Lepton Flavor Violation
μ3e @ PSI

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

CHIPP 2013
Sursee, June 26 ‘13

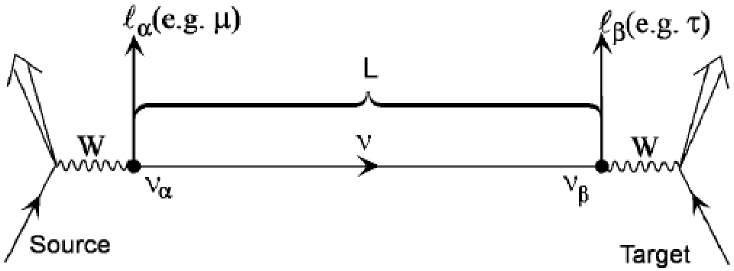
Alessandro Bravar

LFV in "Standard Model"

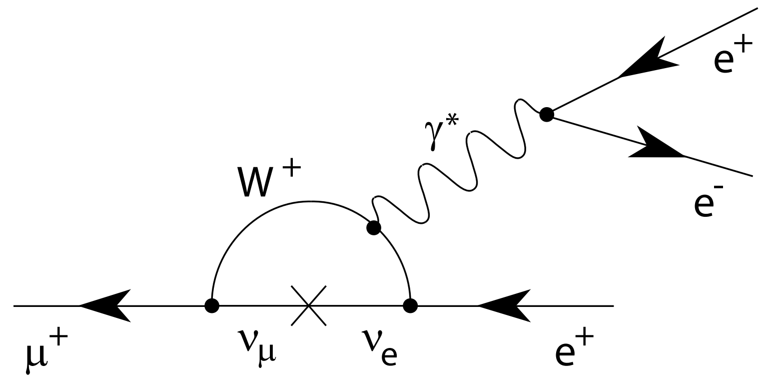
In SM ($m_\nu = 0$) Lepton Flavor is strictly conserved !

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

neutrino oscillations



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



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

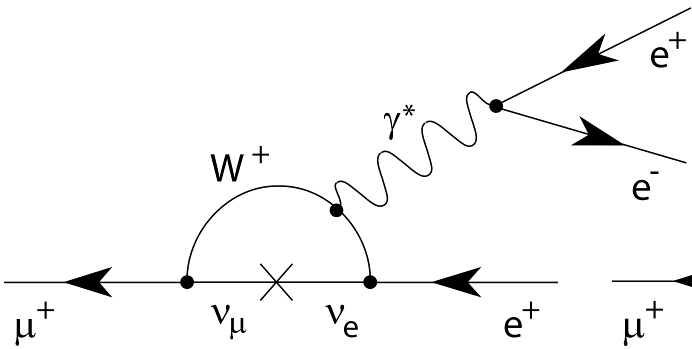
→ measurement not affected by SM processes

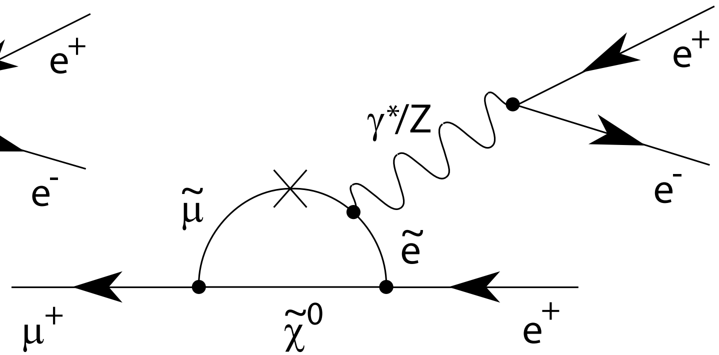
Flavor Conservation in the charge lepton sector:

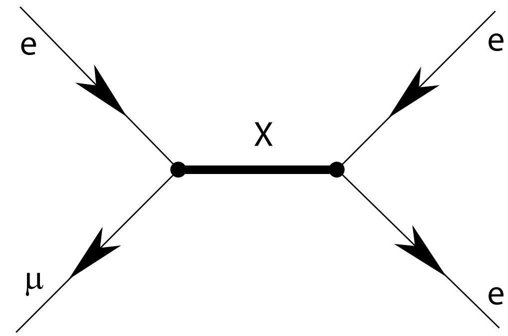
processes like $\mu A \rightarrow e A$
$\mu \rightarrow e + \gamma$
$\mu \rightarrow e\, e\, e$ have not been observed yet.

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

Lepton Flavor Violation in $\mu \to eee$







neutrino oscillations **SUSY** **"exotic" particles**

current experimental limit

$BR(\mu \to eee) < 10^{-12}$ (90% c.l., SINDRUM 1988)

this experiment (μ3e @ PSI)

$BR(\mu \to eee) < 10^{-15}$ (90% c.l. exclusion) phase I (2015 – 2017)

$BR(\mu \to eee) < 10^{-16}$ (90% c.l. exclusion) phase II (2018 – 2020)

$BR(\mu \to eee) = 3 \times 10^{-16}$ (5 σ discovery)

explore physics up to the PeV scale

complementary to direct searches at LHC

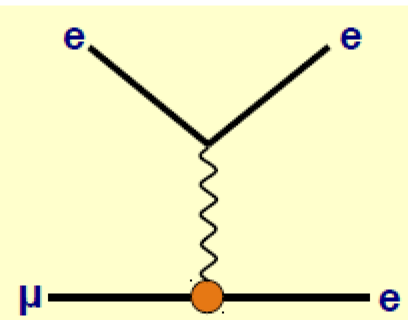
Model Comparison ($\mu \to e\gamma$ and $\mu \to eee$)

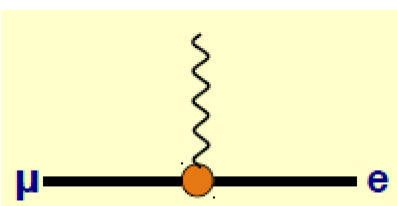
Effective charge LFV Lagrangian ("toy" model) (Kuno and Okada)

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

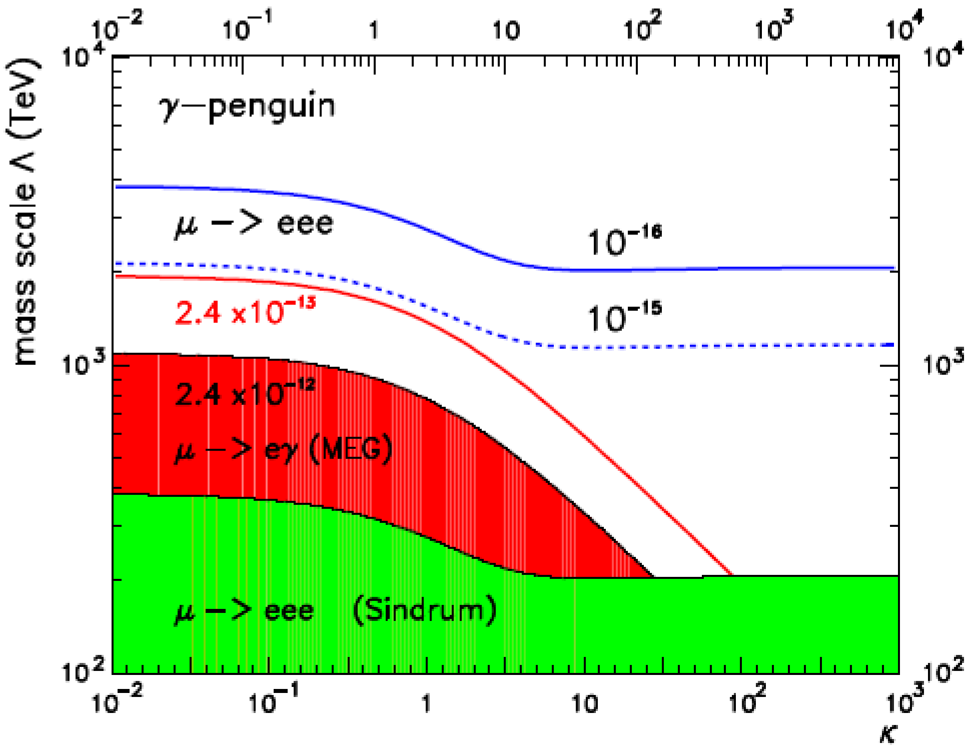
Λ = effective mass scale

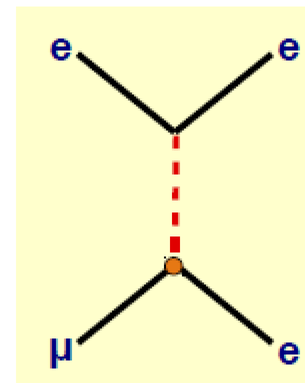
κ = "parameter" of toy model





$\kappa \to 0$





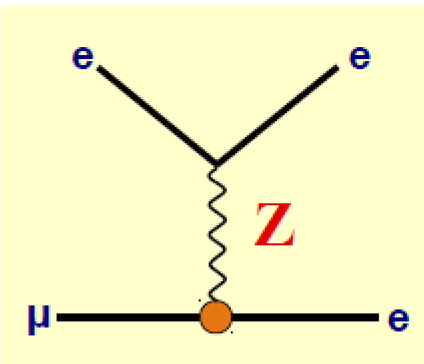
$\kappa \to \infty$

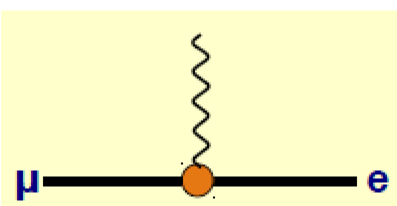
$$\frac{BR(\mu^+ \to e^+ e^- e^+)}{BR(\mu^+ \to e^+ \gamma)} \sim 0.006$$

