

大強度ミューオンビームで切り拓く新物理フロンティア
— レプトンフレイバー破れ探索の現在と未来 —

ミューオン稀崩壊探索の 将来展望

Future prospects for searches of rare muon decays



内山 雄祐

September 14, 2026
日本物理学会第81回年次大会
@ UTokyo, Komaba campus

シンポジウム：
荷電レプトンフレーバー非保存探索による
LHC時代の素粒子物理

DCミュオンビームによる cLFV探索

2013年3月26日
日本物理学会第68回年次大会
@広島大学



素粒子物理国際研究センター
内山 雄祐

13 years ago, when MEG DAQ is about finish,
MEG II & Mu3e proposal had just been approved.

'HL-LHC時代'のDCミュオン ビームによるcLFV探索

1	物理からの要請： 大いにある (LHC, COMETなどの結果。それらと相補的。)
2	利用可能なDCミュオン源： 前途有望 (複数のプロジェクトが欧米日で進行中。)
3	洗練された実験アイデア： ??

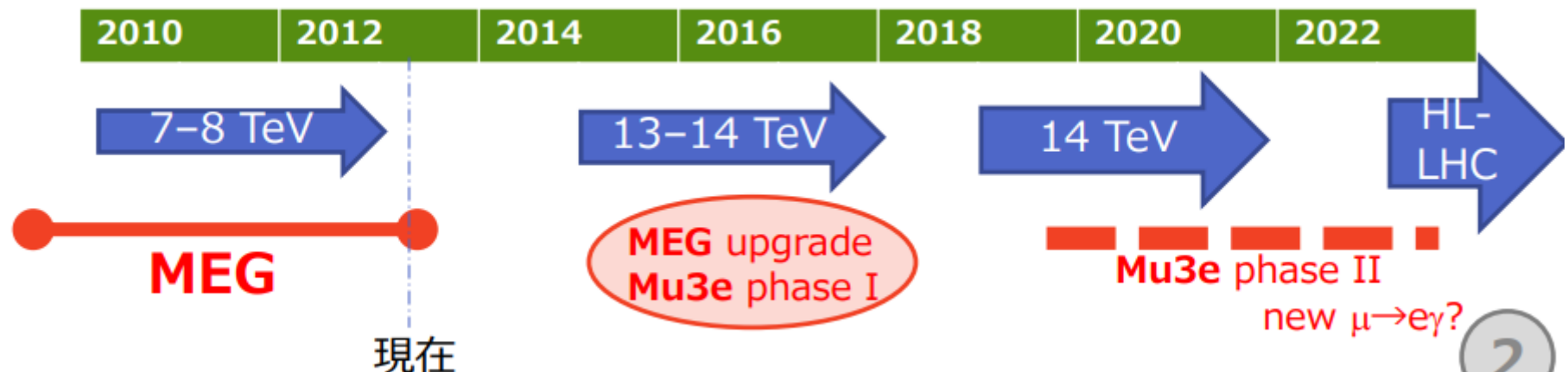
時間スケールが構想から実現までO(10年)。
次の実験を考えだす時期か。

- 堅実に一步一步改善していく。
- 技術革新・画期的アイデアで一気に。
- まずは
 - ✓ 10^{-15} 台での $\mu \rightarrow e\gamma$ 探索ができないか？
 - ✓ Mu3eよりよい $\mu \rightarrow eee$ 実験アイデアを考えられるか？

2013/Mar/26 JPS

Yusuke UCHIYAMA/ The University of Tokyo

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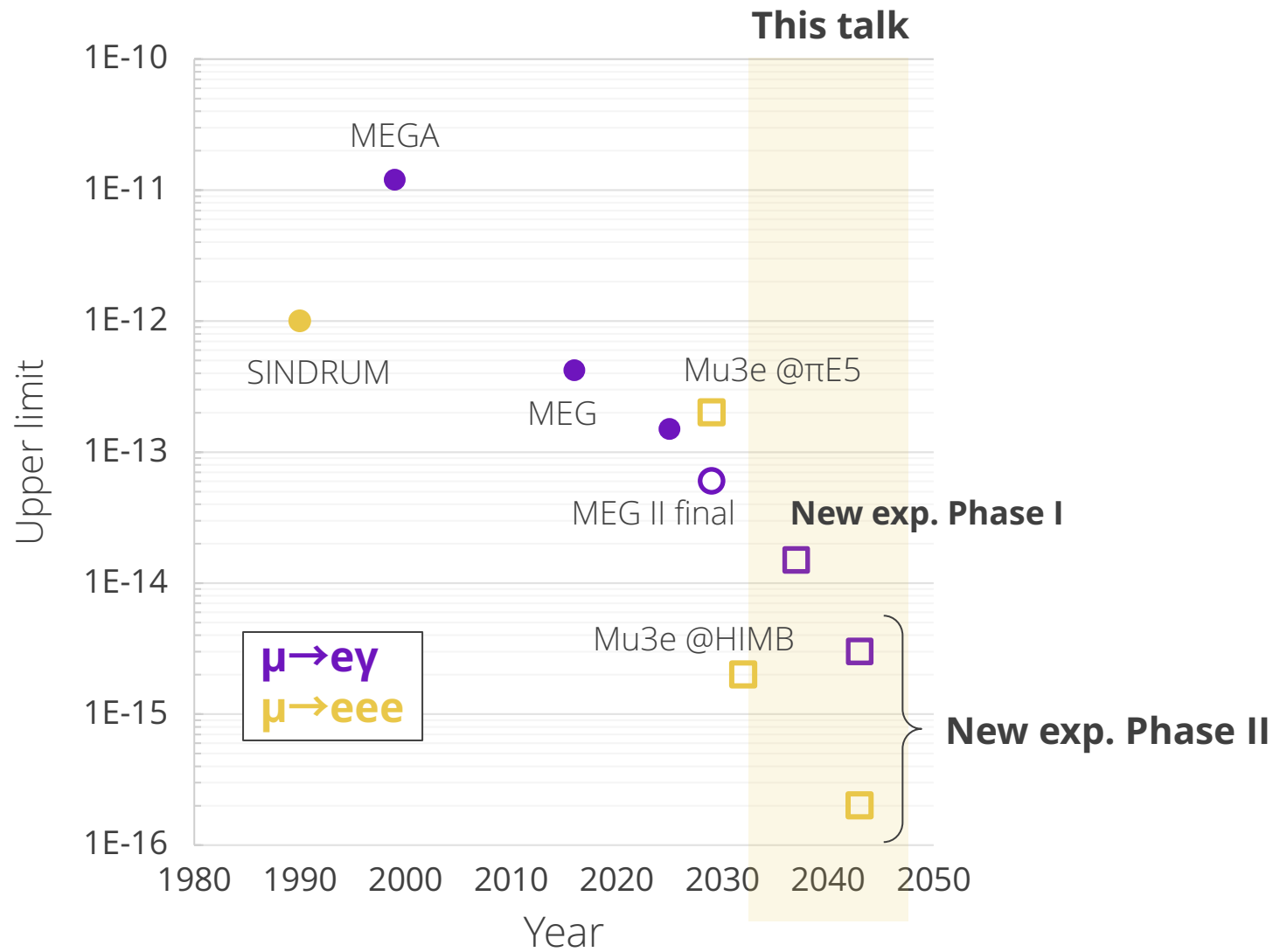


