A novel experiment searching for the lepton flavour violating decay

$\mu \to eee$

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Pittsburgh, April 2012

Overview

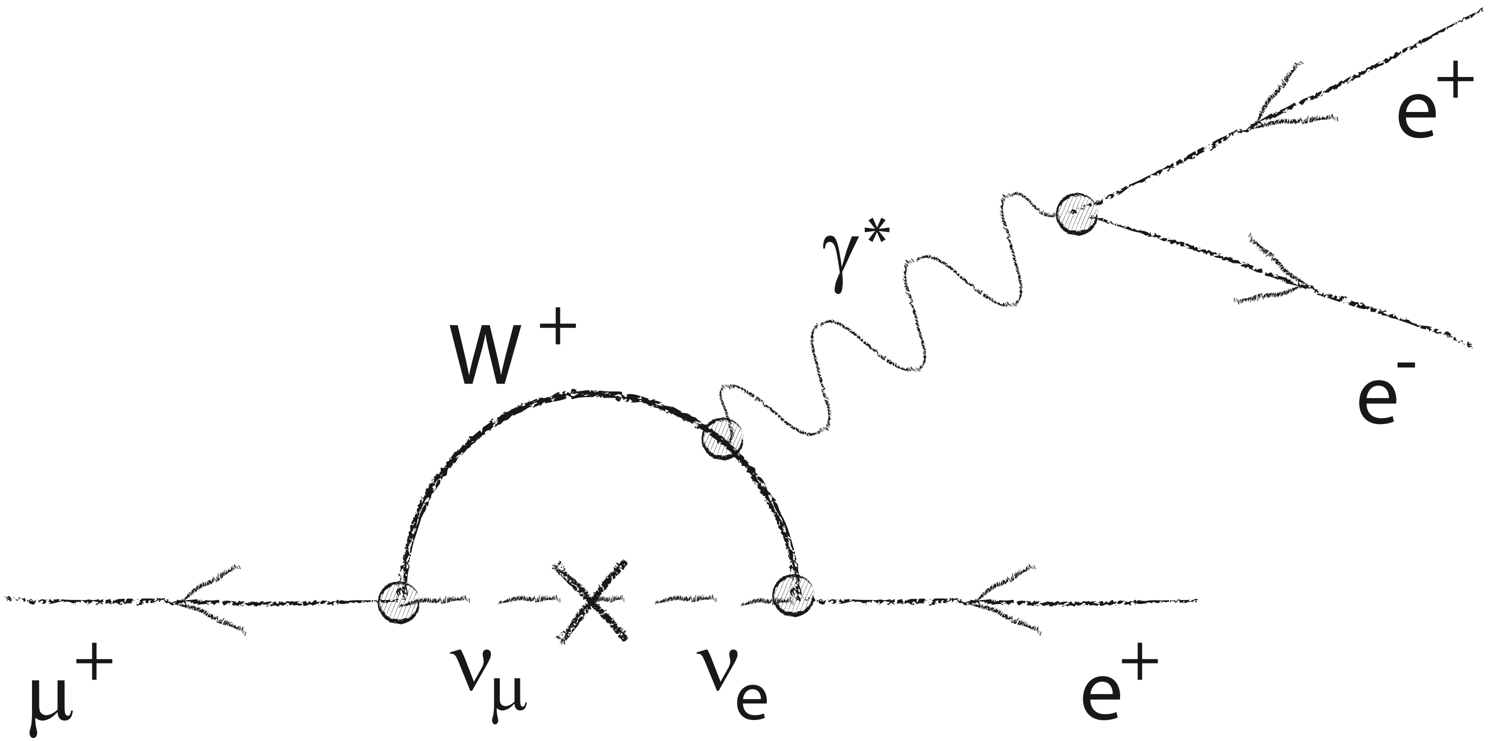
- Why
  searching for lepton flavour violation?
- Where
  can lepton flavour violation come from?
- Why
  do it in $\mu \rightarrow eee$?
- How
  to reach a sensitivity of
  $BR(\mu \rightarrow eee) < 10^{-16}$?

In the Standard Model of particle physics
lepton flavour is conserved

Neutrino Oscillations!

Why searching for LFV?

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



Where to search for LFV?

Lepton decays

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

Meson decays

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

LFV

Conversion on Nucleus

- $\mu N \to eN$

Fixed target experiments (proposed)

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

Collider experiments

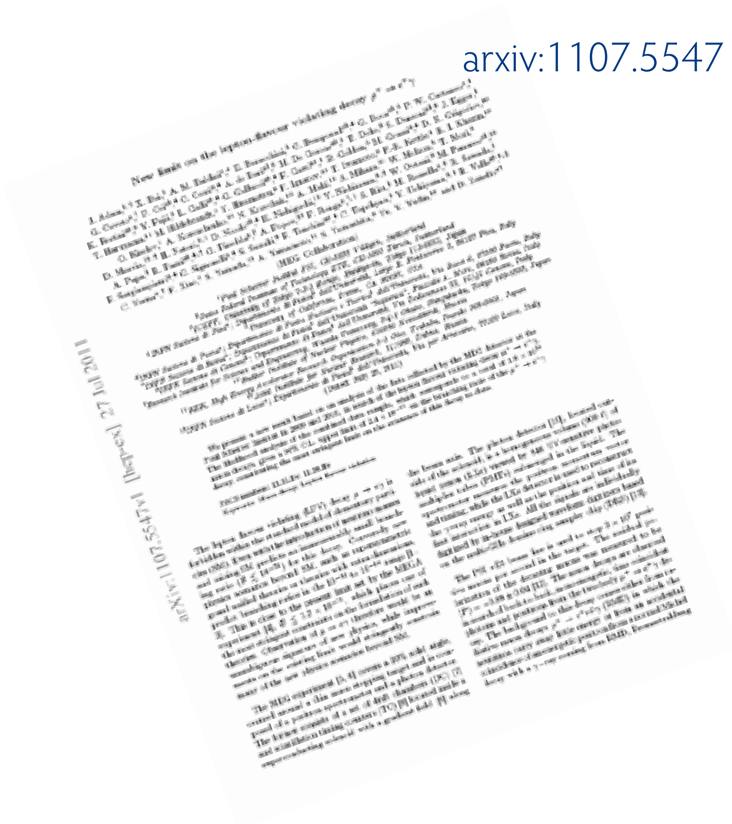
- $ep \to \mu(\tau) X$ (HERA)
- $Z' \to ll'$ (LHC)
- $\chi^{0,\pm} \to ll' X$ (LHC)

Experimental Status

Purely leptonic LFV

- BR($\mu \to e\gamma$) $< 2.4 \times 10^{-12}$ (MEG 2011)
  $< 10^{-13}$ (MEG, projected)
- BR($\tau \to e(\mu)\gamma$) $<\sim 4\times10^{-8}$ (B-Factories)
- BR($\mu \to eee$) $< 10^{-12}$ (SINDRUM)
  $< 10^{-16}$ (Our proposal)
- BR($Z \to e\mu$) $< 10^{-6}$ (LEP)

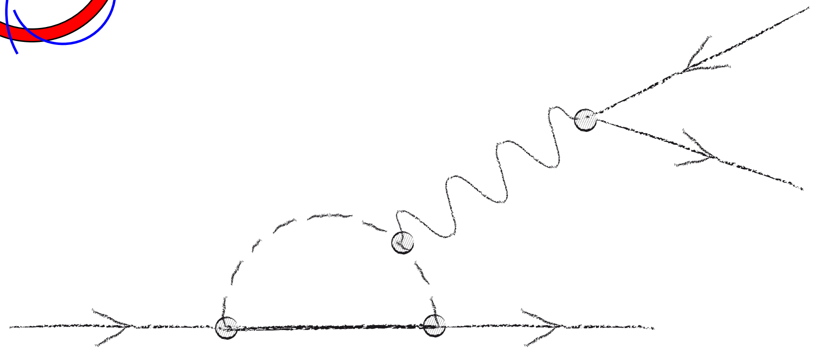
arxiv:1107.5547

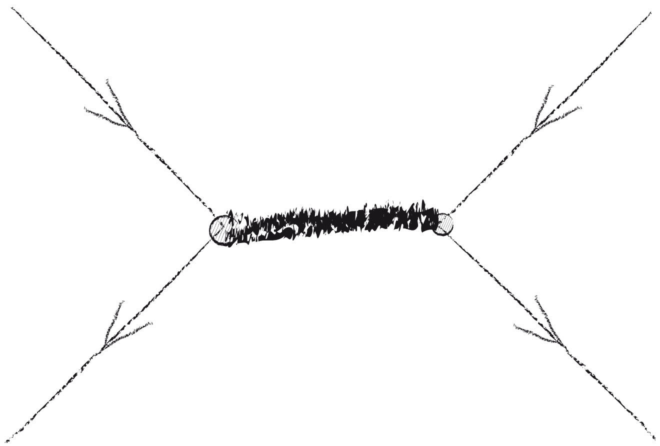


Semi-hadronic LFV

- BR($K \to \pi e\mu$) $<\sim 10^{-11}$
- BR($\mu N \to eN$) $<\sim 10^{-12}$ (SINDRUM 2)
  $<\sim 10^{-14}$ (DeeMe, projected)
  $<$ down to 10^{-17} (projected: Mu2e, COMET, Prism)

Models for LFV



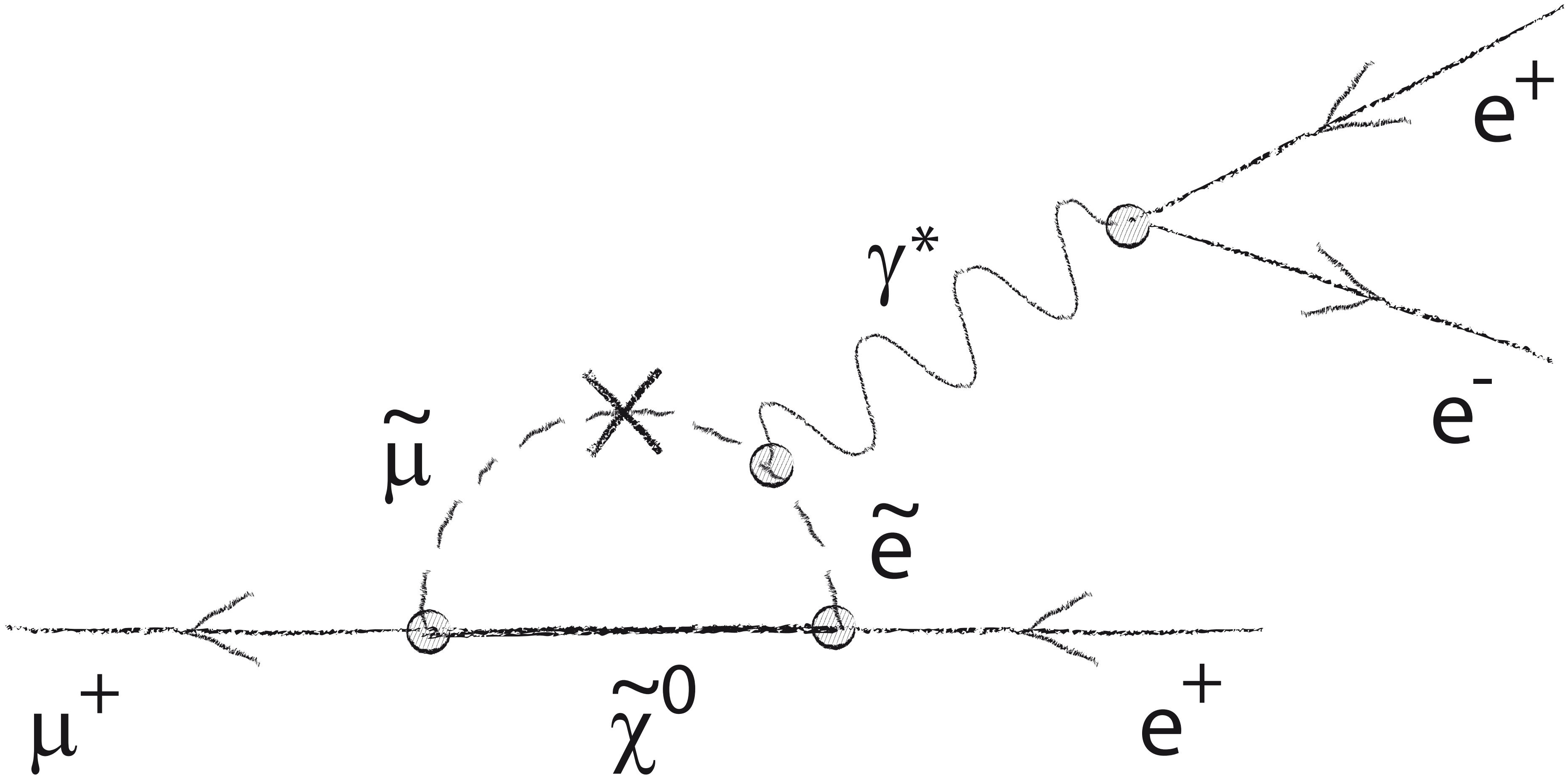


Models for physics beyond the standard model often naturally induce LFV, either through loops or exchange of heavy intermediates

- 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

Models for LFV: SUSY

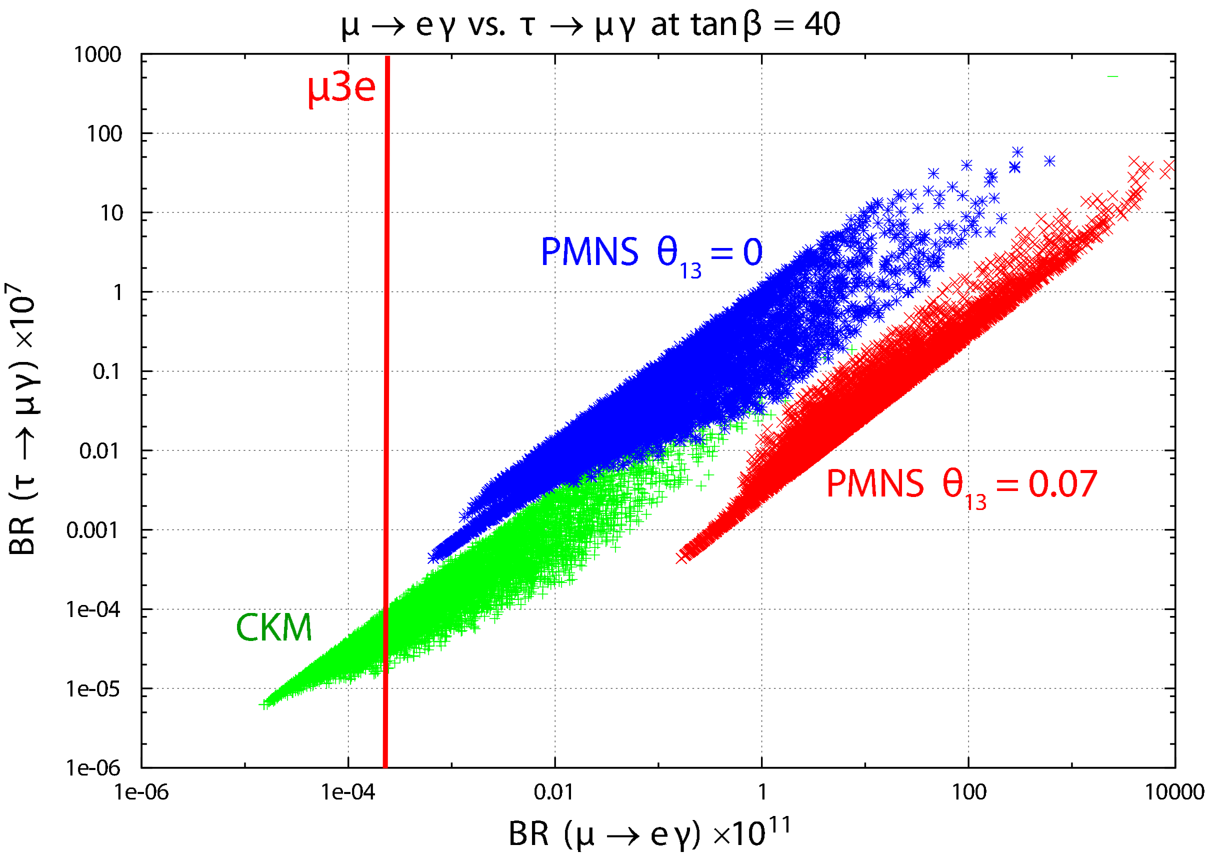
- Supersymmetry with slepton mixing
- Lepton mixing is large; would naturally expect large slepton mixing



LFV with SUSY SO(10) GUT

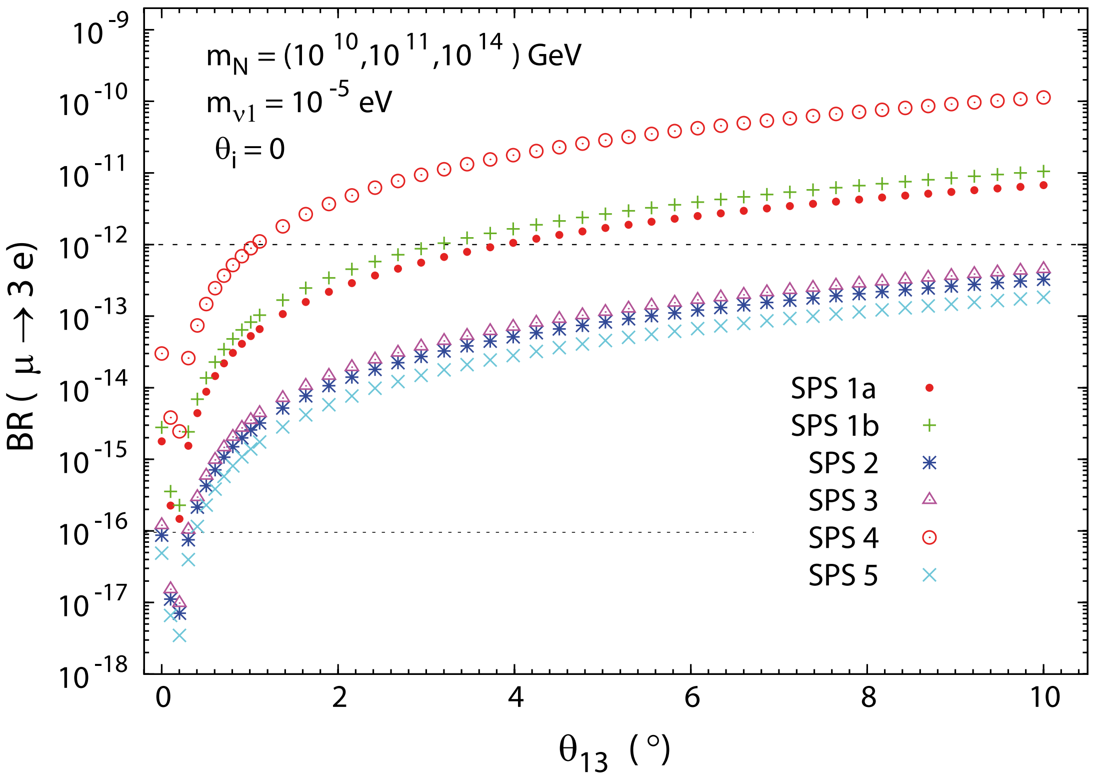
- For these models:
  $BR(\mu \to eee) = 0.006 \times BR(\mu \to e\gamma)$
- Points: SUSY LHC parameters

