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 $\mu A \rightarrow e A$

$\mu \rightarrow e + \gamma$

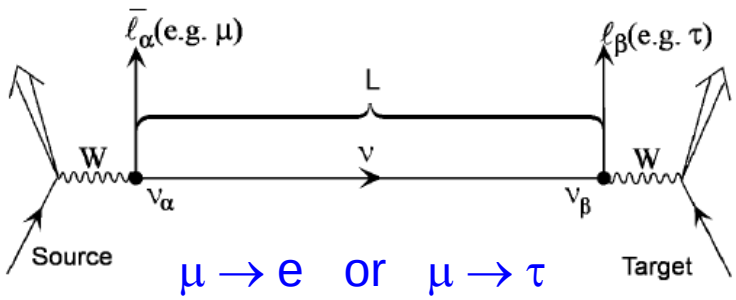
$\mu \rightarrow e\, e\, e$ have not been observed yet (down to 10^{-13} !).

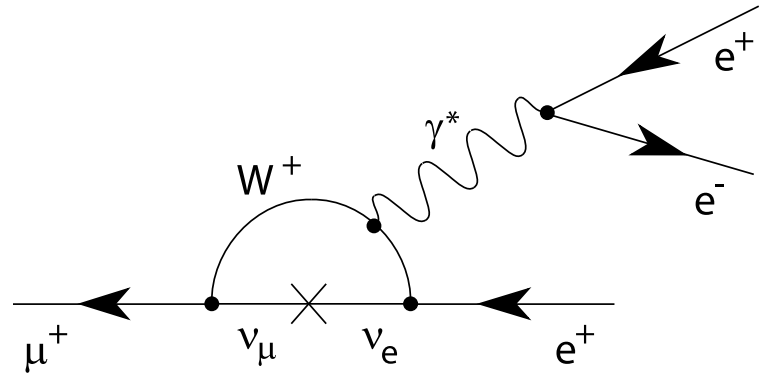
In SM ($m_\nu = 0$) Lepton Flavor is conserved absolutely (not by principle but by structure !)

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

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

neutrino oscillations

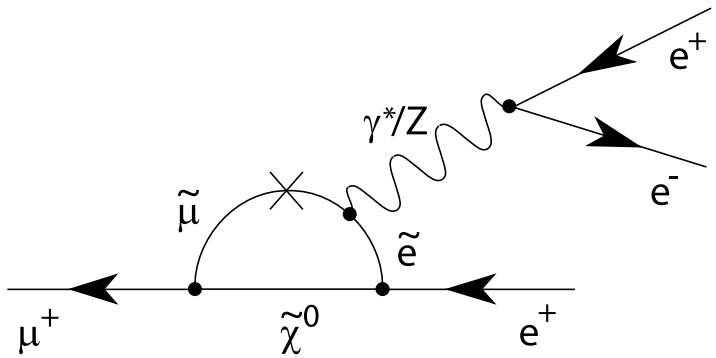


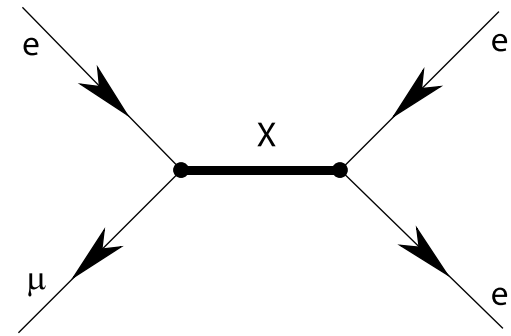


$$\sim \left(\frac{\Delta m_\nu^2}{M_W^2} \right)^2 \Rightarrow BR\left(\mu^\pm \rightarrow e^\pm e^+ e^-\right) < 10^{-54}$$

