Search for μ->e conversion on Titanium with SINDRUM II Detector

Vasily Dzhordzhadze

For SINDRUM II Collaboration

Advances in Lepton Flavor Violation Searches

A3 Workshop at BNL, May 14, 2005

Search for $\mu^- \to e^-$ Conversion on Titanium

S. Eggli, R. Engfer, Ch. Findeisen, E.A. Hermes, T. Kozlowski[*], F. Muheim[†],
C.B. Niebuhr[‡], H.S. Pruys, M. Rutsche, and A. van der Schaaf

Physik-Institut der Universität Zürich, CH-8057 Zürich, Switzerland

W. Bertl, J. Egger, and B. Krause[‡]

Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

J. Hofmann, and S. Playfer[†]

Institut für Teilchenphysik der ETH Zürich, CH-5232 Villigen PSI, Switzerland

V. Djordjadze[¶‖]

High Energy Physics Institute of the Tbilisi State University, 380086 Tbilisi, Georgia

C. Dohmen, W. Honecker, J. Kaulard, G. Otter, A. Schüngel, S. Starlinger, and P. Wintz[‖]

III. Physikalisches Institut B der RWTH Aachen, D-52056 Aachen, Germany

(SINDRUM II Collaboration)

Outline

- Motivation
- Experimental Principle
- Beam and Target
- SINDRUM II spectrometer
- Data taking, analysis and results
- Summary

Limitation of the Standard Model

- Quark and lepton family replication is not explained
- Gravitation is not included
- Dark matter is not understood
- Large number of free parameters – 17 masses (9), mixing angles (4), coupling constants (4)
- Mass origin ?
- Higgs is not discovered yet
- Neutrinos are massless

Test of LFC

- LFC is experimental fact but no symmetry associated with it
- Neutrinos are not massless
- Many models (GUT, LRSM, Technicolor, Composite models, SUSY) predict LFV and include SM as low energy approximation
- Search for LFV – Serch for Physics beyond the SM (BSM)

Upper limits on BR of LFV processes with muons

$\mu^+ \to e^+ \gamma$	1.2×10^{-11}	MEGA
$\mu^+ \to e^+ e^+ e^-$	1.0×10^{-12}	SINDRUM
$\mu^+ e^- \leftrightarrow \mu^- e^+$	8.3×10^{-11}	SINDRUM
$\mu^- Ti \to e^- Ti$	6.1×10^{-13}	SINDRUM
$\mu^- Ti \to e^- Ca^*$	3.6×10^{-11}	SINDRUM
$\mu^- Pb \to e^- Pb$	4.6×10^{-11}	SINDRUM
$\mu^- Au \to e^- Au$	1.9×10^{-11}	SINDRUM

Upper limits on BR of particle decay modes that do not conserve Lepton Flavor

$\tau \to e\gamma$	2.7×10^{-6}	CLEO	$\tau \to 3\mu$	1.9×10^{-6}	CLEO
$\tau \to \mu\gamma$	1.1×10^{-6}	CLEO	1.0×10^{-6} BELLE	$2..0\times10^{-6}$	BaBar
$\tau \to 2\mu e$	2.7×10^{-6}	CLEO	$\tau \to \mu 2e$	1.5×10^{-6}	CLEO
$\tau \to 3e$	2.9×10^{-6}	CLEO	$Z^0 \to \mu e$	1.7×10^{-4}	
$K^+ \to \pi^+ \mu e$	2.8×10^{-11}	BNL	$K^0_L \to \mu e$	4.7×10^{-12}	BNL
$K^0_L \to \pi^0 \mu e$	4.4×10^{-10}	Fermi	$B^0 \to \mu e$	1.2×10^{-7}	BaBar
$B^0 \to \tau e$	5.3×10^{-4}	CLEO	$B^0 \to \tau e$	8.3×10^{-4}	CLEO
$Z^0 \to \mu e$	1.7×10^{-6}	OPAL	$Z^0 \to \tau e$	9.8×10^{-6}	
$Z^0 \to \mu\tau$	1.2×10^{-5}				

Experimental Principle

- Low energy muons stopped in nuclear target, forming muonic atoms

Processes occurring with stopped

- Nuclear capture : $\mu^- (A,Z) \rightarrow \nu_\mu (A,Z-1)$
- Three body decay in orbit $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$
- Coherent LFV decay $\mu^- (A,Z) \rightarrow e^- (A,Z)$

Signal is a single mono-energetic electron

Experimental Principle, continued

Rate is normalized to the Nuclear capture rate

$R = \Gamma(\mu^- N \to e^- N)/\Gamma(\mu^- N \to \nu_\mu N')$

$f^{Ti}_{capt} = 85.3\ \%$ and μ^- lifetime in Ti = 329 ns

$E = m_\mu - B_\mu - R_{nucl} = m_\mu - 1.27 - 0.12 = 104.27$ MeV

Charge exchange conversion

$\mu^- (A,Z) \to e^+ (A,Z-2)$

$E = (m_\mu - 2m_e) - \Delta M - B_\mu - R_{nucl}$

Potential Background

- Beam related background may originate from muons, pions and electrons in the beam
- Muon decay in flight (MIF)
- Muon decay in orbit (MIO) Main source
- Radiative muon capture (RMC) $\gamma \to e^+e^-$ (10^{-4})
- Radiation pion capture (RPC) $\gamma \to e^+e^-$ (2%)
- Particle scattering of the target
- Cosmic ray background

Experimental Method

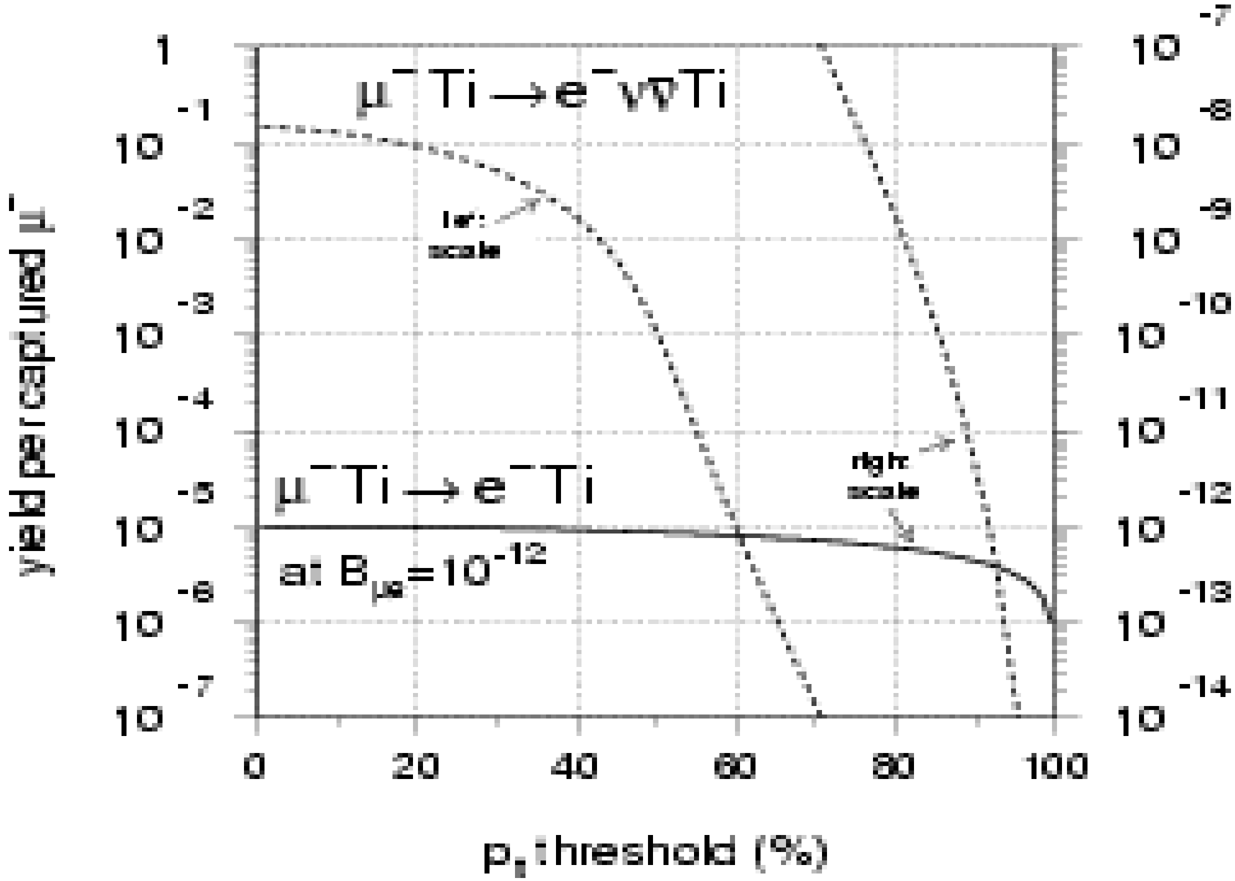


FIG. 1. Total e^- yield, both from bound muon decay and from $\mu \rightarrow e$ conversion assuming $B_{\mu e} = 10^{-12}$, as a function of the threshold on transverse momentum normalized to unity.

