MEG実験の現状と展望

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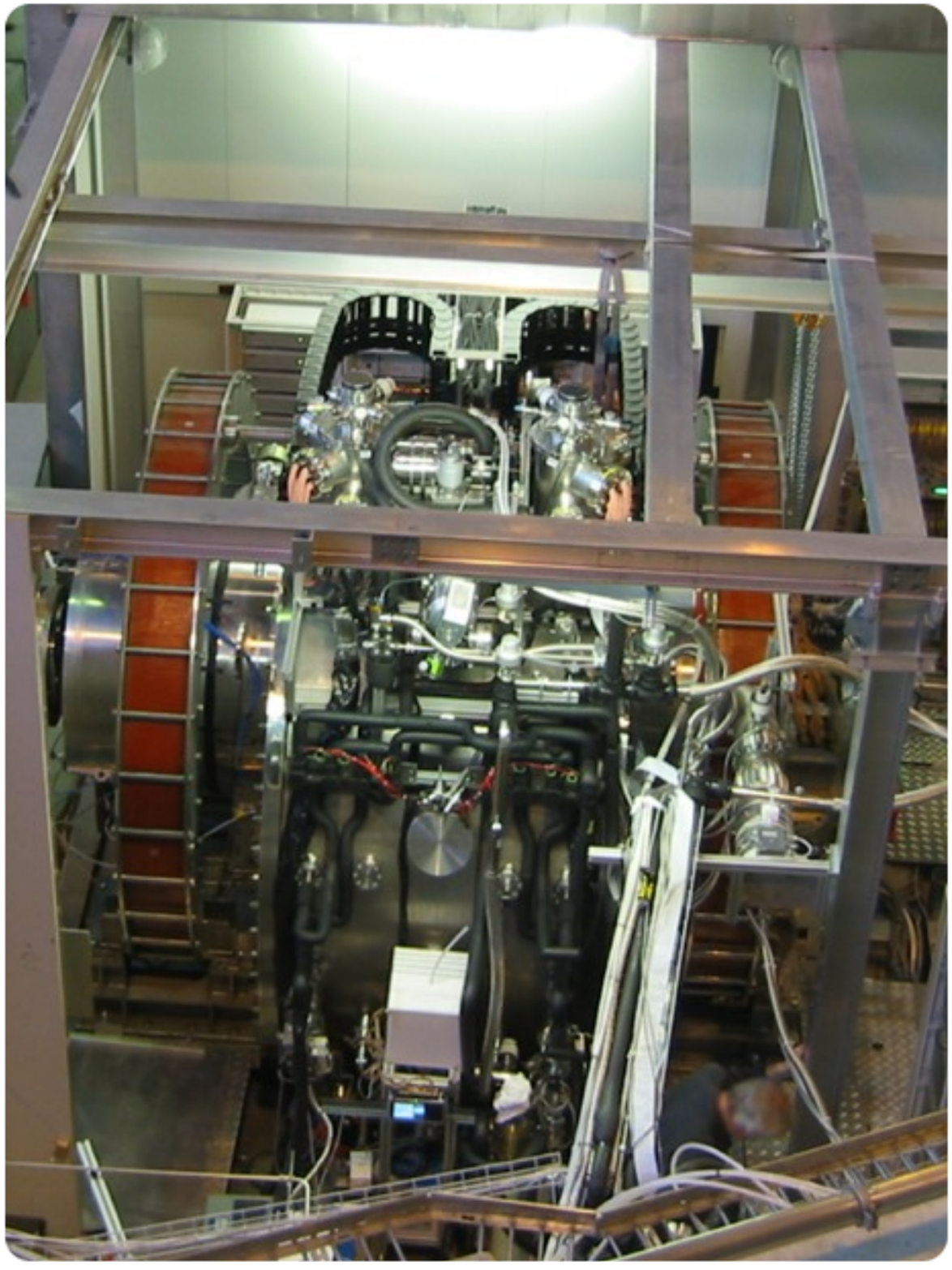
素粒子物理学の進展2011, 2011年3月10日 京都大学

Outline

- MEG experiment
- MEG detector
- Physics analysis of run 2009
- Run 2010
- Prospects for this year and beyond

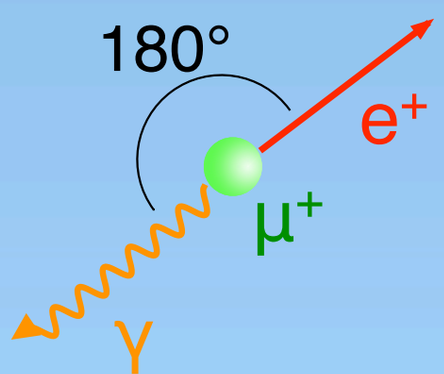


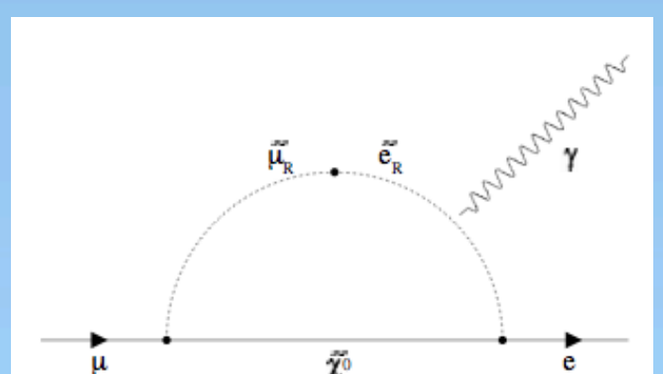
MEG Collaboration

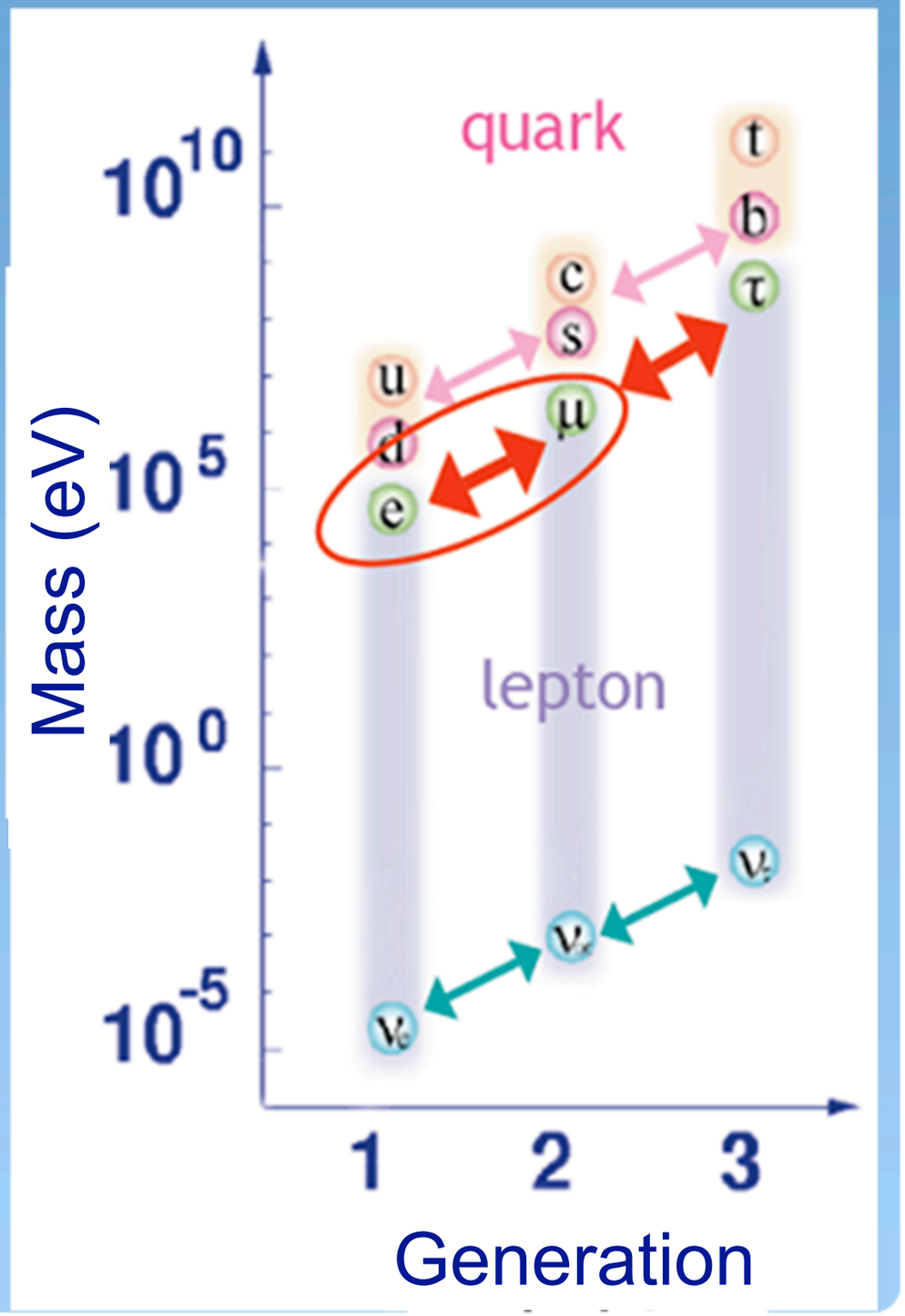
~60 physicists from 13 institutes from 5 countries

MEG Experiment

- MEG searches for the **lepton flavor violating (LFV) decay, $\mu^+ \rightarrow e^+\gamma$**
- Target branching ratio sensitivity at a few $\times 10^{-13}$, improving the present limit by two orders of magnitude

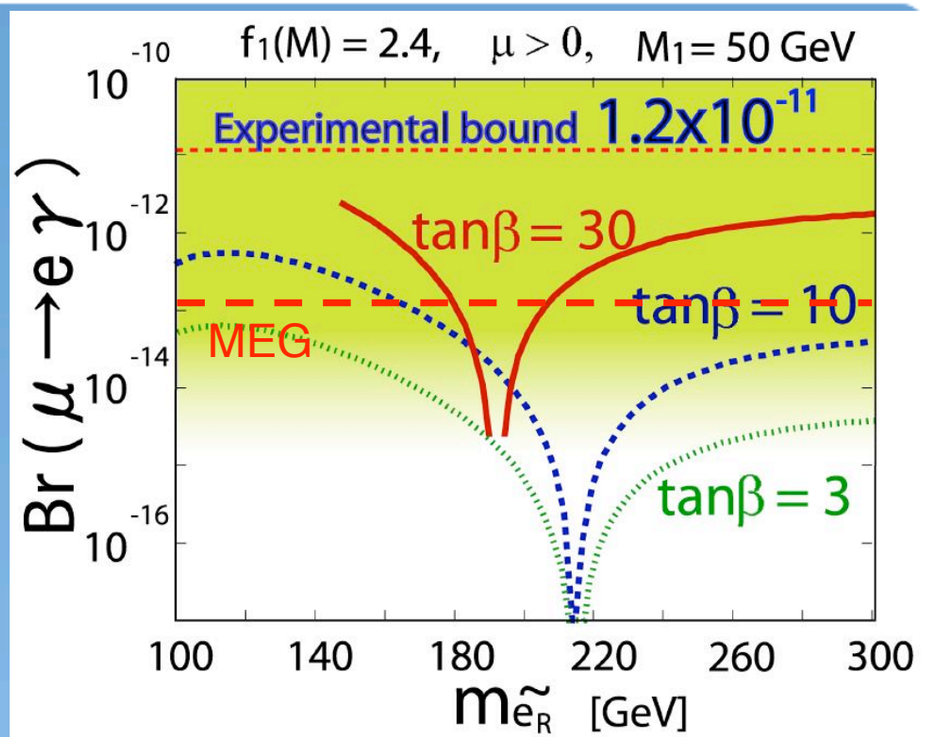




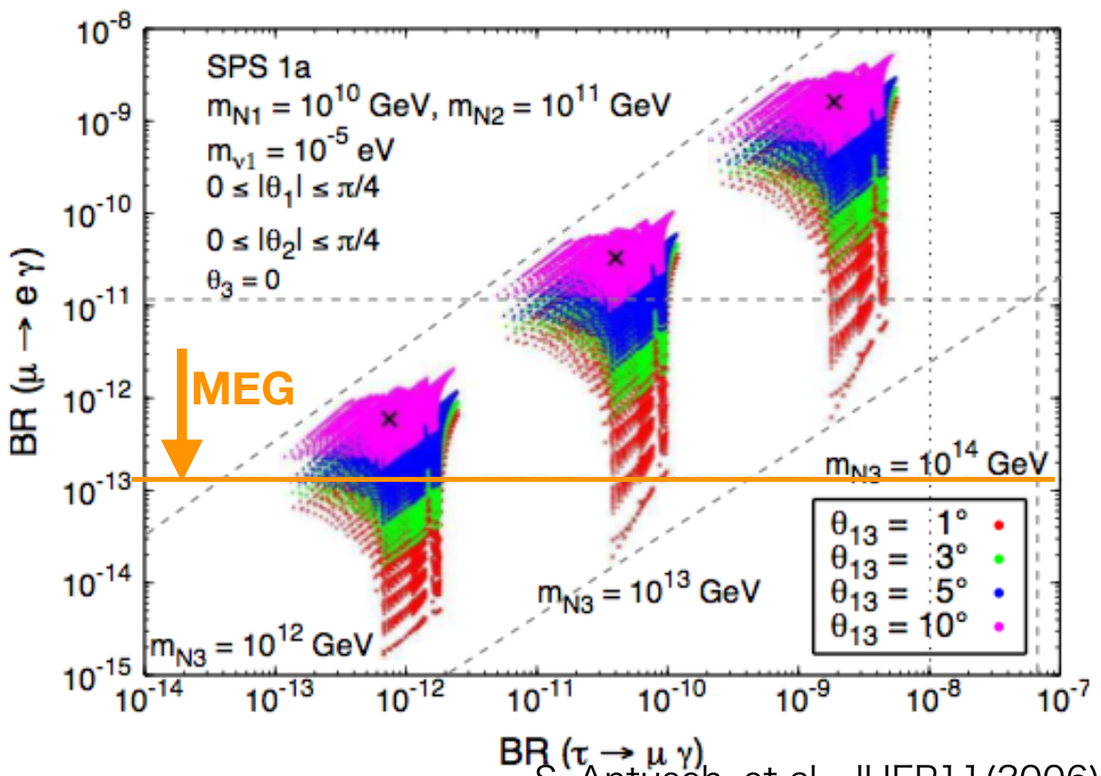


Why to Look for μ→eγ?

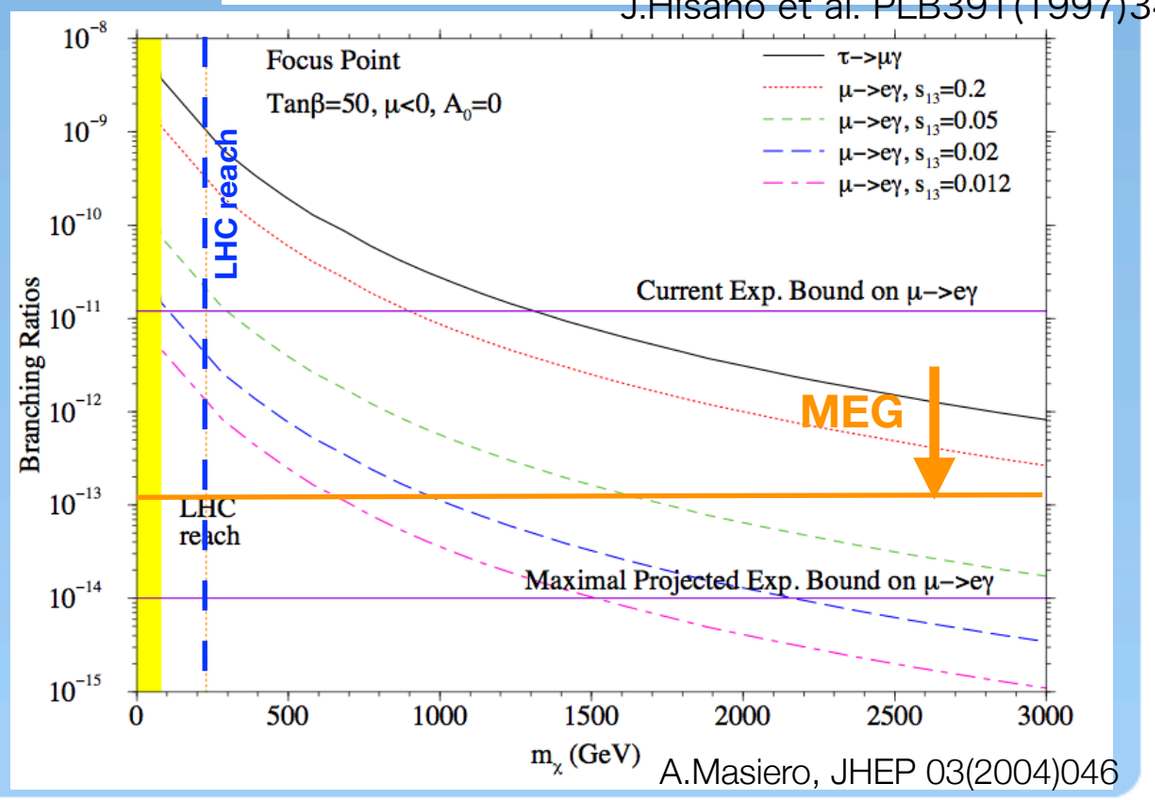
- LFV found in neutral sector. Why not in charged sector?
- Many "positive" predictions in new physics BSM
- No background from SM



J.Hisano et al. PLB391(1997)34



S. Antusch, et al., JHEP11(2006)090

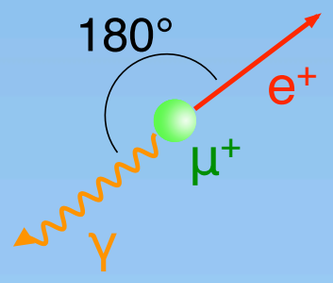


A.Masiero, JHEP 03(2004)046

How to Look for μ→eγ?

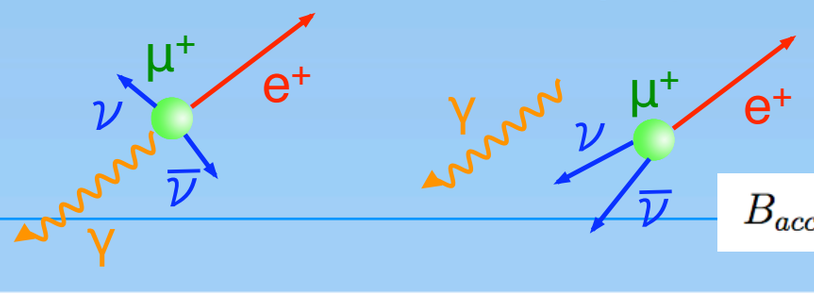
- Good **μ→eγ** search requires...
  - **A lot of muons**
    - High intensity μ^+ beam
    - DC beam to minimize accidental background
  - **Good detector**
    - Precise measurements of energy, timing and angle for both e^+ and γ
    - Running at high rate environment (stability, pileups,...)

- **Signal**
  - Back-to-back
  - Mono-energetic
    - E_e=52.8MeV
      E_γ=52.8MeV
  - Coincident in time



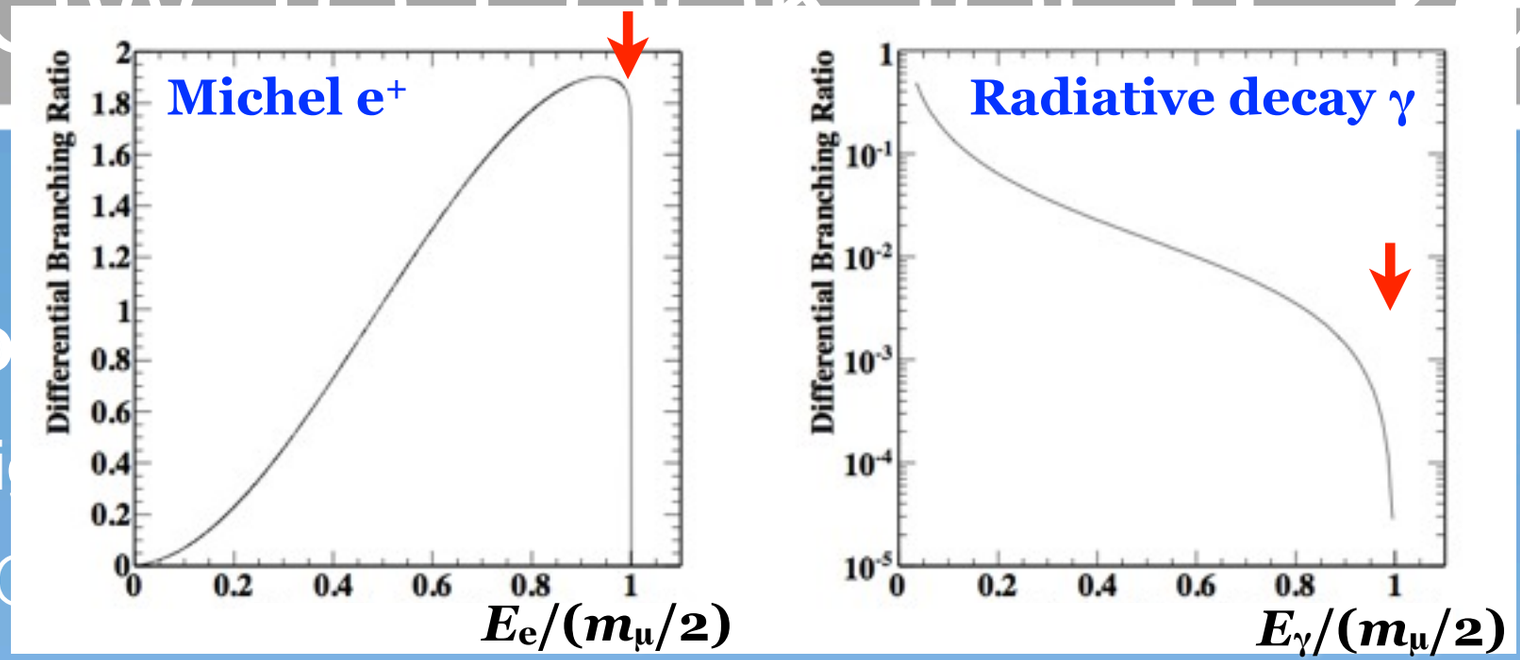
- **Background**
  - Prompt background: μ→eγνν
  - "Accidental" overlap: μ→eνν + γ

Predominant



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

How to Look for μ→eγ?



