MEG-2 and Future $\mu \to e\gamma$

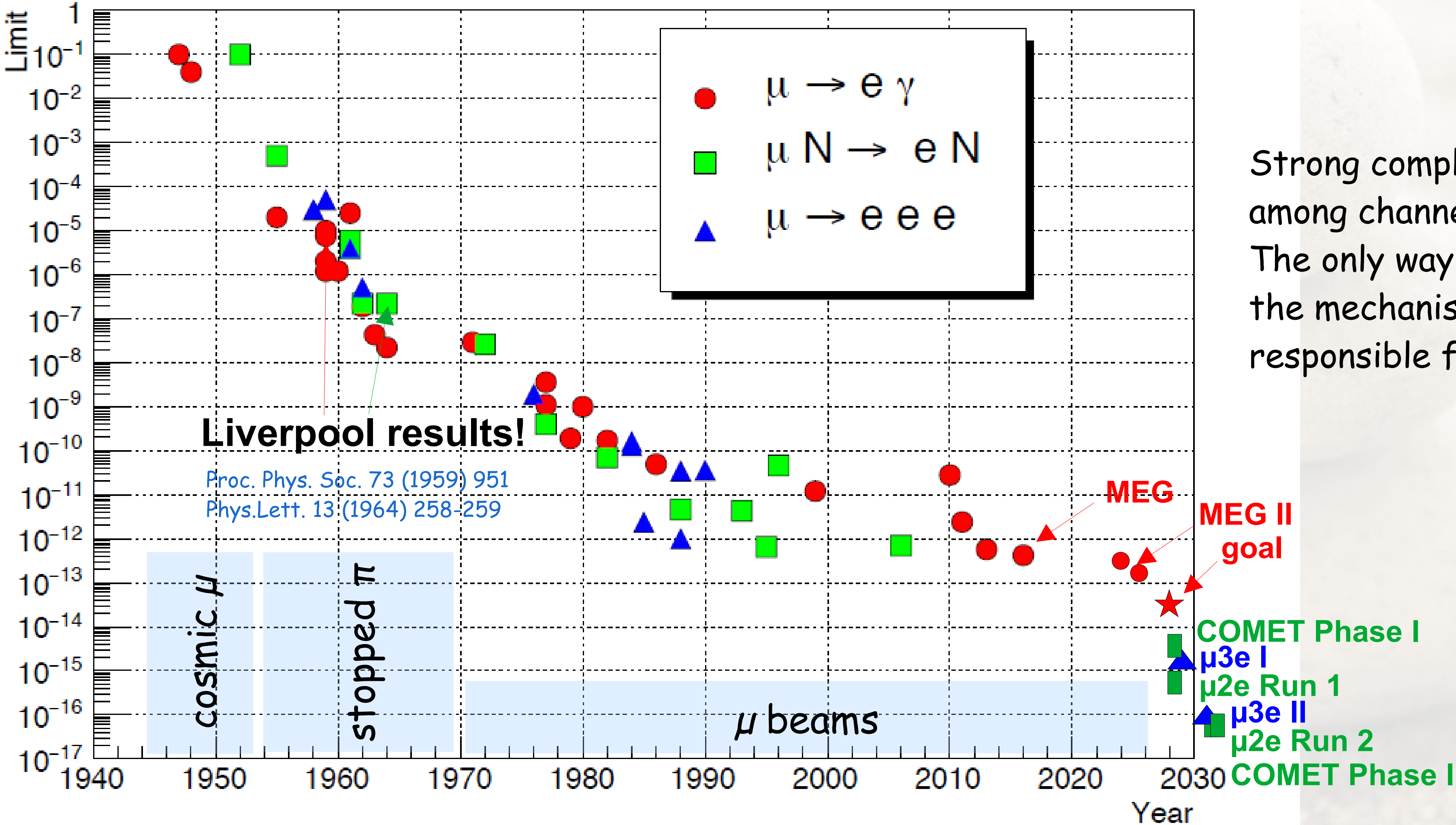
Fedor Ignatov

Muon Group bi-weekly meetings

Liverpool, 23 February 2026

80 year of cLFV

L.Calibbi and G.Signorelli, Riv.Nuovo Cim. 41 (2018) 2, 71-174



Strong complementaries among channels:
The only way to reveal the mechanism responsible for cLFV

Particle Physics at Liverpool's Synchrocyclotron

Dr Nikolaos Rompotis, University of Liverpool

The particle physics group at Liverpool was built thanks to the legacy of Chadwick's cyclotron, which had been operating in the basement of the department of physics since 1939. Sir James Chadwick (1891 – 1974) joined the university in September 1935 and just one month later he was awarded the Nobel prize for the discovery of the neutron. He initiated a research group studying particles in cosmic rays, but his main effort was in the establishment of a state-of-the-art 37-inch cyclotron, which became operational in 1939 and was in part funded by his own Nobel prize money [1].

Atom lab., by courtesy of the Pope

By the Science Editor

BY special dispensation of the Vatican, the construction of Liverpool's atom machine, part of the new nuclear physics laboratory being built by Liverpool University, is progressing.

The only suitable site was a corner of the ground acquired for the great new Roman Catholic cathedral.

Since the plot will not be required for a long time by the cathedral, and since the life of the synchrocyclotron is not more than 30 years, a lease was arranged for that period.

Then it was found that under Roman Catholic law the property could not be ceded for more than ten years. Sanction of the Vatican was obtained—but even the Papal authorities could allow only "20 years plus 10."

I visited the site where the massive concrete foundations are now being laid. It is expected that the machine will be completed next year.

The giant magnet alone weighs 1,600 tons. The poles will be 156 inches in diameter compared with the biggest similar machine now existing at Berkeley, California, which is 184 inches in diameter.

Map, Back Page

Fig. 1: Article in the "News Chronicle" of Thursday, March 24, 1949. The "atom lab" mentioned refers to the synchrocyclotron facility. Newspaper excerpt is courtesy of Cristina Papini.

During World War 2 discussions about the feasibility of a nuclear weapon, among other things, relied on accurate nuclear cross-section information, which was obtained using the Liverpool cyclotron [2]. After the war, Chadwick used his wartime contributions to obtain funding for a machine with much higher energy than the existing cyclotron. These considerations led to a synchrocyclotron, able to accelerate protons to an energy of about 400 MeV [3]. This new machine was too big to fit in the department lab. A new area was found close to the site of Liverpool Catholic Cathedral that was loaned by the Catholic Church authorities to the university (Fig. 1). The first beams were stored in this new 156-inch machine by spring 1954. Subsequently, the team managed to extract the beam from the machine by December

IOP Institute of Physics
History of Physics Group

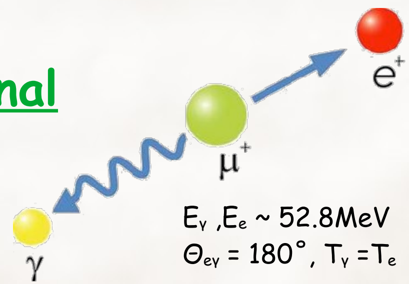
Bulletin No 2, 2024

https://www.iop.org/sites/default/files/2025-01/history-of-physics-group-online-bulletin-no-2.pdf

