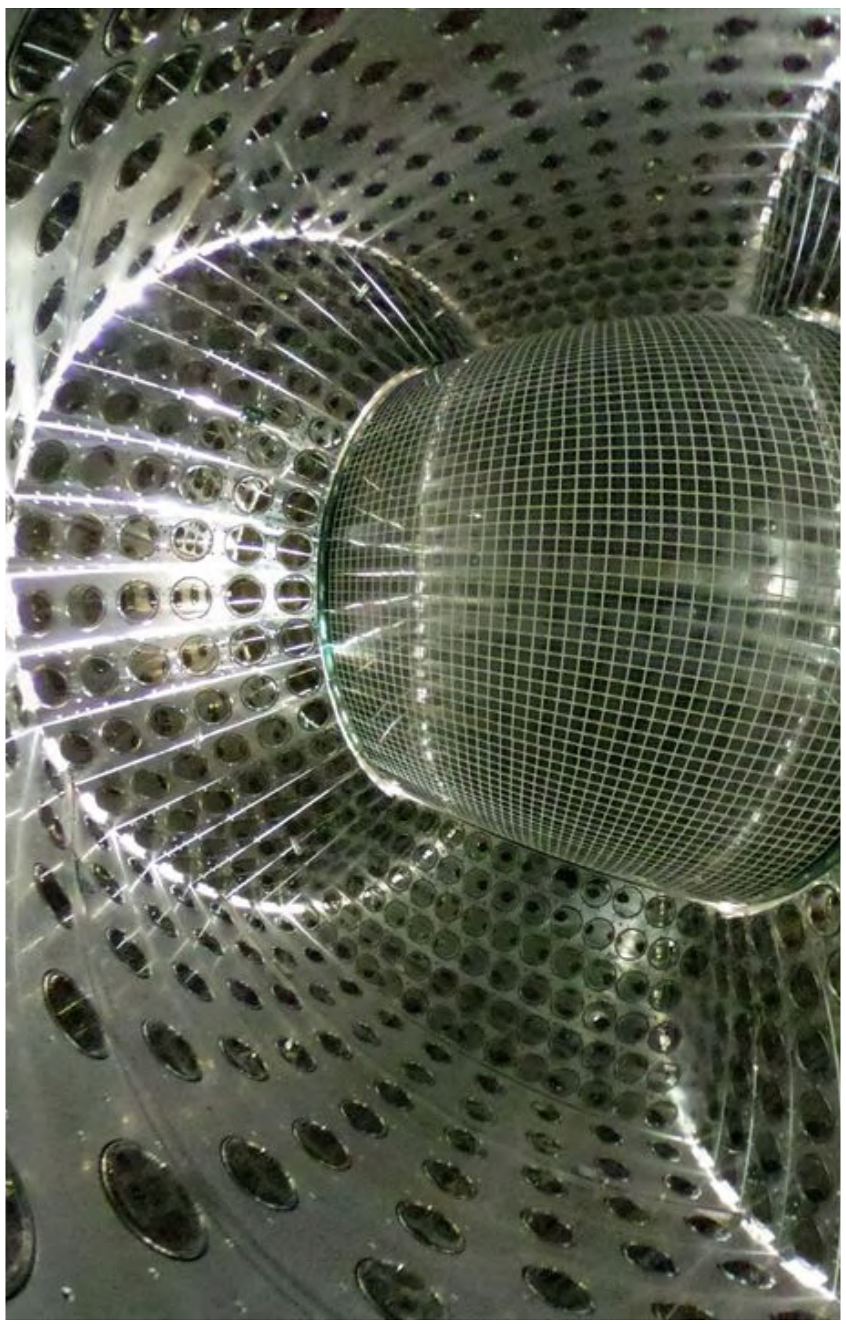
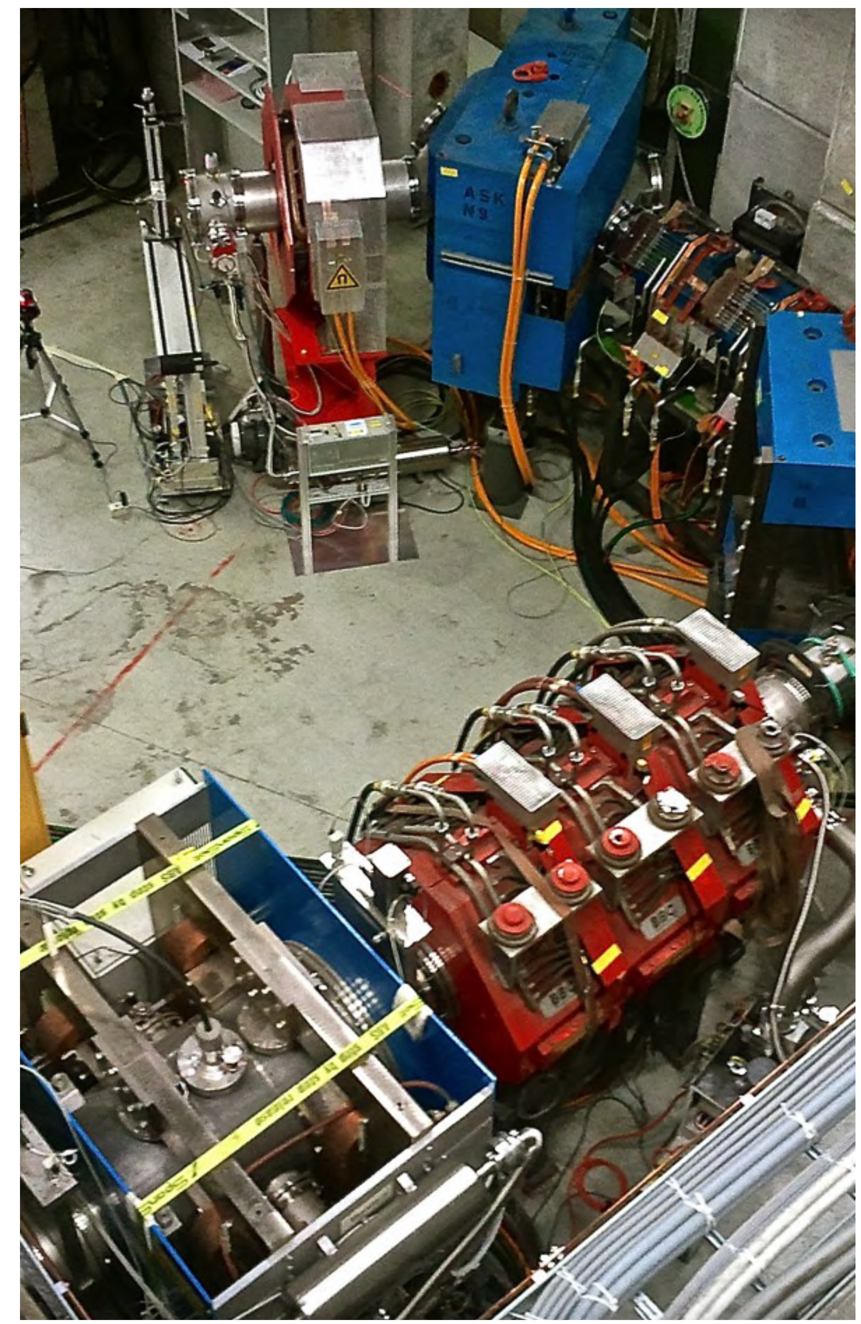
素粒子物理と原子物理の融合が拓く新たなミュー粒子物理のフロンティア

いよいよ始まる次世代のミュー粒子稀崩壊探索実験

東京大学素粒子物理国際研究センター 大谷航

2019年3月14日 日本物理学会年次大会, 九州大学

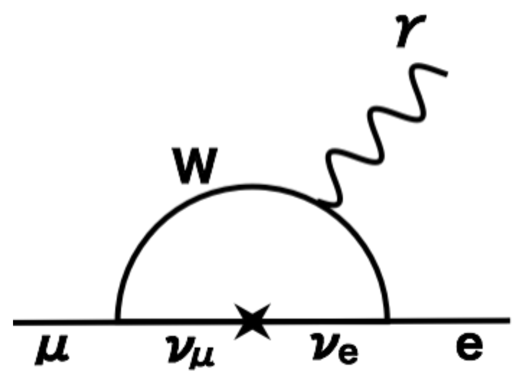


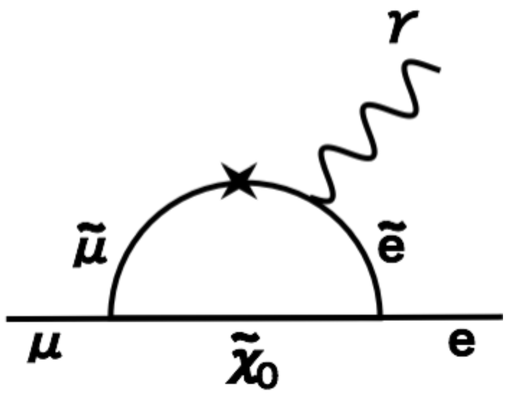


Contents

Lepton Flavour Violating Process

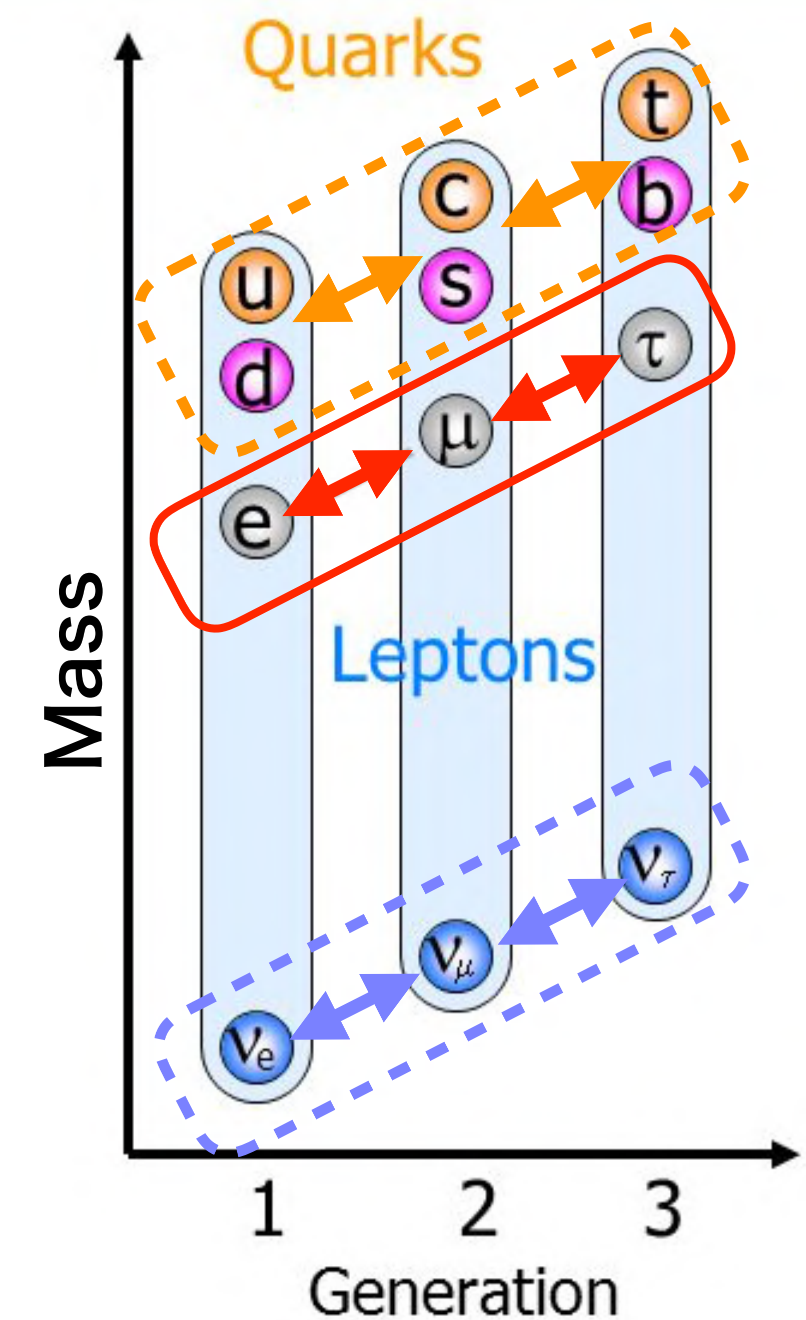
Standard Model | **New Physics**





- **Charged lepton flavour violating (cLFV) process**
  - **μ→eγ, μ→eee (本講演)**, μN→eN (次講演), Mu-$\overline{\text{Mu}}$ conversion,…
  - Rate is too small to be observed in Standard Model ($\mathscr{B}(\mu\to e\gamma) \sim 10^{-54}$)
  - Large enhancement predicted by new physics ($\mathscr{B}(\mu\to e\gamma) \sim 10^{-11}$-$10^{-15}$)

  →Unambiguous evidence of new physics if discovered!
- **Complementary to energy frontier experiment**
  - Colourless particles not strongly constrained by LHC
  - High energy scale beyond LHC is indirectly accessible



Rare Muon Decay μ→eγ vs. μ→eee

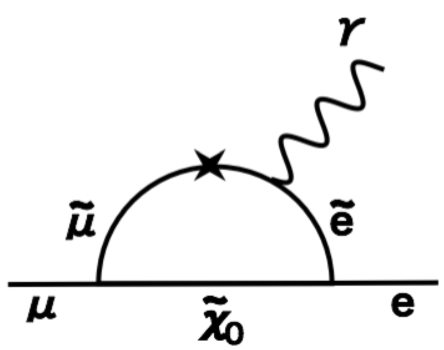
Effective CLFV Lagrangian

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{e}\gamma^\mu e)$$

Λ: Effective mass scale of new physics

κ: Relative size of two effective operators

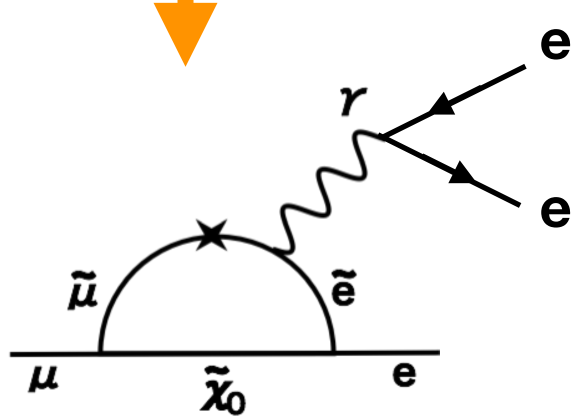
μ→eγ



Photonic (SUSY-GUT)

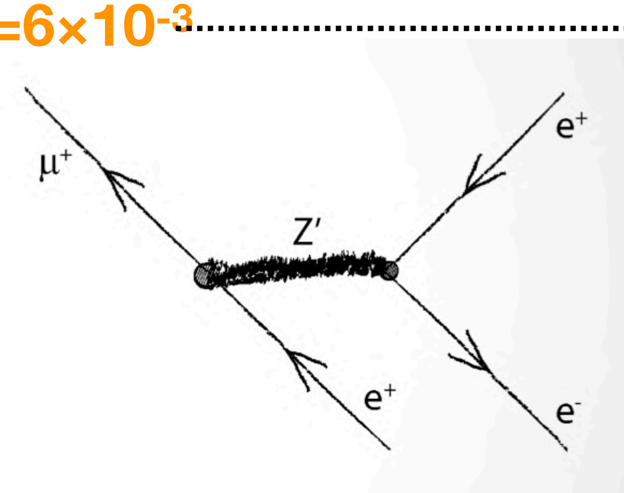
$\mathscr{B}(\mu\to 3e)/\mathscr{B}(\mu\to e\gamma)=6\times10^{-3}$