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Target



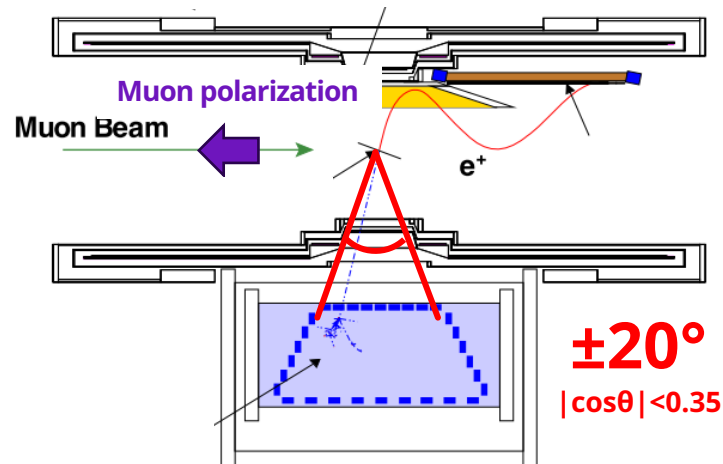
Goals of a 2030s experiment



$\mu^+ \rightarrow e^+ \gamma$ search

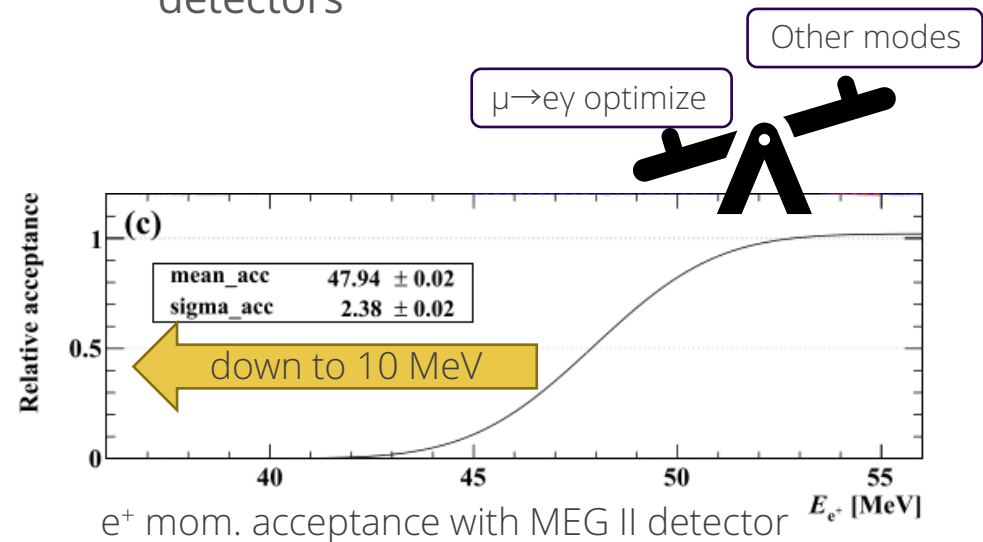
- $O(10^{-15})$ sensitivity to keep highest sensitivity for dipole operator
- Sensitivity for angular distribution with wider geometrical acceptance

$$\frac{dB(\mu^+ \rightarrow e^+ \gamma)}{d \cos \theta_e} = 192\pi^2[|A_R|^2(1 - P_\mu \cos \theta_e) + |A_L|^2(1 + P_\mu \cos \theta_e)],$$



Multi-purpose

- Not “byproducts” but from design.
 - Longer preparation period
 - Budget expansion
- Wider momentum acceptance
- Simultaneously (same dataset) or dedicated run with the same detectors



Letter of Intent

Today's talk is based on this, but...

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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<https://doi.org/10.48550/arXiv.2504.18831>



Not just an advertisement of this,
Not on behalf of the group.

Letter of Intent

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LETTER OF INTENT for a future $\mu^+ \rightarrow e^+ \gamma$ experiment

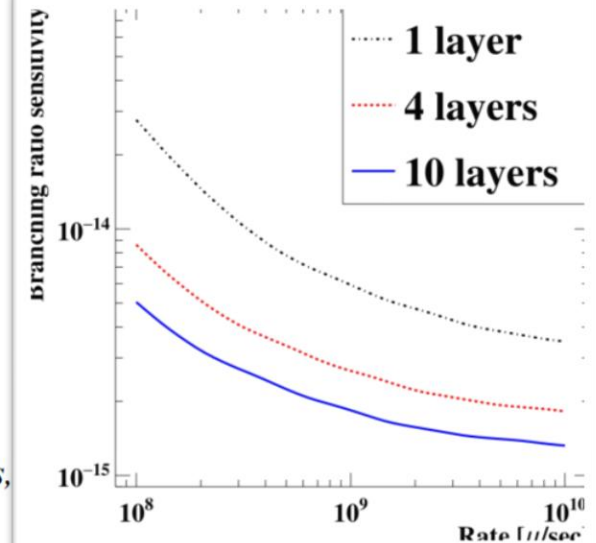
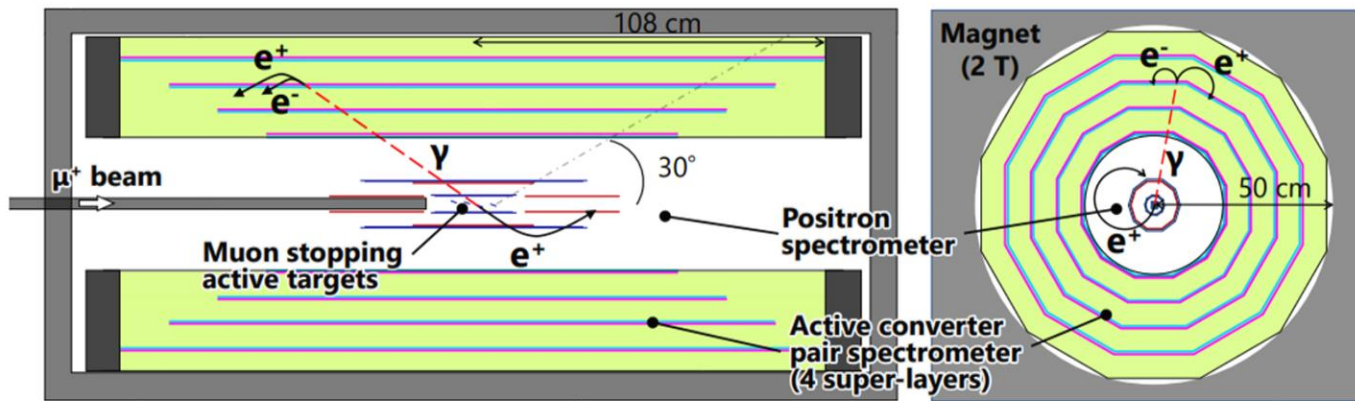


Figure 4: A sketch of a detector for $\mu^+ \rightarrow e^+ \gamma$ decays with a silicon pixel tracker for positrons, and active conversion layers with $e^+ e^-$ trackers for photons, within a single, long solenoid.

