The Mu3e Experiment @ PSI

searching for the neutrinoless muon decay $\mu^+ \rightarrow e^+e^-e^+$

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for the Mu3e Collaboration

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LFV in "Standard Model"

Flavor Conservation in the charged lepton sector :

processes like $\mu A \to e A$

$\mu \to e + \gamma$

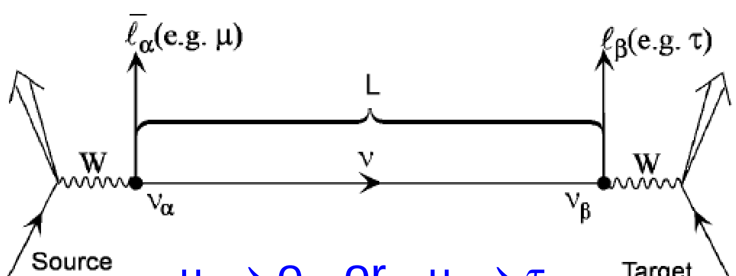
$\mu \to e\, e\, e$ have not been observed yet (down to 10^{-13} !).

In SM ($m_\nu = 0$) Lepton Flavor is conserved absolutely (not by principle but by structure !)

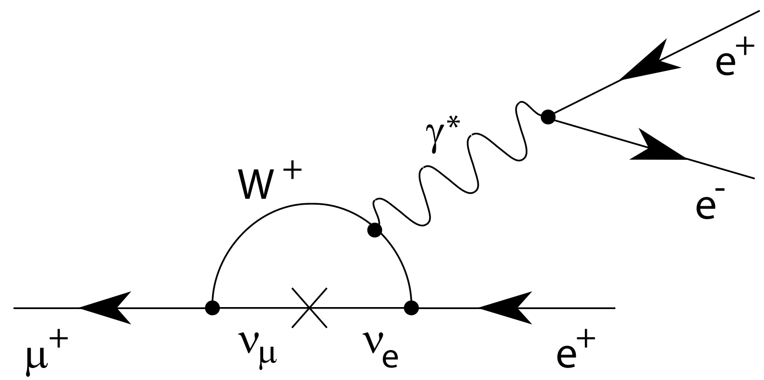
neutrino oscillations $\to m_\nu \neq 0$ & Lepton Flavor is not anymore conserved (ν oscillations)

$\to$ charged LFV possible via loop diagrams, but heavily suppressed

neutrino oscillations



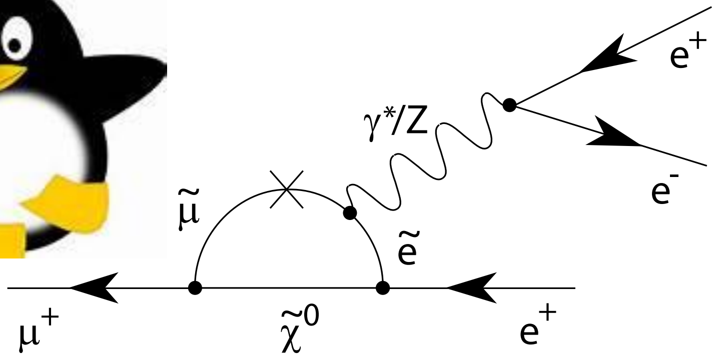
$\mu \to e$ or $\mu \to \tau$

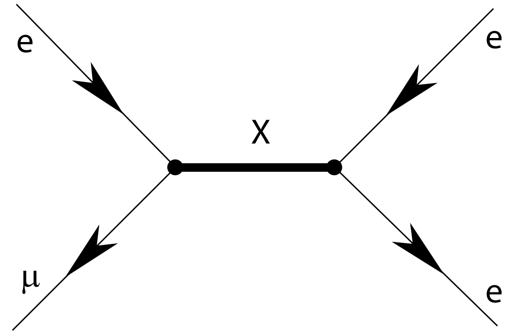


$$\sim \left(\frac{\Delta m_\nu^2}{M_W^2} \right)^2 \Rightarrow BR\left(\mu^\pm \to e^\pm e^+ e^-\right) < 10^{-54}$$

$\to$ measurement not affected by SM processes

New Physics in $\mu \to eee$





Loop Diagrams

- Supersymmetry
- Little Higgs Models
- Seesaw Models
- GUT models (Leptoquarks)
- many other models …

Tree Diagrams

- Higgs Triplet Models
- New Heavy Vector Bosons (Z’)
- Extra dimensions (K-K towers)
- many other models …

several cLFV models predict sizeable effects,
accessible to the next generation of experiments !

if cLFV seen, unambiguous signal for new physics (going beyond Dirac $m_\nu > 0$)

explore physics up to the PeV scale
complementary to direct searches at LHC

LFV Searches : Current Situation

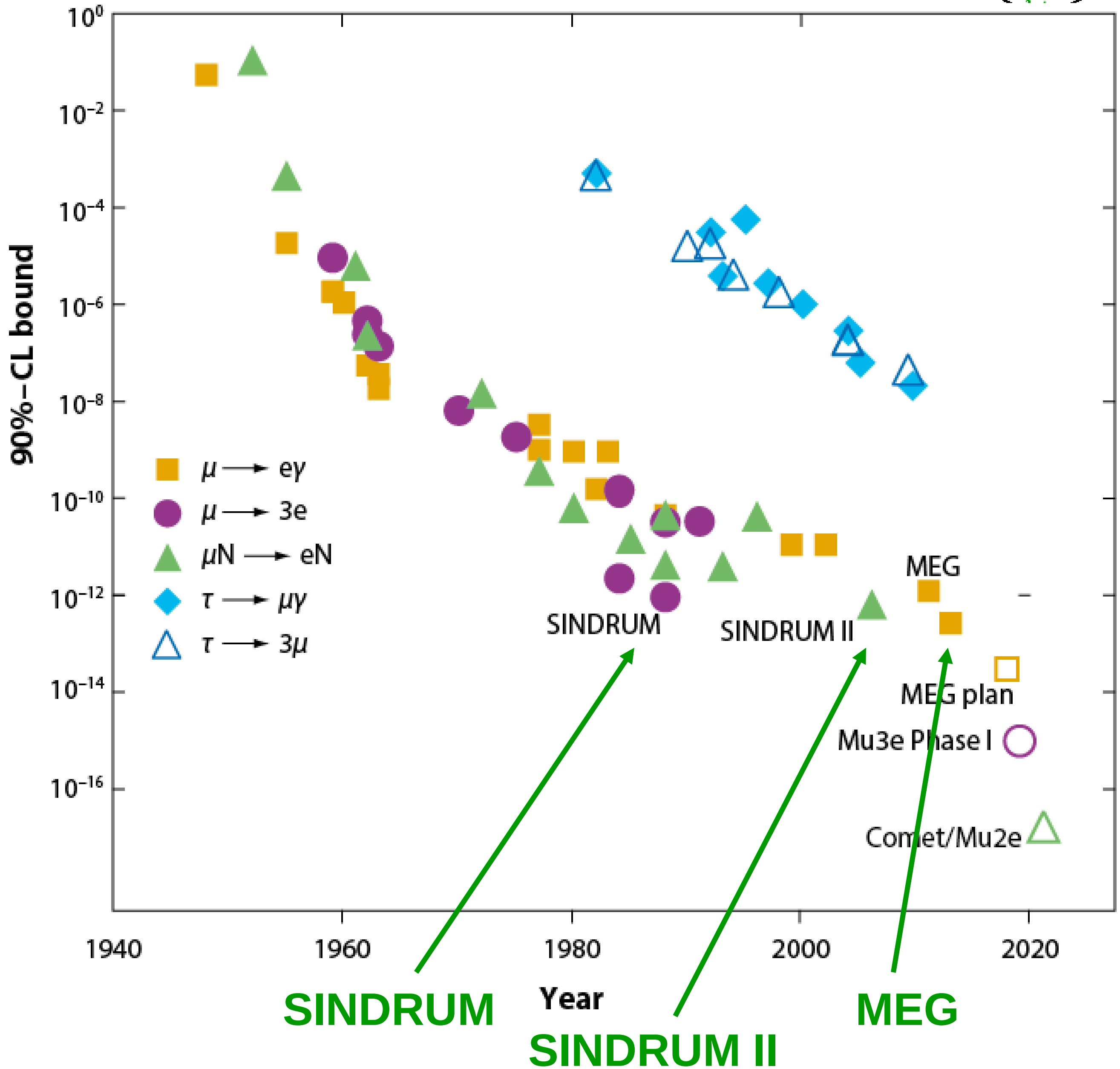
The best limits on LFV come from PSI muon experiments

$\mu^+ \rightarrow e^+e^-e^+$
BR < 1×10^{-12}
SINDRUM 1988

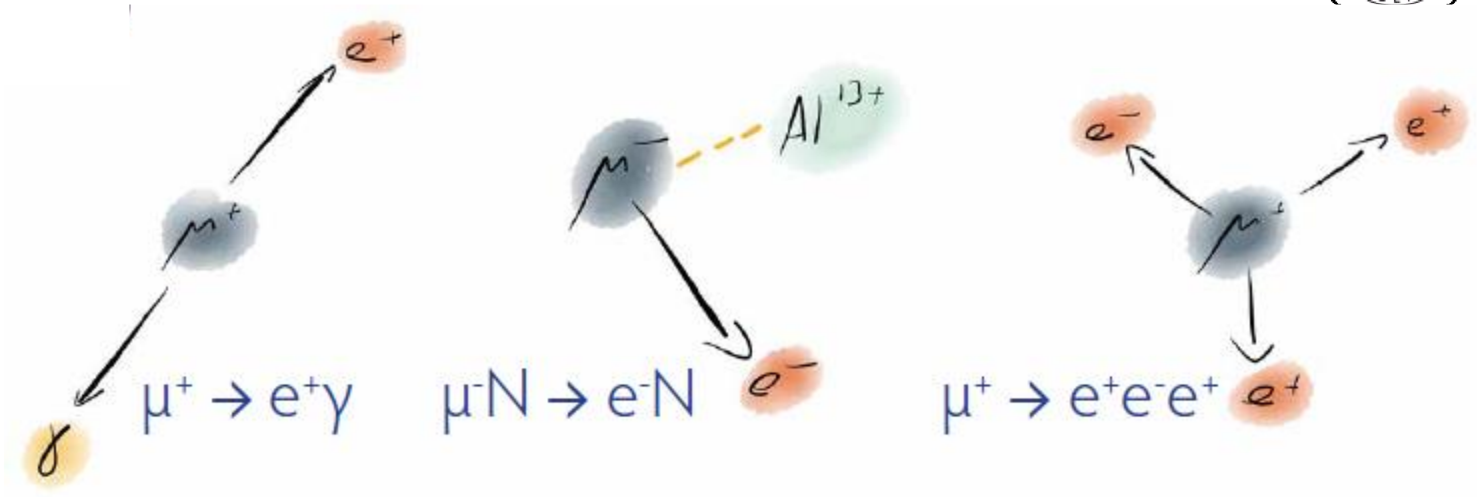
$\mu^- + Au \rightarrow e^- + Au$
BR < 7×10^{-13}
SINDRUM II 2006

$\mu^+ \rightarrow e^+ + \gamma$
BR < 4.2×10^{-13}
MEG 2016

Mu3e $\mu^+ \rightarrow e^+e^-e^+$
Phase I : BR < 10^{-15}
Phase II: BR < 10^{-16}



