

MEGII, Mu3e and HiMB status at PSI

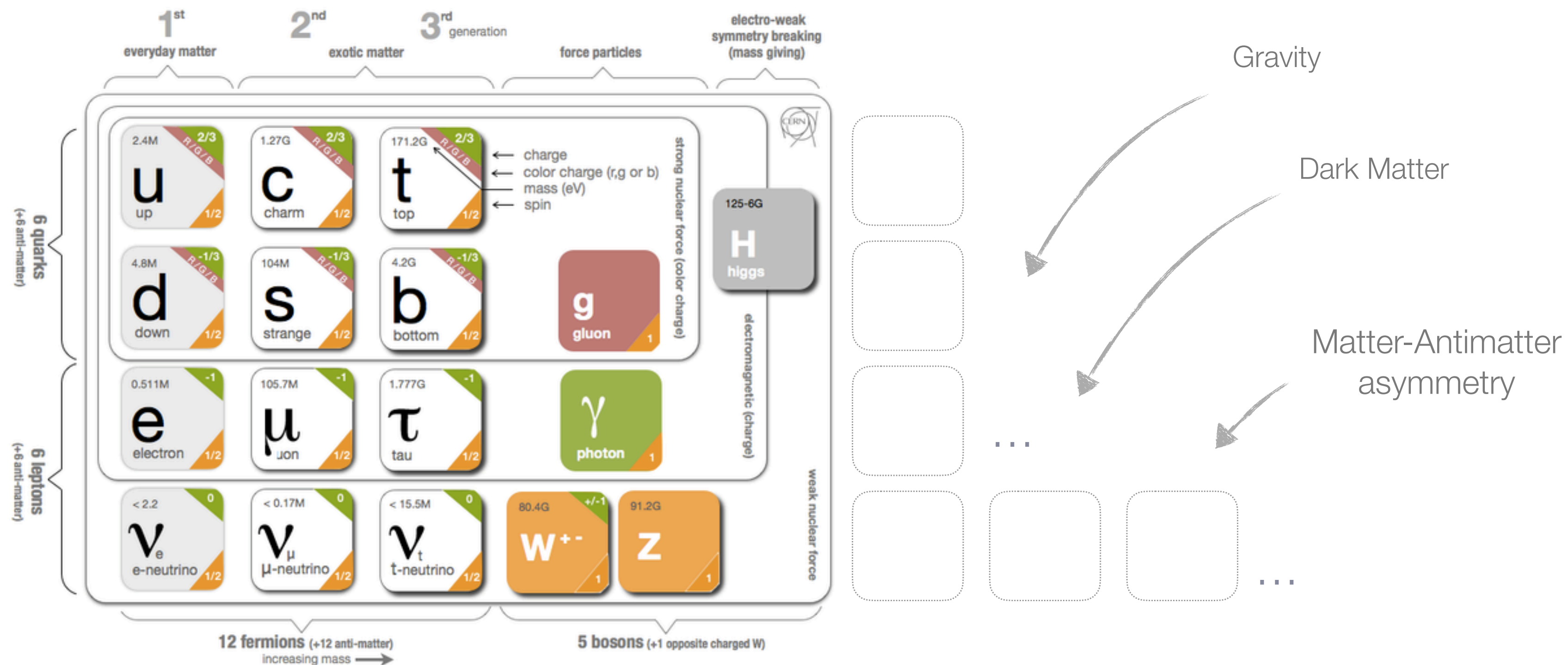
Andreas Knecht and Angela Papa
PROBES meeting
27-28 November 2025
Pisa, Italy

Content

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

The role of the low energy precision physics

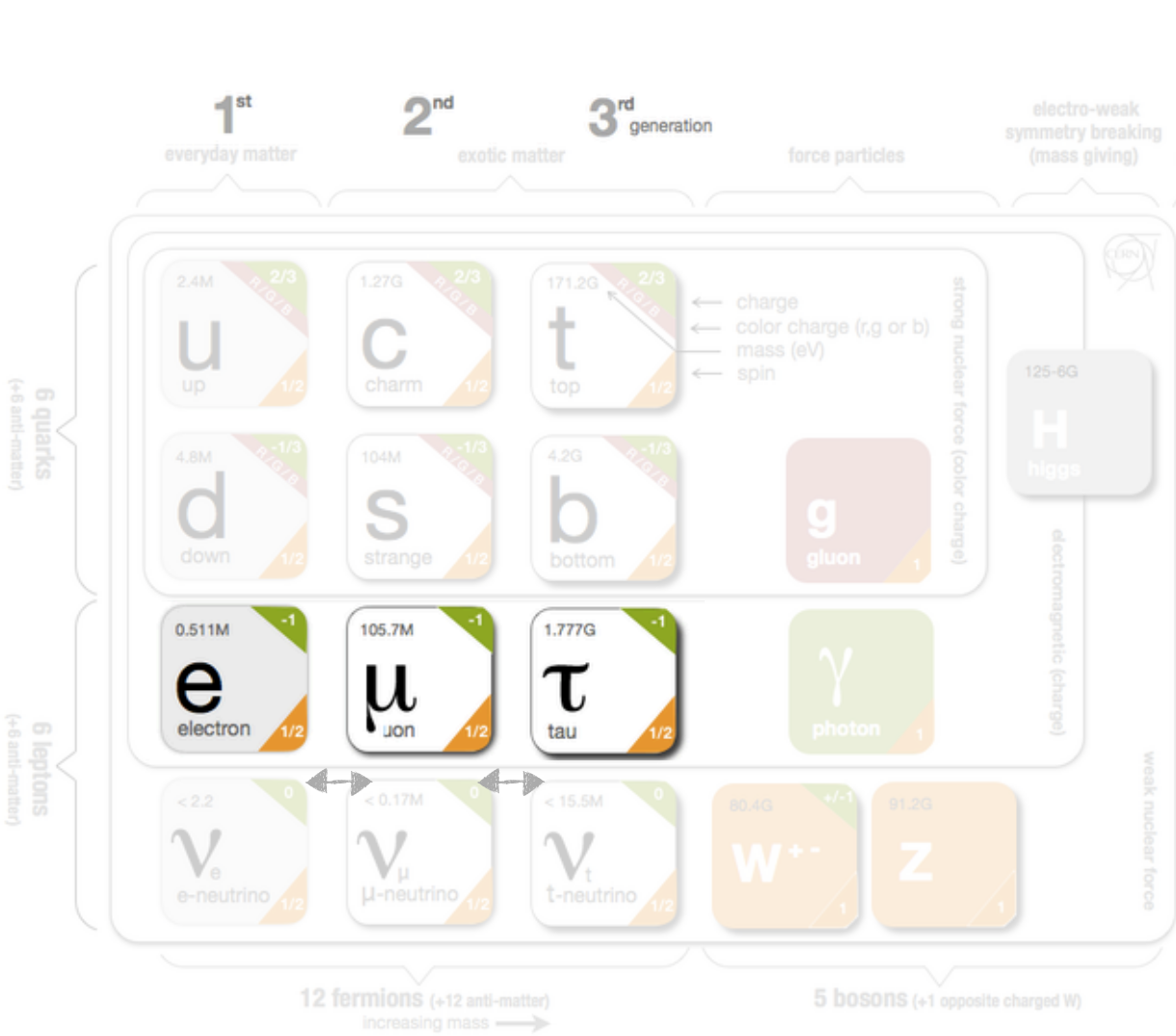
- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory



- 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**

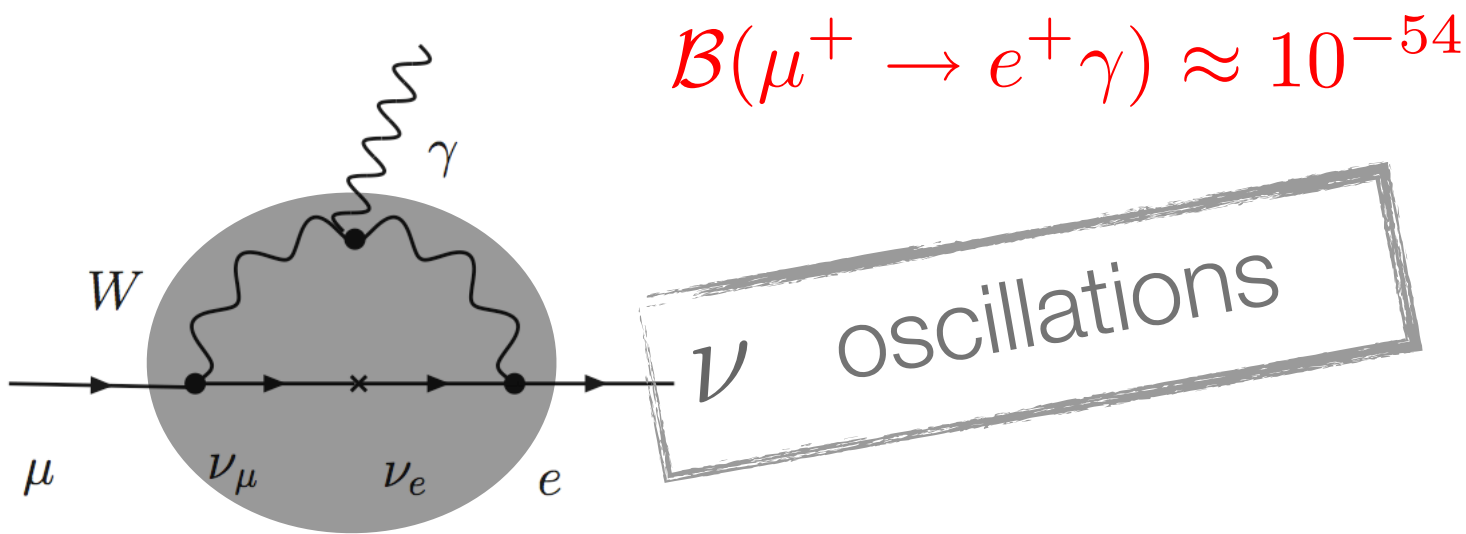
Charged lepton flavour violation search: Motivation

- **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**



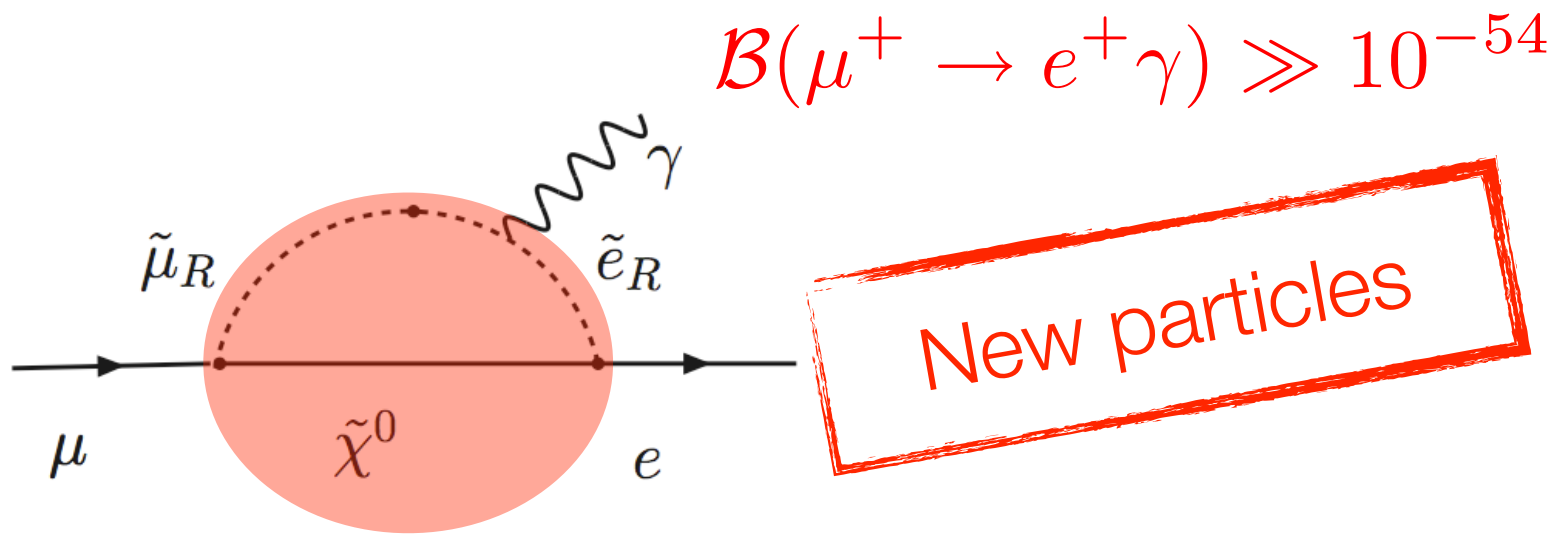
$$\Delta N_i \neq 0 \text{ with } i = 1, 2, 3$$

SM with massive neutrinos (Dirac)



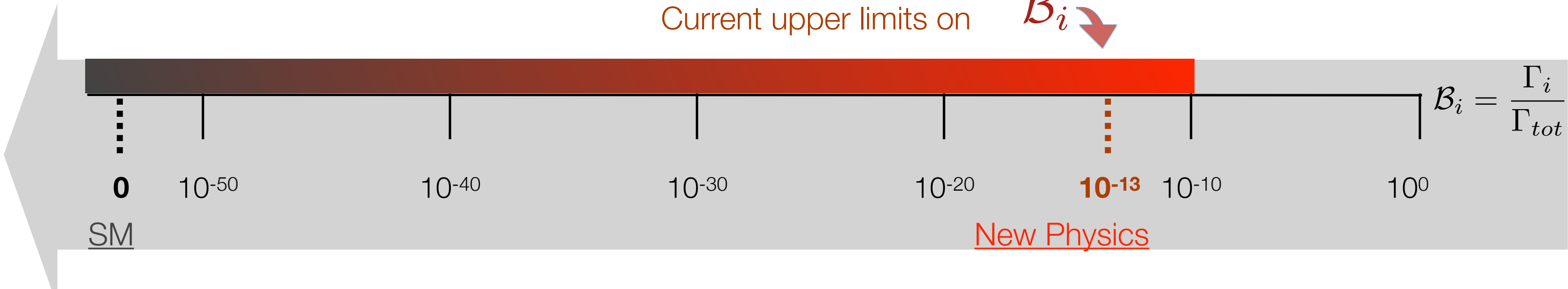
too small to access experimentally

BSM



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

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

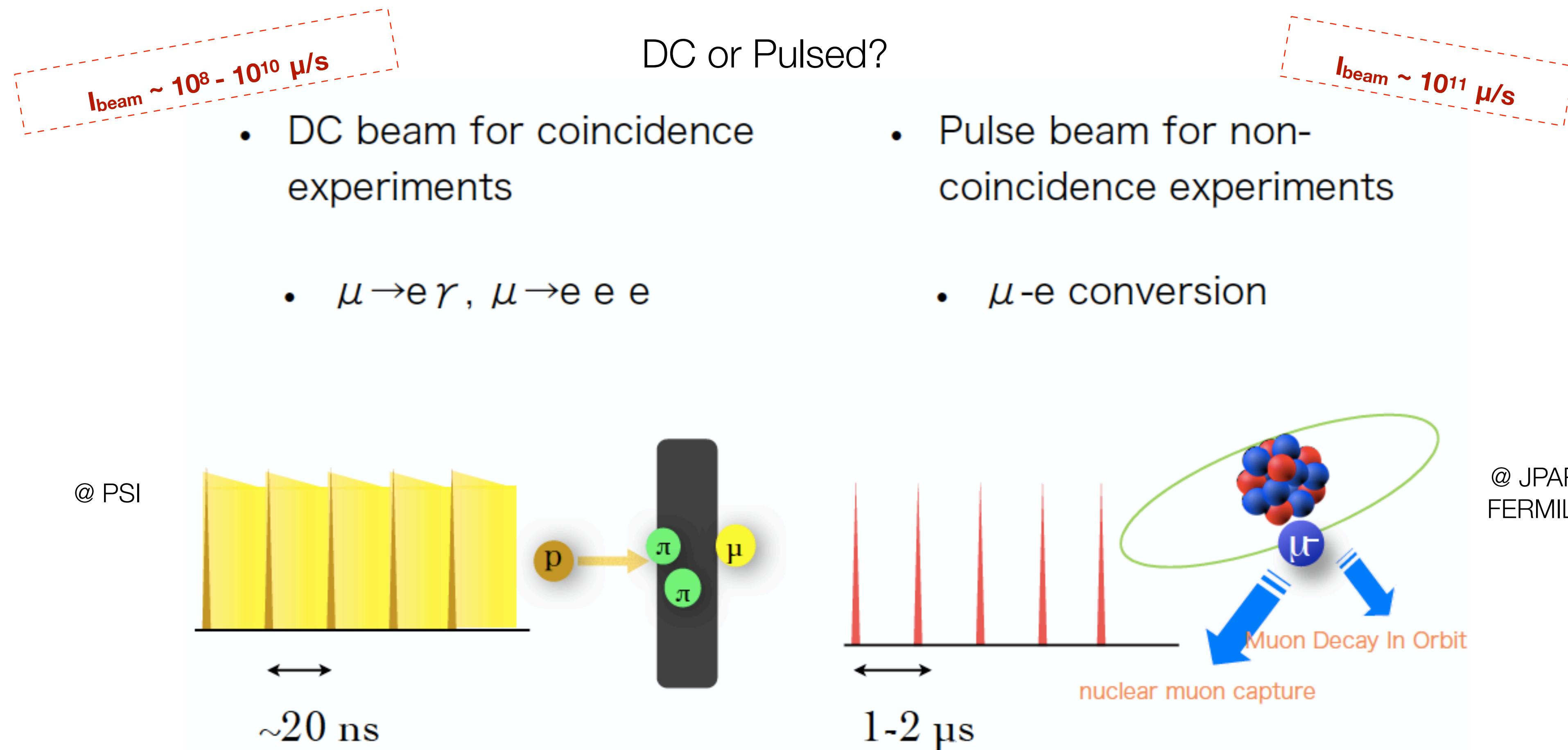


Content

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

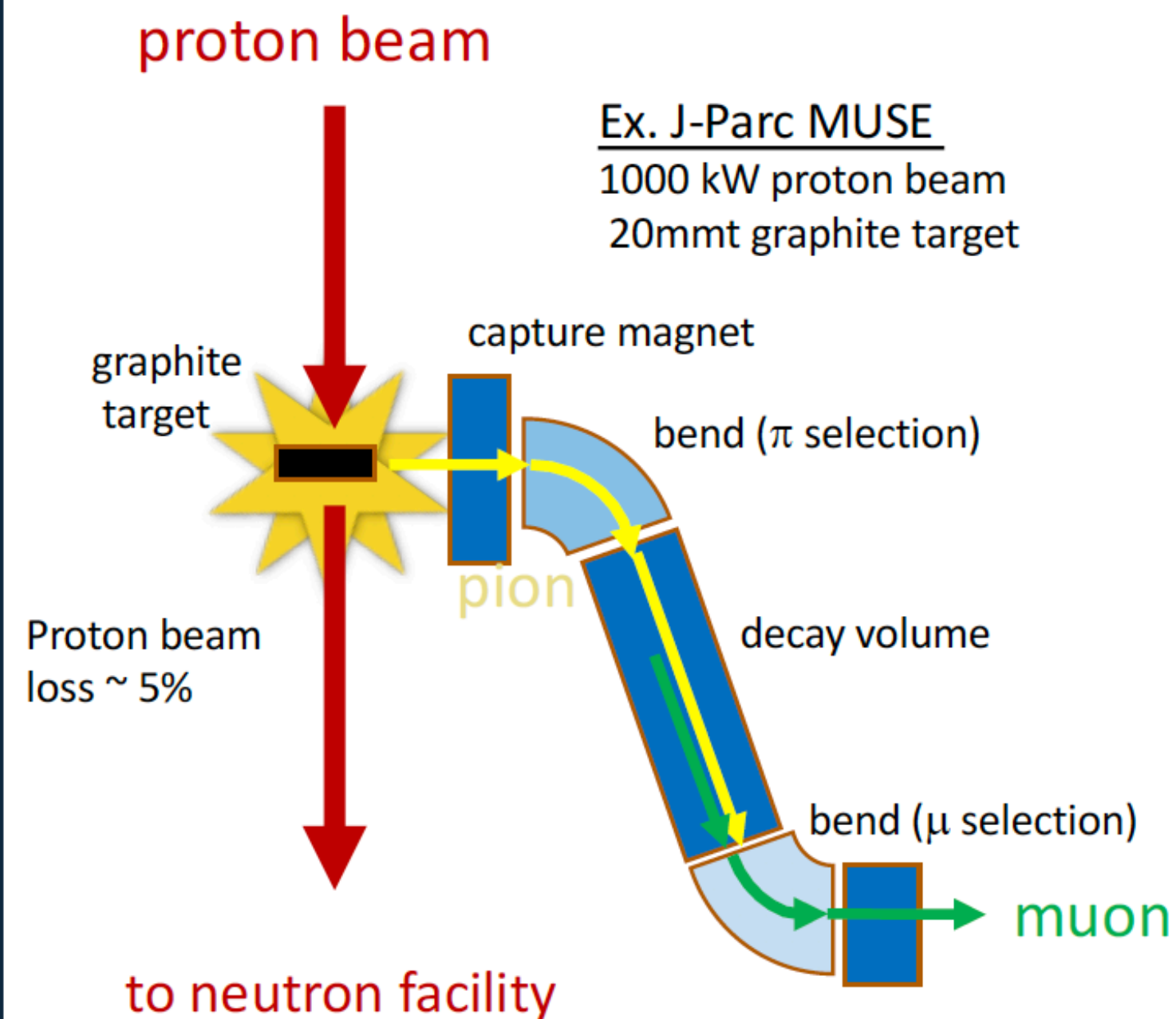
Muon beams

- 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**



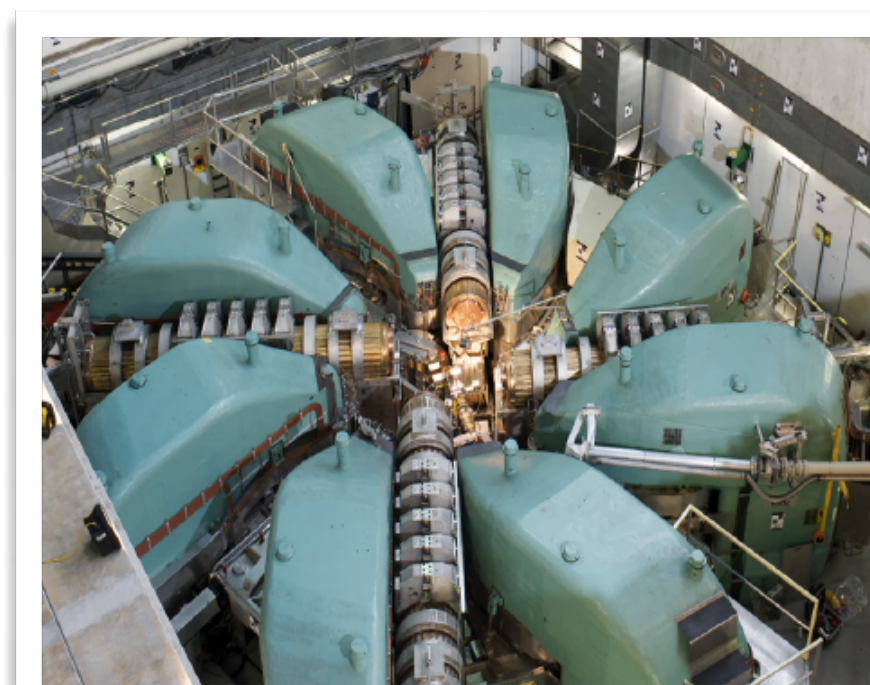
PSI's muon beams

Conventional muon beamline

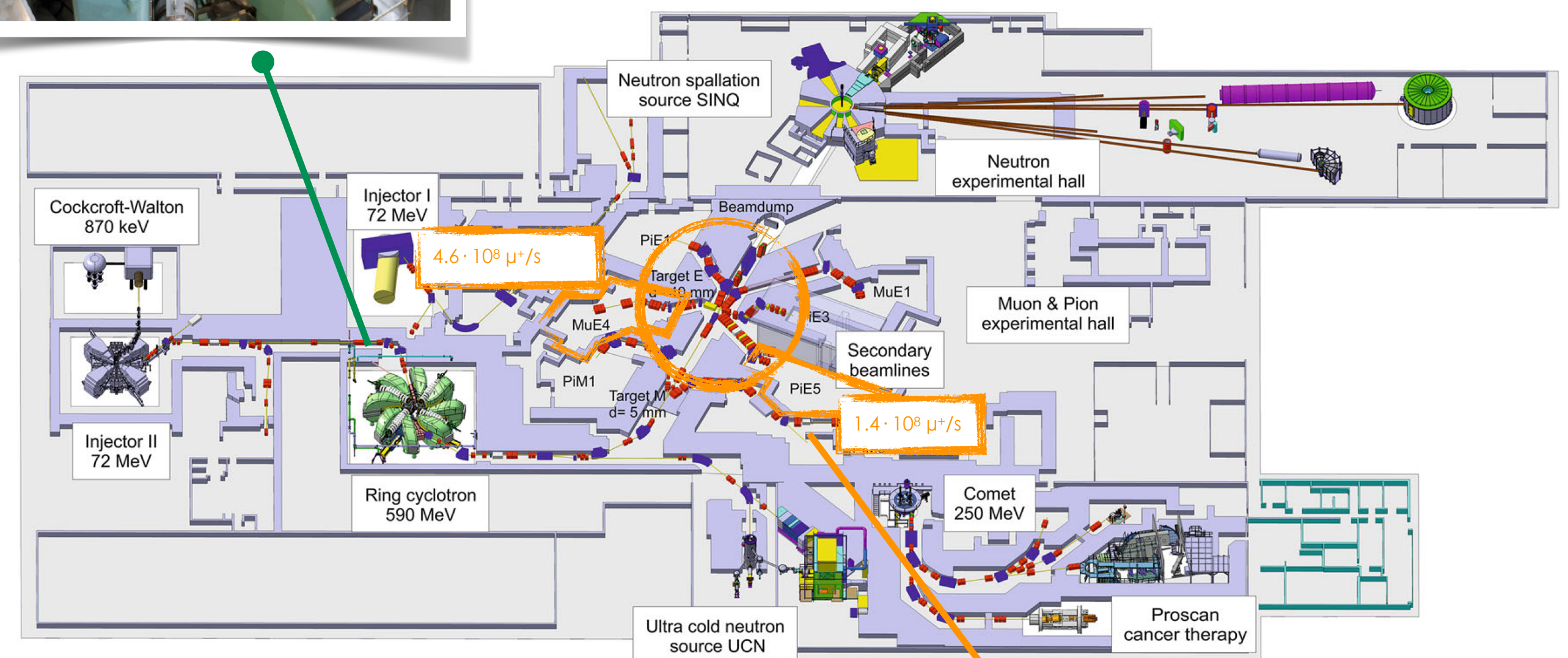


- Thin target ($\sim 20\text{mm}$)
- Small solid angle
- Separate pion and muon momentum selection (obtain highly polarized muon beam)

