \mathrm{MeV}/c$
$\boldsymbol{\sigma(d) \leq 4 \times 10^{-21} e\mathrm{cm}}$

Phase II: Dedicated instrument optimized for high intensity muon beam at $p = 125\mathrm{MeV}/c$
$\boldsymbol{\sigma(d) \leq 6 \times 10^{-23} e\mathrm{cm}}$



Full description: https://arxiv.org/abs/2501.18979

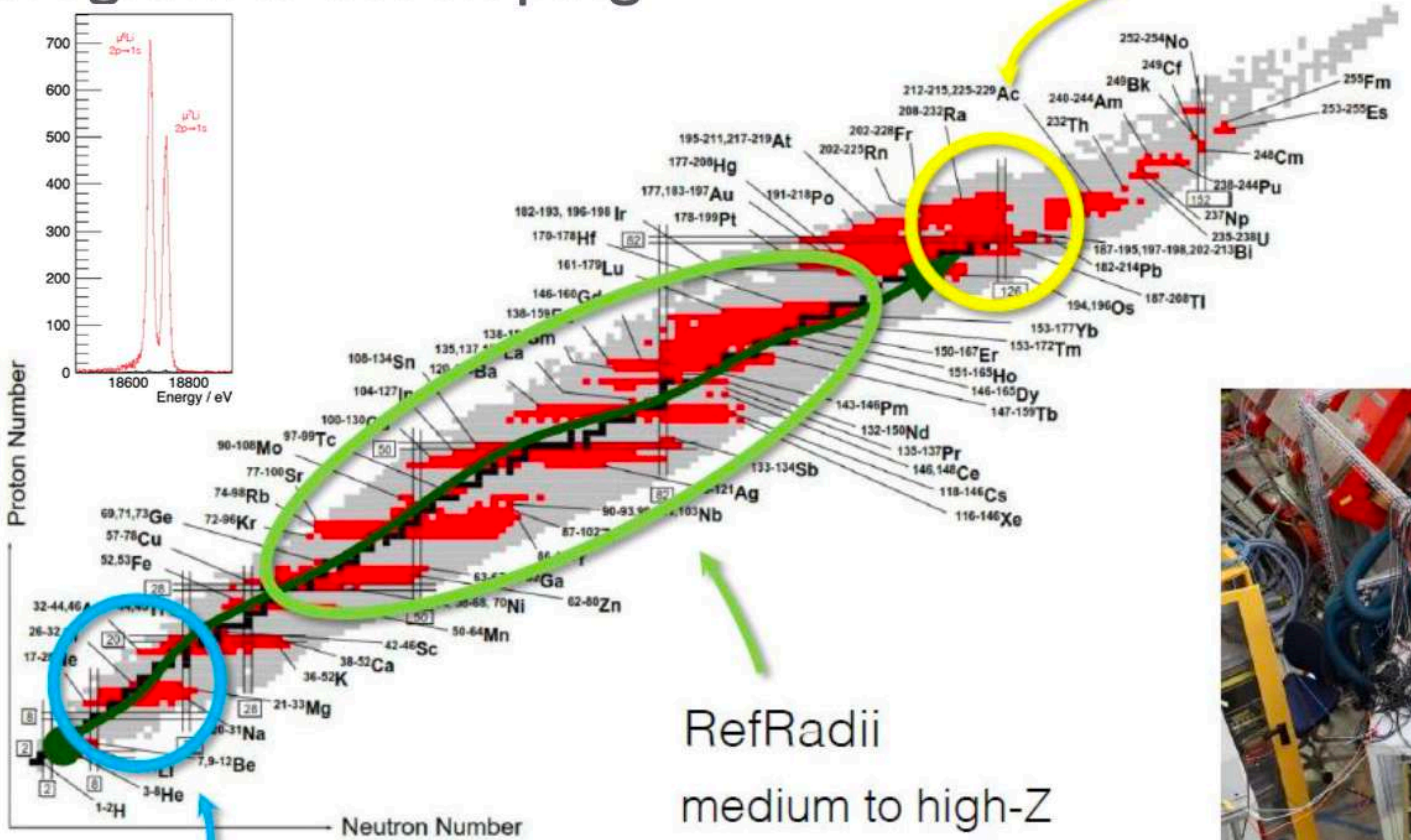
Muonic Atoms and fundamental physics



Courtesy: A. Antognini

