The Mu3e Experiment @ PSI

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

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for the Mu3e Collaboration

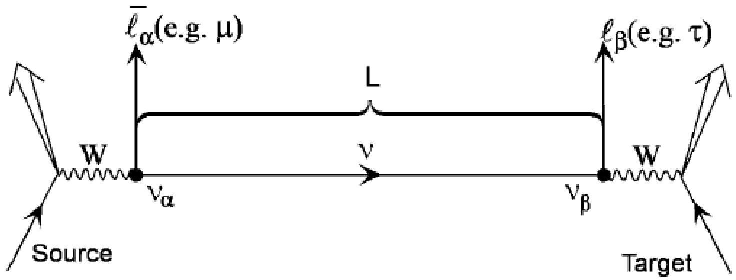
τ 2014
Aachen, September 17 2014

LFV in "Standard Model"

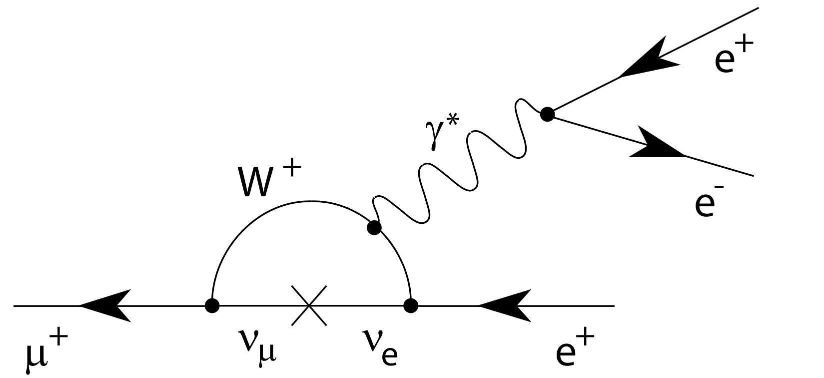
In SM ($m_\nu = 0$) Lepton Flavor is strictly conserved !

neutrino oscillations → $m_\nu \neq 0$ & Lepton Flavor is not anymore conserved (ν oscillations)
→ charged LFV possible via loop diagrams, but heavily suppressed

neutrino oscillations



$\mu+ \rightarrow \tau^+$ (OPERA) or $\mu+ \rightarrow e^+$ (T2K)



$$\sim \left(\frac{\Delta m_\nu^2}{M_W^2} \right)^2 \Rightarrow BR\left(\mu^\pm \rightarrow e^\pm e^+ e^-\right) < 10^{-50}$$

→ measurement not affected by SM processes

Flavor Conservation in the charge lepton sector :

processes like $\mu A \rightarrow e A$

$\mu \rightarrow e + \gamma$

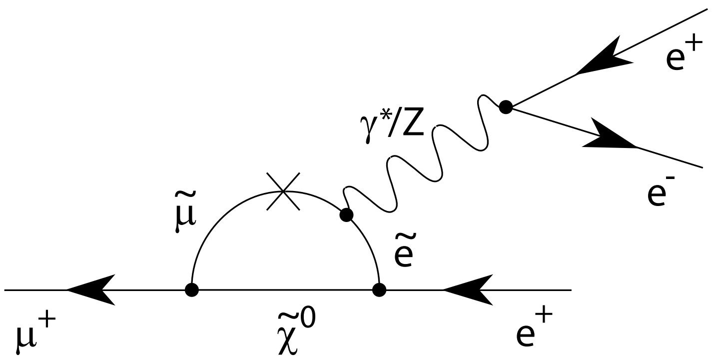
$\mu \rightarrow e\, e\, e$ have not been observed yet.

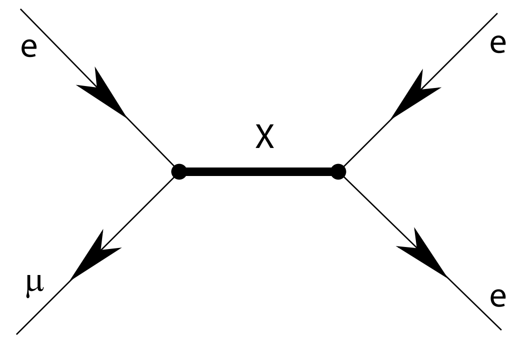
Many models ! however the mechanism and size of cLFV remain elusive.

New Physics in $\mu \to eee$

LFV addresses issues like

– origin of flavor
– neutrino mass generation
– CP violation





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)

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

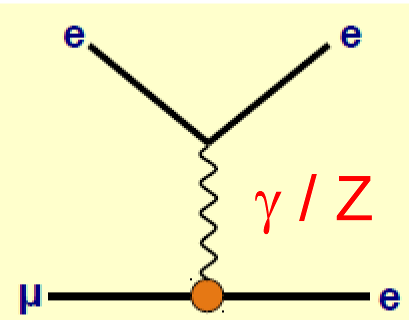
explore physics up to the PeV scale
complementary to direct searches at LHC

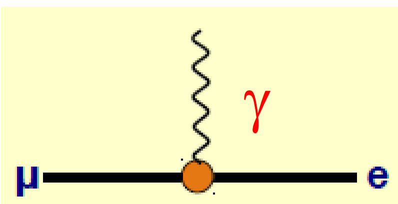
Model Comparison ($\mu \to e\gamma$ and $\mu \to eee$)

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

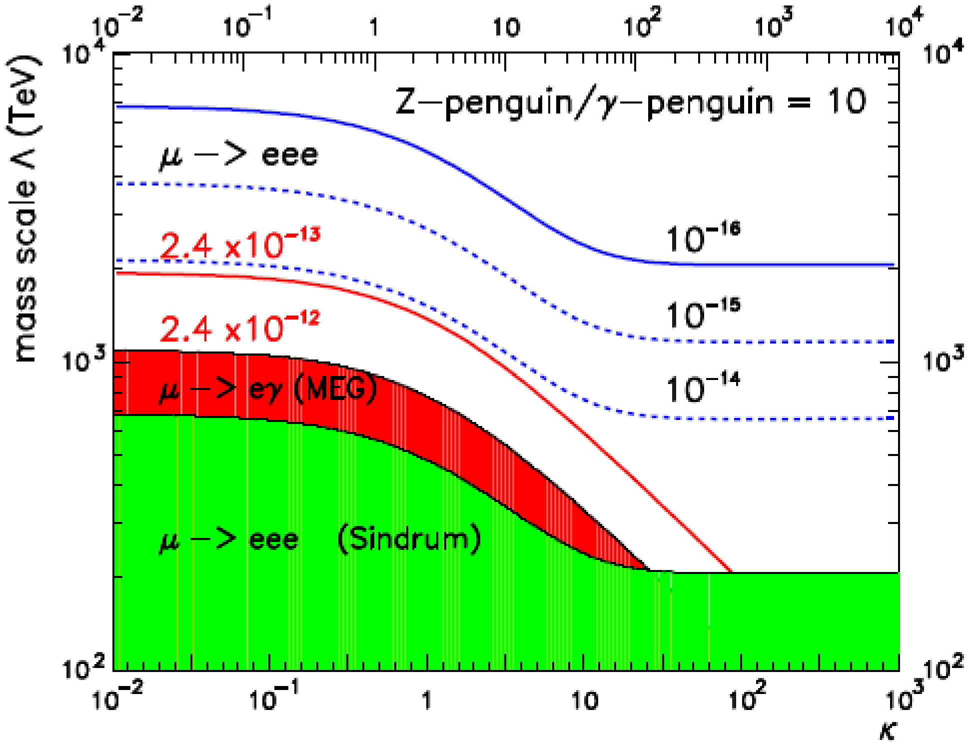
$$L_{LFV} = \frac{m_\mu}{\Lambda^2(1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2(1+\kappa)} J_\sigma^{e\mu} J^{\sigma,ee}$$

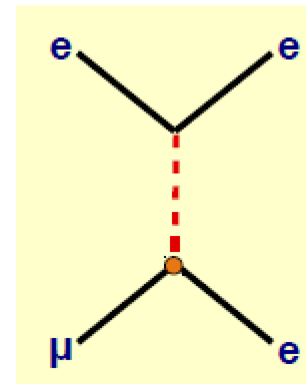
Λ = common effective scale
κ = "contact" vs. "loop"





$\kappa \to 0$





$\kappa \to \infty$

Z – penguin

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

dominates if $\Lambda \gg M_Z$

not suppressed by an extra EM vertex

LFV Searches : Current Situation

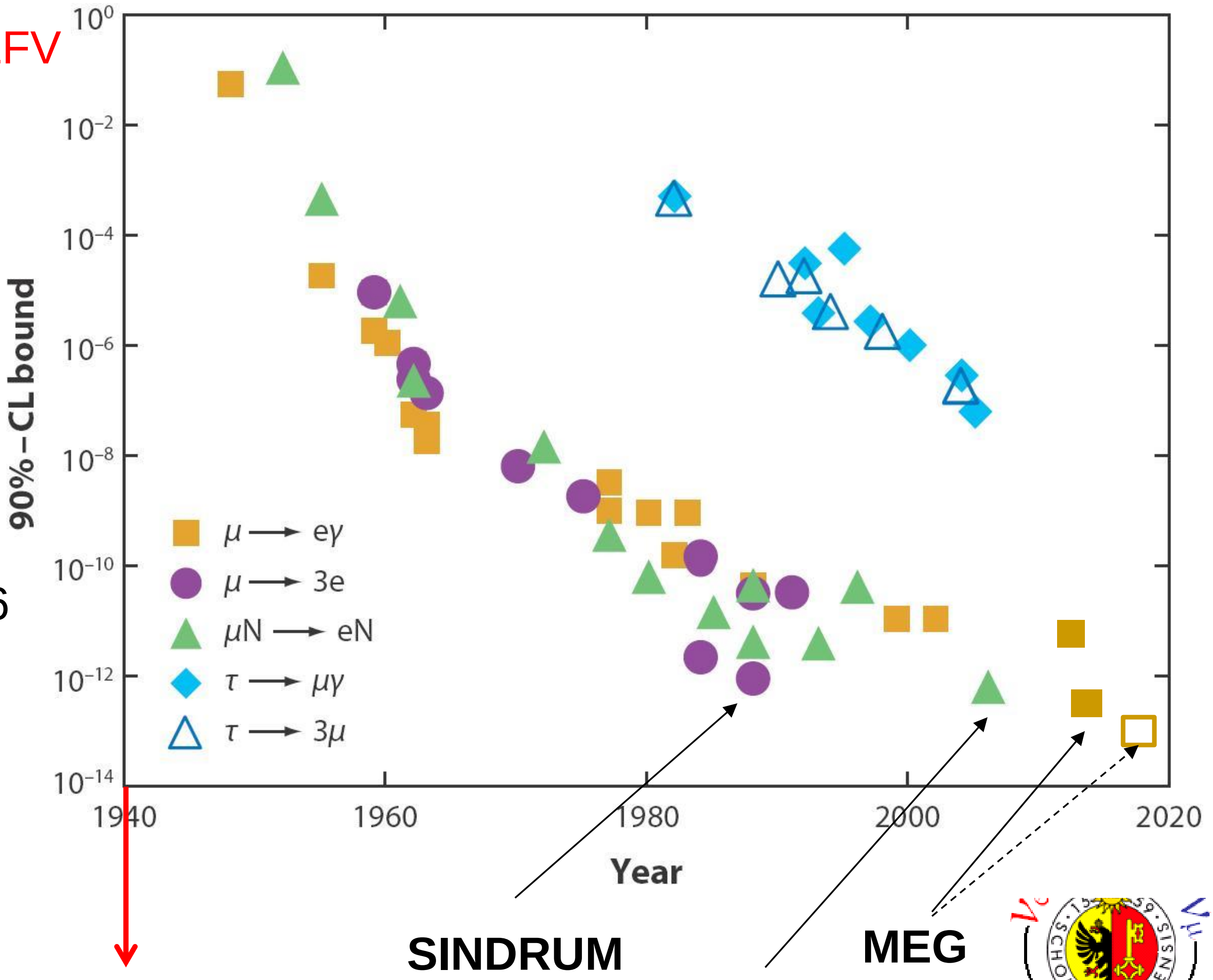
The best limits on LFV come from PSI muon experiments

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

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

$\mu^+ \rightarrow e^+ + \gamma$
BR < 5.7×10^{-13}
MEG 2013

[90 % C.L.]