$\rightarrow$ 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

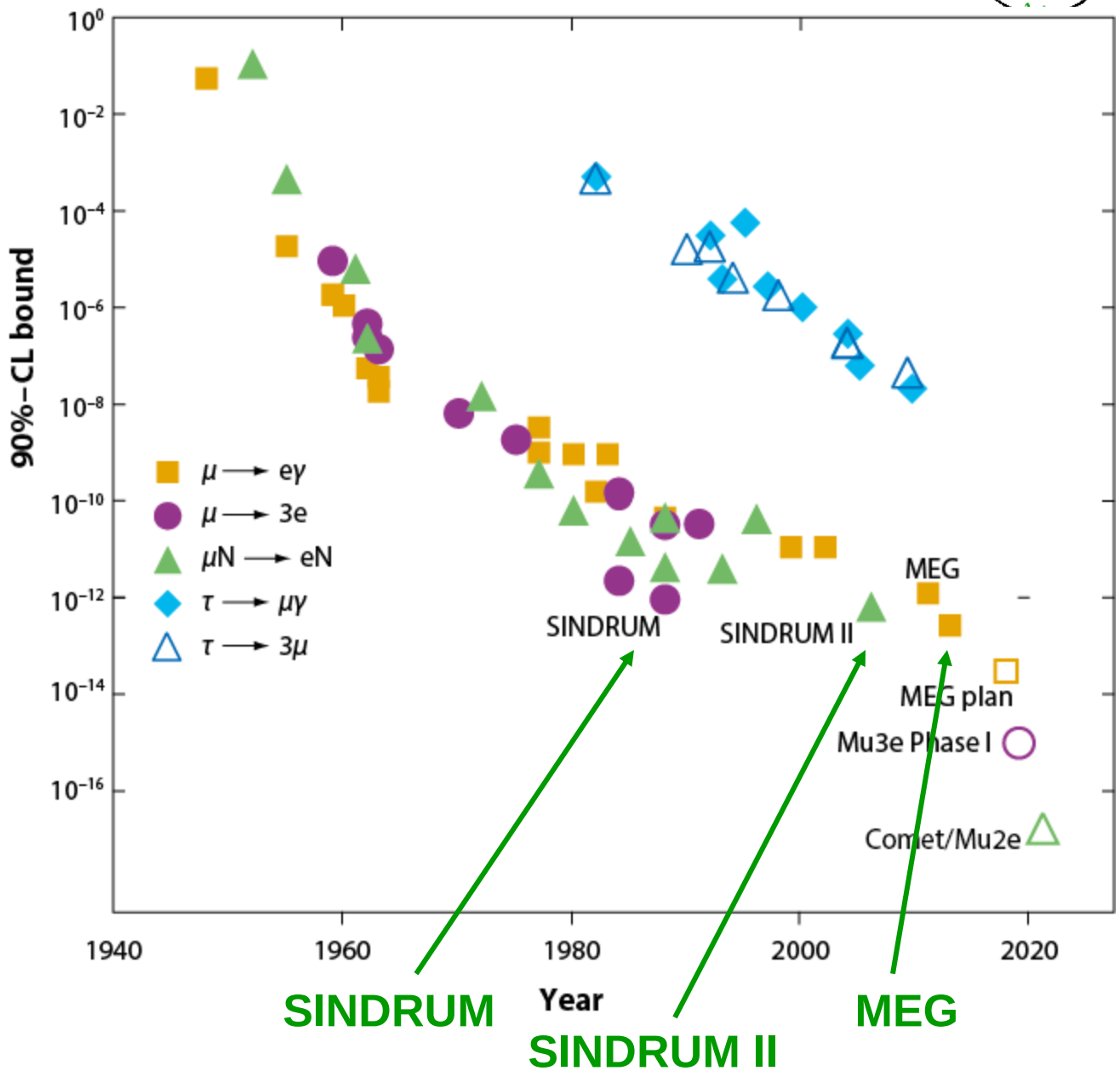
The best limits on LFV come from PSI muon experiments

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



Mu3e @ PSI : the Challenge

search for $\mu^+ \rightarrow e^+ e^- e^+$ with sensitivity BR ~ 10^{-16} (PeV scale)

$\tau_{(\mu \rightarrow eee)}$ > 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 $\mu^+ \rightarrow e^+ e^- e^+$ 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 $\mu^+ \rightarrow e^+e^-e^+$ decay in 10^{16} muon decays)

$\rightarrow$ observe ~10^{17} μ decays (over a reasonable time scale)