muX, QUARTET and RefRadii

A very active nuclear physics program is developing



QUARTET

RefRadii

medium to high-Z

→ Reference for king plot analysis / mass & field shifts

muX

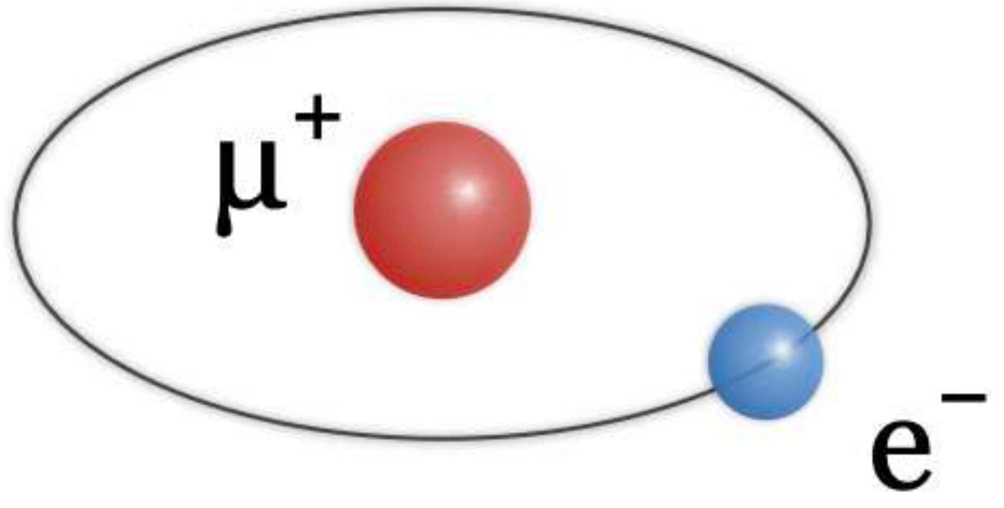
radioactive targets

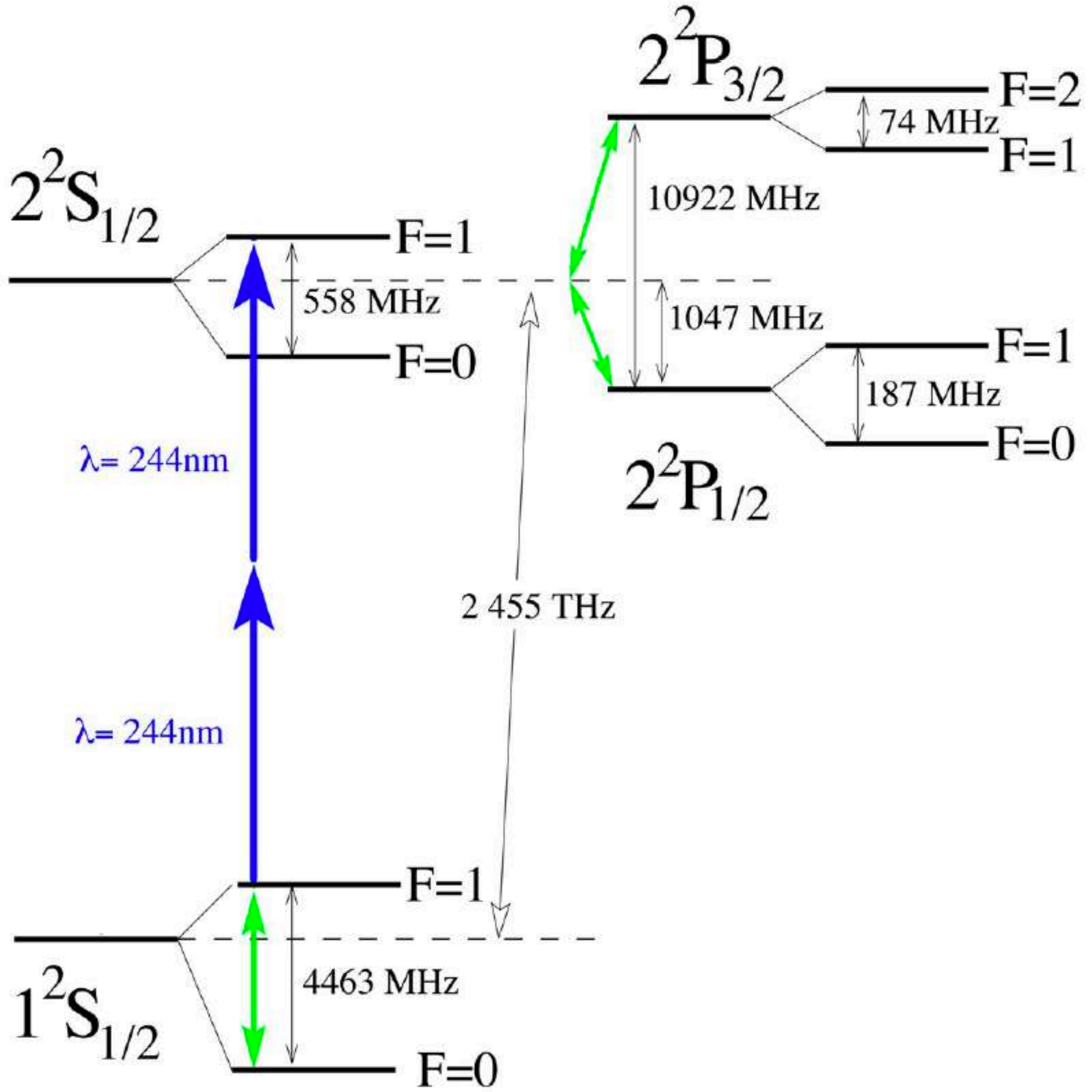
→ Deformed heavy nuclei. E.g. ^{226}Ra is a candidate for APV experiments. Radius needed as an input

