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

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(Dated: August 18, 2009)

A search for the decay $\mu^+ \to e^+\gamma$, performed at PSI and based on data from the initial three months of operation of the MEG experiment, yields an upper limit $\mathrm{BR}(\mu^+ \to e^+\gamma) \leq 3.0 \times 10^{-11}$ (90% C.L.). Positrons and photons from $\sim 10^{11}$ stopped μ^+-decays were measured by a superconducting positron spectrometer and a 900 litre liquid xenon photon detector.

MEG 2008

Satoshi MIHARA

On behalf of the MEG collaboration

Outline

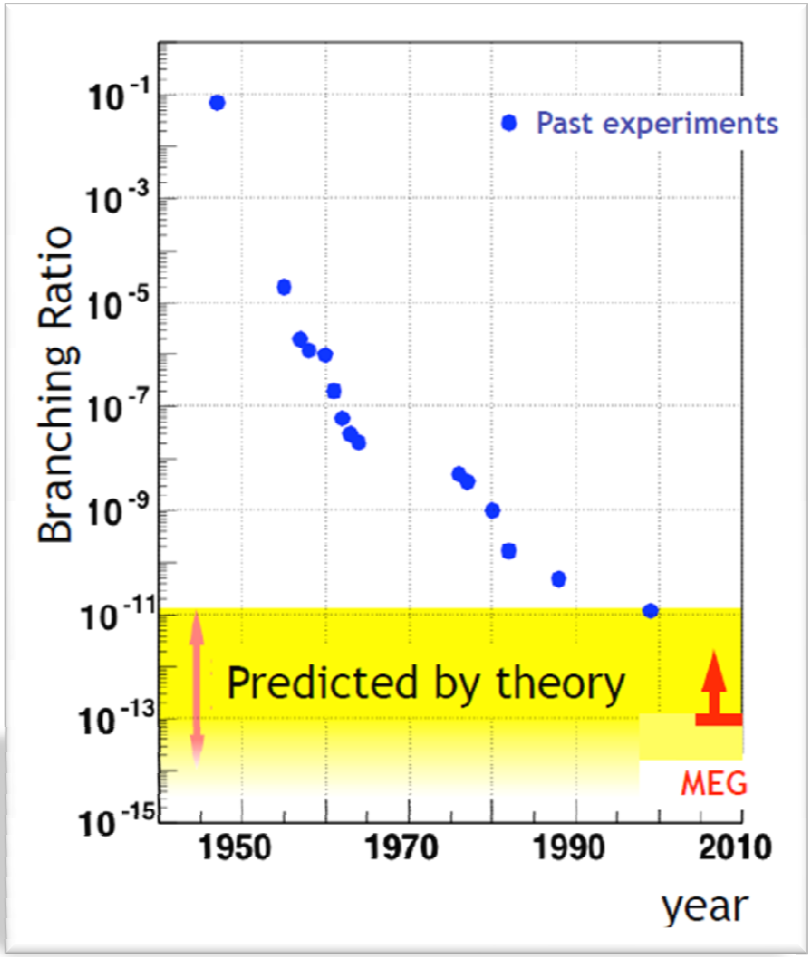
- Introduction
- MEG detector
- MEG data acquisition in 2008
- Analysis
- Summary and prospect of 2009 run

What is MEG?

- Aiming at <u>observing</u> $\mu \rightarrow e\,\gamma$ event with a sensitivity of ~10^{-13}
  - Normal muon decay: $\mu \rightarrow e\bar{\nu}\nu$
  - Radiative muon decay: $\mu \rightarrow e\bar{\nu}\nu\gamma$

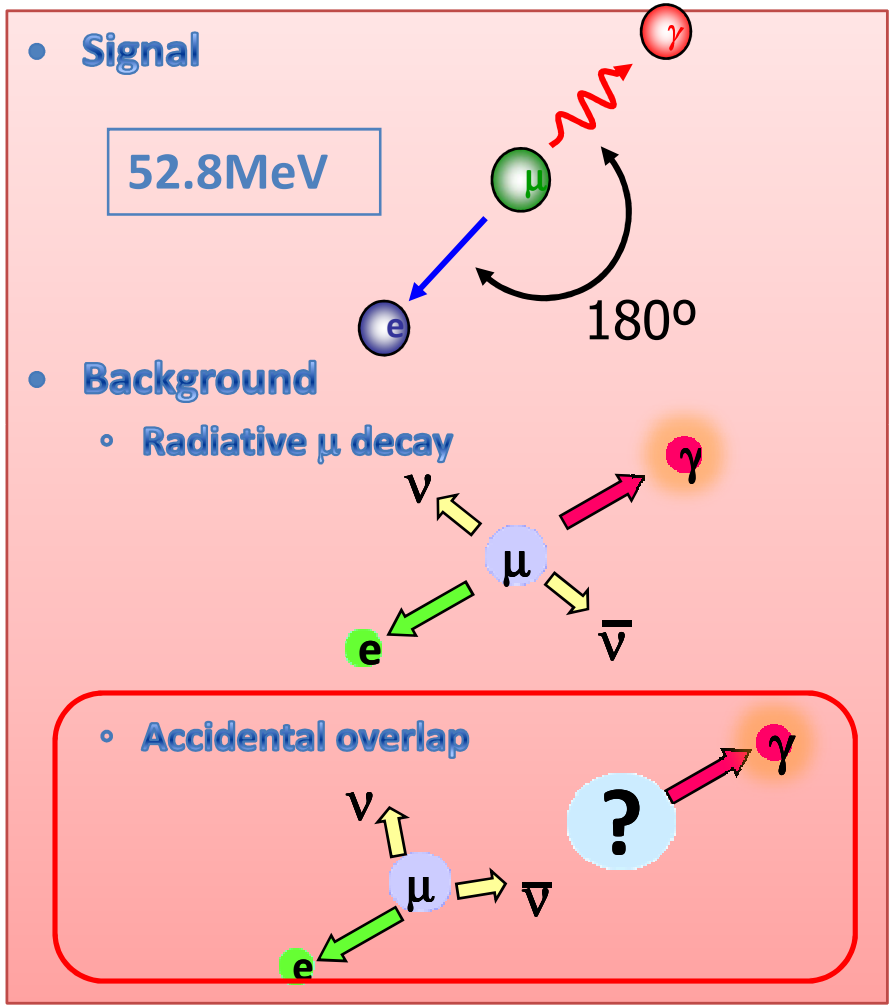
$\mu \rightarrow e\gamma$ Search Chronology

- Muon discovery in 1937
- Order of 10 improvement in 50 years
- Best limit by MEGA collaboration, $Br(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}$
  - $\mu Ti \rightarrow eTi \; < 7 \times 10^{-13}$ (SINDRUM II)
- Strong motivation
  - Neutrino oscillation
  - SUSY GUT



