Overview of the MEG Experiment
Search for the Lepton-Flavour Violating Decay

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

at PSI

Presented by: ***Peter-Raymond Kettle***

(MEG Collaboration)

Physics Motivation

Minimal Standard Model (SM)-

Baryon Number, Lepton Flavour & Lepton Number - conserved !

neutrinos massless - no oscillations !

however

<u>Extensions to SM</u> -(with massive ν's & hence ν-oscillations) -

Predict LFV rates

↪ ***too small to be observed ~ BR $\mathcal{O}(10^{-50})$***

Hence: processes such as $\mu \to e\gamma$, $\mu \to$ e, $\mu \to$ eee, $K^0_L \to \mu e$, $Z^0 \to \mu e$ &

ν-oscillations & $0\nu\beta\beta$-decay are

sensitive tools to probe physics beyond the Standard Model

Physics Motivation (Theory & Experiment)

Extensions beyond SM *- Predict LFV & BNV at a measurable level (e.g. see Barbieri & Hall, Hisano et al.)*

Super Symmetry (SUSY-GUTs)

SU(5) 10-13< Br($\mu \rightarrow e\gamma$) < 10-15

SO(10) 10-11< Br($\mu \rightarrow e\gamma$) < 10-13

Process	Current Limit	SUSY level
$\mu^+ \rightarrow e^+ \gamma$	10^{-11}	10^{-13}
$\mu^- N \rightarrow e^- N$	$\sim 10^{-12}$	10^{-15}
$\tau \rightarrow \mu \gamma$	10^{-6}	10^{-9}

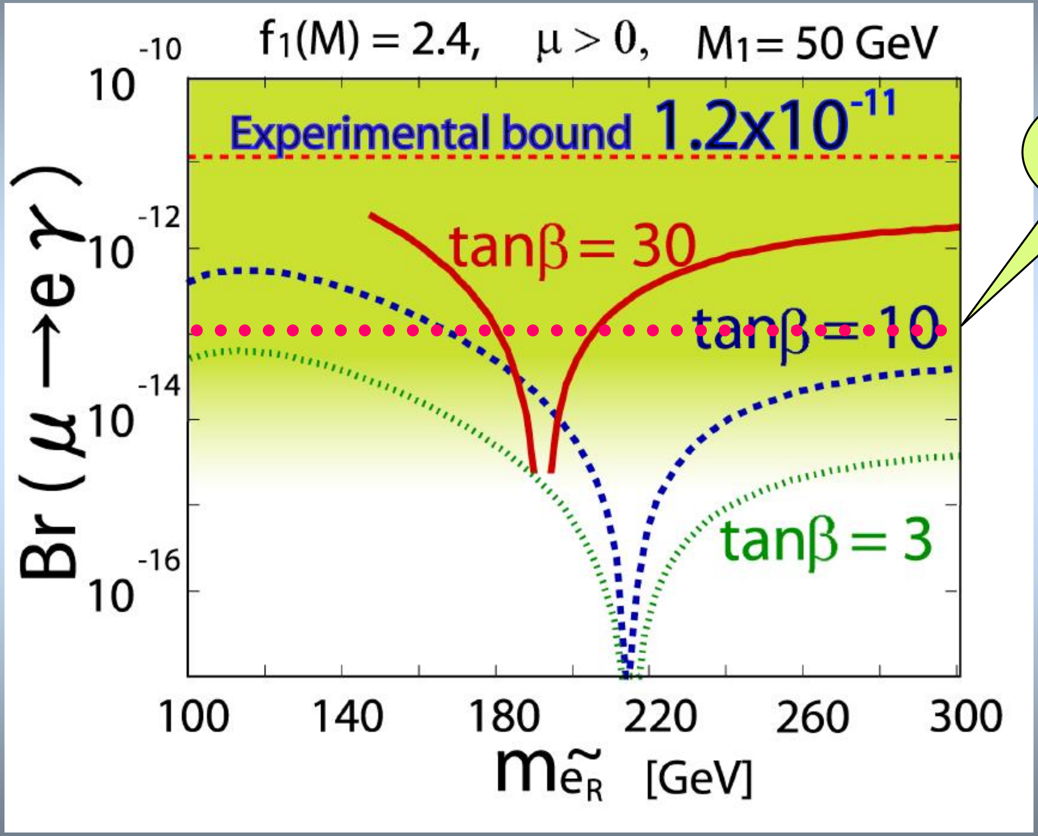
!!! Just below Present Experimental Bound <$1.2 \cdot 10^{-11}$!!!

> *Further Stimulus for the search for LFV in the charged Lepton Sector*

Discovery of ν-oscillations (Super-K, SNO, KAMLAND)
g-2 Results (BNL)
Report of $0\nu\beta\beta$-decay ???(Heidelberg/Moscow)
Report Proton Decay ??? (Kolar Goldfield)

SUSY Predictions

e.g. Prediction Br(μ→eγ) vs. parameter space in SUSY SU(5)
see J. Hisano et al. Phys. Lett. B391 (1997) 341



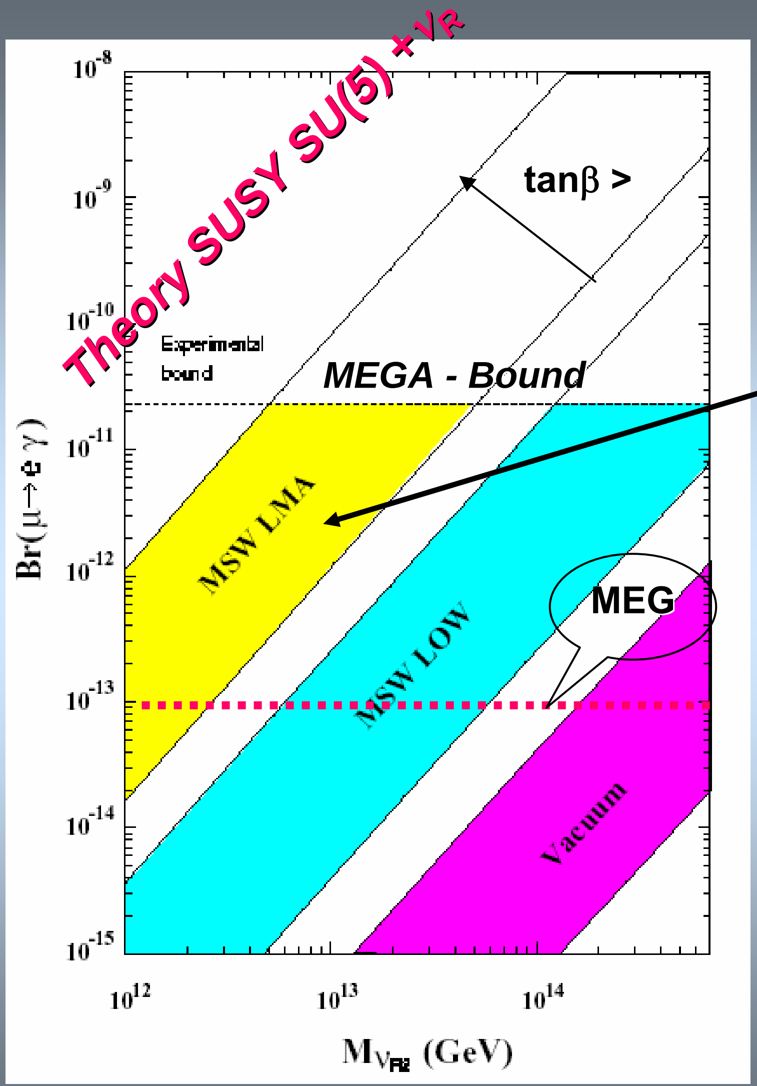
MEG Goal 10^{-13}

Similar plots for
$\mu \to$ e conversion
with
$R_{\mu e}$- ranging between
(10^{-14} - 10^{-17})
over most of the parameter ranges

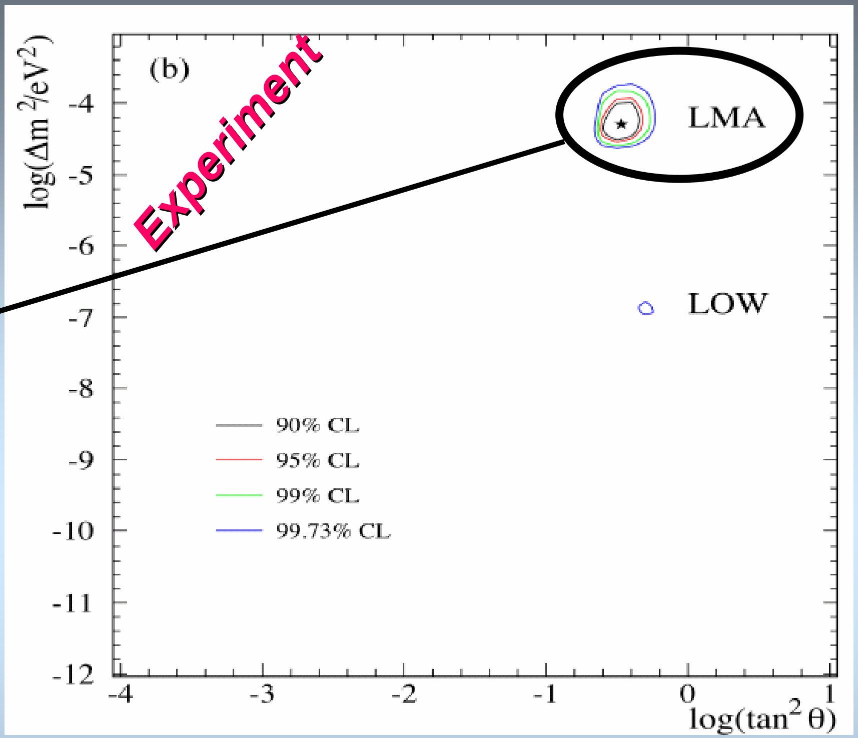
MECO(BNL)-goal single event sensitivity of 2.10^{-17}