Z - penguin

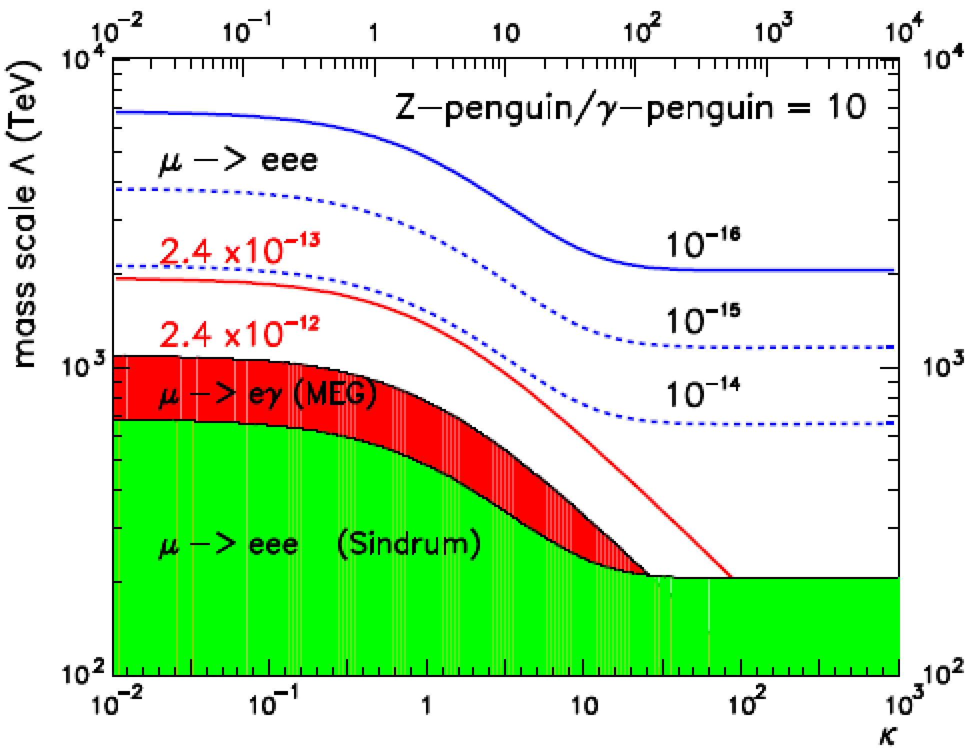
appeared in the literature in 1995 (Hisana et al.) and “rediscovered” recently

dominates if $\Lambda >> M_Z$

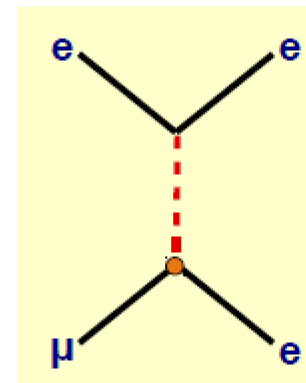




$\kappa \to 0$



Z – penguin enhanced by factor of 10



$\kappa \to \infty$

LFV Searches : Current Situation

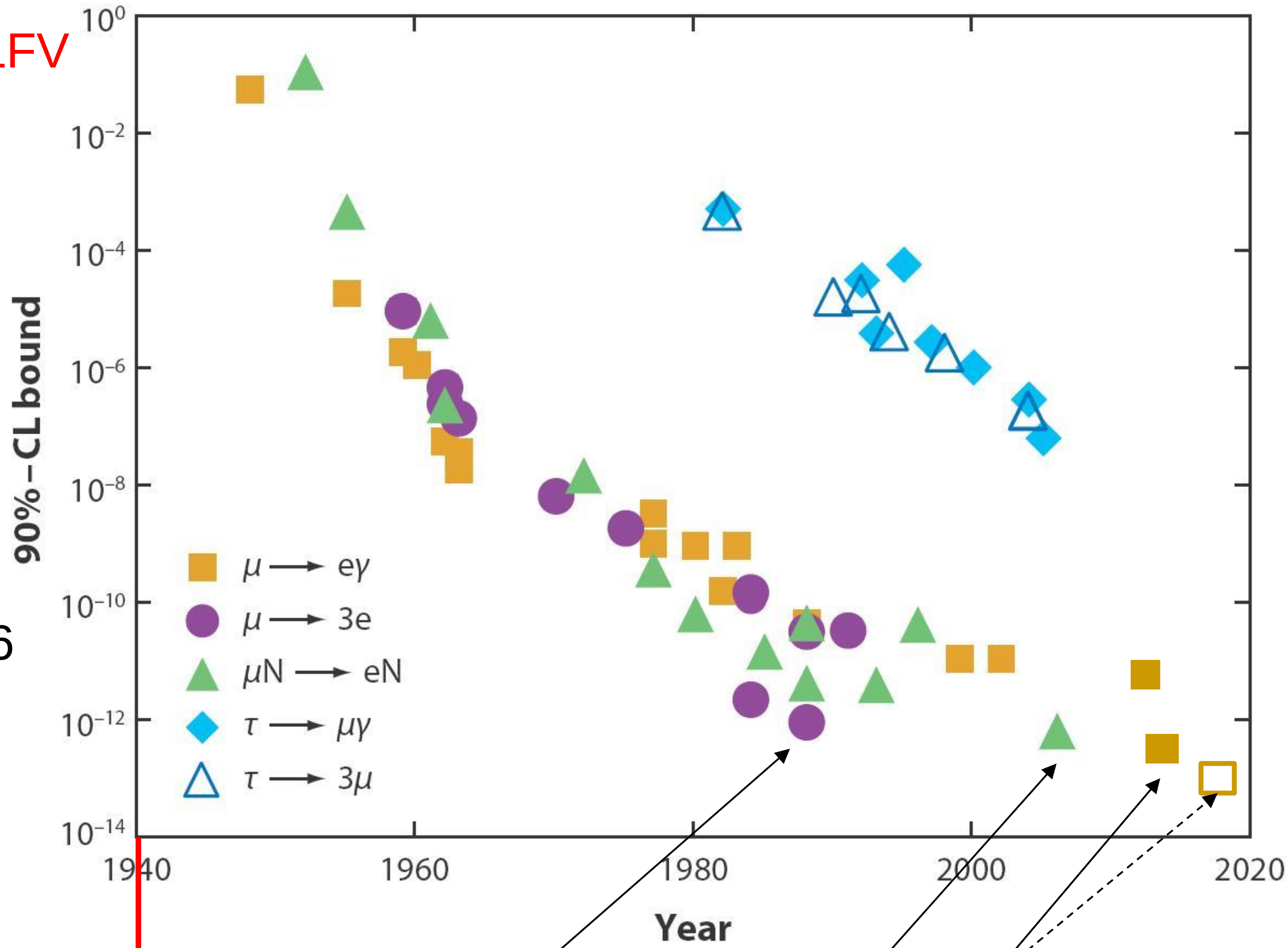
The best limits on LFV come from PSI muon experiments

$\mu^+ \rightarrow e^+ee$
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.]