LFV μ Decays : Experimental Signatures



kinematics :	2-body decay monochromatic e^+, γ back to back	quasi 2-body decay monoenergetic e^-	3-body decay coplanar, $\Sigma \mathbf{p}_i = 0$ $\Sigma E_i = m_\mu$
backgrounds :	accidentals	decay in orbit antiprotons, pions	radiative decay accidentals
beam :	continuous beam	pulsed beam	continuous beam

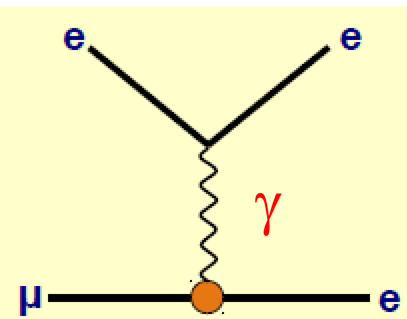
none of these decays, however, have been yet observed experimentally

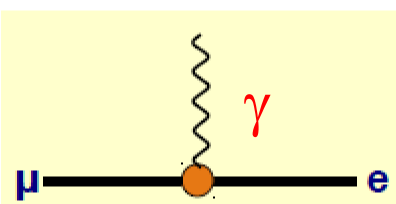
Model Comparison ($\mu \to e\gamma$ and $\mu \to eee$)

Effective charge LFV Lagrangian ("toy" model)   (Kuno and Okada)

$$L_{LFV} = \frac{m_\mu}{\Lambda^2(1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2(1+\kappa)} J^{e\mu}_{\sigma} J^{\sigma,ee}$$

Λ = common effective scale
κ = "contact" vs "loop"

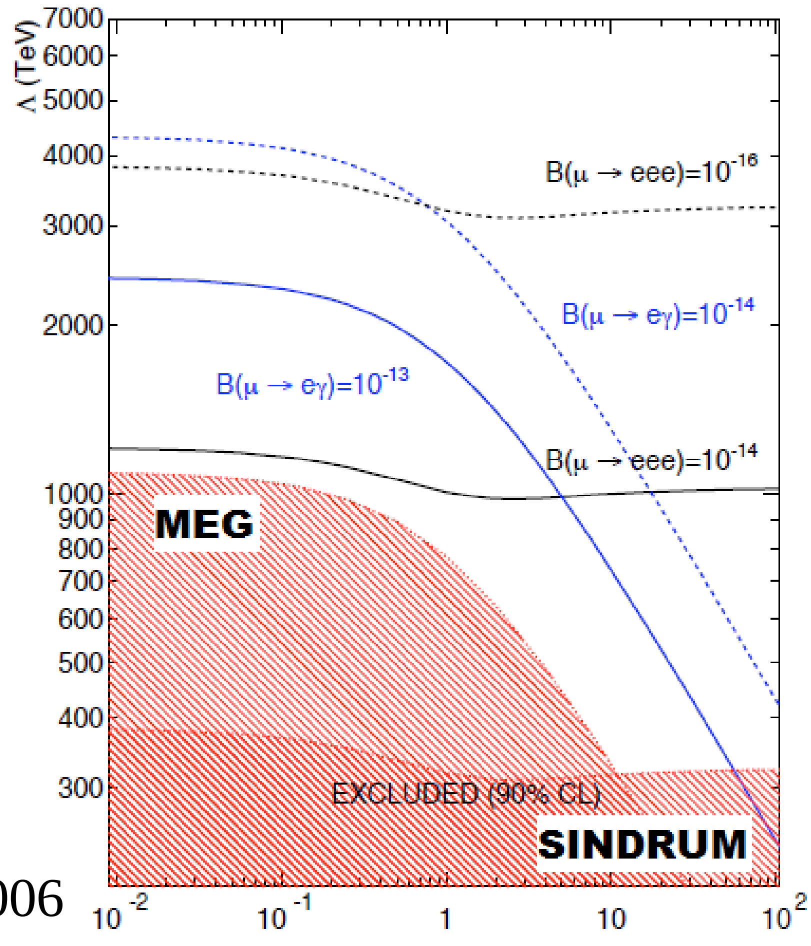


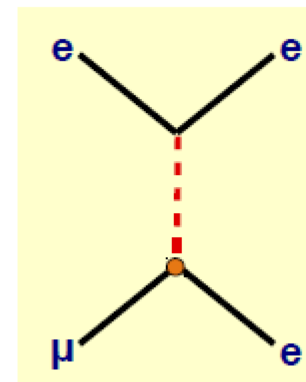


$\kappa \to 0$

$$\frac{BR(\mu^+ \to e^+e^-e^+)}{BR(\mu^+ \to e^+\gamma)} \sim 0.006$$

(suppressed by an extra vertex)





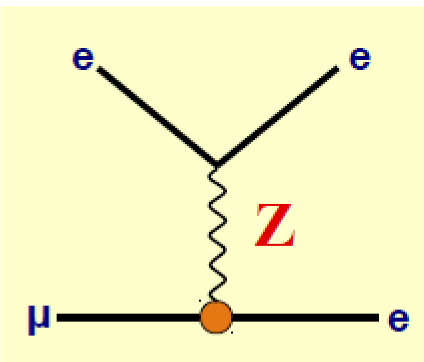
$\kappa \to \infty$

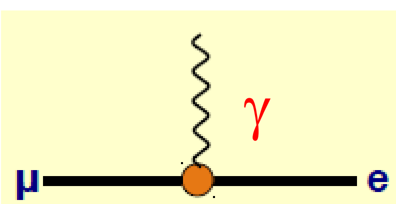
$$\frac{BR(\mu^+ \to e^+e^-e^+)}{BR(\mu^+ \to e^+\gamma)} = \infty$$

Z - penguin

appeared in the literature in 1995 (Hisano et al.) and "rediscovered" recently

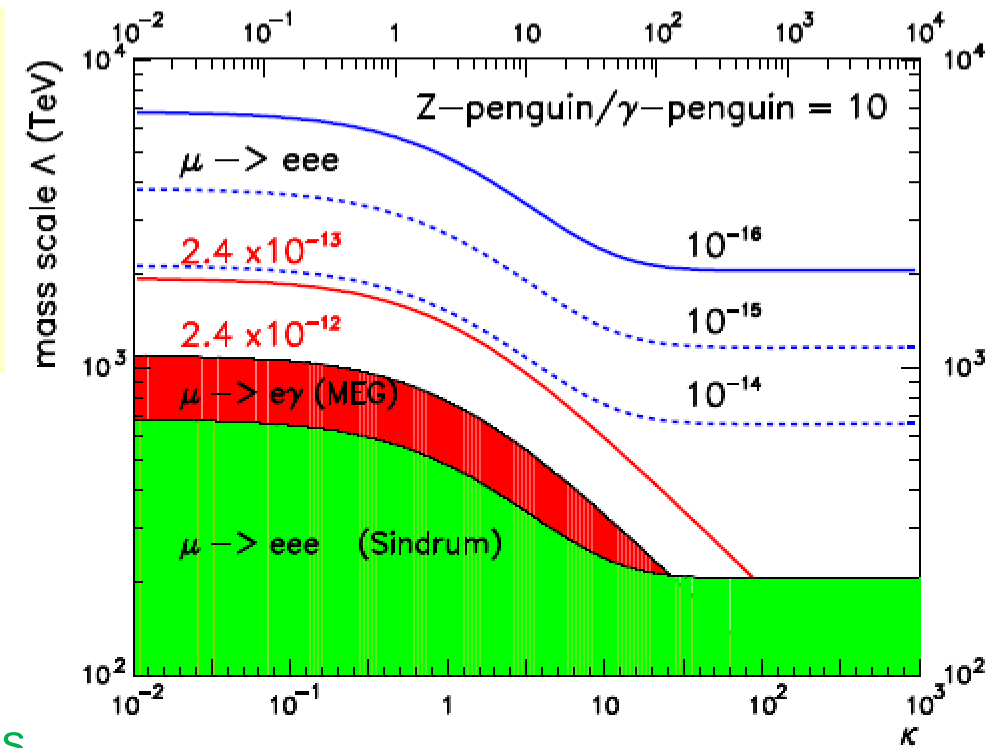
dominates if Λ >> M_Z $\quad BR \propto \frac{m_\mu^4}{m_Z^4} f\left(\Lambda^4\right)$ (no decoupling in some models)



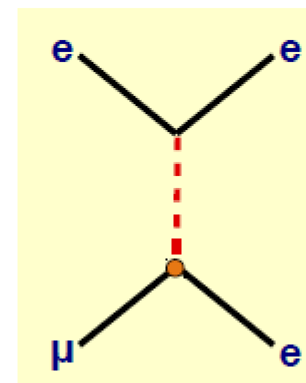


$\kappa \to 0$

the Z $\to$ e e vertex is not suppressed by α_{EM}



Z – penguin enhanced by factor of 10



$\kappa \to \infty$

SINDRUM @ PSI (~ 80s)

beam (πE3 beamline @ PSI):

$5 \times 10^6\ \mu$ / sec

28 MeV/*c* surface muons

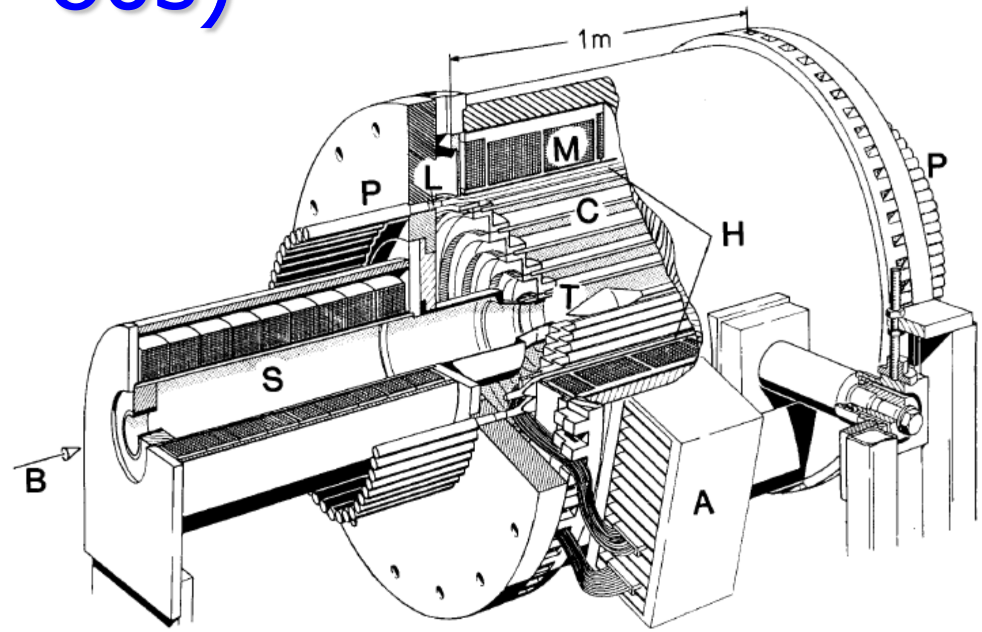
resolution:

$\sigma(p_T) = 0.7$ MeV/c^2

vertex ~ 1 mm

statistics limited!