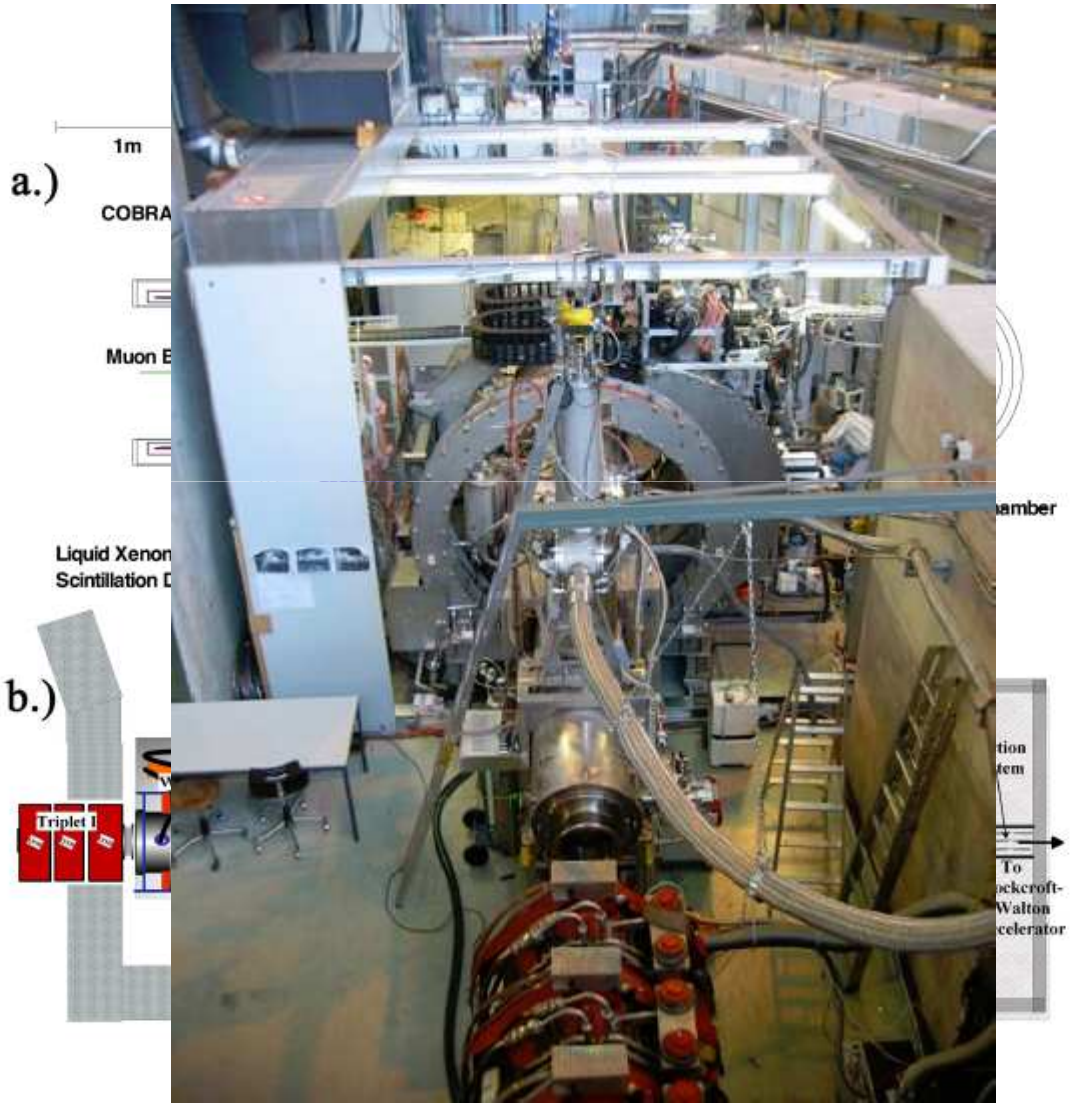
$\mu \rightarrow e\,\gamma$ Signal and its Detection

- High intensity muon beam
  - DC is better than plused
- Large acceptance of the detector system
- Good detector resolutions to suppress background



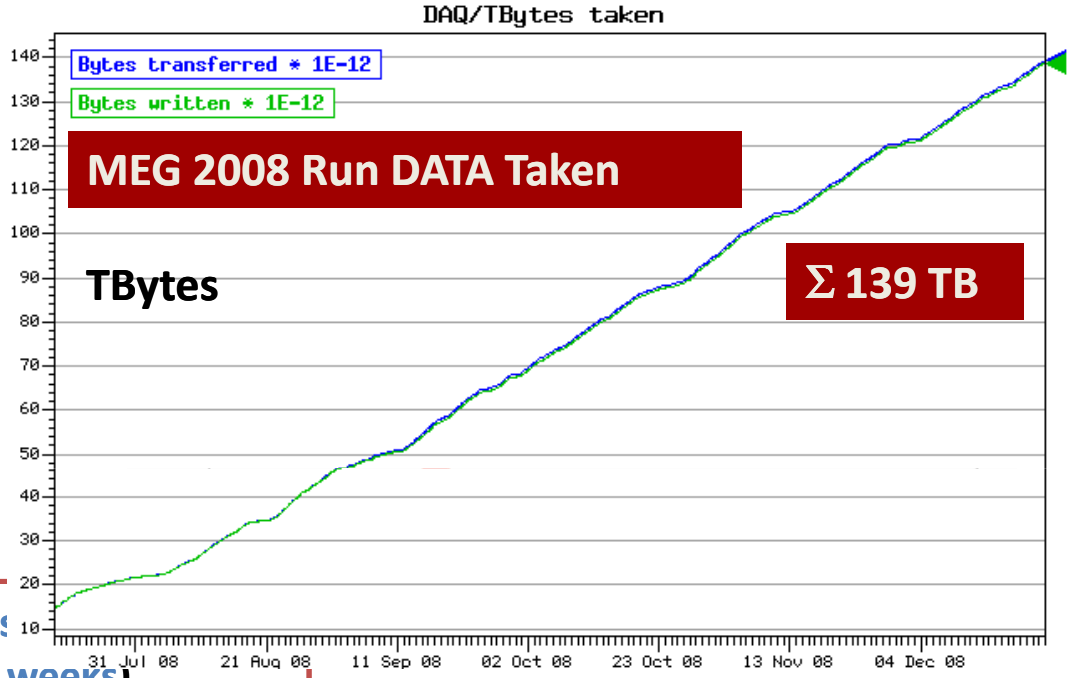
MEG Detector/Muon Beam Line

- Muon Beam
- **PiE5 muon beam line**
  - **1.15×10^8 $\mu^+ s^{-1}$ at the detector entrance**
  - **at 1.8mA, 4cm Tg**
- Photon Detector
  - **900 liter liquid xenon**
  - **846 PMTS in the liquid**
  - **Cooling with a PTR**
  - **purification**
- Positron Detector
  - **COBRA spectrometer**
  - **Low-mass drift chamber**
  - **High resolution timing couter**



Data Acquisition in 2008

- MEG successfully started physics data acquisition 12/Sep/2008
  - $3x10^7$ muon/sec with 2mA primary proton current on 4cm target
  - Total live time $3.4x10^6$ sec
  - $9.4x10^{13}$ muon stops on the target
  - Total 139TB data on disk



Parasitic Run: 19th May- 3rd July ~ 7 weeks
Beam Tests/Tuning (4.5 weeks)

Full Run Part 1: 11th July – 31st August ~7 weeks
CEX 21st July – 31st August (6 weeks)

