Search for $\mu^- Au \rightarrow e^- Au$ conversion with SINDRUM II

Collaboration (2000):

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Lepton Family-number Conservation

- *LFC experimentally well confirmed. BUT: Is there an underlying symmetry?*
- *LFC in Standard Model is a consequence of the assumption m_ν=0*
- *$m_\nu \neq 0$ leads to LFC violation (LFV), but decays are suppressed by* $\propto (\delta m_\nu / m_W)^4$
- *most extensions of the SM predict additional sources of LFV*
- *many searches done for LFV processes in decays of μ,τ,π,K,B,D,W,Z*
- *LFV would be an unambiguous sign of new physics*
- *highest sensitivities reached in μ,K and recently τ experiments*
- *most popular muon decays: $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, μ-e conversion*

$\mu - e$ conversion in muonic atoms

- *muonic atoms μ^-(A,Z) formed in their ground state after stopping μ^- in matter ($\mathcal{O}$(1ns))*
- *decay of μ^-(A,Z) mostly by*

  "muon decay in orbit (MIO)" $\mu^-(\mathrm{A,Z}) \rightarrow e^- \nu_\mu \bar{\nu}_e (\mathrm{A,Z})$

  and "nuclear muon capture (MC)" $\mu^-(\mathrm{A,Z}) \rightarrow \nu_\mu (\mathrm{A,Z\text{-}1})^*$

- *MIO rate ↓ for Z ↑ ; MC rate $\propto Z^4$*

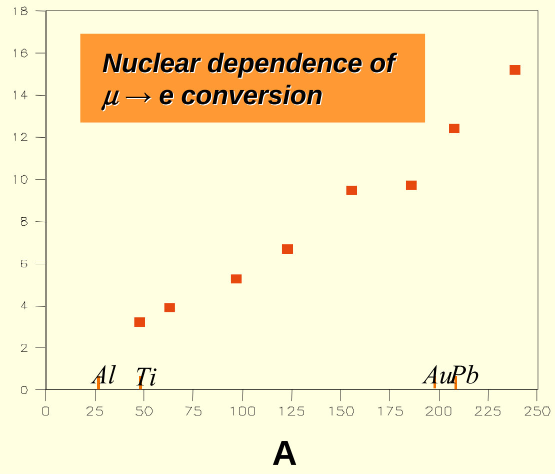
- *if μ-e conversion - leaving the nucleus in its ground state - exists, it's boosted by the coherent action of all quarks over the MC process (excited states experimentally not accessible)*

- *μ-e conversion results in a two body final state → electrons are monoenergetic*

$$E_{\mu e} = m_\mu c^2 - B_\mu(Z) - R(A)$$

μ binding energy — *atomic recoil energy*

$$E_{\mu e}(\mu^- Au) = 95.56 MeV$$



T.S. Kosmas, I.E. Lagaris:

J. Phys. G: Nucl. Part. Phys. ***28*** *(2002) 2907*

Background : a) muon induced

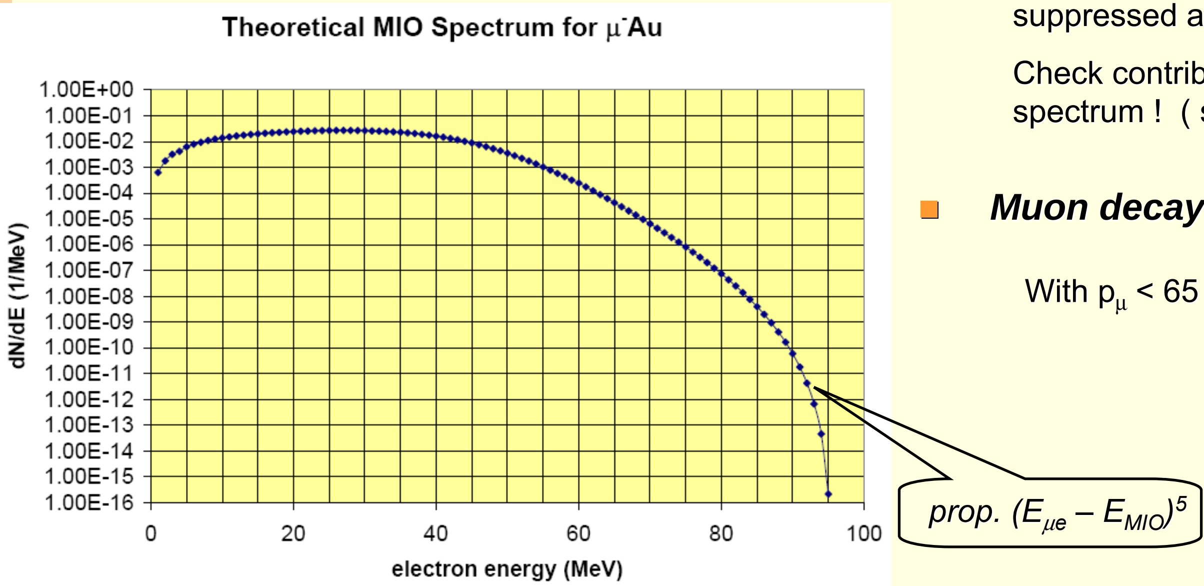
- *μ - decay in orbit (MIO) :*

$$\mu^- Au \rightarrow e^- \nu \bar{\nu} Au$$

Theoretical spectrum :

(R. Watanabe et al.: Atom.Data and Nucl. Data Tab. **54** (1993), 165)

(Lead spectrum, corrected for shift in gold endpoint energy)



resolution of 1-2 MeV (FWHM) sufficient

- ***Radiative Muon Capture (RMC) :***

$$\mu^- Au \rightarrow \nu_\mu + \gamma + Pt^*$$

followed by $\gamma \rightarrow e^+ e^-$

Kinematic endpoint of photon spectrum only 0.7 MeV below $E_{\mu e}$, but strongly suppressed at high energies.