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



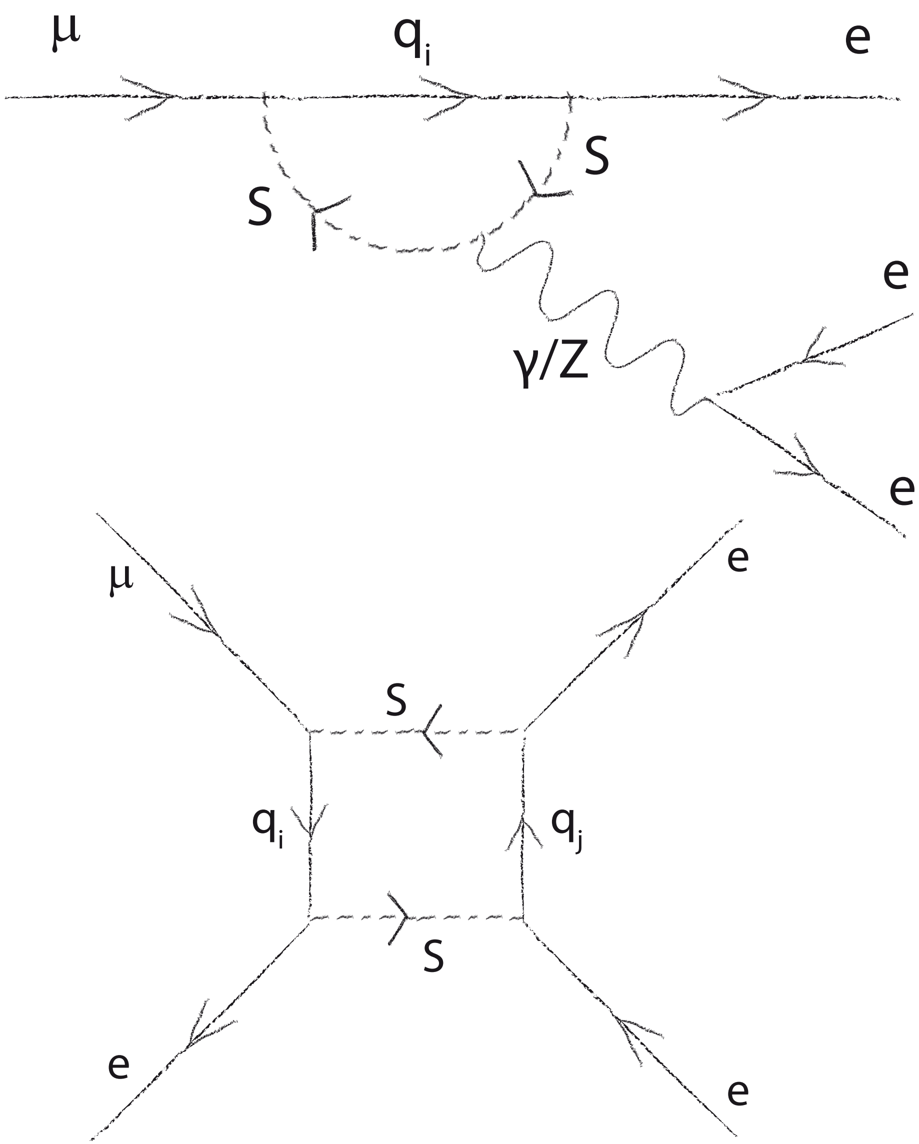
LFV with cMSSM Seesaw

- 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



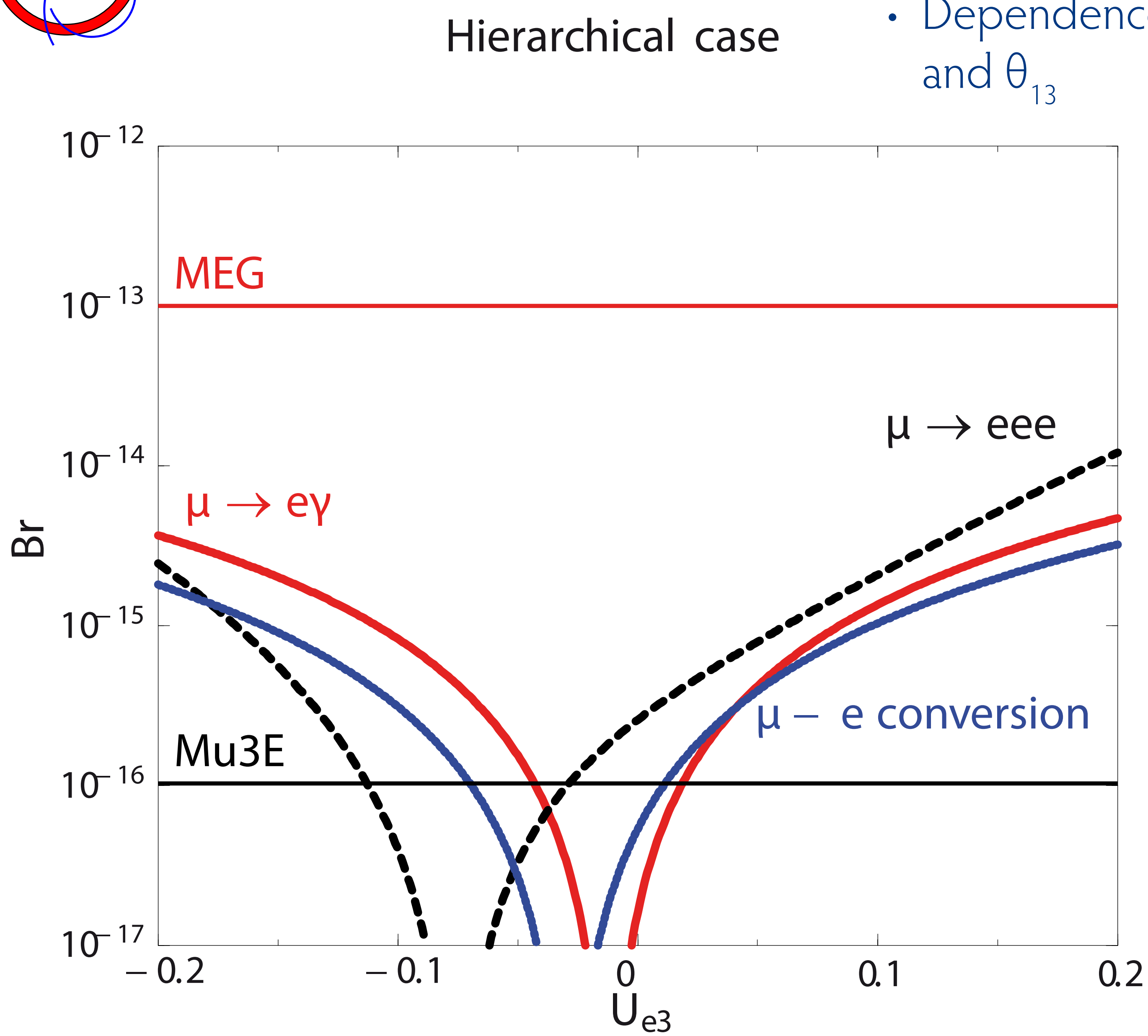
- Leptoquarks can lead to μ → eee at one-loop order
- Access to Leptoquark masses up to ~ 5 TeV

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

LFV in Higgs triplet models

- Dependence on neutrino mass hierarchy and θ_{13}

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



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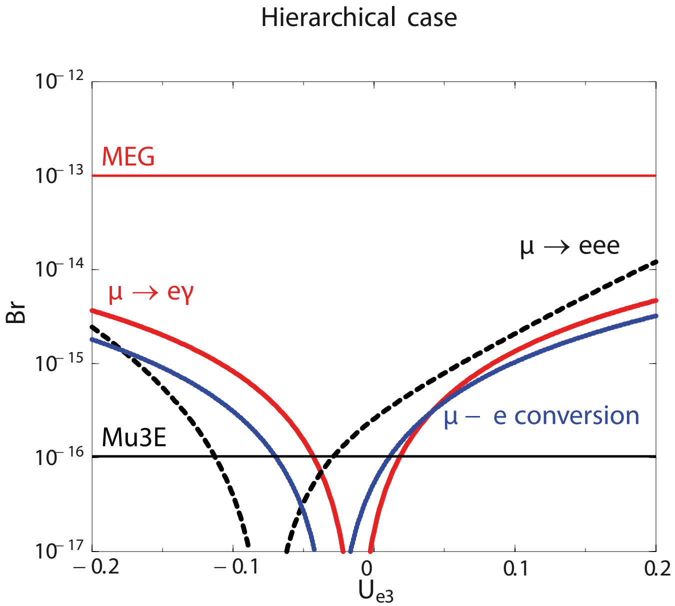
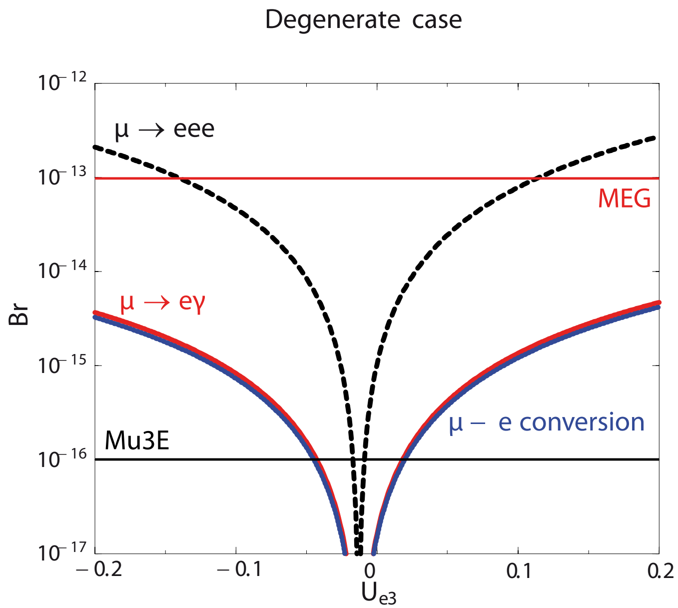
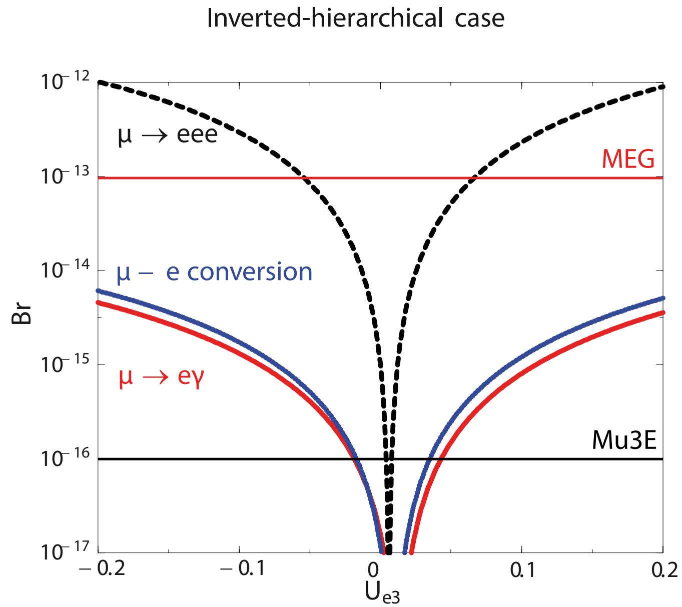


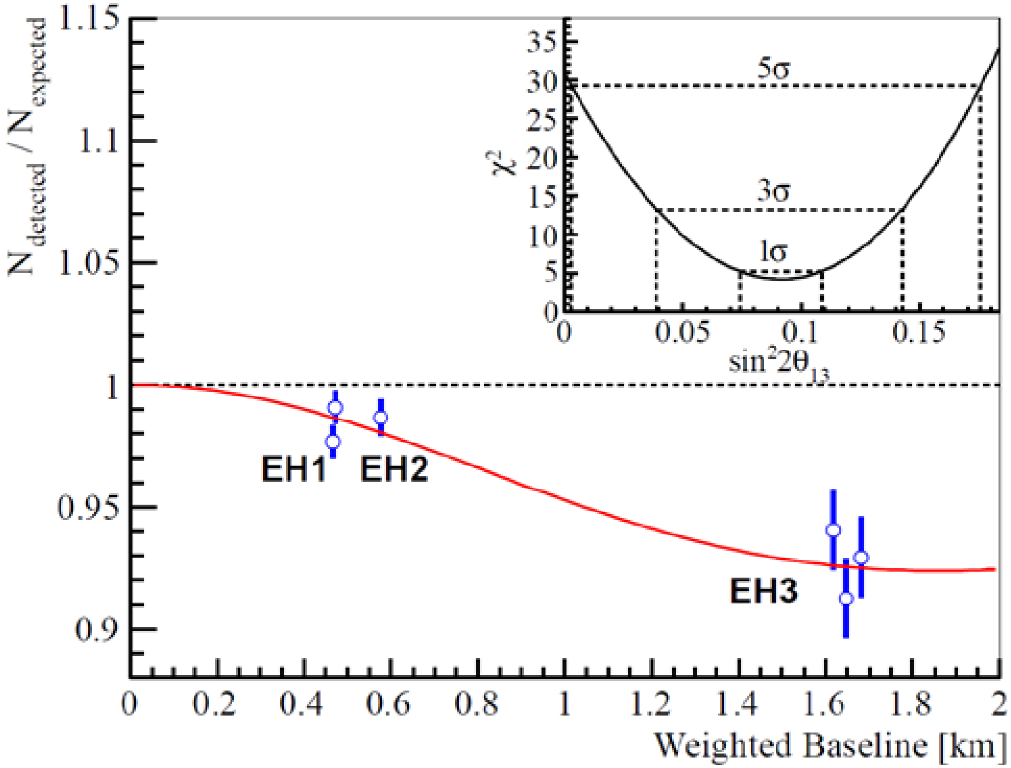


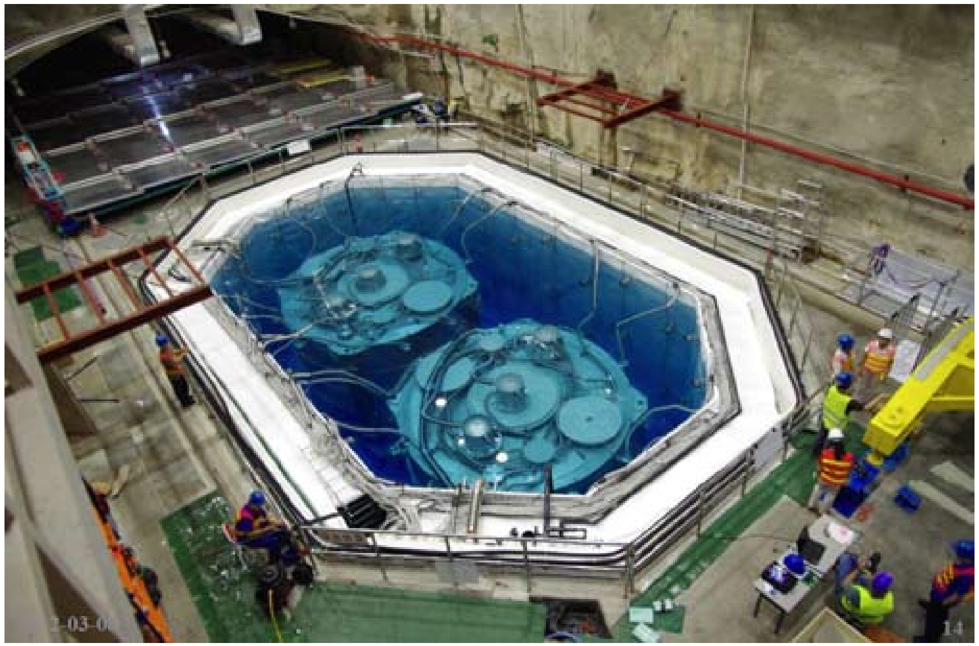


θ_{13} is large!

Recent result from Daya Bay

- θ_{13} is ~ 9°
- Leads to large BF predictions for $\mu \rightarrow eee$





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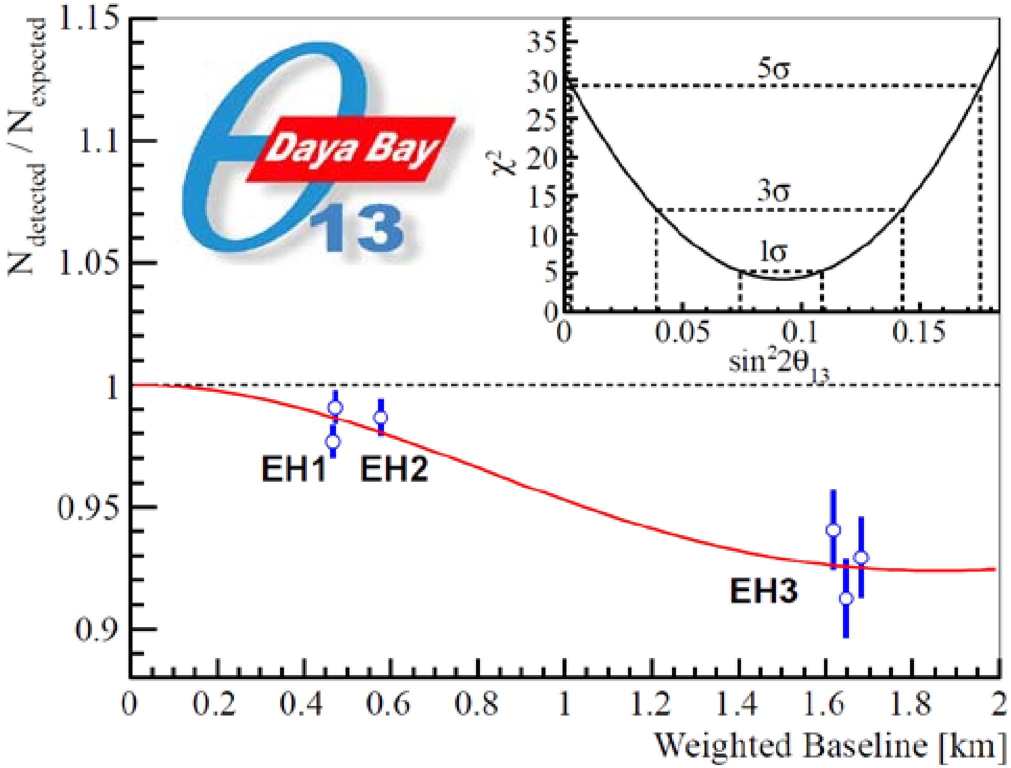
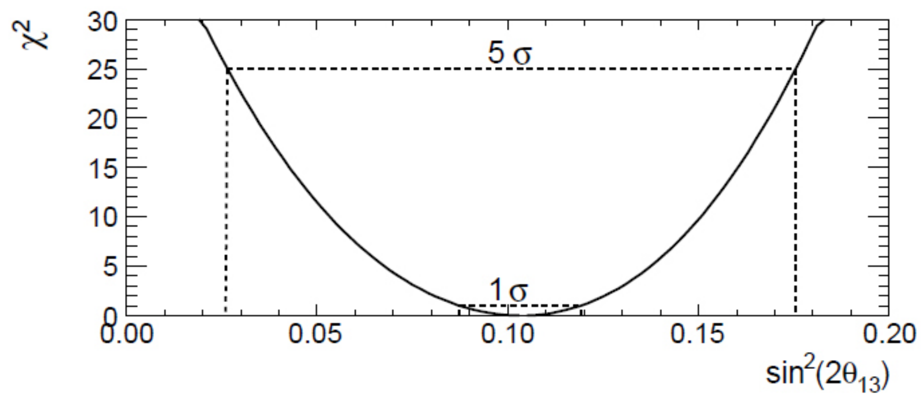
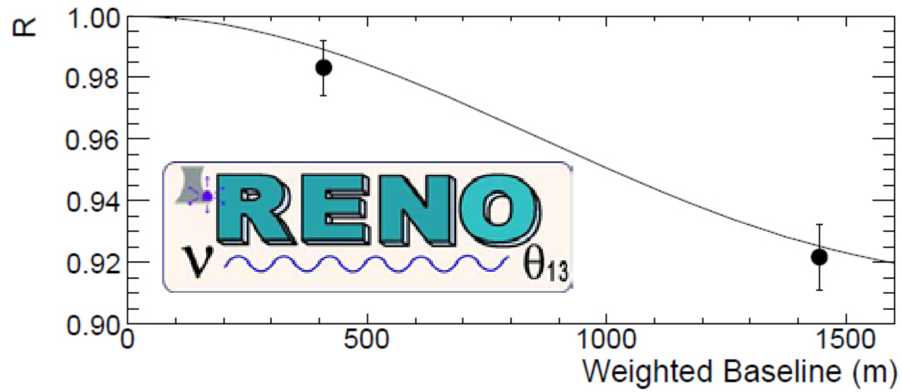
Even more recent result from RENO:

- θ_{13} is indeed ~ 9°

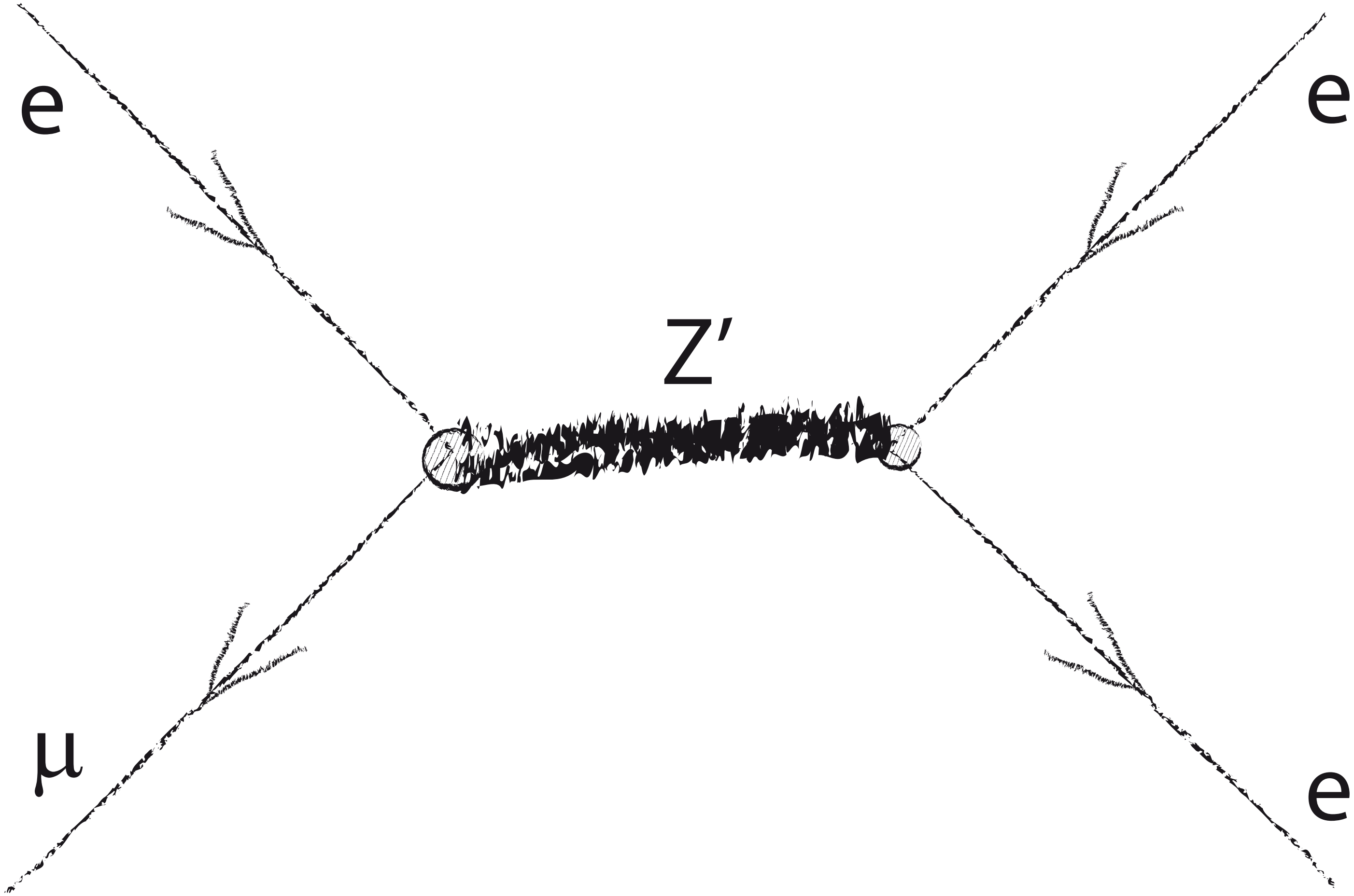






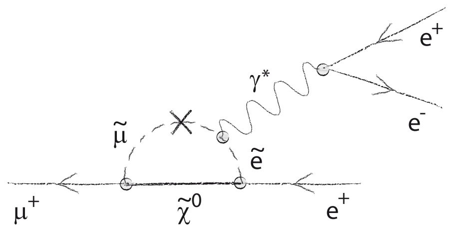
Tree-Level LFV

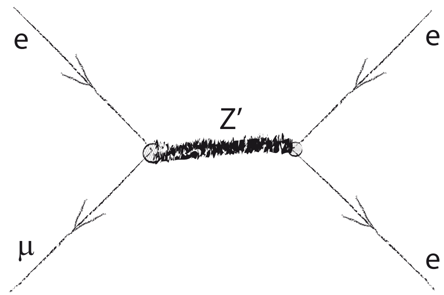
- Models with a Z′ with flavour off-diagonal couplings
- Models with large extra dimensions (Kaluza-Klein states)



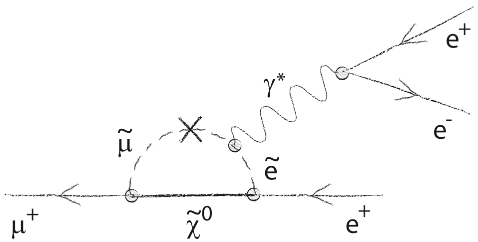
Predictions: $\mu \rightarrow eee$ vs. $\mu \rightarrow e\gamma$

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

$$L_{\mu \to eee} = 2\, G_F\, (\, m_\mu A_R\, \bar{\mu}_R\, \sigma^{\mu\nu} e_L\, F_{\mu\nu} \quad + m_\mu A_L\, \bar{\mu}_L\, \sigma^{\mu\nu} e_R\, F_{\mu\nu}$$

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

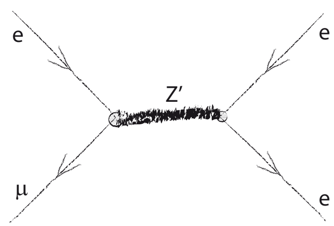
$$+ g_1\, (\bar{\mu}_R e_L)\, (\bar{e}_R e_L) \quad + g_2\, (\bar{\mu}_L e_R)\, (\bar{e}_L e_R)$$

scalar

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

$$+ g_5\, (\bar{\mu}_R \gamma^\mu e_R)\, (\bar{e}_L \gamma^\mu e_L) \quad + g_6\, (\bar{\mu}_L \gamma^\mu e_L)\, (\bar{e}_R \gamma^\mu e_R) \; + H.\, C.\,)$$

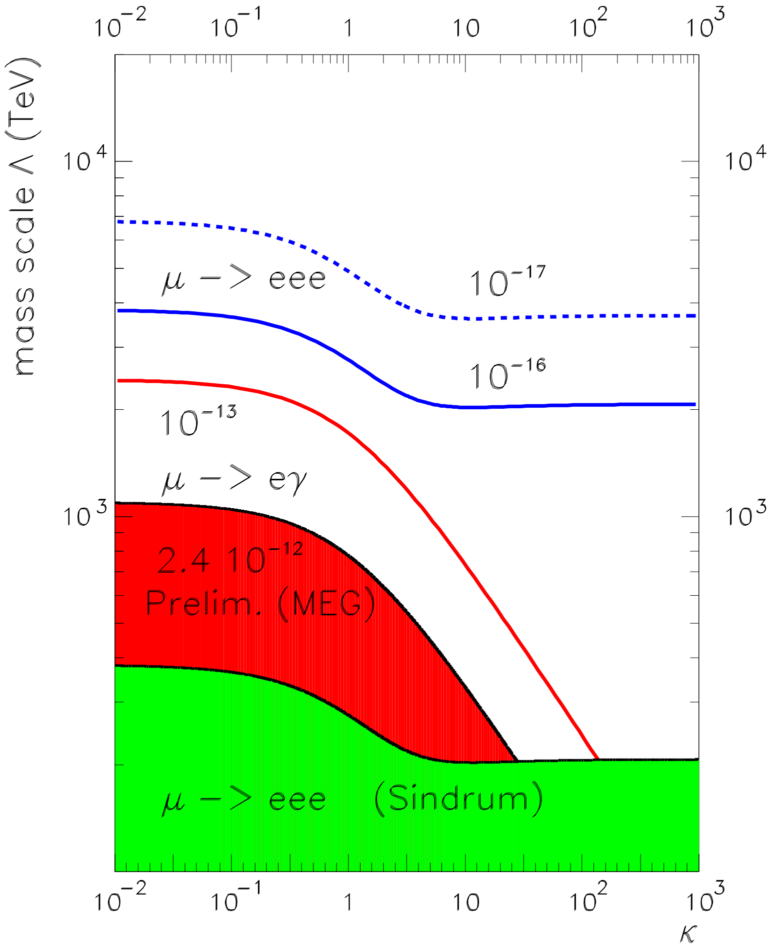
vector



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

And a simpler Lagrangian

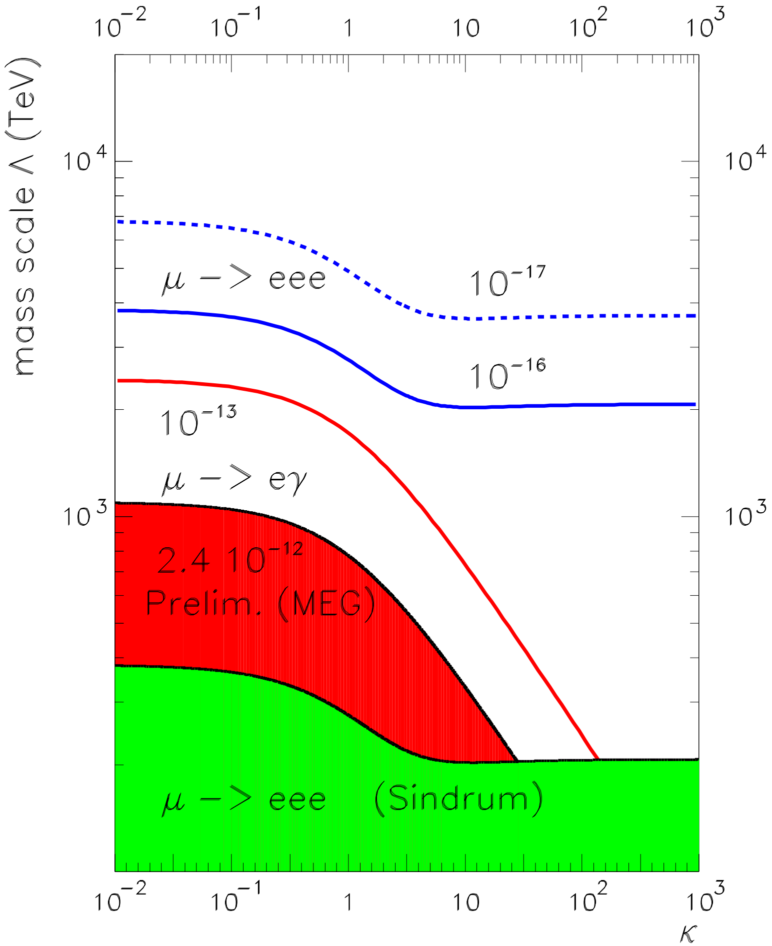
$$L_{LFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2} A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_L \gamma^\mu e_L)$$



- Retain only one loop term and one contact term
- Ratio κ between them
- Common mass scale Λ
- Allows for sensitivity comparisons between μ → eee and μ → eγ
- In case of dominating dipole couplings (κ = 0):

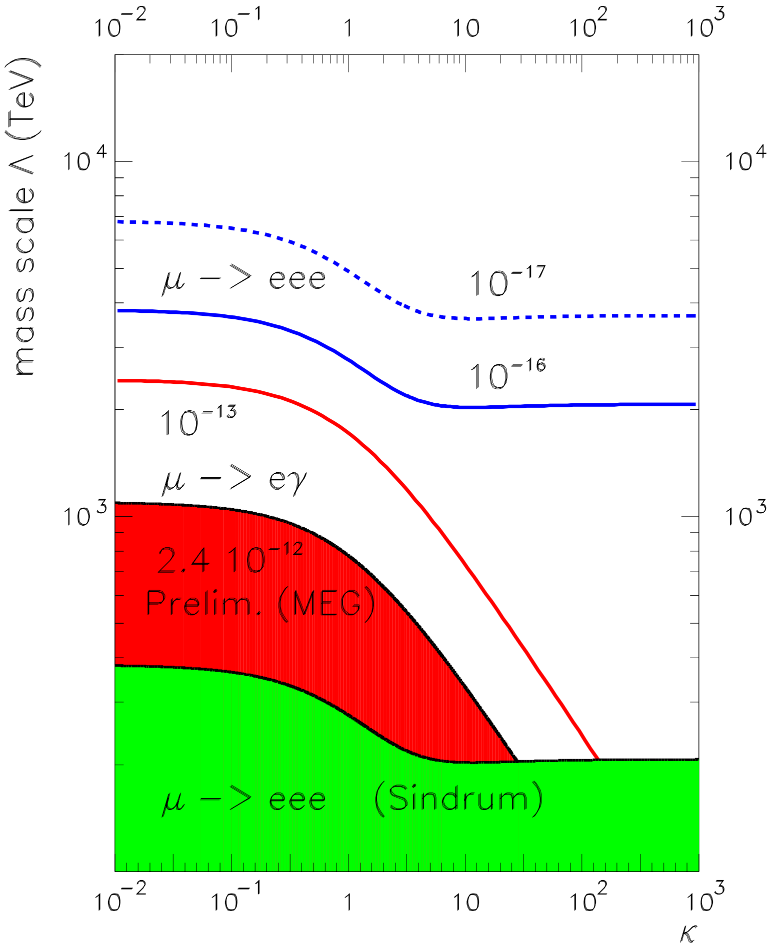
$$\frac{B(\mu \to eee)}{B(\mu \to e\gamma)} = 0.006 \quad (\text{essentially } \alpha_{em})$$

Why μ → eee?



- 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
- Complementary to LFV searches in conversion or μ → eγ
- Complementary to quark flavour physics and LHC
- Reaching mass scales way beyond direct reach of LHC

Why μ → eee?



- Muons are plentiful and clean
- 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 $\mu \to eee$ experiment sensitive to 10^{-16}

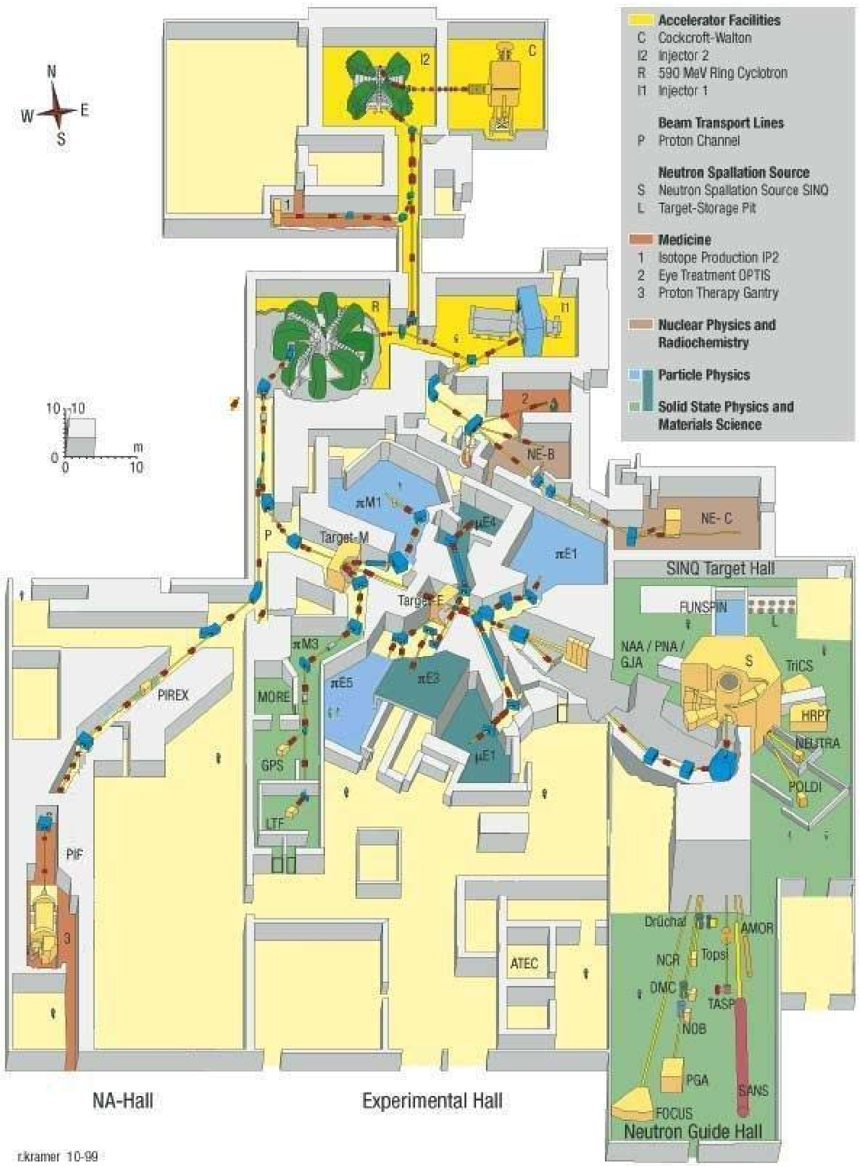
Need a lot of muons

Need to suppress background by 10^{16}

Muons from 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 from PSI



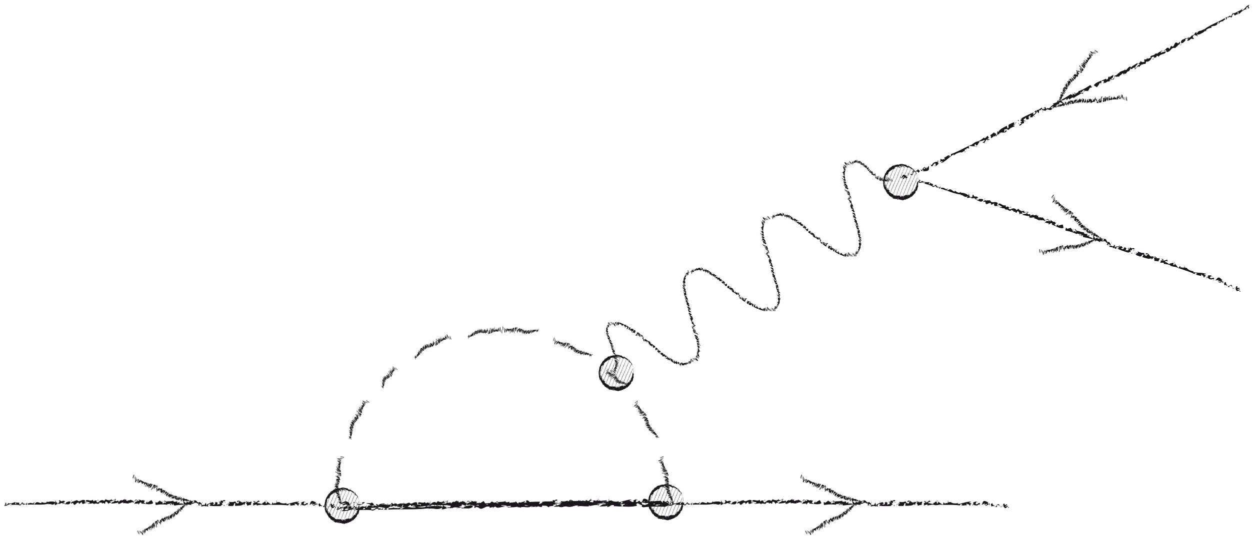
DC muon beams at PSI:

