MEG
Mu-E-Gamma Collaboration

Search for lepton flavor violating muon decay :

Latest result from MEG

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for MEG Collaboration

HQ&L'10

The Xth international conference on
Heavy Quarks & Leptons, 14th Oct. 2010, @Frascati

μ→eγ search

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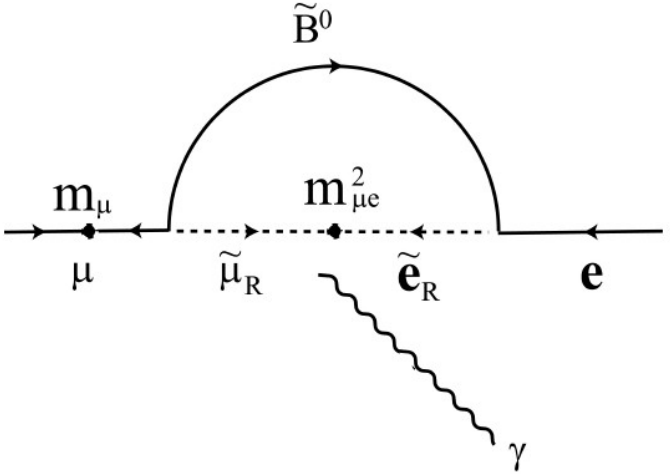
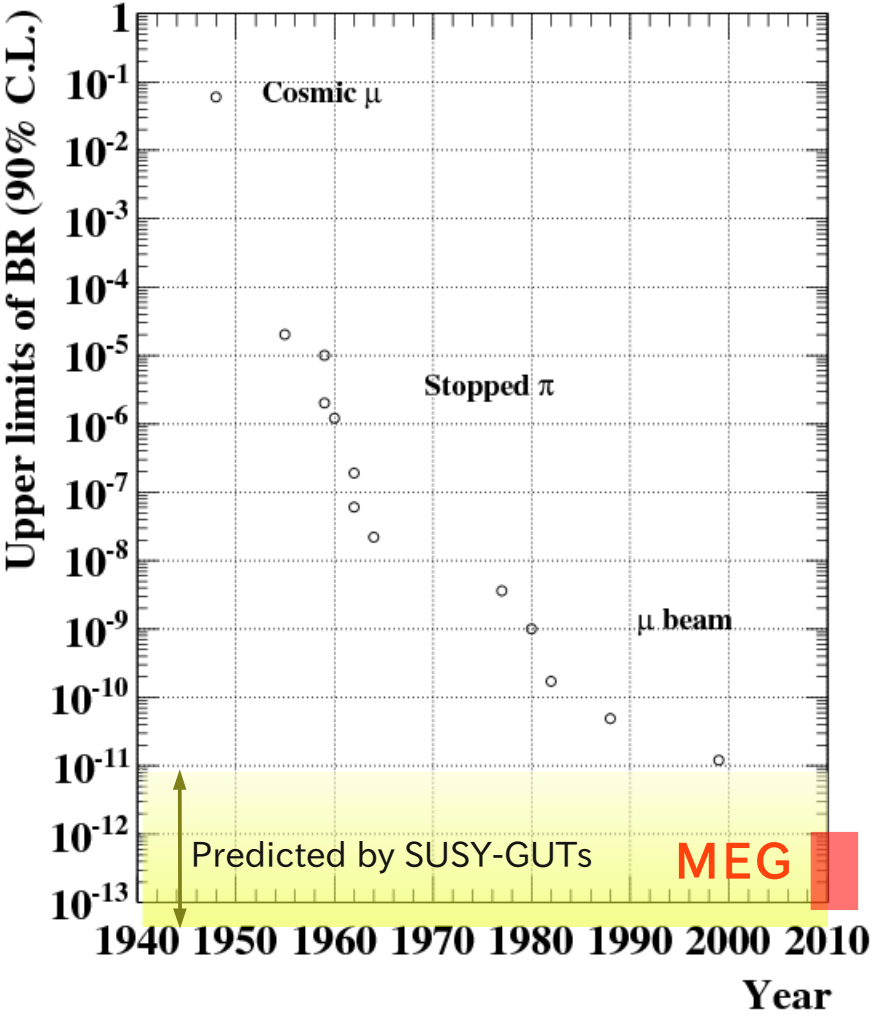
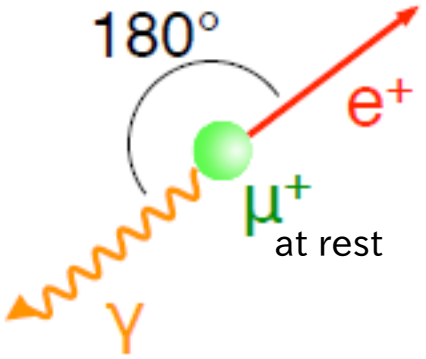
- LFV in charged lepton sector has not been observed.
  - Forbidden in SM (<O(10^{-50}) with finite ν mass)
  - But new physics predict observable rate
    - ex) SUSY-seesaw, SUSY-GUT,
    - BR(μ→eγ) ~ **10^{-15}-10^{-11}**
- Current experimental upper limit
  - BR(μ→eγ) < **1.2×10^{-11}** (1999, MEGA@LAMPF)
- A μ→eγ signal is a clear evidence for new physics
  - No SM background, No hadronic uncertainty
- MEG aims at searching down to O(**10^{-13}**),



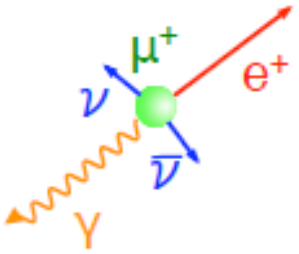
History of $\mu \to e\gamma$ search



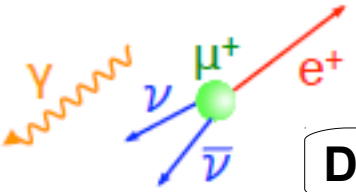
Signal & Backgrounds



- **Signal**
  - 52.8 MeV
  - Back-to-back
  - Time coincidence



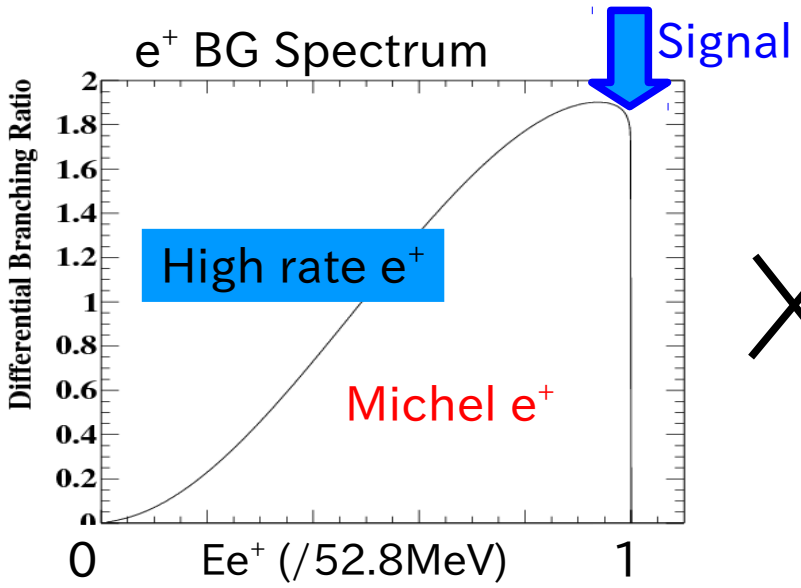
- **Physics BG**
  (radiative decay)
  - <52.8 MeV
  - Any angle
  - Time coincidence

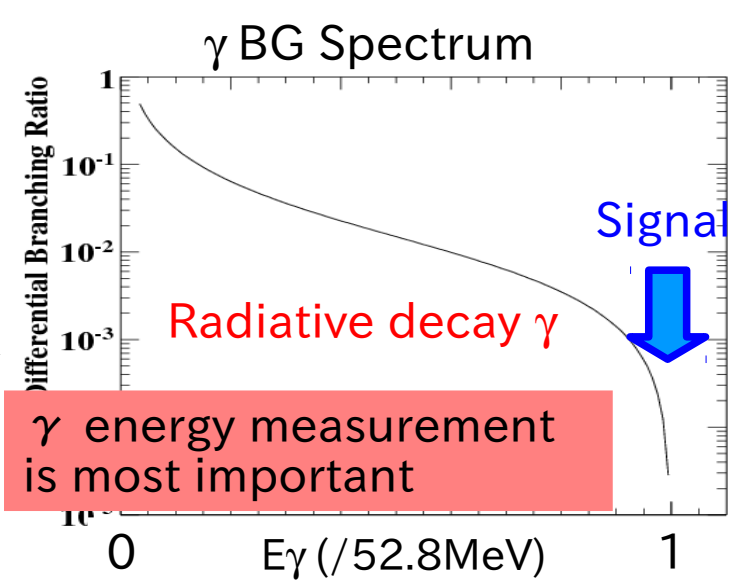


Dominant

- **Accidental BG**
  - <52.8 MeV
  - Any angle
  - Random

$R_{acc} = (R_\mu)^2 \cdot f_e^0 \cdot f_\gamma^0 \cdot (\delta\omega/4\pi) \cdot (2\delta t)$