μ→eee

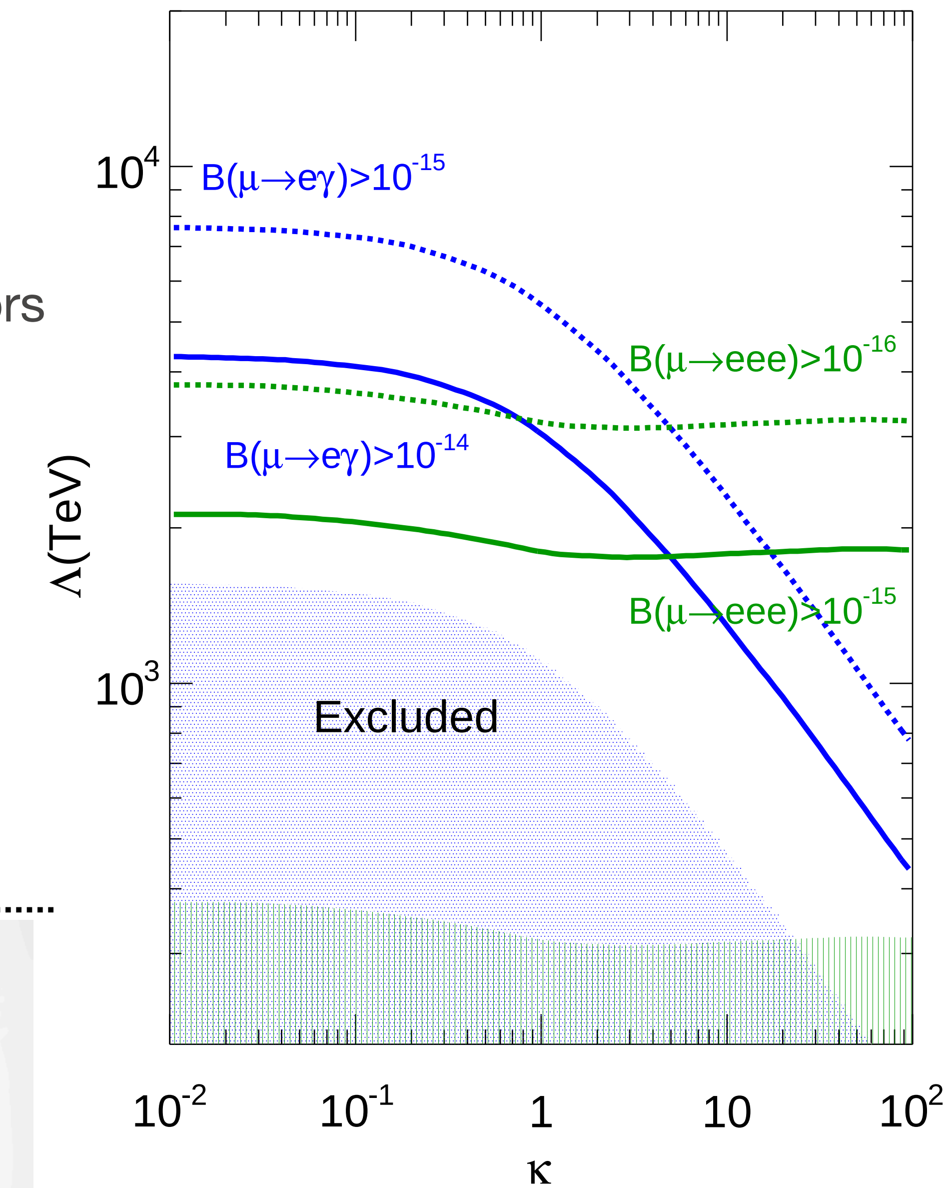


Photonic (SUSY-GUT)

+

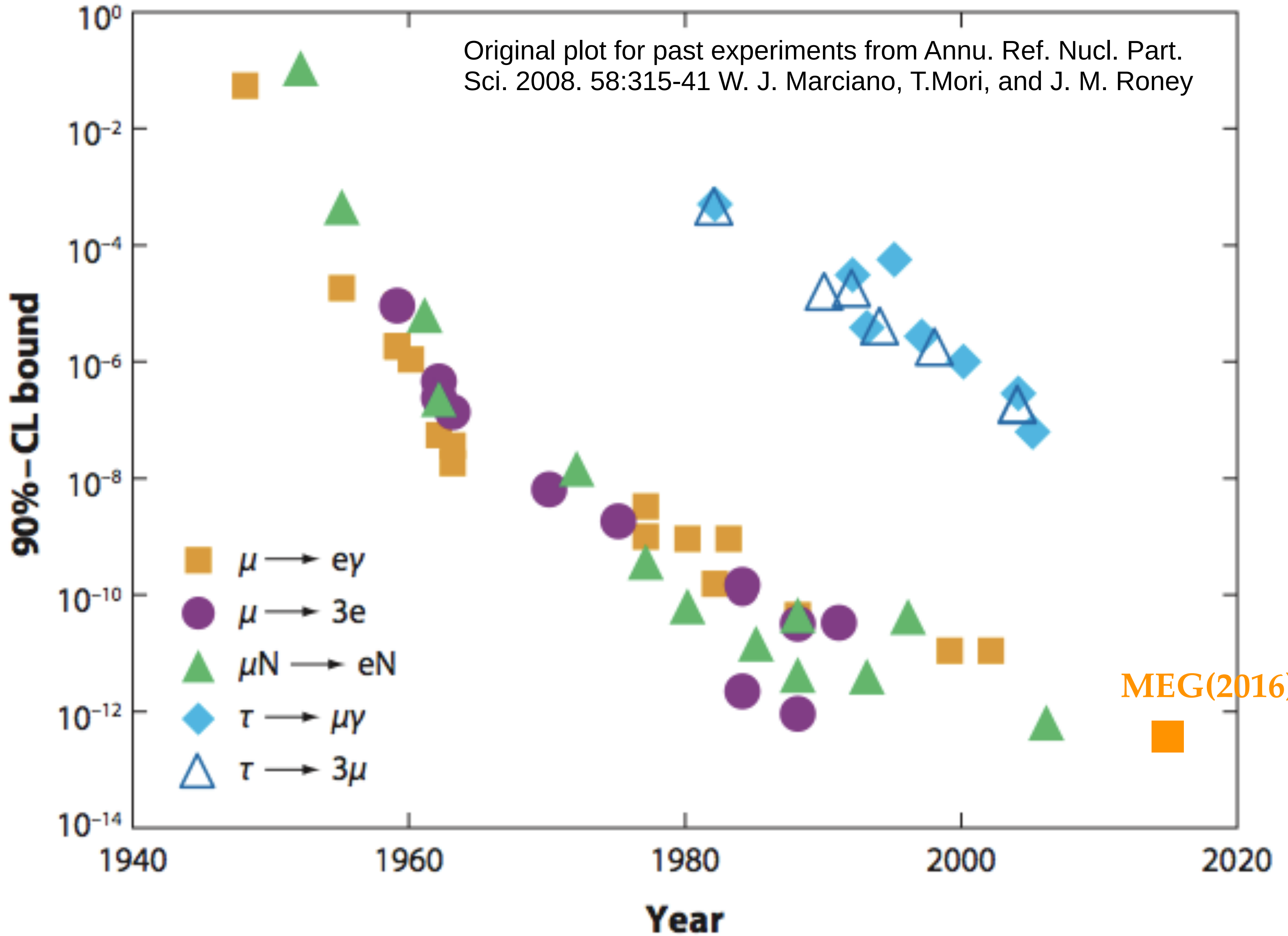


Non-photonic (heavy Z', KK, etc)



Complementarity for cLFV processes!

Search History



- **Getting sensitive enough to explore new physics!**
- **Even more sensitive experiments will start soon**

  μ→eγ: MEG II at 6×10^{-14}
  μ→eee: Mu3e at $\sim10^{-15}$

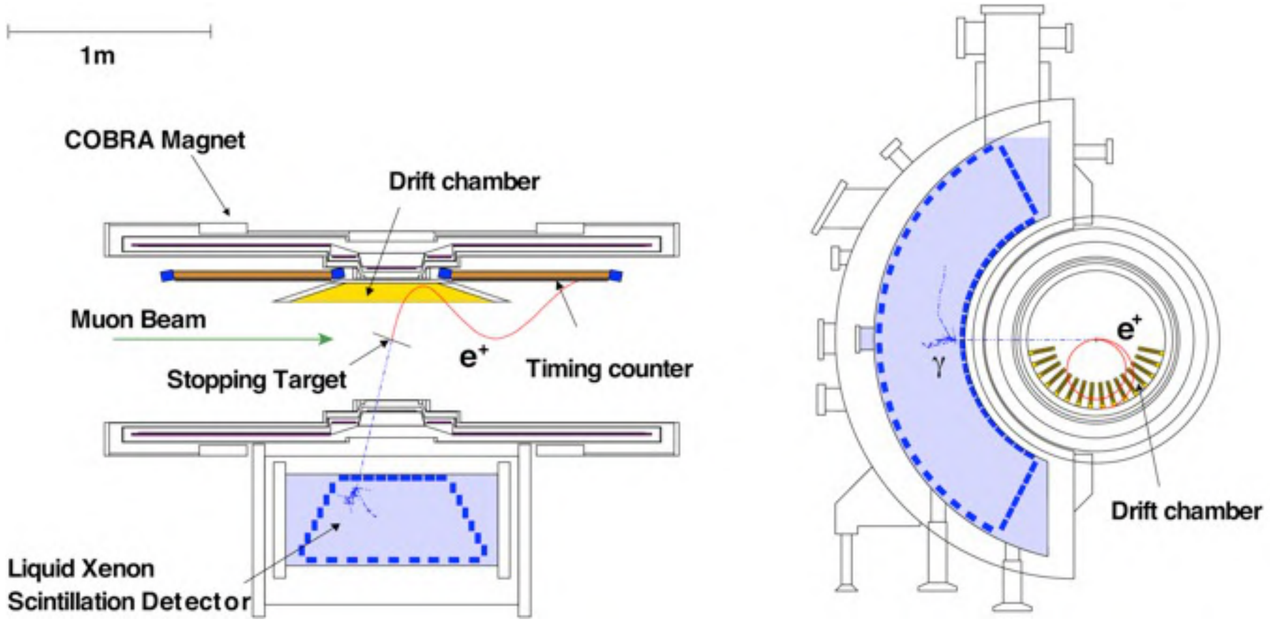
For SUSY
$\mathcal{R}(\mu Al\to eAl)/\mathcal{B}(\mu\to e\gamma)=2.6\times10^{-3}$
$\mathcal{B}(\mu\to 3e)/\mathcal{B}(\mu\to e\gamma)=6\times10^{-3}$

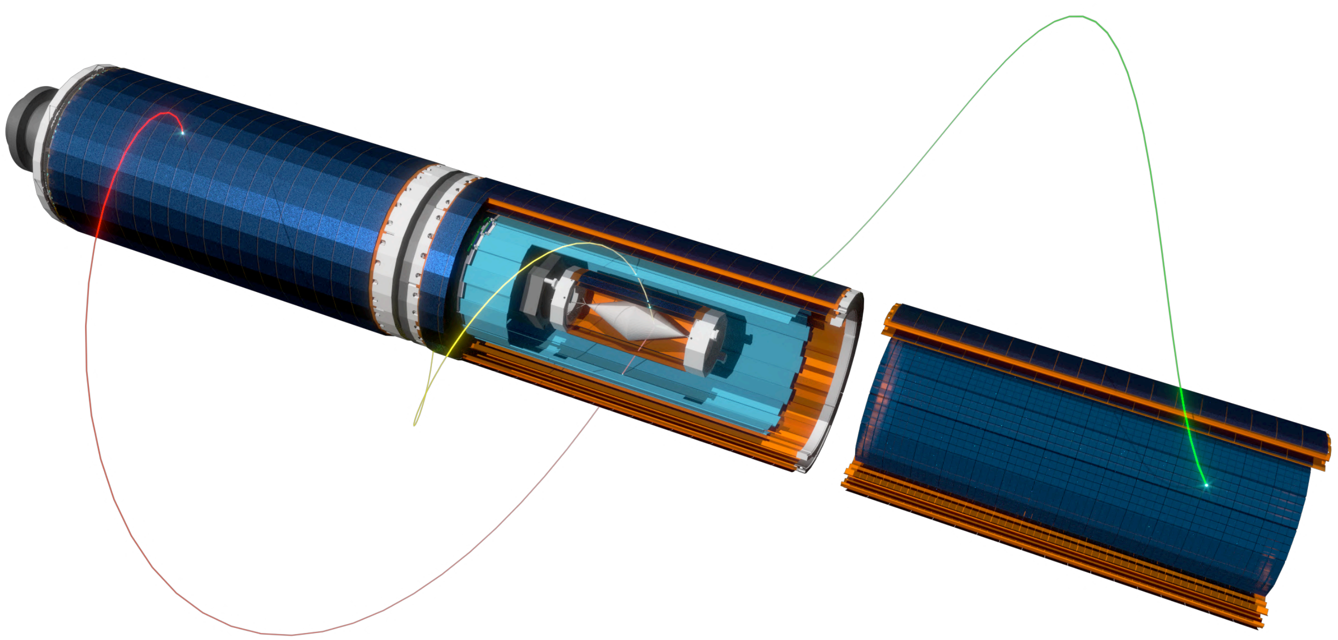
Key Items for Muon Rare Decay Search

Most intense continuous muon beam

→Already exists!

Innovative detectors



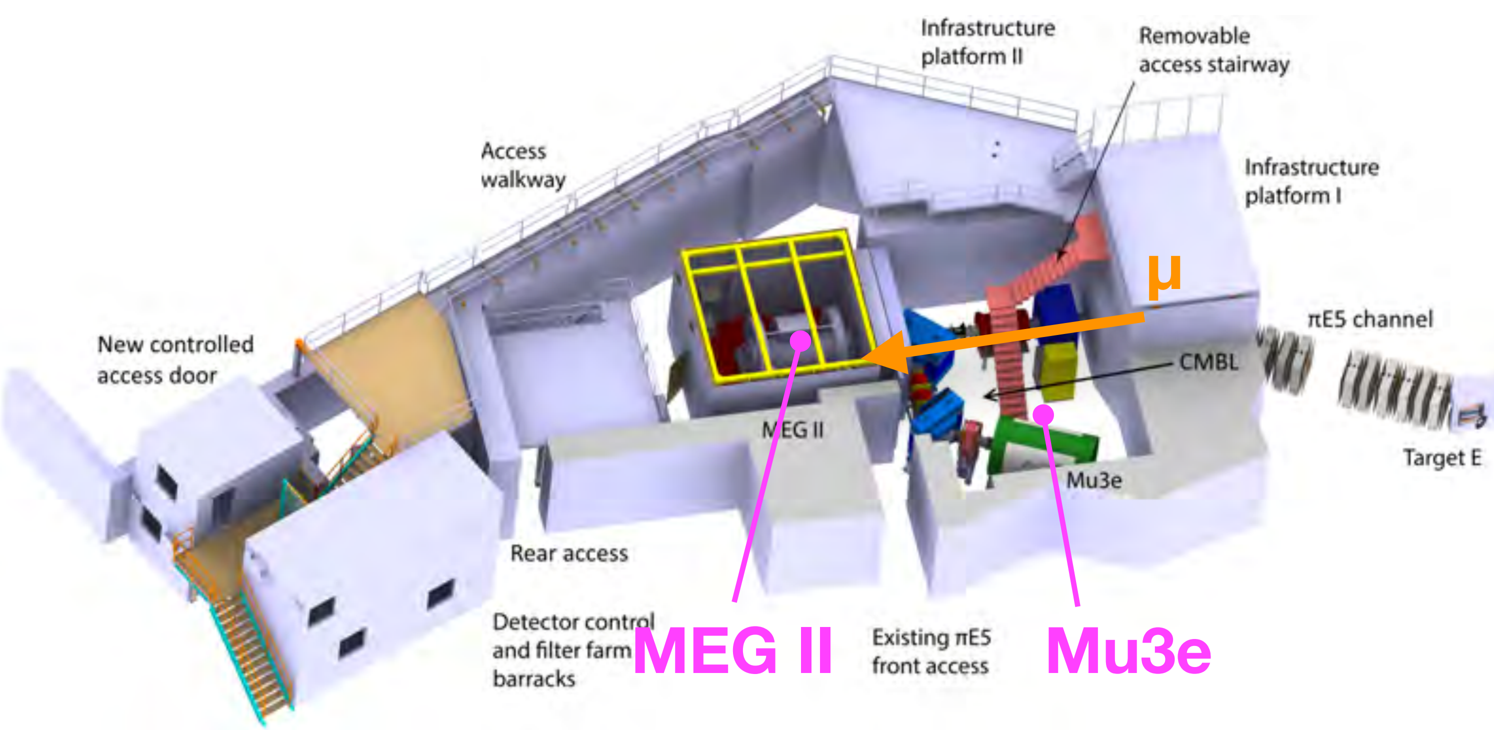


→Need to develop!