Small tan(β) –Excluded LEP SUSY Search

The μ→eγ ν - Connection



J. Hisano and D. Nomura Phys. Rev. D59 (1999)



SOLAR Neutrino Global Analysis
↪ Favours LMA solution

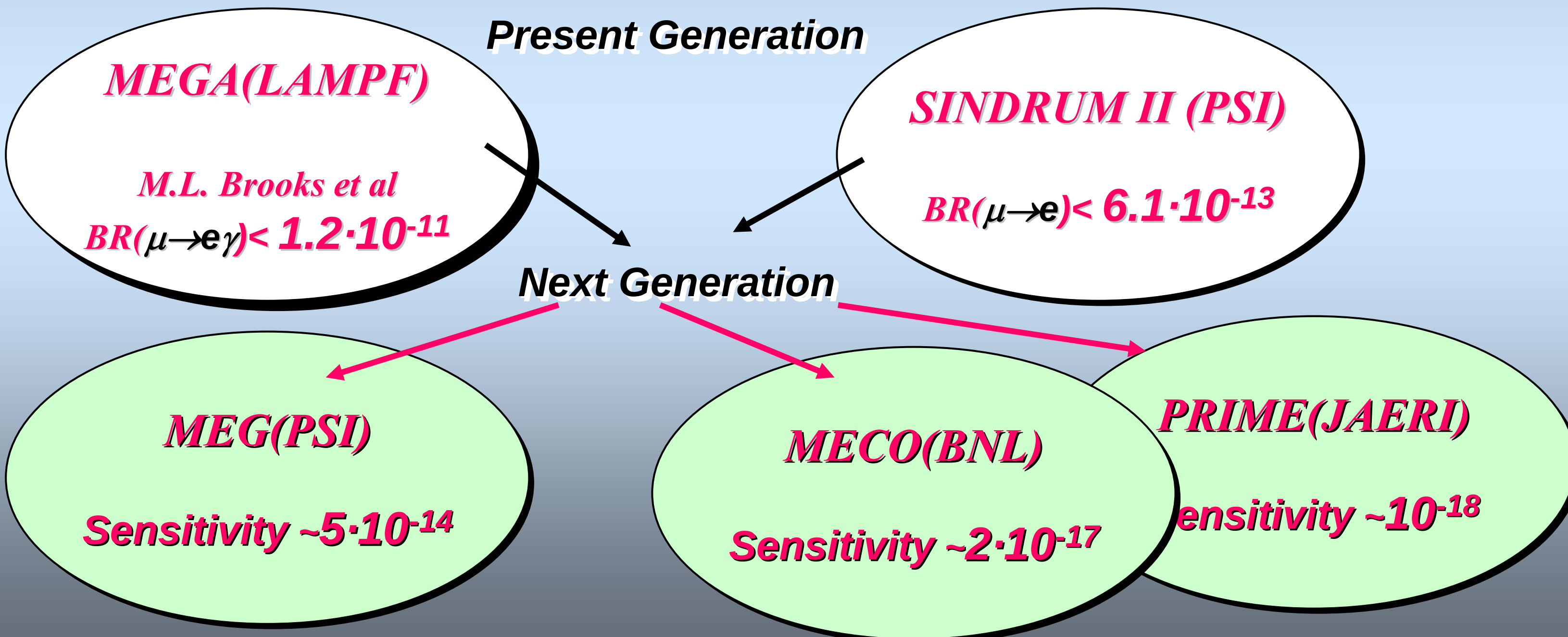
SNO collaboration, Q.R.Ahamd et al., PRL89(2002)010302

2^{nd} Generation LFV Searches

Experimental LFV-Searches have a Long History -

- ***goes back to 1947 E. P. Hincks & B. Pontecorvo, using cosmic rays ($\mu \to e\gamma$)***
- ***Improvement about 2-Orders of Magnitude per Decade***
- ***muons seem to provide the most sensitive limits (copious source, small mass, long life)***

Most Promising Candidates in the Charged Lepton Sector: $\mu \to e\gamma$ & $\mu \to e$

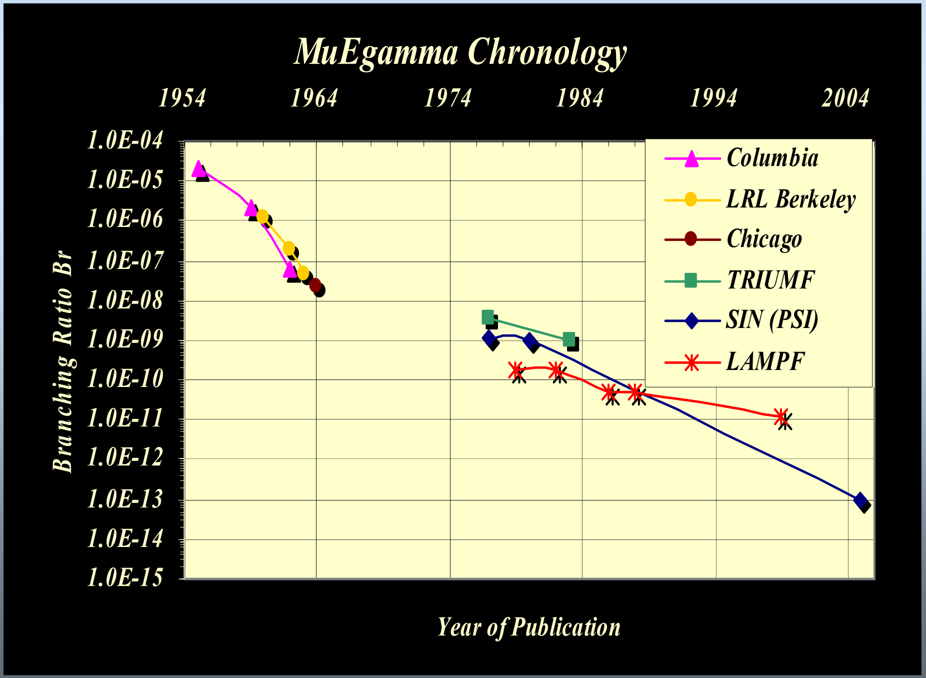


$\mu \rightarrow e\gamma$ Chronology

Laboratory	Collaboration	Year Published	Upper Limit (90%c.l.)
Cosmic rays	E. P. Hincks & B. Pontecorvo	1947	$0^{+0.06\,-0.0}$
Columbia	S. Lokanathan & J. Steinberger	1955	$2\cdot10^{-5}$
Columbia	D. Berley et al.	1959	$2\cdot10^{-6}$
CERN	J. Ashkin et al.	1959	$(1.2\pm1.5)\cdot10^{-6}$
LRL Berkeley	S. Frankel et al.	1960	$1.2\cdot10^{-6}$
Columbia	D. Bartlett et al.	1962	$6\cdot10^{-8}$
LRL Berkeley	S. Frankel et al.	1962	$1.9\cdot10^{-7}$
LRL Berkeley	S. Frankel et al.	1963	$4.3\cdot10^{-8}$
Chicago	S. Parker et al.	1964	$2.2\cdot10^{-8}$
TRIUMF	P. Depommier et al.	1977	$3.6\cdot10^{-9}$
SIN	A. van der Schaaf et al.	1977	$1.1\cdot10^{-9}$
LAMPF	J. D. Bowman et al.	1979	$1.9\cdot10^{-10}$
SIN	A. van der Schaaf et al.	1980	$1.0\cdot10^{-9}$
LAMPF	W. W. Kinnison et al.	1982	$1.7\cdot10^{-10}$
TRIUMF	G. Azuelos et al.	1983	$1.0\cdot10^{-9}$
LAMPF	R. D. Bolton et al.	1986	$4.9\cdot10^{-11}$
LAMPF	R. D. Bolton et al.	1988	$4.9\cdot10^{-11}$
LAMPF	M. L. Brooks et al.	1999	$1.2\cdot10^{-11}$
PSI	MEGCollaboration	>2005 ?	$1.0\cdot10^{-13}$?

PSI
LOI 1998
Proposal 1999
Approval 1999

- ***End of 70's Meson Factories take over competition***
- ***higher intensity beams***
- ***Duty cycle***

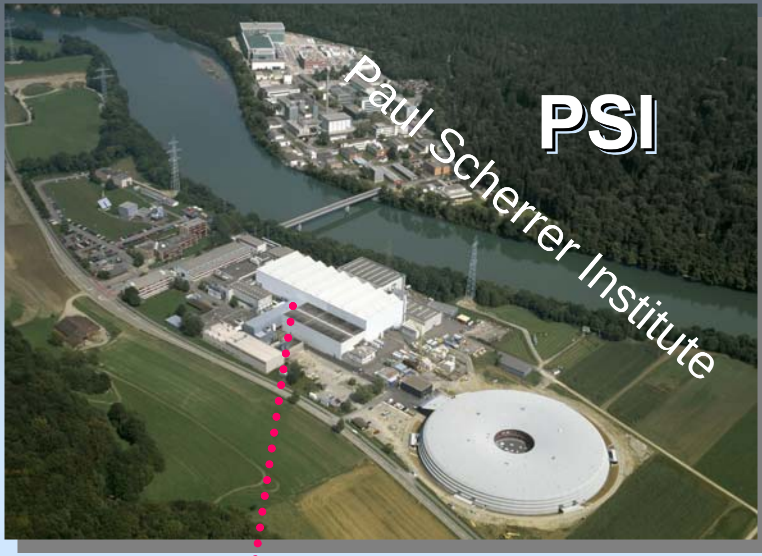


PSI & LFV- Searches

PSI also has a tradition in LFV-searches:

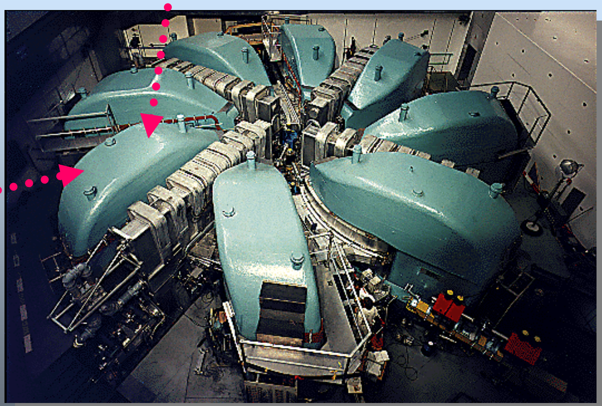
Present most Sensitive Measurements

Reaction	90% CL
$Br(\mu^- Au \to e^- Au)$	New Prelim.
$Br(\mu^- Ti \to e^- Ti)$	$6.1 \cdot 10^{-13}$
$Br(\mu^+ \to e^+ e^- e^+)$	$1 \cdot 10^{-12}$
$Br(\mu^- Pb \to e^- Pb)$	$4.6 \cdot 10^{-11}$
$Br(\mu^- S \to e^- S)$	$7 \cdot 10^{-11}$
$P_{MM}(\mu^+ e^- \to \mu^- e^+)$	$8.3 \cdot 10^{-11}$
$Br(\mu^- Ti \to e^+ Ca)$	$1.7 \cdot 10^{-12}$
$Br(\mu^- S \to e^+ Si)$	$9 \cdot 10^{-10}$

