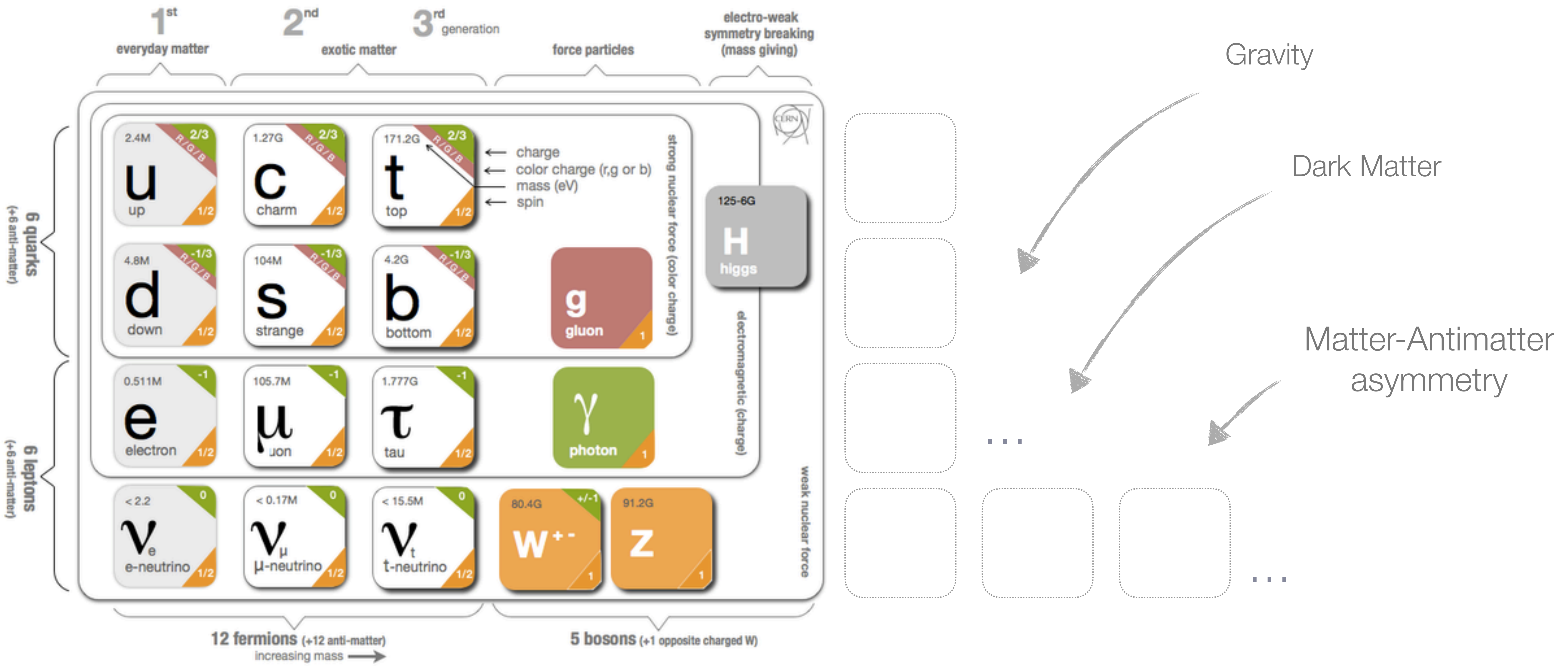
cLFV status and X17 search with the MEG II apparatus

Angela Papa
Lepton Interactions with Nucleons and Nuclei Workshop
Marciana Marina, Sept. 7th 2023

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

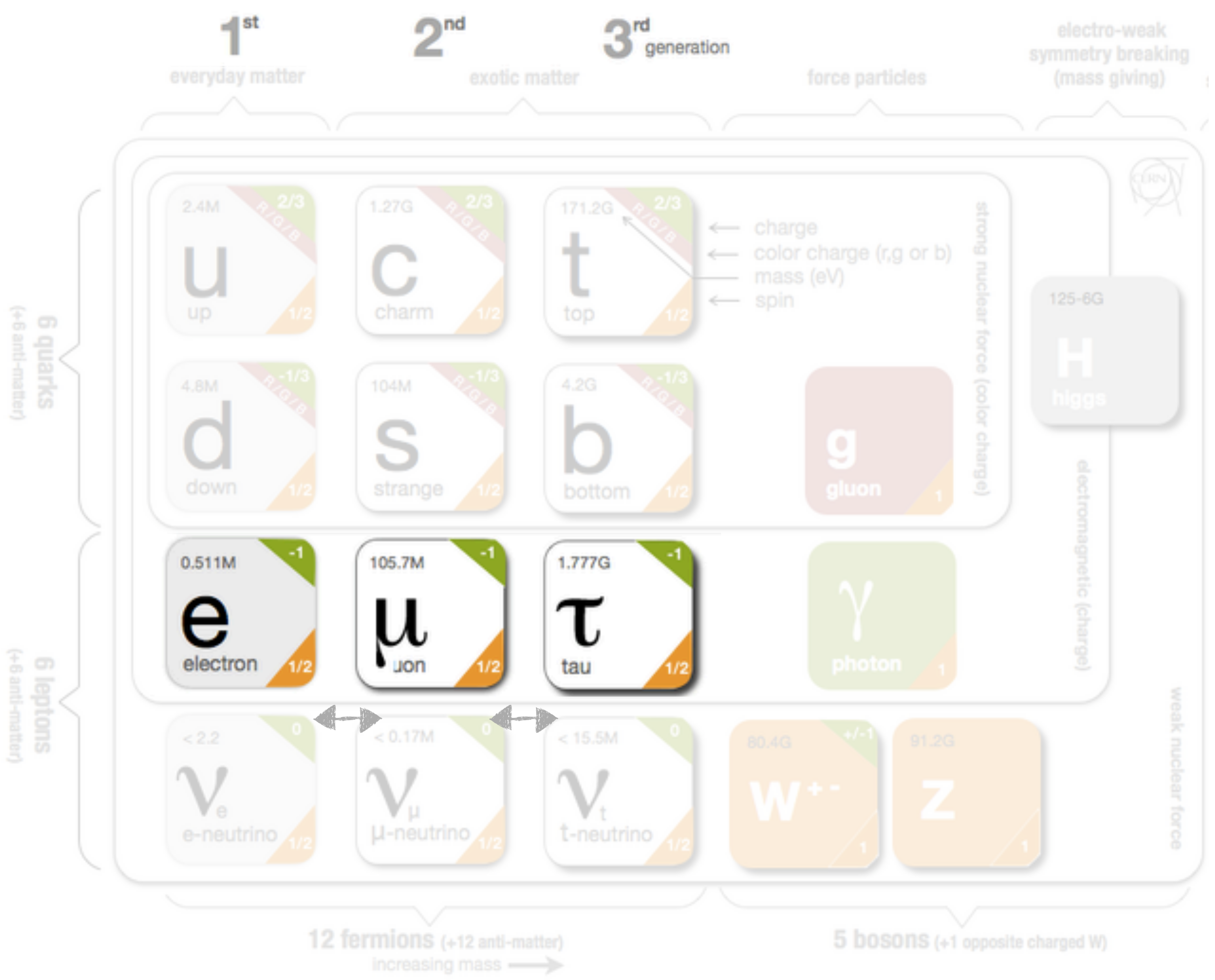


Focus here on:
- muon cLFV

- 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

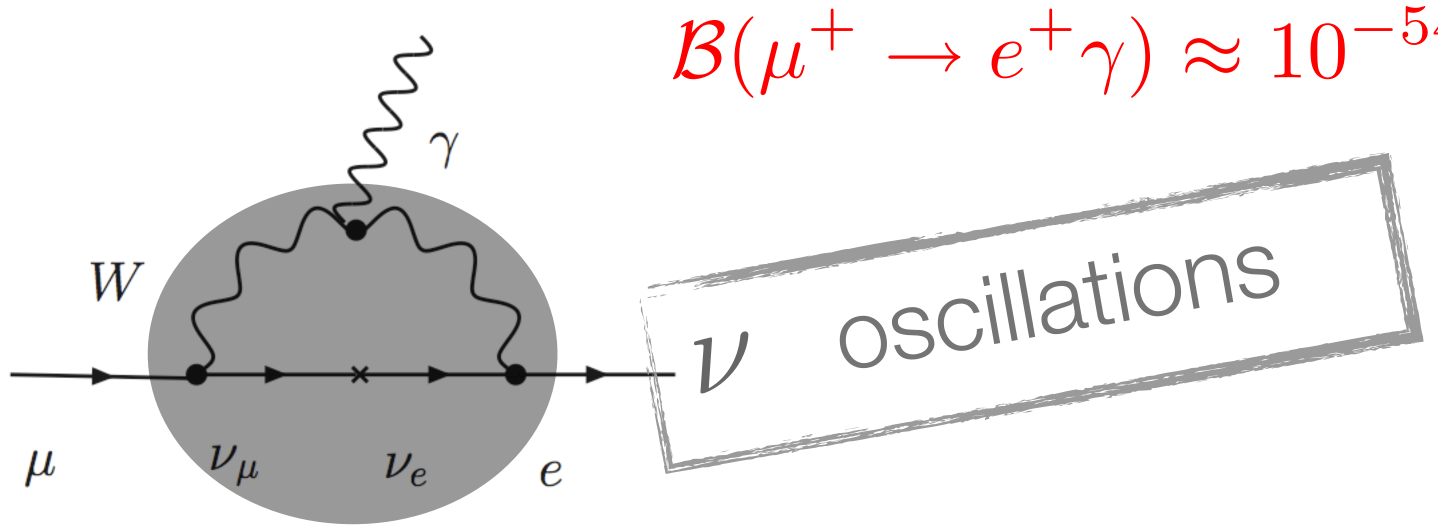
- **Neutrino oscillations**: Evidence of physics Behind Standard Model (BSM). **Neutral lepton flavour violation**
- **Charged lepton flavour violation: NOT** yet observed
- An experimental **evidence** of cLFV at the current sensitivities will be a **clear signature of New Physics**



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

SM with massive neutrinos (Dirac)

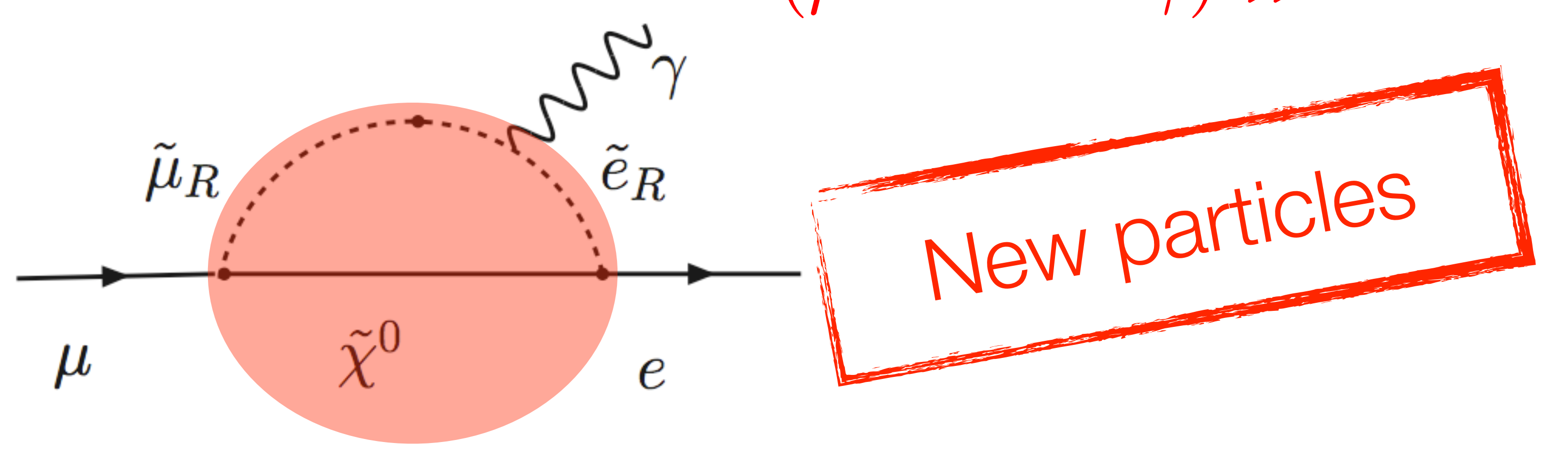
$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$



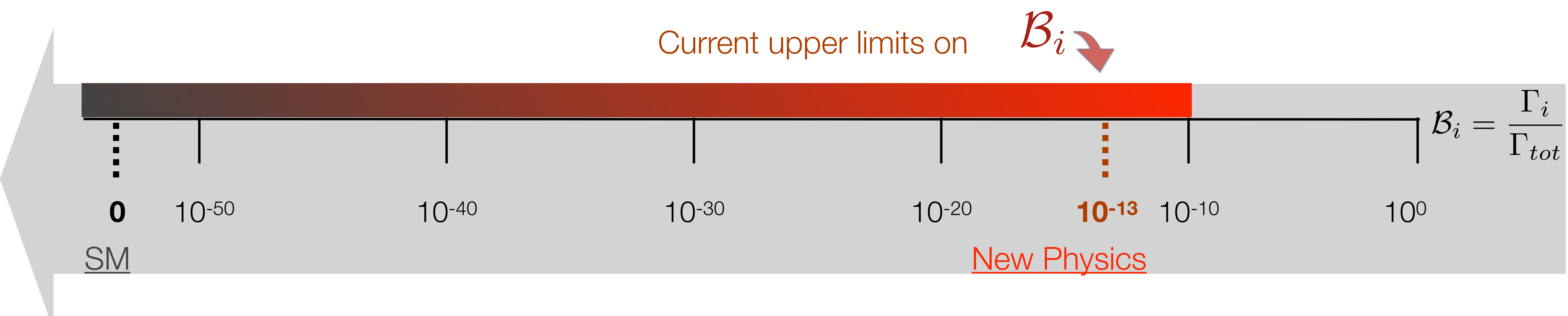
too small to access experimentally

BSM

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

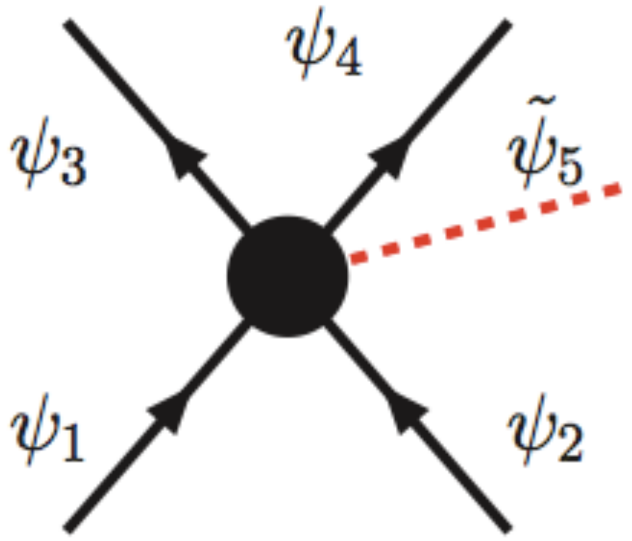


an experimental evidence:
a clear signature of New Physics NP
(SM background FREE)



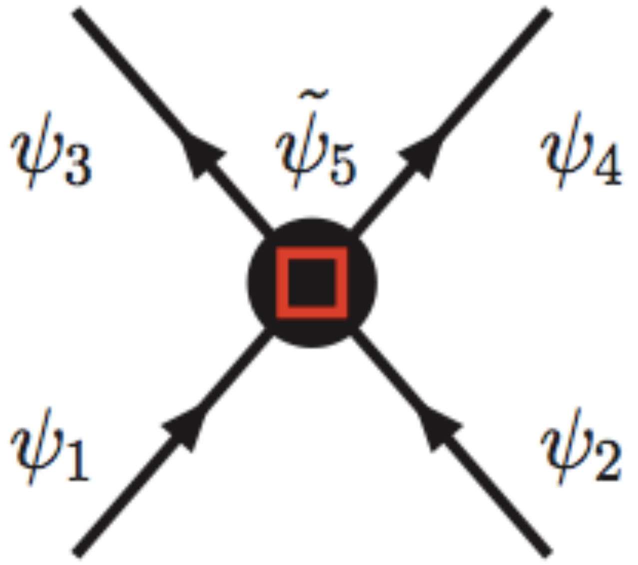
Complementary to “Energy Frontier”

Energy frontier



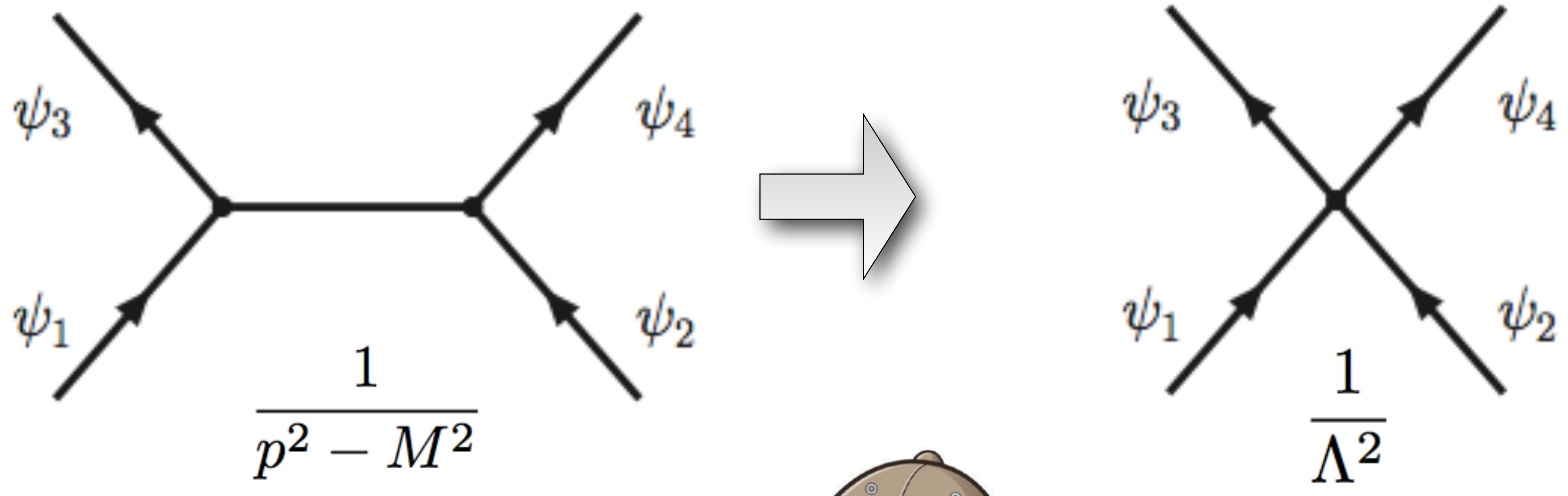
Real BSM particles

Precision and intensity frontier



Virtual BSM particles

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



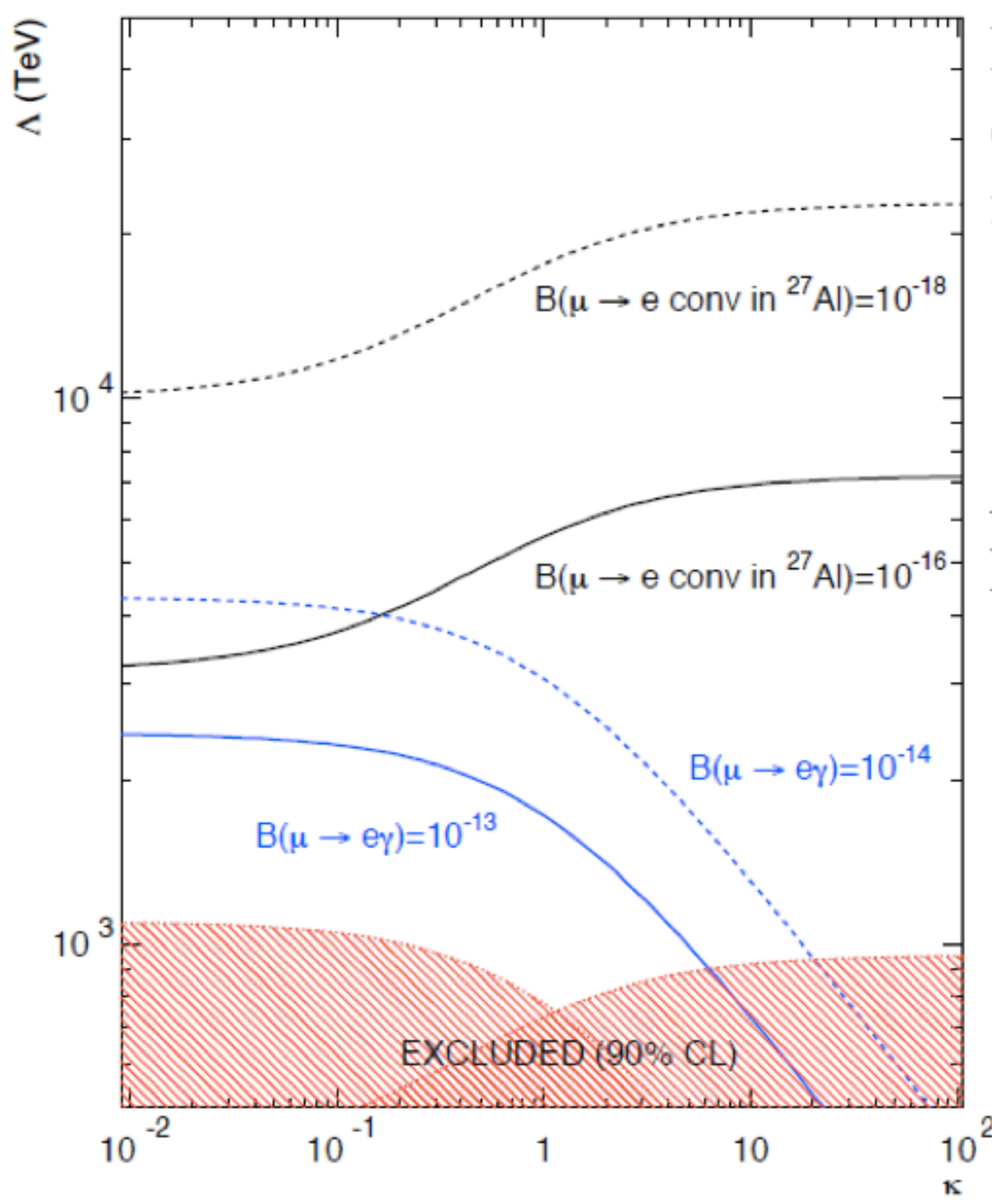
Unveil new physics

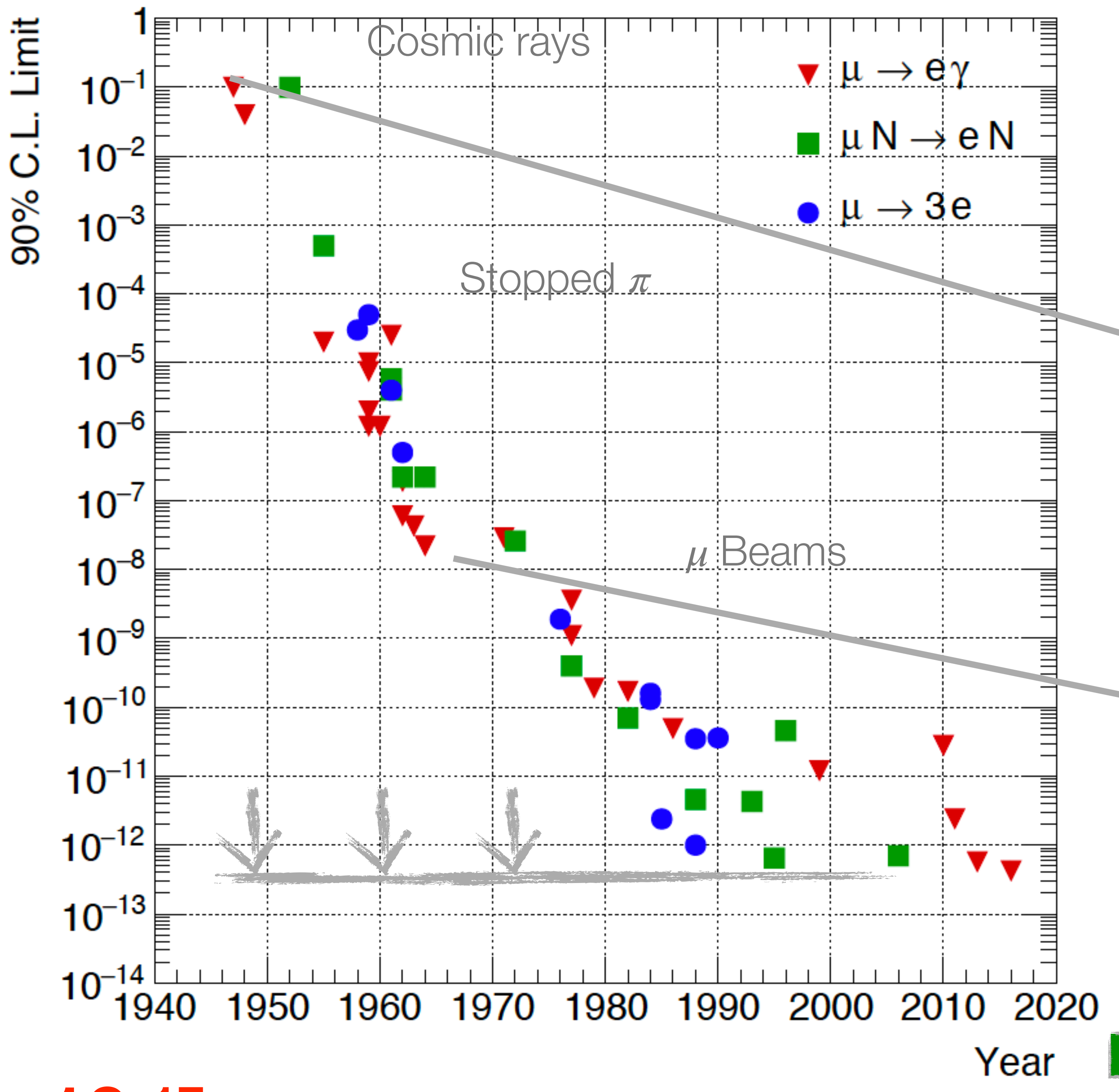
Probe energy scale otherwise unreachable

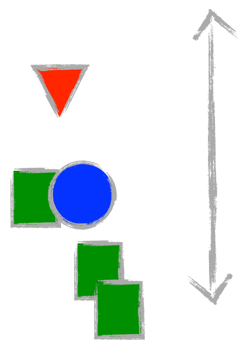
E > 1000 TeV

CLFV searches with muons: Status and prospects

	Current upper limit	Future sensitivity
$\mu \to e\gamma$	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}







10^{-17}

- 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)