SINDRUM

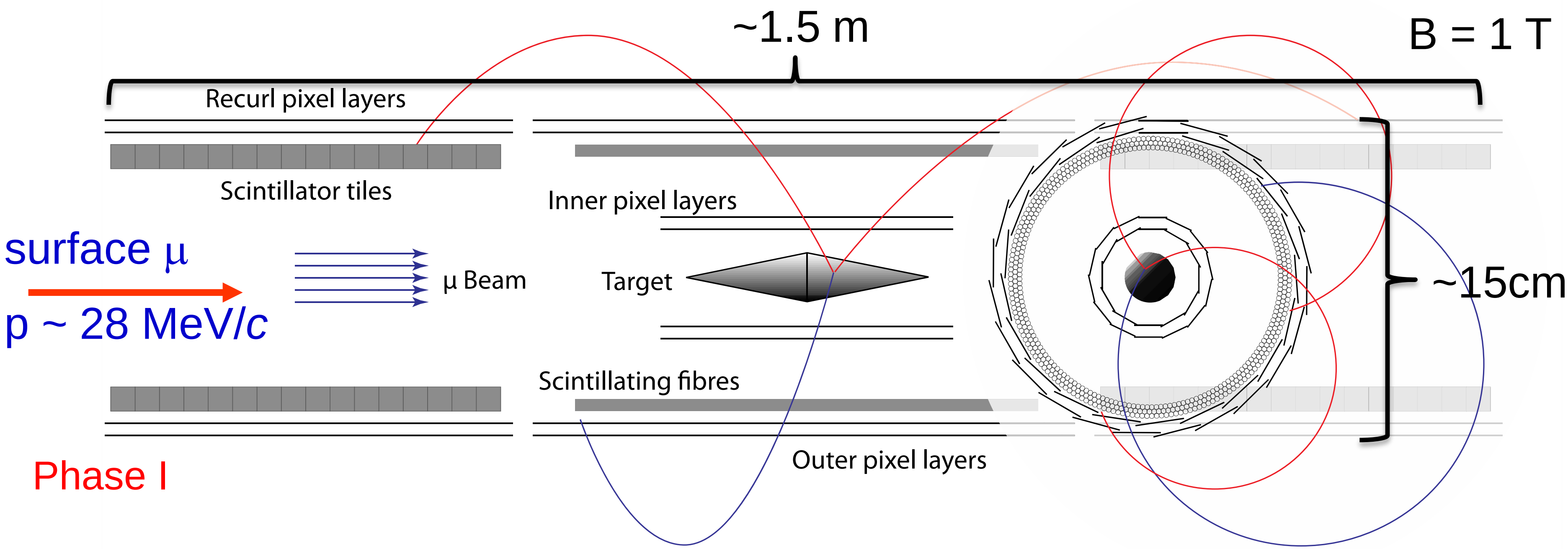
MEG

SINDRUM II

by the end of this decade

Mu3e Baseline Design

search for $\mu^+ \to e^+ e^- e^+$ with sensitivity ~10^{-16} (PeV scale)
using the most intense DC muon beam (p ~ 28 MeV/*c*) in the world
→ observe ~10^{17} μ decays (over a reasonable time scale)
rate ~ 2×10^9 μ decays / sec
→ build a detector capable of measuring 2×10^9 μ decays / sec

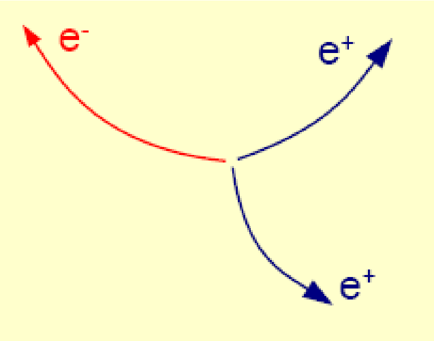


acceptance ~ 70% for μ → eee decay (3 tracks!)

200 M HV-MAPS (Si pixels w/ embedded ampli.) channels
~ 10 k ToF channels (SciFi and Tiles)

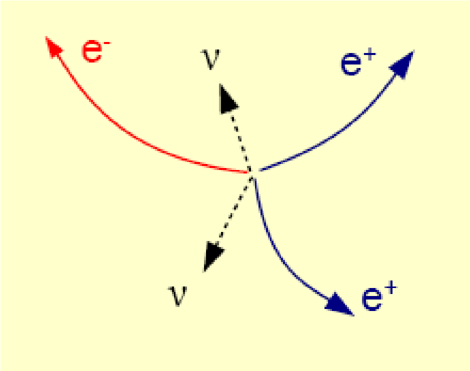
Backgrounds

signal



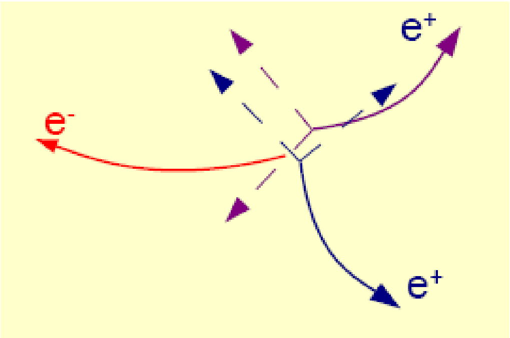
$$\sum_i \vec{p}_i = 0$$
$$\sum_i E_i = m_\mu$$
$$\Delta t_{tracks} \sim 0$$

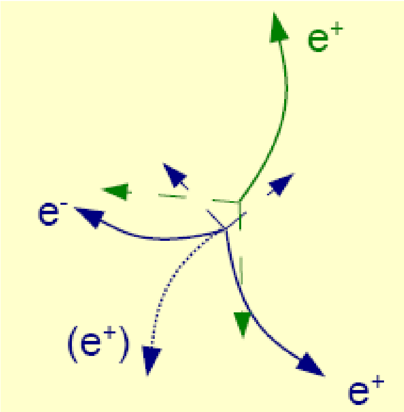
irreducible backgrounds



BR($\mu \to ee e\nu\nu$) = 3.4×10^{-5}

accidental backgrounds



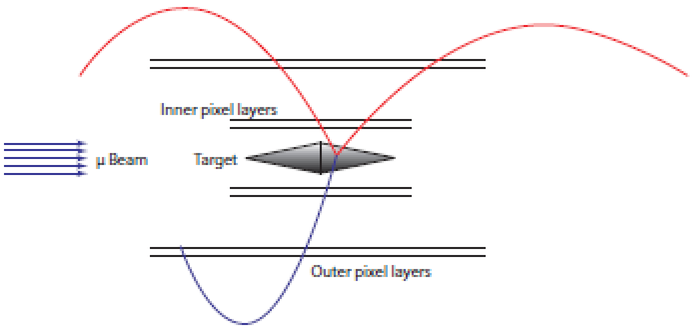


to suppress backgrounds

- precise kinematics (p and E_{TOT} resolution): $\Delta m_\mu < 0.5$ MeV/c^2
- precise timing (ToF): $\Delta t \sim 100$ ps
- precise vertexing: $\Delta x \sim 0.1$ mm

