New limit on the lepton-flavor violating decay $\mu^+ \rightarrow e^+ \gamma$

[arXive:1107.5547v1]

Tomoyuki Saito

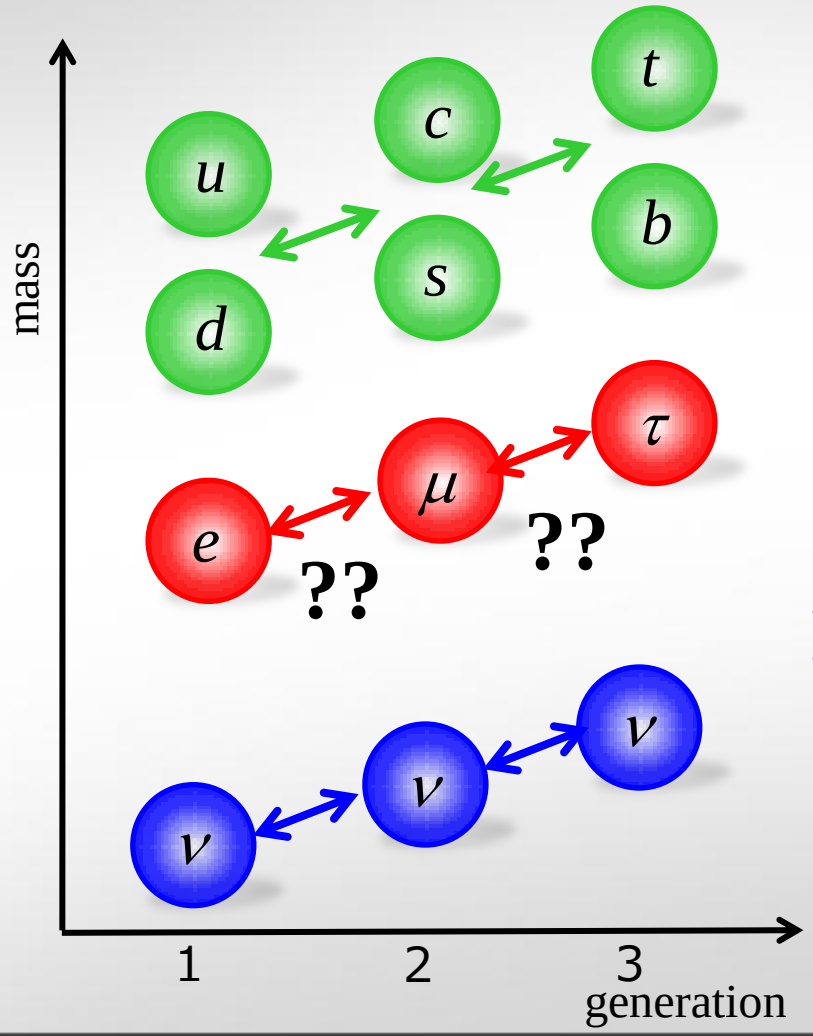
2011/09/16 seminar@lab

Reference

- ”A limit for the μ→eγ decay from the MEG experiment”, Nuclear Physics B 834(2010) 1-12
- Mori-san’s slide@EPS2011
- Ph.D and Master thesis (Tokyo Univ.)
- Nishiguchi-san’s slide@ Spring School on High Energy Physics 2011

LFV

Flavor violation



Quark sector

- Mixed by CKM mechanism(CKM matrix)
- Experimentally Verified⇒ B factories

Charged Lepton Sector

- extremely rare in SM
- never observed yet

Neutral Lepton Sector

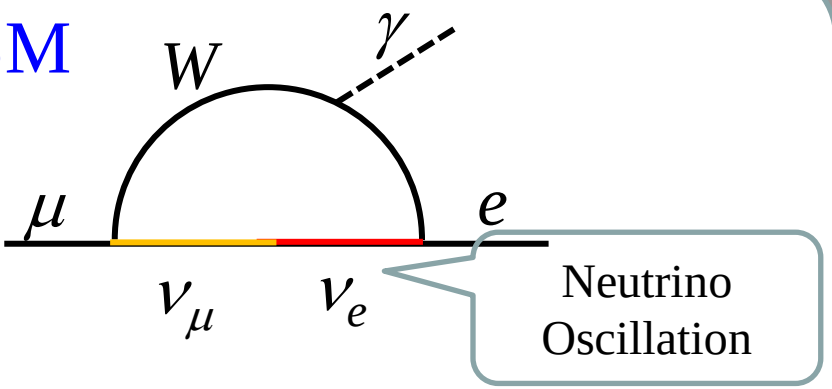
- Mixed by neutrino oscillation (MNS matrix)
- Experimentally Verified
  ⇒ SK, SNO, KamLand, etc

Charged Lepton Flavor Violation

- μ is good tool in Charged LFV search

⇒ Since we can produce a lot.(τ;10^8/year, μ;10^{14}~10^{15}/year)

SM

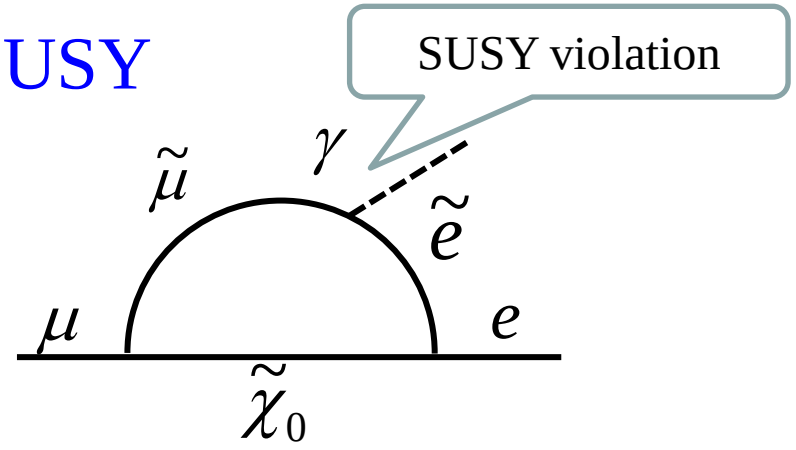


$$Br(\mu \to e\gamma) \propto \left(\frac{\Delta m^2_{\nu_{ij}}}{m_W^2} \right)^2$$

→ $<10^{-54}$ Extremely rare!

New Physics !!!

