A novel experiment searching for the lepton flavour violating decay

$$\mu \to eee$$

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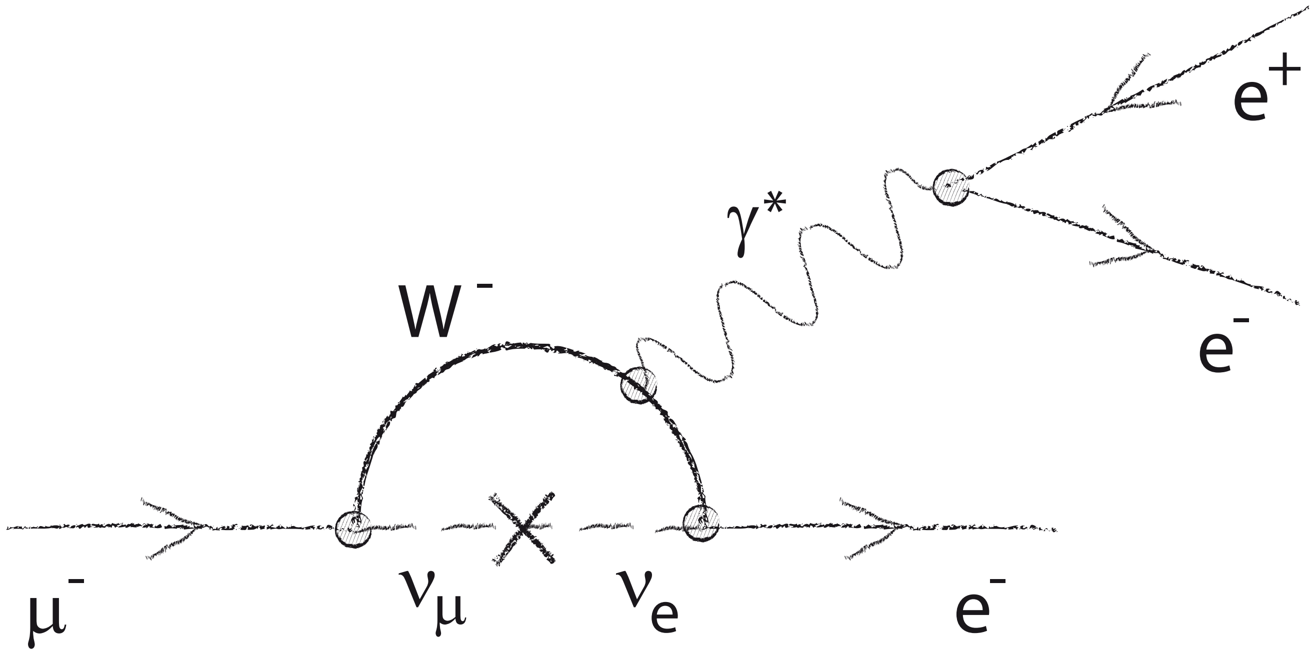
Overview

- **Why**
  searching for lepton flavour violation?
- **Where**
  can lepton flavour violation come from?
- **Why**
  do it in $\mu \rightarrow eee$?
- **How**
  to reach a sensitivity of
  $BR(\mu \rightarrow eee) < 10^{-16}$?

Why searching for LFV

In the Standard Model, lepton flavour is conserved

- Neutrino oscillations!
- What about charged leptons?
- Charged lepton-flavour violation through neutrino oscillations heavily suppressed (BR < 10^{-50})
- Clear sign for new physics



Where to search for LFV?

LFV

Lepton decays

- $\mu \to e\gamma$
- **$\mu \to eee$**
- $\tau \to l\gamma$
- $\tau \to lll \quad l = \mu, e$
- $\tau \to lh$

Conversion on Nucleus

- $\mu N \to eN$

Fixed target experiments (proposed)

- $eN \to \mu N$
- $eN \to \tau N$
- $\mu N \to \tau N$

Meson decays

- $\phi, K \to ll'$
- $J/\psi, D \to ll'$
- $\Upsilon, B \to ll'$

Collider experiments

- $ep \to \mu(\tau) X$ (HERA)
- $Z' \to ll'$ (LHC)
- $\chi^{0,\pm} \to ll' X$ (LHC)

Experimental Status

Purely leptonic LFV

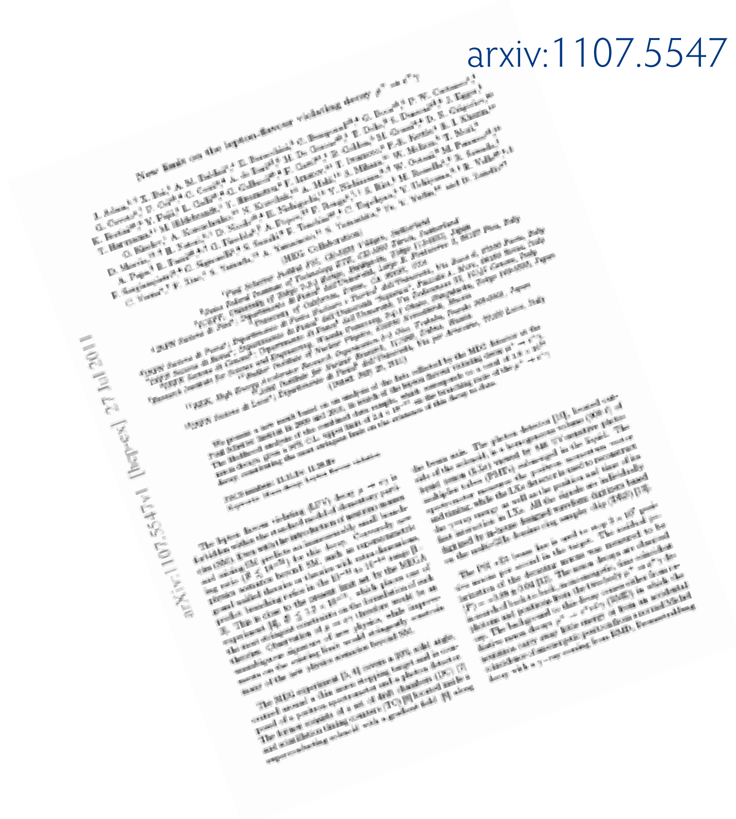
- $BR(\mu \rightarrow e\gamma)$ $< 2.4 \times 10^{-12}$ (MEG)
  $< 10^{-13}$ (MEG, projected)

- $BR(\tau \rightarrow e(\mu)\gamma) <\sim 4\times10^{-8}$ (B-Factories)

- $BR(\mu \rightarrow eee)$ $< 10^{-12}$ (SINDRUM)
  $< 10^{-16}$ (This talk)

- $BR(Z \rightarrow e\mu)$ $< 10^{-6}$ (LEP)

arxiv:1107.5547

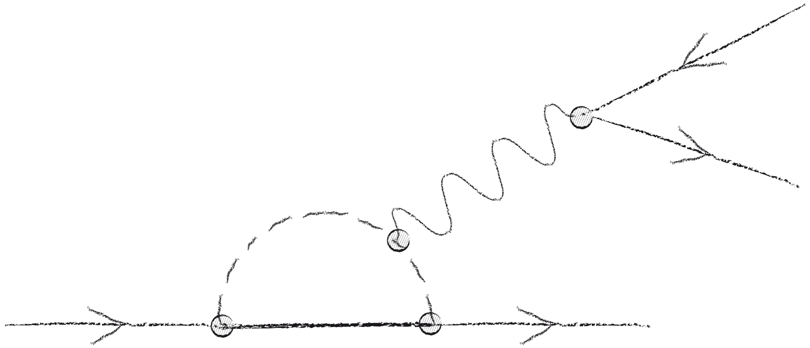


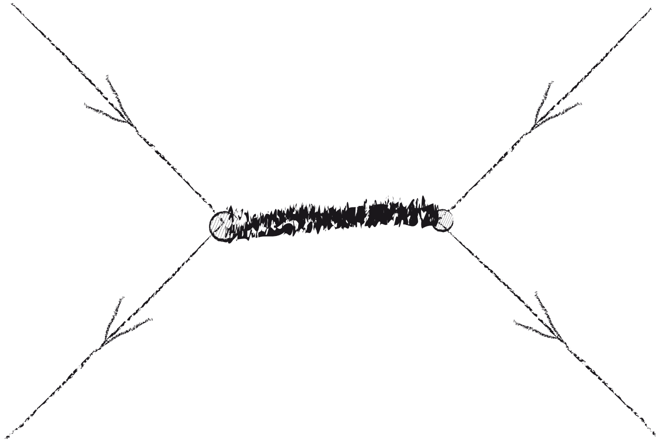
Semi-hadronic LFV

- $BR(K \rightarrow \pi e\mu)$ $<\sim 10^{-11}$

- $BR(\mu N \rightarrow eN)$ $<\sim 10^{-12}$ (SINDRUM 2)
  $<\sim 10^{-14}$ (DeeMe, projected)
  $<$ down to 10^{-17} (projected: Mu2e, COMET, Prism)

Models for LFV

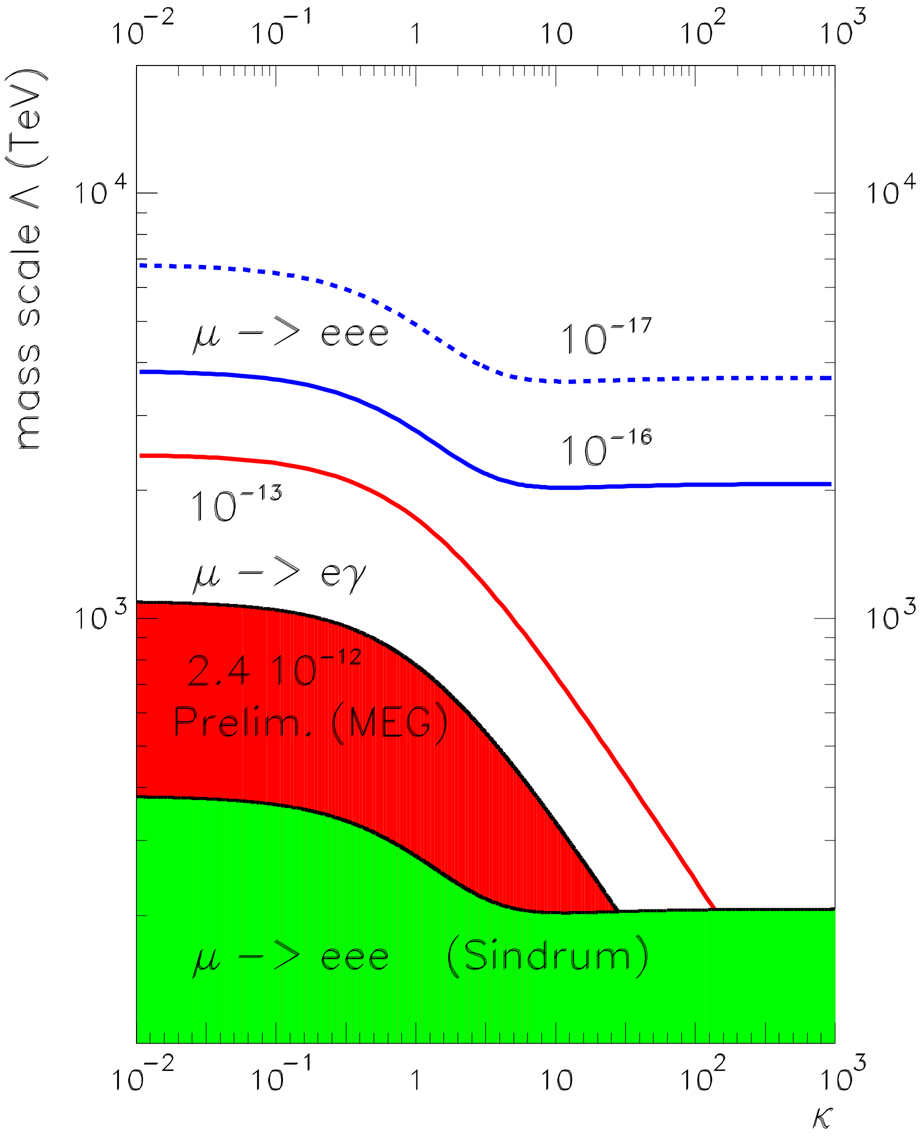




Models for physics beyond the standard model often naturally induce LFV, either through loops or exchange of heavy intermediates

- Supersymmetric models
  - with GUT
  - with Seesaw
- Models with Leptoquarks
- Models with additional Higgs particles
  - Higgs triplet model
- Models with a Z' or large extra dimensions

Why μ → eee?



