Muon physics

a van der schaaf - zürich

	lab/project	WG speaker	gain soon	gain νfac*
Fundamental properties				
g-2	BNL E821		20	200
e.d.m.	BNL E821 loi		1000000	10000000
Normal decay				
muon lifetime	RAL	Tomono	2	200
	PSI	Malgeri	20	200
Michel parameters	TRIUMF 614		30	
e^+ polarisation	PSI	Fetscher		
Lepton flavor violation				
theoretical speculation				
		Shimizu, Shimoyama, Koike, Sato, Babu		
$\mu \to e\gamma$	PSI	Signorelli	500	10000
$\mu^+ \to e^+e^+e^-$, $\mu^+e^- \leftrightarrow \mu^-e^+$				10000
μe conversion	SINDRUM II	v.d. Schaaf	10-100	
	MECO	Aoki	50000	
	PRISM/PRIME	Kuno, Sato		1000000
Bound systems				
μ^+e^- (QED tests)				
μ^-p, μ^-A^* (g_p, nuclear radii, moments)				
μ^- catalysed fusion		Ishida		
(Surface) μsr				
slow muons	PSI			
	KEK	Matsuda		
Beams		Nagamine		
beam requirements (time structure)				

see talk by Nagamine

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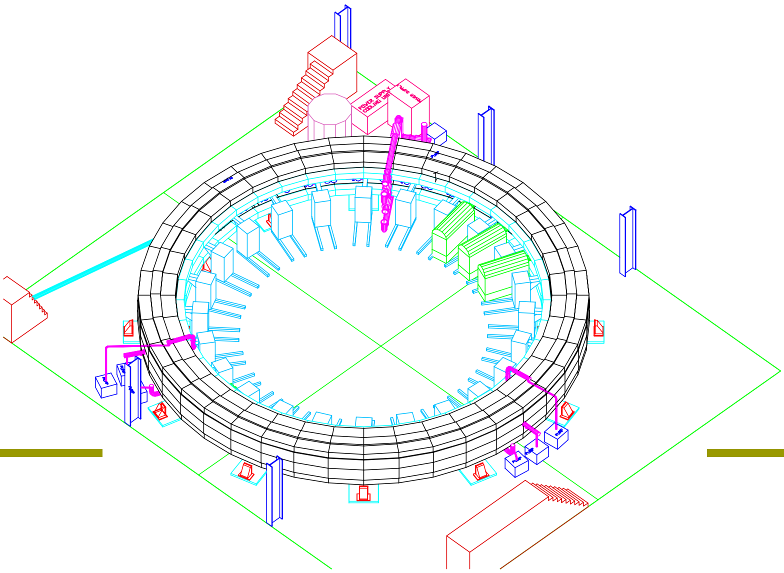
* CERN Stopped Muons Working Group
CERN-TH/2001-231 hep-ph/0109217

London, July 1st 2002

Muon g-2

BNL E821



anomalous magnetic moment $a \equiv (g-2)/2$:

$a_{\mu,e} = 0 + \alpha/2\pi + \ldots$ = $11614098 \times 10^{-10} + \ldots$

for $e^{\pm}$:

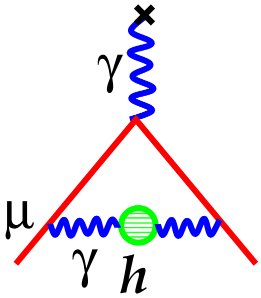
e^{+}	$11596521.879(43) \times 10^{-10}$	(4 ppb)
e^{-}	$11596521.884(43) \times 10^{-10}$	(4 ppb)
calculated (e.m.)	$11596521.54(24)) \times 10^{-10}$	(21 ppb)

the comparison is limited by the knowledge of α
(or a_e is a measure of α).

for μ^{+}:

measured (1999 data)	$11659203(15) \times 10^{-10}$	(1.3 ppm)
calc. (SM total)	$11659176.7(6.7) \times 10^{-10}$	(0.6 ppm)
calc. (e.m.)	$11658470.6(0.3) \times 10^{-10}$	(21 ppb)

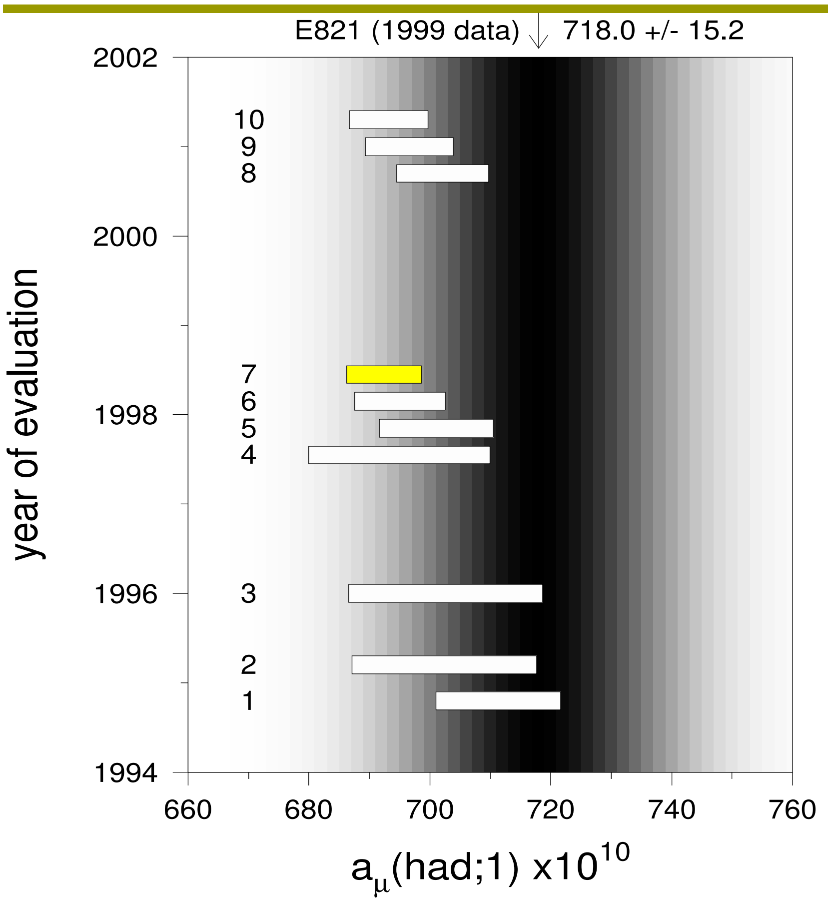
calc. (total non e.m.)	$706.1(6.7) \times 10^{-10}$
calc. (1st order hadronic)	$692.4(6.2) \times 10^{-10}$
measured (1st order hadronic)	$718(15) \times 10^{-10}$
difference	$25(16) \times 10^{-10}$



main uncertainty in S.M. prediction comes from this lowest order hadronic contribution.

