rare μ decays

present limitations

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1. present limits on LFV involving charged leptons

2. work in progress
   - $\mu \to e\gamma$
   - $\mu \to 3e$
   - μe conversion

3. low momentum μ beam at the Proton Accumulator

4. beam requirements for
   10^3 fold increase in sensitivity

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LF violating decays

branching ratio limits

Decay mode	upper limit	Ref.	
$\mu^+ \to e^+\gamma$	1.2×10^{-11}	MEGA	1999
$\to e^+e^+e^-$	1.0×10^{-12}	SINDRUM I	1988
$\mu^- Ti \to e^- Ti$	6.1×10^{-13}	SINDRUM II	1997
$\to e^+ Ca^*$	3.6×10^{-11}	SINDRUM II	1997
$\mu^- Pb \to e^- Pb$	4.6×10^{-11}	SINDRUM II	1996
$\mu^- Au \to e^- Au$	1.9×10^{-11}	SINDRUM II	1999
$\mu^+ e^- \leftrightarrow \mu^- e^+$	8.3×10^{-11}	SINDRUM I	1999
$\tau \to e\gamma$	2.7×10^{-6}	CLEO	1997
$\tau \to \mu\gamma$	3.0×10^{-6}		
$\tau \to 3\mu$	1.9×10^{-6}	CLEO	1998
$\tau \to 2\mu e$	1.8×10^{-6}		
$\tau \to \mu 2e$	1.7×10^{-6}		
$\tau \to 3e$	2.9×10^{-6}		
$K^+ \to \pi^+ \mu e$	2.1×10^{-10}	BNL871	1998
$K_L^o \to \mu e$	4.7×10^{-12}	BNL791	1993
$B^o \to \mu e$	5.9×10^{-6}	CLEO	1994
$\to \tau e$	5.3×10^{-4}		
$\to \tau\mu$	8.3×10^{-4}		
$Z^0 \to e\mu$	1.7×10^{-6}	OPAL	1995
$\to e\tau$	9.8×10^{-6}		
$\to \mu\tau$	1.2×10^{-5}		

rare μ decays

sensitivity limitations

$\mu \to e\gamma$

	$\mu \to e\gamma$	$\mu \to 3e$	μe conversion medium Z	high Z
present limit final/0 evts by	$1.2 \cdot 10^{-11}$ MEGA (1999)	$1.0 \cdot 10^{-12}$ SINDRUM I (1988)	$6.1 \cdot 10^{-13}$? SINDRUM II (1997)	$1.6 \cdot 10^{-11}$ $4 \cdot 10^{-13}$ SINDRUM II (1999)
future/0 evts by	$3 \cdot 10^{-14}$ mini Kamiok.		10^{-16} MECO	
limited by	accidentals	detector rates	μ rate	beam
key param.	E_γ, Δt, θ	coplanarity vertex	momentum high-momentum tail pulsing	 beam purity
improvements (other than beam)	thinner target e^+ spectrom. IB veto	thinner target larger target detector granularity		
goal	10^{-15}	10^{-16}	10^{-18}	10^{-17}

but:

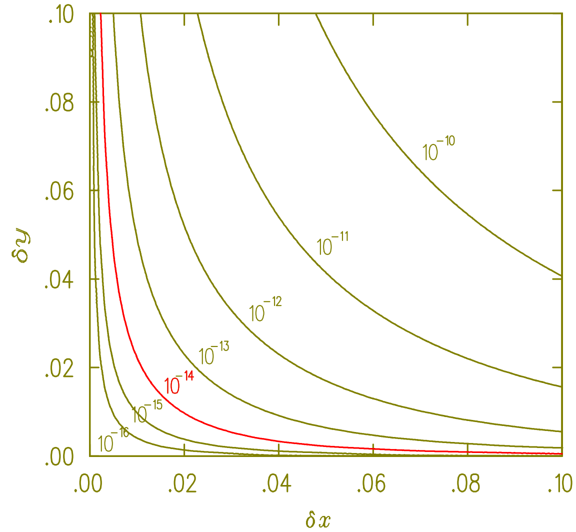
what do we know about detector technology in the year 2010?

$\mu \to e\gamma$ signal and background

$\mu e\gamma$ Sensitivity:

$$S = \frac{1}{N_\mu \cdot t \cdot (\Omega/4\pi)} \times \frac{1}{\varepsilon_e \cdot \varepsilon_\gamma \cdot \varepsilon_{cut}}$$

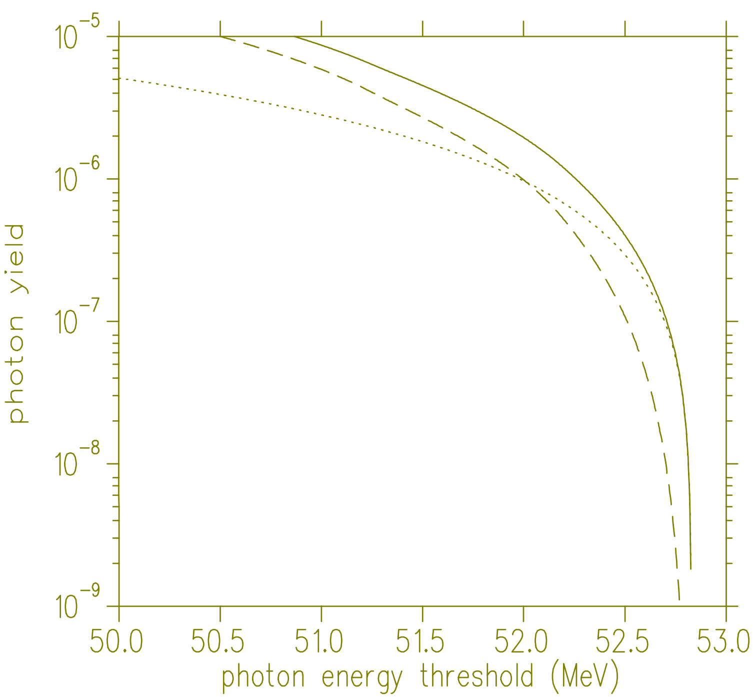
$N_\mu = 3 \times 10^8 s^{-1}$
$t = 10^7$ s
$\Omega/4\pi = 0.1$
$\varepsilon_e = 0.9$
$\varepsilon_\gamma = 0.8$
$\varepsilon_{cut} = 0.6$
$\Rightarrow S = 0.8 \times 10^{-14}$



