Search for μ → eee at the High Intensity and Technology Frontier: The Mu3e Experiment

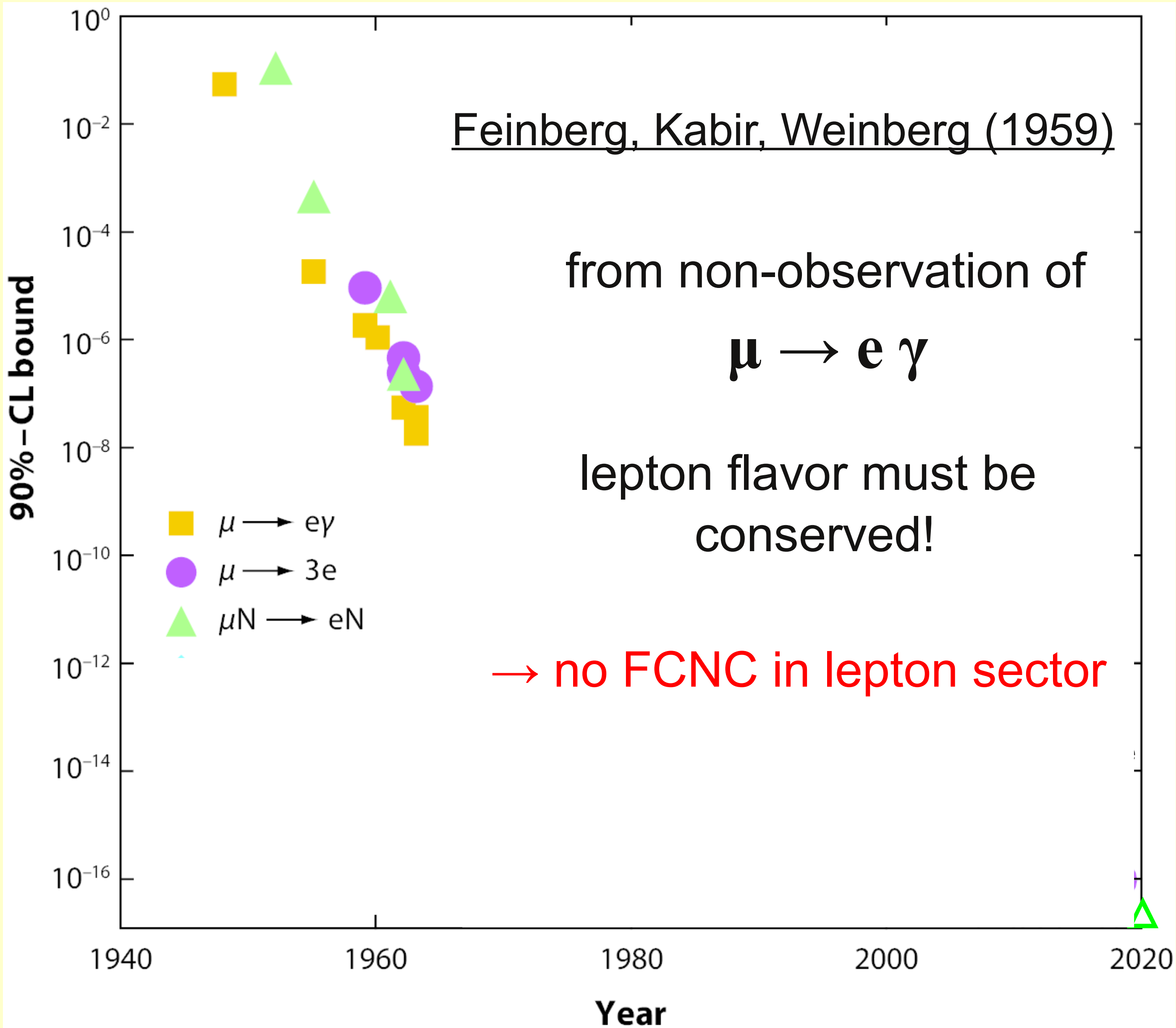
Johns-Hopkins Workshop

Heidelberg, July 21-23, 2014

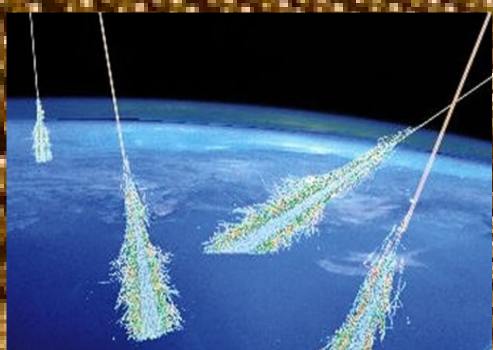
André Schöning

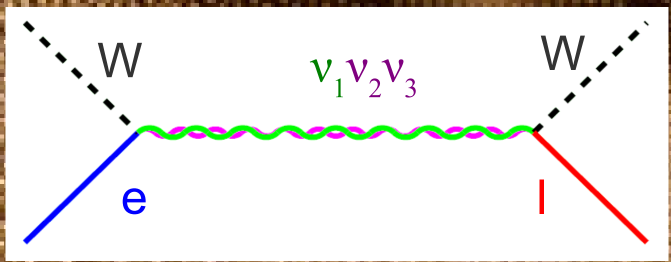
Physikalisches Institut, Universität Heidelberg

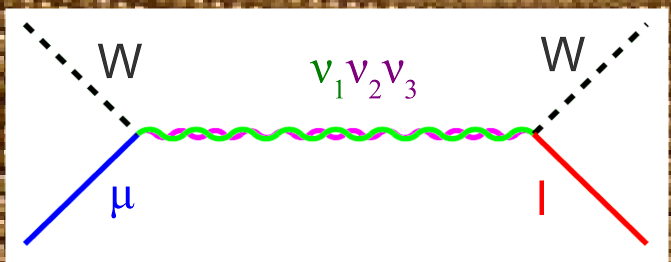
History of LFV Decay experiments



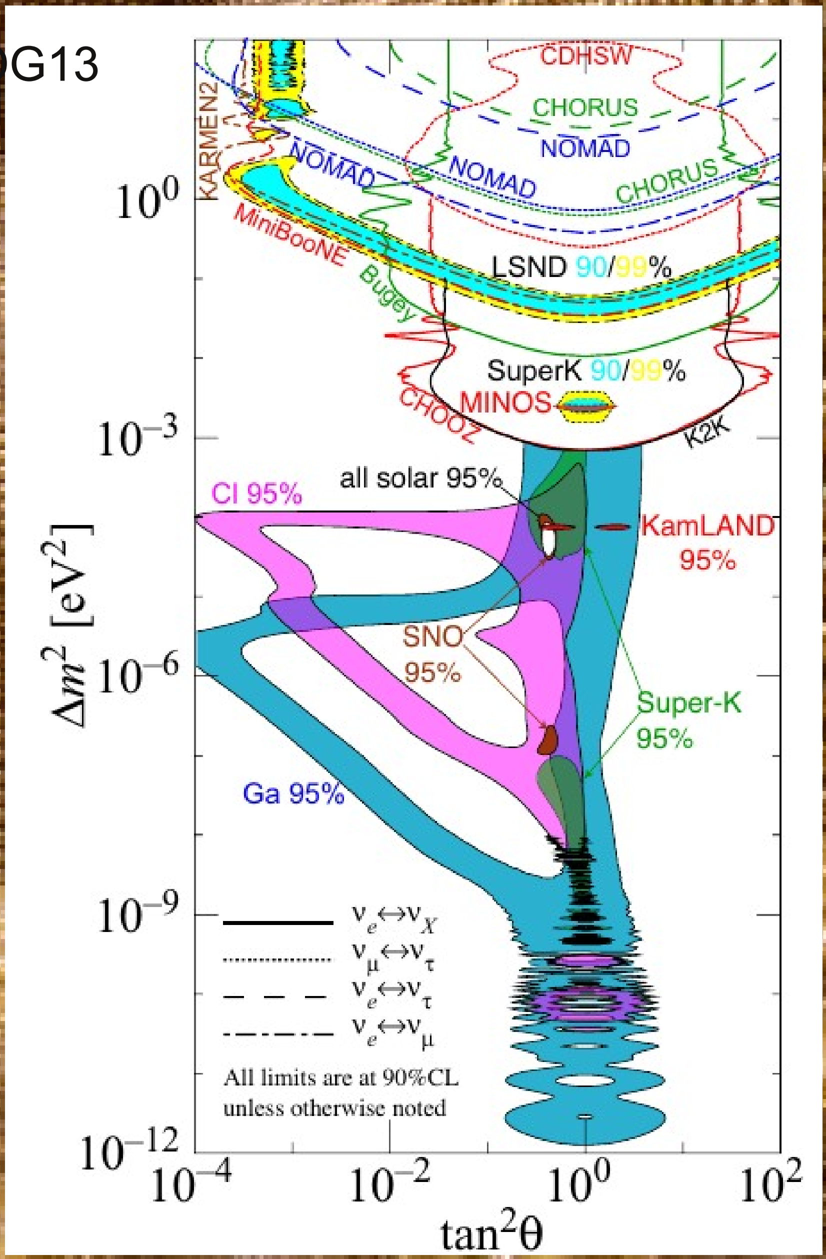
Discovery of Neutrino Oscillations







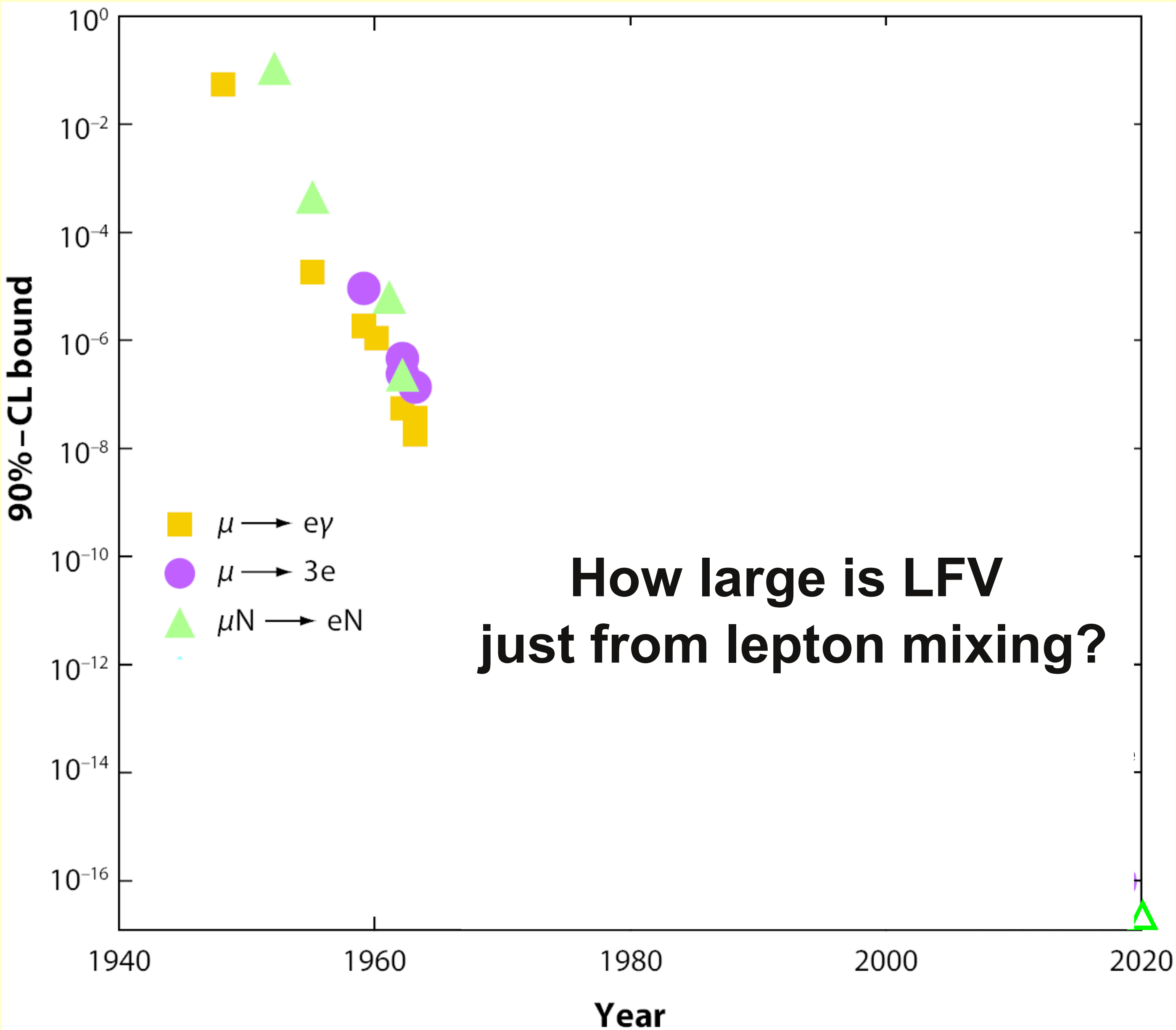
PDG13



neutrino oscillations = FCNC

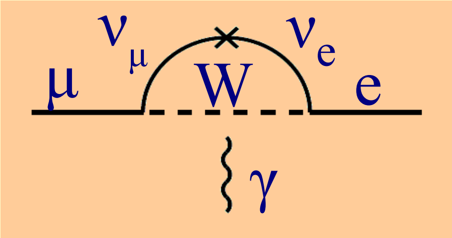
(charged) lepton flavor is **NOT** conserved! → LFV

History of LFV Decay experiments



How large is LFV just from lepton mixing?

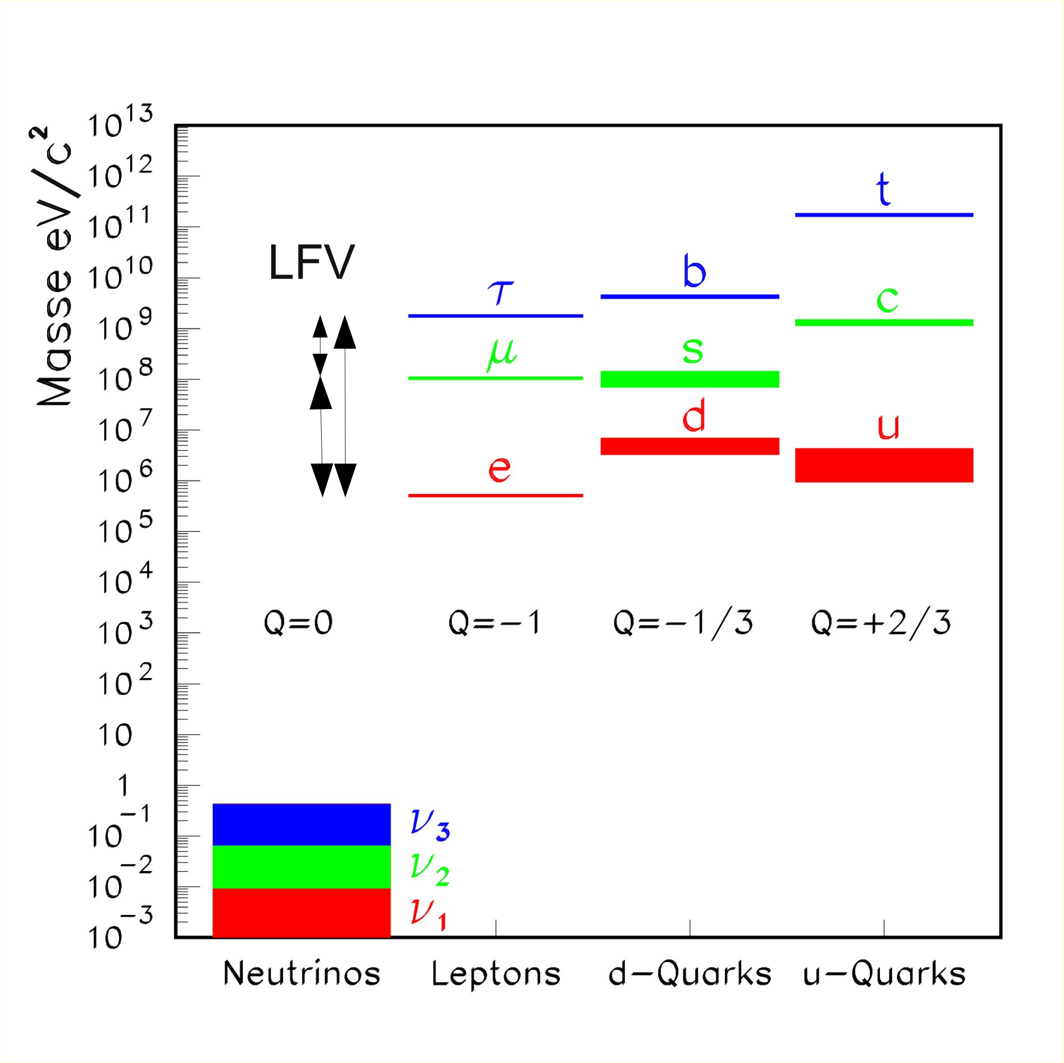
FCNC + Fermion Mass Pattern



- FCNC in SM quark sector ~ 10^{-10}
- FCNC in SM lepton sector < 10^{-40}

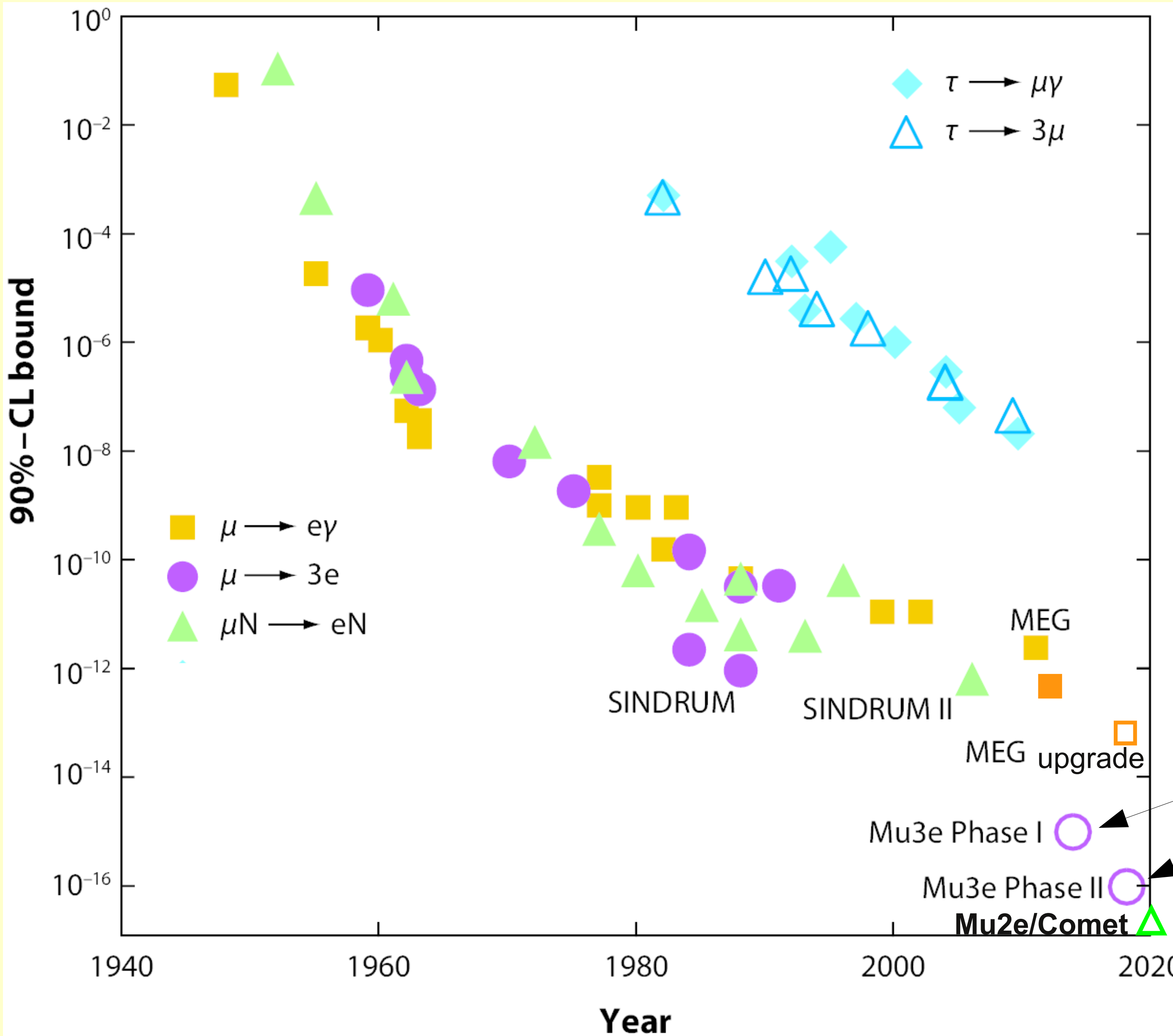
$$BR(l_j \to l_k \gamma) \propto \left| \sum_i V_{ij} V_{jk}^* \frac{m_{\nu_i}^2}{M_W^2} \right|^2$$

$$\sim \left| \frac{\Delta m_{\nu_{jk}}^2}{M_W^2} \right|^2$$



→ Charged LFV is THE signature of new physics!