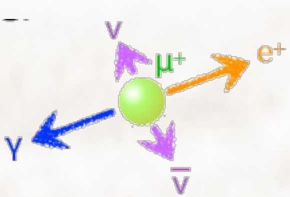
MEGII experiment

$\mu^+ \to e^+\gamma$

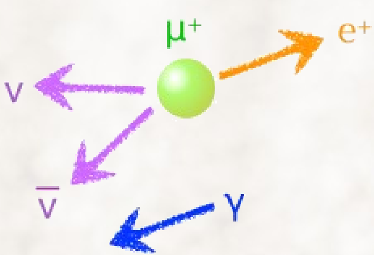
Signal



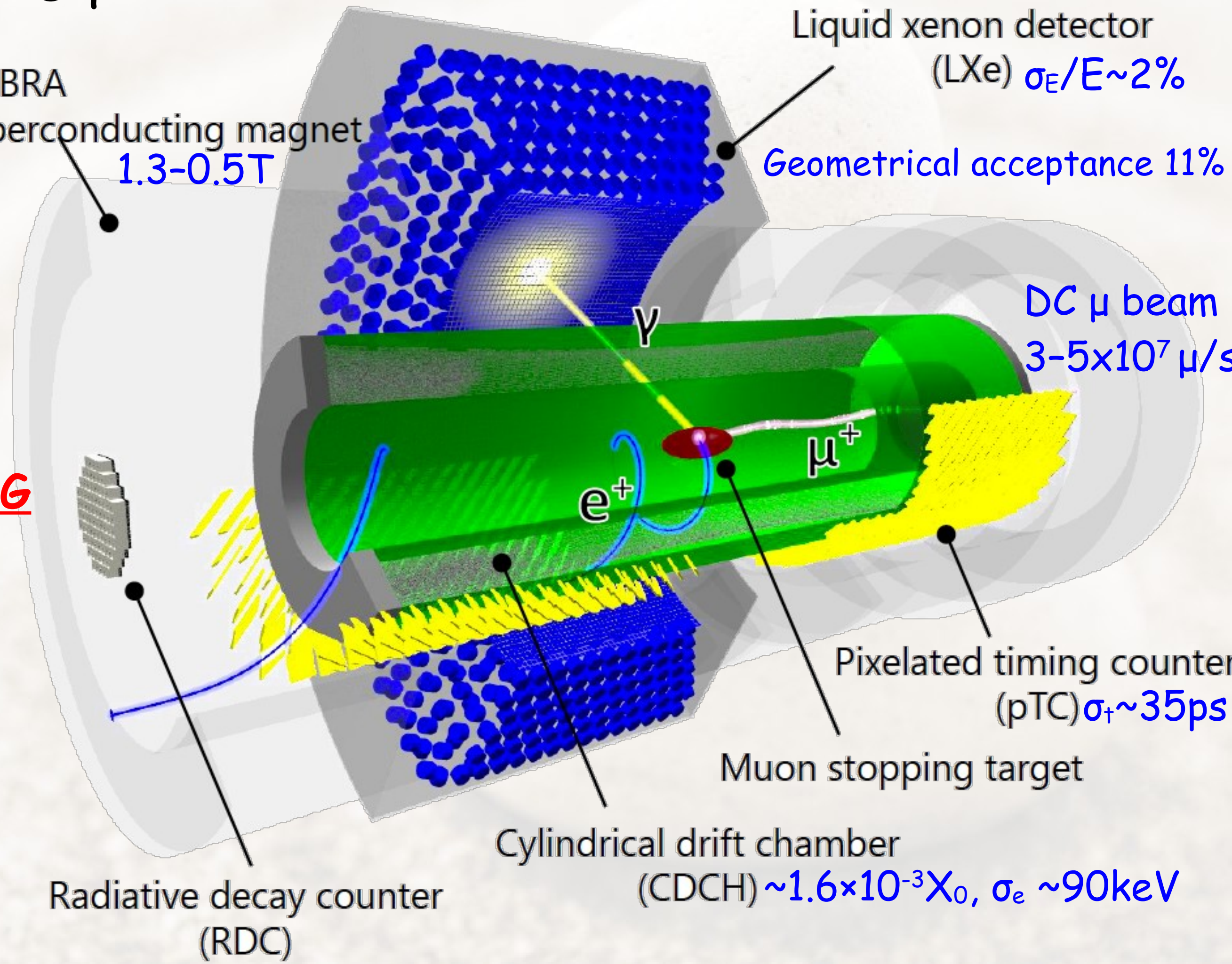
RMD BG



Dominant Accidental BG



✗Search for e+ and γ correlated by time, direction, energy

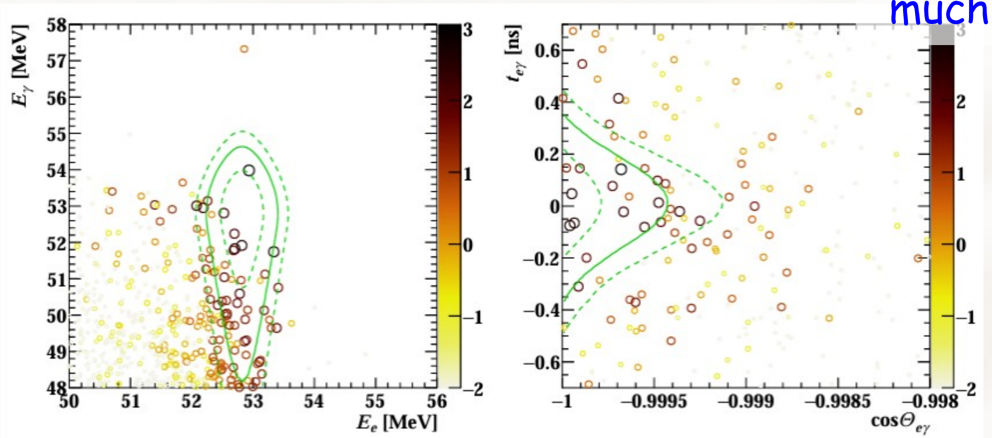


EPJC 84(2024)2, 190

MEGII result 2021+2022 runs

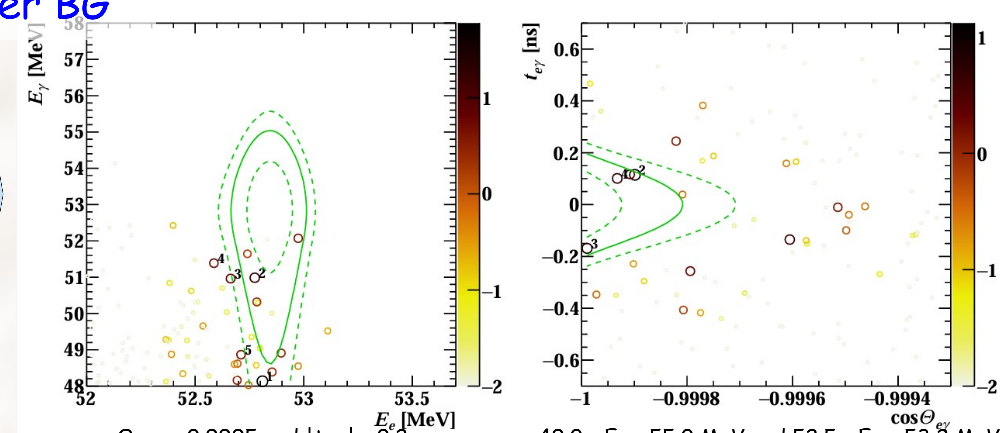
Eur.Phys.J.C 85 (2025) 10, 1177

MEG I 2009-2013

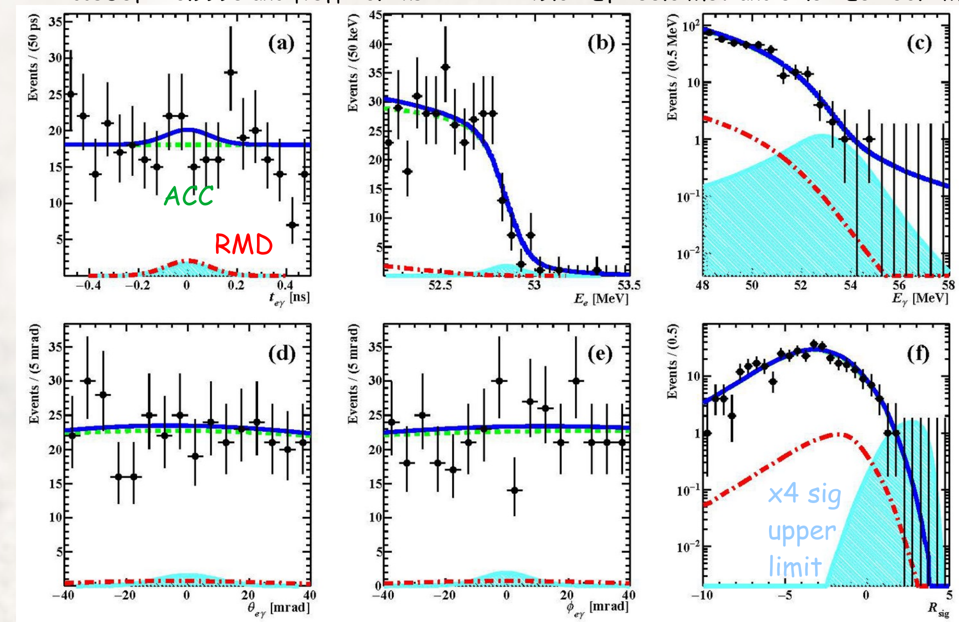


x2 more statistics
much cleaner BG

MEG II 2021+2022



cosΘeγ < −0.9995 and |teγ| < 0.2 ns
49.0 < Eγ < 55.0 MeV and 52.5 < Ee < 53.2 MeV



MEG I final Br($\mu^+ \to e^+\gamma$) < 4.2×10^{-13}

MEG II 2021+2022 Br($\mu^+ \to e^+\gamma$) < 1.5×10^{-13}

2021 data: Eur.Phys.J.C 84 (2024) 3, 216

2021+2022: Eur.Phys.J.C 85 (2025) 10, 1177

MEG II goal Br($\mu^+ \to e^+\gamma$) < 0.5×10^{-13}

2021-2026

Beam Program 2026

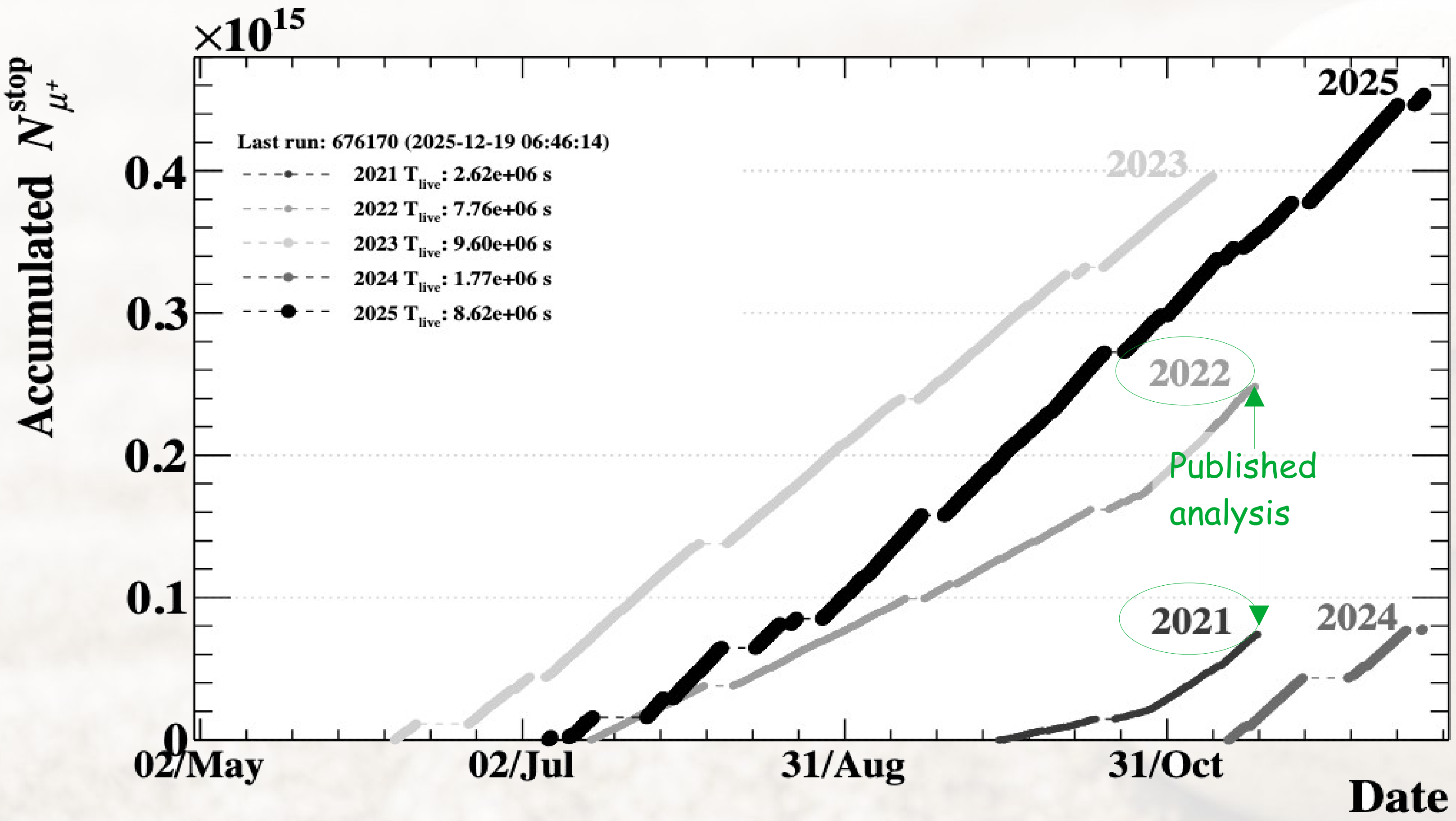
https://www.psi.ch/de/sbl/schedules <stefan.ritt@psi.ch