Check contribution by investigating positron spectrum ! (see below)

- ***Muon decay-in-flight :***

With p_μ < 65 MeV/c always below $E_{\mu e}$

Background : b) pion induced

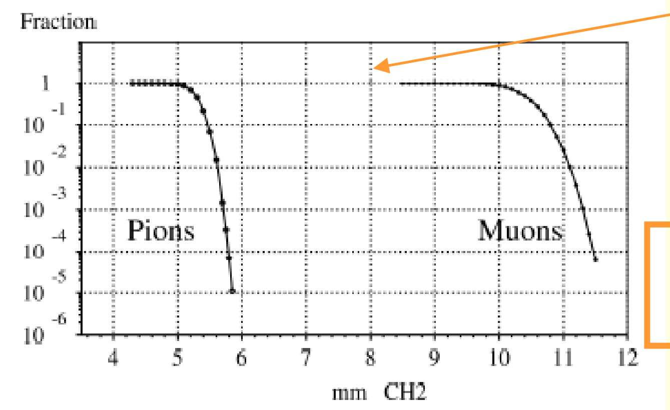
Radiative Pion Capture (RPC) : $\pi^- Au \rightarrow \gamma + Pt^*$ followed by $\gamma \rightarrow e^+ e^-$

Kinematic endpoint of photon spectrum around 130 MeV ! Branching ratio of order 2%.

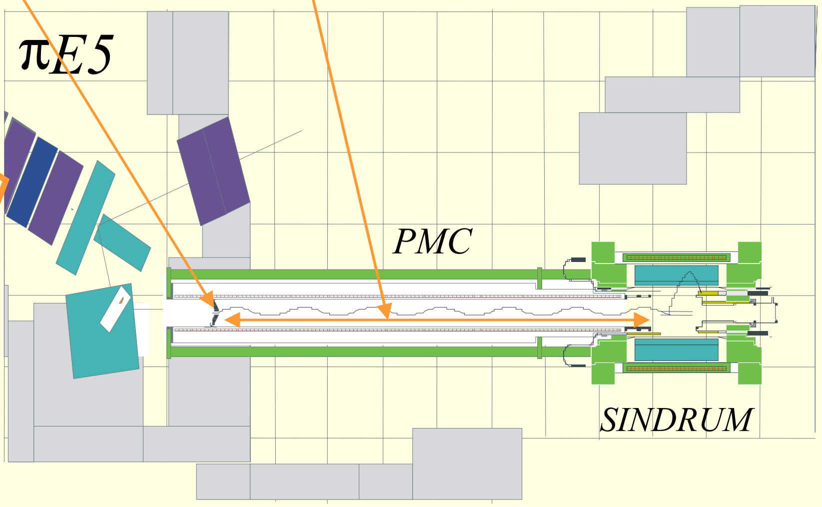
Suppression by

- fast beam veto (RPC is a strong interaction process)
- pulsed beam
- keep π/μ stop rate in target below 10^{-9} (chosen in this experiment)

Achieved by a combination of degrader (10^{-6}) and decay path (8m $\rightarrow 10^{-3}$)



tune beamline to suppress high momentum tail



Probability of π/μ with p=52MeV/c to cross a CH_2 degrader

BUT: distributions broadened by finite beam momentum resolution

Background: c) electron induced

Electrons in the beam may scatter from the target

Suppression by

- beam momentum much below 90 MeV/c

However,

electrons from pion decays in flight before the degrader

and

from RPC in the degrader

may have higher momenta and represent a serious background source.

Suppression achieved by using their time relation with the proton beam's rf-structure together with a reduction in phase space (see below)

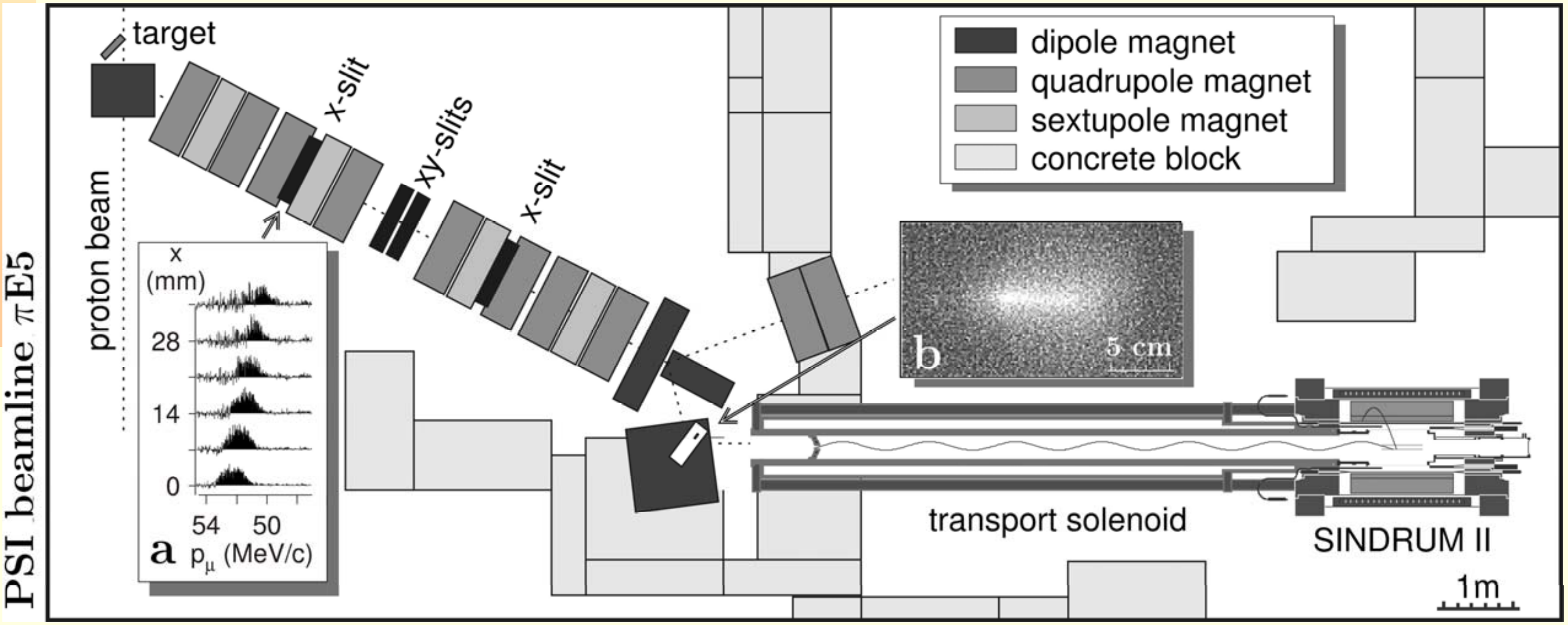
Background: d) cosmic induced

Cosmic radiation produce e^- which may fake a μe event.

