Lepton Flavor Violation
The μ3e 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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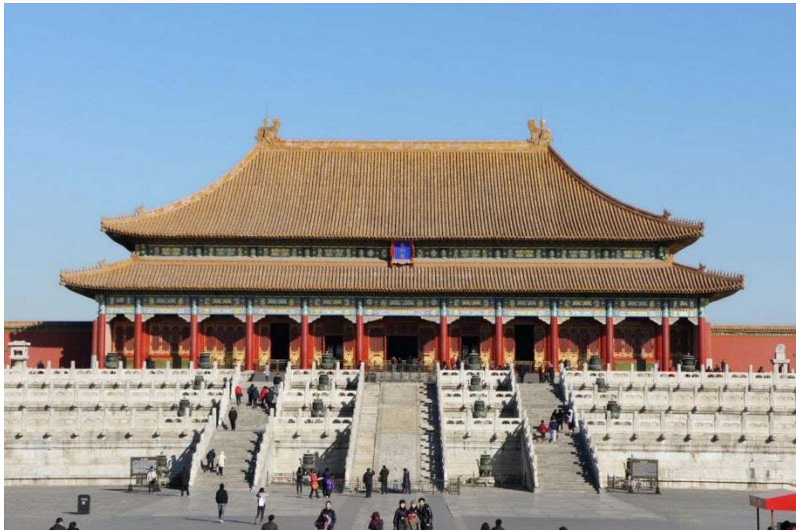
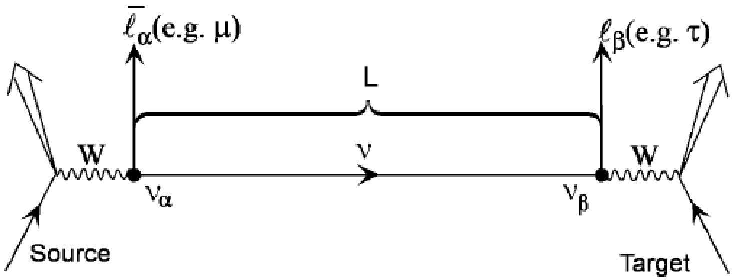


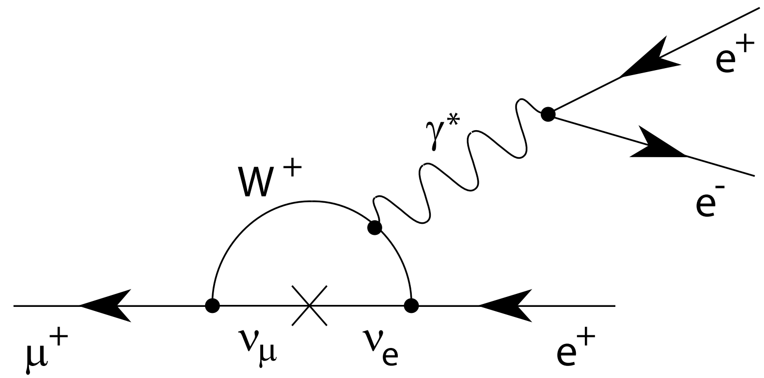
LFV in "Standard Model"

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

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





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

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

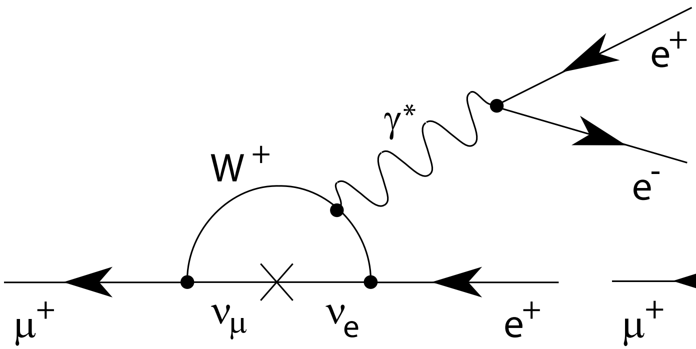
$\rightarrow$ measurement not affected by SM processes

Flavor Conservation in the charge lepton sector :

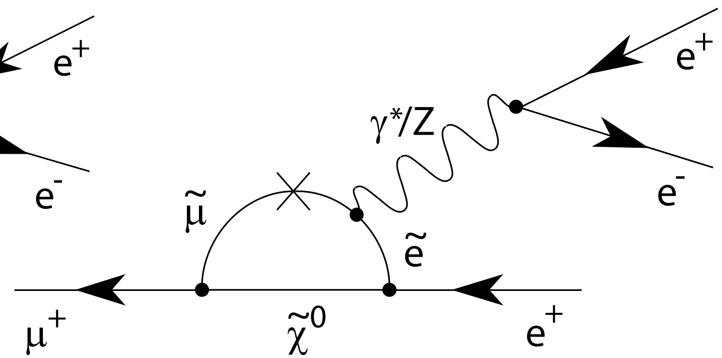
processes like $\mu\, A \rightarrow e\, A$
$\mu \rightarrow e + \gamma$
$\mu \rightarrow e\, e\, e$ have not been observed yet.

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

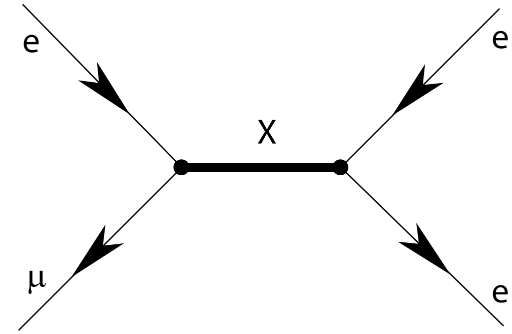
Lepton Flavor Violation in $\mu \rightarrow eee$



neutrino oscillations



SUSY loops



"exotic" particles

current experimental limit

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

this experiment (μ3e @ PSI)

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

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

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

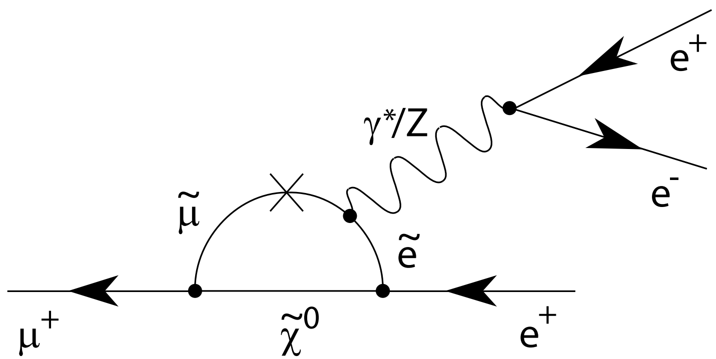
explore physics up to the PeV scale

complementary to direct searches at LHC

New Physics in $\mu \rightarrow eee$

LFV addresses issues like

- – origin of flavor
- – neutrino mass generation
- – CP violation



Loop Diagrams

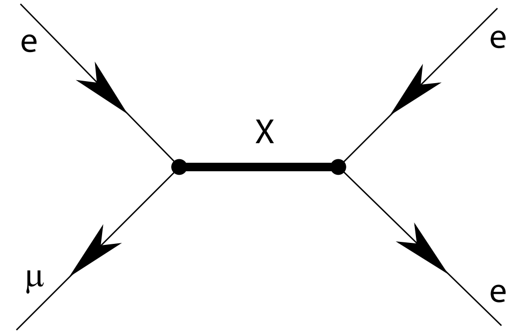
Supersymmetry

Little Higgs Models

Seesaw Models

GUT models (Leptoquarks)

many other models …



Tree Diagrams

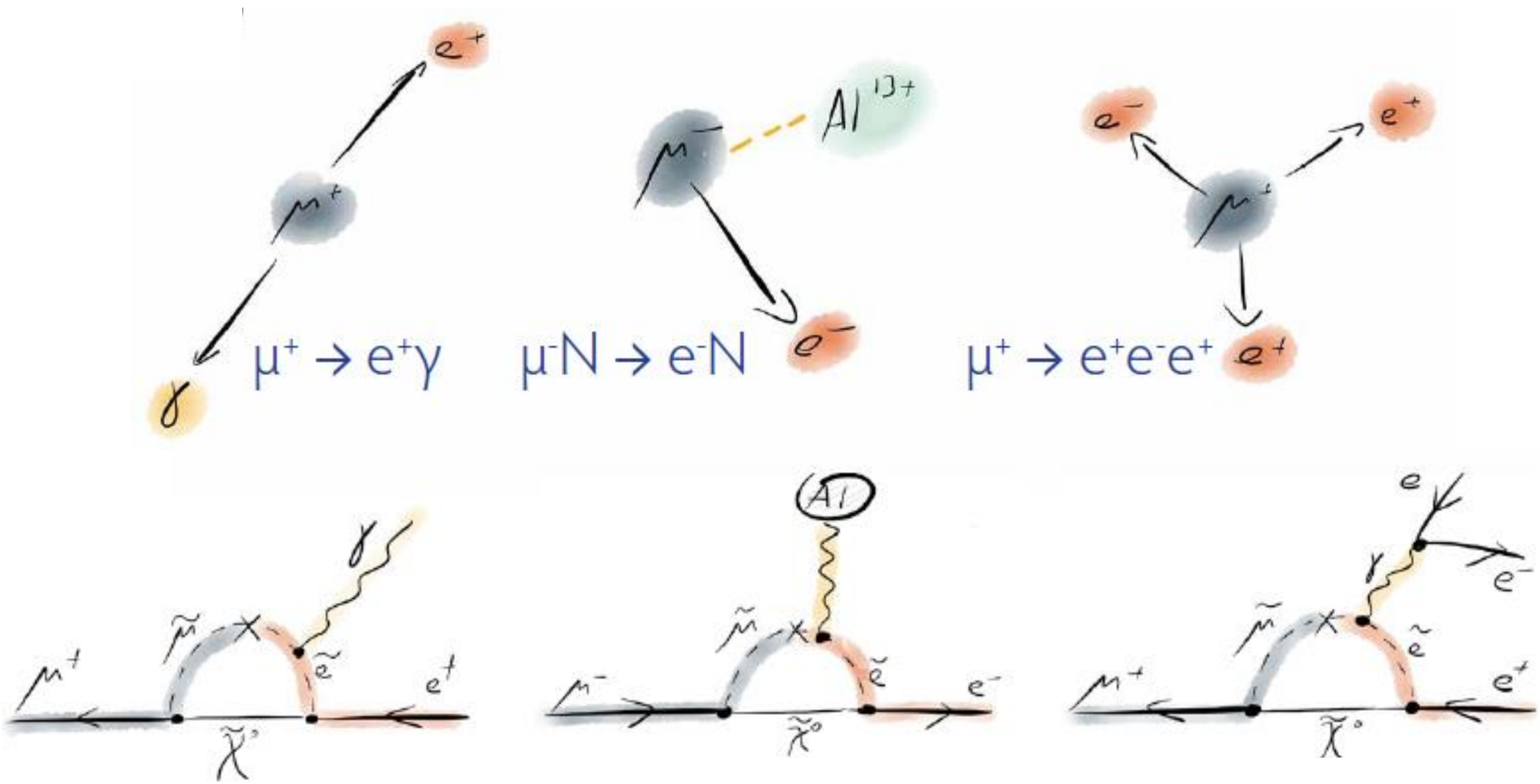
Higgs Triplet Models

New Heavy Vector Bosons (Z')

Extra dimensions (K-K towers)

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

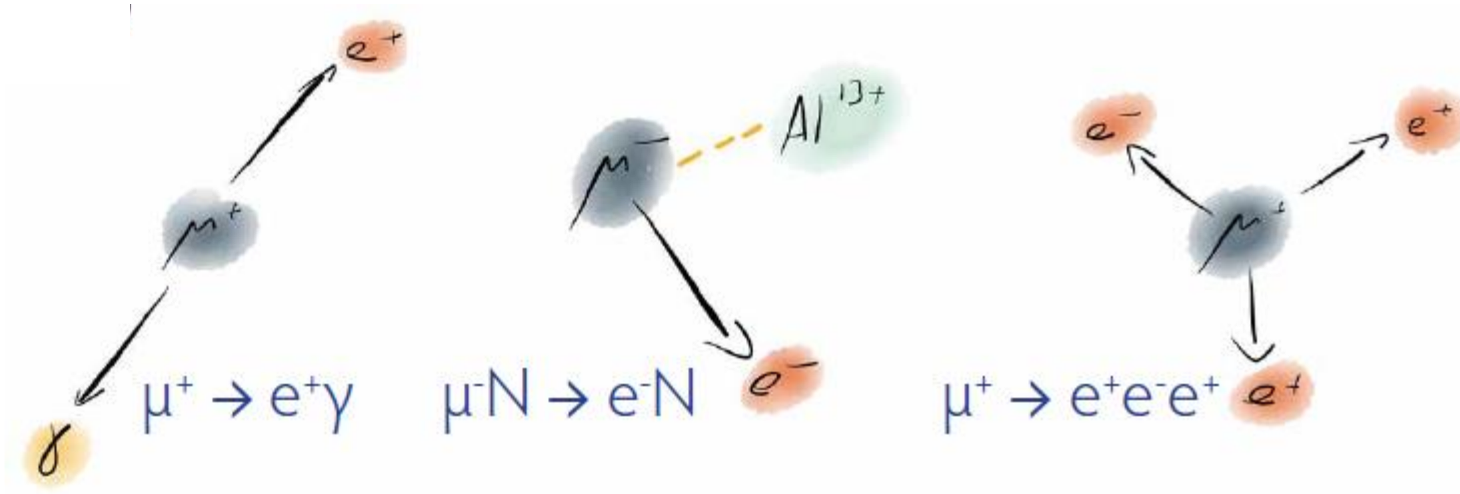
LFV μ Decays : SUSY Loops

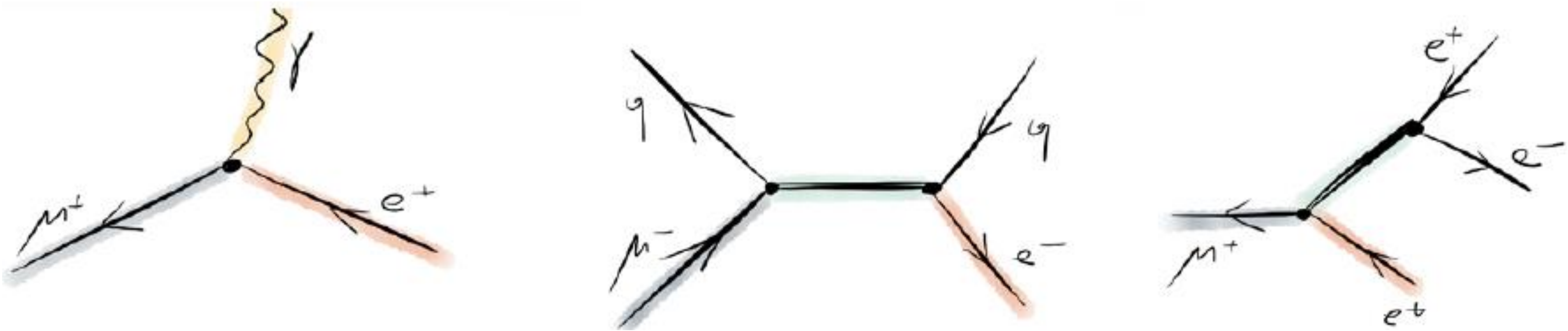


SUSY – like many BSM models – naturally induces LFV

LFV in $\mu \rightarrow e + \gamma$ implies LFV also in $\mu A \rightarrow e A$ and $\mu \rightarrow e\, e\, e$

LFV μ Decays : Tree Diagrams





not allowed

Leptoquarks

new LFV mediator

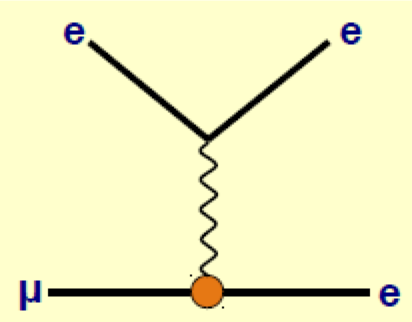
Model Comparison ($\mu \to e\gamma$ and $\mu \to eee$)

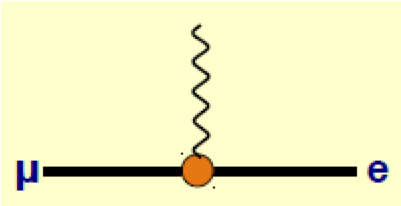
Effective charge LFV Lagrangian ("toy" model) (Kuno and Okada)

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

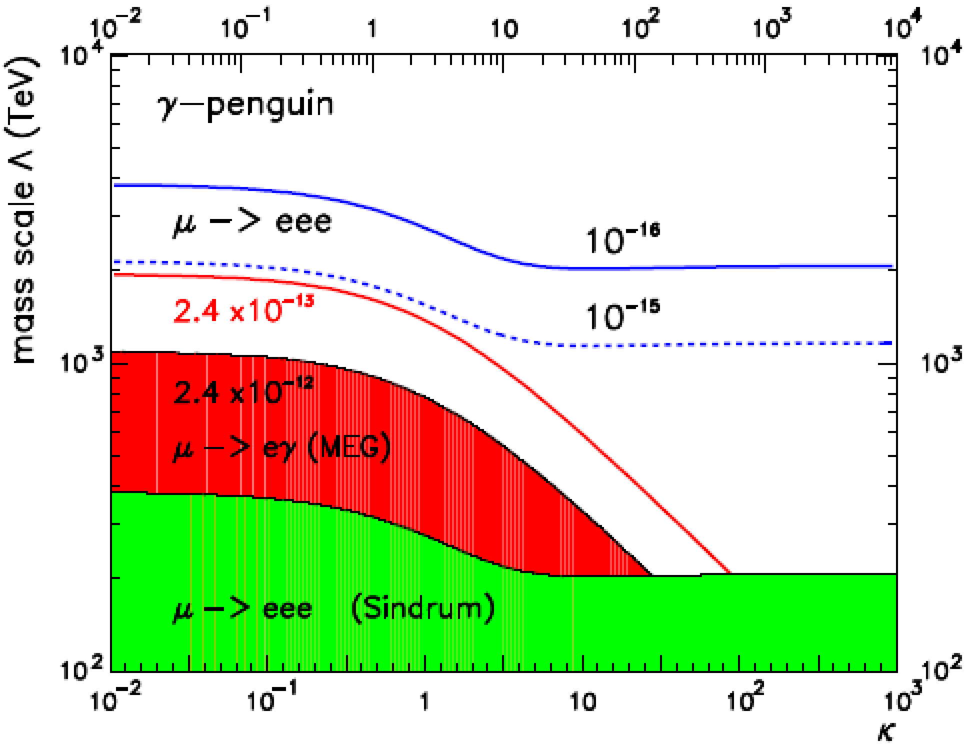
Λ = common effective mass scale

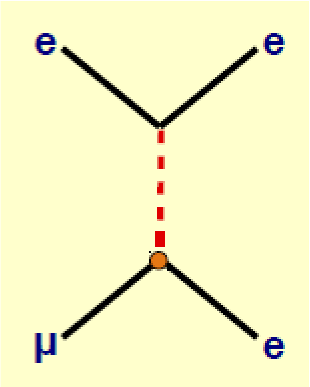
κ = "contact" vs. "loop" amplitude contribution