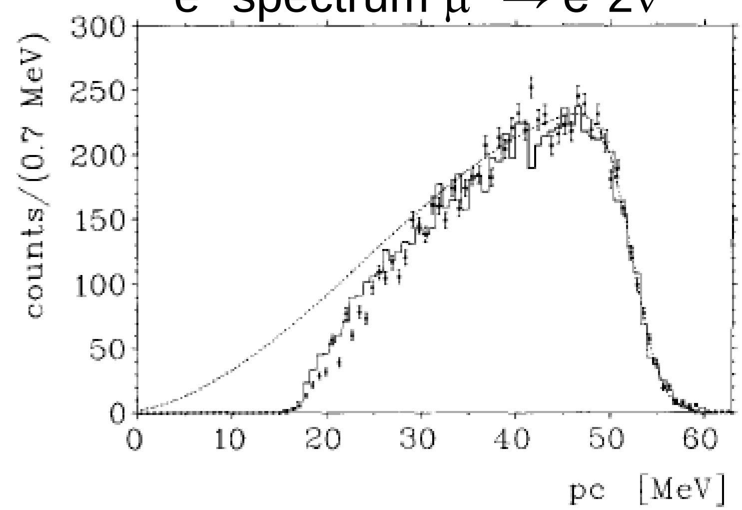
$$\frac{\Gamma\left(\mu^+ \to e^+ e^- e^+\right)}{\Gamma\left(\mu^+ \to e^+ \bar{\nu}_\mu \nu_e\right)} < 10^{-12} \quad (90\%\ \text{CL})$$

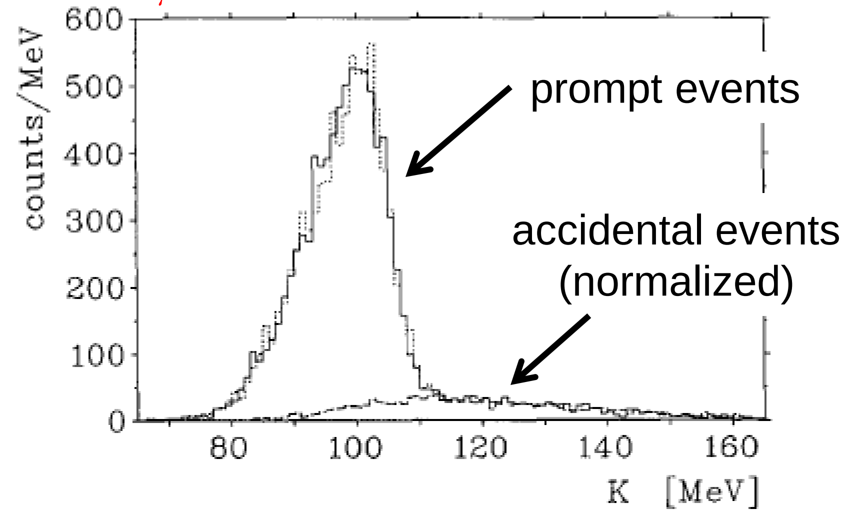


$$K = \sum_i E_i + \left|\sum_i \vec{p}_i c\right| \qquad \mu \to 3e2\nu$$

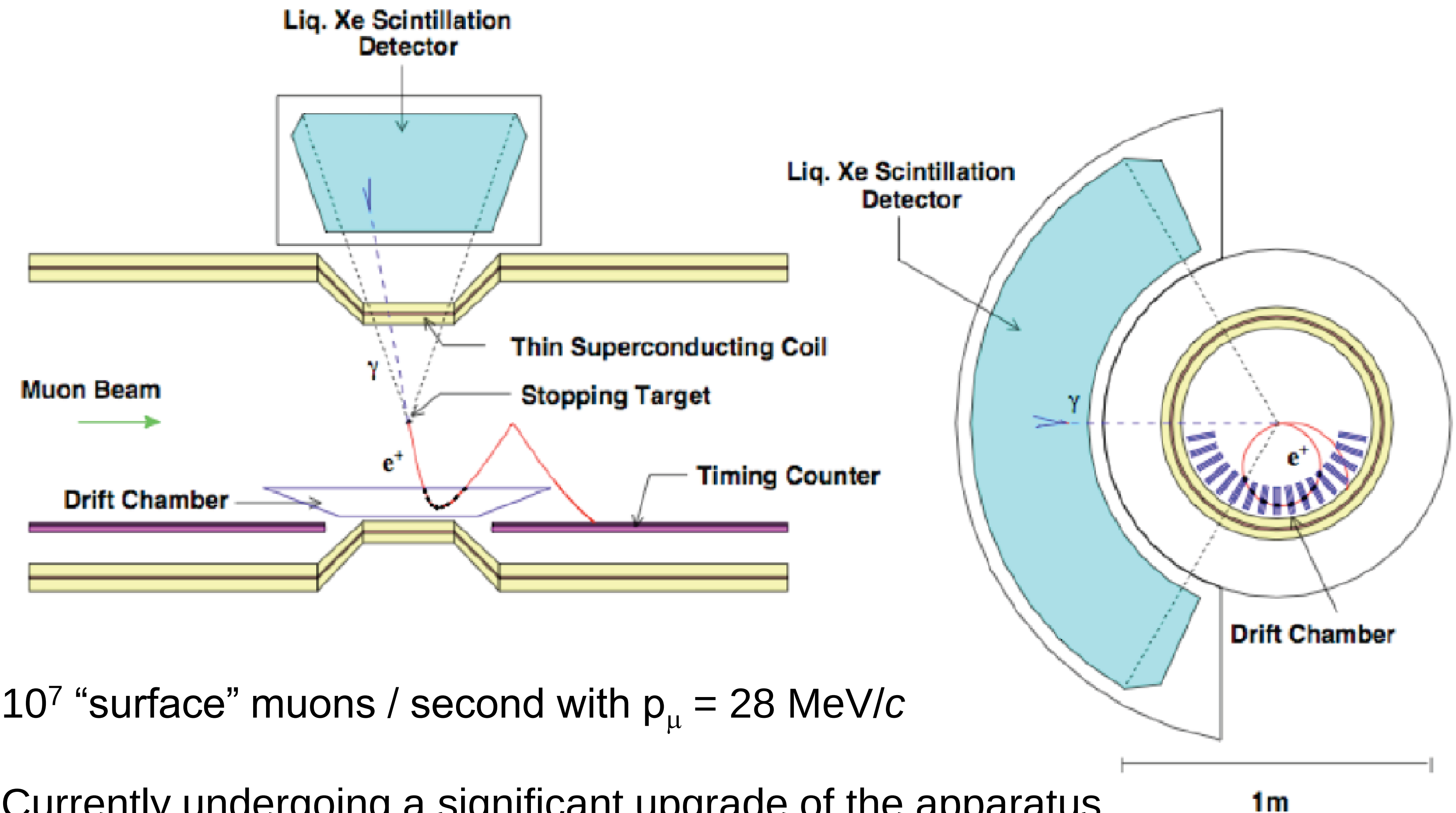
$m_\mu = 105.7$ MeV   0

e+ spectrum $\mu^+ \to e^+ 2\nu$





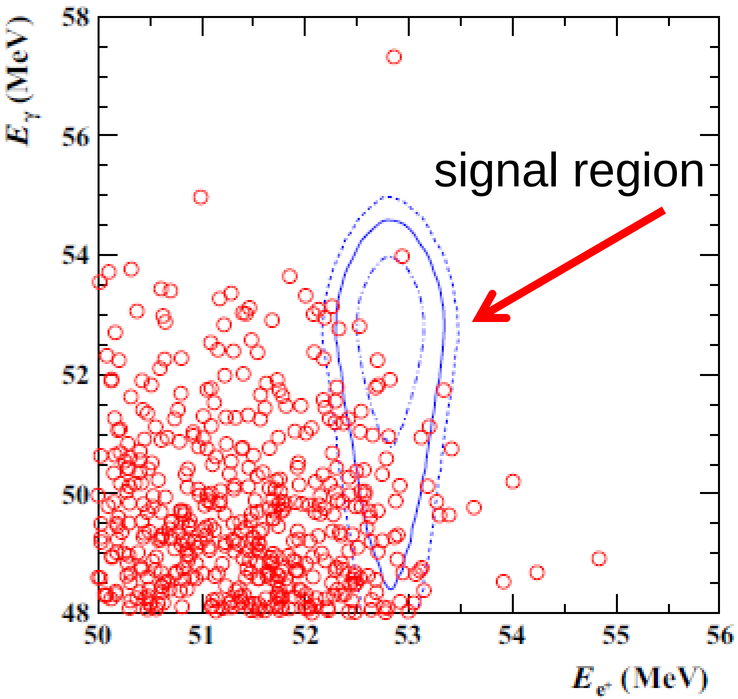
MEG @ PSI : $\mu \rightarrow e + \gamma$ (today)

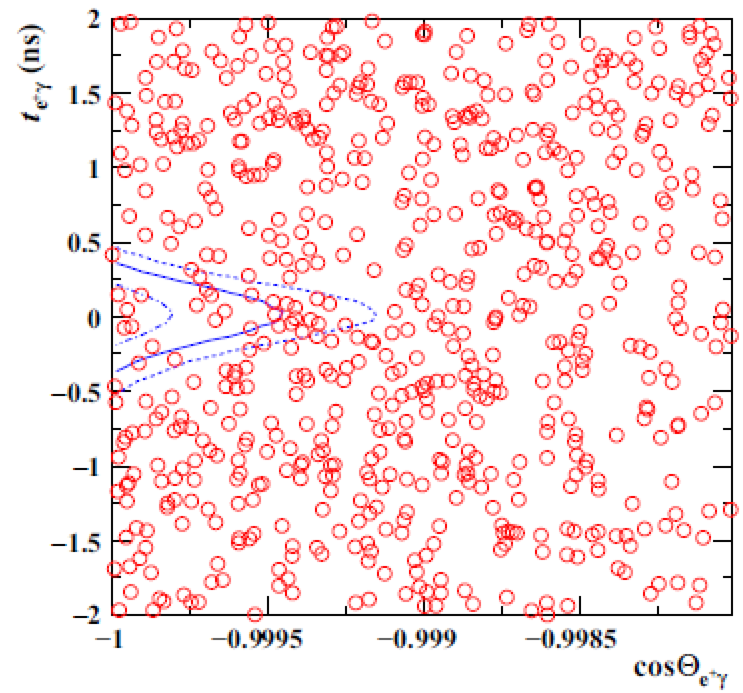


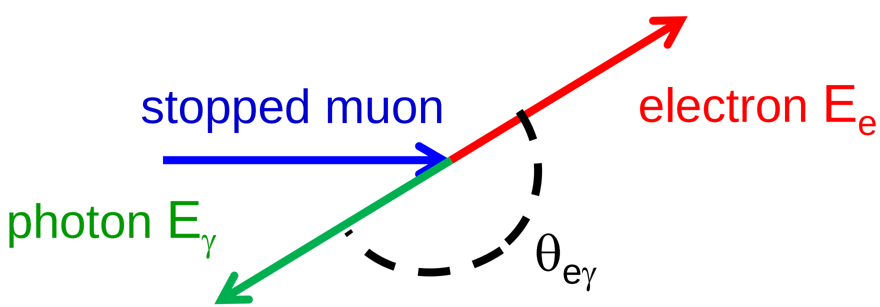
10^7 "surface" muons / second with p_μ = 28 MeV/*c*

Currently undergoing a significant upgrade of the apparatus to improve sensitivity on $\mu \rightarrow e + \gamma$ to $< 5 \times 10^{-14}$ (2016+)

MEG @ PSI : $\mu \rightarrow e + \gamma$ (today)







MEG EPJC76(2016)434

$$B.R.(\mu \rightarrow e + \gamma) \leq 4.2 \times 10^{-13} \text{ @ 90\% C.L.}$$