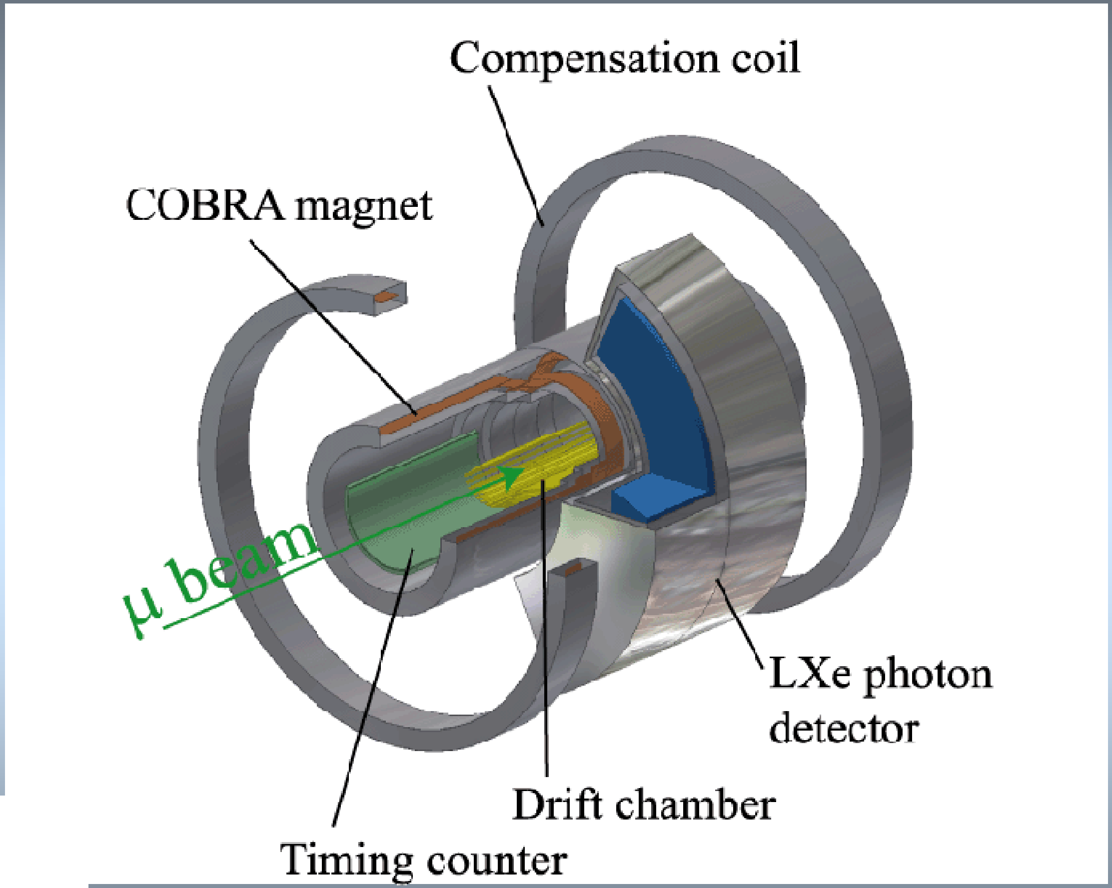


Sindrum II-Collab.
M M- Collab.
SIN-measurements

- 600 MeV Ring Cyclotron
- 1.8-2mA Proton Current
- DC Beam –100% Duty Cycle
- πE5 Surface Muon Beam $>10^8 \mu^+ s^{-1}$



MEG Experiment $\mu \rightarrow e\gamma$ at PSI



Features

Sensitivity down to ~ $5 \cdot 10^{-14}$

Utilize most intense DC surface muon beam available

Liquid Xe photon detector

Gradient field superconducting positron spectrometer (constant bending radius)

Positron tracker & timing counters

MEG Collaboration

The MEG Experiment – Status December 2002

A. Baldini[5*], A. de Bari[6], L. M. Barkov[1], C. Bemporad[5], P. Cattaneo[6], G. Cecchet[6], F. Cei[5], T. Doke[9], J. Egger[7], F. Gatti[2] M. Grassi[5], A. A. Grebenuk[1], D. N. Grigoriev[1], T. Haruyama[3], M. Hildebrandt[7], P.-R. Kettle[7], B. Khazin[1], J. Kikuchi[9], Y. Kuno[4], A. Maki[3], Y. Makida[3], T. Mashimo[8], S. Mihara[8], T. Mitsuhashi[8], T. Mori[8*], D. Nicolò[5], H. Nishiguchi[8], H. Okada[9], W. Ootani[8], K. Ozone[8], R. Pazzi[5], S. Ritt[7], T. Saeki[8], R. Sawada[8], F. Sergiampietri[5], G. Signorelli[5], V. P. Smakhtin[1], S. Suzuki[9], K. Terasawa[9], A. Yamamoto[3], M. Yamashita[9], S. Yamashita[8], J. Yashima[8], K. Yoshimura[8], T. Yoshimura[9]

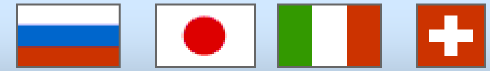
(Collaboration for the $\mu \to e\gamma$ Experiment at PSI)

[1]BINP, Novosibirsk, Russia
[2]University of Genova and INFN, Genova, Italy
[3]KEK, Tsukuba, Japan
[4]Osaka University, Osaka, Japan
[5]University of Pisa and INFN, Pisa, Italy
[6]Univeristy of Pavia and INFN, Pavia, Italy
[7]PSI, Villigen, Switzerland
[8]University of Tokyo, Tokyo, Japan
[9]Waseda University, Tokyo, Japan

December 2002

Now ~ 48 physicists from 10 institutes

$\mu \to e\gamma$ Collaboration



Russia
LXe Tests and Purification
Beam Transport
Solenoid

Japan
LXe Calorimeter,
Superconducting Solenoid,
M.C.

Italy
e+ counter,
Trigger,
M.C.
LXe Calorimeter

Switzerland
Drift Chamber,
Beam Line, DAQ

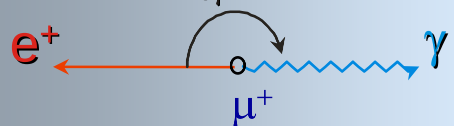
Experimental Principle

Signal Kinematics

- simple
- monoenergetic particles
- back-to-back
- coincident in time

Decay at Rest

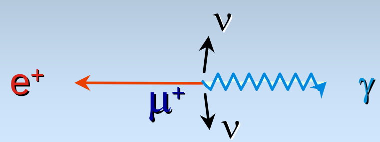
$\theta_{e\gamma} = 180°$



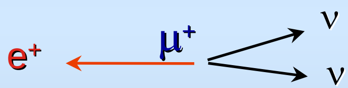
$E_{e+} = 52.8$ MeV $E_\gamma = 52.8$ MeV

Background kinematics

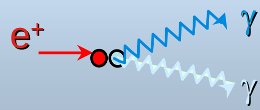
- Radiative muon decay
$\mu \rightarrow e\nu\nu\gamma$



- Michel + accidental photon
  from e.g.



- positron annihilation
  (in-flight)



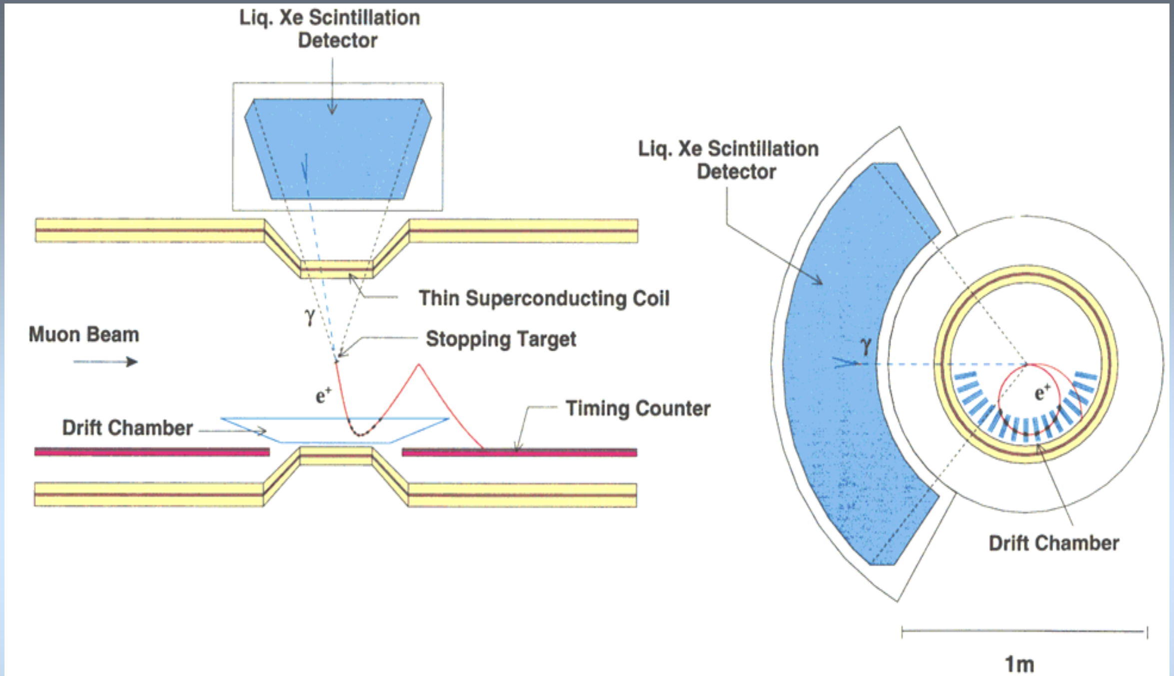
- neutron induced background

Basic Beam & Detector Requirements

- *High stop-density (rate) μ^+ -beam with high duty factor (accidentals)*
- *High resolution γ–detection (angle + energy, accidentals)*
- *Solenoidal magnetic spectrometer (p-determination)*
- *Fast, high resolution tracking chambers for e^+ momentum determination (p- + angle)*
- *Timing counter for e^+ (angle + time)*

