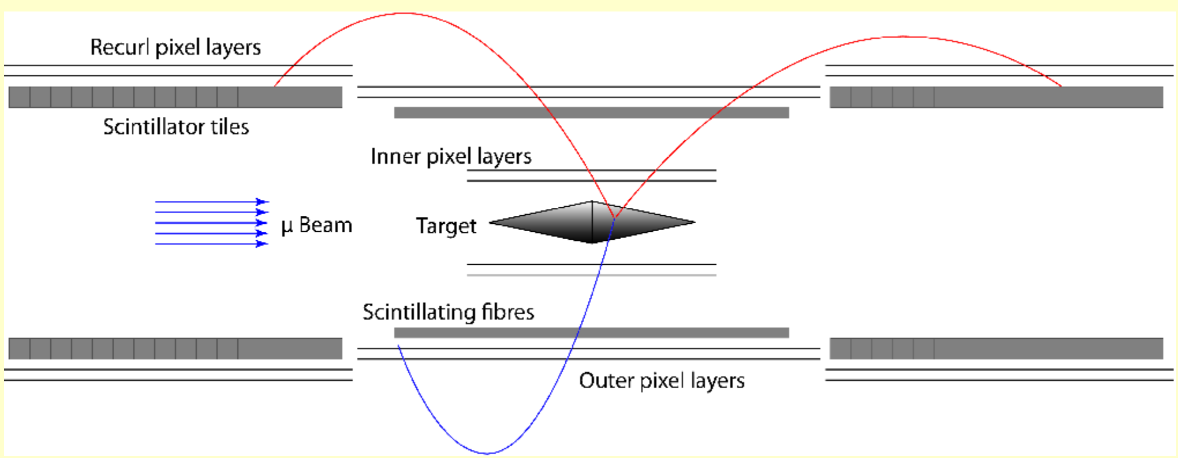
The Mu3e Experiment at PSI

PSI2013 Workshop, September 12, 2013

André Schöning

Physikalisches Institut, Universität Heidelberg

on behalf of the Mu3e collaboration



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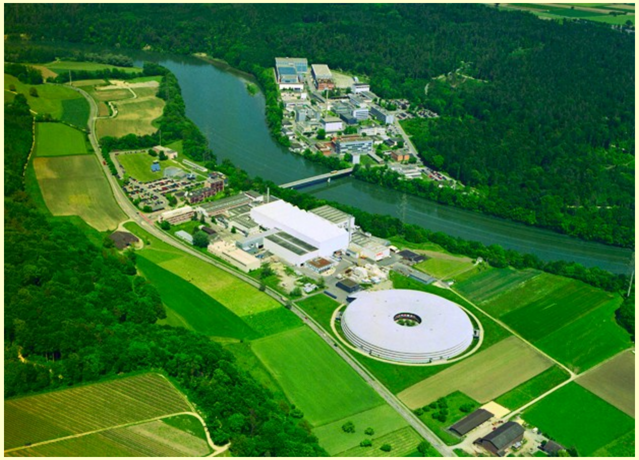
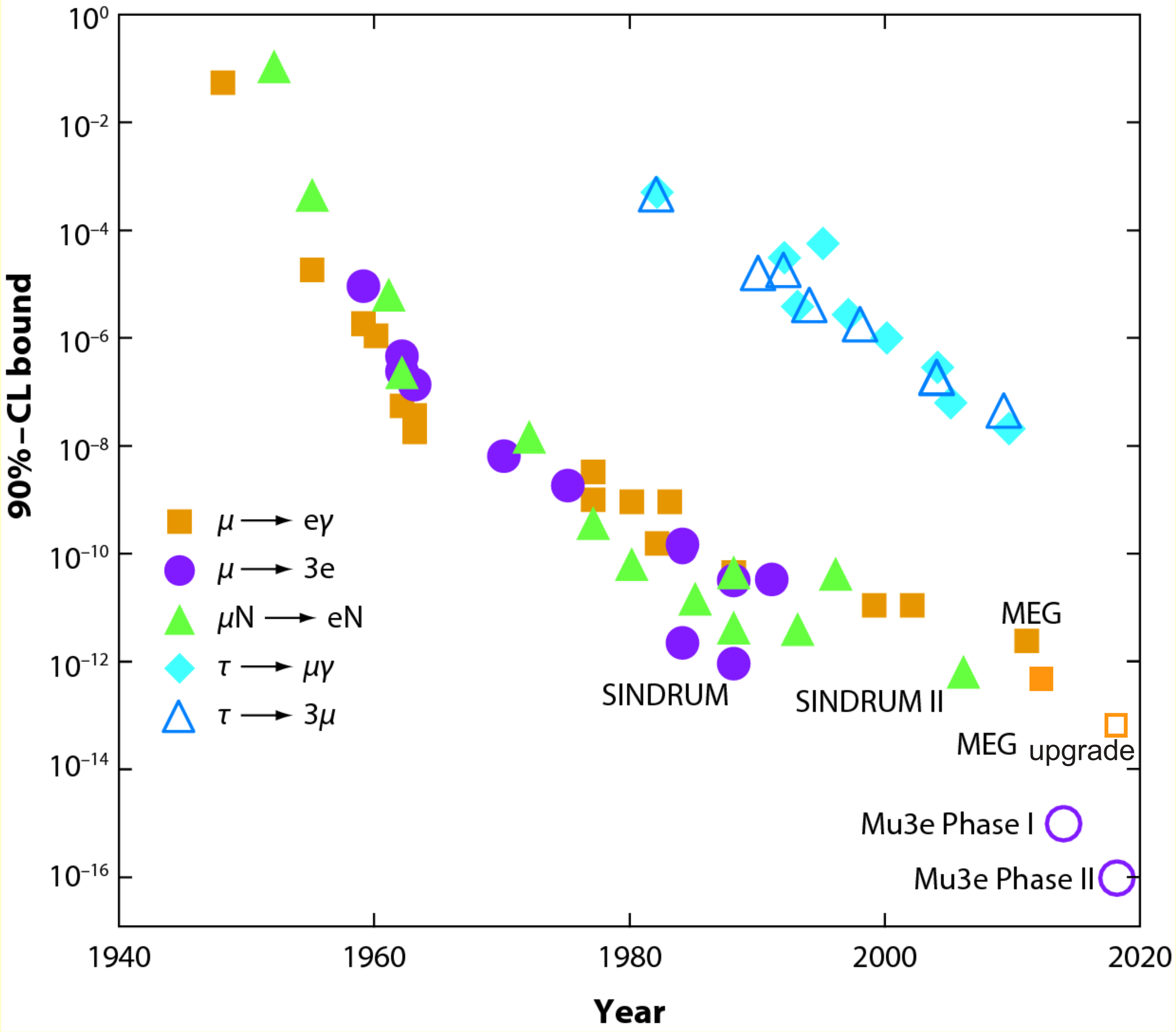
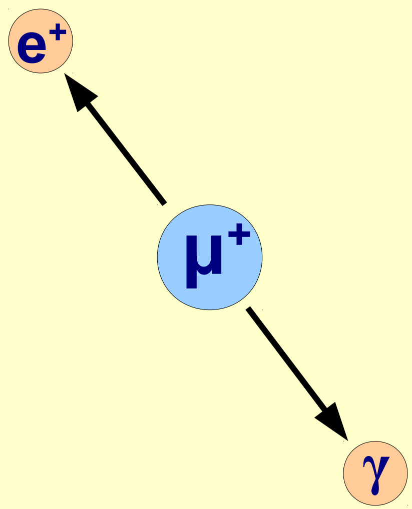


History of LFV Decay experiments



LFV Muon Decays: Experimental Situation

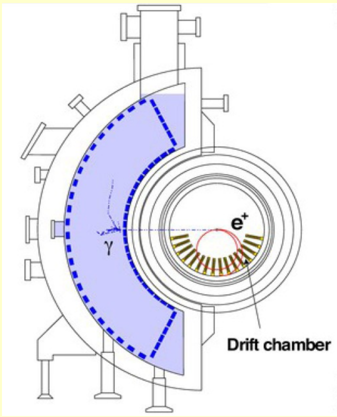
$\mu^+ \rightarrow e^+ \gamma$



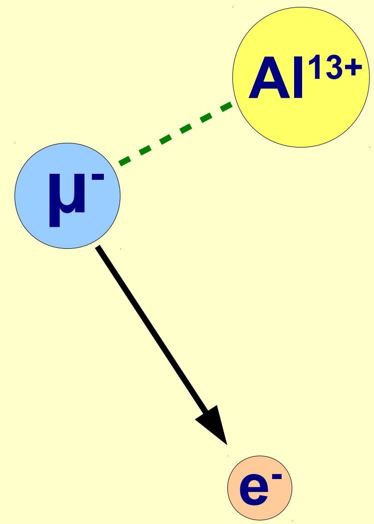
MEG (PSI)

$B(\mu^+ \rightarrow e^+\gamma) \leq 5.7 \cdot 10^{-13}$ (2013)

just finished data taking → upgrade



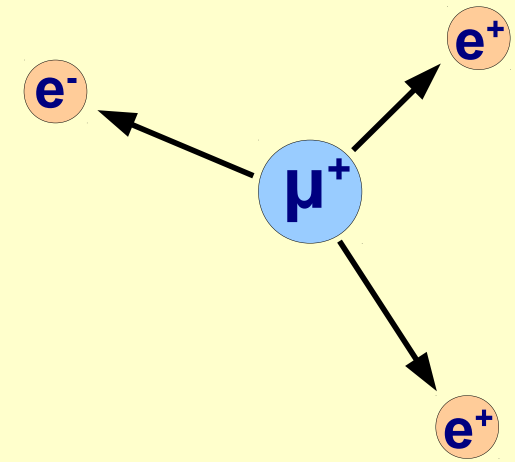
$\mu^- N \rightarrow e^- N$



SINDRUM II (PSI)

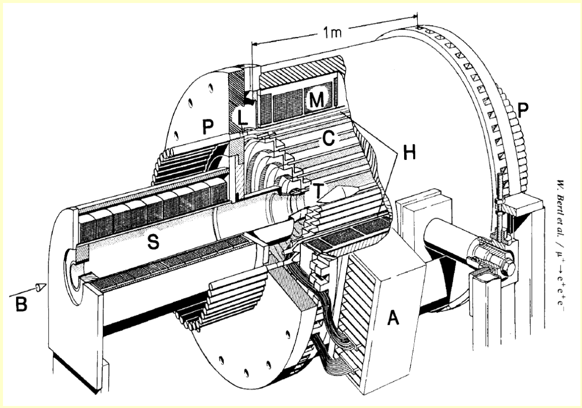
$B(\mu\ Au \rightarrow e\ Au) \leq 7 \cdot 10^{-13}$ (2006)

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



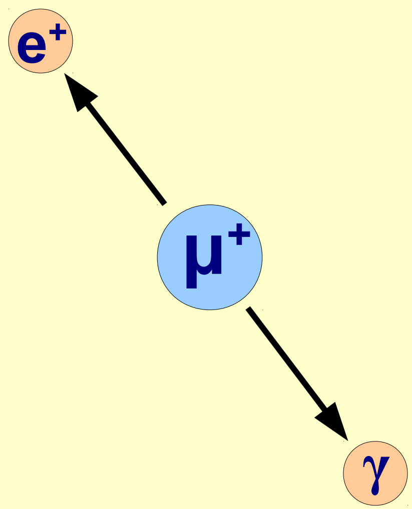
SINDRUM (PSI)

$B(\mu^+ \rightarrow e^+e^+e^-) \leq 10^{-12}$ (1988)

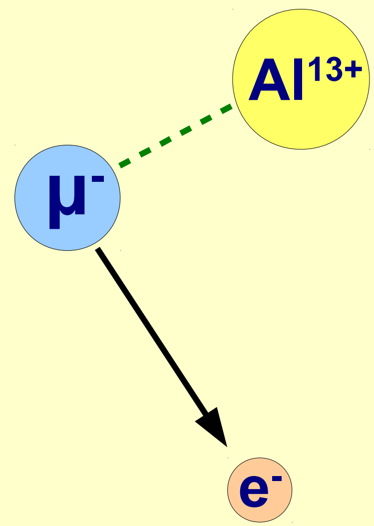


LFV Muon Decays in the SM

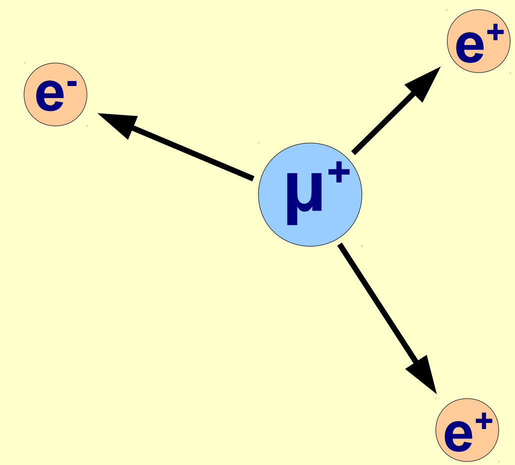
$\mu^+ \rightarrow e^+ \gamma$



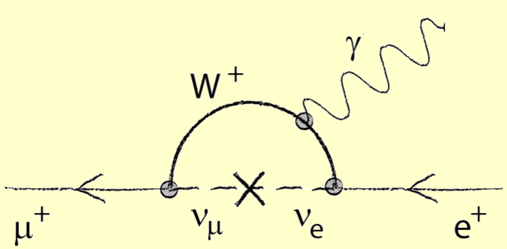
$\mu^- N \rightarrow e^- N$

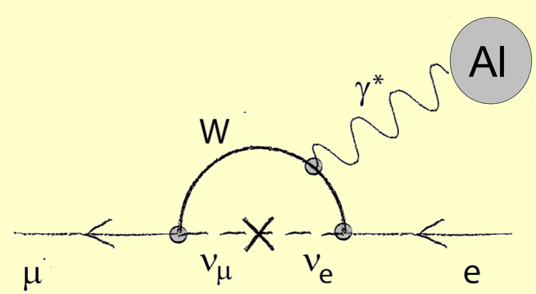


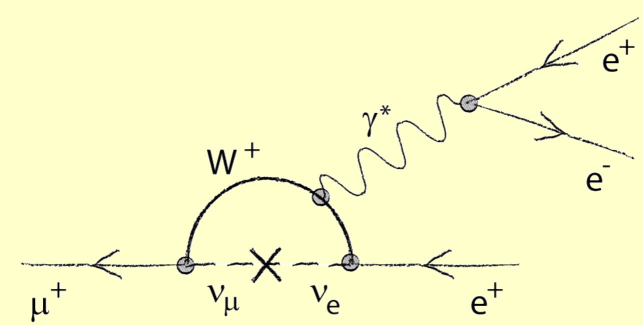
$\mu^+ \rightarrow e^+ e^+ e^-$



SM: LFV loops



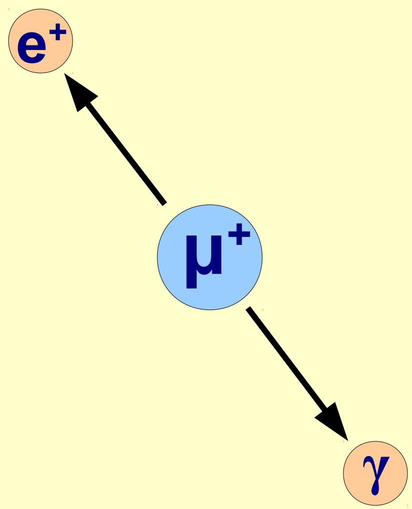




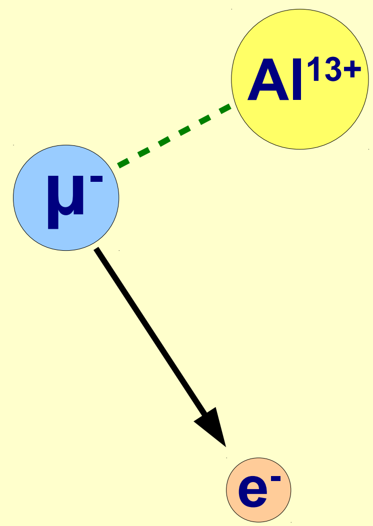
branching ratios suppressed by $\propto \frac{(\Delta m_\nu^2)^2}{m_W^4} \approx 10^{-50}$

LFV Muon Decays from SUSY loops

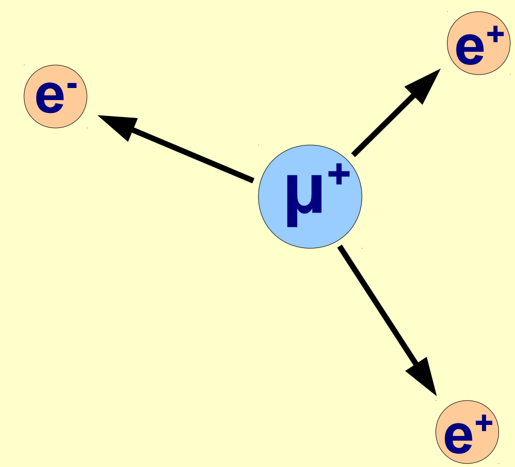
$\mu^+ \rightarrow e^+ \gamma$



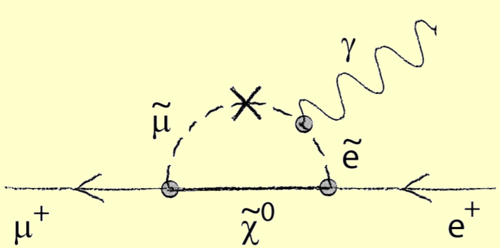
$\mu^- N \rightarrow e^- N$

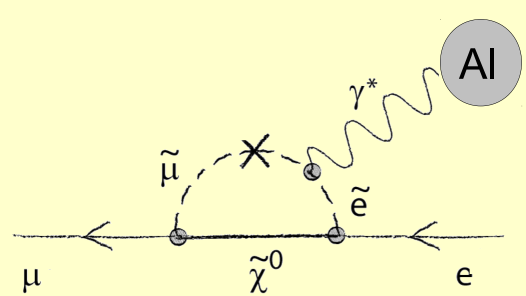


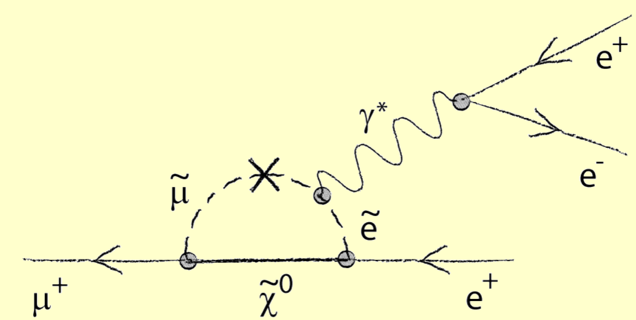
$\mu^+ \rightarrow e^+ e^+ e^-$



SUSY loops



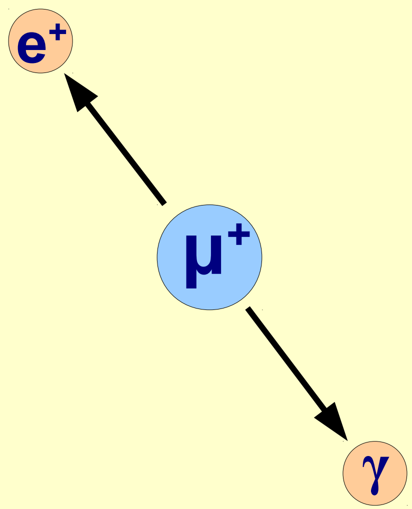


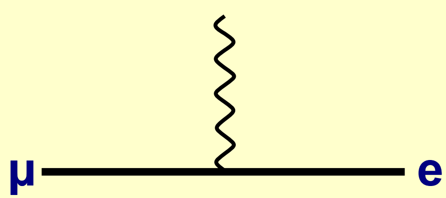


SUSY and many other BSM models induce naturally LFV

LFV "Exotic" Tree Diagrams

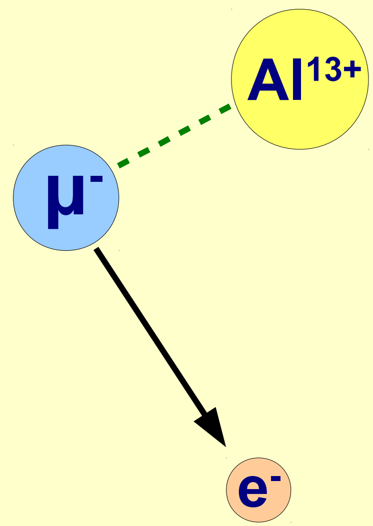
$\mu^+ \rightarrow e^+ \gamma$

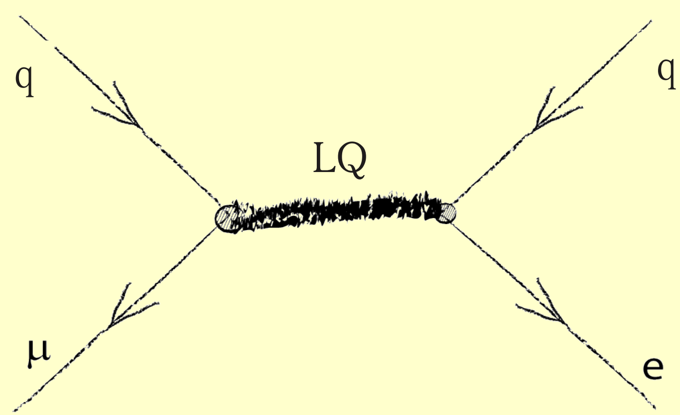




not allowed

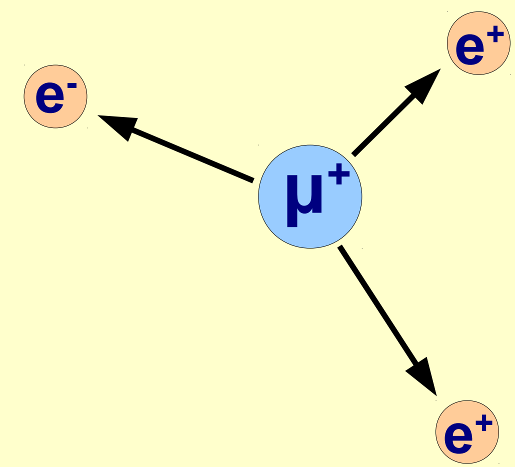
$\mu^- N \rightarrow e^- N$

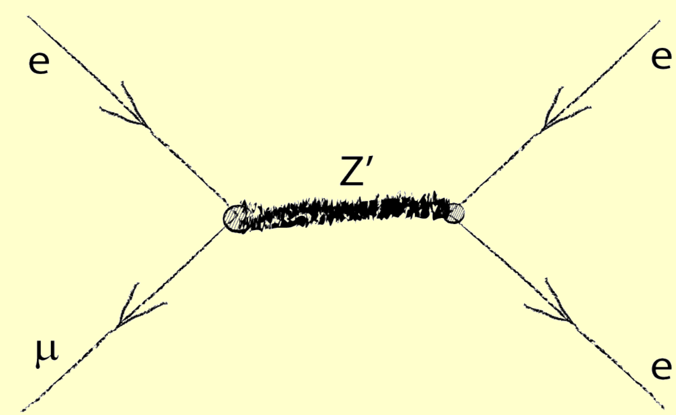




e.g. Leptoquarks

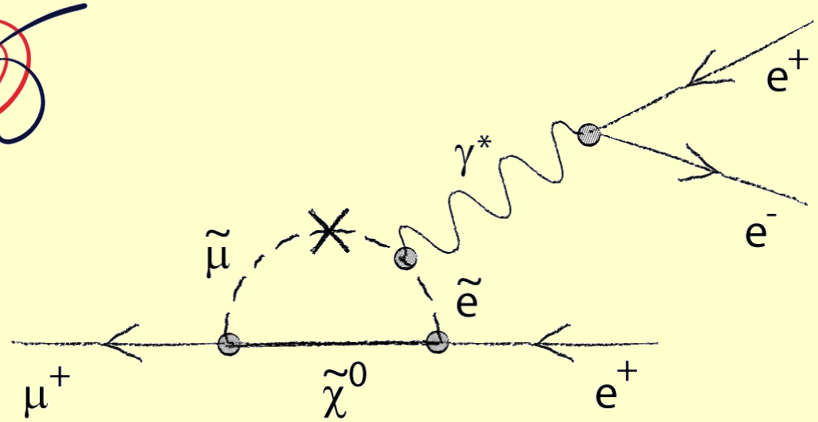
$\mu^+ \rightarrow e^+ e^+ e^-$



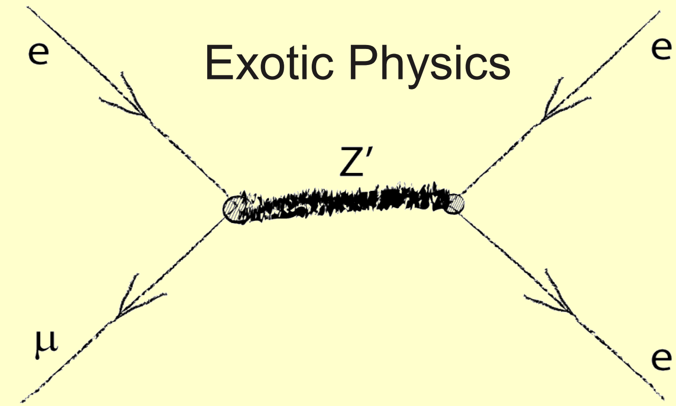


extra Z', LFV Higgs, etc.

Lepton Flavor Violating Decay: $\mu^+ \rightarrow e^+e^+e^-$



loop diagrams



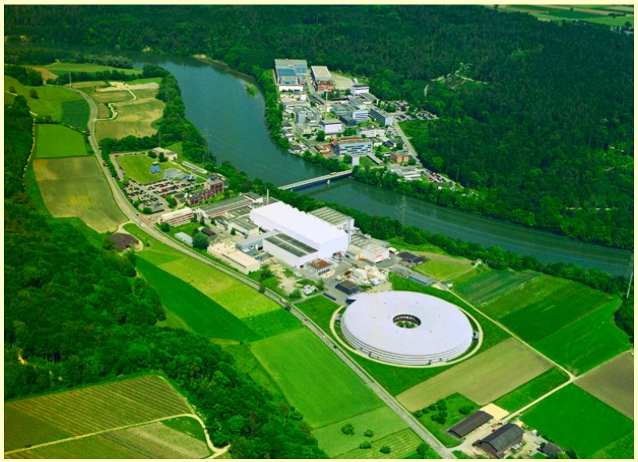
tree diagram

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

- **Higgs Triplet Model**
- **New Heavy Vector bosons (Z')**
- **Extra Dimensions (KK towers)**

Mu3e Experiment

Search for $\mu^+ \rightarrow e^+e^+e^-$ at PSI



- 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

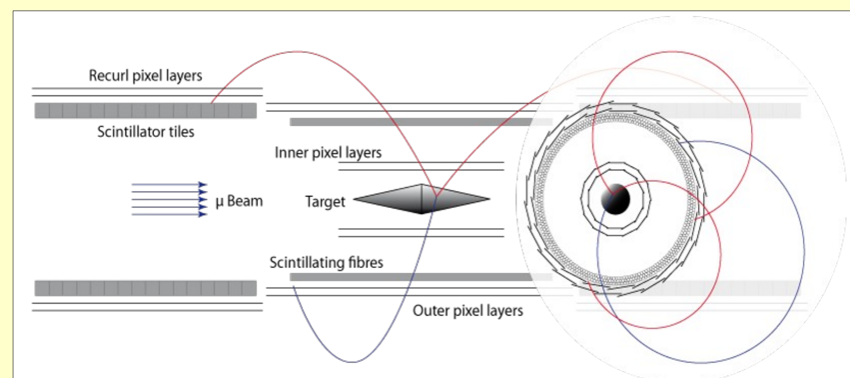
→ project approved in Jan 2013 by PSI

Aiming for a sensitivity of

$BR(\mu \rightarrow e\,e\,e) < 10^{-15}$ (phase I)

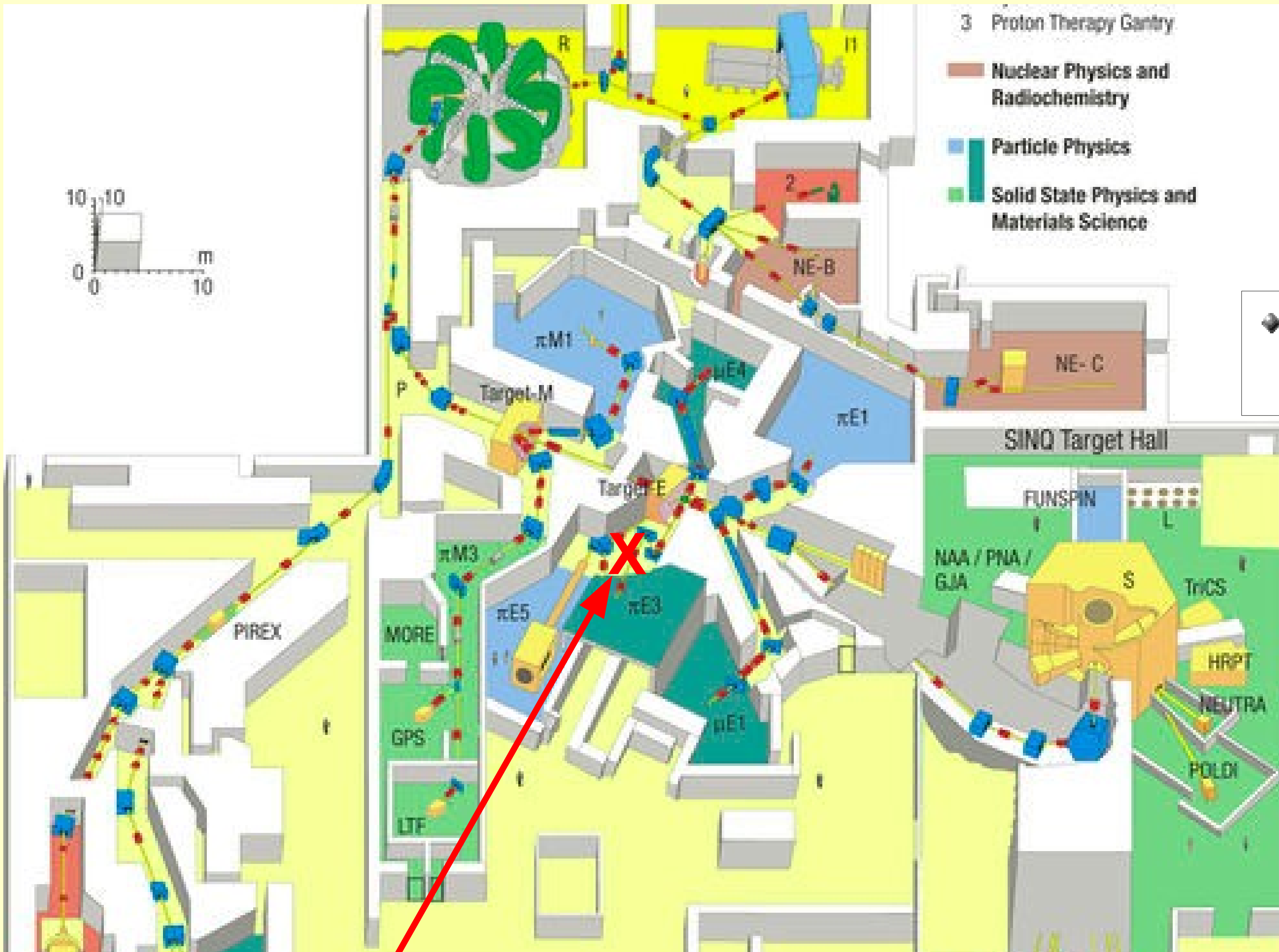
$BR(\mu \rightarrow e\,e\,e) < 10^{-16}$ (phase II)

before end of decade



Requires > 10^9 muons per second → high rate experiment (~LHC)

PSI Facility for Mu3e



- poster by A.Knecht, P.-R. Kettle et al.