Muon g-2

lowest order hadronic contribution



10	Eidelman
9	Troconiz and Indurain
8	Narison
7	Davier and Hoecker
6	Davier and Hoecker
5	Alemany, Davier and Hoecker
4	Alemany, Davier and Hoecker
3	Brown and Worstell
2	Eidelman and Jegerlehner
1	Adel and Indurain

- New e^+e^- data from Novosibirsk have recently been published which will permit a_μ(hadr;1) to be determined to about 6×10^{-10} just from e^+e^- data, without using the hadronic τ decay.

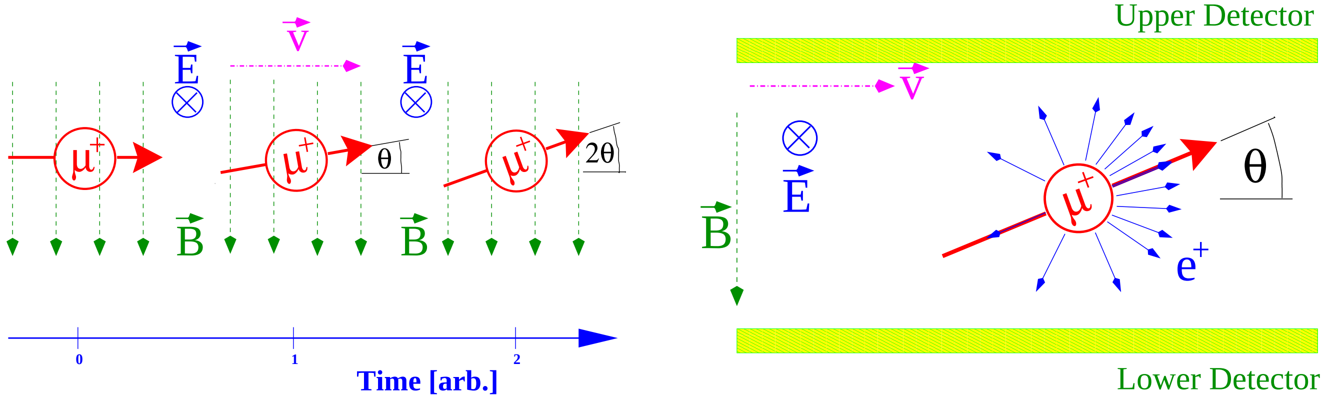
- Davier, Höcker and Eidelman are working on a new analysis of these data.

- BNL E821 hopes to have a new number by the end of the summer. It will have about half the error of the previous result.

Muon electric dipole moment

T violation

	edm (e.cm)
Standard Model:	10^{-35}
present limit:	10^{-18}
proposed sensitivity	10^{-24}
electron limit:	10^{-27}



Principle of a novel muon edm measurement.
Muons move in a magnetic storage ring with a radial E field superimposed. Θ would grow with time.

$$\vec{\omega} = -\frac{e}{m}\{a\vec{B} + (\frac{1}{\gamma^2-1} - a)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B})\}$$

$$\mathrm{edm}_\mu = \frac{\eta}{2}\frac{e\hbar}{2mc}\ \mathrm{e.cm}$$

g-2	$\frac{1}{\gamma^2-1} - a = 0$	$\gamma = 29.3$
edm	$a\vec{B} + (\frac{1}{\gamma^2-1} - a)\frac{\vec{\beta}\times\vec{E}}{c} = 0$	$\gamma = 5$, B=0.24T, E=2MV/m

Normal muon decay

$\mu^+ \to e^+ \nu_e \overline{\nu_\mu}$

TRIUMF experiment 614 (TWIST) *Precision measurement of the Michel parameters from muon decay*

$$\Gamma \propto x^2(3 - 3x + \tfrac{2}{3}\rho(4x-3) + P_\mu \xi z(1 - x + \tfrac{2}{3}\delta(4x-3))$$

$x \equiv 2p_e/m_\mu c$, $z \equiv \cos\theta$

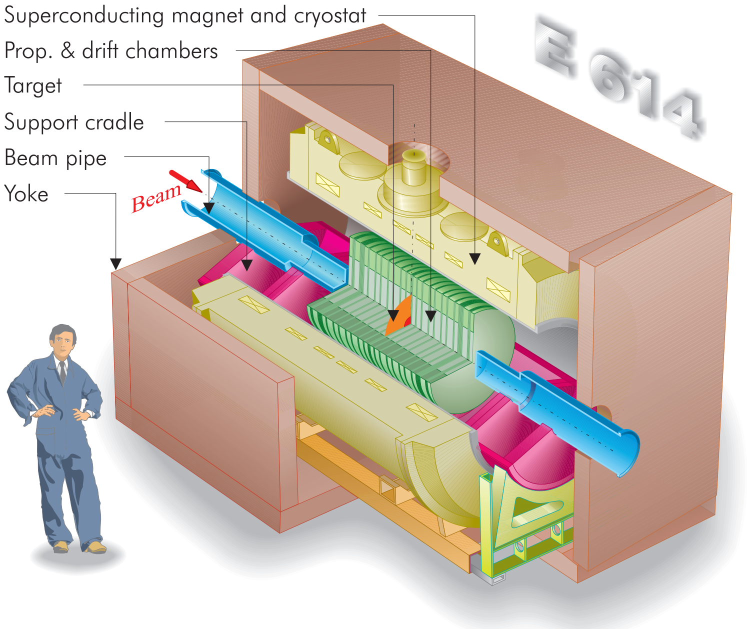
V-A: $\rho = 3/4$, $P_\mu\xi = 1$, $\delta = 3/4$.

Couplings (present limits):

$\lvert g^S_{RR}\rvert$	$<$	0.066	$\lvert g^V_{RR}\rvert$	$<$	0.033	$\lvert g^T_{RR}\rvert$	$\equiv$	0
$\lvert g^S_{LR}\rvert$	$<$	0.125	$\lvert g^V_{LR}\rvert$	$<$	0.060	$\lvert g^T_{LR}\rvert$	$<$	0.036
$\lvert g^S_{RL}\rvert$	$<$	0.424	$\lvert g^V_{RL}\rvert$	$<$	0.110	$\lvert g^T_{RL}\rvert$	$<$	0.122
$\lvert g^S_{LL}\rvert$	$<$	0.55	$\lvert g^V_{LL}\rvert$	$>$	0.96	$\lvert g^T_{LL}\rvert$	$\equiv$	0

V-A: $|g^V_{LL}| = 1$, all others zero.