Courtesy: K. v. Schoeler

Muonium physics

- Mu is the simplest atomic species: μ +e- atom
  - Purely leptonic hydrogen species!
- Rich structure and phenomenology
  - Readily formed
  - Spectrum understood
  - Forms molecules!
  - Decays with free muon lifetime
- 1s-2s transition frequency predicted in QED to 0.6 ppb
  - Minimal hadronic contributions!
- Similar story for 1s hyperfine splitting
- Mu-MASS at PSI
  - Improve 1S-2S measurement three orders of magnitude
  - Improves muon mass determination to 1ppb
- MuSEUM at J-PARC
  - Improve hyperfine measurement one order of magnitude – 1ppb
- The combination will determine the Rydberg constant to 4ppt!





Summary

- Astonishing sensitivities in muon precision physics at intensity frontiers are ongoing and foreseen for the incoming future
- **Rare/forbidden decay searches and symmetry tests remain among the most exciting places where to search for new physics with strong complementarity to the energy frontiers**
- Both very intense, continuous and pulsed, and high brightness muon beams and new detector developments are the keys for addressing this very challenging physics program

Thanks a lot for your attention !!!

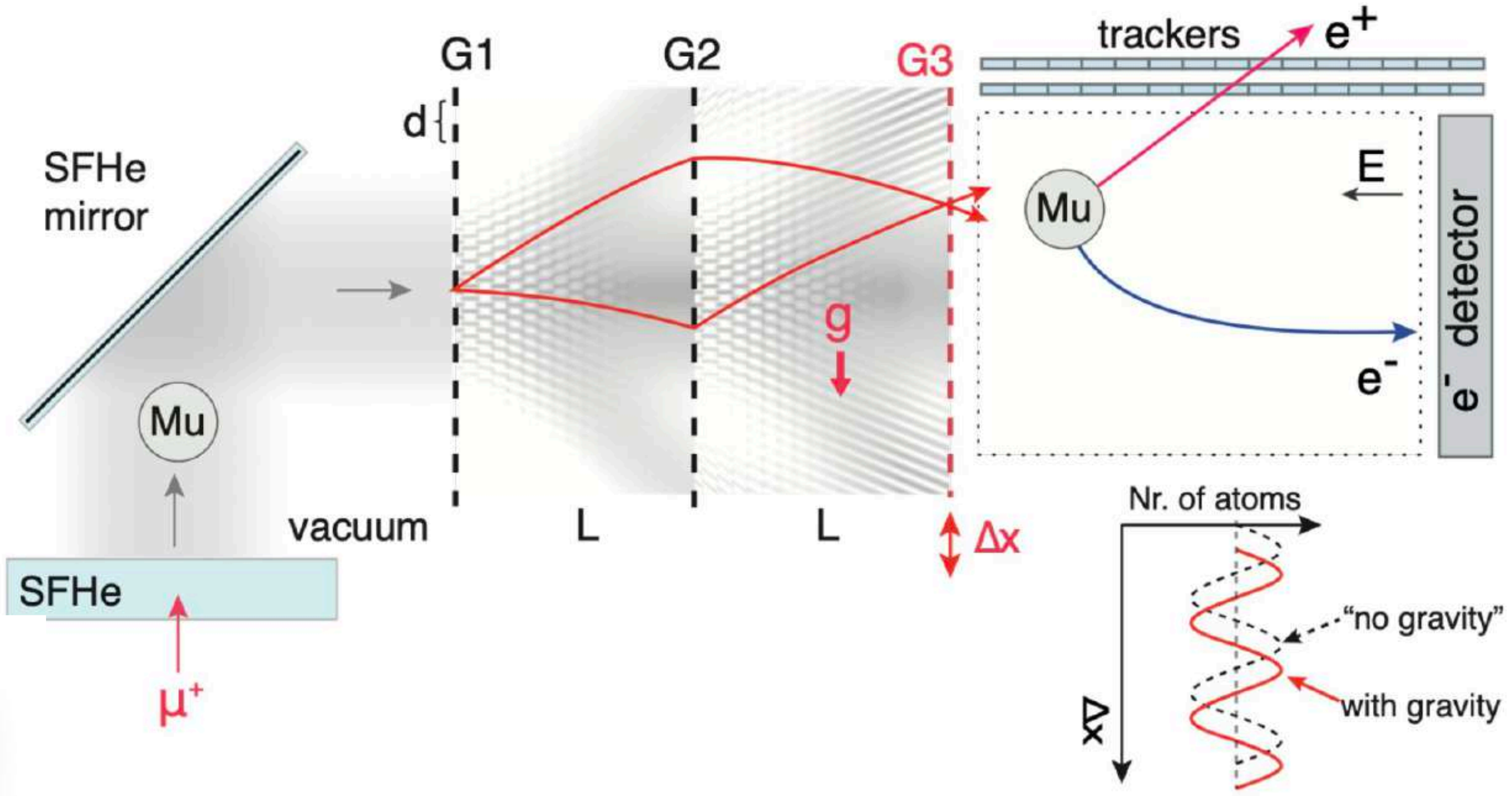
Muon beams worldwide summary

Laboratory	Beam Line	DC rate (μ/sec)	Pulsed rate (μ/sec)