Prompt background from $\mu^+ \to e^+\nu\bar{\nu}\gamma$ v.s. δx and δy.

$$B_{acc} = R_\mu 2\delta x \frac{\alpha}{2\pi}(\delta y)^2(\ln(\delta y) + 7.3)(\delta z/2)^2 2\delta t$$

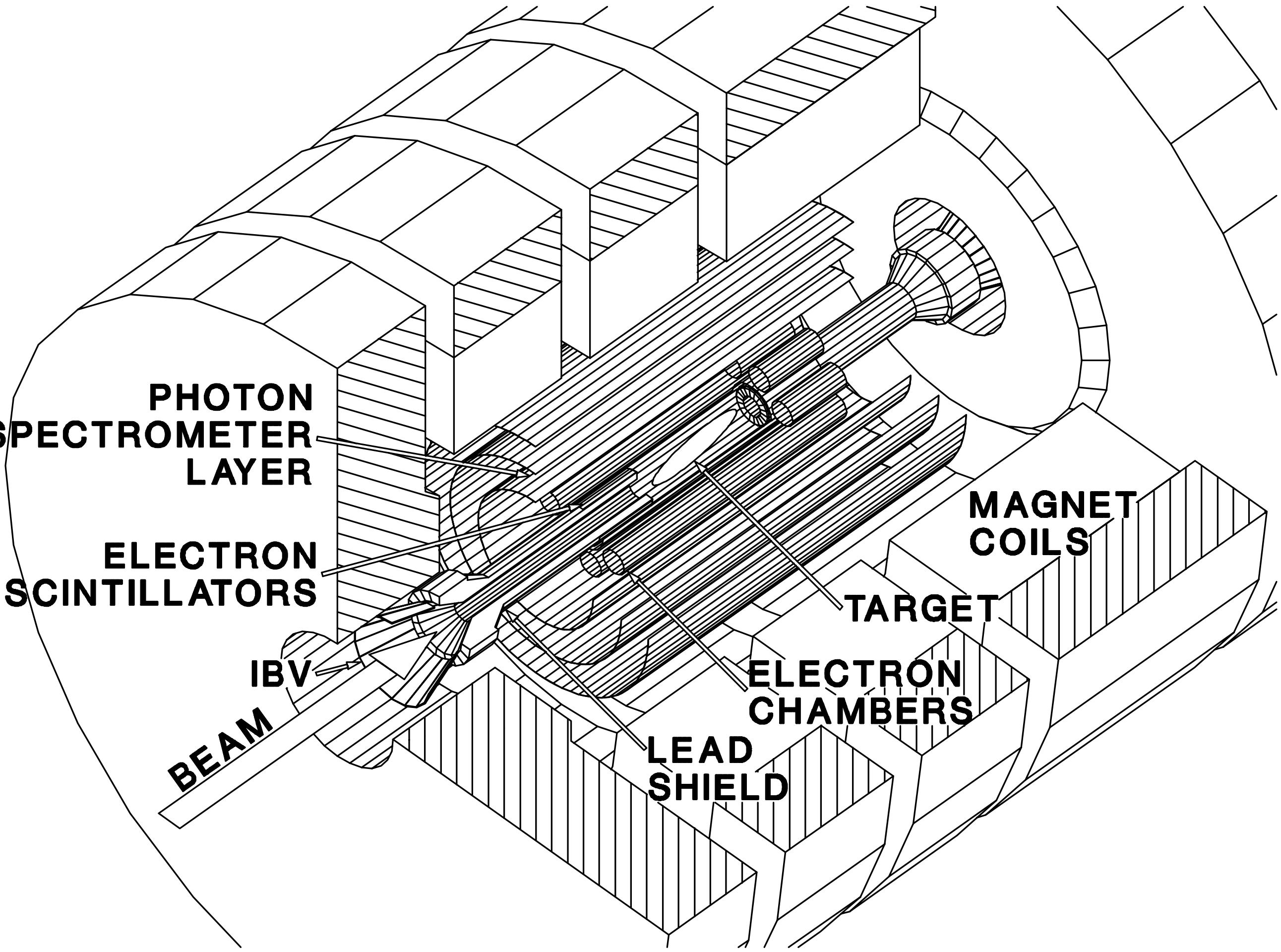
Δx(%)	Δy (%)	$\Delta\theta_{e\gamma}$ (rad)	Δt (ns)	B_{acc}
1	2	0.01	0.3	$2 \cdot 10^{-15}$
0.2	5	0.02	0.1	$2 \cdot 10^{-15}$



Photon yield v.s. threshold:
dotted: annihilation in flight
dashed: radiative muon decay