The MEG Experiment

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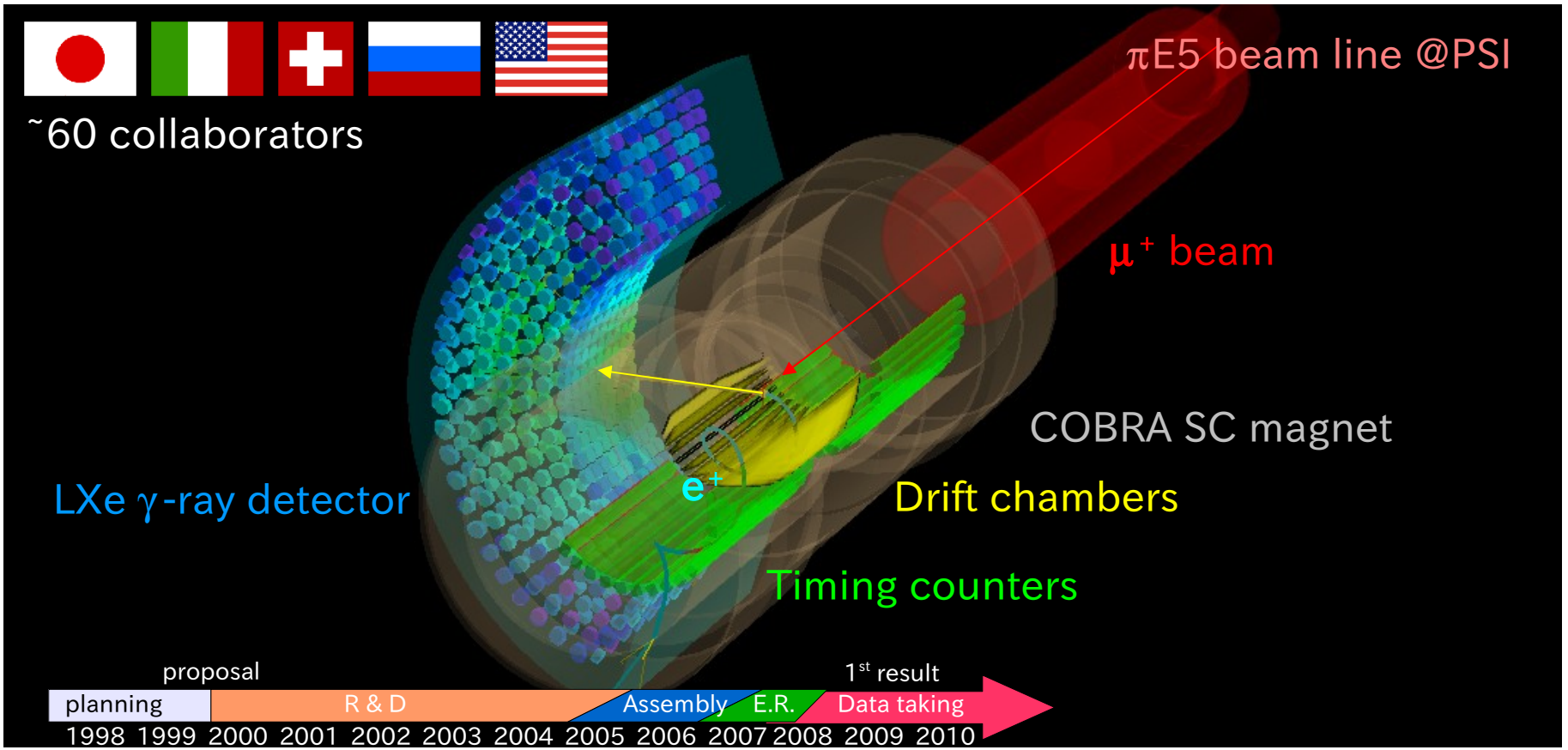
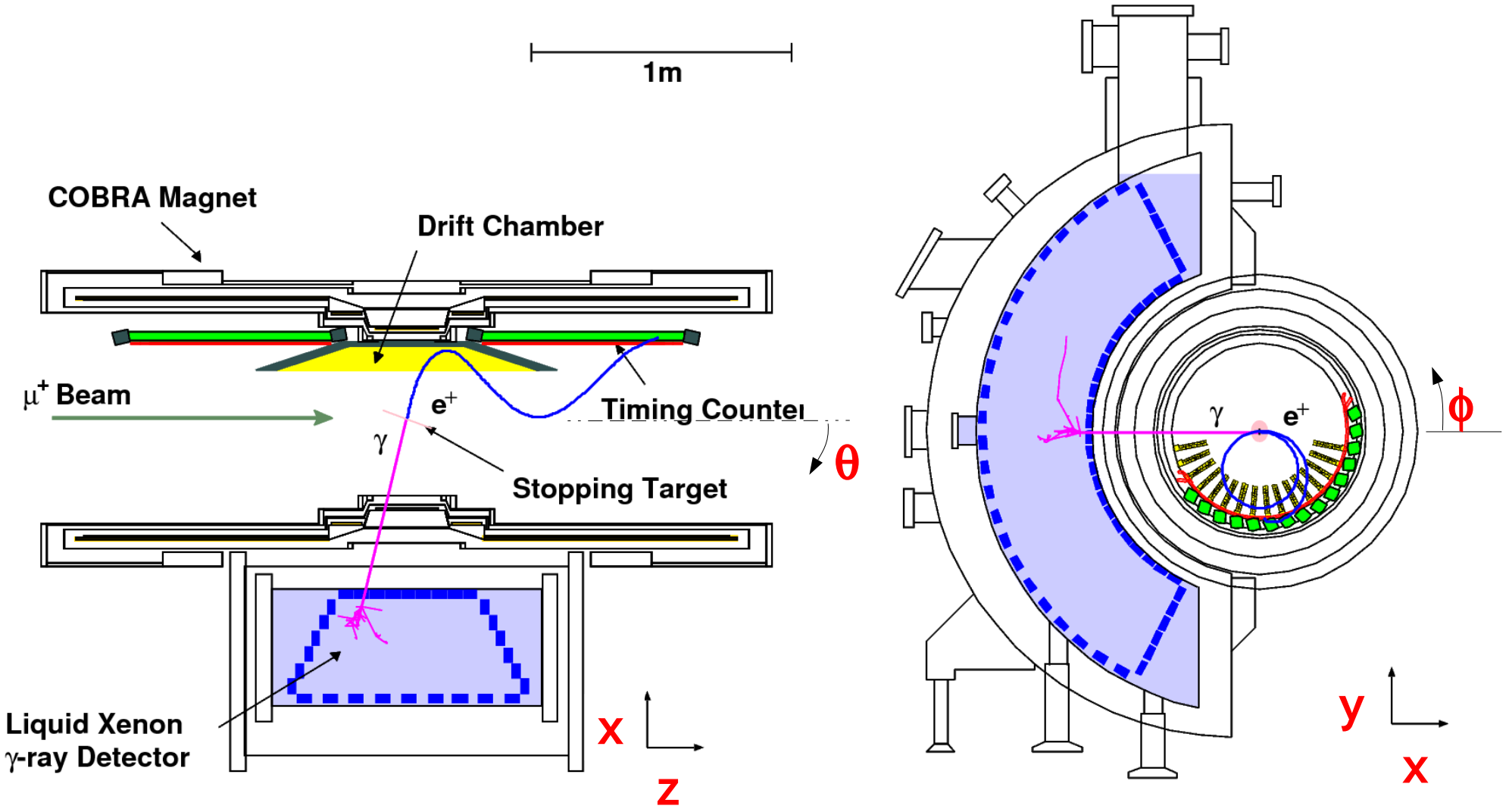
- World's most intense **DC muon beam** @ PSI
- High rate tolerable e^+ spectrometer with **gradient B-field**
- High performance γ-ray detector with **Liquid Xenon**



PSI 1.2MW proton Ring-Cyclotron

MEG Detector

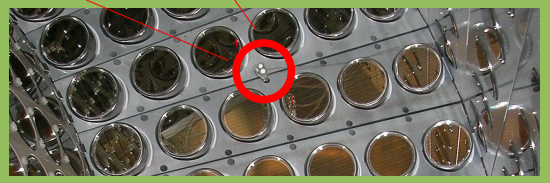


MEG calibrations

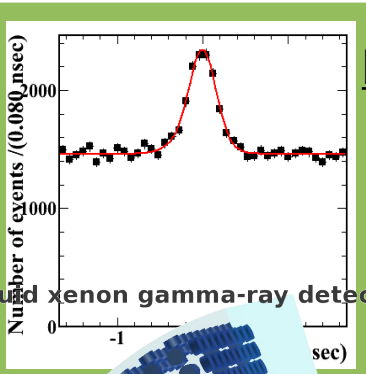
Established

LED

PMT Gain



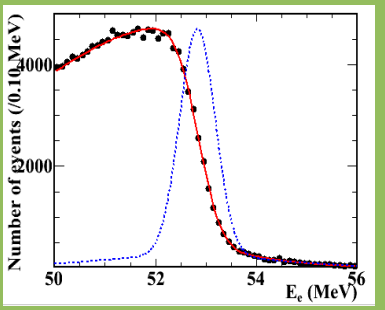
Radiative Decay



$\mu \rightarrow e\nu\bar{\nu}\gamma$

Relative timing

Similar topology

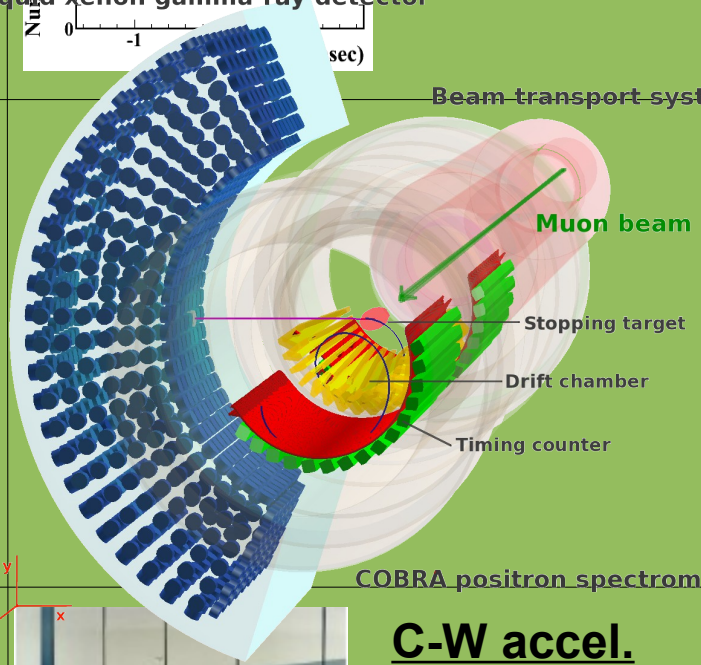


Michel Decay

$\mu \rightarrow e\nu\bar{\nu}$

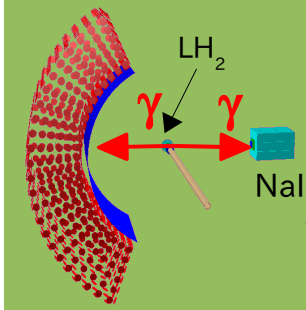
Liquid xenon gamma-ray detector

Beam transport system



COBRA positron spectrometer

$\pi^- p \rightarrow \pi^0 n$



$\pi^0 \rightarrow \gamma\gamma$

55,83,129MeV

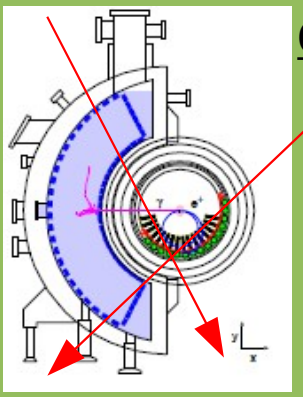
monochoro

$\pi^0 \rightarrow \gamma e^+e^-$

Relative timing

Similar topology

CosmicRay

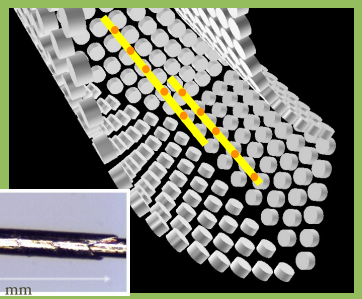


DC alignment

TC uniformity

LXe monitor

Alpha



PMT QE

Am source on wire

C-W accel.

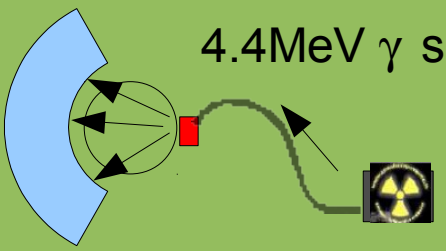
Li(p,γ)Be

- 18MeV γ

B(p,γ)C

- 4,11MeV 2γ

AmBe



4.4MeV γ source

Complementary for completeness
Redundant for cross check

MEG history

1999		Proposal
・・・		・・・ R&D ・・・
2007		Engineering run
2008	Sep - Dec	1st physics data acquisition
2009		Analysis of 2008 data
		Hardware upgrade
	Nov - Dec	2nd physics data acquisition
		Analysis of 2009 data
2010	Aug - Dec	3rd physics data acquisition

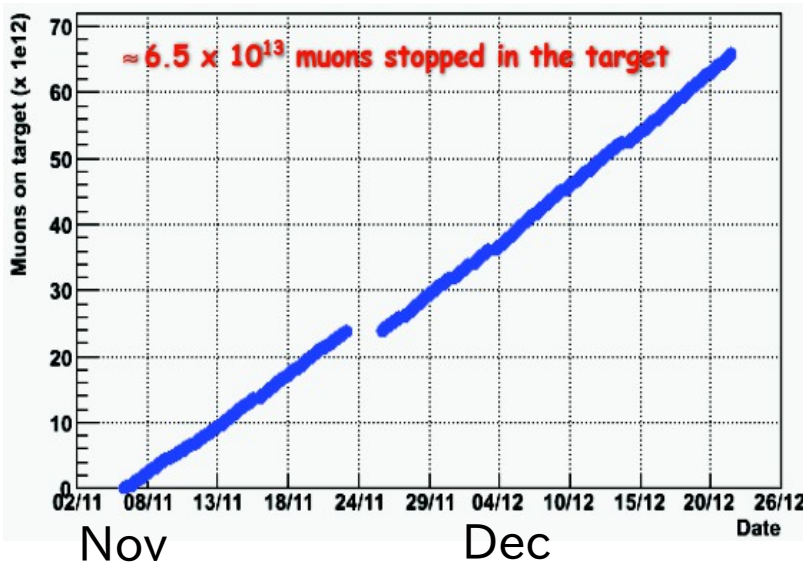
2008 result (Nucl.Phys.**B**834 1)
Sensitivity : 1.3×10^{-11}
90%CL UL : 2.8×10^{-11}

2009 data & performance

	2008	2009(preliminary)
Gamma energy (%)	2.0 (w>2cm)	←
Gamma timing (psec)	80	>67
Gamma position (mm)	5(u,v) / 6(w)	←
Gamma efficiency (%)	63	58
Positron momentum (%)	1.6	0.74(core)
Positron timing (psec)	<125	<95
Positron angle (mrad)	10(φ) / 18 (θ)	7.4(φ,core) / 11.2(θ)
Positron efficiency (%)	14	40
e^+-γ timing (psec)	148	142(core)
Muon decay point (mm)	3.2(R) / 4.5(z)	2.3(R) / 2.8(z)
Trigger efficiency (%)	66	84
Stopping muon rate (/sec)	3×10^7(300μm)	2.8×10^7(300μm)
DAQ time/Real time (days)	48 / 78	35 / 43
Sensitivity	1.3×10^{-11}	-
BR upper limit (obtained)	2.8×10^{-11}	-