Intrinsic Background

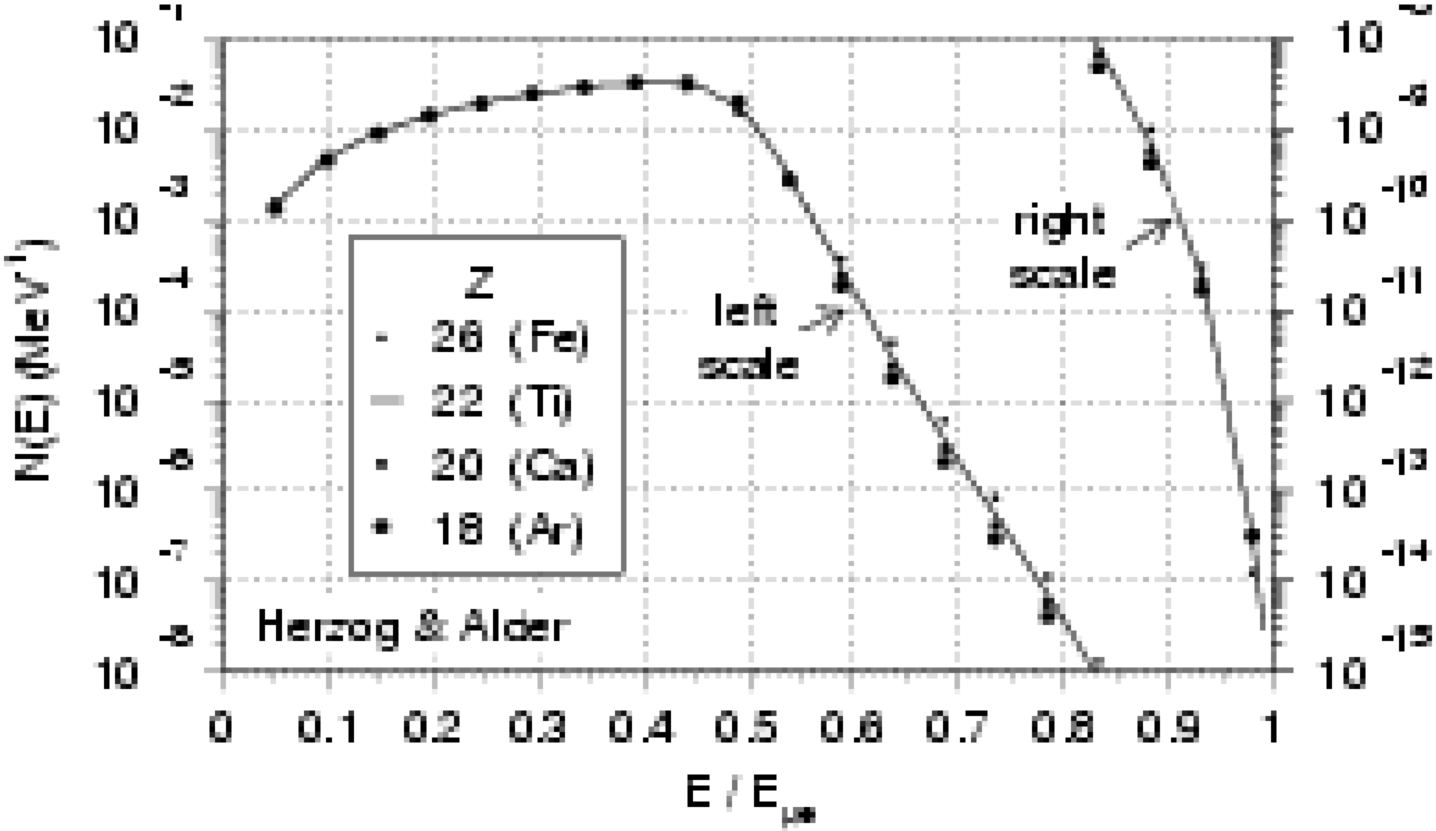


Figure 2. Normalized electron energy spectrum of bound-muon decay for the muonic atoms Ar, Ca, and Fe (from [26]). The spectrum of titanium resulted from these distributions by interpolation.

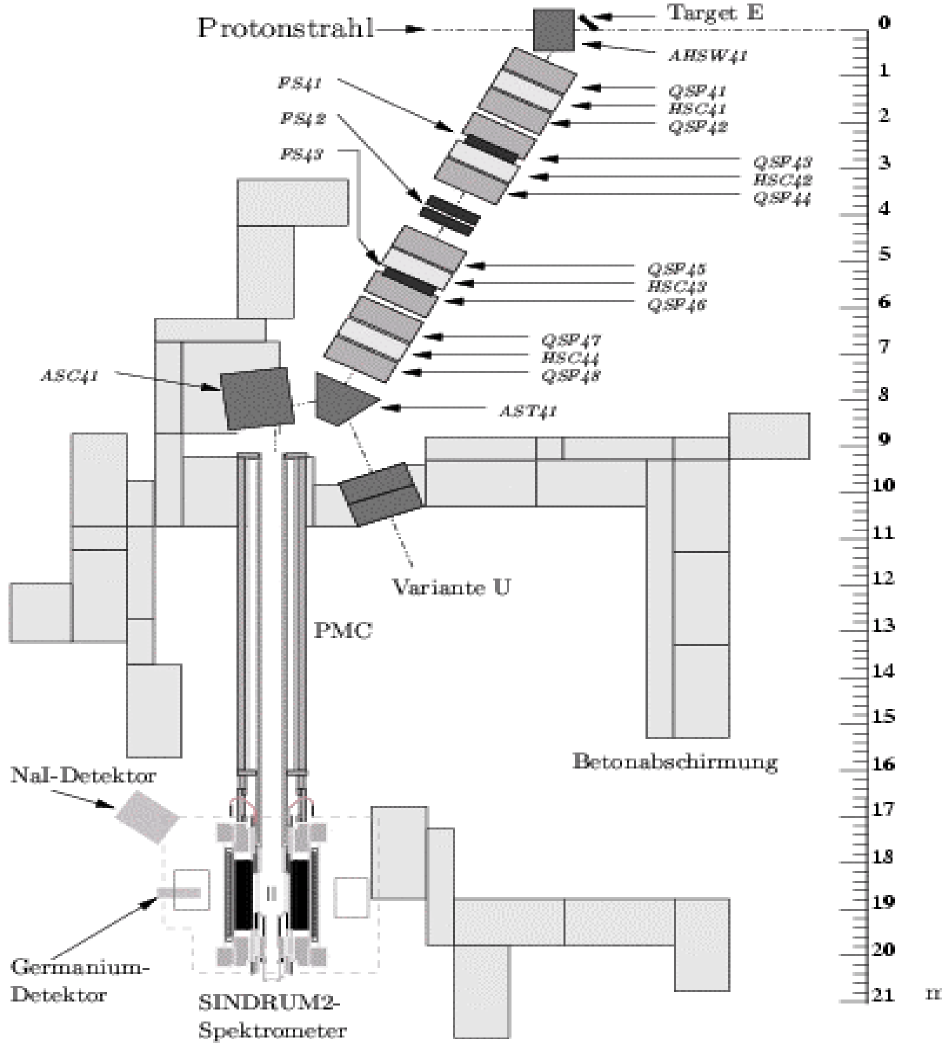
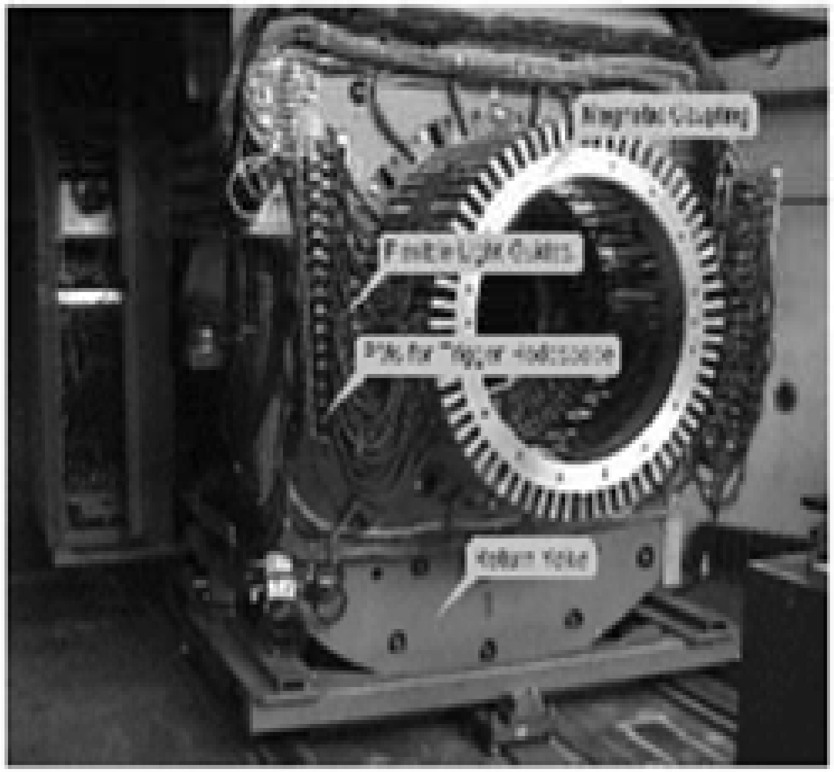