SUSY

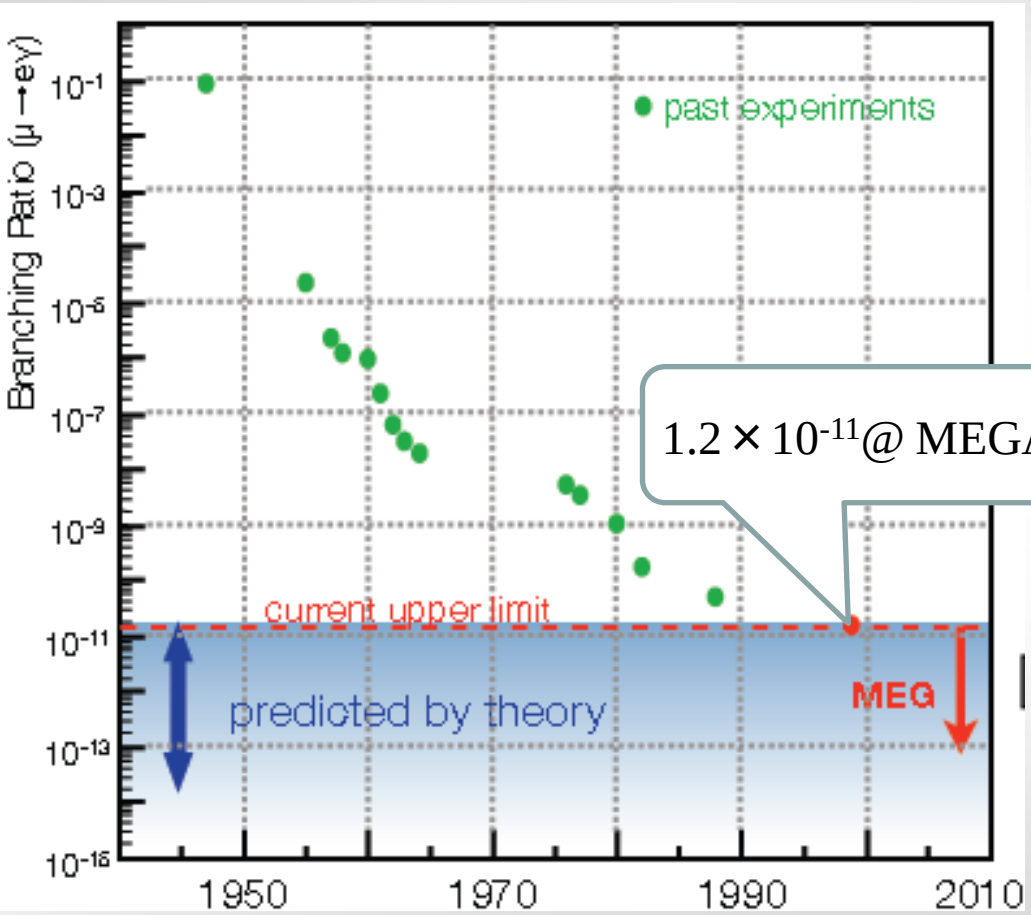


- Higher BR is perdicted

⇒ 10^{-16}~10^{-11}

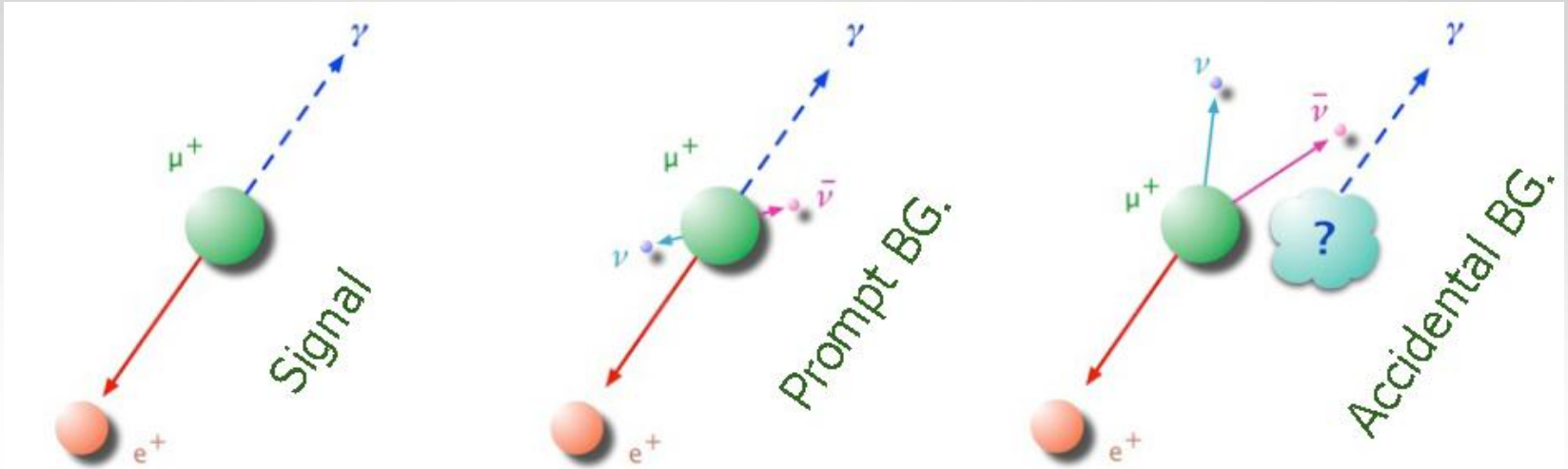
Observable level !

$\mu \to e\gamma$ search history



- History is long
- MEG can approach the predicted region.
- Physics run Start from 2008!

$\mu \rightarrow e\gamma$ search



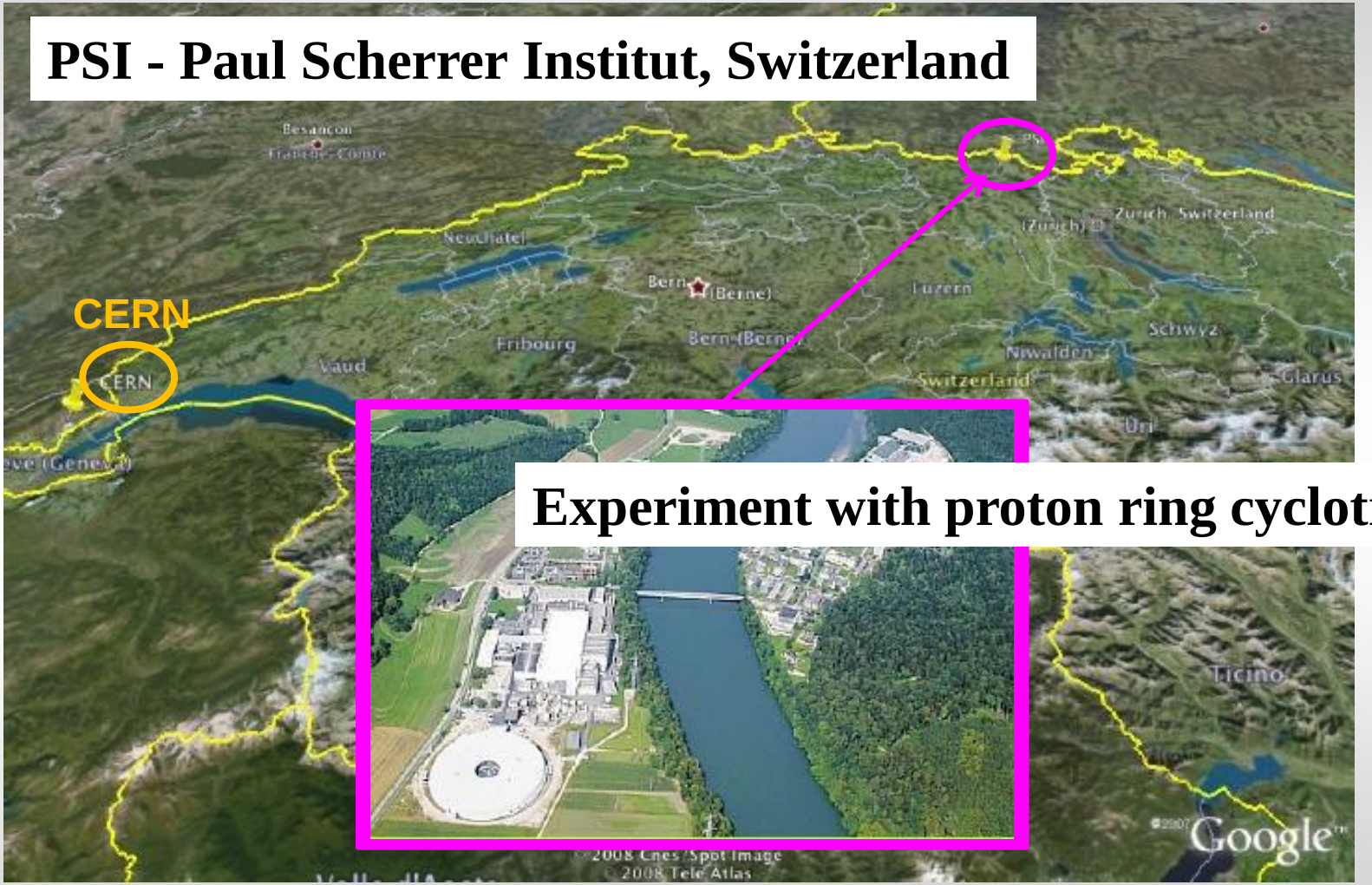
Radiative muon decay (RMD) ~1.4 %

- Point
  - 2-body decay (E_e=E_γ=52.8 GeV、 $\theta_{e\gamma}$=180°、 Time Coincidence)
  - Sensitivity depends on Accidental BG! ∝ **(muon rate)^2**

→
- DC muon beam
- Good resolution under Very High Rate

MEG

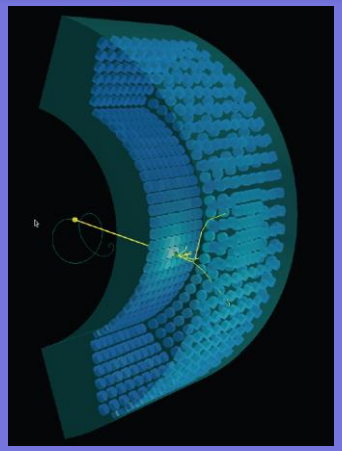
Location on MEG experiment



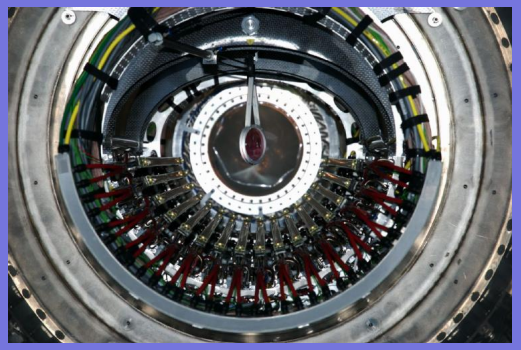
Solution on Accidental BG in MEG

- **DC muon beam**
- **Good resolution detector under high rate**

World Most Intence
DC muon beam @PSI
10^8 muon/sec



Liquid Xenon
Scintillation Detector
[**gamma**]



COBRA Spectrometer
[**positron**]