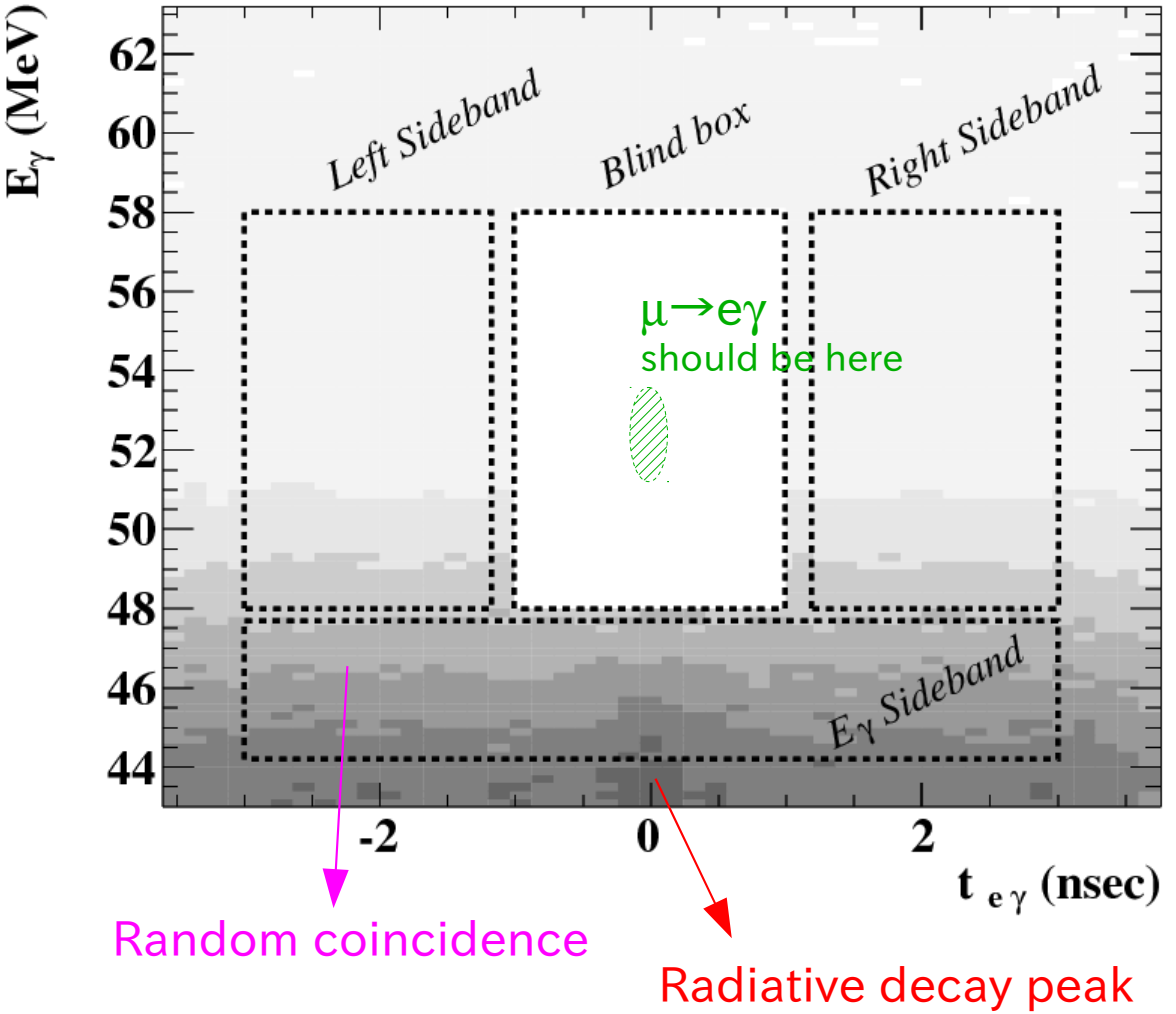
- 43 days physics DAQ
- ~6.5×10^{13} muon stopped
- 22.3M trigger (93 TB data)

- Major improvement
  - Stable operation of full drift chambers
  - Recover efficiency



Analysis procedure

- Blind analysis (Hidden Box)
  - Signal region was hidden until analysis was fixed
  - Any study (calibration, BG estimation, performance evaluation) can be done with events outside the box
  - Hidden parameters (E_γ, $t_{e\gamma}$)
- Sideband
  - Accidental BG can be studied with off-timing sideband data
  - Radiative decay can be studied with low energy sideband data
- Normalization
  - Unbiased Michel data mixed in physics data
- Wide analysis region for likelihood fitting



Likelihood Analysis

$$\mathcal{L}(N_{sig}, N_{RD}, N_{BG}) = \frac{N^{N_o} e^{-N}}{N_o!} \prod_{i=1}^{N_o} \left(\frac{N_{sig}}{N} \cdot S(\vec{\mathbf{x}}_i) + \frac{N_{RD}}{N} \cdot R(\mathbf{x}_i) + \frac{N_{BG}}{N} \cdot B(\vec{\mathbf{x}}_i) \right)$$

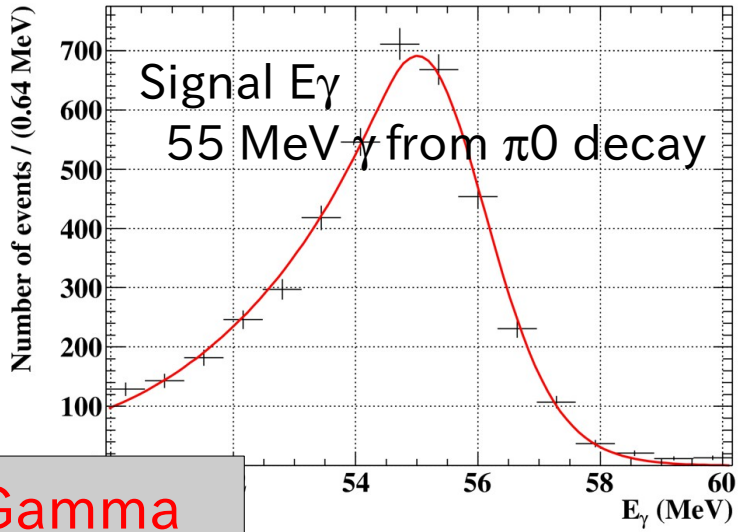
μ→eγ signal

Radiative decay

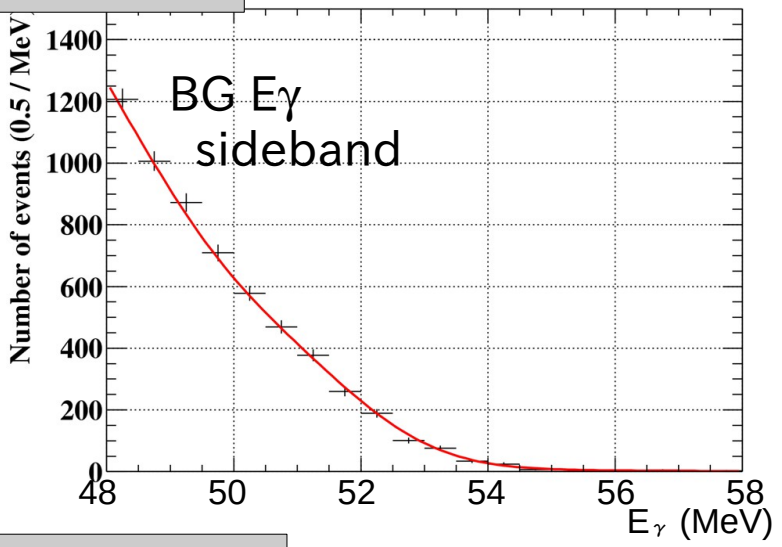
Accidental BG

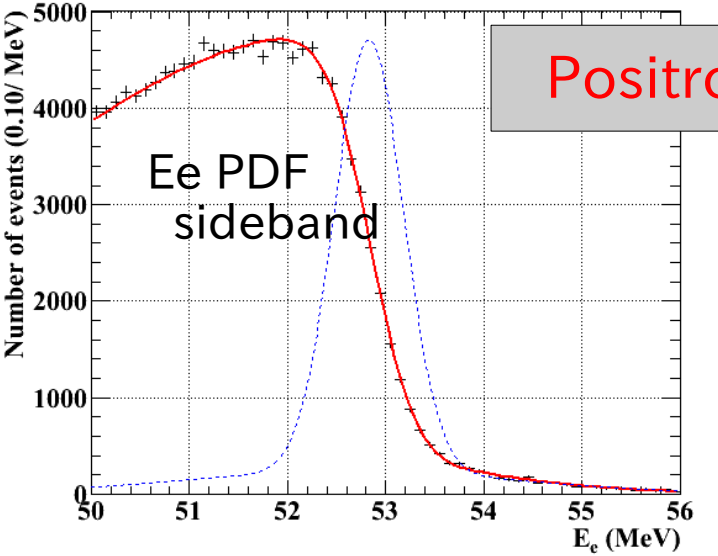
- Extended unbinned maximum likelihood fit on number of events
  - 3 fit parameters : **(N_{sig}, N_{RD}, N_{BG})** , $N=N_{sig}+N_{RD}+N_{BG}$
  - 5 observables : $\vec{x} = (E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})$ (Relative angle)
  - Probability density functions (PDF) for each event type (**S, R, B**)
    - Extract PDFs from data
    - Use maximum information
      - Position dependent PDF for gamma
      - Two-category PDF for positron
  - Fit in wide region (10σ)
    - Fit signal & background simultaneously
  - Three independent analysis tools → check, understand, or find bug
    - Different PDF implementations
    - Fit or input N_{RD}
    - Different statistical treatments (Frequentist or Bayesian)

PDFs

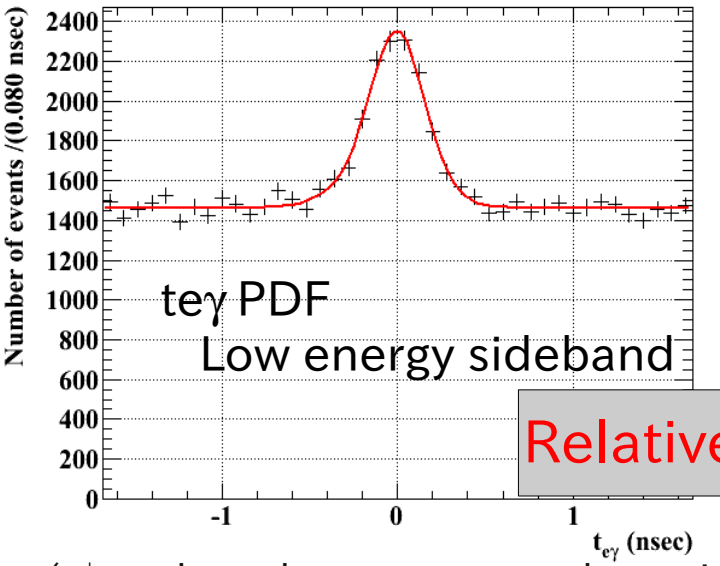


Gamma





Positron



Relative time

- Relative angle Form with measured resolutions (e^+ angle, μ decay vertex, and γ position)
- Form RD PDFs by folding theoretical correlated distribution with measured responses

Number of muon decays

$$\frac{\mathcal{B}(\mu^+ \to e^+\gamma)}{\mathcal{B}(\mu^+ \to e^+\nu\bar{\nu})} = \frac{N_{\rm sig}}{N_{e\nu\bar{\nu}}} \times \frac{f^{e}_{e\nu\bar{\nu}}}{P \cdot \epsilon_{\rm pu}} \times \frac{\epsilon^{\rm trig}_{e\nu\bar{\nu}}}{\epsilon^{\rm trig}_{e\gamma}} \times \frac{\epsilon^{\rm DC}_{e\nu\bar{\nu}}}{\epsilon^{\rm DC}_{e\gamma}} \times \frac{1}{A^{\rm geo}_{e\gamma}} \times \frac{1}{\epsilon_{e\gamma}}$$

- We normalize number of muon decay by counting Michel decay positrons
  - Unbiased Michel trigger data mixed in physics runs
  - At first order cancel
    - Absolute e^+ efficiency and instability of drift chamber
    - Instability of beam rate

Normalization factor

Preliminary

B.R. = Nsig / (1.0 ± 0.1) x 10^{12}

cf.) 5.2 x 10^{11} in 2008

Sensitivity

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- Average upper limit (90%CL) on ensemble of toy-MC experiments
  - Null signal assumption
  - Toy-MC : generate events with obtained PDFs
  - Repeat toy-MC experiments and calculate UL for each experimet in the same way as real data

Preliminary

Sensitivity of RUN2009 : 6.1×10^{-12}

Not include systematics.

cf. Sensitivity of RUN2008 : 1.3×10^{-11}
Current best upper limit : 1.2×10^{-11}

Started searching for unexplored region

- Signal detecting power of our likelihood analysis was also checked by mixing full-MC $\mu \rightarrow e\gamma$ events in toy-experiments

Fictitious analysis on sidebands

- Analyze real data but off-timing

- No signal in sidebands
- Our dominant background is accidental one
- **Good test of our sensitivity**