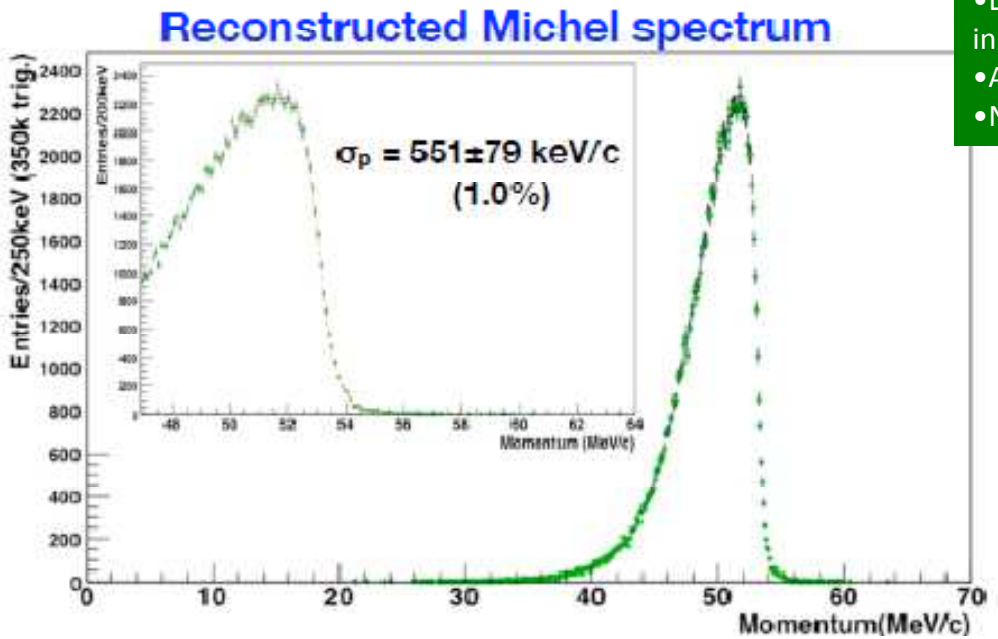
Full Run Part 2: 1st September – 23rd December ~16 weeks
Pre-Physics Data (~ 3 weeks)
Physics Data Part1 35 Days
MEG Maintenance/Repair ~ 7 Days
Physics Data Part 2 43.5 Days
Mini-CEX ~ 7 Days

Polyester/Rohacell target

DETECTOR PERFORMANCE

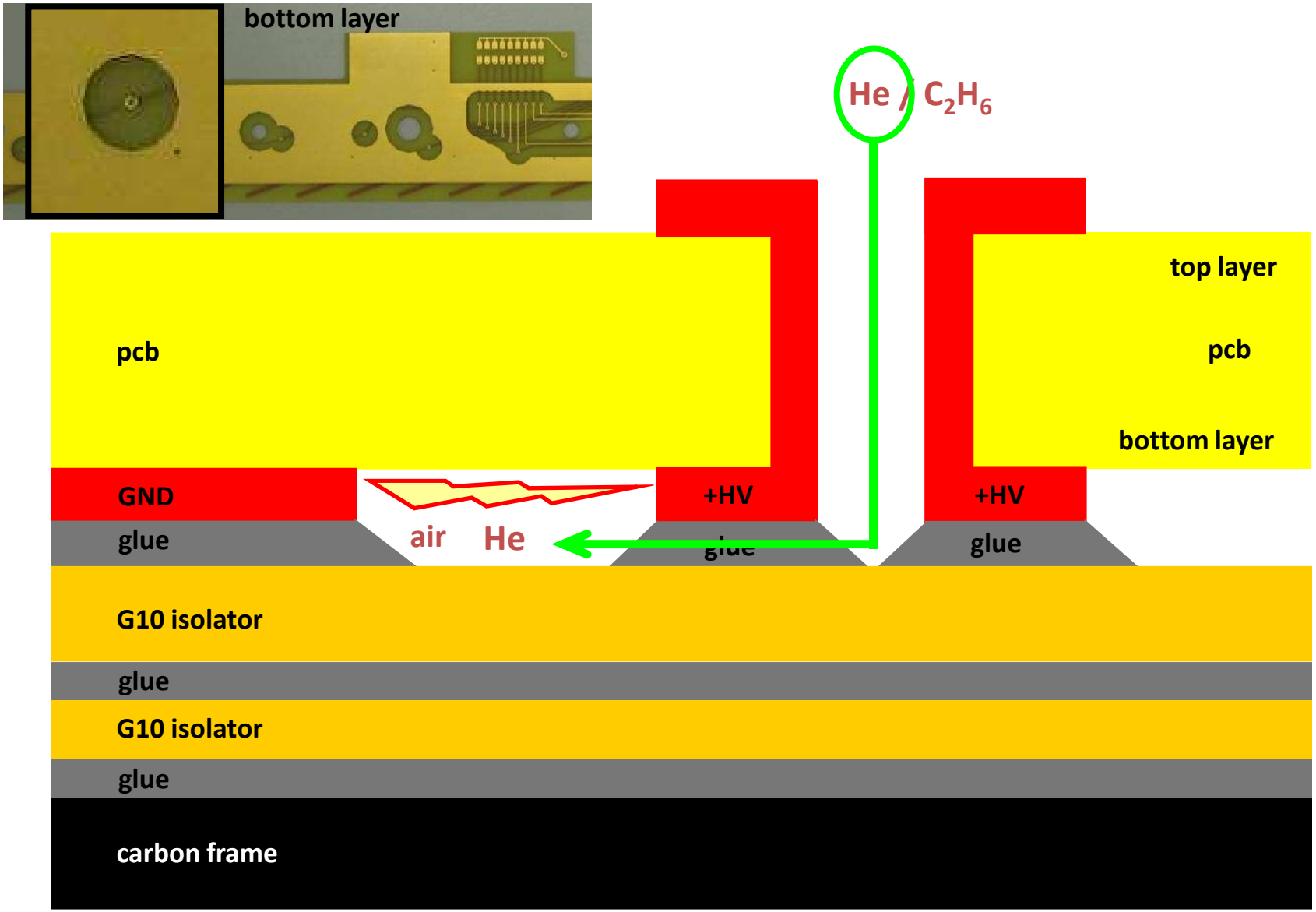
DC Performance in 2008

- End-point is fitted to the convolution of “theoretical response function” and “Gaussian”, with three free parameters:
  - “E_{edge}”,”σ_p” and “Normalization”
  - Problem in 2008 DAQ
    - ***Too many HV trip for stable detector operation***



