The Mu3e Experiment @ PSI

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

Tau 2018
Amsterdam
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for the Mu3e collaboration

LFV in the "Standard Model"

Flavor Conservation in the charged lepton sector :

processes like $\mu\,A \rightarrow e\,A$

$\mu \rightarrow e + \gamma$

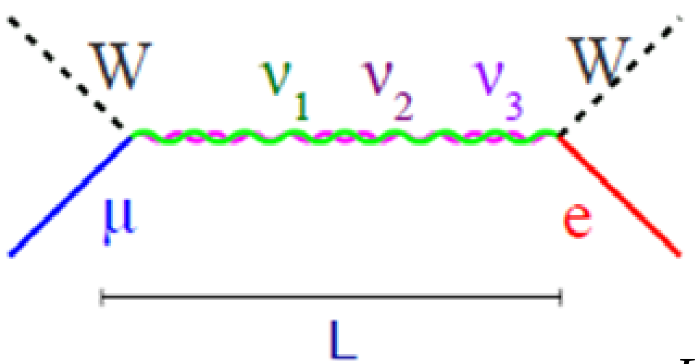
$\mu \rightarrow e\,e\,e$ have not been observed yet (down to 10^{-13} !).

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

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

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

$\mu \rightarrow e$ (or $\mu \rightarrow \tau$) via ν oscillations

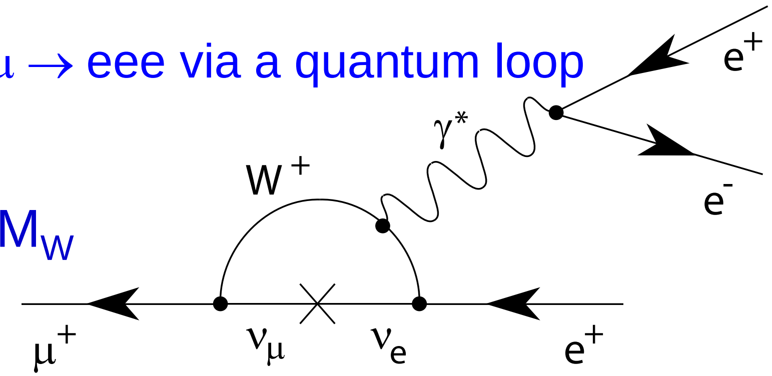


$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) = \sin^2(2\vartheta)\sin^2(\Delta m^2_{\alpha\beta}\frac{L}{4E})$$

L $\rightarrow$ 1 / M_W

$E_\nu \rightarrow M_W$

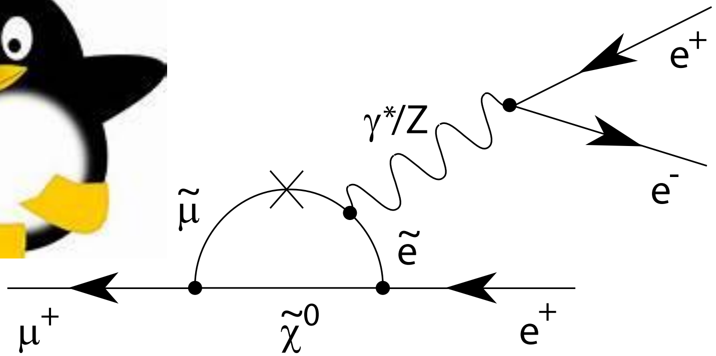
$\mu \rightarrow$ eee via a quantum loop



$$\propto \frac{\Delta m_\nu^4}{M_W^4} \Rightarrow BR\left(\mu^\pm \rightarrow e^\pm e^+ e^-\right) < 10^{-54}$$

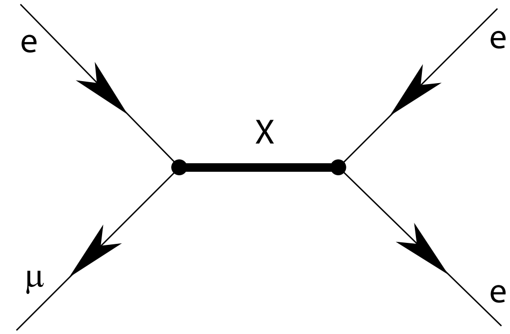
measurement not affected by SM processes

New Physics in $\mu \rightarrow eee$



Dipole (Loop Diagrams)

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



Contact (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

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

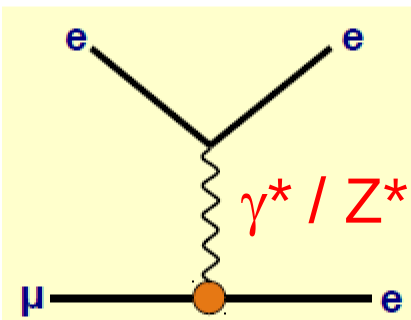
effective charge LFV Lagrangian (“toy” model) Kuno & Okada

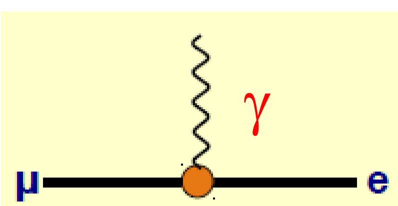
$$L_{LFV} = \frac{m_\mu}{\Lambda^2 (1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2 (1+\kappa)} J_\sigma^{e\mu} J^{\sigma,ee}$$

Λ = common effective scale

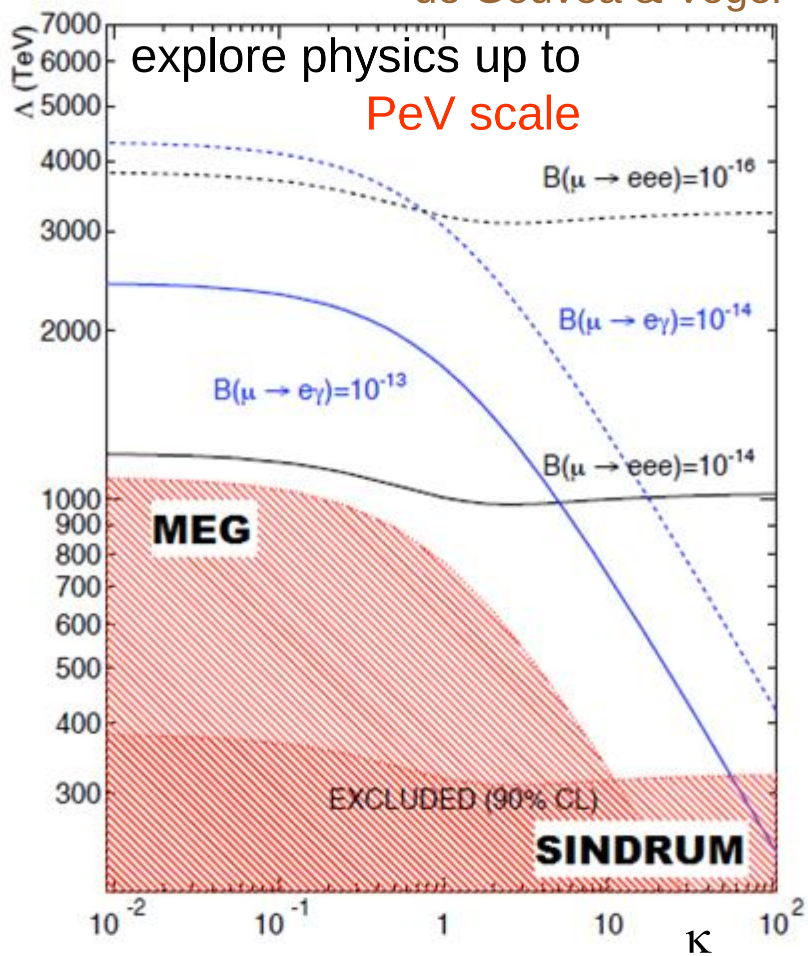
κ = “contact” vs “loop”