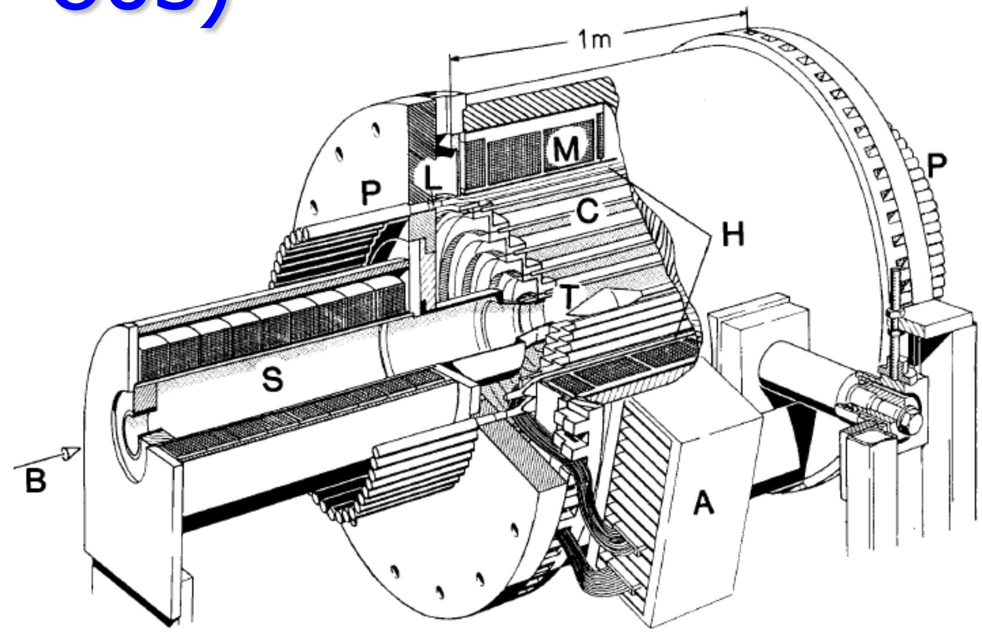
by the end of this decade

SINDRUM @ PSI (~ 80s)

beam (πE3 beamline @ PSI):

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

28 MeV/c surface muons



resolution:

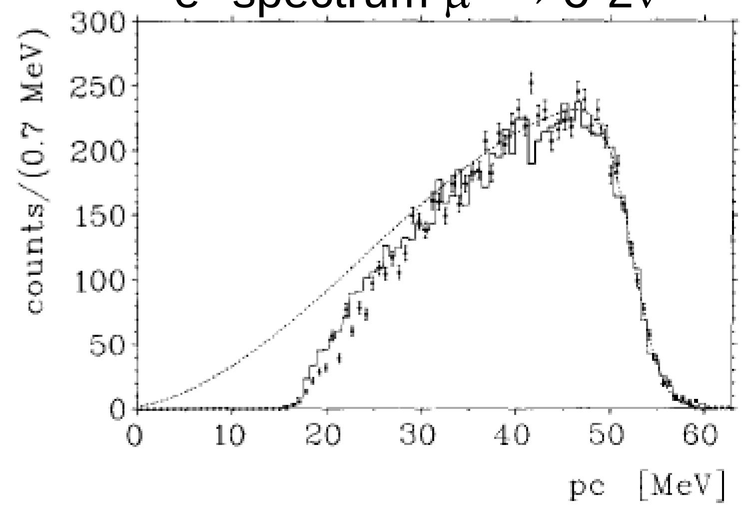
$\sigma(p_T) = 0.7$ MeV/c^2

vertex ~ 1 mm

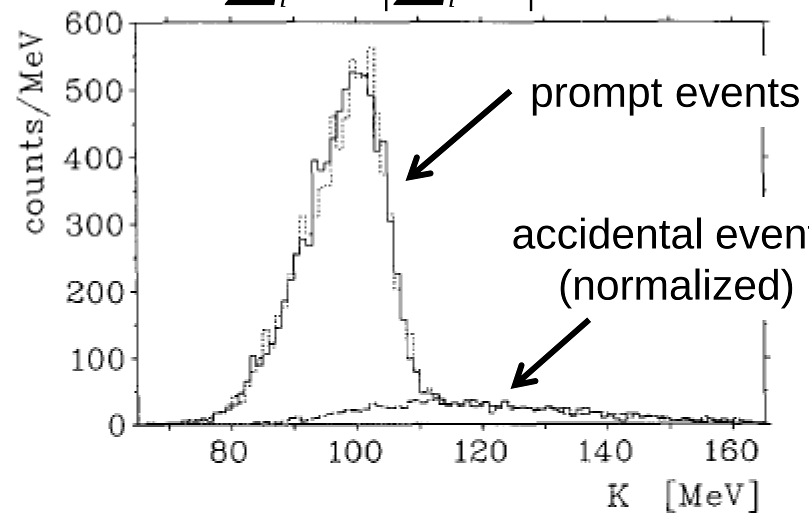
statistics limited!

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

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



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



Mu3e @ PSI : the Challenge

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

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

suppress backgrounds below 10^{-16} (16 orders of magnitude !)

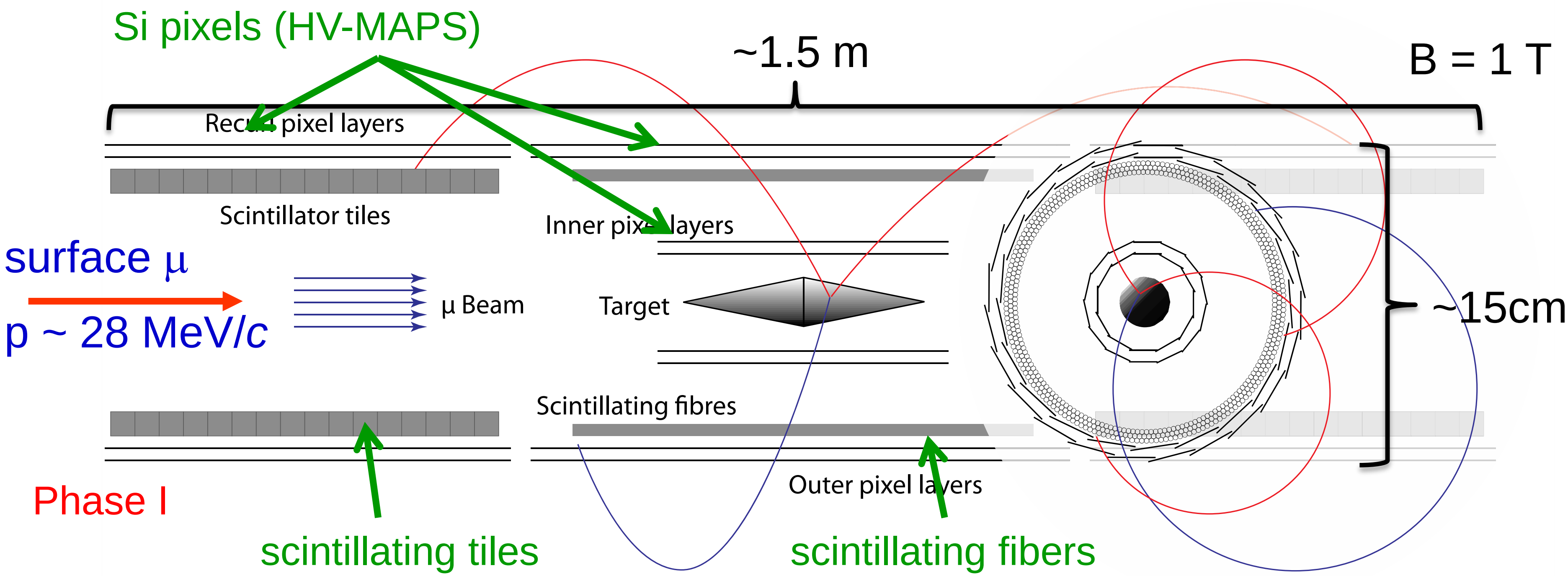
find or exclude $\mu^+ \rightarrow e^+ e^- e^+$ at the 10^{-16} level
4 orders of magnitude over previous experiments (SINDRUM @ PSI)

Aim for sensitivity
10^{-15} in phase I
10^{-16} in phase II
(i.e. find one in 10^{16} muon decays)

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

project 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)

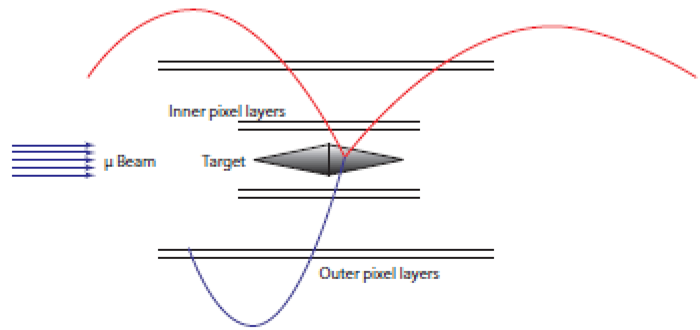
275 M HV-MAPS (Si pixels w/ embedded ampli.) channels

~ 20 k ToF channels (SciFi and Tiles)