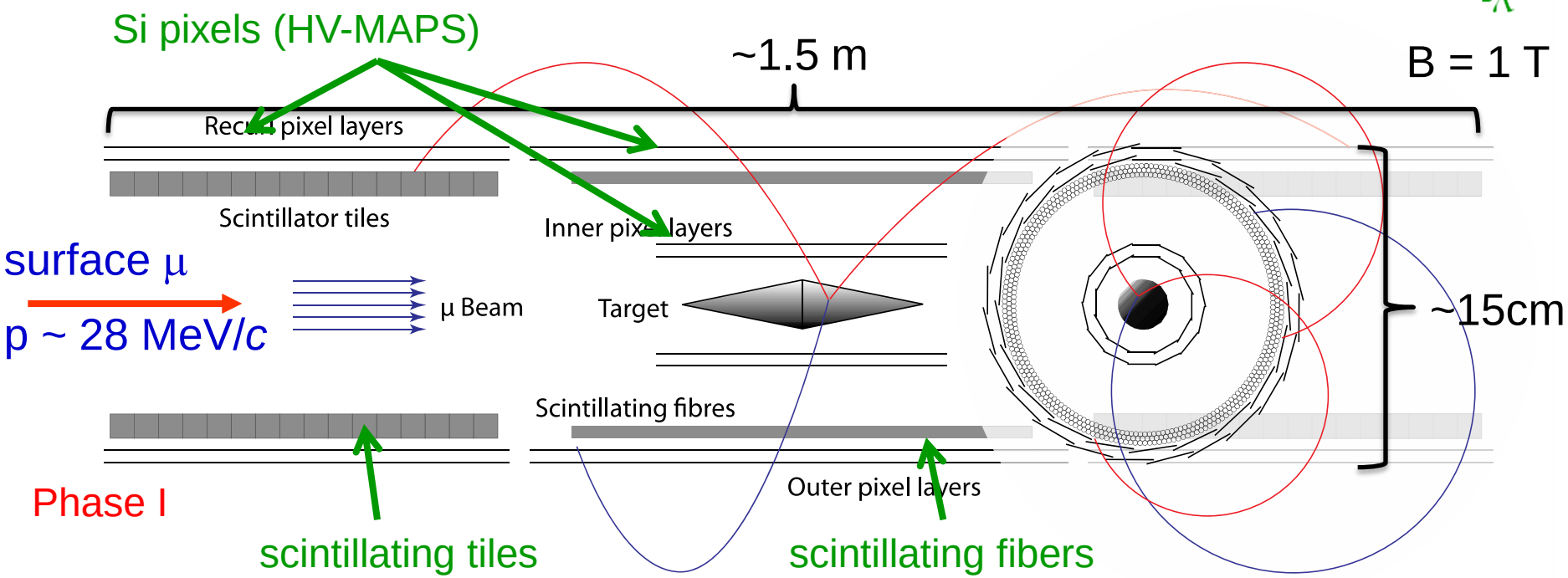
rate ~ 2×10^9 μ decays / s

$\rightarrow$ build a detector capable of measuring 2×10^9 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!)

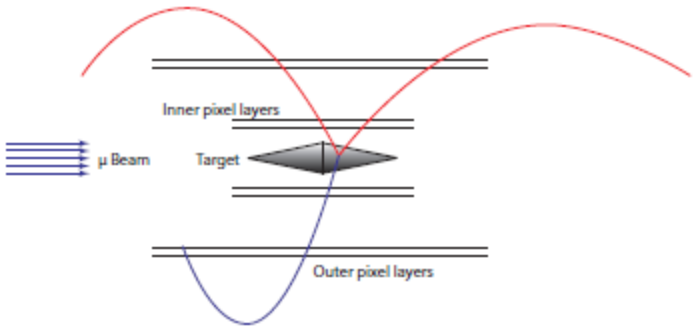
thin (< 0.1% X_0), **fast**, **high resolution** detectors
(minimum material, maximum precision)

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

20 k ToF channels (SciFi and Tiles)