MEGA

LAMF search for $\mu \to e\gamma$

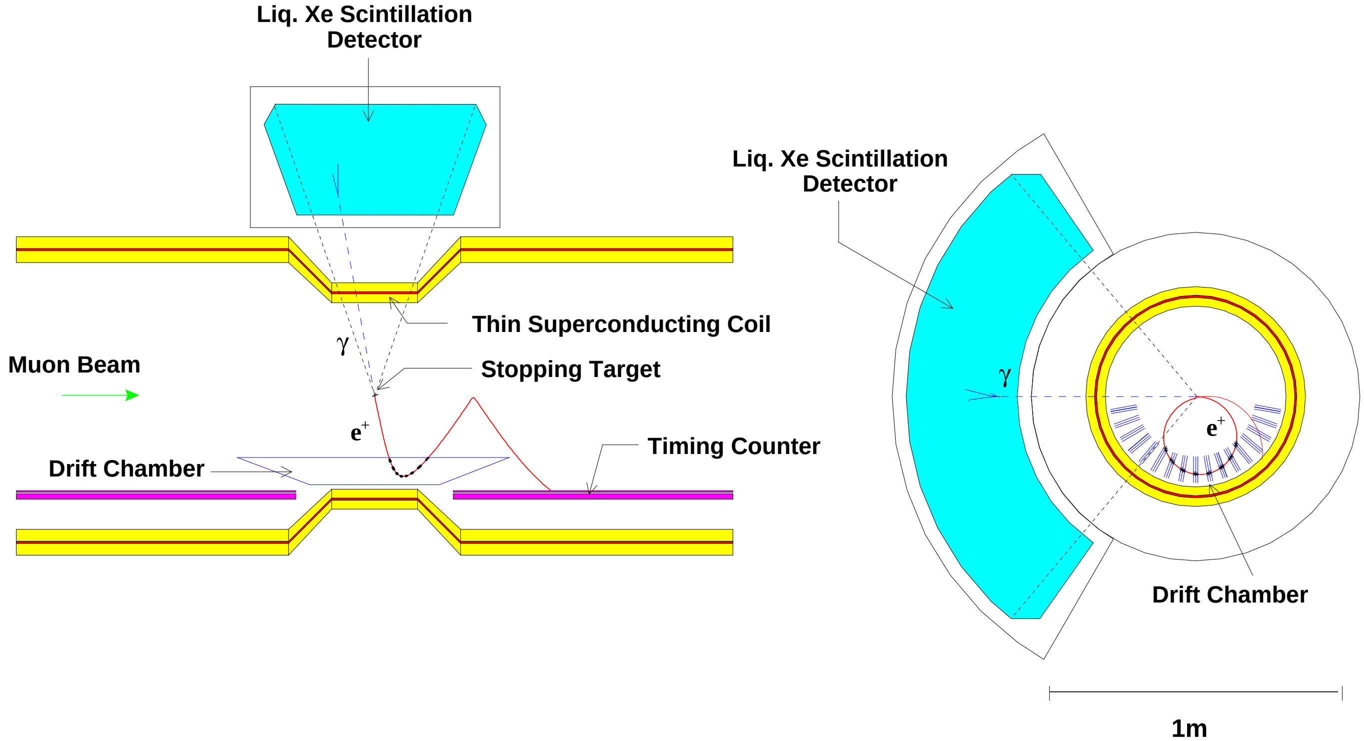


duty cycle	6-7 %
instantaneous stop rate	$2.5 \cdot 10^8 s^{-1}$
total number of stops	$1.2 \cdot 10^{14}$
total detection efficiency	0.43 %
90% C.L. upper limit (events)	5.1
90% C.L. upper limit (B)	$1.2 \cdot 10^{-11}$

Search for $\mu^+ \to e^+ \gamma$

down to 10^{-14} branching ratio

KEK-Nagoya-Novosibirsk-PSI-Tokyo-Waseda



schematic view of the detector (Fig.1 of proposal)

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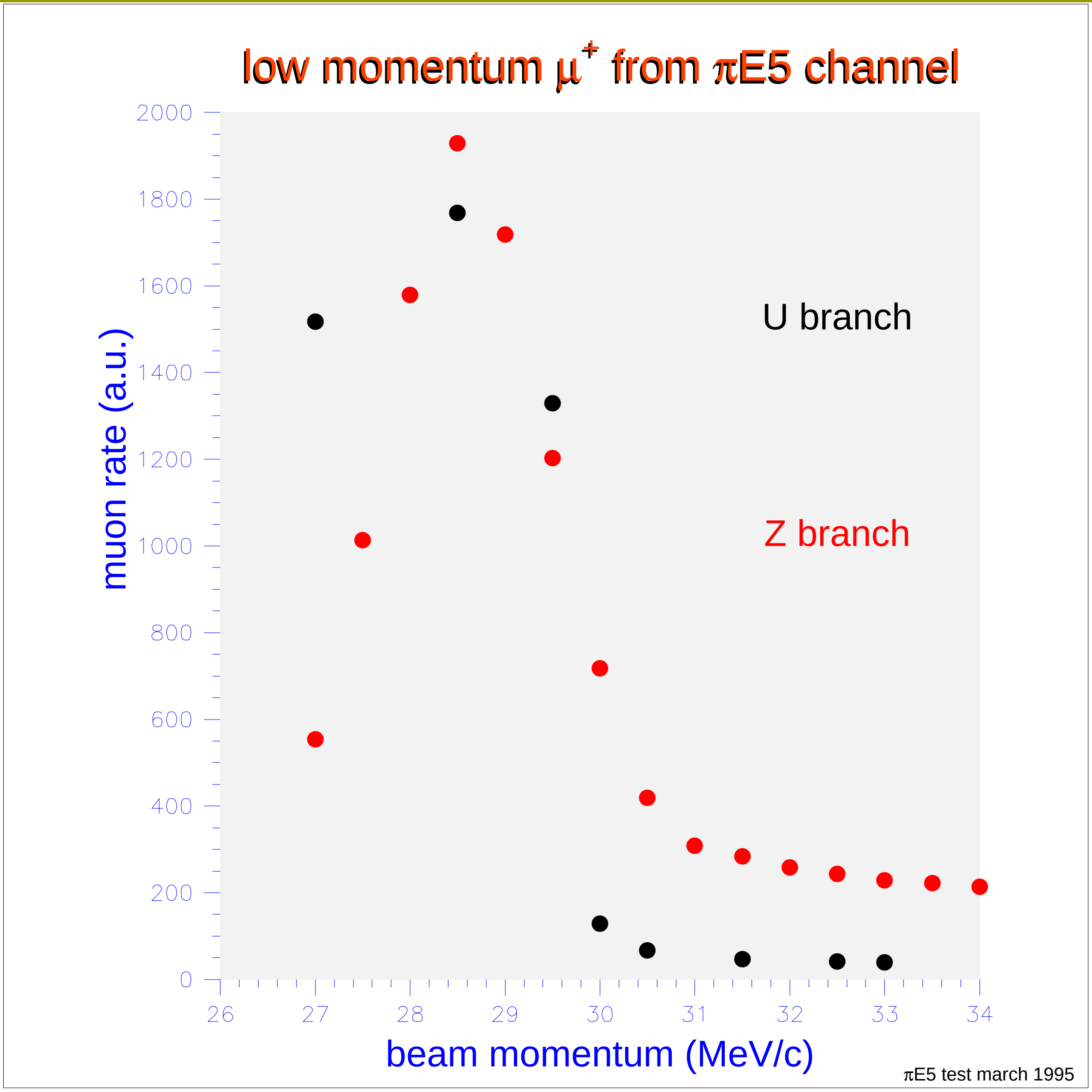
μ beams surface v.s. cloud PSI beam