Staged Approach

Phase IA

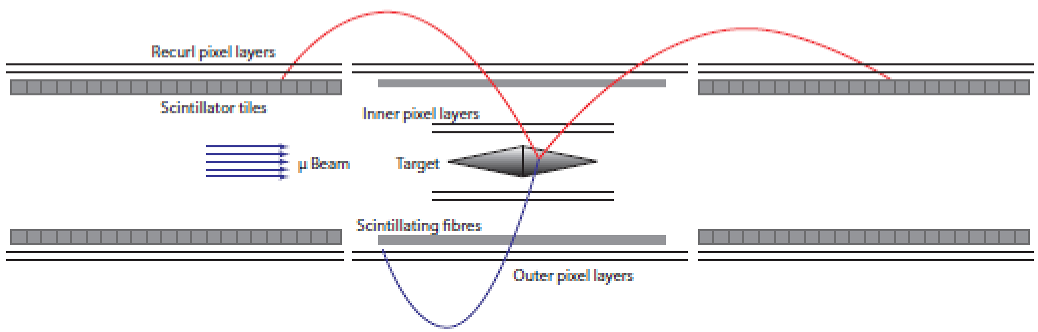
rate $\leq 10^7$ μ / s



only central pixel

Phase IB

rate ~ 10^8 μ / s

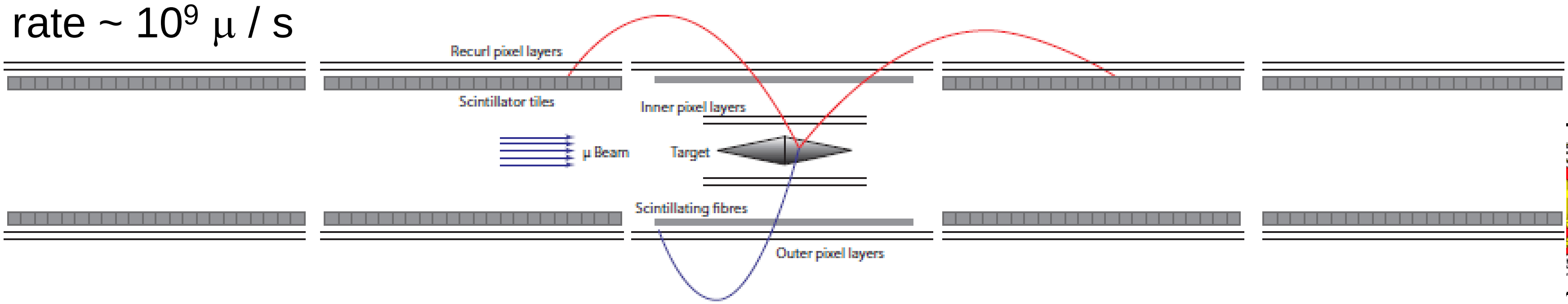


+ inner recurl sta.
+ time of flight

Phase II

rate ~ 10^9 μ / s

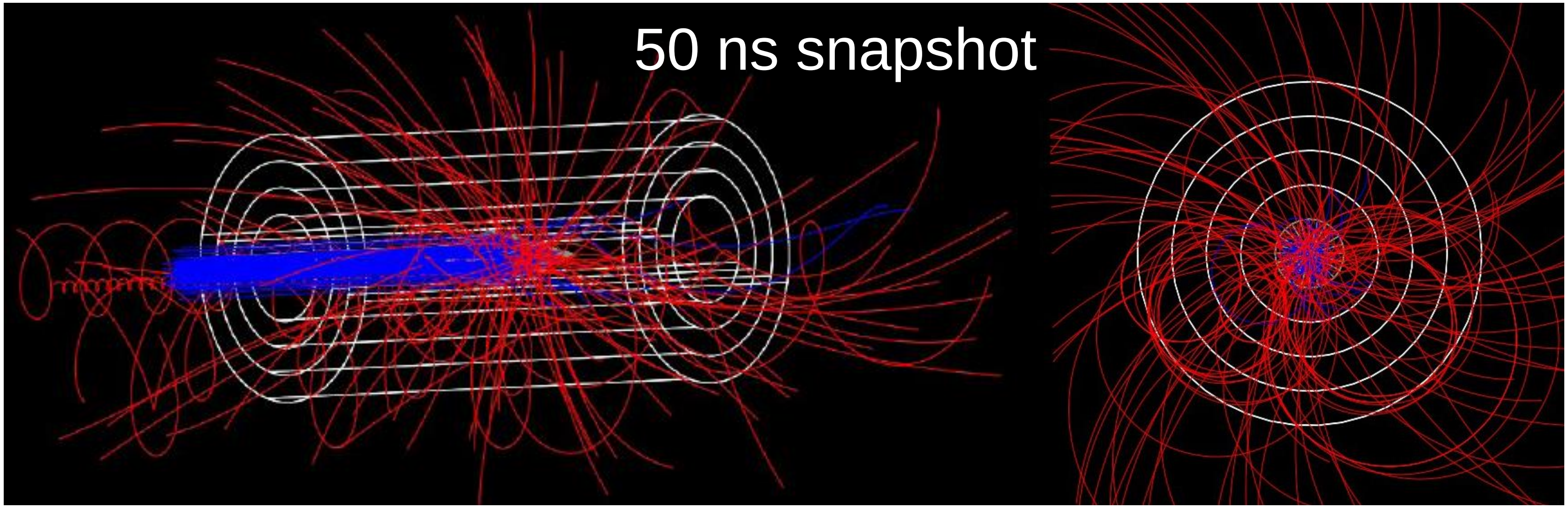
+ outer recurl sta.

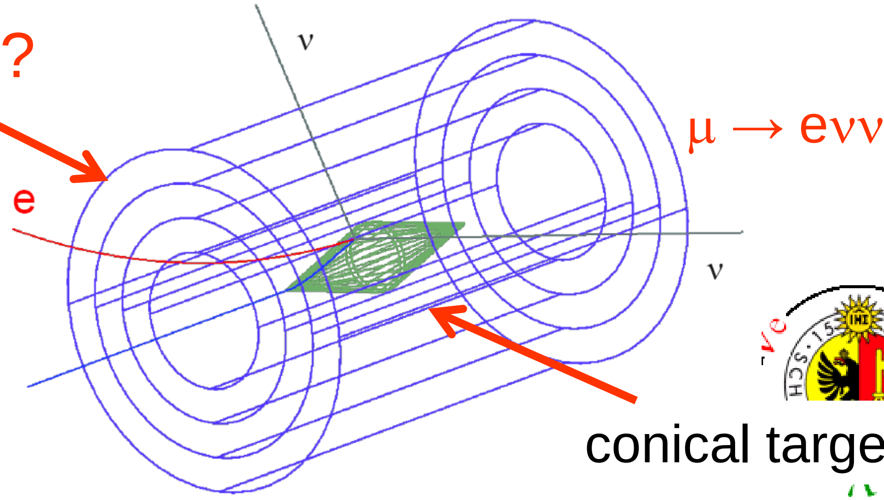


How to Find $\mu^+ \rightarrow e^+ e^- e^+$ Decays

50 nsec time frames (Si “resolution”) → 100 μ decays @ 2 × 10^9 μ stops / s

challenge : isolate μ → eee events



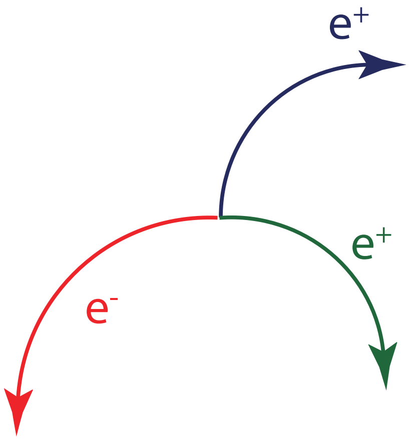


Δt ~ few 100 ps
Time of Flight ~ few 100 ps

precise vertexing ~100 μm

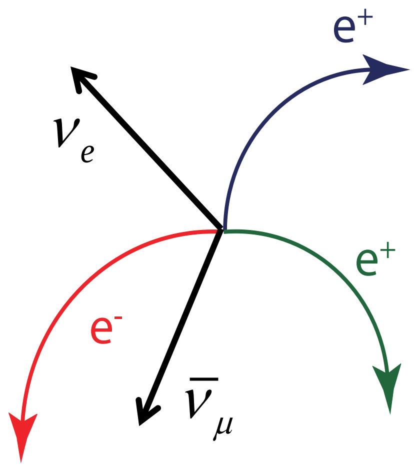
Signal and Backgrounds

signal

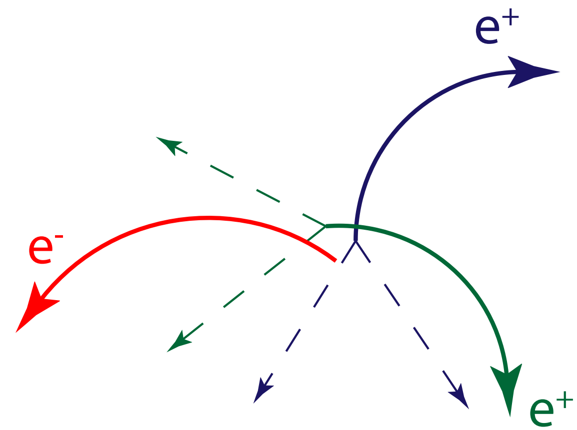


backgrounds

internal conversion



combinatorial



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

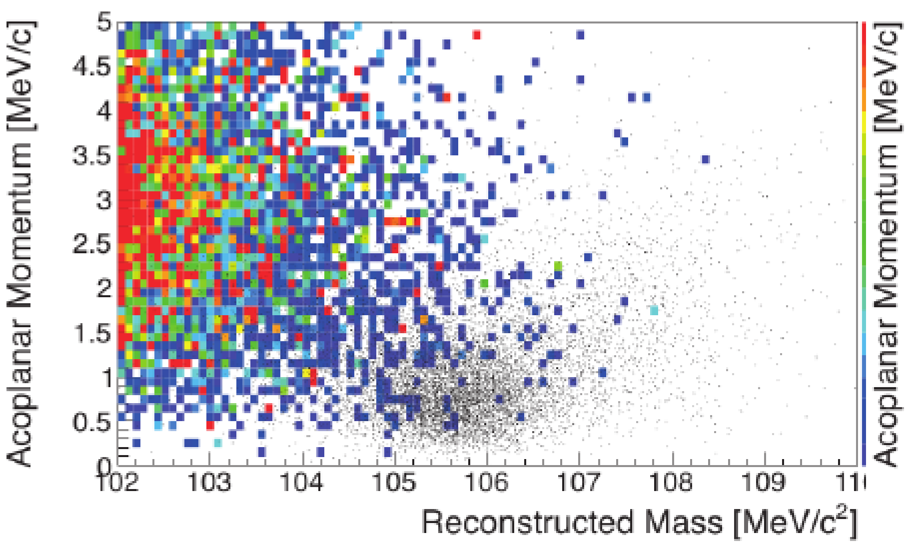
Features

signal	internal conversion	combinatorial
common vertex	common vertex	no common vertex
$\Sigma \mathbf{p}_i = 0$, $\Sigma E_i = m_\mu$	$\Sigma \mathbf{p}_i \neq 0$, $\Sigma E_i < m_\mu$	out of time
$p < ½\, m_\mu = 53$ MeV/c	in time	