- Muons are plentiful and clean
- Complementary to μ → eγ and conversion on nuclei
- Advances in detector technology allow for high rate & high precision experiments
- Three body decay offers more constraints and options to study LFV mechanism and CP violation in case of a discovery
- A search for μ → eee with a sensitivity of 10^{-16} has a large potential to discover LFV or to set very stringent bounds on new physics

An experiment searching for

$\mu \rightarrow eee$

A $\mu \rightarrow eee$ experiment

Need a lot of muons

- Use the world's highest intensity DC muon beam at PSI
- Up to 10^9 muons per second

Need to control backgrounds at the 10^{-16} level

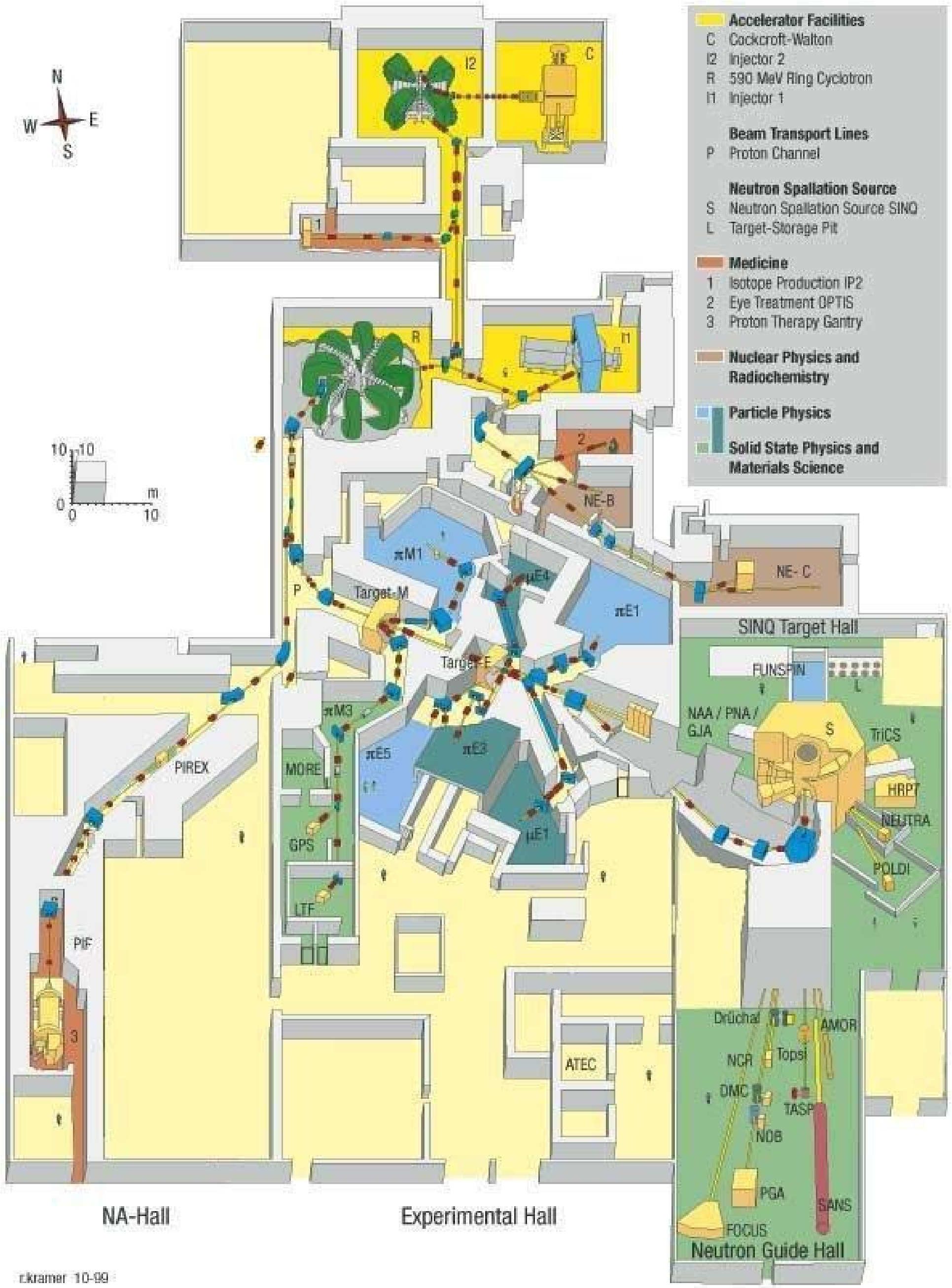
- Need excellent vertex and timing resolution to get rid of accidentals
- Need excellent momentum resolution to get rid of $\mu \rightarrow ee e\nu\nu$ decays

Thin pixel silicon tracker and scintillating fibre timing detector

Muons at PSI

- The Paul Scherrer Institut (PSI) in Villigen, Switzerland has the world's most powerful DC proton beam (2.2 mA at 590 MeV)
- Pions and then muons are produced in rotating carbon targets

Muons at PSI

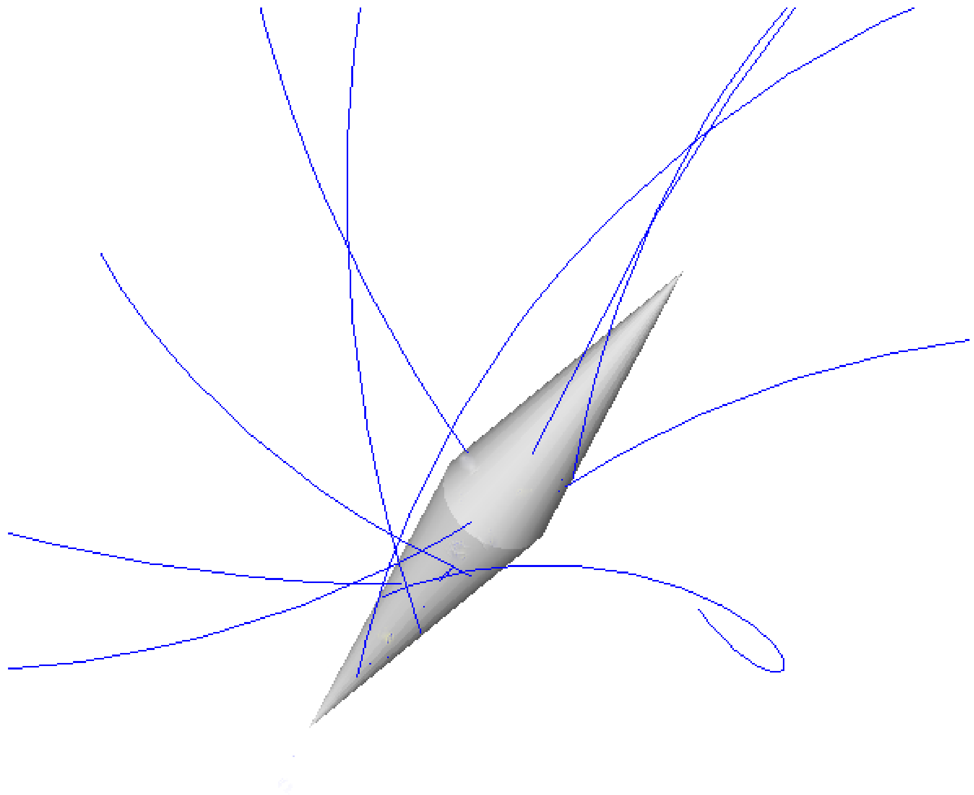


DC muon beams at PSI:

- μE1 beamline: ~ 5×10^8 muons/s
- πE5 beamline: ~ 10^8 muons/s (MEG experiment)
- μE4 beamline: ~ 10^9 muons/s
- SINQ (spallation neutron source) target could even provide ~ 5×10^{10} muons/s

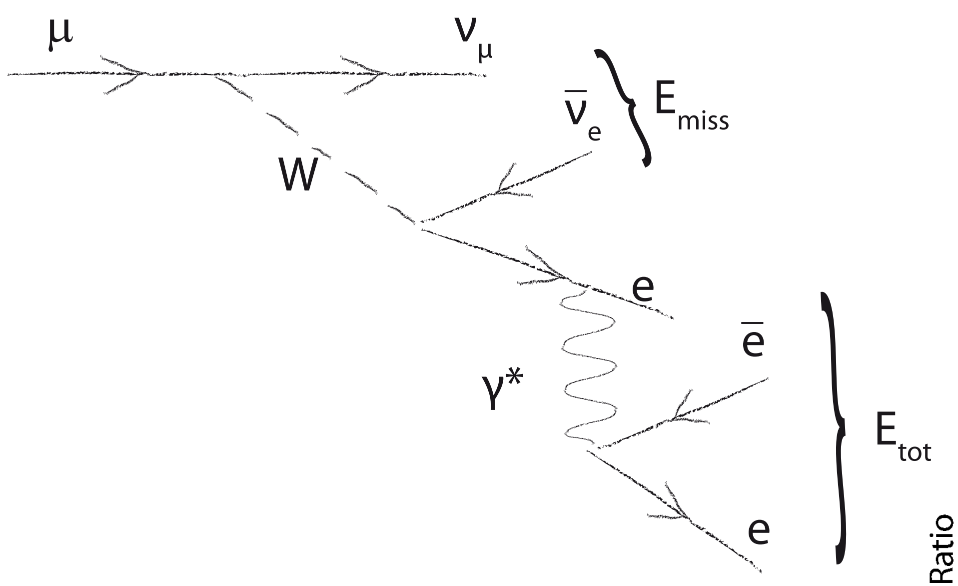
- The $\mu \rightarrow eee$ experiment (final stage) would require 10^9 muons/s focused and collimated on a ~2 cm spot

Backgrounds

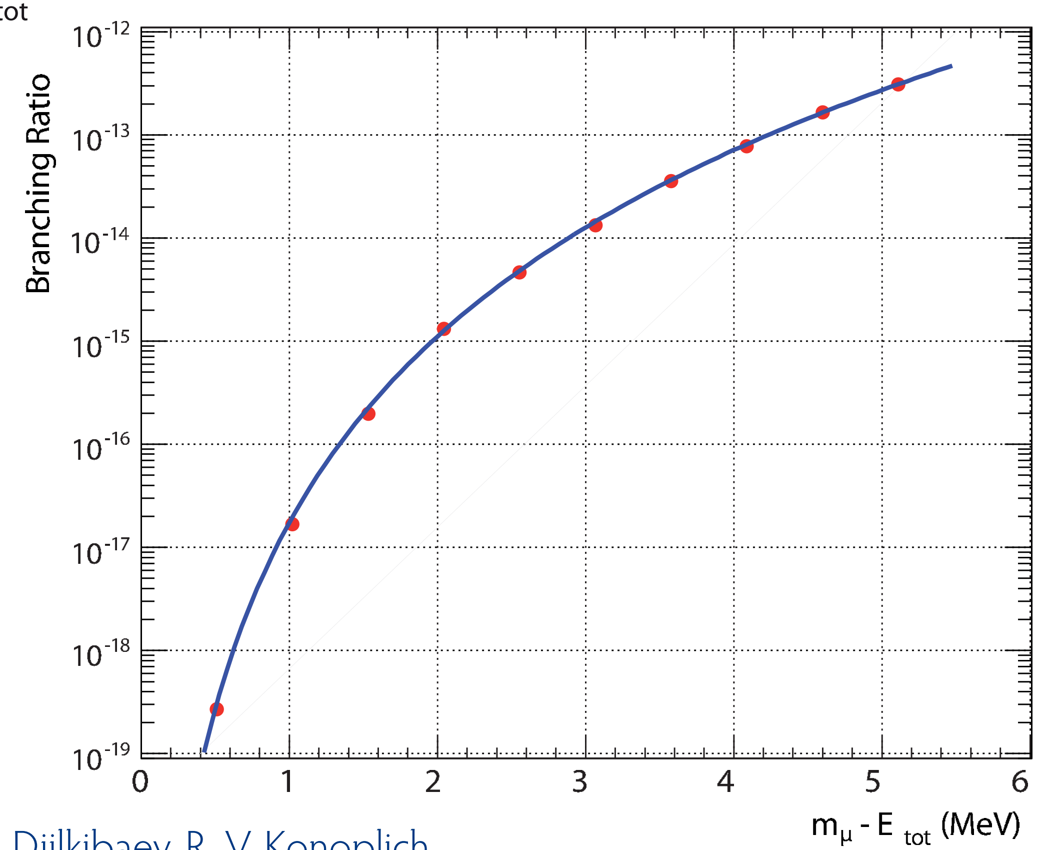


- Accidental coincidences of a decay positron with an electron-positron pair from Bhabha scattering or photon conversion
- Can be suppressed by excellent timing and vertex resolution and a large target area
- Use a hollow double cone target made of aluminium

Main background



- The most severe background is the internal conversion process $\mu \rightarrow ee e\nu\nu$
- Branching fraction 3.4×10^{-5}
- Need excellent momentum resolution to reject this background



(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)