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



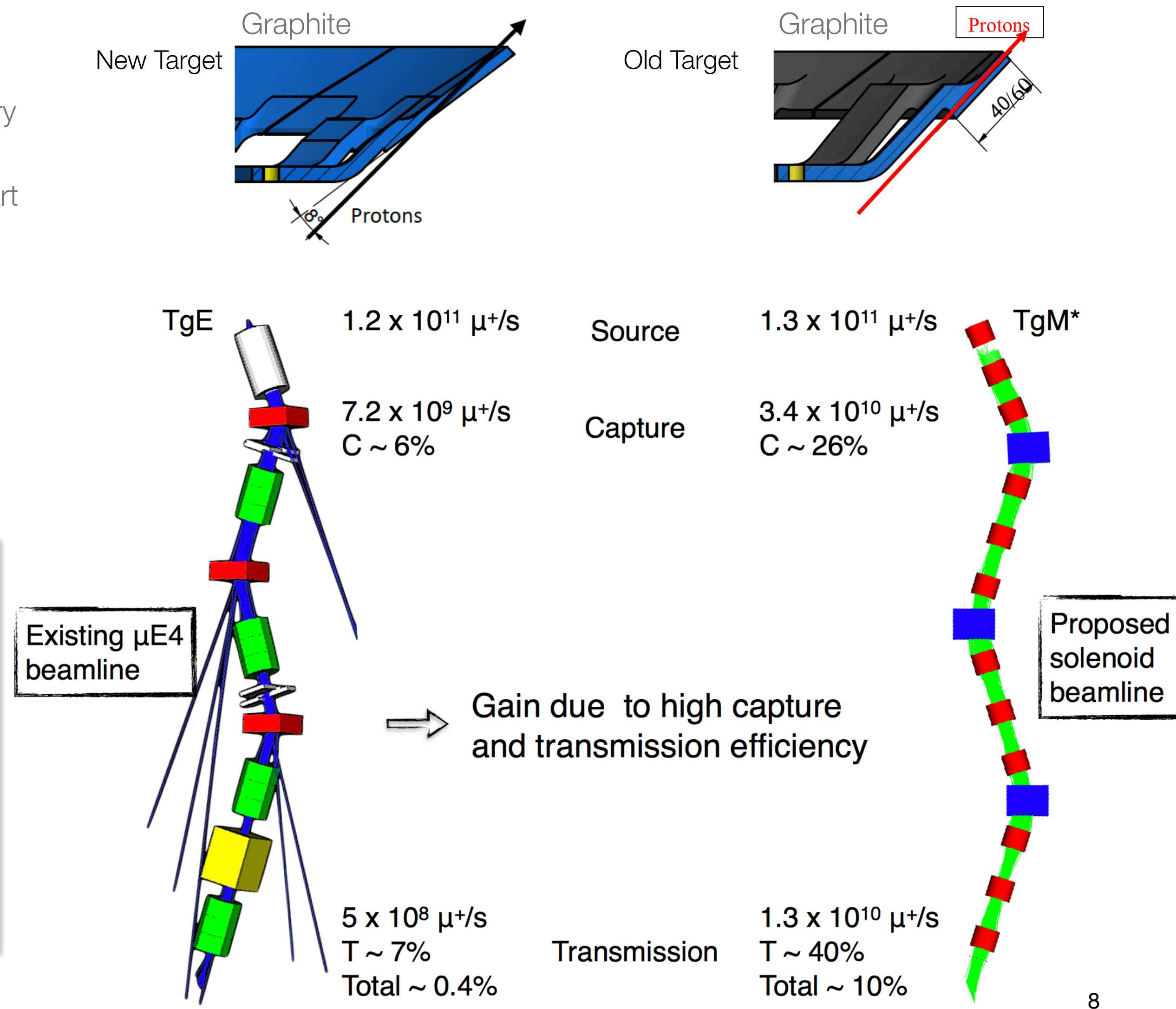
590 MeV proton
ring cyclotron
1.4 MW



MEGII / Mu3e Experimental area

The HiMB (High Intensity Muon Beam) project at PSI

- Aim: $O(10^{10})$ muon/s; Surface (positive) muon beam ($p = 28 \text{ MeV/c}$); **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**



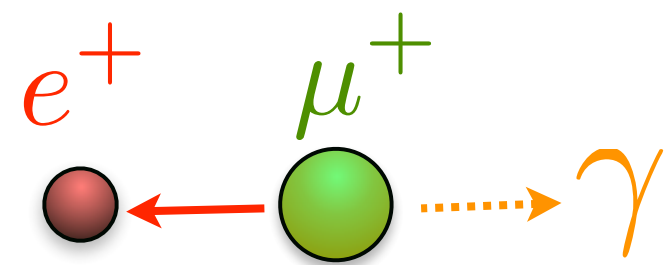
Content

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

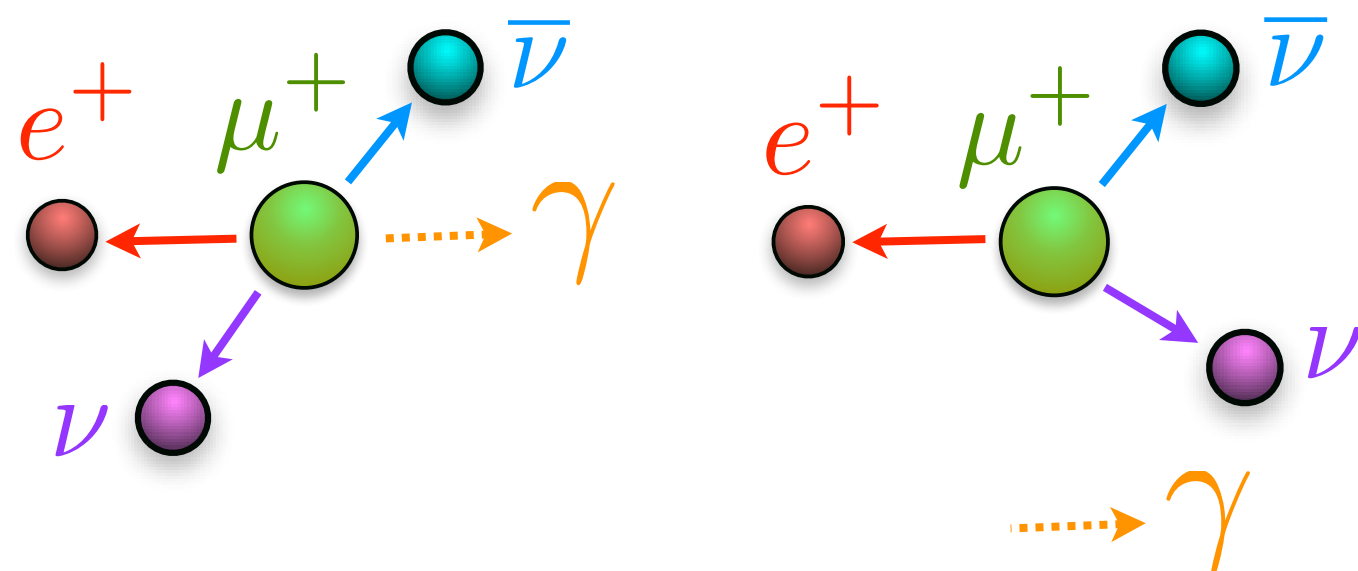
The MEGII experiment at PSI

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

Signature



Backgrounds

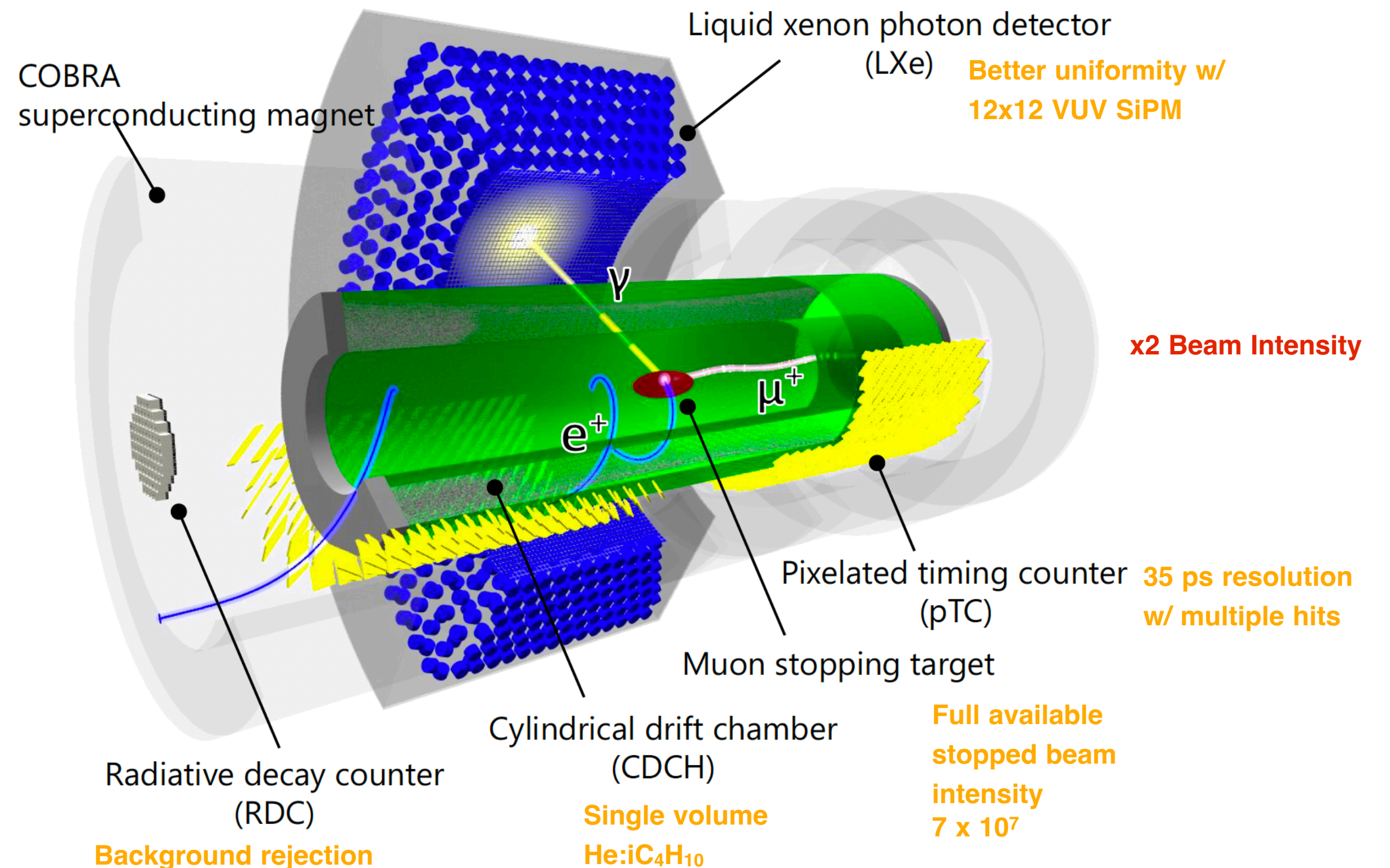


New electronics:
Wavedream

**~ 9000
channels at
5GSPS**

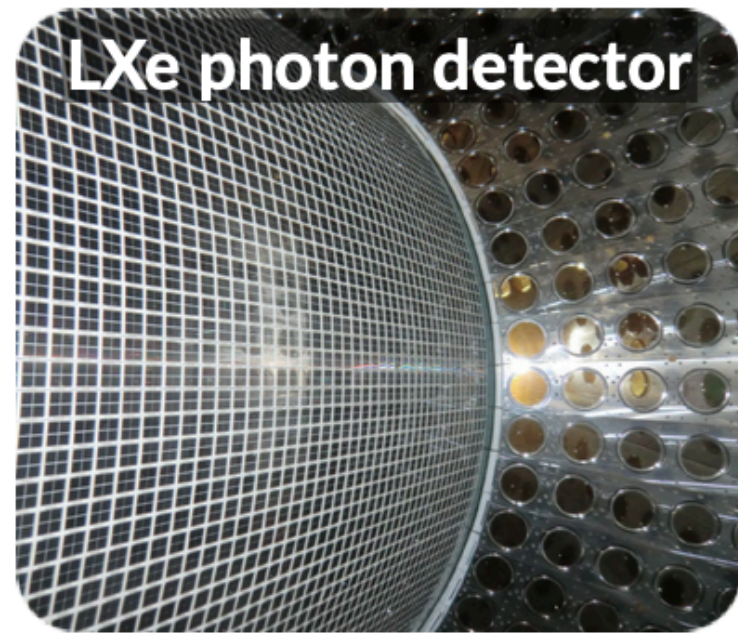
**x2 Resolution
everywhere**

Updated and
new Calibration
methods
**Quasi mono-
chromatic positron
beam**



The MEGII experiment at work

- After a major upgrade, the MEGII detector started data taking in 2021
Eur. Phys. J. C84 (2024) 190



LXe photon detector

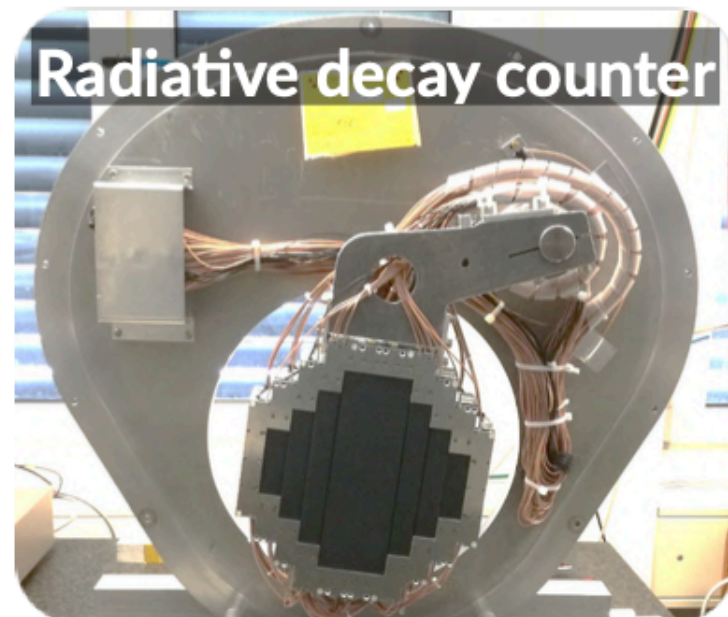
- LXe 900L (~2.7ton)
- Highly granular scintillation readout with SiPM($\times 4092$) + PMT($\times 668$)



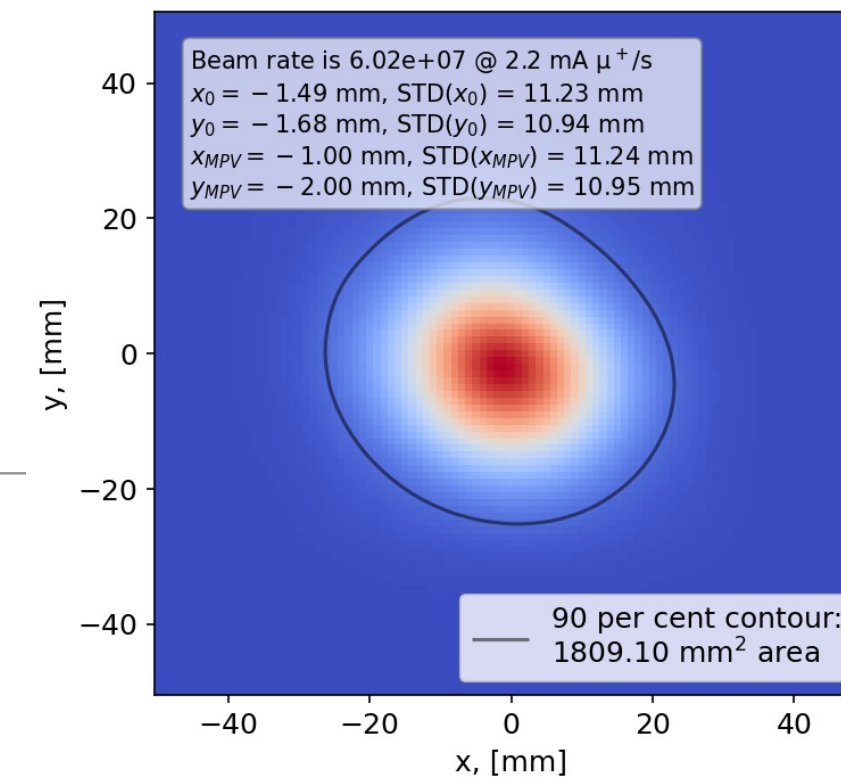
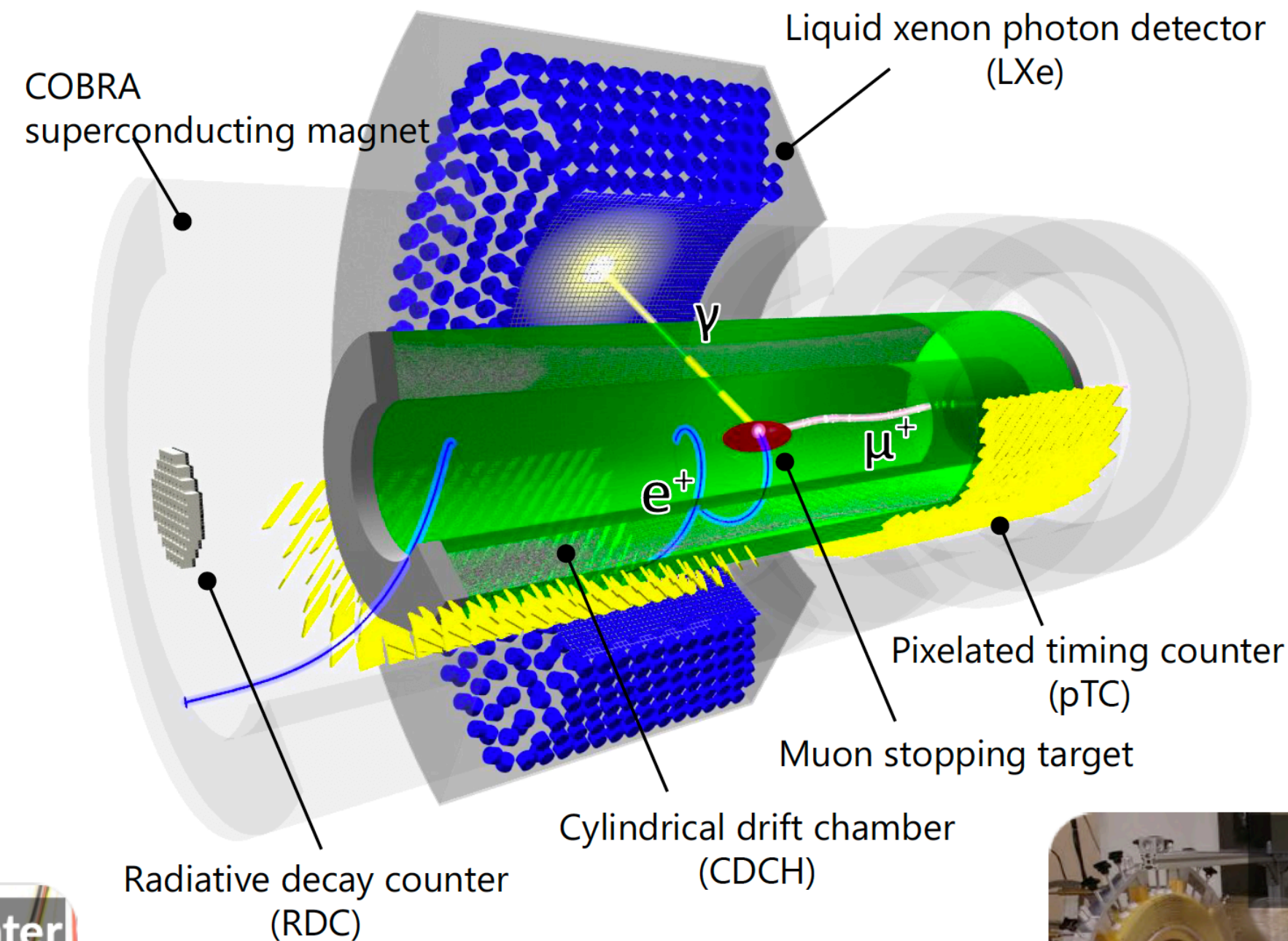
Trigger/DAQ

- ~9000ch waveform readout

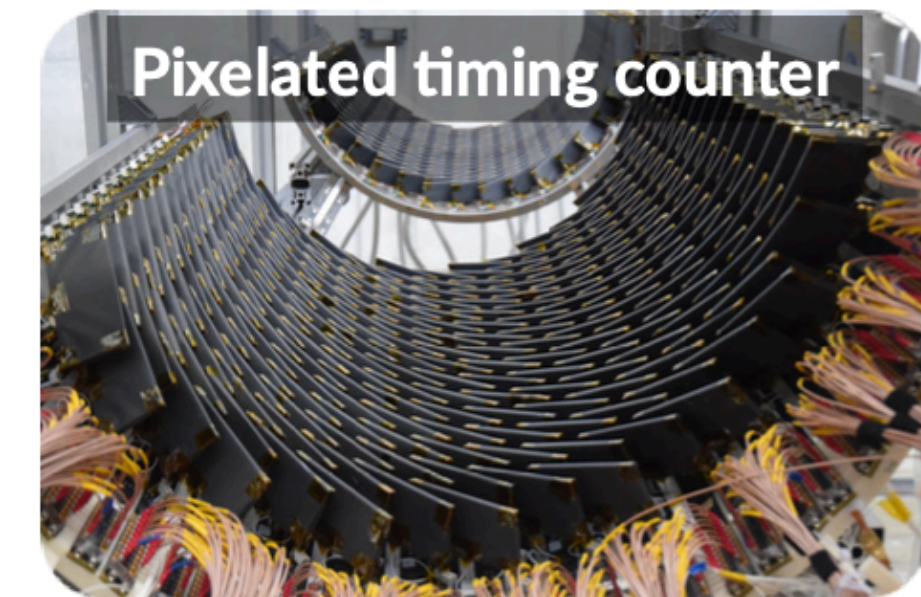
- New in MEG II
- BG- γ suppression by identifying associated low mom. positron



Radiative decay counter



- Up to 5×10^7 stopped μ^+



Pixelated timing counter

- $\times 512$ fast plastic scintillator plates
- 40ps time resolution averaged over multiple hits