Last update: 2/5/2026 12:54:26

Month	April				May				June				July				August					September					October				November				December			
Week number	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
Availability																																						
Days	0	0	0	0	0	0	3	7	7	3	7	6	7	3	7	7	7	4	3	7	7	6	7	3	7	7	6	7	3	7	7	6	7	3	7	7	6	2
Start (Monday)	Apr/6/26	Apr/13/26	Apr/20/26	Apr/27/26	May/4/26	May/11/26	May/18/26	May/25/26	Jun/1/26	Jun/8/26	Jun/15/26	Jun/22/26	Jun/29/26	Jul/6/26	Jul/13/26	Jul/20/26	Jul/27/26	Aug/3/26	Aug/10/26	Aug/17/26	Aug/24/26	Aug/31/26	Sep/7/26	Sep/14/26	Sep/21/26	Sep/28/26	Oct/5/26	Oct/12/26	Oct/19/26	Oct/26/26	Nov/2/26	Nov/9/26	Nov/16/26	Nov/23/26	Nov/30/26	Dec/7/26	Dec/14/26	Dec/21/26
End (Sunday)	Apr/12/26	Apr/19/26	Apr/26/26	May/3/26	May/10/26	May/17/26	May/24/26	May/31/26	Jun/7/26	Jun/14/26	Jun/21/26	Jun/28/26	Jul/5/26	Jul/12/26	Jul/19/26	Jul/26/26	Aug/2/26	Aug/9/26	Aug/16/26	Aug/23/26	Aug/30/26	Sep/6/26	Sep/13/26	Sep/20/26	Sep/27/26	Oct/4/26	Oct/11/26	Oct/18/26	Oct/25/26	Nov/1/26	Nov/8/26	Nov/15/26	Nov/22/26	Nov/29/26	Dec/6/26	Dec/13/26	Dec/20/26	Dec/27/26

Area	Experiment	PSI Contact		Notes
PiM3	MuSR (GPS&LTF)	Luetkens	Luetkens (coord.)	
PiE3	MuSR high field	Scheuermann	Scheuermann (coord.)	
MuE1	MuSR (GPD)	Khasanov	Khasanov (coord.)	
	R-21-02.1 muEDM	Khasanov	Schmidt-Wellenb.	
	R-24-01.1 X-Lent	Khasanov	Collar	
MuE4	MuSR (LEM)	Prokscha	Prokscha (coord.)	
PiE1-1	MuSR (Dolly)	Shiroka	Shiroka (coord.)	Tue morning
PiE1-2	R-16-01.1 muX	Knecht	Knecht	before RefRad
	R-20-01.2 MONUMENT	Knecht	Zinatulina	
	R-21-02.1 muEDM	Schmidt-Wellenb.	Schmidt-Wellenb.	
	R-21-03.1 MuFusE	Antognini	Knaian	
	R-22-01.1 PIONEER	Antognini	Buat	
	R-22-02.1 LEMING	Antognini	Soter	
	R-23-02.1 QUARTET	Antognini	Ohayon	
	R-23-03.1 ReferenceRadii	Antognini	Cocolios	after muX
	R-26-01.1 2Alpha	Knecht	Kawase	
PiE5	R-99-05.2 MEG	Papa	Mori	
	R-12-03.1 Mu3E	Knecht	Schoening	
	R-16-02.1 HyperMu	Knecht	Antognini	
	R-22-01.1 PIONEER	Papa	Kammel	
UCN-S	R-05-03.1 n2EDM	Lauss	Lauss	
UCN-W1	R-23-01.1 tSPECT	Lauss	Fertl	
UCN-W2	UCN Imager	Lauss	Kamiya	
PiM1	R-12-01.2 MUSE	Reggiani	Downie	
	R-22-01.1 PIONEER	Schmidt-Wellenb.	Iwamoto/Buat	
	Praktikum ETHZ	Schmidt-Wellenb.	Berger	
	Praktikum UZH	Schmidt-Wellenb.	Caminada	
	ESTEC	Schmidt-Wellenb.	Losekamm	
	TPC-TC	Schmidt-Wellenb.	Renga	
	uRwell	Schmidt-Wellenb.	Poli Lener	

Only half of data-taking season for MEG-2



<u>2021+2022</u>
published

<u>2023+2024</u>
x2.5 statistics
in total

2024: few times
2 compressors failures
at PSI cryoplant

<u>2025+2026</u>
~x1.8 additional
factor in statistics

2026 Last data-taking season for MEG-2
Can't operate in 2027 , since PSI cryoplant will be not available

X17 boson search runs

Cockcroft–Walton (CW) proton accelerator (<1 MeV) maintenance with HVEE engineering – should be finished in last days

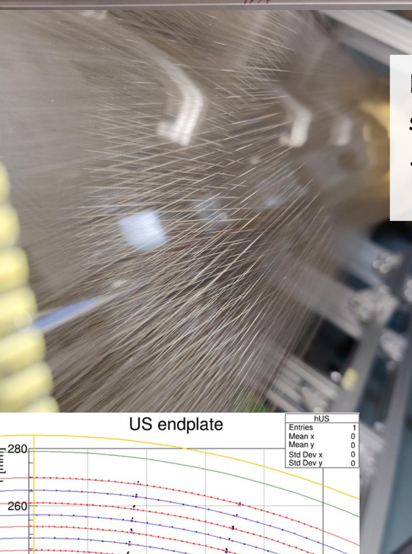
Beamline in preparation

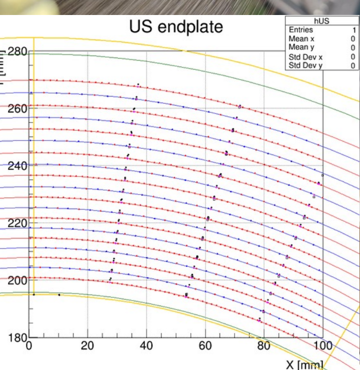
If max HV (1.08 MeV protons) will be working

~ 48 days of data taking: March/May 2026

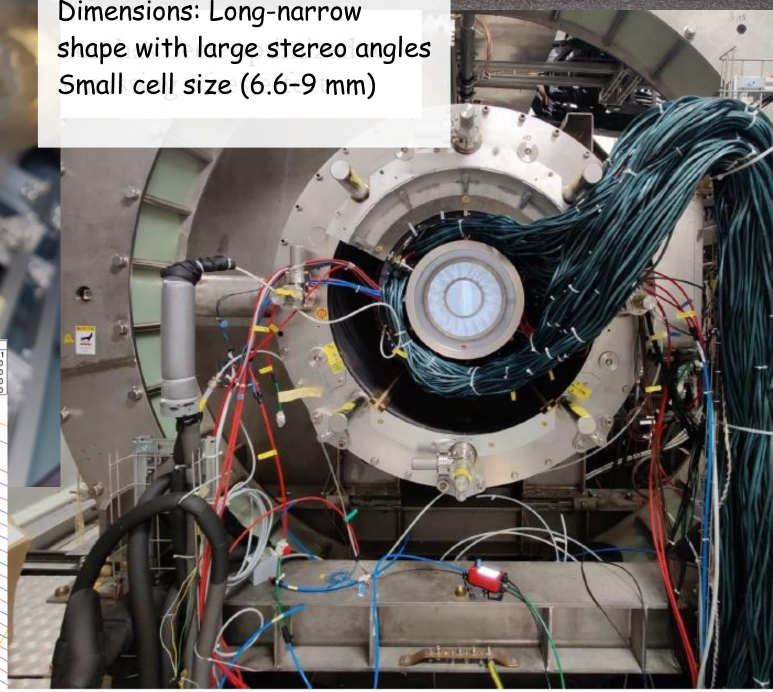
More data first half of 2027

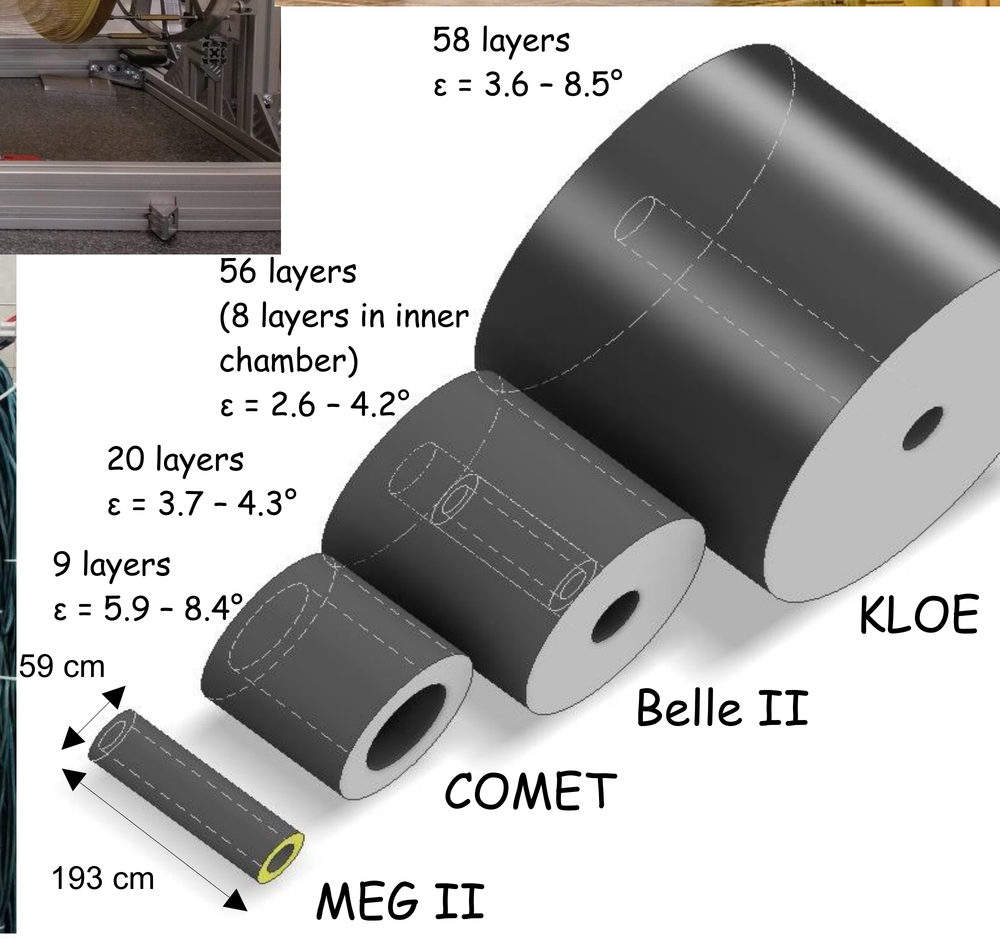
MEG2 CDCH





Dimensions: Long-narrow shape with large stereo angles
Small cell size (6.6-9 mm)





