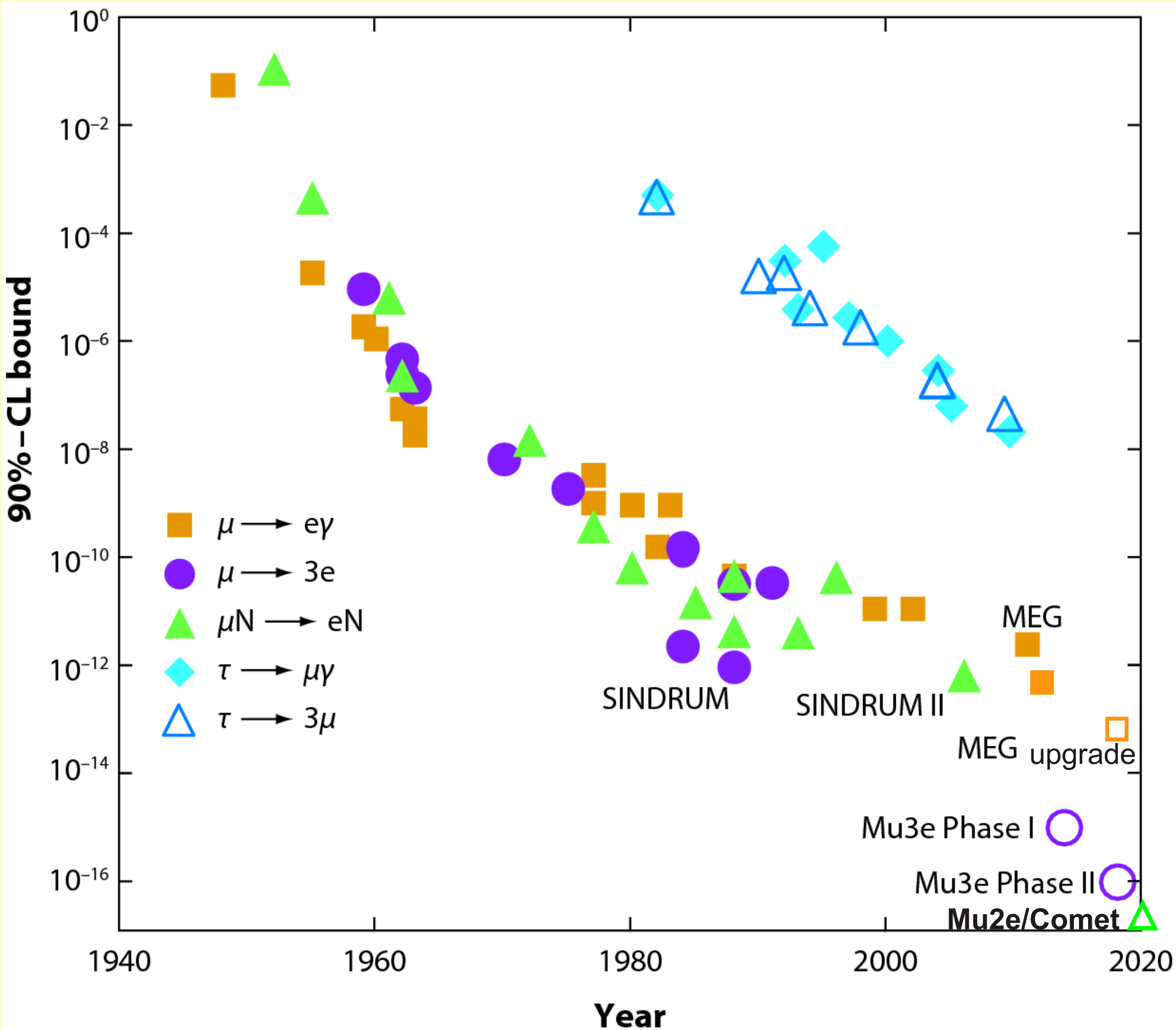
# LFV Muon Decays and a New Experiment to Search for μ→eee (Mu3e)

**BLV 2013 Workshop**

**April 8-12, 2013**

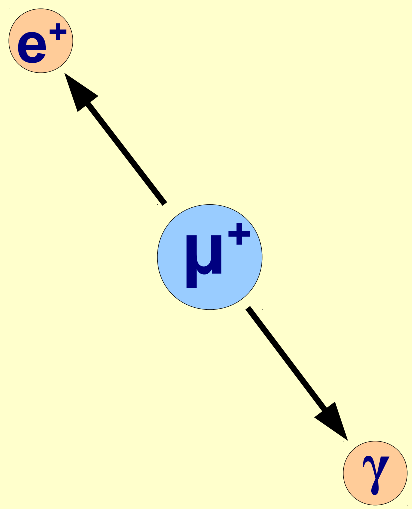
**André Schöning** for the **Mu3e Collaboration**

# History of LFV Decay experiments



# LFV Muon Decays: Experimental Situation

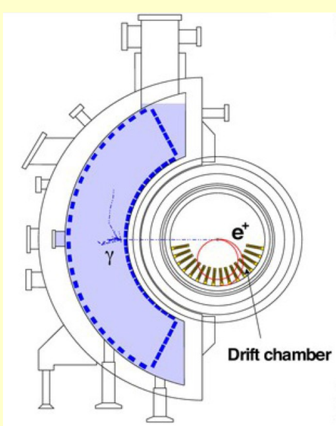
## $\mu^+ \rightarrow e^+ \gamma$



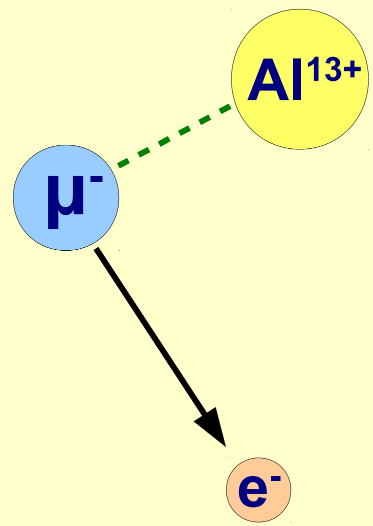

**MEG (PSI)**

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

running



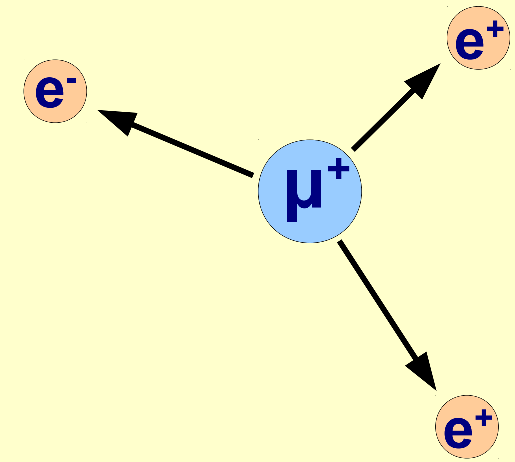

## $\mu^- N \rightarrow e^- N$




**SINDRUM II (PSI)**

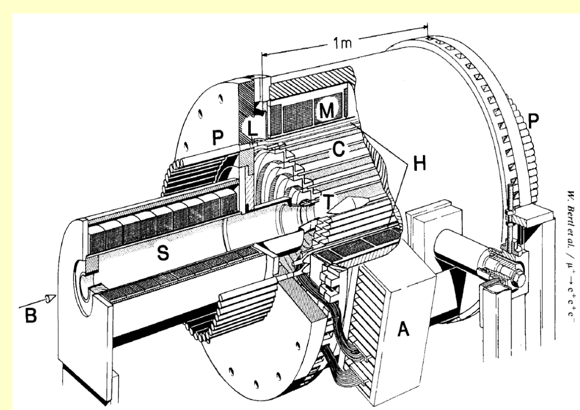
$B(\mu\ Au \rightarrow e\ Au) \leq 7 \cdot 10^{-13}$ (2006)

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



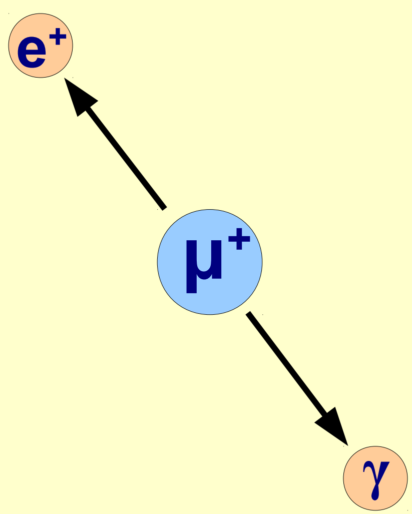

**SINDRUM (PSI)**

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



# LFV Muon Decays in the SM

## $\mu^+ \to e^+ \gamma$

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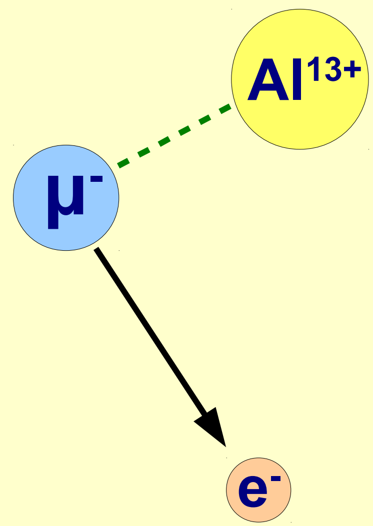
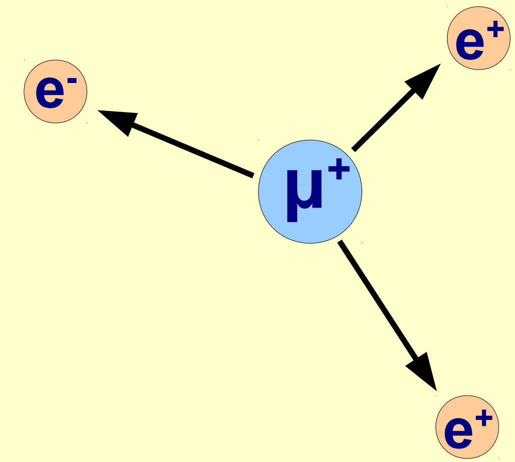
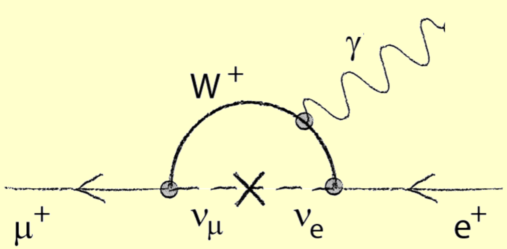
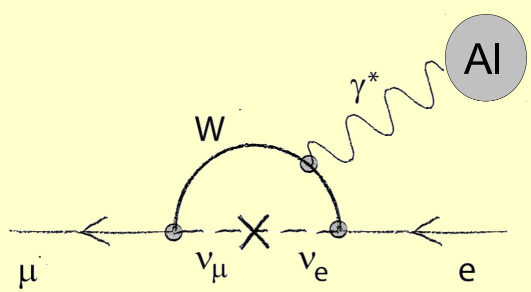


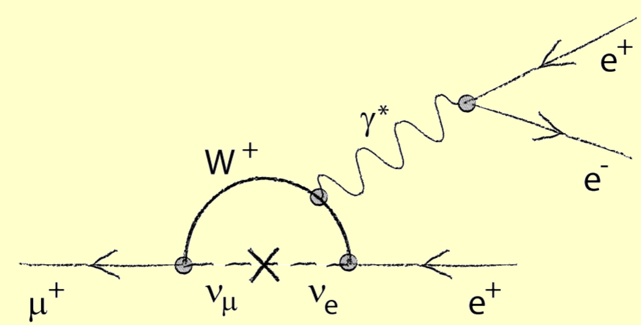

## $\mu^+ \to e^+ e^+ e^-$




**SM: LFV loops**



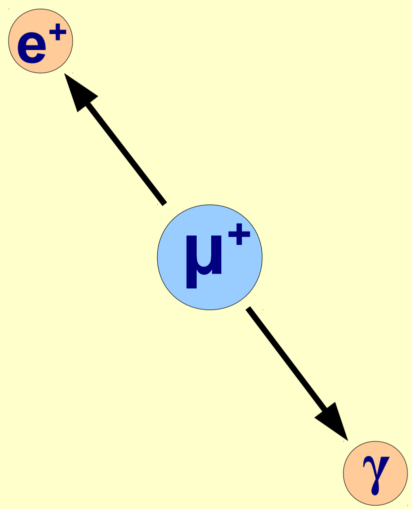



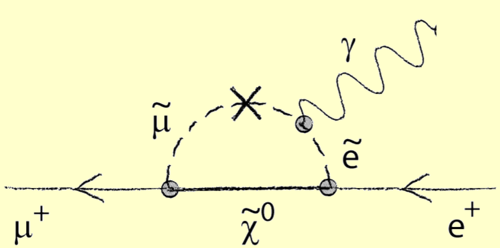

branching ratios suppressed by $\propto \frac{(\Delta m_\nu^2)^2}{m_W^4} \approx 10^{-50}$

# LFV Muon Decays in SUSY

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




**SUSY loops**

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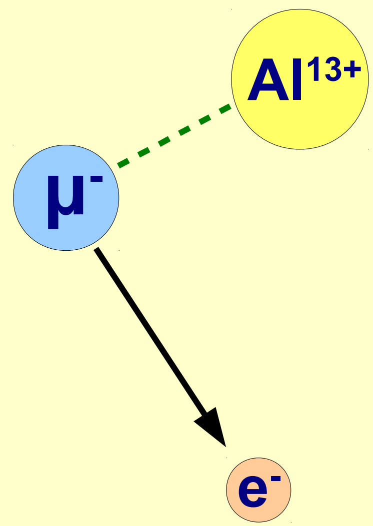
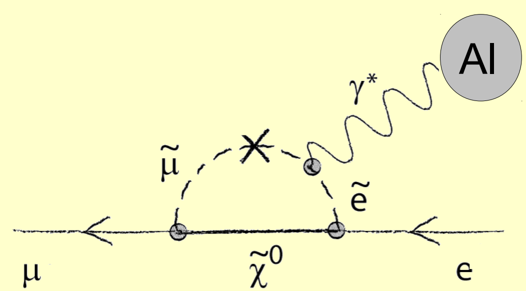
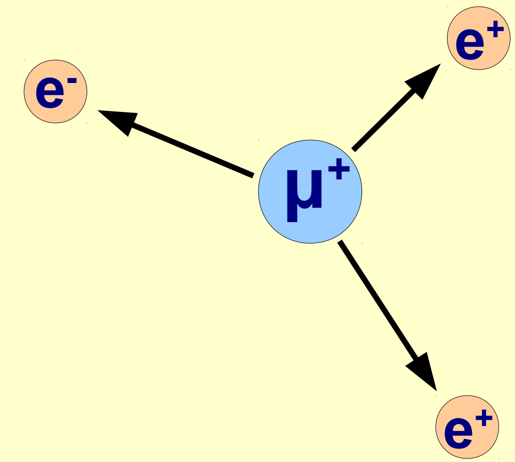
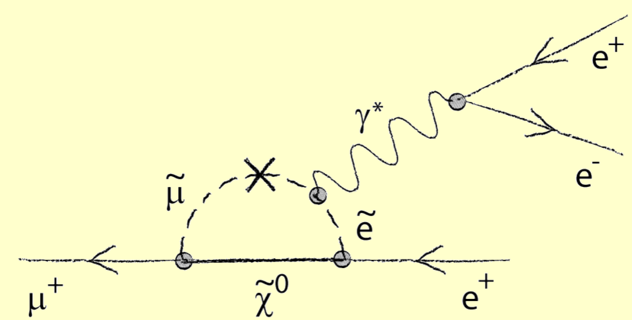



coherent conversion in nucleus field for $Q^2(\gamma^*)\sim 0$

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

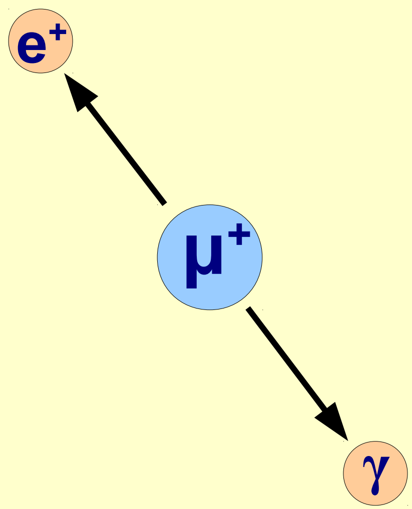



suppressed by extra vertex with respect to $\mu^+ \rightarrow e^+ \gamma$

# LFV Muon Decays from SUSY loops

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

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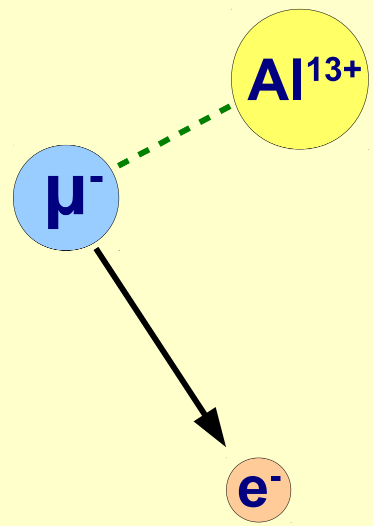


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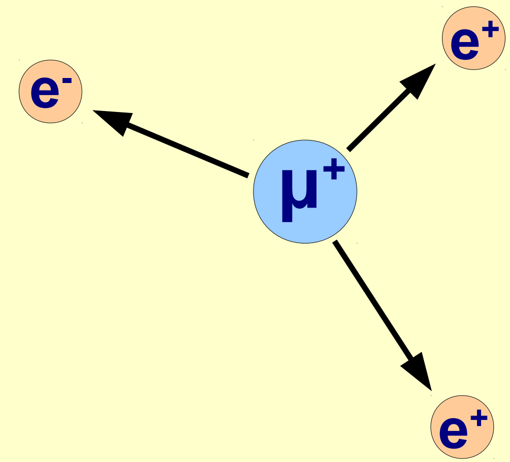
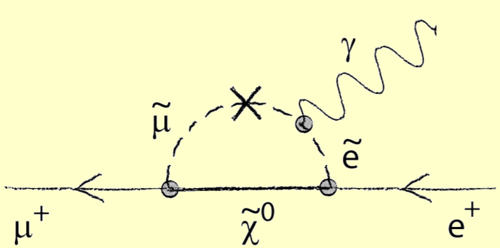
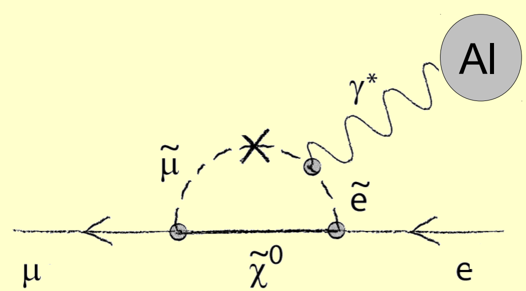
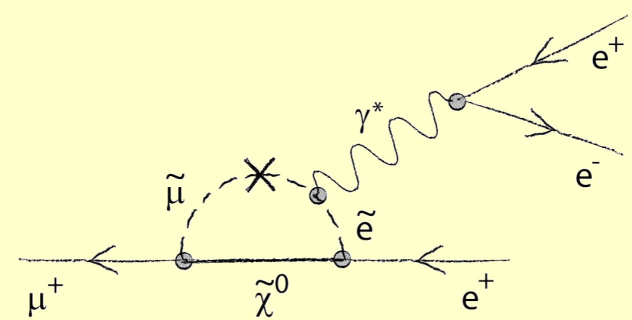



**SUSY loops**



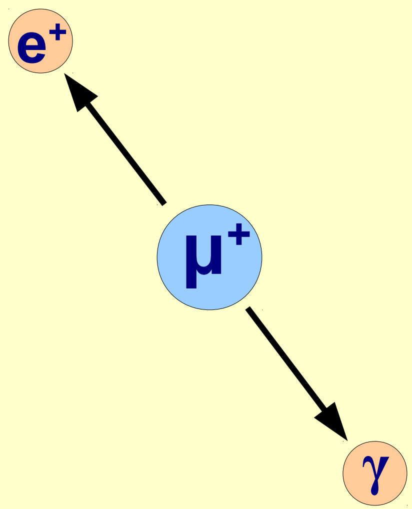




1. SUSY models like many other BSM models induce naturally LFV

# LFV Muon Decays from SUSY loops

## $\mu^+ \to e^+ \gamma$

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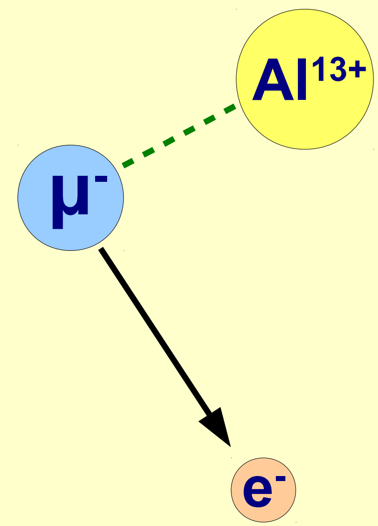
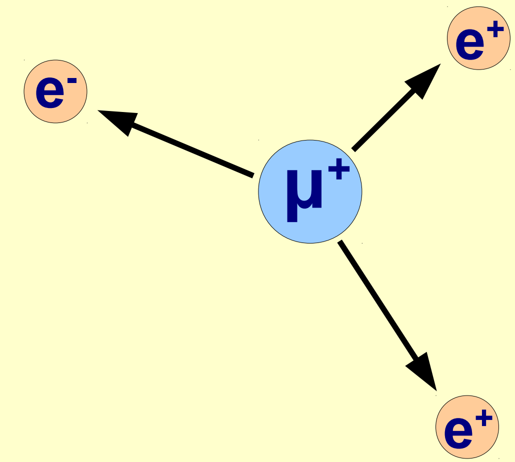
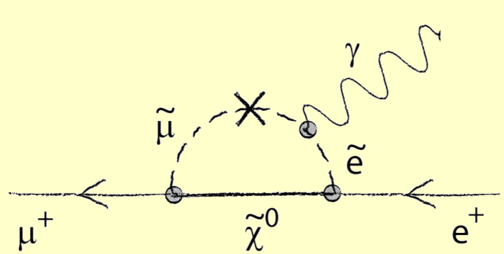
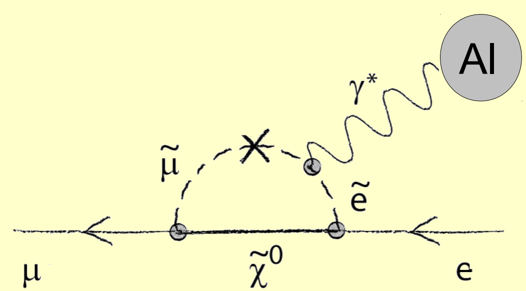