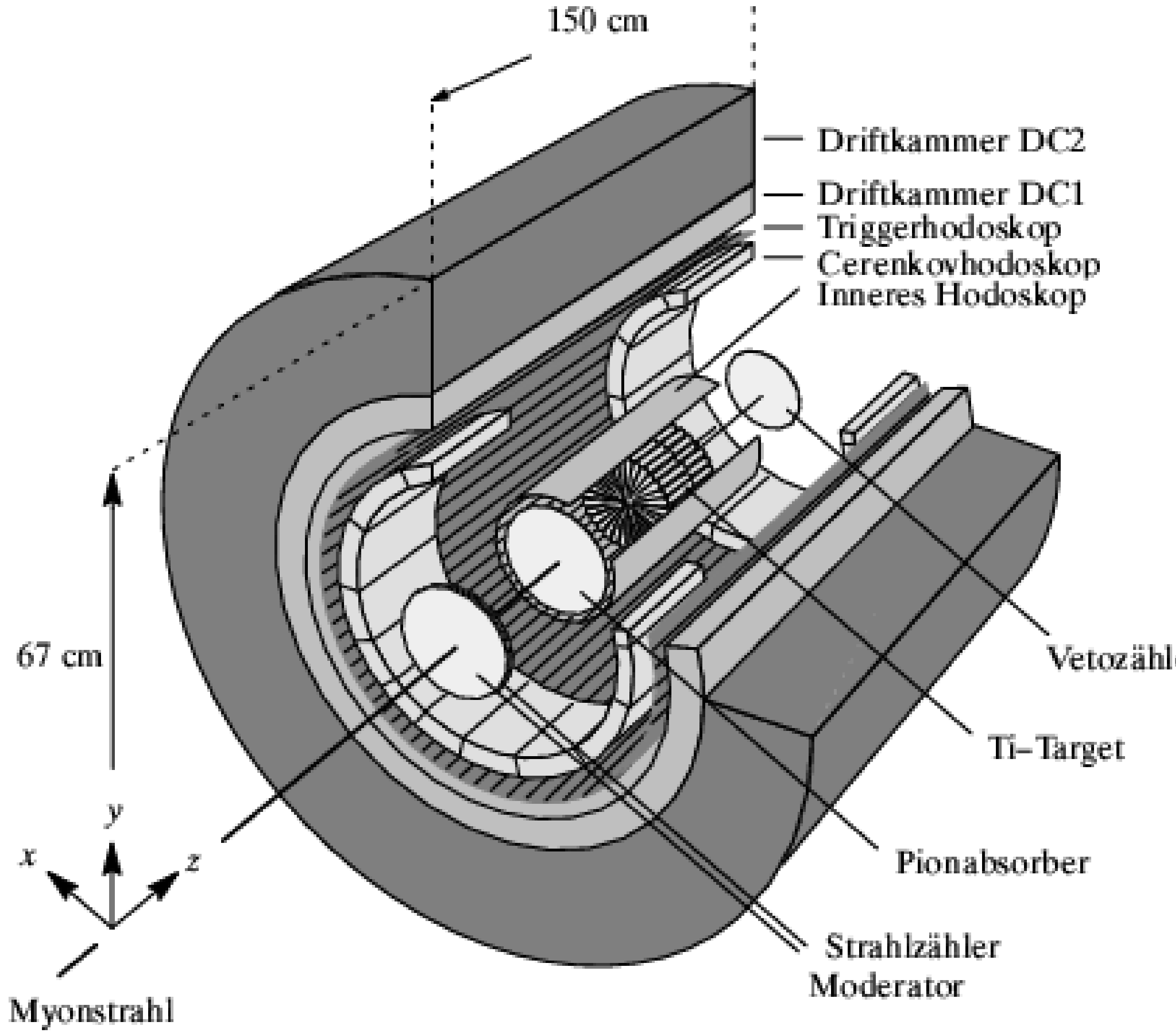
Abbildung 3.1: πE5-Strahlkanal mit SINDRUM2-Areal. Die Skizze zeigt der Aufsicht die Elemente der Strahlführung, den PMC und das SINDRUM Spektrometer. Dipolmagnete werden mit *A*..., Quadrupolmagnete mit *QSF*. und Sextupolmagnete mit *HSC*... bezeichnet. Die Spalte sind mit *FS*... geken zeichnet.

Beam Line

- Pions produced in a 6 cm long carbon target by 590 MeV proton beam are injected into an 8.3 meter long solenoidal magnet.
- Muons from $\pi^- \rightarrow \mu^-\nu$ decays inside solenoid backward in the cms, transported to the area
- Momentum varied by slits to a max. +/-5%
- Intensity rises with momentum and reaches 1.2×10^7 μ^-/s at the momentum of 88 MeV/c with a proton beam current of 0.5A.
- e^- and π^- contamination ~10% and $\sim3\times10^{-6}$

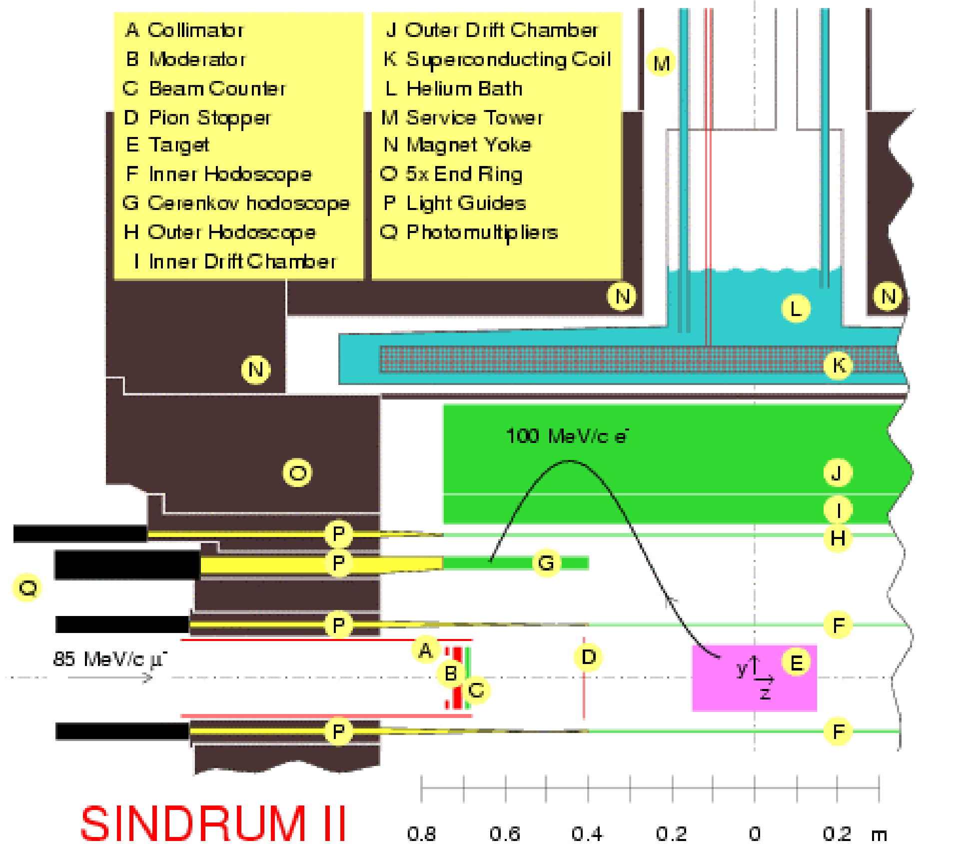
SINDRUM II: best present limit





150 cm
Driftkammer DC2
Driftkammer DC1
Triggerhodoskop
Cerenkovhodoskop
Inneres Hodoskop
67 cm
Vetozähl
Ti–Target
Pionabsorber
Strahlzähler
Moderator
Myonstrahl
y
x
z

SINDRUM II



Former setup
with beamcounter

SINDRUM II

Spectrometer magnet

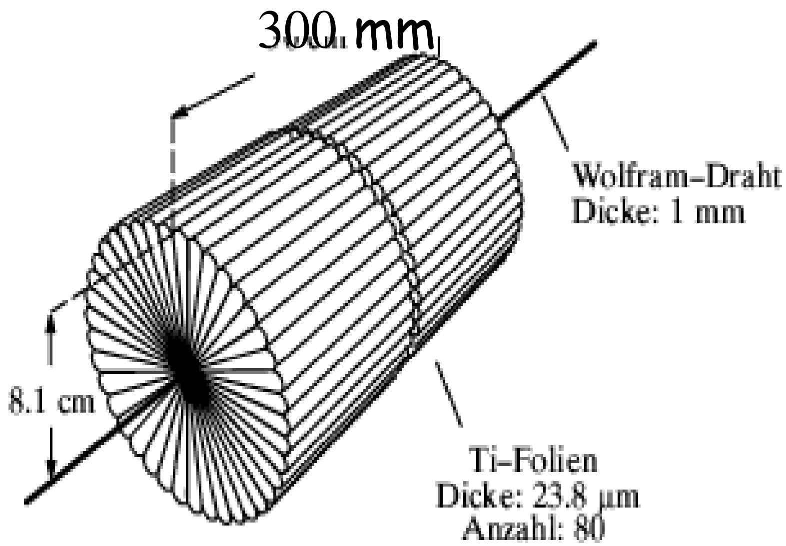
- Superconducting solenoidal magnet previously used at CERN ISR
- Region for particle tracking: 180 cm in length and 130 cm in diameter
- Weight 70 t. End rings, (6t each) produced in Tbilisi, Georgia
- Magnetic field was accurately measured and found a 7% drop at upstream region
- Field map was used for event reconstruction and simulation

Beam counter and target

- Beam crosses CH_2 moderator, plastic scint., and second CH_2 moder. (thick: 21.5, 10, 2 mm)
- First moderator stops pions, resulting in π/μ ratio in the target stops of $\sim 10^{-7}$
- Beam counter used to recognize prompt bgr and monitor beam intensity. PM signals summed and recorded with waveform digitizer
- Second moderator placed close to the target to minimize the spread in π and μ flight time and thus the width for prompt time window

Beam counter and target, continued

- Target is made of Ti foils, thickness 23.8 μm
- Target is arranged symmetrically about the beam axis with x-y cross section resembling a flower with 80 petals
- Target length 300 mm and total mass 427 g



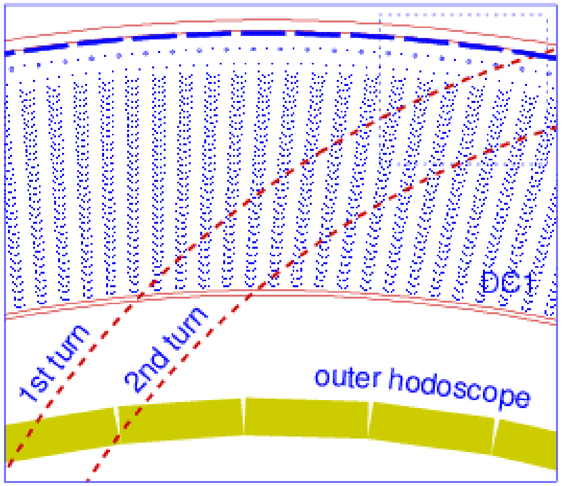
Scintillator hodoscopes

- Outer hodoscope (plastic BC408) determines e^- arrival time and starts drift time measurement
- It has 64 elements, 5 mm thick, 1500 mm len. at radial dist. 349 mm
- Inner hodoscope has 32 strips, 3mm thick, 800 mm length, placed at r = 130 mm.
- The goal of inner hodoscope is to recognize a bgr from $\gamma \rightarrow e^+e^-$ conversions in the target
- Scintillators are viewed at both end by 3/4" PMs (Hamamatsu R1450)
- Thickness 475 mg/cm^2 , # of photoelect. 2x15/MeV
- Time resolution 0.47 ns/strip