Tracking in DCH of MEGII

MEG DCH Operation under high hit rate

Hit rate up to 1.2 MHz per cell at $5{\times}10^{7}\ s^{-1}$ beam rate: 25% cell occupancy in 250ns.

Higher occupancy than in Alice TPC or Belle2 CDC

MEGII CDCH 9 layers vs 159 rows 56 layers

MEG2 Track Finding is harder

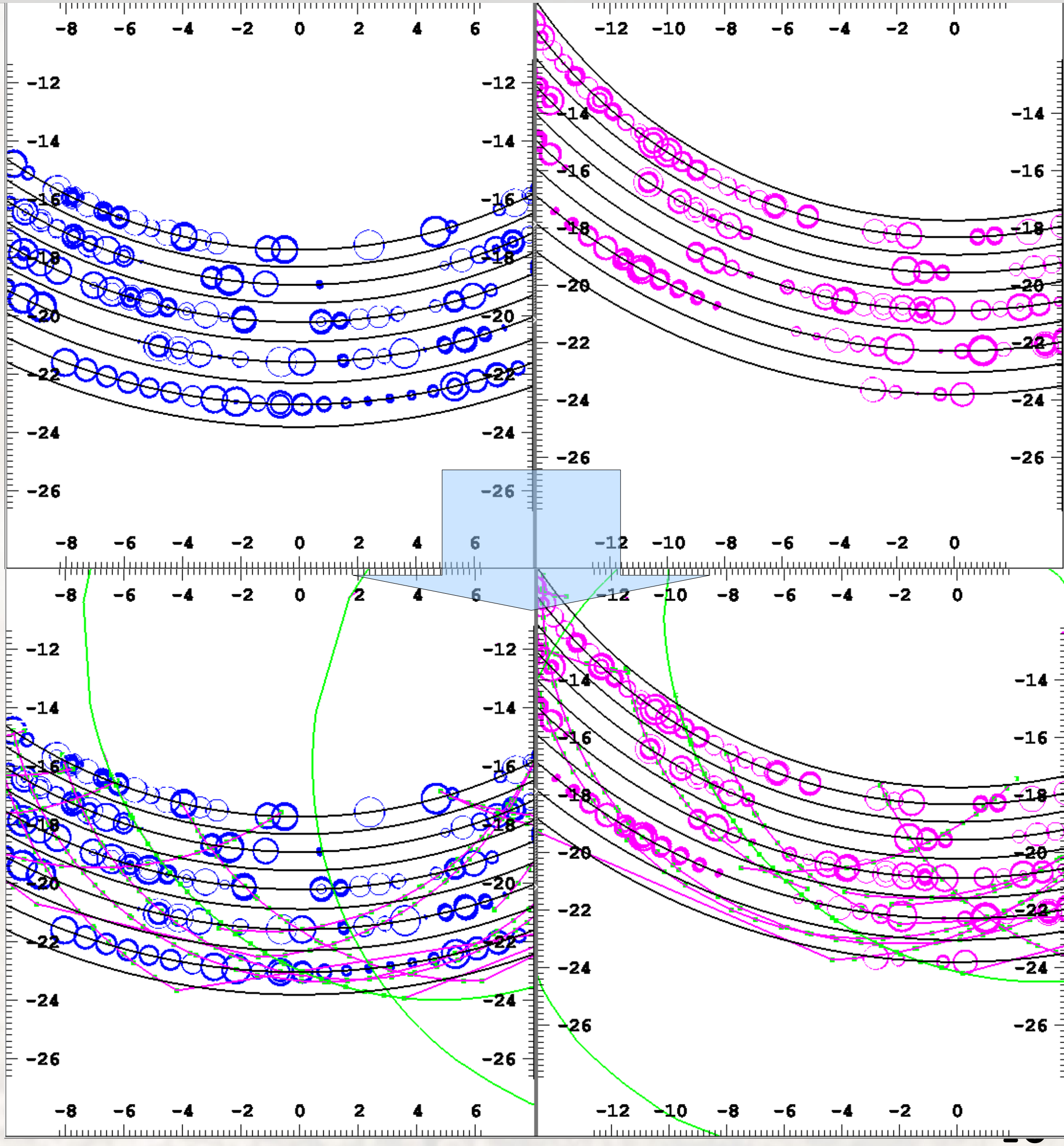
Needs stereo view + 4D reconstruction

(stereo DCH + t0 for each track)

Initial trackfinding pattern recognition (PR) based on conventional Kalman filter with track following method

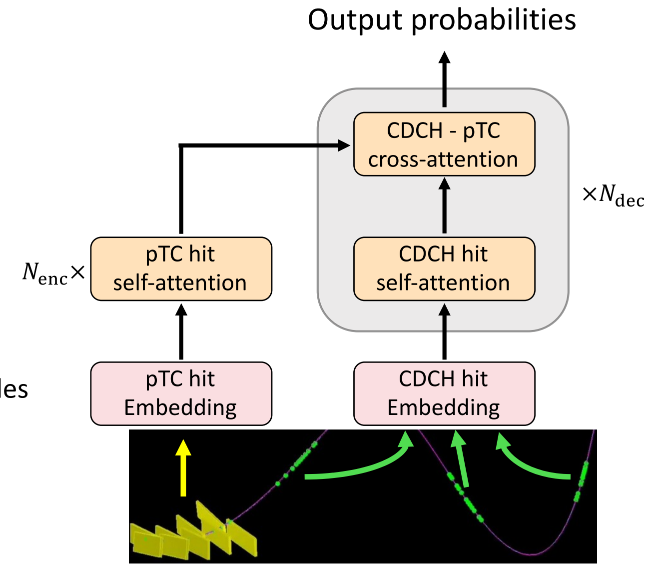
Limitations: local PR, performance struggle with high pile-up

ML: Transformer + GNN as additional prefilter were implemented by collaboration

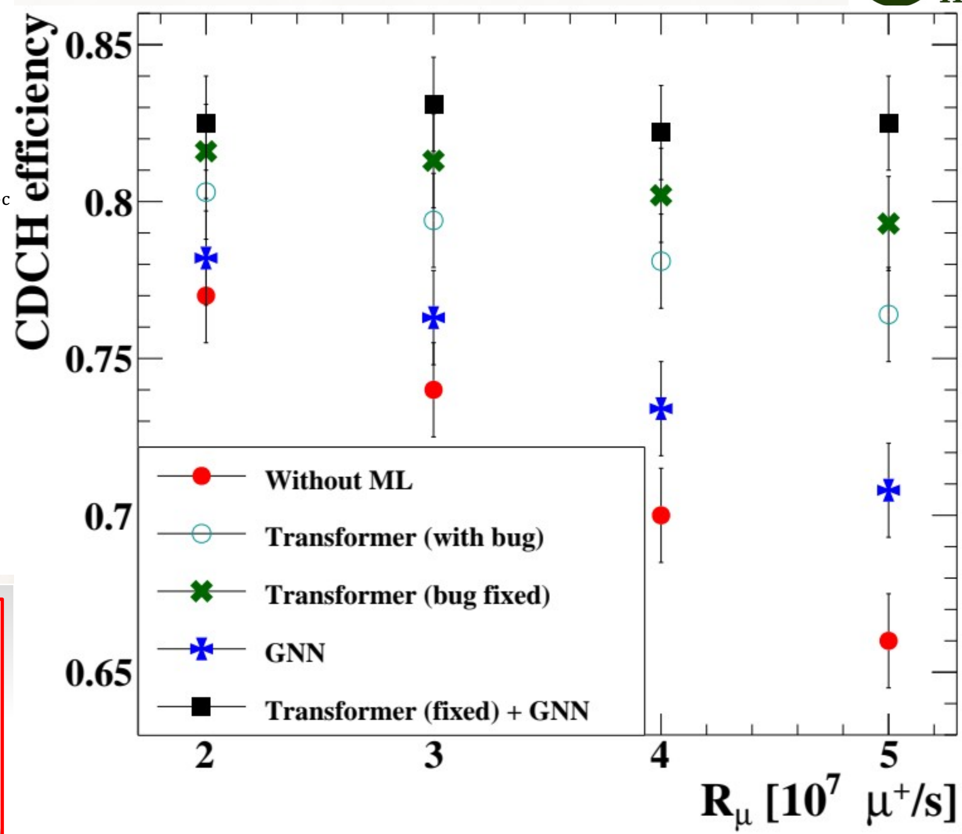


Transformer model adapted to MEG II

- Transformer model for MEG II
  - Leveraging Attention b/w hits
  - CDCH block: **All** chamber hits
  - TC block: Clustered counter hits
- Input features
  - Normal XYZ coordinate
  - Estimated drift time of hit (Defined w.r.t the pTC of interest)
  - Additive features in the next two slides
  - → Feature vector embedded by MLP