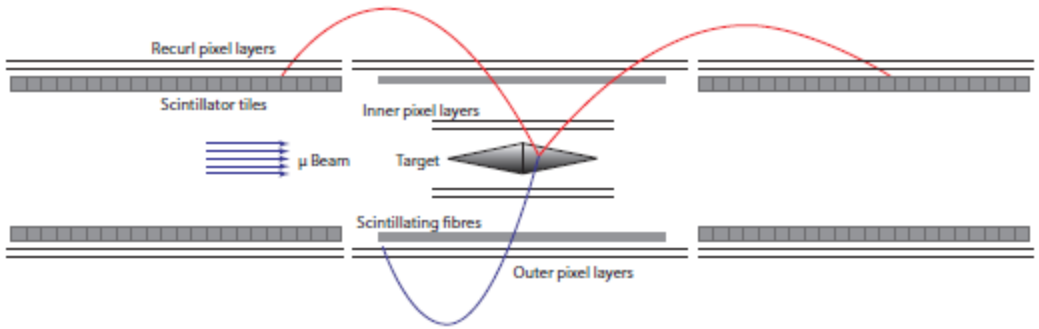
Staged Approach

Phase IA
rate ≤ 10^7 μ / s



only central pixel

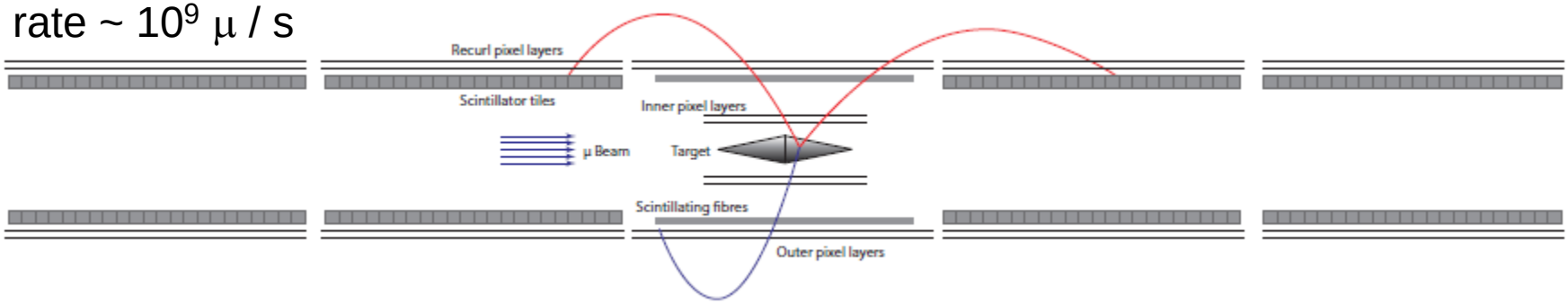
Phase IB
rate ~ 10^8 μ / s



+ inner recurl sta.
+ time of flight

Phase II
rate ~ 10^9 μ / s

+ outer recurl sta.