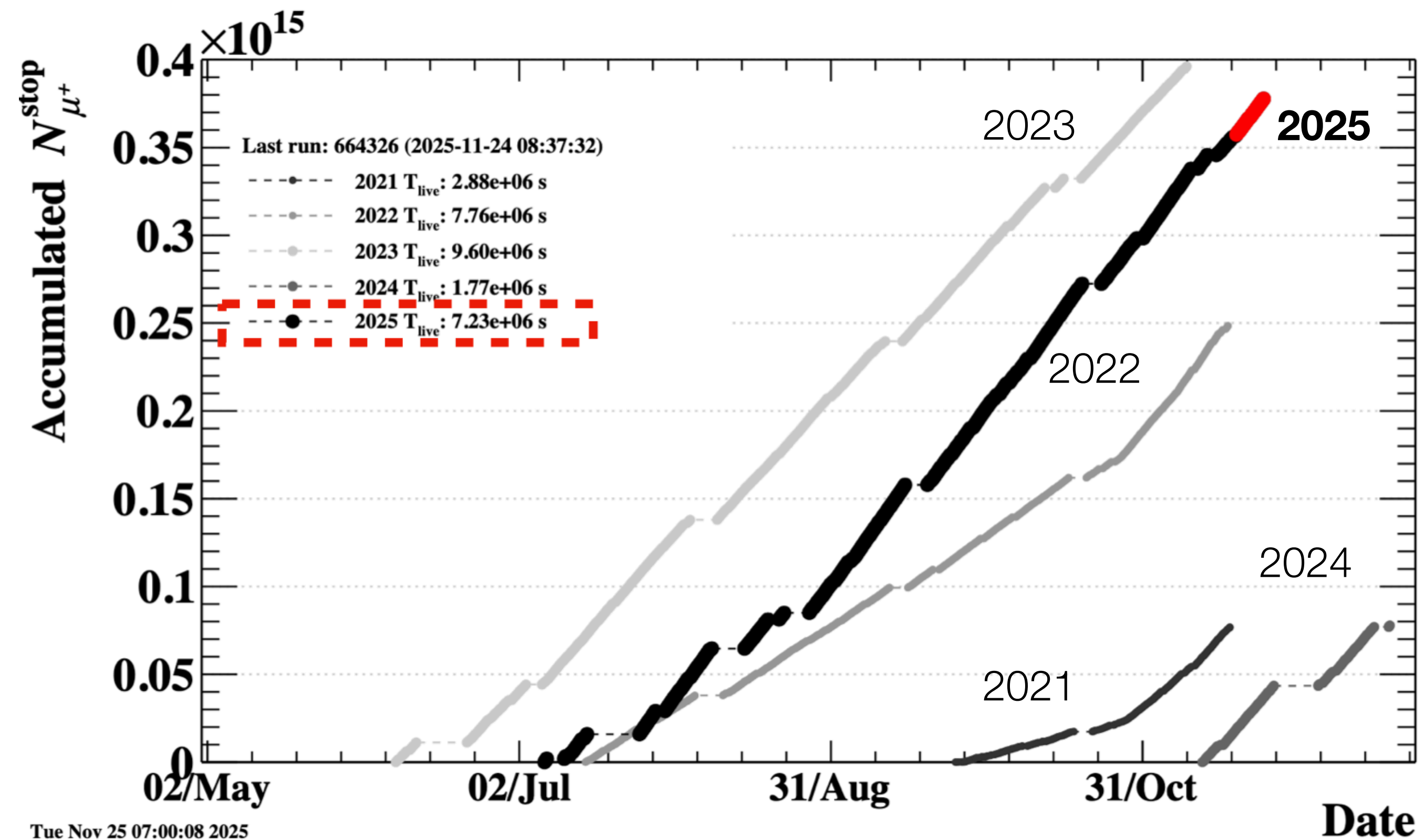


Cylindrical drift chamber

- Ultra-low-mass with single gas-volume
- Drift cells with stereo wires

Physics Run: Data collection

- **2021: first** physics run with the full detector first result of MEGII **published** (Eur. Phys. J. C84 (2024) 216)
- **2022:** long and stable run in optimal conditions: **discussed in this talk and published recently** (Eur. Phys. J. C85 (2025) 1177)
- **2023: largest statistics ever** acquired data analysis ongoing
- **2024: ~5 months in standby** due to technical problem at PSI
- **2025: Ongoing** since beginning of July



$\mu^+ \rightarrow e^+ \gamma$ Analysis Strategy

• Observables to characterise $\mu^+ \rightarrow e^+ \gamma$ signal

$$t_{e\gamma}, E_\gamma, E_e, \theta_{e\gamma}, \phi_{e\gamma}$$

• Blinding signal region

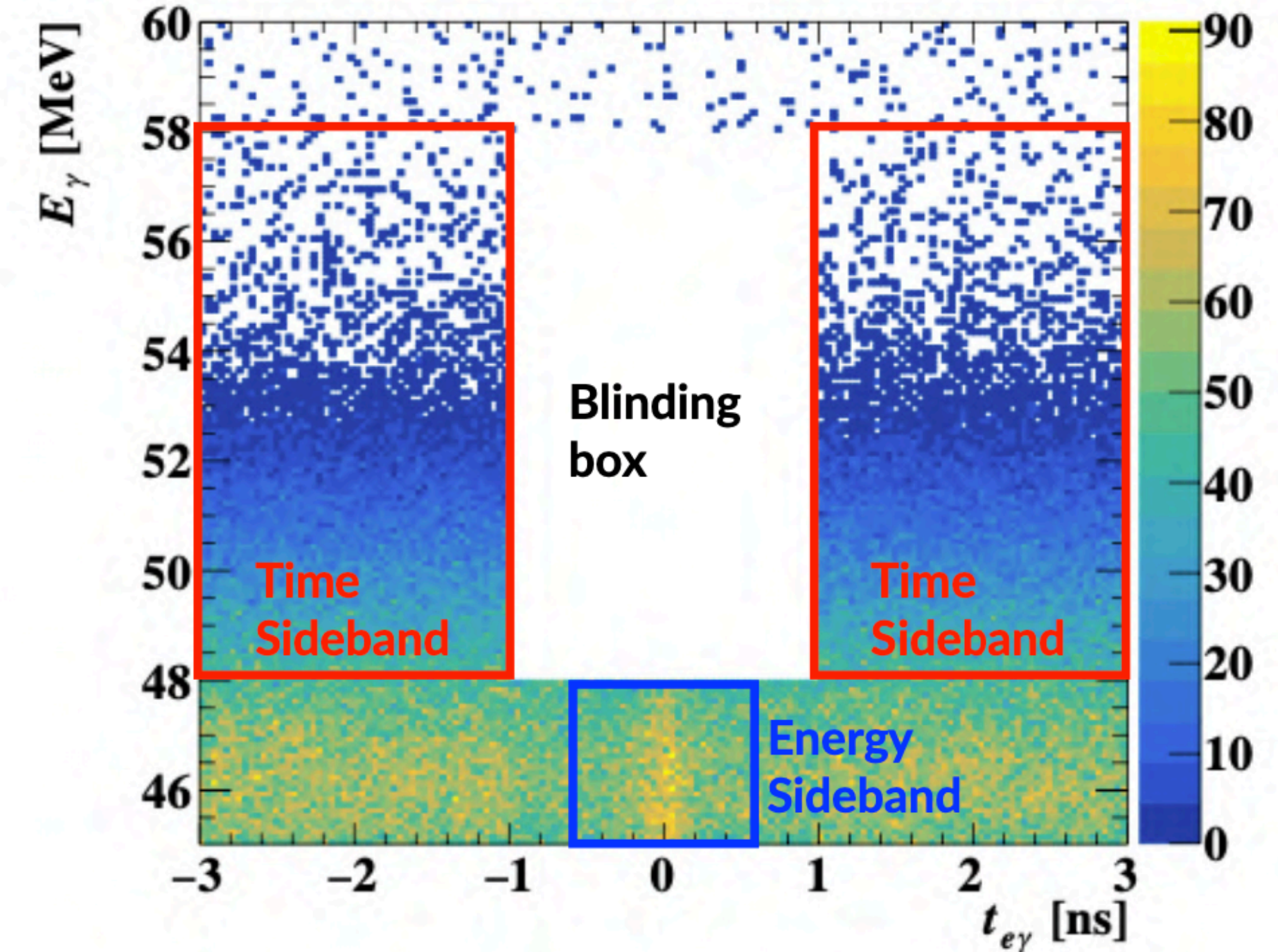
- Blind box: $48 < E_\gamma < 58 \text{ MeV}$, $|t_{e\gamma}| < 1 \text{ ns}$
- BG study at sidebands
 - Accidental BG at time sidebands
 - RMD at energy sidebands

• Maximum likelihood analysis to estimate N_{sig}

- Likelihood fit to analysis window:
 $48 < E_\gamma < 58 \text{ MeV}, 52.2 < E_e < 53.5 \text{ MeV}$
 $|t_{e\gamma}| < 0.5 \text{ ns}, |\phi_{e\gamma}| < 40 \text{ mrad}, |\theta_{e\gamma}| < 40 \text{ mrad}$

• Two independent analyses

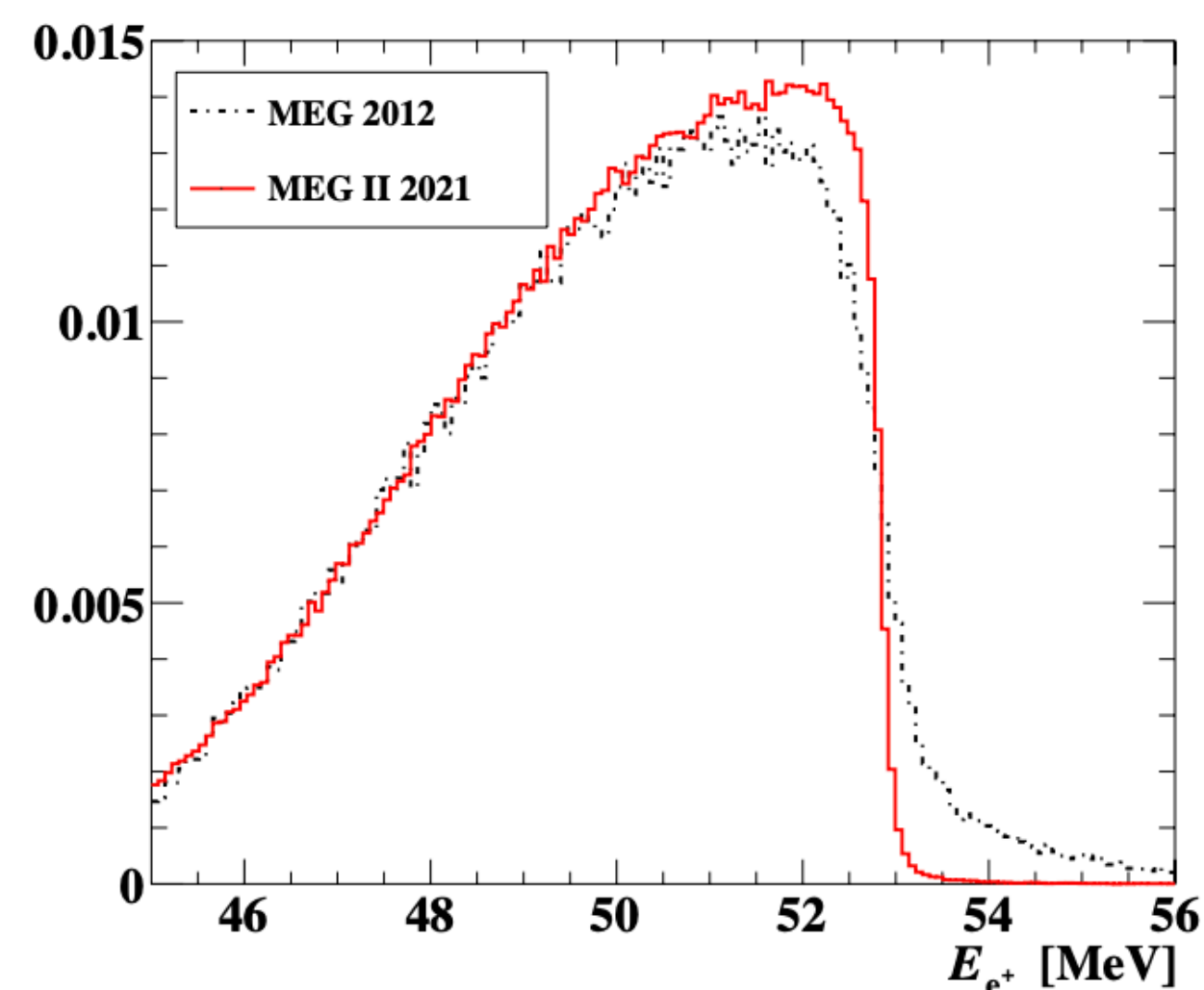
- Per-event PDFs with two angular observables $\theta_{e\gamma}, \phi_{e\gamma}$ ($\leftarrow$ reference)
- Constant PDFs with single angular observable $\Theta_{e\gamma}$ ($\leftarrow$ crosschecking)



$$\mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{ACC}}, x_{\text{T}}) = \frac{e^{-(N_{\text{sig}} + N_{\text{RMD}} + N_{\text{ACC}})}}{N_{\text{obs}}!} C(N_{\text{RMD}}, N_{\text{ACC}}, x_{\text{T}}) \times \prod_{i=1}^{N_{\text{obs}}} (N_{\text{sig}} S(\vec{x}_i) + N_{\text{RMD}} R(\vec{x}_i) + N_{\text{ACC}} A(\vec{x}_i)) ,$$

Detector performance highlights

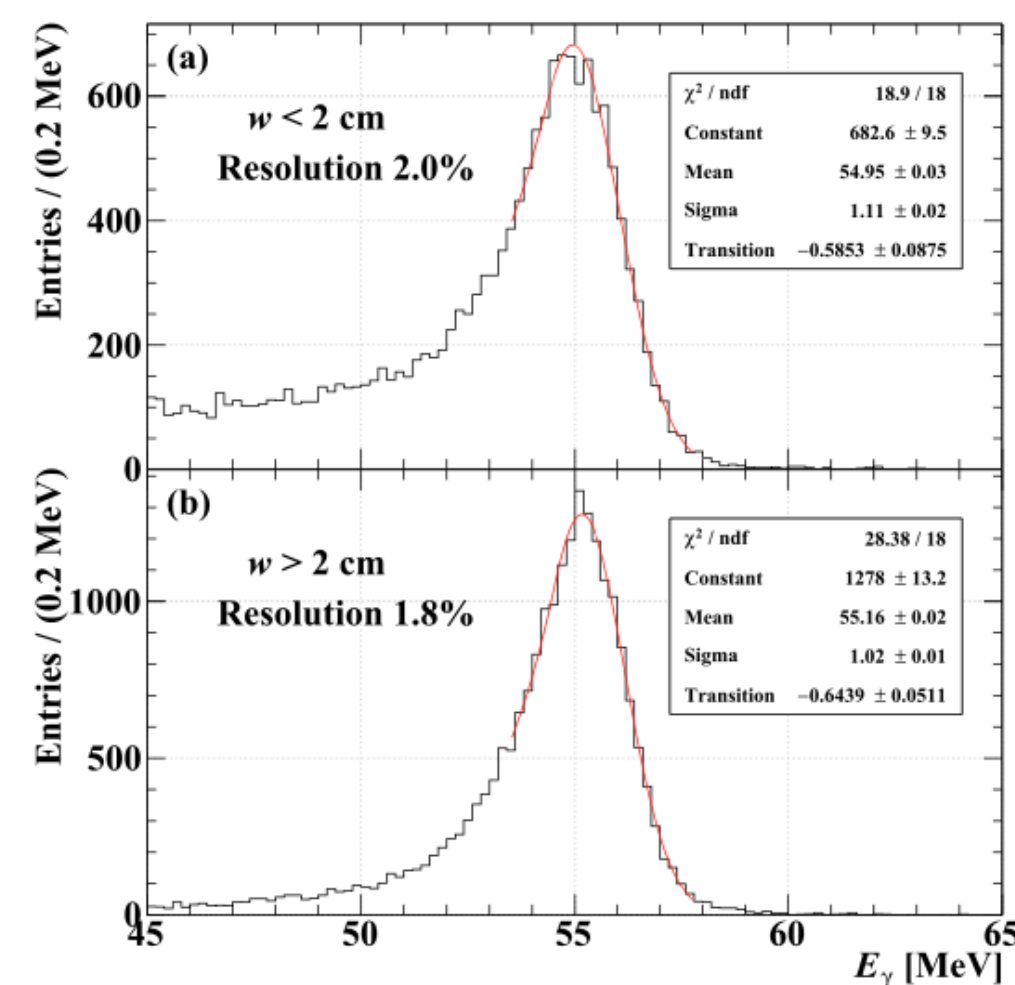
Positron tracking



- Energy resolution: **90 keV**
($\leftrightarrow$ 320 keV@MEG)
- Efficiency: **67 %** @ $3 \times 10^7 \mu/s$
($\leftrightarrow$ 30 % @MEG)

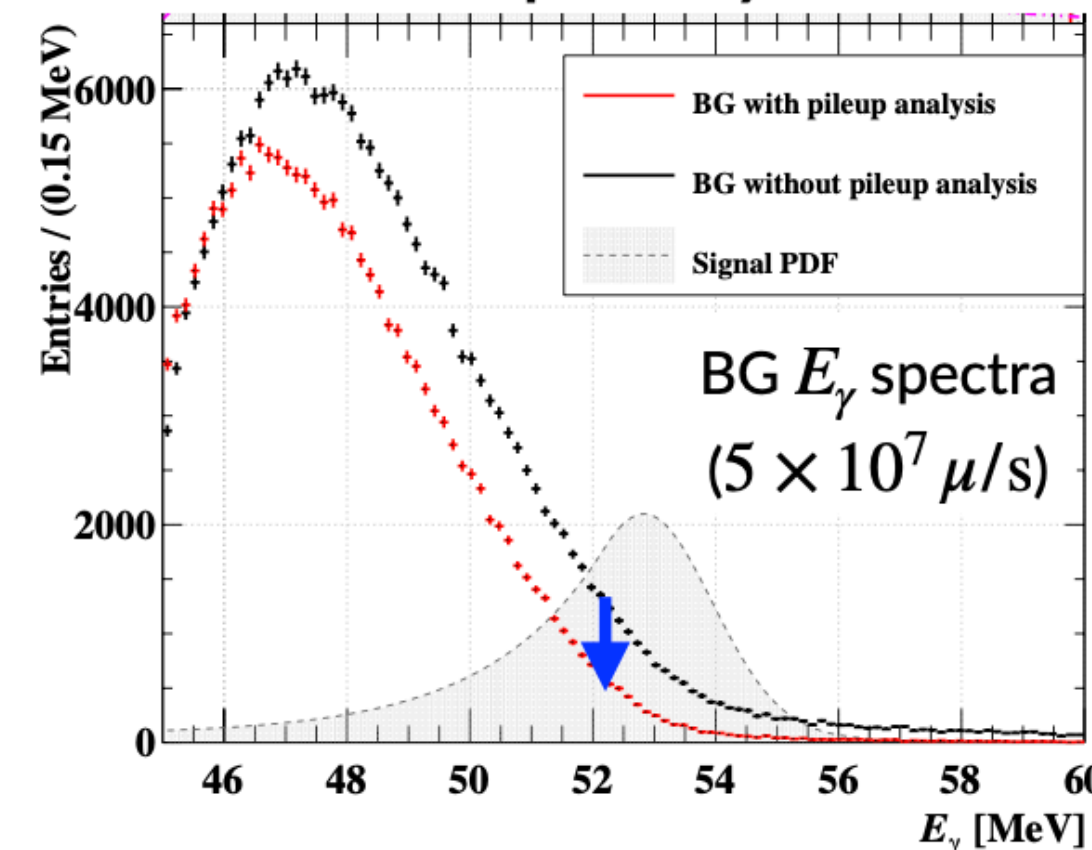
Photon energy

Energy resolution

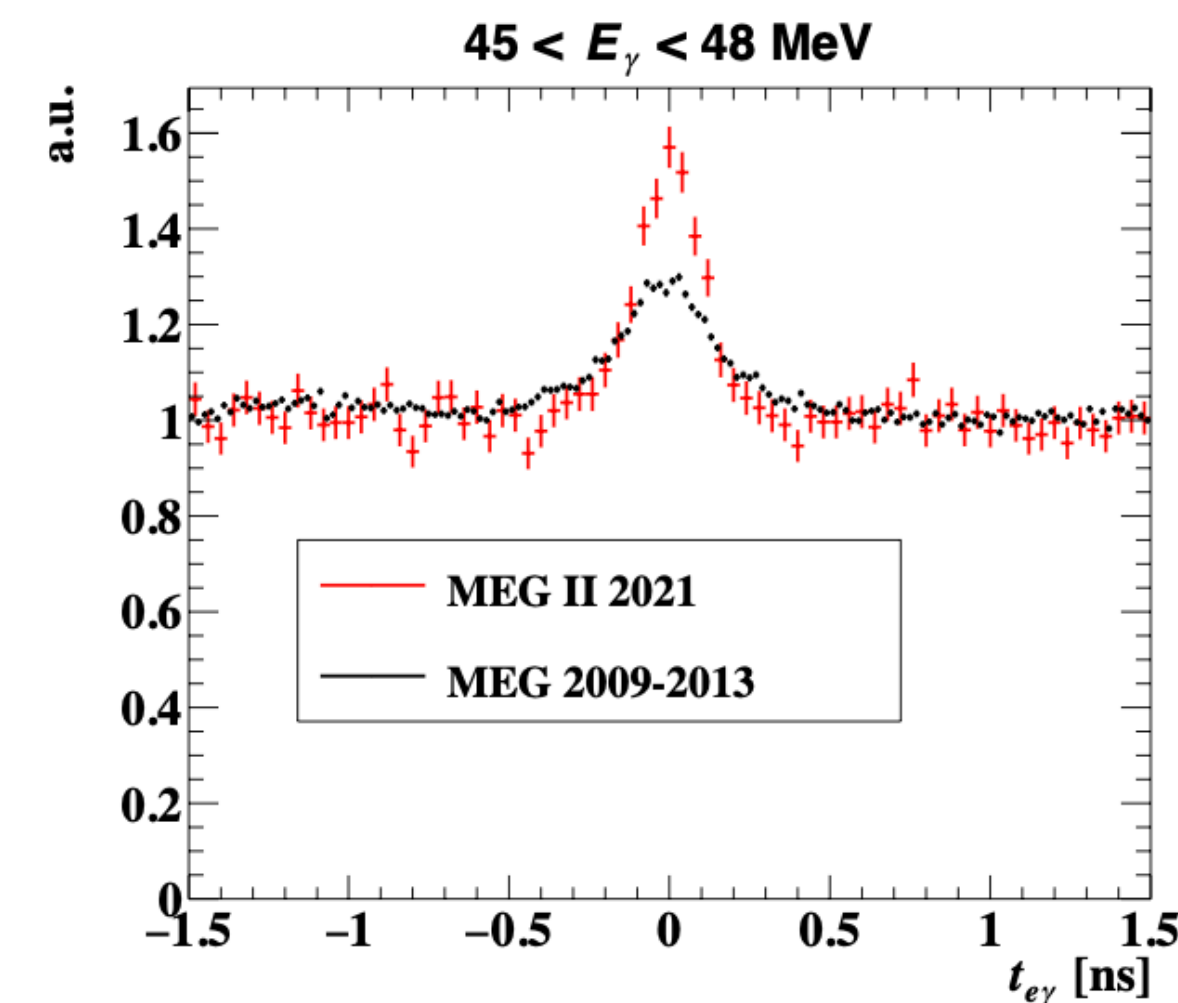


- High-granularity and uniform readout by MPPCs
- Energy resolution: **2.0%/1.8%** for (conv. depth: <2cm/>2cm)
- **Pileup BG reduction by 35%** at 48-58MeV ($5 \times 10^7 \mu/s$)