High-intensity Muon Beamline

(HiMB)

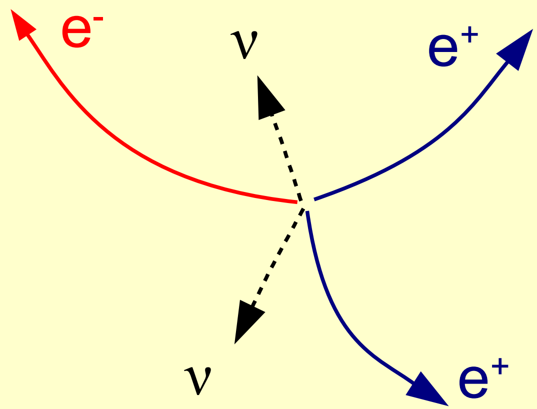
X

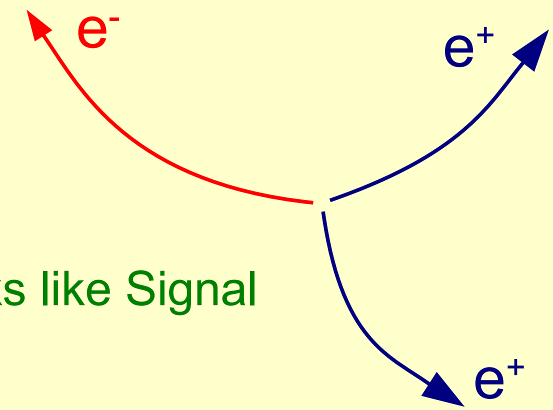
Phase I (2015+): ~10^8 muons/s

Phase II (>2017): >10^9 muons/s

Backgrounds

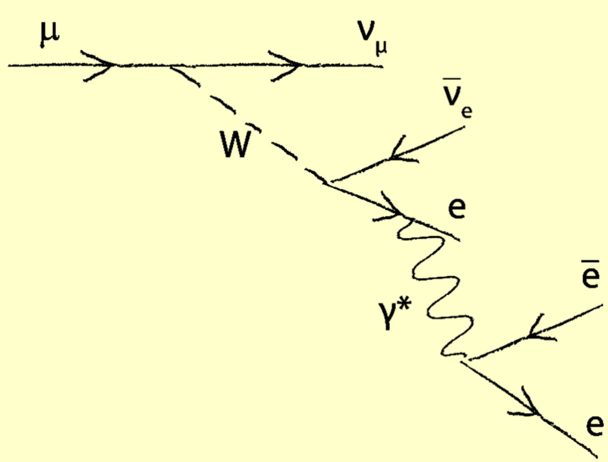
Irreducible BG: radiative decay with internal conversion





looks like Signal

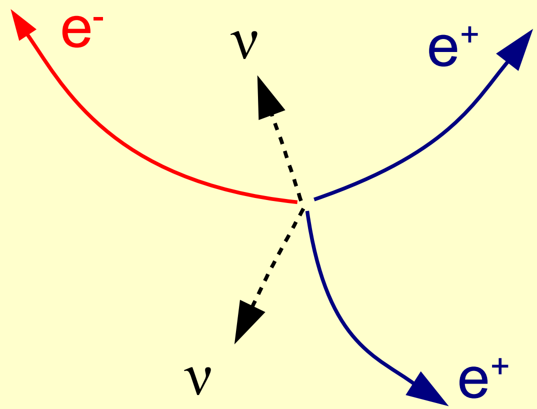
$B(\mu^+ \rightarrow e^+e^+e^- \nu\nu) = 3.4 \cdot 10^{-5}$



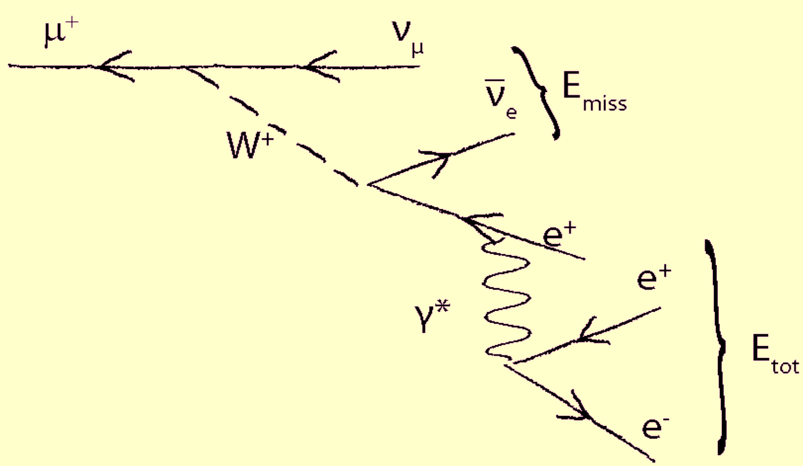
$$\sum_i E_i = m_\mu$$
$$\sum_i \vec{p}_i = 0$$

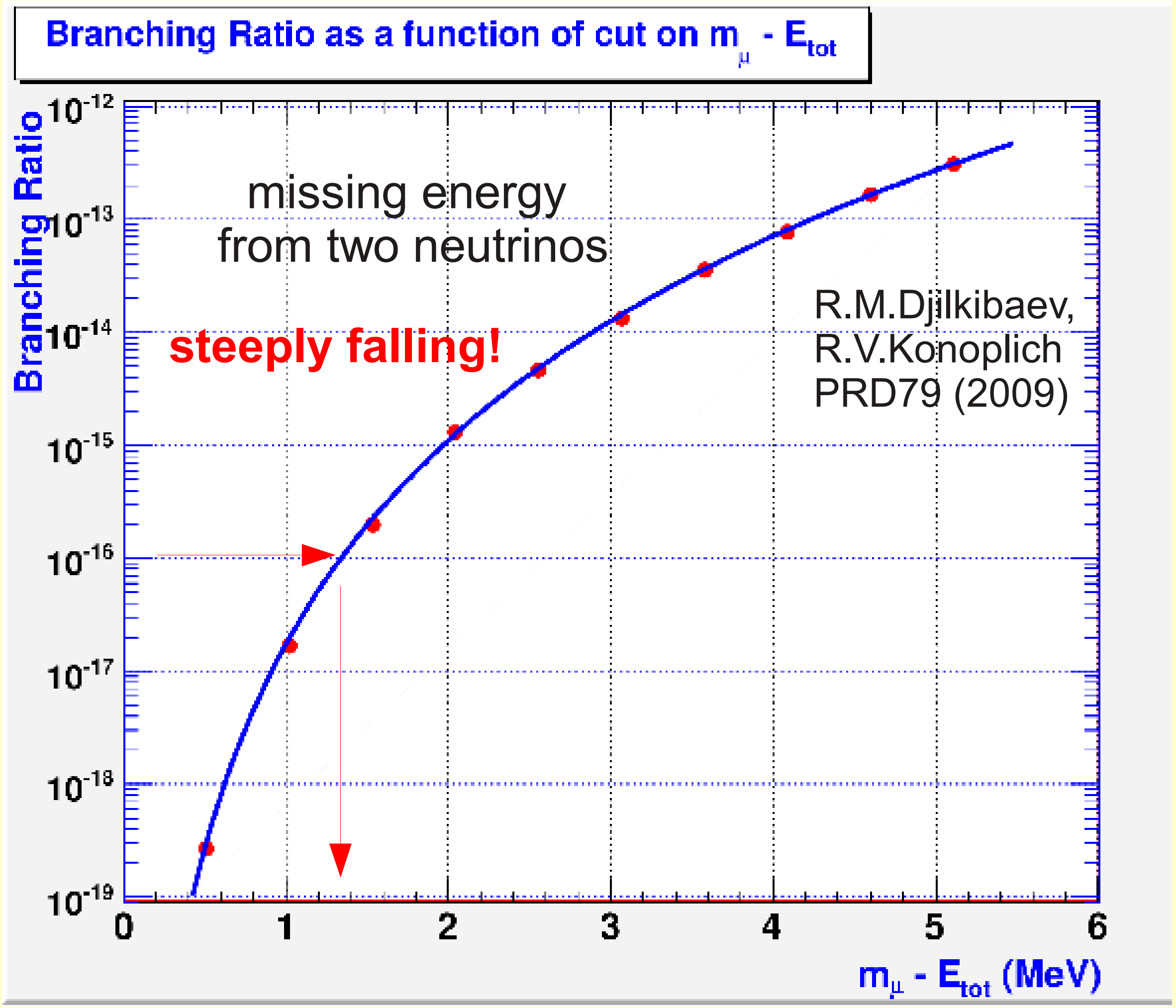
Backgrounds

Irreducible BG: radiative decay with internal conversion



B($\mu^+ \rightarrow e^+e^+e^- \nu\nu$) = 3.4 ·$10^{-5}$

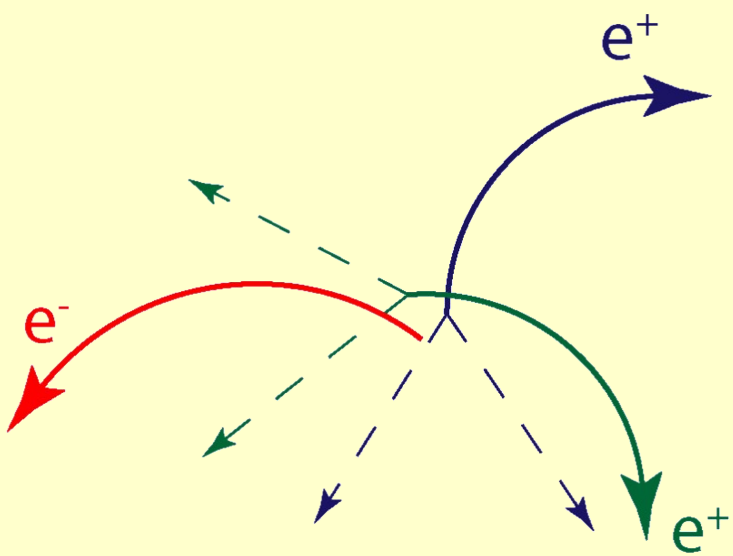


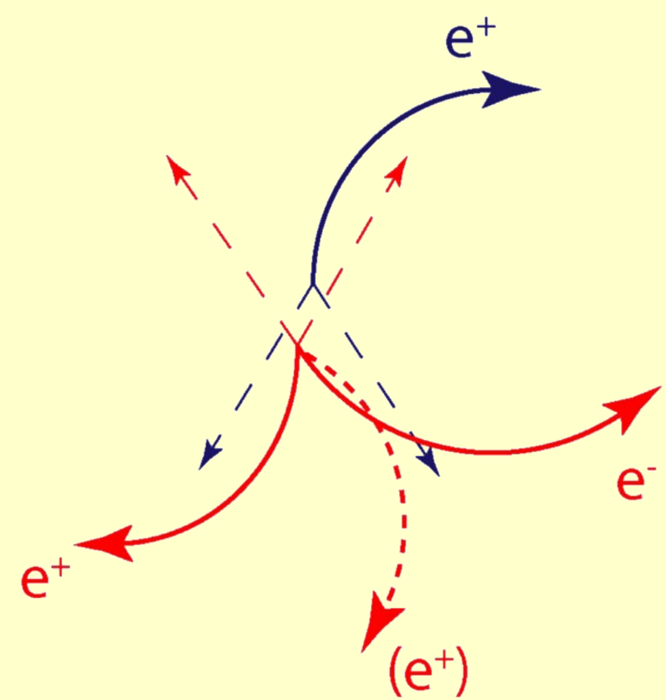


very good momentum +
total energy resolution required!

Accidental Backgrounds

- Overlays of two ordinary muon decays with a (fake) electron
- Electrons from: Bhabha scattering, photon conversion, mis-reconstruction





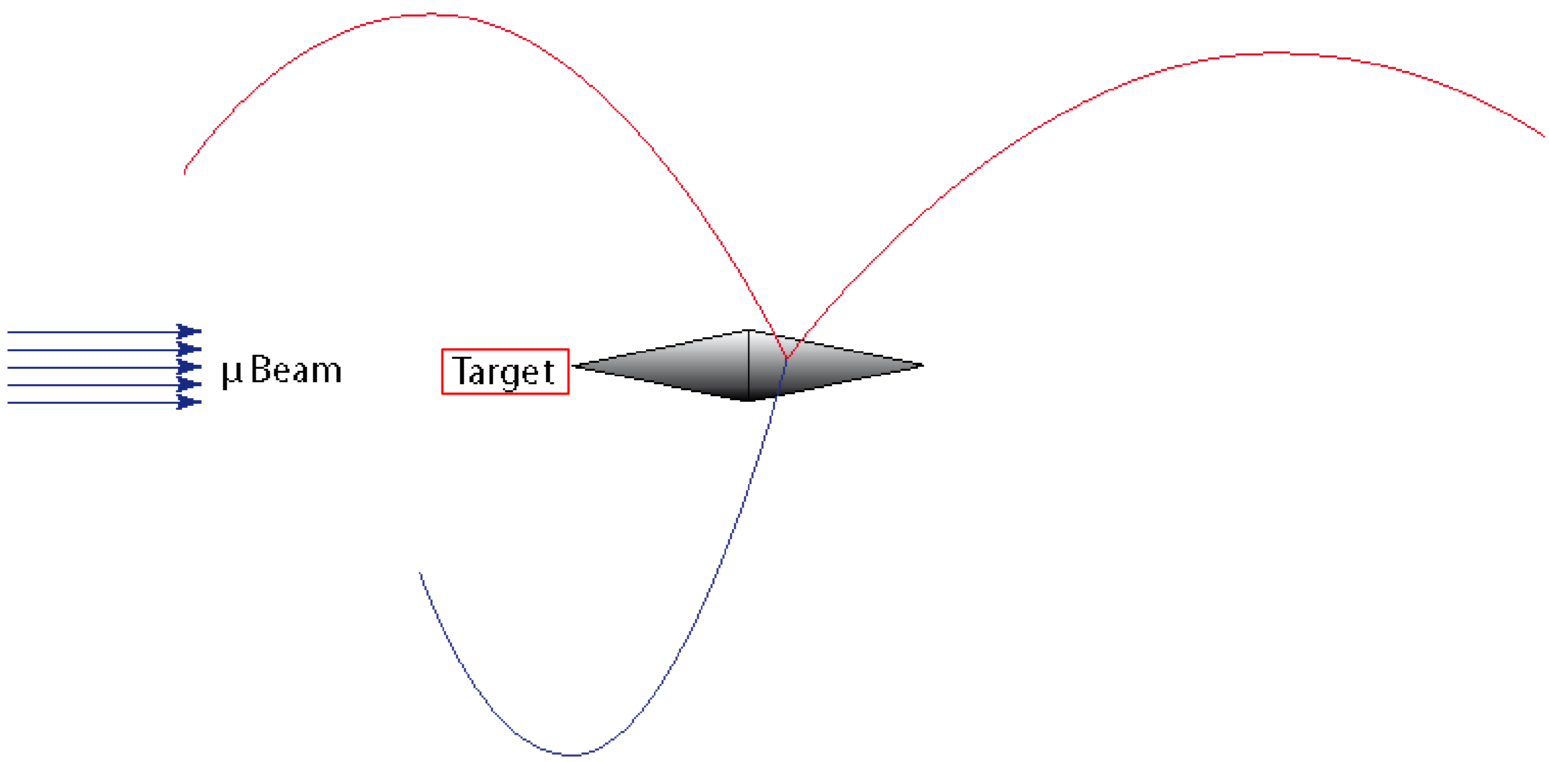
Need excellent:

- **Vertex resolution**
- **Timing resolution**
- **Kinematic reconstruction**

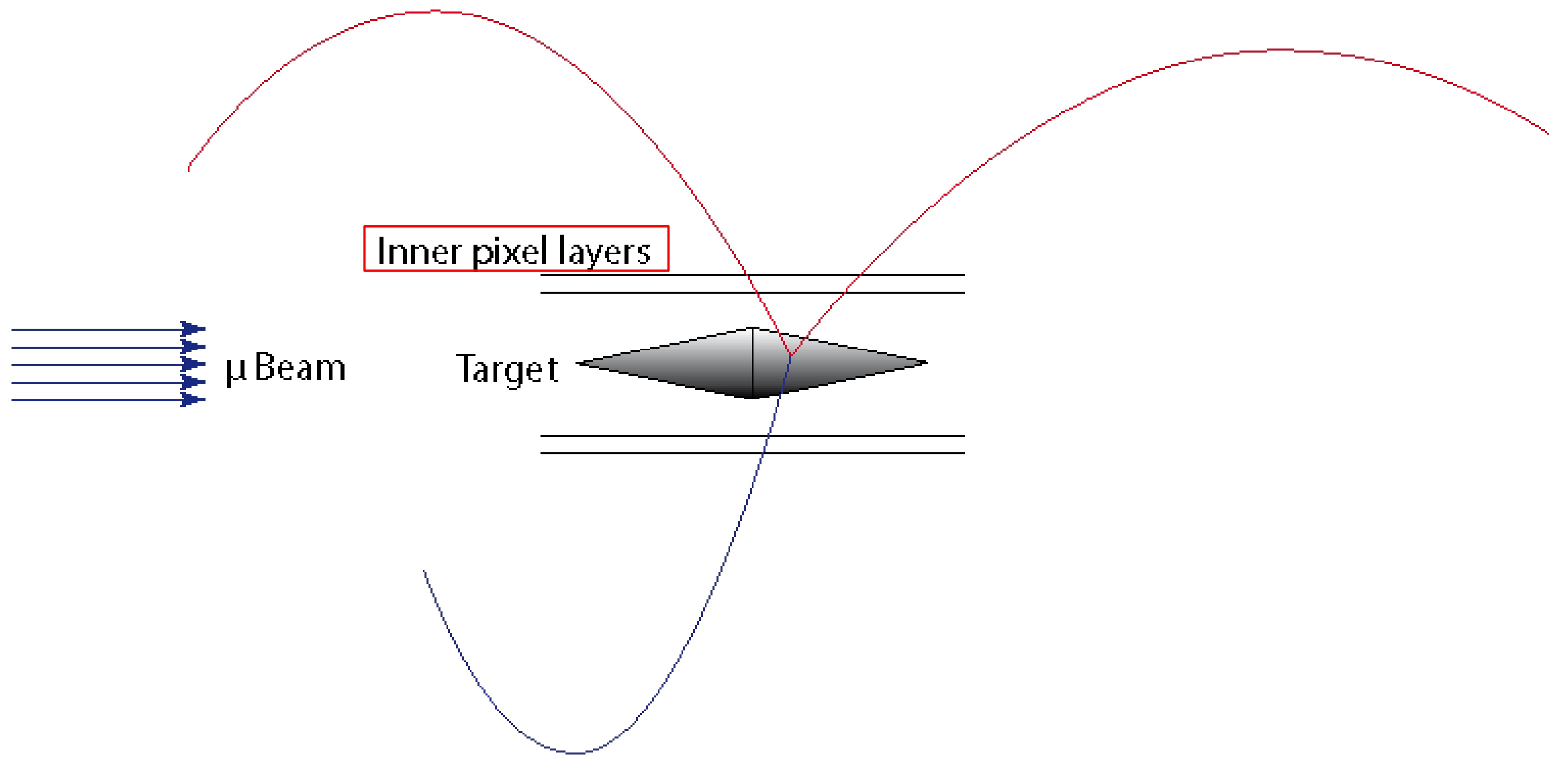
Mu3e Experimental Proposal

Mu3e Baseline Design

Mu3e Baseline Design

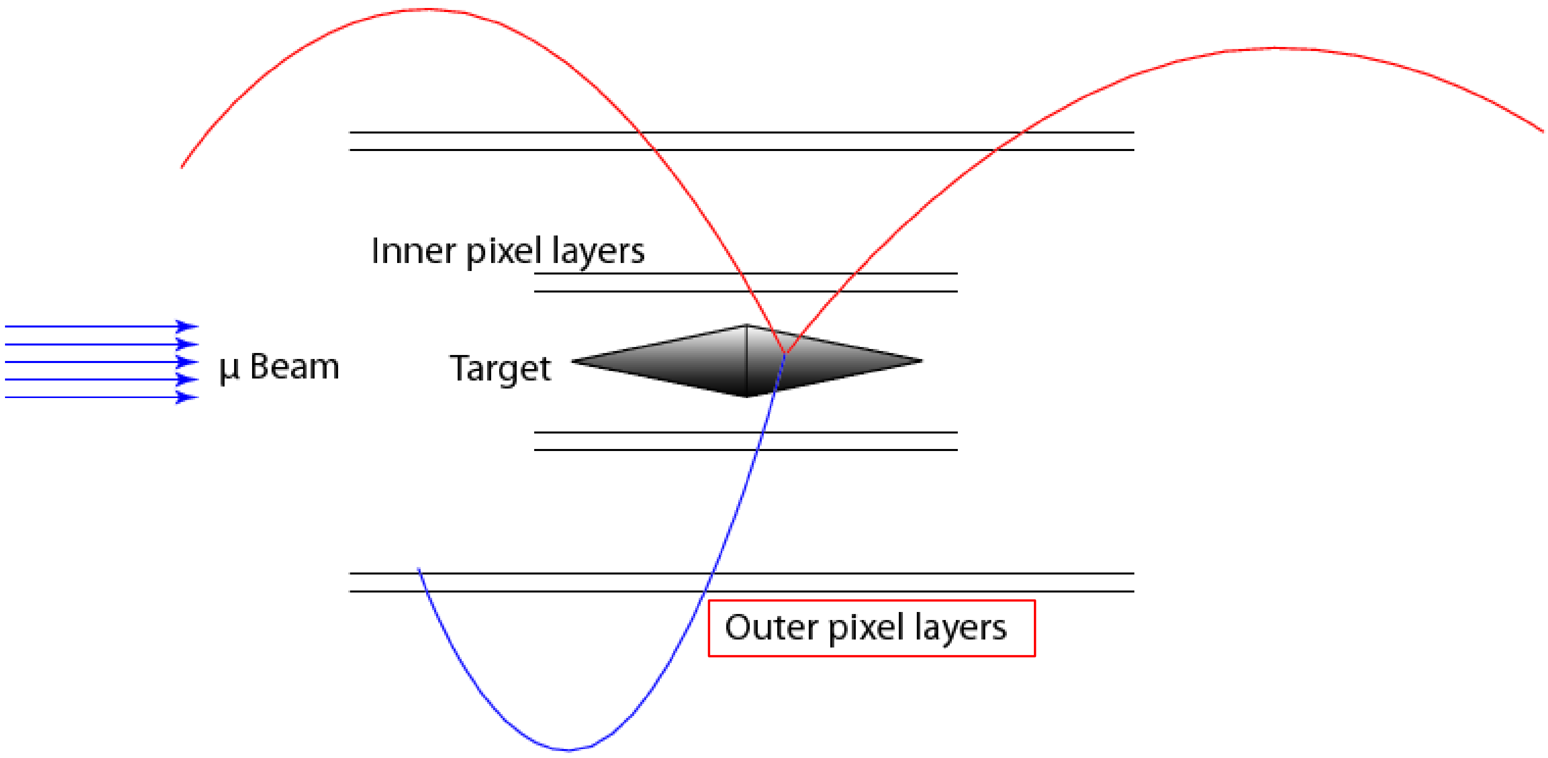


Mu3e Baseline Design

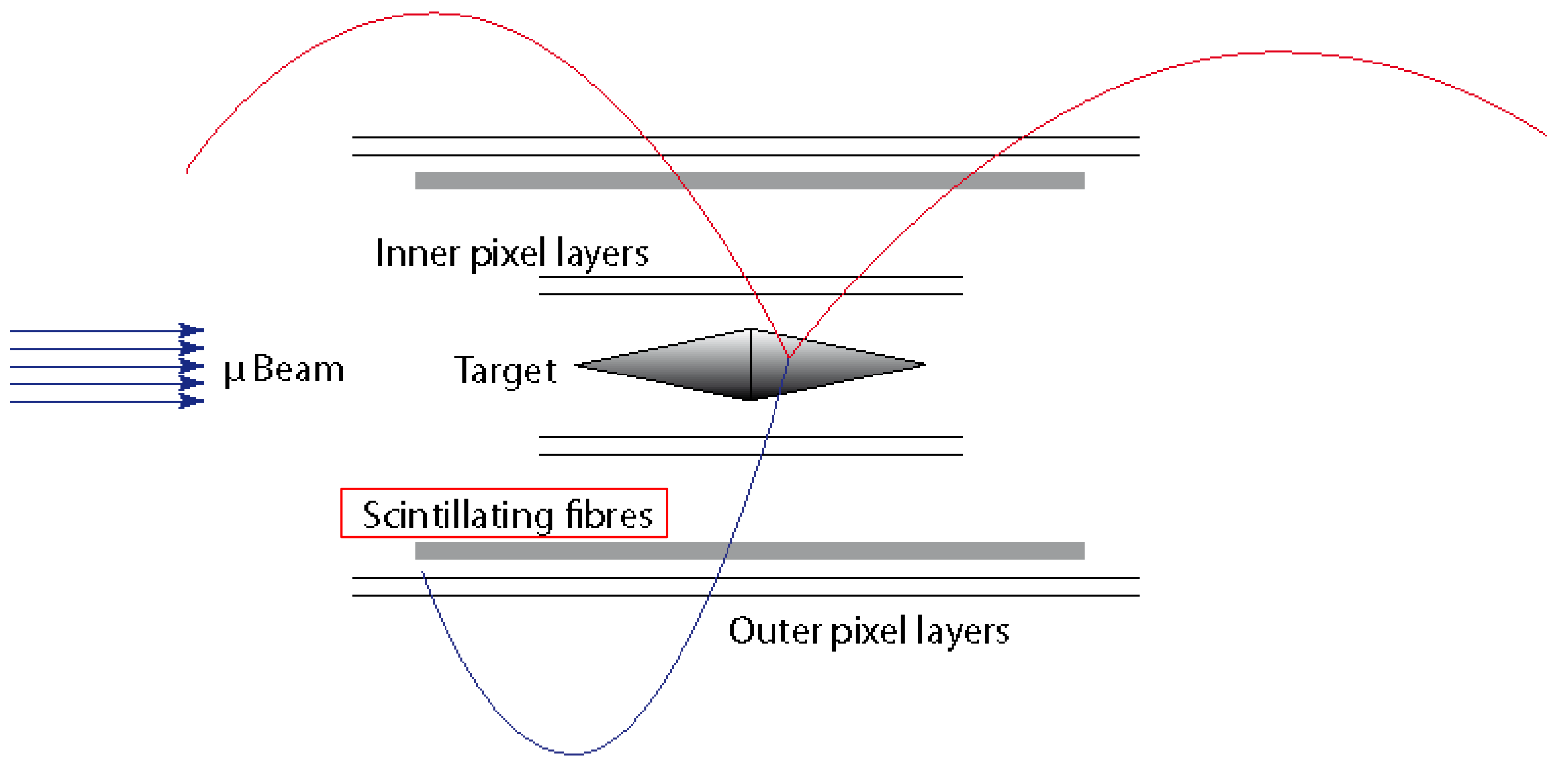


Mu3e Baseline Design

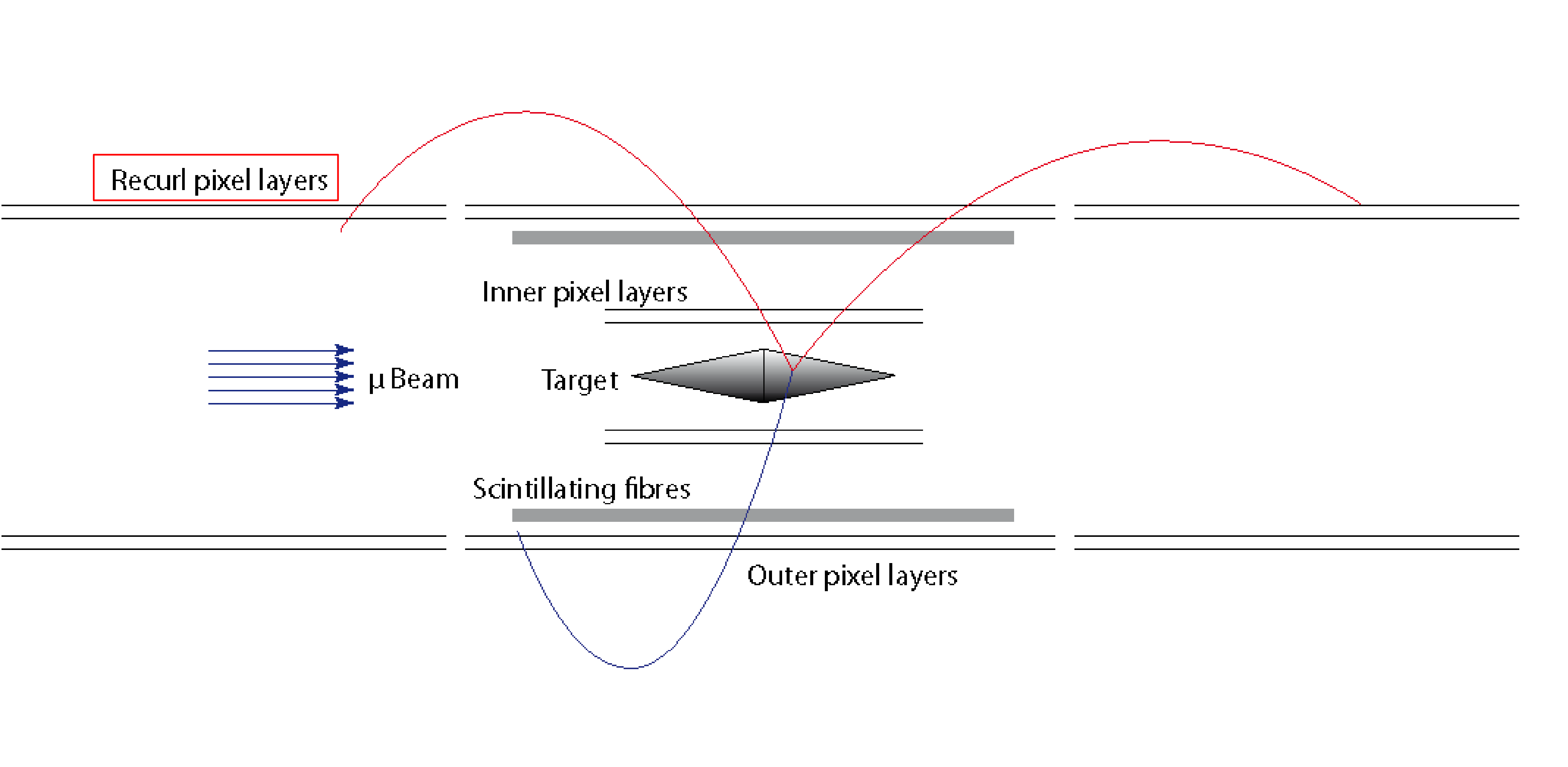
Phase IA Design



Mu3e Baseline Design

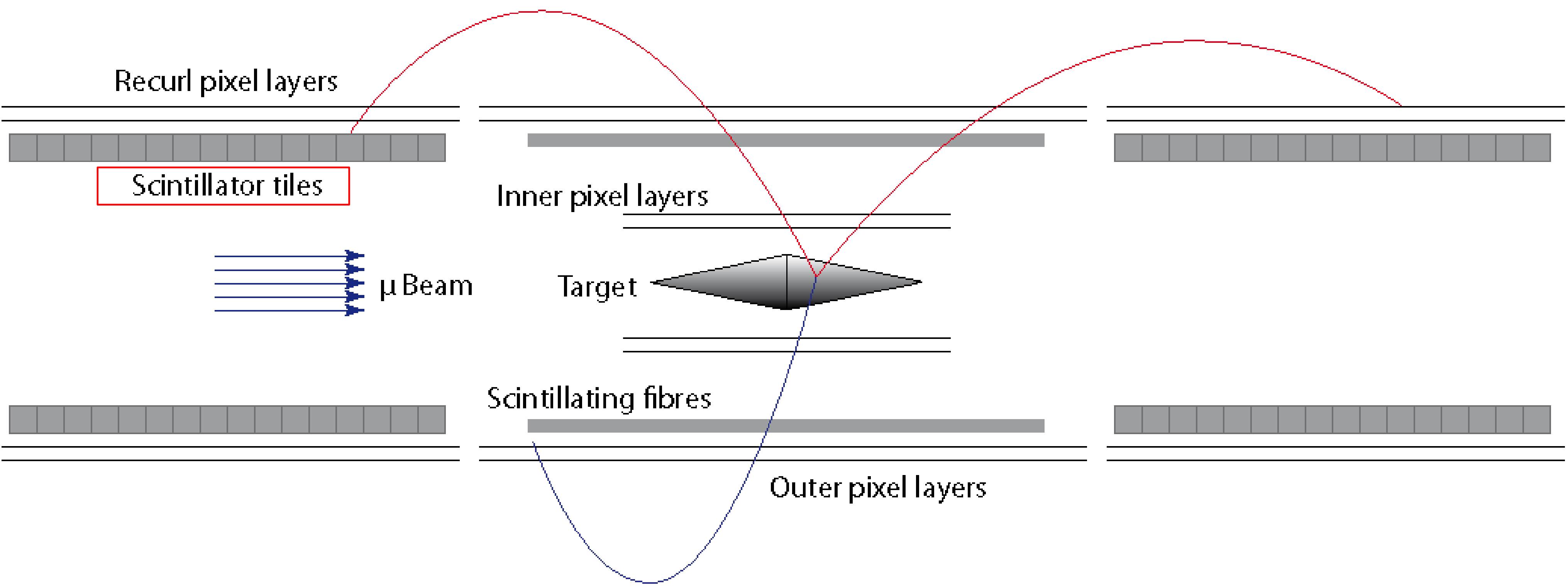


Mu3e Baseline Design



Mu3e Baseline Design

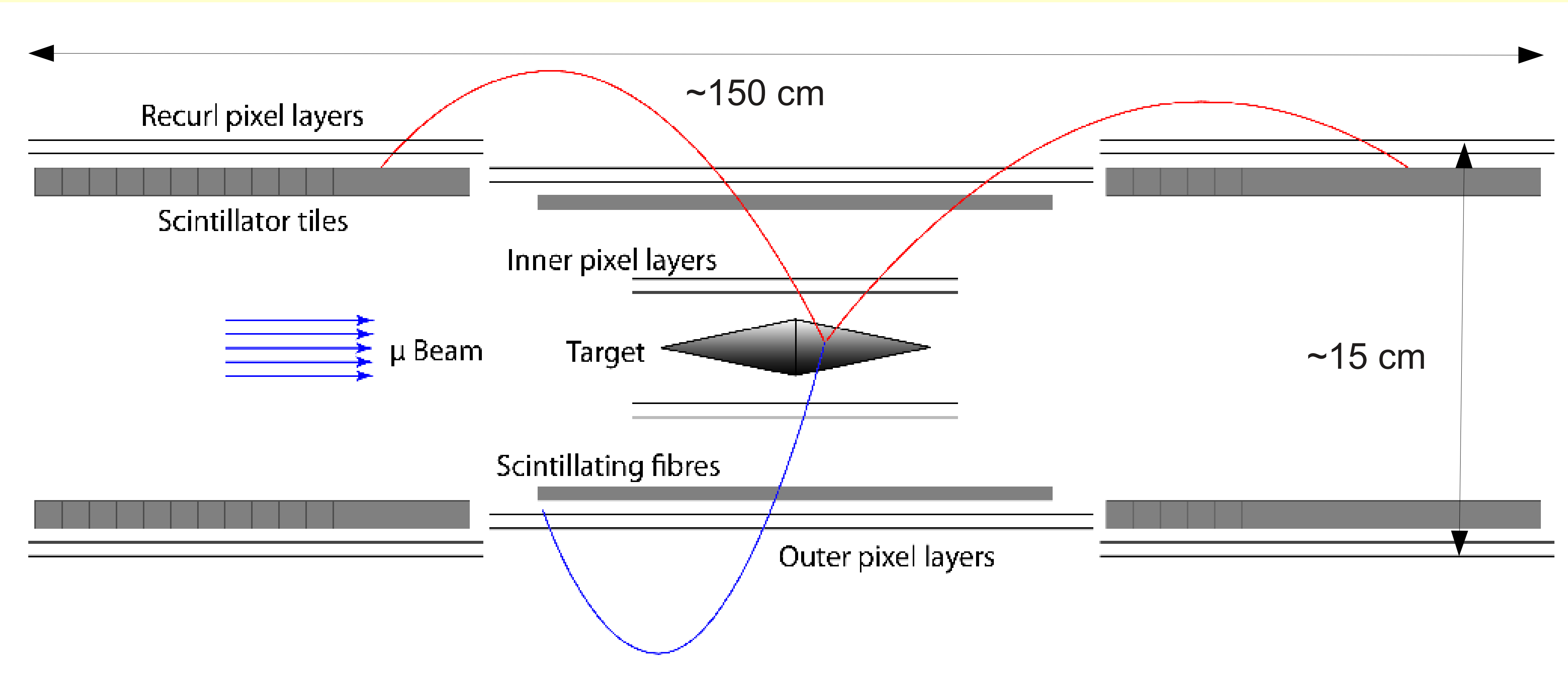
Phase IB Design



Mu3e Baseline Design

Long cylinder!

not to scale!



Mu3e Baseline Design

Long cylinder!

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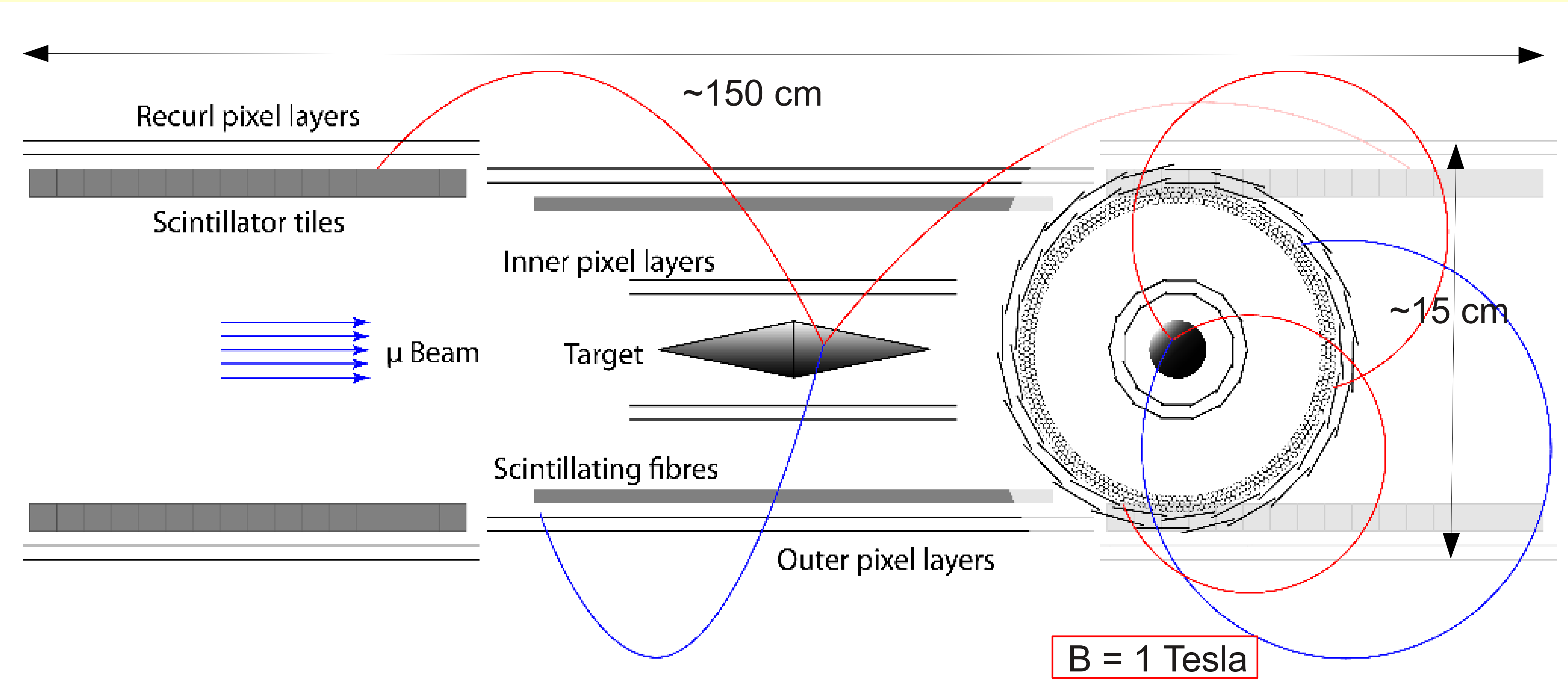
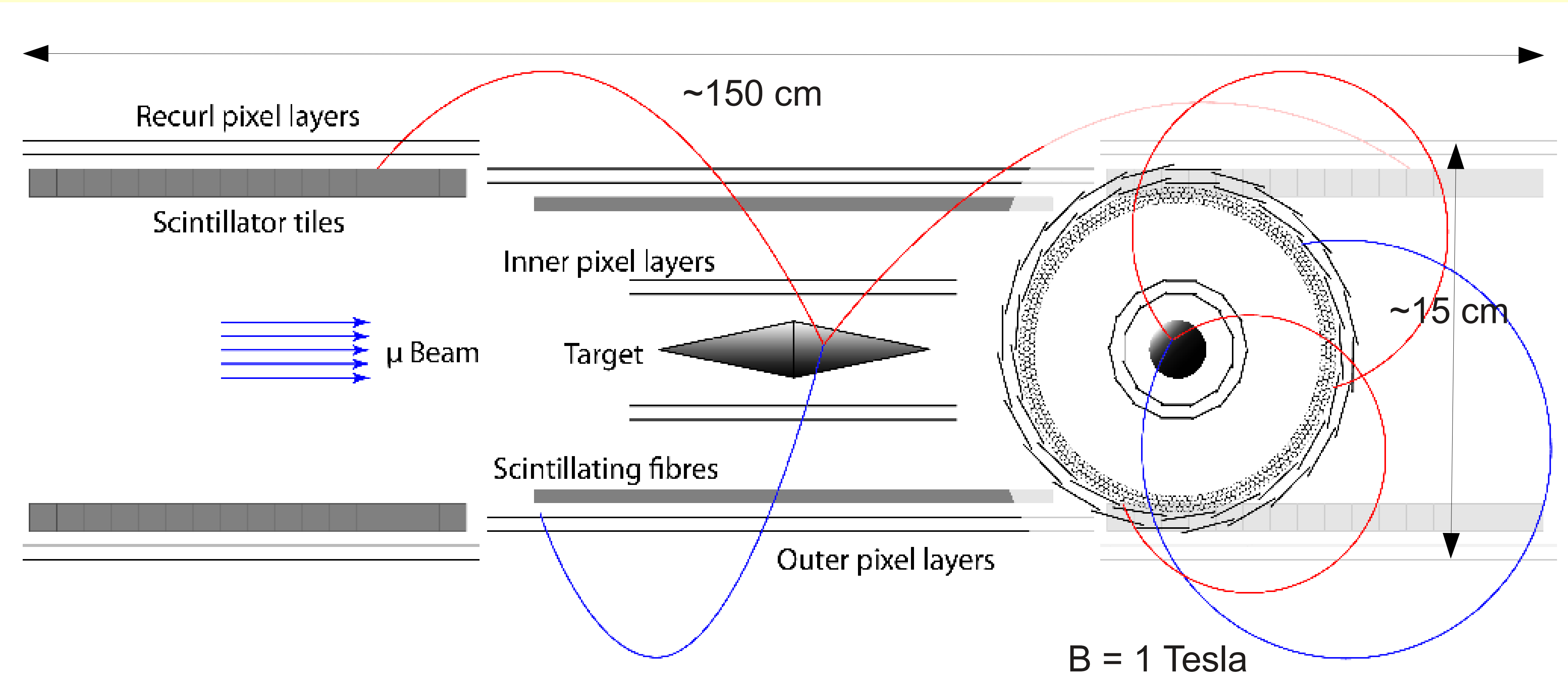


Mu3e Baseline Design

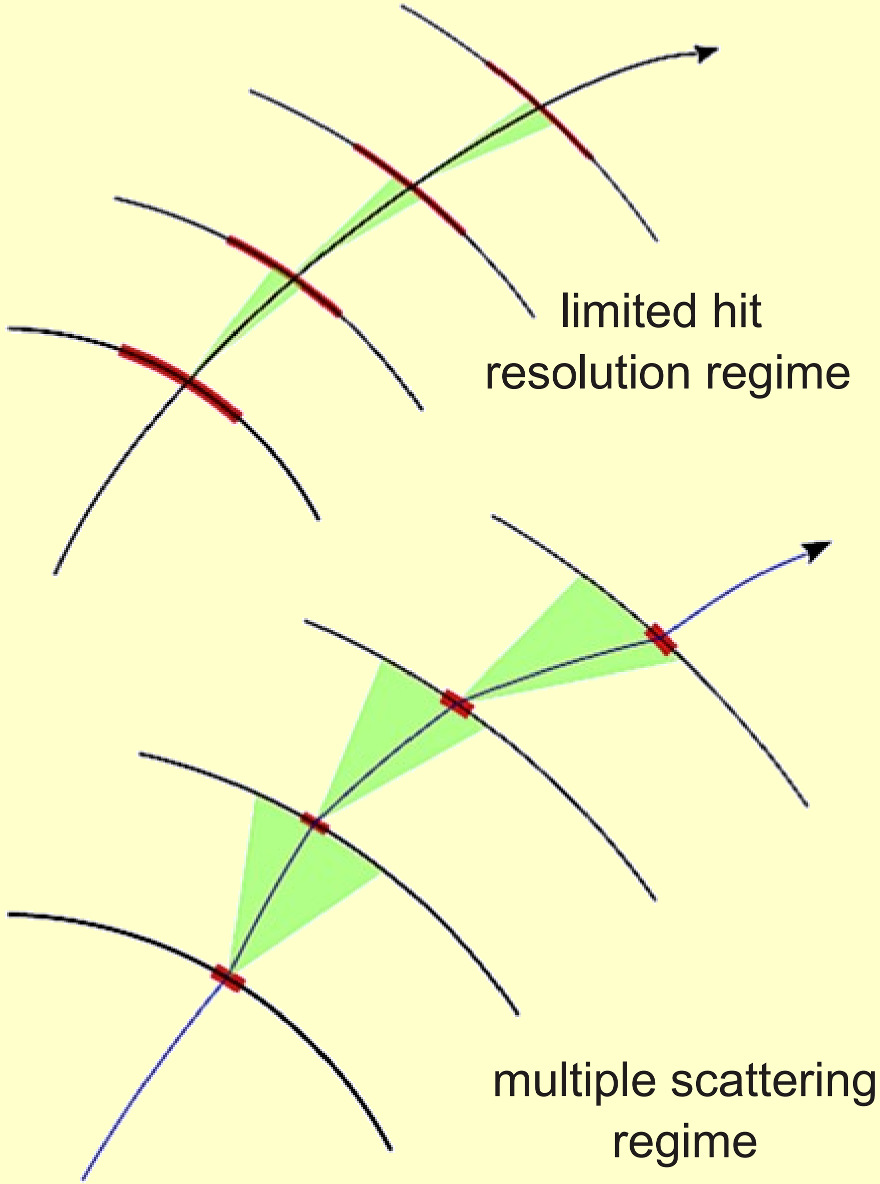
Long cylinder!

not to scale



Geometrical acceptance **~70 % for $\mu^+ \rightarrow e^+e^+e^-$** decay

Challenges for Particle Tracking

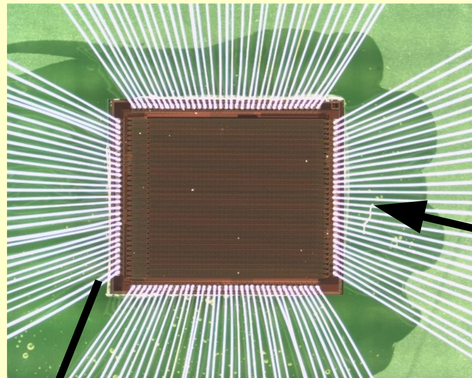


- **Muon decay:**
  → electrons in low momentum range
  $p < 53$ MeV/c
- **Multiple scattering is dominant!**
- **Need thin, fast and high resolution detectors (tracking + time of flight) operated at high rate 10^9 particles/s**

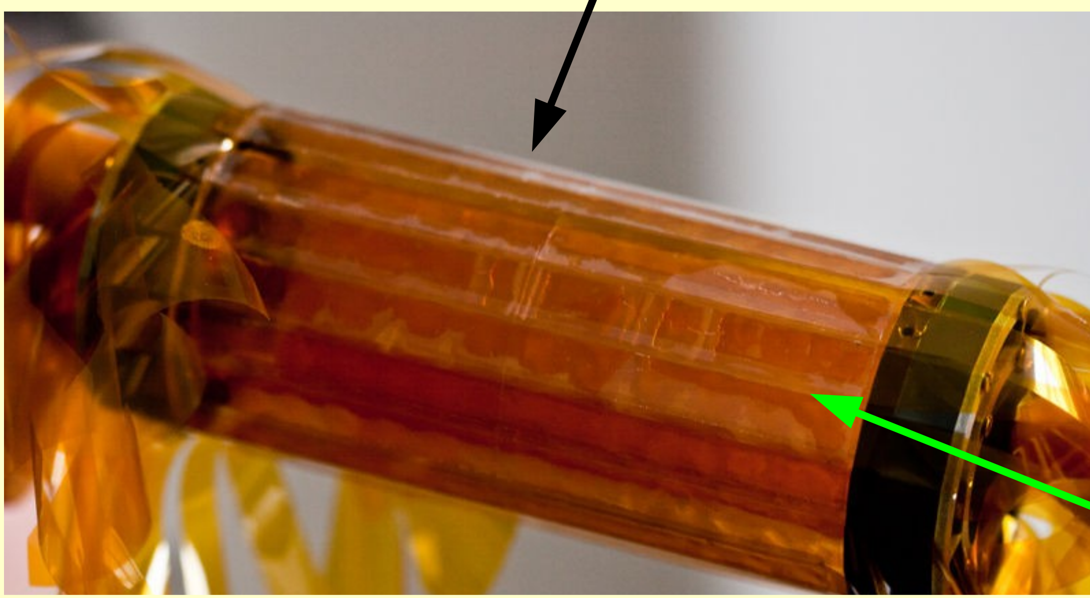
$$\Theta_{MS} \sim \frac{1}{P} \sqrt{X / X_0}$$

Mechanical Prototypes for Pixel Tracker

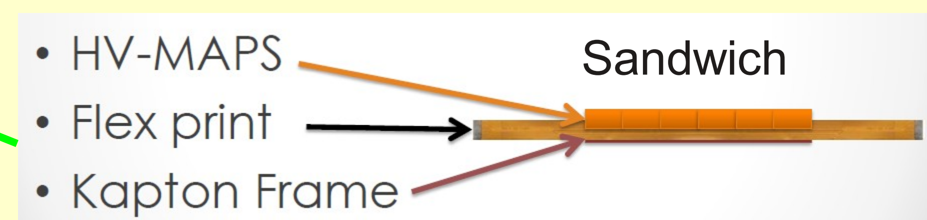
High Voltage
Monolithic Active
Pixel Sensor (HV-MAPS)



50 μm silicon wafer



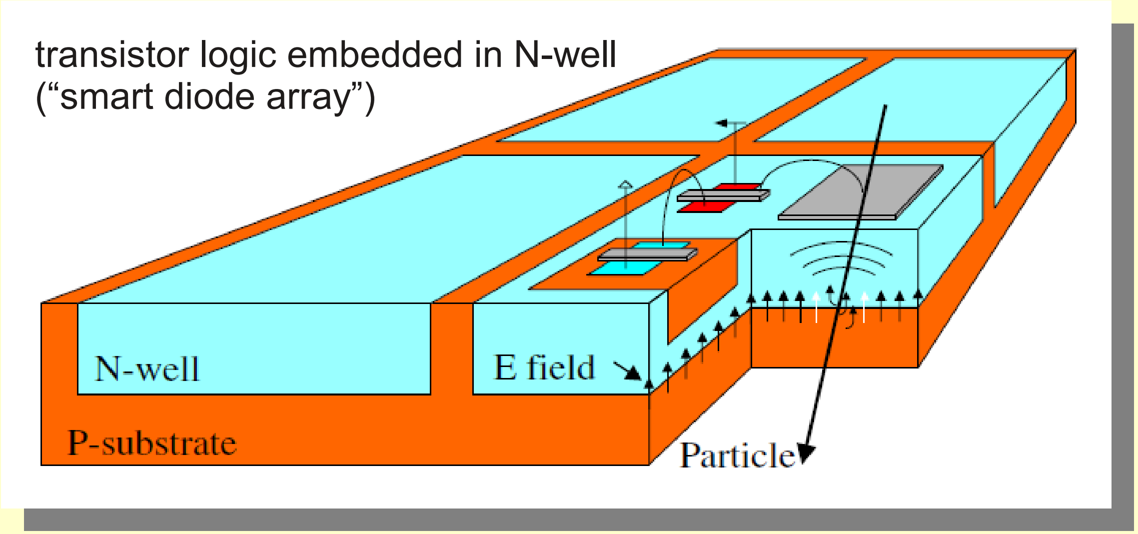
Ultra-thin detector mock-up:
sandwich of 25 μm Kapton®
and 50/100 μm glass (instead of silicon chips)



$X \leq 0.1\%\ X_0$ per layer possible

High Voltage - MAPS Technology

I.Peric, P. Fischer et al., NIM A 582 (2007) 876 (ZITI Mannheim, Uni Heidelberg)

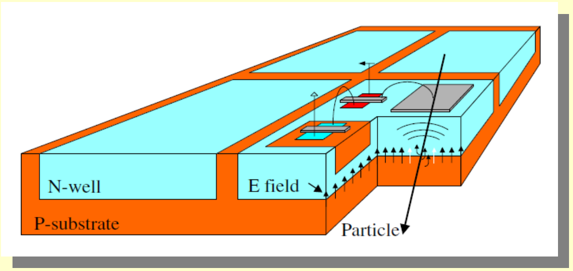


Key Features

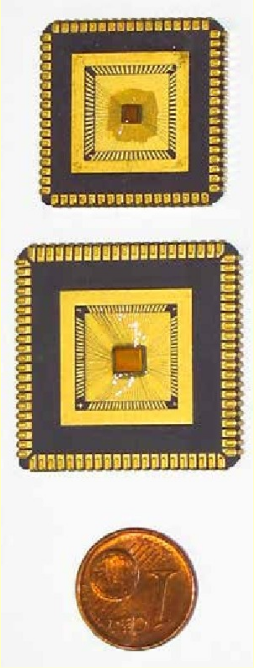
- high precision → pixels 80 x 80 μm^2 (for Mu3e)
- can be "thinned" down to ~**30 μm** (~ 0.0004 X_0)
- low production costs (standard HV-CMOS process, 60-80 V)
- active sensors → small RO bandwidth, no bump bonding required
- triggerless and fast readout (LVDS link integrated)
- low power: ~150 mW/cm^2

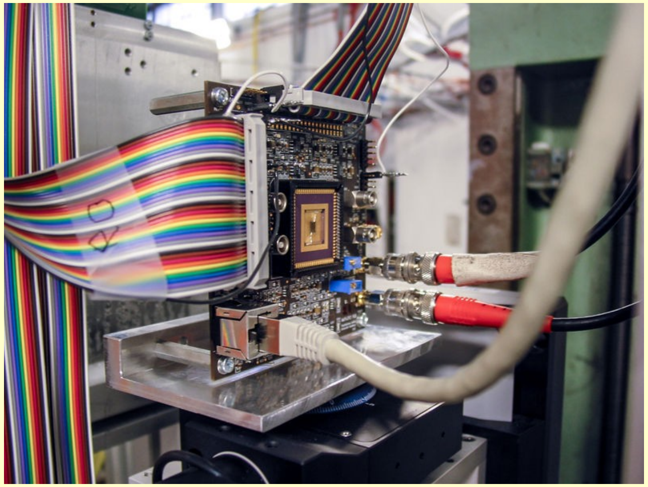
→ talk by **Ivan Peric** (PSI2013/CHIPP session)