$\kappa \to 0$





$\kappa \to \infty$

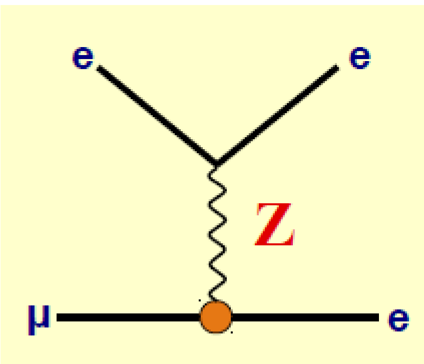
$$\frac{BR(\mu^+ \to e^+e^-e^+)}{BR(\mu^+ \to e^+\gamma)} \sim 0.006$$ (suppressed by an extra vertex)

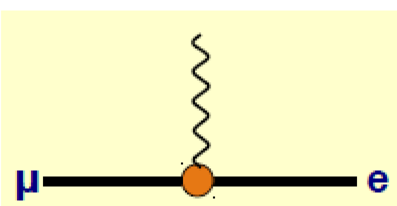
$$\frac{BR(\mu^+ \to e^+e^-e^+)}{BR(\mu^+ \to e^+\gamma)} = \infty$$

Z - penguin

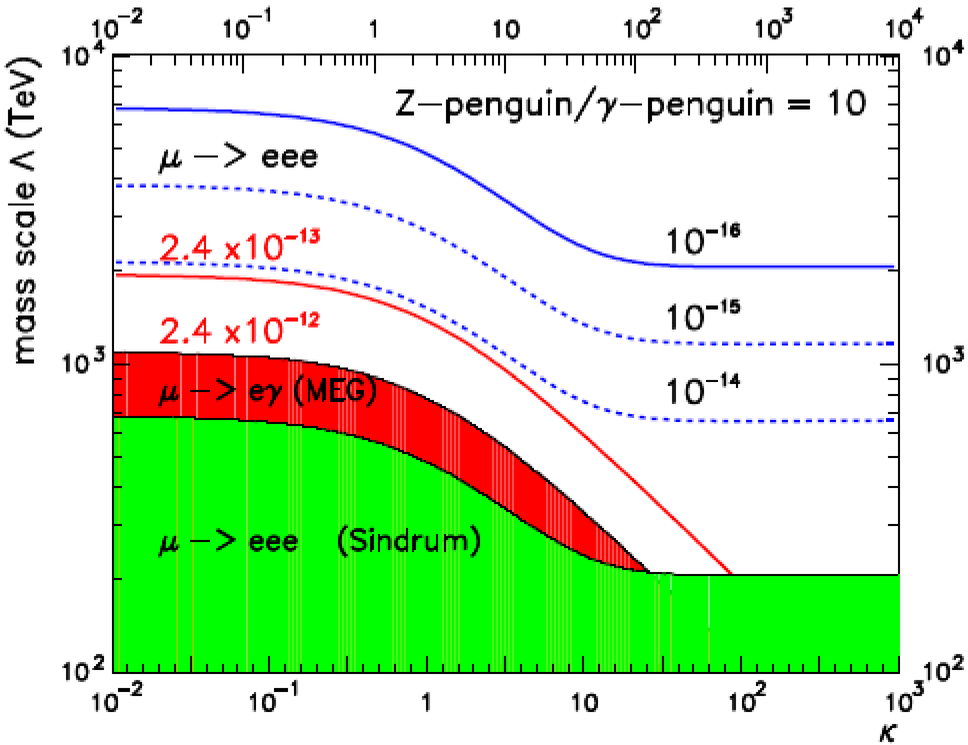
appeared in the literature in 1995 (Hisano et al.) and "rediscovered" recently

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

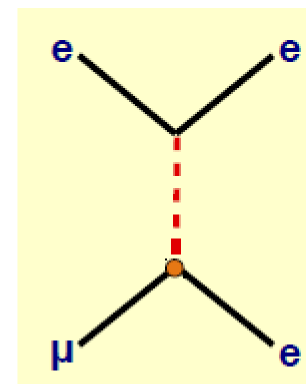




$\kappa \to 0$



Z – penguin enhanced by factor of 10

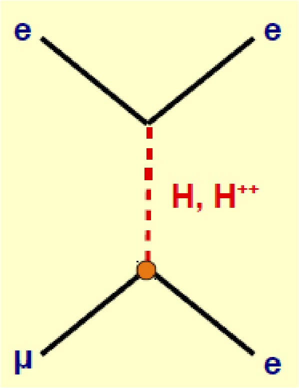


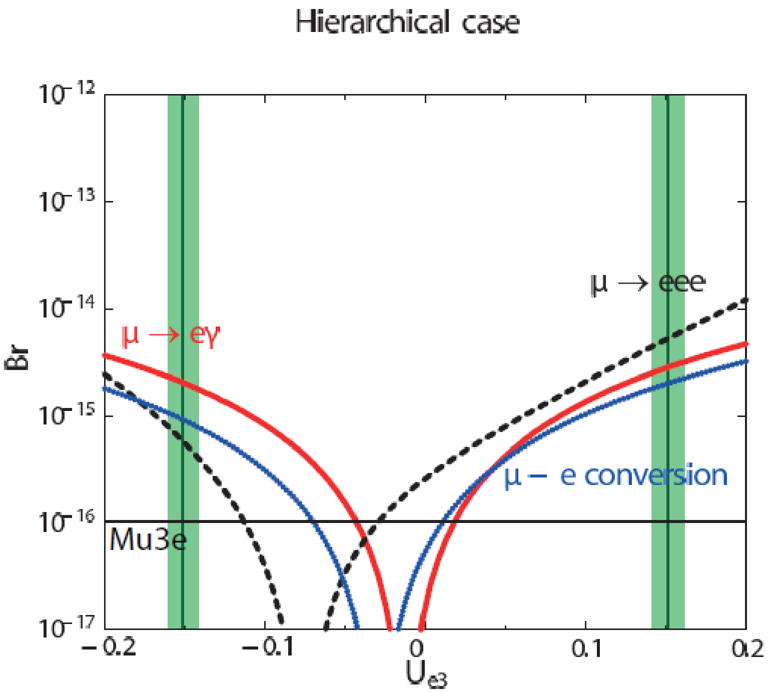
$\kappa \to \infty$

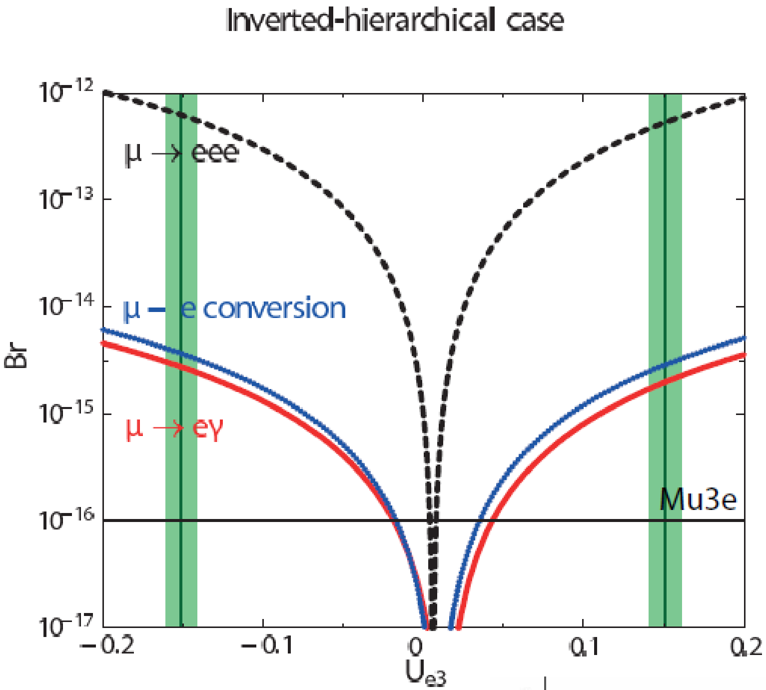
Higgs Triplet Models

motivated by Left-Right symmetric models

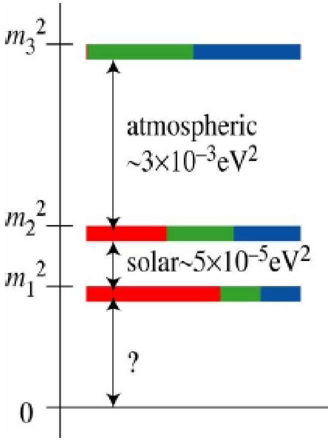
Higgs triplet: neutrino masses generation (Kakizaki et al.)







related to neutrino masses (→ ν mass pattern)

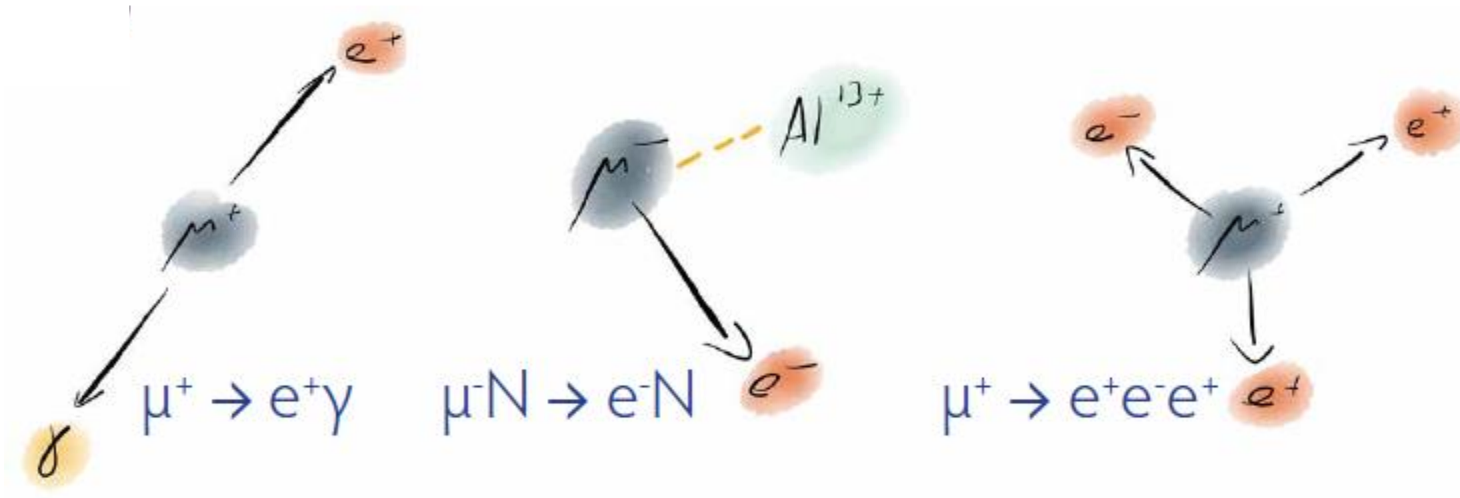


$$BR \propto \frac{A^4}{M^4}$$

A – trilinear coupling (25 eV)

M – mass scale (200 GeV)

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

LFV Searches : Current Situation

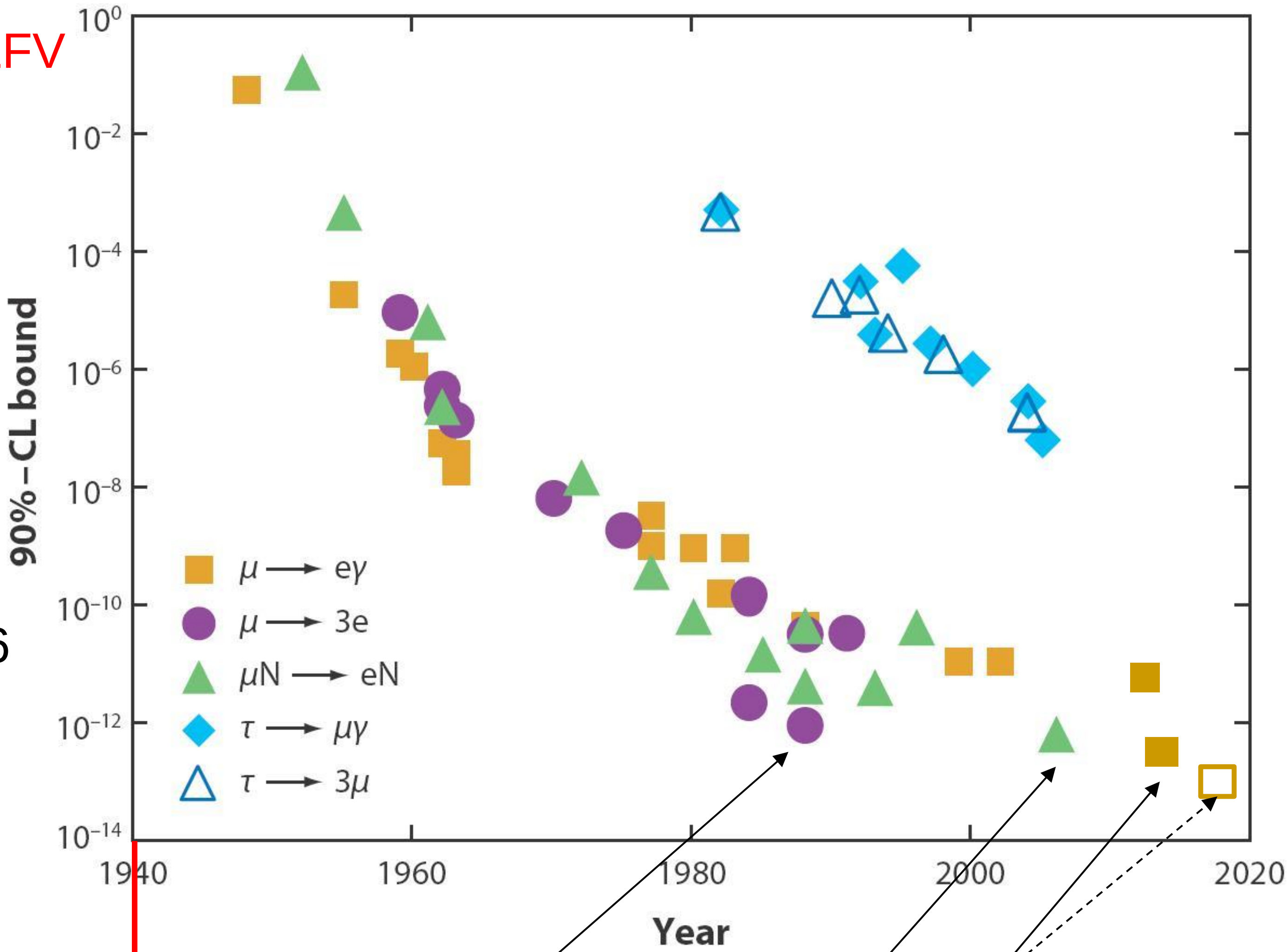
The best limits on LFV come from PSI muon experiments

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

MEG

SINDRUM II

SINDRUM @ PSI (~ 80s)

beam (πE3 beamline @ PSI):

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

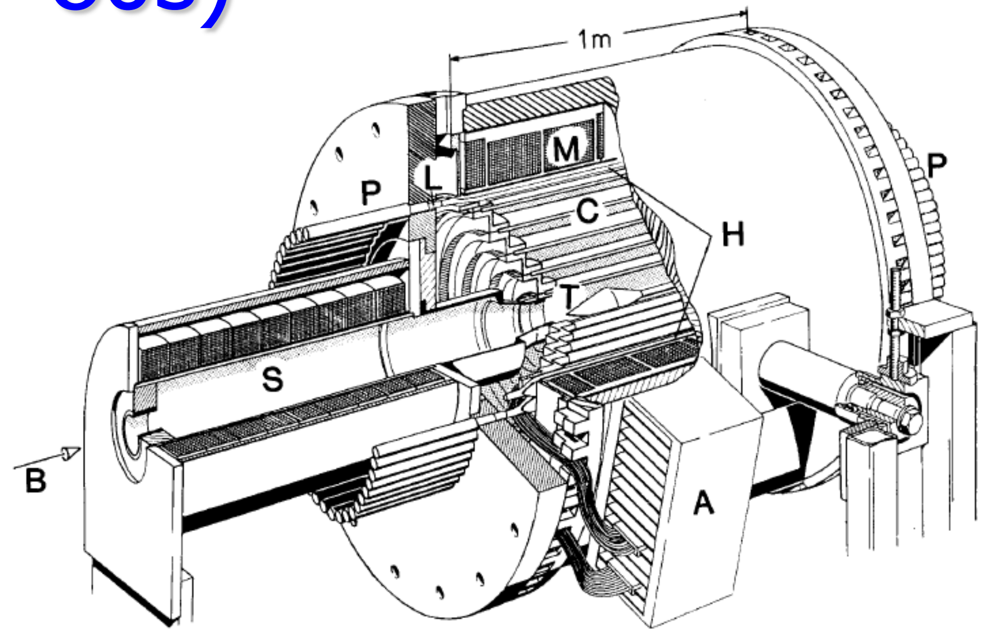
28 MeV/c surface muons

resolution:

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

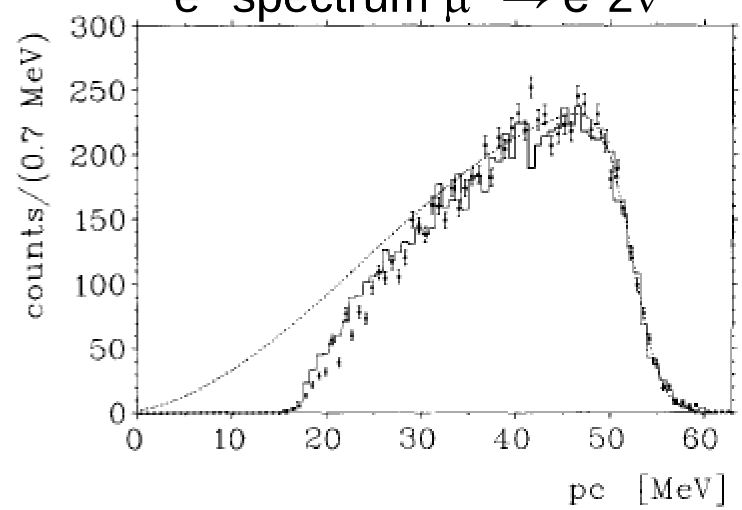
vertex ~ 1 mm

statistics limited!