- Good
  - **A lo**
    - Hi
    - DC
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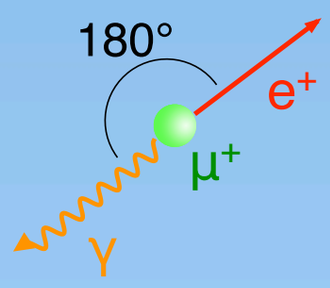

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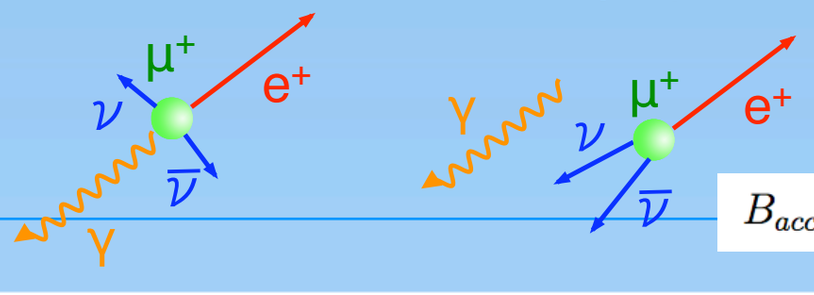
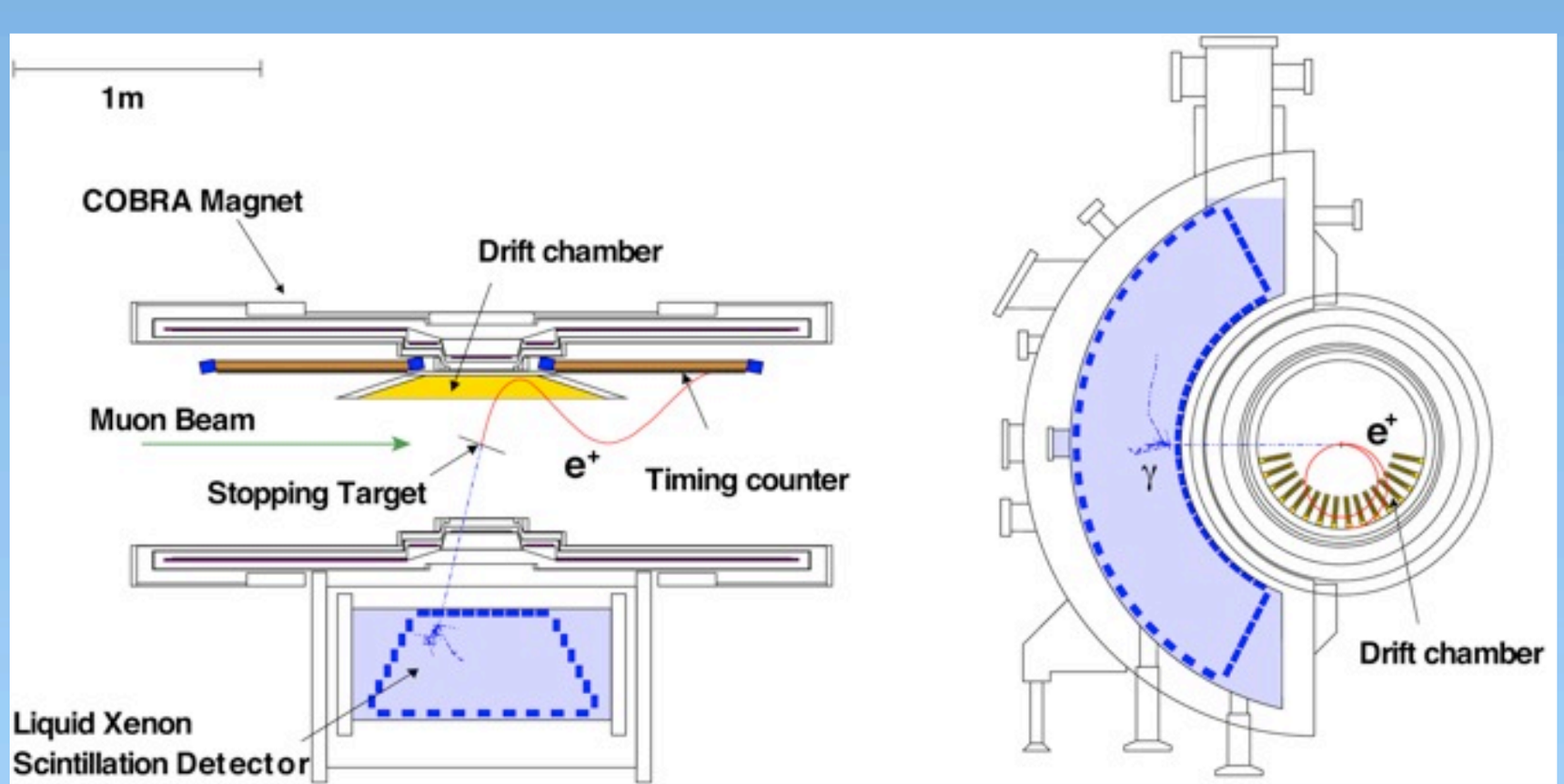


$$B_{acc} \propto \delta E_e \cdot \delta t_{e\gamma} \cdot (\delta E_\gamma)^2 \cdot (\delta \theta_{e\gamma})^2$$

Our Solution

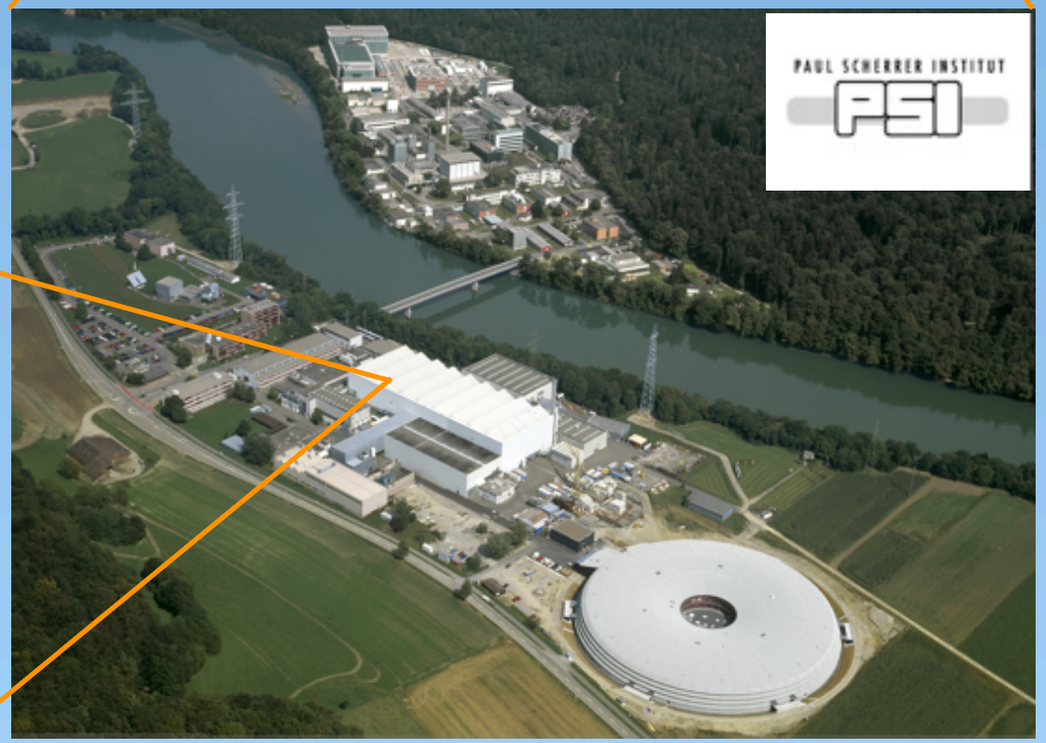
- **World's most intense DC μ^+ beam at Paul Scherrer Institute**
- **MEG detector**
  - γ: **LXe scintillation detector**
  - e^+: **COBRA spectrometer with gradient magnetic field**

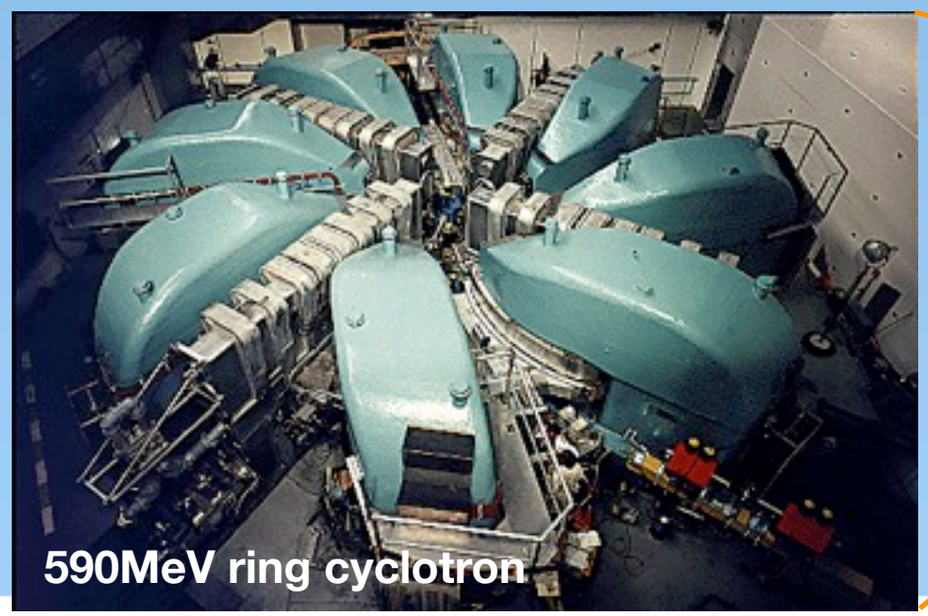


MEG Detector

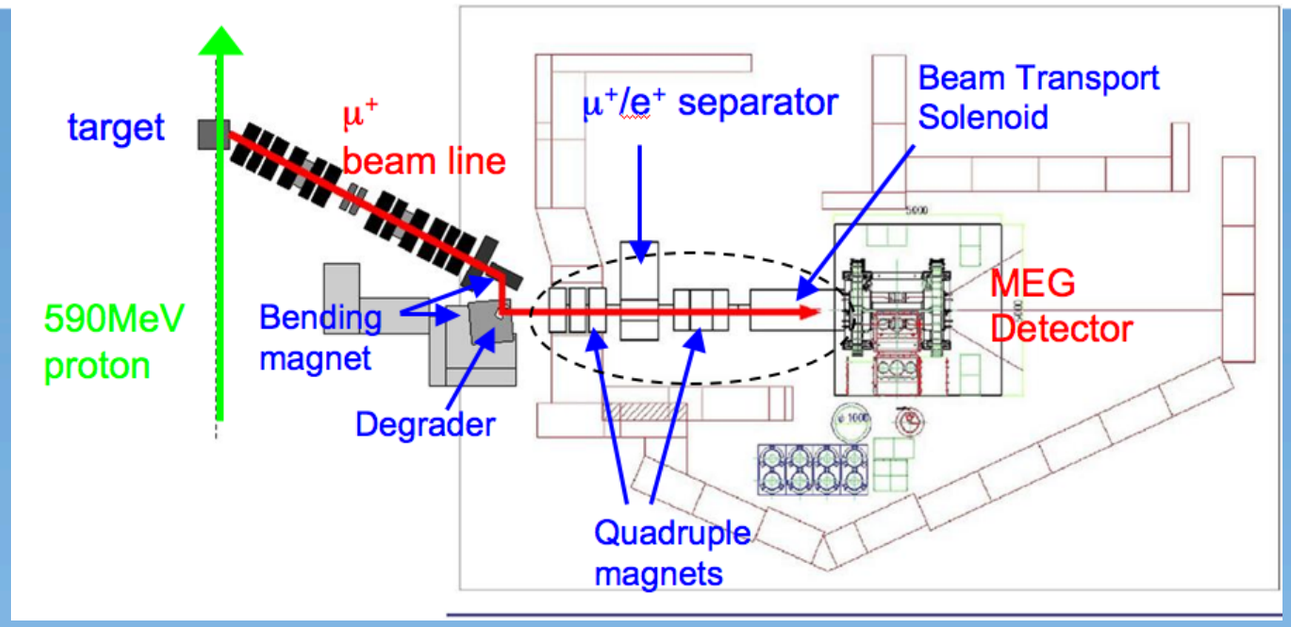
Accelerator

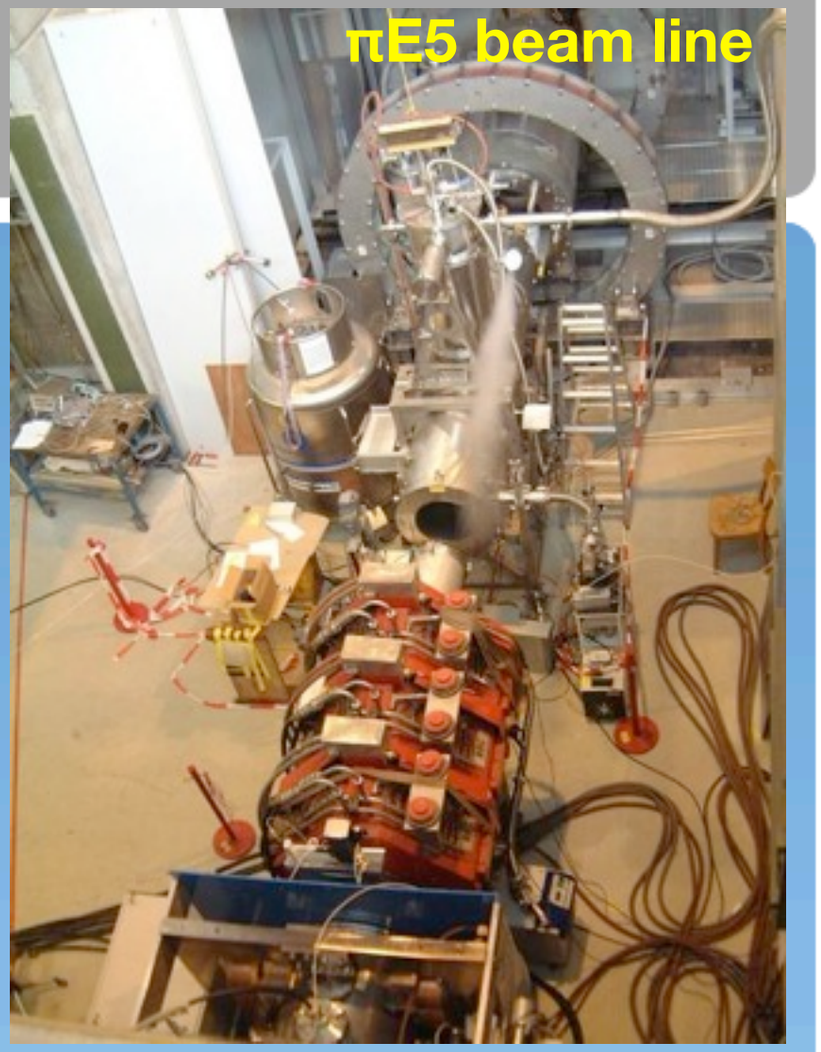
- PSI is the best place for μ→eγ search
- 590MeV proton ring cyclotron (2.2mA, 1.3MW)
- World's most intense continuous muon beam
- MEG at PSI
  - 1998 LOI
  - 1999 Proposal and approval



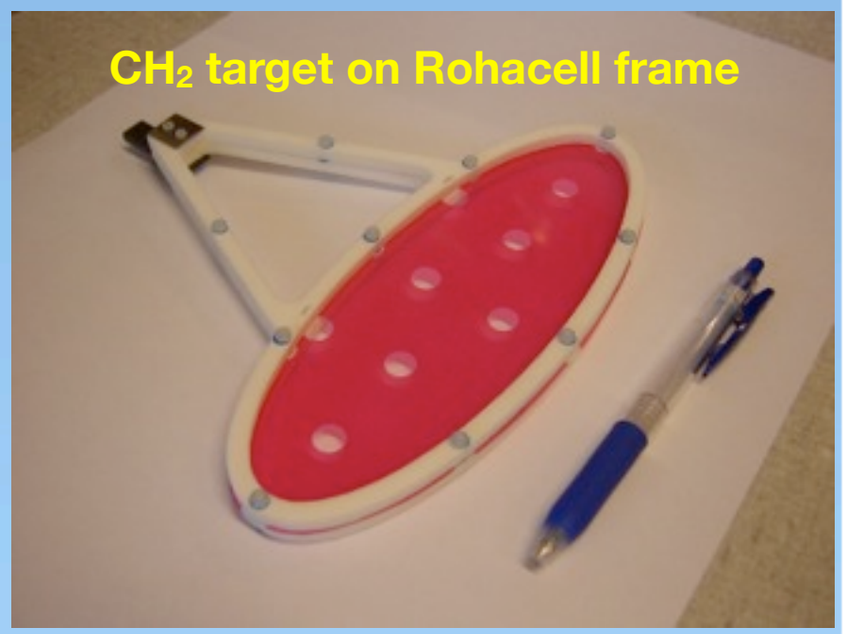

590MeV ring cyclotron

Beam

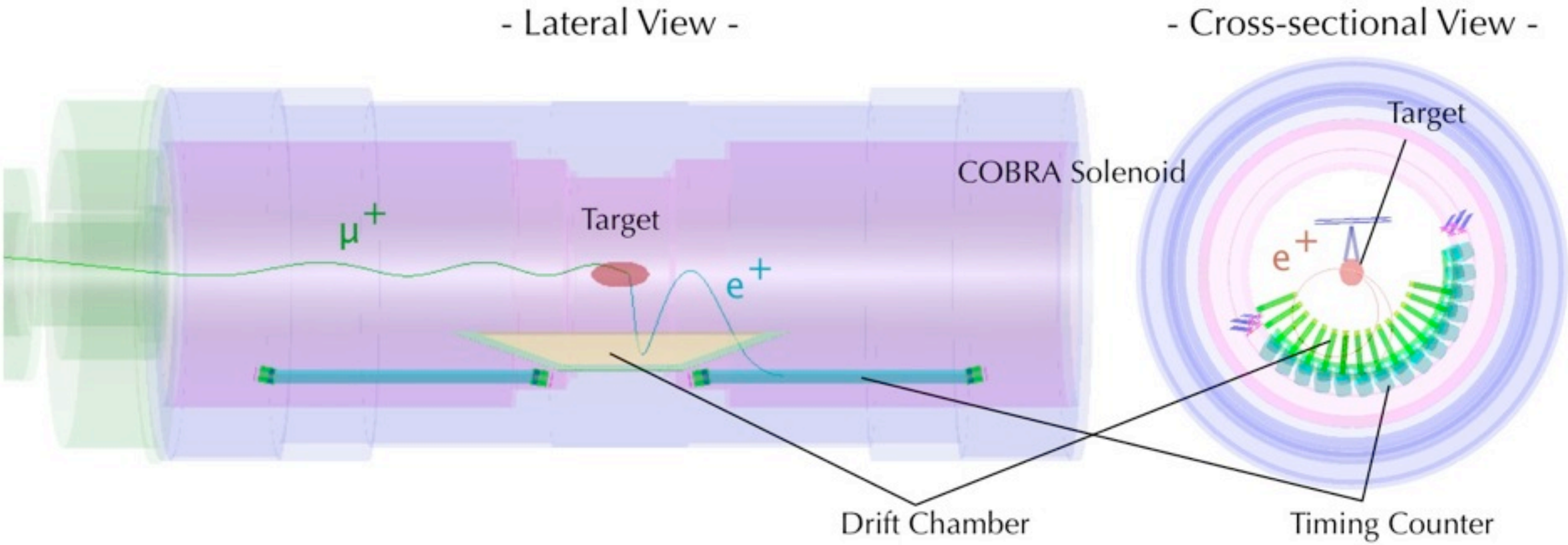




- **MEG beam transport system**
  - 28MeV/c surface μ^+ beam @πE5 beam channel
  - 3×10^7 μ^+/sec stopped in target
  - Wien filter for μ^+/e^+ separation
  - Superconducting transport solenoid with degrader
  - Beam spot size ~10mm(σ)
- **MEG beam transport system**
  - 205μm-thick polyethylene/polyester sandwich target supported by Rohacell frame
  - Slant angle ~20°



COBRA Spectrometer



Solenoid

superconducting solenoid
gradient B-field (0.49-1.27 T)
very thin conductor and
cryostat wall ($0.2X_0$)

Drift Chamber

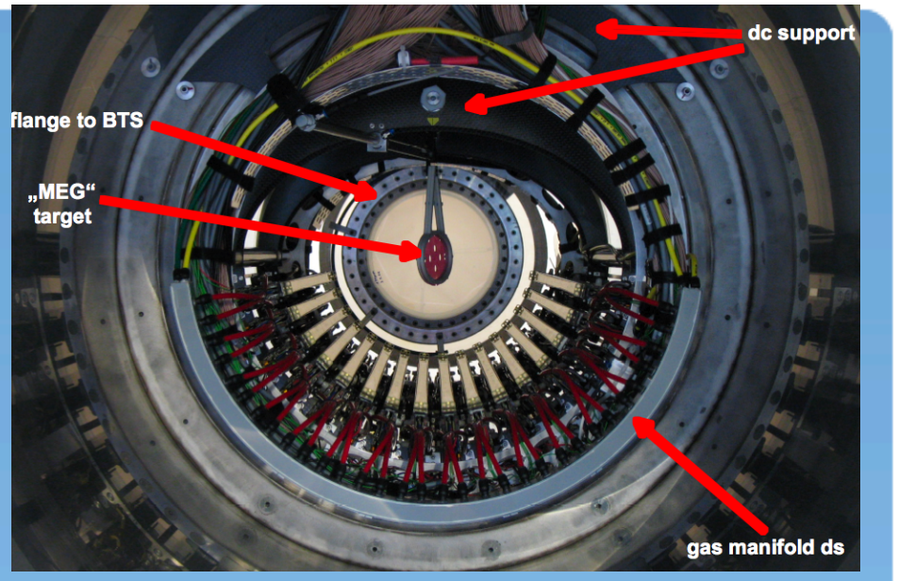
segmented radially (16 sectors)
helium:ethane (50:50)
opened-frame
very thin cathode foil with pads
$2x10^{-3}X_0$ along positron trajectory