HIPA@PSI

- **High Intensity Proton Accelerator (HIPA) at Paul Scherrer Institute (PSI)**
  - 590MeV ring cyclotron, 2.3mA → **1.4MW!**
  - Up to **~10^8 μ^+/sec!**
- **πE5 beam line**
  - To be shared by MEG II and Mu3e (and others)
  - One experiment running at a time

πE5 beam line



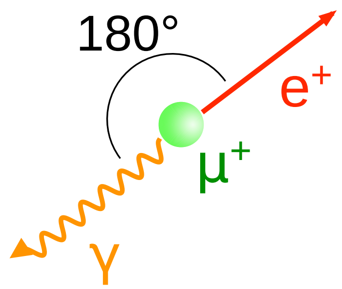
Contents

- Rare Muon Decays
- $\mu^+ \rightarrow e^+\gamma$
- $\mu^+ \rightarrow e^+e^-e^+$
- Future Plans
- Summary

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

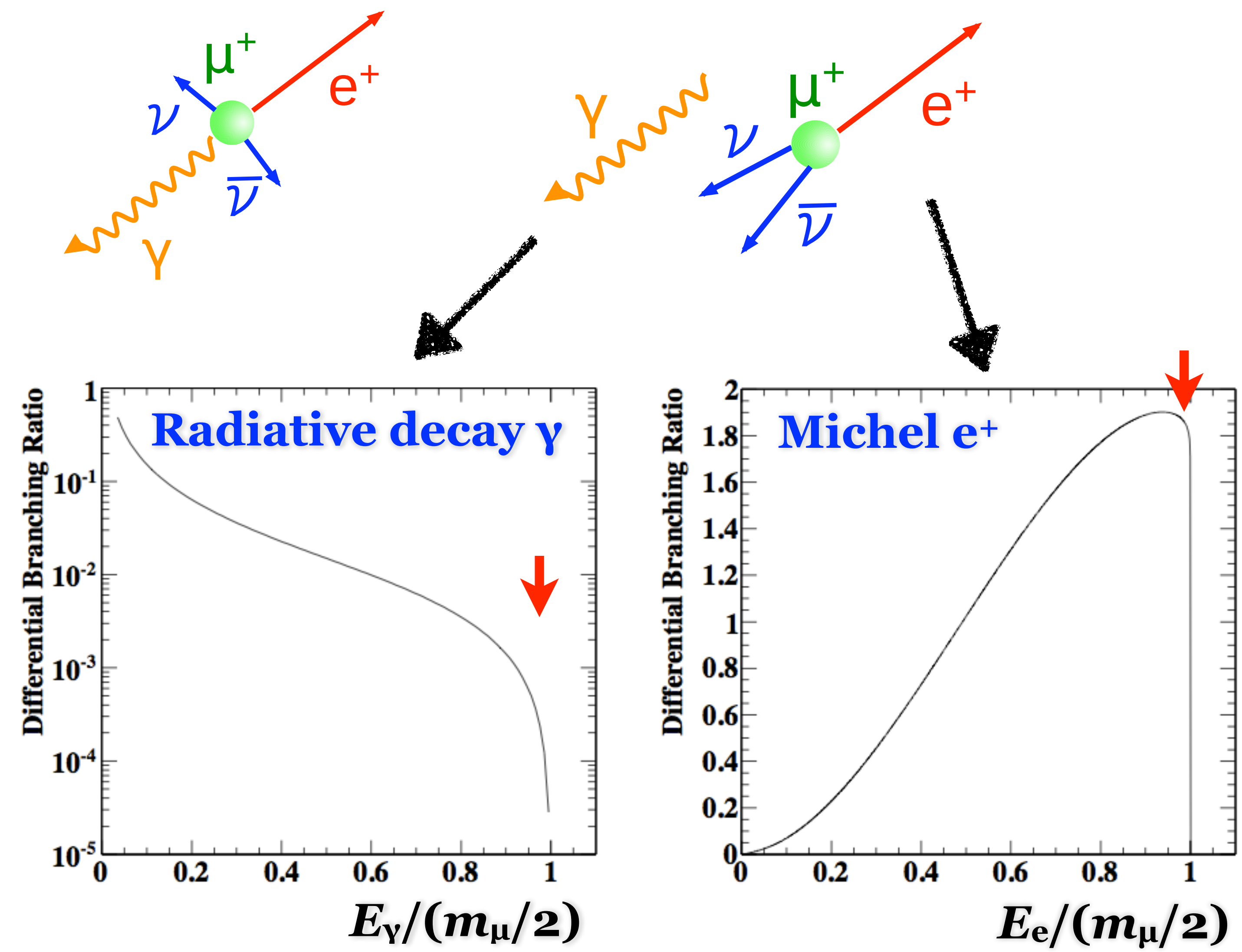
Signal

- Back-to-back
- Mono-energetic
  - E_e=52.8MeV E_γ=52.8MeV
- Coincident in time



Background

- Prompt background: μ→eγνν
- **Accidental overlap**: μ→eνν + γ

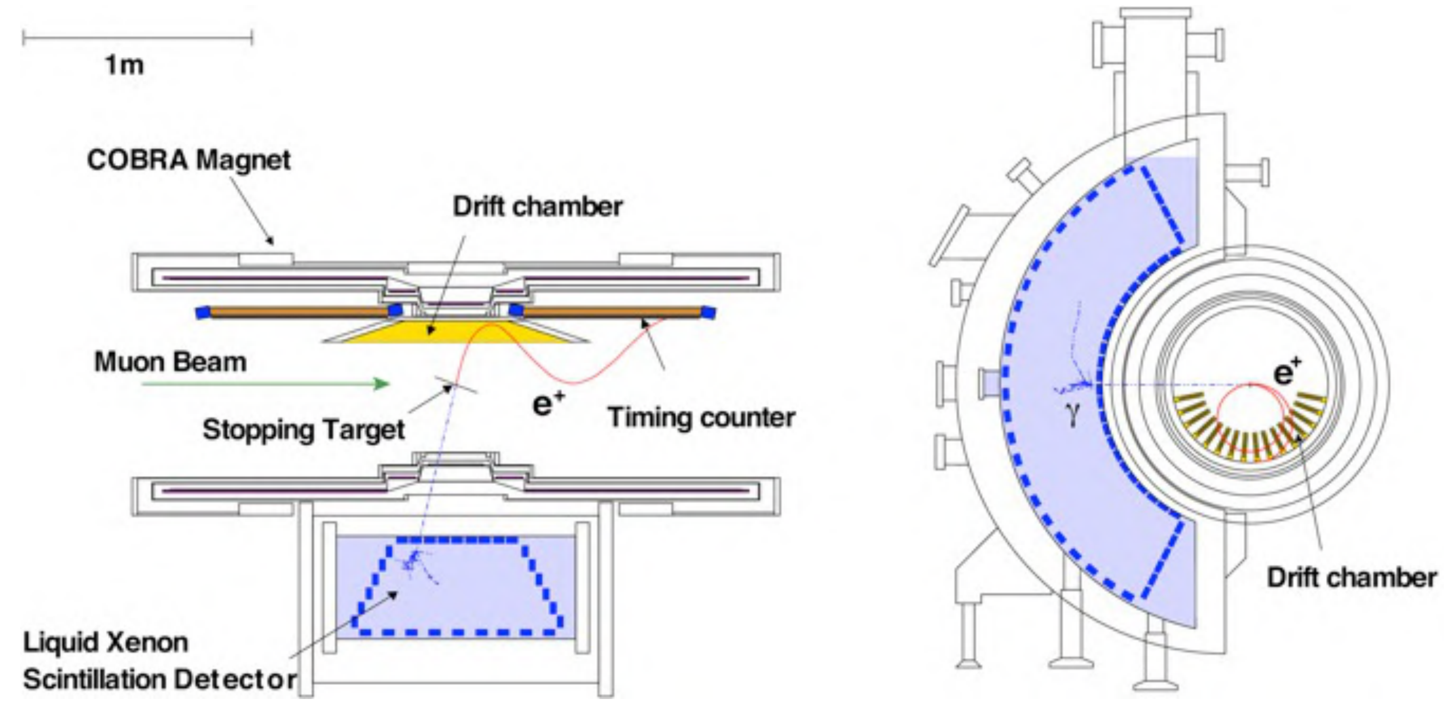


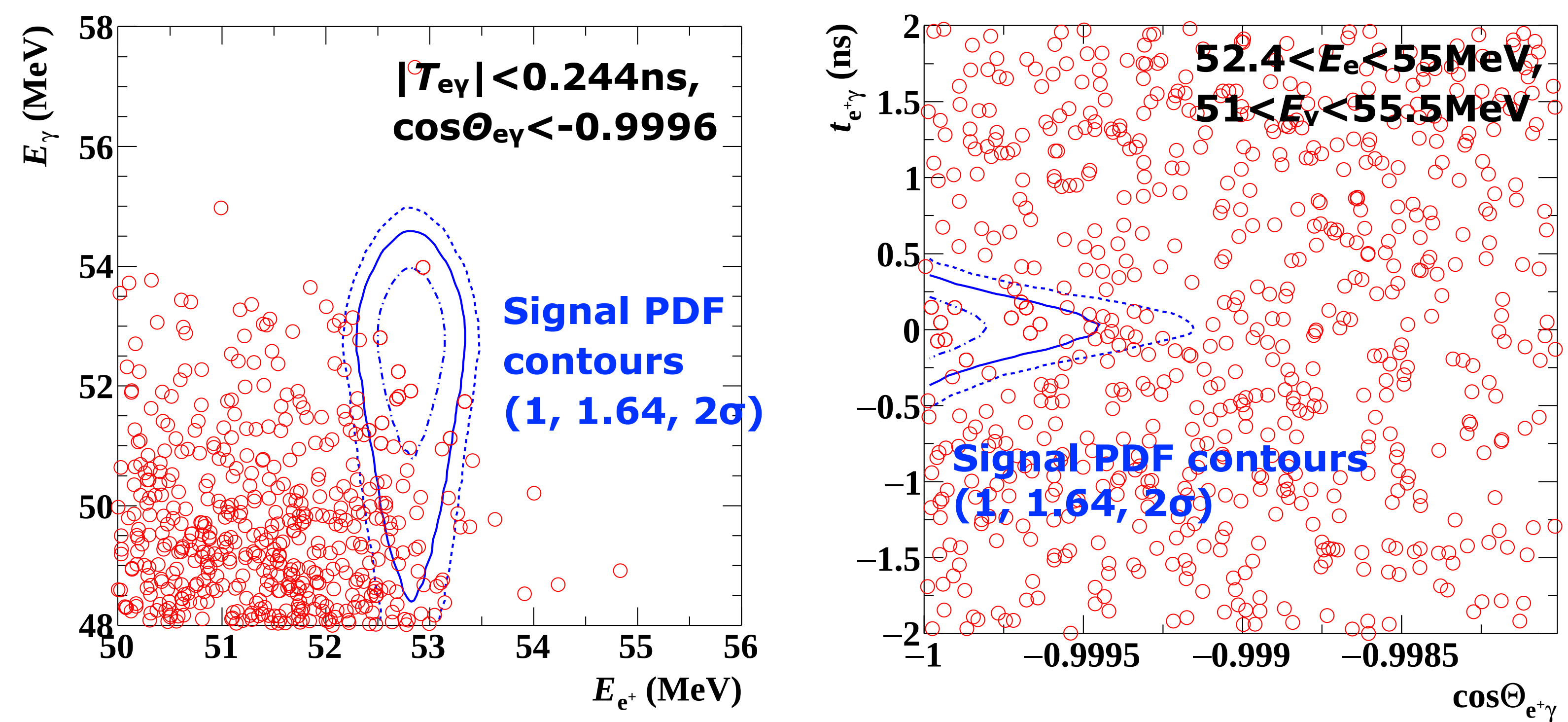
Requirements

- Continuous beam to minimise accidental background
- Precise measurements of energy, timing and angle both for e^+ and γ
- Operational at high rate environment (stability and pileups…)

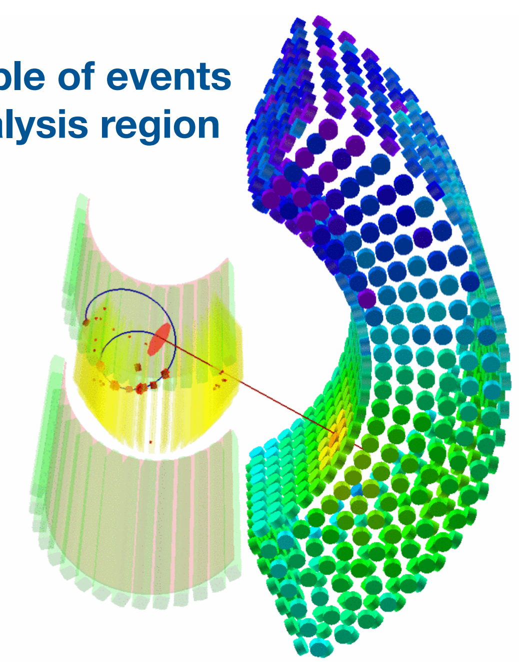
MEG Experiment

- **MEG detectors**
  - γ : 900ℓ LXe scintillation detector
  - e^+ : COBRA spectrometer (low mass drift chambers + fast timing counter in a gradient B-field)
- **Data-taking**
  - 2008-2013
  - Beam intensity 3×10^7 μ^+/sec
  - Total μ^+ stops: ~7.5×10^{14}
  - Final result published in 2016
    Eur. Phys. J. C 76 (2016), 434





Example of events in analysis region

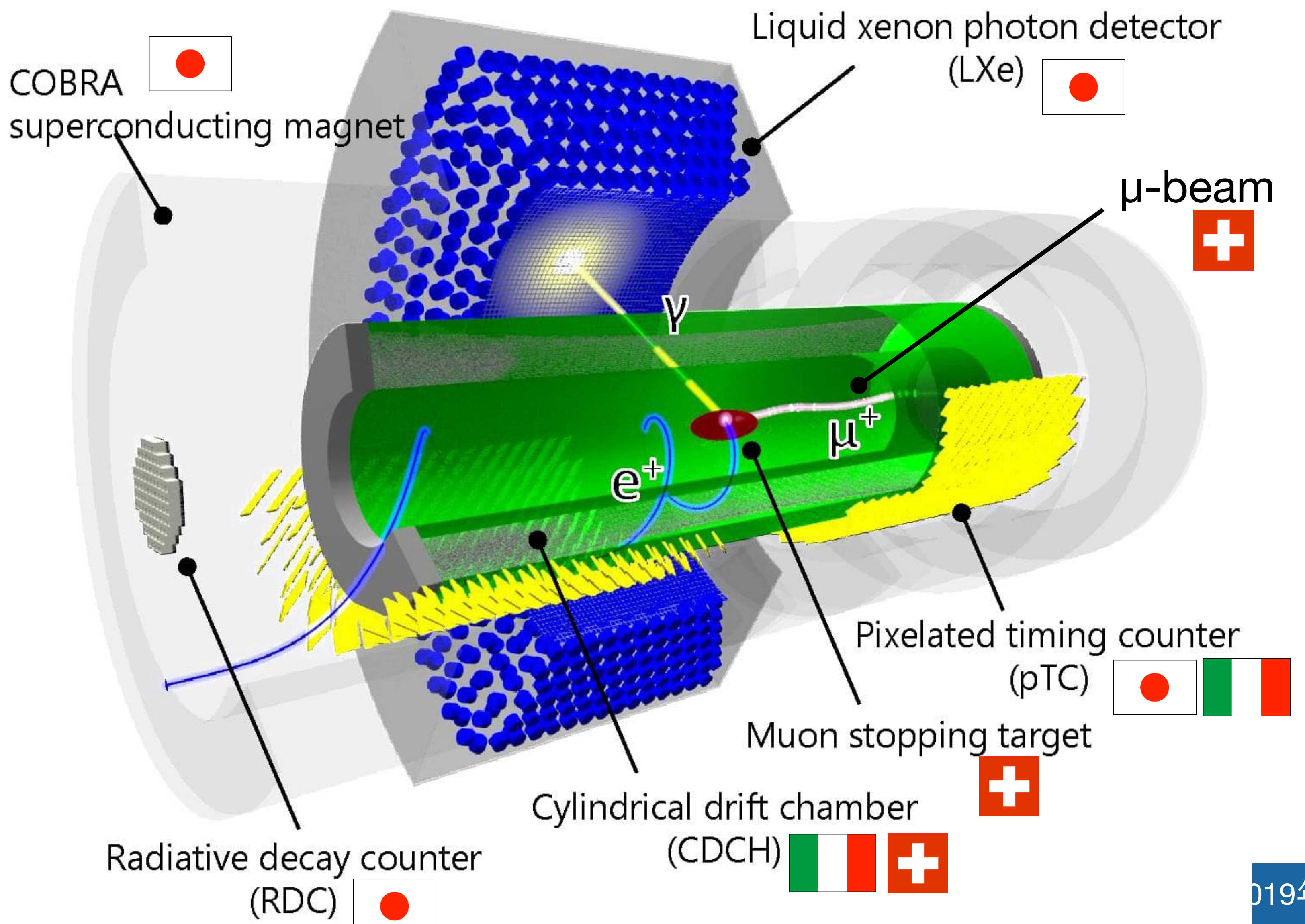


$\mathscr{B}(\mu^+\rightarrow e^+\gamma) < 4.2\times10^{-13}$ (90% C.L.)

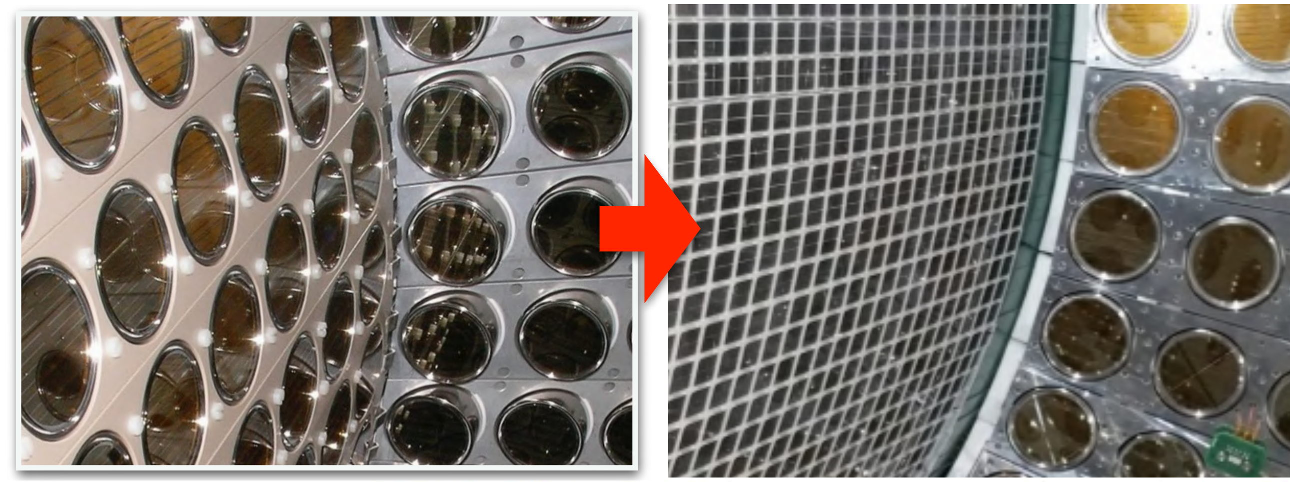
→ ×30 more stringent than previous experiment!