$\mu \neq e^*$

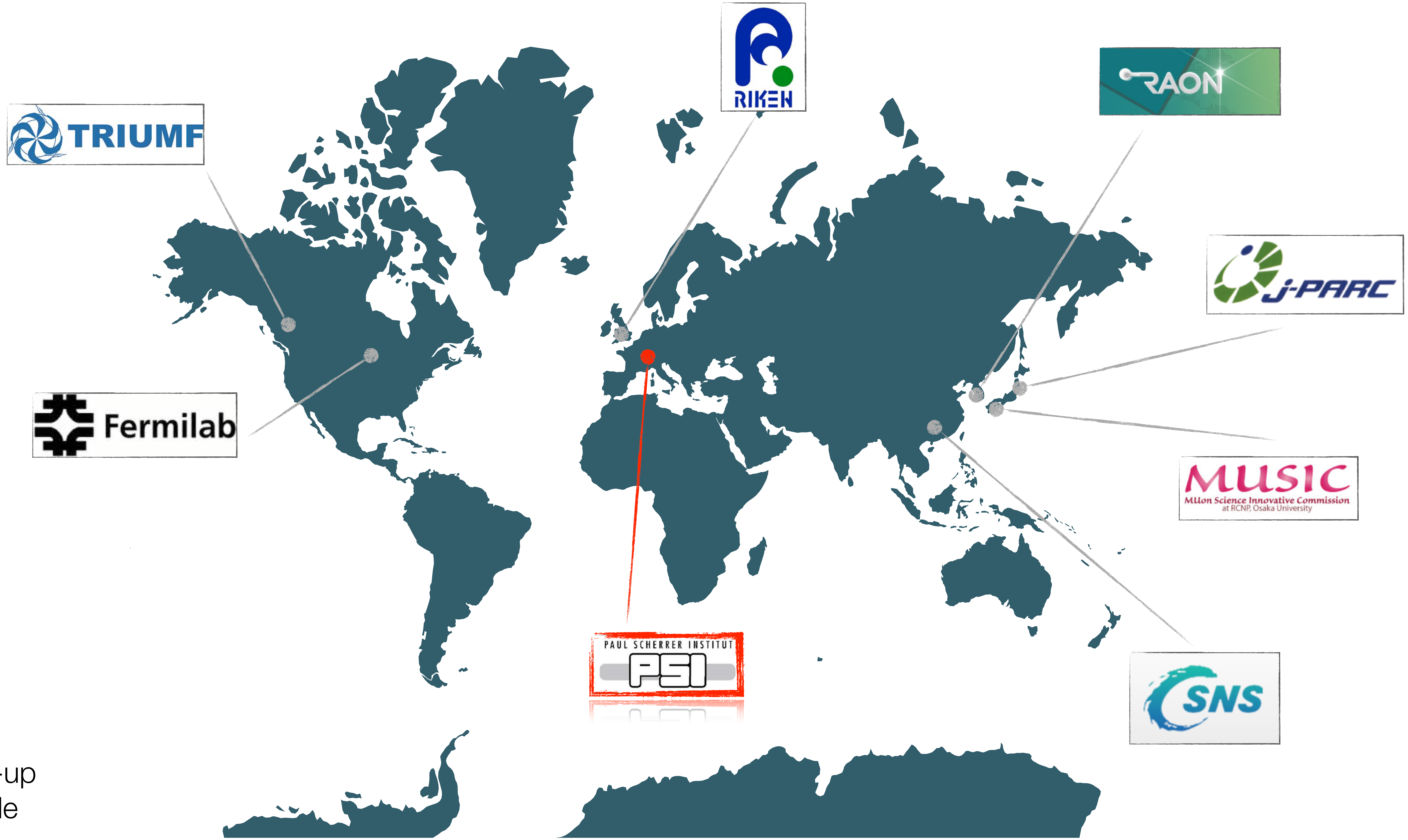
1947:
Pontecorvo and Hincks

1962:
Lederman, Schwartz, and Steinberger
1988 Nobel

$\nu_\mu \neq \nu_e$

In the near future O(5-10) years: Impressive sensitivity

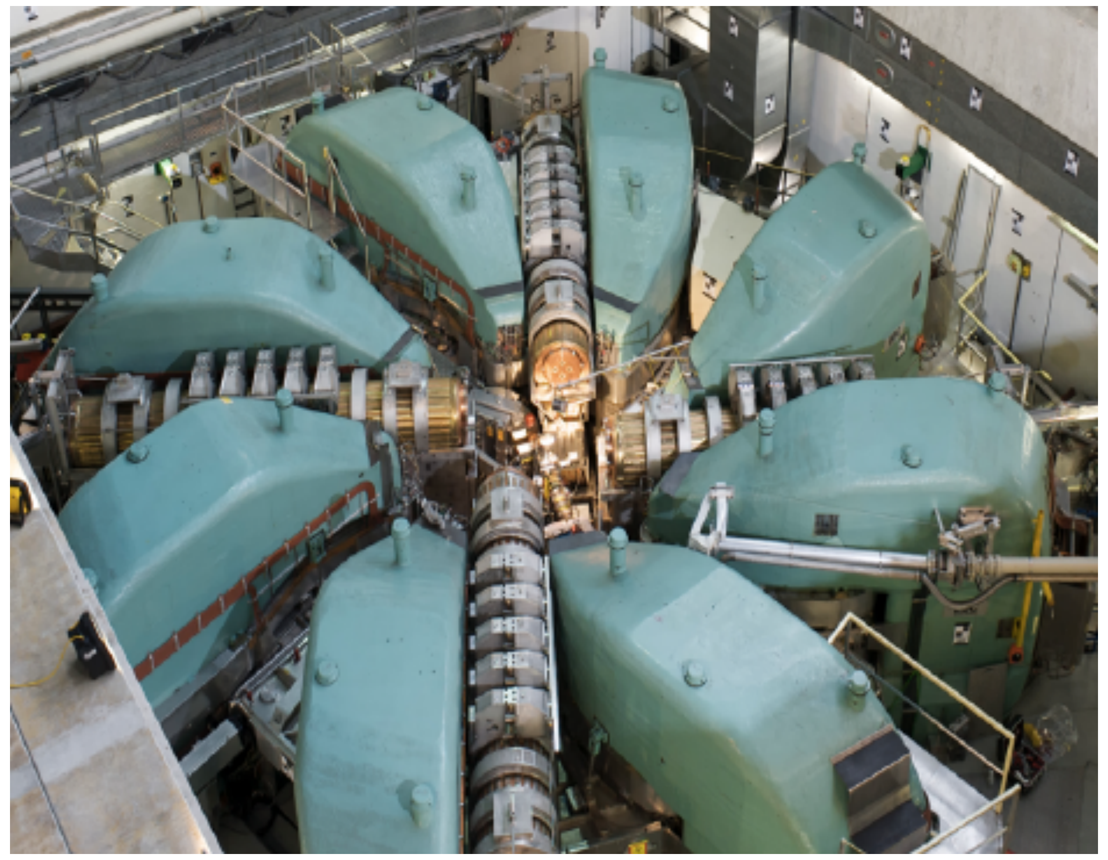
Muon beams worldwide



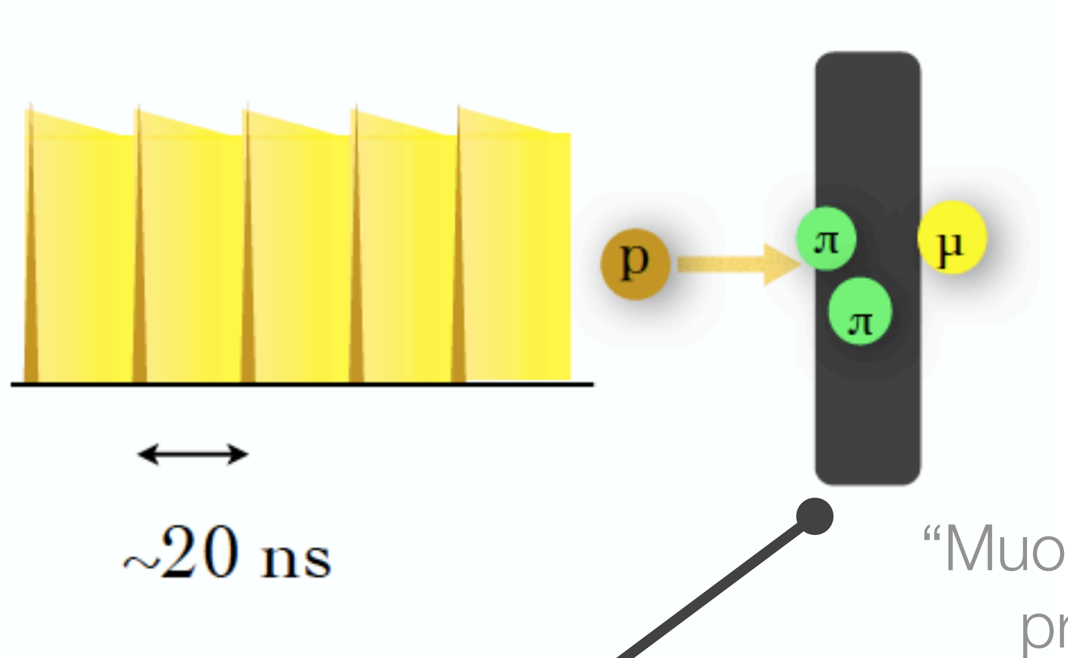
Note: See the back-up for a summary table

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**)

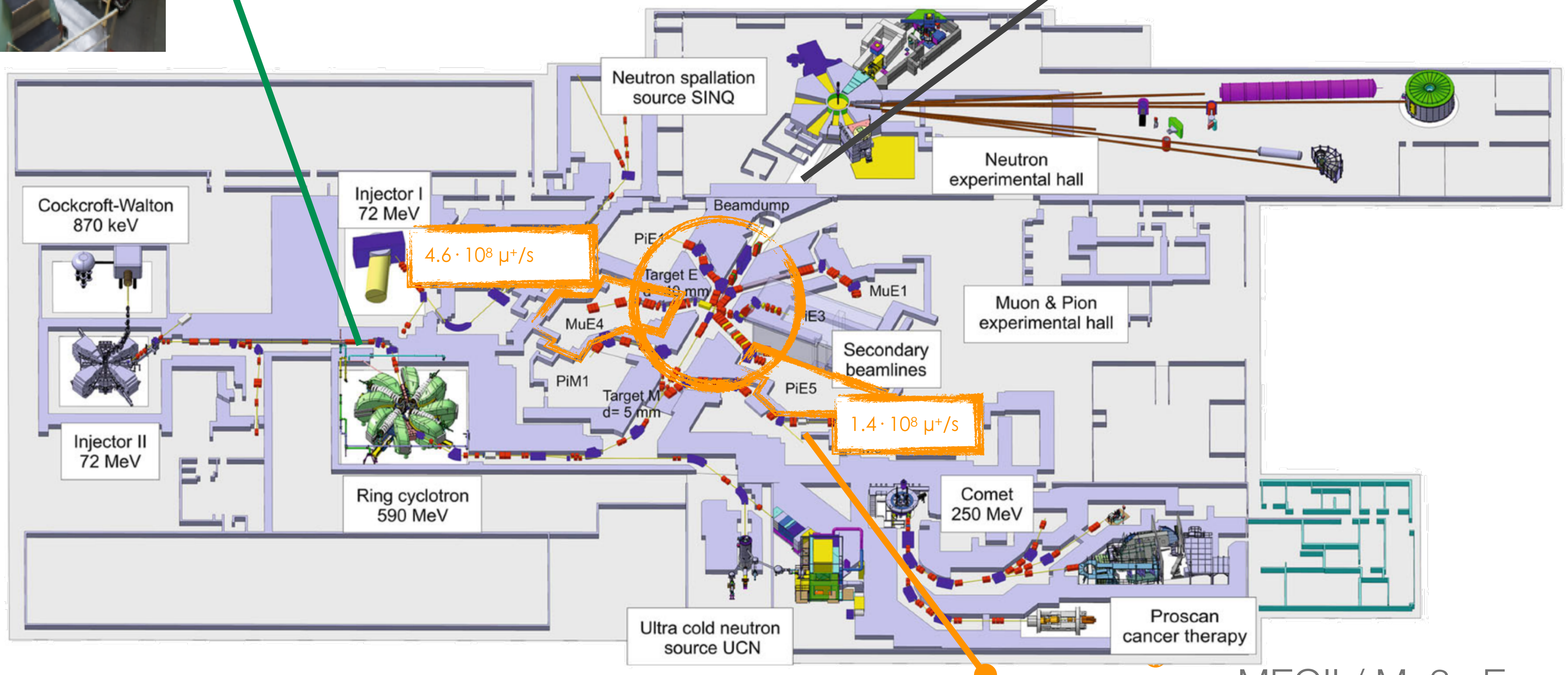


590 MeV proton
ring cyclotron
1.4 MW



Proton RF ~ 50 MHz
“DC” muon beam

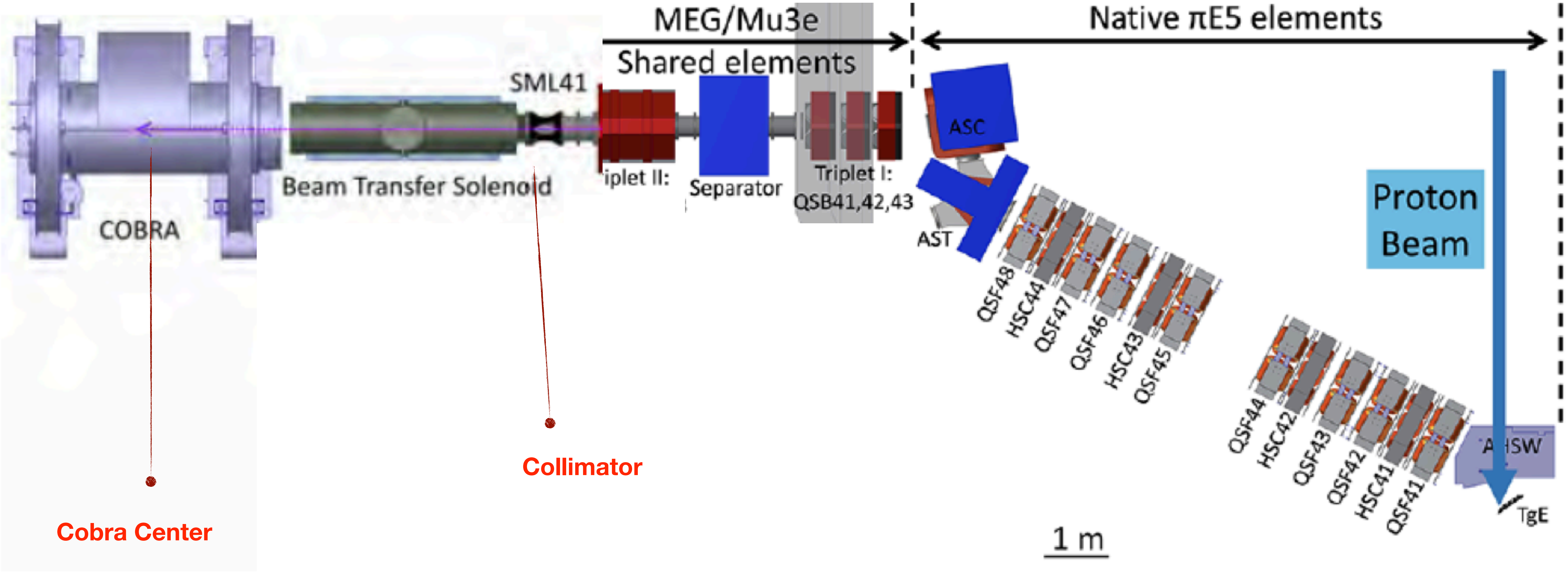
“Muon” Target “E”
production



MEGII / Mu3e Experimental area

The MEGII beam line

- MEGII 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 2.32e8@2.2 mA during the 2023 beam time at the collimator**)

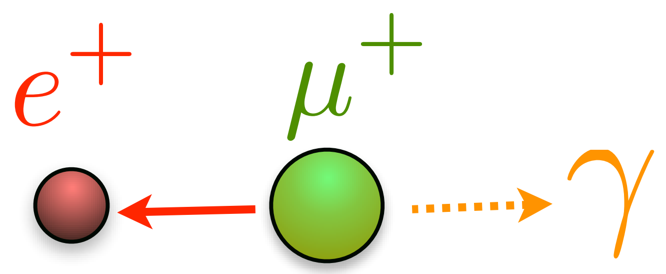


A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C73 (2013) 2365
A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C76 (2016) no. 8, 434

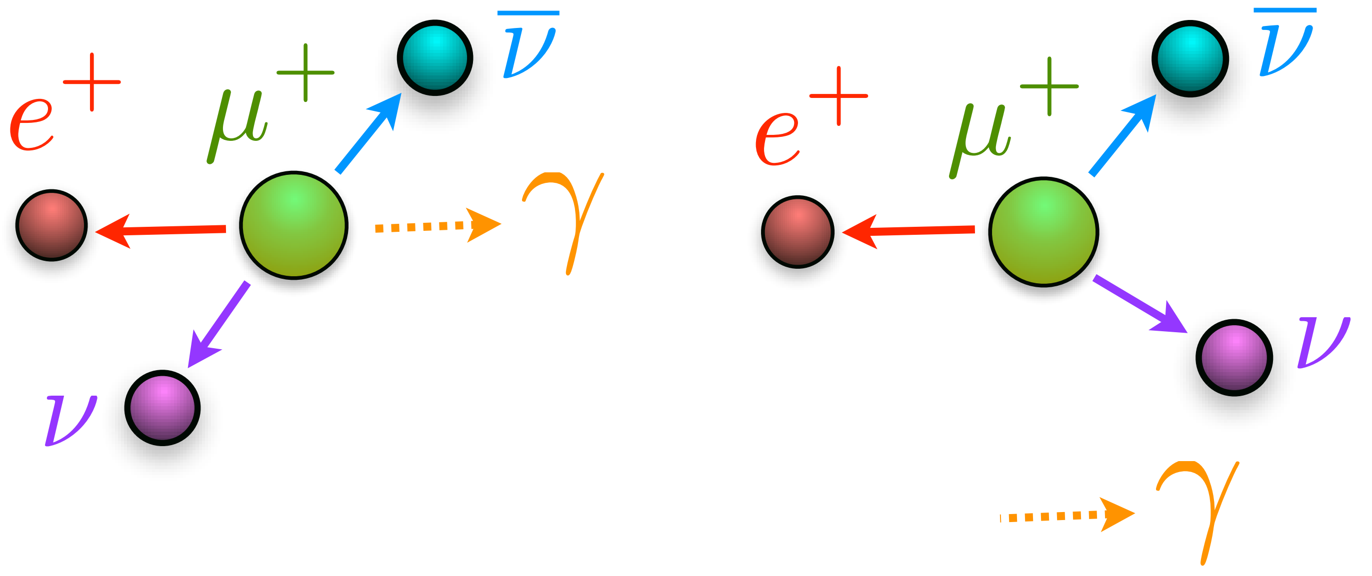
The MEGII experiment at PSI

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

Signature



Backgrounds



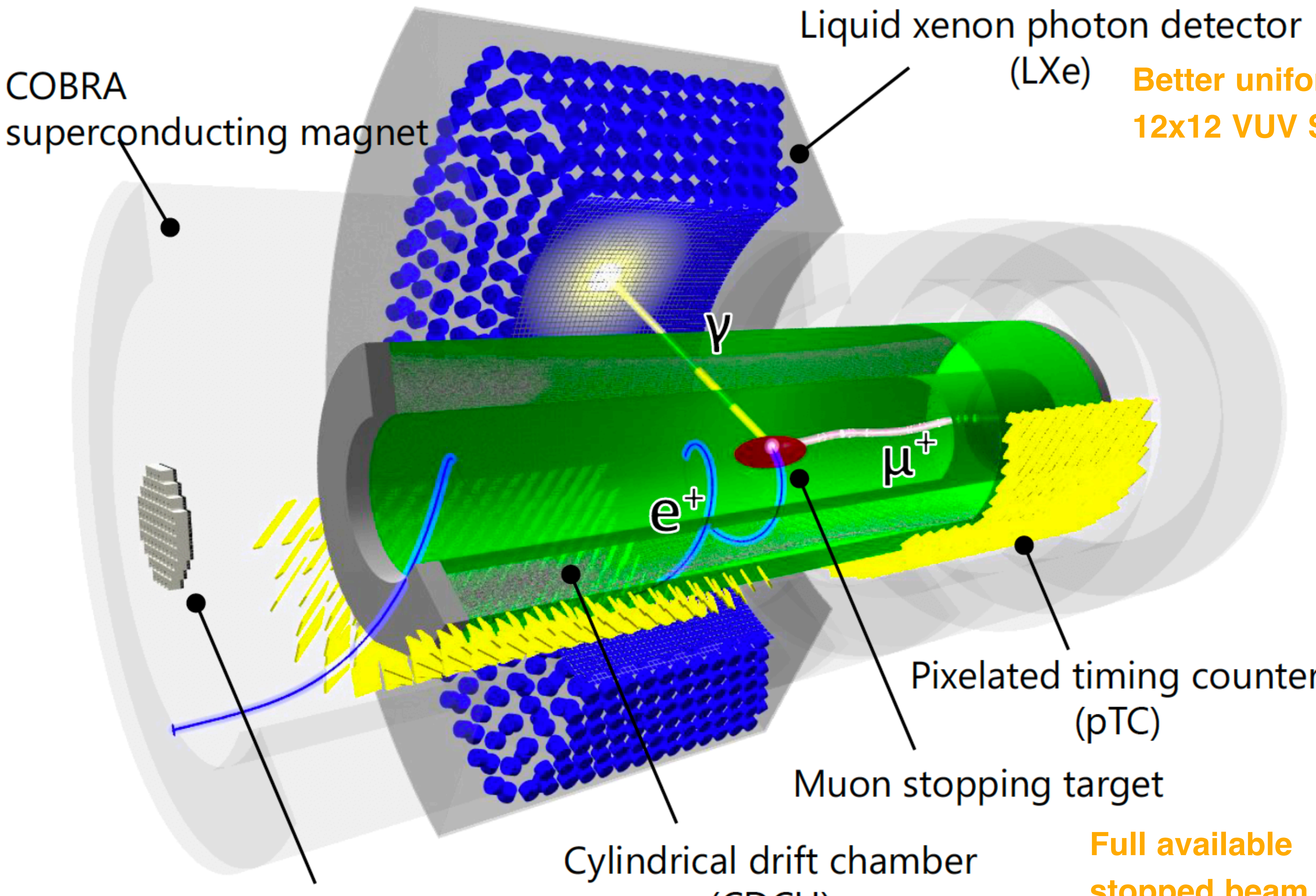
New electronics: WaveDAQ

~9000 channels at 5GSPS

2x Resolution everywhere

Updated and new Calibration methods

Quasi mono-chromatic positron beam



Better uniformity w/ 12x12 VUV SiPM

2x Beam Intensity

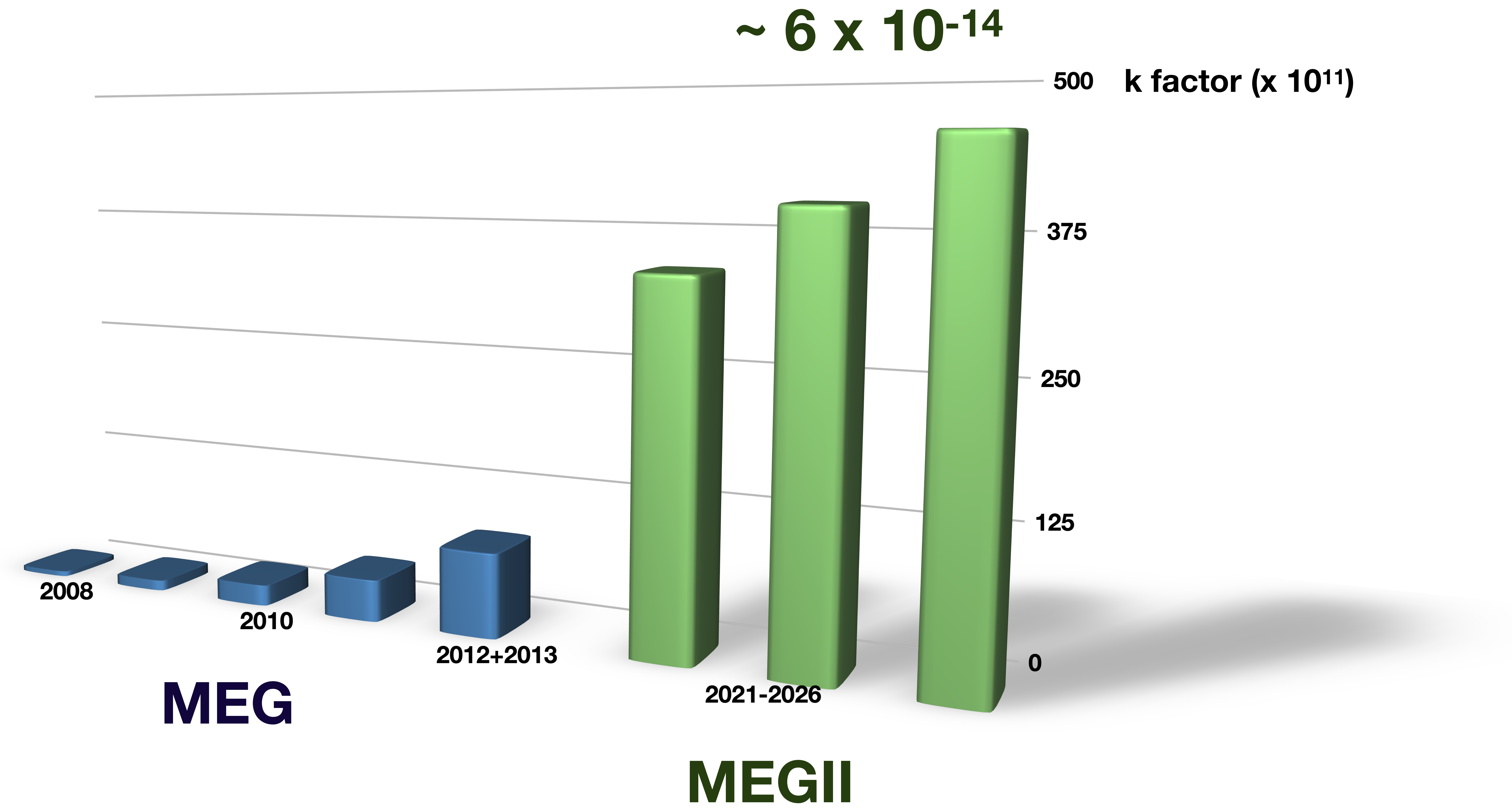
35 ps resolution w/ multiple hits

Full available stopped beam intensity 7×10^7

Single volume $He:iC_4H_{10}$

Background rejection

Where we will be



MEGII: Latest news and currents status

Key points:

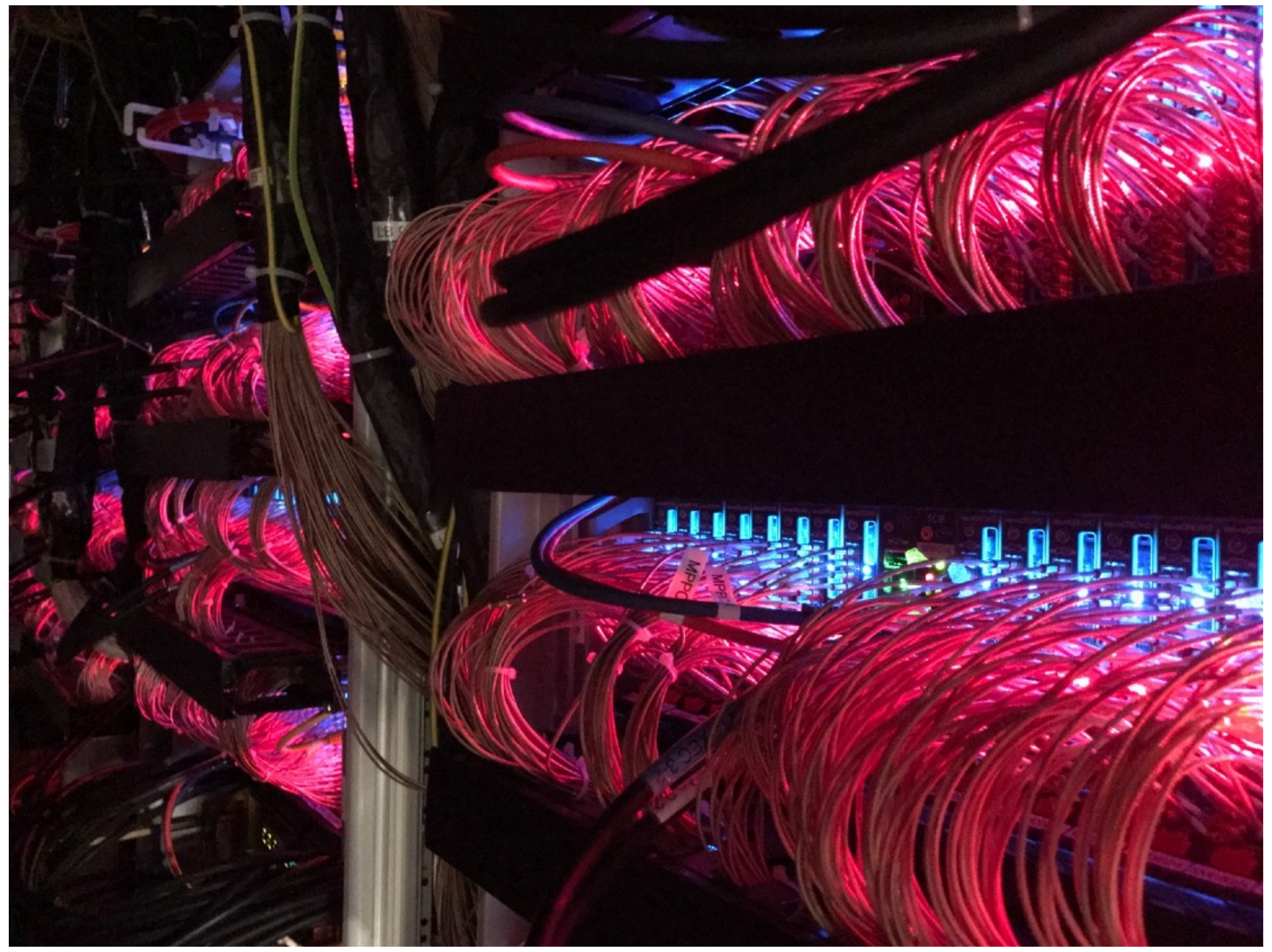
- **Run2021 very successful**
- Electronics fully installed and tested with all sub-detectors and calibration tools
- All calibration and physics trigger configurations released
- Assessed performances of each sub-detectors in the final MEG II conditions
- Collected data at different beam intensities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

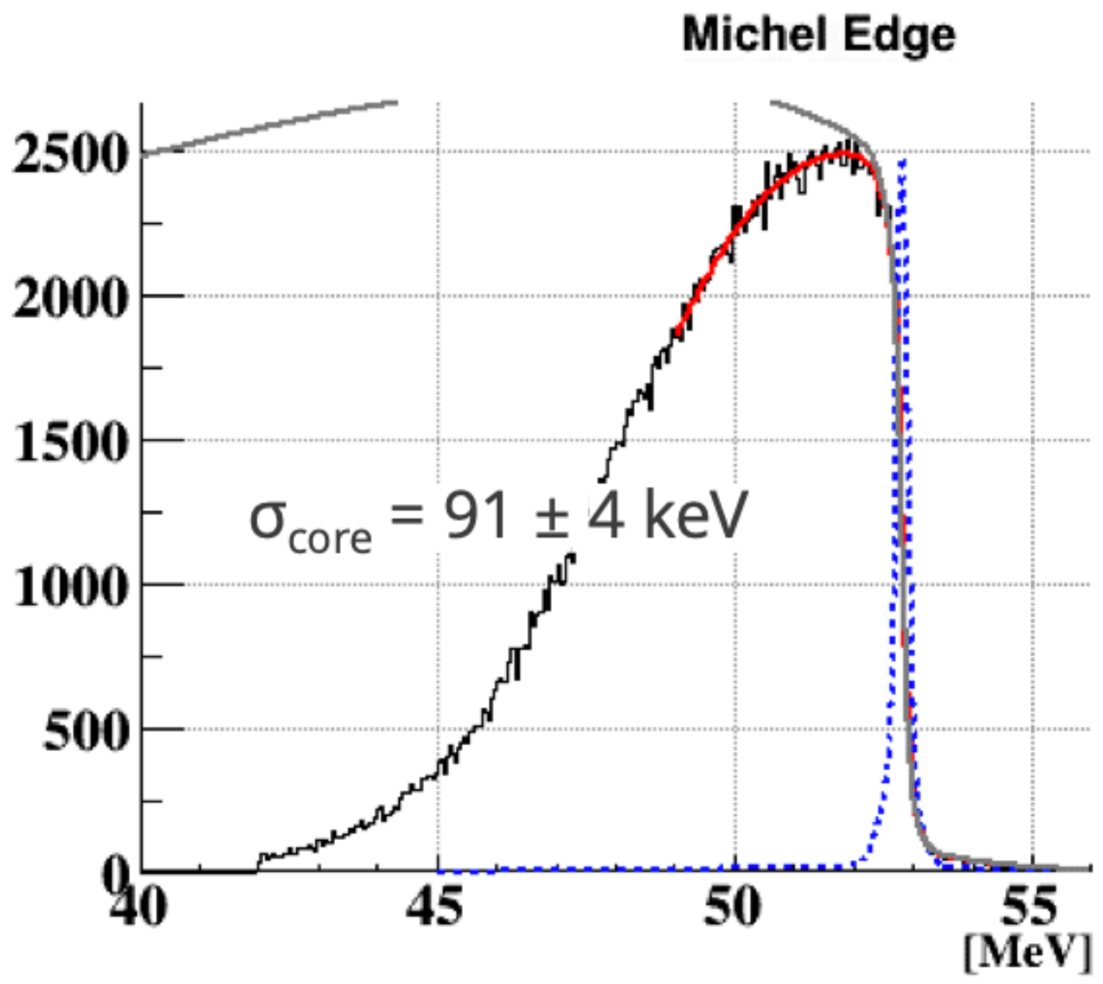
- **Physics run started at the end of September 2021**
- **MEGII beam time 2022 resumed on June 7th and data taking started on July 6th**
- **MEGII beam time 2023 resumed on May 16th and data taking started on June 7th**

Outlook:

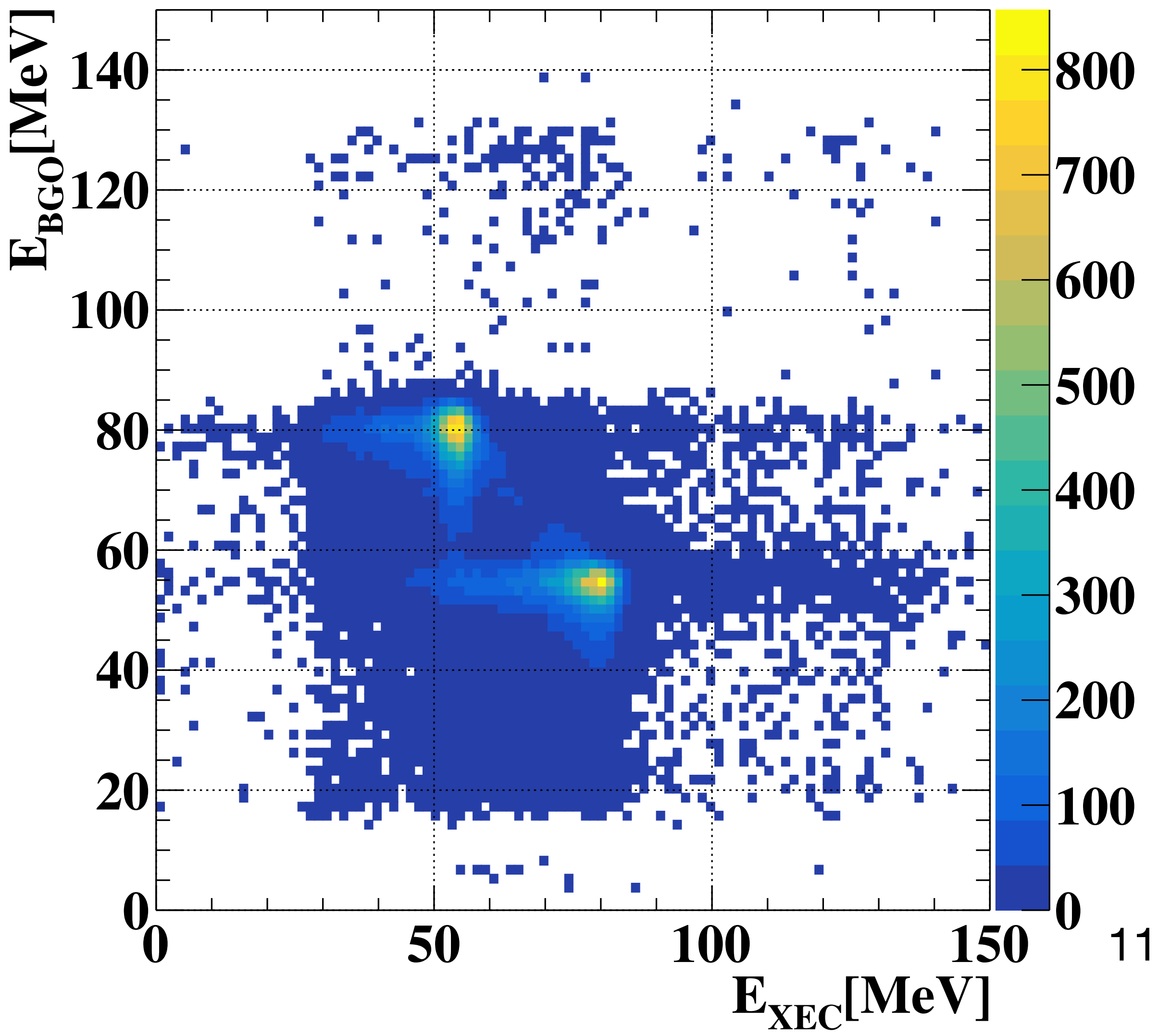
- MEG sensitivity expected to be **already surpassed with the Run 2022**

MEGII **fully** installed!



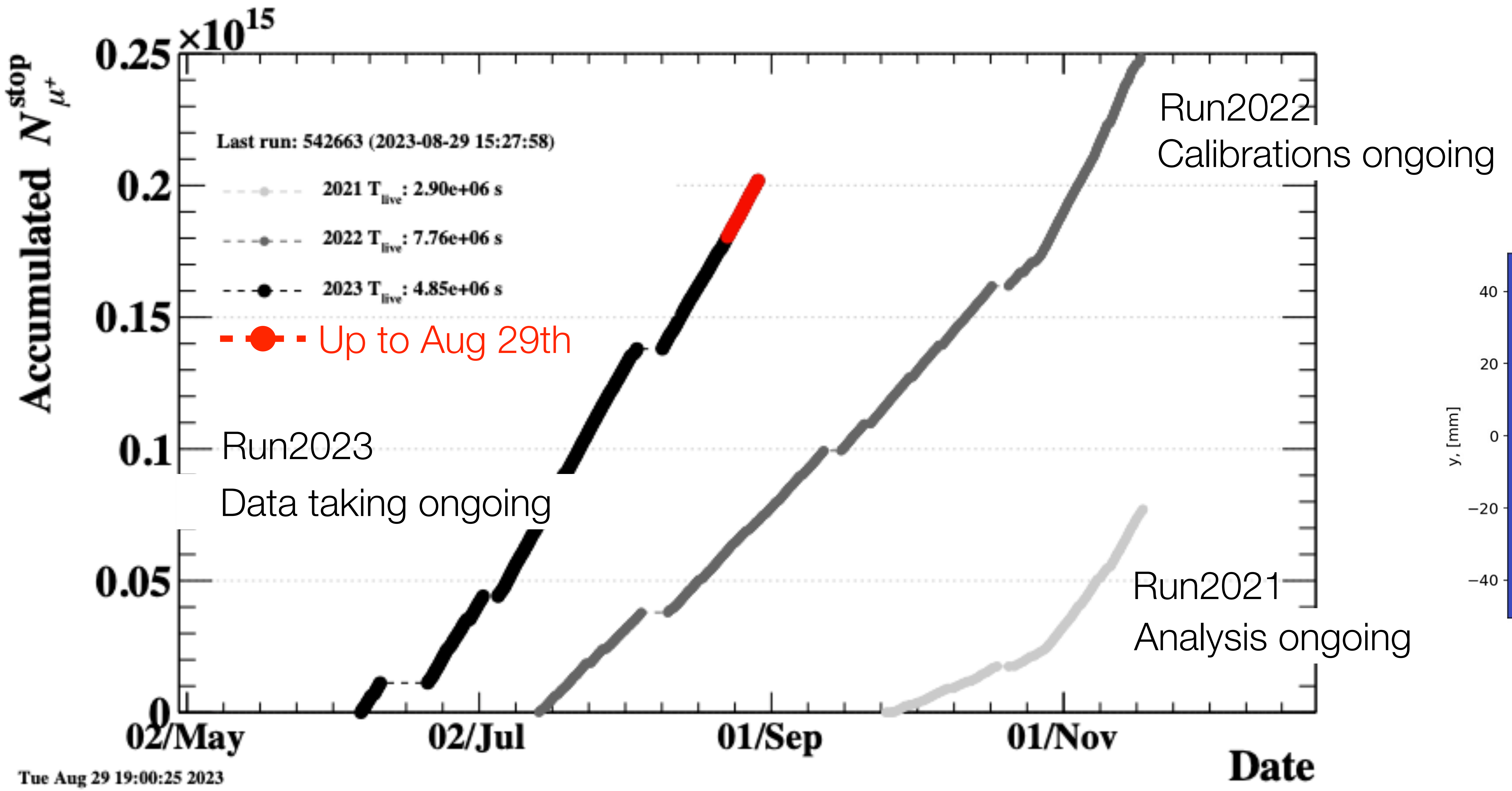


Data from the **first** Physics Run2021

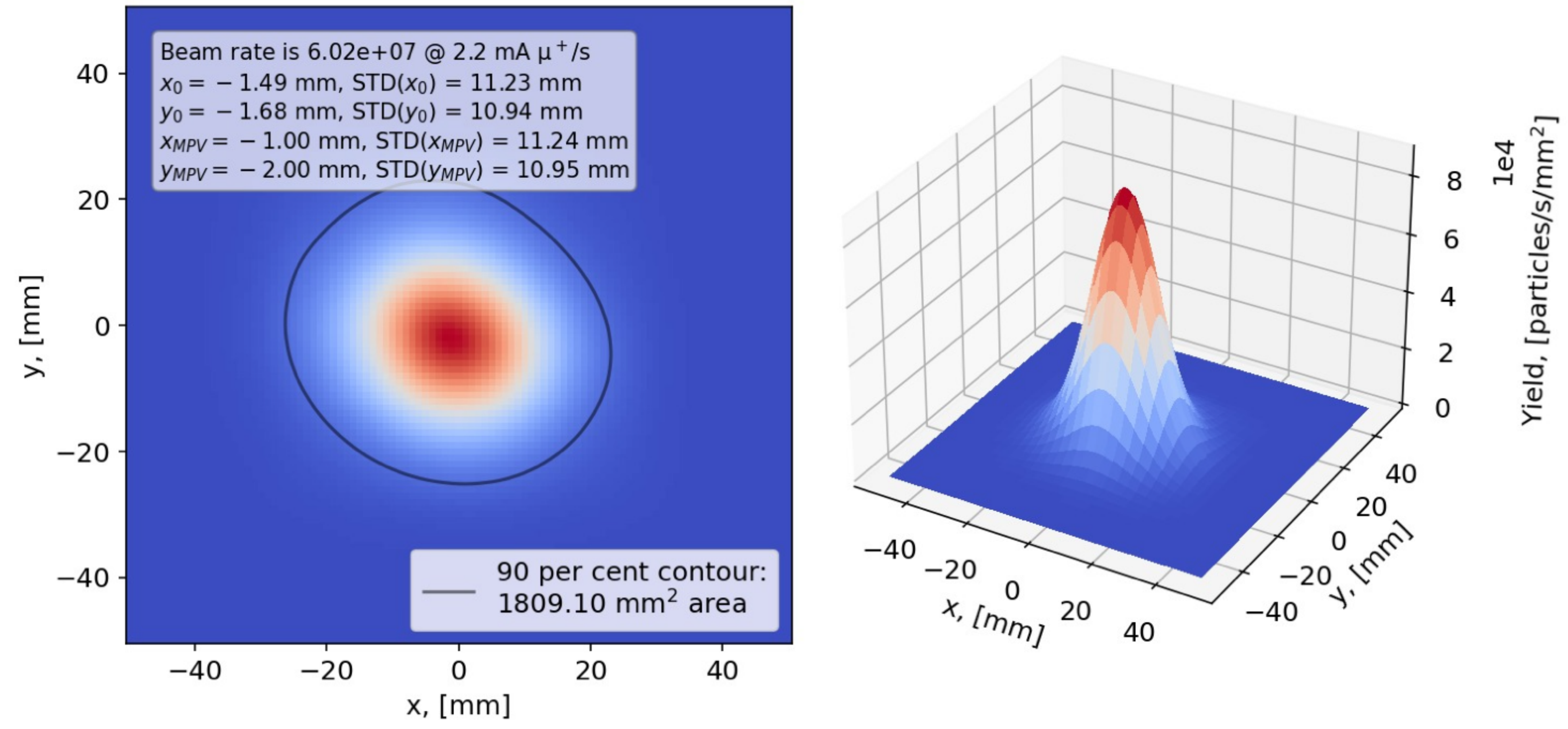


…wishing all the best for the physics run 2023: Just started

- **June 7th 2023: Muegamma data taking started**

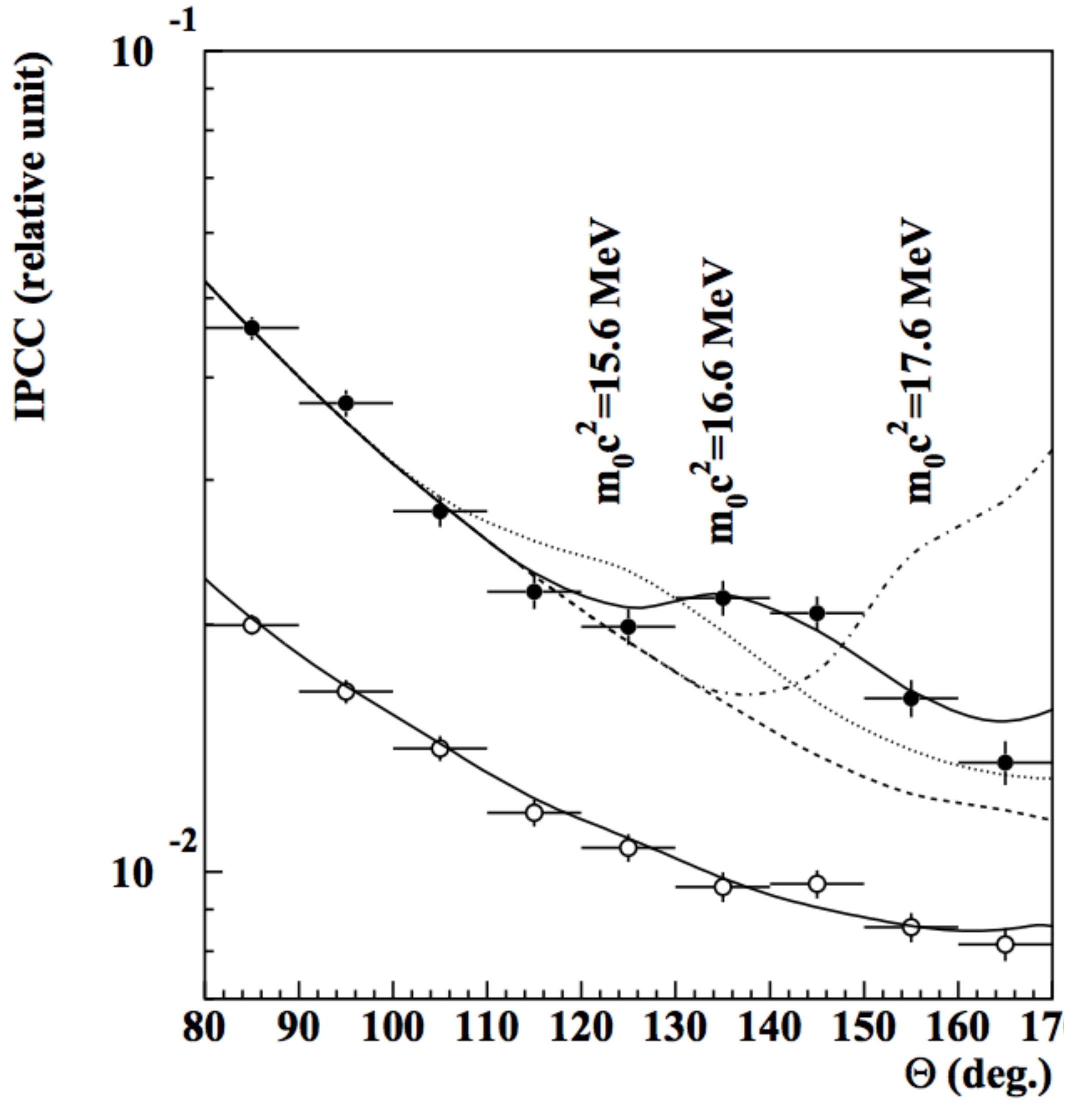


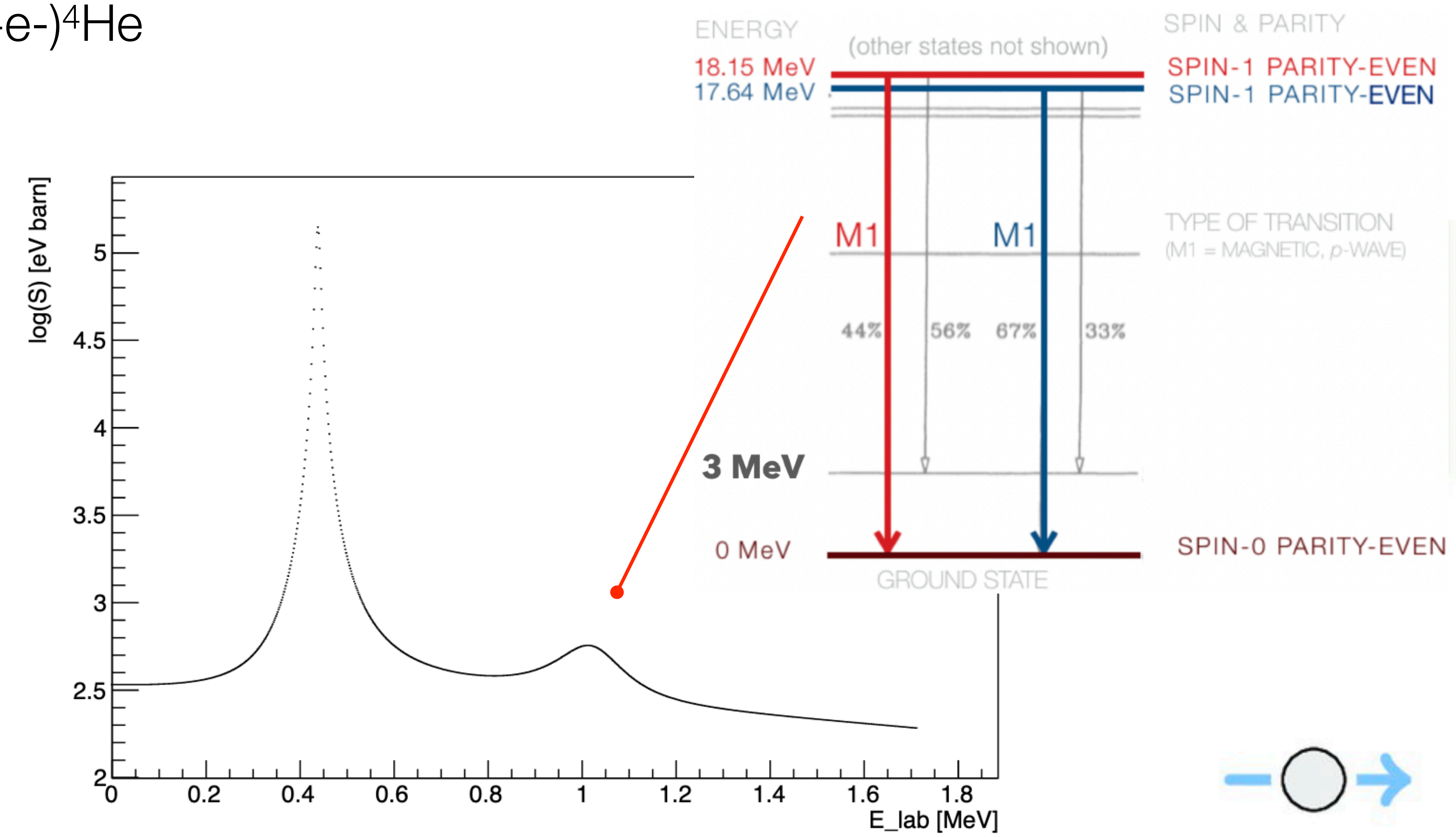
With a beam intensity = **4.27e7** mu/s@1.76 mA

