MEG 実験の最新結果

岩本　敏幸
On behalf of the MEG Collaboration

東京大学素粒子物理国際研究センター

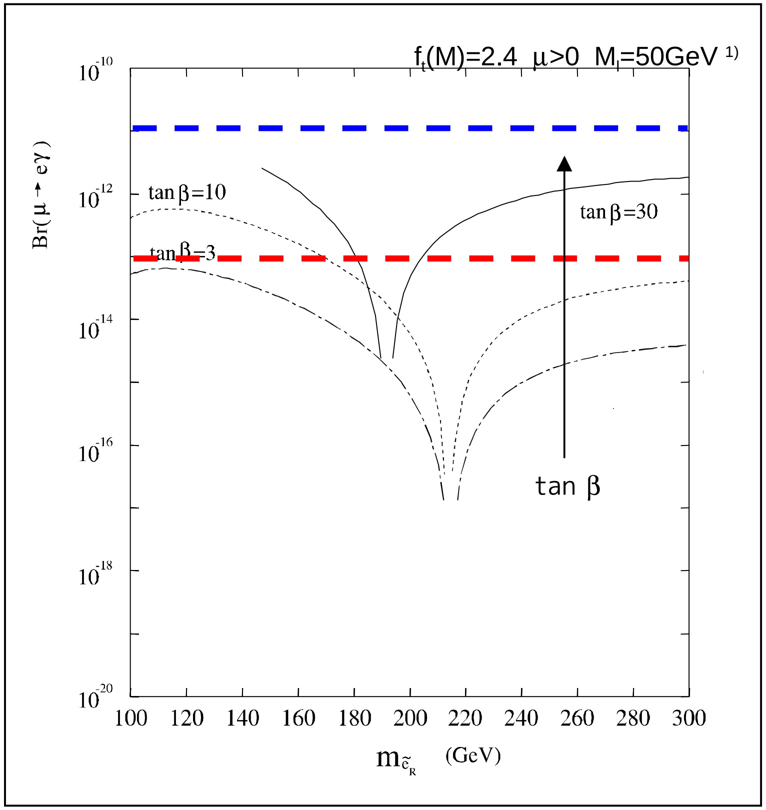
日本物理学会　2010 秋季大会
9 月 11 日ー 14 日　九州工業大学戸畑キャンパス

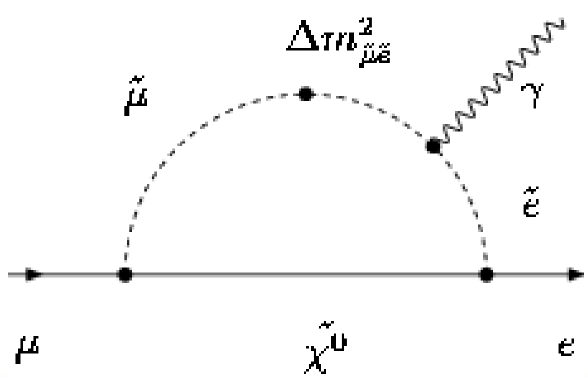
Outline

- Motivation
- MEG Experiment
- MEG Detector
- Calibration & monitoring
- Performance in 2009
- Result in 2009
- Plan and prospects

Motivation

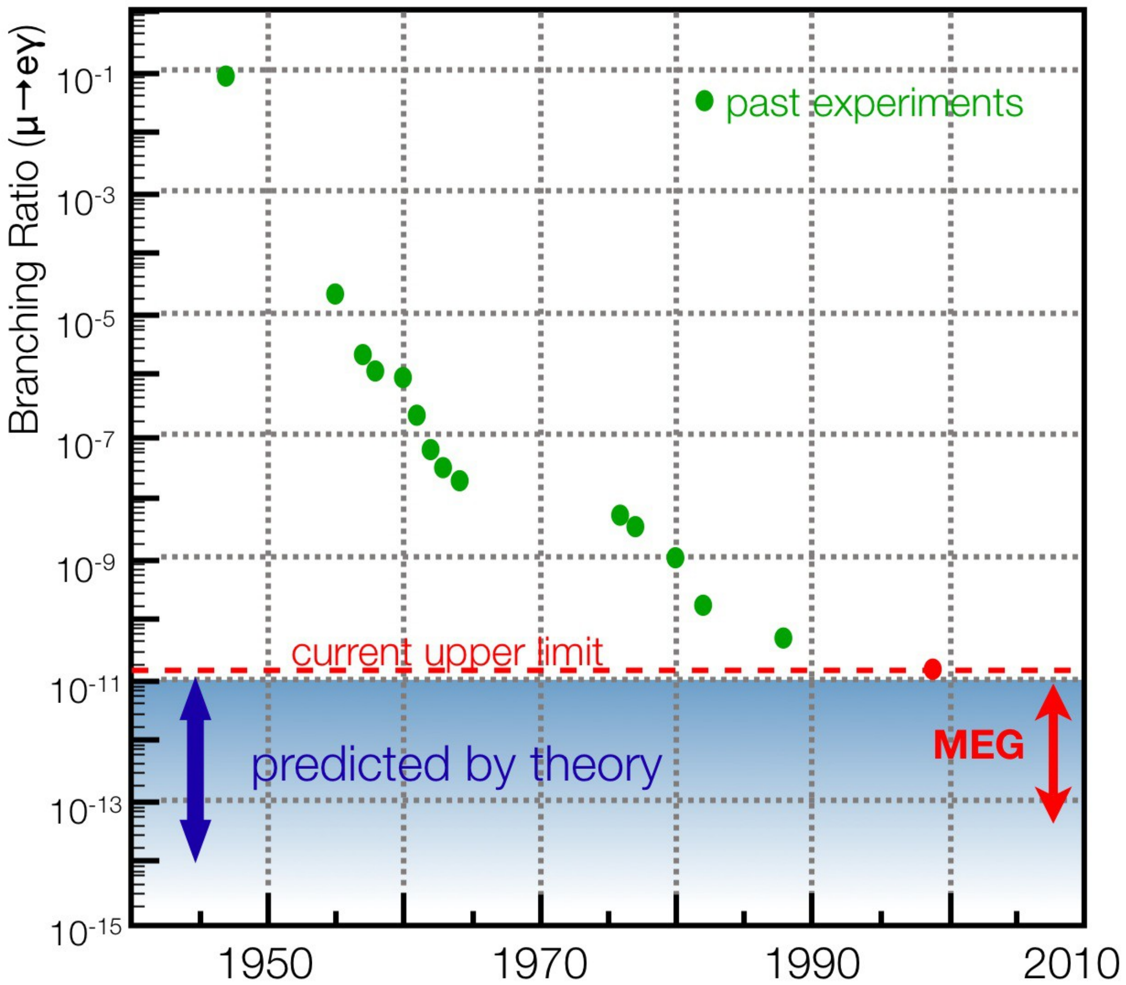
- LFV is forbidden in the Standard Model, and even if the neutrino mass is taken into account, the charged LFV branching ratio(μ->eγ) is almost zero
- Charged lepton flavor violation is a clear evidence of physics beyond the SM
- New physics like SUSY-GUT, SUSY-seesaw predicts measurable LFV just below the current limit





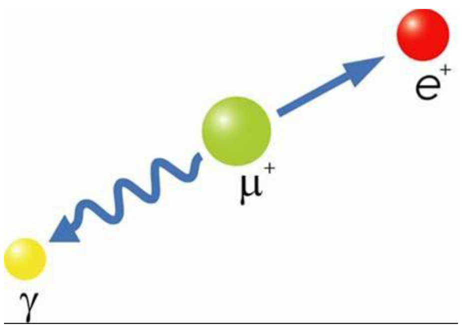
Motivation

- Current experimental bound is set by MEGA
  - $Br(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}$
- MEG goal : $Br(\mu \rightarrow e\gamma) \sim$ a few $\times 10^{-13}$
- Real chance to discover new physics



Signal and Background

- Positive μ decay at rest
- Clear two body kinematics



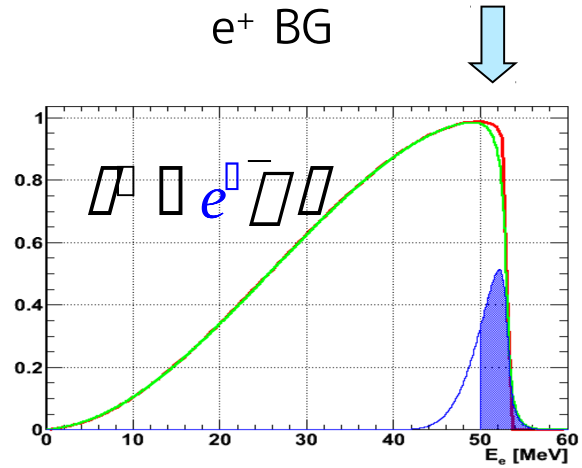
- Back to back ($\theta_{e\gamma}$=180°)
- $E_e \approx E_\gamma$=52.8MeV
- Coincident ($T_{e\gamma}$=0)

Background

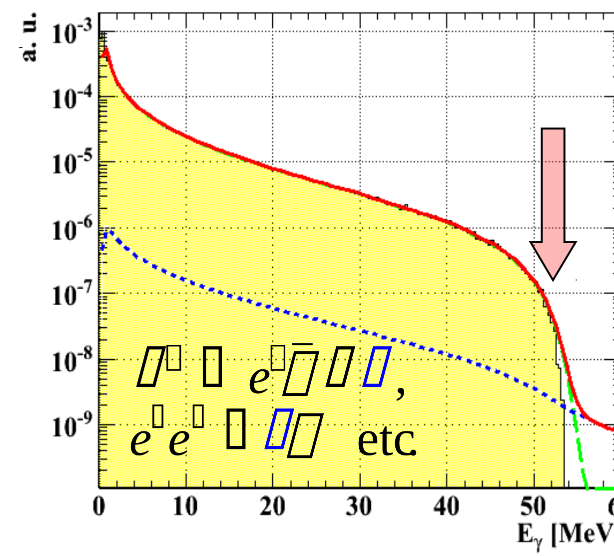
Accidental background is dominant

Michel e^+ + random γ

e⁺ BG



γ BG



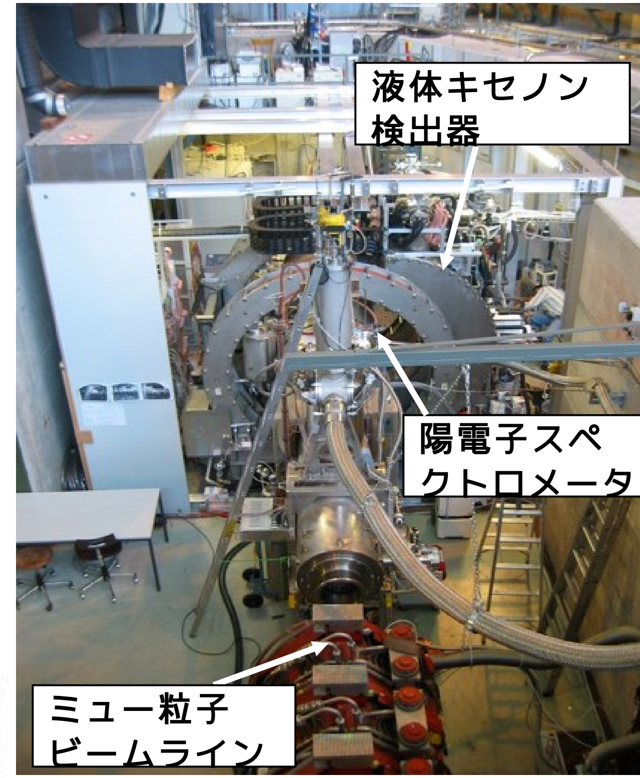
$$B_{acc} \propto \delta E_e \cdot (\delta E_\gamma)^2 \cdot (\delta\vartheta_{e\gamma})^2 \cdot \delta t_{e\gamma}$$

