Analysis of the First MEG Physics Data to Search for the Decay $\mu^+ \to e^+\gamma$

(MEG最初のデータによる$\mu^+ \to e^+\gamma$崩壊の解析)

16/September/2011

日本物理学会2011年秋季大会

ICEPP, the University of Tokyo

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$\mu^+ \to e^+\gamma$ search experiment, MEG started physics data taking in 2008.

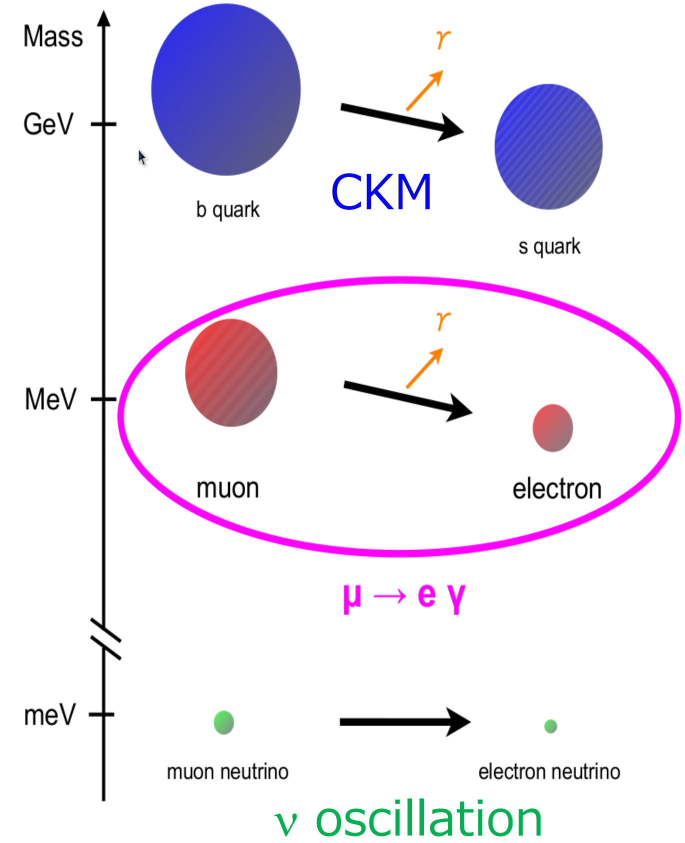
We analyzed the first 3 months data.

The analysis and the result are presented.

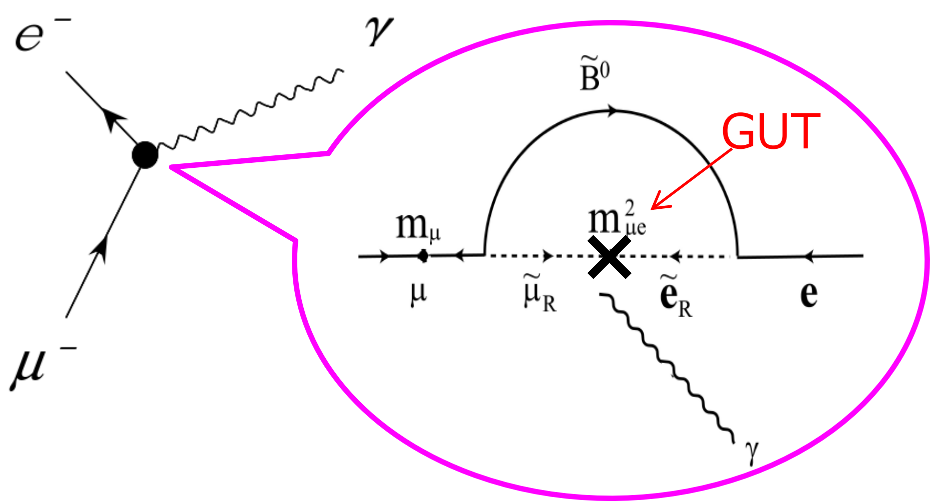
- Introduction
- MEG experiment and apparatus
- RUN2008
- Analysis
  - Detector analysis & performance
  - $\mu^+ \to e^+\gamma$ search analysis
- Discussion
- Status & prospect
- Conclusion

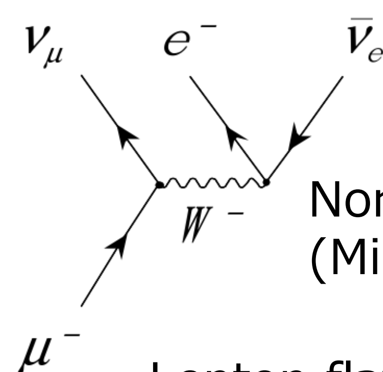
Subject of research

- Lepton-flavor violating muon decay : $\mu \rightarrow e\gamma$
  - charged LFV : Forbidden in SM
  - Out of experimental reach with finite ν mass ($BR<10^{-54}$)
  - Clear probe to new physics beyond SM
    - Large BR is predicted in many new physics models
      - SUSY-seesaw, SUSY-GUT···



- $\mu \rightarrow e\gamma$ decay





Normal muon decay (Michel decay)

Lepton flavors are conserved

$\mu \to e\gamma$ search

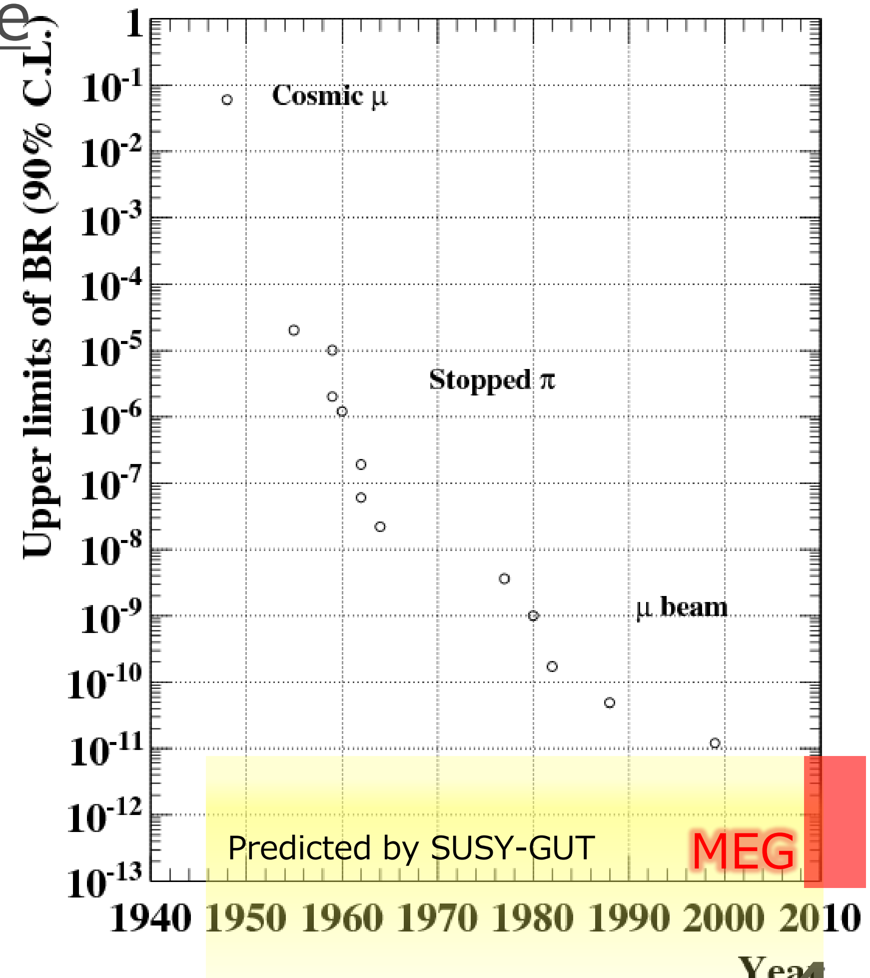
- Existing experimental upper limit
  - $\mathcal{B}(\mu \to e\gamma) < \mathbf{1.2 \times 10^{-11}}$ **(90%CL)**

    (1999, MEGA@LAMPF)

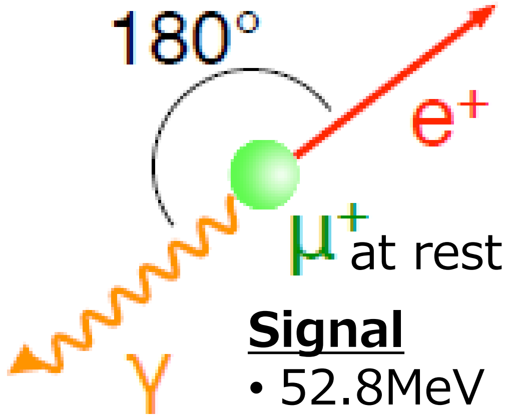
- A $\mu \to e\gamma$ signal is a clear evidence for new physics
  - No SM background, no hadronic uncertainty.

- MEG aims at searching down to O($\mathbf{10^{-13}}$)

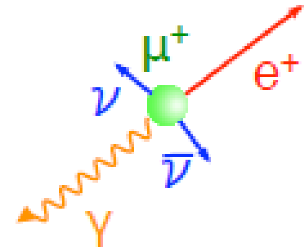
History of $\mu \to e\gamma$ search



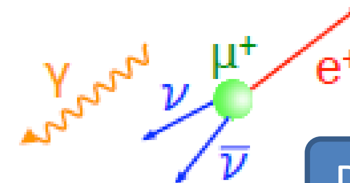
Signal & Background



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



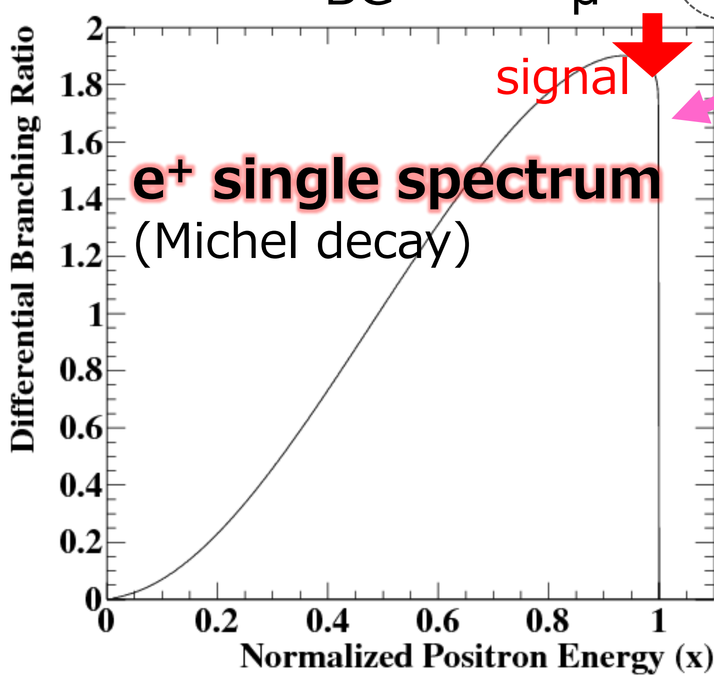
Physics BG
(Radiative muon decay)
- <52.8MeV
- Any angle
- Time coincidence



Dominant

Accidental BG
- <52.8MeV
- Any angle
- Random

$$R_{BG} \propto R_{\mu}^{2} \cdot f_{e} \cdot f_{\gamma} \cdot \delta\omega/4\pi \cdot \delta t$$



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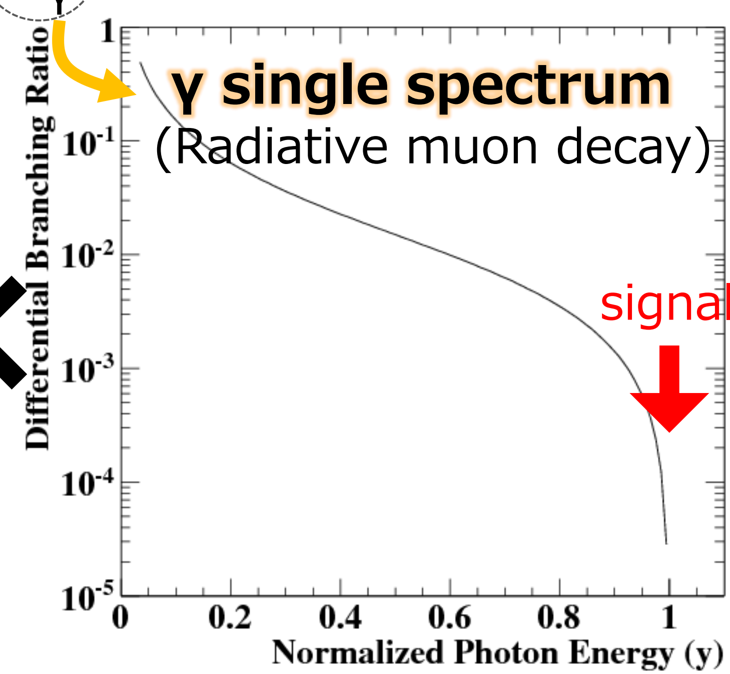
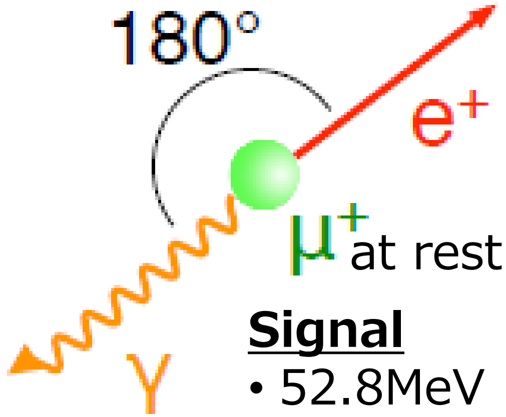


Signal & Background



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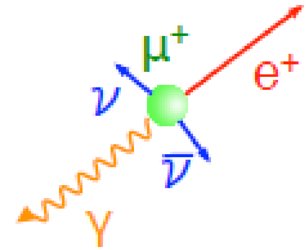

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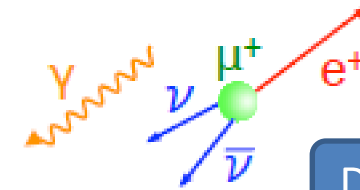

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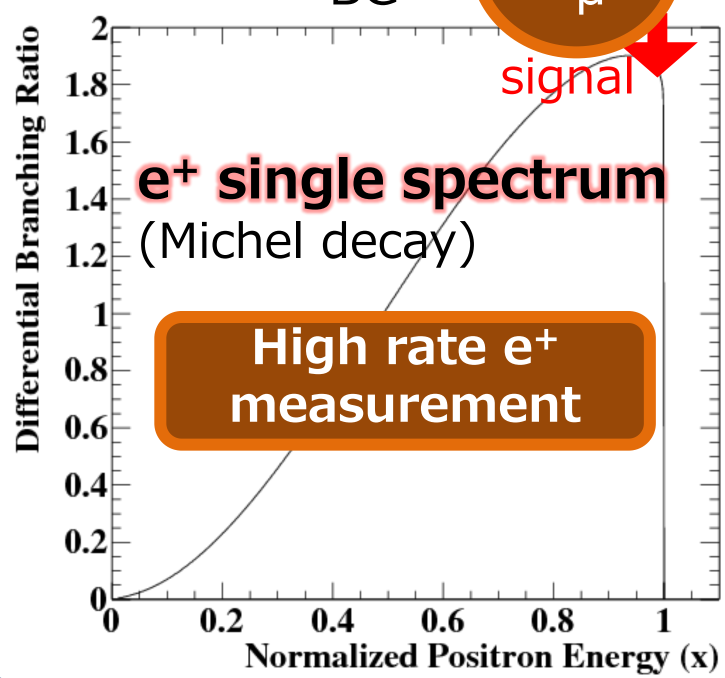

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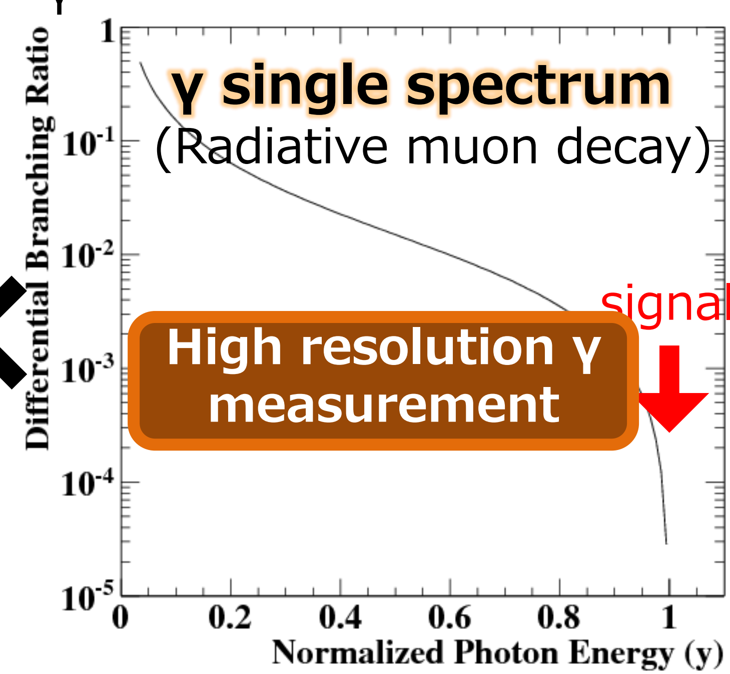


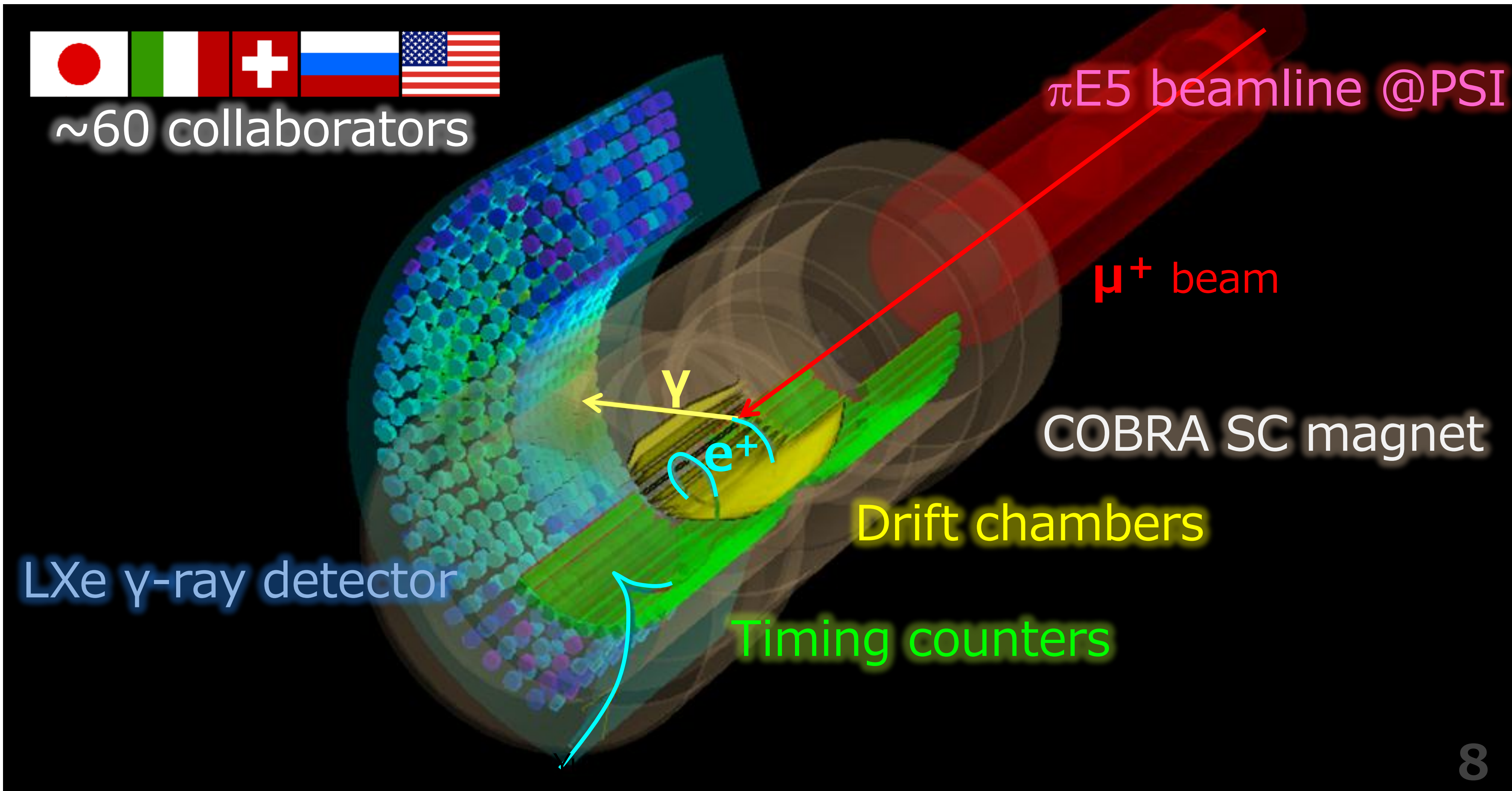
Requirements

- **High intensity DC μ^+ beam**
  - $>10^7$/sec
- **High rate tolerable detectors**
  - All of $>10^7$/sec μ^+ generate e^+
  - Pileup of γs become a source of high energy BG
- **High resolution detectors**
  - γ energy measurement is the most important
  - Angle and time measurements are also effective

The MEG Experiment

MEG Mu-E-Gamma Collaboration

- 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**



MEG History

MEG
MEG Collaboration

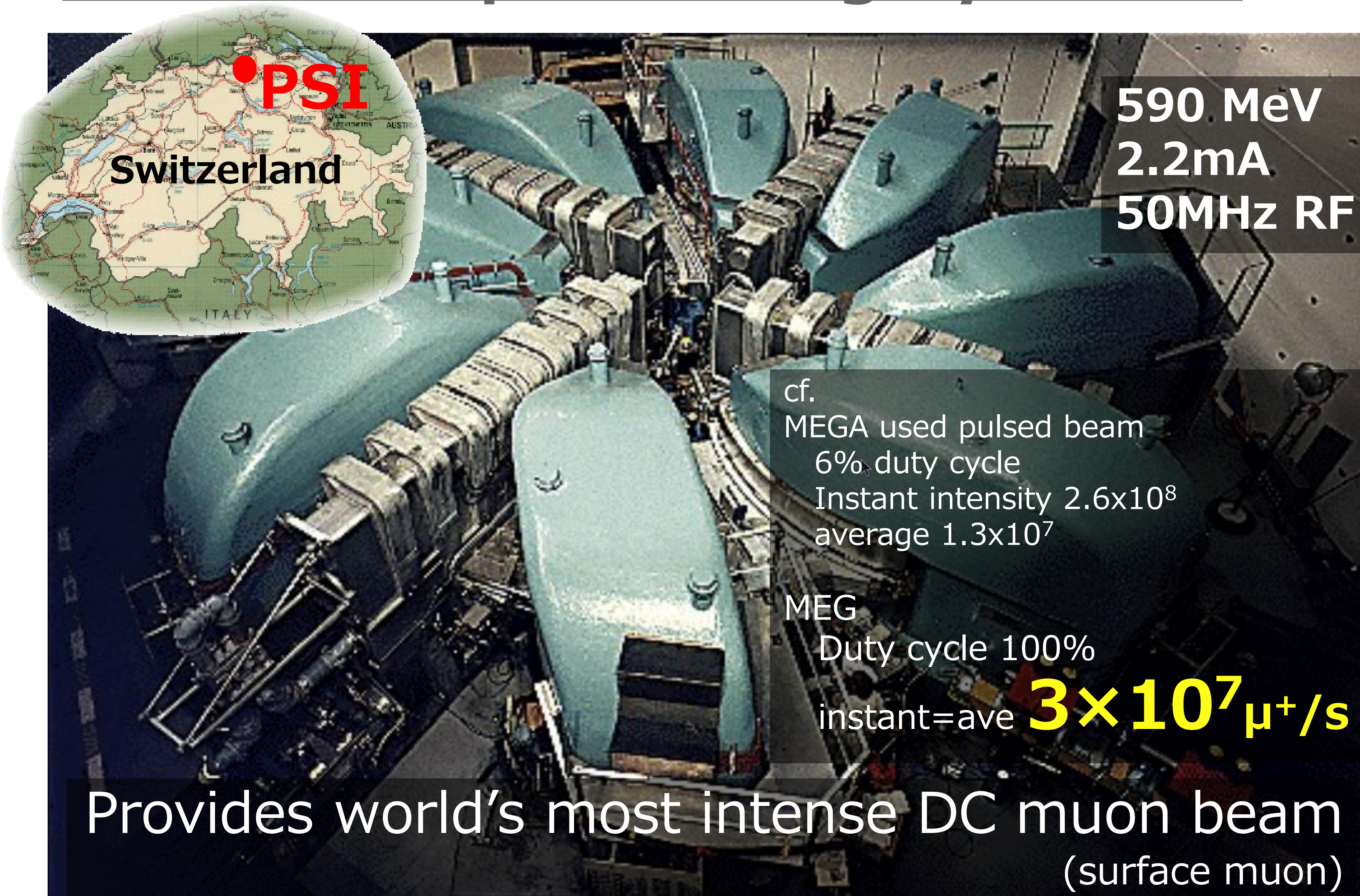
1999		Proposal
…		… R&D …
2007		Engineering run
2008	Sep – Dec	1st physics data acquisition
2009		Analysis of 2008 data
		Hardware upgrade
	Nov – Dec	2nd physics data acquisition
2010		Analysis of 2009 data
	Aug – Oct	3rd physics data acquisition
2011		Analysis of 2009&2010 data
now	July – Nov	4th physics data acquisition
…		…

First result (2008 data)
(Nucl.Phys.B834 1)
Sensitivity : **1.3×10^{-11}**
90% UL : **2.8×10^{-11}**
This talk

Preliminary result of 2009
(presented in conferences)
Sensitivity : **6.1×10^{-12}**
90% UL : **1.5×10^{-11}**

Final result of 2009 & 2010
(arXiv:11075547, accepted PRL)
Sensitivity : **1.6×10^{-12}**
90% UL : **2.4×10^{-12}**

PSI 1.2MW proton ring-cyclotron



590 MeV
2.2mA
50MHz RF

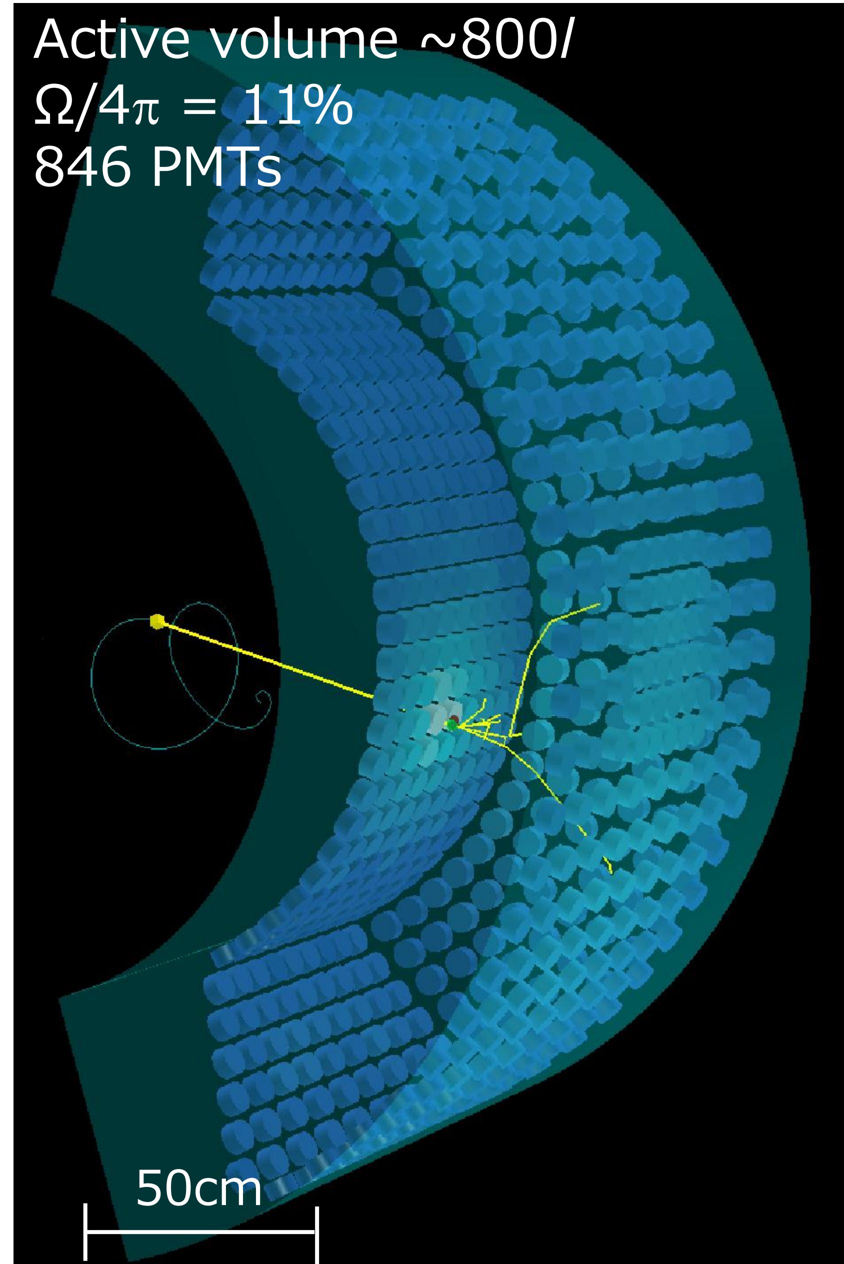
cf.
MEGA used pulsed beam
  6% duty cycle
  Instant intensity 2.6×10^8
  average 1.3×10^7

MEG
  Duty cycle 100%
  instant=ave **$3\times10^7 \mu^+/s$**

Provides world's most intense DC muon beam
(surface muon)

Liquid xenon γ-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 ultra-violet (178nm)
    - Low temperature (165K)
    - Need high purity
  - No segmentation
- Measure energy, position, time at once
  - $\sigma_E/E \sim 2\%$ (@52.8MeV)
  - σ_t = 80 psec
  - σ_x = 5-6 mm



Cryostat

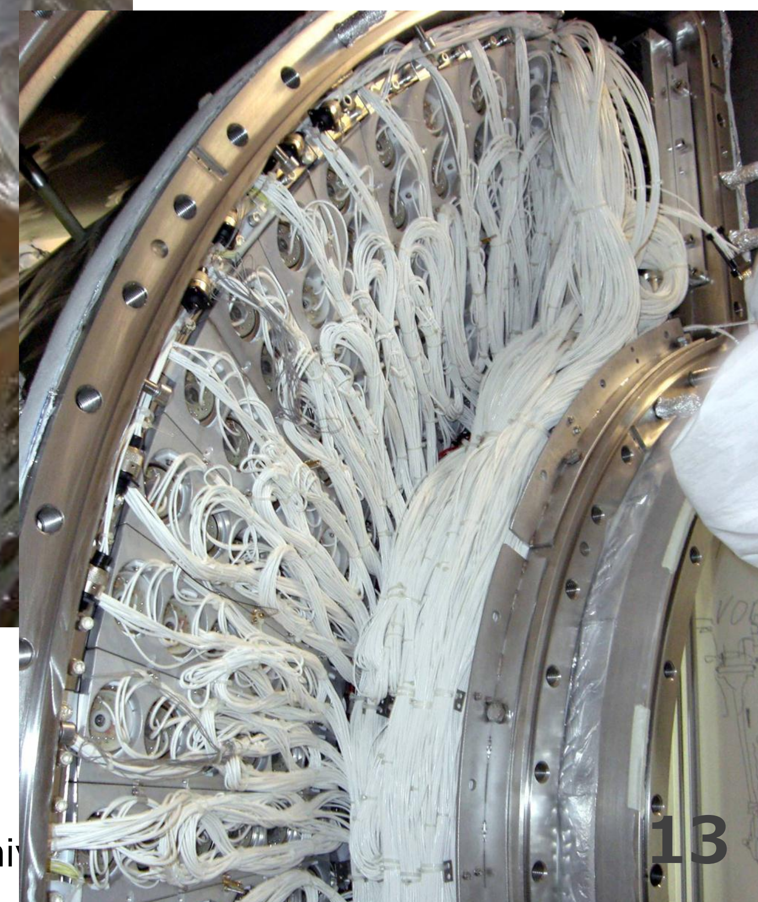
2 layers of vacuum-tight cryostat
Thin window for γ entrance face