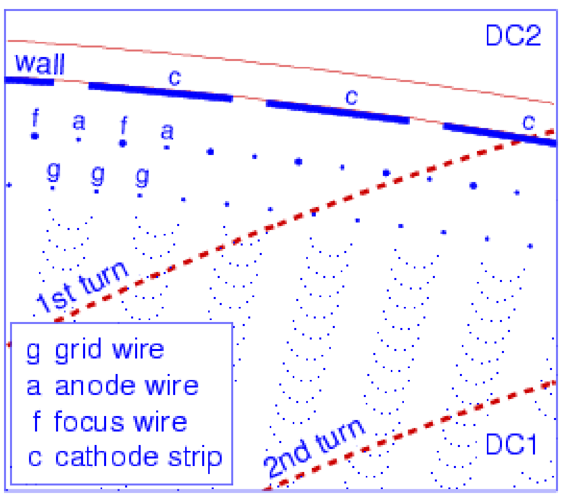
Cerenkov hodoscopes

- Used for triggering and recognises electrons
- Two lucite Cerenkov hodoscopes placed at both ends of the tracking region at r=287 mm
- Each consists of 16 modules 30 mm thickness and 345 mm length
- Used 2" PMs (XP2020)
- # of photo electrons 5/cm
- Time resolution 1.4 ns

SINDRUM II tracking:



Thanks to the damping of the trajectories by energy loss and the radial drift field the first turn is detected first.



Cross section of the main radial drift chamber. The lower view is an enlargement of the region indicated in the upper part. Isochrones are indicated.

DESY, February 2000

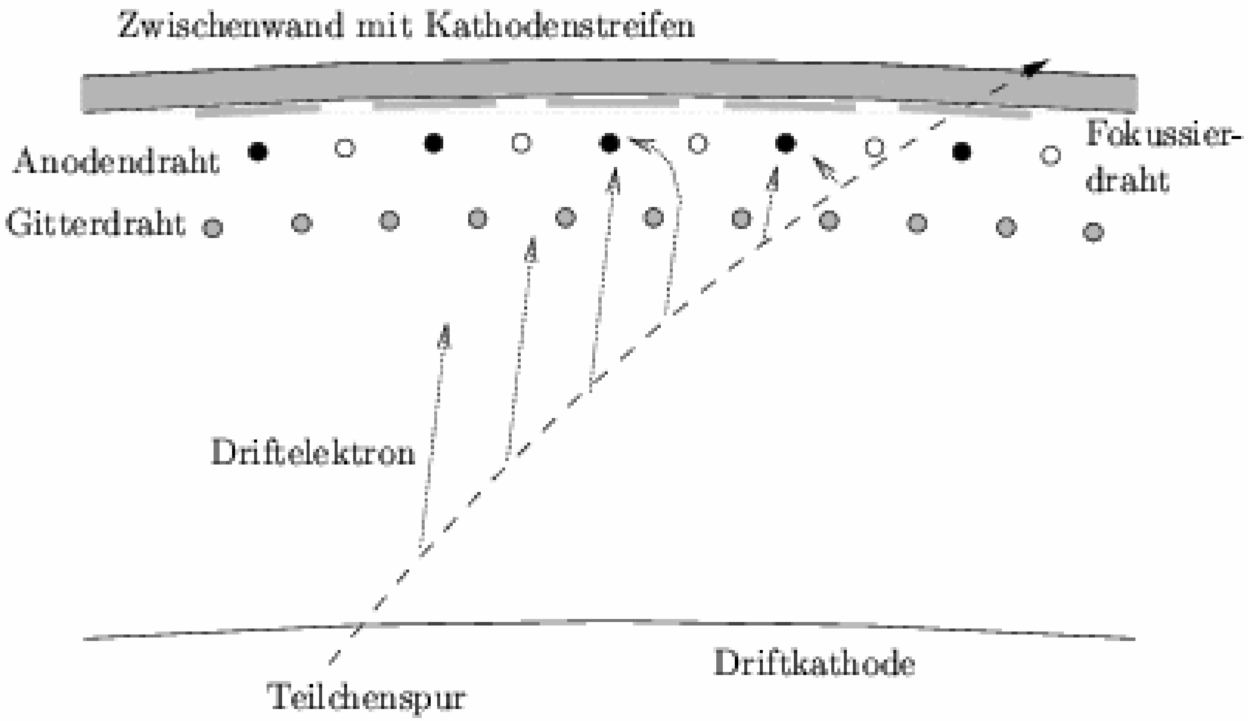


Abbildung 3.11: Schematischer Aufbau der inneren Driftkammer, nicht maßstäblich. Im Schnitt in der x-y-Ebene sind die Spur eines geladenen Teilchens (gestrichelt) sowie die Spuren einiger durch Ionisation erzeugter Driftelektronen (gepunktete Pfeile) angedeutet.

Specification of radial Drift Chambers

	DC1	DC2
Drift region	37.63 - 43.65 cm	44.85 – 64.50 cm
Gas compos.	CO_2/iC_4H_{10} (70/30)	He/iC_4H_{10} (88/12)
Primary ions	120 cm^{-1}	30 cm^{-1}
drift field	800-900 V/cm	290-430 V/cm
max drift time	6.5 μs	18.5 μs
drift speed	0.83-0.93 cm/μs	1.1-1.5 cm/μs
Lorentz angle	6^0	31^0 - 35^0
channels in r - φ	384	96
channels in z	2x192 (4.4 mm)	none
resolution	(r – φ) = 150 μm (z) = 2 mm	(r – φ) = 4 mm

Trigger and data read out

- A time coincidence between a hit in inner hodo, two disjunct hits in outer hodo and Cerenkov signal
- Two of the hits in outer hodo have a distance between 12 and 18 elements
- DC1 pattern in the vicinity of two hits in outer hodo concides with pre-loaded masks, defined by simulation. Both inefficiencies and noise hits have taken into account
- Second trigger level starts digitization of PM time and amplitude signals. Everything is delayed by 8μs to await latest DC signals.

Spectrometer acceptance

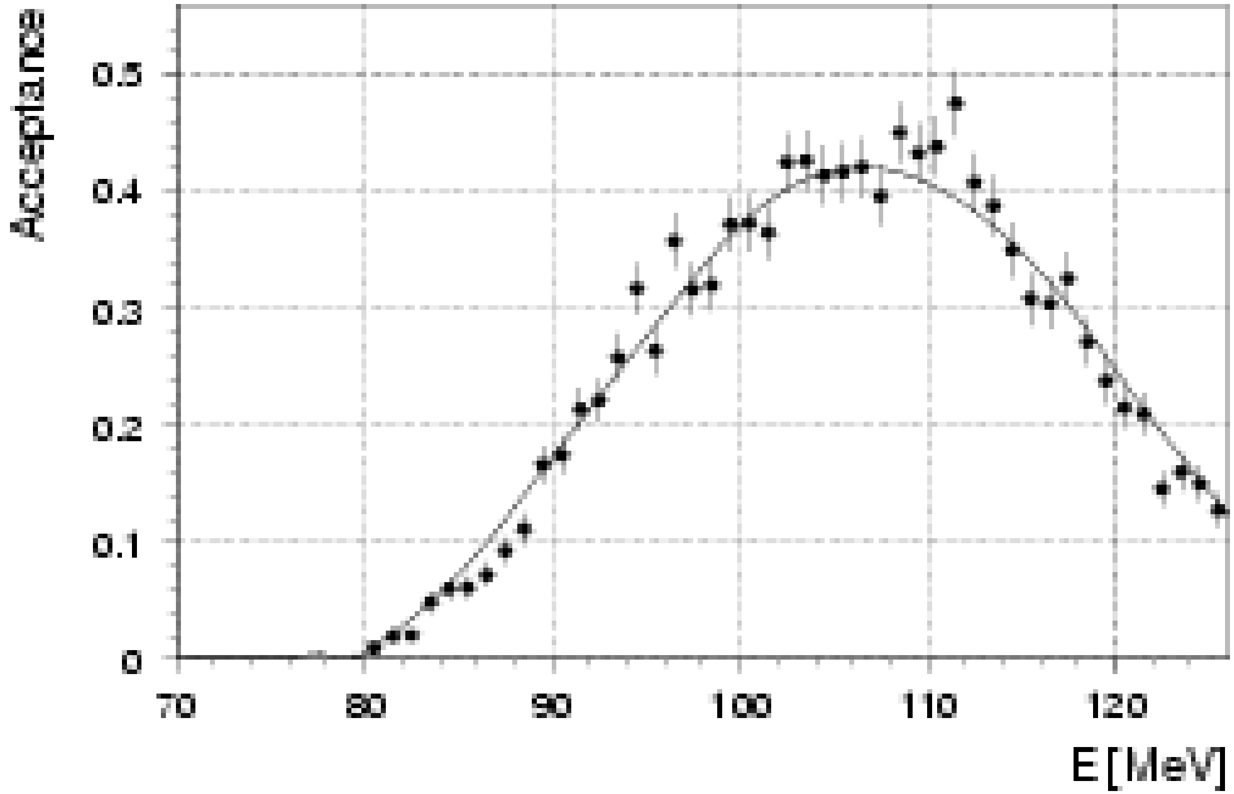


FIG. 5. Spectrometer acceptance A, normalized to unity, as a function of particle energy for electrons emitted isotropically from the titanium target at a field strength of 1.27 T. The solid line is a fit to the points which result from a GEANT simulation.