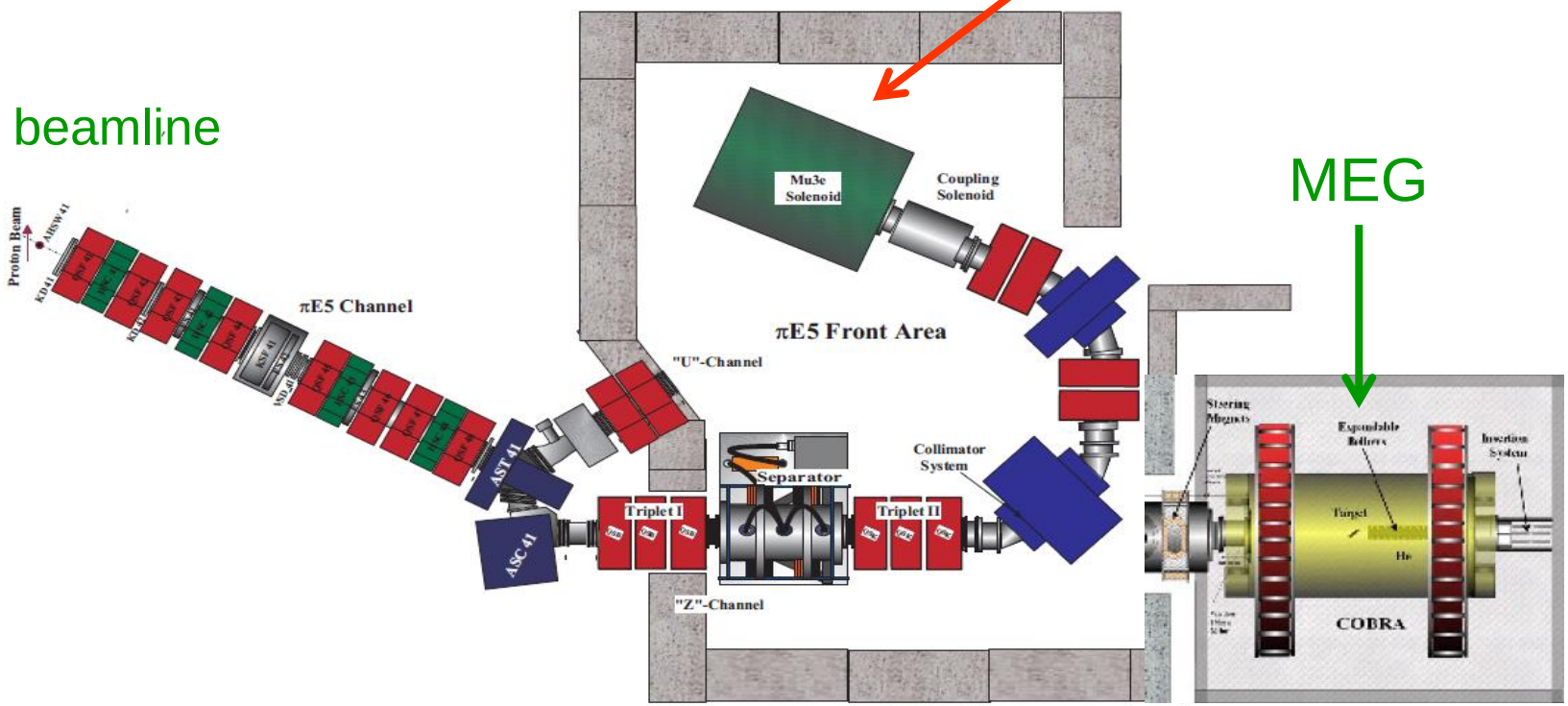
Mu3e – Phase I

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

Mu3e

πE5 beamline

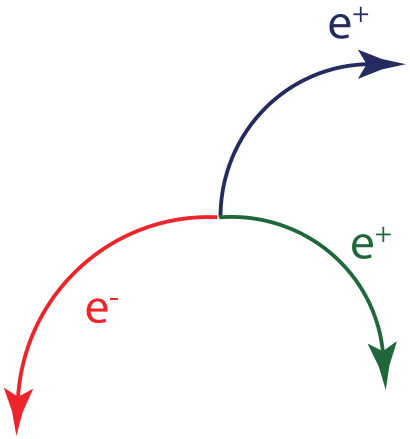
MEG



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

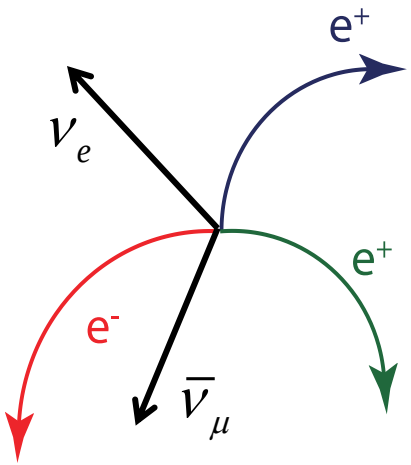
Signal and Backgrounds

signal

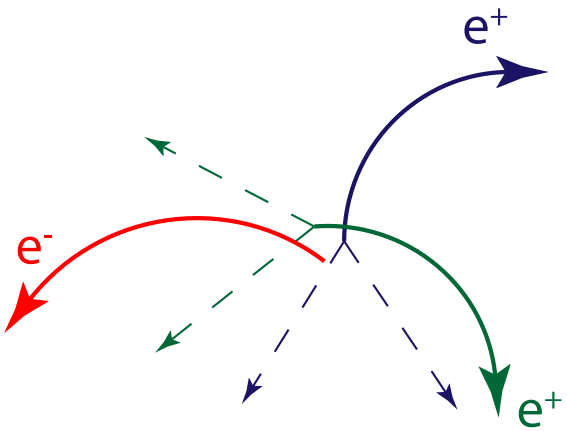


backgrounds