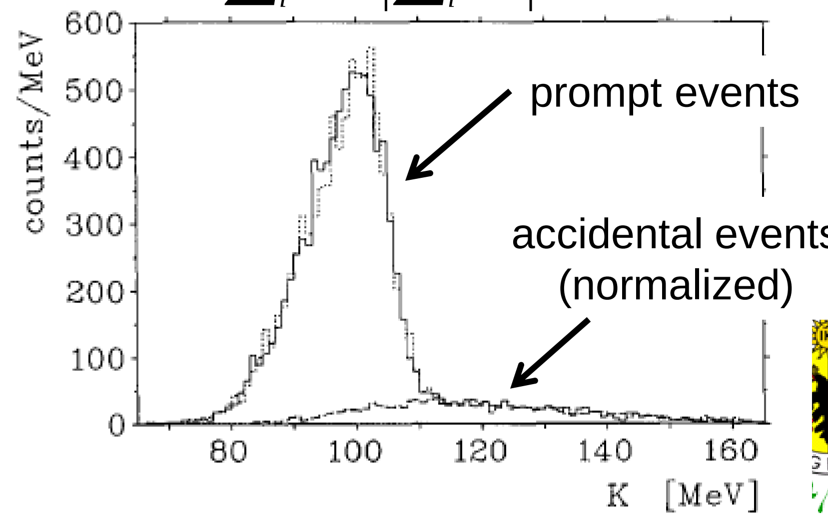


$$\boxed{\frac{\Gamma\left(\mu^+ \to e^+ e^- e^+\right)}{\Gamma\left(\mu^+ \to e^+ \bar{\nu}_\mu \nu_e\right)} < 10^{-12} \quad (90\%\ \text{CL})}$$

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

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

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

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

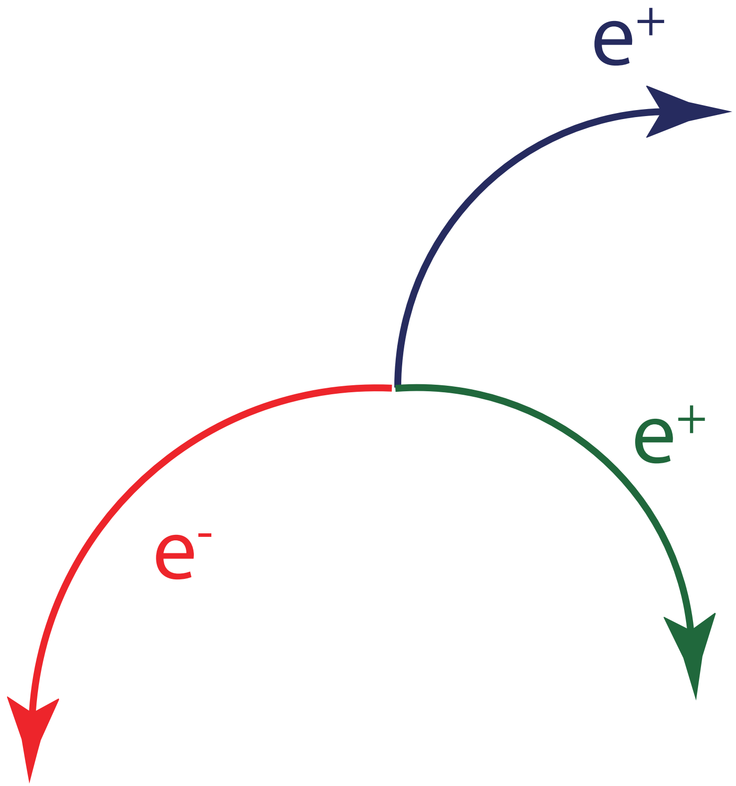
Aim for sensitivity
10^{-15} in phase I
10^{-16} in phase II
(i.e. find one in 10^{16} muon decays)

$\to$ 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 approved in January 2013

The Signal

$\mu^+ \to e^+ e^- e^+$



two positrons, one electron

from same vertex

same time

$\Delta t_{\text{tracks}} \sim 0$

momentum balance
and coplanarity

$\Sigma \mathbf{p}_i = 0$

energy conservation

$\Sigma E_i = m_\mu$

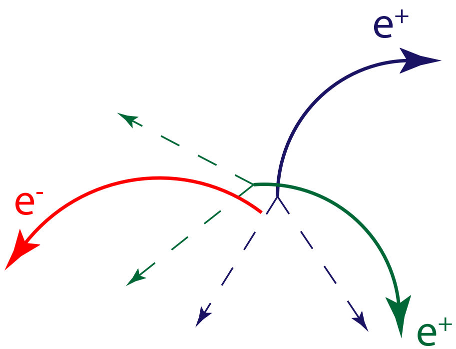
max. momentum

$\frac{1}{2} m_\mu = 53$ MeV/c

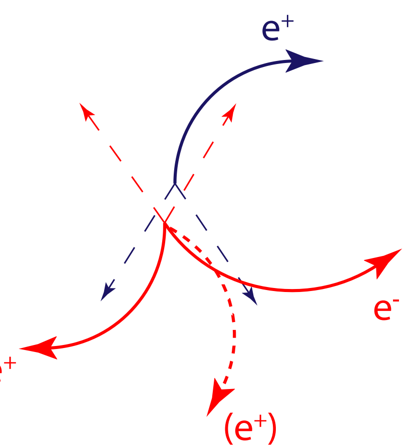
Accidental Backgrounds

overlay of one or two normal muon decays with a “fake” electron(s)

electrons from Bhabha scattering
photon conversions
mis-reconstruction



$\mu^+ \to e^+ \nu\nu$, $\mu^+ \to e^+ \nu\nu$, $\mu e^- \to \mu^+ e^-$



$\mu^+ \to e^+ e^- e^+ \nu\nu$, $\mu^+ \to e^+ \nu\nu$

accidental backgrounds increase with beam intensity

to suppress these backgrounds

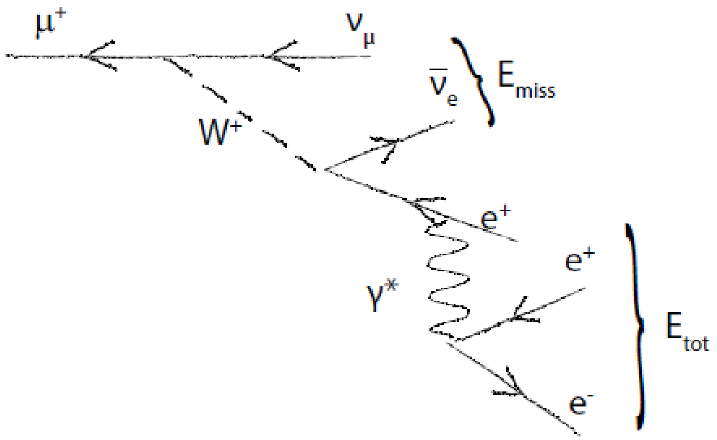
1. precise vertex reconstruction
   $\Delta x \sim 0.1$ mm

2. precise timing (ToF)
   $\Delta t \sim 100$ ps

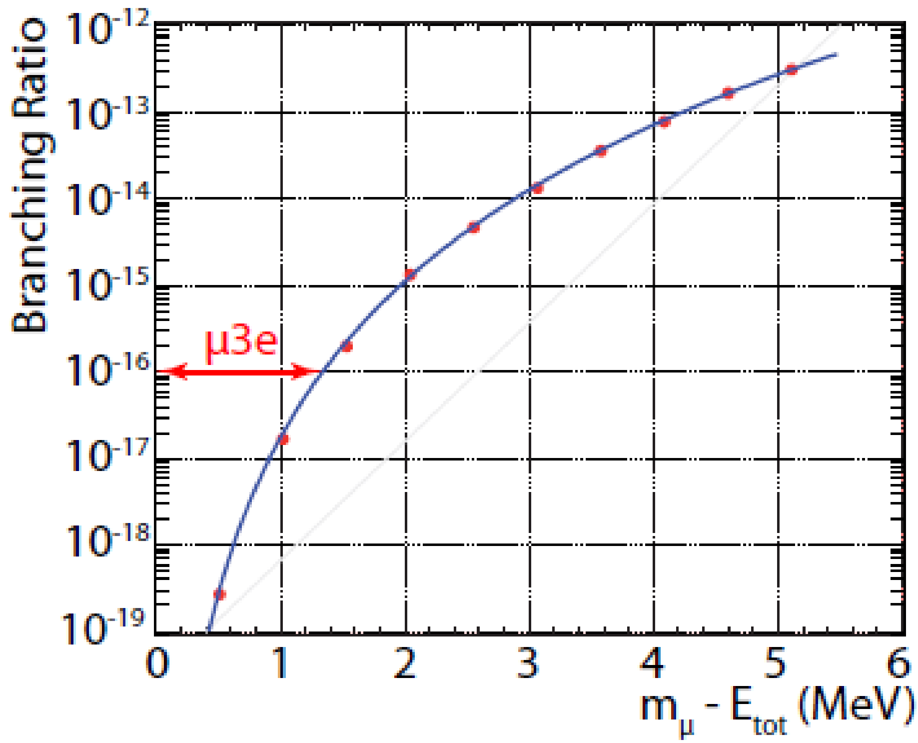
3. precise kinematics reconstruction (p and E_{TOT} resolution):
   $\sigma_p \sim 1$ MeV/c
   $\Delta m_\mu < 0.5$ MeV/c^2

Irreducible Background

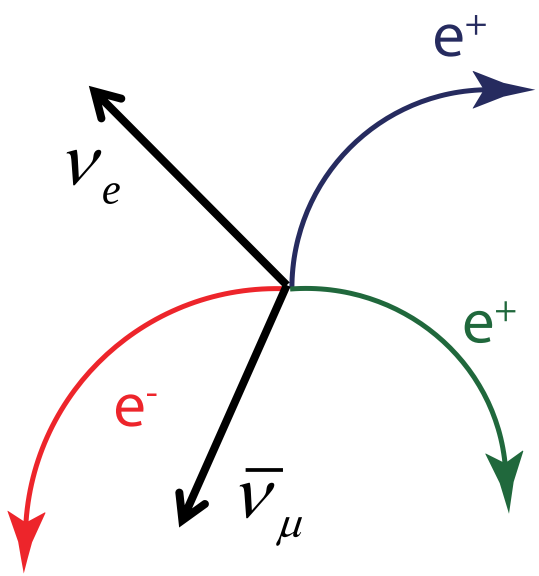
μ radiative decay with internal conversion



Branching ratio as a function of cut on $m_\mu - E_{TOT}$



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

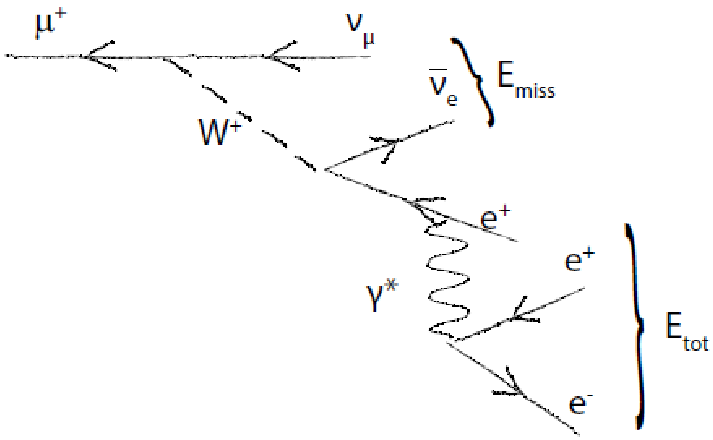


only distinguishing feature:

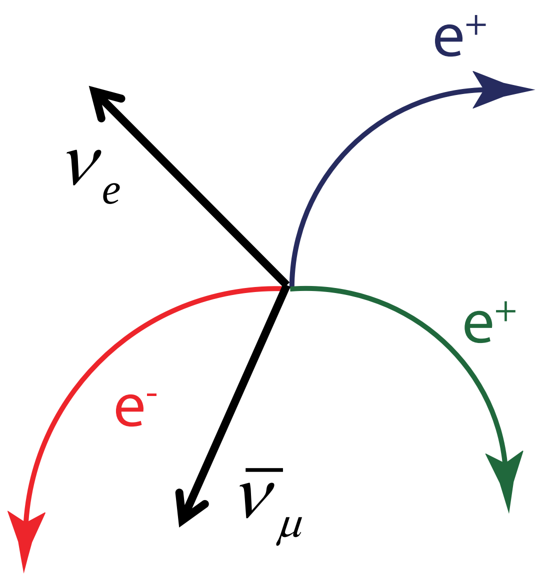
missing energy carried by neutrinos

Irreducible Background

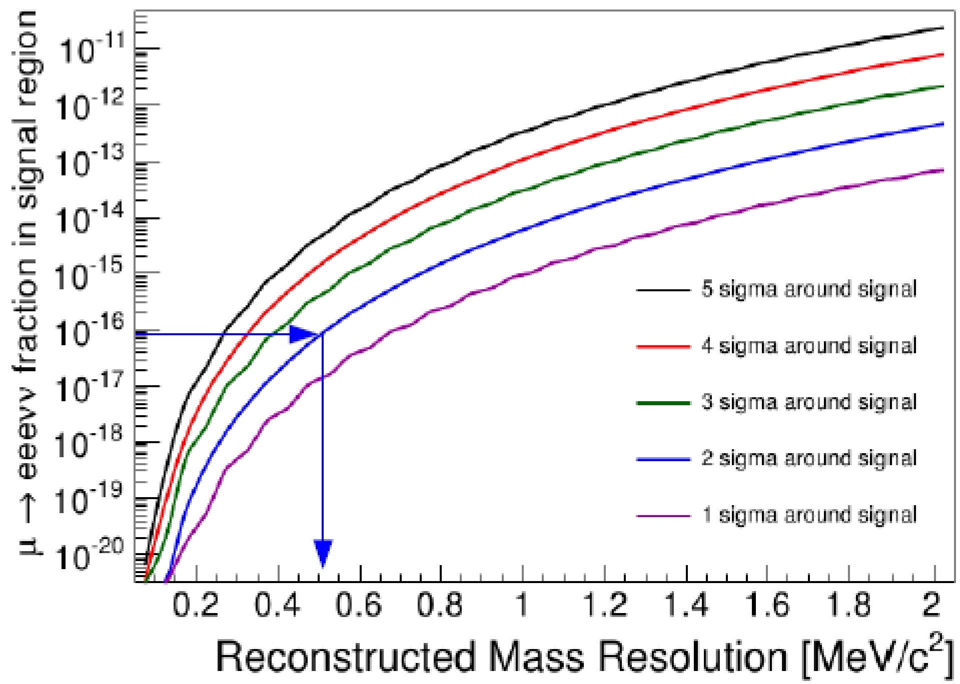
μ radiative decay with internal conversion