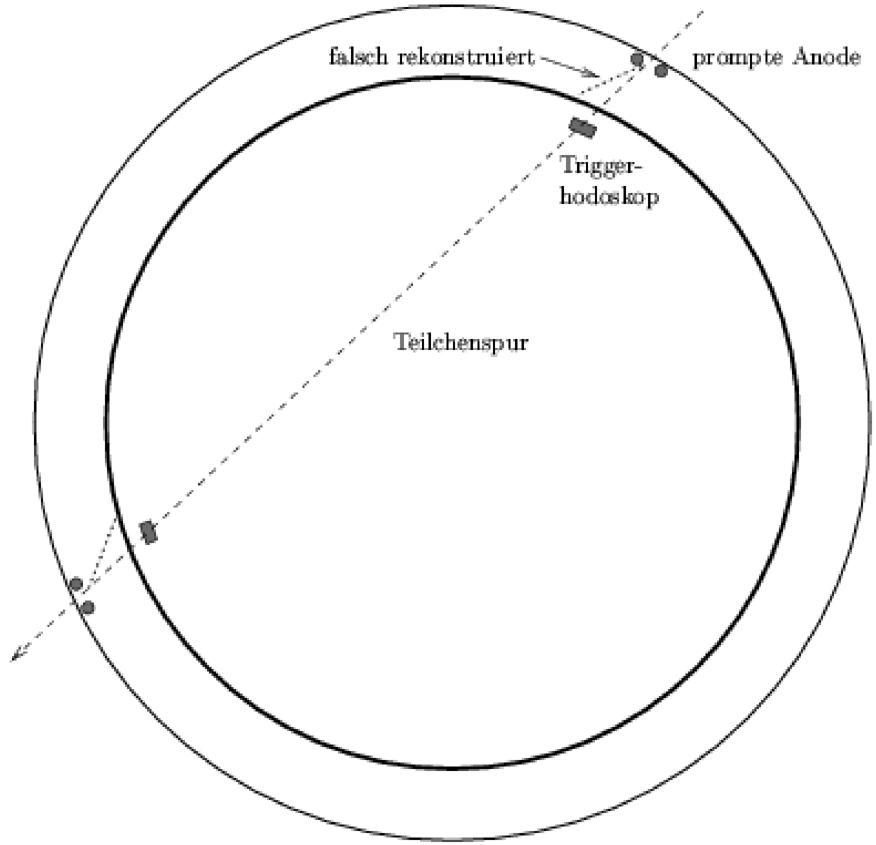
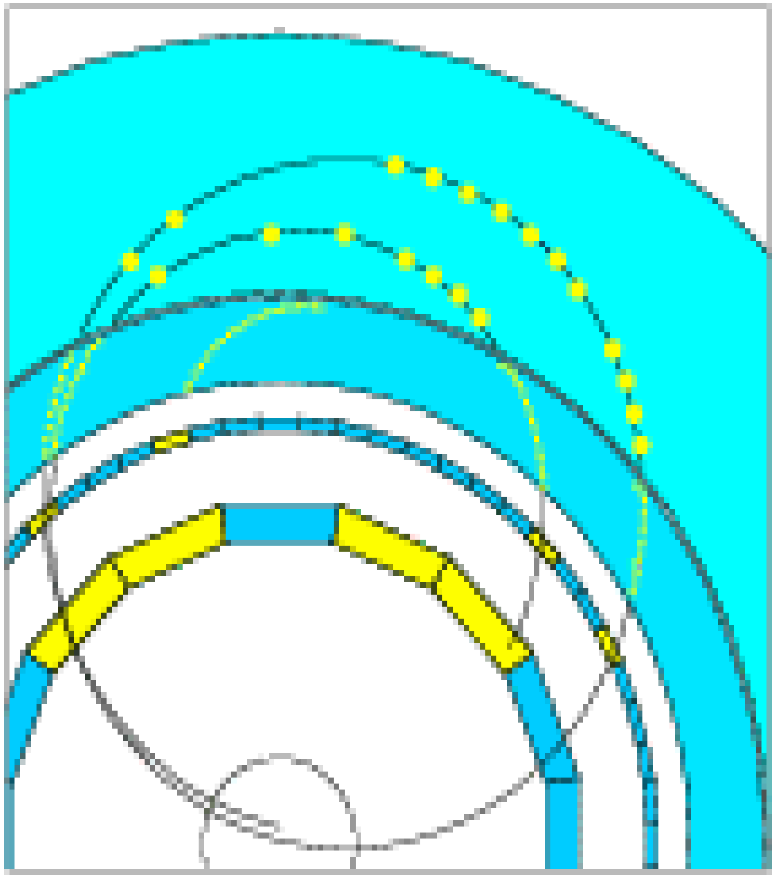
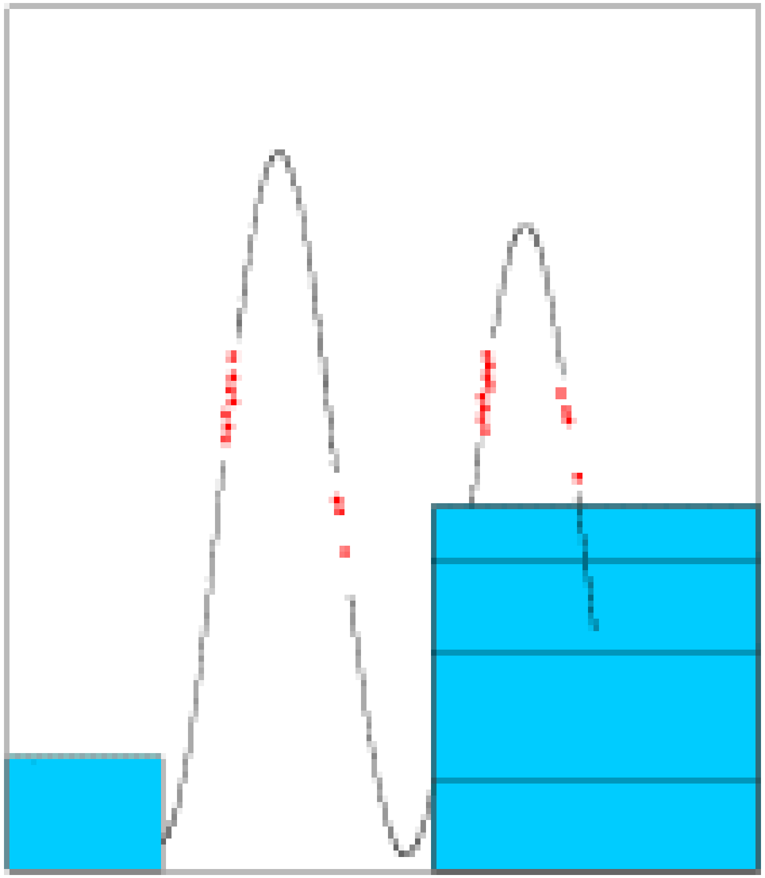


Abbildung 5.1: Schematisches Bild einer Spur zur Kalibrierung der inneren Driftkammer. Es werden nur Spuren benutzt, bei denen genau zwei Paare von jeweils benachbarten Anodendrähten ein promptes Signal aufweisen (in der Zeichnung durch ausgefüllte Kreise angedeutet). Zusätzlich müssen die beiden Segmente des Triggerhodoskops angesprochen haben. Als Beispiel einer Spurrekonstruktion mit falscher Kalibrierung sind die gepunkteten Spurstücke eingezeichnet. Durch die Anpassung der Parameter der Orts-Driftzeit-Beziehung werden diese Spurstücke mit der durch die gestrichelte Linie markierten Teilchenspur zur Deckung gebracht.

SINDRUM II, 100.6 MeV electron





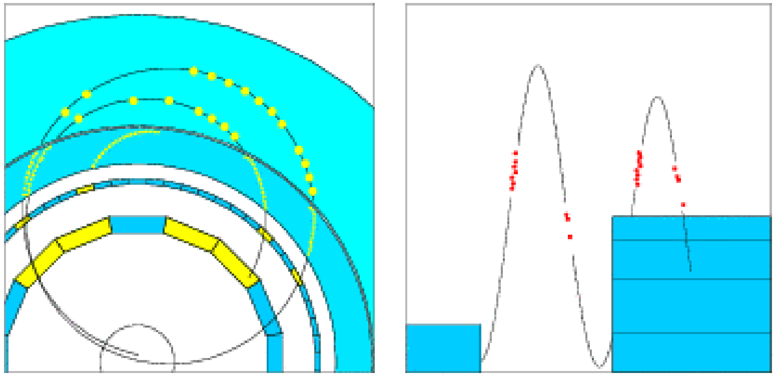
Data taking and analysis

- Measurment life time 50.4 days, 4×10^9 events were recorded with beam
- Beam intensity from BC analysis $1.15 \times 10^7 \mu^- s^{-1}$ which corresponds to 5.0×10^{13} μ^- passing BC
- Beam stop rate 0.616+/-0.025
- $N_{stop} = (3.09 +/- 0.14) \times 10^{13}$
- $\varepsilon^{\mu e}_{trigger} = 0.751 +/- 0.005$
  $\varepsilon^{MIO}_{trigger} = 0.759 +/- 0.010$

SINDRUM II:
tracking and momentum resolution

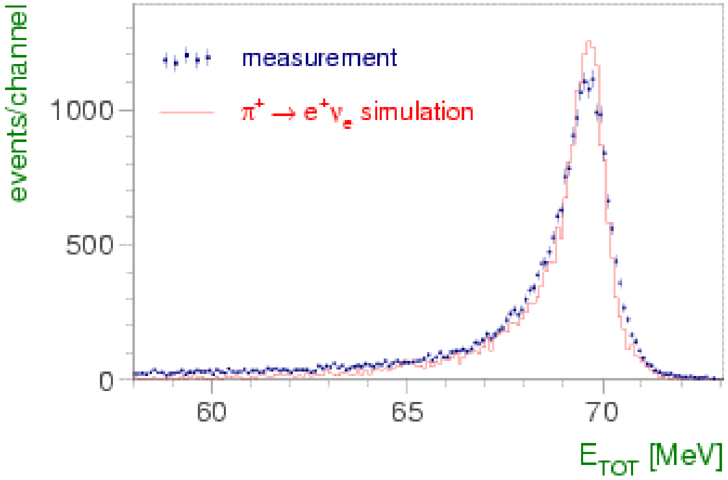
Tracking is performed with two radial drift chambers:

- DC1, filled with CO_2/iC_4H_{10} (70/30), a slow drift gas with only 6^o Lorentz deflection
- DC2, filled with He/iC_4H_{10} (88/12) for its long 1.14 km radiation length



Tracks left in the spectrometer by a 100MeV/c e^-.