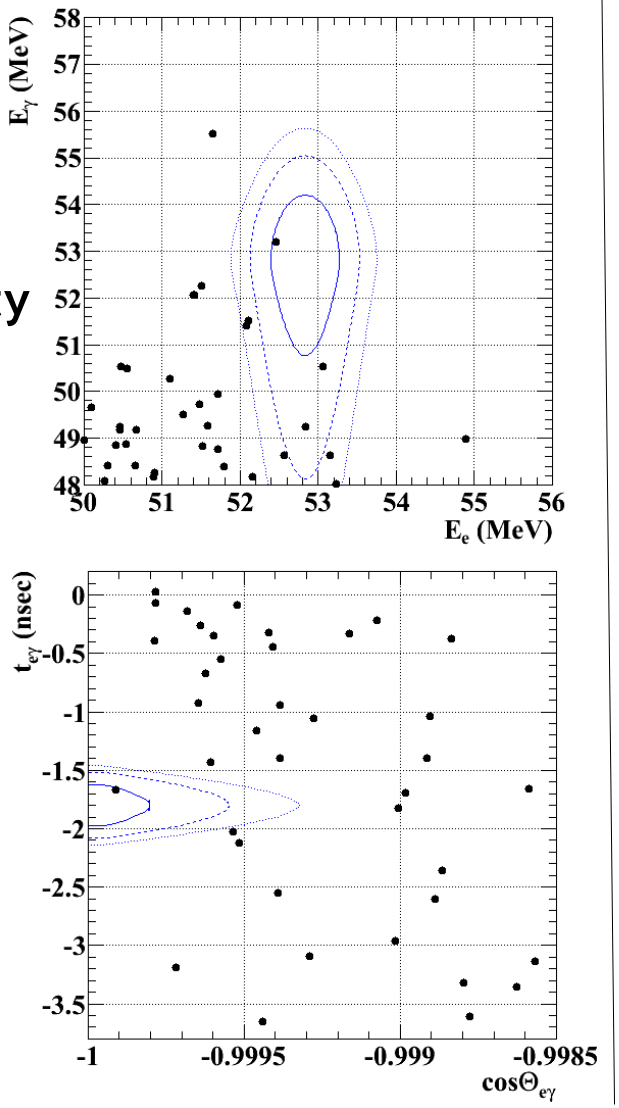
Results of likelihood analysis

BR < $4 - 6 \times 10^{-12}$

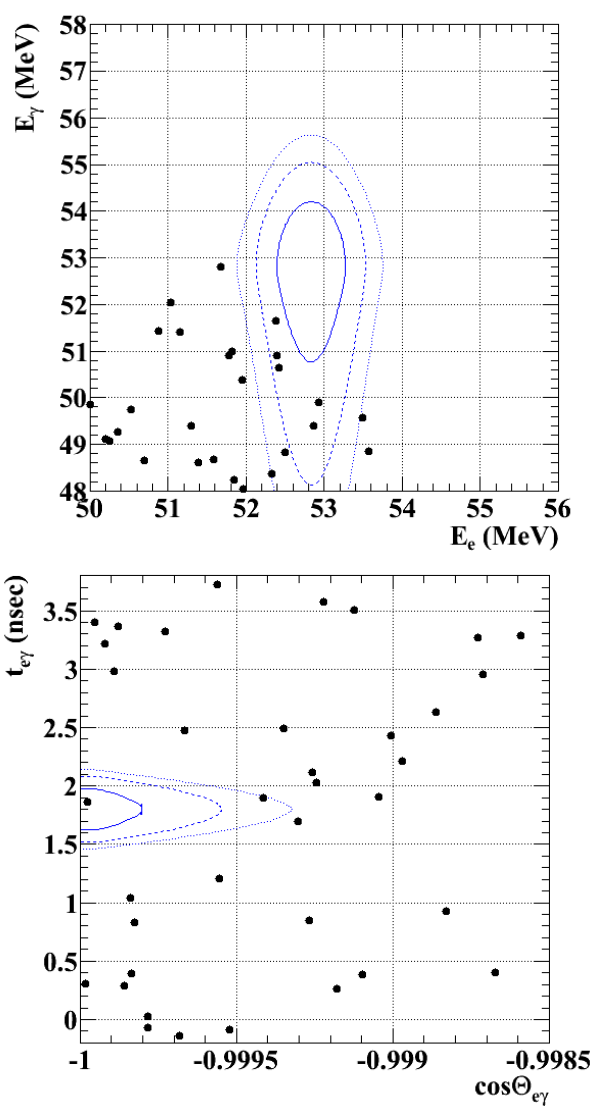
depend on the t0 position

Consistent with the sensitivity

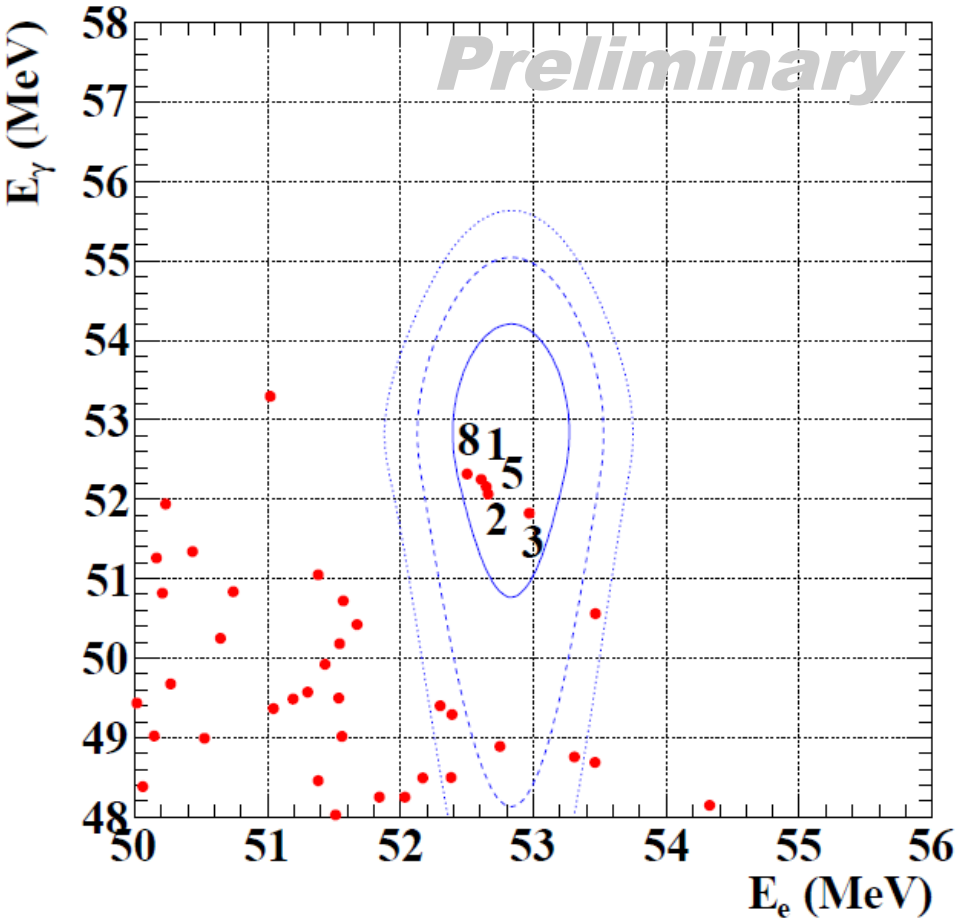
Left sideband

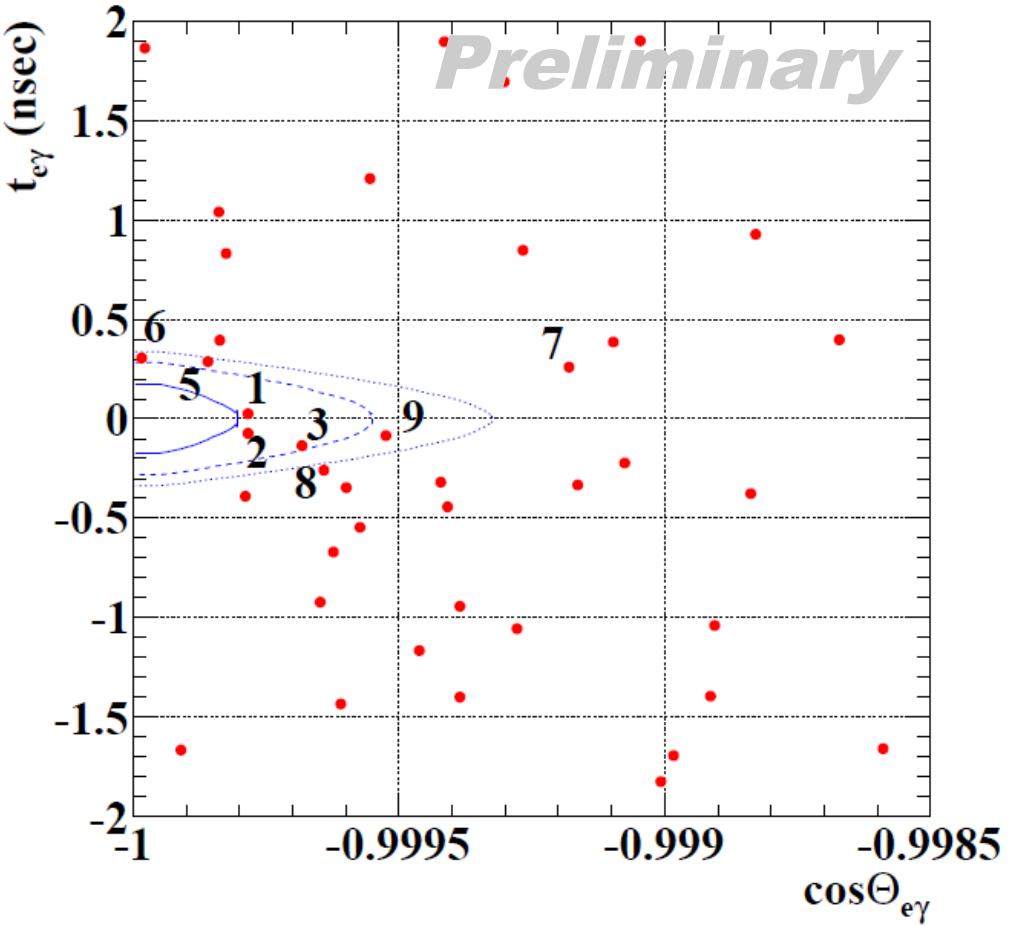


Right sideband



Open blind box



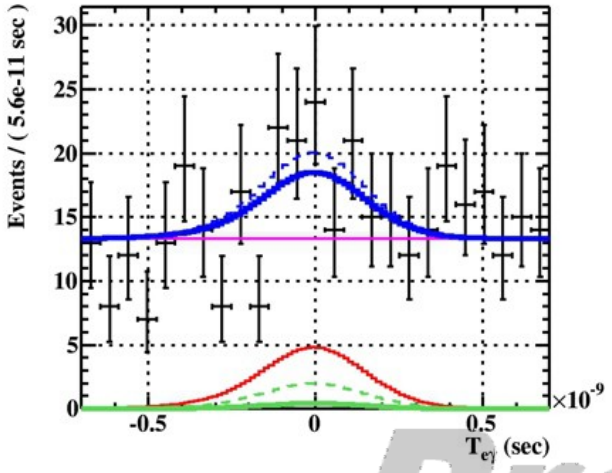


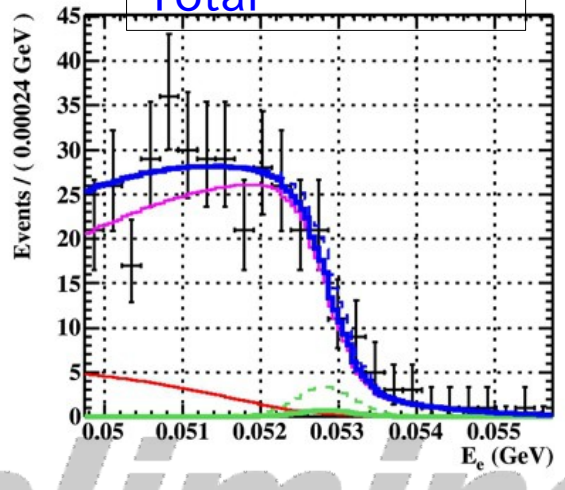
For each plot, cut on other variables for roughly 90% window is applied.
Contours are 2D signal PDF for 1(39.3 %), 1.64(74.2%) and 2(86.5%) sigma regions.
Events correspondence in two plots are shown by numbers of ranking by S/(R+B).