Track finding efficiency



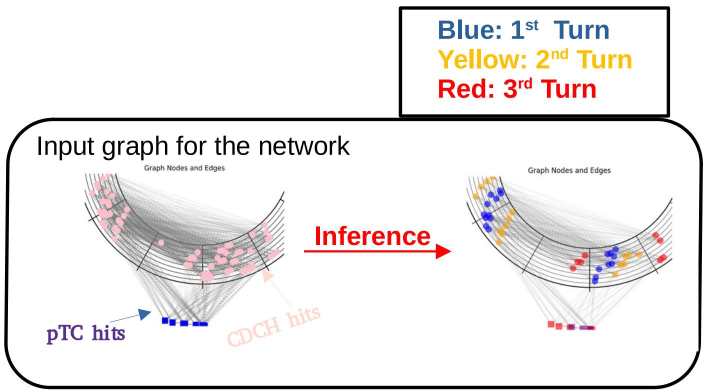
Transformer is **global pattern** recognition:
more like conventional histogramming PR,
search tracks in hyperspace

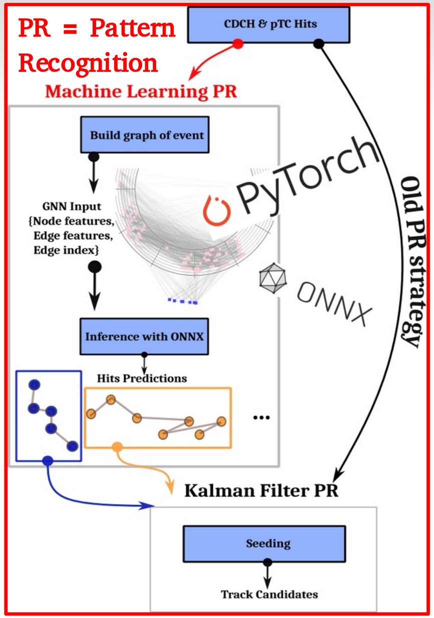
<u>Two limiting factors to operate MEG at higher rate:</u>

DCH: operation + patter recognition

LXe calorimeter: degradation of MPPC sensors under high rate

Graph Neural Network
GNN approach





Liverpool

Transformer-Based Approach to Enhance Positron Tracking Performance in MEG II

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Abstract

We developed a Transformer-based pattern recognition method for positron track reconstruction in the MEG II experiment. The model acts as a classifier to remove pileup hits in the MEG II drift chamber, which operates under a high pileup occupancy of 35 – 50 %. The trained model significantly improved hit purity, leading to enhancements in tracking efficiency and resolution by 15 % and 5 %, respectively, at a muon stopping rate of 5×10^7 μ/sec. This improvement translates into an approximately 10 % increase in the sensitivity of the $\mu \to e\gamma$ branching ratio measurement.

Keywords: Tracking detector, Transformer, Machine Learning

1. Introduction

The MEG II experiment searches for the charged lepton flavor-violating muon decay, $\mu \to e\gamma$ [1]. Data collection began in 2021, and analysis of the first two years of data (up to 2022) set a 90 % C.L. upper limit of 1.5×10^{-13} on the $\mu \to e\gamma$ branching ratio [2]. The experiment is scheduled to continue until 2026, aiming to achieve an upper-limit sensitivity of 6×10^{-14}, with its scientific motivation and impact discussed in Ref. [3]. Located at the $\pi E5$ beam line of PSI [4], the experiment stops a continuous muon beam in a thin plastic target at a rate of 3 – 5×10^7 μ/sec, and measures positrons and photons from muon decays using a positron spectrometer and a liquid xenon detector, respectively.

In this paper, we aim to improve the performance of the positron spectrometer, thereby enhancing the $\mu \to e\gamma$ sensitivity of the experiment. The positron spectrometer must achieve high positron detection efficiency and resolution even at a high muon stopping rate on the target. The efficiency and the stopping rate directly determine the number of muon decays concluded that a muon stopping rate of 4×10^7 μ/sec maximizes the $\mu \to e\gamma$ sensitivity. This value is lower than the rate limit of 5×10^7 μ/sec, which is determined by constraints from the liquid xenon photon detector. The reduced muon rate was chosen because an increase in the stopping rate was observed to degrade the positron tracking efficiency. Since the single-hit efficiency of the tracking detector remains nearly constant across different stopping rates, this degradation was attributed to an inefficiency in the reconstruction algorithm. In particular, the tracking algorithm is inefficient in the track-finding stage, where pattern recognition is highly sensitive to contamination from pileup hits. This underscores the importance of improving the algorithm to make it more robust against pileup.

This paper presents a novel Transformer-based machine learning method for the pattern recognition task in MEG II positron track reconstruction. Sec. 2 provides a brief introduction to the positron spectrometer design and the conventional reconstruction method detailed in Ref. [5]. Next, Sec. 3 reviews related work in the literature on applying machine learning techniques to track reconstruction and discusses the spe-

Future $\mu \rightarrow e\gamma$ experiment

Presented at Open CHRISP PSI Users Meeting BVR57, 4 Feb.2026

LETTER OF INTENT
for a future $\mu^+ \rightarrow e^+\gamma$ experiment
at the High Intensity Muon Beam facility at PSI

THE STUDY GROUP FOR FUTURE $\mu^+ \rightarrow e^+\gamma$ EXPERIMENTS

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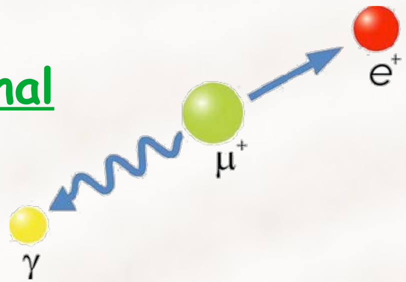
Core : MEG + Mu3e groups

Not a continuation of MEG II,
but a new effort in strong synergy with Mu3e
and open to external contributions

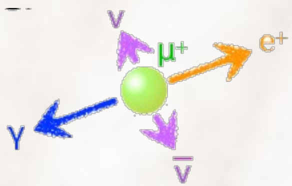
Pathway to higher sensitivity

Signal

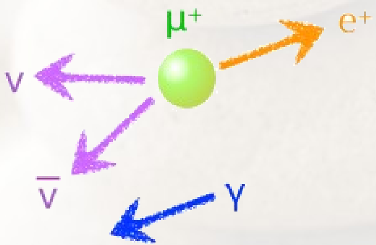


$E_\gamma, E_e \sim 52.8\text{MeV}$
$\Theta_{e\gamma} = 180°, T_\gamma = T_e$

RMD BG



Dominant Accidental BG

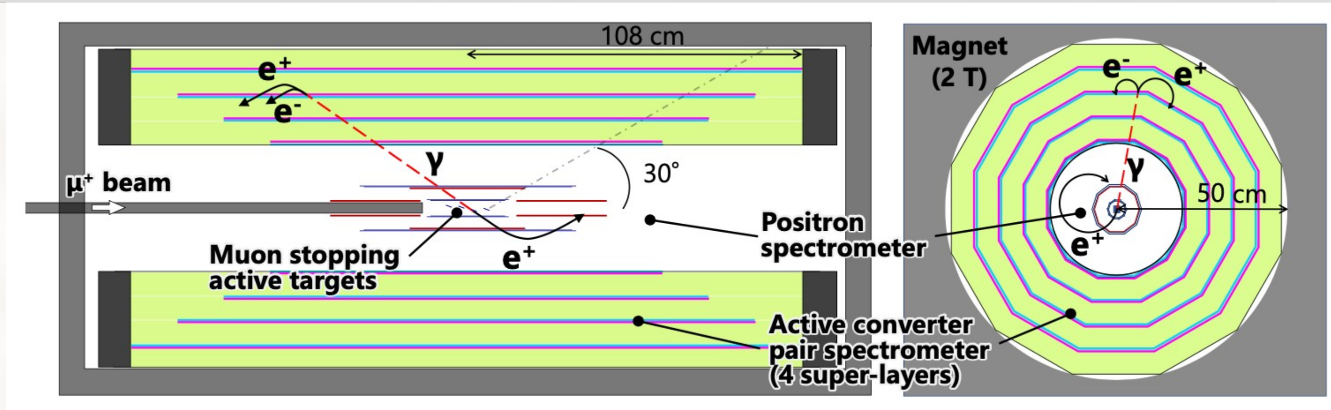


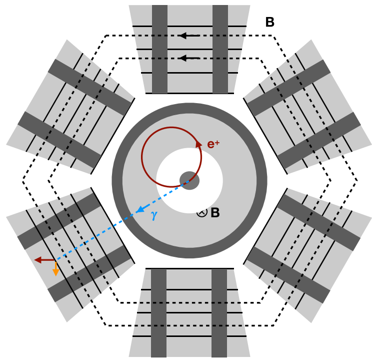
Search for e+ and γ correlated by time, direction, energy:

- ✗ Highest intensity continuous μ beam
- ✗ Detectors tolerant of highest intensities
- ✗ Best resolutions are required to narrow signal region

Detector concept

HIMB μ beam
$5\times10^7 \rightarrow 10^{10}$ μ/s

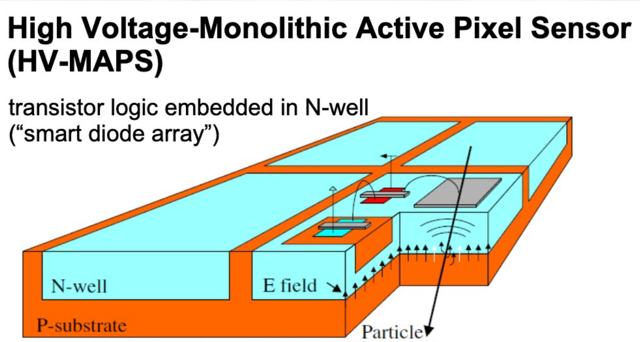




New technology

Tracker: from Mu3e

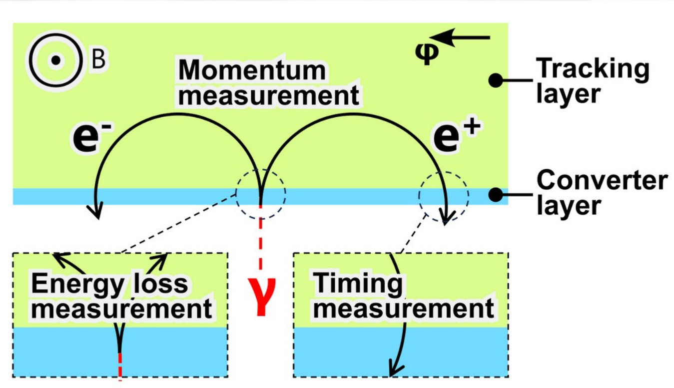
Monolithic silicon pixels (HV-MAPS)
high-rate tolerance,
low material budget,
high granularity