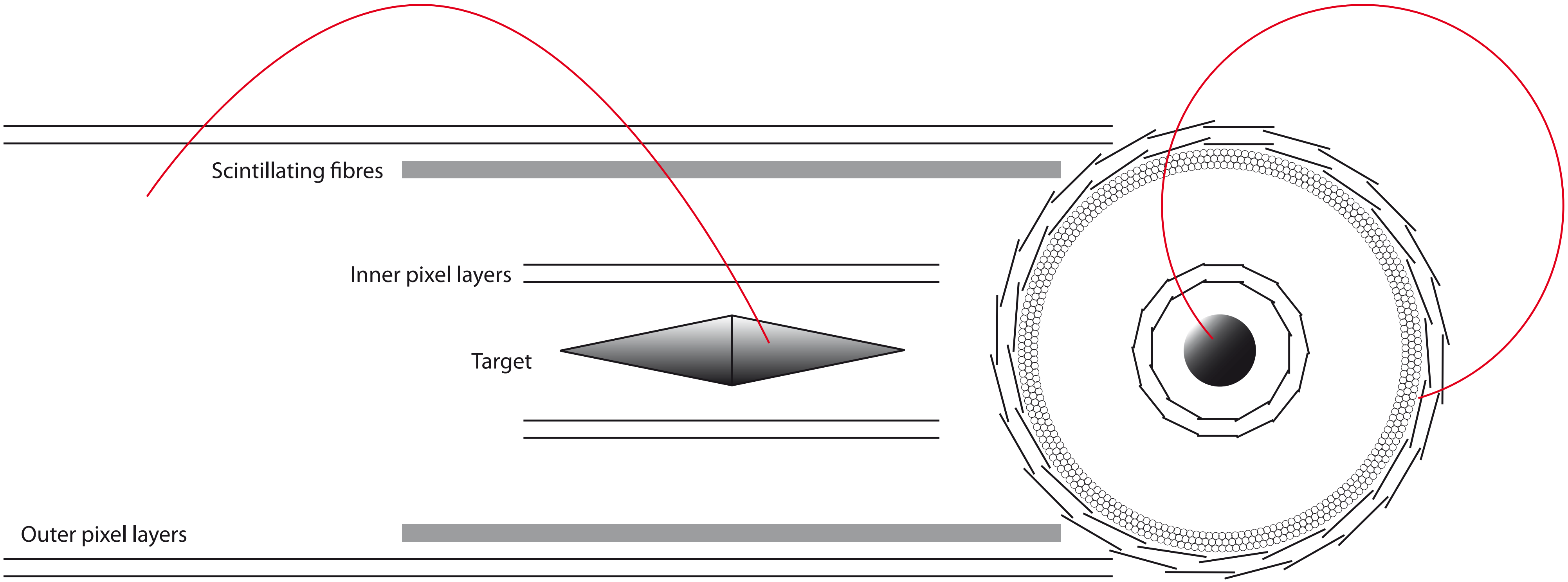
Tracking detector for μ → eee

10^9 electrons/s disfavour a gas detector

- Use silicon
- Fast readout

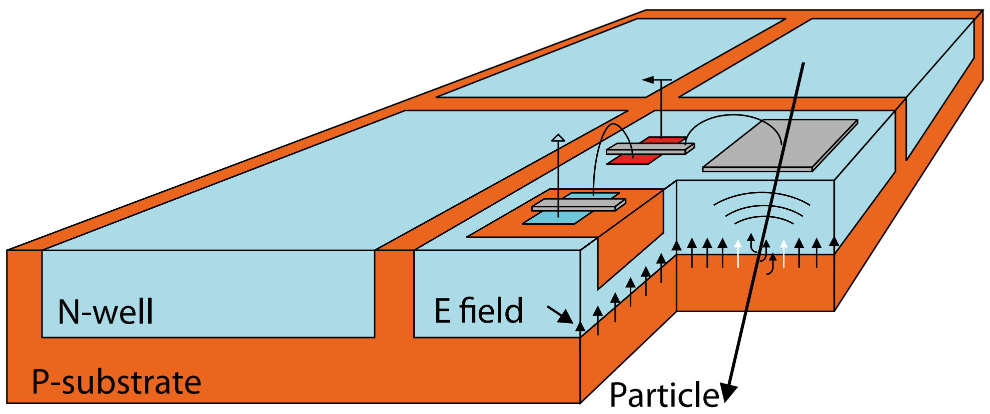
Need best possible momentum and vertex resolution

- Get vertex precision by using a pixel sensor
- Momentum resolution dominated by multiple scattering
- Reduce multiple scattering by making sensor thin
- Use recurlers



Silicon detector technolohies

Technology	Thickness	Speed	Readout
ATLAS pixel	260 µm	25 ns	extra RO chip
DEPFET (Belle II)	50 µm	slow (frames)	extra RO chip
MAPS	50 µm	slow (diffusion)	fully integrated
HV-MAPS	> 30 µm	O(100 ns)	fully integrated



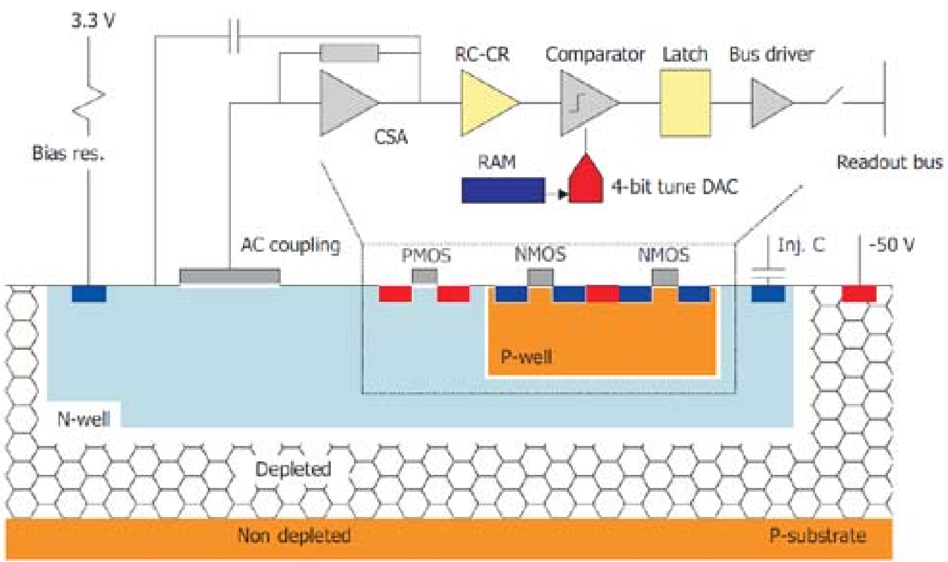
High voltage monolithic active pixel sensors

- Implement logic directly in N-well in the pixel - smart diode array
- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection
- Can be thinned down to < 50 μm
- Low power consumption

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

Sensor Specs

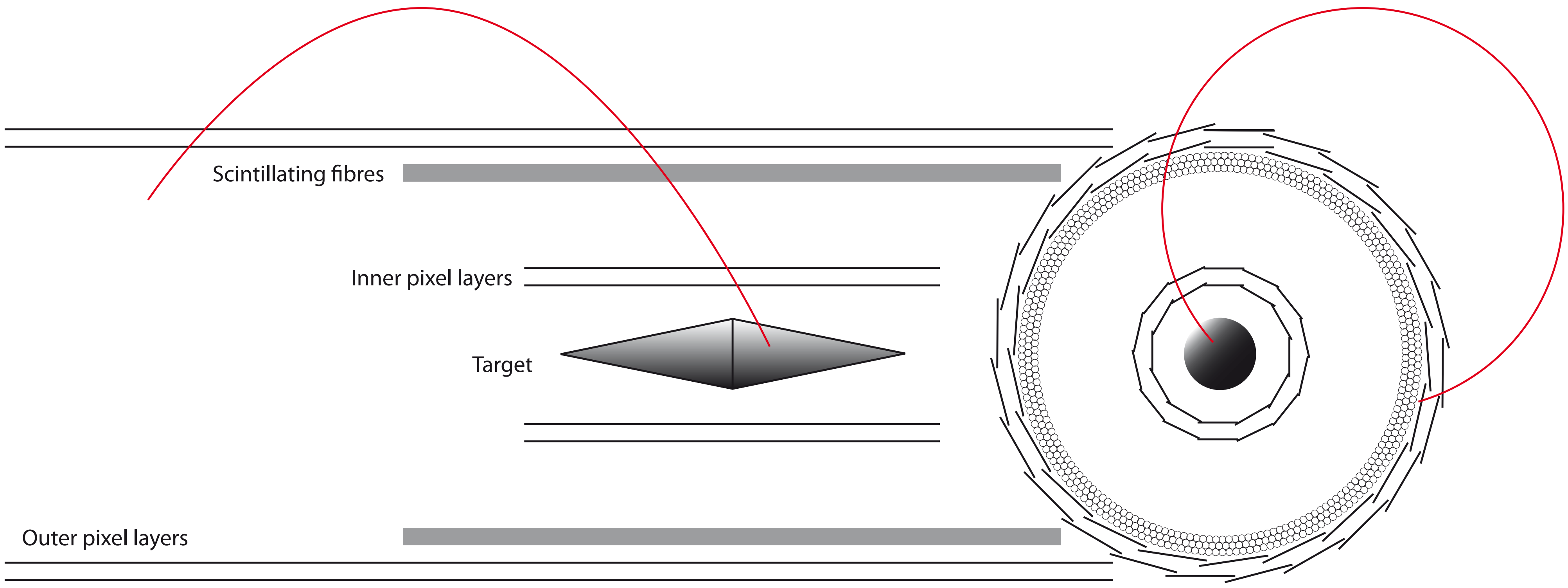
- Module size 6 × 1 cm (inner layers)
  6 × 2 cm (outer layers)
- Pixel size 80 × 80 µm
- Goal for thickness: 50 µm
- 1 bit per pixel, zero suppression with tune DAC on chip
- Power: 150 mW/cm^2
- Data output 800 Mbit/s
- Time stamps every 100 ns (10 MHz clock for low power consumption, air cooling)



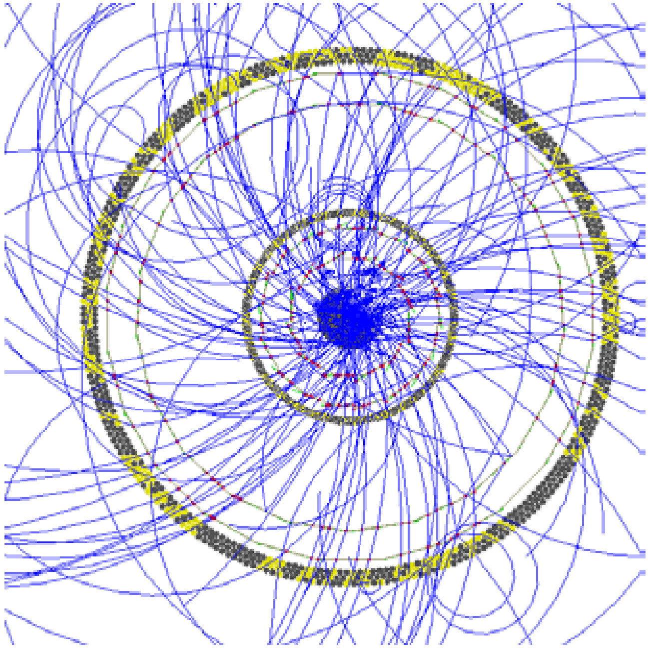
AMS 180 nm sensors being tested - Master thesis of Ann-Kathrin Perrevoort

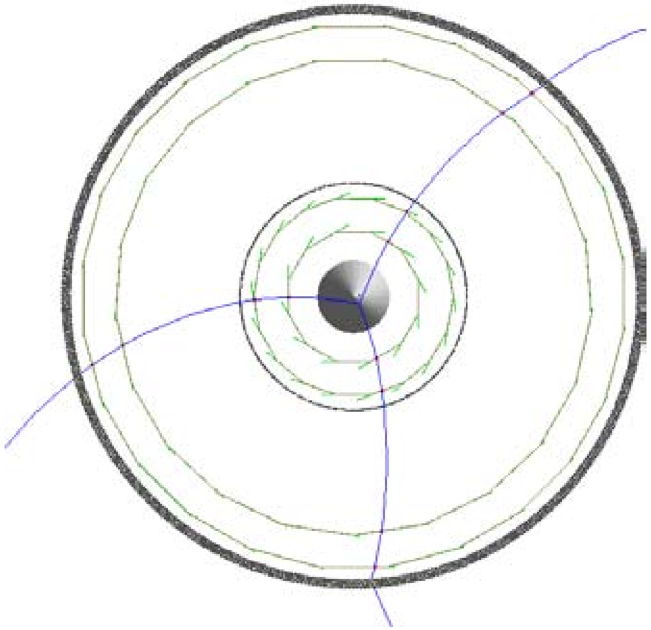
Possible tracker layout

- Support sensors on Kapton™ prints, with aluminium signal and power lines
- Four layers in two groups in a ~ 1-1.5 Tesla field
- Total material few ‰ of X_0, few layers
- Add a scintillating fibre tracker to reduce combinatorics through timing



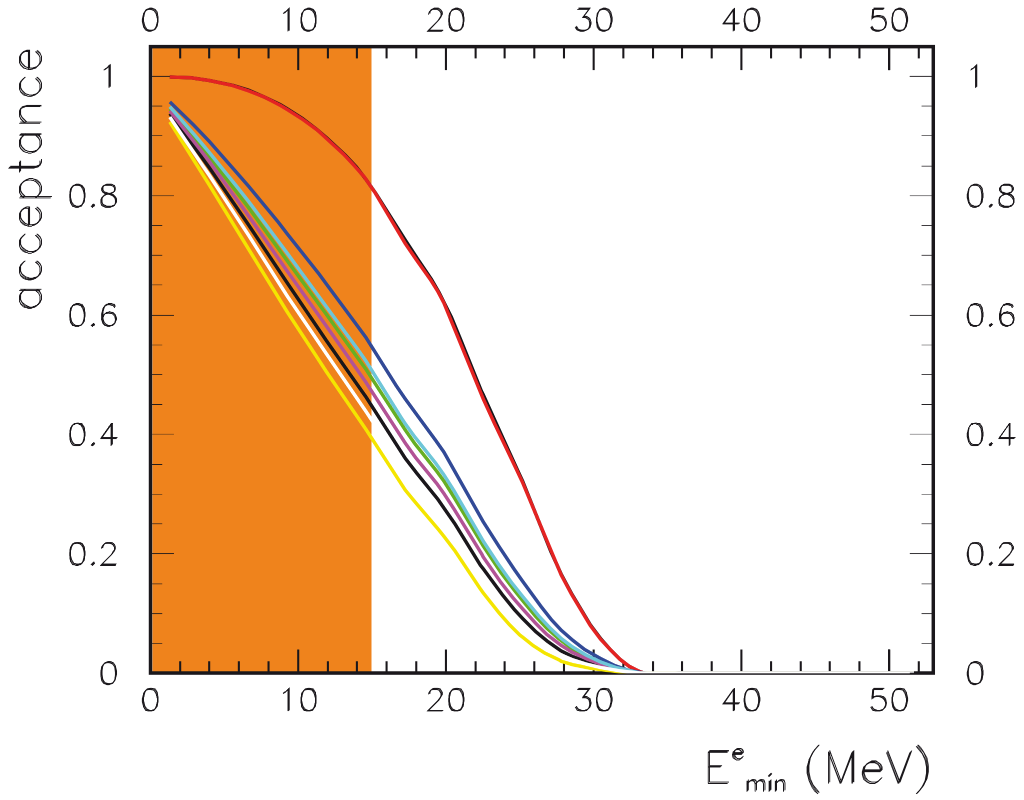
Timing





- The silicon detector is read out with 10 MHz (power consumption)
- Hundred electron tracks in one frame
- Can be resolved by scintillating fibre tracker
- Resolution a few ~ 100 ps - on average a few electrons