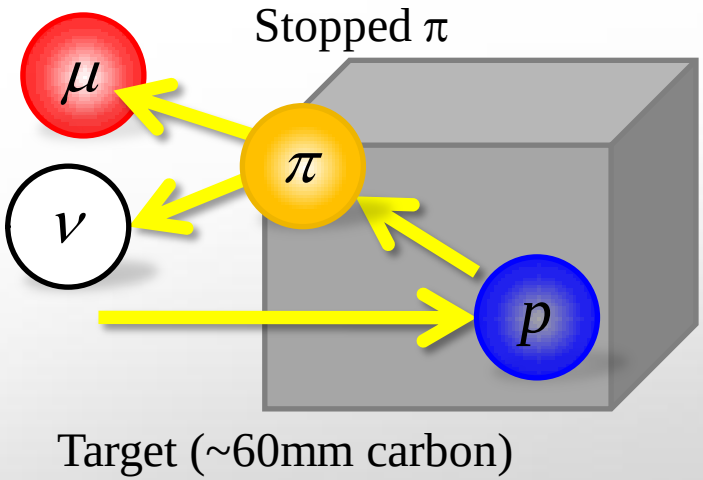
DC muon beam

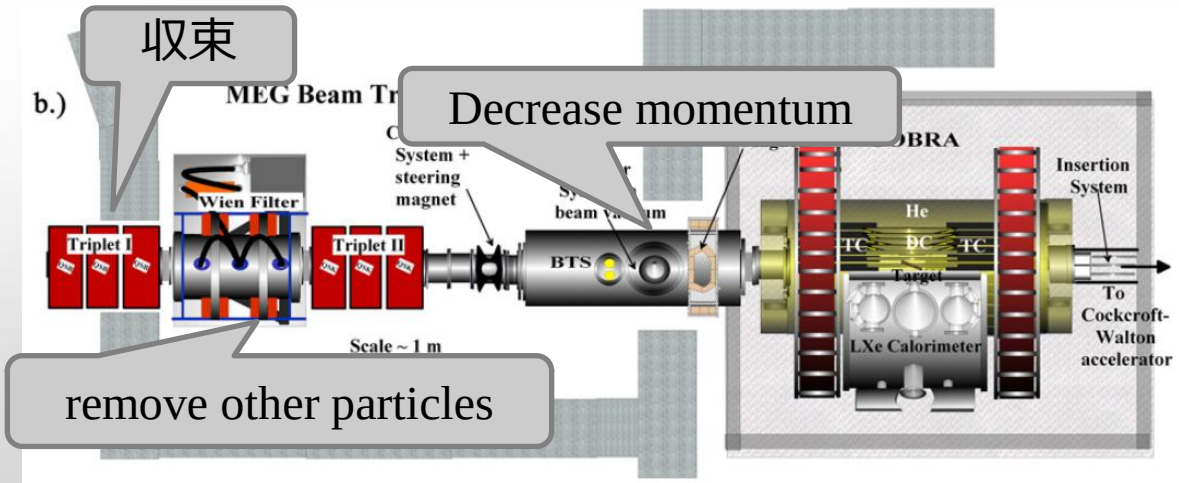
- We want a lot of μ, but

  Accidental BG ∝ (muon rate)^2 → **DC**

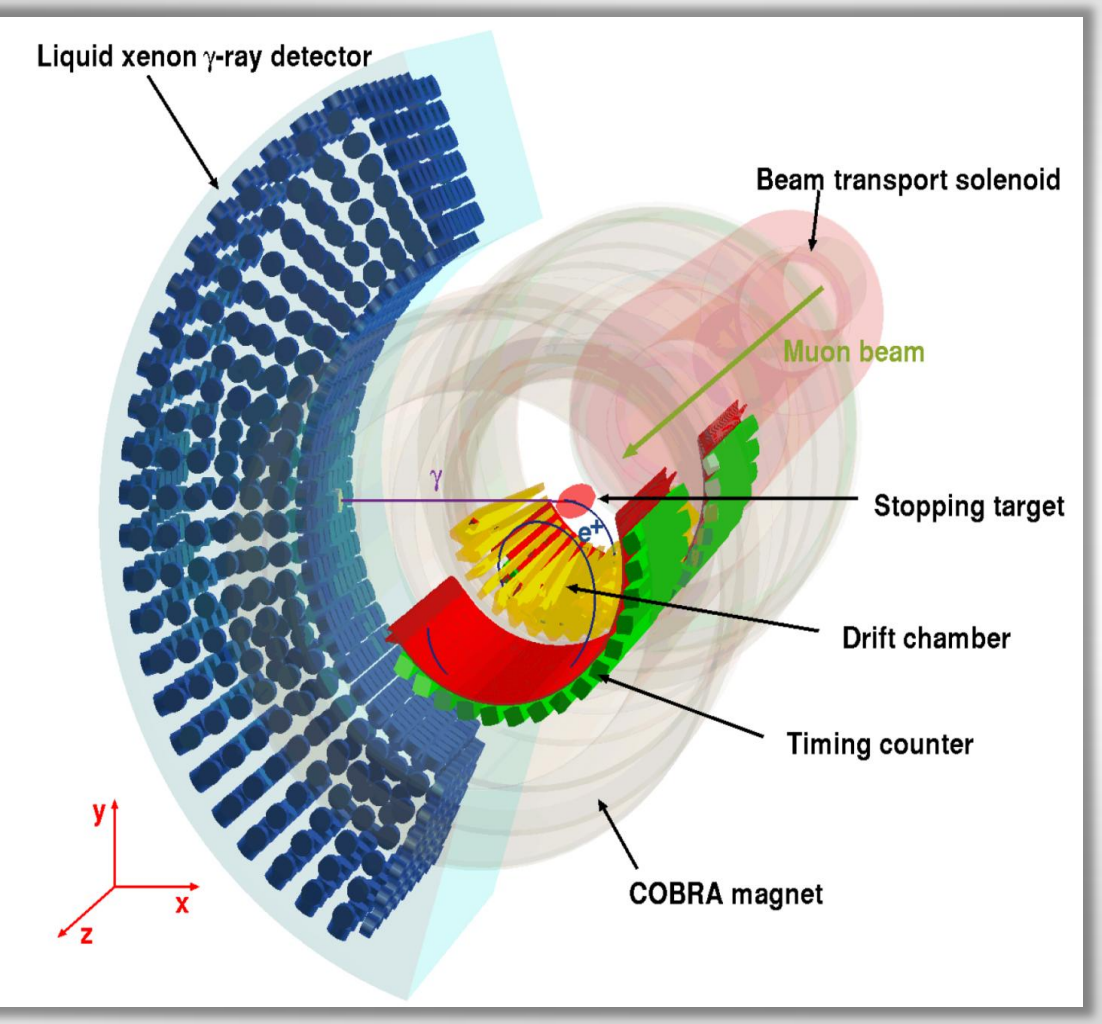
- μ^+ is useful to avoid capturing by nuclear.
- 590MeV proton ring cyclotron
- **Stopped π at the target surface (within a few mm)**

  = **Surface muon** (p = 29MeV/c, $2.9\mu^+$/s)



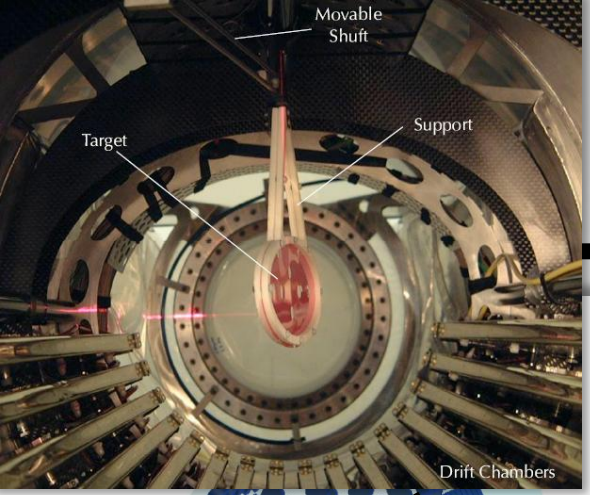


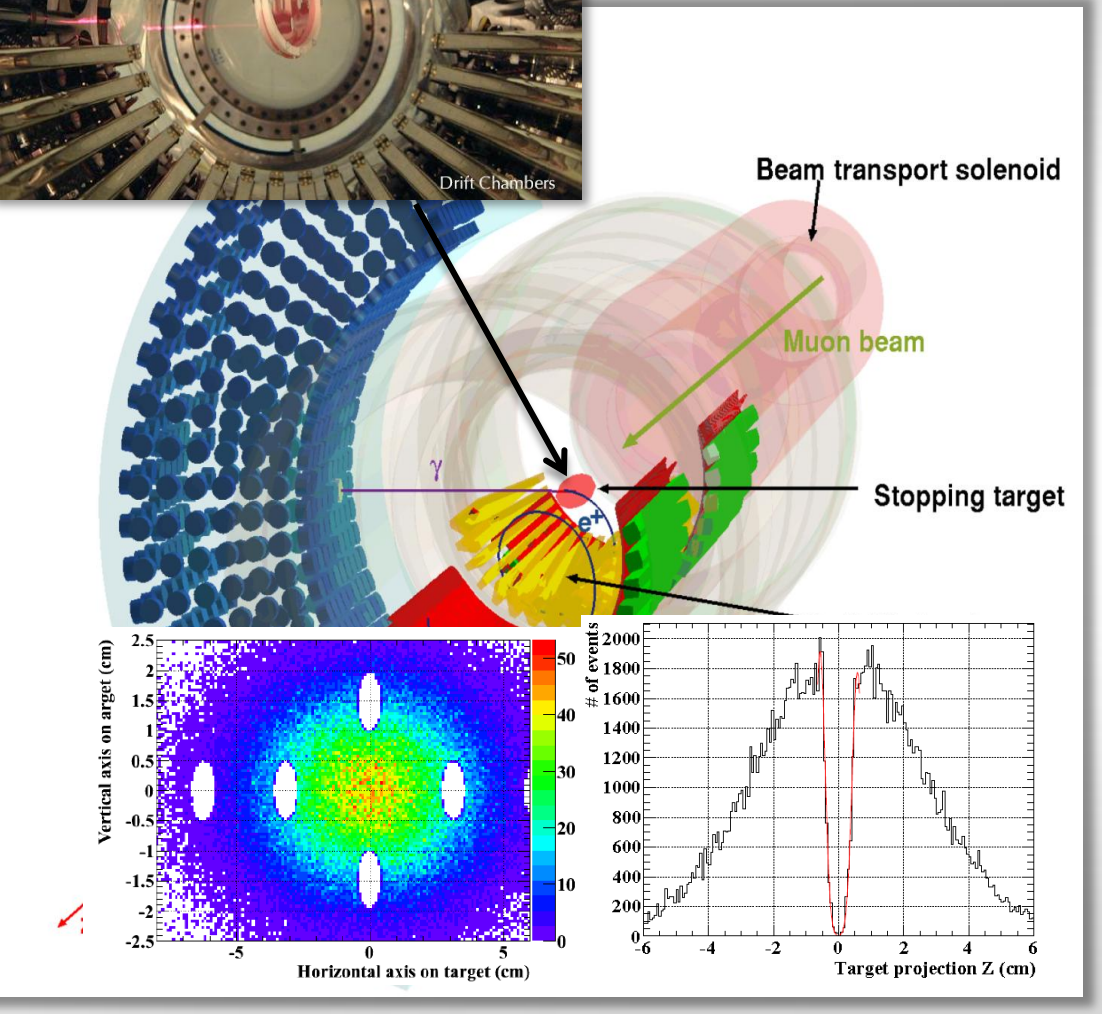
MEG detector



- μ stopping target
  - Polyethylene,
  - 205μm thickness
  - 20cm radius
  - slightly slanted
  - 0.05 g/cm^3, X_0=820cm
  - **6 hole** (used for measuring vertex position resolution)
- e^+ : COBRA spectrometer
- γ →Liquid Xe detector