I.Peric, P. Fischer et al., NIM A 582 (2007) 876

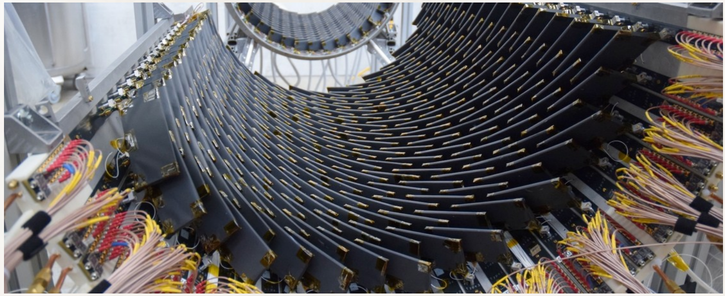
Momentum resolution ~ 100 keV

Calorimeter



Energy resolution: 1 MeV → 0.2 MeV
On price of efficiency 60% → 10%
Time resolution ~ 30ps

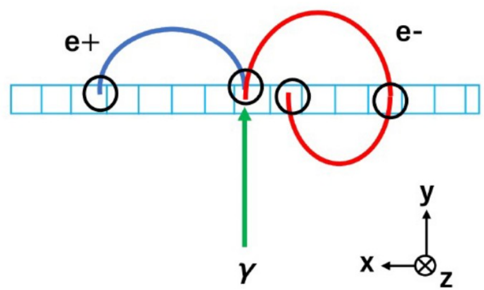
Positron timing

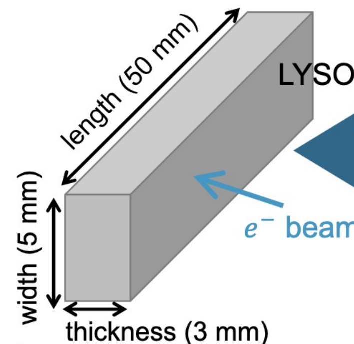


MEGII baseline:
Scintillating tiles + SiPM
with reduced size
Time resolution ~ 30ps

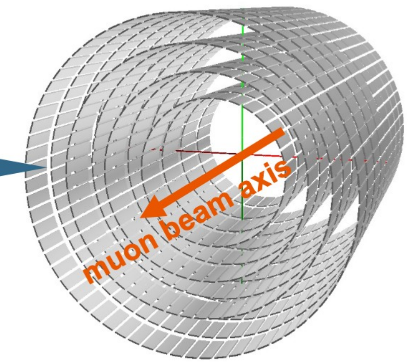
S. Ban *et al.*, arxiv:2512.24209

Active converter



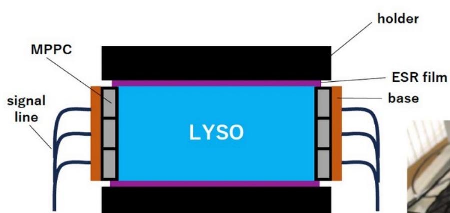


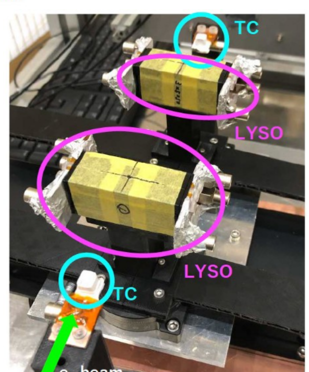
one segment
(standard size)

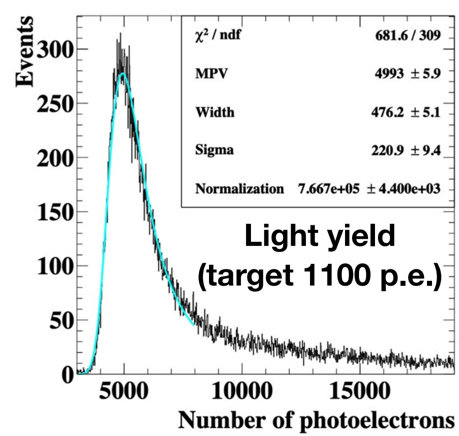


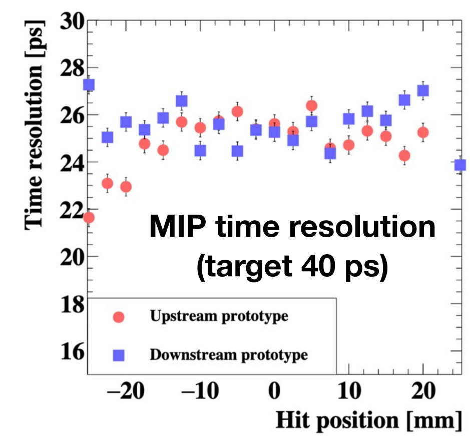
segmentation of converter
in the future experiment

CONVERTER PROTOTYPE

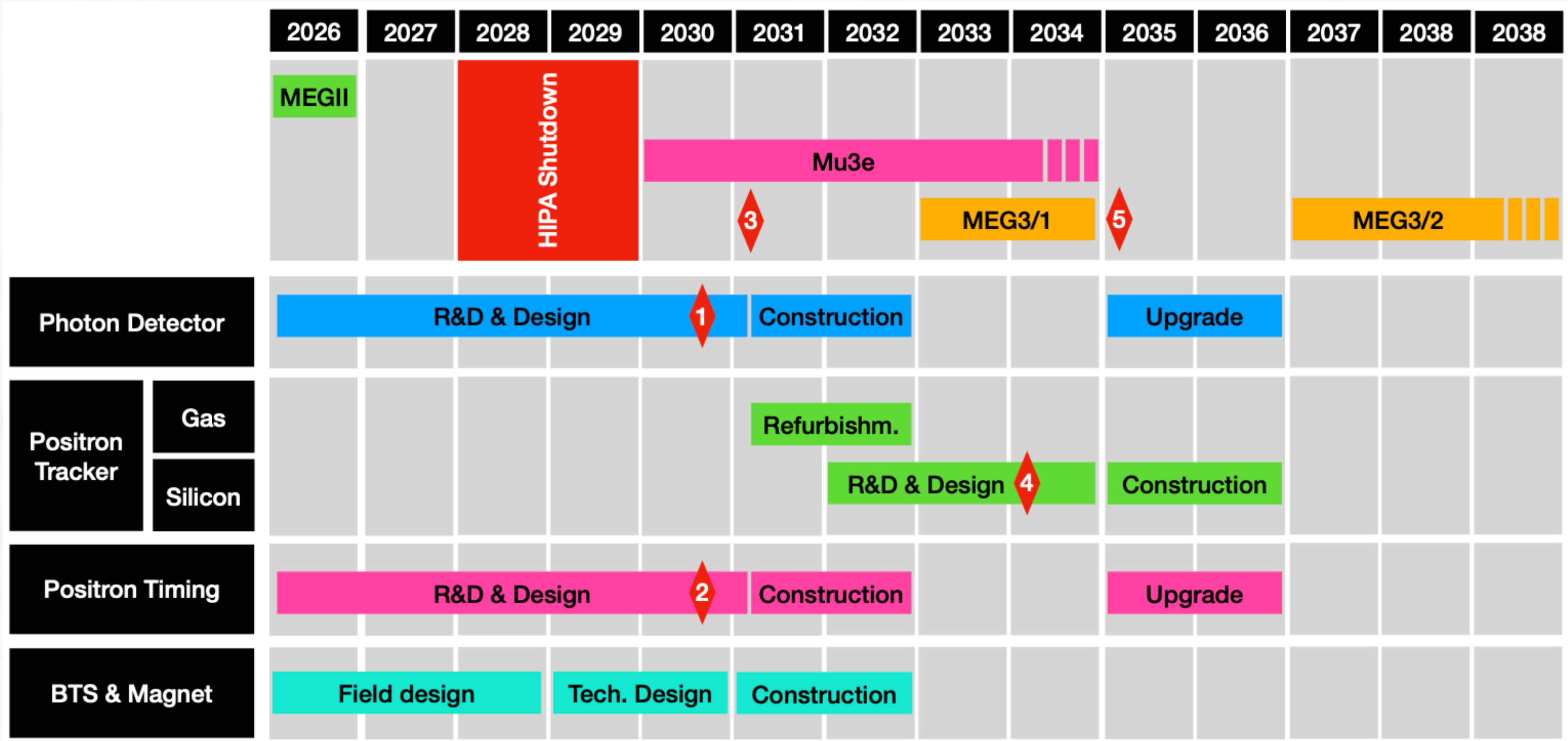








Schedule



Phase-0 (proof-of-concept): a beam test with small photon conversion detector prototype

Phase-1 : at $2\text{x}10^8$ μ/s, reusing some MEG II hardware: COBRA magnet, drift chamber

1 or 2 photon conversion layers

Phase-2: at > 10^9 μ/s, Silicon positron tracker, multiple conversion layers

Sensitivity: $6\text{x}10^{-14}$ (MEG2) → $(2 - 3)\text{x}10^{-15}$

Backup

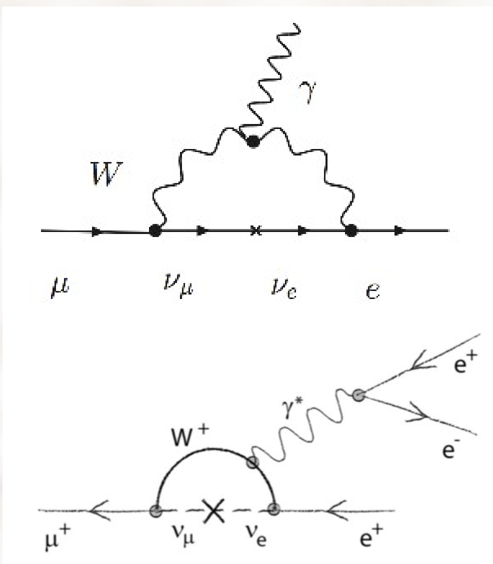
charged Lepton Flavour Violation search

- 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 favour violation: NOT yet observed
- An experimental evidence of cLFV at the current sensitivities will be a clear signature of New Physics