NIKOLAOS KONTOPOULOS,¹ MASSIMO ROSSIGNA,² THOMAS KUDZKI,³ KEI SAKAKIBARA,⁴ SUSANNA SCARPELLINI,^{3ab} TAIKAN SUEHARA,² HIROMU SUZUKI,¹⁹ MASATO TAKAHASHI,¹⁹ MICHELE TAMMARO,²⁰ GIANFRANCO TASSIELLI,^{18ac} YUSUKE UCHIYAMA,¹⁷ RYUSEI UMAKOSHI,² ANTOINE VENTURINI,^{7ab} LUIGI VIGANI,⁴ CECILIA VOENA,^{3ab} JOOST VOSSEBELD,⁶ RAINER WALLNY,¹⁶ KENSUKE YAMAMOTO,² YUJI YAMAZAKI¹⁹

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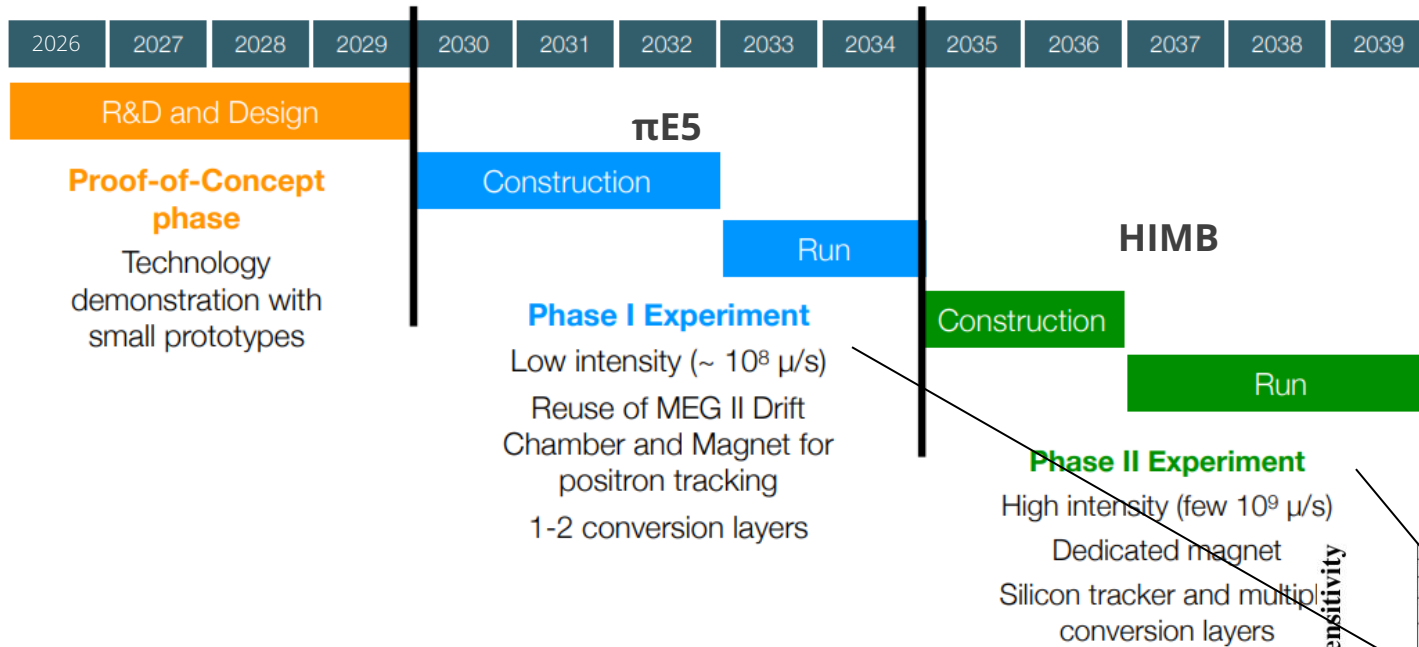


UNIVERSITÀ
DEL SALENTO



Non-trivial and highly challenging

Timeline



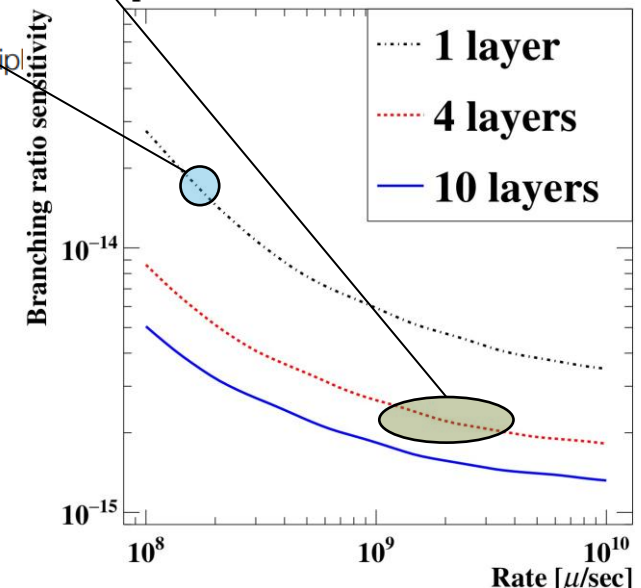
Phase I:

Demonstrate a new γ -ray detector concept.
 Reuse MEG-II apparatus (drift chamber, electronics, magnet?)
 Factor a few improvement from MEG II

Phase II:

Go to HIMB
 e^+ tracker with MAPS

10 years
ahead



Technological innovation required

Detector concept not yet fully defined



Plenty of opportunities to leverage **your expertise.**

Strategy

$$R_{\text{BG}} \propto R_{\mu}^2 \cdot \delta E_e \cdot (\delta E_y)^2 \cdot \delta \omega_{ey} / 4\pi \cdot \delta t_{ey}$$