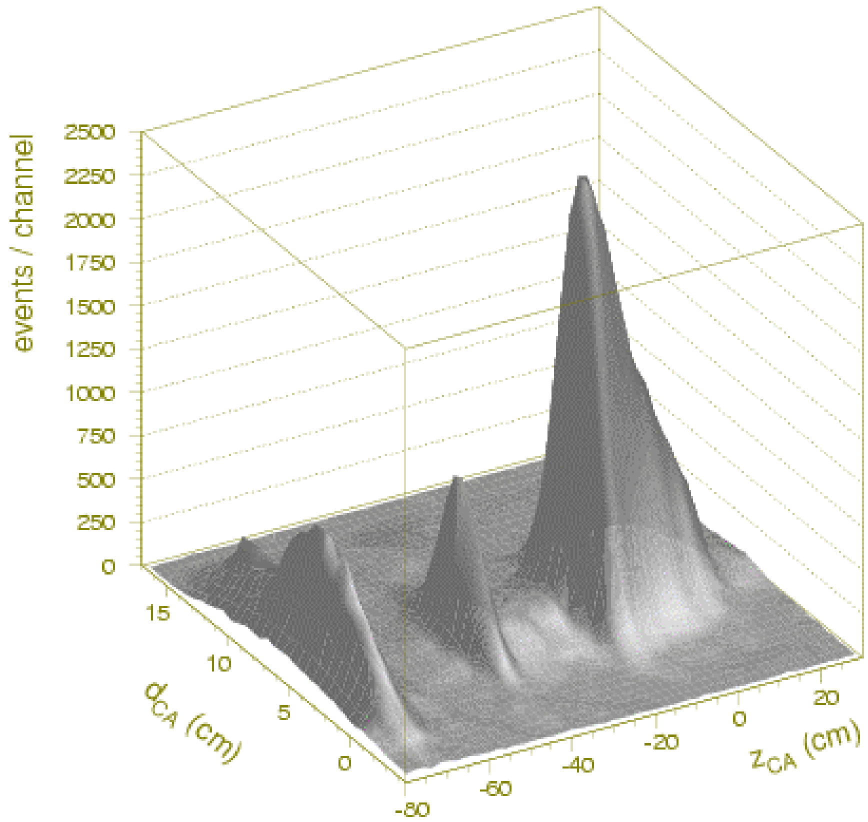
DC1 gives 3-dimensional space points with the help of cathode strip readout.



Positron energy spectrum from π^+ decay. The measured distribution has a FWHM of 1.5 MeV.

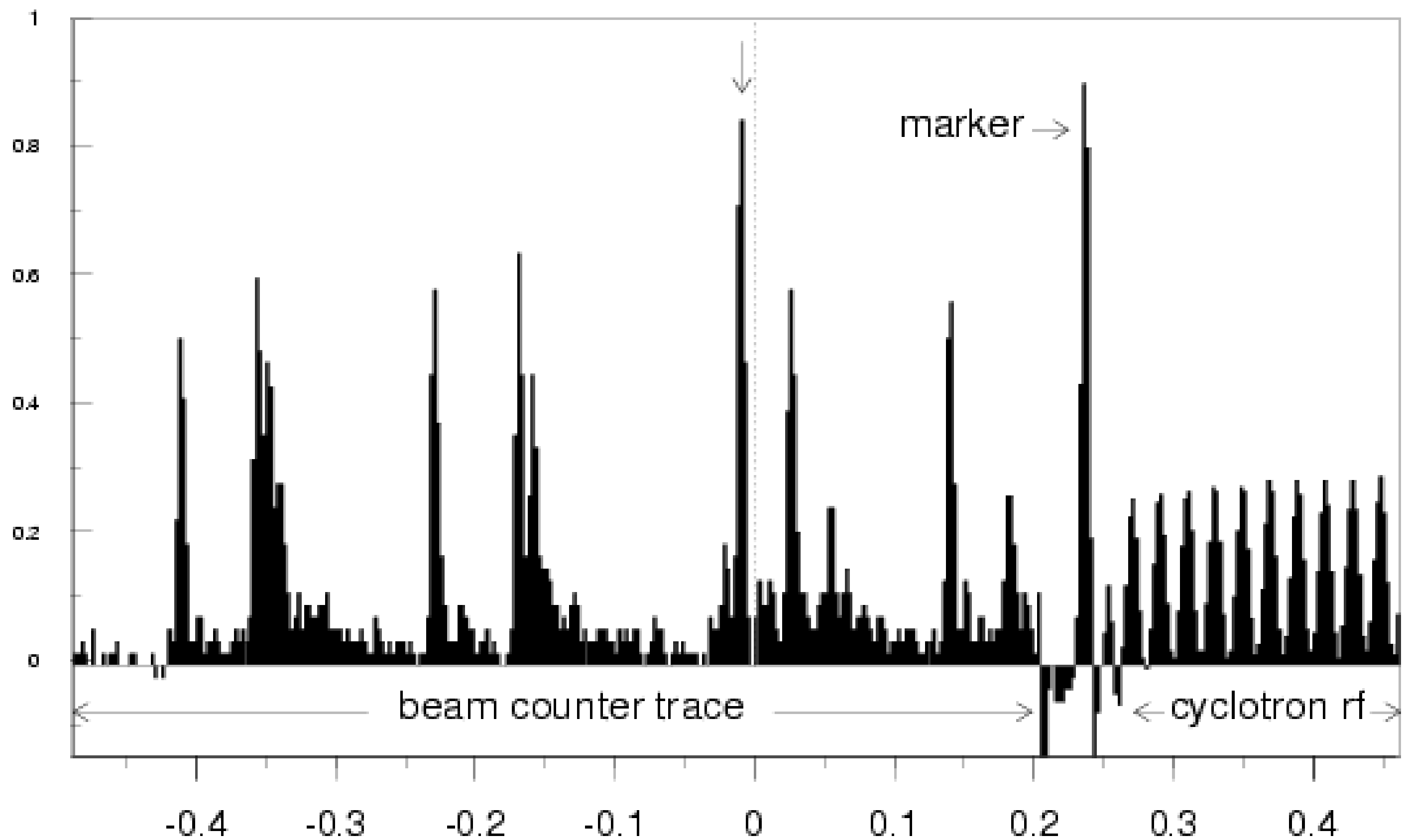
SINDRUM II tracking:

vertex reconstruction



Distribution of the point of closest approach to the beam axis. Events are concentrated at the locations of the beam counter, the second moderator and the target (from the left).

Beam counter analysis



Event Selection

- The electric charge is negative
- Trajectory starts in target
- The beam counter does not exhibits a prompt signal
- No additional detector signals, characteristic for cosmic-ray background is found
- Prompt background cut 13 ns -> intensity ~10^7
- Beam off data taking (44 days) to study and remove cosmic background

$\Gamma(\mu^- \text{Ti} \to e^- \text{Ti})/\Gamma(\mu^- \text{Ti capture}) < 2.3/\, f^{Ti}_{capt} N_{stop} \varepsilon^{\mu e}$

Beam counter analysis, continued

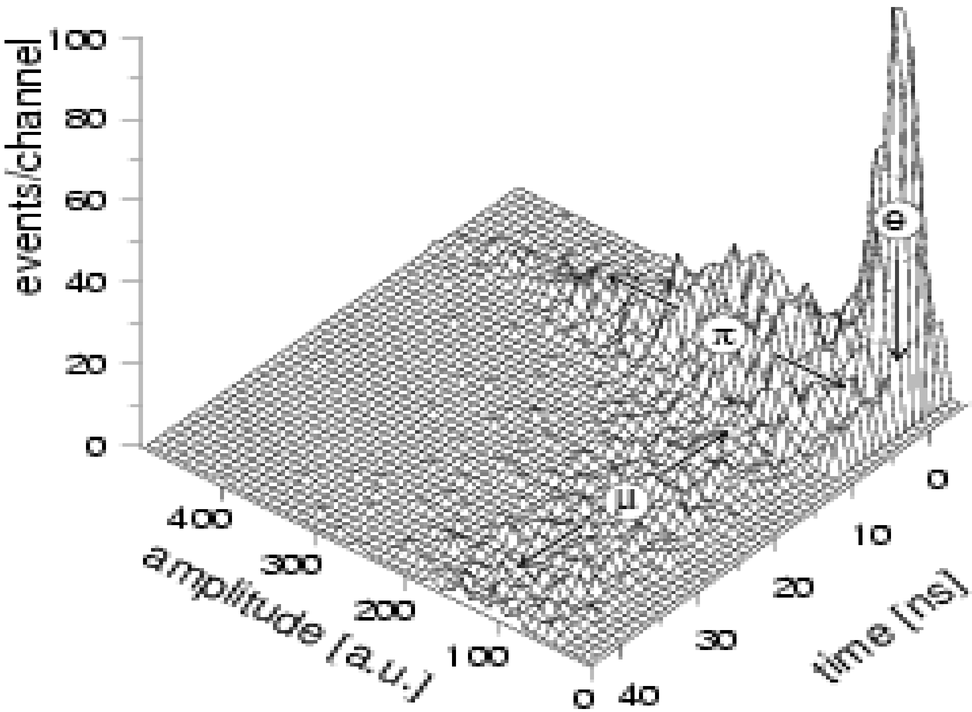


FIG. 10. Distribution of the time delay between the event in the spectrometer and the preceding beam-counter signal versus the amplitude of that signal. Three distinct components can be recognized: an e^- peak around 0 ns with small amplitudes, a π^- peak around 6 ns at larger amplitudes, and a continuous time distribution at intermediate amplitudes from μ^- events. The π/e ratio has been raised by accepting both e^+ and e^- events and by selecting momenta above 88 MeV/c.

