PSI Center for Neutron and Muon Sciences

Fundamental physics with low energy muons

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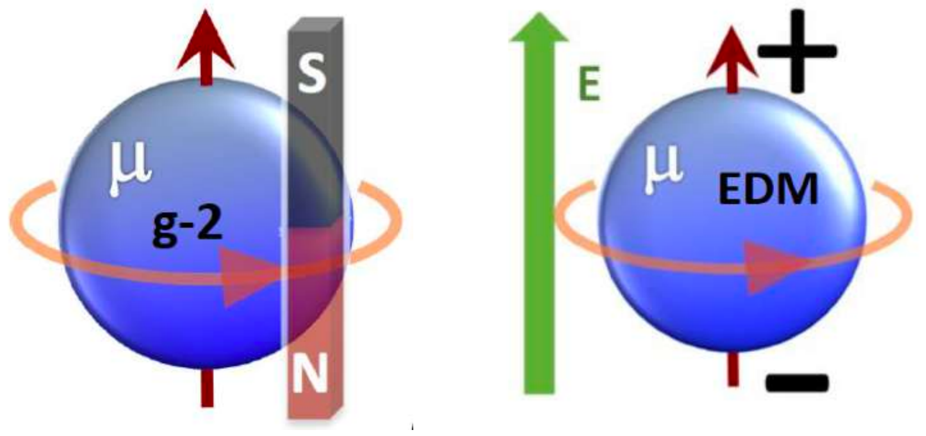
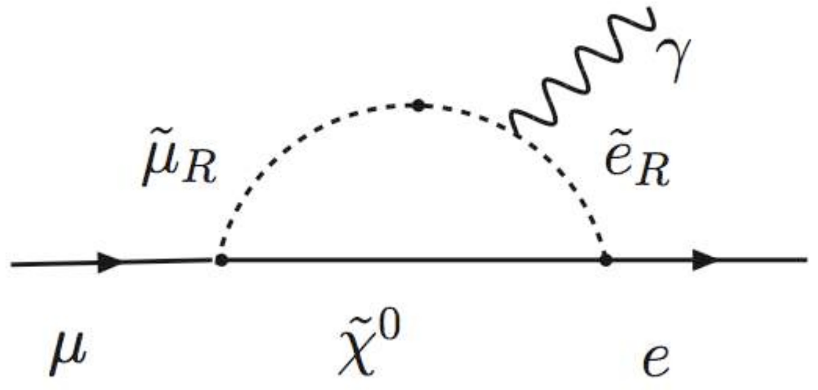
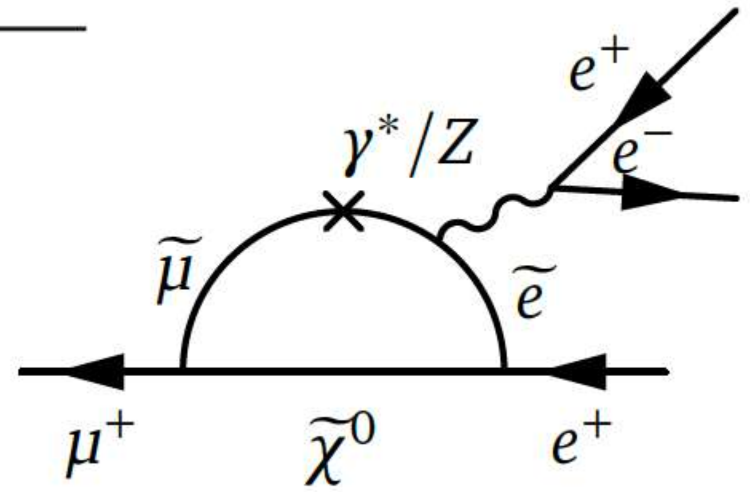
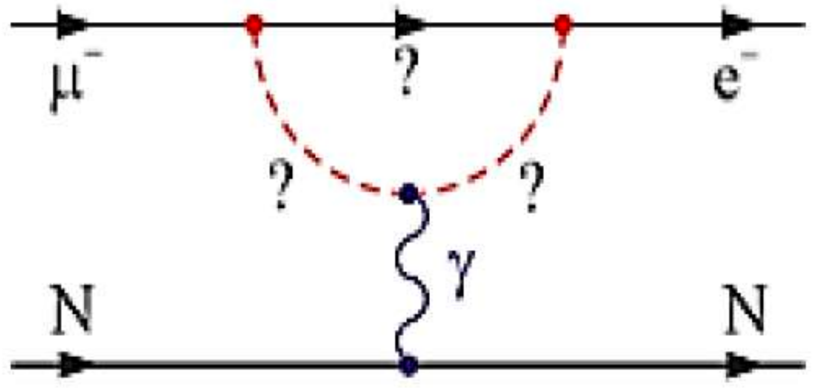
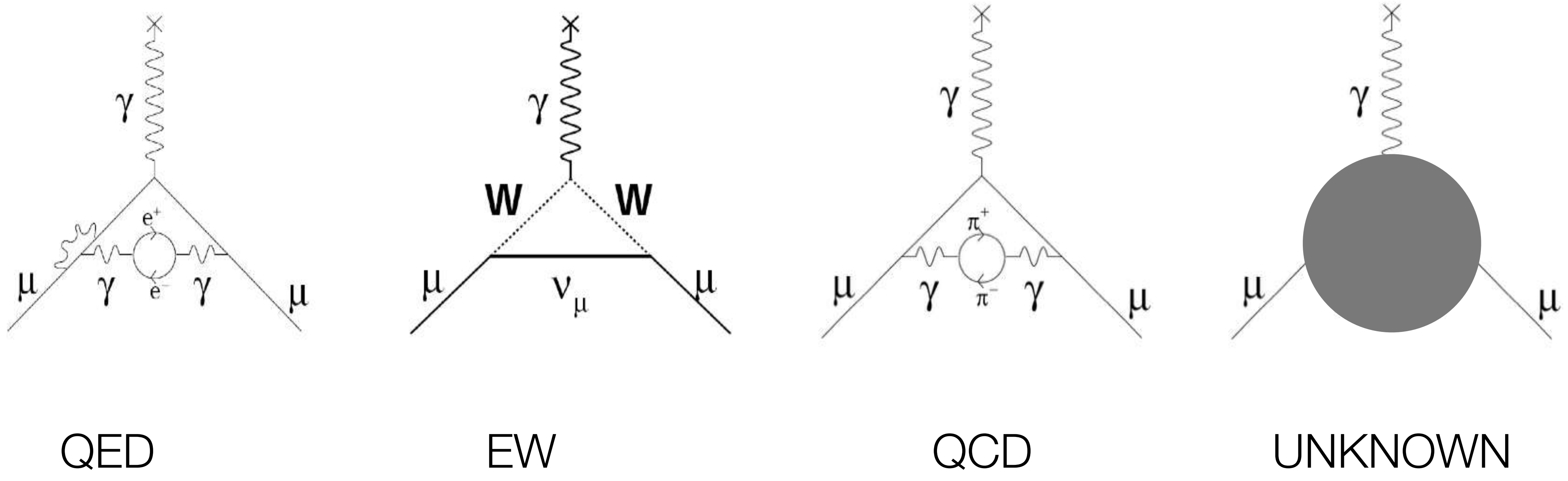










Content

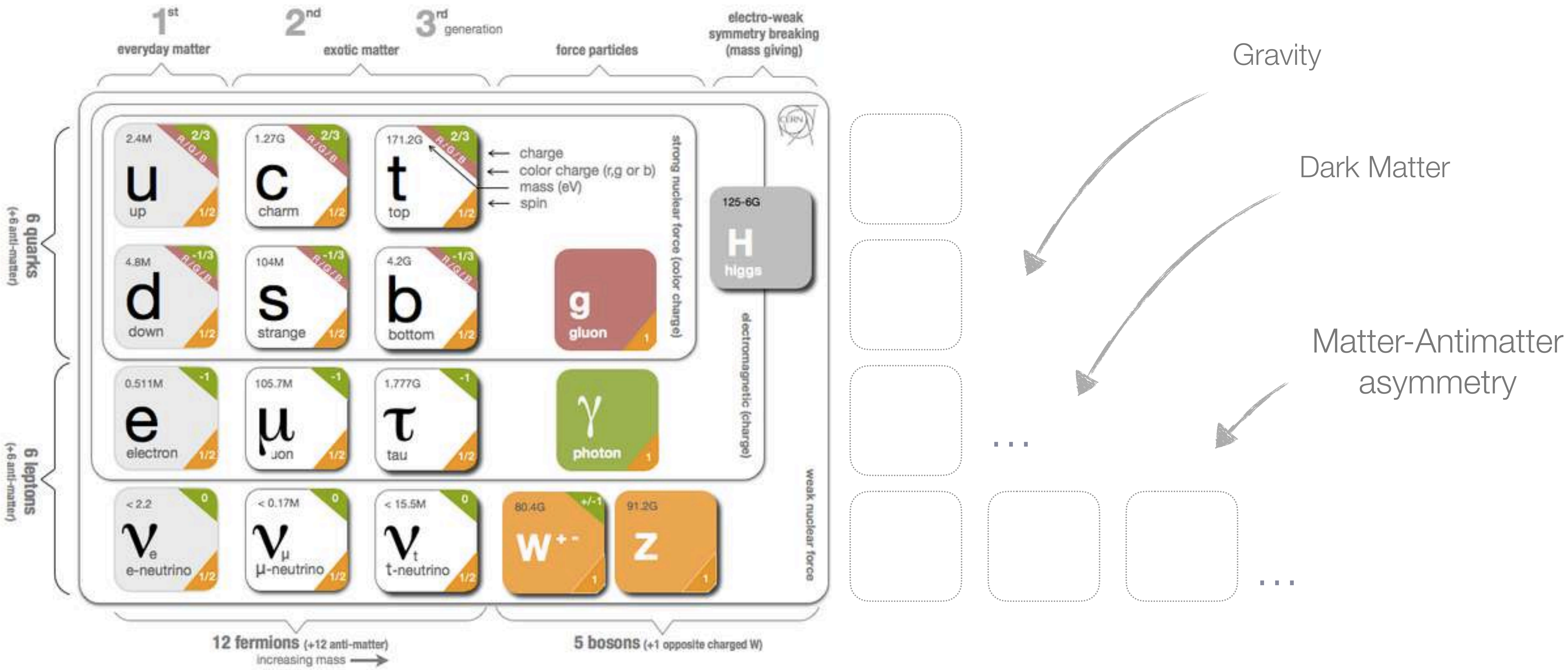
- Muon physics cases
- Muon beams
- Muon experiments

Content

- **Muon physics cases**
- Muon beams
- Muon experiments

The role of the low energy precision physics

- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory



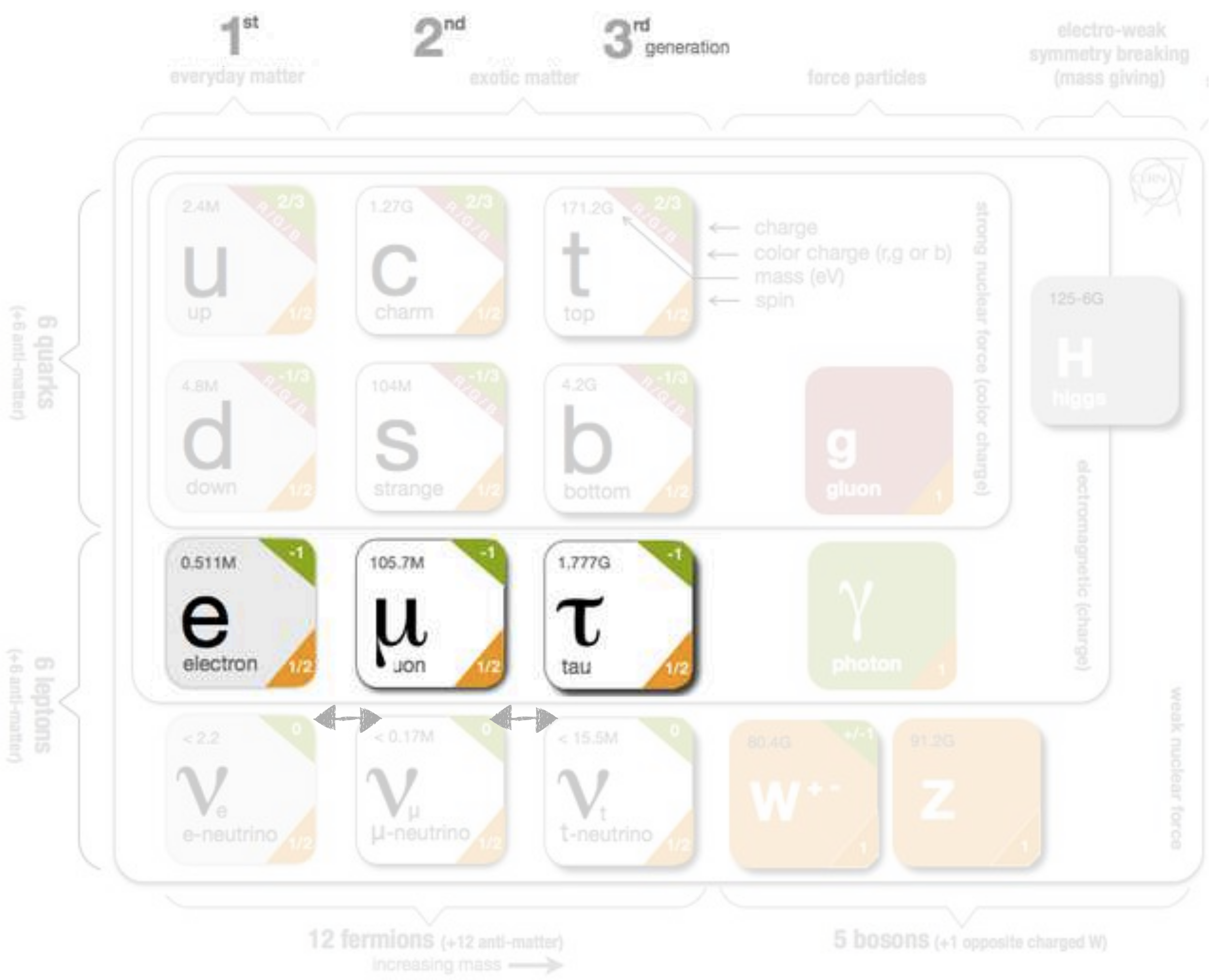
Focus here on:

- **muon cLFV**
- **muon** (g-2/) **EDM**
- **muonium**

- Low energy precision physics: **Rare/forbidden decay searches**, **symmetry tests**, **precision measurements** very sensitive tool for unveiling **new physics** and probing very **high energy scale**

Charged lepton flavour violation search: Motivation

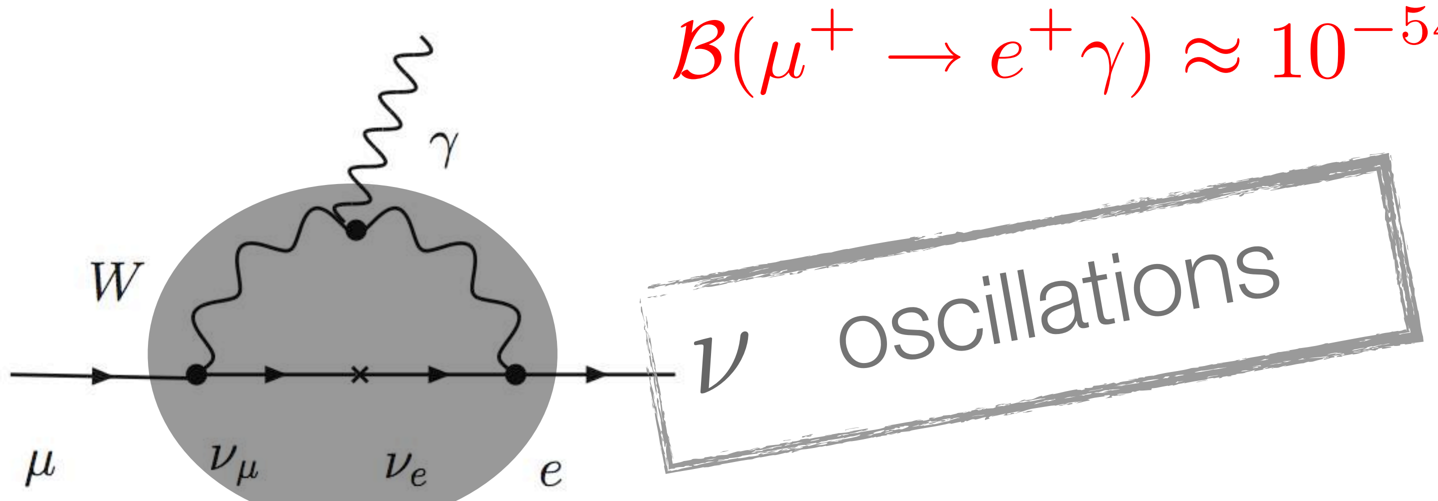
- **Neutrino oscillations**: Evidence of physics Behind Standard Model (BSM). **Neutral lepton flavour violation**
- **Charged lepton flavour violation: NOT** yet observed
- An experimental **evidence** of cLFV at the current sensitivities will be a **clear signature of New Physics**



$\Delta N_i \neq 0$ with i = 1,2,3

SM with massive neutrinos (Dirac)

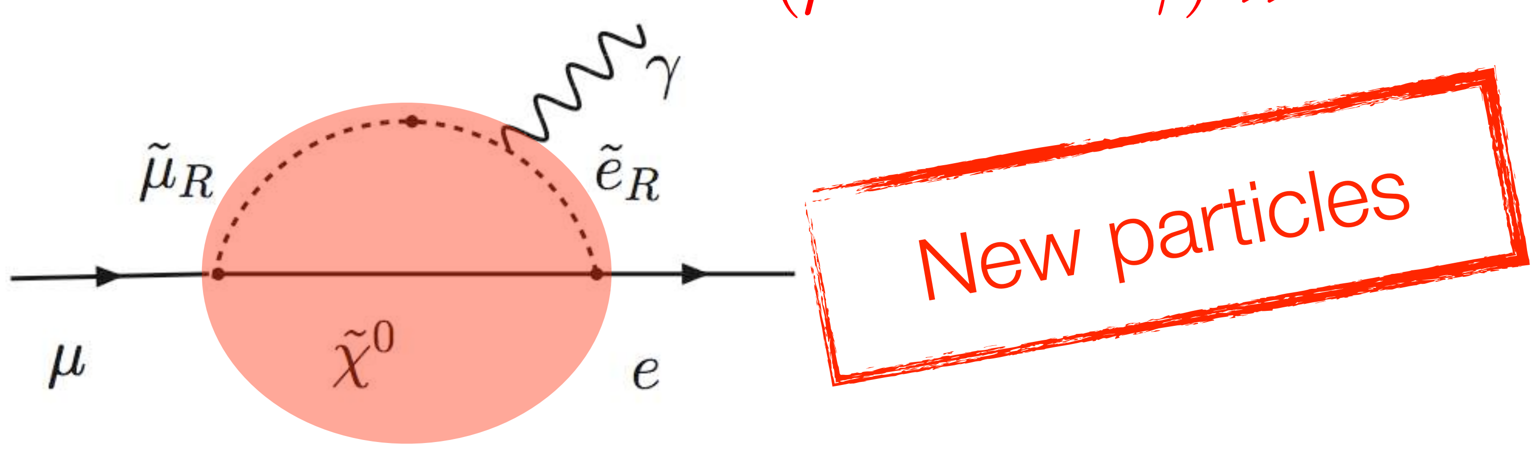
$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$



too small to access experimentally

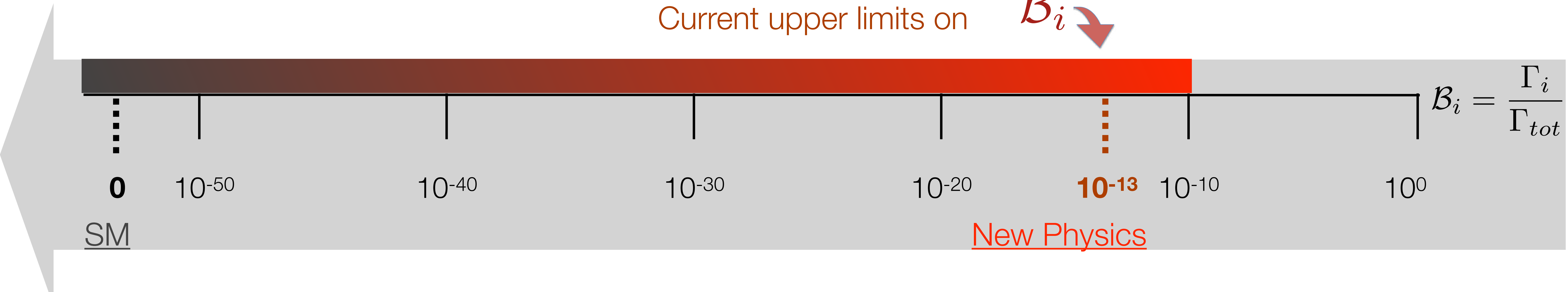
BSM

$\mathcal{B}(\mu^+ \to e^+\gamma) \gg 10^{-54}$



an experimental evidence:
a clear signature of New Physics NP
(SM background FREE)

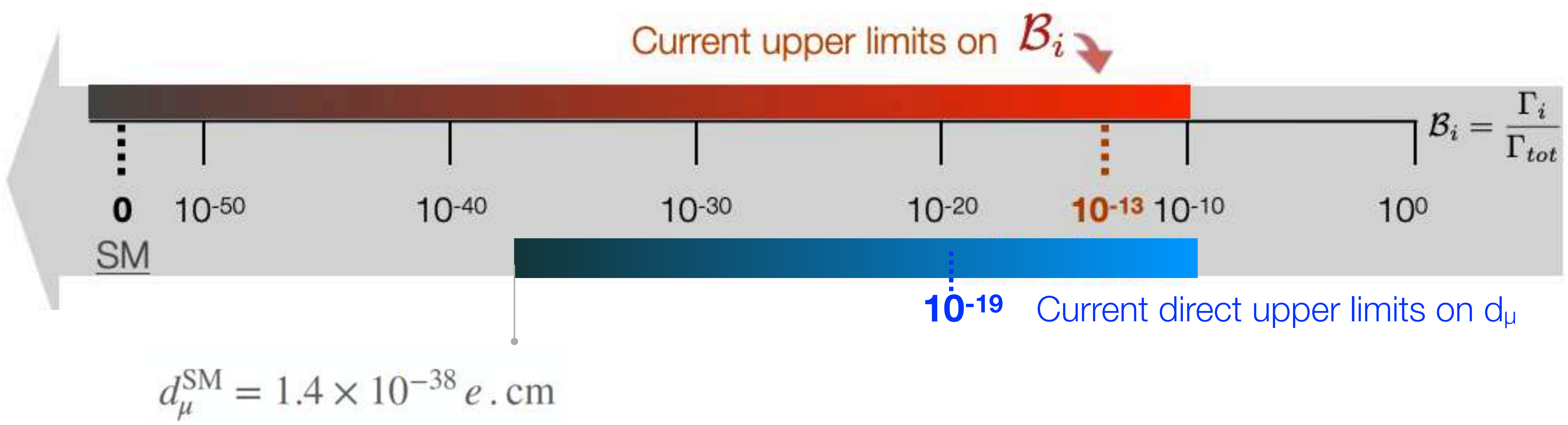
Current upper limits on $\mathcal{B}_i$

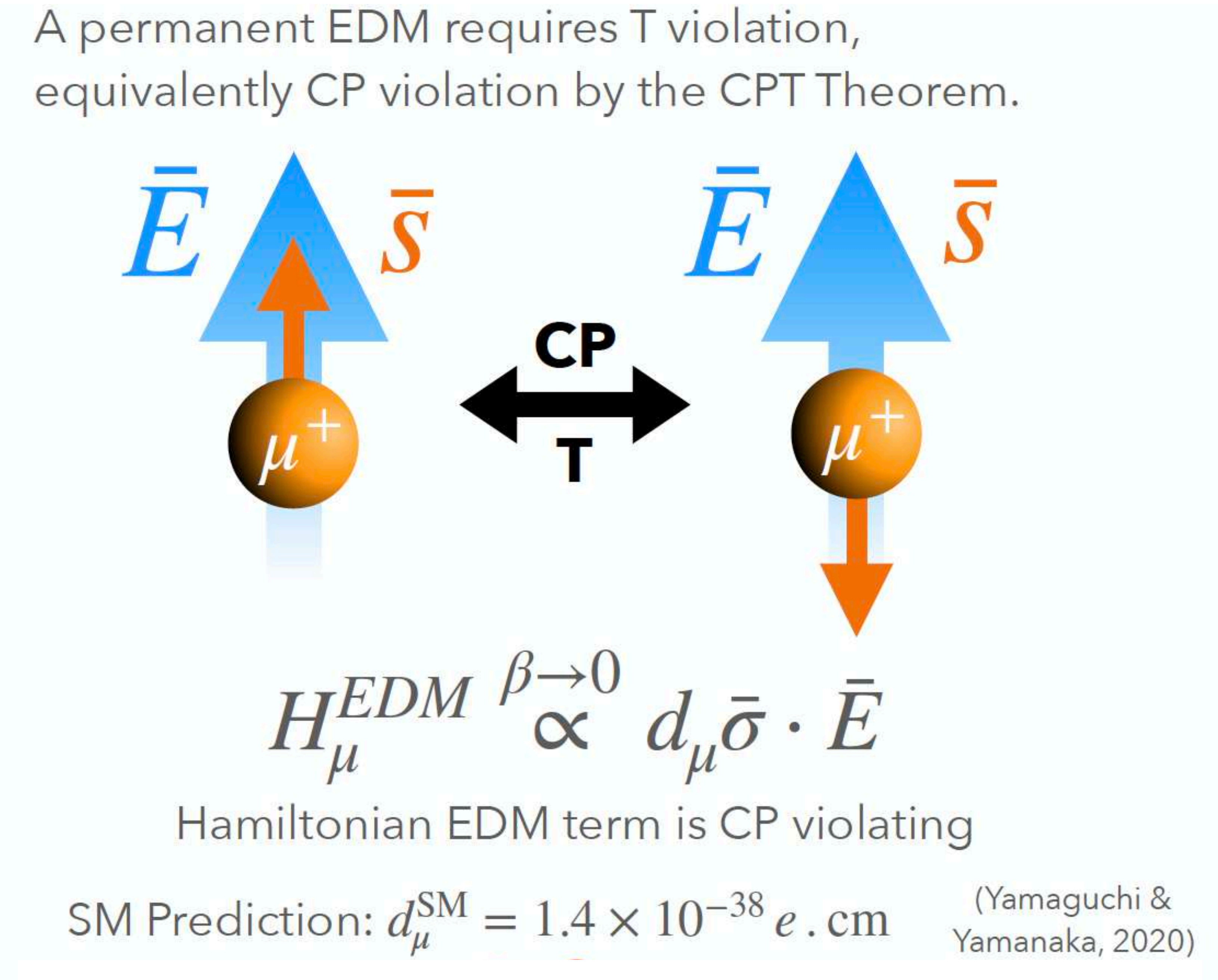


$\mathcal{B}_i = \frac{\Gamma_i}{\Gamma_{tot}}$

muEDM dedicated search: Motivations

- **Baryogenesis**, the creation of more matter over anti-matter, requires additional CP violation (CPV) **beyond the SM (BSM)**
- EDMs of fundamental particles are intimately connected to the **violation** of time invariance **T** and, through the CPT Theorem, the combined symmetry of charge and parity **CP**
- These **additional CPV** underlying interactions **would also result in Electric Dipole Moments (EDMs)** of fundamental particles at the current experimental sensitivity, **well above** the SM predictions

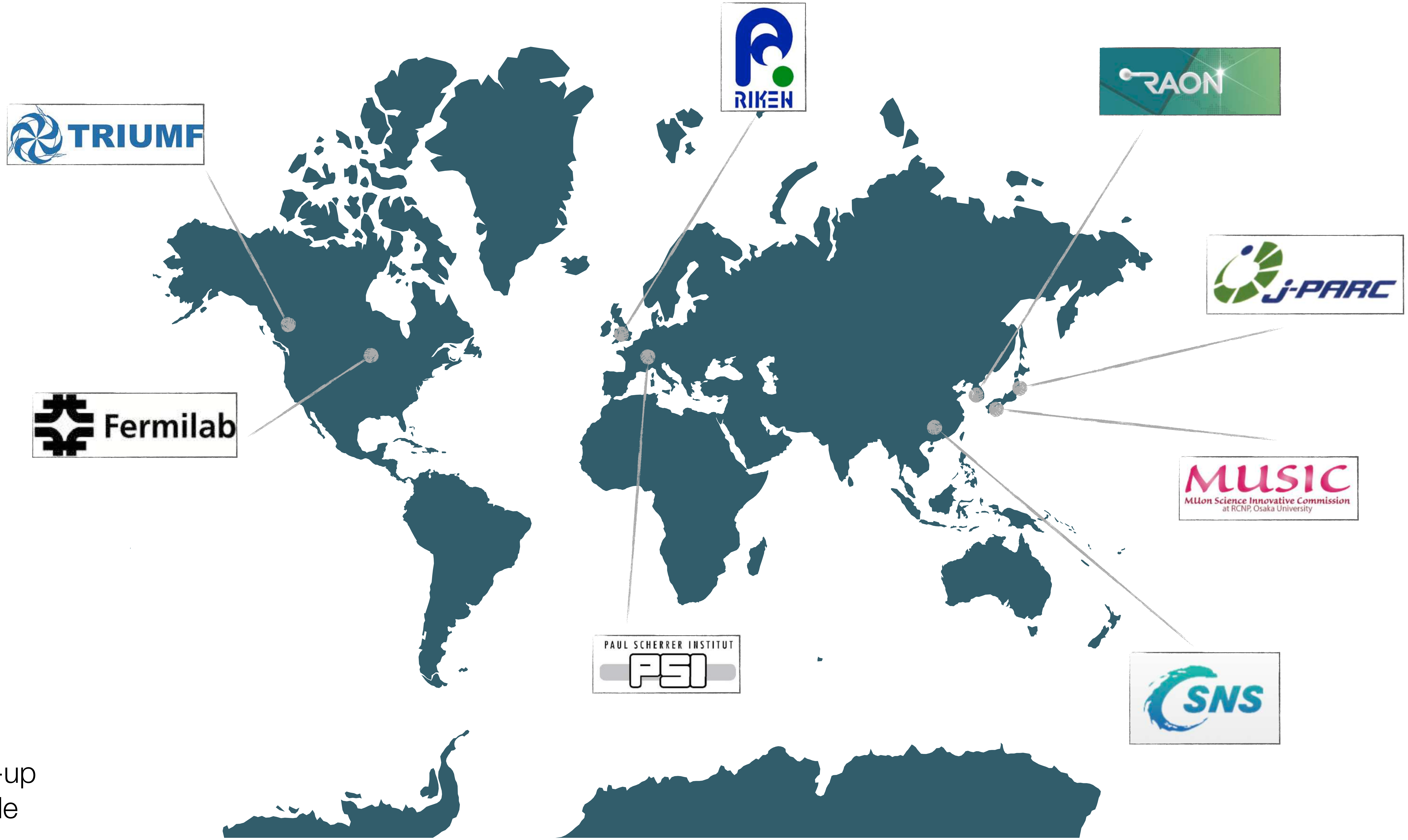




Content

- Muon physics cases
- **Muon beams**
- Muon experiments

Muon beams worldwide



Note: See the back-up
for a summary table

Muon beams

- 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**

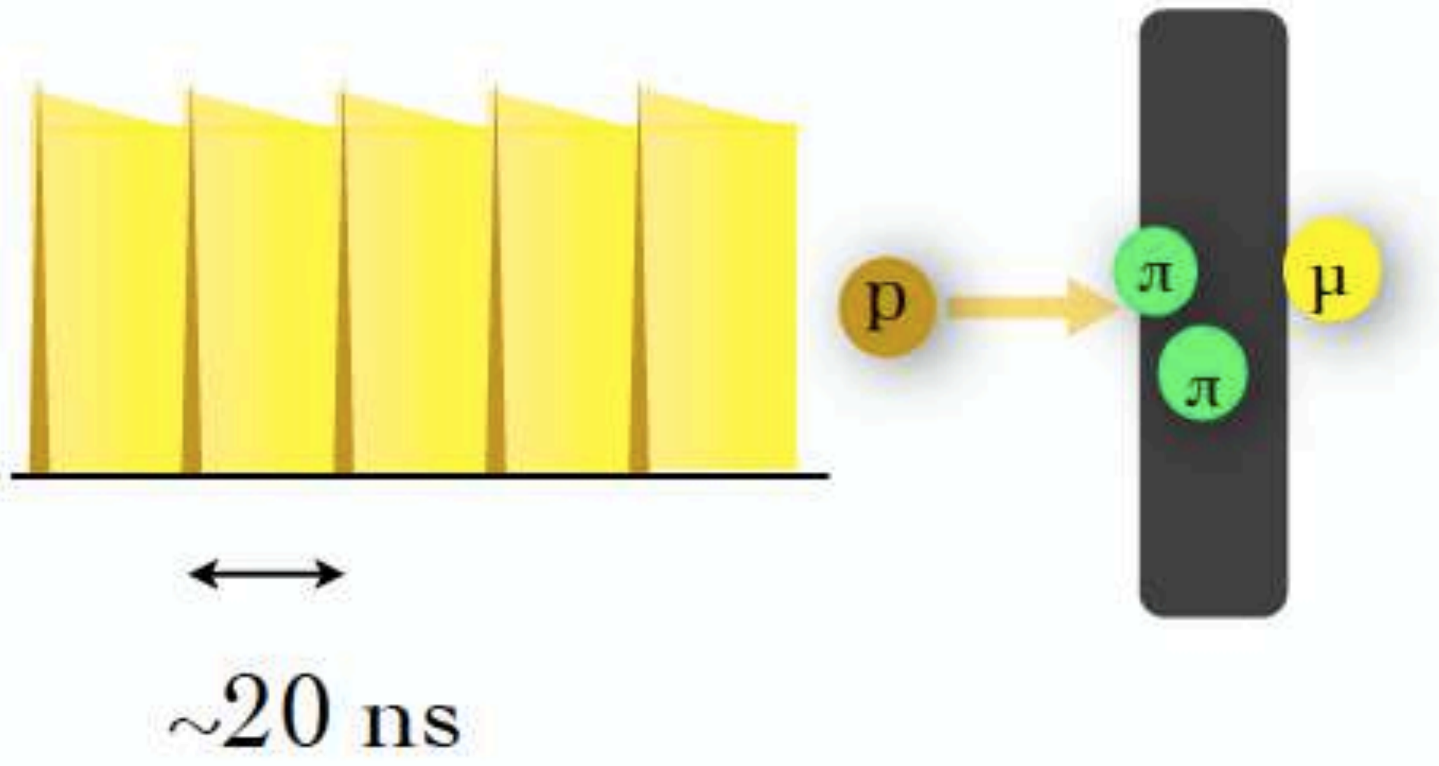
$I_{beam} \sim 10^{8} - 10^{10}$ μ/s

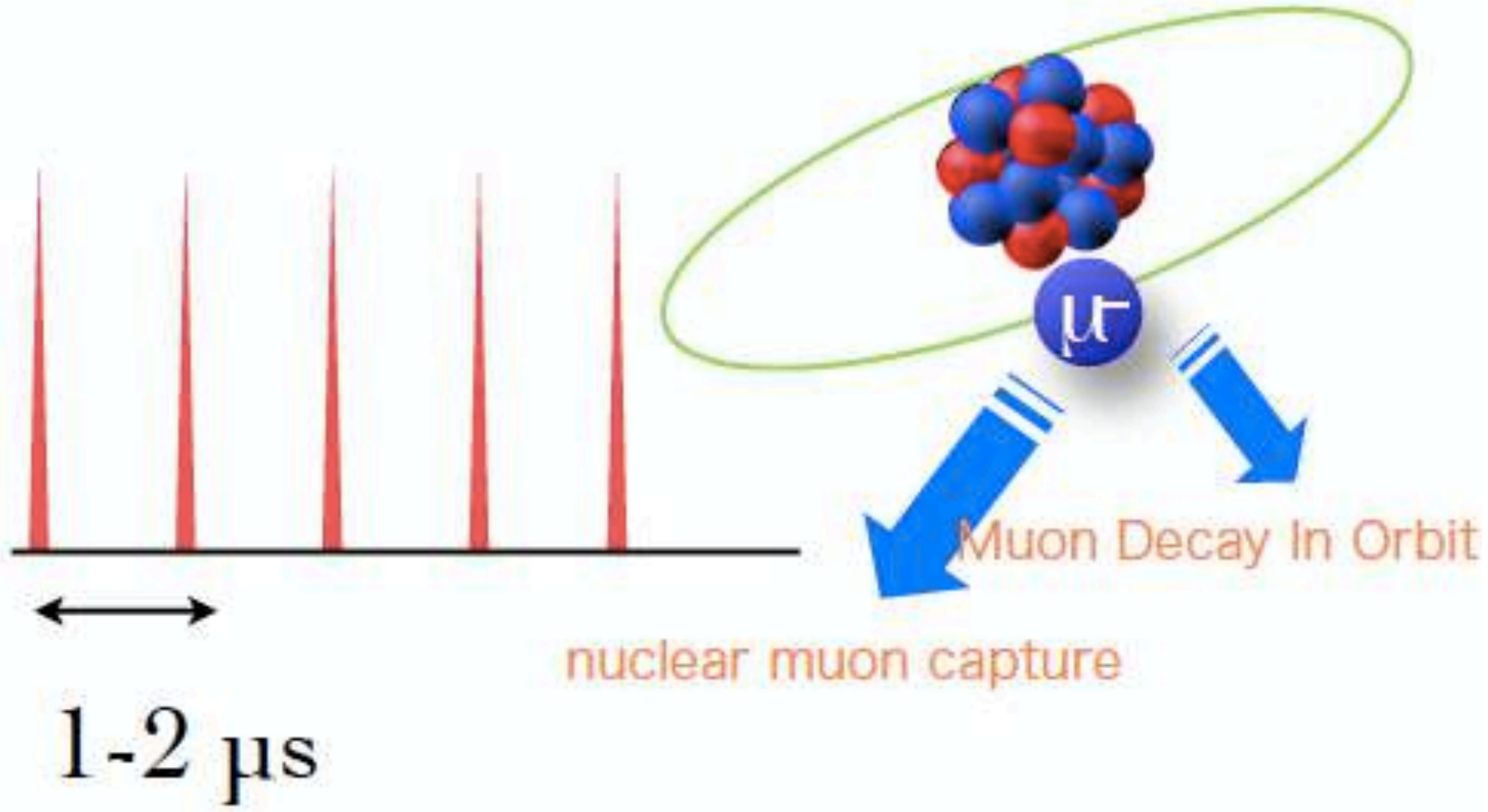
DC or Pulsed?