Pileup analysis



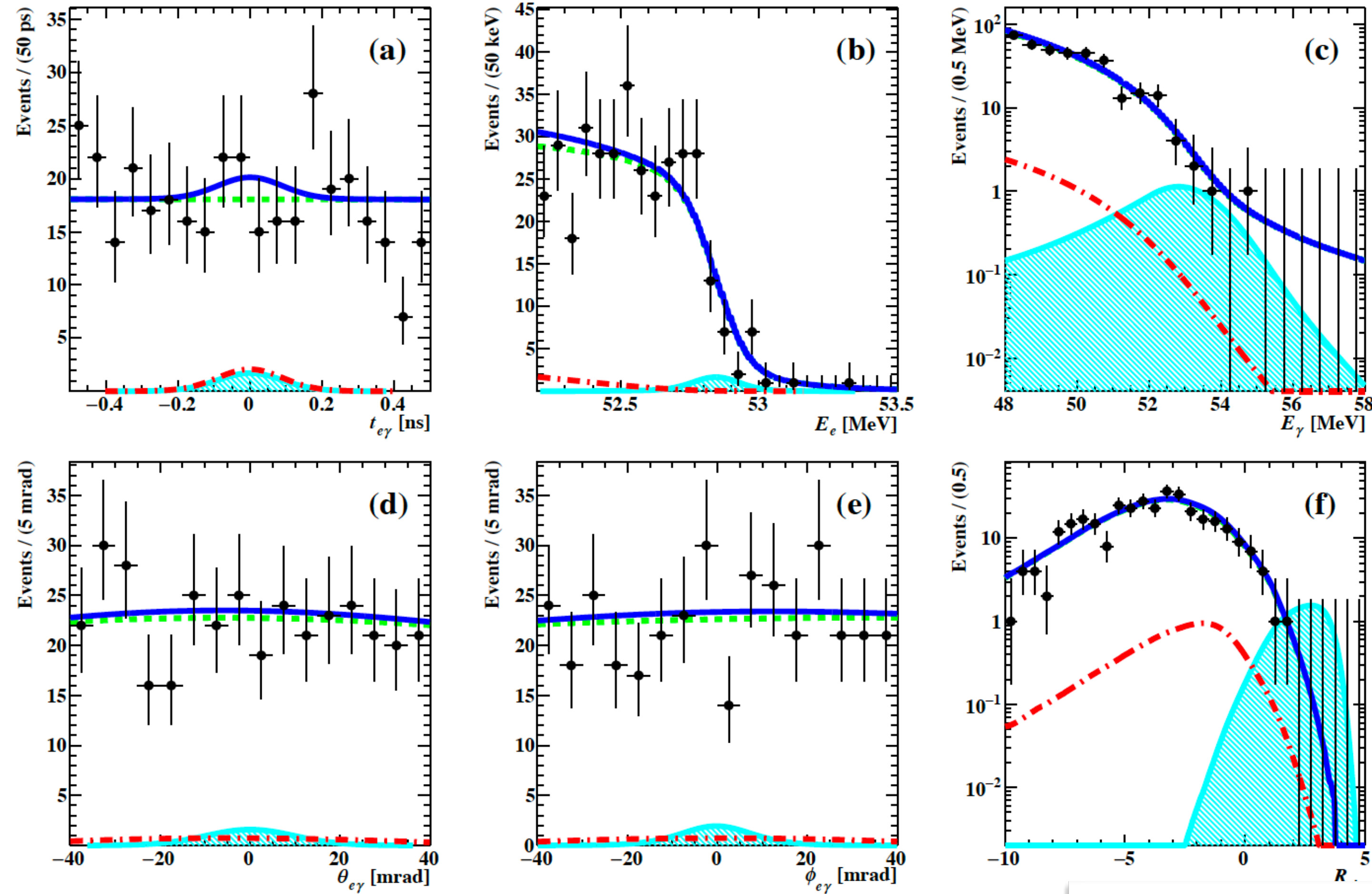
Relative timing



- Overall resolution: **84 ps**
($\leftrightarrow$ 122 ps@MEG)

Significant improvement over MEG

Likelihood fit and result



$N_{\text{sig}} \text{ UL} \times 4$

Accidental

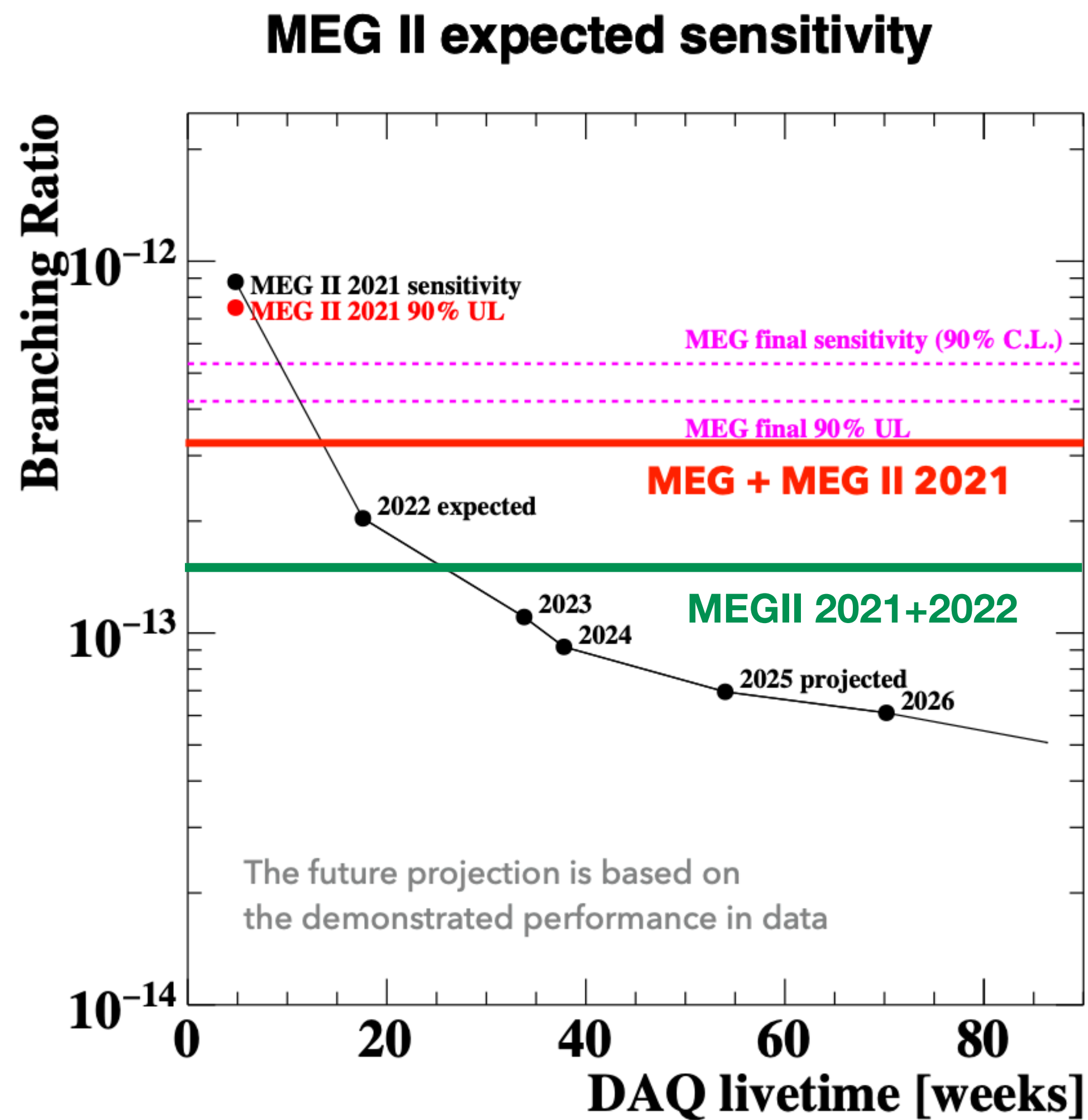
RMD

$$R_{\text{sig}} = \log_{10} \left(\frac{S(x_i)}{f_{\text{RMD}}R(x_i) + f_{\text{ACC}}A(x_i)} \right)$$

The 90% C.L. upper limit on the branching ratio on $\mu^+ \rightarrow e^+ \gamma$ based on 2021+2022 data is

$$\mathcal{B}_{90} = 1.5 \times 10^{-13}$$

Where we are aiming at...



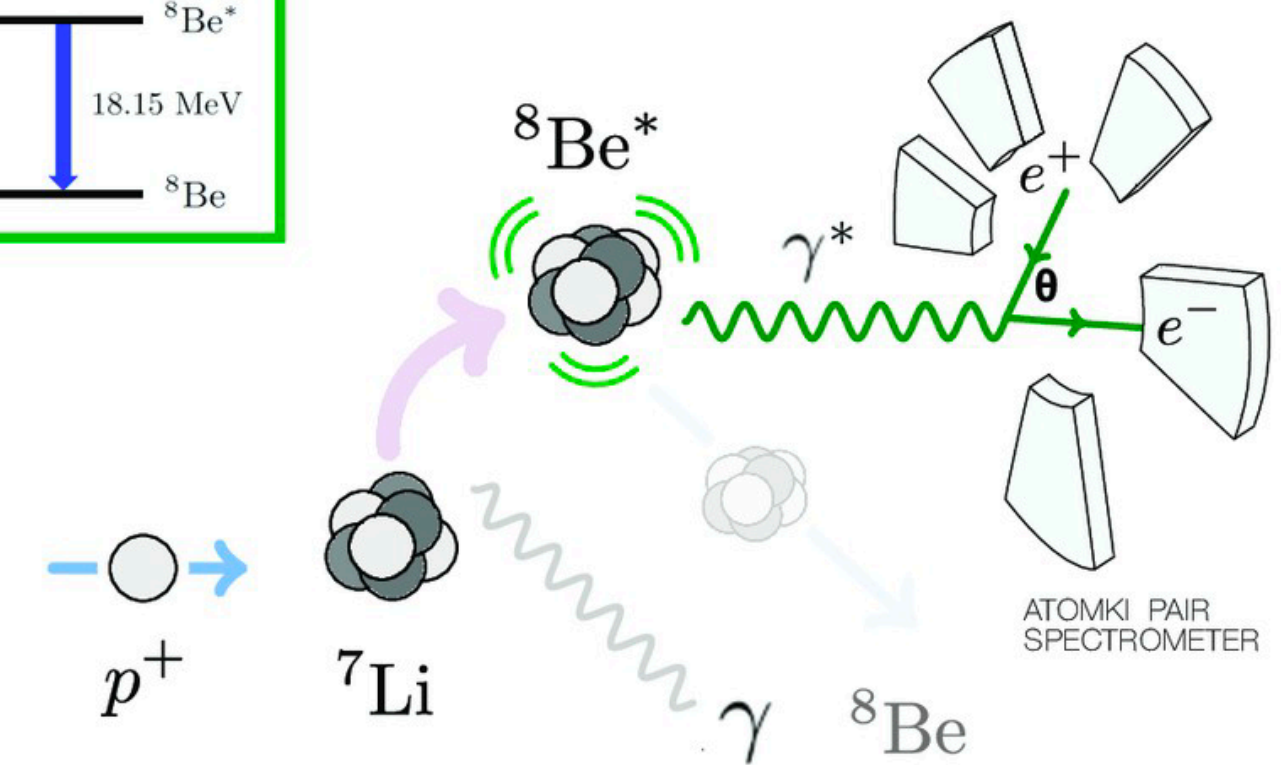
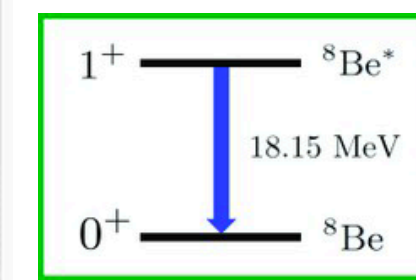
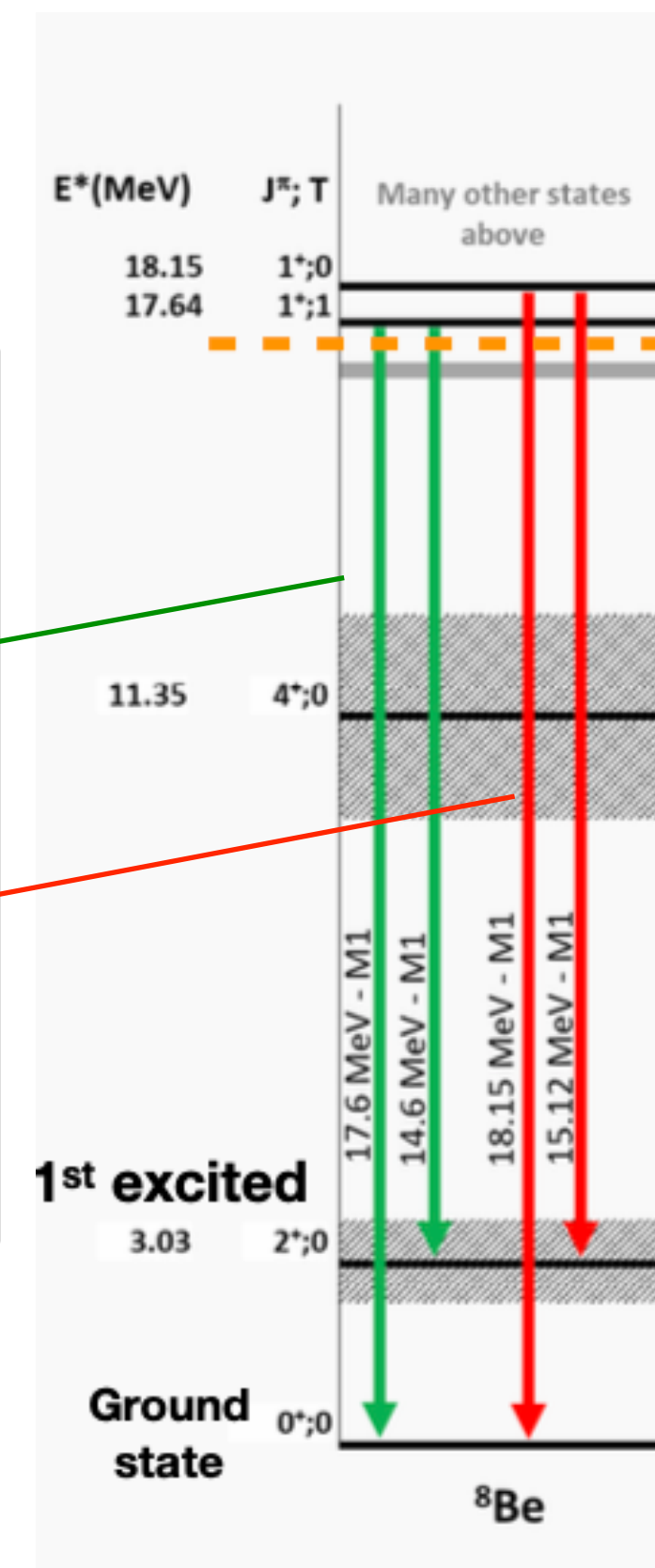
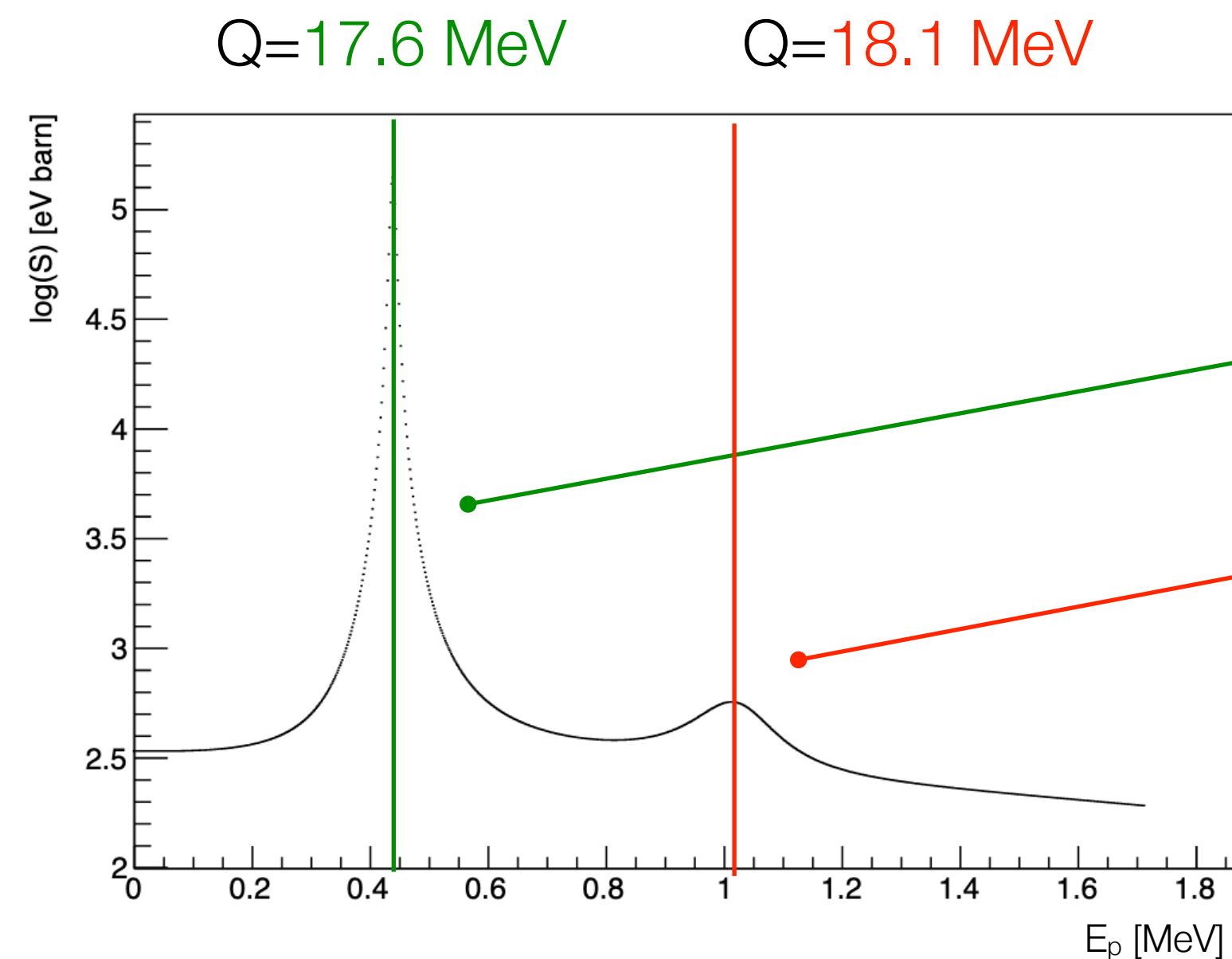
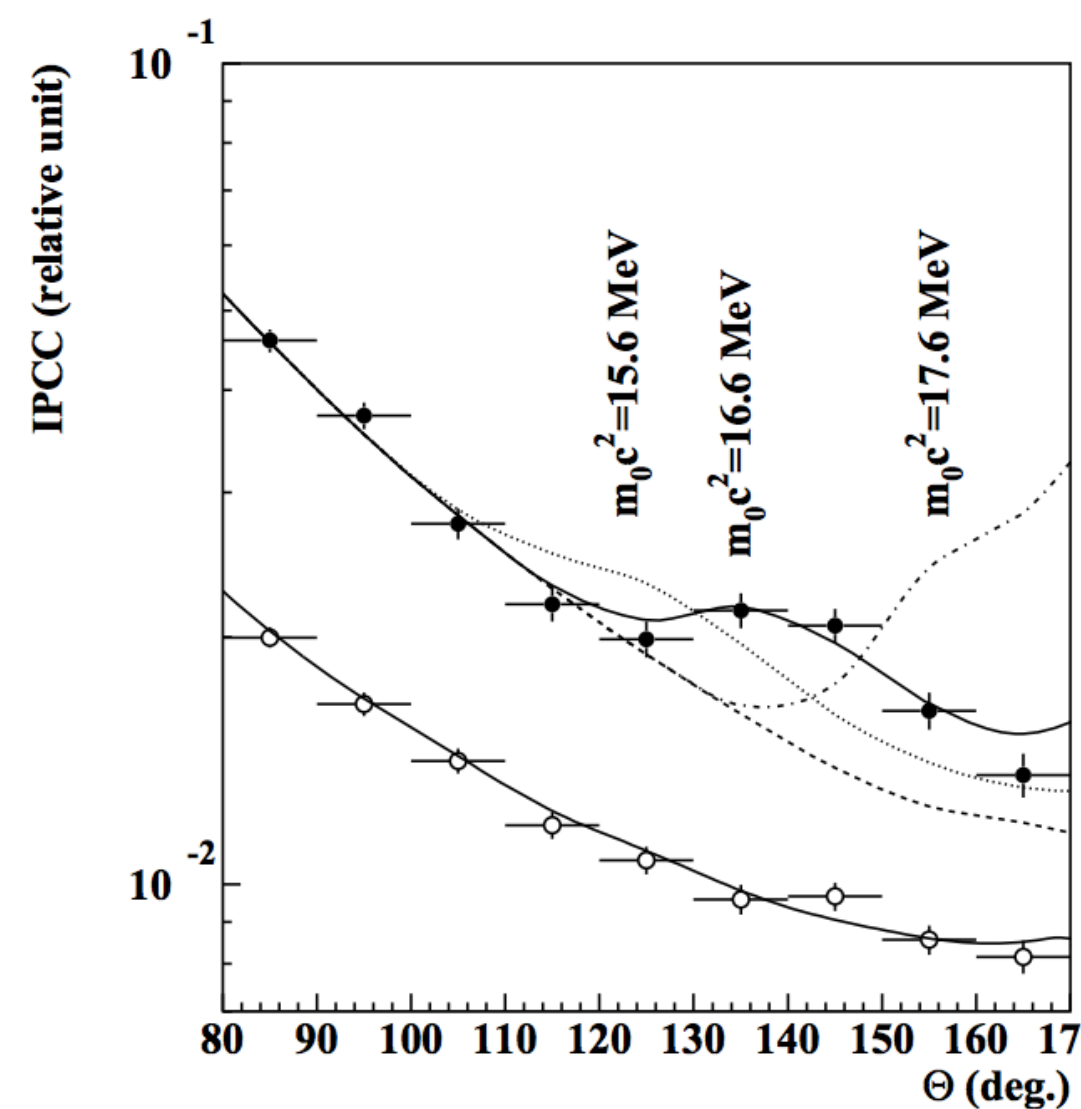
The beryllium anomaly

- Hint for the production of a neutral, 17 MeV boson, potential mediator of a fifth force: X17 (ATOMKI collaboration)
 - Observed in the ${}^7\text{Li}(p, e+e-){}^8\text{Be}$ reaction at 1030 keV (not at 440 keV)
 - Observed in the ${}^3\text{H}(p, e+e-){}^4\text{He}$ and ${}^{11}\text{B}(p, e+e-){}^{12}\text{C}$

Phys. Rev. Lett. 116,
042501
arXiv:2205.07744

Phys. Rev. C 104, 044003

Phys. Rev. D 95, 035017



Excess consistent with

- Light boson mass = $16.95 \text{ MeV}/c^2$
- Branching ratio (X17/gamma) = 6×10^{-6}

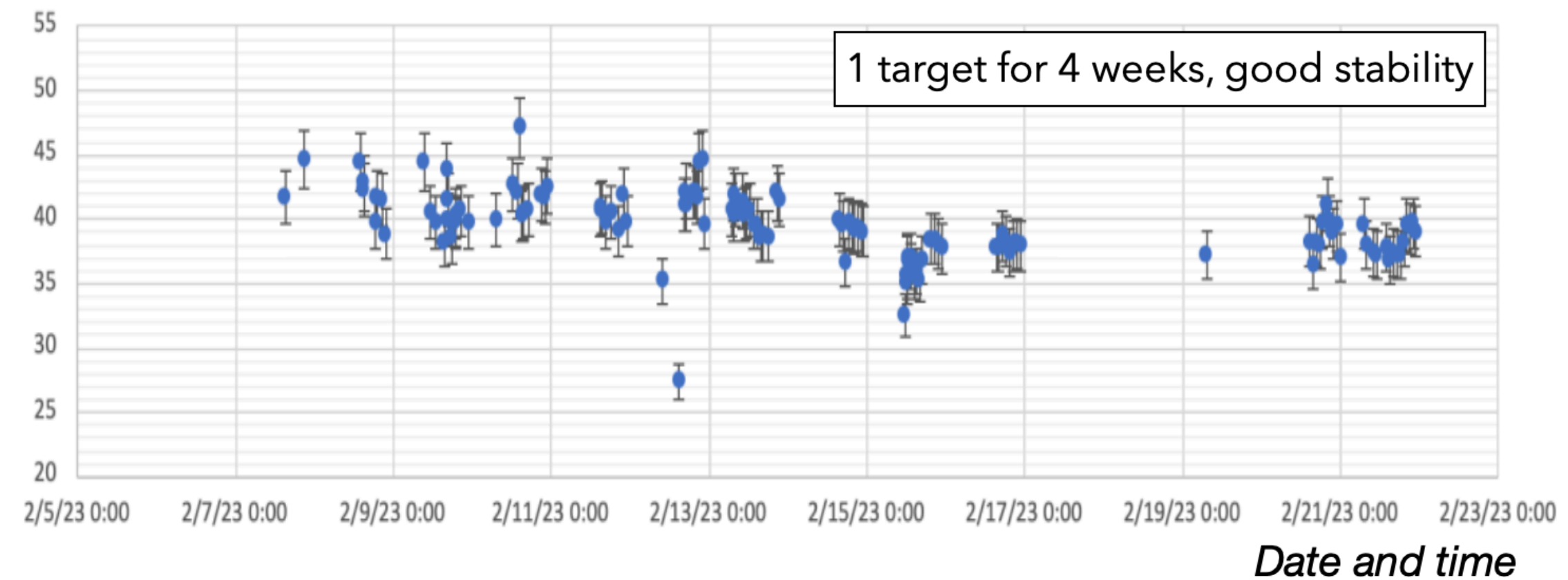
Collected data sample

- **Pivotal** run **2022**: Proton beam tuning, Mechanical/integration test of the new parts, LiF and LiPON target test, Different trigger settings, Optimised Data Taking and Reconstruction Algorithms

