The MEG experiment (and beyond)

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Recent $m^+ \to e^+ \gamma$ Experiments

Lab.	Year	Upper limit	Experiment or Auth.
PSI	1977	$< 1.0 \times 10^{-9}$	A. Van der Schaaf *et al.*
TRIUMF	1977	$< 3.6 \times 10^{-9}$	P. Depommier *et al.*
LANL	1979	$< 1.7 \times 10^{-10}$	W.W. Kinnison *et al.*
LANL	1986	$< 4.9 \times 10^{-11}$	Crystal Box
LANL	1999	$< 1.2 \times 10^{-11}$	MEGA
PSI	~2008	$\sim 10^{-13}$	*MEG*

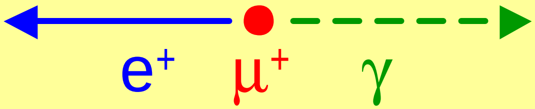
Two orders of magnitude improvement

tough experimental challenge! But
several SUSY GUT and SUSY see-saw
models predict BRs at the reach of MEG

Signal and background

signal

$\mu \rightarrow e \gamma$



$\theta_{e\gamma} = 180°$

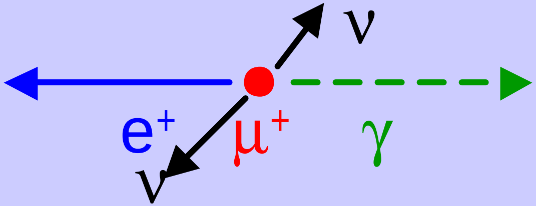
$E_e = E_\gamma = 52.8$ MeV

$T_e = T_\gamma$

background

physical

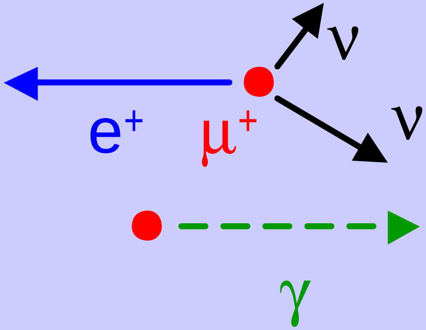
$\mu \rightarrow e \gamma \nu \nu$



accidental

$\mu \rightarrow e \nu \nu$

$$\left\{ \begin{array}{l} \mu \rightarrow e \gamma \nu \nu \\ ee \rightarrow \gamma \gamma \\ eZ \rightarrow eZ \gamma \end{array} \right.$$



Required Performances

The sensitivity is limited by the accidental backg

The n. of acc. backg events (n_{acc}) depends quadratically on the muon rate

Effective BRback (n_{back}/Rμ T) $BR_{acc} \propto R_\mu \times \boxed{? E_e \times ? E_?^2} \times ? ?_{e?}^2 \times ? t_{e?} \approx 2\ 10^{-}$

(BRphys ≈ 0.1 BRacc)

Integral on the detector resolutions of the Michel and radiative decay spectra

allows BR ($\mu \to e\gamma$) $\approx 10^{-13}$ but needs

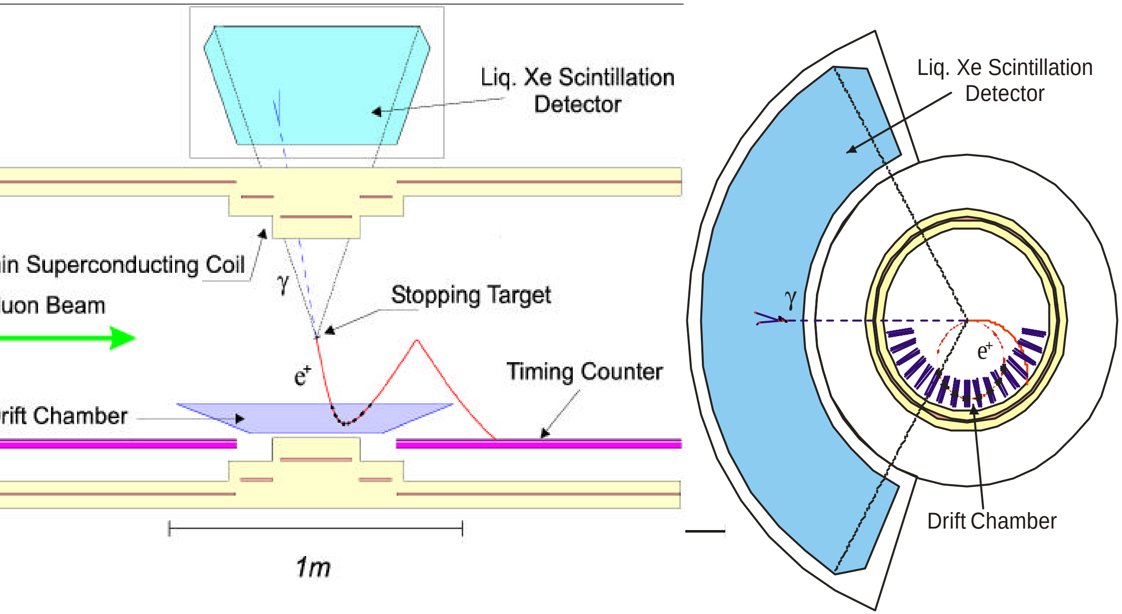
FWHM

Exp./Lab	Year	DE_e/E_e (%)	DE_γ/E_γ (%)	$Dt_{e\gamma}$ (ns)	$Dq_{e\gamma}$ (mrad)	Stop rate (s^{-1})	Duty cyc.(%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^5	(6..9)	4.9×10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5×10^8	(6..7)	1.2×10^{-11}
MEG	2008	0.8	4	0.15	19	2.5×10^7	100	1×10^{-13}

Need of a DC muon beam

Experimental method

Detector outline

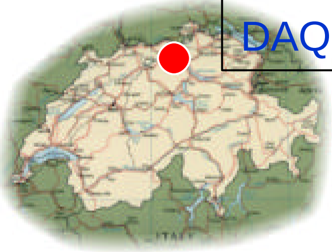


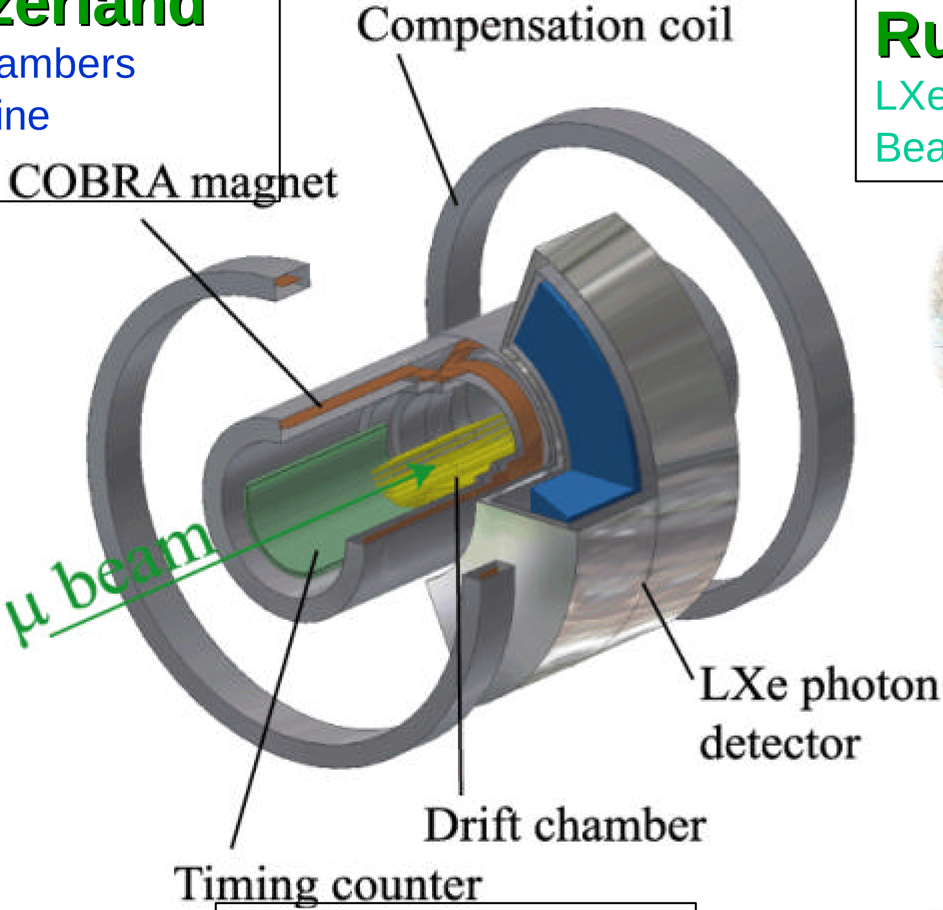
1. Stopped beam of 3 10^7 μ /sec in a 150 μm target
2. Solenoid spectrometer & drift chambers for e^+ momentum
3. Scintillation counters for e^+ timing
4. Liquid Xenon calorimeter for γ detection (scintillation)