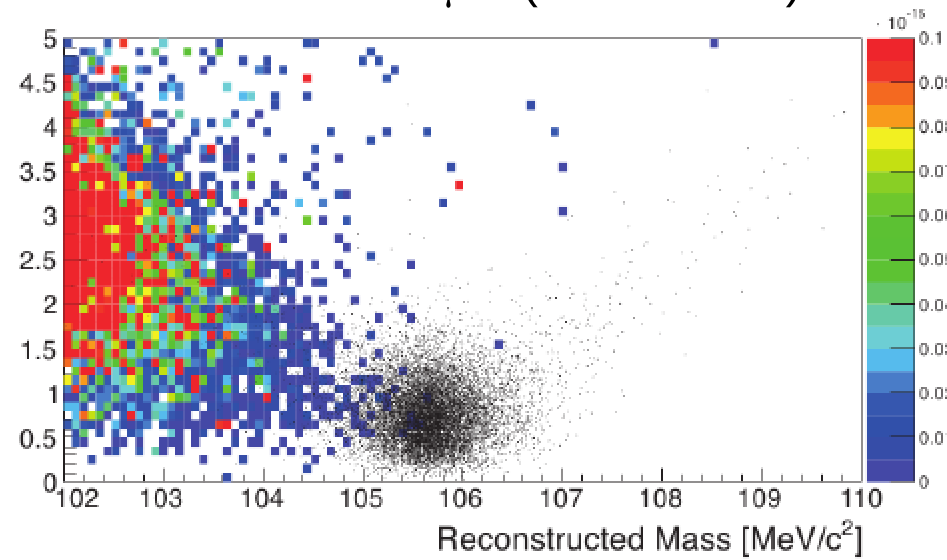
Rejecting the background requires $\sigma_p < 0.5$ MeV/c
$\sigma_t < 0.5$ ns

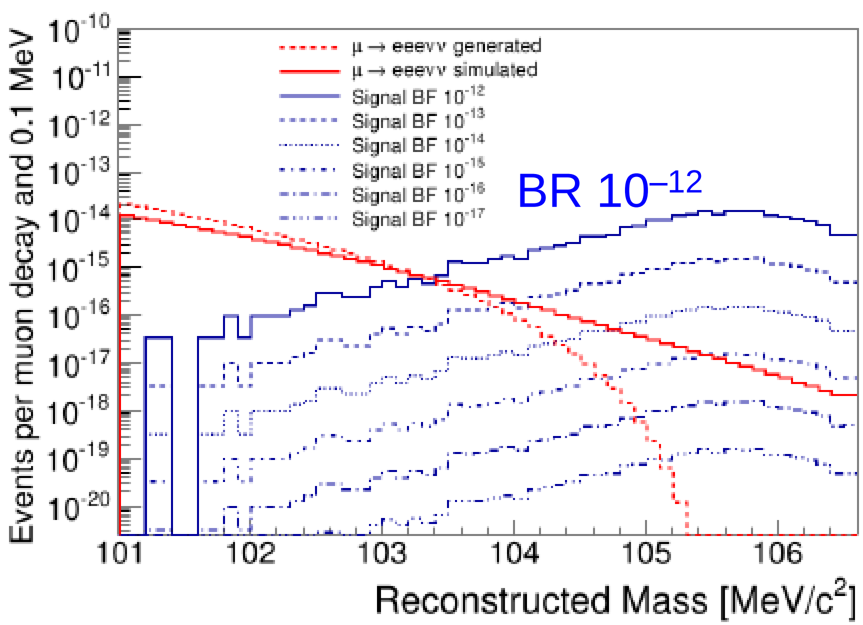
$\mu \to$ eee Signal Simulations

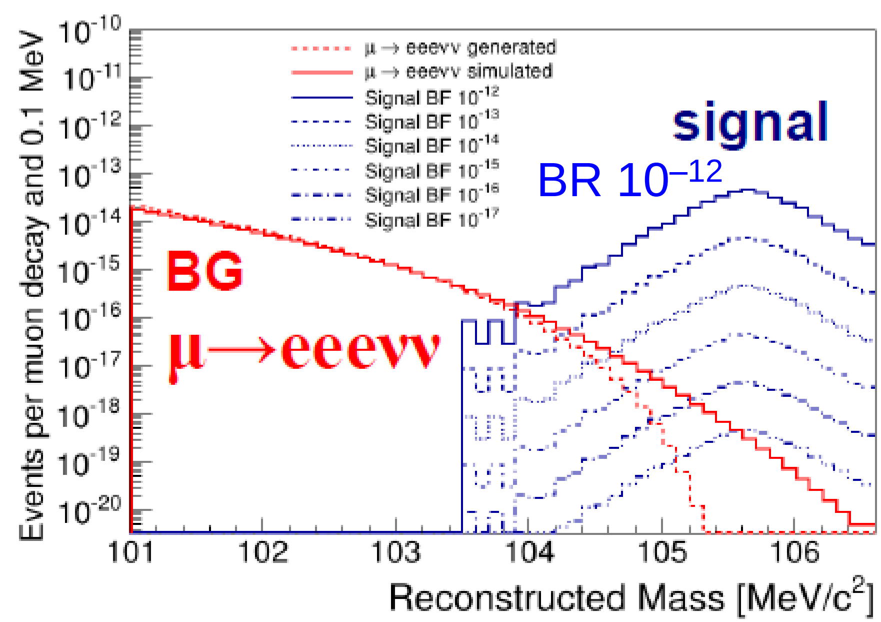
Phase IA: ~ 2×10^7 μ/s (central pixel)



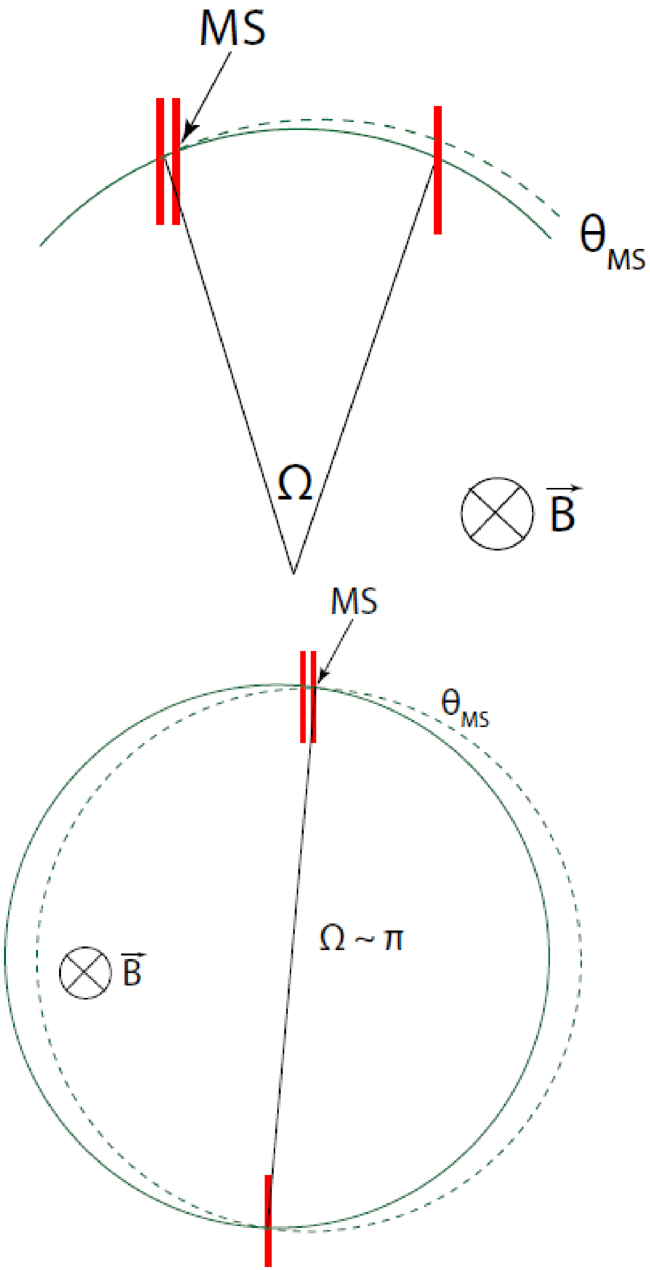
Phase II: ~ 2×10^9 μ/s (full detector)







Momentum Measurement



measure momenta in the range
p = 15 – 53 MeV/*c*

resolution dominated by multiple scattering

momentum resolution (1st order)