- **Physics** run **2023**: 4 weeks producing mainly the 17.6 MeV gamma-line

- Proton energy at 1080 keV
- Beam composition: H+ (~75%) and H2+ (~25%)
- Thick LiPON (~7 μm)
- Both 440 keV and 1030 keV excited simultaneously

Gamma rate in BGO per current unit [Hz/ μA]

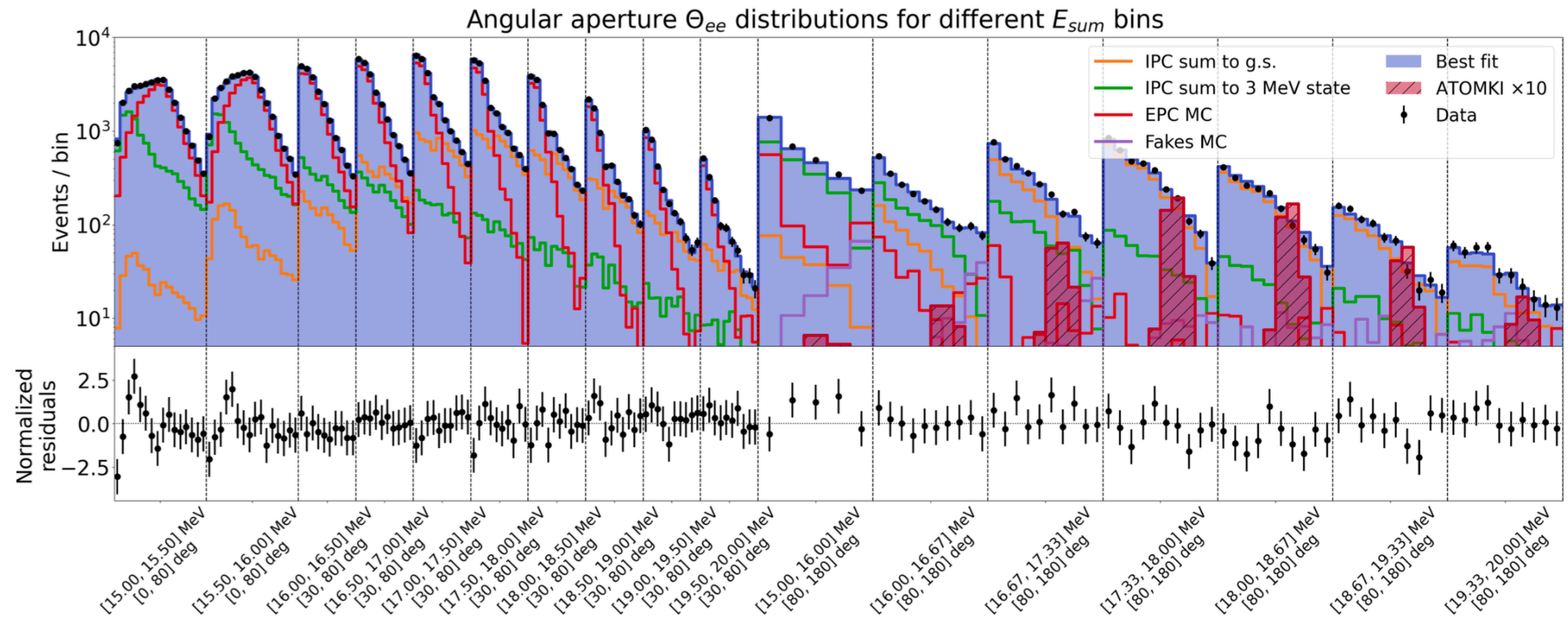


- Statistics:
 - ~75 M Events
 - ~**500 K** Events Reconstructed pairs
- On full range of the Esum and Angular Opening angle observables:
 - ~60% EPC (Dominant at low angle), ~40% IPC (Dominant in the signal region)

Results from the ML fit

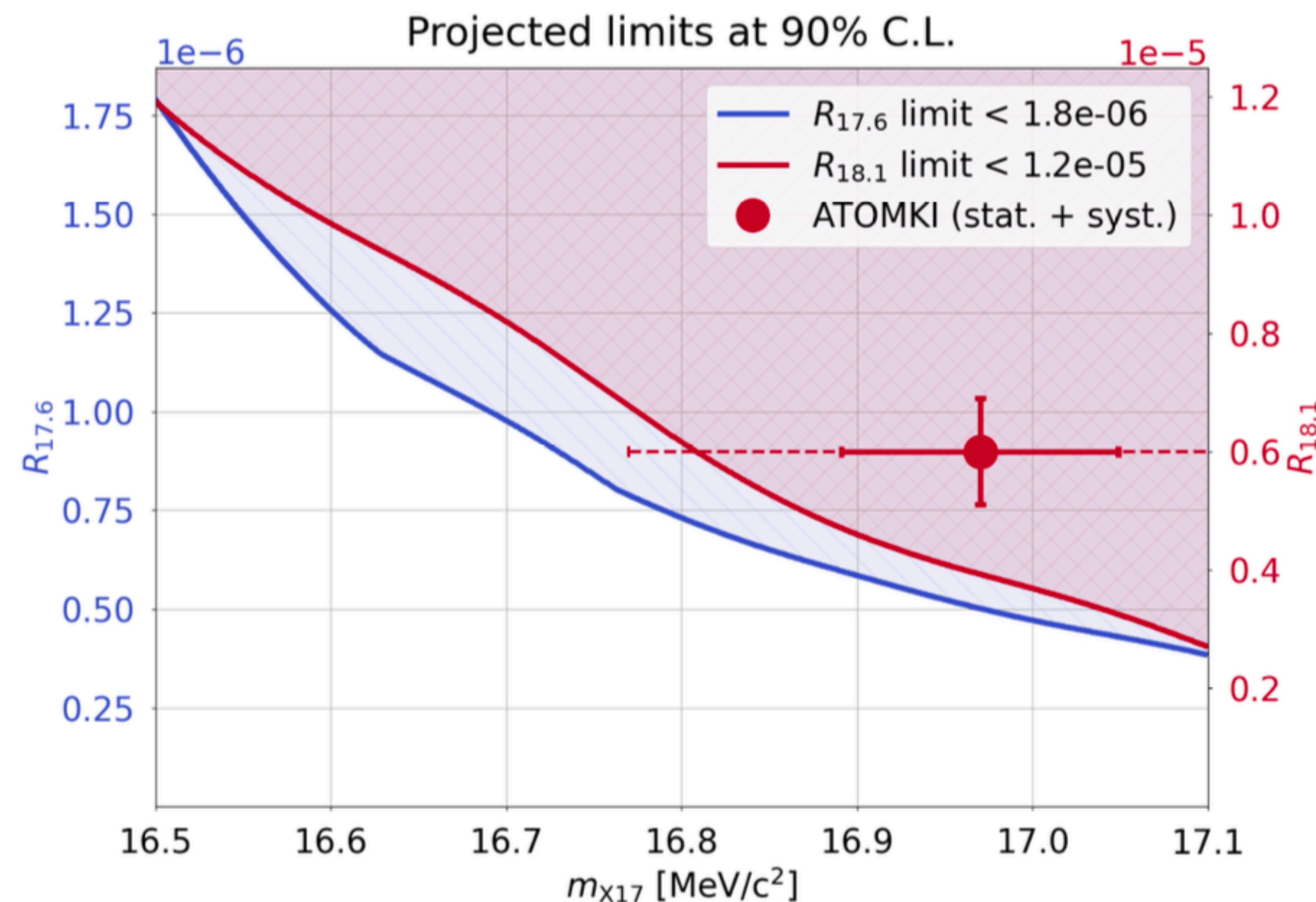
Best fit

- Sample of **17.6 MeV** [78.4%] and **18.1 MeV** [21.6%]
- **10+-92 signal events at Q = 18.1** MeV for a $m_{X17} = 16.5$ MeV, $O(100)$ expected based on ATOMKI
- **0+-68 signal event at Q = 17.6** MeV - for a $m_{X17} = 16.5$ MeV, $O(300)$ expected based on ATOMKI/Feng et al.
- IPC: **12.6(9)%** Q = 18.1 MeV and **45.8(13)%** Q = 17.6 MeV
- Goodness-of-fit: p-value = **10%**



90% Confidence Limits

- Systematic effects (energy scale, resolution, mass dependence, relative acceptance) are all included as nuisance parameters



$$R_{17.6} < 1.8 \times 10^{-6}$$

corresponding to $N_{\text{sig}}(17.6) < 200$

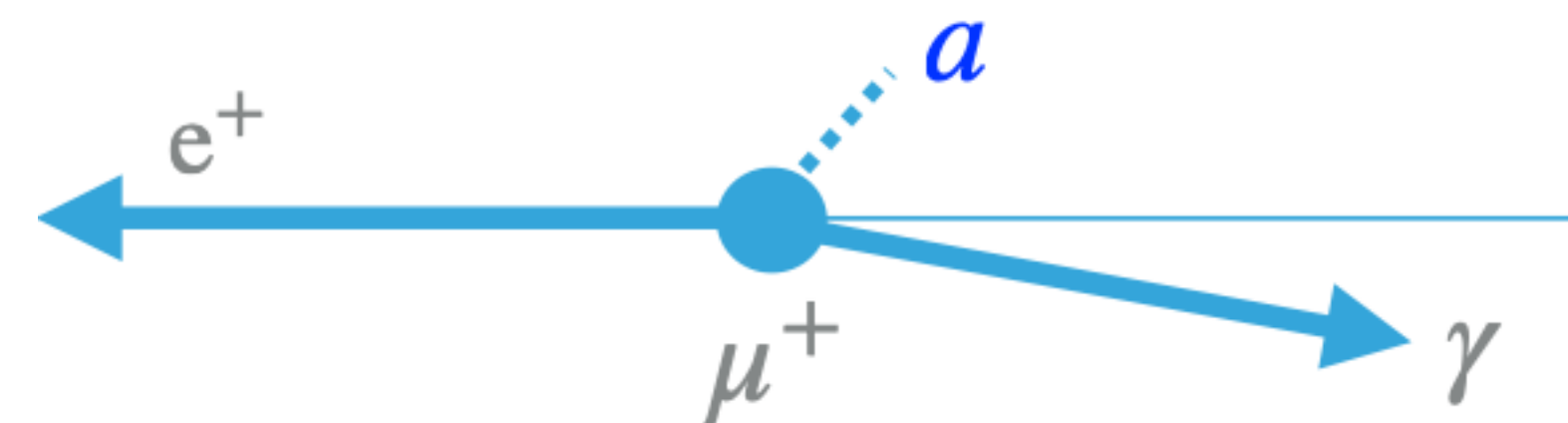
$$R_{18.1} < 1.2 \times 10^{-5}$$

corresponding to $N_{\text{sig}}(18.1) < 230$

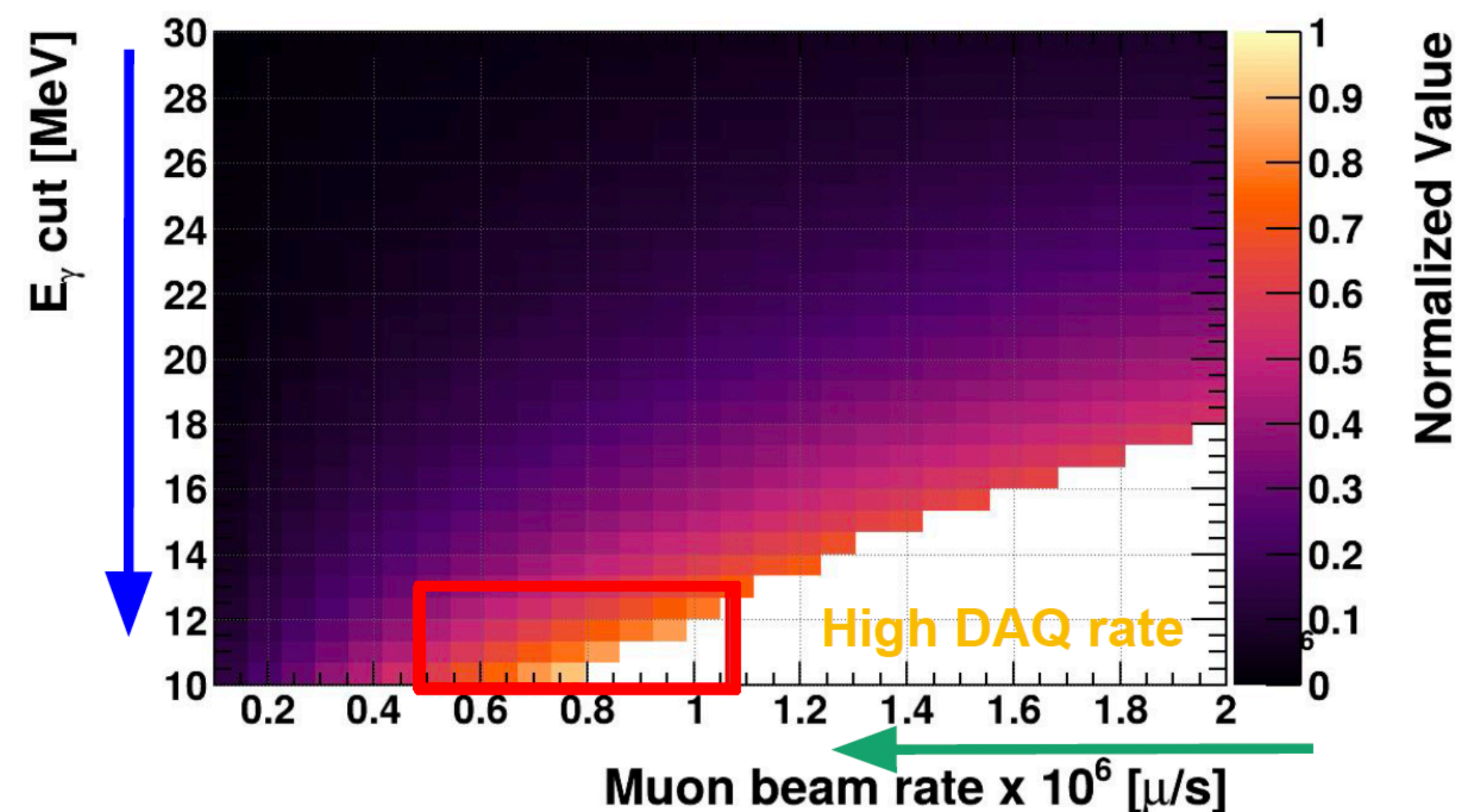
- MEGII plans to continue X17 data taking during the next HIPA shutdown 2026, Exploiting further the only 1030 keV resonance (assuming NO conflicts with the main MEG data taking)

Axion-like particle (ALP) searches with MEGII

- The muon decay to ALP should just look like a radiative muon decay (RMD)
- It features different topology from MEG decay $\rightarrow$ 3 body instead of 2 in the final state
 - different trigger selections to maximize signal acceptance
 - low photon energy cut $\rightarrow E_\gamma > 10$ MeV
 - no back to back topology
 - need for lower beam rate to keep the trigger under 50 Hz
- Use calibration data taken for a few days with low photon energy (>18 MeV) at low beam rate ($\sim 10^6$ /sec)

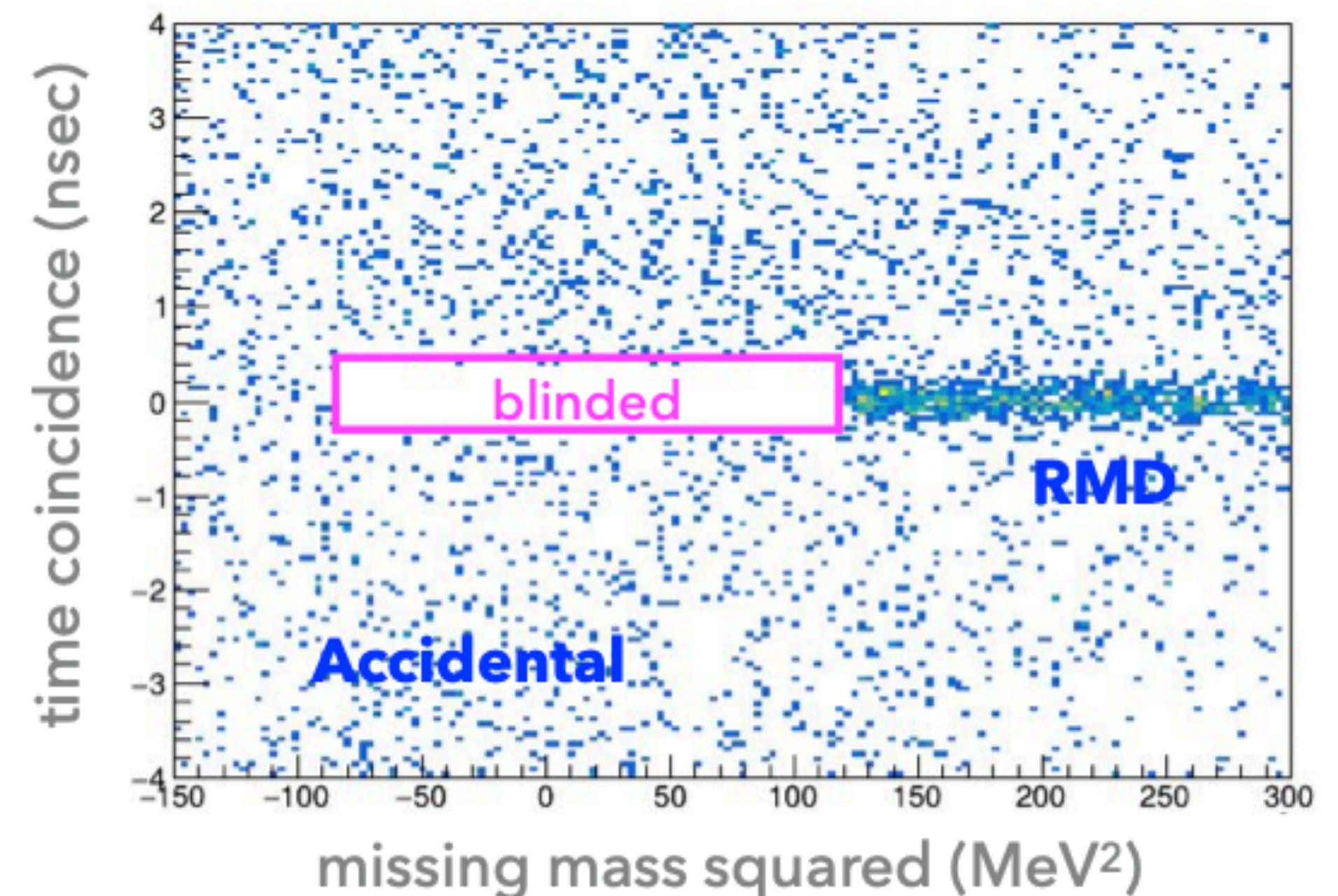
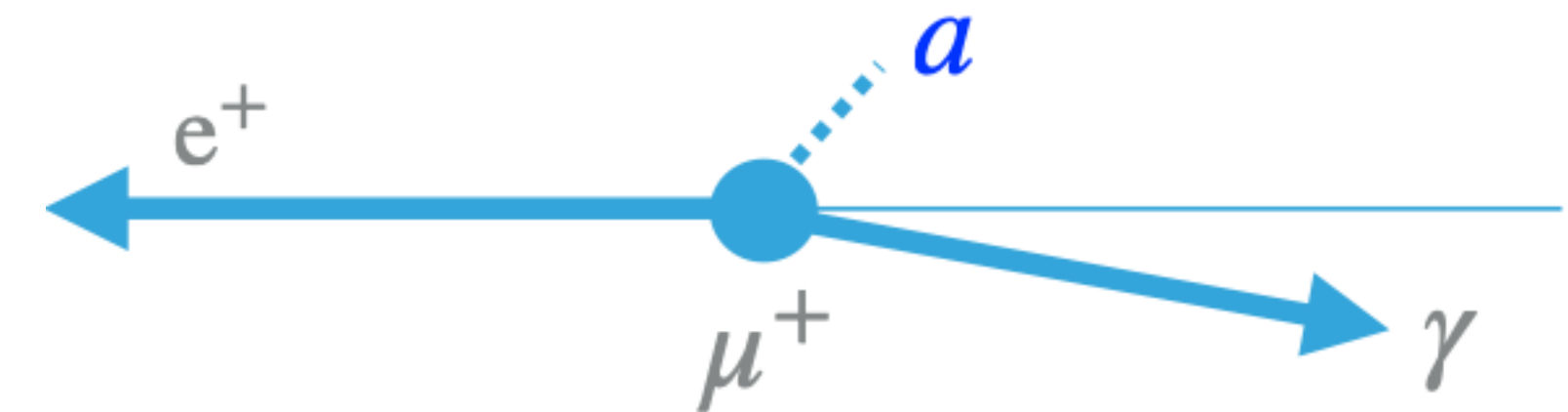


Conditional Normalization Function



Axion-like particle (ALP) searches with MEGII

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- Use calibration data taken for a few days with low photon energy (>18 MeV) at low beam rate ($\sim 10^6/\text{sec}$)
- **The ongoing analysis indicates that we can exceed the TWIST limit**