<u>SM with massive neutrinos (Dirac)</u>

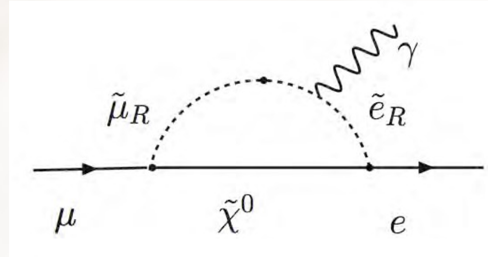
$B(\mu \rightarrow e\gamma \;/\; eee) \sim 10^{-54}$

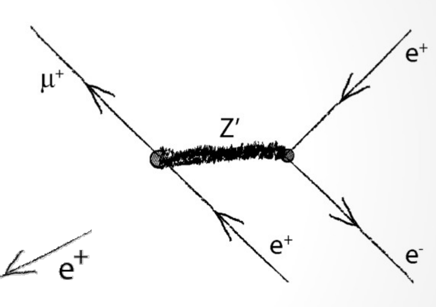
ν oscillations



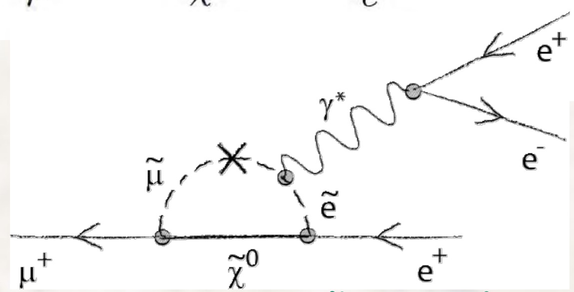
<u>BSM</u>

$B(\mu \rightarrow e\gamma \;/\; eee) \sim 10^{-13} - 10^{-18}$



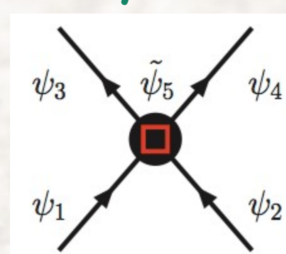


SUSY,sneutrino,
Higgs triplet,
Extra dimension
Extra Z',
...



Most models "naturally" induce lepton flavour violation!

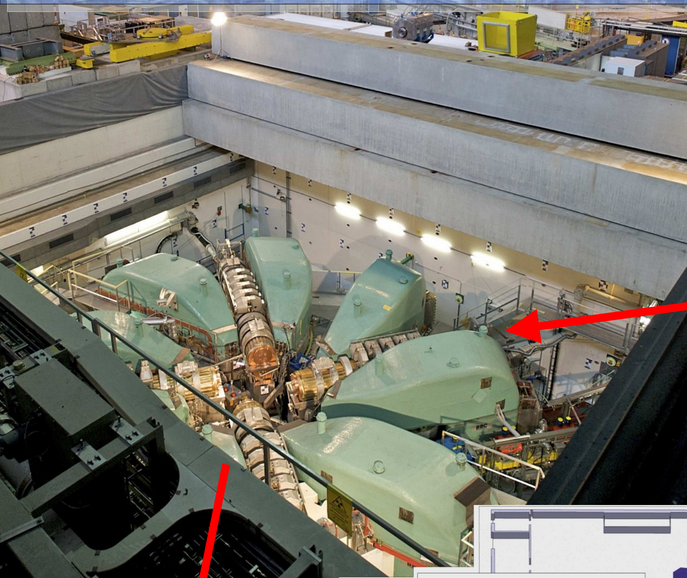
"Intensity Frontier" complementary to "Energy Frontier"