Detector Performance

- surface muon beam 28 MeV/c ~10^8 muons/sec
- thin stopping target 150μm CH_2
- LXe Photon Calorimeter, (vol~800 litres, 3t) viewed by 800 PMs
- ultra thin 3 g/cm2 ($T\gamma$=95%) super conducting solenoid (gradient field) 1.26T
- 17 azimuthally segmented, staggered mini-cell layers, of drift chambers
- double layer of scintillator hodoscope arrays, as e+-trigger + timing counters



Present / expected Performance
FWHM

- ΔE_e ~ 0.8%
- ΔE_γ ~ 4%
- $\Delta\theta_{e\gamma}$ ~ 19 mrad
- $\Delta t_{e\gamma}$ ~ 150 ps

$R_\mu \sim 2.5 \cdot 10^7\ s^{-1}$
$T \sim 2.6 \cdot 10^7$ s (65 weeks)
$\Omega/4\pi \sim 0.09$
$\varepsilon_e \sim 0.9$
$\varepsilon_\gamma \sim 0.6$
$\varepsilon_{sel} \sim 0.7$

Detector Sensitivity

Single Events Sensitivity

Limited by the Accidental Background
& hence Detector Performance

Presently:

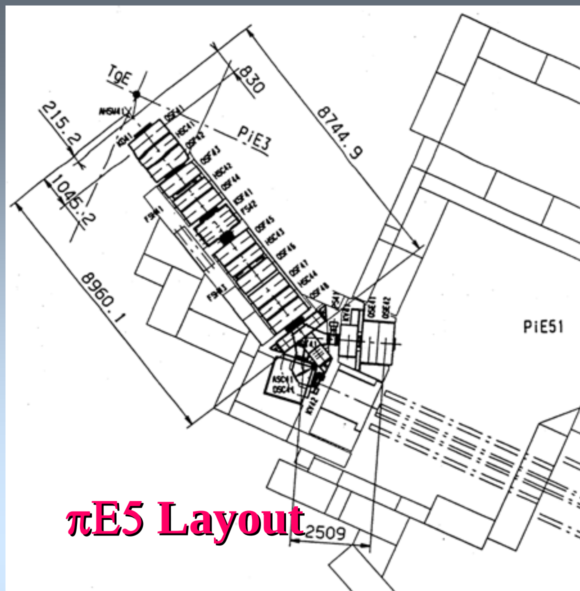
$BR(\mu \to e\gamma) = (R_\mu \cdot T \cdot \Omega/4\pi \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot \varepsilon_{sel})^{-1} \approx 4 \times 10^{-14}$

Prompt Physics Background (Radiative) $BR_{pr} \cong < 3 \cdot 10^{-15}$

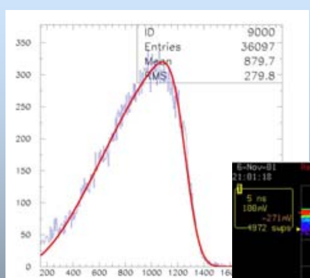
Accidental Background $BR_{acc} \propto R_\mu \cdot \Delta E_e \cdot \Delta t_{e\gamma} \cdot (\Delta E_\gamma)^2 \cdot (\Delta\theta_{e\gamma})^2 \to 3 \cdot 10^{-14}$

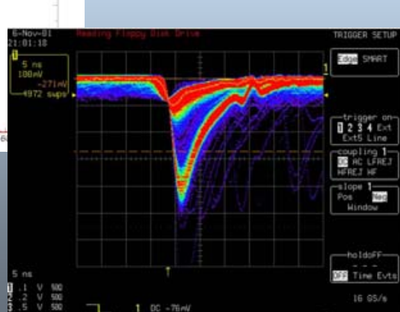
Upper Limit at 90% C.L. for $BR(\mu \to e\gamma) \approx 1 \cdot 10^{-13}$

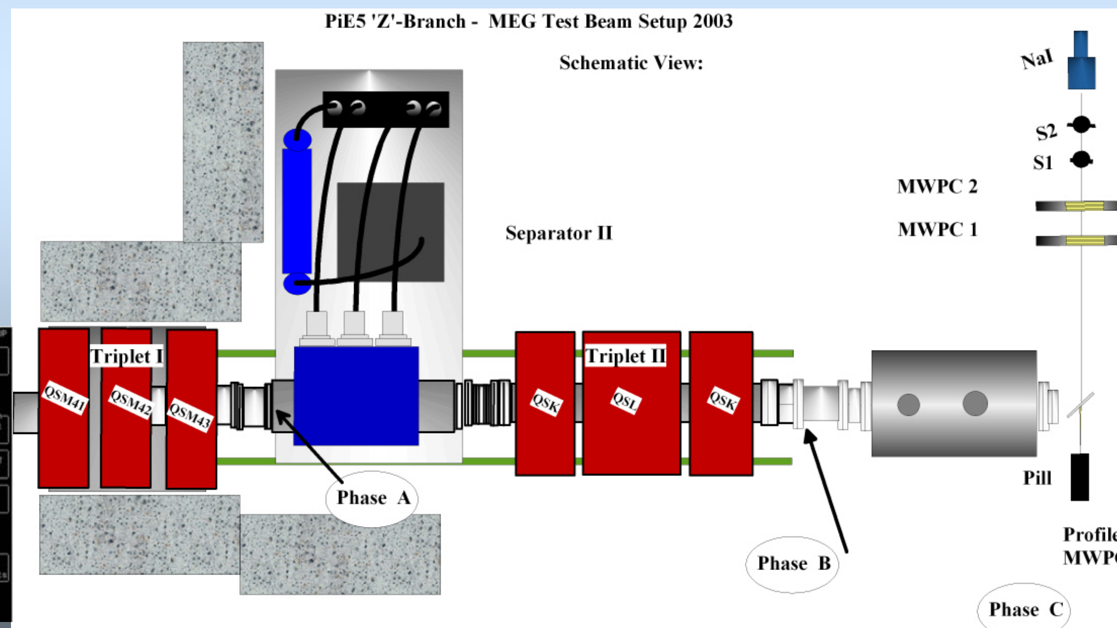
Beam Transport System



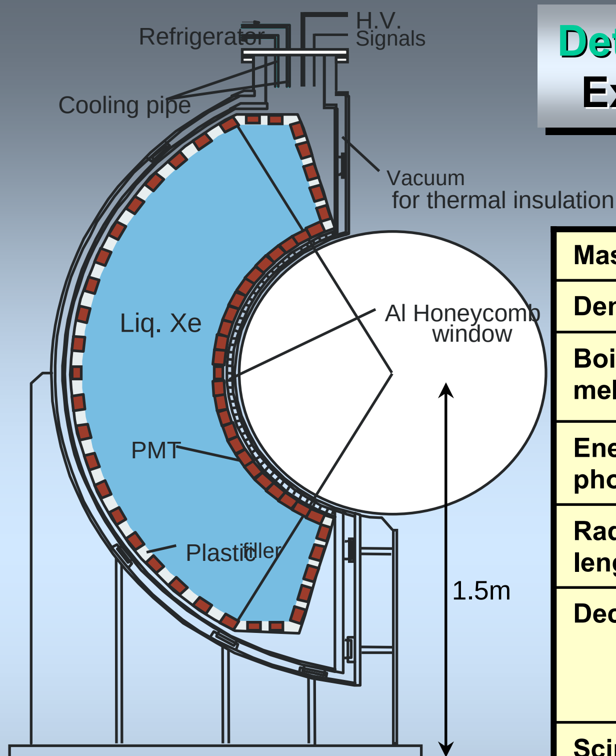
- 28 MeV/c Surface Muon Beam ~ 10^8 s^{-1}
- 2-Stage Separation & Momentum Degrading
- WIEN Filter (ExB)-Separator
- Superconducting Transport Solenoid with Degrader System
- Thin 37mg/cm² CH_2 Target
- Beam-spot $\sigma_X \sim \sigma_Y \sim$ 5mm

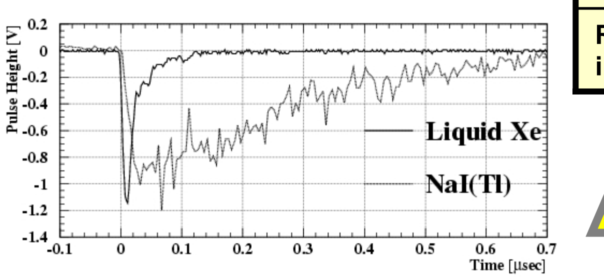






Photon Detection





Detector requirements:
Excellent energy-, timing-, and position resolutions

Mass number	131.29
Density	3.0 g/cm^3
Boiling/ melting points	165 K 161 K
Energy per photon	24 eV
Radiation length	2.77 cm
Decay time (fa) (slow) (recombi.)	4.2 nsec 22 nsec 45 nsec
Scintillation light λ	175 nm
Refractive index	1.57 – 1.75

NaI – too slow
CsI +BGO – poor
ΔE/E at 52.8 MeV
In homo. coverage

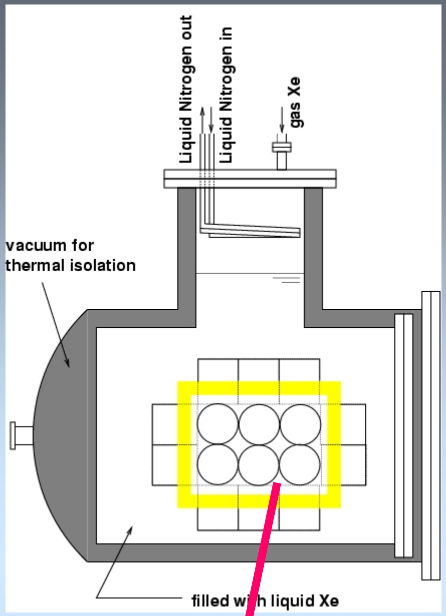
Liquid Xenon Scintillation Detector

Full Design characteristics:

- active Volume 800 litres
- viewed by 800 PMTs immersed in LXe
- high light yield ~ 75% NaI(Tl)
  (energy, timing, position resolution)
- fast signal, short decay time
  (minimize pile-up)
- spatially uniform response
  (no segmentation needed)

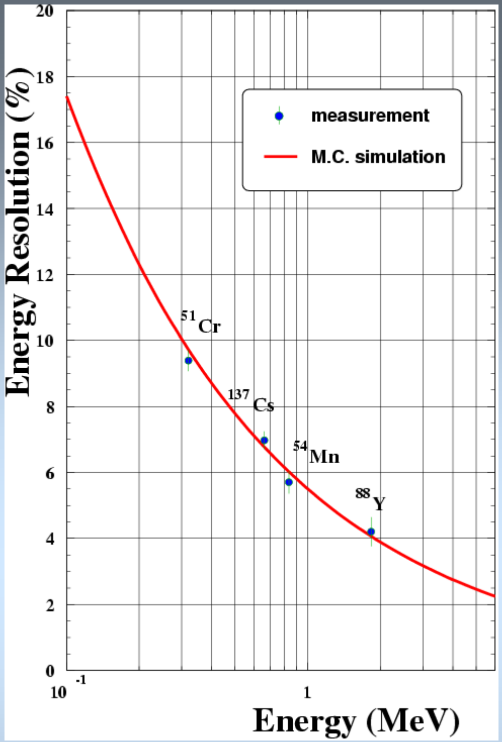
VERY AMBITIOUS !!! – needs Staged PROTOTYPE STUDIES

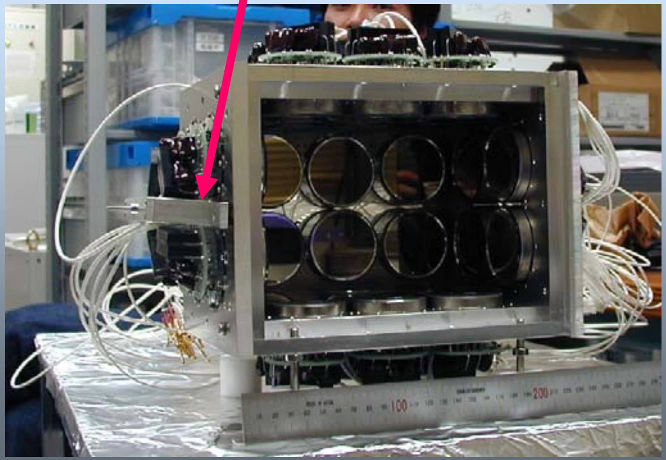
Photon Calorimeter – Small Prototypes



SMALL PROTOTYPE

- Total 32 x PMTs
- Active Xe volume
  116 x 116 x 174 mm^3 (2.3liter)
- Energy-, Position-, and Timing resolution measured for gammas up to 2MeV





Simple extrapolation to 52.8 MeV gammas implies:

σ_{energy} ~ 1%,
$\sigma_{position}$ ~ a few mm,
σ_{time} ~ 50psec

Scale-up to Large Prototype

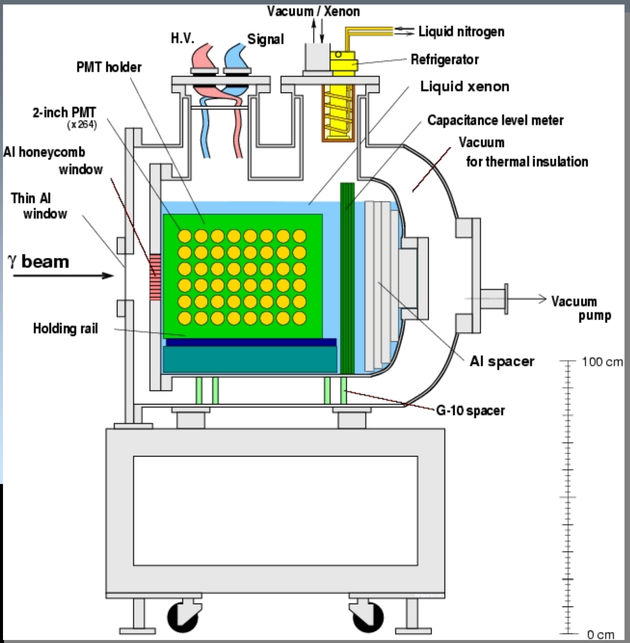
Photon Calorimeter – Large Prototype

PURPOSE:
- test long-term cryogenic operation
- measure LXe properties
- check reconstruction methods
- Measure ΔE, Δl, Δt

How

- Cosmics, α- Sources
- 60 MeV e^- KSR Storage Ring
- 40 MeV γ's TERAS SR (Compton backscatter)
- 55 MeV γ's $\pi^- p \rightarrow \pi^0 n$ PSI

Currently :
World's LARGEST LXe-Detector
(40x40x50) cm^3
- 228 PMTs
- 69 litres LXe necessary to test Response > 20MeV



PROPOSAL
Performance Parameters to be achieved

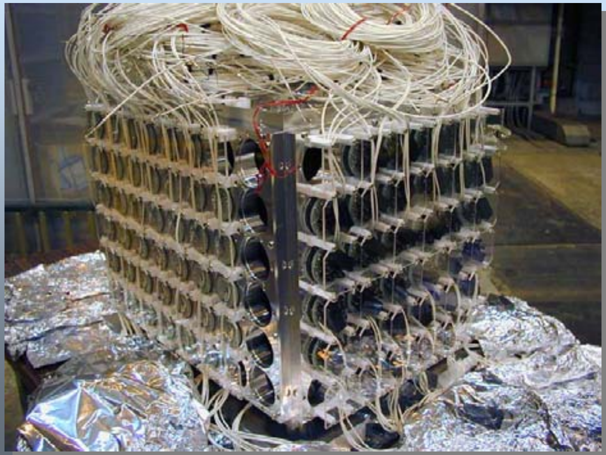
lateral δ_x~4mm,

depth δ_z~16 mm

ΔE~ 1.4 – 2 %,

Δt~ 100 ps

(all FWHM)

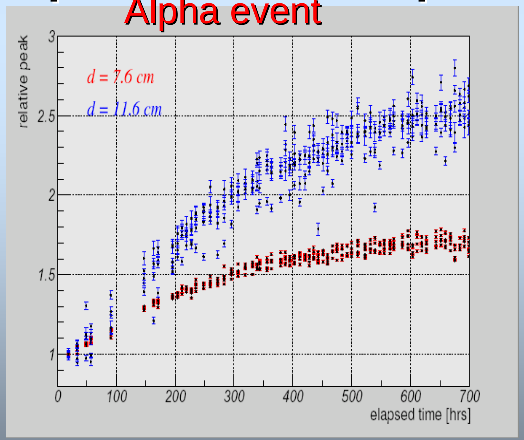


Photon Detector Performance

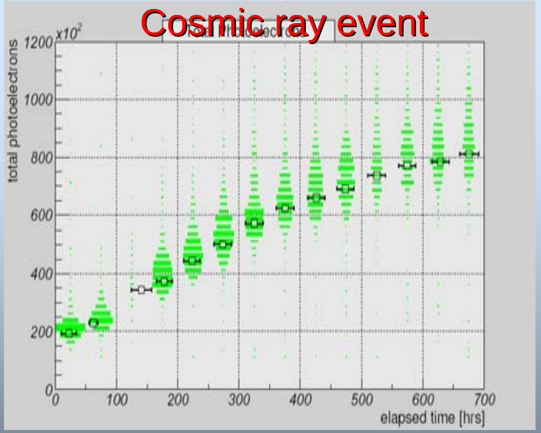
Calorimeter Performance **Strongly dependent** on
Optical Properties of LXe e.g. Absorption Length λ_{abs}> 1m

to reach $\Delta E/E$ ~ few % ($\lambda_{abs} = \infty$ gives $\Delta E/E$ ~ 2.5% FWHM)
⇨Initial results with Large Prototype: **Dramatic loss of light !!! (90%)**
⇨ λabs ~ 10cm !!!
Problems with Contaminants mainly H_2O

Improvement with purification (Oxysorb/getter/re-circulation)