History of LFV Decay experiments



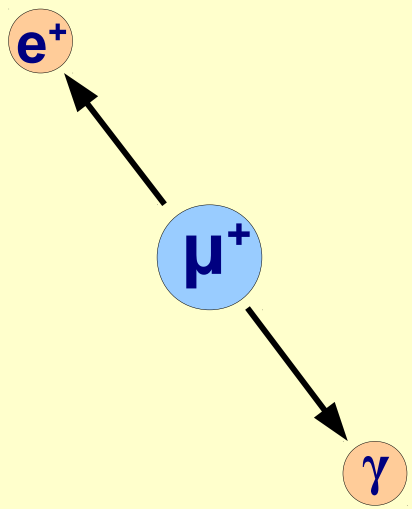
$B(\mu^+ \rightarrow e^+e^+e^-)$

Phase I: 10^{-15}

Phase II: 10^{-16}

LFV Muon Decays: Experimental Situation

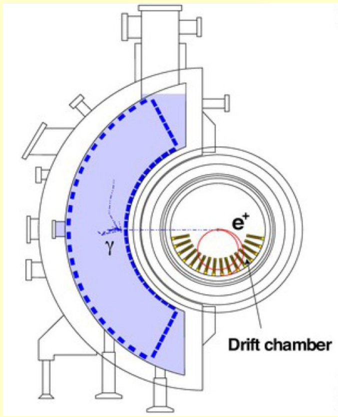
$\mu^+ \rightarrow e^+ \gamma$



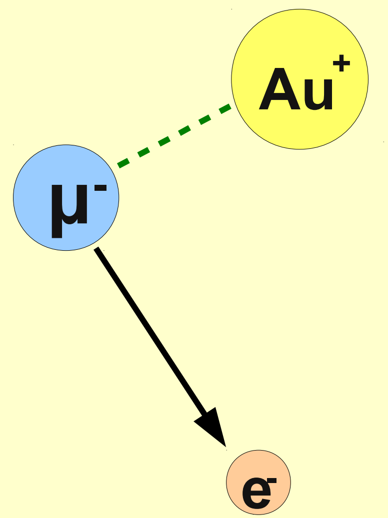
MEG (PSI)

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

running



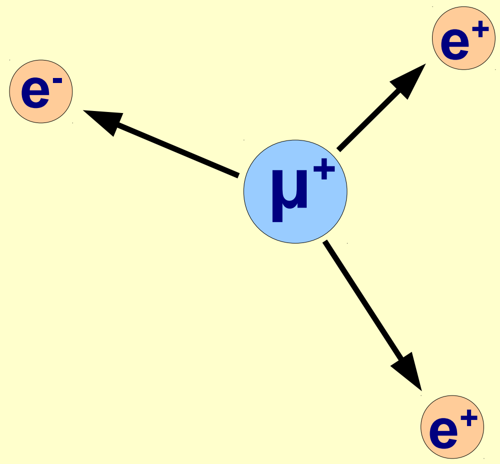
$\mu^- N \rightarrow e^- N$



SINDRUM II (PSI)

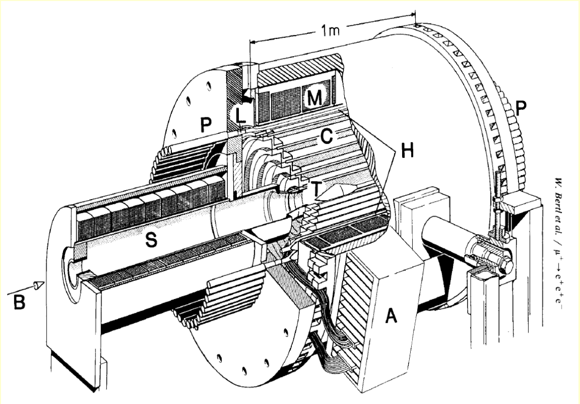
$B(\mu\,\mathrm{Au} \rightarrow e\,\mathrm{Au}) \leq 7\cdot 10^{-13}$ (2006)

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



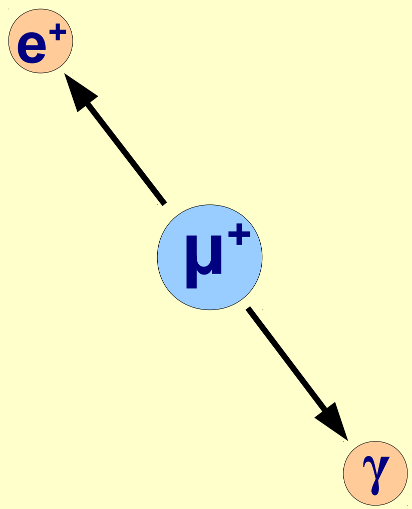
SINDRUM (PSI)

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

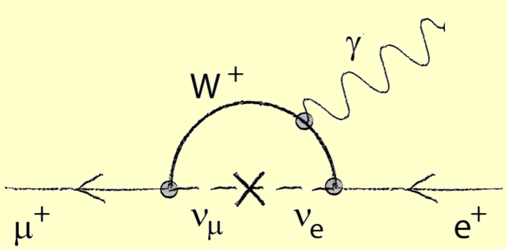


LFV Muon Decays in the SM

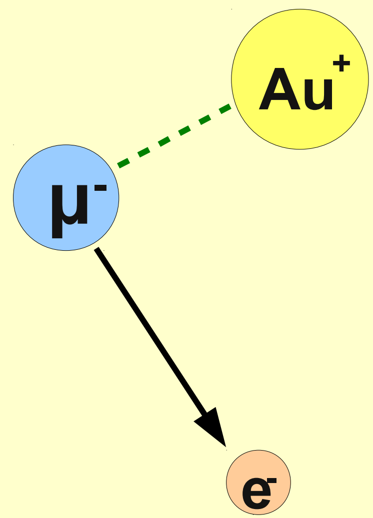
$\mu^+ \rightarrow e^+ \gamma$

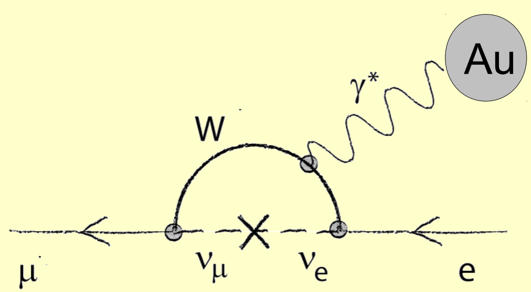


SM: LFV loops

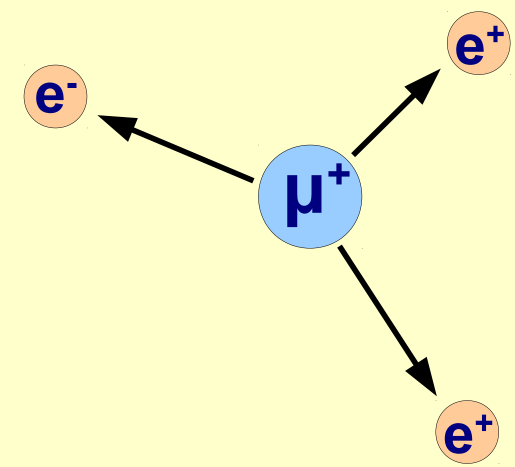


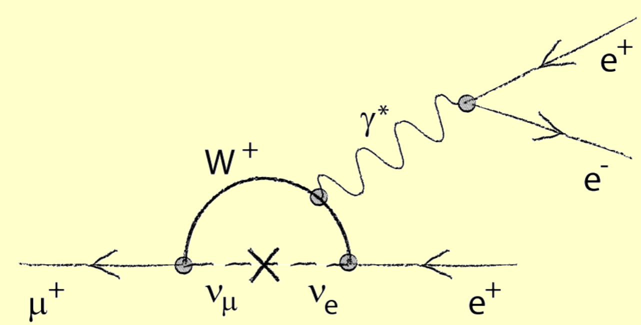
$\mu^- N \rightarrow e^- N$





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

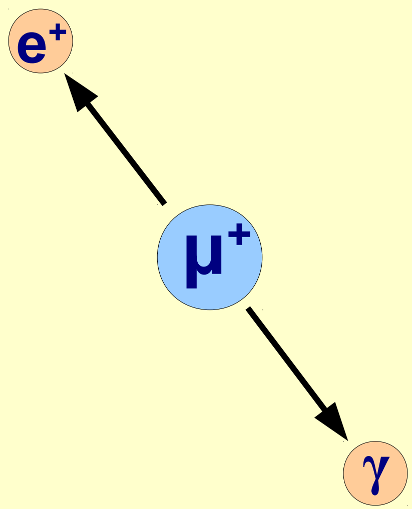




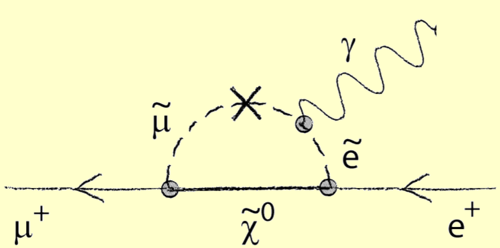
branching ratios suppressed by $\propto \frac{(\Delta m_\nu^2)^2}{m_W^4} \approx 10^{-50}$

LFV Muon Decays from SUSY Loops

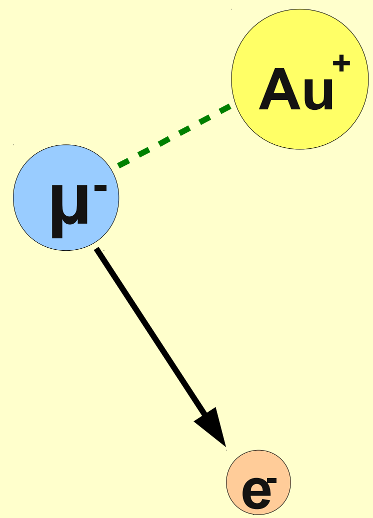
$\mu^+ \rightarrow e^+ \gamma$

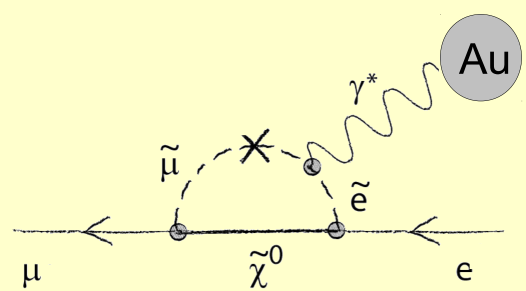


SUSY loops



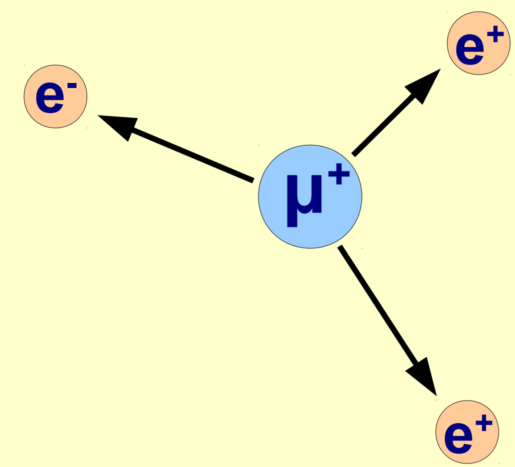
$\mu^- N \rightarrow e^- N$

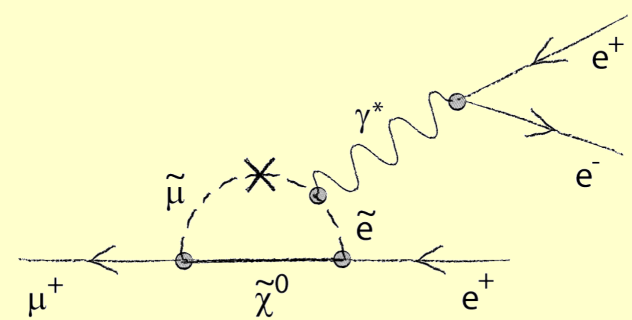




coherent conversion in nucleus field for $Q^2(\gamma^*)\sim 0$

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

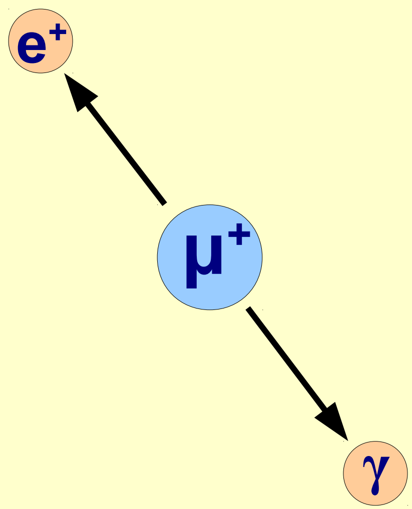




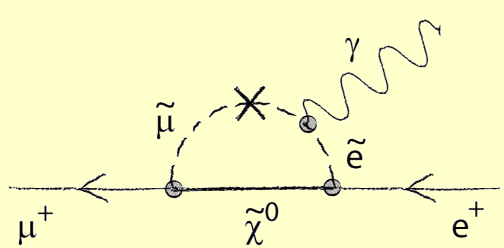
suppressed by extra vertex with respect to $\mu^+ \rightarrow e^+ \gamma$

LFV Muon Decays from SUSY Loops

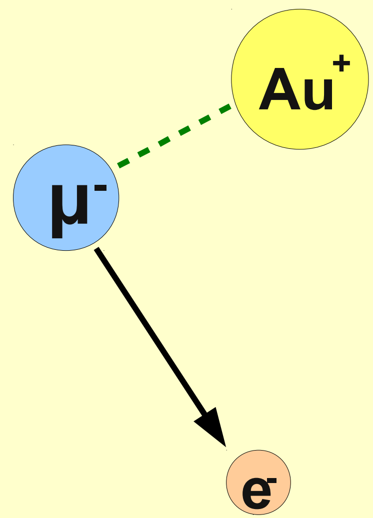
$\mu^+ \rightarrow e^+ \gamma$

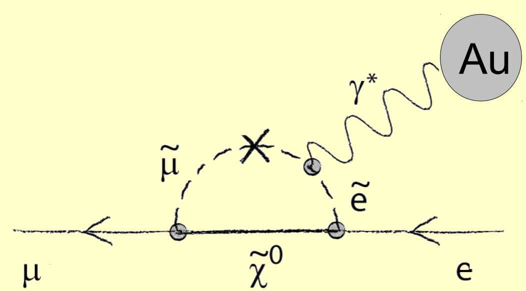


SUSY loops

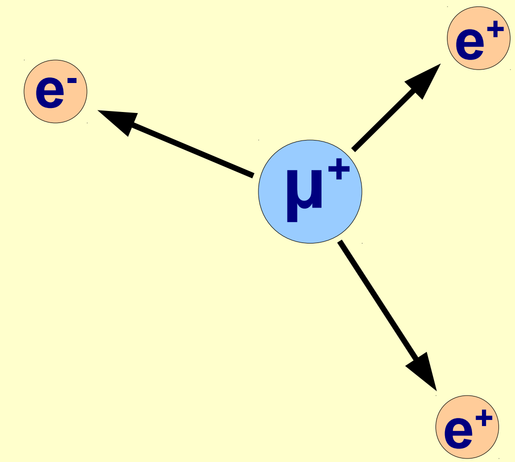


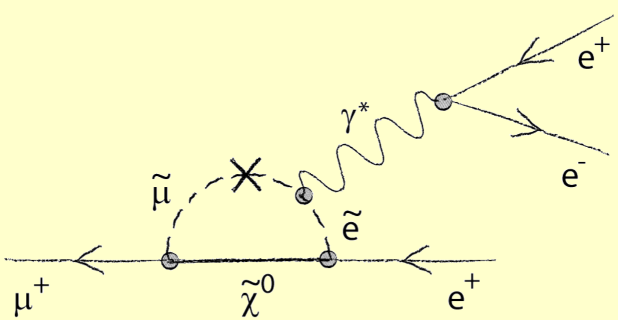
$\mu^- N \rightarrow e^- N$





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

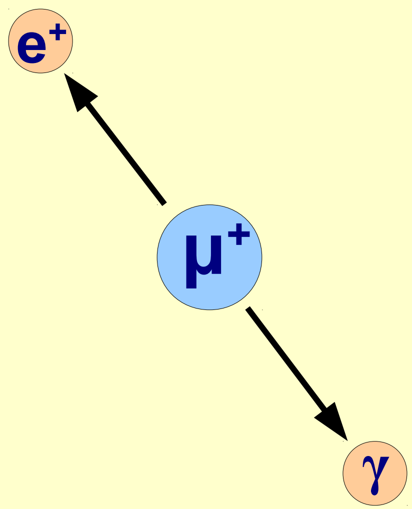


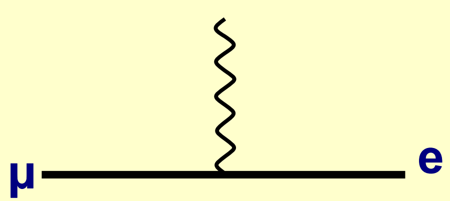


Most BSM models (e.g. SUSY) induce naturally LFV

LFV Tree Diagrams

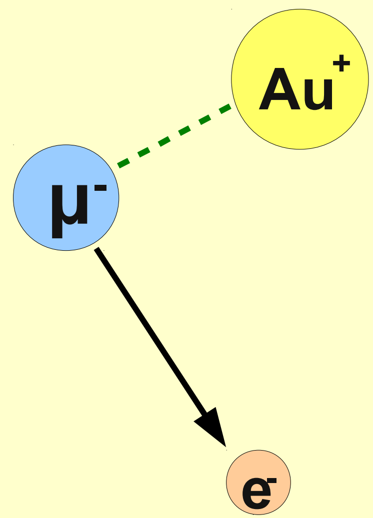
$\mu^+ \rightarrow e^+ \gamma$

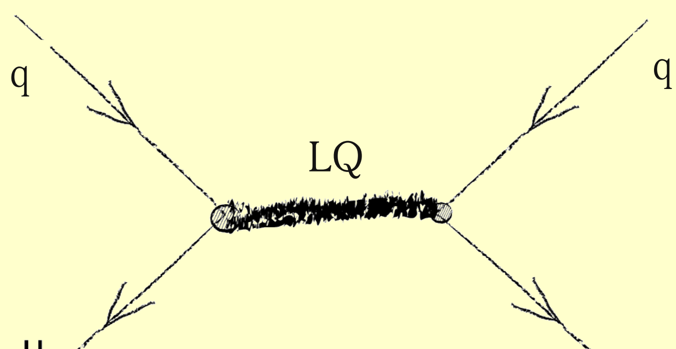




not allowed

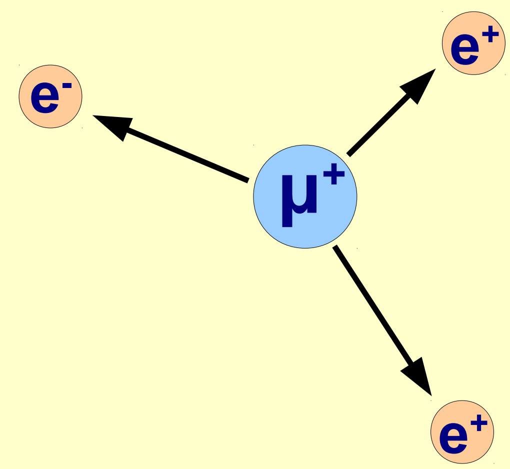
$\mu^- N \rightarrow e^- N$

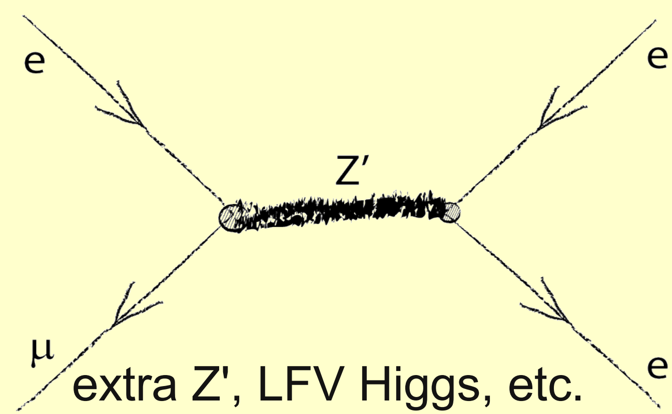




e.g. Leptoquarks

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

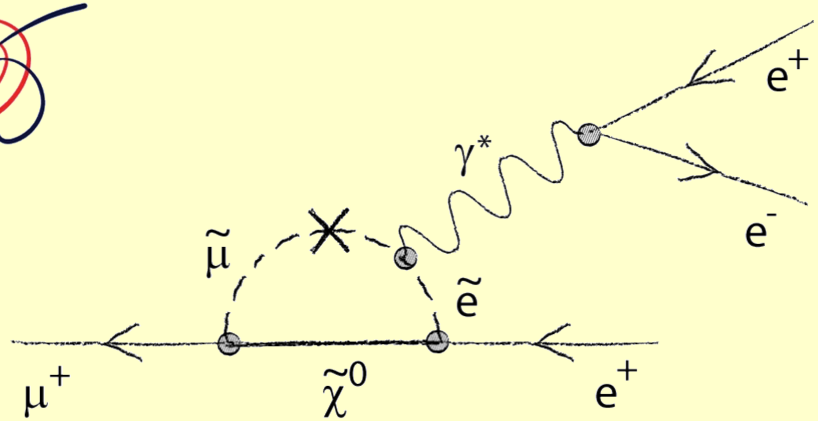




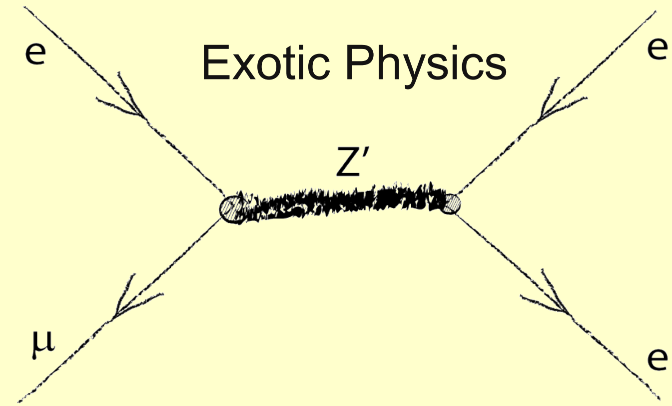
extra Z', LFV Higgs, etc.

Additional BSM tree diagrams in $\mu N \rightarrow eN$ and $\mu N \rightarrow eee$

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



loop diagrams



tree diagram

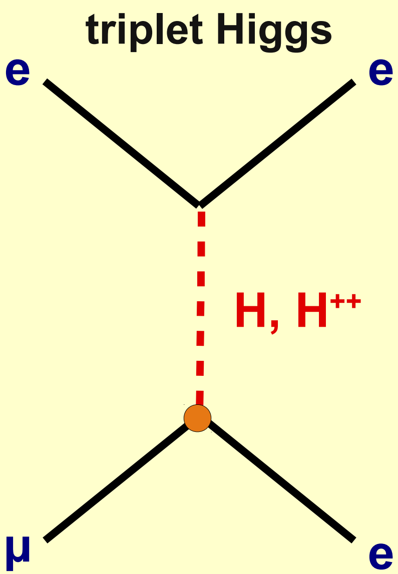
- **Supersymmetry**
- **Little Higgs Models**
- **Seesaw Models**
- **GUT models (Leptoquarks)**
- **many other models**

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

Example I: Higgs Triplet Models

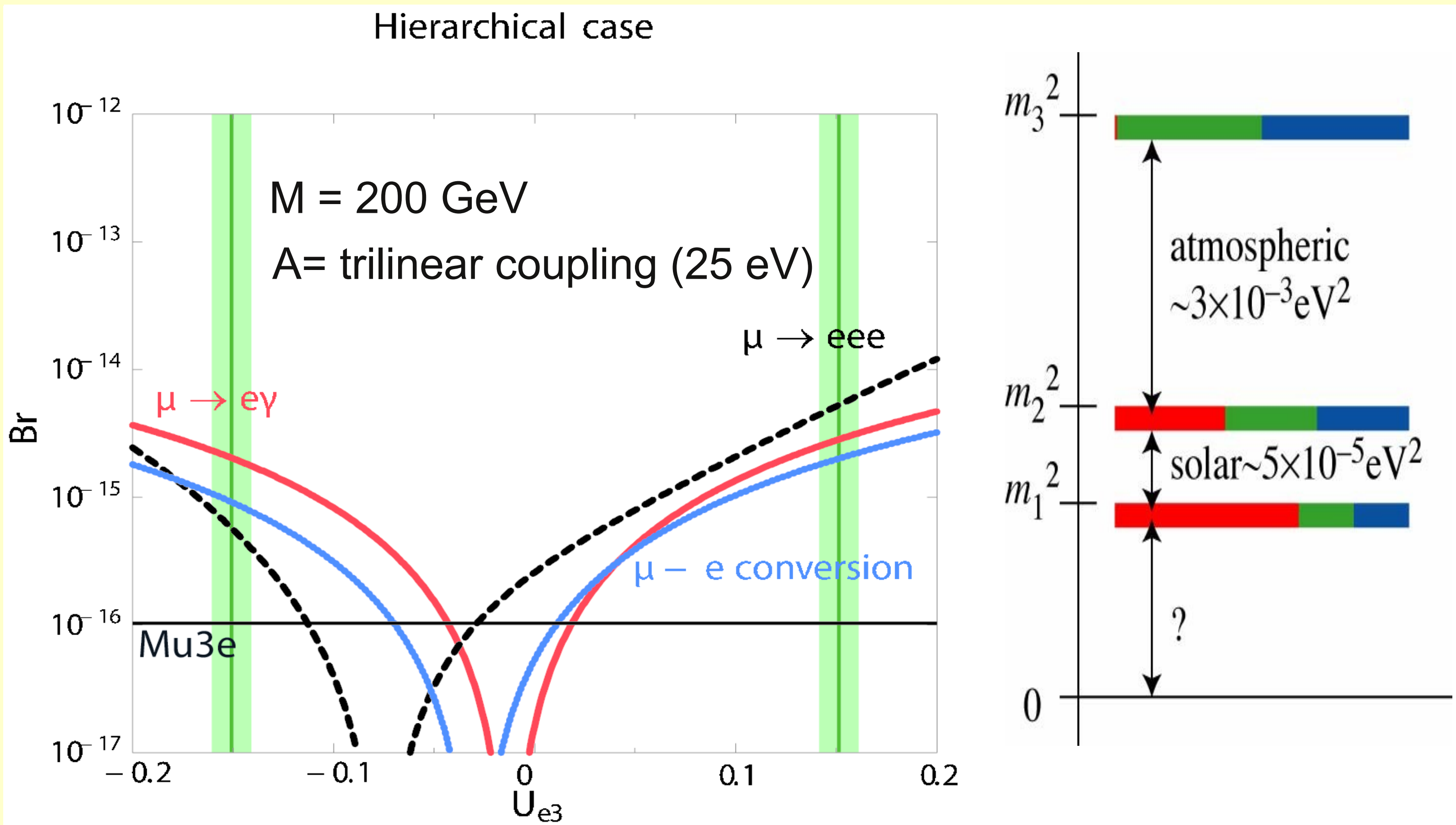
M.Kakizaki et al., Phys.Lett. **B566** 210, 2003