internal conversion



accidental



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

Features

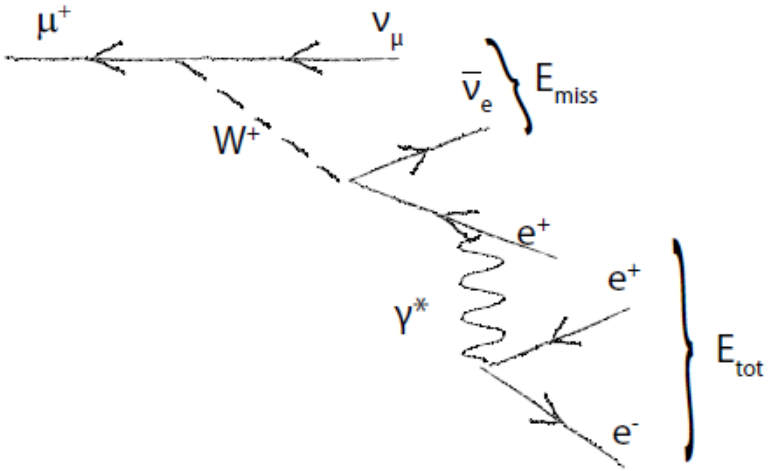
common vertex	common vertex	no common vertex
$\Sigma \mathbf{p}_i = 0$, $\Sigma E_i = m_\mu$	$\Sigma \mathbf{p}_i \neq 0$, $\Sigma E_i < m_\mu$	$\Sigma \mathbf{p}_i \neq 0$, $\Sigma E_i \neq m_\mu$
in time	in time	out of time