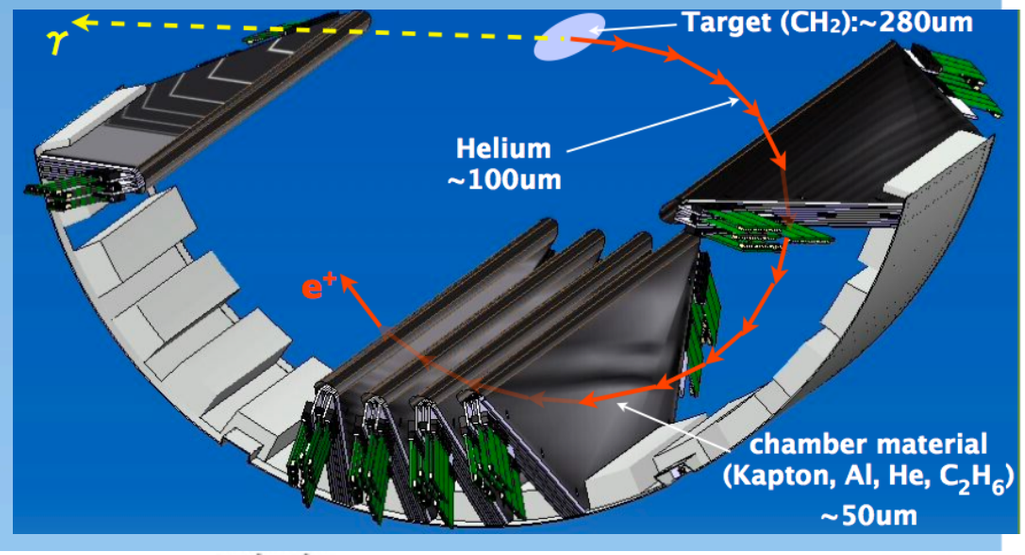
Timing Counter

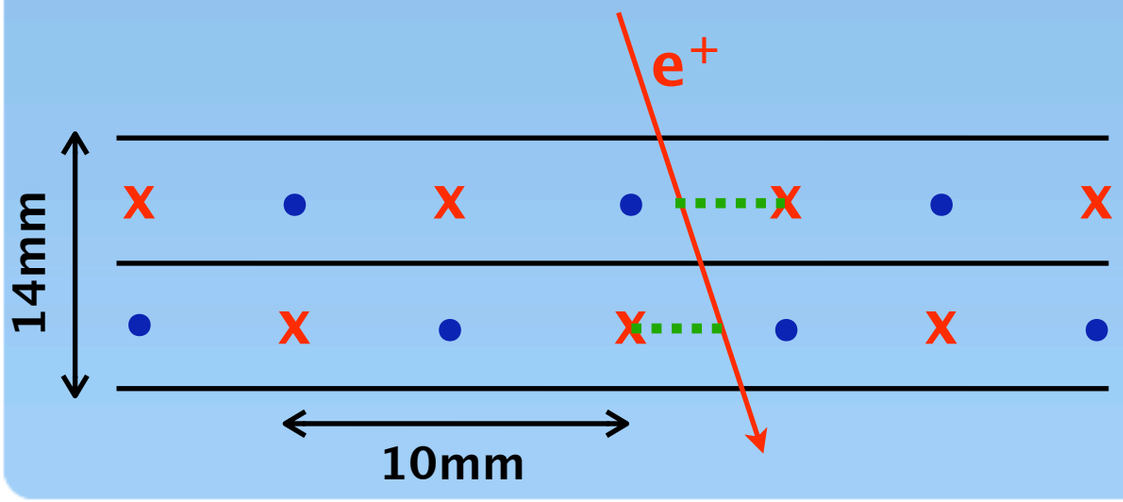
2-layers of scintillators
- scintillator bars (outer)
- scintillator fibers (inner)

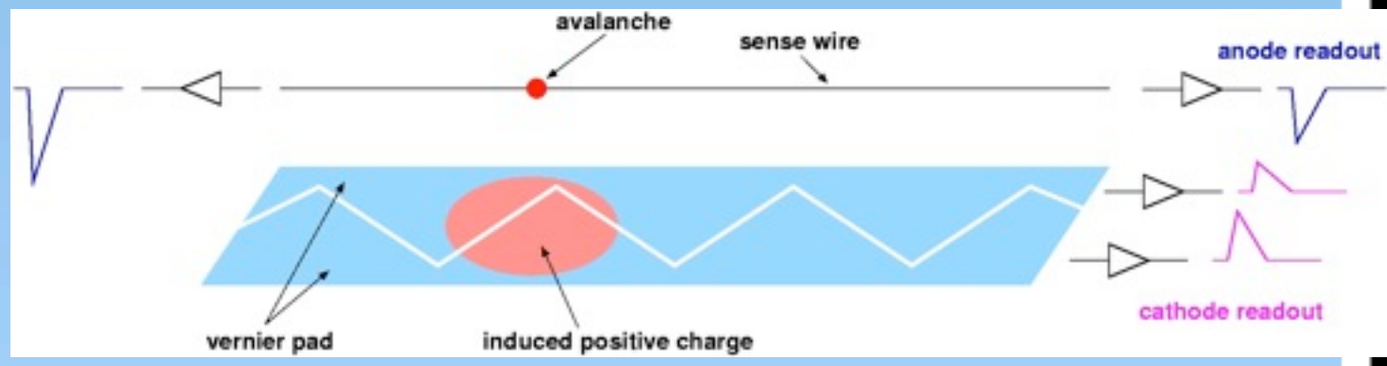
Drift Chambers

- 16 chambers radially aligned with 10° intervals
- Low mass to avoid multiple-scattering and annihilation photon BG
- Two staggered layout of drift cell for R measurement
- Charge division on anode wire and Vernier pattern cathode pad for Z measurement



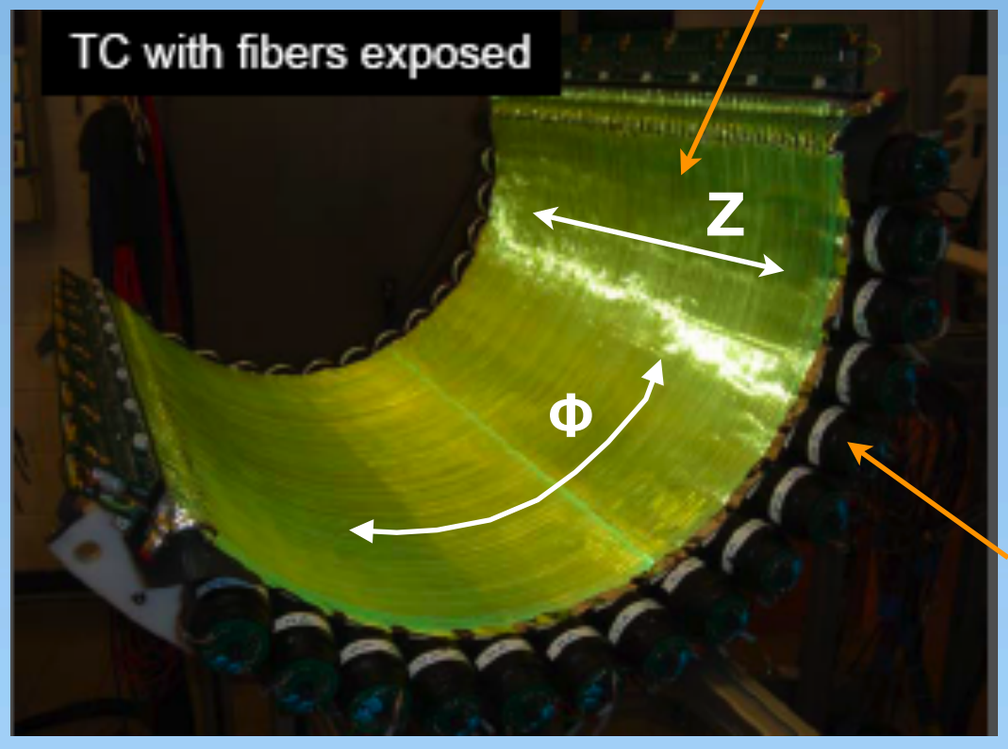






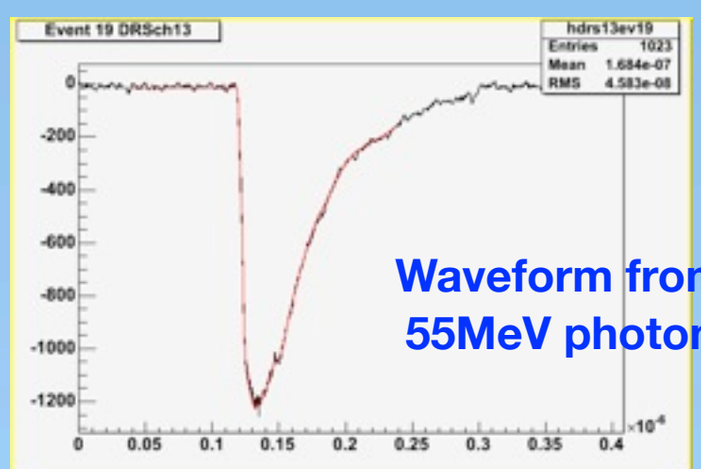
Timing Counter

- Double-layered fast timing counters for positron
  - Scintillator bars along z read out by fine-mesh PMTs at both ends to measure positron timing
  - Scintillator fibers along Φ read out by APD for additional trigger information

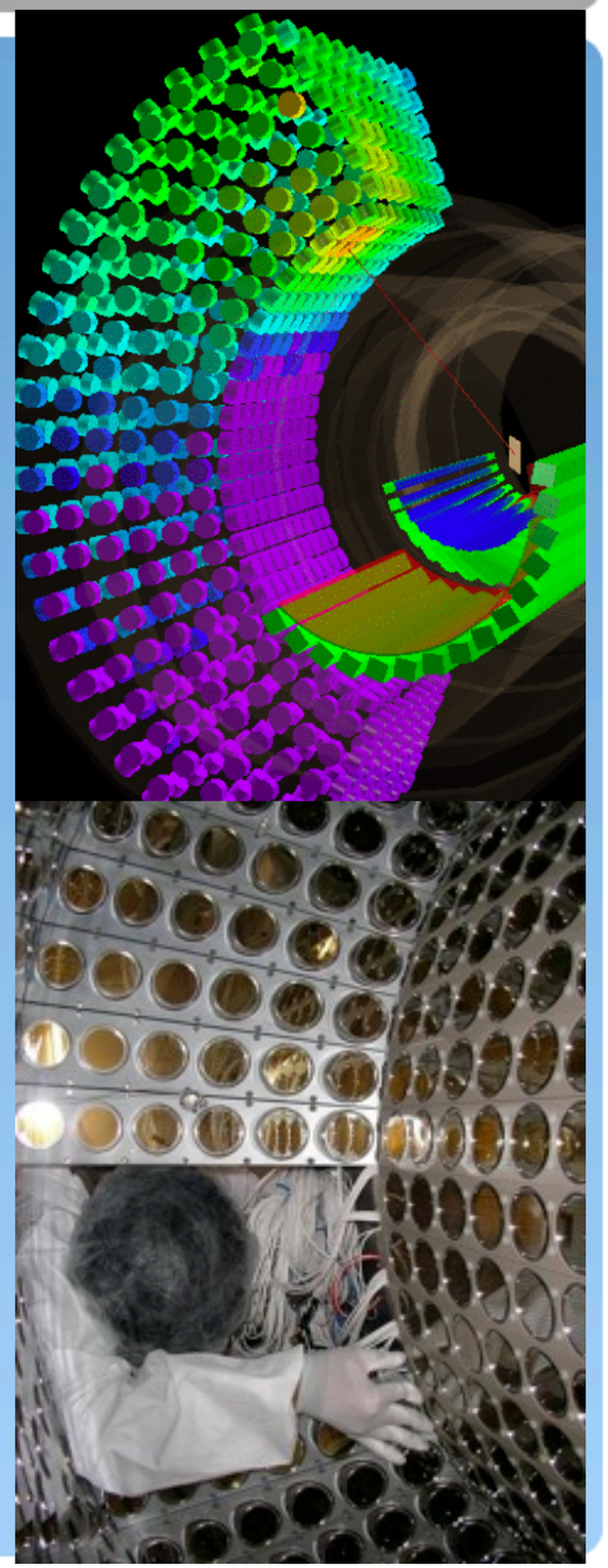


Liquid Xenon γ-Detector

- World's largest LXe scintillation detector
- C-shaped 900L-LXe surrounded by 846 PMTs
- How to measure gamma-ray
  - Energy: sum of PMT charge
  - Position: light distribution
  - Time: average PMT time
- All PMTs read out by waveform digitizer (DRS4)
  - pileup analysis, particle ID

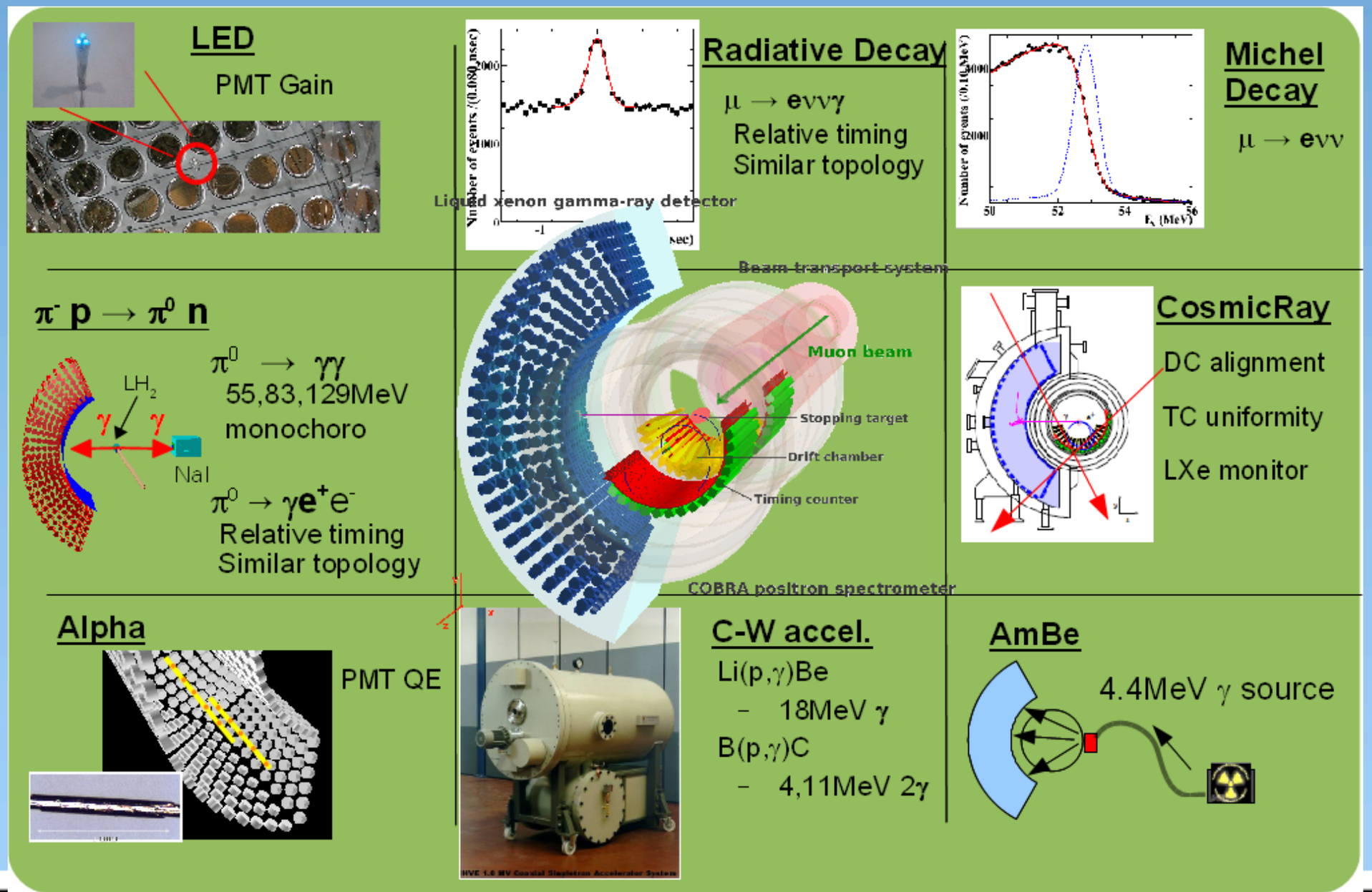


Waveform from 55MeV photon



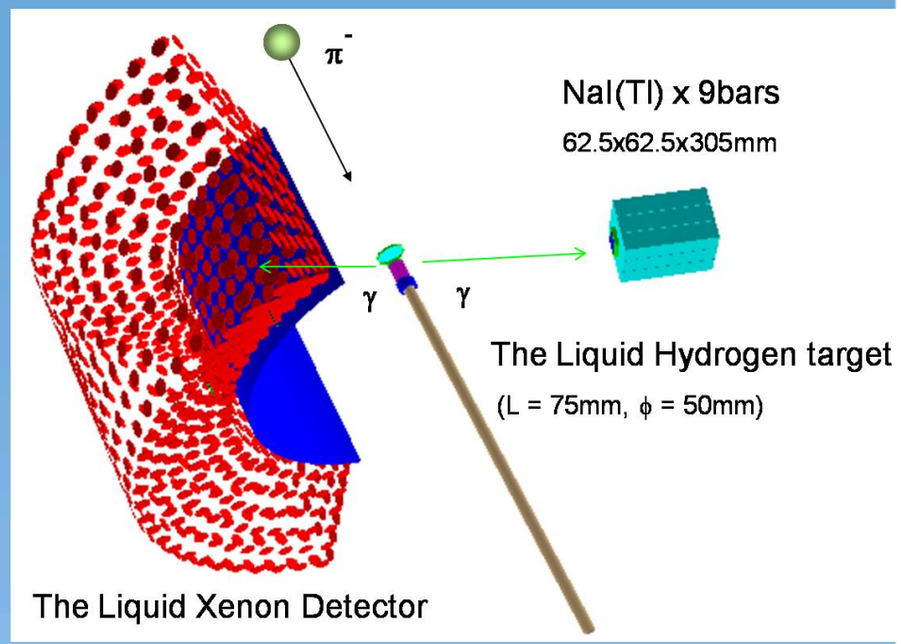
Calibration/Monitoring

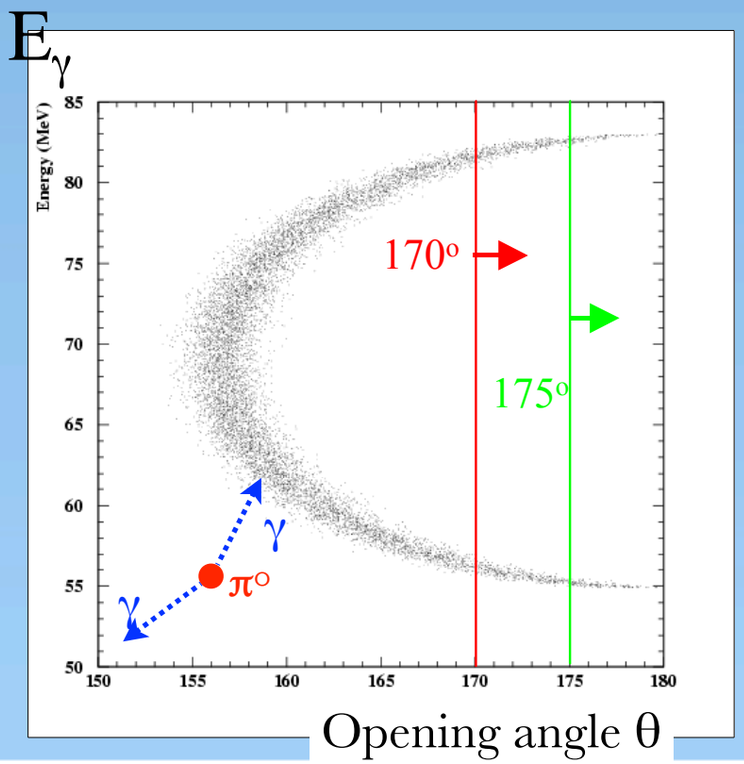
- Precise detector calibration and monitoring is crucial especially for LXe detector.
- Various calibration tools are developed.