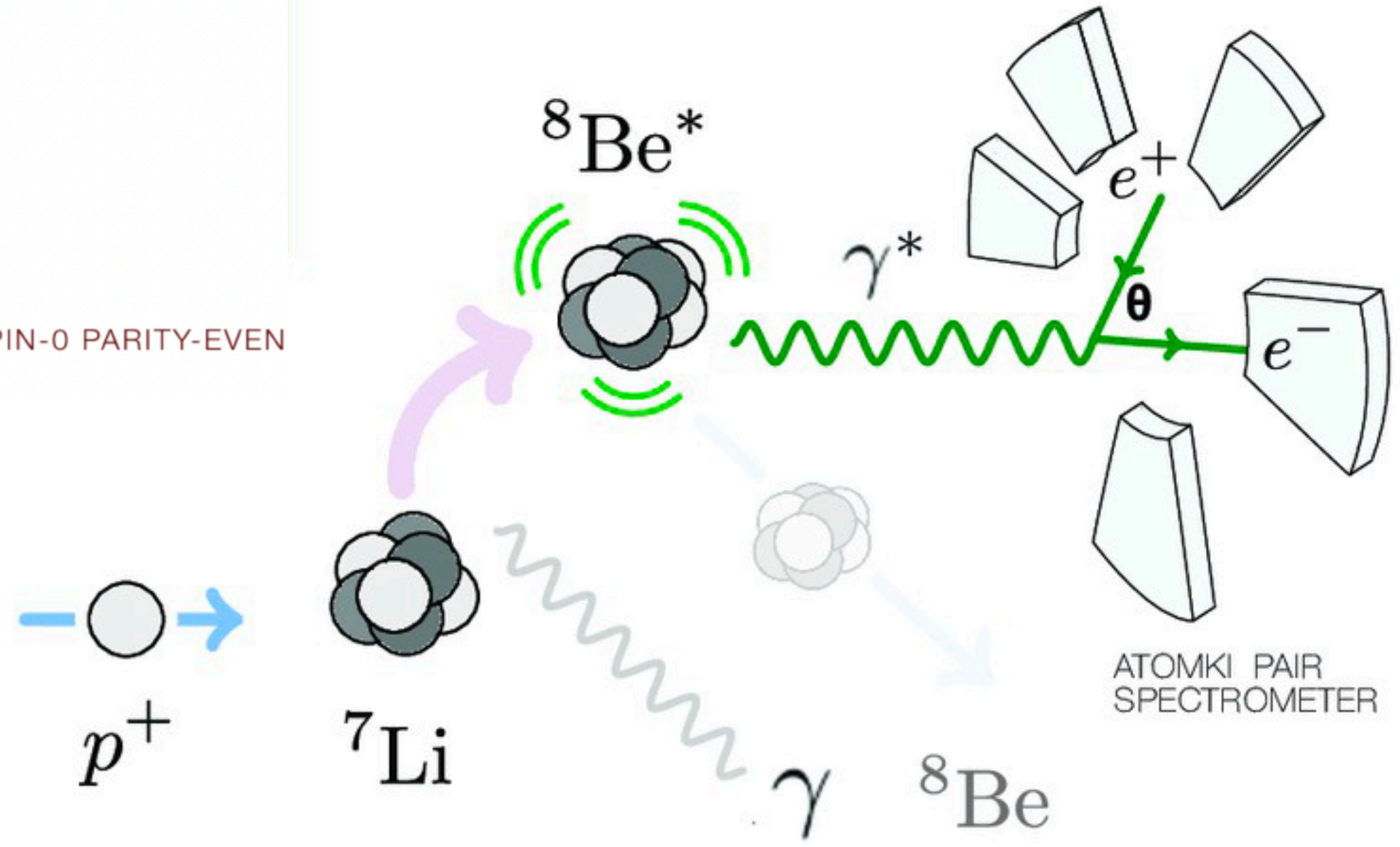


The beryllium anomaly

- Hint for the production of a neutral, 17 MeV boson, potential mediator ad a fifth force: X17 (ATOMKI collaboration)
  - Observed in the ^{7}Li(p, e+e-)^{8}Be reaction at 1100 keV and confirmed at other proton energies (450, 650, 800 keV)
  - Observed in the ^{3}H(p,e+e-)^{4}He







Excess consistent with

- Light boson mass = 16.95 MeV/c2
- Branching ratio (X17/gamma) = 6 x 10^{-6}

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

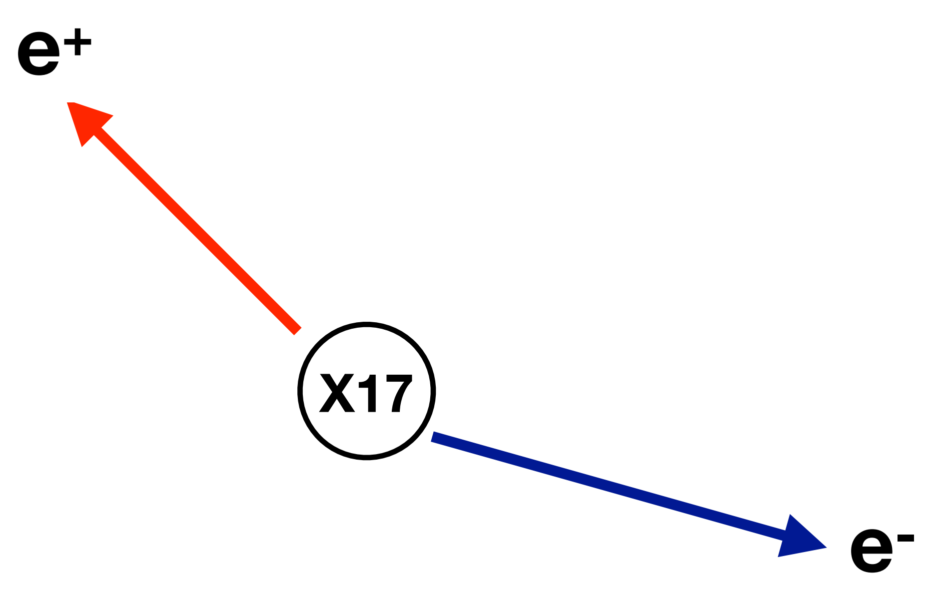
Phys. Rev. C 104, 044003

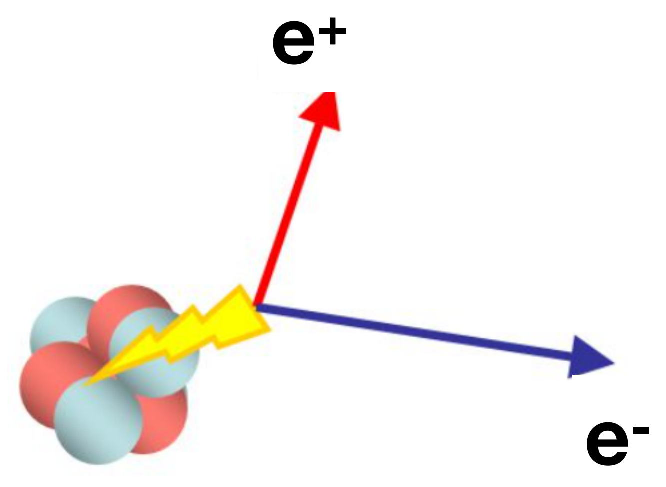
Phys. Rev. D 95, 035017

The X17 search with the MEG II apparatus

- The new MEGII spectrometer can be used for X17-Boson searches by replacing the muon target with a dedicated one for the X17-Boson production, adjusting the magnetic field and using it together with the MEGII CW accelerator, combined with the XEC and other gamma auxiliary detectors, an optimised TDAQ and an extended analysis code

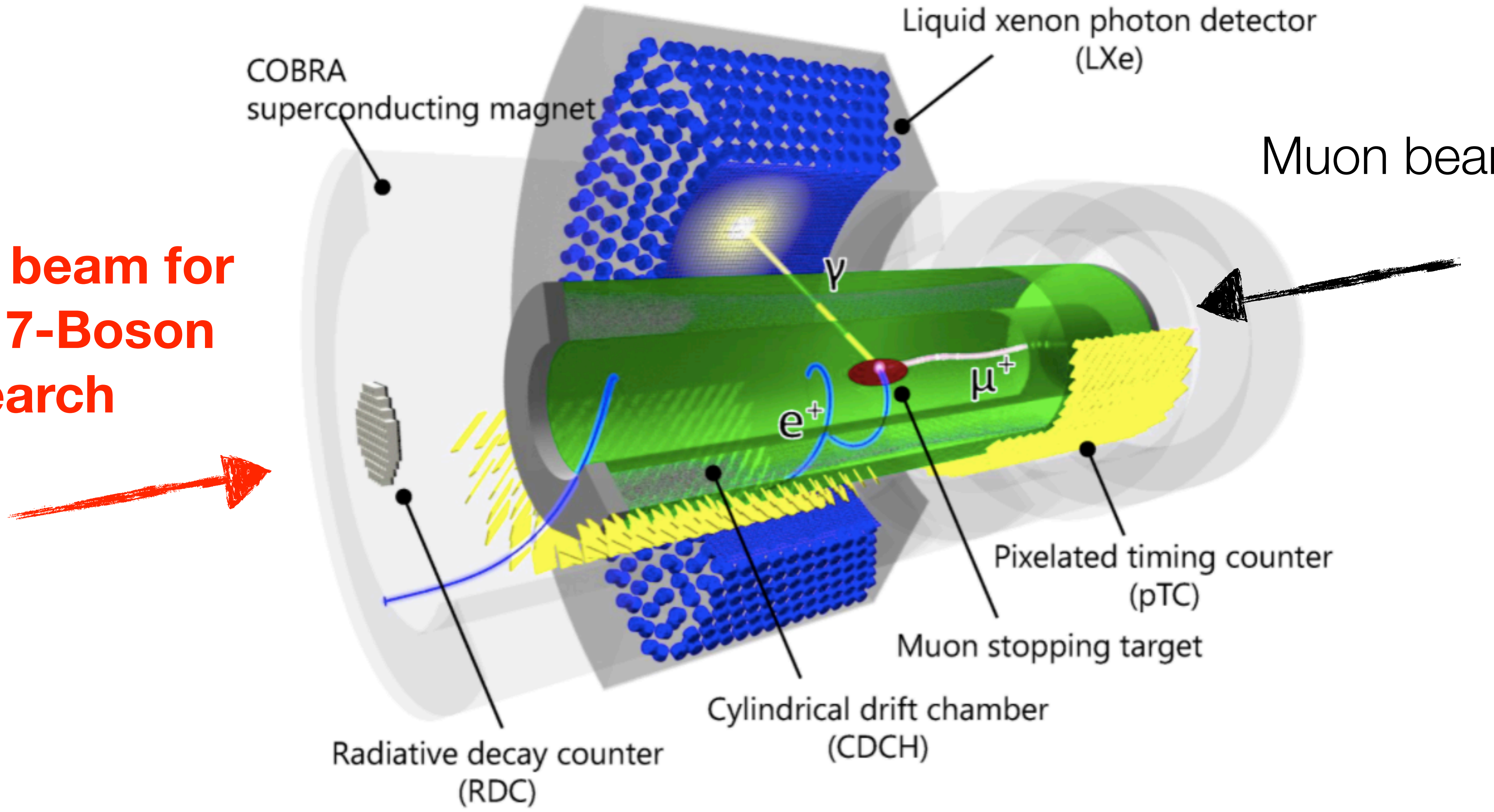
Signal





Backgrounds:
Gamma Internal and External Pair Conversion (IPC, EPC)
- IPC: Resonant and non-resonant
- EPC: Experimental setup material budget

Proton beam for the X17-Boson search



with MEG II

→ **Better** invariant mass resolution

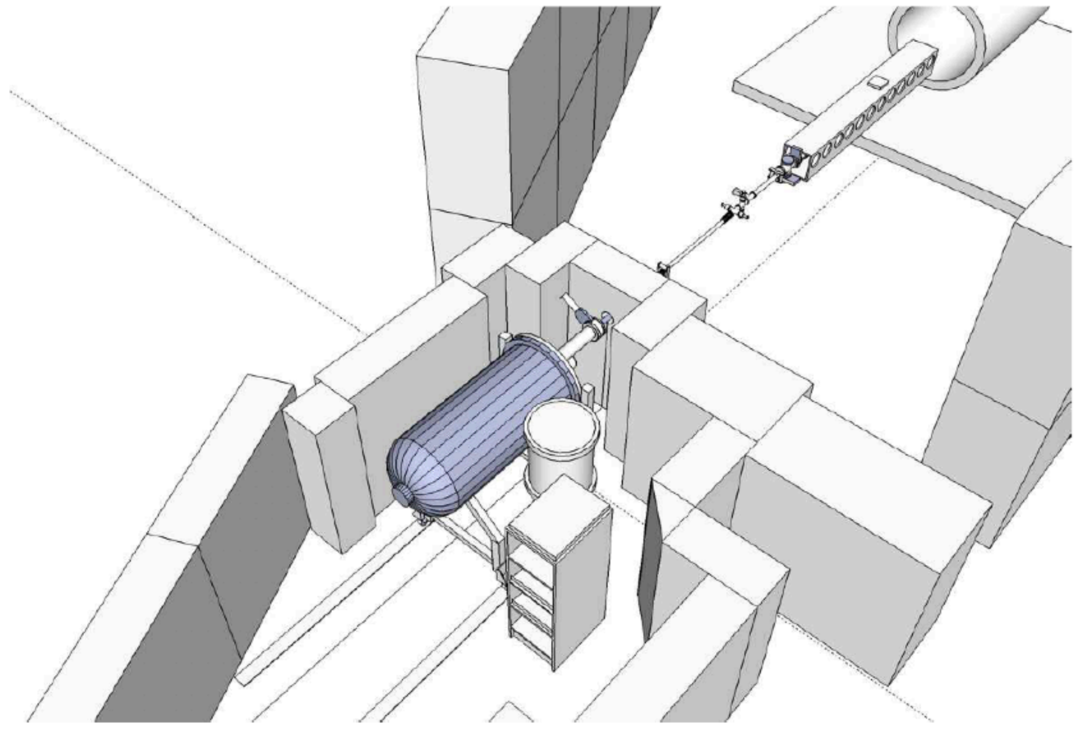
→ Detection in an **estended** angular range

The X17 search: The experimental setup

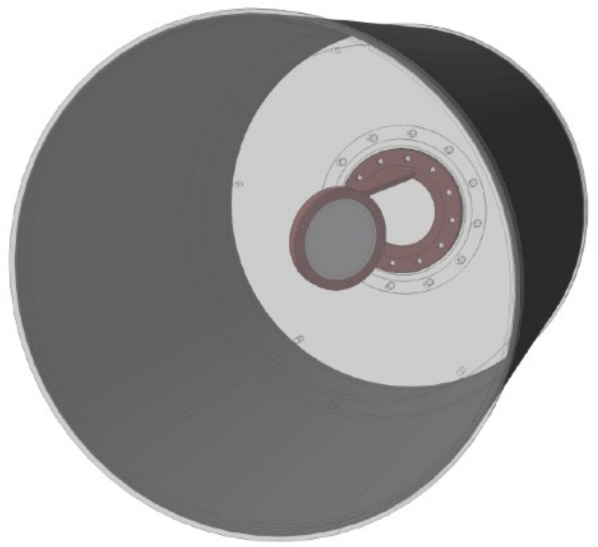
Key points:

- Proton beam from the CW accelerator
- New Vacuum Chamber and tilted Li based target (LiPON, LiF)
- CDCH and pTC detectors
- Reduced magnetic field (~6x less than the MEG II settings)
- XEC and auxiliary gamma detectors for
  - directly measuring the gamma backgrounds
  - stability monitoring
  - normalising the data sample
- Optimised TDAQ for
  - efficiently selecting the signal
  - rejecting the background
- Extended and optimised analysis code for
  - reconstructing both positive and negative charge particles

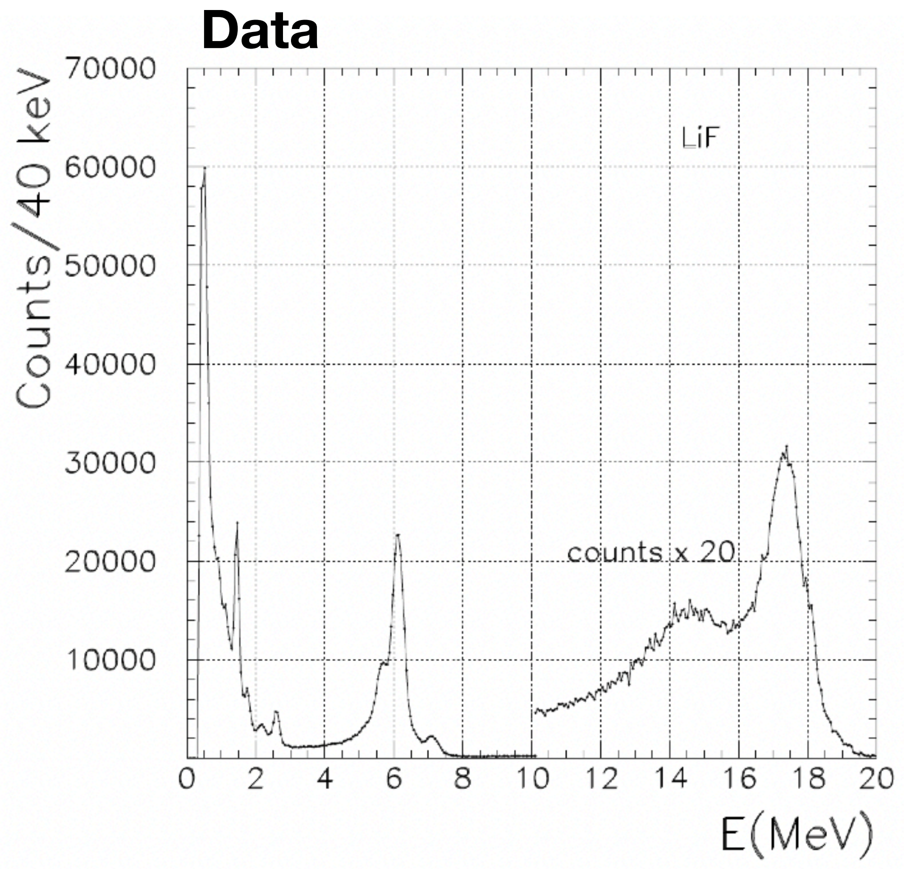
The MEG II CW accelerator and its beamline



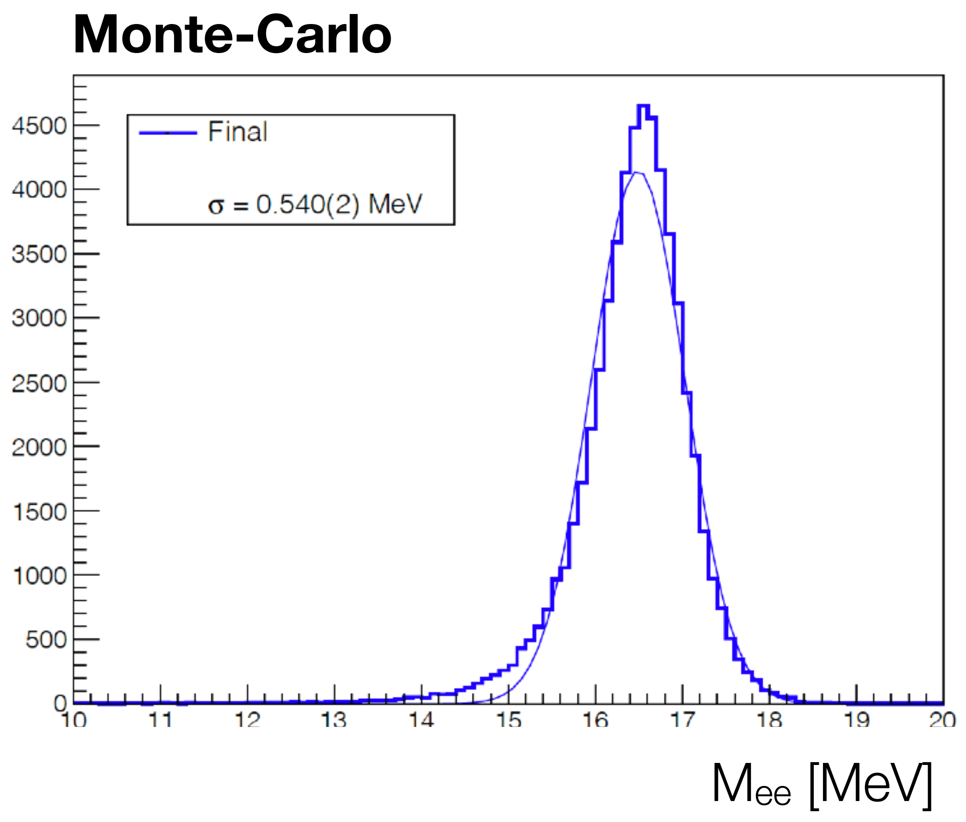
The new X17-Boson target region



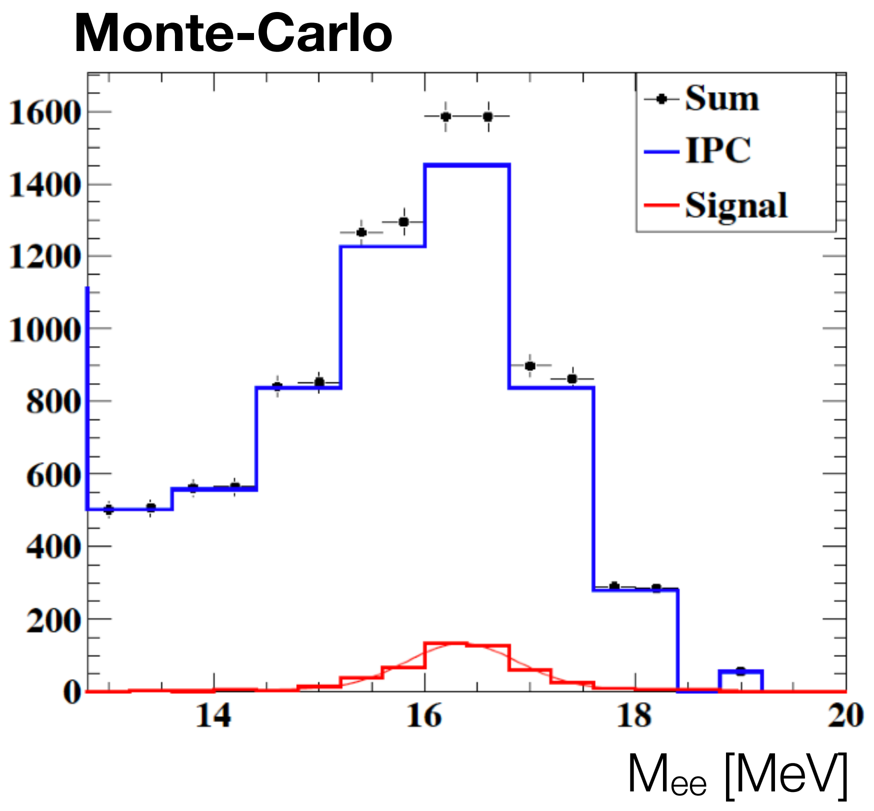
In blue the 17.6 MeV gamma line used for calibrating the XEC detector



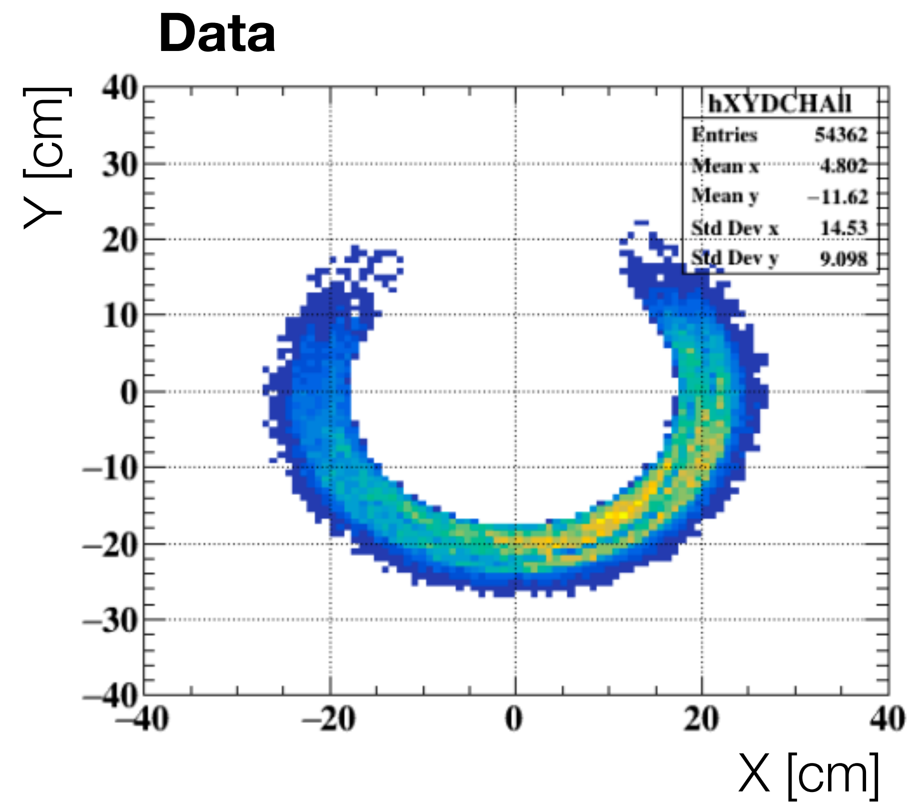
The expected reconstructed invariant mass of the e+/e- pair with the MEGII apparatus



The invariant mass distribution for the e+/e- pair produced either from the hypothetical X17 or the IPC (Internal Pair Conversion). The sum of the two is also given



An example of hit distribution (real data) in the CDCH during the pivotal data collection performed in February 2022



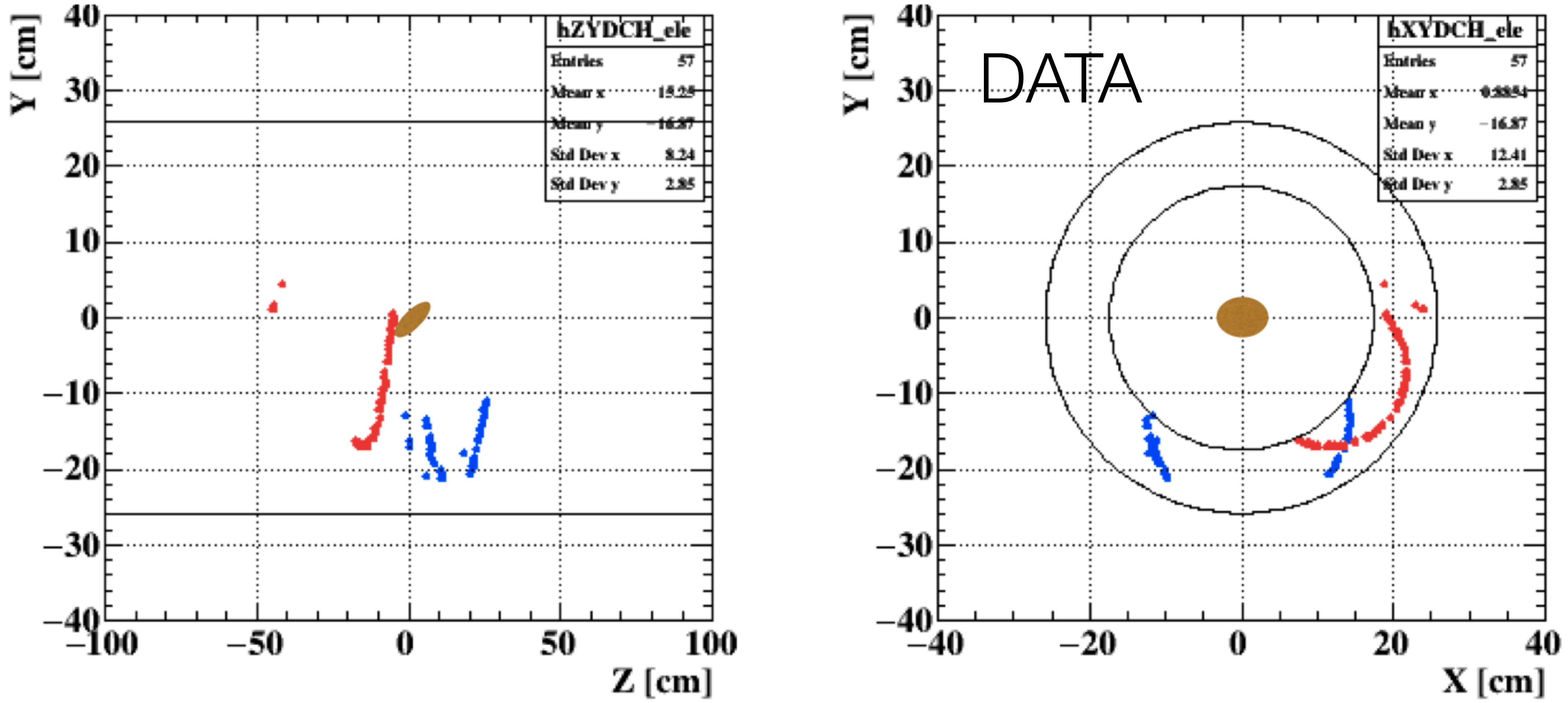
X17 analysis status: a typical reconstructed e+ e- event [DATA]