- 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

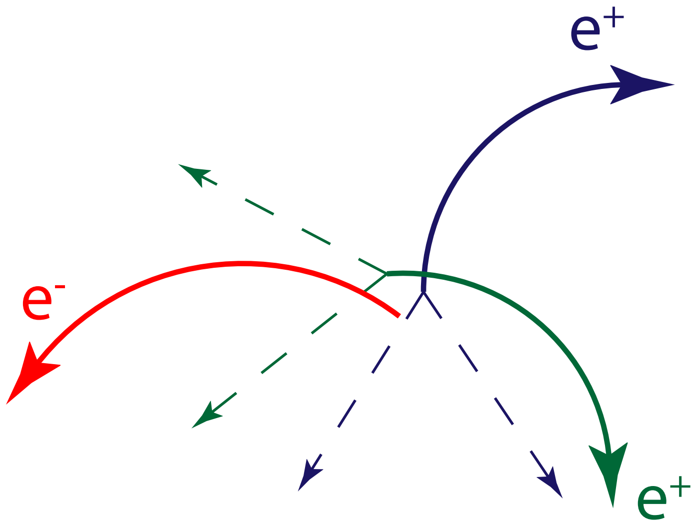
- The μ → eee experiment (final stage) requires 2 × 10^{9} muons/s focused and collimated on a ~2 cm spot

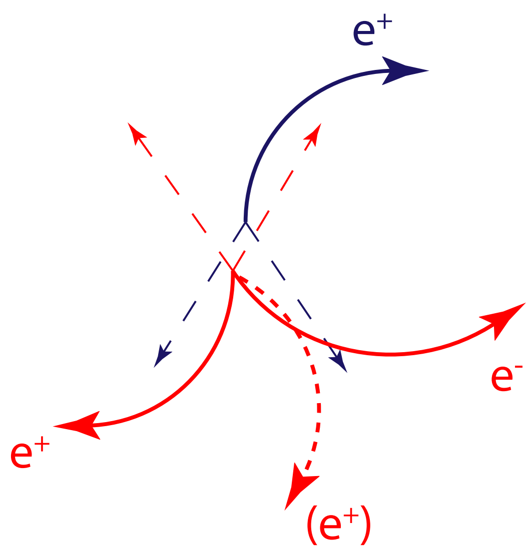
Signal

- Two positrons and one electron
- Coincident in time and vertex
- In a plane
- Energies sum up to muon mass



Accidental Background





- Overlays of two normal muon decays with an electron
- Electrons from Bhabha-scattering, photon conversion, mis-reconstruction

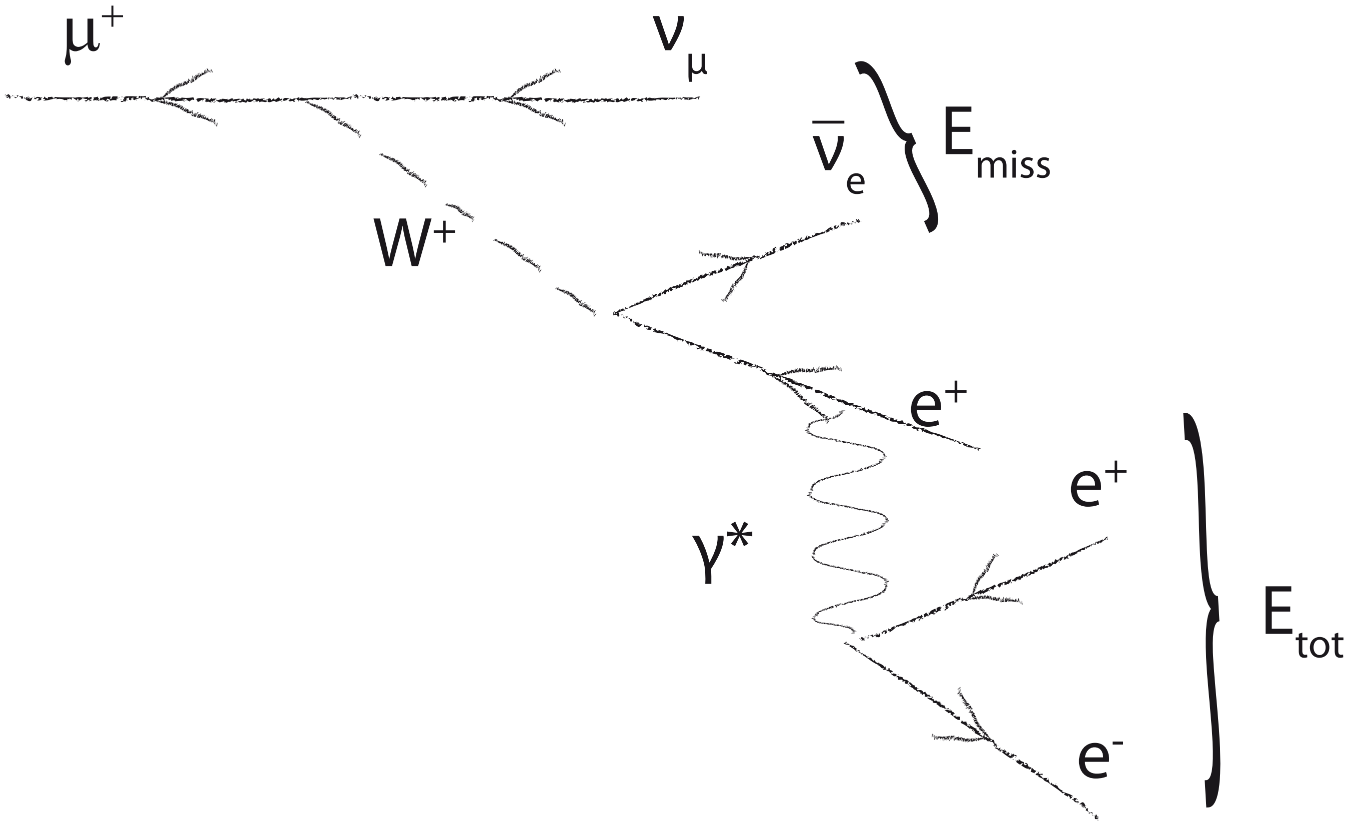
Need excellent:

- Vertex resolution
- Timing resolution
- Kinematics reconstruction

Internal Conversion Background

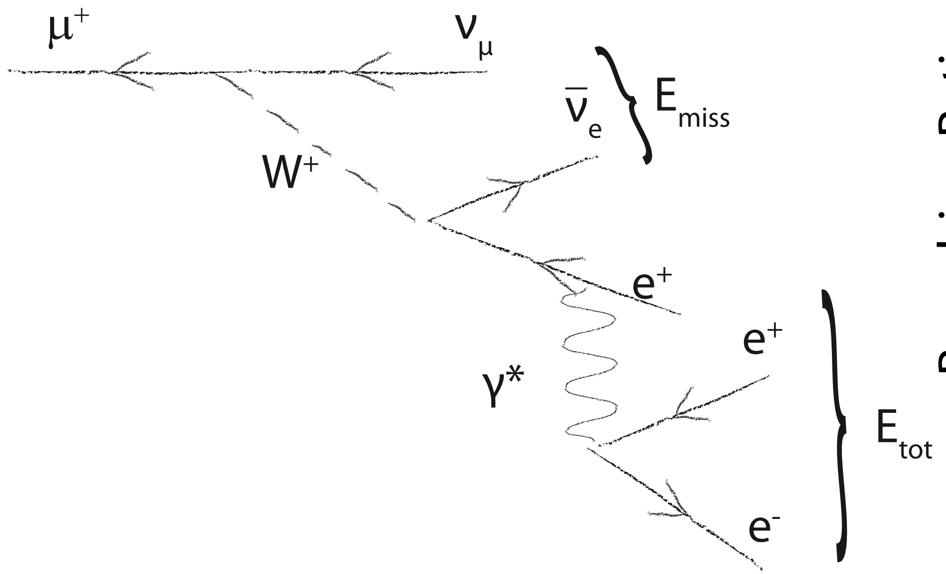
Radiative muon decay with internal conversion

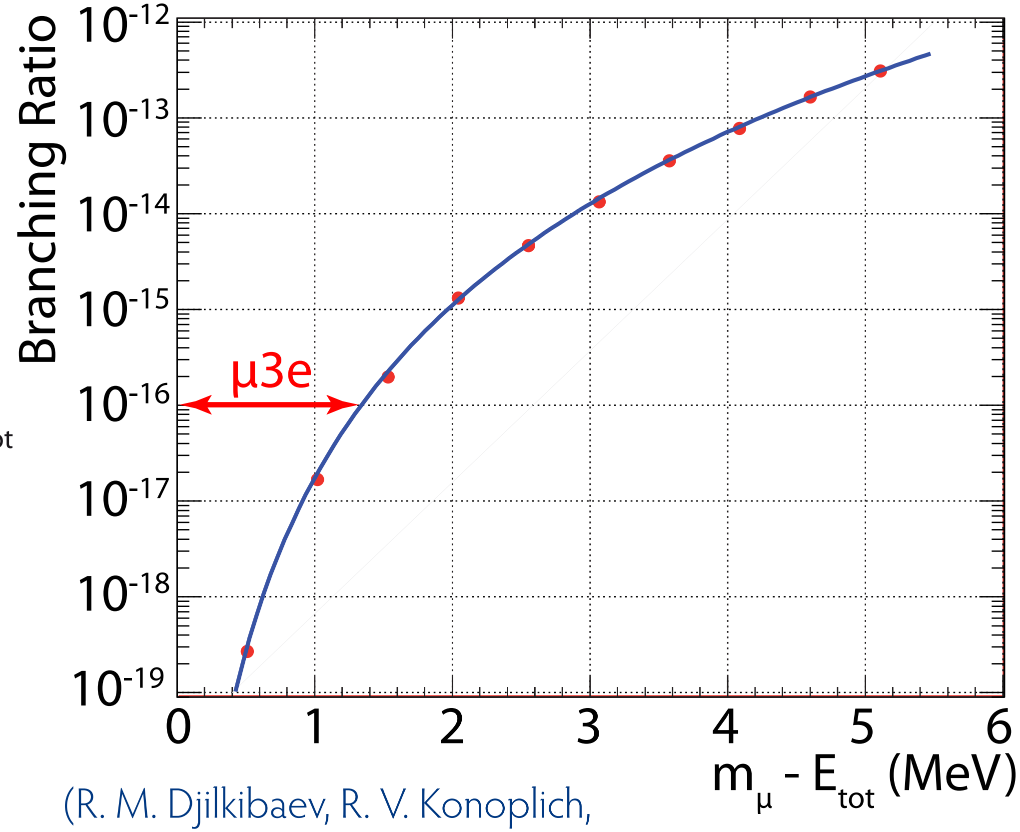
- Looks like signal
- Except for missing energy



Internal Conversion Background

- Branching fraction 3.4×10^{-5}
- Need excellent momentum resolution to reject this background



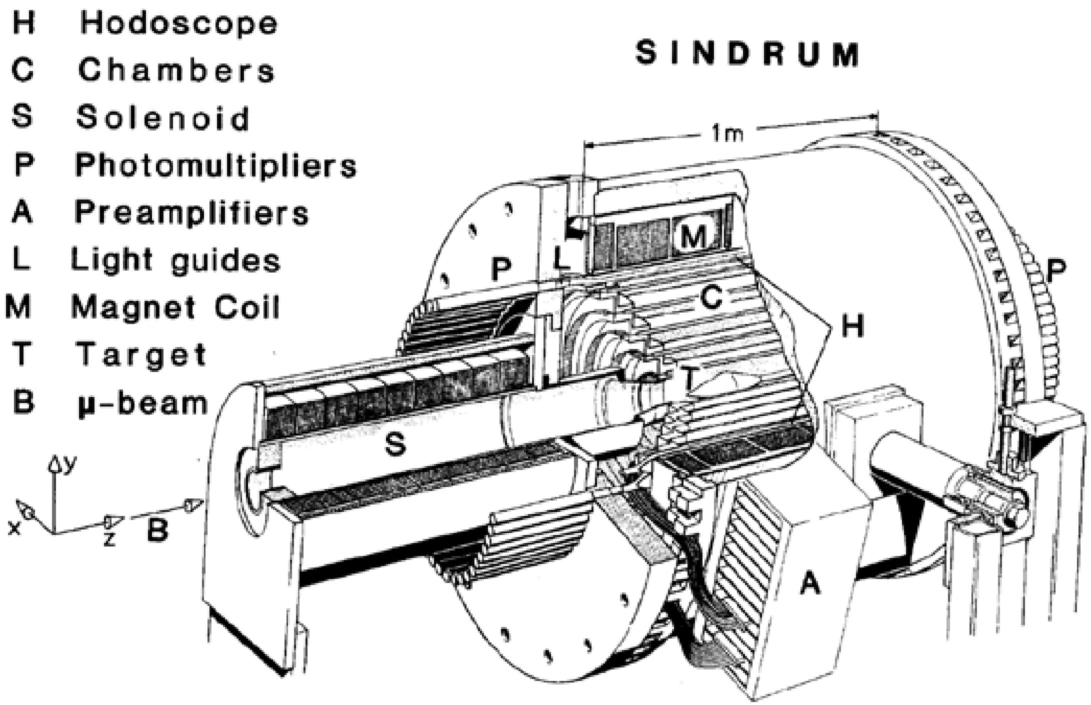


(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)

Last Experiment: SINDRUM

SINDRUM (1988)

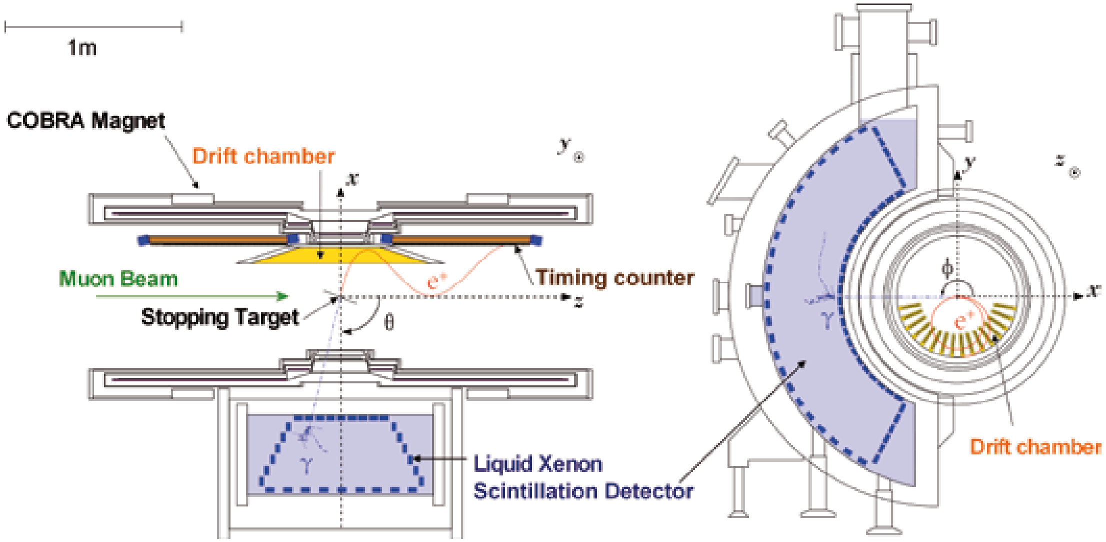
- σ_p/p (50 MeV/c) = 5.1%
- σ_p/p (20 MeV/c) = 3.6%
- σ_θ (20 MeV/c) = 28 mrad
- Vertex: $\sigma_d \approx 1$ mm
- X_0 (MWPC) =0.08 - 0.17% per layer



State of the art: MEG

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



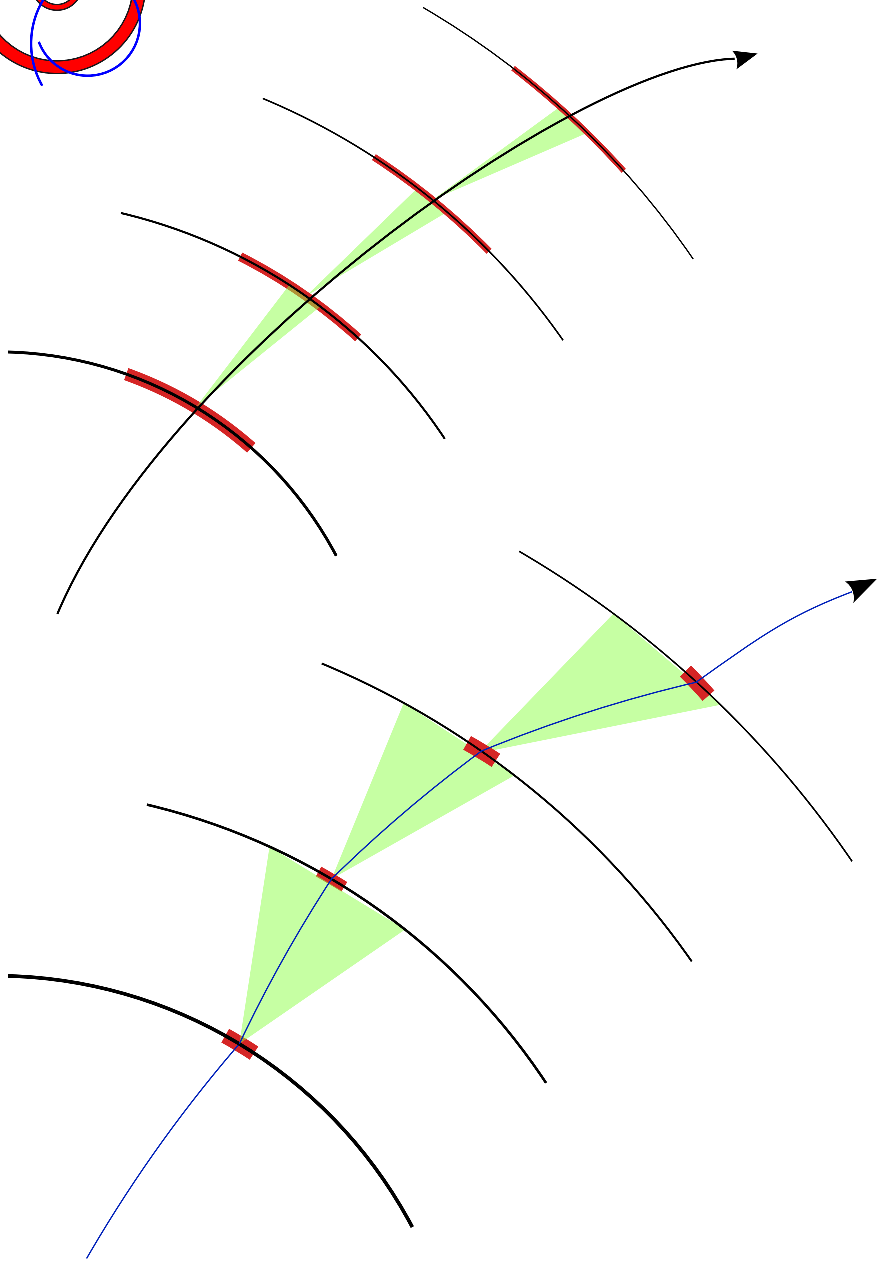
The challenge: Rates and precision

Tracking of 2×10^9 electrons/s

With sub-MeV momentum resolution

In a multiple scattering dominated regime

Multiple scattering



- Decay particles are electrons with momenta < 53 MeV/c

- Strong multiple scattering

$$\propto \sqrt{X/X_0} \times 1/p$$

- Need a thin, fast, high resolution detector

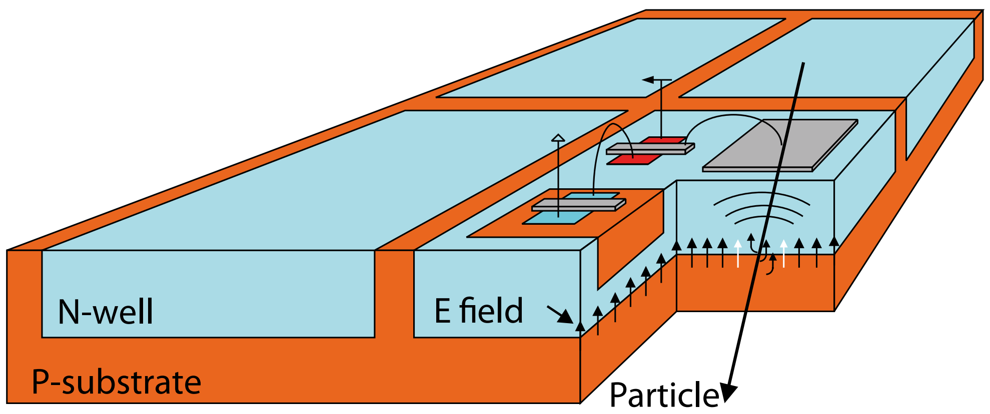
- Rates and aging speak against a gaseous detector

- Silicon is heavy - or is it?