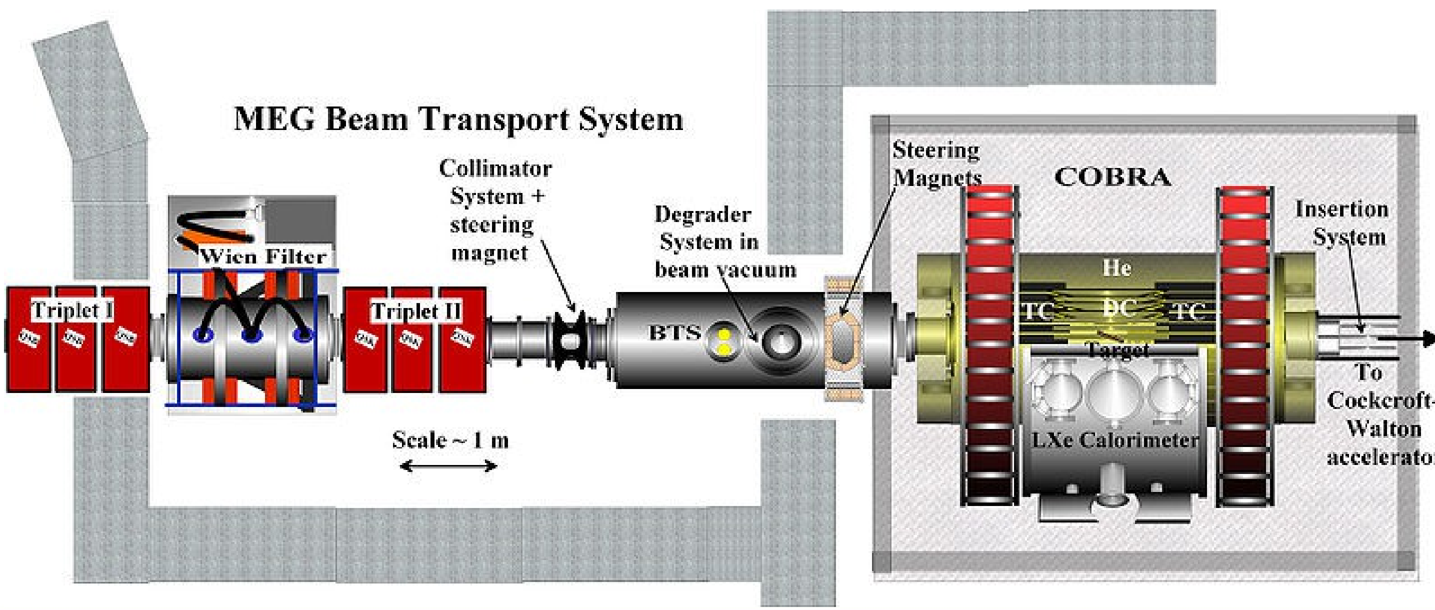
Good detector performance is essential (especially, Eγ)
High rate e^+ measurement with intense μ beam
Pileup rejection is necessary

11aSA-6: MEG 実験 背景ガンマ線の研究 澤田龍

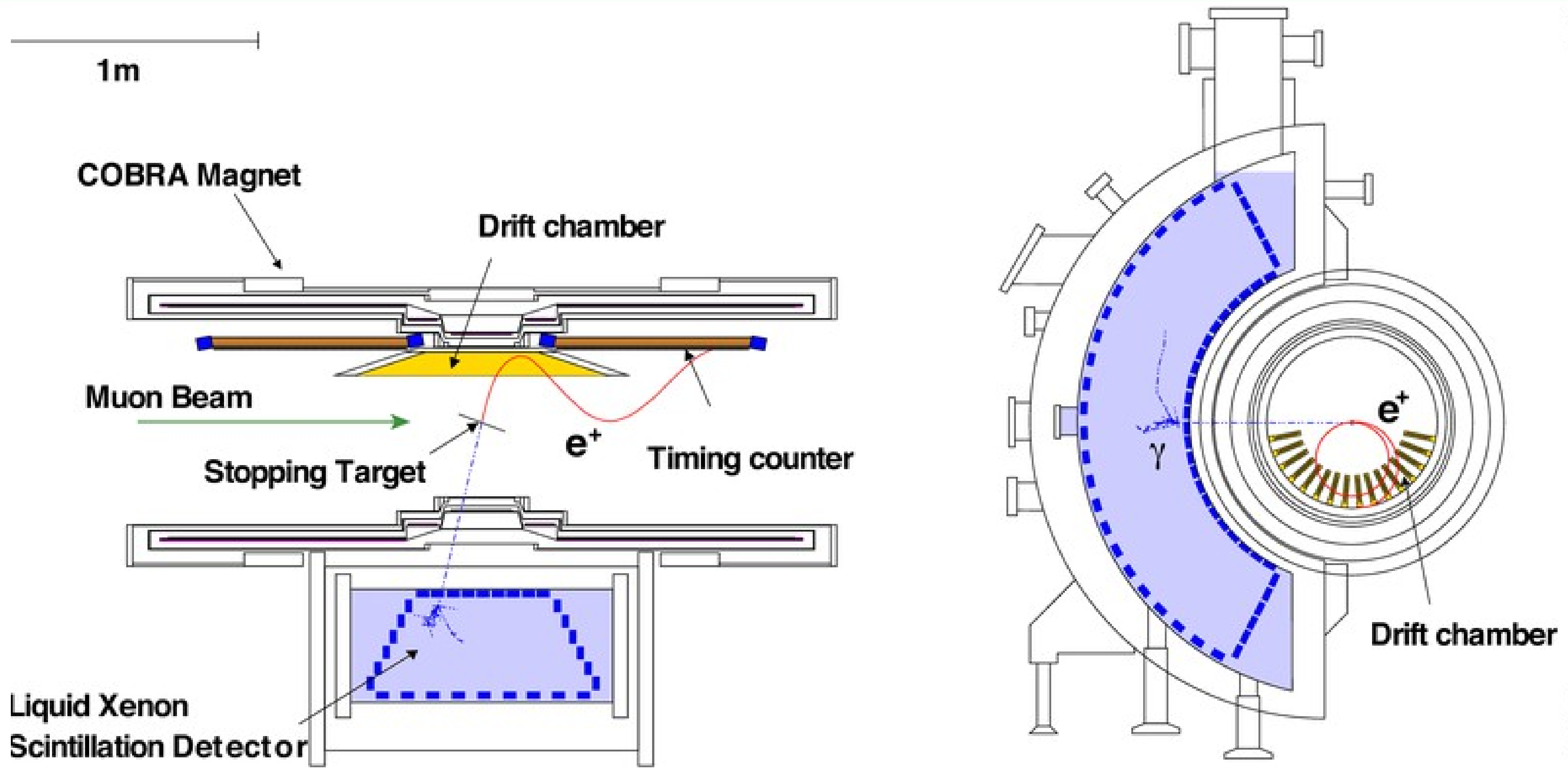
PSI accelerator and MEG beamline

- 1.3MW most intense proton accelerator at PSI in Switzerland
- DC muon beam $3\times10^7\mu/s$ (possible up to $\sim1\times10^8\mu/s$)
  - DC beam is suitable to reduce accidental background





MEG Experiment



- High precision low mass positron spectrometer
  - SC magnet and low mass drift chamber, timing counter
- High performance photon detector
  - 900 liter liquid xenon + 846 PMTs
- Waveforms of all detectors are recorded by waveform digitizer
  - Essential for pileup reduction

MEG history

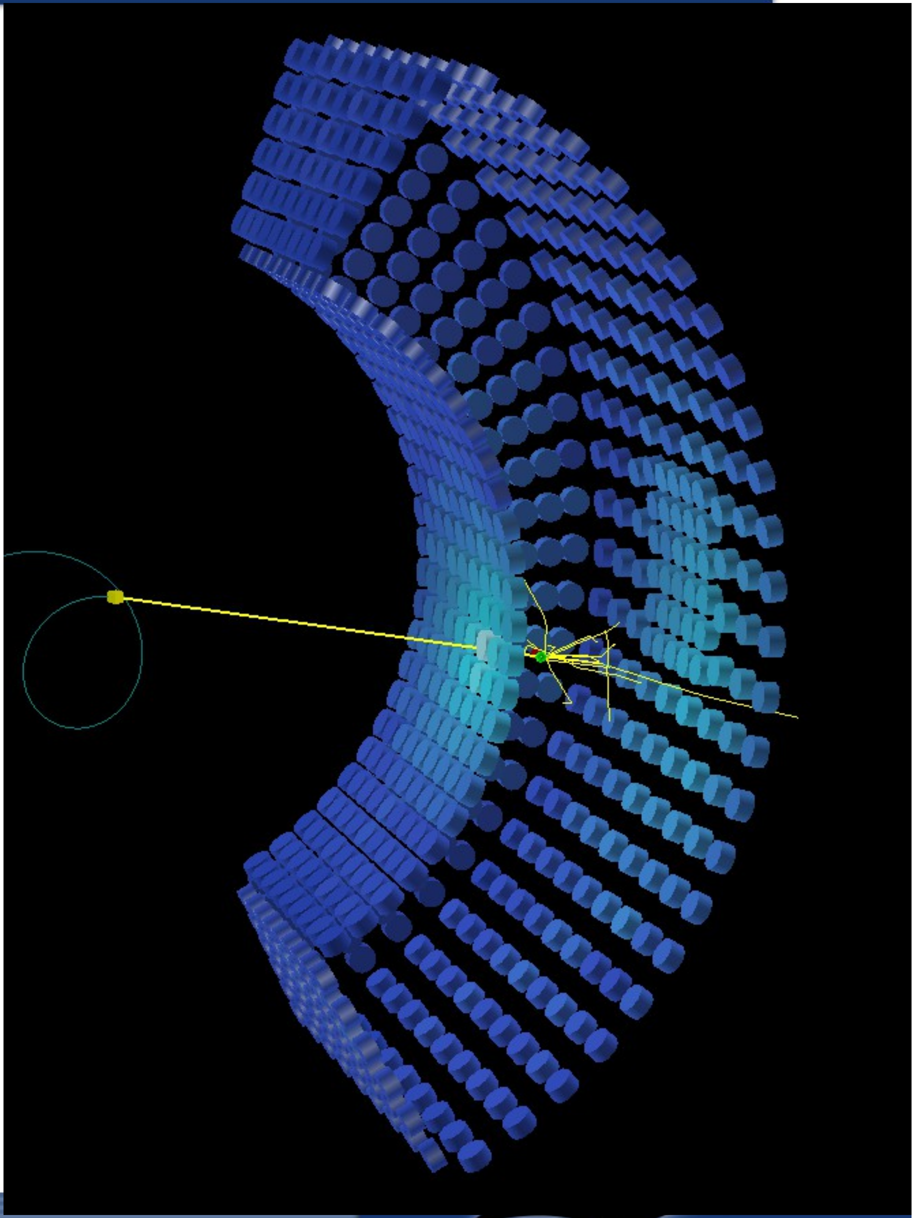
- 1999: Proposal to PSI
- 2007: all detectors ready
- 2008: 78days physics runs
  - Positron detection efficiency(~1/3), sensitivity ~1.3×10^{-11}
  - $Br(\mu^+ \to e^+\gamma) < 2.8 \times 10^{-11}$ (90%C.L.), Nucl.Phys.B834(2010)1-12
- 2009: 43days physics runs
  - Other experiment used our beamline, repair work for positron spectrometer
- 2010: physics run restarted in August
  - 10 days CEX calibration at the end of August, 117days physics run expected

MEG Collaboration
~70 physicists from Japan, Switzerland, Italy, Russia and USA

MEG Detector

Liquid Xenon Detector

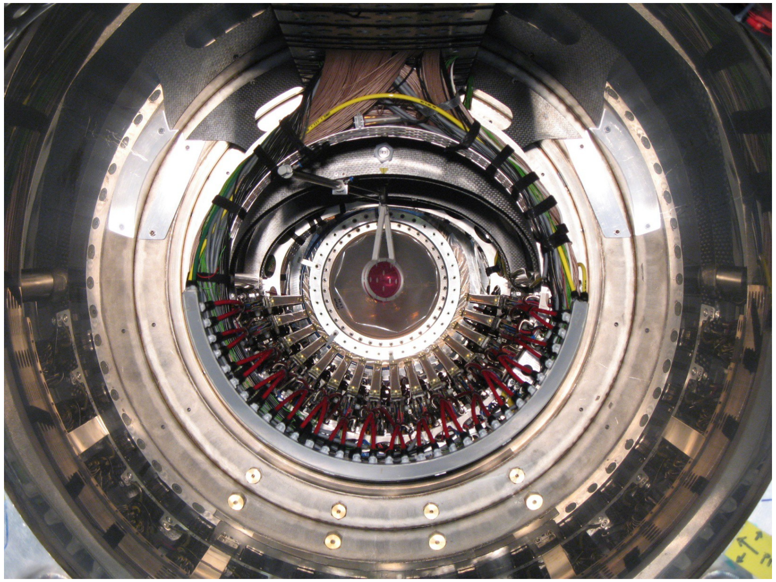
- 900 liter liquid xenon
- 846 2" PMTs (Hamamatsu R9869)
  - immersed in LXe directly
- Good uniformity (homogeneous, liquid)
- High light output (~75% of NaI)
- Short decay time (45ns)
- High density ($3g/cm^3$)
- Short scintillation wavelength ~ 175nm
  - Quartz window for PMT
- Low temperature 165K
  - pulse tube cryocooler developed by KEK
- Purification to remove H_2O, O_2, N_2 etc.