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



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

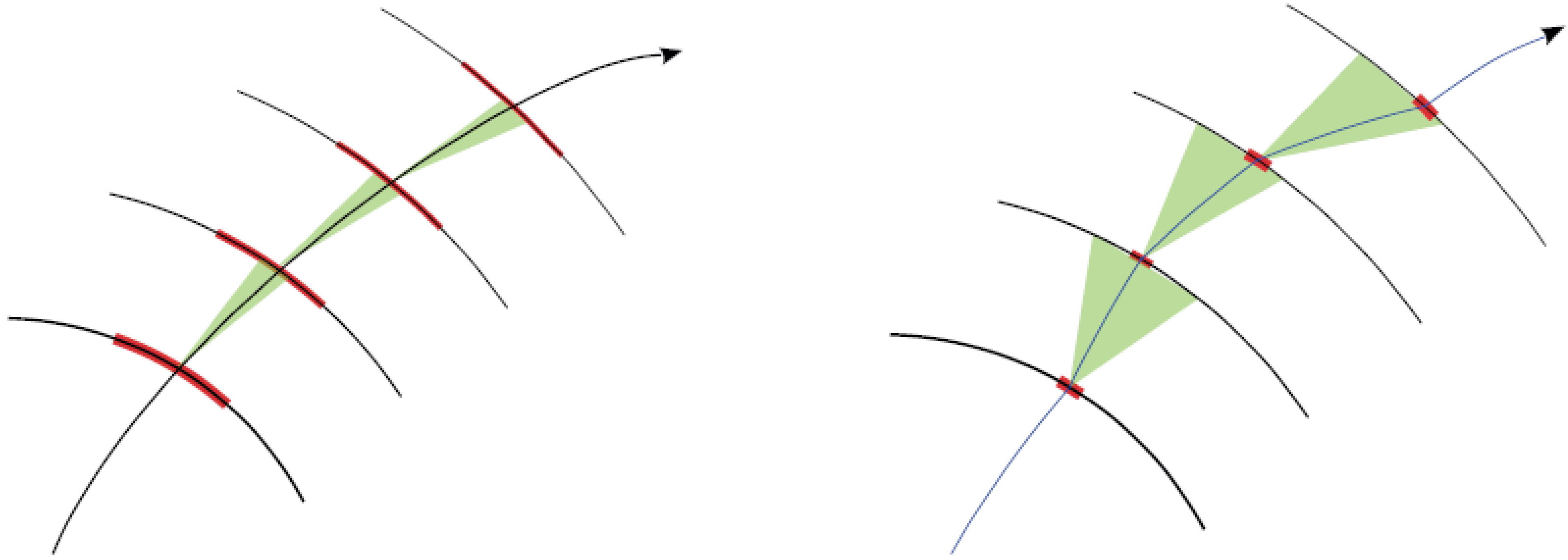


high momentum and energy resolution to suppress this background

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

Momentum Measurement

tracking resolution

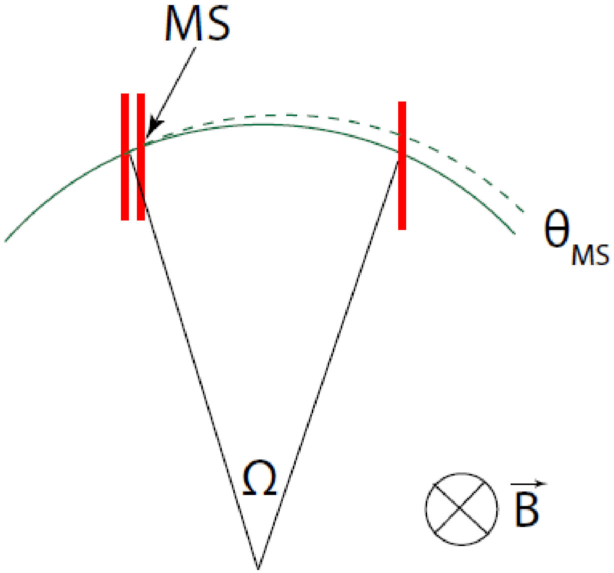


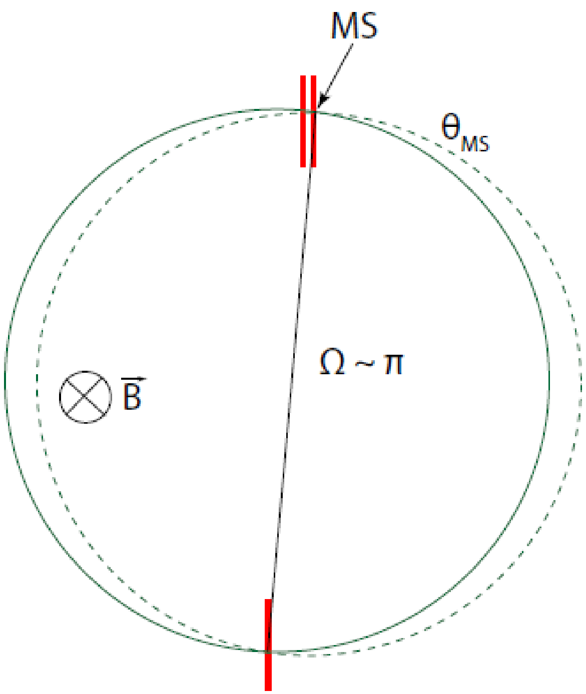
spatial resolution dominates

multiple scattering dominates

need thin and high resolution detectors
i.e. minimum material, maximum precision

Momentum Measurement (II)





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}

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

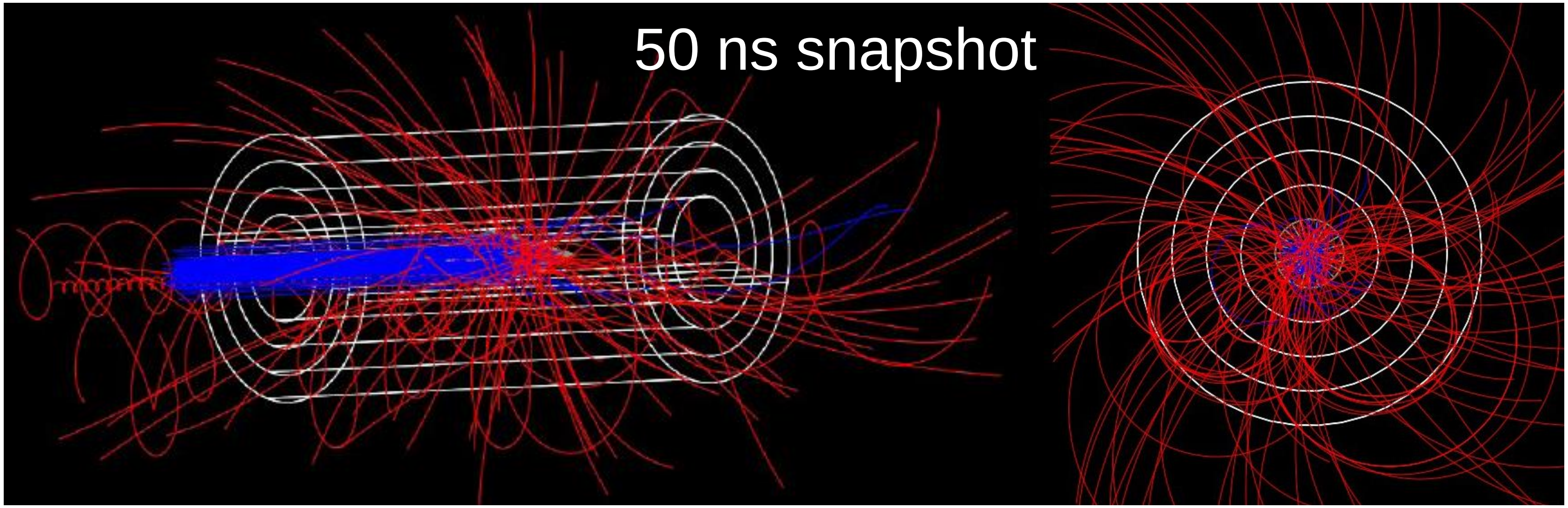
$$\frac{\sigma_p}{p} \sim o\left(\Theta_{MS}^2\right)$$

design tracking detector for measuring recurlers

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

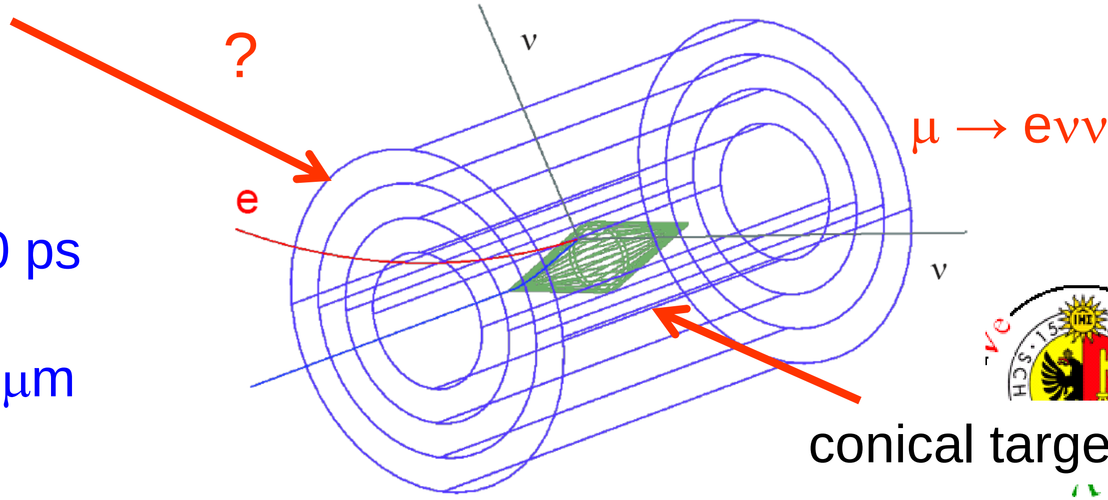
50 nsec time frames (Si "resolution") → 100 μ decays @ 2 × 10^9 μ stops / s

challenge : isolate μ → eee events

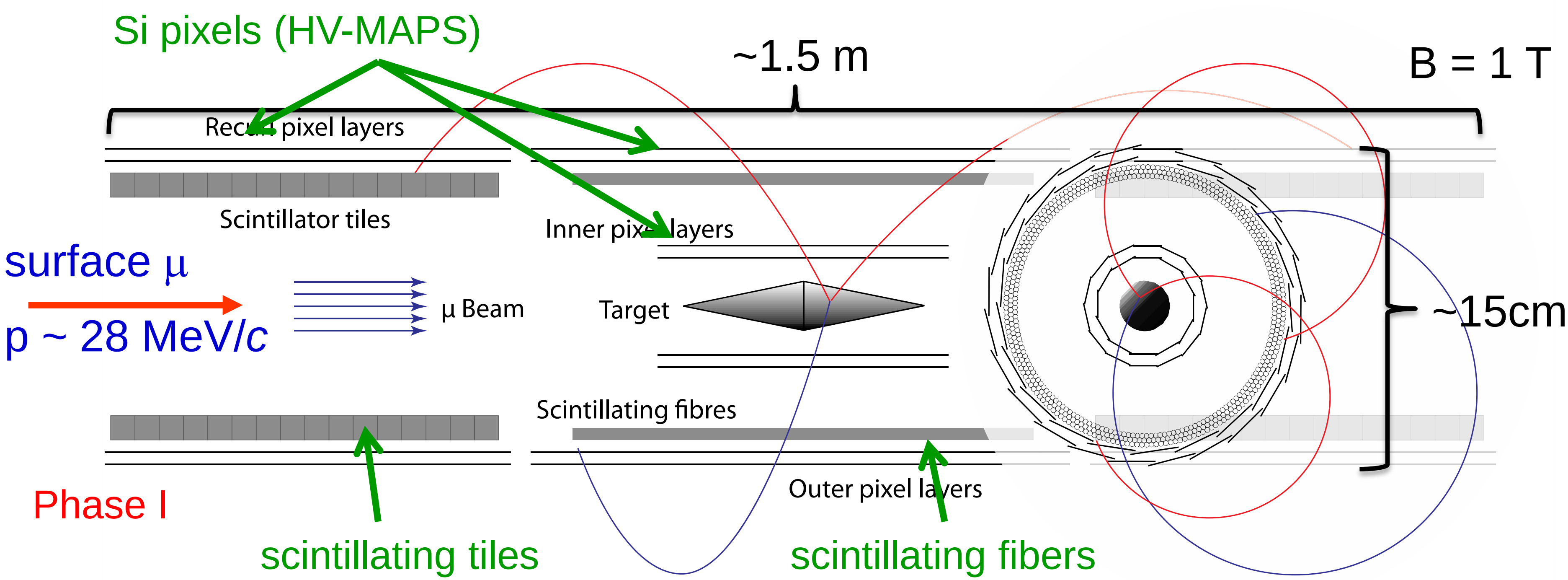


Δt ~ few 100 ps
Time of Flight ~ few 100 ps

precise vertexing ~100 μm



Mu3e Baseline Design



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

thin, **fast**, **high resolution** detectors
(minimum material, maximum precision)

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

~ 10 k ToF channels (SciFi and Tiles)

Mu3e Collaboration

DPNC, University of Geneva

Physics Institute, Heidelberg University

KIP, Heidelberg University

ZITI Mannheim, Heidelberg University

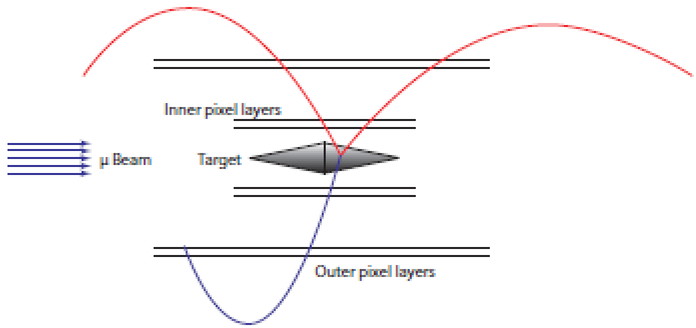
Paul Scherrer Institute (PSI)

Physics Institute, University of Zurich

Institute for Particle Physics, ETH Zurich

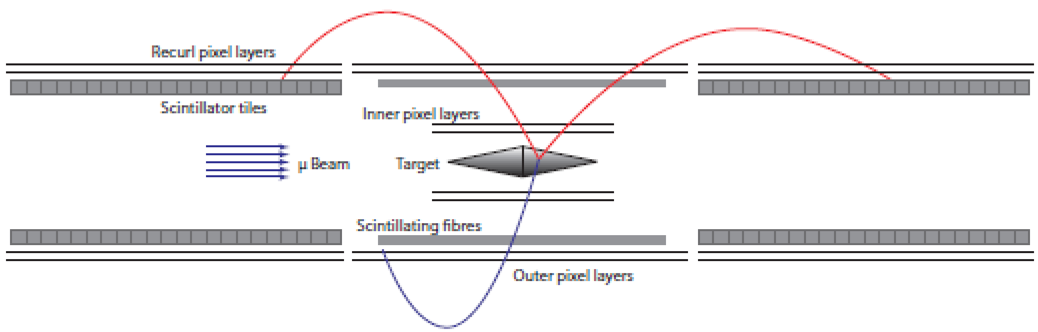
Staged Approach

Phase IA
rate $\leq 10^7\ \mu$ / s



only central pixel

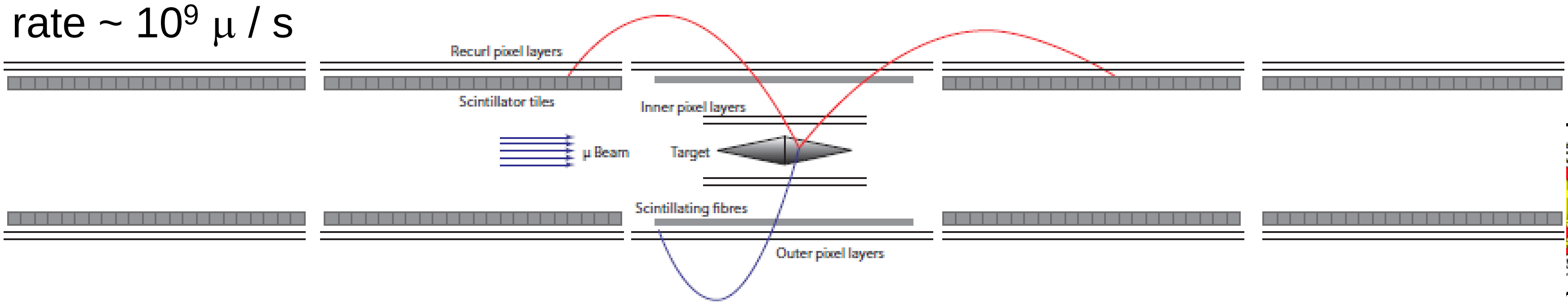
Phase IB
rate ~ $10^8\ \mu$ / s



+ inner recurl sta.
+ time of flight

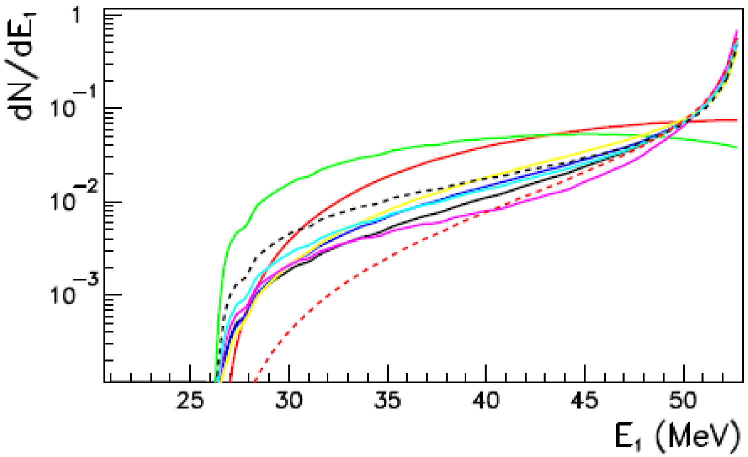
Phase II
rate ~ $10^9\ \mu$ / s

+ outer recurl sta.