$$\frac{\sigma_p}{p} \sim \frac{\Theta_{MS}}{\Omega}$$

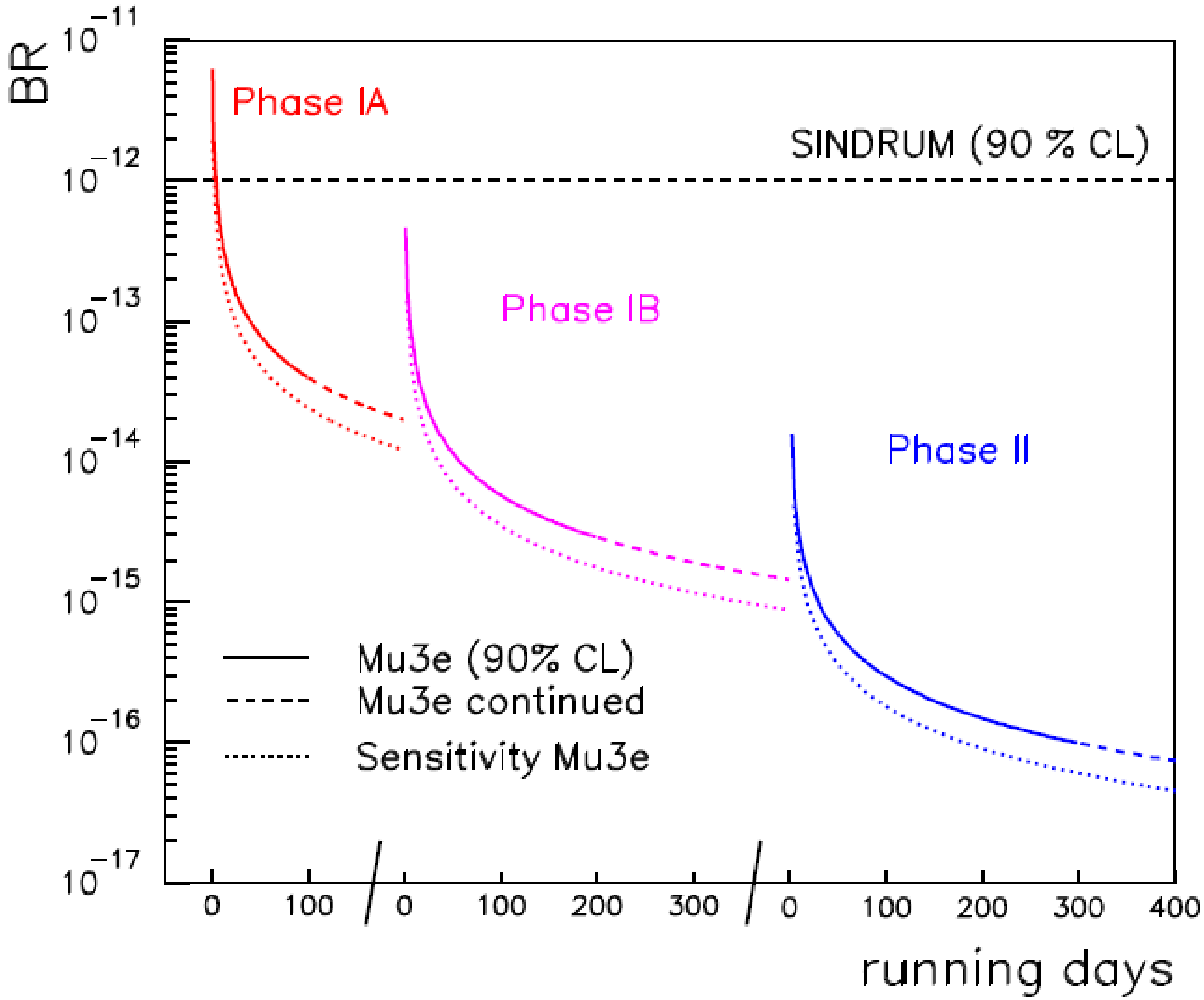
precision requires large lever arm
(large bending angle Ω, not too strong **B**)
and low multiple scattering Θ_{MS}
detector thickness < 0.1% X_0

best precision for half turns ($\Omega \sim \pi$)

$$\frac{\sigma_p}{p} \sim o\left(\Theta_{MS}^2\right)$$

design tracking detector for measuring recurlers

Sensitivity Projection



Muons @ PSI

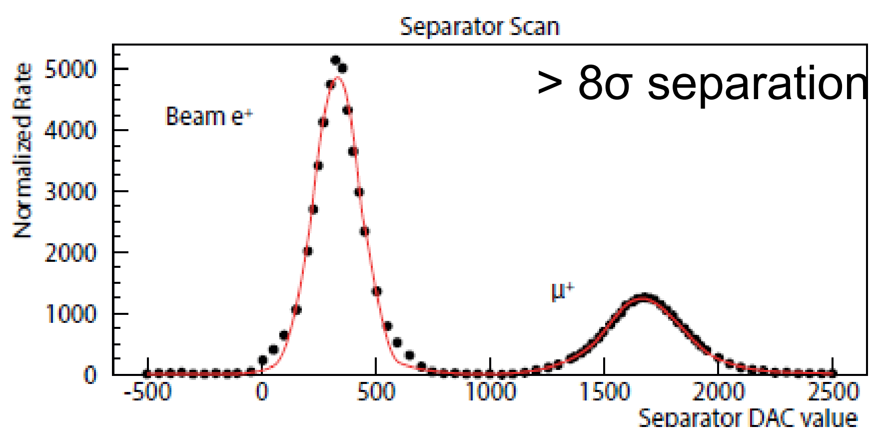
most intense DC muon beam

590 MeV/c proton cyclotron

πE5 beamline $> 10^8\ \mu$ / s
- surface muons ~ 28 MeV/c
- high intensity monochromatic beam
  ($\Delta P/P < 8\%$ FWHM)
- polarization ~ 90%

(MEG exp., Mu3e phase I)

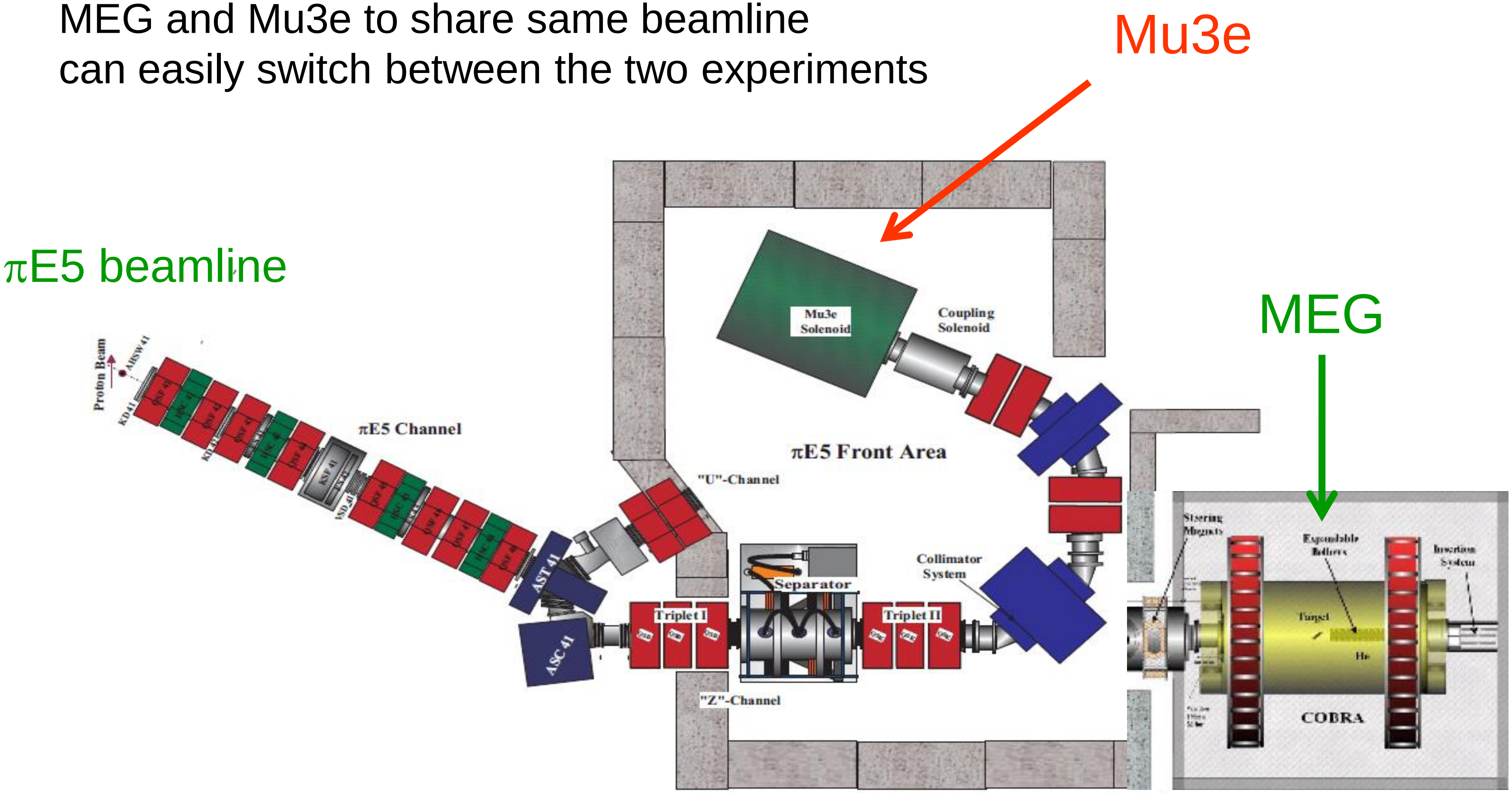
SINQ (spallation neutron source)
could even provide $5 \times 10^{10}\ \mu$ / s
High-intensity Muon Beamline (HiMB)



e / μ 12 cm separation at last collimator

Mu3e – phase I

MEG and Mu3e to share same beamline
can easily switch between the two experiments



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

Rate of 2×10^{8} μ / s needed to reach BR of 10^{-15} (90% CL) in 3 years

The High-intensity Muon Beamline (HiMB)

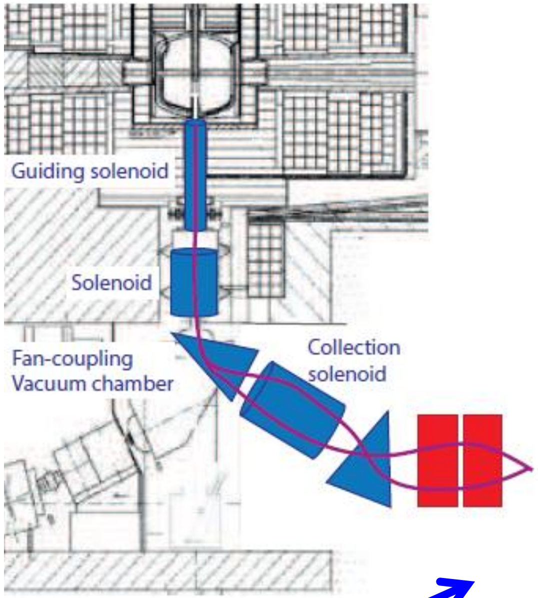
Phase II sensitivity requires GHz muon beam

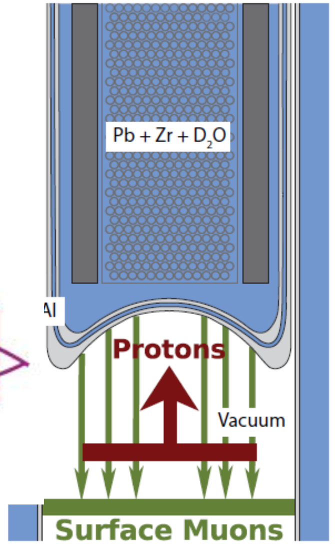
HiMB – **H**igh-**i**ntensity **M**uon **B**eam Concept