As basic premise,
avoid increasing beam intensity too much

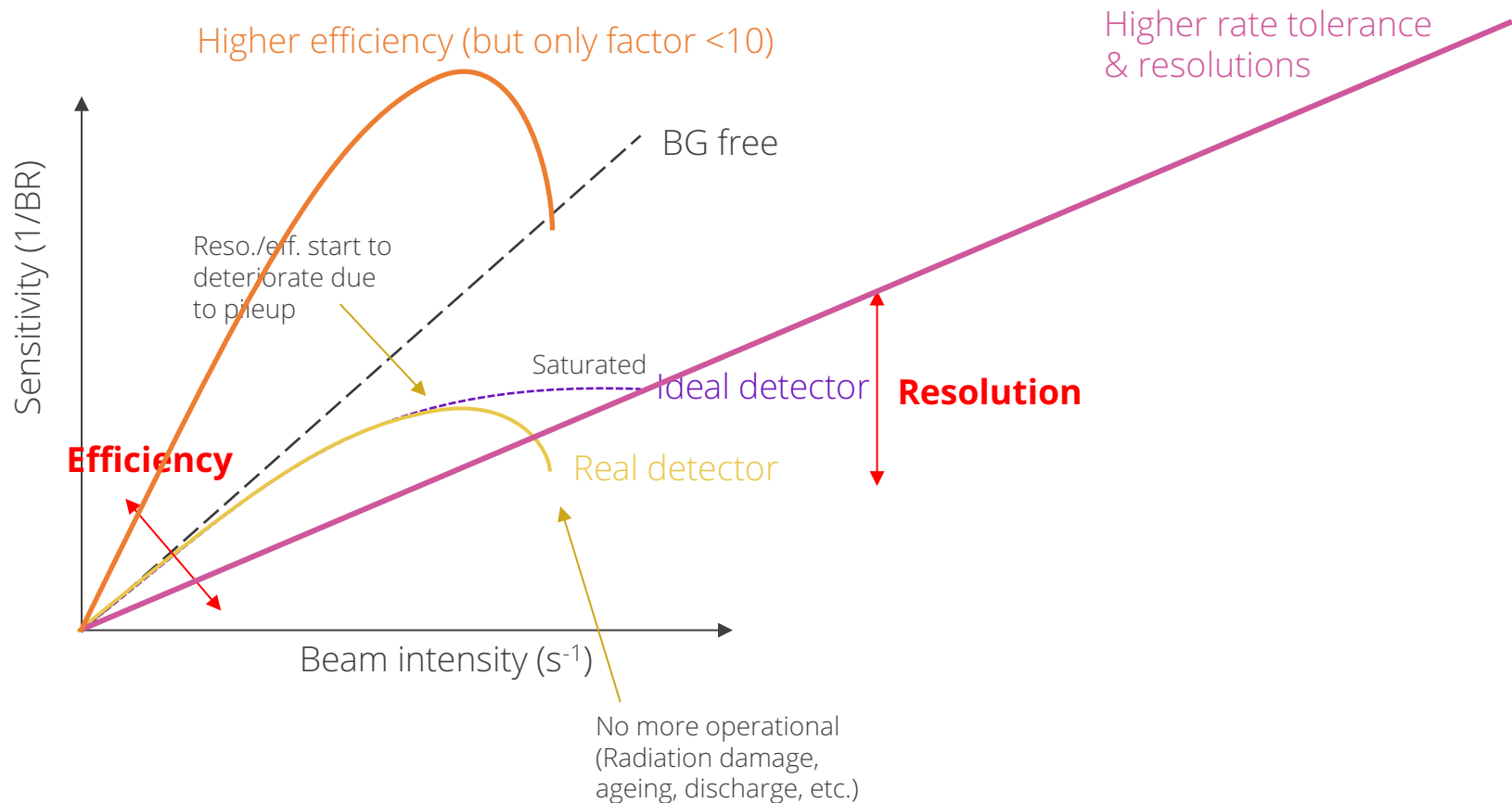
- ❑ Experiment becomes difficult
- ❑ $N_{\text{BG}} \propto R_{\mu}^2$
- ❑ Increasing acceptance & efficiency is more effective.

100-fold intensity
beyond imagination

Beam intensity & sensitivity

π E5 max beam intensity: $\sim 2 \times 10^8 \text{ s}^{-1}$

$\Leftrightarrow$ MEG II limit (optimal): **$5 \times 10^7 \text{ s}^{-1}$**



Strategy

As basic premise,
avoid increasing beam intensity too much

- ❑ Experiment becomes difficult
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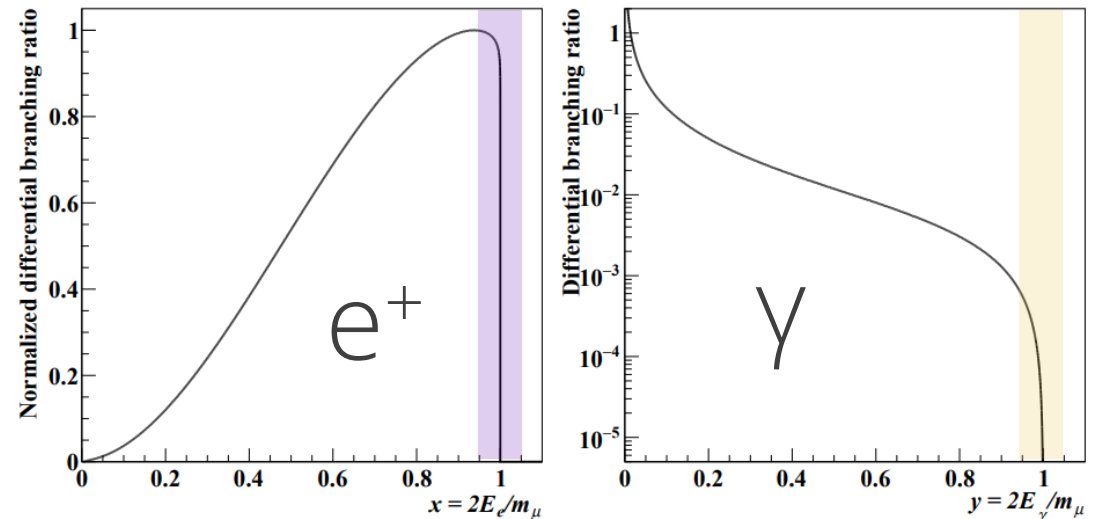
Improve photon energy resolution

- ❑ $N_{BG} \propto \delta E_\gamma^2$

Improve high-rate capability of e^+ detectors.

$$R_{BG} \propto R_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta \omega_{e\gamma} / 4\pi \cdot \delta t_{e\gamma}$$

100-fold intensity
beyond imagination



Proposed detector concept

Wider geometrical acceptance

- ▣ Cover $\sim 85\%$ ($\pm 60^\circ$)