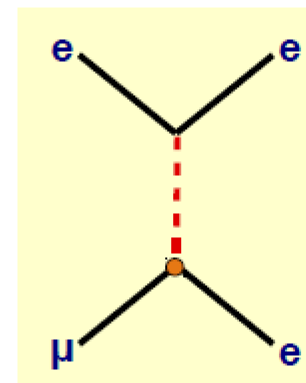
de Gouvea & Vogel





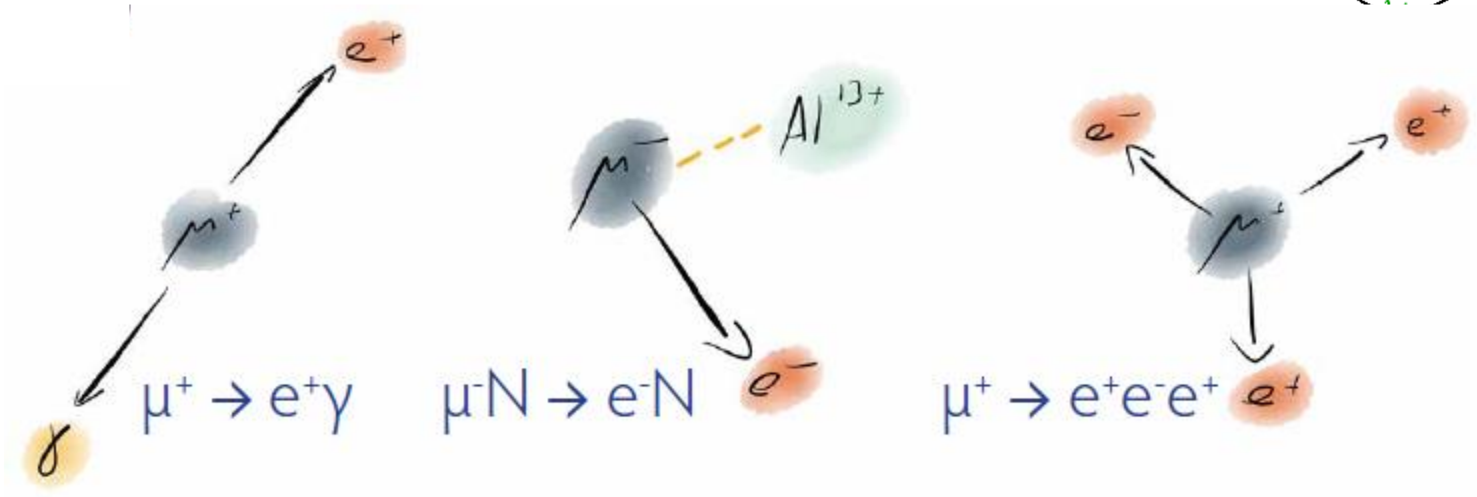
$\kappa \to 0$





$\kappa \to \infty$

LFV μ Decays : Experimental Signatures



kinematics :	2-body decay monochromatic e^+, γ back to back	quasi 2-body decay mono-energetic 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

Mu3e @ PSI : the Challenge

search for $\mu^+ \rightarrow e^+ e^- e^+$ with sensitivity BR ~ 10^{-16} (PeV scale)
$\tau_{(\mu \rightarrow eee)}$ > 1000 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}

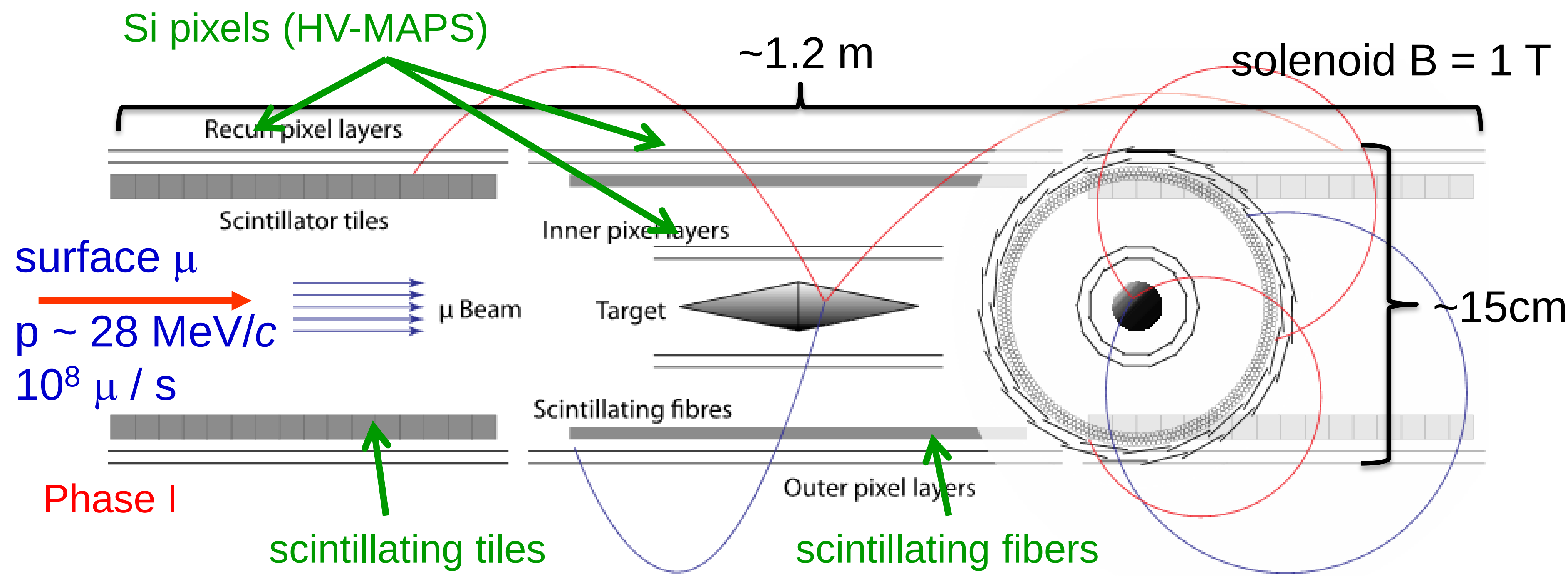
find or exclude $\mu^+ \rightarrow e^+ e^- e^+$ at the 10^{-16} level
4 orders of magnitude over previous experiments (SINDRUM @ PSI)

aim for sensitivity / staged approach
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 x 10^9 μ decays / s
$\rightarrow$ build a detector capable of measuring 2 x 10^9 μ decays / s
minimum material, maximum precision

project (Phase I) approved in January 2013

Mu3e Baseline Design – Phase I



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

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

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

10 k ToF channels (SciFi and Tiles)

Muons @ PSI

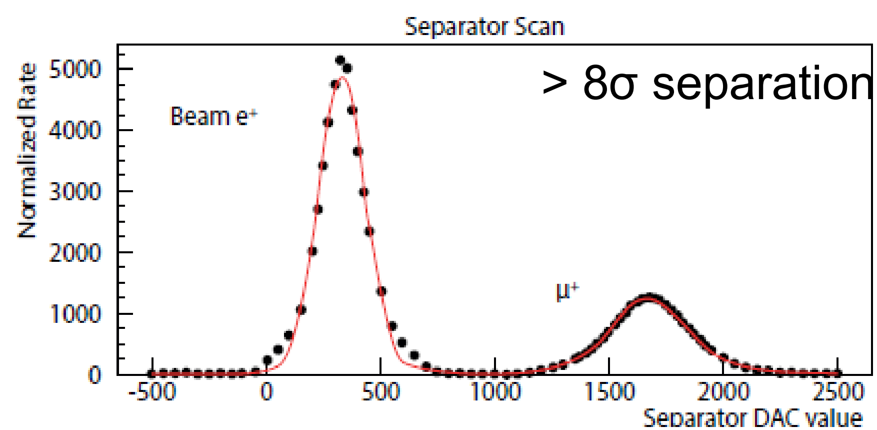
most intense DC muon beam

590 MeV/c proton cyclotron, 1.4 MW

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)