Mu3e @ PSI : the Challenge

search for $\mu^+ \to e^+ e^- e^+$ with sensitivity BR ~ 10^{-16} (PeV scale)
$\tau_{(\mu \to eee)}$ > 700 years (τ_μ = 2.2 μs)

using the most intense DC (surface) muon beam in the world (p ~ 28 MeV/*c*)

suppress backgrounds below 10^{-16}

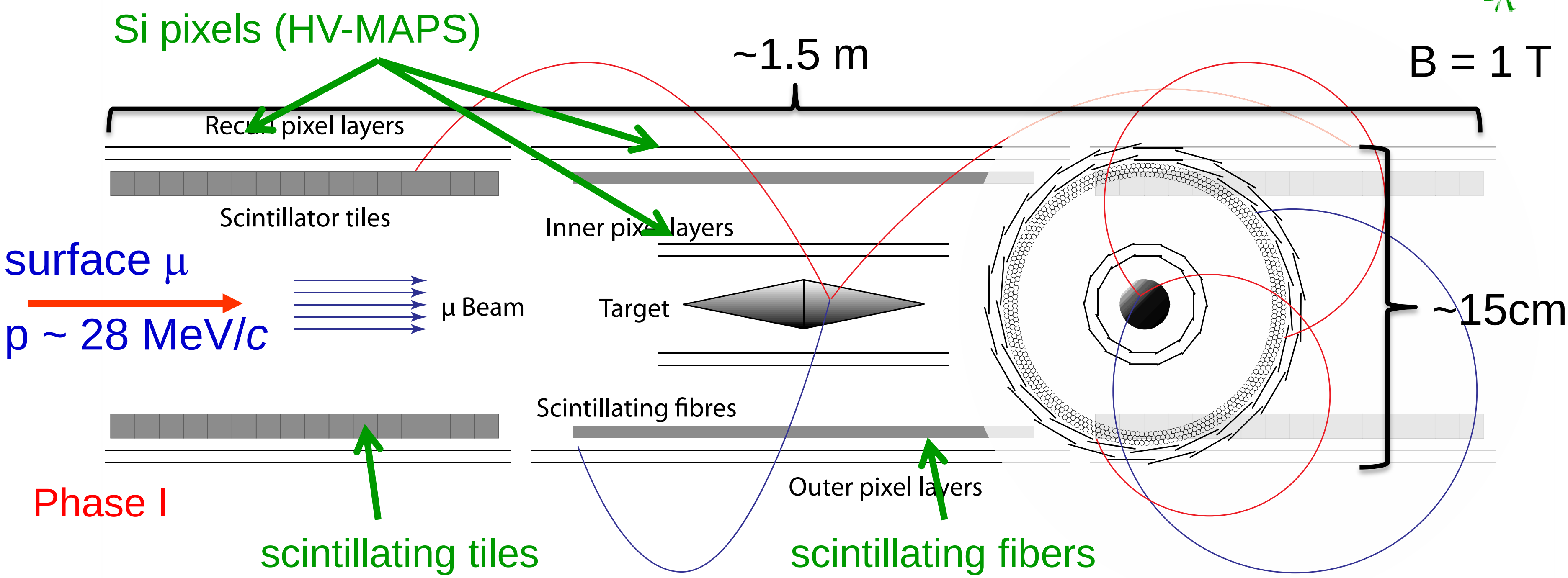
find or exclude $\mu^+ \to e^+ e^- e^+$ at the 10^{-16} level
4 orders of magnitude over previous experiments (SINDRUM @ PSI)

Aim for sensitivity
10^{-15} in Phase I
10^{-16} in Phase II
(i.e. find one $\mu^+ \to e^+e^-e^+$ decay in 10^{16} muon decays)

$\to$ observe ~10^{17} μ decays (over a reasonable time scale)
rate ~ 2 $\times$ 10^9 μ decays / s
$\to$ build a detector capable of measuring 2 $\times$ 10^9 μ decays / s
minimum material, maximum precision

project (Phase I) approved in January 2013

Mu3e Baseline Design



acceptance ~ 70% for $\mu^+ \rightarrow e^+ e^- e^+$ decay (3 tracks!)

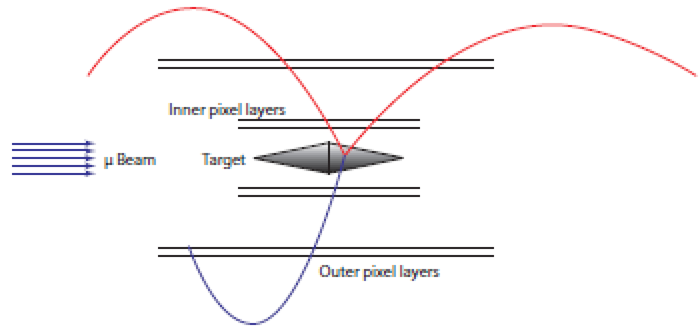
thin (< 0.1% X_0), **fast**, **high resolution** detectors
(minimum material, maximum precision)

275 M HV-MAPS (Si pixels w/ embedded amplifiers) channels

20 k ToF channels (SciFi and Tiles)

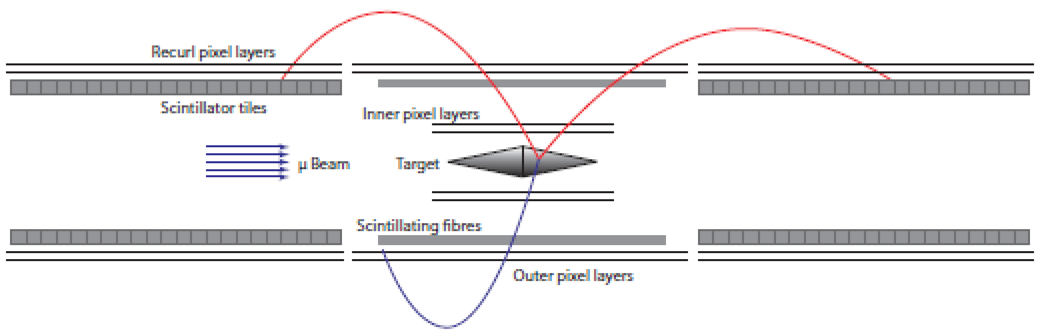
Staged Approach

Phase IA
rate $\leq 10^7$ μ / s



only central pixel

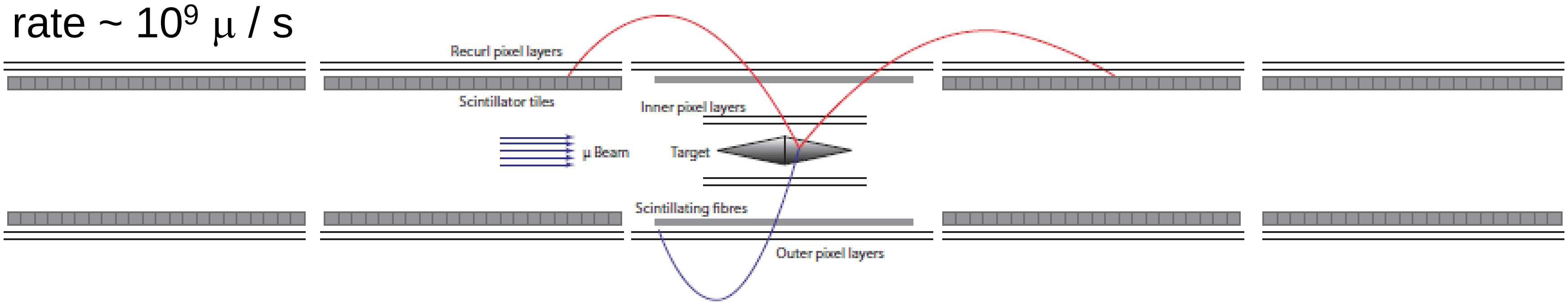
Phase IB
rate ~ 10^8 μ / s



+ inner recurl sta.
+ time of flight

Phase II
rate ~ 10^9 μ / s

+ outer recurl sta.



Muons @ PSI

most intense DC muon beam

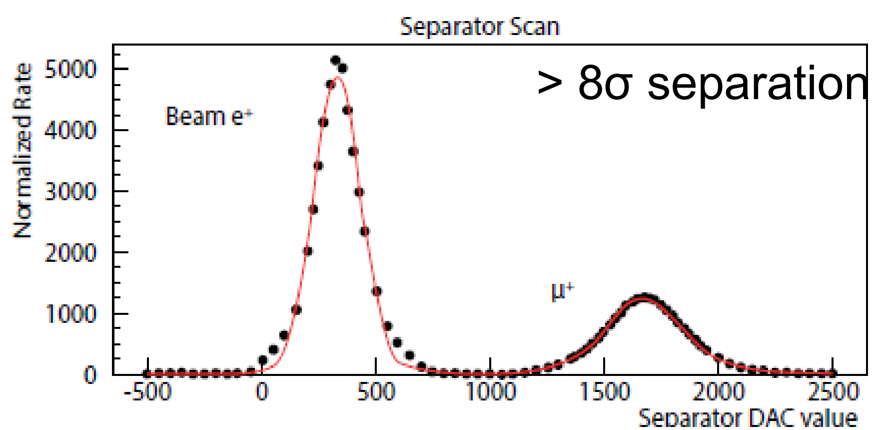
590 MeV/c proton cyclotron

πE5 beamline > 10^8 μ / s

- surface muons ~ 28 MeV/c
- high intensity monochromatic beam
  (ΔP/P < 8% FWHM)
- polarization ~ 90%

(MEG exp., Mu3e phase I)

SINQ (spallation neutron source)
could even provide 5×10^{10} μ / s
High-intensity Muon Beamline (HiMB)