Silicon detector technologies

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

HV-MAPS



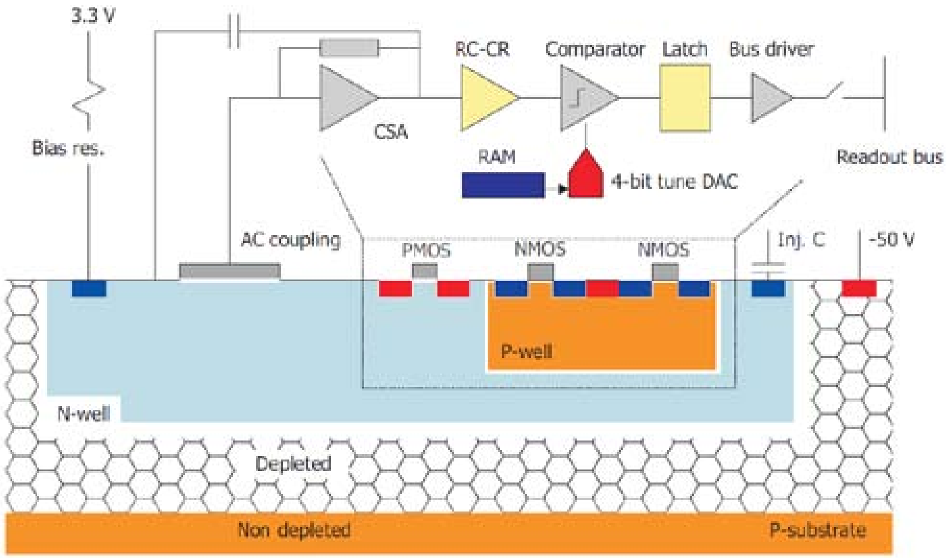
High voltage monolithic active pixel sensors

- 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 via drift
- Can be thinned down to < 50 µm
- Low power consumption

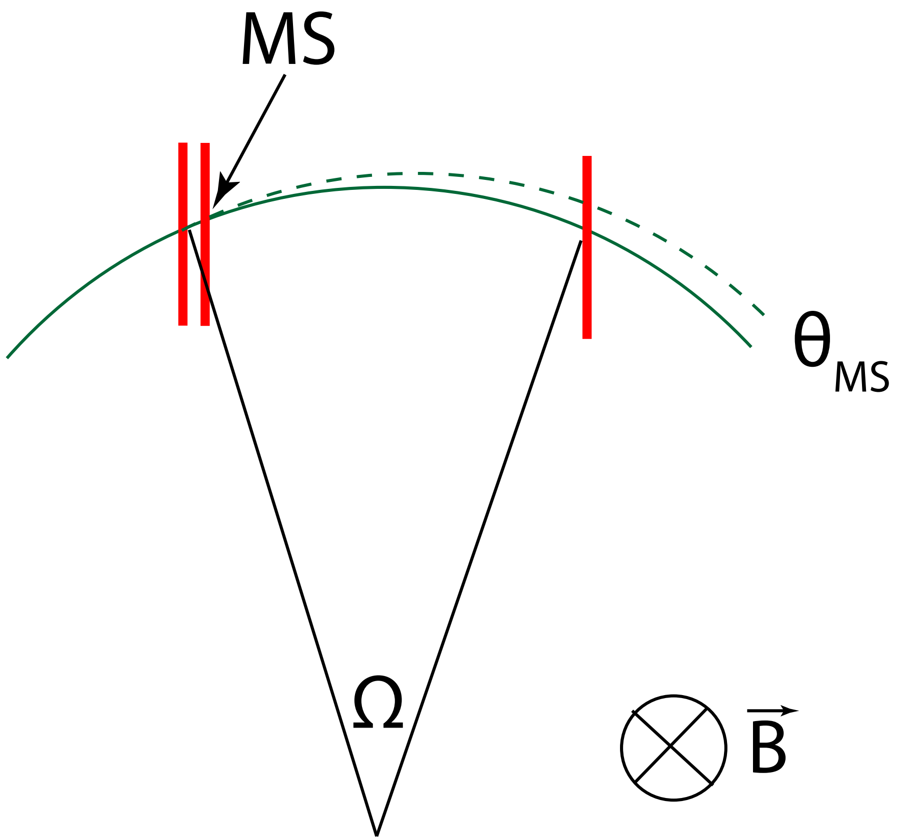
(I.Peric, P. Fischer et al., NIM A 582 (2007) 876
(ZITI Mannheim, Uni Heidelberg))

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 on chip
- Power: 150 mW/cm^2
- Data output up to 3.2 Gbit/s
- Time stamps every 50 ns
  (20 MHz clock for low power consumption, gas cooling)



Momentum measurement



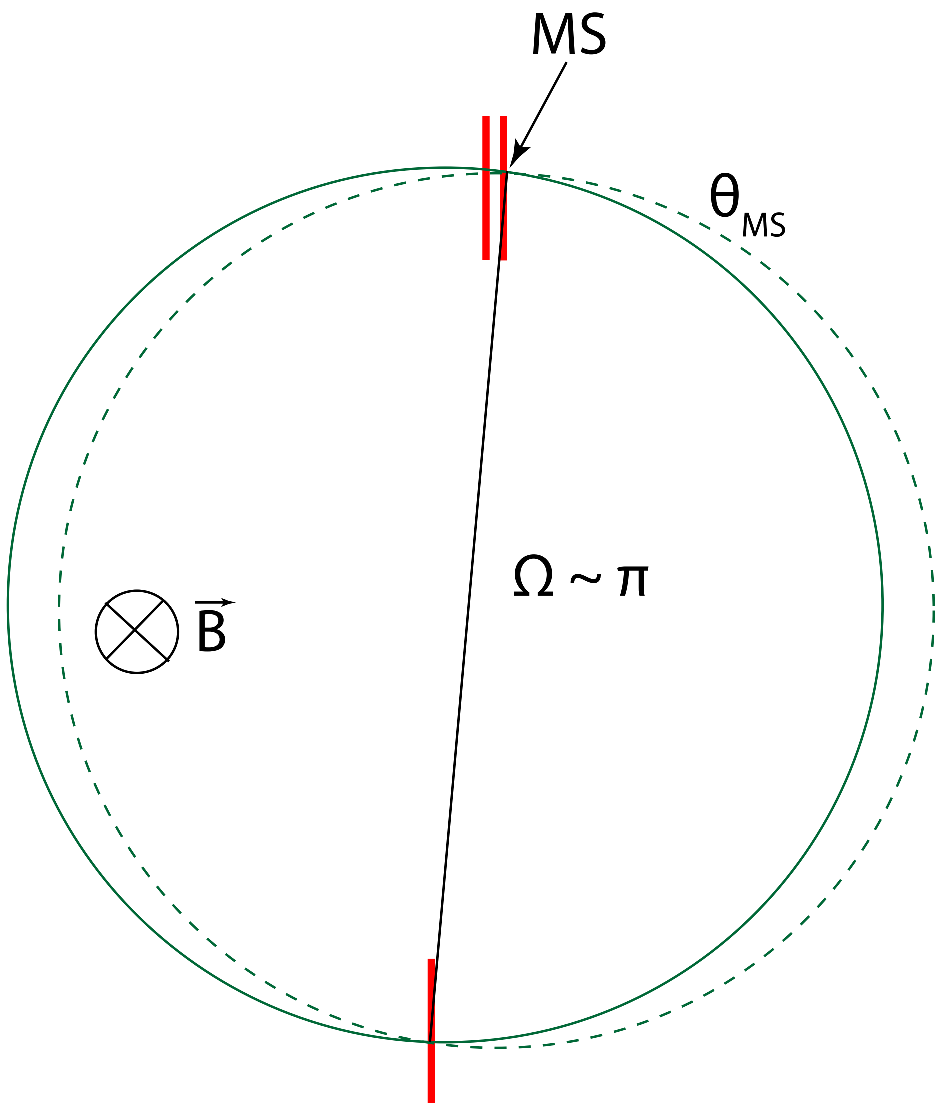
Momentum resolution given by (linearised):

$$\sigma_P/P \sim \theta_{MS}/\Omega$$

- Precision requires large lever arm (large bending angle Ω)

Momentum measurement

Momentum resolution for half turns given by

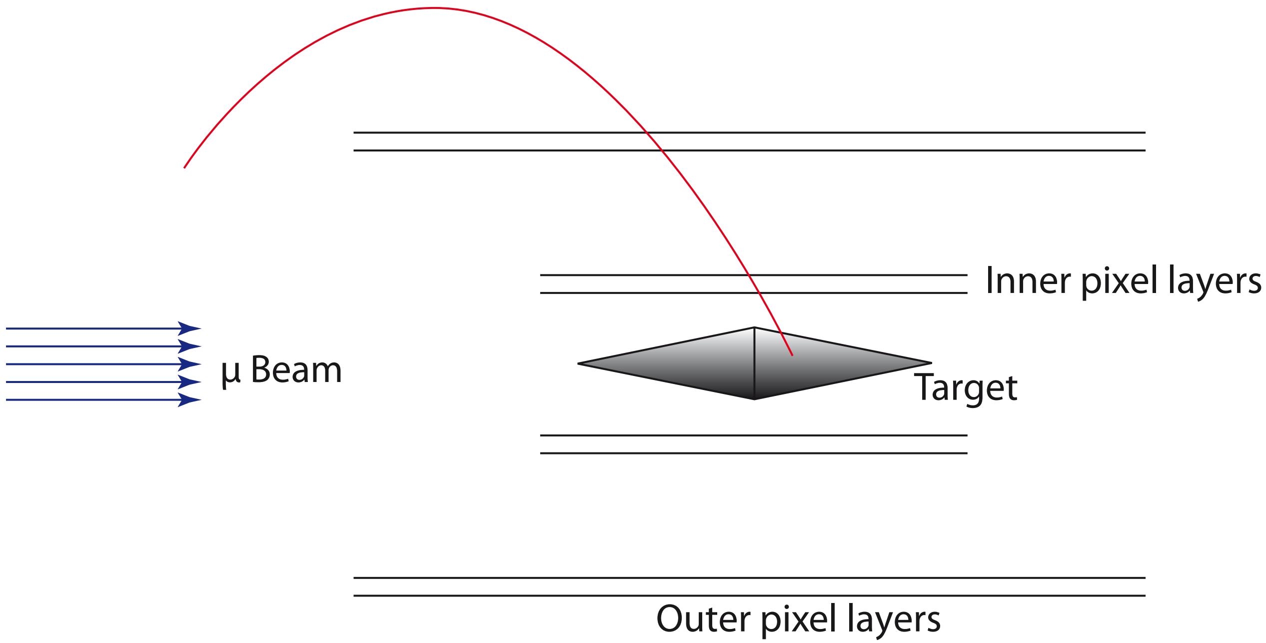


$$\sigma_P / P \sim O(\theta^2_{MS})$$

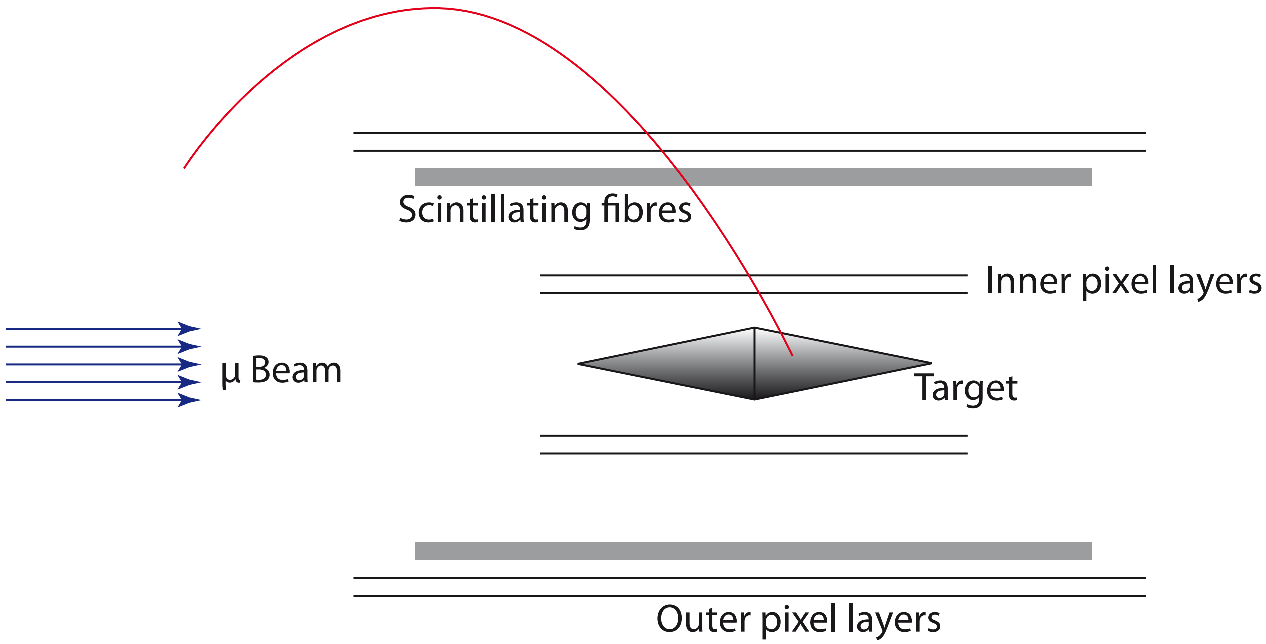
- Best precision for half turns
- Design tracker to measure recurlers

Detector concept

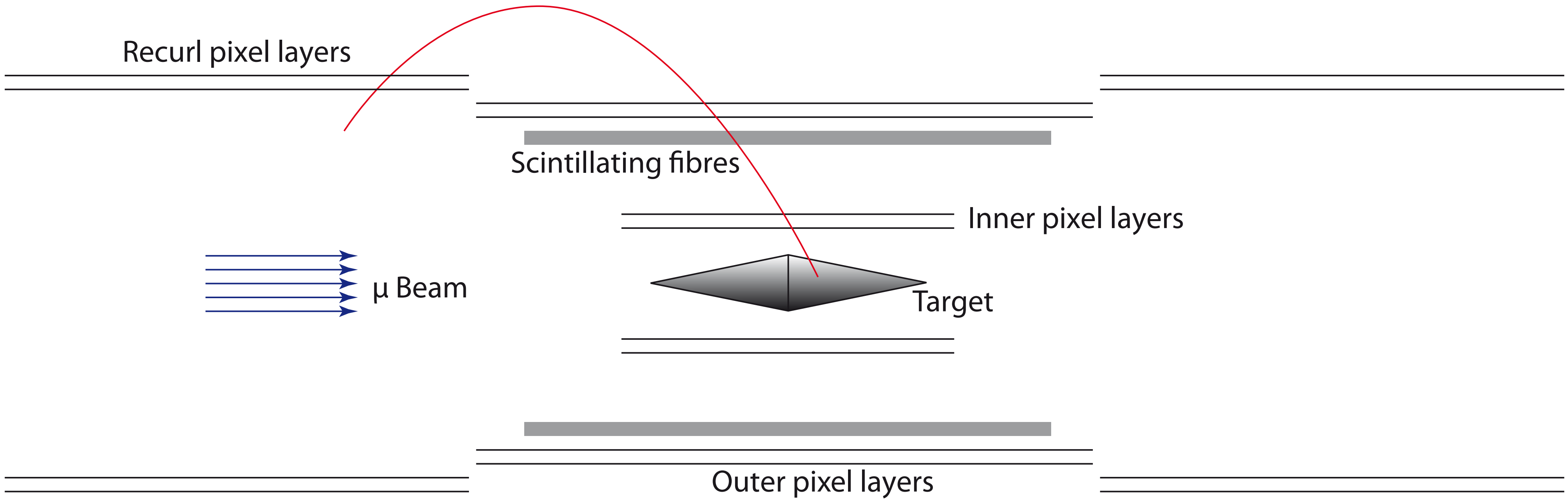
Detector concept



Detector concept



Detector concept



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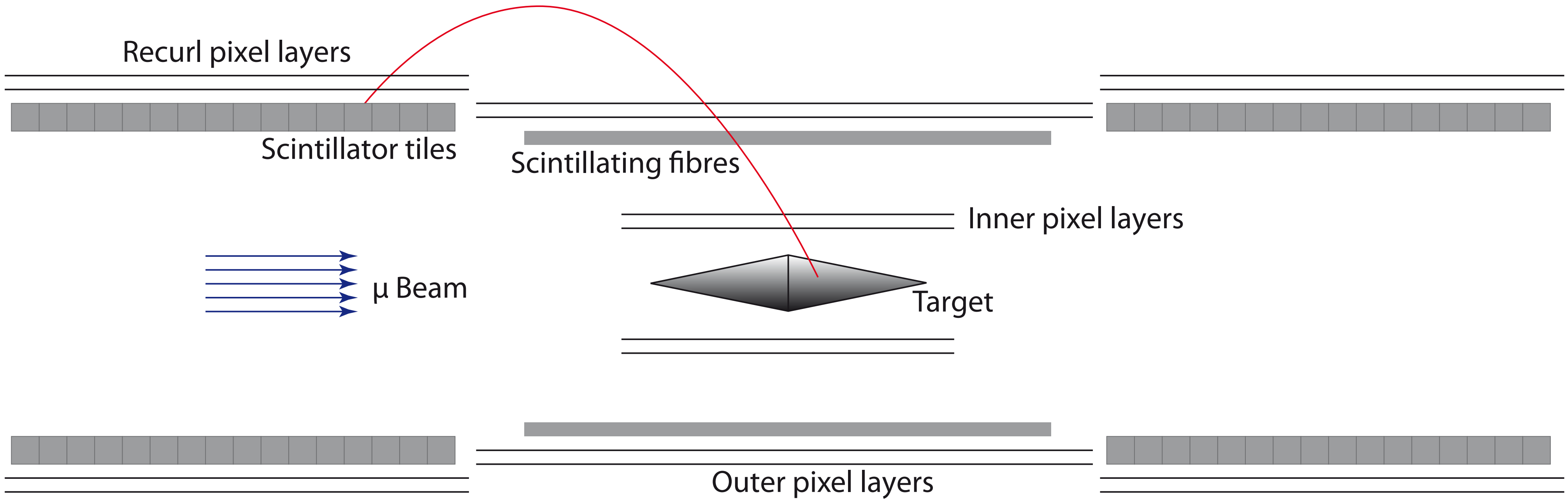
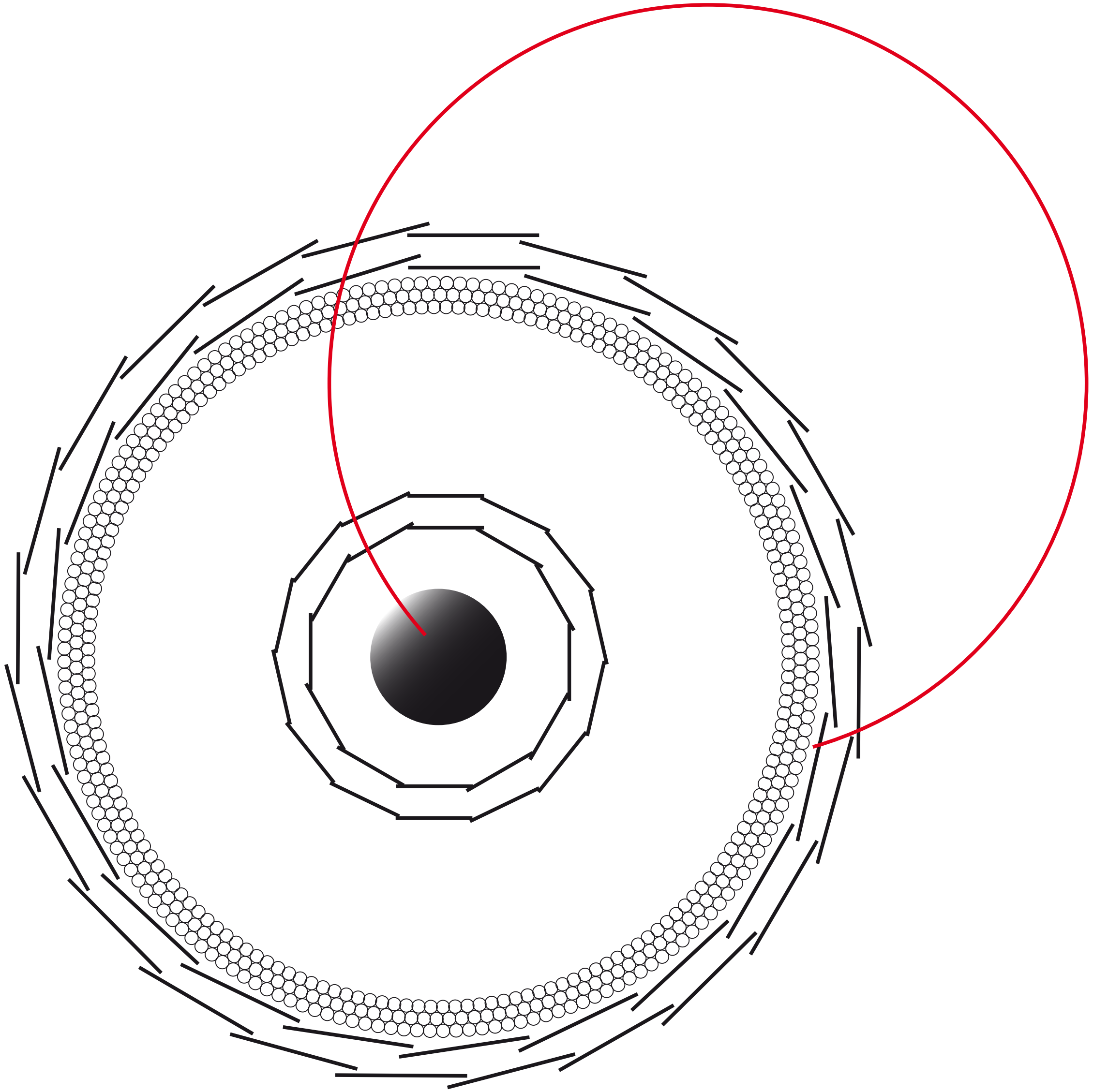