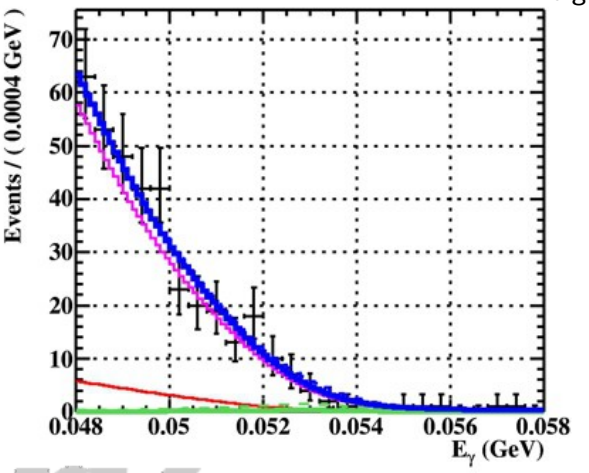
Fit result

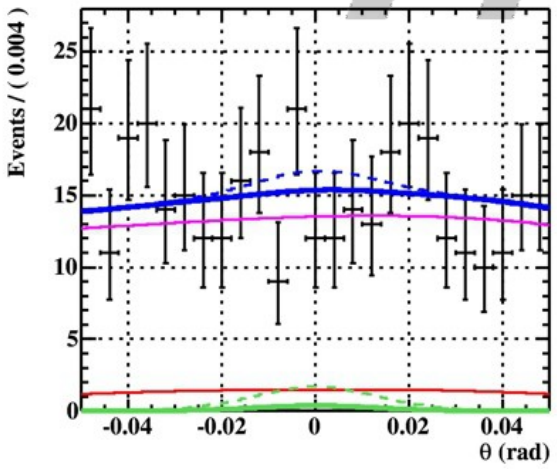
Accidental BG
Radiative Decay
Signal
Total

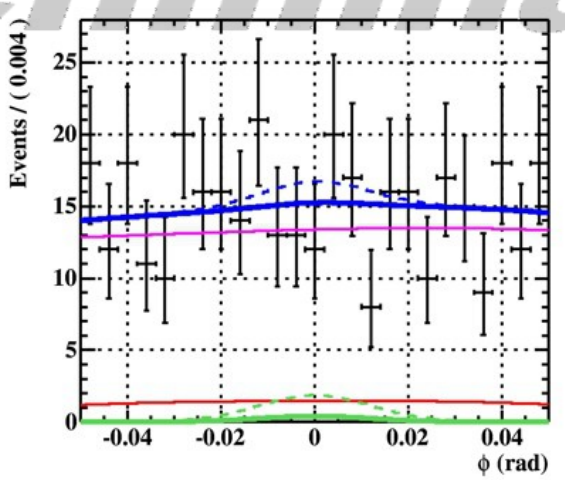
Dashed lines: 90%CL UL on N_{sig}











Best-fit value

$(N_{sig}, N_{RD}) = (3.0, 35^{+24}_{-22})$

Expectation : 32±2

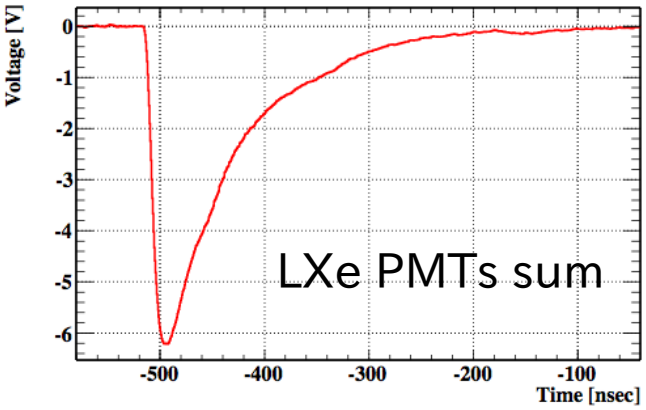
N_{sig} < 14.5 @ 90% CL with Feldman-Cousins approach

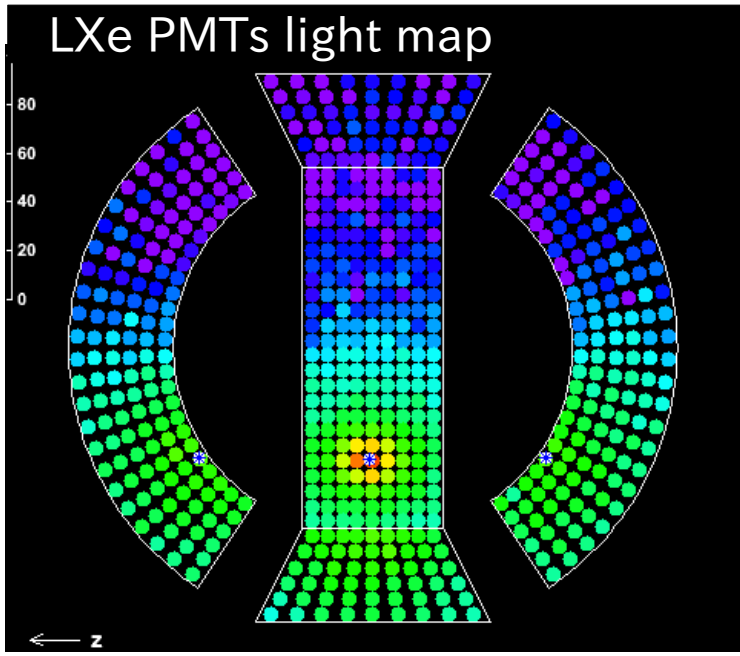
N_{sig} = 0 is in 90%-confidence region

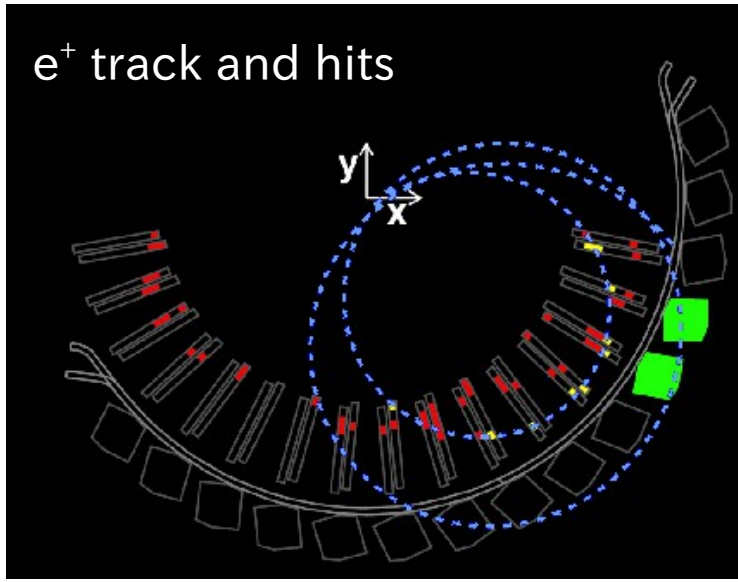
* The best-fit value & UL range 3.0-4.5 & 12-14.5 depending on analysis methods

Signal-like event

- High rank events were checked carefully
- This is one of the most signal-like event







E_{γ} = 52.25 MeV
E_{e+} = 52.84 MeV
$\Theta_{e\gamma}$ = 178.8 deg
$t_{e\gamma}$ = 26.8 psec

Systematic Uncertainties

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	Uncertainty	
Normalization	8 %	e^+ mementum dep. ⊕ γ det. ε ⊕ trigger ε
E_γ scale	0.4 %	Light yield stability, gain shift
E_γ resolution	7 %	
E_e scale	50 keV	From Michel edge
E_e resolution	15 %	
$t_{e\gamma}$ center	15 ps	
$t_{e\gamma}$ resolution	10 %	RD peak
Angle	7.5 mrad	Tracking ⊕ LXe position
Angle resolution	10 %	
E_e-ϕ_e correlation	50%	MC evaluation

- Systematic effects are taken into account in the calculation of confidence region by fluctuating PDFs according to the uncertainty values.
  - Effect of each component is evaluated by looking at the change of best-fit value when the parameter is changed according to the uncertainty.
  - Effect is small compared to the statistical uncertainties

Upper Limit

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- Obtained upper limit on branching fraction (including systematic uncertainty)

Preliminary

$$\frac{\mathcal{B}(\mu^+ \to e^+\gamma)}{\mathcal{B}(\mu^+ \to e^+\nu\bar{\nu})} < 1.5 \times 10^{-11}$$

at 90% C.L.

cf.

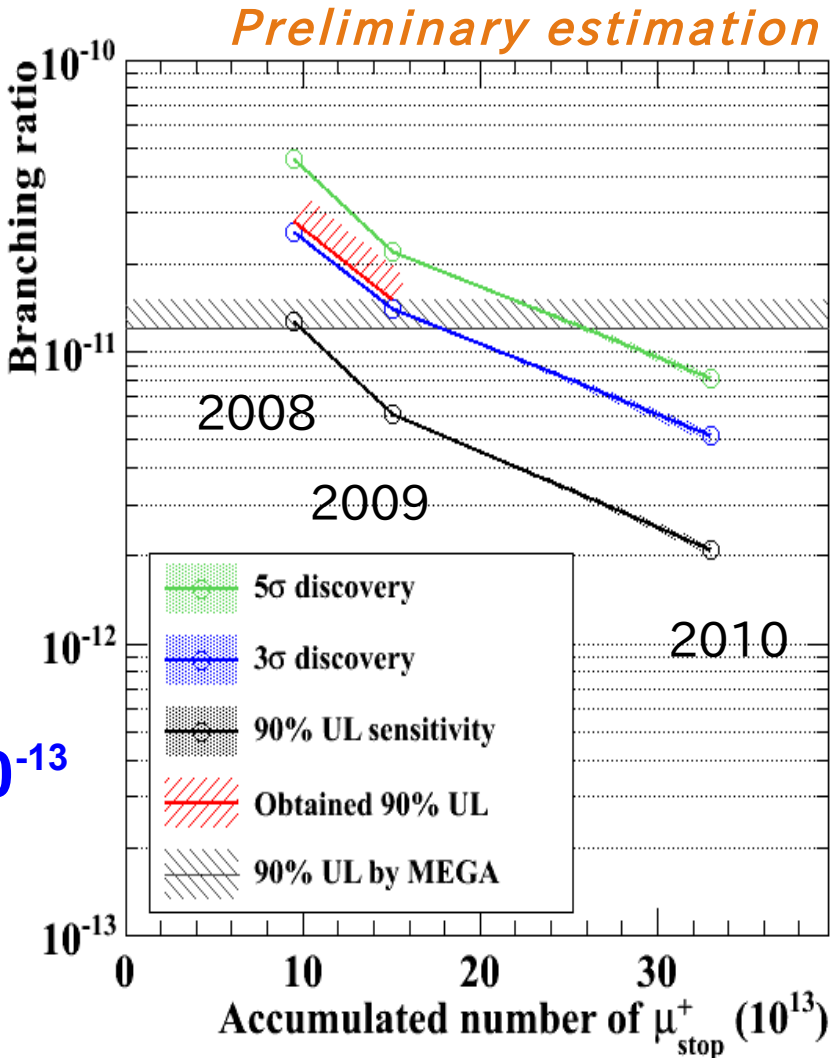
Current best UL	1.2 x 10^-11
MEG2008 UL	2.8 x 10^-11
90%CL-sensitivity	6.1 x 10^-12

- No lower limit is set
  - Confidence level at zero : 40 – 60 % (depending on statistical approach)

Current status & Prospects

- MEG is running
  - We resumed data taking since August
  - Will acquire x3 statistics in this year
  - Sensitivity will improve accordingly
- We will run at least until 2012
  - Another two-year full run.
  - No clear schedule for further years
  - We will **clarify the situation (2009 result) by ourselves** with long term stable data taking
- Our goal is a sensitivity of **a few × 10^{-13}**

To achieve final goal,
gaining statistics (≒ improving efficiency)
is most important



Conclusion

- **In 2009, MEG successfully carried out 2 months DAQ with stable detector operation**
- **Preliminary result from 2009 data**
  - **Sensitivity : 6.1 x 10^{-12}**
  - **90%CL-upper limit : 1.5 x 10^{-11}**
  - **N_{sig}=0 is in the 90%CL region**
- **MEG will clarify the situation by ourselves with 3 years DAQ until the end of 2012**

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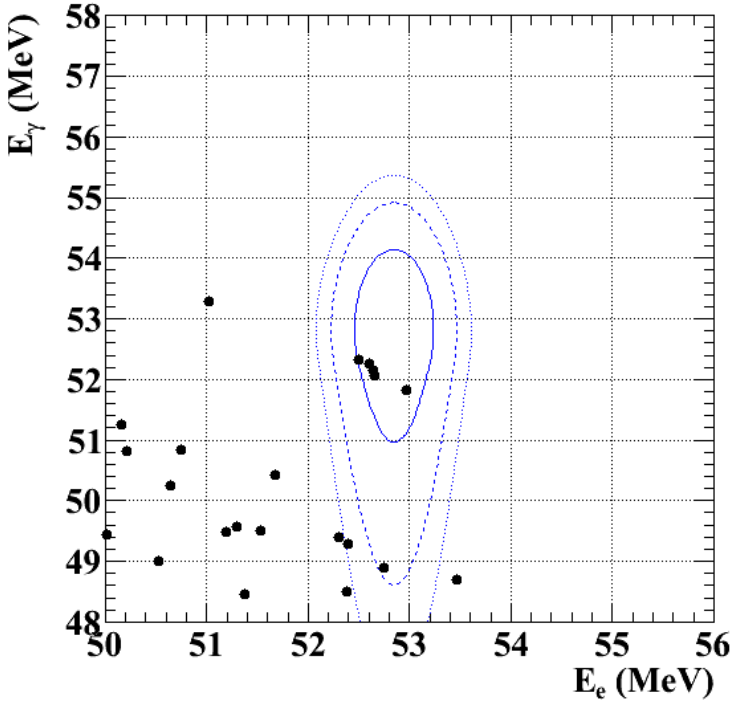
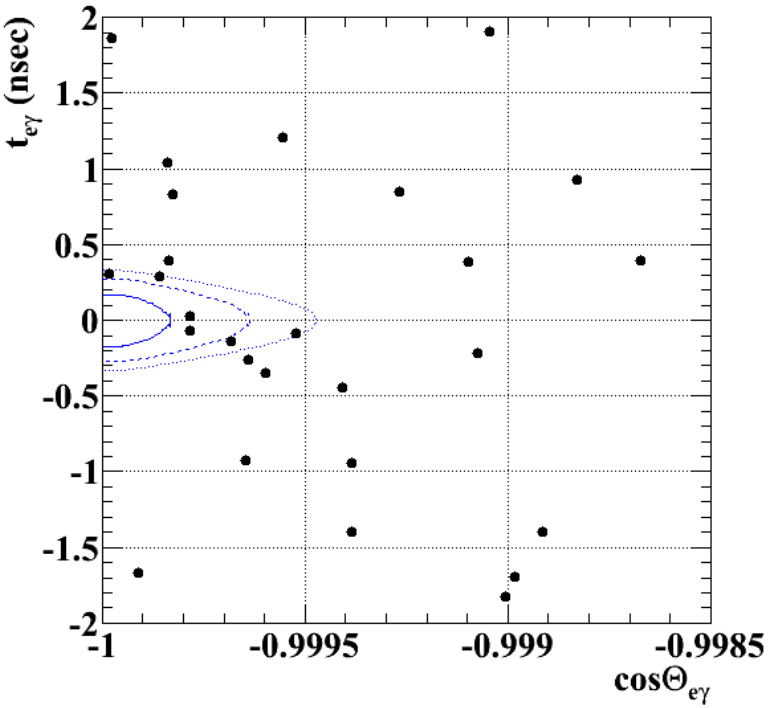
End

Event check

- High rank events were carefully checked
  - No strange behavior was found in measurement, reconstruction, etc.
  - Ex) High-rank events have good tracking quality

Applying tracking quality cut.