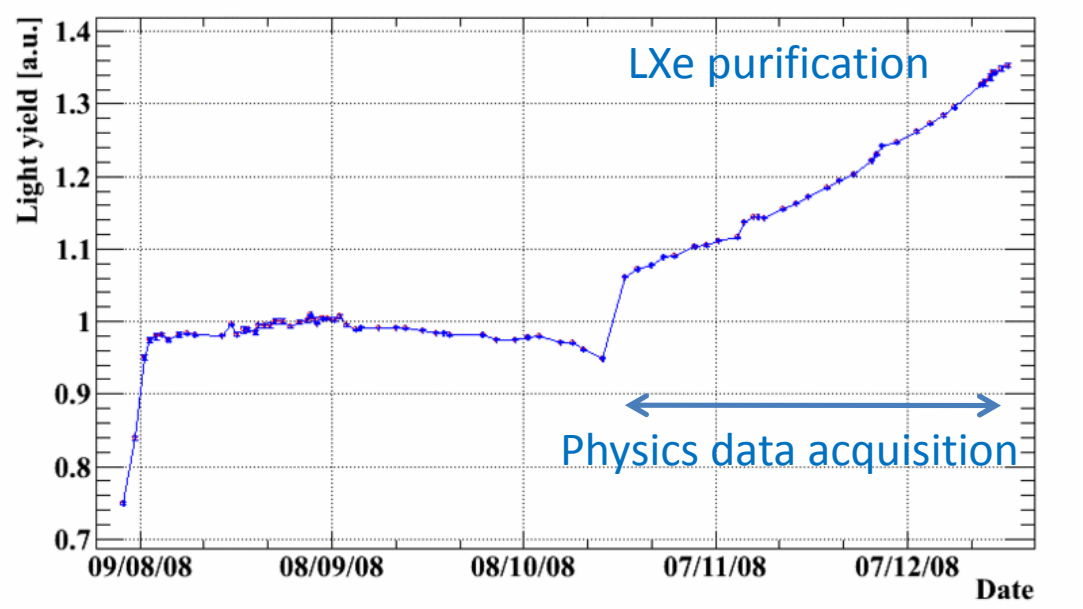
•After 2-3 months of operation, DC system showed frequent HV trips.
•This is not due to gas aging.
•Due to the HV trip, e+ detection efficiency was ~1/3 of design value in average.
•A week point was located on PCB.
•New design was made to separate HV and ground line to layers.

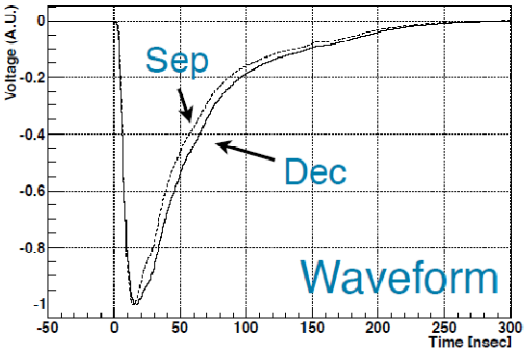
PCB Cross Section

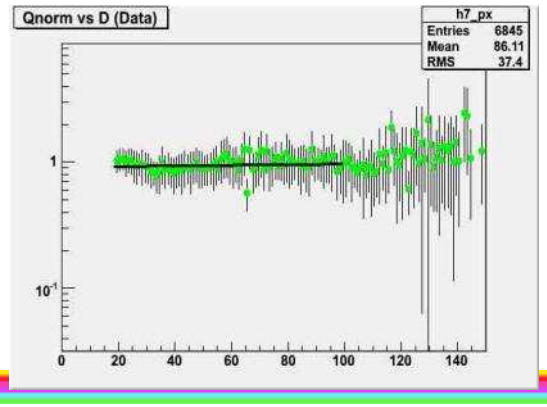


LXe Operation Summary in 2008

- Successful operation with very few dead channels (~0.5%)
- Light yield and waveform was changing by purification of LXe.
  - Frequent monitor of the change by using several calibration sources.
  - Absorption length was confirmed to be long enough
  - Light emission was probably affected by impurity



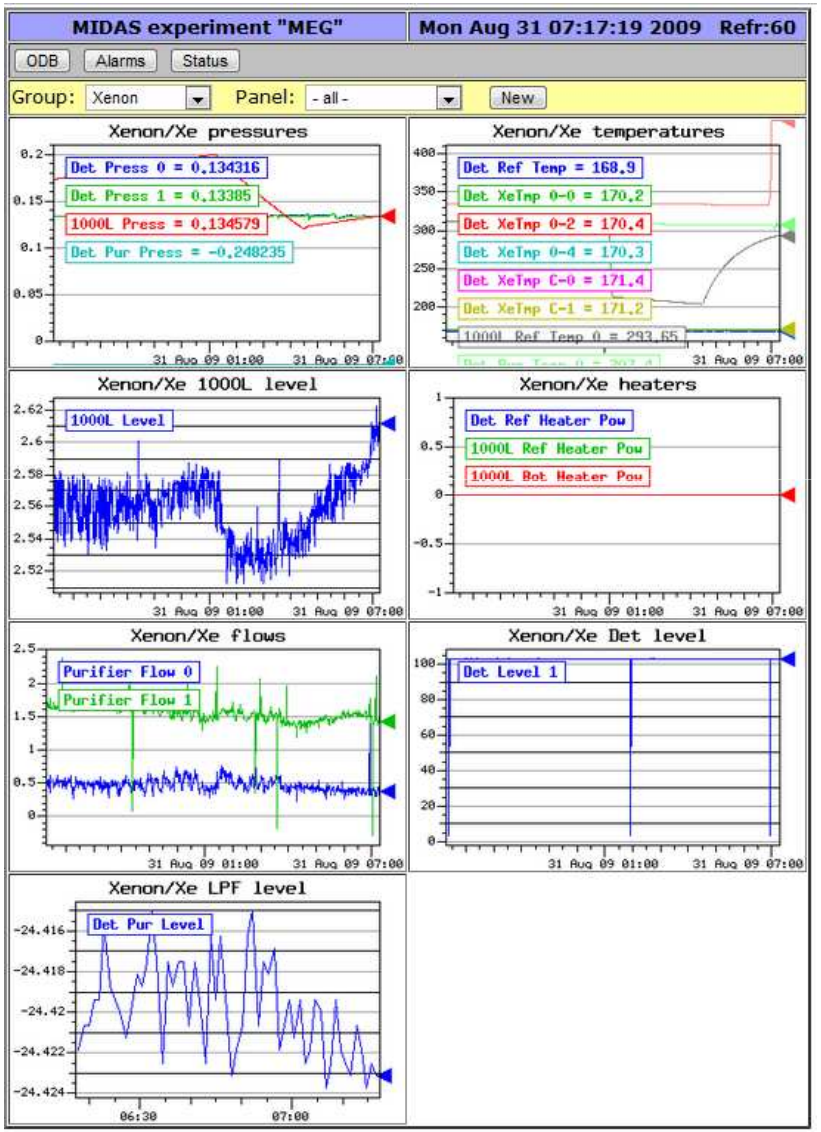




Monitoring and Calibrations

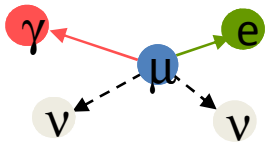
- Primitive level
  - Temperature, pressure, gas flow, gas composition
  - All are broadcasted via web so that everyone can monitor at different time zones

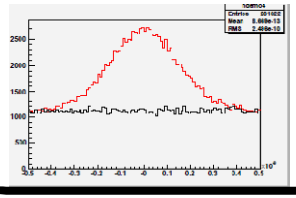
- Additional measurements to calibrate and synchronize the sub-detectors
  - Cockcroft-Walton acc (CW)
  - Radiative Muon Decay (RMD)
  - Pion charge-exchange (CEX) reaction runs



Xenon Calibration

μ radiative decay





Lower beam intensity < 10^7

Is necessary to reduce pile-ups

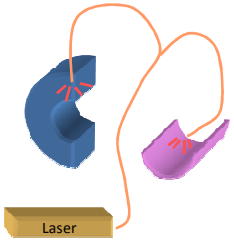
Better σ_t, makes it possible to take data with higher beam intensity

A few days ~ 1 week to get enough statistics

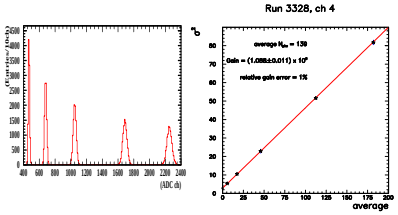
Laser

(rough) relative timing calib.