$I_{beam} \sim 10^{11}$ μ/s

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

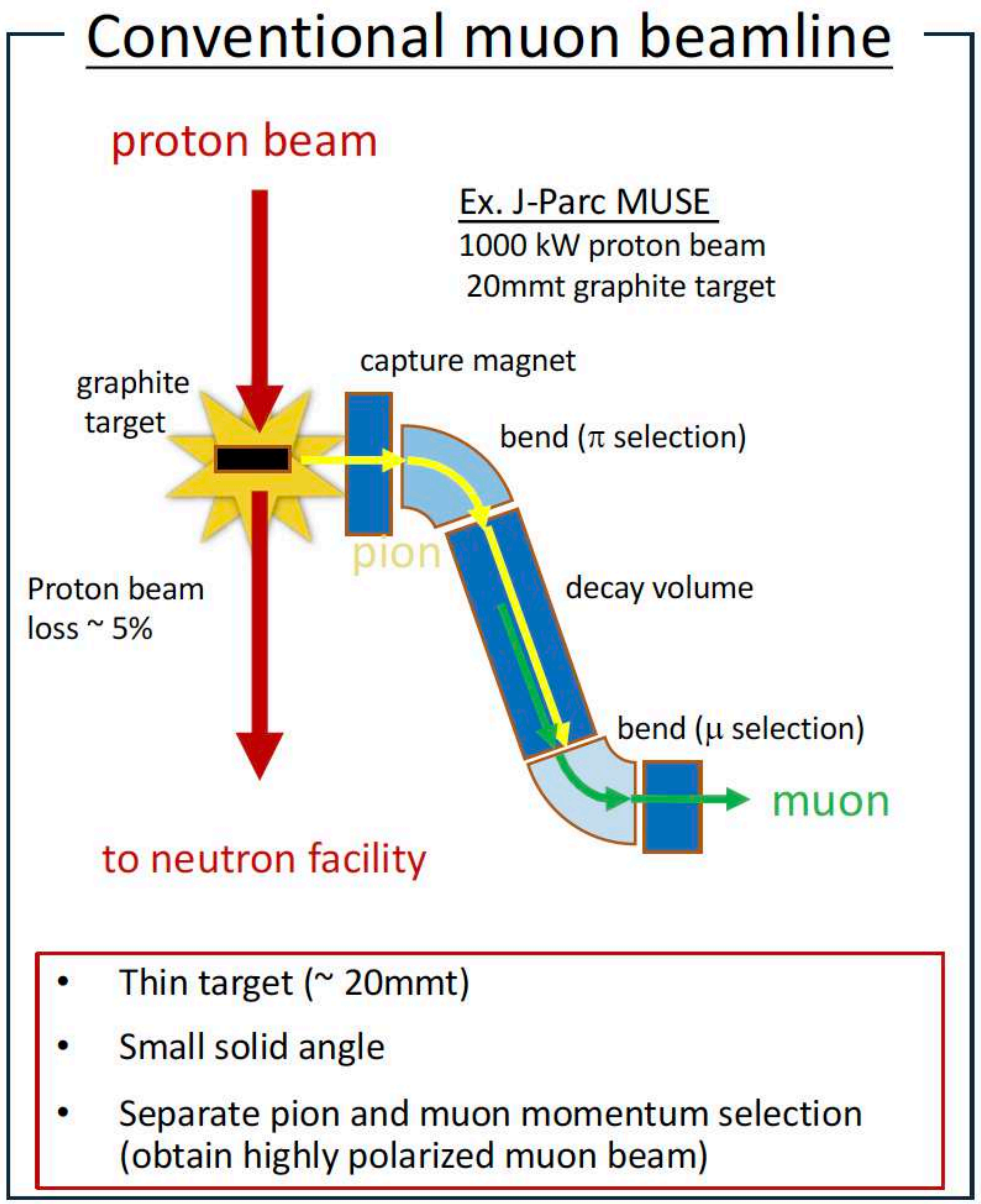
@ PSI

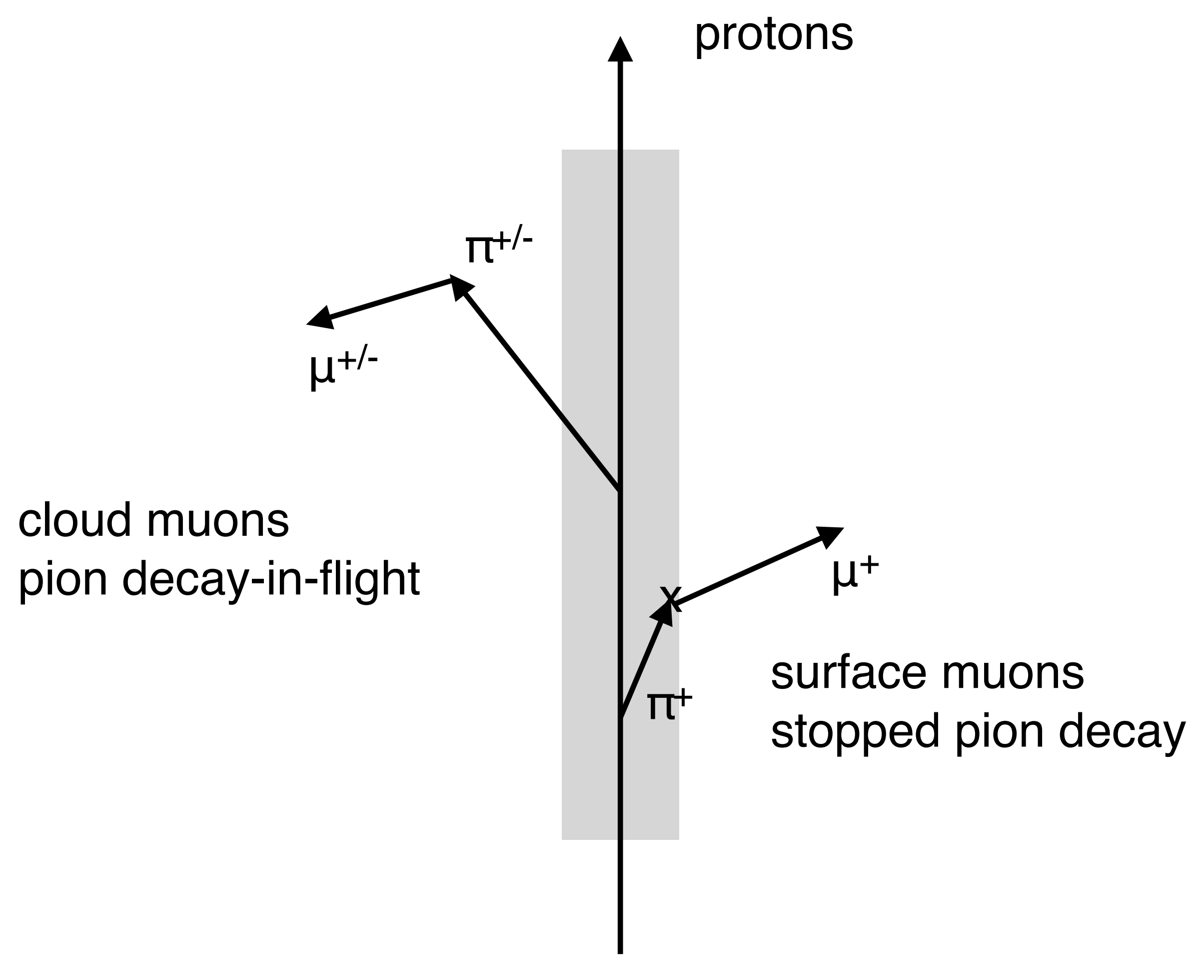


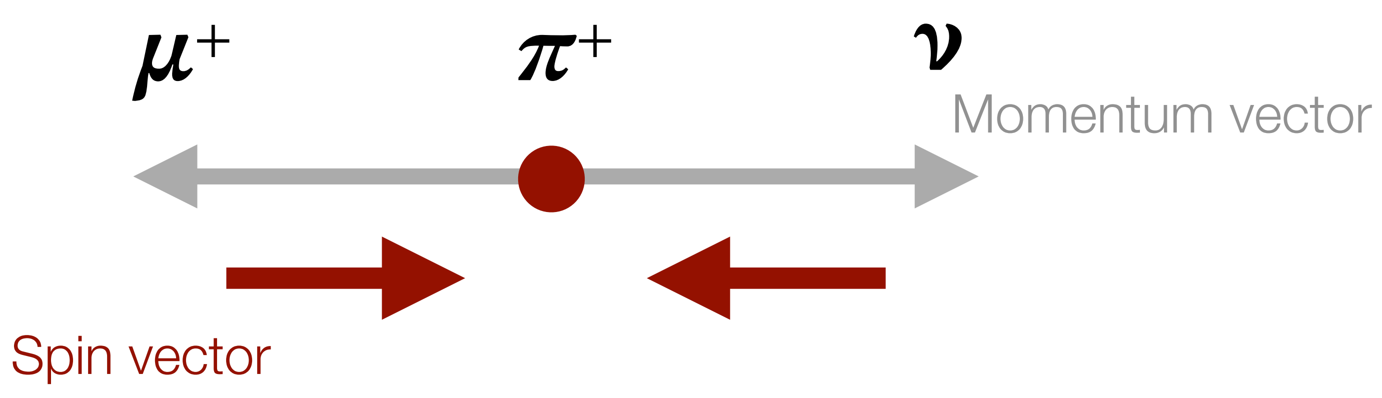


@ JPARC, FERMILAB

PSI’s muon beams



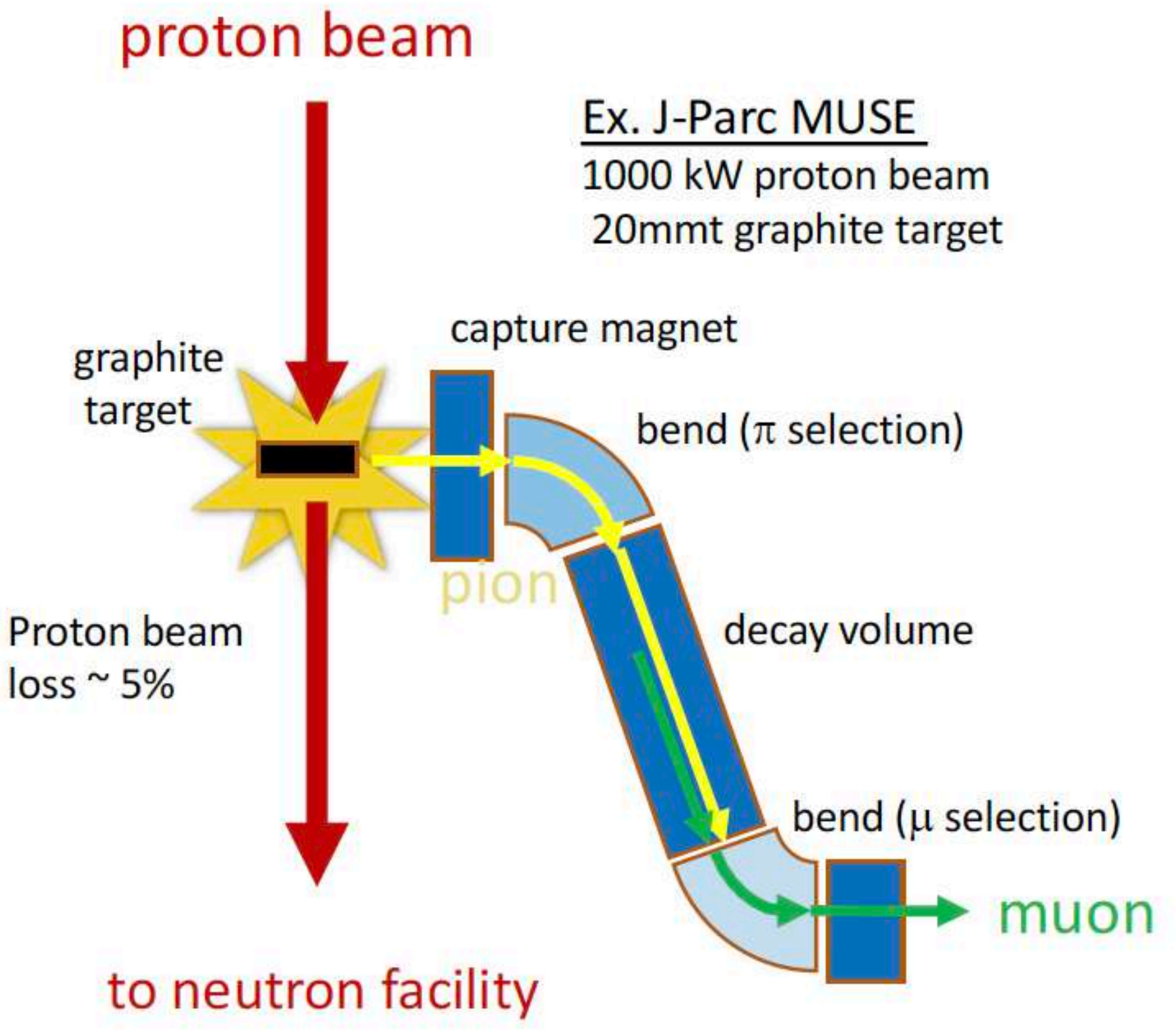




- Muon beams: **secondary** beam lines
- Low-energy muon beam lines typically tuned to surface-μ^+ at ~ 28 MeV/c
- **Note:** surface-μ —> polarised positively charged muons (spin antiparallel to the momentum)
- Contribution from cloud muons at similar momentum about 100x smaller
- Negative muons only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

PSI's muon beams

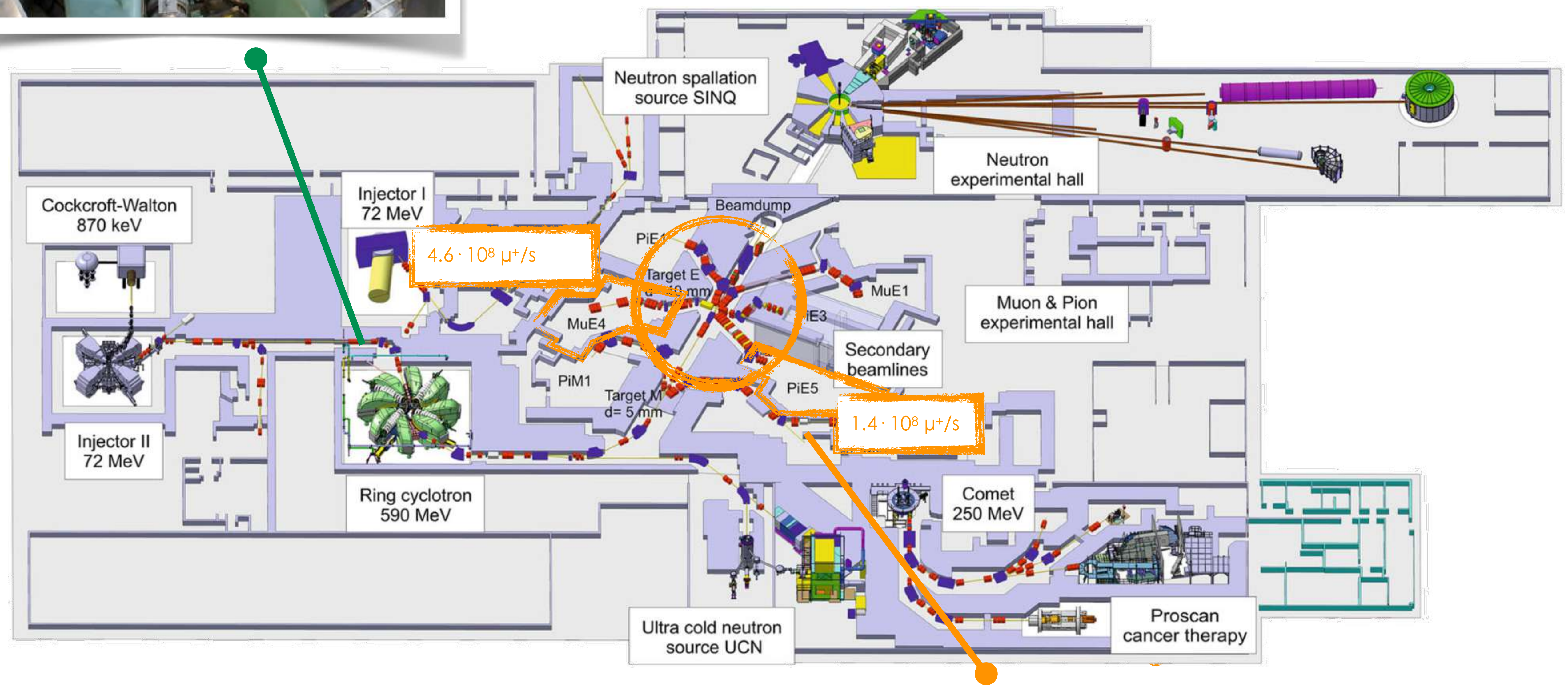
Conventional muon beamline



- 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

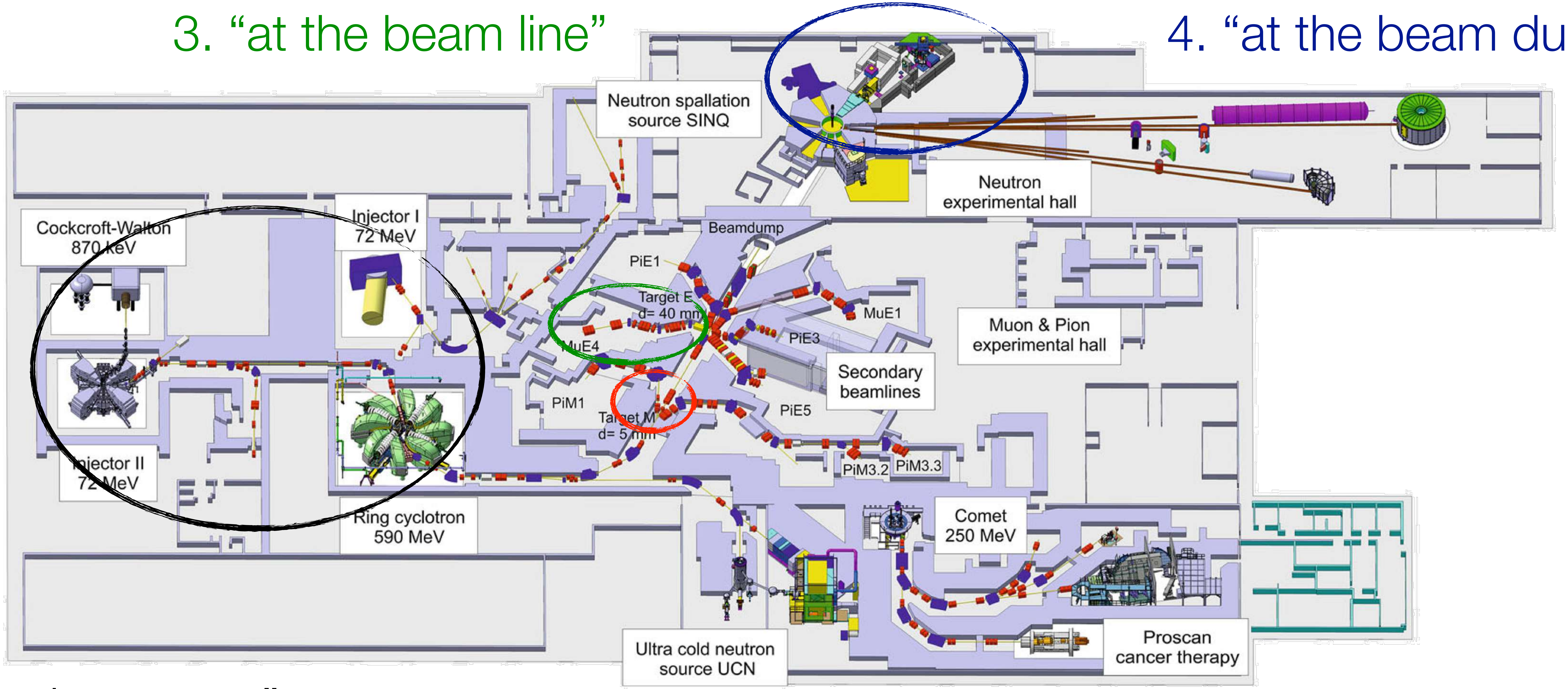


MEGII / Mu3e Experimental area

How the beam intensity can be increased…

3. “at the beam line”

4. “at the beam dump”

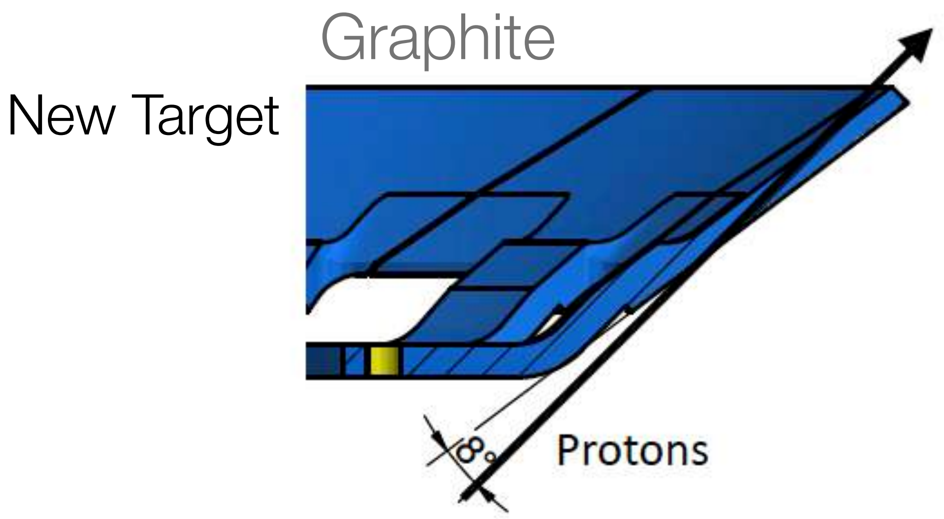


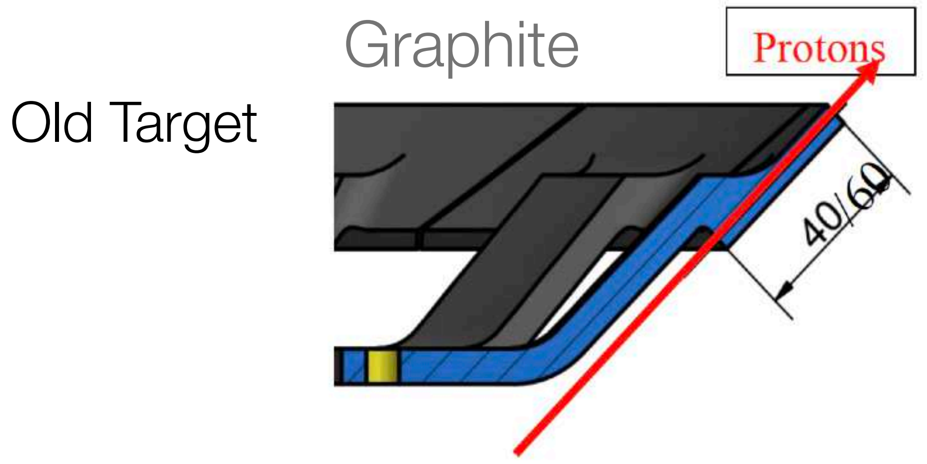
1. “at the source”

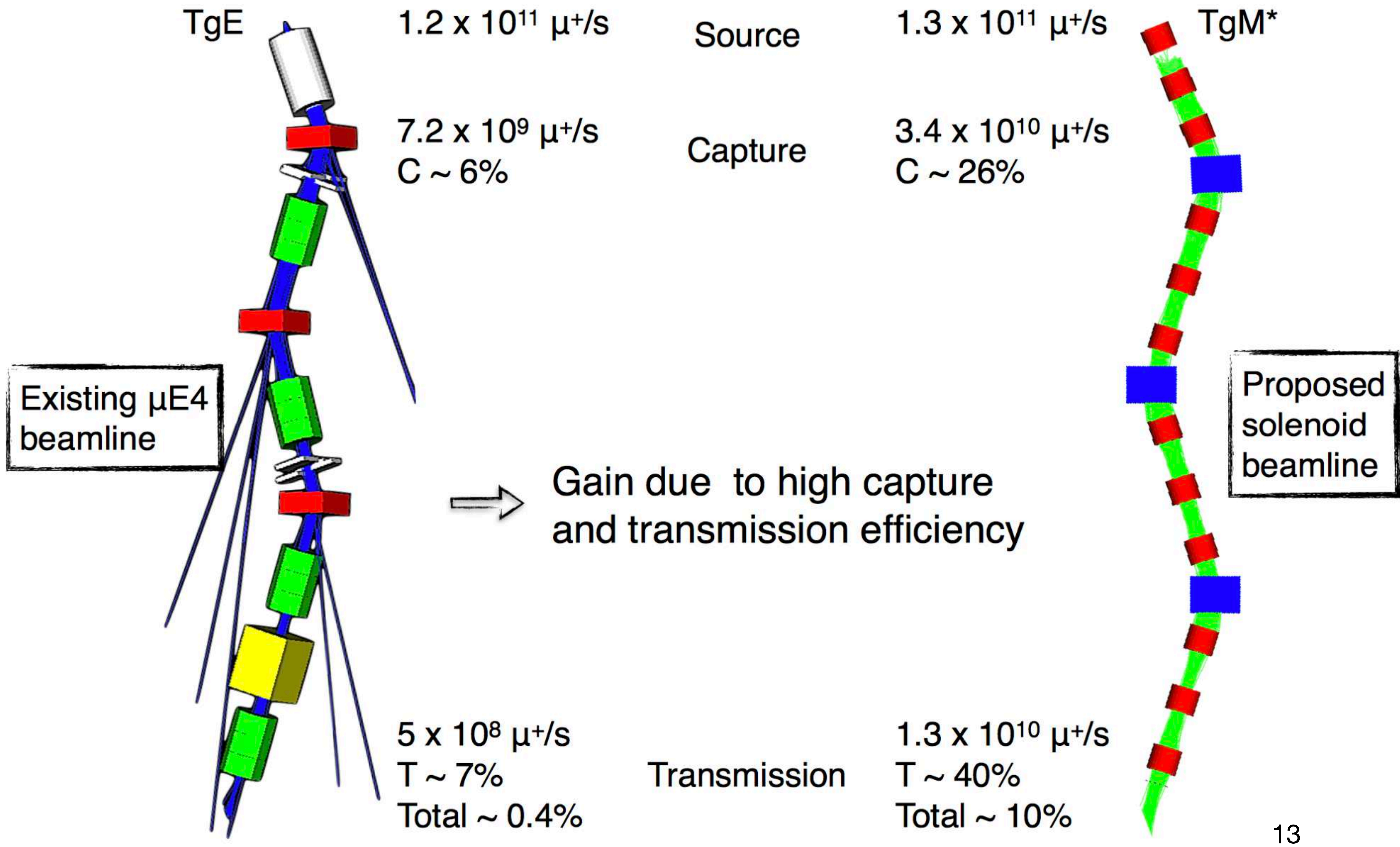
2. “at the target production”

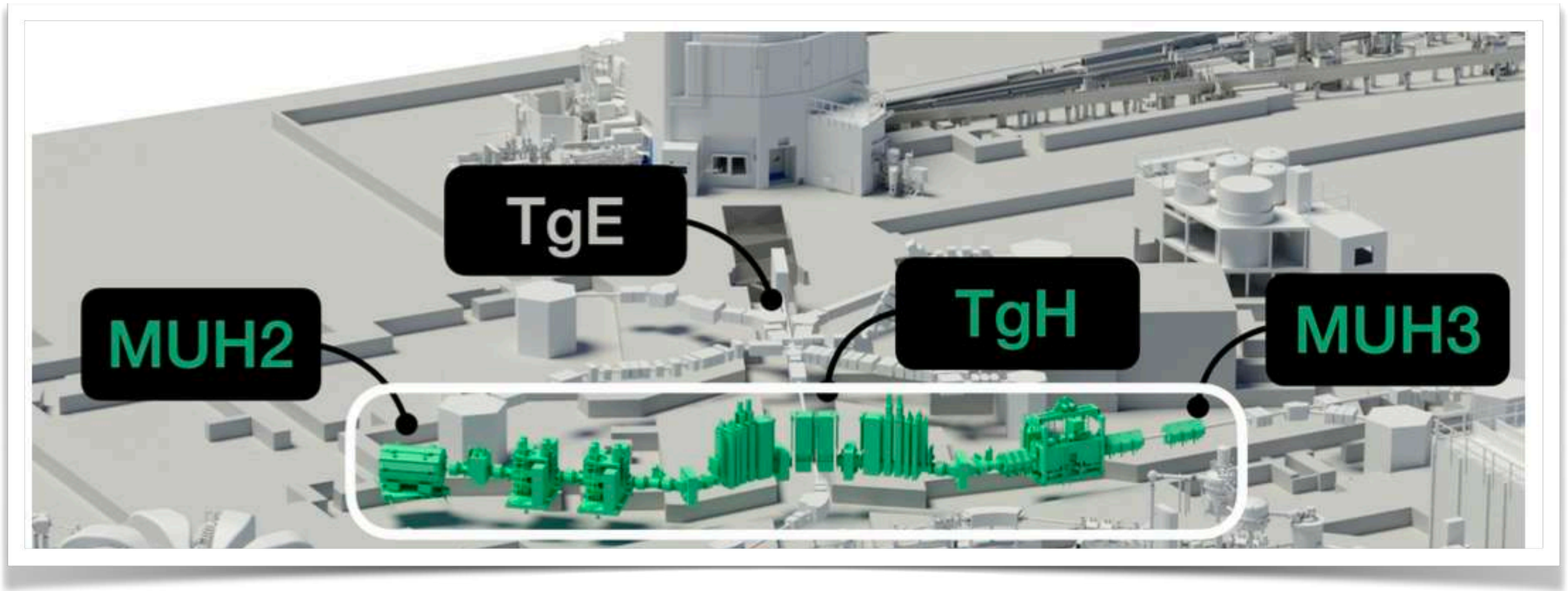
The HiMB (High Intensity Muon Beam) project at PSI

- 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: **2027-28. HiMB from end of 2028**



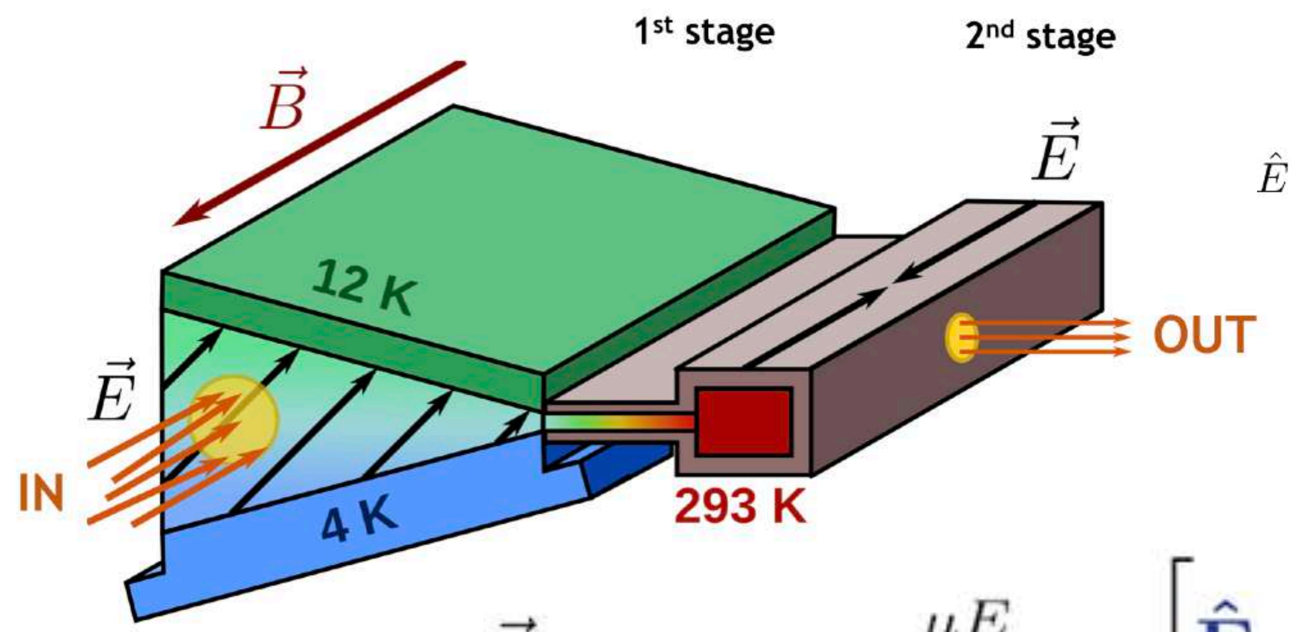


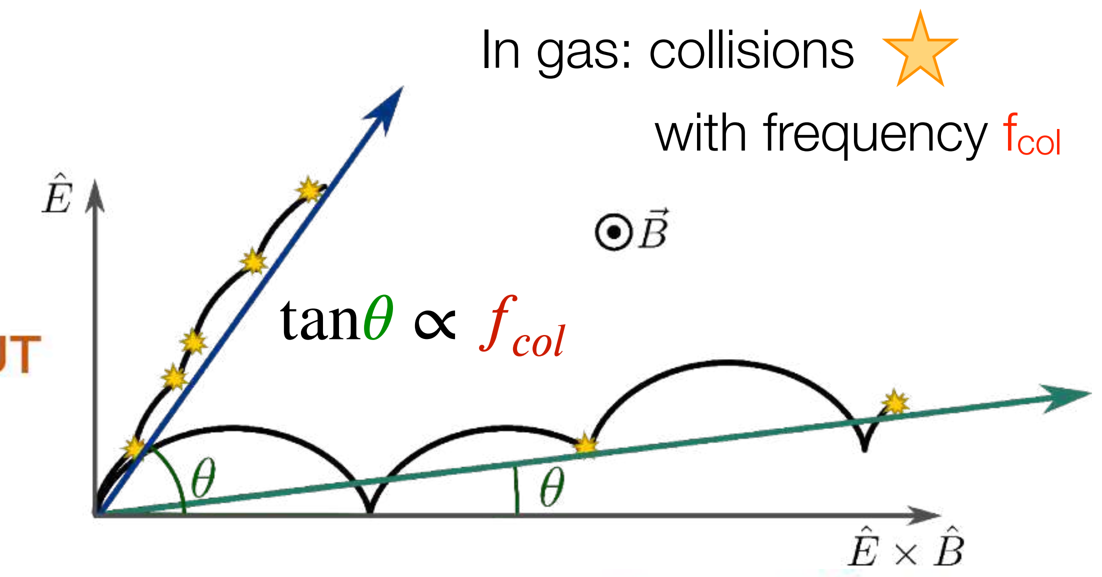




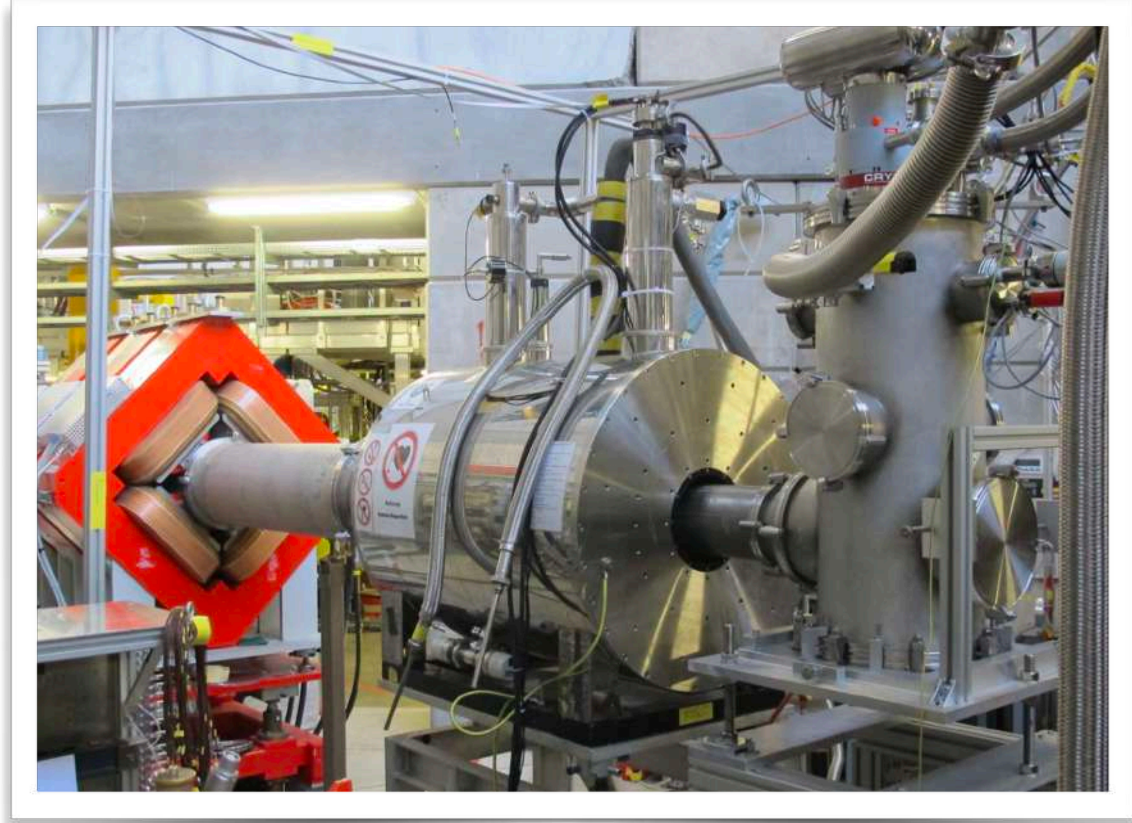
The muCool project at PSI

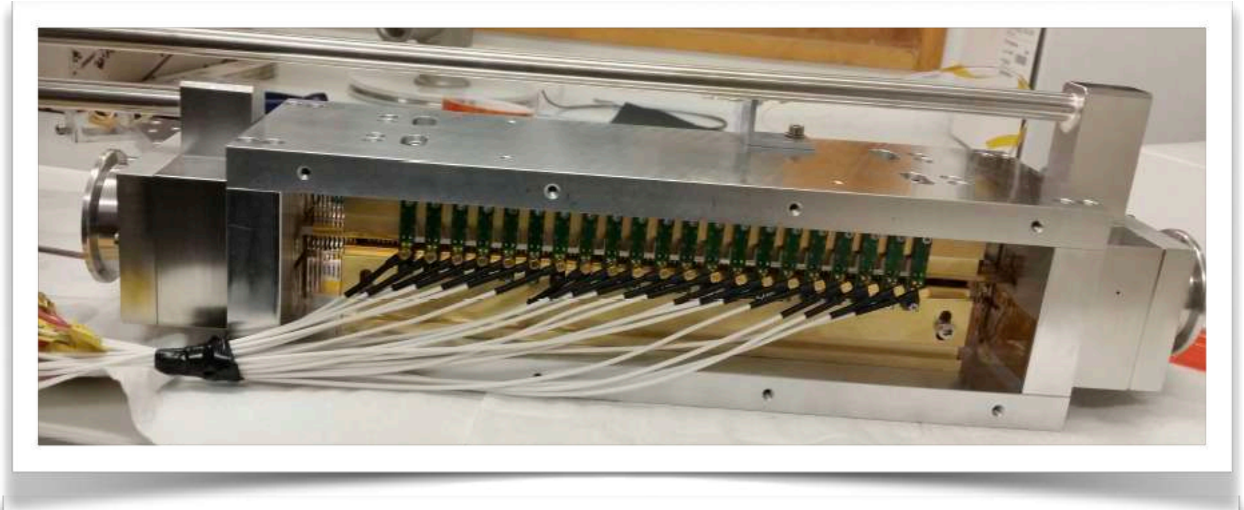
- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor **10^{10}** with an efficiency of **10^{-4}**
- Longitudinal and transverse compression (1st stage +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