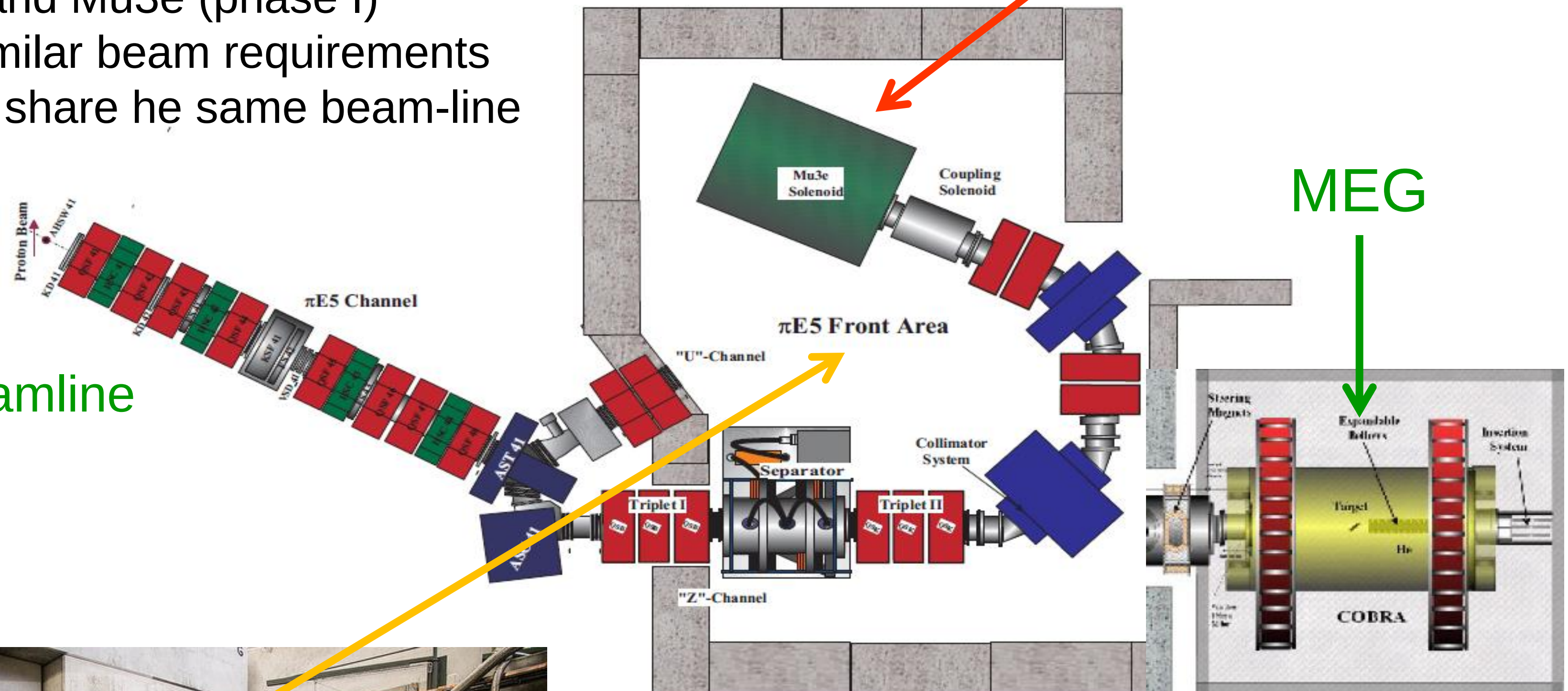
SINQ (spallation neutron source)
could even provide 5×10^{10} μ / s
High-intensity Muon Beamline (HiMB)



e / μ 12 cm separation at last collimator

Mu3e – Phase I

MEGII and Mu3e (phase I)
have similar beam requirements
and will share he same beam-line

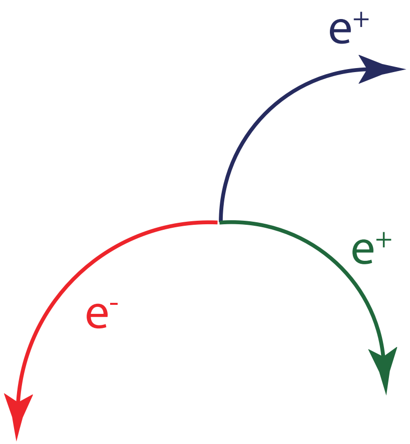


can easily switch between the two experiments
intensity O(10^8 muon/s)
low momentum p = 28 MeV/c
small straggling
good identification of the decay region

Proof-of-Principle:
delivered 8 x 10^7 muon/s during 2016 test beam

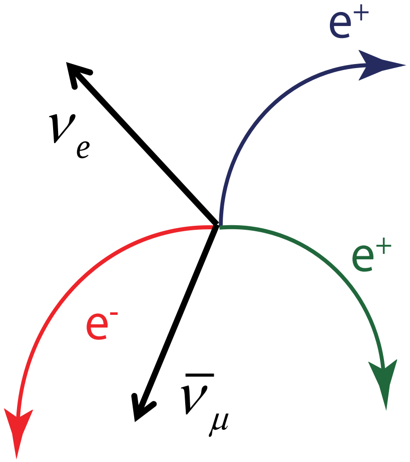
Signal and Backgrounds

signal

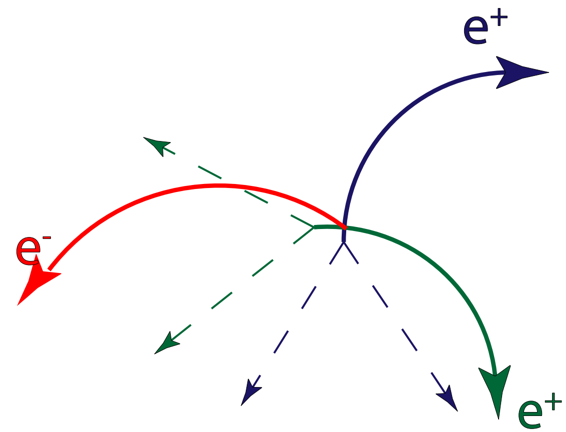


backgrounds

internal conversion



accidental



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

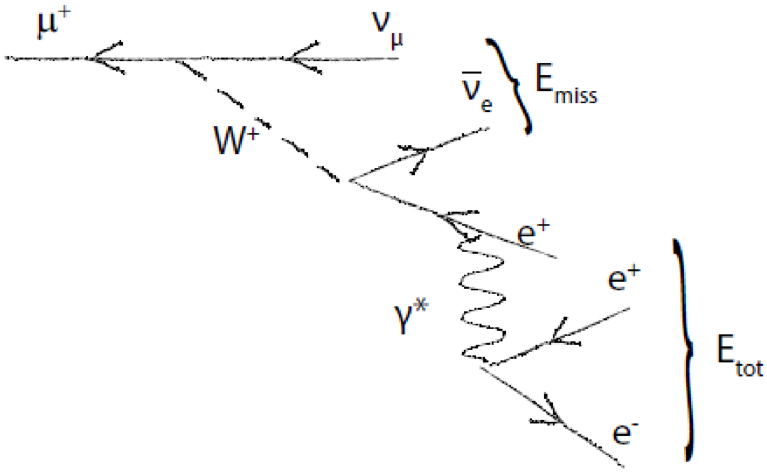
features

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

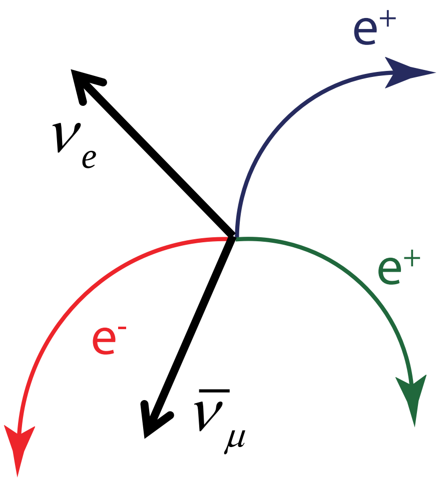
rejecting the background requires:
- $\sigma_{vtx} < 300\ \mu m$
- $\sigma_p < 0.5$ MeV/c
- $\sigma_t < 0.5$ ns