Suppression:

- Most of them identified by hits not belonging to main track (see below).
- $\gamma \rightarrow e^+e^-$ pair production in the target :
  - use passive shielding
  - veto counter systems
  - small target mass

Experimental Set-up

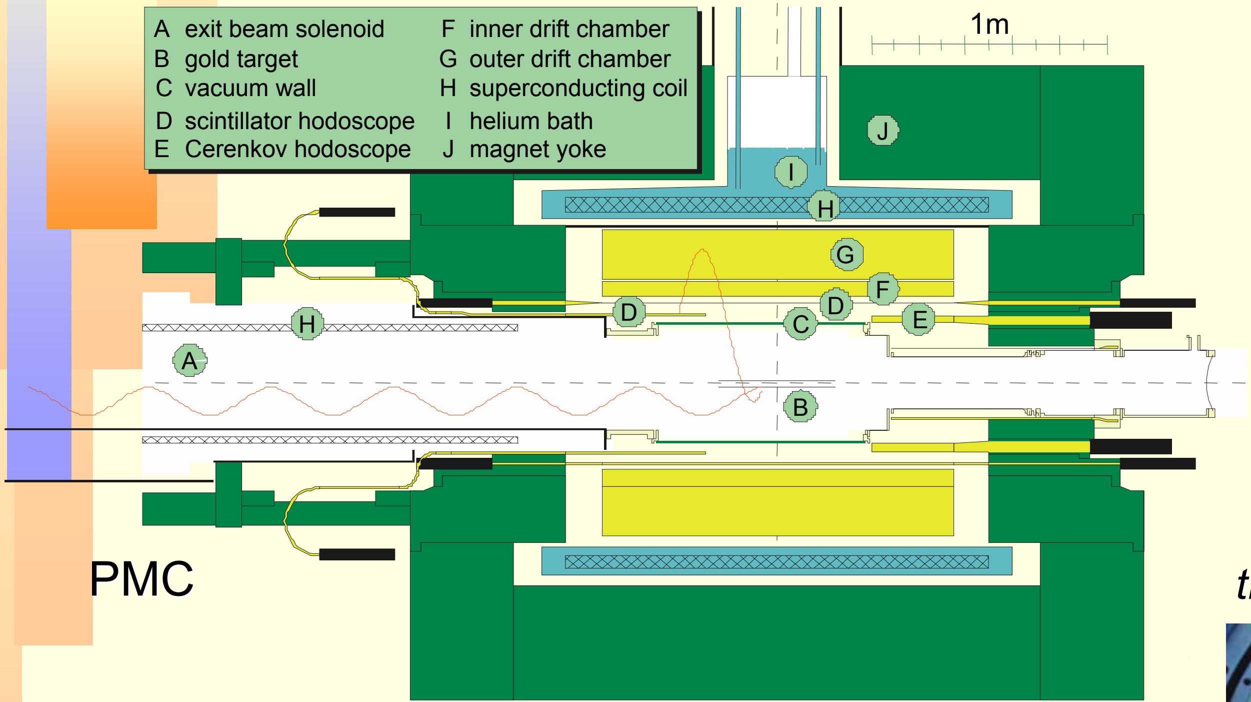


Proton beam: 590 MeV, time structure: bursts 0.3 ns wide every 19.75 n

πE5-beam line: 52 or 53 MeV/c with ± 2% FWHM (limiting high momentum tail)

Transport solenoid PMC: 1.1 T, lead collimator with 60mm hole followed by a 8mm CH_2 degrader

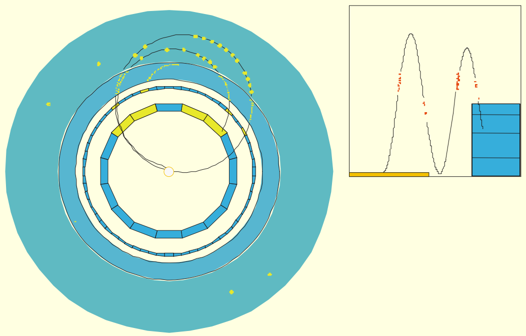
SINDRUM II Spectrometer



SINDRUM II

Schematic event display:

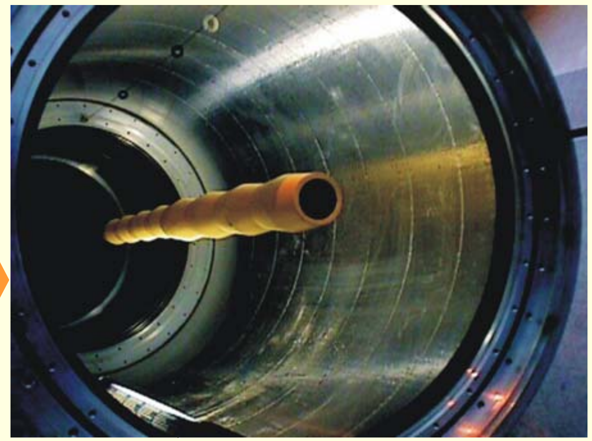
rφ *rz*



tracks left by a 100 MeV e⁻

Gold Target (B) (produced by galvanic process to avoid low Z contaminations):