- Examples of events from the pivotal February DATA sample
- Reconstruction algorithm for e^+e^- pairs

LiPON data 02/22

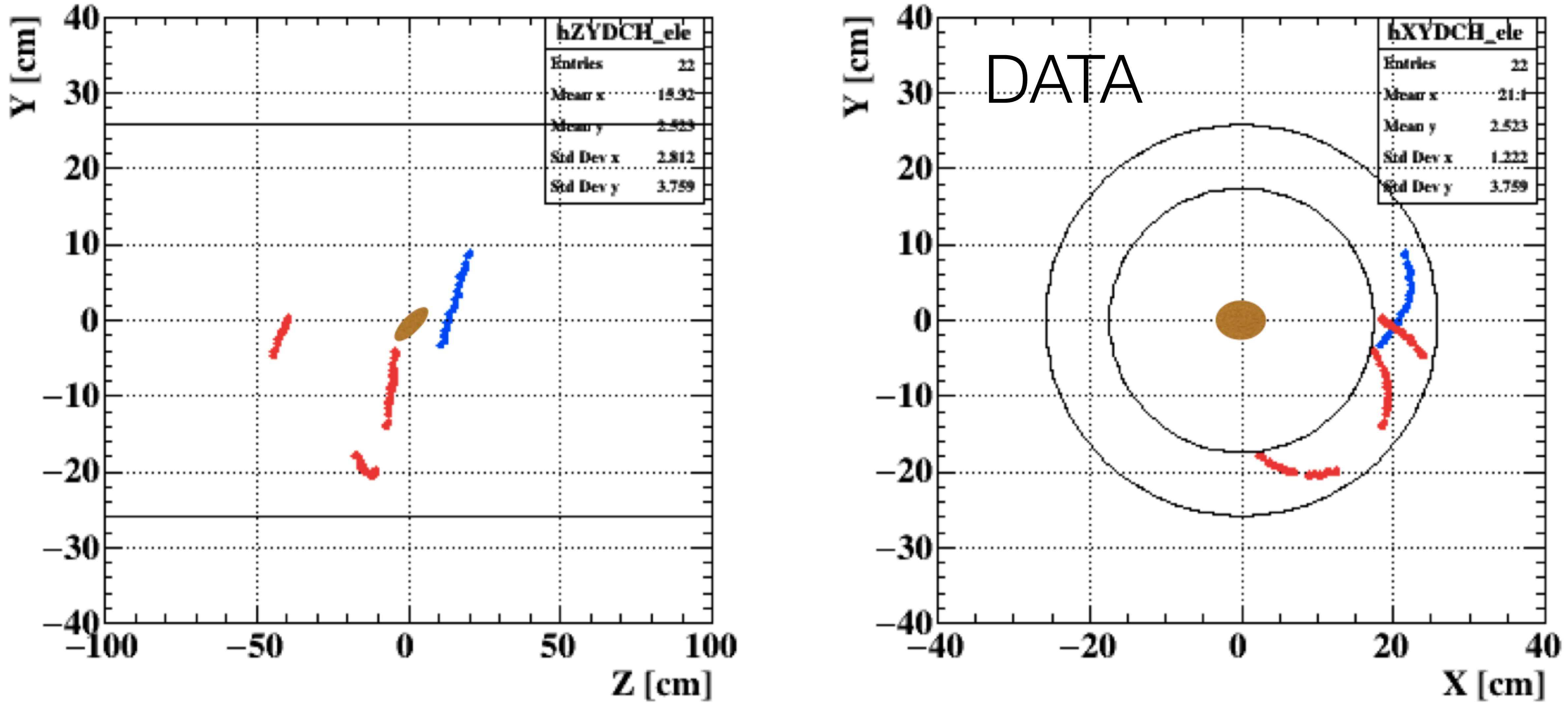
- **Event A**

p+ = 6.7 MeV
p- = 8.3 MeV
angle = 141°



- **Event B**

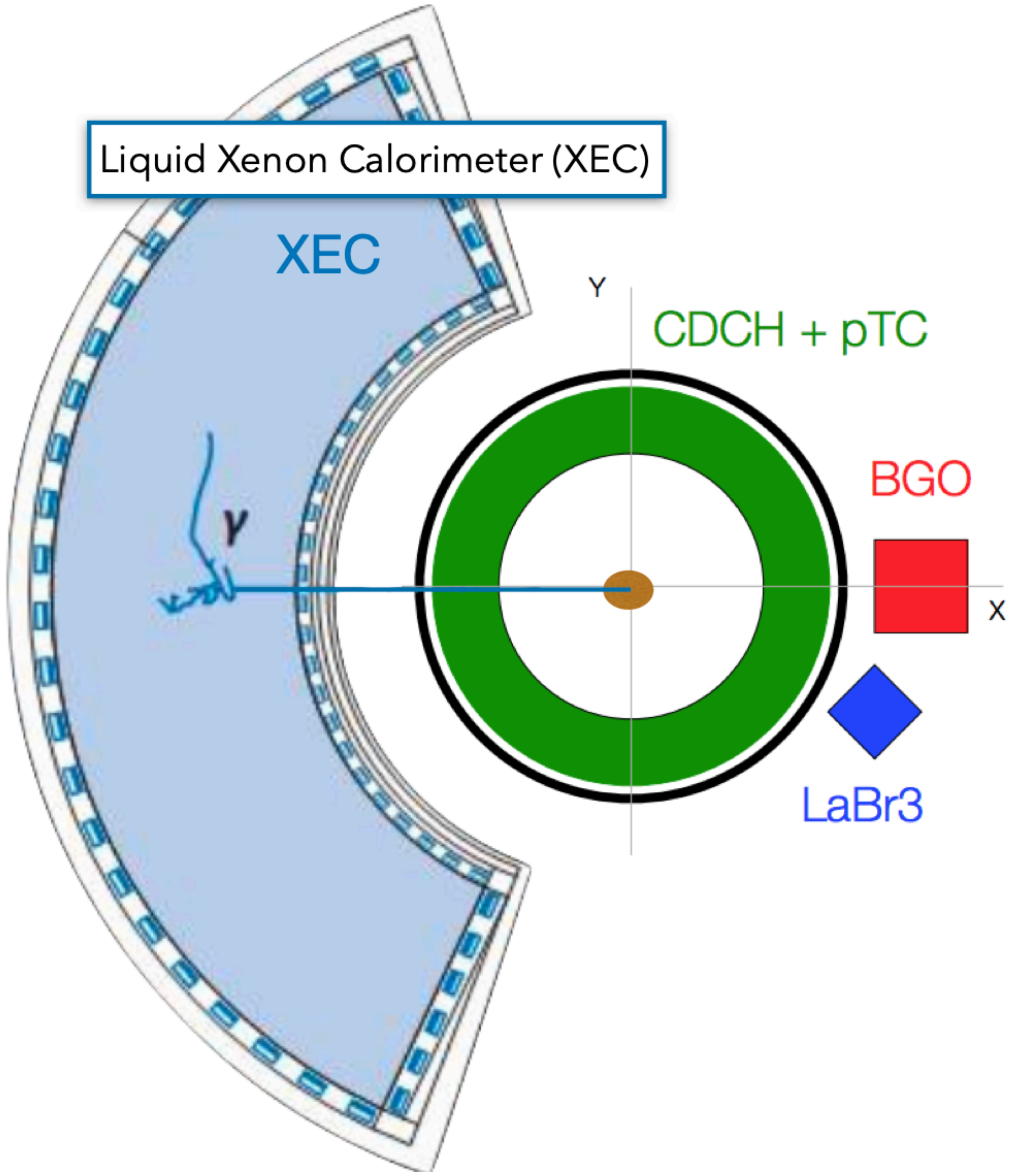
p+ = 6.7 MeV
p- = 6.9 MeV
angle = 101°

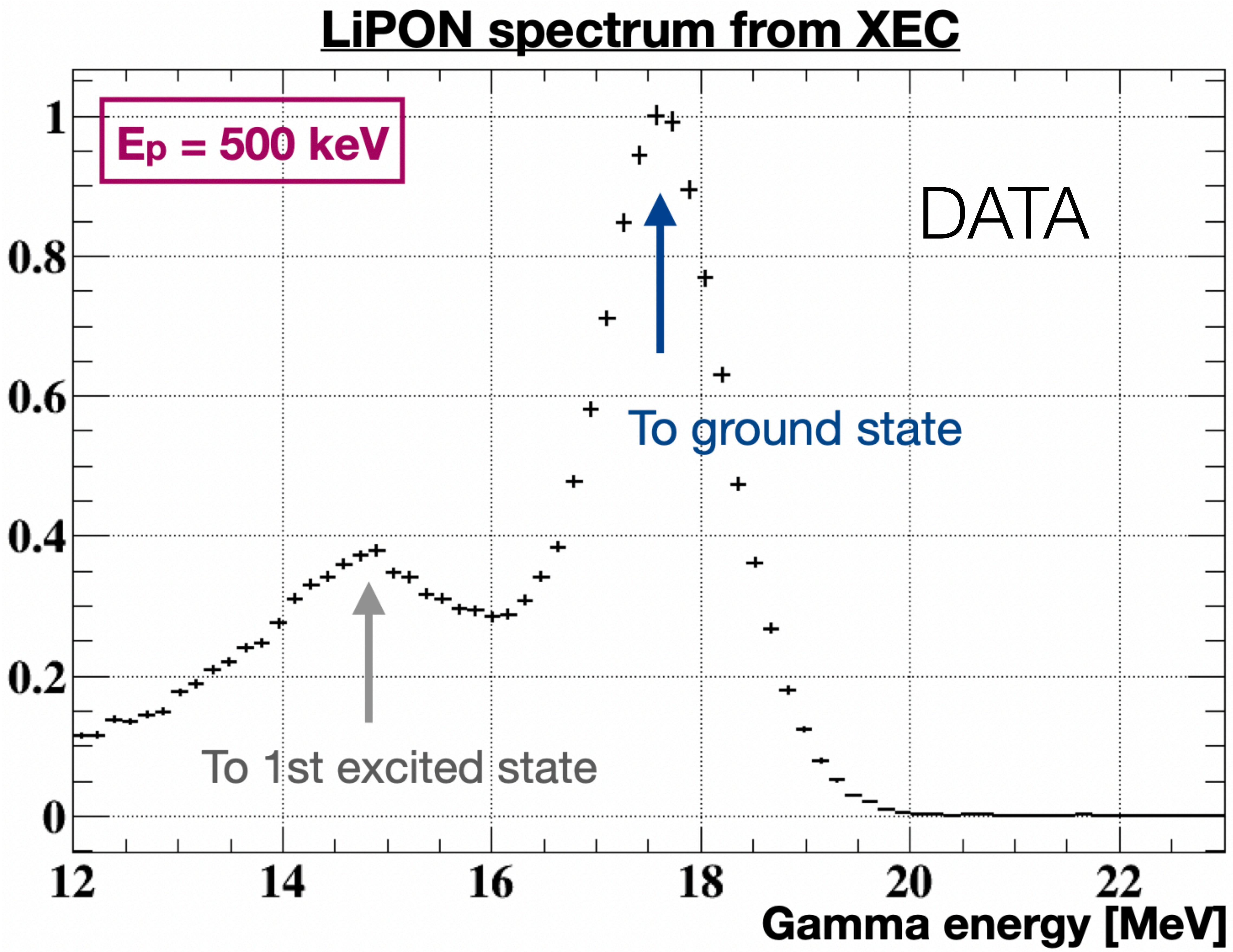


- e+ hit
- e- hit
- target

X17 analysis status: Gamma spectra [DATA]

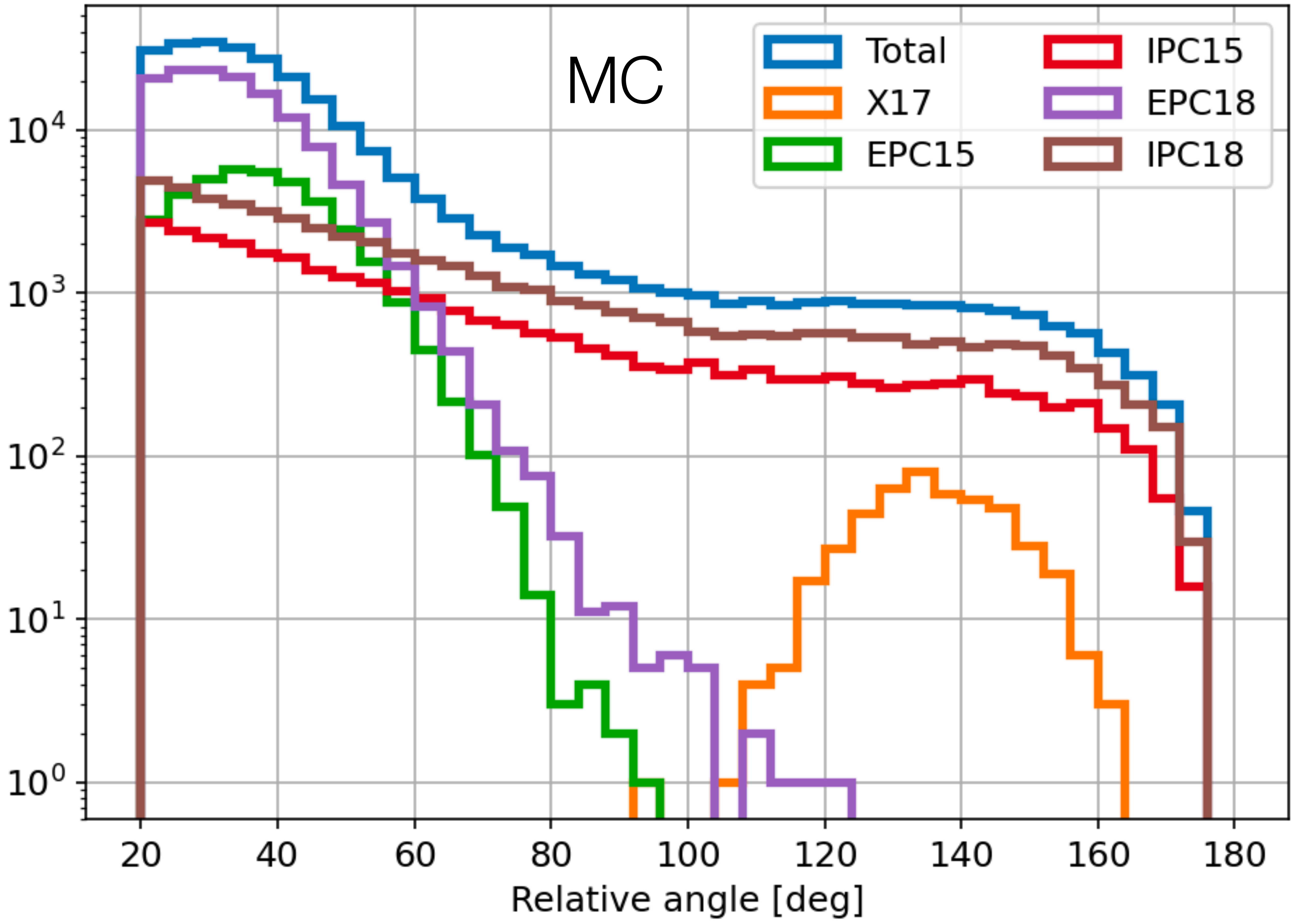
- Gamma spectra and rate crucial for the proof-of-quality of the measurement
- LXe calorimeter for background measurements
- Auxiliary gamma detectors for online monitoring (BGO and LaBr crystals)





Signal and Backgrounds [Monte Carlo]

- Simulated Signal (ATOMKI BR) and Backgrounds in MEGII - current status



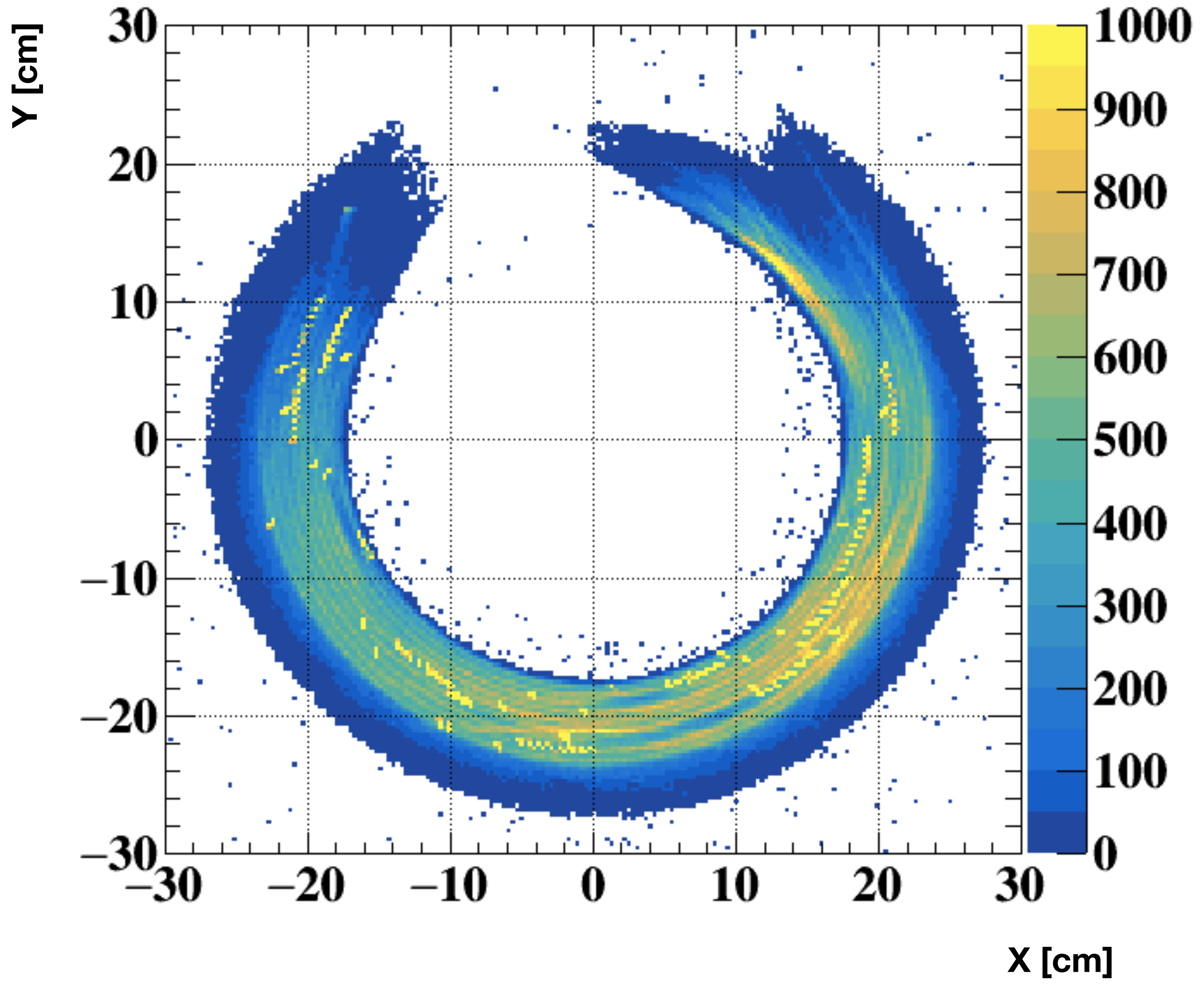
Collected data sample

- 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 at Ep = 1080 keV
  - ~75 M Events
  - ~**300 K** Events Reconstructed pairs

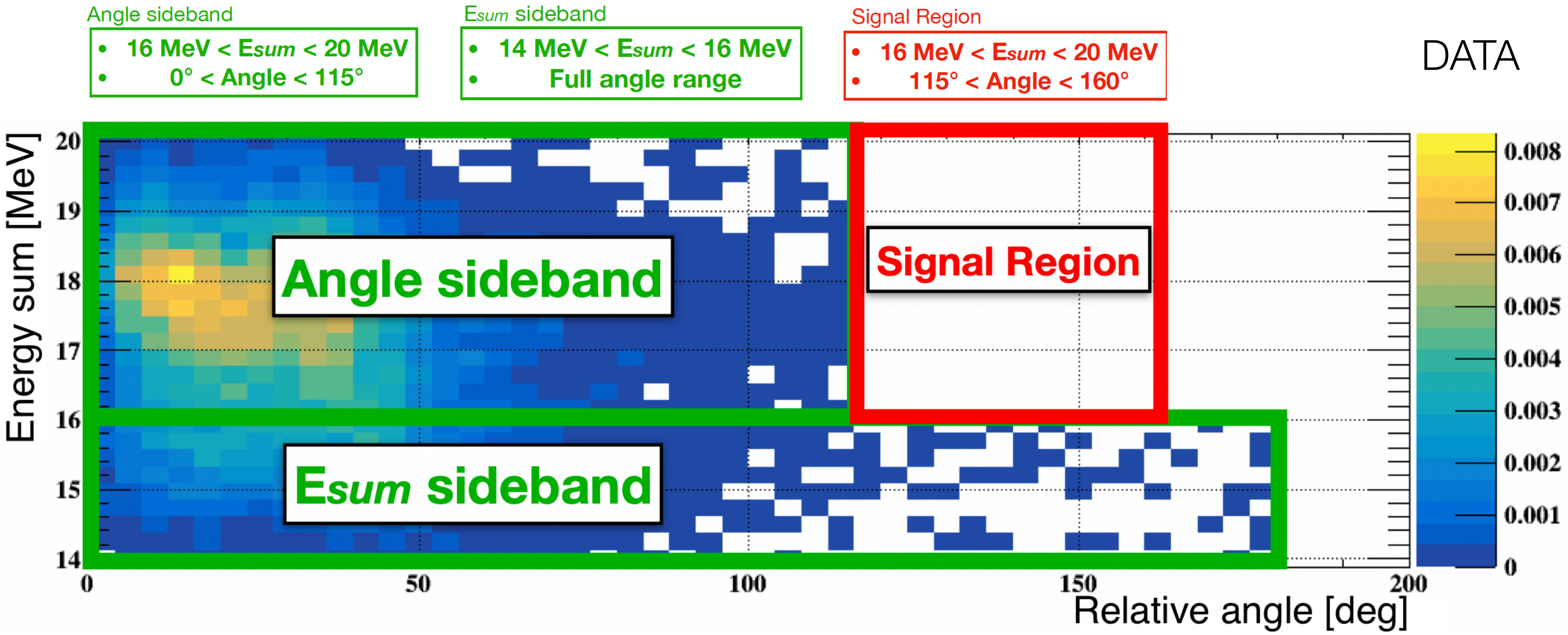
- On full range of the Esum and Angular Opening angle observables:
  - ~60% EPC (15 + 18 MeV)
    - Dominant at low angle, negligible in the signal region
  - ~40% IPC (15 + 18 MeV)
    - Dominant in the signal region

DATA



Analysis strategy

- 2D Likelihood maximization: **E$_{sum}$** vs **Angular Opening** Observables
- Blinded **Signal Region**
- Background studies on the **Side Bands**



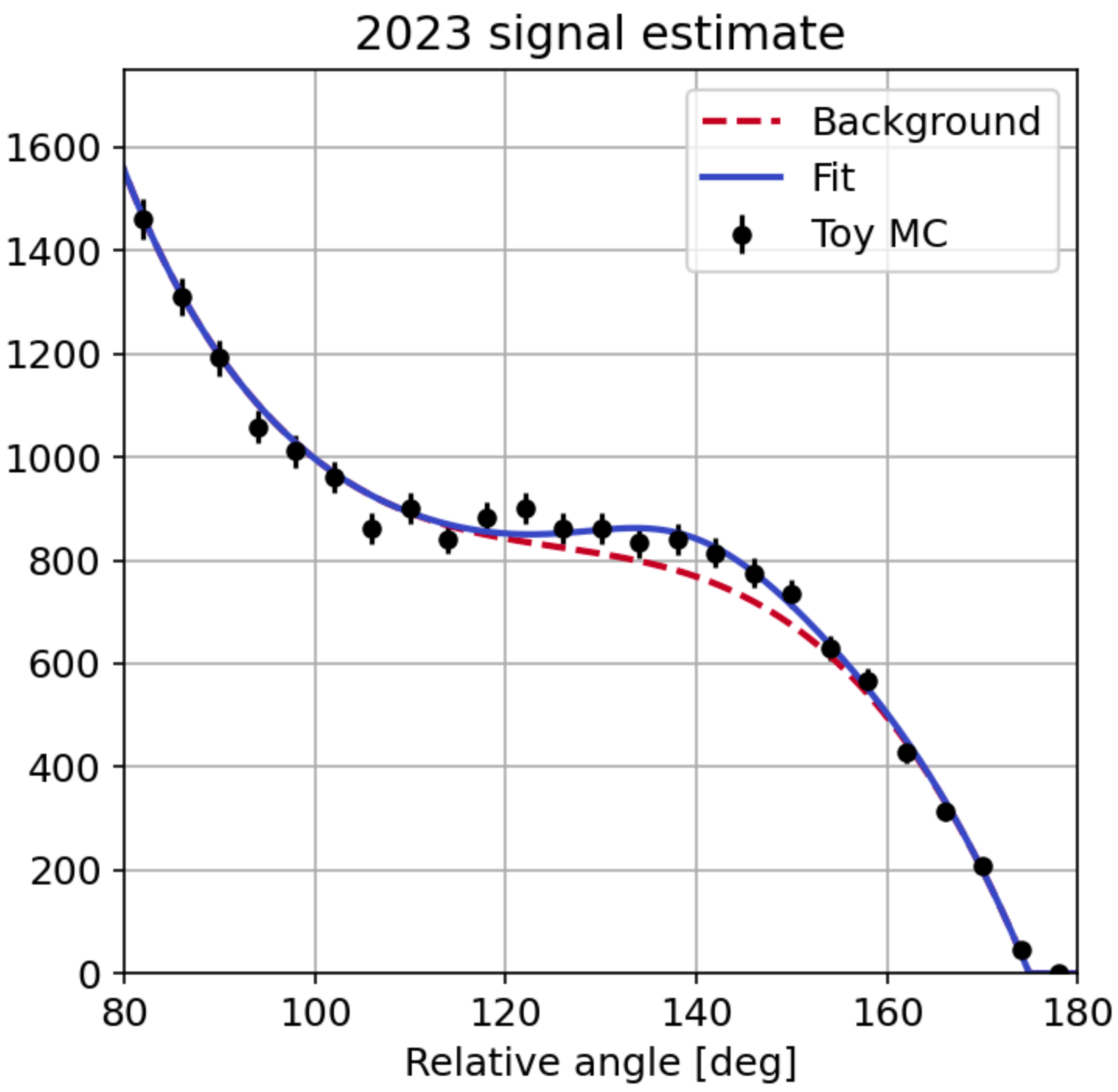
Likelihood and signal estimate

- The analysis will be a full Feldman-Cousins construction to set C.L. on the X17 branching ratio and mass using Esum and the Angular opening as variables
- The likelihood is defined as the following:

$$\mathcal{L} = \mathcal{L}(\mathbf{x}|\hat{N}_S, \hat{N}_{EPC15}, \hat{N}_{IPC15}, \hat{N}_{EPC18}, \hat{N}_{IPC18})$$

$$\mathcal{L} = \frac{\hat{N}^N e^{-\hat{N}}}{N!} \prod_{i=1}^{m} \Big(\sum_{j=0}^{4} \frac{\hat{N}_j}{\hat{N}} pdf_j(x_i) \Big)^{N_i}$$

- Based on:
  - ATOMKI BR (X17/gamma) = 6 x 10^{-6}
  - BR (IPC) = 3 x 10^{-3}
- **Expected**: O(400 X17) - 2023 data set