Wider momentum acceptance

- ▣ High-rate tolerant e^+ tracker with MAPS

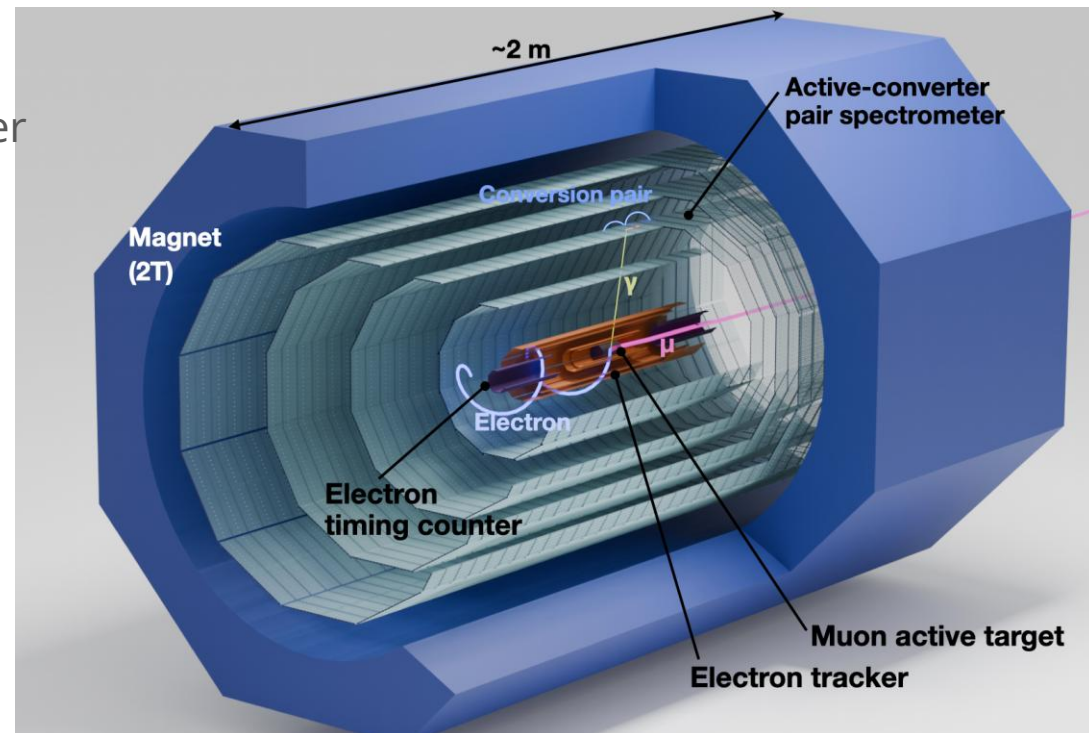
Better E_γ resolution

- ▣ Aim at 0.4% ($\times 5$ better than MEG II)
- ▣ with active converter pair spectrometer

Measure γ direction &

Spread the decay points over multiple targets

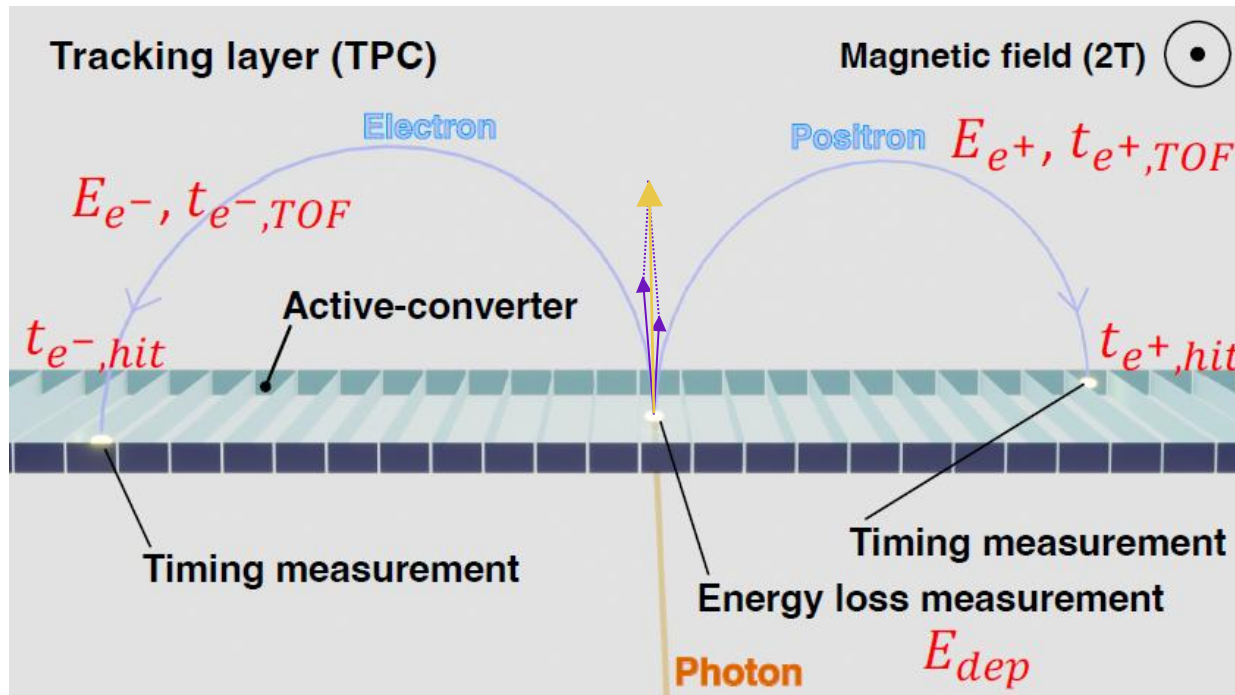
- ▣ and active target (optional)



Photon detector

Pair spectrometer with active converter

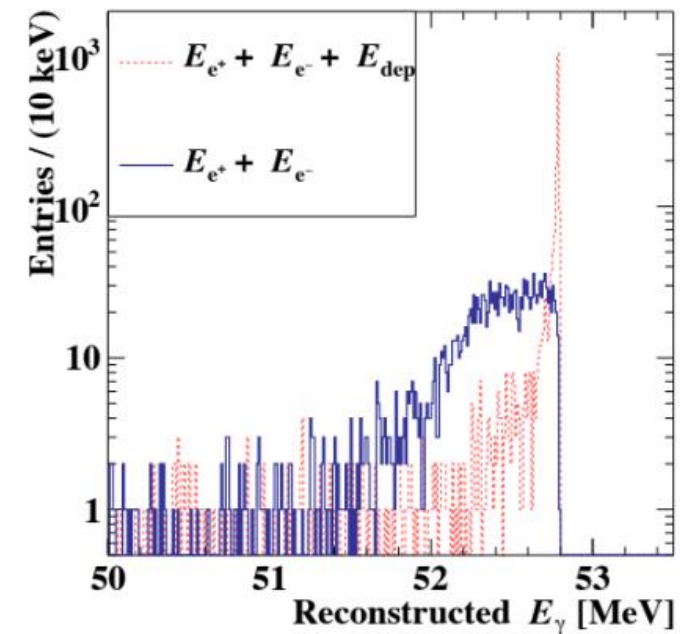
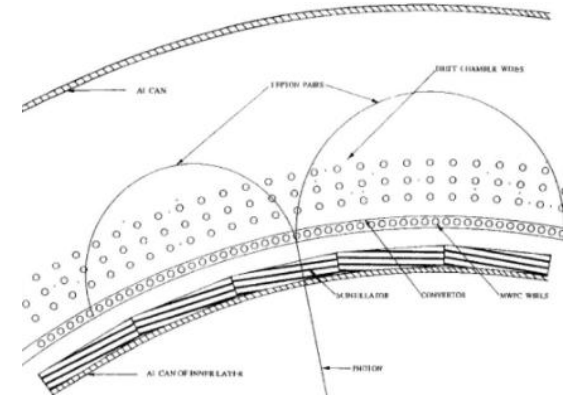
- ▣ High energy & position resolution by tracking e^+e^-
- ▣ High pileup tolerance
- ▣ Can reconstruct photon direction
- Low efficiency $\Rightarrow$ multiple layers