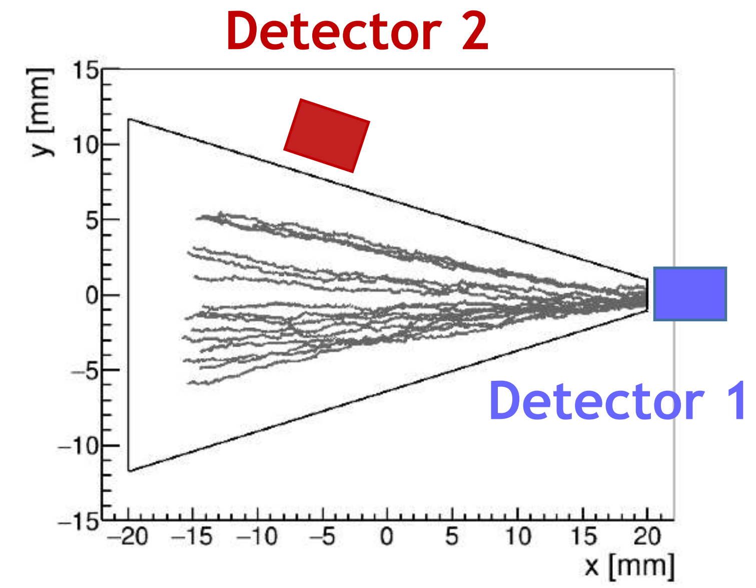


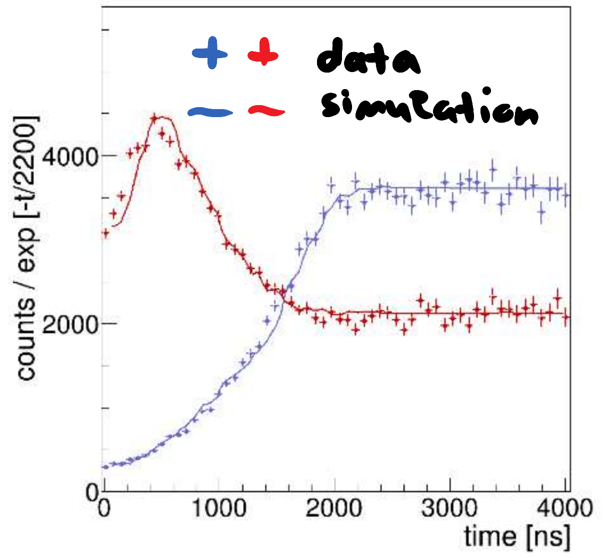
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$



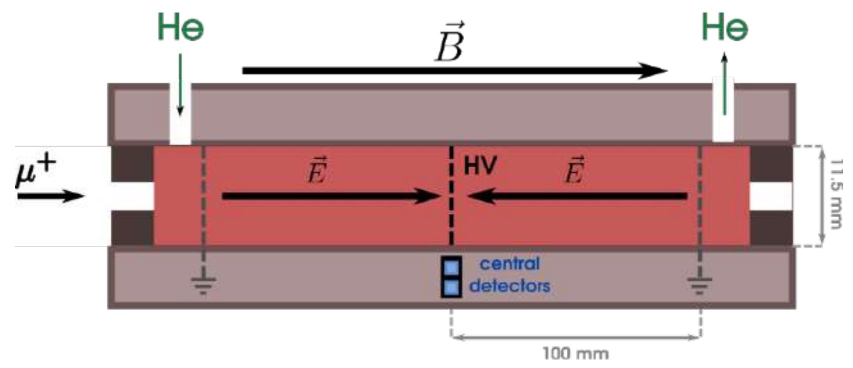


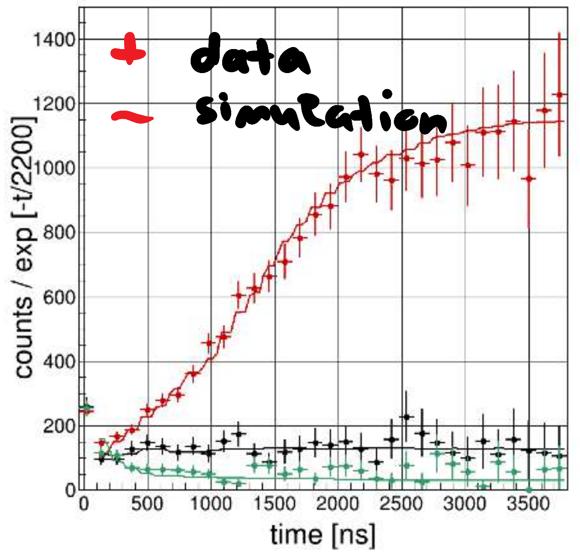
Transverse Compression



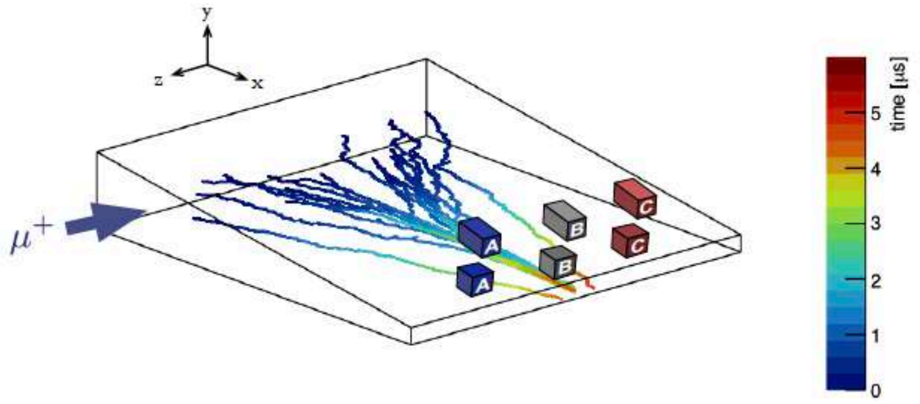


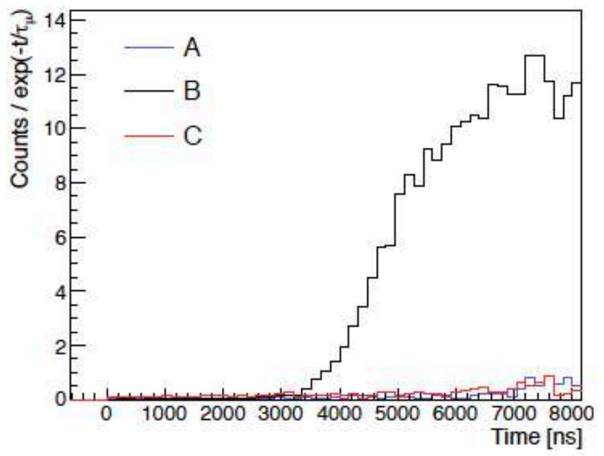
Longitudinal Compression



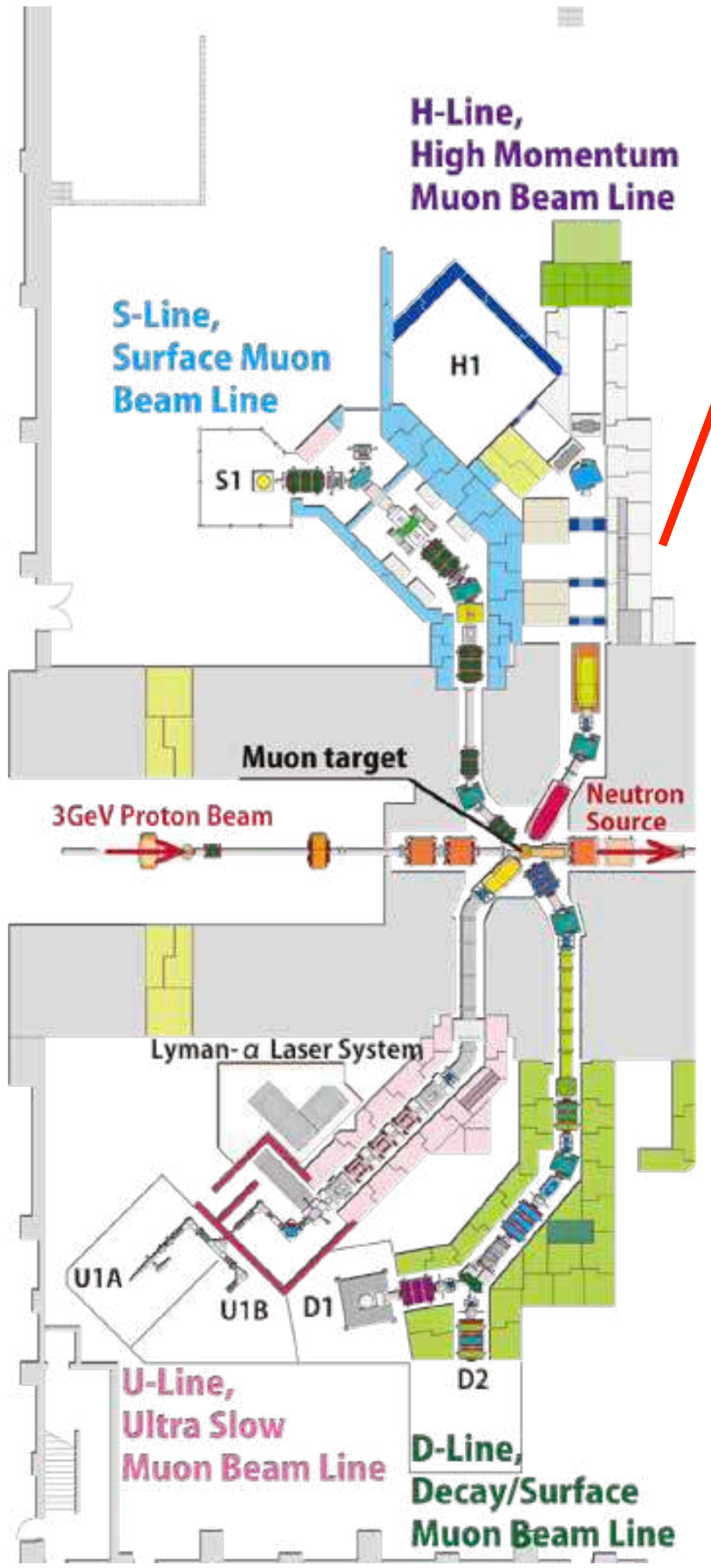


Longitudinal+ Transverse Compression



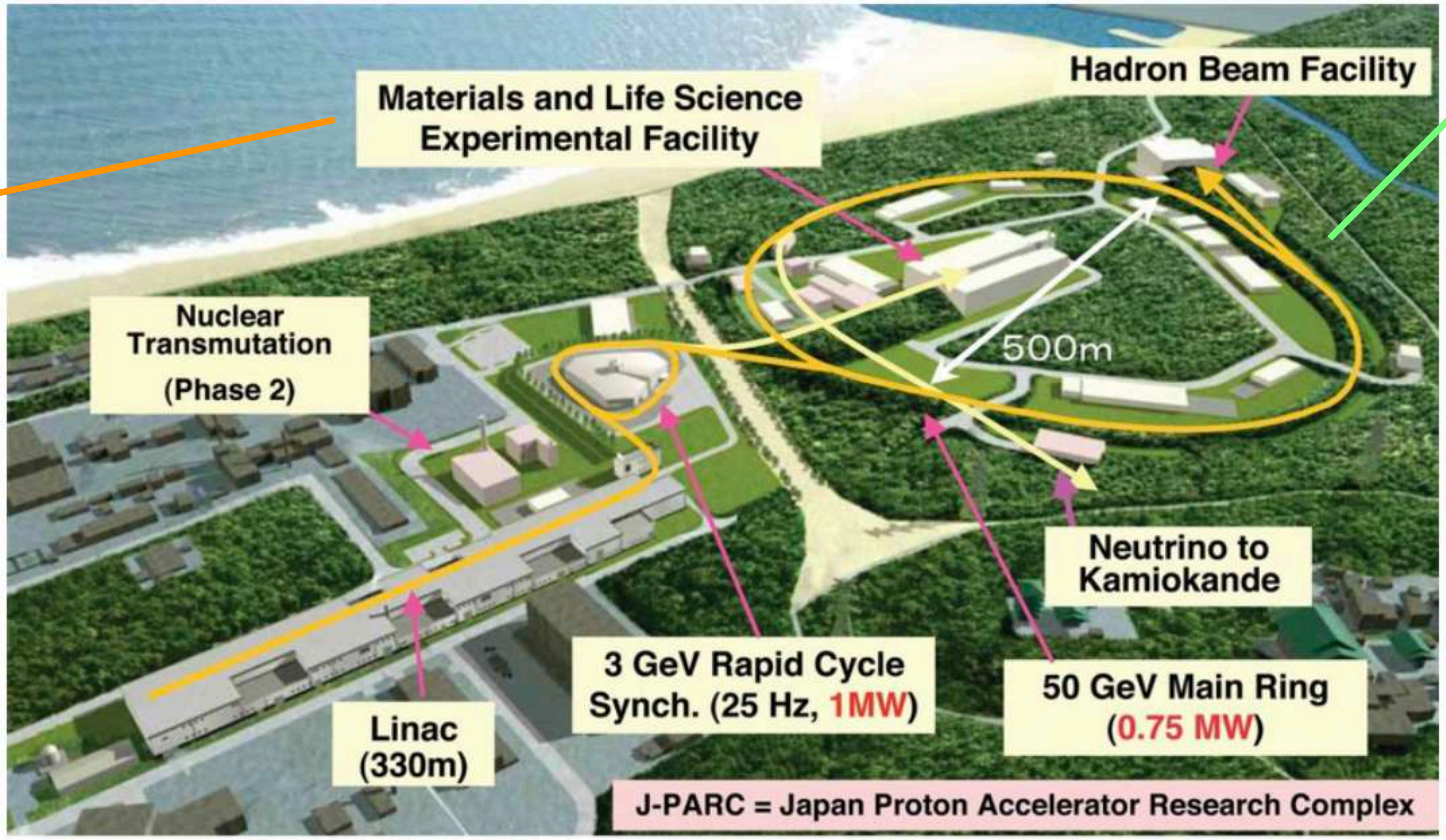


J-PARC muon beams



10^8 muons/s

MuSEUM and
g-2/EDM @ MUSE



- **Bunched** 8 GeV protons extracted from the Main Ring and delivered to the pion target production inside a capture solenoid
- **Muons** are charged and momentum selected using curved superconducting solenoids

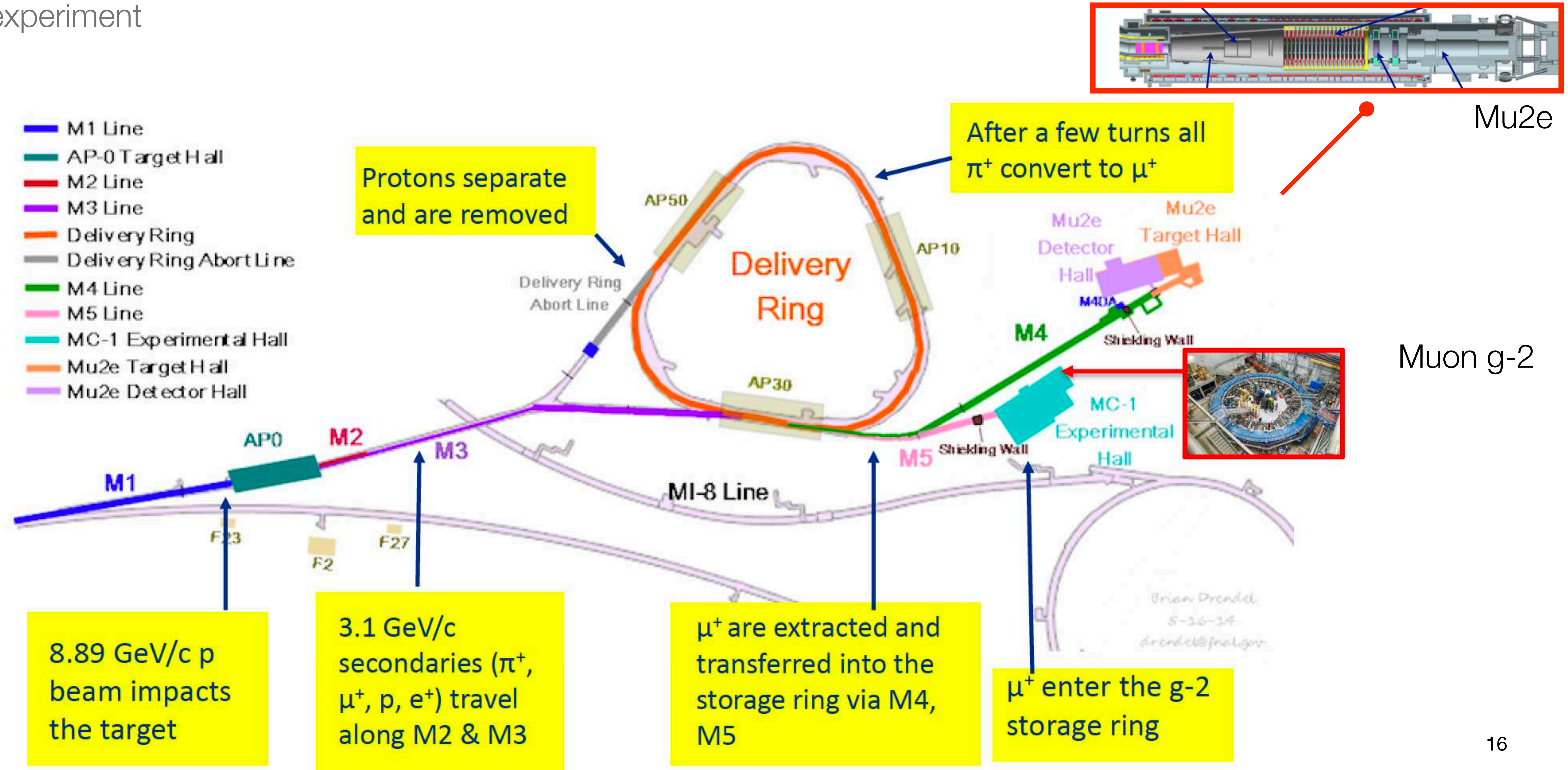
2×10^{11} muons/s from 56 kW

COMET @ Main Ring

Fermilab's muon beams

- A dedicated accelerator facility to provide beams to muon g-2 and Mu2e experiments has been designed and constructed at Fermilab
- **Muon g-2** precedes **Mu2e** (that will follow). The delivered muon beam is free of protons and pions, which created a major background in the BNL experiment

- **Booster** provides 8 GeV protons to the **Recycler**
- **Recycler** stacks protons into 4 bunches
- **Delivery Ring** takes 1 out of every 4 bunches from the **Recycler**
- **Mu2e** slow extracts **protons** every 1695 ns



Content

- Muon physics cases
- Muon beams
- **Muon (present) experiments**

CLFV searches with muons: Status and prospects

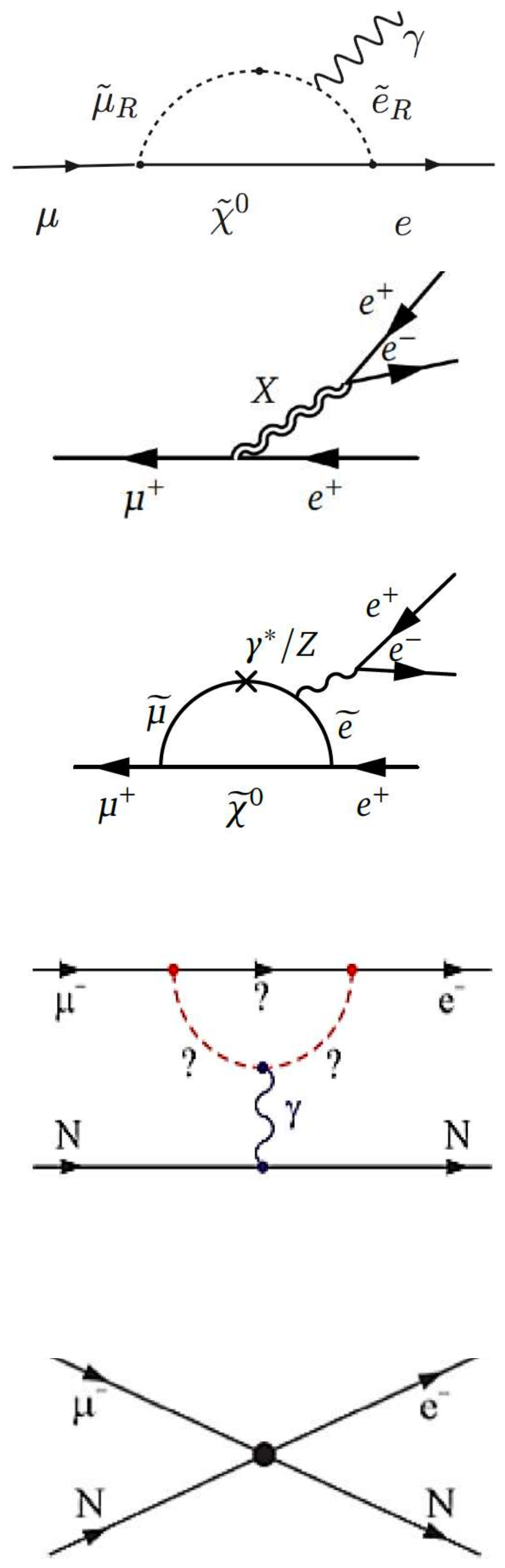
- In the near future impressive sensitivities via the so called “golden” muon channels
- **Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV**

	Current upper limit	Future sensitivity
$\mu \to e\gamma$	(MEGI) 4.2 x 10^{-13}	~ 6 x 10^{-14}
$\mu \to eee$	1.0 x 10^{-12}	~1.0 x 10^{-16}
$\mu N \to eN'$	7.0 x 10^{-13}	few x 10^{-17}

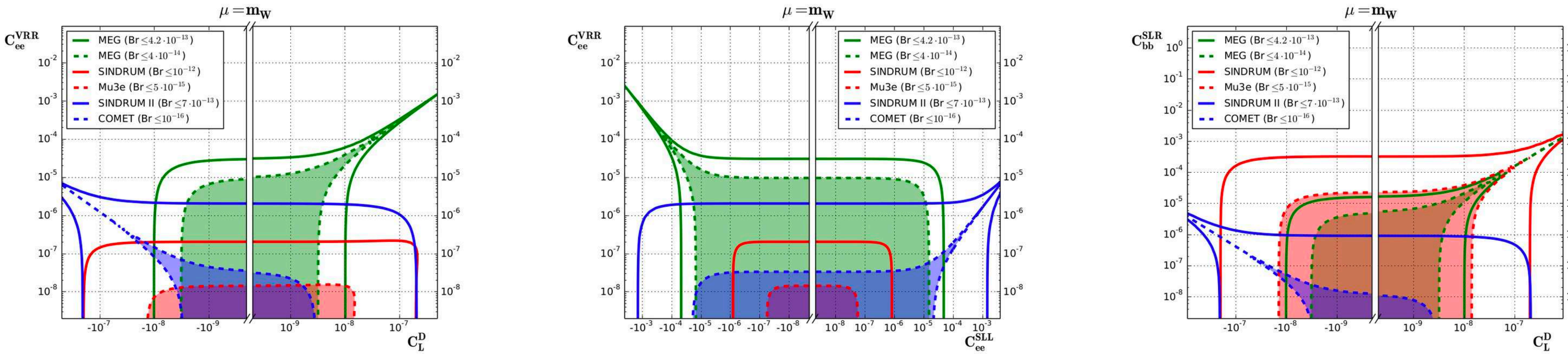
$\mu \to e\gamma$

$\mu \to eee$

$\mu N \to eN'$



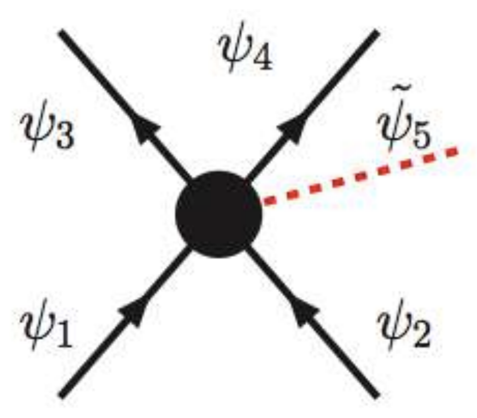
$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum \mathcal{O}_5 + \frac{1}{\Lambda^2}\sum \mathcal{O}_6$$



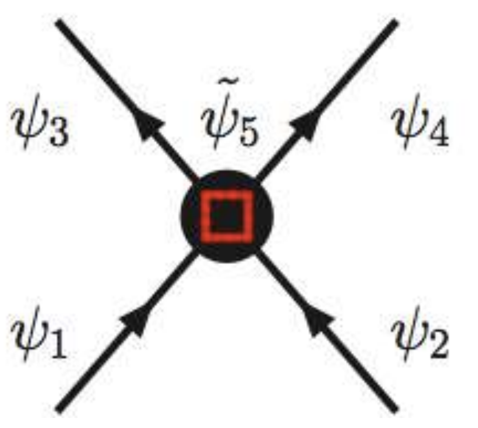
Crivellin, Davidson, Pruna, Signer, JHEP 05 117 (2017)

CLFV searches with muons: Status and prospects

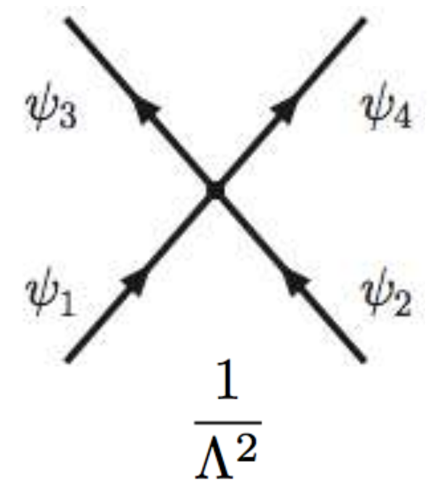
- In the near future impressive sensitivities via the so called “golden” muon channels
- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV
- **Probing energy scale otherwise unreachable at the energy frontiers**
- Note: τ ideal probe for NP w. r. t. μ (Smaller GIM suppression, stronger coupling, many decays). μ most sensitive probe due to huge statistics (= muon campus)



Energy frontier



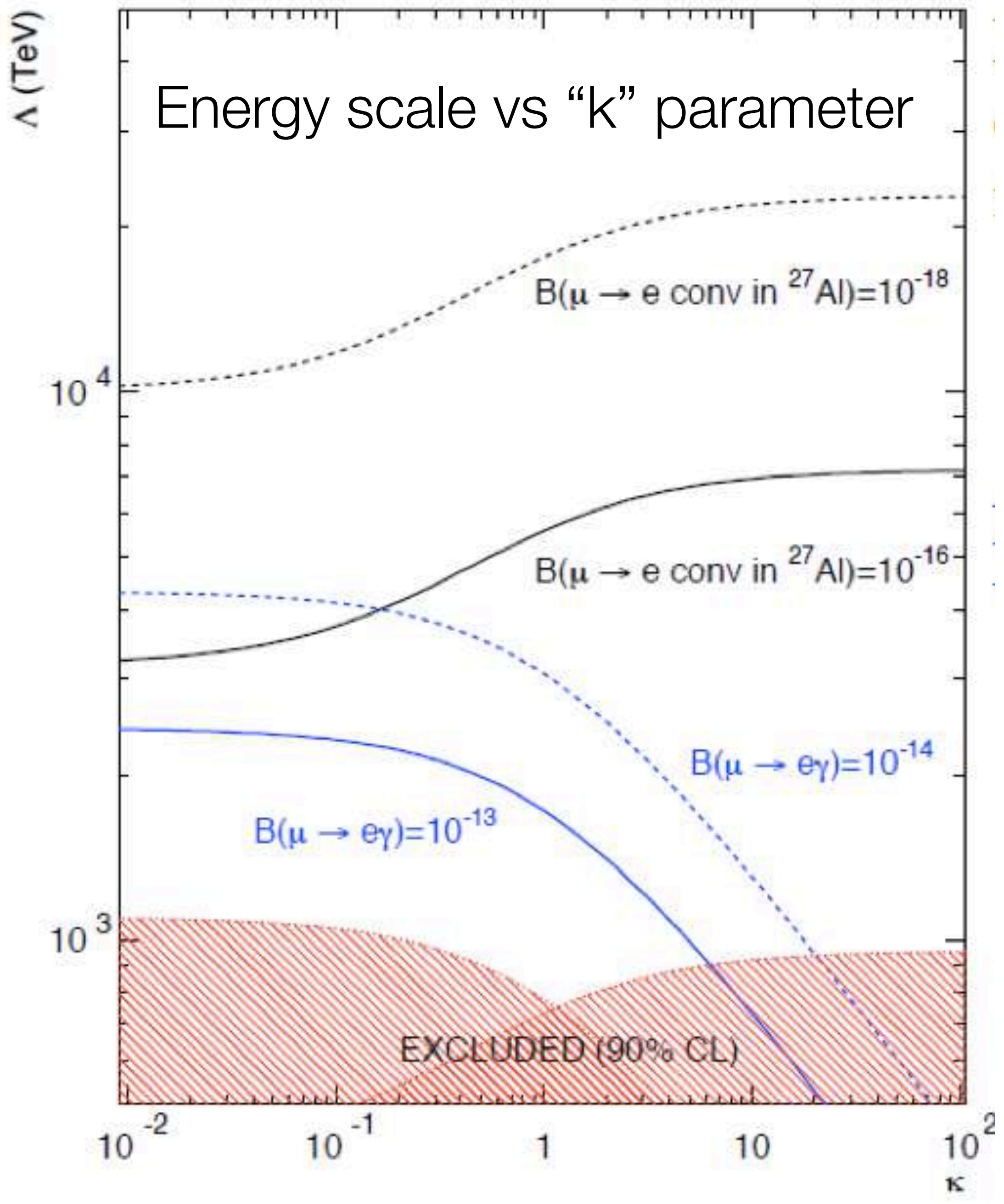
Precision and intensity frontier



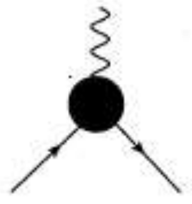
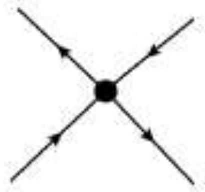
Probe energy scale otherwise unreachable

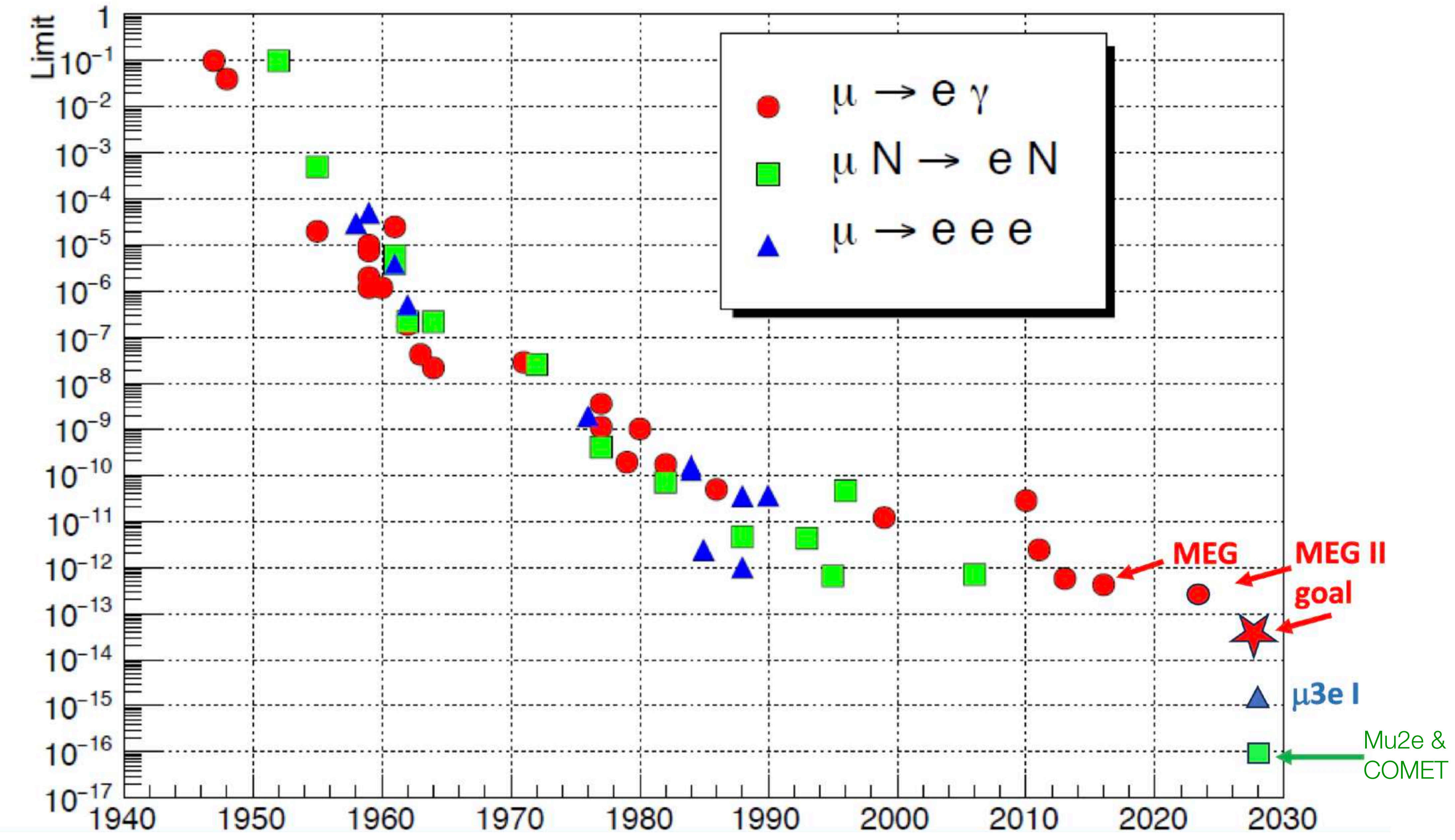
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$

E > 1000 TeV



Model independent Lagrangian

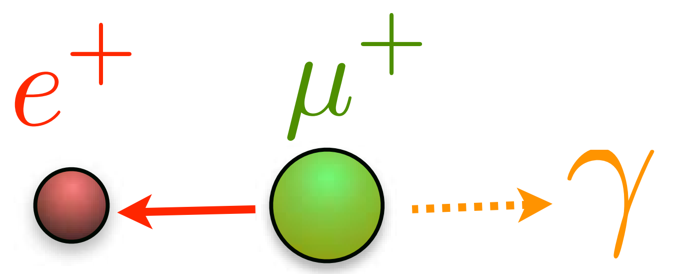
$$\underbrace{\frac{m_\mu}{(\kappa+1)\Lambda^2} \times}_{\mu \to e\gamma}$$  $$+ \underbrace{\frac{\kappa}{(\kappa+1)\Lambda^2} \times}_{\substack{\mu \to eee \\ \mu N \to eN}}$$ 