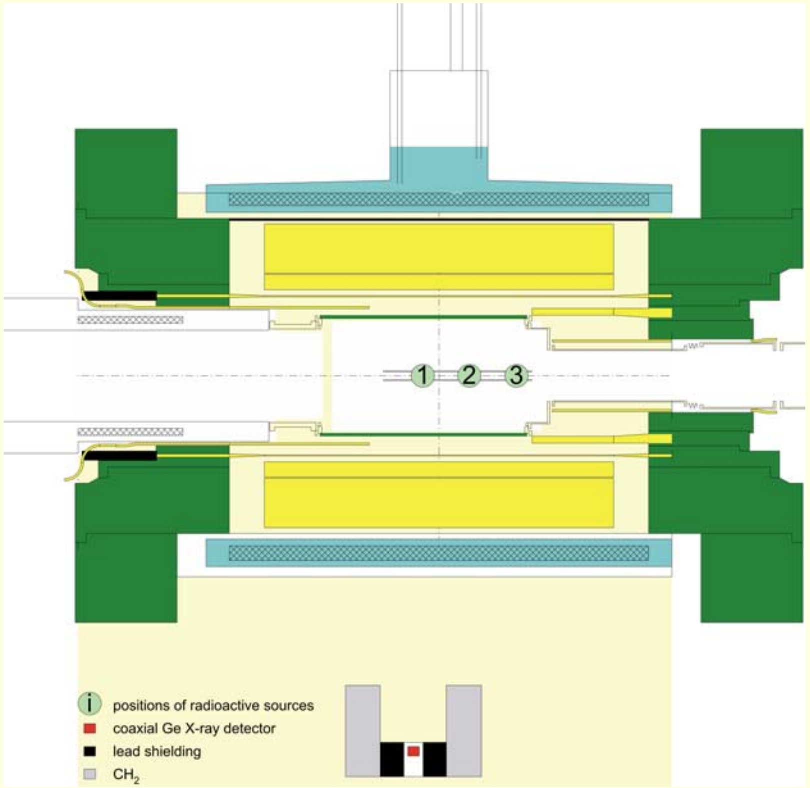
- diameter ~ 40 mm
- wall thickness 75 mg/cm^2
- length 65 cm (no beam focus exists)



Determine μ stops: a) Principle

- Muonic X-ray detection from μ^-Au capture
- Method:
  - using a Germanium diode to monitor yield of $4f_{5/2} \rightarrow 3d_{3/2}$ transition (899 keV)
    or (respectively)
  - using a large NaI crystal detector to monitor yield of $2p \rightarrow 1s$ transitions (5765 and 5595 keV)
  - Well known X-ray -intensities (F.J.Hartmann et al. TU München) and -energies (B.Robert-Tissot et al. Univ. Fribourg)
- Calibration:
  - Acceptance for Ge-diode measured with calibrated sources :
    ^{137}Cs (662 keV), ^{60}Co (1117,1333 keV)
    at 3 different z positions
    Reproduced by simulation within ±3%
  - Simulation used to determine acceptance for gold transition (899keV) & measured stop distribution
    $A^{Ge} = (1.02 \pm 0.05_{stat} \pm 0.07_{sys}) \times 10^{-6}$
  - Acceptance for NaI (5765,5595 keV) from (simultaneous) Ge measurement
    $A^{NaI} = (1.01 \pm 0.06_{stat} \pm 0.08_{sys}) \times 10^{-5}$

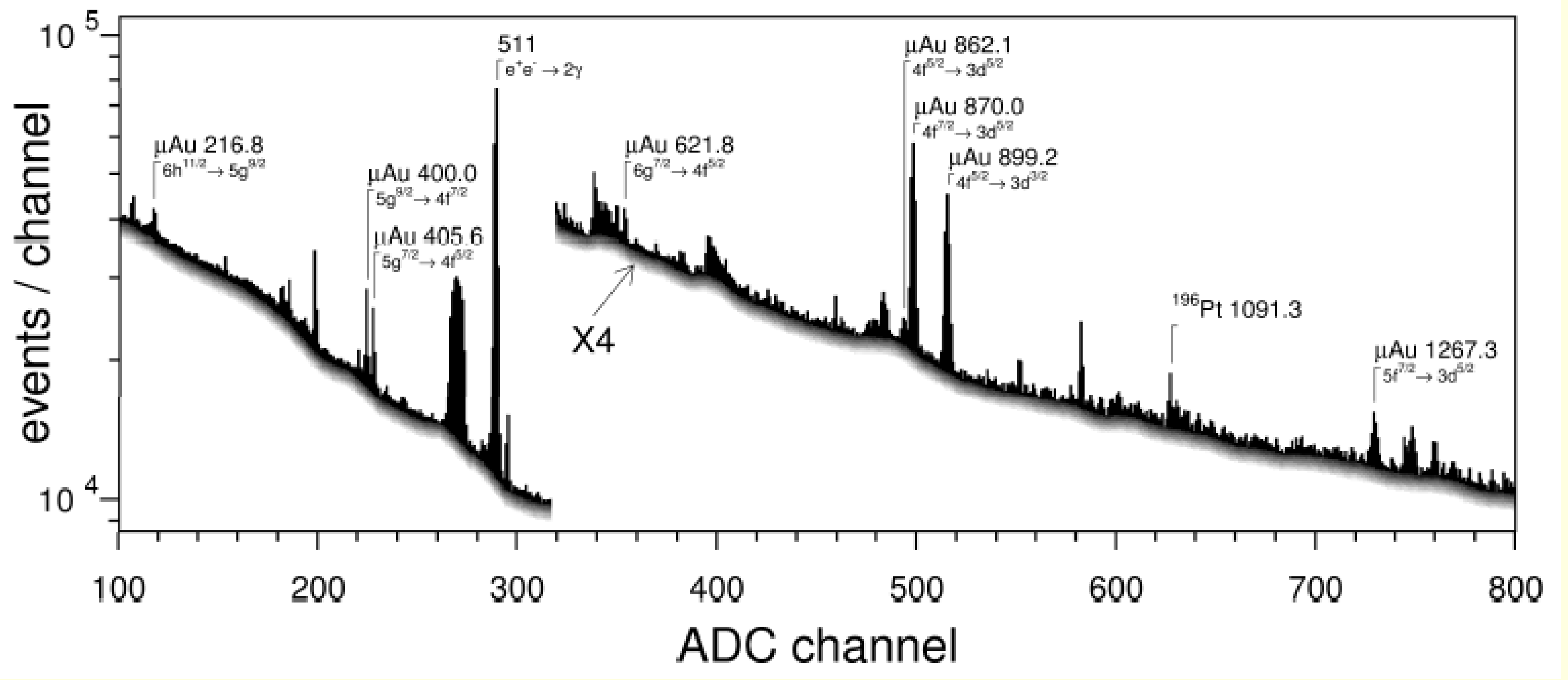
SINDRUM II spectrometer + X-ray detector (Ge)