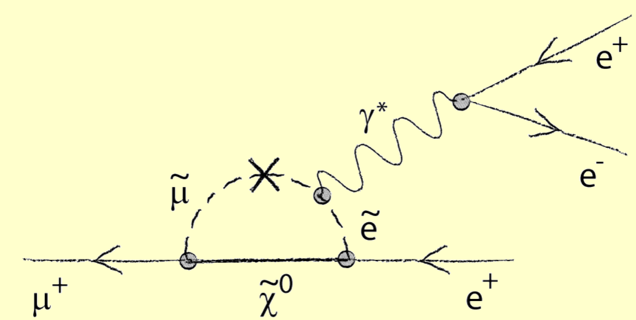

## $\mu^+ \to e^+ e^+ e^-$




**SUSY loops**



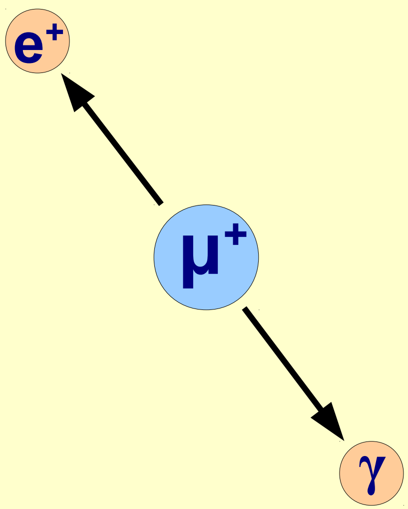



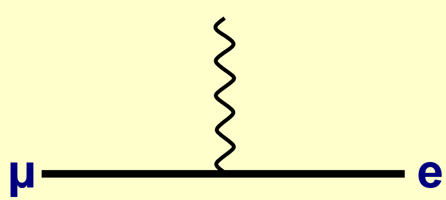




2. LFV in $\mu \to e\gamma$ implies LFV in both $\mu N \to eN$ and $\mu N \to eee$

# LFV Tree Diagrams

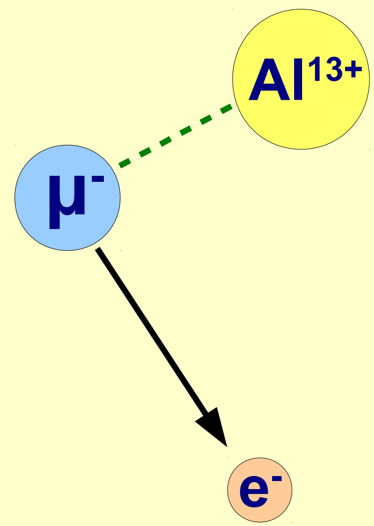
## $\mu^+ \to e^+ \gamma$

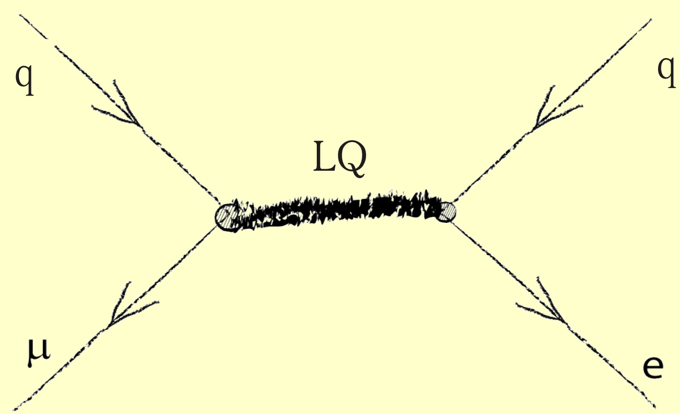



not allowed

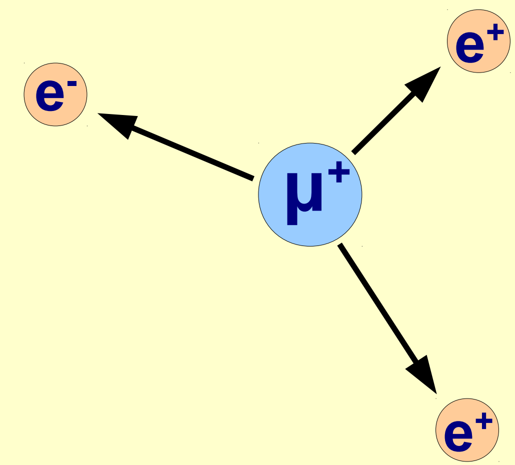
## $\mu^- N \to e^- N$

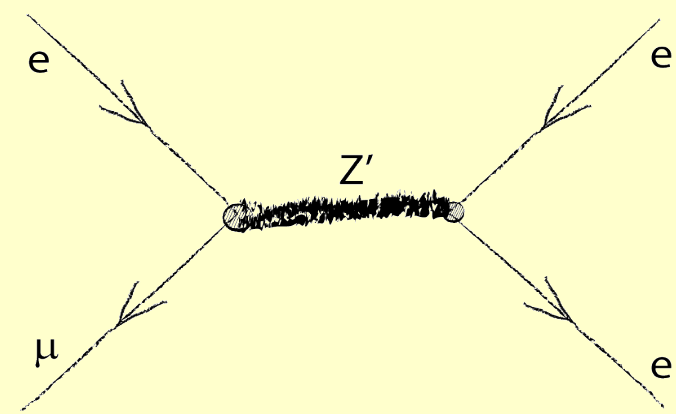



e.g. Leptoquarks

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



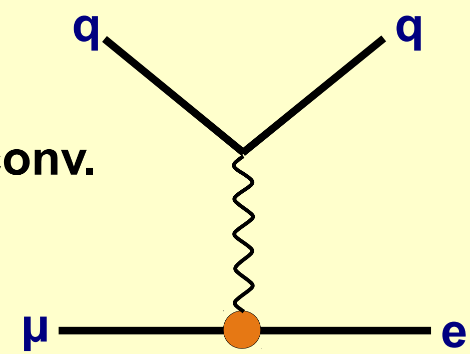




extra Z', LFV Higgs, etc.

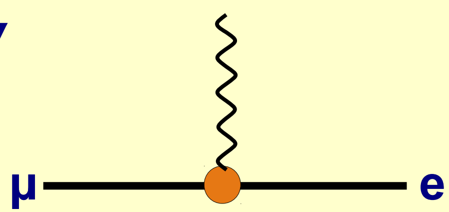
# Model Independent Comparison

**dipole couplings**

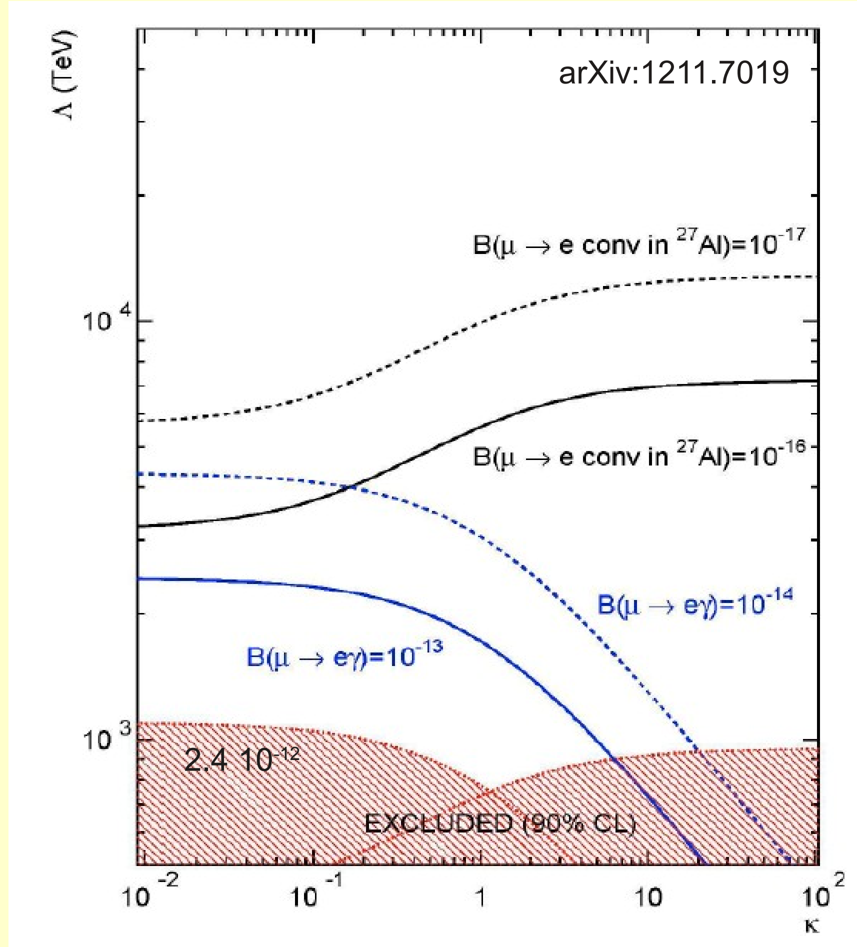
**$\mu \rightarrow e$ conv.**



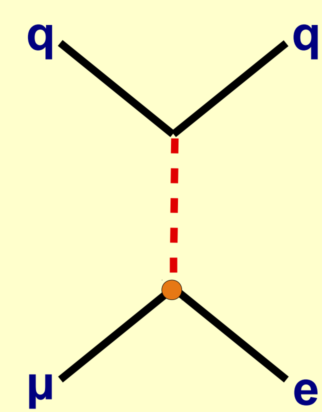

**$\mu^+ \rightarrow e^+ \gamma$**




$\kappa \rightarrow 0$




**eμqq contact IA**




$\kappa \rightarrow \infty$

$\kappa$ = model parameter

$\Lambda$ = common effective mass scale

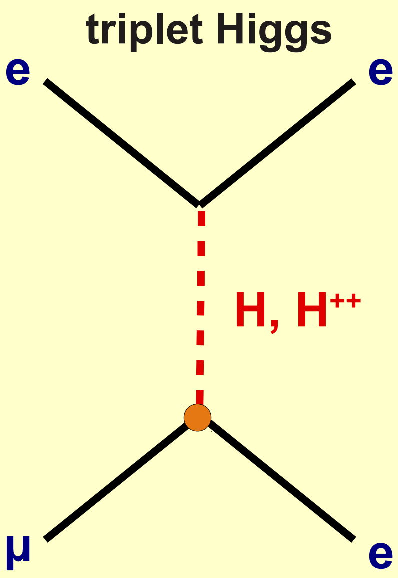
**Effective cLFV Lagrangian:**

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

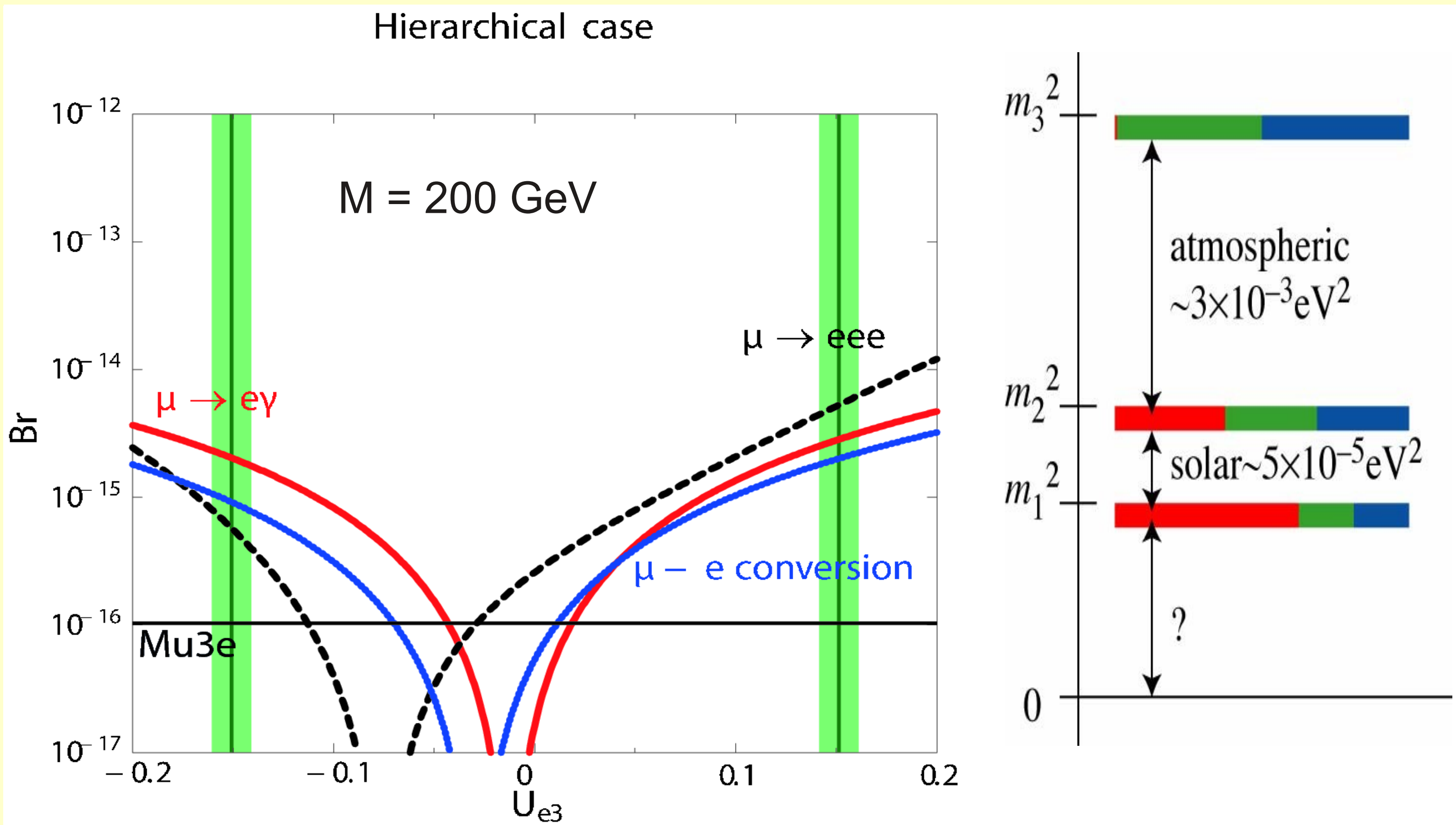
# Example: Higgs Triplet Models

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

- Motivated by Left-Right Symmetric Models




+ loop diagrams

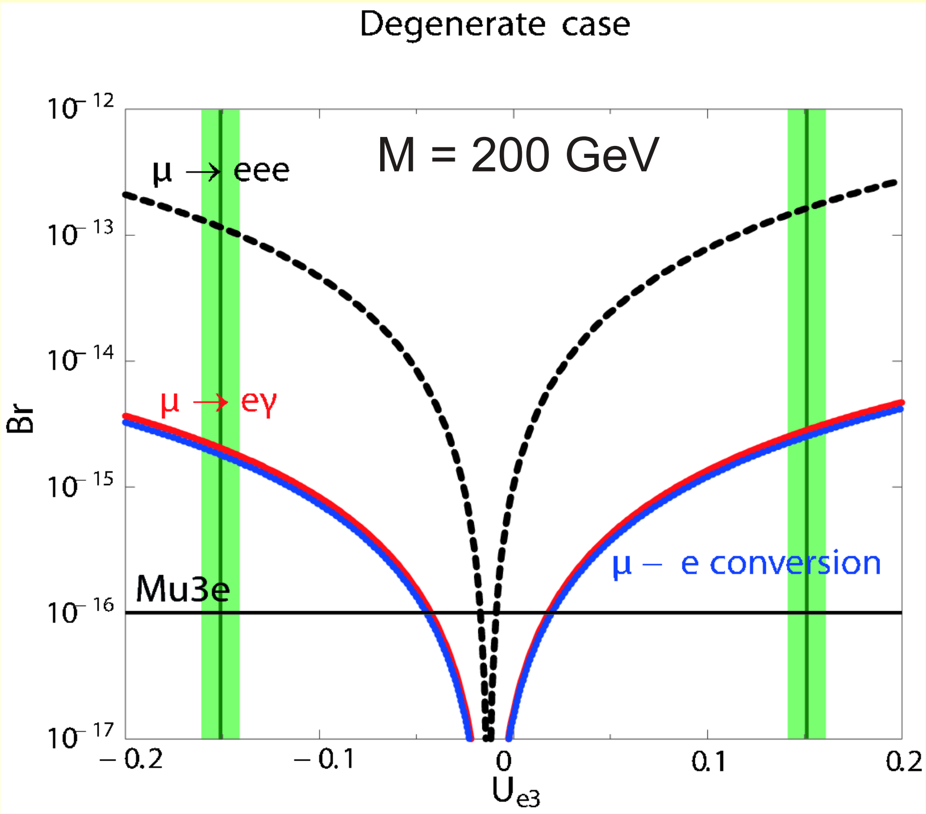


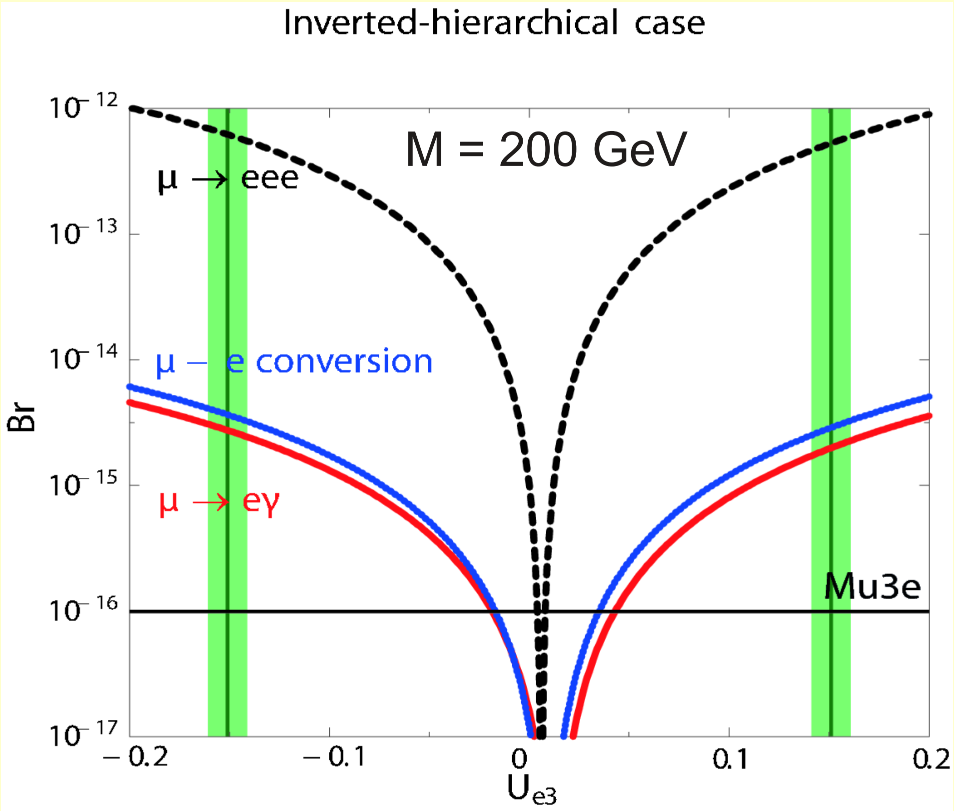

related to neutrino masses (→ ν mass pattern)

# 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:

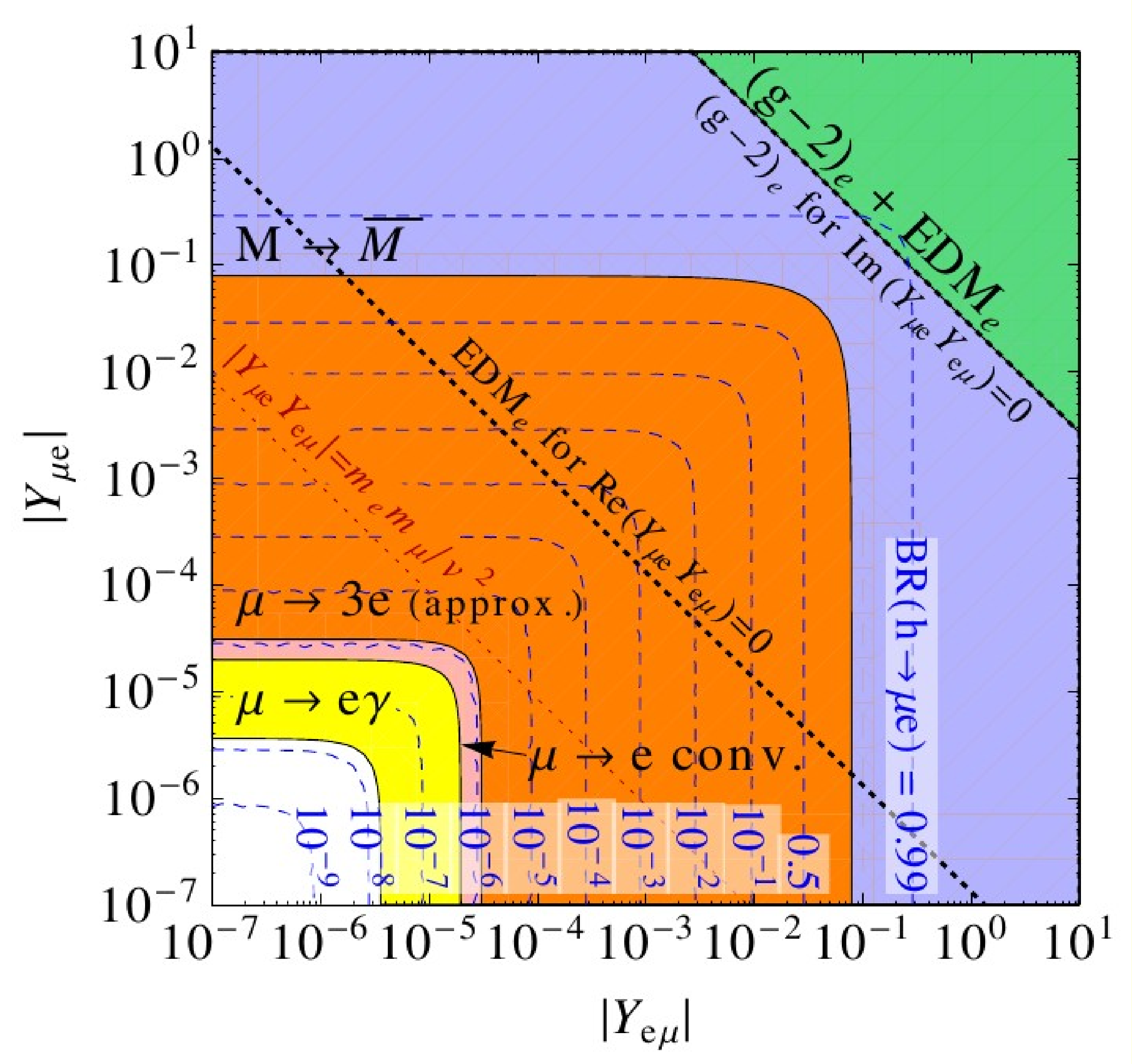
$$\mathrm{BR}(h \to \ell^\alpha \ell^\beta) = \frac{\Gamma(h \to \ell^\alpha \ell^\beta)}{\Gamma(h \to \ell^\alpha \ell^\beta) + \Gamma_{\mathrm{SM}}}$$

LFV muon decay:

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

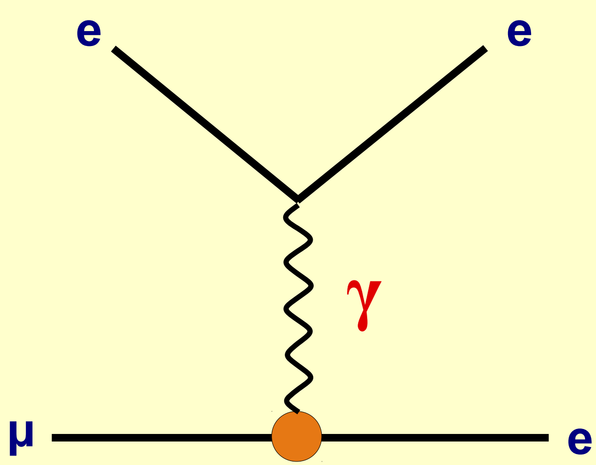
**LHC and muon decay exper. are largely complementarity!**

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

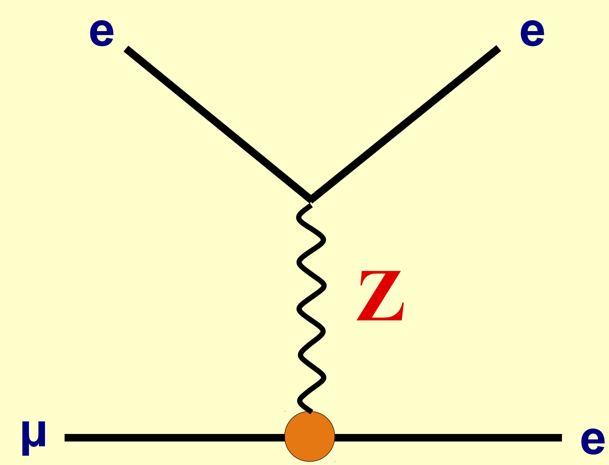


# The Z-Penguin Diagram in $\mu^+ \rightarrow e^+e^+e^-$

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




photon penguin




Z - penguin

from dimensional analysis:

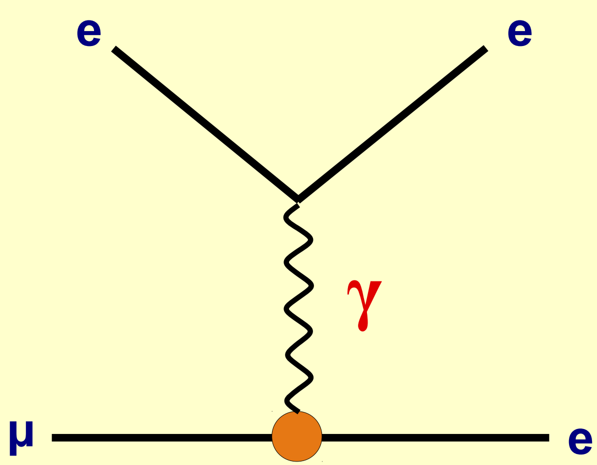
$$Br \propto \frac{m_\mu^5}{\Lambda^4}$$