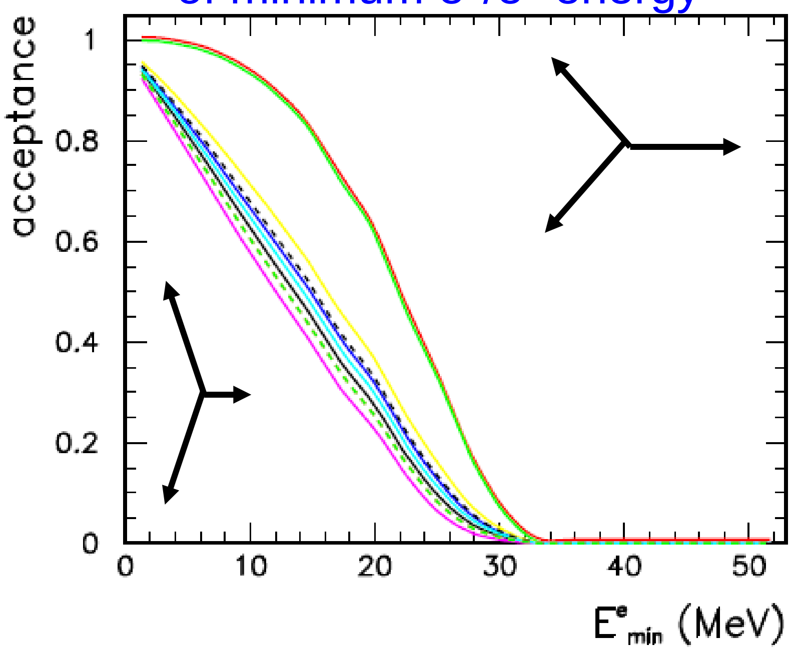


Acceptances

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

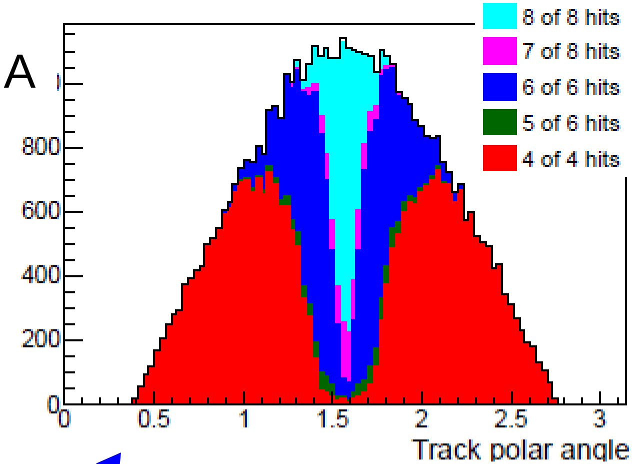


acceptance as a function of minimum e^+/e^- energy

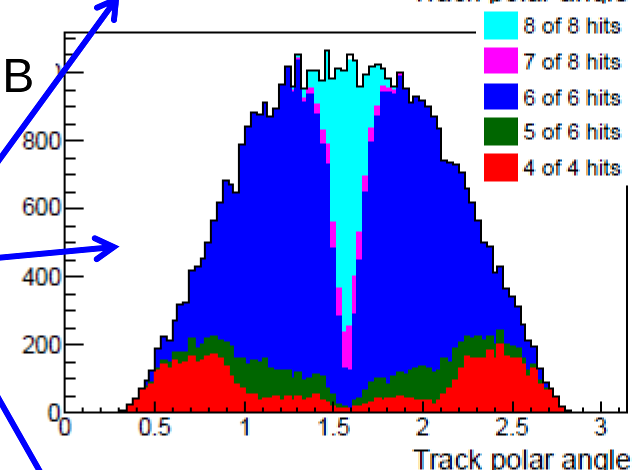


hits per track

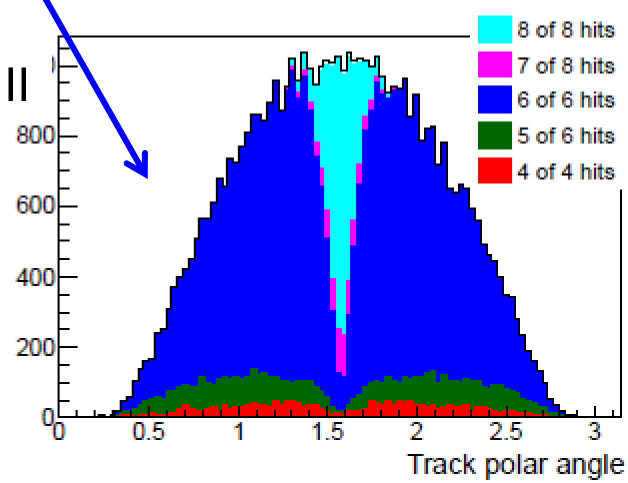
phase IA



phase IB



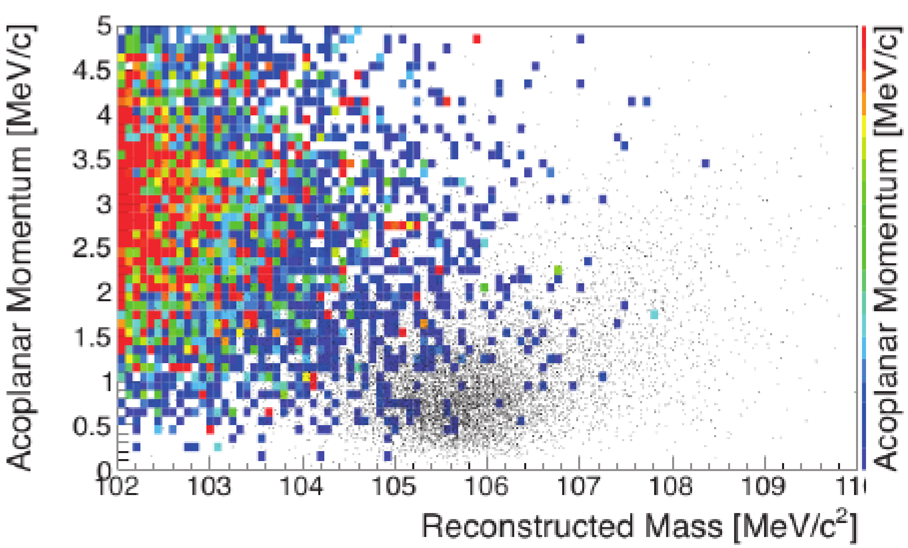
phase II

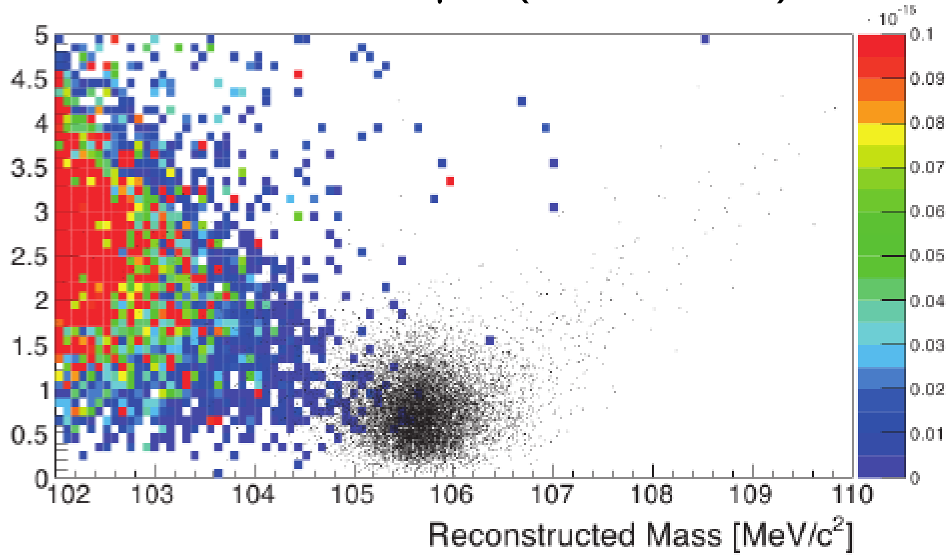


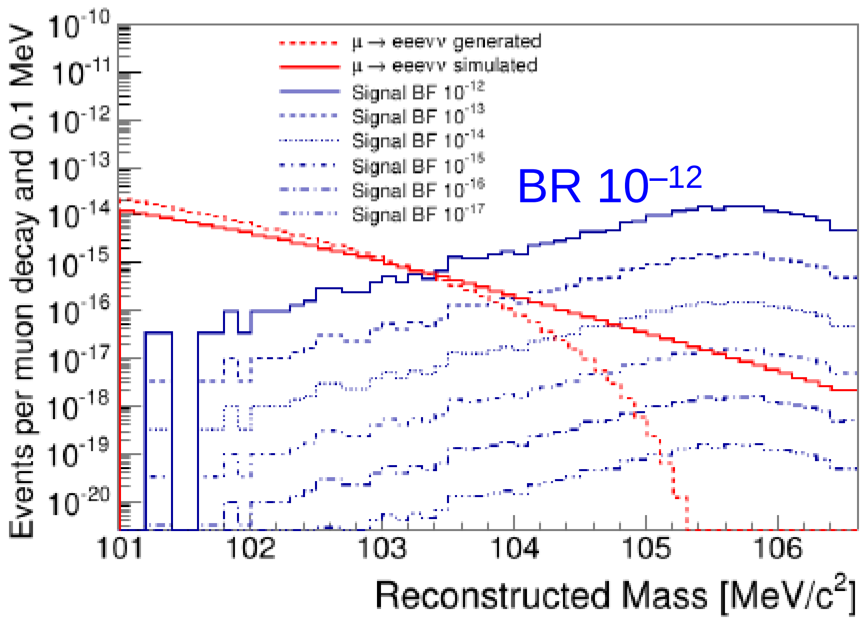
μ → eee Signal Simulations

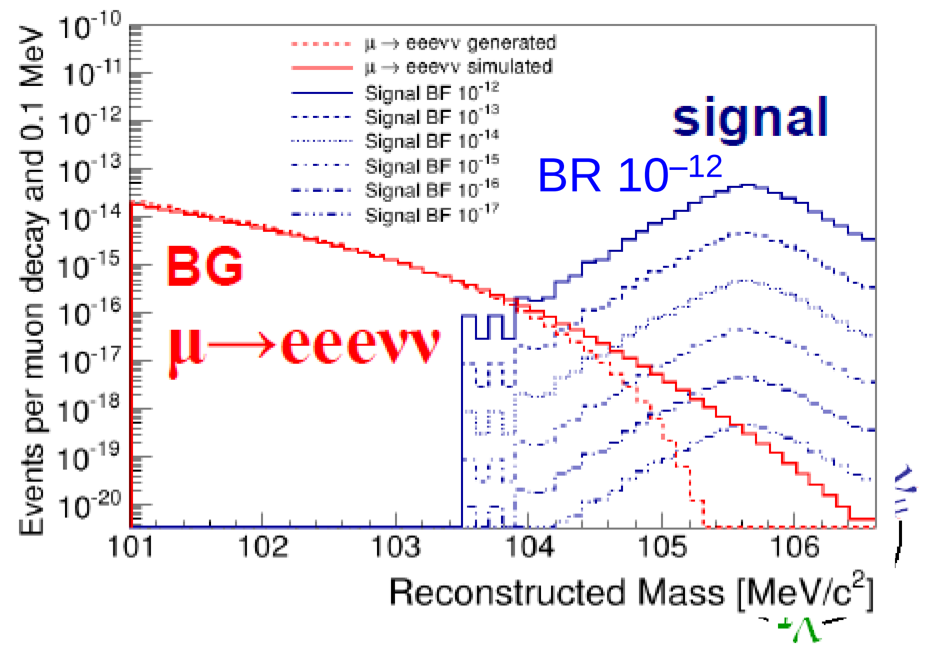
Phase IA: ~ 2 × 10^7 μ/s (central pixel)

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

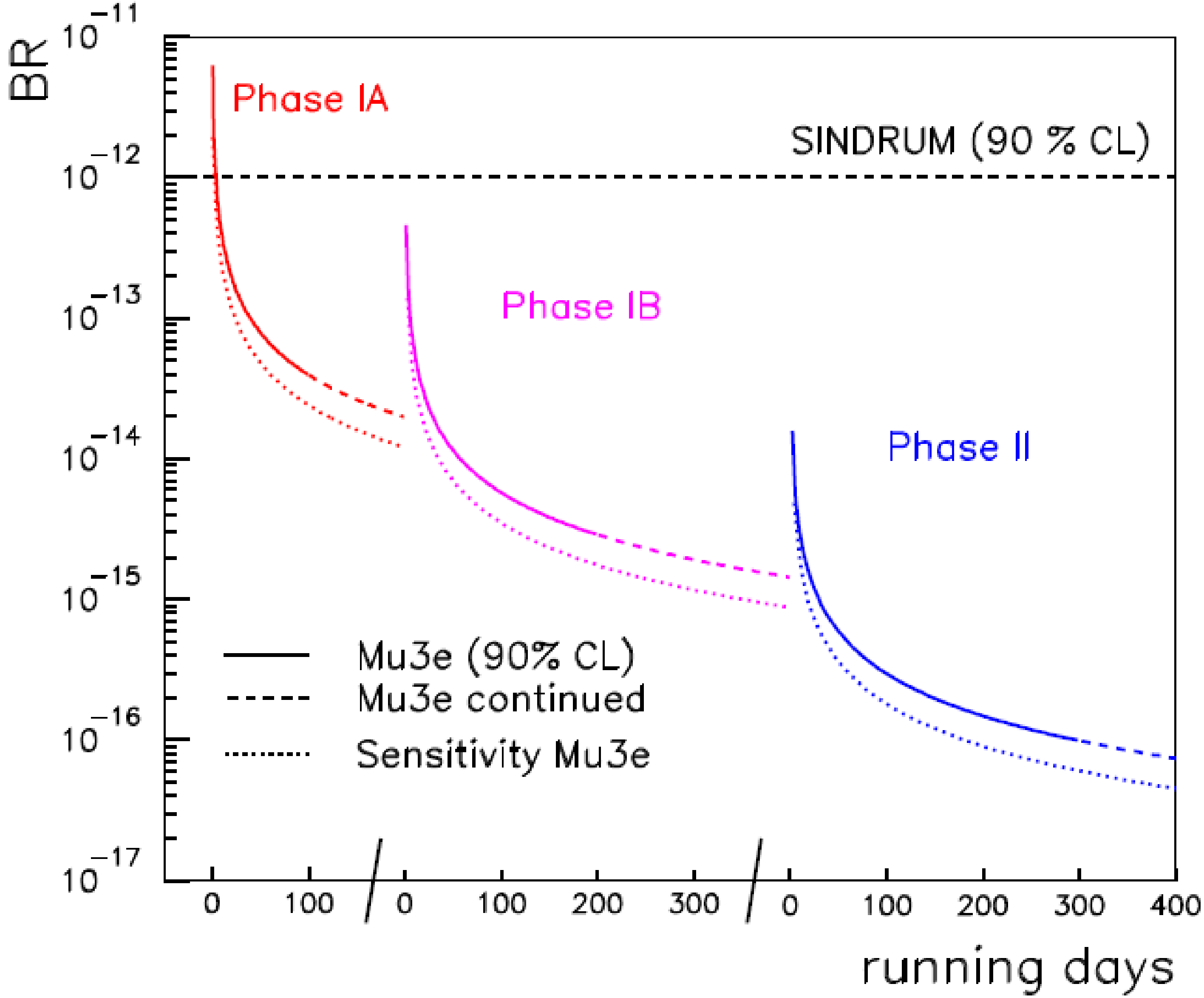








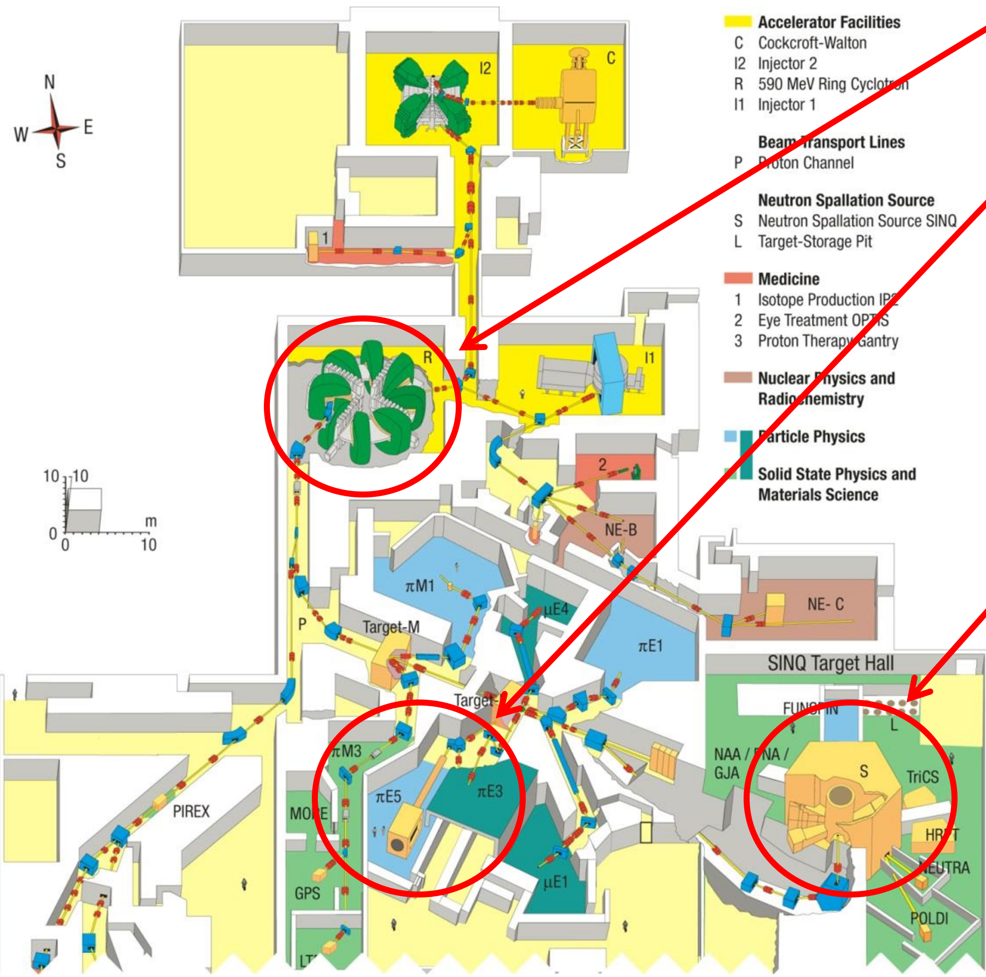
Sensitivity Projection



Muons @ PSI

most intense DC muon beam

590 MeV/c proton cyclotron

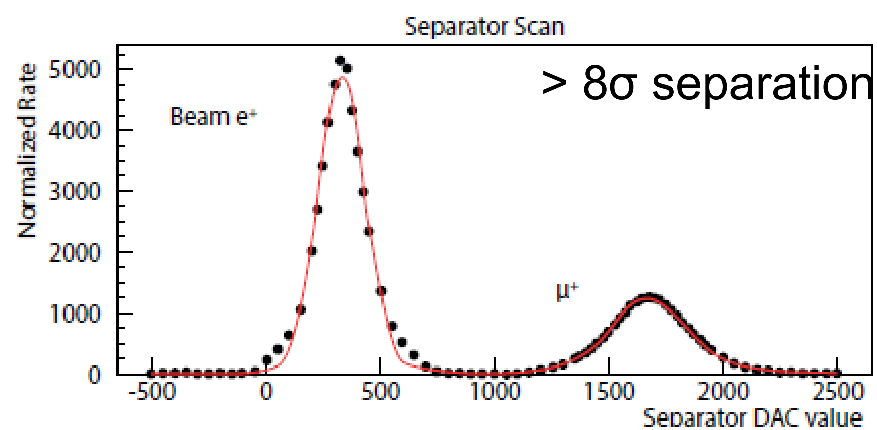


πE5 beamline > 10^8 μ / s

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

(MEG exp., Mu3e phase I)