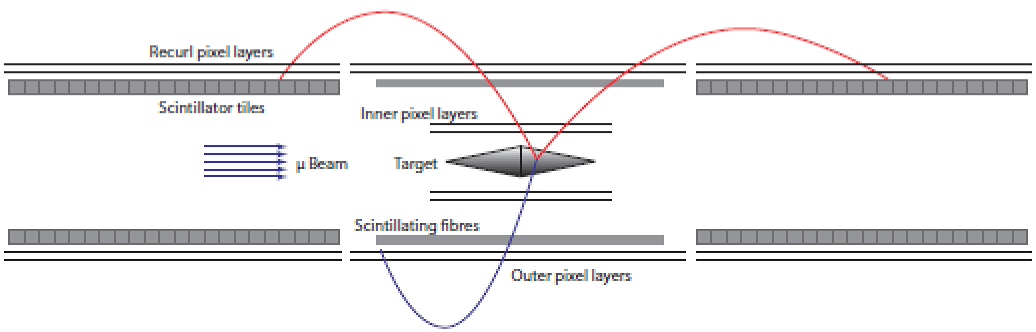
Staged Approach

Phase IA
rate $\leq 10^7$ μ / s



only central pixel

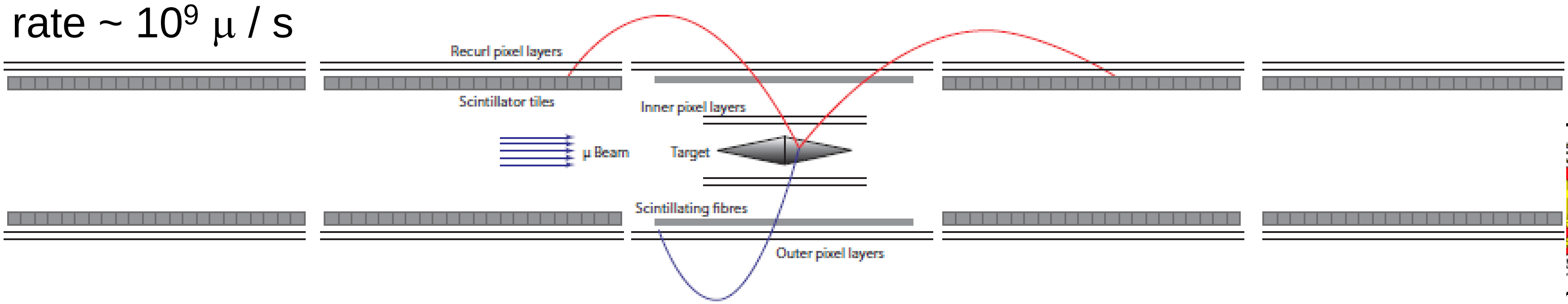
Phase IB
rate ~ 10^8 μ / s



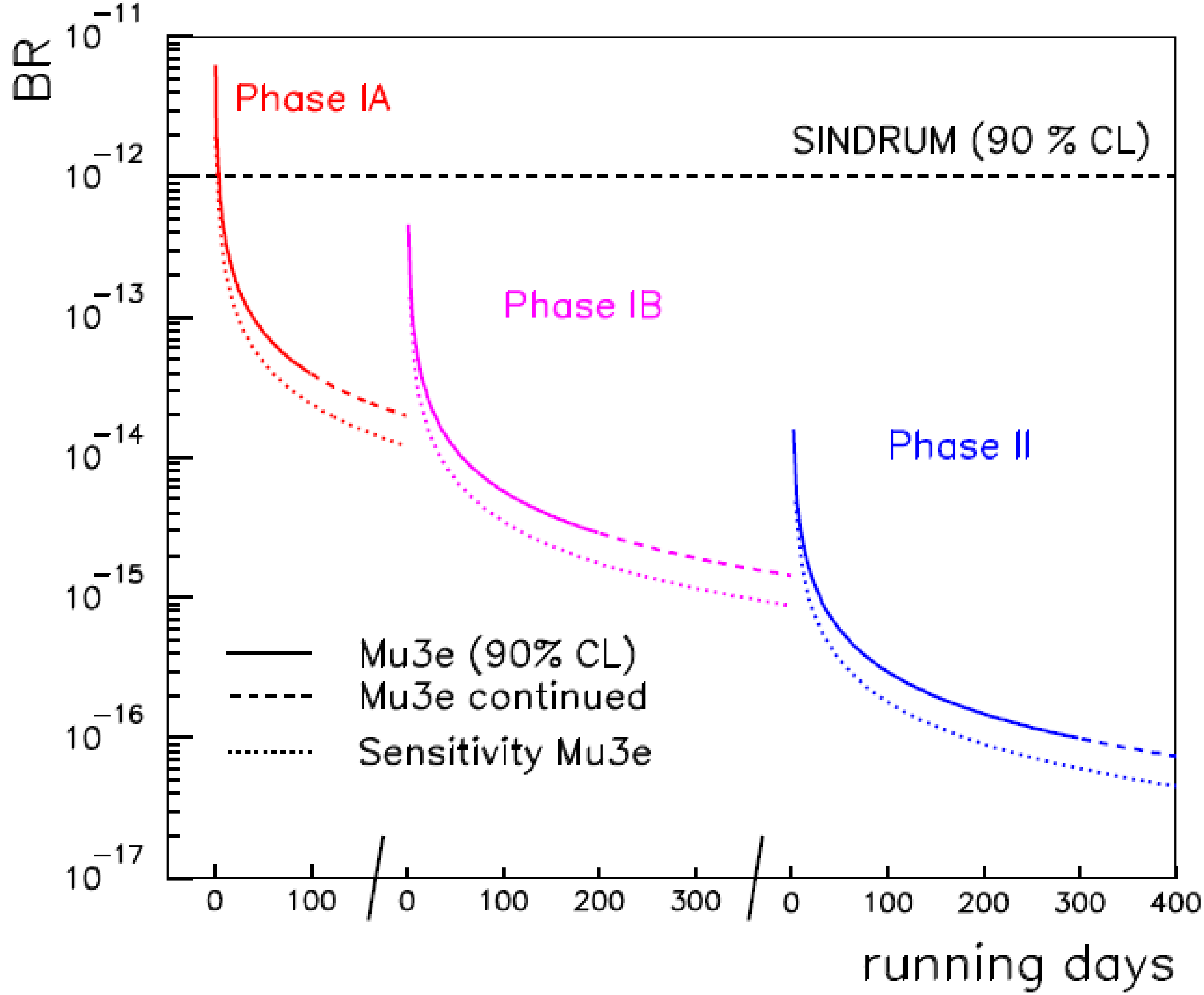
+ inner recurl sta.
+ time of flight

Phase II
rate ~ 10^9 μ / s

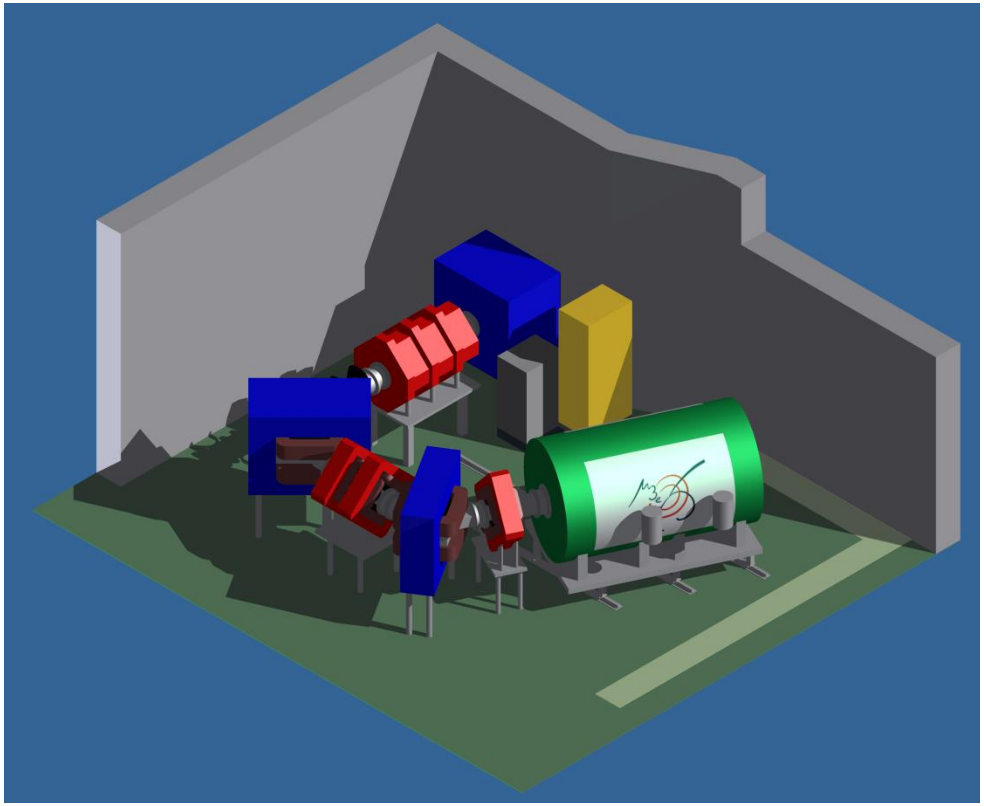
+ outer recurl sta.



Sensitivity Projection



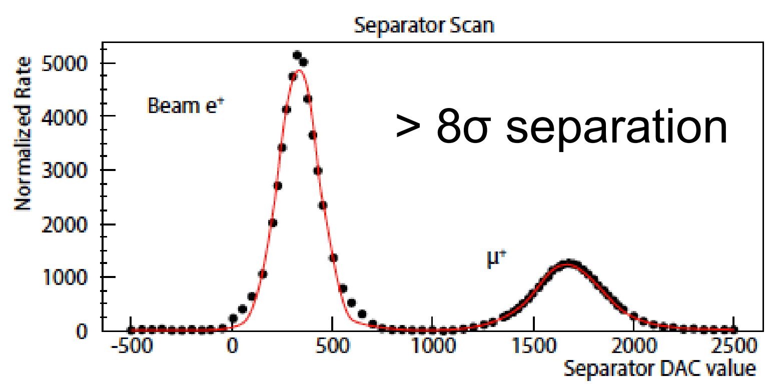
PHASE I – Compact Muon Beam Line for πE5 Area at PSI



One of the world's highest intensity surface muon beams - 28 MeV/c from stopped π-decay at target surface (capable > 10^8 $\mu^+ s^{-1}$)

Must share πE5 Area with MEG-Experiment
⇒ hence "compact" beam line in front-part of area without removing MEG Detector