HV-MAPS R&D Test Measurements

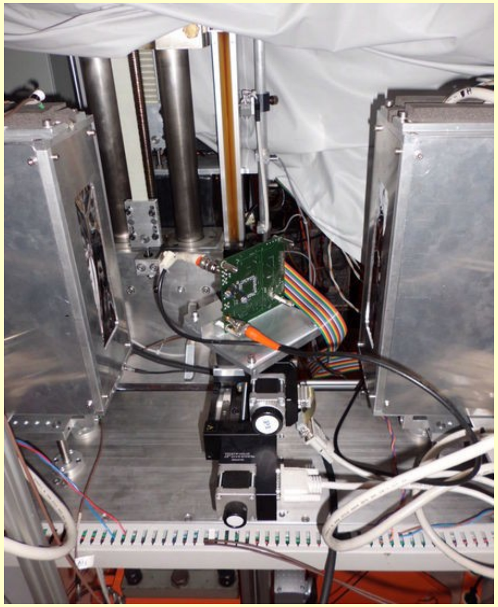


prototype sensors

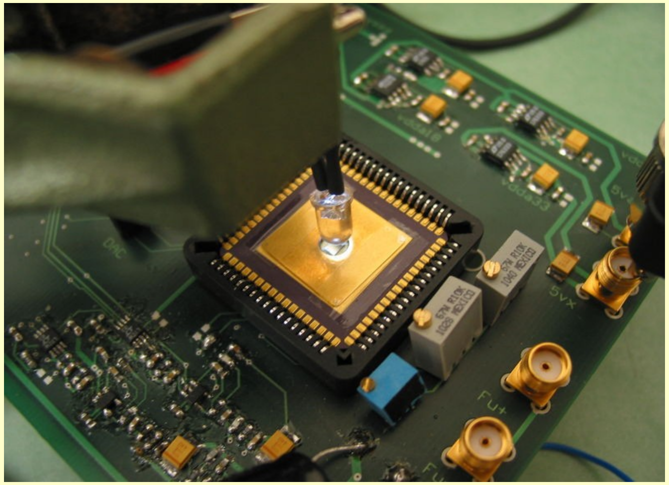




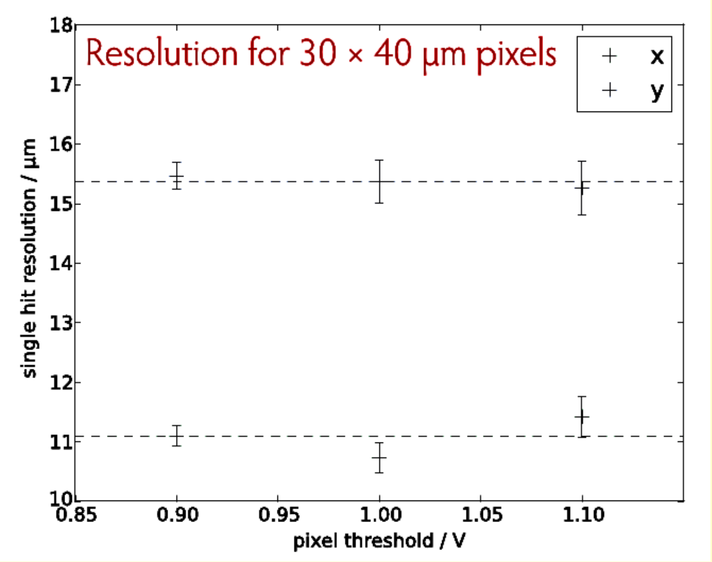
DESY test beam



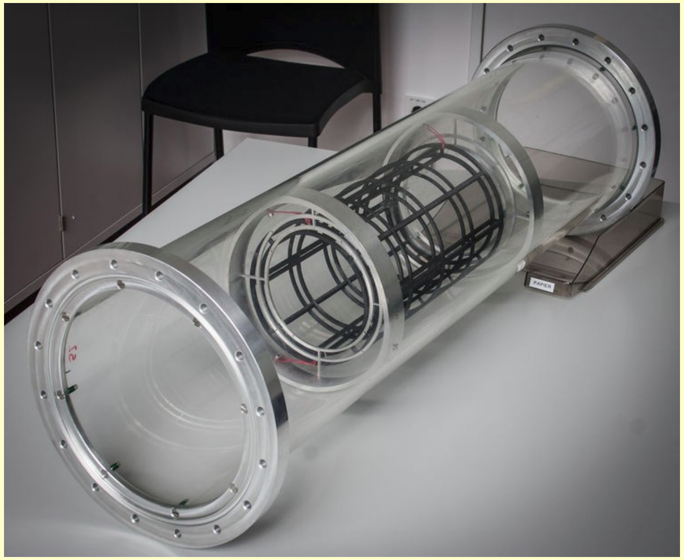
CERN test beam



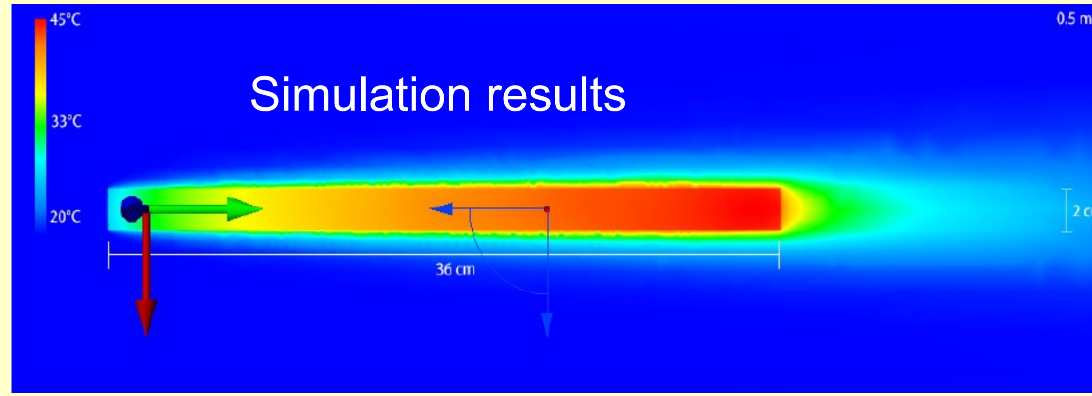
LED test in lab



Tracker Cooling with Gaseous Helium

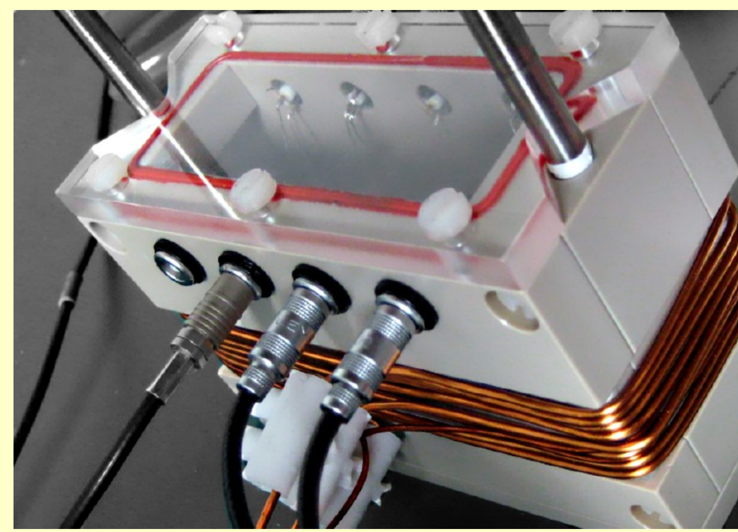


Cooling flow reactor for tests



Flow box with integrated inductive heating

metallized Kapton

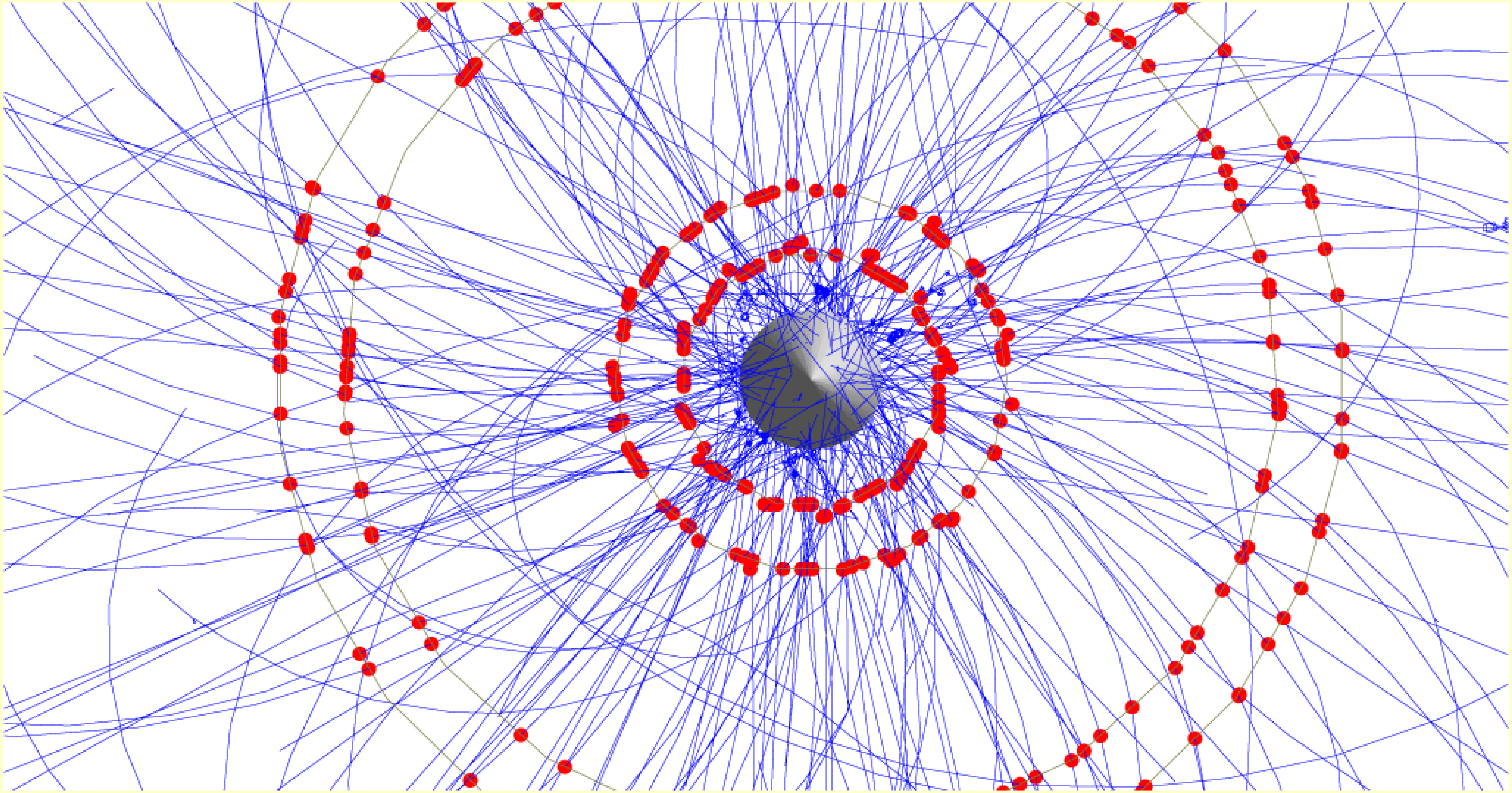


$V_{helium} \sim$ **0.1 – 1 m/s**

Timing

Pixel Detector: Readout Frames @ 20 MHz

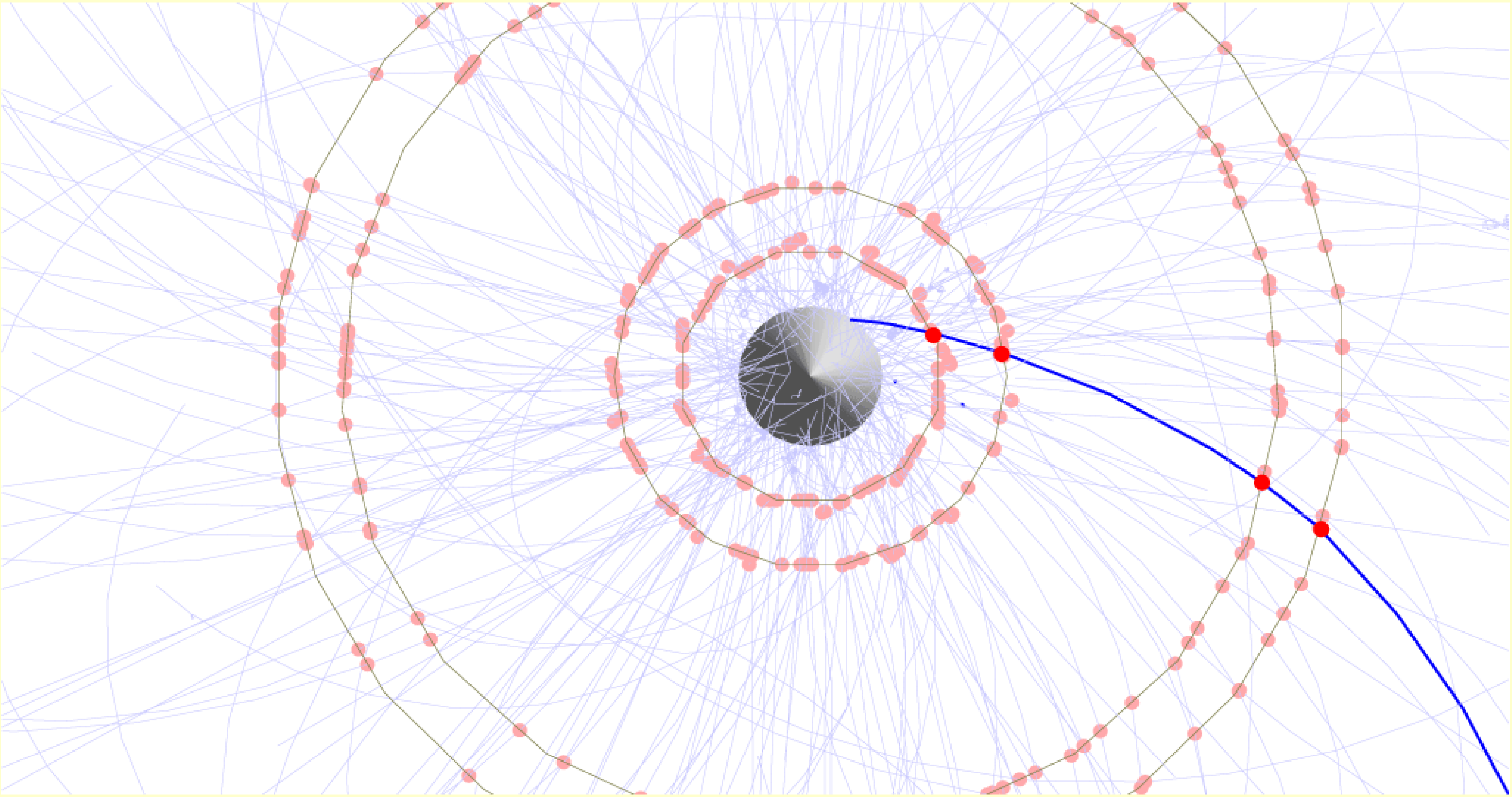
100 muon decays @ rate $2 \cdot 10^{9}$ muon stops/s



50 ns snapshot

Pixel: Readout Frames 50 ns

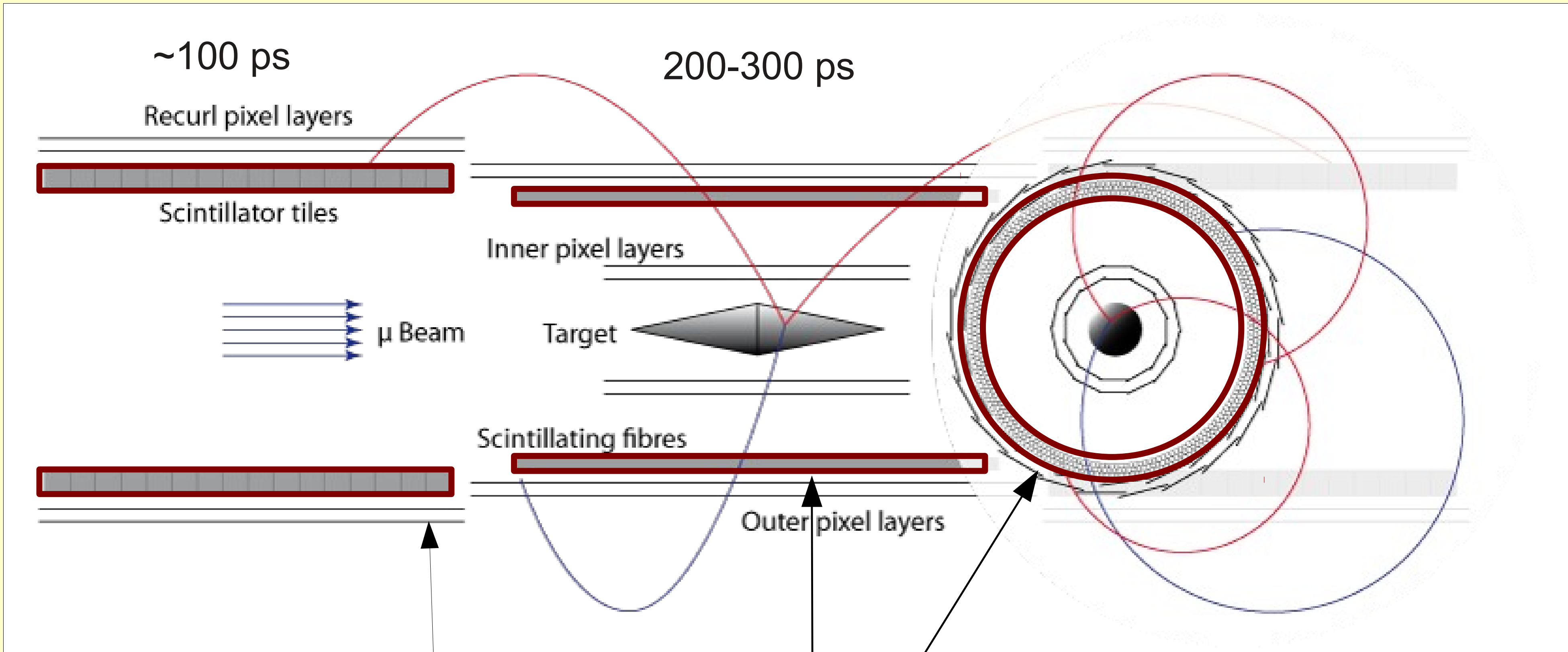
100 muon decays @ rate $2 \cdot 10^9$ muon stops/s



- **Additional Time of Flight (ToF) detectors required < 1ns**

Mu3e Time of Flight System

not to scale

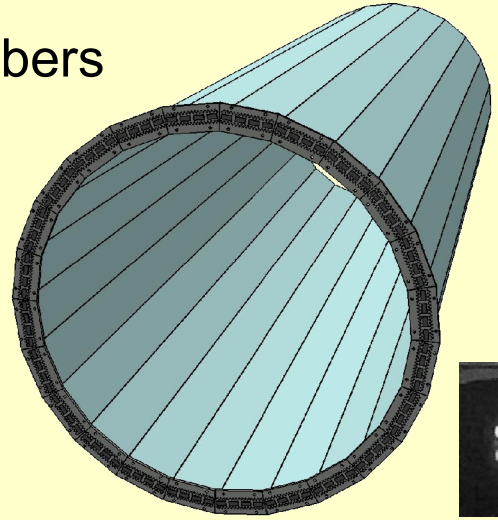


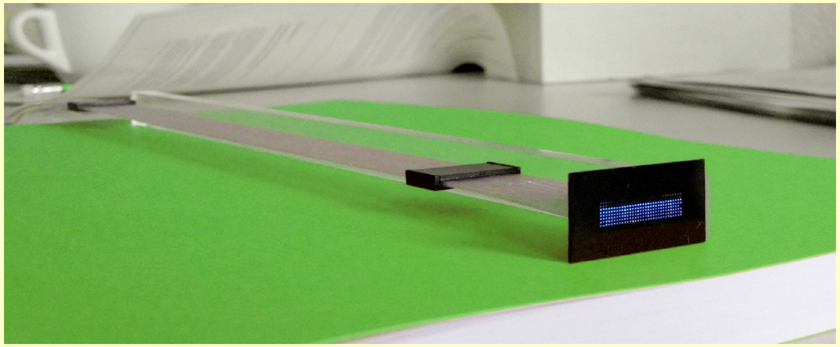
Scintillating tiles

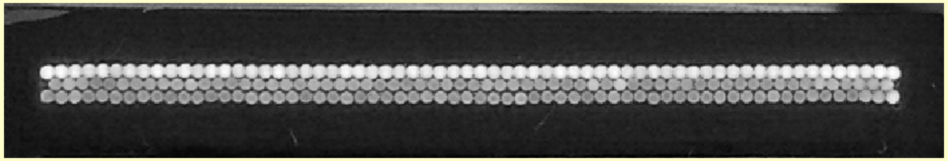
Scintillating fibers

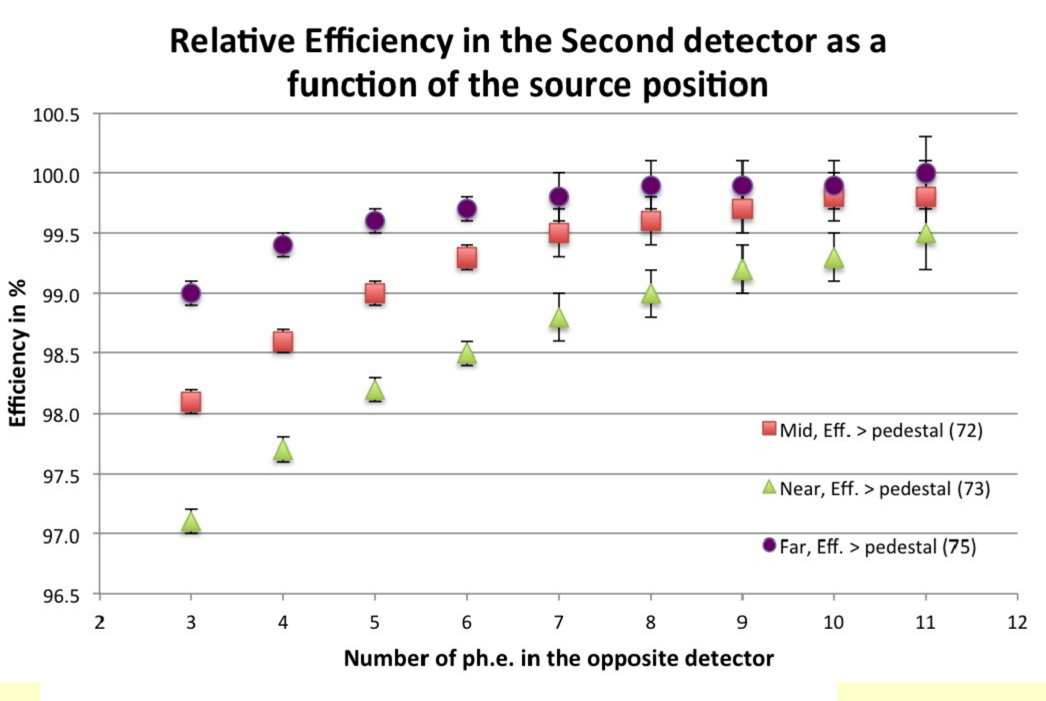
R&D for Scintillating Fiber Tracker

- 3 layers of scintillating fibers
  Ø = 250 µm (Kuraray)
- readout by SiPMs and
  custom ASICs
- time resolution <1 ns

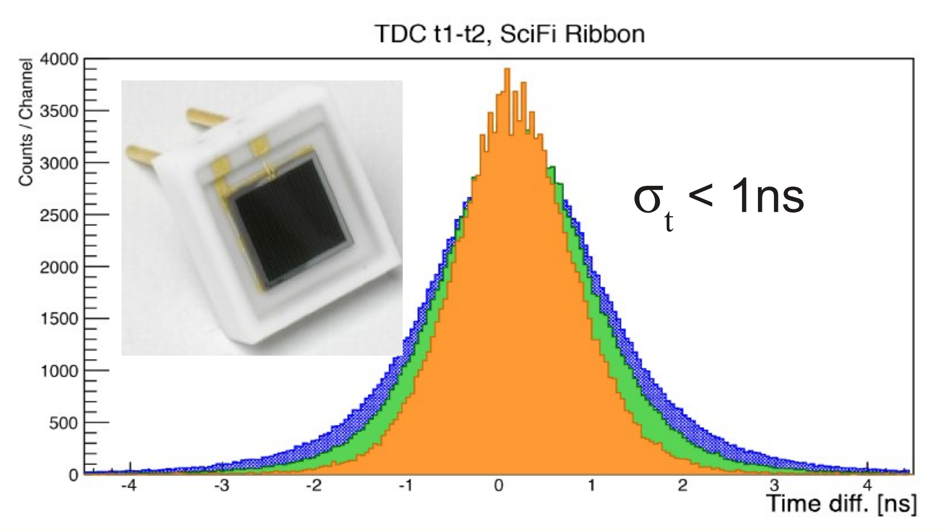




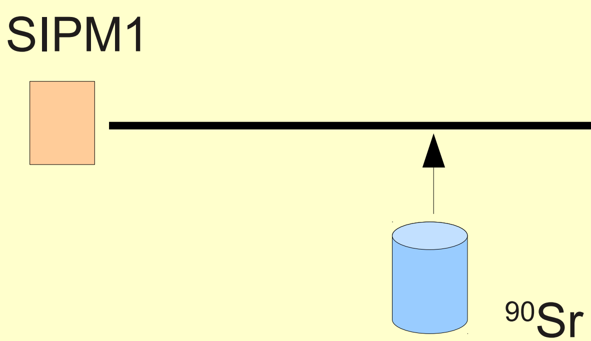


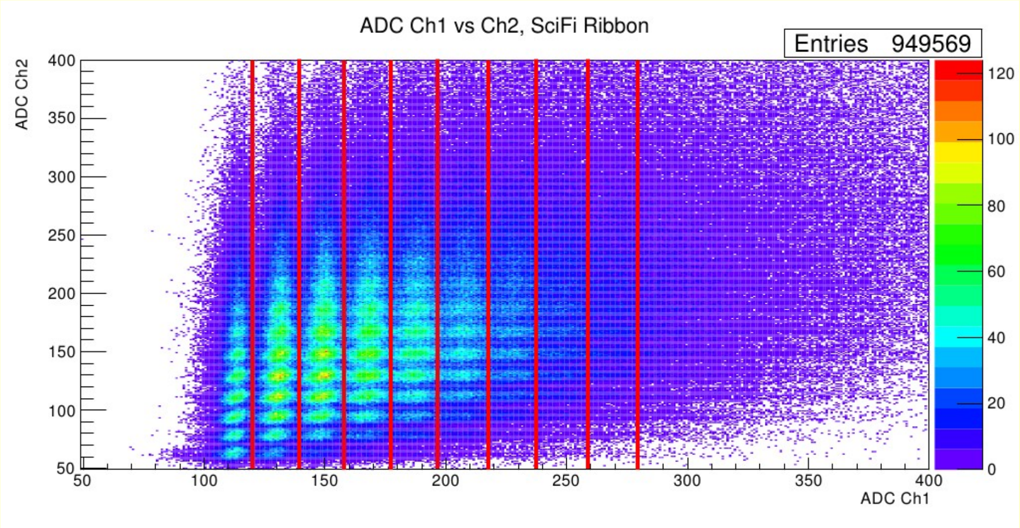


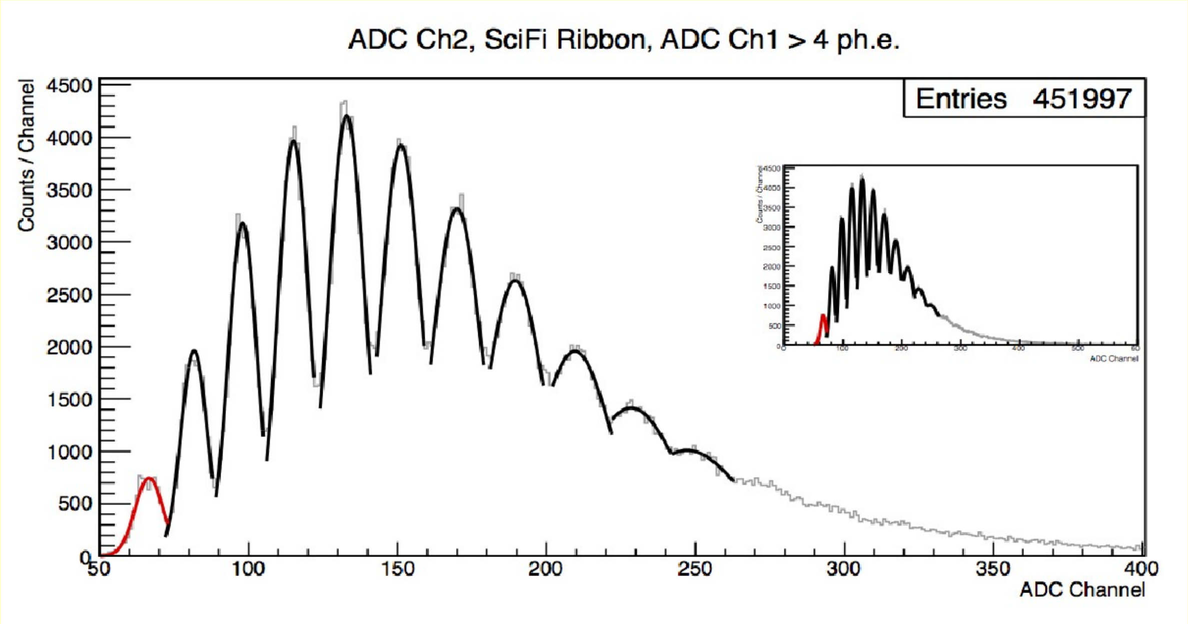
[90]Sr source, SiPMs, S10362-33-050C by Hamatsu,



Scintillating Fiber Performance



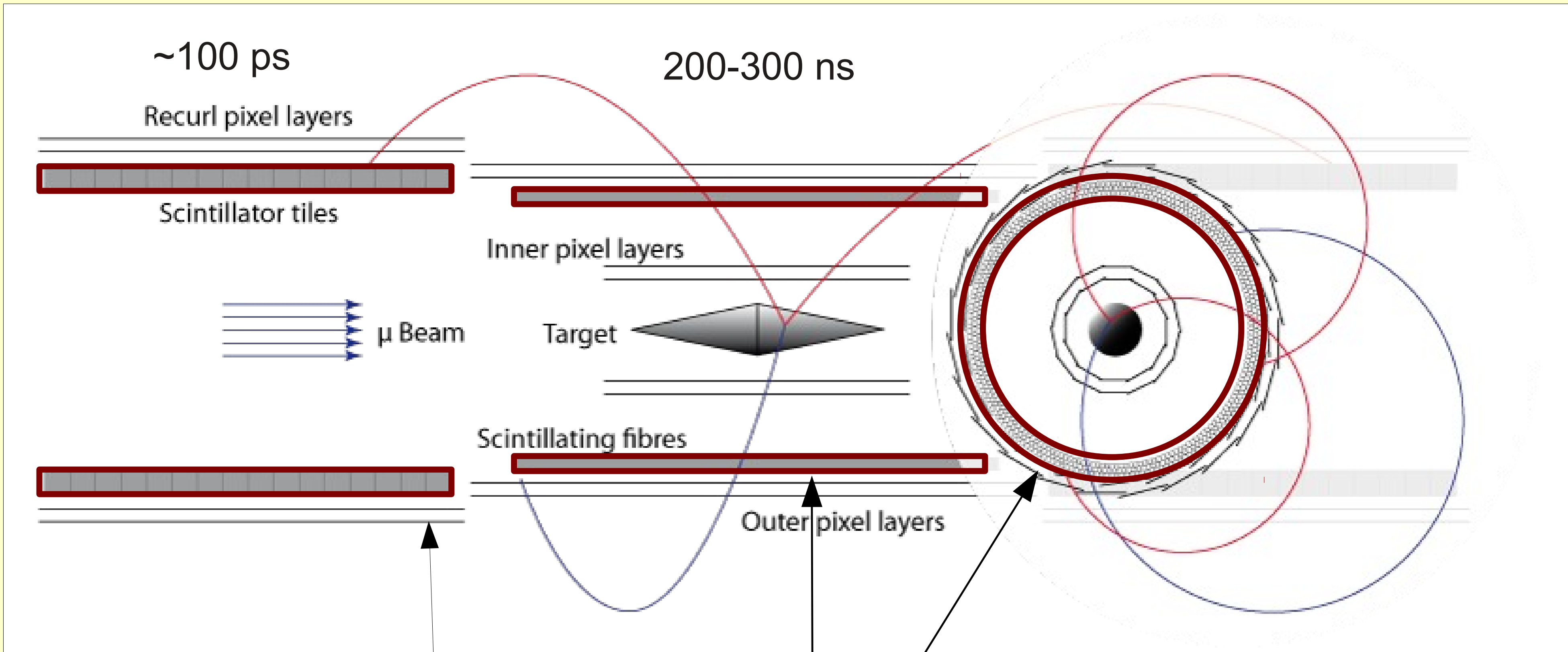




clear photoelectron peaks!