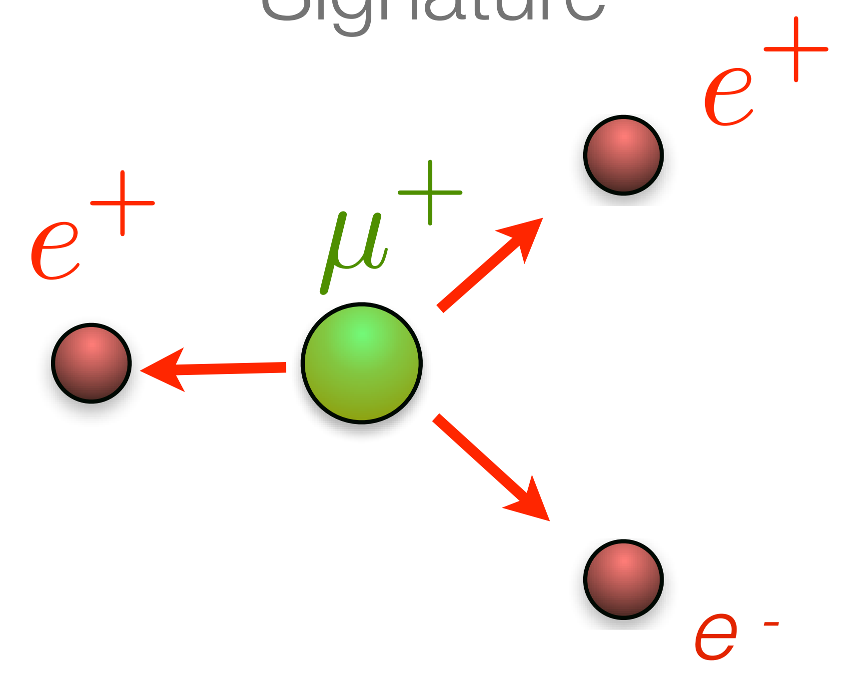
Status and next steps

- 2022 engineering run and 2023 physics run **DONE**
- Pair reconstruction and track selection **DONE**
- 2023 data reprocessing **ONGOING**
- Sidebands check **ONGOING**
- Mass MC production **TO BE STARTED**
- Unblinding **TO BE DONE**

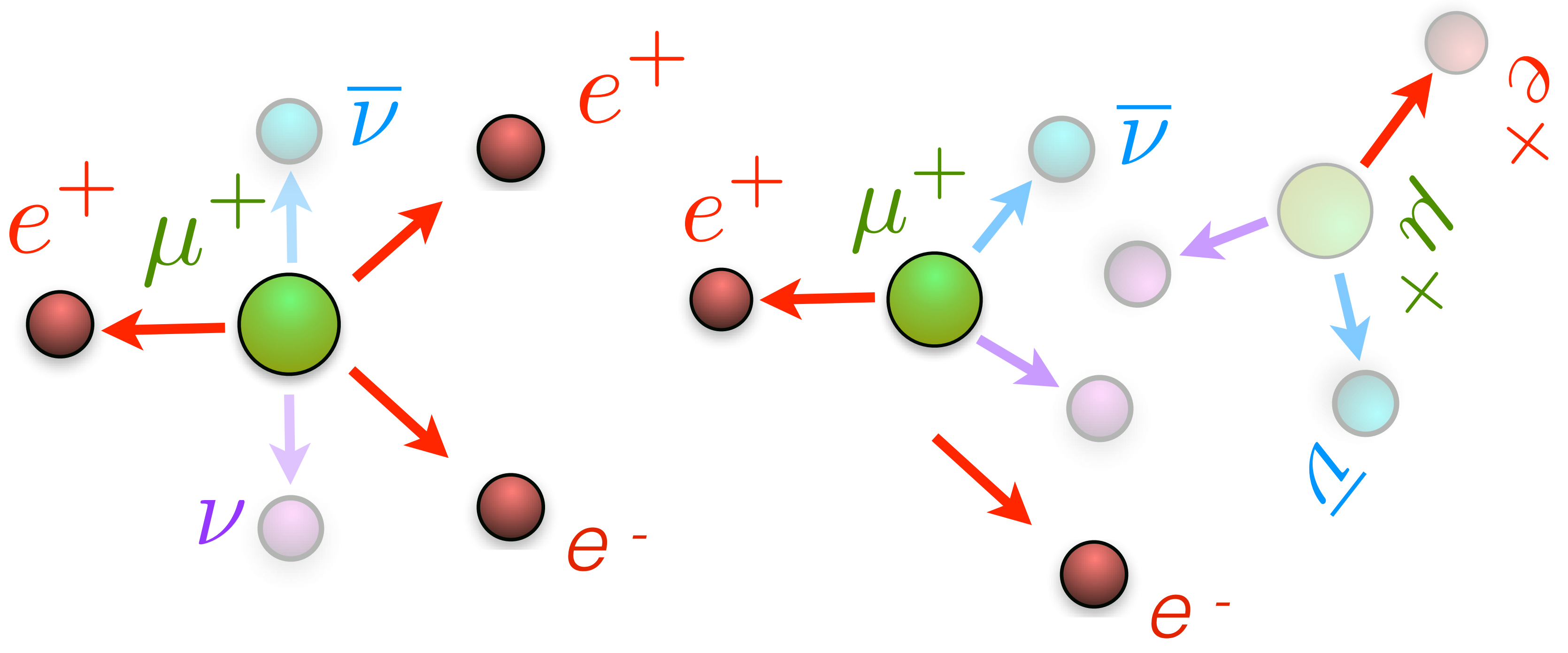
The Mu3e experiment at PSI

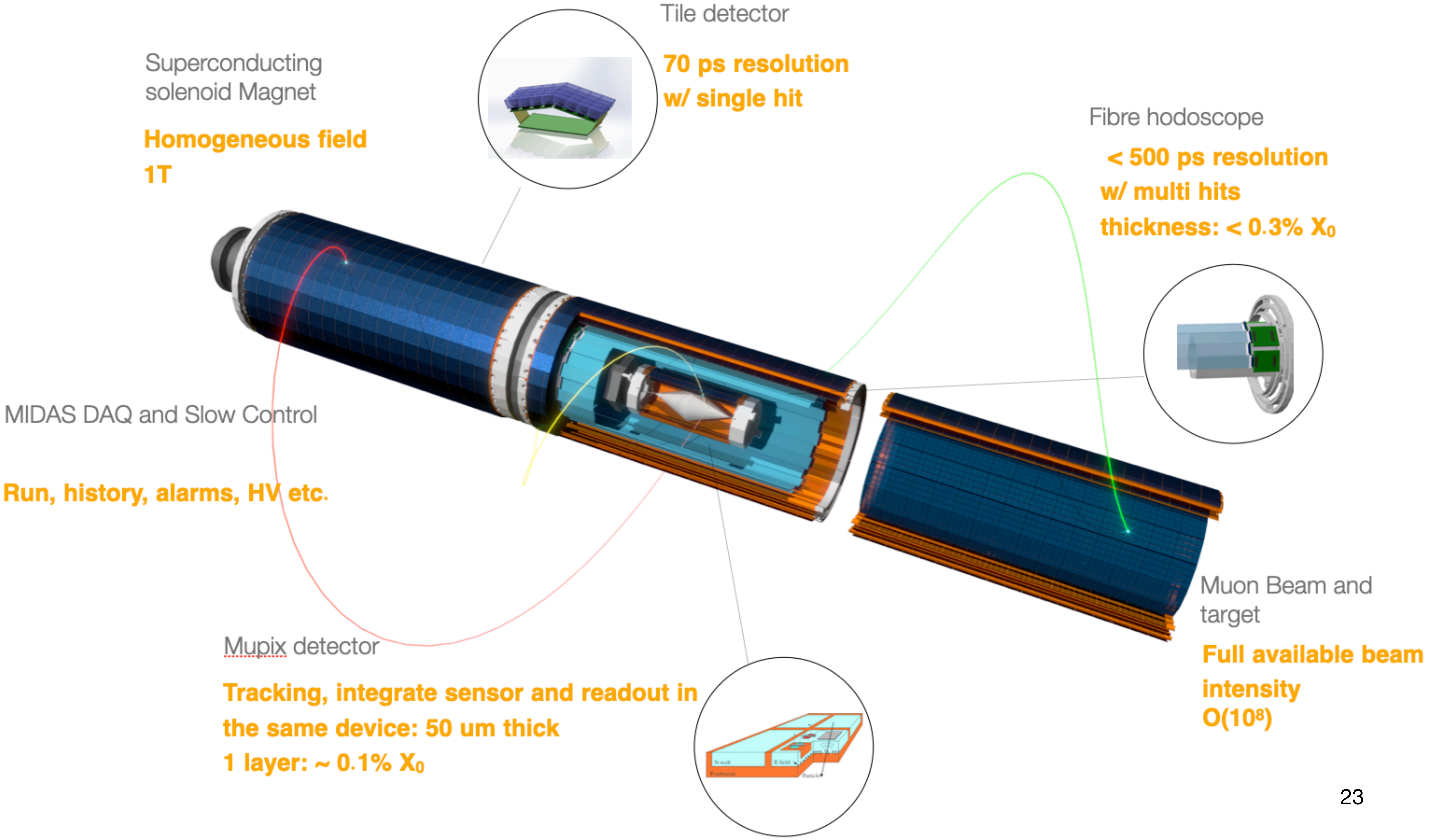
- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of ~10^{-15} (Phase I) up to down ~10^{-16} (Phase II). Previous upper limit $BR(\mu^+ \rightarrow e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by SINDRUM experiment)
- Observables $(E_e, t_e, \text{vertex})$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

Signature



Backgrounds





Mu3e: Latest news and currents status

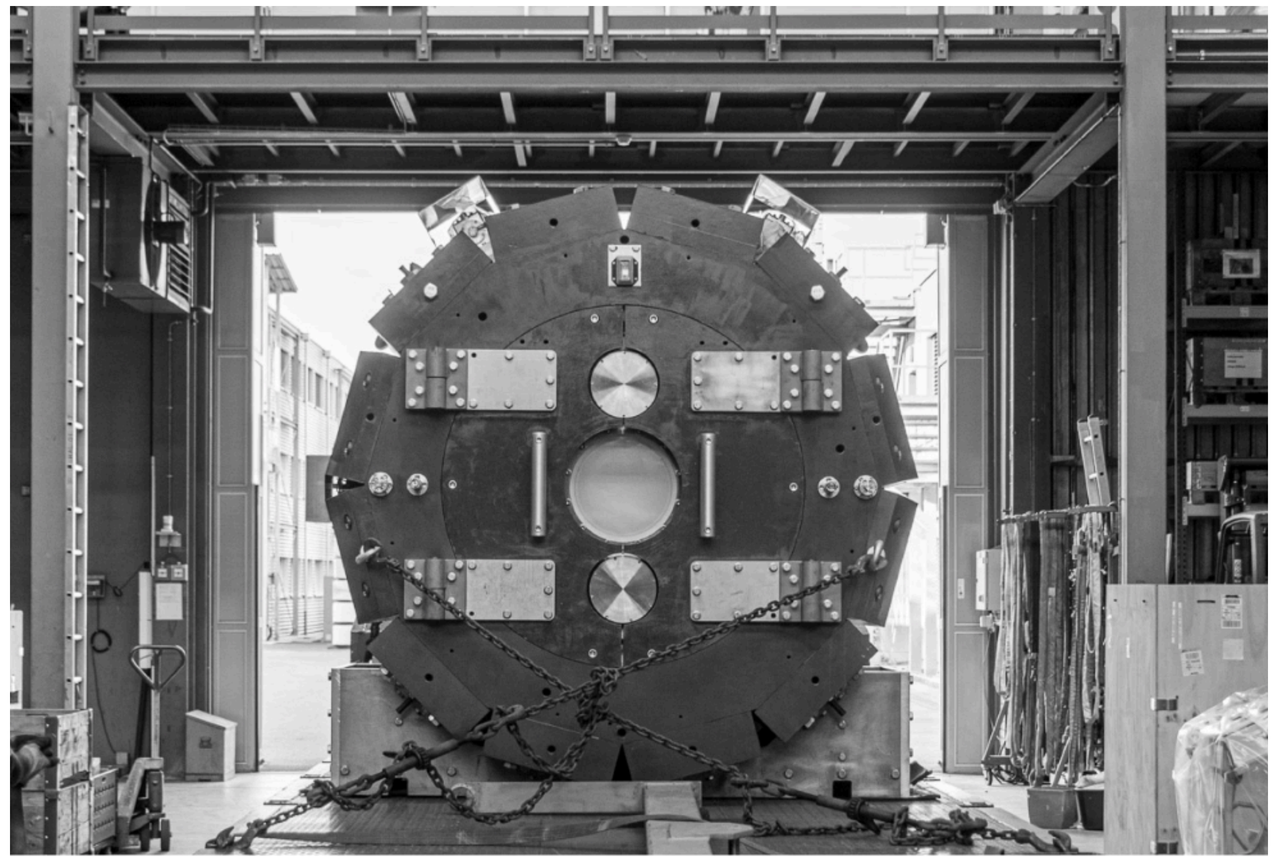
Key points:

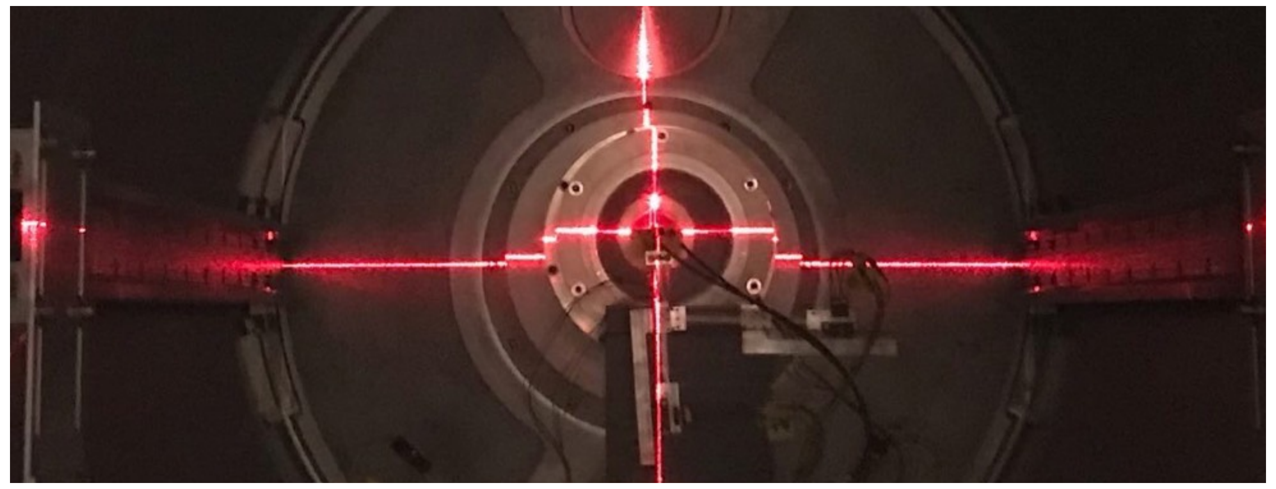
- **First integration Run 2021**
- Inner MuPix layer
- SciFi ribbons
- Sub-detector services

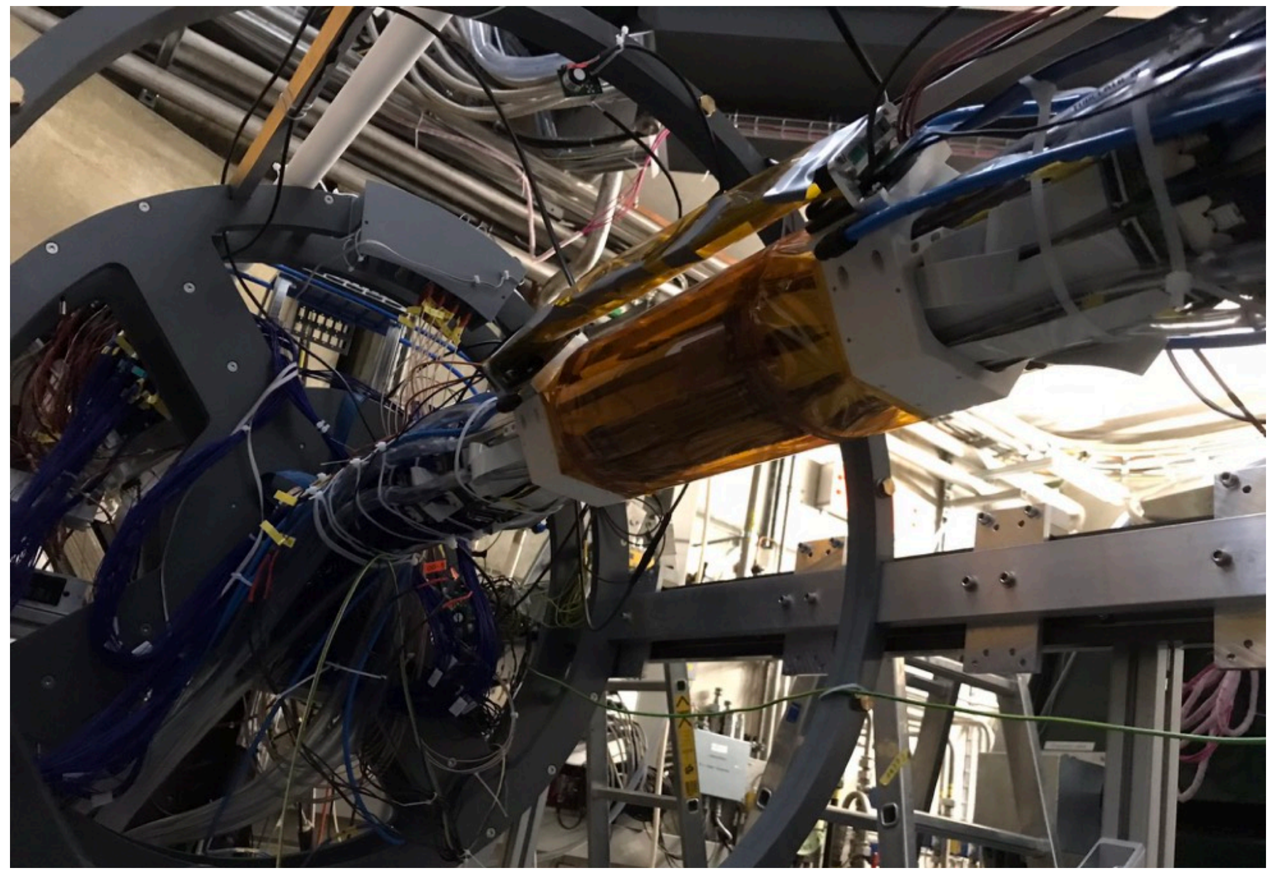
- **Full beam line commissioning 2022**
- Very successful: TDR promised values **matched!**
  - **2.49e10⁸ mu/s @2.4 mA** (at the collimator): The highest beam rate in pie5 at the collimator
  - **1.02e10⁸ mu/s @2.4 mA** (Mu3e magnet): Several beam configurations studied, some of them connected with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

Outlook:

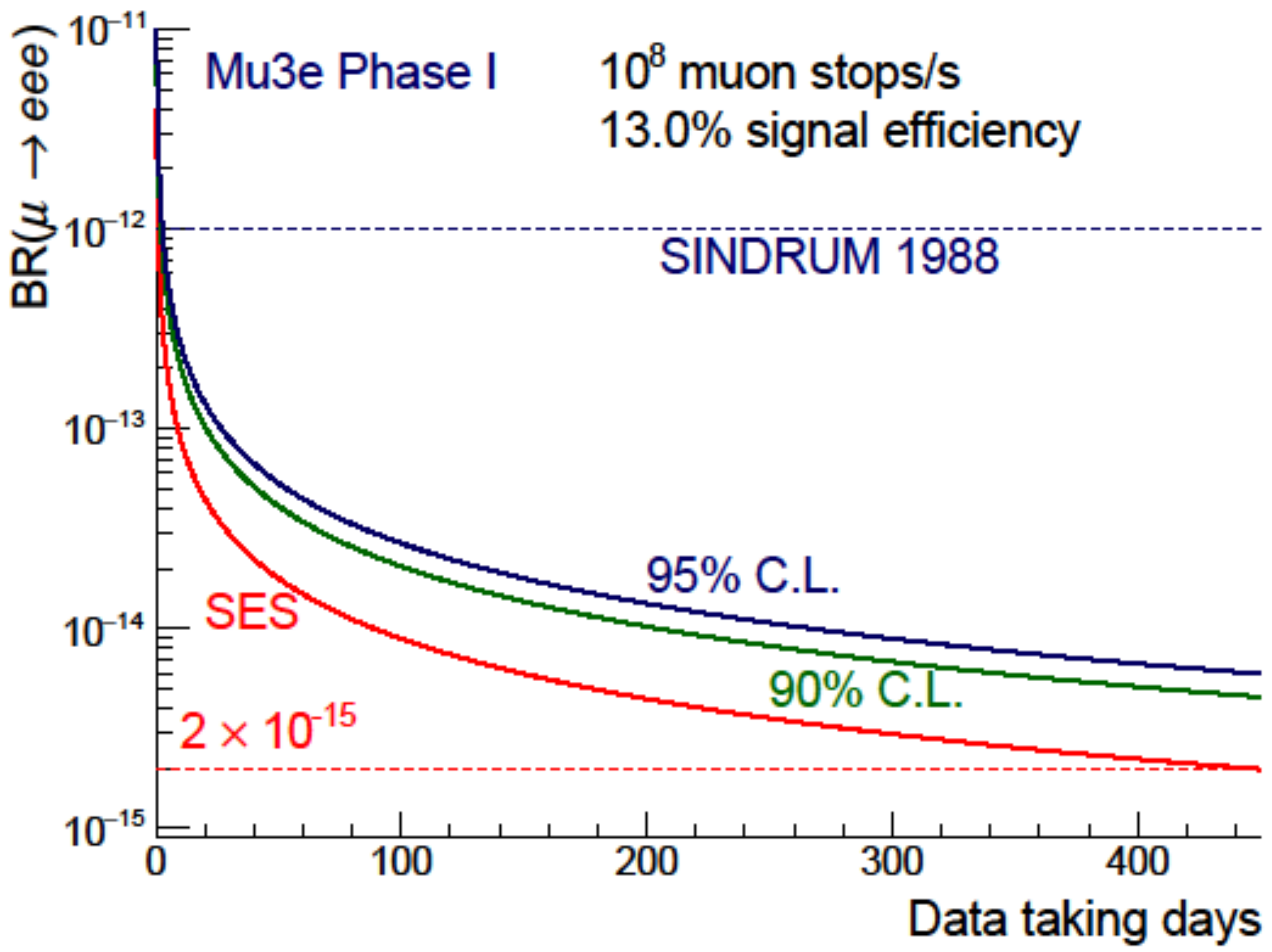
- Cosmic Ray Run ongoing outside the experimental area with all sub-detector services
- MuPix mass production: ongoing
- Complete integration run: 2023
- Engineering run: 2024
- First physics run: 2025



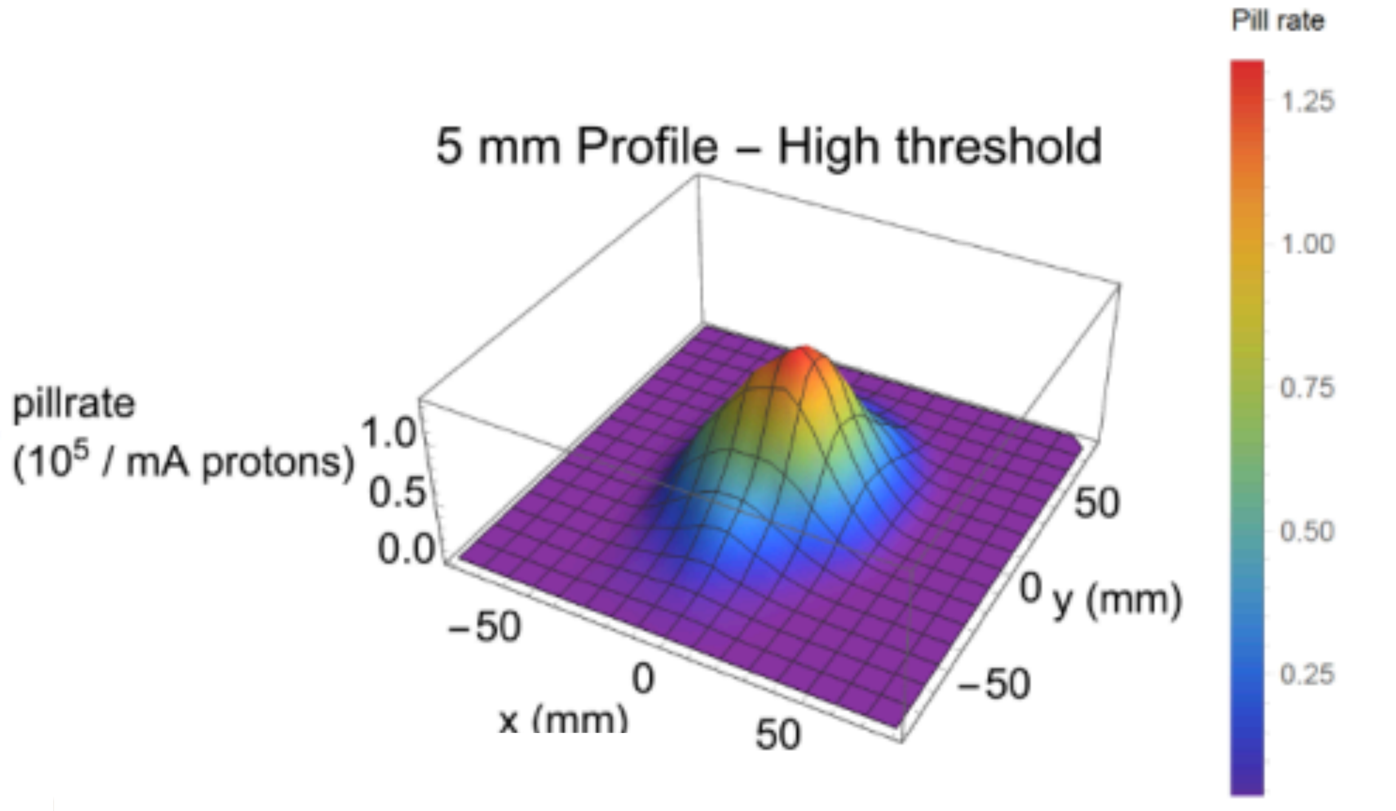




Full analysis performed on Simulated data



Beam commissioning **2022**



2.49e10⁸ mu/s @2.4 mA

DC vs pulse beams

- Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world's highest beam intensities

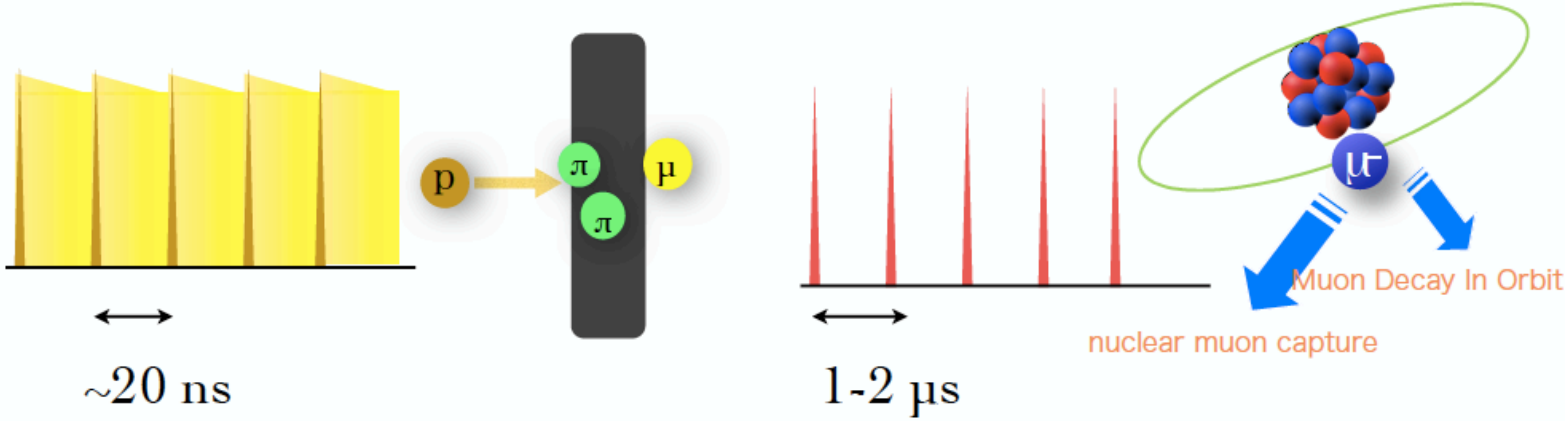
$I_{beam} \sim 10^{8} - 10^{10}$ μ/s

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

DC vs pulse beams

- Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world's highest beam intensities

DC or Pulsed?