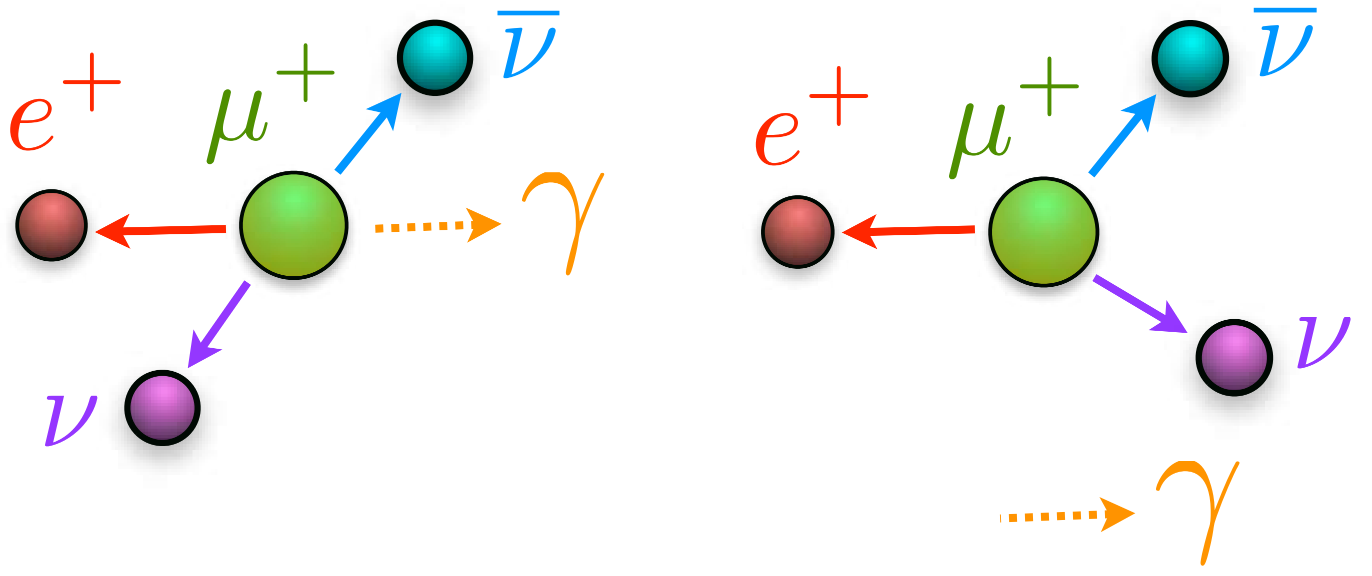
The MEGII experiment at PSI

- 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



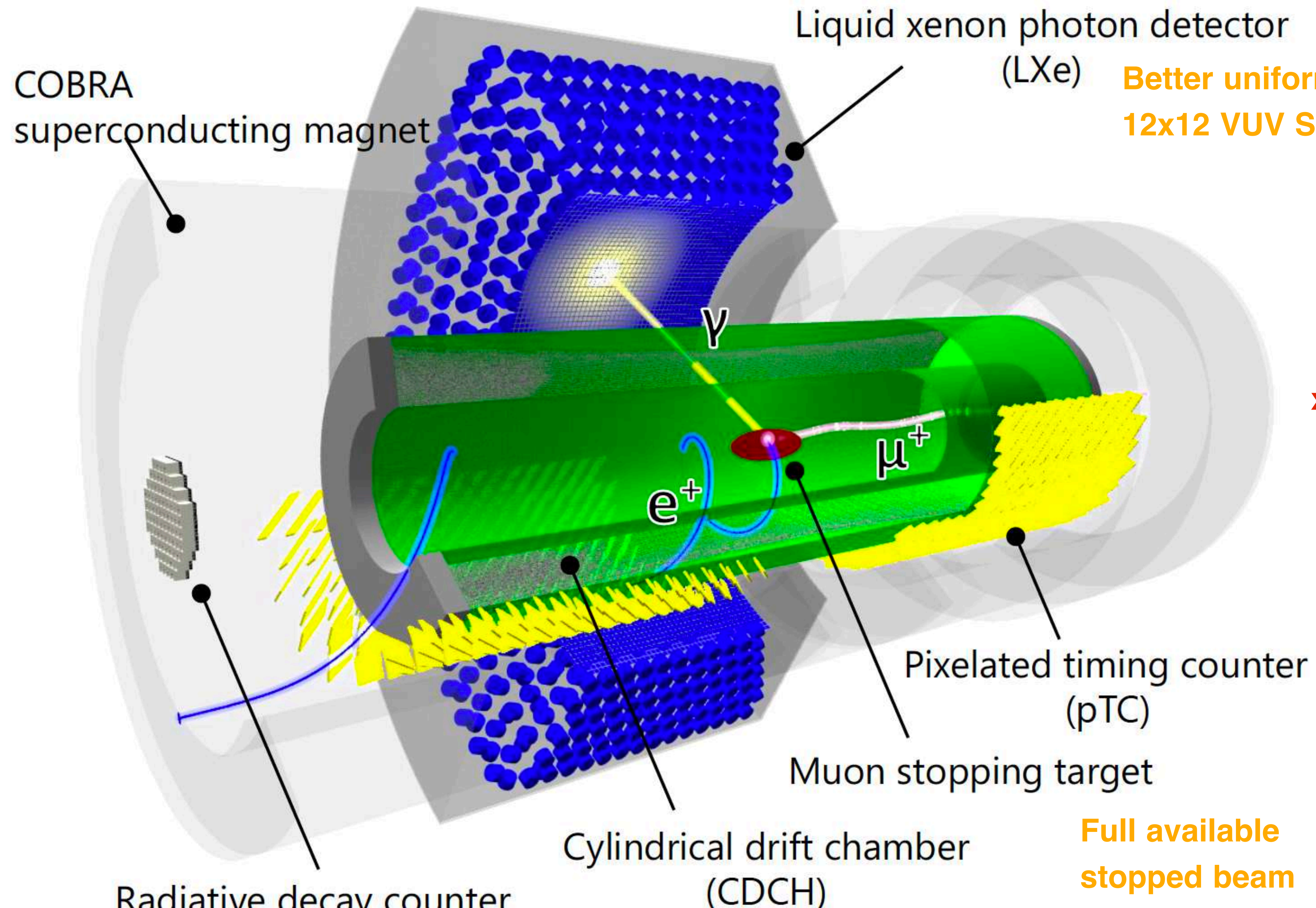
New electronics:
Wavedream

~9000 channels at 5GSPS

x2 Resolution everywhere

Updated and new Calibration methods

Quasi mono-chromatic positron beam



Better uniformity w/ 12x12 VUV SiPM

x2 Beam Intensity

35 ps resolution w/ multiple hits

Full available stopped beam intensity 7×10^7

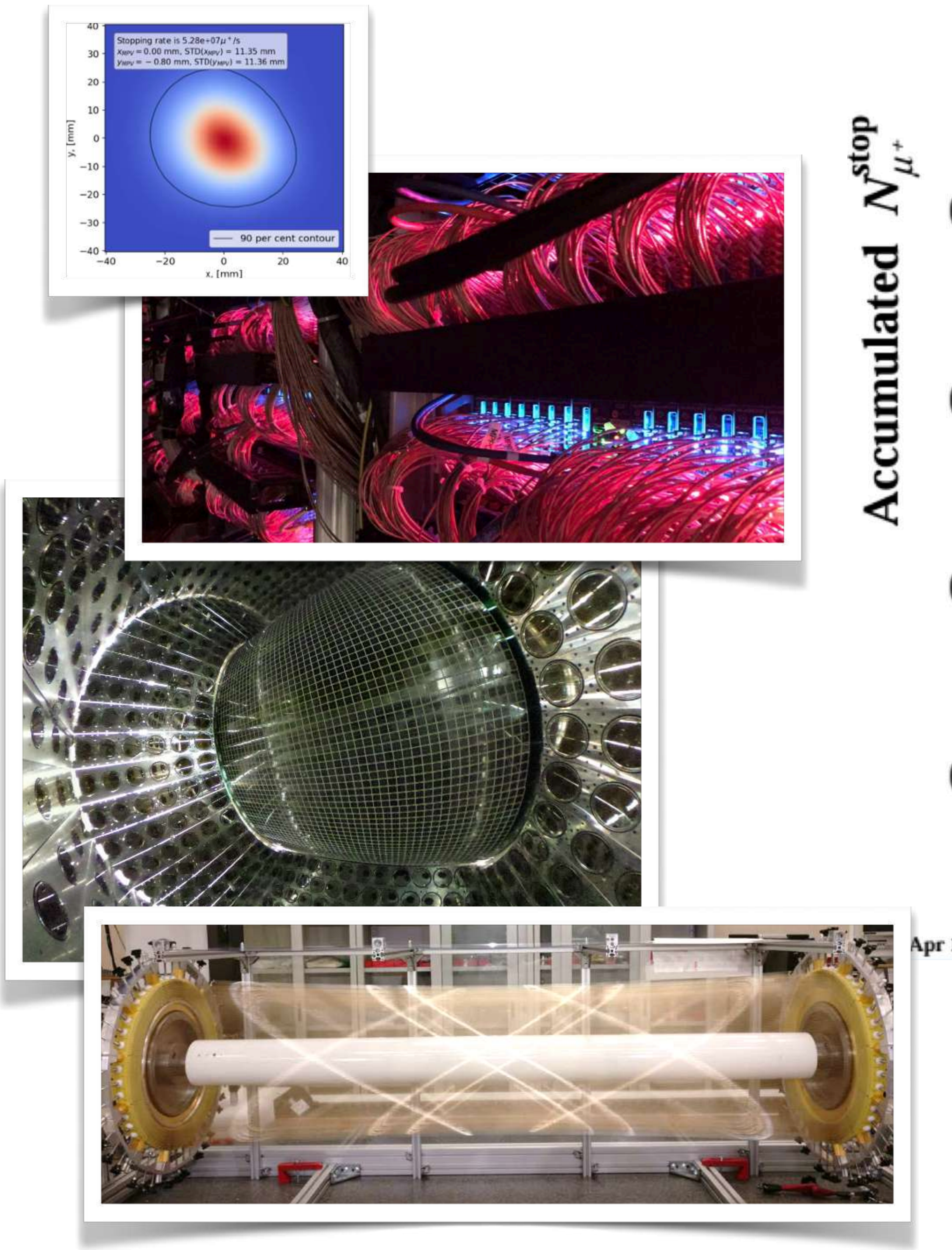
Single volume $He:iC_4H_{10}$

Background rejection

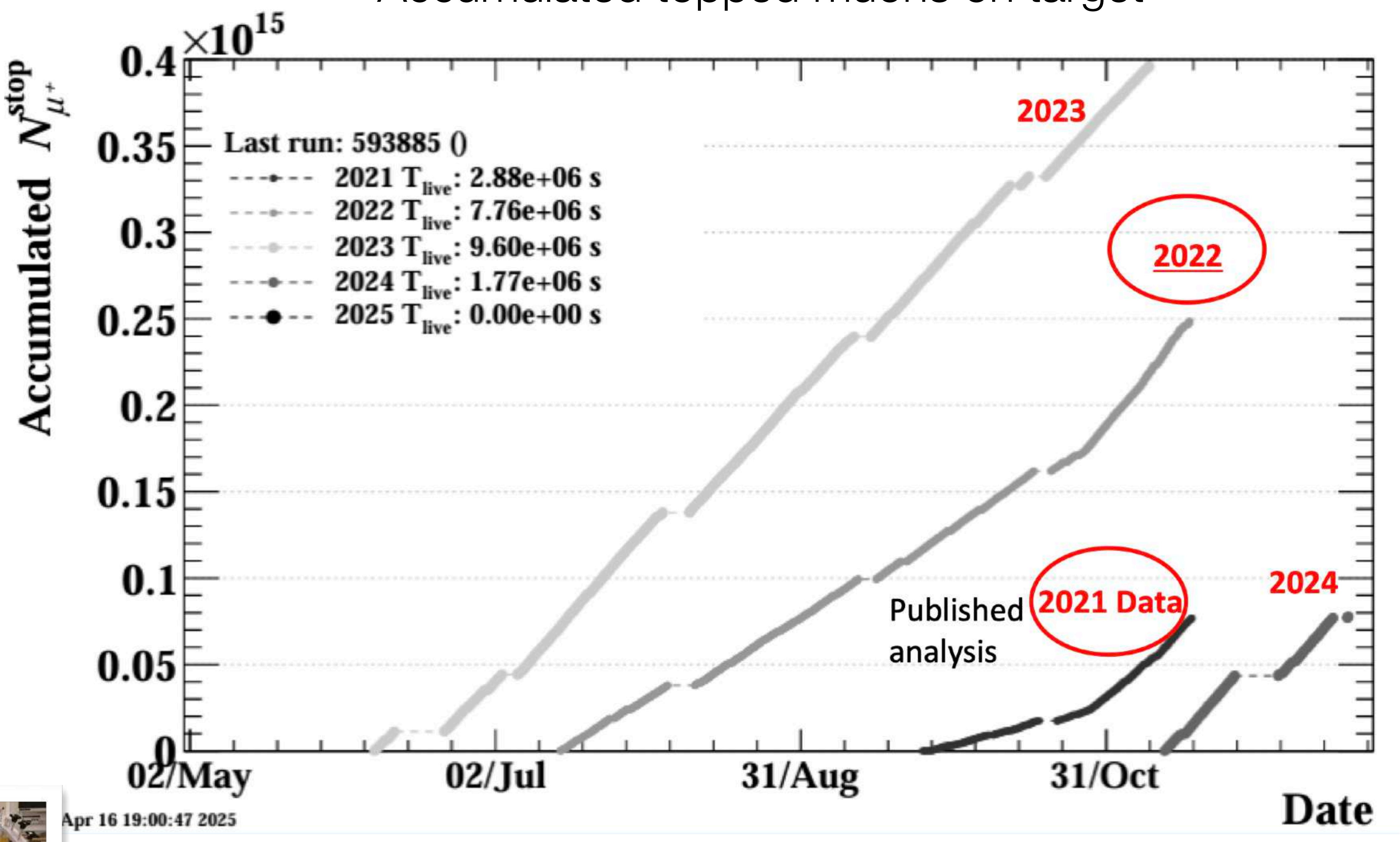
https://arxiv.org/pdf/2504.15711

MEGII status: New Physics Results and data taking

- MEGII started data taking in 2021 and is expected to run until 2026
- A **new Physics Result** has recently been released based on the data 2021+2022

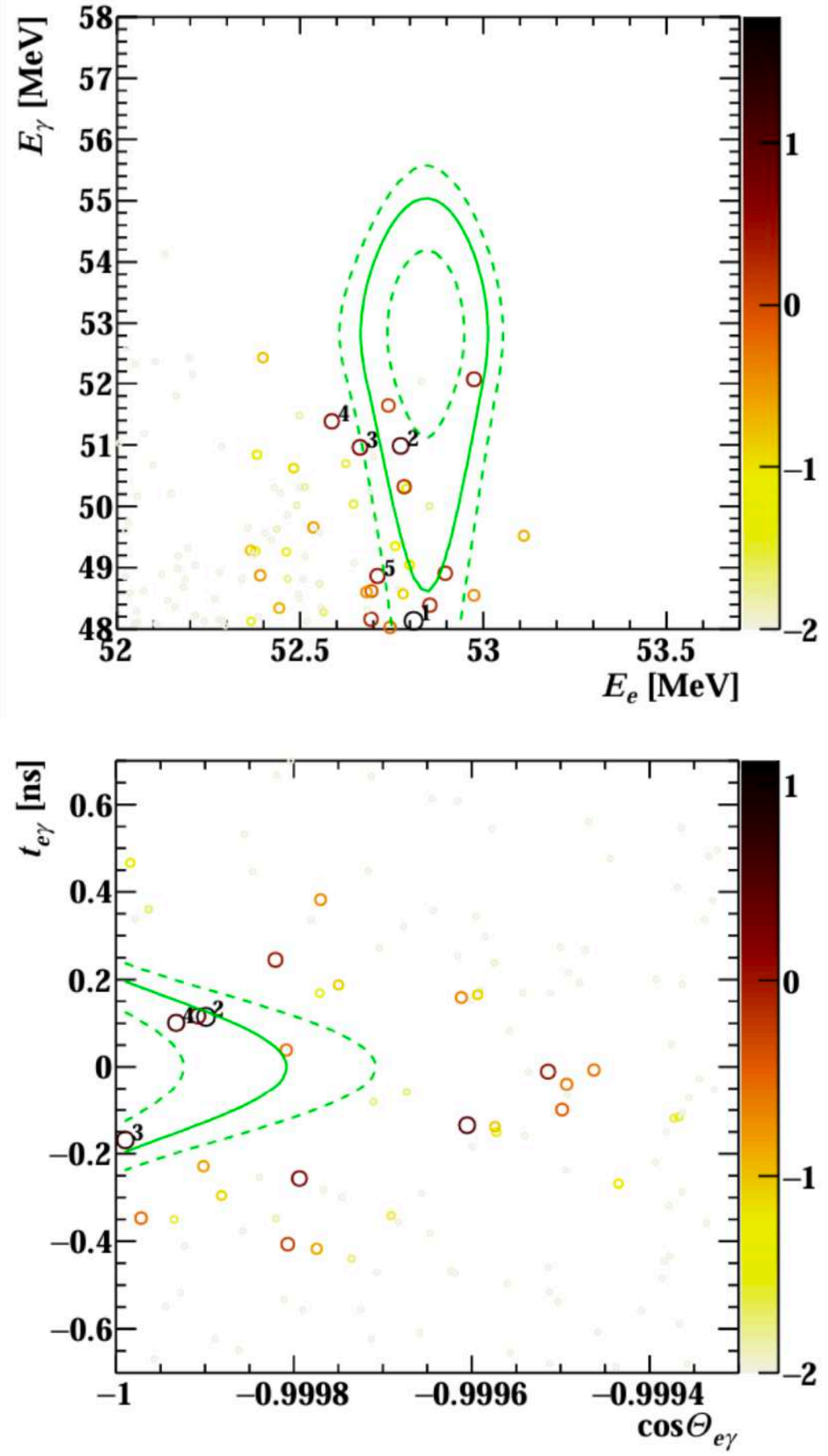


Accumulated topped muons on target



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

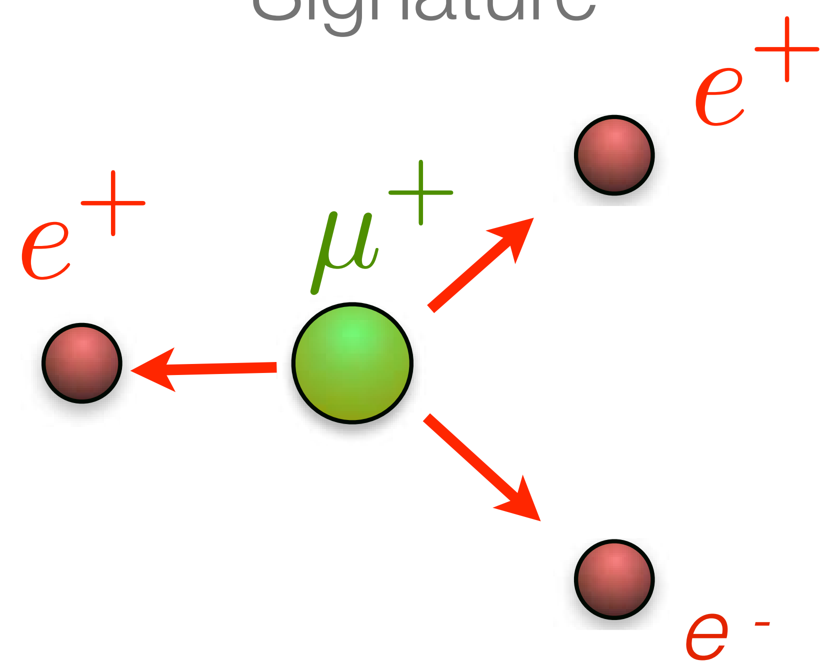
Data 2021+2022: Opening the signal region



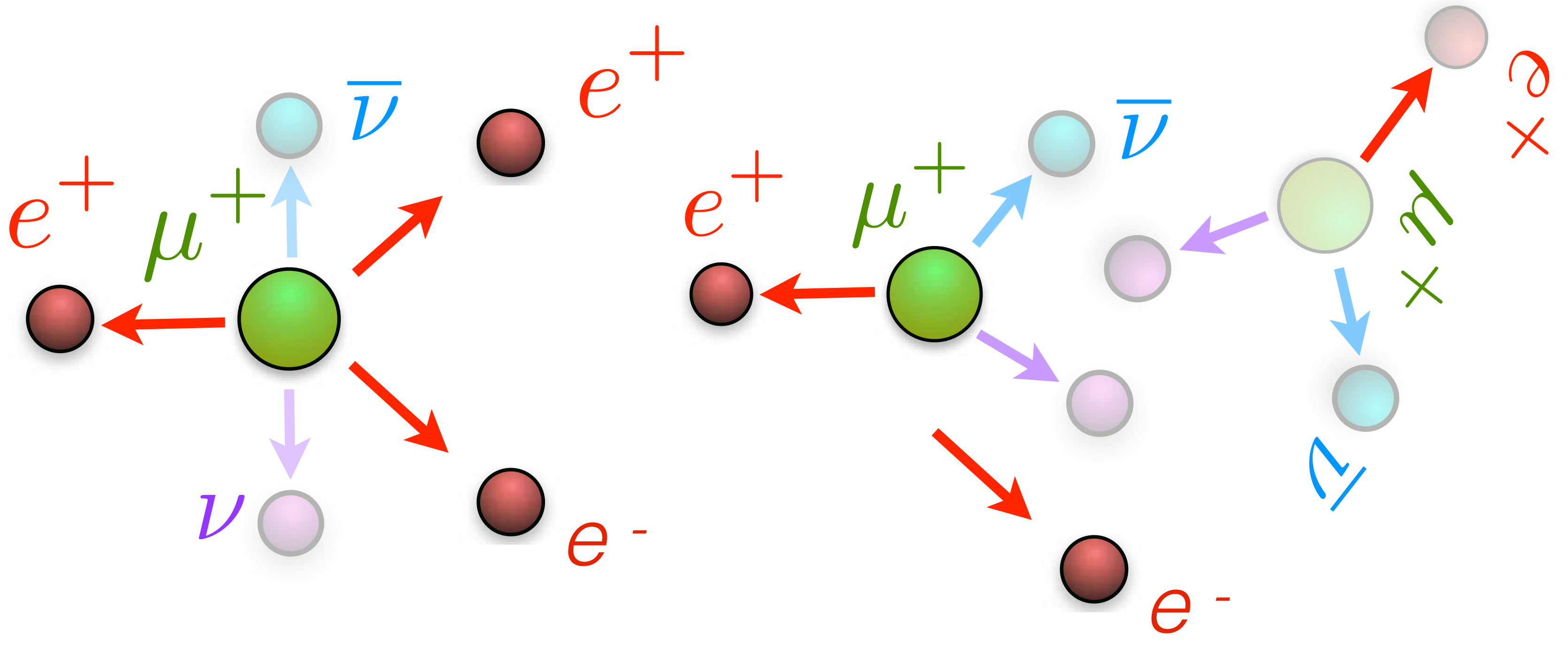
The Mu3e experiment at PSI

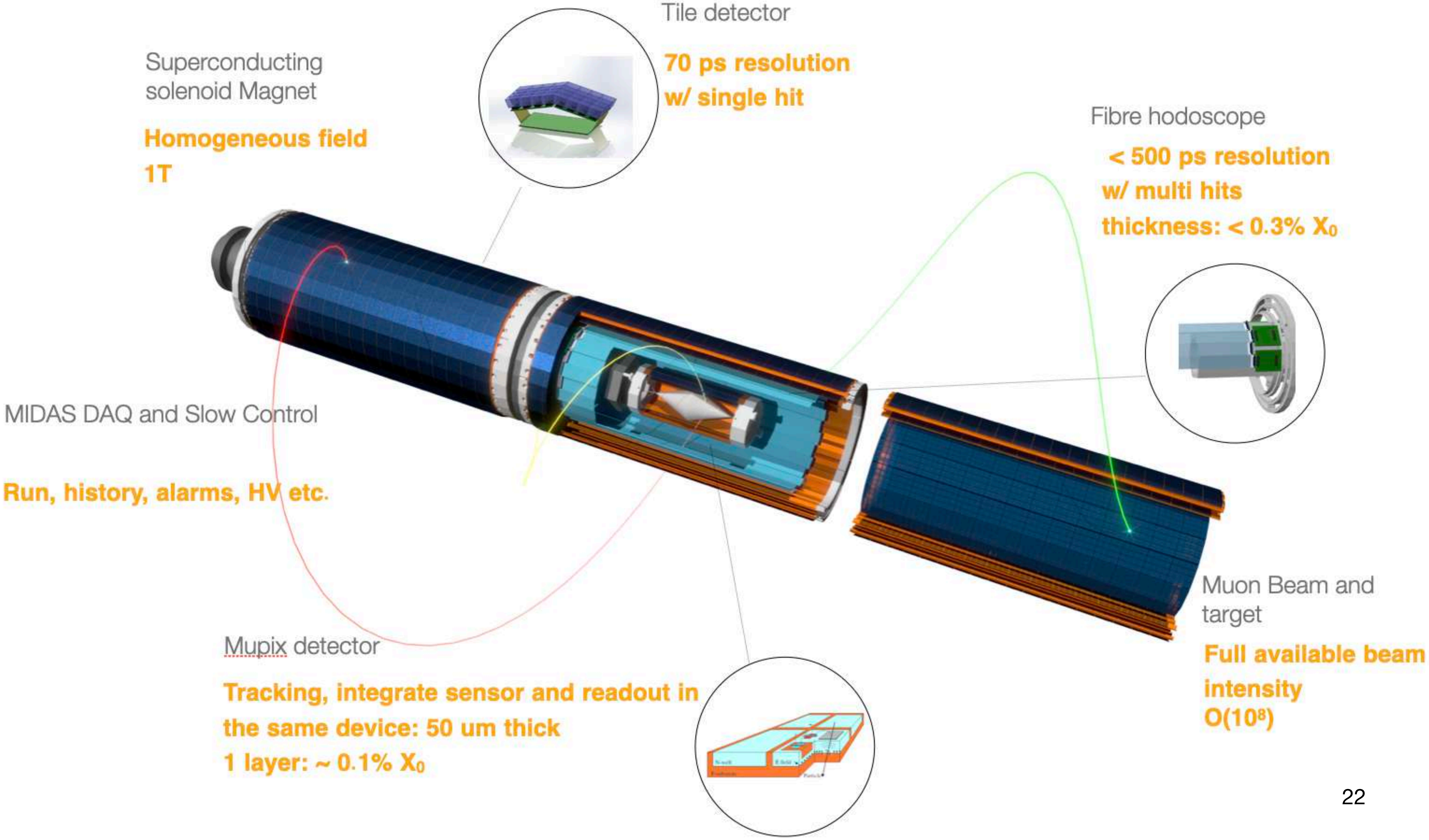
- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of ~10^{-15} (Phase I) up to down ~10^{-16} (Phase II). Previous upper limit BR($\mu^+ \rightarrow e^+ e^+ e^-$) $\leq 1 \times 10^{-12}$ @90 C.L. by SINDRUM experiment)
- Observables (E_e, t_e, vertex) to characterize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

Signature



Backgrounds





Mu3e: Latest news and currents status

Key points:

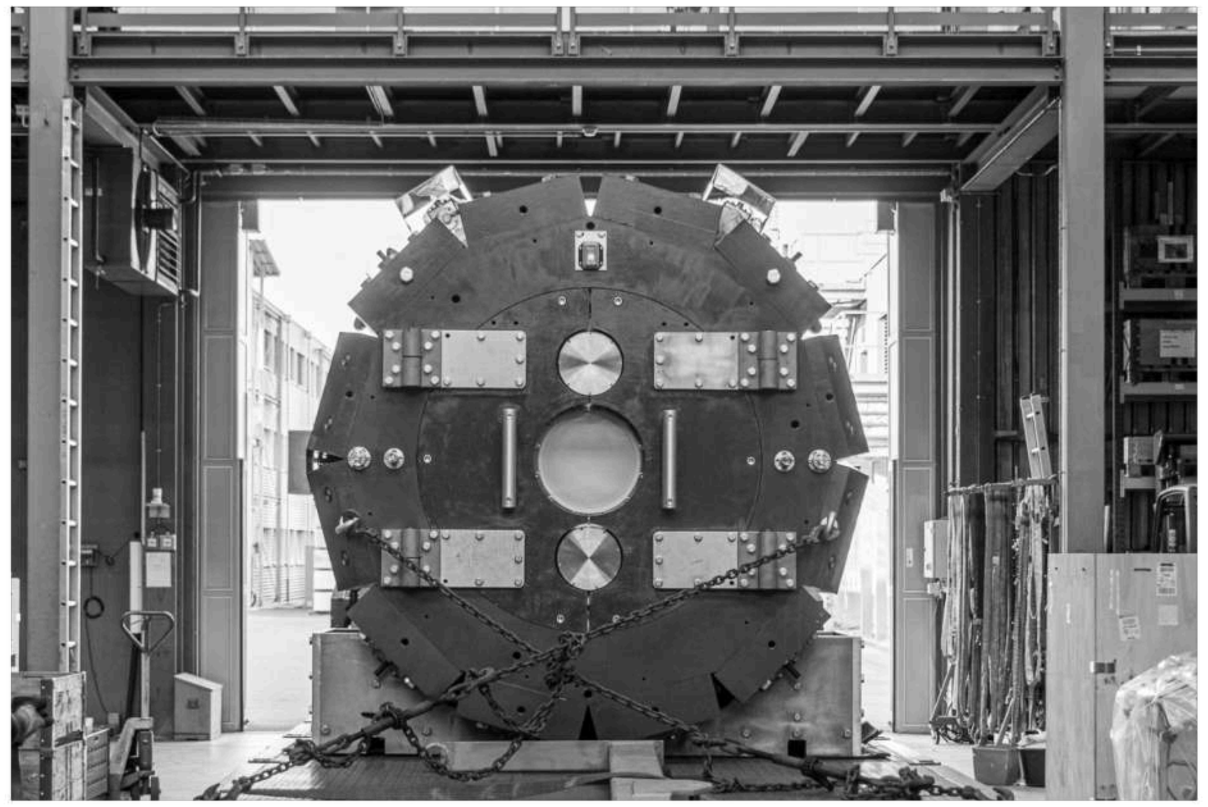
- **First integration Run 2021**
- Inner MuPix layer
- SciFi ribbons
- Sub-detector services

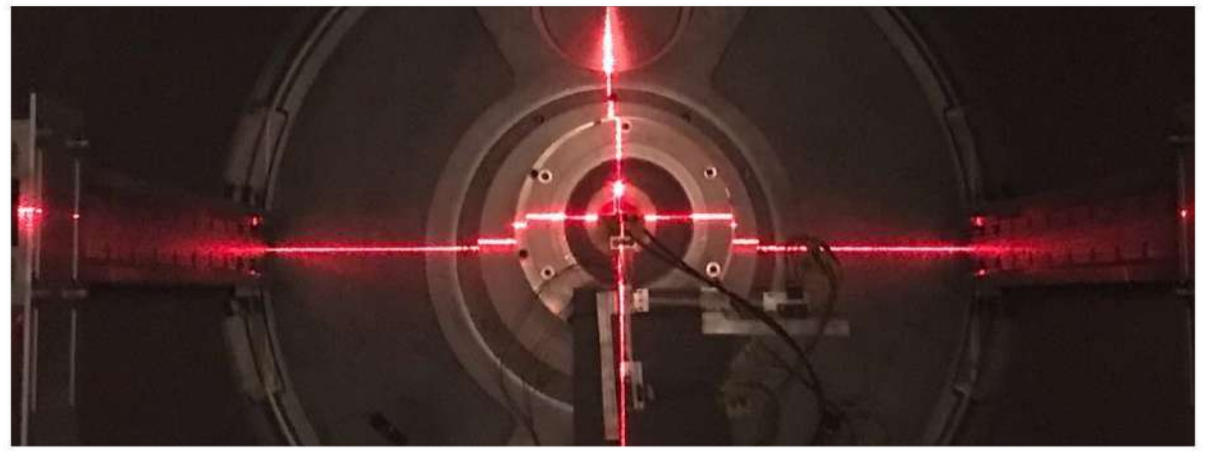
- **Full beam line commissioning 2022 and fine tuning 2023**
- Very successful: TDR promised values **matched!**
  - **2.49e10⁸ mu/s @2.4 mA** (at the collimator): The highest beam rate in pie5 at the collimator
  - **1.02e10⁸ mu/s @2.4 mA** (Mu3e magnet): Several beam configurations studied, some of them connected with possible Mu3e magnetic field intensity optimisation

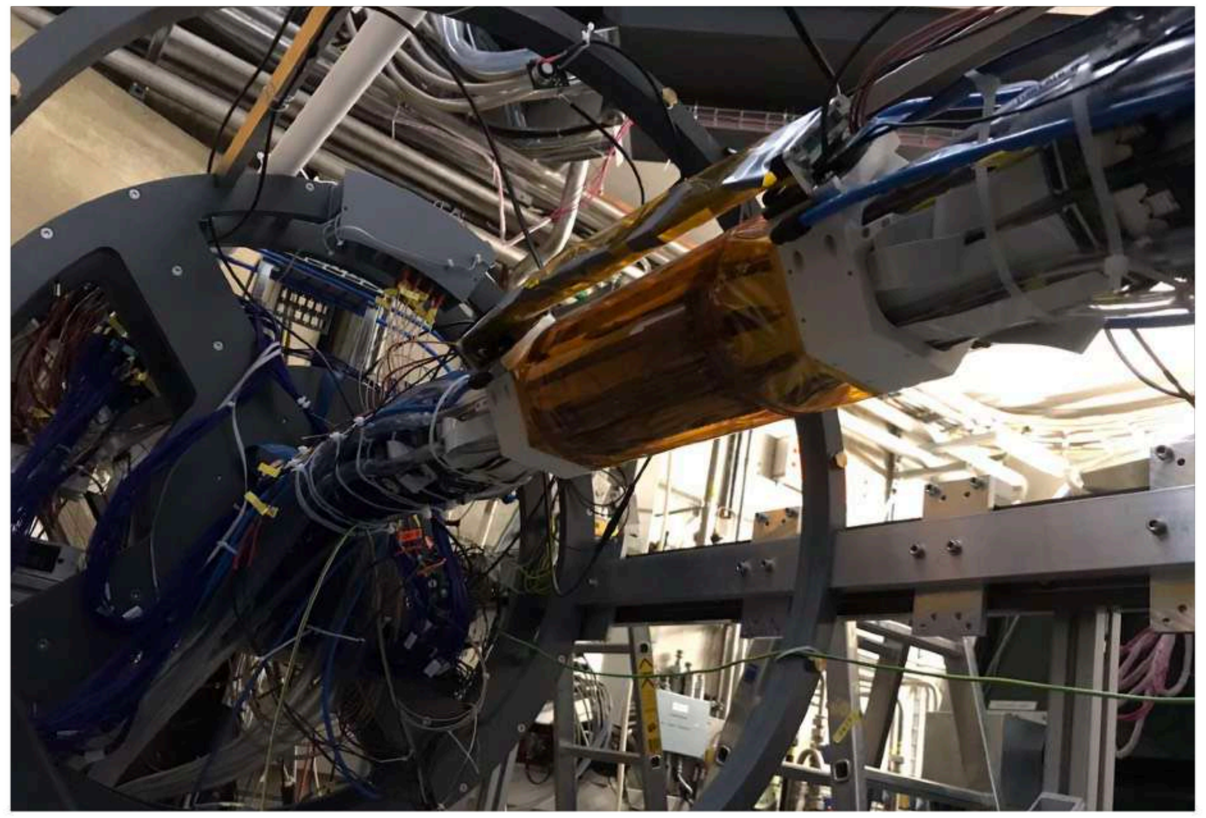
Time line phase I (exploiting current beam-line intensity)

- Engineering run: 2025
- First physics run: 2026

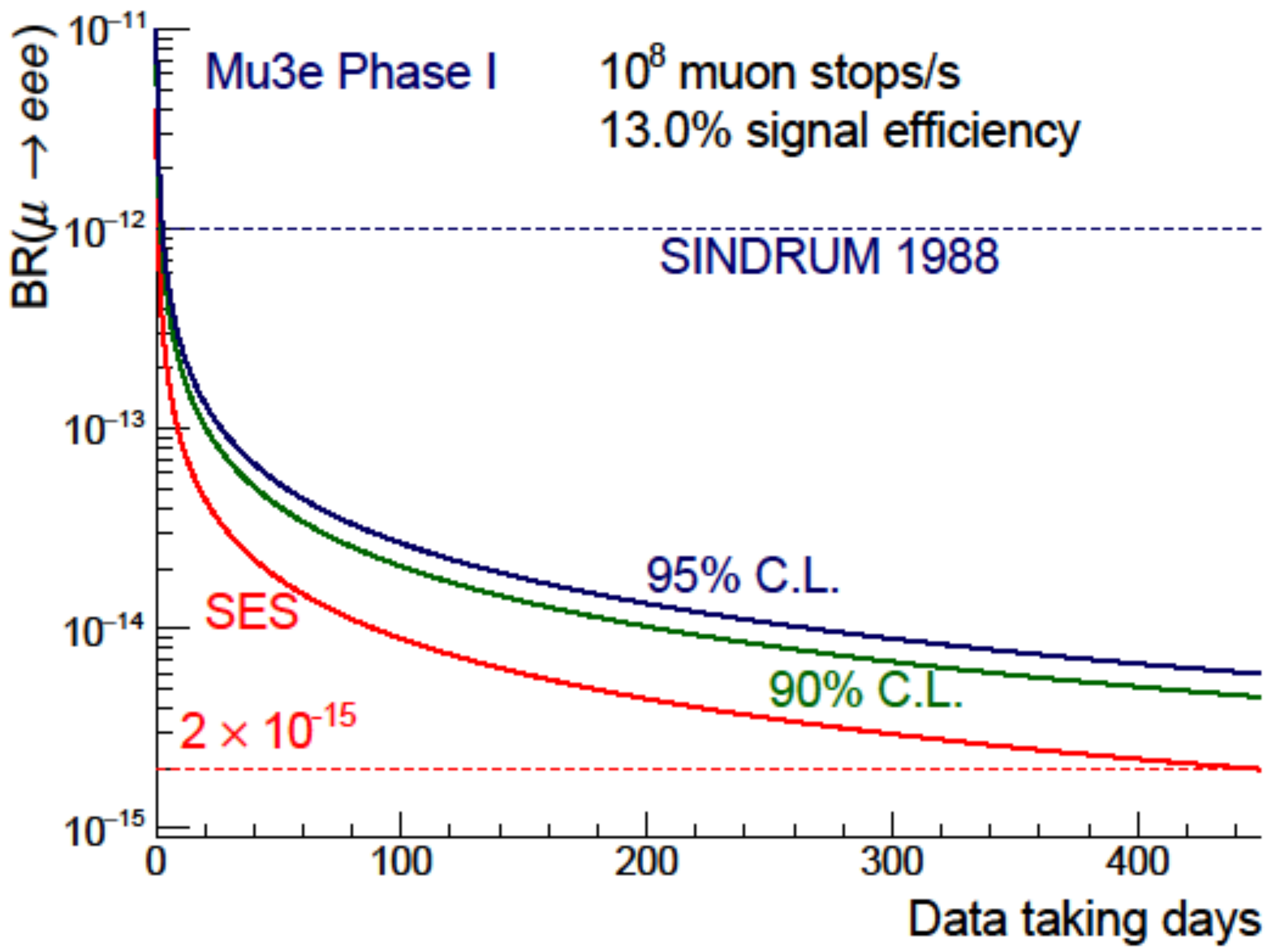
Phase II: It requires 10^9 mu/s —> **HiMB**