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

dominates if $\Lambda >> m_Z$

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

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

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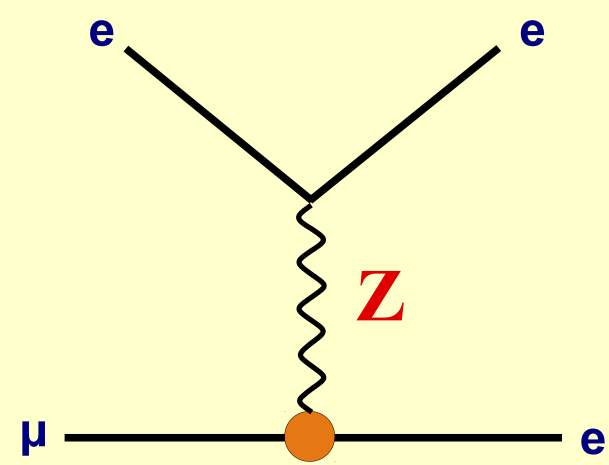



Z - penguin

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!**

# Many Recent Papers on/with Z-penguin

**Hirsch et al., *Enhancing $l_i \rightarrow 3l_j$ with the $Z^0$-penguin* [arXiv:1202.1825]**

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

del Aguila et al., *Lepton flavor violation in the Simplest **Little Higgs** model* [arXiv:1101.2936]

Dreiner at al., *New bounds on trilinear **R-parity** violation from lepton flavor violating observables* [arXiv:1204.5925]

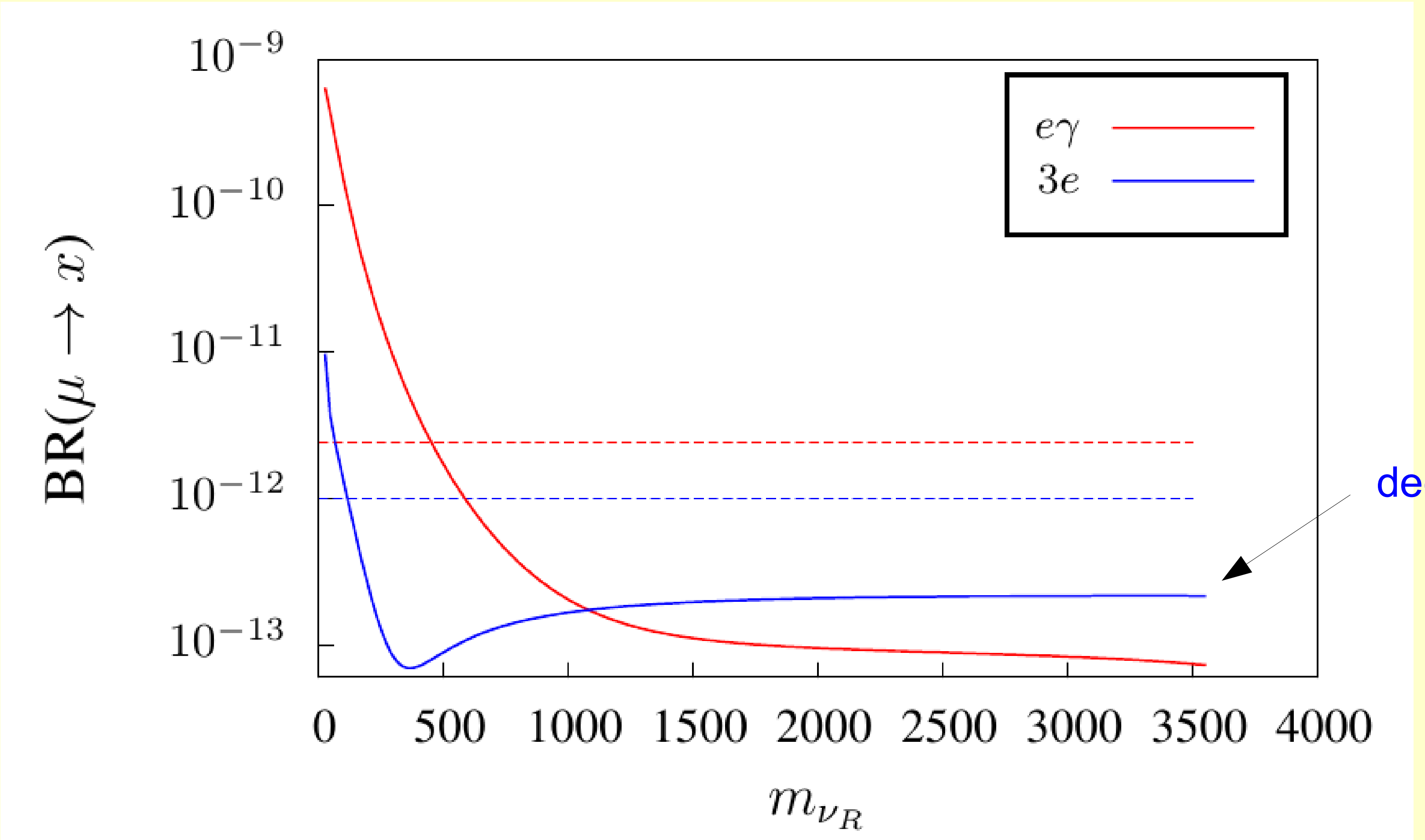
x Abada et al., *Enhancing lepton flavour violation in the **supersymmetric inverse seesaw** beyond the dipole contribution* [arXiv:1206.6497]

Ilakovac et al., *Charged Lepton Flavour Violation in Supersymmetric **Low-Scale Seesaw** Models* [arXiv:1212.5939]

Aristizabal Sierra et al., *Minimal lepton flavor violating realizations of **minimal seesaw** models* [arXiv:1205.5547]

**Hirsch et al.**, ***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'

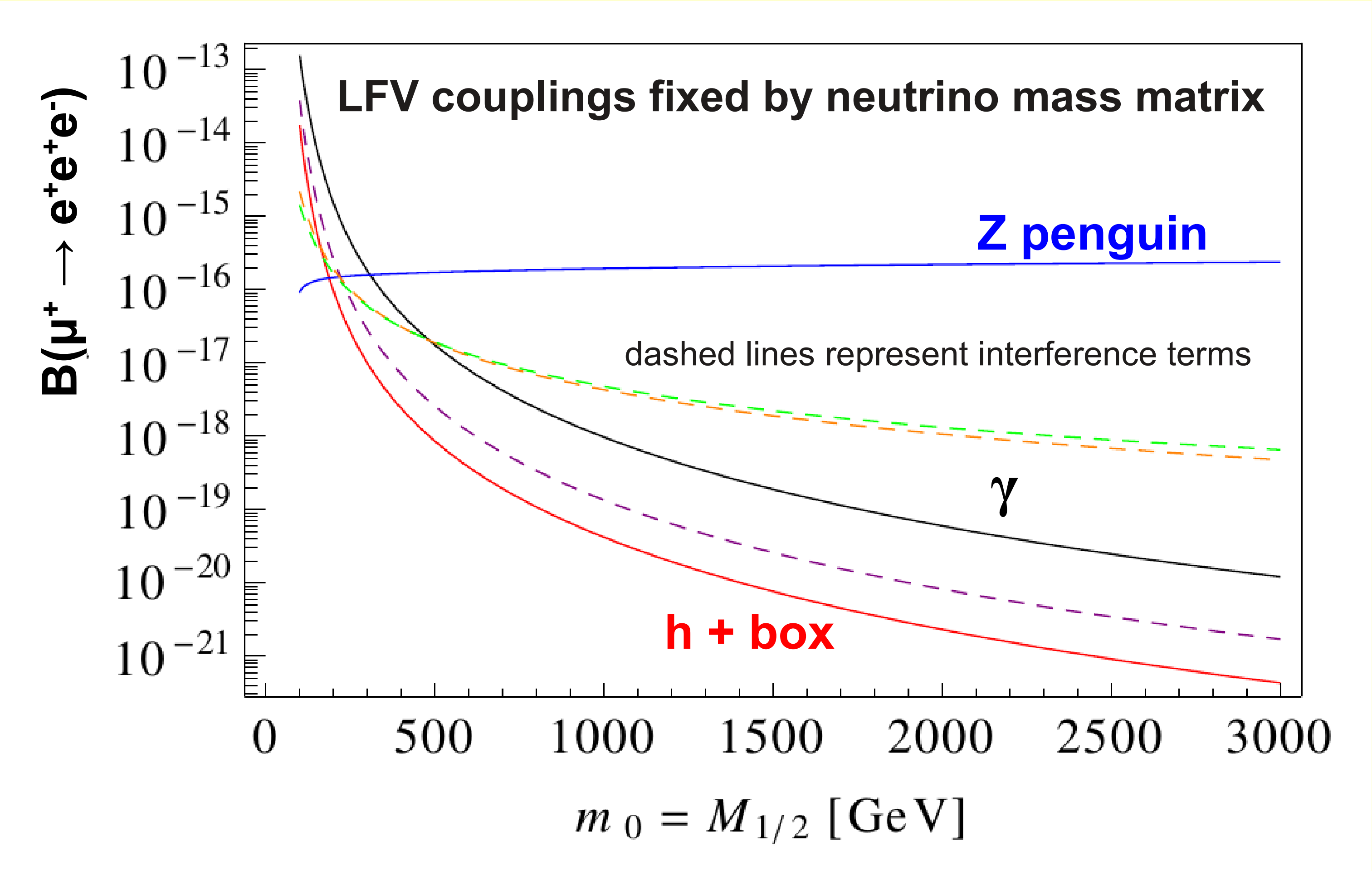



decoupling!

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

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

## Inverse Seesaw Model

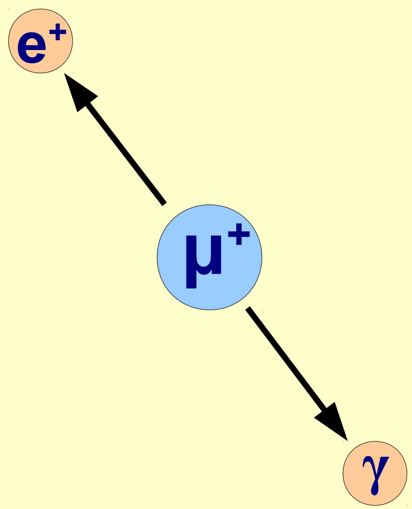



## Non-decoupling behaviour of Z-penguin contribution

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

# LFV Muon Decays: Experimental Situation

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

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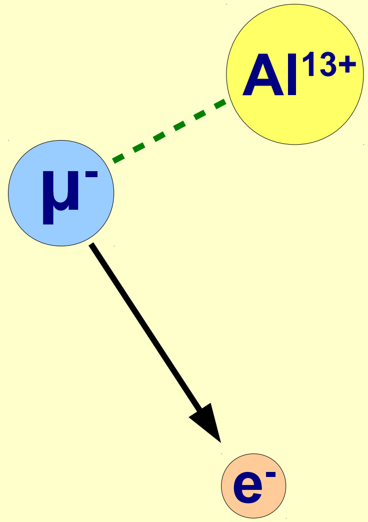
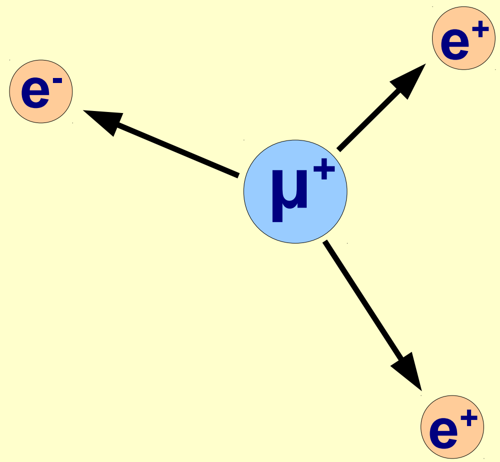



## $\mu^+ \rightarrow e^+ e^+ e^-$



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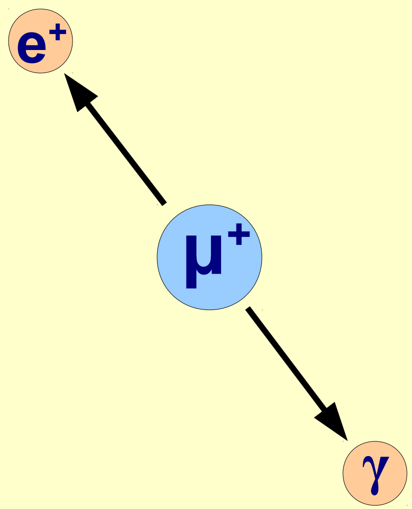
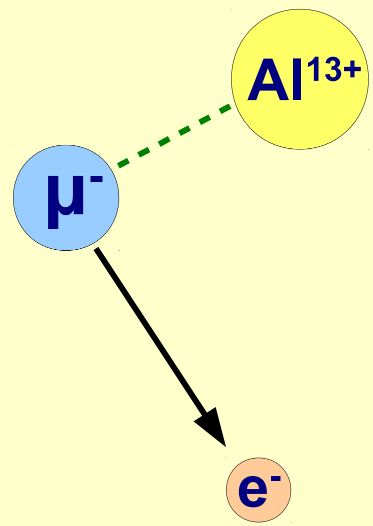



**Kinematics**

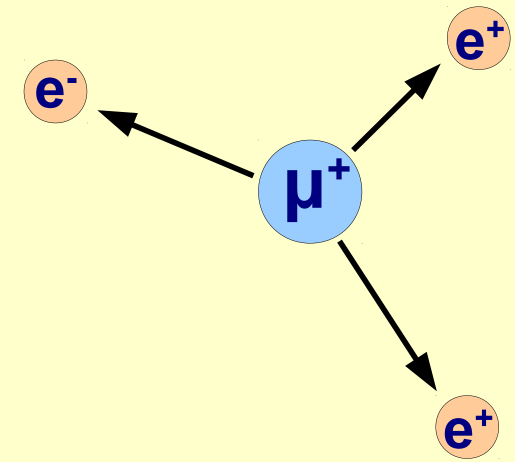
- 2-body decay
- mono-energetic e,γ
- back-back topology

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




- quasi 2-body decay
- mono-energetic electron
- single particle detected

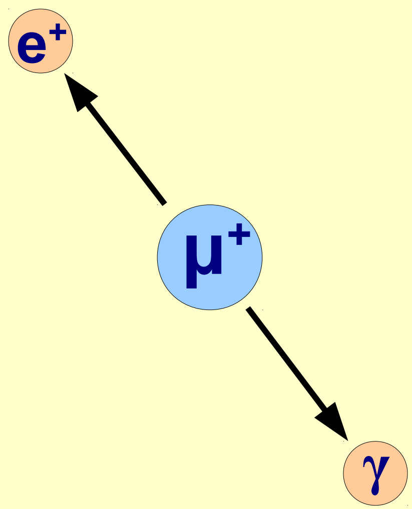
## $\mu^+ \rightarrow e^+ e^+ e^-$




- 3-body decay
- invariant mass constraint
- $|\Sigma\, p_i| = 0$

# LFV Muon Decays: Experimental Situation

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



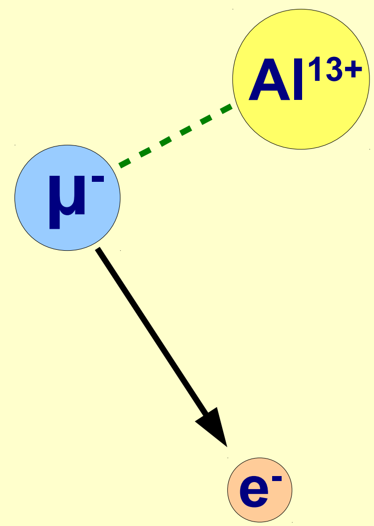

**Kinematics**

- 2-body decay
- mono-energetic e,$\gamma$
- back-back topology

**Backgrounds**

- accidental BG

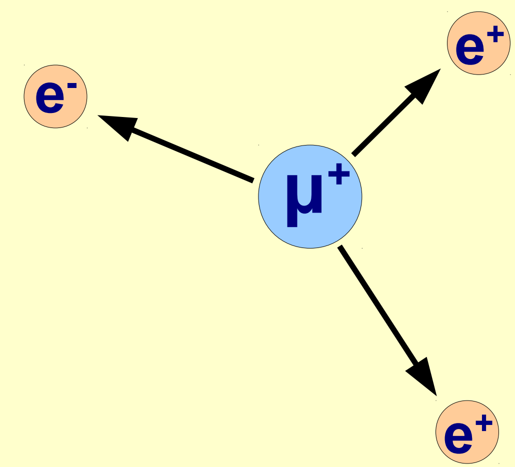
## $\mu^- N \rightarrow e^- N$




- "2-body decay"
- mono-energetic electron
- single particle detected

- decay in orbit (DIO)
- anti-protons
- (captured) pion decays

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

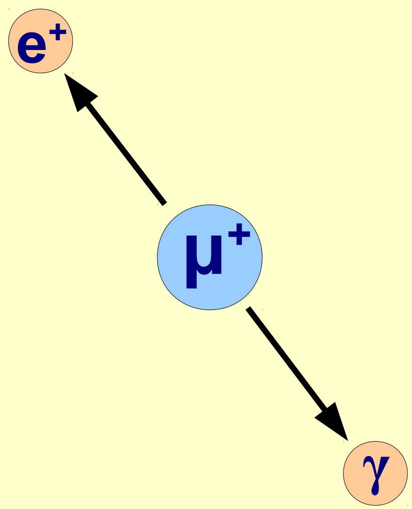



- 3-body decay
- invariant mass constraint
- $| \Sigma p_i | = 0$

- radiative decay
- accidental BG

# LFV Muon Decays: Experimental Situation

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




**Kinematics**

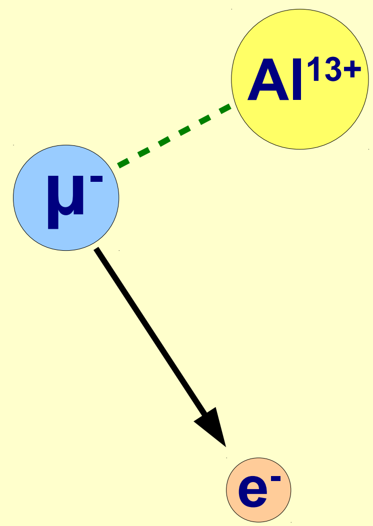
- 2-body decay
- mono-energetic e,γ
- back-back topology

**Backgrounds**

- accidental BG

**→ requires continues beam**

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

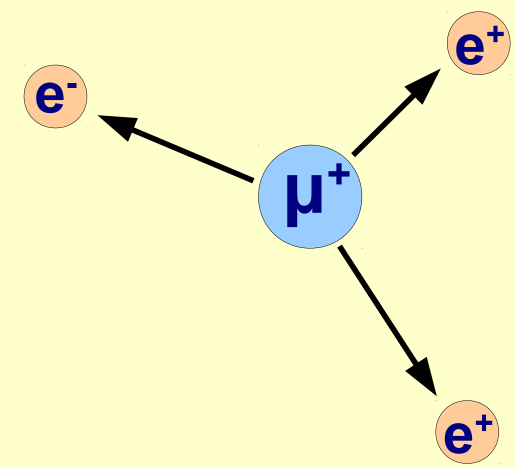



- "2-body decay"
- mono-energetic electron
- single particle detected

- decay in orbit (DIO)
- anti-protons
- pion decays

**→ requires pulsed beam**

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



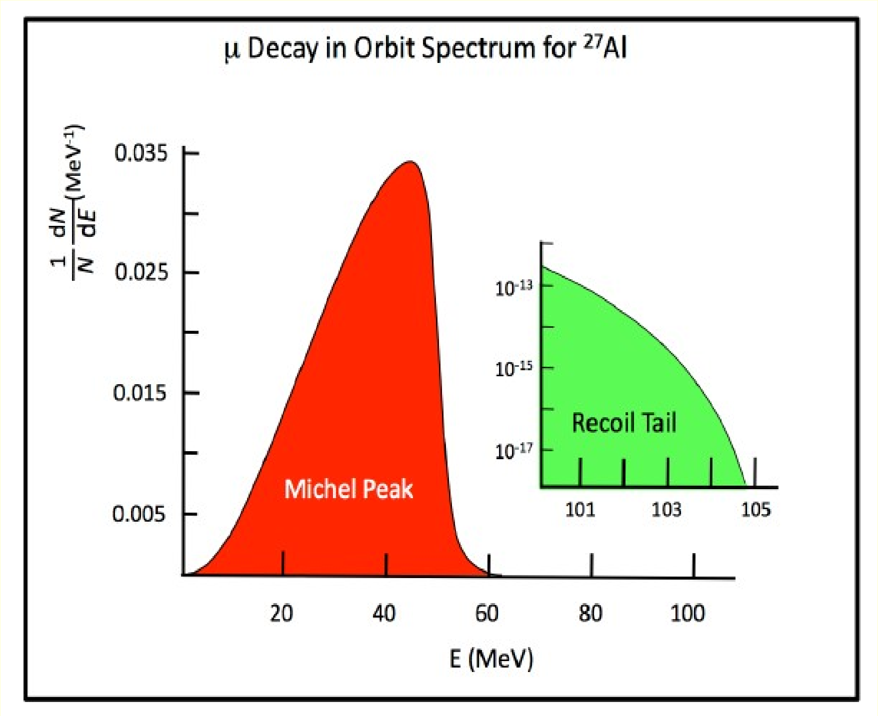

- 3-body decay
- invariant mass constraint
- $| \Sigma p_i | = 0$

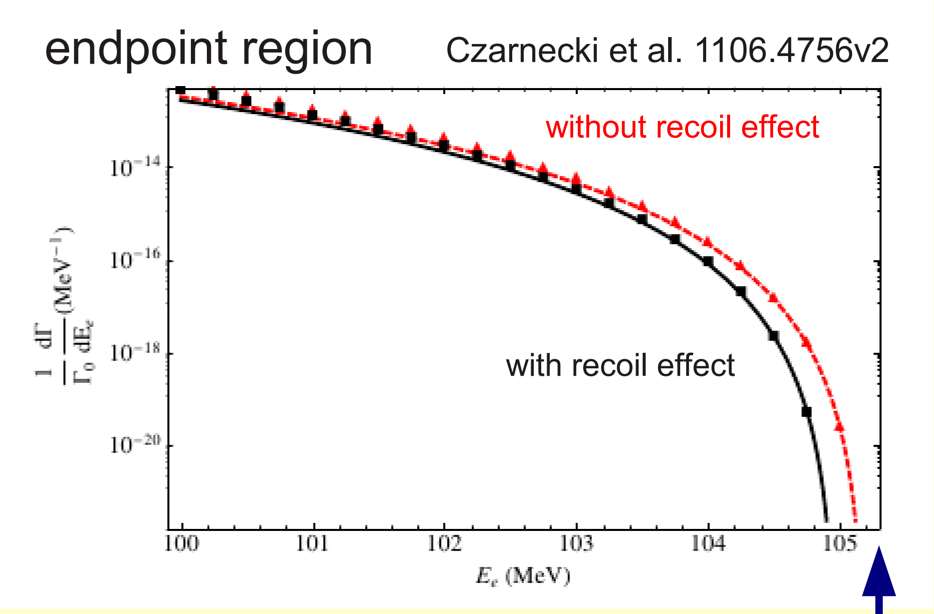
- radiative decay
- accidental BG

**→ requires continues beam**

# $\mu$ N $\rightarrow$ e N Conversion Experiments

Signature: $\mathbf{E_e = 105}$ **MeV**




signal

➜ almost BG free process

good energy(momentum) resolution is crucial!