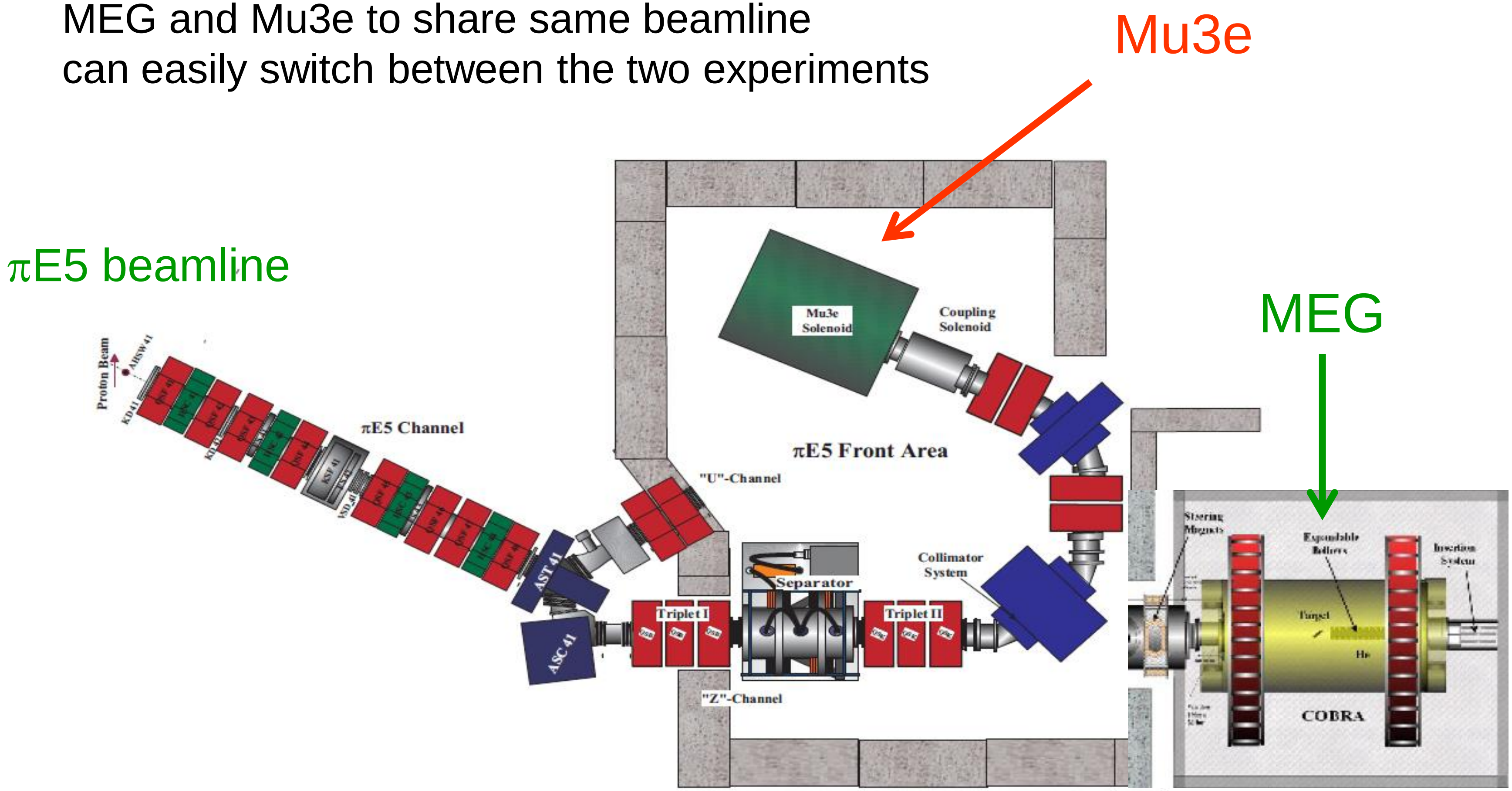
SINQ (spallation neutron source)
could even provide 5×10^{10} μ / s
High-intensity Muon Beamline (HiMB)



e / μ 12 cm separation at last collimator

Mu3e – phase I

MEG and Mu3e 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)

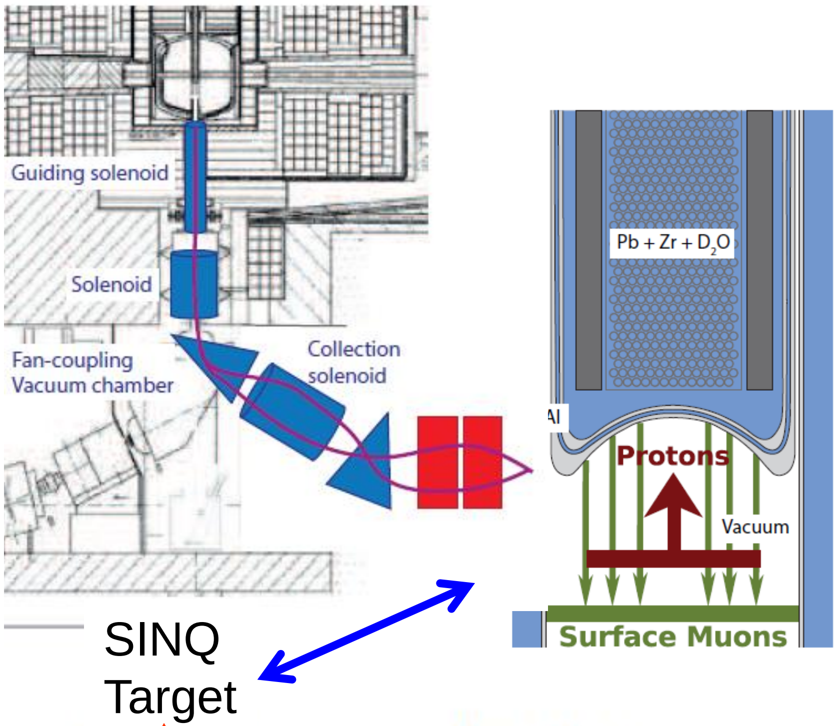
Phase II sensitivity requires GHz muon beam

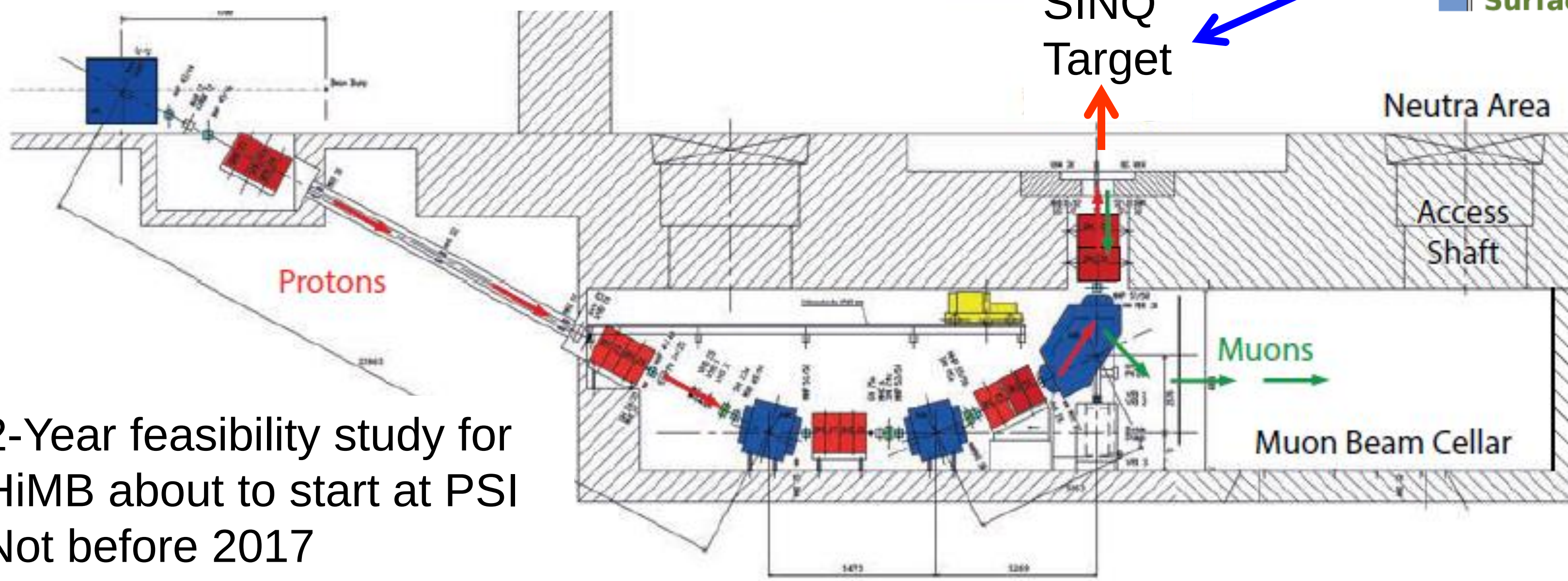
HiMB – **H**igh-**i**ntensity **M**uon **B**eam Concept

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



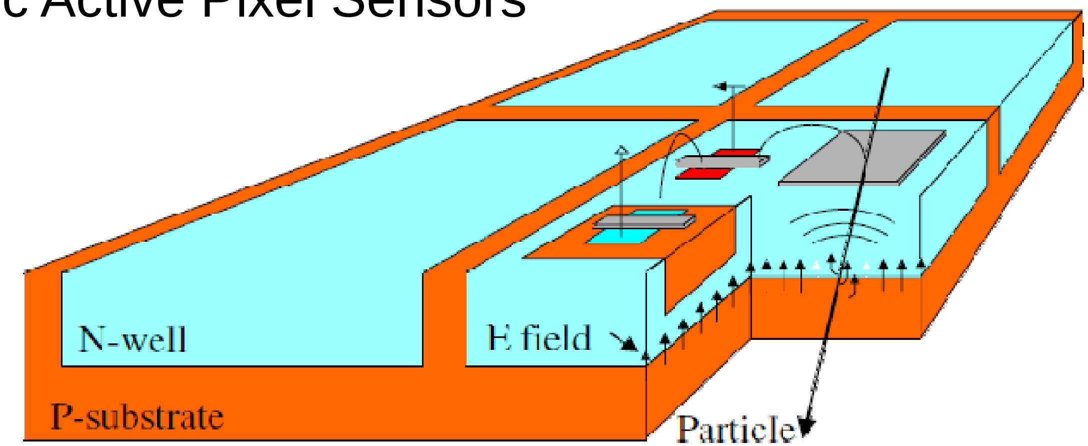


2-Year feasibility study for HiMB about to start at PSI
Not before 2017

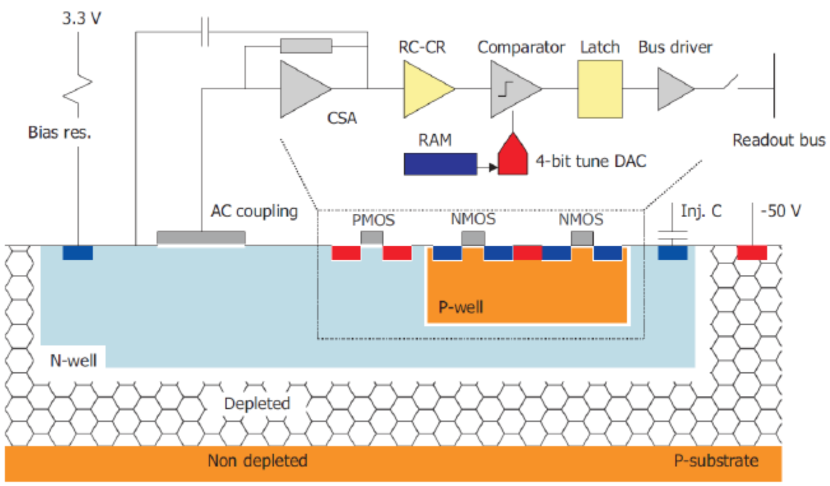
HiMB
Mu3e

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
small active region → fast charge collection
low noise
low power
radiation hard