Acceptance

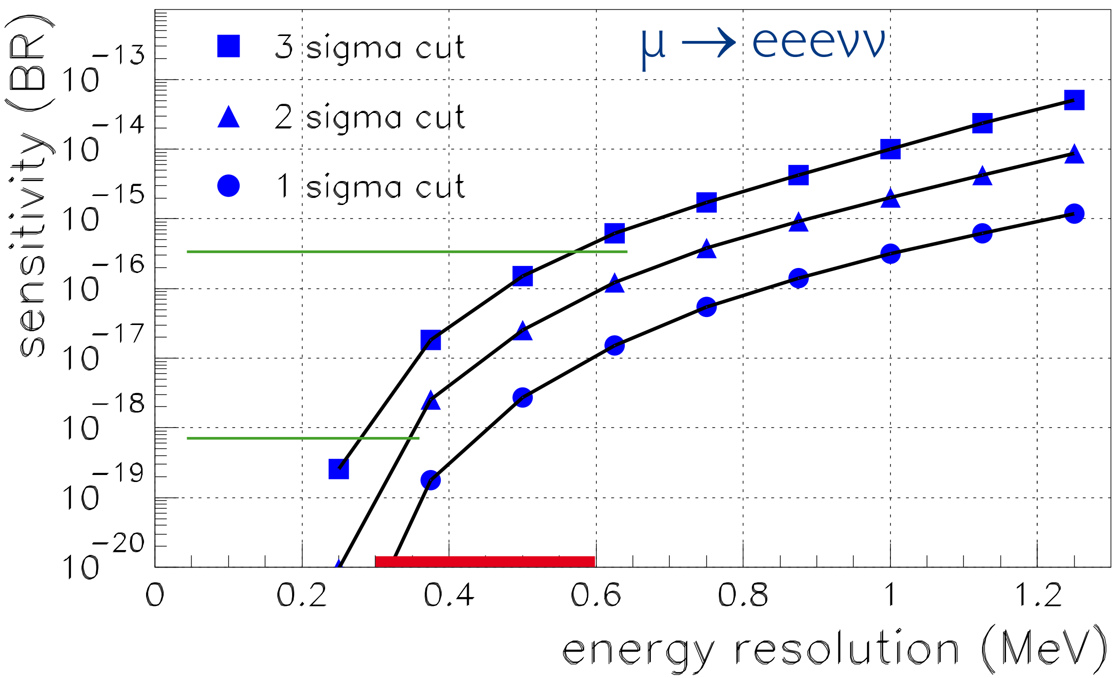


Track electrons from with p = 15 -53 MeV/c

- Acceptance depends on the model
- Generally better for four-fermion (red) than for photon penguin graphs
- Low minimum momentum required

$$L_{\mu \rightarrow eee} = 2 G_F (m_\mu A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + m_\mu A_L \bar{\mu}_L \sigma^{\mu\nu} e_R F_{\mu\nu}$$
$$+ g_1 (\bar{\mu}_R e_L) (\bar{e}_R e_L) + g_2 (\bar{\mu}_L e_R) (\bar{e}_L e_R)$$
$$+ g_3 (\bar{\mu}_R \gamma^\mu e_R) (\bar{e}_R \gamma^\mu e_R) + g_4 (\bar{\mu}_L \gamma^\mu e_L) (\bar{e}_L \gamma^\mu e_L)$$
$$+ g_5 (\bar{\mu}_R \gamma^\mu e_R) (\bar{e}_L \gamma^\mu e_L) + g_6 (\bar{\mu}_L \gamma^\mu e_L) (\bar{e}_R \gamma^\mu e_R) + H.C.)$$

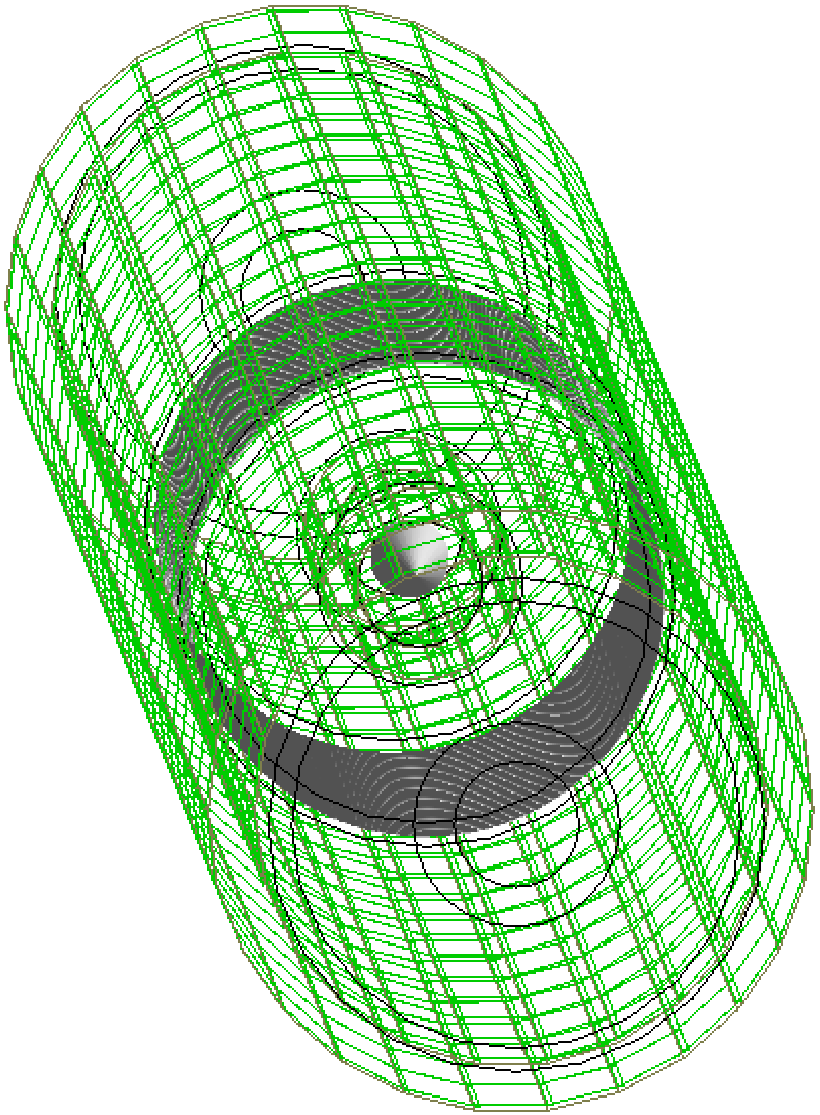
Performance studies



(All very preliminary)

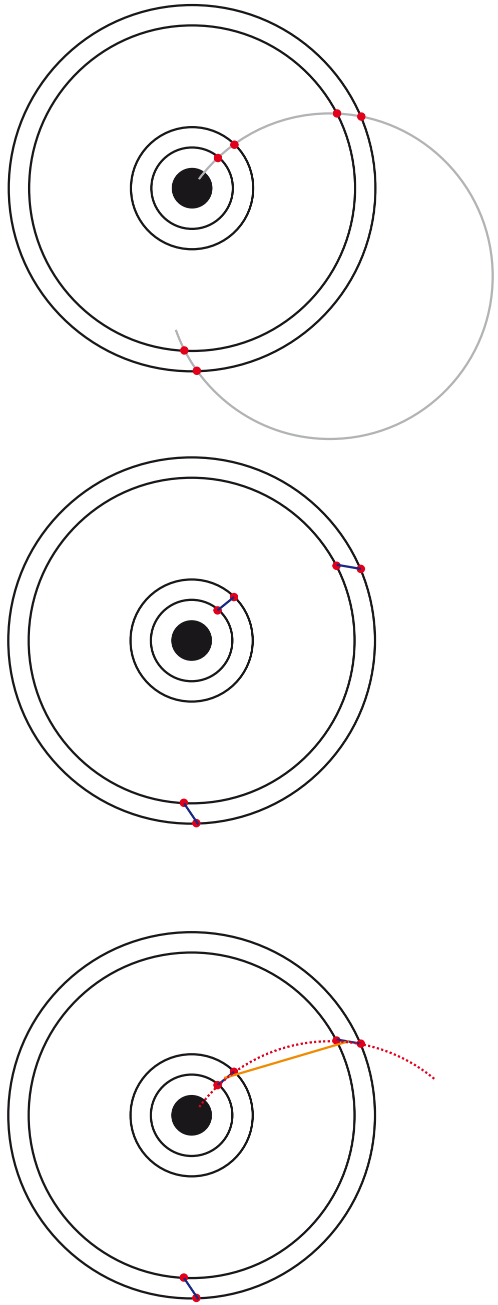
- Performance depends on background rejection
- Background rejection for $\mu \rightarrow eee\nu\nu$ depends on momentum resolution
- For σ_E = 0.3 - 0.6 MeV, sensitivity even below 10^{-16} possible

Simulating the experiment



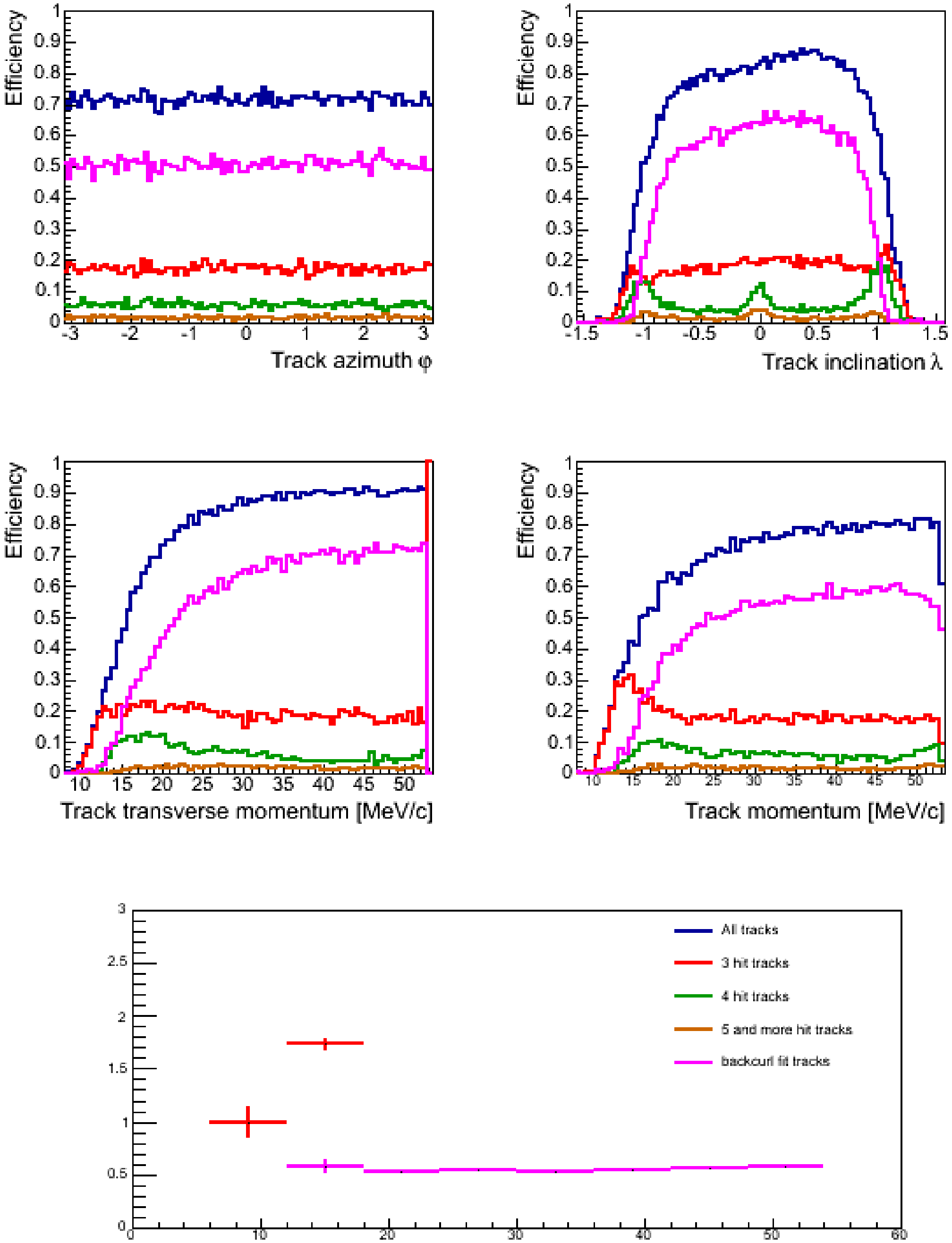
- Generate muons shortly before the target (Exercise 3...)
- Use the Geant4 code package to propagate and decay the muons, then propagate the electrons through the detector
- All based on Monte Carlo methods
- I provide particle input and a detailed description of the detector geometry
- I have to select and tune the appropriate physics processes in Geant4 - not always easy
- I have to provide routines turning energy deposits into read-out signals