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



Mu3e: Latest news and currents status

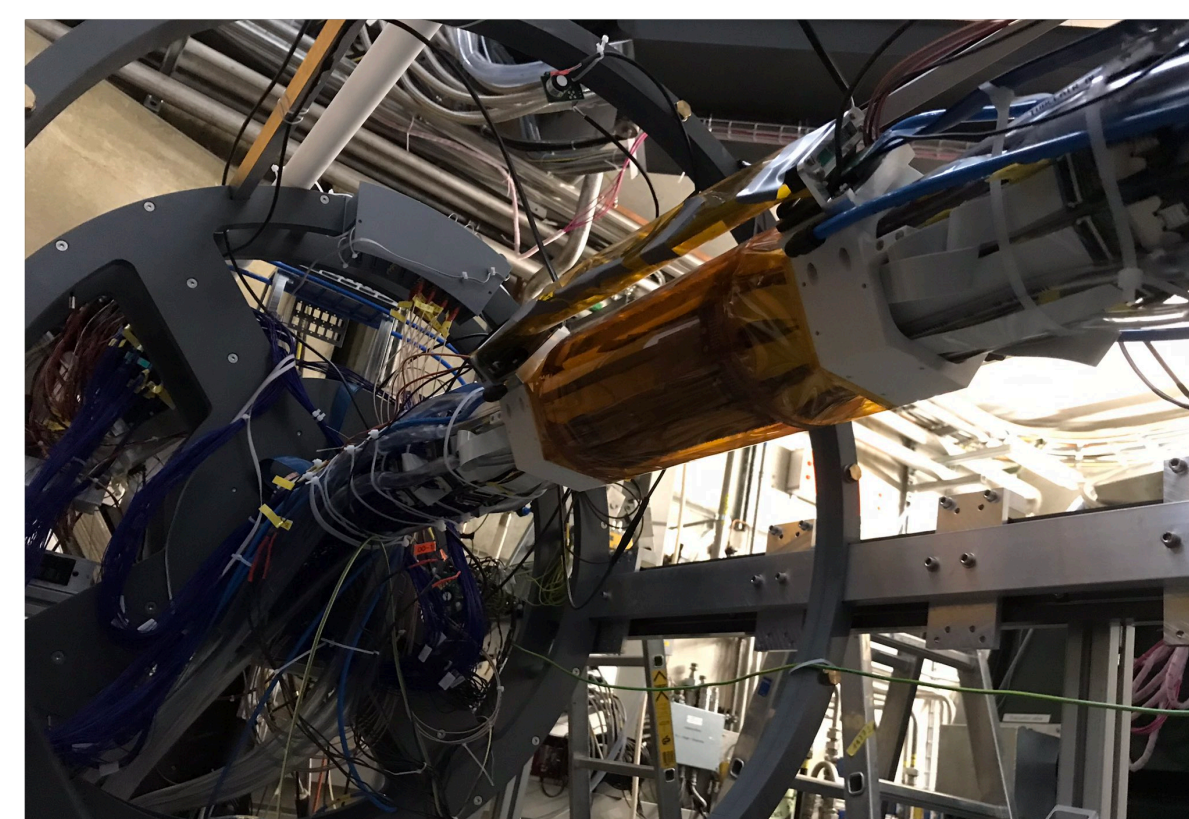
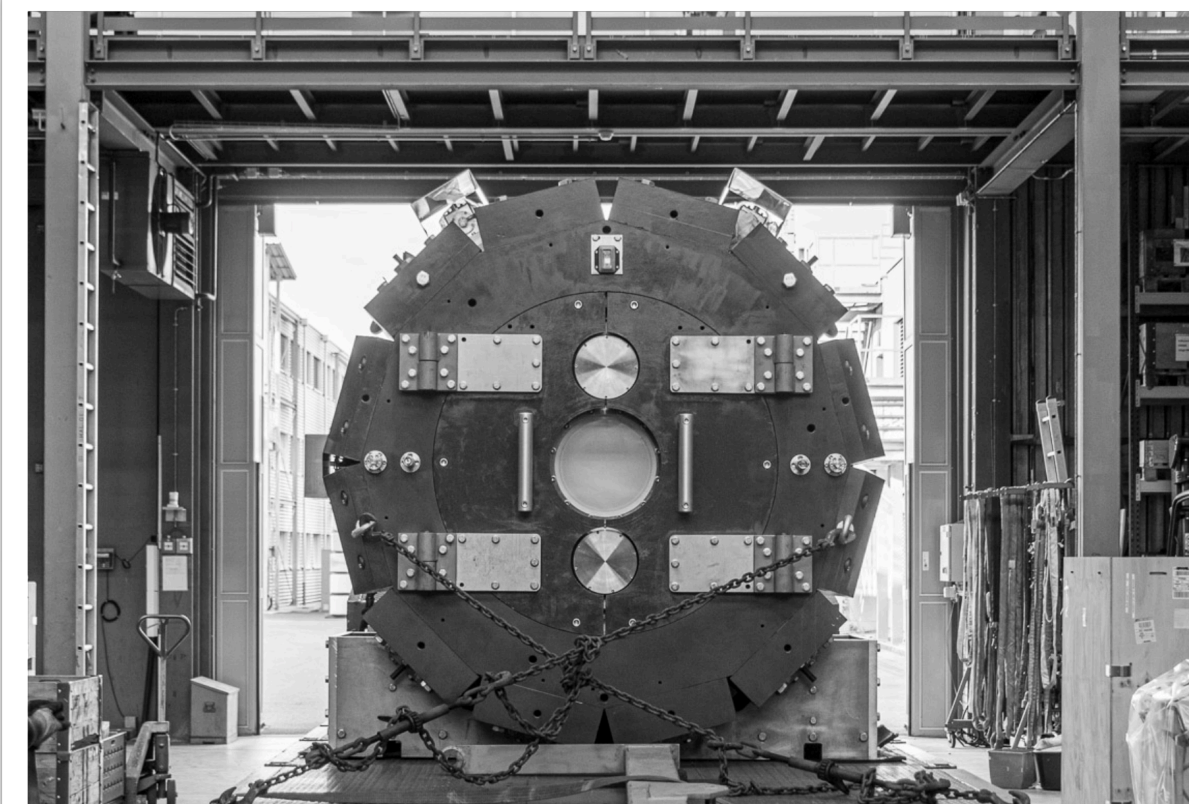
Key points:

- **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!**
 - **2.49×10^8 mu/s @2.4 mA** (at the collimator): The highest beam rate in pie5 at the collimator
 - **1.02×10^8 mu/s @2.4 mA** (Mu3e magnet): Several beam configurations studied, some of them connected with possible Mu3e magnetic field intensity optimisation

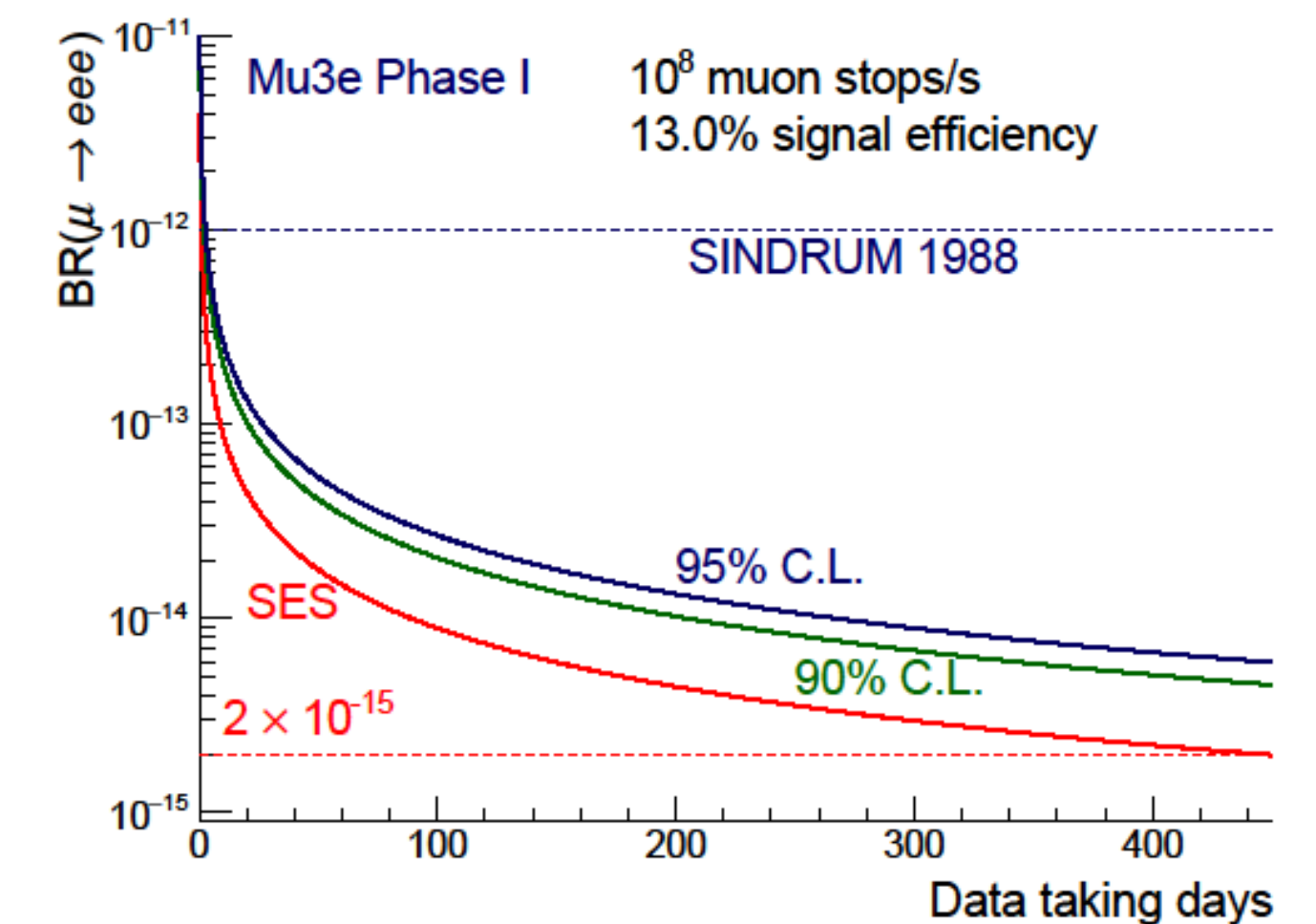
Time line phase I (exploiting current beam-line intensity)

- **Engineering run: 2025**
- First physics run: 2026

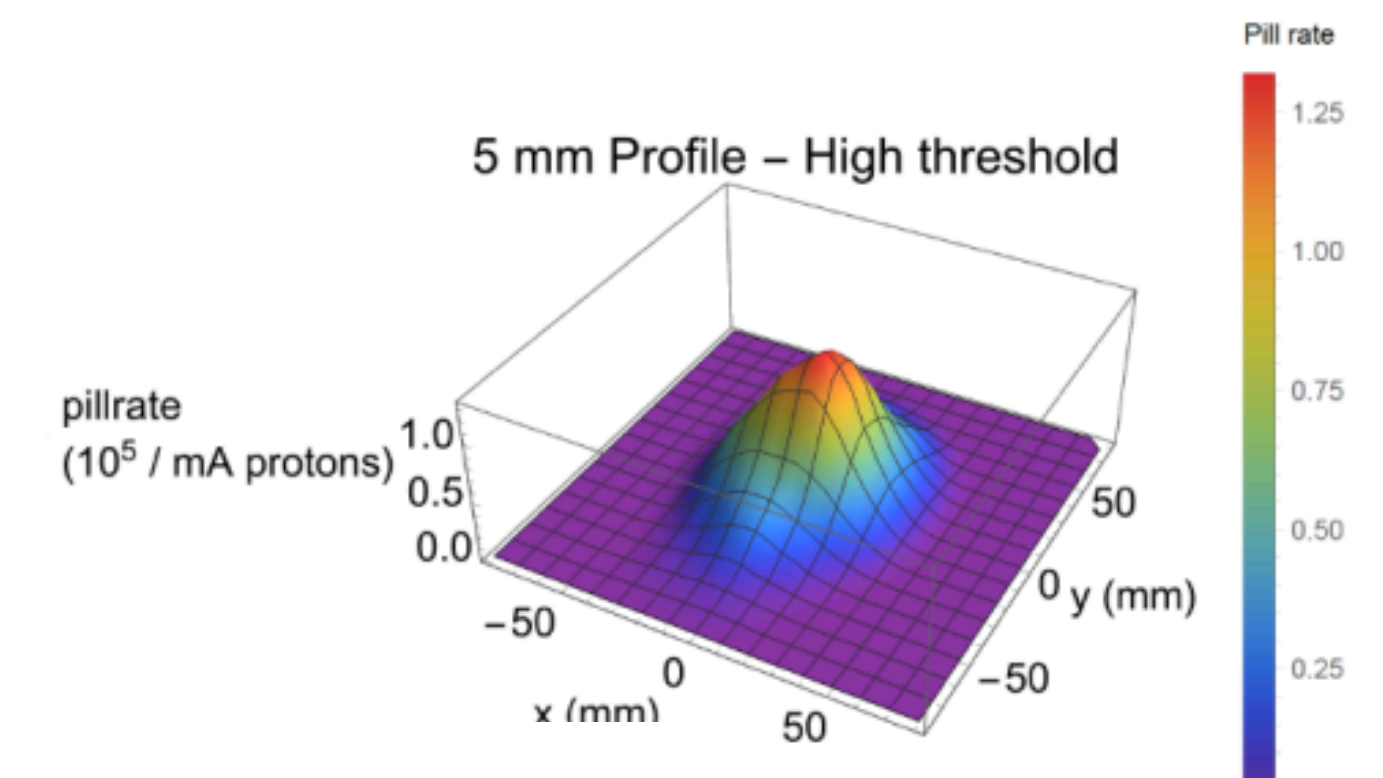
Phase II: It requires 10^9 mu/s $\rightarrow$ **HiMB**



Full analysis performed on
Simulated data

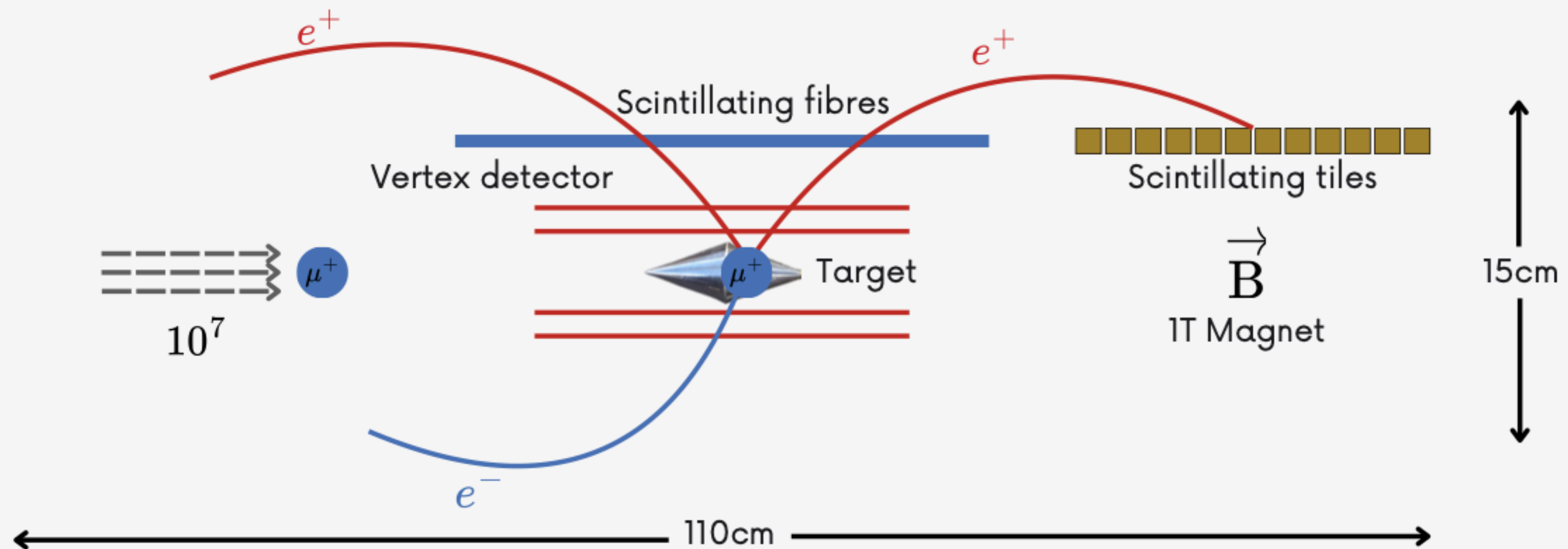


Beam commissioning



2.49×10^8 mu/s @2.4 mA

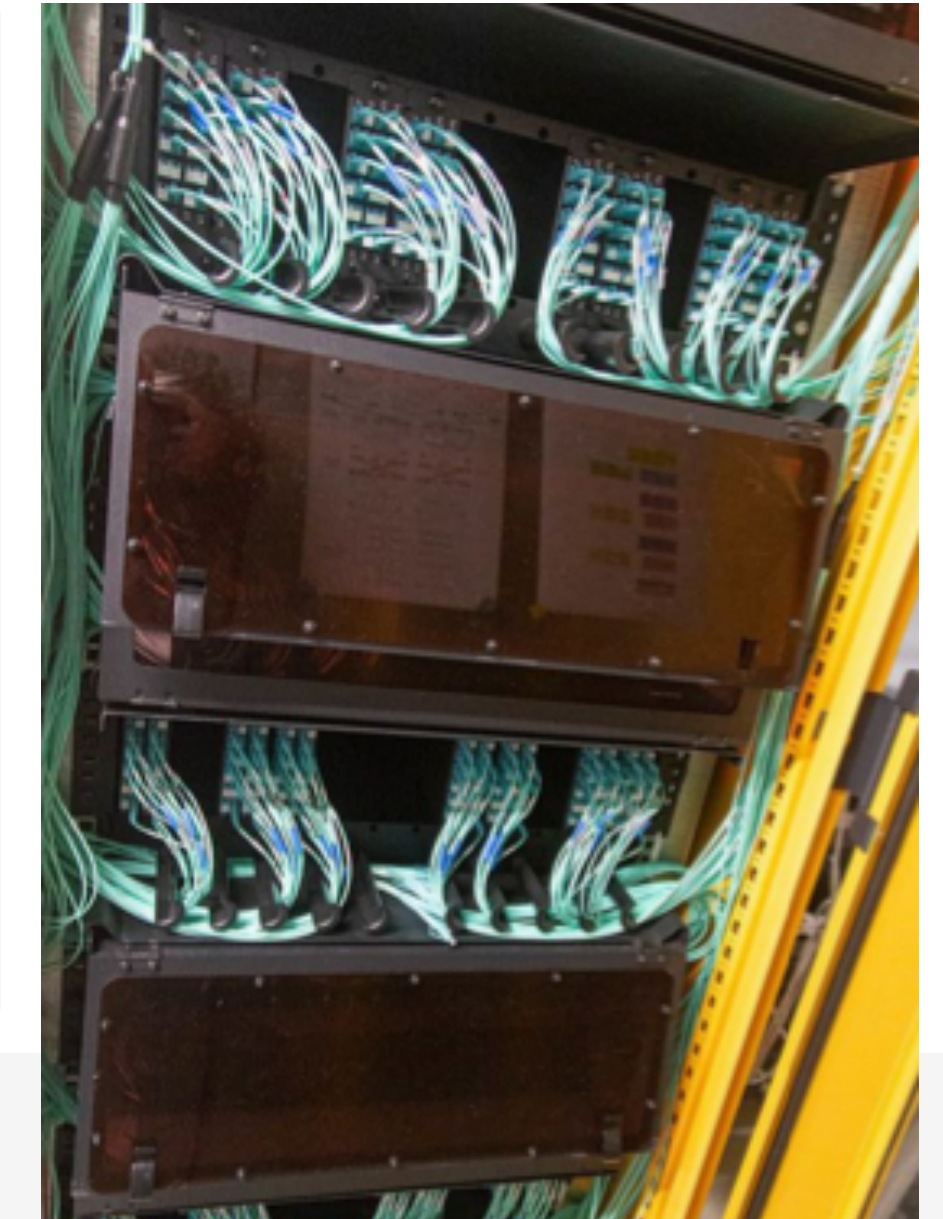
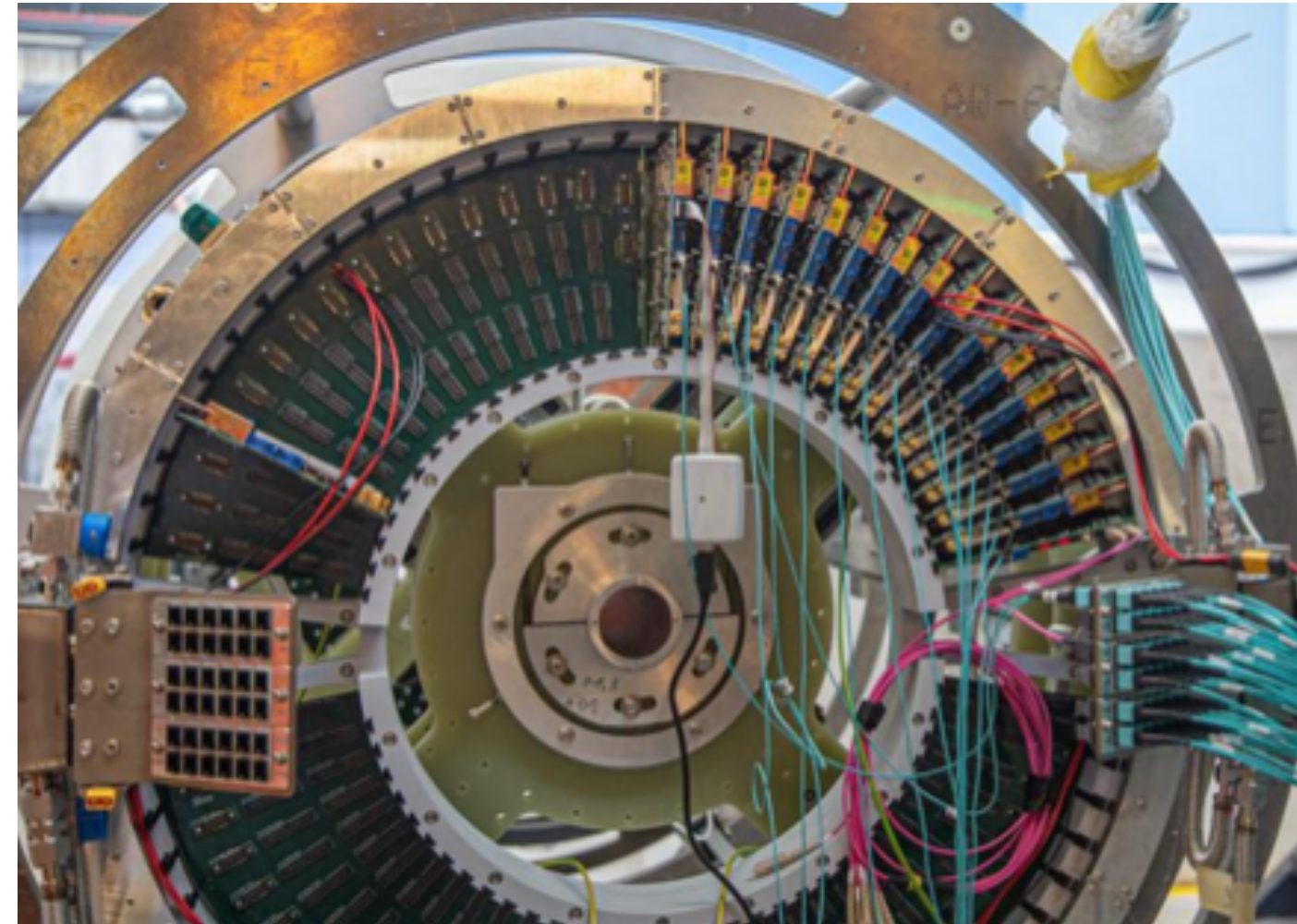
The Engineering run: 2025



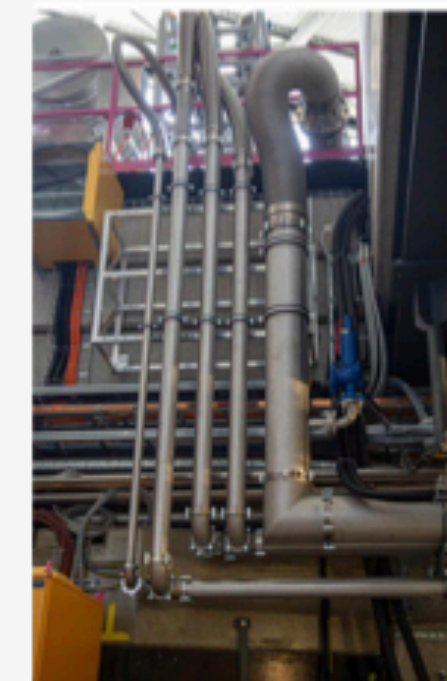
Minimal detector configuration

Mu3e installation

- Installation
 - First all services have to be installed and tested
 - Vertex comes with flex connections installed which connect to the uTP cables
 - DAQ fibre optical cables
 - LV, HV, gasus helium system, etc.