e / μ 12 cm separation at last collimator

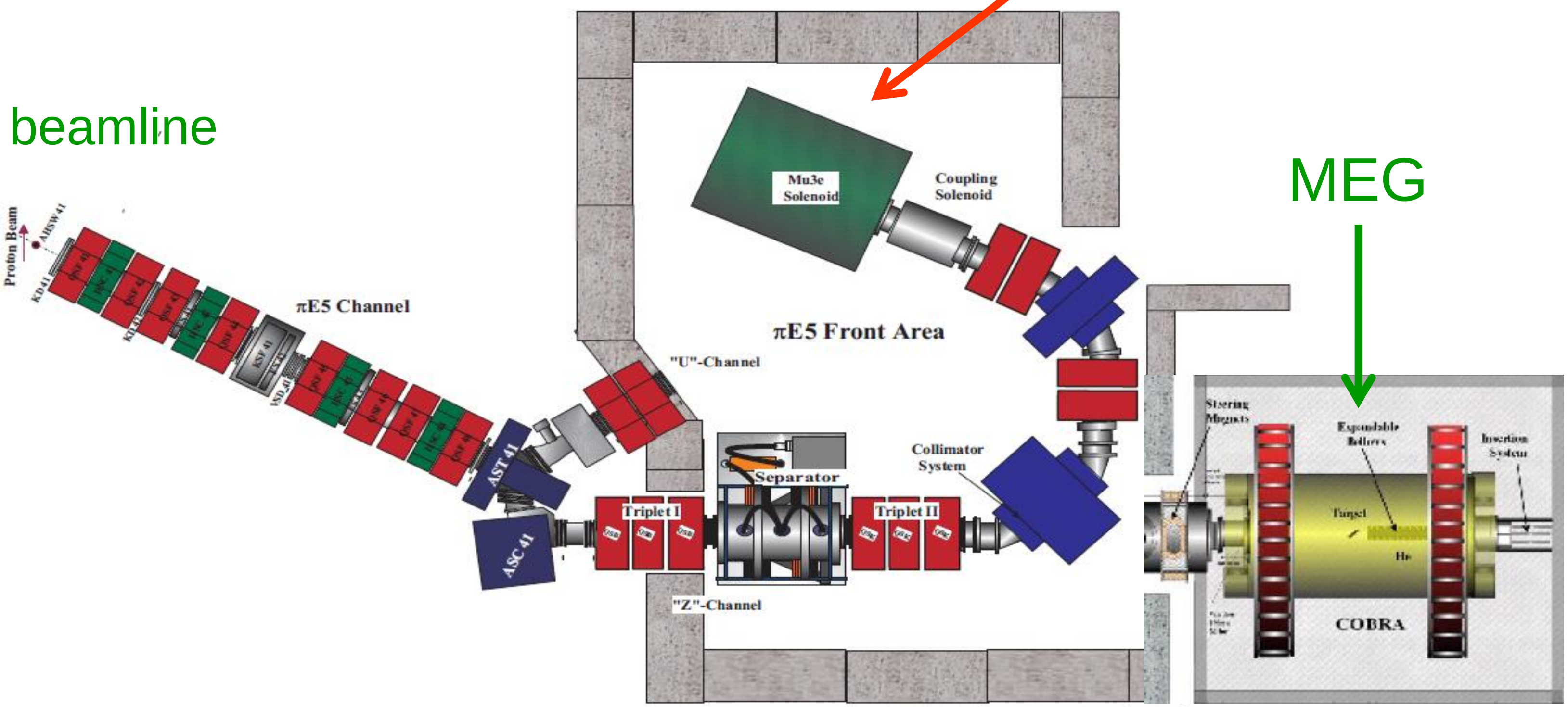
Mu3e – Phase I

MEG and Mu3e will share he same beam-line
can easily switch between the two experiments

Mu3e

πE5 beamline

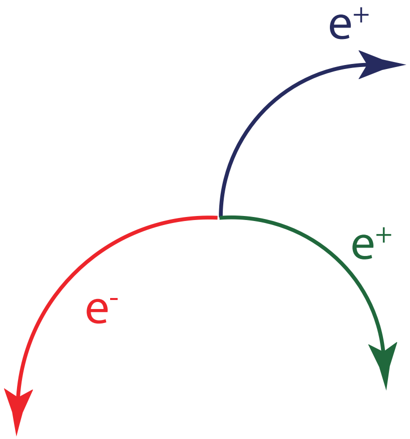
MEG



muon rates of 1.4 × 10^8 μ / s achieved in the past

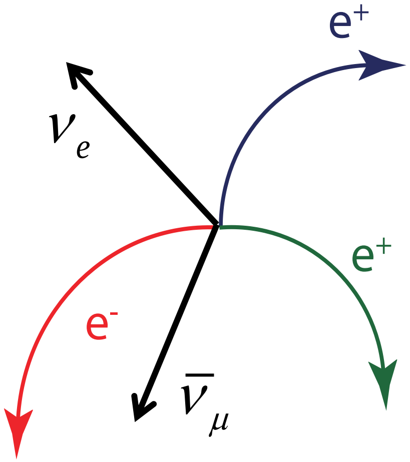
Signal and Backgrounds

signal

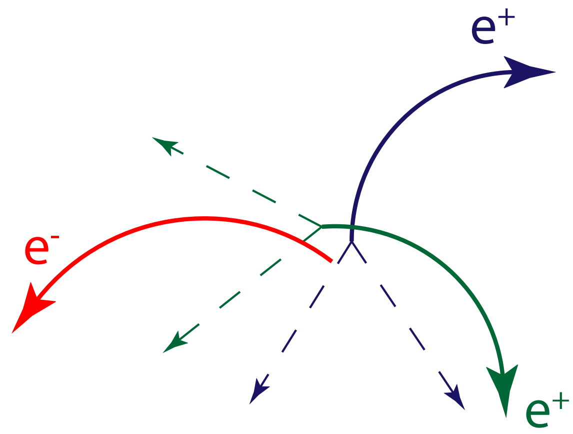


backgrounds

internal conversion



accidental



BR $(\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu) = 3.5 \times 10^{-5}$

Features

signal	internal conversion	accidental
common vertex	common vertex	no common vertex
$\Sigma \mathbf{p}_i = 0, \quad \Sigma E_i = m_\mu$	$\Sigma \mathbf{p}_i \neq 0, \quad \Sigma E_i < m_\mu$	$\Sigma \mathbf{p}_i \neq 0, \quad \Sigma E_i \neq m_\mu$
in time	in time	out of time

Rejecting the background requires

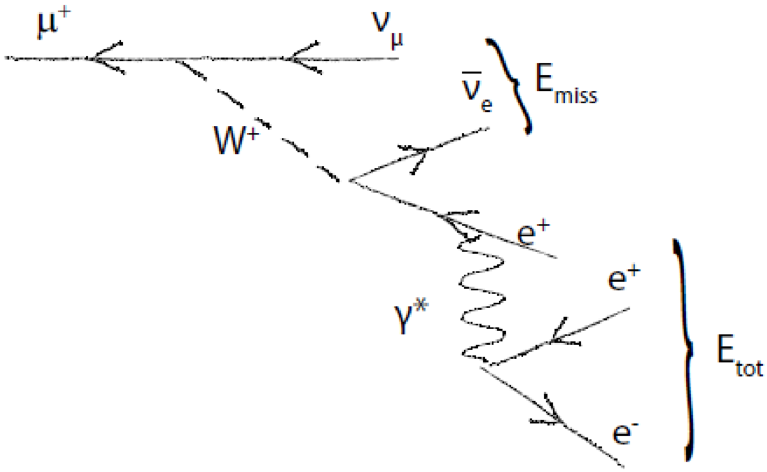
$\sigma_{vtx} < 300\ \mu m$

$\sigma_p < 0.5$ MeV/*c*

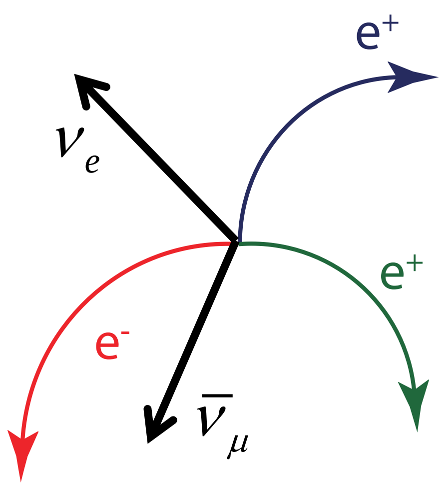
$\sigma_t < 0.5$ ns

Irreducible Background

μ radiative decay with internal conversion

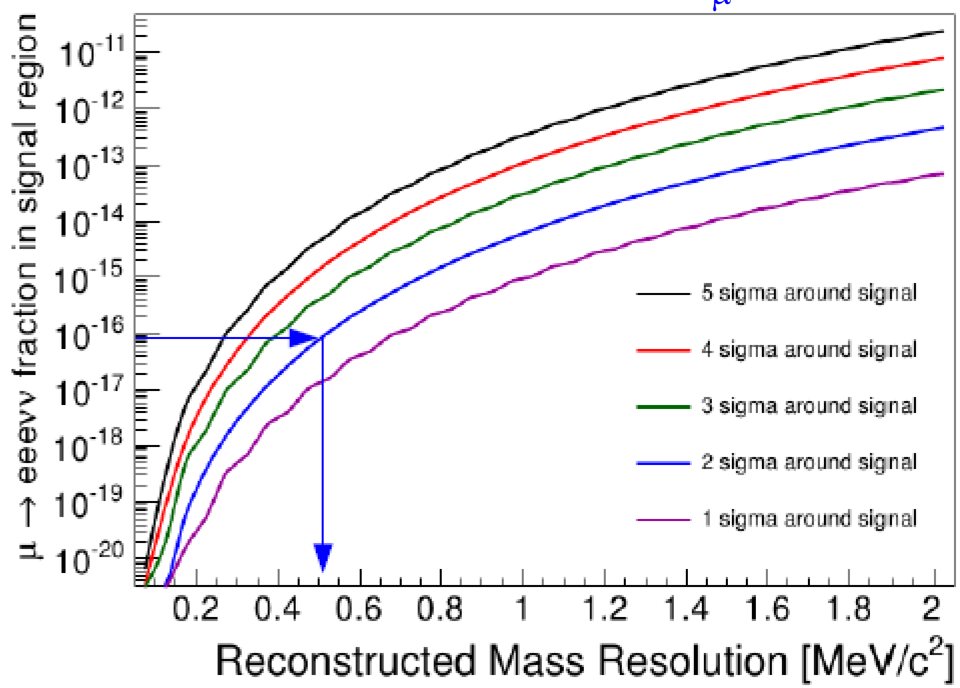


BR ($\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu$) = 3.5 x 10^{-5}



$\Sigma \mathbf{p}_i \neq 0, \quad \Sigma E_i \neq m_\mu$

$\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu$ fraction in signal region as a function of Δm_μ

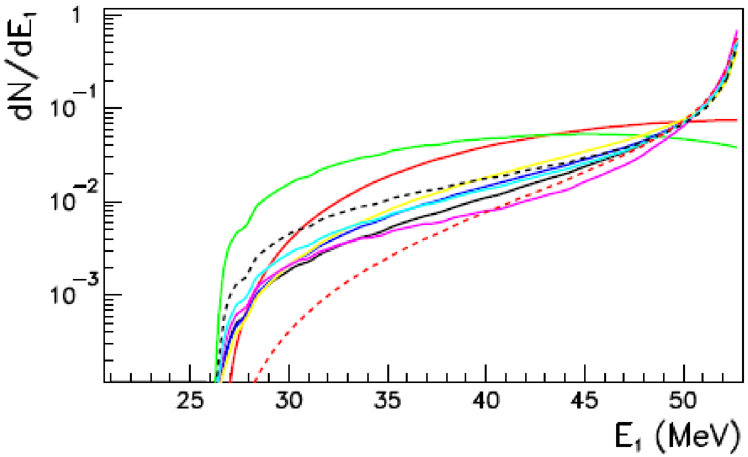


high momentum and energy resolution required to suppress this background

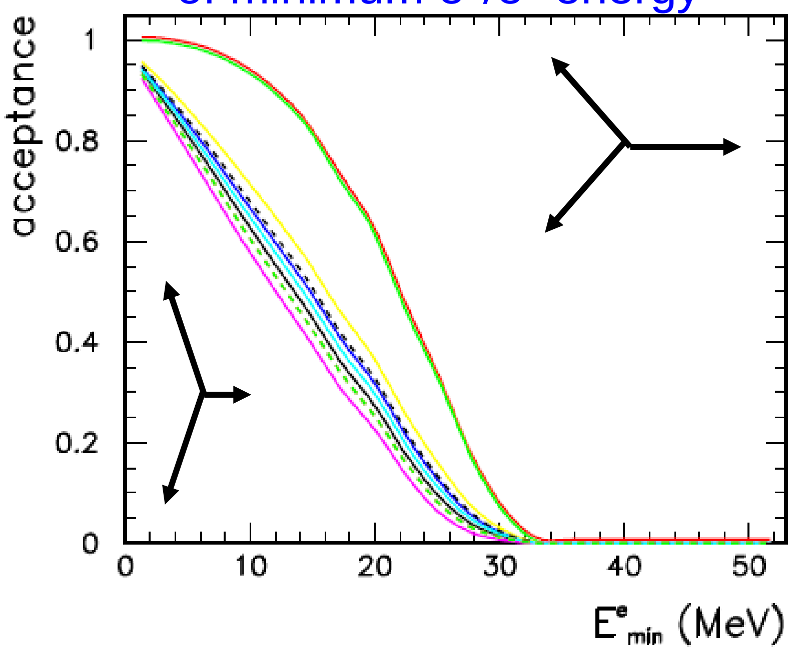
$\sigma_p < 0.5$ MeV/c and $\Delta m_\mu < 0.5$ MeV/c^2