Reconstruction



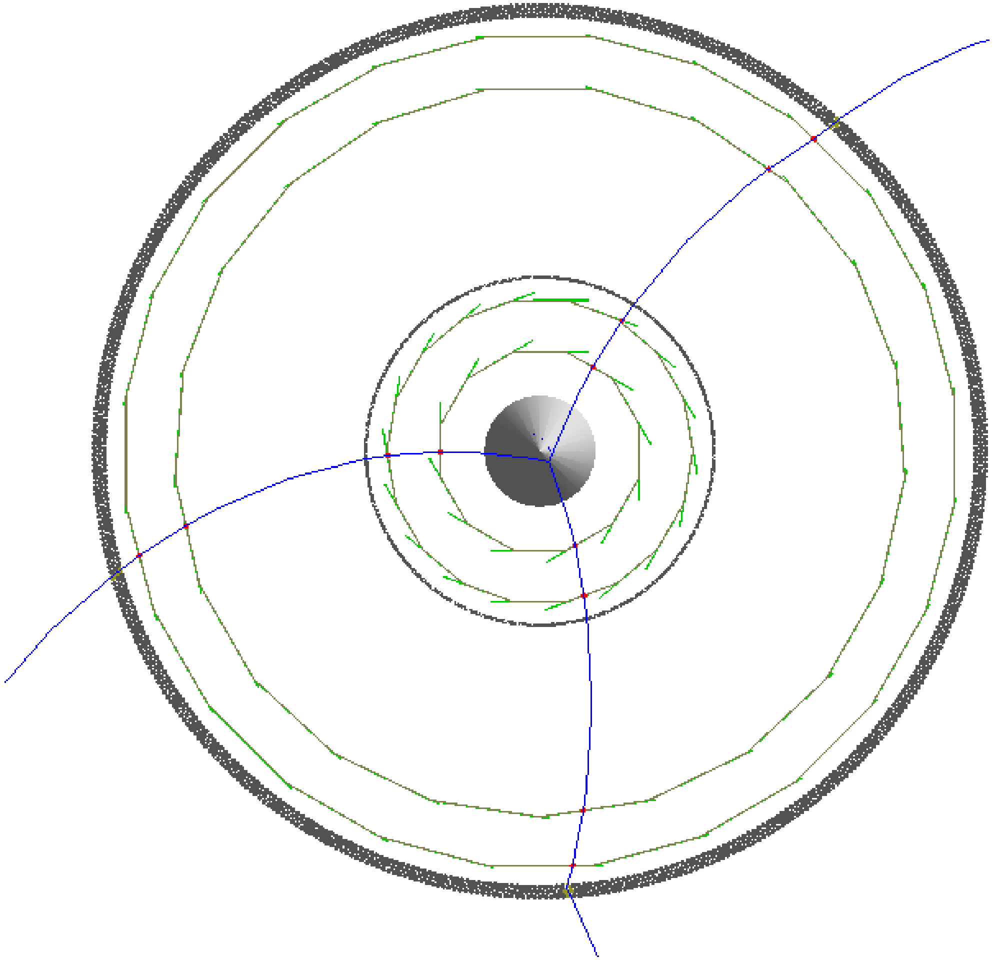
- Around 100 electron tracks produce 400+ hits in the detector - which belong to which track?
- Start with doublets, do combinatorics, do a simple fit - circle in the transverse plane, straight line in longitudinal plane
- Keep candidates with good fit, attach additional hits
- Later: Do more advanced fit taking into account multiple scattering for best resolution (Diploma thesis Moritz Kiehn)

Analysis



- Take output of reconstruction to find μ → eee
- Still at very early stage - currently determining resolution and efficiency of different detector designs
- Iterate a lot:
  Problems in design →
  Change design in simulation →
  Run simulation →
  Adapt reconstruction →
  Determine performance →
  Problems in design
- Software design important:
  Easy to change and extend, fast, more than one developer

Status of the project



- Interesting idea at an early stage
- Work on sensors and mechanics as well as track reconstruction at Heidelberg University
(S. Bachmann, C. Dressler, P. Fischer, M. Kiehn, R. Narayan, I. Peric, A.-K. Perrevoort, S. Rabenecker, A. Schöning, D. Wiedner, B. Windelband, N. Berger)
- Collaboration beyond Heidelberg forming
- Letter of intent planned for early 2012
- Always looking for thesis students - opportunity to see the "birth" of an experiment, influence the final design, see almost all aspects

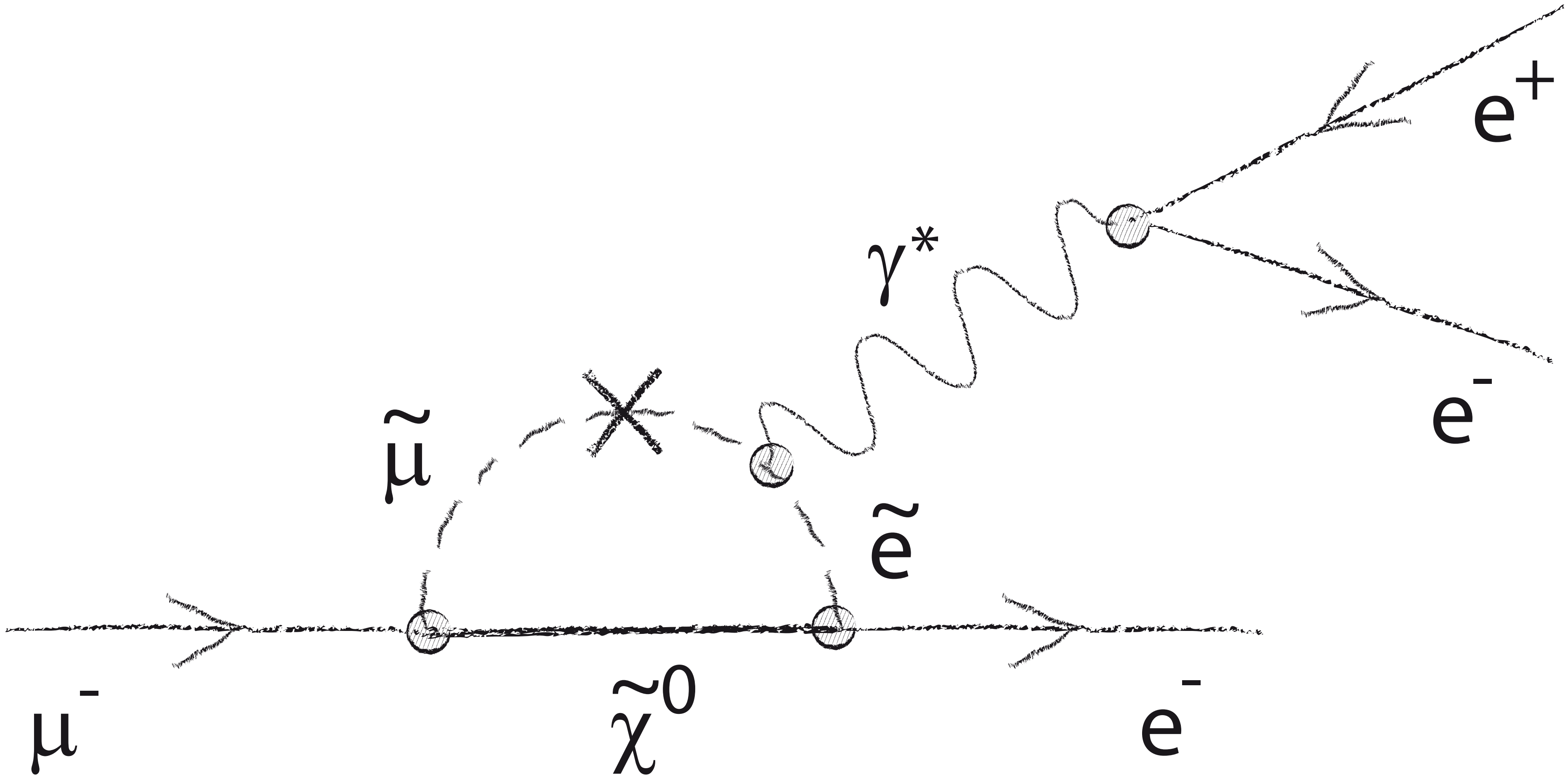
Summary

- Lepton flavour violation might be just around the corner
- Novel concept for an experiment searching for $\mu \rightarrow eee$
- Technologies: HV monolithic pixel sensor and fibre tracker
- Sensitivity of 10^{-16} seems feasible
- First pixel tracker prototype in 2012?
- Great project to work on

Backup Material

Models for LFV: SUSY

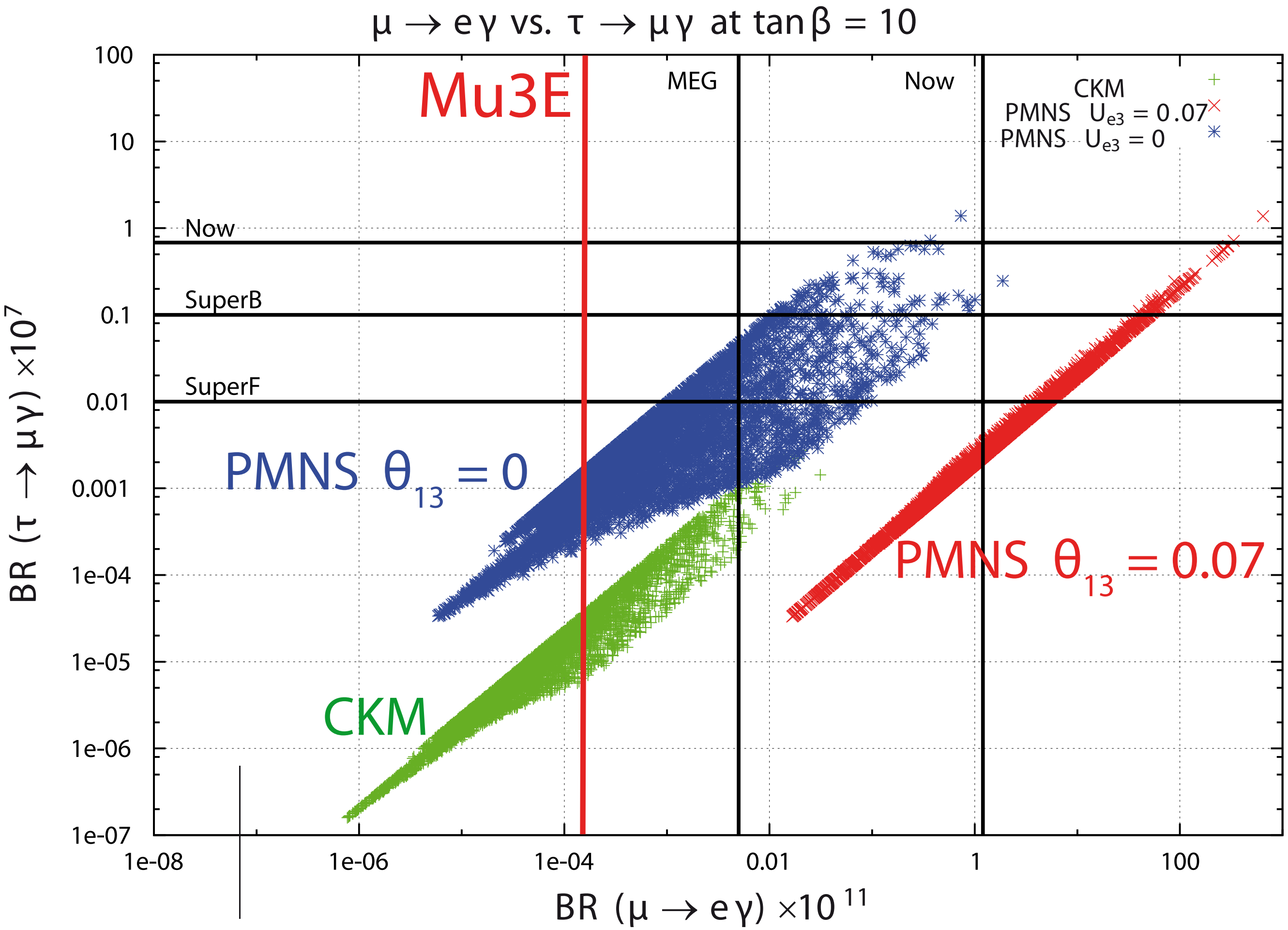
- Supersymmetry with slepton mixing
- Lepton mixing is large; would naturally expect large slepton mixing



LFV with SUSY SO(10) GUT

- For these models:
  $BR(\mu \to eee) = 0.006 \times BR(\mu \to e\gamma)$
- Points: SUSY LHC parameters

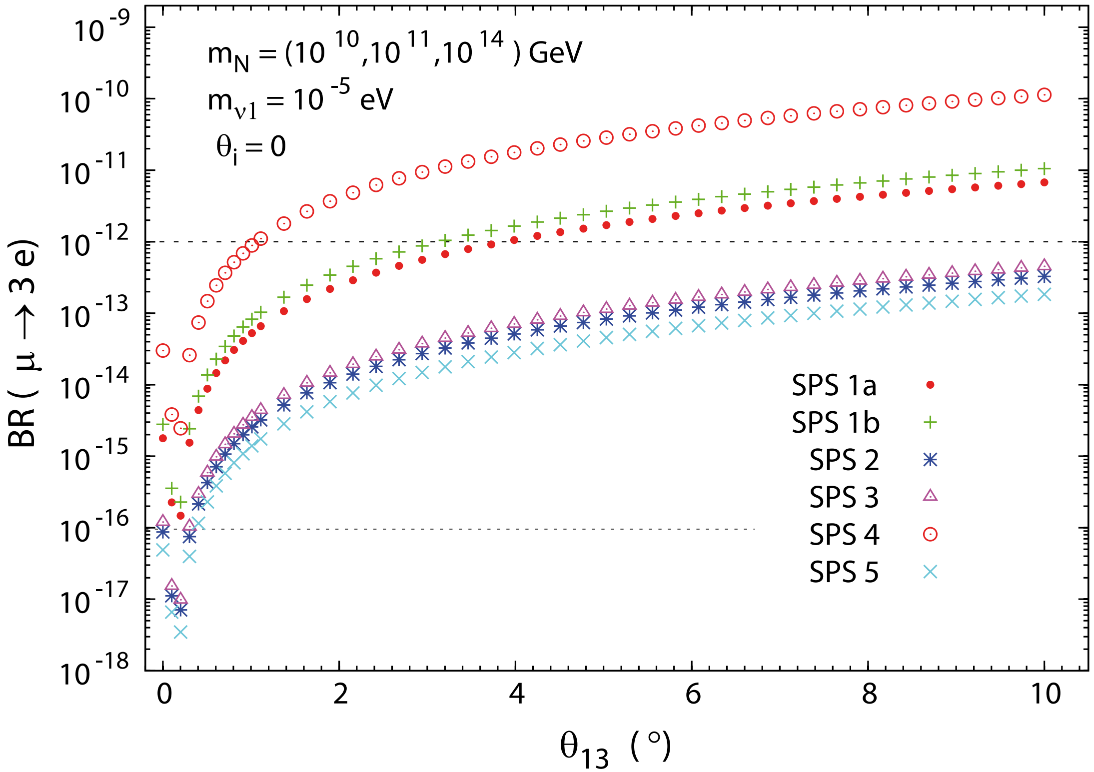
(L. Calibbi, A. Faccia, A. Masiero, S.K. Vempati, Phys.Rev. D74 (2006) 116002)