13pSM-3: MEG 実験 液体キセノン検出器の性能：白雪

Positron spectrometer

- SC magnet produces special gradient magnetic field, 1.27(at z=0) ~0.49Tesla
  - To sweep out low momentum e^+
- Timing counter (T_e, σ_{Te}<50ps)
  - Plastic scintillator + fine-mesh PMTs
  - Scintillating fiber + APD

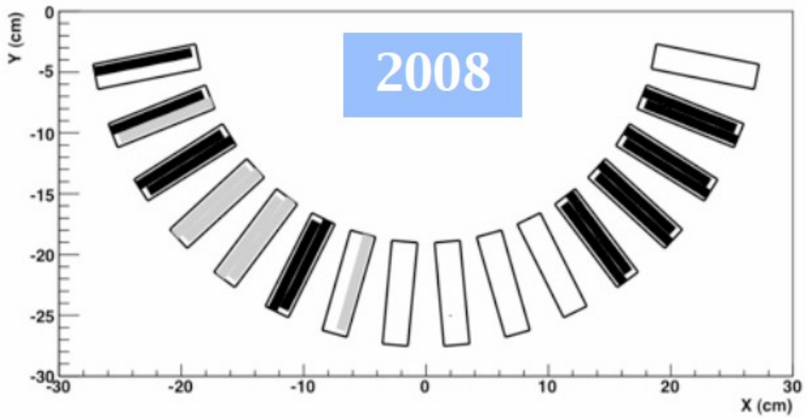


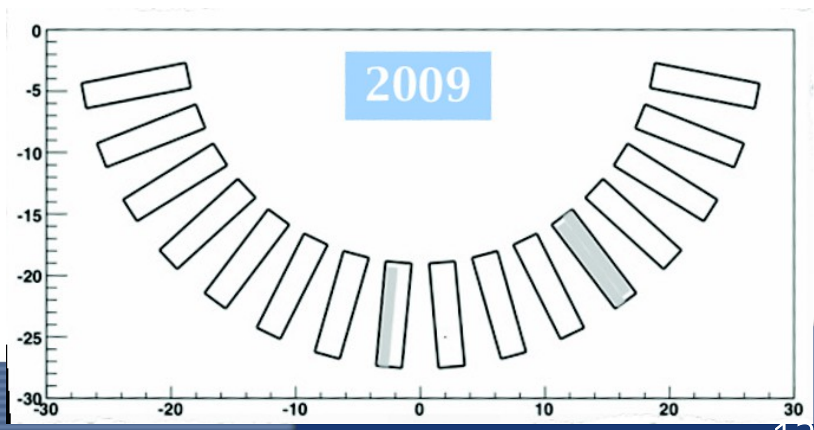
- Drift chamber (E_{e+}, θ_{e+}, ϕ_{e+})
- 16 segmented chambers radially
- Position resolution ~ 200μm(r), 500μm(z)
- Momentum resolution ~ 1%
- Low material budget (low multiple scattering, low γ background)

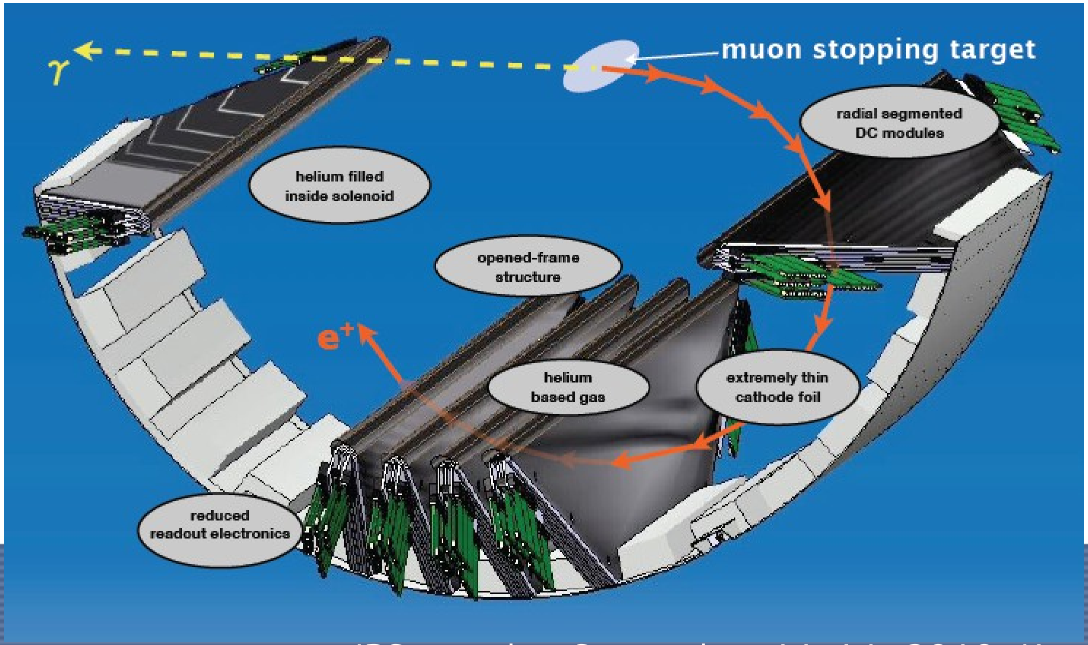
13pSM-1: He/C2H6 を用いたドリフトチェンバーの高頻度照射下でのエイジング 西口創
13pSM-2: MEG 実験 陽電子スペクトロメータの性能評価 藤井祐樹

Drift chamber

- 2008
  - Discharge problem reduced e^+ detection efficiency and resolution for positron measurement
    - ε ~14%(~1/3), σ_E, $\sigma_{\theta\phi}$ were worse
  - The problem was long term exposure to helium, fixed before physics run in 2009
- 2009
  - e^+ detection efficiency(30~40%, including TC matching) and resolutions improved

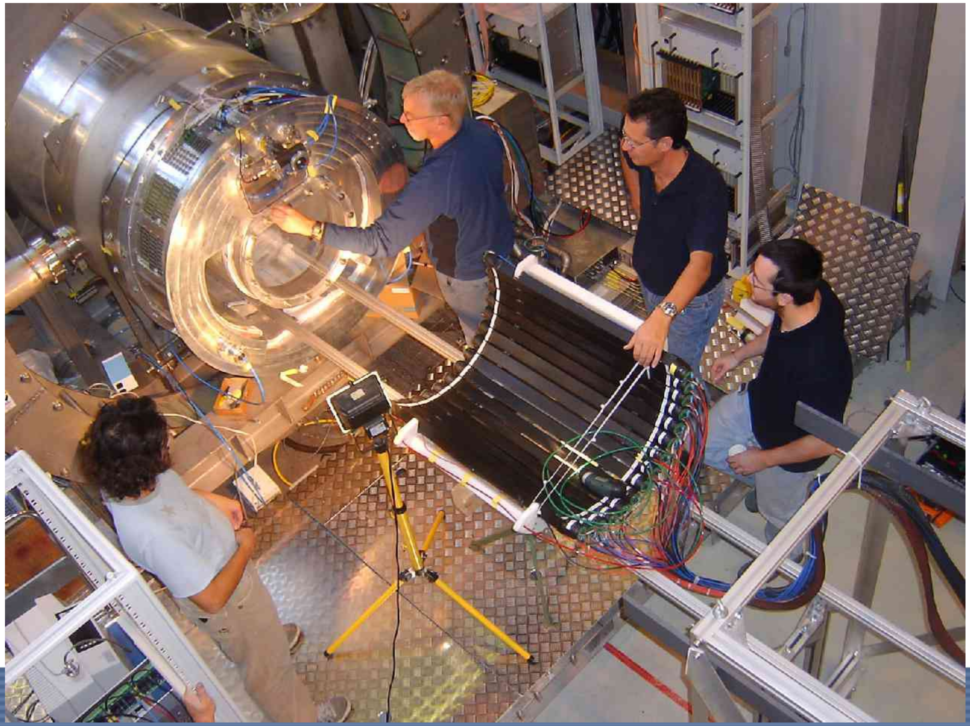


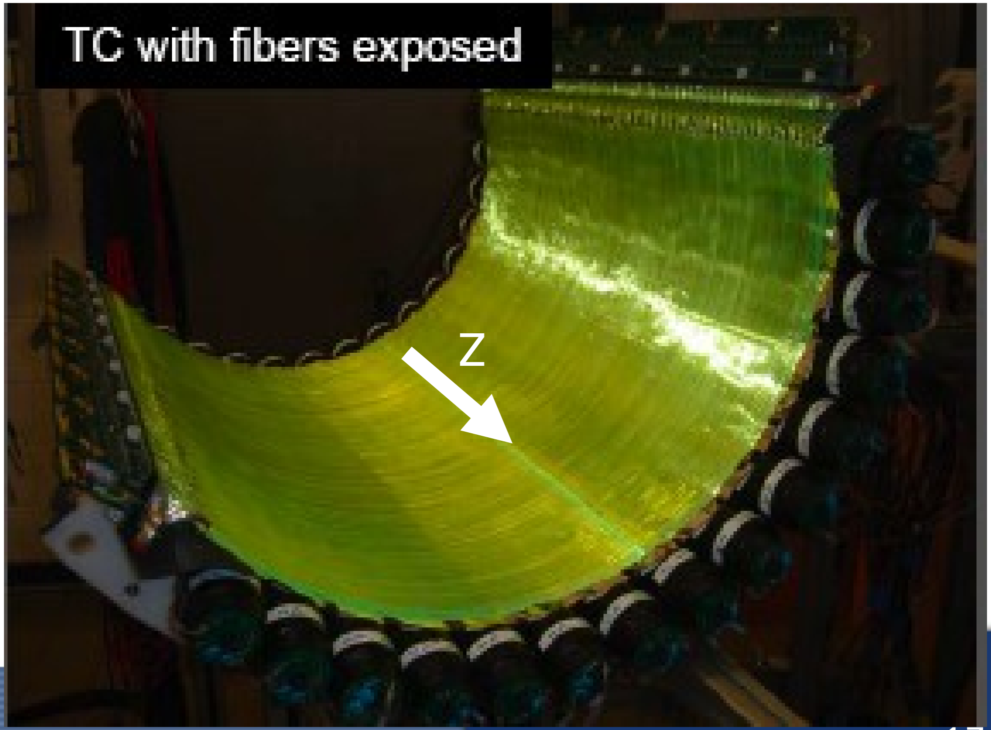




Timing counters

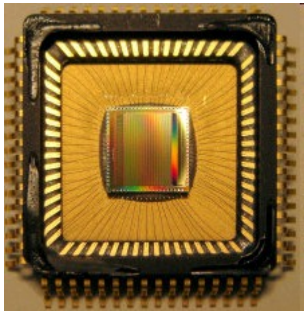
- Two layers of scintillators at each end of spectrometer
  - outer:plastic scintillator + PMT (ϕ, z)
  - Inner: scintillating fiber + APD (z)
- Measure the positron impact position and the precise timing for both trigger and physics analysis