Irreducible Background

μ radiative decay with internal conversion

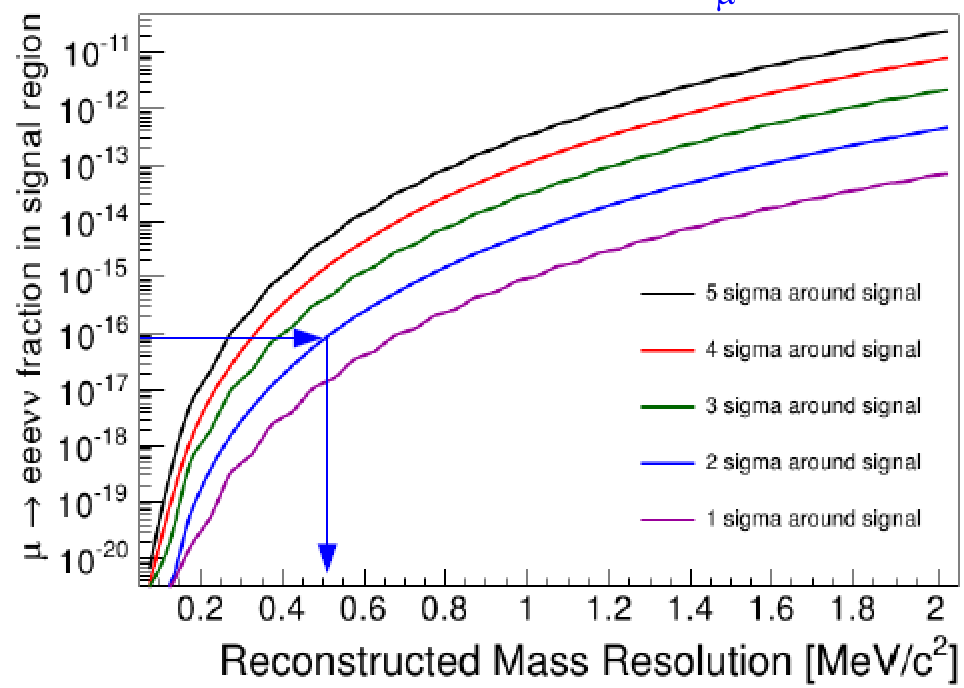


BR ($\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu$) = 3.5 x 10^{-5}



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

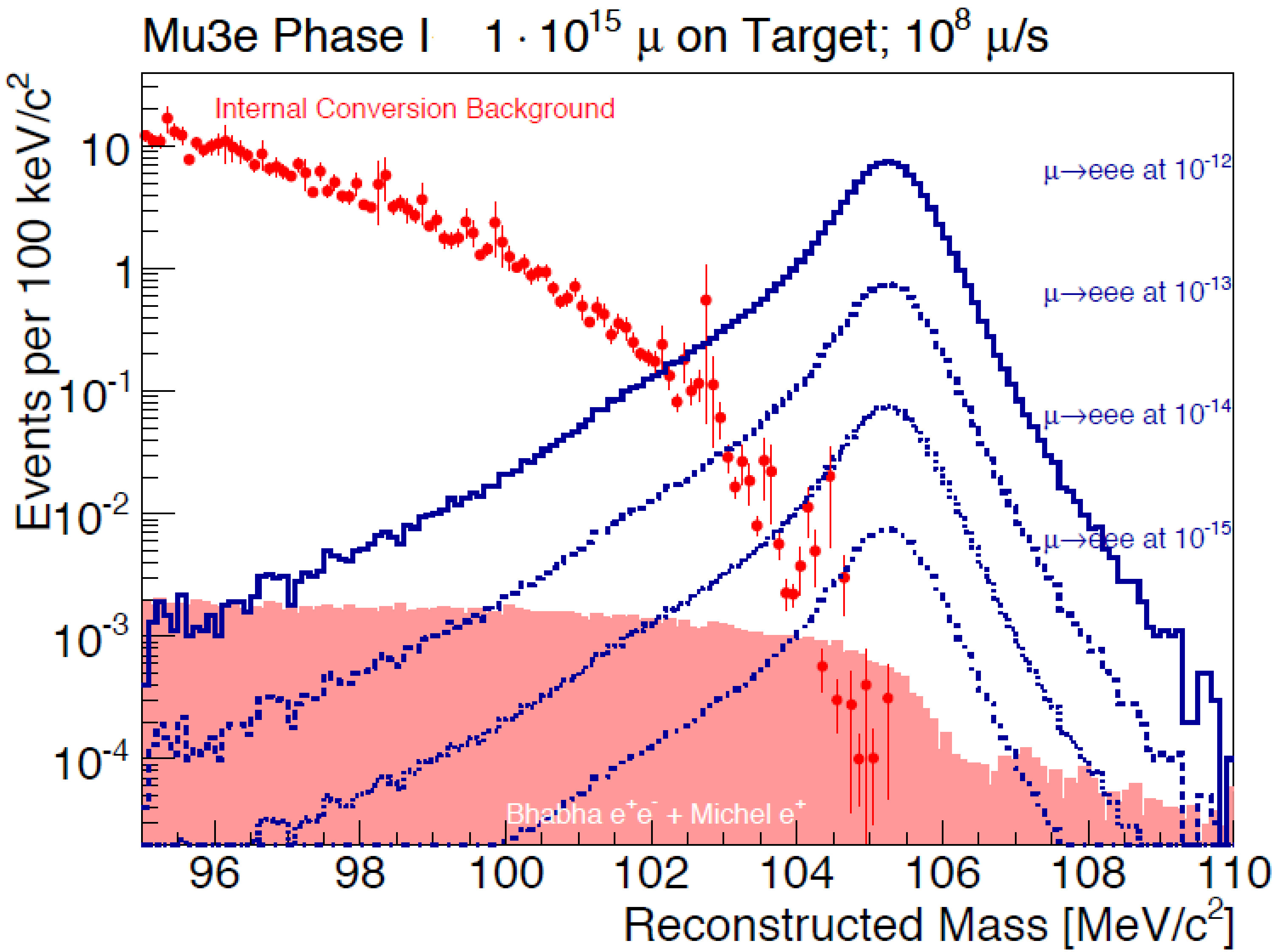
$\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu$ fraction in signal region as a function of Δm_μ



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

Background Suppression



background rejected with tracking and timing

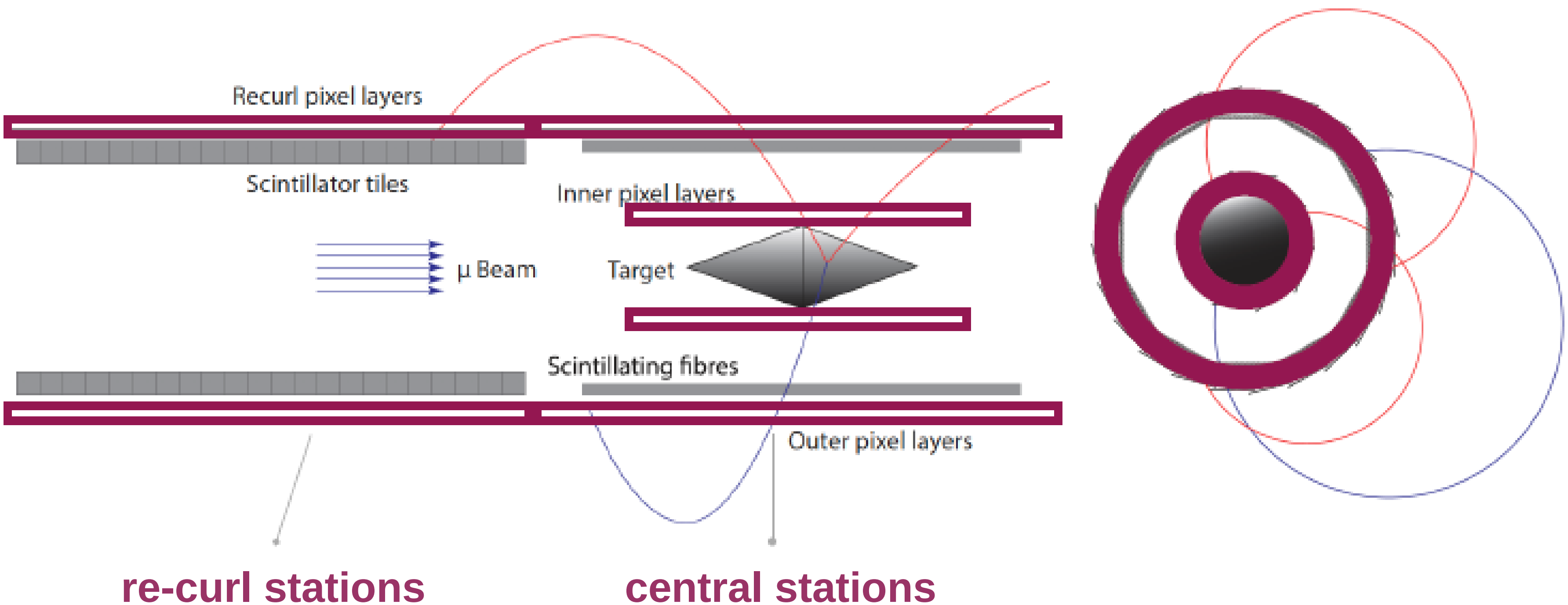
(tracking alone not sufficient to reject accidental background)