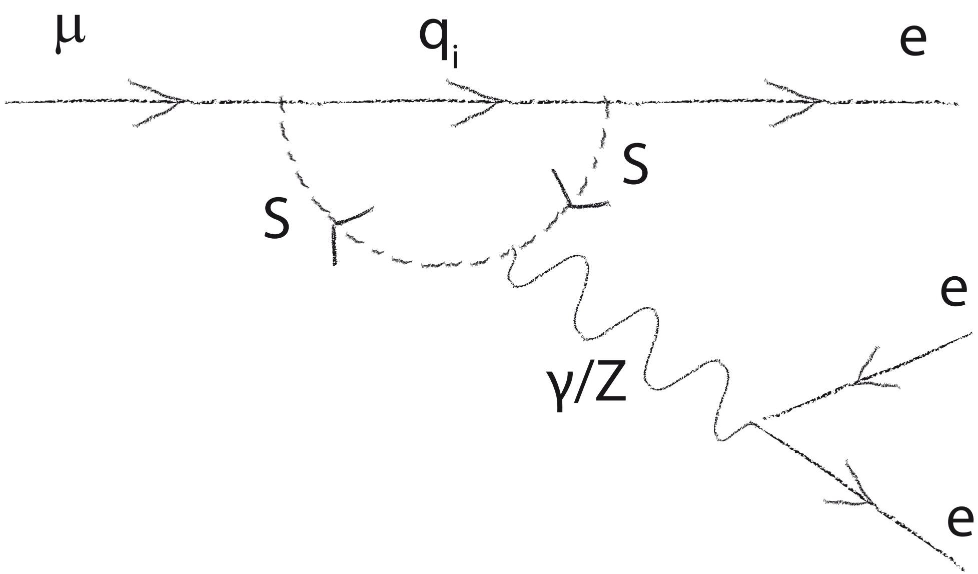
LFV with cMSSM Seesaw

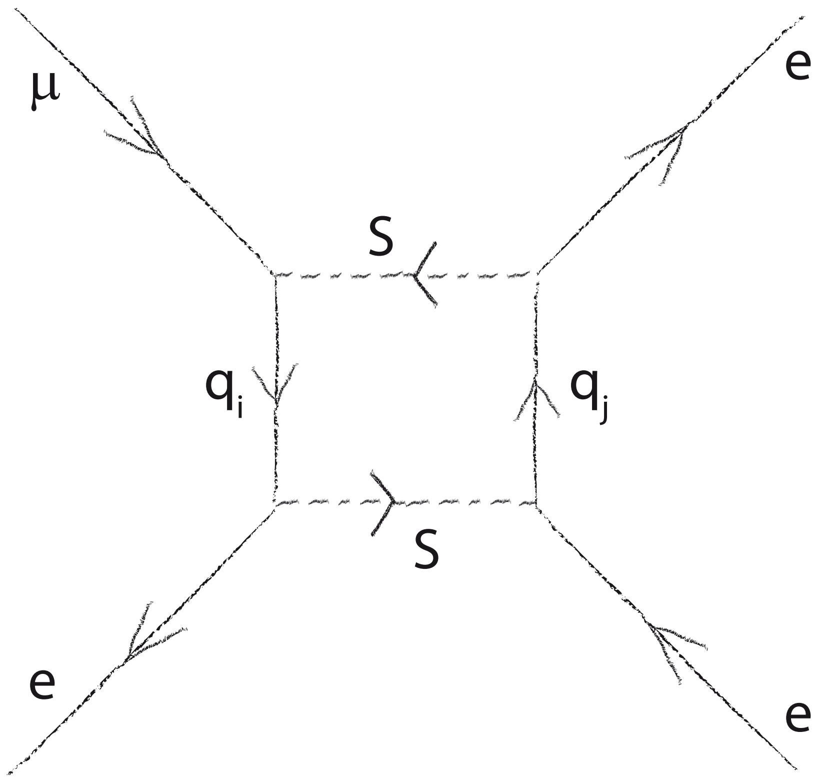
- Constrained Minimal Supersymmetric Model with Seesaw neutrino masses and leptogenesis
- General feature: Strong dependence on θ_{13}

(S. Antusch, E. Arganda, M.J. Herrero, A.M. Teixeira, JHEP 0611 (2006) 090)



LFV with Leptoquarks



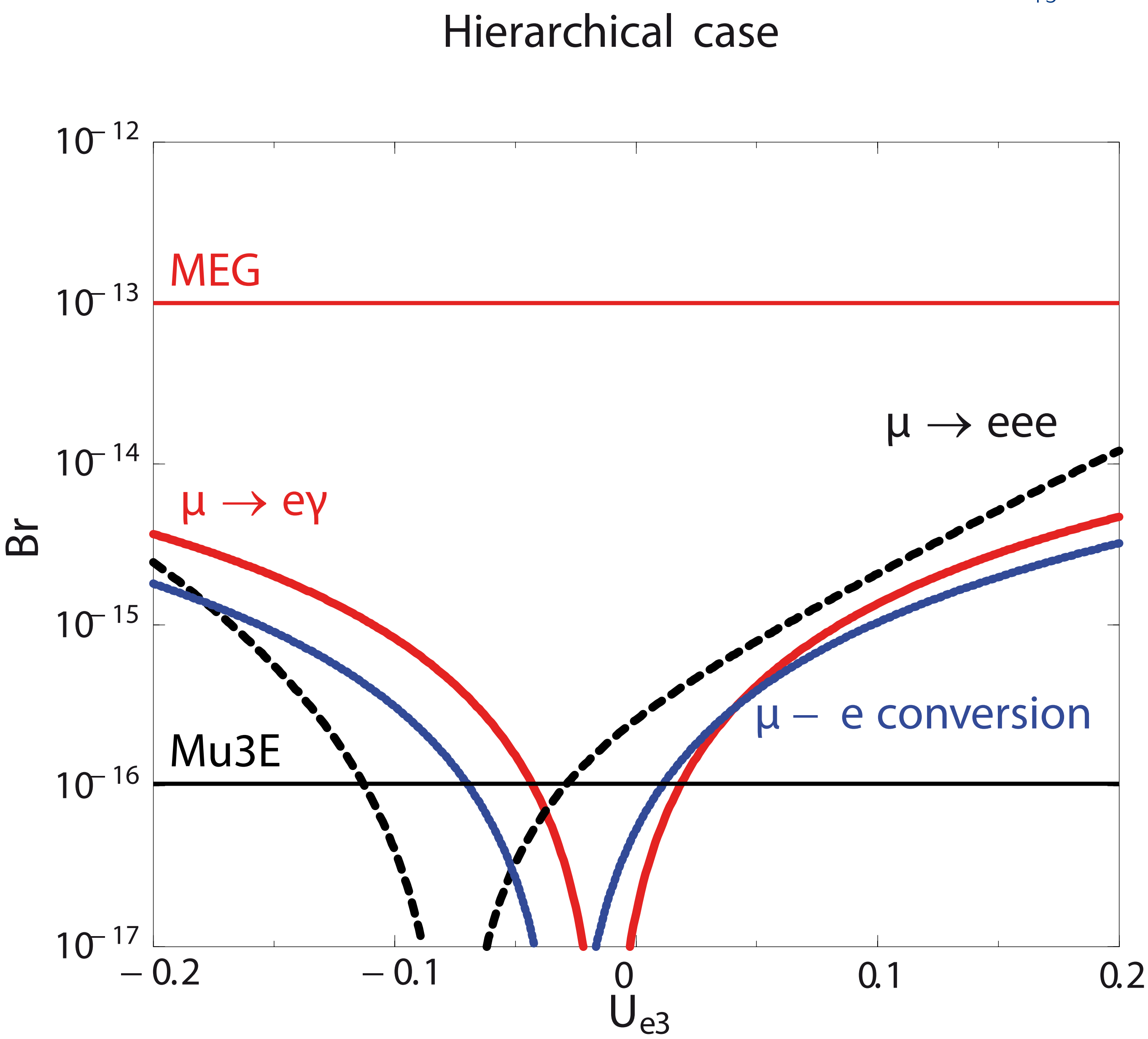


- Leptoquarks can lead to $\mu \rightarrow eee$ at one-loop order
- Expect enhancement with regards to $\mu \rightarrow e\gamma$, where a GIM-like suppression is at work
- Complementary to conversion experiments: access to all quark flavours
- Access to Leptoquark masses up to ~ 5 TeV

(K.S. Babu and J. Julio, Nucl.Phys. B841 (2010) 130)

- Dependence on neutrino mass hierarchy and θ_{13}

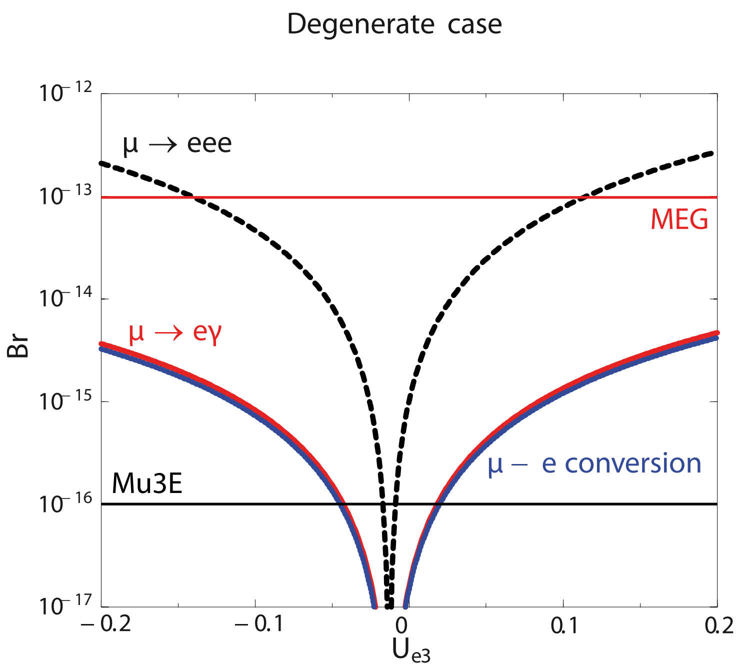
(M. Kakizaki, Y. Ogura, F. Shima, Phys.Lett. B566 (2003) 210)

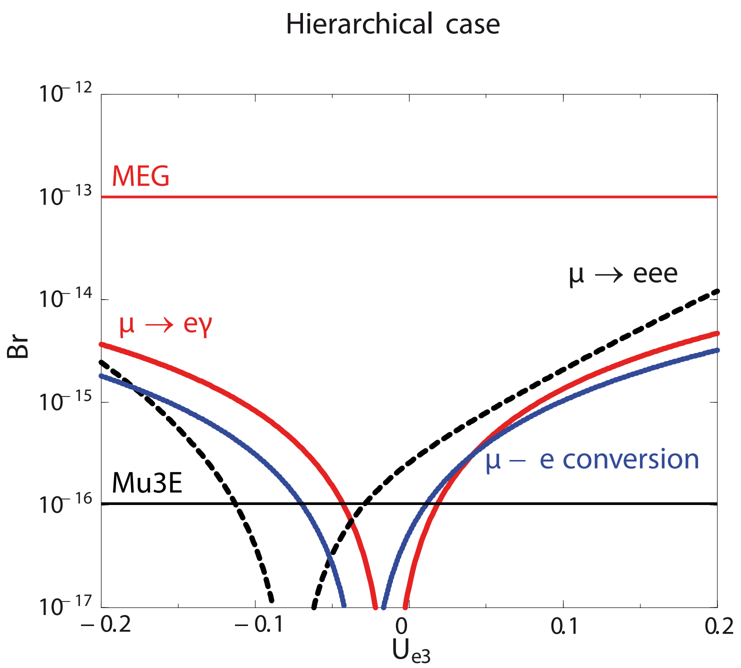


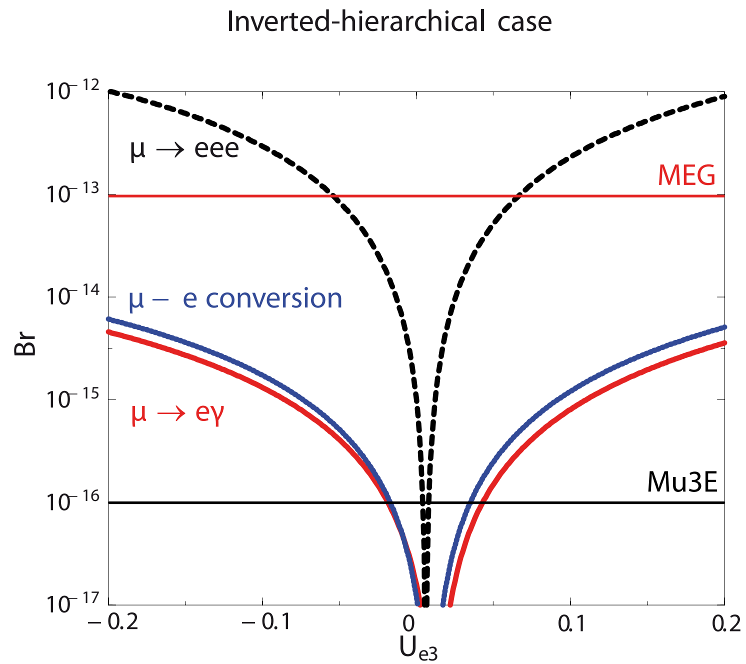
LFV in Higgs triplet models

- Dependence on neutrino mass hierarchy and θ_{13}

(M. Kakizaki, Y. Ogura, F. Shima, Phys.Lett. B566 (2003) 210)