MEG detector





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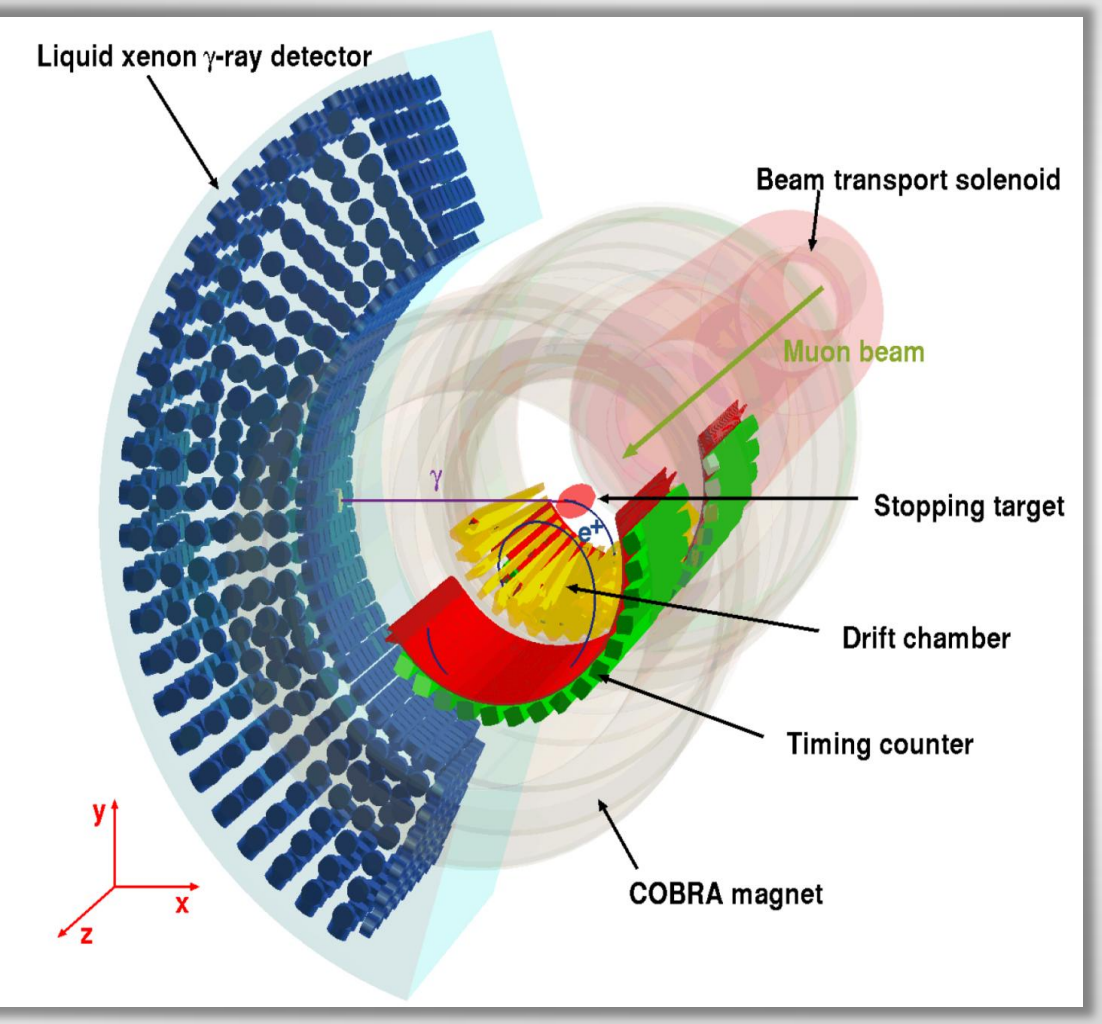

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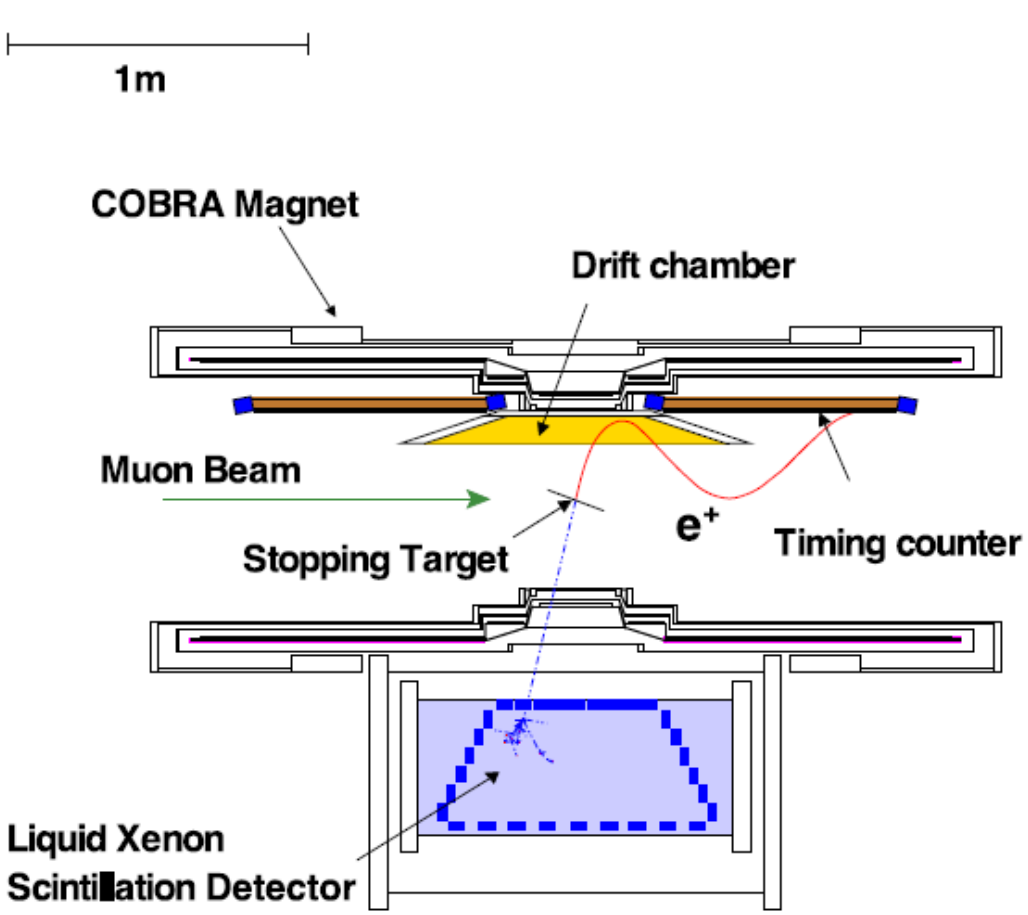
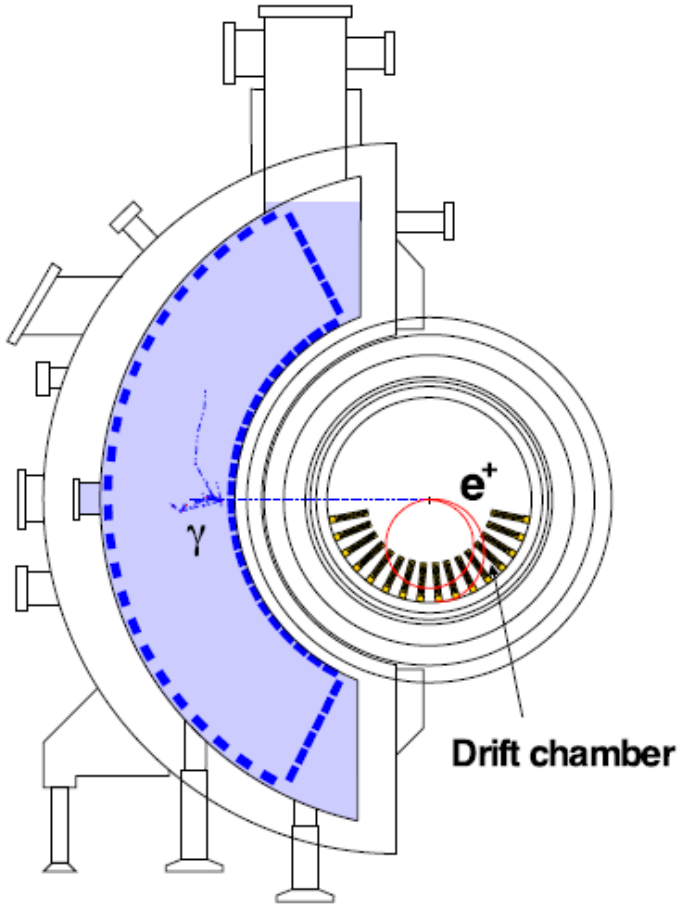