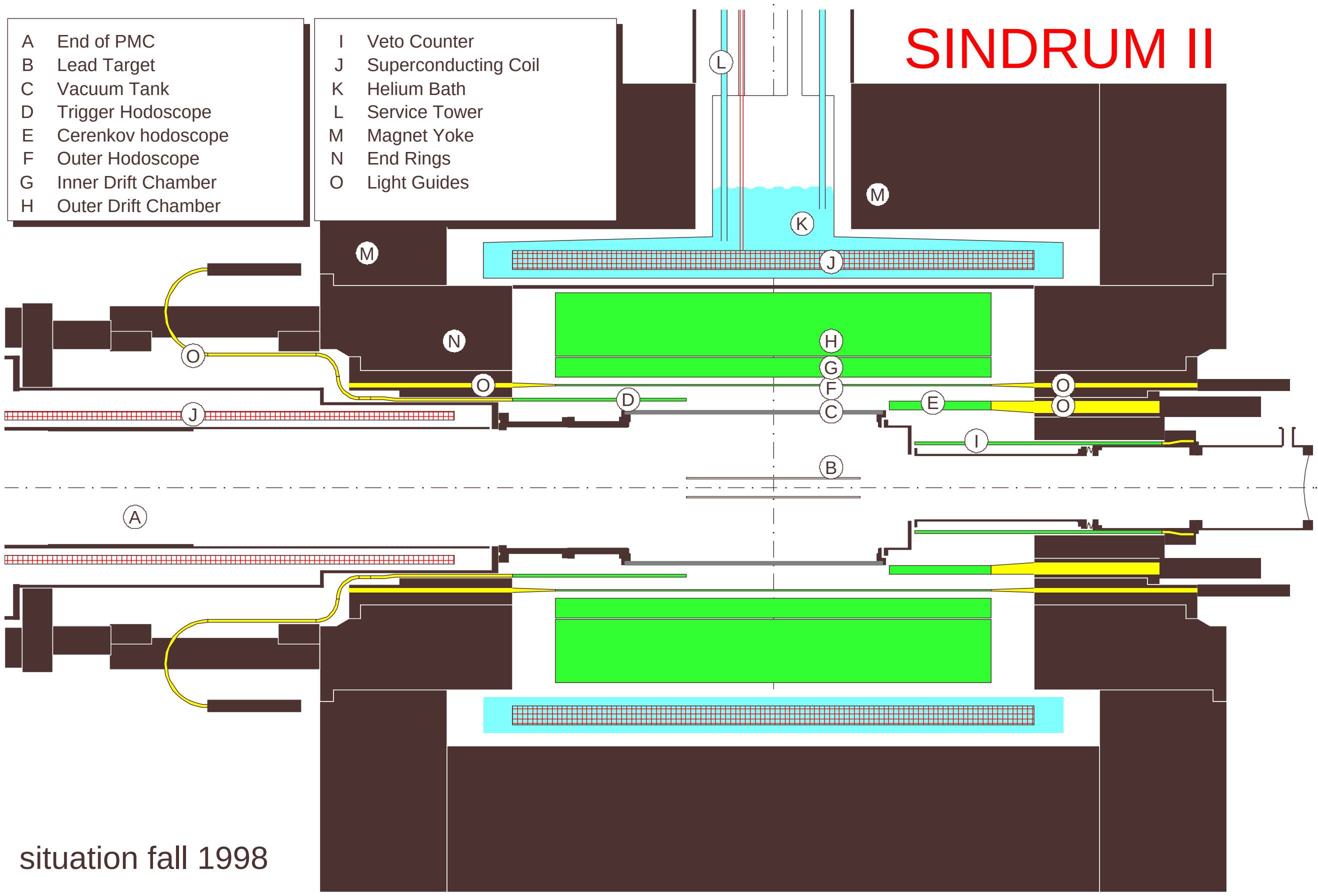
Z branch gives
≈ 3 times more surface μ^+ and
≈ 15 times more cloud μ^+ (and μ^-)

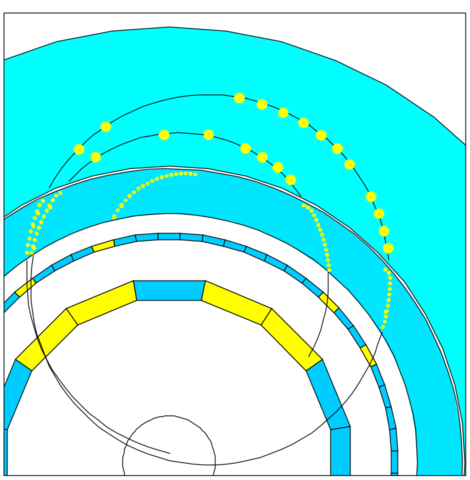
i.e. (for $\approx$6% momentum band)