< 2~3 nsec



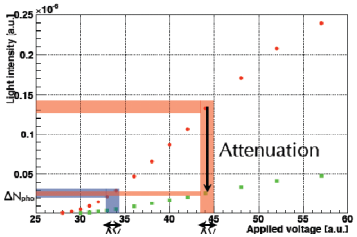
LED



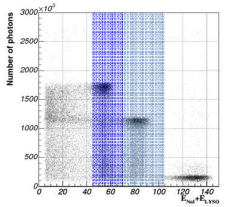
PMT Gain

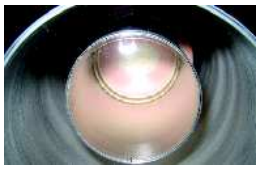
Higher V with light att.

Can be repeated frequently



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





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

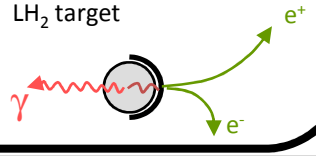
$\pi^0 \rightarrow \gamma\gamma$ (55MeV, 83MeV)

$\pi + p \rightarrow \gamma + n$ (129MeV)

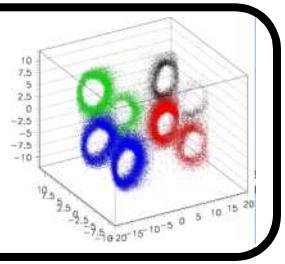
10 days to scan all volume precisely

(faster scan possible with less points)

LH_2 target



alpha

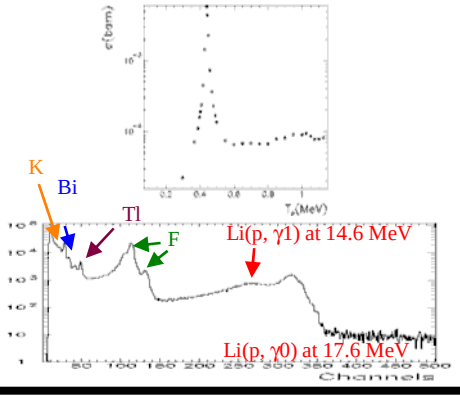


PMT QE & Att. L

Cold GXe

LXe

Proton Acc



Li(p,γ)Be

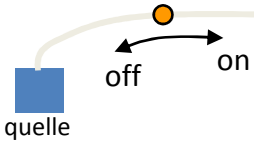
LiF target at COBRA center

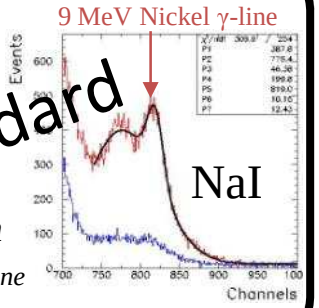
17.6MeV γ

~daily calib.

Can be used also for initial setup

Nickel γ Generator





Not Yet Standard

Illuminate Xe from the back

Source (Cf) transferred by comp air → on/off

3 cm 20 cm

Polyethylene

0.25 cm Nickel plate

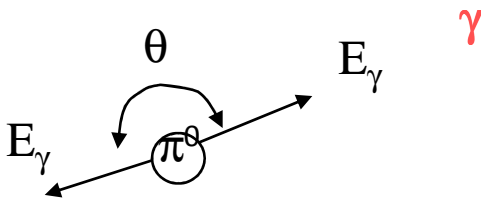
Photon Energy Calibration

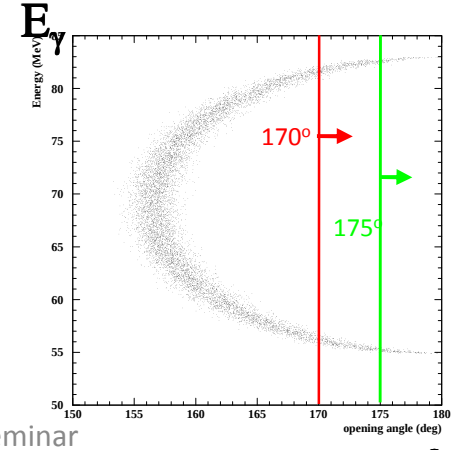
- CW runs
  - Proton on $Li_2B_4O_7$ target
  - 17.6 MeV γ to monitor the detector energy scale
  - Coincident γ's of 4.4, 11.6MeV to determine time offsets of TCs
  - Repeated 3 times in a week

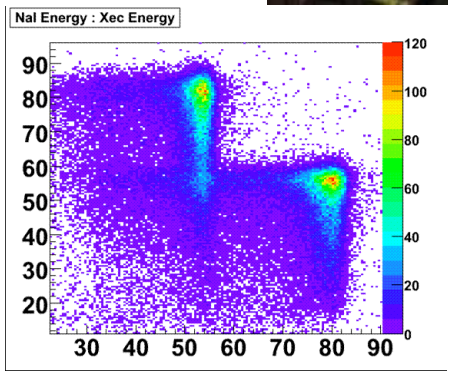
Reaction	*Resonance energy*	σ peak	γ-lines
Li(p,γ)Be	*440 keV*	5 mb	17.6 MeV, 14.6 MeV
B(p,γ)C	*163 keV*	$2\ 10^{-1}$ mb	4.4 MeV, 11.7 MeV, 16.1 MeV

C-W proton ACC

- CEX reaction runs
  - $\pi^- p \rightarrow \pi^0 n$
    - π^0(28MeV/c)→γ γ
    - 54.9MeV<E(γ)<82.9 MeV
  - Dalitz decays $\pi^0 \rightarrow \gamma e^+e^-$ collected to study the detector time synchronization and resolution