(NaI detector not shown)

Determine μ stops: b) Results

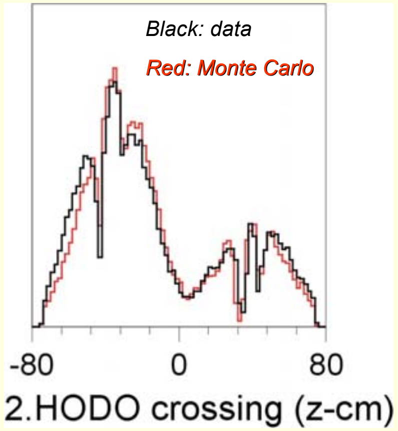
Example of a raw m -Au X-ray spectrum taken during a 3 hour run



Total μ-stops in Au-target:

$N_\mu = (4.37 \pm 0.27_{stat} \pm 0.17_{sys}) \times 10^{13}$

Event simulation



μ-e conversion, MIO and π-decay-in-flight events simulated with GEANT

Exact description of geometry:

- target position
- active elements
- flanges of vacuum tube

Light propagation & attenuation in scintillator and Čerenkov counters

Discriminator threshold & time resolution of each individual counter (from observed values)

Variation of DC1 anodes & cathodes efficiencies during measurement time taken into account

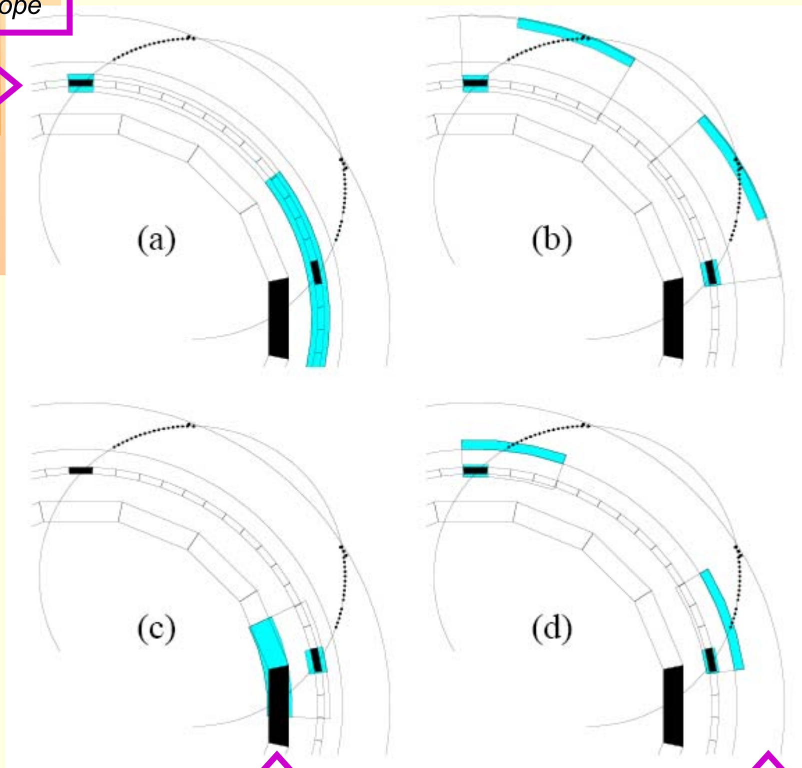
B-field map used for event reconstruction and simulation

μ-stop distribution over target adjusted to measurement

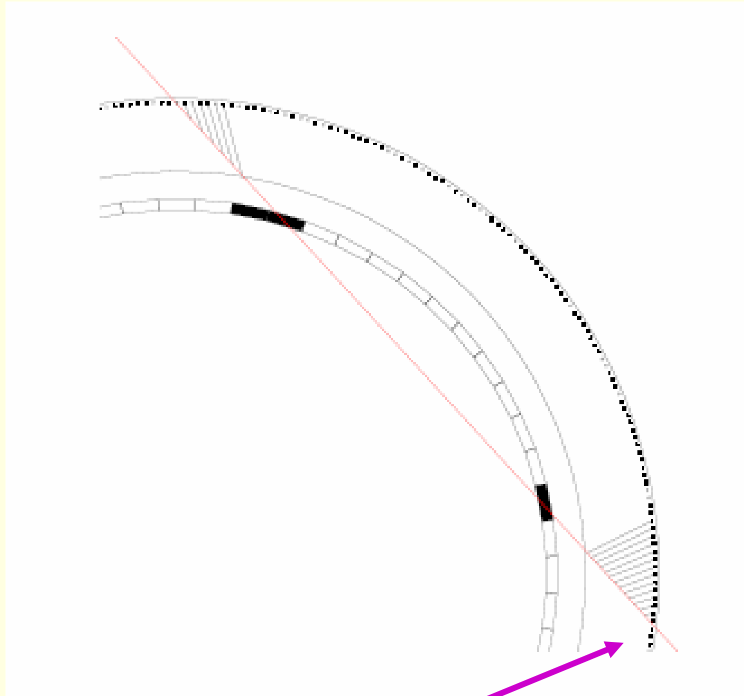
Trigger condition

Scintillator hodoscope

Circular track trigger



Straight track trigger



Endcap detector

Used for main data taking and energy calibration (see below)