Entrance window with honeycomb structure

PMT installation

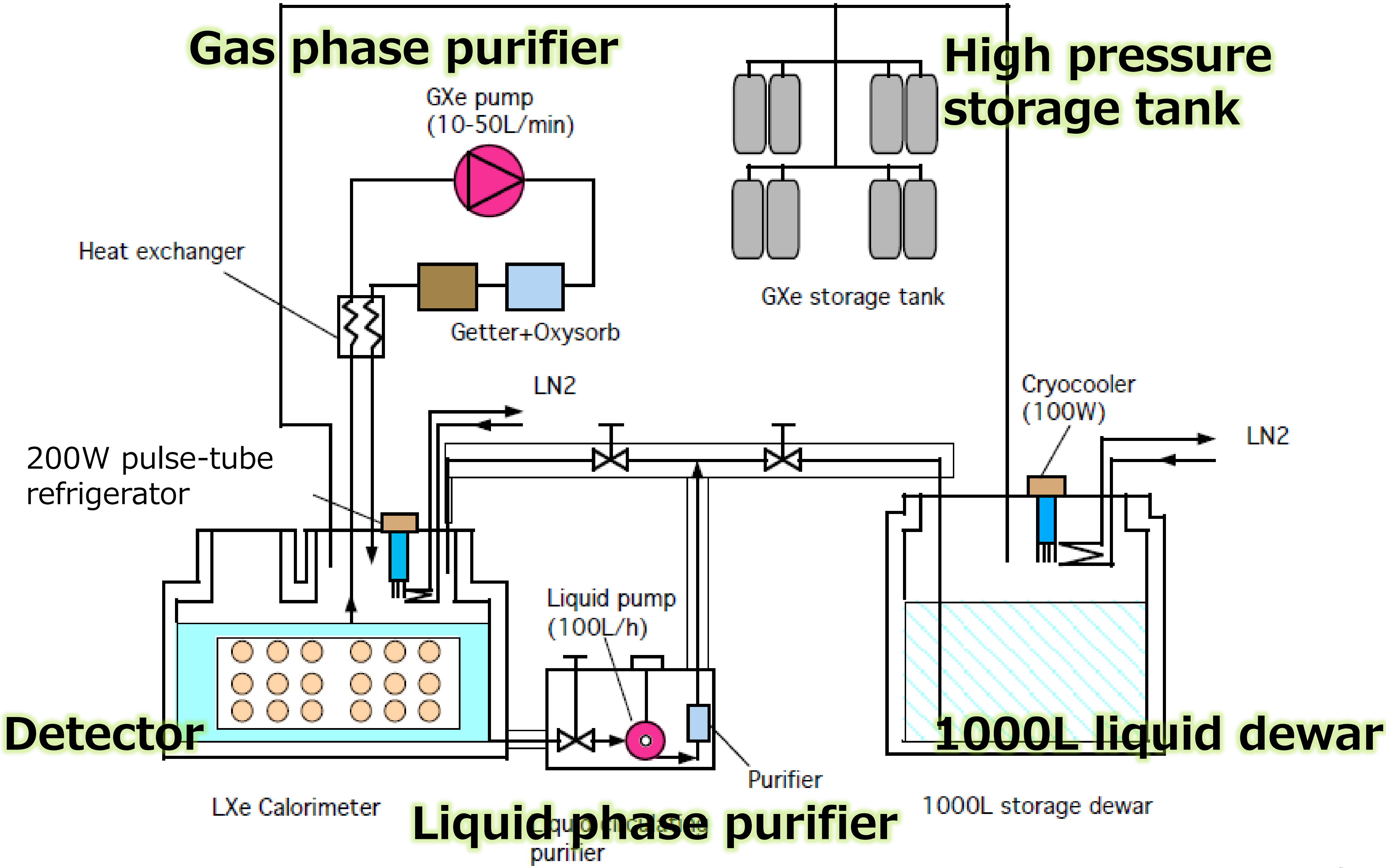
2”PMT developed for MEG

- Quartz window for VUV
- K-Cs-Sb photocathode
- Al strip on photocathode
- Metal-channel dynodes
- Zener diode at last step of Bleeder

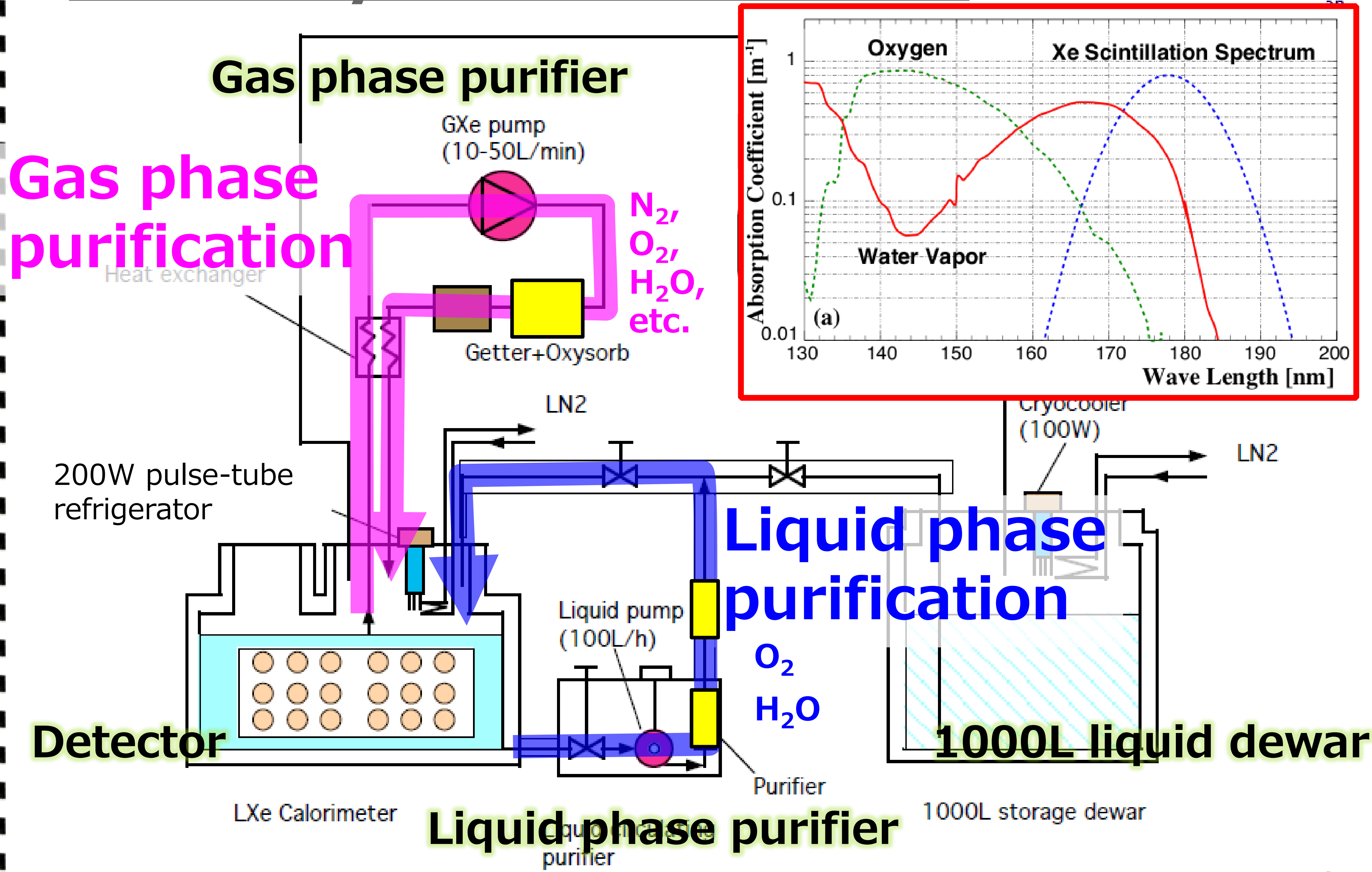


MEG
Mu-E-Gamma Collaboration

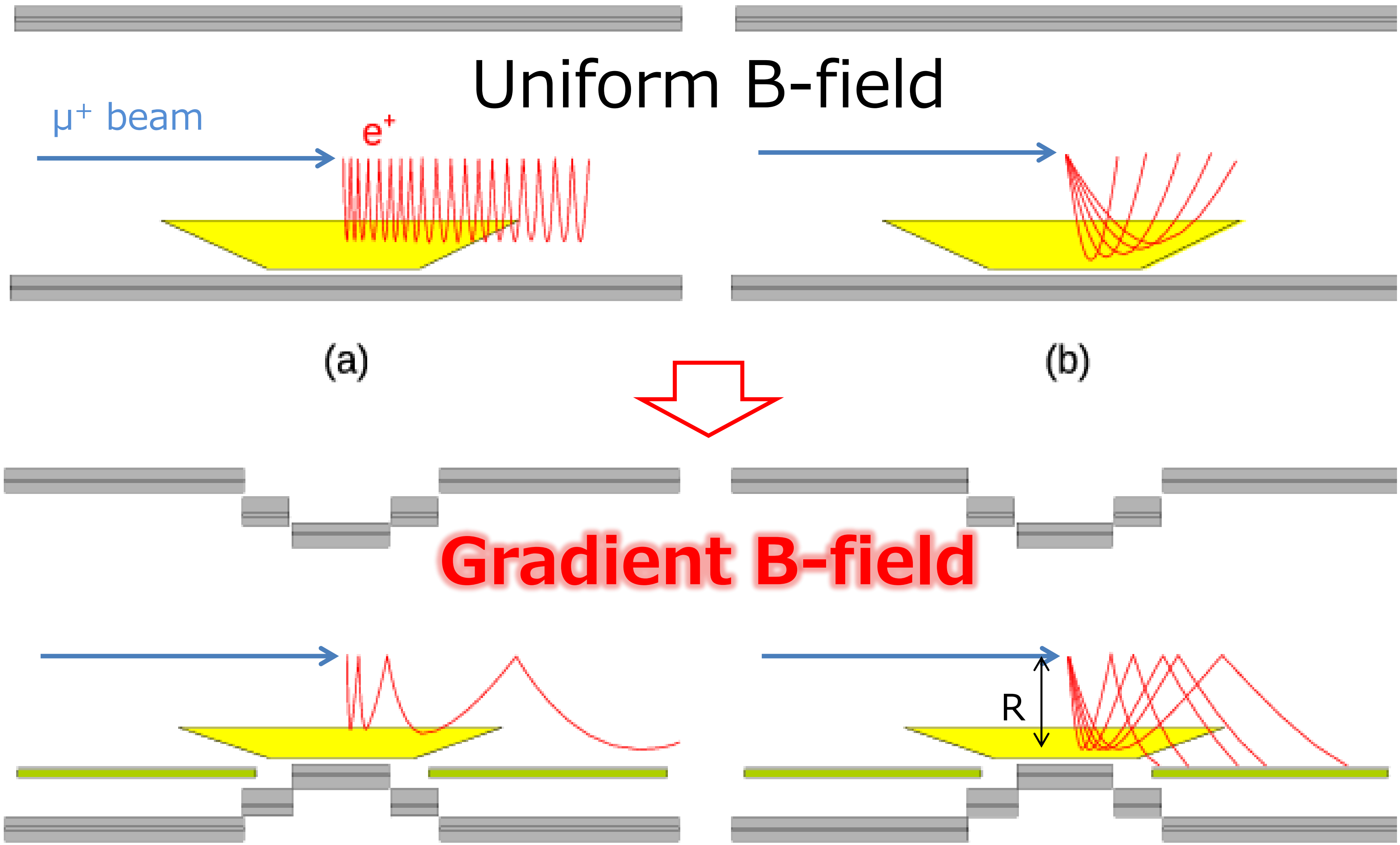
Xenon system



Xenon system:Purification



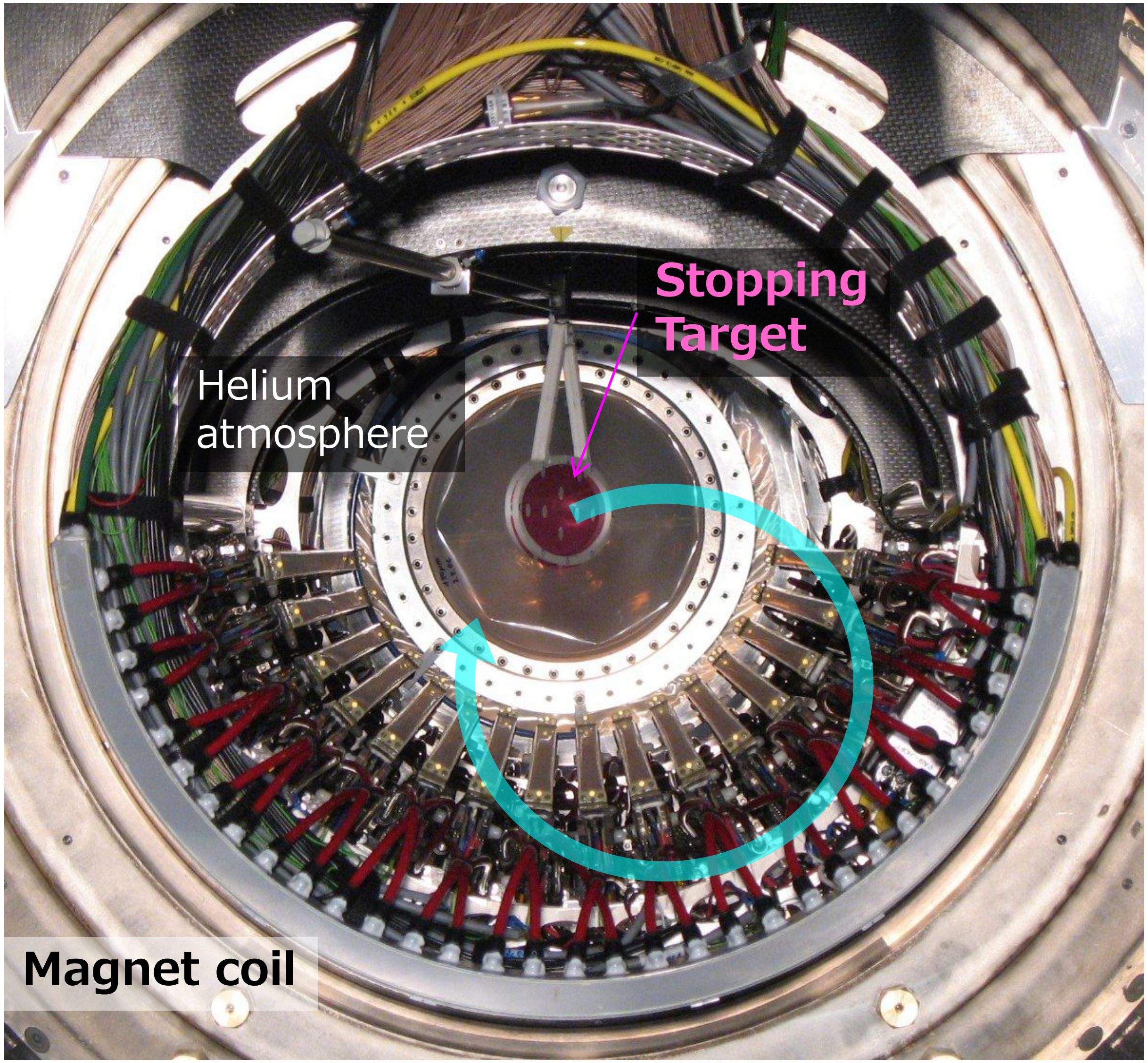
e⁺ spectrometer



e⁺ quickly swept out

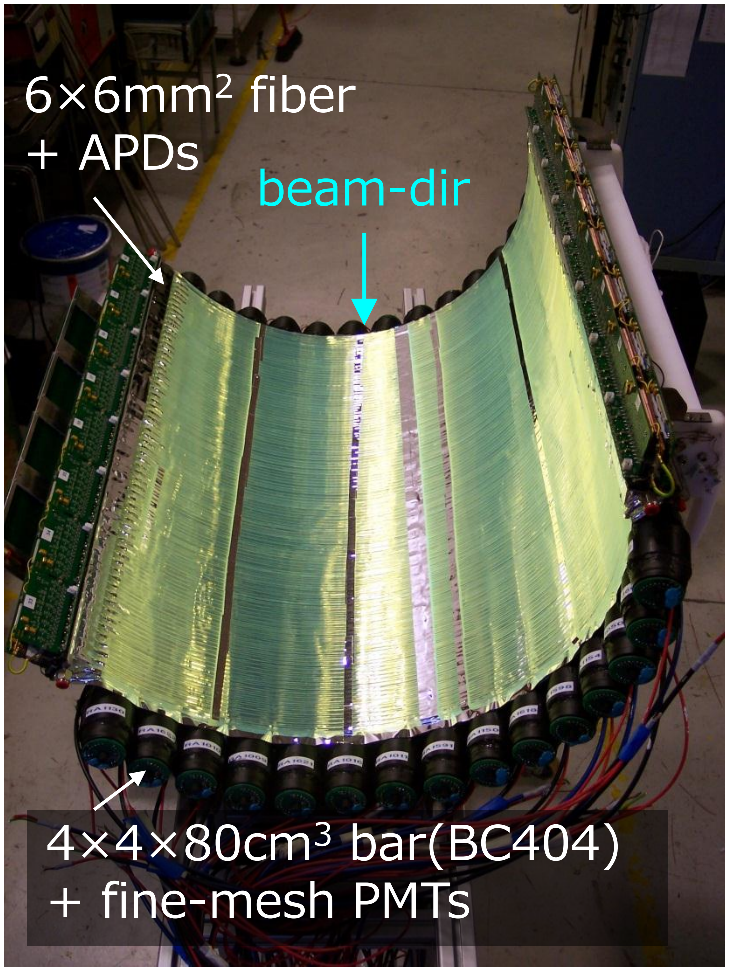
Constant bending radius independent of emission angles

Drift chamber

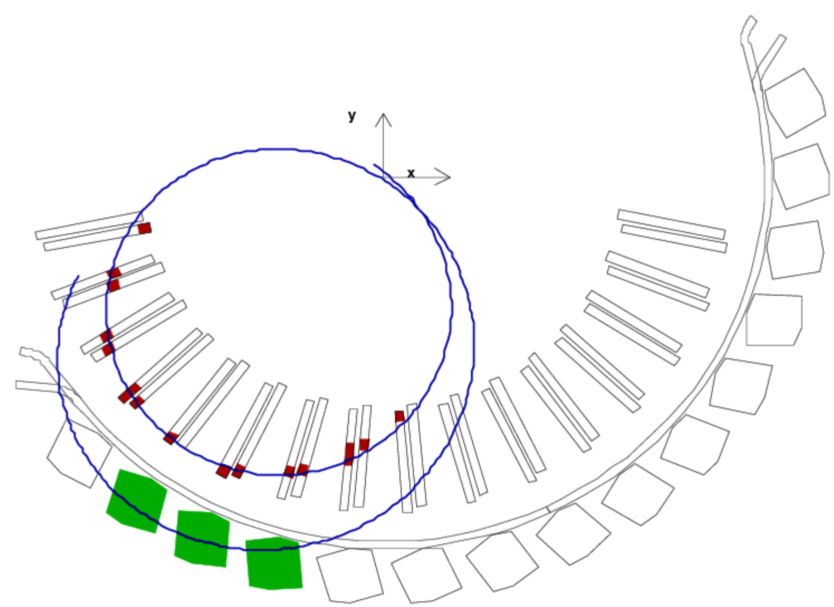


- 16 modules
  - Aligned concentrically (10.5°)
  - 2 layers per module
- 12.5 μm thick cathode foil with vernier pattern
- He:ethane = 50:50
- Ultra low mass chamber
  - Multiple scatter limits the performance
  - Suppress γ BG source
  - In total, along e^+ trajectory $\sim 2.0\times10^{-3}\ X_0$
- Tracking with Kalman filter
  - Reconstruct e^+ momentum vector on target
    - $\sigma_E/E = 0.7\ \%$
    - $\sigma_\theta \sim 18$ mrad
    - $\sigma_\varphi \sim 10$ mrad

Timing counter

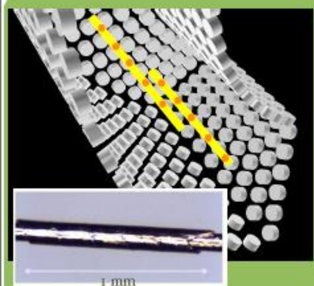


- e^+ time measured by a set of timing counter
  - Two layers of plastic scintillator
  - (z-measuring fiber counter is not used in 2008)
  - $\sigma_{TC} \sim 65$ psec
- Reconstruct muon decay time
  - TC hit time - e^+ flight length from DC
  - LXe hit time - γ flight length (line)
  - $\mathbf{t_{e\gamma} = t_{e+} - t_\gamma}$
- Total resolution : $\sigma_{te\gamma} = 148$ psec



MEG Calibrations

Established



Am source on wire

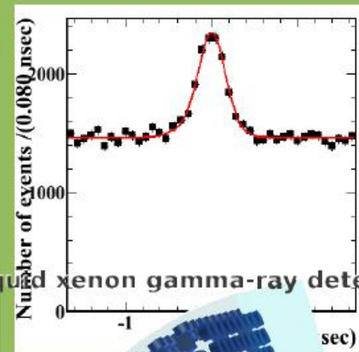
LED

PMT Gain

Alpha

PMT QE

Absorption

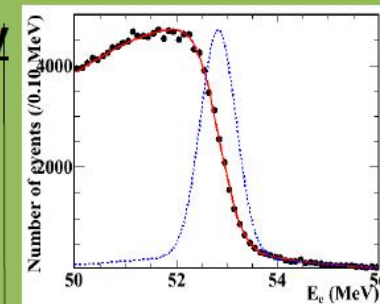


Radiative Decay

$\mu \to e\nu\nu\gamma$

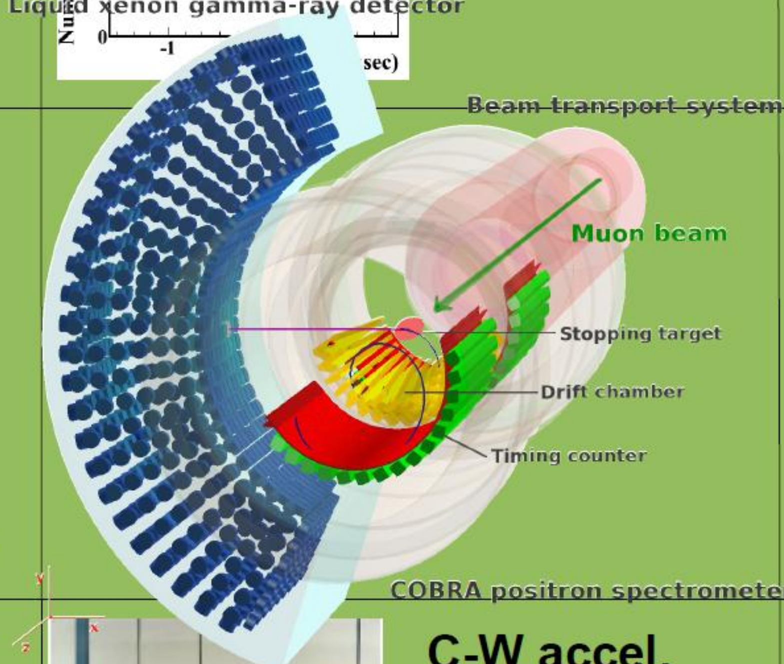
Relative timing

Similar topology

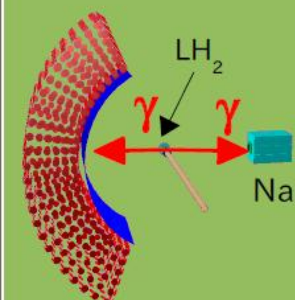


Michel Decay

$\mu \to e\nu\nu$



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



$\pi^0 \to \gamma\gamma$

55,83,129MeV

monochoro

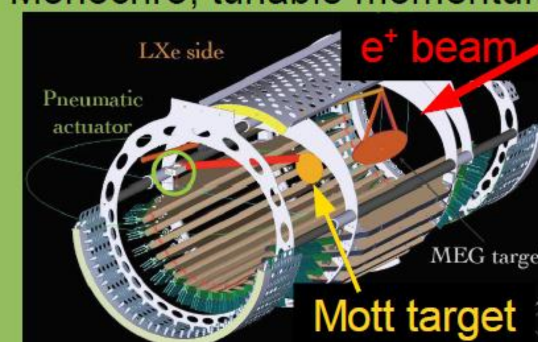
$\pi^0 \to \gamma e^+ e^-$

Relative timing

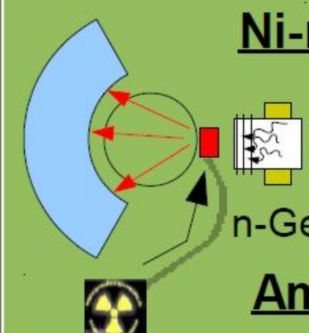
Similar topology

e^+ Mott-scatter

Monochro, tunable momentum



Ni-n



9MeV γ source

n-Generator

AmBe

AmBe source 4.4MeV γ source

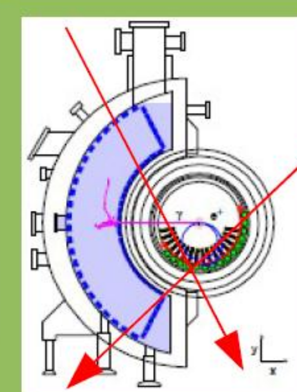
C-W accel.

Li(p,γ)Be

– 18MeV γ

B(p,γ)C

– 4,11MeV 2γ



CosmicRay

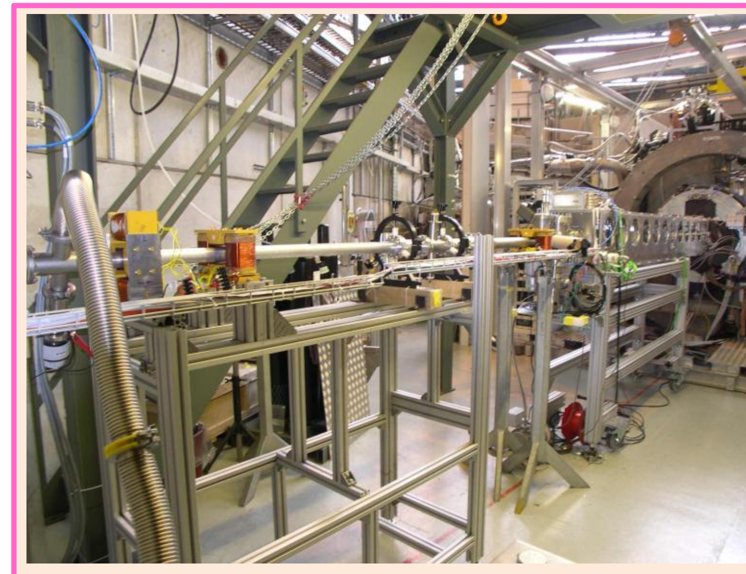
DC alignment

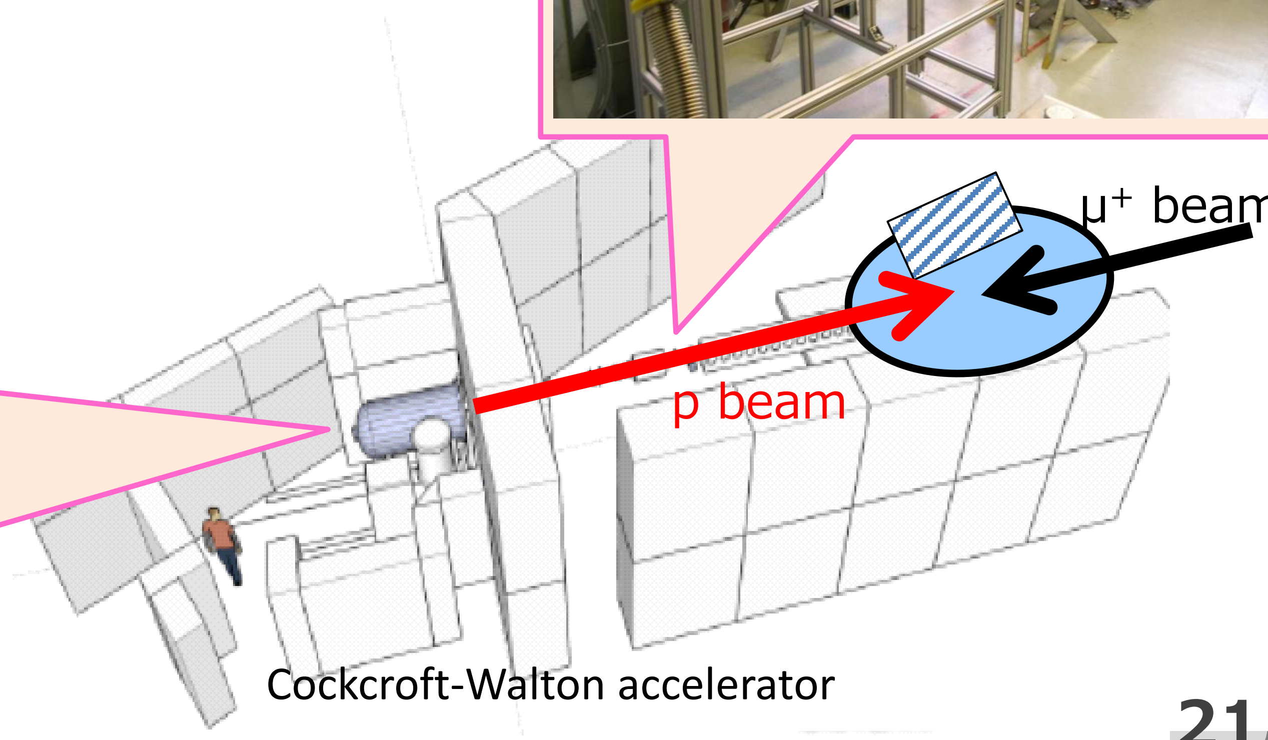
TC uniformity

LXe monitor

Calibration1: CW

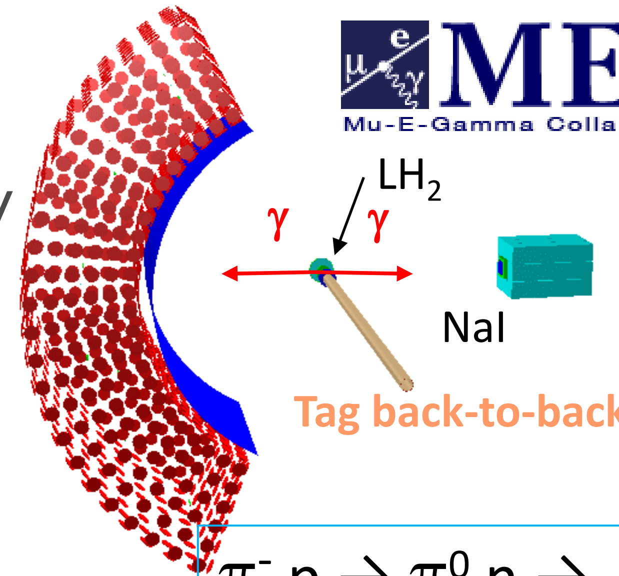
- 17.6 MeV γ from Li(p,γ)Be reaction
  - Prepared dedicated Cockcroft-Walton accelerator
  - Shoot ***p*** beam from opposite side
  - Easy to switch (20min)
  - 3 times per week
- Non-uniformity calibration
- Light yield monitor



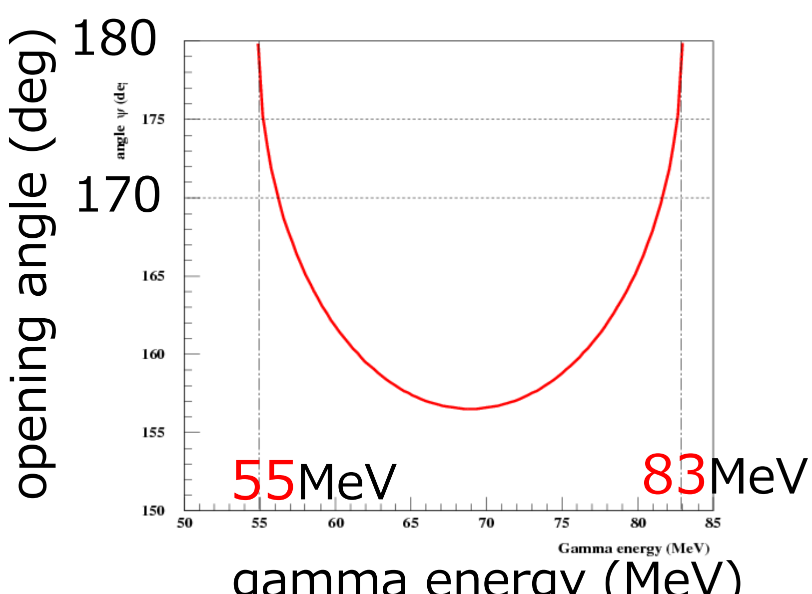


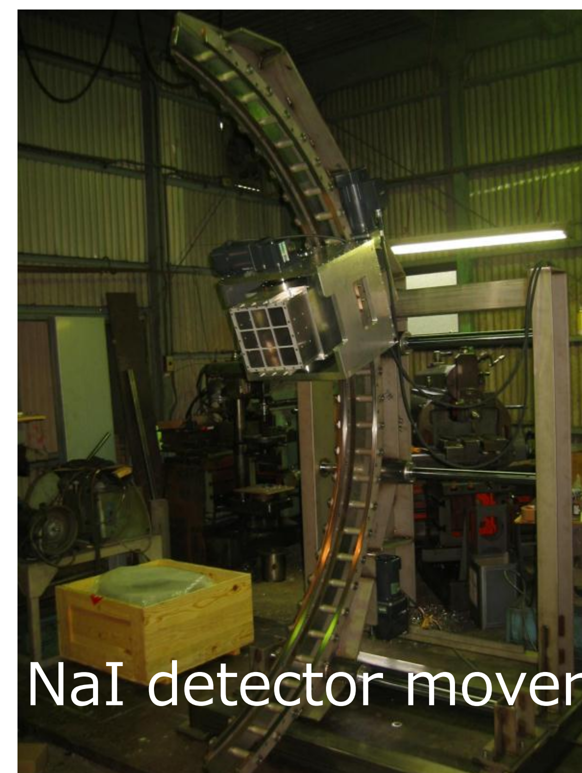
Calibration2: π^0

- 55MeV high-energy γ from π^0 decay
  - Evaluate resolutions
    - (energy, position, time)
  - Calibrate energy scale
- π^- from same beamline as μ^+
  - LH_2 target
  - Take several days for setup
  - Conducted at beg. & end of physics run
- Tag back-to-back γs with NaI detector