MEGA

(250 μm Pb foil $\times$ 2) $\times$ 3 layers

Detection ε 2.4%

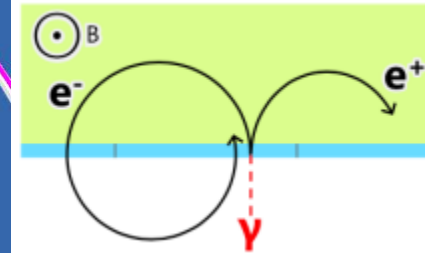


Active converter

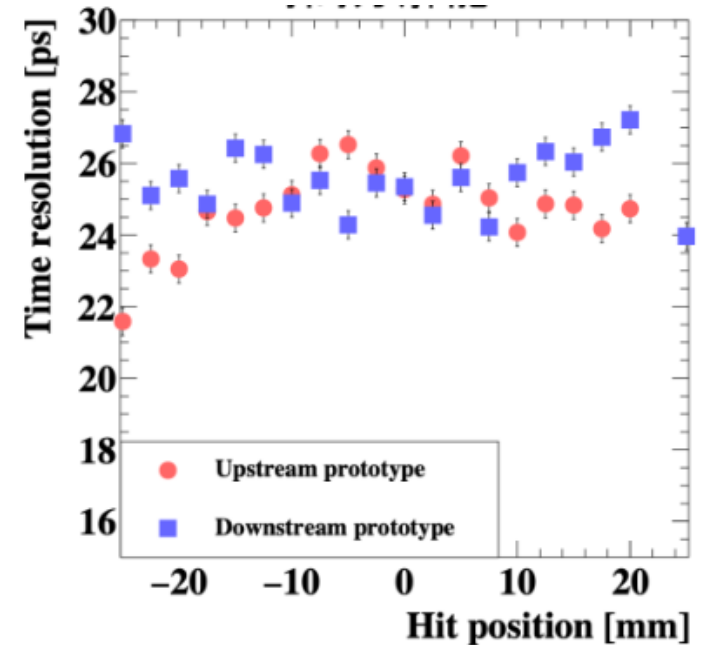
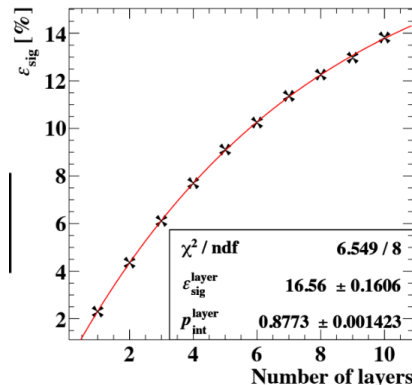
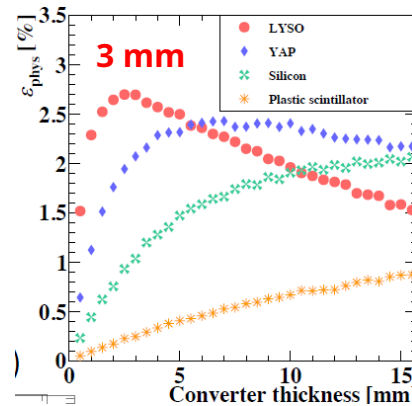
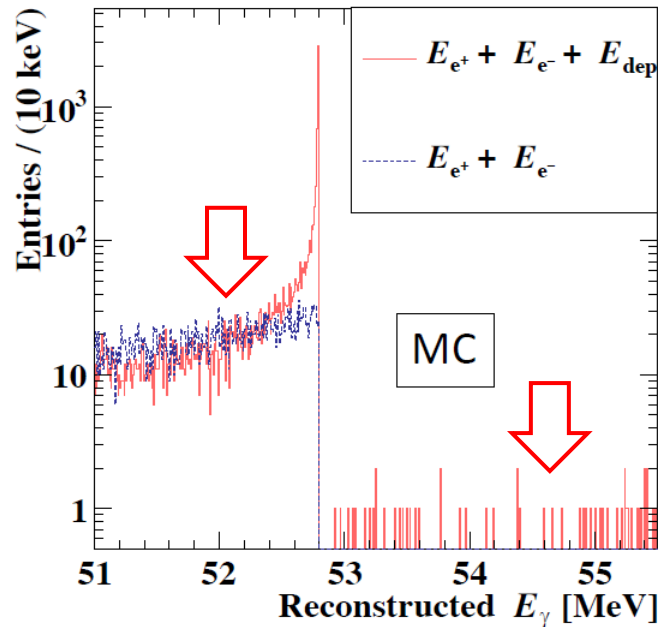
Optimize material and dimensions

□ LYSO, $5 \times 50 \times 3 \text{ mm}^3 \Rightarrow O(10^4)$ cells, $O(100 \text{ kg})$

Performance evaluation with test beams



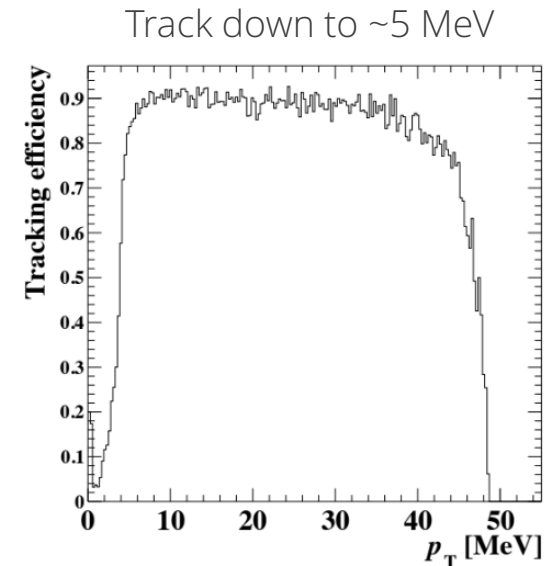
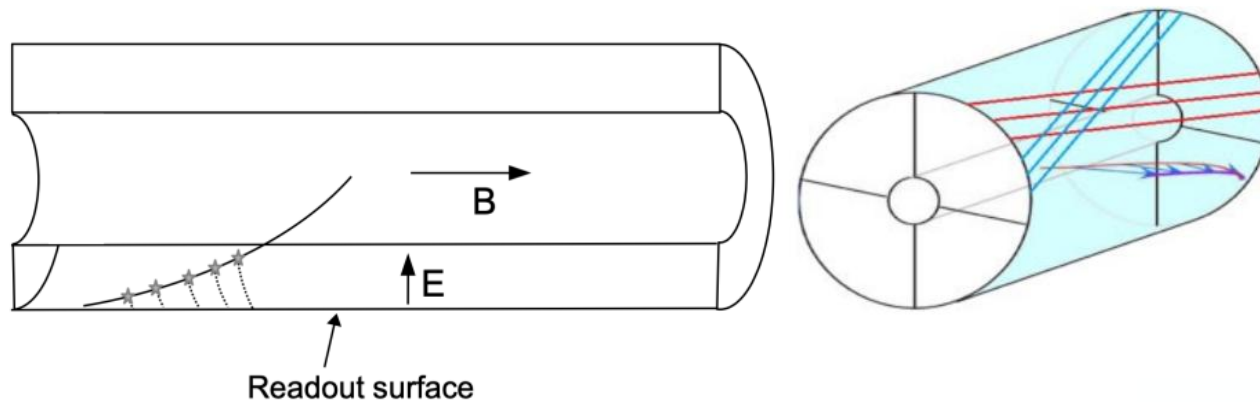
Over correction