ターゲットで傾いているのは
？

COBRA Spectrometer

COBRA Spectrometer：positron detection
(energy, position, timing)

Requirement

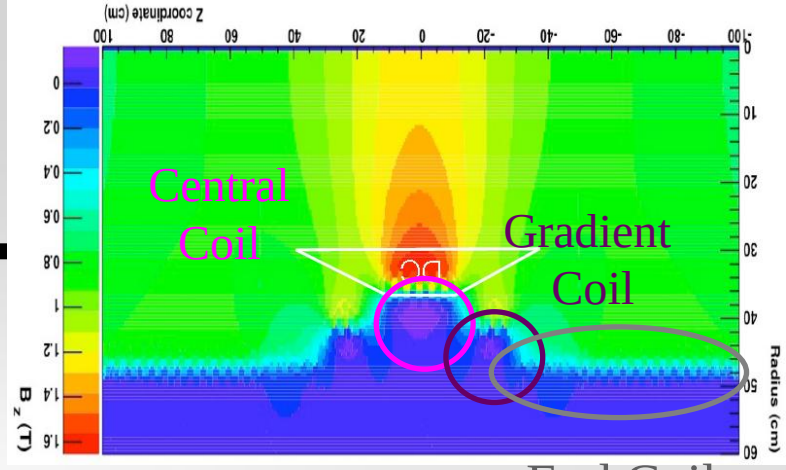
- 3×10^{7}の μ rateで安定動作
- low material
- high position resolution
- high timing resolution(to remove Acidental BG)

- COBRA magnet : Superconducting magnet (Al)
- Drift chamber
- Timing counter

COBRA magnet

- COnstant Bending RAdius

  ⇒Gradient B-field



Uniform B-field

Drift chamber

e^+

(a) (b)

Low momentum e^+

Signal e^+

Gradient B-field

(c) (d)

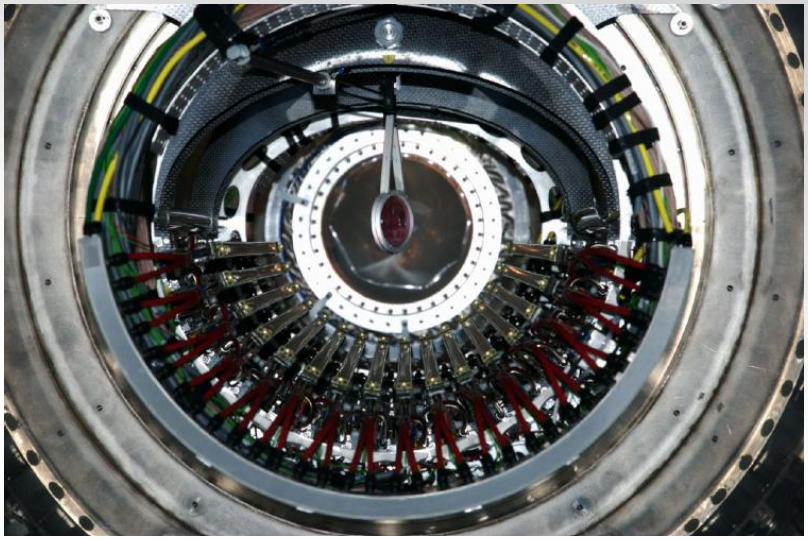
Low energy e^+ quickly swept out

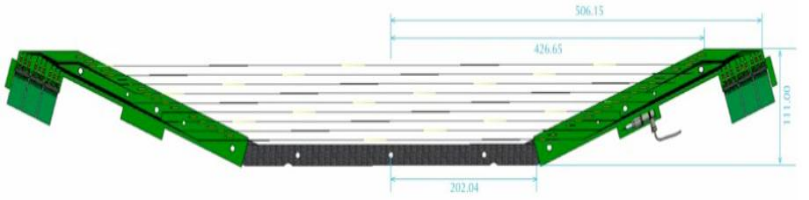
Constant bending radius independent of emission angles

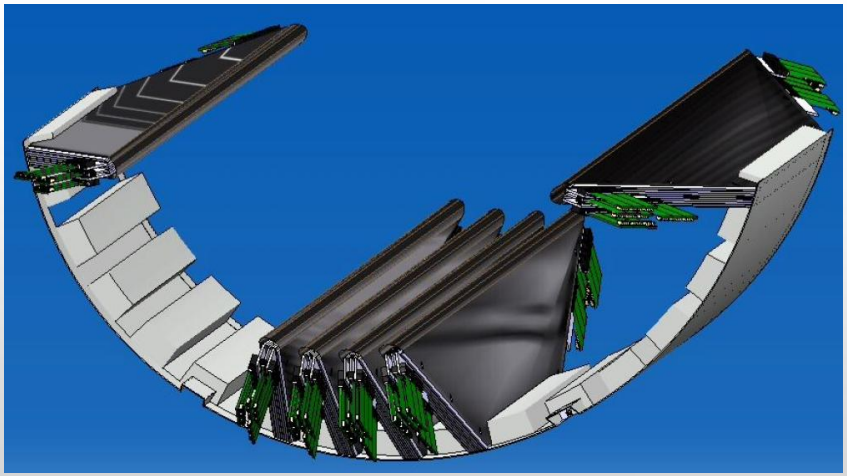
Drift Chamber

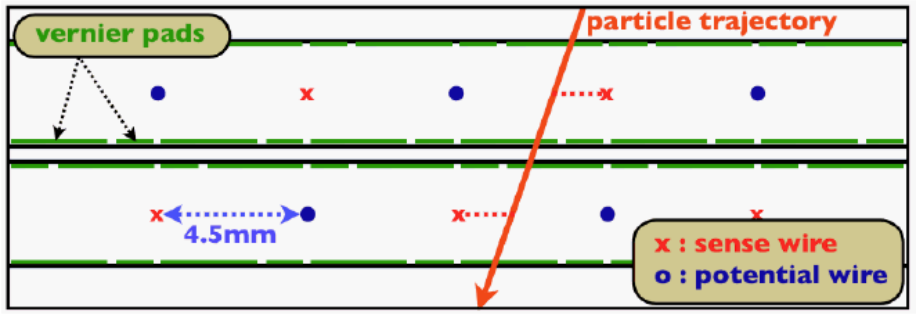
- Light material and high resolution
- He-Ethane＝50：50 gas
- 16 module

  1 module：wire 9×2 layer

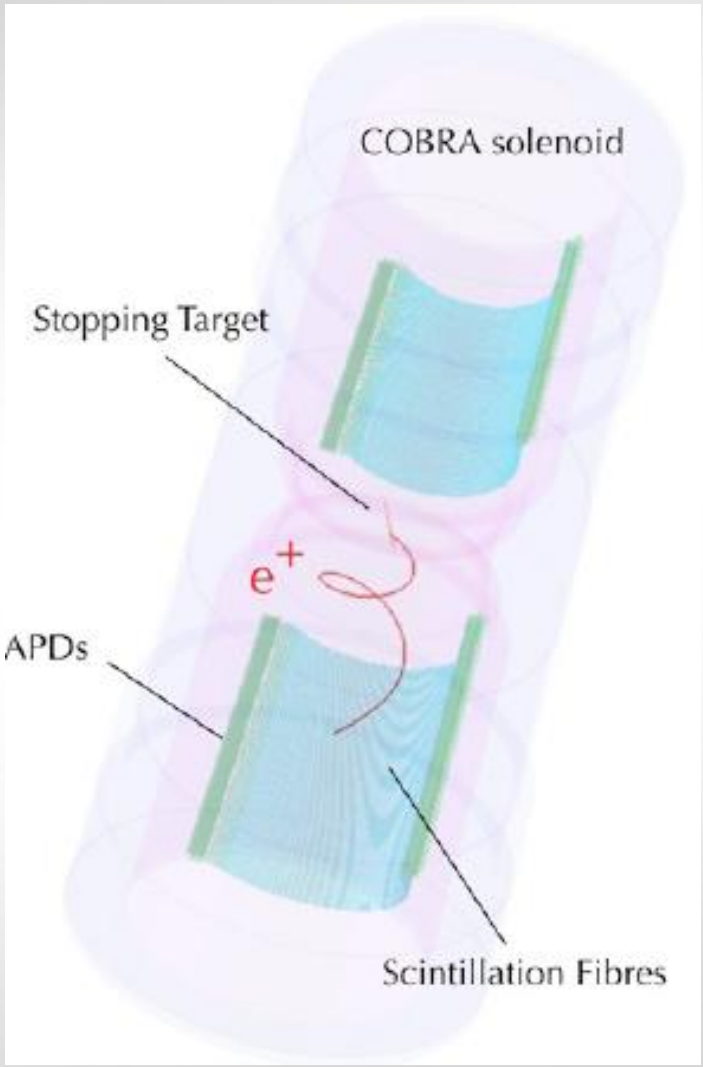






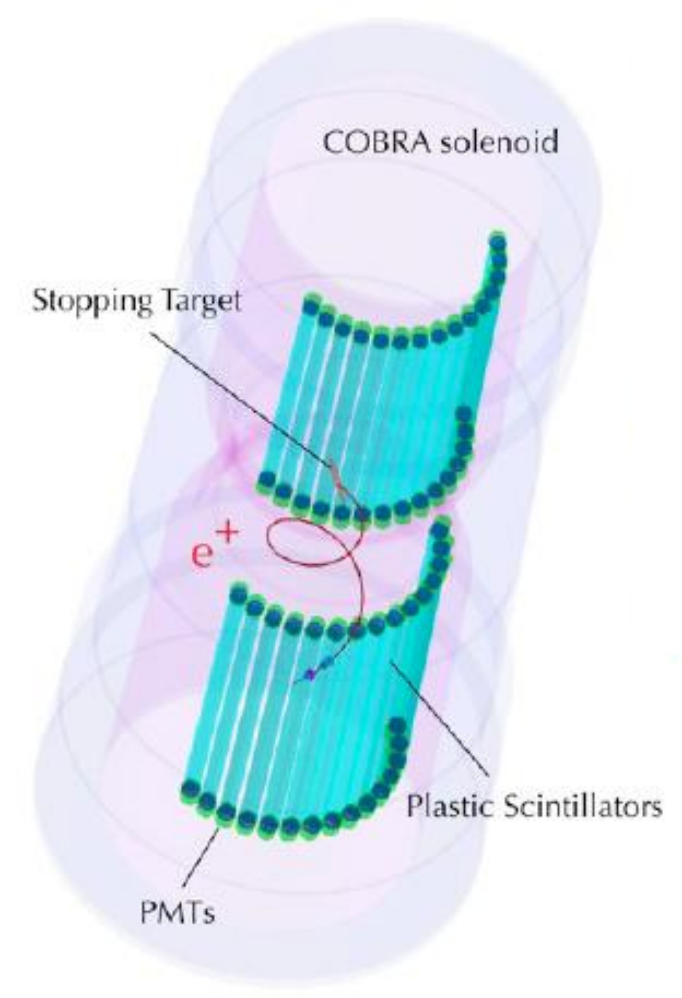


Timing counter(inner)