Goal: reduce errors in parameters by factors 25-60.
limits on couplings by factors 3-10.
in particular $1 - |g^V_{LL}|$ by factor 100



cloud μ^+ rejected by timing

select 25μm skin of production target for minimal depolarization

data taking started in May

this experiment is not limited by beam intensity

TRIUMF 614

status and prospects

Dave Gill:

year	action	comment
2001	engineering run	specs met
2002	spectrometer field map	inhomogeneity can be neglected at present
2002	beam study	performs as expected

Nufact'02

2002	1st physics run	ρ and δ at 10^{-3}
2004		ρ and δ at 10^{-4}
		$P_\mu \xi$ at 10^{-3}
2005		$P_\mu \xi$ at 10^{-4}

LF violating decays

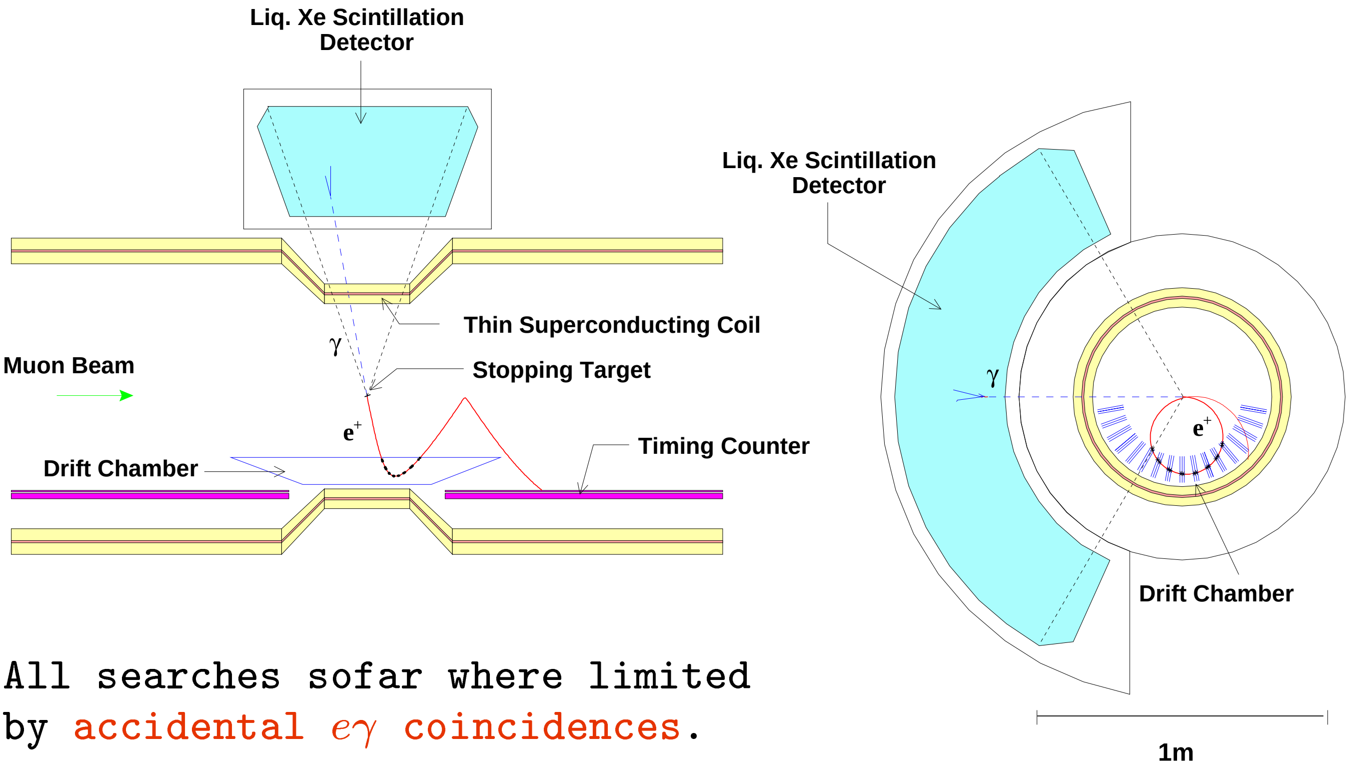
branching ratio limits

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}		
$K^+ \to \pi^+\mu e$	2.8×10^{-11}	BNL 865	2000
$K_L^o \to \mu e$	4.7×10^{-12}	BNL 871	1998
$K_L^o \to \pi^0\mu e$	3.1×10^{-9}	FERMI 799	1998
$B^o \to \mu e$	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}		

see Giovanni Signorelli on Wednesday

Search for $\mu^+ \rightarrow e^+\gamma$
down to 10^{-14} branching ratio

KEK-Nagoya-Novosibirsk-Pisa-PSI-Tokyo-Waseda



All searches sofar where limited by accidental $e\gamma$ coincidences.

Figure of merit for signal/background:

$$\boxed{M \equiv \frac{\text{Duty cycle/rate}}{\Delta x \Delta^2 y \Delta t \Delta^2 \theta}}$$

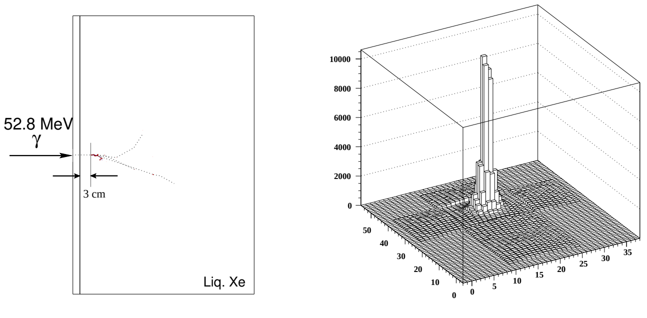
Exp.	year	Δx %fwhm	Δy %fwhm	$\Delta t_{e\gamma}$ ns	$\Delta\theta_{e\gamma}$ mrad	μ^+ rate 1/s	Duty cycle	M
SIN (PSI)	'77	8.7	9.3	1.4	-	$5 \cdot 10^5$	1	$4.7 \cdot 10^7$
TRIUMF	'77	10	8.7	6.7	-	$2 \cdot 10^5$	1	$2.5 \cdot 10^7$
LANL	'79	8.8	8	1.9	37	$2.4 \cdot 10^6$	0.06	$1.7 \cdot 10^7$
Cryst.Box	'86	8	8	1.3	87	$4 \cdot 10^5$	0.075	$3.7 \cdot 10^7$
MEGA	'99	1.2	4.5	1.6	17	$1.5 \cdot 10^7$	0.075	$4.4 \cdot 10^8$
PSI		0.7	1.4	0.15	12	10^8	1	$3.4 \cdot 10^{11}$