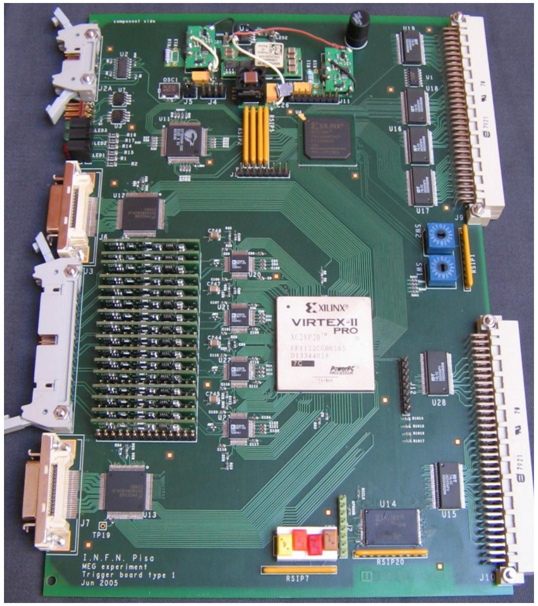




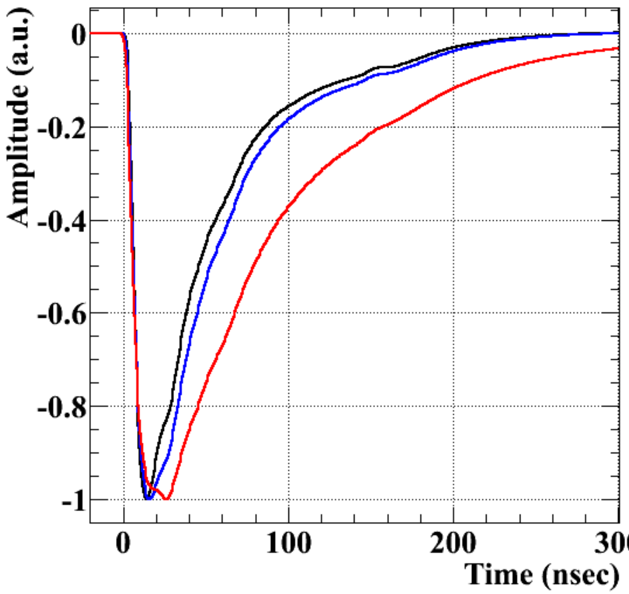
Electronics and trigger

- Waveform digitizer(DRS4)
  - Up to 5GHz sampling speed, 12bits resolution
  - Essential to remove pileup events
  - 1.6GHz sampling for XEC,TC
  - 0.8GHz sampling for DC





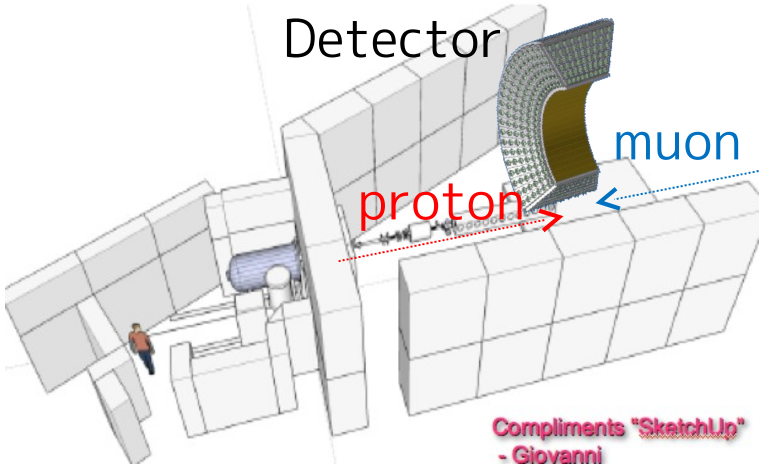
- MEG trigger
  - Built on FADC-FPGA architecture
  - LXe total charge & TC total charge
  - Direction match & timing coincidence
  - 6Hz DAQ rate during MEG run

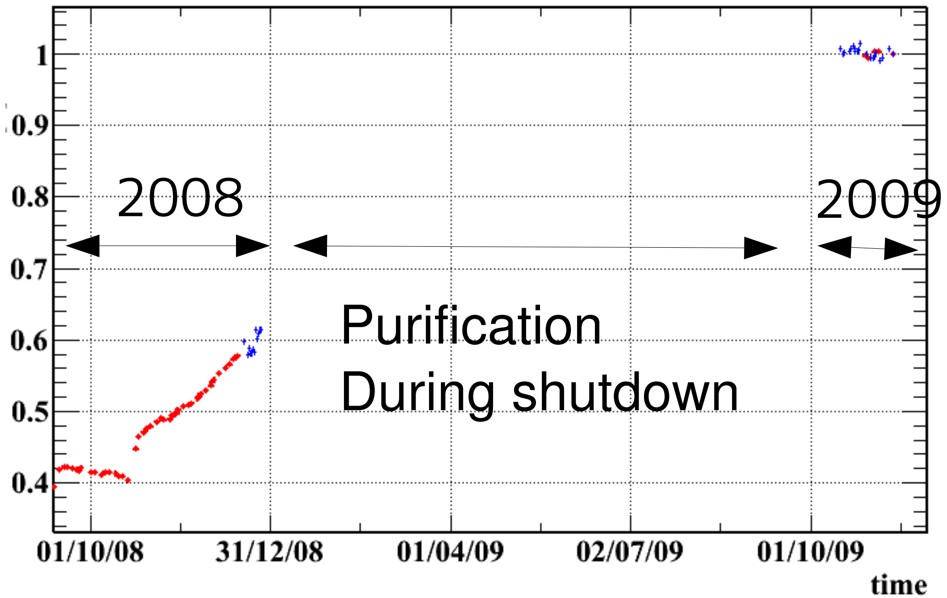


Calibration and Monitoring

XEC detector

- PMT gain monitored by LED, QE by α
- Light yield monitoring (CW, CR, AmBe etc.)
- Cockcroft-Walton proton accelerator
  - 17.6MeV γ by Li(p,γ)Be reaction
  - Light yield monitoring & σ_E at 17.6MeV





2008 physics run and shutdown:
gaseous purification to increase light yield

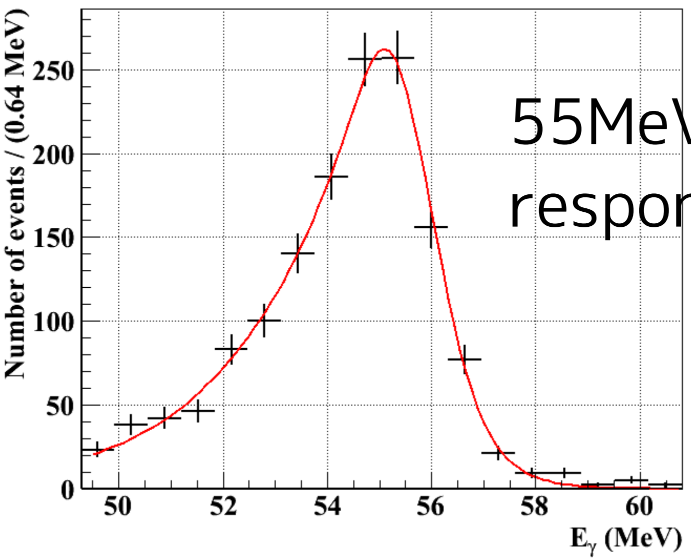
Light yield became as much as expected
And decay time of γ waveform changed

2009 physics run: no purification

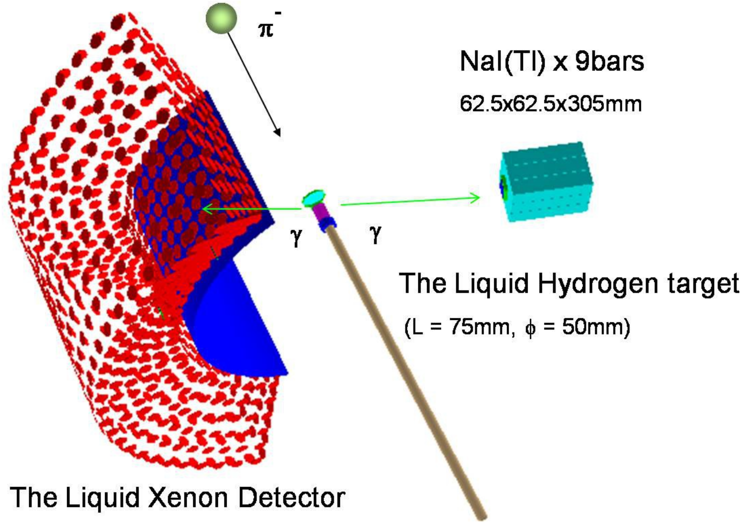
Light yield monitoring: < 1% level

CEX calibration (E_γ, T_γ, XY_γ)

- $\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$ (CEX reaction)
  - 55, 83MeV γs are available once back-to-back photons are selected
  - Energy close to our signal (52.8MeV)
- Tagging detector - NaI + APD array
- LH_2 target
- $\pi^0 \rightarrow e^+e^-\gamma$(Dalitz decay) for absolute time offset measurement



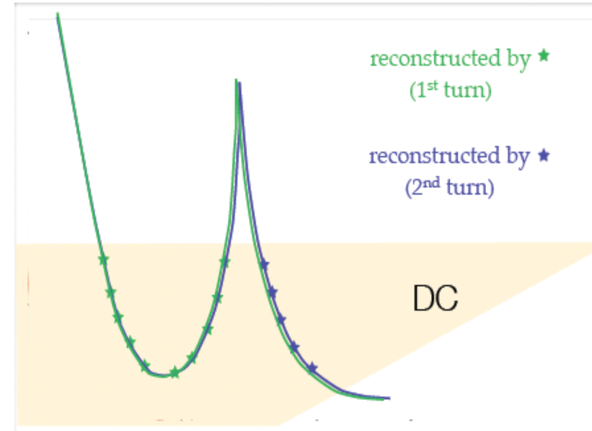
55MeV γ response

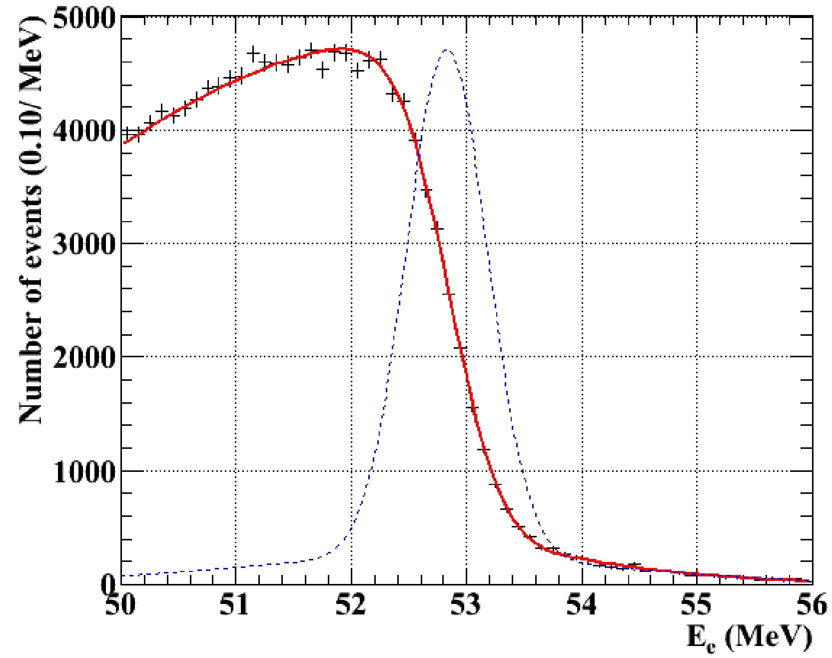


- Energy, timing, and position resolution
  - 2.1%(depth>2cm), >68ps, 5mm(XY), 6mm(depth)
- Position dependence by moving NaI
- Signal response function
- γ efficiency: 58%