- fast: 4 / 22 / 45 ns
- high LY: ~ 0.8 * NaI
- short X_0: 2.77 cm

Detector Construction

Switzerland
Drift Chambers
Beam Line
DAQ

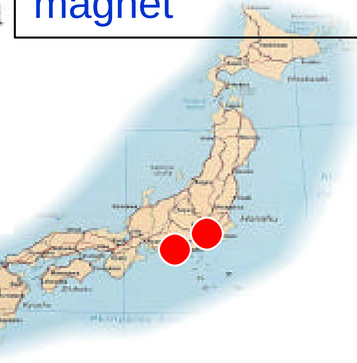




Russia
LXe Tests
Beam line

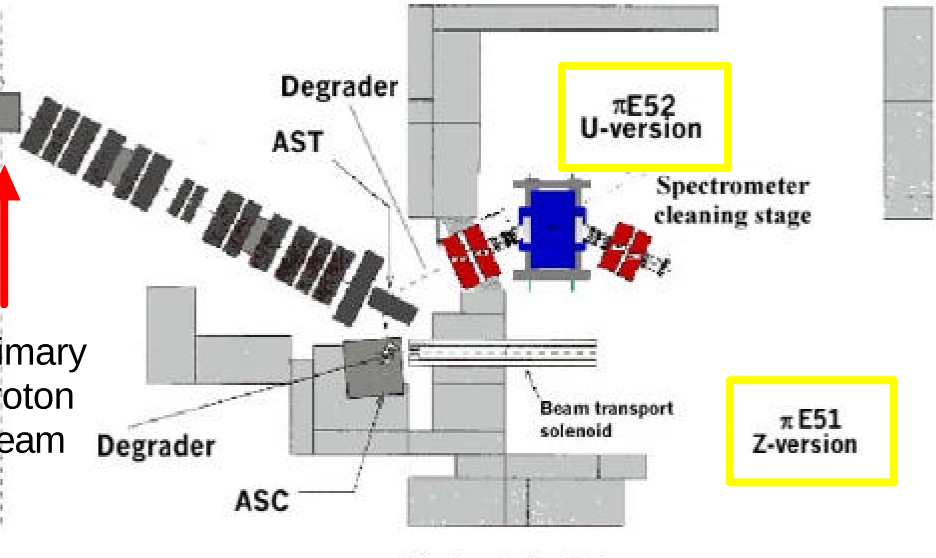
taly
+ counter
rigger LXe
alorimeter

Japan
LXe Calorimeter,
Spectrometer’s
magnet



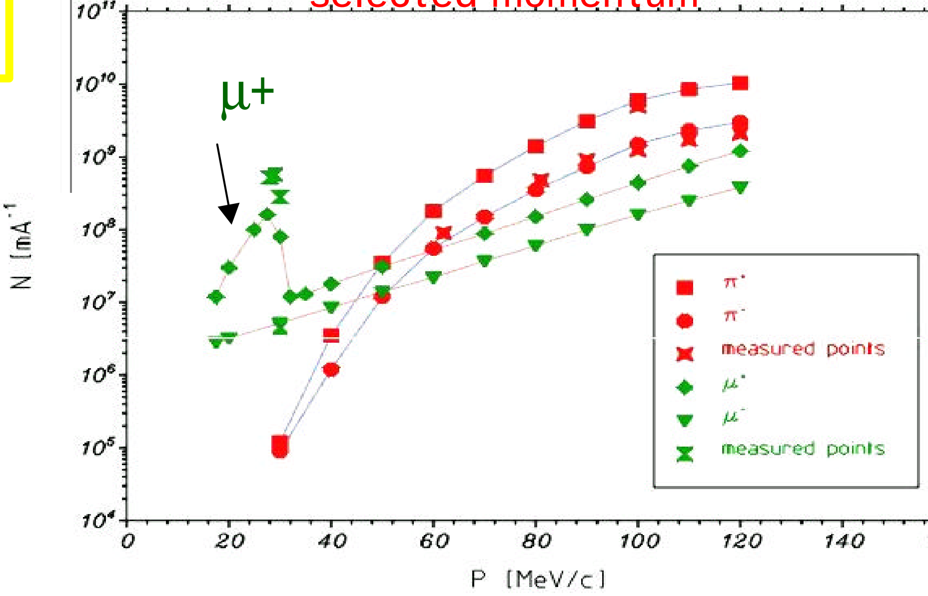
USA(UCI)
Calibrations

1) The PSI πE5 DC beam



The layout of πE5

Particles intensity as a function of the selected momentum

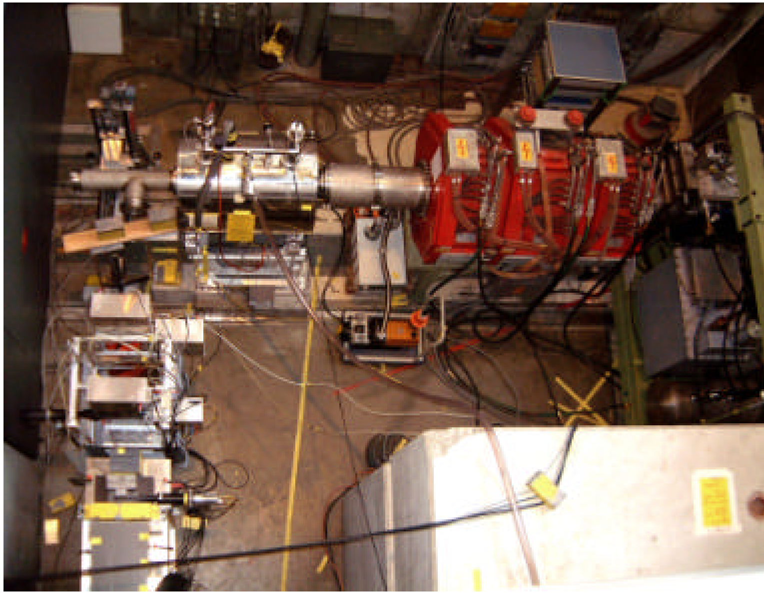


- **1.8 mA of 590 MeV/c protons (most intense DC beam in the world)**
- **29 MeV/c muons from decay of π stop at rest: fully polarized**

Beam studies

Optimization of the beam elements:

- **Wien filter** for μ/e separation
- **Degrader** to reduce the momentum stopping in a 150 μm CH_2 target
- **Solenoid** to couple beam with COBRA spectrometer



Results (4 cm target):

	Z-version
• Rμ (total)	$1.3*10^8\ \mu^+/s$
• Rμ (after W.filter & Coll.)	$1.1*10^8\ \mu^+/s$
• Rμ (stop in target)	$6*10^7\ \mu^+/s$
• Beam spot (target)	$\sigma \approx 10$ mm
μ/e separation (at collimator)	$7.5\ \sigma$ (12 cm)

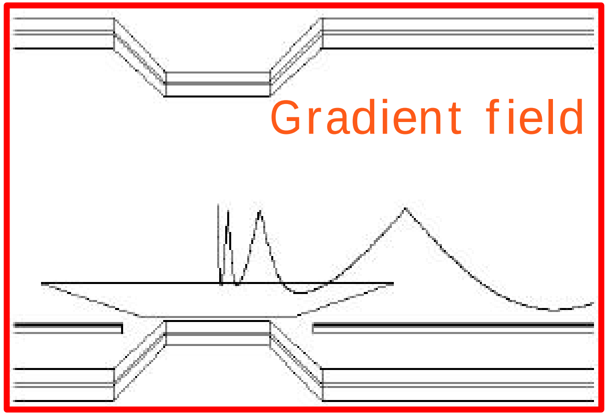
} Extrapolated from measurements to the final magnets configuration

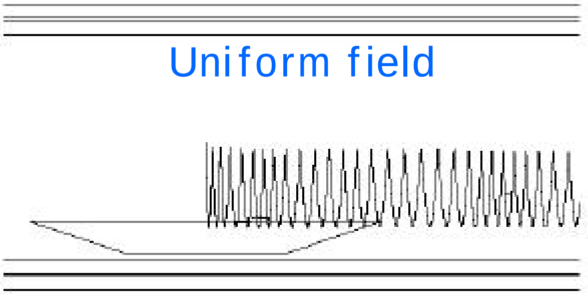
10^8 μ/s could be stopped in the target but only $3x10^7$ will be used because of accidental background

2) COBRA spectrometer

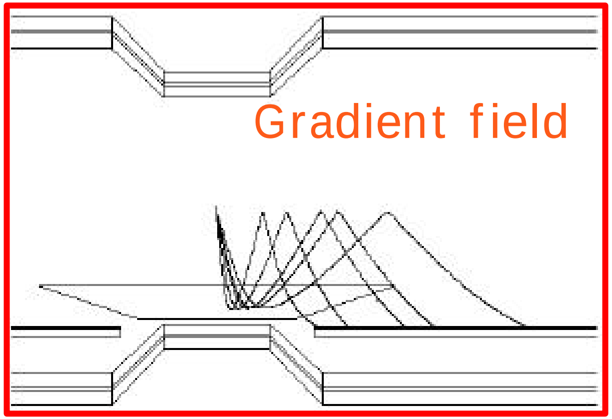
COnstant Bending RAdius (COBRA) spectrometer