PSI (CH) (590 MeV, 1.3 MW)	$\mu E4, \pi E5$ HiMB at EH	$2 \div 4 \times 10^8$ (μ^+) $\mathcal{O}(10^{10})$ (μ^+) (>2018)	
J-PARC (Japan) (3 GeV, 210 kW) (8 GeV, 56 kW)	MUSE D-Line MUSE U-Line COMET		$3 \times 10^7 (\mu^+)$ $6.4 \times 10^7 (\mu^+)$ $1 \times 10^{11} (\mu^-)$(2020)
FNAL (USA) (8 GeV, 25 kW)	Mu2e		$5 \times 10^{10} (\mu^-)$(2020)
TRIUMF (Canada) (500 MeV, 75 kW)	M13, M15, M20	$1.8 \div 2 \times 10^6 (\mu^+)$	
RAL-ISIS (UK) (800 MeV, 160 kW)	EC/RIKEN-RAL		$7 \times 10^4 (\mu^-)$ $6 \times 10^5 (\mu^+)$
KEK (Tsukuba, Japan) (500 MeV, 25 kW)	Dai Omega		$4 \times 10^5 (\mu^+)$(2020)
RCNP (Osaka, Japan) (400 MeV, 400 W)	MuSIC	$10^4 (\mu^-) \div 10^5 (\mu^+)$ $10^7 (\mu^-) \div 10^8 (\mu^+)$(>2018)	
JINR (Dubna, Russia) (660 MeV, 1.6 kW)	Phasotron	$10^5 (\mu^+)$	
RISP (Korea) (600 MeV, 0.6 MW)	RAON	$2 \times 10^8 (\mu^+)$(>2020)	
CSNS (China) (1.6 6eV, 4 kW)	HEPEA	$1 \times 10^8 (\mu^+)$(>2020)	

LEMING at PSI: Muonium gravity

- Measurement of gravitational acceleration of muonium, and next generation laser spectroscopy, testing the weak equivalence with and elementary, second generation (anti)lepton

  - Muonium source and mirror
  - Mach-Zehnder interferometer
    - 100nm!
  - Muonium decay trigger detectors
  - Sign of g in 1 day at 100kHz
  - ~month to precision comparison