Comparison of exper./MIO simulation

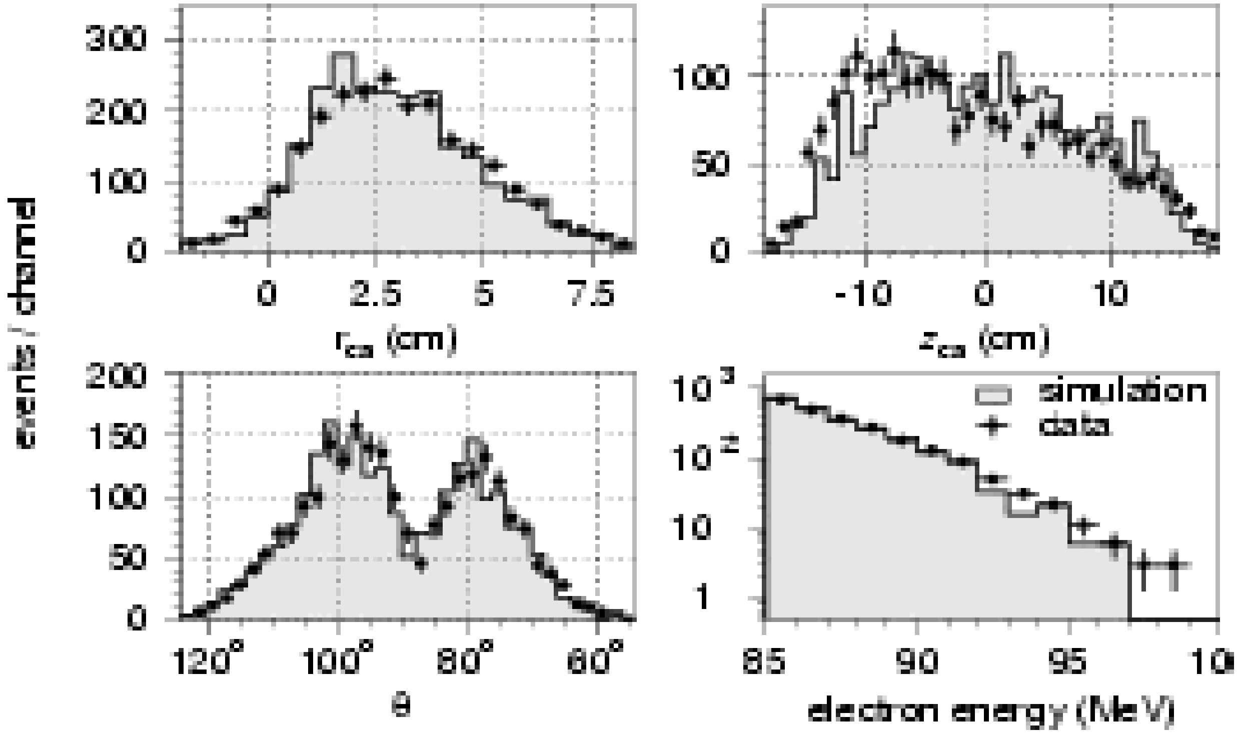
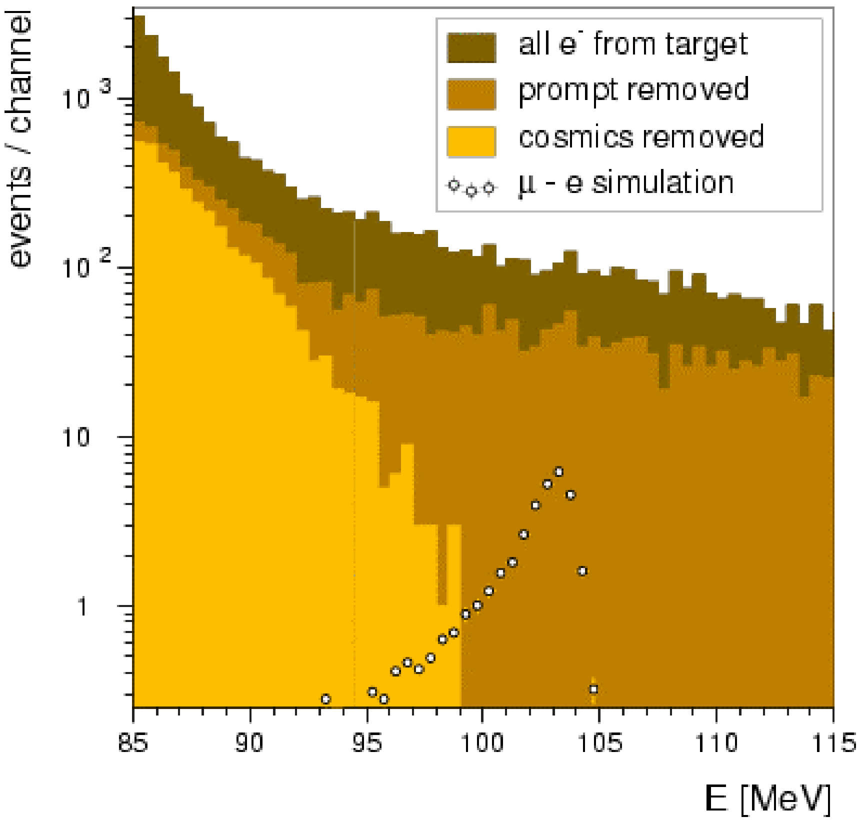


Figure 7. Kinematical distributions of electrons from bound-muon for data and simulation. r_{ca} and z_{ca} are the radial distance and corres ing z-coordinate of the closest point of the trajectory to the spectr axis. Θ is the angle of the trajectory relative to the z axis.

SINDRUM II:

Search for $\mu^- \rightarrow e^-$ conversion on titanium



Electron energy distribution at three stages of the event selection and as predicted by a GEANT simulation of μe conversion at $B_{\mu e} = 4 \cdot 10^{-12}$.

measuring time	50 days
muon stops	3.1×10^{13}
capture fraction	85%
acceptance	42%
efficiency	35%
1/sensitivity	3.9×10^{12}
sensitivity	2.6×10^{-13}
events seen	<2.3 (90% C.L.)
90% C.L. limit	6.1×10^{-13}

DESY, February 2000

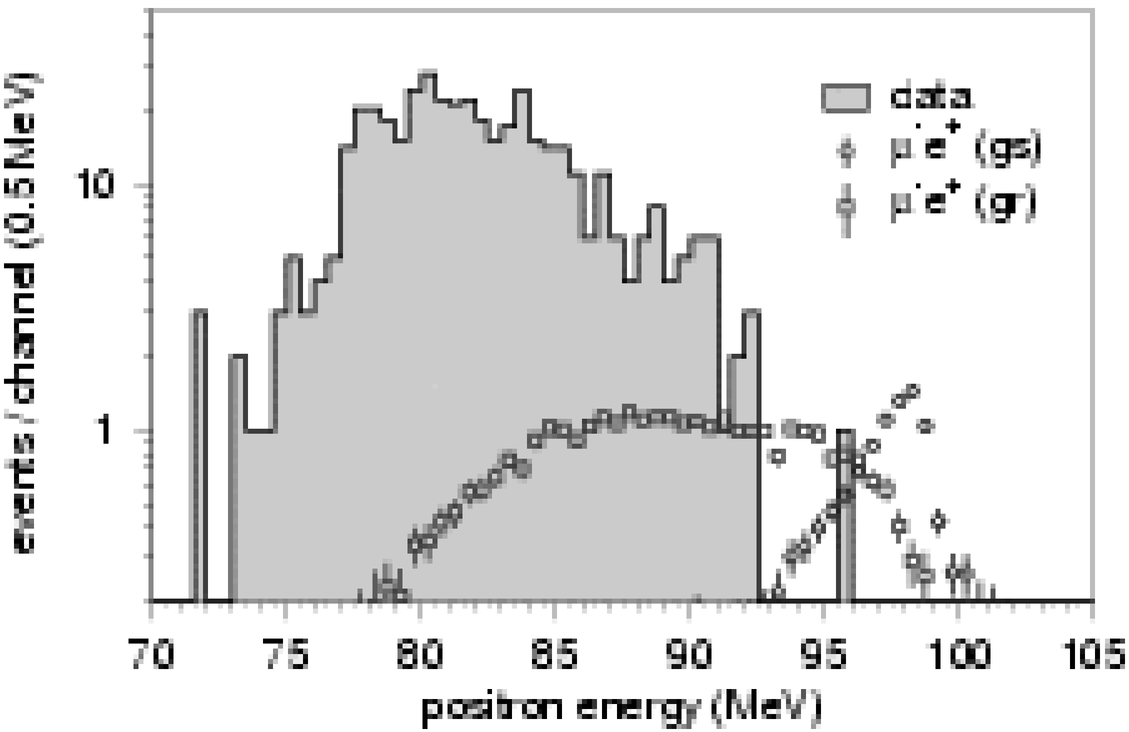


Figure 8. Energy distribution of the final positron data sample. A simulation of $\mu^- \rightarrow e^+$ conversion with Ca in ground state (gs) and with a giant resonance excitation (gr) shows the expected signals using $B_{\mu e}^{gs} = 4.3 \times 10^{-12}$ and $B_{\mu e}^{gr} = 8.9 \times 10^{-11}$.