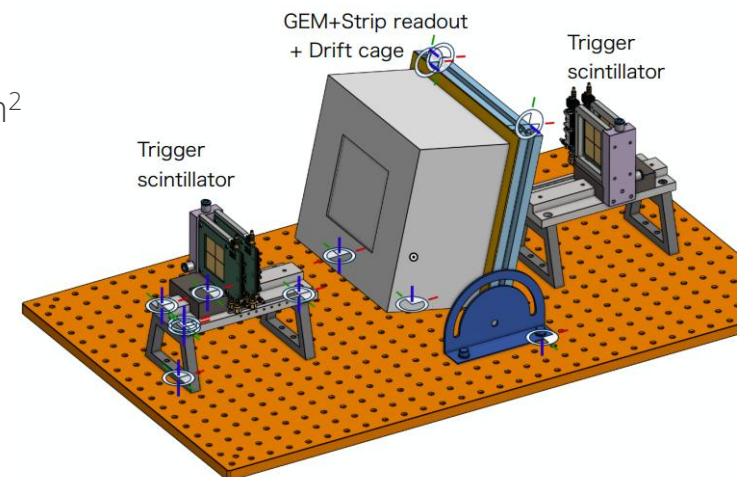
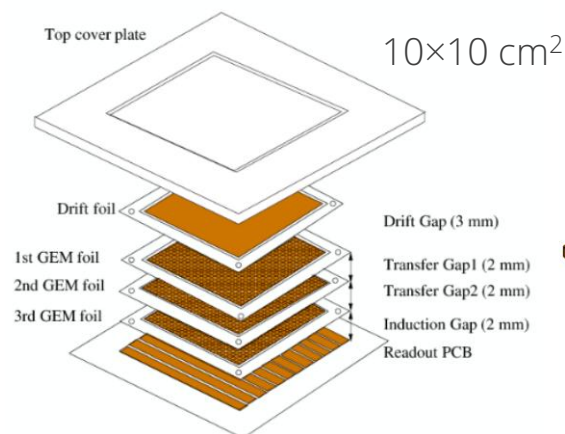
Pair tracker

Radial TPC

- Continuous sampling allows low-energy tracks to be detected.
- Short drift distance with $E \perp B$ (< 10 cm)
- Strip readout at ends



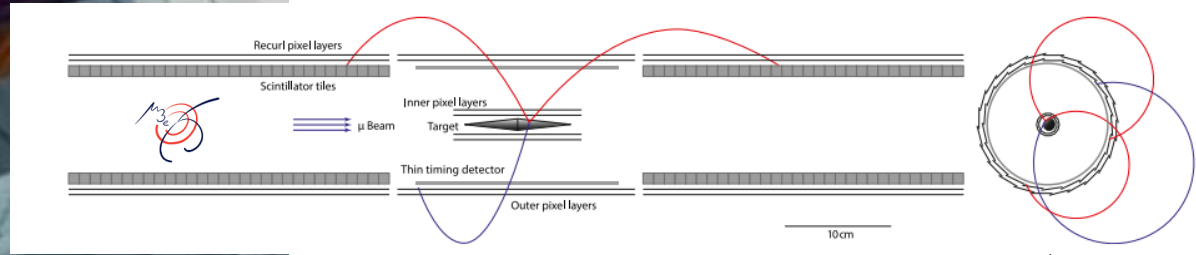
Prototype with GEM
Test beam @PSI this Oct.



Electron detector



⇒ Unify with Mu3e Phase II!



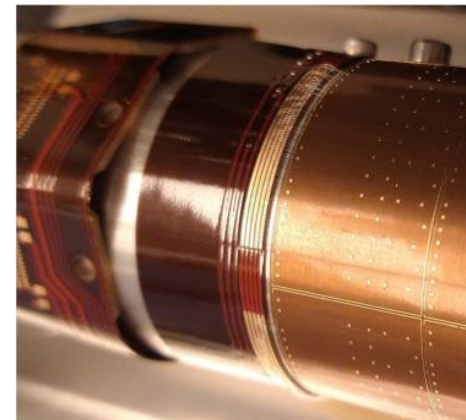
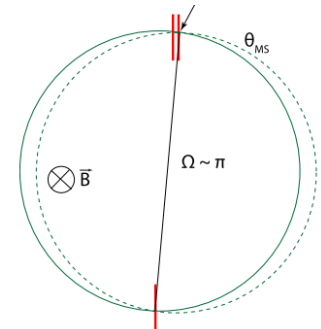
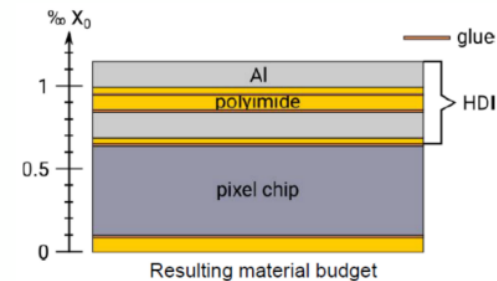
Phase I: drift chamber

Phase II: Si pixel tracker

- ❑ Primary candidate: Mu3e MuPix (HV-MAPS), 50 μm thick
- ❑ Excellent rate tolerance $\Rightarrow$ track low-mom $e^\pm$
- Resolutions limited by multiple Coulomb scattering, challenging to achieve MEG II comparable performance.
- Develop thinner MAPS!

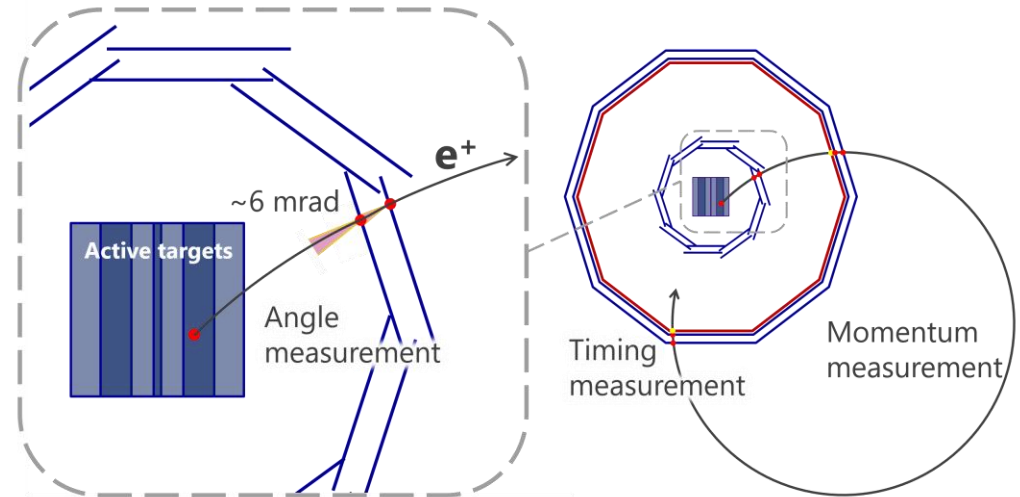
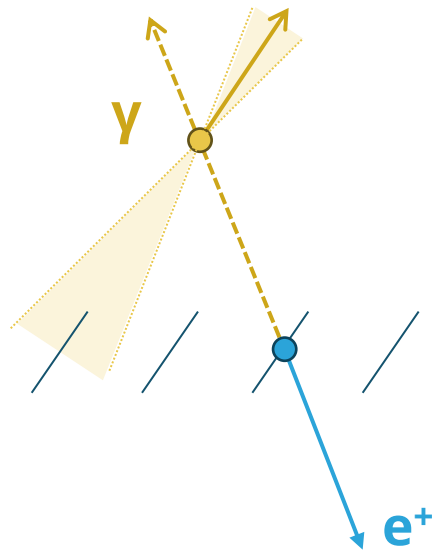
Timing detector