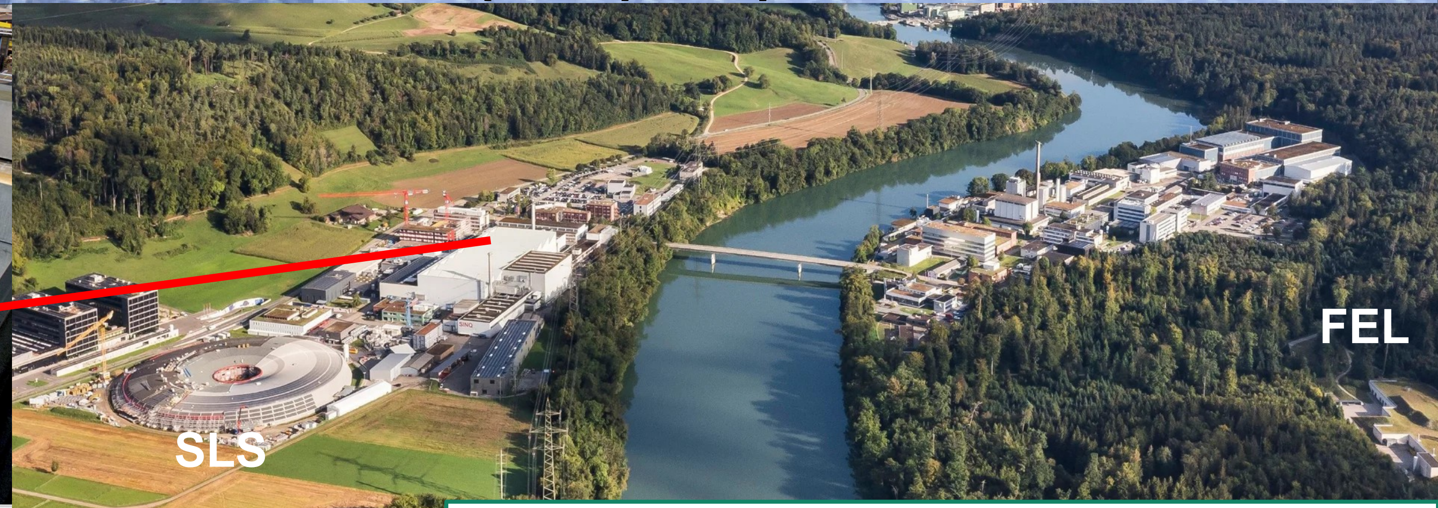


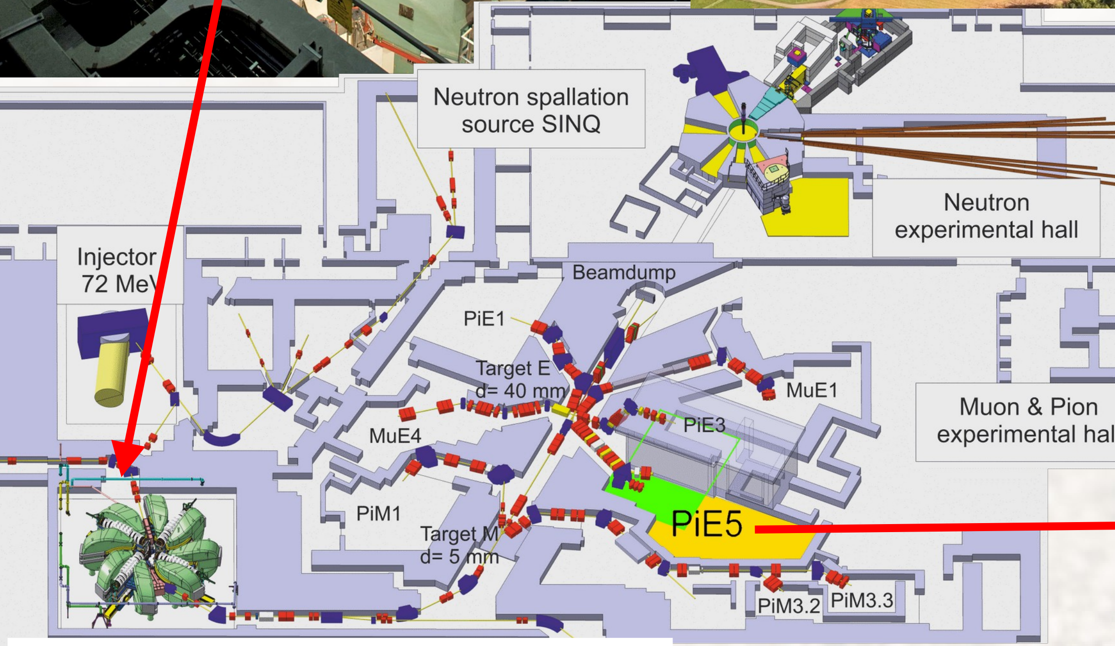
$$\frac{1}{\Lambda^2}$$

Probe energy scale otherwise unreachable: **E > 1000 TeV**

Paul Scherrer Institute (PSI) experiments



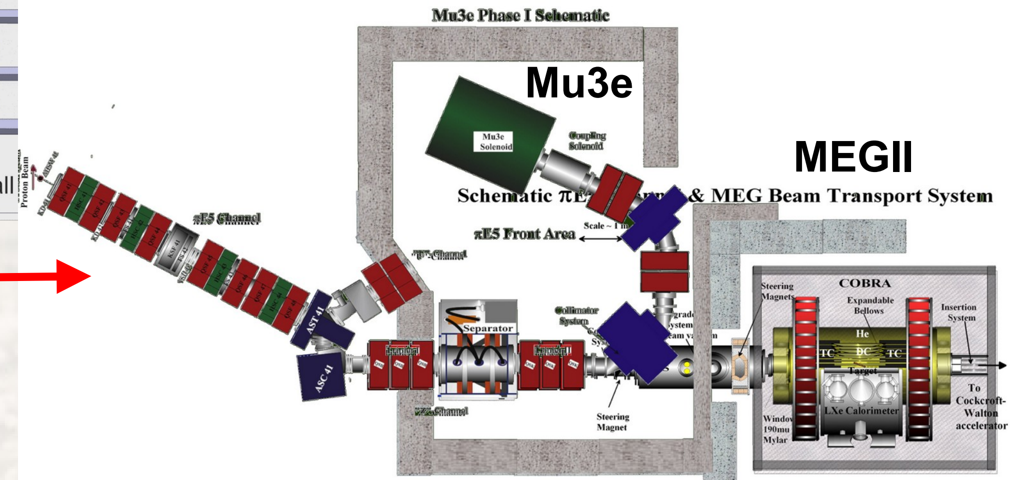


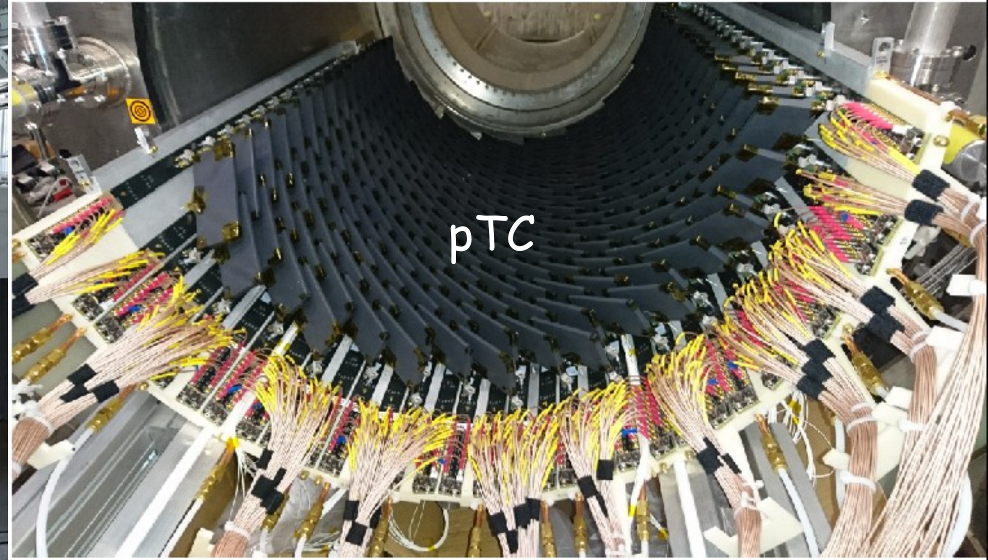


590 MeV cyclotron, proton beam
2.4 mA, 1.4 MW World record (2011)

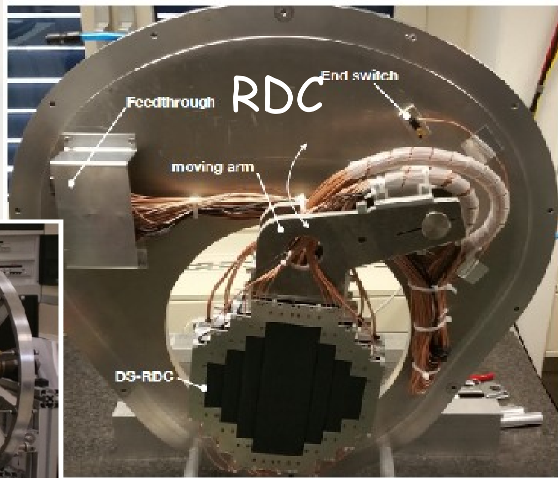
PiE5 Muon Beamline:

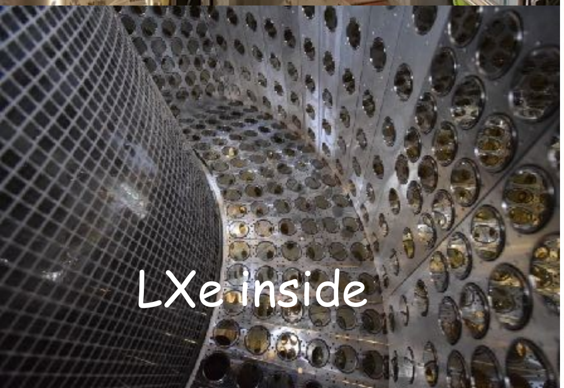
- World's most intense continuous muon beam 2×10^{8} μ+/sec
- Low momentum muons ~28 MeV/c
- PiE5 beamline shared between MEGII and Mu3e

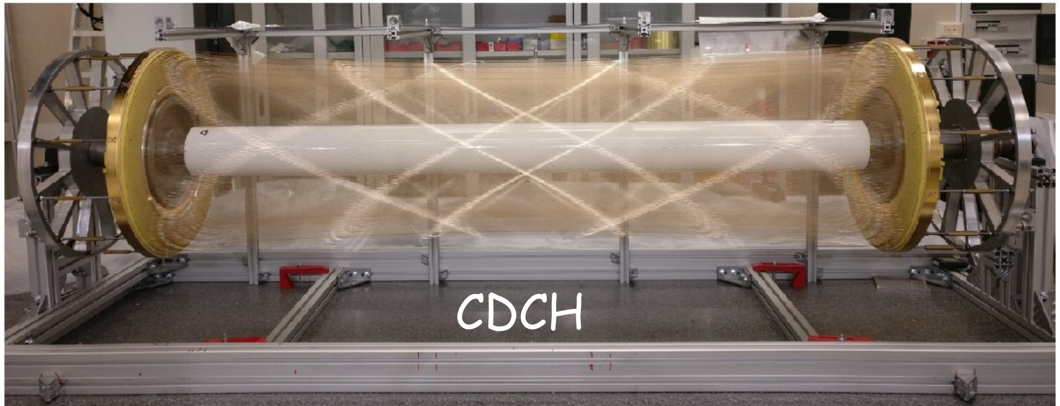




MEG II proposal 2013
Detector R&D 2012-2015
Construction in 2015-2020
Commissioning and physics run 2021-





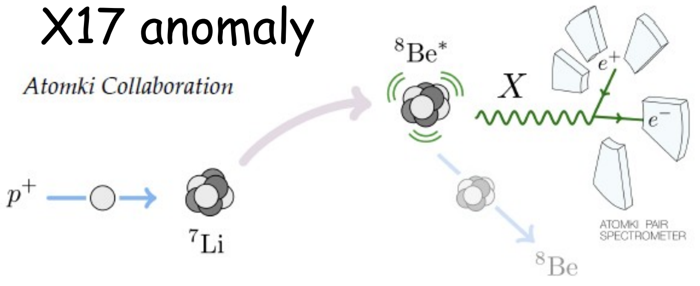


X17 boson search

Search for the X17 particle in $^{7}Li(p,e^{+}e^{-})^{8}Be$ processes with the MEG II detector

ATOMKI
X17 anomaly

Atomki Collaboration



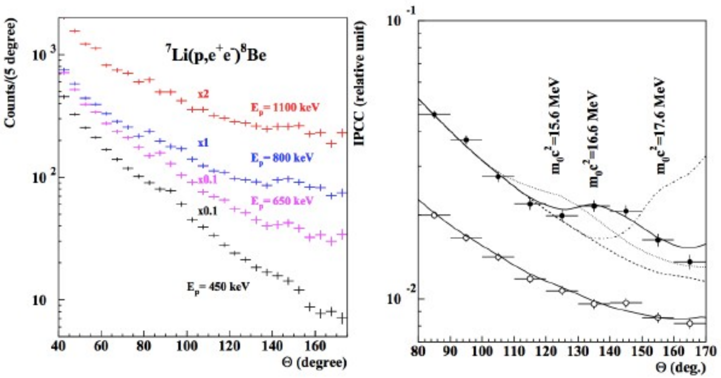
$^{7}Li(p,e^{+}e^{-})^{8}Be$ studied at
$E_p =$ 450, 650, 800, 1100 keV

e+/e- energy sum and angular correlation Θ

- Internal Pair Conversion (IPC) distribution shows excess at Θ~140° at several beam energies

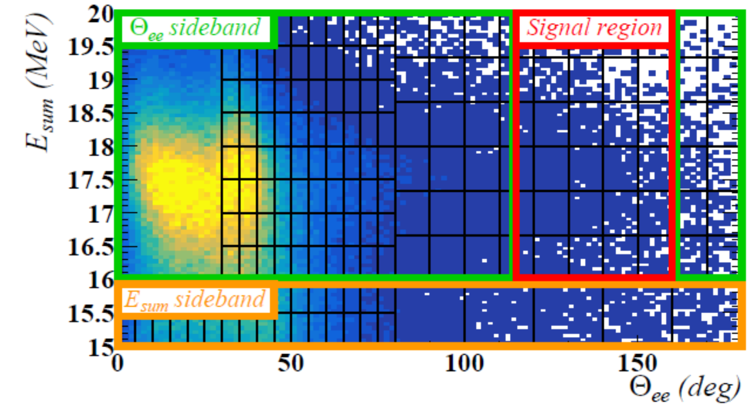
decay of a light particle

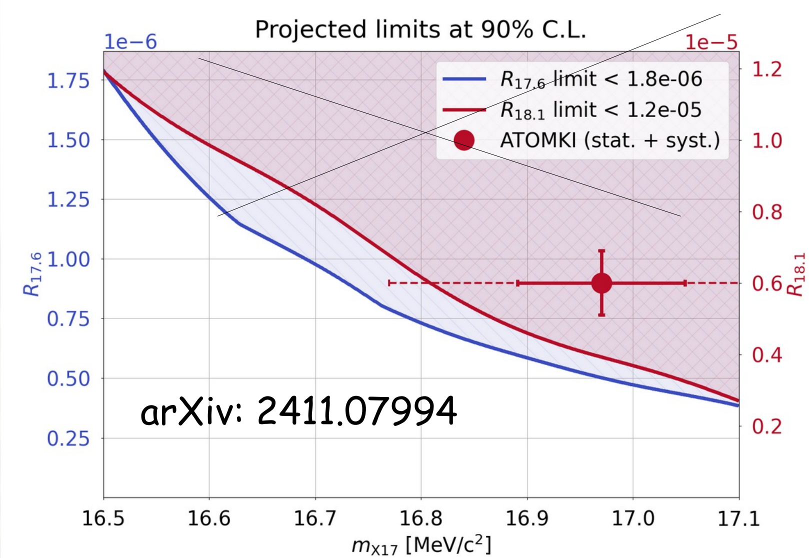
best fit $m_X = 16.95\ \mathrm{MeV/c^2}$, $BR(X) = 6 \times 10^{-6}$



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

MEGII dedicated X17 runs using CW proton beam





MEGII unblinded analysis at 13 November 2024

No significant signal observed
ATOMKI result was excluded at 94%

MEG2 Tracking

1. Hit detection from the waveform data
2. Track finding
3. Operation under high hit rate