The Pixel Tracker

central tracker: four layers
re-curl tracker: two layers

minimum material budget: tracking in multiple scattering dominated regime

momentum resolution < 0.5 MeV/*c* over a large phase space
geometrical acceptance ~70%
X/X_0 per layer ~0.011%



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 x 80 μm^2

final chip size 2 x 2 cm^2

time resolution < 15 ns

efficiency > 99%

175 M pixels

radiation hard

operated at –85 V

1 Gb/s LVDS readout (30 M hits /s)

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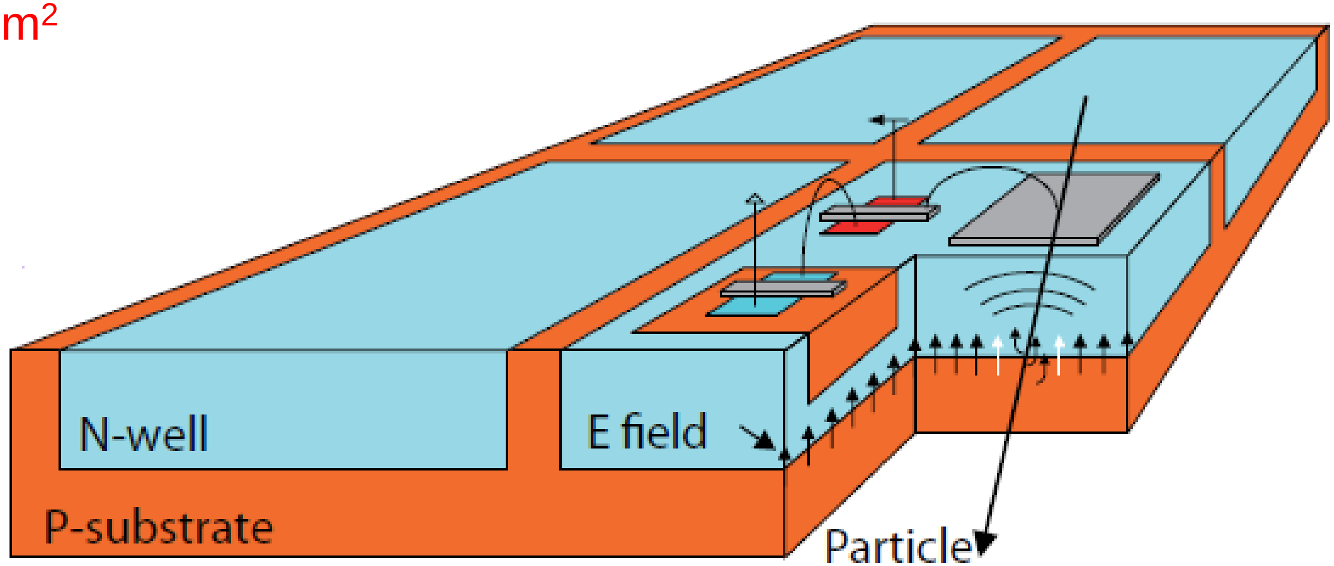
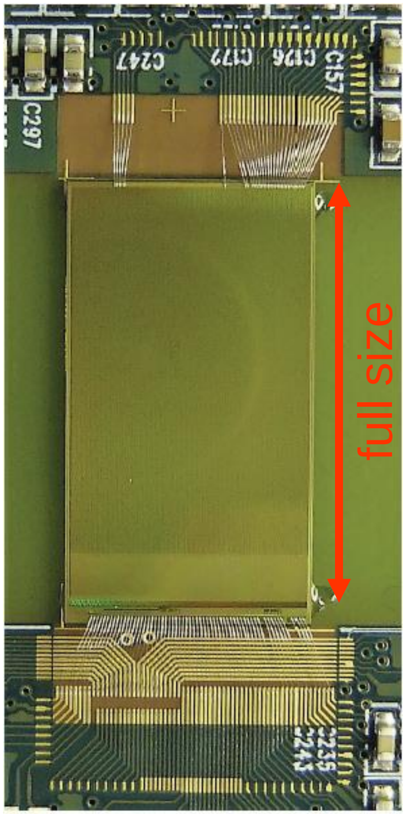


HV-MAPS R & D

Latest prototype: MUPIX 8 (→ MUPIX X)