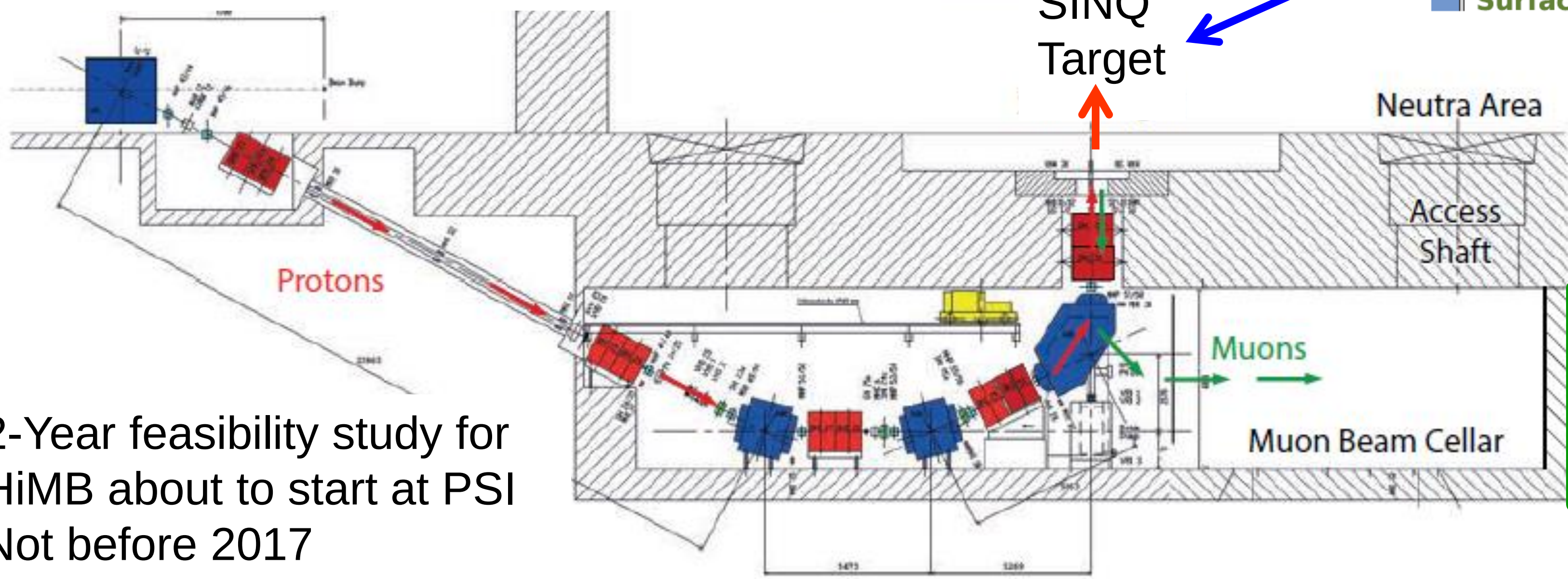
muon rates in excess of 10^{10} μ / s possible

use spallation neutron source target window as a high-intensity source of surface muons

muons extracted downwards opposite to incoming proton beam using solenoidal channel + conventional dipole/quadrupole channel



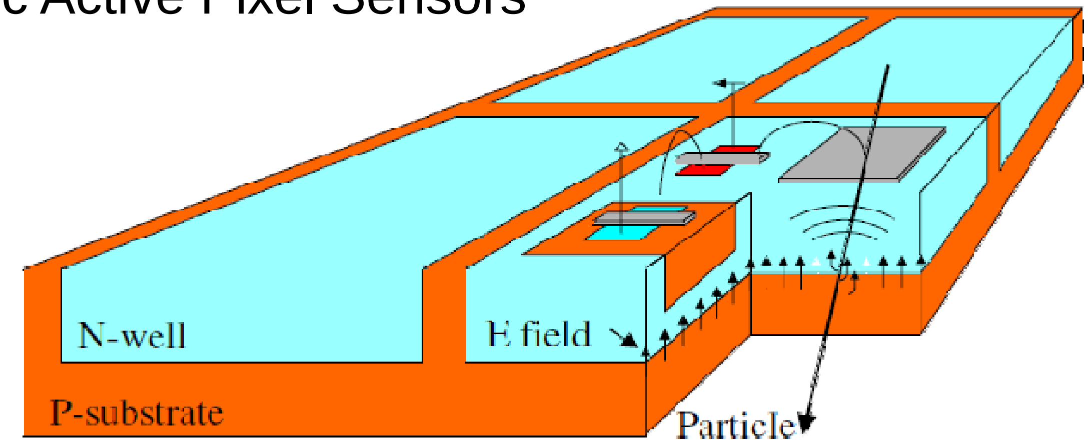




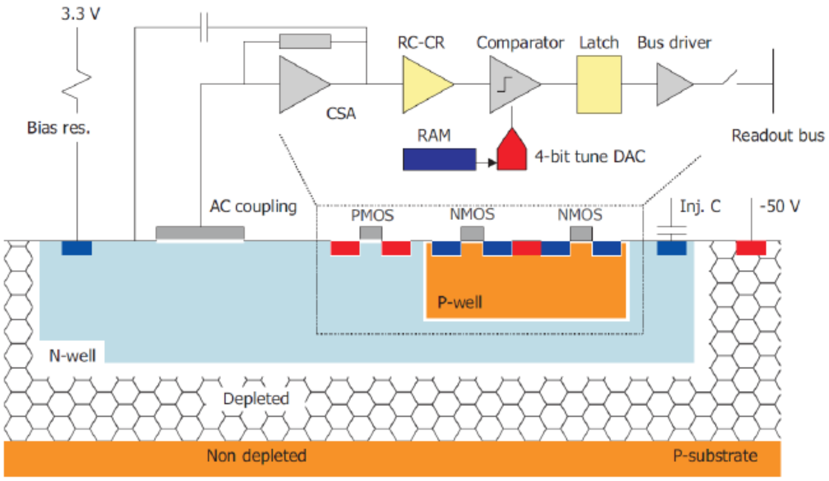
2-Year feasibility study for HiMB about to start at PSI
Not before 2017

Silicon Pixel Detector HV-MAPS

High Voltage Monolithic Active Pixel Sensors



logic embedded in N-well in the pixel "smart diode array"



< 50 μm thickness
active sensors → small readout BW
standard CMOS technology (low cost)
trigerless and fast readout
thin active region → fast charge collection
low noise
low power
radiation hard