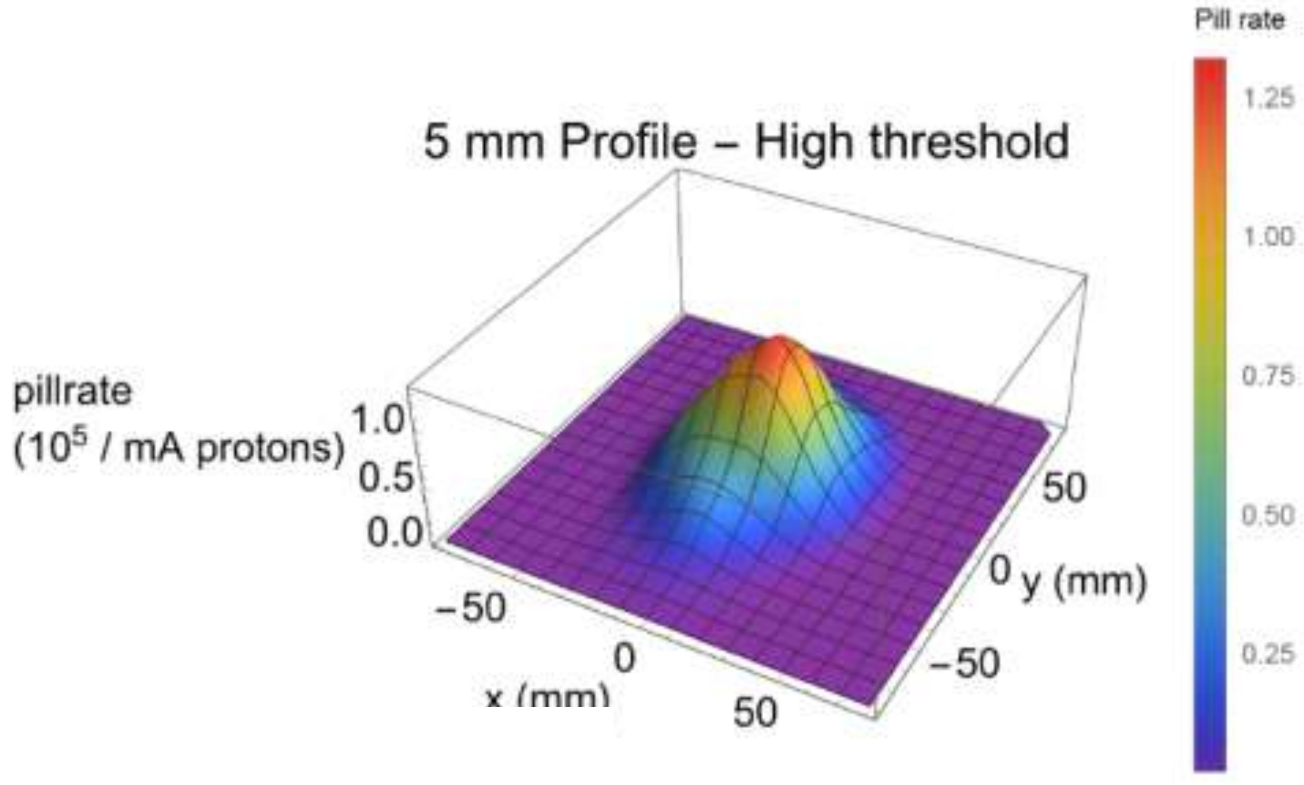




Full analysis performed on Simulated data



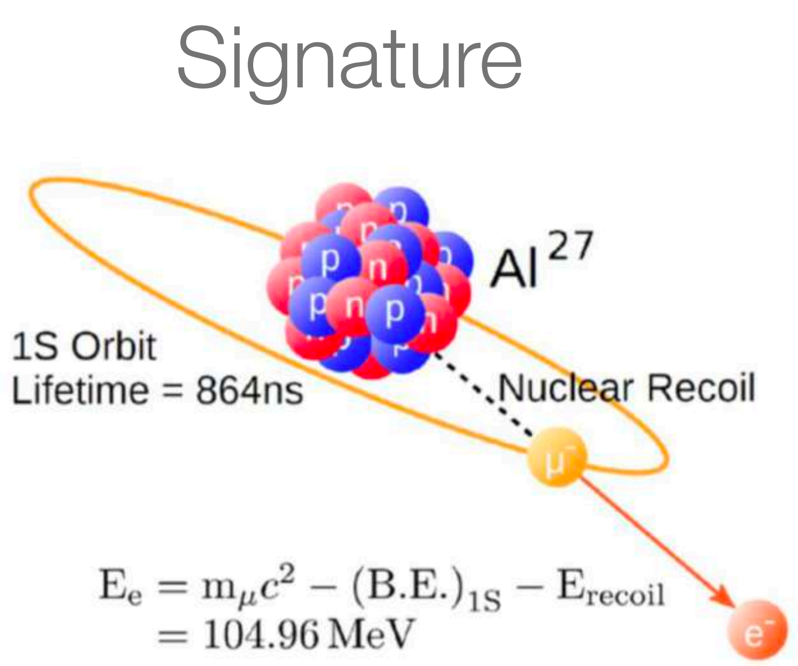
Beam commissioning

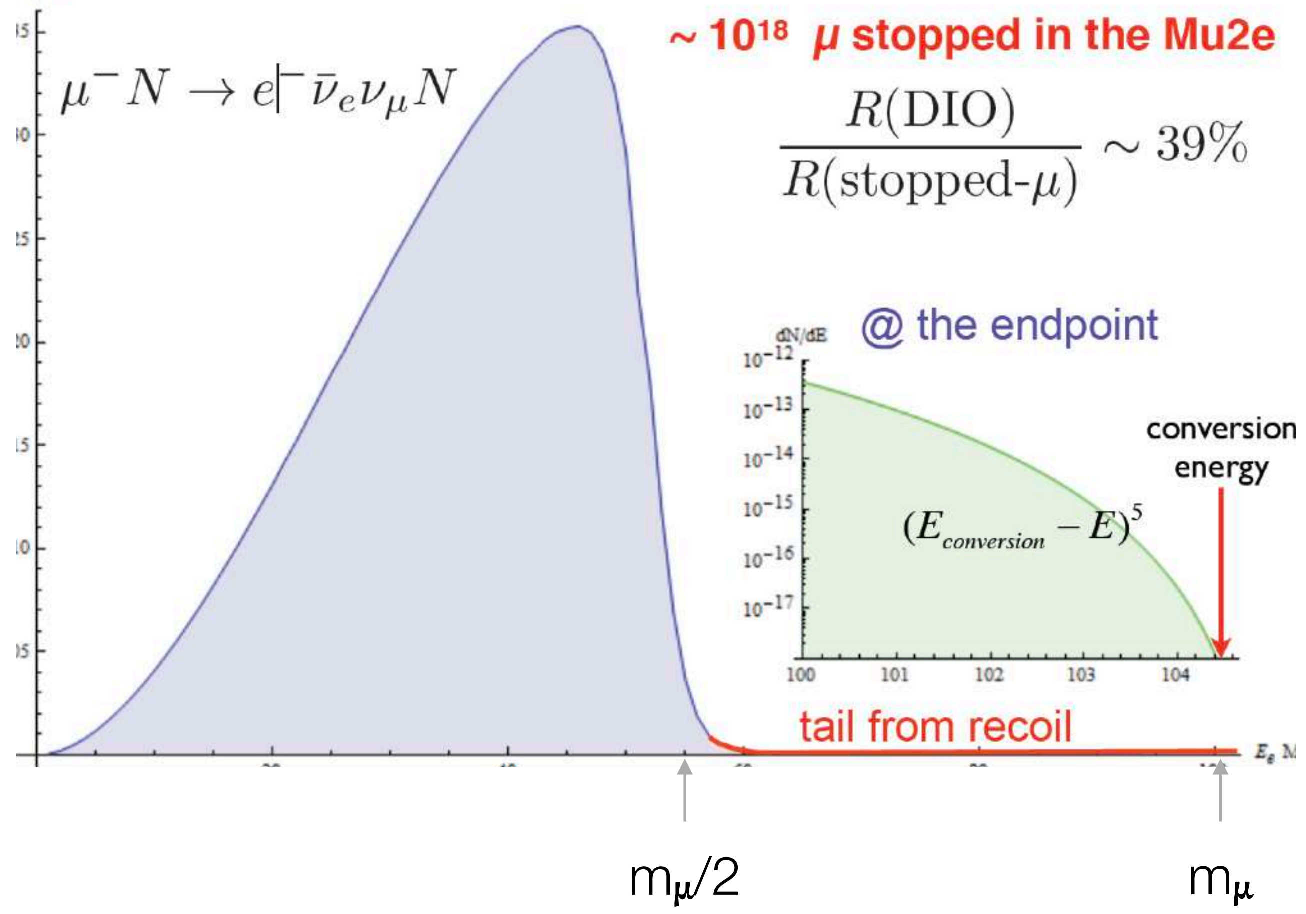


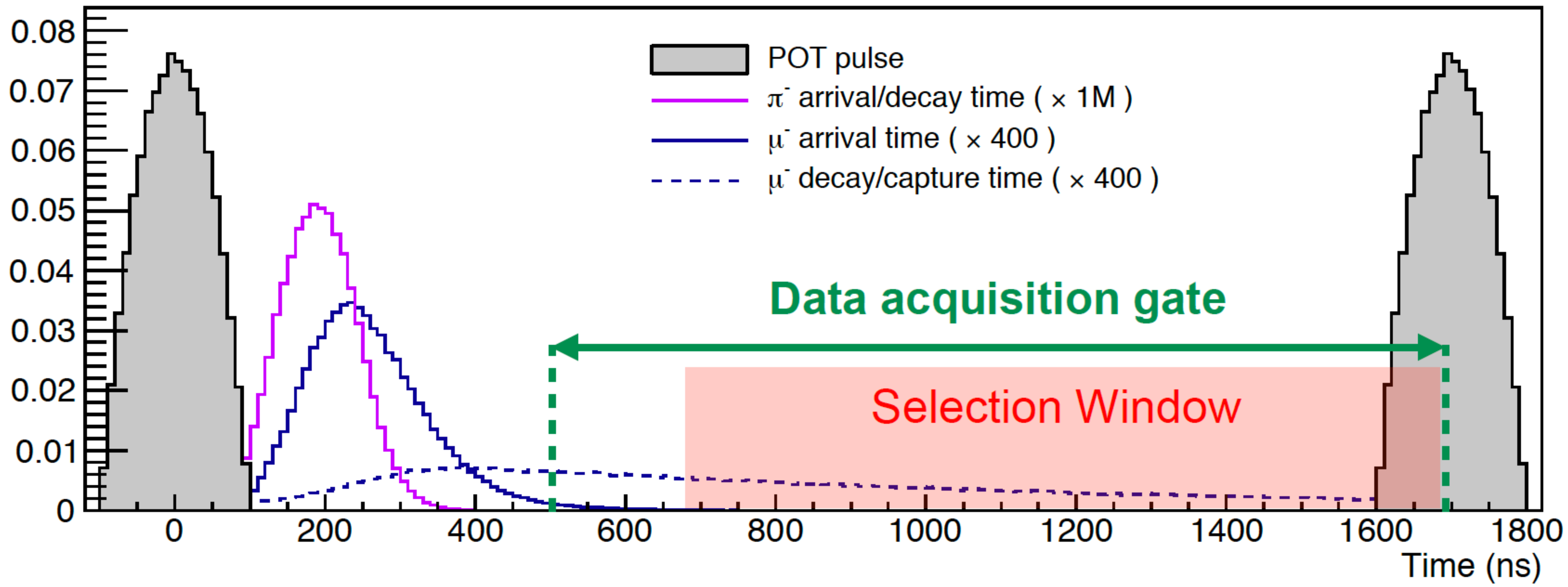
2.49e10⁸ mu/s @2.4 mA

$\mu^- N \rightarrow e^- N$ experiments: general concept

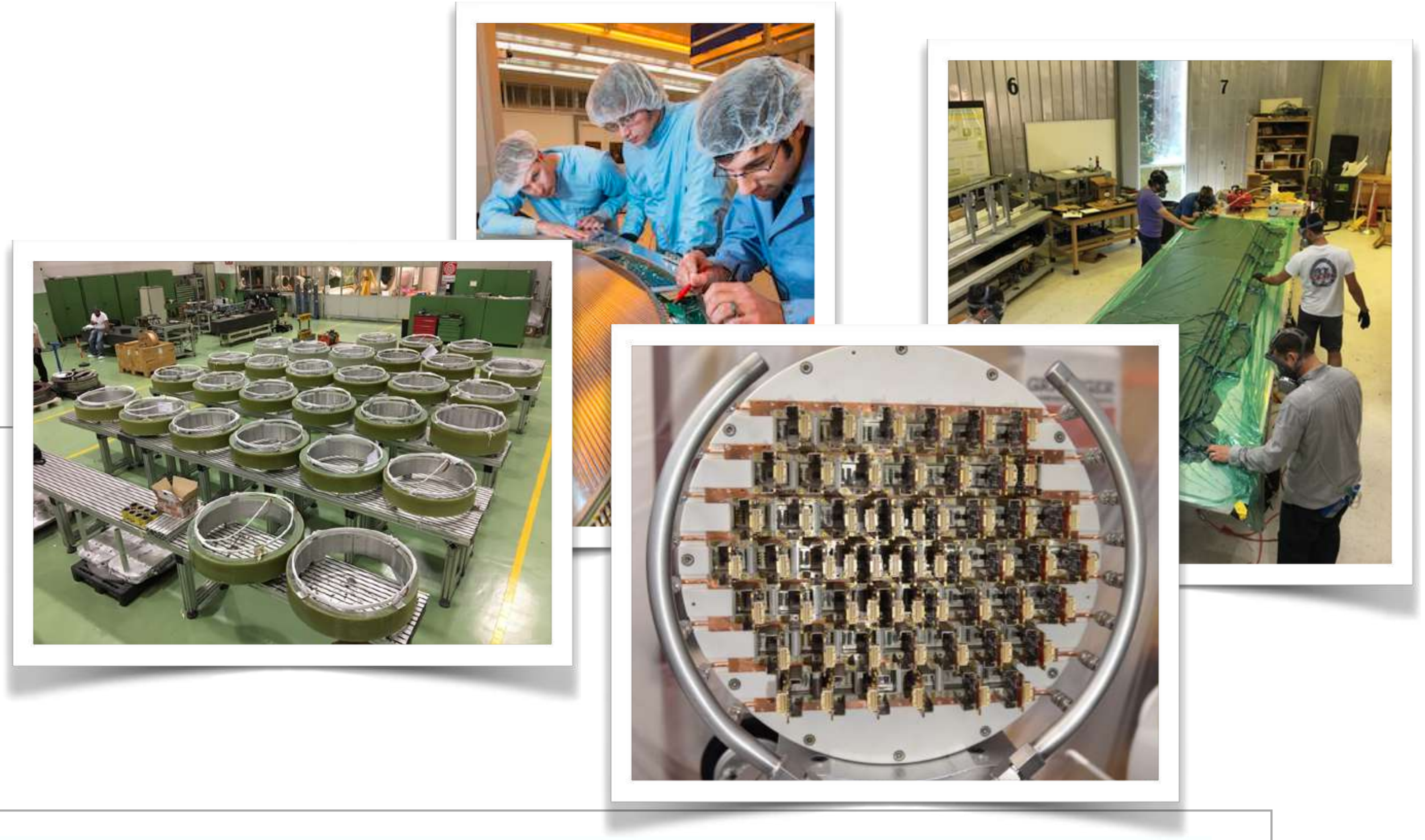
- Signal of mu-e conversion is single mono-energetic electron
- Stop a lot of muons! $O(10^{18})$
- Backgrounds:
  - Beam related, Muon Decay in orbit, Cosmic rays
- Use timing to reject beam backgrounds (extinction factor 10^{-10})
  - Pulsed proton beam 1.7 μs between pulses
  - Pions decay with 26 ns lifetime
  - Muons capture on Aluminum target with 864 ns lifetime
- Good energy resolution and Particle ID to defeat muon decay in orbit
- Veto Counters to tag Cosmic Rays



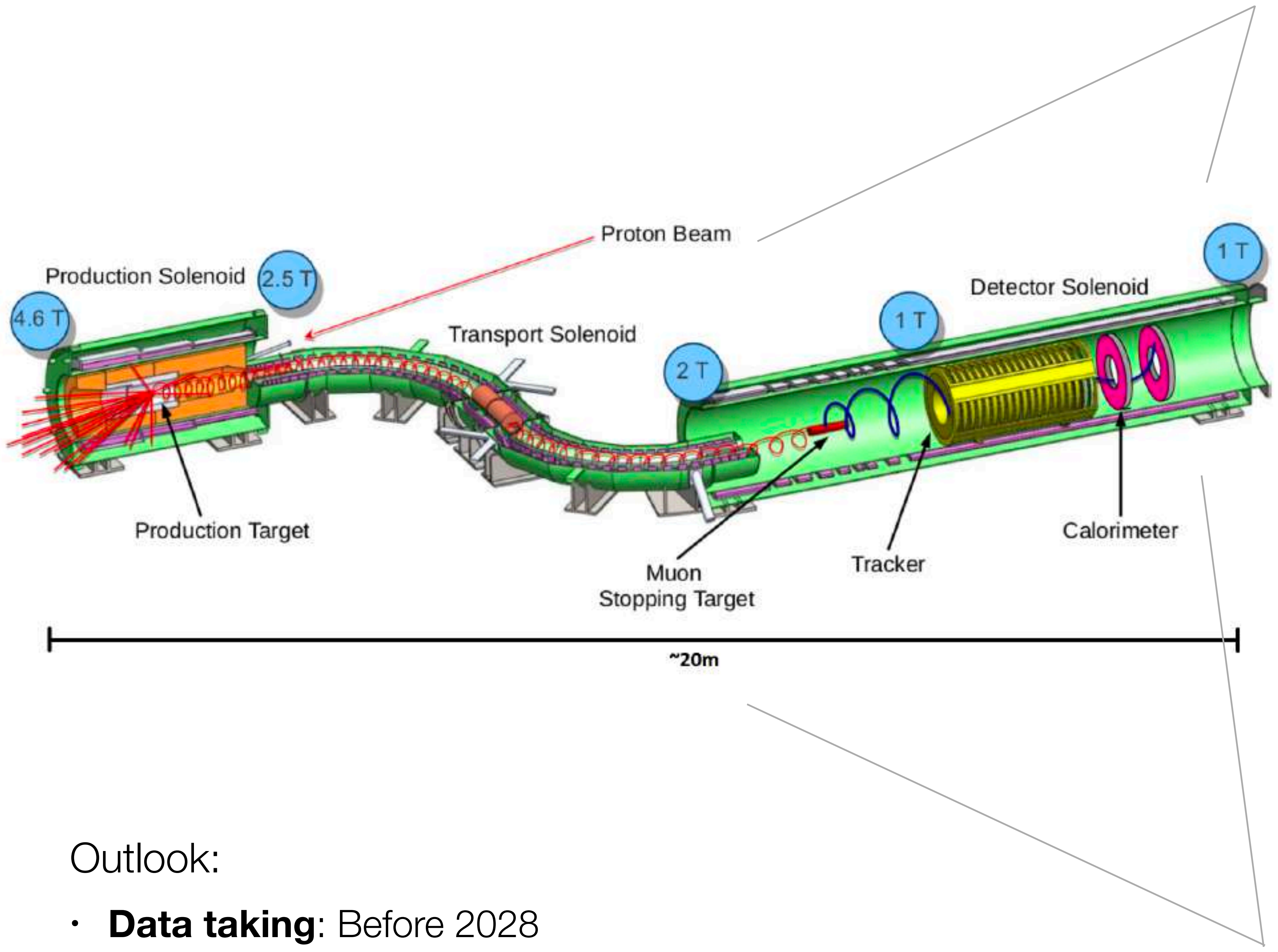


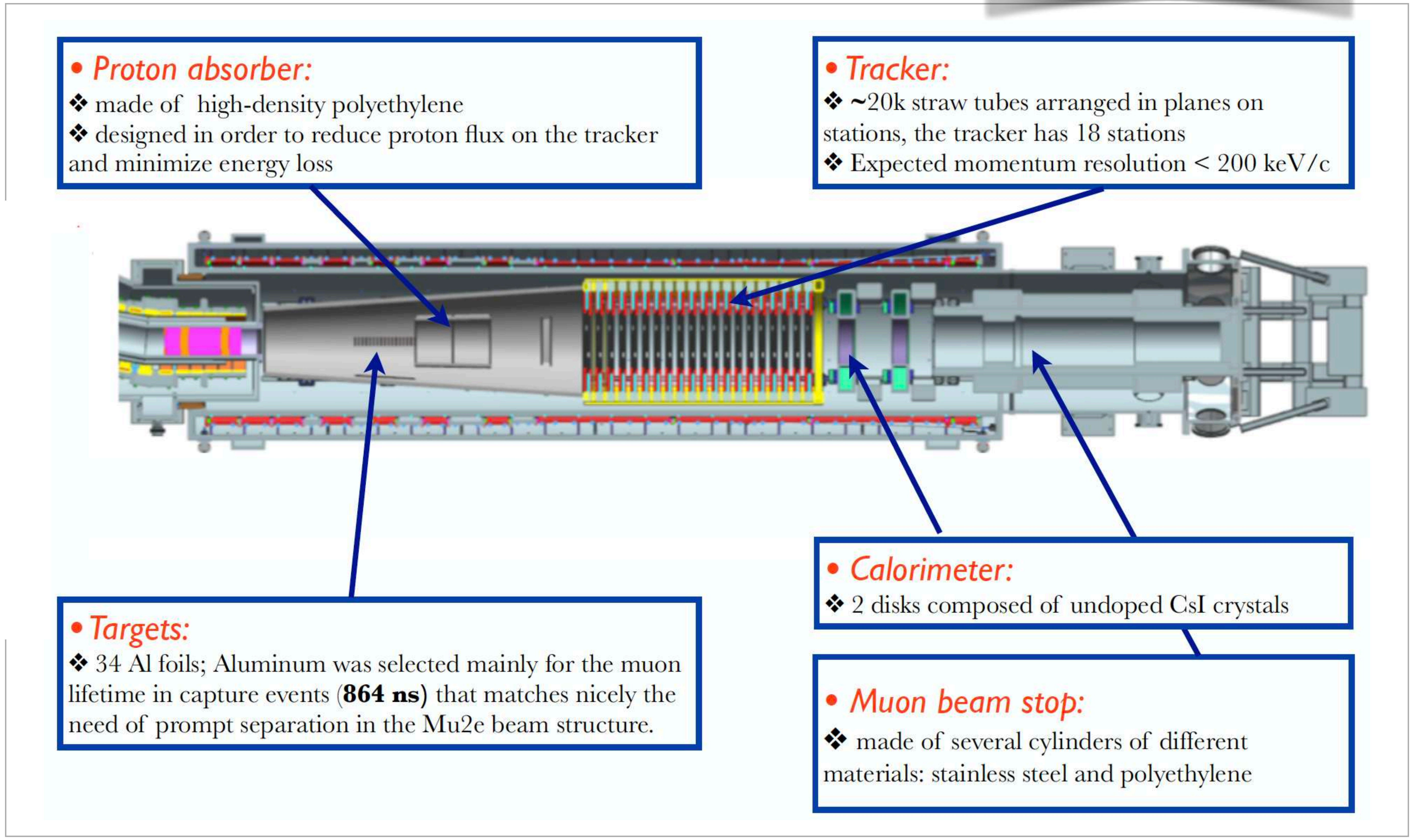


Mu2e: Detector installation ongoing



- The Mu2e experiment aims to search for μ^- N→ e^- N with a final sensitivity of ~10^{-17}
- Previous upper limit BR(μ^- N→ e^- N) ≤ 7 x 10^{-13} @90 C.L. by SINDRUM experiment)



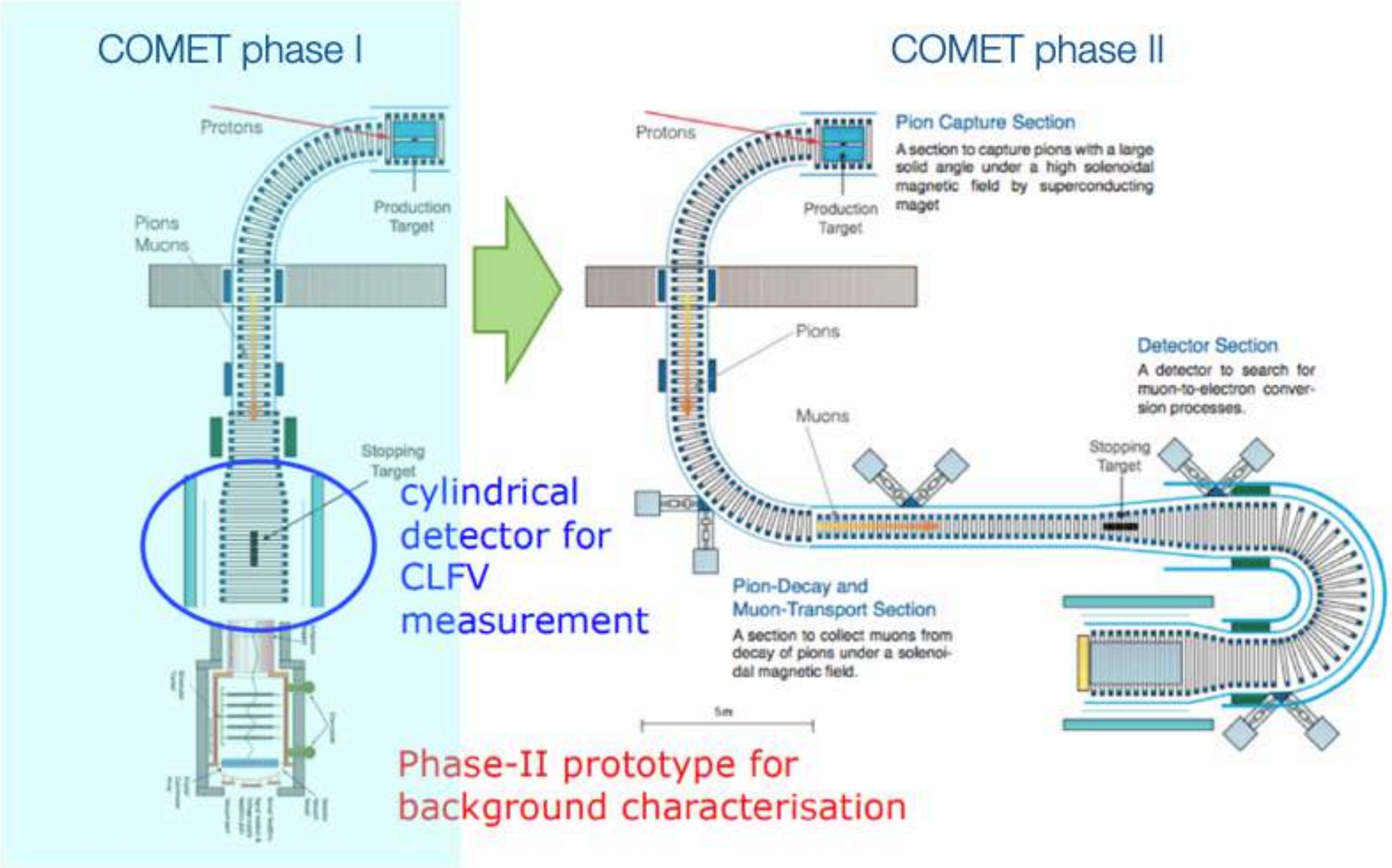


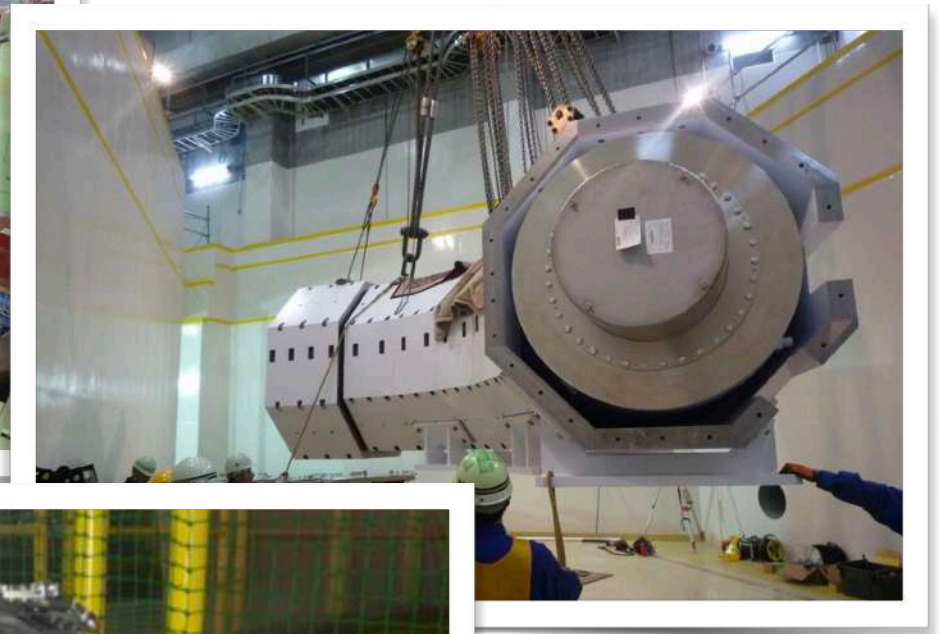
Outlook:

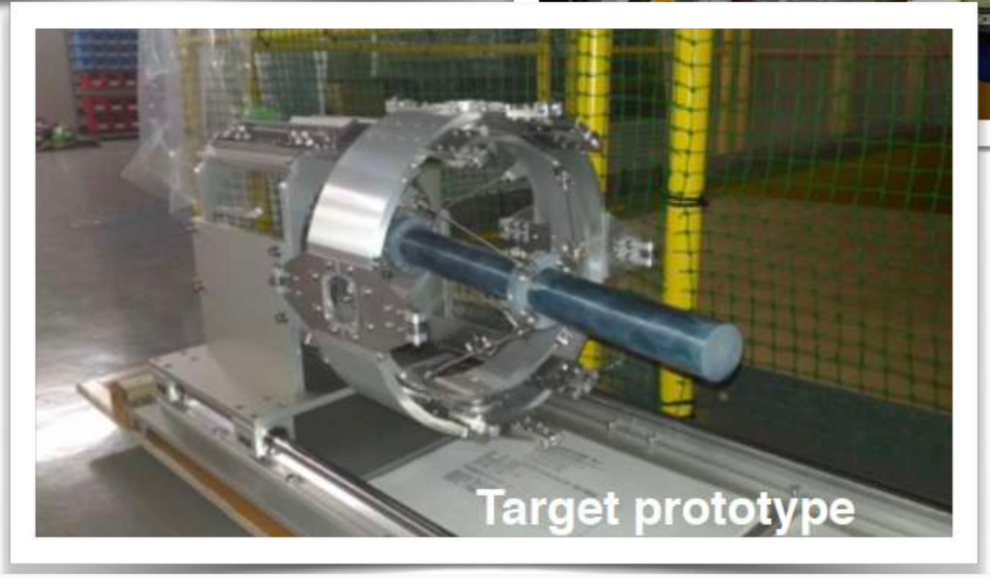
- **Data taking**: Before 2028

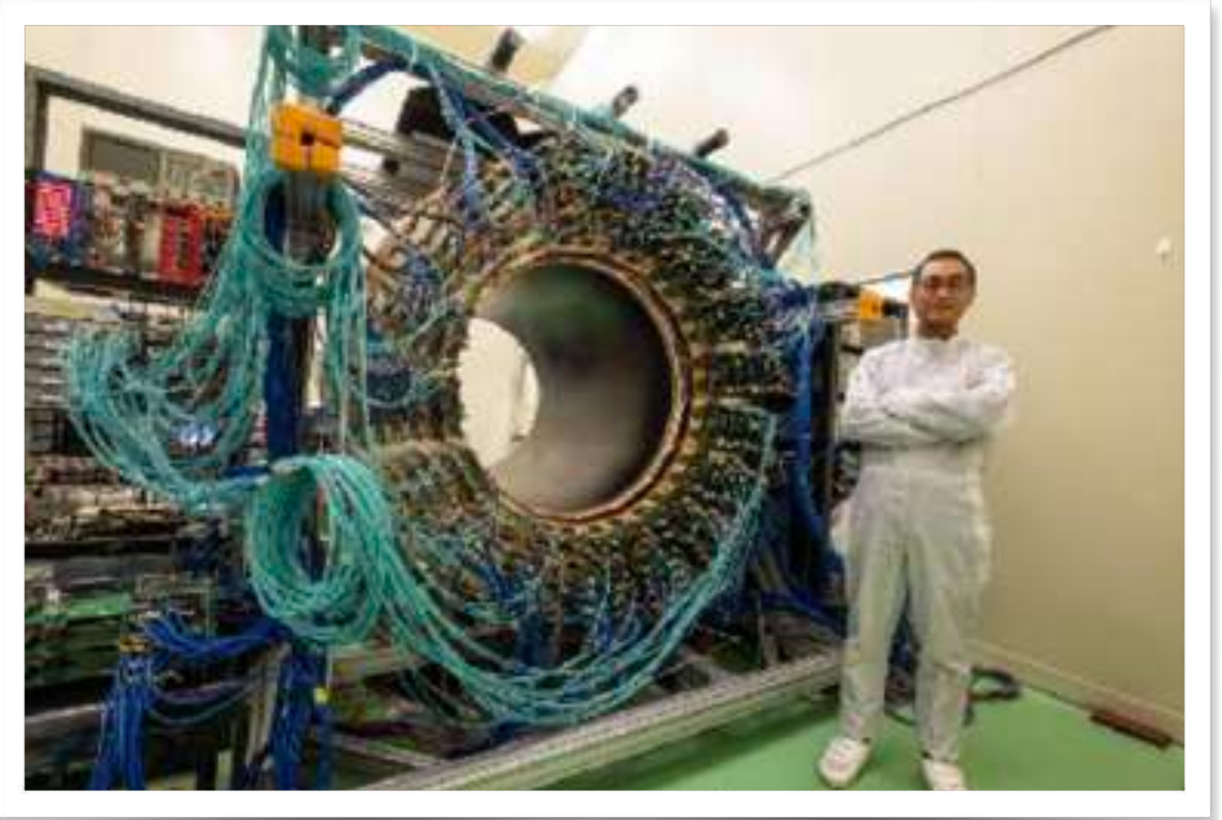
COMET: Preparation in view of the Physics run

- The COMET experiment aims to search for $\mu^- N \to e^- N$ with a final sensitivity of $\sim 10^{-17}$ with a Stage phase approach: Phase I and Phase II
- Previous upper limit $BR(\mu^- N \to e^- N) \leq 7 \times 10^{-13}$ @90 C.L. by SINDRUM experiment)







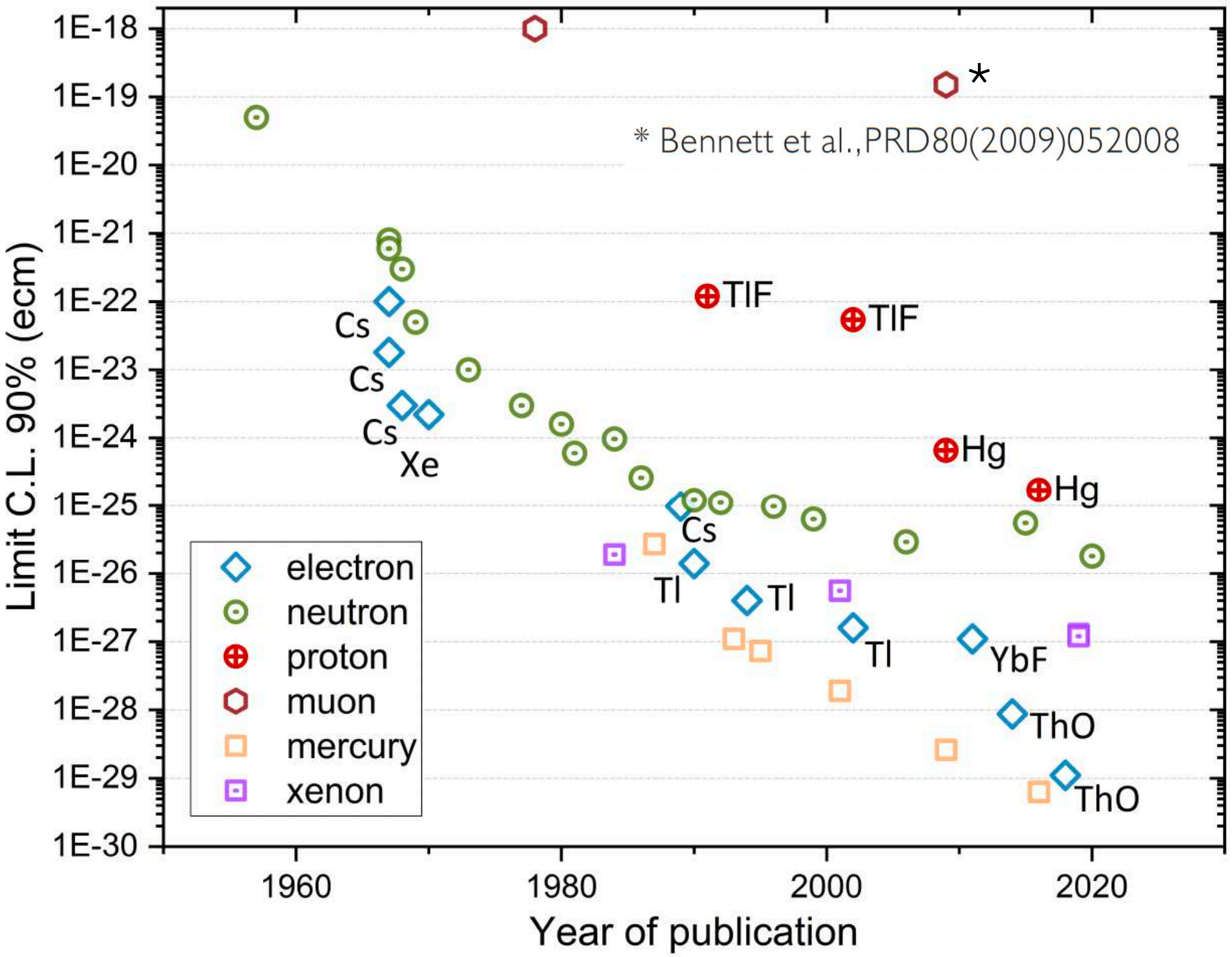


Outlook:

- **Data taking**: By 2026

muEDM dedicated search at PSI: Current status and Motivations

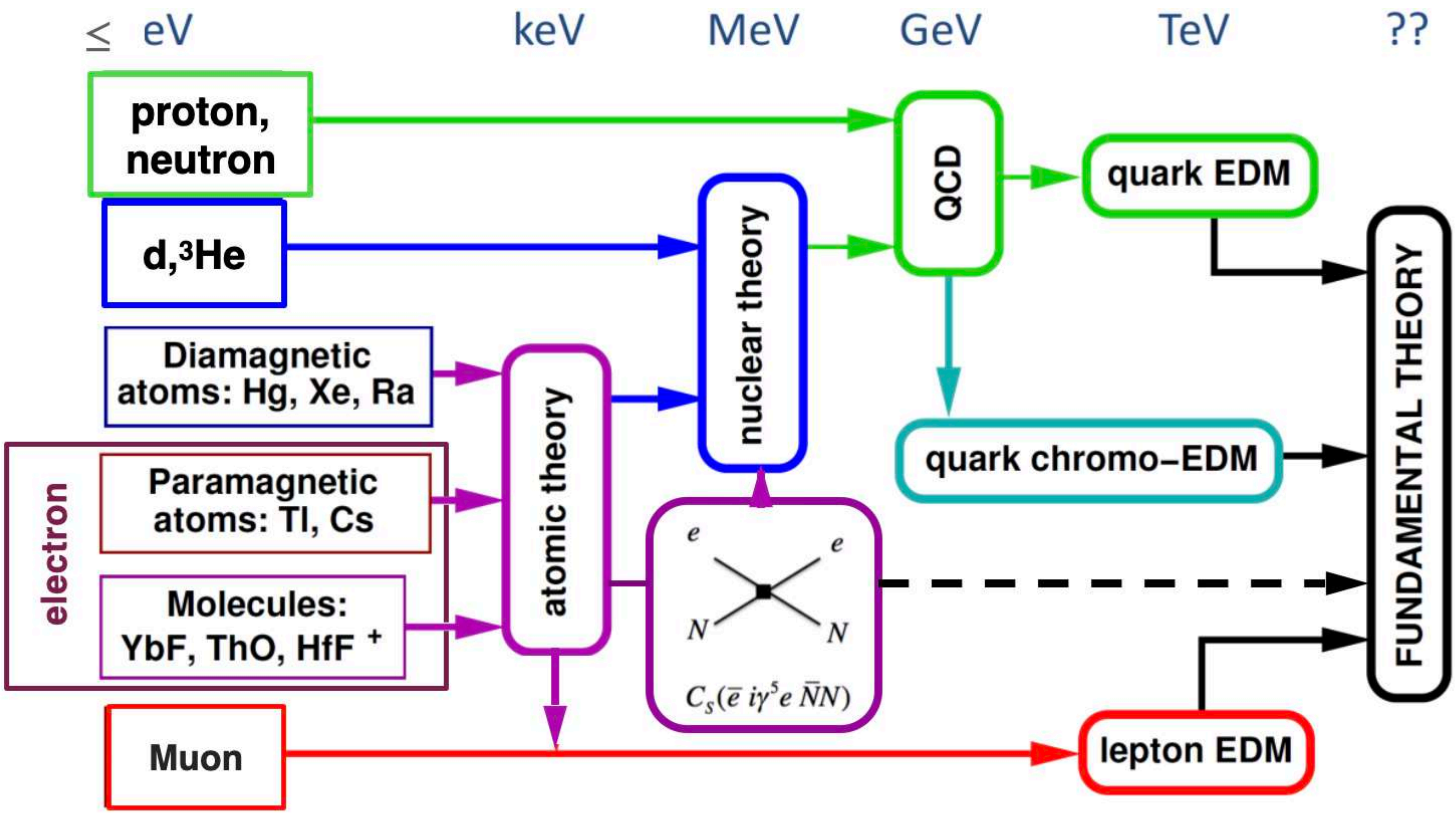
- The different EDM searches are sensitive to **different**, **specific** combinations of underlying **CPV sources**
- **Muon unique** feature: the only currently direct accessible EDM of a **naked** fundamental particle



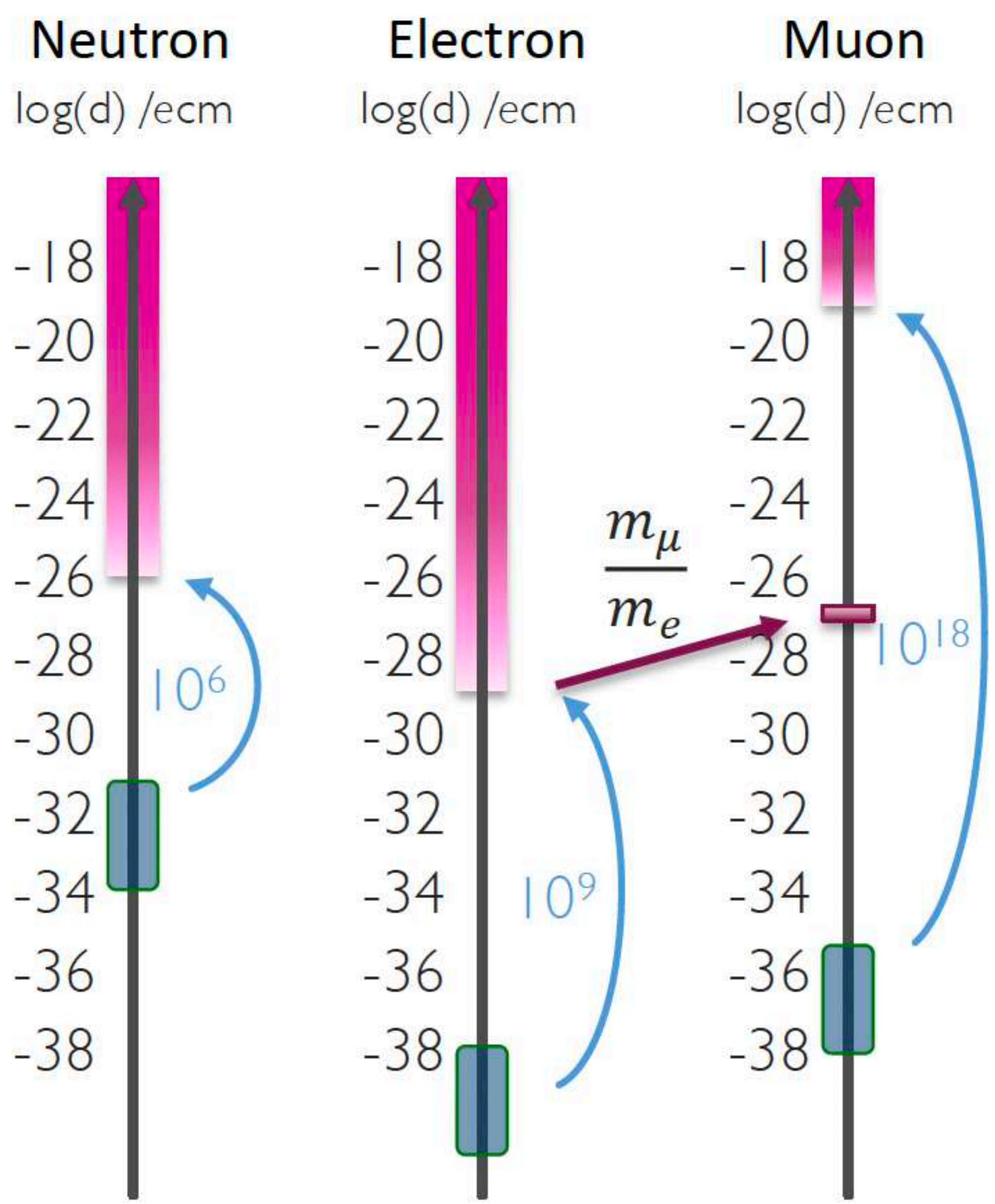
Quite poor current direct limit

d_μ **<1.5×10^{-19} $e$cm (CL 90%)**

Complementarity of EDM searches



muEDM direct search: Why now?