characteristics

thickness 50 μm

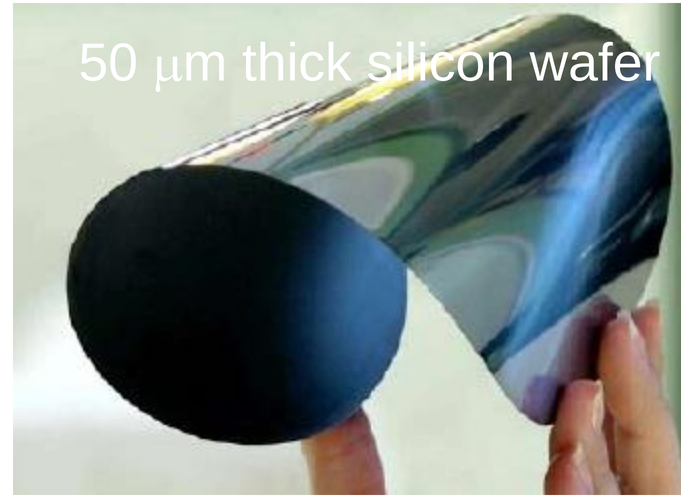
pixel size 80 x 80 μm^2

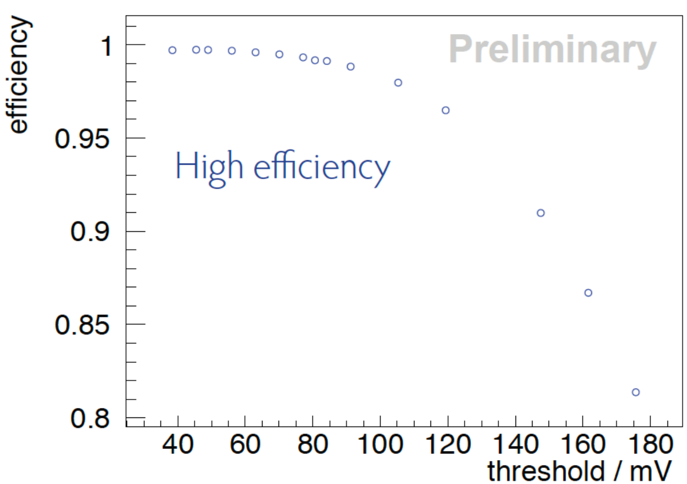
chip size 19 x 10 mm^2

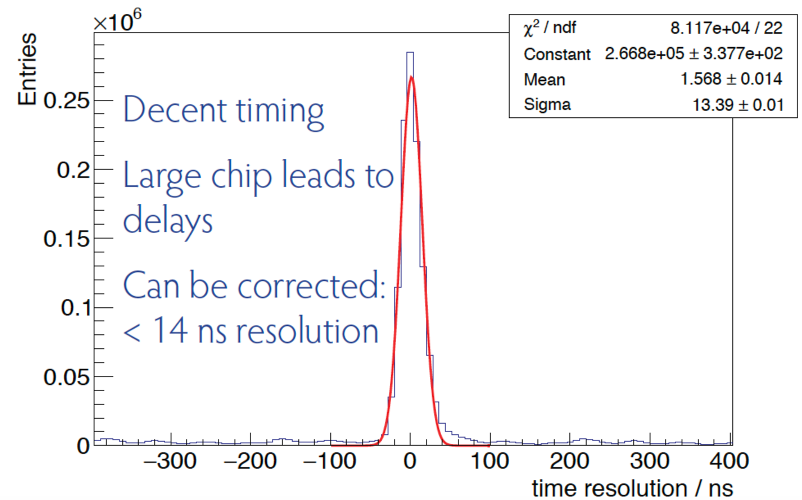
performance

efficiency > 99 %

time resolution < 14 ns

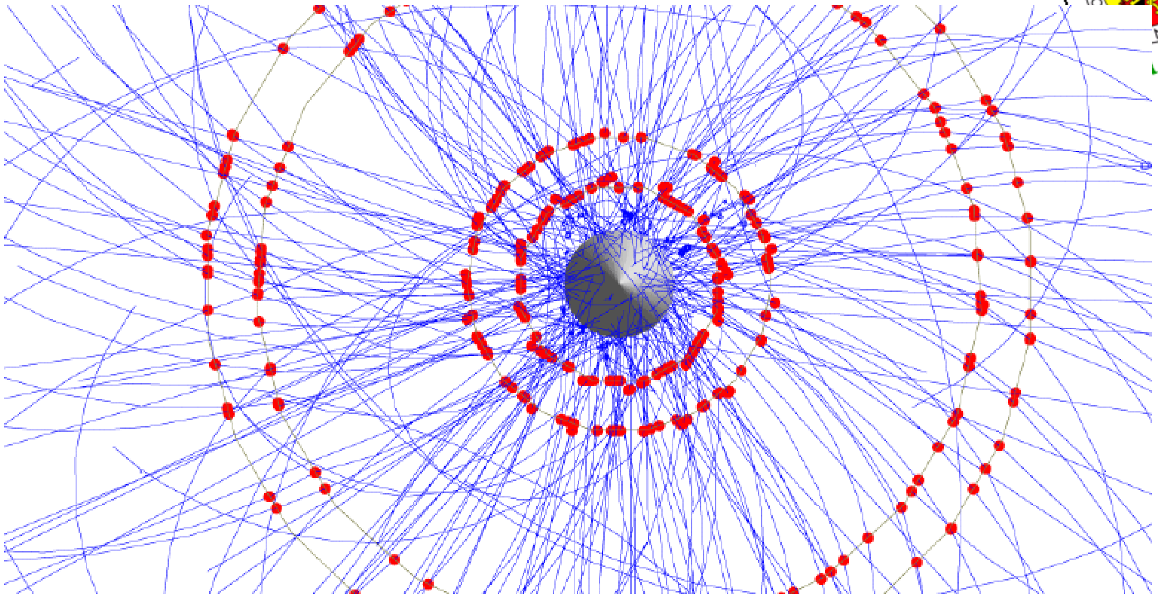




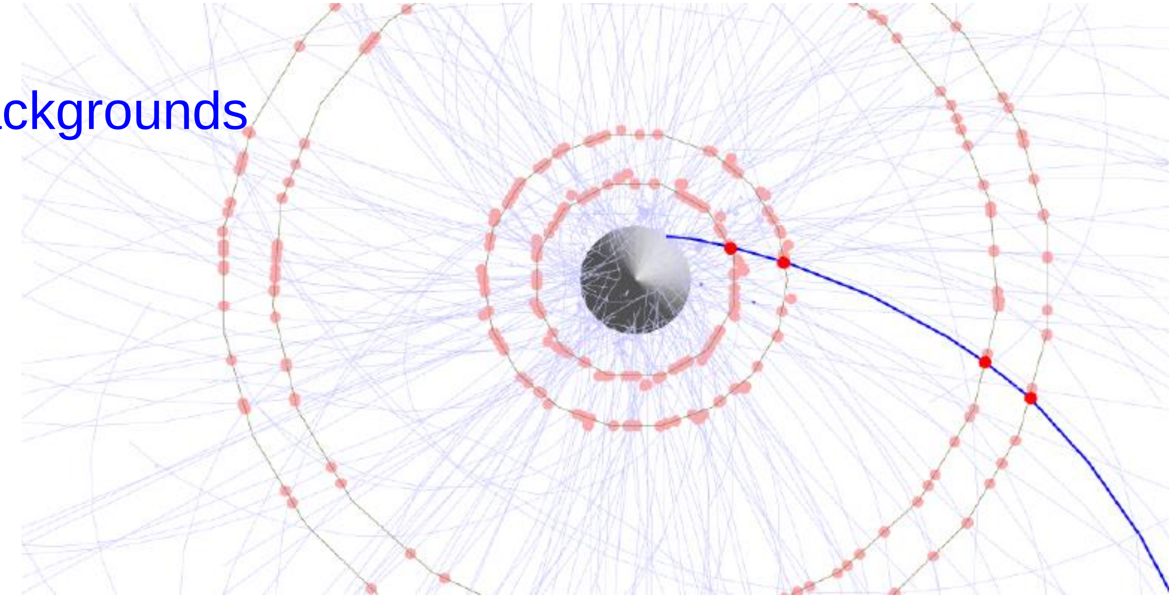


Timing

50 ns snapshot (readout frame): 100 μ decays



additional ToF information < 500 ps



to suppress accidental backgrounds requires excellent timing

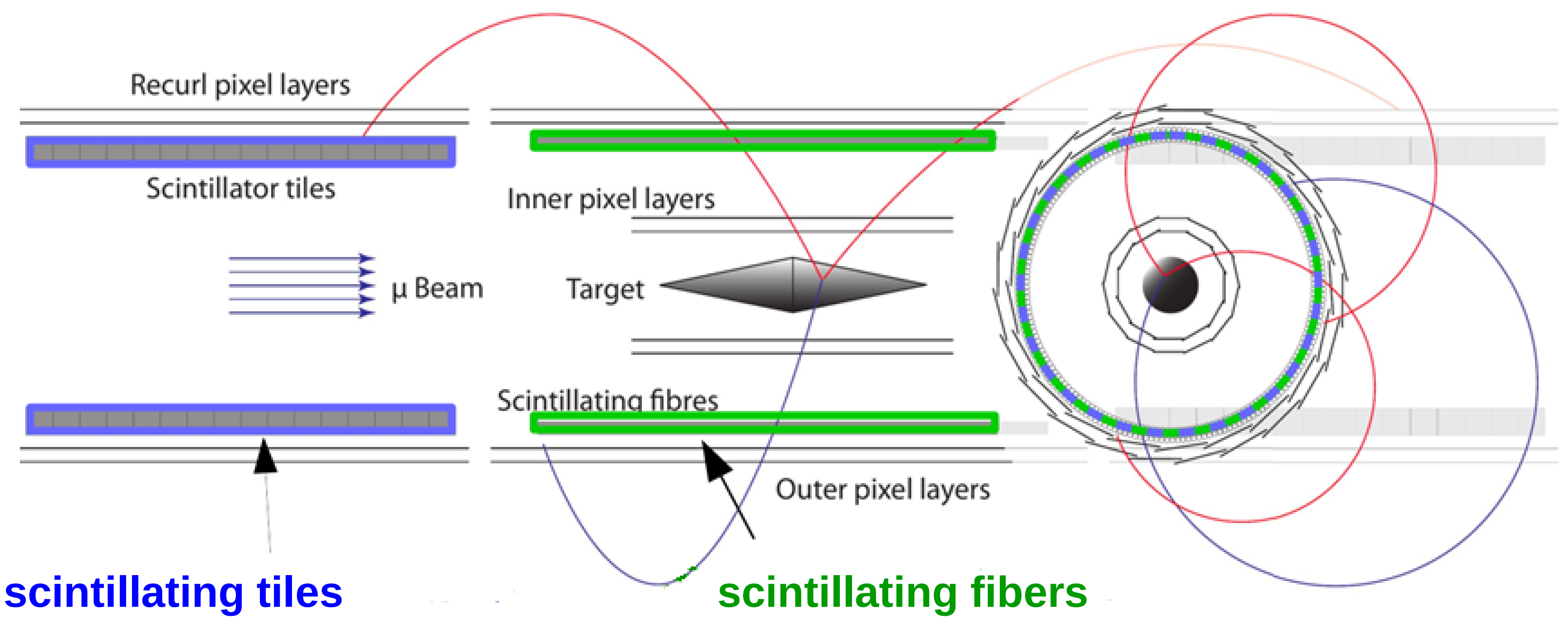
- < 500 ps SciFis
- < 100 ps scint. tiles