- ❑ Candidates: scintillator, LGAD, PicoSEC



e.g.,
ALICE ITS3

μ stopping targets



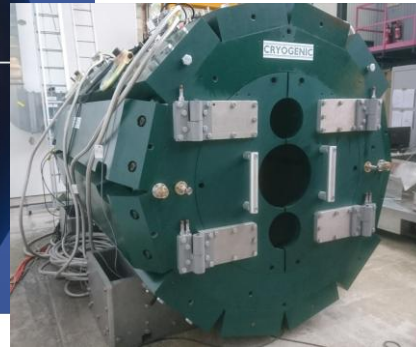
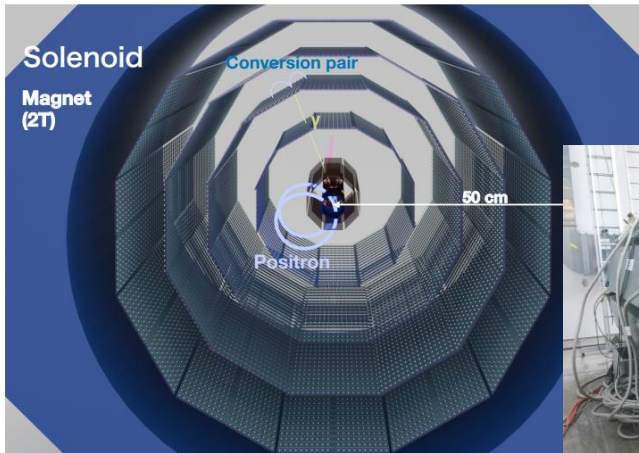
γ angle can be reconstructed with $\sim 100 \text{ mrad}$

- ▣ Spread decay vertex over multiple targets.

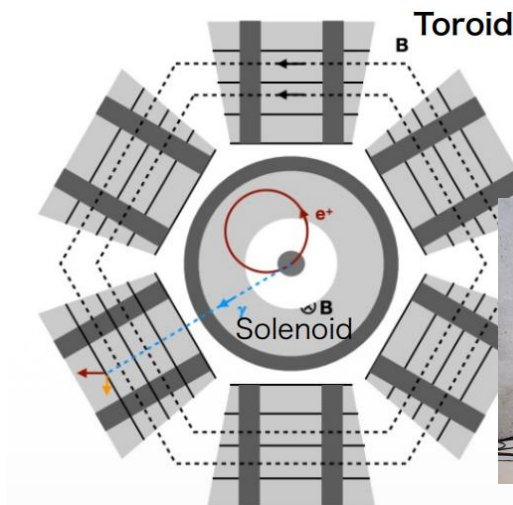
Angular reso. is limited by the multiple scattering at 1st layer.

- ▣ A way to improve is measure the decay vertex.

Magnetic fields



Could be Mu3e solenoid



Central solenoid could be
MEG one (COBRA)

Single solenoid

- ❑ Simple configuration
- ❑ Low material budget in front of γ detector

Solenoid (e^+) + toroid (γ)

- ❑ Separately optimize fields for e^+ and γ
- ❑ TPC with normal $E \parallel B$
- ❑ Radii of γ converter get larger

Target performance

	Resolutions/efficiencies	MEG II
Photon energy	200 keV	1 MeV
Photon position	200 μm	2.5 mm
Photon timing	30 ps	65 ps
Photon angle	150 mrad	—
Photon detection efficiency (4 layers)	10 %	64%
Positron energy	100 keV	90 keV
Positron angle	6 mrad	6 mrad
Positron timing	30 ps	40 ps
Positron detection efficiency	70 %	75%
Geometrical acceptance	85 % (36 %)	11%

- ❑ Largely improve γ measurement
- ❑ Keep performance for e^+ under high-rate environment
- ❑ Enlarge geometrical (& momentum) acceptance

Other modes

Multi-purpose

□ Not “byproducts” but from design.

▶ $\mu^+ \rightarrow e^+ e^- e^+$

▶ $\mu^+ \rightarrow e^+ \gamma \gamma$

▶ Precision measurement of Michel spectrum

- Michel parameters

- $\mu^+ \rightarrow e^+ X, \mu^+ \rightarrow e^+ \chi \chi$

▶ $\mu^- \rightarrow e^- \gamma$ ($\mu^- N \rightarrow e^- N \gamma$)

□ Simultaneously (same dataset) or dedicated run with the same detectors

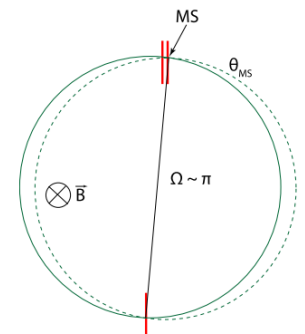
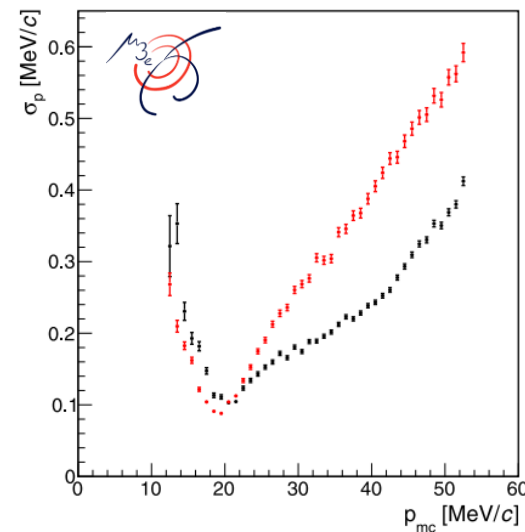
Realtime tracking

$\mu \rightarrow e \gamma$ optimize

Other modes



Detector optimization is not trivial!



Consider other modes together and reflect into the design

Any other ideas?

Rare μ -decay searches in 2030–2040s

- ❑ at PSI HIMB with up to 10^{10} s^{-1}
- ❑ Requires technological innovations
- ❑ Phased approach would be effective
- ❑ Extend detector to multi-purpose

MEG II DAQ is about to finish,
focus on the new exp.

- ❑ New exp. is not a continuation of MEG (NOT MEG III)
- ❑ Join us now!

Take-home messages

Detector concept not yet fully defined



Plenty of opportunities to leverage **your expertise.**

Theorists

Consider other modes together and reflect into the design

Any other ideas?