I_{beam} ~ 10^8 - 10^{10} μ/s

- DC beam for coincidence experiments
  - $\mu \to e\gamma$, $\mu \to e e e$

@ PSI

I_{beam} ~ 10^{11} μ/s

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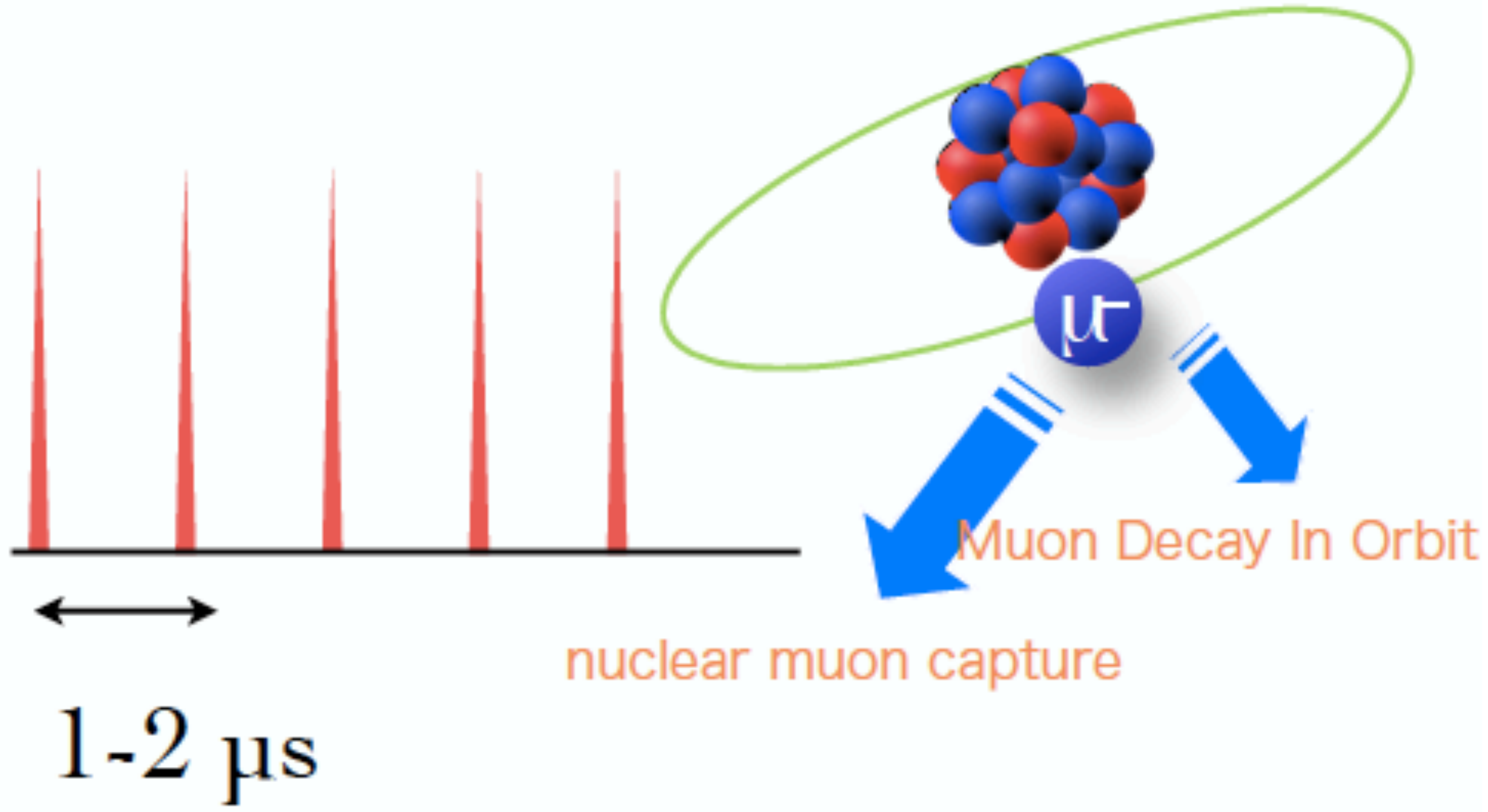
  - μ-e conversion



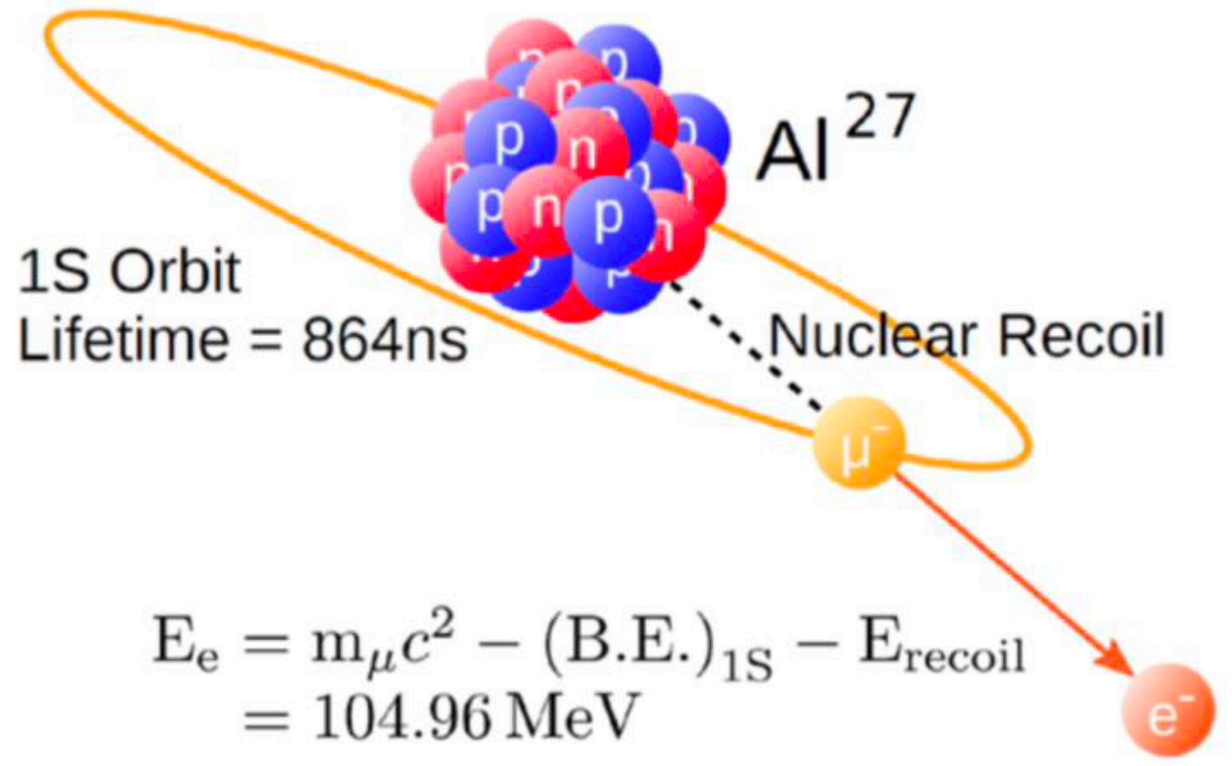
@ JPARC, FERMILAB

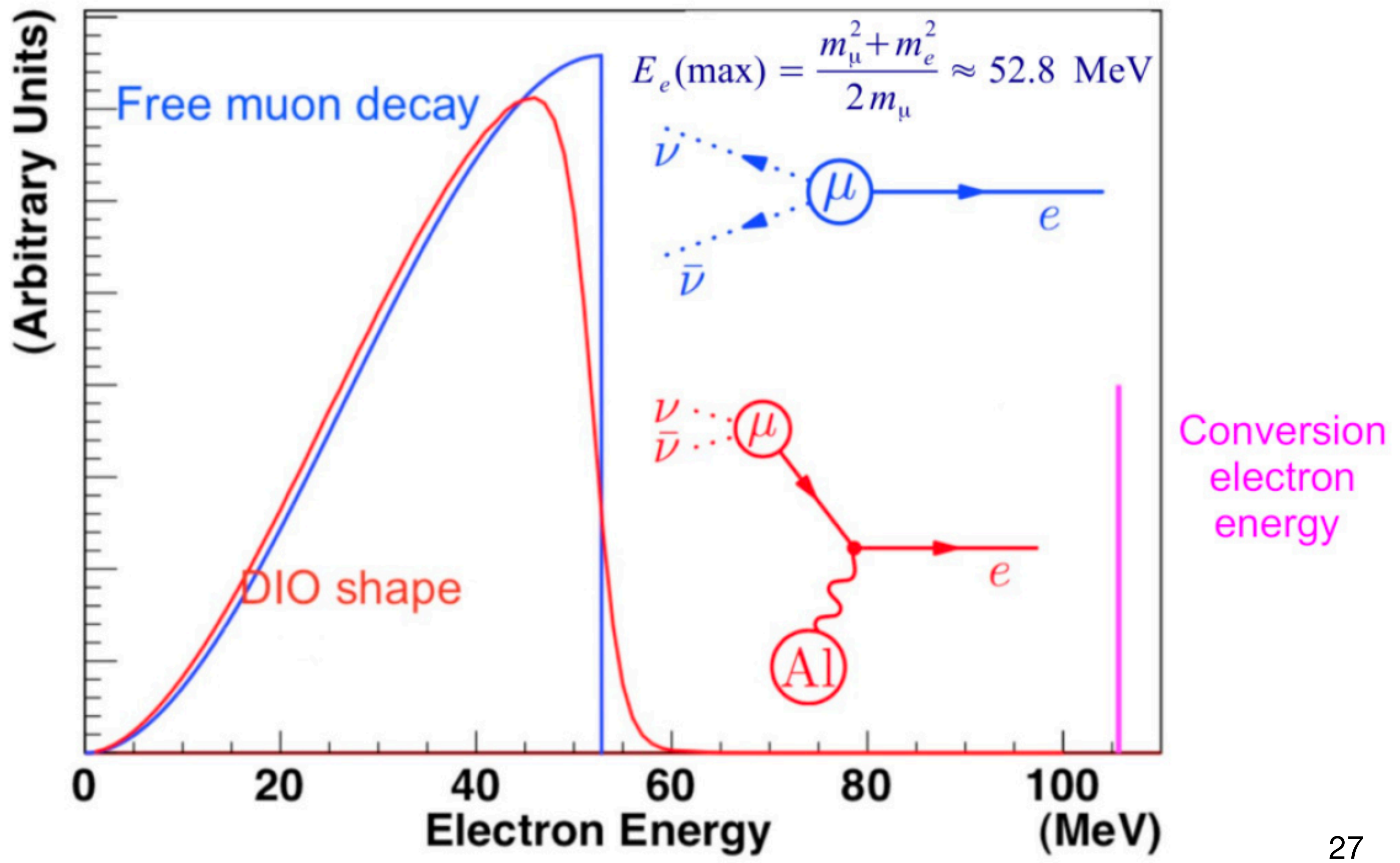
μ^- N → e^- N experiments with PULSED beams

- Signal of mu-e conversion is single mono-energetic electron

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$$

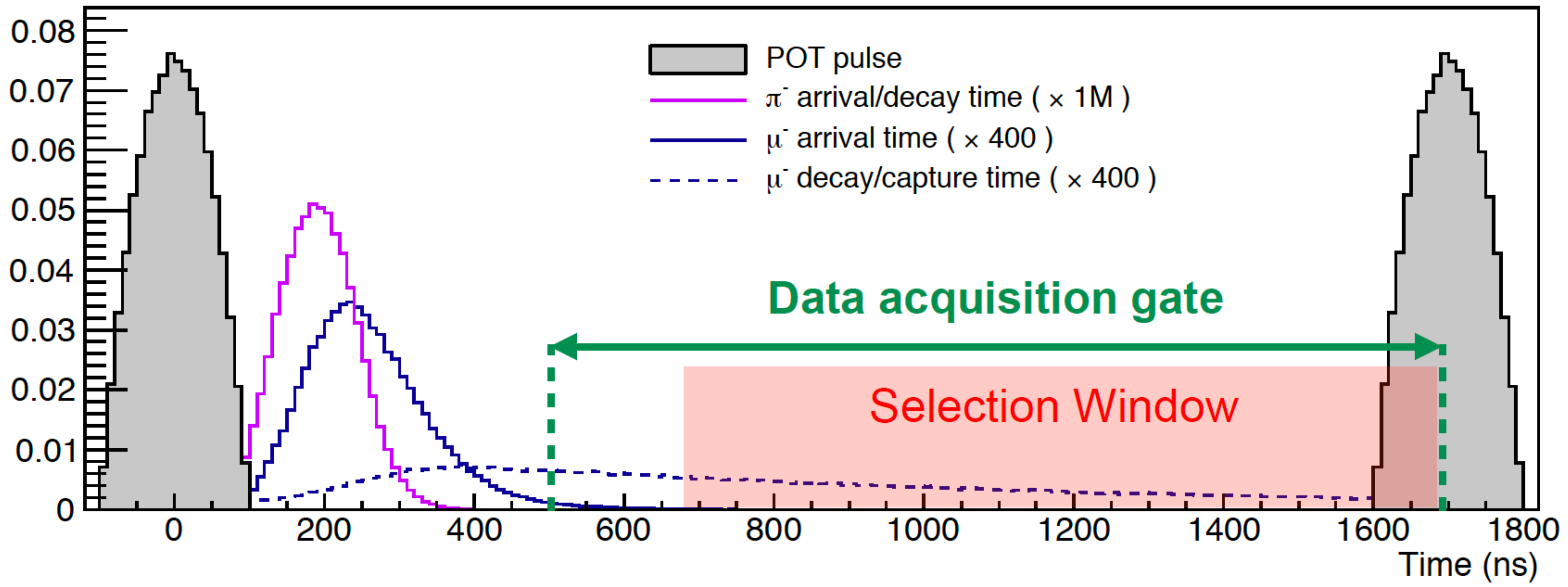
- Background: Any event at the endpoint energy can mimic the signal





$\mu^- N \rightarrow e^- N$ 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**

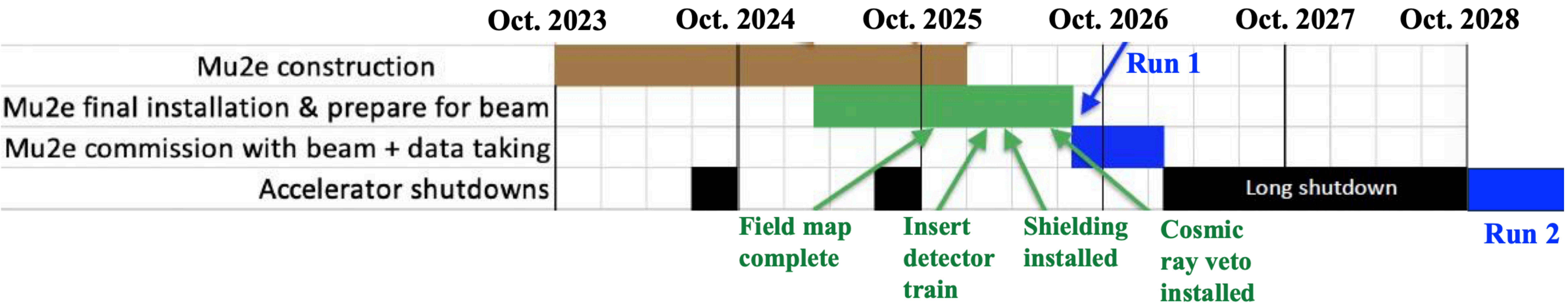


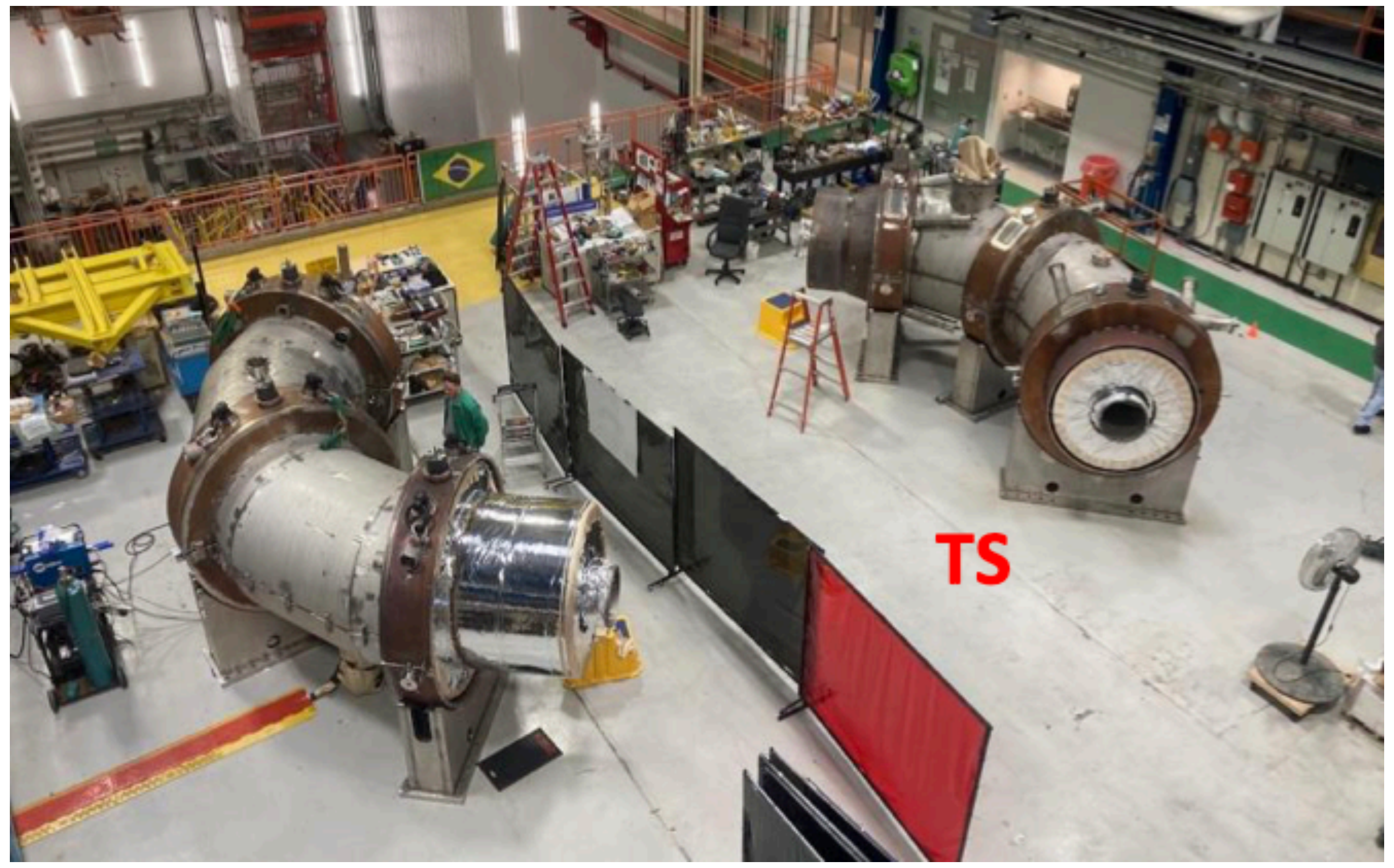
The Mu2e experiment at Fermilab

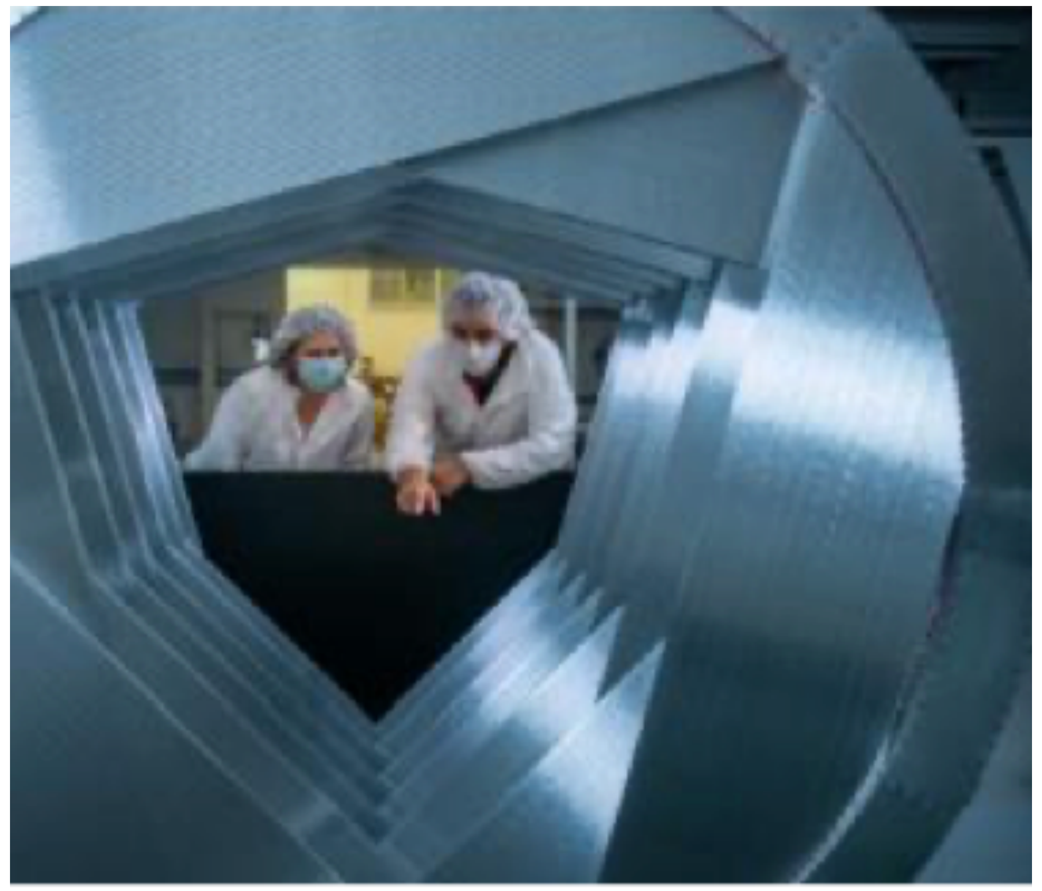
- The Mu2e experiment will search for the muon-to-e conversion in nuclei with a sensitivity **R(Al at 90% CL) < 8e10^{-17}** process in Al and improve on this limit by four orders of magnitude (previous experiment, SINDRUM II: R(Au)< 7 10^{-13})

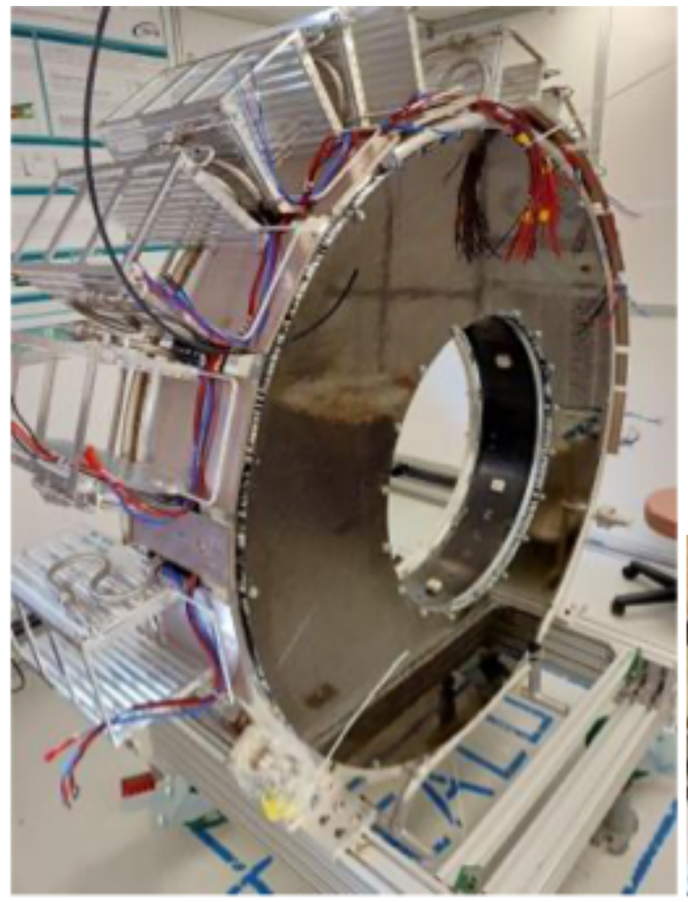
Mu2e: Latest new and current status

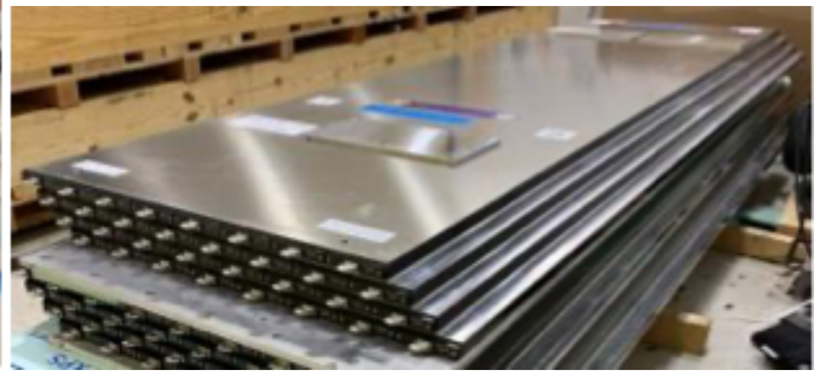
- Beam line and detector construction: Well Advanced!
- Detector installation and beam by beginning of 2025
- Data taking: 2026