The Timing Detectors: Fibers and Tiles

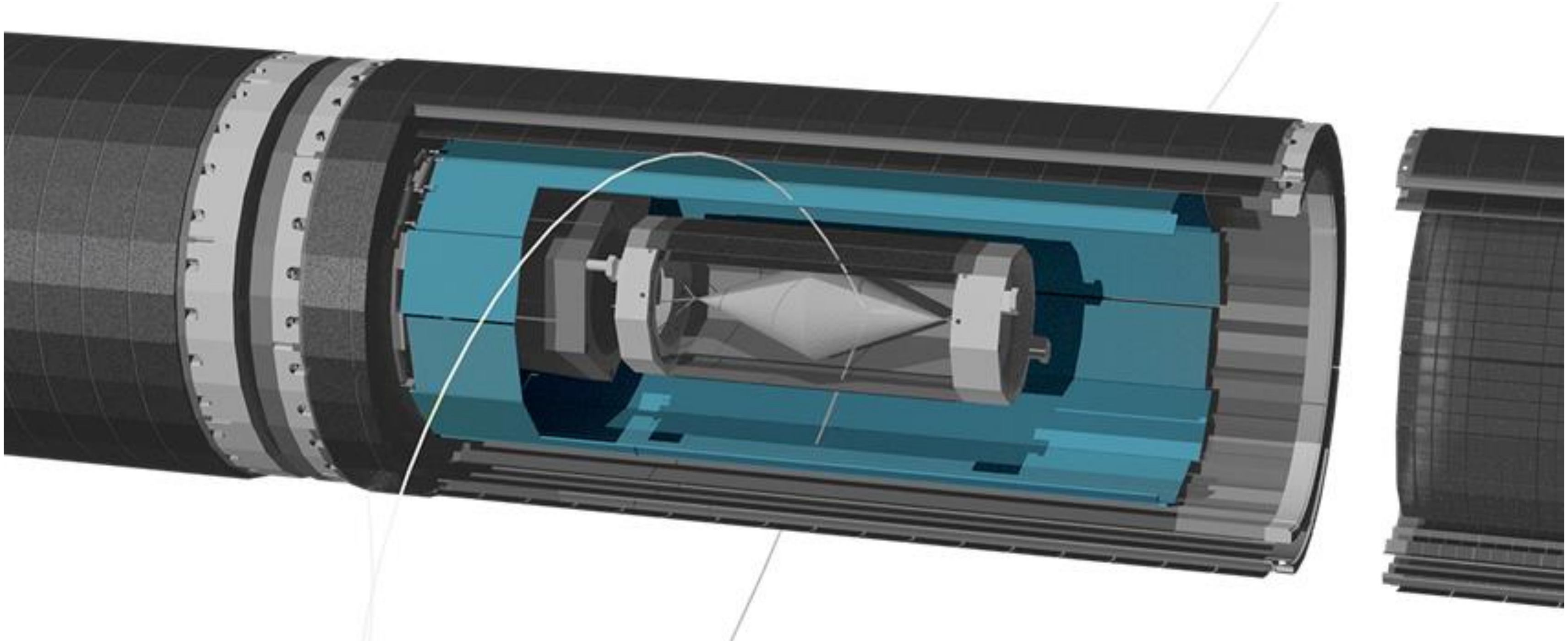
precise timing measurement: critical to reduce accidental BKGs
determine sign of re-curling tracks (SciFi)

scintillating fibers (SciFi) ~250 ps, detection efficiency > 95 %

scintillating tiles ~70 ps, detection efficiency > 99 %



The SciFi Detector



Design

cylindrical
- ~12 cm diameter
- length ~30 cm

3 staggered layers round fibers
multi-clad 250 µm round fibers
readout with Si-PM arrays on both ends
MuSTiC ASIC

Requirements

high detection efficiency > 95%
time resolution < 0.5 ns
thickness X/X_0 ~ 0.2 % (< 700 µm)
handle high occupancy: up to 250 KHz/fiber
limited space for electronics and cabling

SciFi Perforomance

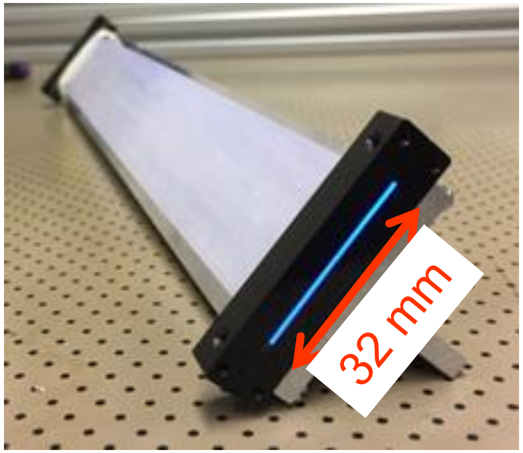
different fibers have been evaluated

SCSF 78 MJ, SCSF 81 MJ, NOL 11, BCF 12 w/ and w/o TiO_2 coating, 3 & 4 layers, …

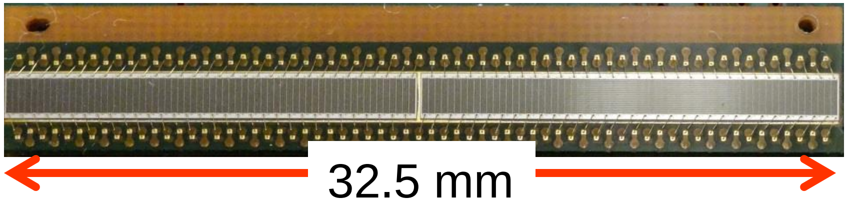
detection efficiency > 96 % @ 0.5 phe thr

timing resolution ~200 ps (mean time)