Detector Concept

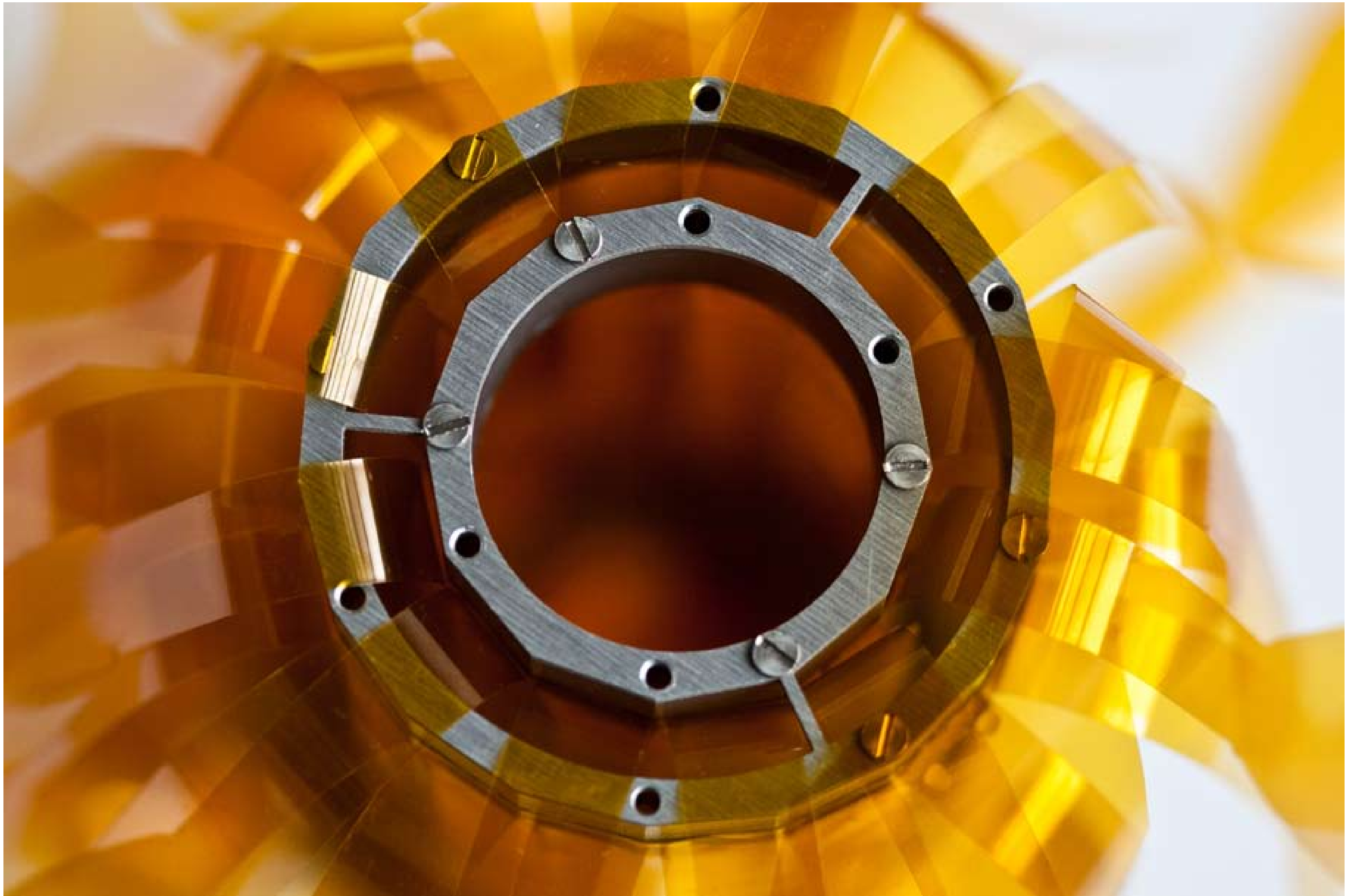


Mechanics

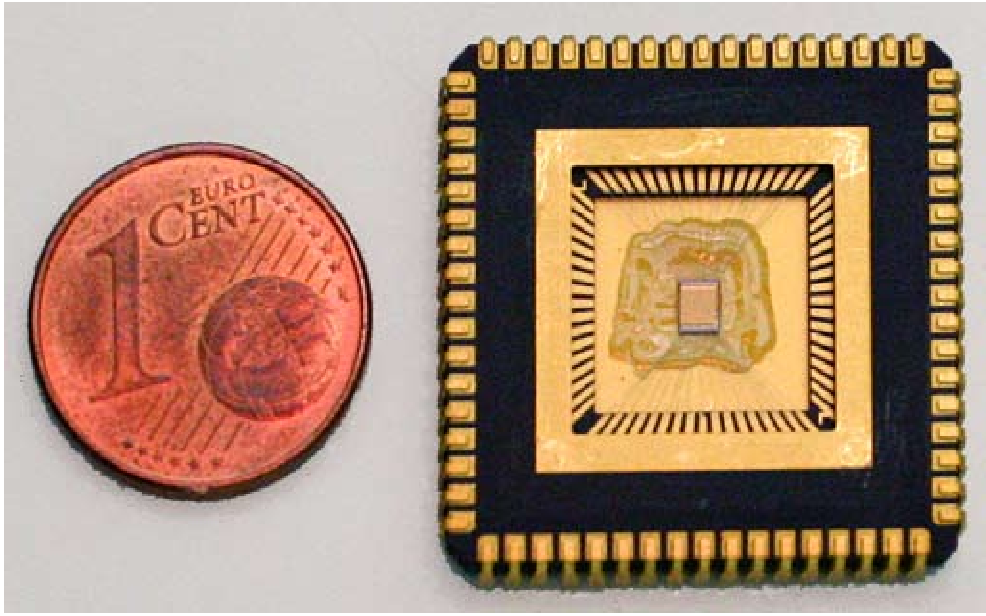
- 50 µm silicon is not self-supporting...
- Use 25 µm Kapton flexprints for support and connection
- Very light and surprisingly sturdy

Mechanics

Mechanics

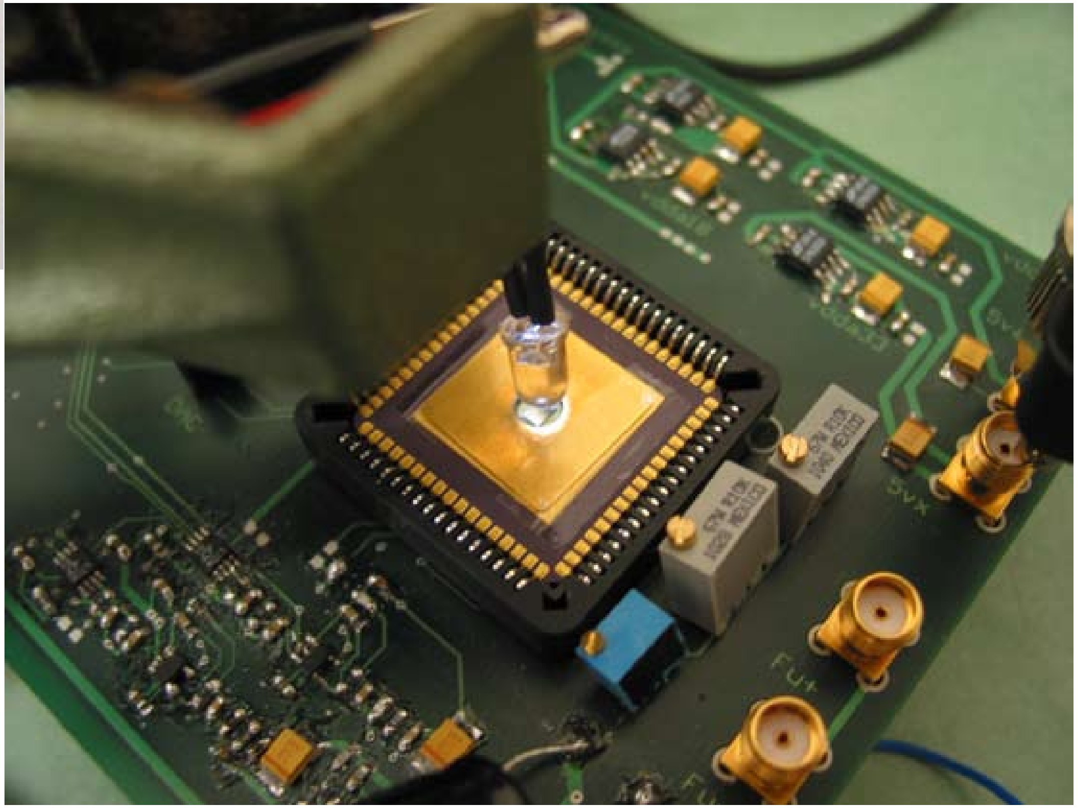


Sensor prototype

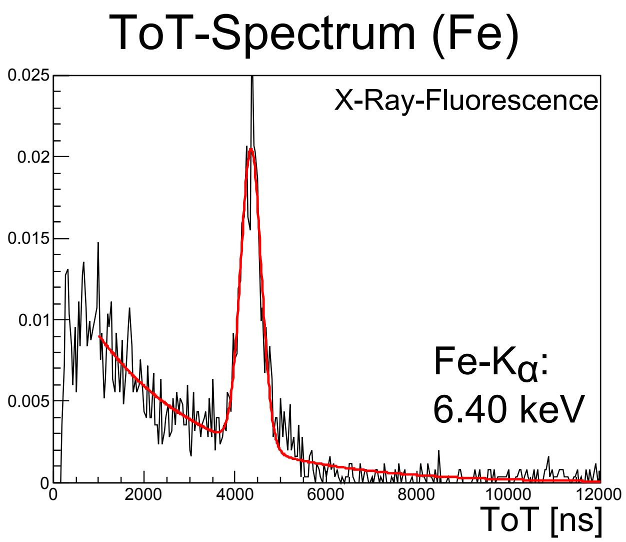


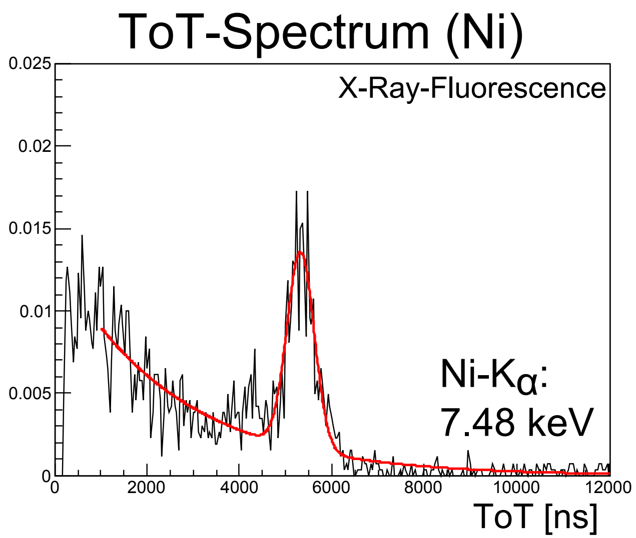
University of Heidelberg/ZITI Mannheim

- Prototype in IBM 180 nm process under test



Sensor tests

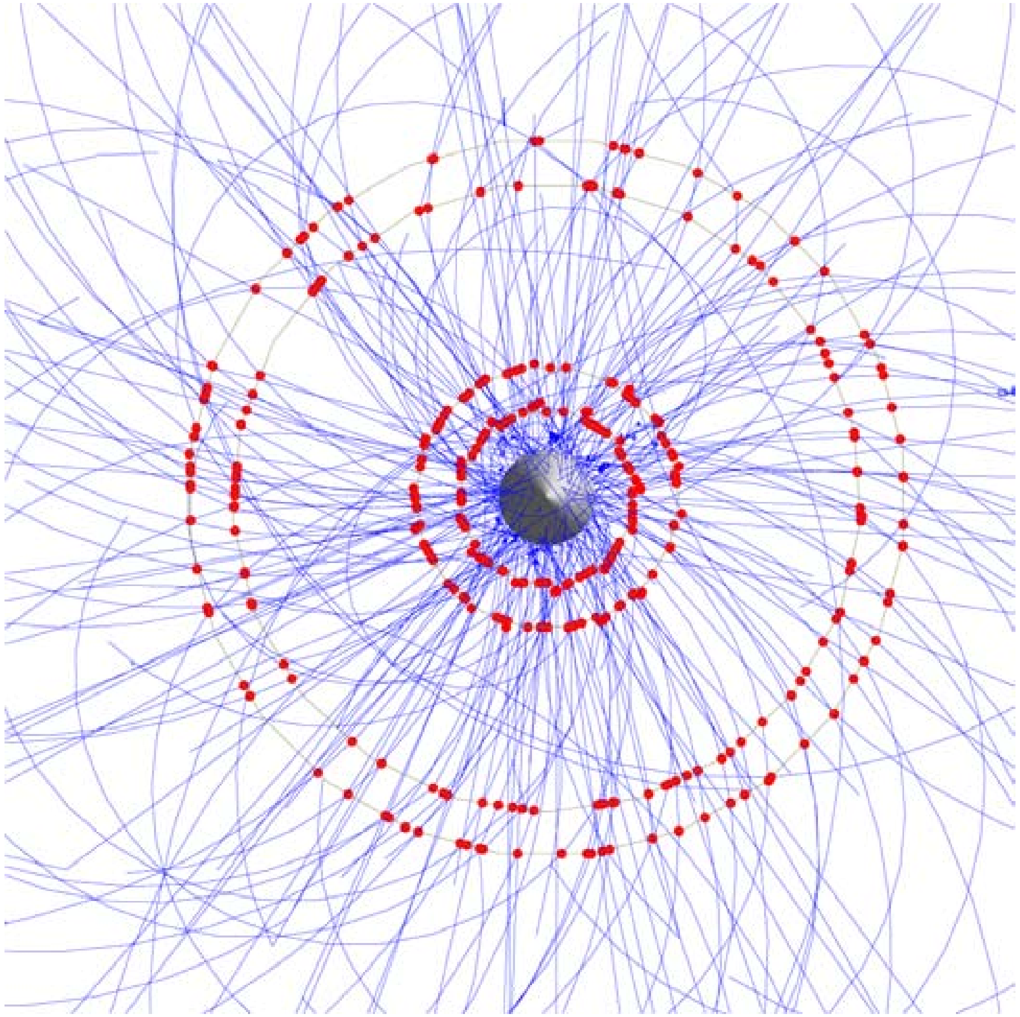




Prototype sensors perform well

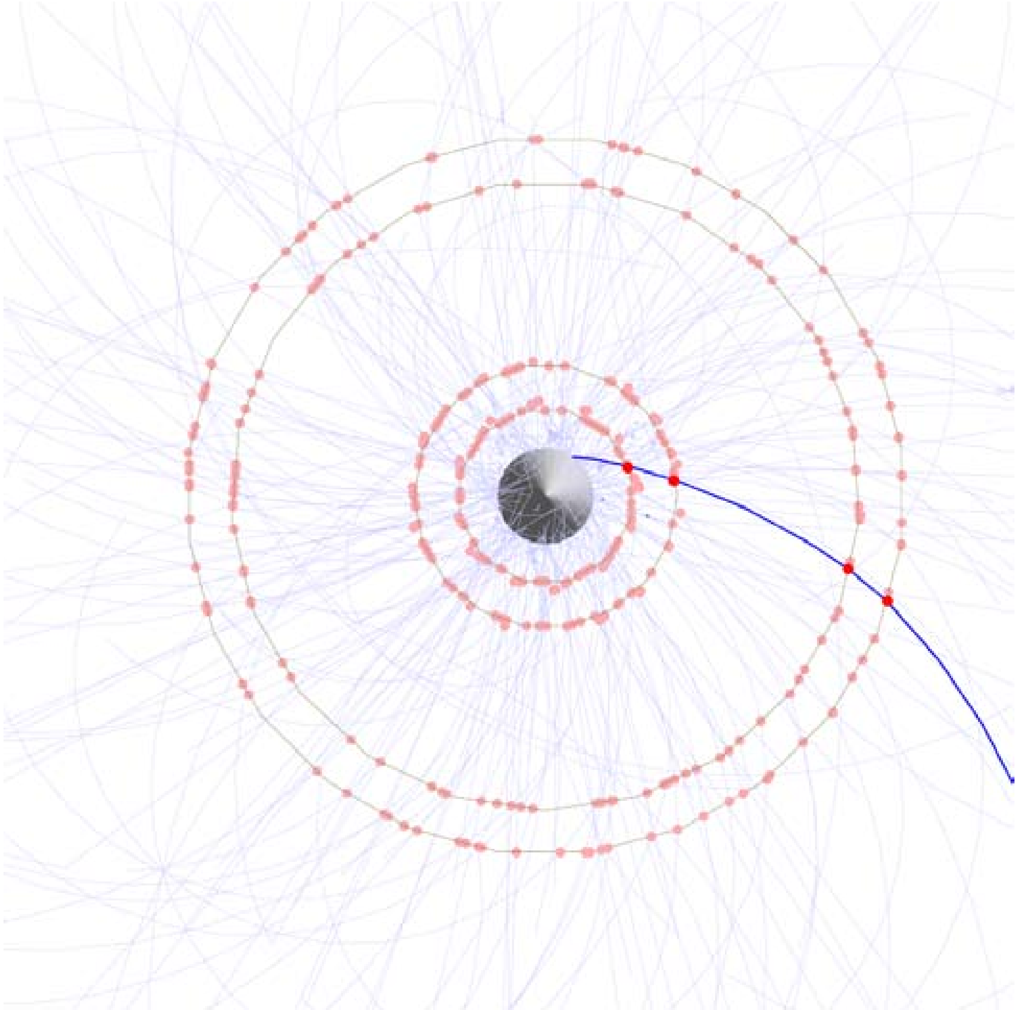
- Signal/Noise > 40
- Nice time-over-threshold spectra (X-ray fluorescence)