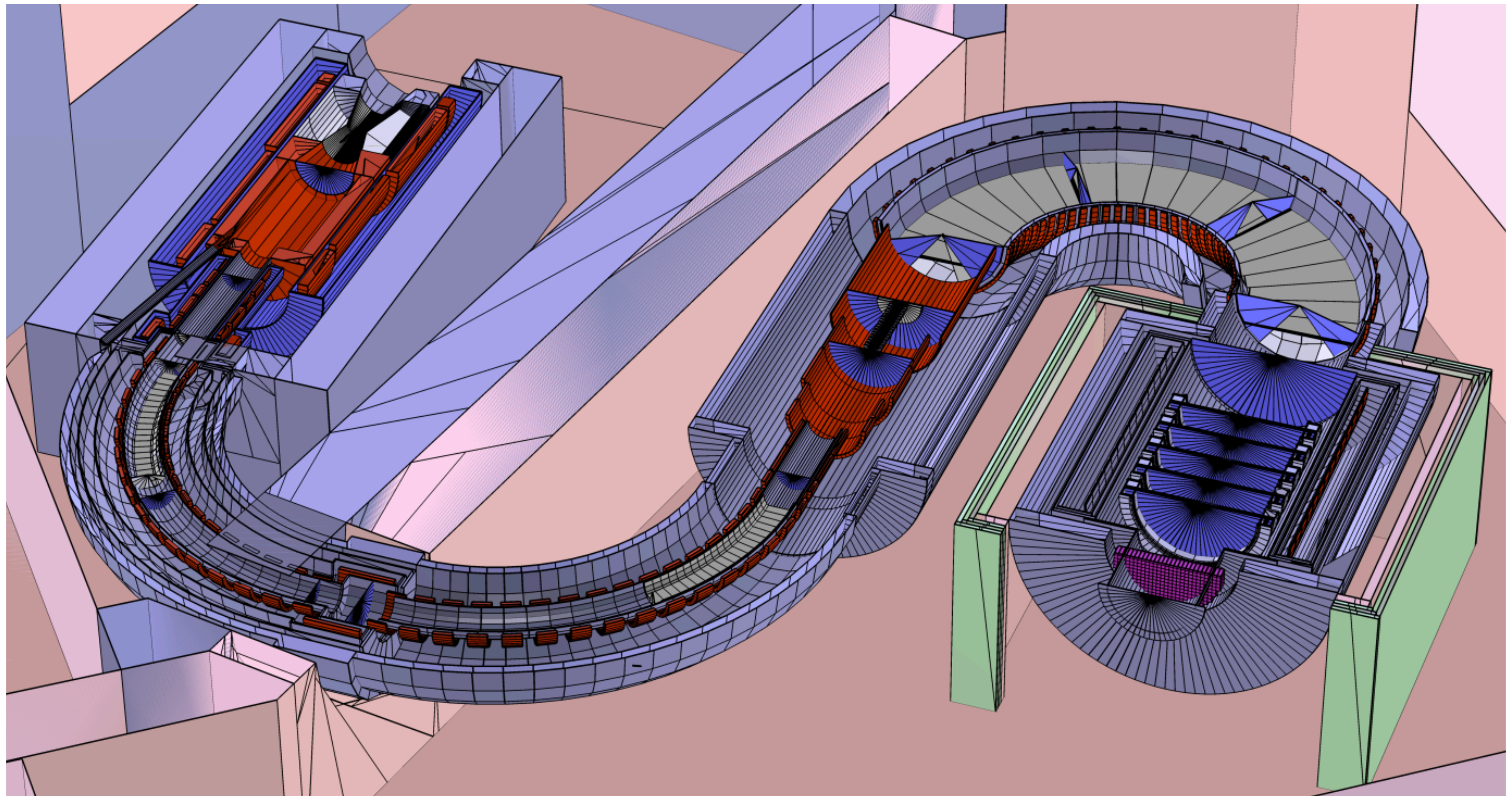


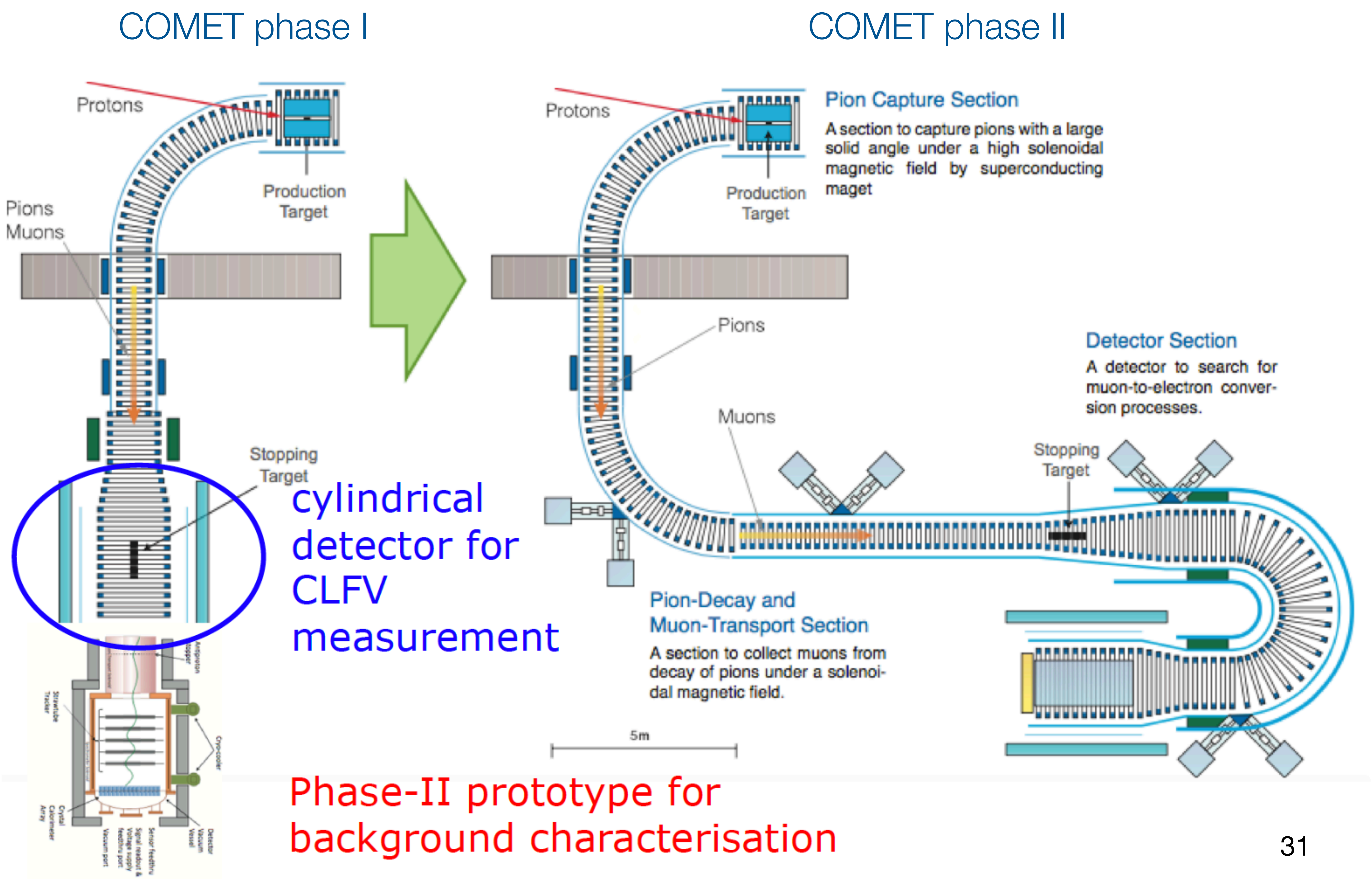


The COMET experiment at J-PARC

- The COMET experiment will search for the muon-to-e conversion in nuclei with an ultimate sensitivity **R(Al at 90% CL) < 10^{-18}** process in Al and improve on this limit by four orders of magnitude (previous experiment, SINDRUM II: R(Au)< 7 10^{-13})

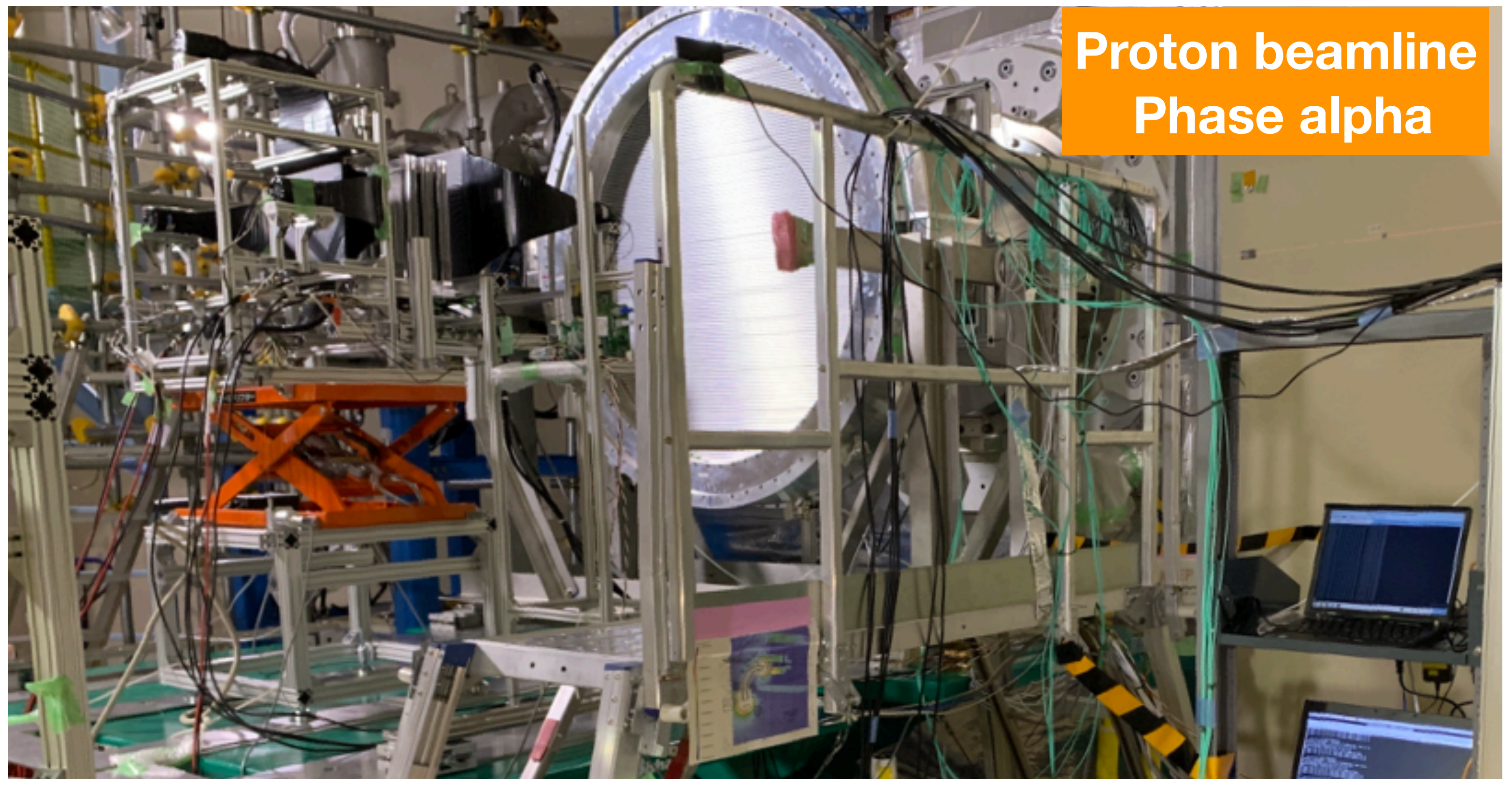
- It follows a stage approach
  - Phase I (2 x 10^{-15})
  - Phase II (O~ 10^{-18})

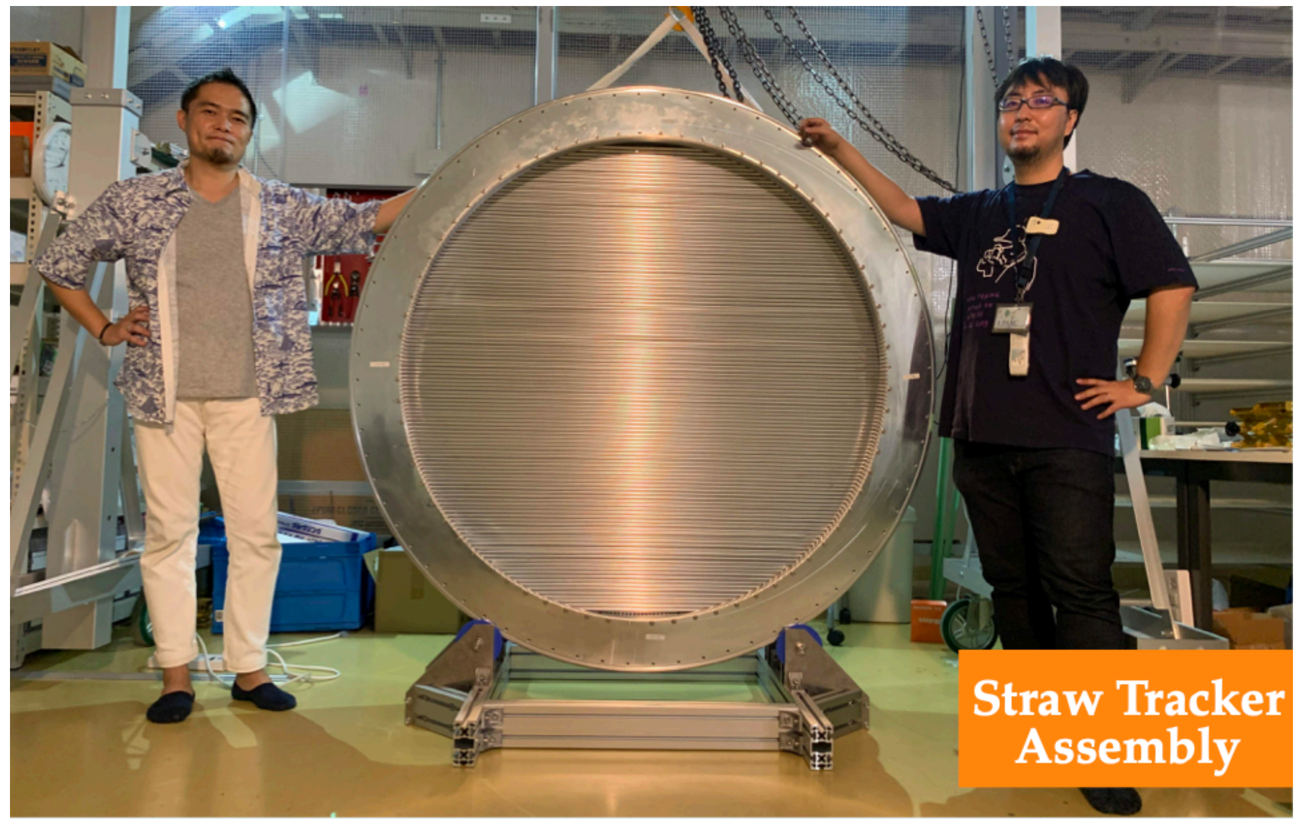


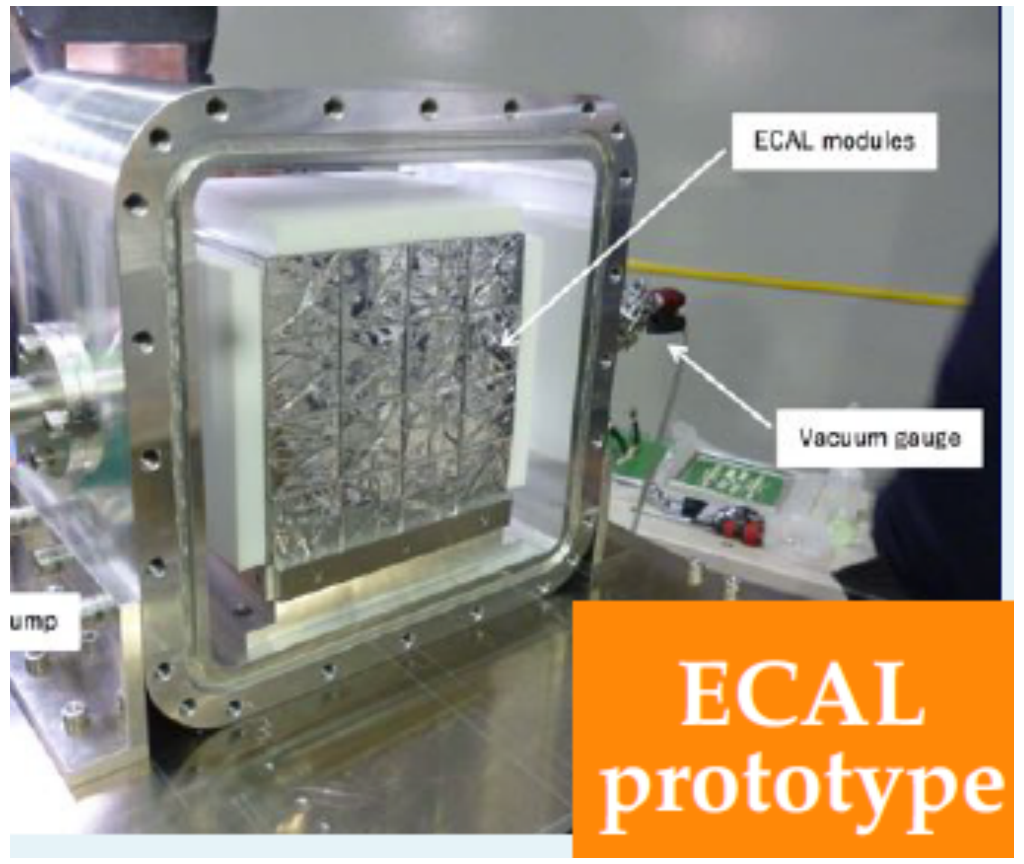


COMET: Latest new and current status

- Towards phase I:
  - Dedicated proton beam line, Completed
  - Curved transport solenoid, Completed
  - Unfinished solenoids, Will be delivered at beginning of JFY2024
  - Detector construction, Will be completed by the end of JFY2024
  - Commissioning Run will be performed in JFY2025, then the physics data-taking will follow







Summary

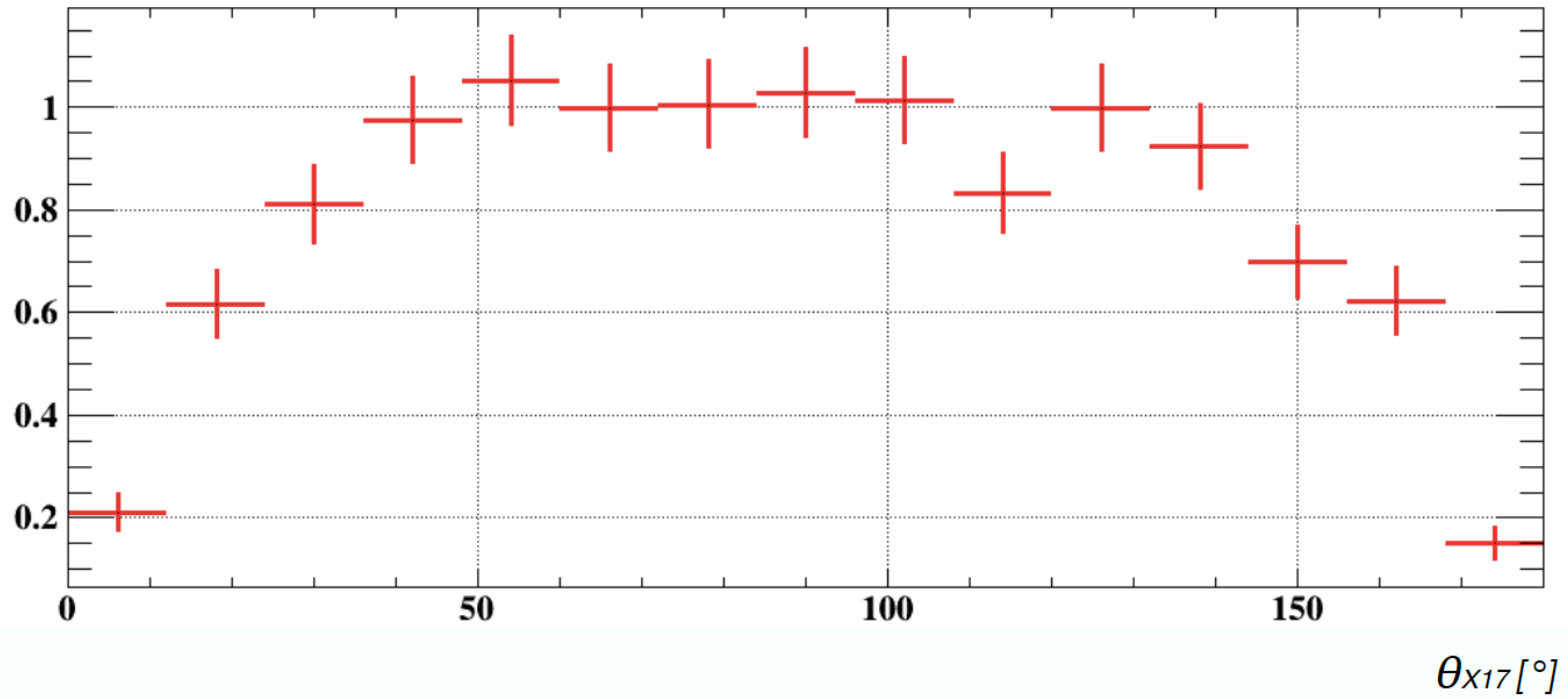
- Astonishing sensitivities in muon precision physics at intensity frontiers are ongoing and foreseen for the incoming future
- **Rare/forbidden decay searches, precision measurements and symmetry tests remain among the most exciting places where to search for new physics with strong synergy and connection with the energy and cosmology frontiers**
- MEGII started data taking since 2021 and is expected to accomplish his scientific aim collecting all needed data by 2026
- The X17 search with the MEGII apparatus started: A first data sample has been collected. Analysis ongoing…

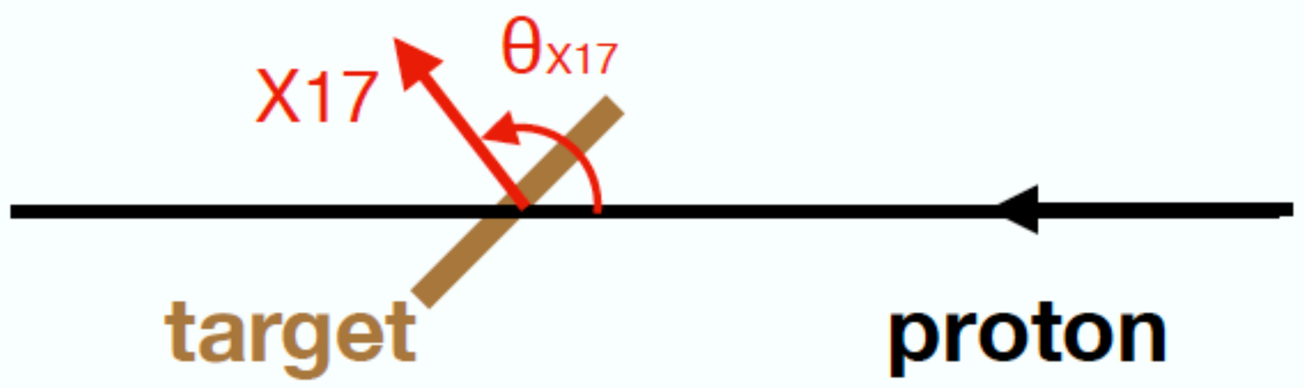
Thanks a lot for your attention and…STAY TUNED !!!

Back-Up

Reconstruction in non-orthogonal planes

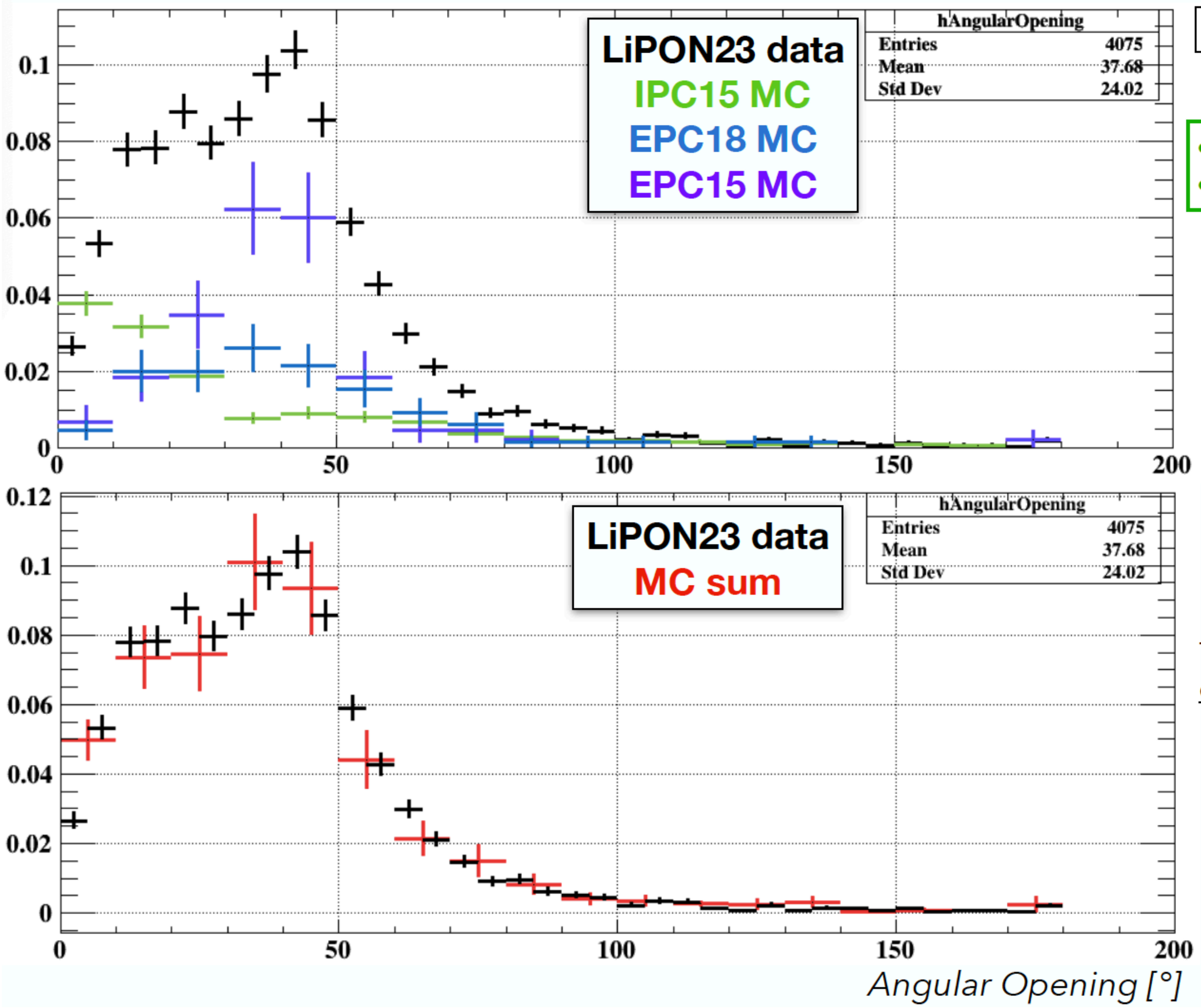
Efficiency wrt to X17 production [%] → includes trigger, detector acceptance and reconstruction





- X17 reconstructed not only in orthogonal plane
- 1% efficiency in planes between 40° and 140°

Esum sideband: 14 MeV < Esum < 16 MeV



5% of 2023 data are used here

E_{sum} sideband

- **14 MeV < E_{sum} < 16 MeV**
- **Full angle range**

–> monotonously decreasing IPC tail