Mu3e Time of Flight System

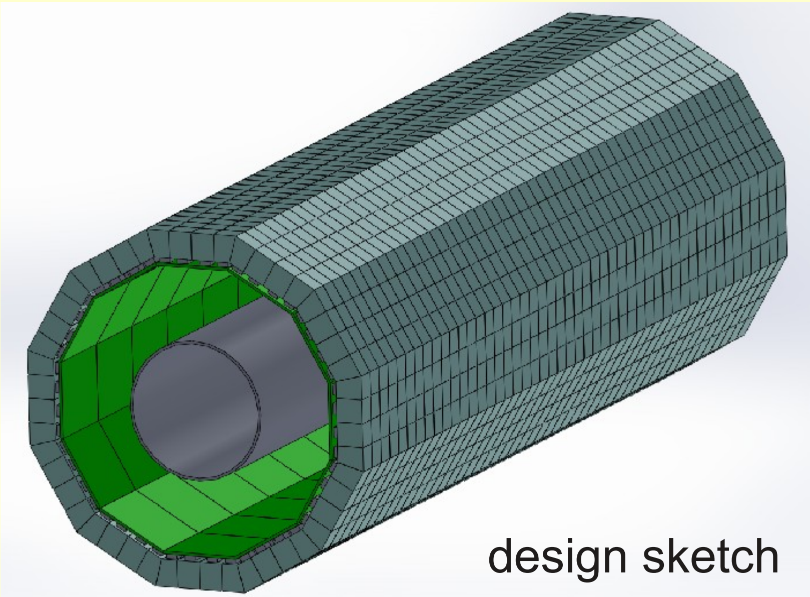
not to scale



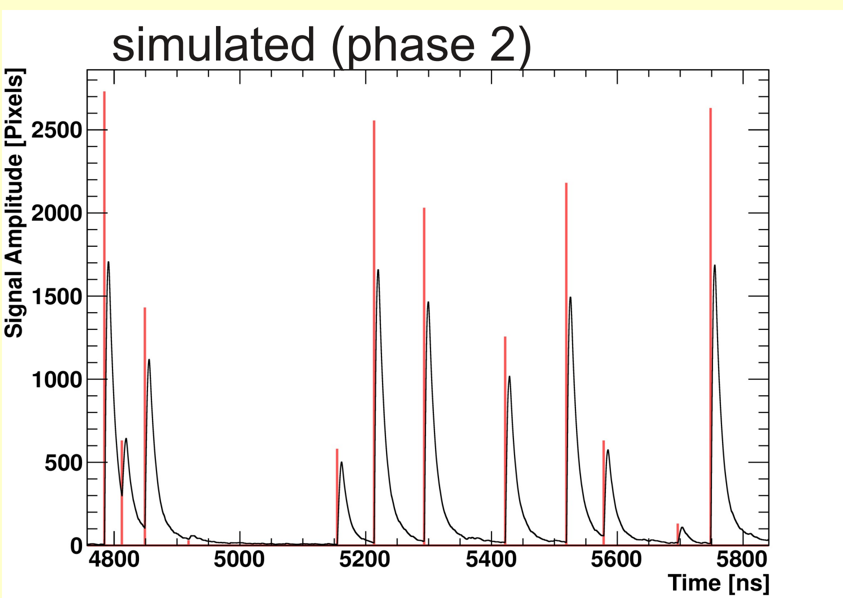
Scintillating tiles

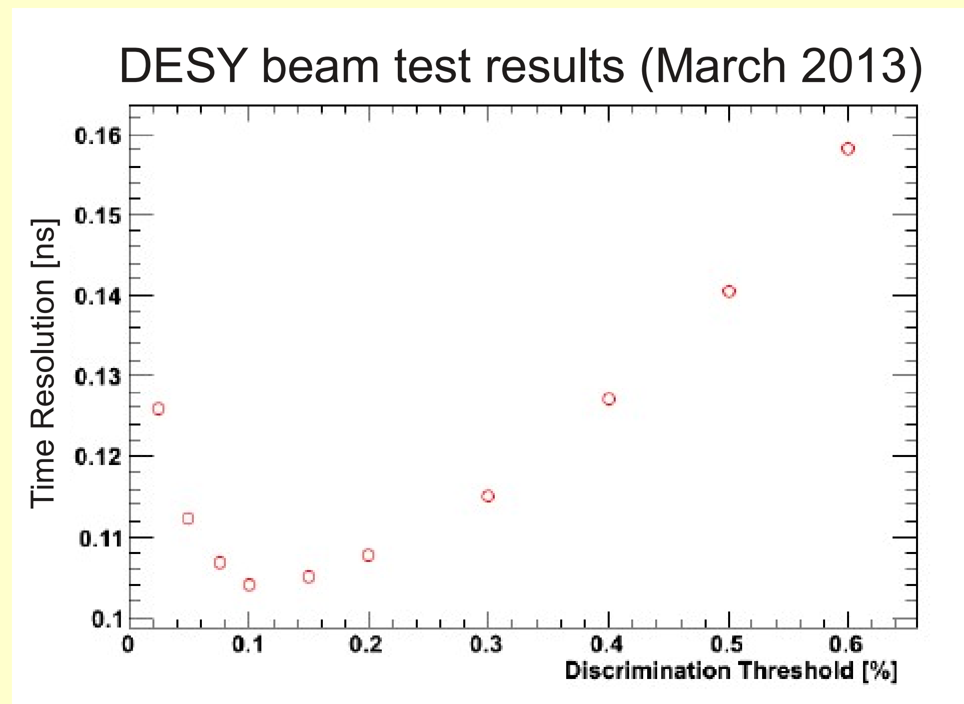
Scintillating fibers

R&D for Scintillating Tile Detector



- scintillating tiles of size ~ 1 cm^2
- timing resolution of about 100 ps
- photosensors (SiPM) readout by custom ASICs



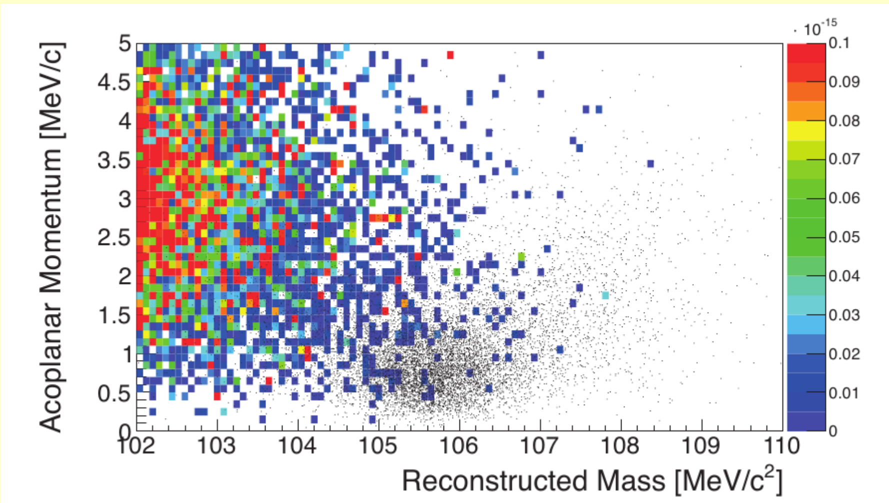


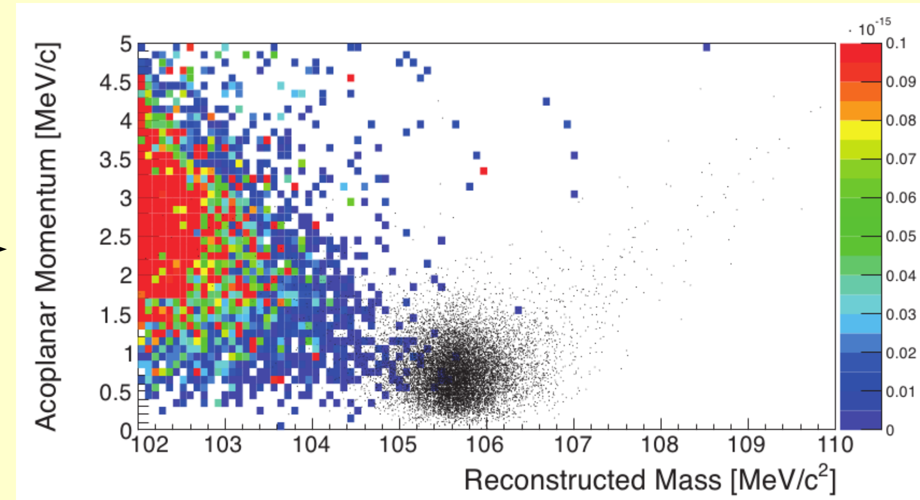
Sensitivity Study

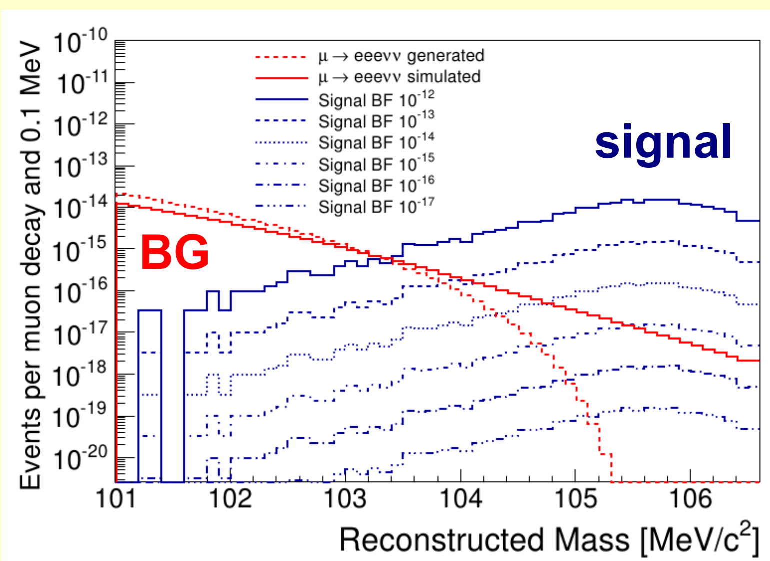
→ Research Proposal arXiv:1301.6113

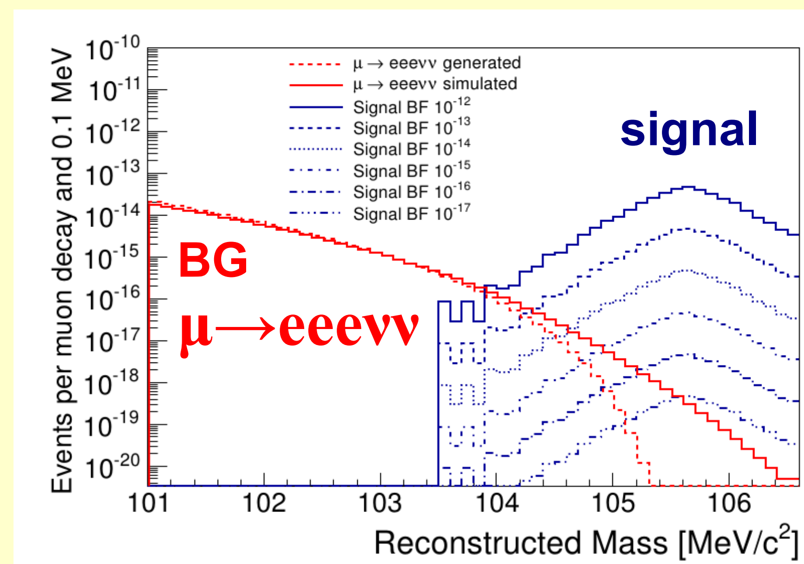
Phase IA: rate ≤ $2 \cdot 10^7$ muons/s

Phase II: rate ~ $2 \cdot 10^9$ muons/s

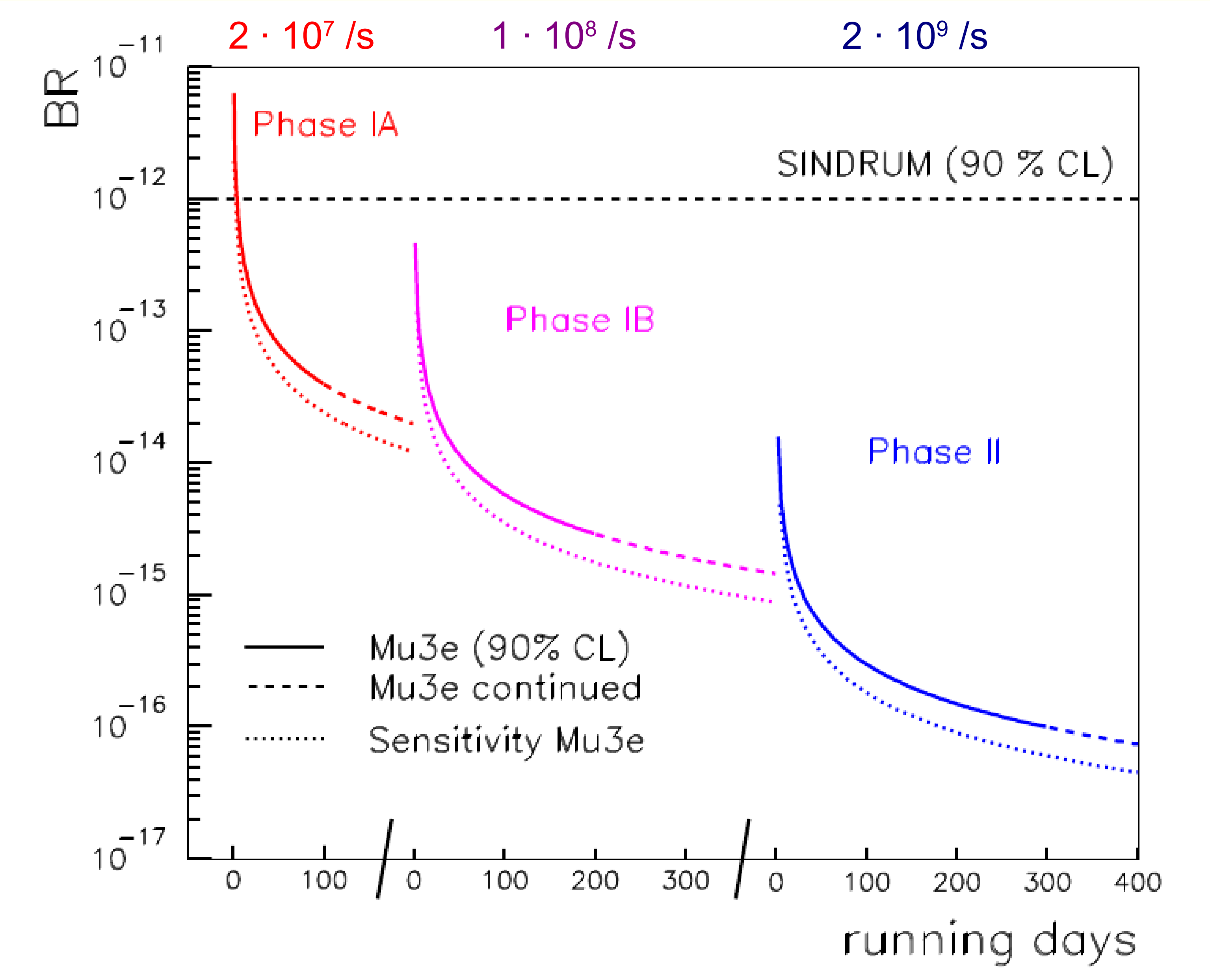








Sensitivity Projection



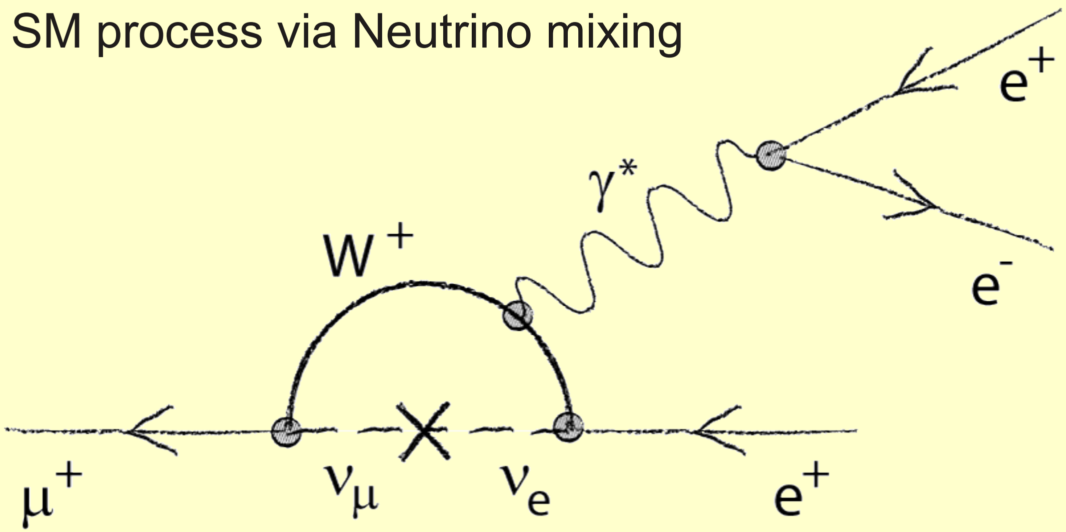
Conclusions

- **Charged LFV almost "unavoidable" in many BSM models**
- **Search for $\mu \to eee$ at the 10^{-16} level is complementary to other searches and well motivated**
- **The new HV-MAPS technology is a promising alternative for gaseous tracking detectors at low energy and high rate**
- **Successful R&D program:**
  - first large scale HV-MAPS detector next year
  - Timing at the **100 ps – 1 ns** level with scintillating tiles and fibers using SiPM readout
- **Start data taking 2015/16 (Phase 1A)**
- **Hopefully 2 billion muons per second at HIMB after 2017 (Phase2)**

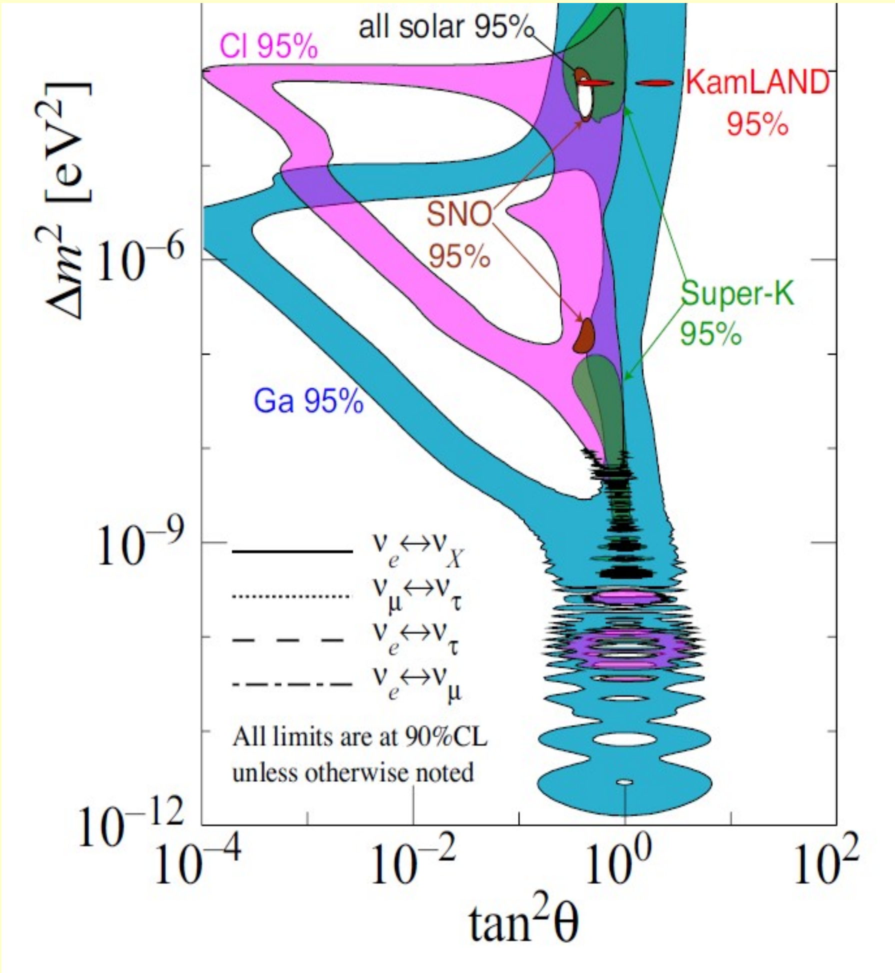
Backup

LFV in the Standard Model

SM process via Neutrino mixing



Neutrino Oscillation Summary Plot (part)



process is heavily suppressed due to small mass difference of neutrinos!

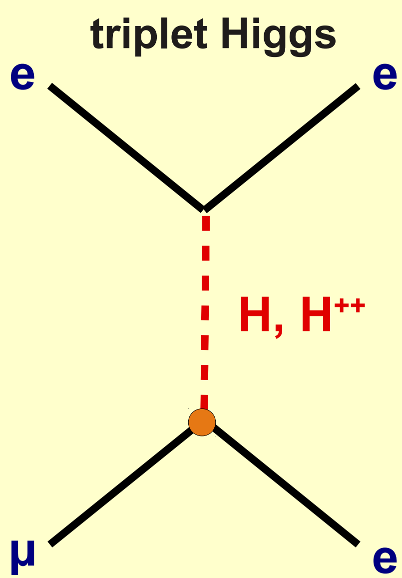
$$\propto \left(\frac{\Delta m_\nu^2}{M_W^2} \right)^2$$

B($\mu^+ \rightarrow e^+ e^+ e^-$) ~ O(10^{-56})

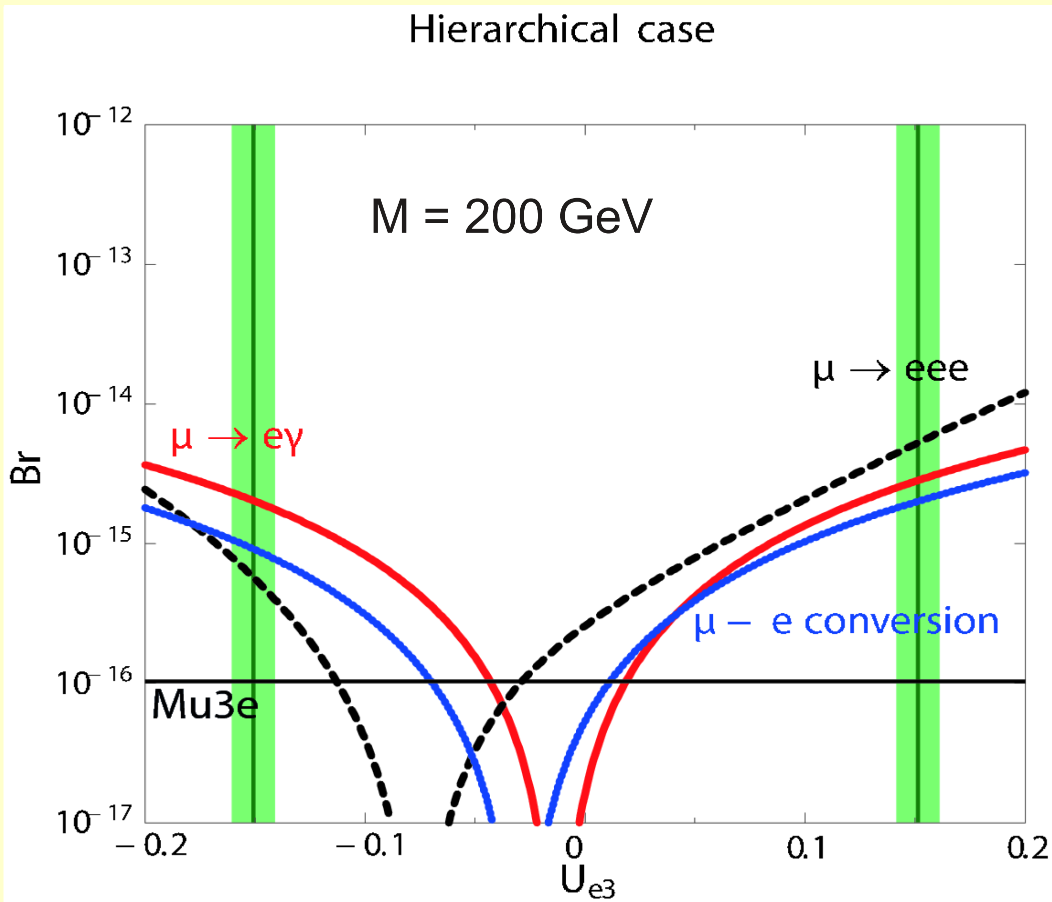
Example: Higgs Triplet Models

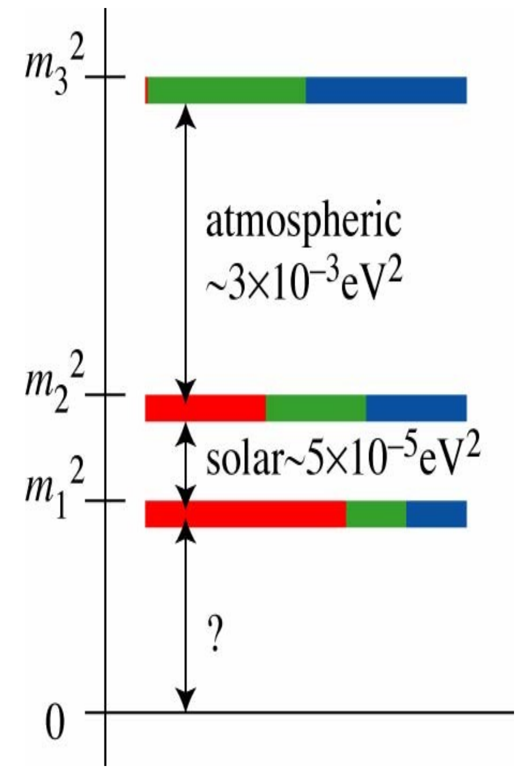
M.Kakizaki et al., Phys.Lett. **B566** 210, 2003

- Motivated by Left-Right Symmetric Models



+ loop diagrams



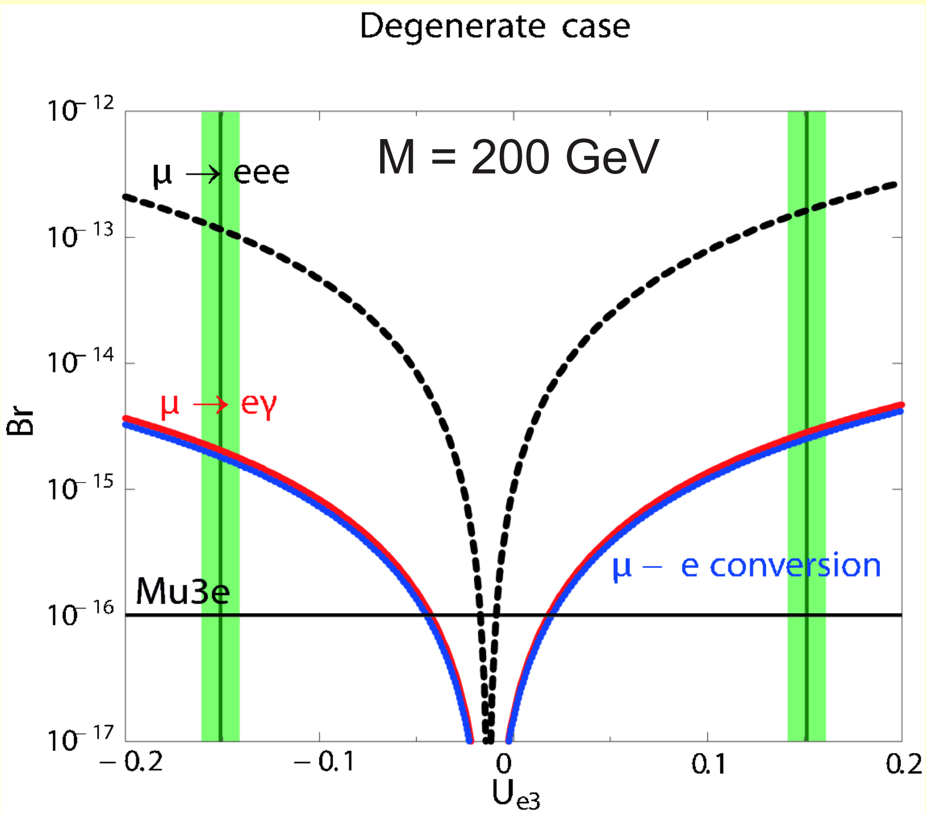


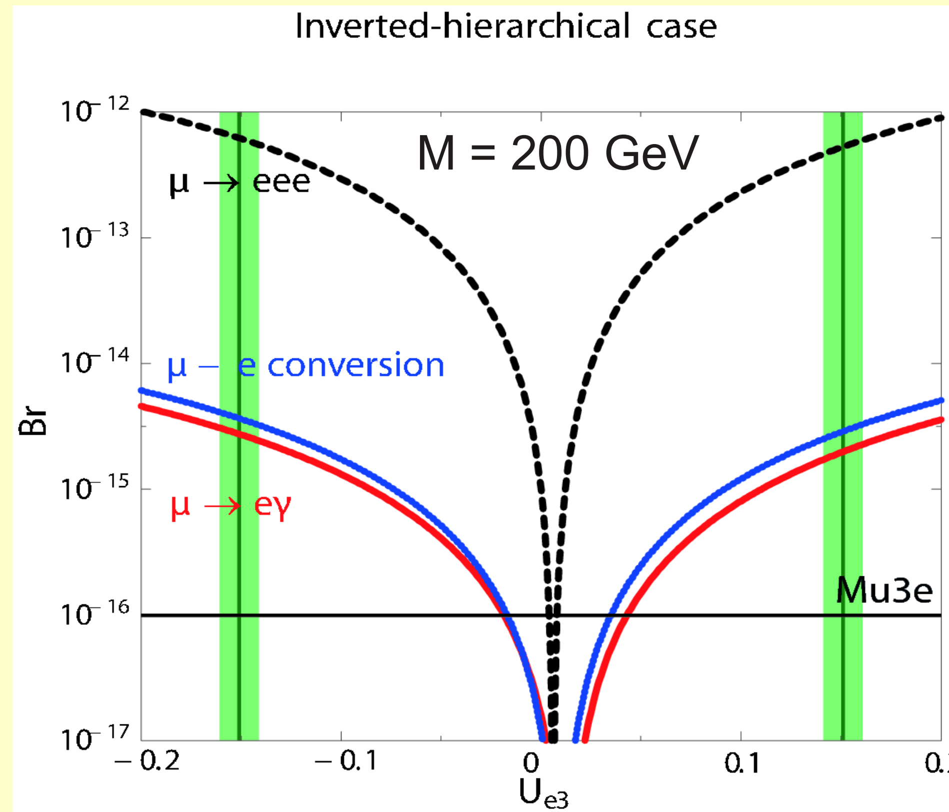
related to neutrino masses (→ mass pattern)