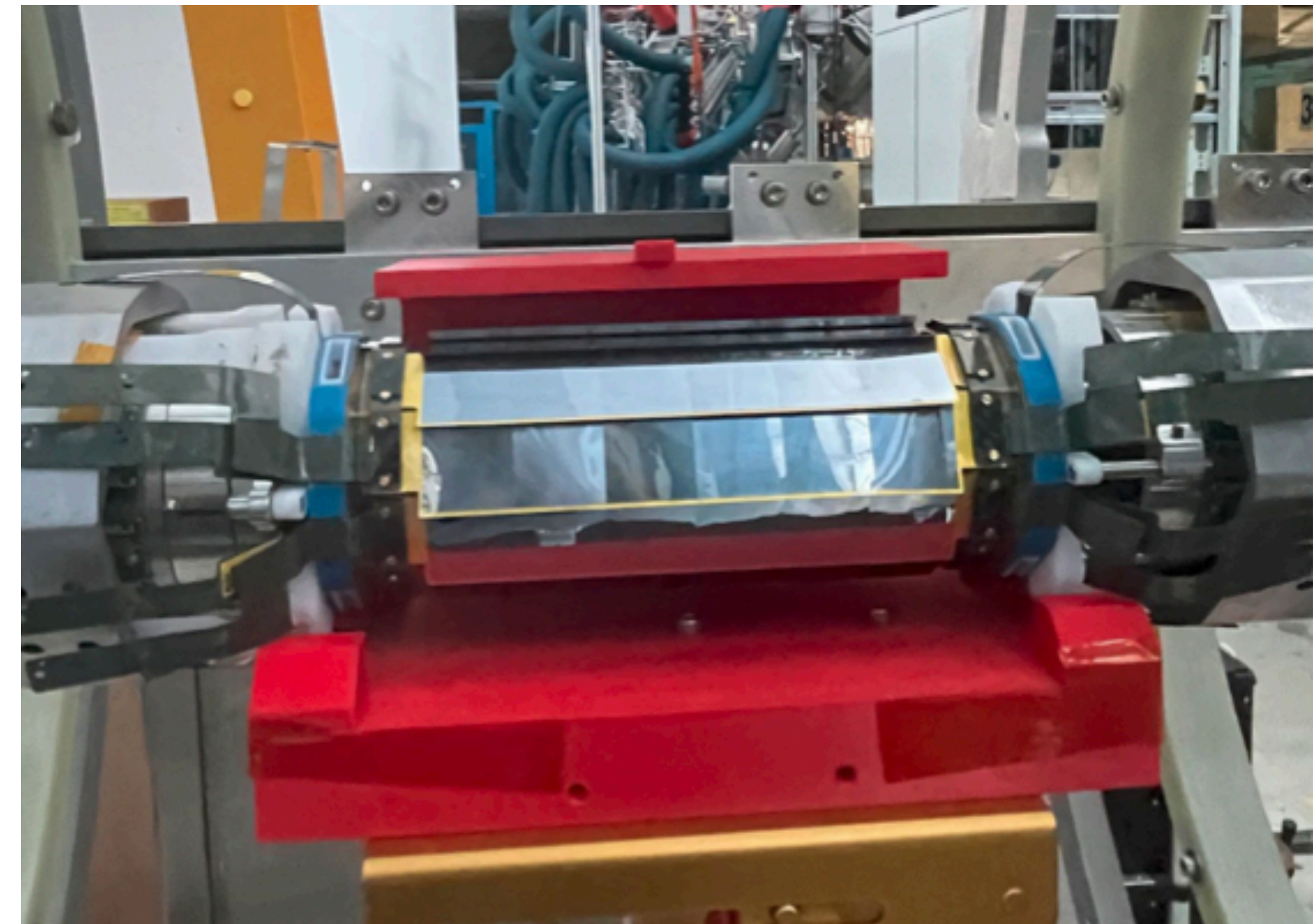
Turbo compressors for helium cooling



General service area

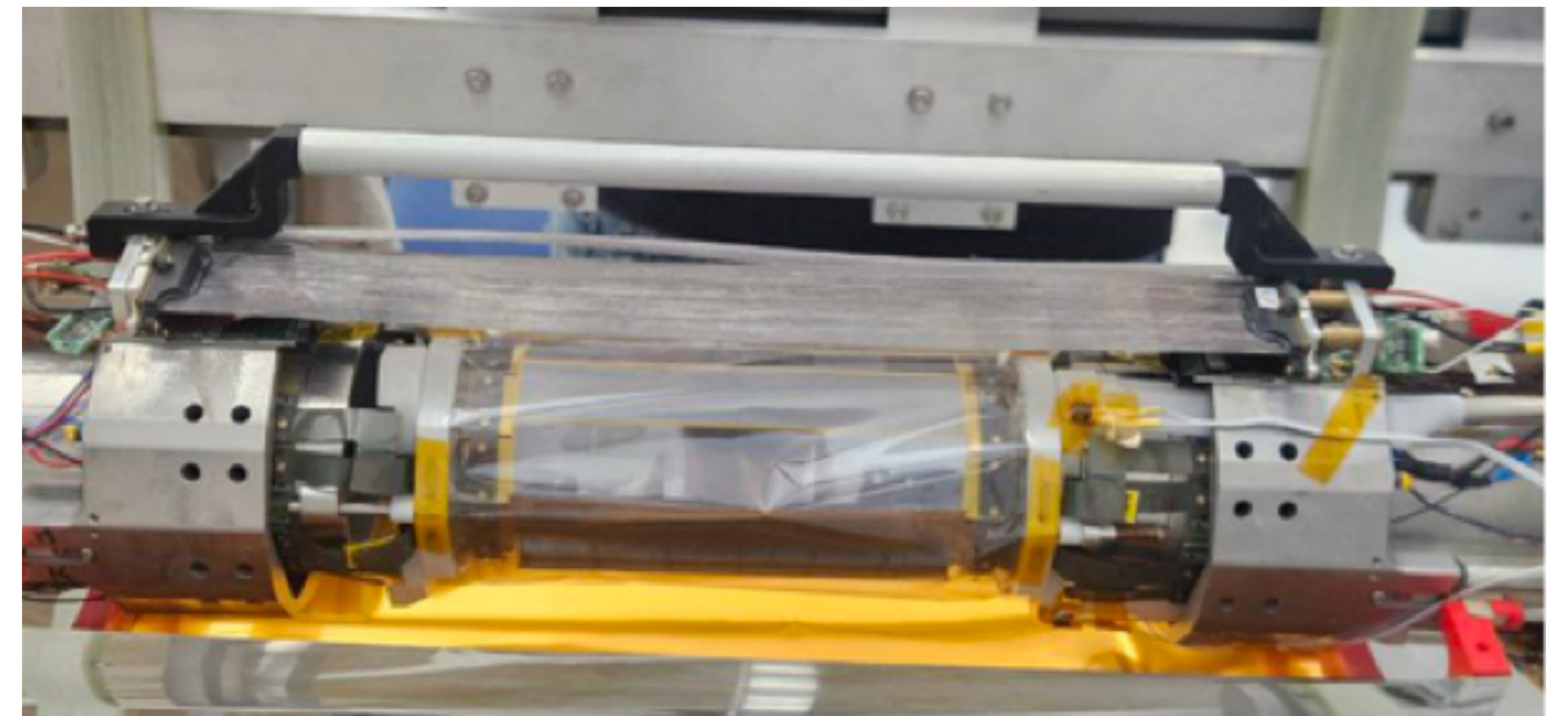
Mu3e installation

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 - DAQ fibre optical cables
 - LV, HV, gasus helium system, etc.
 - Vertex detector installation



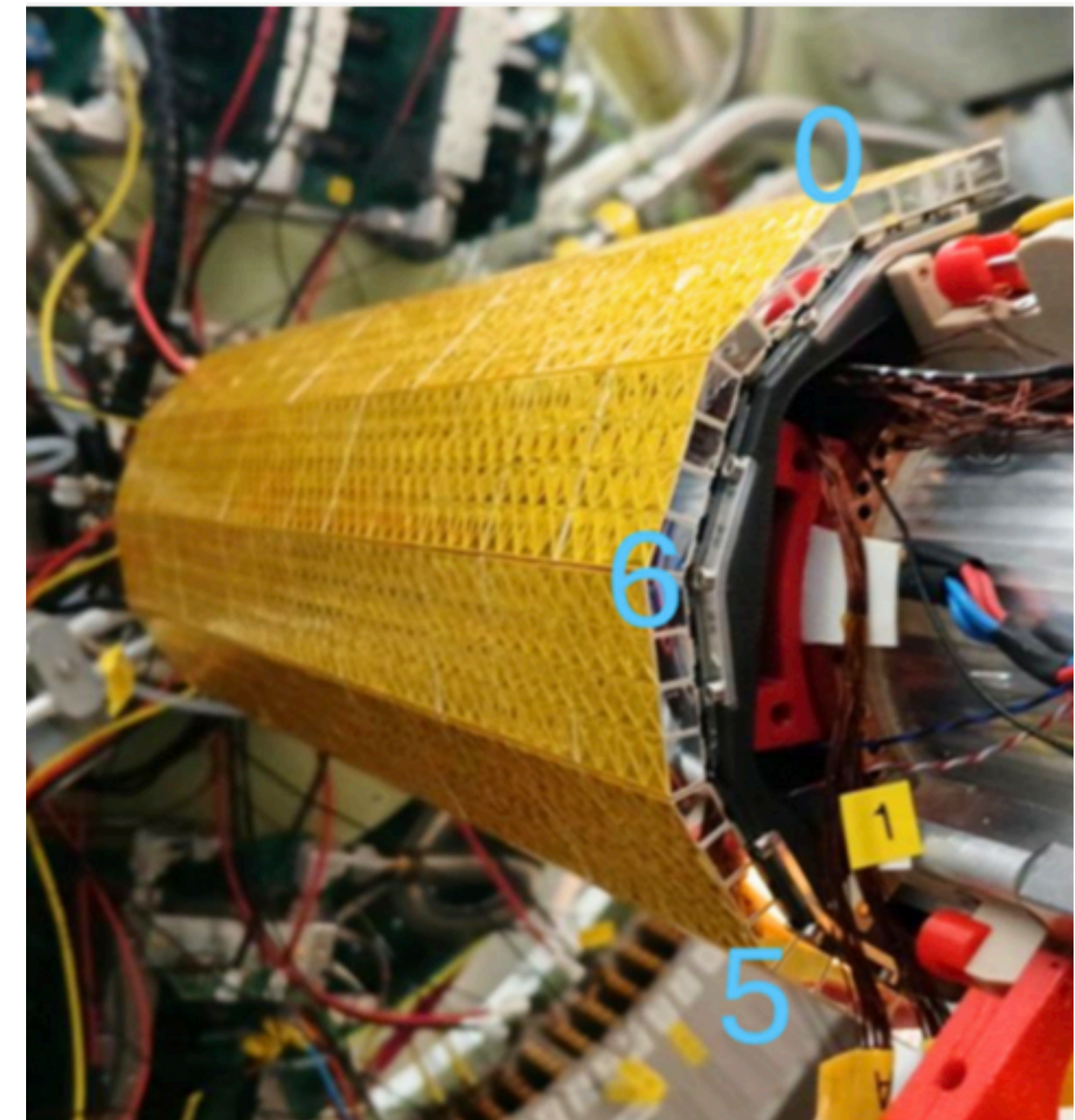
Mu3e installation

- Installation
 - First all services have to be installed and tested
 - Vertex comes with flex connections installed which connect to the uTP cables
 - DAQ fibre optical cables
 - LV, HV, gasus helium system, etc.
 - Vertex detector installation
 - Installation of the SciFi detector

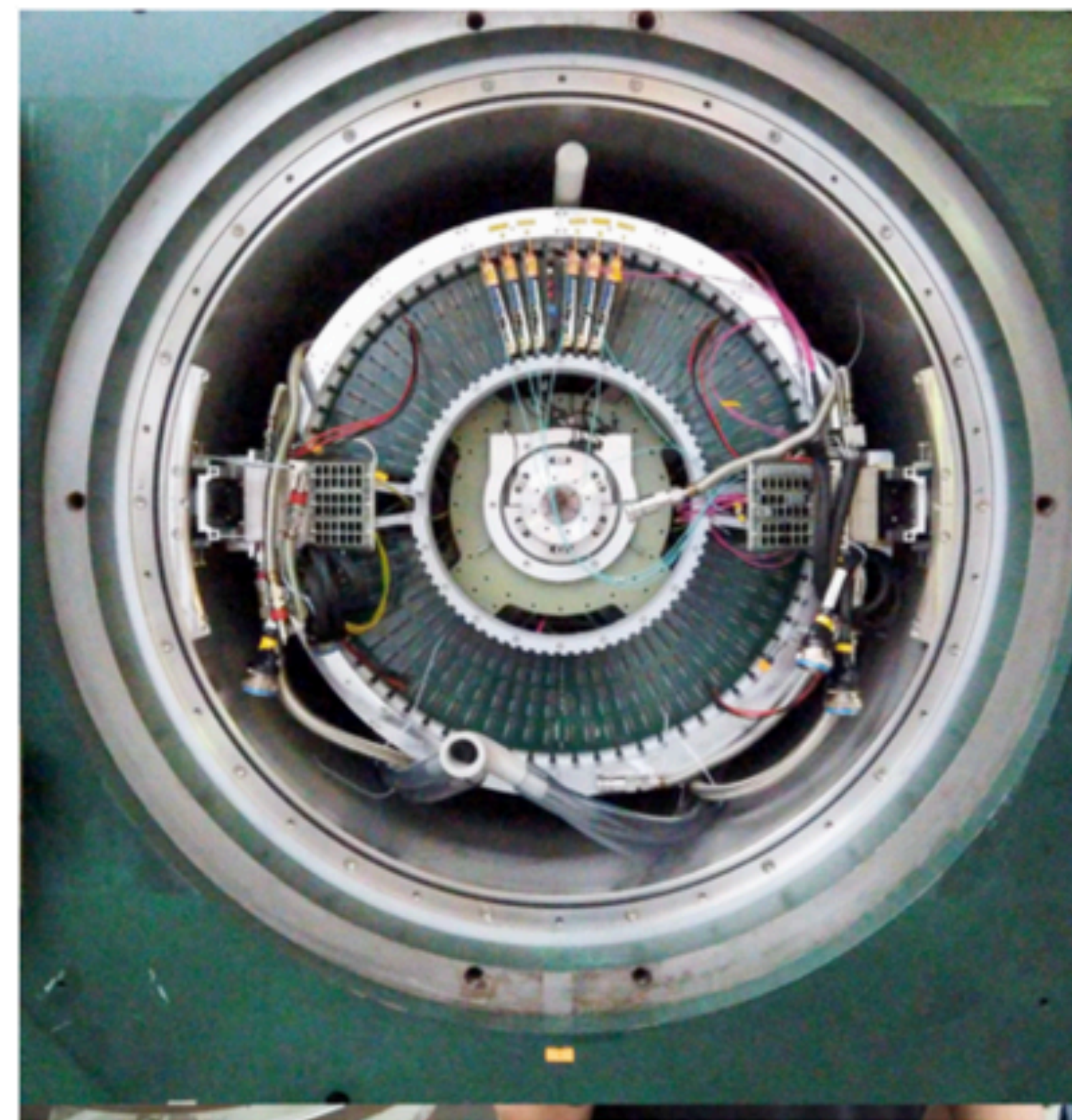
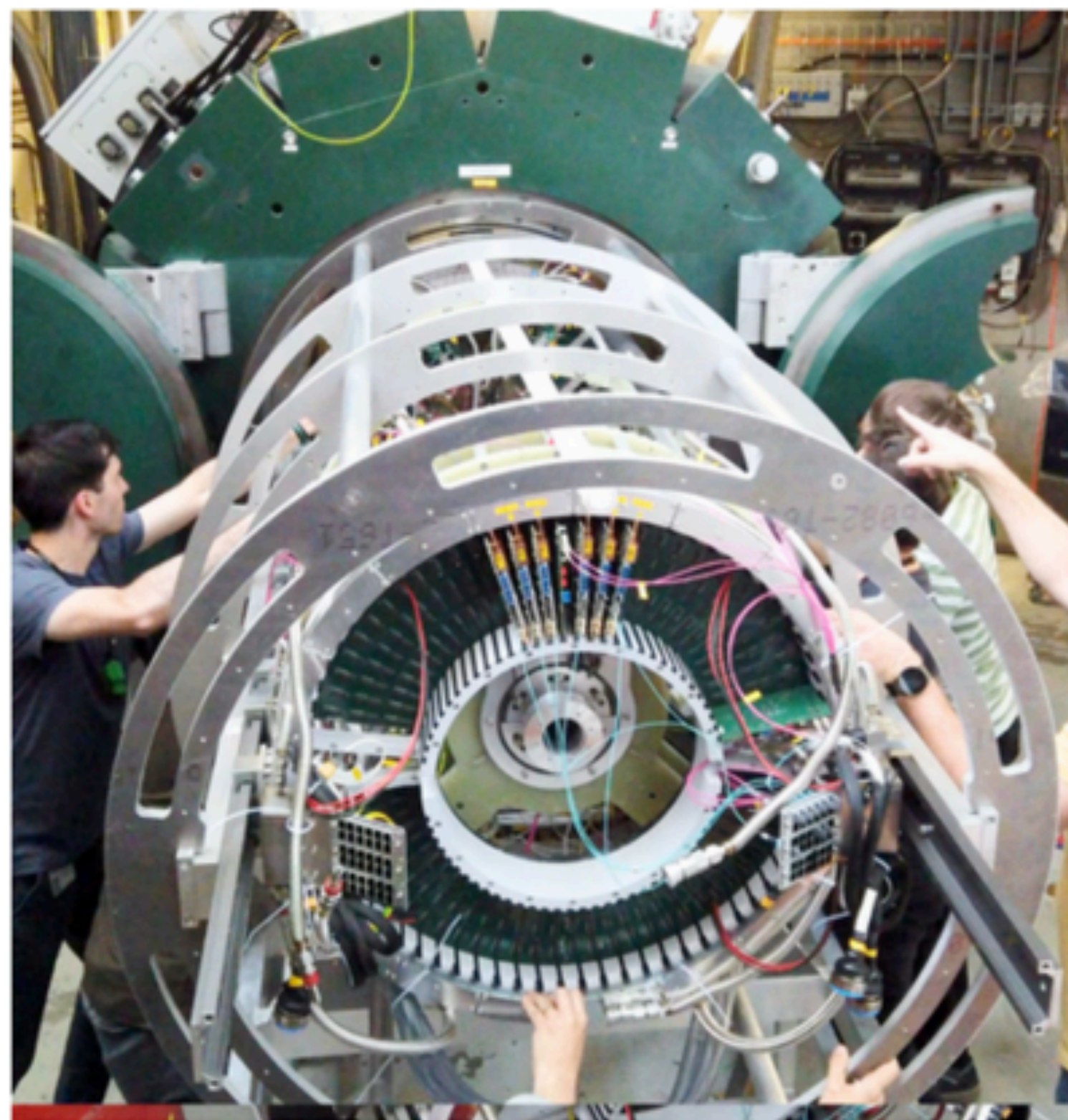


Mu3e installation

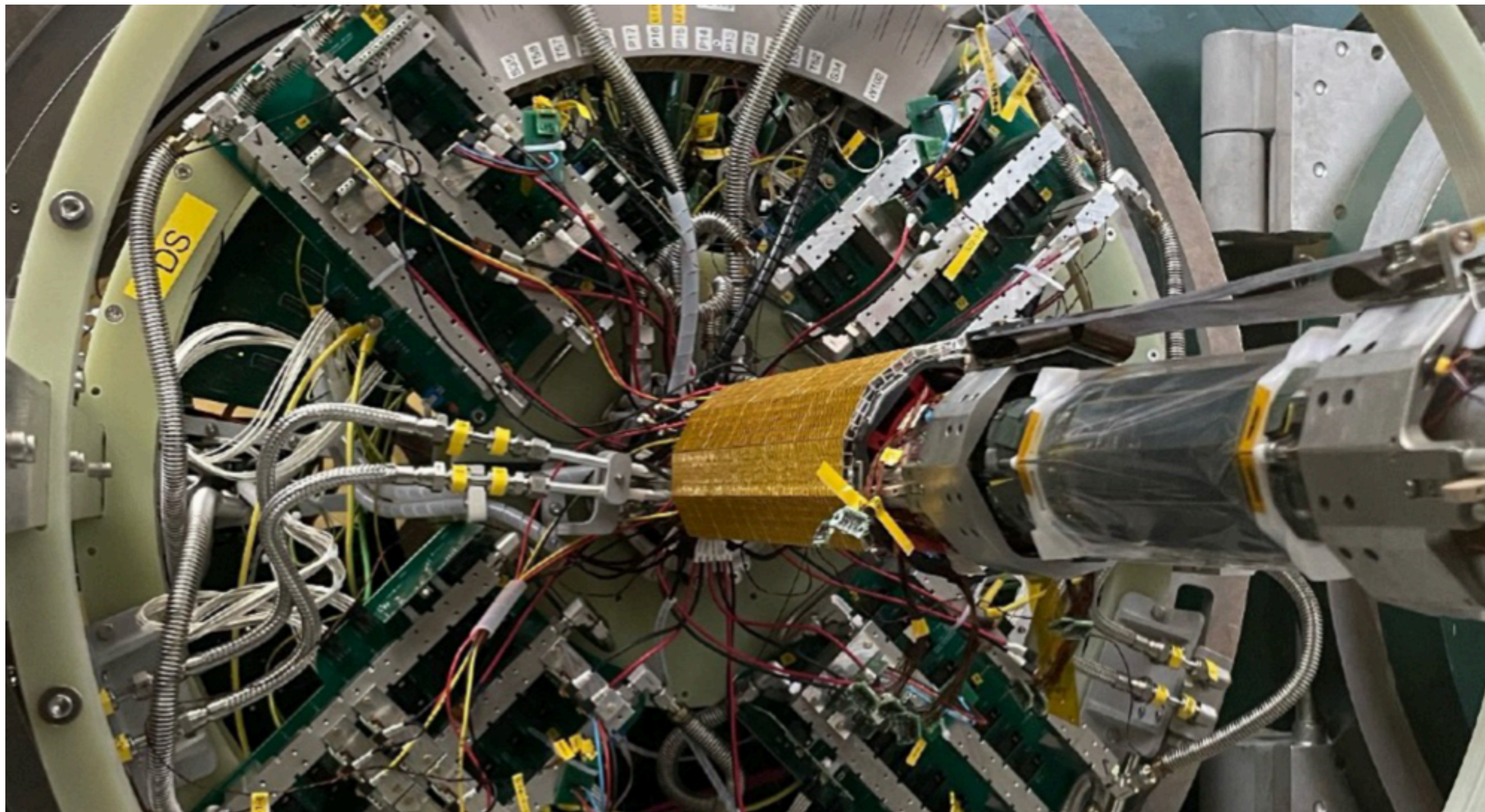
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 - Vertex comes with flex connections installed which connect to the uTP cables
 - DAQ fibre optical cables
 - LV, HV, gasus helium system, etc.
 - Vertex detector installation
 - Installation of the SciFi detector
 - Installation of the Tile detector