80 × 80 μm^2 pixels
275 M channels

The MuPix Chips

Mu3e design specifications

80 × 80 μm² pixel size

1 × 2 cm² area, 95% active

MuPix2

30 × 39 μm² pixel size

1.8 × 1mm² active area

proof of concept

MuPix3/4

80 × 92 μm² pixel size

2.9 × 3.2 mm² active area

MuPix6

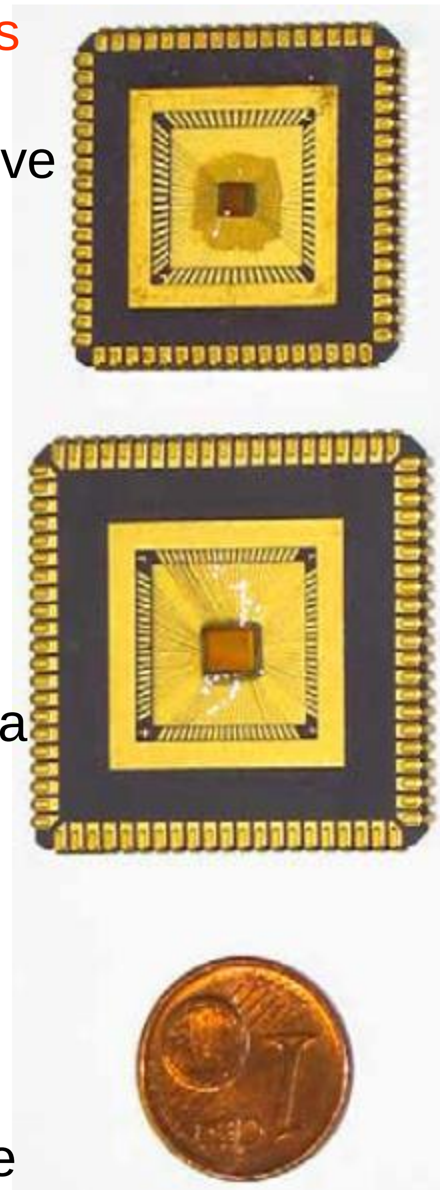
same geometry

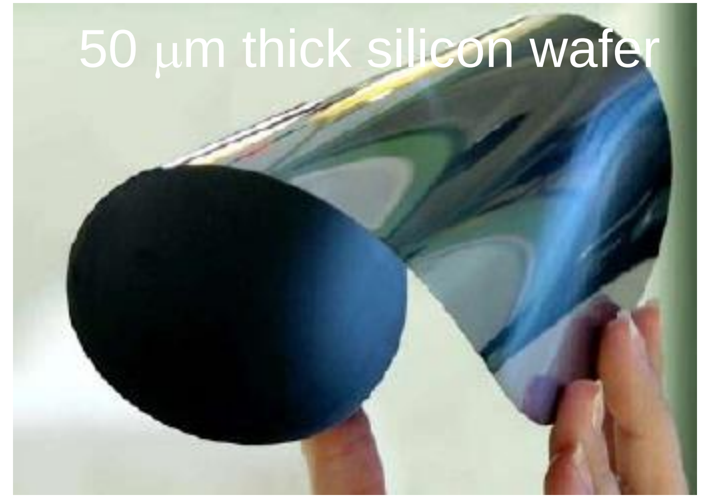
updated analog part

MuPix7

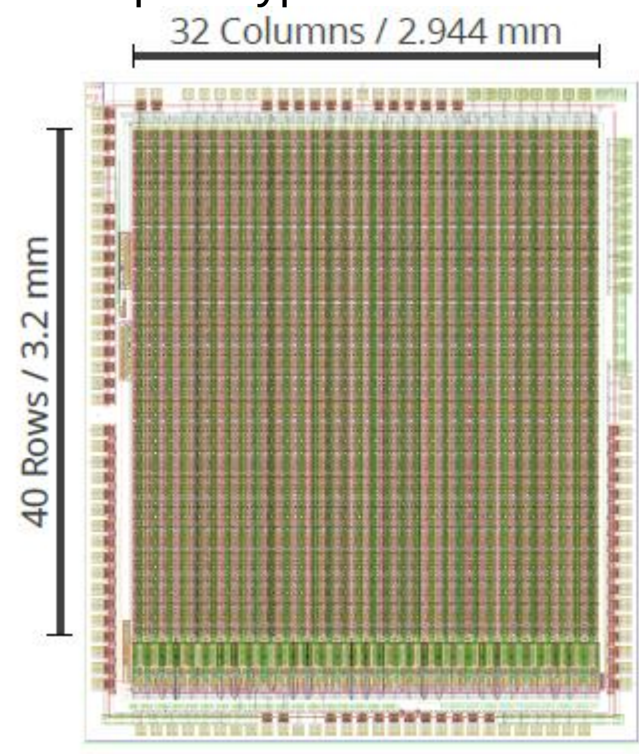
still small scale prototype

full digital logic

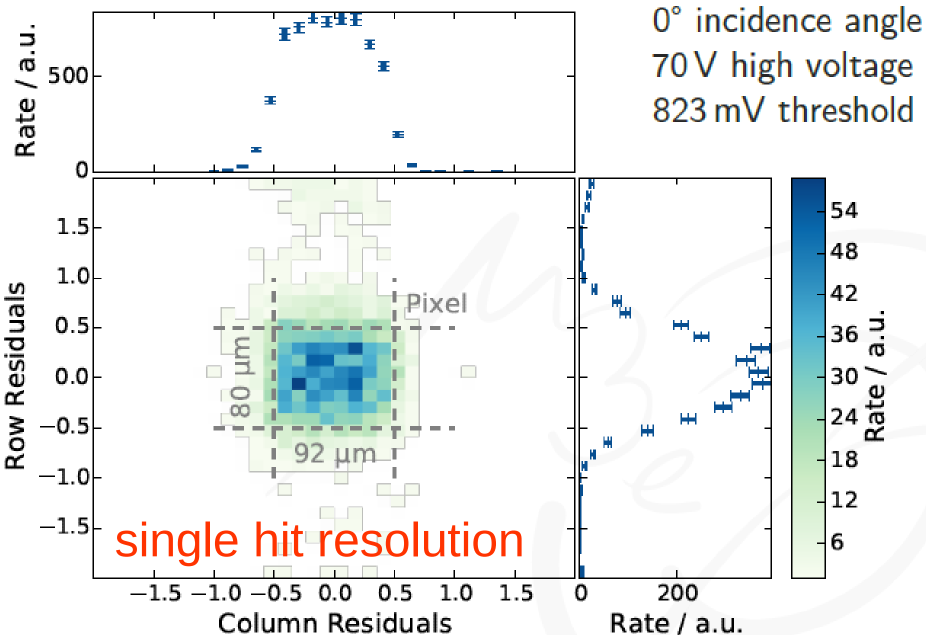


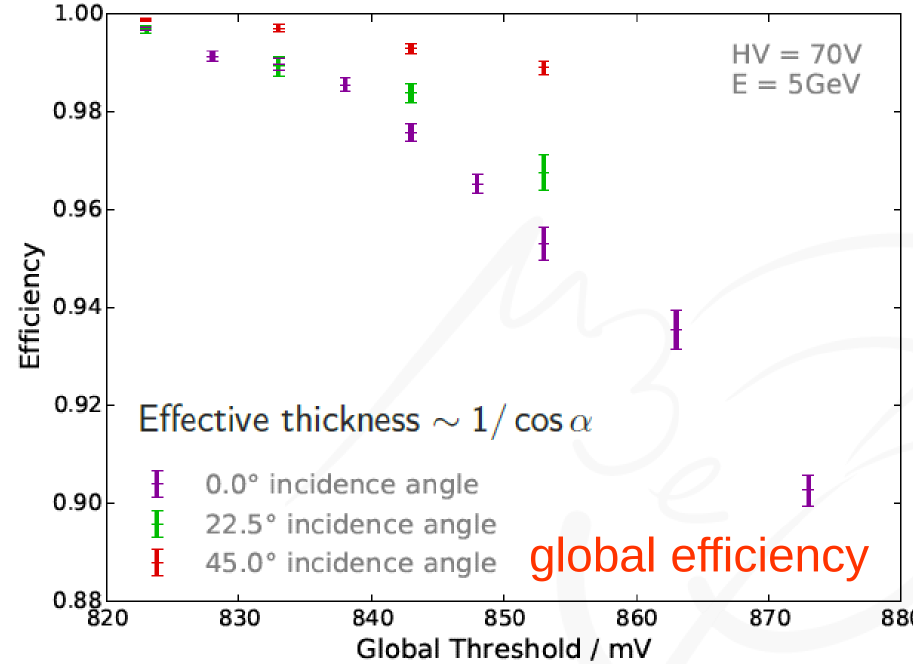


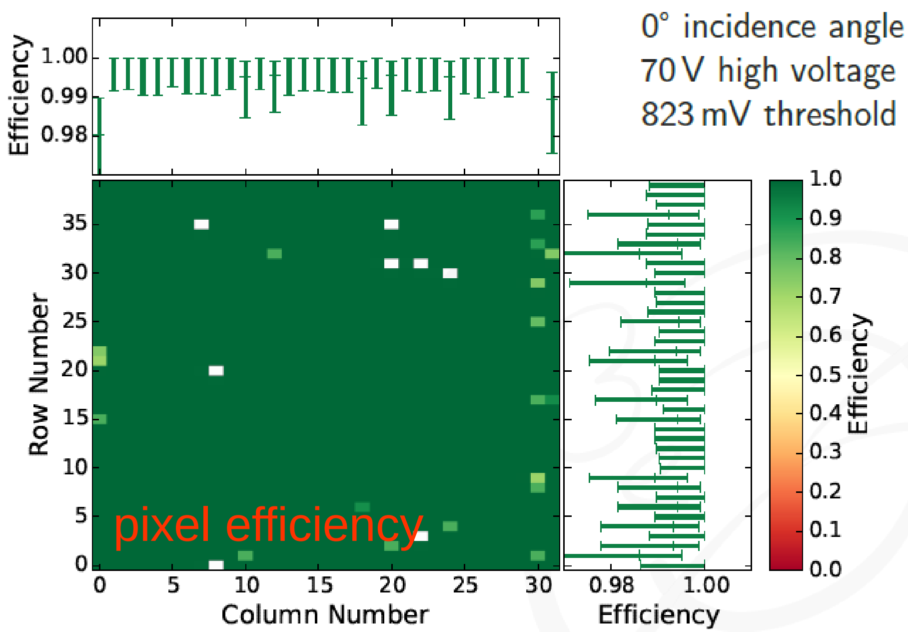
MuPix4 prototype

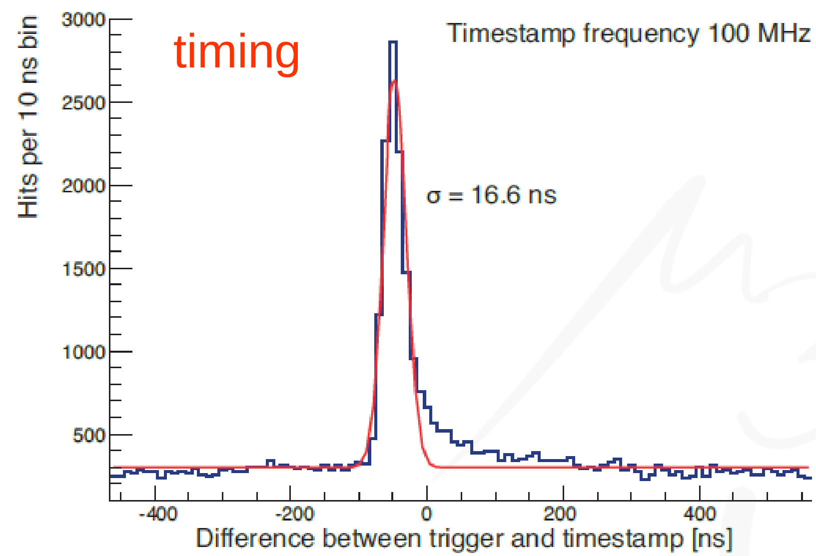


MuPix Perfromance



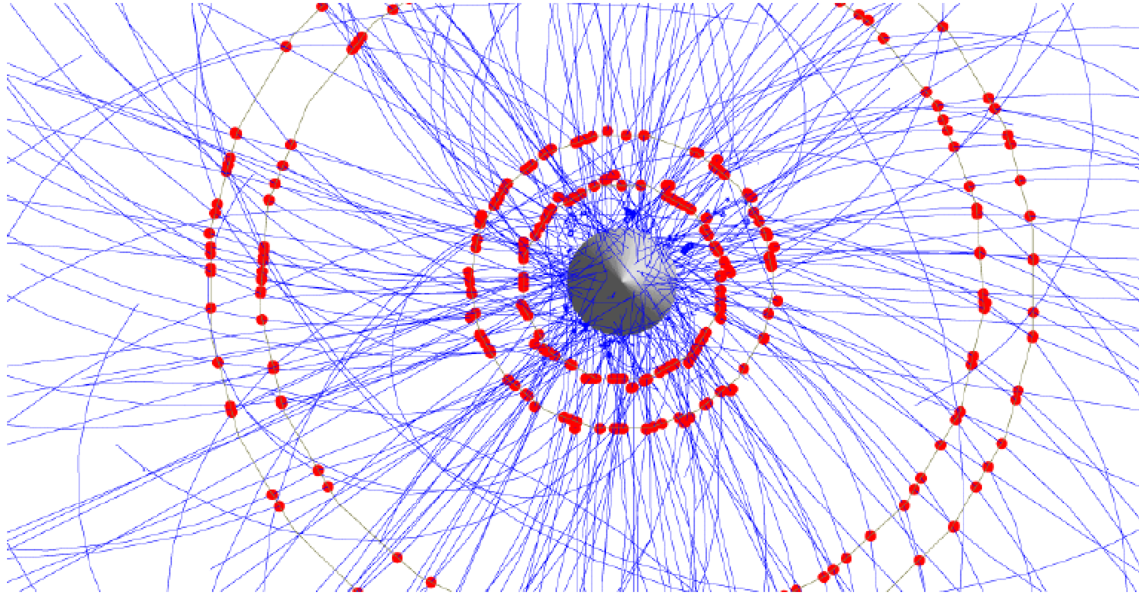




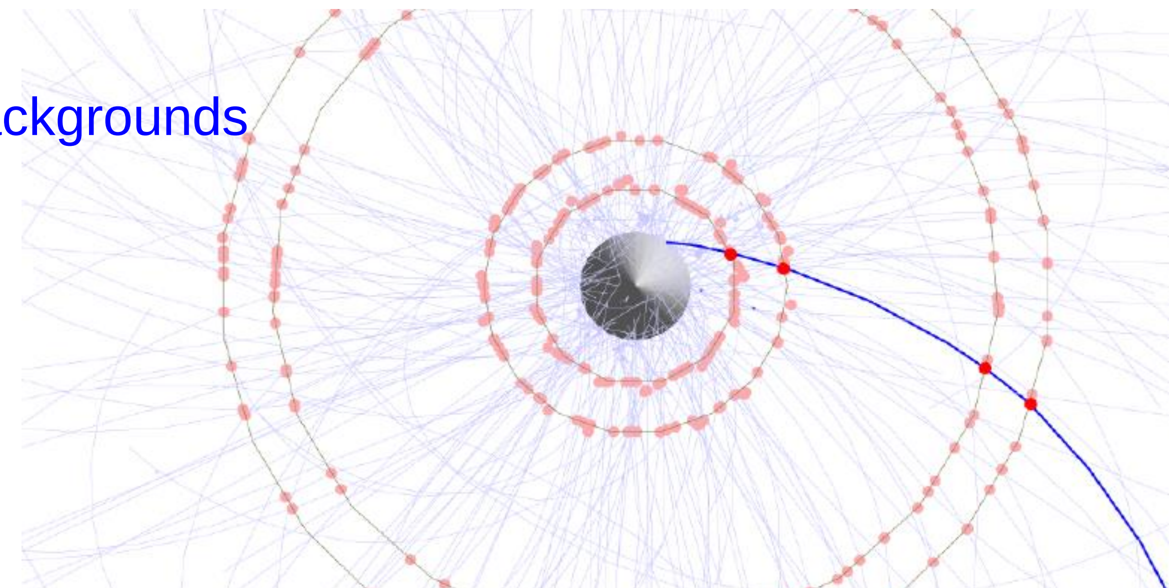


Timing

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

SciFi Performance (preliminary)

scintillating fibers 250 μm ∅

3 – 5 staggered layers

high spatial resolution (matching with silicon hits)