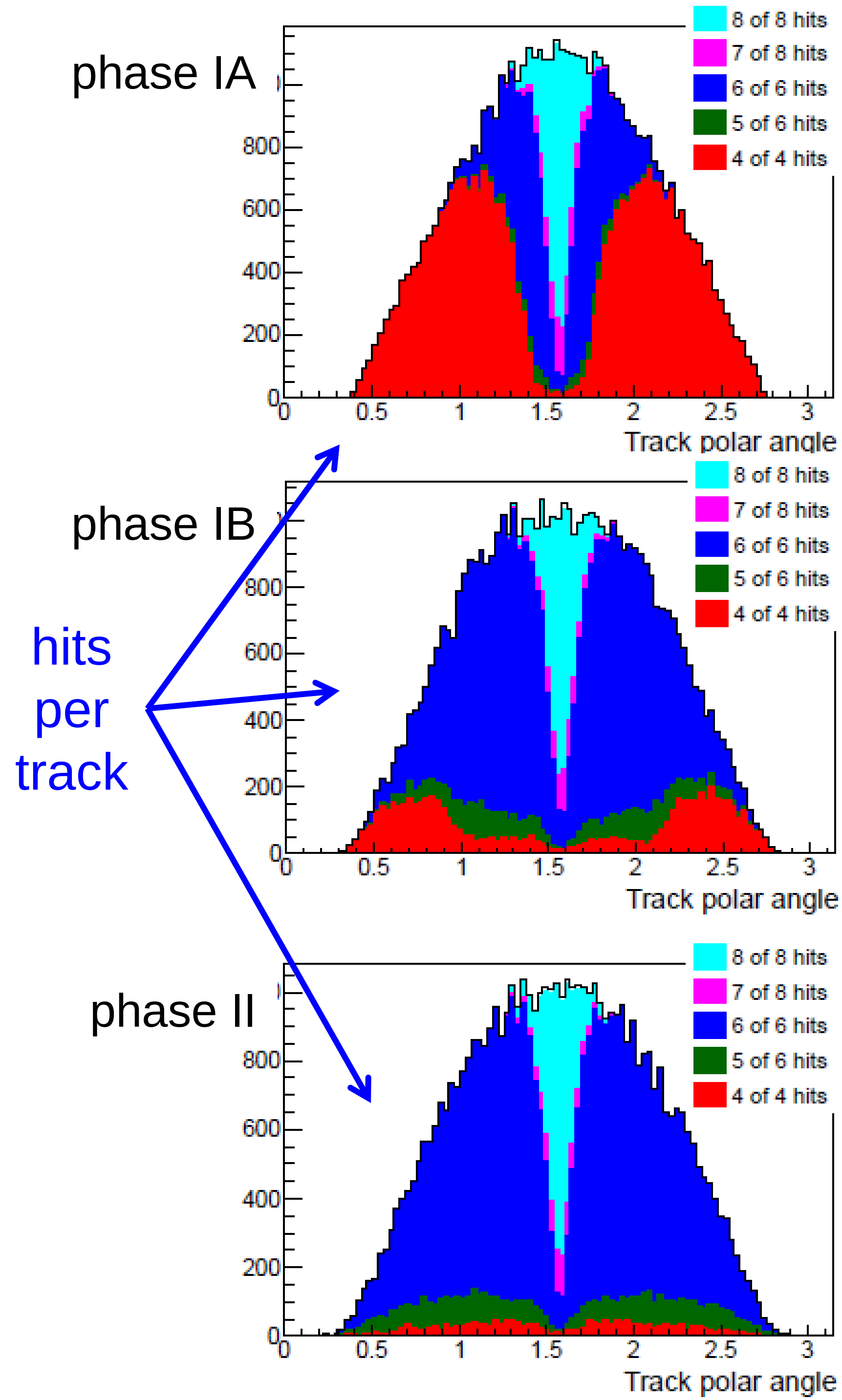
Acceptances

highest energy e^+ from $\mu^+ \to e^+ e^- e^+$



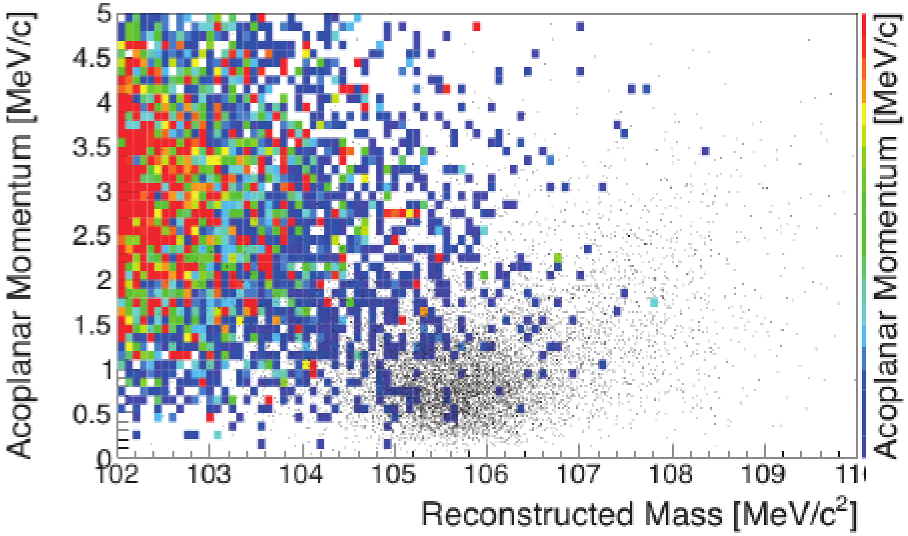
acceptance as a function of minimum e^+/e^- energy



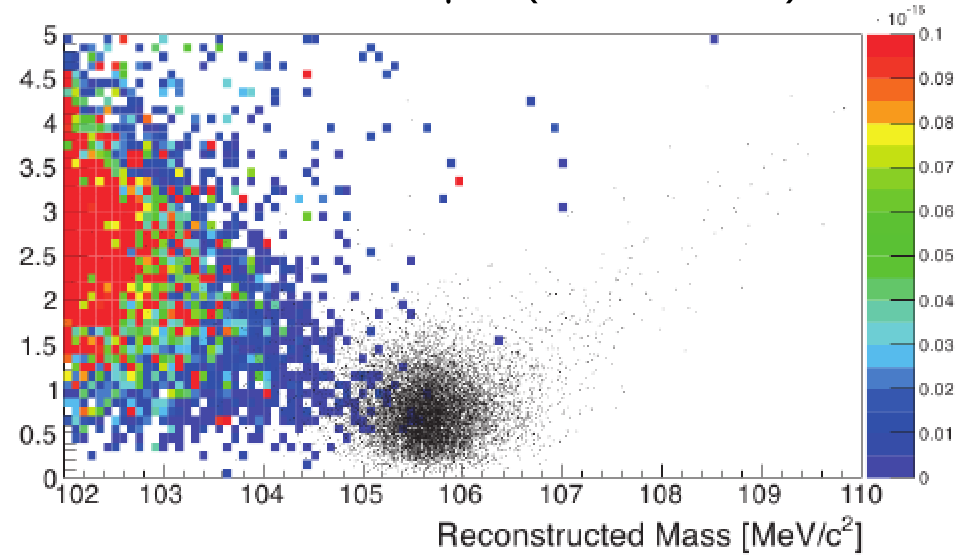


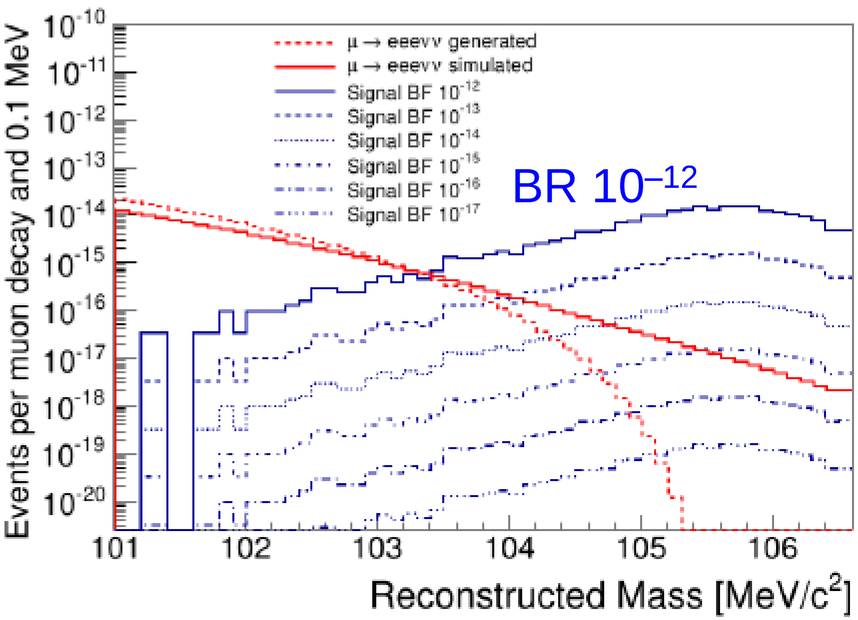
$\mu \to$ eee Signal Simulations

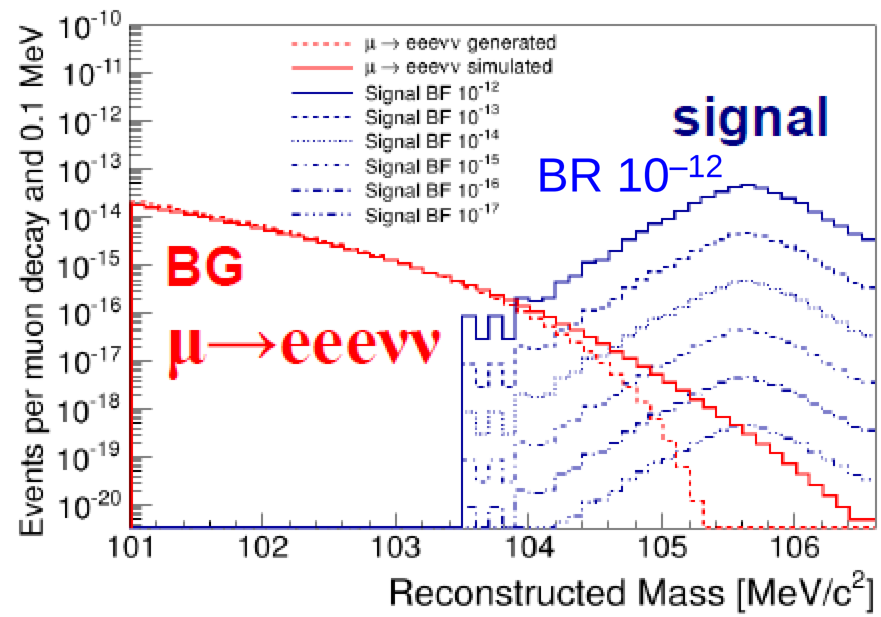
Phase IA: ~ 2×10^7 μ/s (central pixel)