Positron resolution

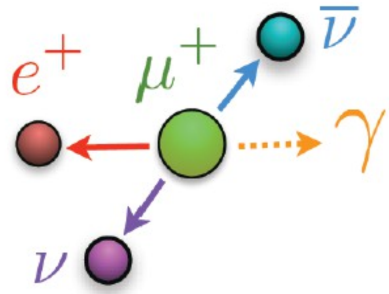
- Resolution and signal response can be extracted from residuals of two turn tracks
  - Momentum resolution
    - σ_E ~ 0.74% core
  - Angle resolution
    - σ_ϕ ~ 7.1mrad (core)
    - σ_θ ~ 11.2mrad
- Background spectrum
  - Michel spectrum fit smeared by detector resolution
  - Double Gaussian plus acceptance

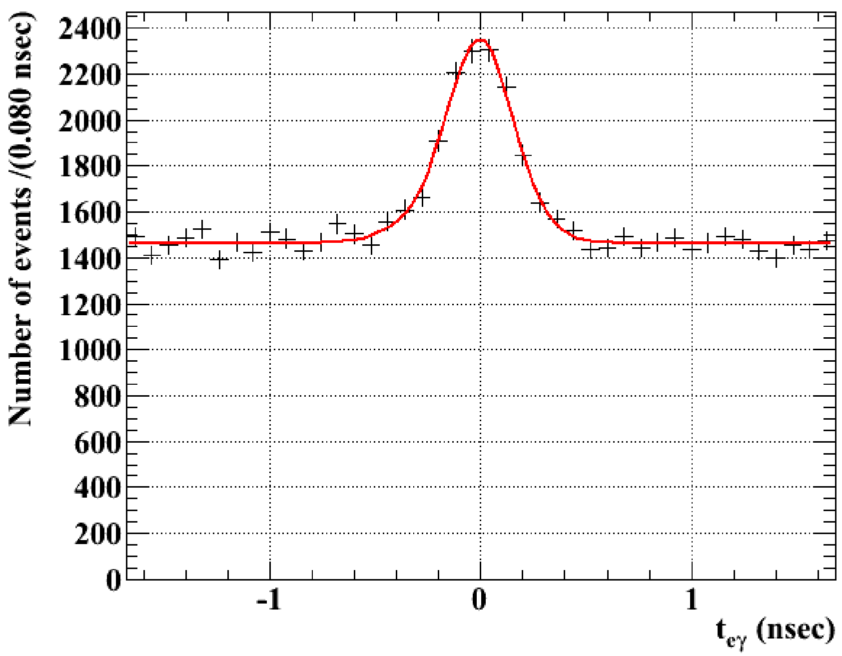




Radiative muon decay ($T_{e\gamma}$)

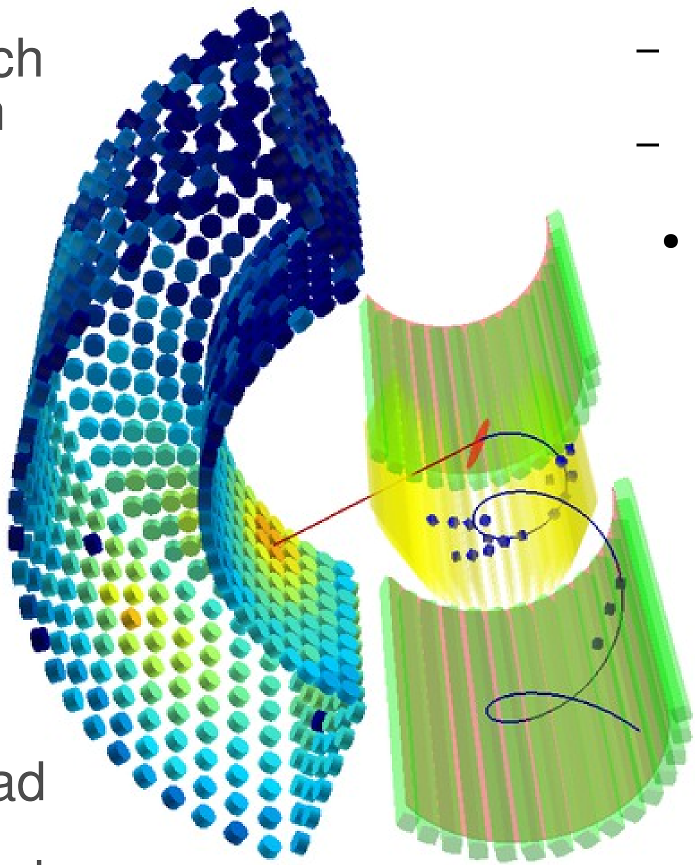
- Relative timing resolution can be estimated directly by physics data (RMD)
  - Coincident, not back-to-back, γ low energy
  - $\sigma_{Te\gamma}$ consists of each detector resolution, tracking ambiguity etc.
  - Good test to detect $\mu \rightarrow e\gamma$ events, and possible to measure $\sigma_{Te\gamma}$ directly
  - Can be also used to check overall detection efficiency
  - $\sigma_{Te\gamma}$ ~ 142ps (core)



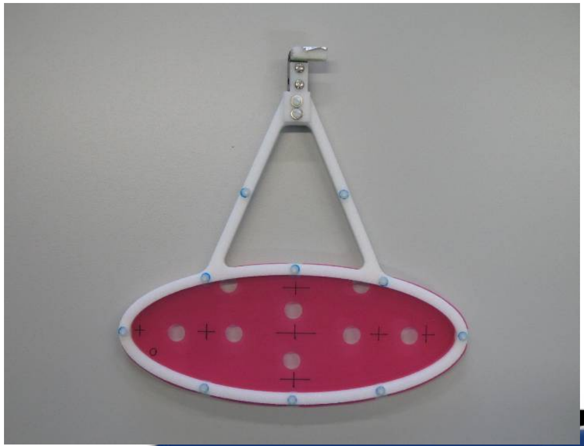


Relative angle ($\theta_{e\gamma}$, $\phi_{e\gamma}$)

- Relative angle resolution is combination of each detector resolution
- Xenon detector position resolution
  - x,y : 5mm
  - Depth: 6mm
- In total,
  - $\theta_{e\gamma}$ ~ 14.6mrad
  - $\Phi_{e\gamma}$ ~ 12.5mrad



- Positron angle resolution
  - θ: 11.2mrad
  - ϕ: 7.1mrad (core)
- Vertex resolution on the target
  - Extrapolation from the track
  - Resolution by two turn tracks
  - R: 2.3mm
  - Z: 2.8mm



Performance

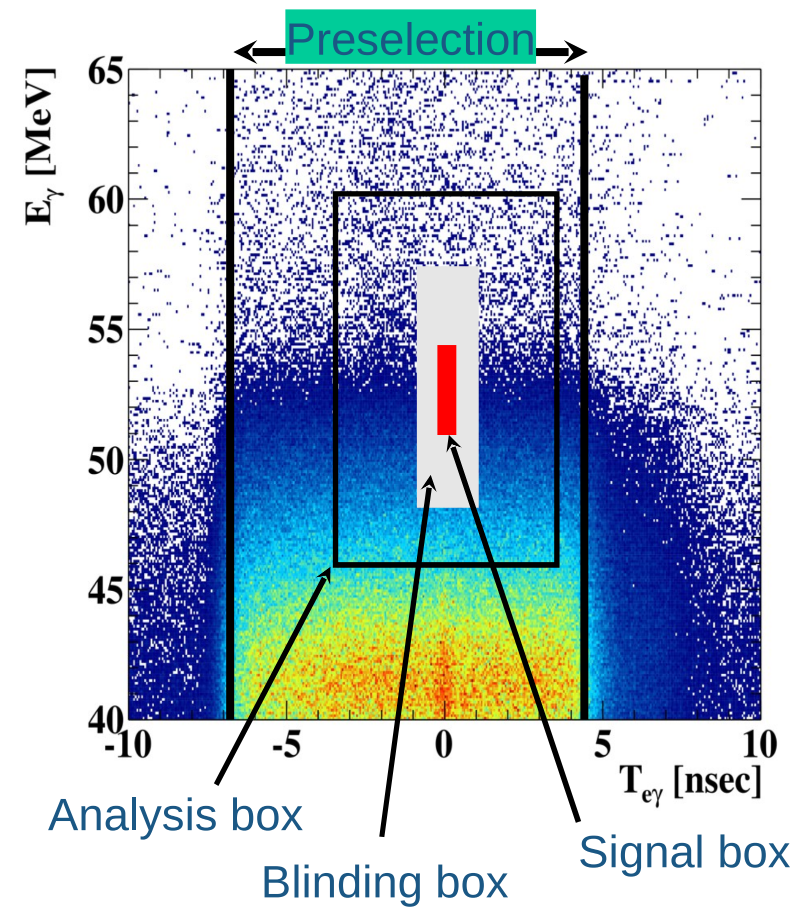
	2008	2009 (preliminary)
Gamma Energy (%)	**2.0 (w>2cm)**	**2.1 (w>2cm)**
Gamma Timing (psec)	**80**	**>67**
Gamma Position (mm)	**5(u,v)/6(w)**	▯
Gamma Efficiency (%)	**63**	**58**
e^+ Timing (psec)	**<125**	▯
e^+ Momentum (%)	**1.6**	**0.74(core)**
e^+ efficiency (%)	**14**	**30~40%**
e^+ angle (mrad)	**10(ϕ)/18(θ)**	**7.4(ϕ core)/11.2(θ)**
e^+ - gamma 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^{-1})	**$3x10^7$**	**$2.8x10^7$(300μm)**
DAQ time / Real time (days)	**48/78**	**35/43**
Sensitivity	**$1.3x10^{-11}$**	
BR upper limit (obtained)	**$2.8x10^{-11}$**	

- In 2008, sensitivity was $1.3x10^{-11}$, and our result was the BR UL $2.8x10^{-11}$ (90%C.L.)
- 2009 DAQ time is shorter than 2008
- e^+ efficiency, resolutions improved
- Trigger efficiency improved
- Statistics in 2009 : ~x2

MEG 2009 Results

Analysis procedure

- **Blind analysis to avoid human bias**
  - $T_{e\gamma}$(-1ns<$T_{e\gamma}$<1ns), E_γ(48<E_γ<57.6MeV)
- **Optimization of analysis algorithms and background study using sideband data**
- **Open the box**
- **Likelihood fit for data, and calculate confidence intervals with toy MC simulation**
- **N_{sig} normalized to the number of observed Michel decays**
- **BR($\mu^+ \rightarrow e^+\gamma$) = N_{sig} / (Normalized factor)**

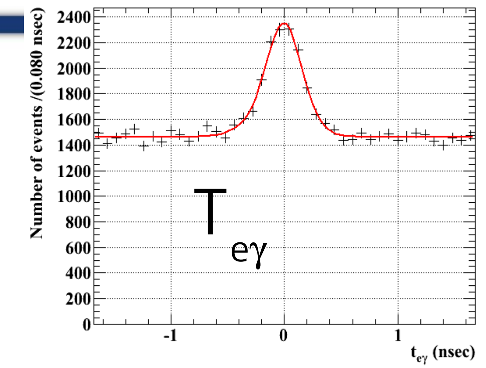


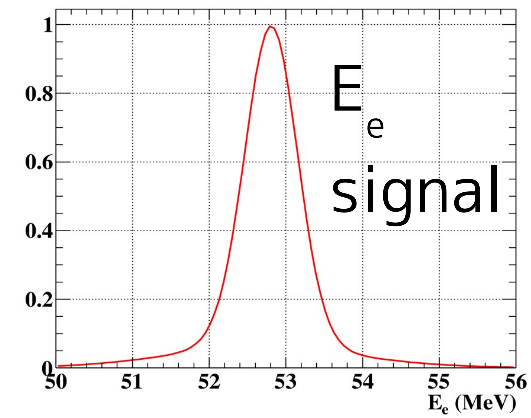
E_γ vs T distribution without any selection.