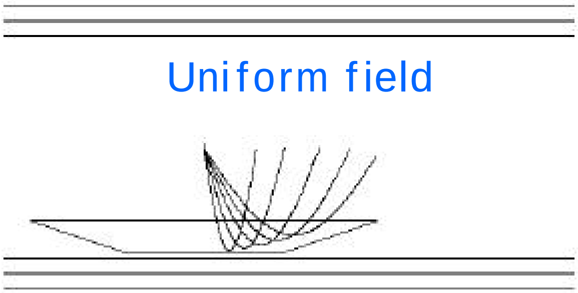
- High p_T positrons quickly swept out



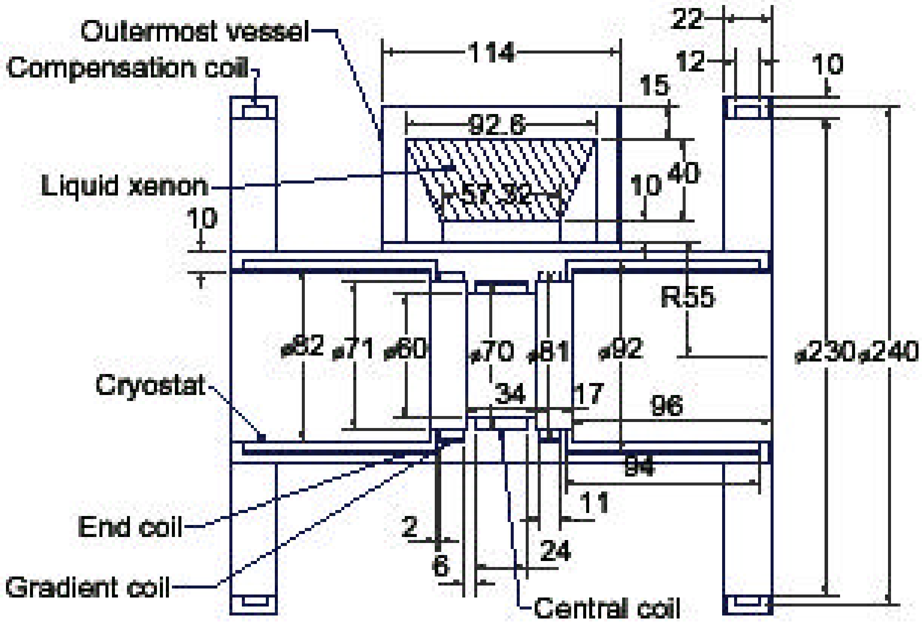


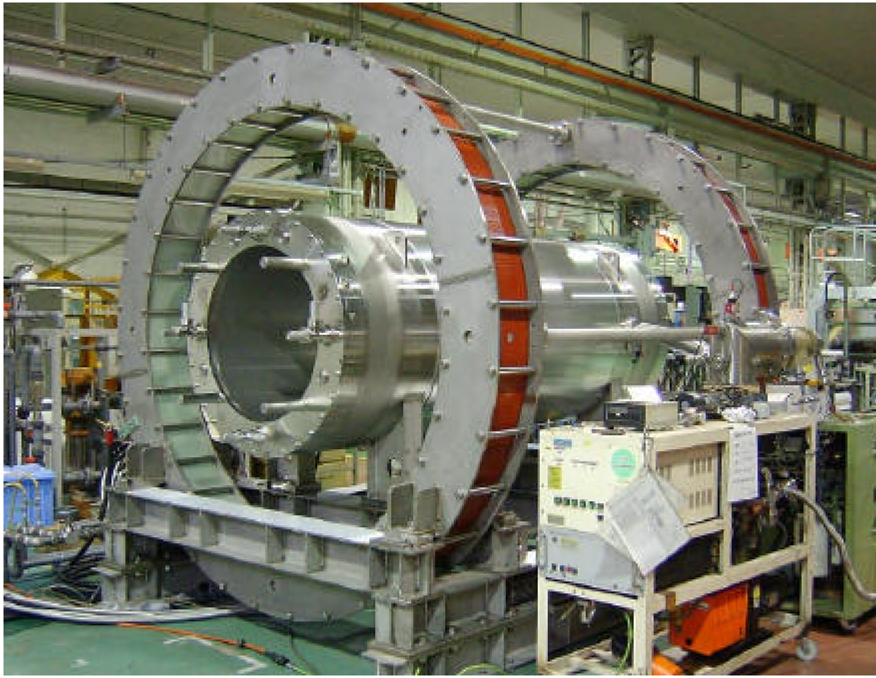
- Constant bending radius independent of emission angles





The magnet (KEK+Tokyo)





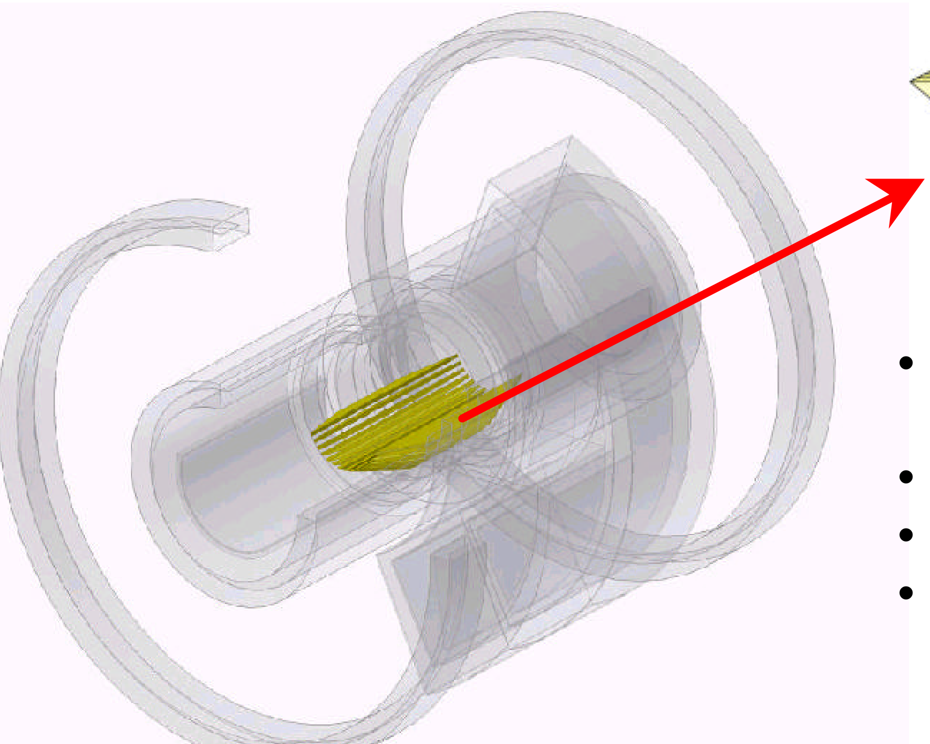
- B_c = 1.26T current = 359A
- Five coils with three different diameters
- Compensation coils to suppress the stray field around the LXe detector
- High-strength aluminum stabilized superconductor

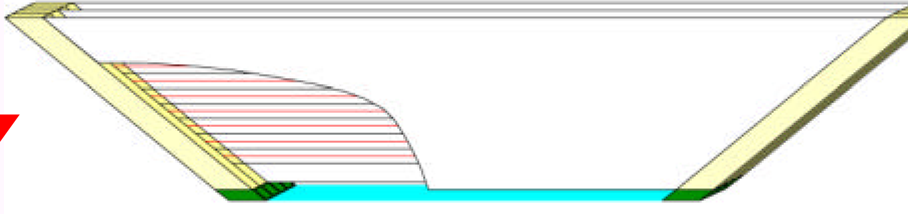
⇒thin magnet

(**1.46 cm Aluminum**, **0.2 X_0**)