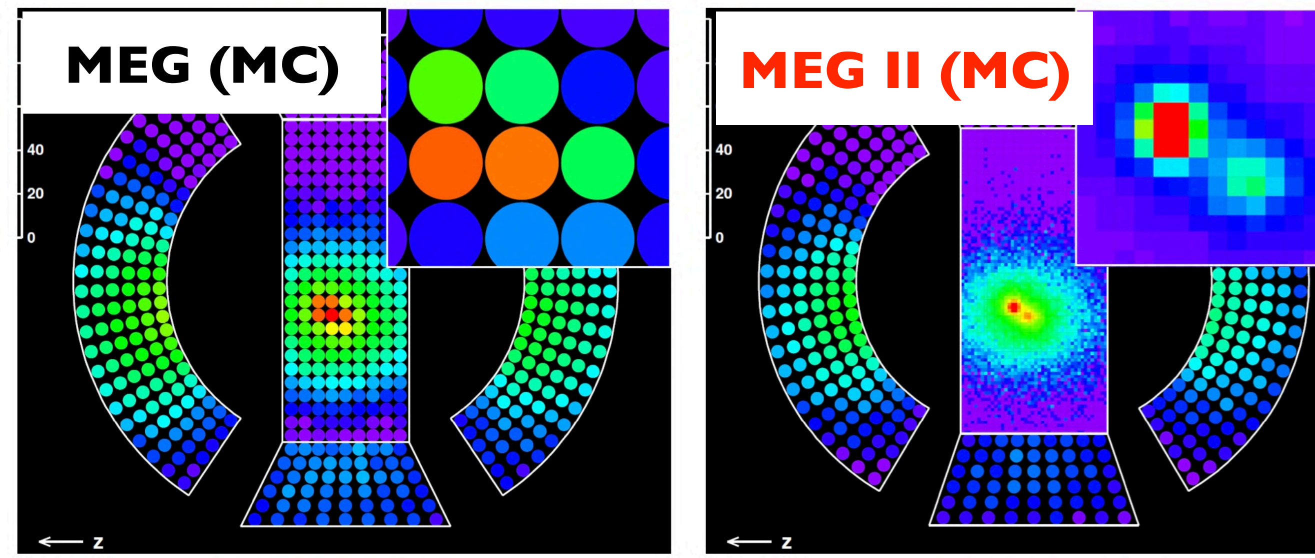
MEG II Experiment

- **Goal: ×10 higher sensitivity: ~6×10^{-14}**
  - **Retain experimental concept**
    - LXe detector for γ detection, e^{+} spectrometer with a gradient magnetic field
  - **Fully exploit maximum beam intensity @PSI up to ~10^{8} μ^{+}/sec**
  - **Detector performance should be significantly improved**
    - Resolutions: ×2 improved for all observables
    - Efficiency: ×2-3 improved



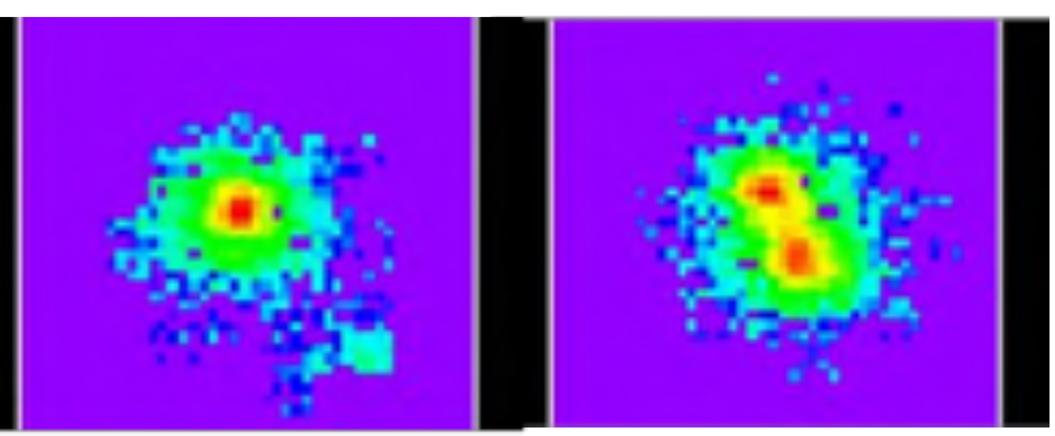
LXe Photon Detector





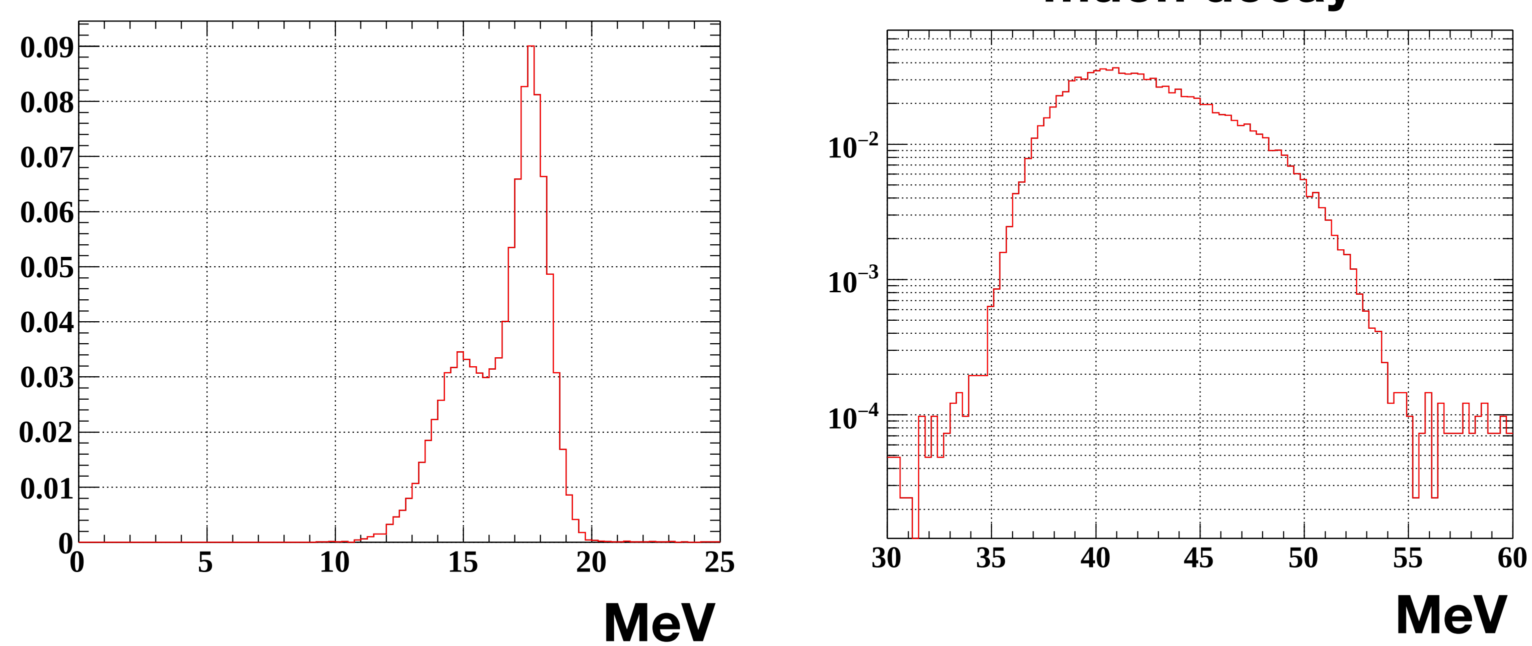
- **Highly granular scintillation readout**
  - 216 × PMTs(2-inch) on γ-entrance face are replaced with **4092 × VUV-MPPCs (139mm² each)**
  - **Energy and position resolutions will be improved by a factor of two.**
- **Construction completed. Under commissioning**
  - Sensor calibration (PMT, MPPC)
  - LXe purification to maximise light yield
  - Noise reduction
  - Performance test with calibration γ-source and BG-γ

BG-γ **BG-γ with pileup**



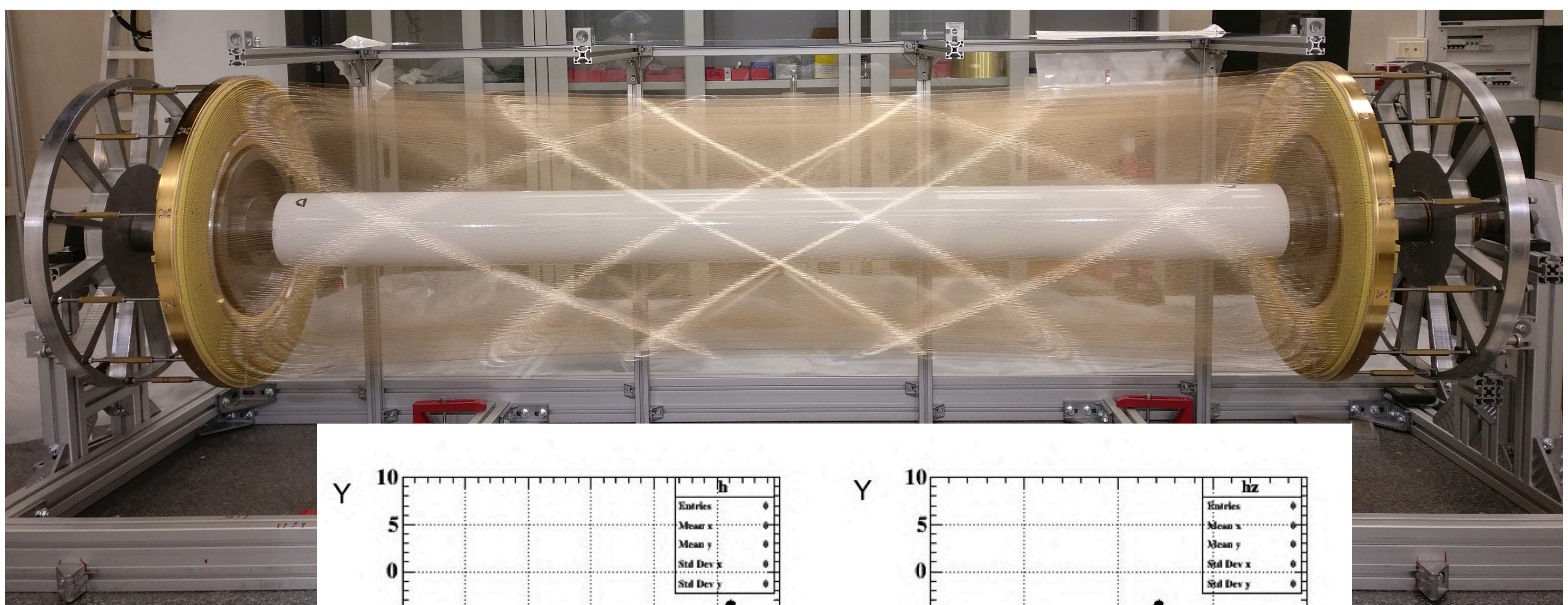
Monochromatic 17.6MeV-γ

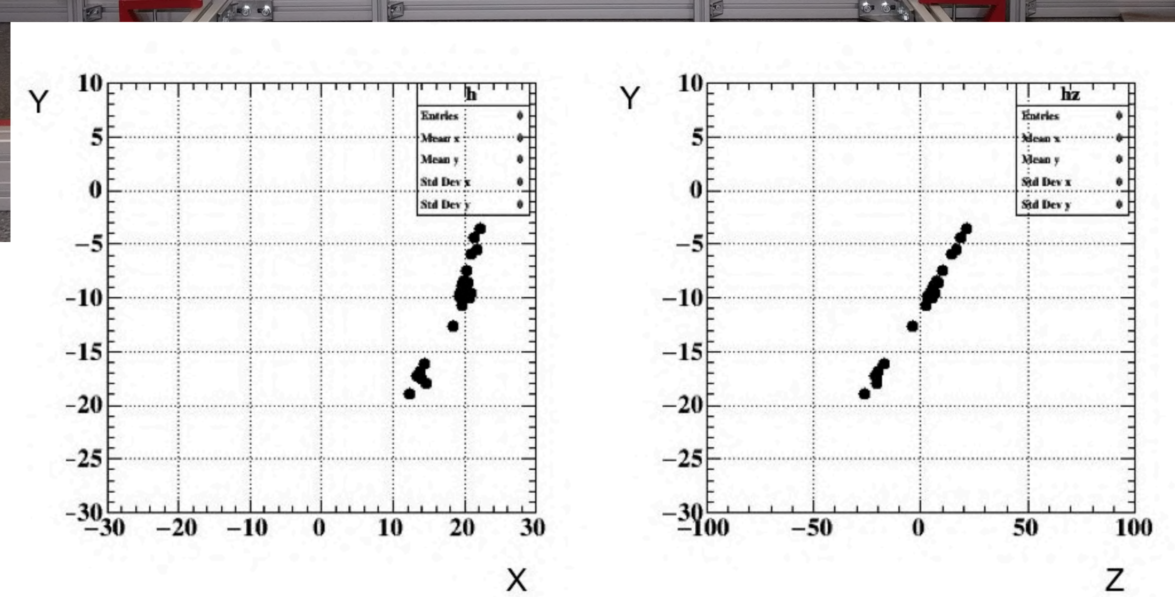
BG-γ from radiative muon decay

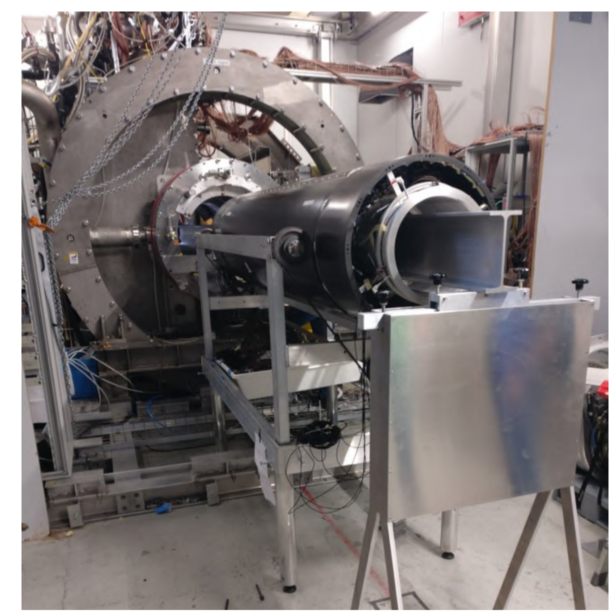


Cylindrical Drift Chamber

- **Single cylindrical gas volume, U-V stereo angle wire configuration**
- **Construction completed and installed into spectrometer magnet**
- **Under commissioning**
  - Measured cosmic ray track
  - Measured Michel positrons measured at full beam intensity
  - Not able to apply nominal HV for inner layers due to some instability