π^0 Calibration

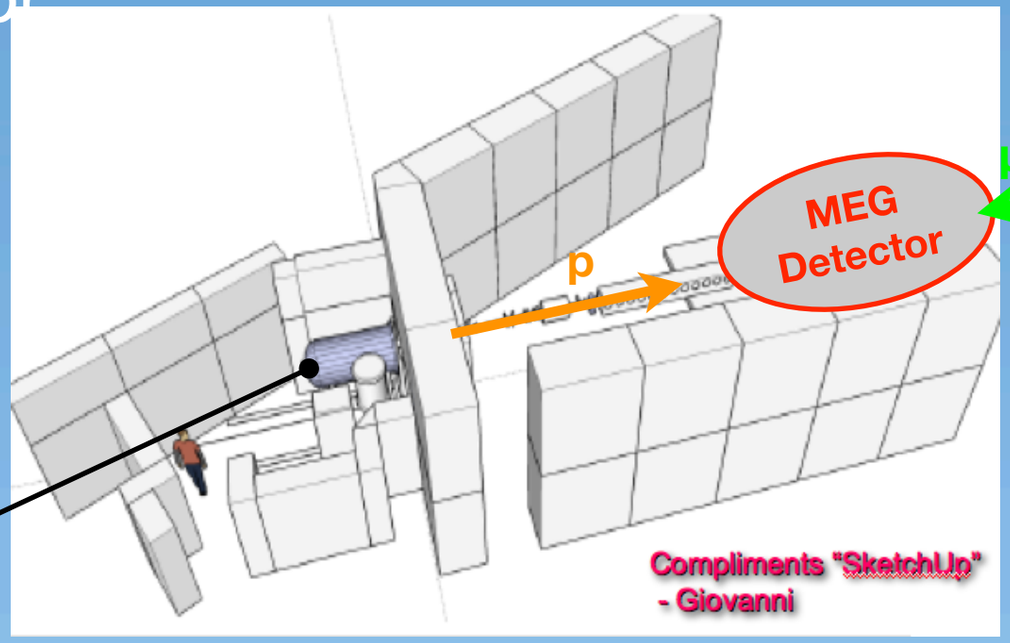
- Two γs from π^0 produced in charge exchange (CEX) process, $\pi^- + p \rightarrow \pi^0 + n$
  - Almost monochromatic 55 and 83MeV photons by selecting two photons with an opening angle ~180°
- 129MeV photon from radiative capture process, $\pi^- + p \rightarrow \gamma + n$.
- We measured the performance in the full detector acceptance.
  - Resolutions (energy, timing and position)
  - Energy scale



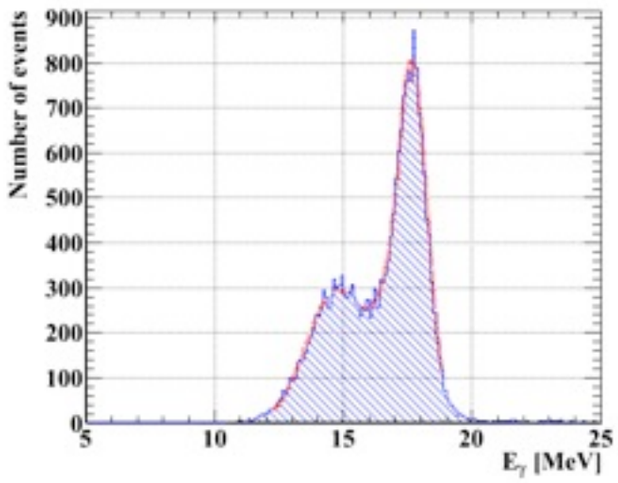


Cockcroft-Walton Accelerator

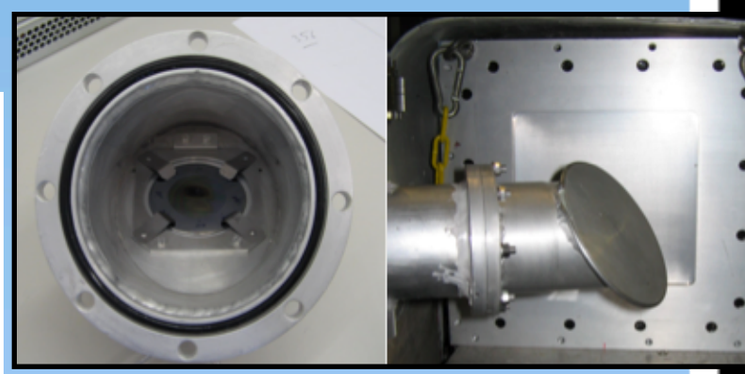
- **Cockcroft-Walton proton accelerator**
  dedicated to calibration of LXe detector
- **Mono-energetic γ**
  - Li(p, γ)Be: **17.6 MeV**
  - B(p, γ)C: **4.4MeV**, **11.6MeV**
- Monitoring light yield
- Study detector non-uniformity



500keV Cockcroft-Walton accelerator



Spectrum for 17.6MeV γ



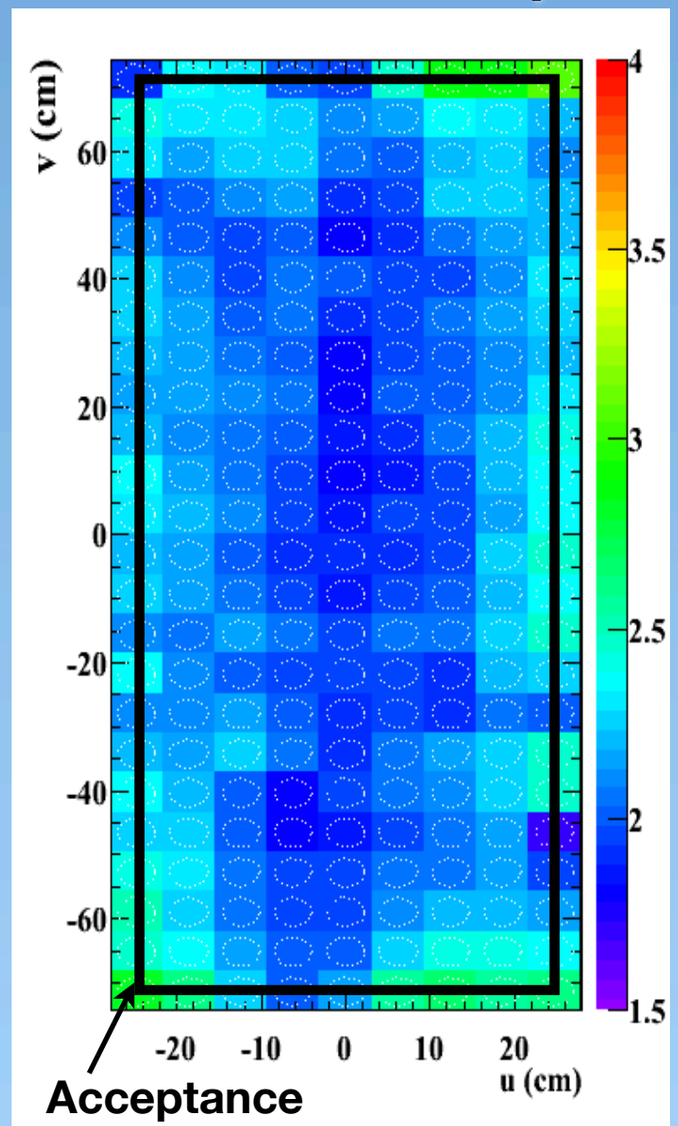
LiF target

Detector Performance

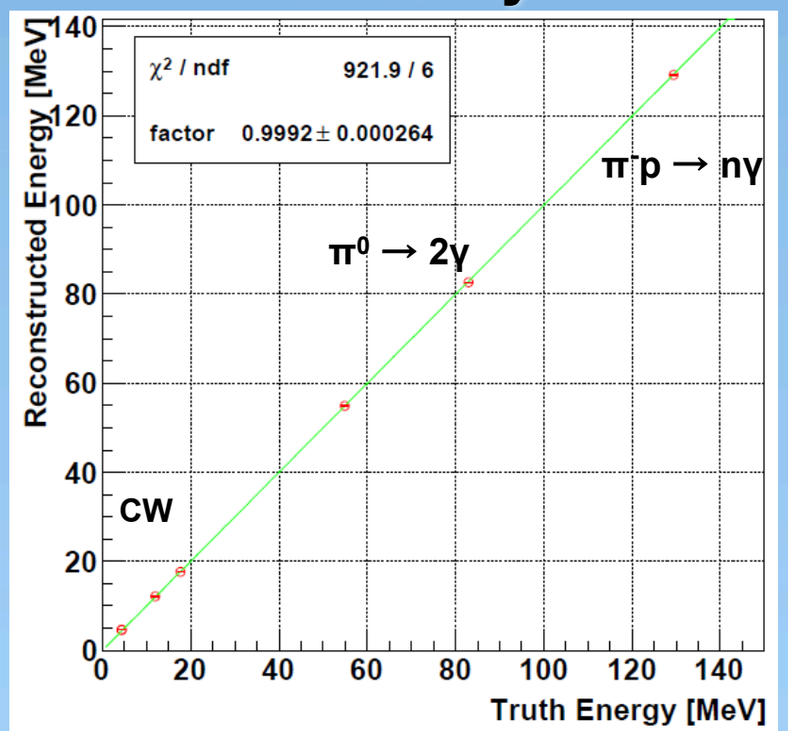
Gamma Energy

- Energy resolution and energy scale were measured with 55MeV-γ from π^0 decay in CEX run.
  - Average resolution (σ at right side)
    - **2.1% (conversion depth > 2cm)**
    - **2.8% (conversion depth > 1-2cm)**
    - **3.3% (conversion depth > 0-1cm)**

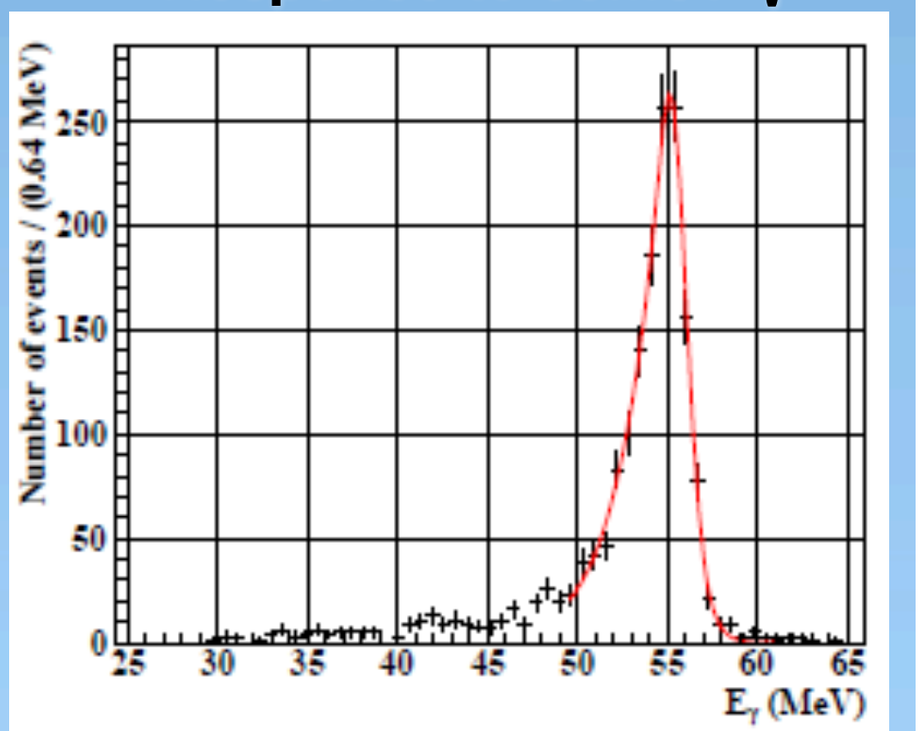
Resolution map



Linearity

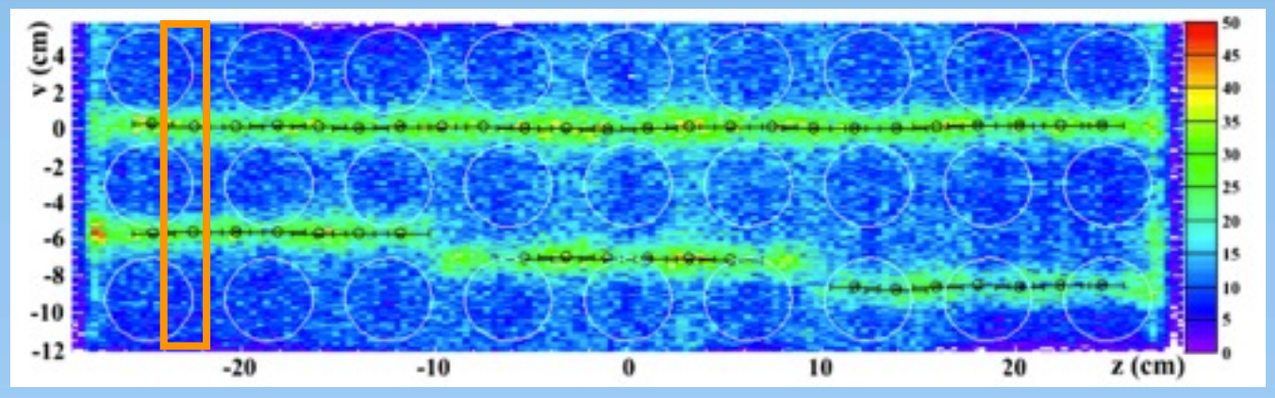


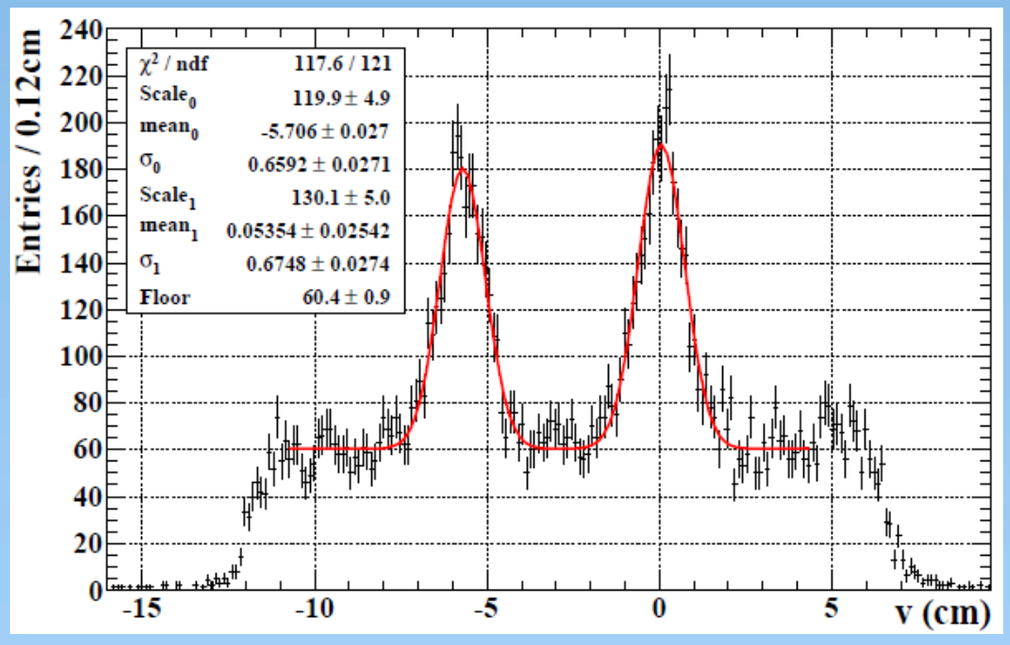
Response to 55MeV-γ



Gamma Position

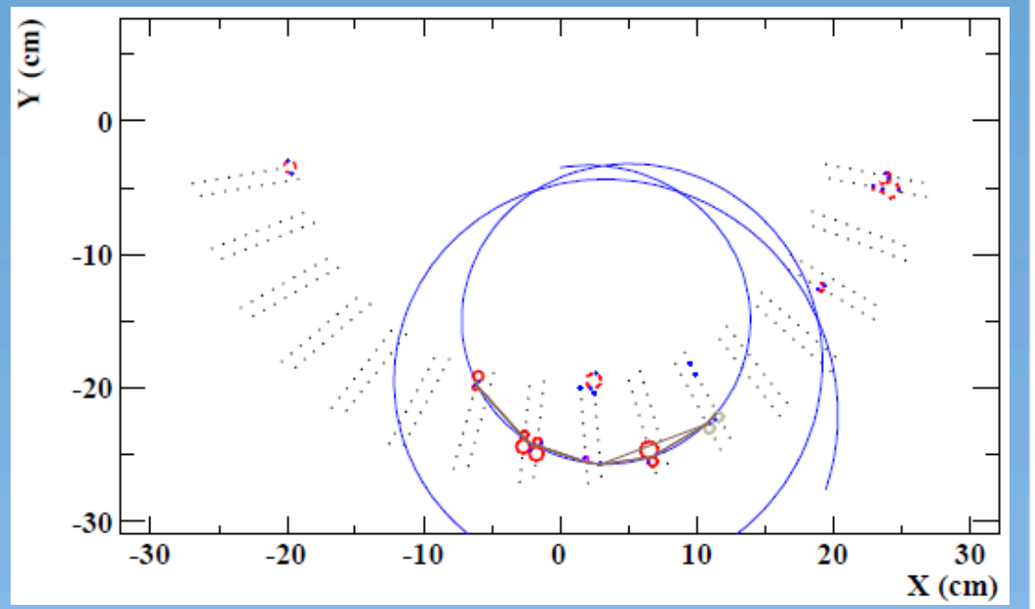
- Light distribution around incident position fitted with PMT solid angle.
- Position-dependent resolution is evaluated by MC with a small correction to match the measured distribution in dedicated CEX run by placing a lead slit collimator in front of LXe detector.
- Response function is described by a double Gaussian function.
  - $\sigma_{xy} \sim 5mm$, $\sigma_{depth} \sim 6mm$

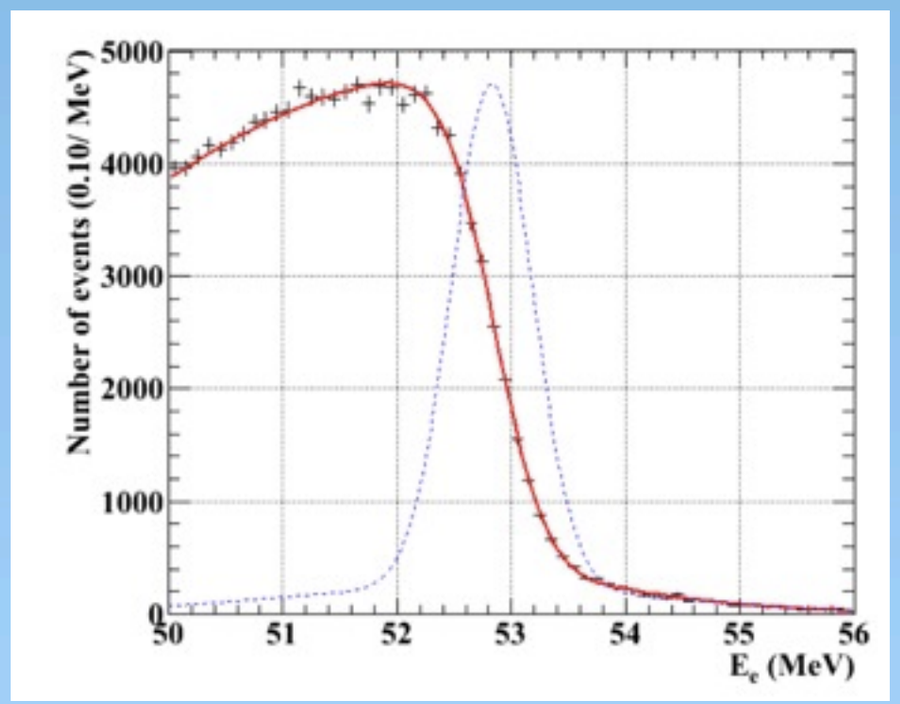


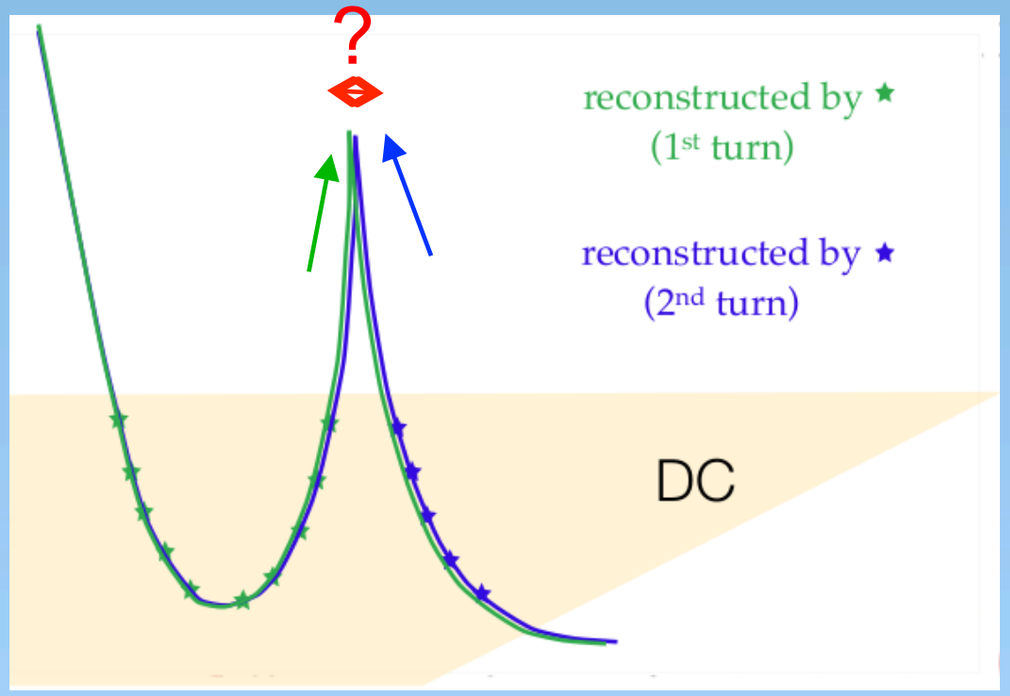


Positron Tracking

- Positron momentum response is measured at kinematic edge of Michel spectrum.
  - **σ_{mom} = 0.74% (core)**
- Positron angular resolution is measured from difference between two track segments in a double-turn track.
  - **σ_{θ} = 11.2mrad**
  - σ_{Φ} = 7.1mrad (core)

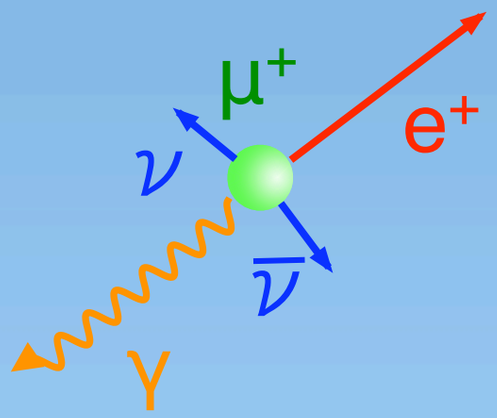


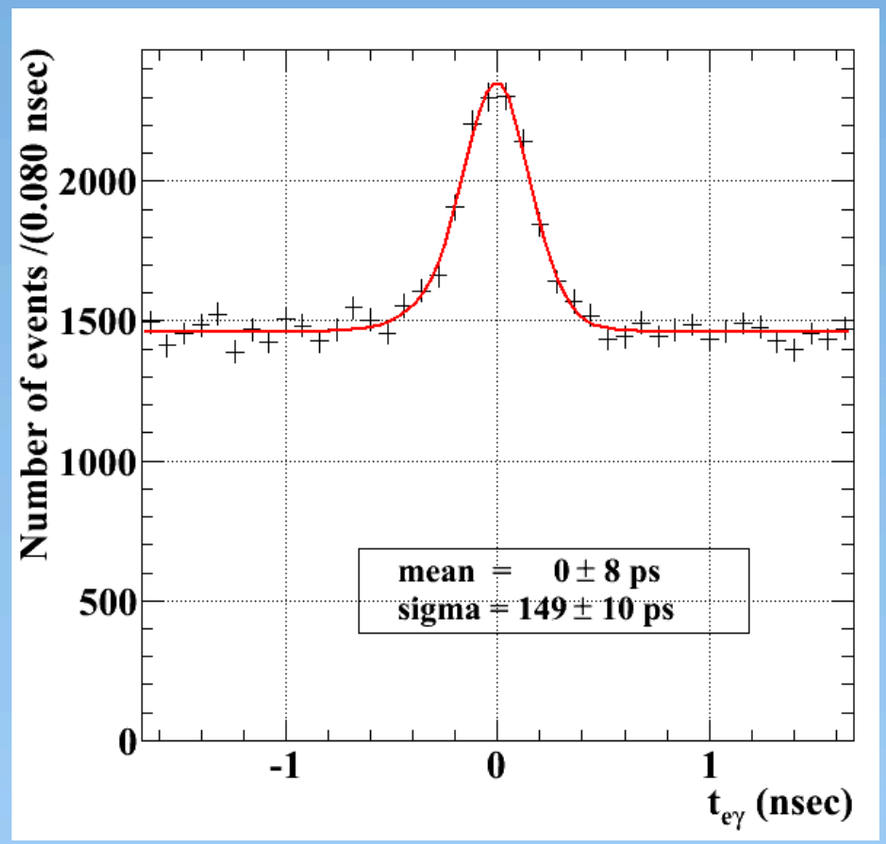




Relative Timing

- Resolution of γ-e^+ relative timing is extracted from a peak for radiative muon decays (RMD) observed in sideband.
  - **$\sigma_{Te\gamma}$ = 142ps**