Phase II: ~ 2×10^9 μ/s (full detector)

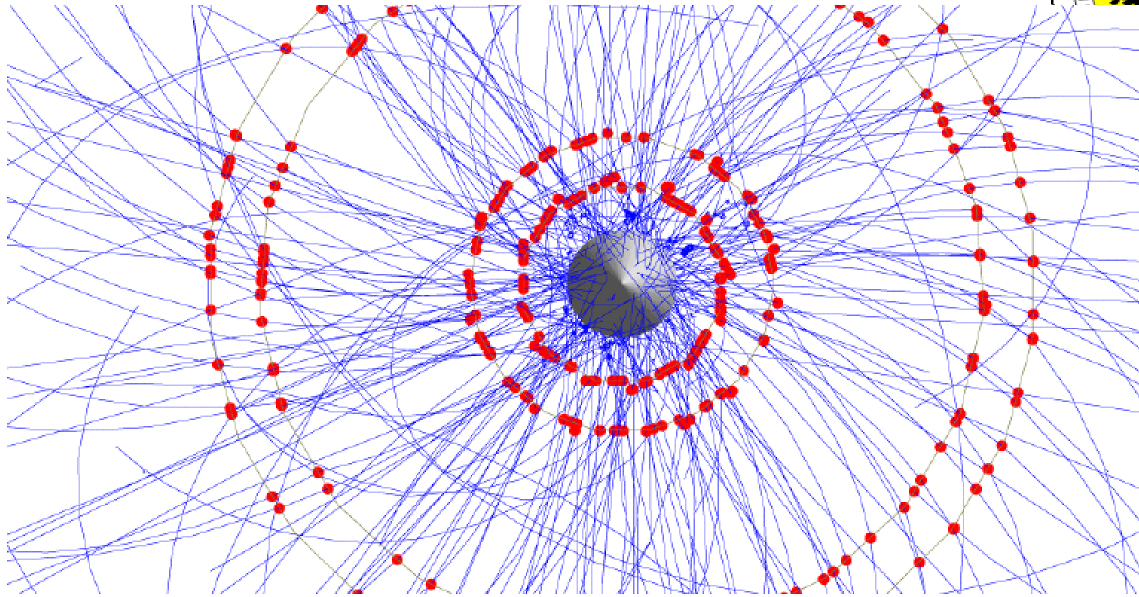




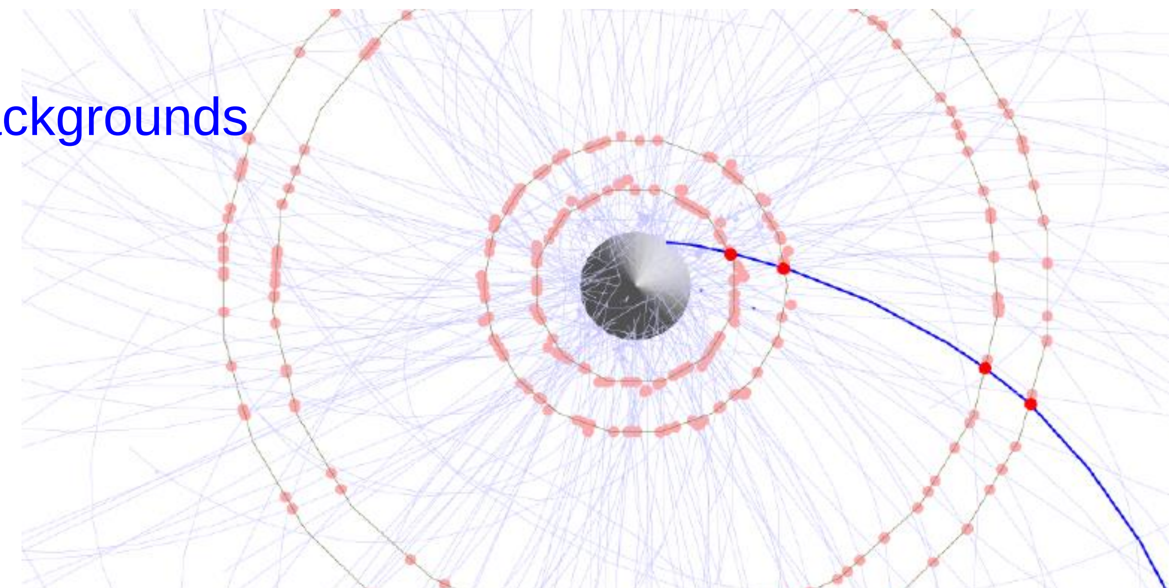


Timing

50 ns snapshot (readout frame): 100 μ decays



additional ToF information < 500 ps

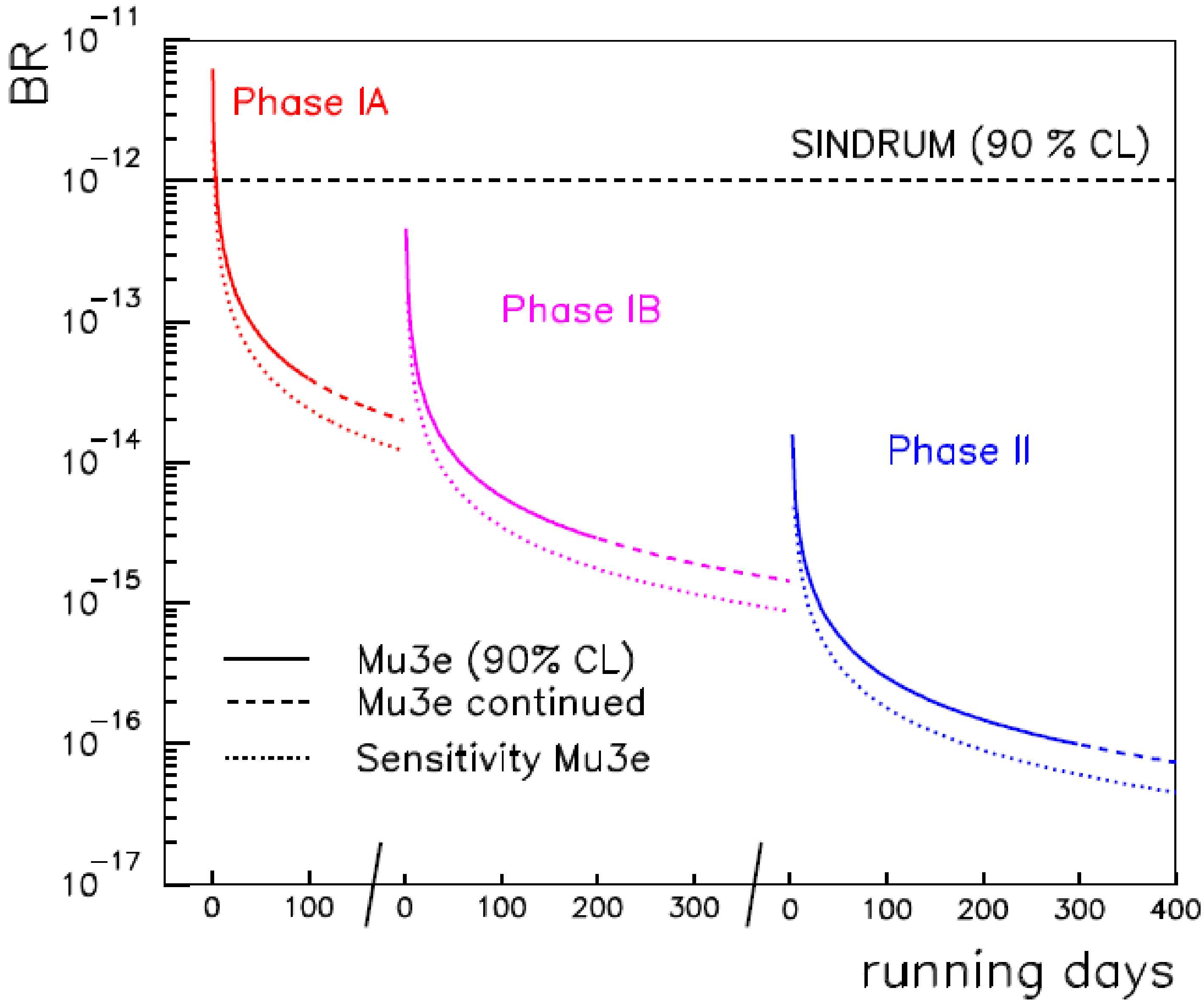


to suppress accidental backgrounds
requires excellent timing

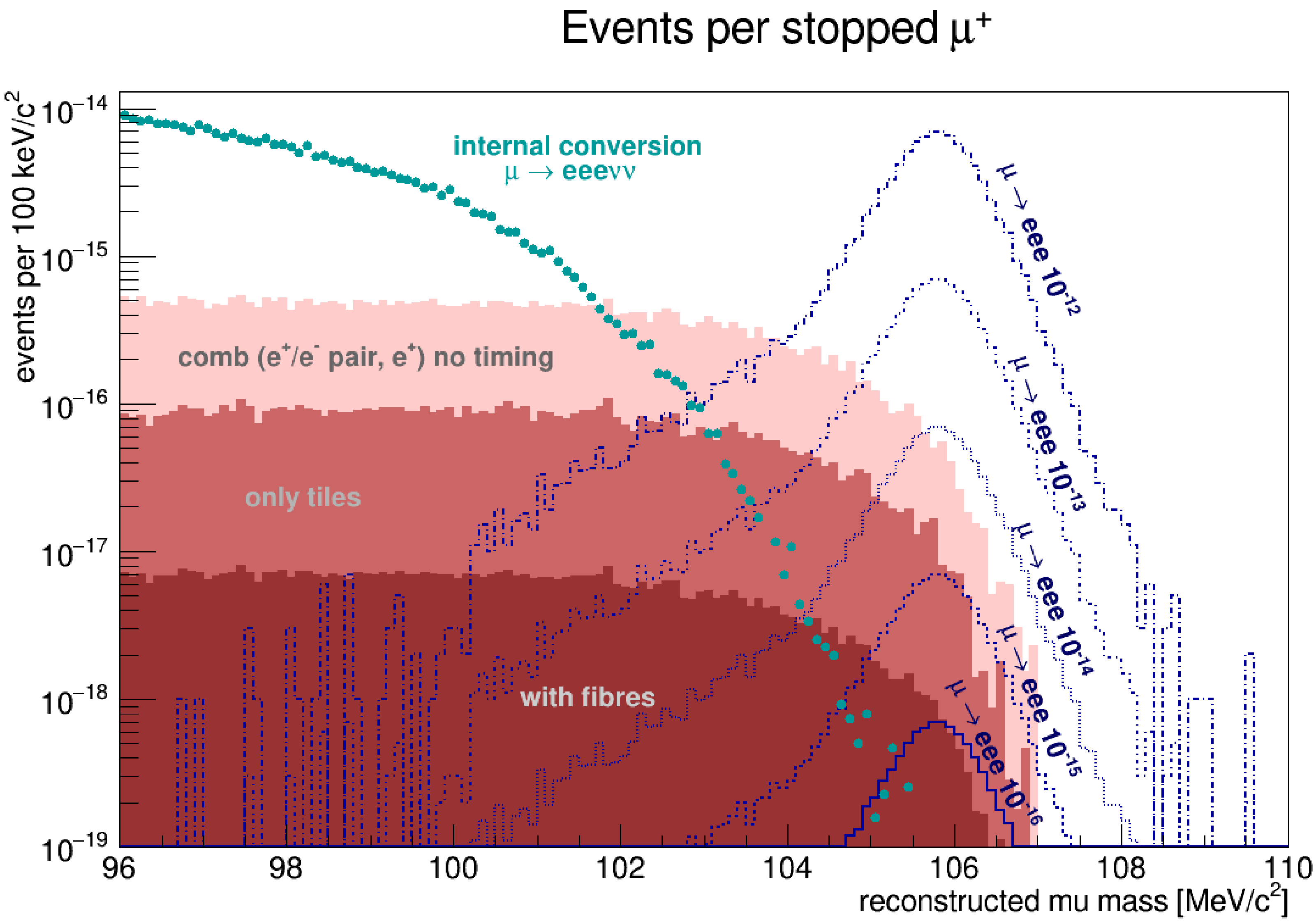
< 500 ps SciFis

< 100 ps scint. tiles

Sensitivity Projection



Background Suppression



background rejected with tracking and timing

(tracking alone not sufficient to reject accidental background)