Fraction of high-quality events : 59%

Possible improvements

- Z-measuring timing counter (scintillation fiber)
  - Improve θ_e estimation on trigger → improve trigger efficiency
  - Improve tof of e^+ → improve timing resolution
  - Integrated into data acquisition in 2010 (now tuning)
- Double buffering of DAQ system
  - Dead-time free. DAQ ε : 83 → 99%
  - Together with TC fiber, trigger ε : 84 → 95%
  - Possibly from the 2nd half of 2010 data taking
- e^+ ε is limited (to <50%) by material
  - Use thinner cable can improve ε by 15%(rel.)
    - Possibly from 2012
  - To go further, major upgrade of detector is necessary
- Timing resolution is improved in 2010 by electronics modification
- Improve tracking algorithm
  - More careful study and fine tuning
- Develop sophisticated gamma energy reconstruction algorithm

Expected performance

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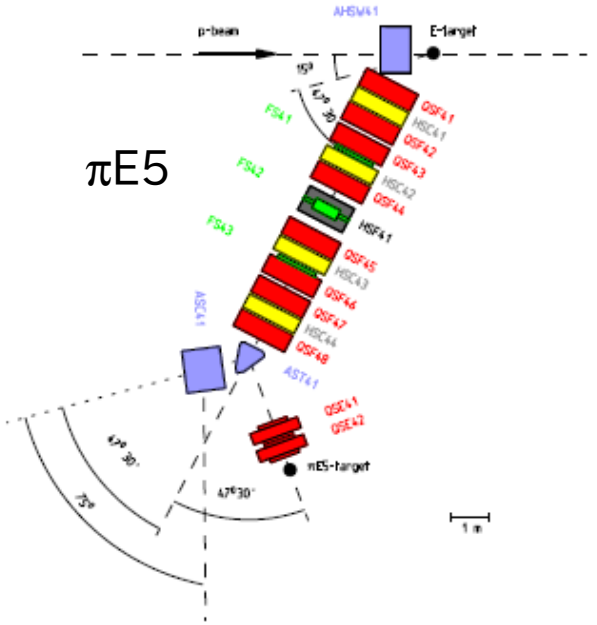
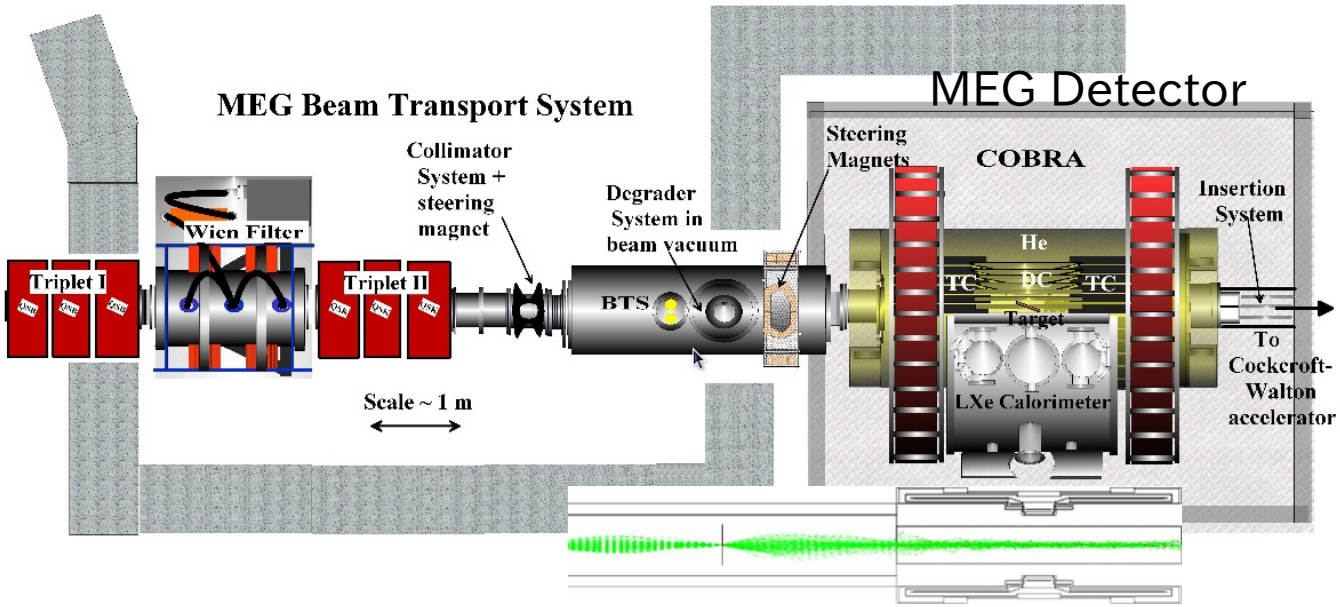
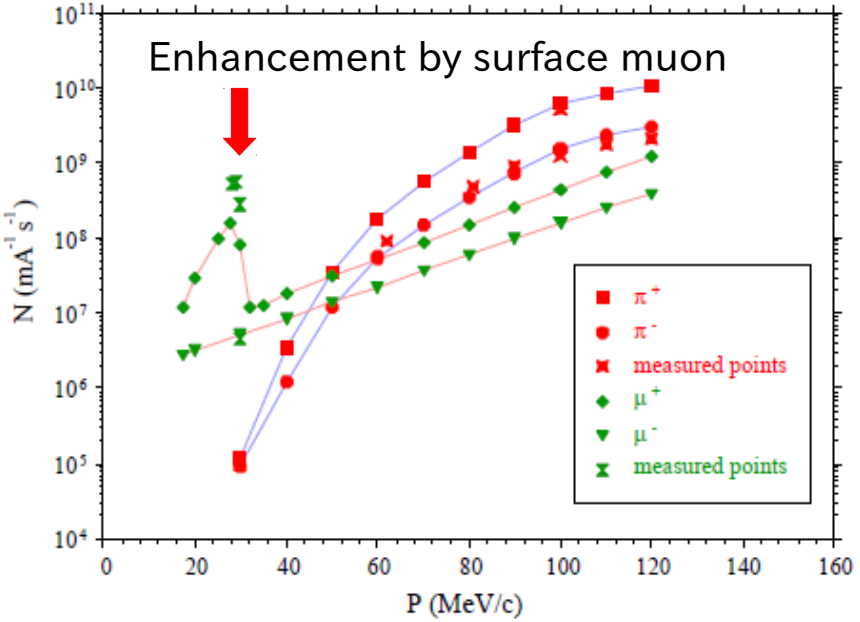
	2008	2009(preliminary)	2010(preliminary estimate)
Gamma energy (%)	2.0 (w>2cm)	←	1.5(w>2cm)
Gamma timing (psec)	80	>67	68
Gamma position (mm)	5(u,v) / 6(w)	←	←
Gamma efficiency (%)	63	58	←
Positron momentum (%)	1.6	0.74(core)	0.7
Positron timing (psec)	<125	<95	←
Positron angle (mrad)	10(ϕ) / 18 (θ)	7.4(ϕ,core) / 11.2(θ)	8(ϕ) / 8(θ)
Positron efficiency (%)	14	40	40
e+-g timing (psec)	148	142(core)	120
Muon decay point (mm)	3.2(R) / 4.5(z)	2.3(R) / 2.8(z)	1.4(R) / 2.5(z)
Trigger efficiency (%)	66	84	84-94
Stopping muon rate (/sec)	3×10^{7}(300μm)	2.8×10^{7}(300μm)	2.9×10^{7}(300μm)
DAQ time/Real time (days)	48 / 78	35 / 43	95 / 117
Sensitivity	1.3×10^{-11}	6.1×10^{-12}	$(2.0\text{-}2.2)\times10^{-12}$
BR upper limit (obtained)	2.8×10^{-11}	1.5×10^{-11}	-

'Surface muon' Beam Transport System



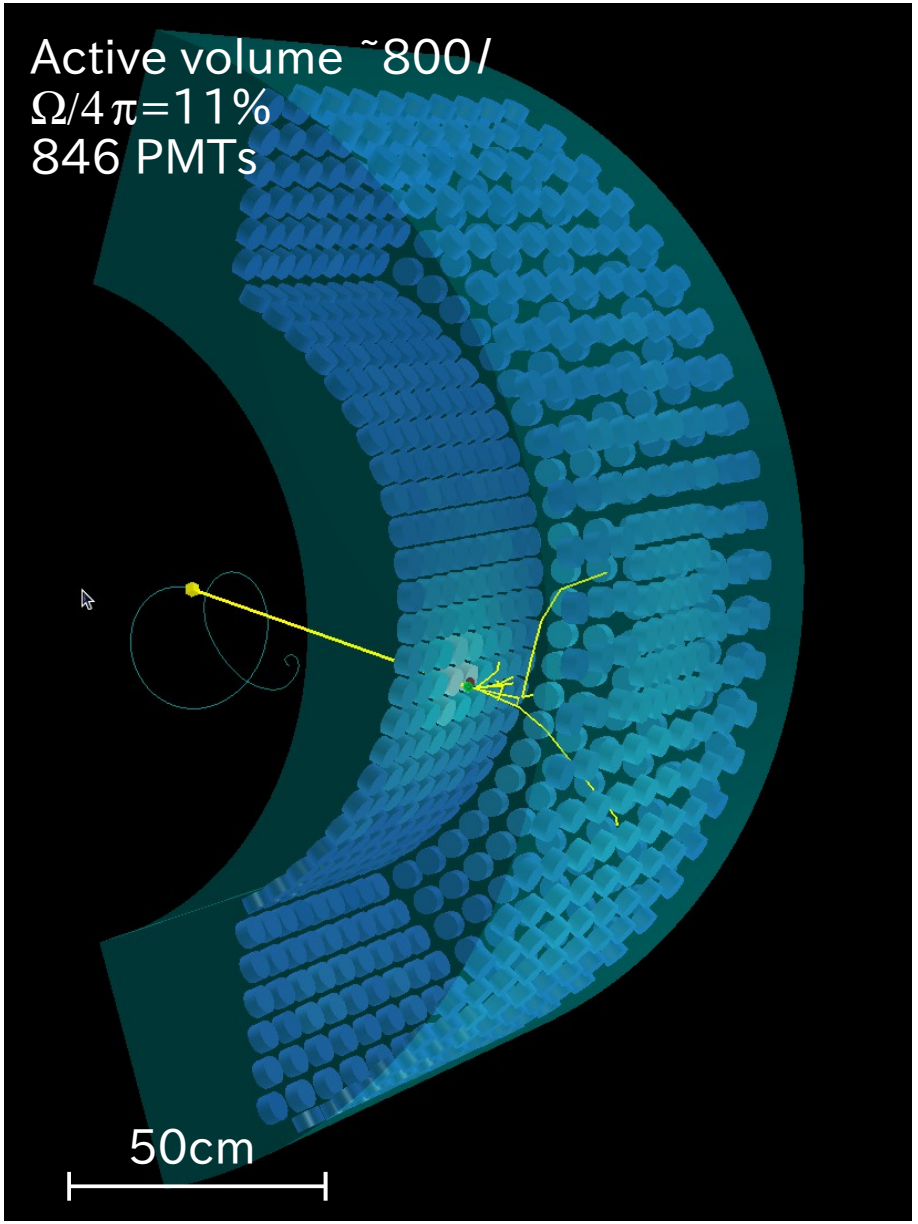




- Surface μ^+: μ^+ originating from pion stopped on the surface of prod. target
  - Extract at 175° from the primary p beam
  - Low momentum(29MeV/C) with small variance μ^+ beam
- Through the beam transport system
  - Separate e^+ ・degrade ・tune beam profile
- **$3\times10^7 \mu^+$/sec** stop on target
  - 10mm spot size
  - 200μm polyethylene film target , placed at 20.5°slant angle from beam-axis
    - Suppression of scatter & BG VS stopping power