Performance Summary

Performance summary (run 2009)

Gamma energy (%)	2.1% (w>2cm)
Gamma position (mm)	5 (u,v) / 6 (w)
Positron momentum (%)	0.74 (core)
Positron angle (mrad)	7.1 (Φ,core), 11.2 (θ)
Vertex position (mm)	3.4 (Z), 3.3(Y)
Gamma-positron timing (ps)	142 (core)
Gamma efficiency (%)	58
Trigger efficiency (%)	84

Resolution in sigma

Physics Analysis of Run 2009

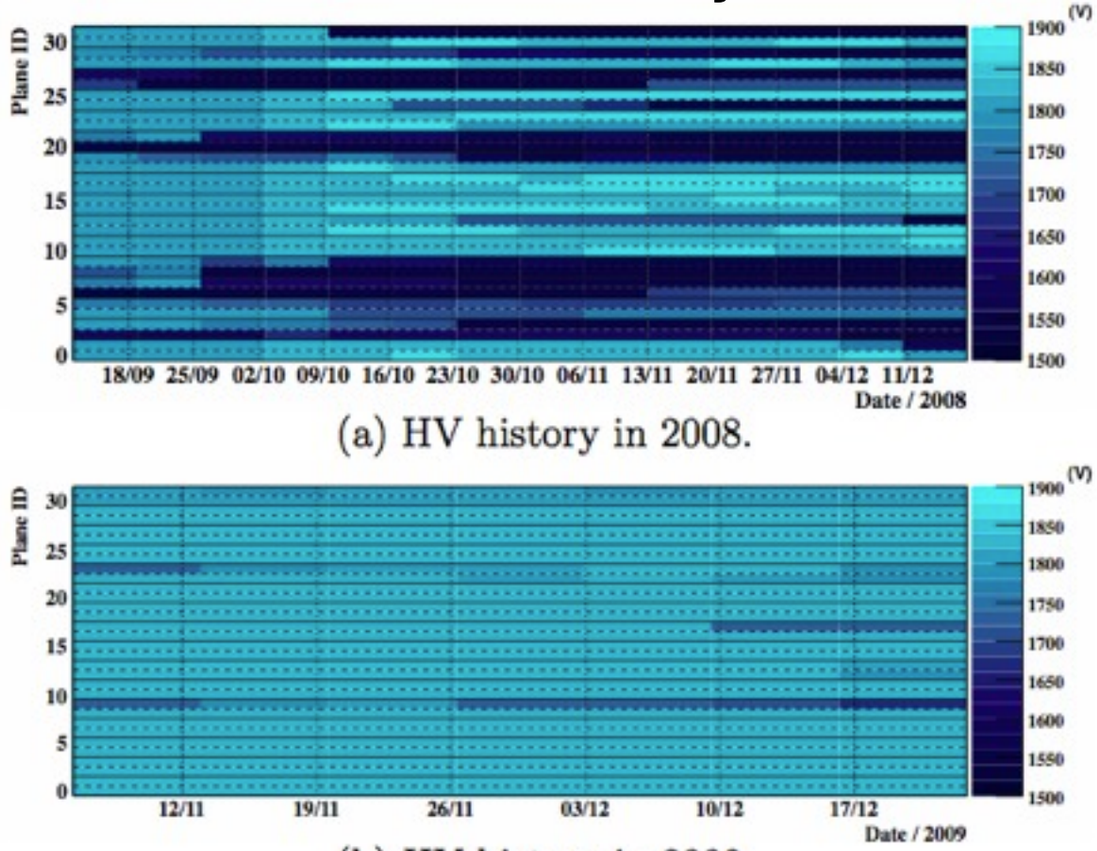
MEG Run History

- Run history
  - **2006**: Commissioning of positron spectrometer
  - **2007**: Pilot run with positron spectrometer and LXe γ-detector
  - **2008**: **First physics run**
    - BR sensitivity 1.3×10^{-11}, BR upper limit: 2.8×10^{-11} (90% C.L.)
  - **2009**: **First fully-efficient physics run**
    - Preliminary results were presented in ICHEP2010
  - **2010:** Stable physics run
    - Twice higher data statistics w.r.t. run 2009
  - **2011:** First “a year-long” physic run planned

Run 2009

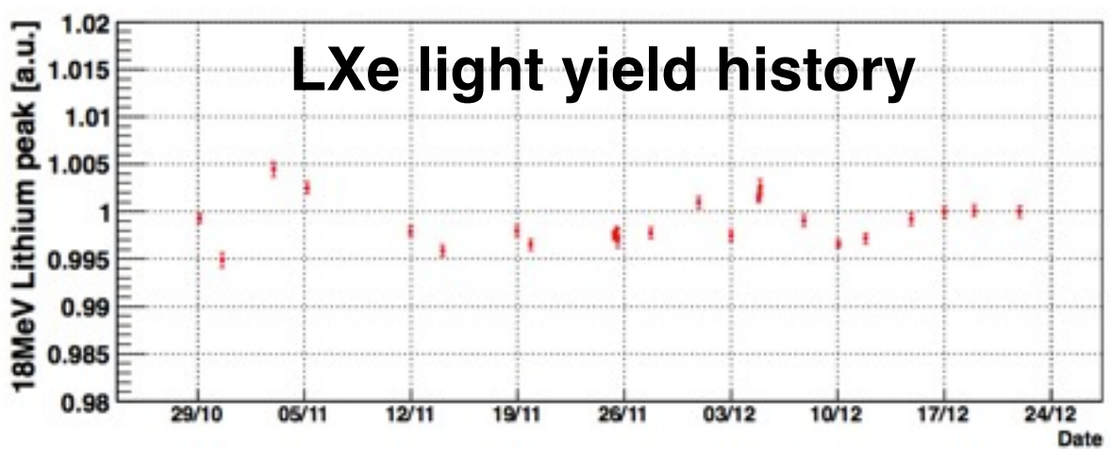
- **First fully-efficient physics run**
  - Improved DC efficiency
  - Stable LXe light yield at maximum level
- Physics run ~43 days (Nov.-Dec., 2009)
- μ-stop rate: **2.9×10^{7} s^{-1}**
- Total μ-stop: **6.5×10^{13}**

DC HV history



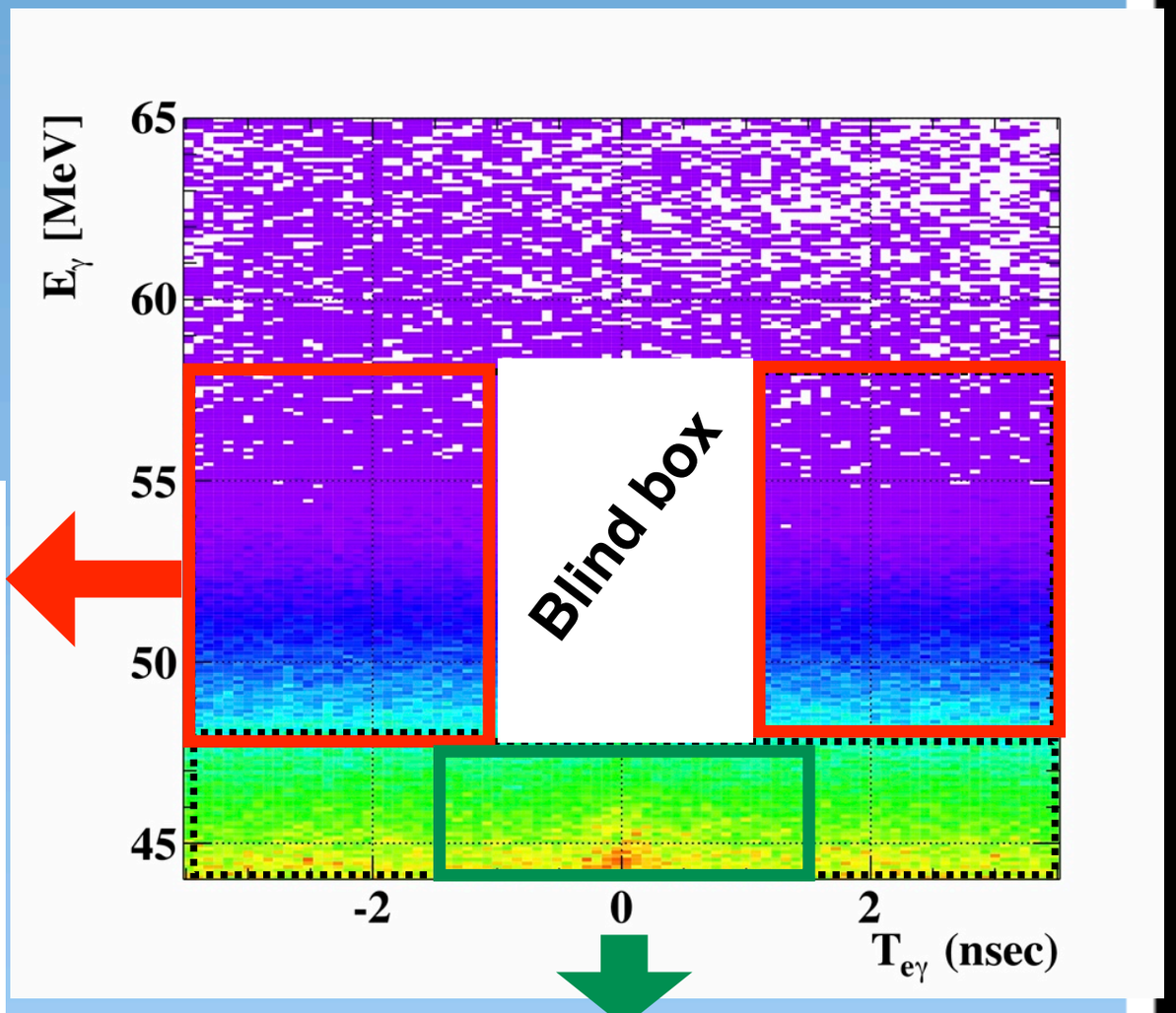
(a) HV history in 2008.

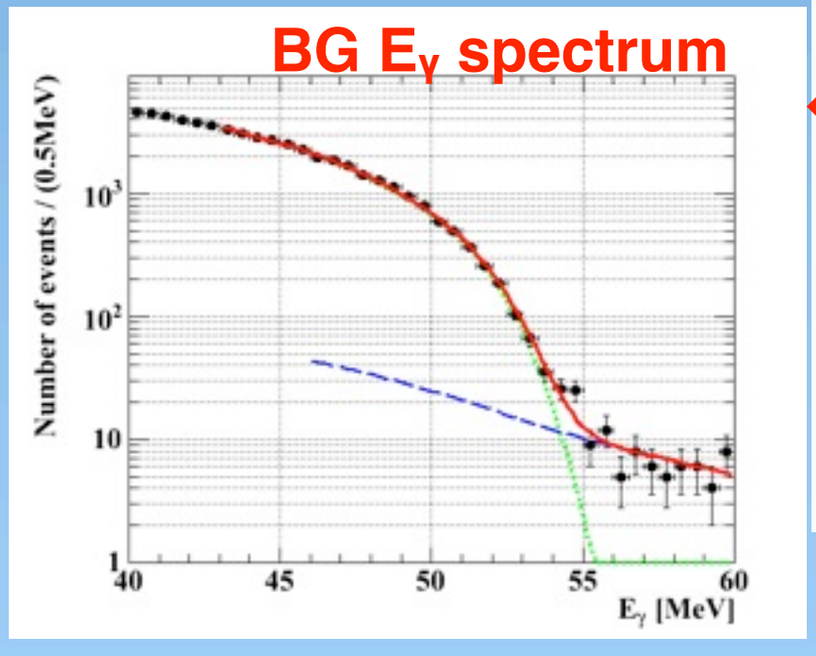
(b) HV history in 2009.

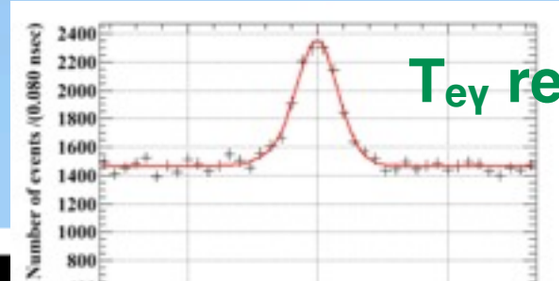


MEG Physics Analysis

- **Preselection**
  - -6.9 < $T_{e\gamma}$ < 4.4ns, DC track(s) with TC hits
  - Data size reduced down to ~20%
- **Blinding**
  - Analysis optimization and BG study are done in side-bands.







MEG Physics Analysis

- **Maximum likelihood analysis to extract N_{signal}**
- An extended maximum likelihood function
  - Three event types: **signal, radiative μ decay (RMD), accidental BG**
  - Observables x_i : E_γ, E_e, $T_{e\gamma}$, $\theta_{e\gamma}$, $\varphi_{e\gamma}$
  - Fit parameters: N_{signal}, N_{RMD}, N_{BG}
- **PDFs are formed mostly from data**
  - Signal: measured detector response function
  - RMD: theoretical spectrum convoluted with detector response
  - BG: measured BG spectrum

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

Signal PDF　RMD PDF　BG PDF

Normalization

- Normalize N_{sig} to number of Michel positrons counted simultaneously in physics run
  - Independent of instantaneous beam rate
  - Insensitive to spectrometer acceptance and efficiency

$$\begin{aligned} N_{sig} &= N_\mu \times Br_{e\gamma} \times \tau_{e\gamma} \times \epsilon_{e\gamma}^{trig} \times G_{e\gamma}^{DC} \times A_{e\gamma}^{TC} \times \epsilon_{e\gamma}^{DC} \times A_{e\gamma}^{LXe} \times \epsilon_{e\gamma}^{LXe} \\ N_{e\nu\bar{\nu}} &= N_\mu \times Br_{e\nu\bar{\nu}} \times \tau_{e\nu\bar{\nu}} \times \epsilon_{e\nu\bar{\nu}}^{trig} \times G_{e\nu\bar{\nu}}^{DC} \times A_{e\nu\bar{\nu}}^{TC} \times \epsilon_{e\nu\bar{\nu}}^{DC} \times f_{e\nu\bar{\nu}}^{E} \times P \end{aligned}$$

$$\mathrm{BR}(\mu^+ \to e^+\gamma) = \frac{N_{\mathrm{signal}}}{k}$$

k (run2009) = (1.0±0.1)×10^{12}

Preliminary

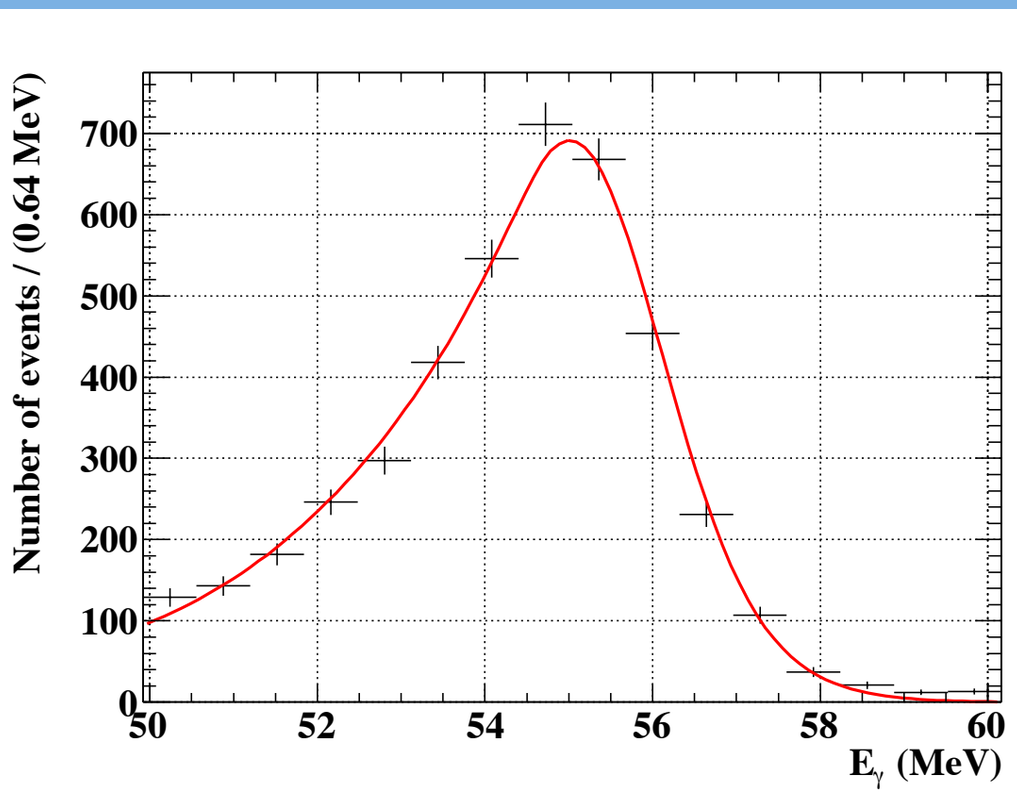
MEG Physics Analysis

- Different types of likelihood analyses performed to check possible systematics.
  - Two independent analyses in frequentist approach
    - Analysis 1: **Event-by-event PDF, observables (E_γ, E_e, $T_{e\gamma}$, $\theta_{e\gamma}$, $\Phi_{e\gamma}$)**
    - Analysis 2: **Constant PDF for γ, observables (E_γ, E_e, $T_{e\gamma}$, $\Theta_{e\gamma}$)**
  - Bayesian approach for cross-check