- Motivated by Left-Right Symmetric Models



+ loop diagrams

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

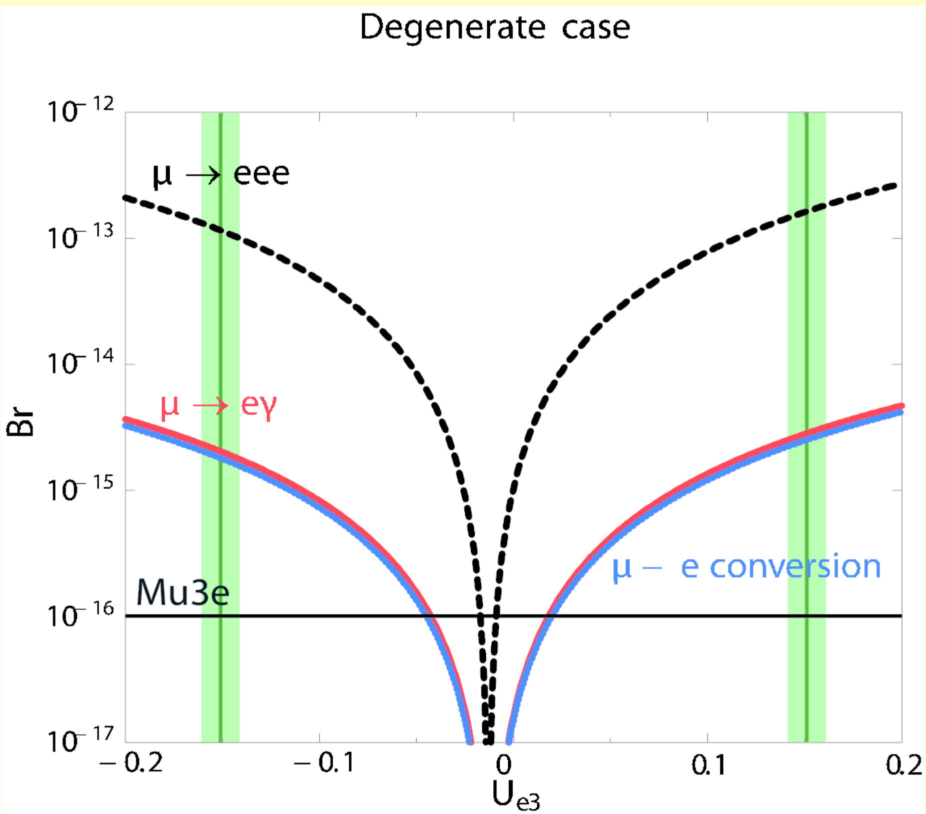


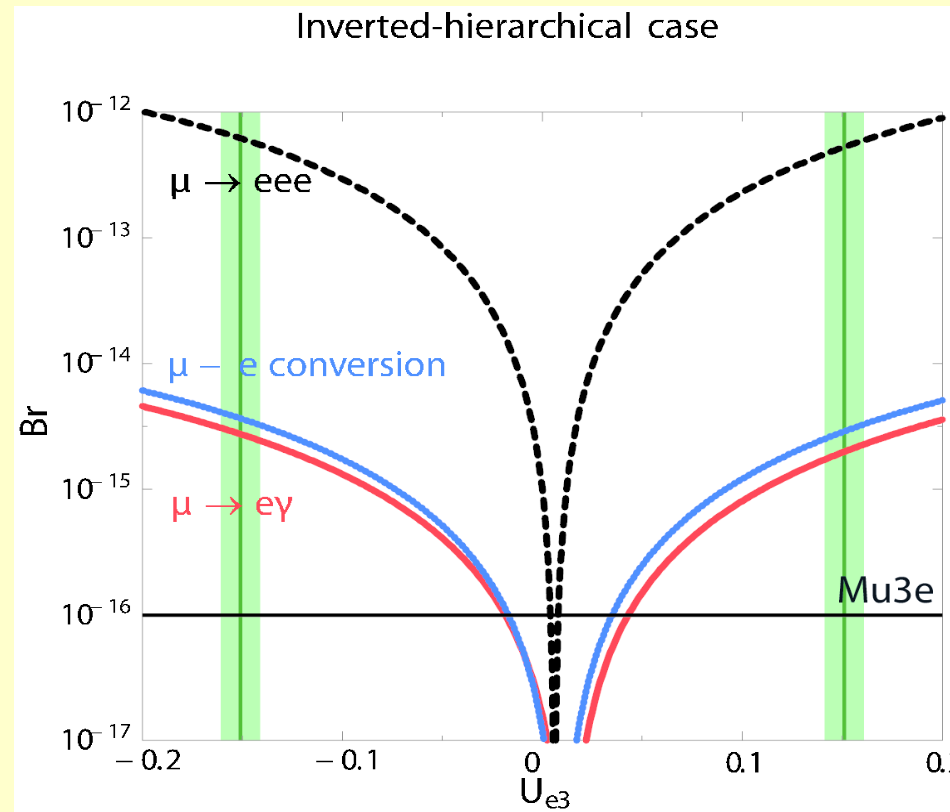
related to neutrino masses (→ mass pattern)

Example I: Higgs Triplet Models (cont'd)

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

- Motivated by Left-Right Symmetric Models





M = 200 GeV

A= trilinear coupling (25 eV)

Example II: LFV Higgs Couplings

Framework

LFV

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

LFV decays of SM Higgs:

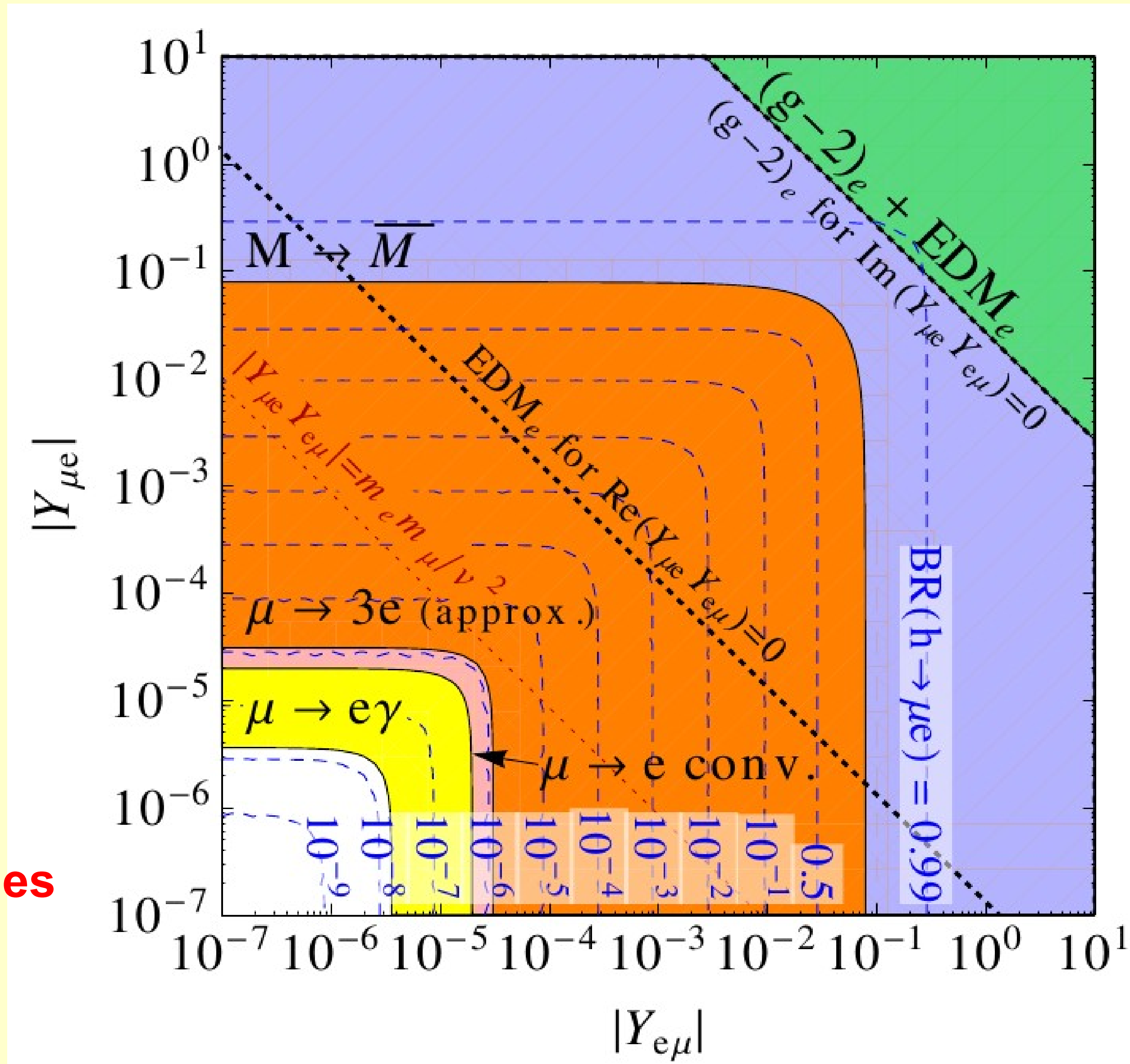
$$\mathrm{BR}(h \to \ell^\alpha \ell^\beta) = \frac{\Gamma(h \to \ell^\alpha \ell^\beta)}{\Gamma(h \to \ell^\alpha \ell^\beta) + \Gamma_{\mathrm{SM}}}$$

LFV muon decay:

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

LHC and muon decay searches are largely complementary!

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



Example III: Low Scale Seesaw Model

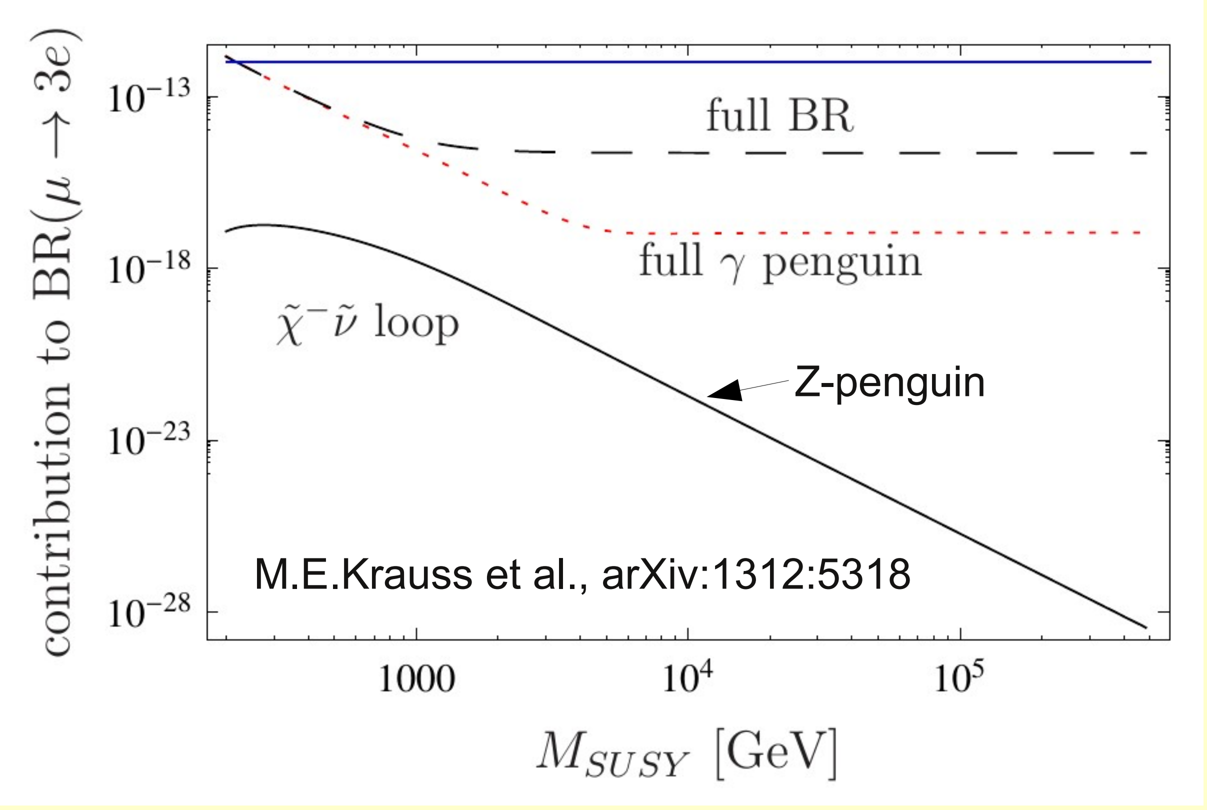
"Inverted Seesaw Model"

$$W_{IS} = W_{\mathrm{MSSM}} + Y_\nu \hat{\nu}^c \hat{L} \hat{H}_u + M_R \hat{\nu}^c \hat{N}_S + \frac{\mu_N}{2} \hat{N}_S \hat{N}_S$$

right-handed neutrinos

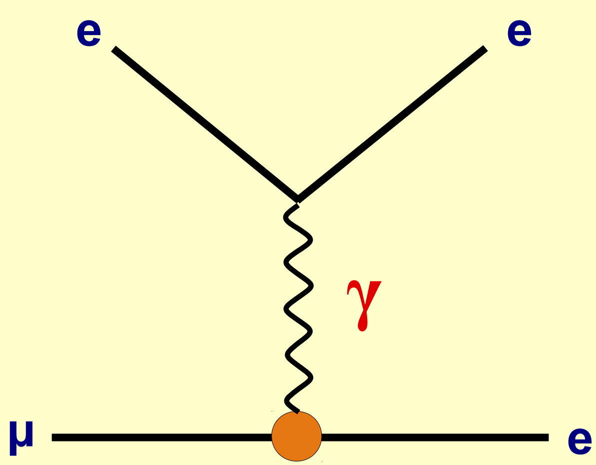
leptonic gauge singlets

$$m_\nu \propto \mu_N$$

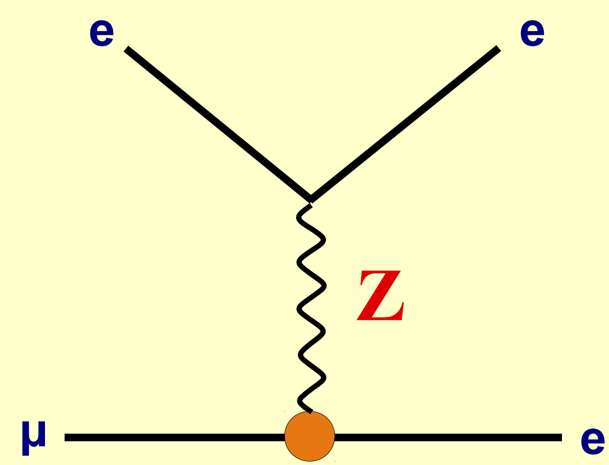


$\mu^+ \rightarrow e^+e^+e^-$ Penguin Loop and Box Diagrams

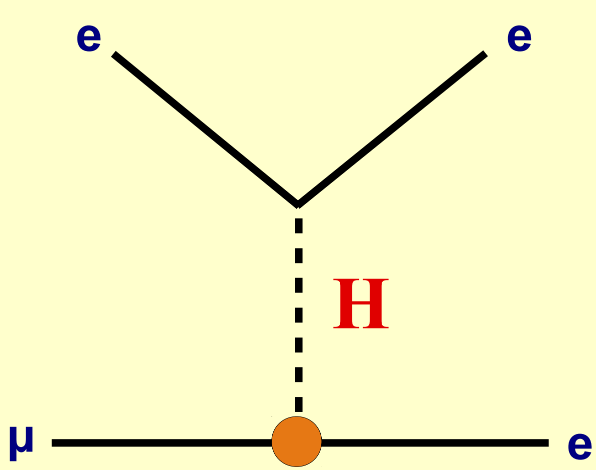
$\mu^+ \rightarrow e^+e^+e^-$



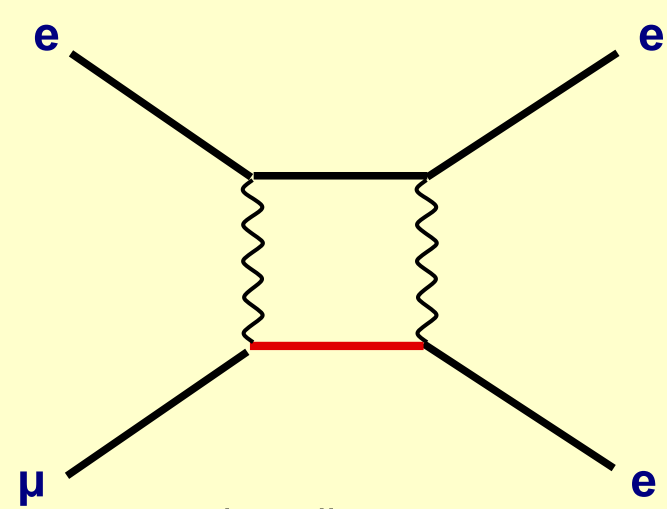
photon penguin



Z - penguin

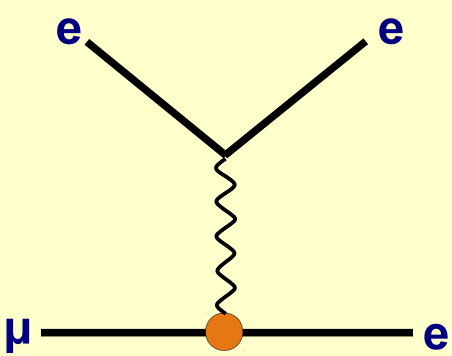


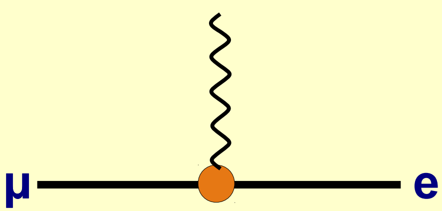
Higgs-penguin



box diagram

Model Independent Comparison





$\kappa \rightarrow 0$

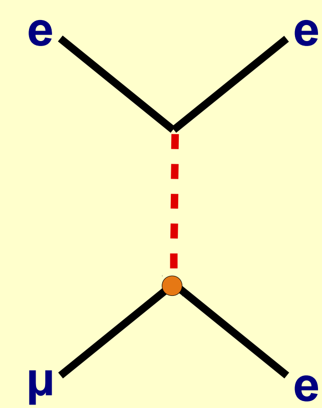
Effective cLFV Lagrangian:

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

κ = parameter

Λ = common effective mass scale

μeee contact IA

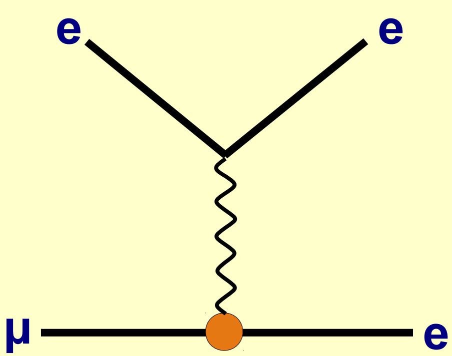


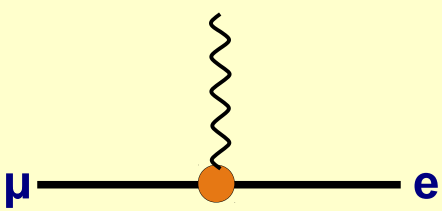
$\kappa \rightarrow \infty$

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

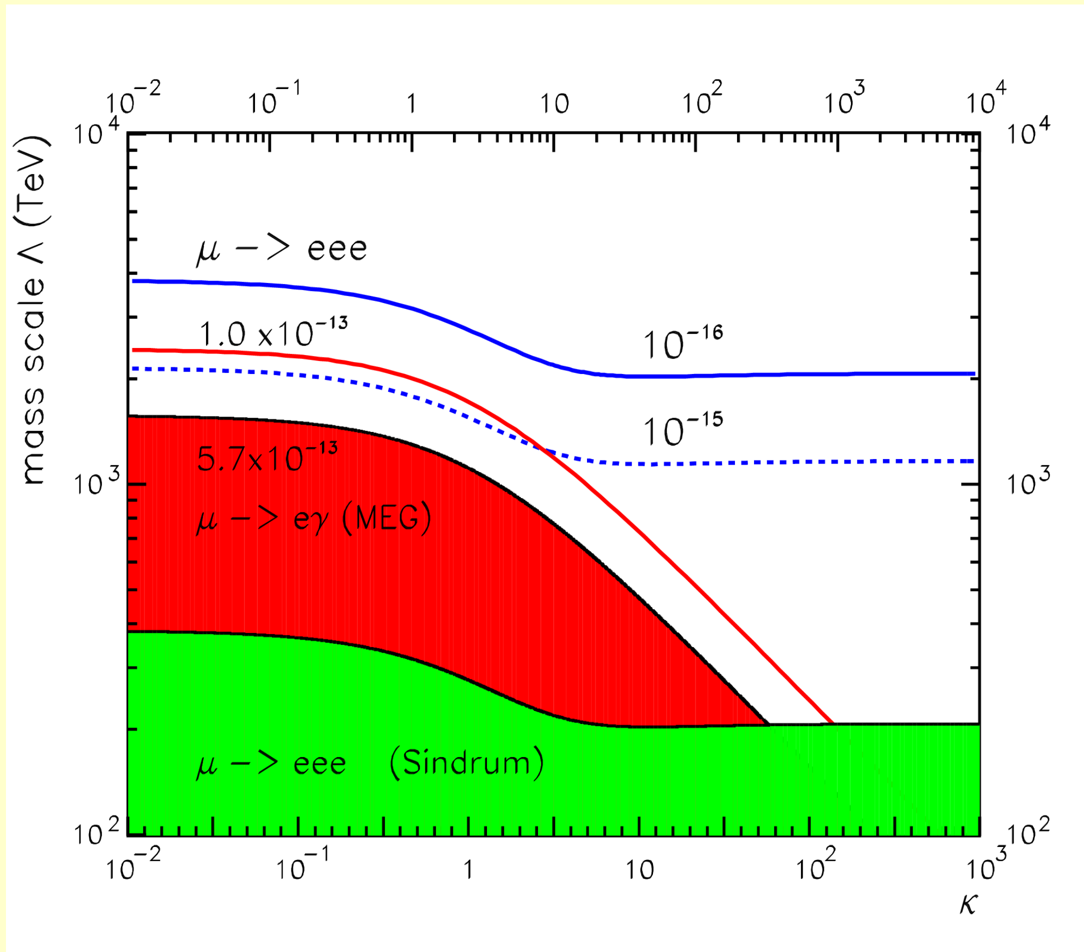
$$\frac{B(\mu^+ \rightarrow e^+e^+e^-)}{B(\mu^+ \rightarrow e^+\gamma)} = \infty$$

Model Independent Comparison

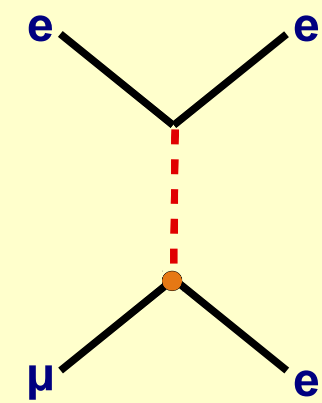




$\kappa \rightarrow 0$



μeee contact IA



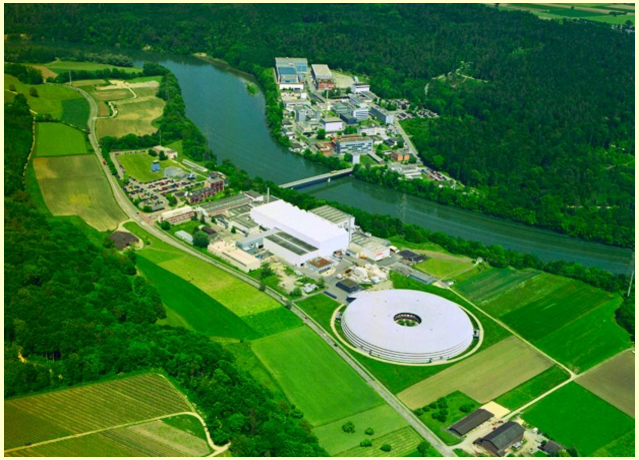
$\kappa \rightarrow \infty$

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

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

Mu3e Experiment

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



project approved in Jan 2013

- 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

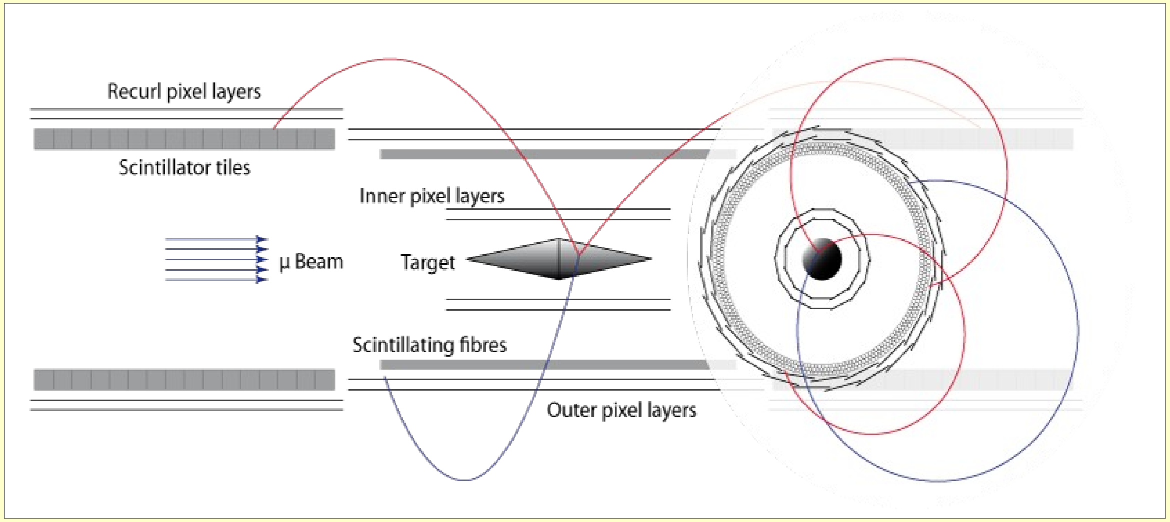
new collaborators KIT (Karlsruhe) + Uni Mainz