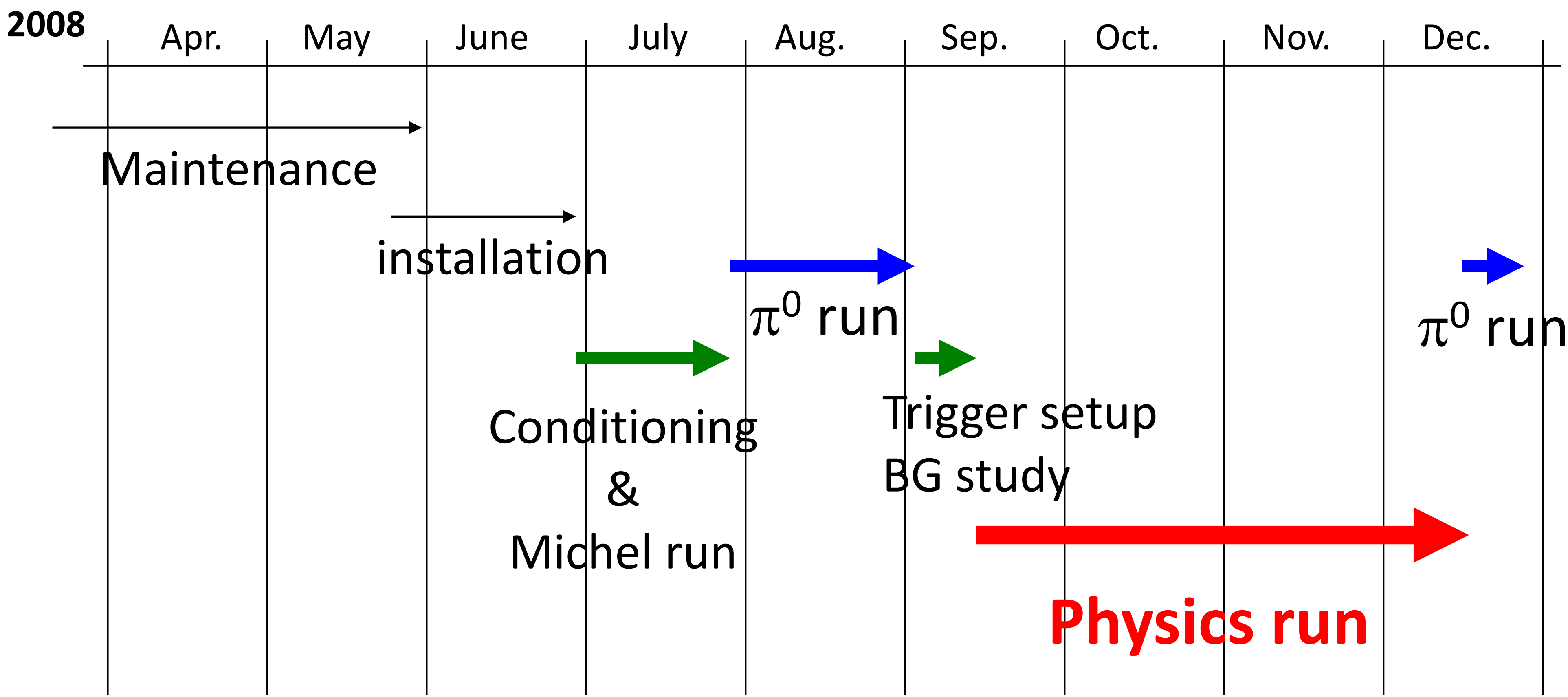
$\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$





RUN 2008

2008

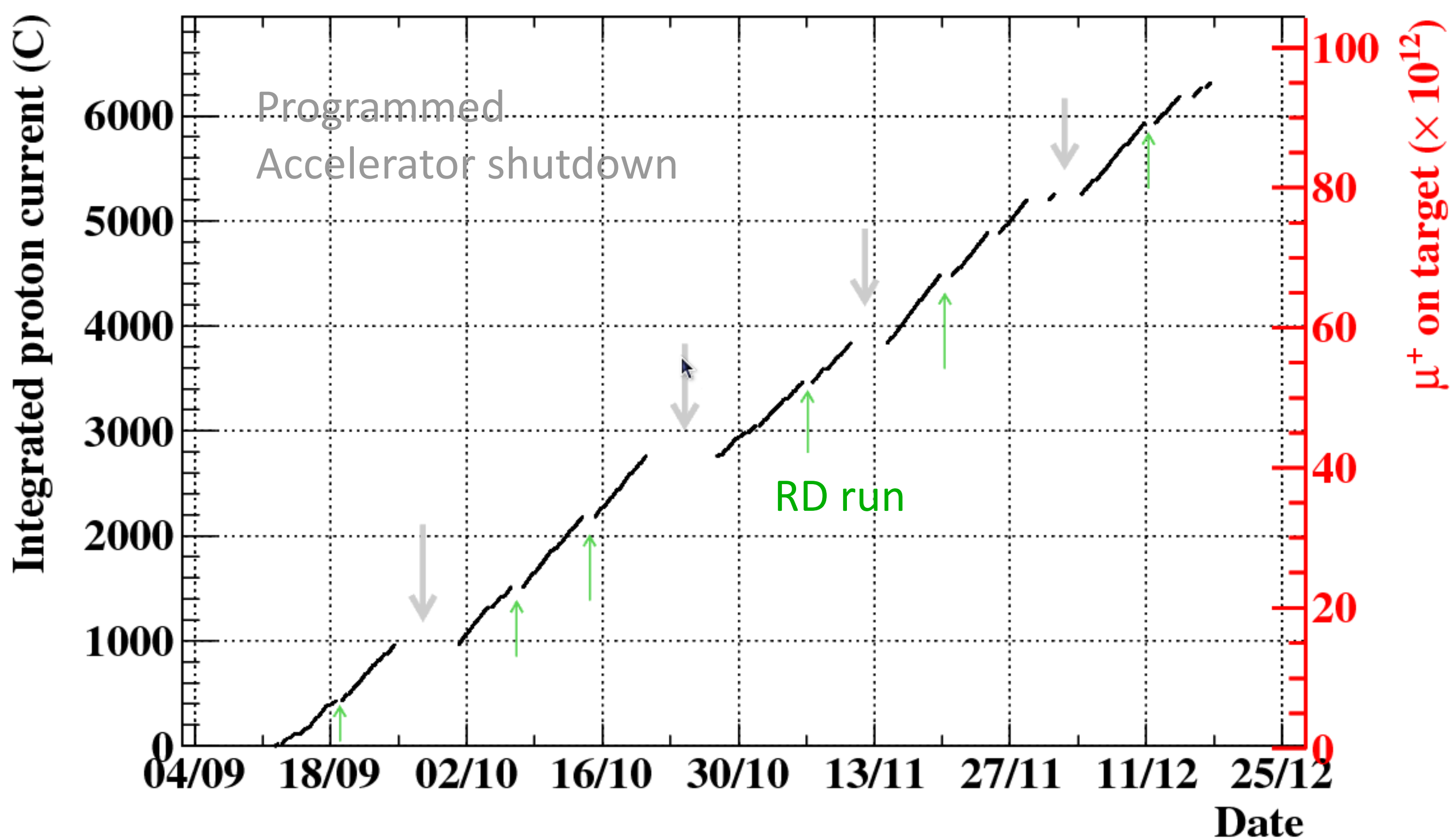


2008
Apr.
May
June
July
Aug.
Sep.
Oct.
Nov.
Dec.
Maintenance
installation
π0 run
Conditioning
&
Michel run
Trigger setup
BG study
π0 run
Physics run

2008 Data

- The first 3 months data of MEG
  - Normal physics data-taking
    - **MEG run** w/ 11 mixed trigger
    - Daily LED calibration w/ beam
    - 3/week Full calibration sets
    - 24h/week **RD (low-intensity) run**

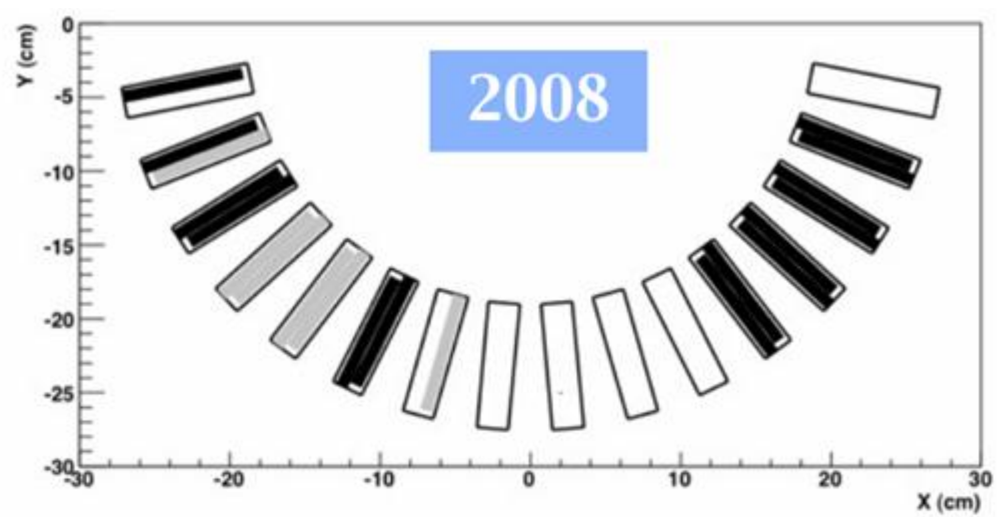
Stopping rate	$3.0 \times 10^7 \mu^+/\text{sec}$
Trigger rate	6.5 Hz, 9 MB/sec
Live time	3.3×10^6 sec (85%)
Total μ^+ on target	9.5×10^{13}



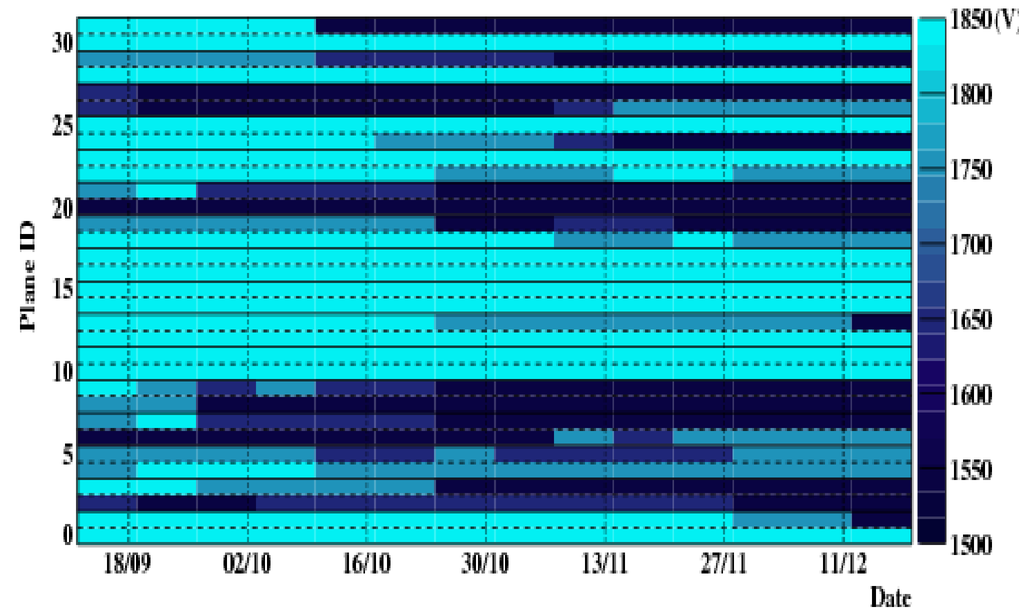
DCH discharge problem

- DCH frequently discharged
  - After a few months,
    - Gradually some chambers started to discharge
  - Inside magnet is filled with pure-Helium
    - DCH-outside is exposed in He atmosphere (HV line)
- Finally, out of 32 planes,
  - 18 planes were operational
  - Only 12 planes worked at nominal voltage

Degradation of e^+ measurement (**efficiency** / resolution)



Helium permeated into HV line slowly...



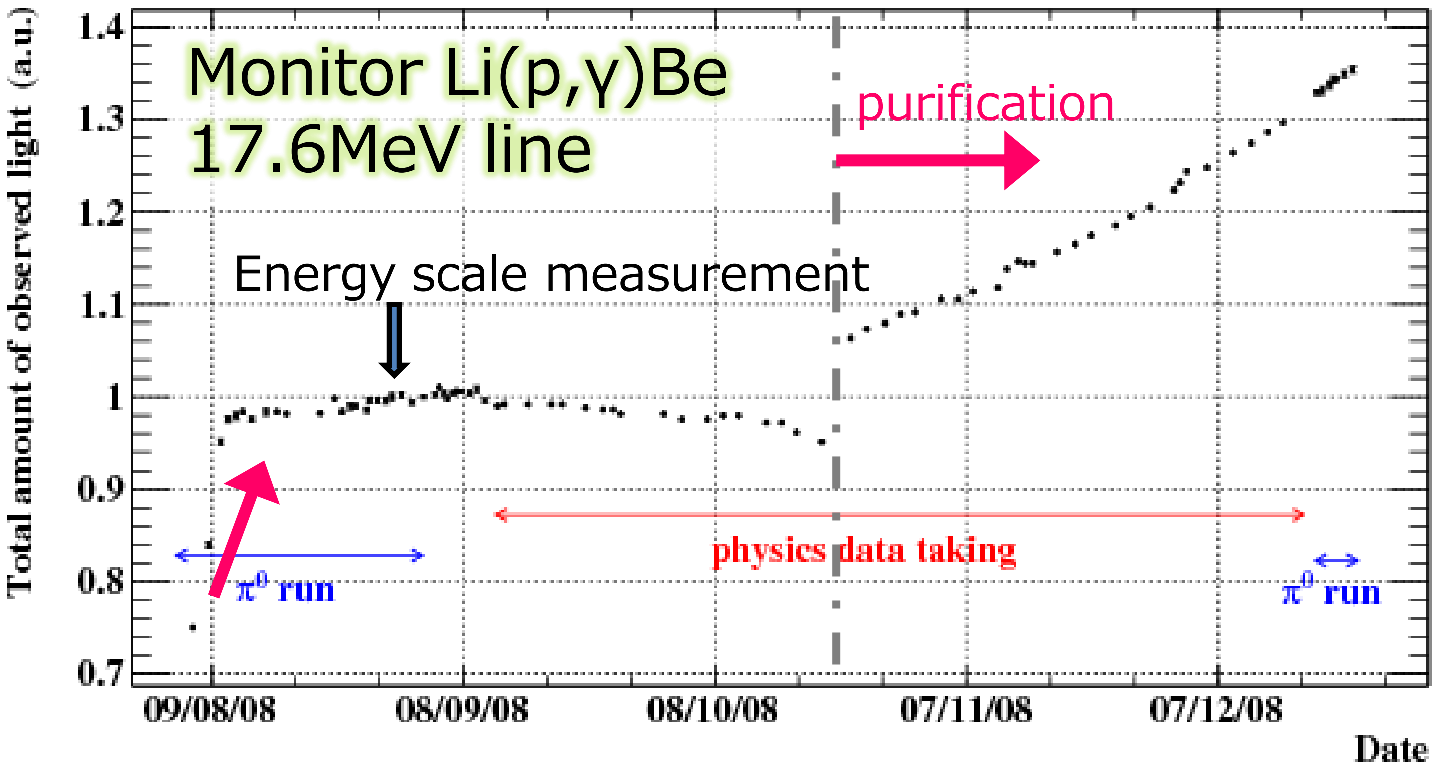
Variation of LXe light yield

MEG
Mu-E-Gamma Collaboration

- Lower than expected
- Recover by purification
- Decrease by (possible) leak

Confirmed light yield monitoring using several kinds of daily calibration

We decided to continue purification in parallel with DAQ
(gas phase: continuously, liquid phase: intermittently(beam shutdown))

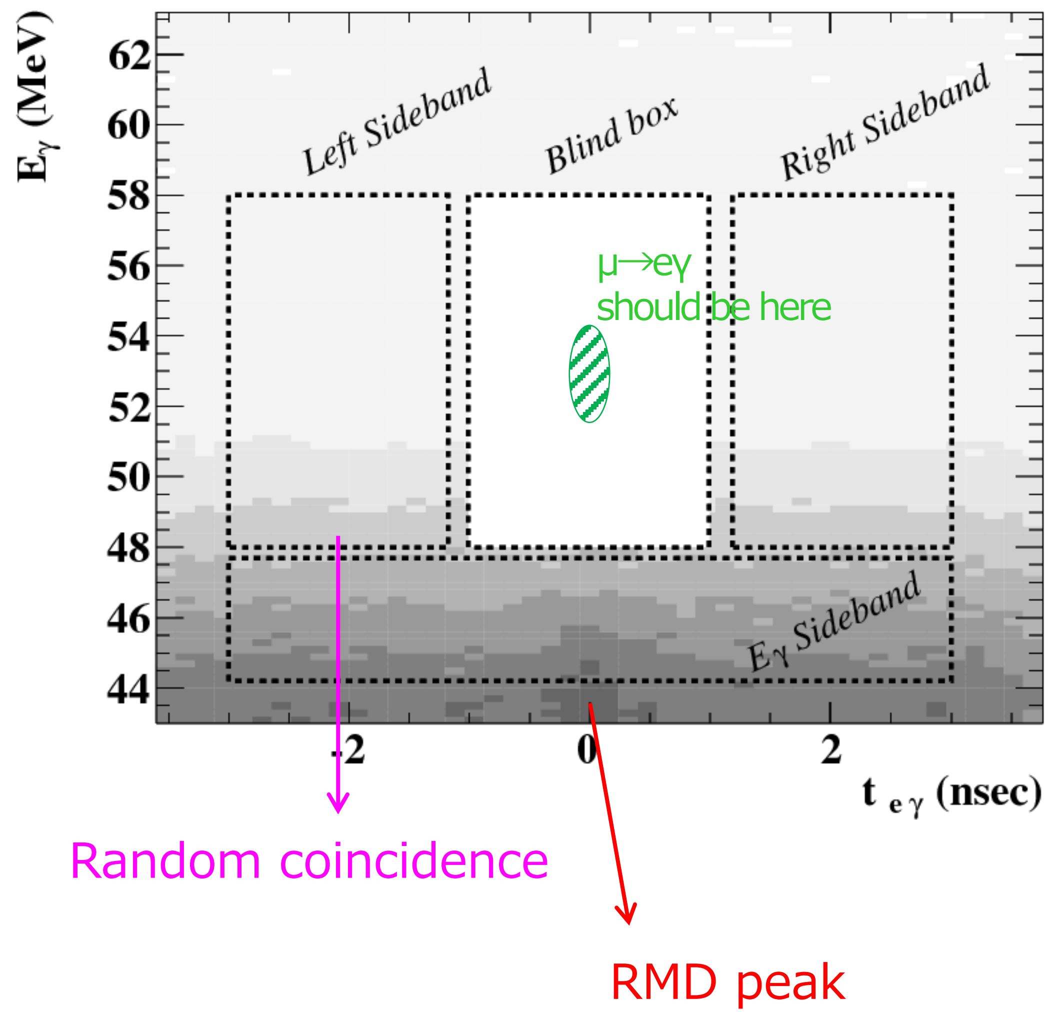


Finally, keep overall energy scale uncertainty under **0.4%**

Analysis

Analysis

- Blind analysis
  - Hidden parameters: (E_γ, $t_{e\gamma}$)
  - Any study (calibration, BG estimation, performance evaluation) can be done with events outside the box
- Sideband
  - Accidental BG can be studied with off-time sideband
  - Radiative muon decay(RMD) can be studied with low-energy E_γ sideband
- Normalization
  - Count unbiased Michel sample mixed in physics data
- Wide analysis region for likelihood fitting
  - Estimate Sig & BG simultaneously.
  - PDFs mostly from data



Likelihood fit

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

μ→eγ signal

Accidental BG

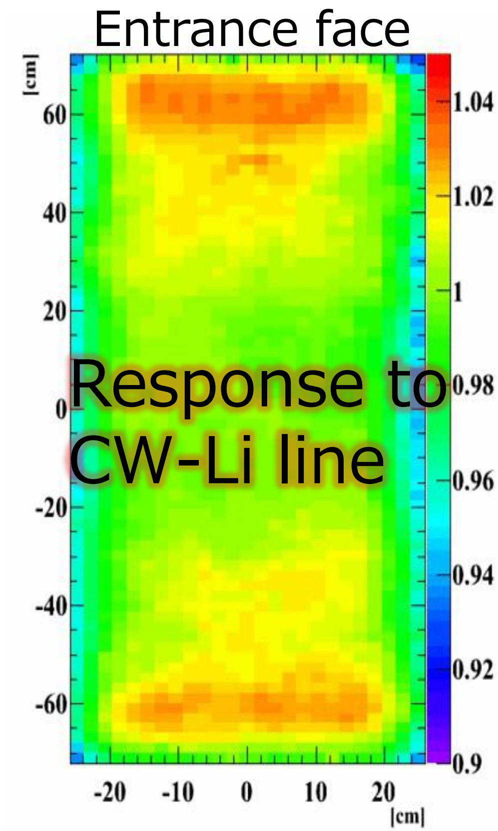
Radiative muon decay

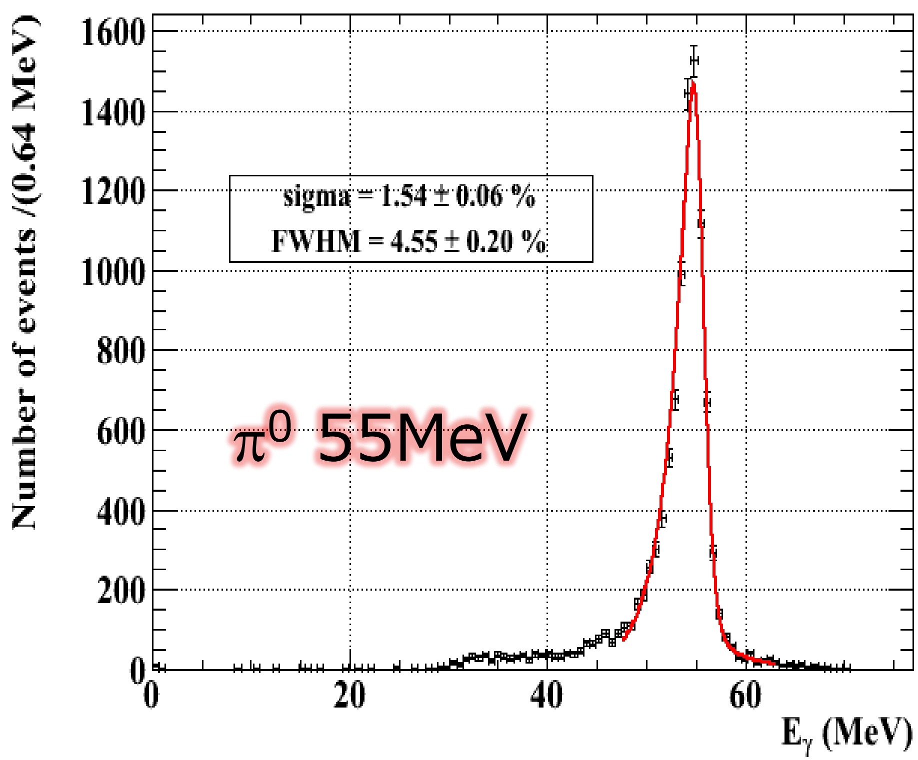
- **Extended unbinned maximum likelihood fit** on number of events
  - 3 fit parameters : $(N_{sig}, N_{RMD}, N_{BG})$, $N=N_{sig}+N_{RMD}+N_{BG}$
  - 5 observables : $\vec{x} = (E_\gamma, E_e, t_{e\gamma}, \underbrace{\theta_{e\gamma}, \varphi_{e\gamma}})$

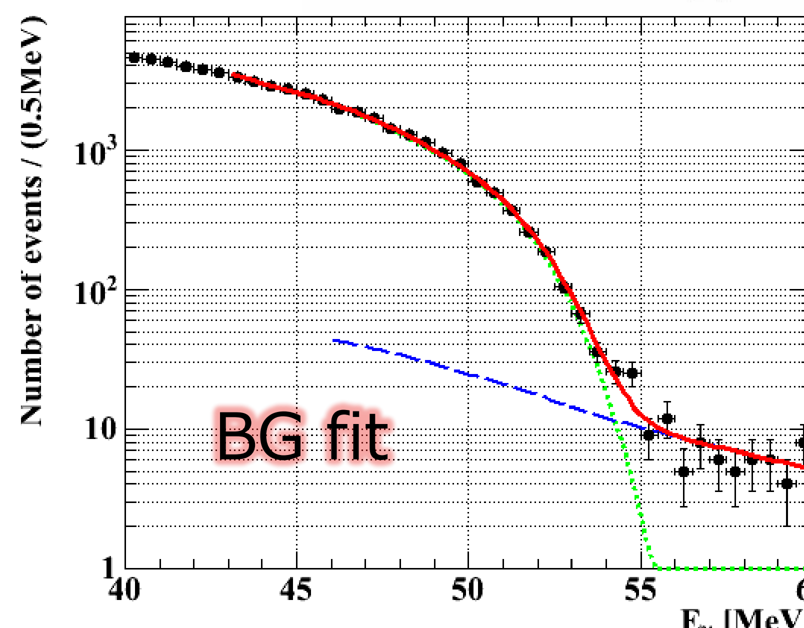
    relative angle (inverse e+ direction – γ direction)
  - Probability density functions (PDFs) for each event type (***S, R, B***)
    - Extract PDF from data
  - Fit in wide region (10σ) to extract signal & background simultaneously

Gamma energy

- Calibrate position-dependent response using CW-Li 17MeV γ
- Measure response using π^0-55MeV γ
  - extract position dependently
- Cross check with BG shape fit







e+ momentum

MEG
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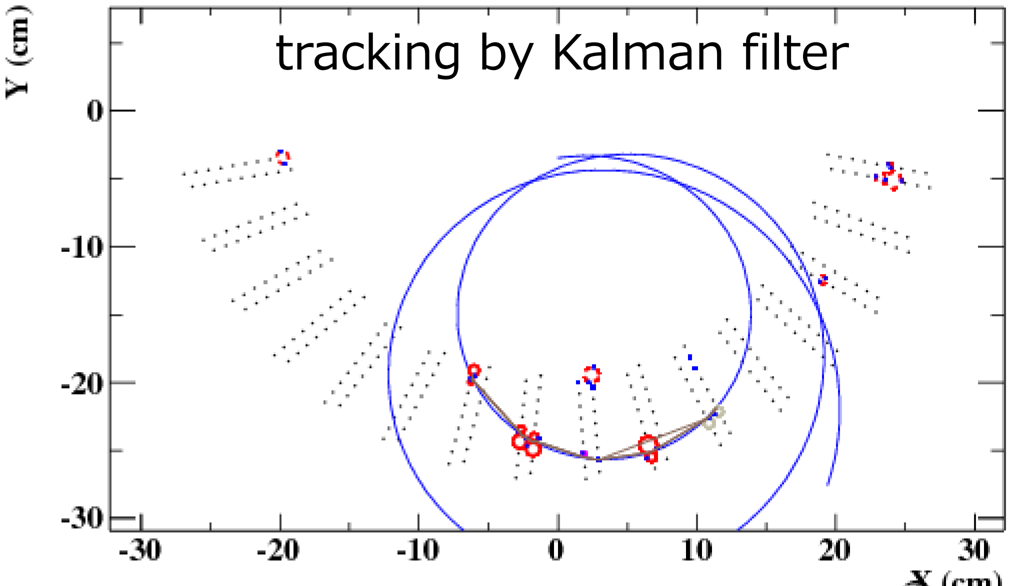
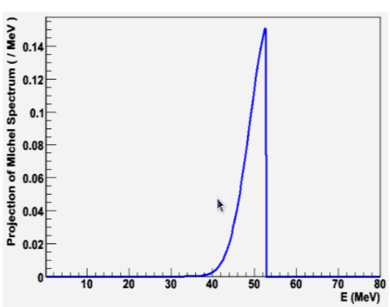
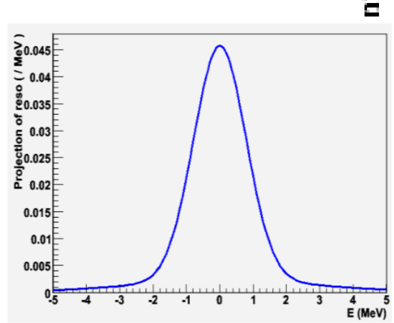
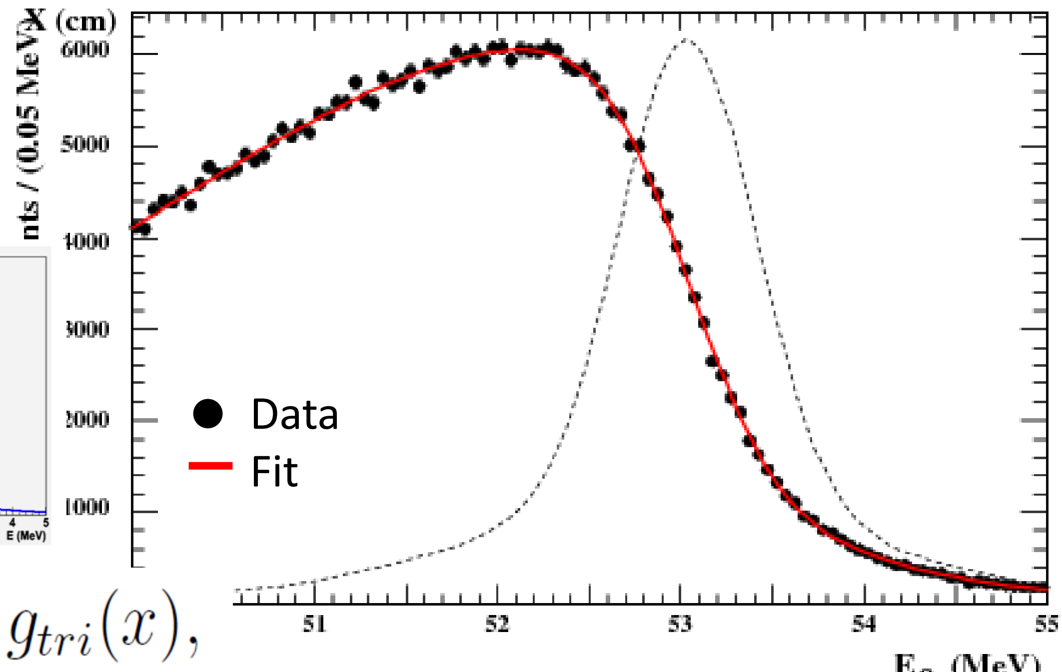


- Evaluate momentum response by fitting kinematical edge (52.8MeV) of Michel spectrum