13aSK-1: MEG 実験 μ+→e+γ 探索の最新結果 西村康宏

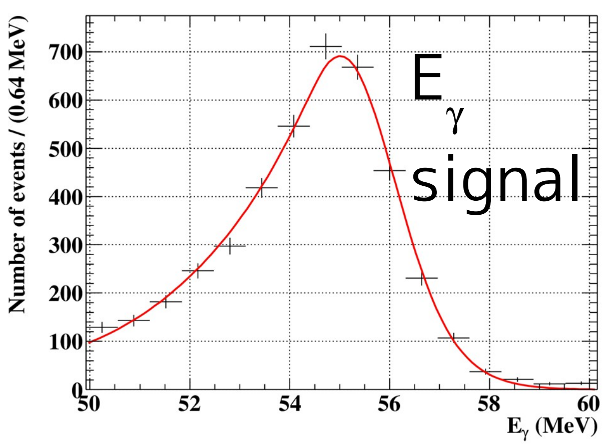
Analysis Method

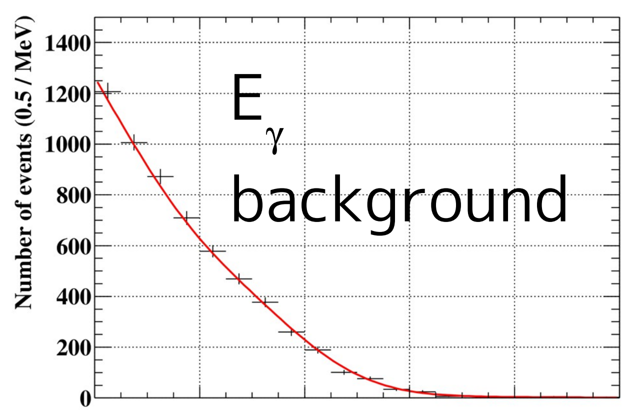
$$\mathcal{L}(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{BG}}) = \frac{N^{N_{\mathrm{obs}}} \exp^{-N}}{N_{\mathrm{obs}}!} \prod_{i=1}^{N_{\mathrm{obs}}} \left[\frac{N_{\mathrm{sig}}}{N} S + \frac{N_{\mathrm{RMD}}}{N} R + \frac{N_{\mathrm{BG}}}{N} B \right]$$

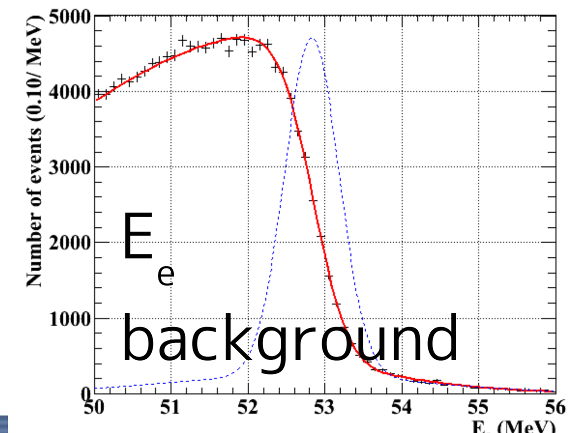




- **Extended unbinned maximum likelihood analysis**
- **Fitting parameters (N_{BG}, N_{RMD}, N_{signal})**
-
- **PDF preparation**
  - **(S, R, B) : PDF for ($\mu \rightarrow e\gamma$, RMD, Background)**
    - **Product of PDFs for the five observables (E_γ, E_e, $t_{e\gamma}$, $\theta_{e\gamma}$ and $\phi_{e\gamma}$)**
- **Most PDFs can be obtained by data**
- **Position, time, and positron tracking quality dependence etc. included**



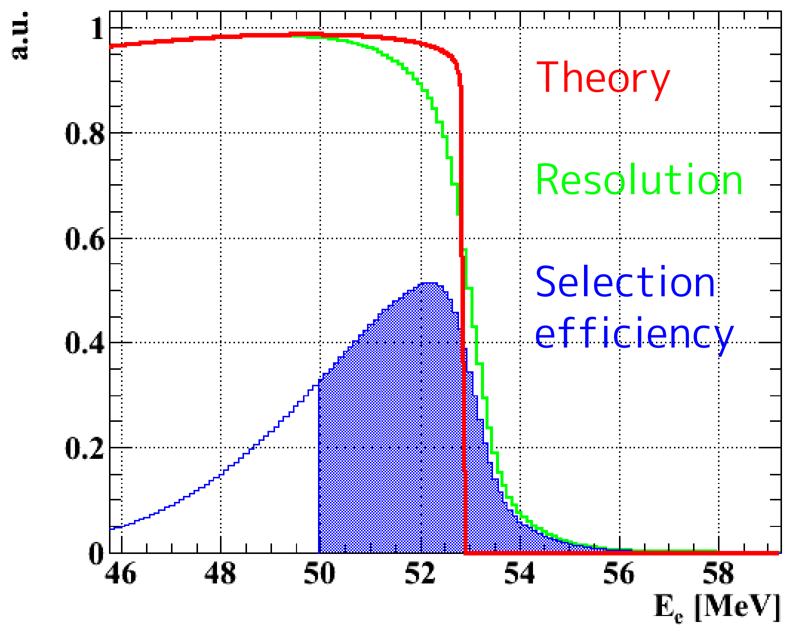




Number of Michel decay

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

- **Count the number of detected Michel positrons**
  - **$N_{e\nu\nu}$ obtained simultaneously with the signal**
- **The upper limit on BR($\mu^+ \to e^+\gamma$) is calculated by normalizing N_{sig} to the N_{enn}**
- **Independent of instantaneous beam rate and insensitive to positron acceptance and efficiency**



B.R. = Nsig / 1.0 ± 0.1 × 10^{12} (Preliminary)

Sensitivity

Preliminary

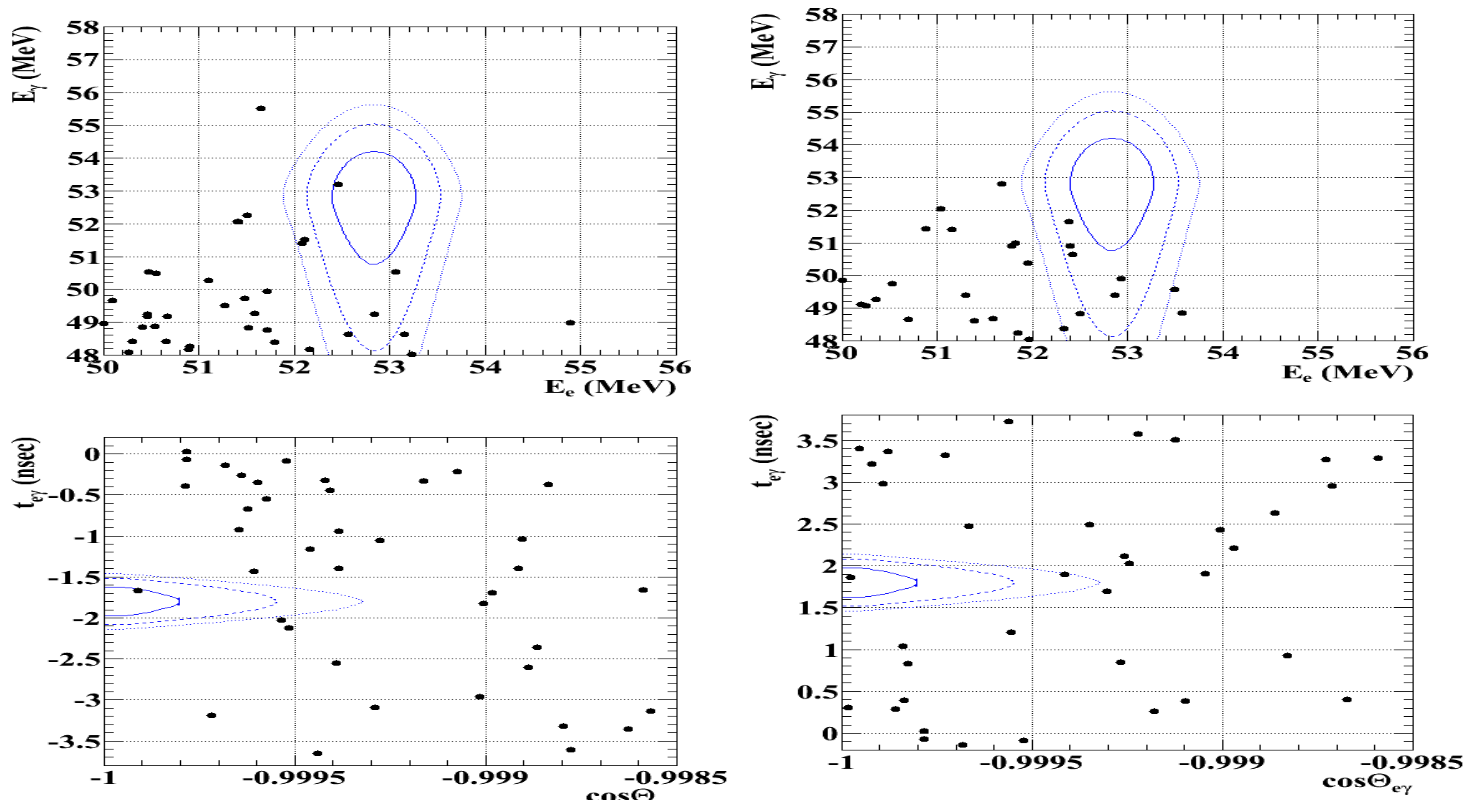
Average 90% C.L. upper limit of toy MC with null signal.

Sensitivity : 6.1×10^{-12}

Sideband fit result is consistent. Br < $4 \sim 6\times10^{-12}$

Negative $T_{e\gamma}$ sideband

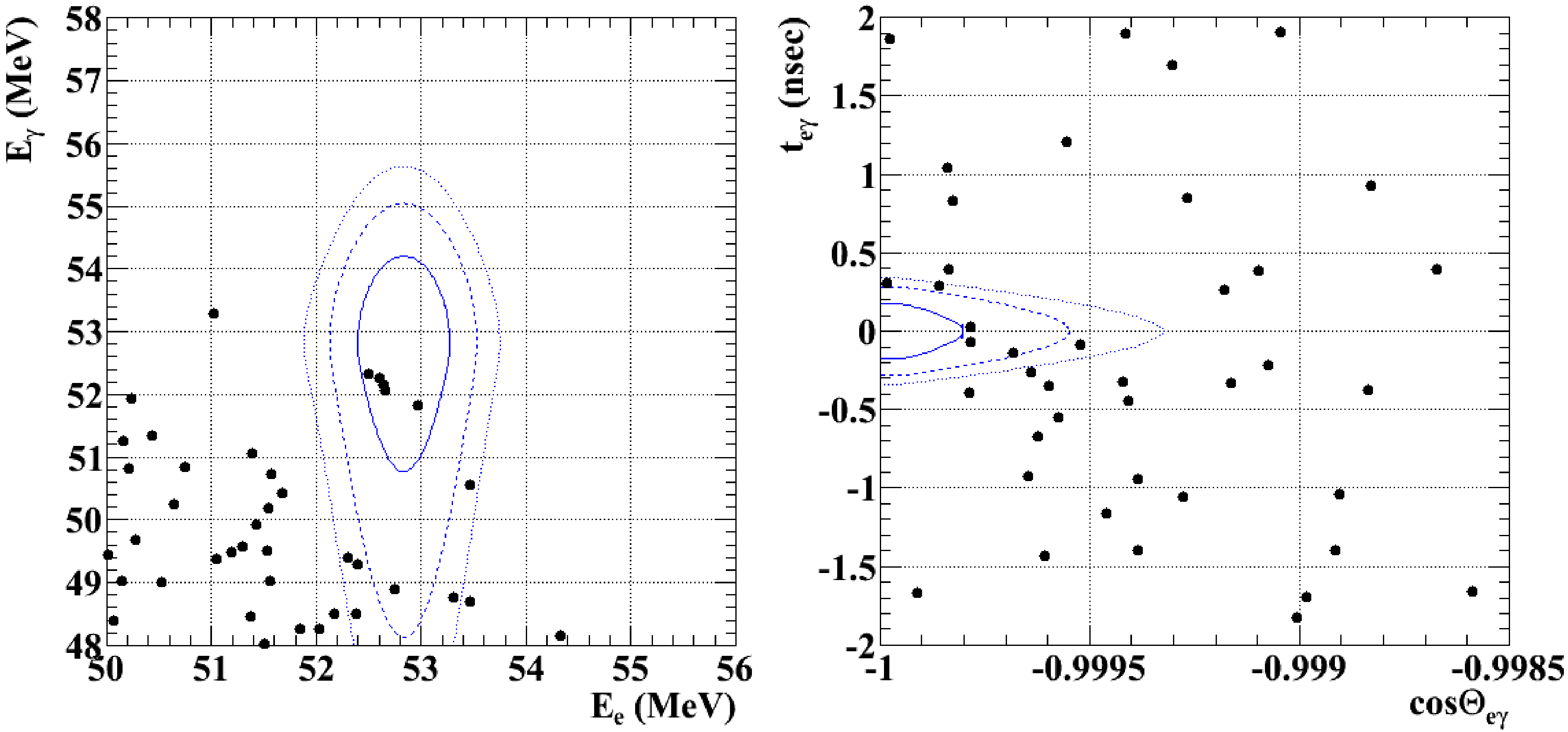
Positive $T_{e\gamma}$ sideband



(Current B.R. upper limit is 1.2×10^{-11} by MEGA)