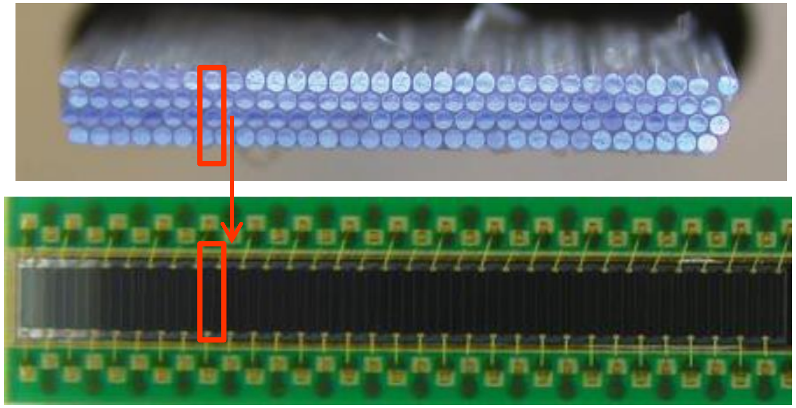
high efficiency

good time resolution < 500 ps

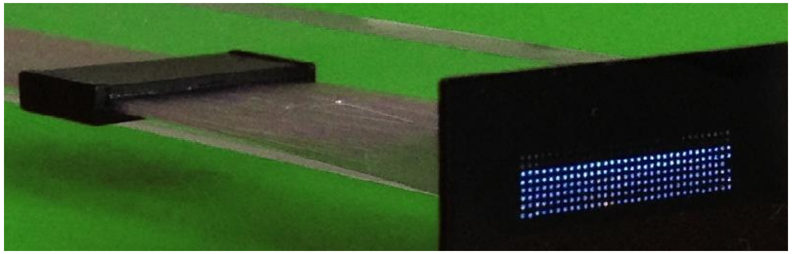
rate: several MHz / SciFi ch.

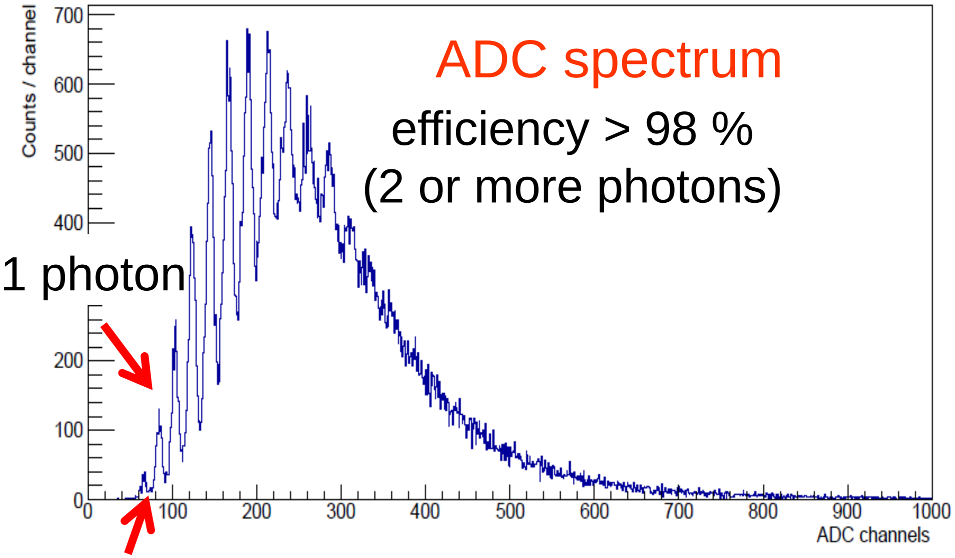
readout with Si-PMs : arrays or single fiber

column readout

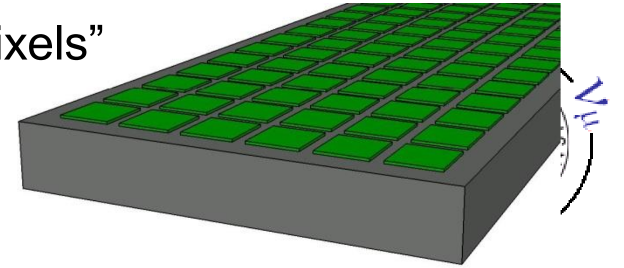


single fiber readout
minimal occupancy
tracking ?

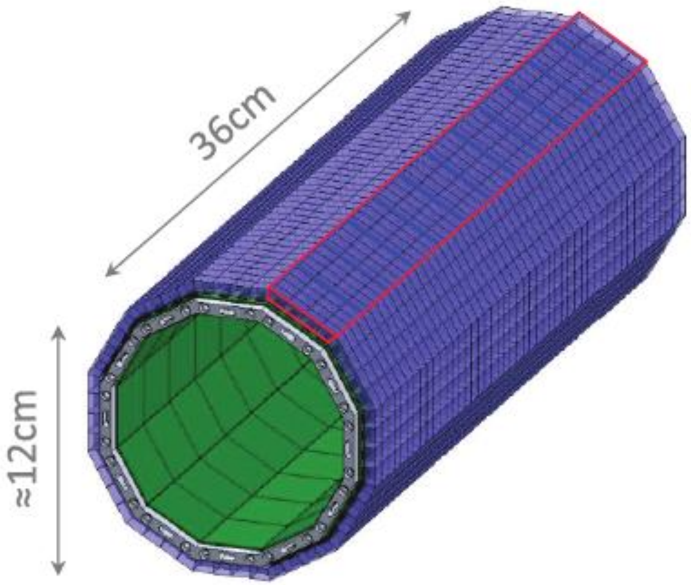




Si-PM "pixels"



Scintillating Tile Detector



recurling tracks
(2^{nd} time measurement)

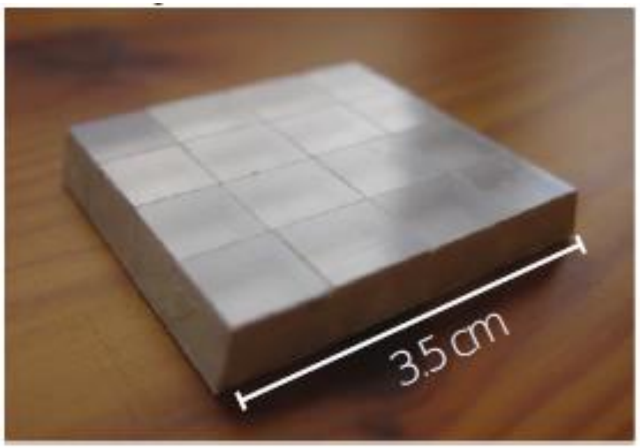
~6000 scintillating tiles
$1 \times 1 \times 0.5$ cm^3

timing < 100 ps

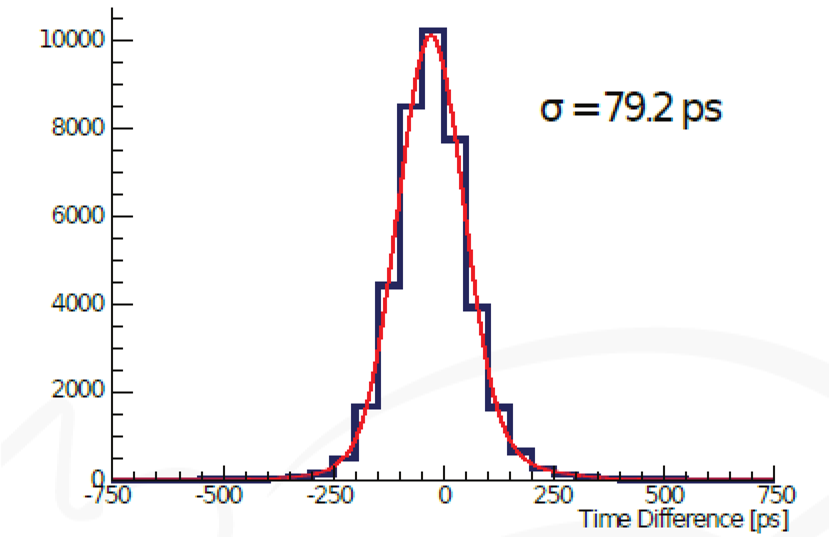
readout Si-PMs and
custom ASICs

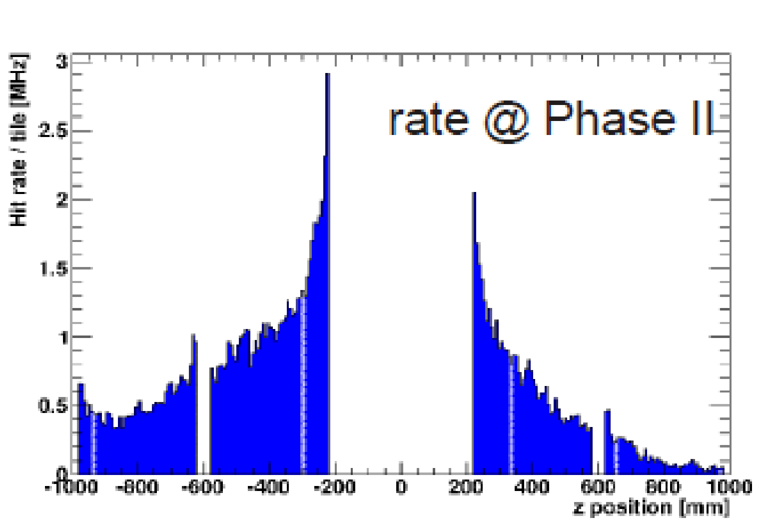
rate ~few MHz

tile prototype



time resolution





Conclusion

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 !)

Staged approach

Stage I (2016+ – 2018)

~ 10^8 μ decays / s BR($\mu \rightarrow eee$) < 10^{-15}

approved in January 2013

Stage II (2019+)

~ 2×10^9 μ decays / s BR($\mu \rightarrow eee$) < 10^{-16}

HiMB feasibility study already started

Start data taking in 2016+

Mu3e Collaboration

University of Geneva

Heidelberg University

Karlsruhe Institute of Technology

Mainz University

Paul Scherrer Institute (PSI)

Physics Institute, University of Zurich

Institute for Particle Physics, ETH Zurich