<u>Aiming for a sensitivity of</u>

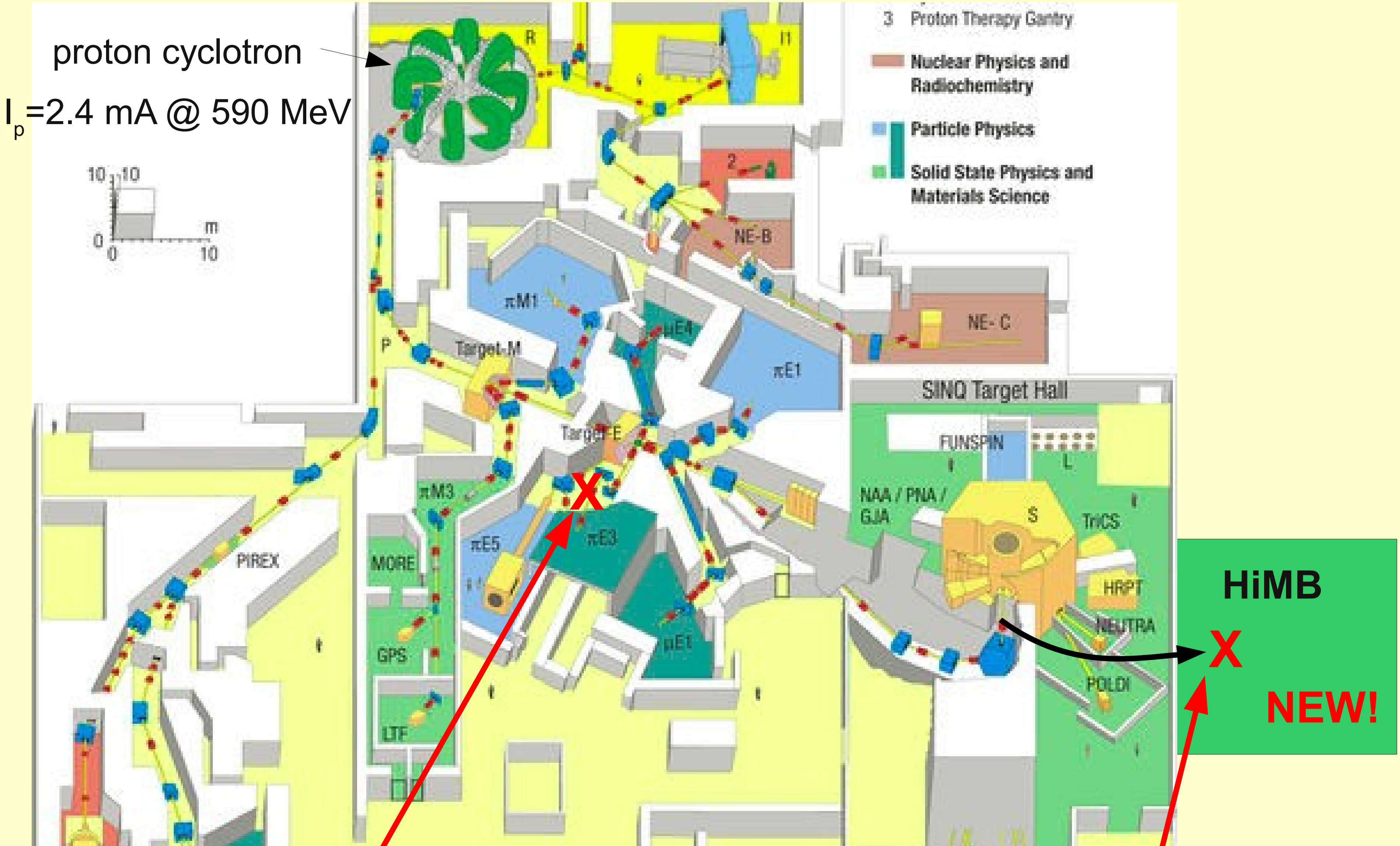
$BR(\mu \rightarrow e\,e\,e) < 10^{-15}$ (phase I)

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

before end of this decade



PSI Facility for Mu3e

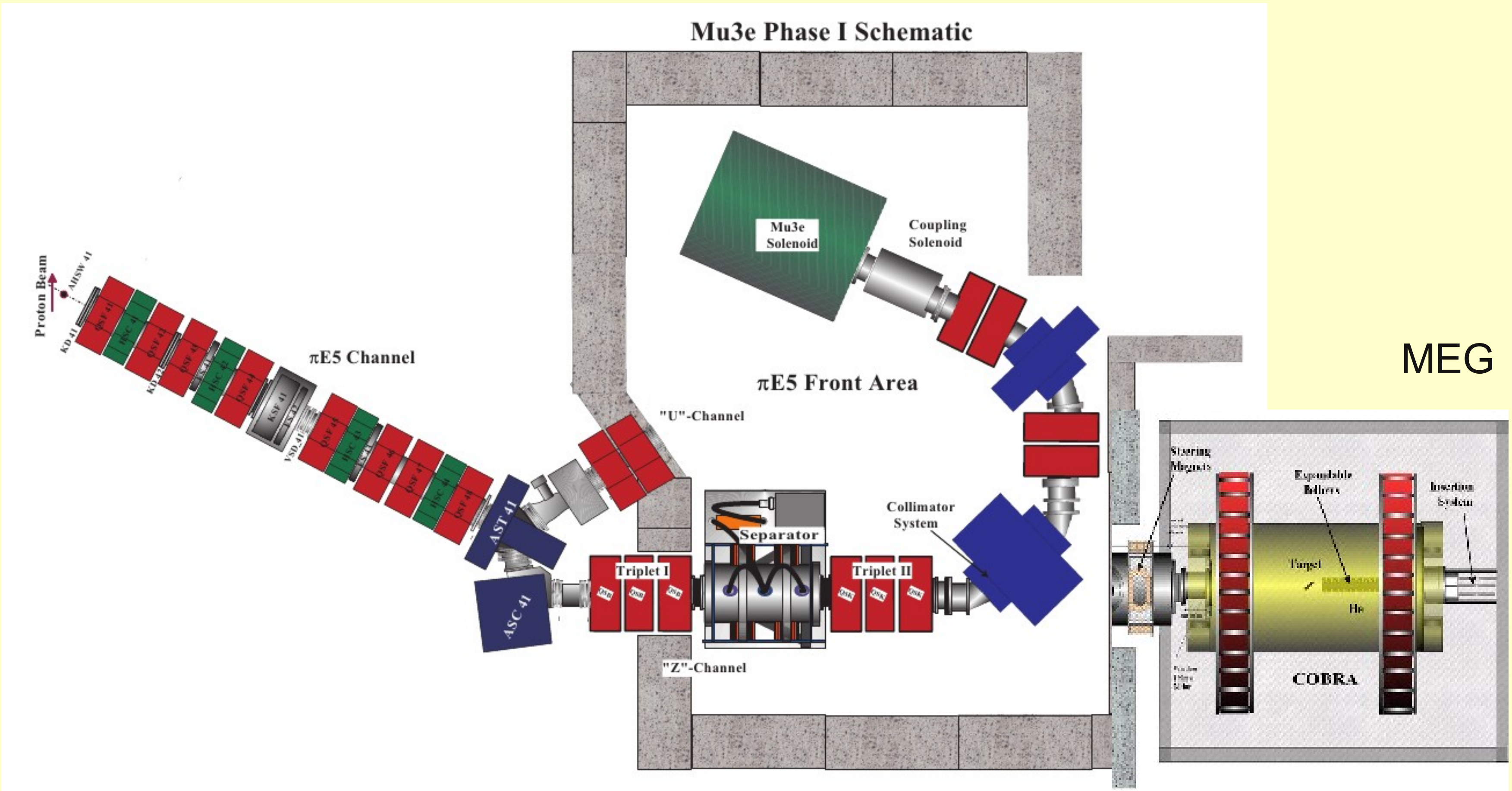


Phase I (2015+): ~10^8 muons/s

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

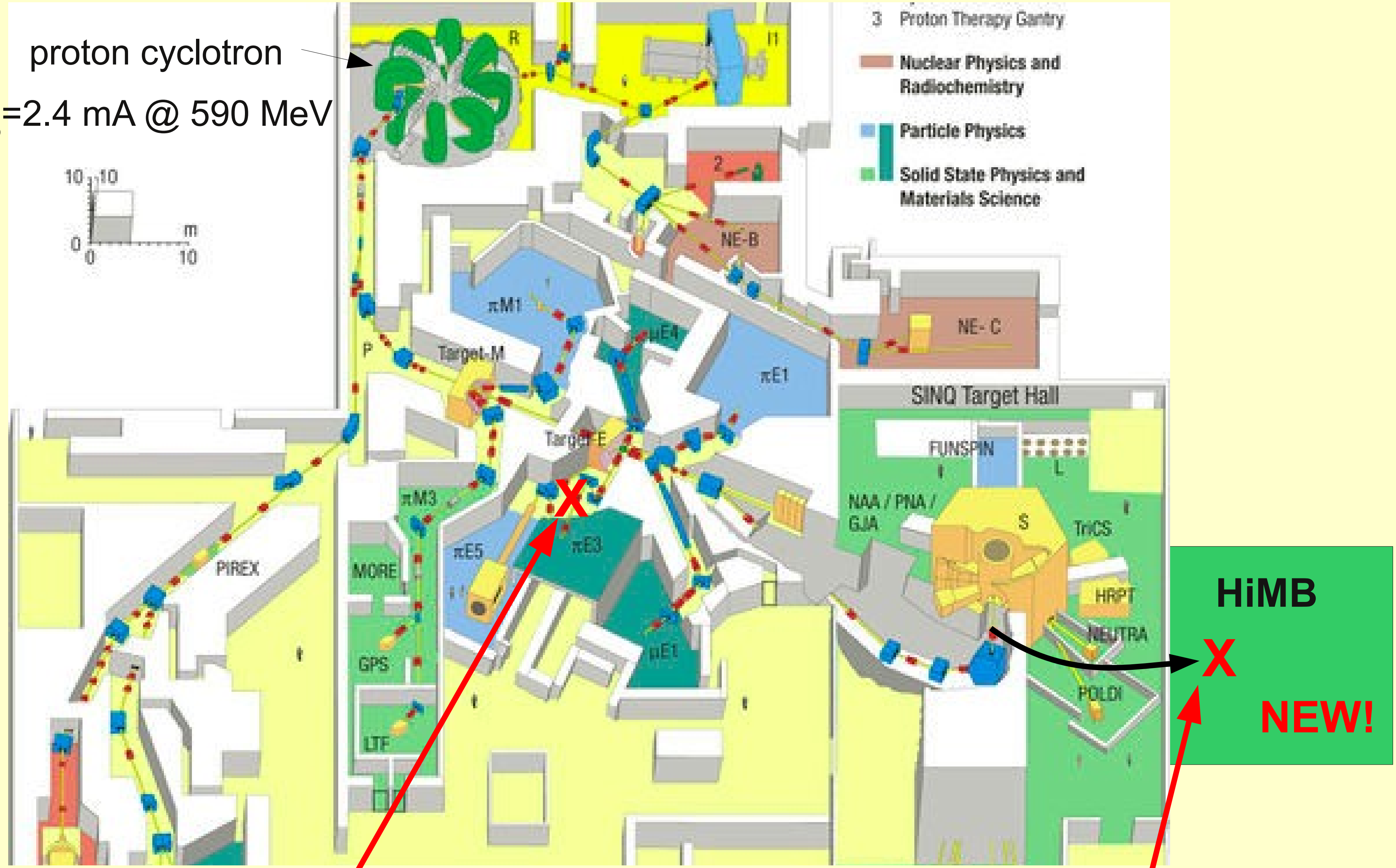
πe5 Beamline (Phase I)

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



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

PSI Facility for Mu3e



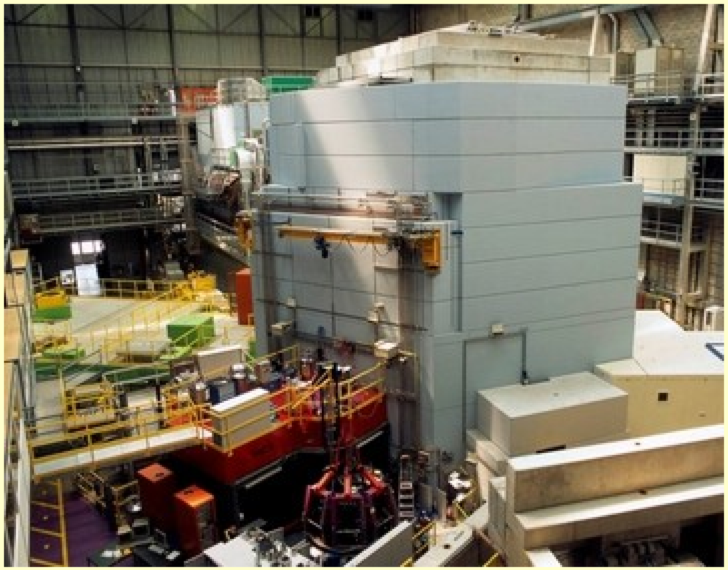
Phase I (2015+): ~**10^8** muons/s

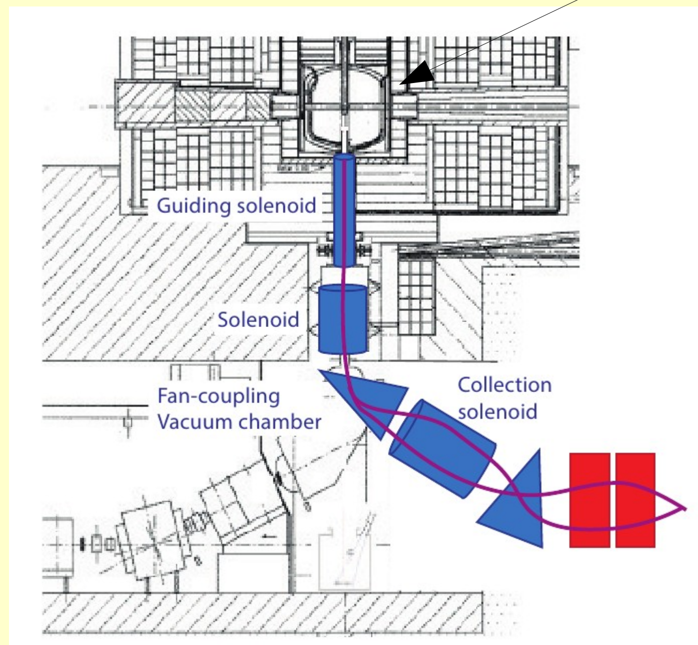
Phase II (>2017): **>10^9** muons/s

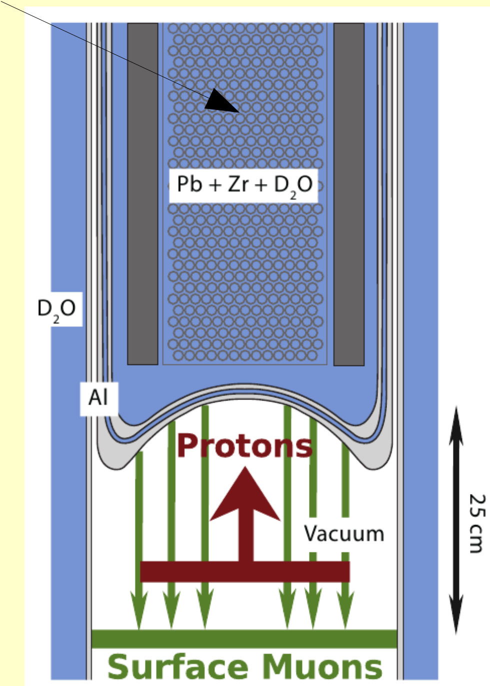
High Intensitiy Muon Beamline (Phase II)

HiMB = High Intensity Muon Beamline

10^{11} muons



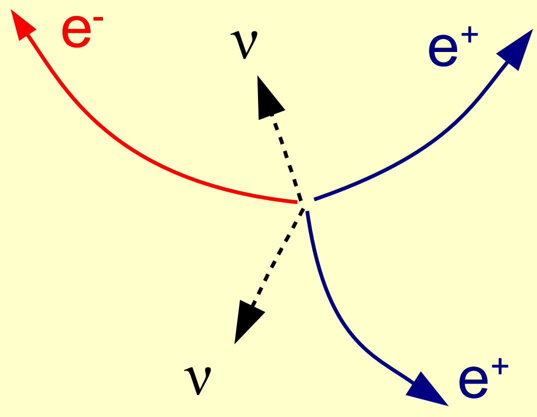


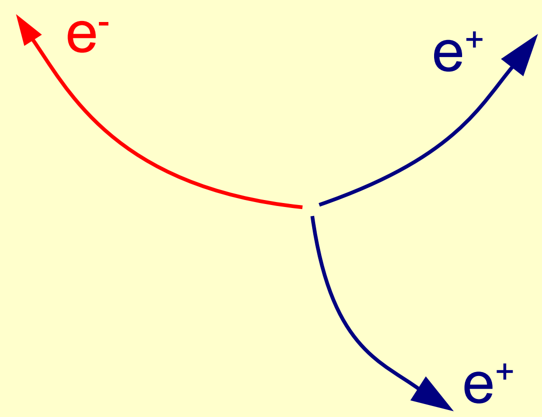


- Muon rates in excess of 10^9 per second in beam phase acceptance possible
- **$2 \cdot 10^9$ muons/s** needed to reach ultimate goal of **$B(\mu^+ \rightarrow e^+e^+e^-) < 10^{-16}$**
- **Not before 2019**

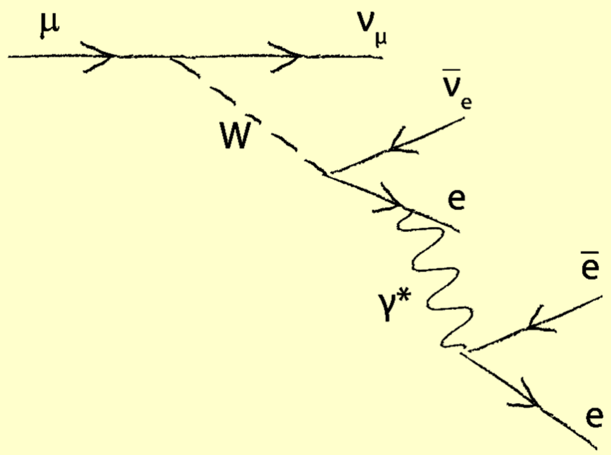
Backgrounds

Irreducible BG: radiative decay with internal conversion





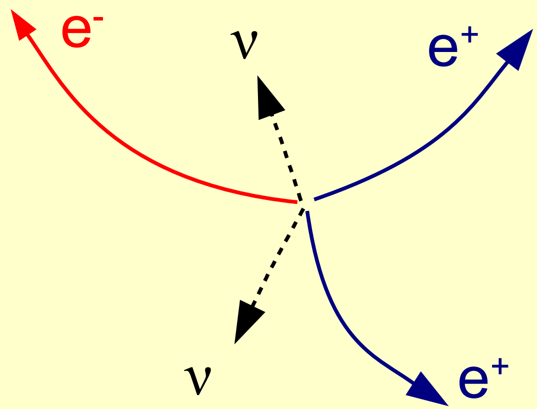
$B(\mu^+ \rightarrow e^+e^+e^- \nu\nu) = 3.4 \cdot 10^{-5}$



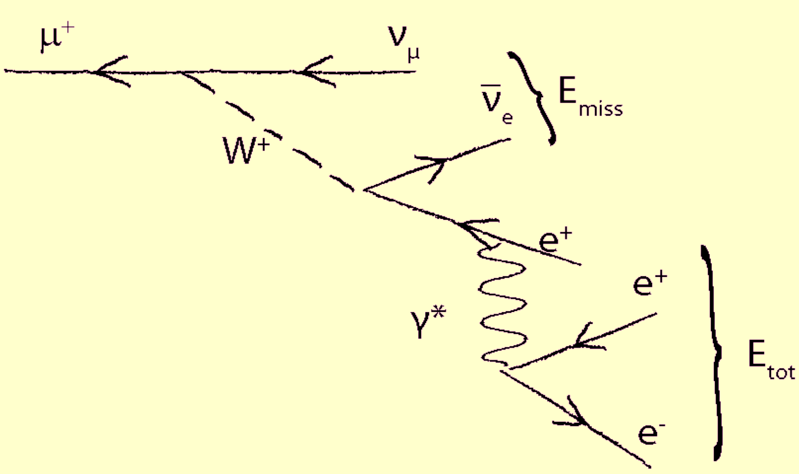
$$\sum_i E_i = m_\mu$$
$$\sum_i \vec{p}_i = 0$$

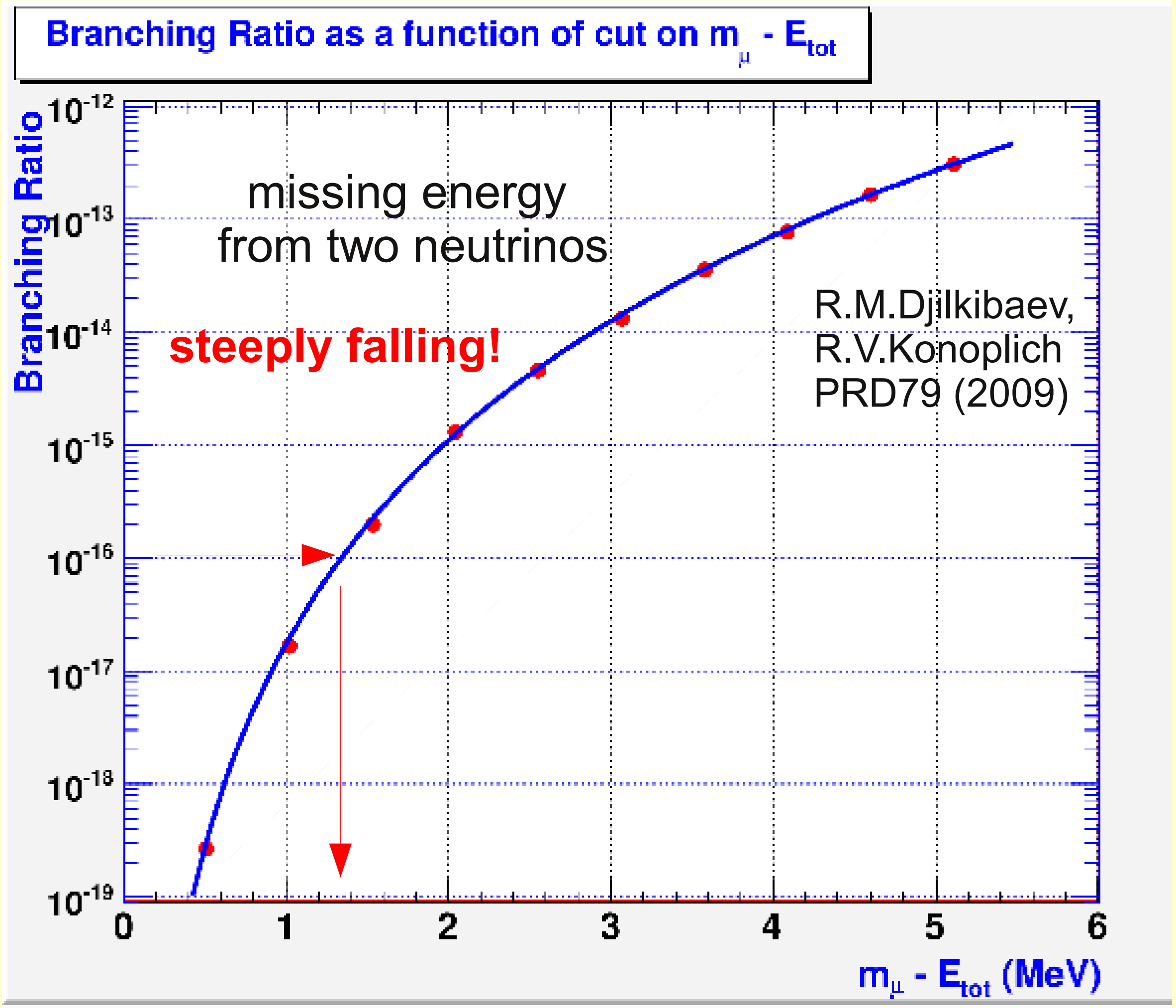
Backgrounds

Irreducible BG: radiative decay with internal conversion



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

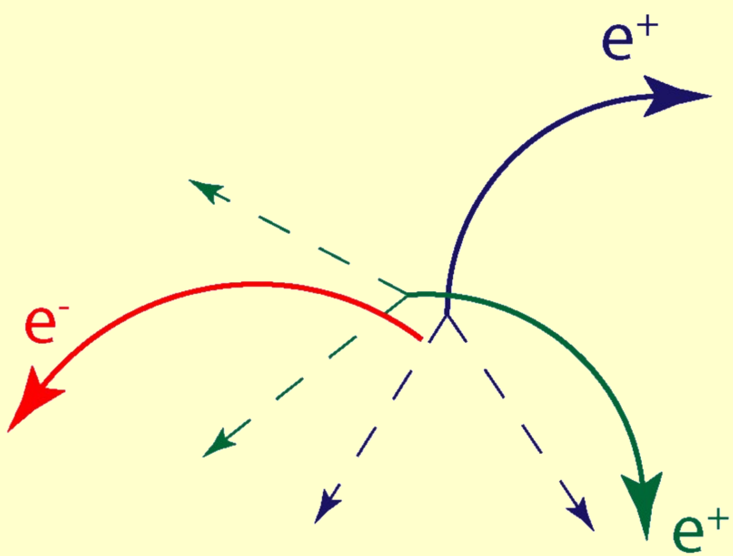


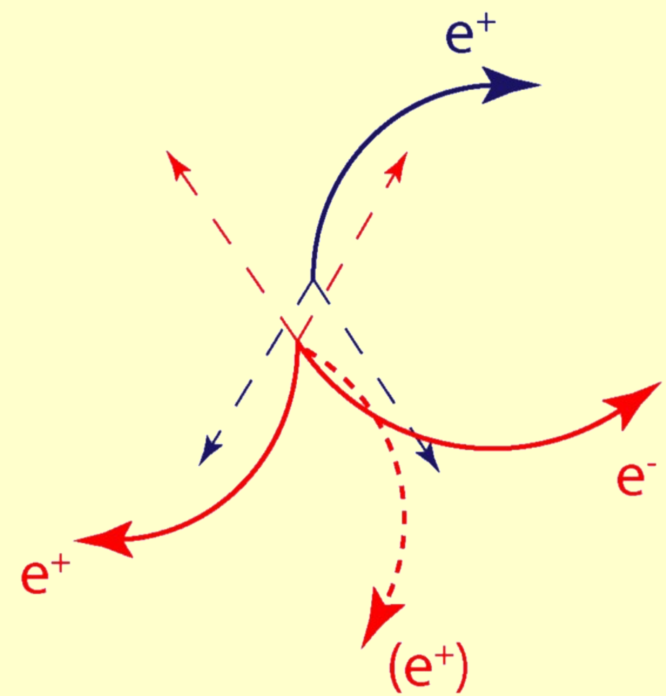


very good momentum +
total energy resolution required!