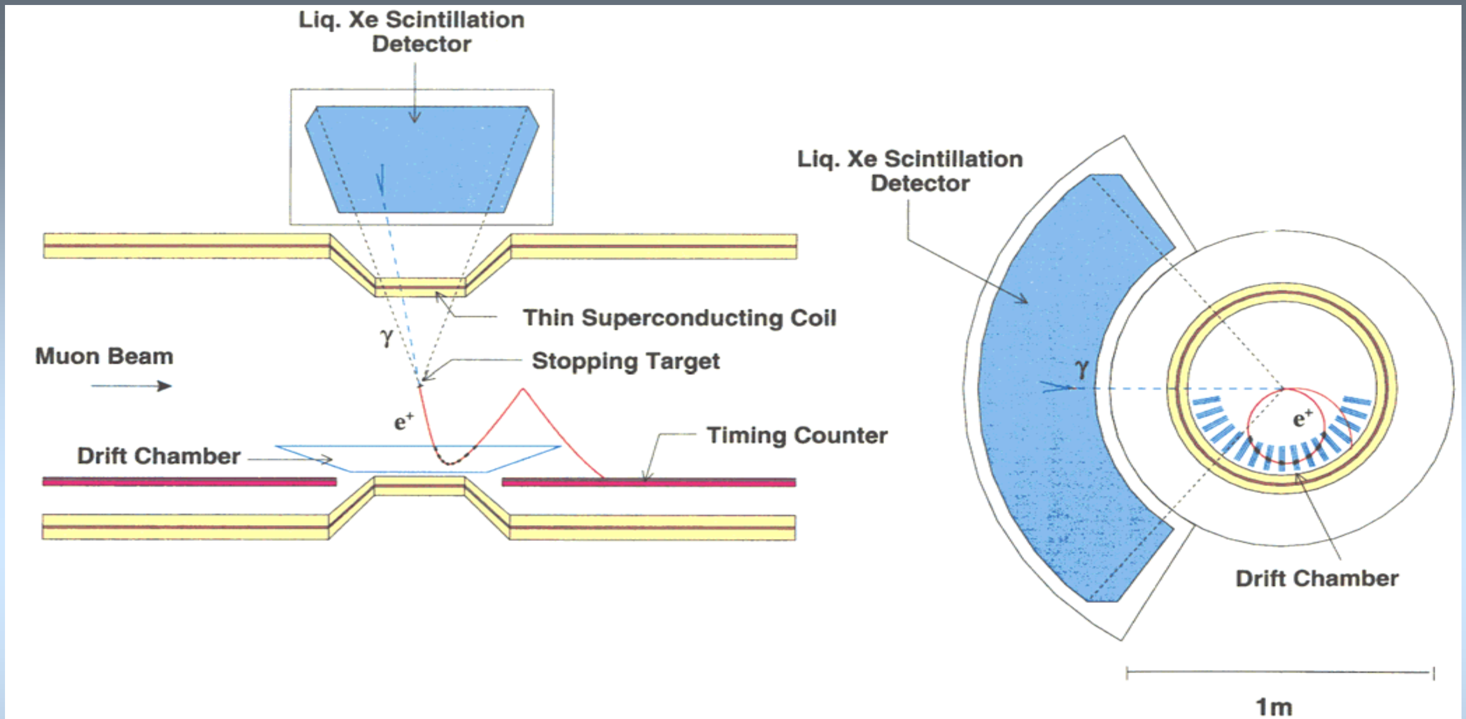


Light yield
vs
Purification time



⇨New continuous purification system being implemented
⇨ **Presently λabs > 1m 90% CL**

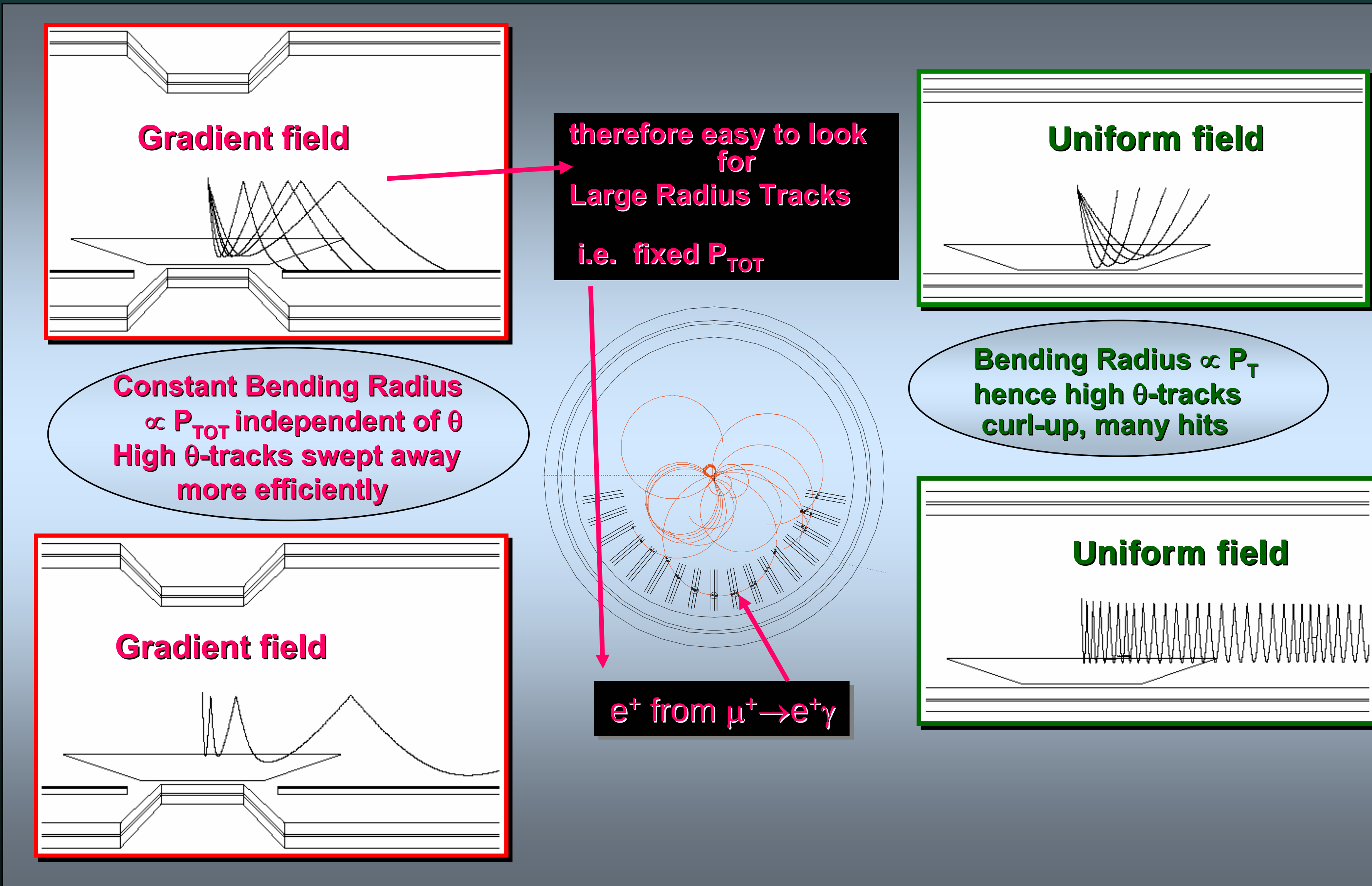
Positron Detection



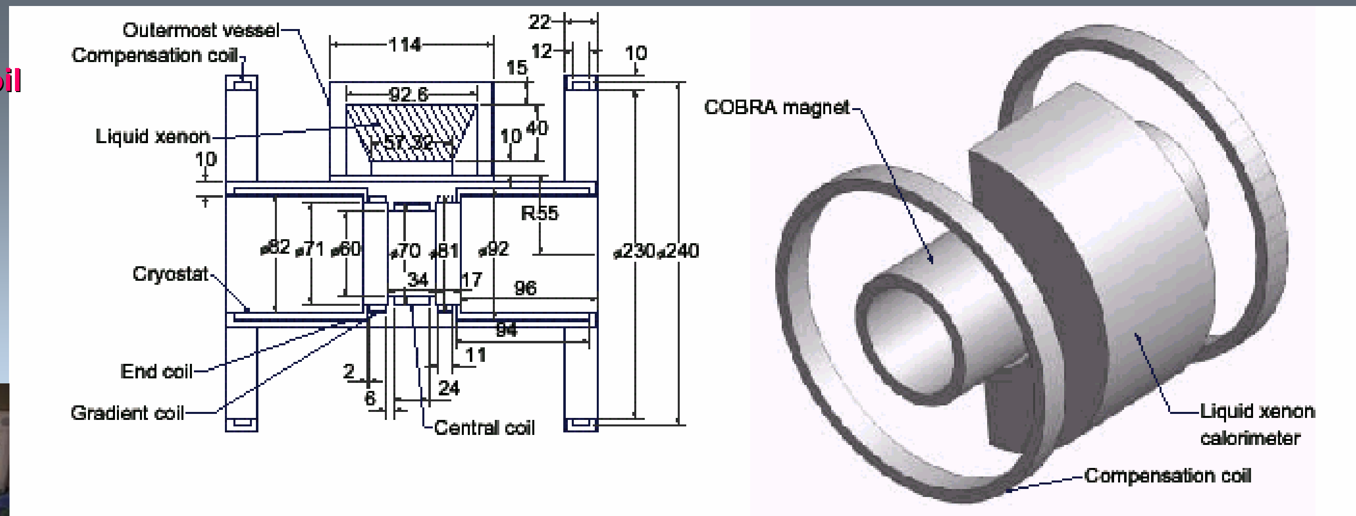
COBRA – Spectrometer (Constant Bending Radius)

- Thin superconducting magnet with gradient field
- Drift chambers for positron tracking
- Scintillation counter arrays for positron timing & triggering