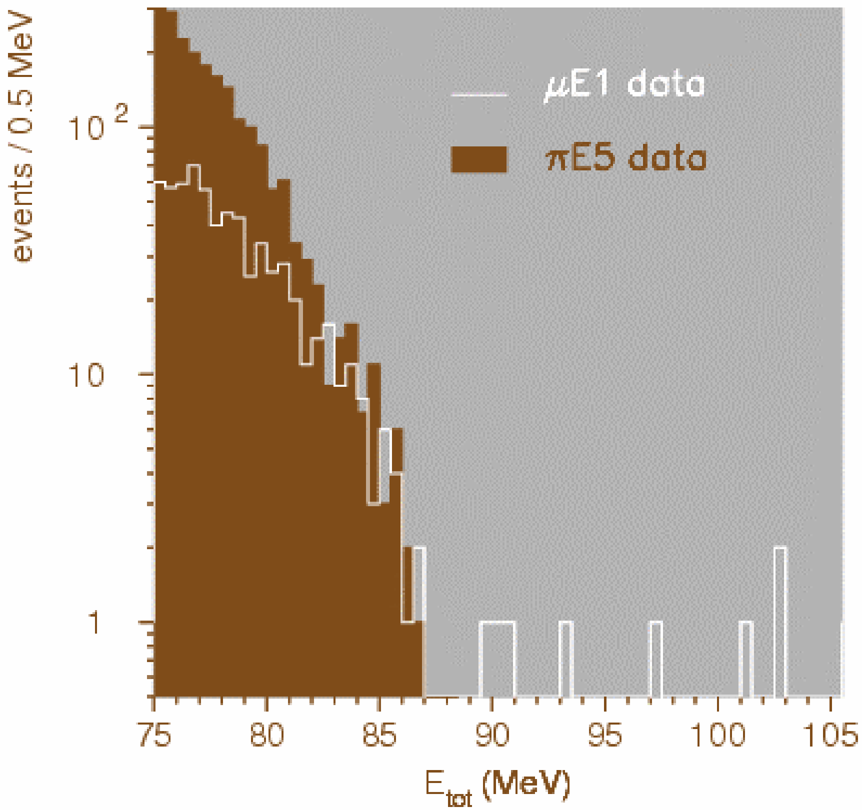
Summary

- Increasing evidence for neutrino mixing observed past years indicates that generation numbers is not conserved, neither for quarks nor for leptons. The standard model needs a revision
- Observation of the Lepton Flavor Violation would give an unambiguous signal for a new physics beyond the Standard Model
- Flavor-changing neutral currents among quarks and leptons would signal a much more extension to the model
- Proposed MECO Project to reach muon to electron conversion rate at -16 level will be a major breakthrough in understanding of basic laws of the nature

Additional Plots

SINDRUM II:

Search for $\mu^- \to e^-$ conversion on heavy targets



experimental area	μE1	πE5
beam momentum (MeV/c)	90	25
target	lead	gold
mass (g)	415	18
e^- resolution (%)	3	1.2
event selection:		
cosmic suppression	yes	yes
beam veto	yes	
remaining background:		
π^- induced	some	
e^- induced	some	
μ^- induced	some	some

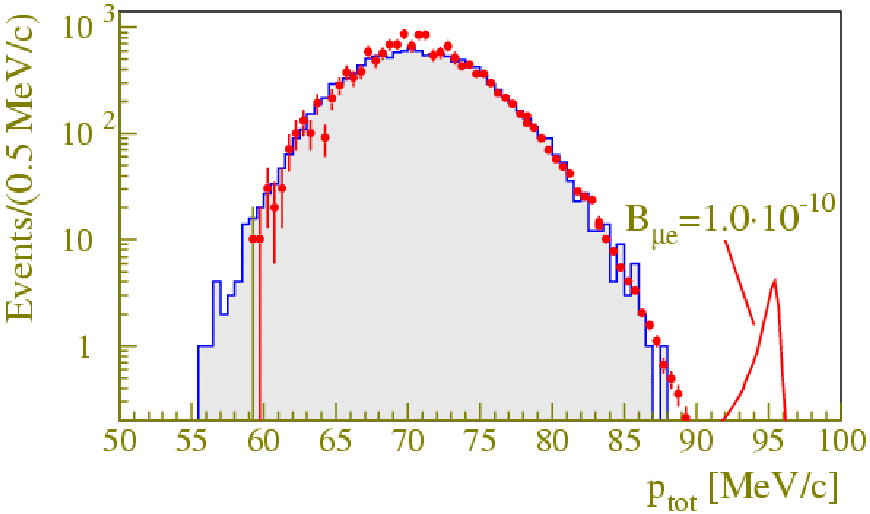
$$B_{\mu e}^{\mathrm{Au}} < 1.9 \times 10^{-11} \quad (90\% \text{ C.L.})$$

F.Riepenhausen, 1999

For increased sensitivity, i.e.
higher stop rate: raise beam momentum

SINDRUM II:

Search for $\mu^- \rightarrow e^-$ conversion on gold

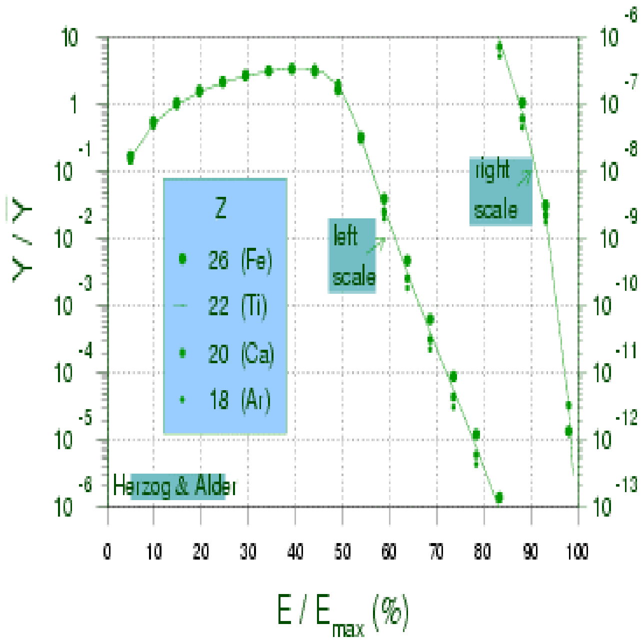


measured data

simulated data (only decay in orbit and conversion)

SINDRUM II:results at old beamline

The only intrinsic background originates in μ decay in orbit:



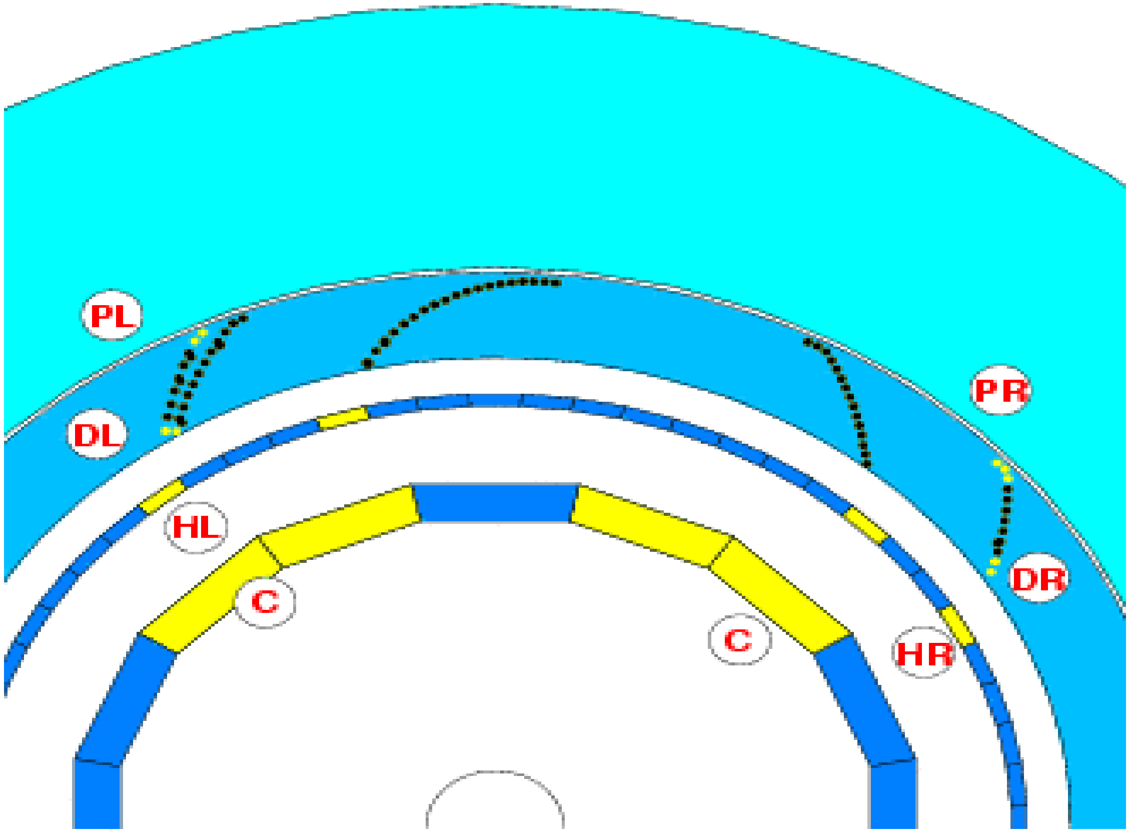
Electron energy distributions from muonic-atom decay

Other sources of background are:

- π^- radiative capture, followed by $\gamma \to e^+e^-$ pair production
- μ^- decay in flight
- scattered beam electrons
- cosmic rays

Prompt background can be removed by:

- beam counter
- pulsed beam
- beam quality


PL
DL
HL
C
C
PR
DR
HR