Accidental Backgrounds

- **Overlays** of two ordinary **μ^+ decays** with a (fake) **electron (e^-)**
- Electrons from: Bhabha scattering, photon conversion, mis-reconstruction

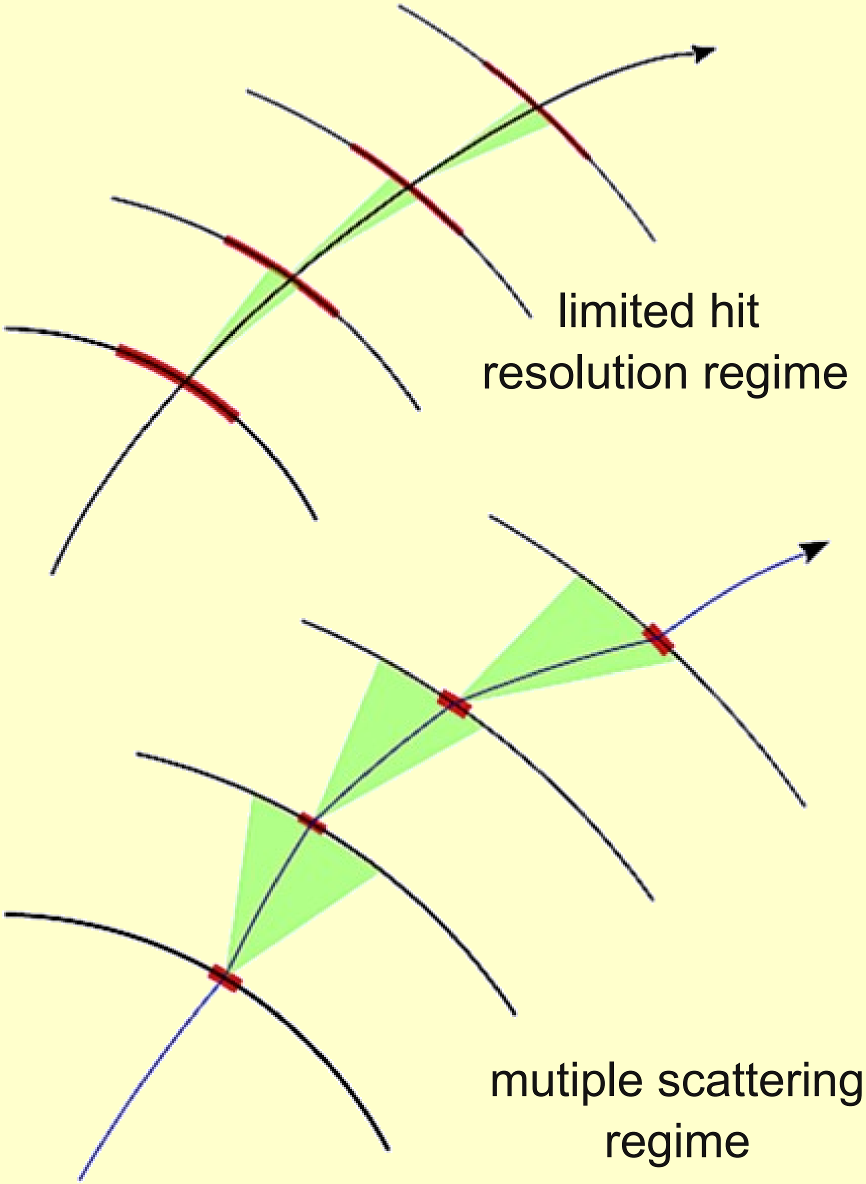




Need excellent:

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

Kinematic Resolution + Multiple Scattering



- <u>Muon decay:</u>

  → electrons in low momentum range
  p < 53 MeV/c

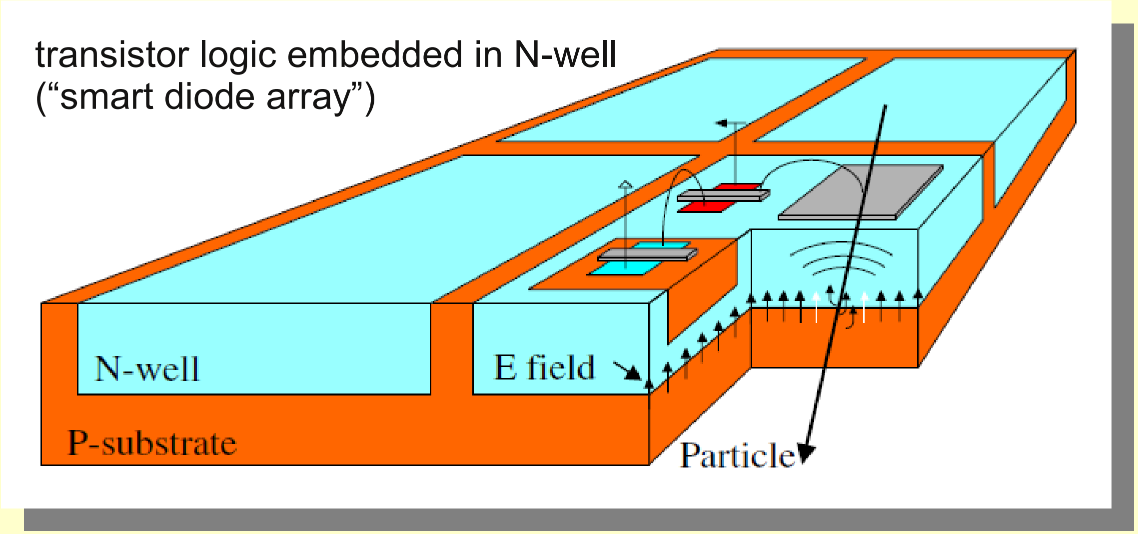
- Multiple scattering is dominant!

➔ **Need thin, fast and high resolution tracking detectors operated at high rate of ~ 10^9 particles/s**

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

Silicon Pixel Detector

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



Technology Choice

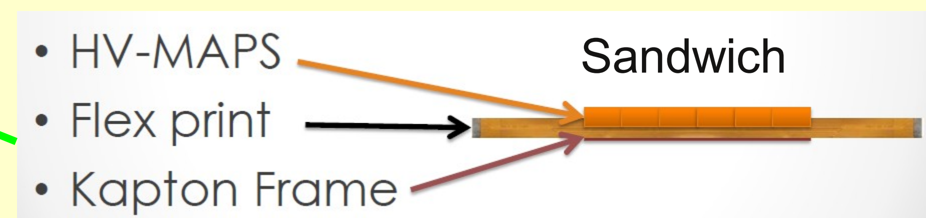
High Voltage Monolithic Active Pixel Sensors (HV-MAPS)

- high precision → pixels 80 x 80 μm^2
- can be "thinned" down to ~**35 μm** (~ 0.0005 X_0)
- low production costs (standard HV-CMOS process, 60-80 V)
- active sensors → hit finding + digitisation + readout
- triggerless and fast readout (LVDS link integrated)
- low power: ~150 mW/cm^2

Mechanical Prototypes for Pixel Tracker

<u>Ultra-thin detector mock-up:</u>
- sandwich of 25 µm Kapton®
- 50/100 µm glass (instead of Si)