Driftchamber DC1

Cosmic muon trigger used for drift chamber calibration once a day

Event reconstruction and selection

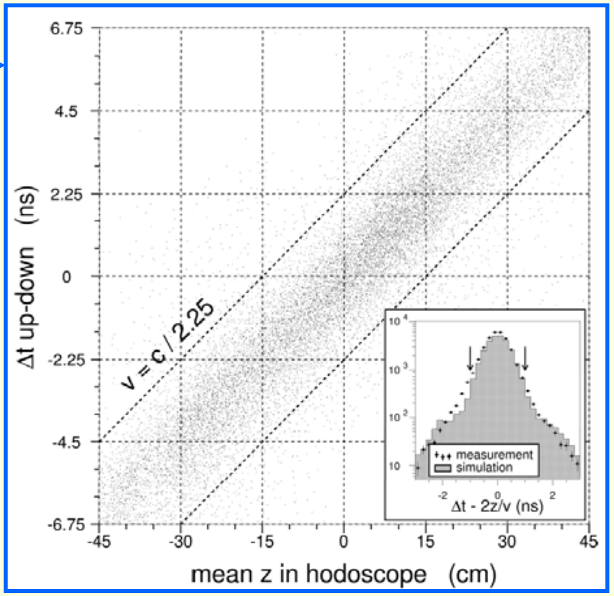
Trajectory reconstruction:

• search for DC1 track elements in drift time patterns of sense wire and cathode strips, independently

• sense wire & cath. track elements combined pair wise to maximize number of coincident signals

•Drift time conversion to r x ϕ coordinates

→ check that track elements point to hodoscope hit



• pairs of track elements are combined into turns and trajectories are fitted (taking account multiple scattering)

Drift time ↔ position relation described by 6 parameters received from “straight track calibration” runs

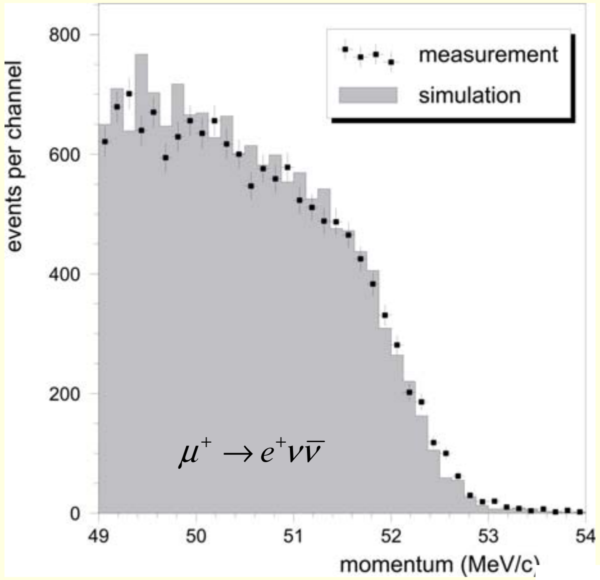
Energy calibration & resolution

Method:

use e⁺ spectrum from $\mu^+ \rightarrow e^+\nu\bar{\nu}$
stopped in the target

Requires:

- *mirror B-field (e⁺ track instead e⁻ track)*
- *lower B-field (by 52/95)*
- *check B-field linearity (Hall-probe)*
- *change beam line polarity*
- *lower beam momentum (→44 MeV/c)*

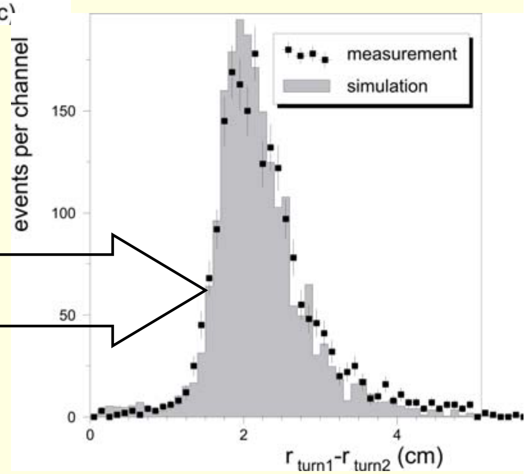


$B_{\mu e}$ = 1.069 ± 0.001 T
(central value)

Check resolution (at μe settings):
Compare radius of helical trajectories between 1. and 2. turn

Edge rise over 3mm gives
$\Delta p_t/p_t \approx 1\%$ *FWHM*

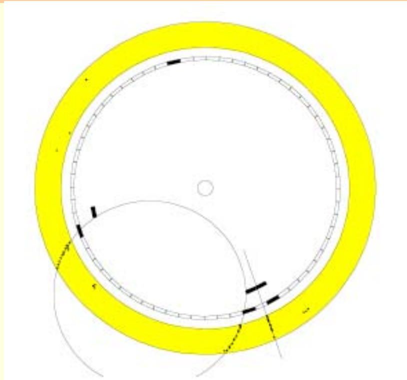
Edge position very sensitive to material budget



Cosmic ray induced background

3 classes of cosmic background events:

1) a track element from a high energetic cosmic muon is present together with a knock-on electron circular trajectory



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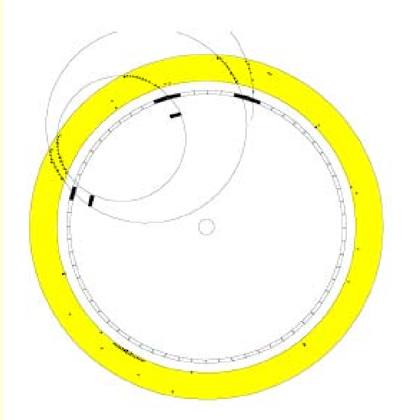
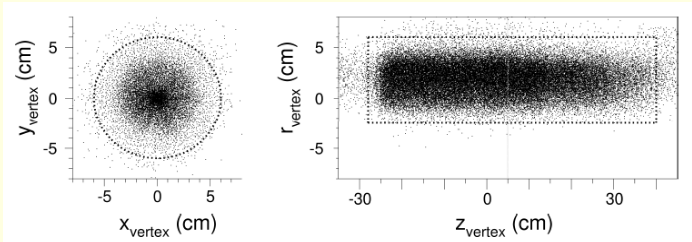
2) an electron enters the tracking region from outside → track does not origin in the target or has an early signal in one of the fast counters



Cuts applied in reconstruction are shown



3) a "cosmic" photon creates an asymmetric e^+e^- pair in the target

Minimized by:

- shielding from magnet return yoke and lateral lead walls
- low target mass
- a hole in the yoke on top (for supply lines) excluded in acceptance (loss ~4%)

Pion induced background

a) pion stops in target → negligible (beam tuning!)

b) rad. π capture in degrader + pair prod.