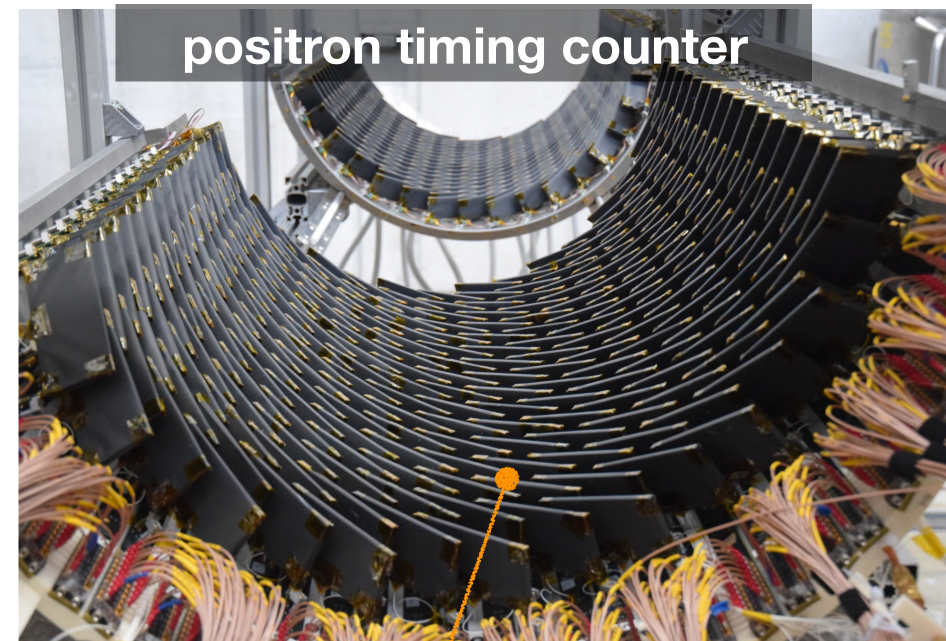


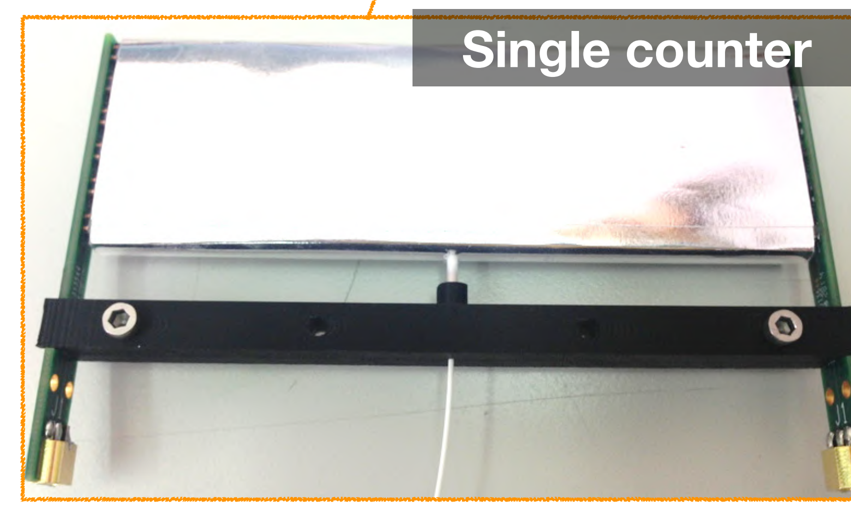




Positron Timing Counter

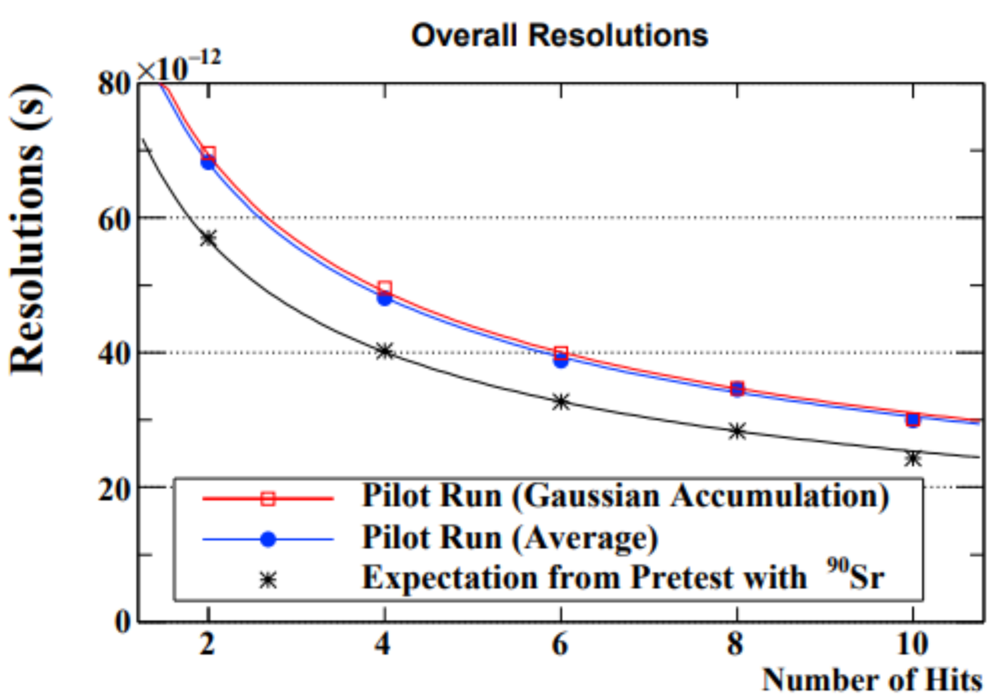
- **Segmented timing counter**
  - 516 fast scintillator counters (256 counters for each up- and down-stream side)
  - Each counter readout by 6 SiPMs connected in series at each side
  - Excellent time resolution <40ps by measurement with multiple positron hits
- **Fully commissioned**





$$\sigma^2_{\mathrm{overall}}(N_{\mathrm{hit}}) = \frac{\sigma^2_{\mathrm{single}}}{N_{\mathrm{hit}}} + \frac{\sigma^2_{\mathrm{inter\text{-}pixel}}}{N_{\mathrm{hit}}} + \sigma^2_{\mathrm{MS}}(N_{\mathrm{hit}})$$

σ_{single}~70-80ps, $\sigma_{inter\text{-}pixel}\lesssim$30ps, σ_{MS}~5ps



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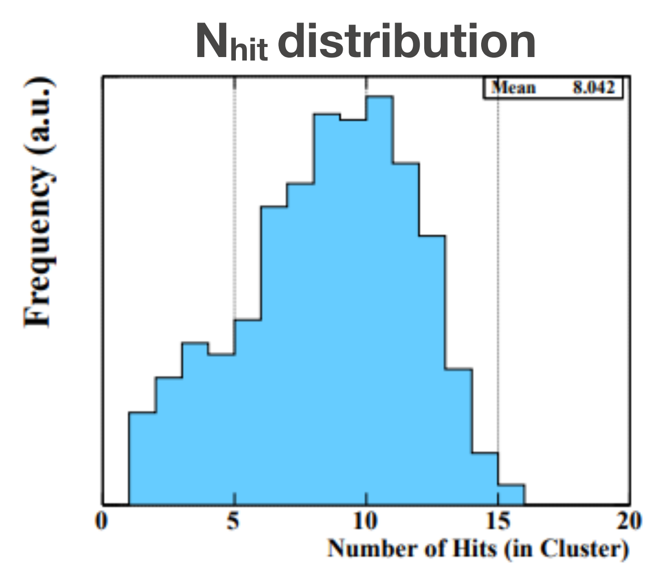
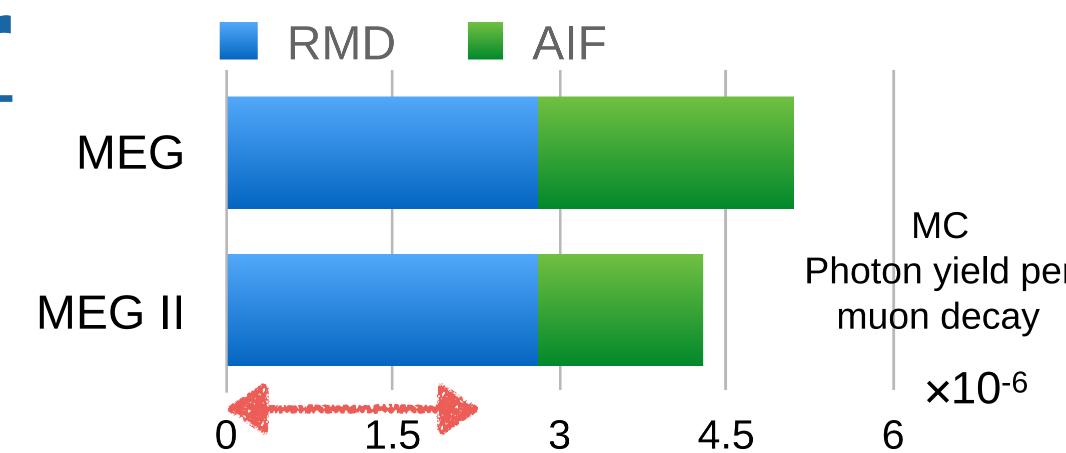


= **39ps**

関連講演 14aK209-8(大矢), 17aK104-1(恩田)

Radiative Decay Counter

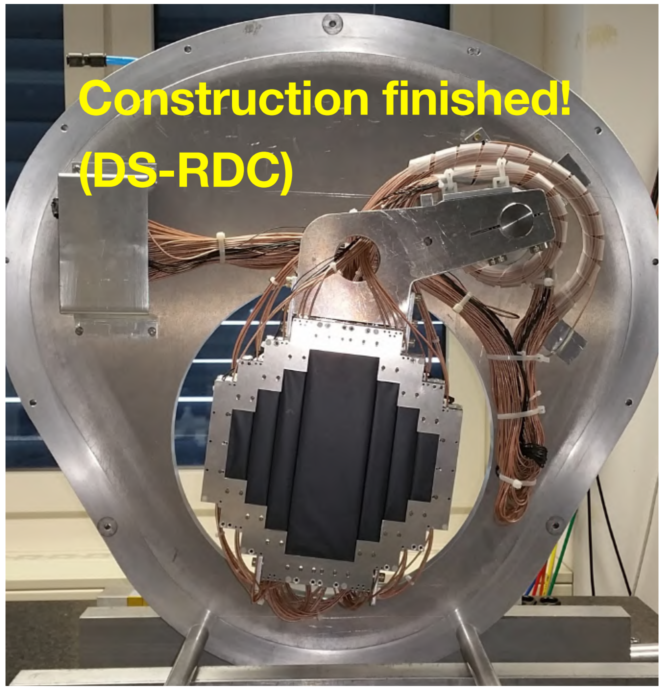
- **New detector in MEG II**
- **Identify BG-γ from RMD by tagging low mom. positron associated with RMD**
  - Upstream: completed and fully commissioned
  - Downstream: under development

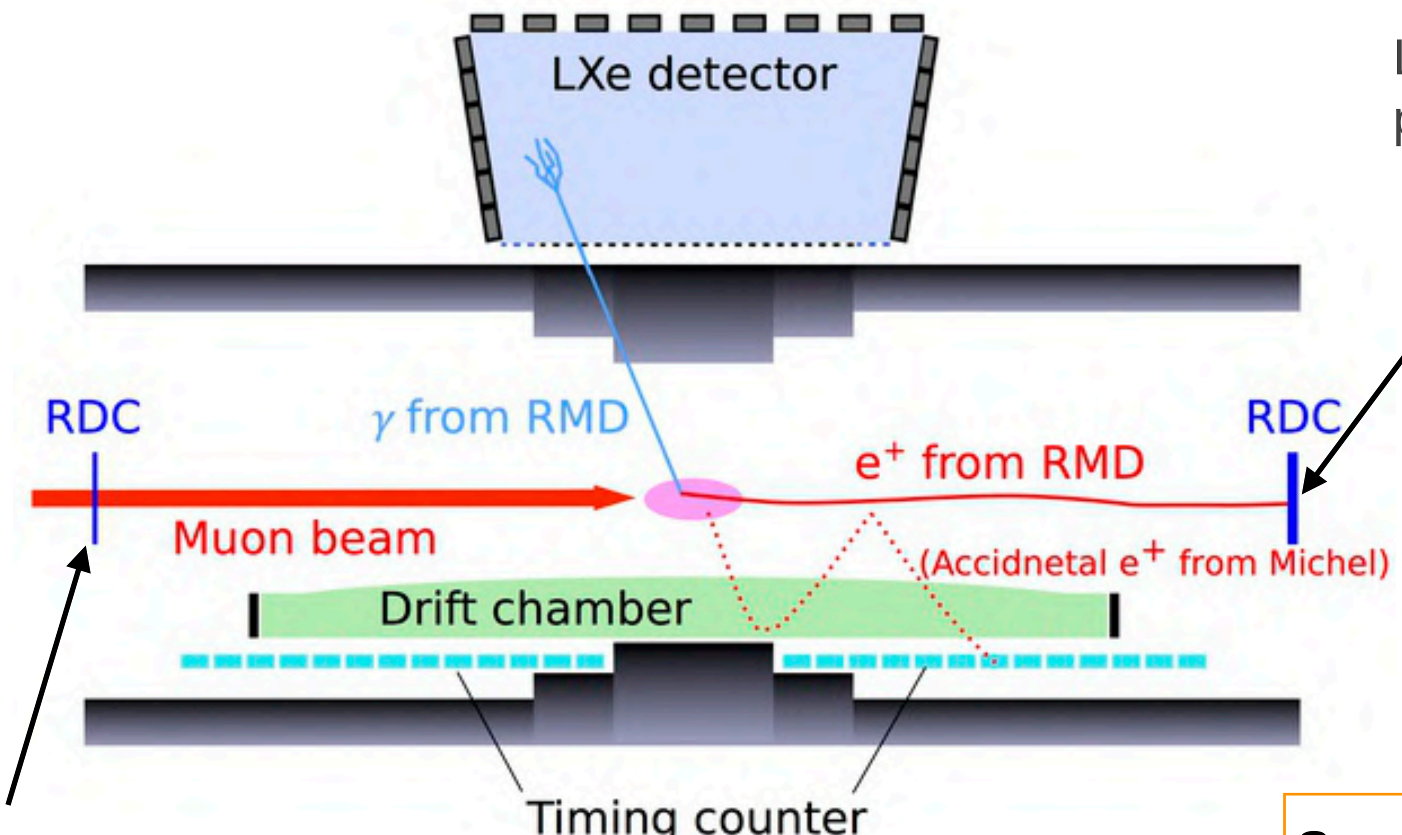


A new detector (RDC) can identify RMD events.

Downstream (DS)

LYSO crystals and plastic scintillators



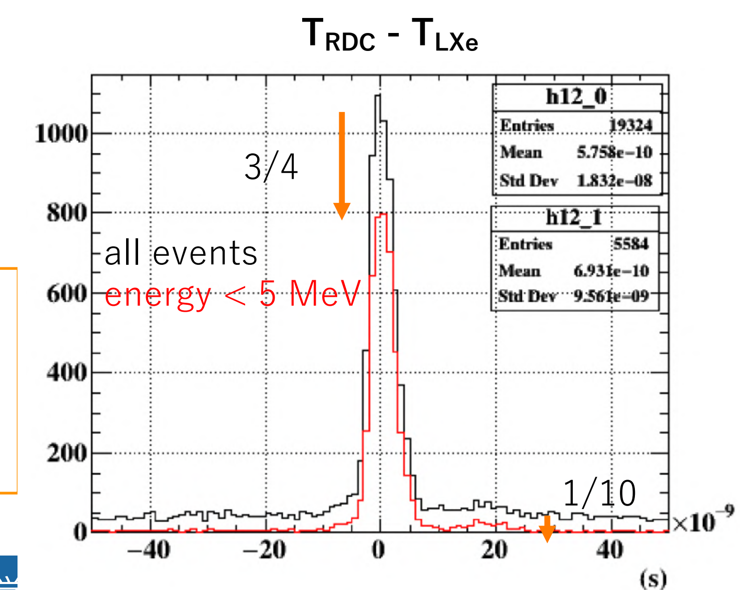


Upstream (US)

Under development as a future option

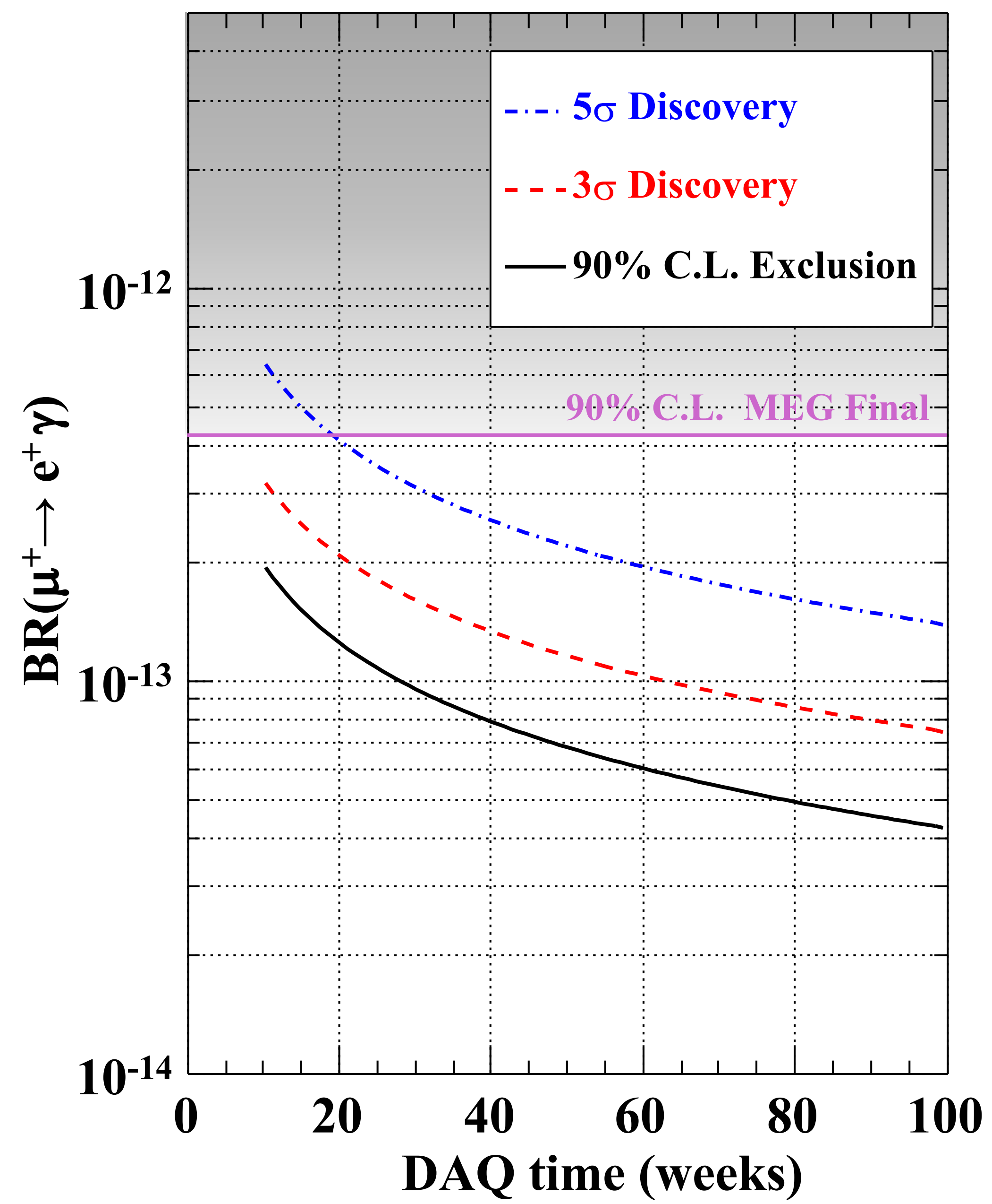
Successfully detected coincident BG-γ at LXe!