Liquid Xenon scintillator

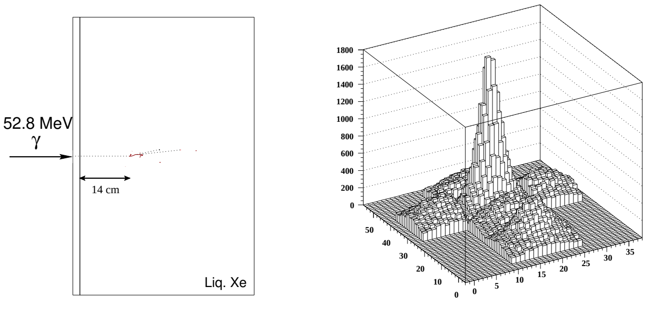
mini-Kamiokande

properties of liquid xenon

density	3.0 g/cm^2
refractive index	1.57
boiling point	165 K
melting point	161 K
photons per MeV	40000
radiation length	2.77 cm
decay time	4.2-45 ns
wave length	174 nm
absorption length	?



(a)



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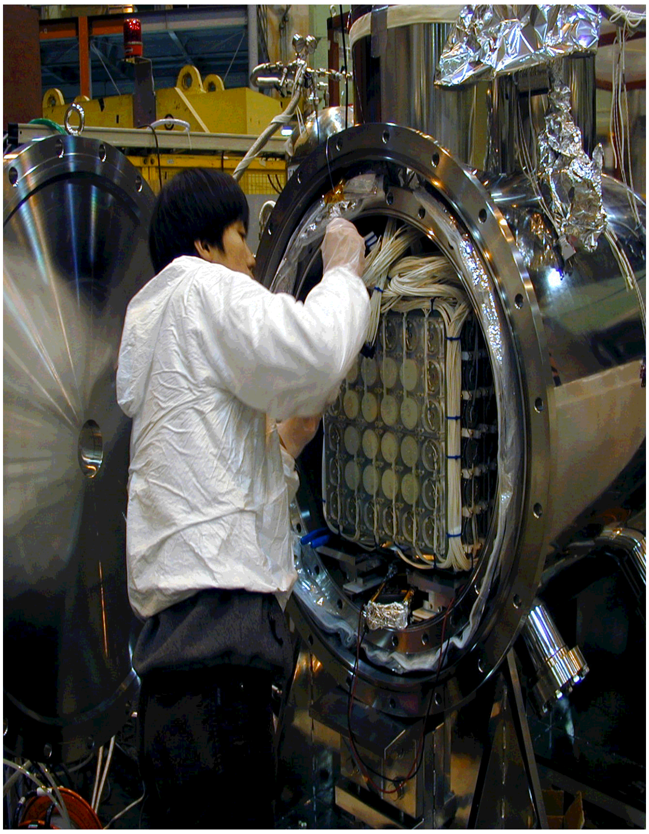
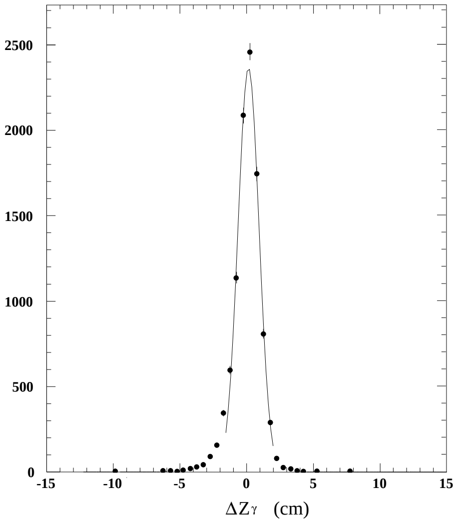
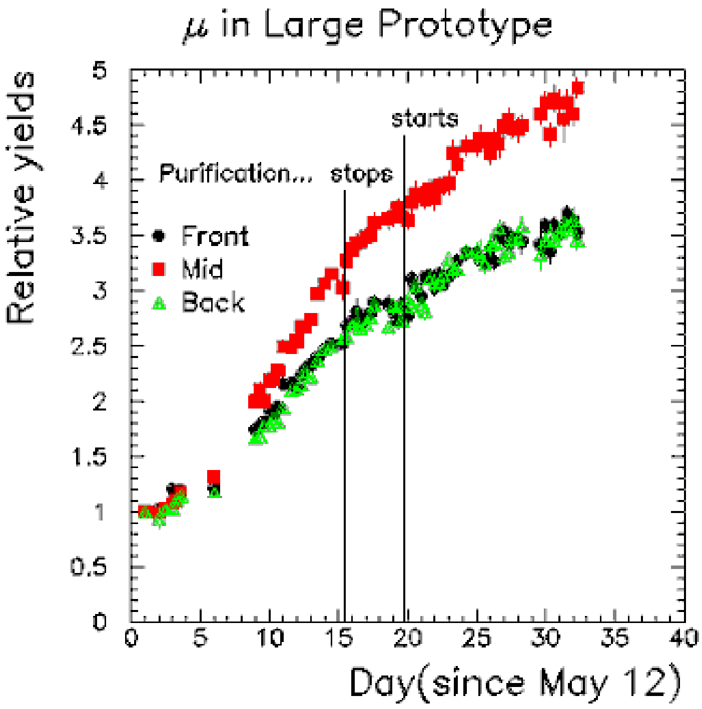


1/3 scale prototype

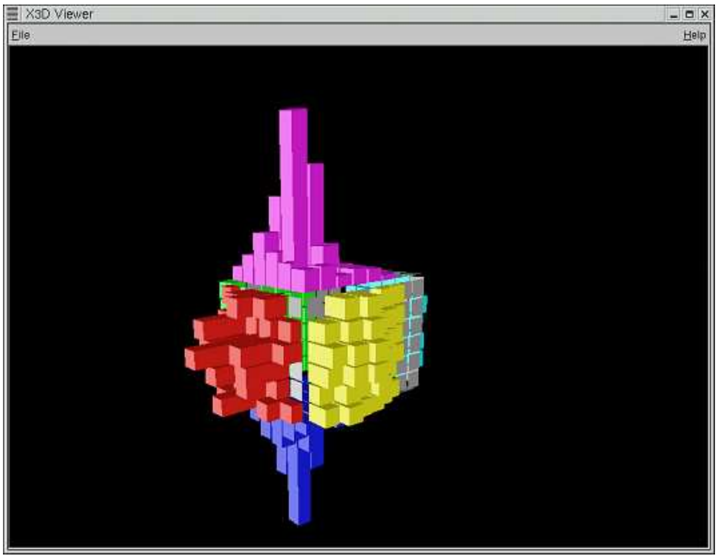


mini-Kamiokande

recent progress on Xenon purity



fighting H_2O
contamination



cosmic muon seen by
the mini-Kamiokande
prototype

μe conversion searches

π^- induced background

strategies against beam-related background

1985	TRIUMF	beam counter
1993	PSI μE1	beam counter
2000	PSI πE5	beam quality
2006	BNL AGS	pulsed beam
2010	ν-factory (PRISM)	pulsed/quality

beam quality means:

- radiative π^- capture followed by $\gamma \to e^+e^-$ conversion

  at most 10^5 pions may stop in the target during the full measurement

- μ^- decay in flight

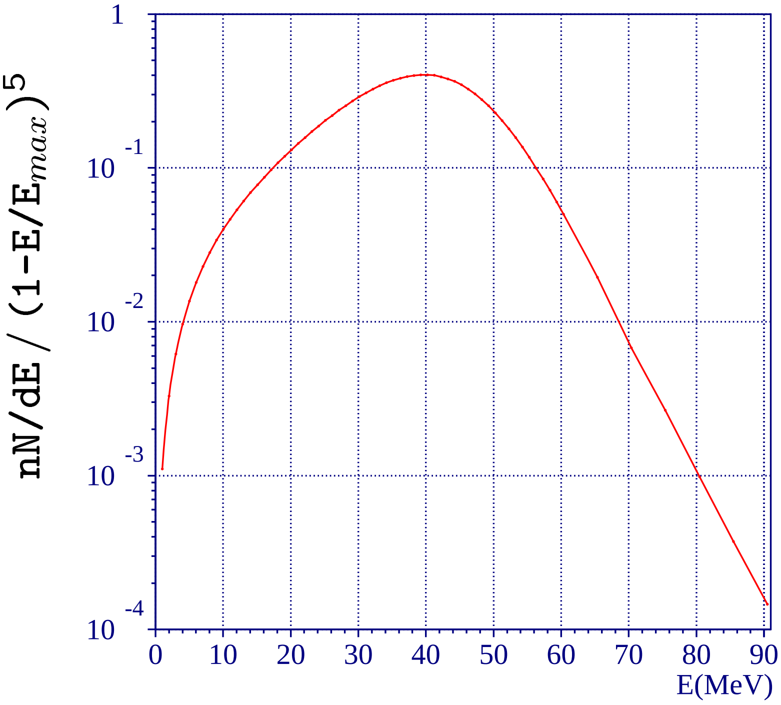
  beam momentum has to be below 60 MeV/c

Background processes

μ decay in orbit

The theoretical spectrum for μ decay in orbit was scaled from the lead spectrum

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



- fit to tabulated rates

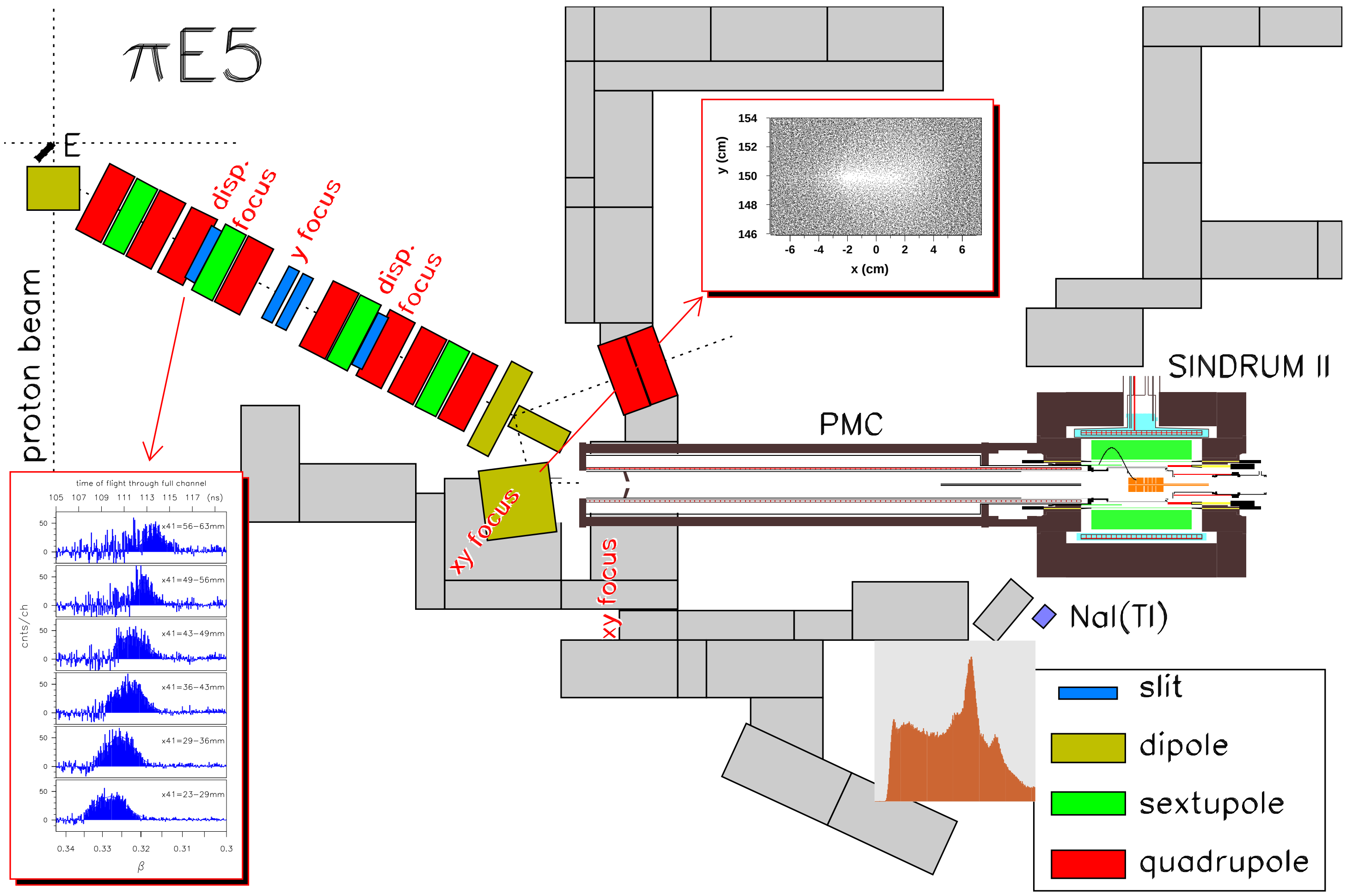
rate v.s. energy threshold for decay of muonic gold

threshold (MeV)	partial rate
70	1.72×10^{-5}
75	2.11×10^{-6}
80	1.64×10^{-7}
85	6.66×10^{-9}