•Ready: at PSI

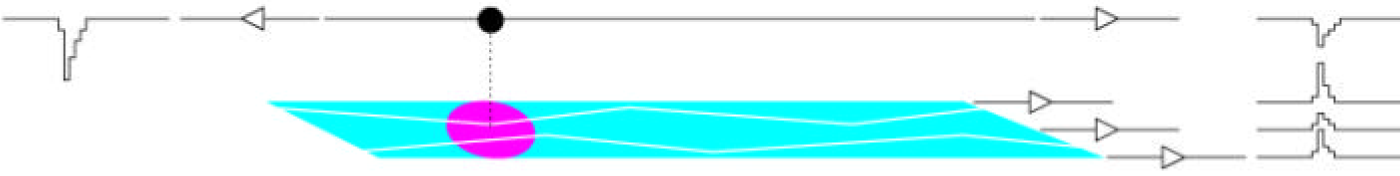
Positron Tracker



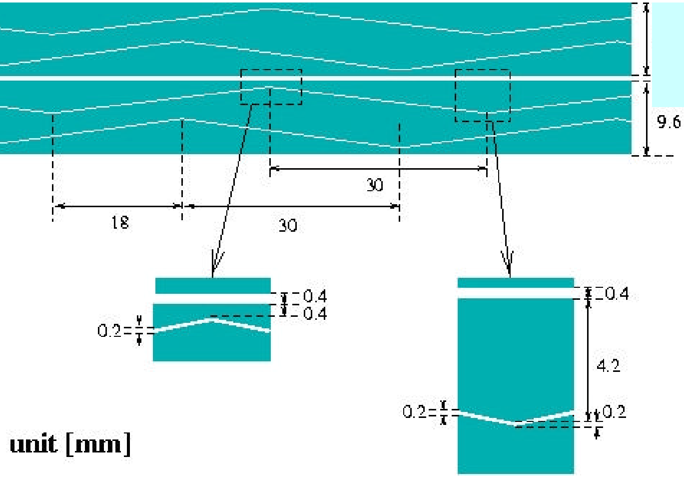


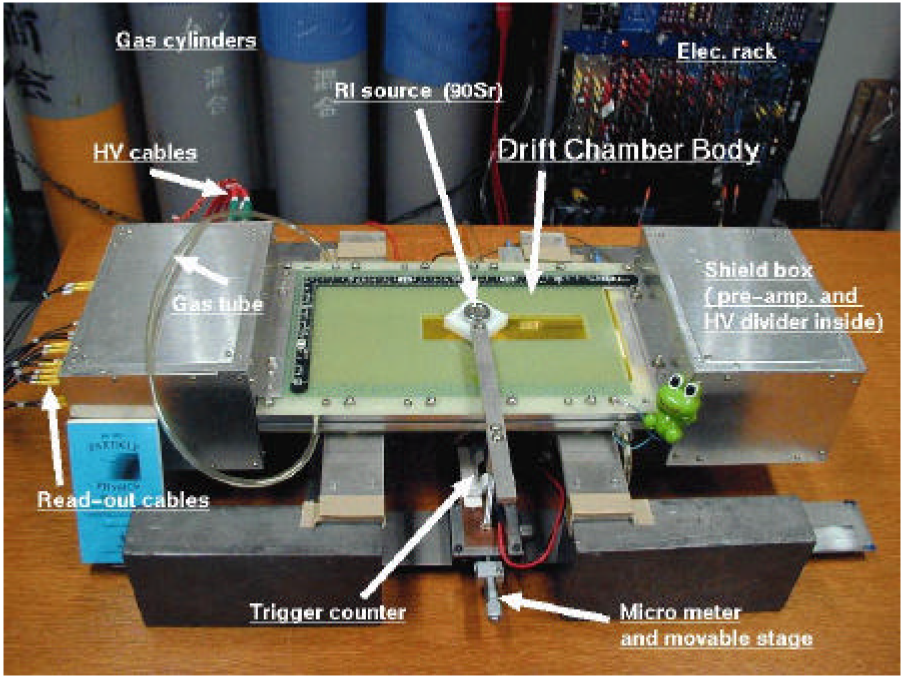
- 17 chamber sectors aligned radially with 10°intervals
- Two staggered arrays of drift cells
- Chamber gas: He-C_2H_6 mixture
- Vernier pattern to measure z-position made of 15 μm kapton foils

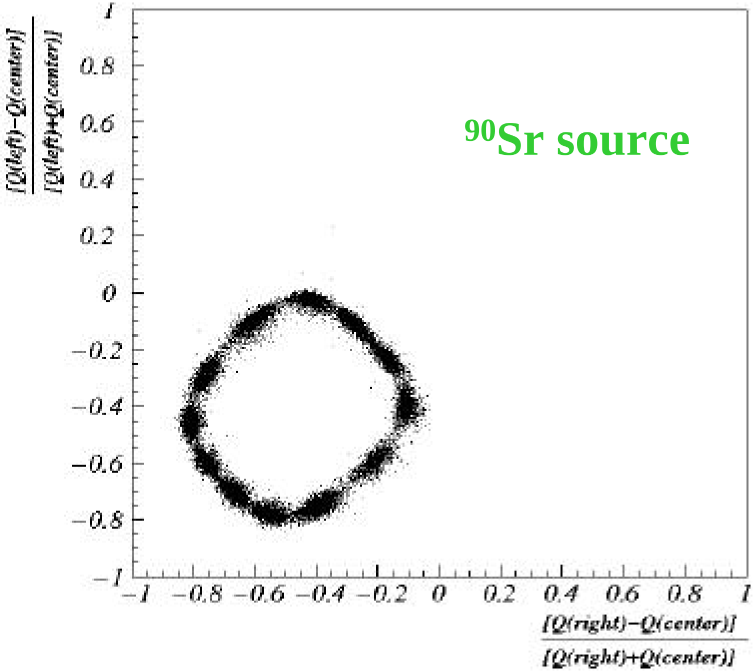
goals σ(X,Y) ~200 μm (drift time) σ(Z) ~ 300 μm (charge division vernier strips)



Drift chambers R&D (1)