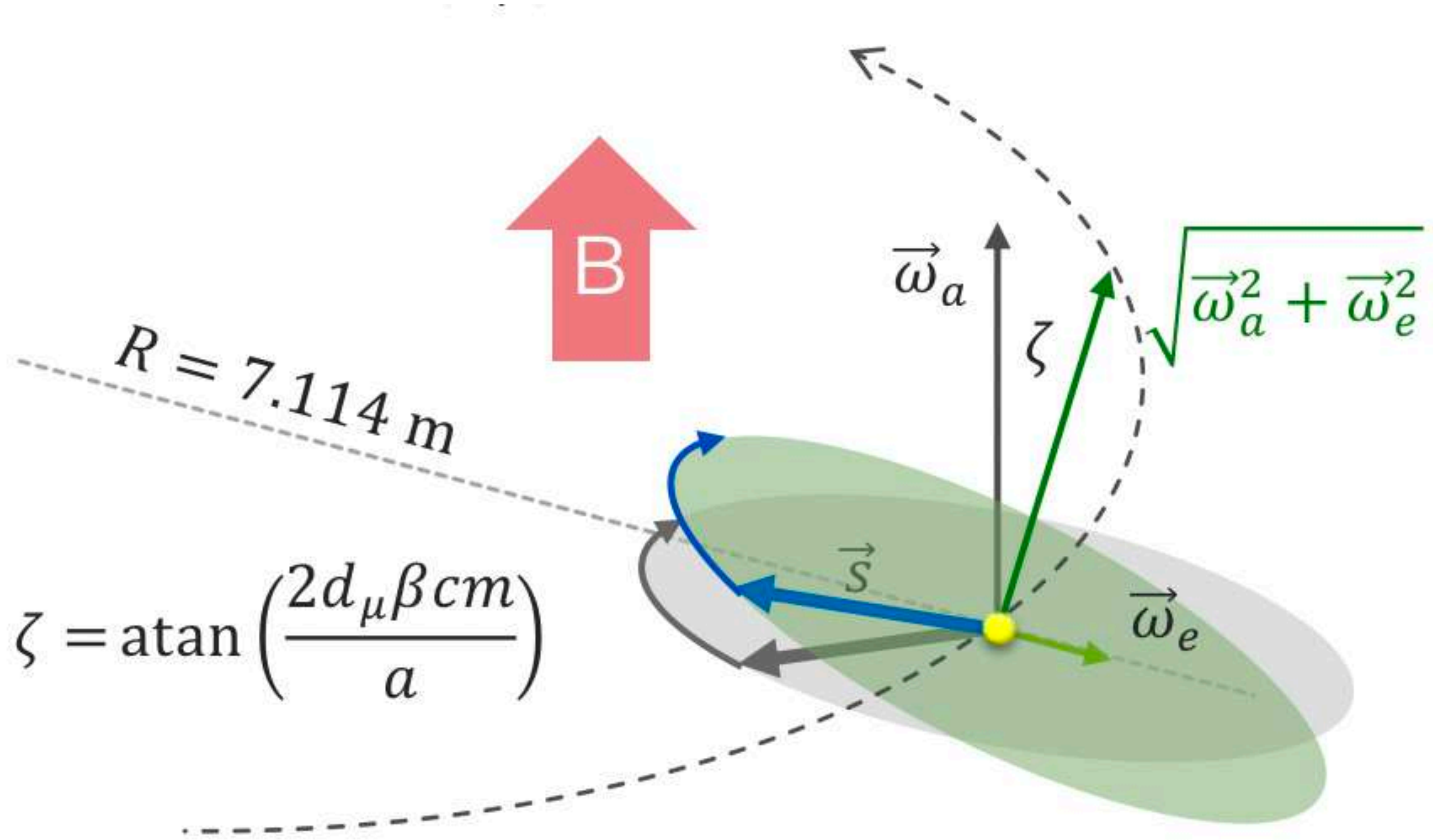
- Impressive limits on the electron EDM deduced from measurements using atoms or molecules, e.g., thorium oxide molecules $d_e <$ 1.1×10^{-29} ecm (CL 90%) lead to $d_\mu < 2.3\times10^{-27}$ ecm (CL 90%), which is many orders of magnitude better than the direct limit d_μ
  - m_μ/m_e naive rescaling assumes minimal flavor violation (MFV), that is a model dependent assumption
- FNAL/JPARC g-2 experiments aims at d_μ ~ $O(10^{-21})$ ecm **(via g-2)**
- **Direct muEDM search at PSI in stages:**
  - **Precursors: $d_\mu < 3\times10^{-21}$ ecm**
  - **Final: $d_\mu < 6\times10^{-23}$ ecm**
- **Proof-of-principle of a complete new experimental technique that can pave the way to other EDM searches**

EDM search: From the “frequency” approach…

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

ω_a ω_e

- 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

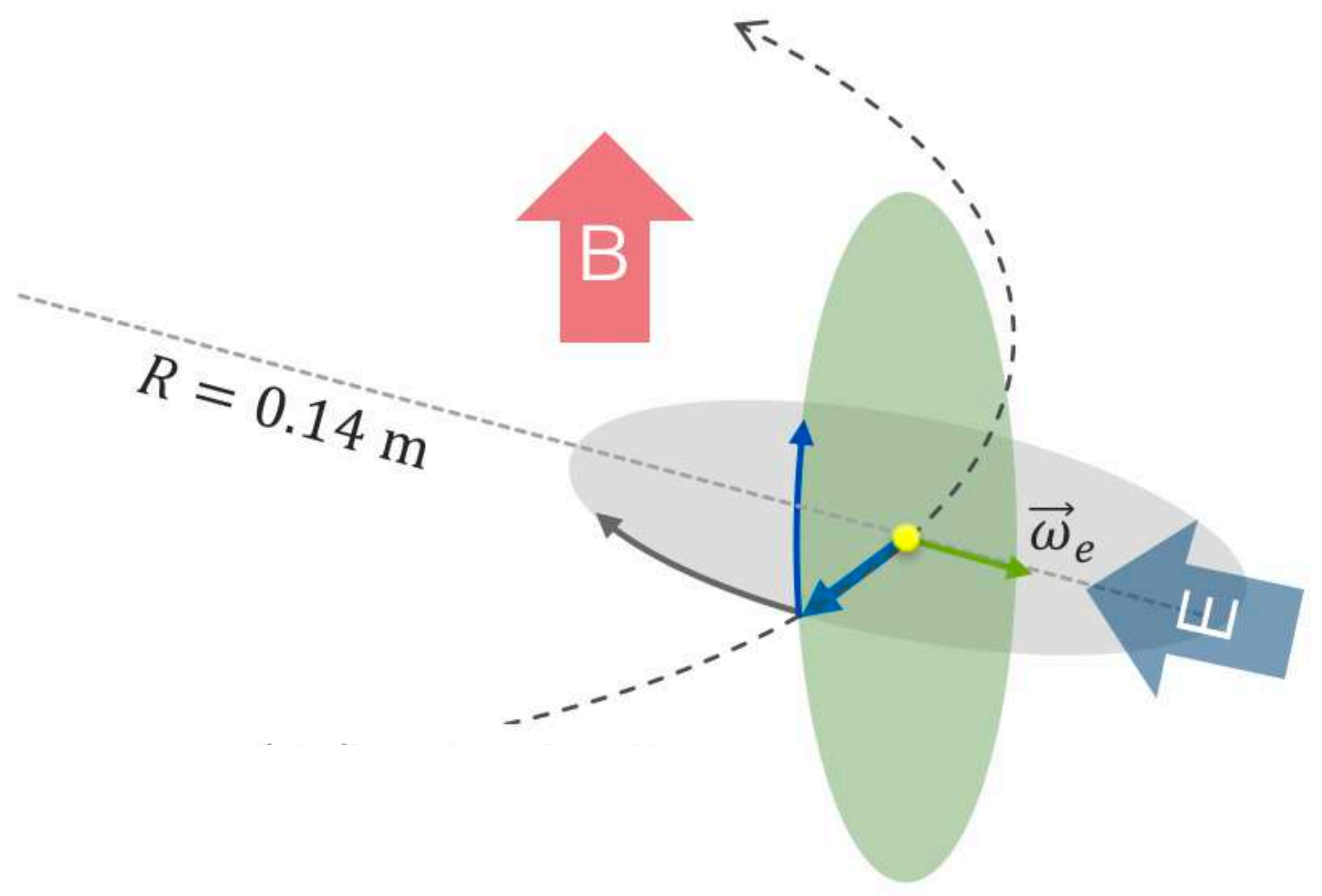
$$\vec{\omega} = \underbrace{\frac{q}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]}_{\omega_a} + \underbrace{\frac{q}{m}\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)}_{\omega_e}$$

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

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

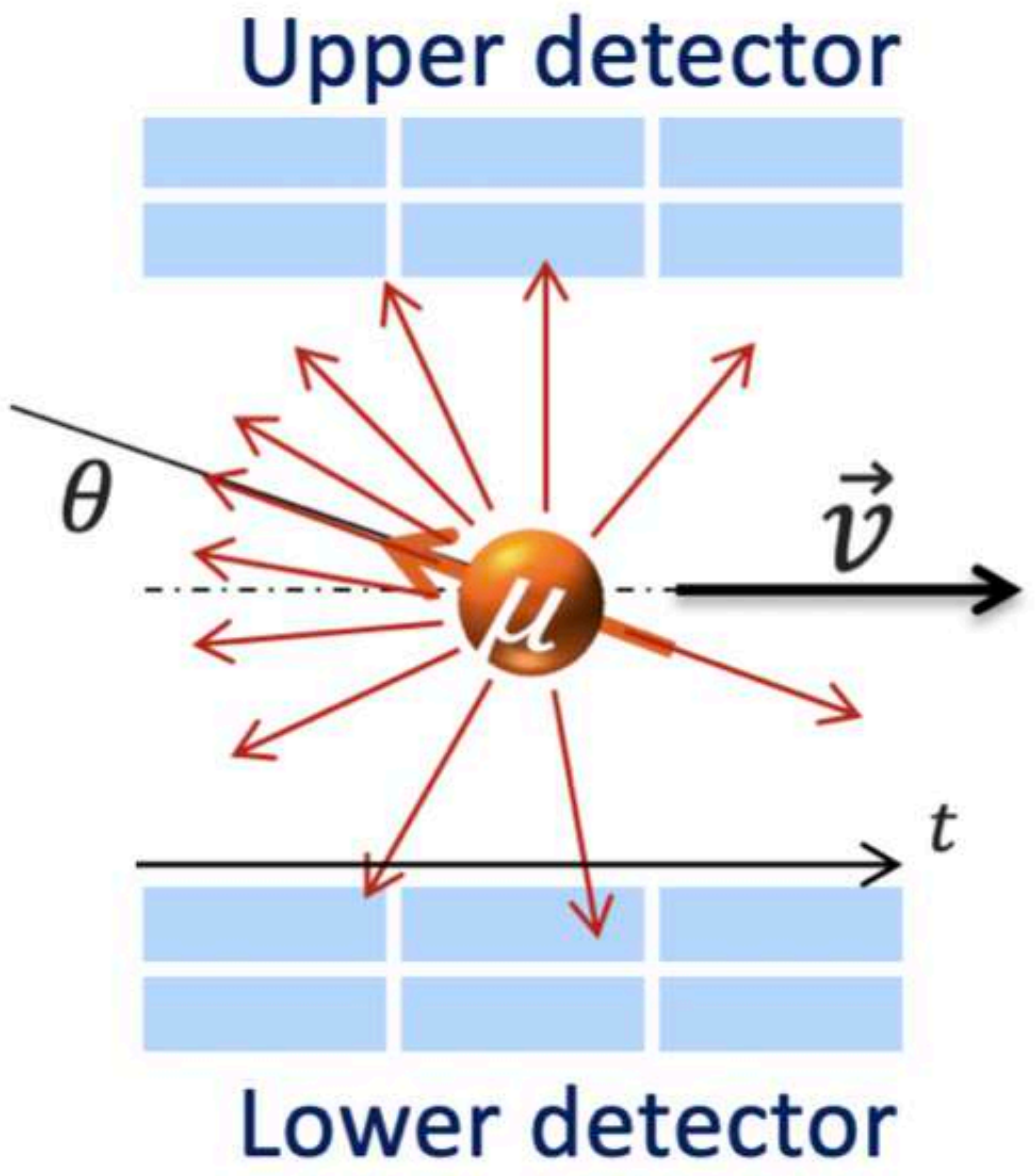
- Without EDM, ω = 0, the spin follows the momentum vector as for an ideal Dirac spin-1/2 particle, while with an EDM it will result in a precession of the spin with $\omega_e \parallel E$

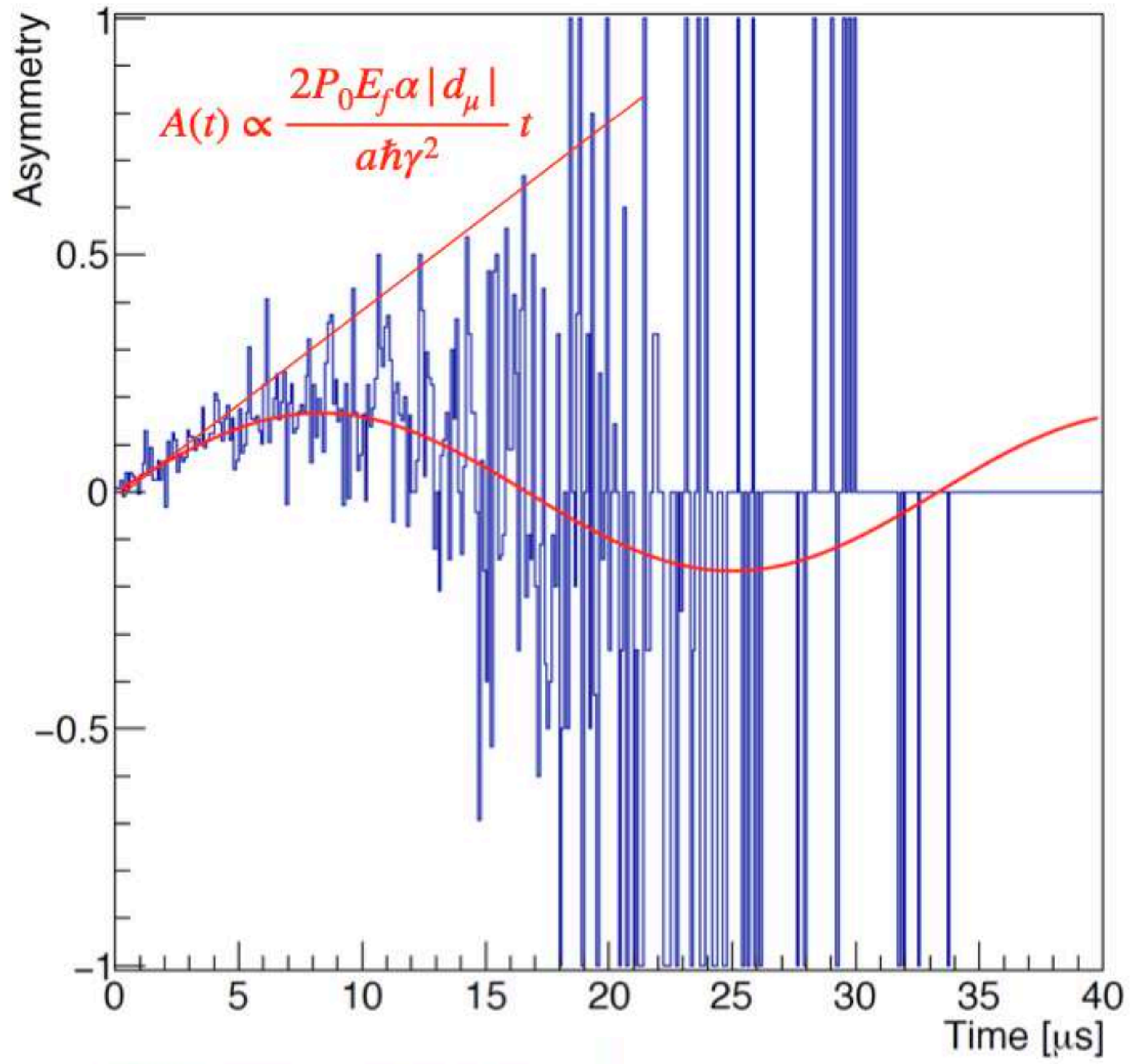
- The sensitivity to a muon EDM is given by the asymmetry up/down of the positron from the muon decay



Signal: asymmetry up/down positron tracks

- Positron are emitted predominantly along the muon spin direction
- The sensitivity to muon EDM is extracted from the **asymmetry up/down** of the **positron** from the muon decay, averaged over the muon decay time distribution (lifetime = $\gamma\tau_\mu$)





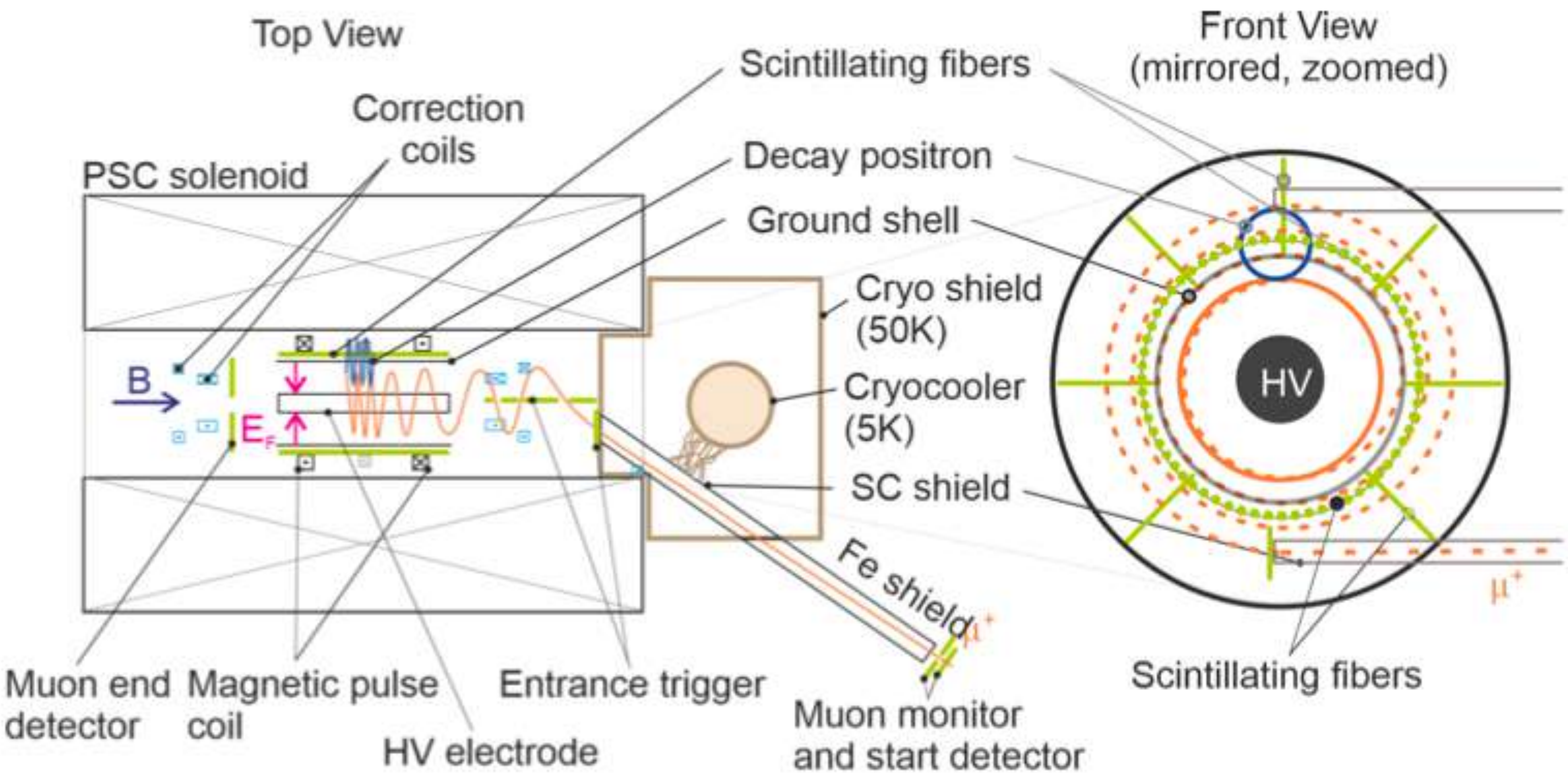
- P_0 = initial muon polarisation
- E_f = electric field in the lab frame
- N = number of observed decays
- τ_μ = muon lifetime
- α = mean decay asymmetry (~ 0.3)
- a = anomalous magnetic moment
- γ = gamma factor of the muon

$$A(t) = \frac{N_\uparrow(t) - N_\downarrow(t)}{N_\uparrow(t) + N_\downarrow(t)} \propto \frac{2P_0E_f\alpha|d_\mu|}{a\hbar\gamma^2}t$$

$$\sigma(|d_\mu|) = \frac{d|d_\mu|}{d\bar{A}}\sigma(\bar{A}) \sim \frac{a\hbar\gamma}{2P_0E_f\sqrt{N}\tau_\mu\alpha}$$

The general experimental idea

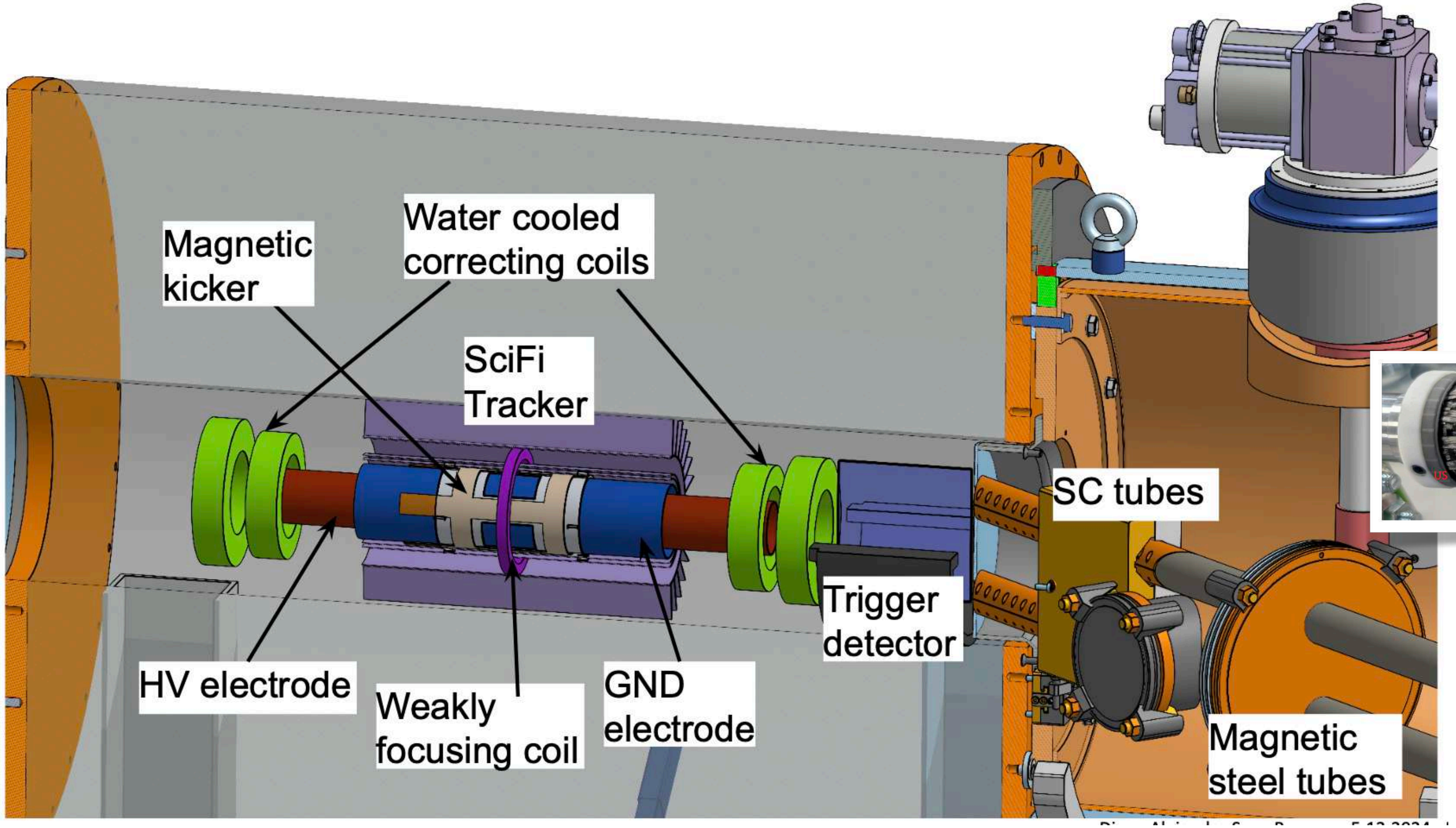
- Muons enter the **uniform magnetic** field region via **SC injection lines. Correction coils** are used to increased the storage efficiency
- A **radial magnetic** field pulse stops them within **a weakly focusing** where they are **stored**
- **Radial electric** field **“freezes” the spin** so that the precession due to the magnetic dipole moment is cancelled

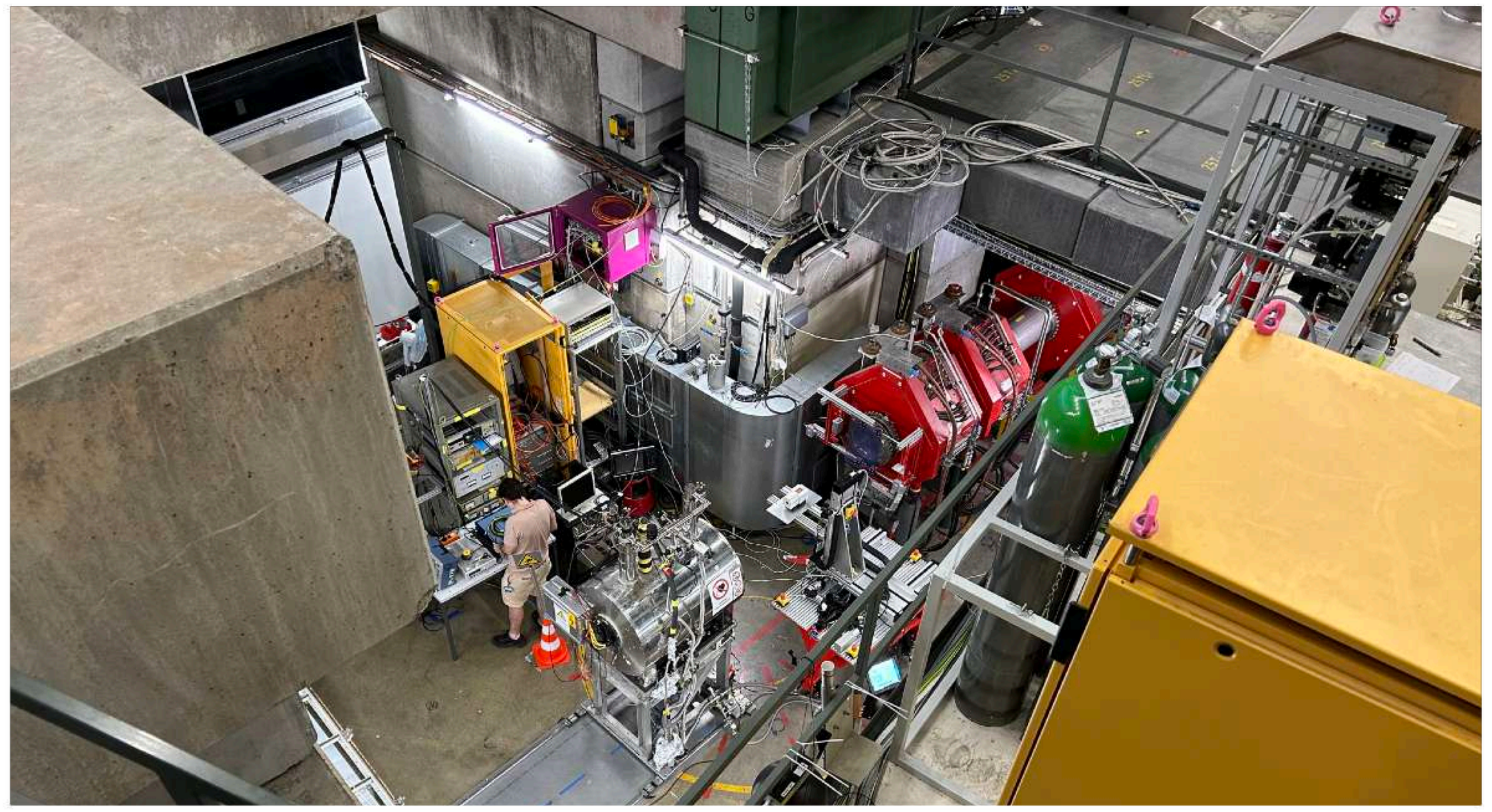


https://arxiv.org/html/2501.18979v1

Where muEDM is: Integration phase

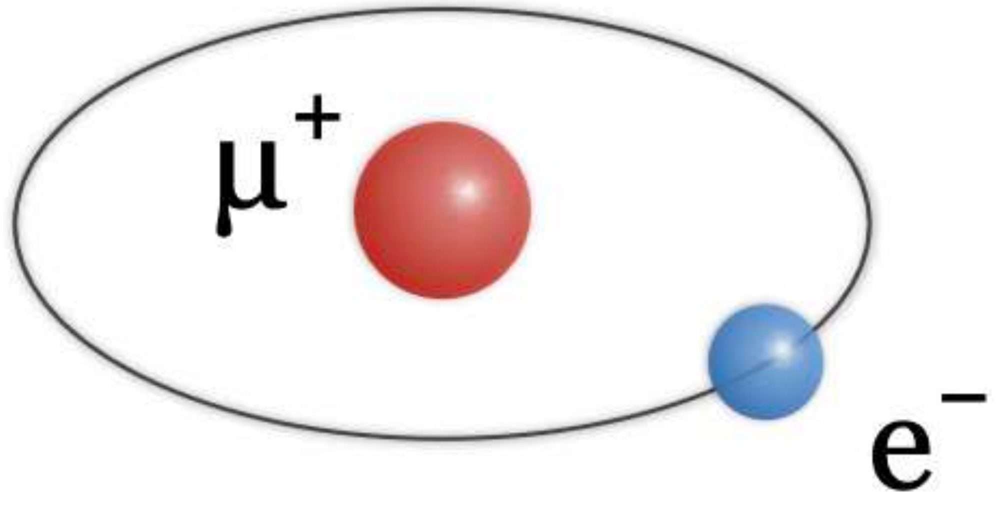
- Proof-of-principle of the frozen-spin technique and start of data taking by the end of 2026

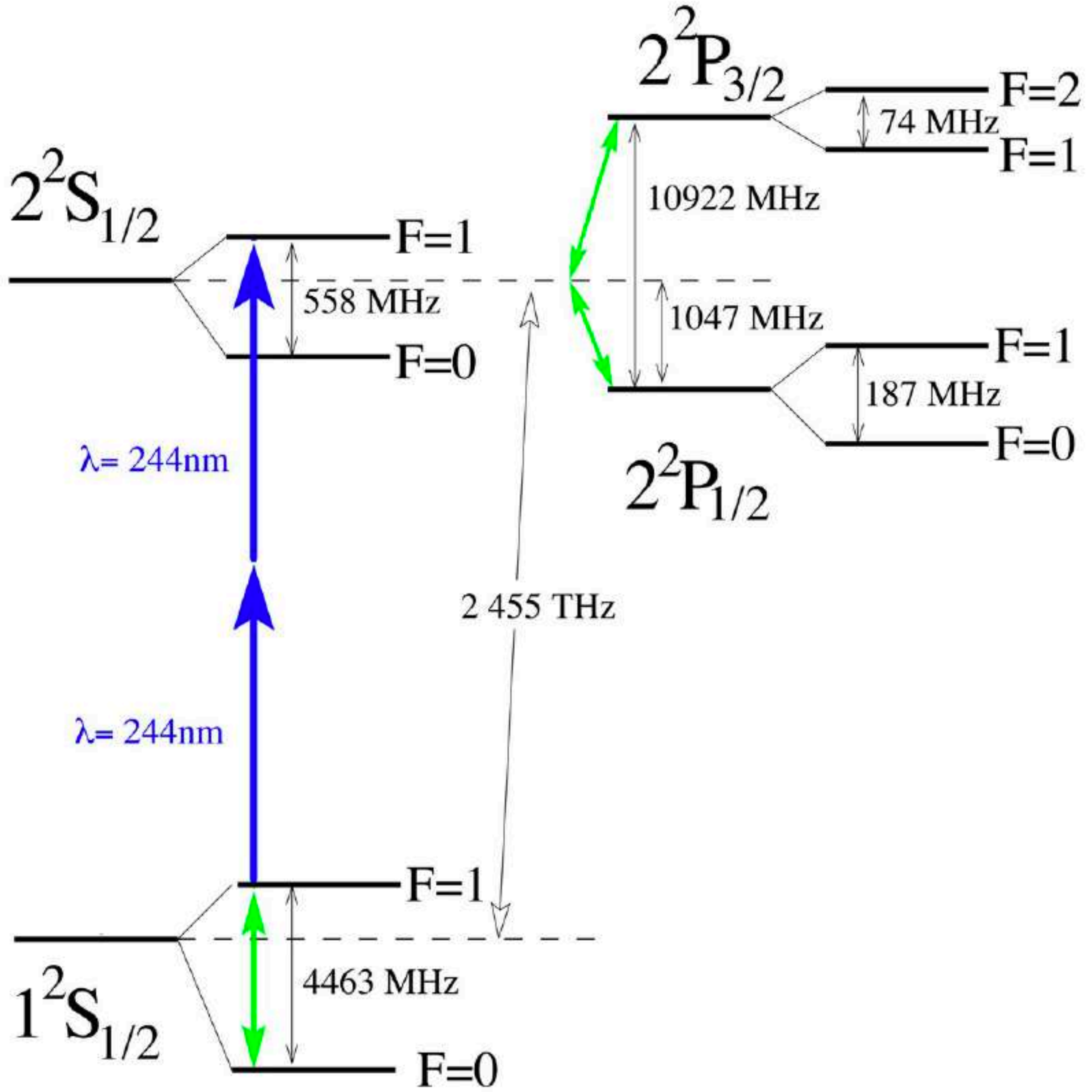




Muonium physics

- 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!