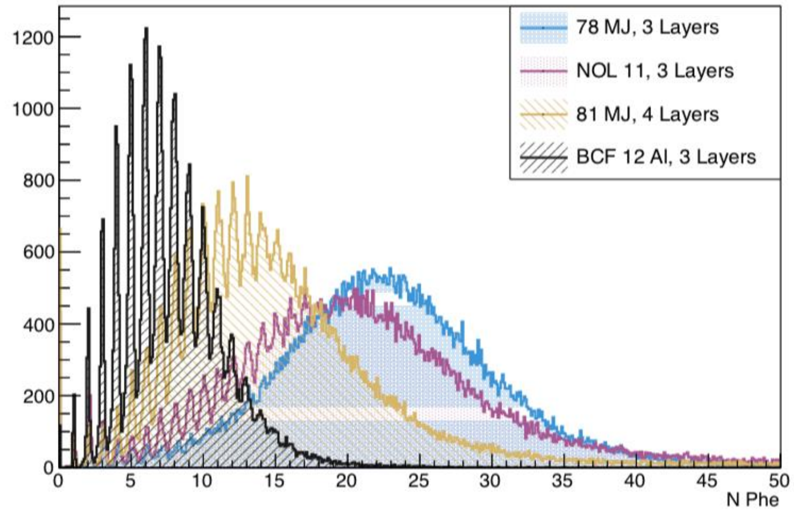
full size SciFi ribbon prototype



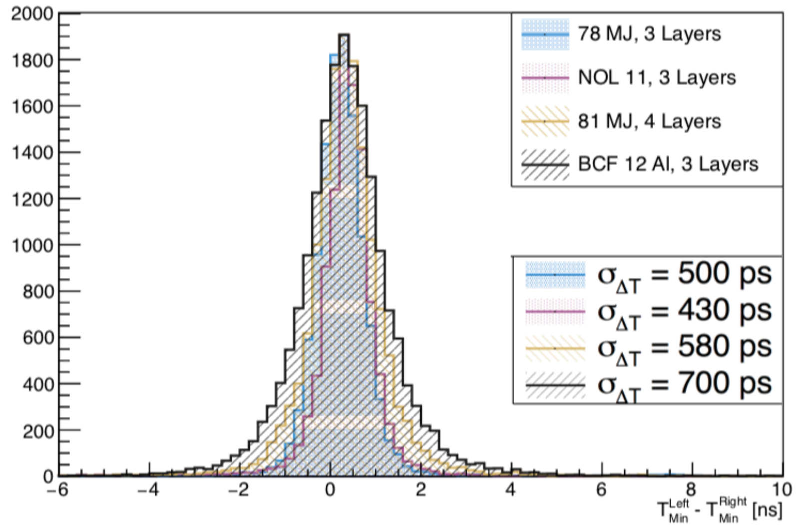
Si-PM array 2 x 64 ch., 250 μm pitch
common cathode



light yield



time resolution



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 (scintillating fibers and tails)
they meet the requirements

Staged approach

Stage I (2020 – 2024)
$\sim 10^8$ μ decays / s — BR($\mu \rightarrow eee$) < 10^{-15}
approved in January 2013

Stage II (> 2025)
$\sim 2 \times 10^9$ μ decays / s — BR($\mu \rightarrow eee$) < 10^{-16}
HiMB feasibility study already started

Construction in 2018/2019 (incl. magnet)
Commissioning 2020

LFV Searches : Current Situation

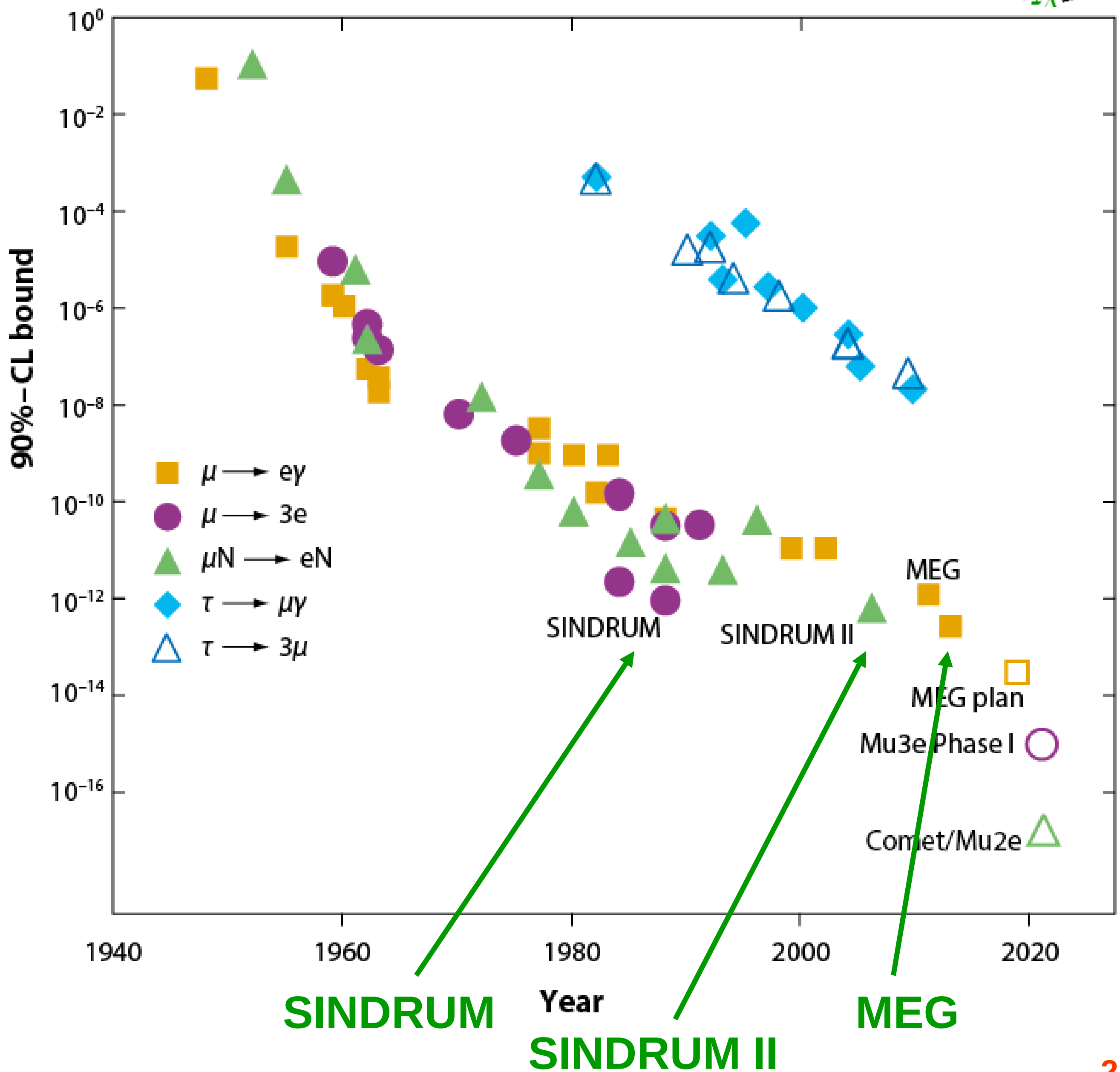
The best limits on LFV come from PSI muon experiments

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

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

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

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



SINDRUM @ PSI (~ 80s)

beam (πE3 beamline @ PSI):

5 ´ 10^6 μ / sec

28 MeV/*c* surface muons

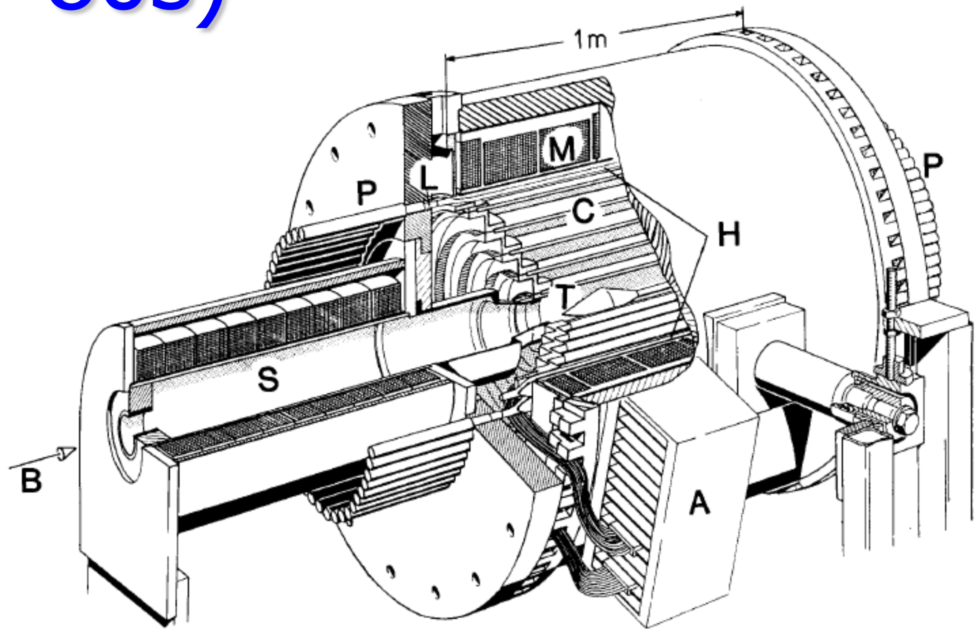
resolution:

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

vertex ~ 1 mm

statistics limited!

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



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

$$m_\mu = 105.7 \text{ MeV} \qquad 0$$

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