JPARC: DeeMe $R_{\mu e} \sim 10^{-14}$ by ~2015

COMET $R_{\mu e} \sim 10^{-16}$ by ~2020

PRISM $R_{\mu e} \sim <10^{-16}$ by >2020

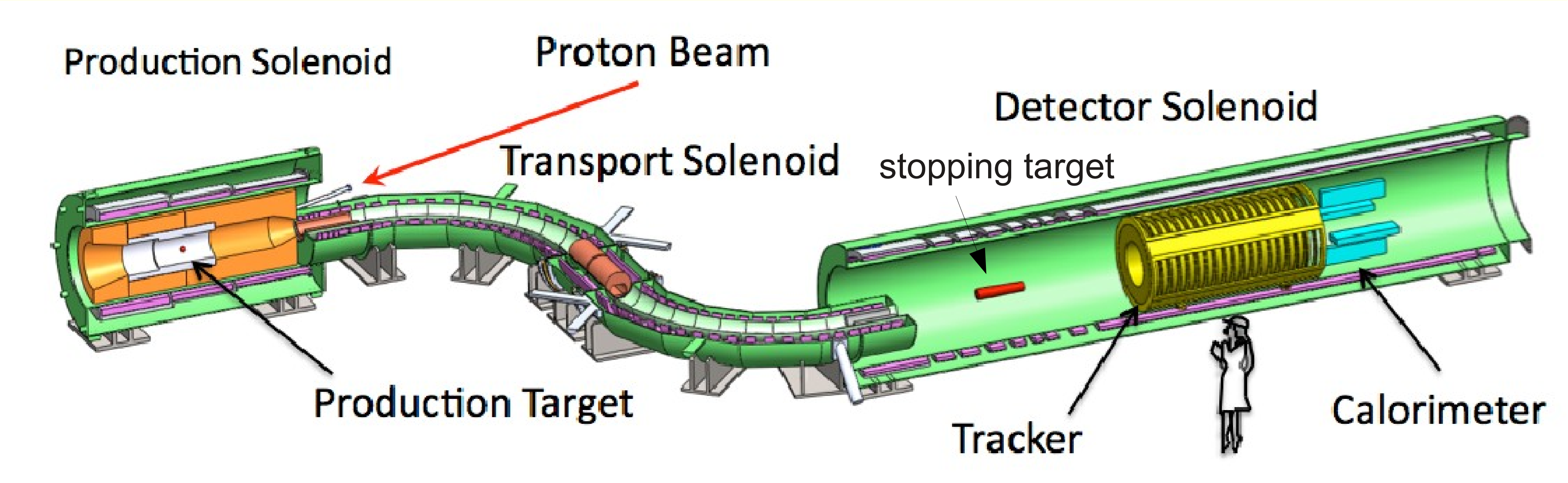
→ Fermilab: Mu2e Experiment $R_{\mu e} \sim 10^{-17}$ - $10^{-16}$

# Mu2e Experiment (Fermilab) → talk by R.Ehrlich

Concenptual Design Report arXiv:1211.7019


Modifications
- 8 GeV Proton Booster
- recycler
- debuncher
- new muon transport line

- costs 200-300 M$
- collaborations ~200 members




- start operation ~2020
- expected sensitivity: $R_{\mu e} \sim 10^{-17} - 10^{-16}$

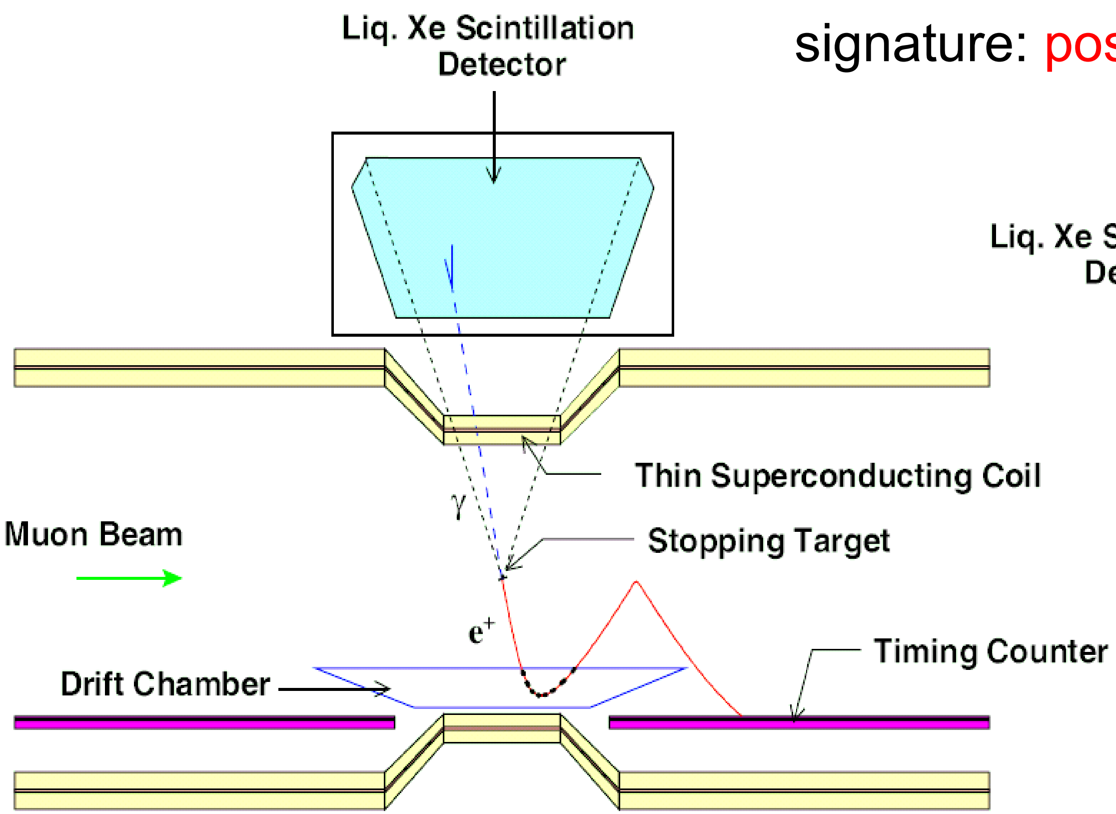
- helical tracks in straw tubes
- calorimeter for trigger and PID

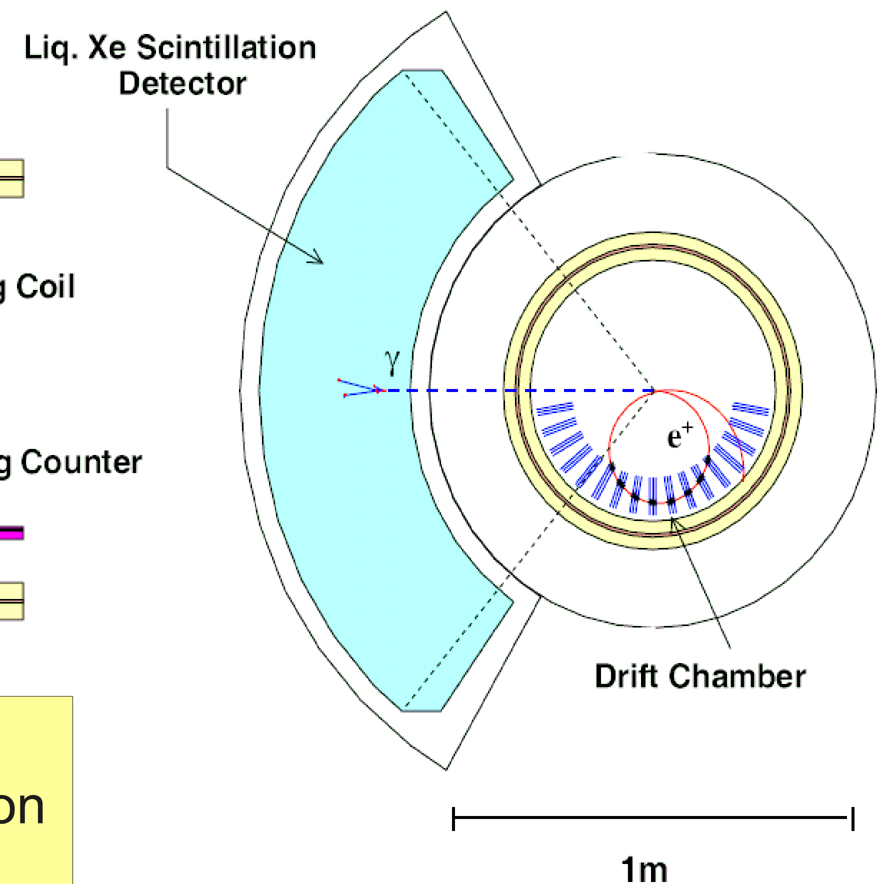
# MEG Experiment at PSI

➨ talk by G.Cavoto

signature: positron-muon back-to back

in operation since 2009




Main requirements:
- good energy (momentum) resolution
- good spatial (angular) resolution
- good timing

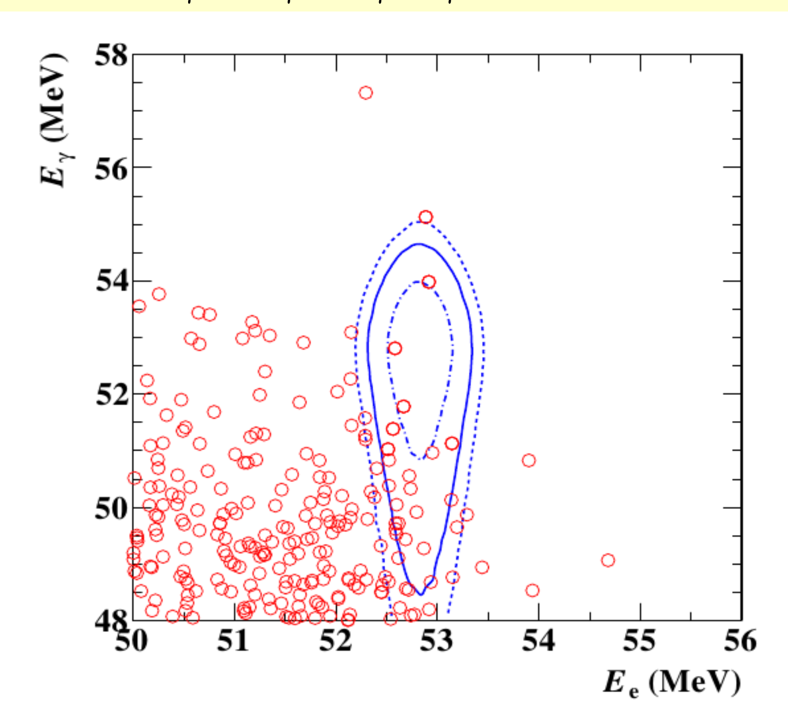
# MEG Experiments at PSI

➜ talk by G.Cavoto

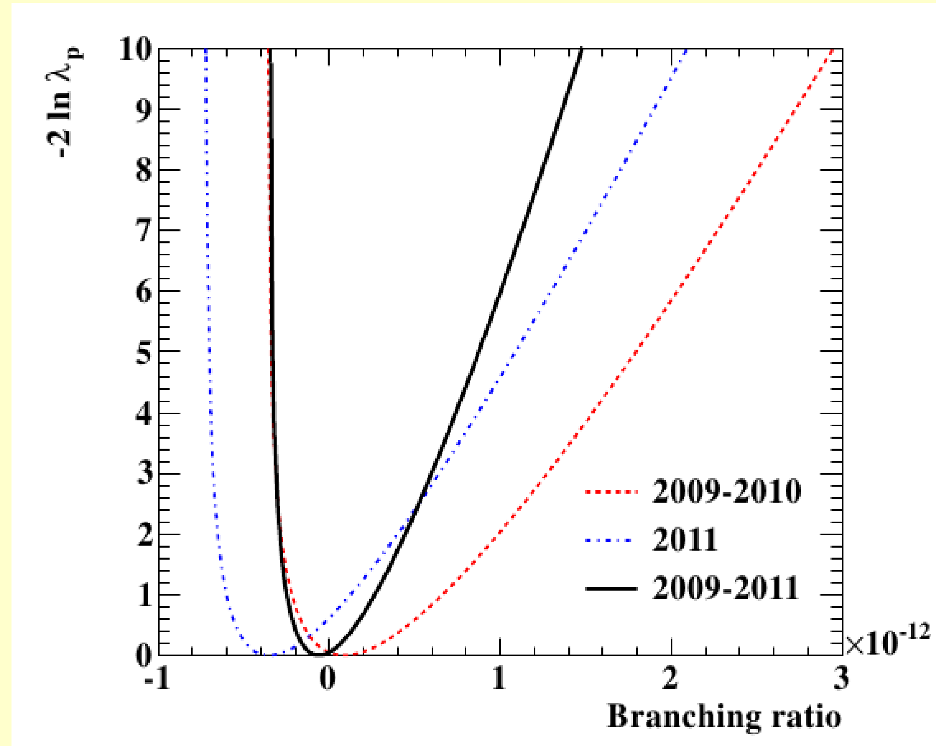
- Result from 2012 (90% CL):

  $BR(\mu^+ \rightarrow e^+ \gamma) < 2.4 \cdot 10^{-12}$

- Improved Analysis:
  - Tracking using Kalman filter
  - Better elimination of pile-up
- Analysis of new 2011 data set
- Multivariate analysis of 5 variables ($E_e$, $E_\gamma$, $\Theta_{e\gamma}$, $\Phi_{e\gamma}$, $t_{e\gamma}$)



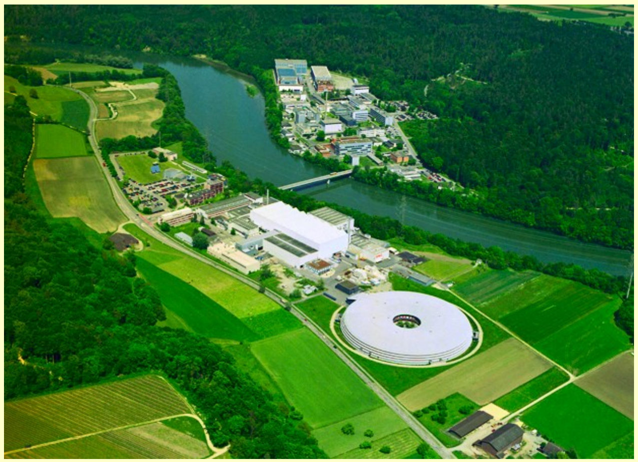

New combined result (arXiv:1303.9754)




| Dataset | $\mathcal{B}_{\text{fit}} \times 10^{12}$ | $\mathcal{B}_{90} \times 10^{12}$ | $\mathcal{S}_{90} \times 10^{12}$ |
|---|---|---|---|
| 2009–2010 | 0.09 | 1.3 | 1.3 |
| 2011 | −0.35 | 0.67 | 1.1 |
| 2009–2011 | −0.06 | $\boxed{0.57}$ | 0.77 |

# 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

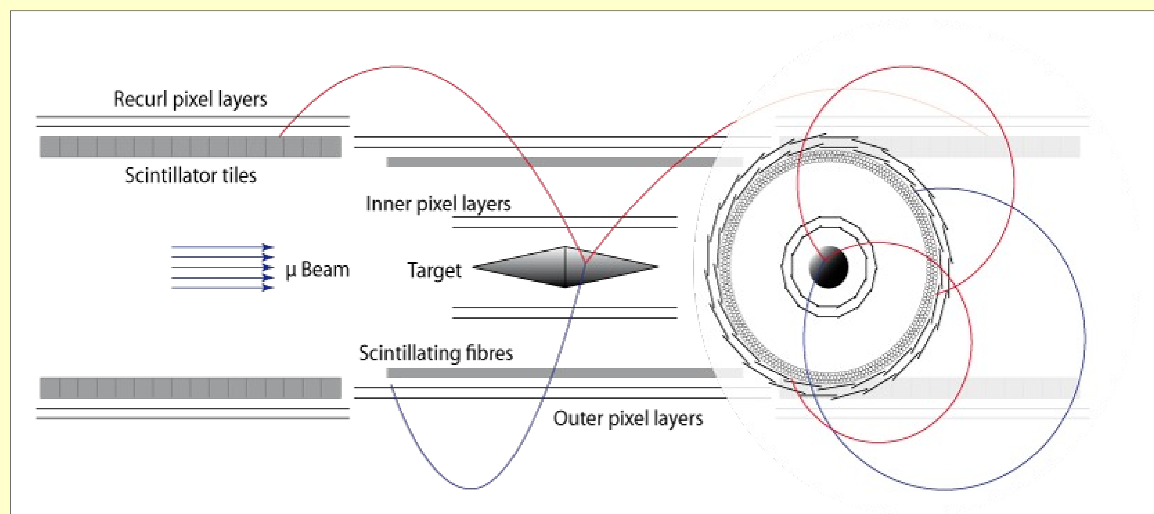
project approved in Jan 2013

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

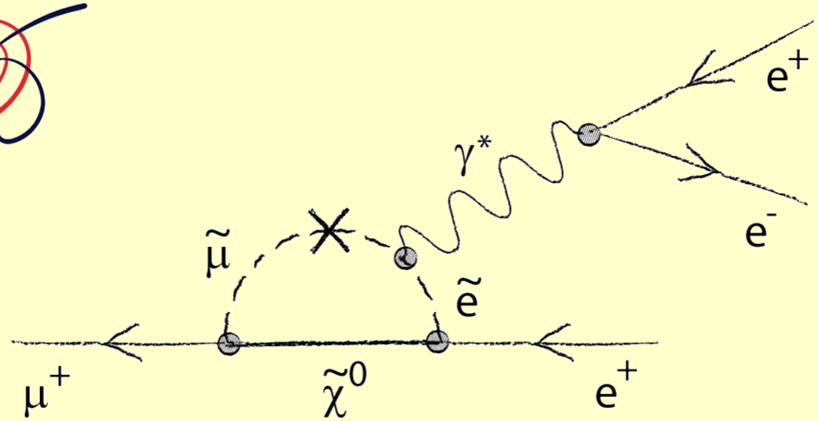
$BR(\mu \rightarrow e\,e\,e) < 10^{-15}$ (phase I)

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

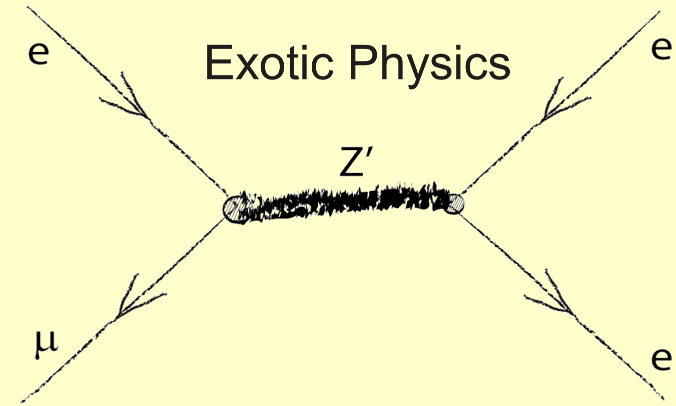
before end of decade



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




loop diagrams

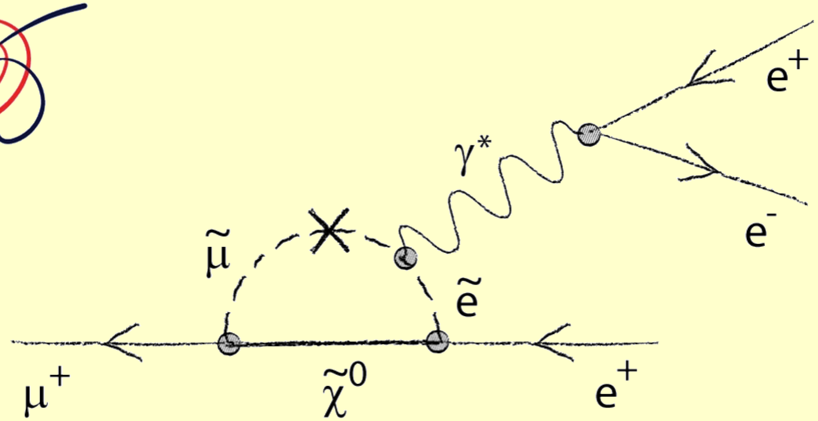



tree diagram

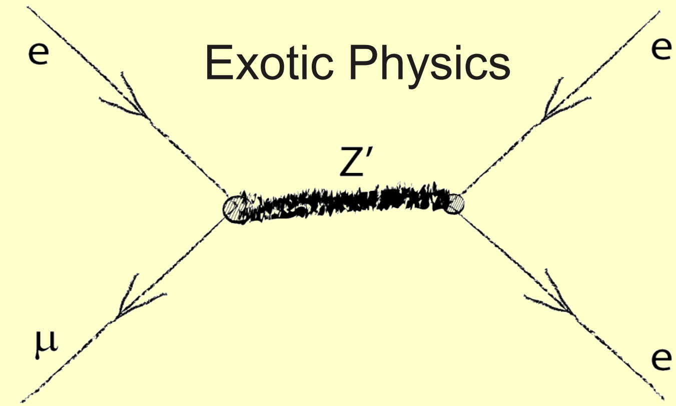
- **Supersymmetry**
- **Little Higgs Models**
- **Seesaw Models**
- **GUT models (Leptoquarks)**
- **many other models**

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

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




loop diagrams




tree diagram

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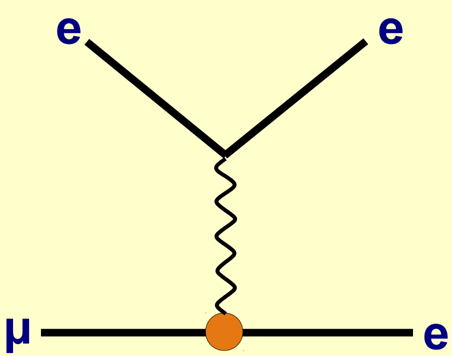
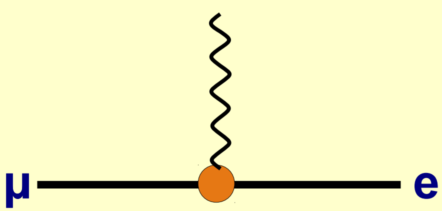
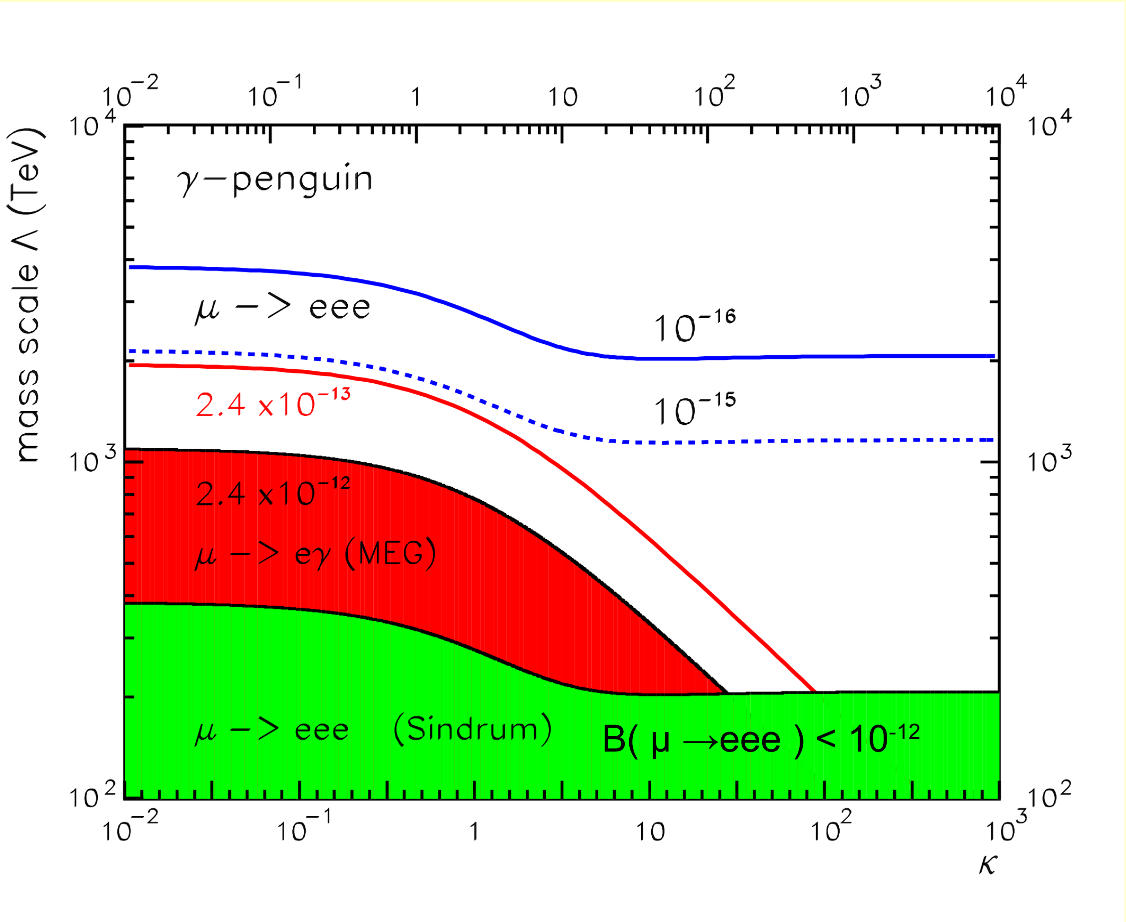
# Model Independent Comparison

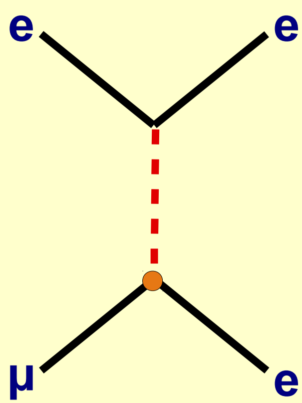



$\kappa \to 0$




**eμee contact IA**




$\kappa \to \infty$

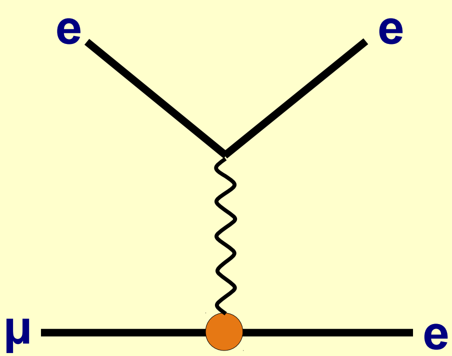
## Effective cLFV Lagrangian:

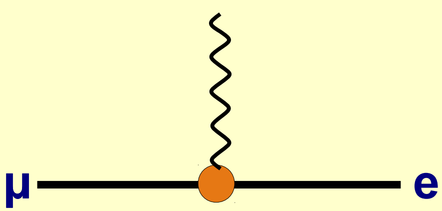
$$L = \frac{m_\mu}{\Lambda^2 (1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2 (1+\kappa)} J_\nu^{e\mu} J^{\nu,ee}$$

$\kappa$ = parameter

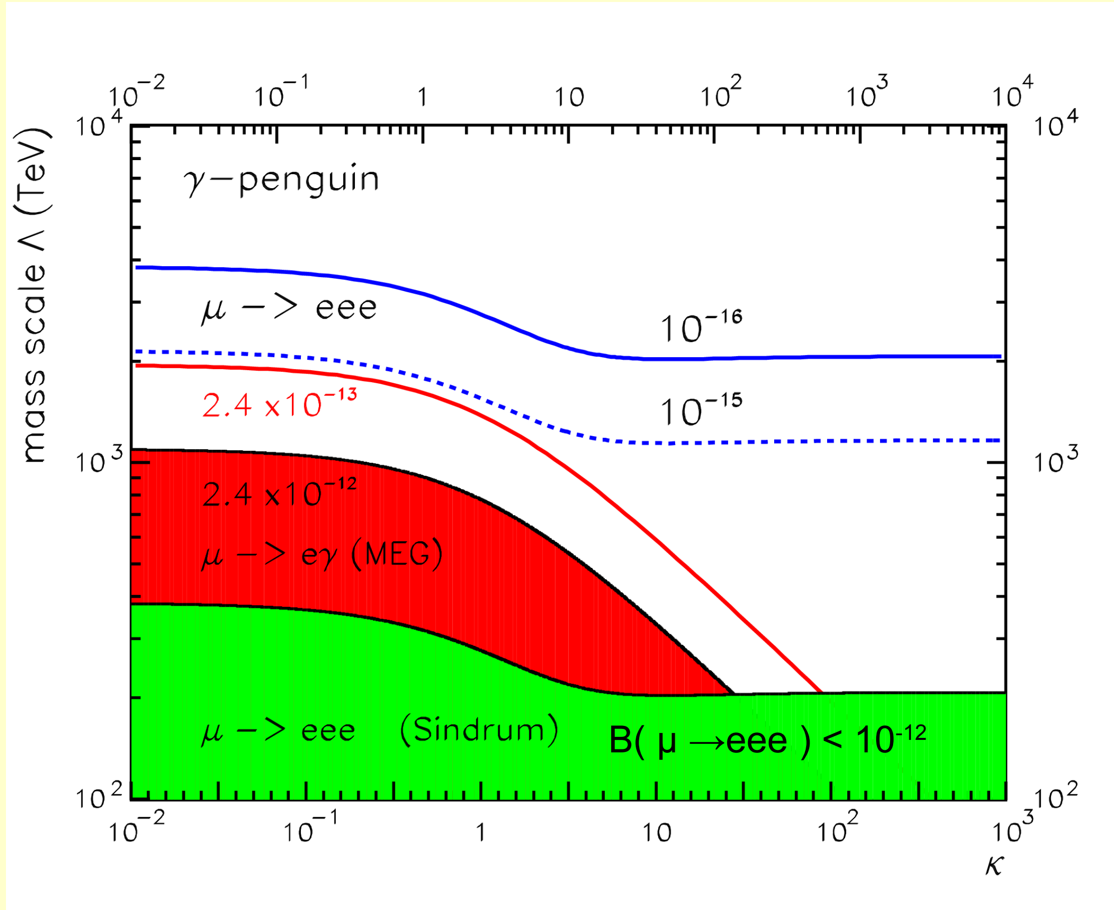
$\Lambda$ = common effective mass scale

# Model Independent Comparison

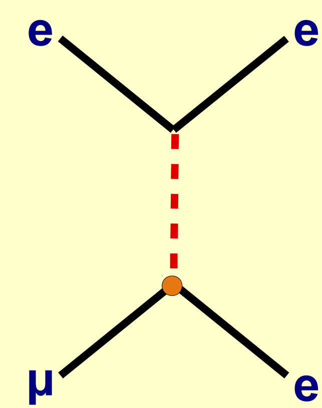



$\kappa \rightarrow 0$




**eμee contact IA**



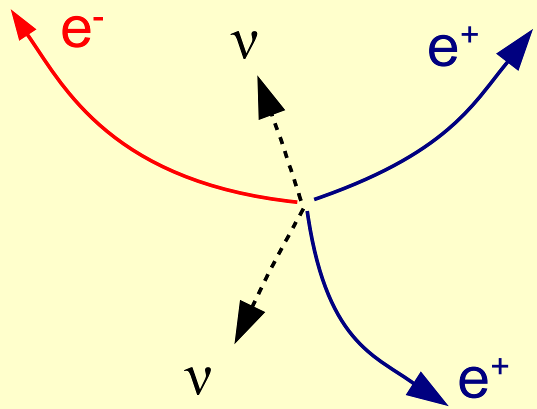

$\kappa \rightarrow \infty$

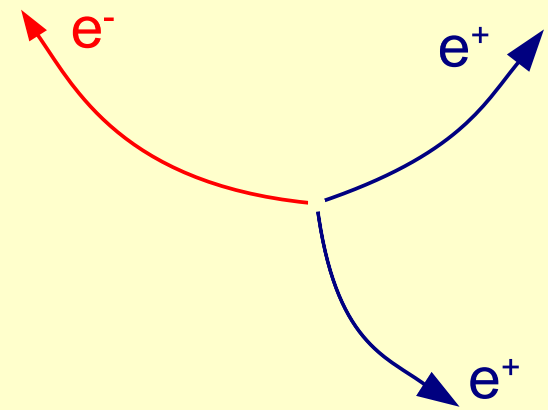
$$\frac{B(\mu^+ \rightarrow e^+e^+e^-)}{B(\mu^+ \rightarrow e^+\gamma)} \sim 0.006$$

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

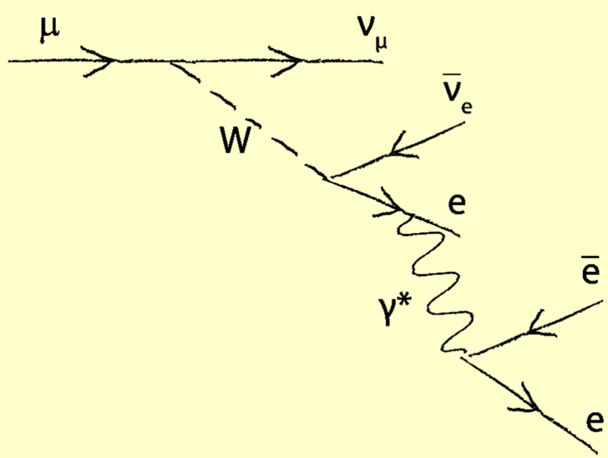
# Backgrounds

Irreducible BG: radiative decay with internal conversion



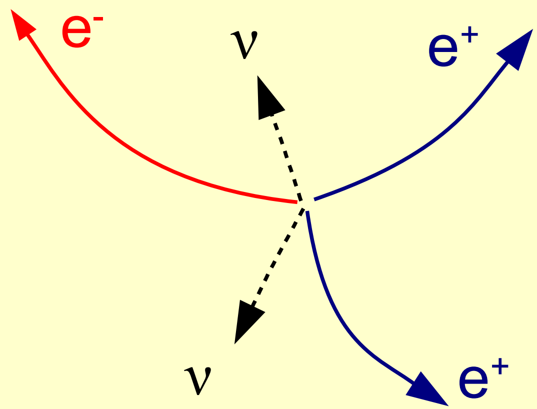

**$B(\mu^+ \rightarrow e^+e^+e^- \nu\nu) = 3.4 \cdot 10^{-5}$**

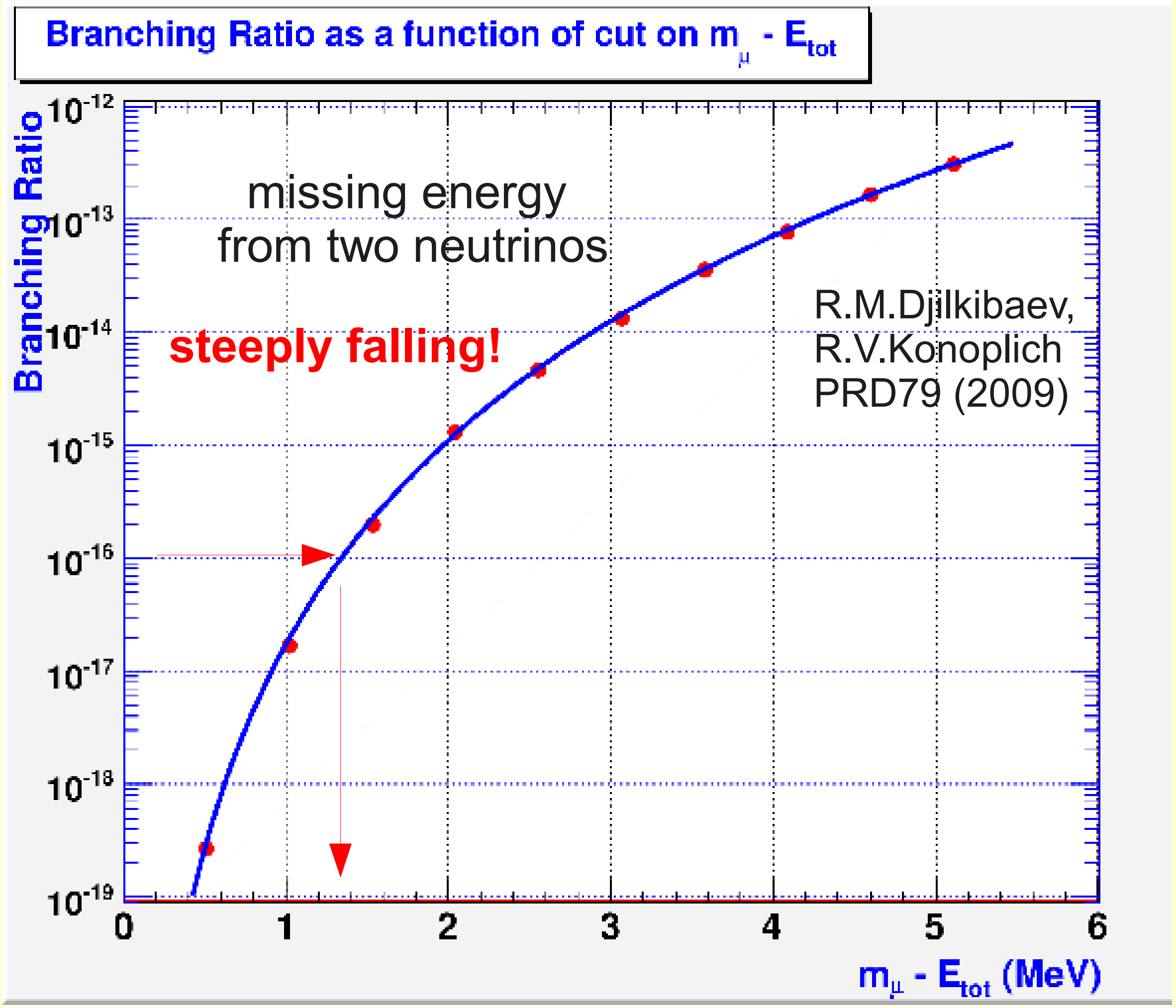



$$\sum_i E_i = m_\mu$$
$$\sum_i \vec{p}_i = 0$$

# Backgrounds

Irreducible BG: radiative decay with internal conversion

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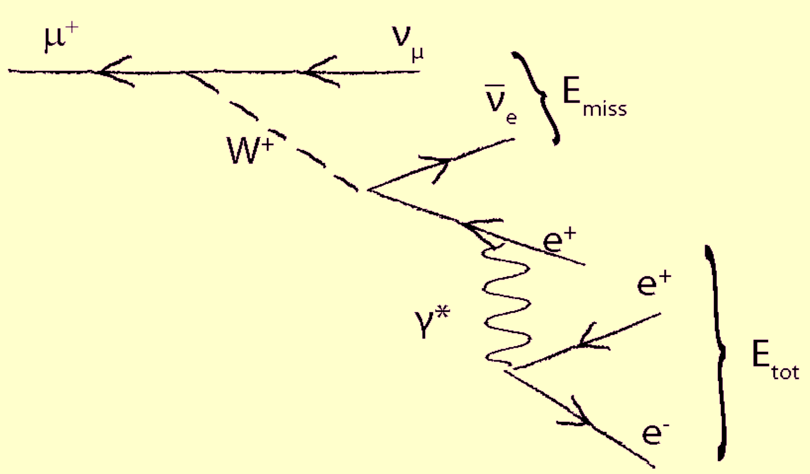
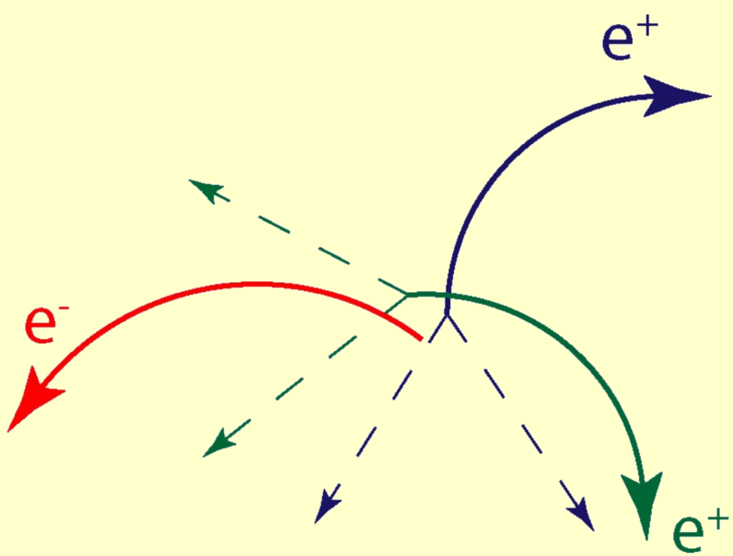
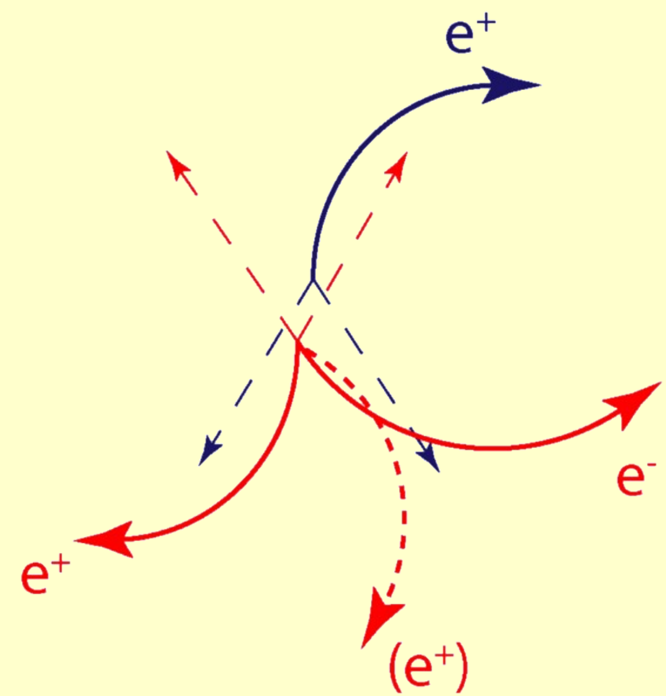



**very good momentum +**
**total energy resolution required!**

# Accidental Backgrounds

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



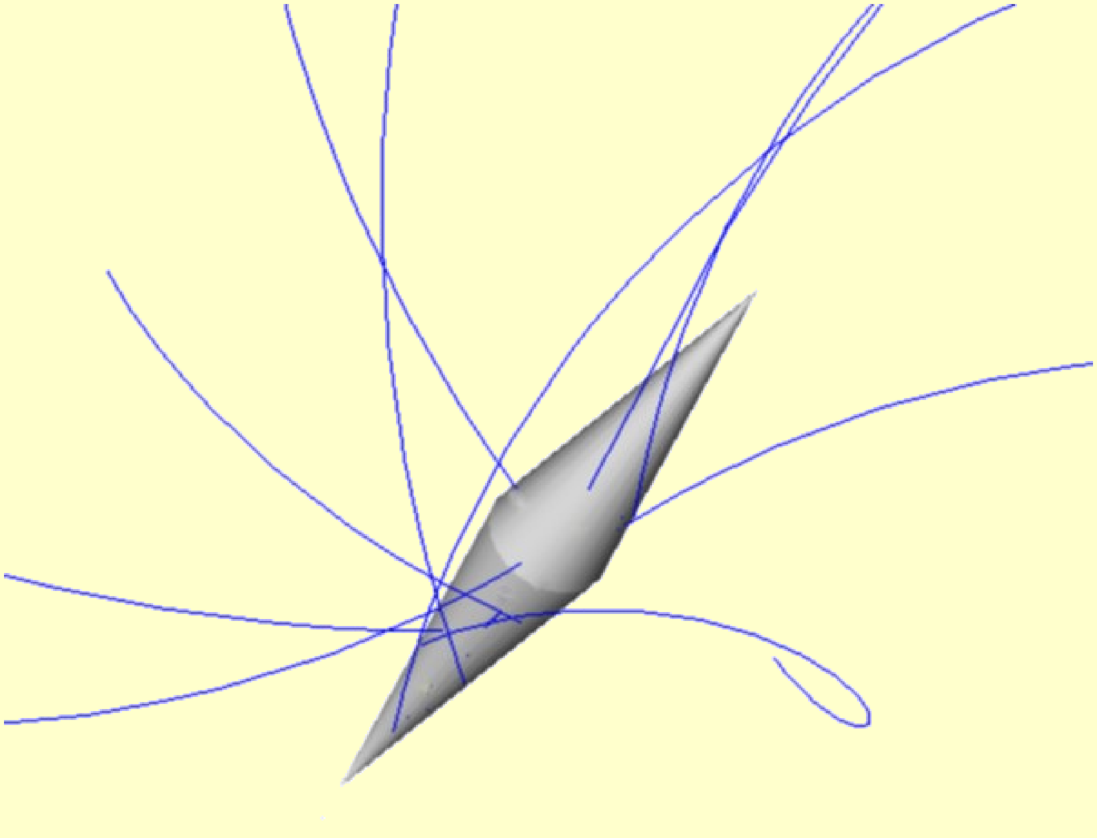




**Need excellent:**

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

# The Target

## Spread muon decays in space and time

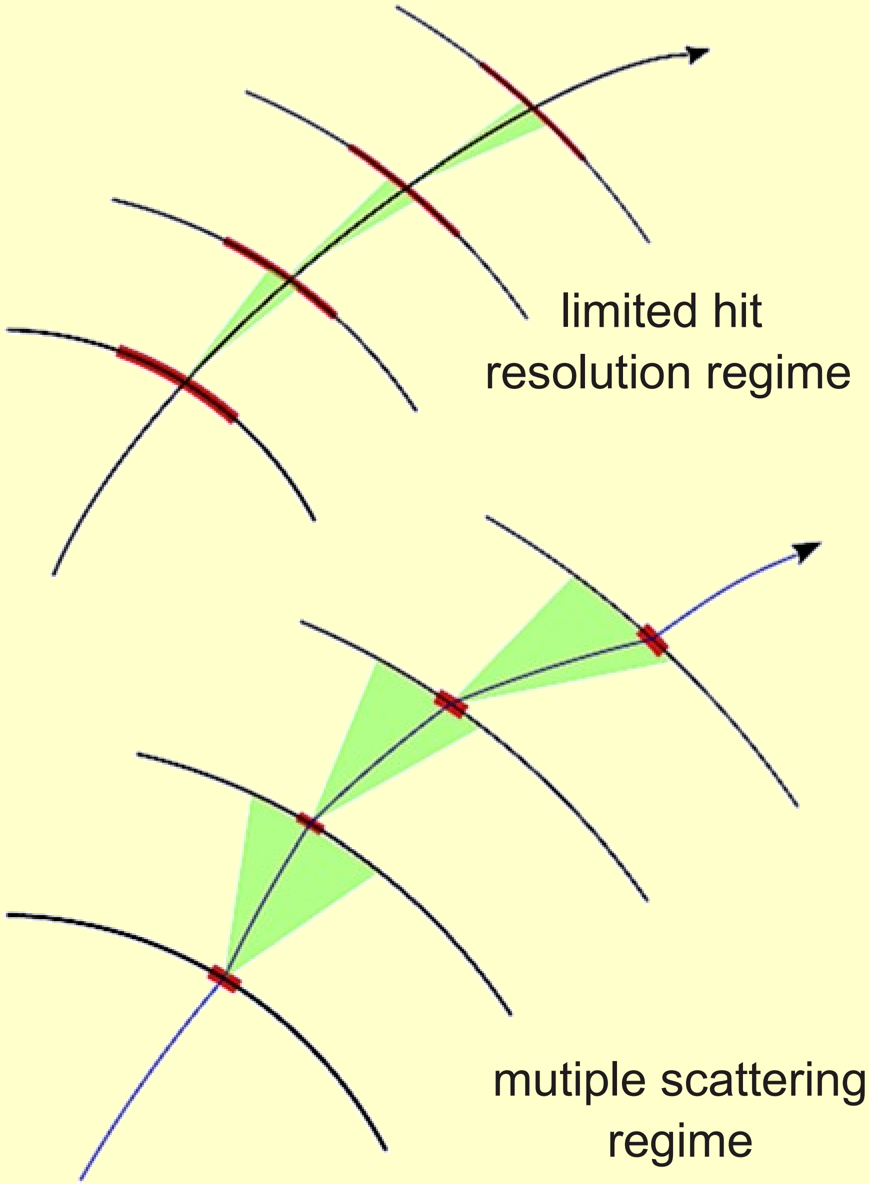


- DC Muon beam (PSI)
- about 4000 muons resting on target at same time
- large stopping target
- good **vertexing** and **timing** resolution required

e.g. Sindrum-like extended target

➔ hollow double cone (e.g. 30-80 μm Al)

# Kinematic Resolution + Multiple Scattering




- Muon decay:

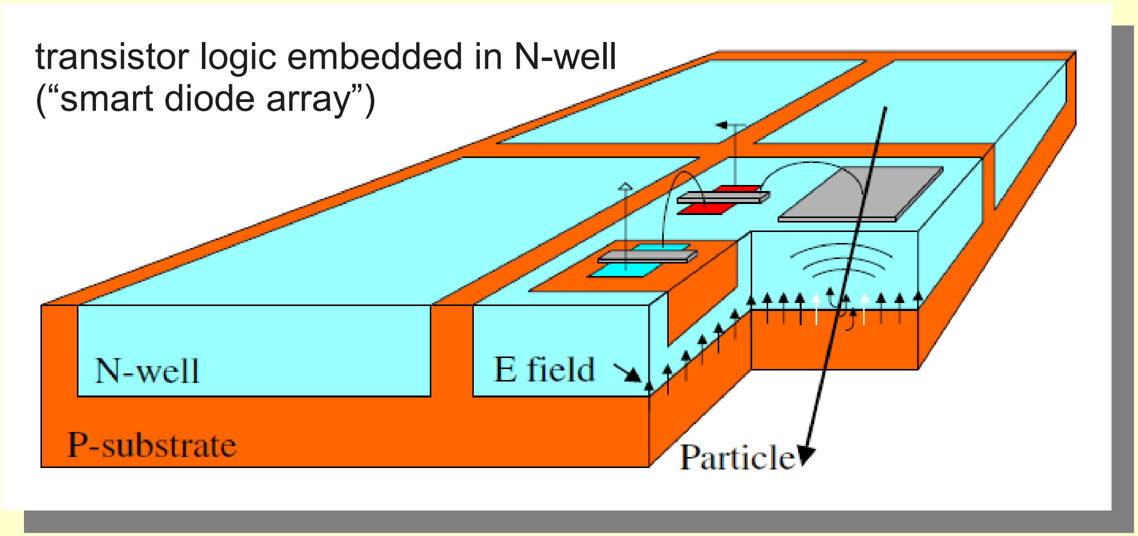
  → electrons in low momentum range
  **p < 53 MeV/c**