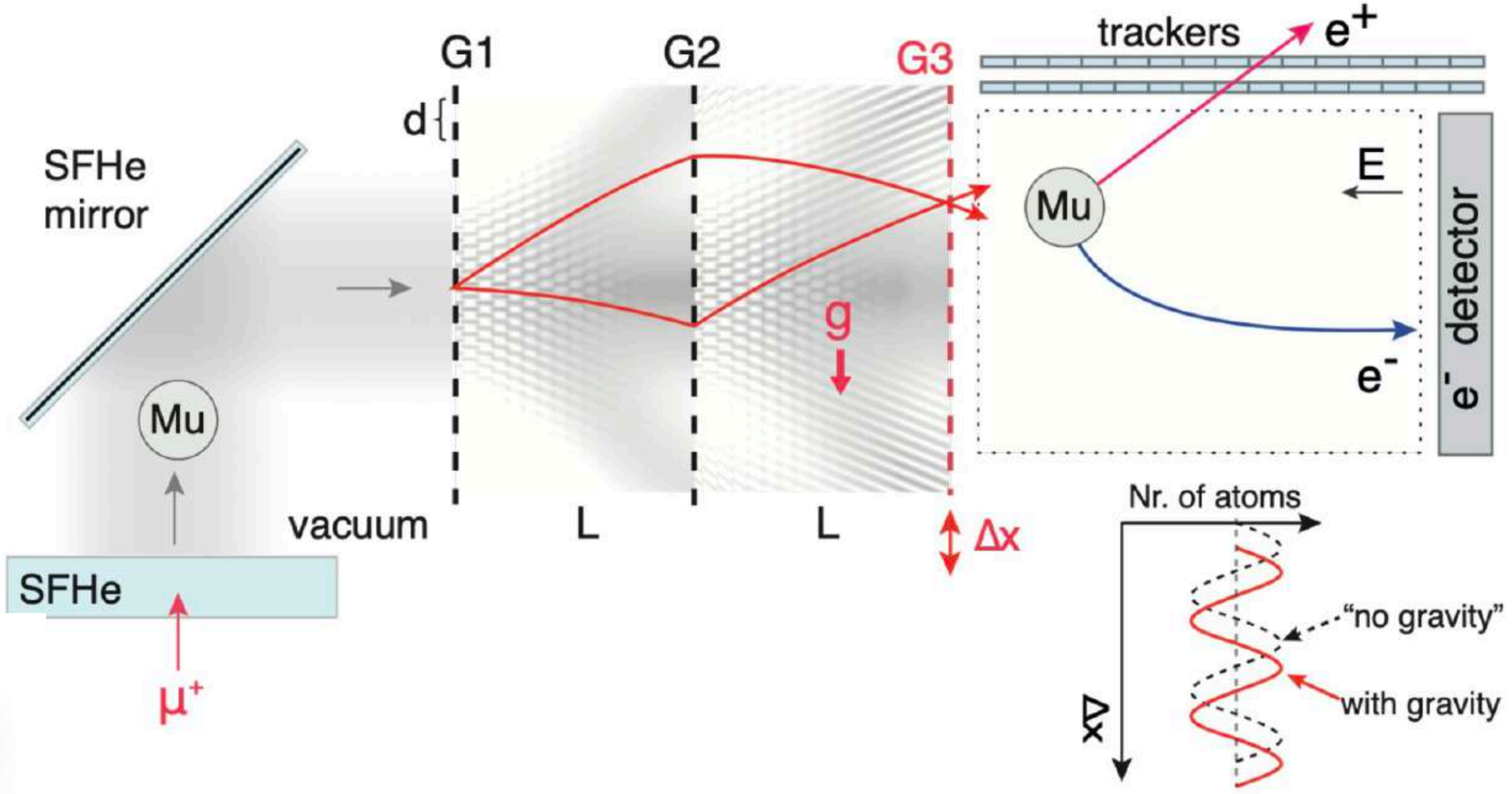




LEMING at PSI: Muonium gravity

- 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

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 complementary to the energy frontier research program**
- Achieving such remarkable sensitivity requires both **advanced beamlines**—operating in either continuous or pulsed mode—and the development of **new detector technologies**. The emergence of next-generation beamlines at PSI, Fermilab, and J-PARC underscores the growing importance and global commitment to this research area and stimulates new projects

Thanks a lot for your attention !!!

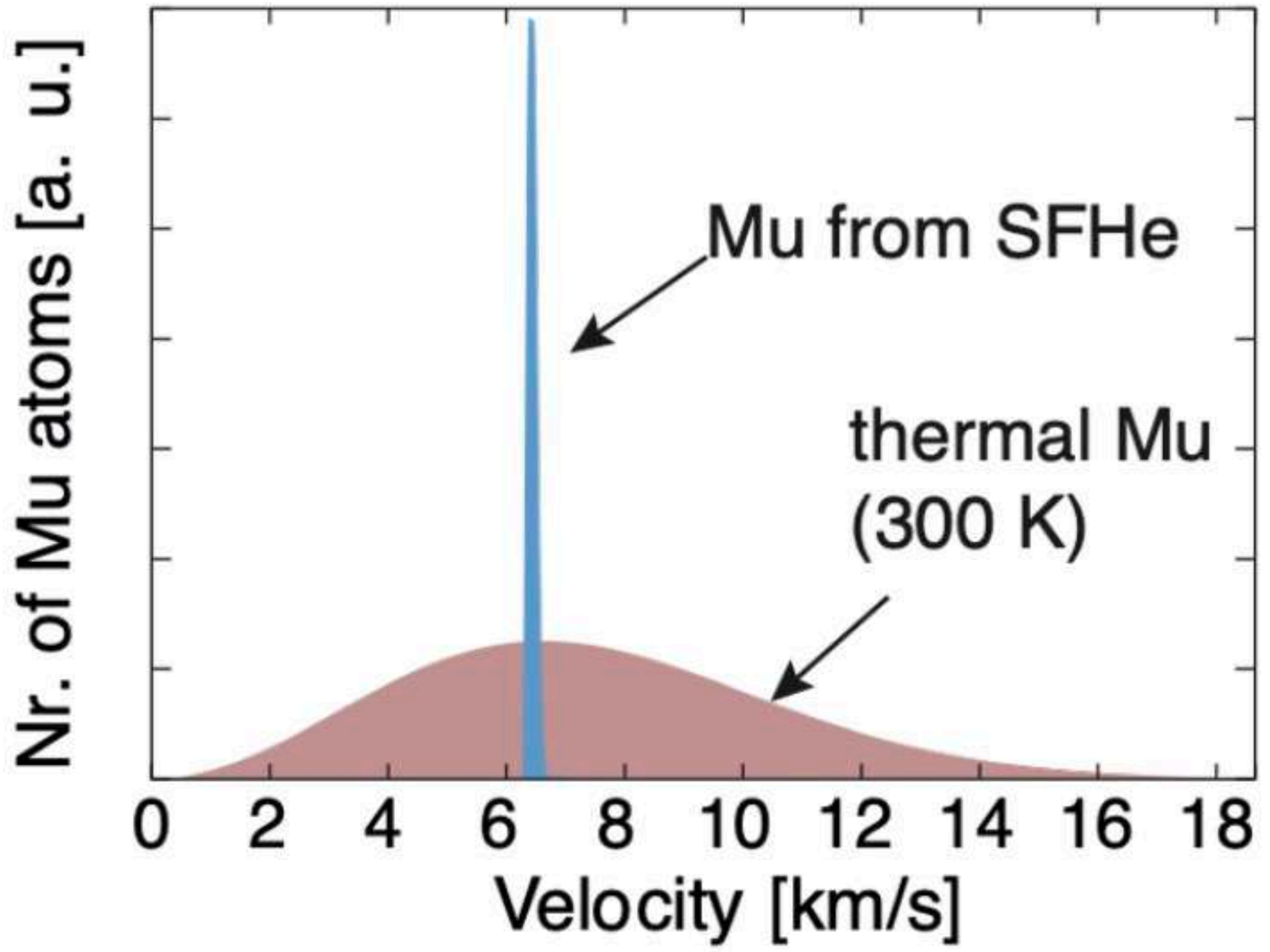
Back-up

Muon beams worldwide summary

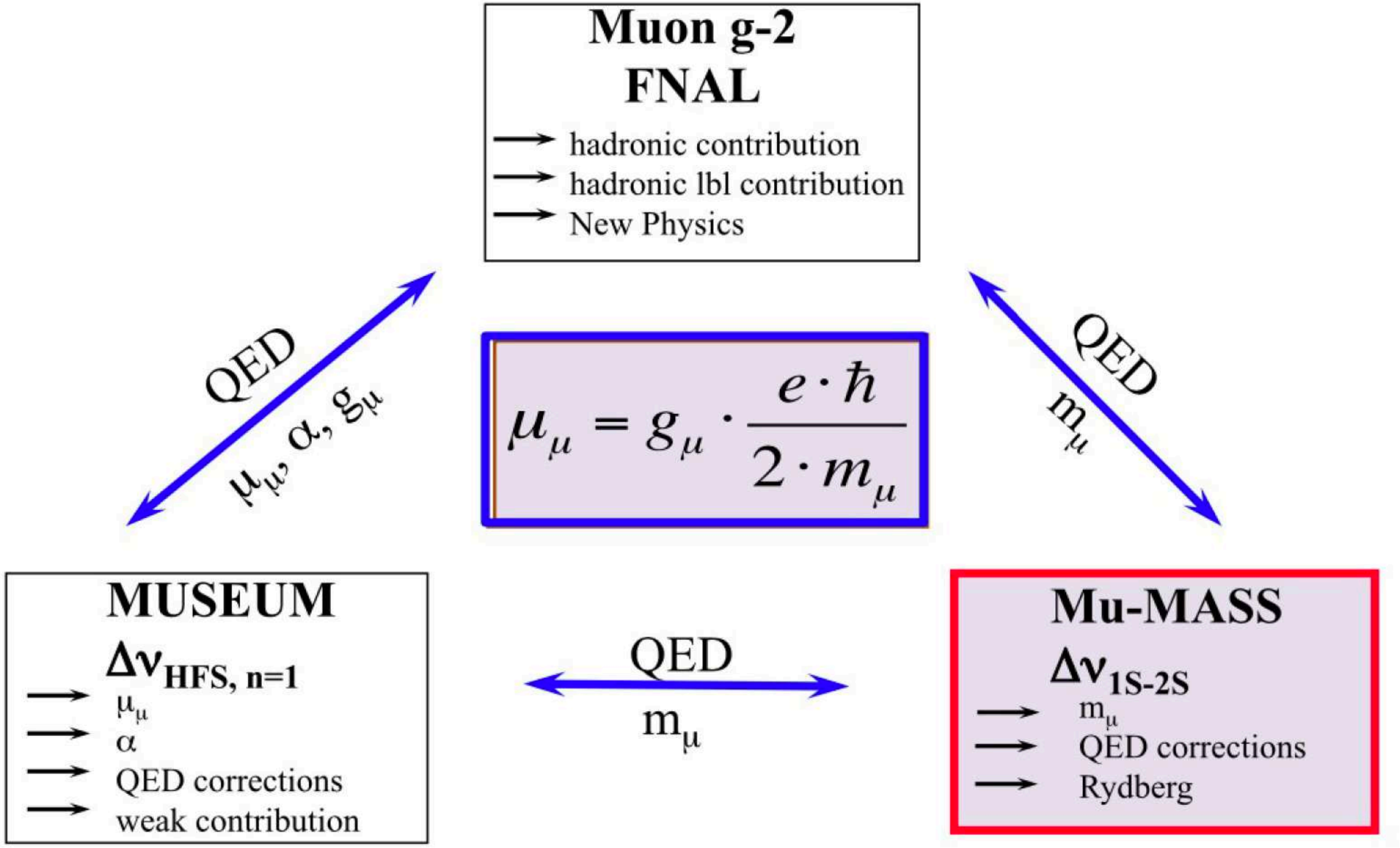
Laboratory	Beam Line	DC rate (μ/sec)	Pulsed rate (μ/sec)
PSI (CH) (590 MeV, 1.3 MW)	$\mu E4, \pi E5$ HiMB at EH	$2 \div 4 \times 10^8$ (μ^+) $\mathcal{O}(10^{10})$ (μ^+) (>2018)	
J-PARC (Japan) (3 GeV, 210 kW) (8 GeV, 56 kW)	MUSE D-Line MUSE U-Line COMET		$3 \times 10^7 (\mu^+)$ $6.4 \times 10^7 (\mu^+)$ $1 \times 10^{11} (\mu^-)$(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)	

Muonium production

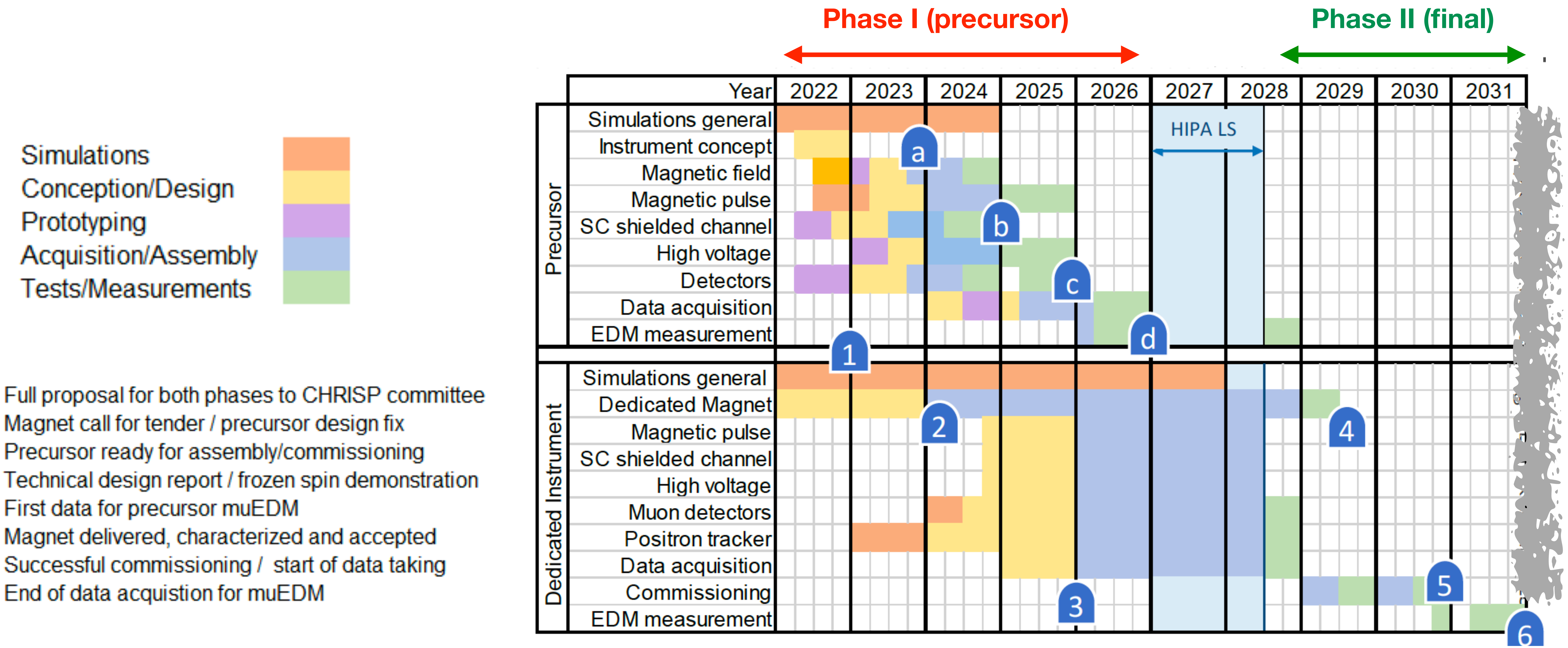
- Stop (nearly!) a positive muon beam in a target in vacuum; some of the muonium will be ejected into the vacuum space
- J-PARC g-2 plans to utilize laser ablated silica aerogel
  - This yields of order 1% muonium in vacuum, with thermal momentum distribution
  - Thermal Mu requires cooling for beam 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



muEDM schedule



1 Full proposal for both phases to CHRISP committee
2/a Magnet call for tender / precursor design fix
b Precursor ready for assembly/commissioning
3/c Technical design report / frozen spin demonstration
d First data for precursor muEDM
4 Magnet delivered, characterized and accepted
5 Successful commissioning / start of data taking
6 End of data acquistion for muEDM

Signal: asymmetry up/down positron tracks

- Positron are emitted predominantly along the muon spin direction
- The sensitivity to muon EDM is extracted from the **asymmetry up/down** of the **positron** from the muon decay, averaged over the muon decay time distribution (lifetime = $\gamma\tau_\mu$)

Final muEDM Experiment Sensitivity

μE1 Beamline Flux $2 \times 10^8 \mu^+/s$

Momenta $\gamma = 1.55$

Polarisation $P_0 \approx 0.95$

Av. Decay Asymmetry $A \approx 0.3$

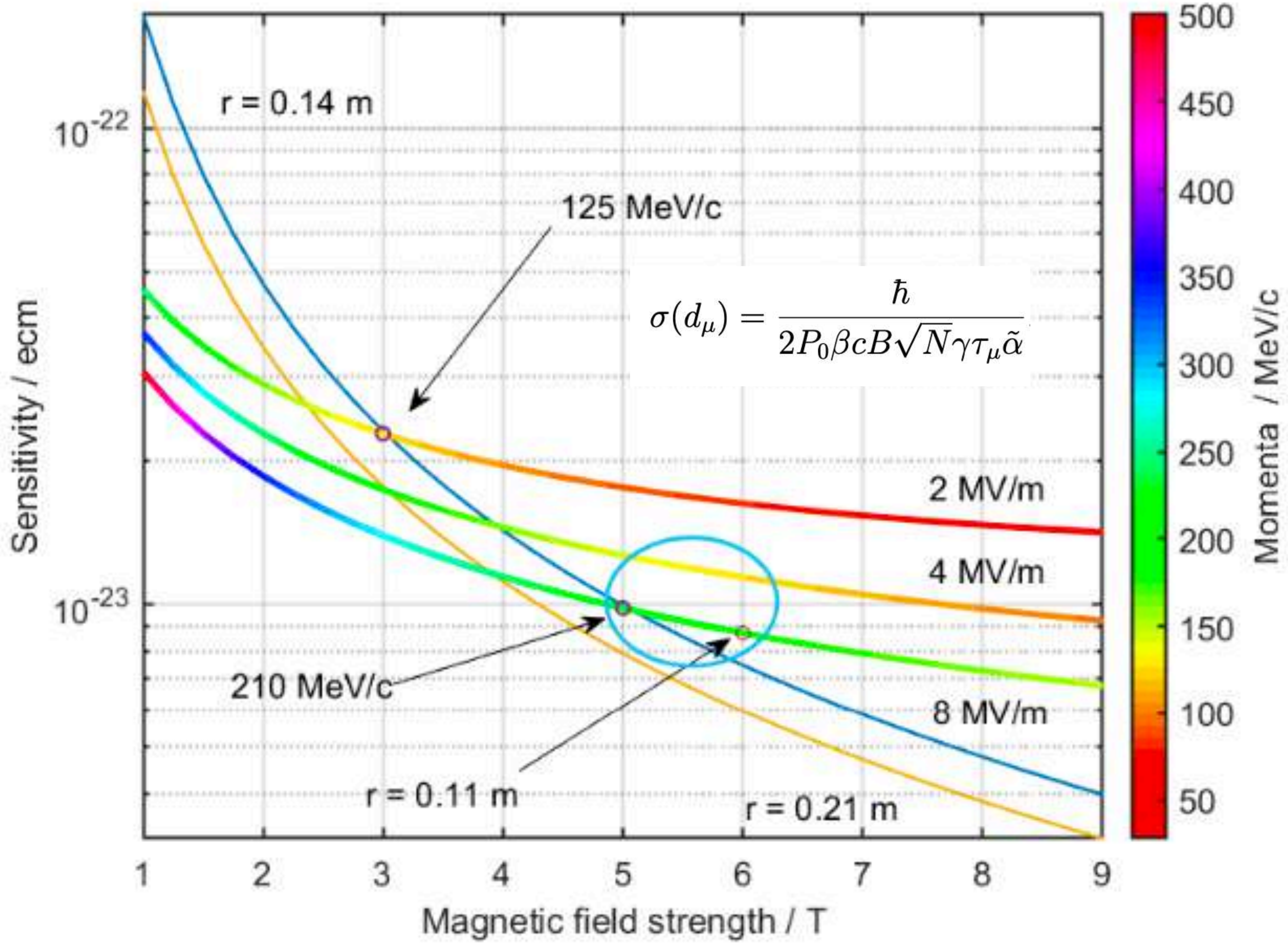
Electric Field $E_f = 2\,\mathrm{MV/m}$

$$\sigma(d_\mu) = \frac{a\hbar\gamma}{2P_0 E_f \sqrt{N}\tau_\mu A}$$

$$\sim 6 \times 10^{-23} e\,.\,\mathrm{cm}$$

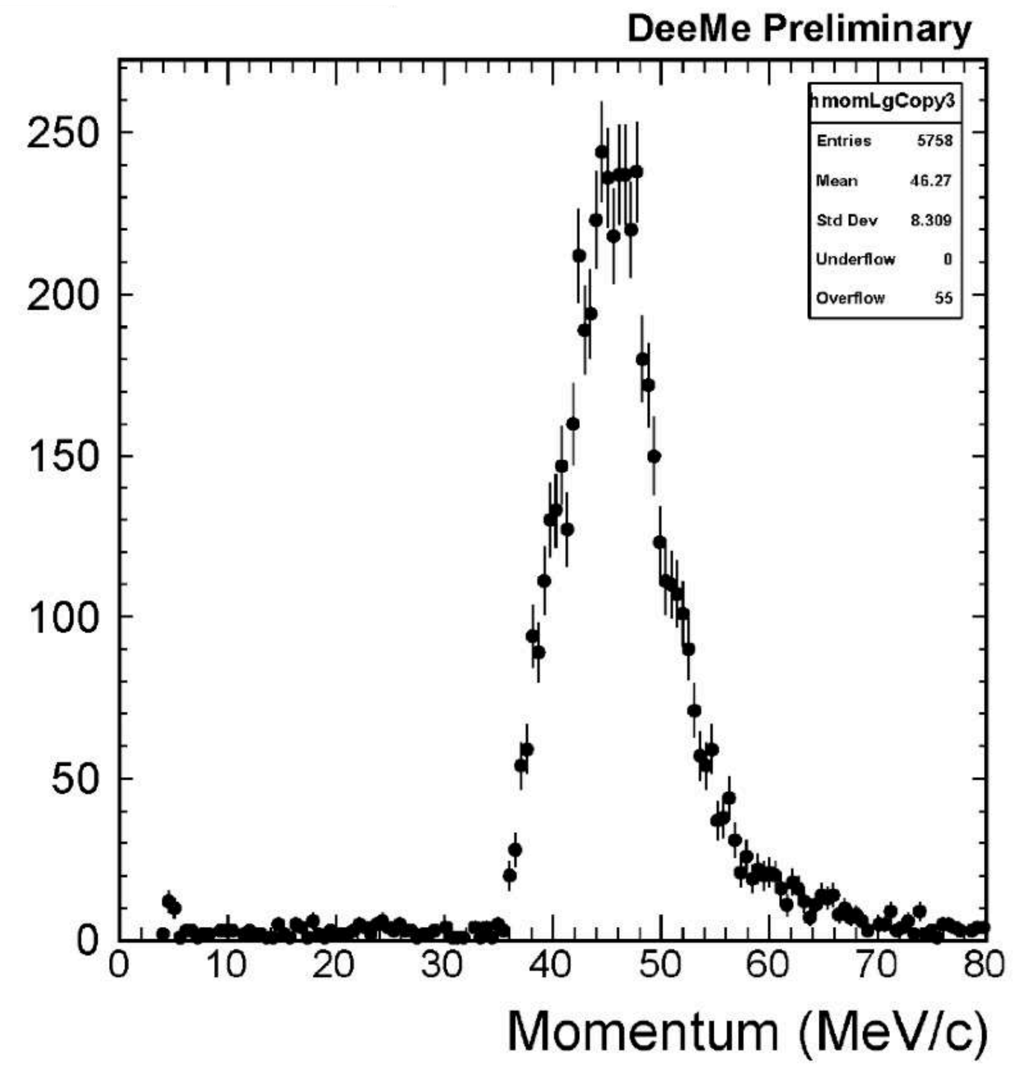
(with $N = 200$ days)

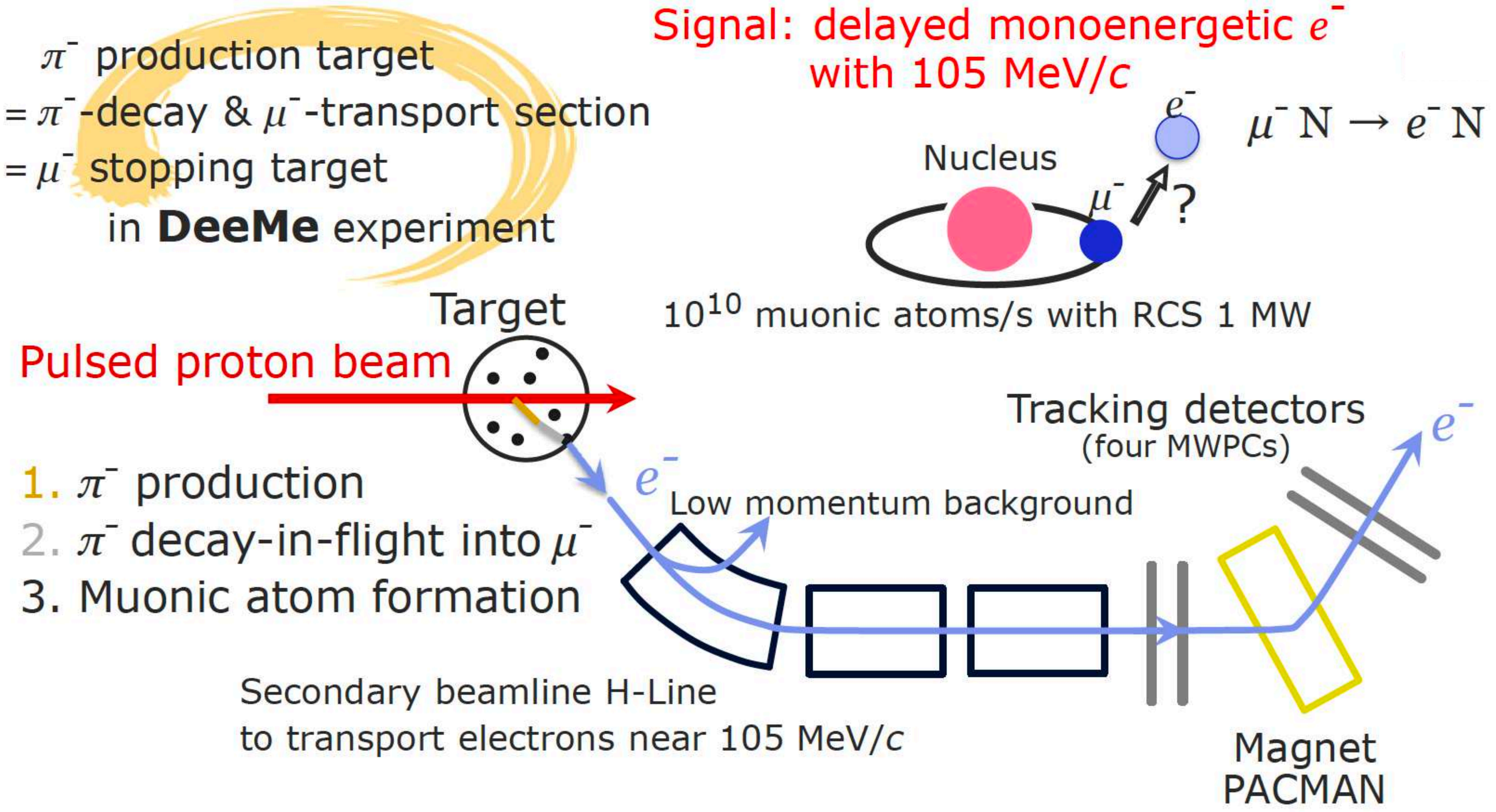
Sensitivity vs B and Momentum

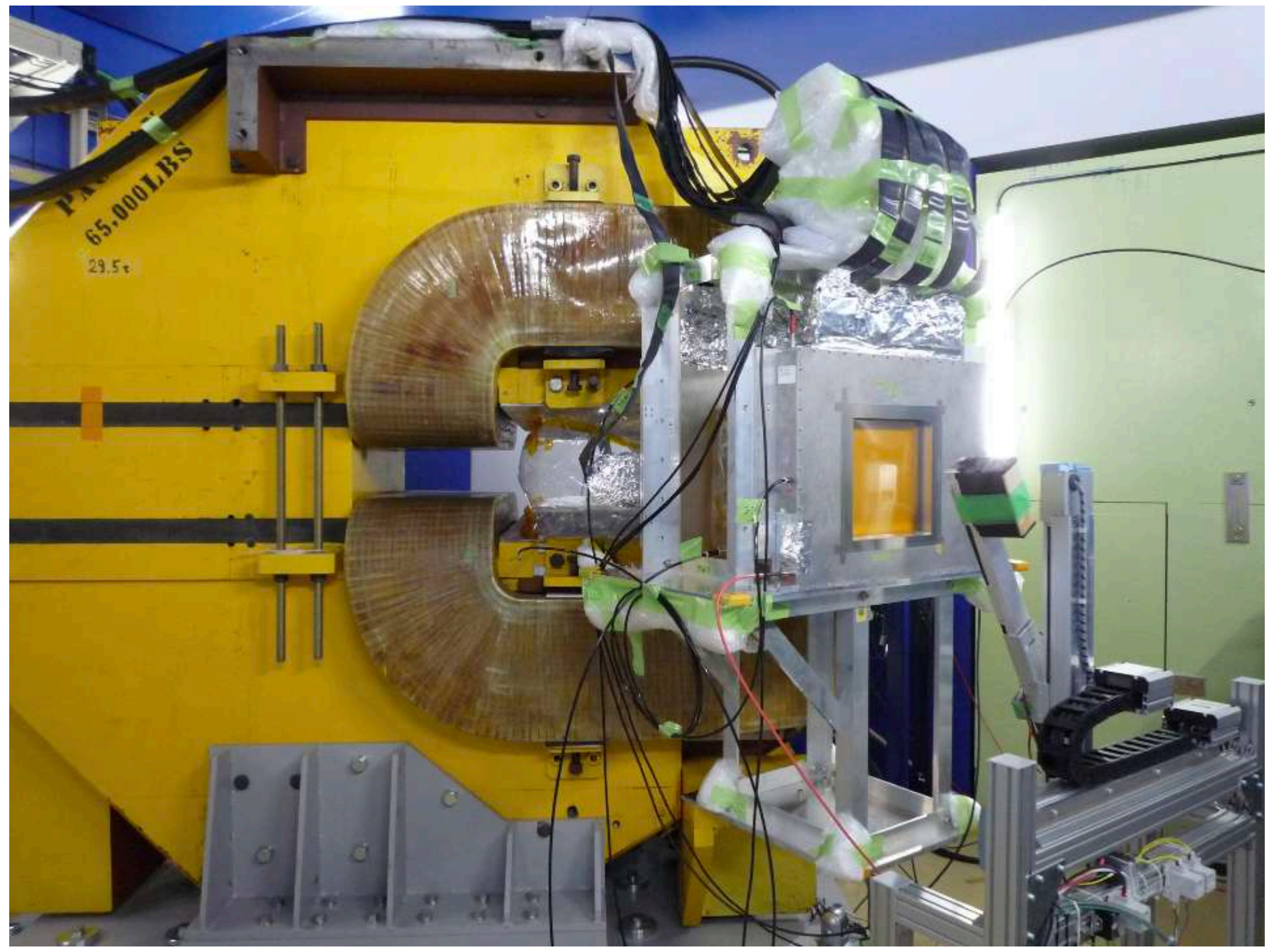


DeeMe experiment

- Pulsed proton beams from 3 GeV RCS (fast extraction)
- Muon production target = stopping target
- SES ~ 10^{-13} (Carbon target, 1 year)
- Detector commissioning in Jun-2022
- Momentum reconstruction successful & More beam-time expected later this year

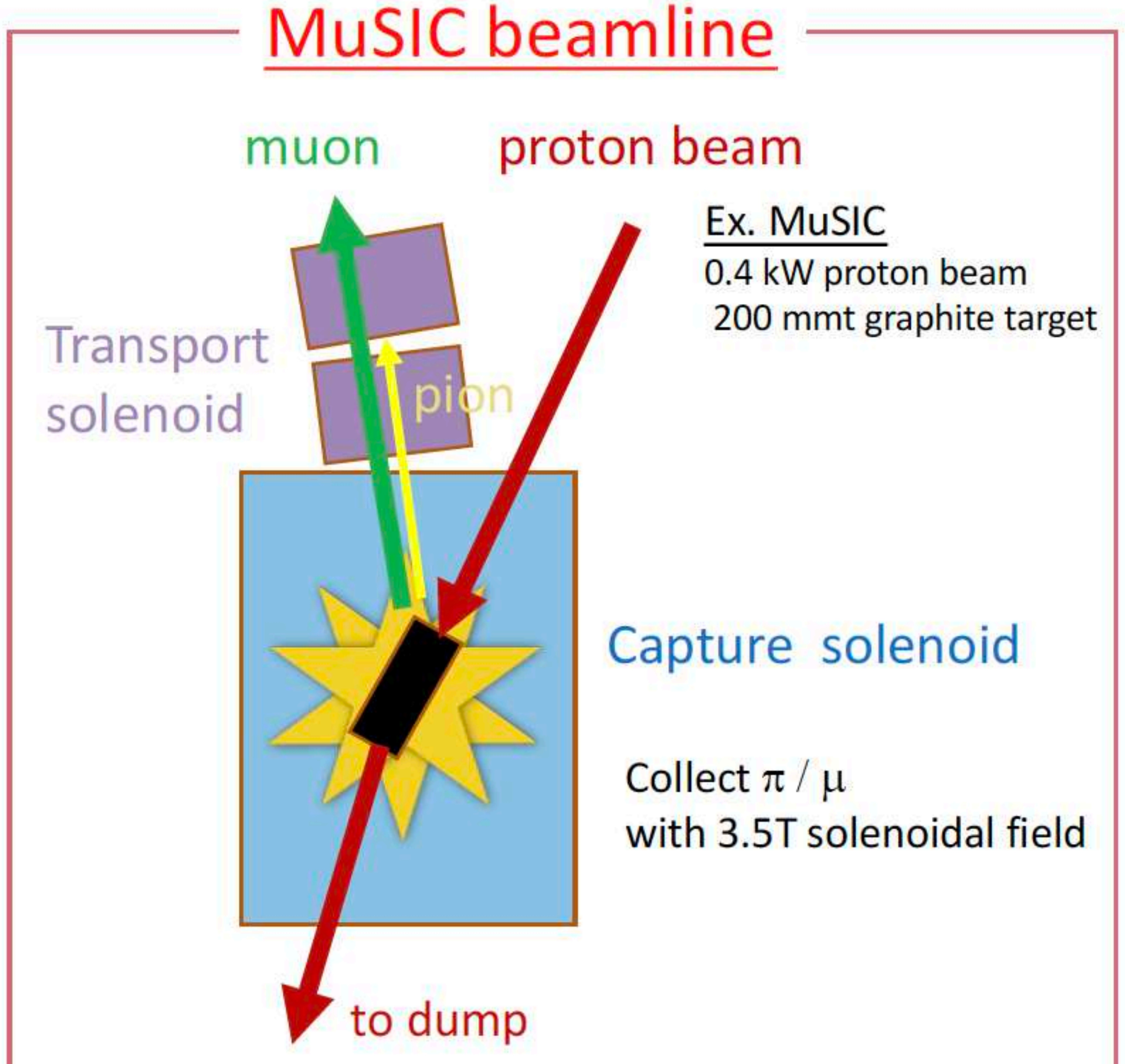




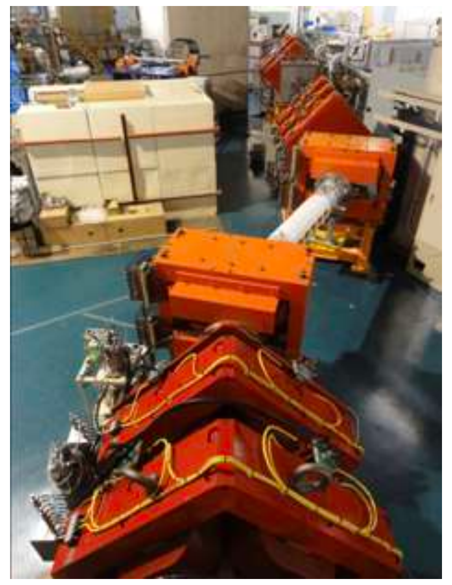


MuSIC's muon beams

- Aim: O(10^8 muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam

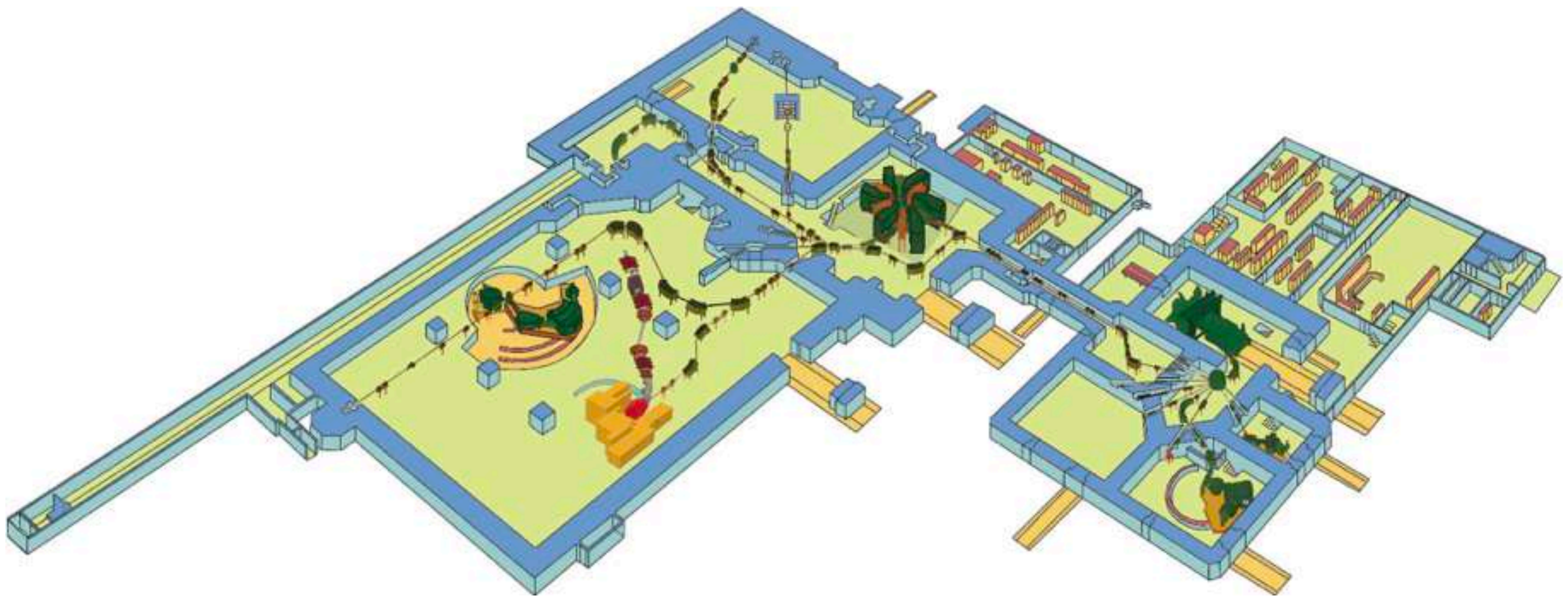


- Thick target (200mmt)
- Large solid angle, good collection efficiency
- No muon spin selection (no selection of pion / muon momentum)