PSI πE5

Z branch

μe



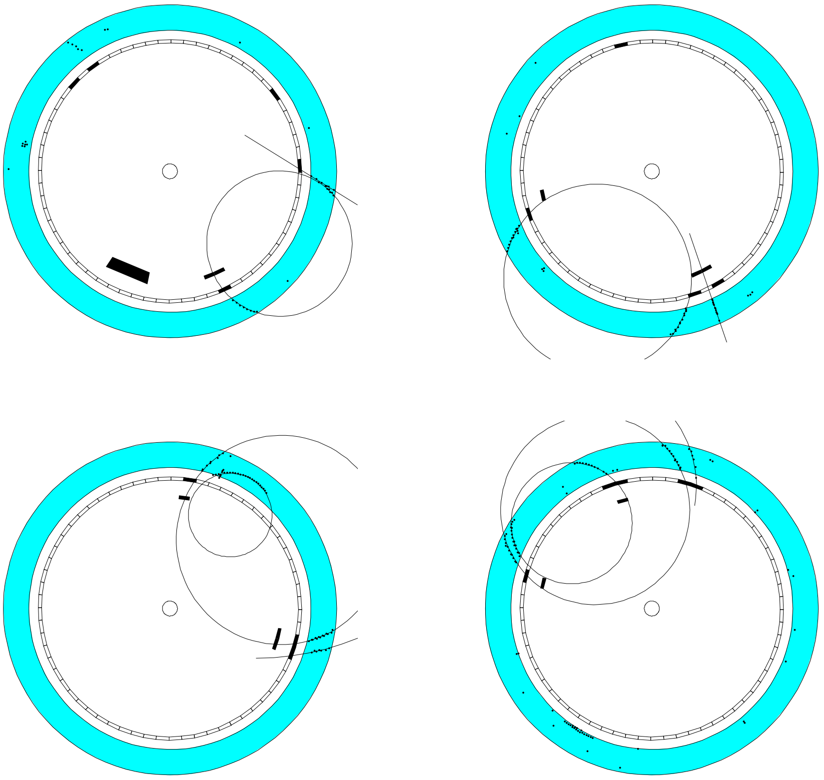
- The beam is tuned to 53 MeV/c with minimal high momentum tail

- muons just cross the moderator at the solenoid entrance

- pions stop there

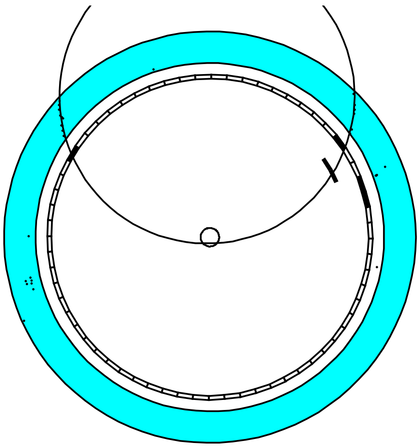
Background processes

cosmic background



Examples of cosmic background recognised by the track reconstruction.

These events do not enter the sample of contained events



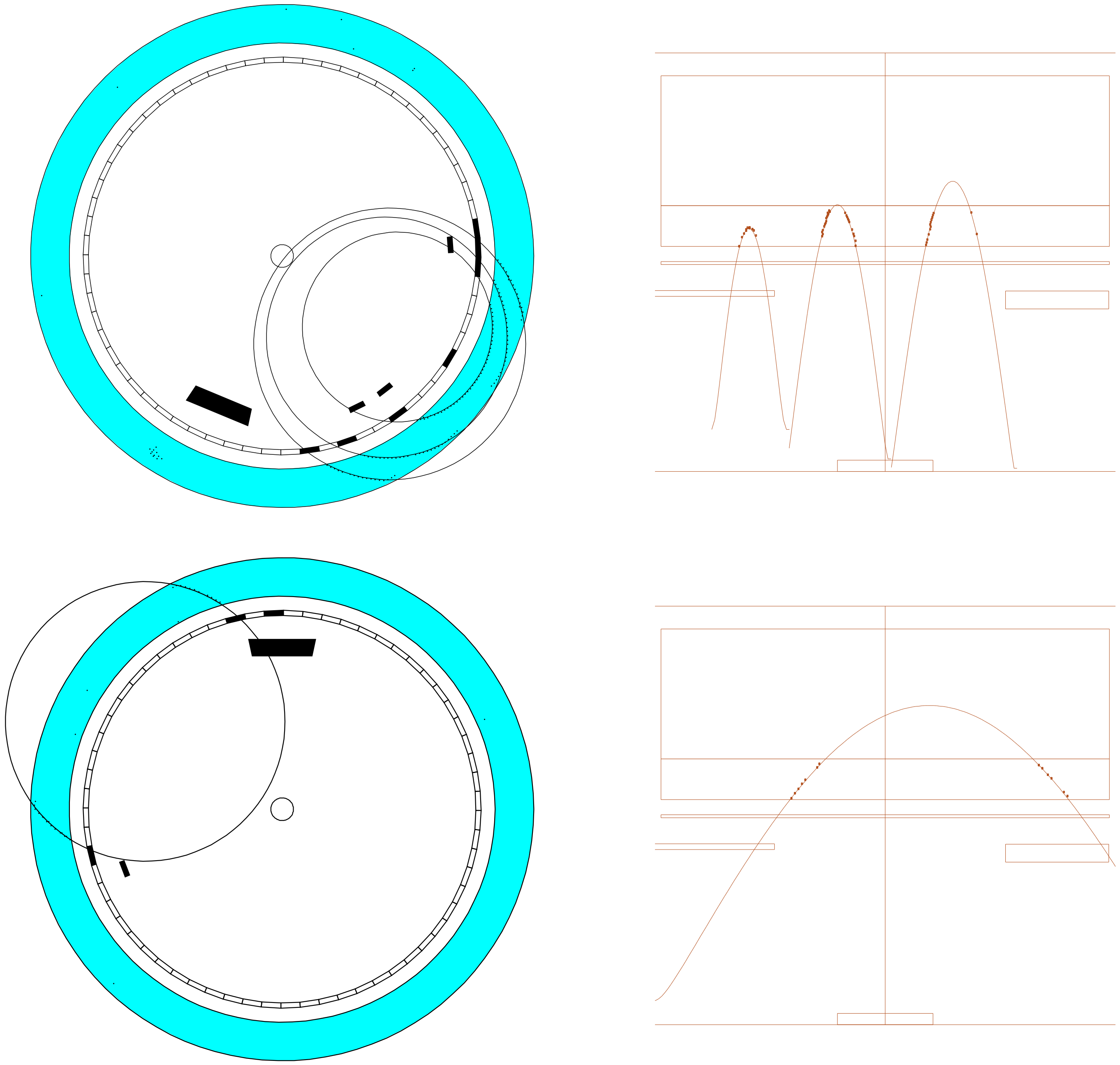
Cosmic background event recognised by the occurrence of additional detector signals.