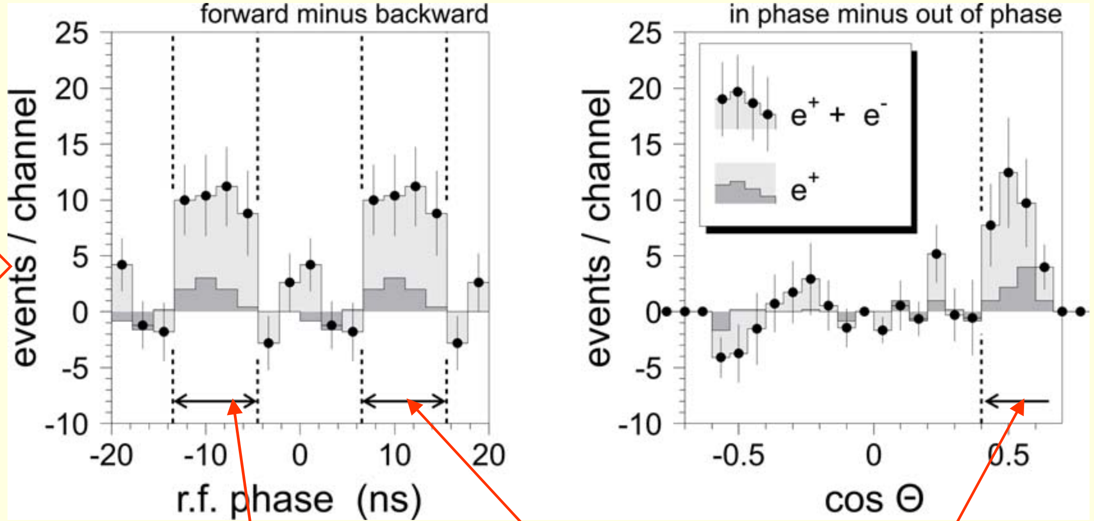
c) π decay in flight just before degrader

} e^- scattering off the target

b) is charge symmetric, c) not

e^+,e^- tracks with p>87MeV/c

(signal region excluded)



Expected:
flat background between 80 and 100 MeV/c (O(10) events)

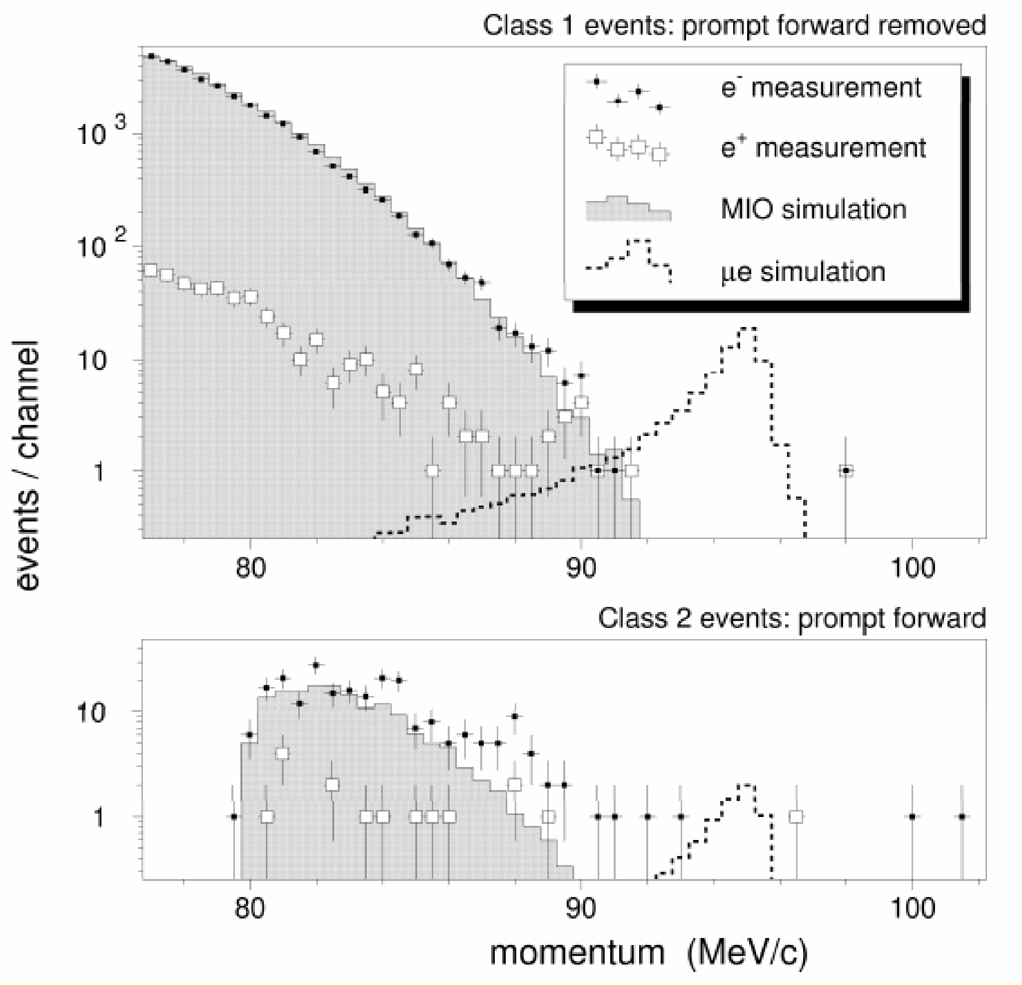
Beam correlated region containing pion induced events