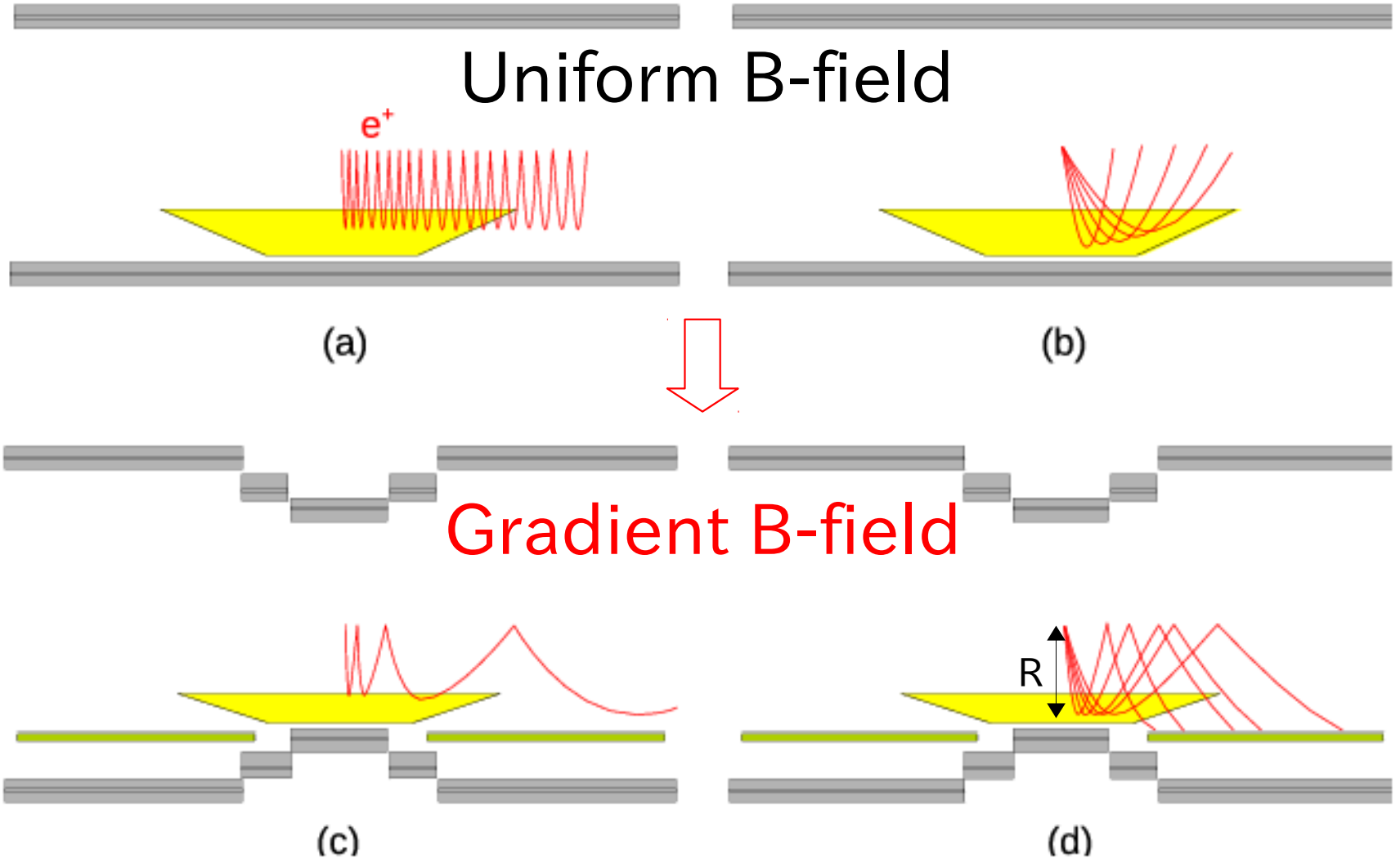
Liquid Xenon Gamma-ray Detector

- 900 liter liquid xenon
  - Scintillation medium
    - High light yield (75% of NaI(Tl))
    - Fast response (τ_{decay}=45ns)
    - High stopping power (X_0=2.8cm)
    - No self-absorption
    - Uniform, no-aging
  - Challenges
    - Vacuum ultraviolet (178nm)
    - Low temperature (165K)
    - Need high purity
  - No segmentation
- Measure energy,position,time at once
- Identify pileup events
  - Light distribution
  - time distribution
  - waveform



First ton-scale LXe detector in use

Specially Graded B-Field

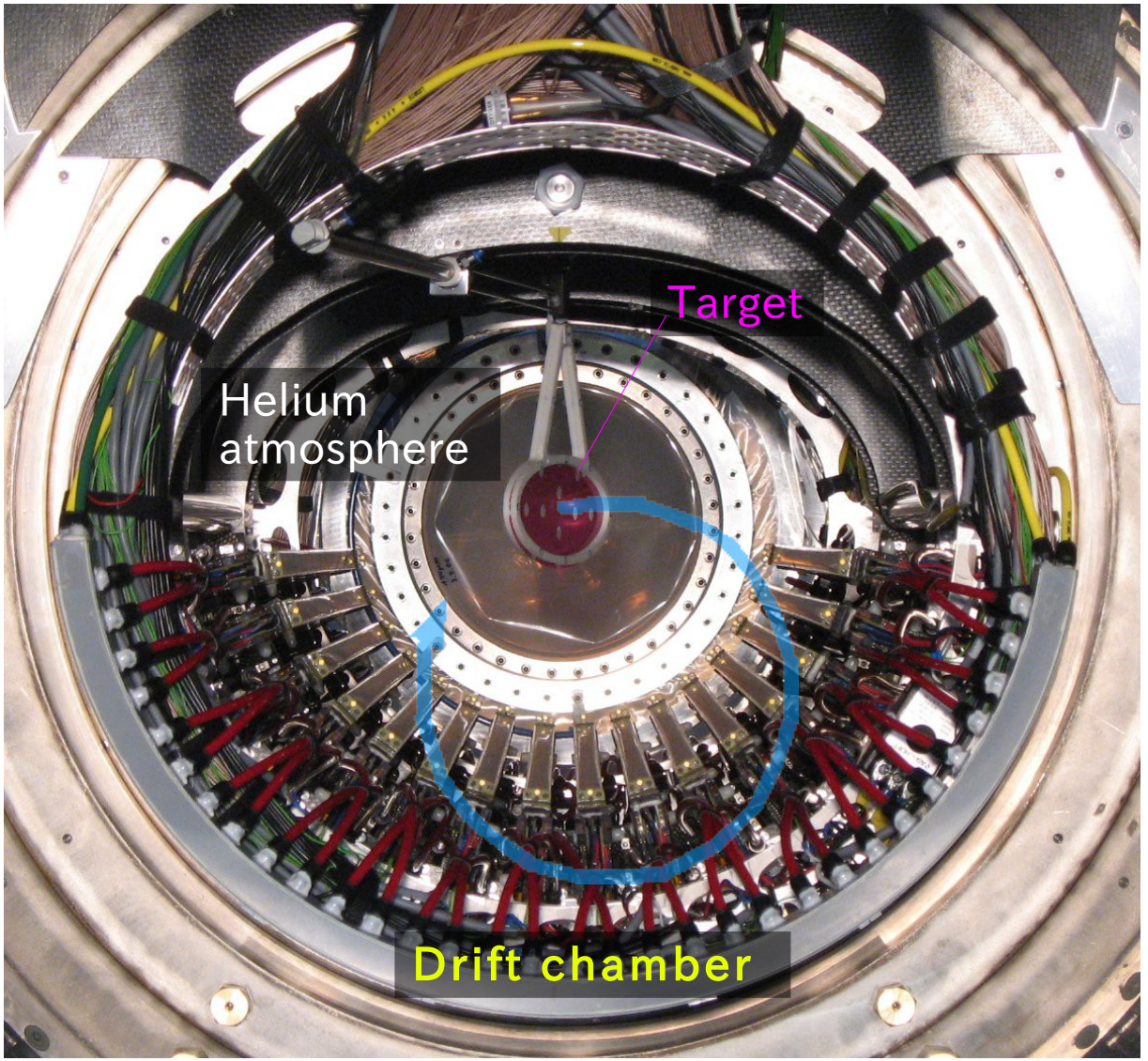


e^+ quickly swept out

Same momentum ⇒ same radius
(**CO**nstant **B**ending **RA**dius)

Enable measurement in high rate

Drift Chamber System

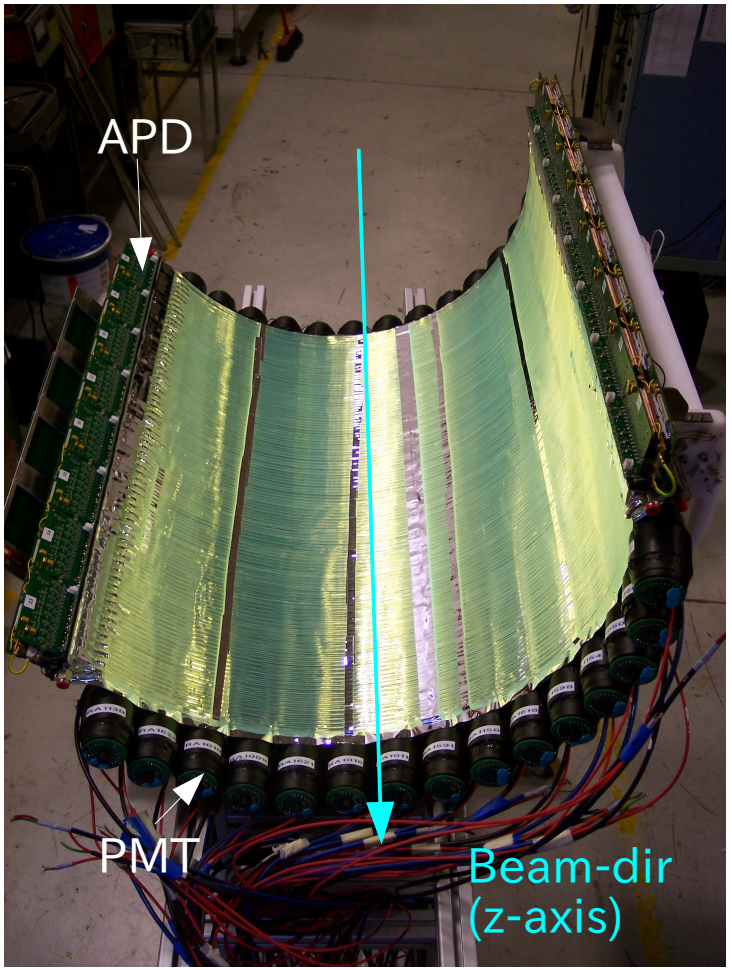


- 16 modules
  - Arranged concentrically (10.5°interval)
  - 2 layers per 1 module

- Ultra low mas chamber
  - Multiple-scattering limits the performance
  - To suppress γ BG source
  - In total along e^+ trajectory

  ~2.0×10^{-3} X_0

Timing Counter

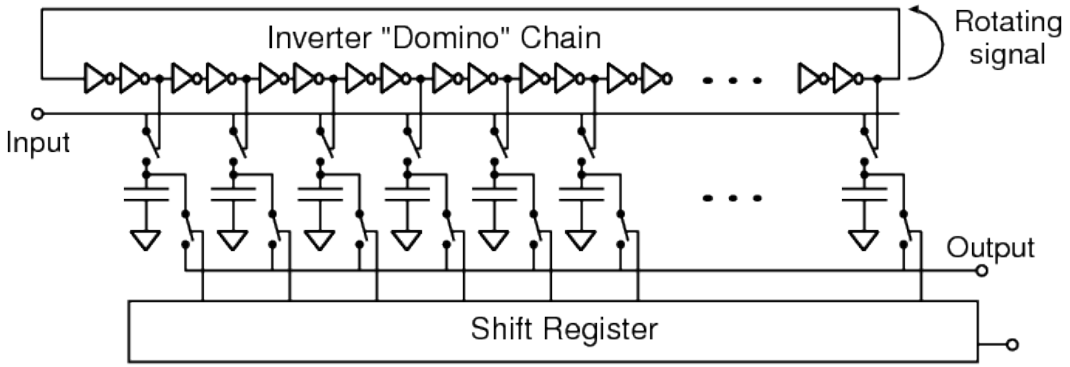


- Hit timing counter one turn after exit of DC. Measure hit timing
- Two layers of plastic scintillator arrays
  - Outer : Scintillation bars
    - $4x4x80cm^3$
    - 15 bars concentrically
    - Fine-mesh PMT at two ends
    - High precision time measurement
  - Inner : Scintillating fiber
    - $5x5mm^2$
    - 128 fibers along z-dir.
    - Readout by APD
    - Hit pattern → trigger