80 × 80 μm^2 pixels
275 M channels

The MuPix Chips

MuPix2

36×42 pixels

$30 \times 39\ \mu m^2$ pixel size

$1.8\ mm^2$ active area

MuPix3

40×32 pixels

$80 \times 92\ \mu m^2$ pixel size

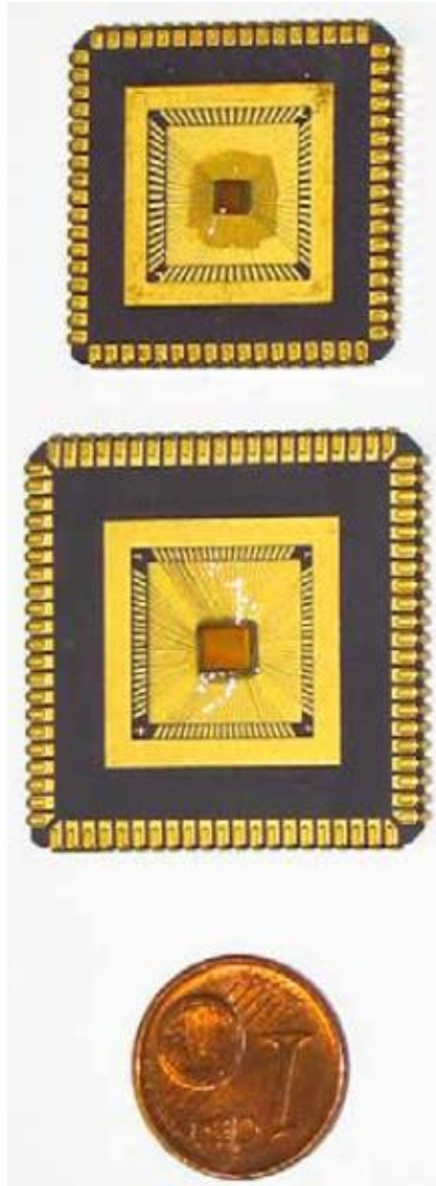
$9.4\ mm^2$ active area

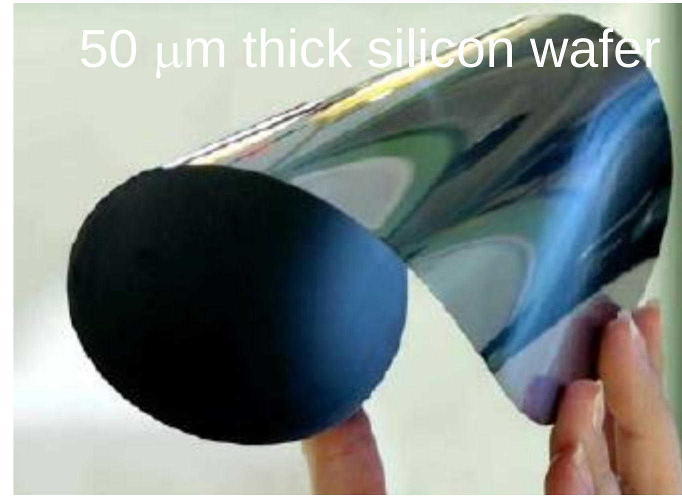
for Mu3e

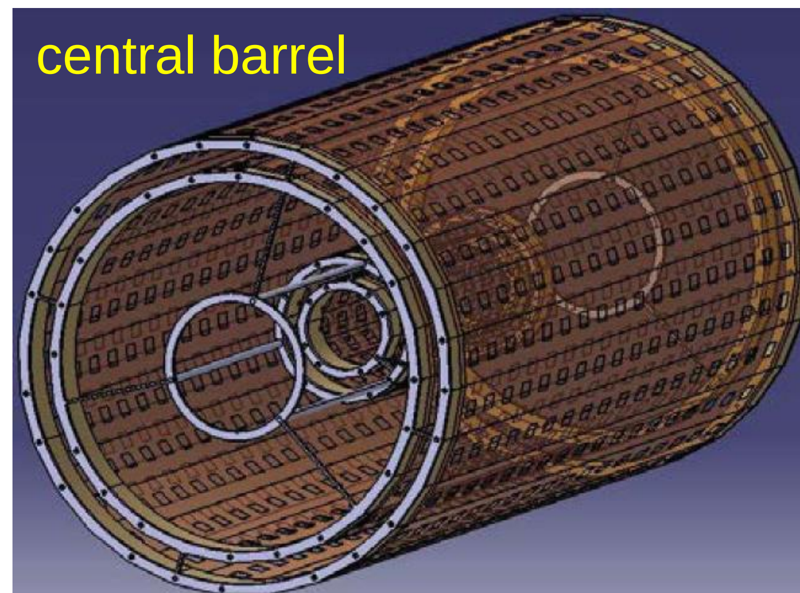
256×256 pixels

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

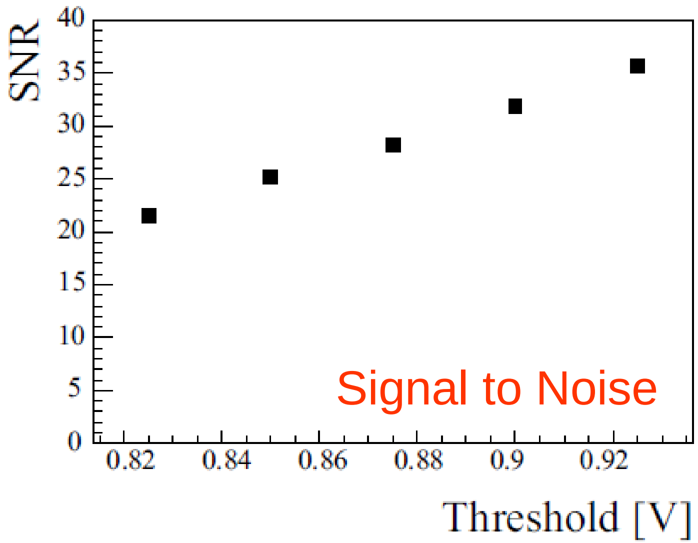
$4\ cm^2$ area, 95% active

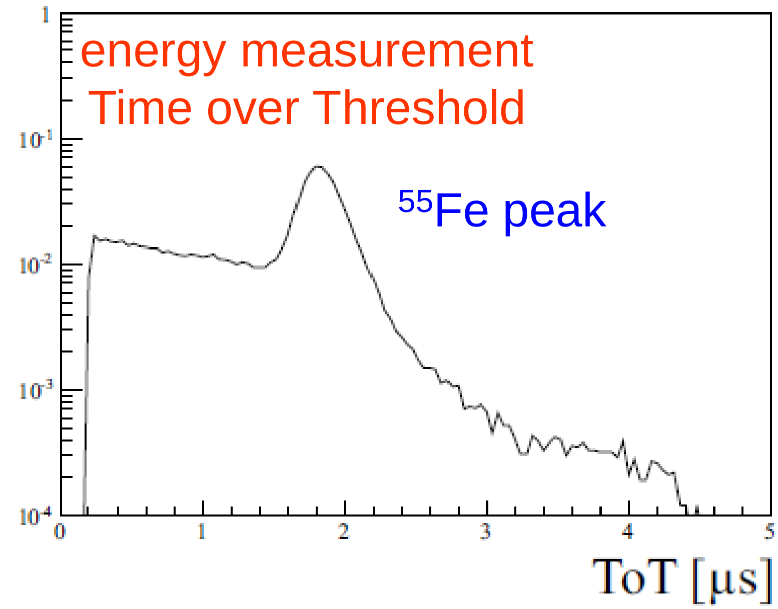


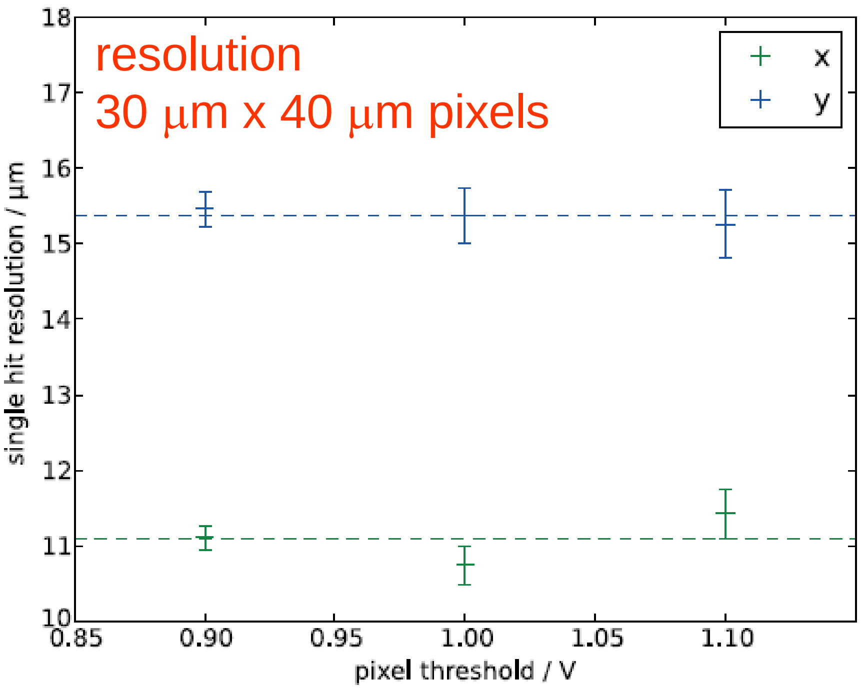


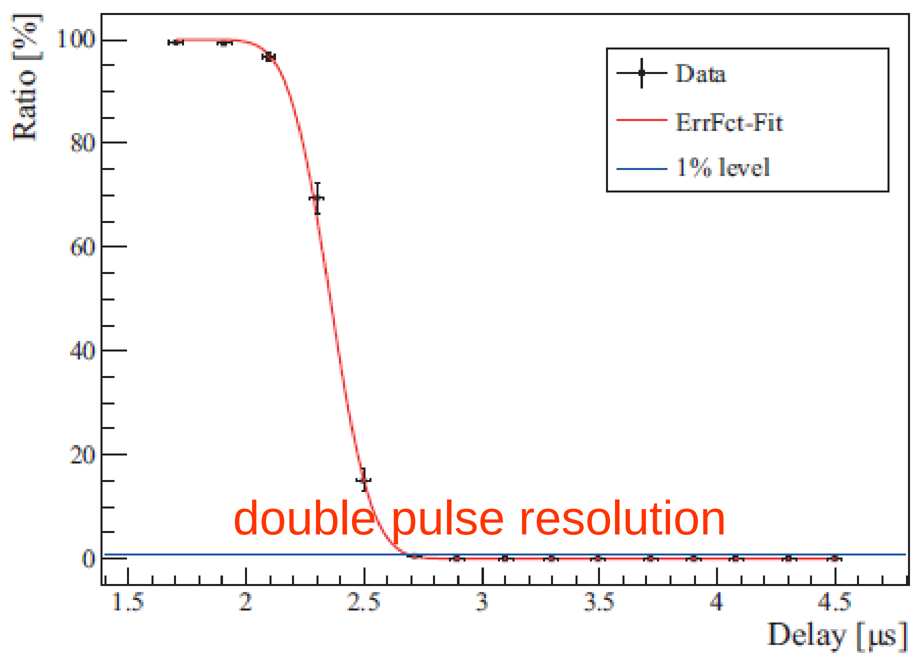


MuPix Perfromance (preliminary)



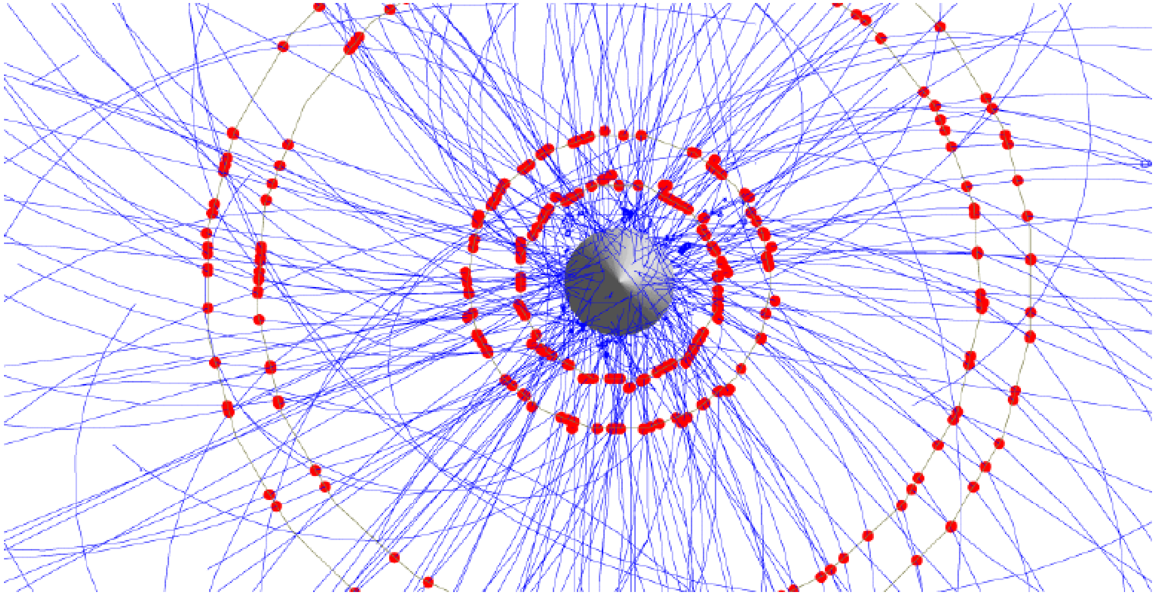




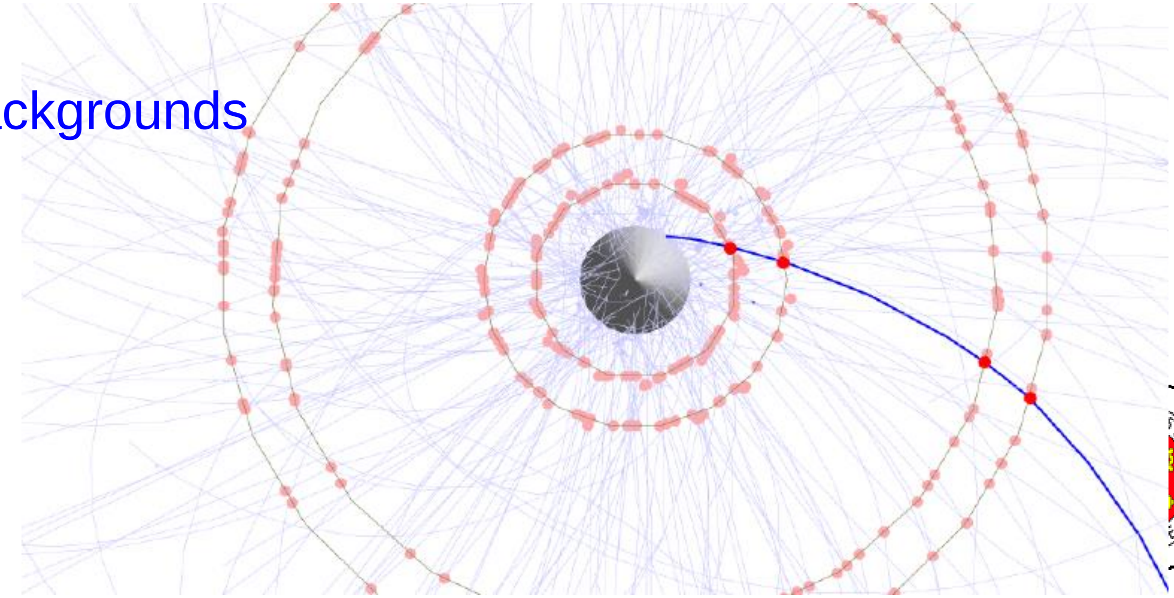


Timing

50 ns snapshot (readout frame): 100 μ decays



additional ToF information < 500 ps

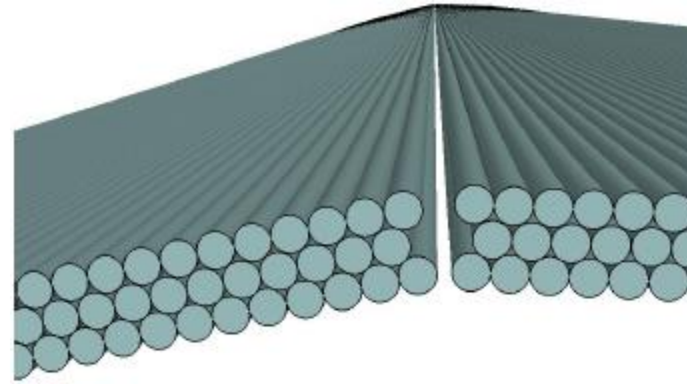


to suppress accidental backgrounds requires excellent timing

< 500 ps SciFis

< 100 ps scint. tiles

Sci-Fi Tracker - ToF

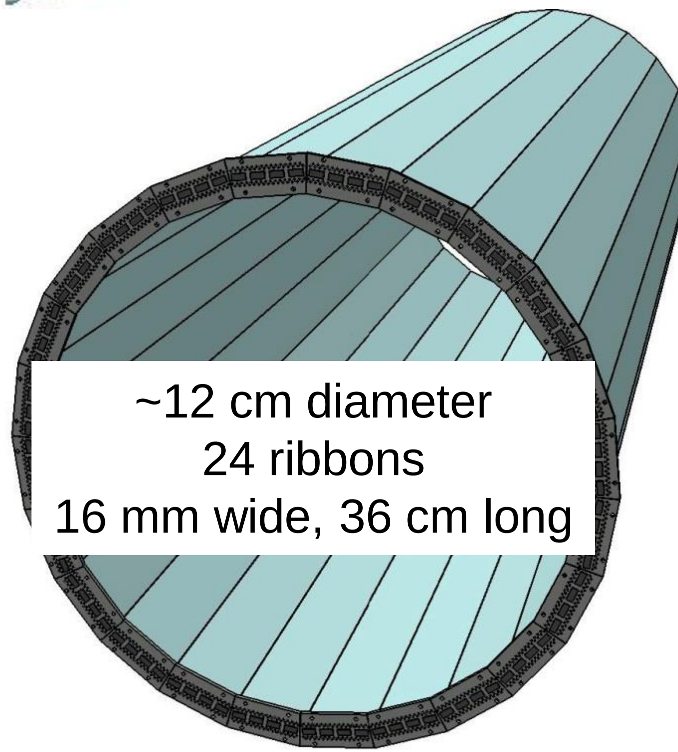


high spatial resolution (matching with silicon hits)

good time resolution < 500 ps

scintillating fibers 250 μm ∅ (3 staggered layers)

24 Sci-Fi ribbons (16 mm × 360 mm)



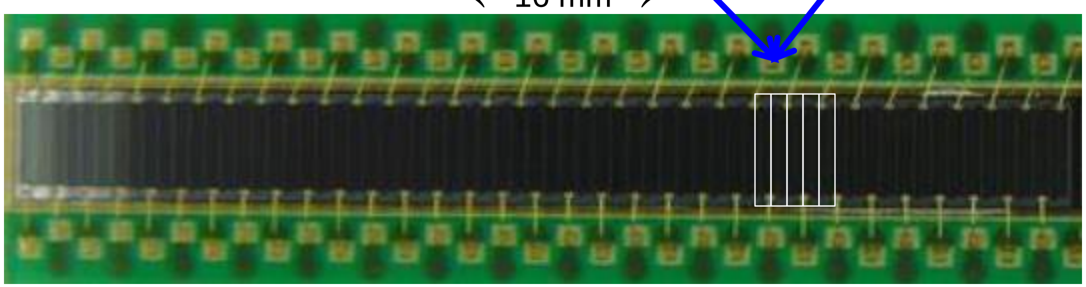
readout with Si-PMs arrays on both ends

- 64 channel monolithic device, ~3000 ch. total
- 250 μm "pitch", 50 μm cells
- common bias voltage
- (individual fiber readout ?)

5 × 20 cells
readout ch.

← 16 mm →

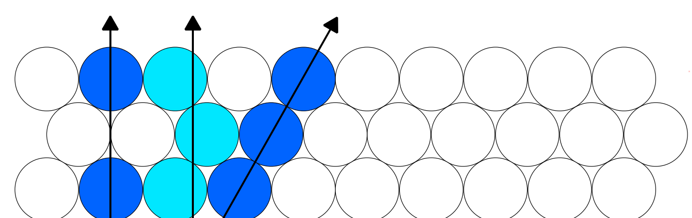
↑ 1 mm ↓



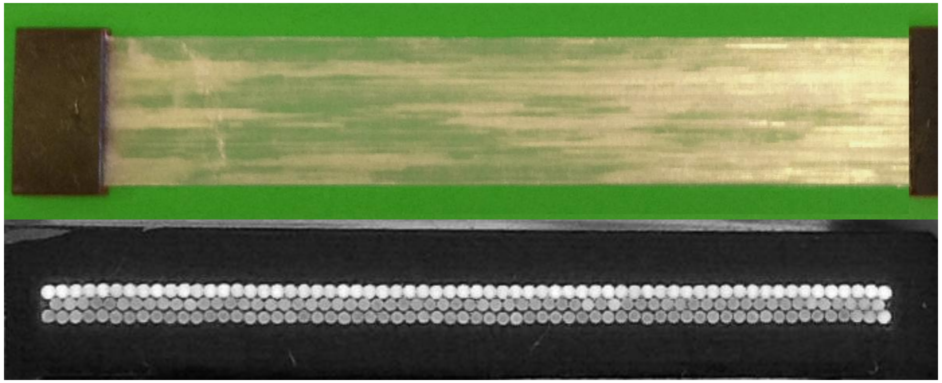
rate: several MHz / SciFi ch.

readout with the DRS waveform digitizer (custom ASIC)

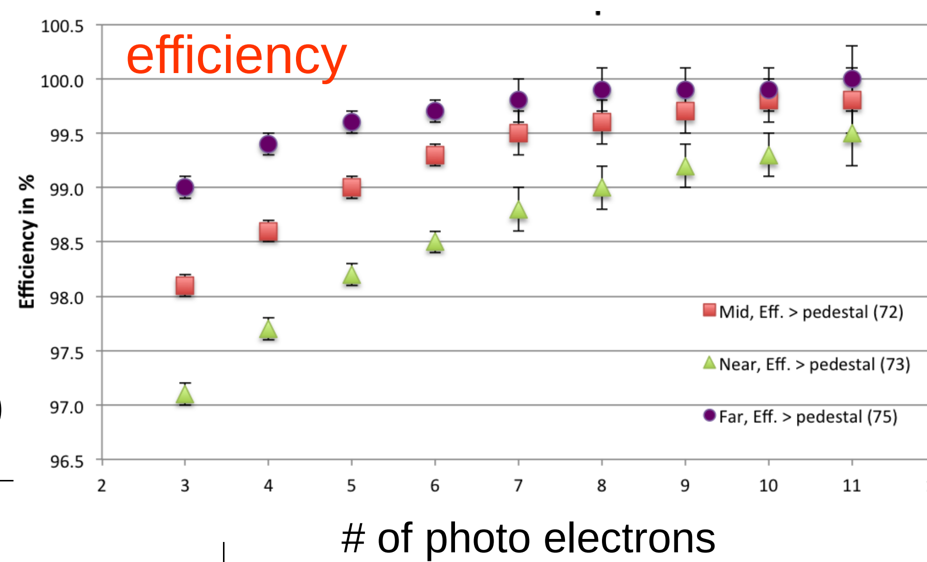
occupancy and optical cross talk?