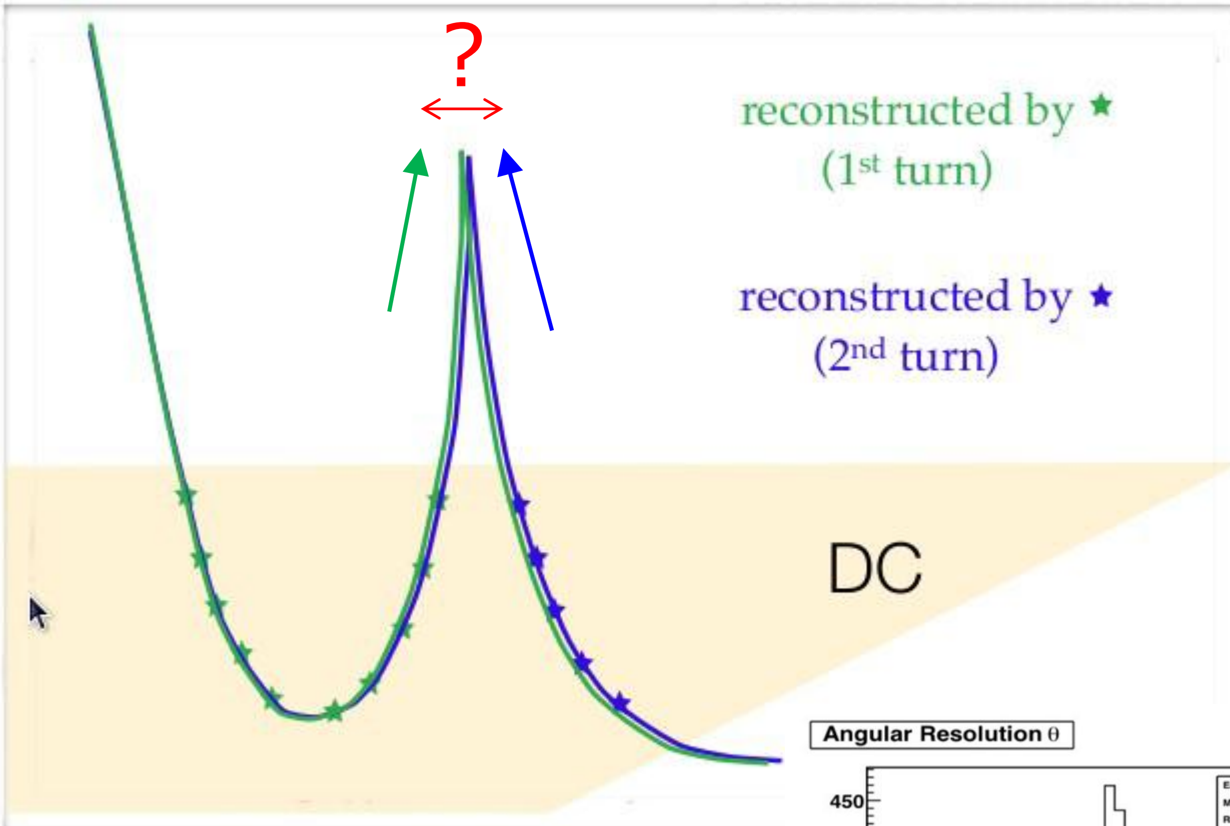
$\otimes$





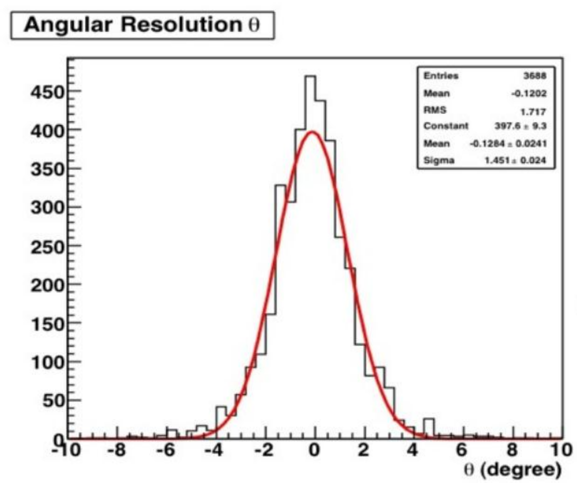
$$f(x) = (f_{\mathrm{theo}}(x) \times \epsilon_{acc}(x)) \otimes g_{tri}(x),$$

e+ emission angle

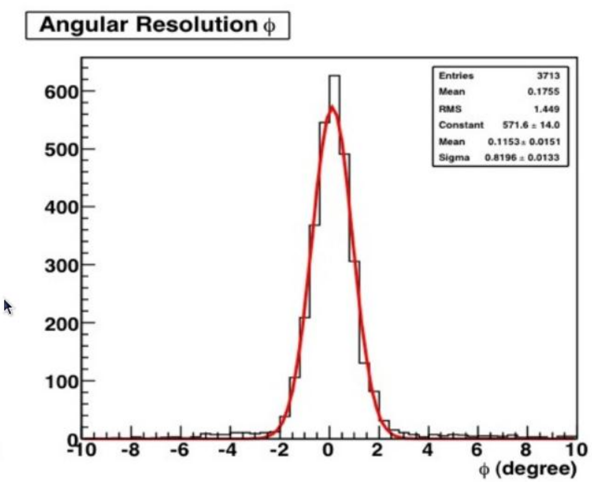


- Evaluate angular resolution using 2-turn events
- See difference of reconstructed angles by individual turns

$$\sigma_\theta = 18 \text{ mrad}$$
$$\sigma_\varphi = 10 \text{ mrad}$$

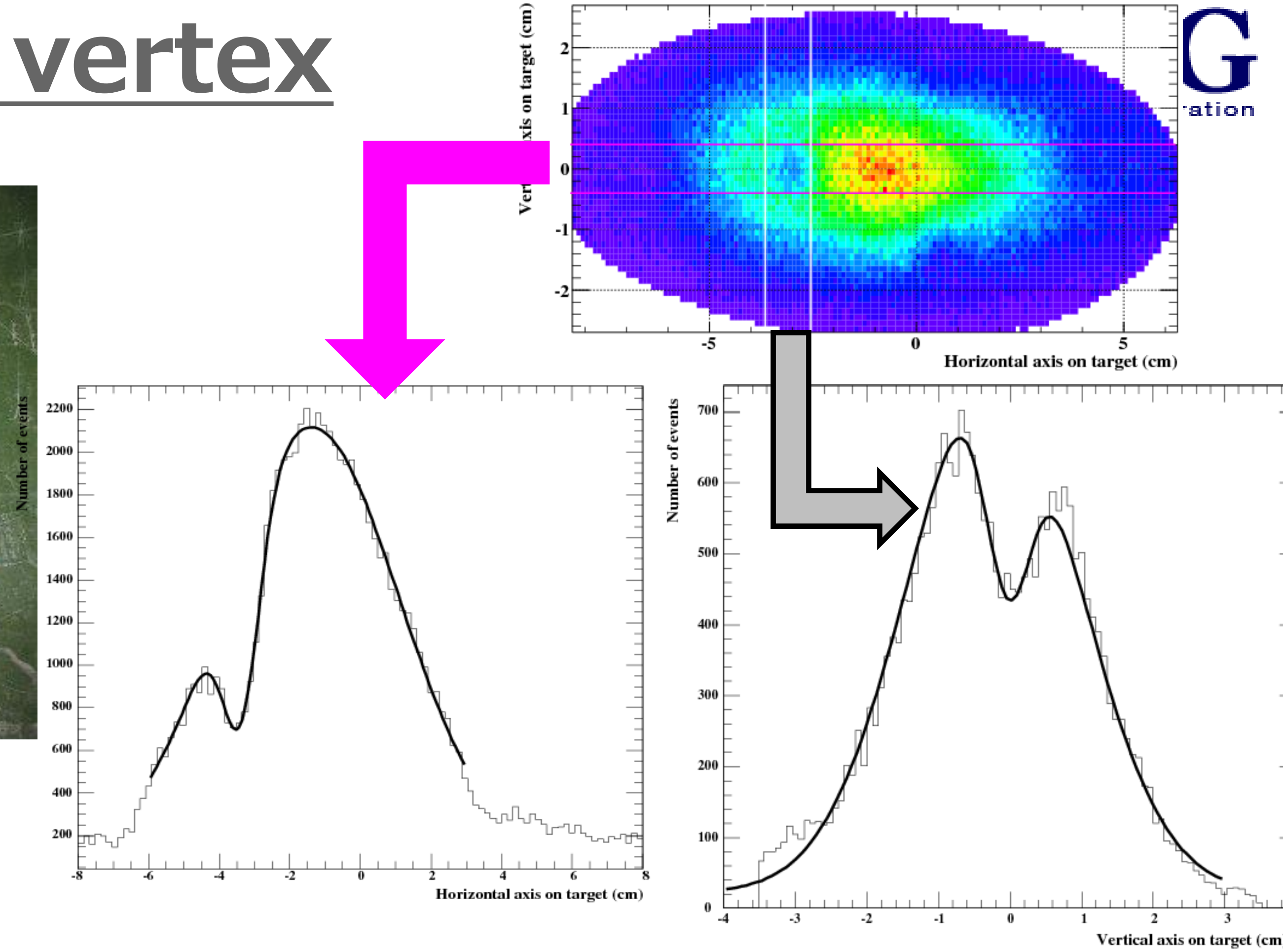


- $\sigma_\theta = 1.45$ deg. $/\sqrt{2}$ $\approx$ **18 mrad.**



- $\sigma_\phi = 0.81$ deg. $/\sqrt{2}$ $\approx$ **10 mrad.**

Muon decay vertex



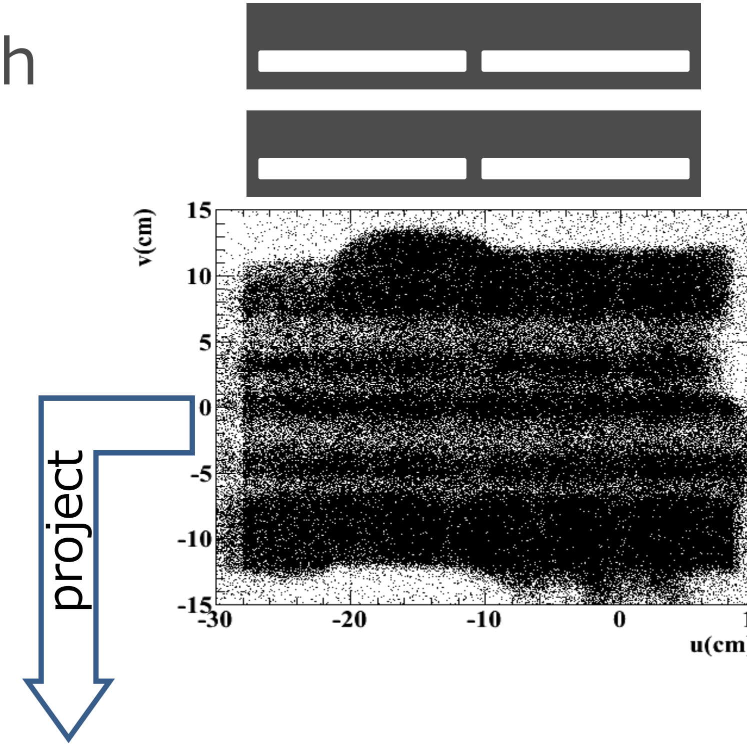
- Reconstruct μ-decay vertex as a point crossing e^+ track and target plane
- Evaluate resolution with
  - Using holes on target
  - Using 2-turn events

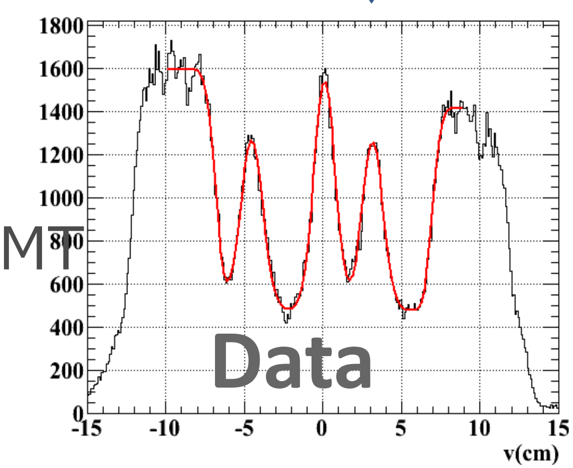
σ_x = 4.5 mm
σ_y = 3.2 mm

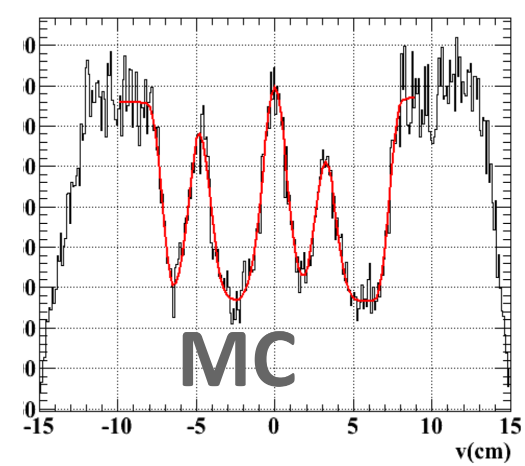
Gamma position

- Evaluate resolution with π^0 run with Pb bricks
  - Shadow of brick gives resolution and bias
  - Results
    - σxy = 4.5~5mm, bias(RMS)=0.7mm
    - Compared with MC
      - 1.8mm worse (in quadrature) than MC (← QE error)
- Detailed study with MC
  - Take in the difference
  - Resolution dependence on relative position to PMT

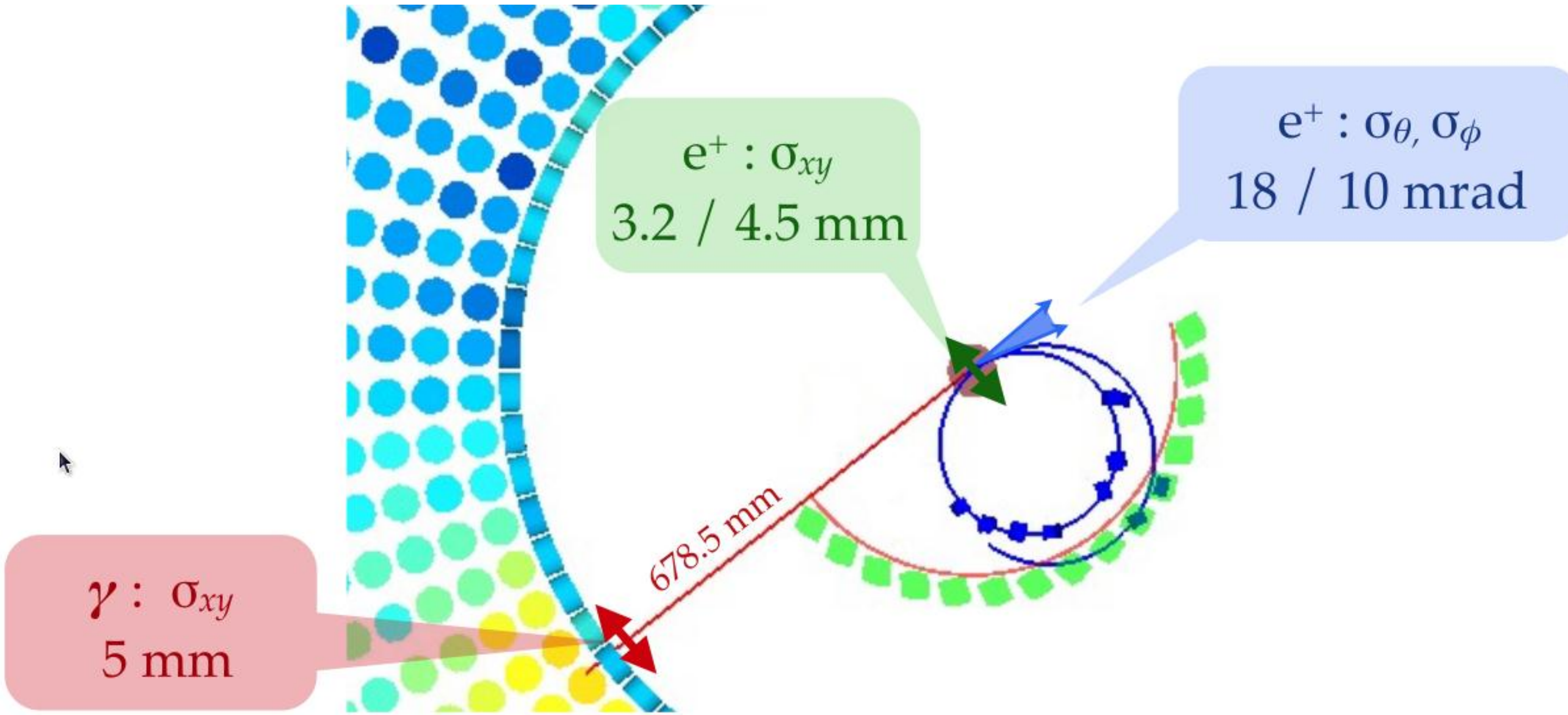
$\sigma_{xy} \sim 5$ mm
$\sigma_r \sim 6$ mm







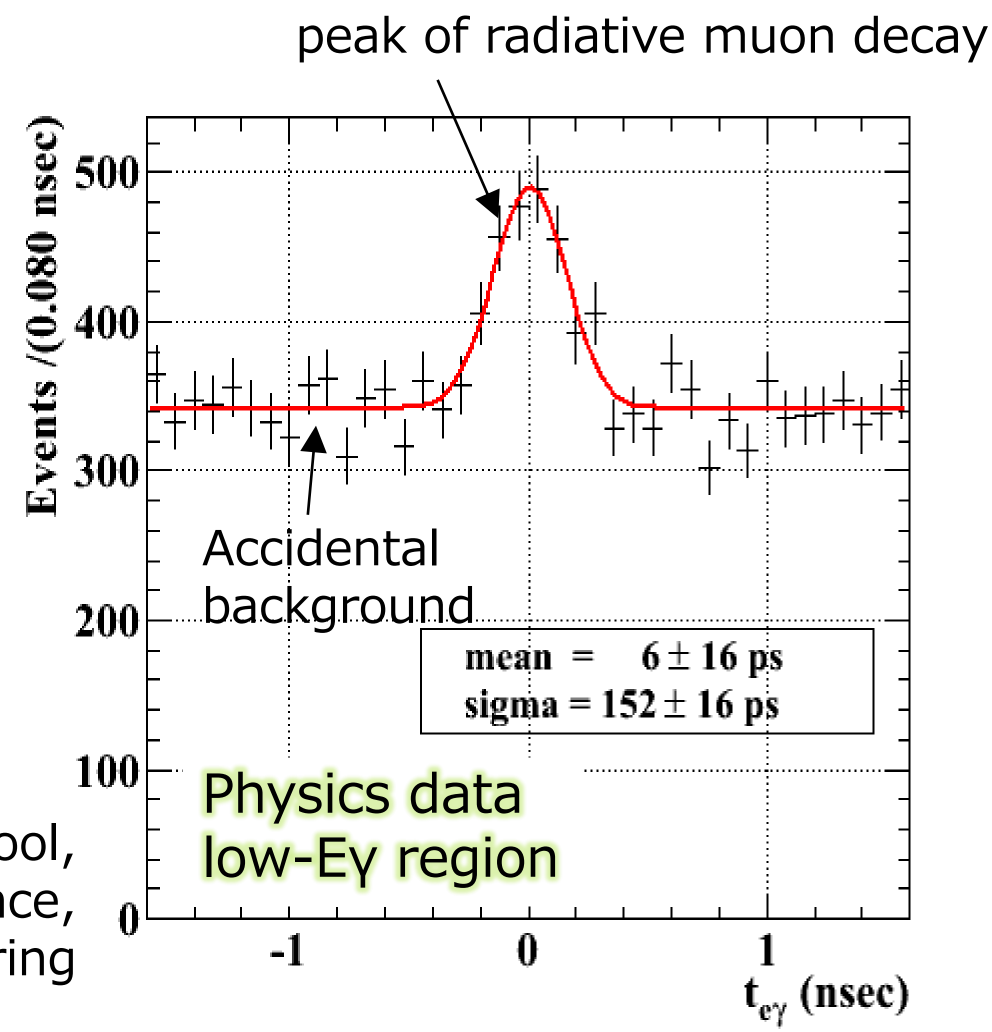
Opening angle



- Not able to measure gamma direction
  - Direction of the line b/w μ-vertex and γ interaction point
- Combined resolution: $\sigma_{\theta e\gamma}$ = 20.6mrad, $\sigma_{\varphi e\gamma}$ = 13.9mrad

Time resolution

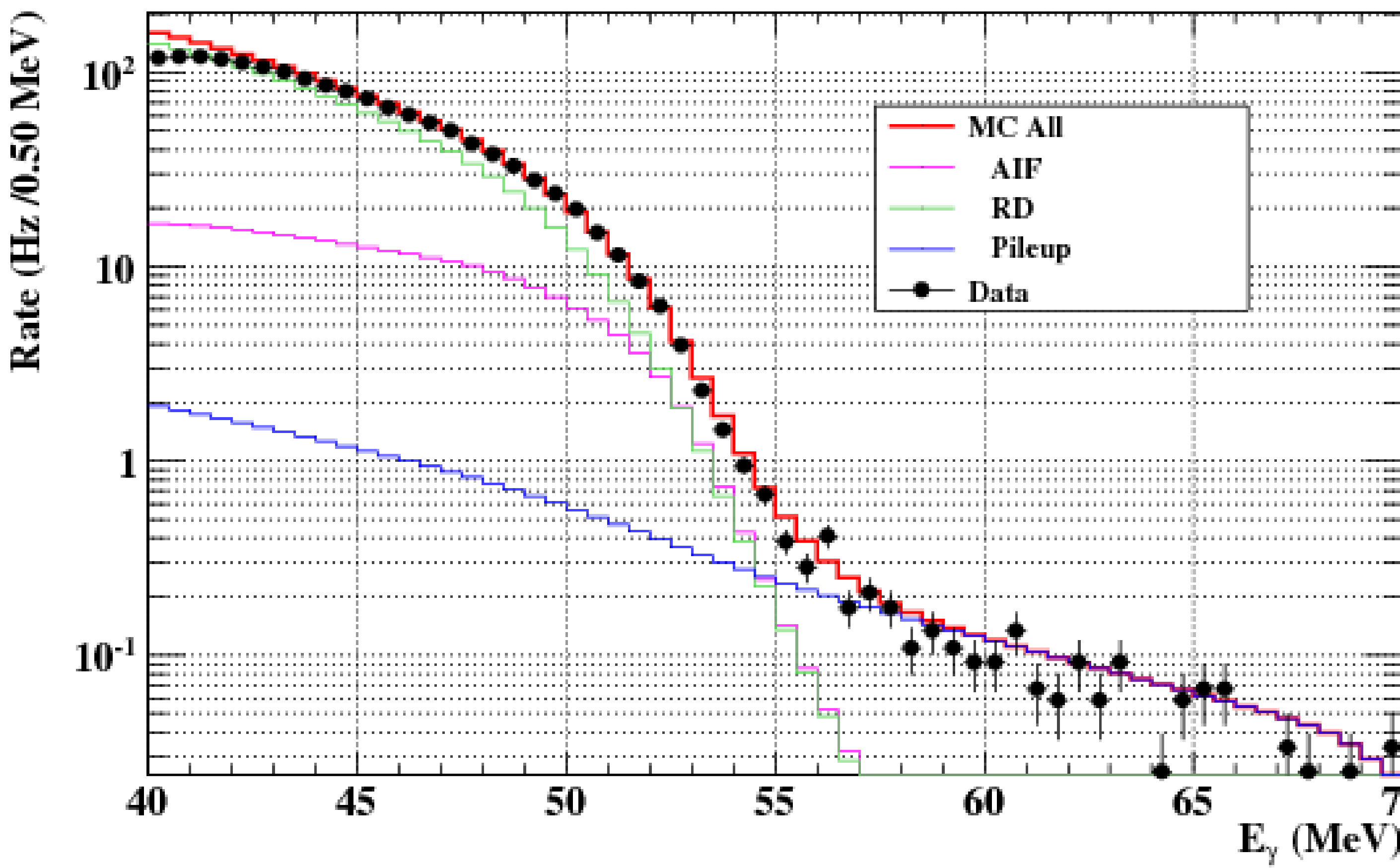
- Reconstruct muon decay time
  - TC hit time - e^+ flight length from DC
  - LXe hit time - γ flight length (line)
  - $\mathbf{t_{e\gamma} = t_{e+} - t_{\gamma}}$
- Observe RMD peak in normal intensity data
- Total resolution
  - small correction for E_γ
  - $\sigma_{te\gamma}$ = 148±27 ps



RMD peak is a powerful time calibration tool, measure all detector contribution at once, in situ monitoring

Background I

- Background rate
  - Measure with self-trigger data
  - Compare with MC
    - Reproduce well the rate and shape



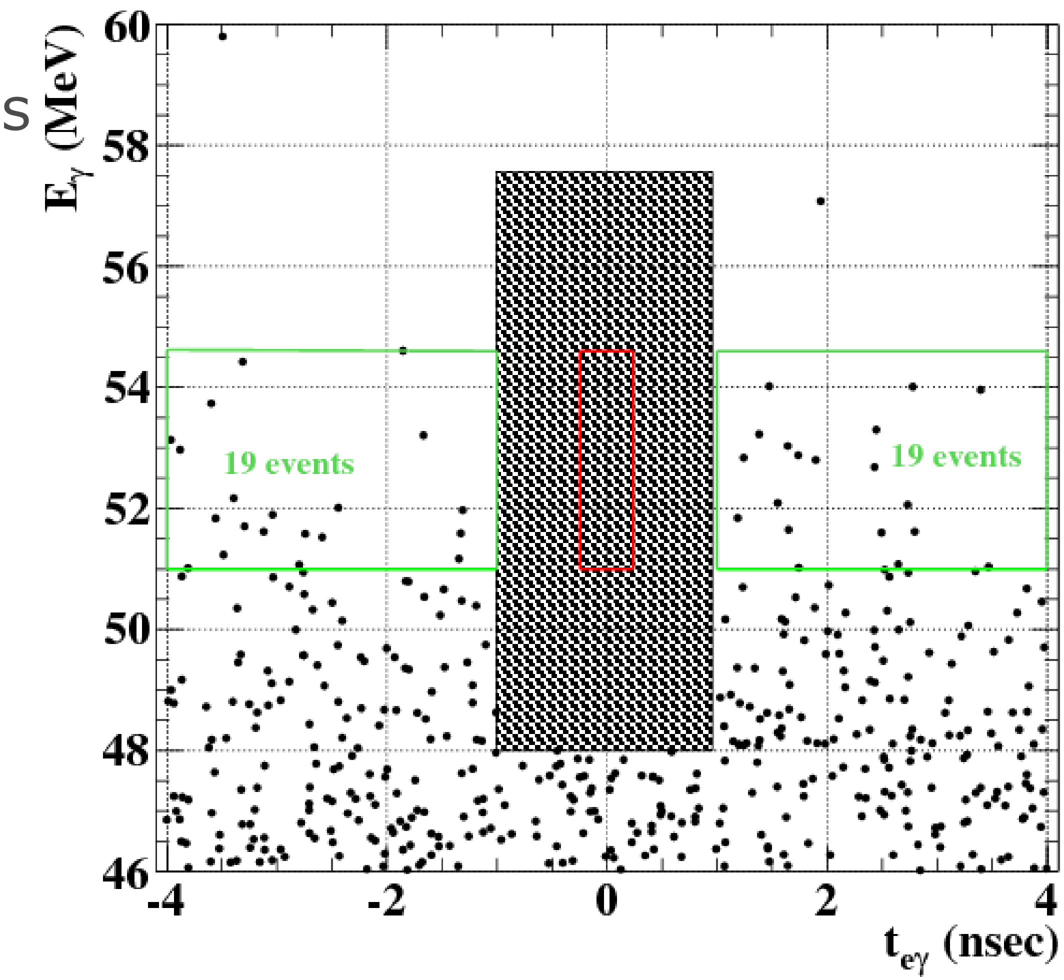
MC
3.7×10^7 μ^+decay/sec
Convolve response
Uncertainty ~7%

Not a fit

Background II

- Background level
  - Difficult to get feeling of BG with likelihood analysis

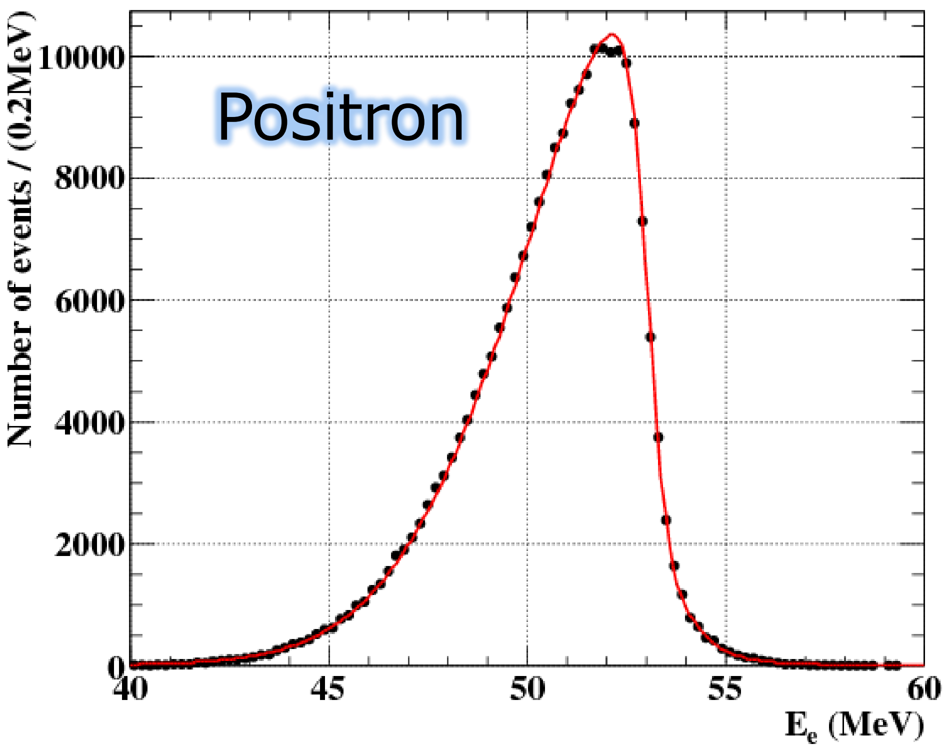
  → Define signal box by resolution (1.64σ)
  - Accidental BG
    - Estimate using sideband
    - Wider time & angle window
    - **0.95±0.15** events
  - RMD events
    - **0.02±0.004** events

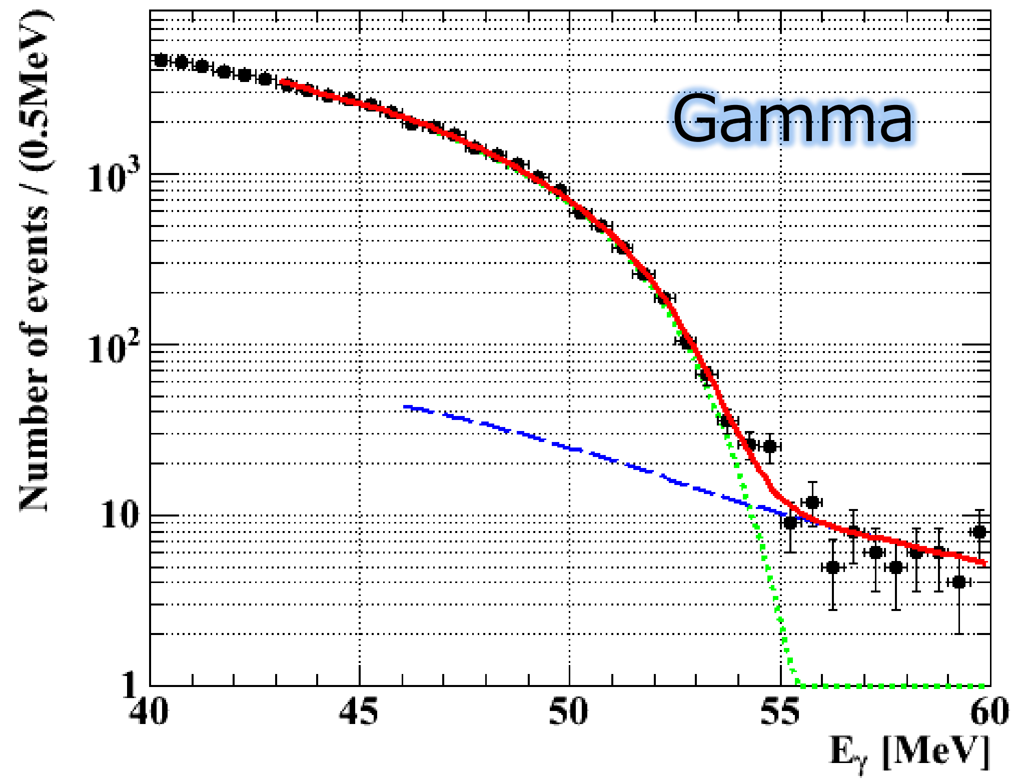


* wider window for angle

Background III

- Obtain BG PDF from time-sideband data





- Smooth function of fitted MC spectrum⊗response as PDF
  - Reduce systematic error from low statistics at high energy
- Position dependent (γ)

Number of muons

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- Normalize signal events by # of muon decays counted in control samples
  - Normalization channel 1: Count Michel e^+
    - Unbiased Michel trigger data mixed in physics run

$$\frac{\mathcal{B}_{e\gamma}}{\mathcal{B}_{e\nu\overline{\nu}}} = \frac{N_{sig}}{N_{MD}} \times \frac{f^E_{e\nu\overline{\nu}}}{P_{e\nu\overline{\nu}}} \times \frac{\epsilon^{trig}_{e\nu\overline{\nu}}}{\epsilon^{trig}_{e\gamma}} \times \underline{\frac{A^{TIC}_{e\nu\overline{\nu}}}{A^{TIC}_{e\gamma}} \times \frac{\epsilon^{DCH}_{e\nu\overline{\nu}}}{\epsilon^{DCH}_{e\gamma}}} \times \frac{1}{\epsilon^{\gamma}_{e\gamma}} \times \frac{1}{A^{\gamma}_{e\gamma}}$$

    - Insensitive to beam-rate or detector-condition variations

Normalization factor

$$\boxed{\mathcal{B}(\mu^+ \rightarrow e^+\gamma) = N_{sig} / (5.2 \pm 0.5)\times 10^{11}}$$

- Cross check with other methods
  - channel 2: Count RMD events
    - In E_γ-sideband
  - channel 3: Accidental BG rate
    - In time-sideband
  - Those three methods are complementary
    - Most of the systematics are independent.
    - Consistency check → good agreement

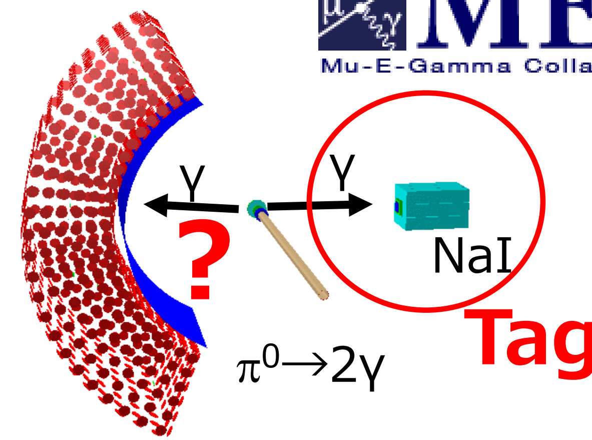
Table 8.2: Summary of normalization.