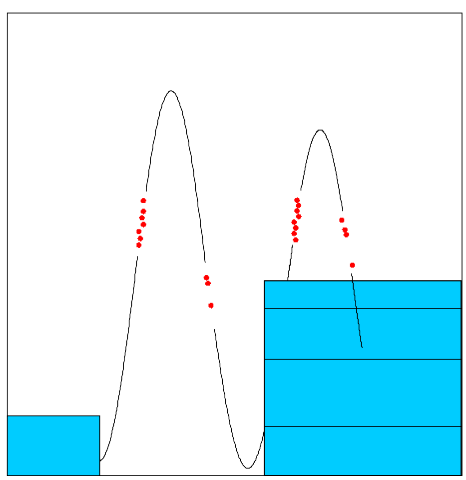
$3 \cdot 10^8\ \mu^+ s^{-1}$	around 28 MeV/c	
$3 \cdot 10^7\ \mu^- s^{-1}$	around 50 MeV/c	at 1.5 mA p on 6cm C

SINDRUM II

Search for $\mu^-(A,Z) \rightarrow e^-(A,Z)$







traces left by a 100.6 MeV/c e^- (1993 titanium data)

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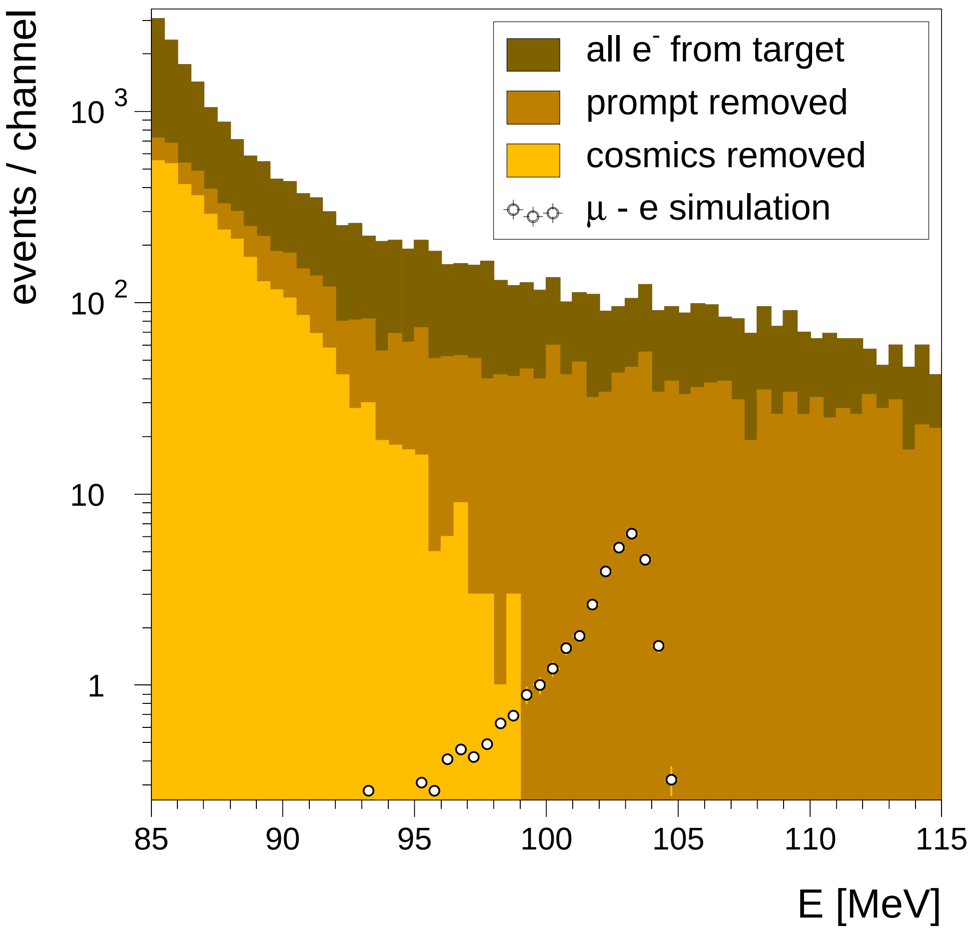
SINDRUM II