(width given by beam momentum spread)

Final momentum spectra

2 event classes defined based on polar angle Θ and rf-phase t_{rf} :

1) $\cos\Theta < 0.4$ or $|t_{rf} - 10\ ns| > 4.5\ ns$
2) $\cos\Theta > 0.4$ and $|t_{rf} - 10\ ns| < 4.5\ ns$



Class 1: No sign for μ-e conversion events

Class 2: Approximately flat high energy component as expected from pion induced background

Single event sensitivity $S_{\mu e}$

$$S^i_{\mu e} = \frac{1}{N_\mu \cdot R_{capt} \cdot \Omega \cdot \varepsilon_i} \qquad i = 1,2$$

N_μ	$= (4.37 \pm 0.32) \times 10^{13}$	total number of muons stopped
R_{capt}	$= 0.9717 \pm 0.0002$	probability of muon capture in gold
Ω	$= 0.44$	spectrometer acceptance
ε_1	$= 0.19$	efficiency for events of class 1
ε_1	$= 0.014$	efficiency for events of class 2

$$S^1_{\mu e} = (2.8 \pm 0.2) \times 10^{-13}$$
$$S^2_{\mu e} = (3.7 \pm 0.2) \times 10^{-12}$$

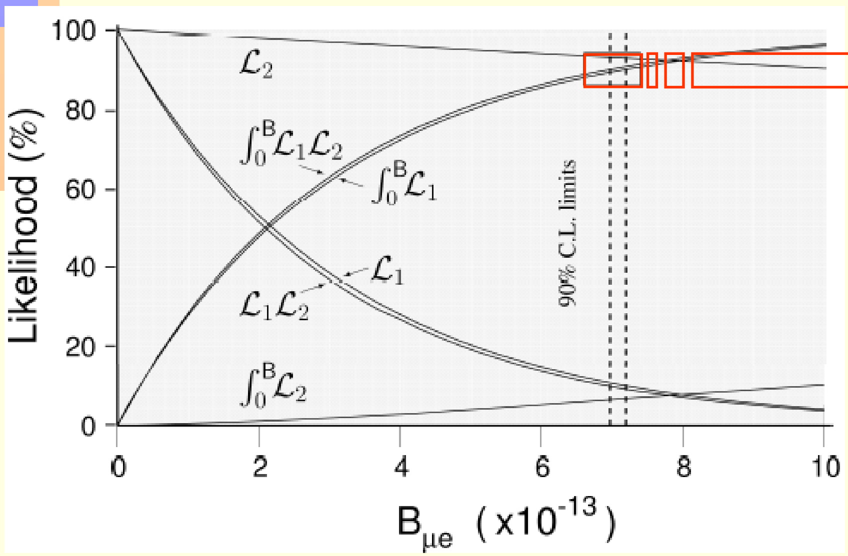
ε_i : derived from simulation with most parameters adjusted from measurements. Spectrum shape well reproduced. Finally lowered by ~10% to equate numbers of measured and expected MIO events

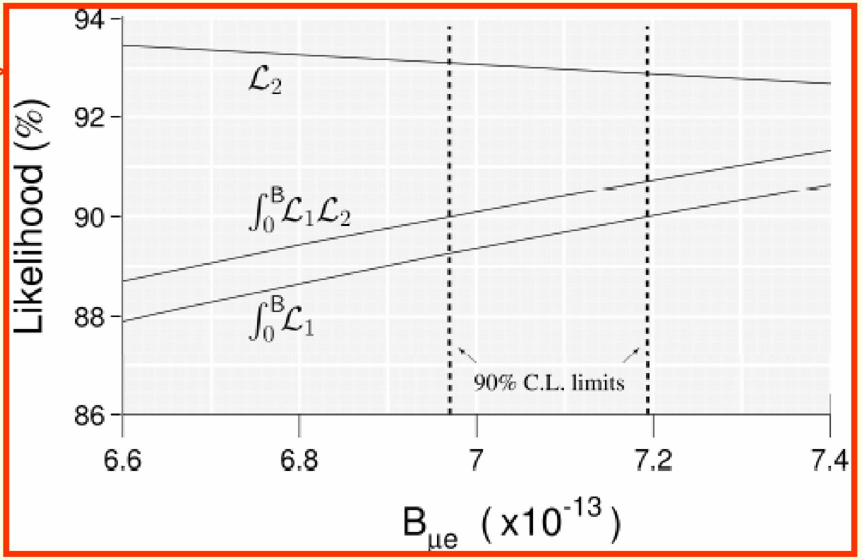
Likelihood analysis

4 contributions to the momentum spectra of class 1 and 2 events considered:

- *muon decay in orbit (MIO)*
- *μ – e conversion*
- *contribution from processes with intermediate photons (like RMC) (taken from observed e^+ spectrum)*
- *a flat component ($\pi \to e\nu$ decay-in-flight or cosmic backgrd.)*

Likelihood distribution $\mathcal{L}_{tot} = \mathcal{L}_1 \times \mathcal{L}_2$ ($\mathcal{L}_1$: class 1, $\mathcal{L}_2$: class 2):





Final Result

$$B_{\mu e} \equiv \Gamma\left(\mu^- Au \to e^- Au_{g.s.}\right) / \Gamma_{capture}\left(\mu^- Au\right)$$

Likelihood analysis ► zero μ-e conversion events are most likely

The upper limit at 90% confidence level is given by:

$$\int_0^{B_{\mu e}^{90\% C.L.}} \mathcal{L}_{tot}\, dB = 0.9$$

$$B_{\mu e}^{Au} < 7 \times 10^{-13}$$

(Accepted for publication in European Physical Journal C)

Improvement :
by 2 orders of magnitude to the previous best limit
W. Honecker et al.,(SINDRUM) Phys. Rev. Lett. 76, (1996) 200
and 3 orders of magnitudes to the best pre-SINDRUM limit
S. Ahmad et al. (TRIUMF) Phys. Rev. D 38 (1988) 2102.