Rejecting the background requires

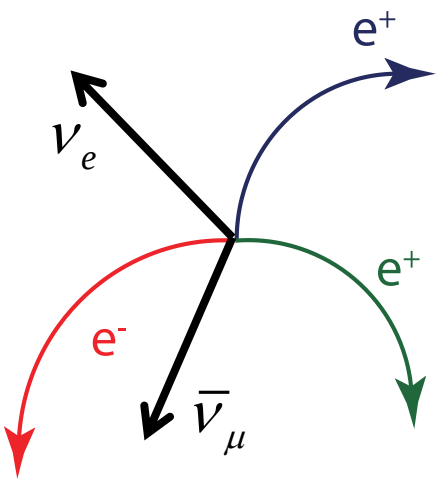
$\sigma_{vtx} < 300\ \mu m$
$\sigma_p < 0.5$ MeV/*c*
$\sigma_t < 0.5$ ns

Irreducible Background

μ radiative decay with internal conversion

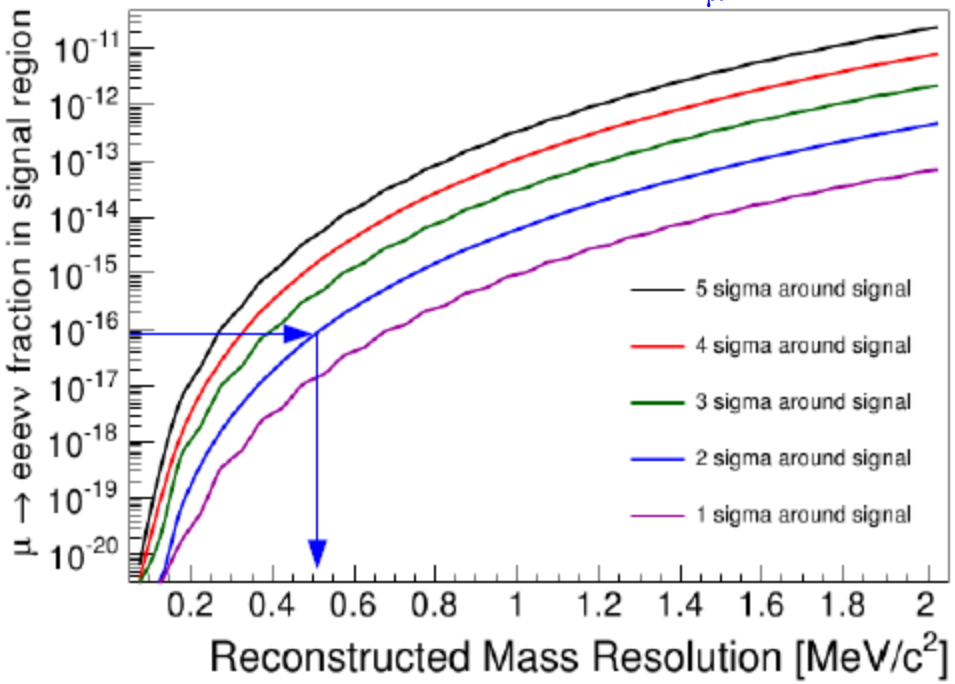


BR ($\mu^+ \to e^+ e^- e^+\nu_e\nu_\mu$) = 3.5 x 10^{-5}



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

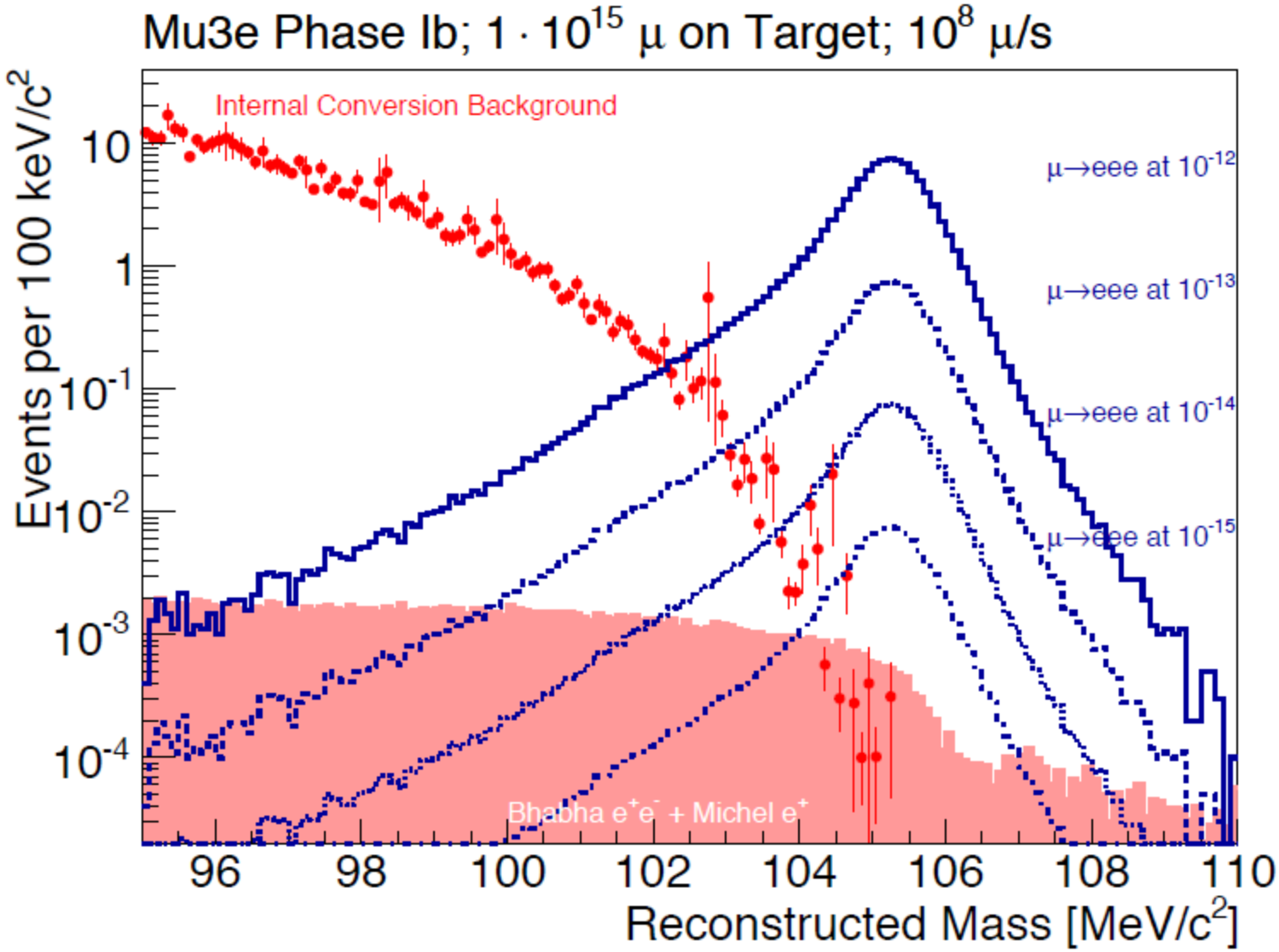
$\mu^+ \to e^+ e^- e^+\nu_e\nu_\mu$ fraction in signal region as a function of Δm_μ



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

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) → fast charge collection via drift