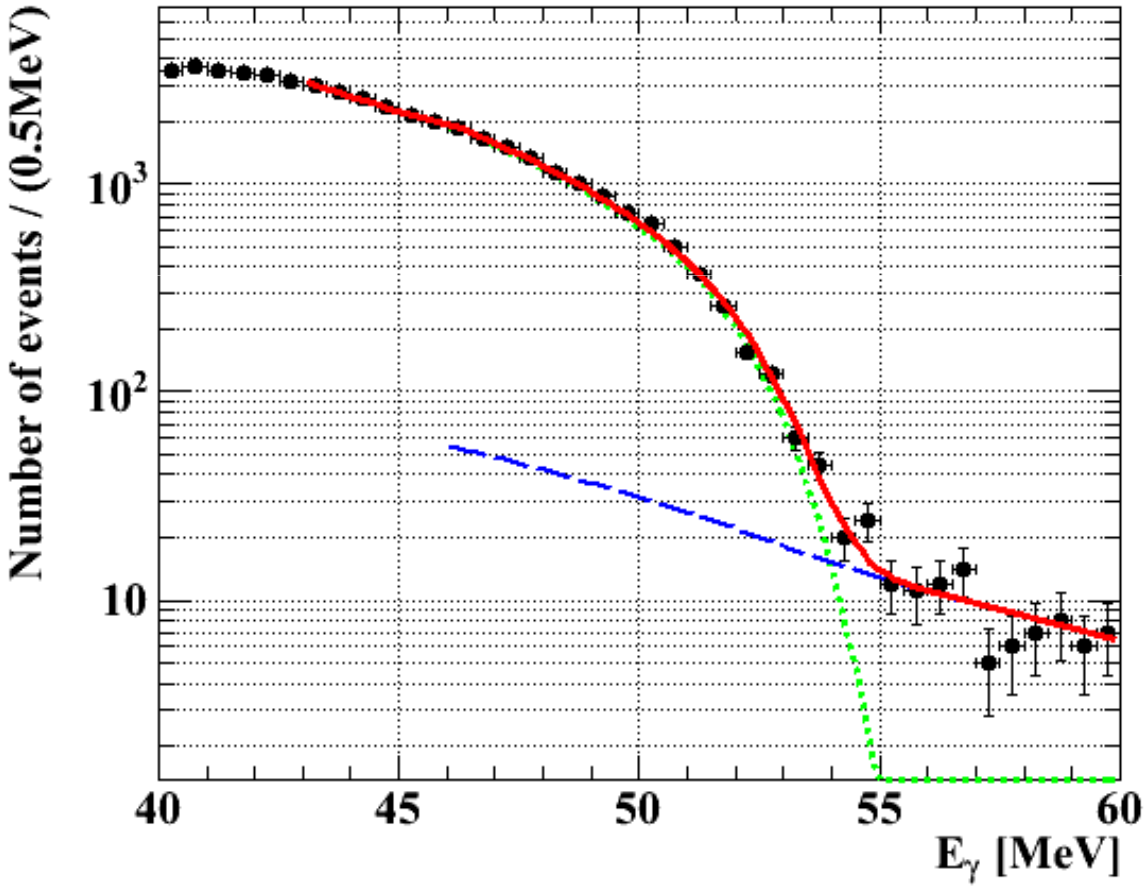






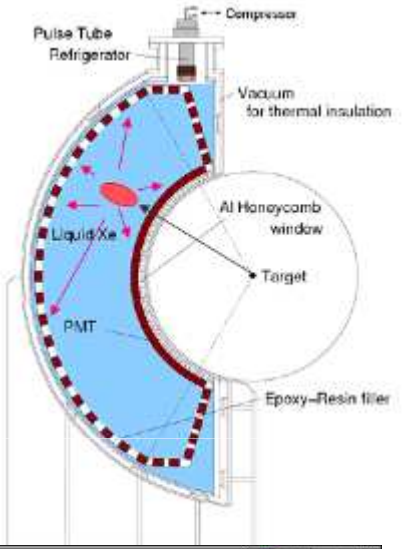
RMD Photons for Energy Scale Monitoring

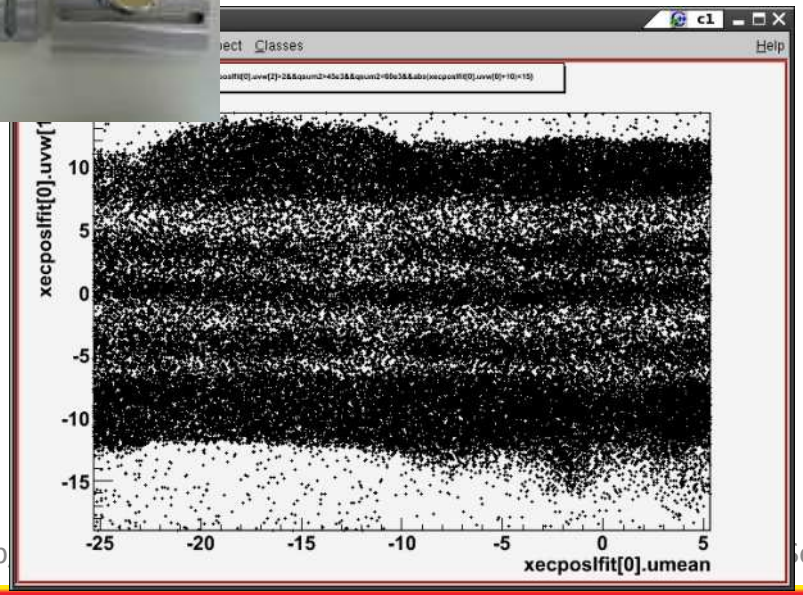
- and also for background study

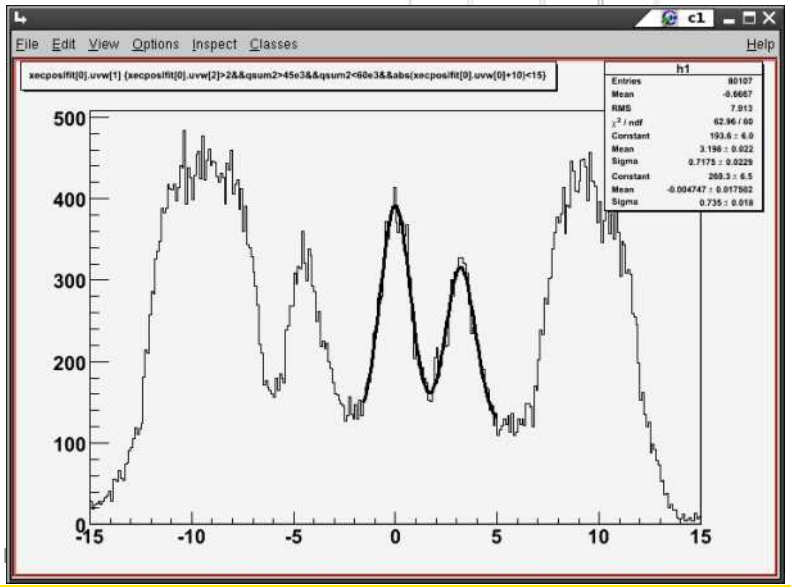


Photon Position Reconstruction

- Position reconstruction by using the light distribution seen by the PMTs near the incident position
- Performance evaluation by a Monte Carlo simulation validated in a CEX run with a lead collimator
  - ~5mm along the LXe surface and ~6mm along the radial directions