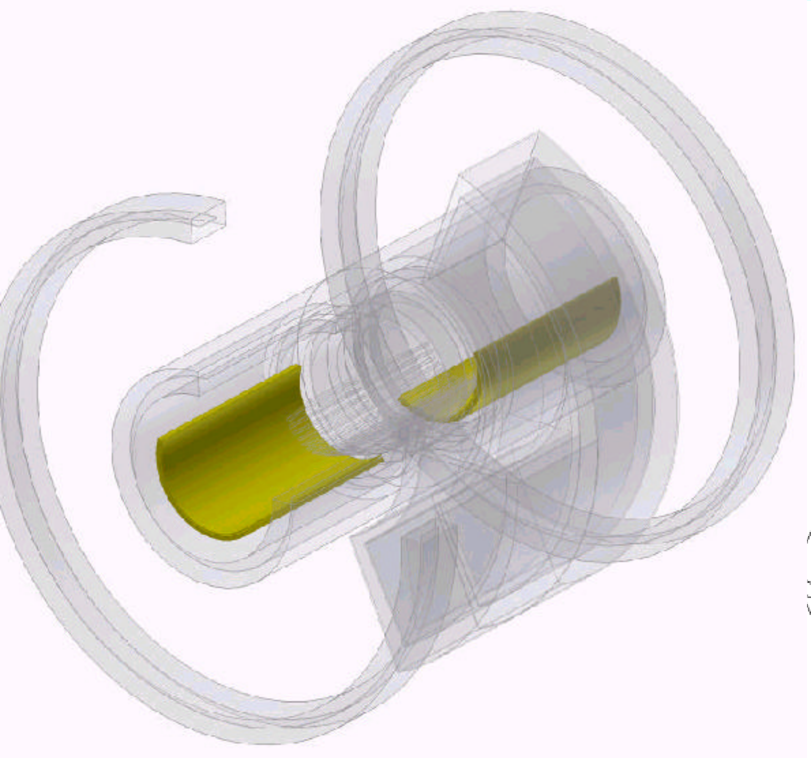


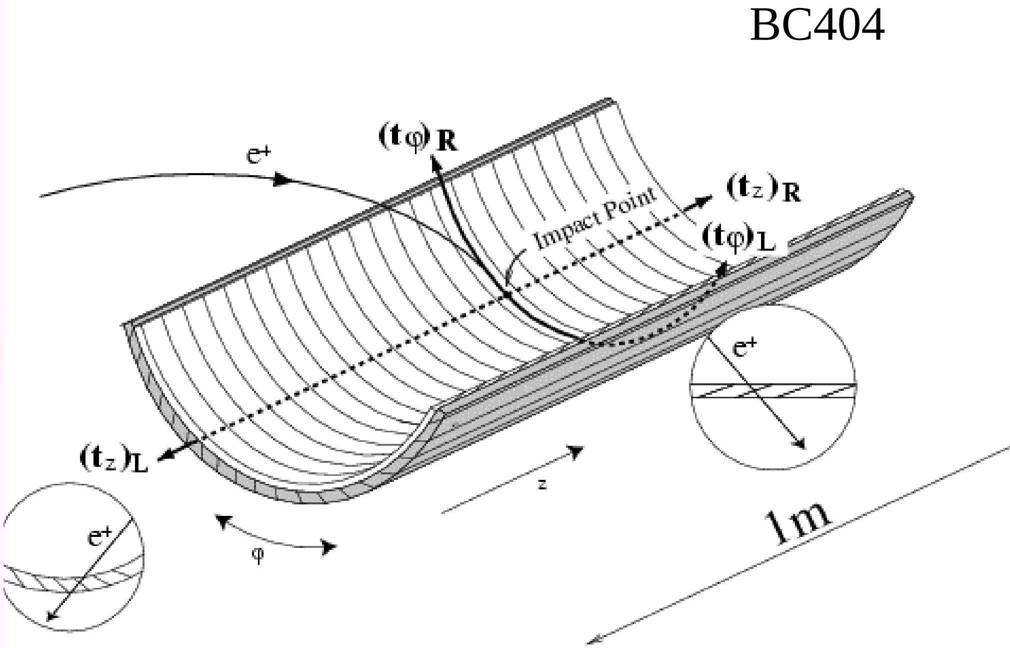


$$s_R = 93 \pm 10 mm$$

$$s_Z = 425 \pm 7 mm$$

3) Positron Timing Counter



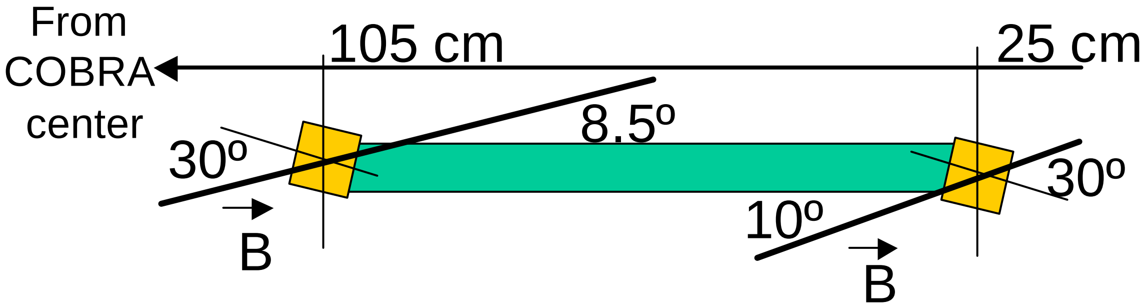


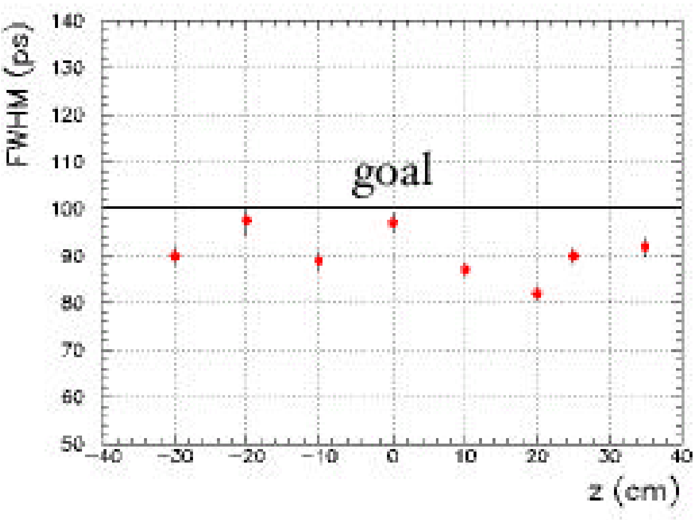
- One (outer) layer of scintillator read by PMTs : timing
- One inner layer of scintillating fibers read by APDs: trigger (the long. Position is needed for a fast estimate of the positron direction)

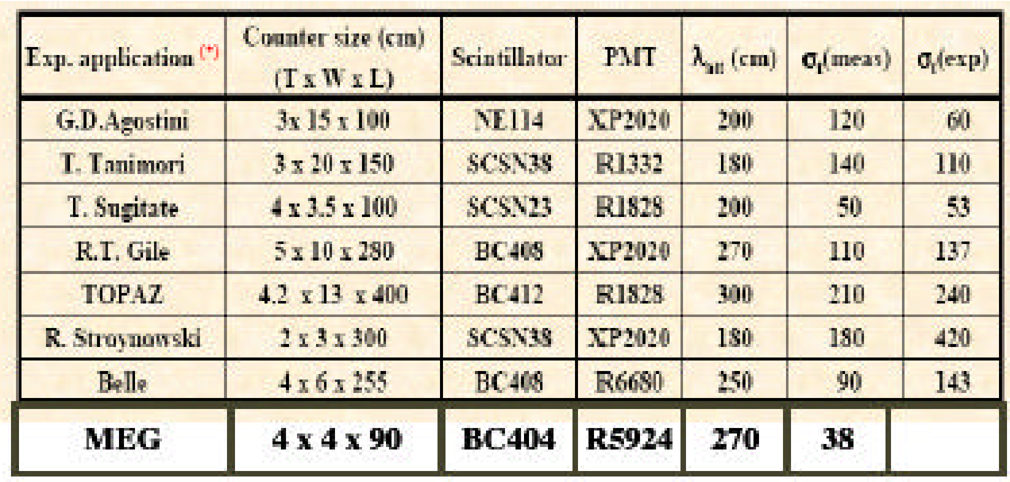
5 x 5 mm^2

•Goal σ_{time}~ 40 psec (100 ps FWHM)

Timing counter measured resolution







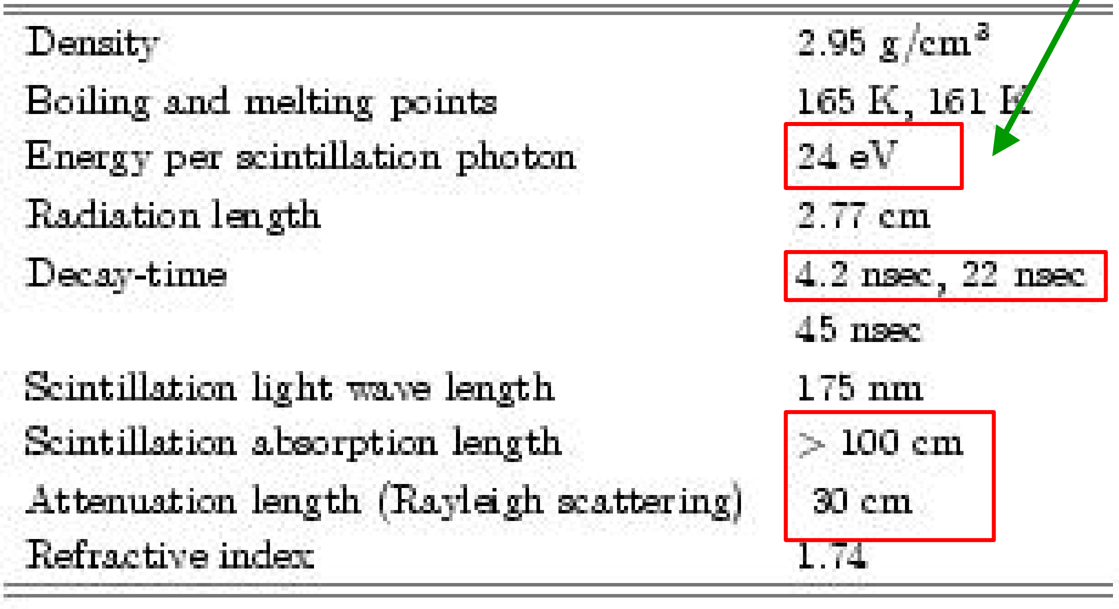
Exp. application (*)	Counter size (cm) (T x W x L)	Scintillator	PMT	λ_{att} (cm)	σ_t(meas)	σ_t(exp)
G.D.Agostini	3x 15 x 100	NE114	XP2020	200	120	60
T. Tanimori	3 x 20 x 150	SCSN38	R1332	180	140	110
T. Sugitate	4 x 3.5 x 100	SCSN23	R1828	200	50	53
R.T. Gile	5 x 10 x 280	BC408	XP2020	270	110	137
TOPAZ	4.2 x 13 x 400	BC412	R1828	300	210	240
R. Stroynowski	2 x 3 x 300	SCSN38	XP2020	180	180	420
Belle	4 x 6 x 255	BC408	R6680	250	90	143
MEG	**4 x 4 x 90**	**BC404**	**R5924**	**270**	**38**	

Best existing TC

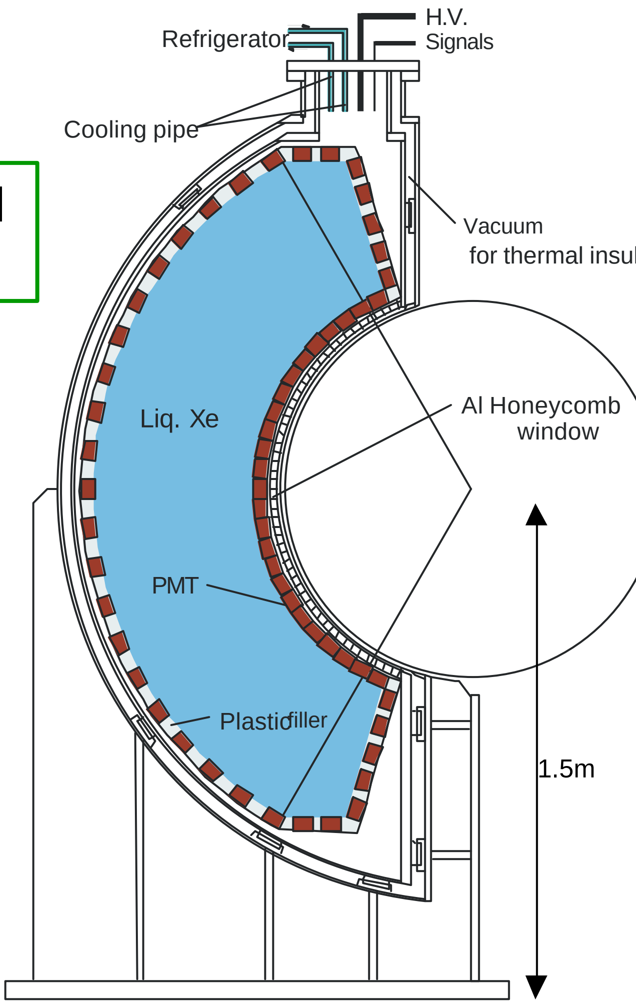
4) Liquid Xe calorimeter

- 800 l of Liquid Xe
- ~800 PMT immersed in LXe
- Only scintillation light
- High luminosity
- Unsegmented volume