Search for $\mu^- Ti \rightarrow e^- Ti$

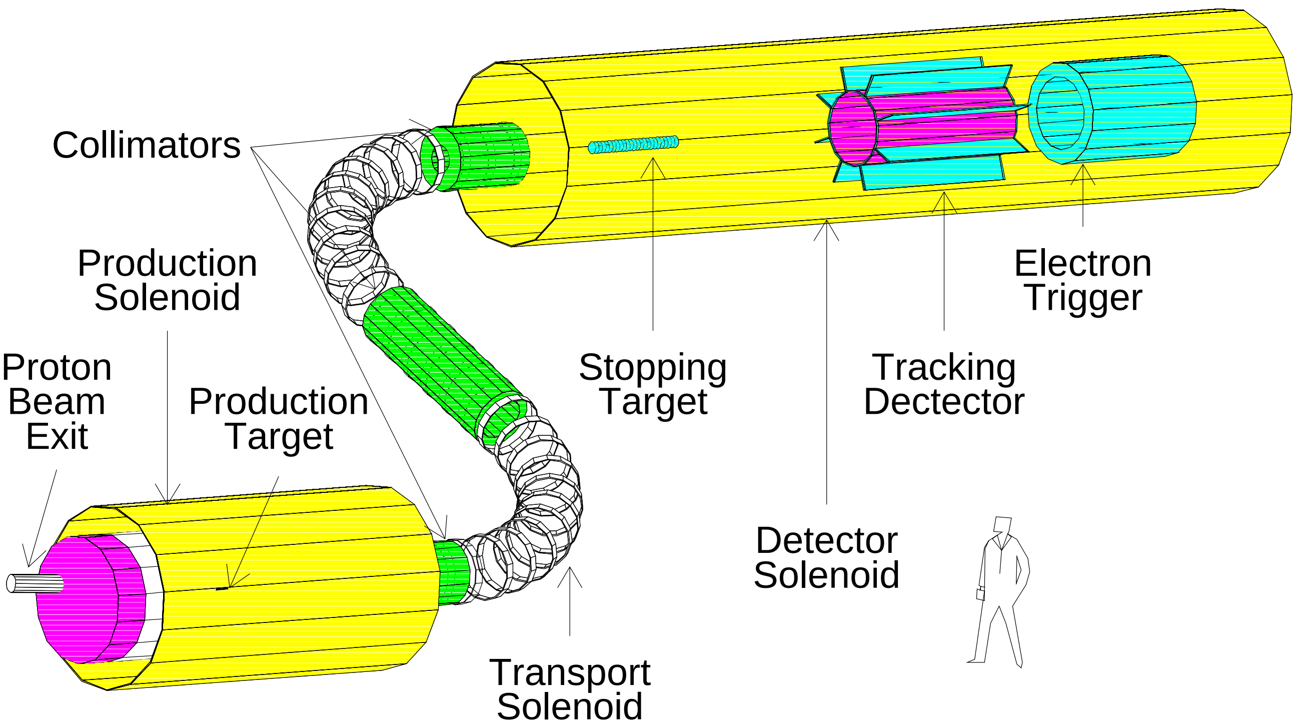


Electron energy distribution
at three stages of the event selection and as predicted by a GEANT simulation of μe conversion at $B_{\mu e} = 4 \cdot 10^{-12}$.

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}

MECO:

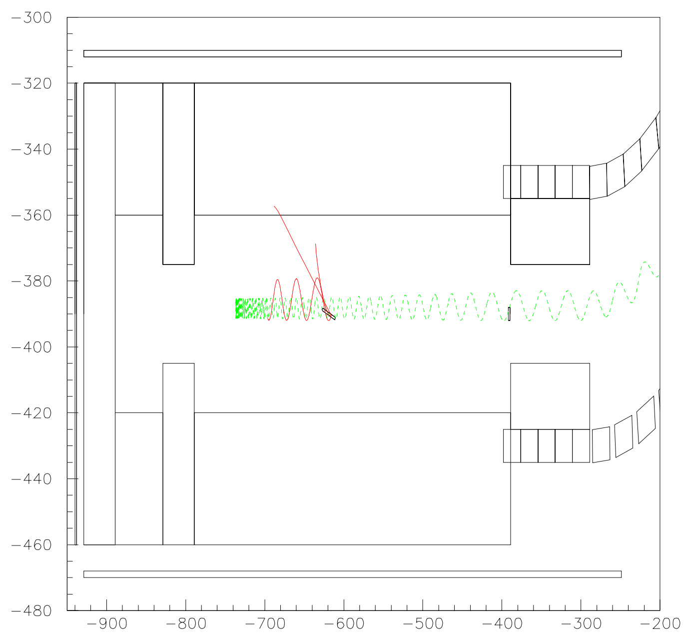
Search for $\mu^- N \to e^- N$ with Sensitivity Below 10^{-16}



The MECO beam and detector system.
The proton beam enters the production solenoid from the right side.

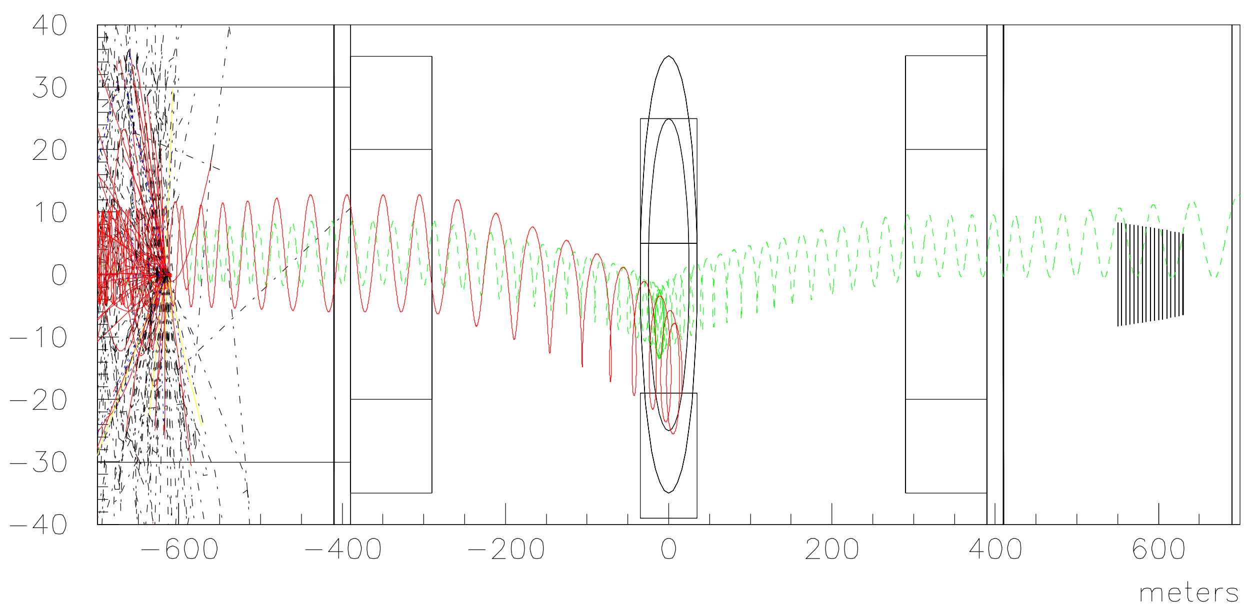
MECO:

Production and transport solenoids



π^- are produced in a 16 cm W target.