PDF: Gamma

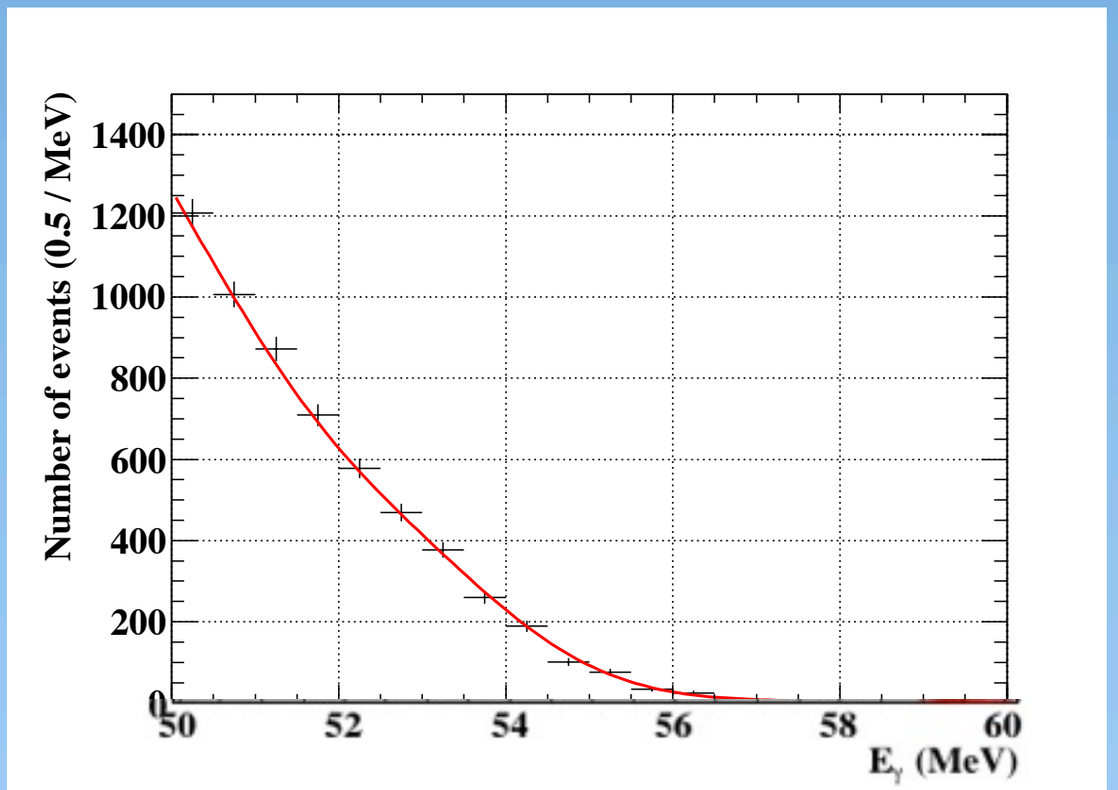
Signal E_γ

- Measured in π^0 run
- Position dependent



BG E_γ

- Measured in sideband
- Position dependent



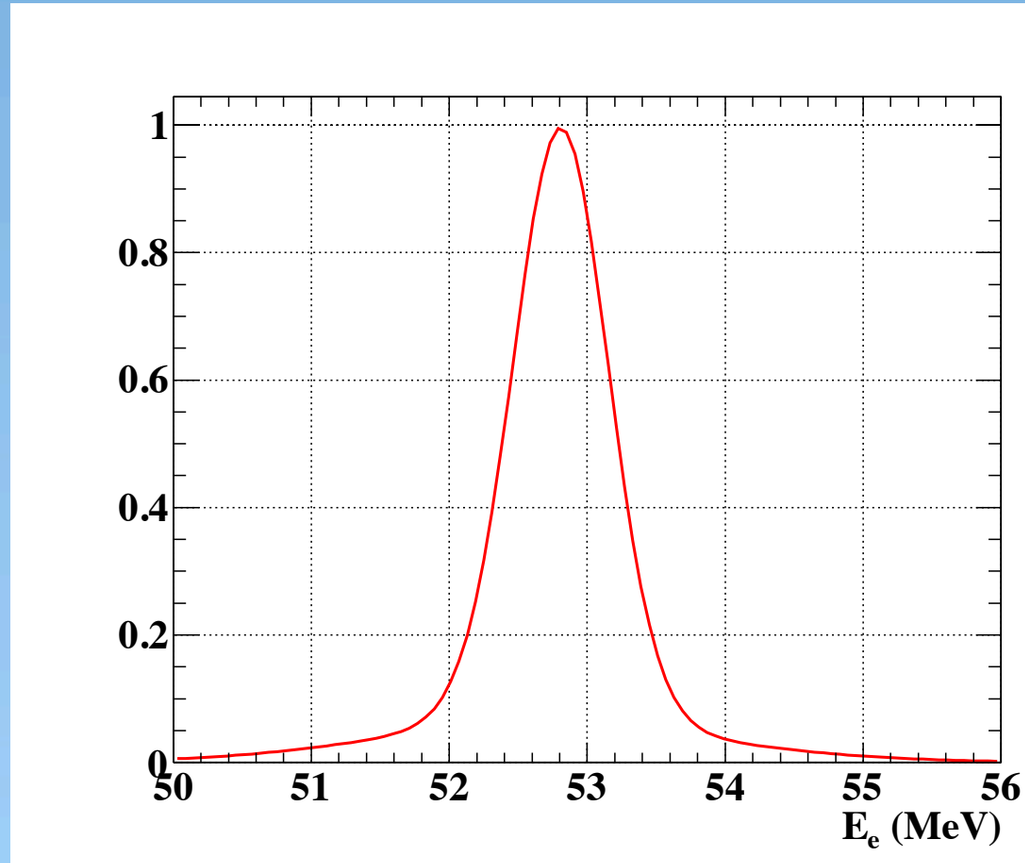
PDF: Positron

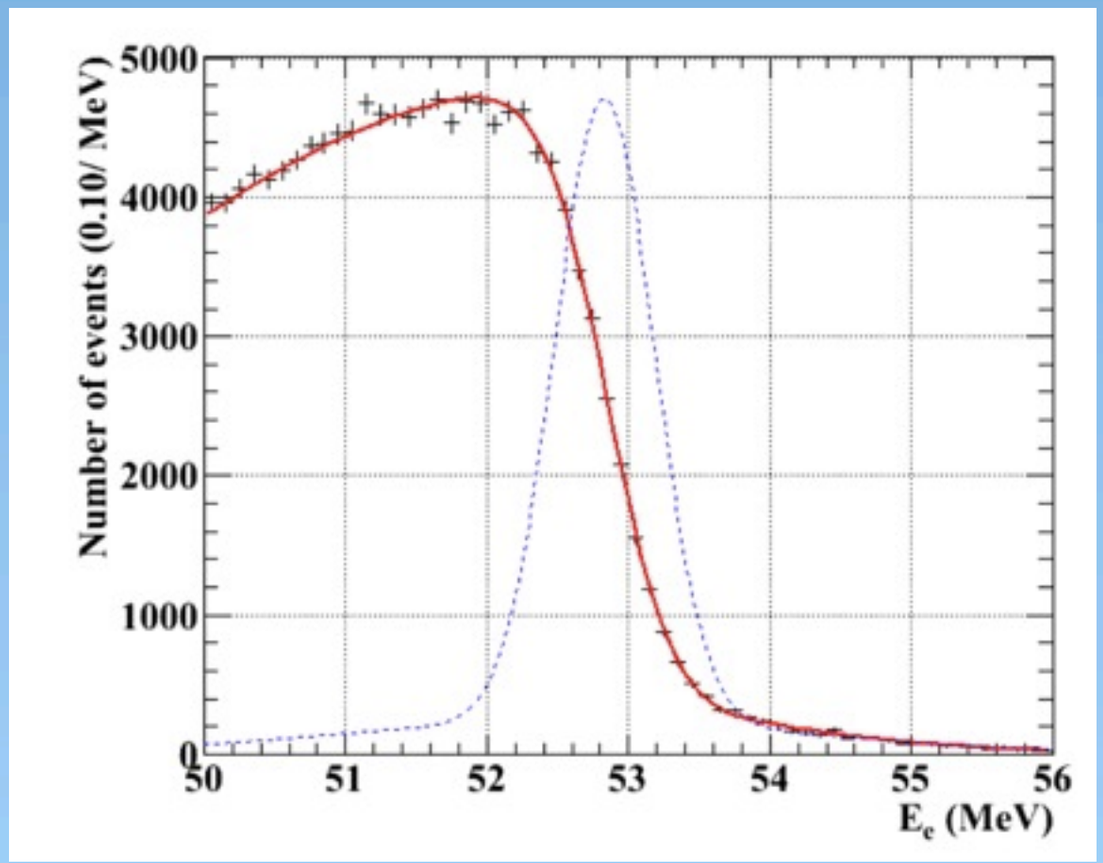
Signal E_e

- Fitting at kinematical edge of measured Michel spectrum
- tracking-quality dependent

BG E_e

- Measured Michel spectrum
- tracking-quality dependent

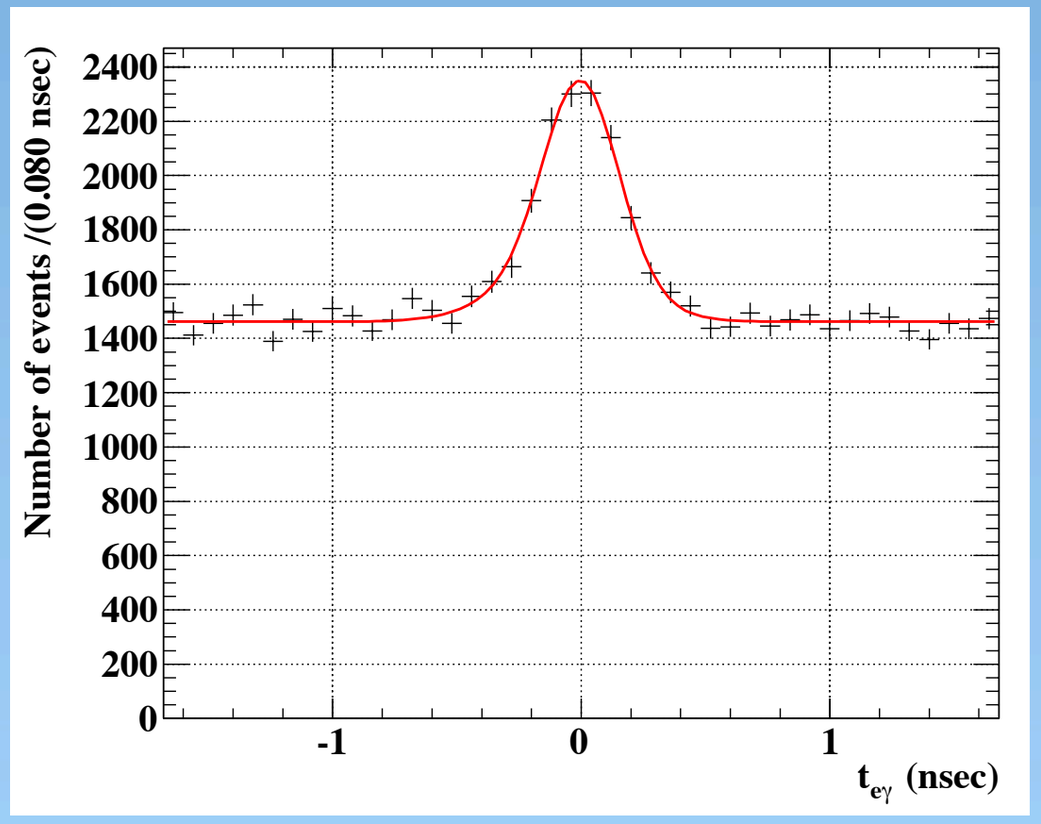




PDF: Relative Time/Angle

Signal $T_{e\gamma}$

- RMD peak measured in E_γ-sideband
- Small E_γ correction



Signal angle

- Combined measured resolutions

BG angle

- Measured distribution in sideband

RMD

- Theoretical spectrum folded by measure resolutions (E_γ, E_e, $\theta_{e\gamma}$, $\Phi_{e\gamma}$ are correlated)

Sensitivity

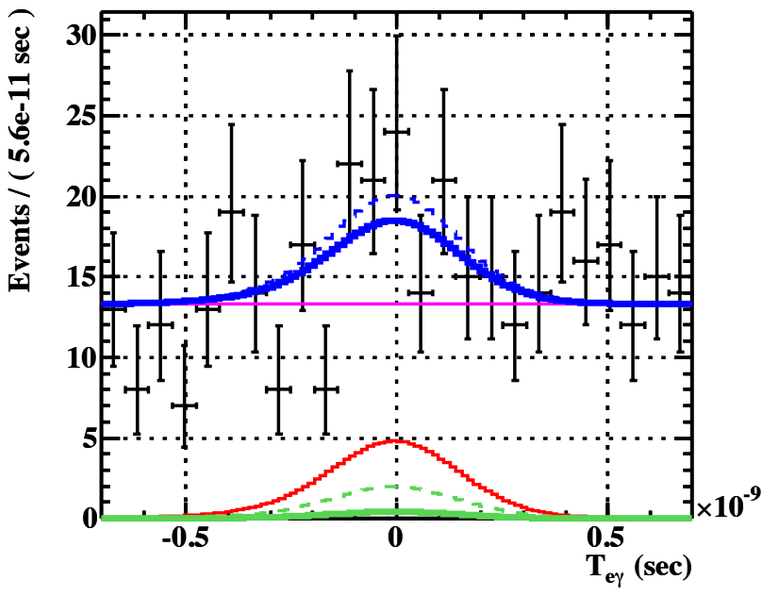
- Sensitivity of data 2009 is calculated as an average upper limit (90% C.L.) over an ensemble of the simulated many experiments with the same BG rate and null signal hypothesis.
  - **BR sensitivity ~6.1×10^{-12}**
  - BR sensitivity is twice better than current experimental bound.
- Consistent with the upper limits obtained in the sideband analysis of (4-6)$\times10^{-12}$

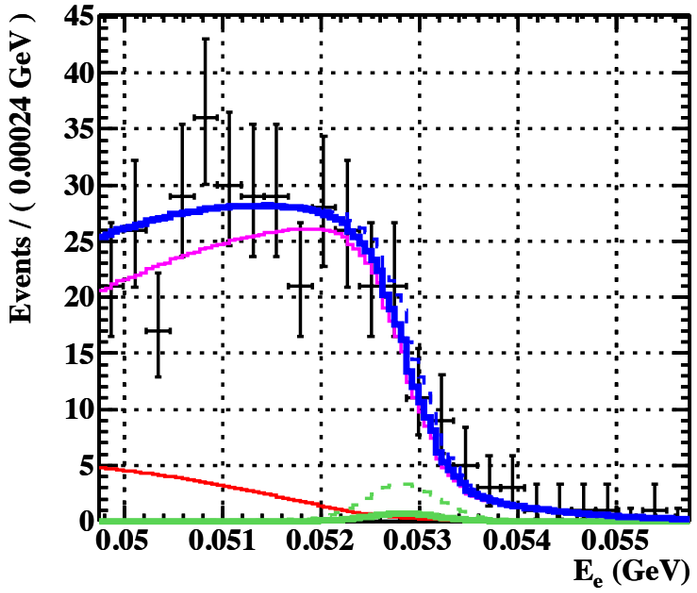
Preliminary

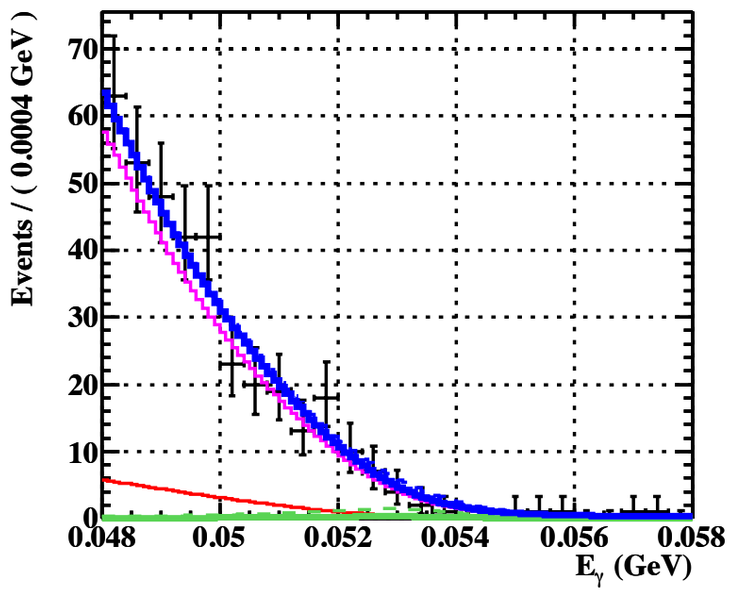
N.B. present experimental bound set by MEGA : 1.2×10^{-11}

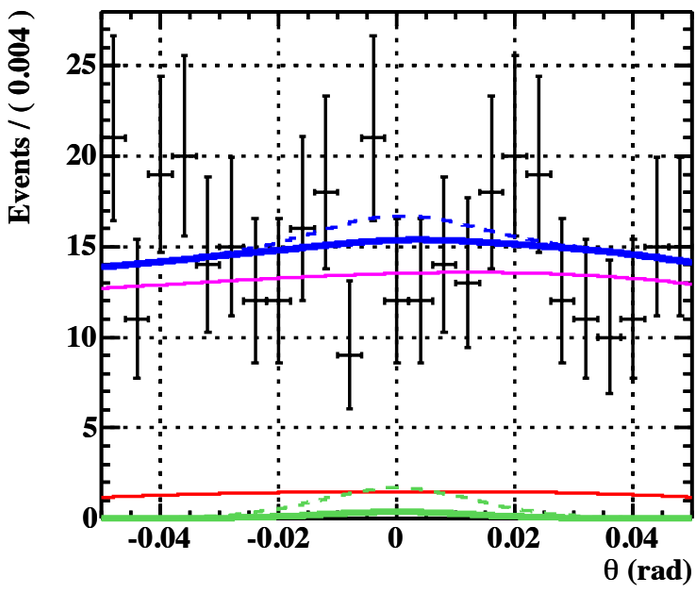
Fit Result

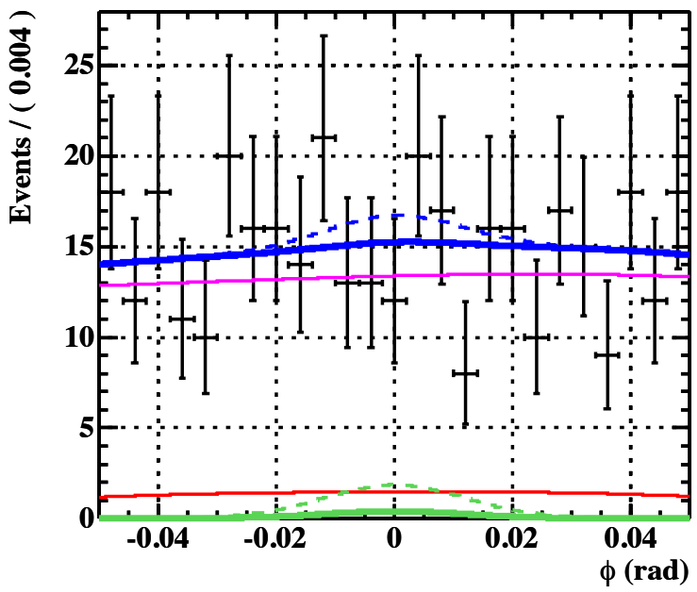
Fit region: **$48<E_\gamma<58$MeV, $50<E_e<56$MeV, $|T_{e\gamma}|<0.7$ns, $|\theta_{e\gamma}|<50$mrad, $|\Phi_{e\gamma}|<50$mrad**











- BG (best fit)
- RMD (best fit)
- Signal (best fit)
- Total
- Signal (UL 90%C.L.)
- Total w/ signal UL

Best fit:

$N_{signal} = 3.0$ **Preliminary**

$N_{RMD} = 35^{+24}_{-32}$

Upper Limit

- Best fit
  - **N_{signal} = 3.0**
  - **N_{RMD} = 35$^{+24}_{-22}$** (expectation from sideband: 32±2)
- **Upper limit for N_{signal} : 14.5 (90% C.L.) (sys. included)**
- **N_{signal}=0 is within 90% confidence interval.**

Preliminary

- Branching ratio upper limit for run 2009

BR($\mu^+ \to e^+\gamma$) < 1.5×10^{-11} (90% C.L.) (sys. included)

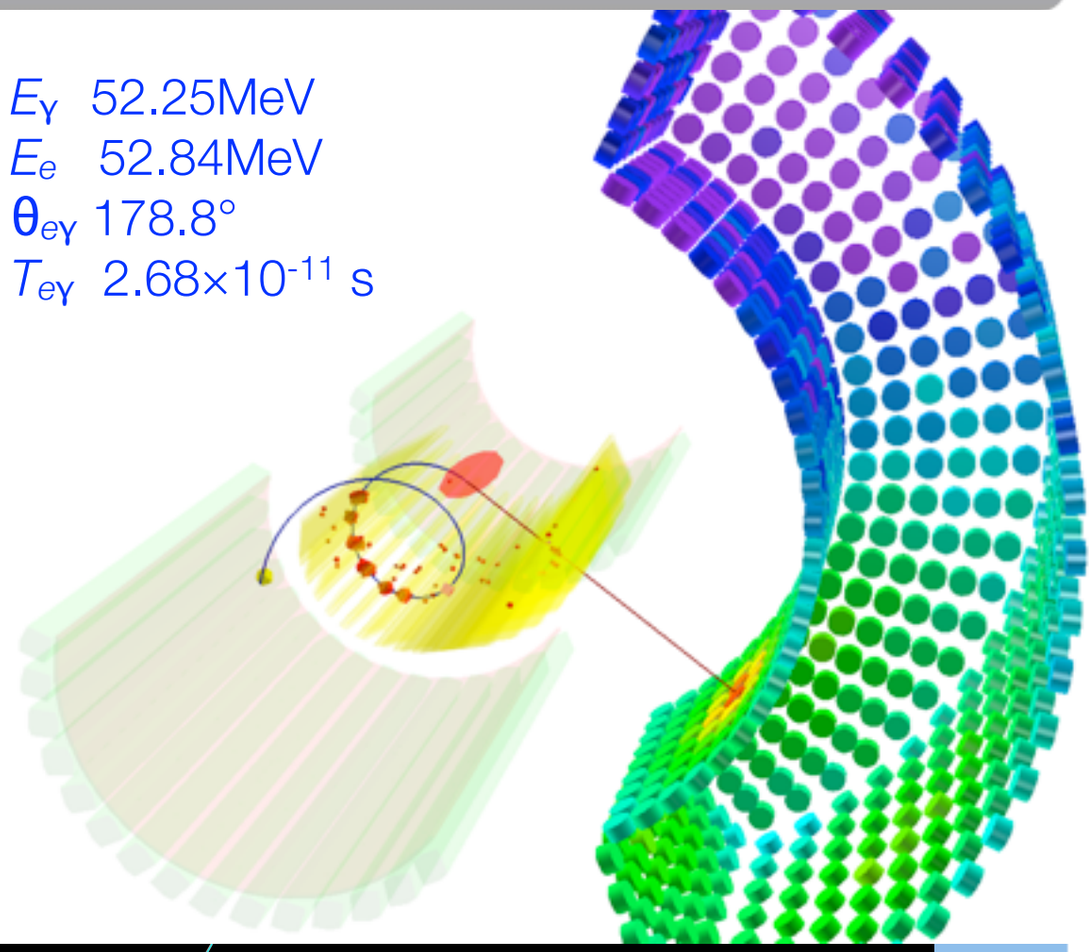
Preliminary

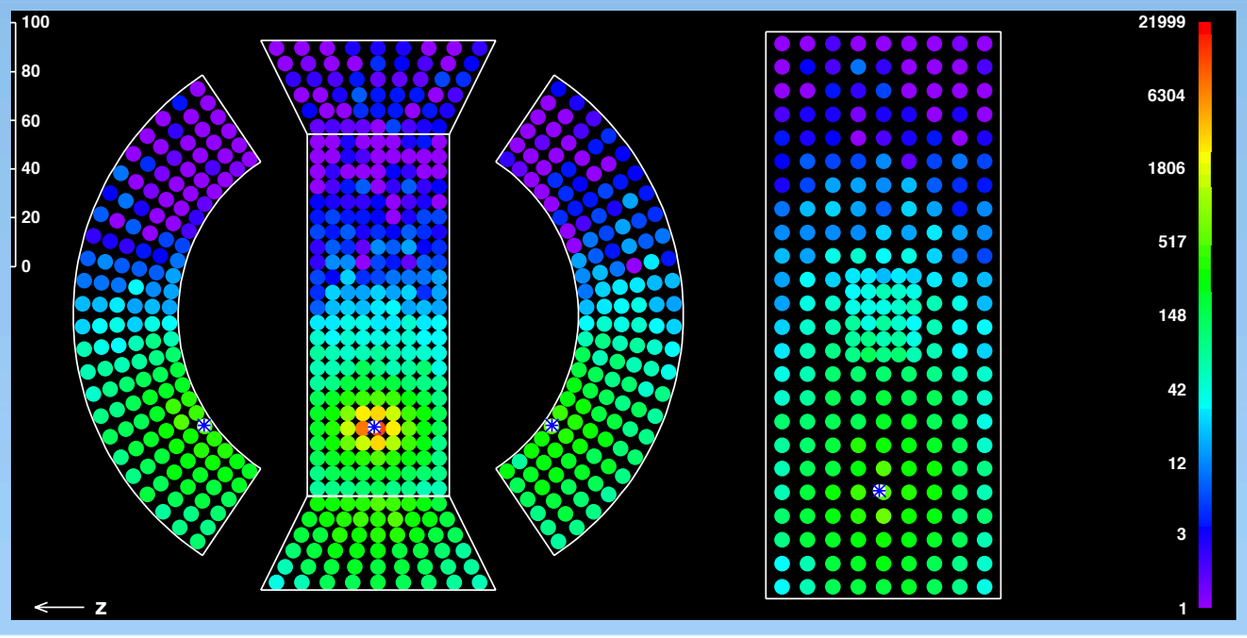
N.B. present experimental bound set by MEGA : 1.2×10^{-11}

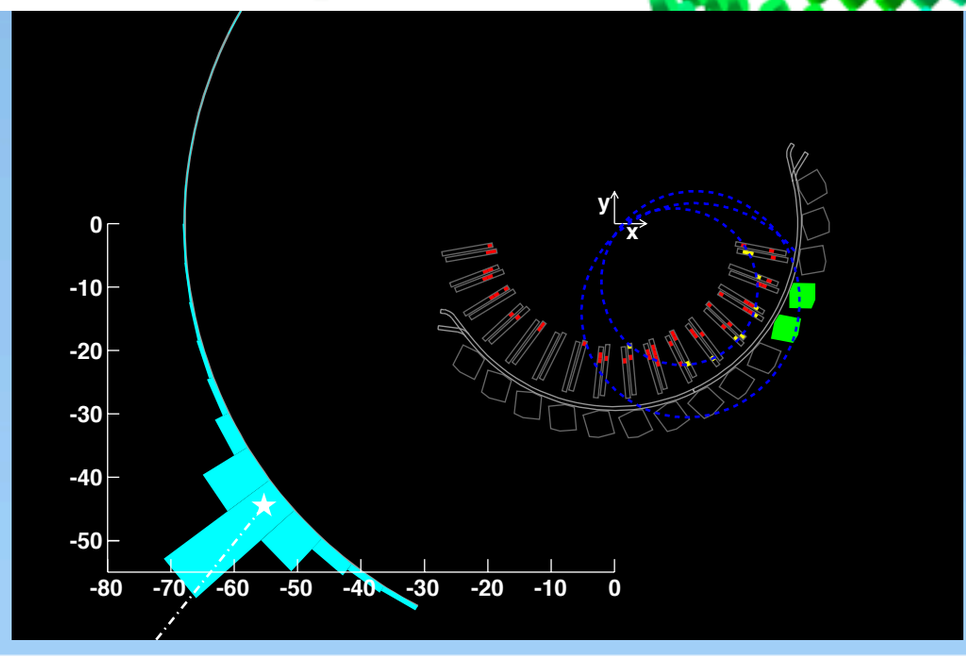
Signal-like Event

- Example of event display for signal-like event
- Nothing strange for highly-ranked events
  - Randomly distributed in detector acceptance
  - Detector condition was fine when the events were recorded.