Example: Higgs Triplet Models II

M.Kakizaki et al., Phys.Lett. **B566** 210, 2003

- Motivated by Left-Right Symmetric Models





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

A= trilinear coupling (25 eV)

LFV SM - Higgs Couplings

Framework

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

LFV decays of SM Higgs:

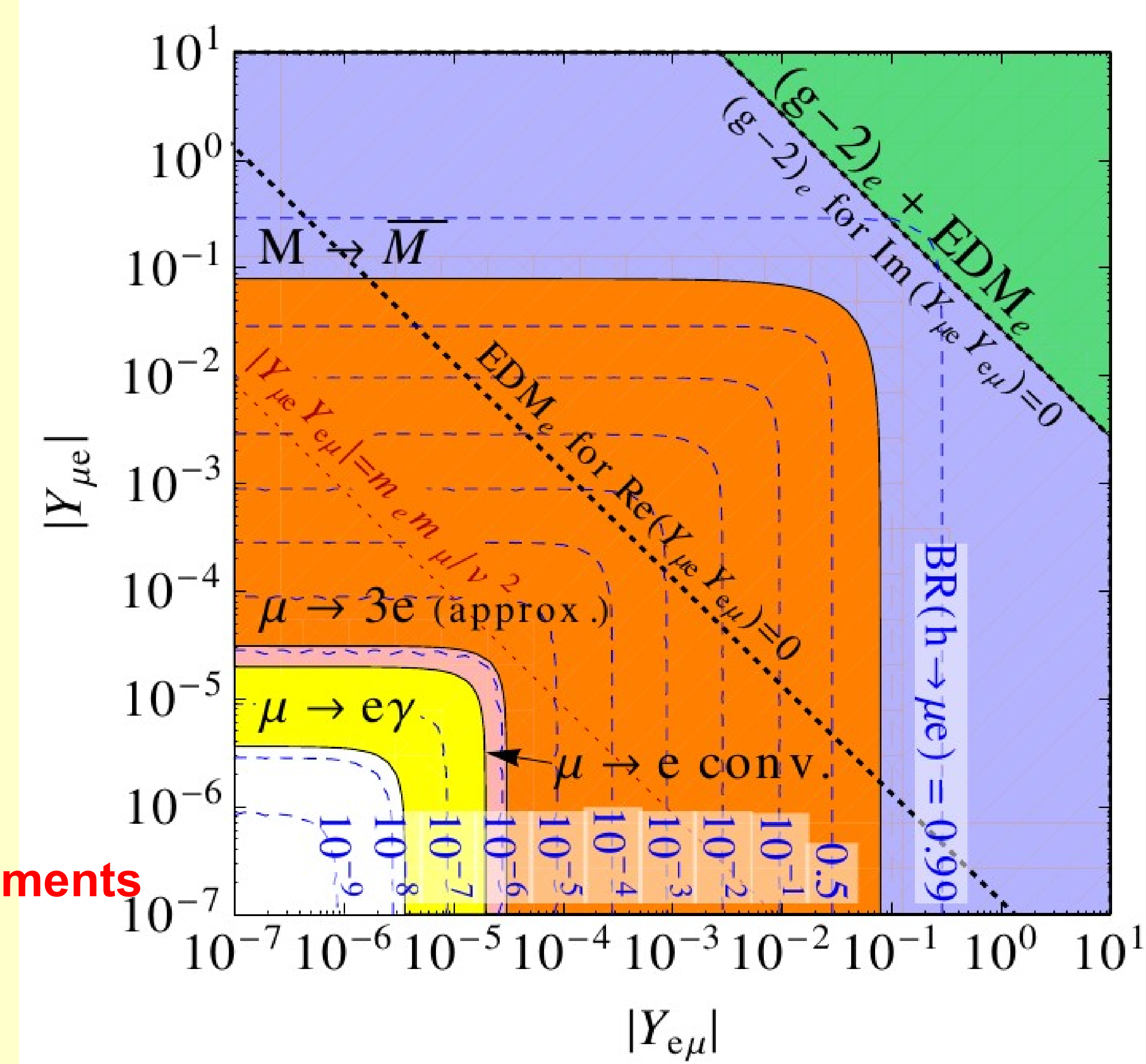
$$\mathrm{BR}(h \to \ell^\alpha \ell^\beta) = \frac{\Gamma(h \to \ell^\alpha \ell^\beta)}{\Gamma(h \to \ell^\alpha \ell^\beta) + \Gamma_{\mathrm{SM}}}$$

LFV muon decay:

$$\sim \sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2}$$

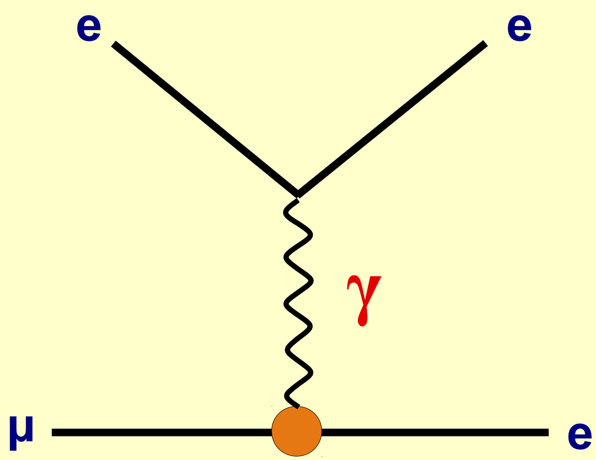
LHC and muon decay experiments are largely complementary!

R. Harnik, J. Kopp J, Zupan [arXiv:1206.6497]

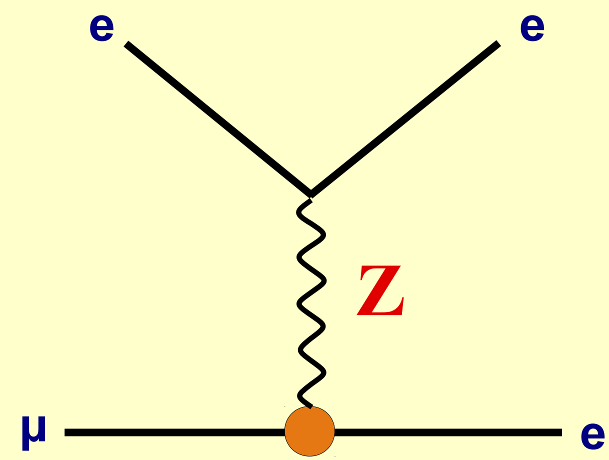


$\mu^+ \rightarrow e^+e^+e^-$ Penguin Loop and Box Diagrams

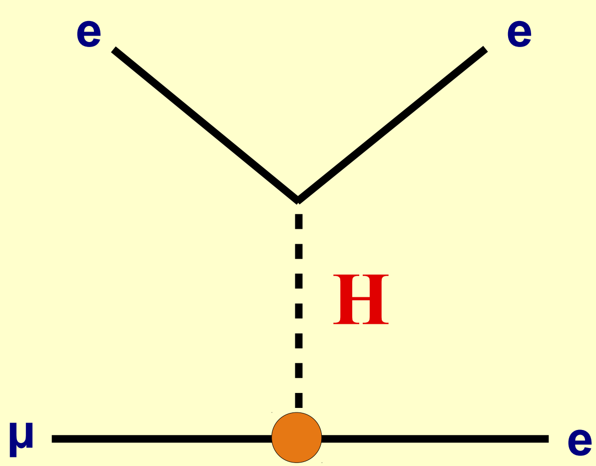
$\mu^+ \rightarrow e^+e^+e^-$



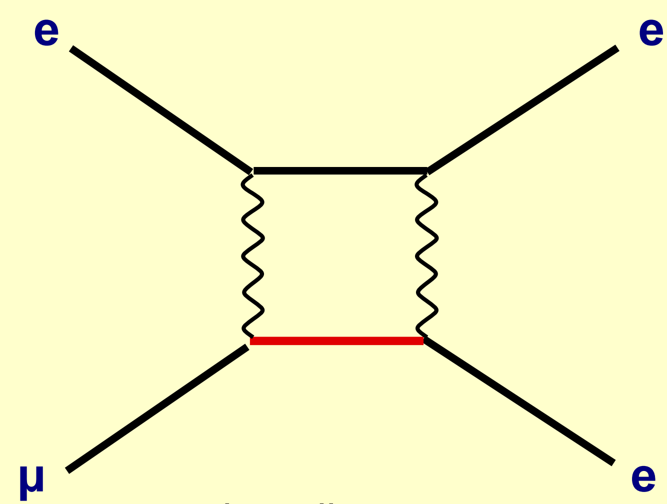
photon penguin



Z - penguin



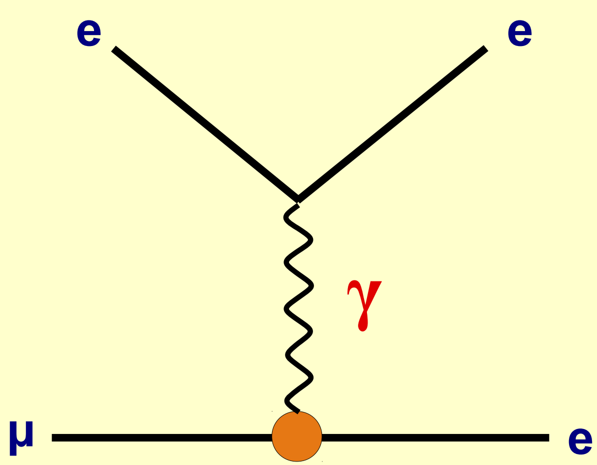
Higgs-penguin



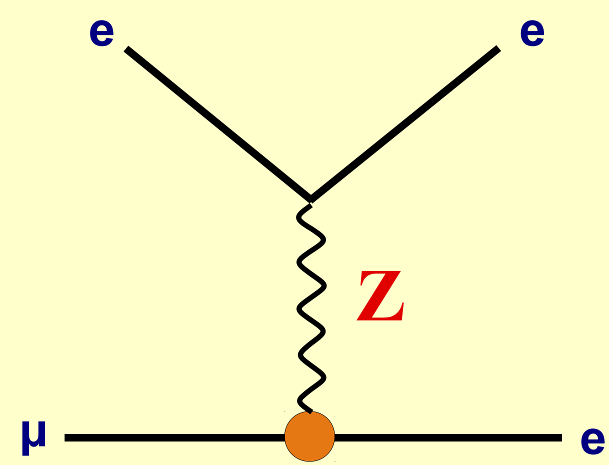
box diagram

The Z-Penguin Diagram in $\mu^+ \rightarrow e^+e^+e^-$

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



photon penguin



Z - penguin

from dimensional analysis:

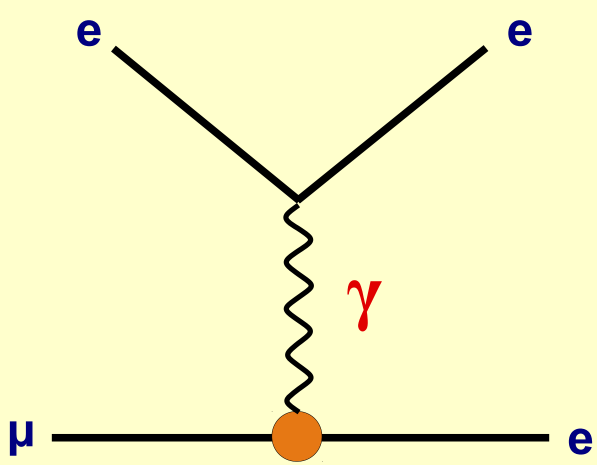
$$Br \propto \frac{m_\mu^5}{\Lambda^4}$$

$$Br \propto \frac{m_\mu^5}{m_Z^4} f\left(\Lambda^4\right)$$

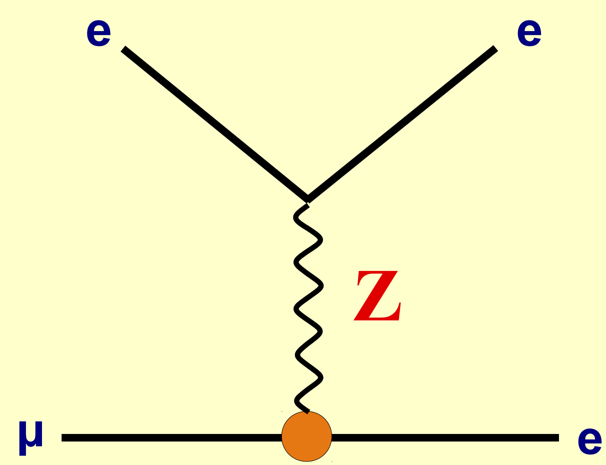
can dominate if $\Lambda >> m_Z$

The Z-Penguin Diagram in $\mu^+ \rightarrow e^+e^+e^-$

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



photon penguin



Z - penguin

from dimensional analysis:

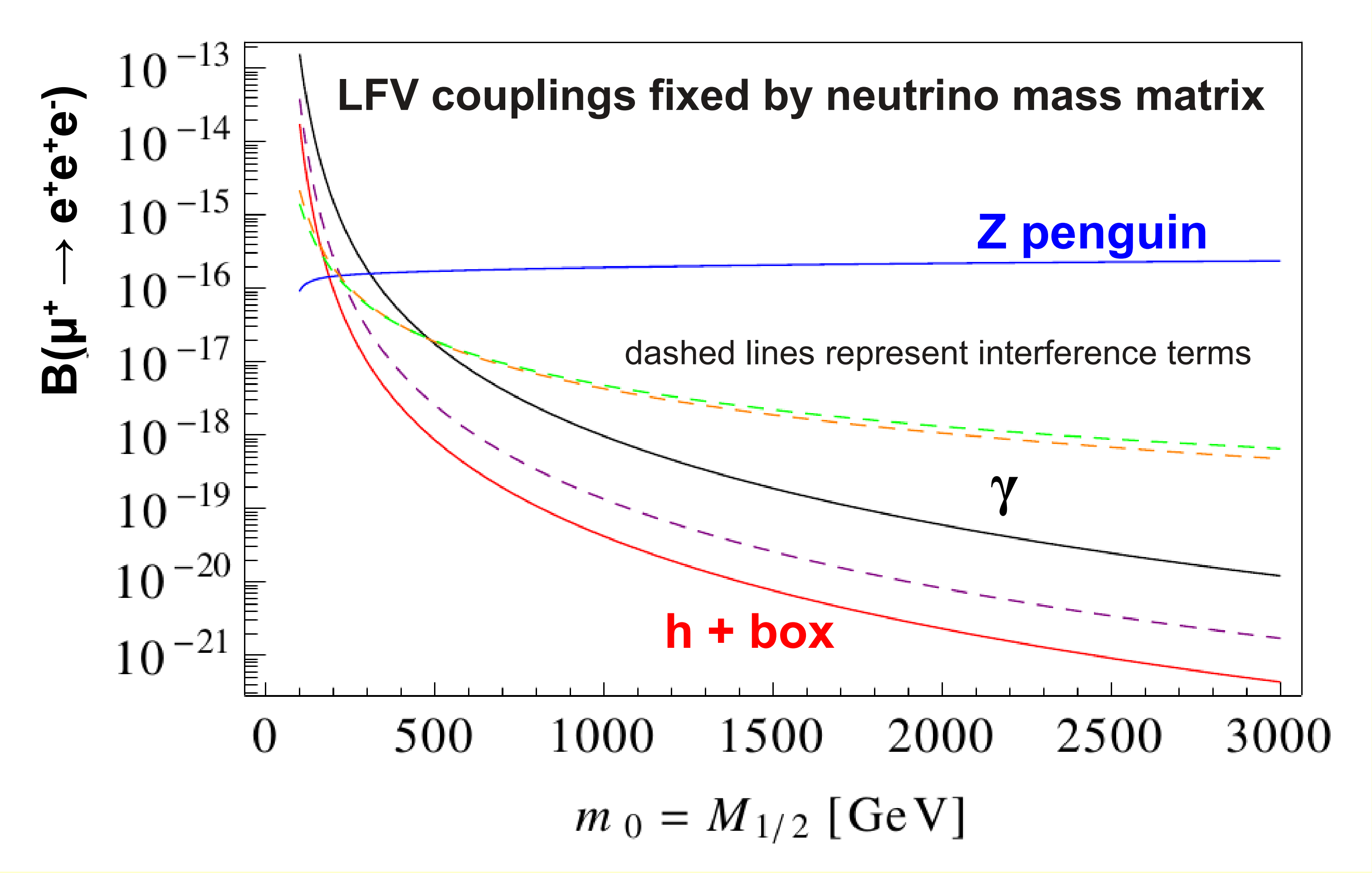
$$Br \propto \frac{m_\mu^5}{\Lambda^4}$$

$$Br \propto \frac{m_\mu^5}{m_Z^4} f\left(\Lambda^4\right)$$

no decoupling in many models!

<u>Abada et al.</u>, *Enhancing lepton flavour violation in the supersymmetric inverse seesaw beyond the dipole contribution* [arXiv:1206.6497]

Inverse Seesaw Model

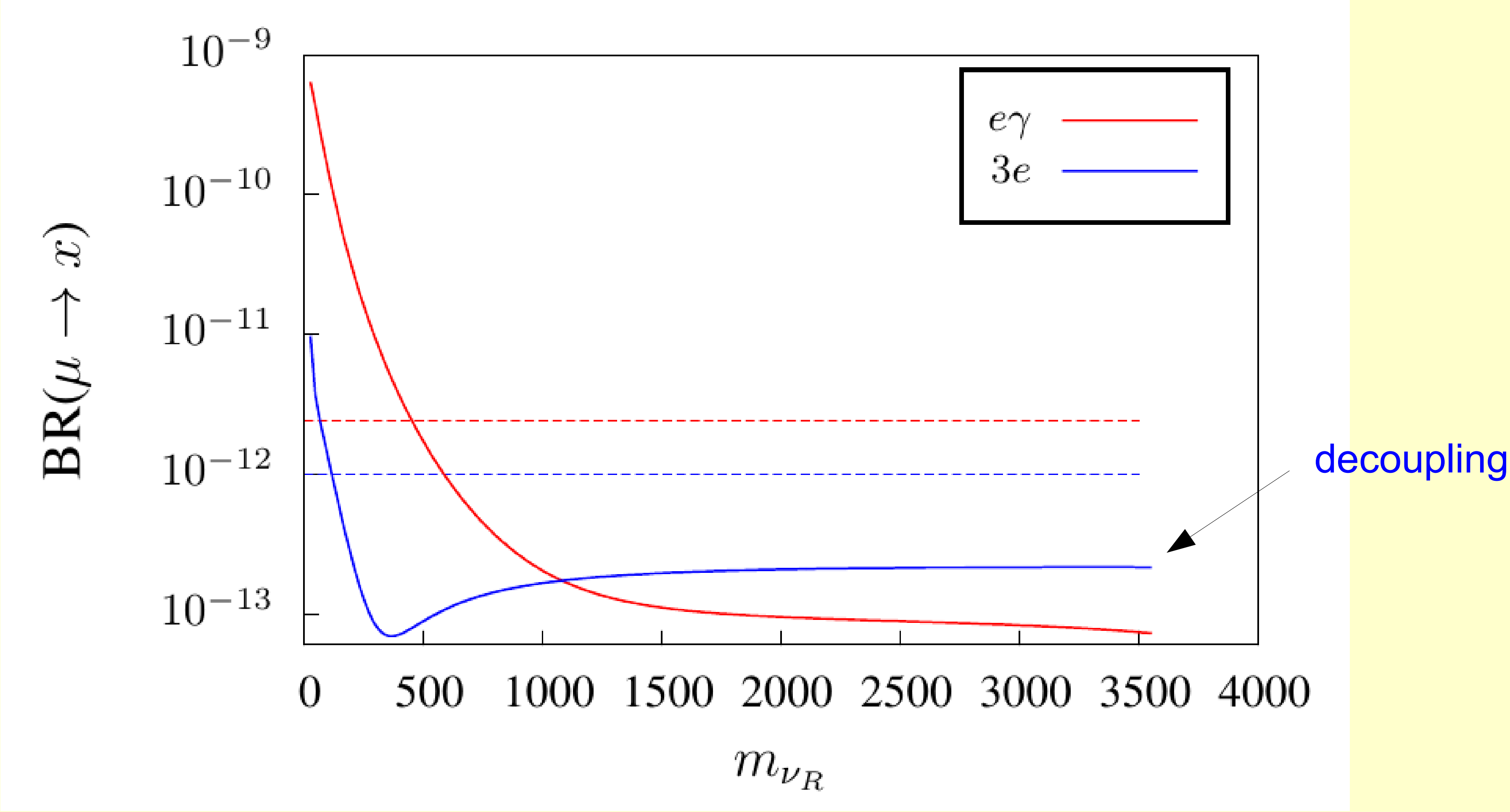


Non-decoupling behaviour of Z-penguin contribution

Note $\mu^+ \rightarrow e^+e^+e^-$ dominates over $\mu^+ \rightarrow e^+ \gamma$ for m_0> 1 TeV

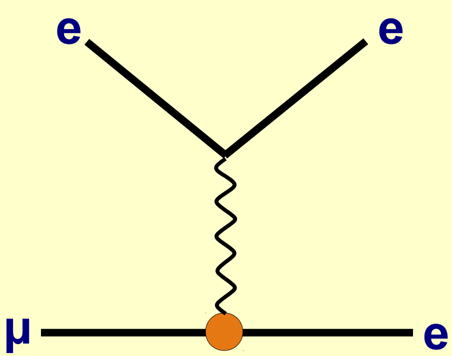
<u>Hirsch et al.</u>, *Phenomenology of the minimal supersymmetric $U(1)_{B-L} \times U(1)_R$ extension of the standard model* [arXiv:1206.3516]

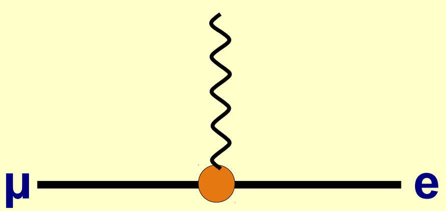
MSSM Model with heavy right-handed neutrino and Z'



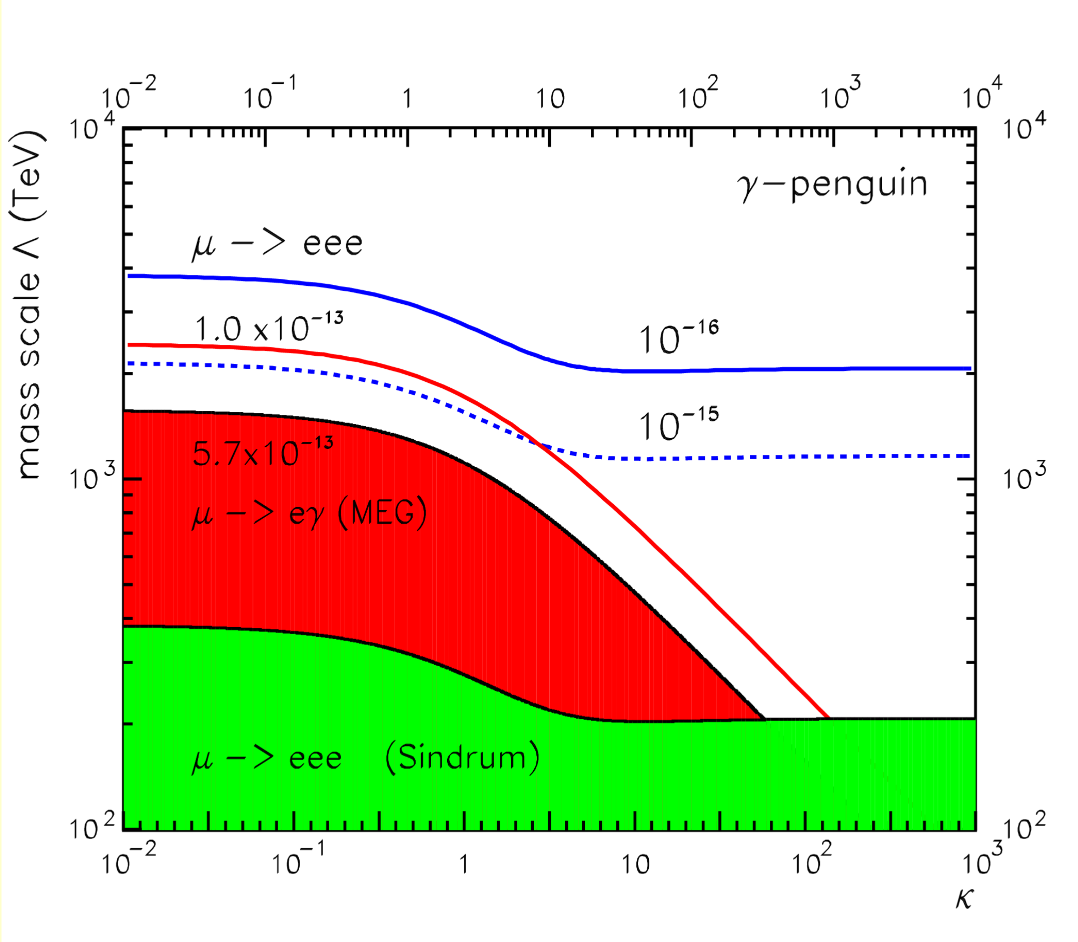
m_0 = 800 GeV, $M_{1/2}$ = 1200 GeV, tan β = 10, A_0 = 0
v_R = 10 TeV, tan β_R = 1.05, μ_R = −500 GeV, m_{AR} = 1000 GeV.