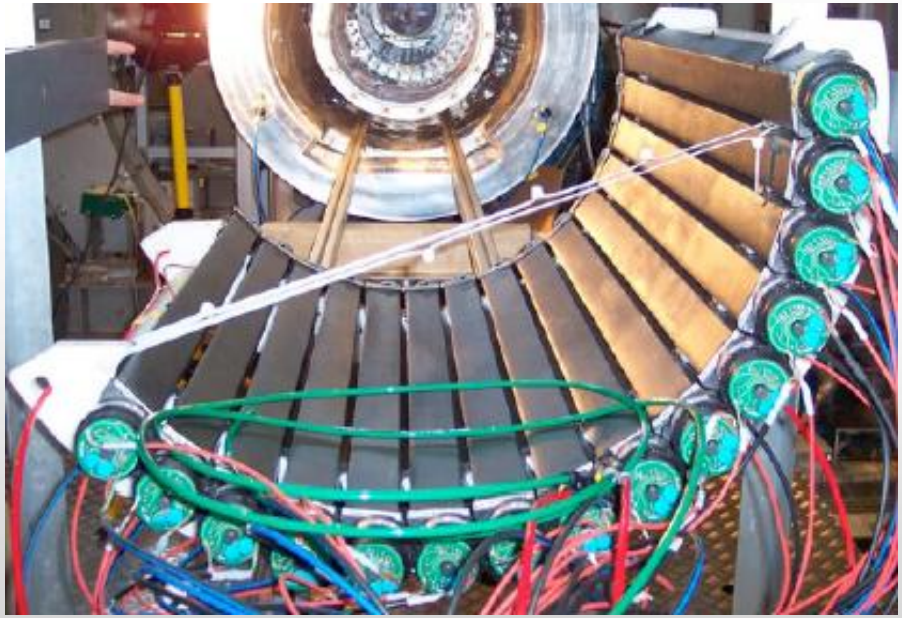


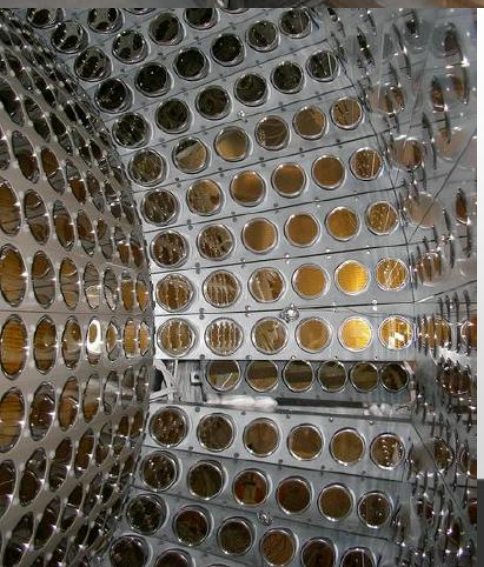
- Trigger for Z direction
- 256 Scintillation Fiber
- APD at the both side
  (Avalanche Photo Diode)

Timing counter (outer)



- Trigger for Φ direction
- 30 Plastic Scintillator Bars
- Fine mesh PMT at both side





Liquid *Xe* γ detector

- Liquid Xe Scintilator
  - quick response
  - small dependence on position
- Covered with 846 PMT
- Liquid X_e : 900 litre
  (sensitive volume 800 litre)
- First large detector with liquid X_e in the world

	LXe	LAr	NaI(Tl)	CsI(Tl)	BGO	LSO(Ce)	$PbWO_4$
密度 (c/cm^3)	2.98	1.40	3.67	4.51	7.13	7.40	8.3
放射長 (cm)	2.77	14	2.59	1.86	1.12	1.14	0.89
モリエル半径 (cm)	4.2	7.2	4.13	3.57	2.23	2.07	2.00
崩壊時間 (ns)	45	1620	230	1300	300	40	30/10*[1]
シンチレーション光波長 (nm)	178	127	410	560	480	420	425/420
相対光量	75	90	100	165	21	83	0.083/0.29

Calibration and sensitivity

Calibration

- **LXe PMT** : check by LED and α-source everyday
- **Lxe :** Cockcroft-Walton(CW) accelerator
  - check by γ from nuclear reaction (in $Li_2B_4O_7$ target) of *proton* from CW . 3 /week.
- **RMD data taking run** : under low beam intensity. 1/week.

Sensitivity

- **Two Charged exchanged reaction(CEX) run** : Results by using LX_e and NaI crystal are compared on the start and end of data-taking run.
  - γ energy and homogeneity on the LXe by $\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$
  - The coincidence and sensitivity are checked by $\pi^0 \rightarrow \gamma e^+ e^-$ reaction

Performance Summary

	2009	2010
Gamma Energy (%)	1.9	1.9
Gamma Timing (psec)	96	67
Gamma Position (mm)	5 (u,v), 6 (w)	5 (u,v), 6 (w)
Gamma Efficiency (%)	58	59
e^+ Timing (psec)	107	107
e^+ Momentum (keV)	310 (80% core)	330 (79% core)
e^+ θ (mrad)	9.4	11.0
e^+ ϕ (mrad)	6.7	7.2
e^+ vertex Z/Y (mm)	1.5 / 1.1 (core)	2.0 /1.1 (core)
e^+ Efficiency (%)	40	34
e^+-gamma timing (psec)	146	122
Trigger efficiency (%)	91	92
Stopping Muon Rate (sec^{-1})	2.9×10^7	2.9×10^7
DAQ time/ Real time (days)	35/43	56/67
Expected 90% C.L. Upper Limit	3.3×10^{-12}	2.2×10^{-12}

CEX

MC with PMT data

Track with 2 turn

Target hole

RMD

- Timing improvement by waveform digitizer upgrade
- The e^+ tracking slightly worse due to DC noise problem

Analysis

First, I explain about the analysis 2008 run data (published on Mar. 2010) , then about 2009 and 2010 run data.

Data Analysis

- Observables: E_γ, E_e, $t_{e\gamma}$, $\theta_{e\gamma}$, $\phi_{e\gamma}$|
- Blind Analysis
  - no bias
  - Sideband data are used for calibration study.
- Analysis window:

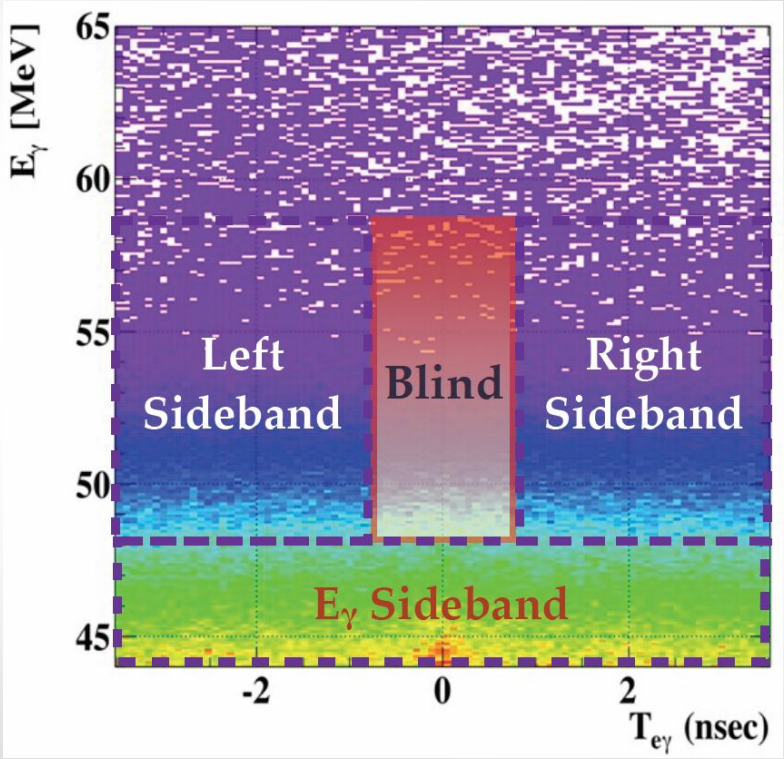
  $46<E_\gamma<60$MeV,

  $50<E_e<56$MeV,

  $|t_{eg}|<1$ns,

  $|\theta_{e\gamma}|<100$mrad,

  $|f_{e\gamma}|<100$mrad (another window in 2009 & 2010)