$T_{RDC} - T_{LXe}$



Status and Prospects of MEG II

- **All detectors deployed in PSI πE5 beam line**
- **Run 2018**
  - All detectors deployed
  - There are still some issues
    - Full electronics will be ready in 2019
    - Higher noise than expected
    - Serious instability of inner layers of CDCH
- **Run 2019**
  - Repair of CDCH
  - Mass production of readout electronics
  - Full engineering run
- **From 2020 onward**
  - Production of physics data
  - Surpass MEG sensitivity in a few months
  - 4-5 year running to reach target sensitivity

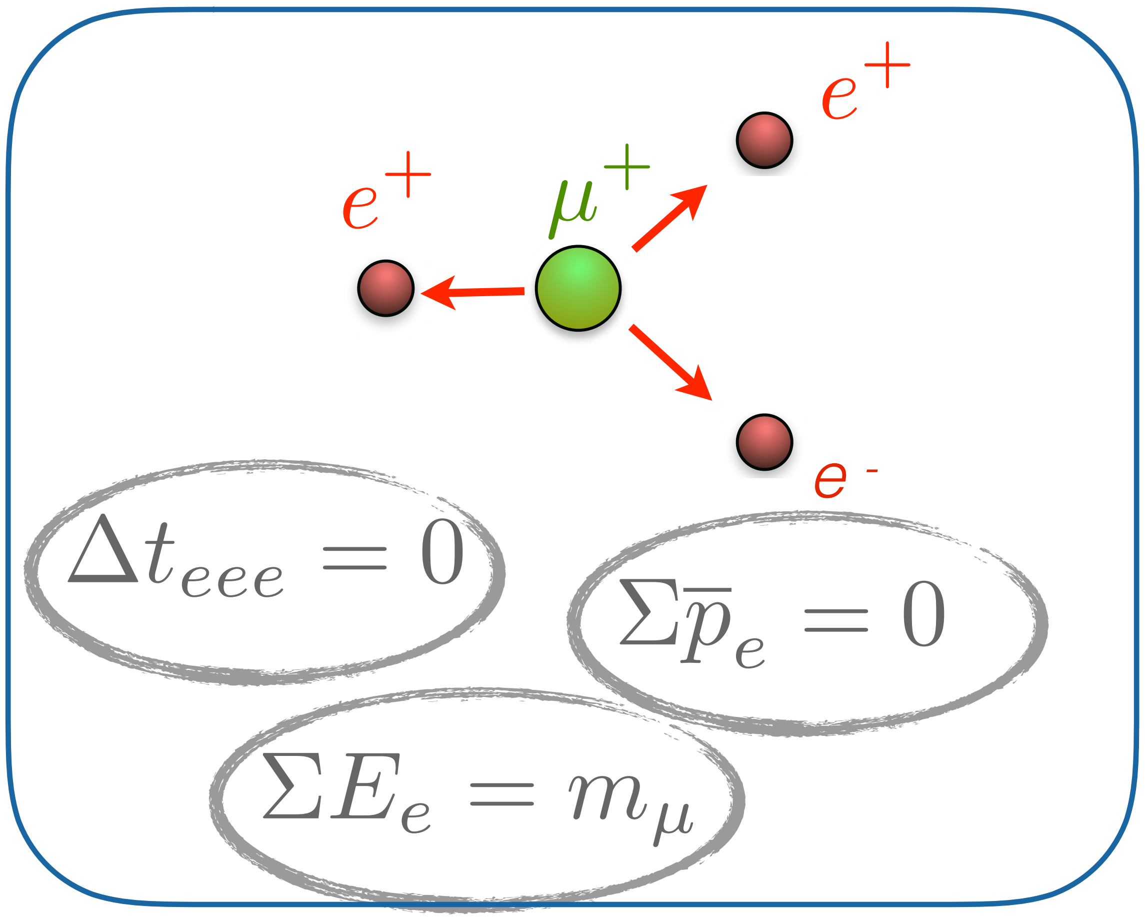


Contents

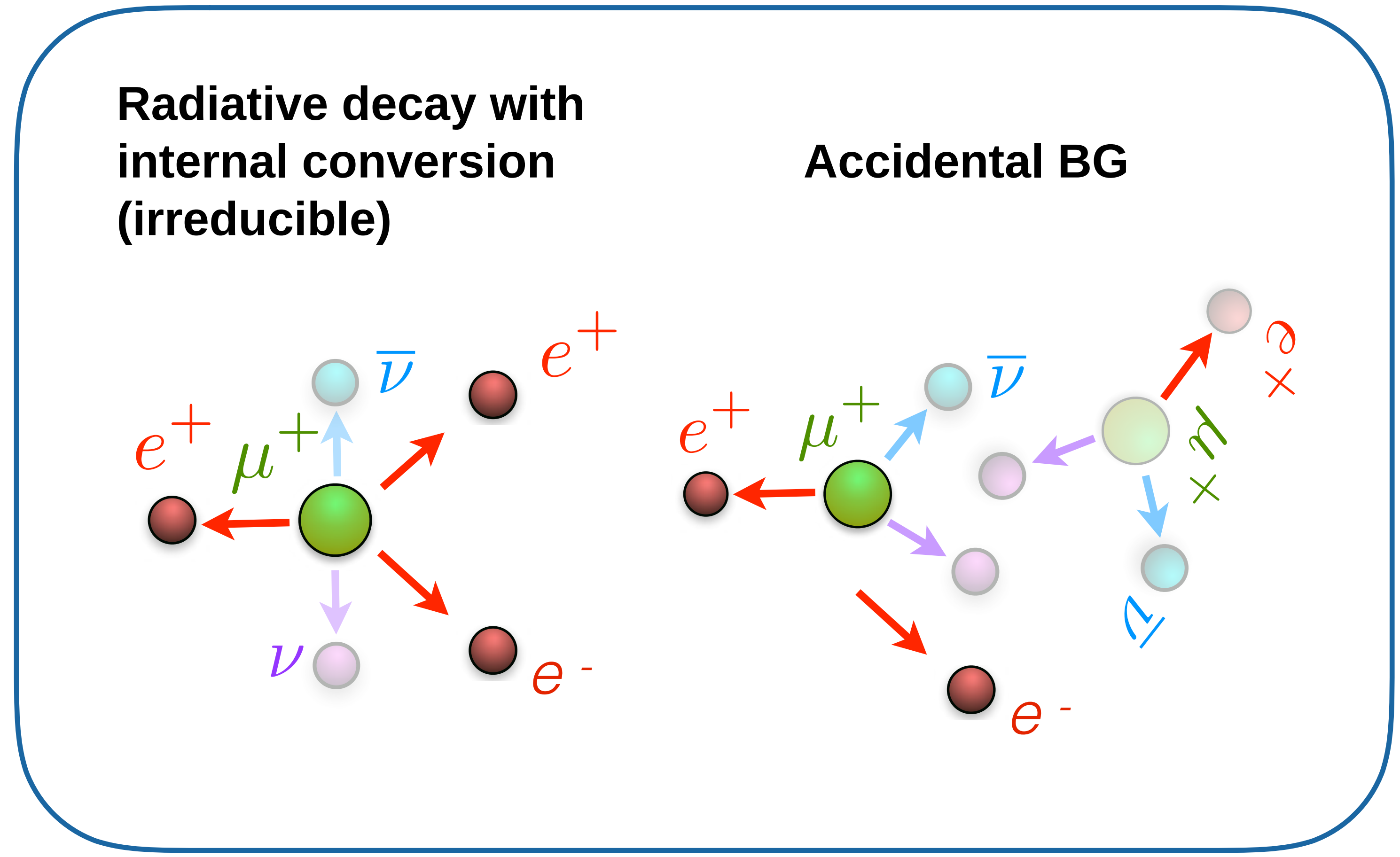
Materials by courtesy of A. Schönig and A. Papa

$\mu^+ \rightarrow e^+e^-e^+$

Signal



Background

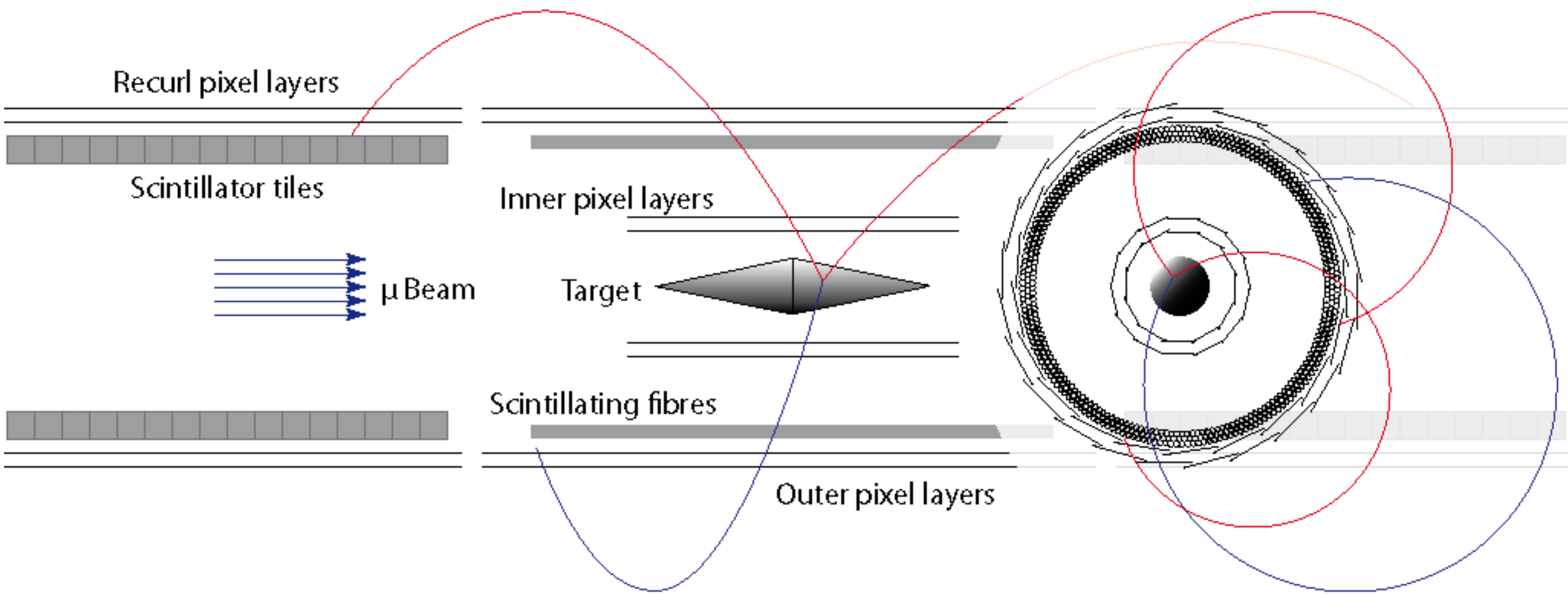


Requirements

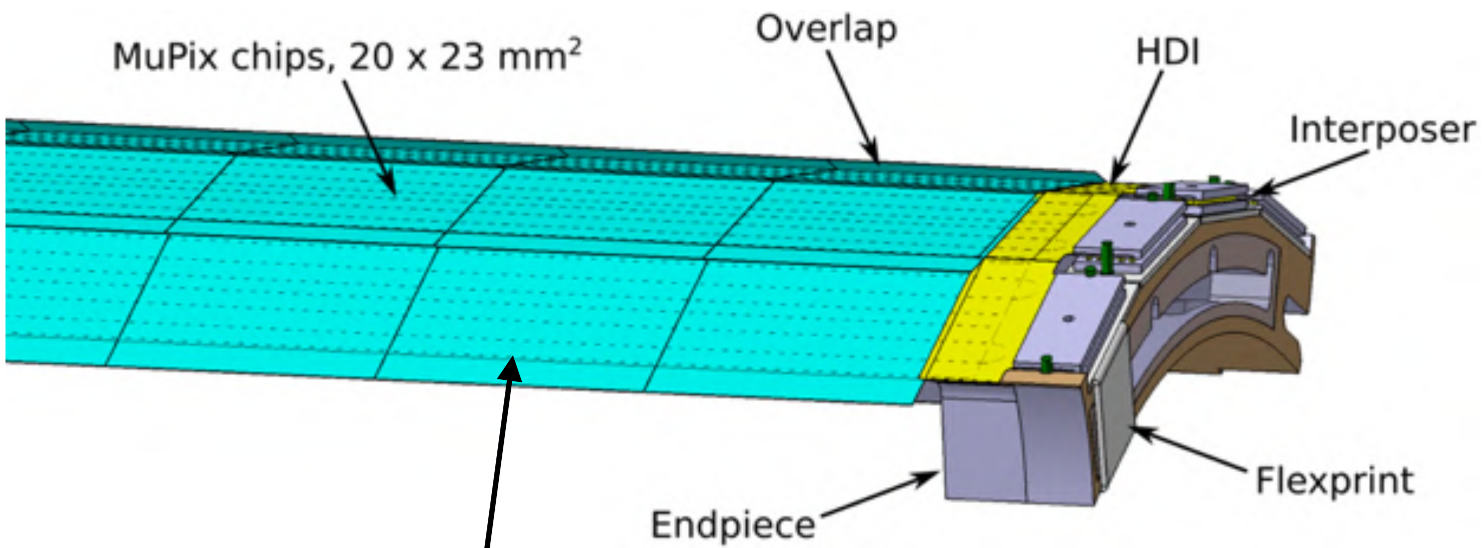
- Continuous beam to minimise accidental background
- High momentum resolution to suppress irreducible background
- Good vertex and timing resolutions to reduce accidental BG

Mu3e Experiment (Phase I)

- **Sensitivity goal: 2×10^{-15}** (SES)
- **πE5@PSI with 10^{8} μ^{+}/s**
- **Mu3e detector**
  - **Ultra thin Si pixel detector** (HV-MAPS): 0.1% X_0/layer
  - High precision tracking using **recurring tracks**
  - **Fast timing detectors** (SciFi & tile)
  - He-gas cooling

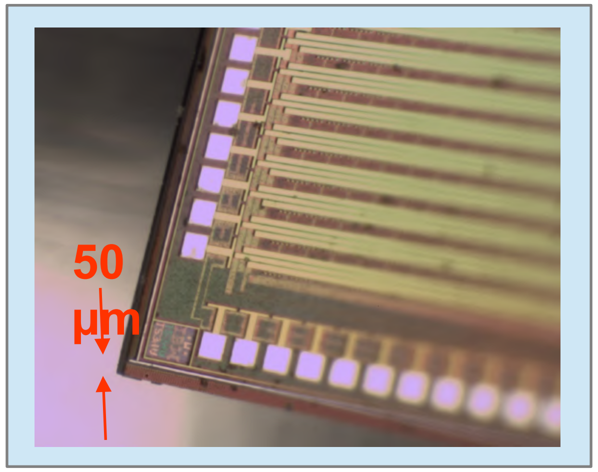


Si Pixel Detector



- **Based on HV-MAPS**
  - Pixel dimension: 80×80μm²
  - Ultra-thin: ᵗ50μm
  - Active area: ~20×20mm²
  - Power consumption < 350mW/cm²
- **MuPix8**
  - First large area prototype: 160mm²

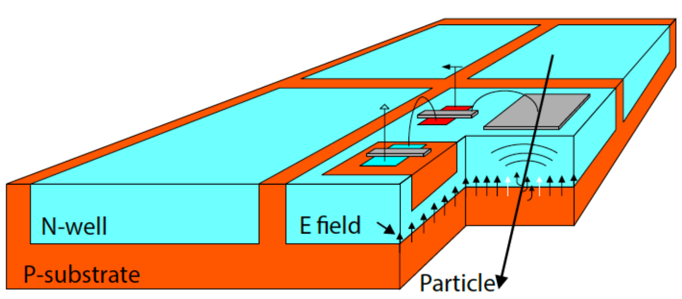
MuPix (HV-MAPS)