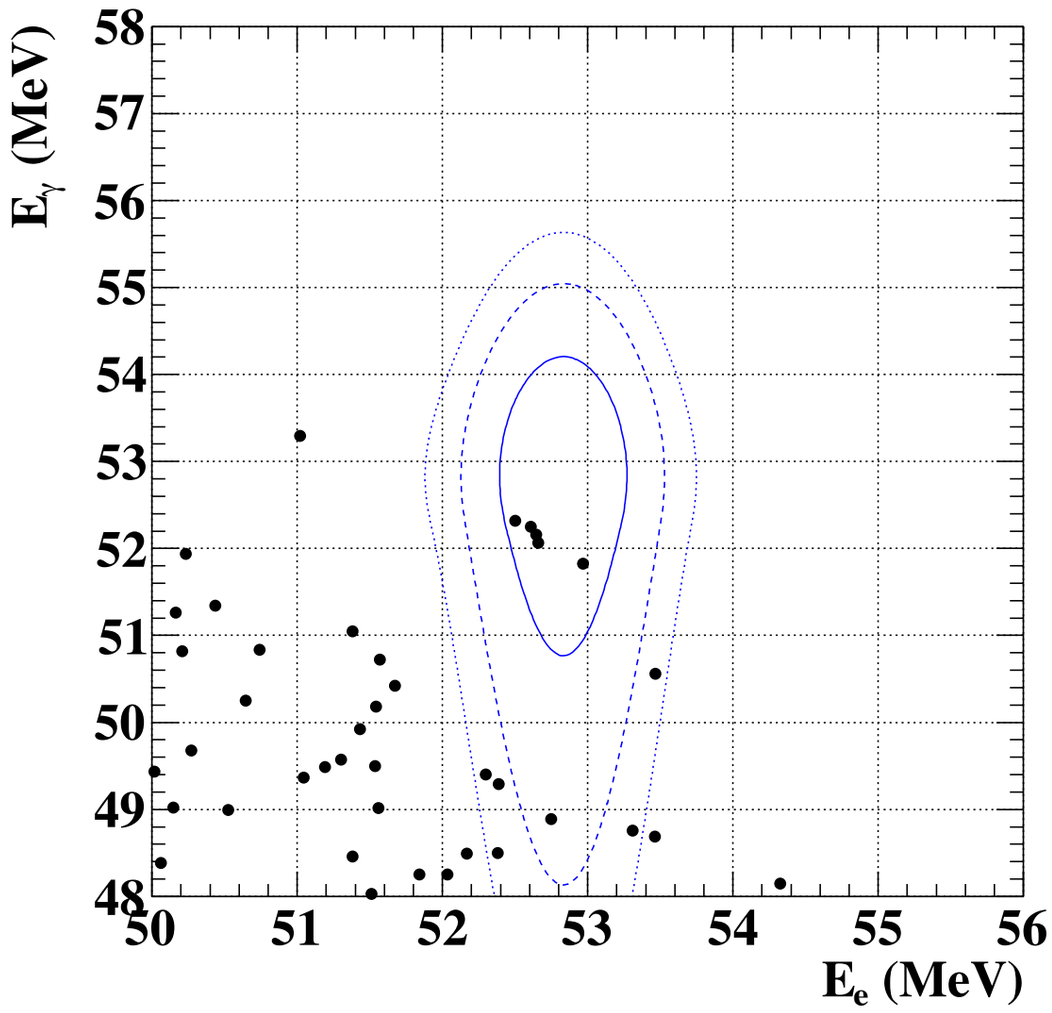
E_γ 52.25MeV
E_e 52.84MeV
$\theta_{e\gamma}$ 178.8°
$T_{e\gamma}$ 2.68×10^{-11} s

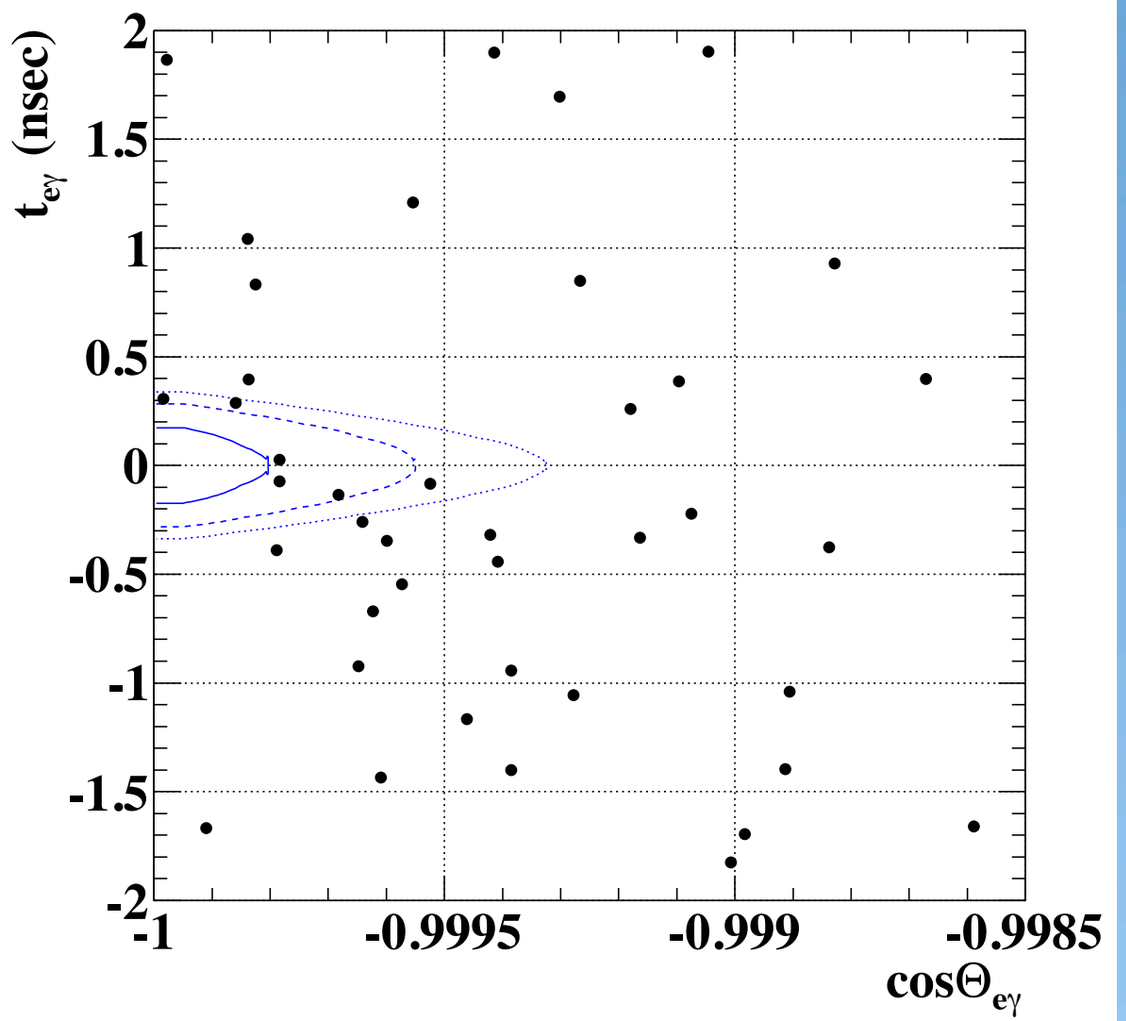






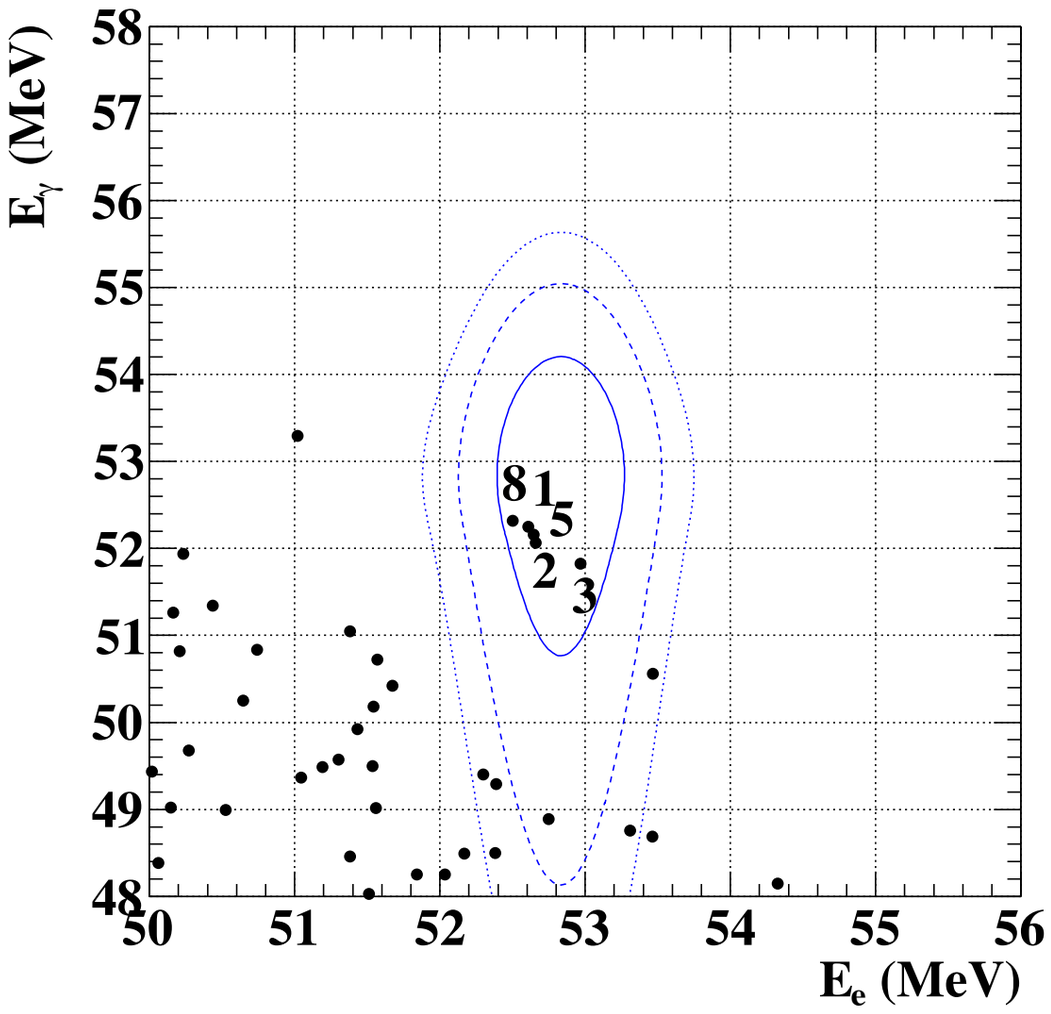
Event Distribution

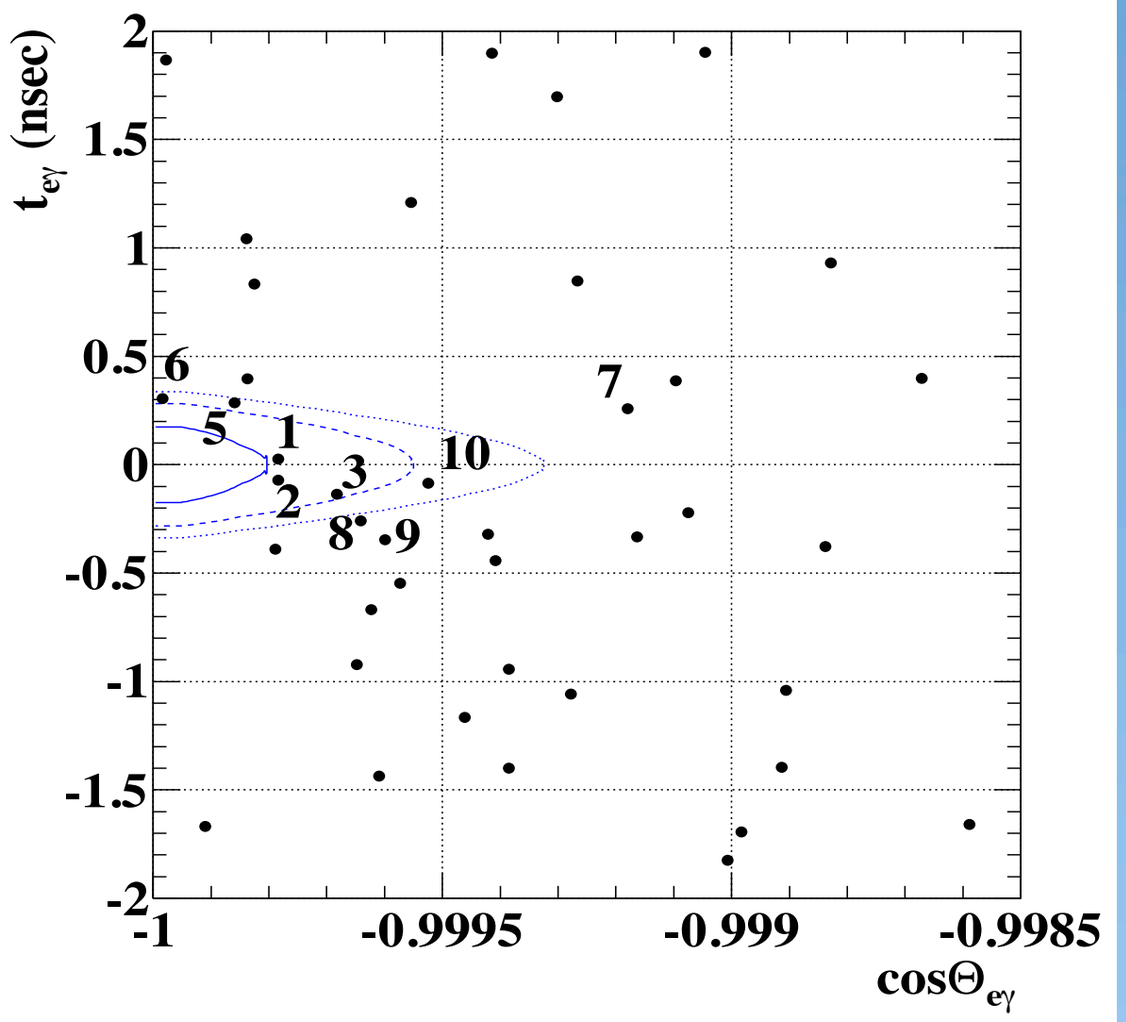




- Blue lines: Signal PDF contours (1, 1.64, 2σ)
- ~90% efficiency cut for other variables on each plot
- Numbered in terms of relative signal-likelihood

Event Distribution

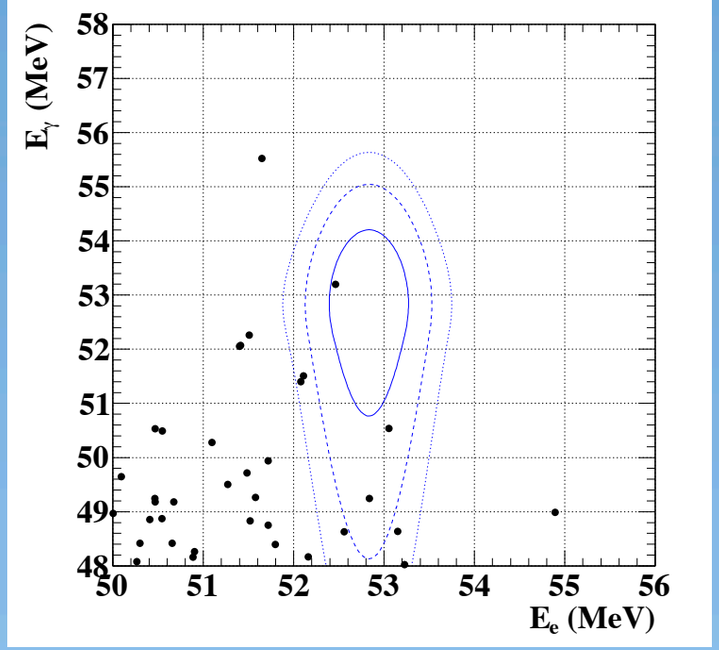


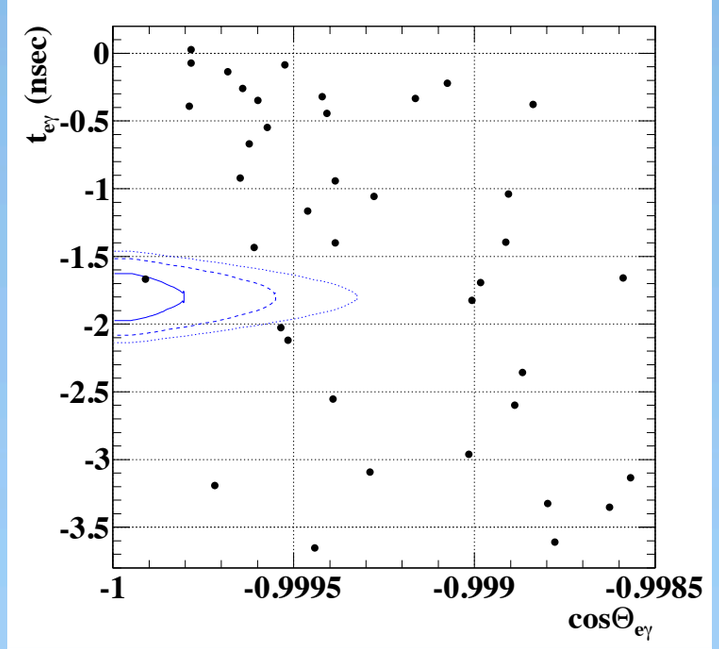


- Blue lines: Signal PDF contours (1, 1.64, 2σ)
- ~90% efficiency cut for other variables on each plot
- Numbered in terms of relative signal-likelihood

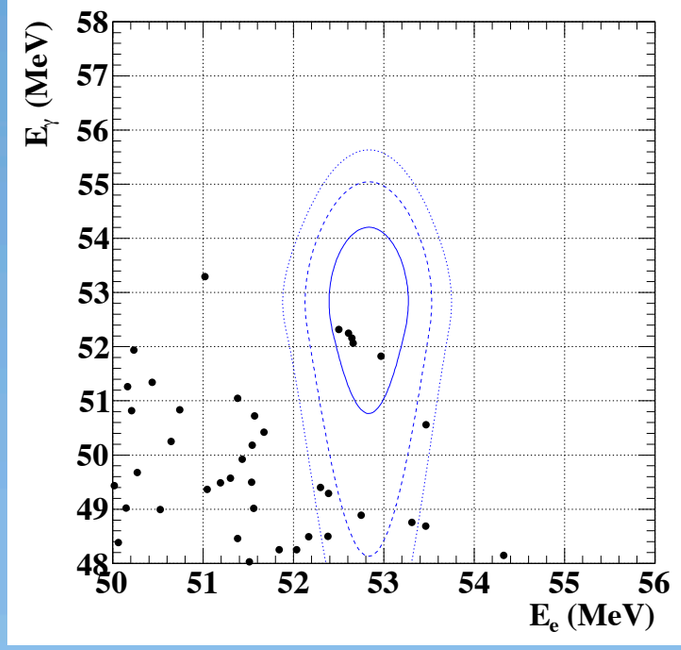
Event Distribution

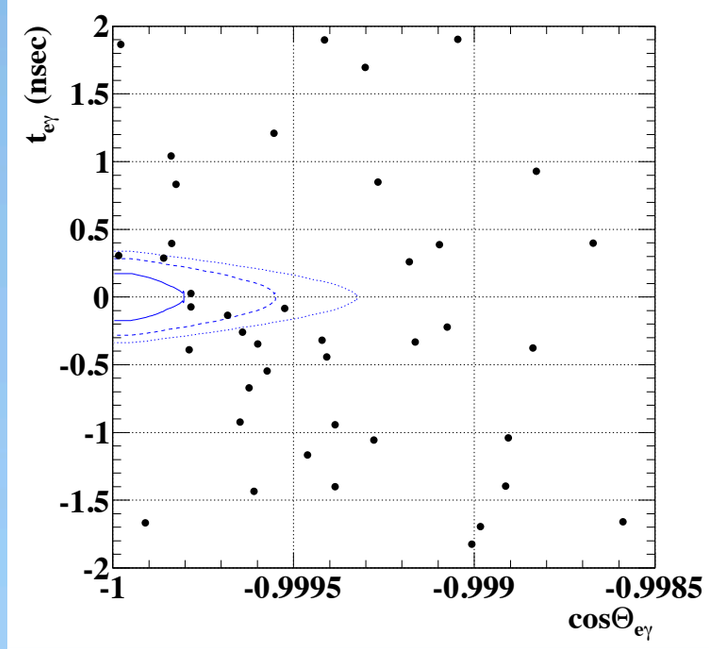
Sideband ($T_{e\gamma}$<0)



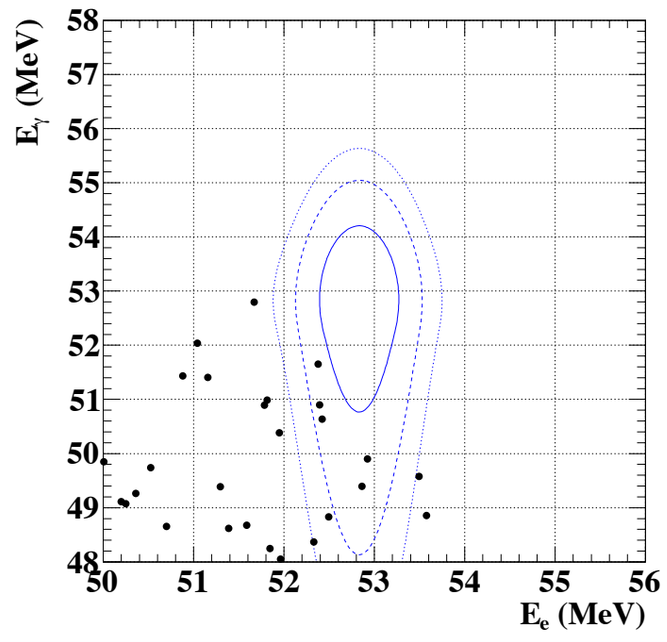


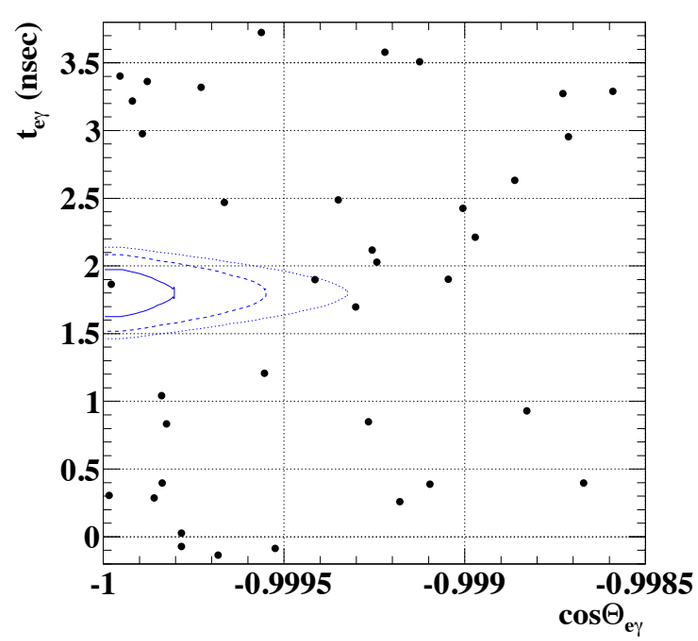
Analysis region





Sideband ($T_{e\gamma}$>0)





Update of Physics Analysis 2009

- **Redoing physics analysis of run 2009 after ICHEP2010**
  - Understood major sources of systematic uncertainty
    - Treatment of magnetic field in positron reconstruction
    - Relative alignment bw/ LXe detector and drift chambers
  - Switched to calculated B field since it shows slightly better tracking performance than the measured one.
    - Measured B field has small systematic distortion
  - Improved likelihood analysis
    - Constraint from BG rate measured in sideband

Update of Physics Analysis 2009

	Preliminary (July 2010)	Update (Feb 2011)
Positron momentum (%)	0.74 (core)	0.61 (core)
Positron angle (mrad)	7.1 (Φ,core), 11.2 (θ)	6.2 (Φ,core), 9.2 (θ)
Trigger efficiency (%)	84	91

Resolution in sigma

- Improved resolutions in positron reconstruction

  → Better sensitivity

- **Updated result will come this summer.**

Summary of Run 2009

- Preliminary result from run 2009
  - **BR sensitivity: 6.1×10^{-12}**
  - **N_{signal} best fit: 3.0**
  - **BR upper limit: 1.5×10^{-11} (90% C.L.)**
  - N_{signal}=0 is within 90% confidence interval.