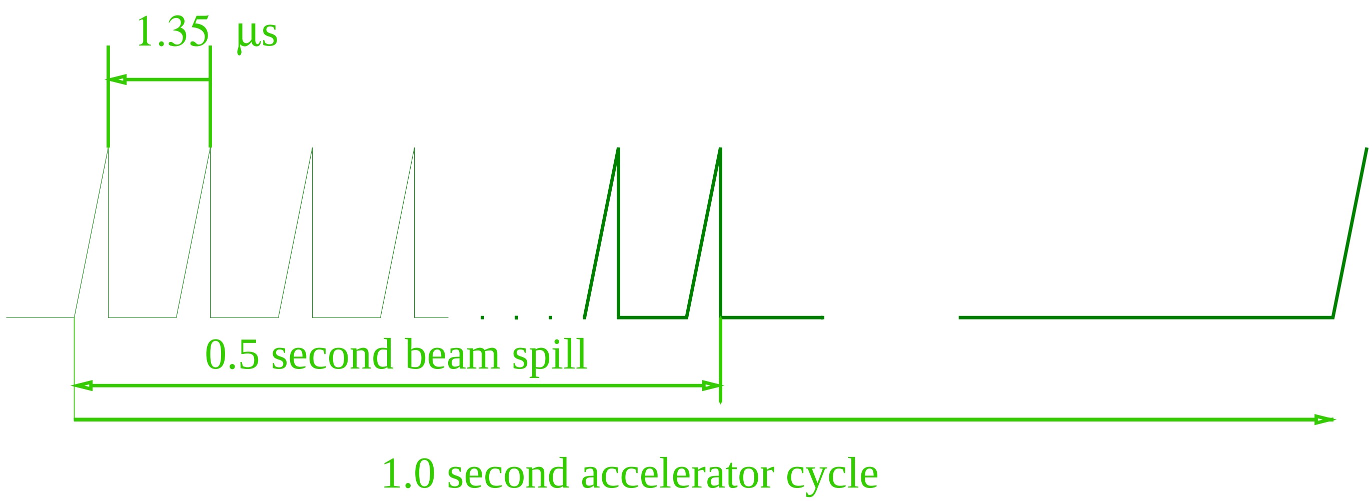
Decay μ^- are collected with a graded magnetic field.



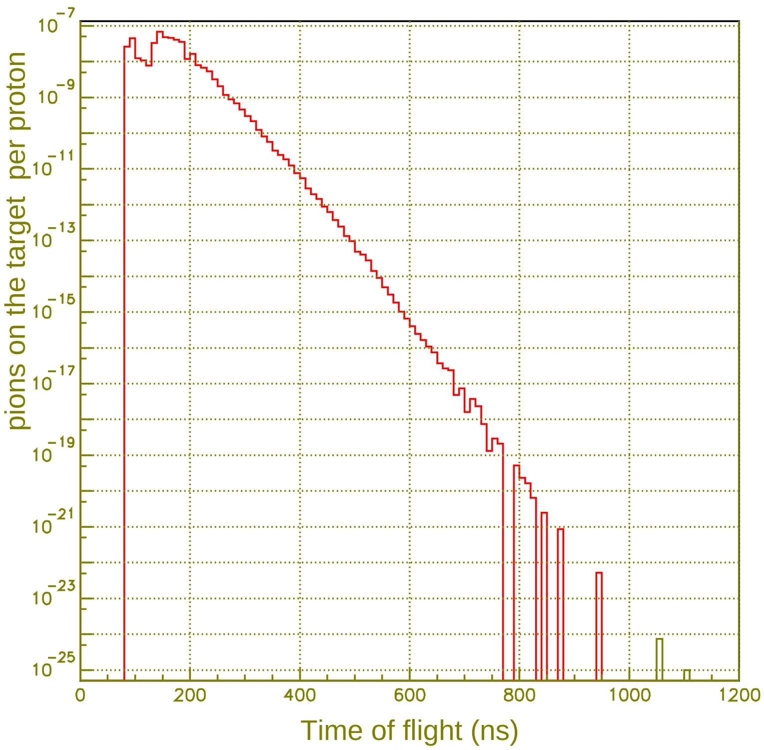
Simulated trajectories in production and transport solenoids. The downward drift in the curved solenoid depends on momentum. Positive charge drifts upward.

MECO:

beam pulsing



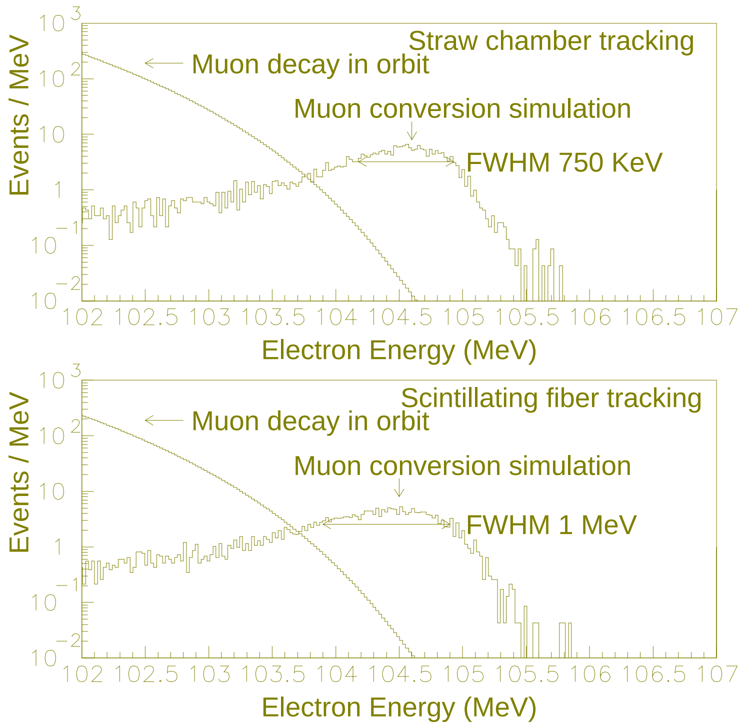
Proton beam structure.
Data are taken during second half of the time between two RF buckets.
The beam extinction in between the buckets has to be better than 10^{-9}.