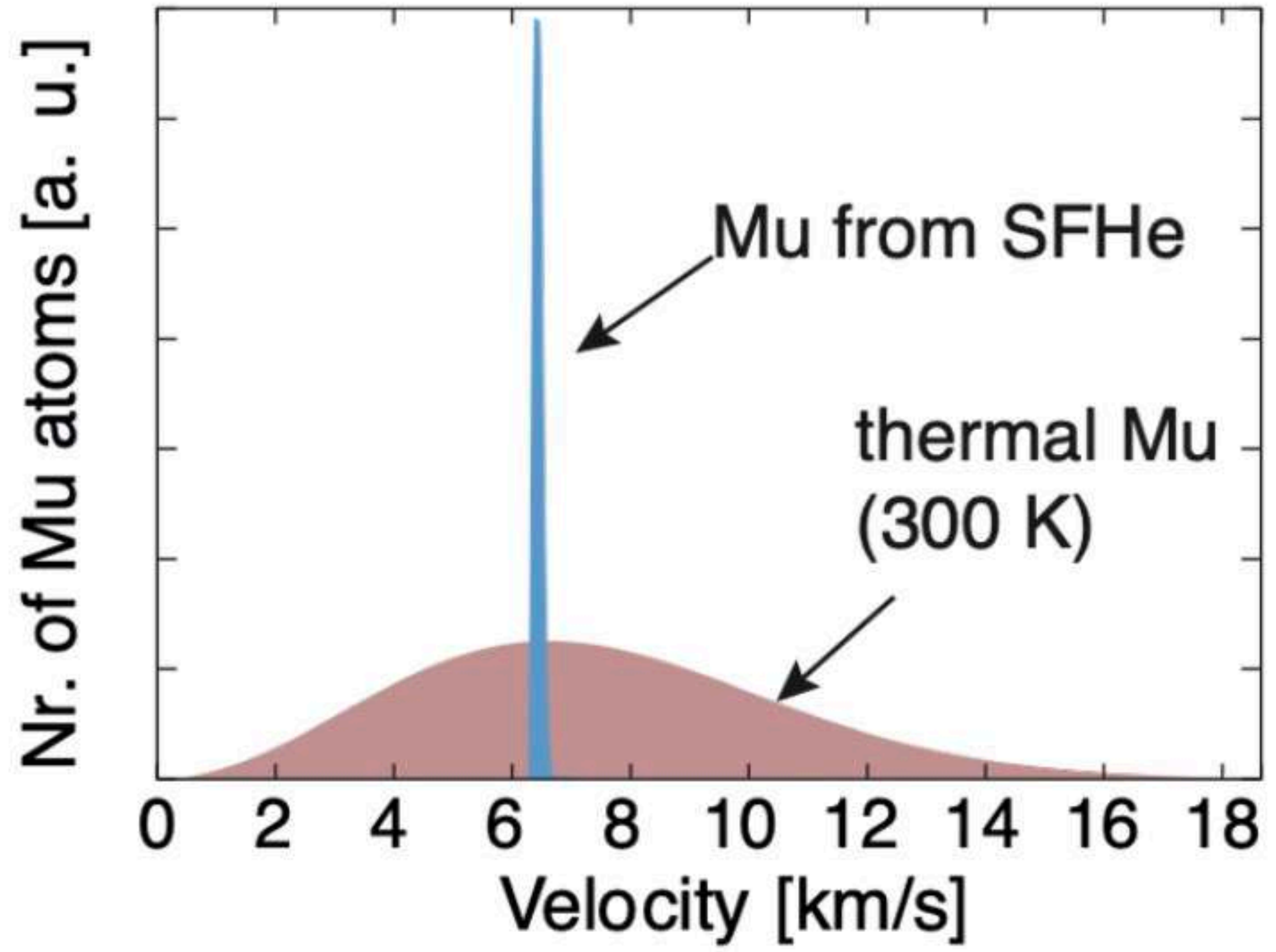


Timeline

Courtesy: A. Soter

Muonium production

- Stop (nearly!) a positive muon beam in a target in vacuum; some of the muonium will be ejected into the vacuum space
- J-PARC g-2 plans to utilize laser ablated silica aerogel
  - This yields of order 1% muonium in vacuum, with thermal momentum distribution
  - Thermal Mu requires cooling for beam formation
- PSI and Fermilab muonium experiments plan to use layers of superfluid helium on target surfaces
  - "Hydrogen" is immiscible in superfluid helium → stopped Mu ejected from the surface with a very narrow momentum spread (chemical potential)
  - Naturally cooled and emitted at 6,300 m/s normal to surface
  - A superfluid layer can also be used as a slow Mu mirror



Precision Muonium physics