Such events do enter the sample of contained events

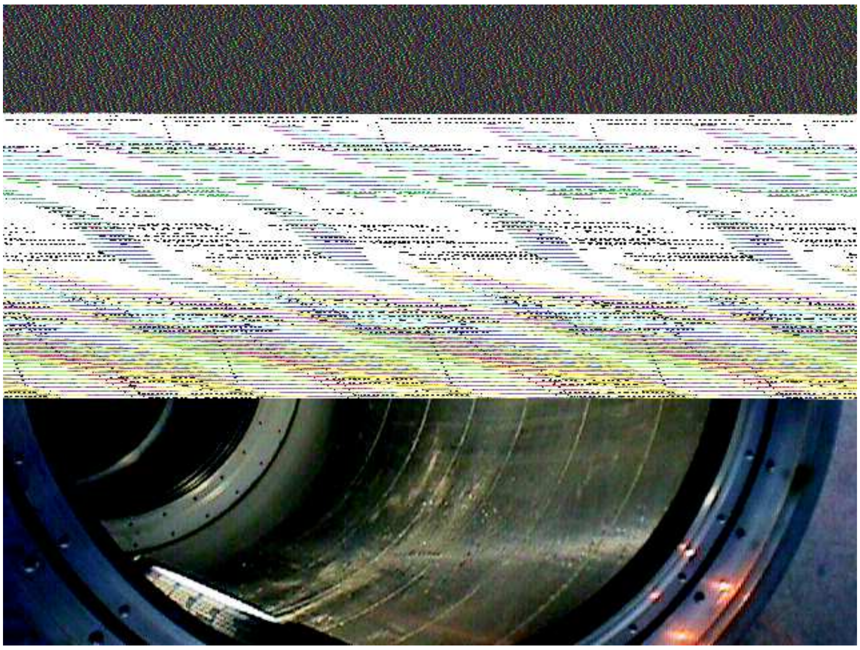
Background processes

cosmic background

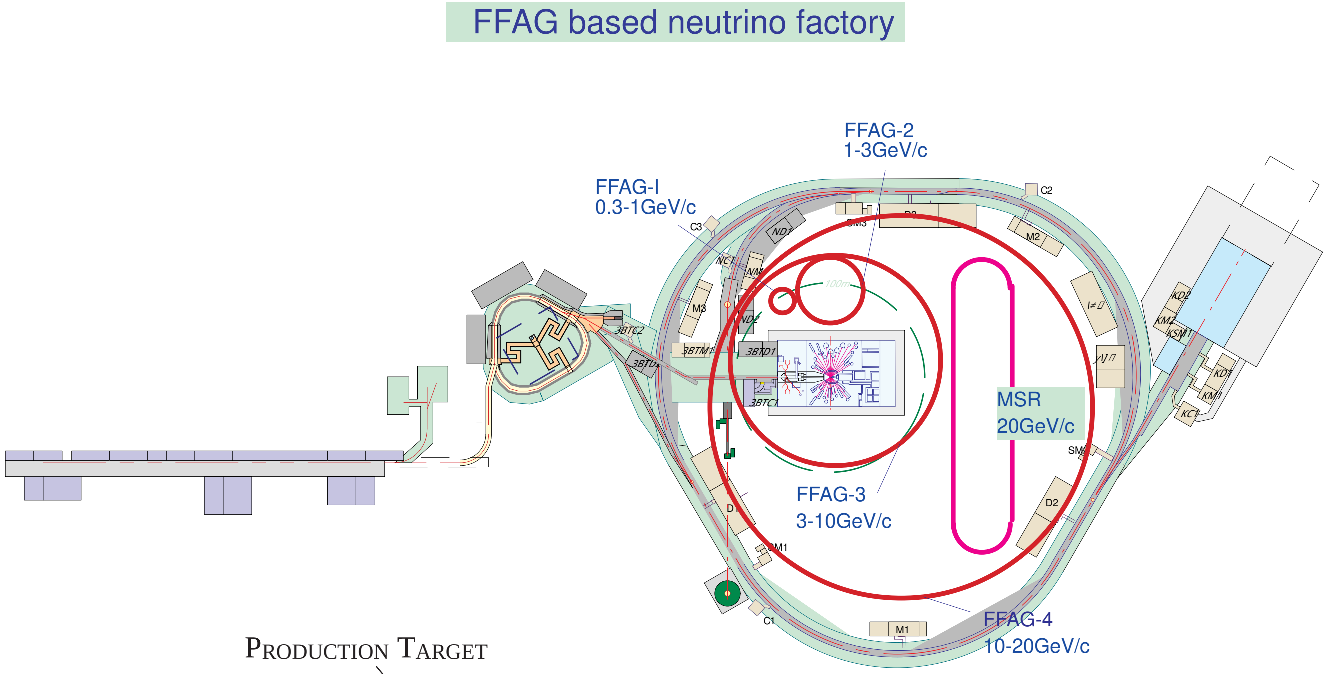
background2

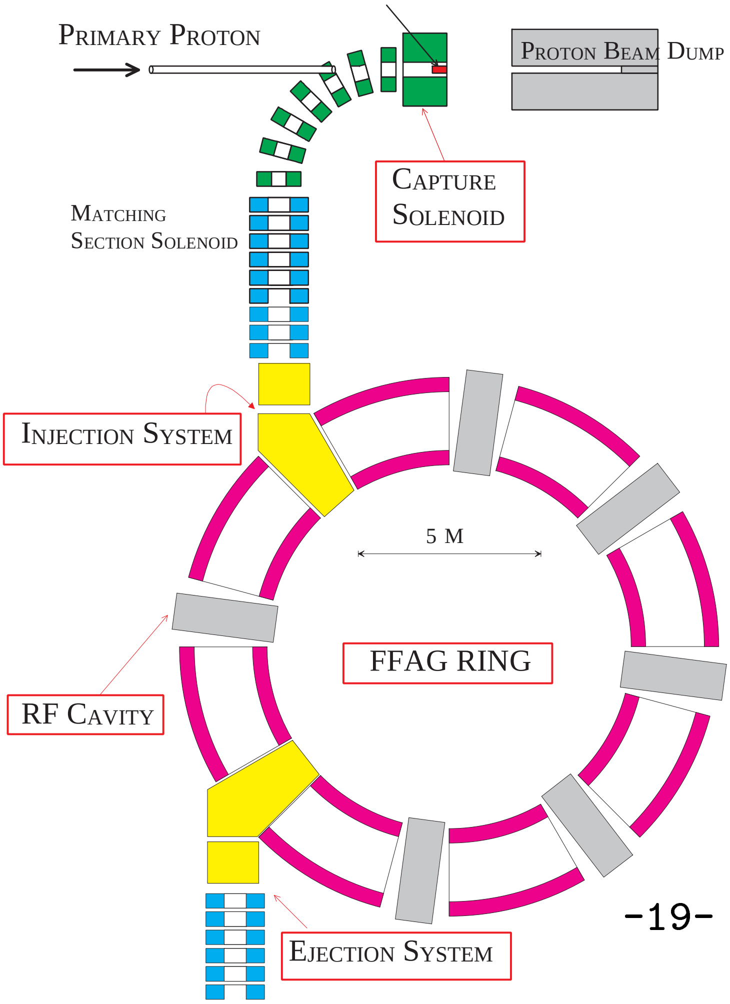


- these contained events are characterised by opposite end-cap signals



the Japanese ν factory



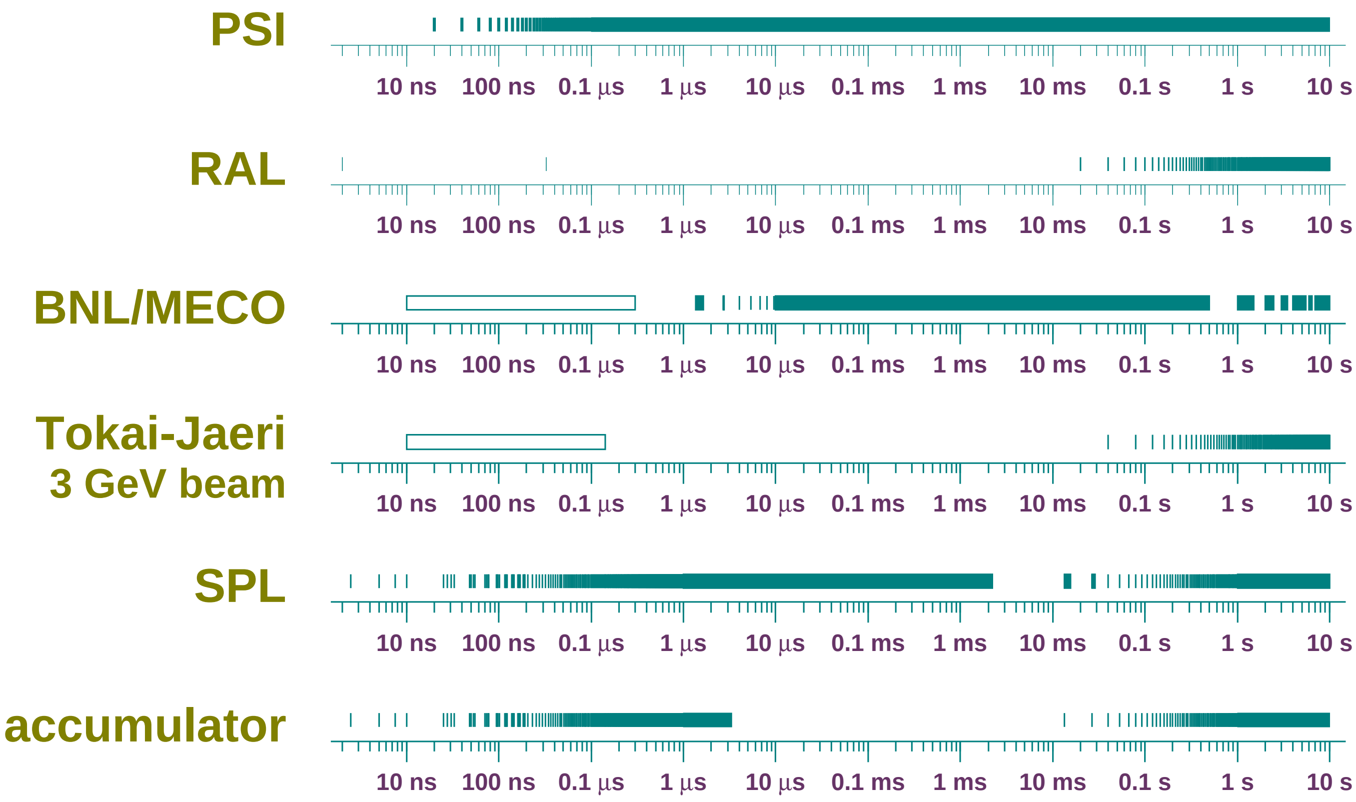


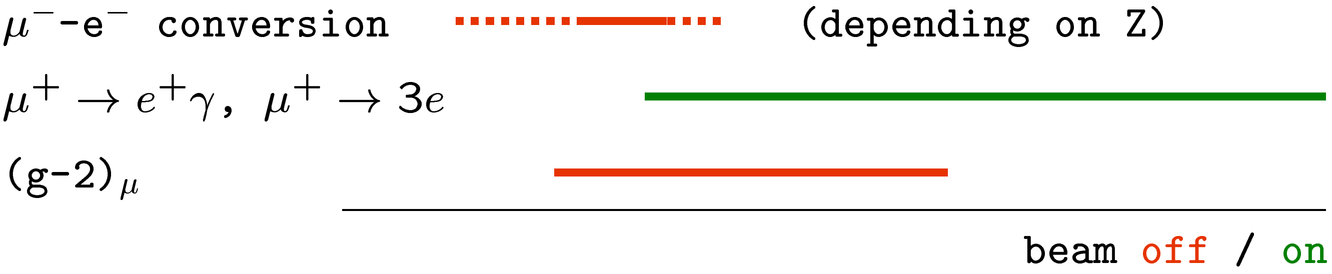
PRISM:
phase space rotated μ beam

- fast muons decelerated
  slow muons accelerated
- 68 ± 1 MeV/c
- 10^{11-12} μ^{-}/s
- no π^{-} contamination
- sensitivity of 10^{-18}
  on any target

Proton time structure

of various accelerators (CERN perspective)





μ^--e$^-$ conversion (depending on Z)

$\mu^+ \to e^+\gamma$, $\mu^+ \to 3e$

(g-2)$_\mu$

beam off / on

to be discussed this week:

- what time structures are possible at what cost?
- DC beam ?
- what instantaneous μ rate can a μe search live with?

London, July 1st 2002