Positron Spectrometer COBRA

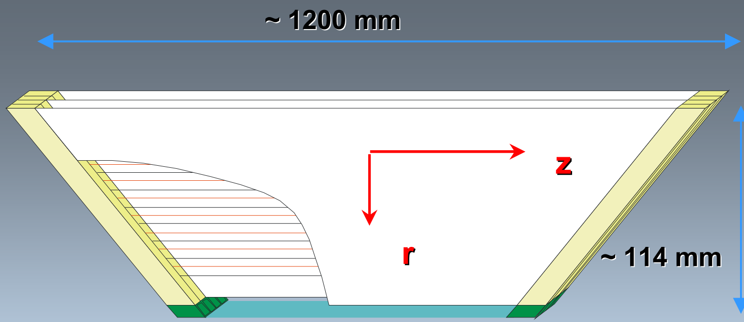


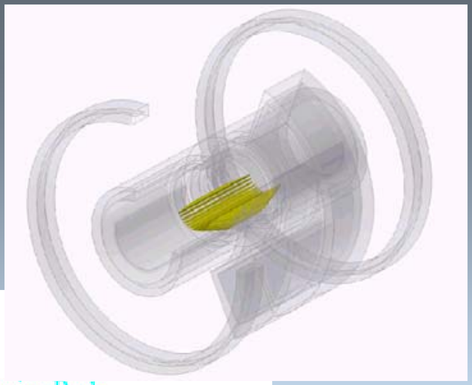
COBRA Magnet

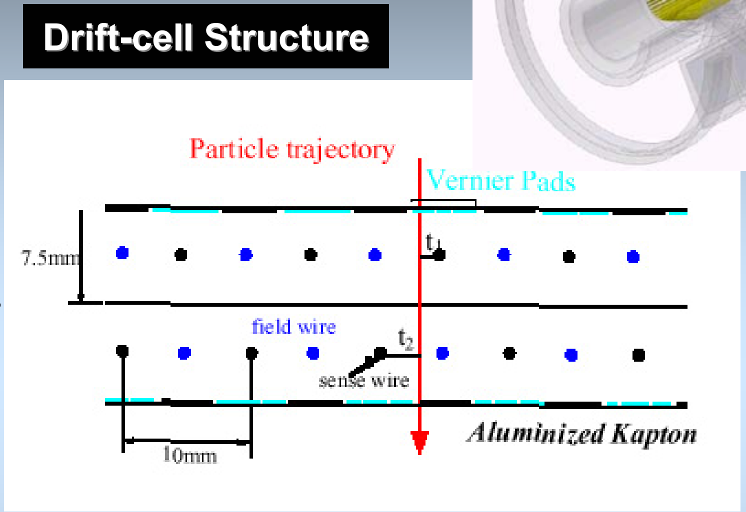


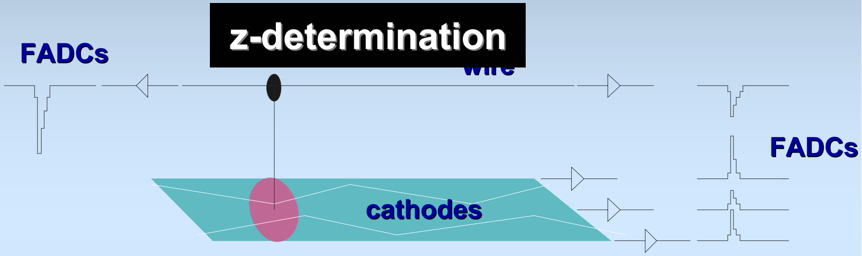
- High-strength aluminum stabilized thin superconducting coil ~ 0.2 X_0
- Five coils with three different diameters to realize gradient field
- B_c = 1.26T, $B_{z=1.25m}$=0.49T,
- operating current I_{opt}= 359A
- Compensation coils to suppress the residual field around the LXe detector to < 50 Gauss (PMTs)

Positron Tracking – Drift Chambers

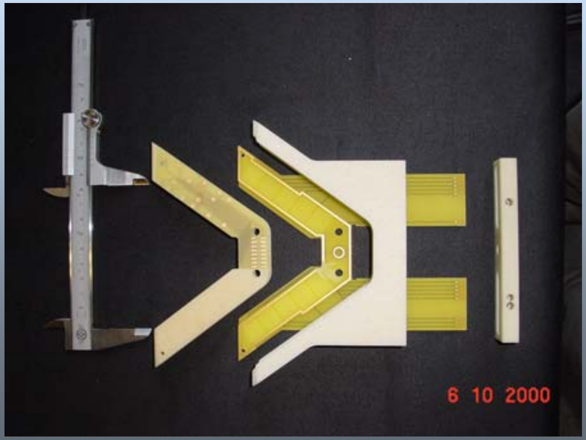






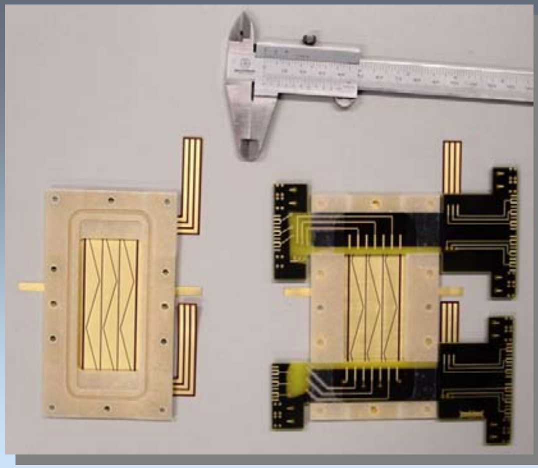


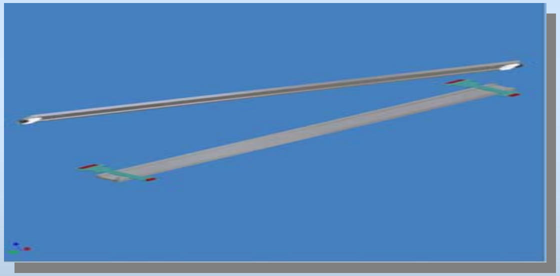
- 17 planar chambers
- aligned radially at ~ 10° intervals
- Staggered cells measure both position $r \propto (t_1 - t_2)$
  $\sigma_r \sim 200\ \mu m$ and time $t \propto (t_1 + t_2)/2$ $\sigma_t \sim 5$ ns
- He – C_2H_6 gas to reduce multiple scattering
- Vernier pattern to determine z-coordinate
  via Charge Division $\sigma_z \sim 300\ \mu m$

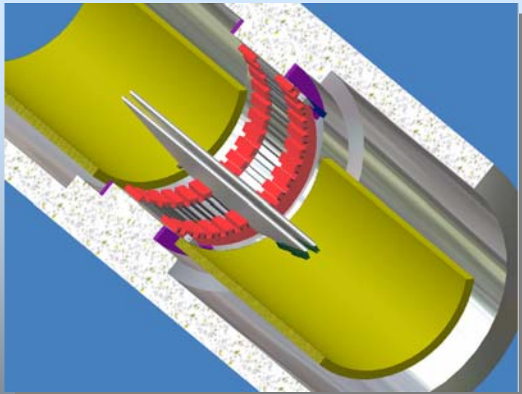


Prototype DCs

- Two prototypes are under test at PSI.
  - "Double cathode" chamber
    - Two separated double-strip cathodes for each chamber layer
      → homogeneous position sensitivity
    - Test in 1 Tesla magnetic field
  - "Charge division" chamber
    - Charge division test
    - 1m-long W(330W/m) or Steel(1200W/m)
- Supporting system is also under development.



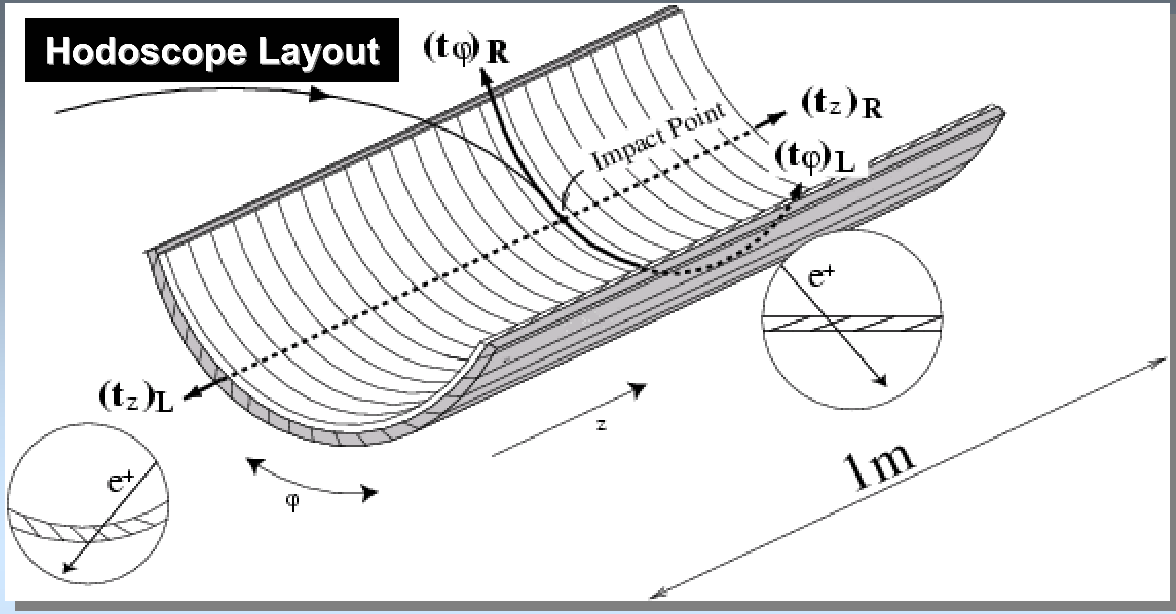


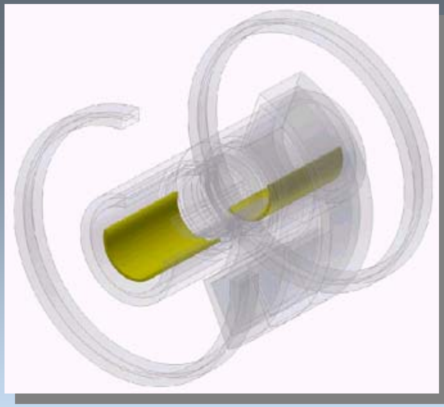


Want: FWHM
$\delta P_e / P_e \cong 0.8\%$
$\delta\theta_e \sim 9 \rightarrow 12$ mrad
$\delta x_{Tg} \sim 2.1 \rightarrow 2.5$ mm

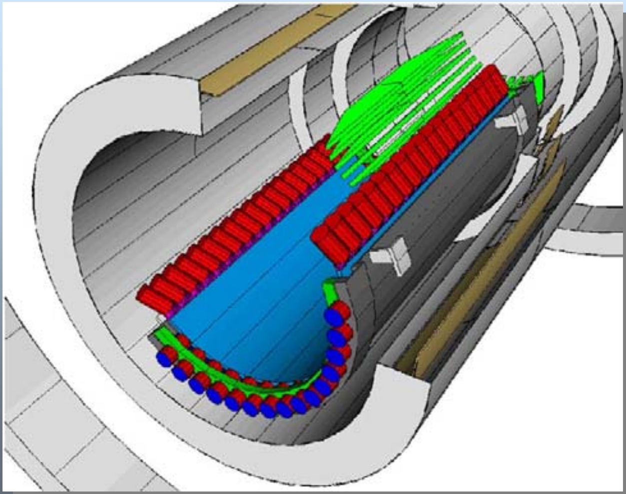
TOKYO Test DC Resolution(σ)	
Drift time measurement	100-150μm
Vernier cathode measurement	425μm
Charge division measurement	2cm
Drift velocity and drift time	4-12ns