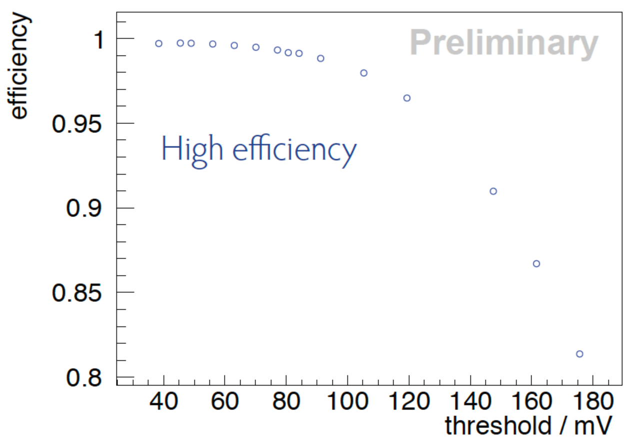
Monolithic pixel sensor in 180 nm HV-CMOS

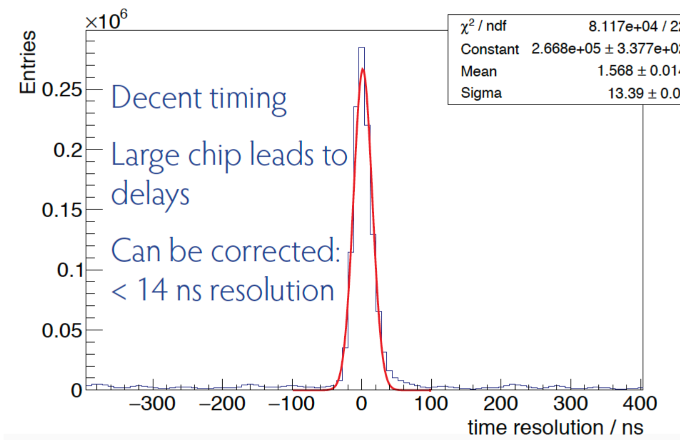
MuPix8

HV-MAPS



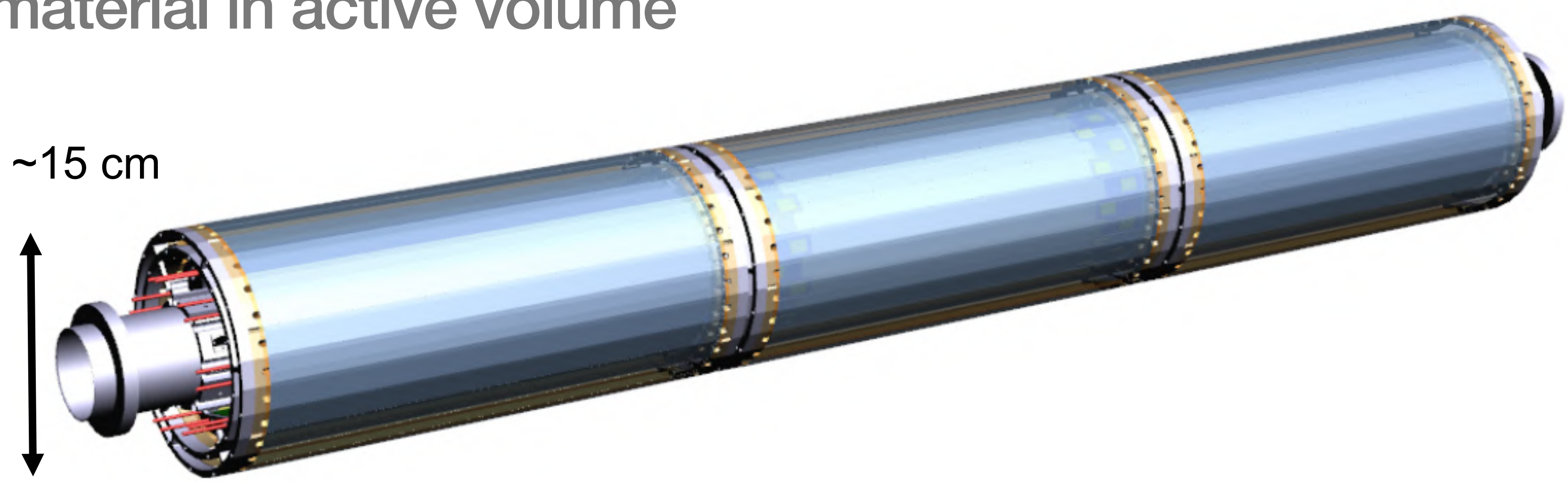
Ivan Peric, Nucl.Instrum.Meth. A582 (2007) 876-885

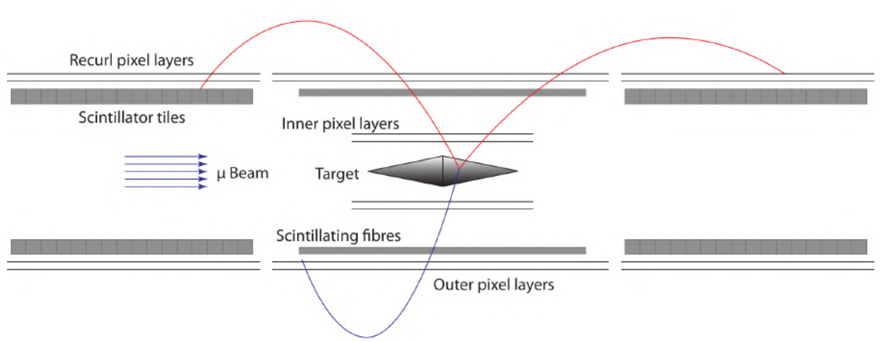


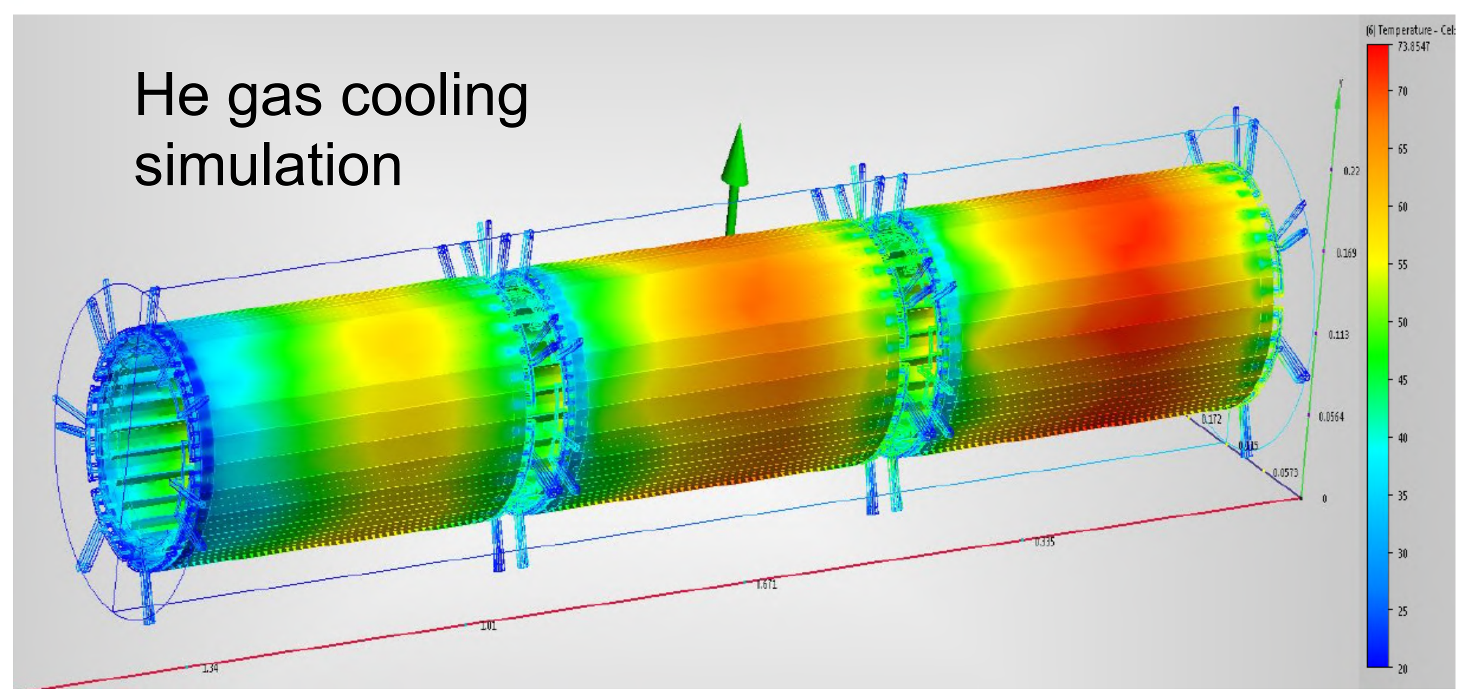


Helium Gas Cooling for Pixel Detector

- **Need cooling for 200M pixels for central and two recurl stations**
- **Helium gas cooling concept**
  - Temperature 20-50°C
  - No extra material in active volume

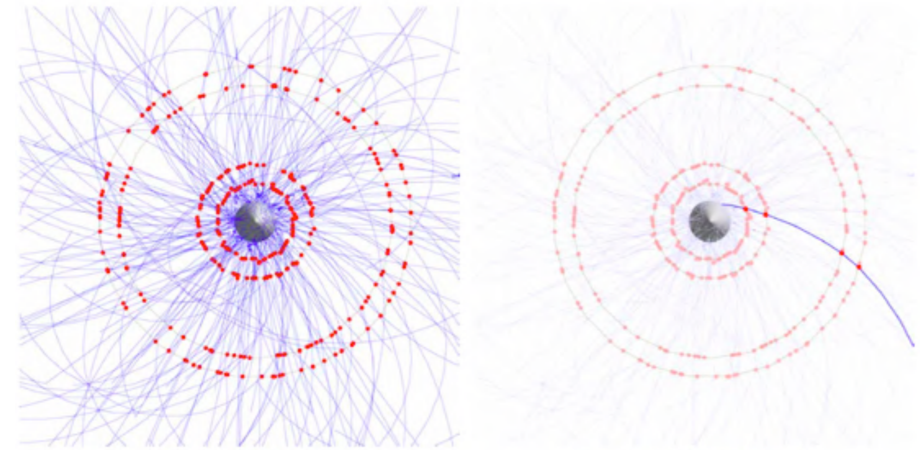






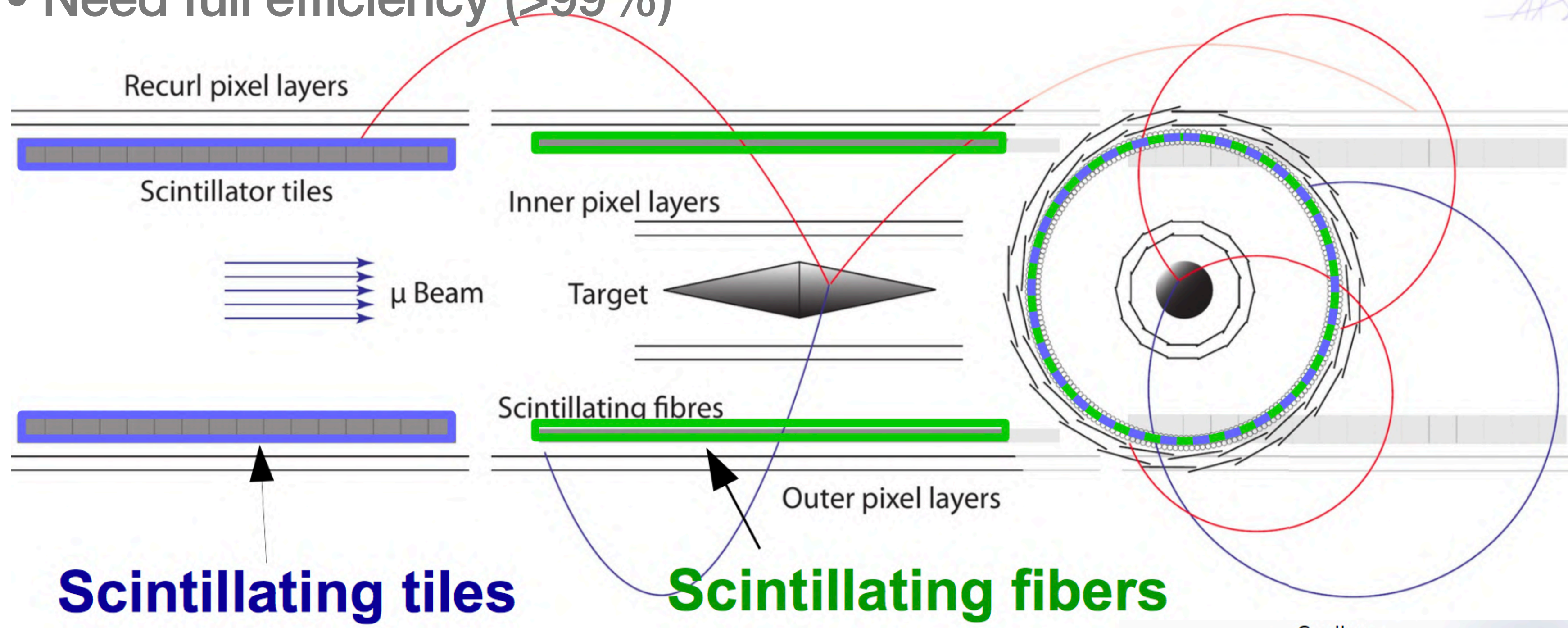
Timing Detectors

- **Precise time measurement to reduce accidentals**
  - Scintillating fibres: O(1ns)
  - Scintillating tiles: O(100ps)
  - Need full efficiency (>99%)

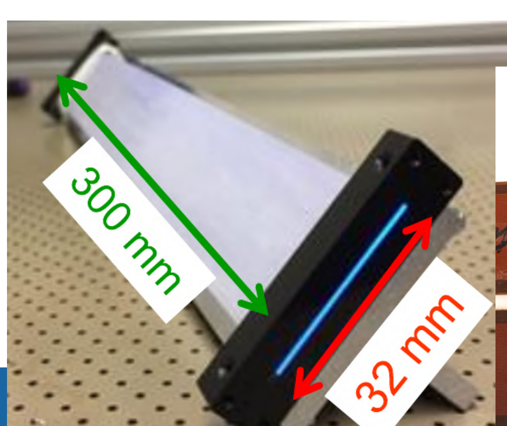


Pixels: O(50 ns)

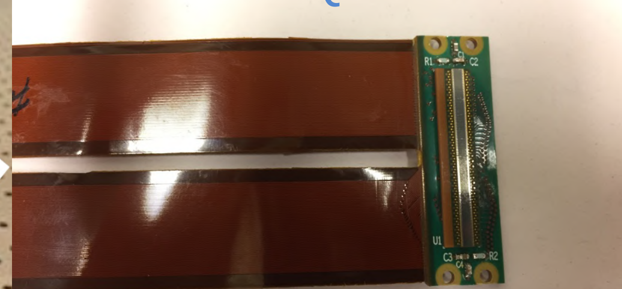
Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

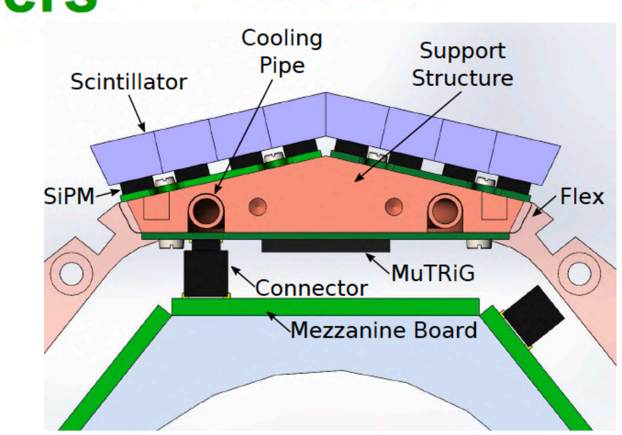


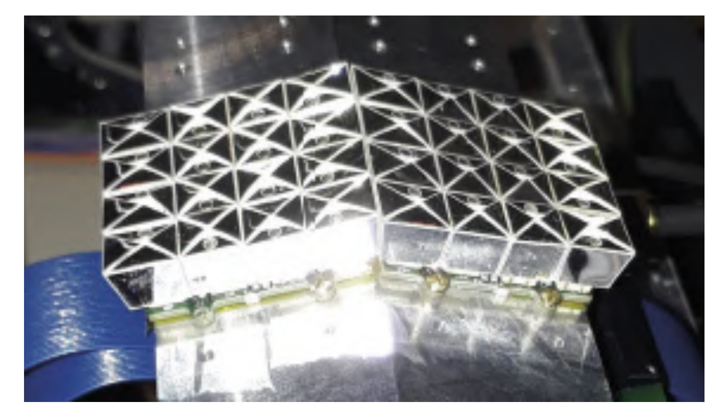
- 3 staggered layers of 250μm scintillating fibres (0.2%X_0)
- Readout by SiPM array
- 366ps for prototype test