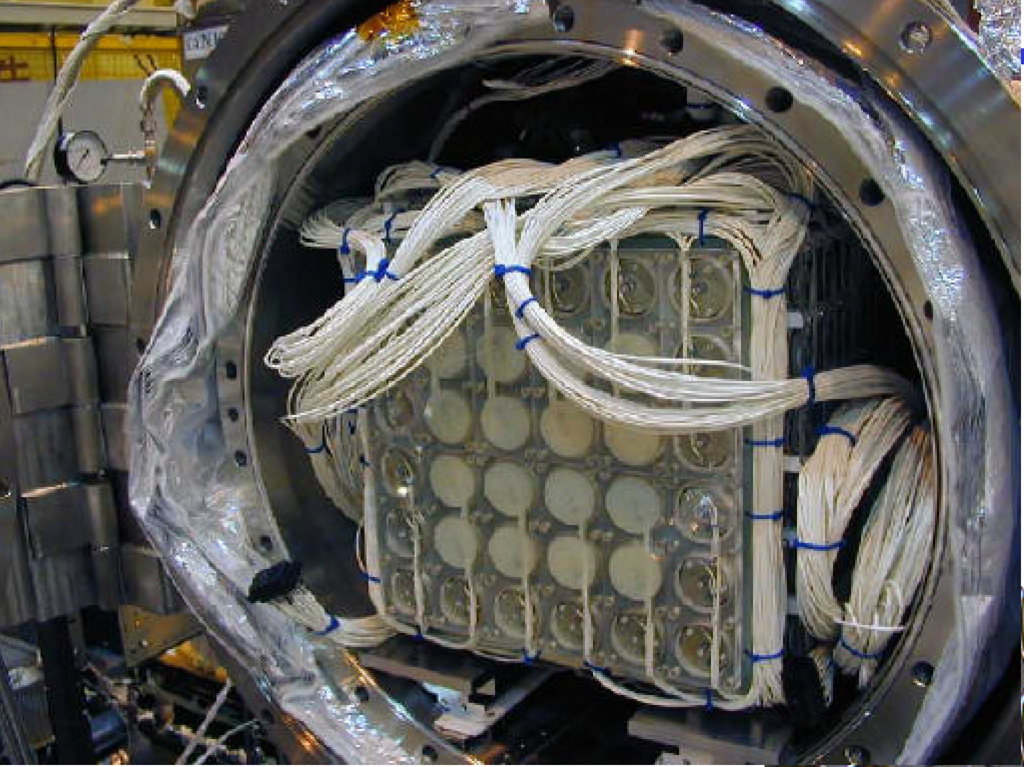
Experimental check



Density	2.95 g/cm^3
Boiling and melting points	165 K, 161 K
Energy per scintillation photon	24 eV
Radiation length	2.77 cm
Decay-time	4.2 nsec, 22 nsec 45 nsec
Scintillation light wave length	175 nm
Scintillation absorption length	> 100 cm
Attenuation length (Rayleigh scattering)	30 cm
Refractive index	1.74

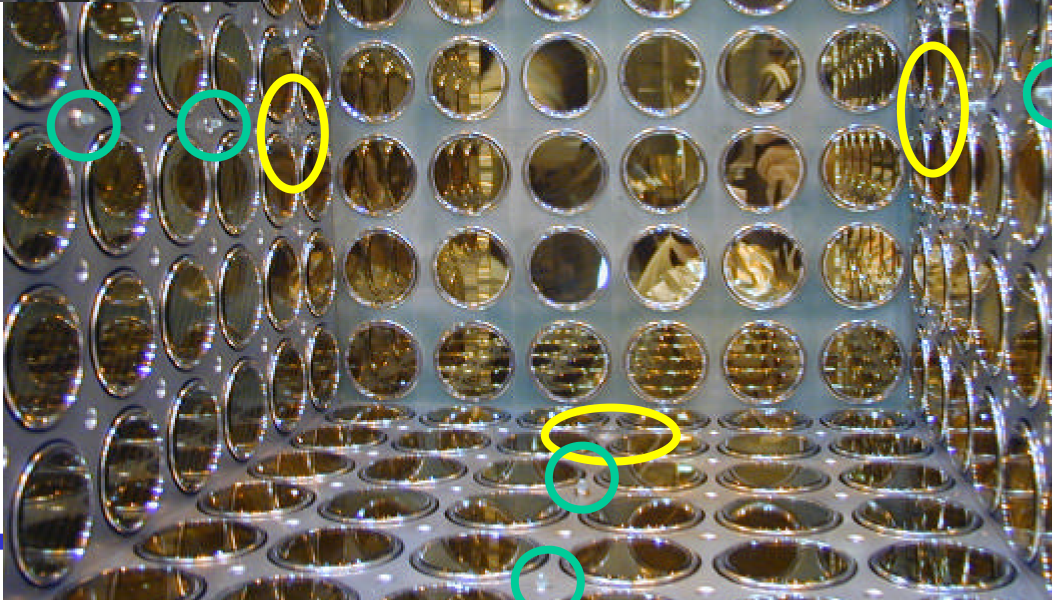


The LP (100 liters of Lxe)



α-sources ○

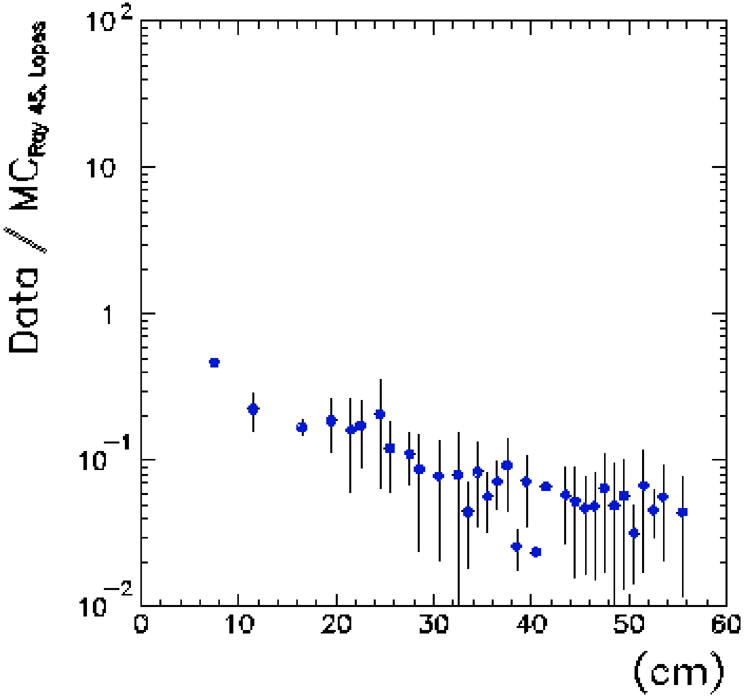
LEDs ○



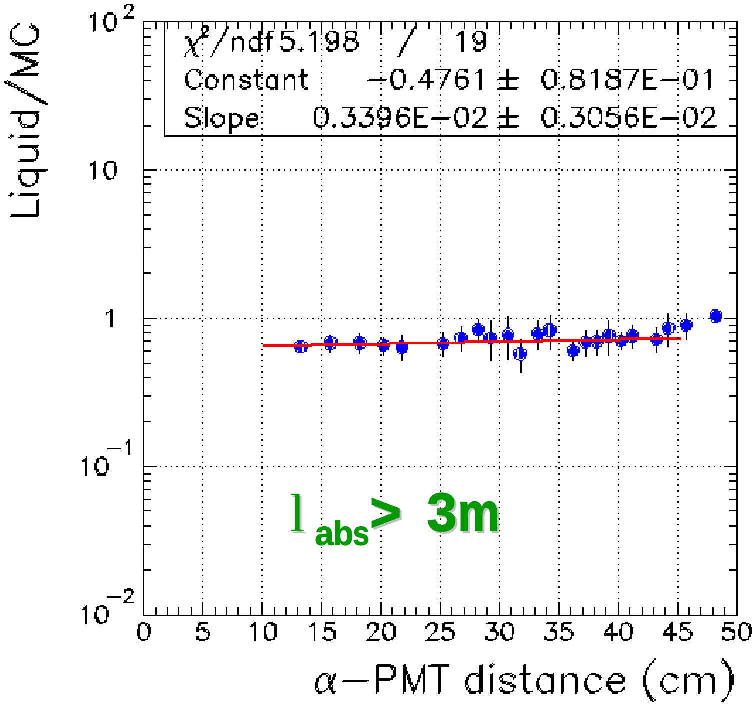
LP: LXe optical properties

- First tests showed that the number of scintillation photons was MUCH LESS than that expected
- It improved with Xe cleaning: Oxysorb + gas getter + re-circulation (took time)
- There was a strong absorption due to contaminants (mainly H_2O)