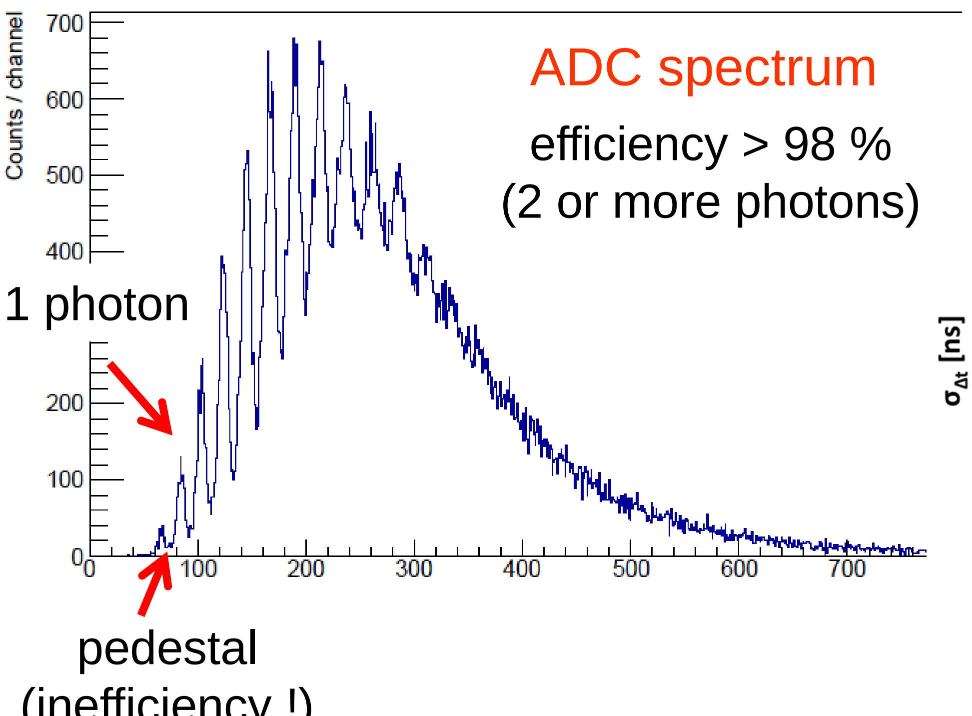


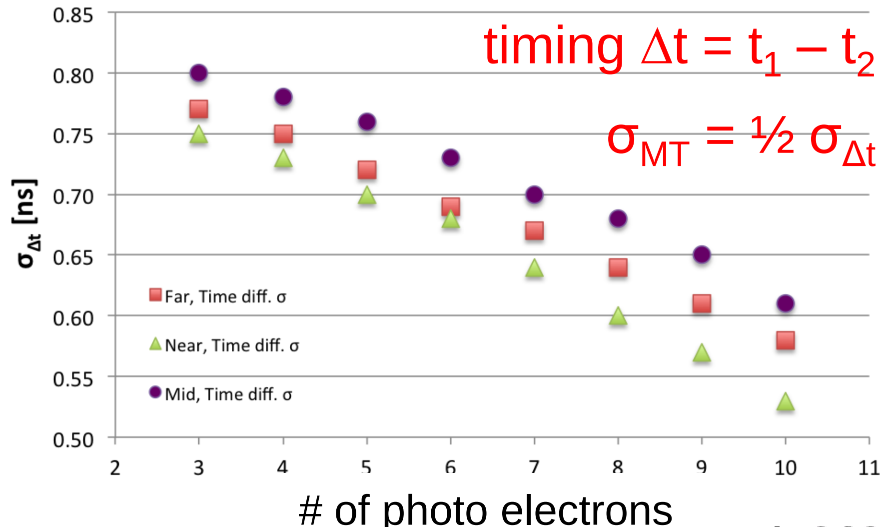
SciFi Performance (preliminary)



readout on both sides with single channel
3×3 mm^2 100 μm cell Si-PM (Hamamatsu)

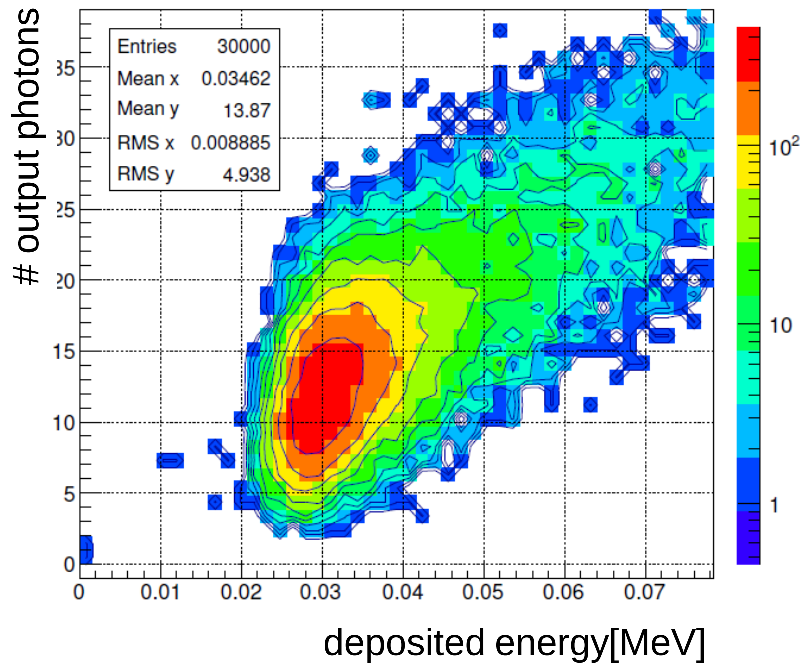




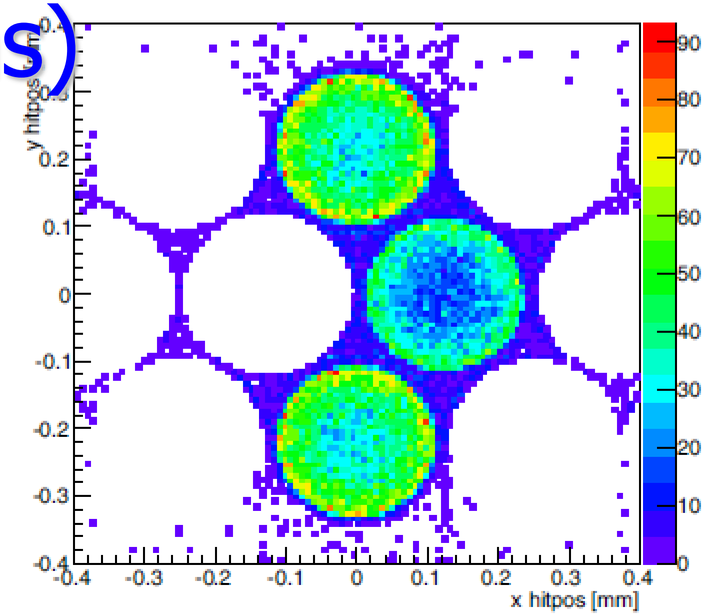


Light in SciFis (simulations)

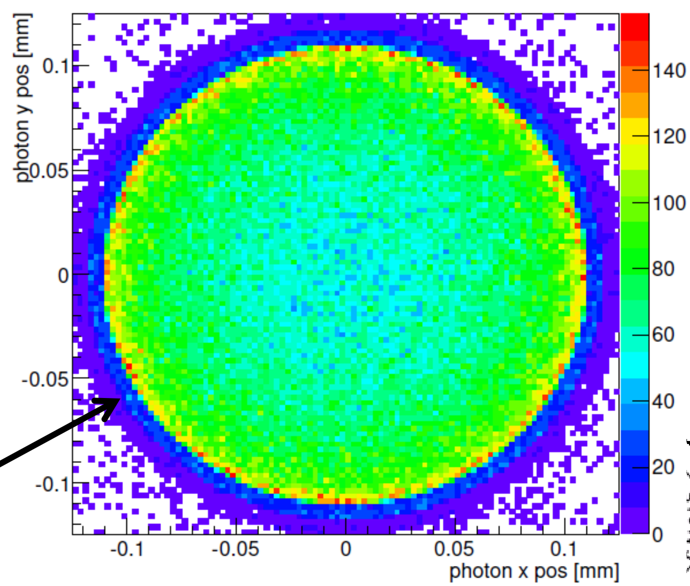
photon yield w/ P.D.E. ~ 25%

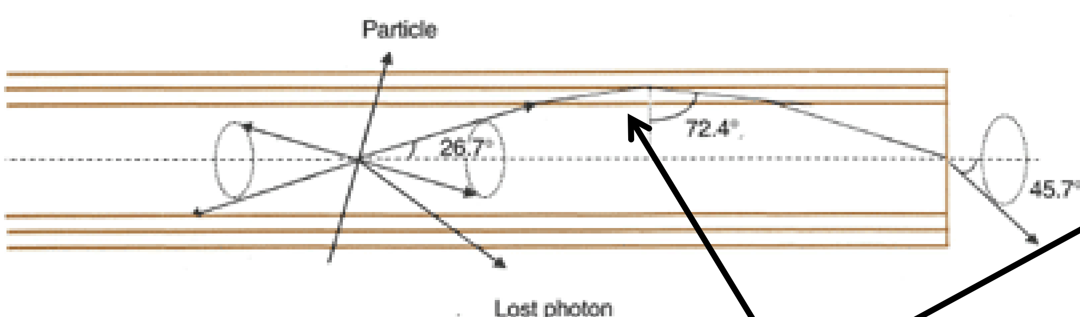


in agreement with measurements



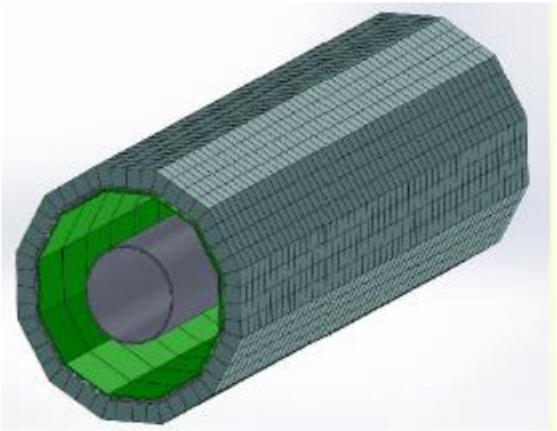
light propagation





light "travels" in the cladding

Scintillating Tile Detector



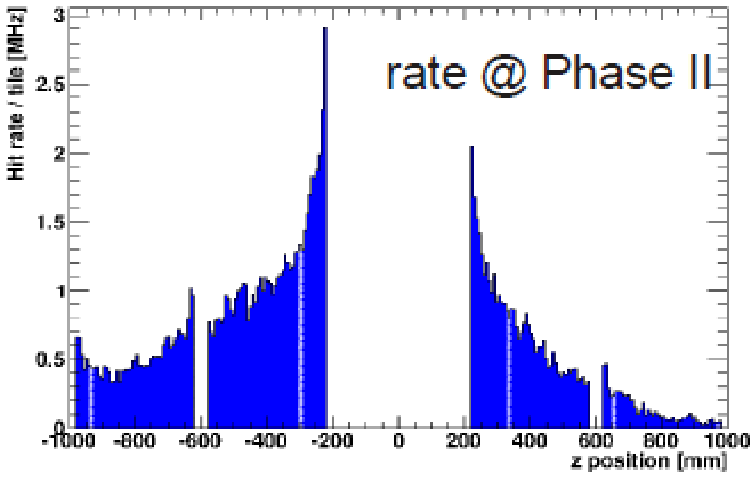
recurling tracks
(2nd time measurement)

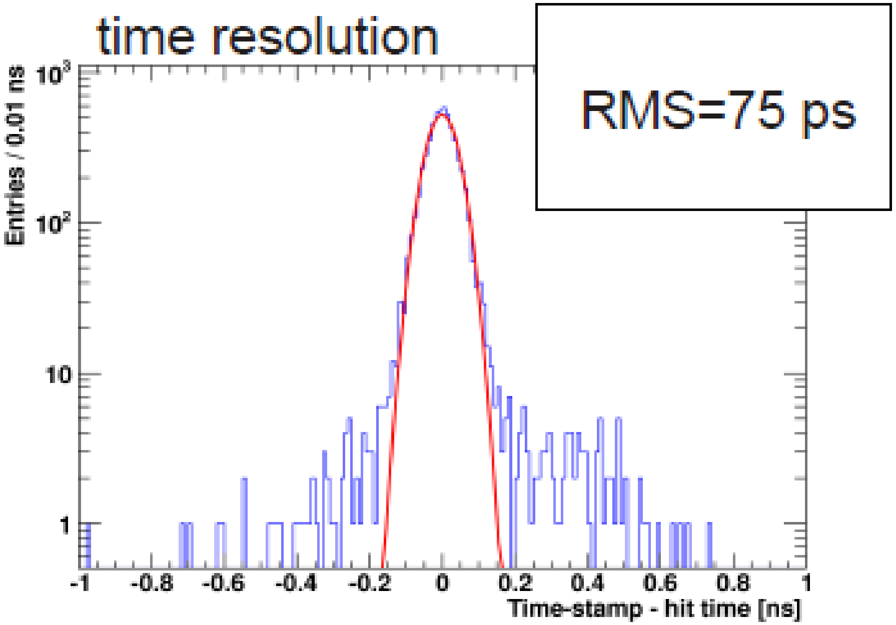
~6000 scintillating tiles
$1 \times 1 \times 0.5\ cm^3$

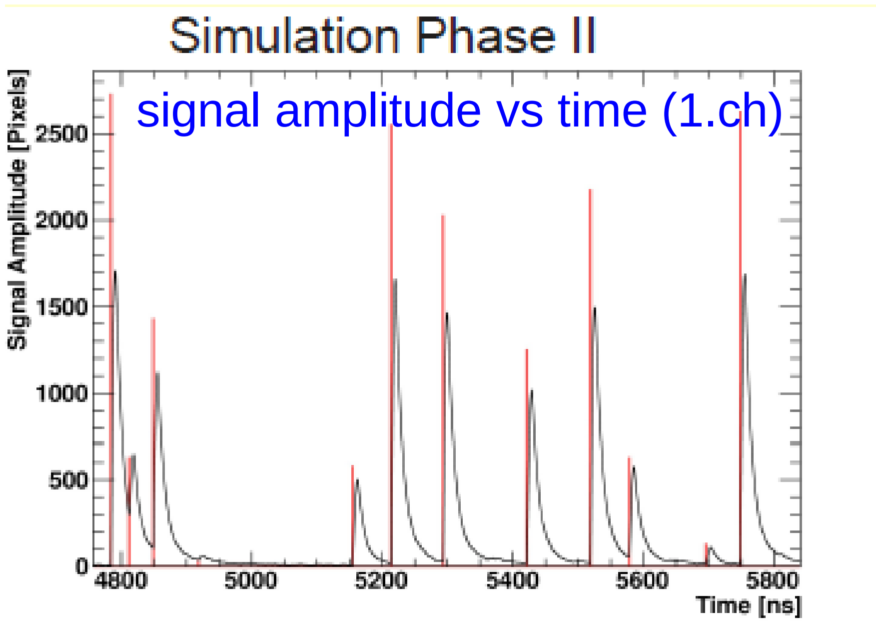
timing < 100 ps

readout Si-PMs and
custom ASICs (DRS)

rate ~few MHz







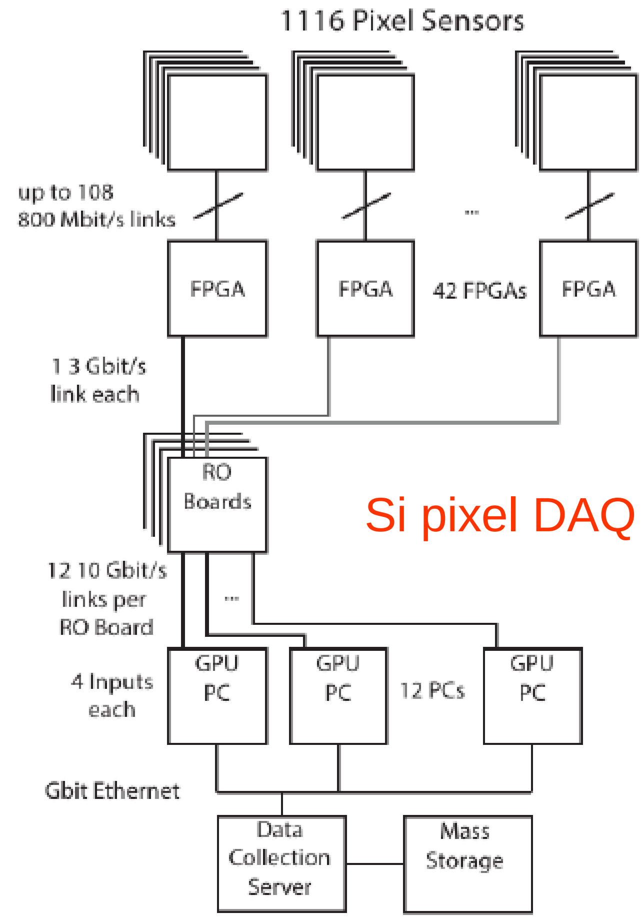
Data Acquisition

275 M Si-pixel channels
2000 hits / 50 ns redout frame
continuous frontend readout (no trigger)

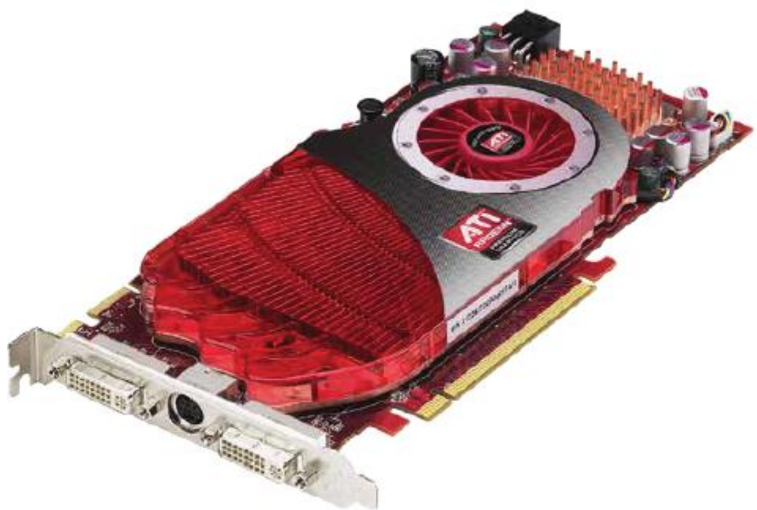
Central pixel detector (phase I)
Frontend data rate of 90 Gbit/sec

Full pixel detector (phase II)
Frontend data rate of 1500 Gbit/sec

Online event reconstruction using
Graphical Processing Units (GPUs)



Si pixel DAQ



50 PCs with GPUs

on tape < 100 Mby / s

ch. larger than LHC
data rate smaller than LHC

Conclusion

Flavor is the real issues in BSM physics (B. Gavela)

Mu3e aims at 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 (2015 – 2017)
~ 10^8 μ decays / s BR($\mu \rightarrow$ eee) < 10^{-15}
approved in January 2013

Stage II (2018+)
~ 10^9 μ decays / s BR($\mu \rightarrow$ eee) < 10^{-16}
HiMB 2 year feasibility study to start this summer

Start data taking in 2015

High precision experiments at National Laboratories promoted by European Strategy for HEP