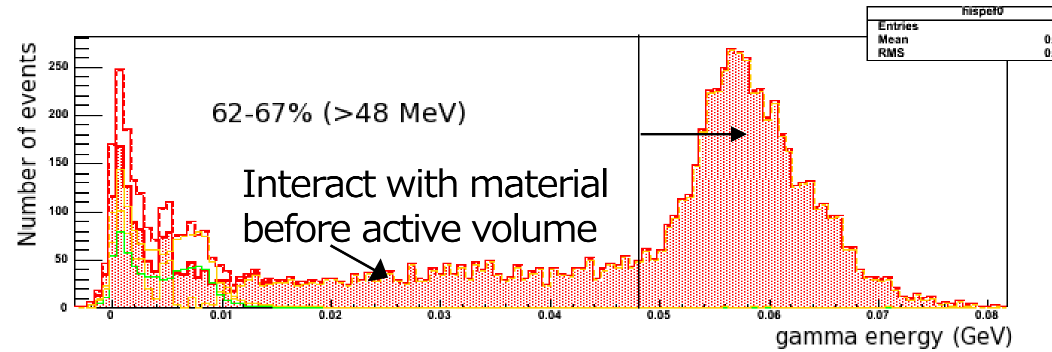
	Michel	RD	BG
k (10^{11})	5.2 ± 0.5	4.4 ± 1.1	5.2 ± 0.8

Gamma efficiency

- Detection efficiency
  - $\pi^0 2\gamma$: NaI single trigger
  - MC
  - μ data single spectrum
  - In analysis region
    (46<E_γ<60 MeV)
    - ε_{det} = 66%

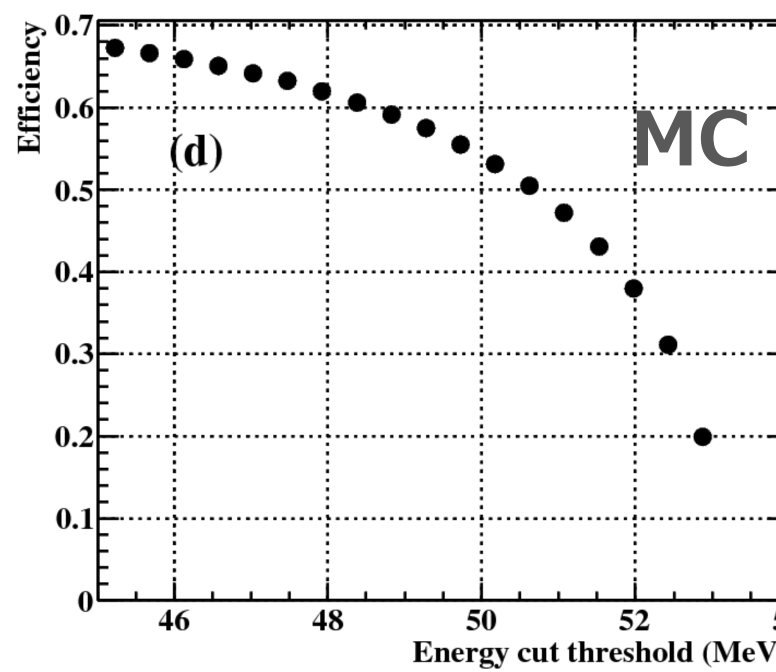
Consistent within 5%





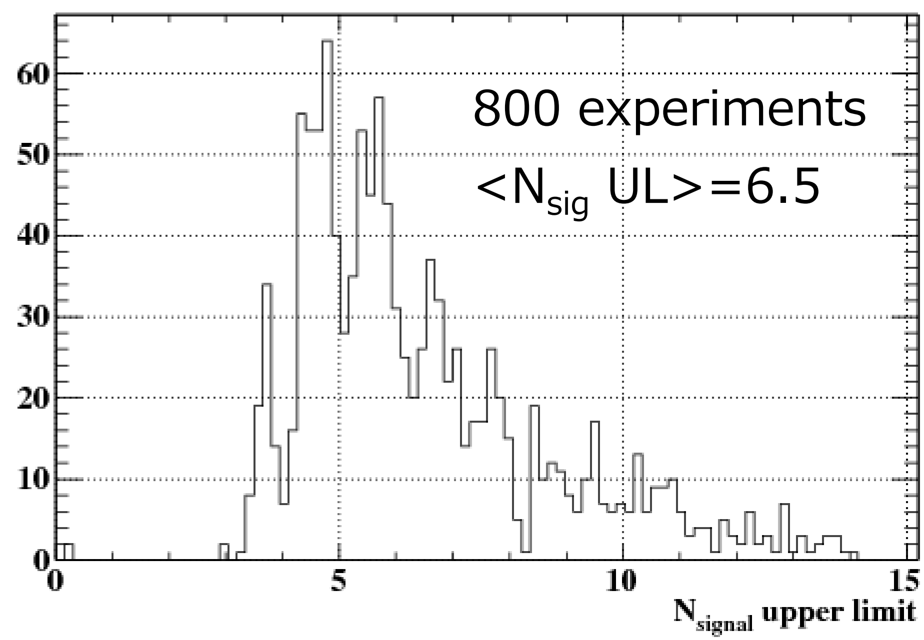
- Analysis efficiency
  - Inefficiency by cuts
    - (pileup cut, CR cut)
    - 5.5%

$$\boxed{\varepsilon_\gamma = (63 \pm 4)\ \%}$$



Sensitivity

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

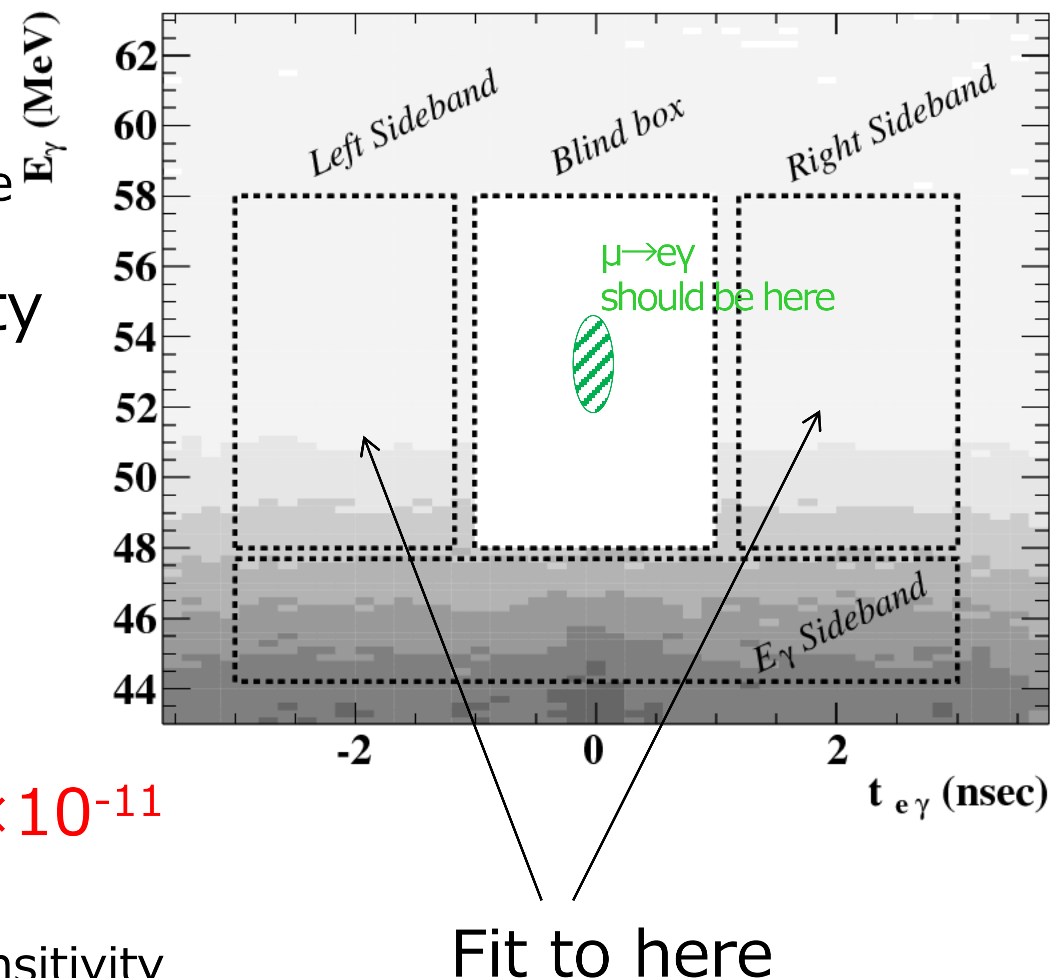


Sensitivity of RUN2008 : 1.3×10^{-11}

c.f. Existing best upper limit: 1.2×10^{-11}

Sideband analysis

- Analyzed real data but off-timing



- No signal in sidebands
- Our dominant BG is accidental one

→ Good test of our sensitivity

Results of likelihood analysis

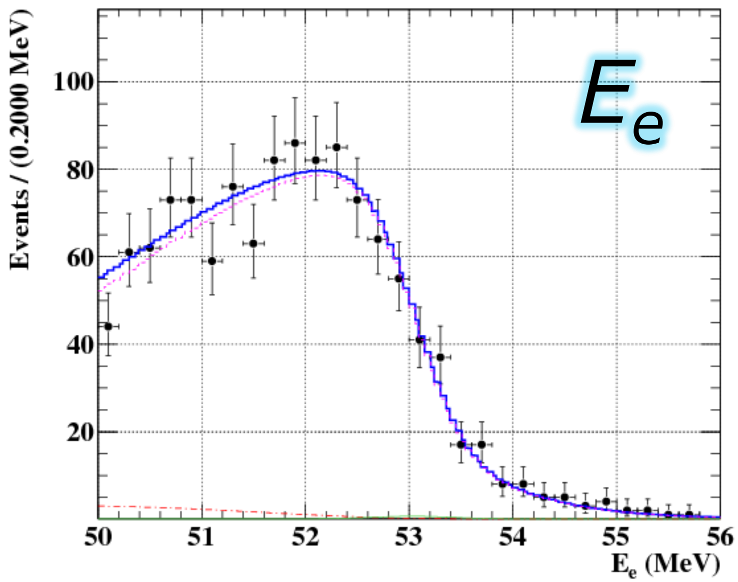
$\mathcal{B}(\mu\rightarrow e\gamma) <$ 0.9×10^{-11}, 2.0×10^{-11}

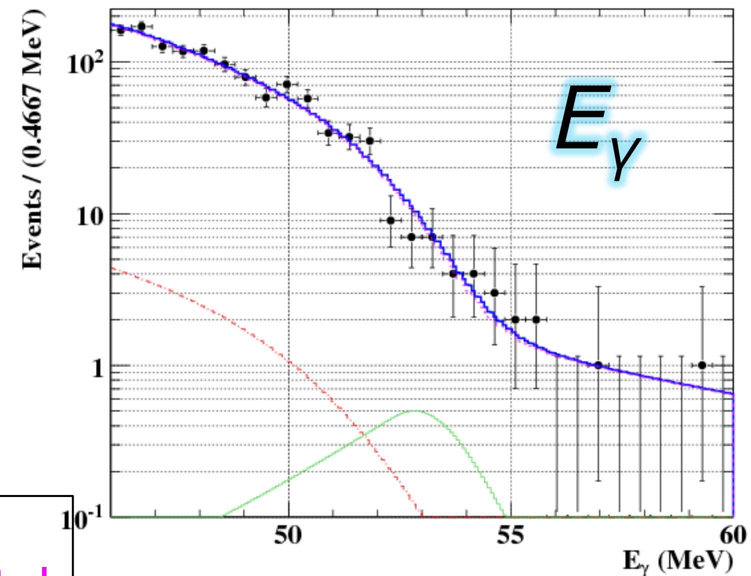
consistent with the sensitivity

Result

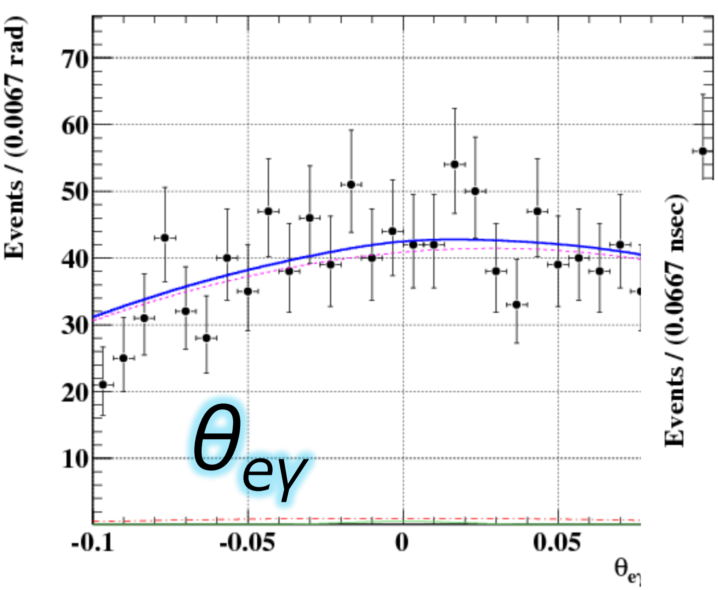
Opened the blind box …

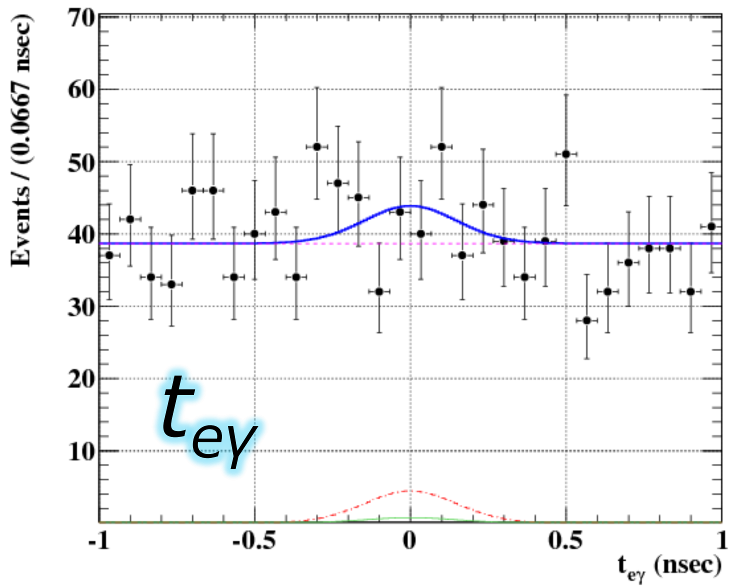
Fit to data (projected distributions)

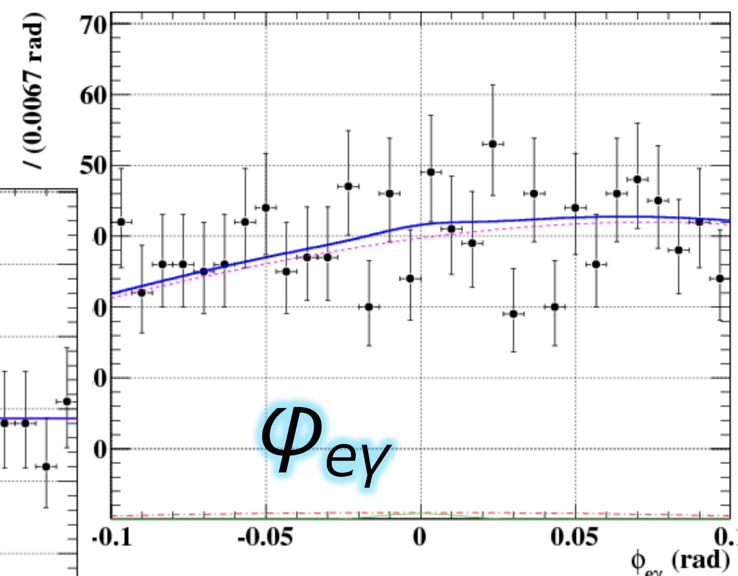




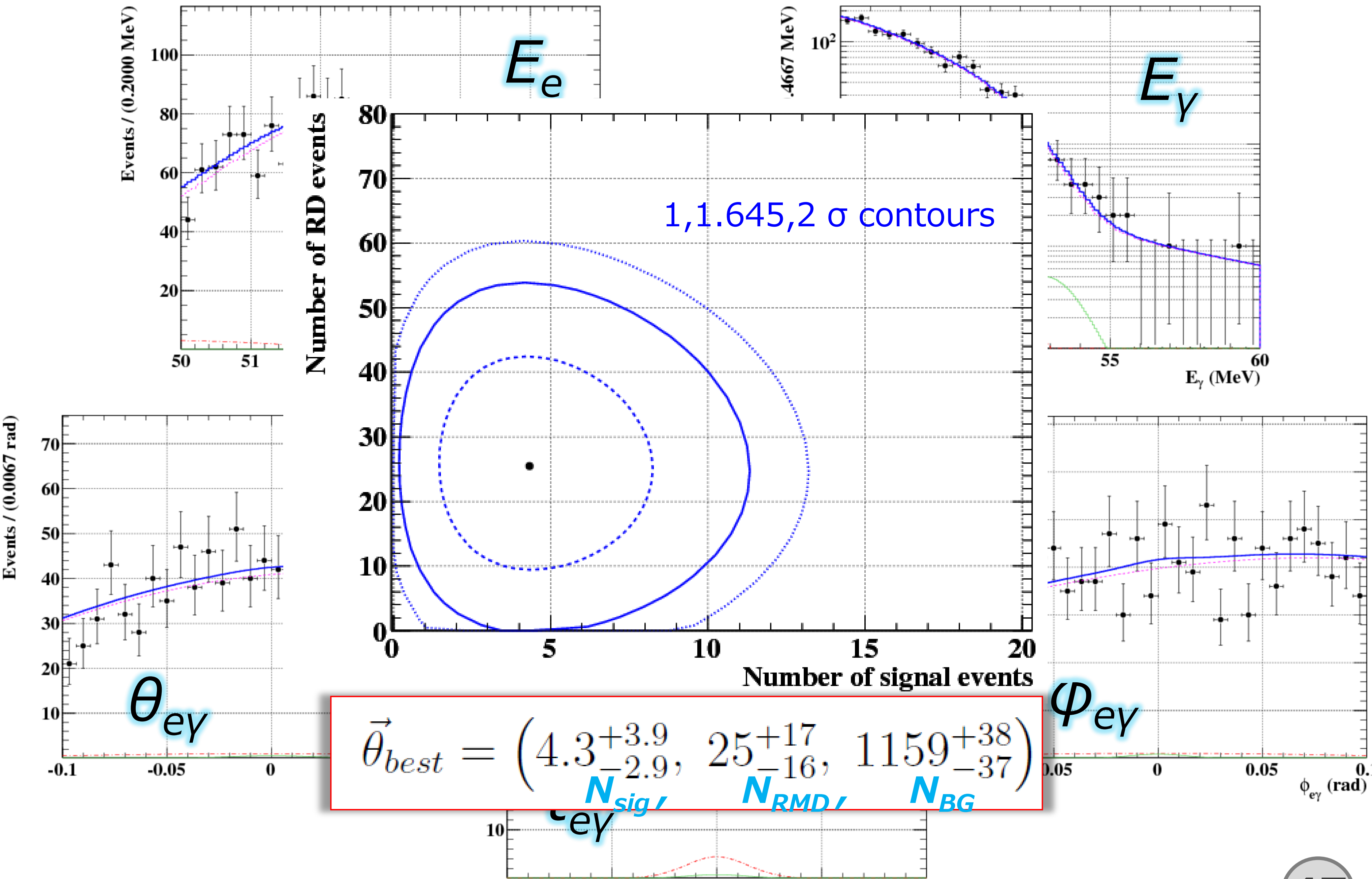
Total
Accidental
Radiative
Signal







Fit to data (likelihood function)



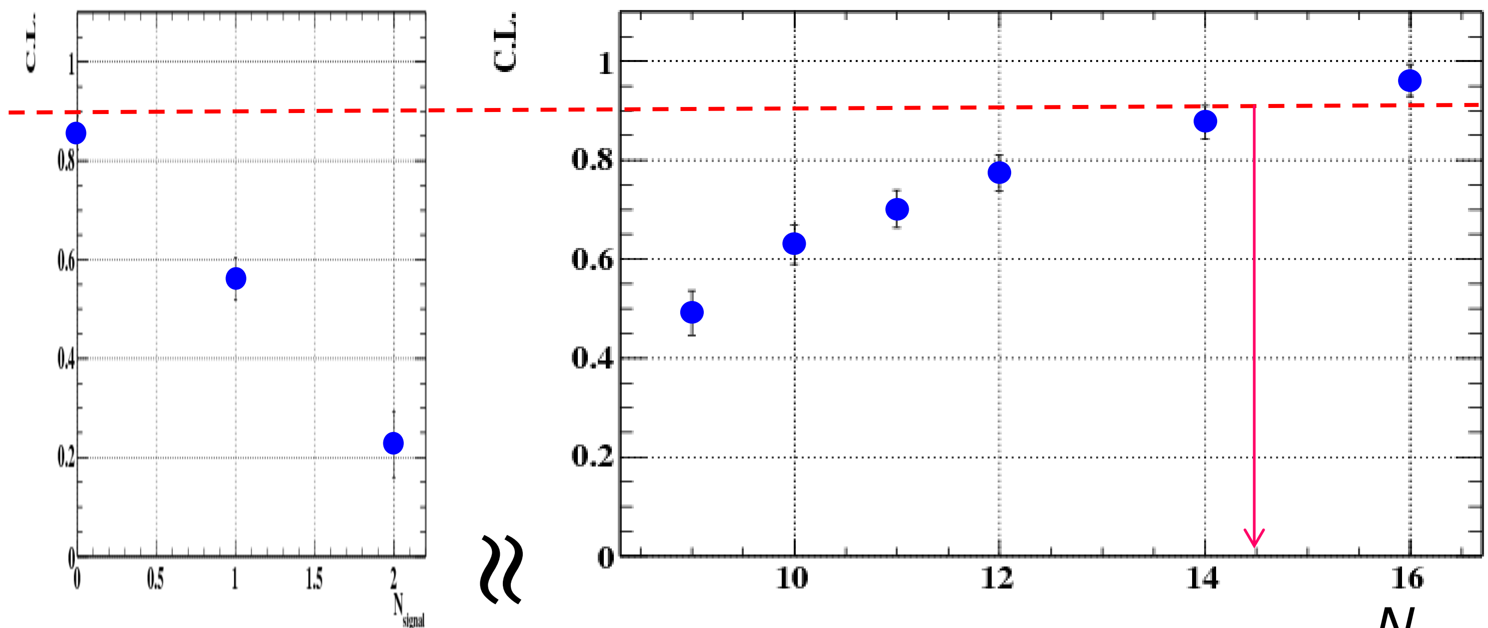
$$\vec{\theta}_{best} = \left(4.3^{+3.9}_{-2.9},\ 25^{+17}_{-16},\ 1159^{+38}_{-37}\right)$$

N_{sig}, N_{RMD}, N_{BG}

Upper limit on Nsig

- Set confidence region with Frequentist approach
  - Feldman-Cousins method in (N_{sig},N_{RMD}) 2D plane

Scan on N_{RD} best-fit value



N_{sig}

- 90% confidence interval contains $N_{sig} = 0$
- The upper limit is given as $N_{sig} < 14.5$

Systematic uncertainties

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- Estimate the impact of systematics by performing fit with alternative parameters
  - See the variation of the best-fit N_{sig} value
  - UL : 14.5 → 14.7

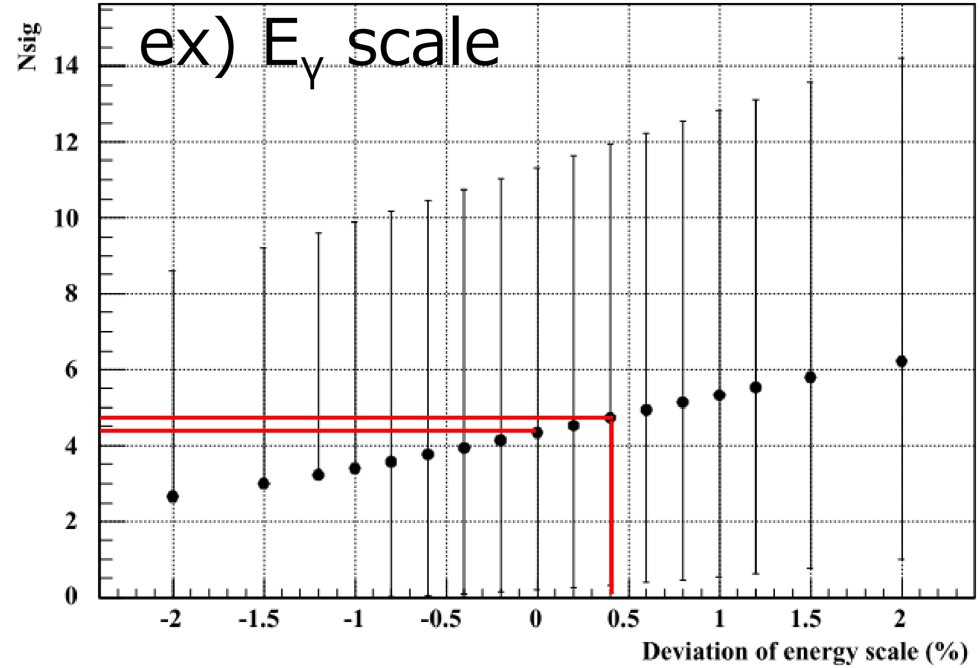

Table 8.4: Summary of systematic uncertainties.

factor	estimated value	impact on N_{sig}
Gamma-ray energy scale	0.4%	0.4
Gamma-ray energy resolution	10-15%	negligible
Positron spectrum	–[1]	1.14
Angular resolution	1 mrad	0.35
Time resolution	17 ps	negligible
Time center	16 ps	negligible
Normalization factor	10%	–

[1]given as alternative parameter sets.

Precision of 55MeV peak :0.08%
Trace of light yield :0.3%
Uncert of gain shift corr. : 0.2%
Total : 0.4%

Gamma: 6%
Positron: 7%

Discussion

Why the obtained UL is much larger than the sensitivity?

Candidate events

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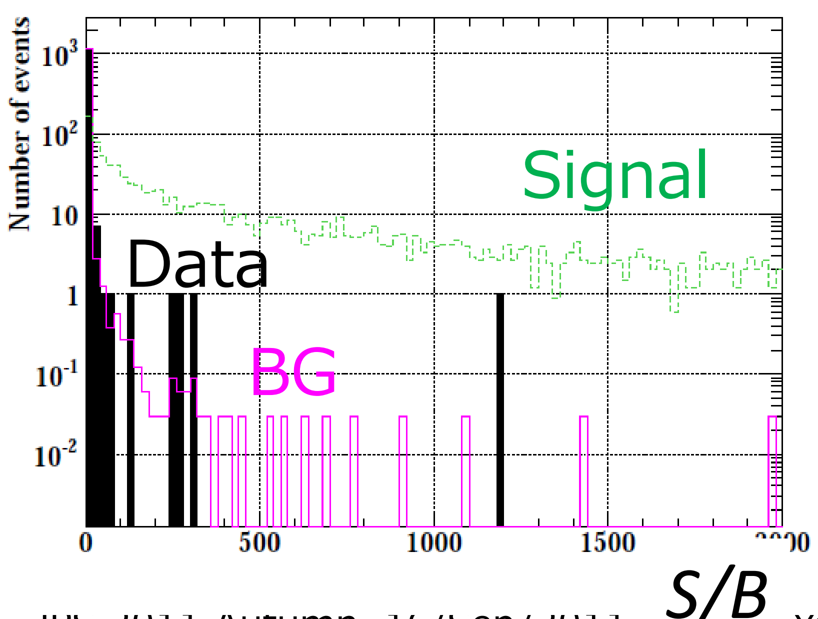
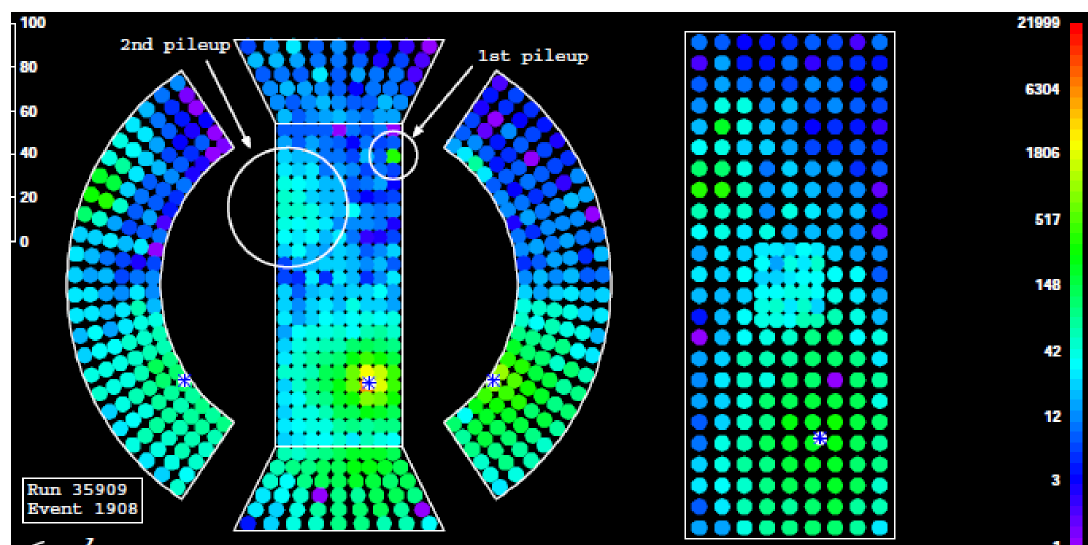
Table 8.6: List of events with large likelihood ratio S/B.