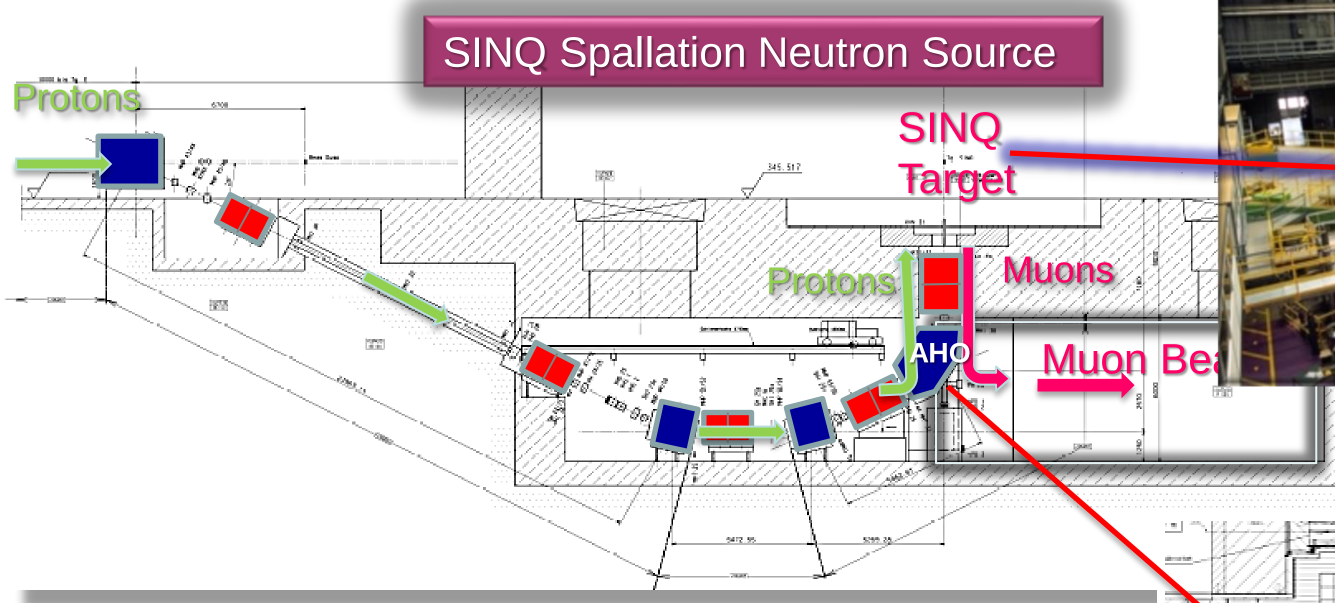
- high intensity almost monochromatic beam ($\Delta P/P < 8\%$ FWHM)
- maximum stopping rate in thinnest target ~ 150 mg/cm^2
- polarization ~ 90%
- optimal 8x higher beam correlated e^+ background suppression (Wien filter)

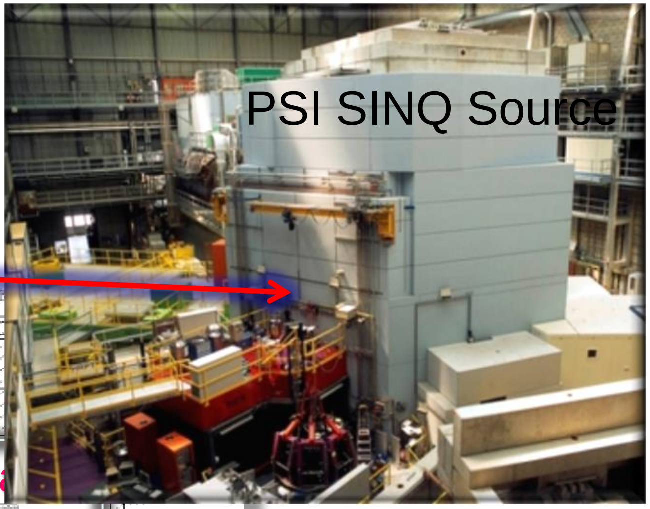


Time-scale Phase I: ~ (2015 – 2017)

PHASE II – GHz Muon Beam from SINQ Spallation Neutron Target

Phase II O(10^{-16}) Sensitivity requires GHz Muon beam





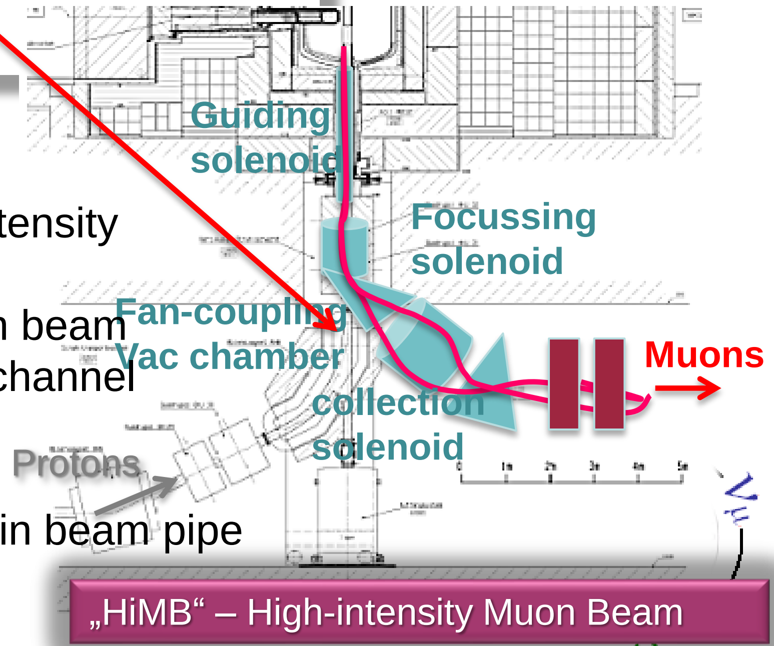
"HiMB" – High-intensity Muon Beam Concept:

- 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
- Initial MCNPX MC-simulations of source optimistic give

R_{μ} ~ $7 \cdot 10^{10}$ μ^{+} s^{-1} @ 2.4 mA Proton current

μ's of correct E, 25 cm below window travelling downwards in beam pipe

2-Year Feasibility Study for HiMB about to start at PSI



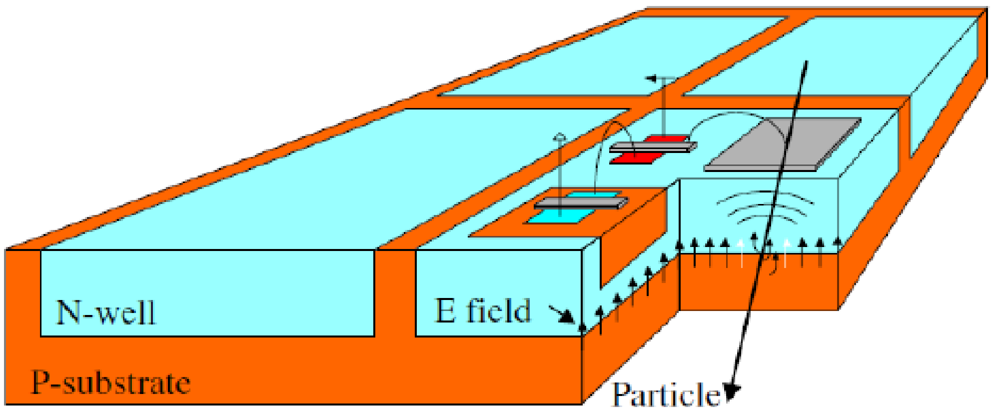
Mu3e Proto-Collaboration

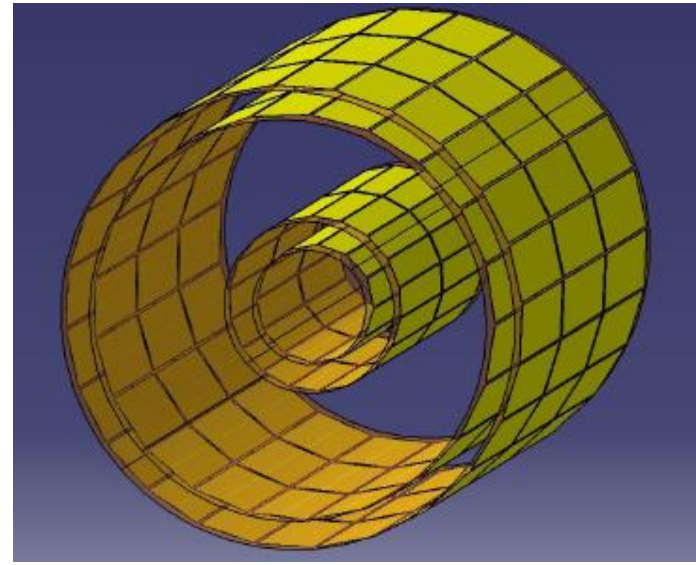
- DPNC Geneva University
- Physics Institute, University Heidelberg
- KIP, University Heidelberg
- ZITI Mannheim, University Heidelberg
- Paul Scherrer Institute
- Physics Institute, University Zurich
- Institute for Particle Physics, ETH Zurich