Likelihood Analysis

- Extended likelihood analysis

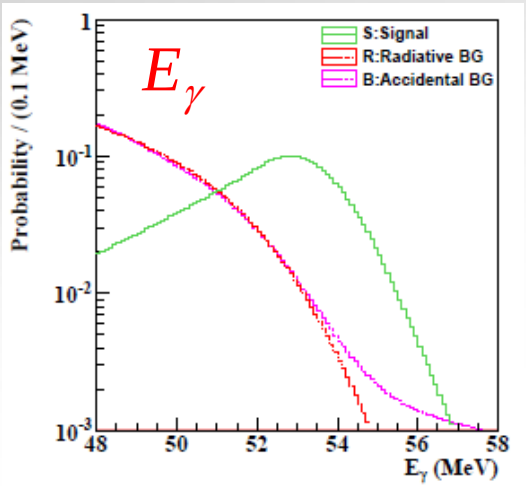
$$\mathcal{L}(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{BG}}) = \frac{N^{N_{\mathrm{obs}}} \exp^{-N}}{N_{\mathrm{obs}}!} \prod_{i=1}^{N_{\mathrm{obs}}} \left[\frac{N_{\mathrm{sig}}}{N} S + \frac{N_{\mathrm{RMD}}}{N} R + \frac{N_{\mathrm{BG}}}{N} B \right]$$

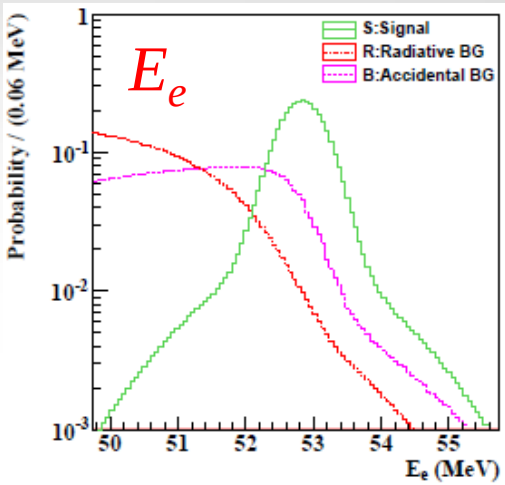
Considered with the fluctuation of N_{obs}

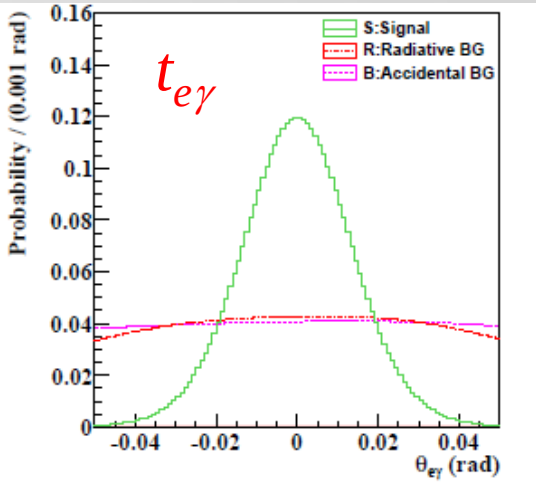
N_{obs} : Number of observed event in analysis window (=1189)
$N = N_{sig}+N_{RMD}+N_{BG}$
S, N, B : Probability Density Function(PDF) on Signal, RMD, BG

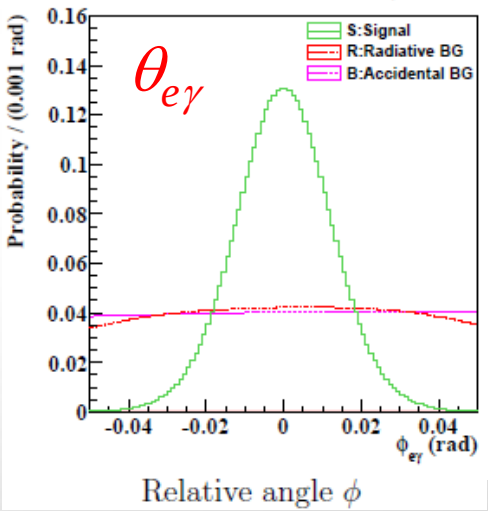
- PDF
  - Accidental BG : Side bands
  - signal : Measured
  - Radiative BG : Theory + Detector Resolution

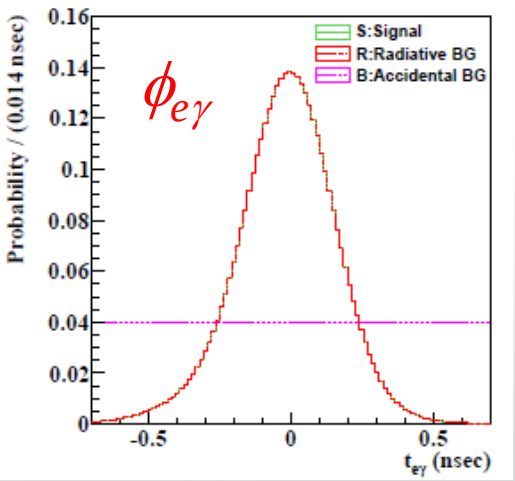
Probability Density function(PDF)





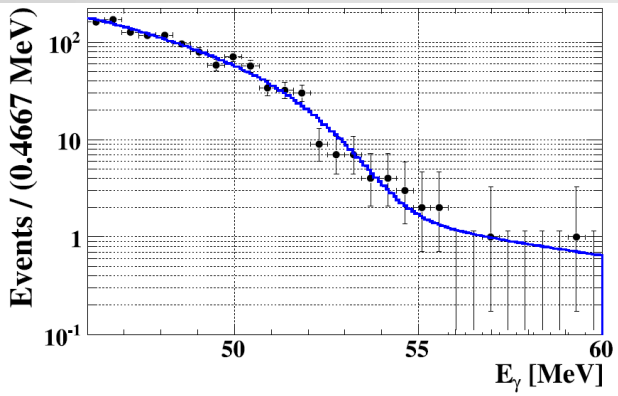


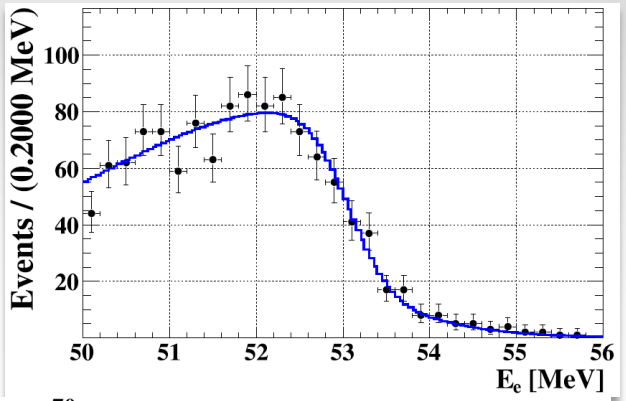


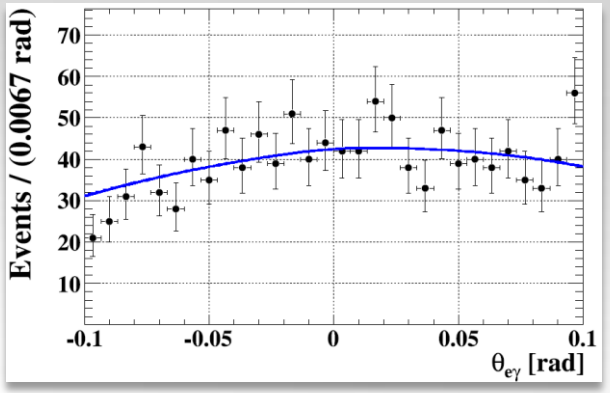


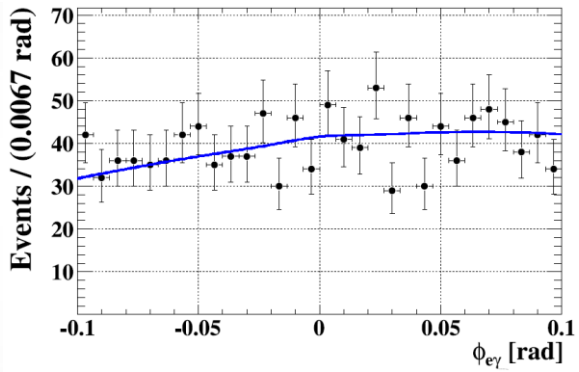
5 observables

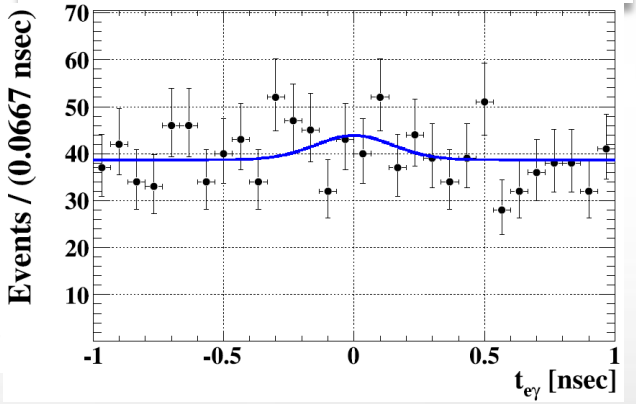
プロット：データ
青線：データをfitした
Likelihood function











N_{sig}<14.7 at 90% C.L.
(Toy MC)