- Multiple scattering is dominant!
- **Need thin, fast and high resolution detectors (tracking + time of flight) operated at high rate $10^9$/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)

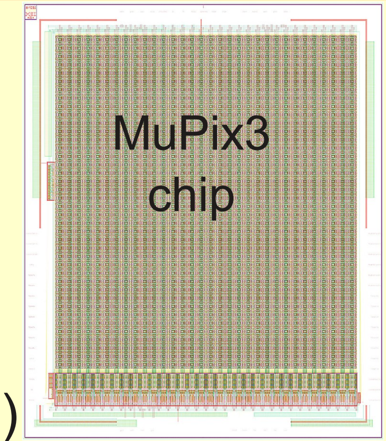


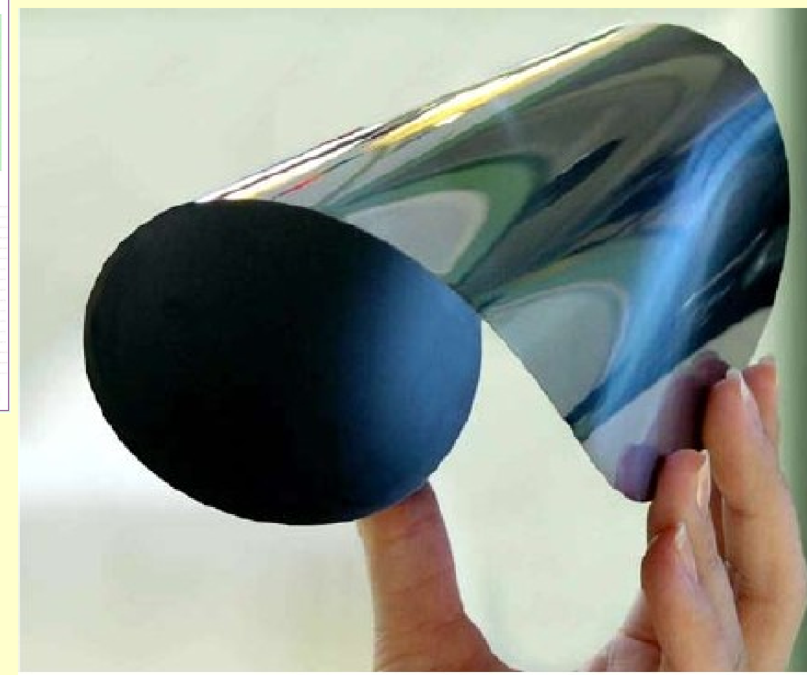

## Technology Choice

**High Voltage Monolithic Active Pixel Sensors (HV-MAPS)**

- high precision → pixels 80 x 80 μm$^2$
- can be "thinned" down to ~**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

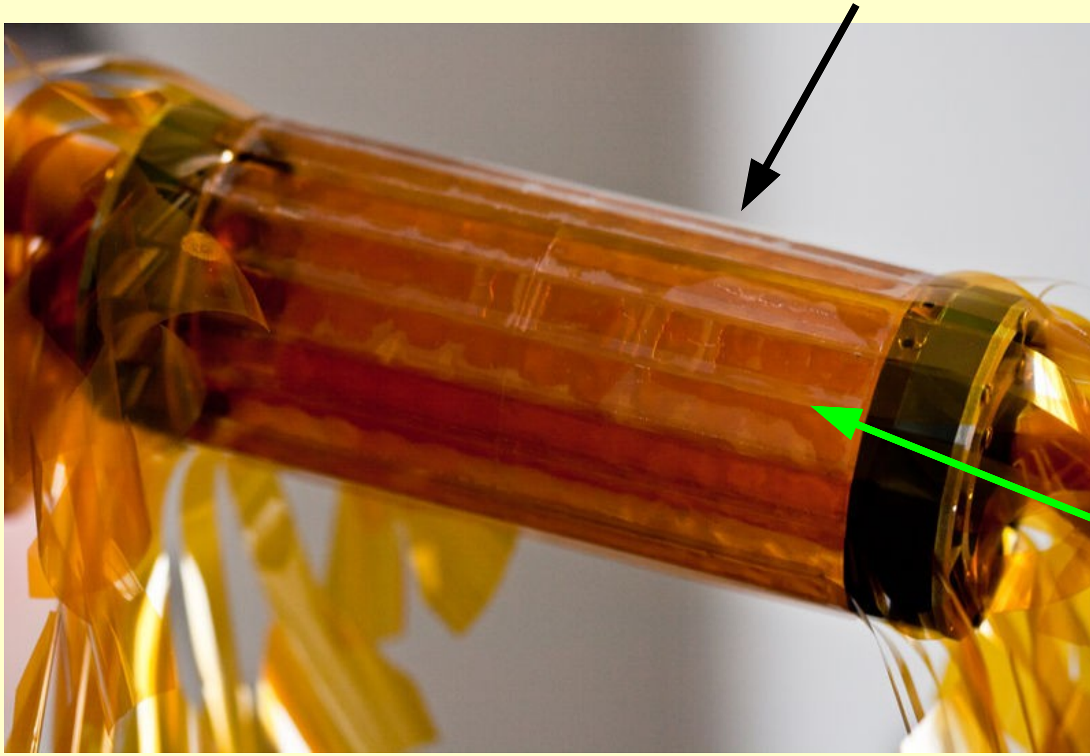
# Mechanical Prototypes for Pixel Tracker

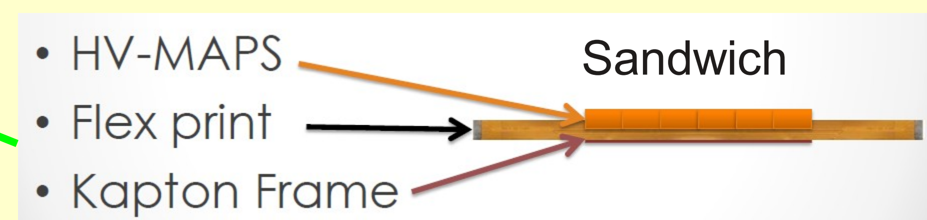


50 mu silicon wafer

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



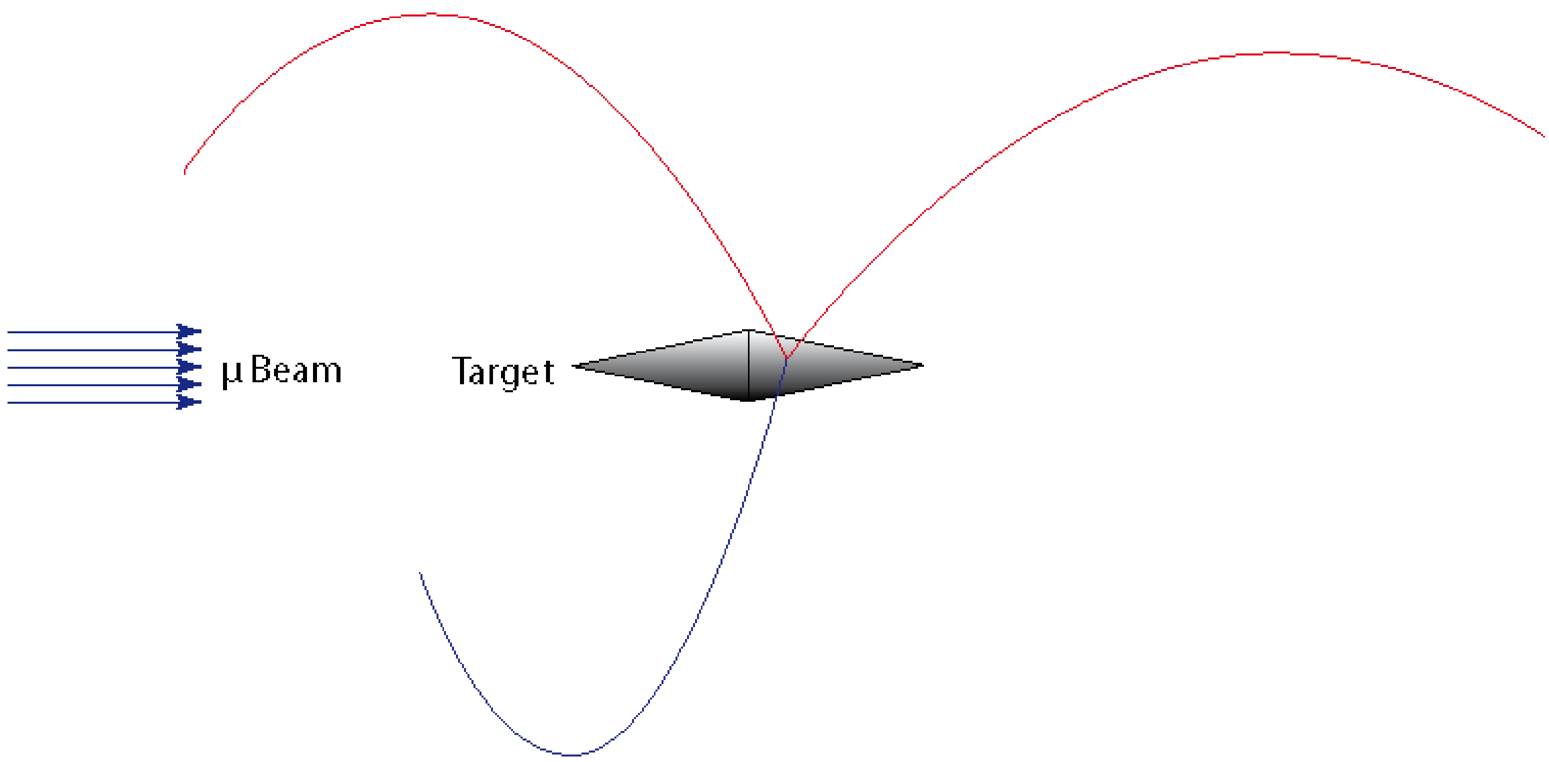



**$X \leq 0.1\% \, X_0$ per layer possible**

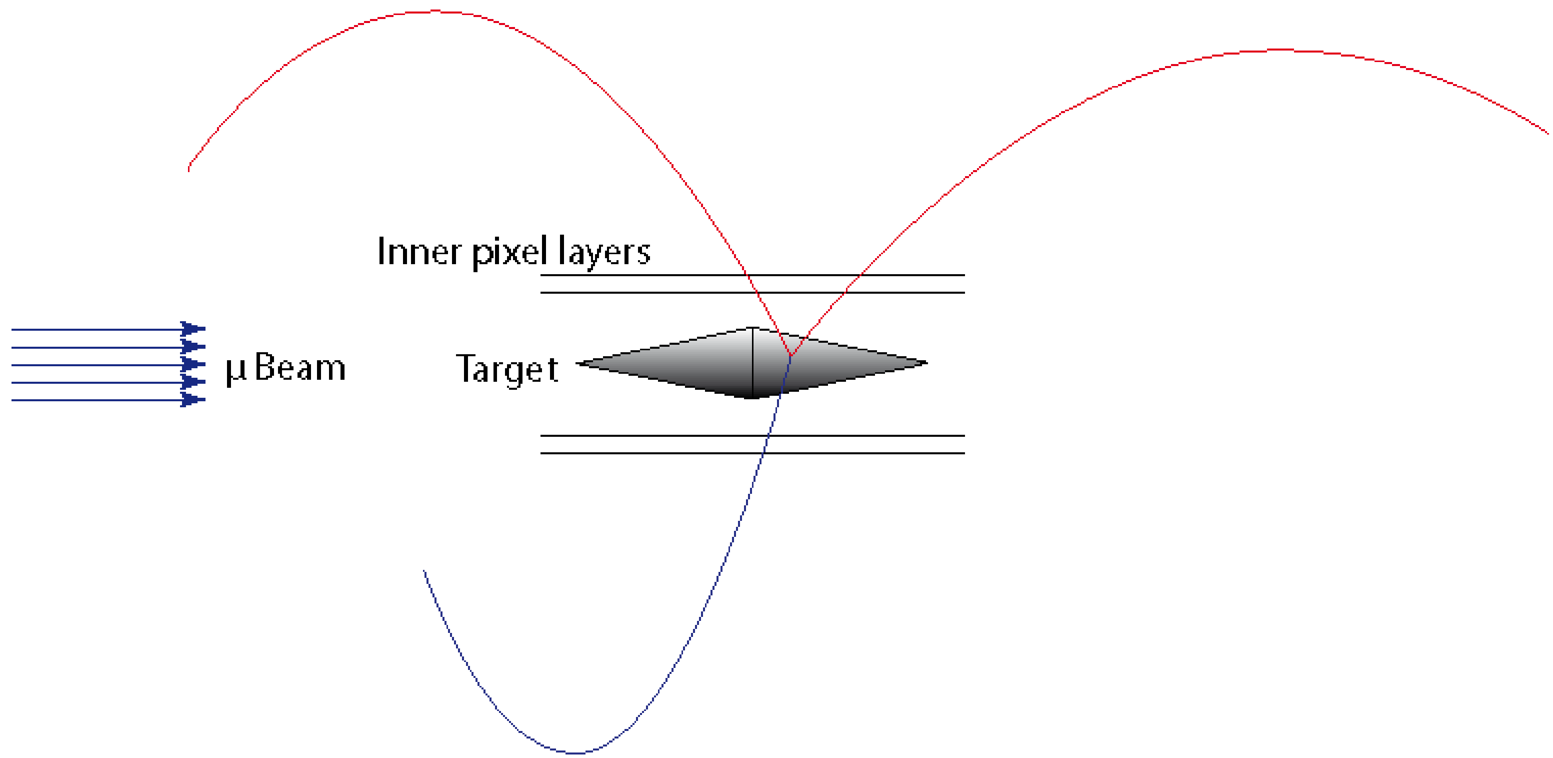
# Mu3e Experimental Proposal

# Mu3e Baseline Design

# Mu3e Baseline Design



# Mu3e Baseline Design



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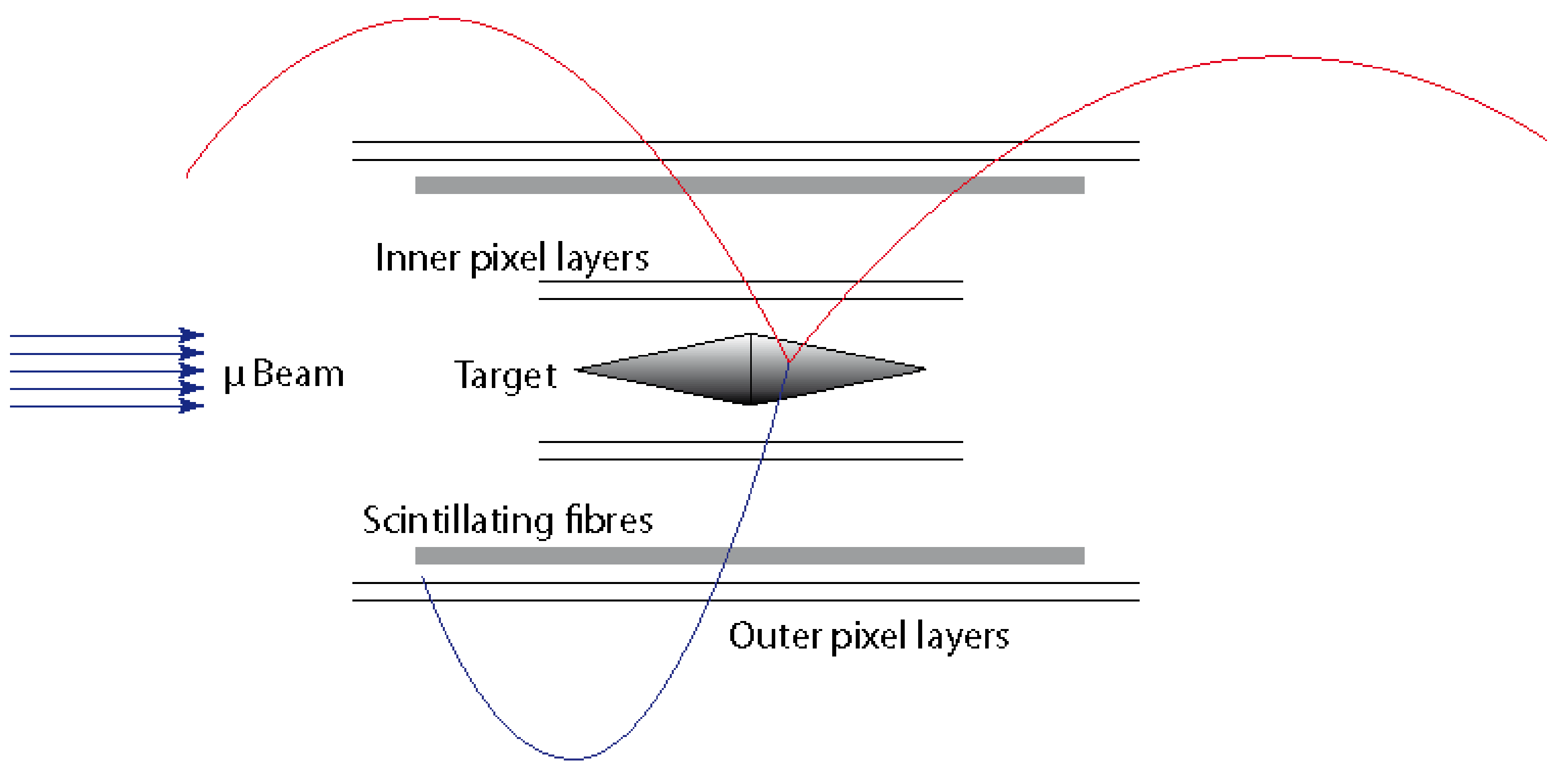
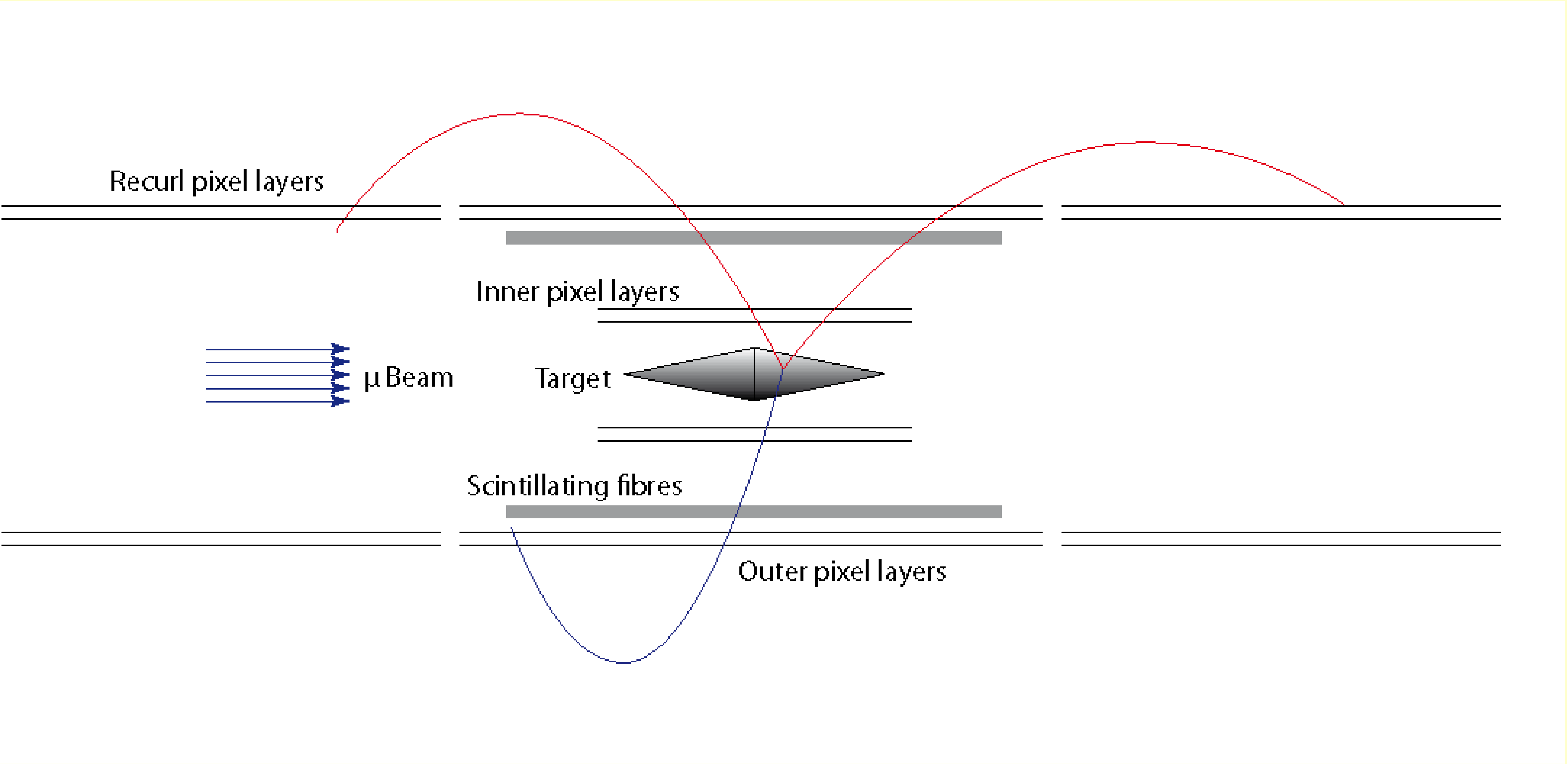
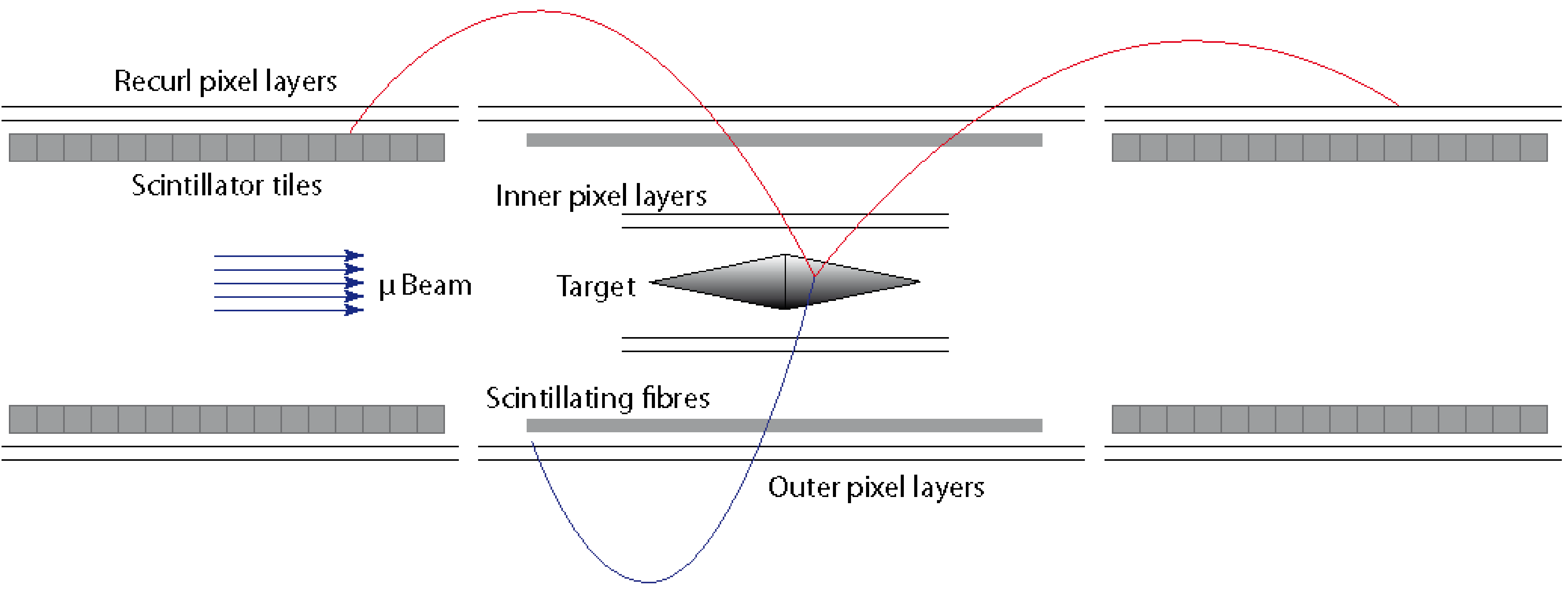


# Mu3e Baseline Design



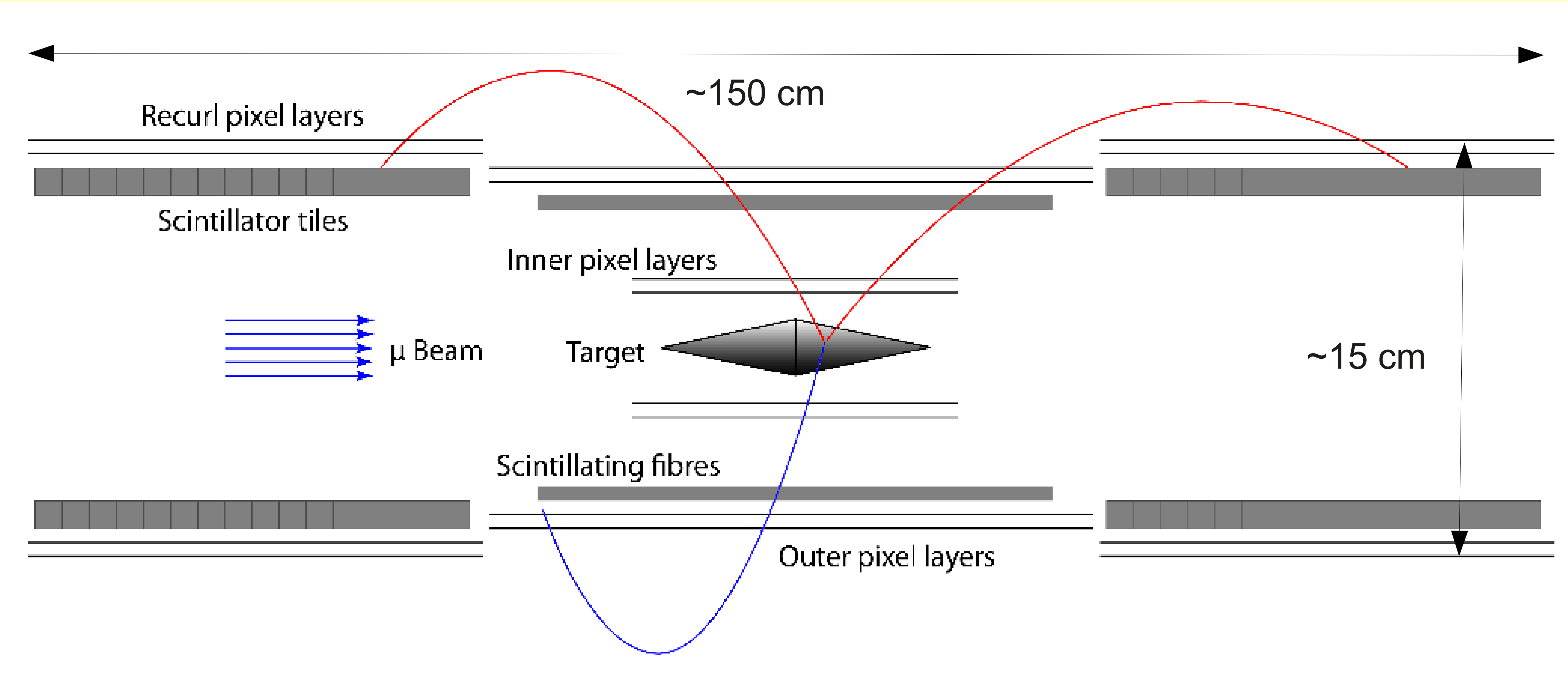
# Mu3e Baseline Design



# Mu3e Baseline Design

Long cylinder!

not to scale!