March 2002

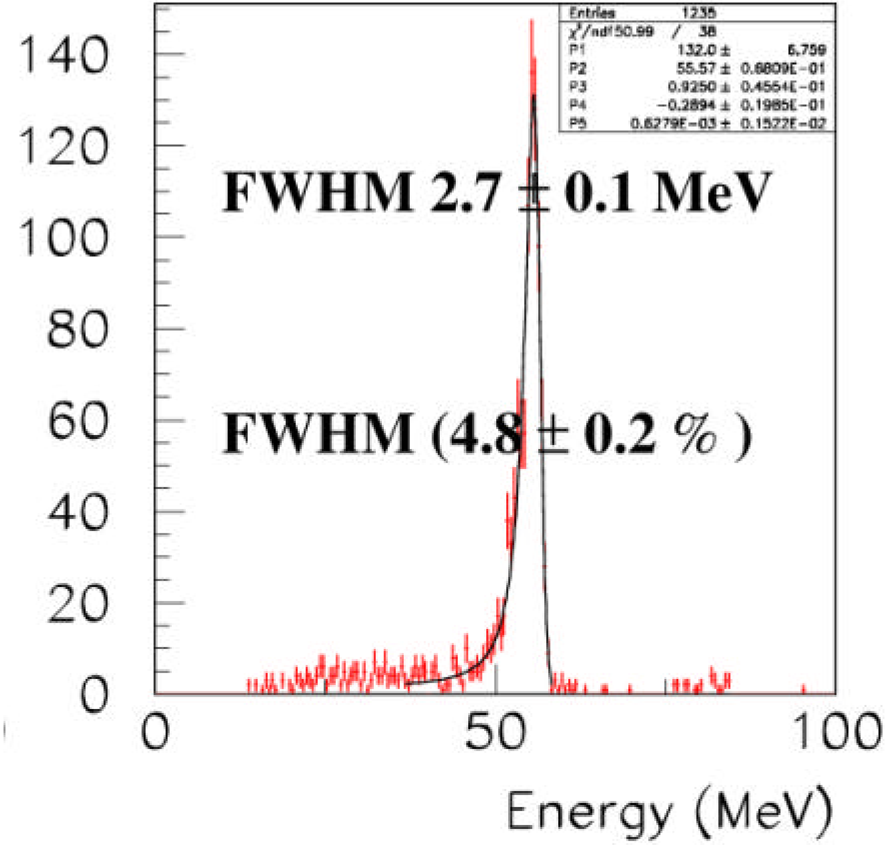


Present (oct. 2004)



$l_{abs} > 3m$

Experimentally measured resolutions



p^{-} **p** ® p^{0} **n** **e** p^{0} ® g g

4.8 % FWHM

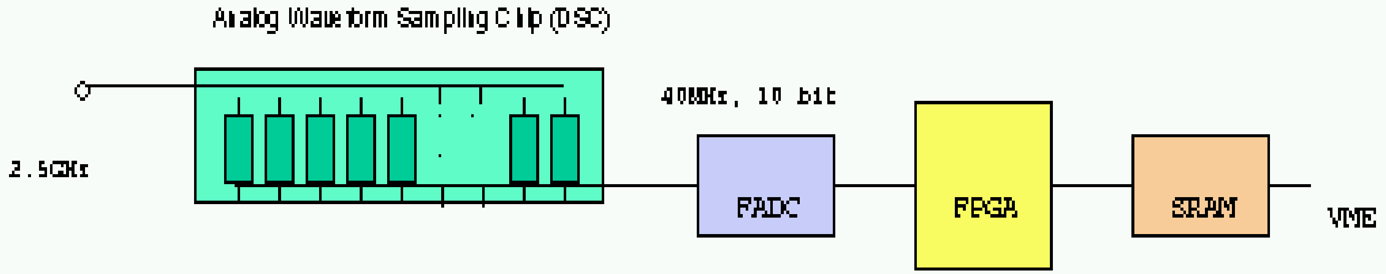
FWHM(T) ≈ 150 ps

σ_x= 2 - 4 mm

PMT Development Summary

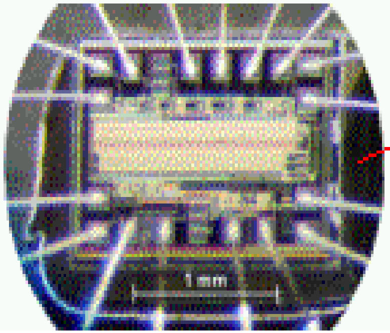
1st generation R6041Q	2nd generation R9288TB	3rd generation R9288ZA
		
228 in the LP (2003 CEX and TERAS) 127 in the LP (2004 CEX)	111 In the LP (2004 CEX)	Not used yet in the LP
Rb-Sc-Sb Mn layer to keep surface resistance at low temp.	K-Sc-Sb Al strip to fit with the dynode pattern to keep surface resistance at low temp.	K-Sc-Sb Al strip density is doubled. 4% loss of the effective area.
1st compact version QE~4-6% Under high rate background, PMT output reduced by 10-20% with a time constant of order of 10min.	Higher QE ~12-14% Good performance in high rate BG Still slight reduction of output in very high BG	Higher QE~12-14% Much better performance in very high BG

Readout electronics



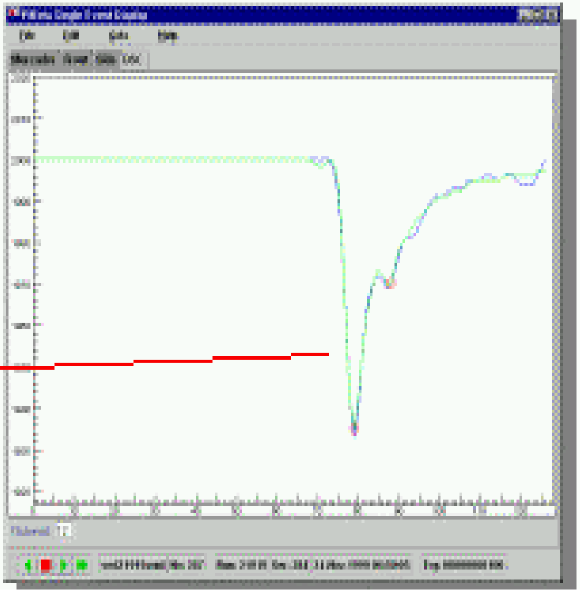
- Waveform digitizing for all channels
- Custom domino sampling chip designed at PSI
- 2.5 GHz sampling speed @ 40 ps timing resolution
- Sampling depth 1024 bins

- Drift chamber signals go directly to FADC (100MHz)



Previous Version

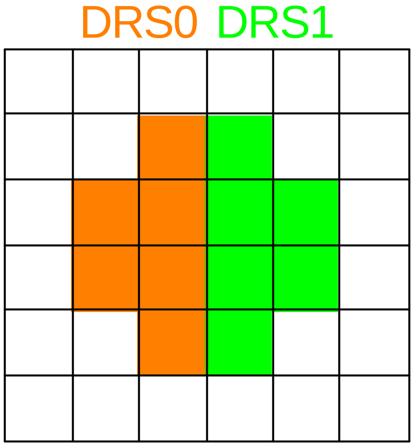
1.2 GHz



LP Front Face

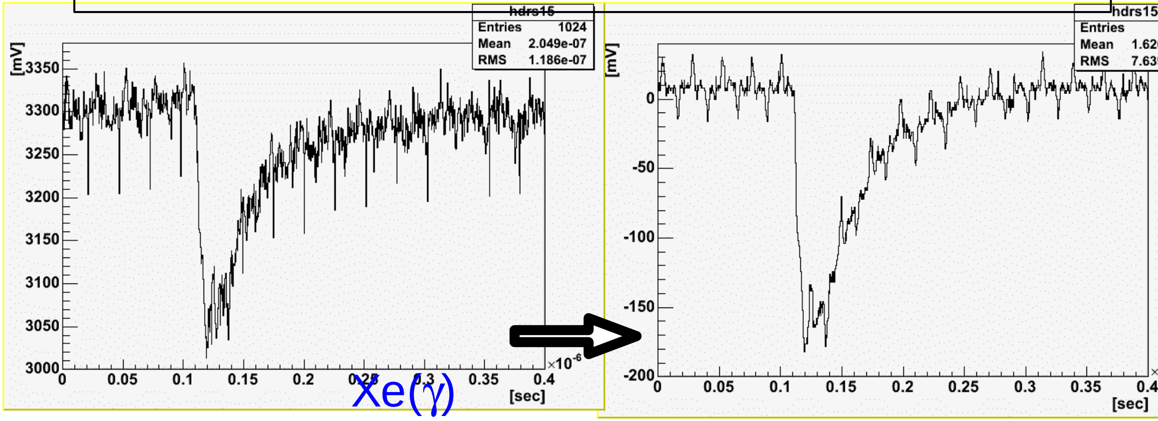
wo DRS chips in the recent PSI test

- 10ch/chip (8 for data and 2 for calibration) → in total 16 for data
- 2.5GHz sampling (400ps/sample)
- 1024 sampling cells
- Readout 40MHz 16bit
- Free running domino wave stopped by trigger from LP



- **DRS inputs**
  - LP: central 12 PMTs
  - LYSO: 2 anode signals for each DRS chip as time reference

- DRS chip calibration
  - Spike structure left even after calibration, which will be fixed by re-programming FPGA on the board.