Silicon Pixel Detector HV-MAPS

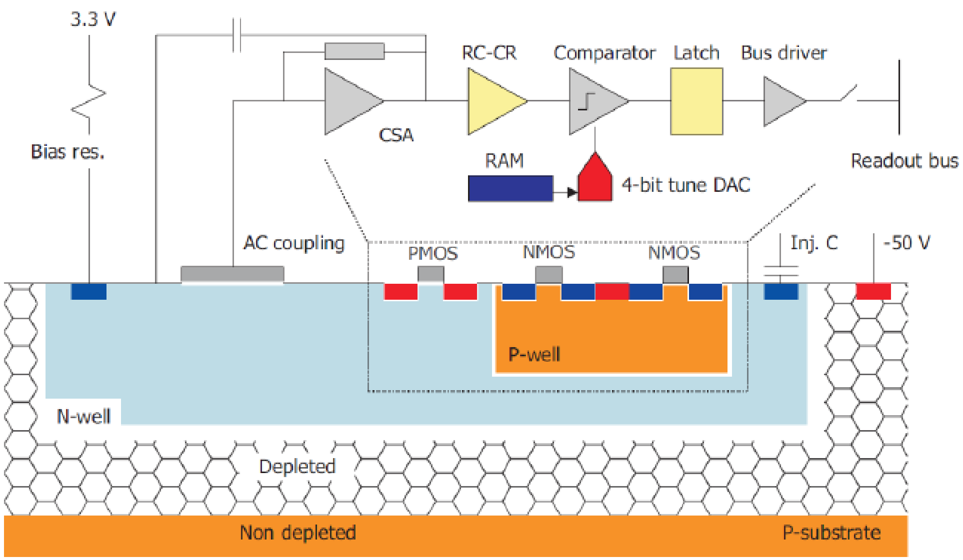
Heidelberg

High Voltage Monolithic Active Pixel Sensors





transistor logic embedded in N-well



< 50 μm thickness
active sensors
standard CMOS process (low cost)
low noise
low power

~ 80 × 80 μm² pixels
200 M channels

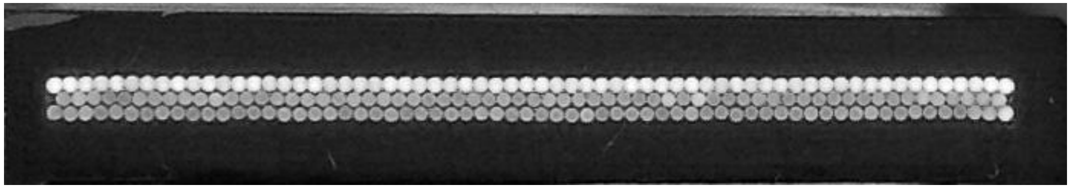
Sci-Fi Tracker - ToF

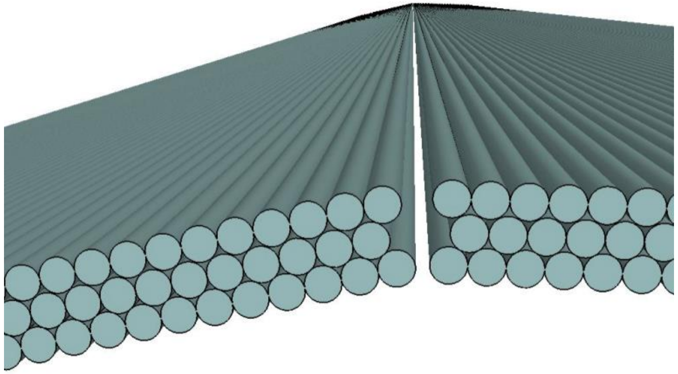
high spatial resolution (matching with Si hits)

good time resolution < 1 ns

scintillating fibers 250 μm ∅ (3 staggered layers)

24 Sci-Fi ribbons (16 mm x ~400 mm)

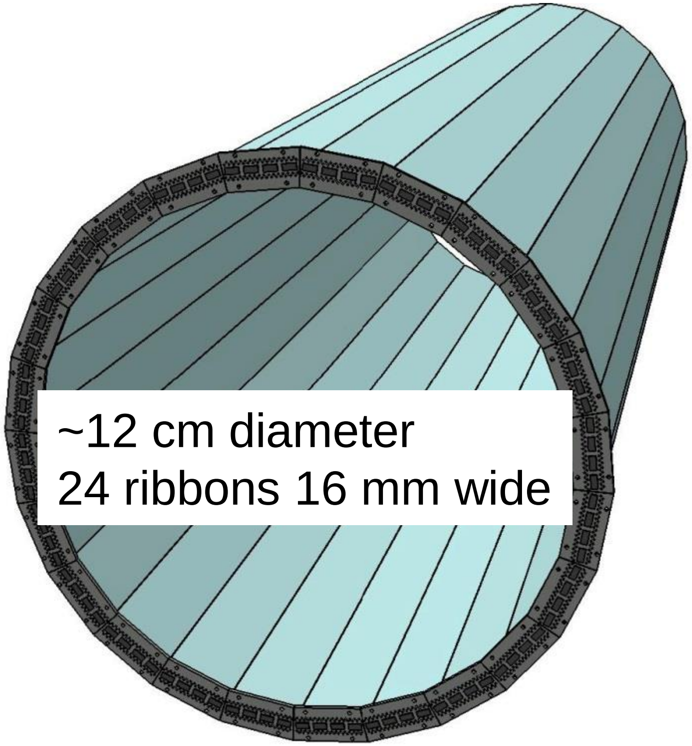




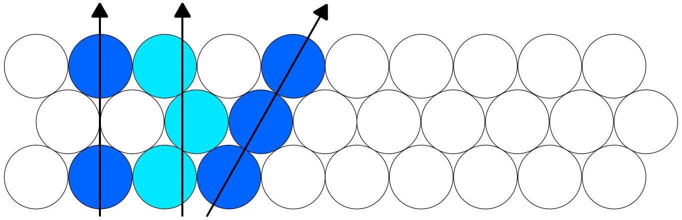
readout with Si-PMs on both ends
- Si-PM arrays (à la LHCb) ~ 3000 ch.
- individual fiber readout ~ 9000 ch.

rate: several MHz / SciFi ch.

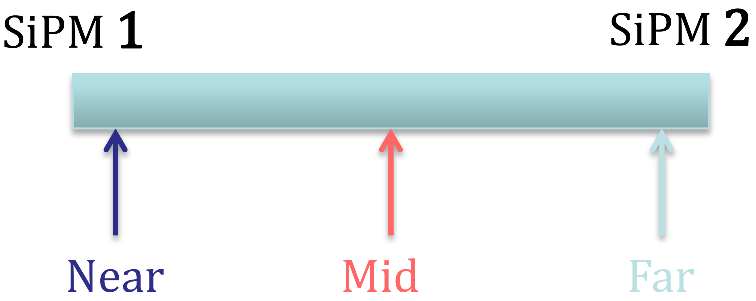
readout with the DRS waveform digitizer



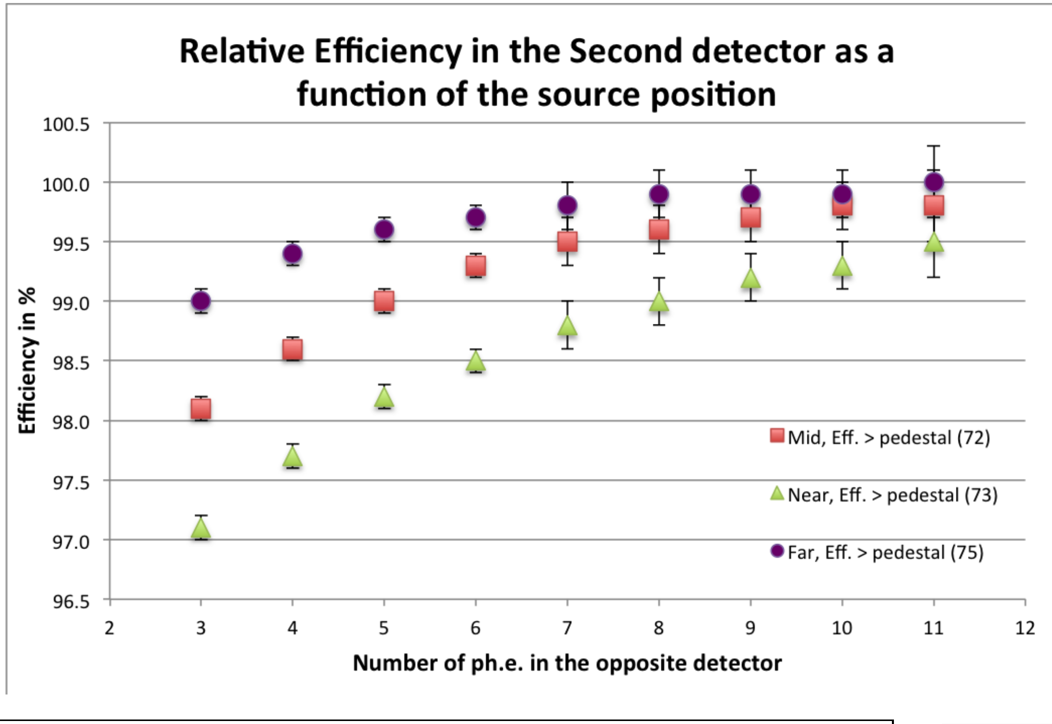
occupancy ?