Model Independent Comparison

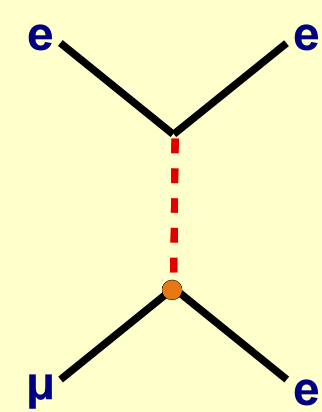




$\kappa \rightarrow 0$



eμee contact IA



$\kappa \rightarrow \infty$

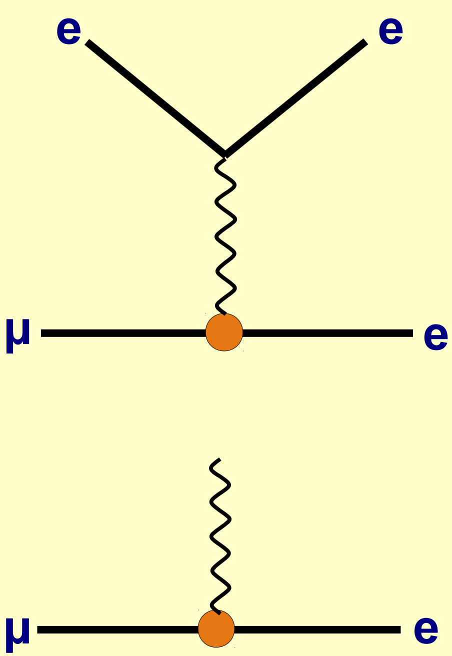
Effective cLFV Lagrangian:

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

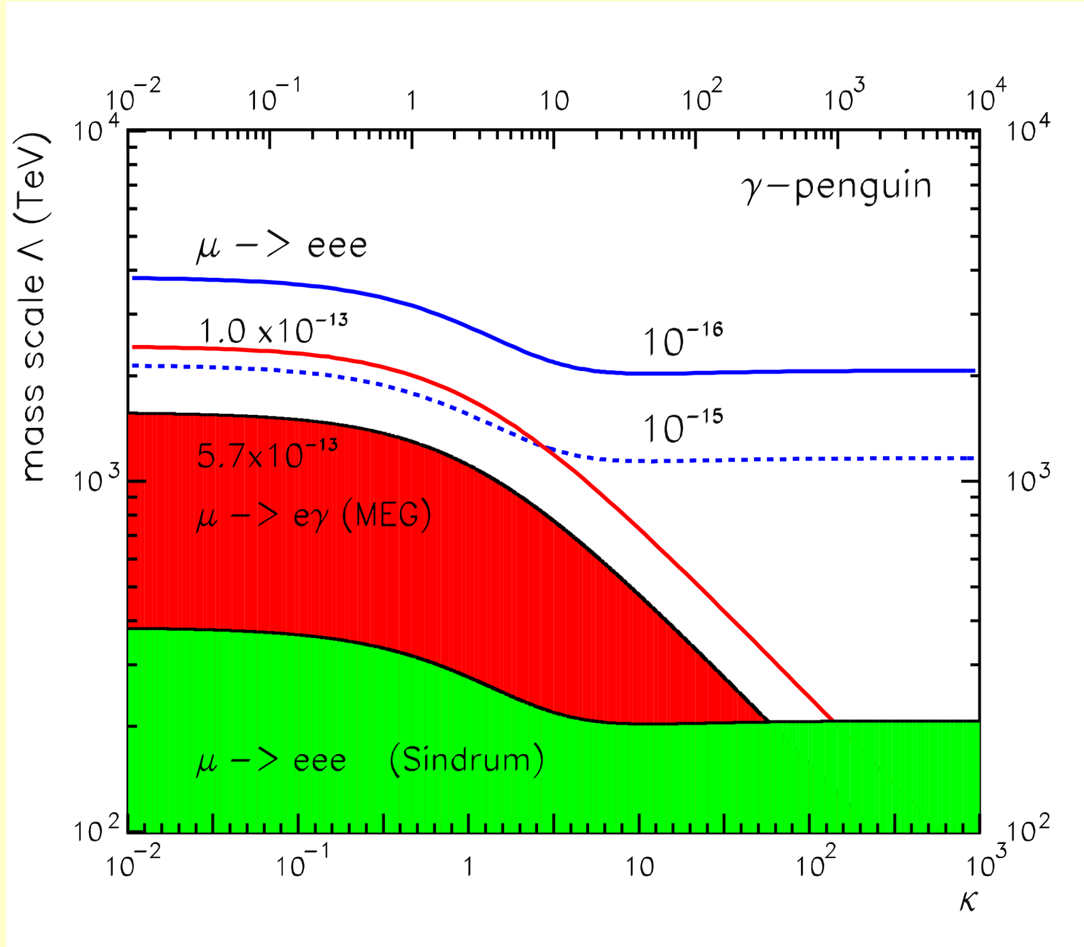
κ = parameter

Λ = common effective mass scale

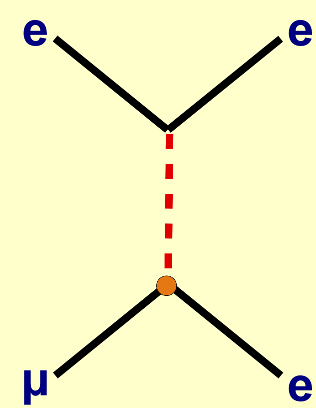
Model Independent Comparison



$\kappa \rightarrow 0$



eμee contact IA



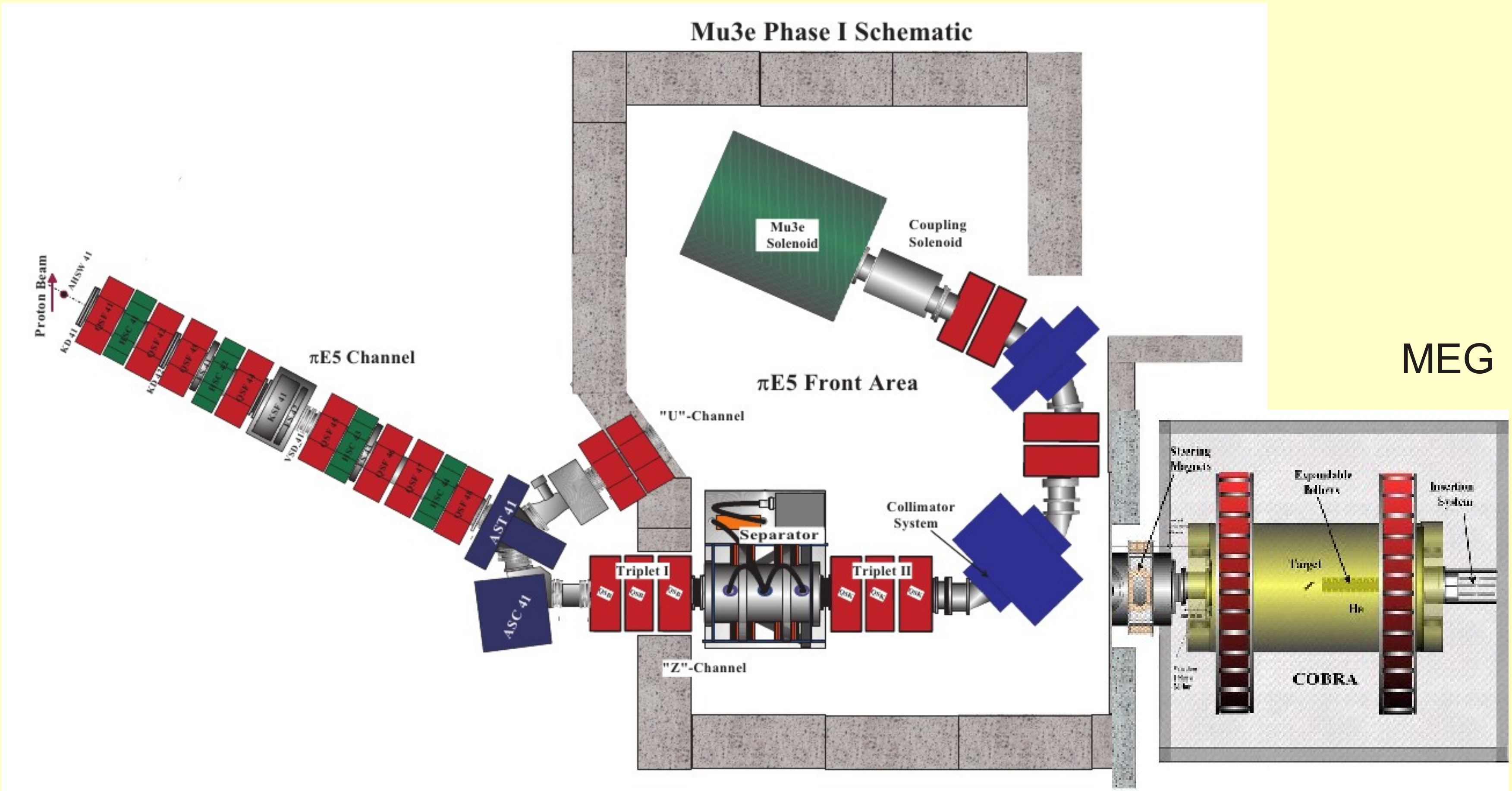
$\kappa \rightarrow \infty$

$$\frac{B(\mu^+ \rightarrow e^+e^+e^-)}{B(\mu^+ \rightarrow e^+\gamma)} \sim 0.006$$

$$\frac{B(\mu^+ \rightarrow e^+e^+e^-)}{B(\mu^+ \rightarrow e^+\gamma)} = \infty$$

πe5 Beamline (Phase I)

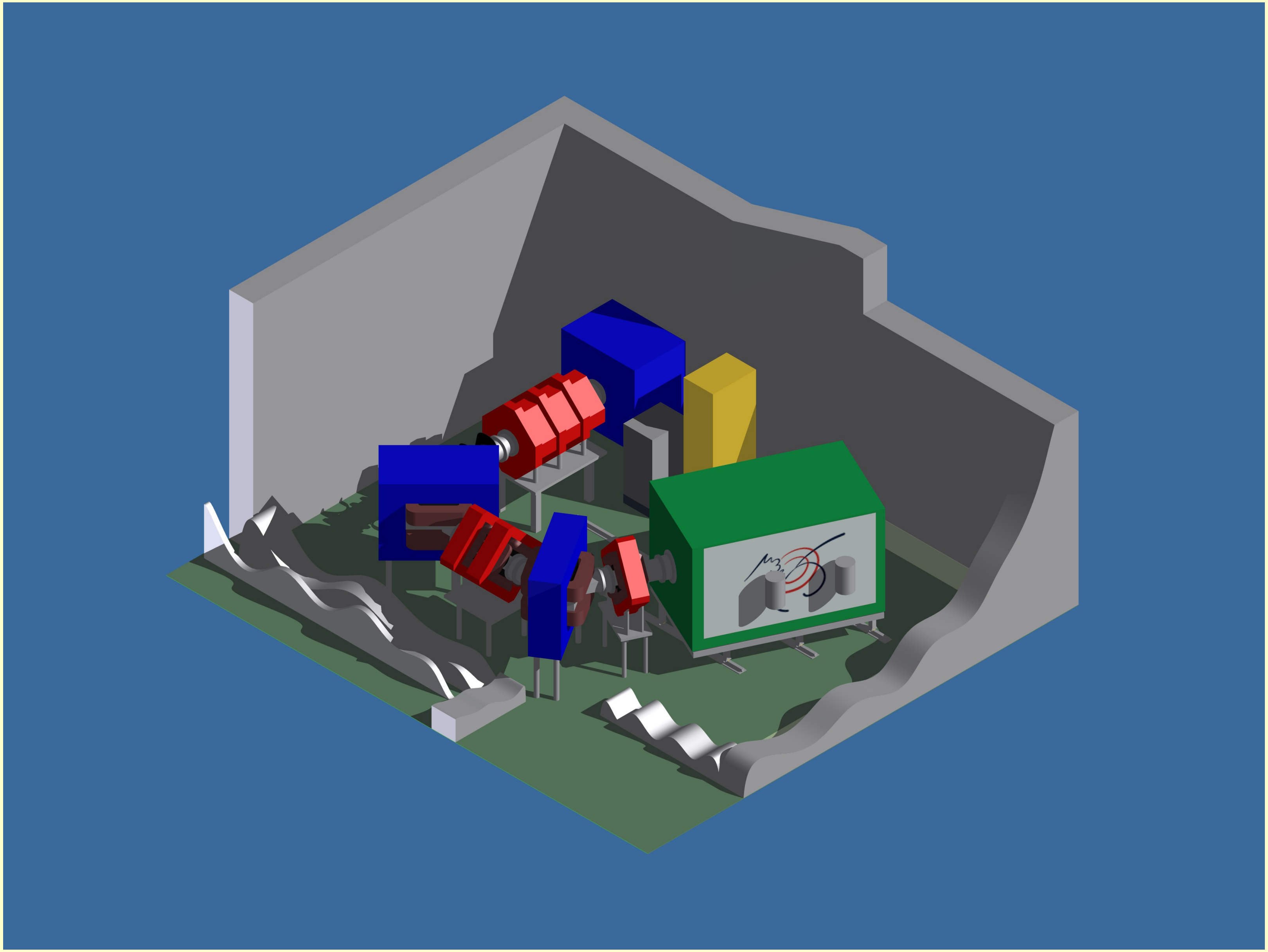
MEG and Mu3e could co-exist if MEG is to be upgraded



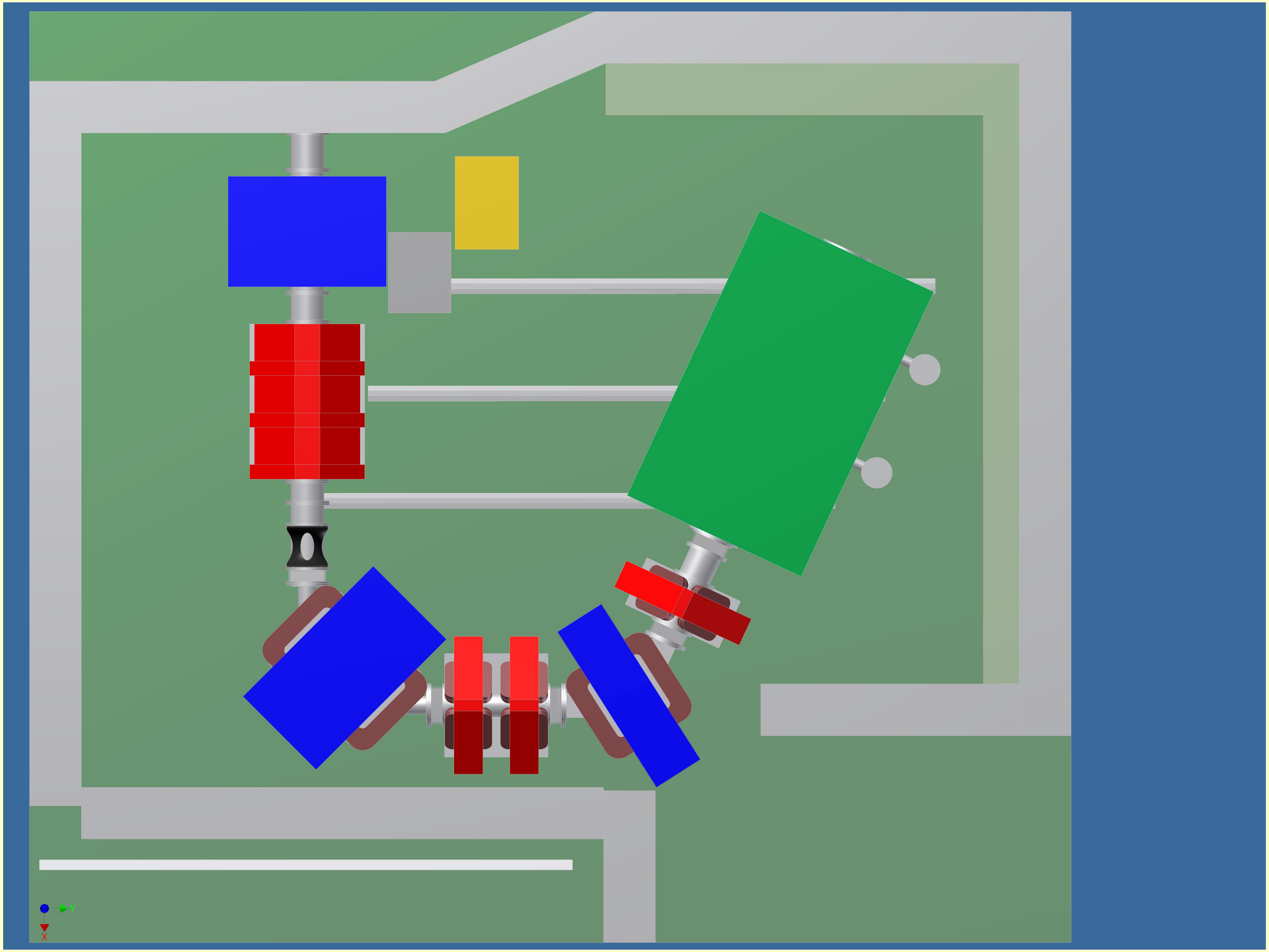
MEG

- muon rates of **1.4 · 10⁸/s** achieved in past
- rate of **10^8/s muons** needed to reach **B($\mu^+ \to e^+e^+e^-$) ~ 2 ·10^{-15}** (90%CL)

πe5 Beamline (Phase I)

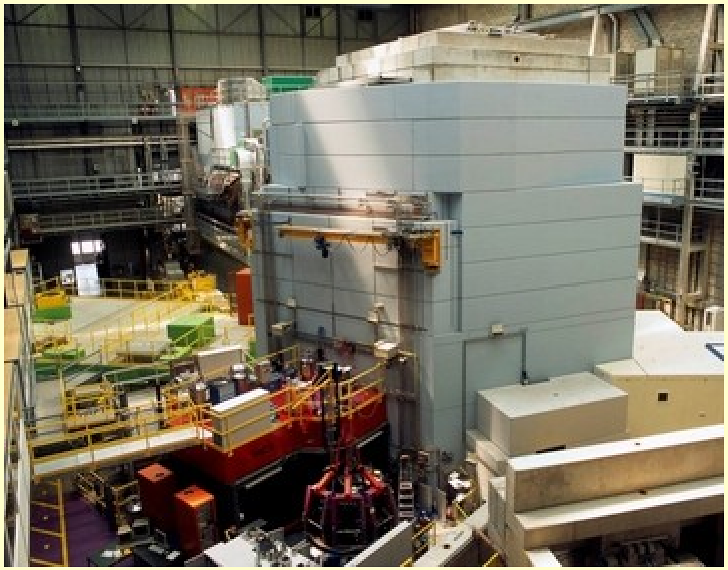


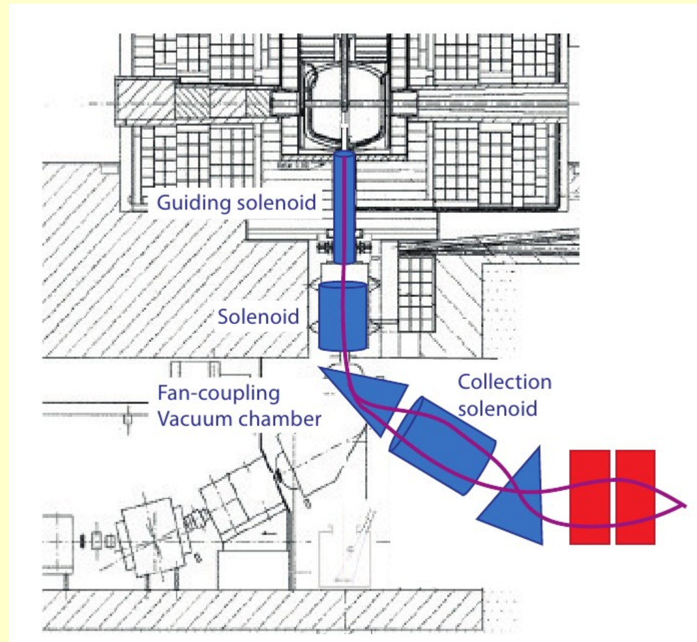
πe5 Beamline (Phase I)

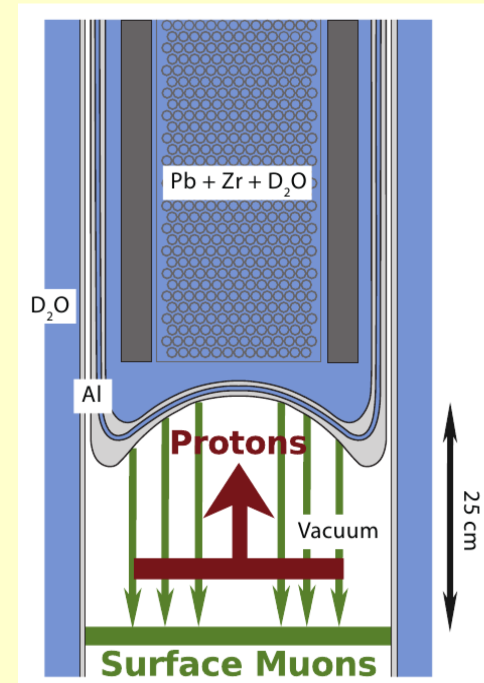


High Intensitiy Muon Beamline (Phase II)

HiMB = High Intensity Muon Beamline



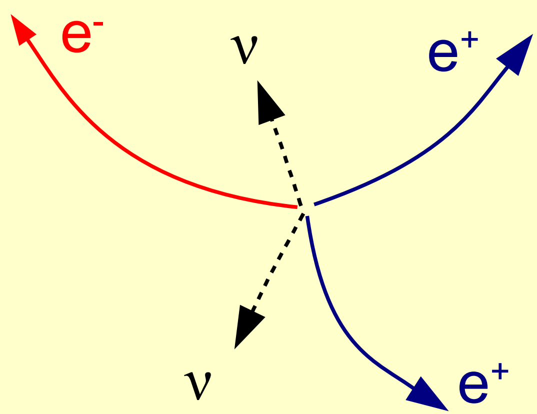




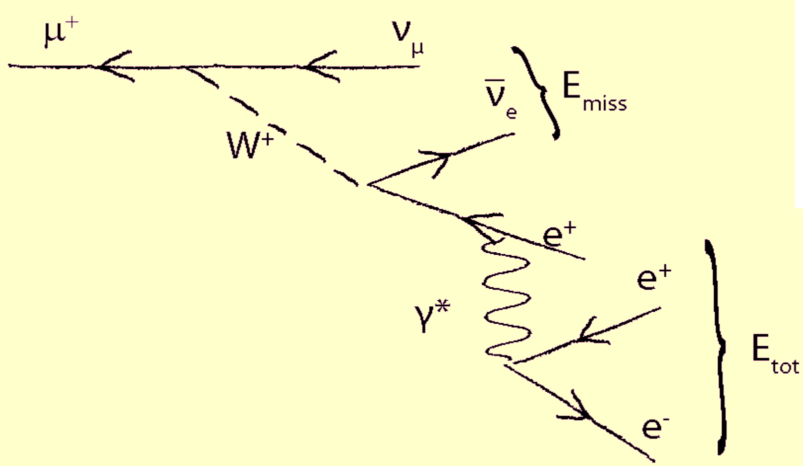
- Muon rates in excess of 10^{10} per second in beam phase acceptance possible
- **$2 \cdot 10^9$ muons/s** needed to reach ultimate goal of **$B(\mu^+ \rightarrow e^+e^+e^-) < 10^{-16}$**
- **Not before 2017**

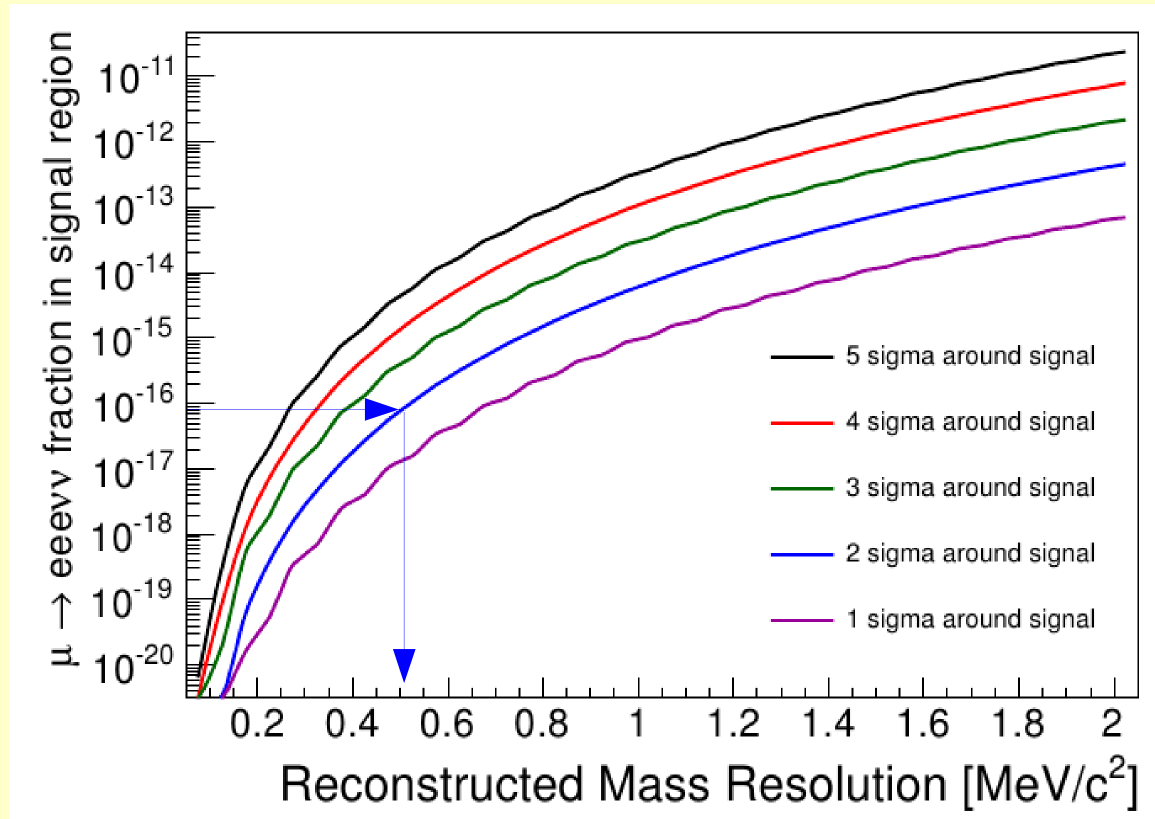
Backgrounds

Irreducible BG: radiative decay with internal conversion



B($\mu^+ \rightarrow e^+e^+e^- \nu\nu$) = 3.4 ·10^{-5}

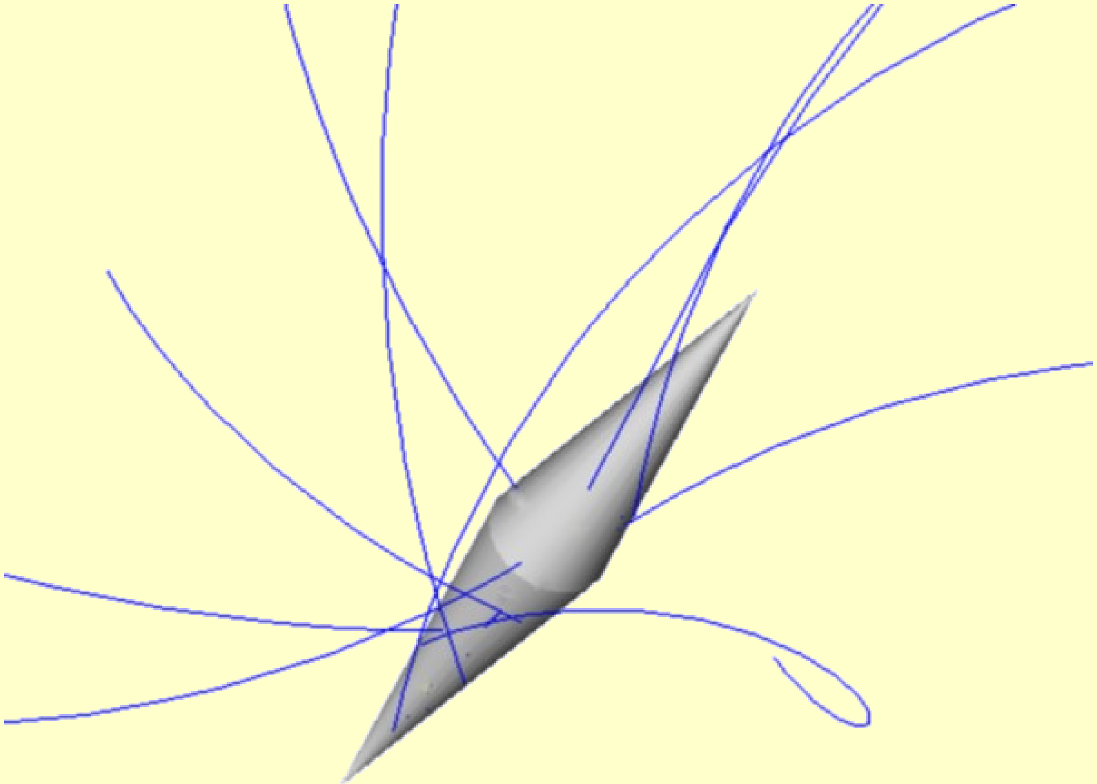




very good momentum +
total energy resolution required!

The Target

Spread muon decays in space and time



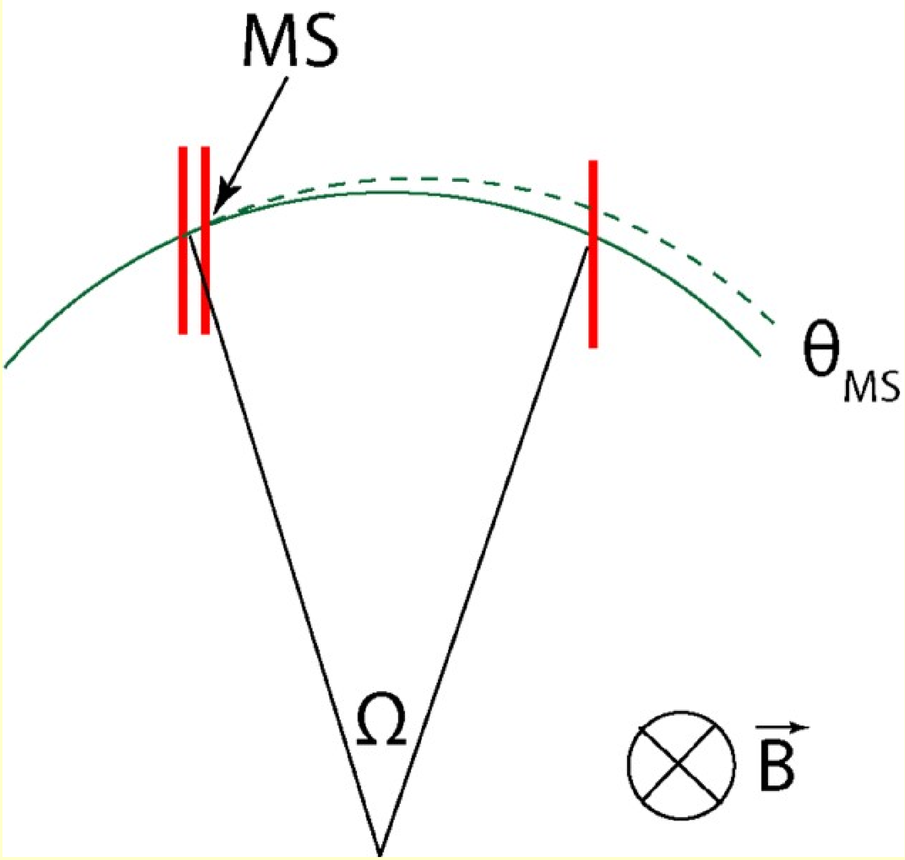
- DC Muon beam (PSI)
- about 4000 muons resting on target at same time
- large stopping target
- good **vertexing** and **timing** resolution required

e.g. Sindrum-like extended target

- hollow double cone (e.g. 30-80 μm Al)
- alternative Aerogel?