Event distribution after unblinding

6/July the blind box was opened

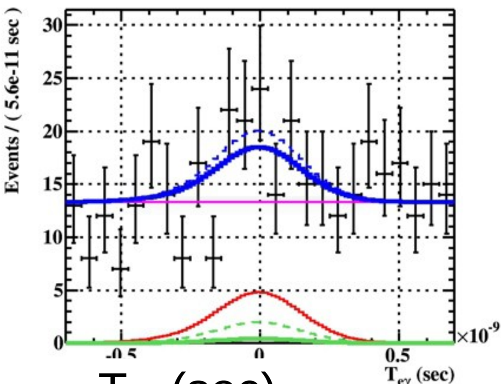


Blue lines are 1(39.3 % included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions.

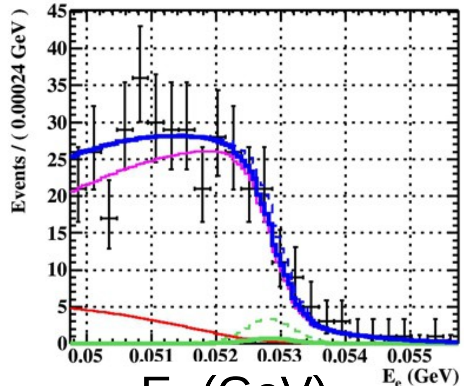
For each plot, cut on other variables for roughly 90% window is applied.

Fit result

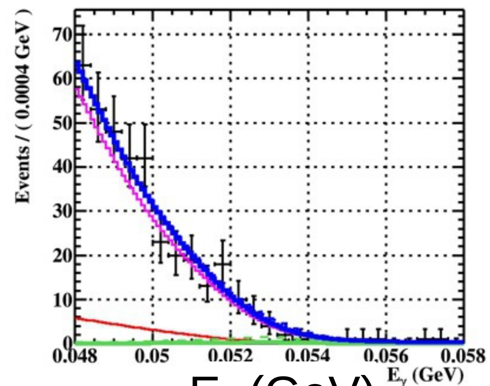
Preliminary



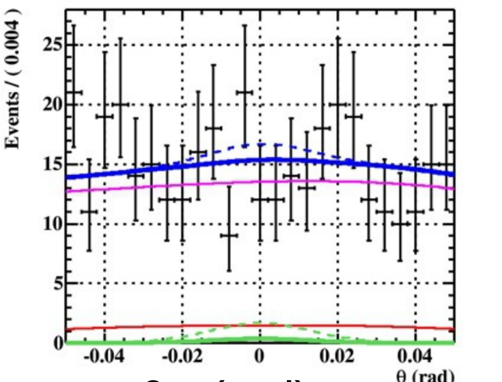
$T_{e\gamma}$ (sec)



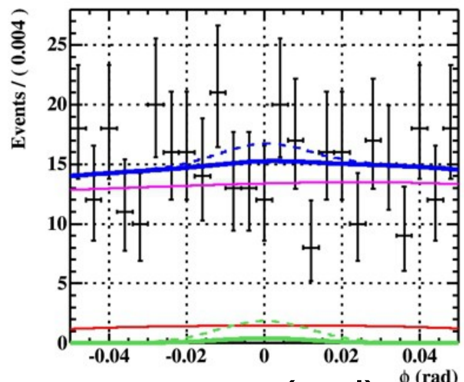
E_e (GeV)



E_γ (GeV)



$\theta_{e\gamma}$ (rad)



$\varphi_{e\gamma}$ (rad)

Accidental BG
RMD
Signal
Total

$N_{RMD}=35^{+24}_{-22}$
(Expectation from sideband = 32±2)

Dashed lines : 90% C.L. UL of Nsig

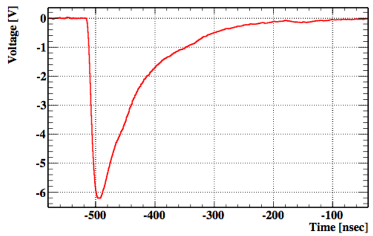
Nsig best fit = 3.0

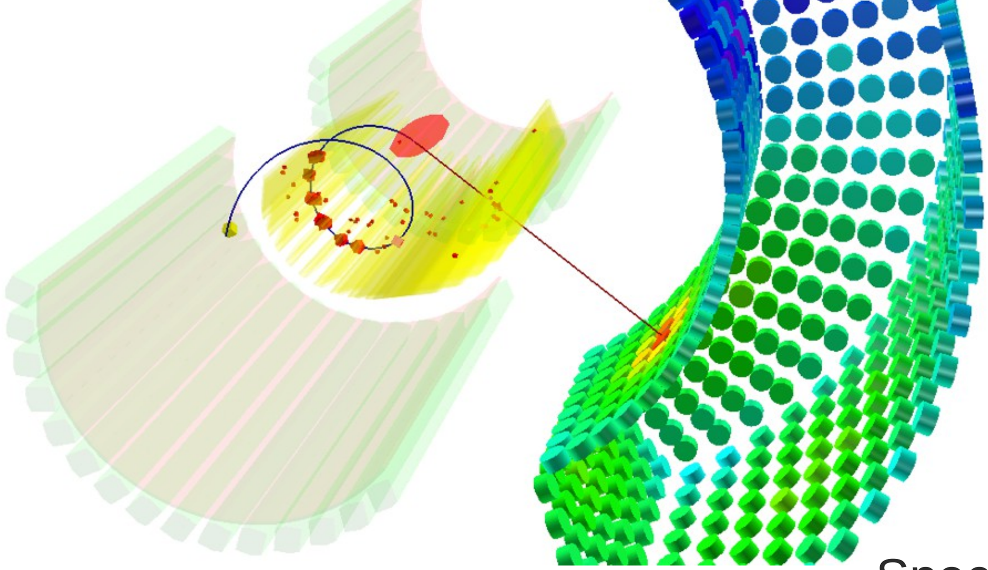
Nsig < 14.5 @ 90% C.L → Br($\mu^+ \rightarrow e^+\gamma$) <1.5x10^{-11} @ 90% C.L.
Nsig=0 is in 90% confidence region

Fitting was done by three groups with different parametrization, analysis window and statistical approaches, and confirmed to be consistent (Nsig best fit = 3.0-4.5, UL = 1.2-1.5×10^{-11})

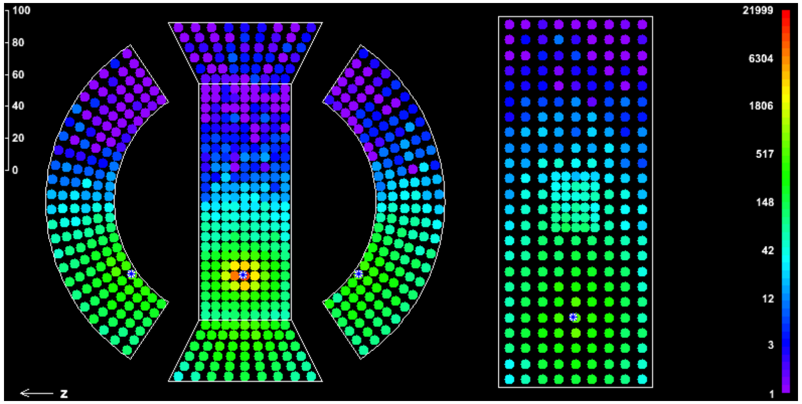
Event display

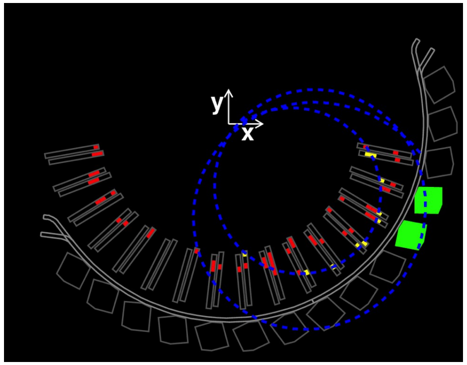
Calorimeter sum WF





Calorimeter PMT hit map





Spectrometer hits and a track

Each highly ranked event is checked carefully.

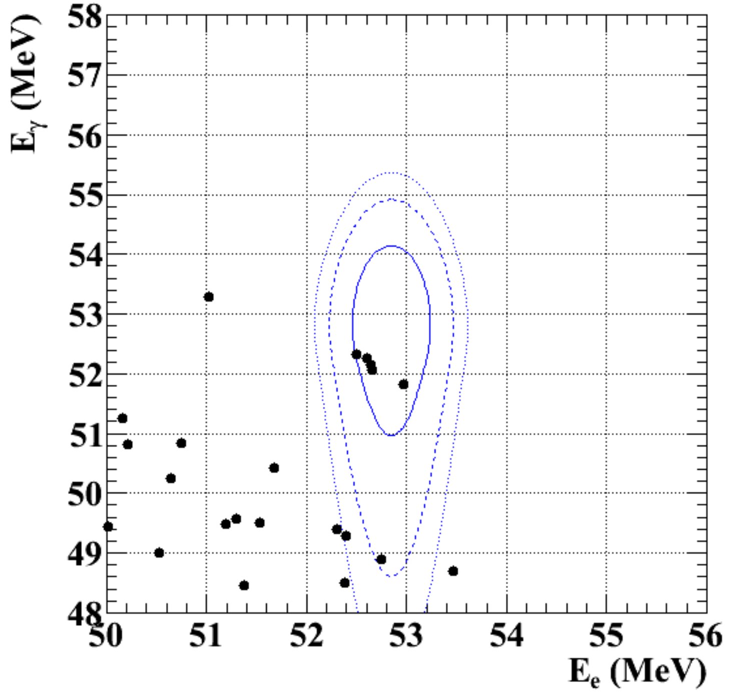
Event quality check

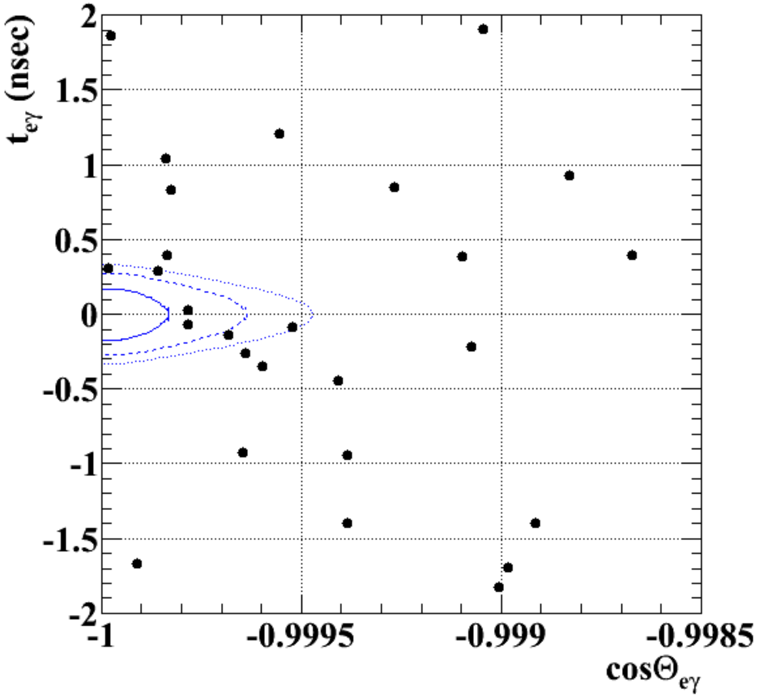
High quality e^+ track category events

Selected by number of drift chamber(DC) hits, E_e, θ_e, φ_e fitting uncertainties, track fitting χ^2, r and z difference between timing counter hit and extrapolation of a track.