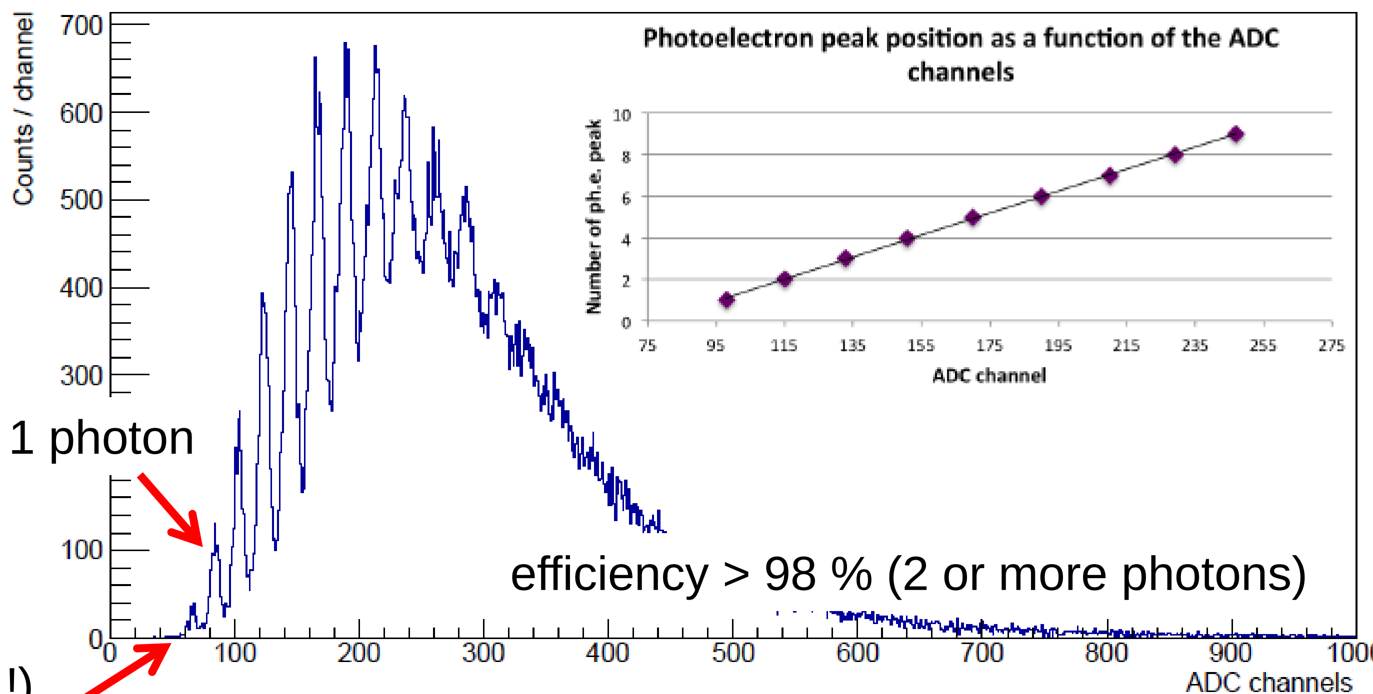


Efficiency



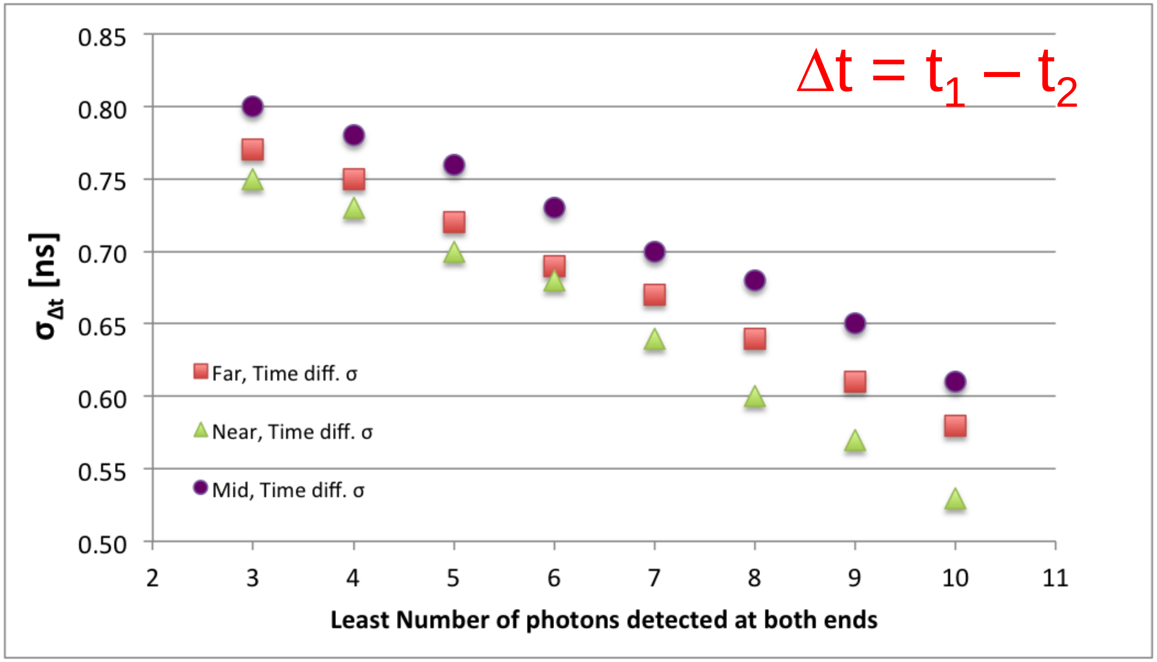
β source
crosses ribbon at 90^0

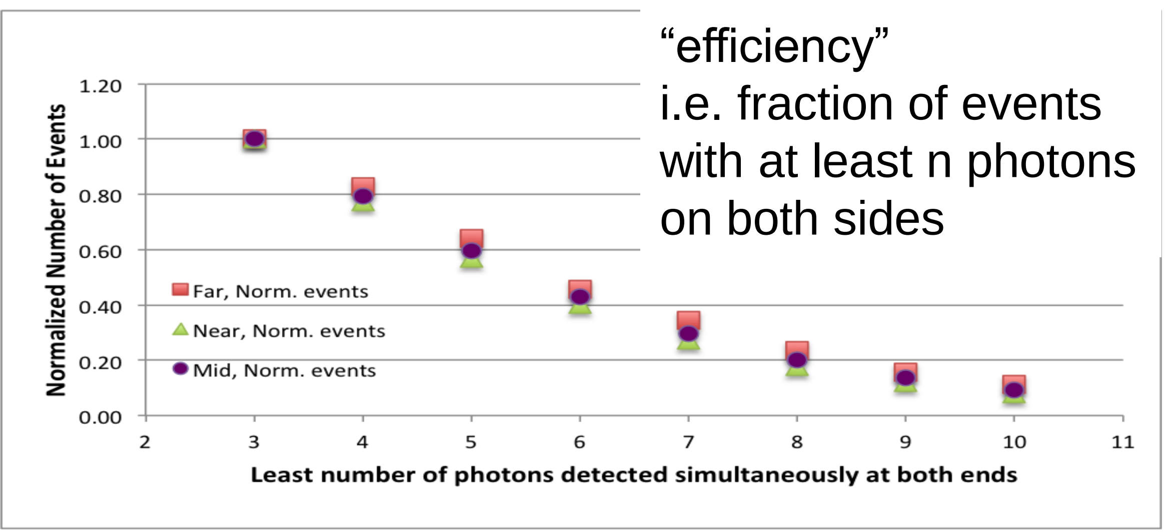




pedestal
(inefficiency !)