Run/Event	E_e (MeV)	E_γ (MeV)	$t_{e\gamma}$ (ps)	$\theta_{e\gamma}$ (mrad)	$\phi_{e\gamma}$ (mrad)	S/B
35909/1908	52.7	54.1	-262	9.5	6.3	1206.6
34221/2058	52.6	50.8	60.2	3.3	1.8	303.2
30109/1371	52.5	51.6	-50.8	-11.9	11.3	271.9
40330/ 853	53.2	50.7	82.0	-28.6	-2.3	250.4
40077/1210	53.8	50.1	143.6	3.0	14.4	128.6

- Rank events by event-type likelihood ratio *S/B*
- Found the most signal-like event is double-pileup event
  - Pileup elimination only worked on the 1st pileup γ
  - If we eliminate the 2nd one as well, then E_γ was 47.7 MeV



Most likely, this event is an accidental BG



Impact of the candidate event

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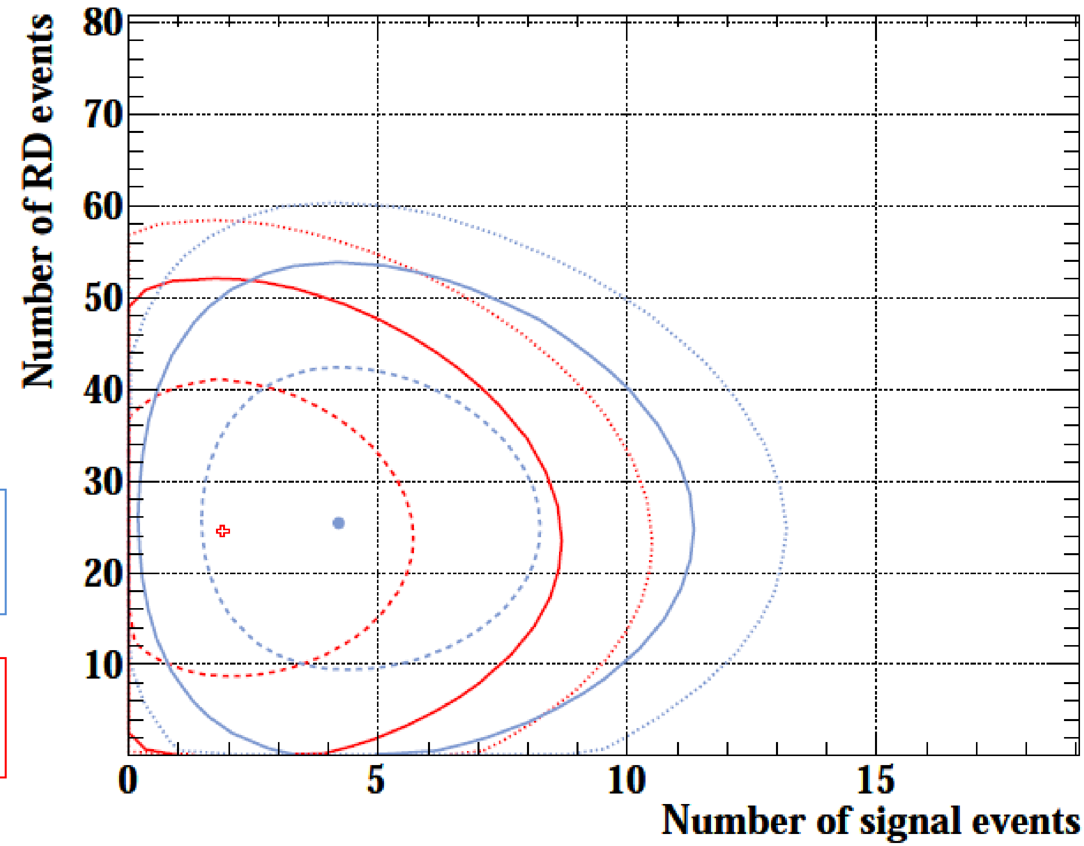
- Investigate impact of the event
  - Set lower threshold for pileup search
  - to eliminate the 2nd pileup
  - Repeat the analysis



$$\vec{\theta}_{best} = \left(4.3^{+3.9}_{-2.9},\ 25^{+17}_{-16},\ 1159^{+38}_{-37}\right)$$

$$\vec{\theta}_{best} = (2.0^{+3.8}, 24^{+17}_{16}, 1119^{+37}_{-37}).$$

- N_{sig} UL becomes 11.4 (←14.5)
  - Probability of N_{sig} UL > 11.4 is 5%

Cut analysis

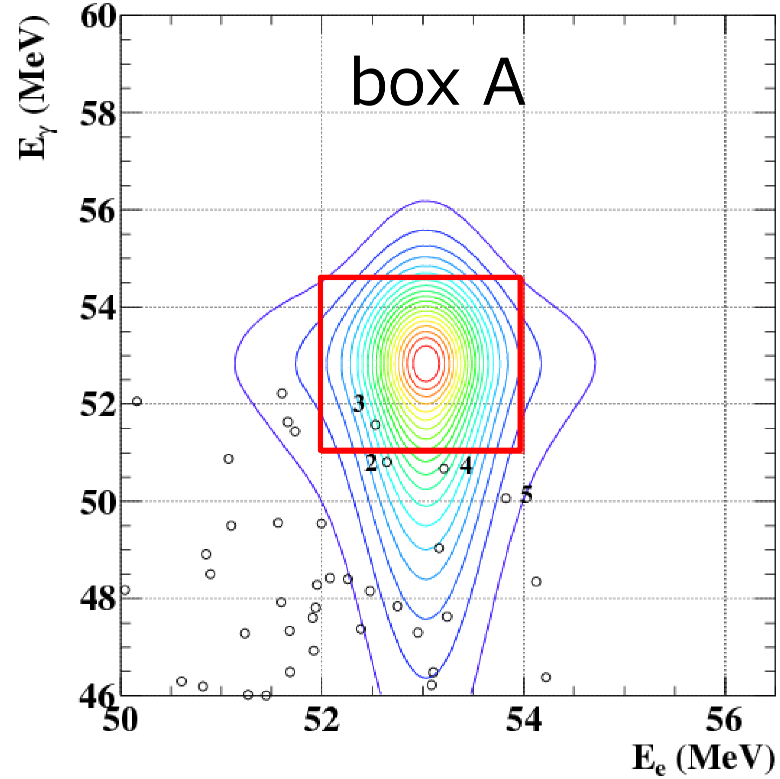
- For cross-check and better understanding BG, performed cut analysis
  - Two signal boxes
    - A : 1.64σ box
    - B ; Optimized box

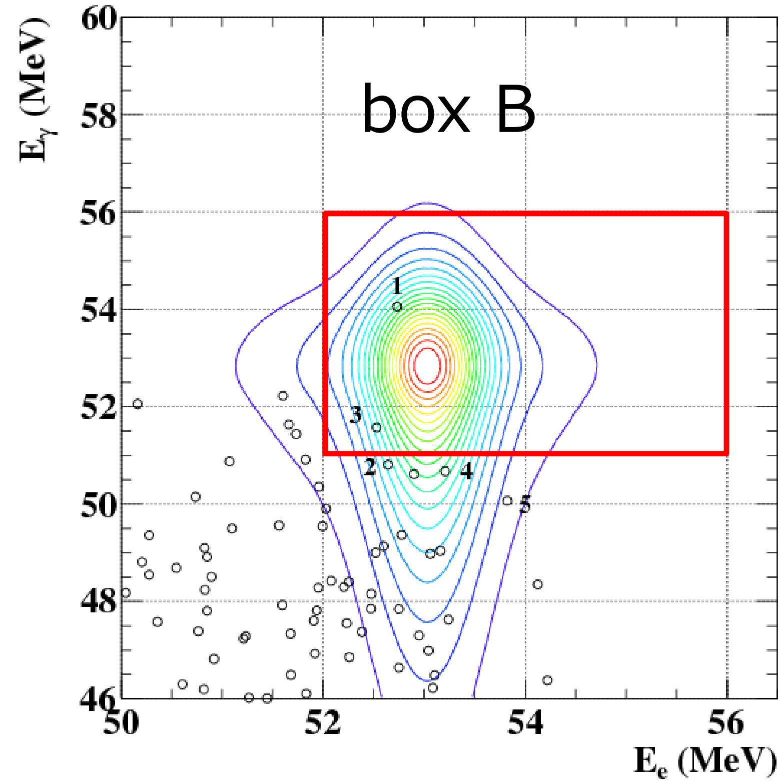
Table 8.5: Summary of cut analyses.

	1.64σ box (A)		optimized box (B)	
	range	($\epsilon_{\rm rel}$)	range	($\epsilon_{\rm rel}$)
E_e (MeV)	[52.2, 53.8]	(0.85)	[52.0, 56.0]	(0.92)
E_γ (MeV)	[51.0, 54.6]	(0.64)	[51.0, 56.0]	(0.70)
$\lvert t_{e\gamma}\rvert$ (ps)	< 242	(0.90)	< 273	(0.94)
$\phi - \Theta_{e\gamma}$ (mrad)	< 33	(0.80)	< 42	(0.94)
SES (10^{-12})	5.0	(0.39)	3.5	(0.56)
$N_{BG}^{\rm exp} + N_{RD}^{\rm exp}$	0.95+0.02		2.08+0.03	
$N^{\rm obs}$	1		2	
Upper limit (10^{-11})	1.68		1.32	

BG are well consistent with the expectations

$$\mathcal{B}_{\rm boxA} < 1.7 \times 10^{-11},$$
$$\mathcal{B}_{\rm boxB} < 1.3 \times 10^{-11}$$





Discussion

- The large UL is considered to be statistical fluctuation
  - A very rare event is observed accidentally
  - If we set different pileup threshold, then the result is well consistent with
    - Null result
    - Sensitivity
    - Cut analysis
- Nevertheless, the obtained UL is statistically valid without any bias

Table 8.7: Summary of the upper limit and sensitivity.

	$\mathcal{B}$ upper limit[1] (10^{-11})
Analysis window	2.8
Analysis window (tighter pileup cut)	2.2
Cut analysis (optimized box)	1.3
Sideband ($t_{e\gamma} > 0$)	2.0
Sideband ($t_{e\gamma} < 0$)	0.89
Sensitivity	1.3

[1] before incorporating systematic uncertainties.

MEG RUN2008 result

$$\mathcal{B}(\mu^+ \to \mathrm{e}^+\gamma) < 2.8 \times 10^{-11}$$

$$(90\ \%\mathrm{C.L.})$$

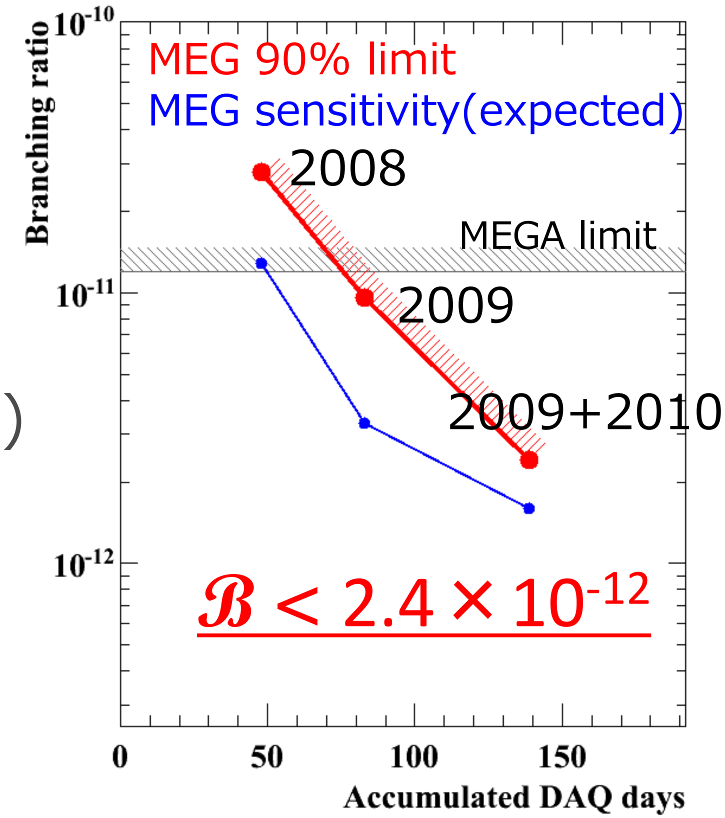
- MEGA UL : 1.2×10^{-11}
- MEG2008 sensitivity : 1.3×10^{-11}

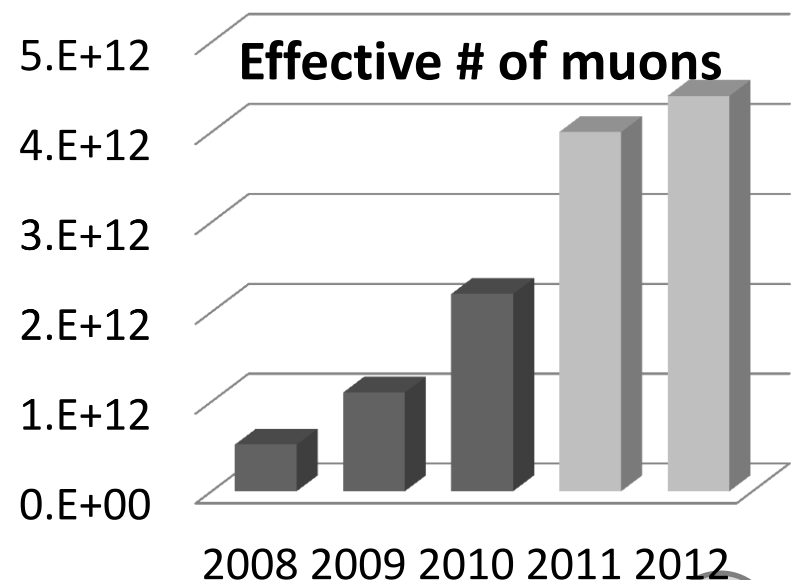
Status & prospect

- Before 2009 run,
  - solved DCH discharge problem
  - reached full LXe light yield → stable
  - improved trigger efficiency (66→91%)

- Many improvement in analysis
  - For the latest result, see talks in this meeting
    - 17pSE2-3: LXe detector
    - 17pSH1: e^+ spectrometer
    - 19aSD1: Detector performance
    - 19aSD2: Physics analysis & result

- MEG is running
  - Run at least until the end of 2012
  - to reach our goal of sensitivity a few $\times 10^{-13}$





Conclusion

- We started MEG data taking in Sep. 2008.
- Searched for lepton-flavor violating decay $\mu^+ \to e^+\gamma$ with sensitivity 1.3×10^{-11}
  - Observed some excess, but still consistent with null signal
- Set an upper limit:

$$\mathcal{B}(\mu^+ \to e^+\gamma) < 2.8\times10^{-11} \quad @\ 90\%\ C.L.$$

  - The first result of MEG experiment
  - Could not give a record limit, but set an independent limit with a comparable sensitivity search

- MEG is putting more & more stringent limit on new physics, with possibility of the discovery.

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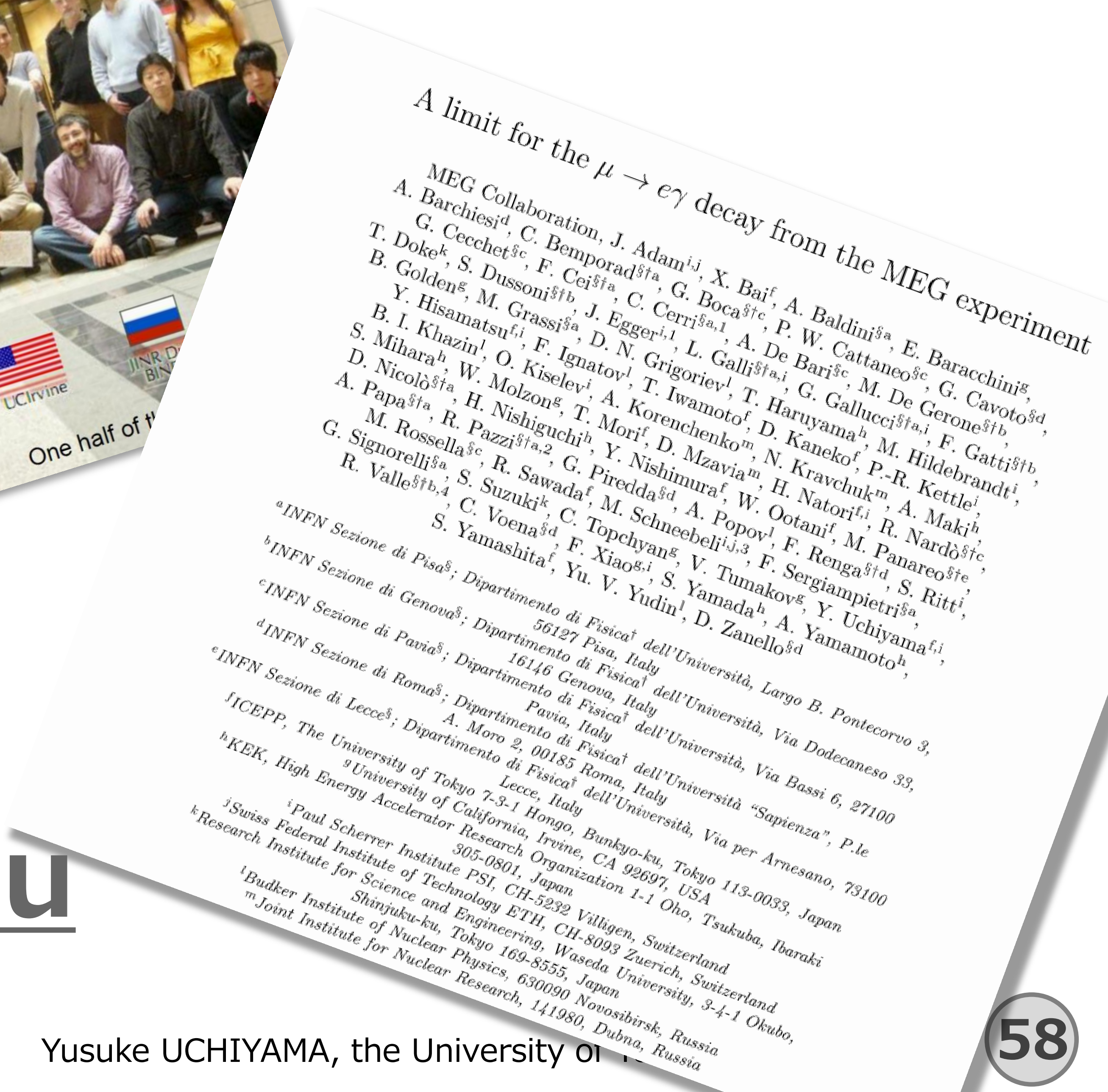

A limit for the $\mu \to e\gamma$ decay from the MEG experiment

MEG Collaboration, J. Adam[i,j], X. Bai[f], A. Baldini[§a], E. Baracchini[g], A. Barchiesi[d], C. Bemporad[§†a], G. Boca[§†c], P. W. Cattaneo[§c], G. Cavoto[§d], G. Cecchet[§c], F. Cei[§†a], C. Cerri[§a,1], A. De Bari[§c], M. De Gerone[§†b], T. Doke[k], S. Dussoni[§†b], J. Egger[i,1], L. Galli[§†a,i], G. Gallucci[§†a,i], F. Gatti[§†b], B. Golden[g], M. Grassi[§a], D. N. Grigoriev[l], T. Haruyama[h], M. Hildebrandt[i], Y. Hisamatsu[f,i], F. Ignatov[l], T. Iwamoto[f], D. Kaneko[f], P.-R. Kettle[i], B. I. Khazin[l], O. Kiselev[i], A. Korenchenko[m], N. Kravchuk[m], A. Maki[h], S. Mihara[h], W. Molzon[g], T. Mori[f], D. Mzavia[m], H. Natori[f,i], R. Nardò[§†c], D. Nicolò[§†a], H. Nishiguchi[h], Y. Nishimura[f], W. Ootani[f], M. Panareo[§†e], A. Papa[§†a], R. Pazzi[§†a,2], G. Piredda[§d], A. Popov[l], F. Renga[§†d], S. Ritt[i], M. Rossella[§c], R. Sawada[f], M. Schneebeli[i,j,3], F. Sergiampietri[§a], G. Signorelli[§a], S. Suzuki[k], C. Topchyan[g], V. Tumakov[g], Y. Uchiyama[f,i], R. Valle[§†b,4], C. Voena[§d], F. Xiao[g,i], S. Yamada[h], A. Yamamoto[h], S. Yamashita[f], Yu. V. Yudin[l], D. Zanello[§d]

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[f] ICEPP, The University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
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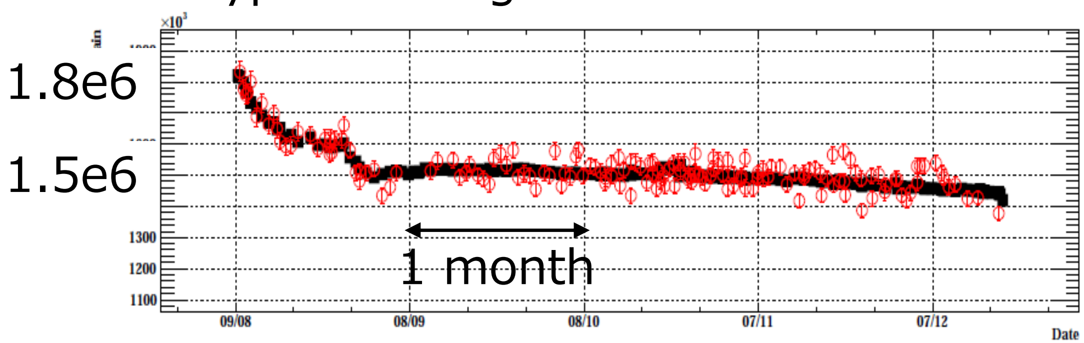
[k] Research Institute for Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan
[l] Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia
[m] Joint Institute for Nuclear Research, 141980, Dubna, Russia

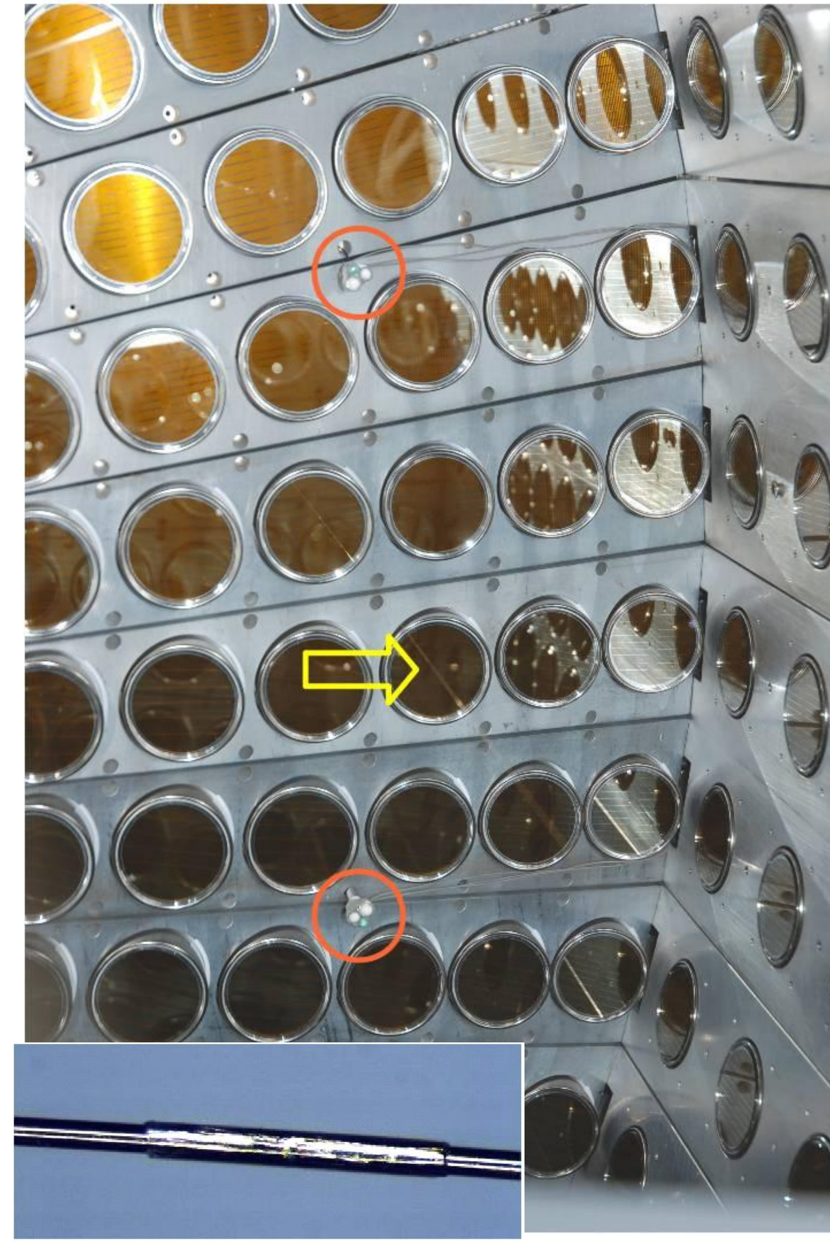
Thank you

Calibration1: PMT

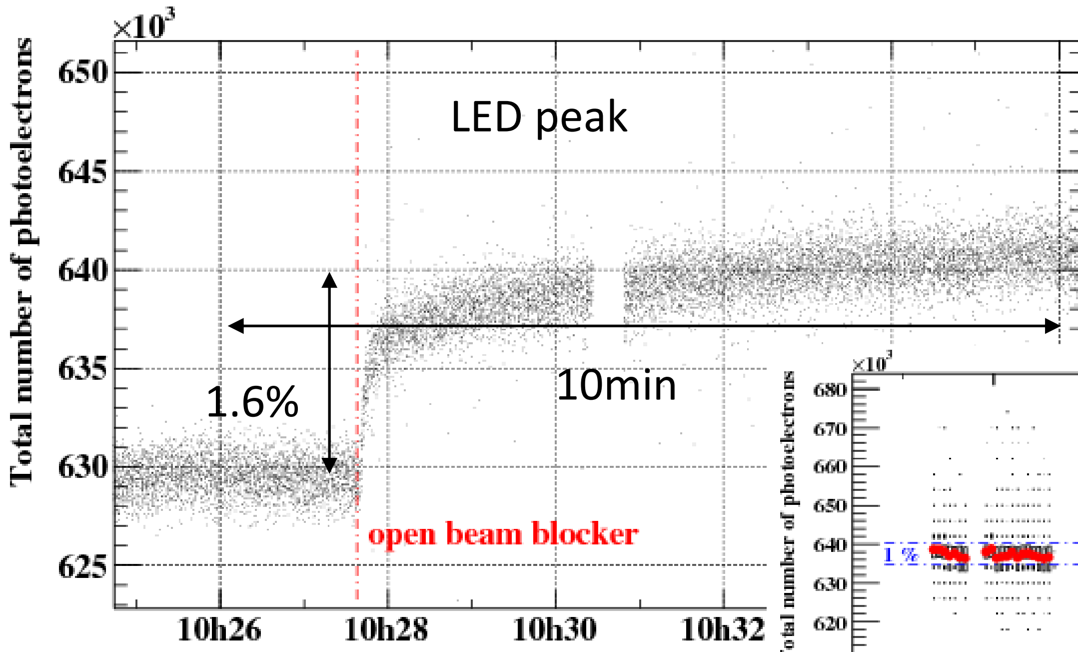
- LED, α source inside LXe volume
  - frequent & precise calibration
    - daily

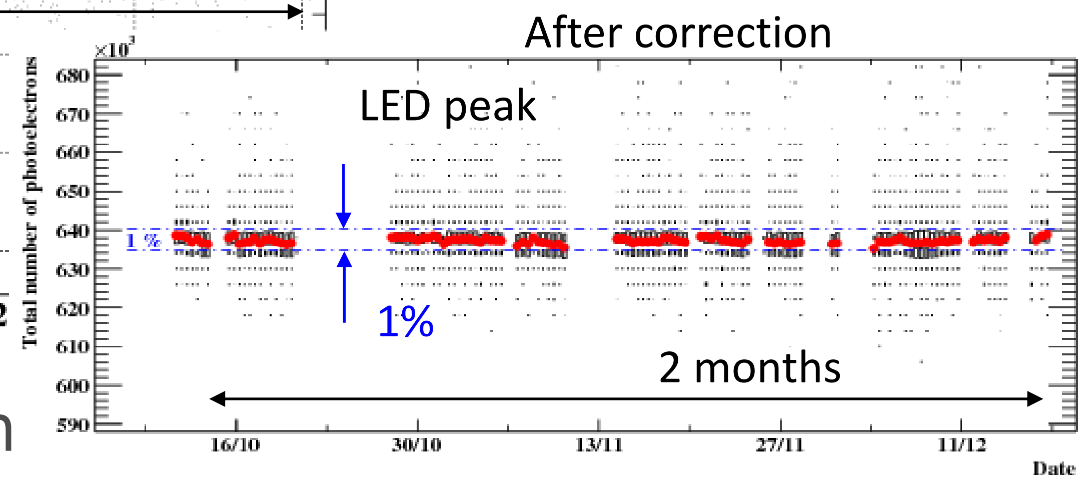
Typical PMT gain evolution





LXe PMT rate dependent gain shift



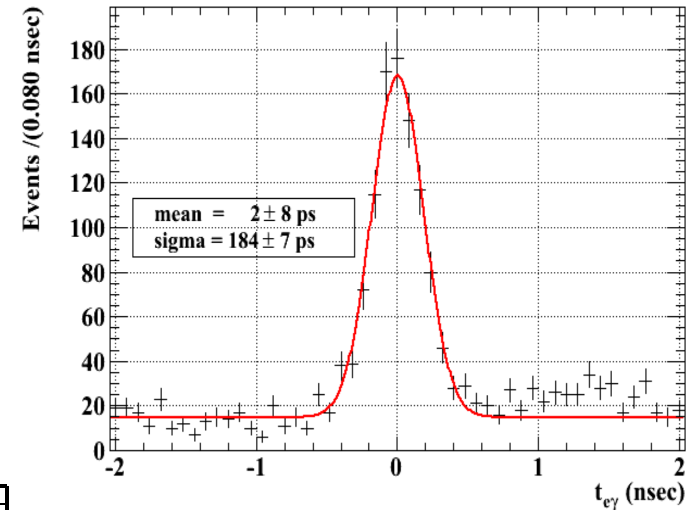


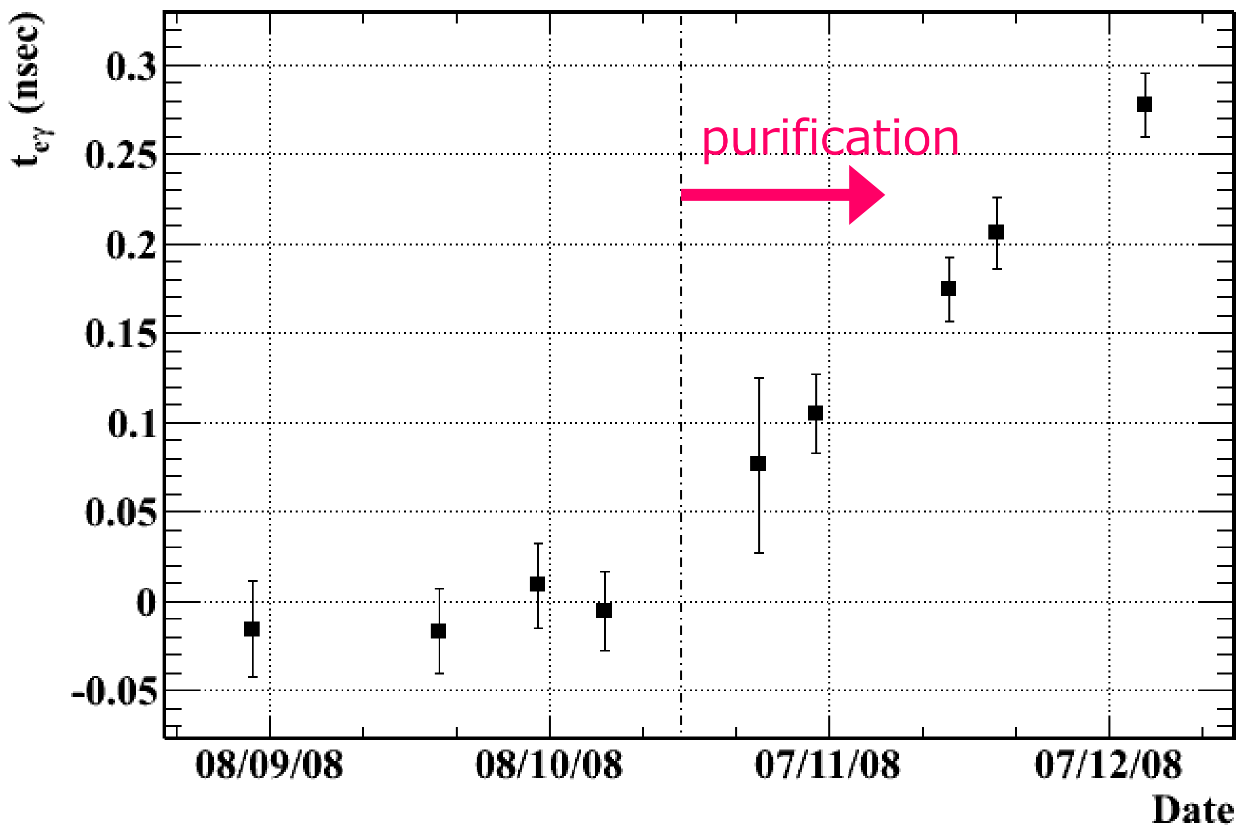
- Observed shift of PMT gain
  - Time scale of some dozens of minutes
  - Rate dependent
  - However, the amount of the shift is stable over long period
- Measure LED during beam on, correct with beam info
  - Correct with precision of 0.1 %
  - However, shift in π^0 run was unknown
    → Uncertainty of energy scale

December π^0 run

Time measurement

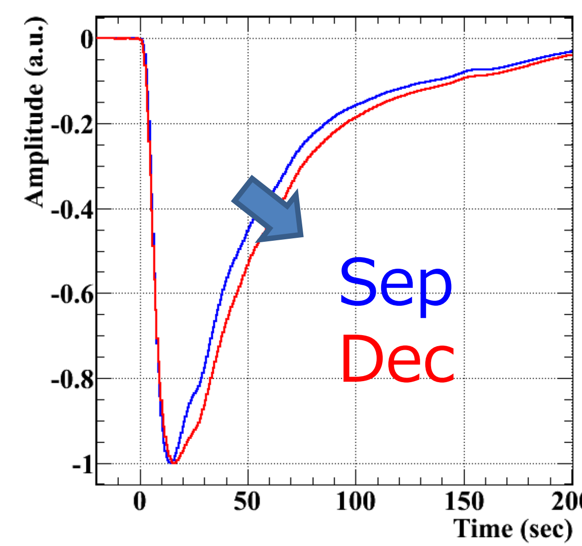
- Monitor & correct t_0 with RMD peak in low intensity run
  - 24 h/week, ×25 lower μ^+ intensity
  - Much better S/N





Observe drift of t_0

- due to change of LXe pulse shape
- as improvement of purity



Stability after the correction < 20 psec

Confidence Region

- Calculate 2D confidence region in (N_{sig},N_{RD}) with **Feldman-Cousins method**
  - At each point (N_{sig},N_{RD}), conduct many toyMC experiments
  - Calculate likelihood ratio for each experiment
    - $R_{data} = L_{data,max} / L_{data}(N_{sig},N_{RD})$
    - $R_{MC} = L_{MC,max} / L_{MC}(N_{sig}, N_{RD})$
  - If the number of experiments with $R_{data} < R_{MC}$ is less than 90%, then the point (N_{sig},N_{RD}) is in the 90% confidence region
- Found there is no correlation between (N_{sig},N_{RD}) from the shape of likelihood function
- **Upper limit** (or confidence interval) on N_{sig} is on the best fit N_{RD}