Momentum Resolution in MS Regime

- Momentum resolution of spectrometer:



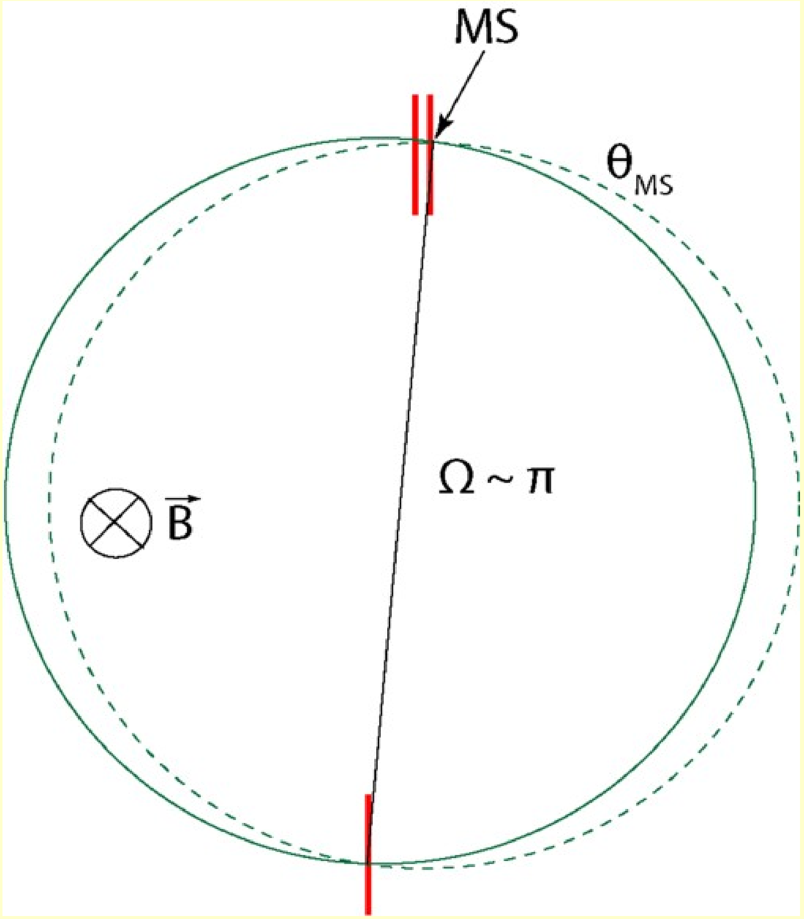
$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega}$$ (linearised)

precision requires large lever arm

large bending angle Ω

Momentum Resolution in MS Regime

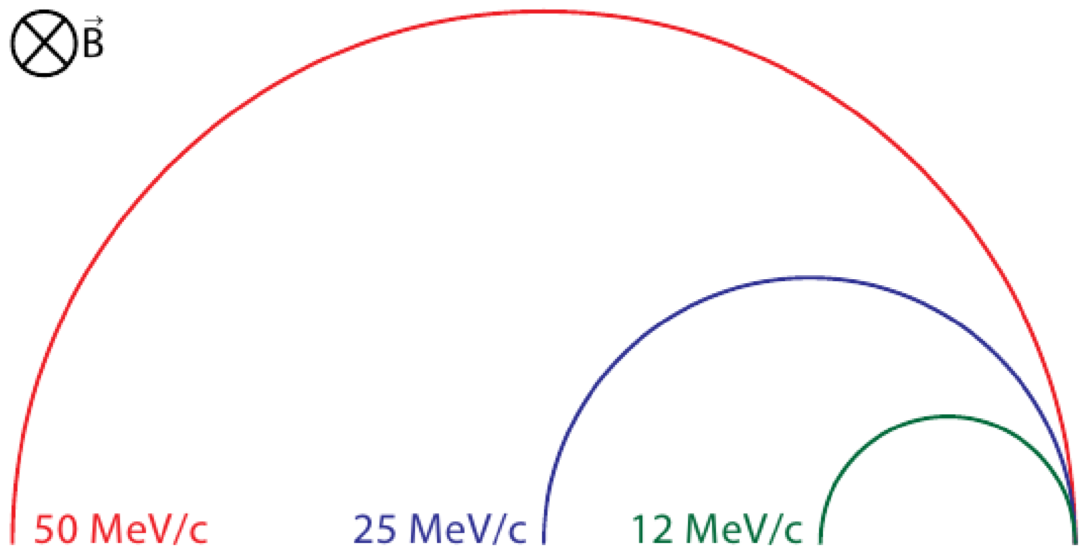
- Momentum resolution of “half turn” spectrometer:



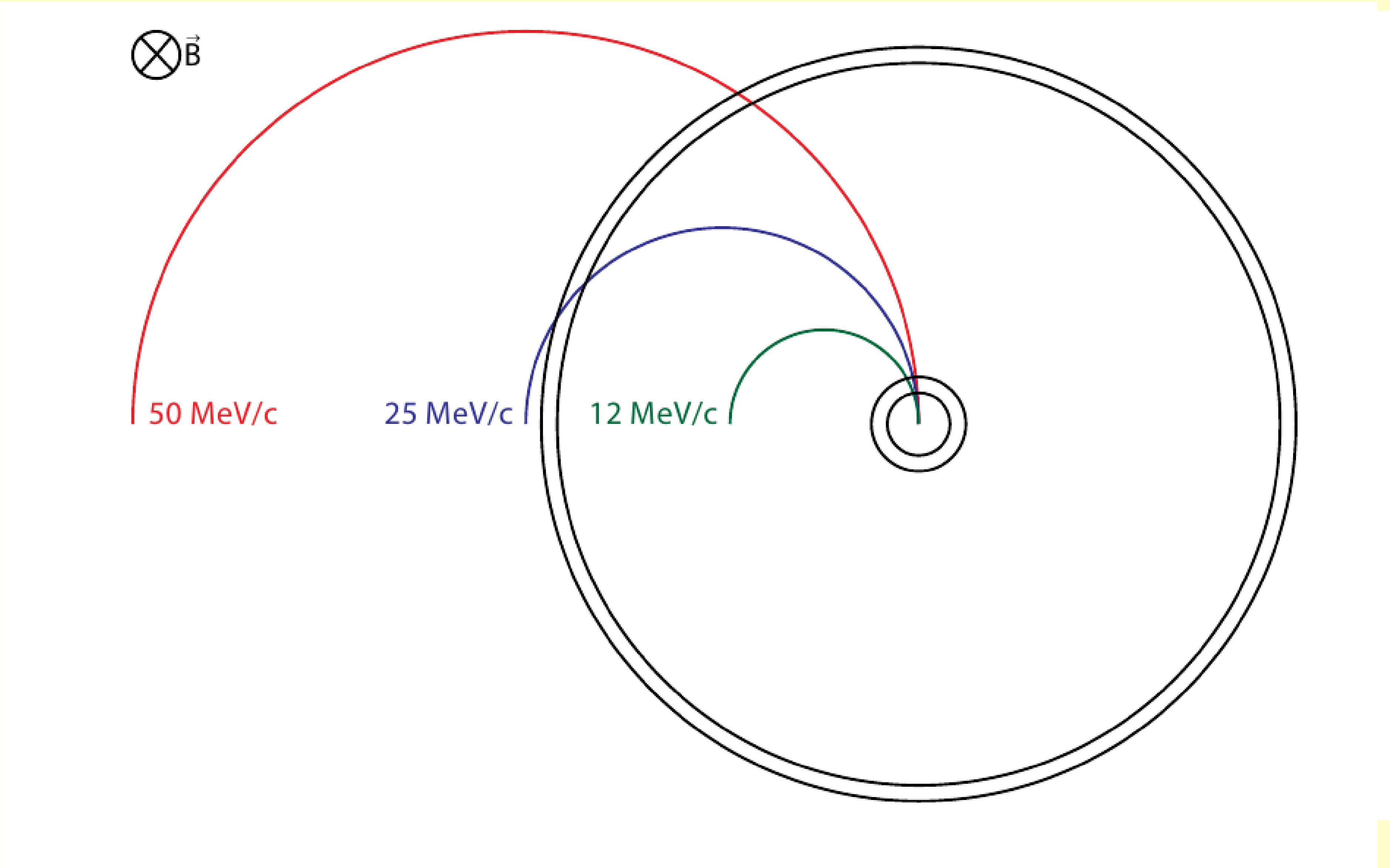
$$\frac{\sigma_p}{P} \sim O\left(\Theta_{MS}^2\right)$$

- **best precision for half turn tracks**
- **have to measure recurlers**

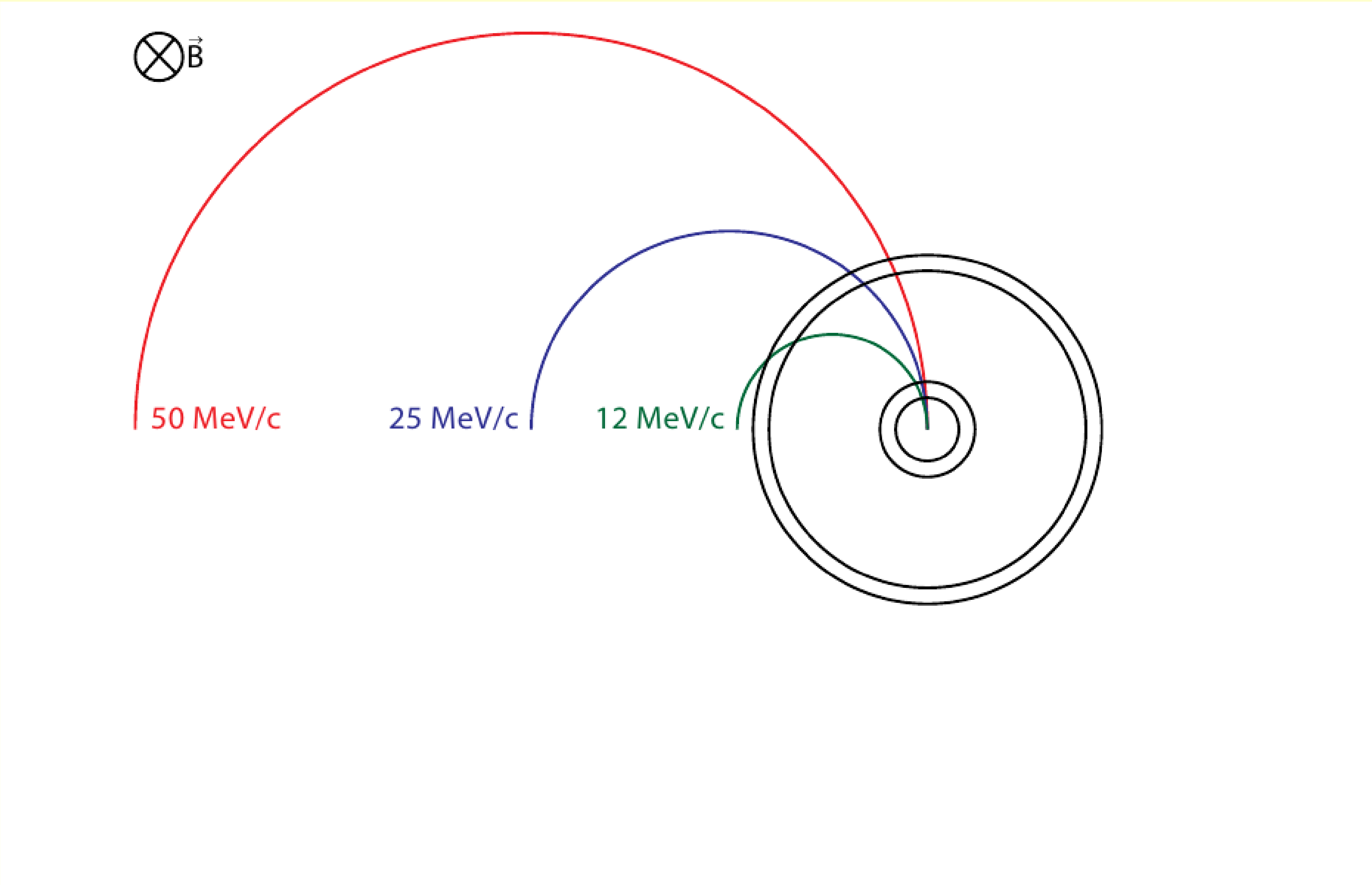
Tracking Design Considerations



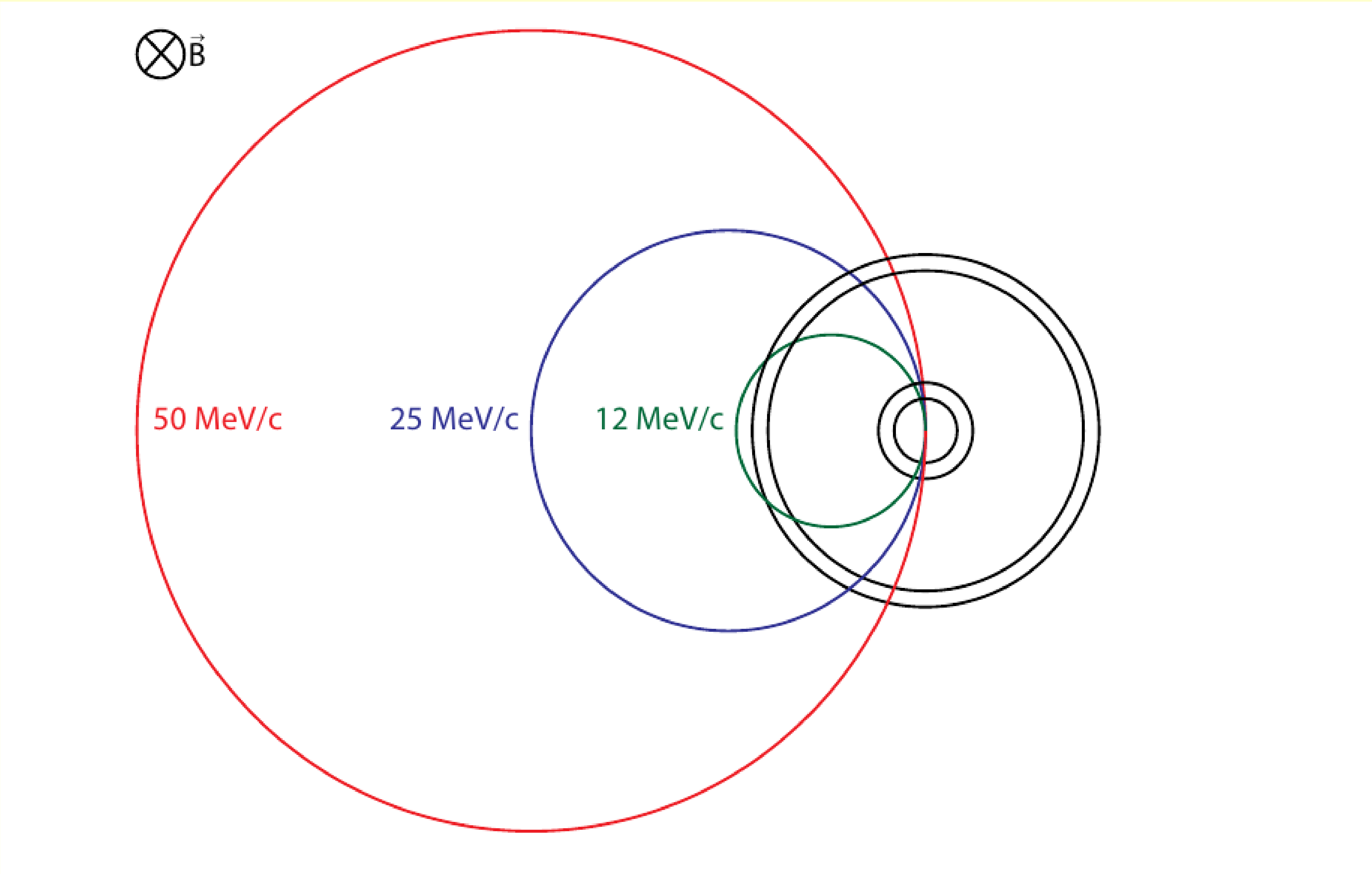
Tracking Design Considerations



Tracking Design Considerations

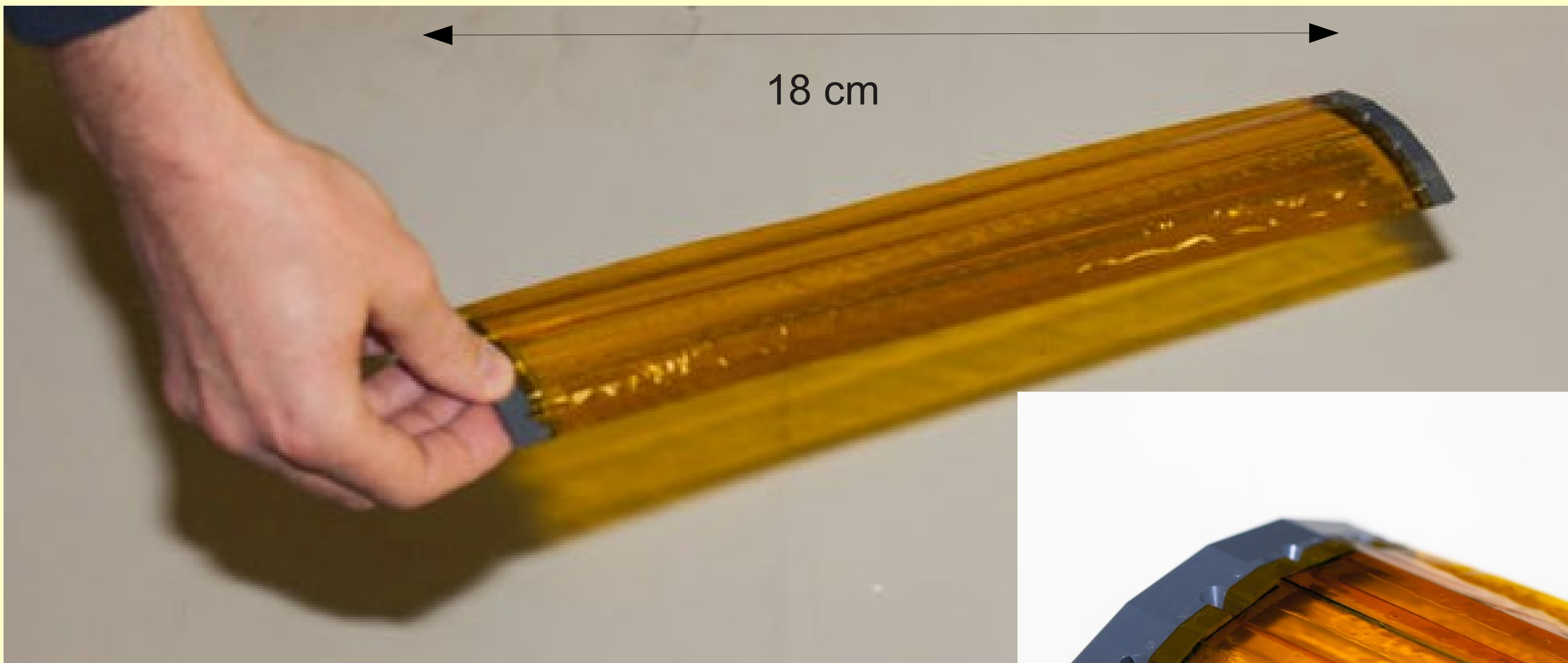


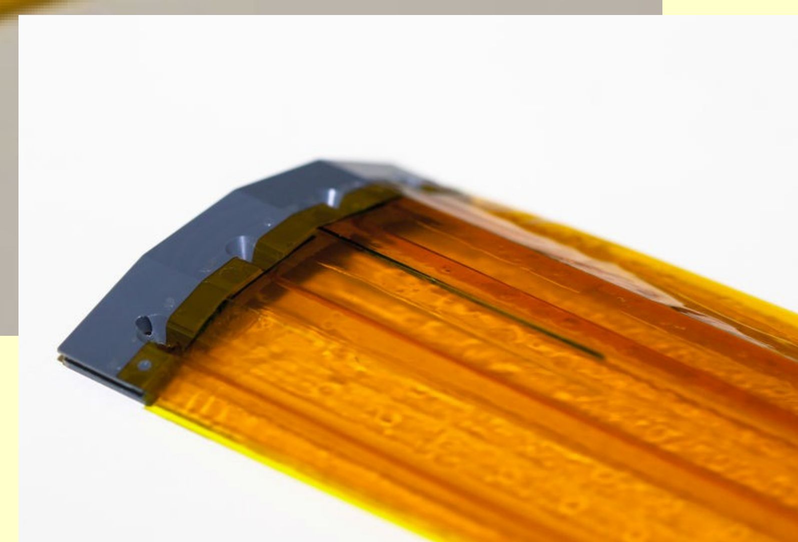
Tracking Design Considerations



Mechanical Prototypes for Pixel Tracker

even larger stable structures with 100 µm thickness possible

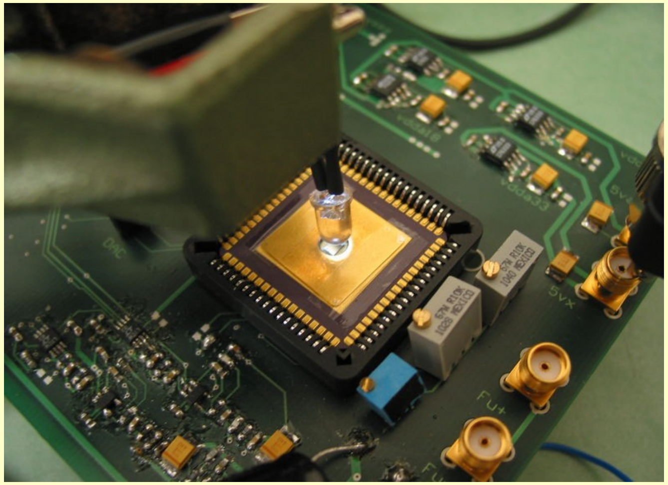


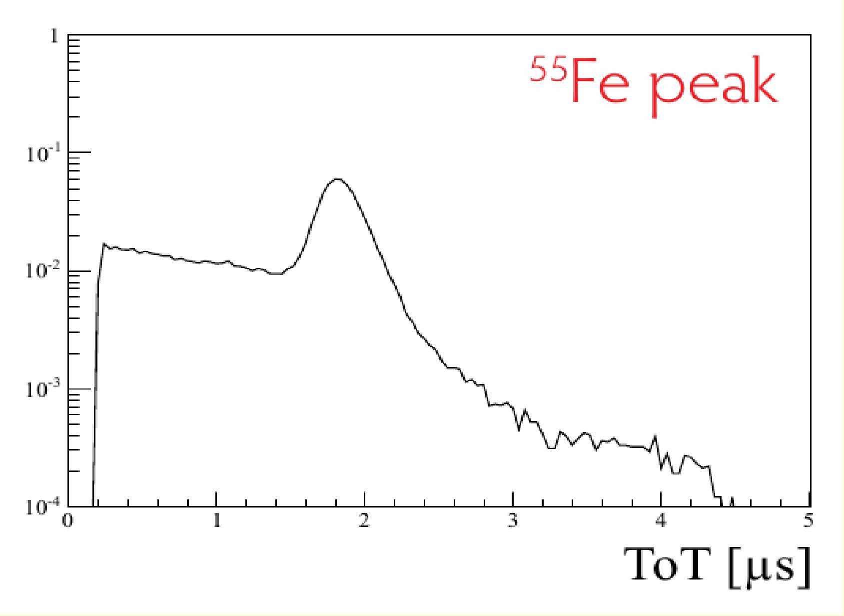


by using Kapton folds

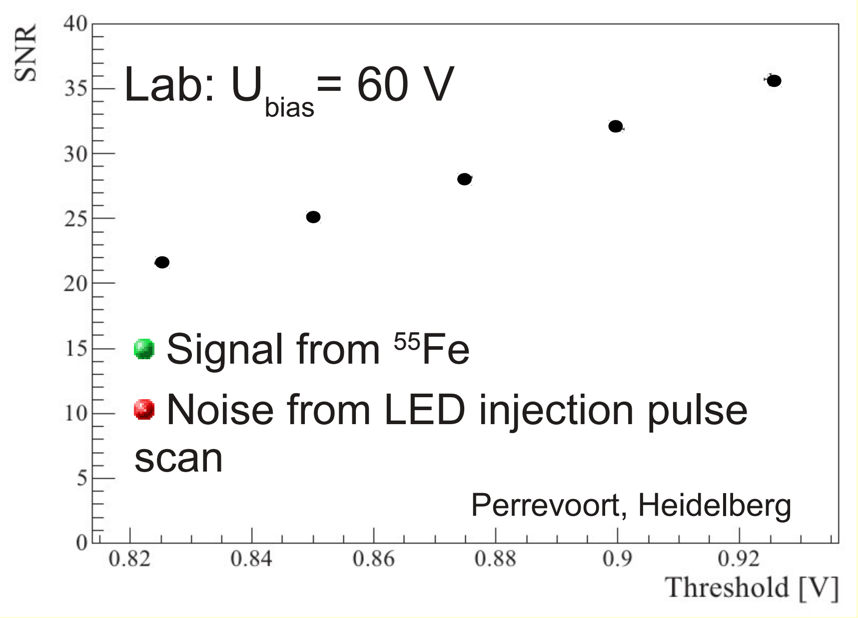
Pixel Detector Tests in Lab

MuPix2 chip under LED test



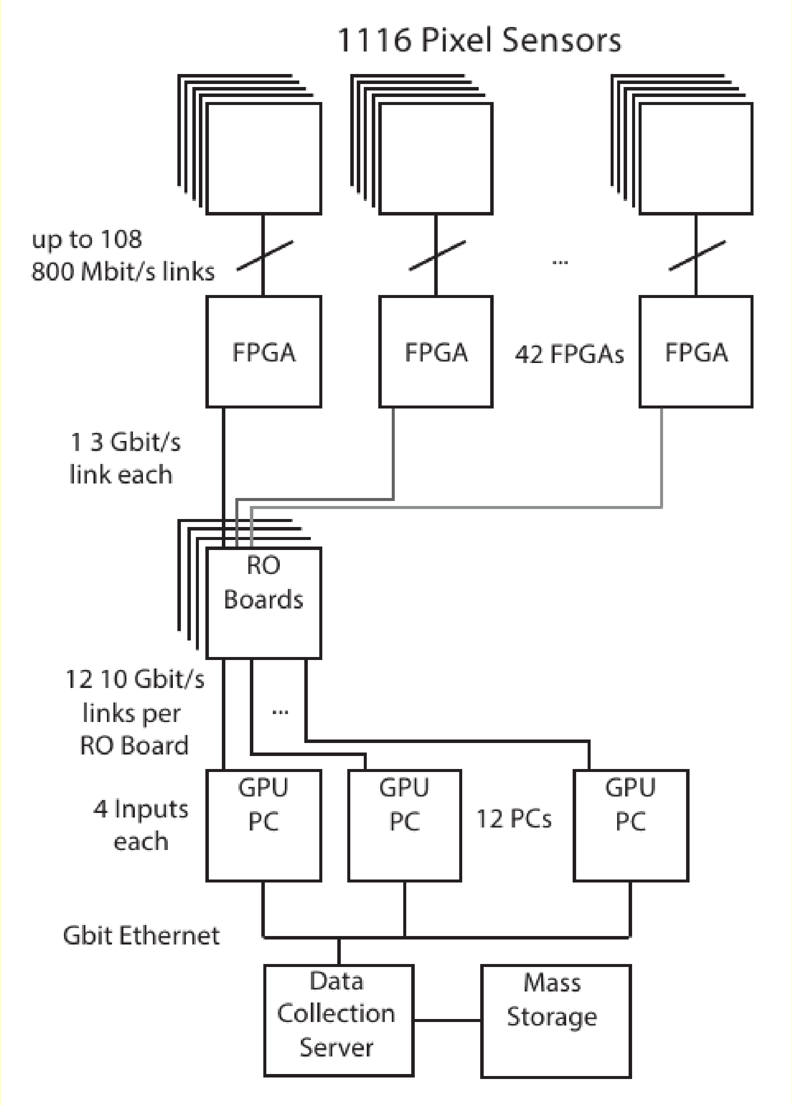


- good energy resolution
- very good signal to noise (SNR)



Data Acquisition

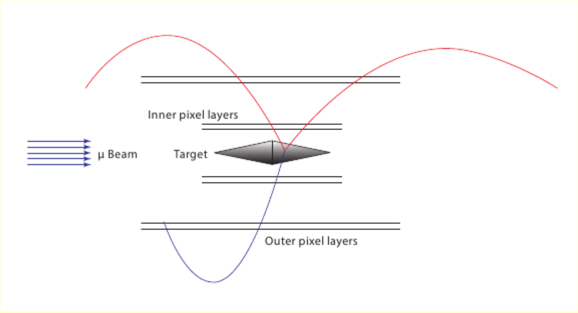
- Total number of pixels ~280 mill (+fibers+tiles)
- Frontend data rate of ~1 Tbit/s (Phase II)
- Online event reconstruction (no trigger)
- FPGA based switching network
- Graphics Processing Units (~50 GPUs)

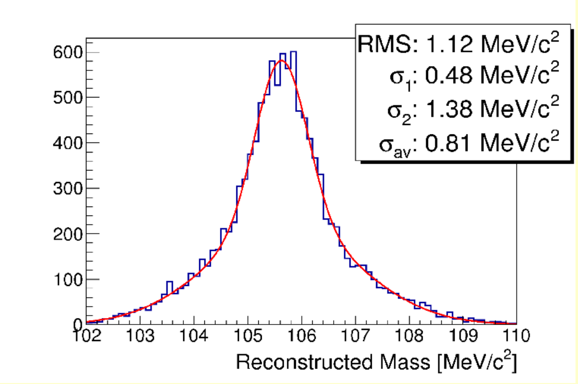


Logging rate ~50-100 MB/s

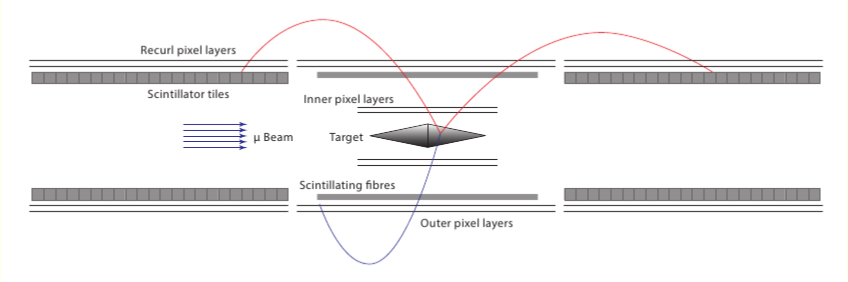
Invariant Mass Resolution of Signal

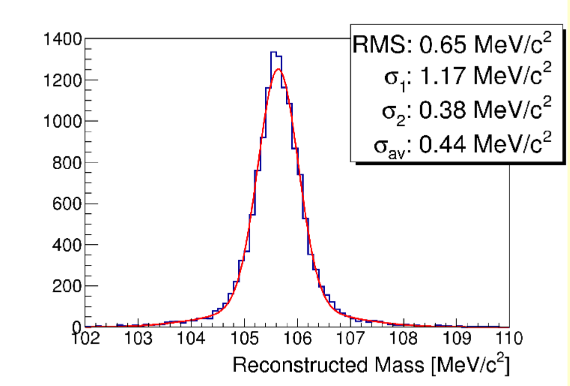
Phase IA:
rate ~ 2 · 10^7 muons/s





Phase IB:
rate ~ 2 · 10^8 muons/s





Phase II:
rate ~ 2 · 10^9 muons/s