Sensitivity Summary

Detector parameters $T = 2.6 \cdot 10^{7}\ s$ $R_{\mu} = 0.3 \cdot 10^{8}\ {}^{\mu}\!/_{s}$ $\frac{O}{4p} = 0.09$

$e_{e} \approx 0.9$ $e_{sel} \approx (0.9)^{3} = 0.7$ $e_{?} \approx 0.6$

Cuts at 1,4×FWHM

Signal $N_{sig} = BR \cdot T \cdot R_{\mu} \cdot \frac{\Omega}{4p} \cdot e_{e} \cdot e_{g} \cdot e_{sel}$

Single Event Sensitivity $SES = 1 \Big/ T \cdot R_{\mu} \cdot \frac{\Omega}{4p} \cdot e_{e} \cdot e_{g} \cdot e_{sel}$ $\approx 4\times10^{-14}$

Backgrounds $BR_{acc} \propto R_{\mu} \times ?E_{e} \times ?E_{?}^{2} \times ??_{e?}^{2} \times ?t_{e?} \approx 2\times10^{-14}$

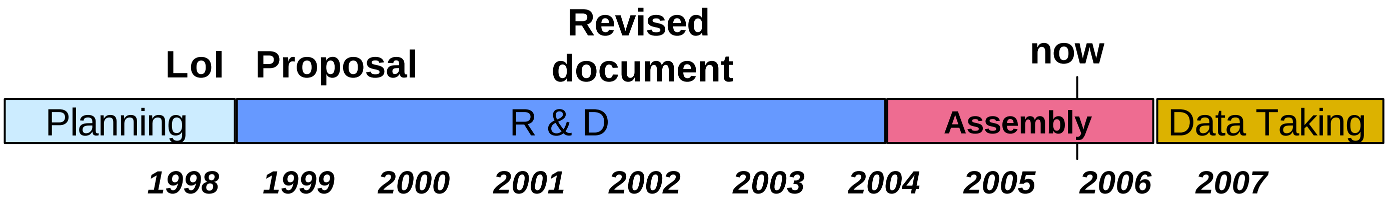
$BR_{phys} \approx 3\times10^{-15}$

Upper Limit at 90% CL $BR(\mu\rightarrow e\gamma) \approx 1\times10^{-13}$

Discovery 4 events (P = 2×10^{-3}) correspond $BR = 2\times10^{-13}$

Time Scale

- We hope to get a significant result before entering the LHC era
- Measurements and detector simulation make us confident that we can reach the SES of 4 x 10^{-14} to $\mu \rightarrow e\gamma$ (BR 10^{-13}) and possibly below…
- Time profile



More details at

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

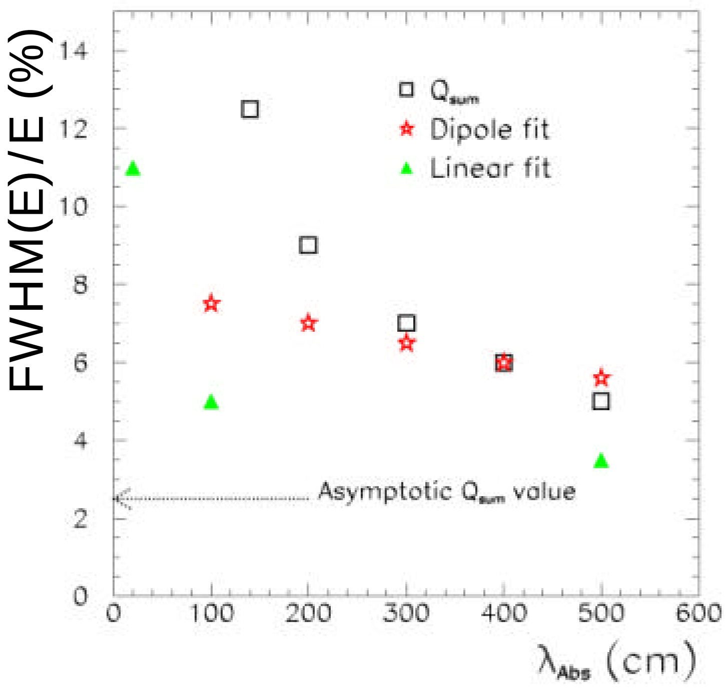
Possible improvements (how to reduce the accidental background) in MEG (and beyond): 1) ? $E_?$

(J. Aysto et al., Physics with low-energy muons at a neutrino factory complex, CERN-TH/2001-231)

- In order to use 10^8 μ/s a factor 10 in the reduction of acc. background must be achieved

$$BR_{acc} \propto ?\, E_?^2$$

- Complete MC simulation
- At l$_{\mathrm{abs}}$® ¥ the resolution is dominated by photostatistics FWHM(E)/E ≈ 2.5% (including edge effects)
- Future better detectors with high enough acceptance ?

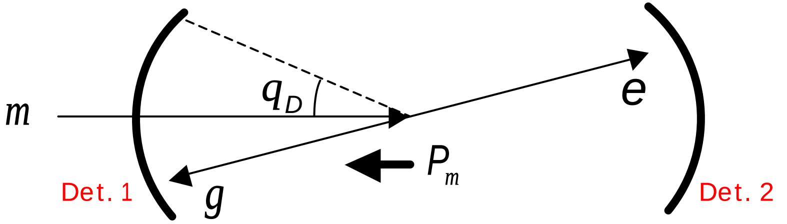


Possible improvements in MEG (and beyond): 2) Pμ

(Y. Kuno et al., MEG TN1, 1997 and references)

$$\text{H.E.}\gamma \text{ in } \mu^+ \to e^+\nu\bar{\nu}\gamma : (1+P_\mu \cos\theta_\gamma)$$

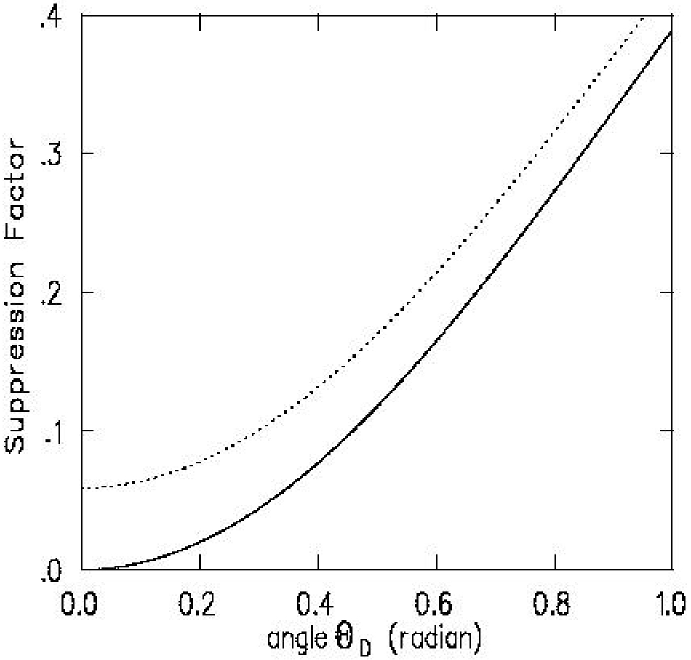
$$\text{H.E.}e^+ \text{ in } \mu^+ \to e^+\nu\bar{\nu} : (1+P_\mu \cos\theta_e)$$



$\Rightarrow$ *Suppression factor η (for isotropic μ → eγ decay)*

$$\eta = \frac{\int_{\cos\theta_D}^{1} d\cos\theta_D\,(1+P_\mu\cos\theta_D)(1-P_\mu\cos\theta_D)}{\int_{\cos\theta_D}^{1} d\cos\theta_D}$$

Figure 1: Suppression factor for accidental background for $\mu^+ \to e^+\gamma$ search.



- For suitable geometry big η factors can be obtained
- This is not the case for MEG (detailed calculations are necessary)
- In some theories (minimal SU(5) model) the positron has a definite helicity

➔ Pμ is less effective

Beyond: sensitivity to 10^{-15} ?

- Increase of the muon stopping rate by one order of magnitude➔ quadratic increase of the accidental background...

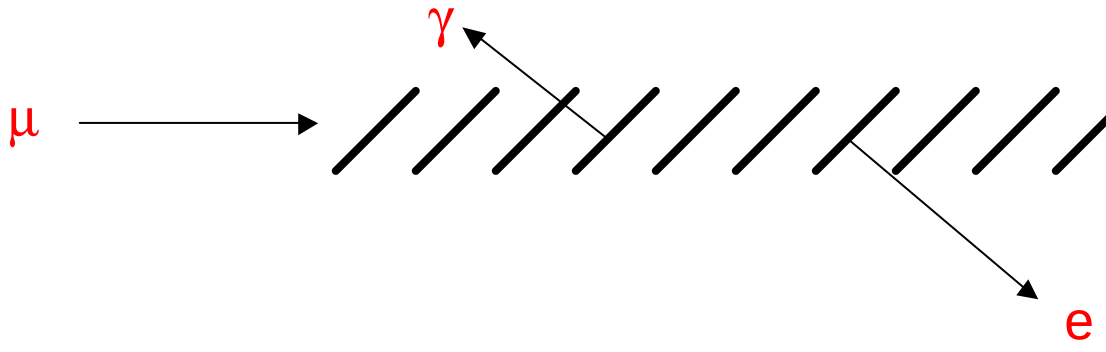
Beyond... (Ideas) 3) ? E_{e^+}

- Use of beta spectrometers: ? E_{e^+} /E_{e^+} from 1% ➔ .1% (background reduction of one order of magnitude)

Beyond... (Ideas) 4) ? q_{e^+g}

- Determined by m.s. in the stopping target ➔ reduction of the target thickness (one order of magnitude ➔ reduction of a factor 3 in ? q_{e^+g}➔ factor 10 reduction in the accidental background)

Beyond... (Ideas) 5) target subdivision



- Spread of two individual (normal) decays in space: (another factor 10)

BUT

- Photon detector must have a good directionality to distinguish between two targets
- How to combine with the acceptance of a beta spectrometer ?

CONCLUSIONS

- MEG will start its data taking sometimes next year and hopes to get significant results before the LHC era
- Future improvements in the sensitivity of $\mu \to e\gamma$ experiments are possible at the cost of intense detectors R&D, very careful apparatus design and probably high costs
- worth taking into account the possibility of studying related processes: $\mu \to e$ conversion (see Y. Kuno's talk)