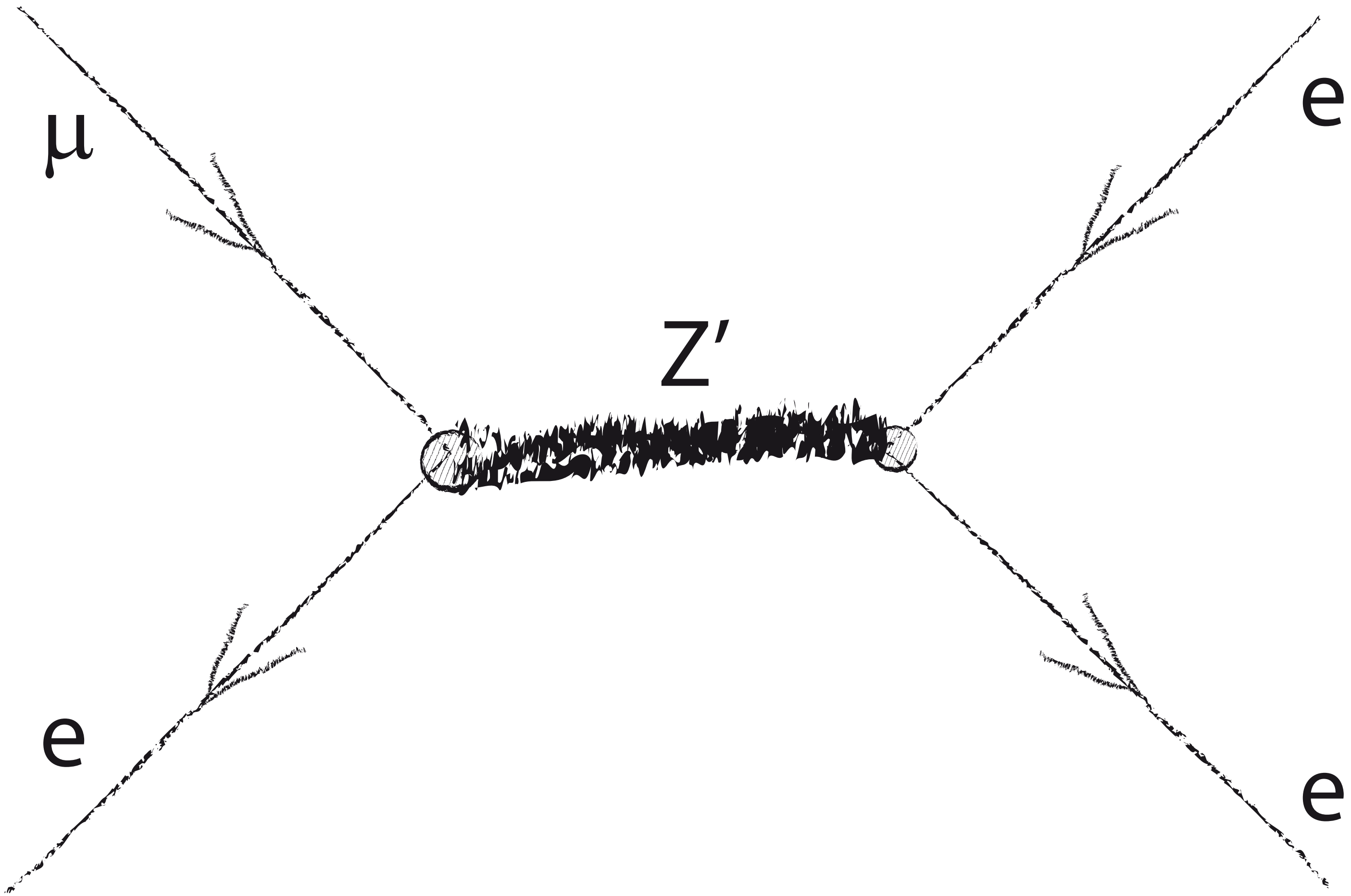






Tree-Level LFV

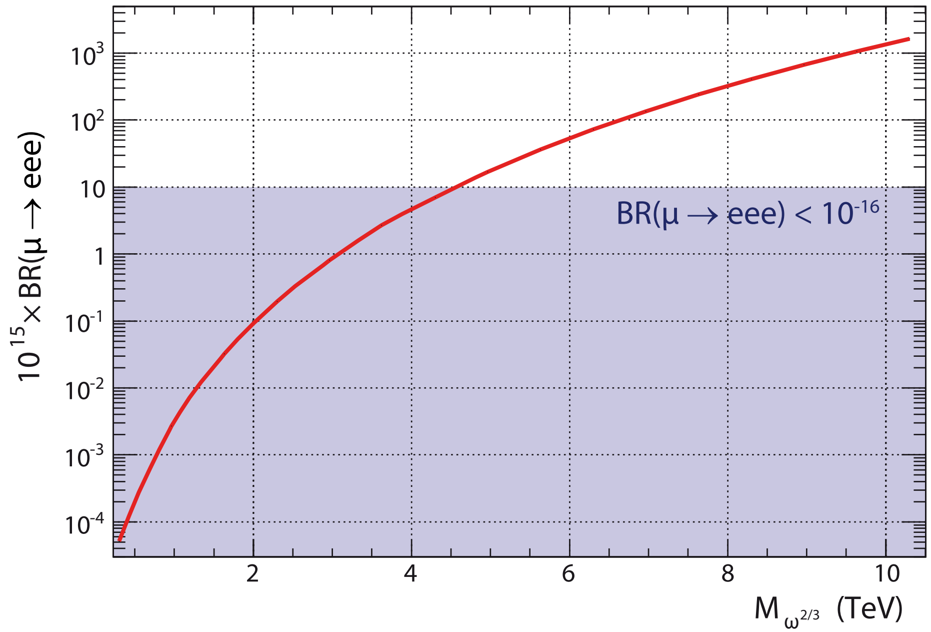
- Models with a Z′ with flavour off-diagonal couplings
- Models with large extra dimensions (Kaluza-Klein states)



- Can derive μ → eee branching ratio from fitting neutrino masses and constraints from μ → e conversion on nuclei

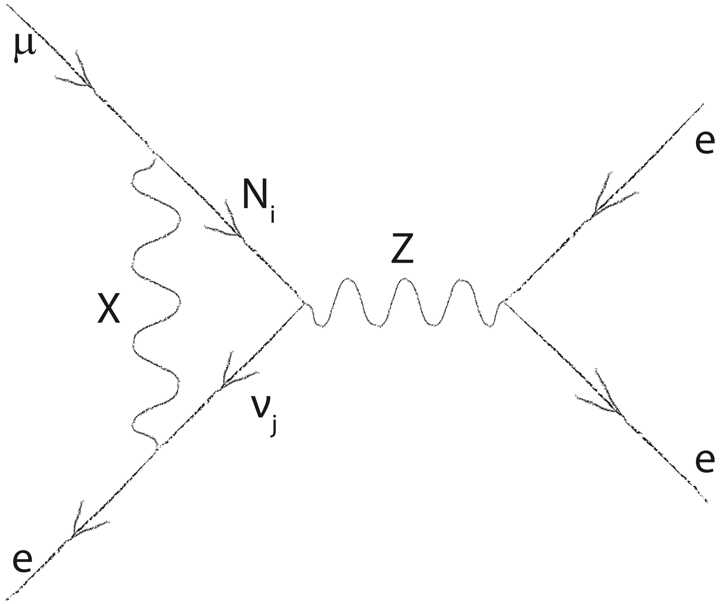
(K.S. Babu and J. Julio, Nucl.Phys. B841 (2010) 130)