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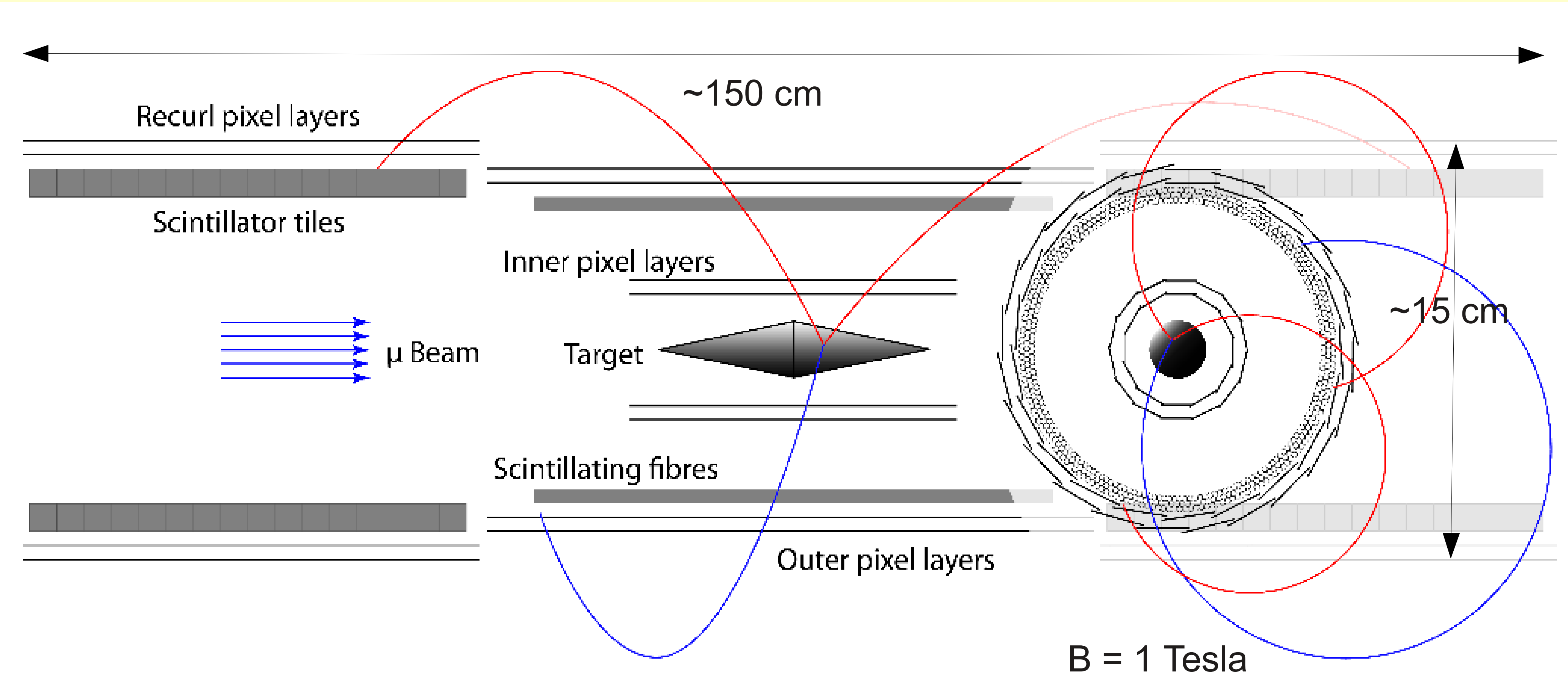

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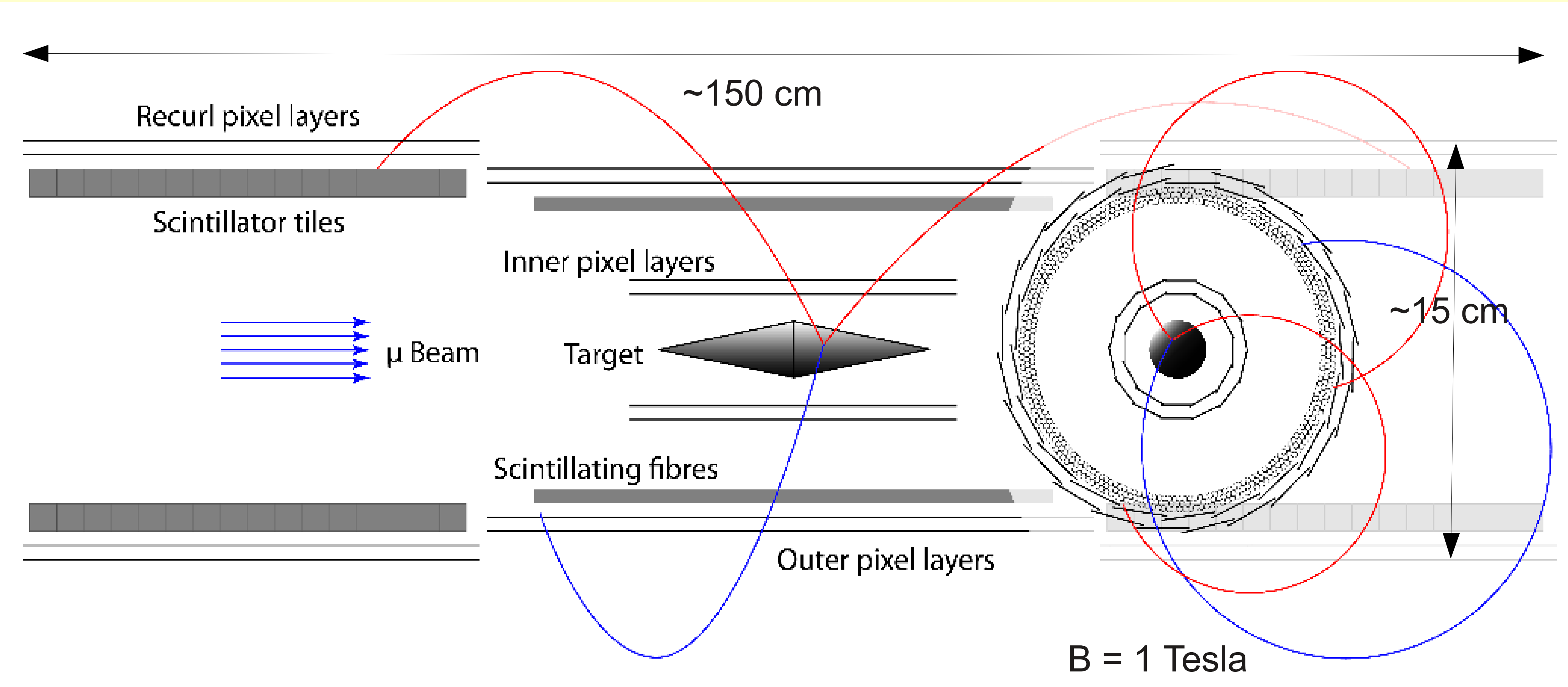
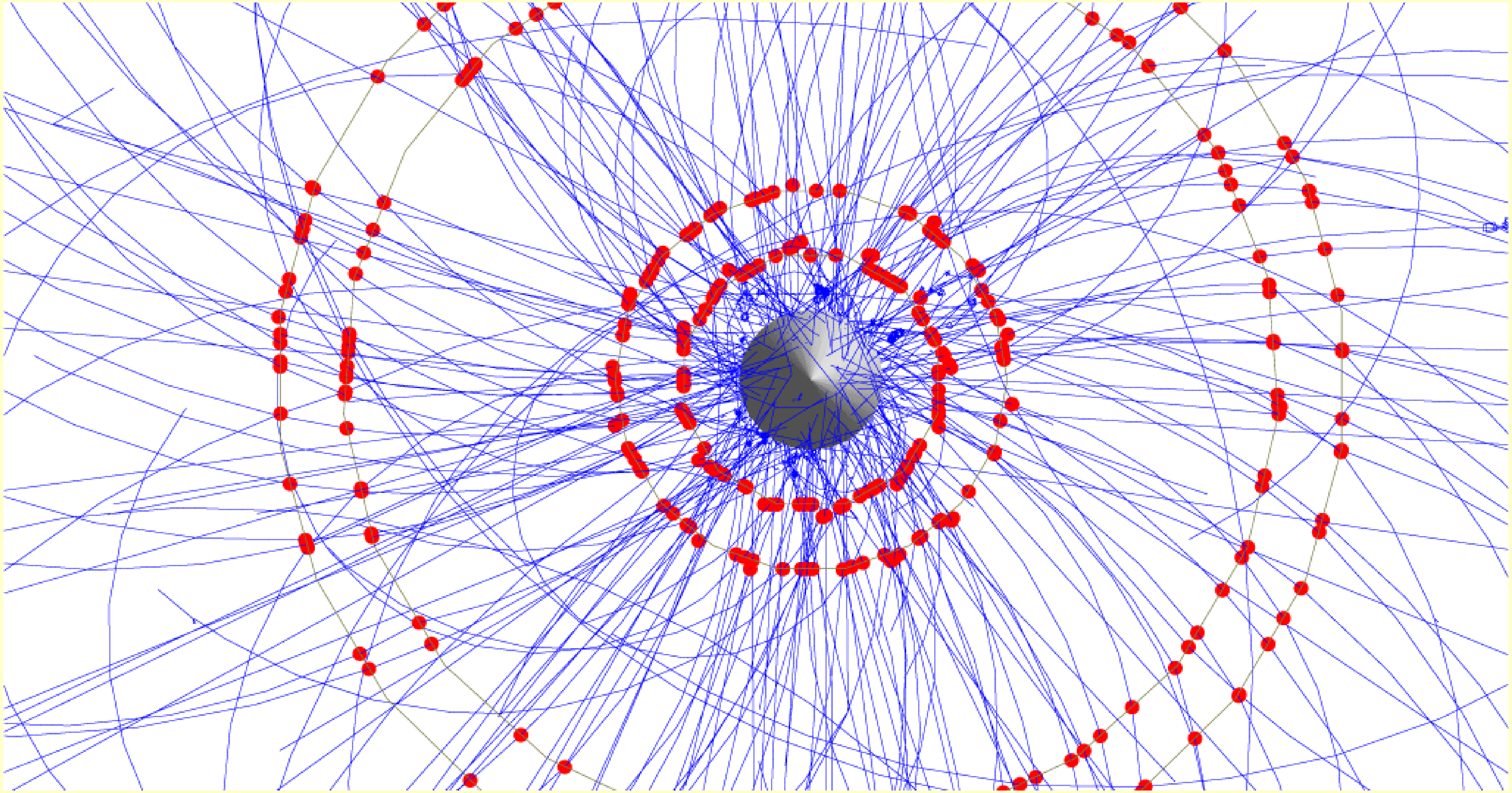



Geometrical acceptance **~70 %** for **$\mu^+ \rightarrow e^+e^+e^-$** decay

# Timing

# Pixel Detector: Readout Frames @ 20 MHz

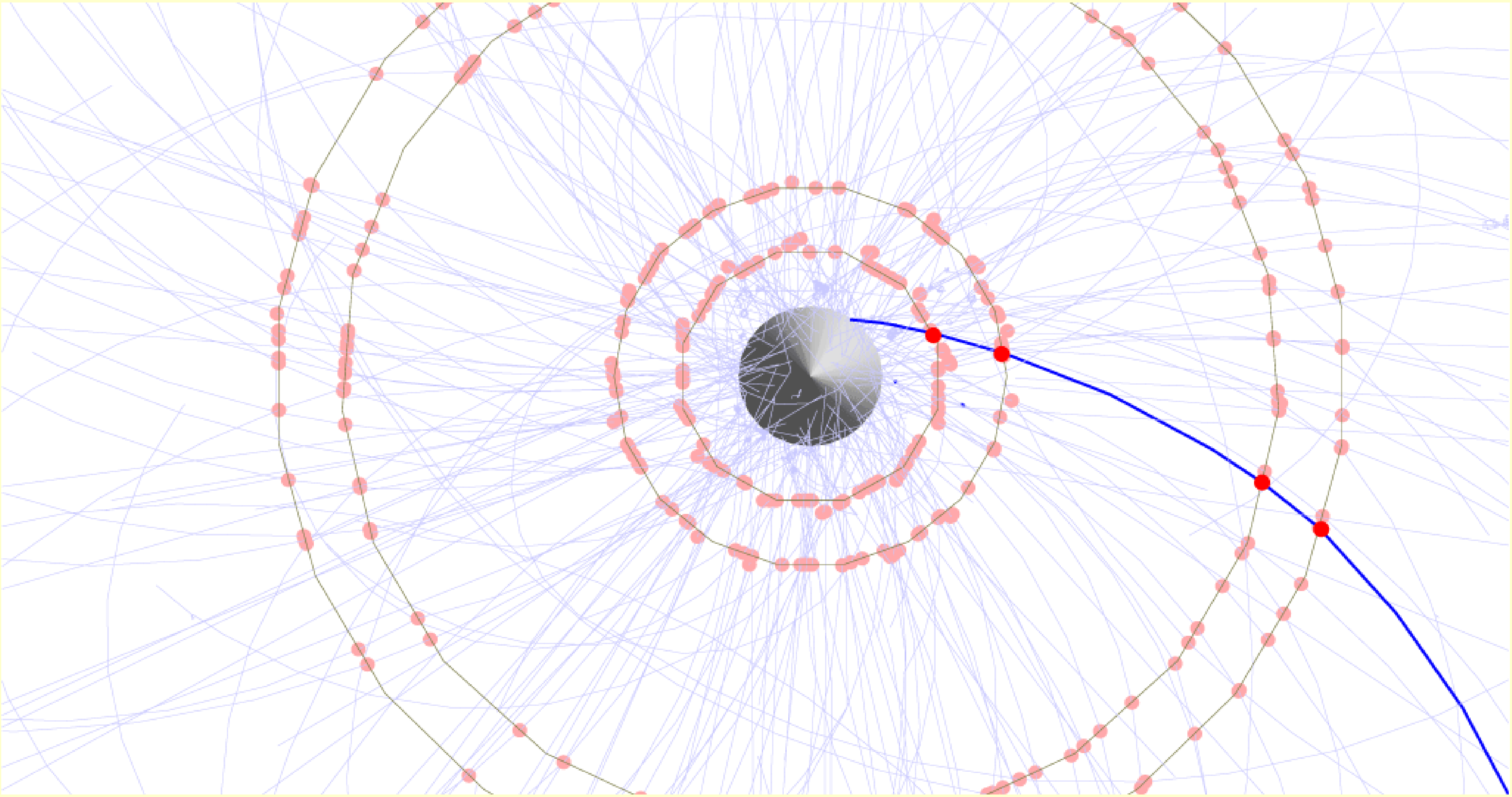
**100 muon decays @ rate 2 · 10$^9$ muon stops/s**



50 ns snapshot

# Pixel: Readout Frames 50 ns

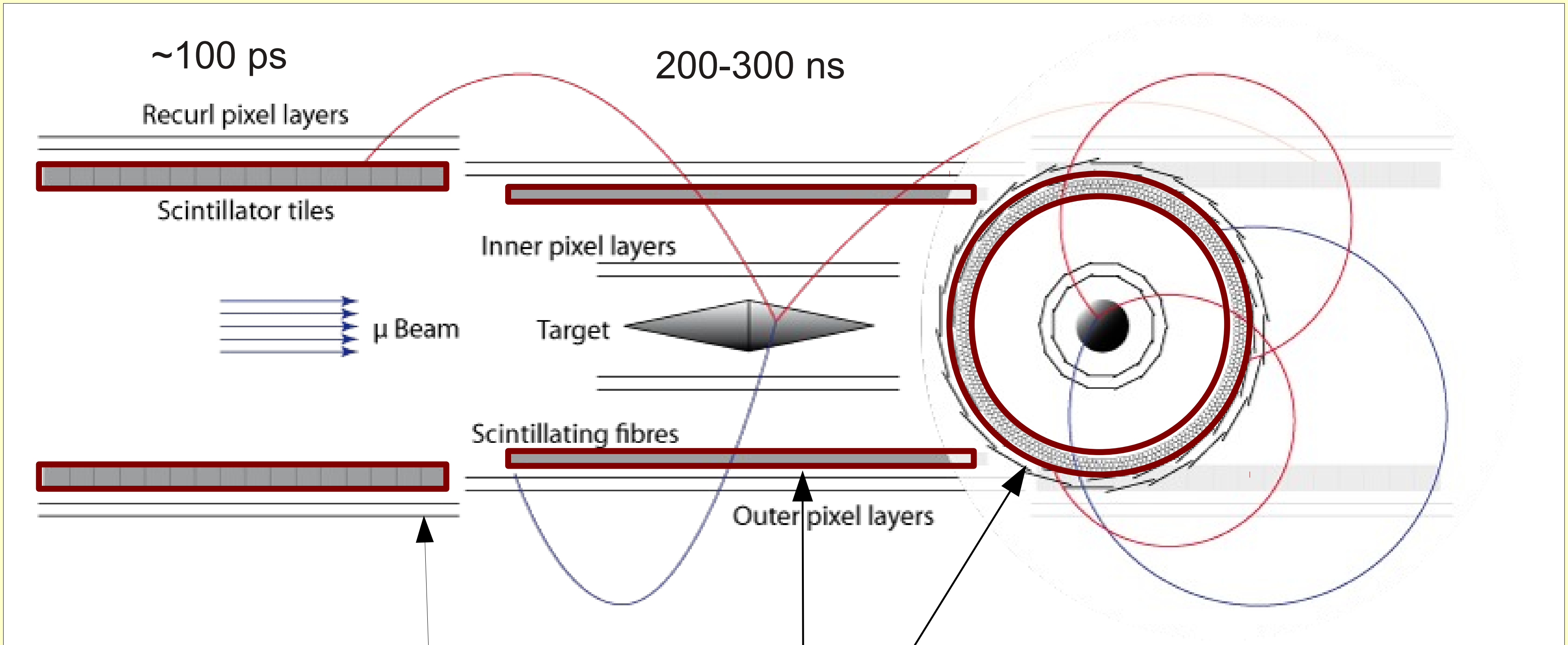
**100 muon decays @ rate $2 \cdot 10^9$ muon stops/s**