Silicon Pixel Detector HV-MAPS

High Voltage Monolithic Active Pixel Sensors : HV-MAPS

readout logic and amplifiers embedded in the pixel n-well

thin active region (10 μm) $\rightarrow$ fast charge collection via drift

< 50 μm thickness

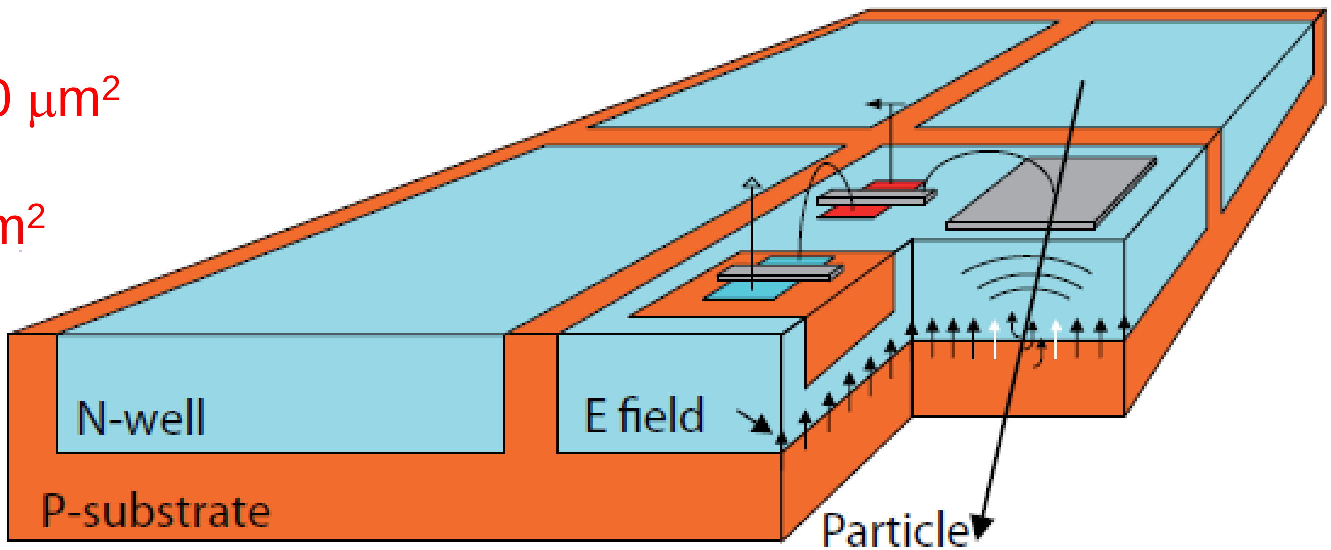
final pixel size 80×80 μm^2

final chip size 2×2 cm^2

> 270 M pixels

radiation hard

operated at 85 V



HV-MAPS R & D

Latest prototype: MUPIX 7

Characteristics

thickness 50 μm

pixel size $103 \times 80\ \mu m^2$

chip size $3.2 \times 3.2\ mm^2$

32×40 pixel matrix

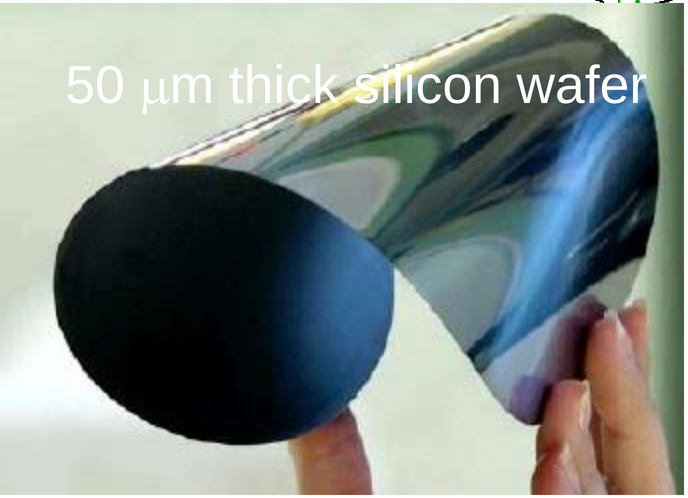
LVDS link 1.25 Gbit / s
(~30 M hits / s)

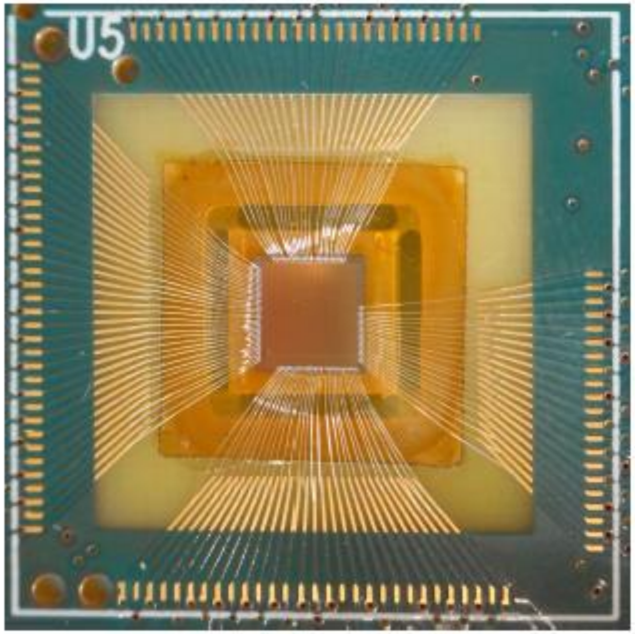
Performance

efficiency > 98 %

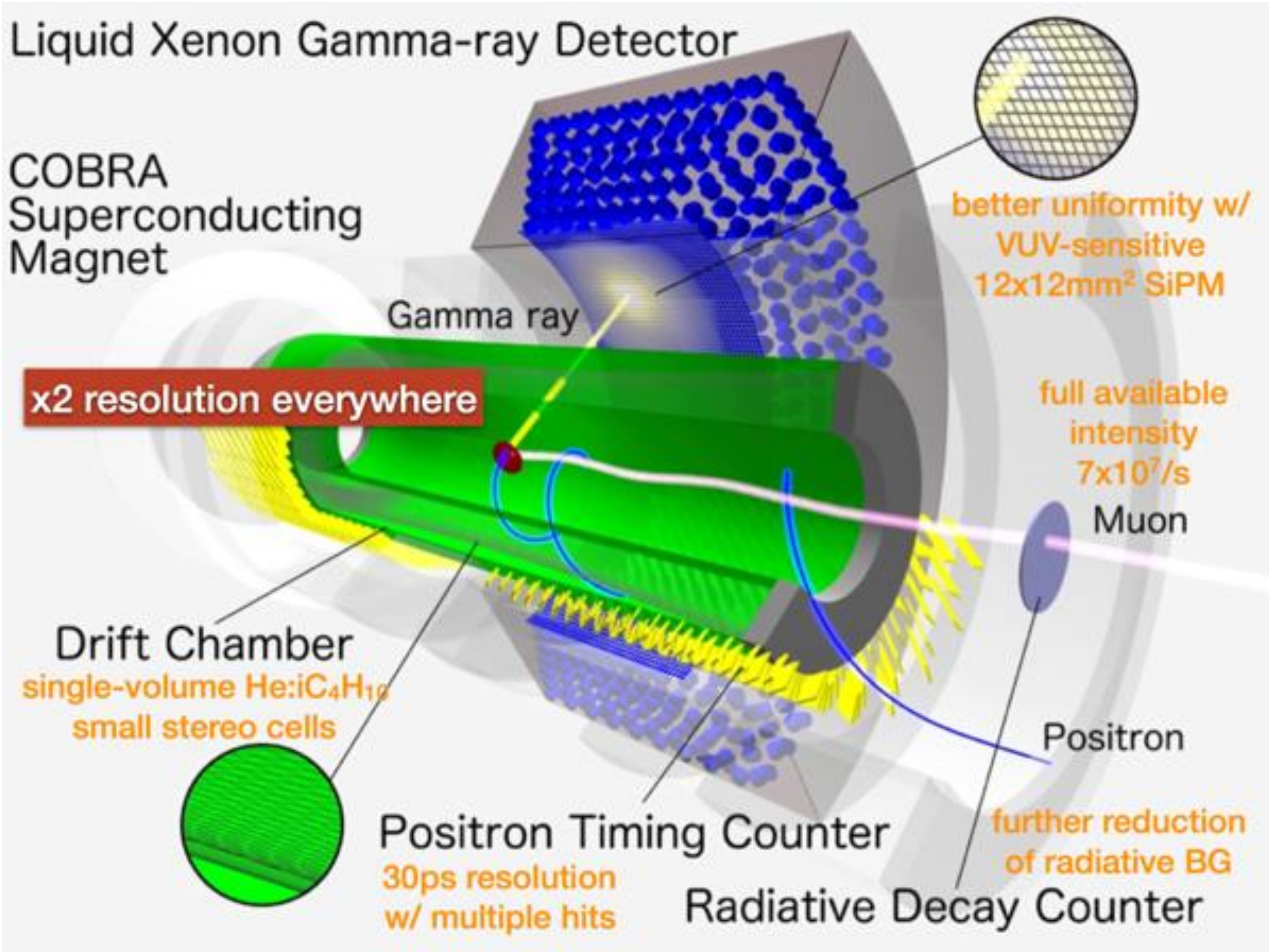
time resolution < 14 ns

First large scale $10 \times 21\ mm^2$ just submitted





MEG II at a Glance



MEG II aims at $B.R.(\mu \rightarrow e + \gamma) \leq 6 \times 10^{-14}$ @ 90% C.L. by the end of the decade

Summary

Mu3e will search for the neutrinoless muon decay $\mu \rightarrow e^+e^-e^+$
with a sensitivity at the level of 10^{-16} i.e. at the PeV scale
$\rightarrow$ suppress backgrounds below 10^{-16} (16 orders of magnitude !)

Novel technologies:

HV-MAPS (Si pixels, 50 μm thickness)
Si-PMs (SciFi fibers and tails)
they meet the requirements

Staged approach

Stage I (2018 – 2020)
~ 10^8 μ decays / s — BR($\mu \rightarrow$ eee) < 10^{-15}
approved in January 2013

Stage II (> 2020)
~ 2×10^9 μ decays / s — BR($\mu \rightarrow$ eee) < 10^{-16}
HiMB feasibility study already started

Construction in 2017 (incl. magnet)
Commissioning earliest 2018

Mu3e Collaboration

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