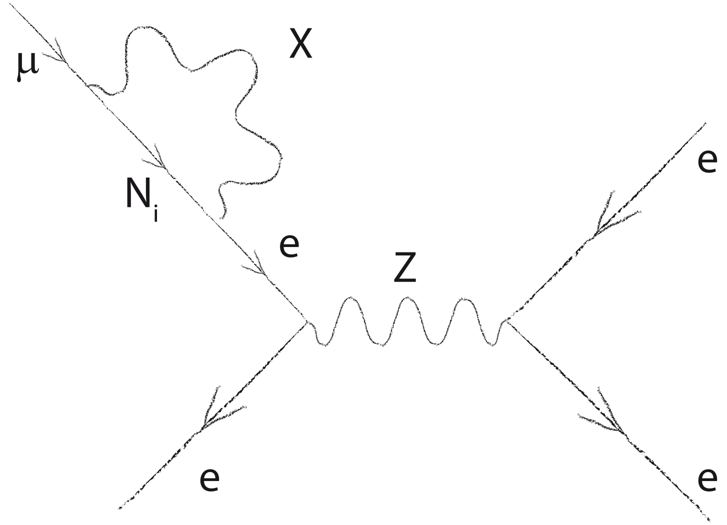
- Sensitive to multi-TeV leptoquarks

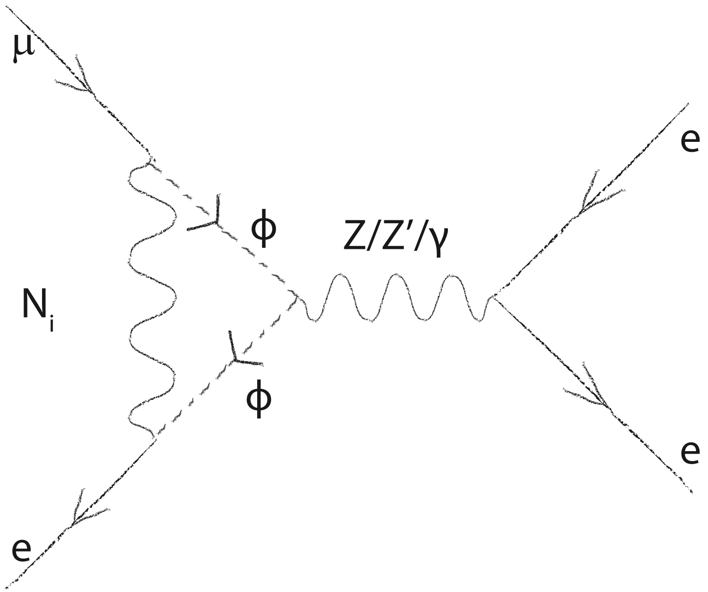


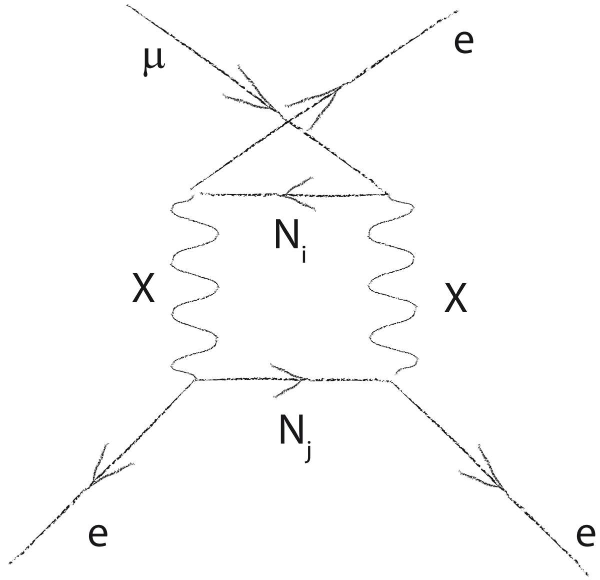
LFV in Little Higgs Models

Little Higgs models allow for $\mu \rightarrow eee$

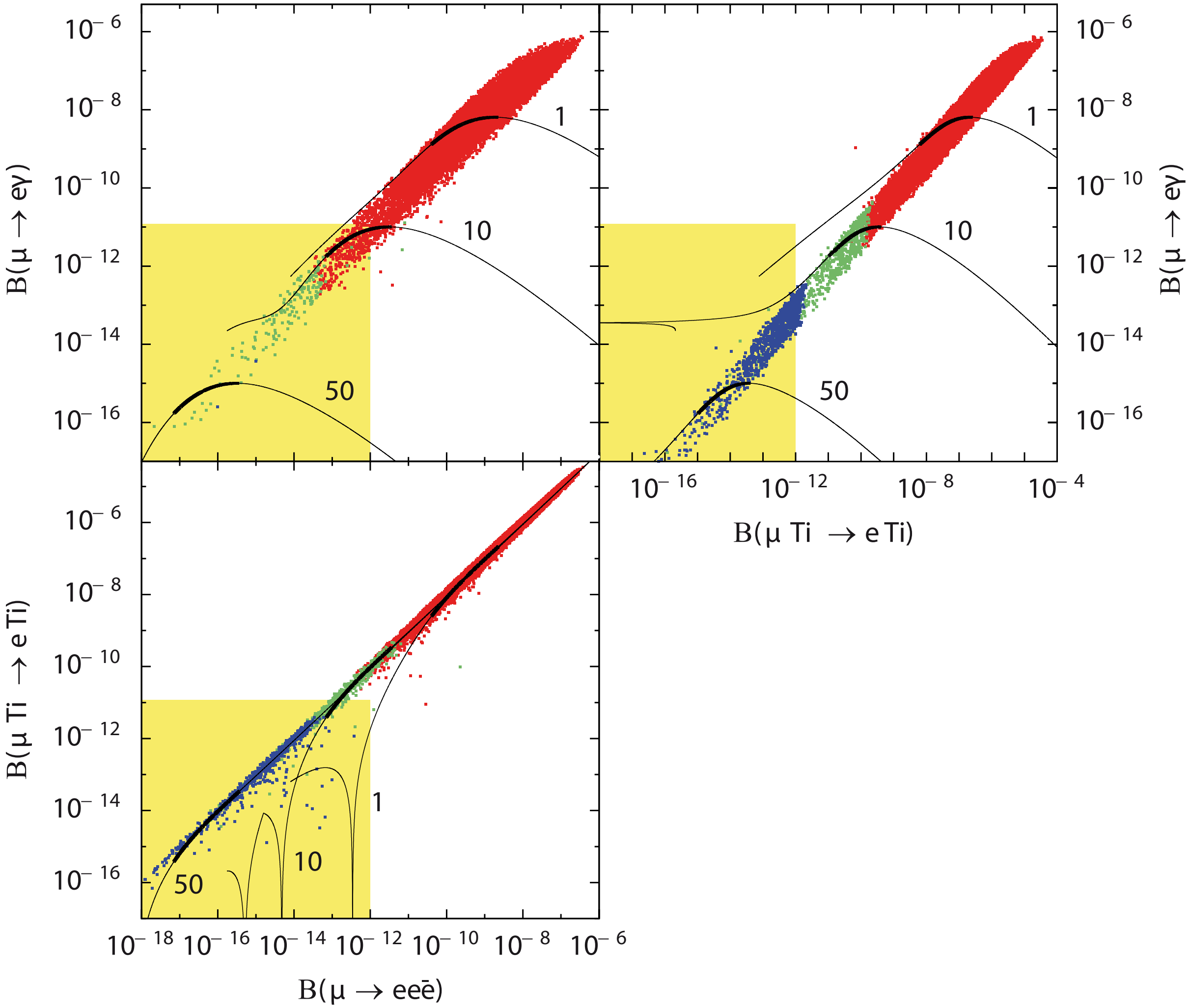








LFV in Little Higgs Models

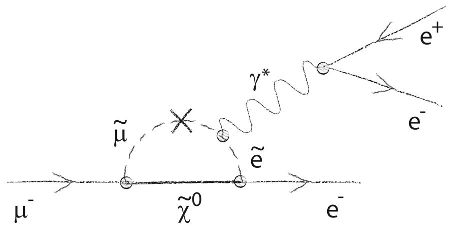


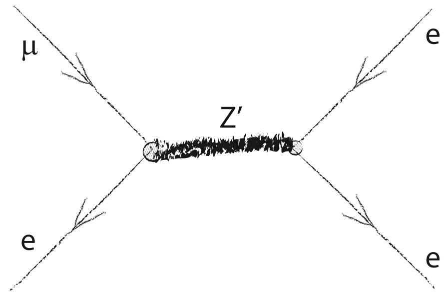
- Simplest Little Higgs Model
- Conversion experiments provide strongest constraints
- Access to scales > 50 TeV (curves)

(F. del Aguila, J.I. Illana, M.D. Jenkins, JHEP 1103 (2011) 080)

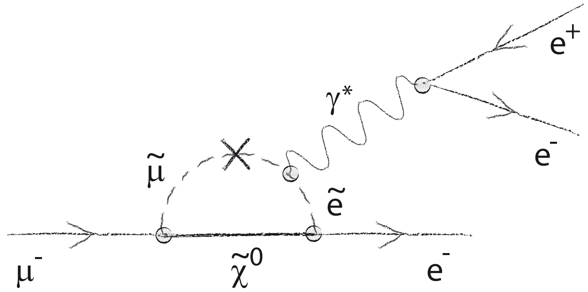
Predictions: $\mu \rightarrow eee$ vs. $\mu \rightarrow e\gamma$

Model	$B(\mu \rightarrow eee)/B(\mu \rightarrow e\gamma)$ (predicted)	$B(\mu \rightarrow eee)$ (experimental constraint)
mSugra with seesaw	$\sim 10^{-2}$	$< 2.5 \times 10^{-14}$
SUSY with SO(10) GUT	$\sim 10^{-2}$	$< 2.5 \times 10^{-14}$
SUSY + Higgs	$\sim 10^{-2}$	$< 2.5 \times 10^{-14}$
Z', Kaluza-Klein	> 1	$< 10^{-12}$
Little Higgs	0.1 - 1	$< 10^{-12}$
Higgs Triplet	10^{-3} - 10^{3}	$< 10^{-12}$





A general effective Lagrangian



Tensor terms (dipole) e.g. supersymmetry

$$L_{\mu \rightarrow eee} = 2 G_F \left(m_\mu A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + m_\mu A_L \bar{\mu}_L \sigma^{\mu\nu} e_R F_{\mu\nu} \right.$$

Four-fermion terms e.g. Higgs, Z', doubly charged Higgs....

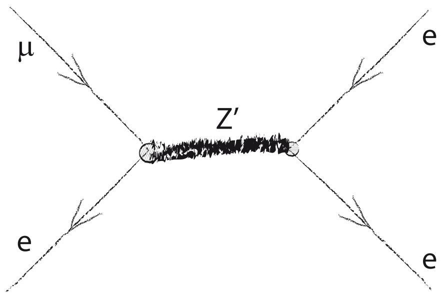
$$+ g_1 (\bar{\mu}_R e_L)(\bar{e}_R e_L) \qquad + g_2 (\bar{\mu}_L e_R)(\bar{e}_L e_R)$$

scalar

$$+ g_3 (\bar{\mu}_R \gamma^\mu e_R)(\bar{e}_R \gamma^\mu e_R) \qquad + g_4 (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_L \gamma^\mu e_L)$$

$$\left. + g_5 (\bar{\mu}_R \gamma^\mu e_R)(\bar{e}_L \gamma^\mu e_L) \qquad + g_6 (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_R \gamma^\mu e_R) + H.C. \right)$$

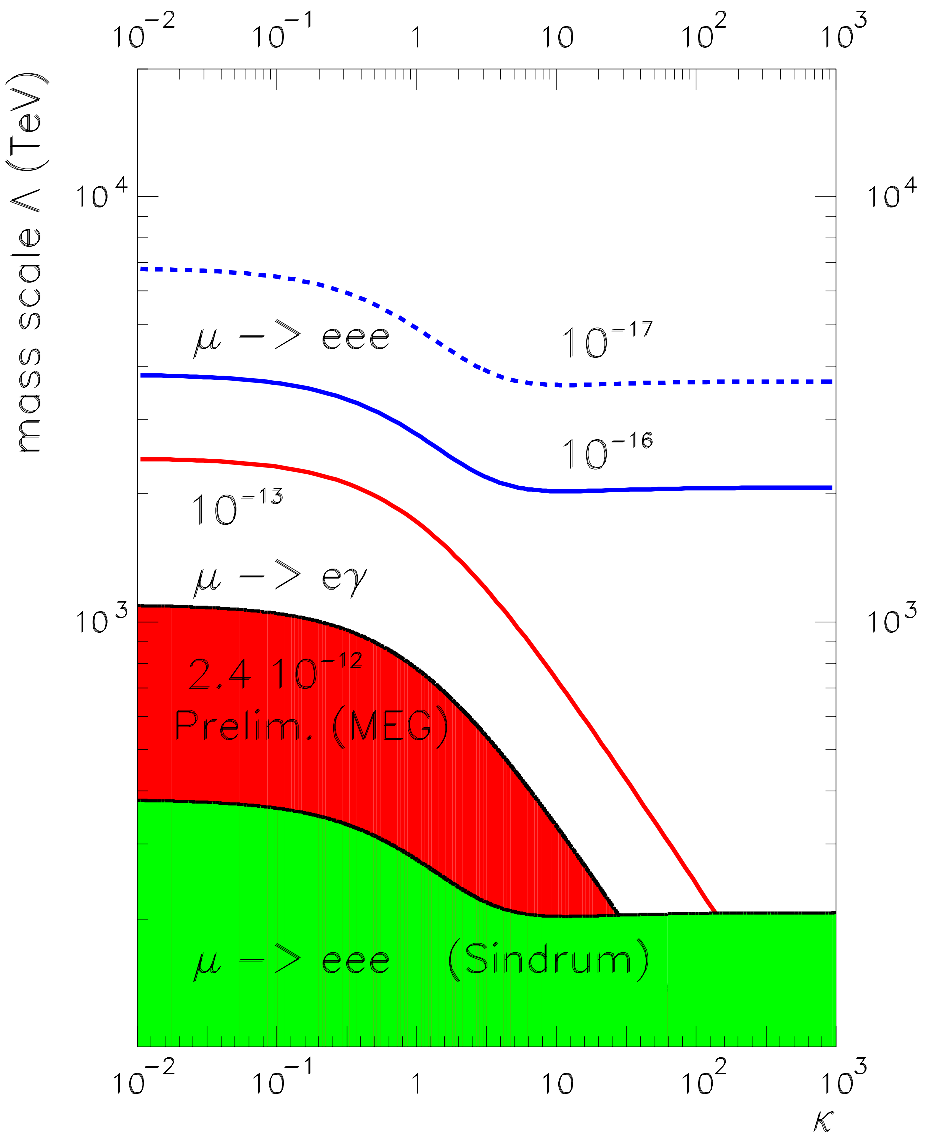
vector



(Y. Kuno, Y. Okada, Rev.Mod.Phys. 73 (2001) 151)

And a simpler Lagrangian

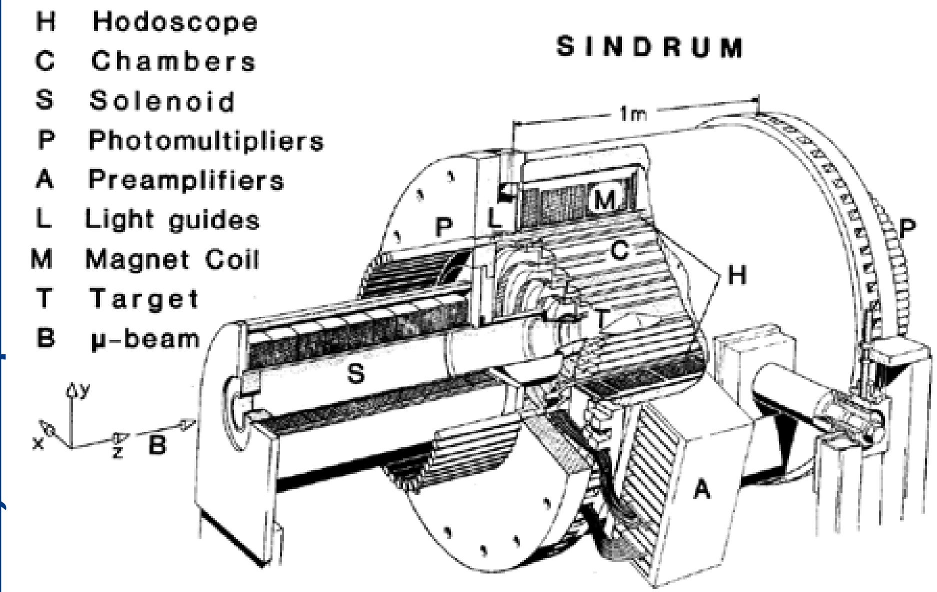
$$L_{LFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2} A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_L \gamma^\mu e_L)$$

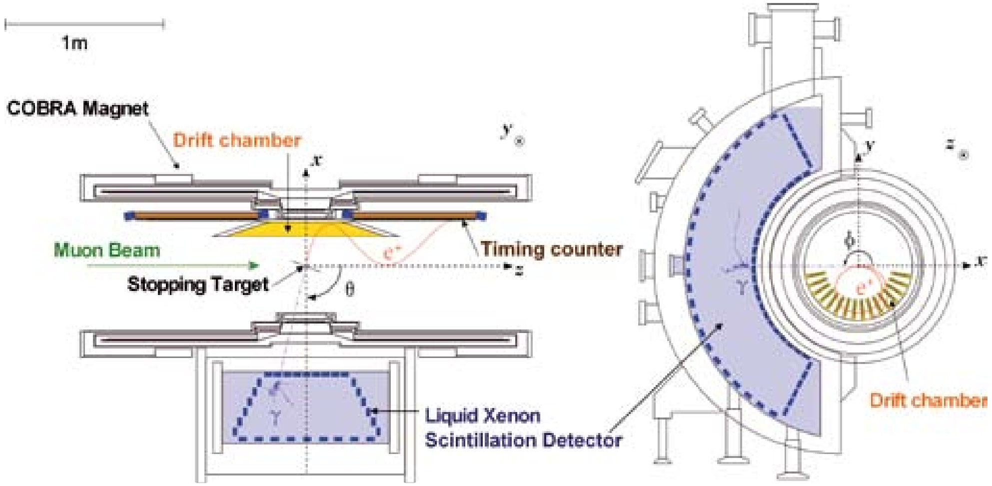


- Retain only one loop term and one contact term
- Ratio κ between them
- Common mass scale Λ
- Allows for sensitivity comparisons between $\mu \to eee$ and $\mu \to e\gamma$
- In case of dominating dipole couplings ($\kappa = 0$):

$$\frac{B(\mu \to eee)}{B(\mu \to e\gamma)} = 0.006 \quad (\text{essentially } \alpha_{em})$$

Previous muon decay experiments





SINDRUM (1988)

- σ_p/p (50 MeV/c) = 5.1%
- σ_p/p (20 MeV/c) = 3.6%
- σ_θ (20 MeV/c) = 28 mrad
- Vertex: $\sigma_d \approx 1$ mm
- X_0 (MWPC) =0.08 - 0.17% per layer

MEG (2010)

- σ_p/p (53 MeV/c) = 0.6 %
- σ_θ (53 MeV/c) = 11 mrad
- σ_ϕ (53 MeV/c) = 7 mrad
- Vertex: $\sigma_r \approx 1.1$ mm, $\sigma_z \approx 2.0$ mm

Aim for similar angular and momentum resolution, high rates and better vertex resolution