Timing



- The silicon detector is read out with 20 MHz (power consumption)
- Hundred electron tracks in one frame
- Can be resolved by hodoscope
- Scintillating fibres in central part ~ 1 ns
- Scintillating tiles in extensions ~ 100 ps
- Resolution ~ 100 ps - on average one electron

Timing



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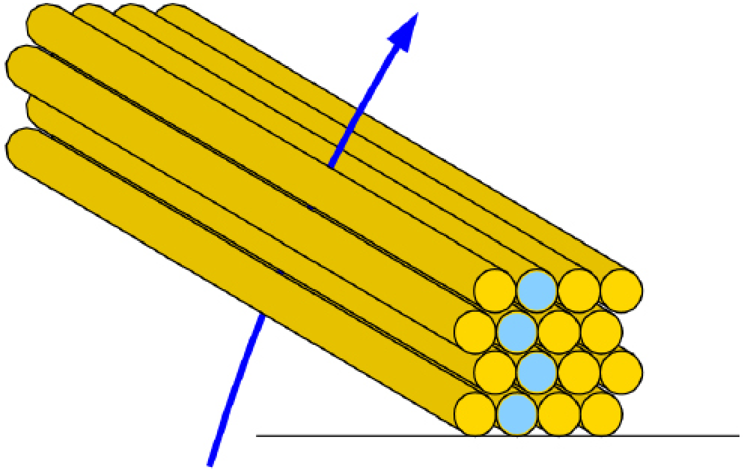
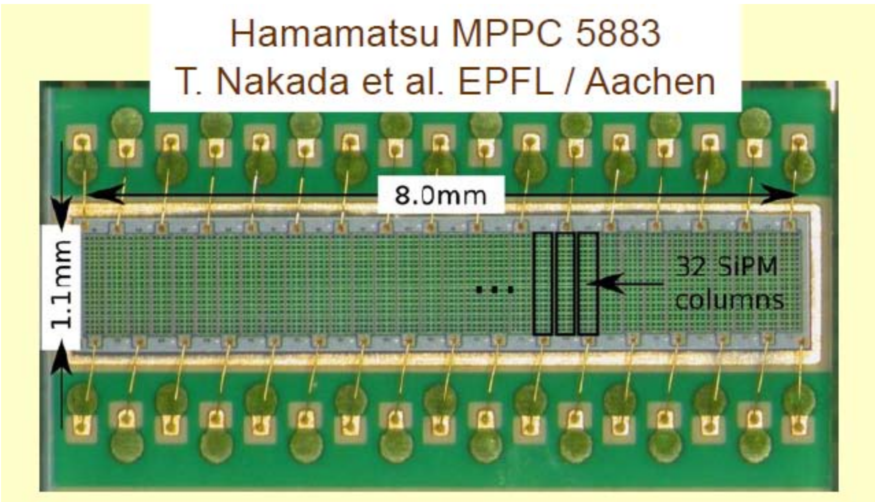
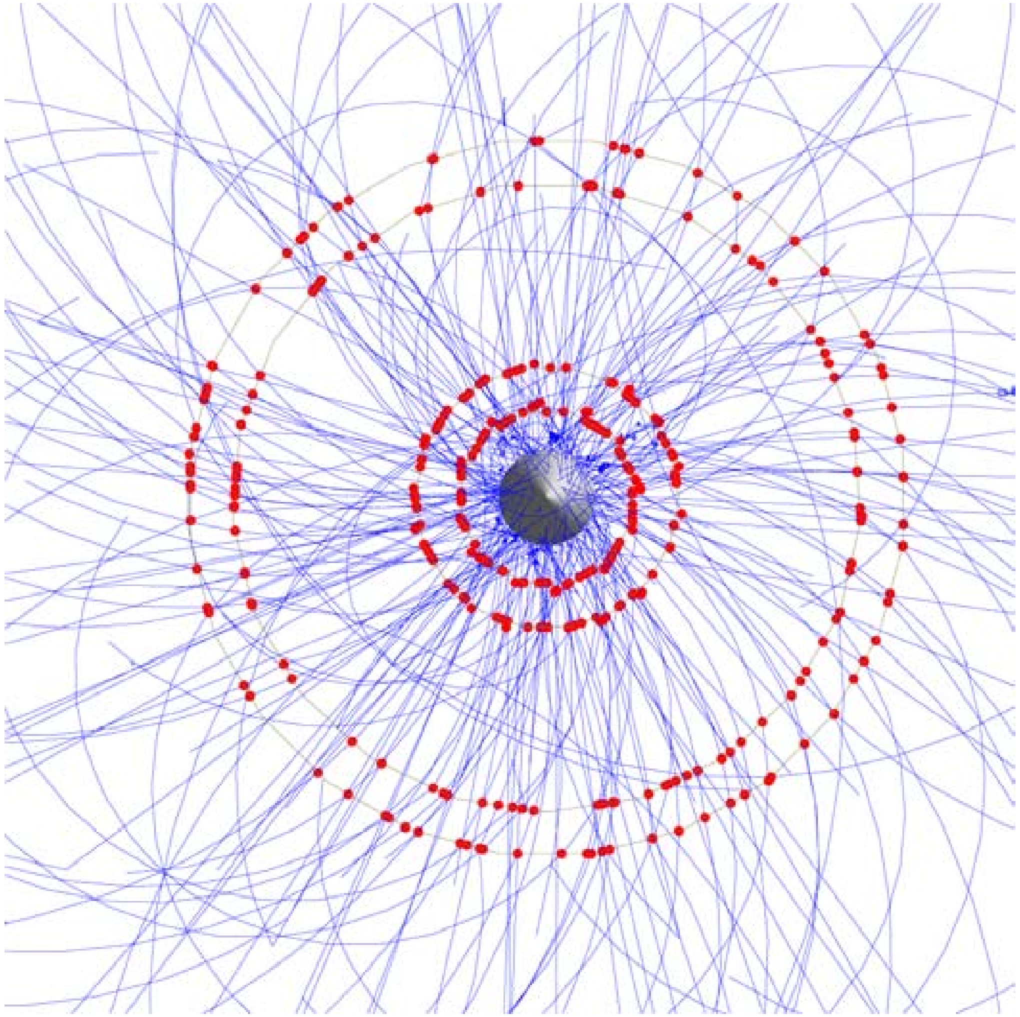
Scintillating fibres





- High spatial resolution for matching with pixels
- 200-250 μm fibres
- Photosensor: SiPM array;
  high gain, high frequency
- Readout via switched capacitor array
  (PSI developed DRS5 chip)

Data acquisition



Pixel detector:

- 250 million (zero suppressed) channels
- ~ 2000 hits per 50 ns frame

Fibre tracker:

- ~ 10'000 (zero suppressed) channels

For a muon stop rate of 2×10^9/s:

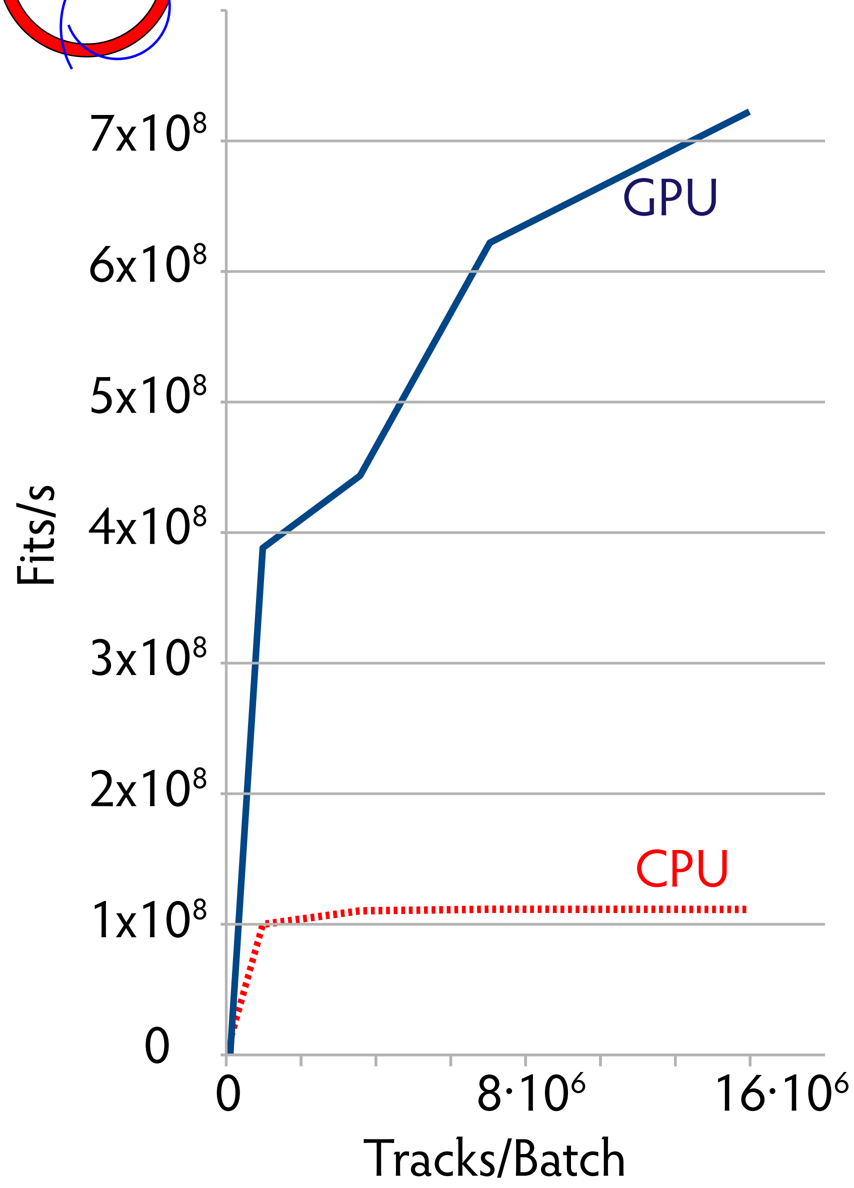
- Data rate ~ 150 Gbyte/s

Online filter farm

Online software filter farm

- Continuous front-end readout (no trigger)
- FPGAs and Graphics Processing Units (GPUs)
- Online track and event reconstruction
- Data reduction by factor ~1000
- Data to tape < 100 Mbyte/s

Starting simple: GPU circle fits



- Send data to GPU - process - return results (double buffered)
- Fit circle to four points
- Using non-iterative algorithm by V. Karimäki (~400 FLOPS/ 32 bytes input)
- OpenCL implementation on AMD Radeon HD 7990 (3 GB) on an AMD FX 8150 system
- Factor 7 faster than 8 core CPU

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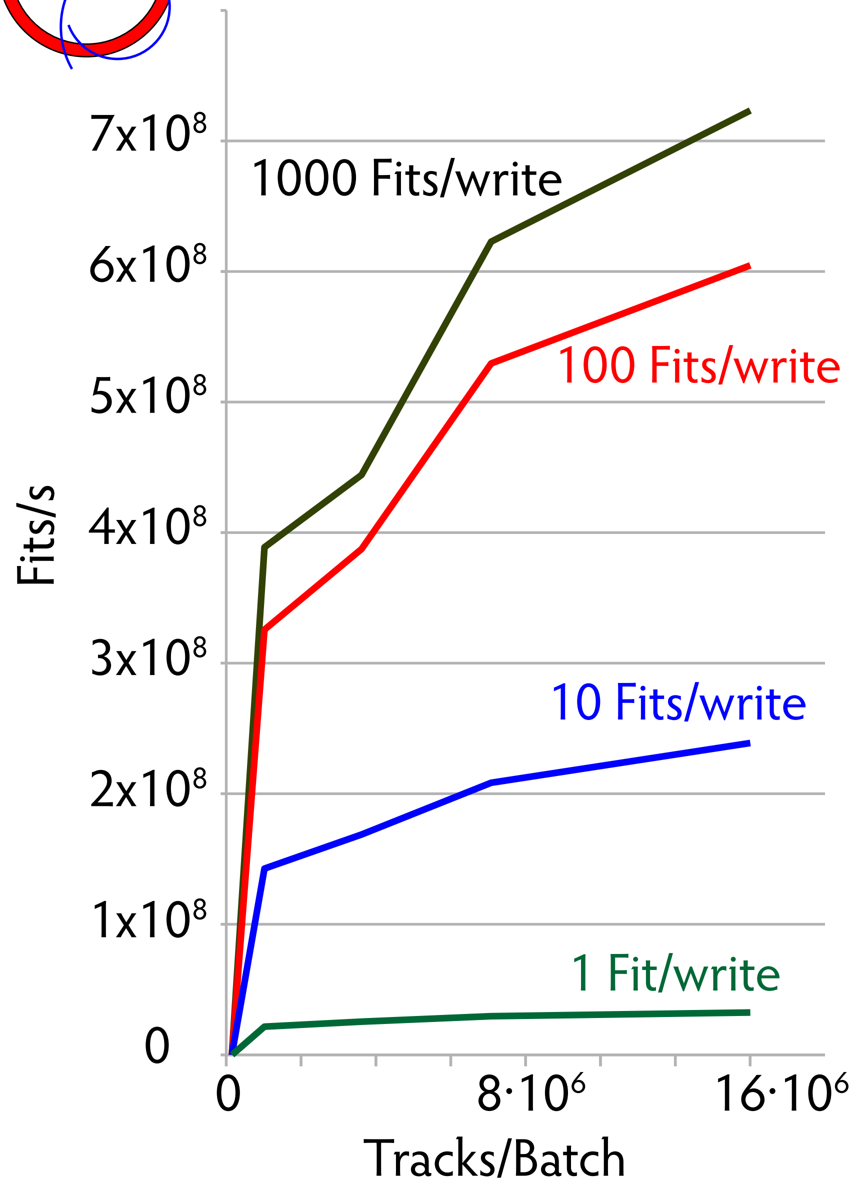

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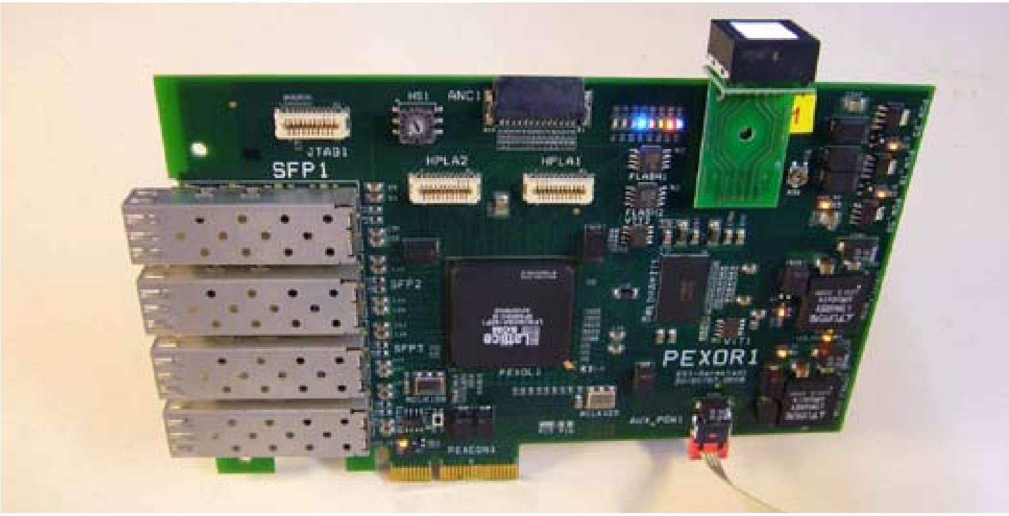
- Factor 7 faster than 8 core CPU
- Needs lots of data
- Limited by PCI bus

Onwards...

Technical challenge: Getting data into and out of GPU fast enough

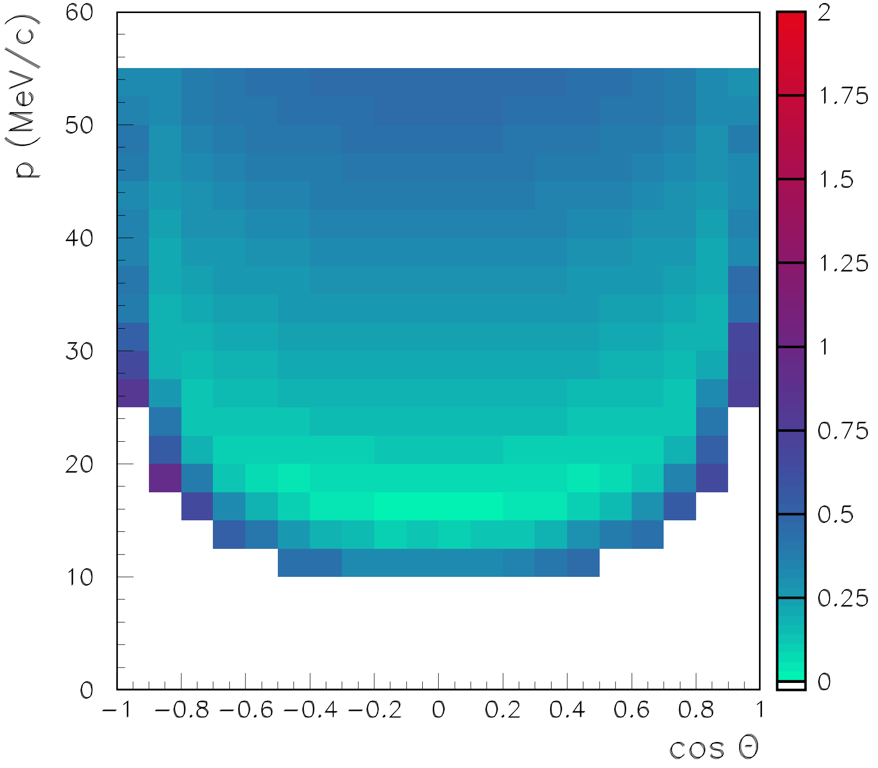
- PCIe 3.0
- PCI cards with optical links will do DMA to GPU memory (PANDA development)



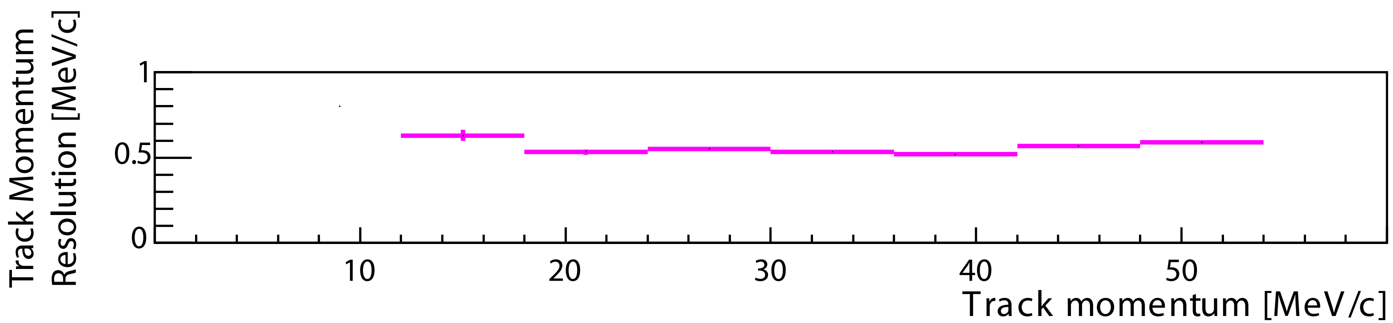
M. Turany et al., GSI/Giessen University