- **Systematic error :**

  Event selection on γ pile-up event, Response function of E_{e+}

  E_γ scale, Angle Resolution on e^+

Upper limit on $BR(\mu^+ \to e^+\gamma)$

- Normalization to the number of Michel positron

→independent on beam rate & insensitive to the detector efficiencies.

$$\mathrm{BR}(\mu^+ \to e^+\gamma) = \frac{N_{\mathrm{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f^E_{e\nu\bar{\nu}}}{P} \times \frac{\epsilon^{\mathrm{trig}}_{e\nu\bar{\nu}}}{\epsilon^{\mathrm{trig}}_{e\gamma}} \times \frac{A^{\mathrm{TC}}_{e\nu\bar{\nu}}}{A^{\mathrm{TC}}_{e\gamma}} \times \frac{\epsilon^{\mathrm{DCH}}_{e\nu\bar{\nu}}}{\epsilon^{\mathrm{DCH}}_{e\gamma}} \times \frac{1}{A^{\mathrm{g}}_{e\gamma}} \times \frac{1}{\epsilon_{e\gamma}}$$

N_{enn} : Number of Micheal positron（=11414)
P : Prescale factor in the trigger used to select Michel positron (=10^7)
F_{enn} : Fraction of the Michel positron spectrum above 50MeV
$\varepsilon^{\mathrm{trig}}$: Trigger efficiency
A^{DCH} : DCH – TC matching efficiency
ε : DCH reconstruction efficiency and acceptance
A^g : Geometrical acceptance for signal γ given an accepted signal positron
ε : Efficiency of γ reconstruction and selection criteria

$$\mathrm{BR}(\mu^+ \to e^+\gamma) \leqslant 2.8 \times 10^{-11} \quad (90\%\ \mathrm{C.L.})$$

Sensitivity：toyMCでNsig=0、accidental BGとNRはデータと同じと仮定
⇒1.3×10-11
このsensitivityのときBRが2.8×10-11以上になるのは5%程度

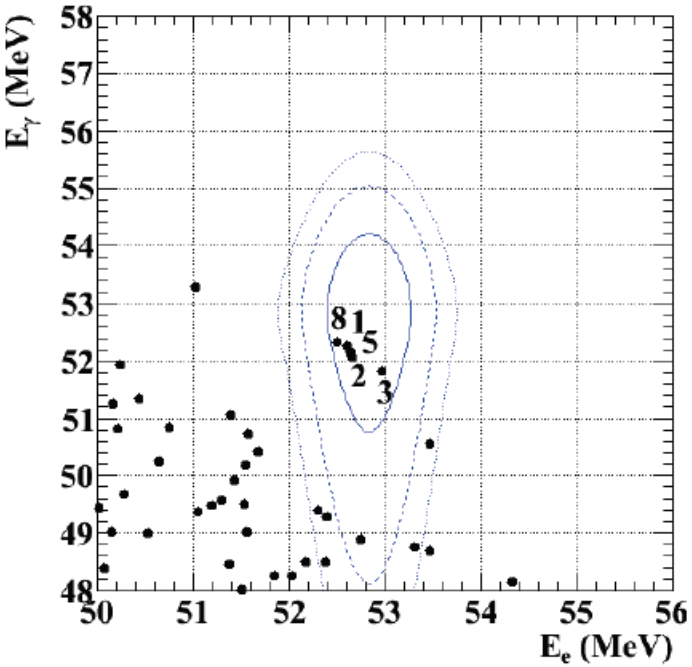
2009 data result (not published)

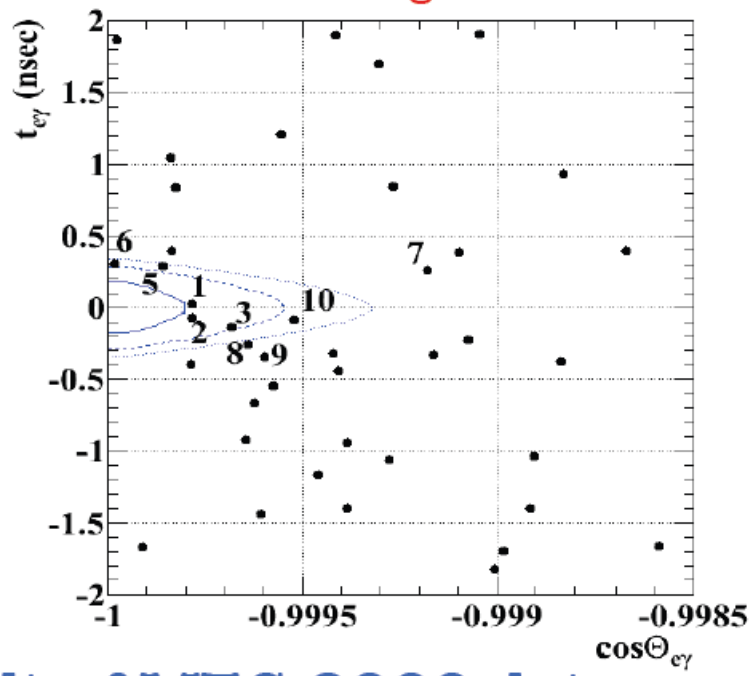
Event distribution after unblinding

BR < 1.5×10^{-11} @90%CL

6.1×10^{-12} expected

Nsig = 3.0





preliminary result of MEG 2009 data

Blue lines are 1(39.3 % included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions.

For each plot, cut on other variables for roughly 90% window is applied.

Numbers in figures are ranking by $L_{sig}/(L_{RMD}+L_{BG})$. Same numbered dots in the right and the left figure are an identical event.

2010 data result

- Data :
  - 2009 & 2010(twice statistics of 2009) data
    → $1.8\times10^{14}\mu^{+}$ decay
  - The 2008 data are not used.

- Alignments inside/among detectors

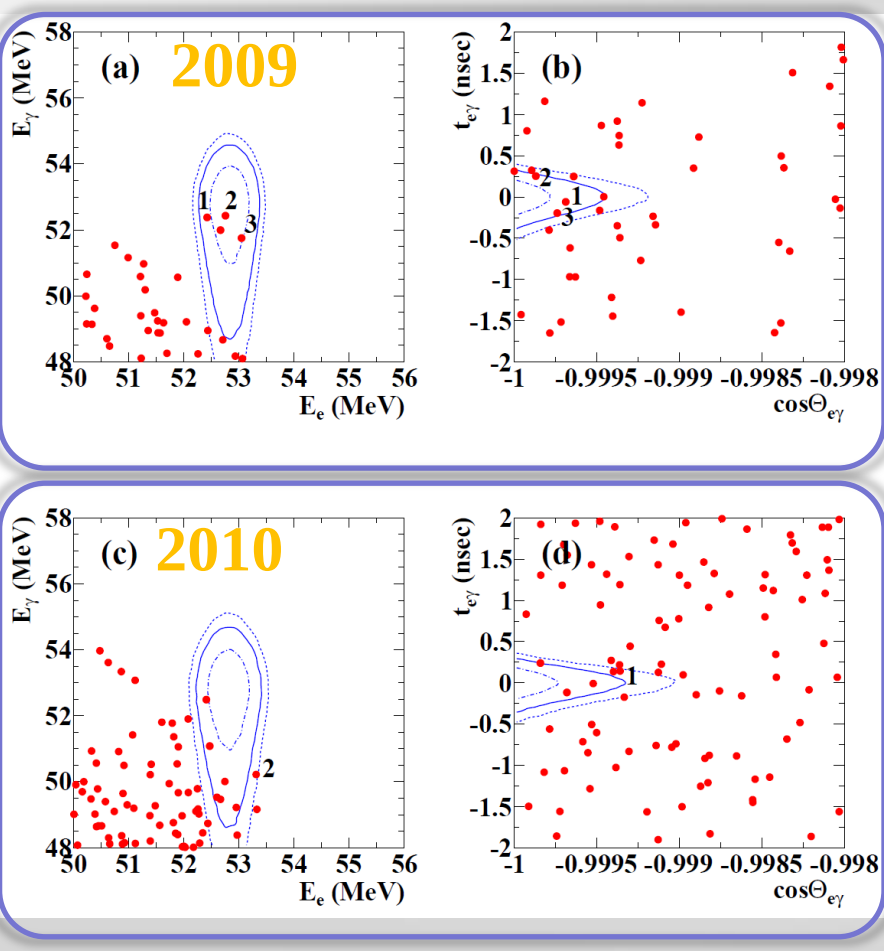
- Treatment of B-field

- Profile likelihood

Result

$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) = \frac{e^{-N}}{N_{\rm obs}!} e^{-\frac{1}{2}\frac{(N_{\rm BG}-\langle N_{\rm BG}\rangle)^2}{\sigma^2_{\rm BG}}} e^{-\frac{1}{2}\frac{(N_{\rm RMD}-\langle N_{\rm RMD}\rangle)^2}{\sigma^2_{\rm RMD}}} \times \prod_{i=1}^{N_{\rm obs}} (N_{\rm sig}S(\vec{x}_i) + N_{\rm RMD}R(\vec{x}_i) + N_{\rm BG}B(\vec{x}_i))$$

Data set	$\mathcal{B}_{\rm fit}$	LL	UL
2009	3.3×10^{-12}	4.0×10^{-13}	1.0×10^{-11}
2010	-9.9×10^{-13}	–	1.7×10^{-12}
2009 + 2010	-1.5×10^{-13}	–	2.4×10^{-12}



Summary

- 2009+2010 data consistent with no signal
- New physics is now constrained by 5×tighter upper limit :

  BR<2.4×10^{-12} @ 90% C.L.

- MEG is accumulating more data this and next year to **reach O(10^{-13}) sensitivity**