MuSIC
M1 Beam line

Ring
Cyclotron
~392MeV
(variable)
1.1uA
proton,
(0.4kW)



- proton beam energy is only 100 MeV above pion production threshold (～$2m_\pi$)
- muon source with low proton power (1.1 uA ~0.4kW, 5 uA in future)

from P. Paradisi's talk

Few scalings model-independent predictions

- $\mathrm{BR}(\ell_i \to \ell_j \gamma)$ **vs.** $(g-2)_\mu$

$$\mathrm{BR}(\mu \to e\gamma) \approx 3 \times 10^{-13} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{e\mu}}{10^{-5}}\right)^2$$

$$\mathrm{BR}(\tau \to \mu\gamma) \approx 4 \times 10^{-8} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{\ell\tau}}{10^{-2}}\right)^2$$

- **EDMs assuming "Naive scaling"** $d_{\ell_i}/d_{\ell_j} = m_{\ell_i}/m_{\ell_j}$

$$d_e \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 10^{-28} \left(\frac{\phi_e^{CPV}}{10^{-4}}\right) e\,\mathrm{cm}\,,$$

$$d_\mu \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 2 \times 10^{-22}\, \phi_\mu^{CPV}\; e\,\mathrm{cm}\,.$$

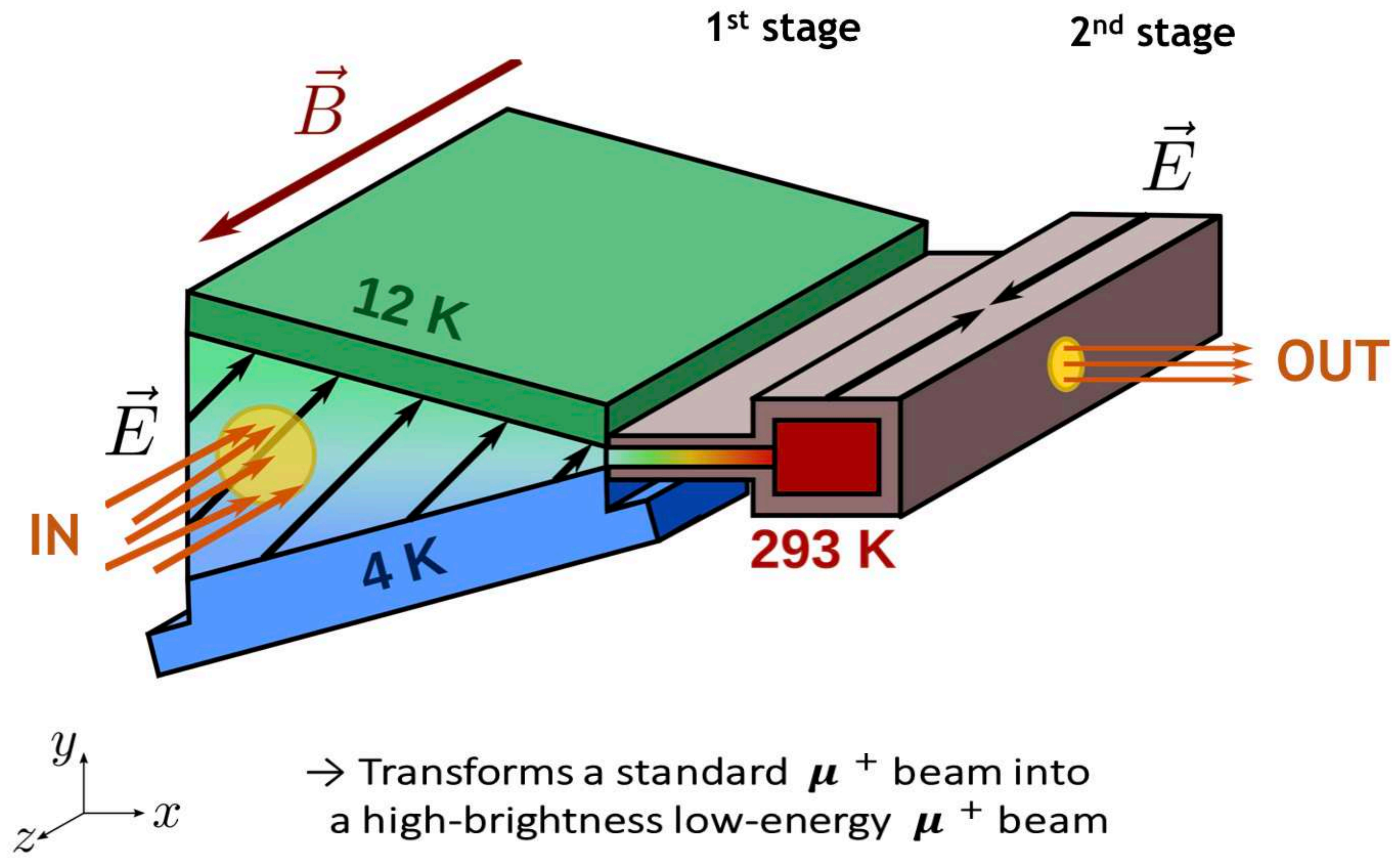
- **Main messages:**
  - $\Delta a_\mu \approx (3 \pm 1) \times 10^{-9}$ **requires a nearly flavor and CP conserving NP**
  - **Large effects in the muon EDM** $d_\mu \sim 10^{-22}\, e\,\mathrm{cm}$ **are still allowed.**

D. Taqqu, PRL 97 (2006) 194801

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

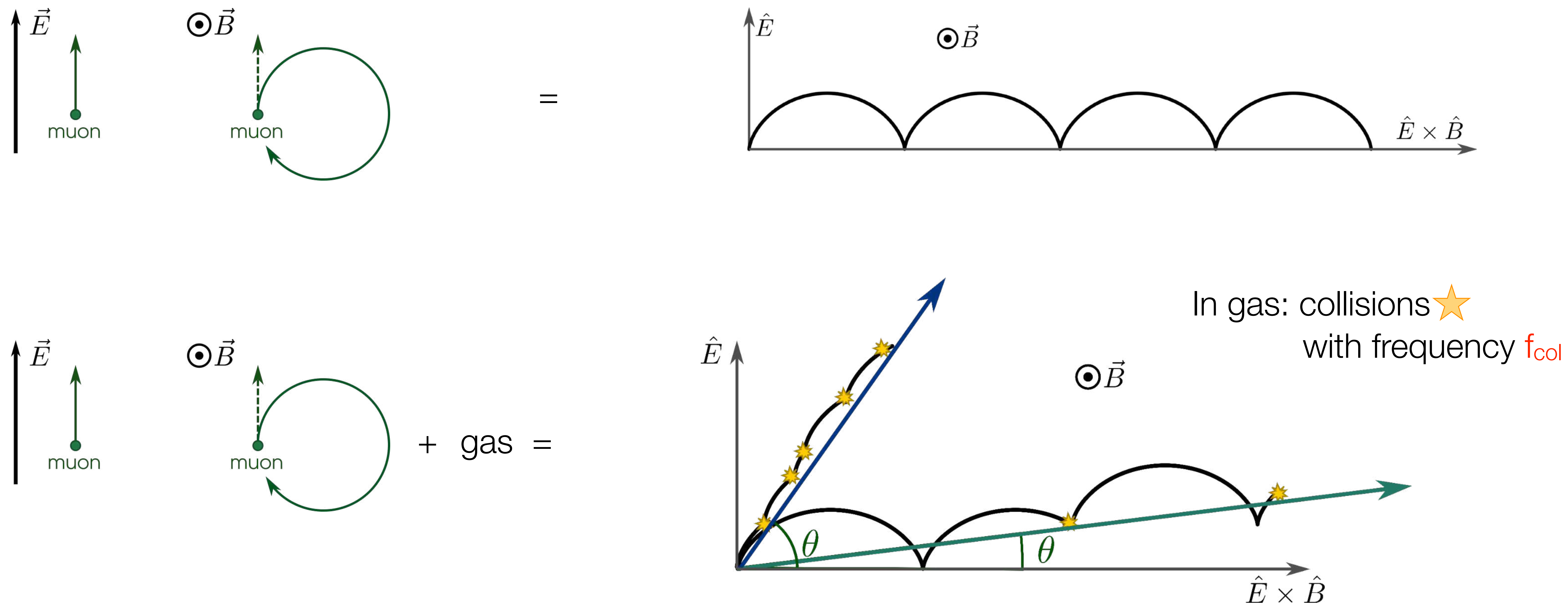


muCool/tertiary μ^+ beam
- σ < 1mm
- E < eV
- Tagged

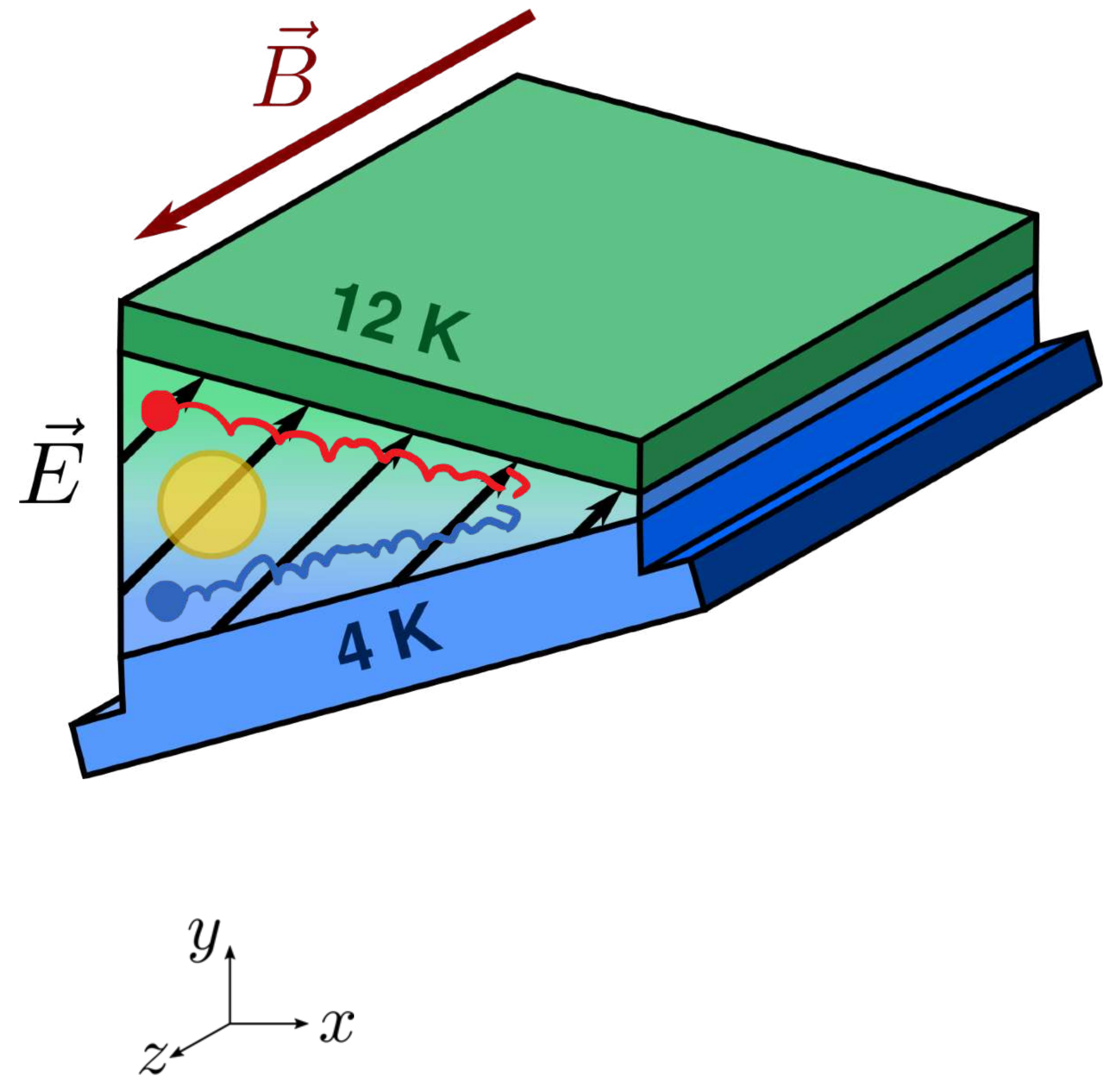
→ Transforms a standard μ^+ beam into a high-brightness low-energy μ^+ beam

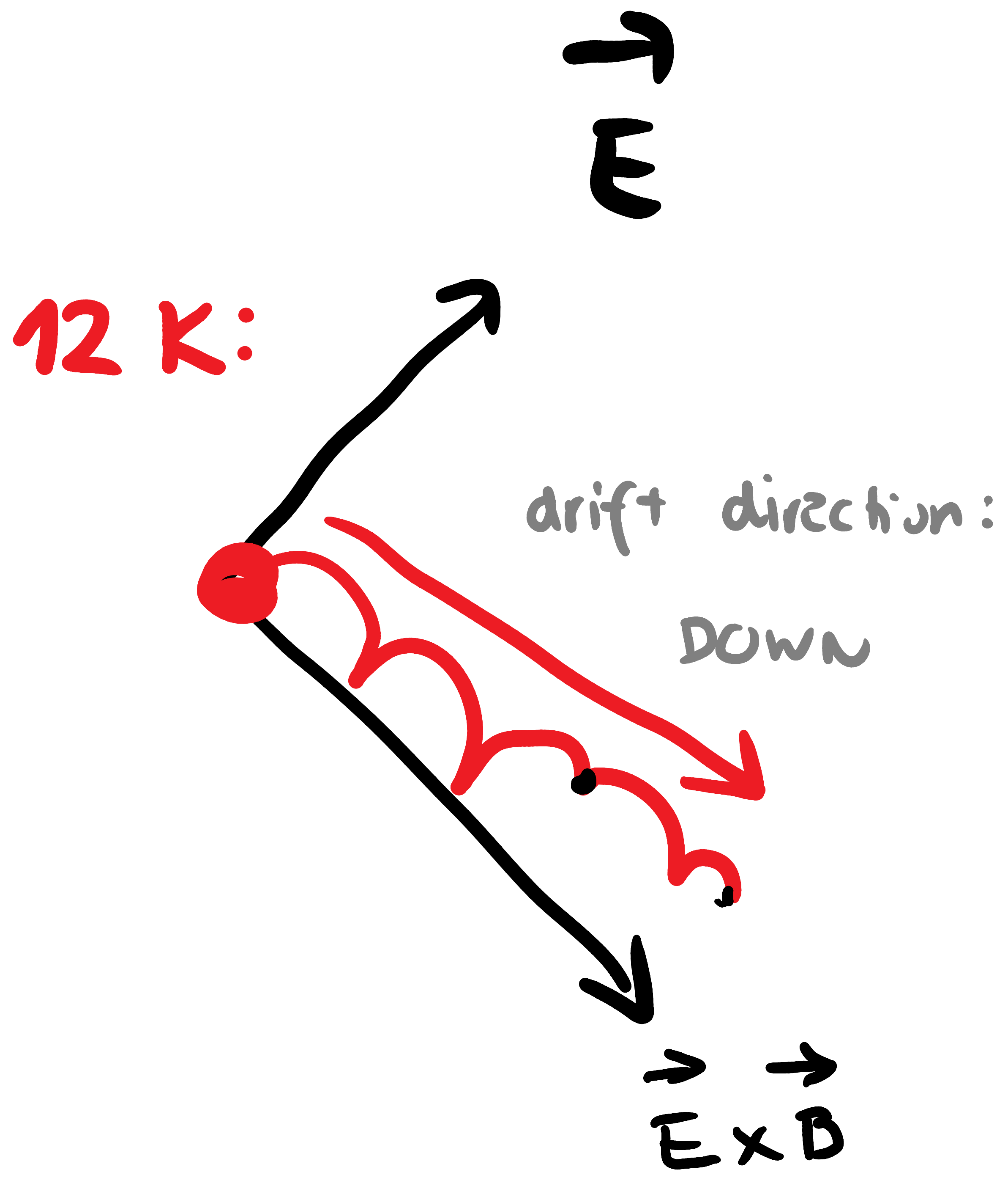
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

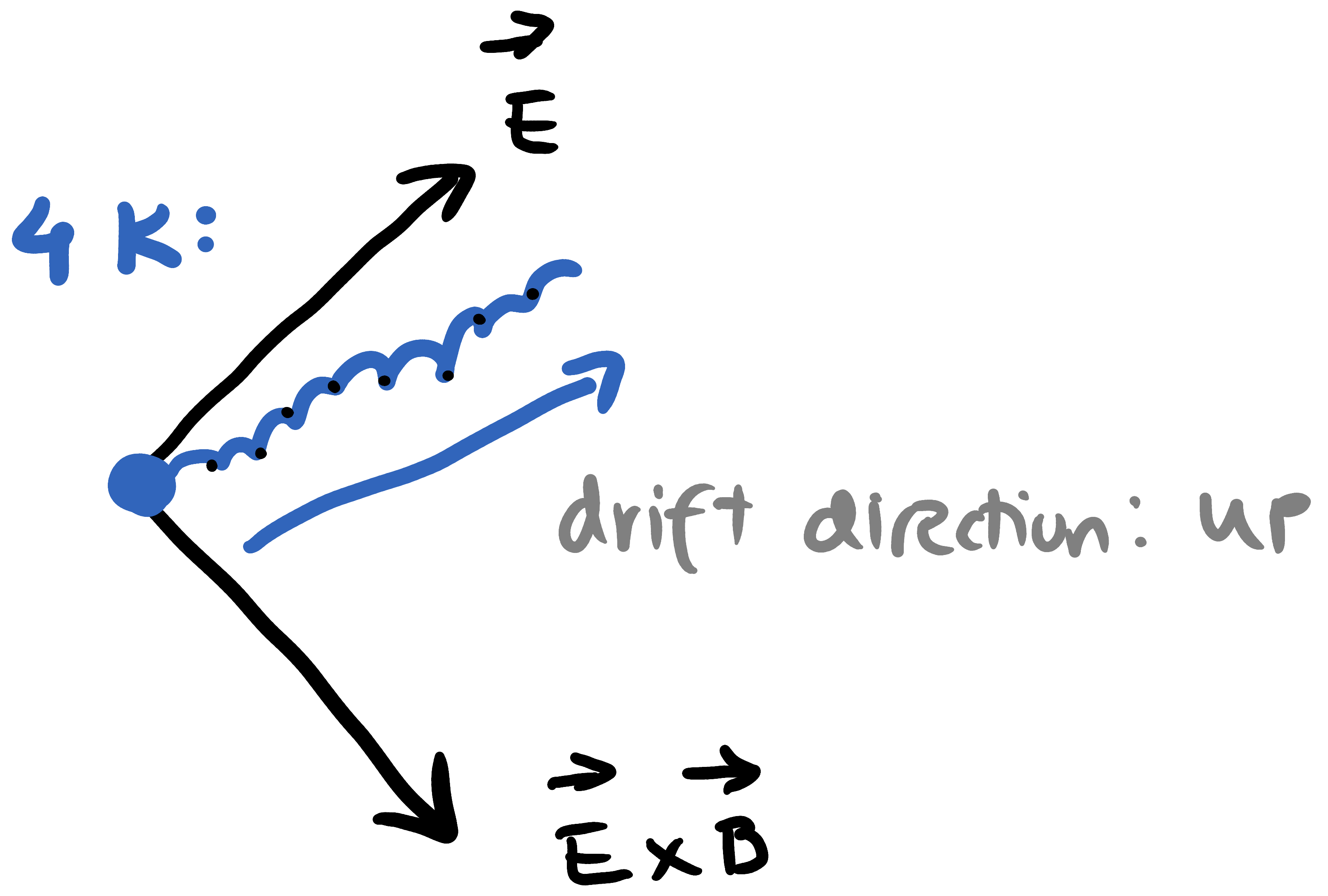
Trajectories in E and B field



Working principle: 1st Stage

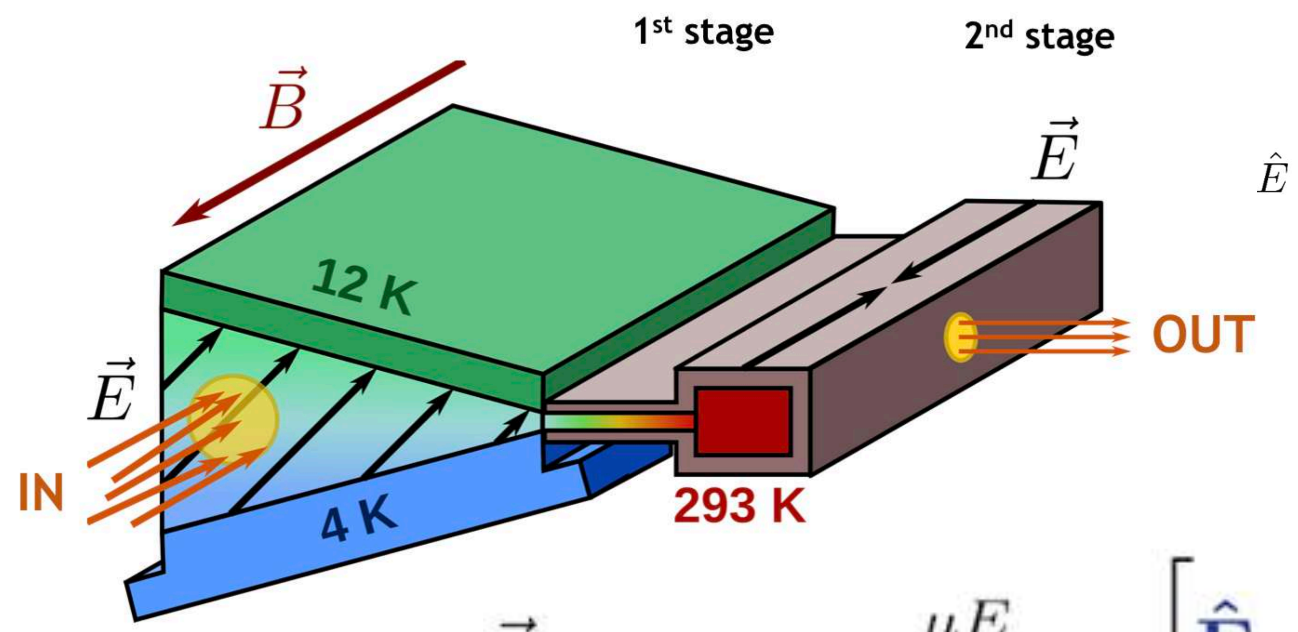


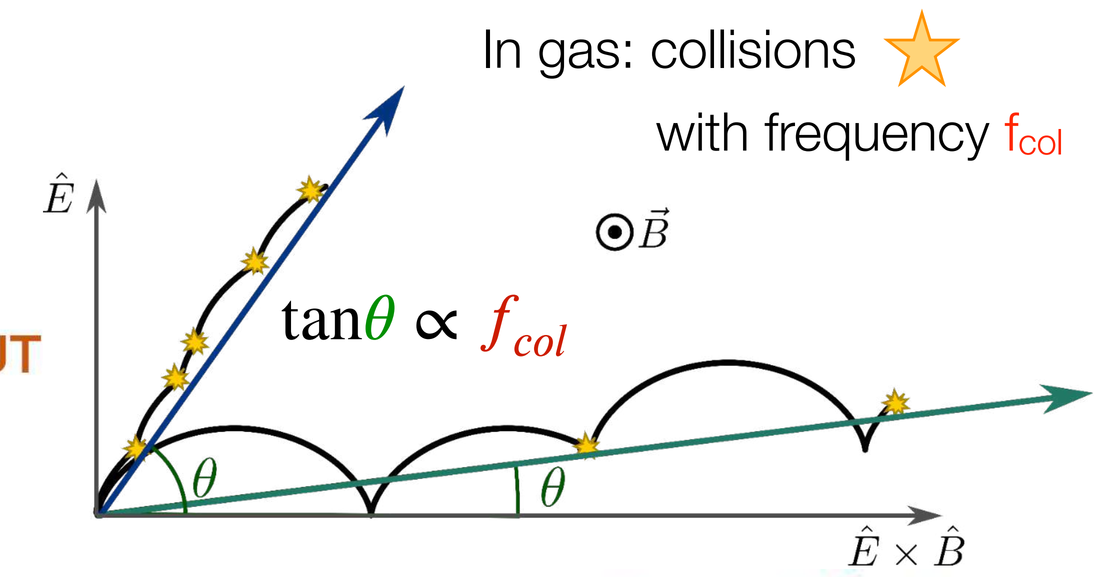




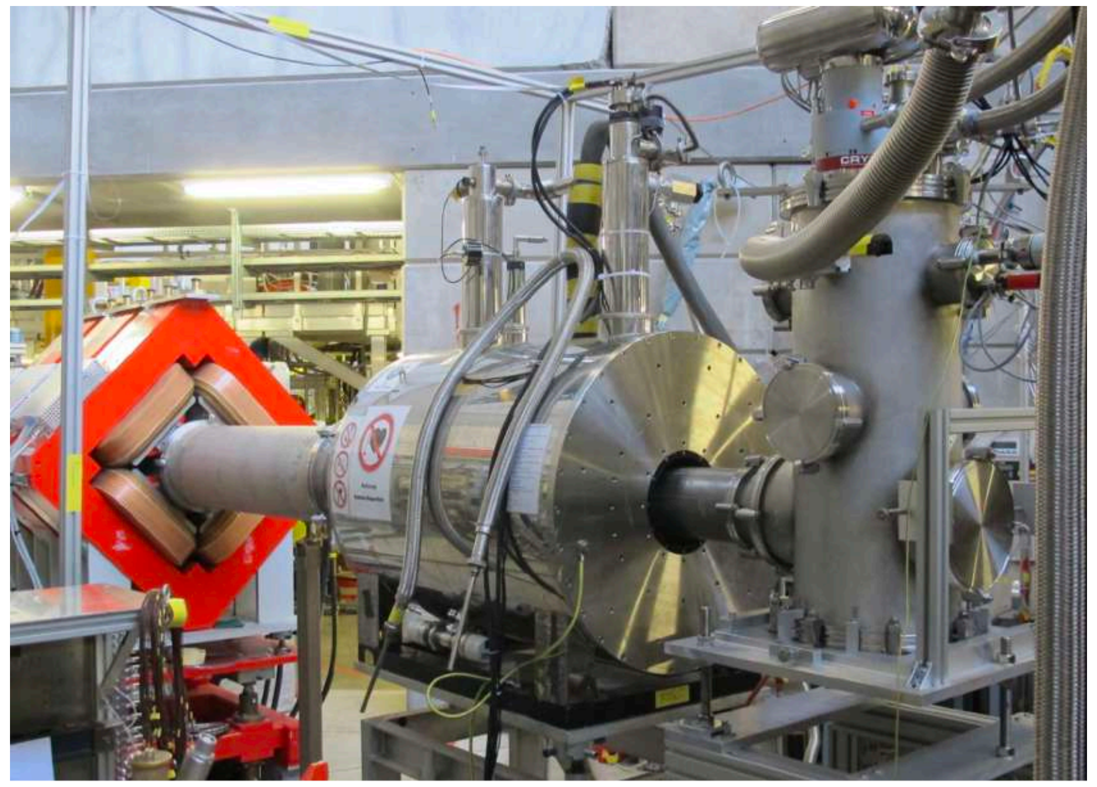
Summary: The muCool project at PSI

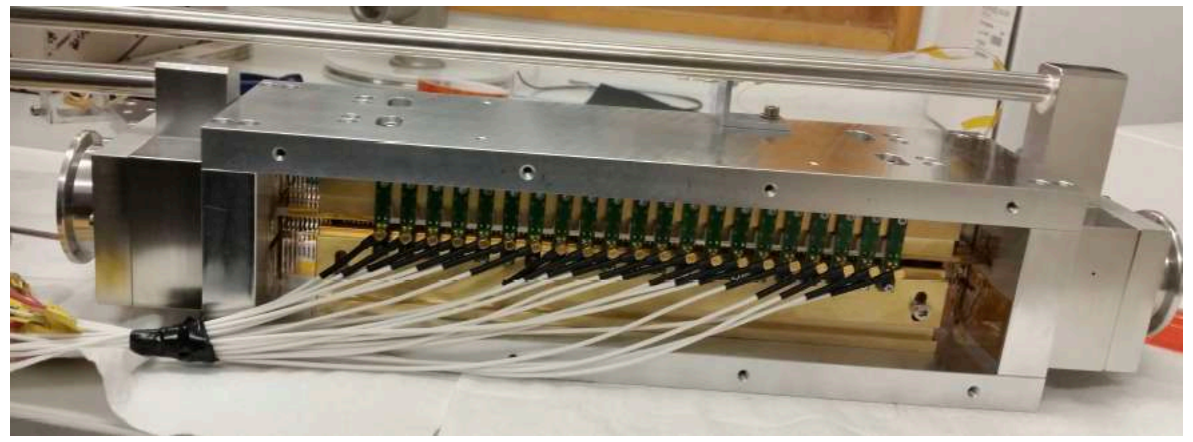
- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor **10^{10}** with an efficiency of O(**10^{-4}**)
- Longitudinal and transverse compression (1st stage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

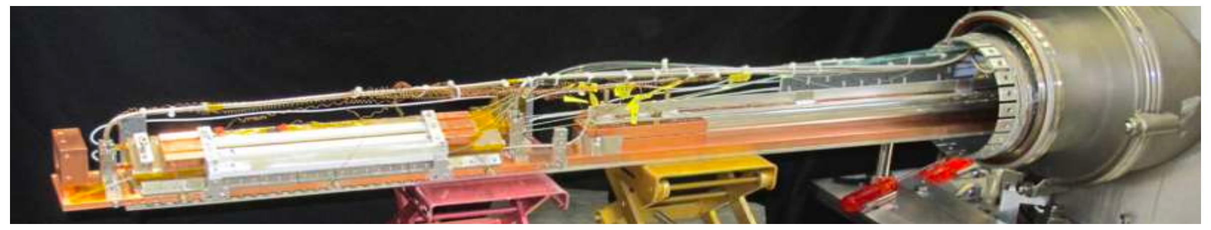




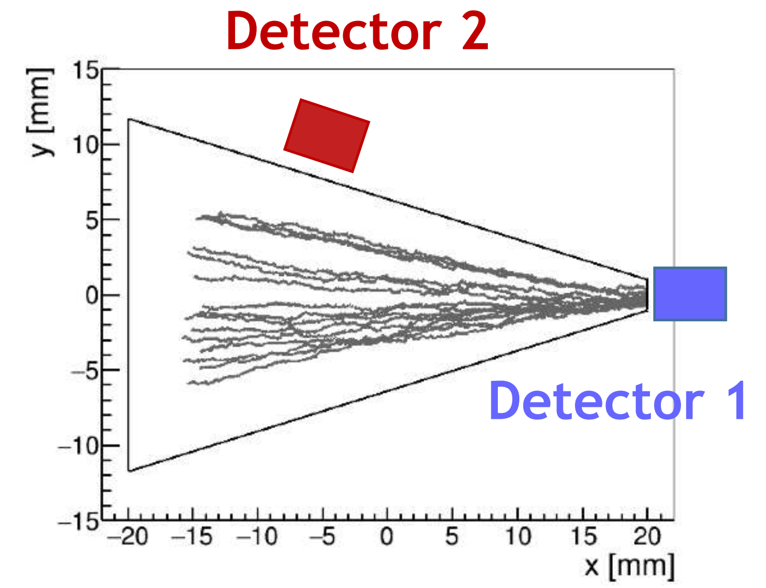
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

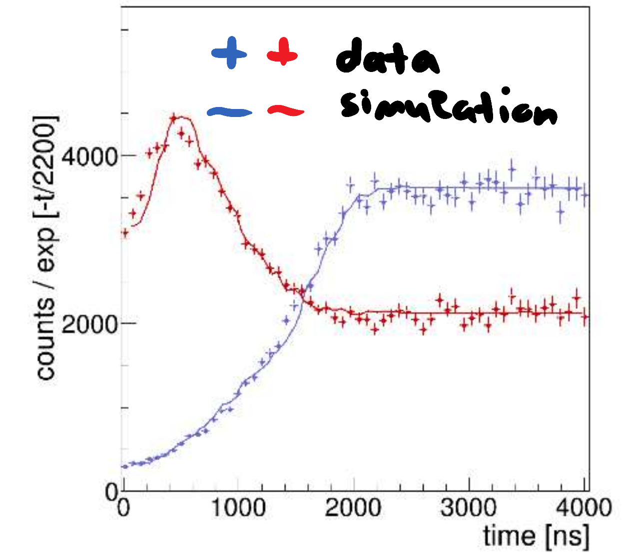




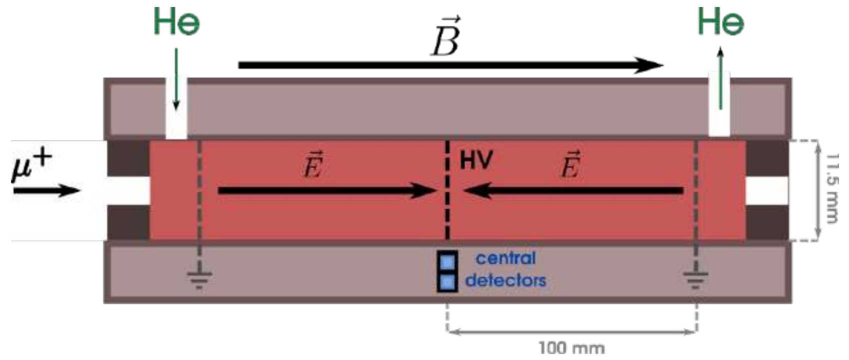


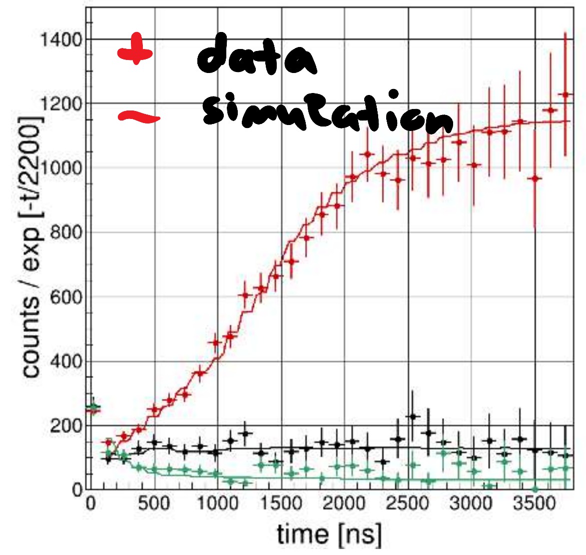
Transverse Compression



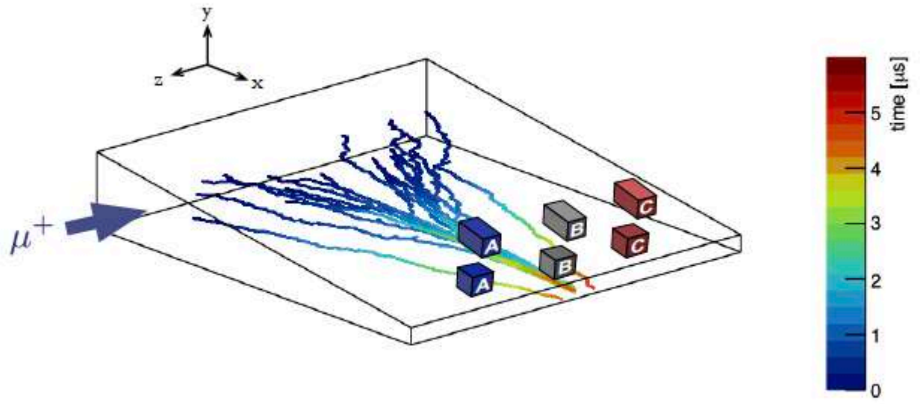


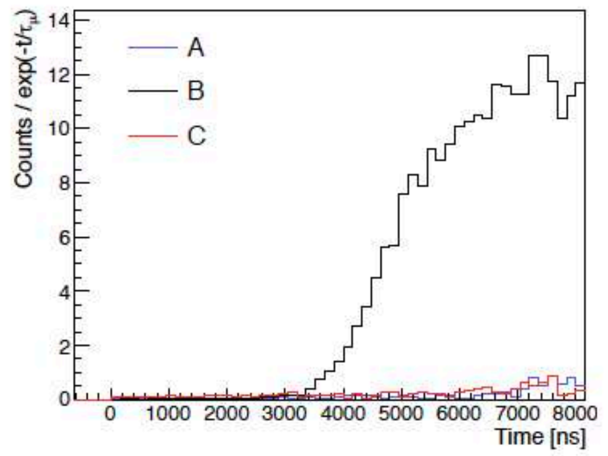
Longitudinal Compression





Longitudinal+ Transverse Compression





Summary: 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 ("towards the new M-target") successfully done (2019) and installed as "default" target since 2020
  - **Increase surface muon rates for all connected beam lines (30-60% increase depending of the beamline): Confirmed**
  - **Increase safety margin for "missing" target with the proton beam: Confirmed**
  - **Slanted target final place: Current "M" target**
- PSI Long shut-down: **2017-18. HiMB from 2018**