SiPM Array: Hamamatsu S13552-HQR



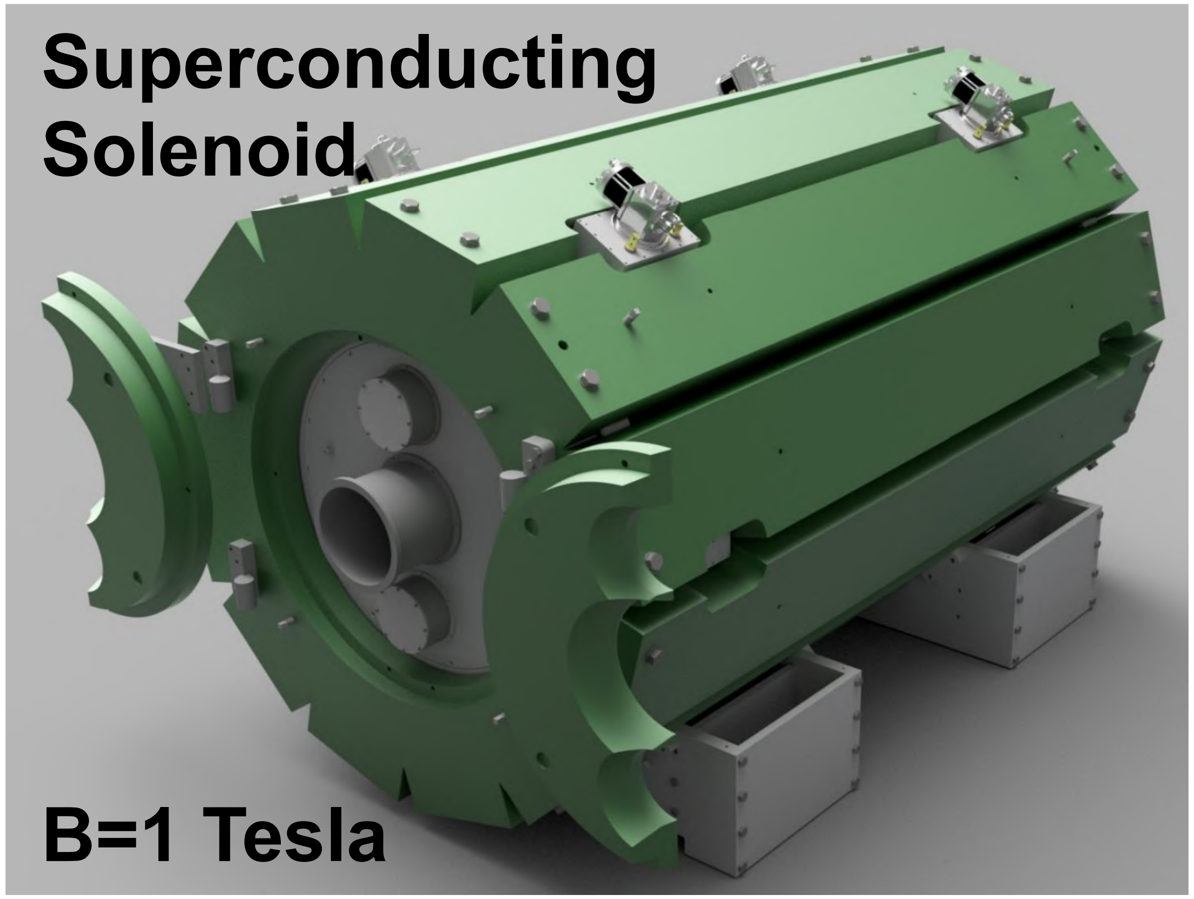




- Scintillator tile: 6.5×6.5×5mm^3
- SiPM: 3×3mm^2
- O(60ps) for prototype test

Status and Prospects of Mu3e (phase I)

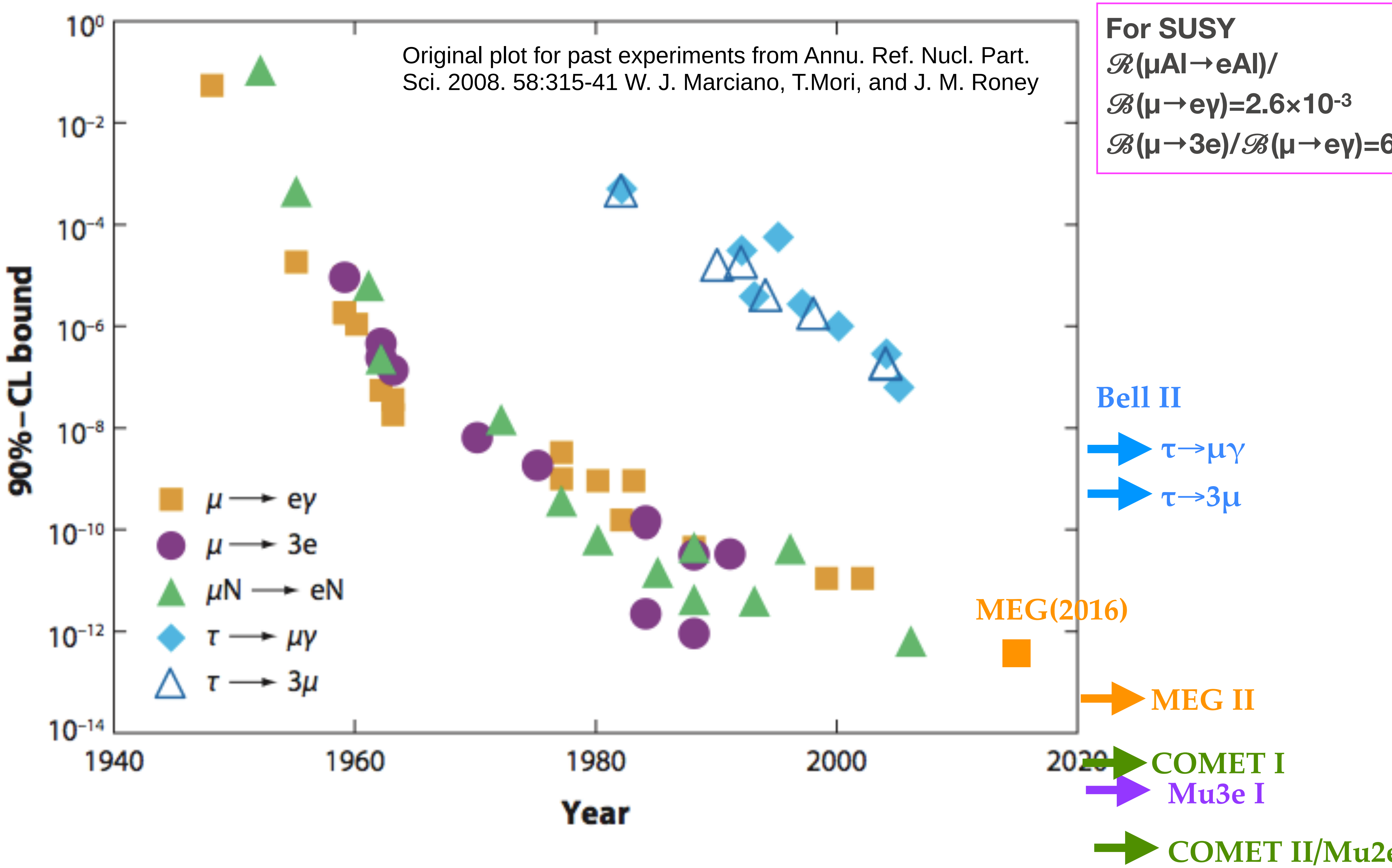
- **Moving from R&D phase to construction phase**
  - Ready for production in 2019
  - Detector construction in 2020
- **Commissioning start in 2021**



To be delivered in summer 2019

Perspectives

For SUSY
$\mathcal{R}(\mu Al \to eAl) / \mathcal{B}(\mu \to e\gamma) = 2.6 \times 10^{-3}$
$\mathcal{B}(\mu \to 3e) / \mathcal{B}(\mu \to e\gamma) = 6 \times 10^{-3}$



Contents

- Rare Muon Decays
- $\mu^+ \rightarrow e^+\gamma$
- $\mu^+ \rightarrow e^+e^-e^+$
- Future Plans
- Summary

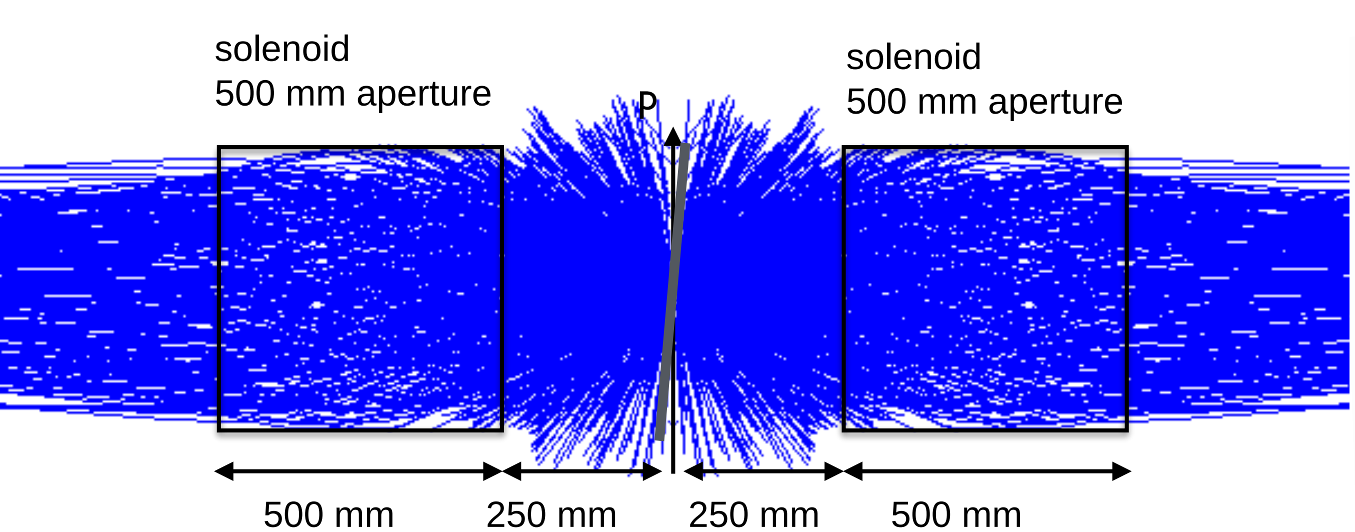
Future Plans

Not the end of the story, even if discovered

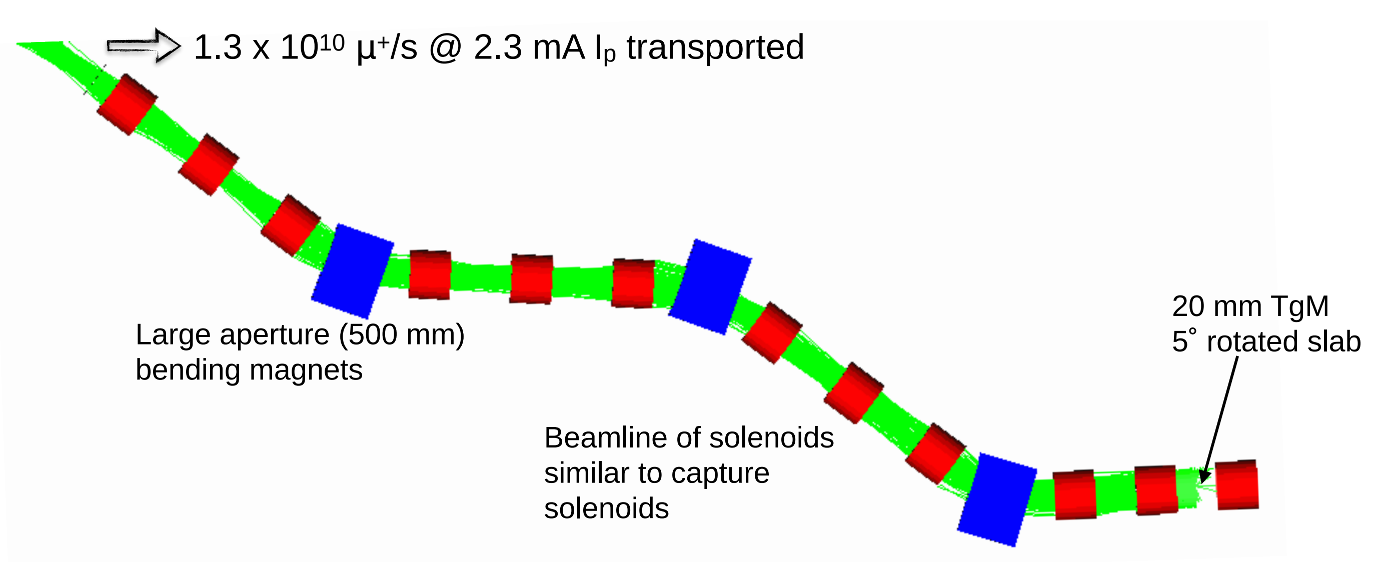
- **From “Discovery” to “Measurement”**
  - Branching ratio
  - Angular distribution

    →**Energy scale and symmetry of new physics**
- **High intensity Muon Beam (HiMB) project at PSI**
  - **Aim: $\mathcal{O}(10^{10})$ μ^+/s**
  - **Slanted target with split capture solenoid**
  - **Time schedule: $\mathcal{O}$(2025)**

Split capture solenoid



Solenoid beam line for target M

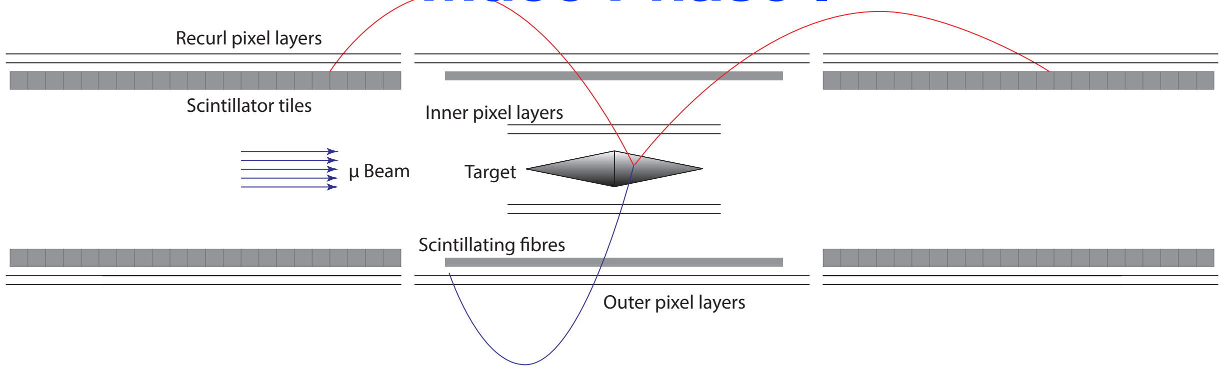


Future Plans

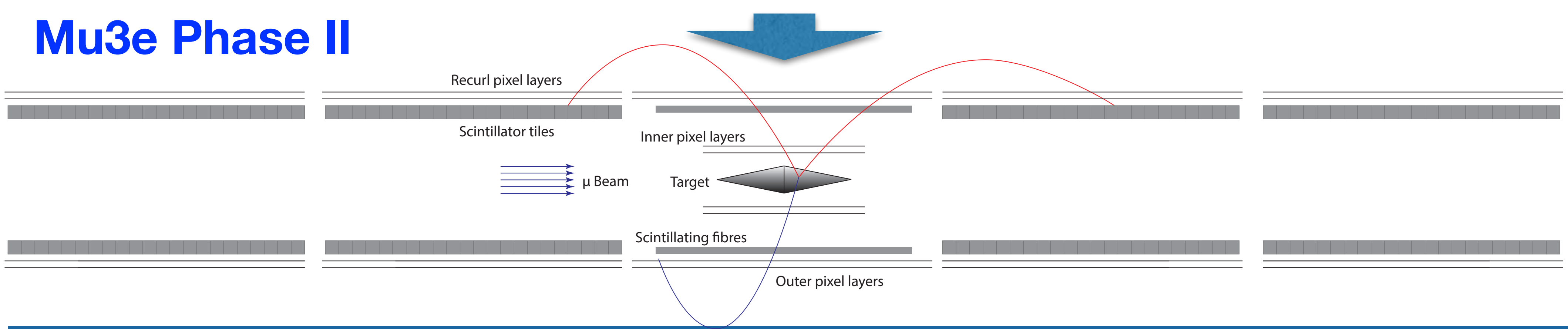
- **Mu3e Phase II**
  - Another pair of recurl stations improve momentum resolution to fully cover inner tracker acceptance
  - Target sensitivity: **10^{-16}**
- **Beyond MEG II?**
  - Starting discussion
  - Need new detector concept to go beyond MEG II

    e.g. more precise measurement of photon and positron with extremely thin Si detector (e.g. HV-MAPS)

Mu3e Phase I



Mu3e Phase II



Summary

- **Muon rare decays are powerful tools to explore new physics**
  - Most intense DC μ-beam at PSI + Innovative detectors
  - Already sensitive enough to test many of new physics models
  - Complementarity btw/ various processes
- **New experiments with further improved sensitivities coming soon!**
  - $\mu \rightarrow e\gamma$: MEG II
  - $\mu \rightarrow eee$: Mu3e (Phase I)
- **Future plans also planned or under discussion**
  - "Measurement" of rare decay would give us a hint on energy scale and symmetry of new physics