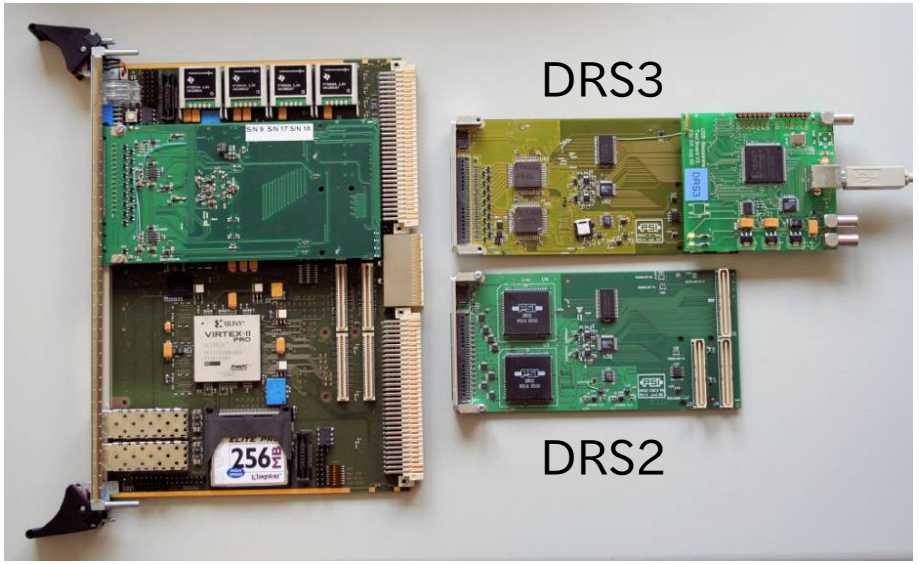
Not used in 2009 analysis
Defects in APD readout

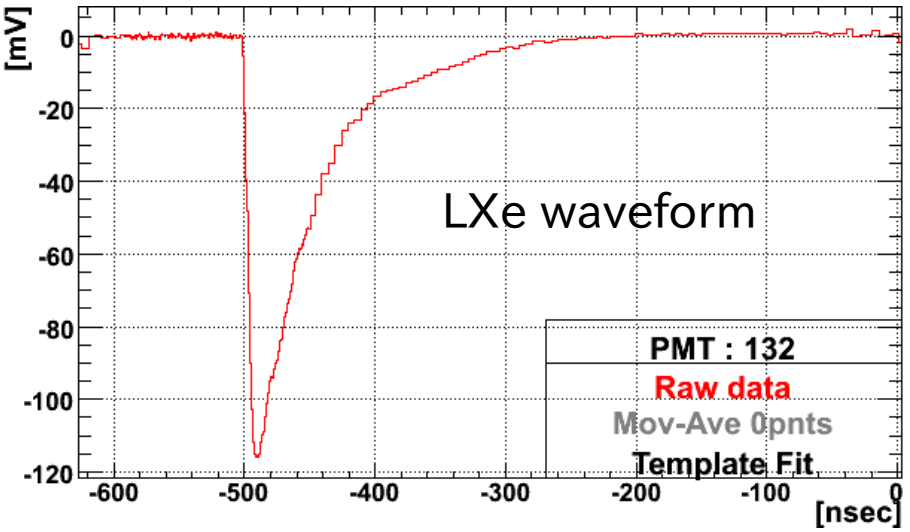
Readout Electronics

- Record waveform from all sub-detectors (no ADC,TDC)
  - DRS chip (Domino Ring Sampler)
    - Up to 5GSPS, 1024cell, 8ch/chip
  - Sampling speed : **1.6GHz** for LXe&TC, **500MHz** for DC



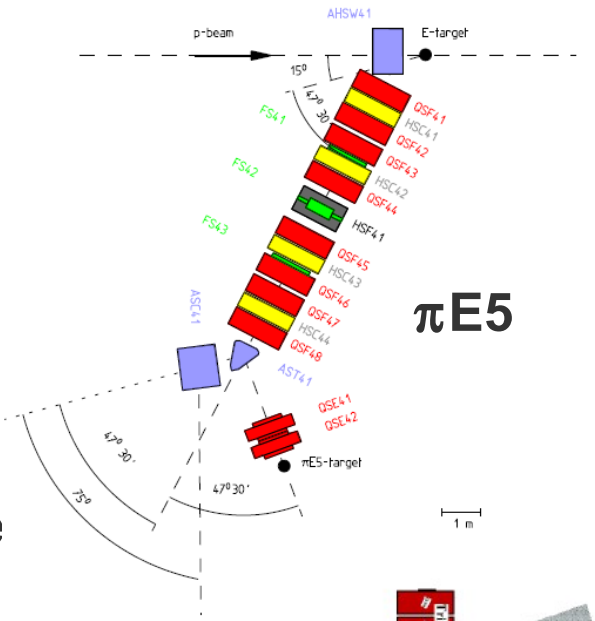
Data size
Typ. 1.5MB/event





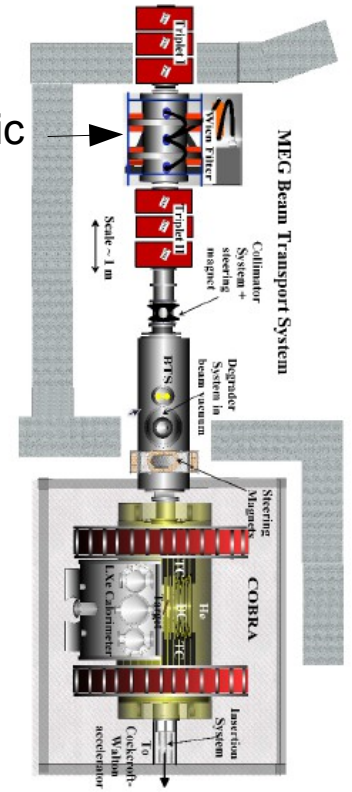
New calibration method 1

- Spectrometer calibration with **e^+ Mott scattering**
  - Coherent elastic scatter of e^+ on light nuclei
    - **Precisely known cross-section**
  - **e^+ beam**
    - High intensity @ PiE5 beamline
      - For MEG, e^+ are separated and rejected
    - **Monochromatic, and momentum tunable**
      - Select momentum with low momentum bite (~100keV)
  - **Target** (light nuclei → Carbon is best solution)
    - MEG target (thickness of 205μm)
    - Dedicated target
      - Pure CH2 (thickness of 2mm)
      - Mounted inside COBRA magnet
  - **Calibrate and study**
    - Momentum resolution
    - Efficiency and uniformity
      - Cross section & angular distribution well known

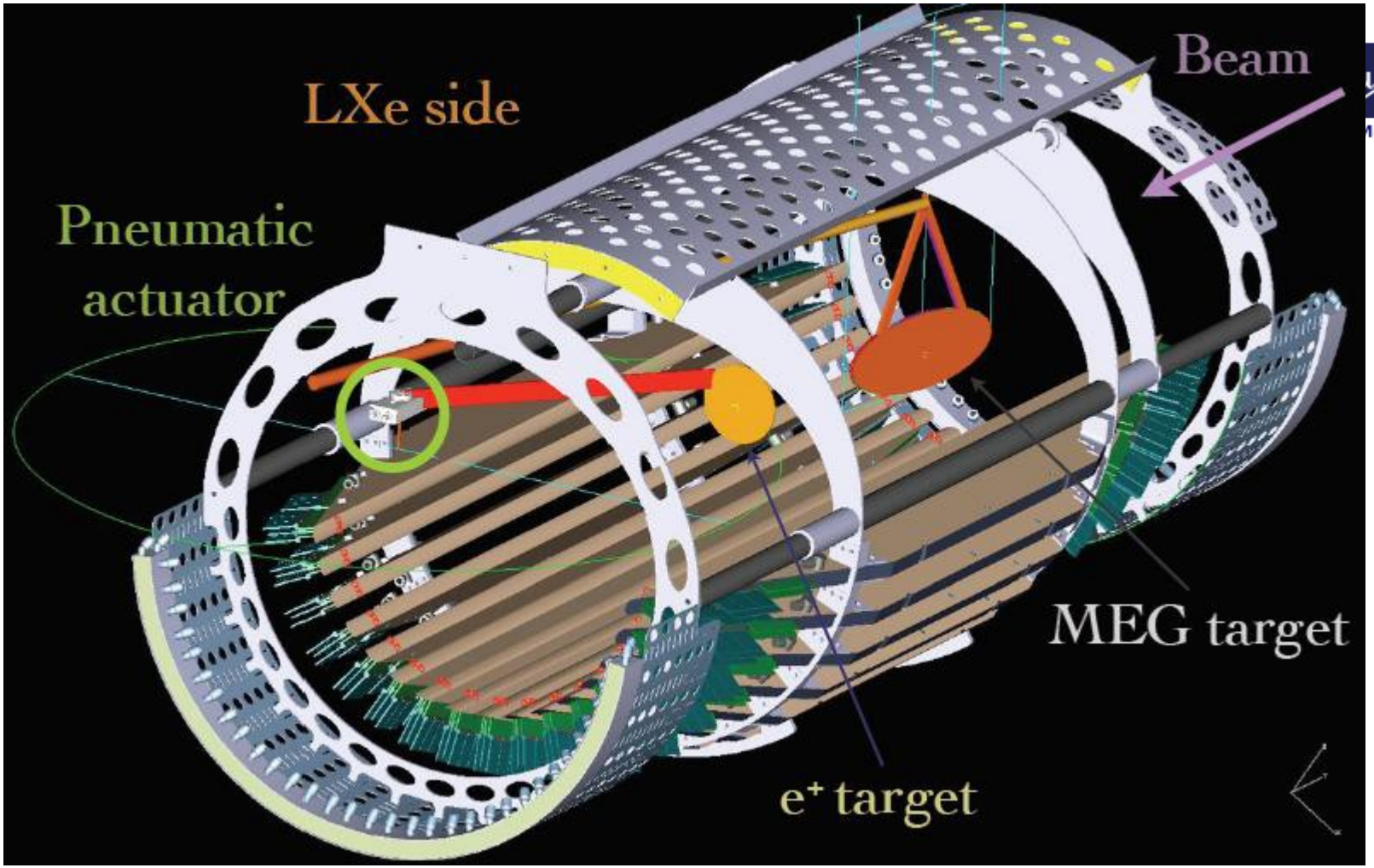


πE5

electrostatic separator



First test in May (feasibility test)
Analysis underway
→ Modification, optimization



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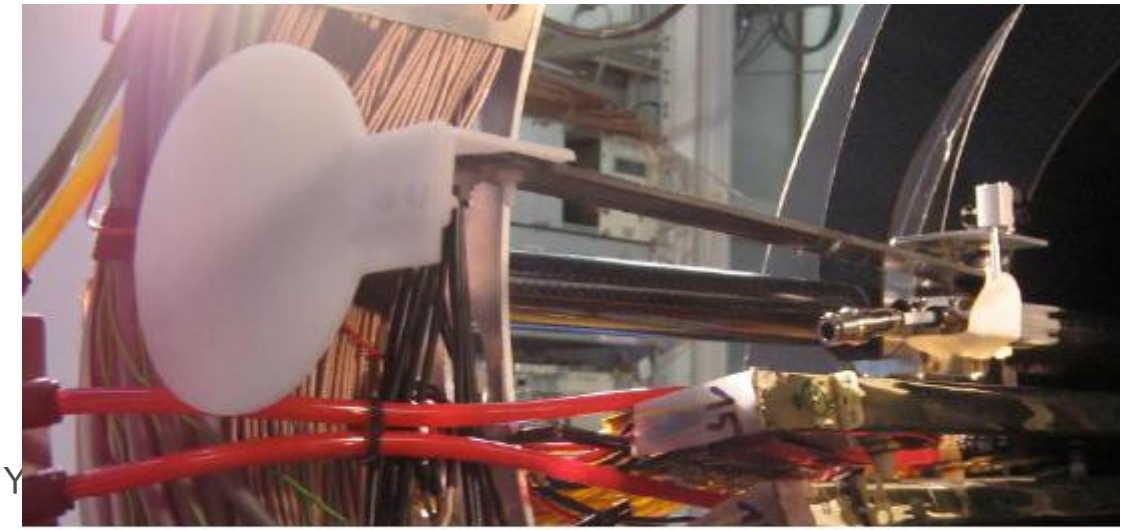
Mounted (May 2010)



New calibration method 2

- **9 MeV gamma** from n-Ni reaction
  - Thermal neutron capture on Ni
  - Unique possibility of calibrating LXe with gamma under ***beam ON***.

  - **Neutron generator** as n-source
    - D-D reaction
    - Pulsed operation (better S/N under beam condition)
    - Easy to switch ON/OFF
      - Frequent monitoring (any time)