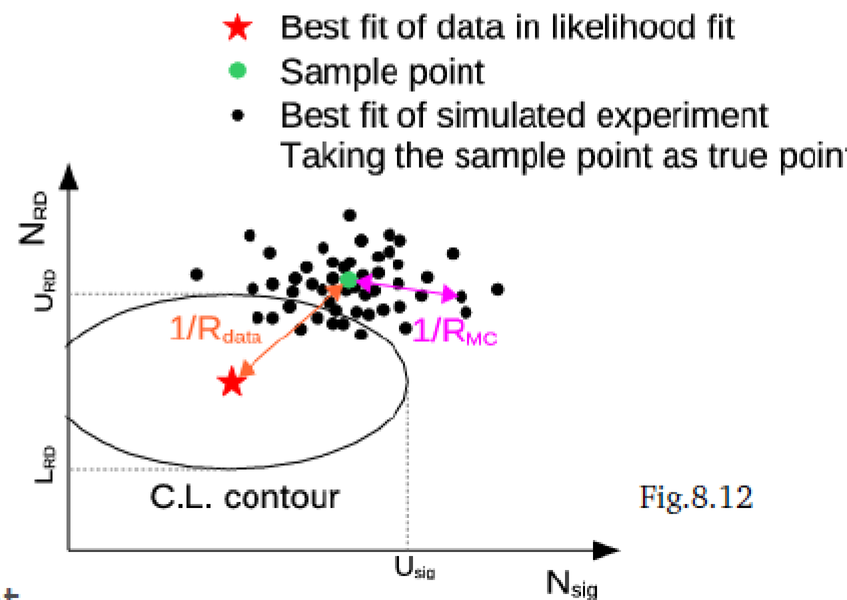
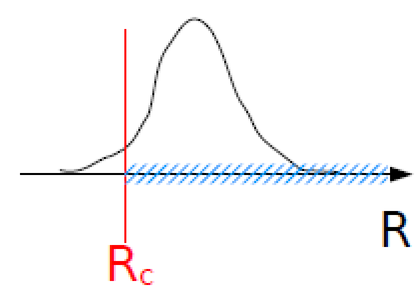
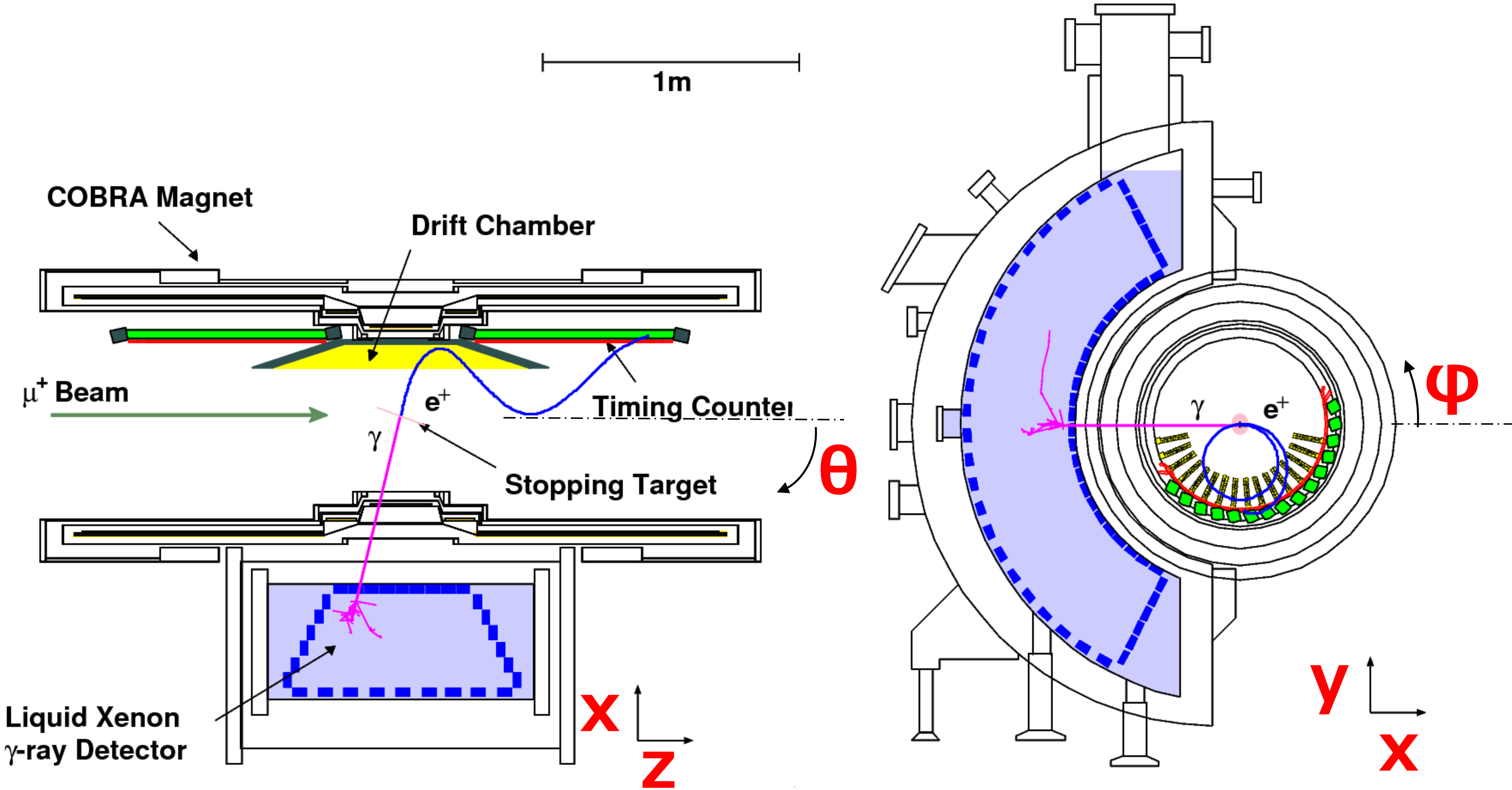


Fig.8.12

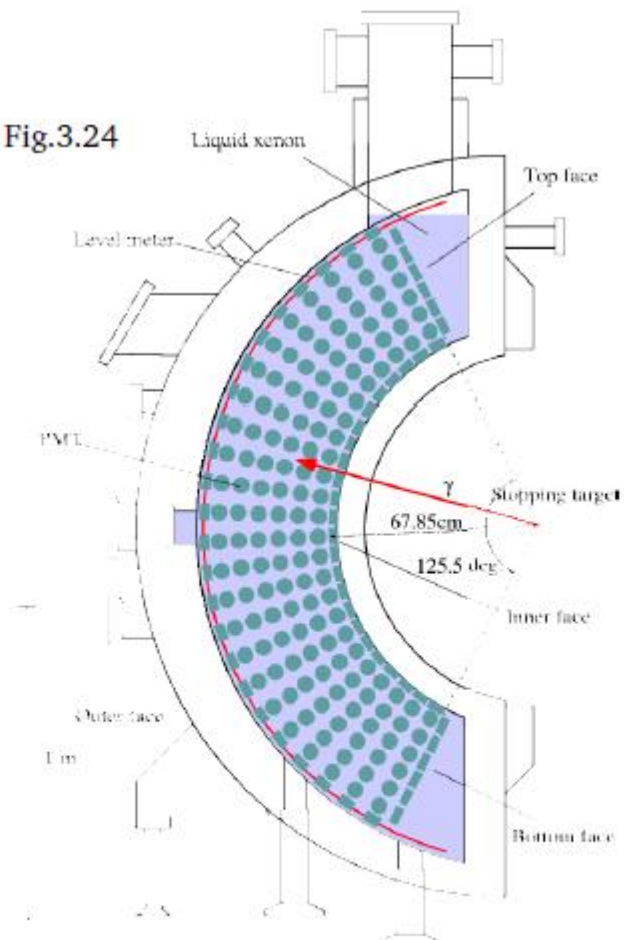


MEG Detector



Liquid Xenon Gamma-ray Detector

Fig.3.24



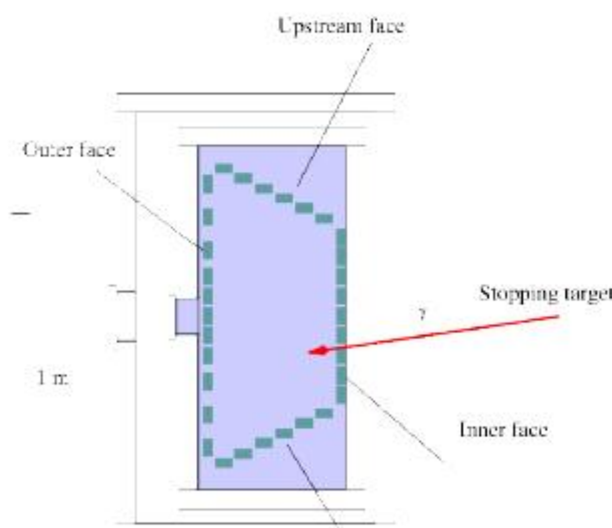
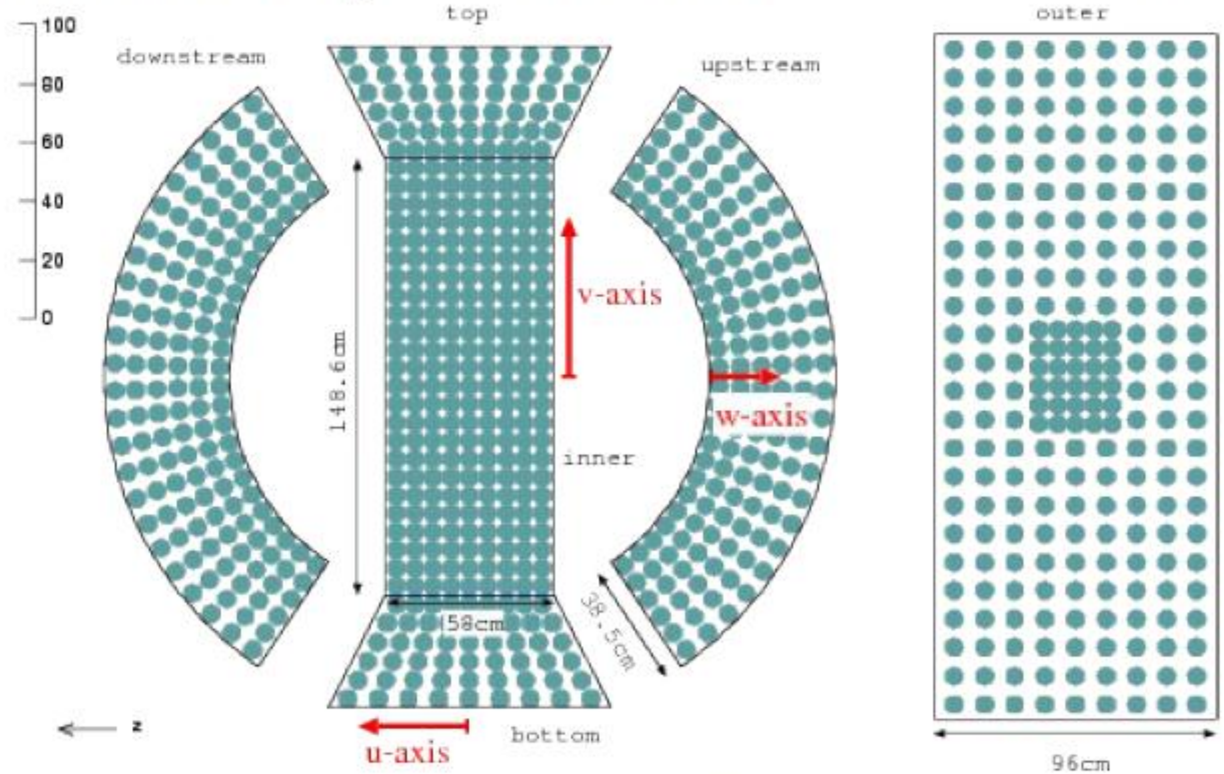


Fig.3.25



Development view

Xenon Scintillation

- De-excitation process (fast)
  - $Xe + Xe^* \rightarrow Xe_2^* \rightarrow 2Xe + h\nu$

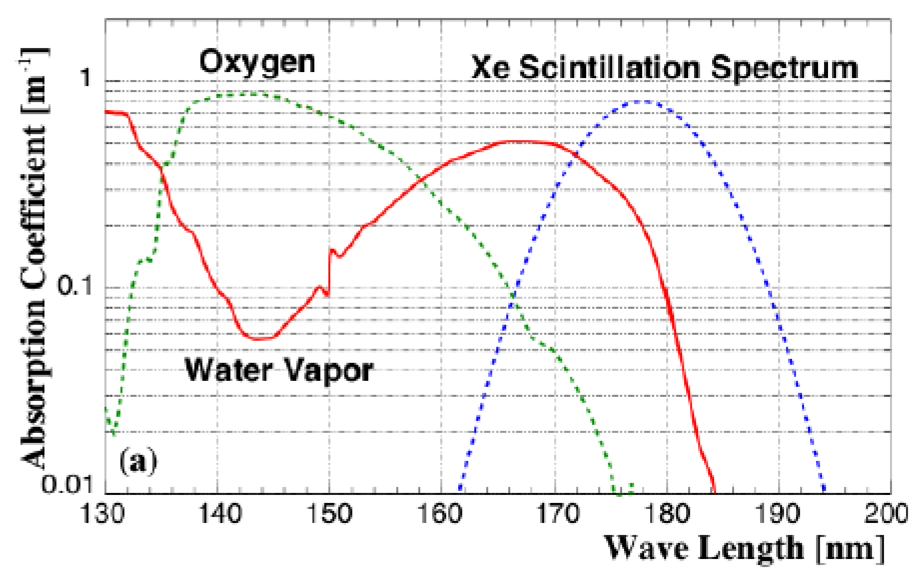
- Recombination process (slow)
  - $Xe^+ + Xe \rightarrow Xe_2^+$
  - $Xe_2^+ + e^- \rightarrow Xe^{**} + Xe$
  - $Xe^{**} \rightarrow Xe^* + \text{heat}$
  - $Xe + Xe^* \rightarrow Xe_2^* \rightarrow 2Xe + h\nu$

Quench

- $Xe_2^* + N_2 \rightarrow 2Xe + N_2$
  O_2 O_2

(two-body collision)

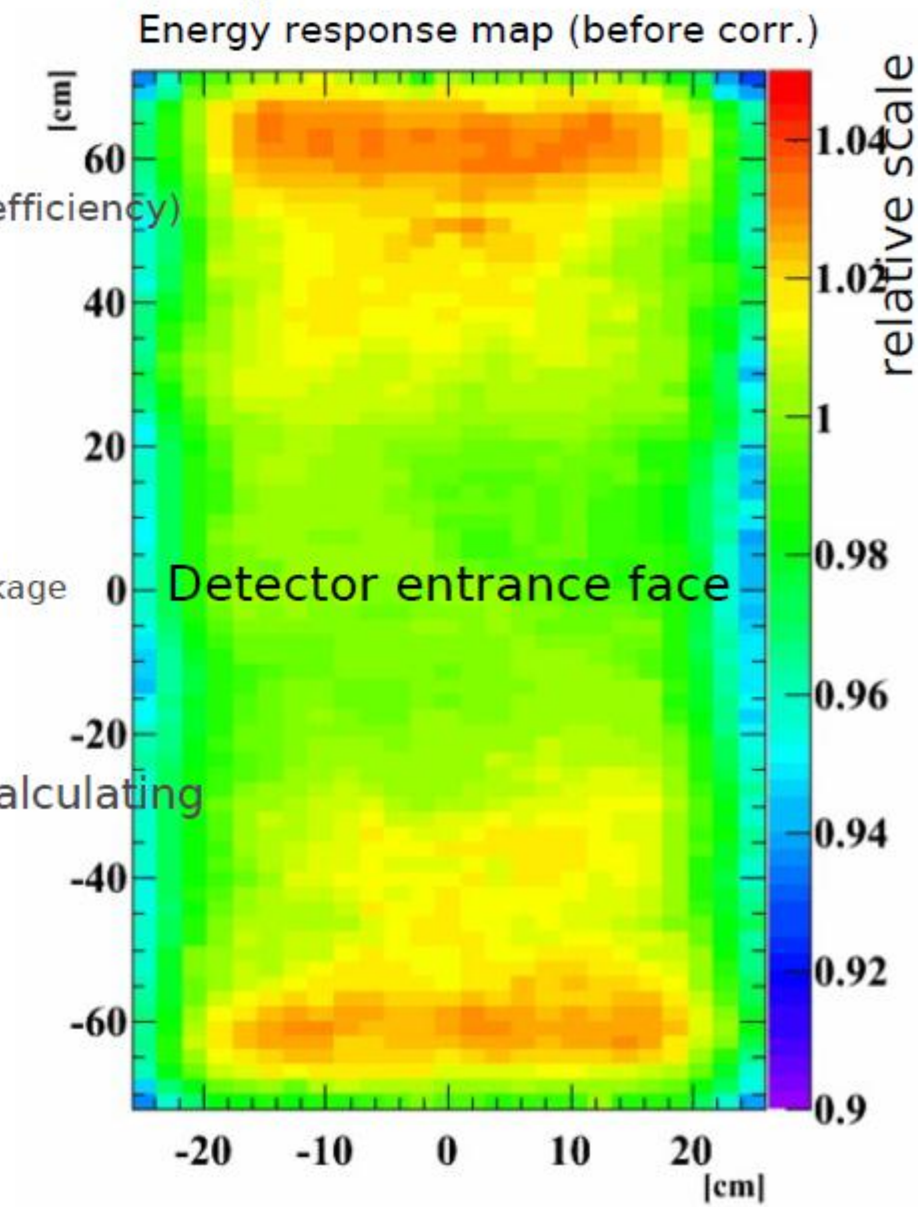
Absorption

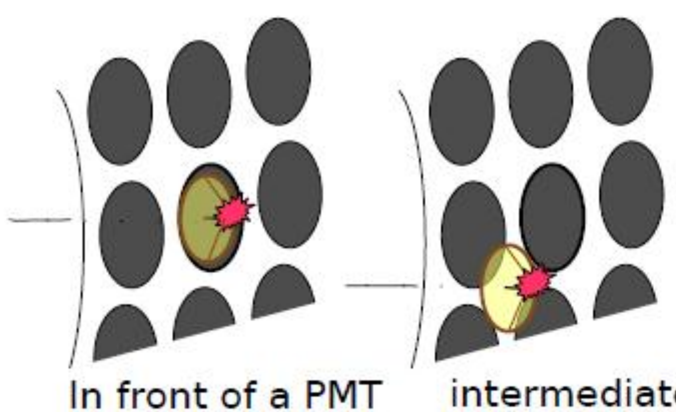


Gamma Energy I

- Reconstruction
  - Sum of PMT outputs
  - Correction of non-uniformity (collection efficiency)
    - Use 17.6MeV γ from Li(p,γ)Be reaction
      - Uniformly illuminates the detector.
  - Treatment of shallow events
    - Low resolution at shallow part
      - Shower escape
      - Large variation of photon collection, Photon leakage
      - Saturation of signal (dyn.range of elec.)
    - But want to use for statistics.
    - Recovered saturation using waveform
    - Correct photon collection efficiency by calculating solid angle

Fig.6.10(b)

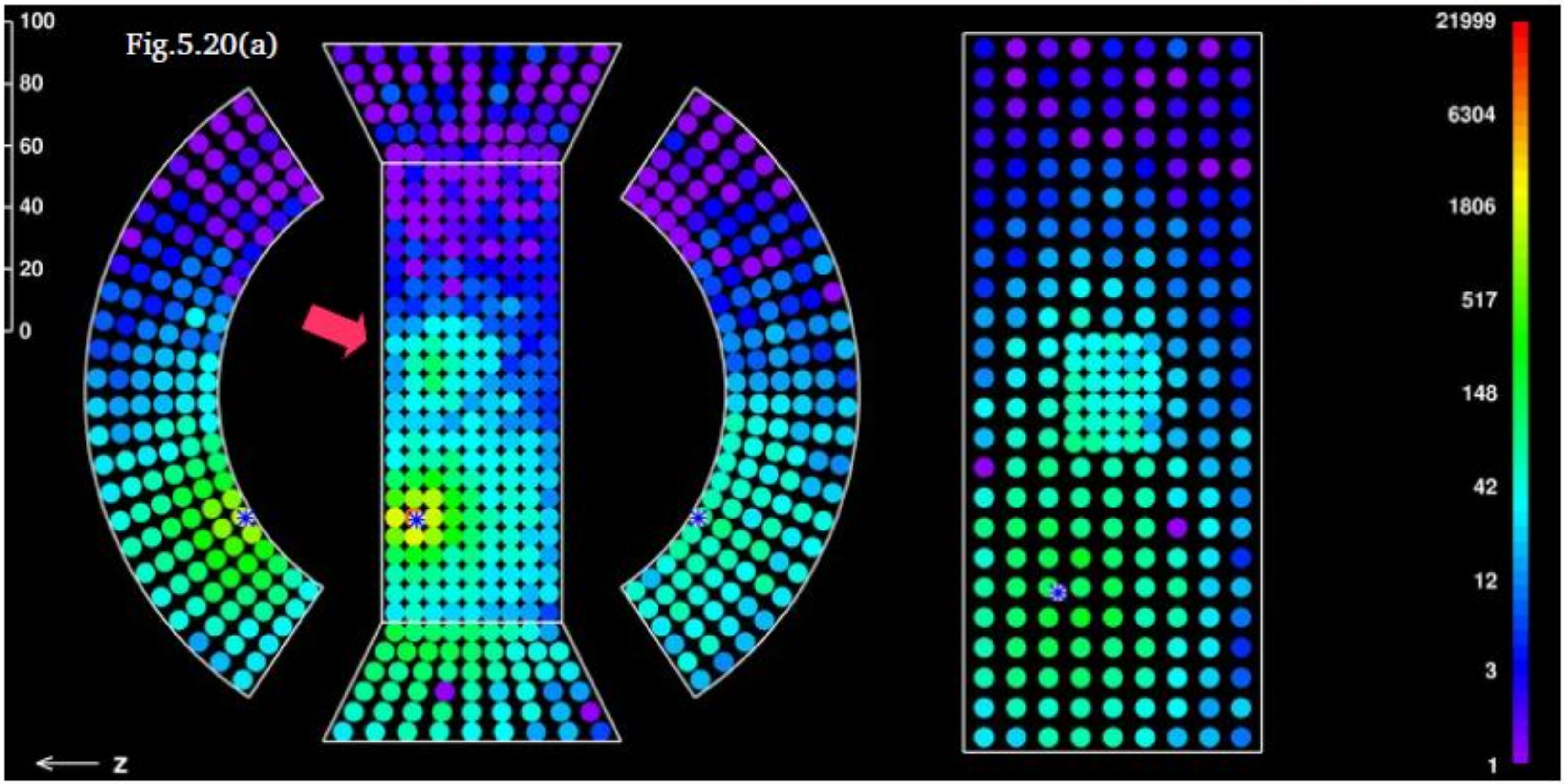




Gamma Energy II

- Recover of pileup events
  - Not discard pileup events, but use with unfolding.
  - Improve efficiency

ε ~8% gain

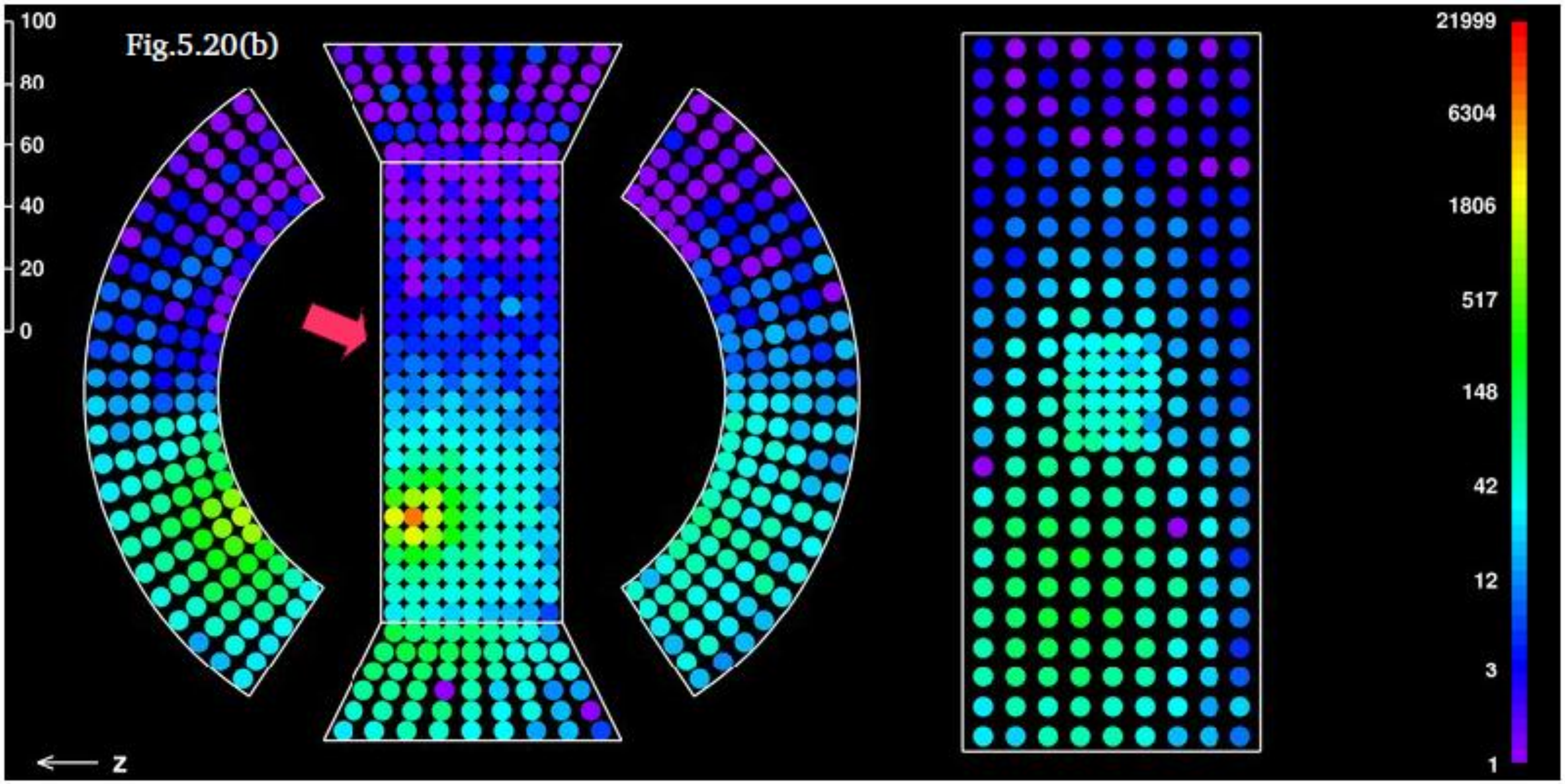


- ID pileup → reconstruct energy using region without pileup → replace PMT outputs for pileup region with estimated charge → then normal reconstruction

Gamma Energy II

- Recover of pileup events
  - Not discard pileup events, but use with unfolding.
  - Improve efficiency

ε ~8% gain



  - ID pileup → reconstruct energy using region without pileup → replace PMT outputs for pileup region with estimated charge → then normal reconstruction

Gamma Energy III

- π^0 55MeV

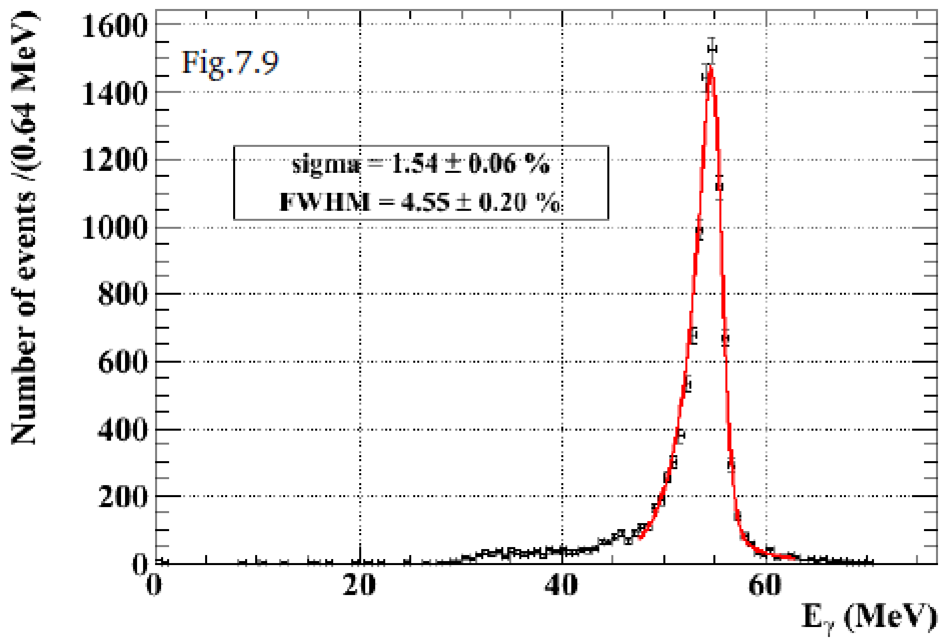
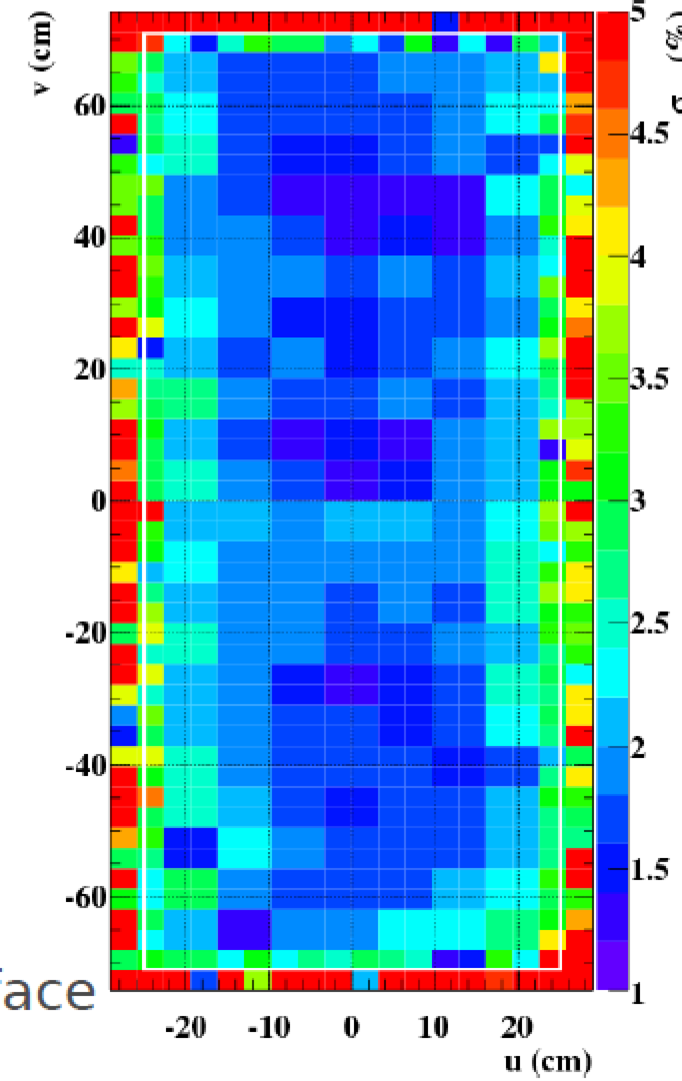
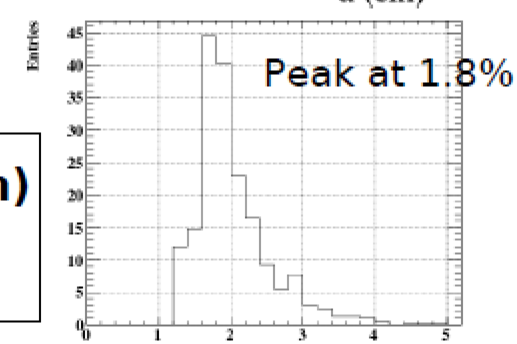


Fig.7.11(a) Resolution map



- Evaluate responses for all over the entrance face



Average resolution (averaged over the event distri. in MEG run)

σ_{up}=2.0% for deep(>2cm), 3.0% (1~2cm), 4.2% (0~1cm)

Determine energy scale

Gamma Timing I

- Reconstruction
  - Subtract scinti.-photon propagation time from PMT hit time.

$$t_{hit,i} = t_{PMT,i} - t_{delay,i} - t_{offset,i},$$

$$t_{delay} = t_{prop}(d, v_{eff}) + t_{indir}(\eta) + t_{walk}(N_{pe}).$$

  - Combine a lot of measurement by different PMTs (~150PMTs) (χ^2 fit).