Floating point power sufficient to fit $O(10^{10})$ tracks on O(50) devices

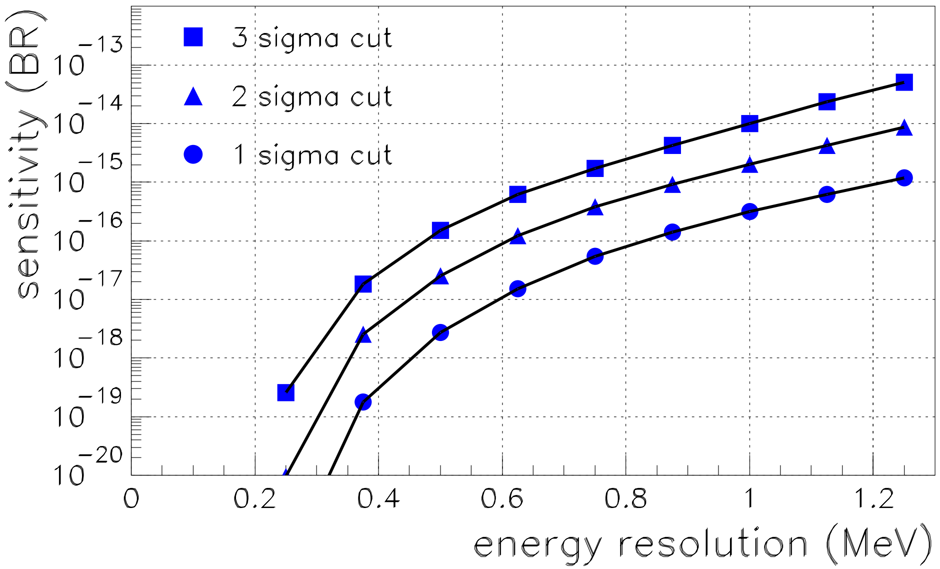
Performance



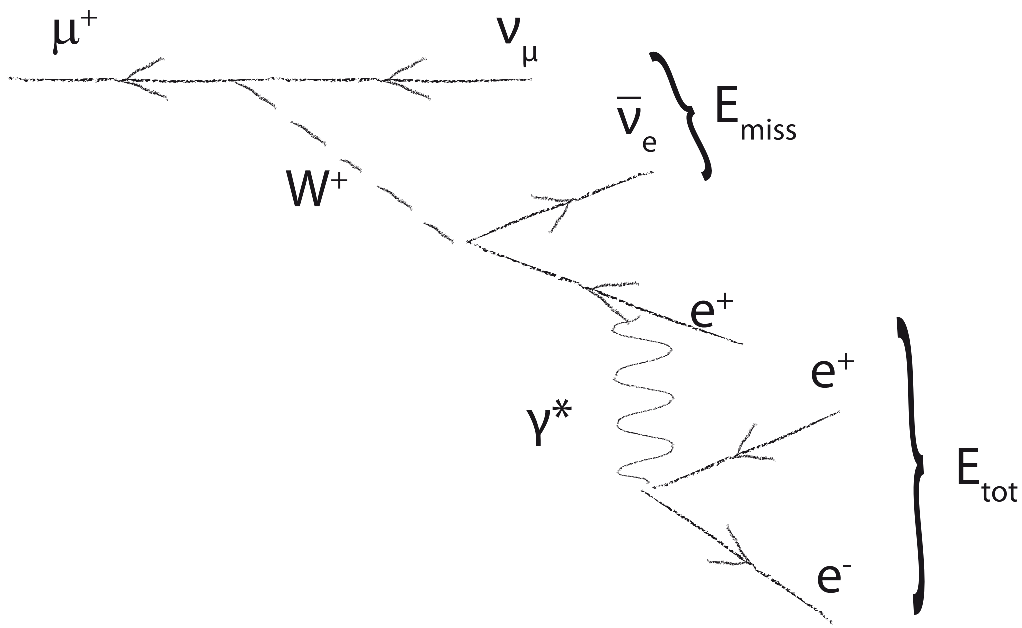
- Use both analytical estimates and a full Geant4 simulation
- Momentum resolution below 0.5 MeV/c achievable over large phase space
- Fully 3D track fit in preparation
- Track finding with 100 tracks/frame interesting challenge
- Geometrical acceptance ~70%



Performance: background rejection



- Suppressing accidental background fairly straightforward
- Internal conversion background is limiting
- Sensitivity down to 10^{-16} achievable with < 0.5 MeV/c momentum resolution



Collaboration

UNIVERSITÉ DE GENÈVE

PAUL SCHERRER INSTITUT

PSI

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

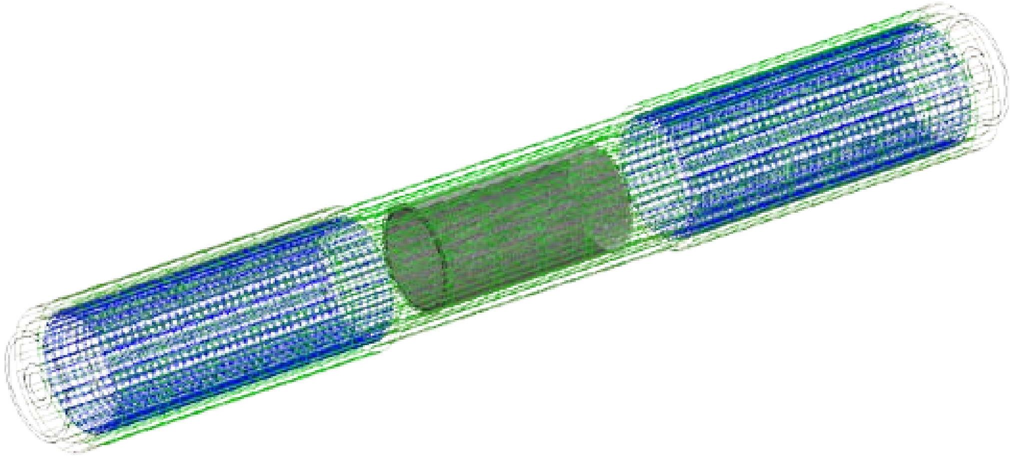
A proto-collaboration has formed and submitted a letter of intent to PSI

- University of Geneva
- University of Heidelberg
- Paul Scherrer Institut (PSI)
- University of Zurich
- ETH Zurich

Also in contact with other interested groups

Goal: Detailed Research Proposal by 2013

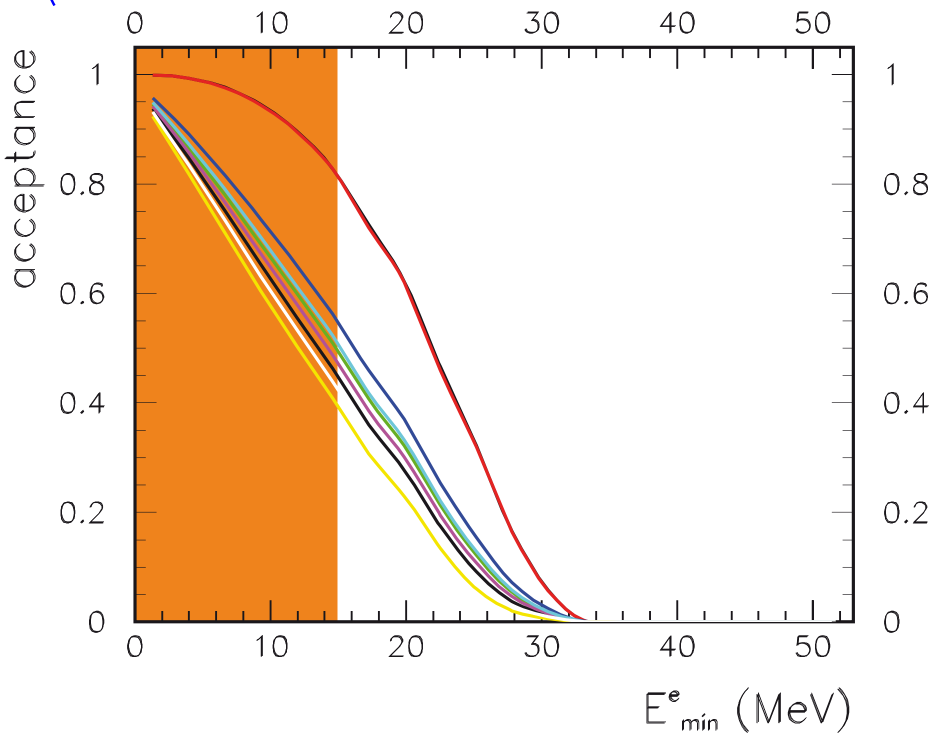
Summary



- 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} feasible
- After more than 20 years, time has come to go beyond the very successful SINDRUM experiment

Backup Material

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

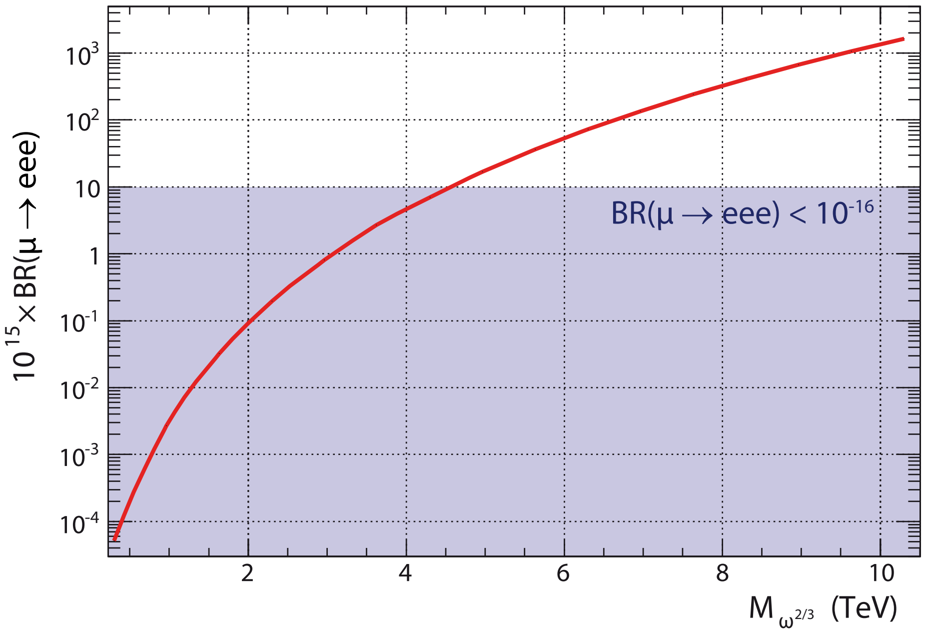
$$
\begin{aligned}
L_{\mu \rightarrow eee} = 2 G_F \big(& m_\mu A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} && + m_\mu A_L \bar{\mu}_L \sigma^{\mu\nu} e_R F_{\mu\nu} \\
& + g_1 (\bar{\mu}_R e_L)(\bar{e}_R e_L) && + g_2 (\bar{\mu}_L e_R)(\bar{e}_L e_R) \\
& + g_3 (\bar{\mu}_R \gamma^\mu e_R)(\bar{e}_R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

LFV with Leptoquarks

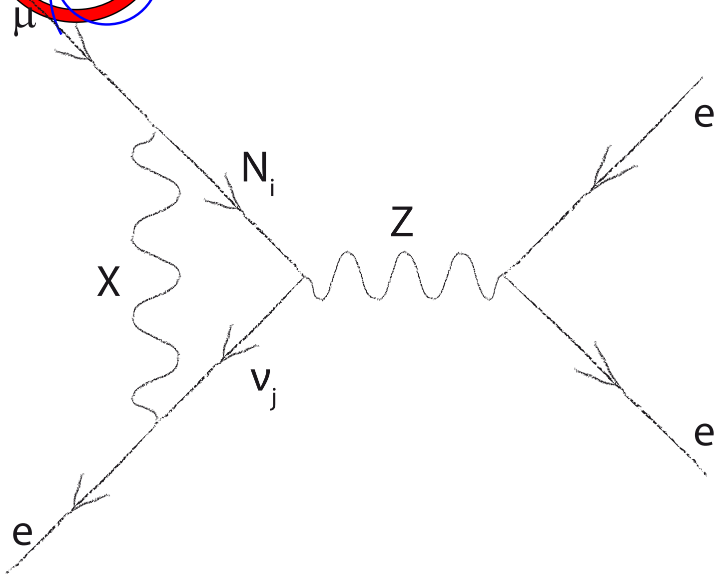
- Can derive $\mu \rightarrow eee$ branching ratio from fitting neutrino masses and constraints from $\mu \rightarrow e$ conversion on nuclei

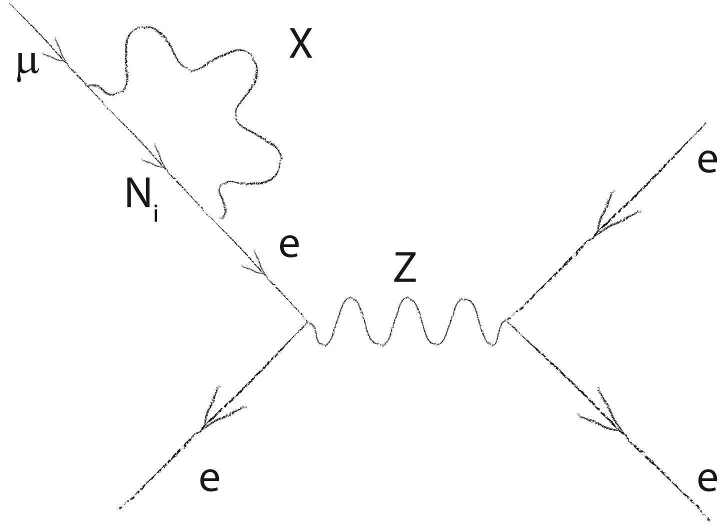
(K.S. Babu and J. Julio, Nucl.Phys. B841 (2010) 130)

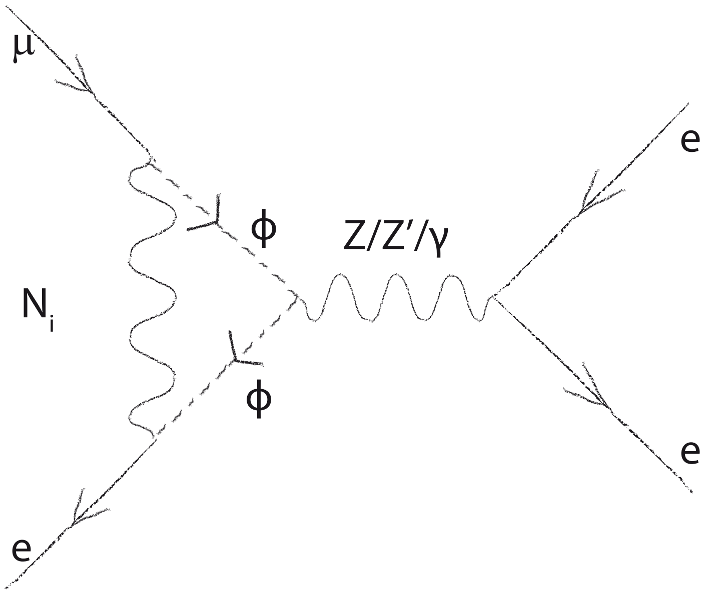
- Sensitive to multi-TeV leptoquarks

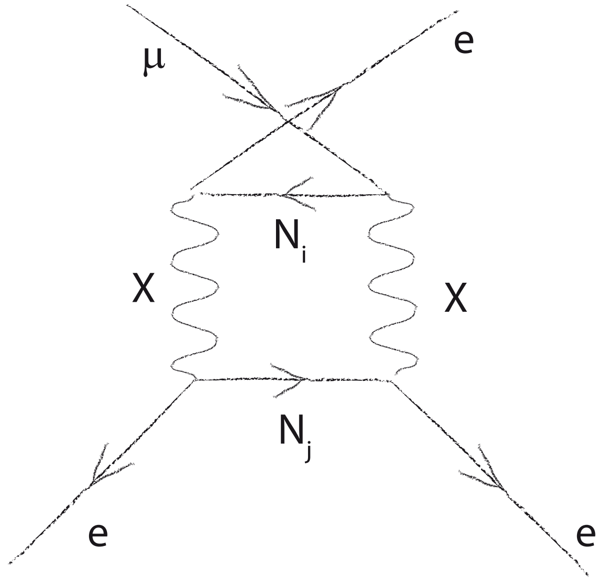


LFV in Little Higgs Models

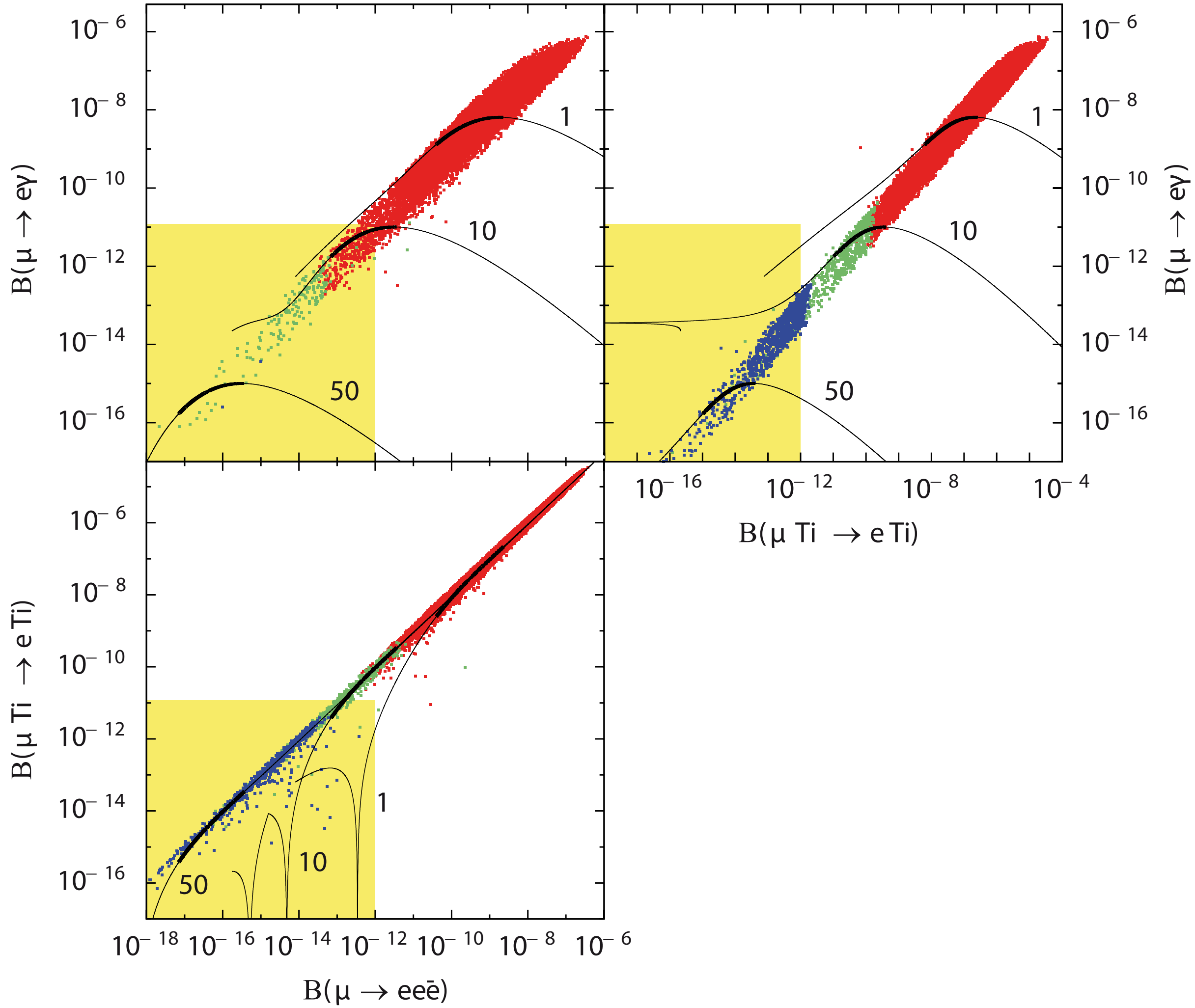








LFV in Little Higgs Models



- 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)