Timing





"efficiency"
i.e. fraction of events with at least n photons on both sides

$\sigma_{\Delta t} \approx 800$ ps
with at least 3 ph.e. detected
(almost 100 % efficient)

$\Rightarrow \sigma_{MT} \approx 400$ ps ≥ 3 ph.e.
mean time does not depend on hit position ☺

$\sigma_{MT} = ½\, \sigma_{\Delta t}$

$\sigma_{\Delta t} \approx 600$ ps
with at least 10 ph.e. detected on each side
(~10% "efficient")

$\Rightarrow \sigma_{MT} \approx 300$ ps, ≥ 10 ph.e.
(mean time)

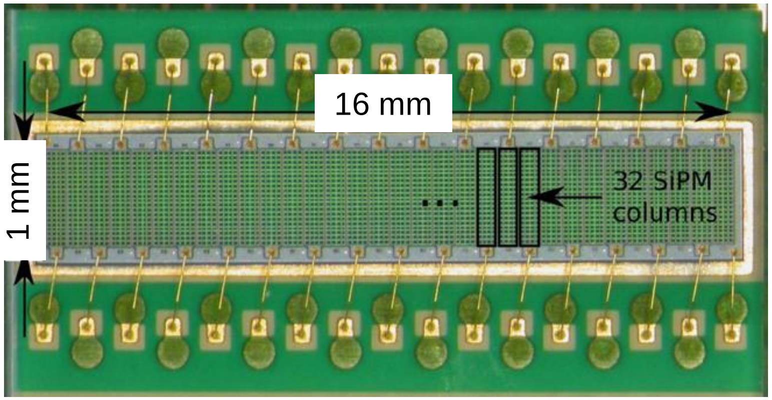
obtained with risetime compensated discriminator, not a digitizer (DRS4)

A. Damyanova (UniGE)

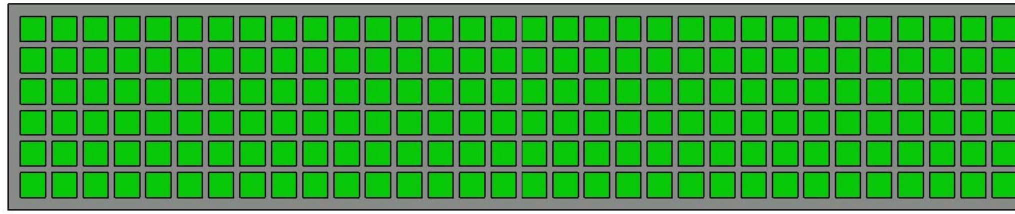
Read-out of Sci-Fis

At present considering two options with Hamamatsu recent developments: pixels with trenches increased P.D.E. ?

Si-PM arrays

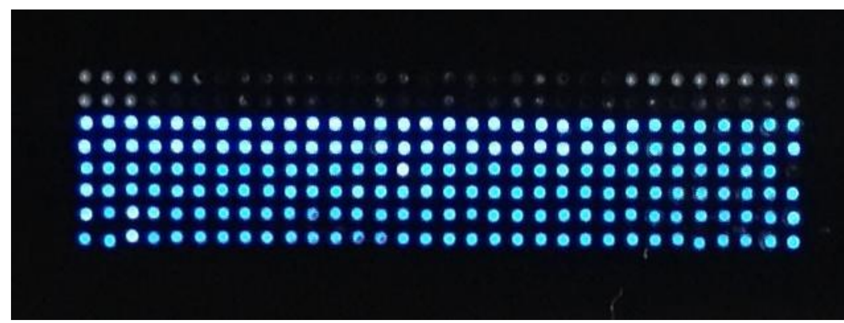


Single Fiber readout

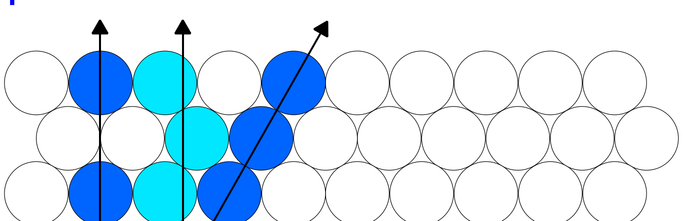


monolithic device with 6 x 32 independent sensors
0.4 $\times$ 0.4 mm^2 with 100 μ pixels and 100 μ spacing
(bias voltage regulated for reach sensor ΔV~0.5 V)

64 channel monolithic device à la LHCb
250 μ “pitch”, 50 μ pixels
common bias voltage

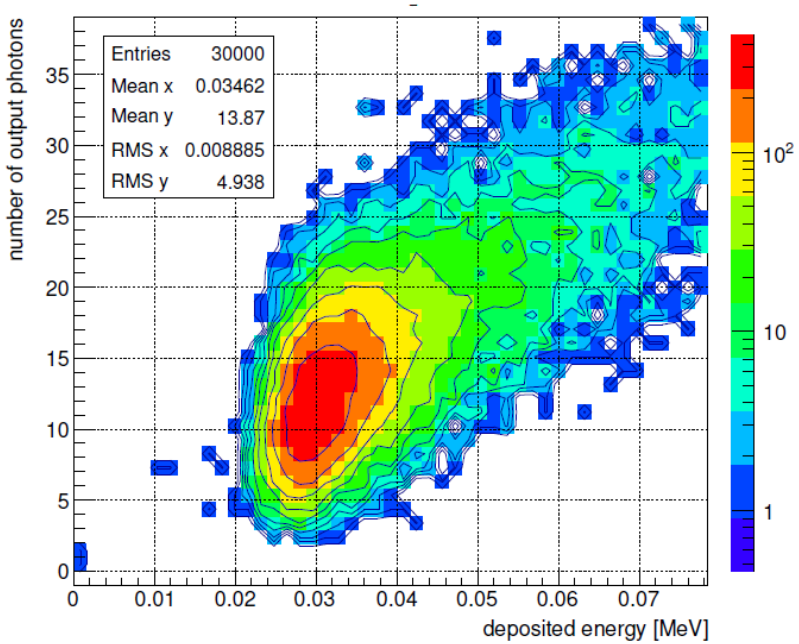


occupancy is the issue
keep rate 1 to 2 MHz / ch.

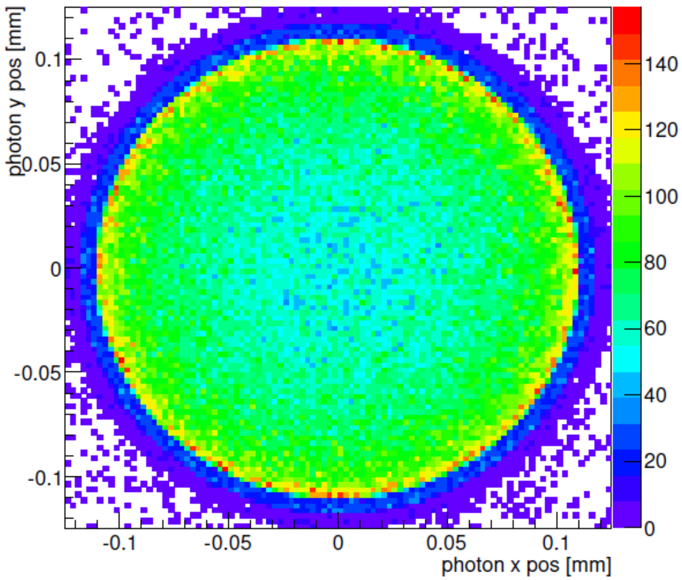


fibers are glued in a matrix with same geometry as the photo-device

SciFi Simulations



photon yield
(cfr. ADC spectrum
w/ P.D.E. ~ 25%)



light propagation

R. Gredig (UniZH)

in Mu3e

from Mu3e proposal
(only construction of the Mu3e detector)

component	who
beam	PSI
target	PSI (+ Heidelberg)
SciFi tracker	UniGE, UniZH, ETHZ, PSI
timing electronics	PSI, UniGE, UniZH, ETHZ
slow control	PSI
infrastructure	PSI

Outlook

Letter of Intent — January 2012

Research Proposal — January 2013

- Stage I approved
- HiMB 2 year feasibility study to start this summer

Technical review — January 2014

High precision experiments at National Laboratories promoted by European Strategy

Staged approach

- Stage I (2015 – 2017)
  - ~ 10^8 μ decays / s — $BR(\mu \to eee) < 10^{-15}$
- Stage II (2018+)
  - ~ 10^9 μ decays / s — $BR(\mu \to eee) < 10^{-16}$

Funding applications submitted