Fig.6.12

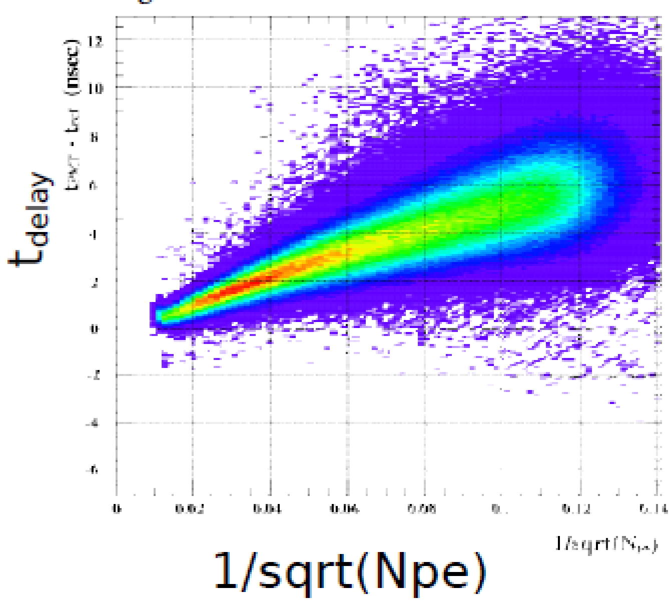
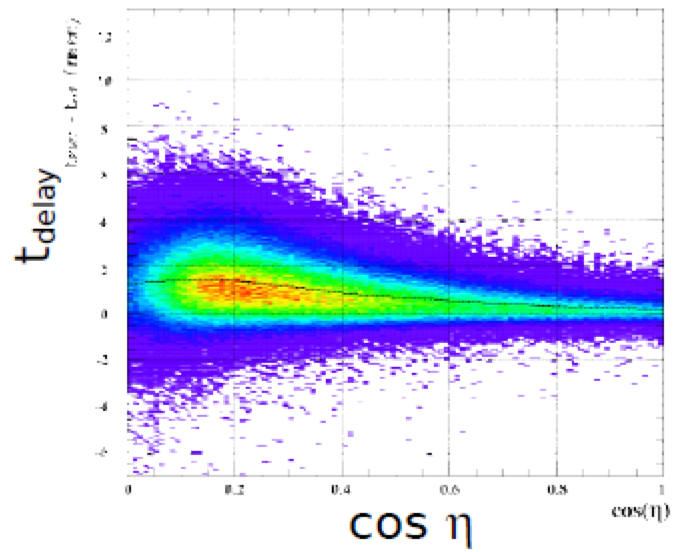
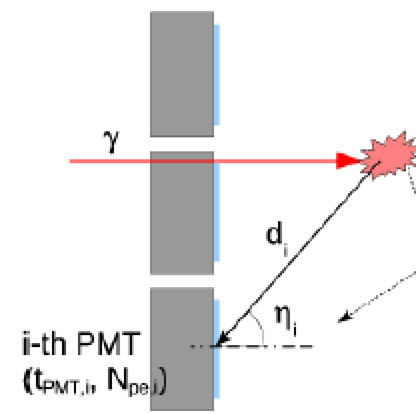


Fig.6.13

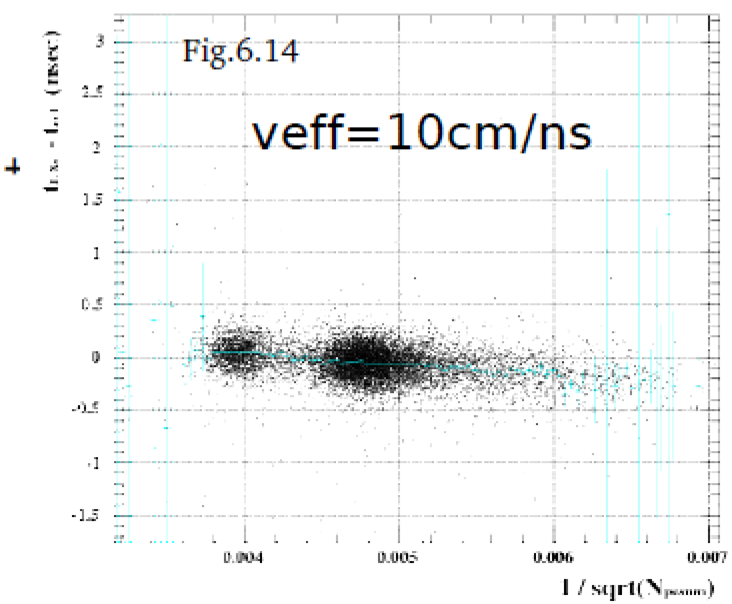


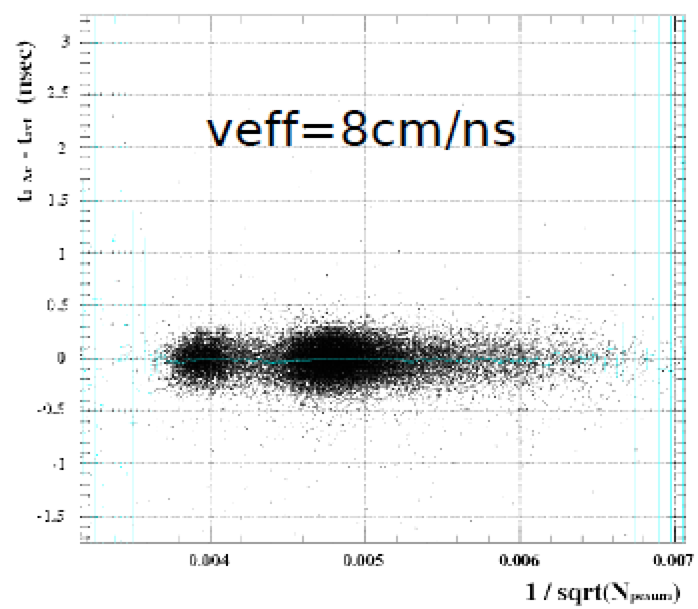


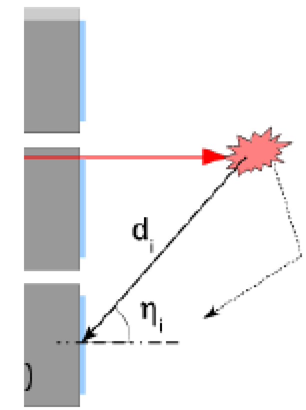
Gamma Timing I

- Reconstruction
  - Subtract scinti.-photon propagation time from PMT hit time.
  - $$t_{hit,i} = t_{PMT,i} - t_{delay,i} - t_{offset,i},$$
  - $$t_{delay} = t_{prop}(d, v_{eff}) + t_{indir}(\eta) + \cancel{t_{walk}(N_{pe})}.$$
  - Combine a lot of measurement by different PMTs (~150PMTs) (χ^2 fit).

Disentangle those three terms by looking at energy dependence

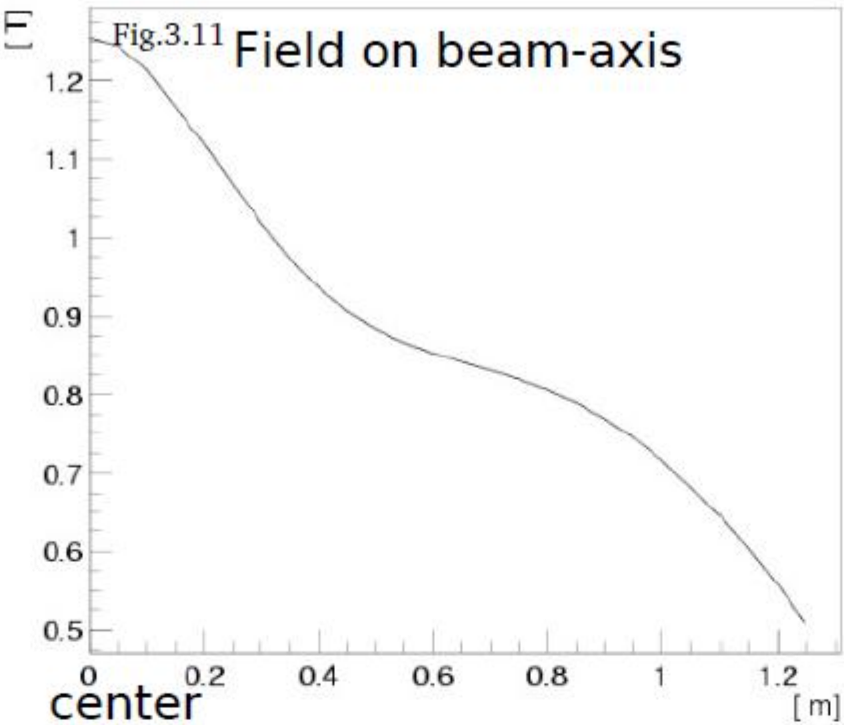


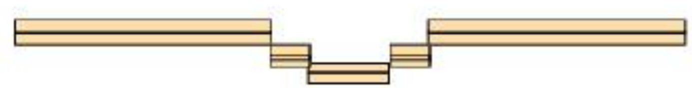




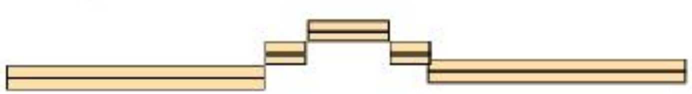
“COBRA” Magnet

- Superconducting solenoid form <u>highly gradient magnetic field</u>
  - Center 1.27 T → edge 0.49 T





Step structure solenoid



Other features
- Thin coil
  - $<0.2X_0$, to transmit γ-ray(85%)
- Rapid switch on/off
  - stabilize ~30min (cooling with GM ref.)
- Two compensation coils suppress fringe field (no return yoke)
  - Low B around LXe detector for PMT <50Gauss

DCH Design

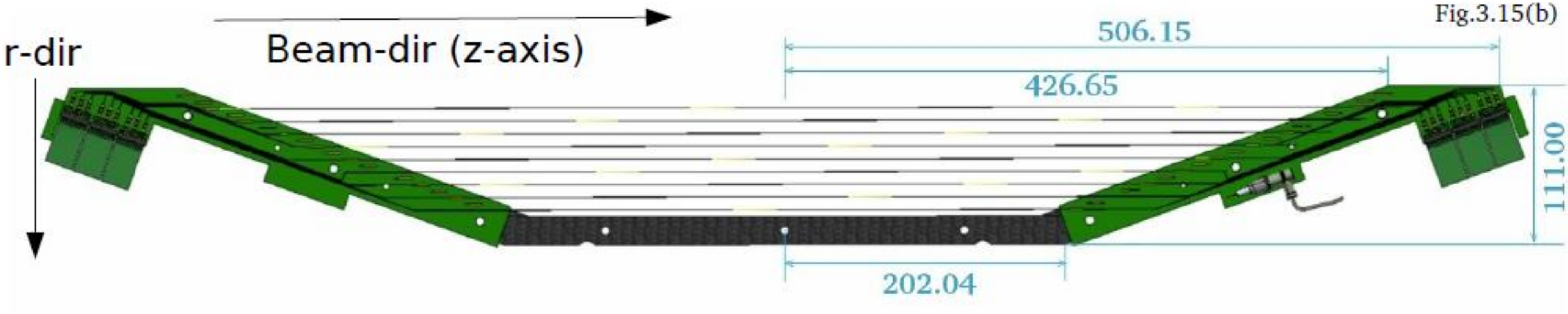


Fig.3.15(b)

2 layers staggered by half cell
9 drift-cells in 1 layer

Open-frame structure
Form cell only with cathode foils

12.5μm cathode foil
Vernier pattern → z reconstruction

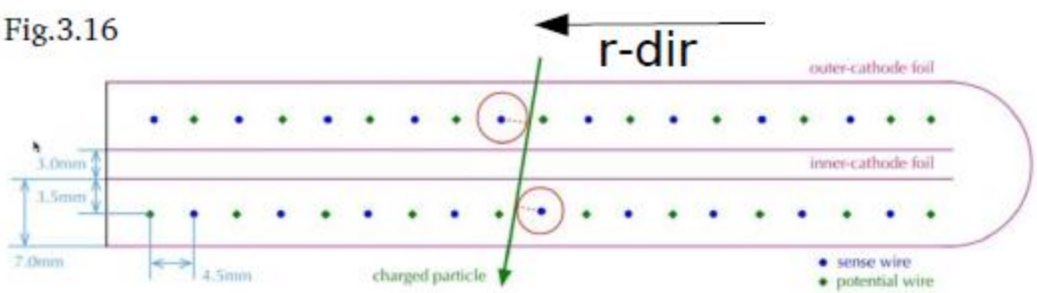


Fig.3.16

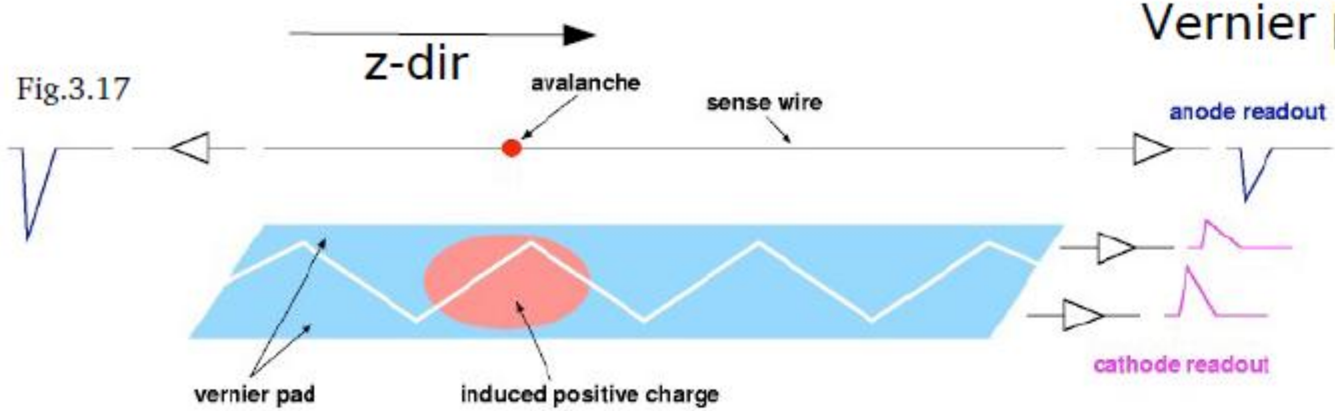
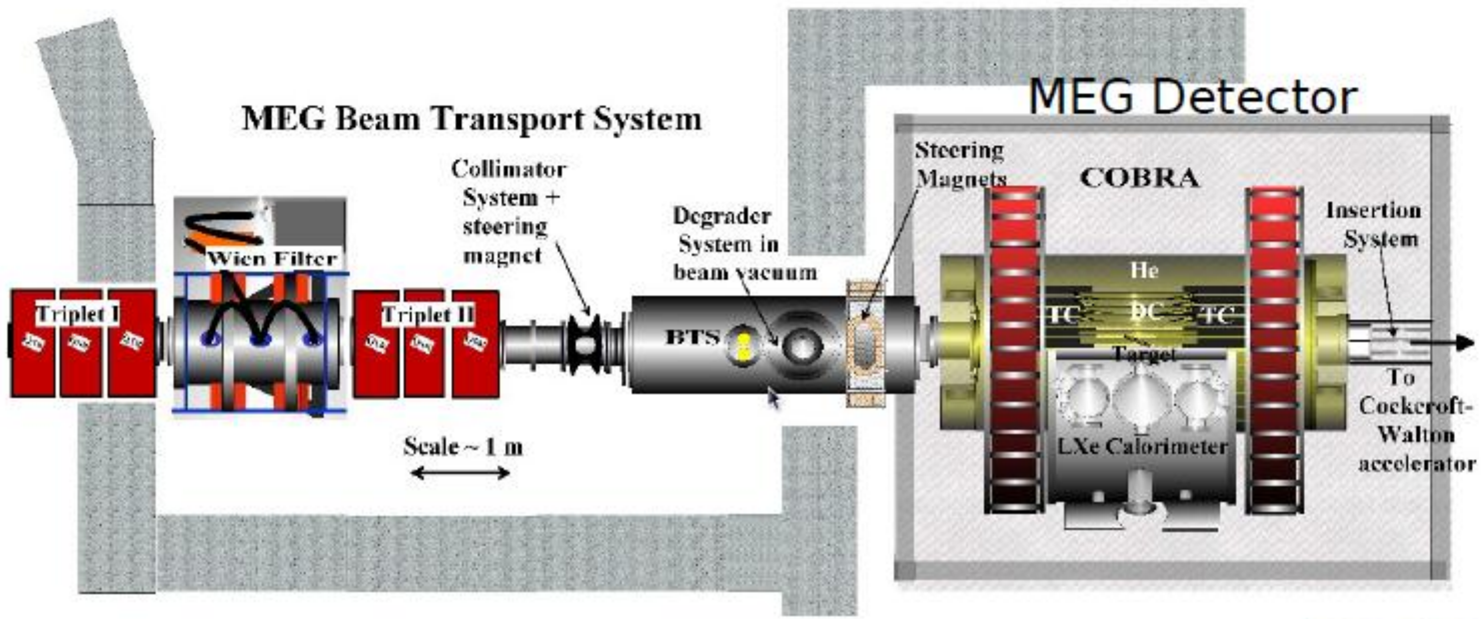
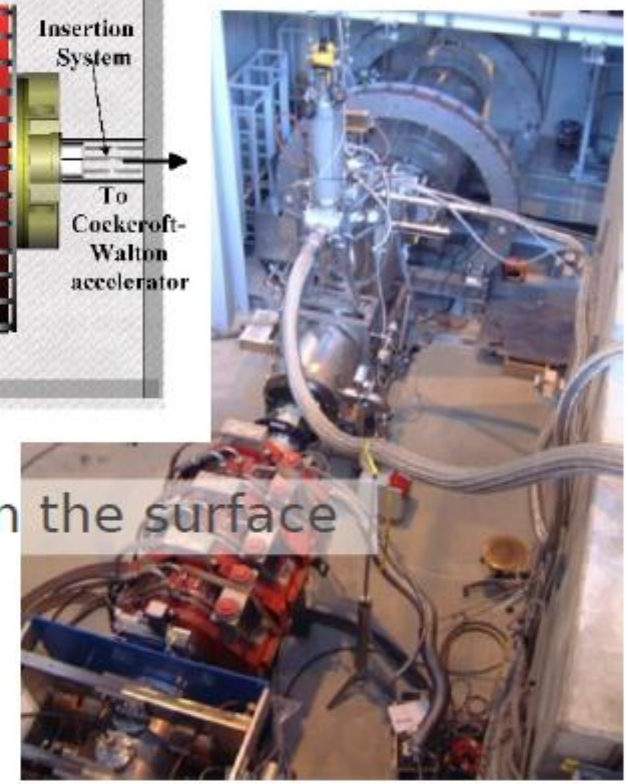


Fig.3.17

'Surface muon' Beam Transport System



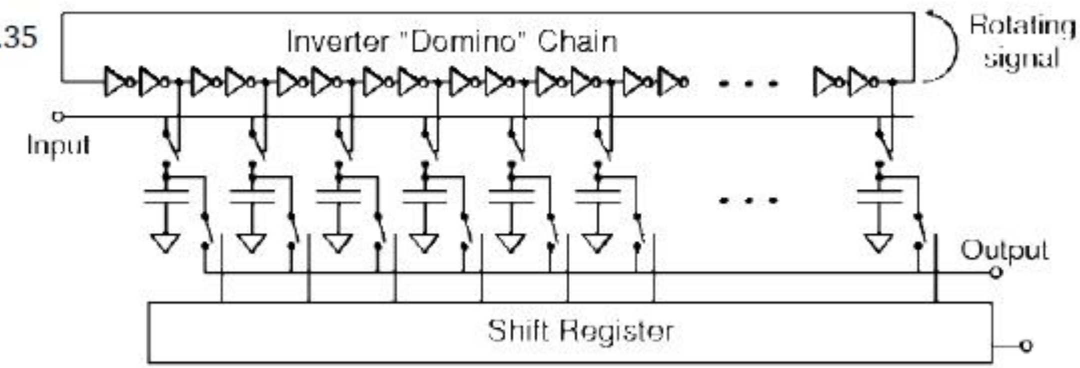


- Surface μ^+: μ^+ originating from pion stopped on the surface of prod. target
  - Extract at 175° from the primary p beam
  - Low momentum(29MeV/C) with small variance μ^+ beam
- Through the beam transport system
  - Separate e^+ · degrade · tune beam profile
- **$3\times10^7\mu^+$/sec** stop on target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

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&TIC, **500MHz** for DCH

Fig.3.35



Data size
Typ. 1.5MB/event

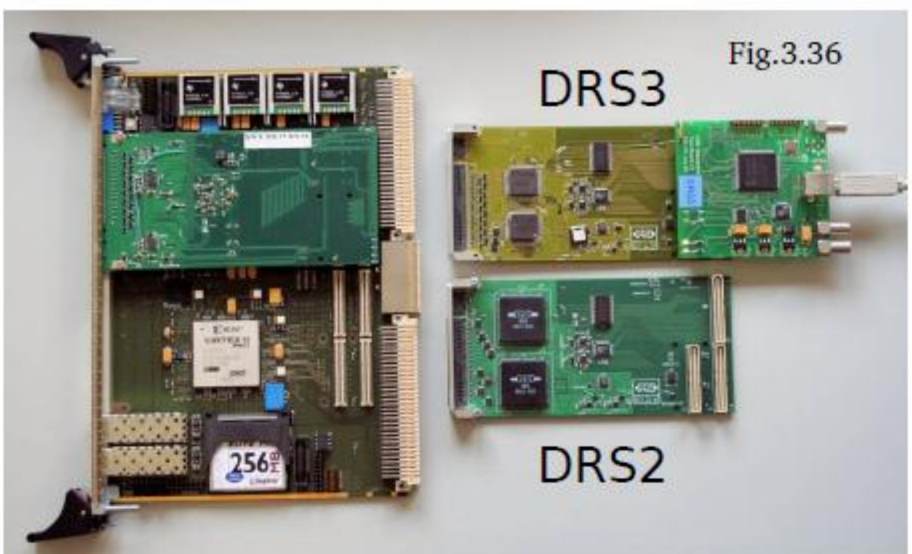
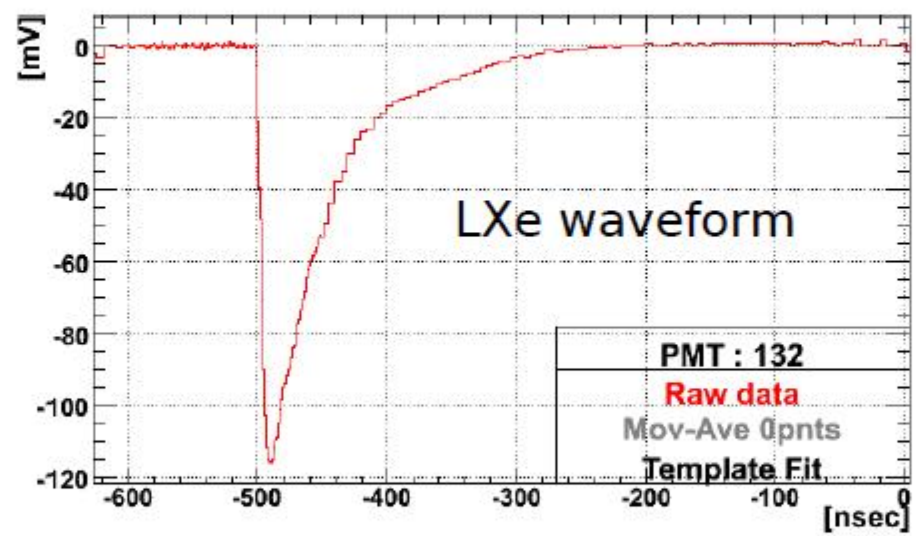
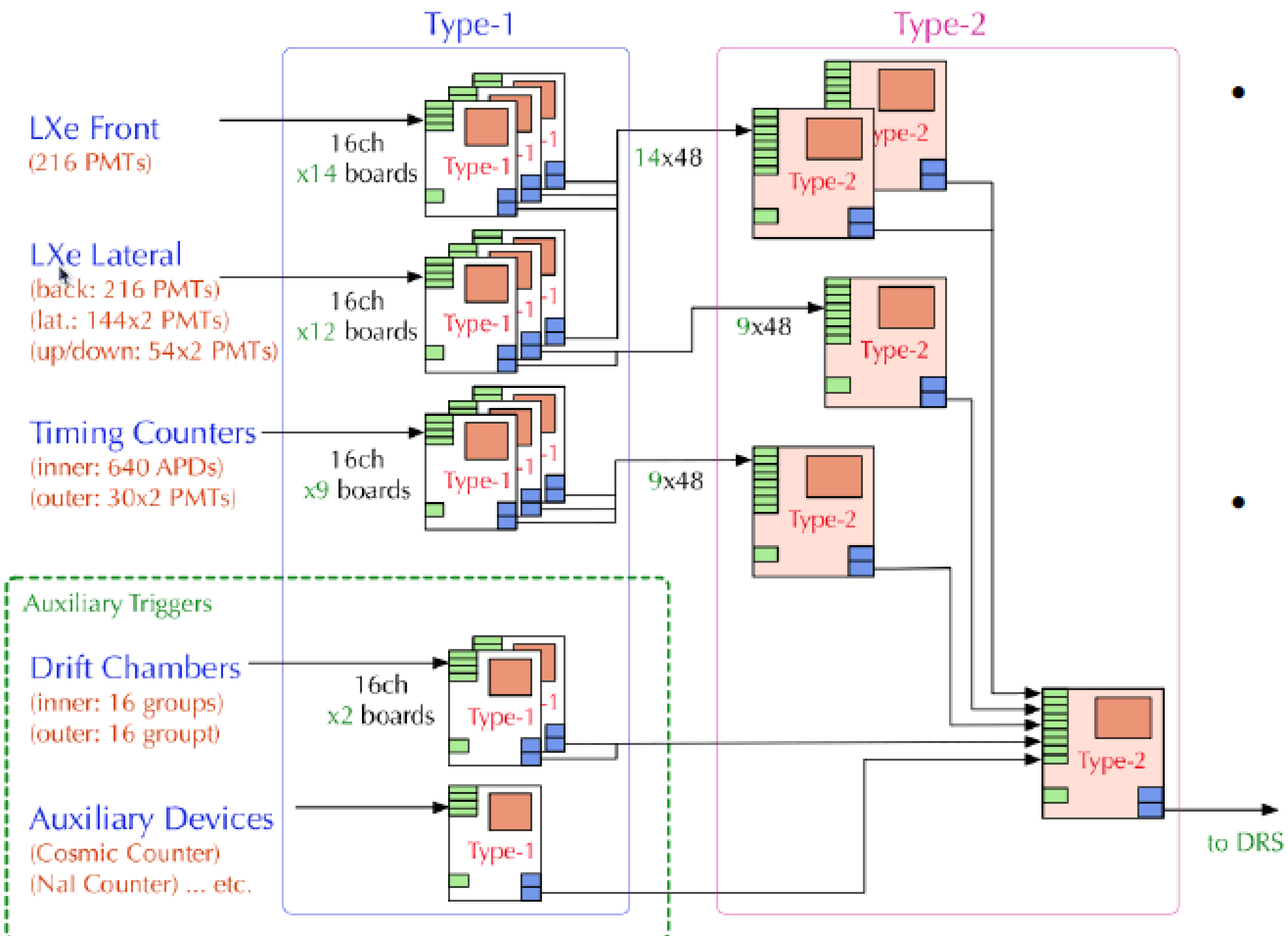


Fig.3.36



Trigger



- FPGA-FADC architecture
  - 100MHz FADC on VME boards
- MEG trigger
  - γ energy
  - e^+-γ coincidence
  - e^+-γ direction match (back-to-back)
    - Max output PMT in LXe
    - TC hit position
- In addition, 10 trigger types are mixed in normal data taking
  - Calibration, normalization

Beam rate	$3x10^7s^{-1}$
Fast LXe Q sum (>40MeV)	$2x10^3s^{-1}$
Time coincidence	$100s^{-1}$
Direction match	$10s^{-1}$

Summary of performance

	2009	2010
γ energy	1.9%(w>2cm) 2.4%((w<2cm)	1.9%(w>2cm) 2.4%((w<2cm)
γ timing	96ps	67ps
γ position	5mm(u,v), 6mm(w)	5mm(u,v), 6mm(w)
γ efficiency †	58%	59%
e^+ timing	107ps	107ps
e^+ energy	0.31MeV (core 80%)	0.32MeV (core 79%)
e^+ angle (θ)	9.4mrad	11.0mrad
e^+ angle (ϕ)	6.7mrad	7.2mrad
e^+ vertex (Z/ Y)	1.5mm/1.1mm(core)	2.0mm/1.1mm(core)
e^+ efficiency	40%	34%
$e^+-\gamma$ timing	146ps	122ps
Trigger efficiency	91%	92%
$e^+-\gamma$ angle (θ)	14.5mrad	17.1mrad
$e^+-\gamma$ angle (ϕ)	13.1mrad	14.0mrad
Stopping μ rate	$2.9\times10^7 s^{-1}$	$2.9\times10^7 s^{-1}$
DAQ time/ Real time	35days/43days	56days/67days
Total μ stops on target	6.5×10^{13}	1.1×10^{14}

e^+ tracking slightly worse in 2010 due to noise problem

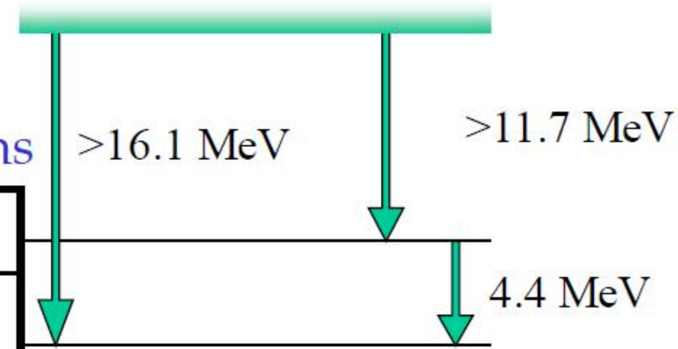
improvement by waveform digitizer upgrade in 2010

† $\varepsilon_{detection}\times\varepsilon_{analysis}$ for E_γ >48MeV

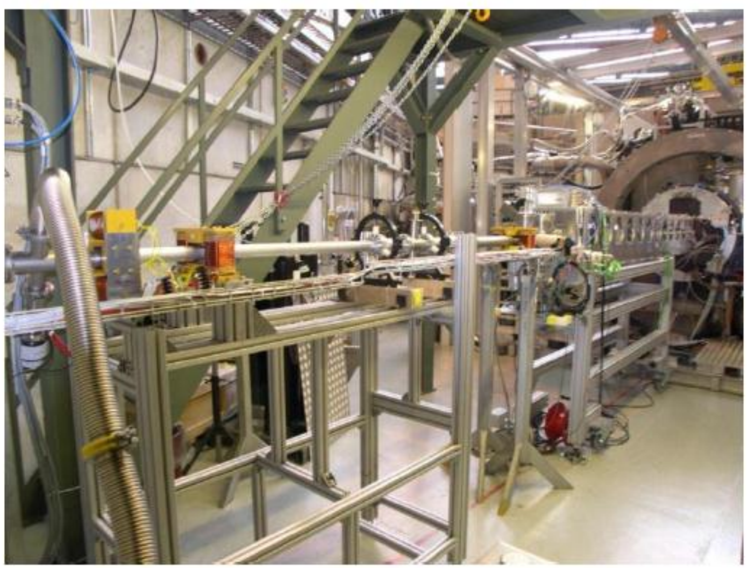
(p,γ) reaction

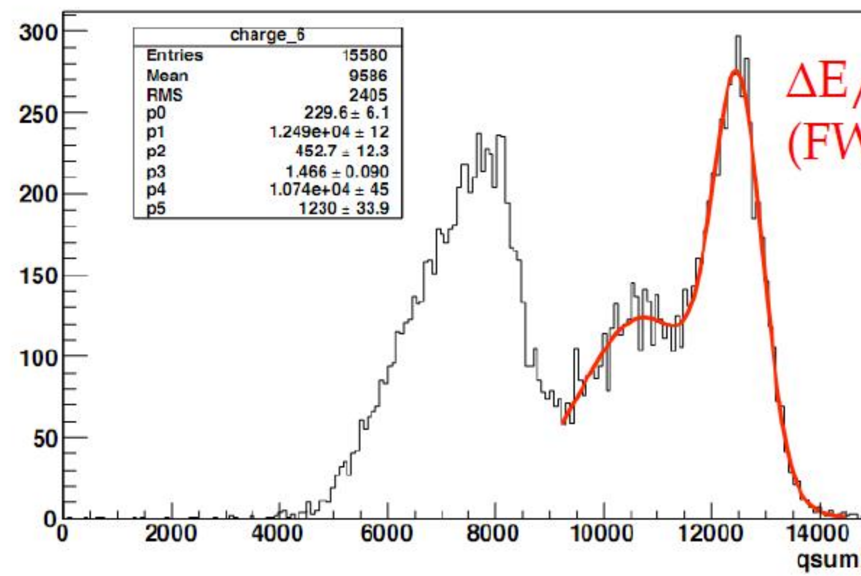
MEG
Mu-E-Gamma Collaboration

- Makes us of a Cockcroft-Walton accelerator to deliver tunable-energy protons to a $Li_2B_4O_7$ target
  - Li: high rate, higher energy photon
  - B: two (lower energy) time-coincident photons



Reaction	E_{res}	σ_{res}	*γ-lines*
Li(p,γ)Be	440 keV	5 mb	(17.6, 14.6) MeV
B(p,γ)C	163 keV	$2\ 10^{-1}$ mb	(4.4, 11.7, 16.1) MeV





ΔE/E = 8.5% (FWHM)

Positron Efficiency

- e^+ detection efficiency
  - $\varepsilon_e = \varepsilon_{DCH} \times A_{DCH\text{-}TIC}$
    - ε_{DCH} : tracking efficiency. Measure with TIC-self trigger data.
    - $A_{DCH\text{-}TIC}$: DCH-TIC matching probability. Make inefficiency if e^+ interacts with material and annihilates or changes its direction largely.
      Measure with DCH-self trigger data.

- ε_e decreased gradually during the run
  - DCH discharge problem

- Expectation (full DCH) : ~40% (= 80x50)

$$\boxed{\varepsilon_e = (37 \times 38) = 14\%}$$