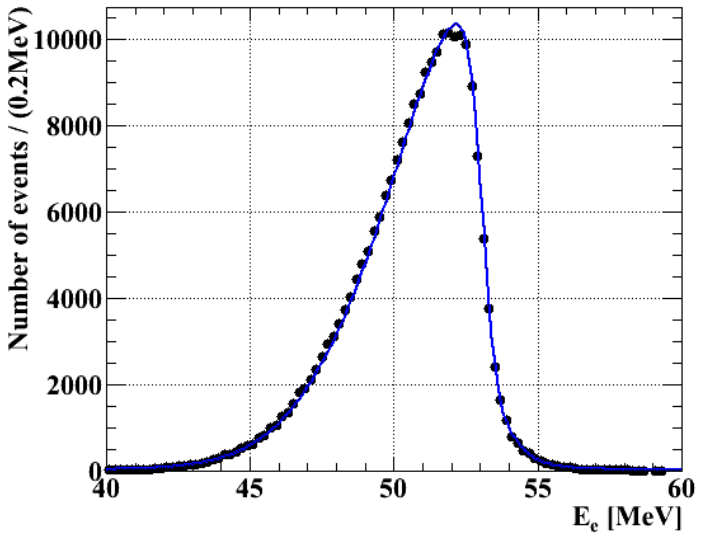


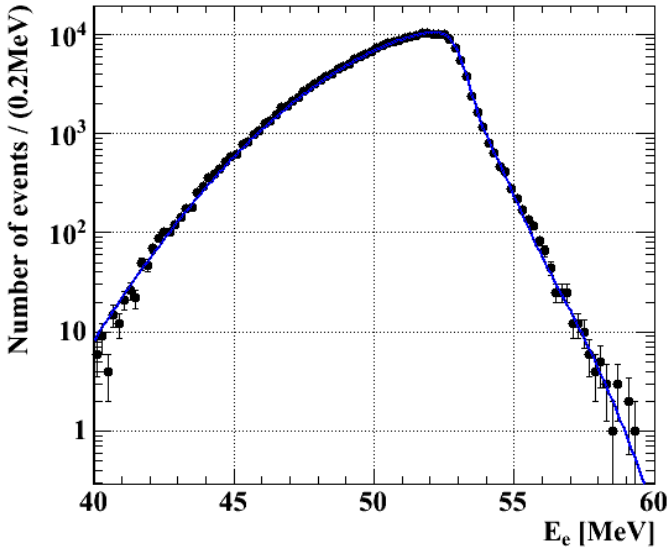




Positron Momentum

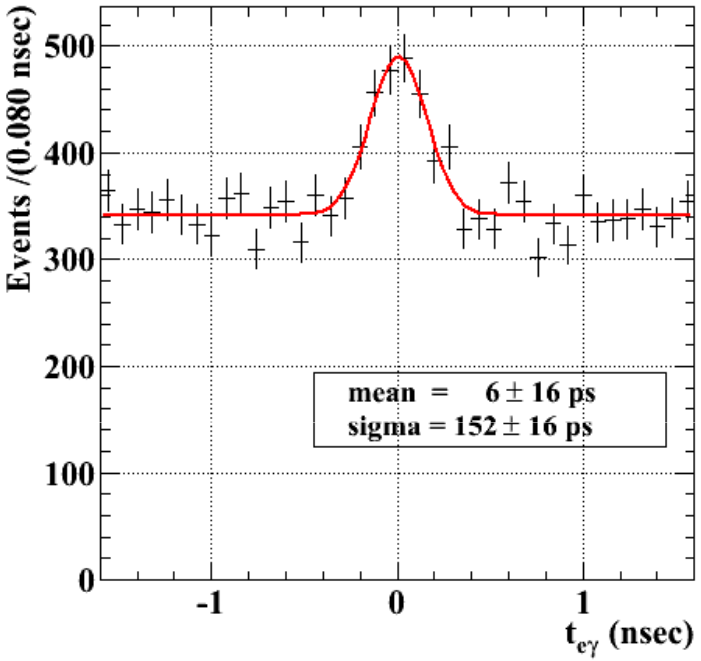
- Track reconstruction with the Kalman filter technique
- Energy scale and resolution are evaluated by fitting the Michel spectrum at 52.8MeV
- Resolution function with core and tail components
  - Core : 374keV (60%), tails: 1.06 MeV (33%) and 2.00MeV (7%)

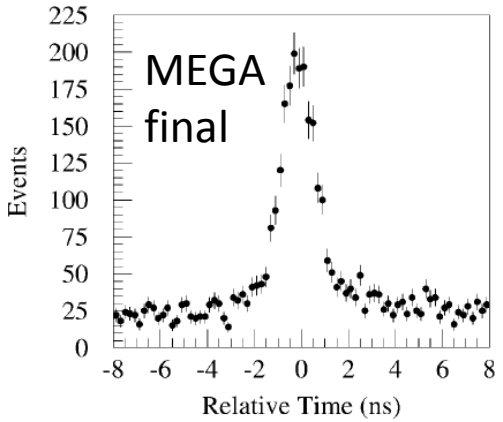




Photon-Positron teγ

- Calibration using
  - Laser data
  - CW Boron data
  - CEX run data
- Photon-Positron Relative time $t_{e\gamma}$
  - Positron time measured by TC is corrected by the time-of-flight
  - Photon time by the time-of-flight (depth reconstruction important)
  - RMD peak is clearly visible
    - 40<Eγ<45 MeV
    - Eγ dependence evaluated in CEX run data
    - $\sigma_{te\gamma}$=148+/-17 psec
      - Stability better than 20psec



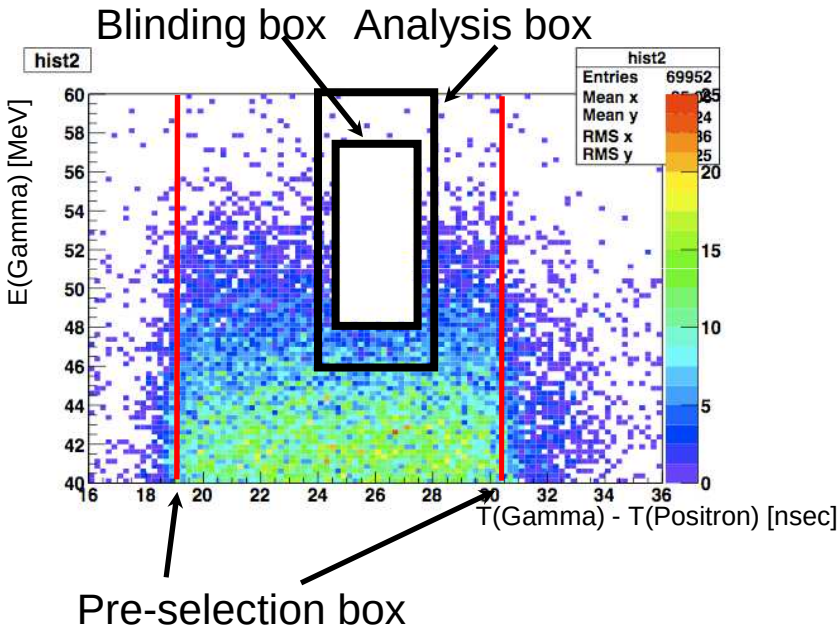


All results are **PRELIMINARY** since we are still doing several systematic checks !!!