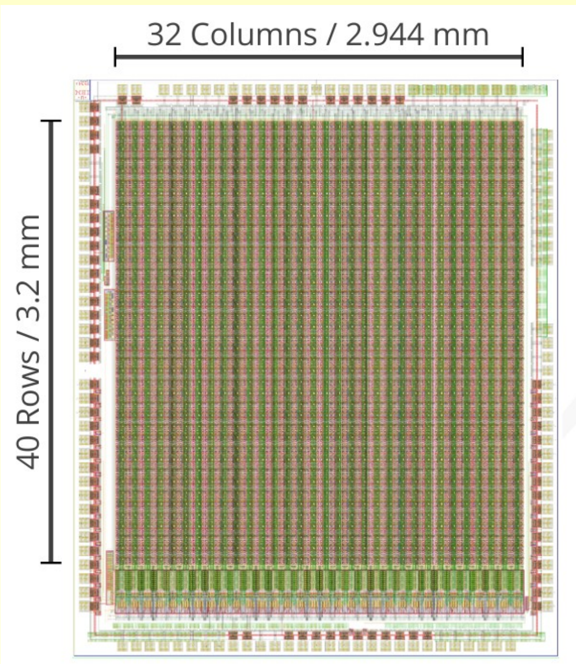
50 mu silicon wafer

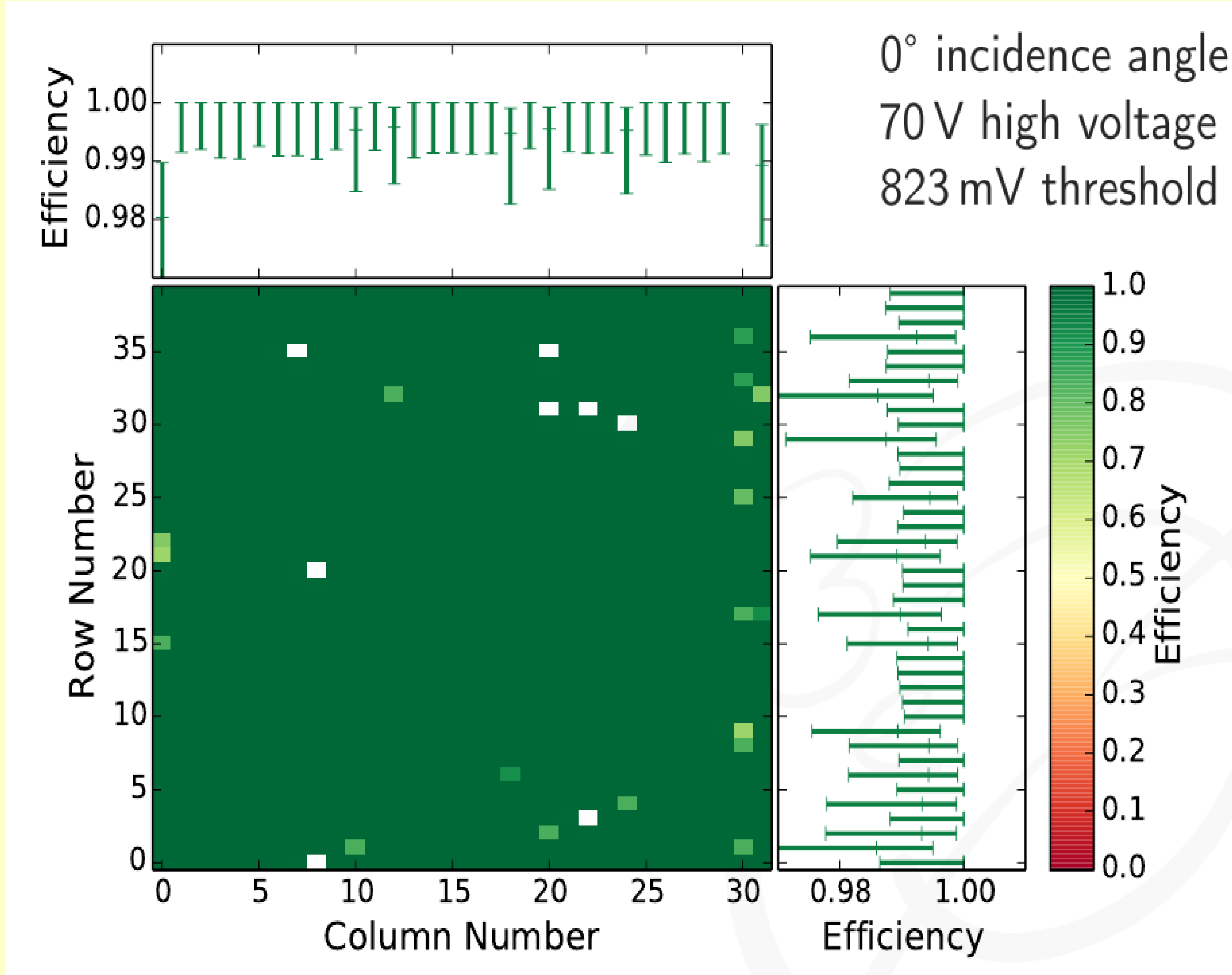


$X \leq 0.1\%\ X_0$ per layer possible

Test Beam Results for HV-MAPS

MuPix4 Prototype



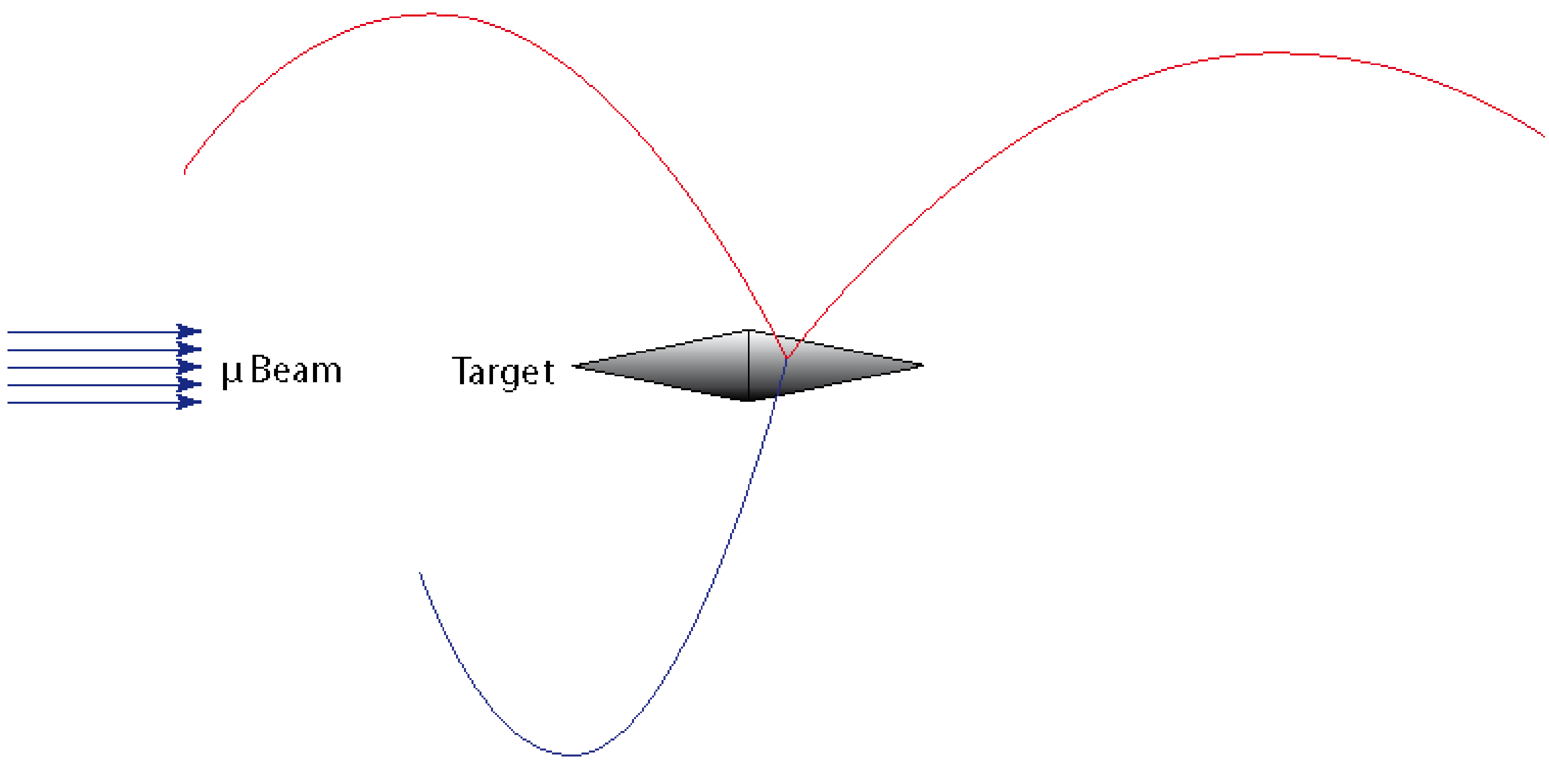


sensor efficiency > 99.5%

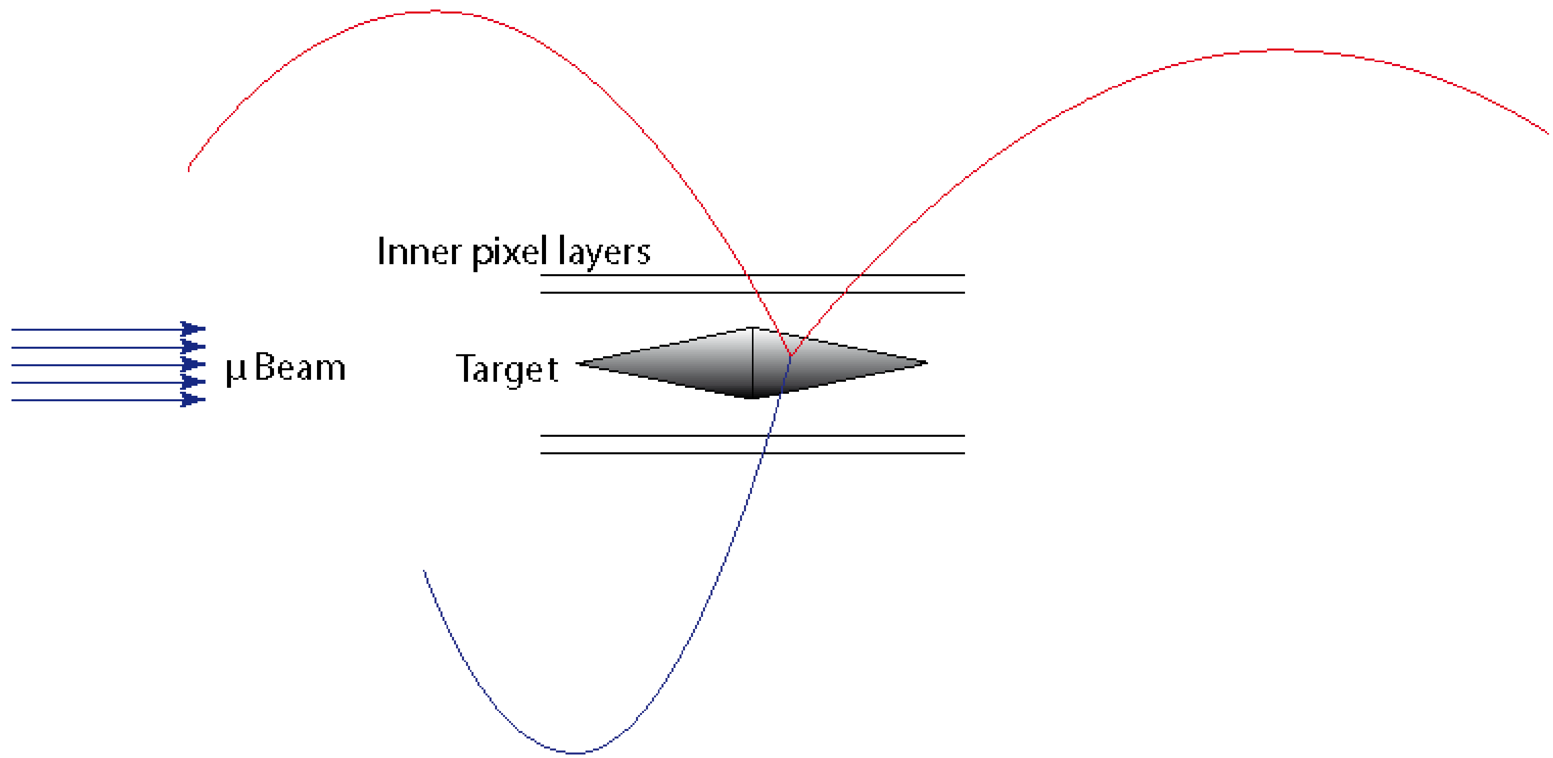
Mu3e Experimental Proposal

Mu3e Baseline Design

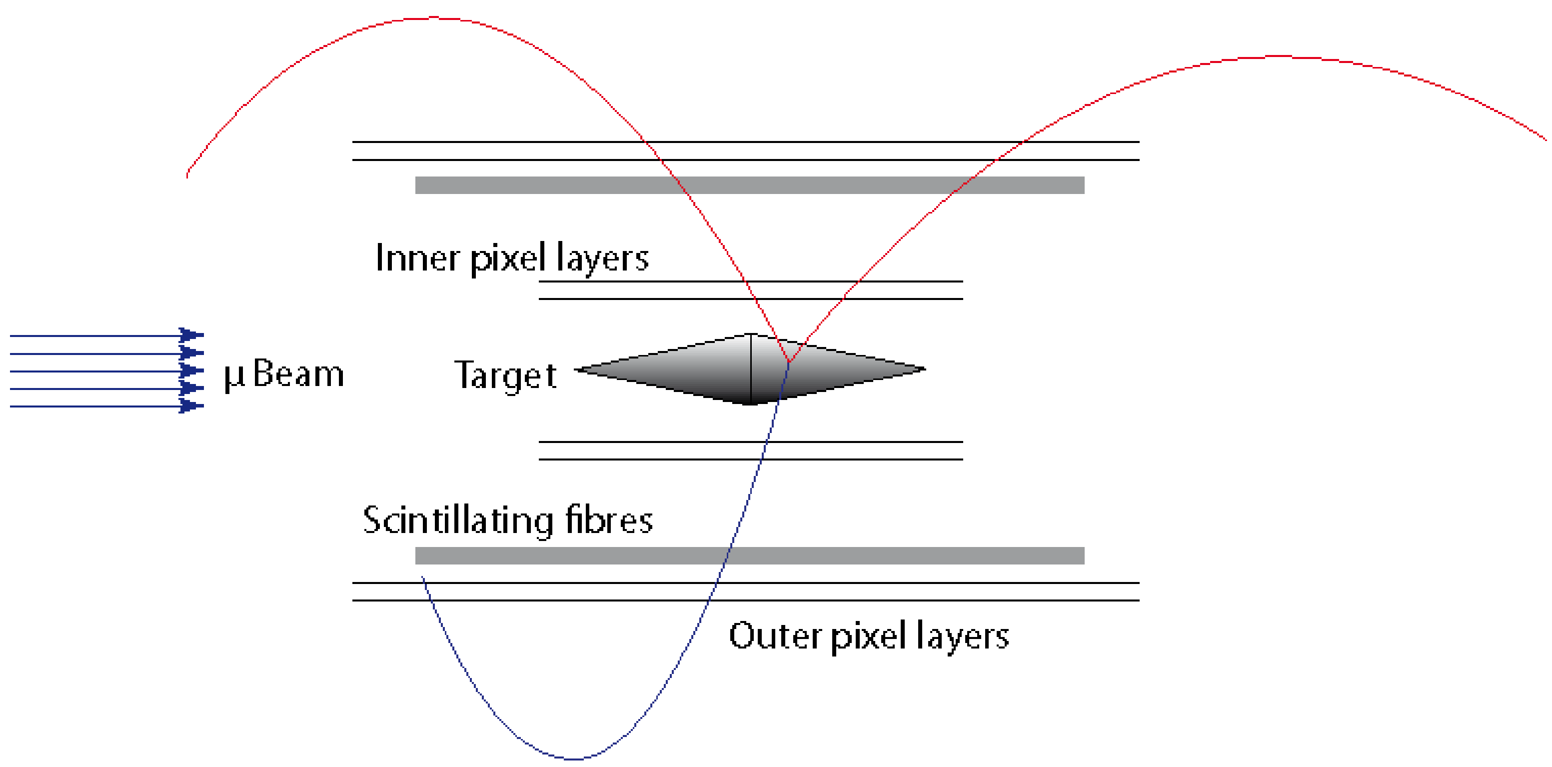
Mu3e Baseline Design



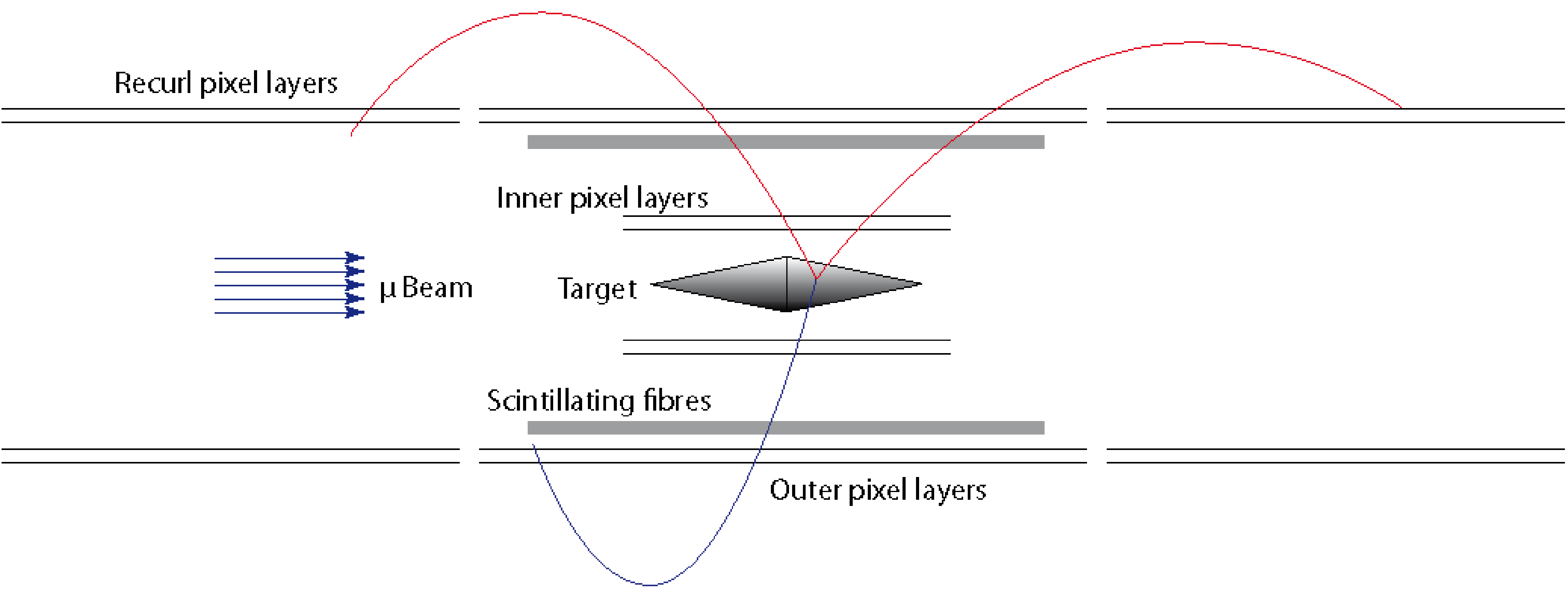
Mu3e Baseline Design



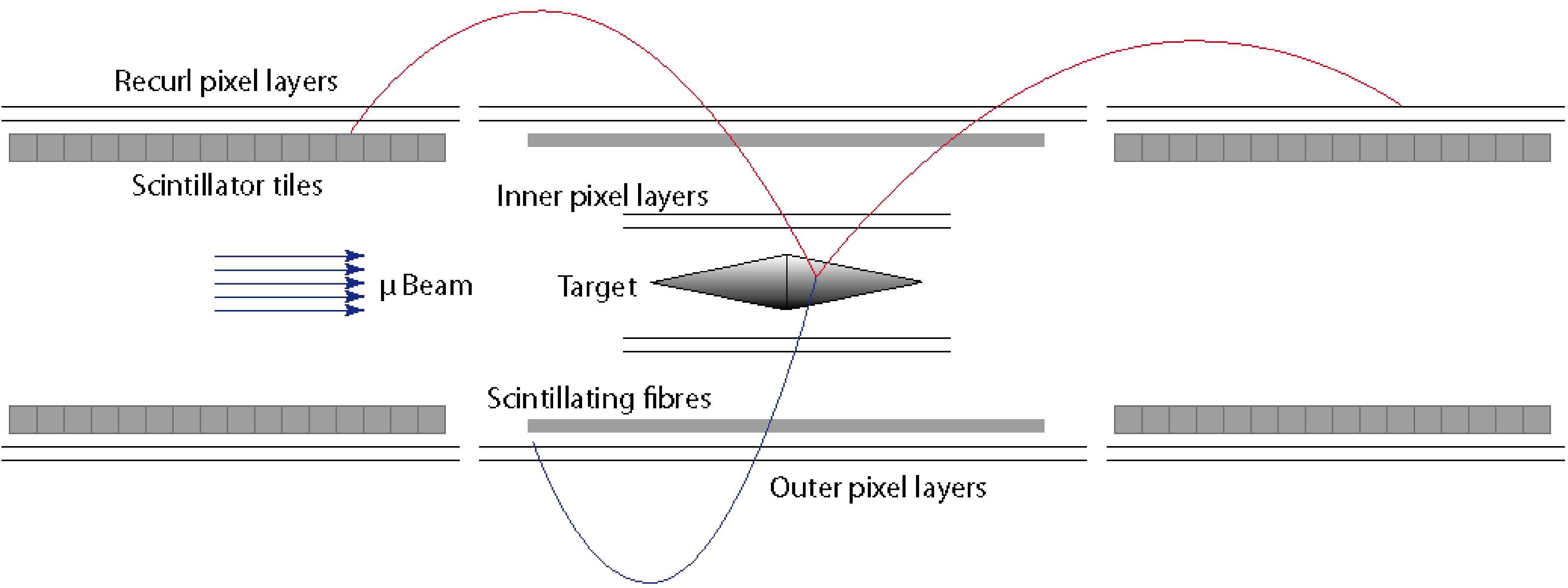
Mu3e Baseline Design



Mu3e Baseline Design



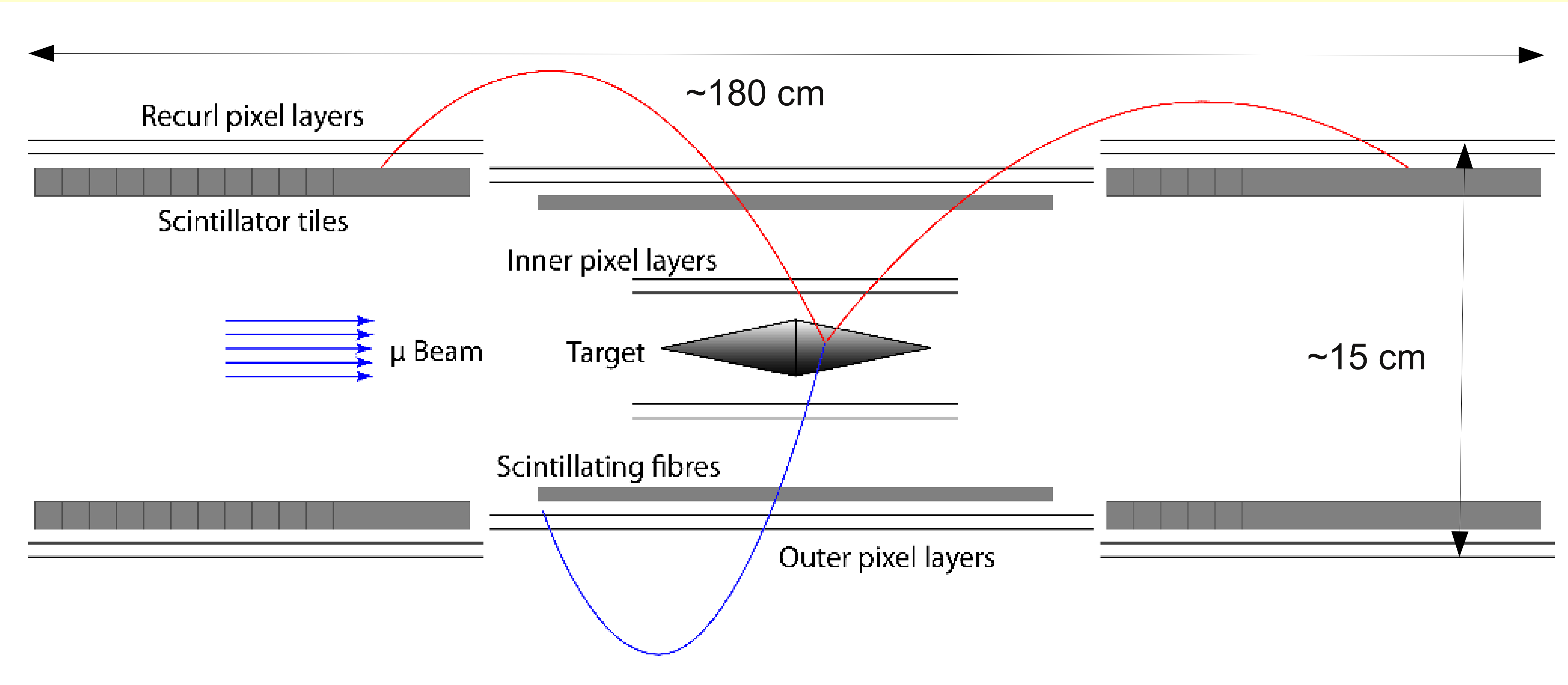
Mu3e Baseline Design



Mu3e Baseline Design

Long cylinder!

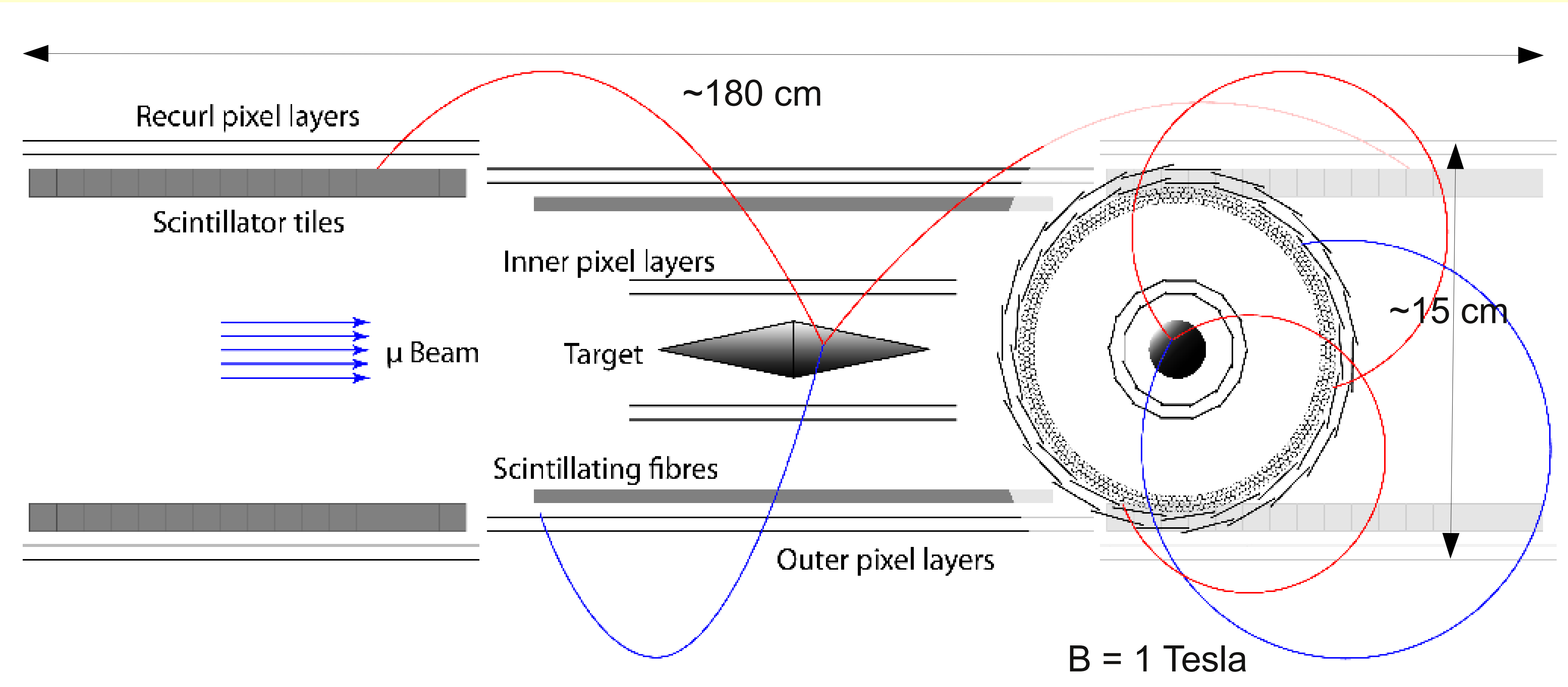
not to scale!



Mu3e Baseline Design

Long cylinder!

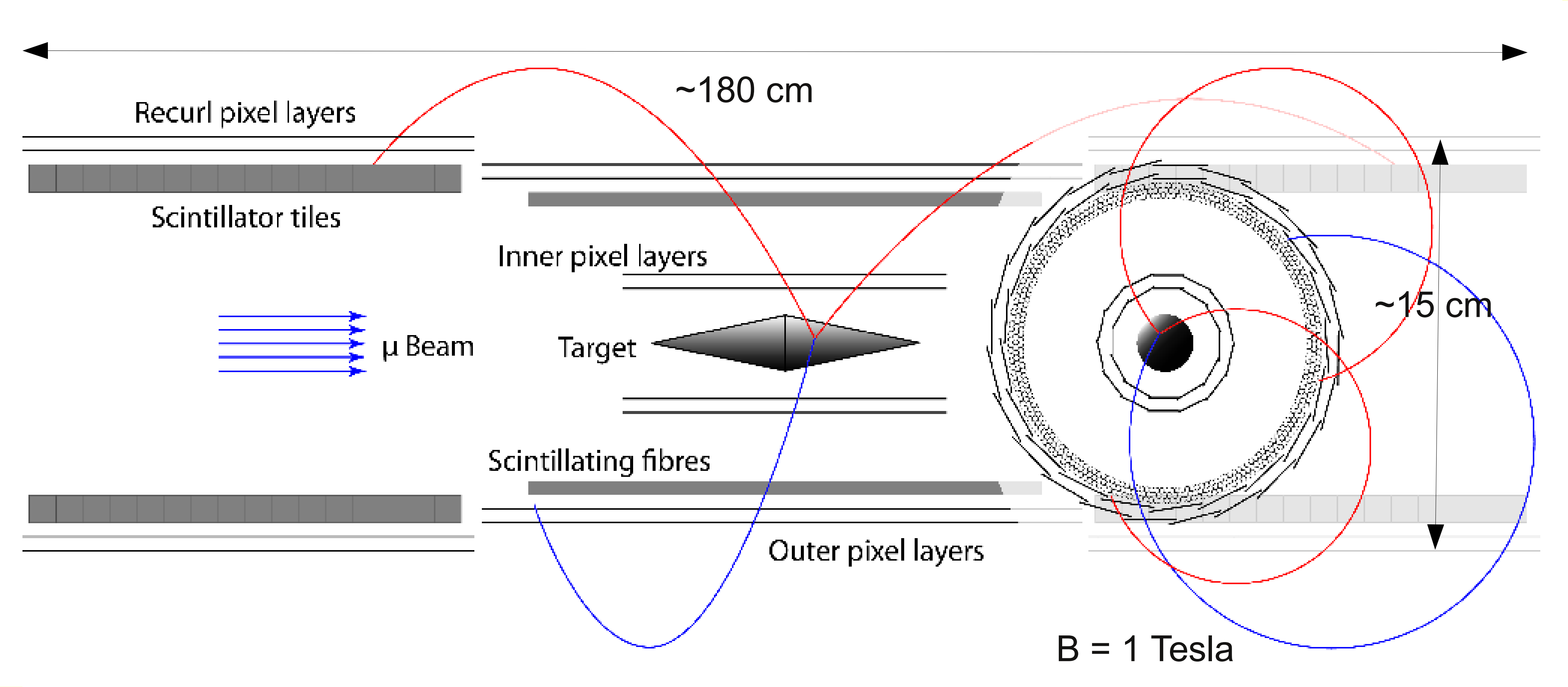
not to scale



Mu3e Baseline Design

Long cylinder!

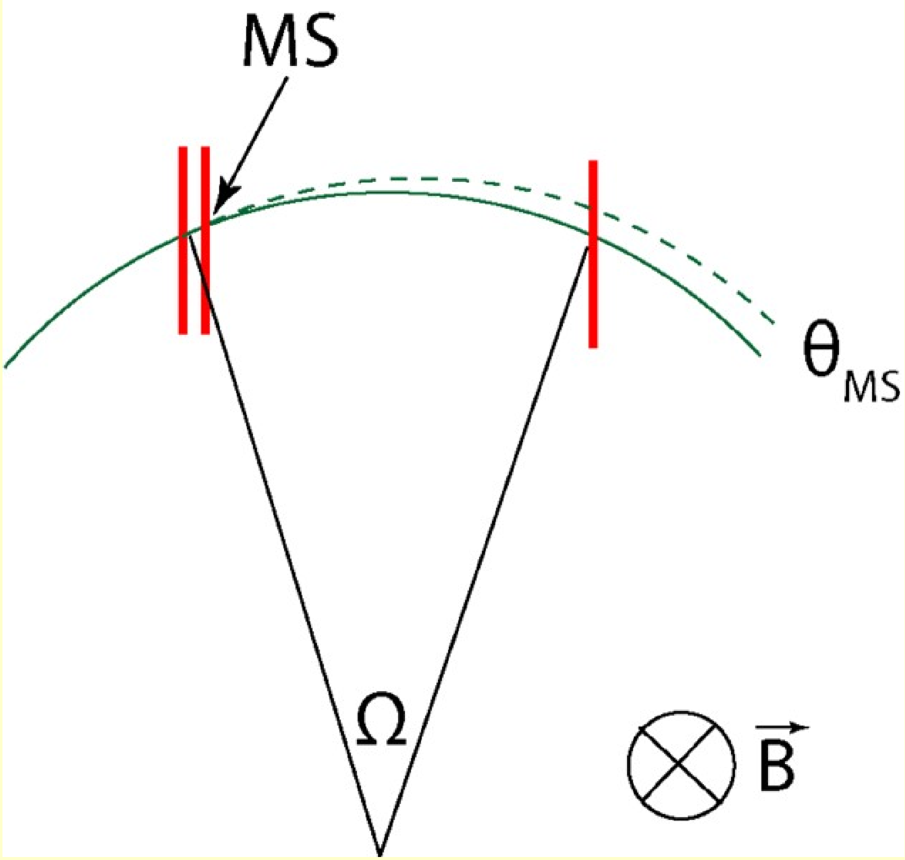
not to scale



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

Momentum Resolution in MS Regime

- Standard spectrometer:



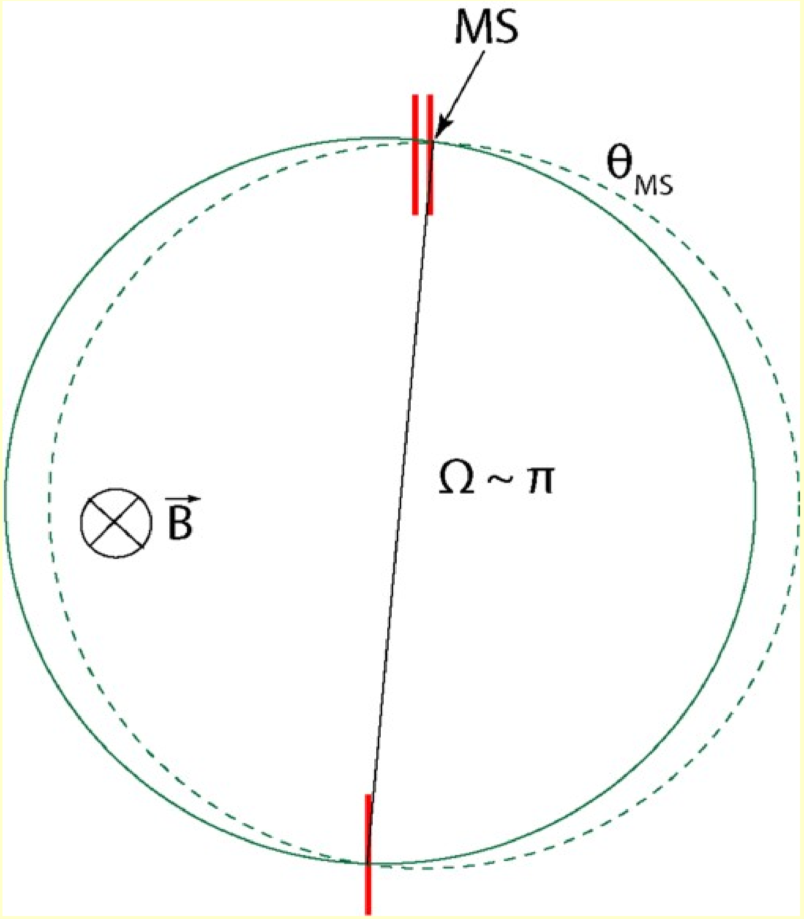
$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega}$$ (linearised)

precision requires large lever arm

large bending angle Ω

Momentum Resolution in MS Regime

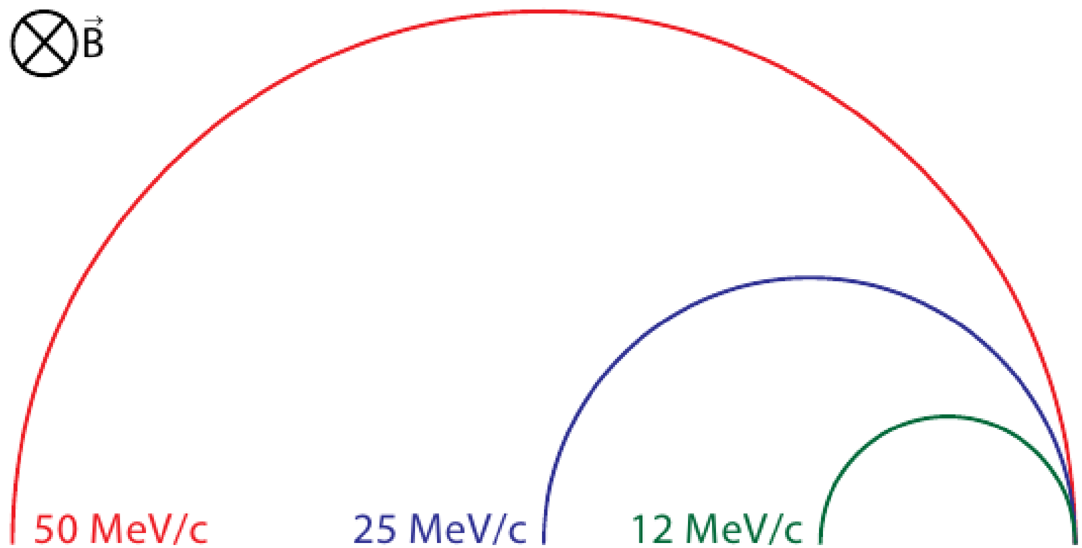
- “Half turn” spectrometer:



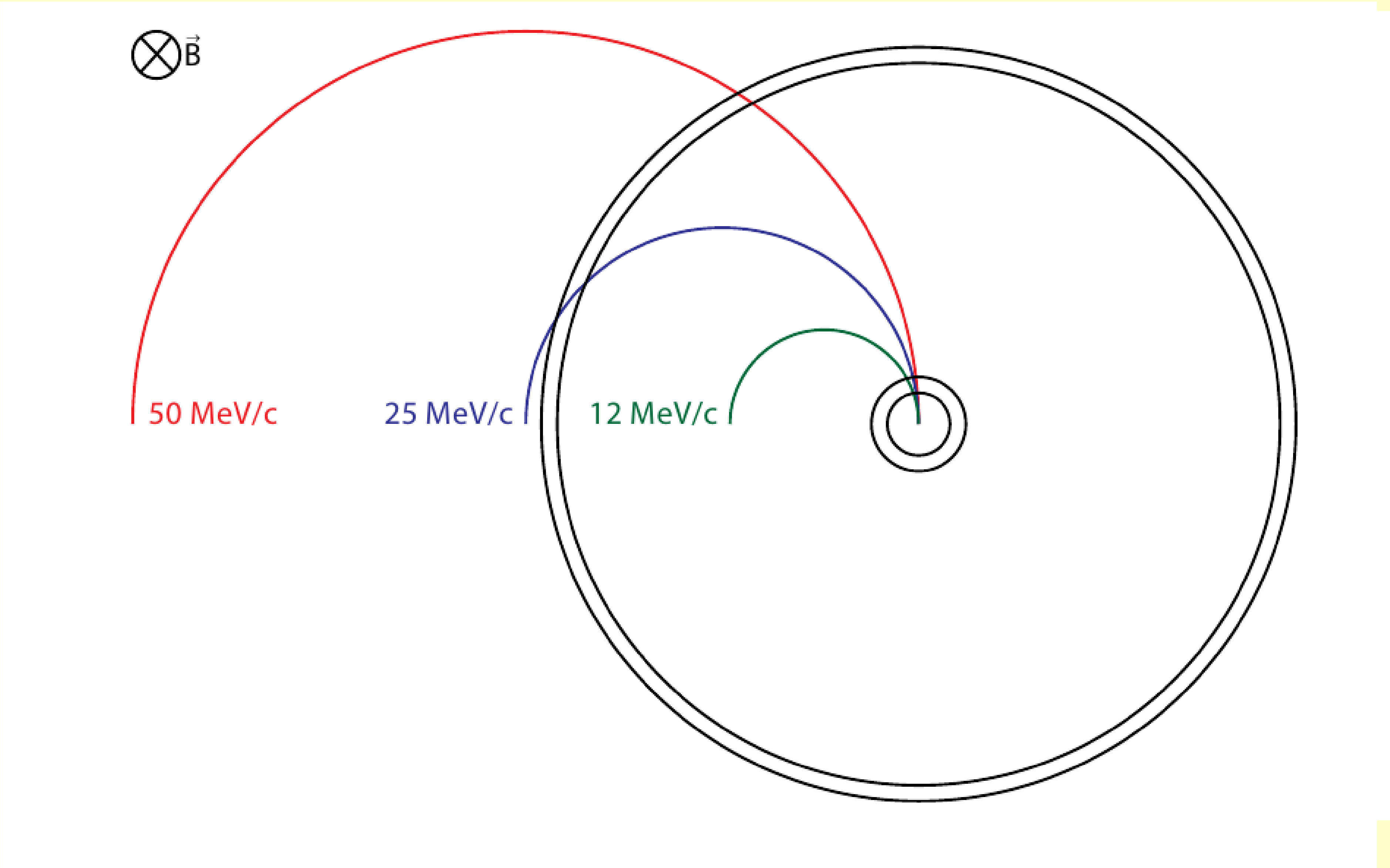
$$\frac{\sigma_p}{P} \sim O\left(\Theta_{MS}^2\right)$$

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

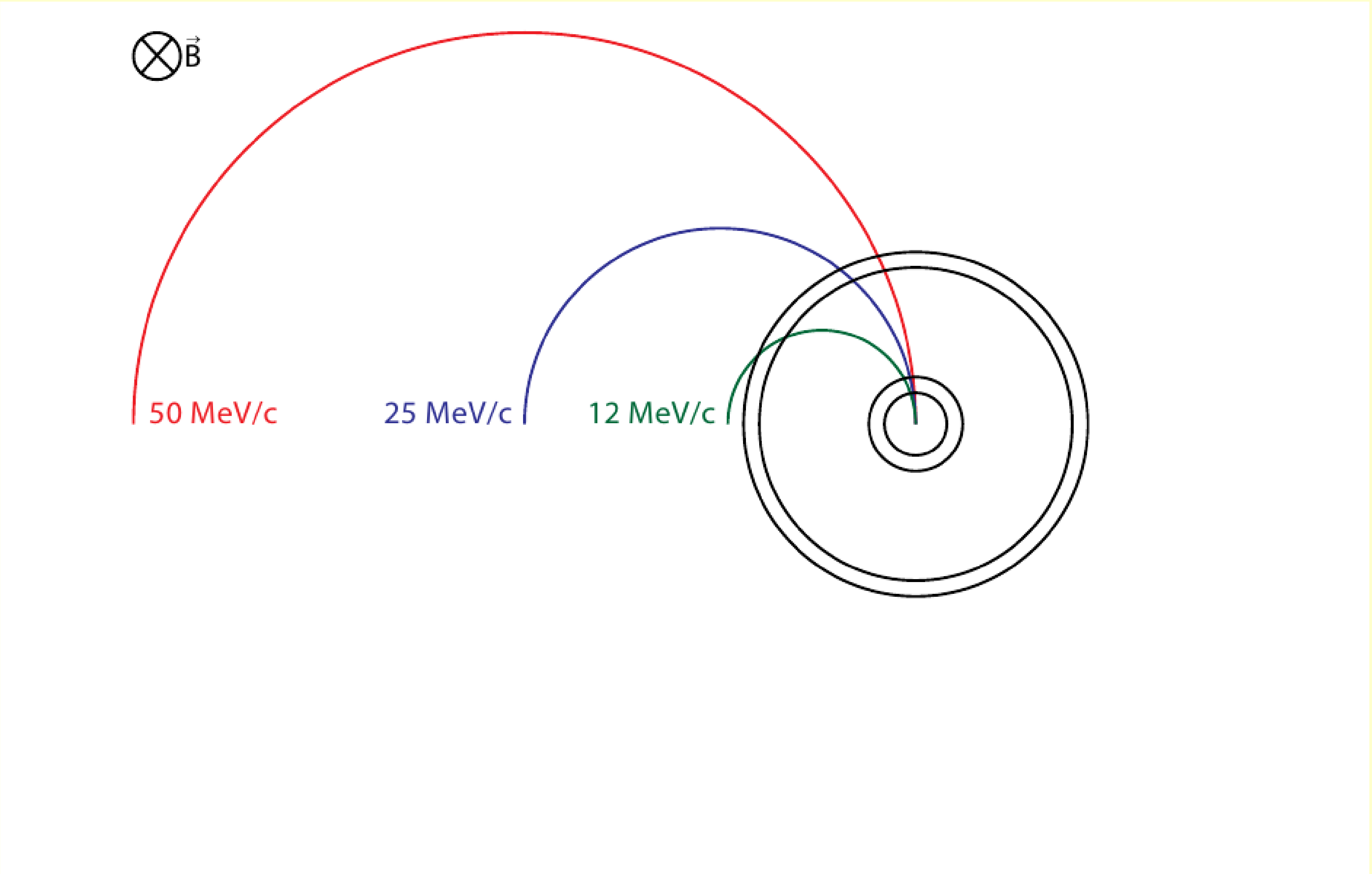
Tracking Design Considerations



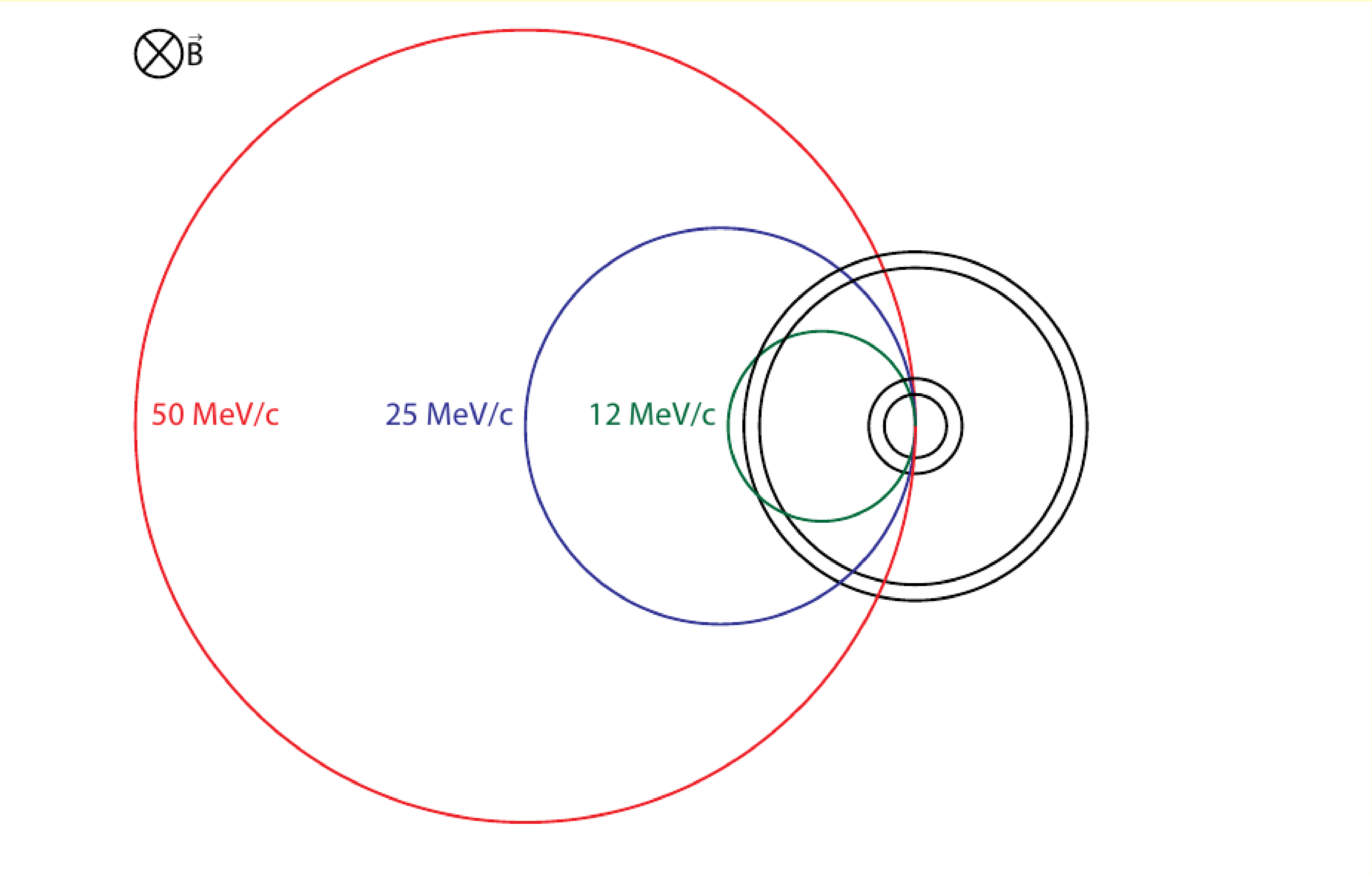
Tracking Design Considerations



Tracking Design Considerations



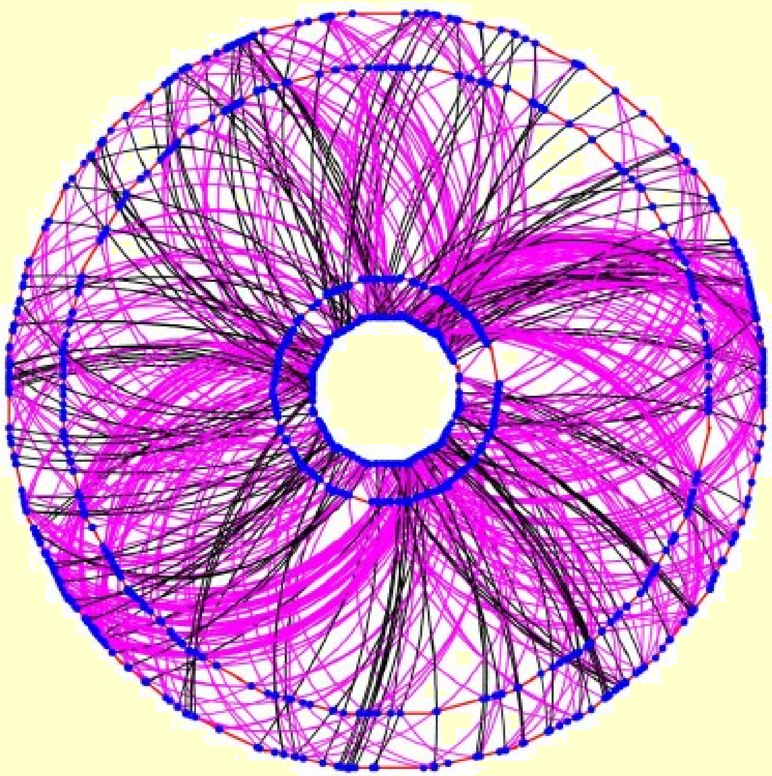
Tracking Design Considerations



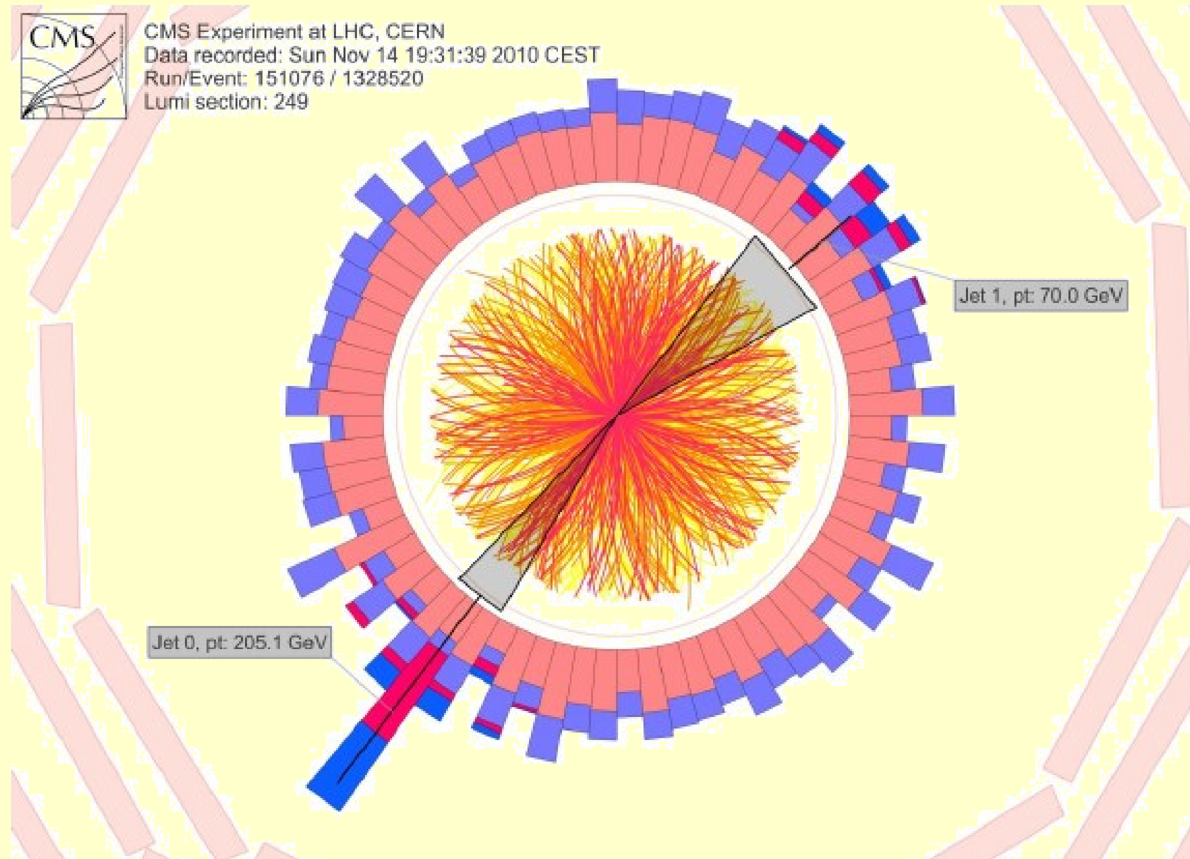
Timing

Pileup

Mu3e: reconstructed 4-hit tracks



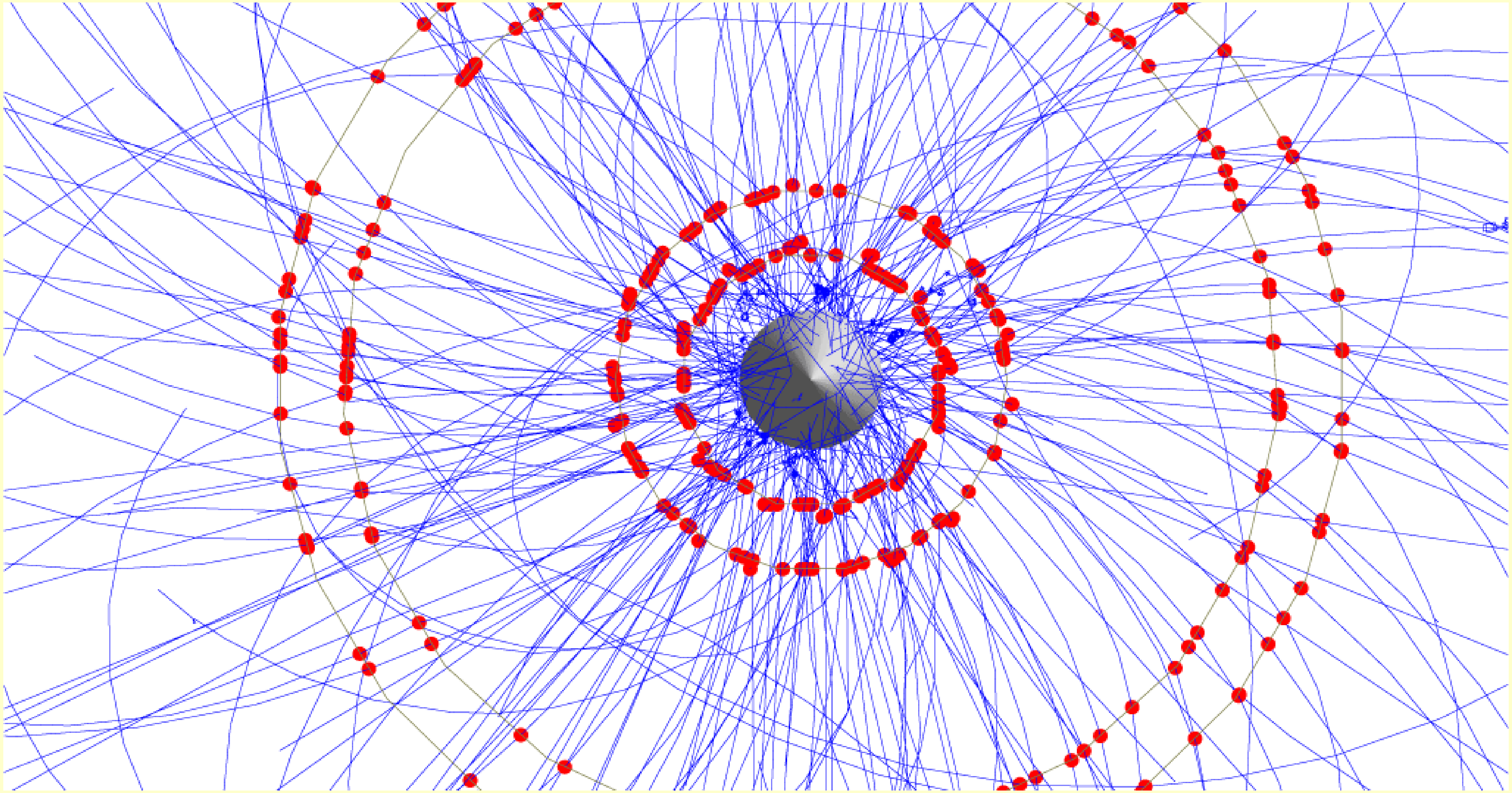
≈16 cm
Readout in frames of 50 ns
E ~ 10-50 MeV



≈2.5 m
Collision every 25 ns
E ~ 200 GeV

Pixel Detector: Readout Frames @ 20 MHz

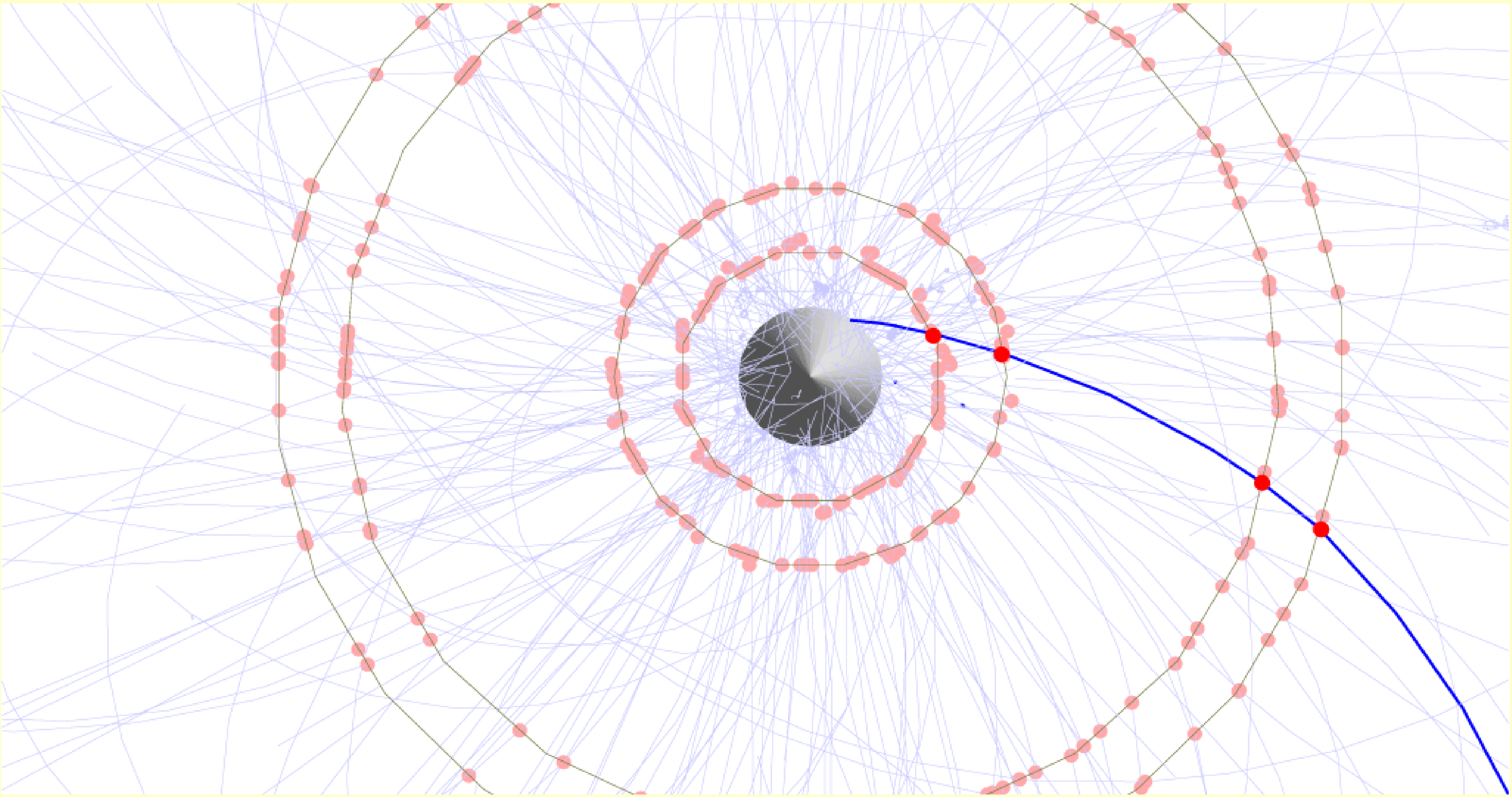
100 muon decays @ rate $2 \cdot 10^9$ muon stops/s