Distribution of π^- arrival time

MECO:

expected result



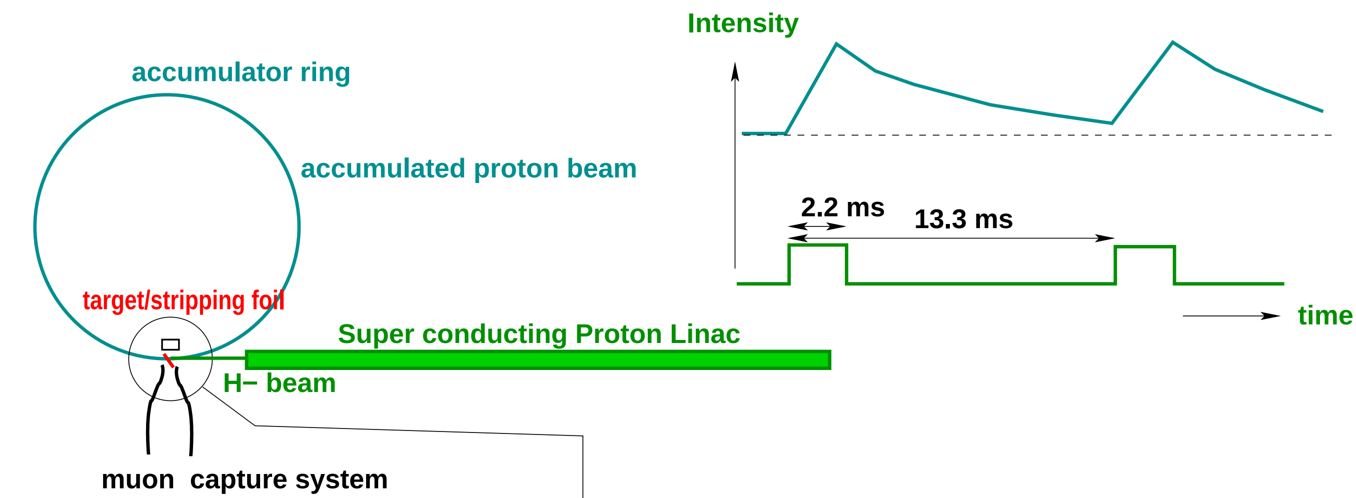
Simulation of expected signals and background at $B=10^{-16}$ in 10^7 s.

proton momentum	8	GeV/c
proton rate	4×10^{13}	/s
μ entering solenoid	1.7×10^{11}	/s
μ stops in target	1.0×10^{11}	/s
μ captured in Al	6×10^{10}	/s
fraction in Δt window	3×10^{10}	/s
"reconstructed"	5×10^{9}	/s
measuring time	10^7	s
seen at $B=10^{-16}$	5	

Proton Accumulator:

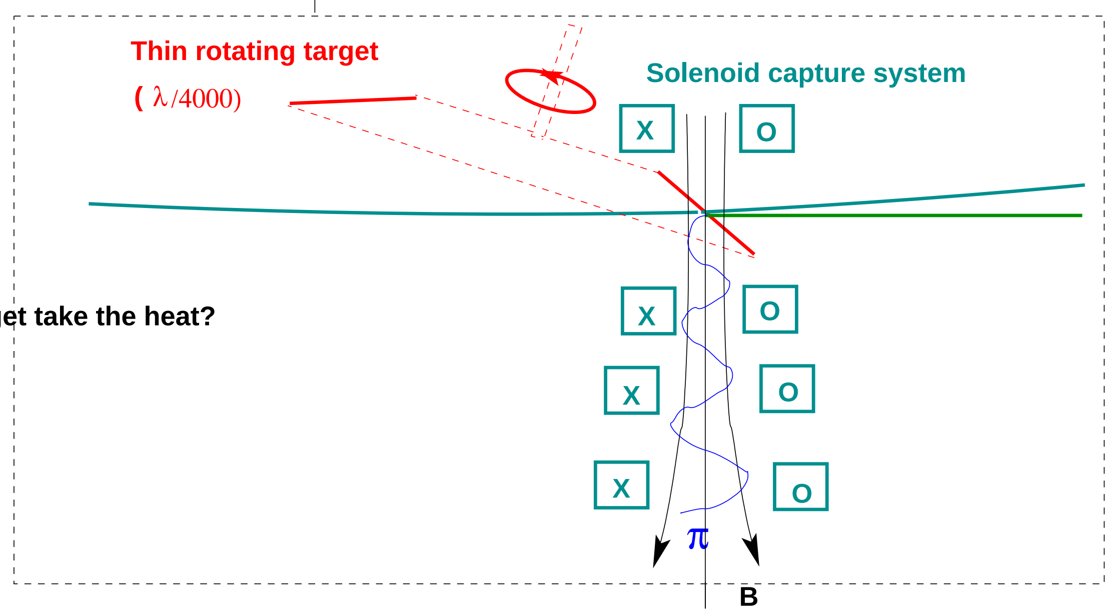
Low-momentum π and μ extraction

beam



A DC beam

from SPL?



issue # 1:

will thin rotating target take the heat?

under study.

surface μ^+

Highest μ^+ yields are obtained from decay at rest of π^+ that stopped in the surface of the production target

cloud μ^-

Low momentum μ^- beams orginate in the decay of slow π^- in the region around the production target.

rare μ decays

beam requirements

hopes and wishes

for $\mu \to e\gamma$ and $\mu \to 3e$:
- (sub)surface μ^+ beam
- DC on the scale of the muon lifetime
- at least 10^{11} $\mu^+ s^{-1}$
- e/μ < 1%

for μe conversion on medium Z target:
- pulsed beam of cloud μ^-
- pulse width ≈100 ns or less
- extinction factor <10^{-11}
- momentum 50-70 MeV/c
- at least 10^{13} $\mu^- s^{-1}$

for μe conversion on any target:
- very clean cloud μ^-
- momentum around 50-60 MeV/c
- momentum resolution few percent for π/μ range separation - long channel (50 m or more) to suppress pions
- at least 10^{12} $\mu^- s^{-1}$
- e/μ < 1%