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

# Mu3e Time of Flight System

not to scale

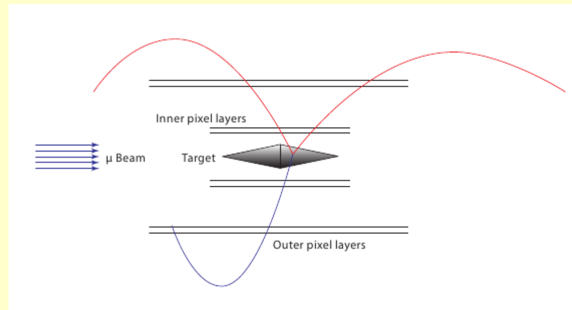


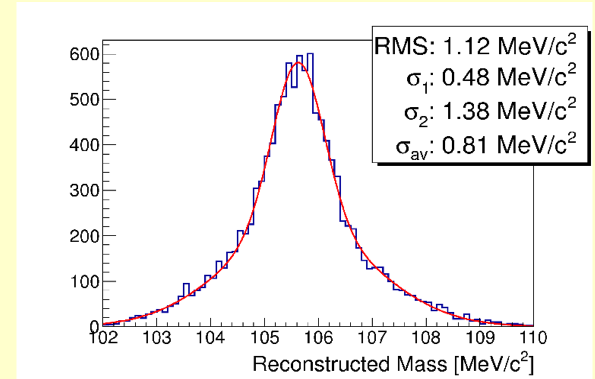

**Scintillating tiles**

**Scintillating fibers**

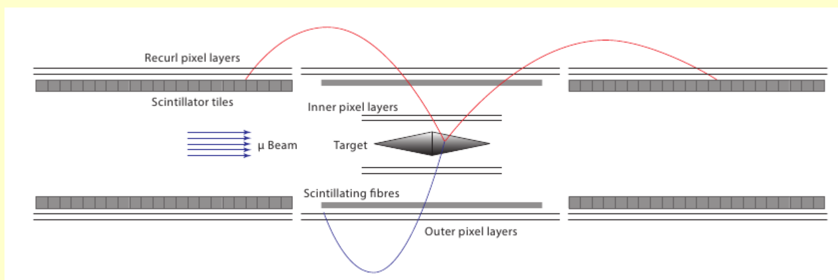
# Invariant Mass Resolution of Signal

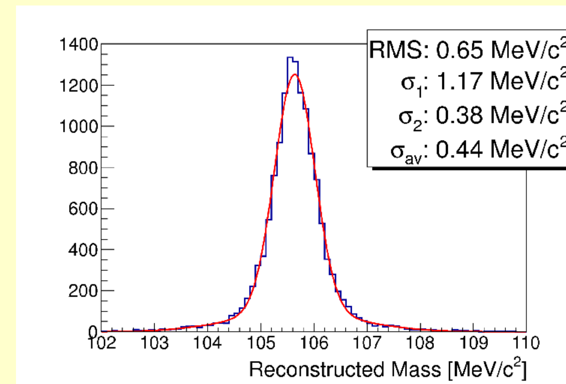
**Phase IA:**
rate ~ 2 · $10^7$ muons/s



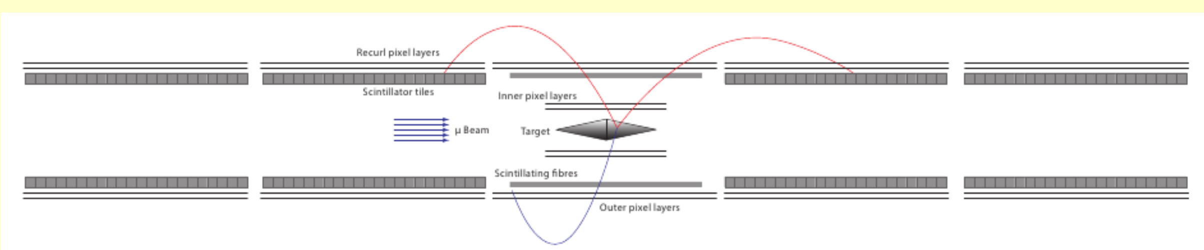



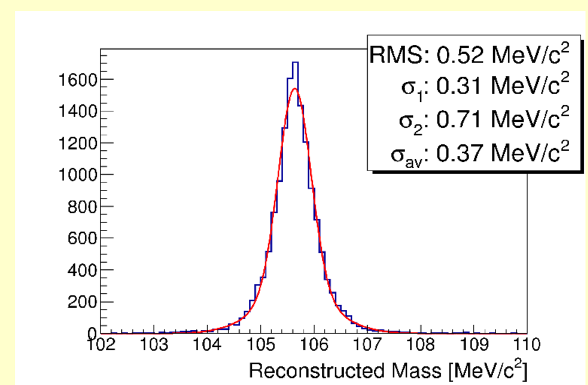

**Phase IB:**
rate ~ 2 · $10^8$ muons/s




**Phase II:**
rate ~ 2 · $10^9$ muons/s

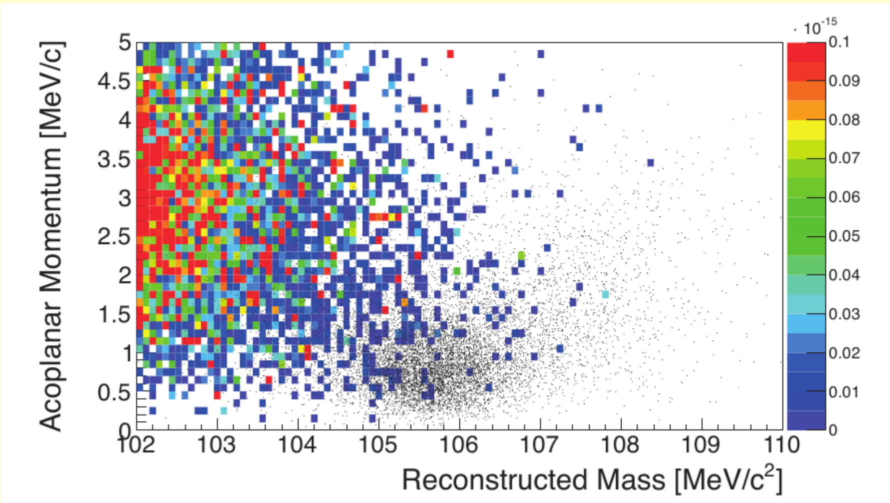


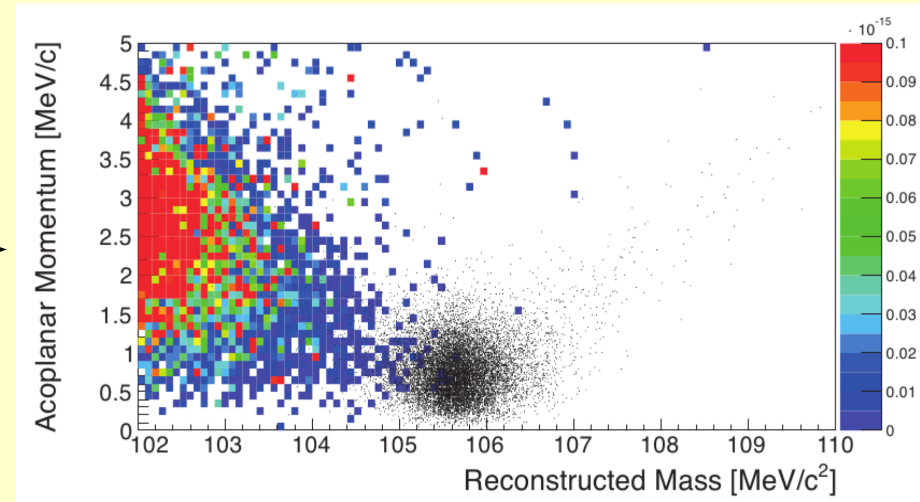



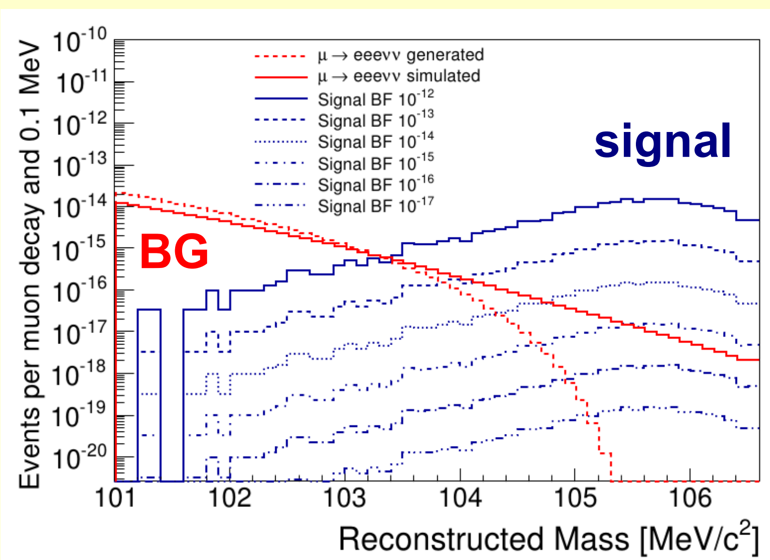
# Sensitivity Study

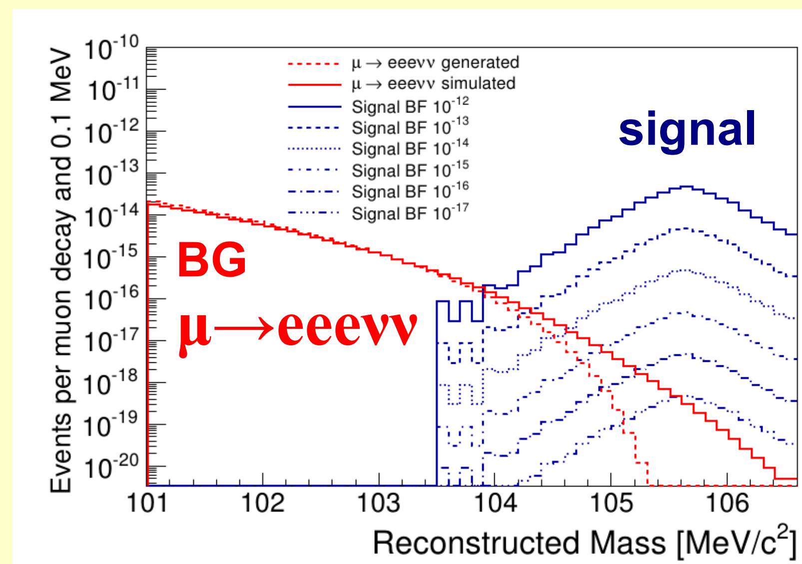
**Phase IA:** rate ≤ $2 \cdot 10^7$ muons/s

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

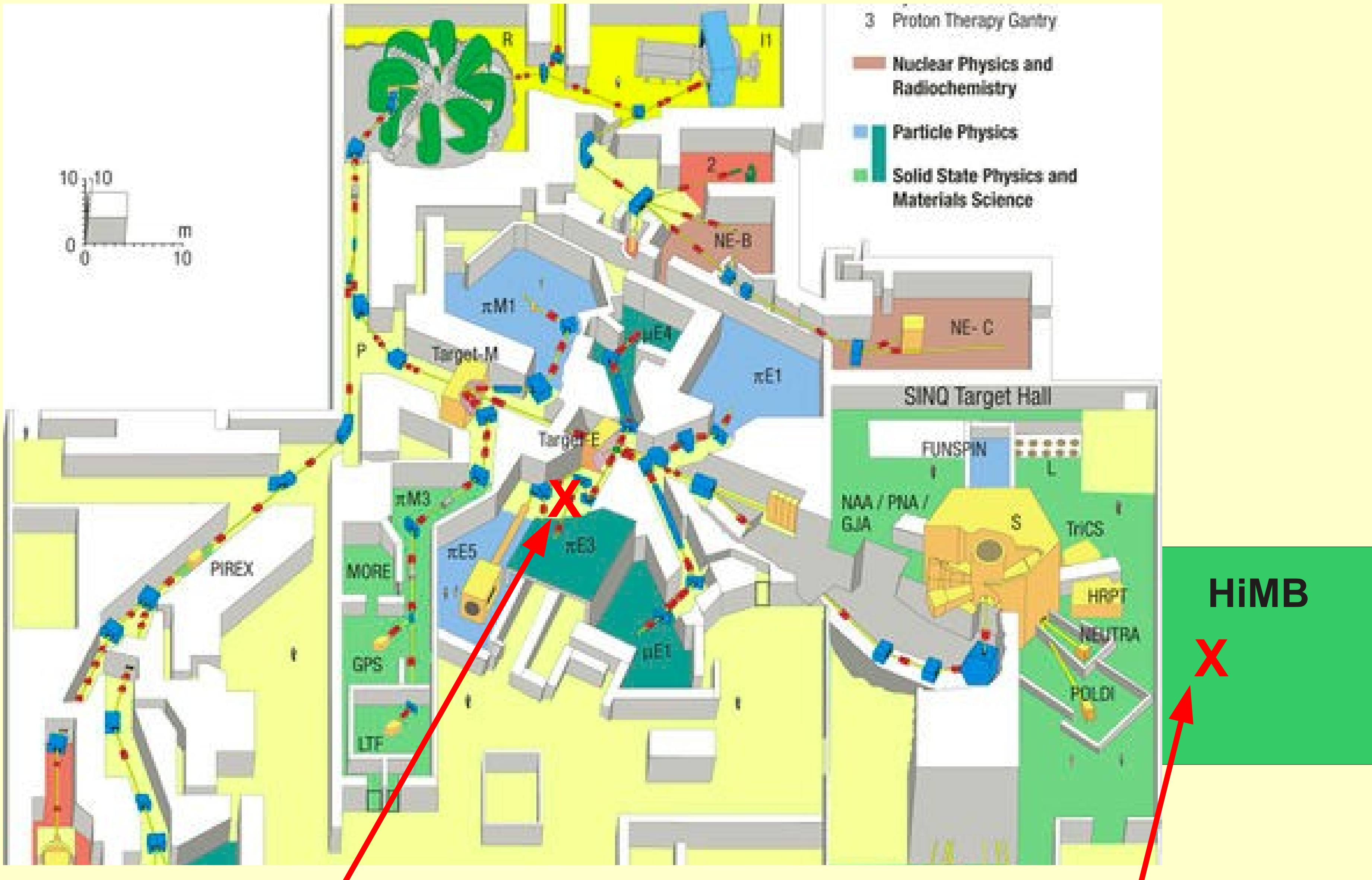


# PSI Facility for Mu3e

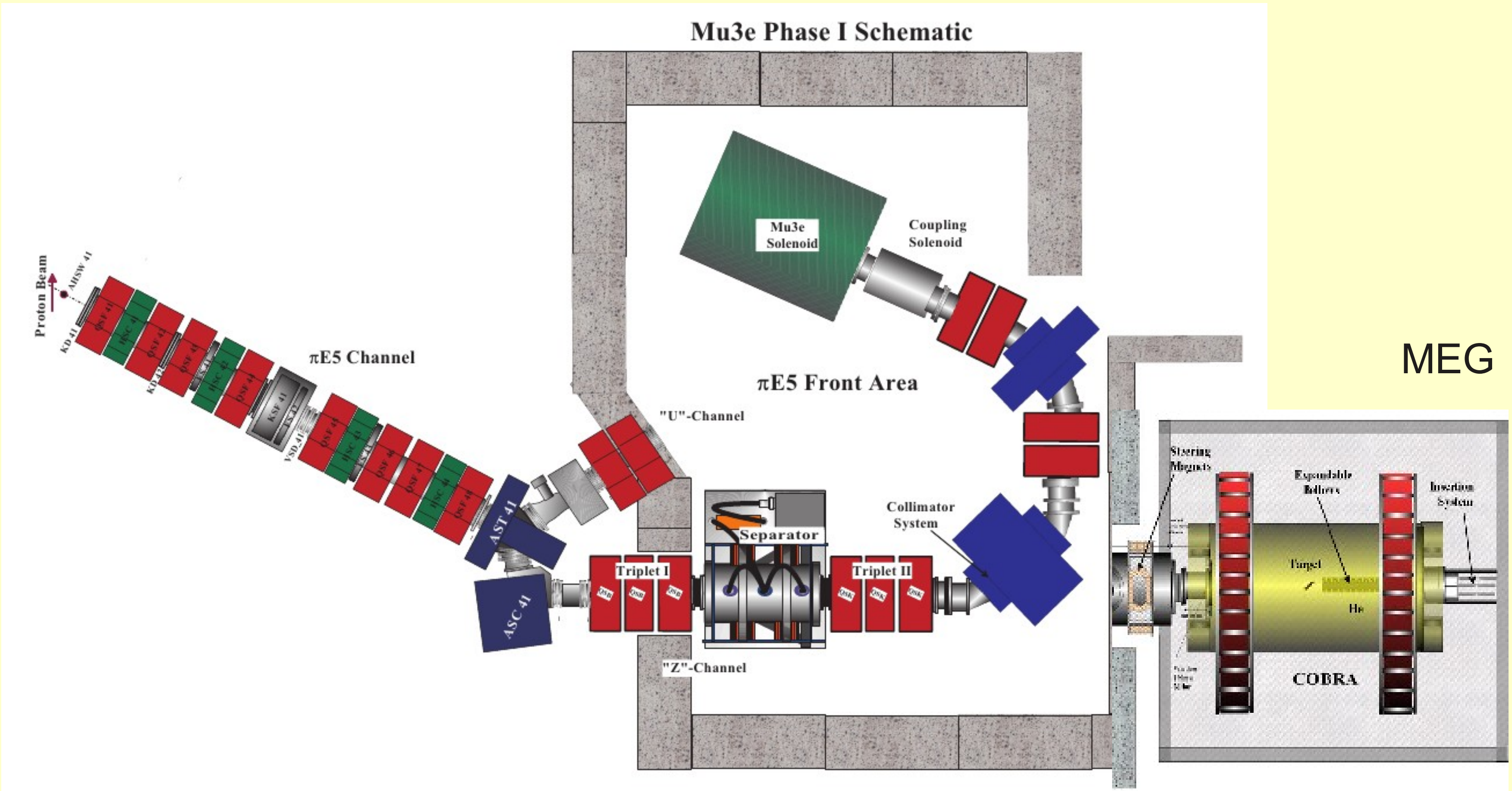



Phase I (2015+): ~$10^8$ muons/s

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

# $\pi$e5 Beamline (Phase I)

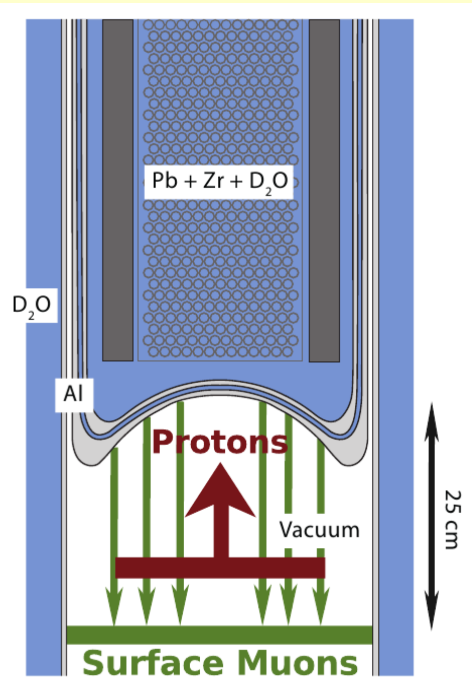
MEG and Mu3e could co-exist if MEG is to be upgraded

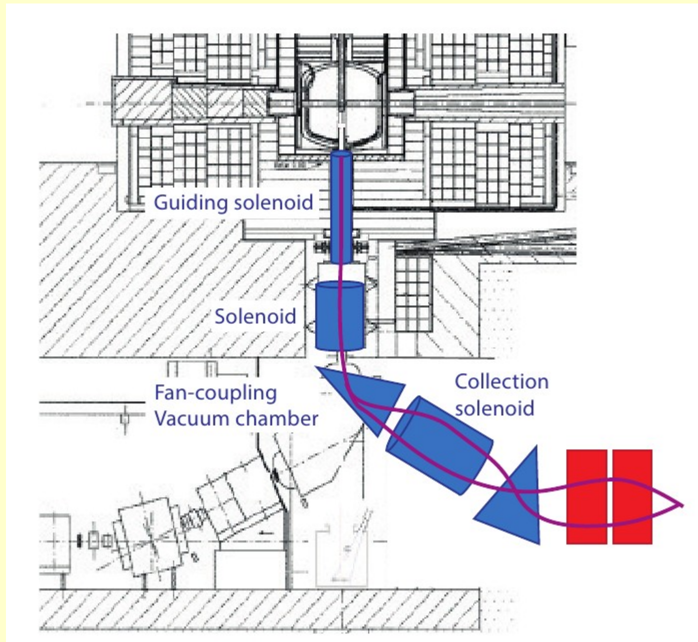


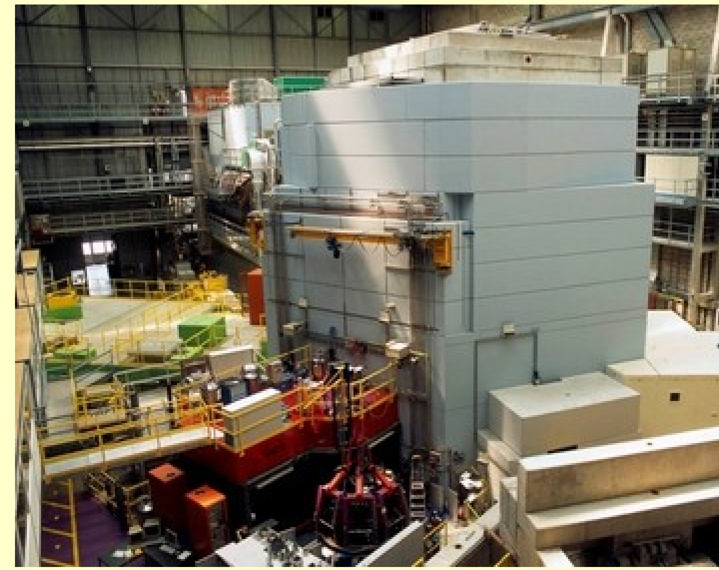

- muon rates of **1.4 · 10$^8$/s** achieved in past
- rate of **10$^8$/s muons** needed to reach **B( $\mu^+ \rightarrow e^+e^+e^-$ ) ~ 2 ·10$^{-15}$** (90%CL)

# High Intensitiy Muon Beamline (Phase II)

**HiMB =High Intensity Muon Beamline**

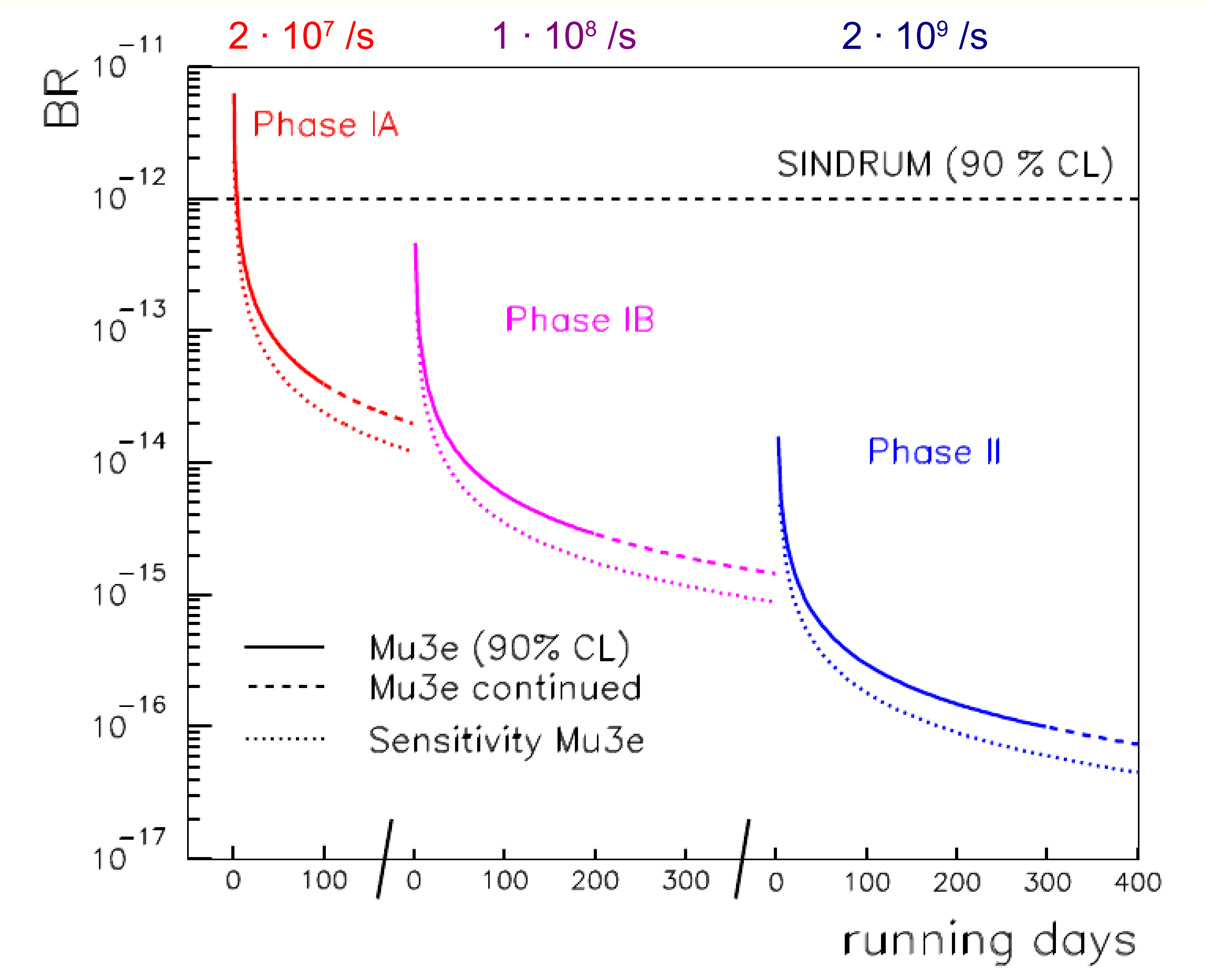


- Muon rates in excess of $10^{10}$ per second in beam phase acceptance possible
- **$2 \cdot 10^9$ muons/s** needed to reach ultimate goal of **$B(\mu^+ \rightarrow e^+e^+e^-) < 10^{-16}$**
- **Not before 2017**

# Sensitivity Projection



# Conclusions

- **Charged LFV "almost unavoidable" in BSM (GUT) models and well motivated**
- **New era of muon decay experiments searching for charged LFV has started**
- **Several projects aiming for sensitivities of $10^{-16}$ or even beyond!**
- **Experiments are well motivated and complimentary to each other and to LHC**

1st conference on Charged Lepton Flavor Violation, 6.-8. May, Lecce, Italy

# 1st International Conference on Charged Lepton Flavor Violation

**Lecce, Italy** — **May 6-8, 2013**

Searches for charged lepton flavor violation (CLFV) are powerful probes of physics beyond the Standard Model. This conference, the first in a projected series, will examine the status of CLFV-predicting models, both SUSY and non-SUSY, after the first LHC results, and investigate the physics accessible in the coming round of experiments. We will learn what searches for CLFV have already told us, and examine the prospects for experiments and new facilities planned for the coming decade.

The Conference will cover the following subjects:

- Theory overview
- CLFV observables at colliders and comparison to muon experiments
- CLFV model constraints from MEG, BELLE/BaBar and LHCb
- Interrelationship between CLFV g-2, EDMs and kaon decays
- Calculation of radiative backgrounds
- Angular distributions and polarization
- MEG: Status and upgrades
- Mu → 3e, Mu2e, COMET, PRISM, DeeMe
- Kaon system: Rare decay Experiments
- CLFV at BaBar/BELLE and LHC

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