High quality fraction = 59%

Events around signal region do not disappear by selecting high quality track events.





Prospects

- Possible improvements
  - Improvement of synchronization of waveform digitizer (DRS4) improves σ_T
  - Possible better calibration with monochromatic positron beam and improve positron tracking
  - Noise reduction and electronics modification for DC
  - Refinement in calorimeter analysis
- 3 years physics data (2010-2012)
  - Sensitivity will reach our goal, a few x 10^{-13}
  - Each detector performance could be improved further!

	2010 (preliminary)
Gamma Energy (%)	1.5 (w>2cm)
Gamma Timing (psec)	68
Gamma Position (mm)	5(u,v)/6(w)
e^+ Timing (psec)	<95
e^+ Momentum (%)	0.7
e^+ angle (mrad)	8(ϕ)/8(θ)
e^+ - gamma timing (psec)	120
Muon Decay Point (mm)	1.4(R)/2.5(Z)
Stopping Muon Rate (sec^{-1})	$2.9x10^7$
DAQ time / Real time (days)	95/117
Sensitivity	$(2.0\text{-}2.2)x10^{-12}$
BR upper limit	-

13aSK-2: MEG 実験 2010 現状と展望 内山雄祐

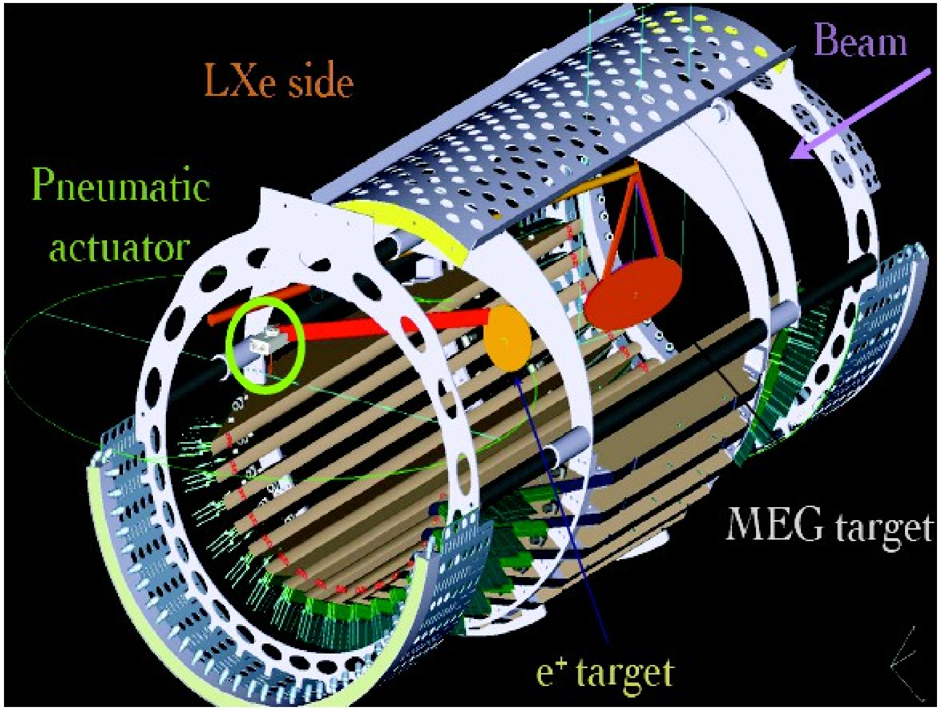
Summary

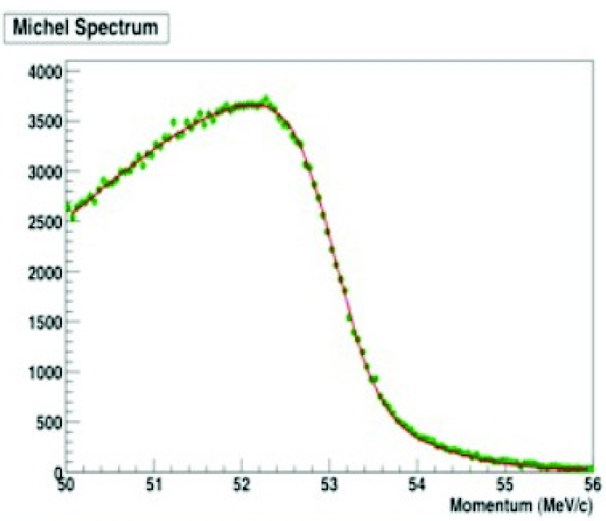
- MEG detector has started operation since 2007, and physics data have been taken in 2008 and 2009.
- Many calibration & monitoring methods have been established to check our detector performance.
- Our result to search for lepton flavor violating $\mu \to e\gamma$ decay is the branching ratio upper limit 1.5×10^{-11}(90%C.L., preliminary) based on 2009 data with the sensitivity 6.1×10^{-12}(90%C.L., preliminary).
- We will have three years data taking(2010-2012) to reach our sensitivity, a few x 10^{-13}. Improvement of our detector performance is the most important for us.

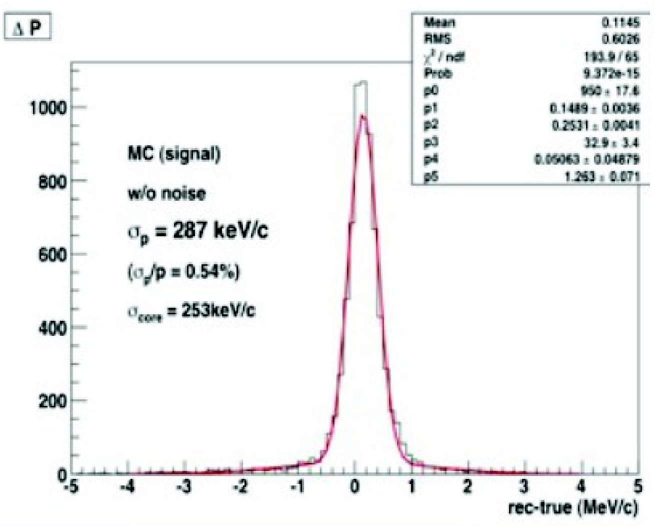
13aSK-3: MEG 実験 $\mu^+ \to e^+\gamma\gamma$ 探索 名取寛顕

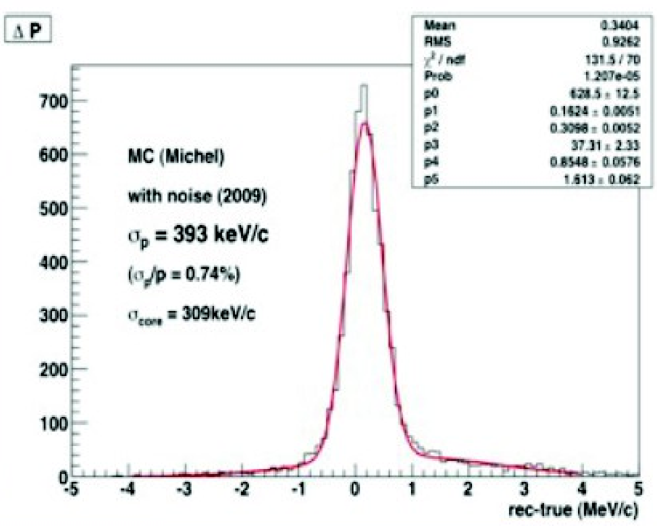
Improve Resolutions, contd.

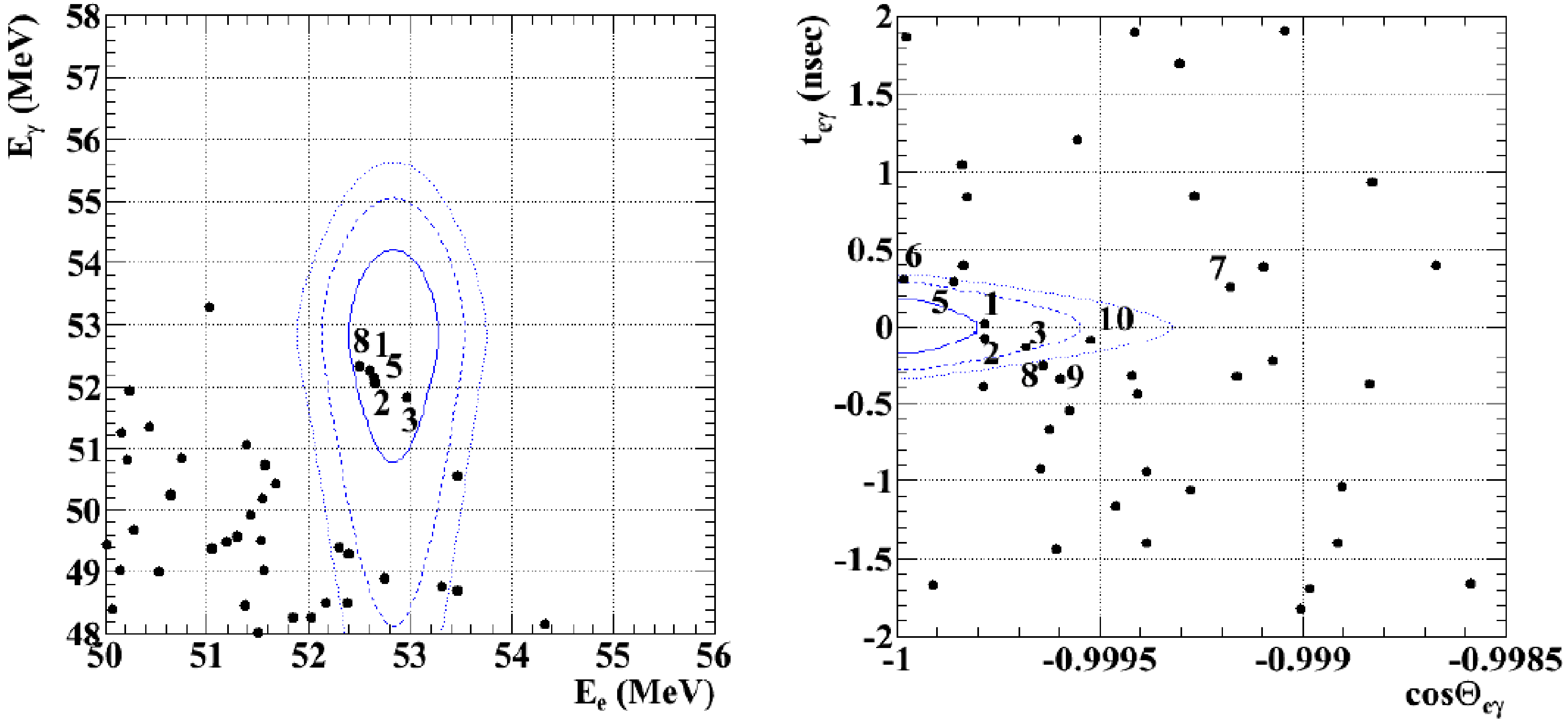
- New Calibration Source will be implemented.
- Using Mott-Scatt. (coherent elastic) on light nuclei.
- " **Variable / Monochromatic** " e^+ is available.
- Momentum Calibration and Resolution Understanding will be improved.











58
57
56
55
54
53
52
51
50
49
48
E_γ (MeV)
50
51
52
53
54
55
56
E_e (MeV)
8
1
5
2
3
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
$t_{e\gamma}$ (nsec)
-1
-0.9995
-0.999
-0.9985
$\cos\Theta_{e\gamma}$
6
5
1
10
3
2
8
9
7