< 50 μm thickness

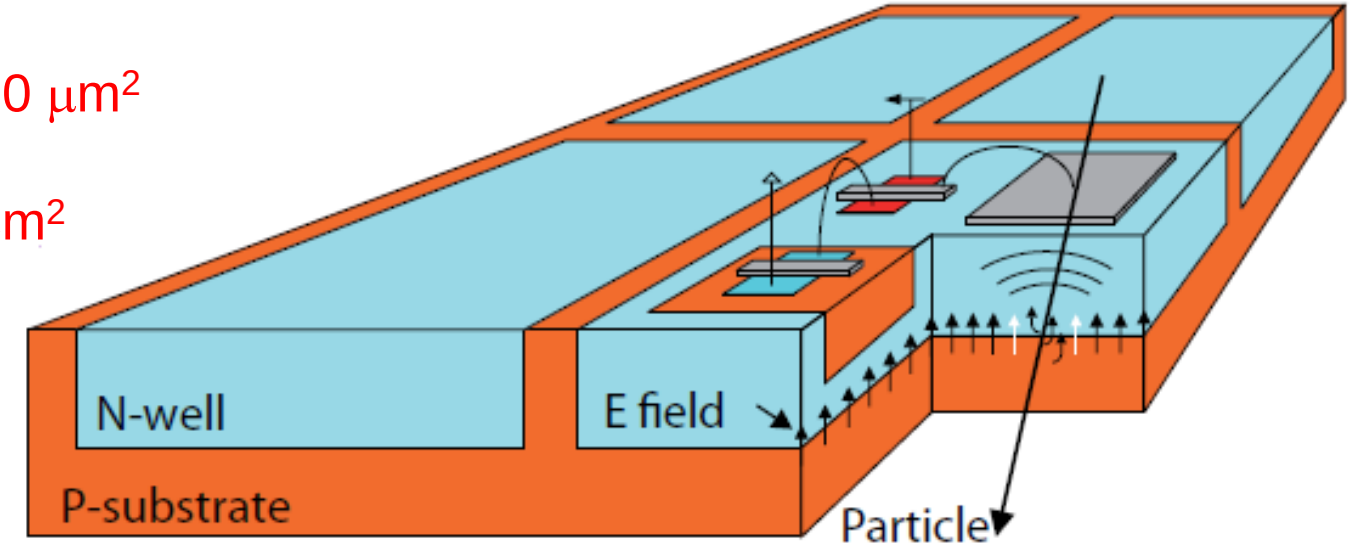
final pixel size 80 × 80 μm^2

final chip size 2 × 2 cm^2

> 270 M pixels

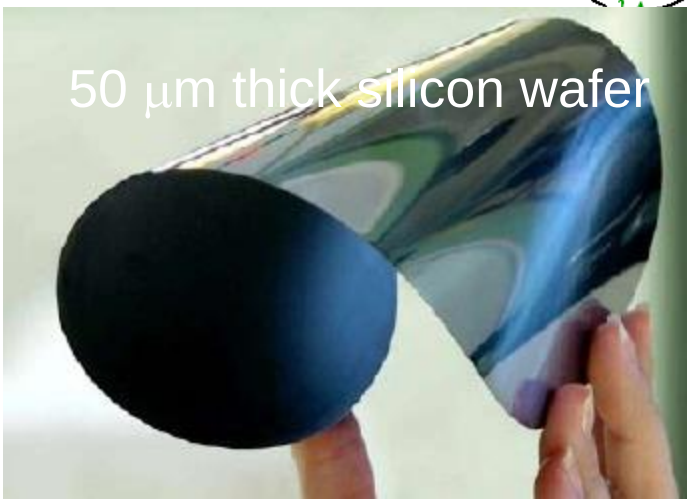
radiation hard

operated at 85 V



HV-MAPS R & D

Latest prototype: MUPIX 7



Characteristics

thickness 50 μm

pixel size 103 × 80 μm^2

chip size 3.2 × 3.2 mm^2

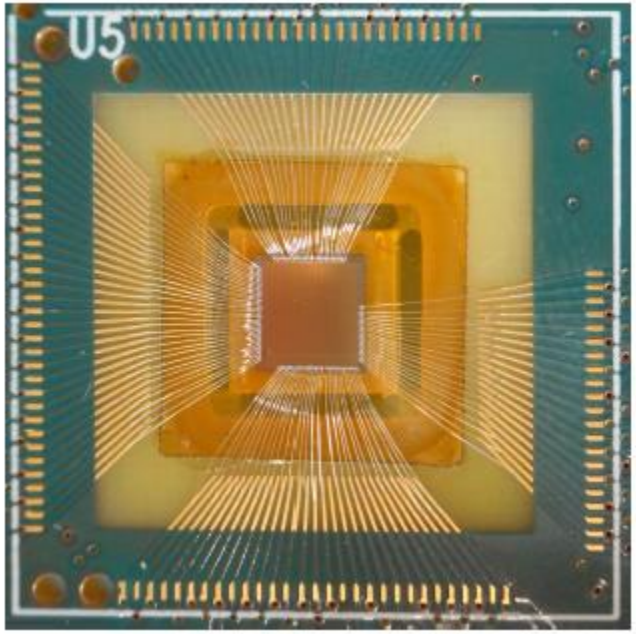
32 × 40 pixel matrix

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

Performance

efficiency > 98 %

time resolution < 14 ns



First large scale 10 × 21 mm^2 just submitted

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 $\qquad$ BR($\mu \rightarrow$ eee) < 10^{-15}

approved in January 2013

Stage II (> 2020)

~ 2×10^9 μ decays / s $\qquad$ 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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Heidelberg University

Karlsruhe Institute of Technology

Mainz University

Paul Scherrer Institut (PSI)

Physics Institute, University of Zurich

Institute for Particle Physics, ETH Zurich