Mu3e installation

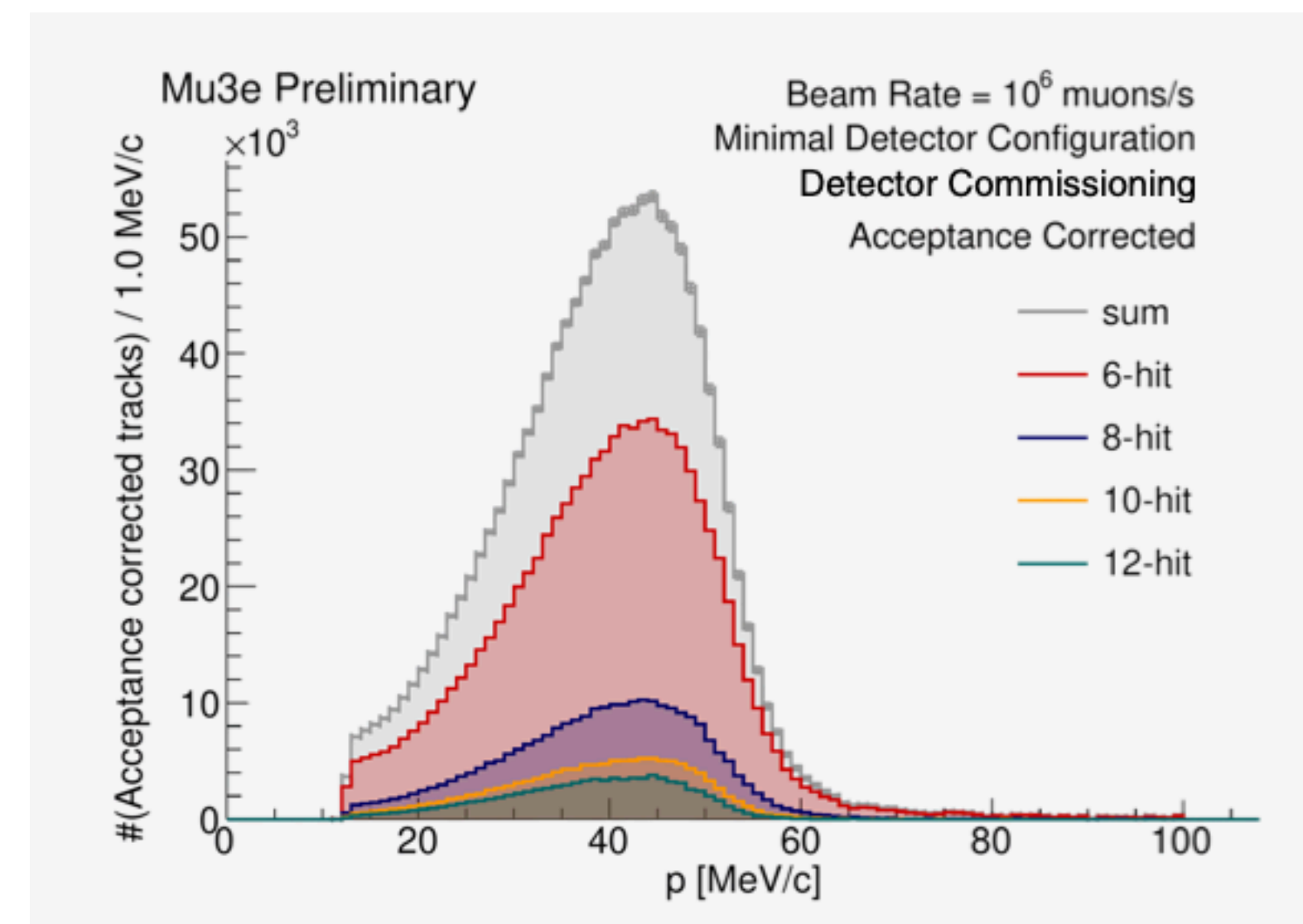
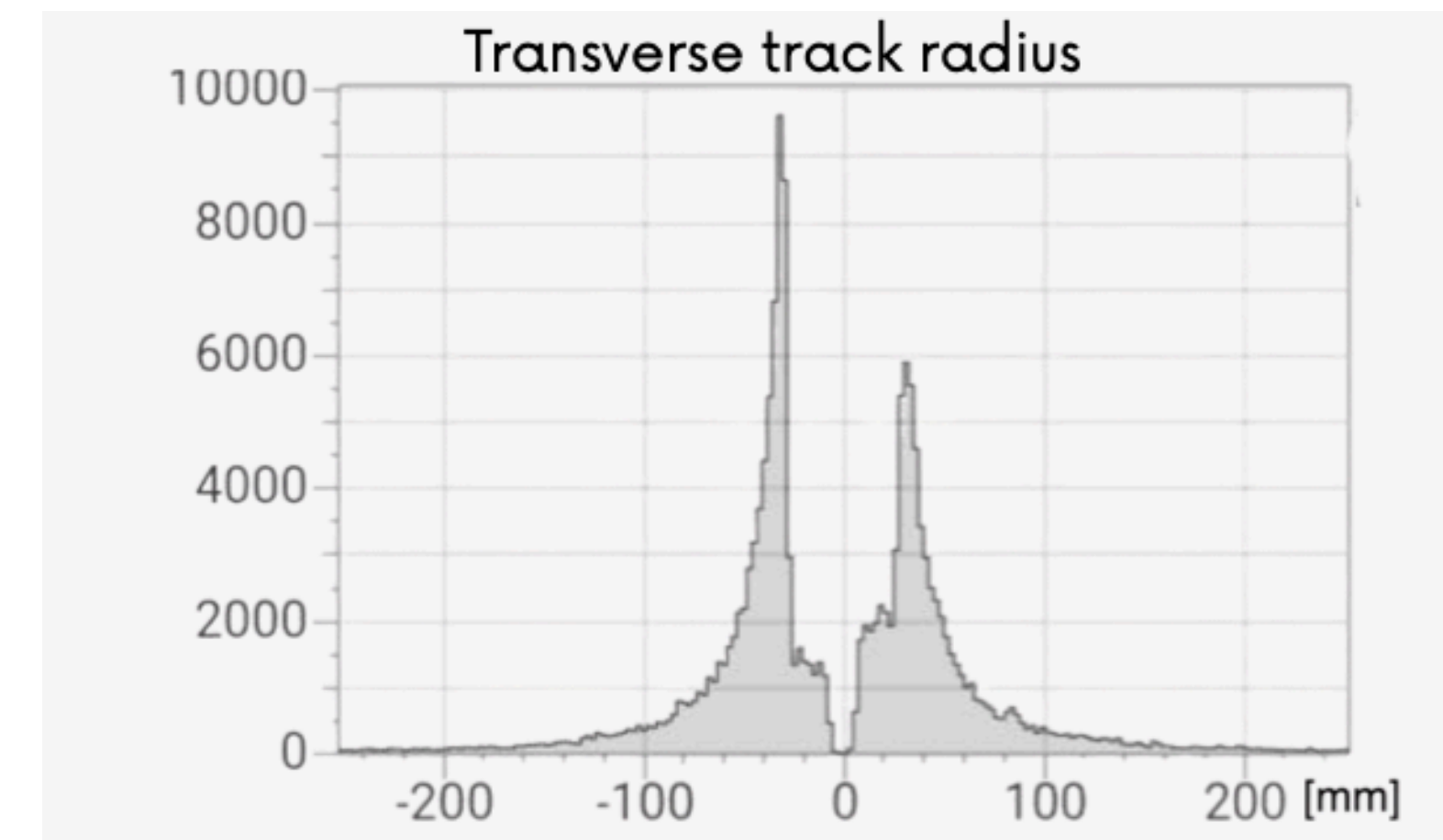
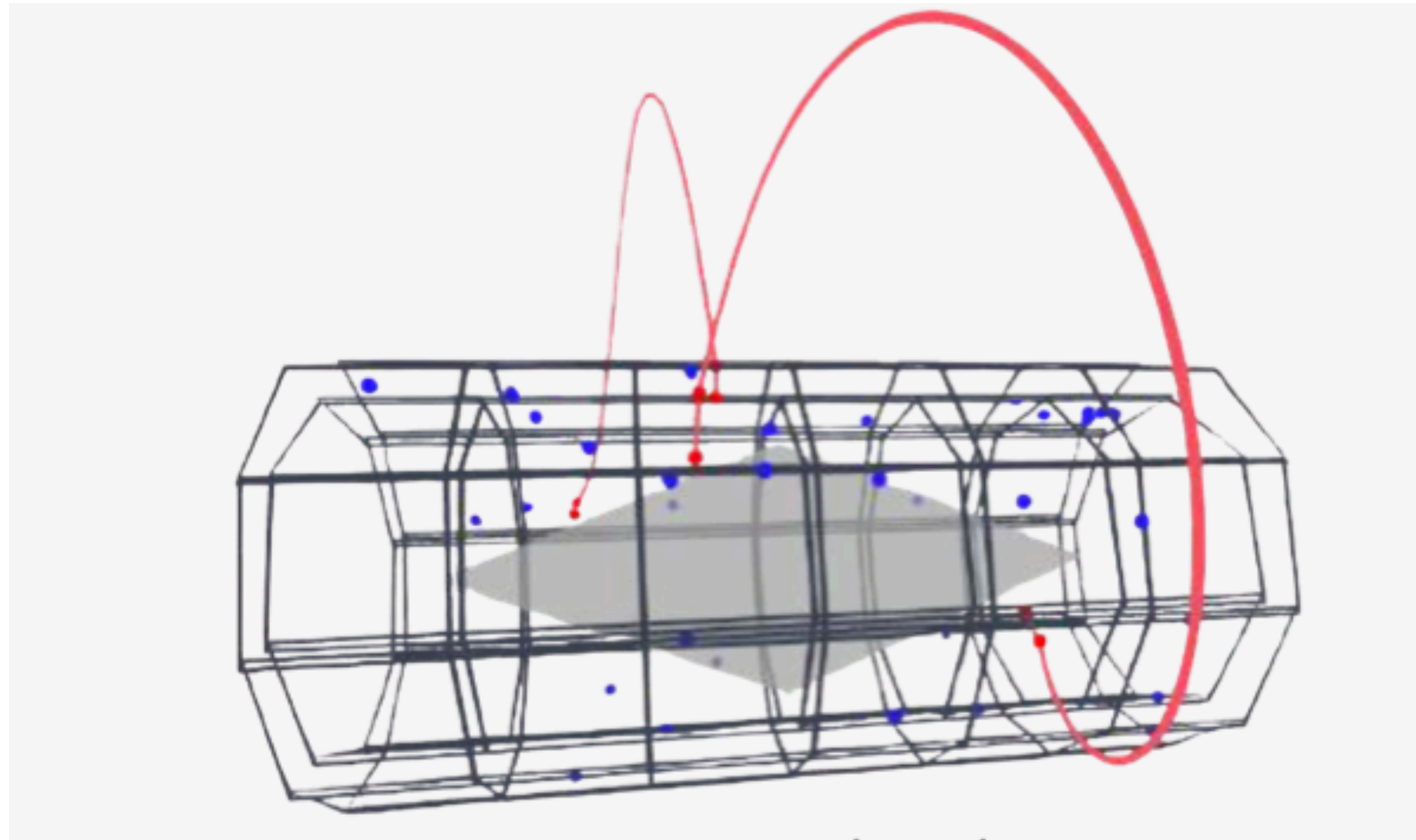


Mu3e installation

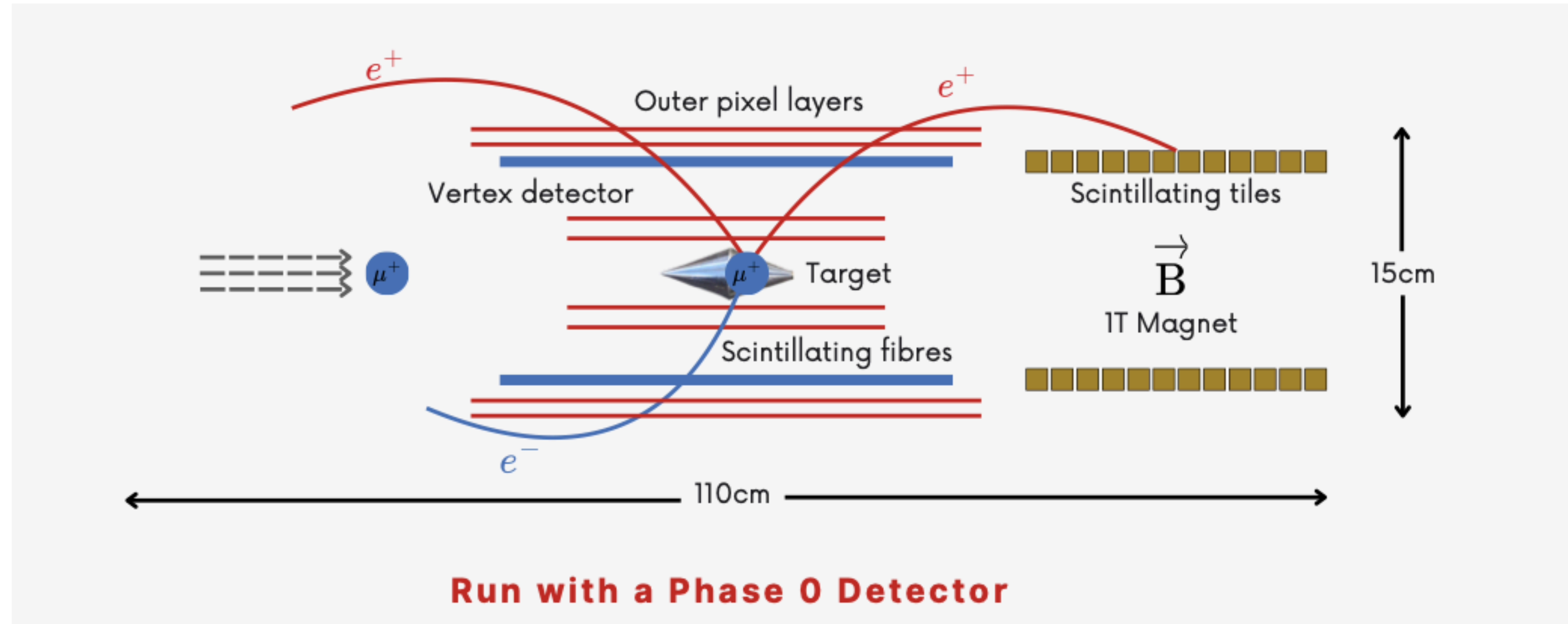


Mu3e installation

- First data
 - Beam intensity 10^6 mu/s

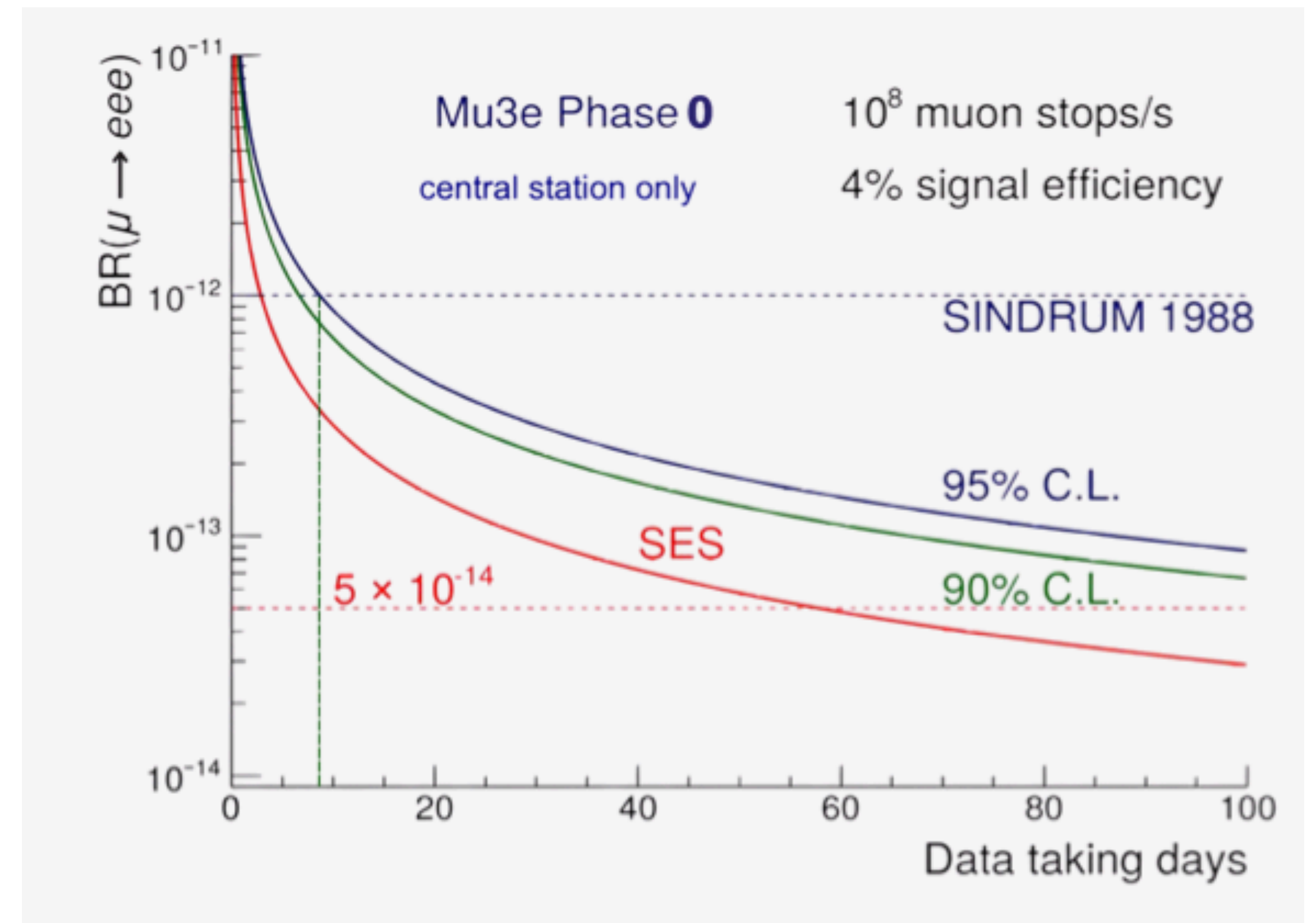


Towards the Run 2026



Towards the Run 2026

- Single Event Sensitivity Projections for the detector planed in 2026
- Surpass the SINDRUM limit in less than two weeks
- Still a lot of MC studies needs to be performed
- Detector efficiencies has to be studied



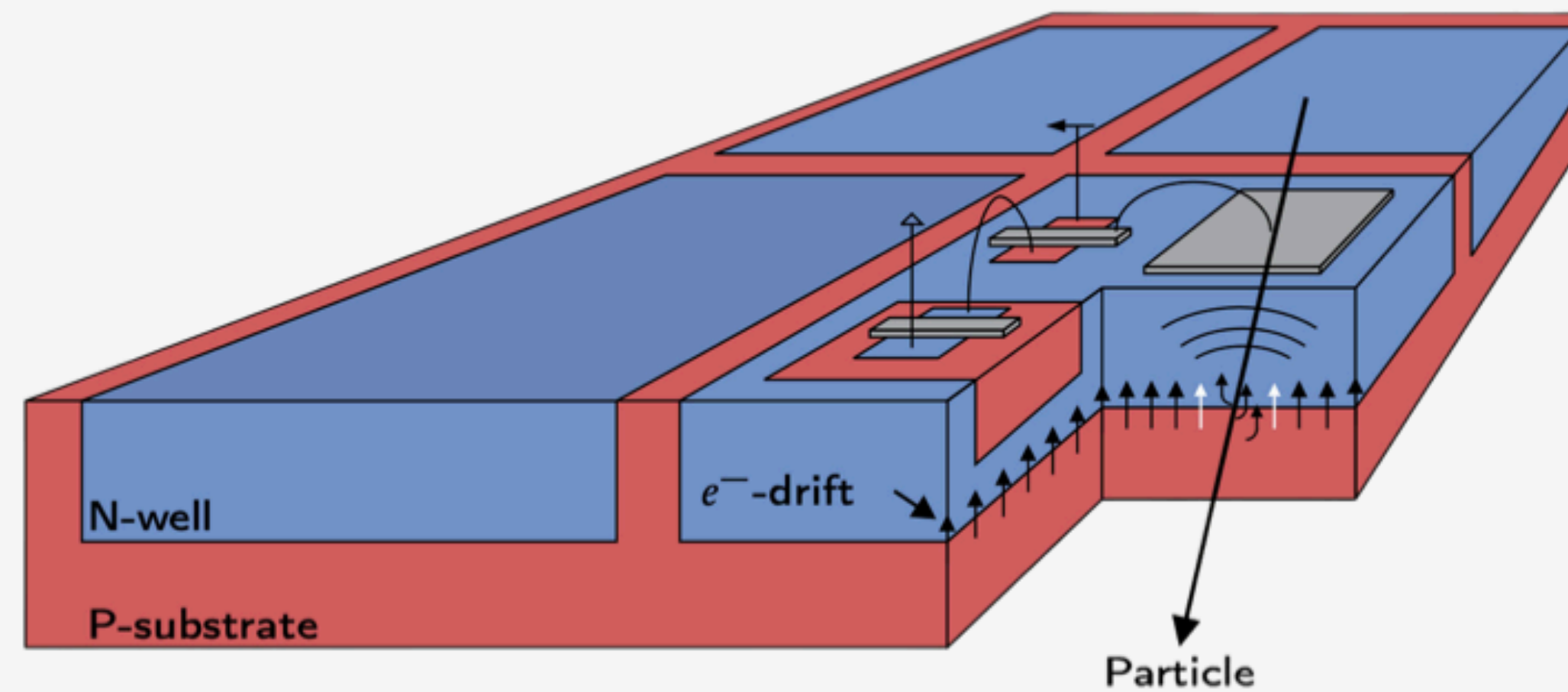
Outlook

- Impressive progresses have been done in all MEGII, Mu3e and HiMB
- MEGII released three major physics results (MEG data taking and X17 search) and a new one related to the ALPs search will be published soon
- HiMB has been fully approved and started the work into the experimental area in view of the long shutdown 2027-28
- Mu3e achieved the first important milestone of collecting some data with/out beam with part of the apparatus in view of a first physics data taking in 2026

Back up

HV-MAPS

High Voltage Monolithic Active Pixel Sensors (HV-MAPS)



Ivan Perić et al., NIM A582 (2007) 876-885

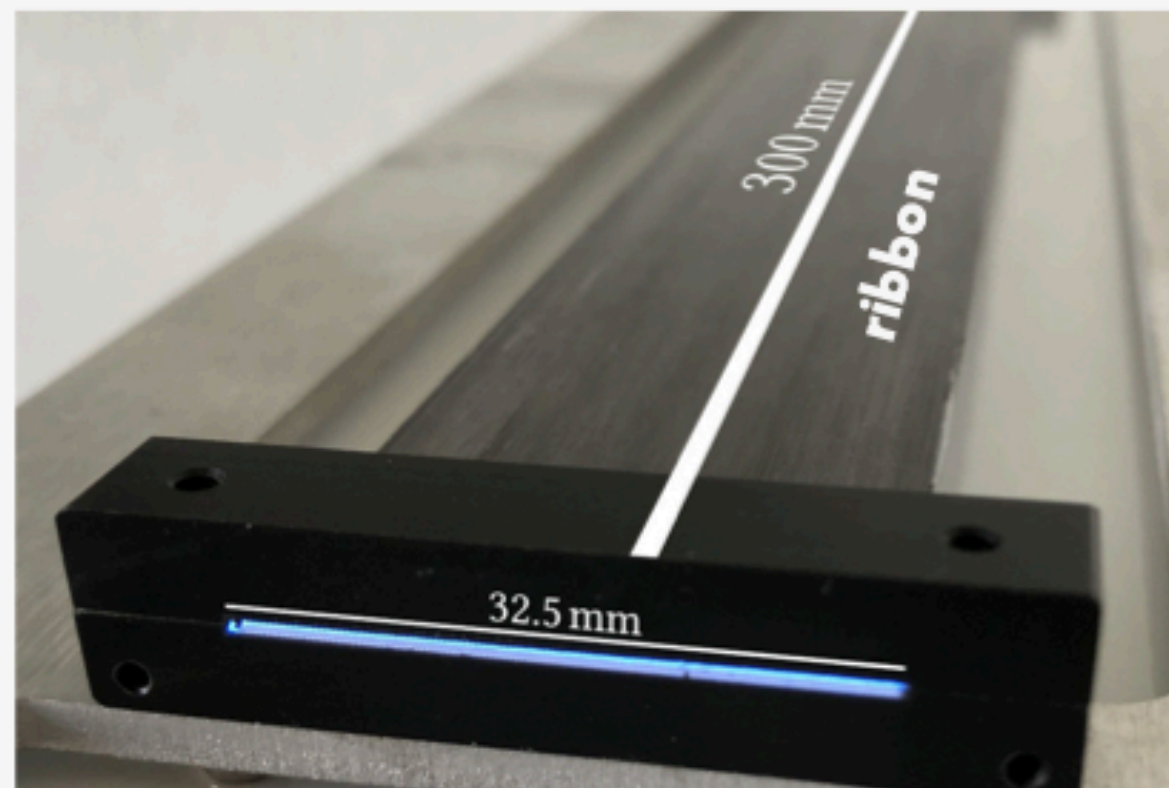
- High Voltage Monolithic Active Pixel Sensors
- **Thinned** down to **50 μm**
- Fast charge collection via **drift**
- **Time resolution** of a few **ns**
- **Digitalization** and **zero suppression** on the chip

good vertex resolution and momentum measurement

Timing detectors

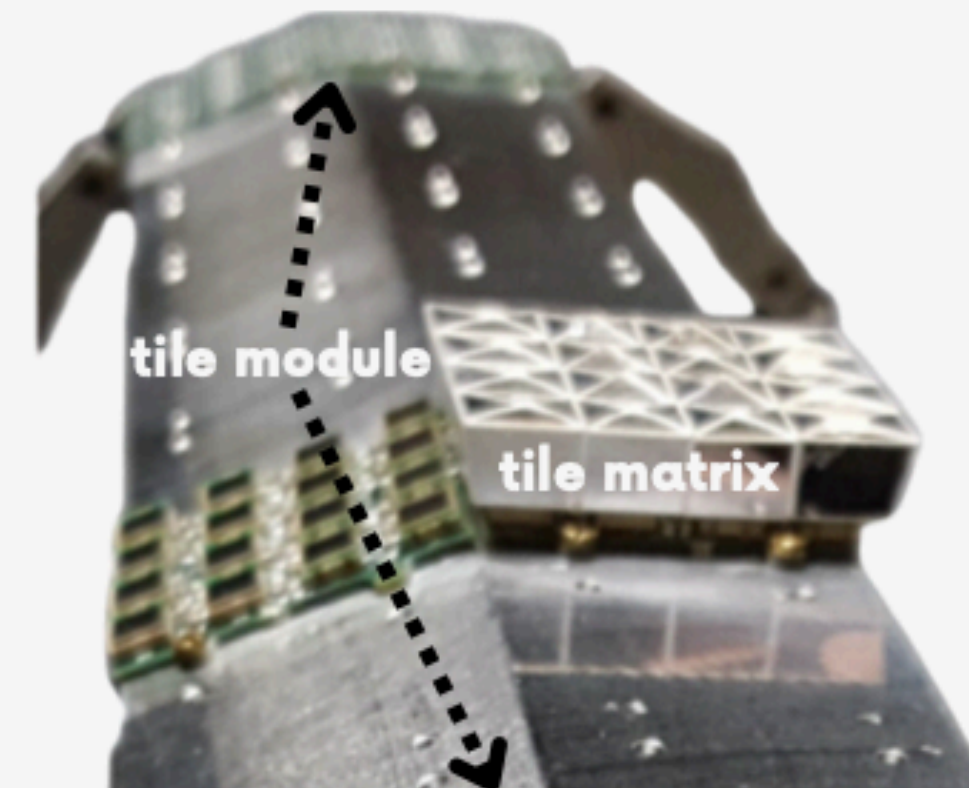
Timing Detectors

Fibre < 250 ps time resolution



- 128 fibres per ribbon
- 3 layers of fibres
- Readout via SiPMs arrays

Tiles < 70 ps time resolution



- $6.3 \times 6.2 \times 5.0 \text{ mm}^3$ tiles
- 4×4 tiles per matrix
- One SiPM per tile

good time resolution