50 ns snapshot

Pixel: Readout Frames 50 ns

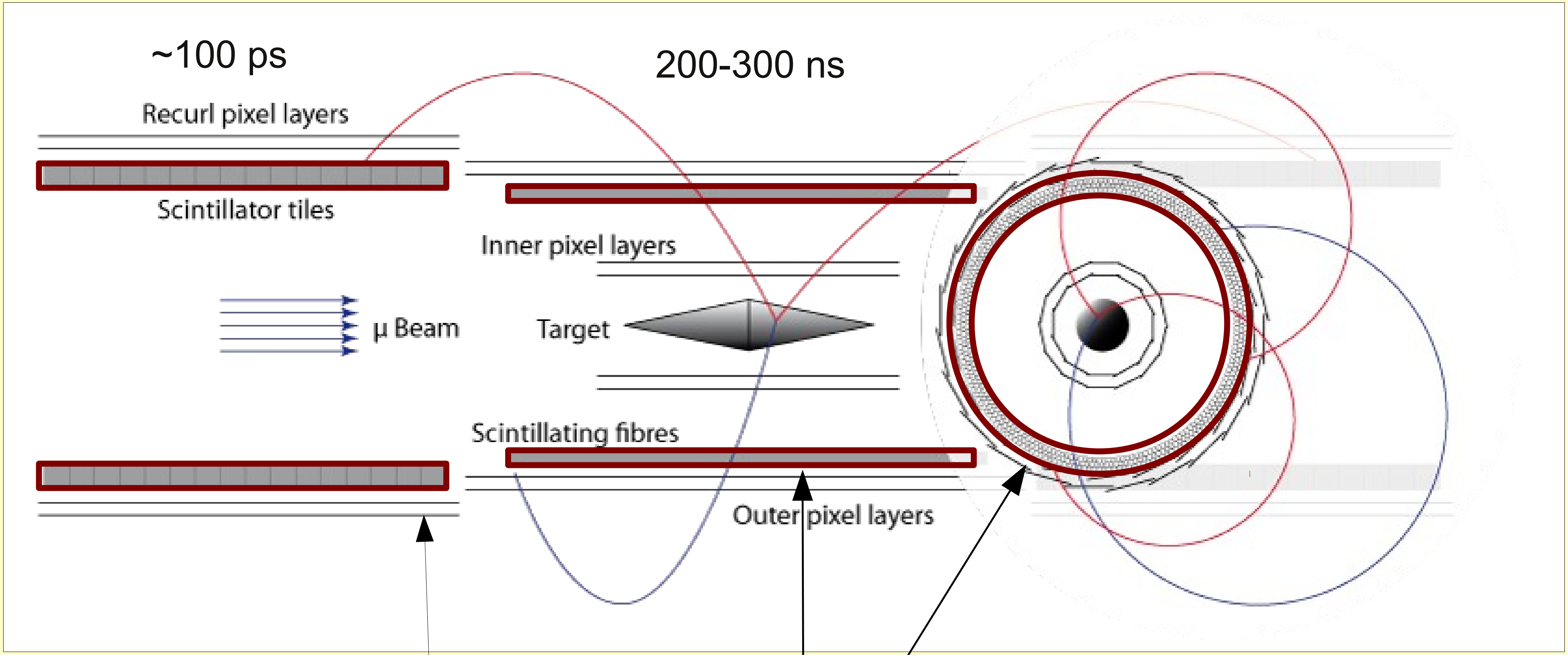
100 muon decays @ rate $2 \cdot 10^9$ muon stops/s



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

Mu3e Time of Flight System

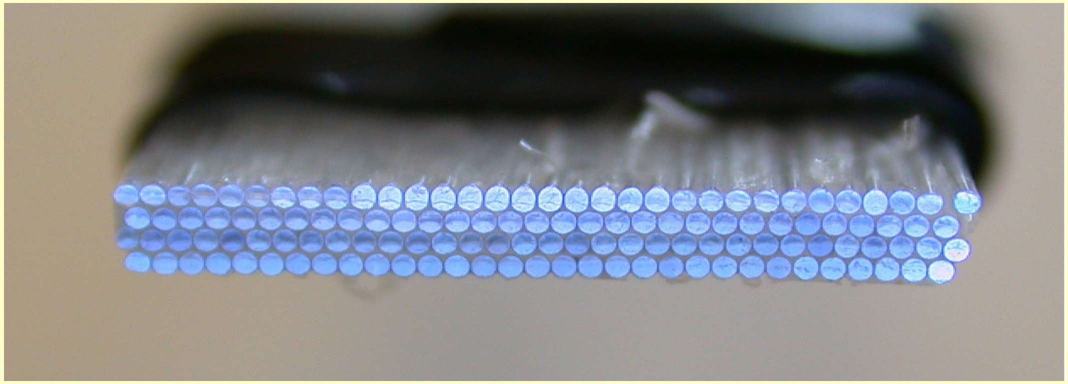
not to scale

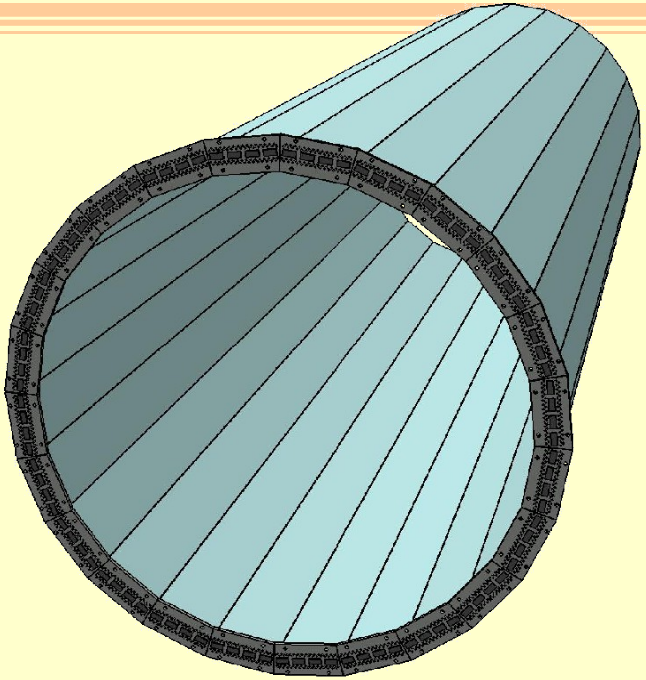


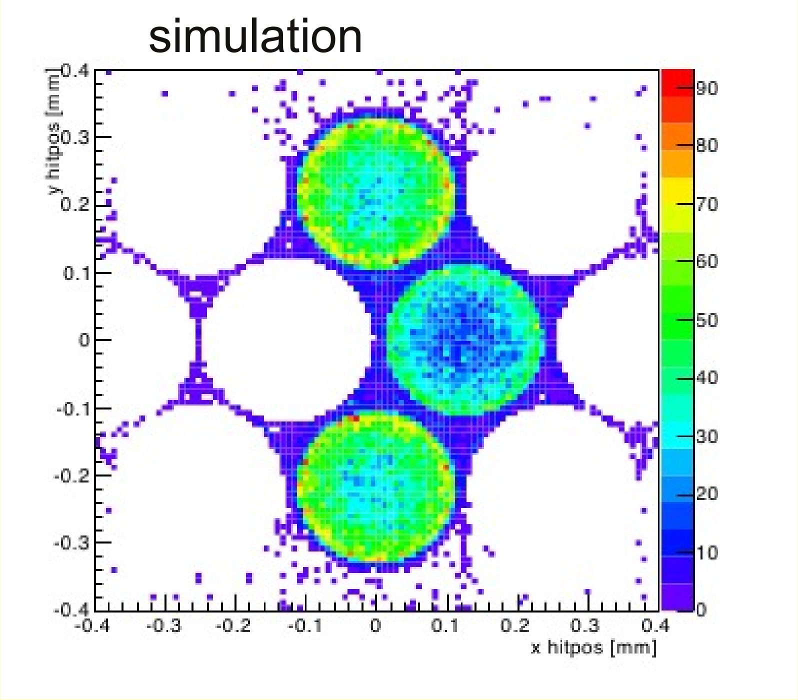
Scintillating tiles

Scintillating fibers

Scintillating Fiber Tracker





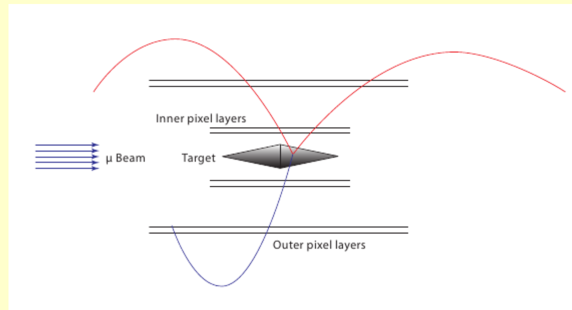


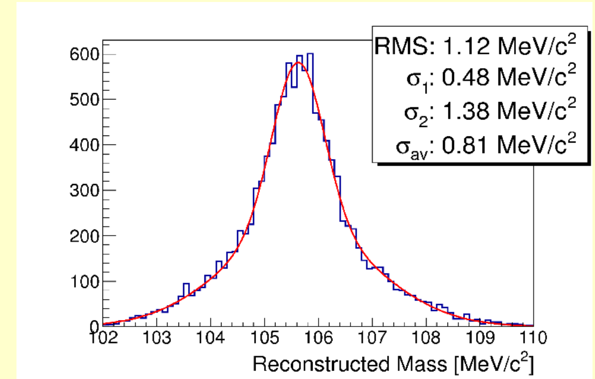
- 2-3 layers of scintillating fibers Ø = 250 µm
- ➔ read-out by silicon photomultipliers (SiPMs) and custom ASICs
- time resolution <1 ns

Invariant Mass Resolution of Signal

Phase IA:

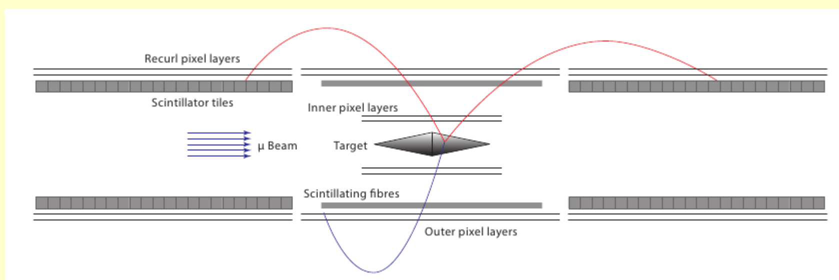
rate ~ 2 · 10^7 muons/s

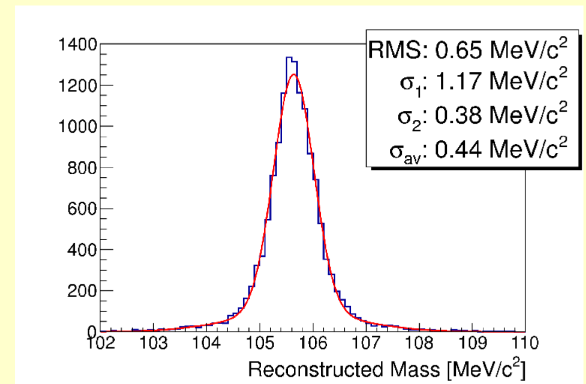




Phase IB:

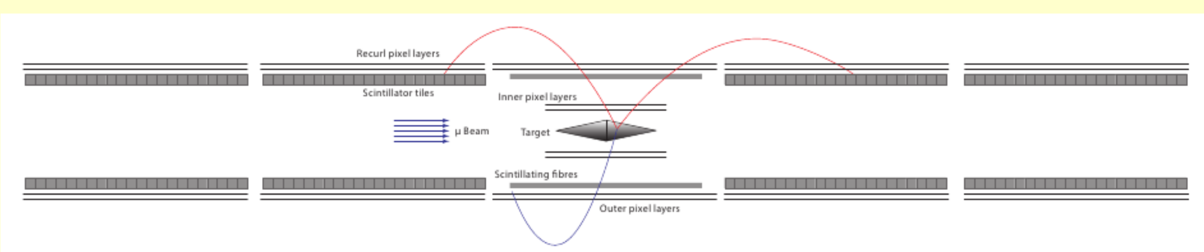
rate ~ 2 · 10^8 muons/s

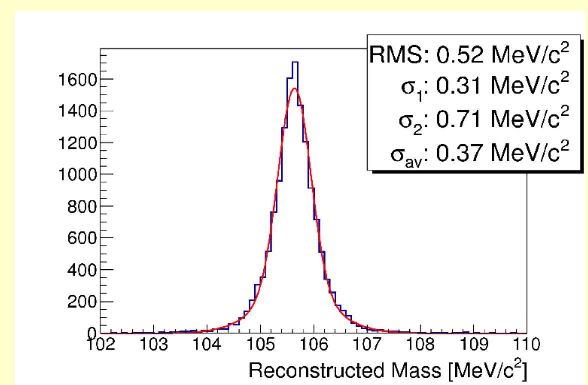




Phase II:

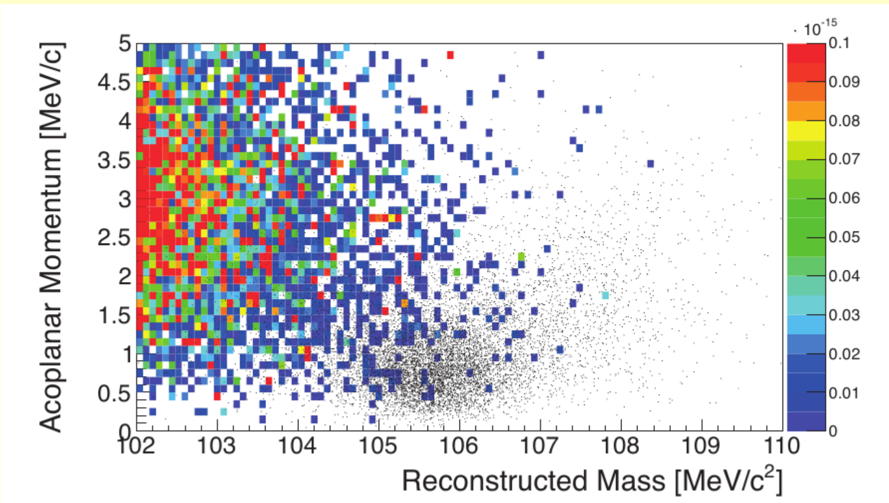
rate ~ 2 · 10^9 muons/s



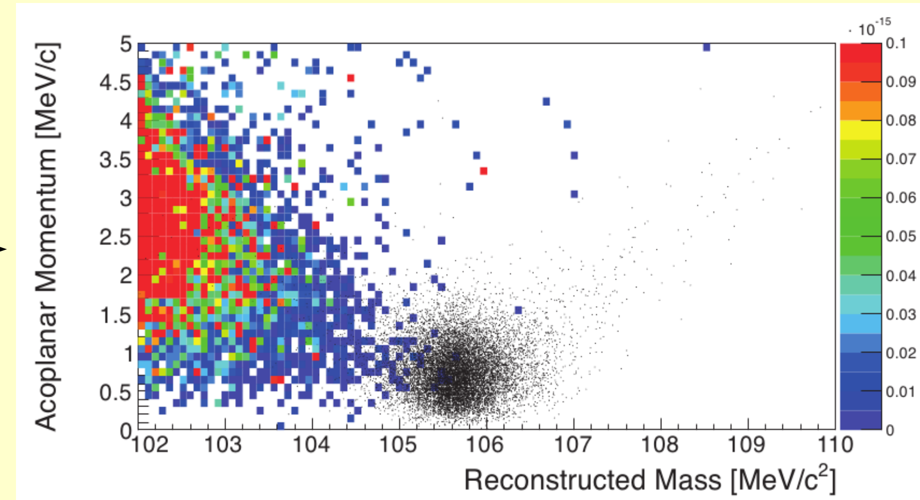


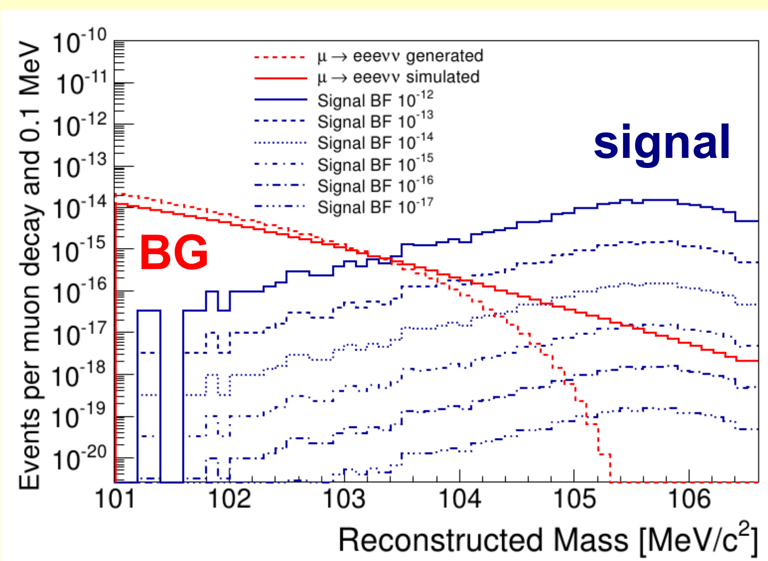
Sensitivity Study

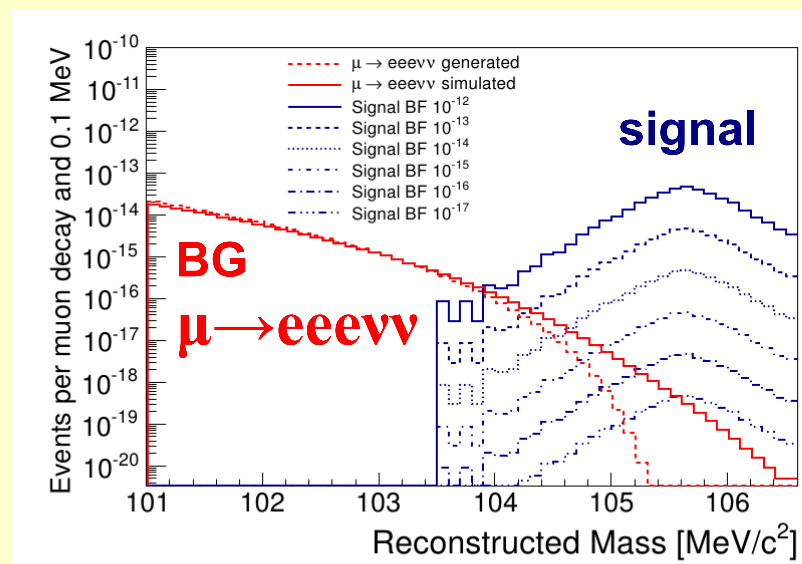
Phase IA: rate ≤ $2 \cdot 10^{7}$ muons/s



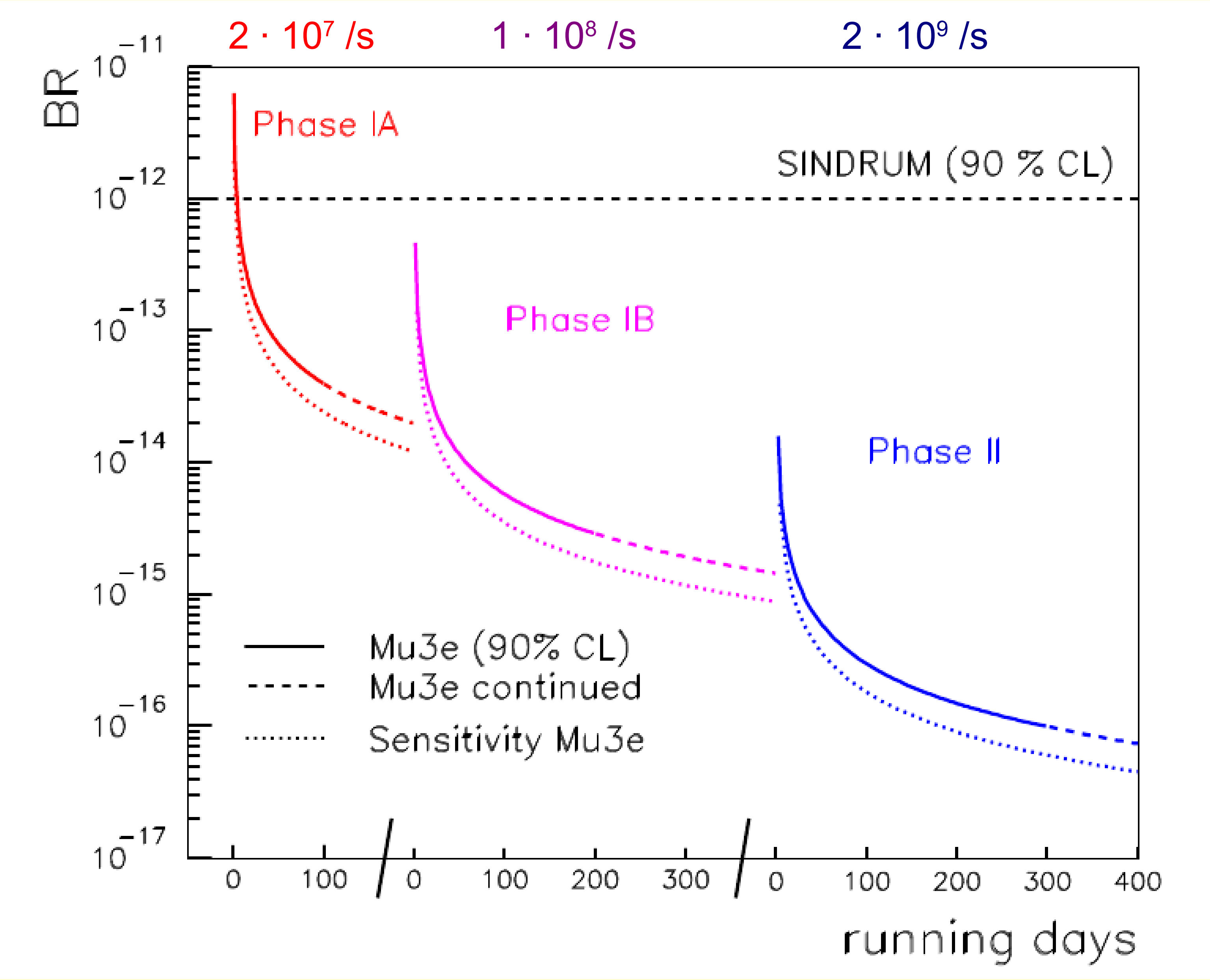
Phase II: rate ~ $2 \cdot 10^{9}$ muons/s







Sensitivity Projection



Conclusions

- Charged LFV well motivated and “almost unavoidable” in BSM models
- New era of high rate muon decay experiments searching for charged LFV
- Several projects including Mu3e aiming for sensitivities of 10^{-16} or even beyond!
- New technologies (HV-MAPS, Si-Photomultiplier) are crucial for high rate precision experiments
- Mu3e Experiment eventually aiming for $B(\mu^+ \rightarrow e^+e^+e^-) < 10^{-16}$ expected to deliver first results in a few years time