Positron Timing Counters

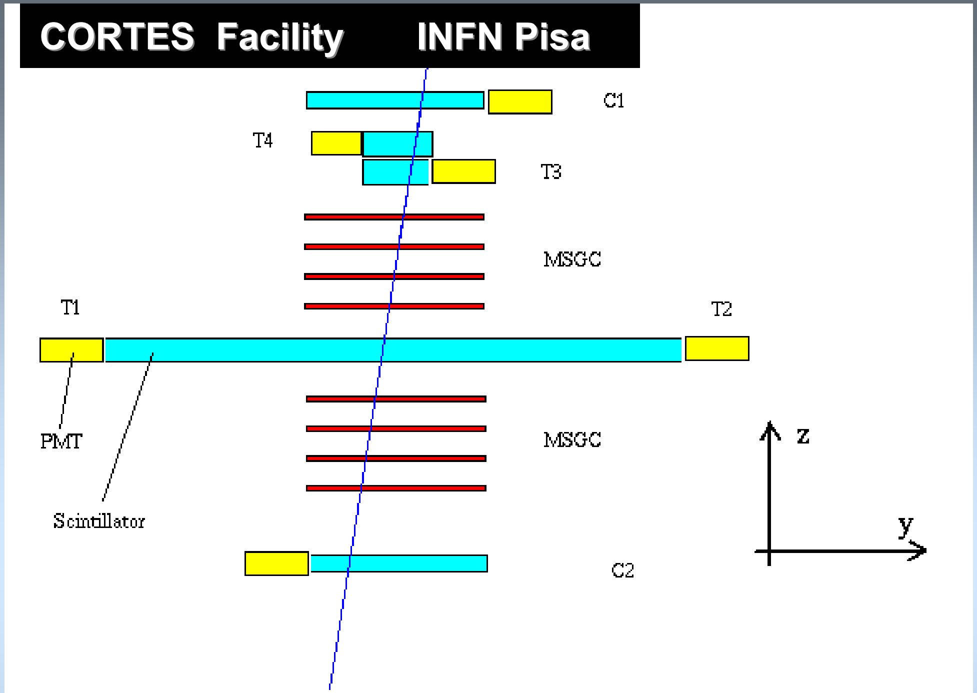




- Double layer of scintillator bars placed at right angles to each other, both up- & down-stream of the DCs
  - Outer: timing measurement
  - Inner: additional trigger information
- Goal σ_{time}~ 40psec (100 ps FWHM)

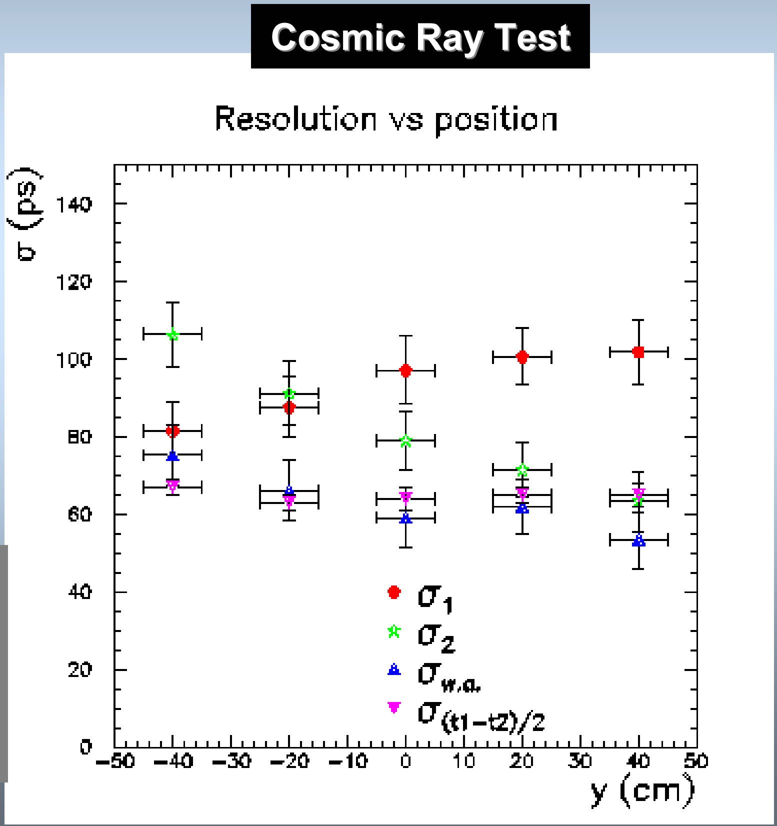


Timing Counter R&D



Cosmic Ray Test

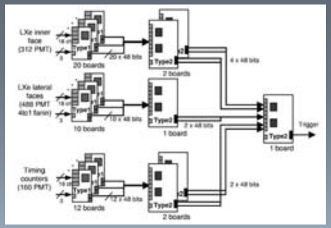
- Scintillator bar (5cm x ^{t}1cm x 100cm long)
- Telescope of 8 x MSGC



- **Measured resolutions** σ_{time}~60psec independent of incident position
- σ_{time} improves as ~1/√Npe

↪ 2 cm thick ?

Trigger

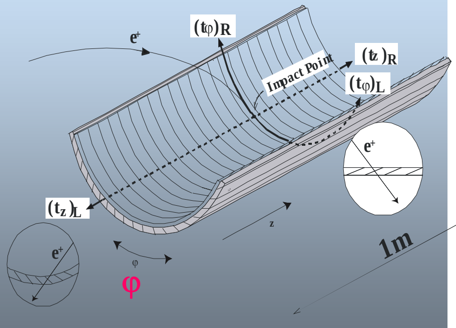


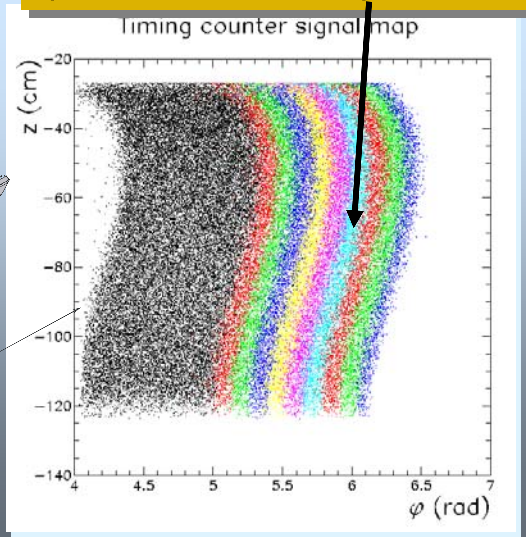
- μ^+-stopping rate — $10^8\ s^{-1}$
- Fast LXe energy sum $\Sigma E_\gamma > 45 MeV$ — $2\times10^3\ s^{-1}$
- time correlation γ – e^+ — $200\ s^{-1}$
- γ interaction point (PM with Q_{max} on front face only) extrapolate to target centre & correlate with e^+ impact point on timing counter
- angular corrlation γ – e^+ — $20\ s^{-1}$
- cut on R_{max} of drift chambers ? — $10\ s^{-1}$

Photon direction selection
7.5° in φ for a $\mu^+\rightarrow e^+\gamma$ event
In LXe Calorimeter to Target
(PMT with Q_{MAX} front face LXe)
gives a
spread over (5 timing counters)
on the e^+- timing counters side
(one coloured band)

Digital Trigger:

- Waveform digitizing for ALL channels
- 2GHz Waveform digitization
- 100 MHz FADCs + FPGAs
- baseline subtraction
- QT-Alogorithm (Q_{max} + t)
- latency 350 ns





Conclusions

Recent Experiments have improved LFV limits in the charged sector
Still NO Signal Found !

$$Br(\mu^+ \rightarrow e^+\gamma) < 1.2 \cdot 10^{-11}$$ **MEGA**

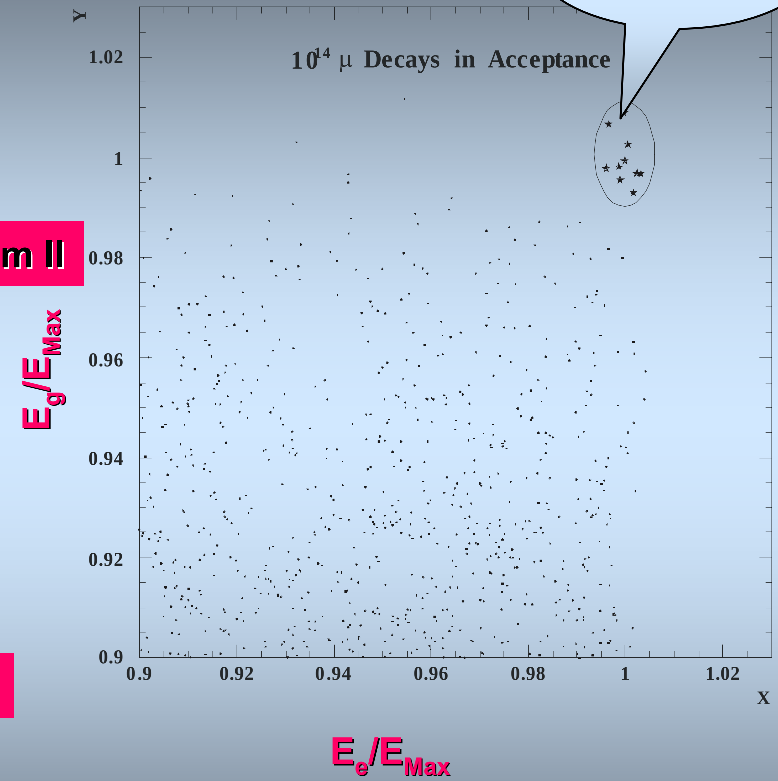
$$R_{\mu e} = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu_\mu N')} < 6.0 \cdot 10^{-13}$$ **Sindrum II**

New Experiments plan to improve
Single Event Sensitivities > 10^3

$$Br(\mu^+ \rightarrow e^+\gamma) < 5 \cdot 10^{-14}$$ **MEG**

$$R_{\mu e} = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu_\mu N')} < 2.0 \cdot 10^{-17}$$ **MECO**

$\mu \rightarrow e\gamma$ at 10^{-13} level



With LFV results from neutrino sector
Prospects for signature of New Physics e.g. SUSY-GUT good !

Simulation – HOPEFULLY REALITY !

Experiment Time Scale

now

Planning	R & D	Assembly	Data Taking

1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007

- **All Detector Systems under development**
- **R&D phase still in progress**
- **Next significant Milestone Large Prototype test NOW**
- **Beam studies PSI πE5 Finishing now**

Further interest

http://meg.icepp.s.u-tokyo.ac.jp
http://meg.pi.infn.it
http://meg.psi.ch