Preliminary

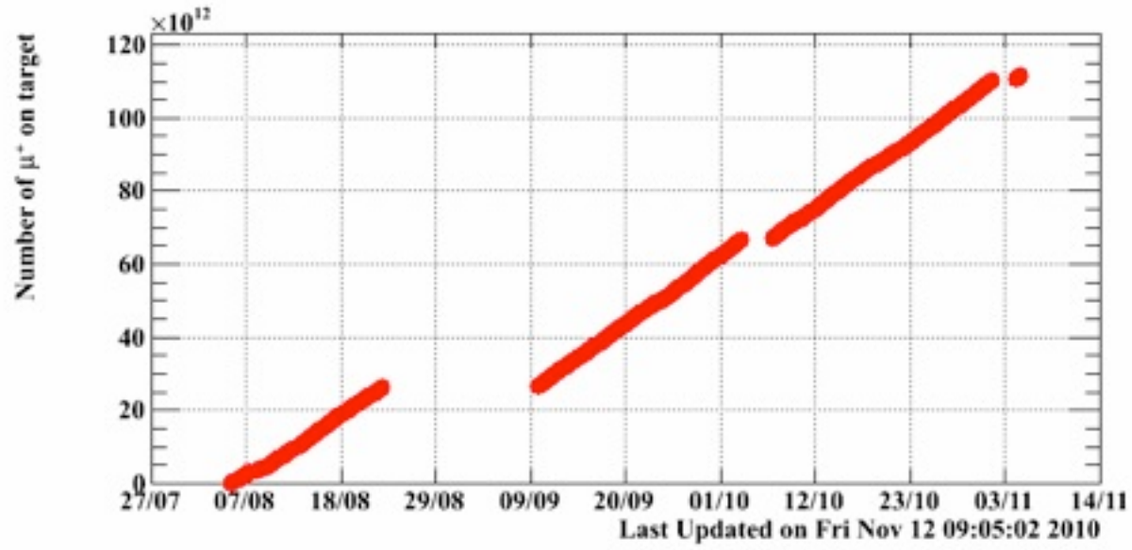
- Updated result from run 2009 with better sensitivity will come this summer.

N.B. present experimental bound set by MEGA : 1.2×10^{-11}

Run 2010

Run 2010

- Physics run ~**67days** (Nov.-Dec., 2009)
- μ-stop rate: **2.9×10^{7} s^{-1}**
- Total μ-stop: **1.1×10^{14}**



- Optimized μ-stop distribution in target
- Improved electronics timing accuracy (DRS4)
- Delay at start-up
  - DC construction, LHe transfer line vacuum leak, muon target accident, injector problem,...
- Smooth and efficient DAQ had to be stopped on Nov. 5th due to problem of beam transport solenoid magnet.
- Data statistics ~**twice higher than in run 2009**

Analysis of Run 2010

- Analysis of run 2010 is in progress.
- Resolutions comparable to run 2009 already obtained
- Some more improvements are anticipated with further calibration and refinement of analysis.
- Hopefully finish the analysis earlier than usual (around this summer)

Prospects for This Year and Beyond

Preparation for Run 2011

- Beam transport solenoid was repaired and successfully tested at low temperature
- Trigger efficiency improved with multi buffer scheme
- Drift chambers
  - Replace bad module, new HV power supply to reduce noise.
- TC fiber counters to be included in trigger
- **First full-year run!**
  - Physics run ~160 days

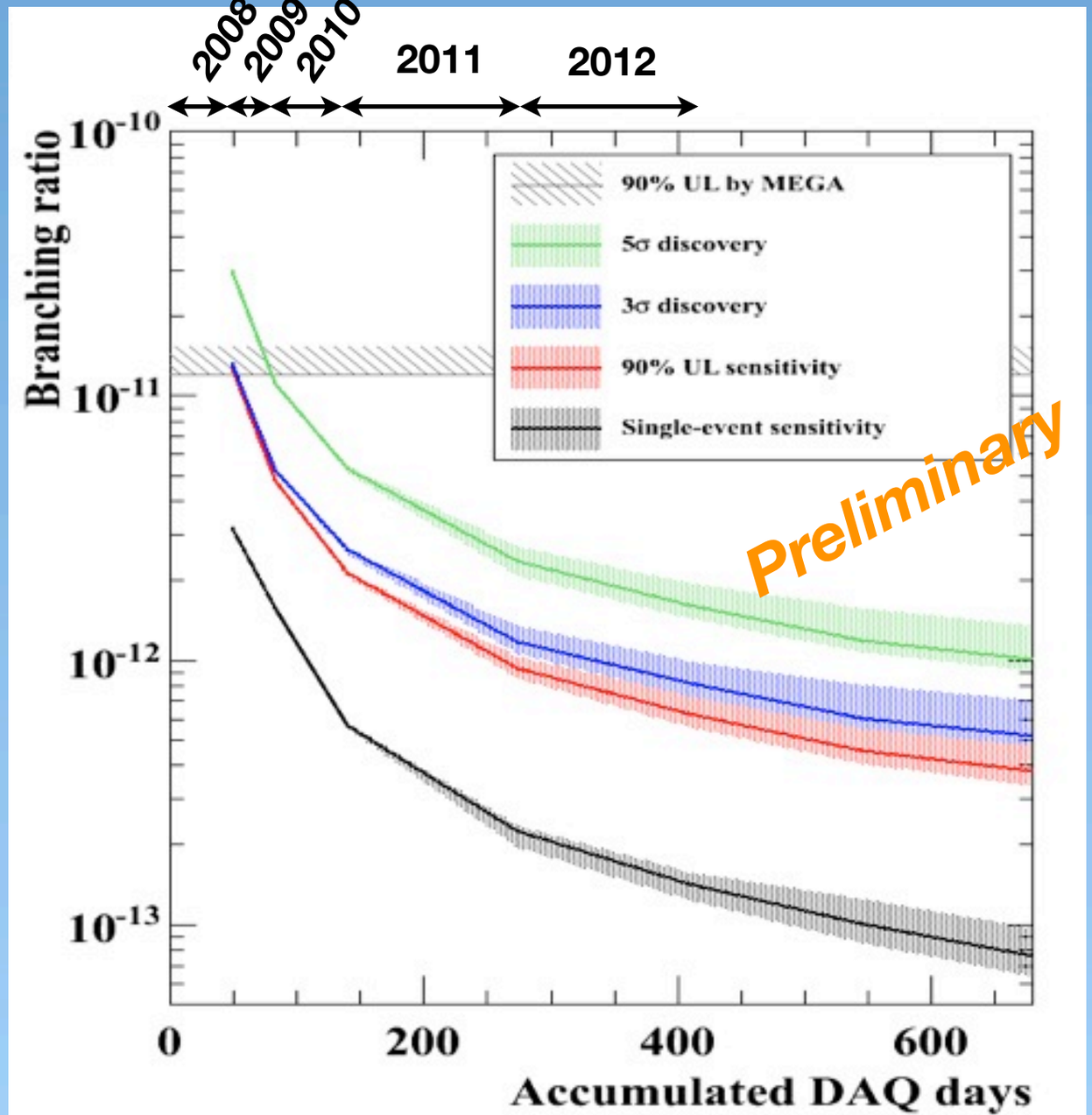
Possible Improvements

- To reach our sensitivity goal, we certainly need to **improve resolutions** as well as to **gain data statistics**.

- **Possible improvements**
  - Improvement of DAQ and trigger efficiency by double buffer scheme.
  - Efficiency improvement with thinner DC cables / optimum cable layout
  - Better positron reconstruction with
    - Reduced noise (adaptive filter/new DC HV)
    - Z-measuring fiber counters
    - Calibration with monochromatic positron beam (Mott scattering)
  - Positron timing
  - E_γ resolution with precise calibration and better reconstruction algorithms
  - Improvement of magnetic field systematics
  - Beam intensity optimization
  - ...

Sensitivity Prospects

- Sensitivity calculated with cut analysis based on relative signal-likelihood
  - N.B. likelihood analysis will give a little better sensitivity



Band:
range of possible improvements of detector performance

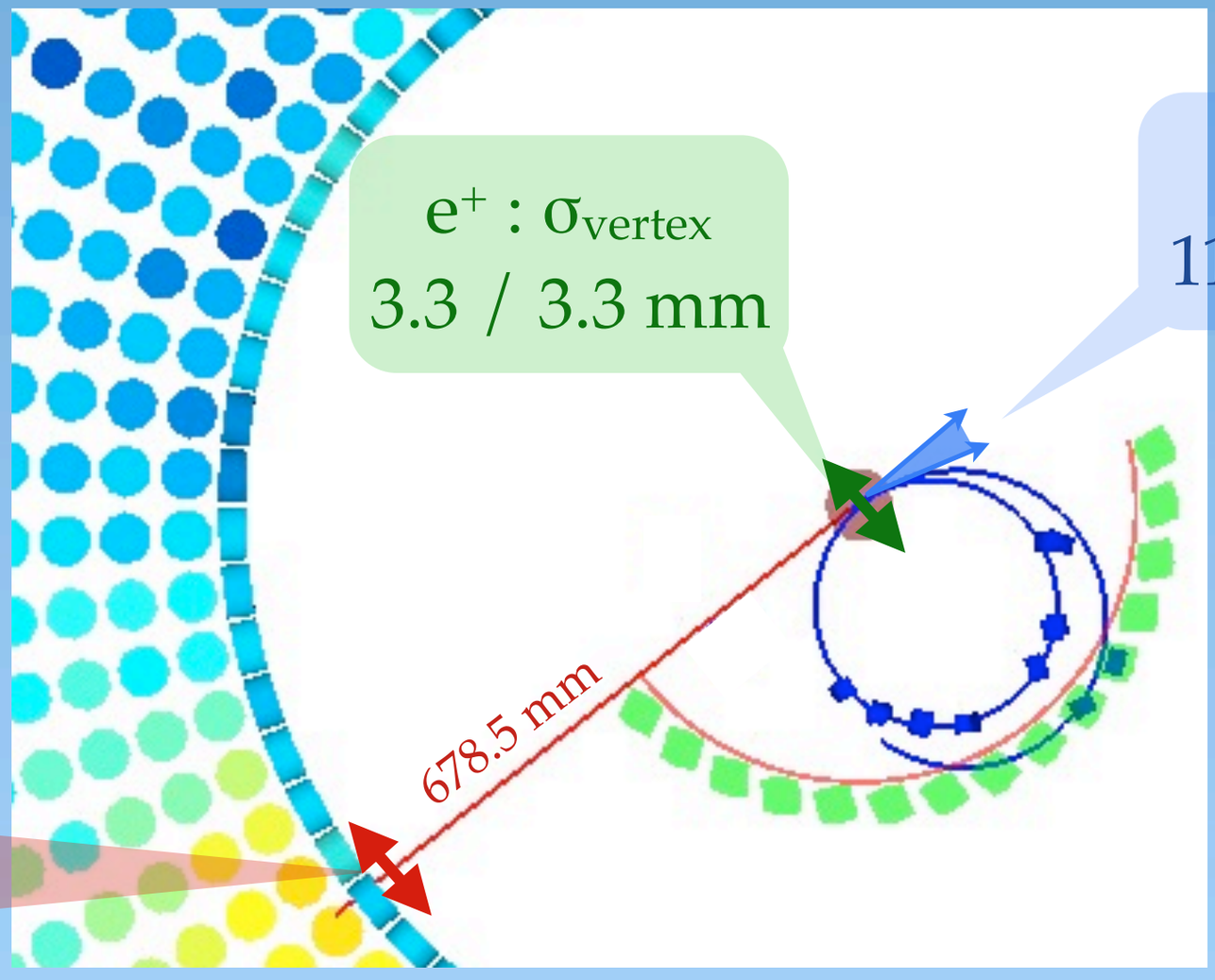
Summary

- MEG is starting to search for lepton flavor violating decay, $\mu^+ \rightarrow e^+\gamma$ with an unprecedented sensitivity.
- Preliminary result from analysis of run 2009
  - BR sensitivity: 6.1×10^{-12}
  - N_{signal} best fit: 3.0 (N_{signal}=0 is within 90% confidence interval)
  - BR ($\mu^+ \rightarrow e^+\gamma$) < 1.5×10^{-11} (90% C.L.)
  - Result from updated analysis of run 2009 with better sensitivity will come this summer.
- Analysis of run 2010 (twice higher data statistics w.r.t. run2009) is in progress and we hope to present this this summer.
- A year-long run is planned for this year (2011).
- We aim at reaching sensitivity of $O(10^{-13})$ in next few years.

Backup

Overall Angular Resolution

- Overall angular resolution obtained by combining resolutions for both LXe detector and spectrometer



Confidence Interval

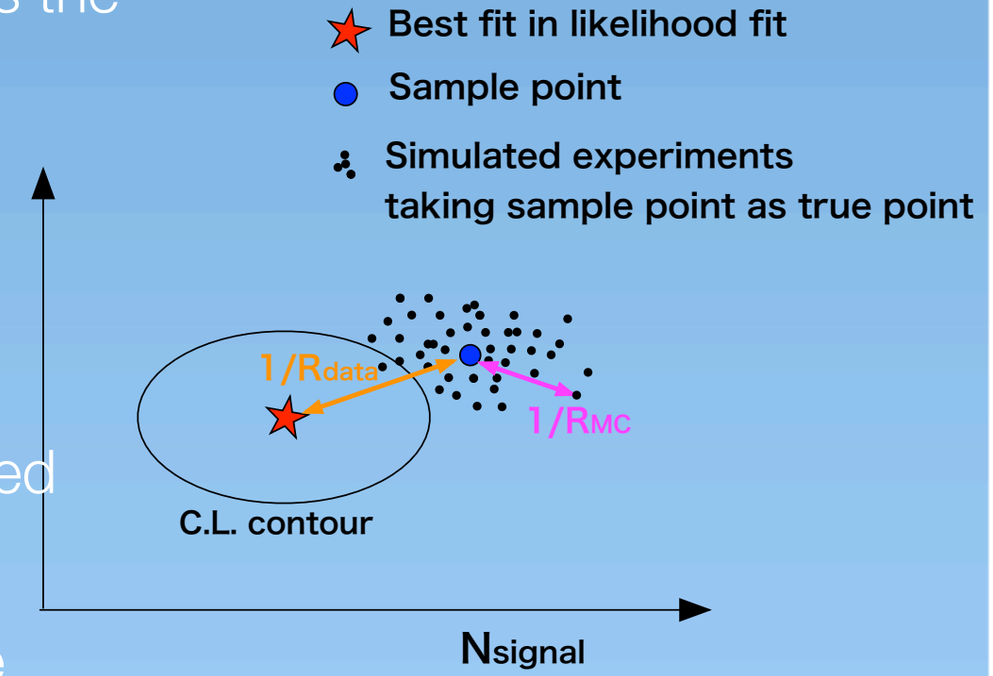
- 90% confidence level contour on (N_{signal}, N_{RMD}) in Feldman-Cousins prescription (likelihood ratio ordering)
  - Calculate likelihood ratio at a sample point (N_{signal}, N_{RMD}).

$$R_{\rm data} = \frac{\mathcal{L}_{\rm data}(N_{\rm signal}, N_{\rm RMD})}{\mathcal{L}_{\rm data,max}}$$

  - Simulate many experiments taking (N_{signal}, N_{RMD}) as the expectation and perform likelihood fit
  - Calculate likelihood ratio for each simulated experiment.

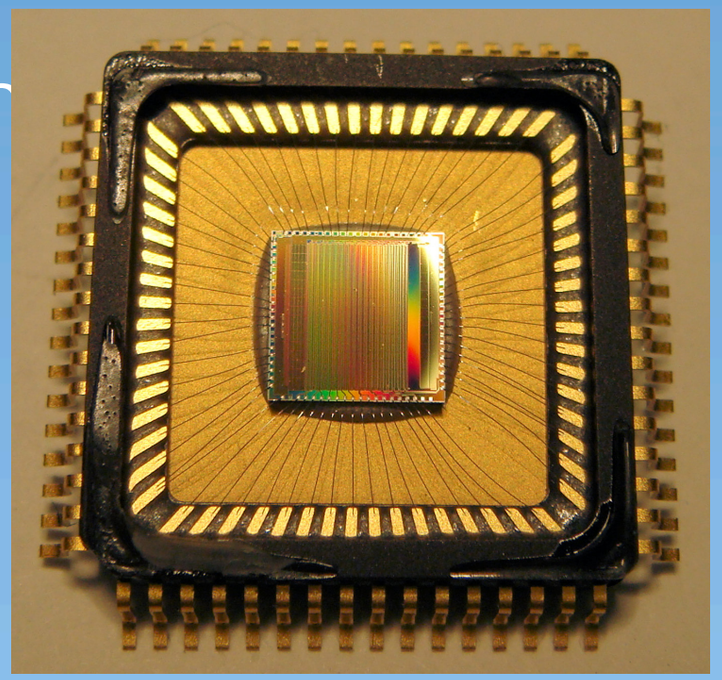
$$R_{\rm MC} = \frac{\mathcal{L}_{\rm MC}(N_{\rm signal}, N_{\rm RMD})}{\mathcal{L}_{\rm MC,max}}$$

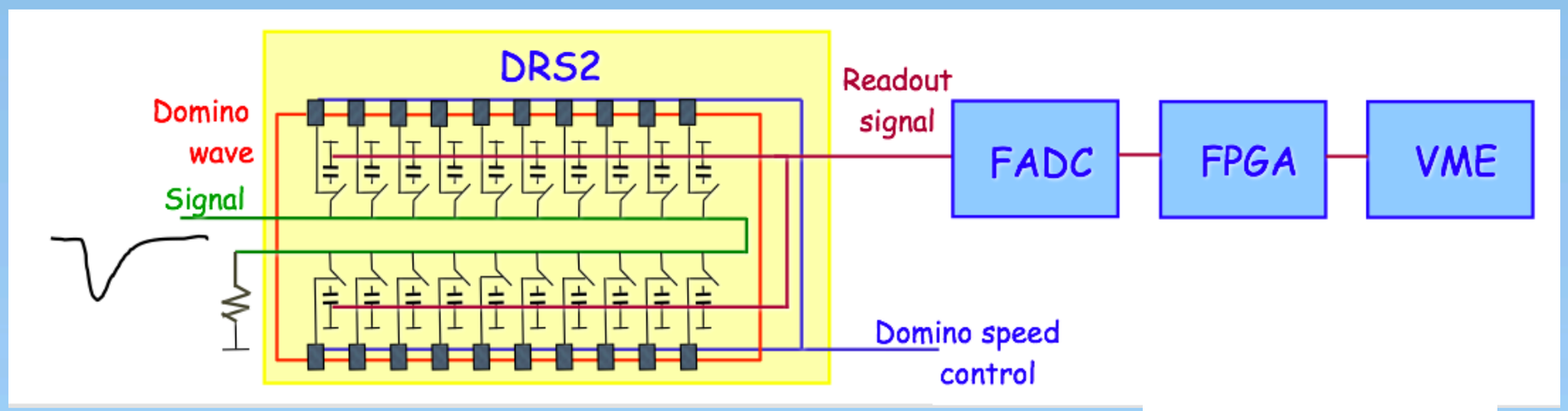
  - Calculate probability of $R_{data}<R_{MC}$ over the simulated experiments
  - If the probability > 0.9, the sample point should be outside the 90% confidence level contour.



Waveform Digitizer

- Waveforms for all detector channels (~3000ch) recorded by waveform digitizer (pileup, baseline subtraction, noise reduction...)
- In-house developed @ PSI





Trigger Electronics

- Digital trigger based on FADC-FPGA architecture on VME boards
- Flexible trigger algorithm
- Trigger rate for $\mu \to e\gamma$ trigger at 3×10^7 μ^+/s ~5Hz
  - LXe energy cut $\wedge$ e^+-γ time coincidence $\wedge$ e^+-γ direction match