PHYSICS ANALYSIS RESULTS

Blinding-Box Analysis

- Pre-selection and blinding
  - Data reduction: 84%
  - Hidden signal box on ($E\gamma$, $t_{e\gamma}$)
  - Event data falling in the blind box is automatically separated (and password protected) and written to a different file from other events
- All analysis procedure is defined and fixed without using hidden data
- Analysis box is defined for the likelihood analysis



Single Event Sensitivity Estimation

$\Omega/4\pi$	0.09	4.6×10^{-3} (from BG rate, E_γ>45MeV, E_e>50MeV)	280/250 (RD sideband data, E_e<48MeV, #expected / #observed)
γ	0.66 x 0.91 (Eγ>46MeV)x(pileup, CR)		
e^+	0.15 (DCH x DC-TC match)		
Trigger	0.66 (DM)		
Selection	0.99 x 0.98 (DCH x γ acc.)		
Nμ	9.4×10^{13} μ stops (3.0×10^7 μ/s/2mA·6290C)		
SES	2.0×10^{-12}	2.2×10^{-12}	2.2×10^{-12}

Expected 90% CL using 2008 Data

- The average expected 90% CL upper limit on BR assuming no signal
  - 1.3×10^{-11}
- The 90% CL upper limit obtained for the side-band data:
  - $(0.9 – 2.1) \times 10^{-11}$

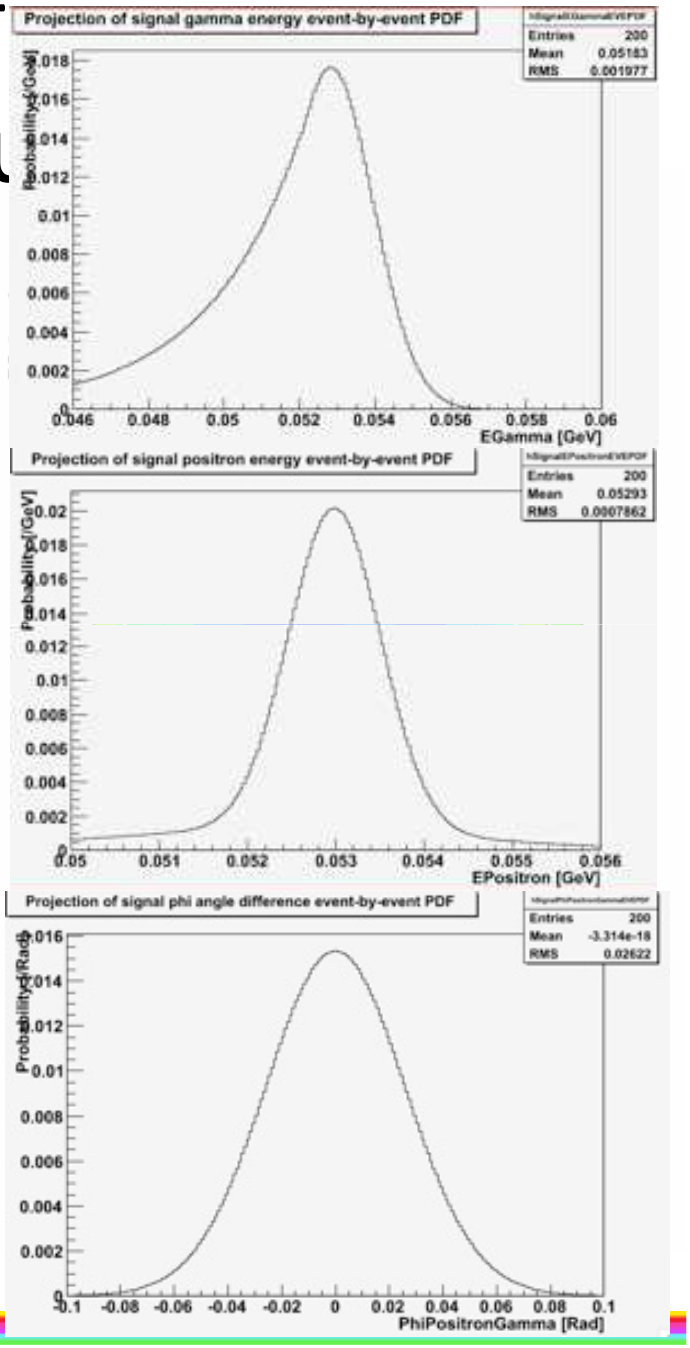
Likelihood Analysis

- The number of $\mu \rightarrow e\gamma$ events is determined by means of a maximum likelihood fit in
  - $46\ \text{MeV} < E_\gamma < 60\ \text{MeV}$
  - $50\ \text{MeV} < E_e < 56\ \text{MeV}$
  - $|t_{e\gamma}| < 1\text{nsec}$
  - $|\theta_{e\gamma}| < 100\text{mrad}$, $|\phi_{e\gamma}| < 100\text{mrad}$

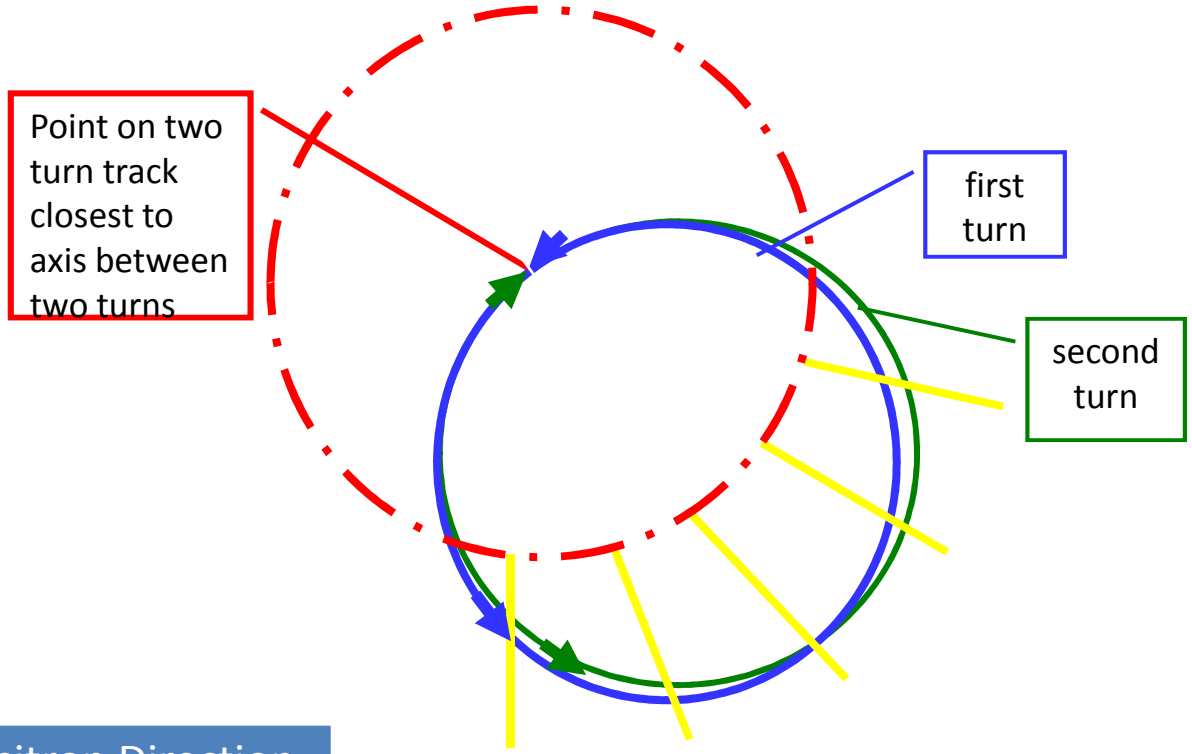
$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) = \frac{N^{N_{\rm obs}} \exp^{-N}}{N_{\rm obs}!} \prod_{i=1}^{N_{\rm obs}} \left[\frac{N_{\rm sig}}{N} S + \frac{N_{\rm RMD}}{N} R + \frac{N_{\rm BG}}{N} B \right]$$

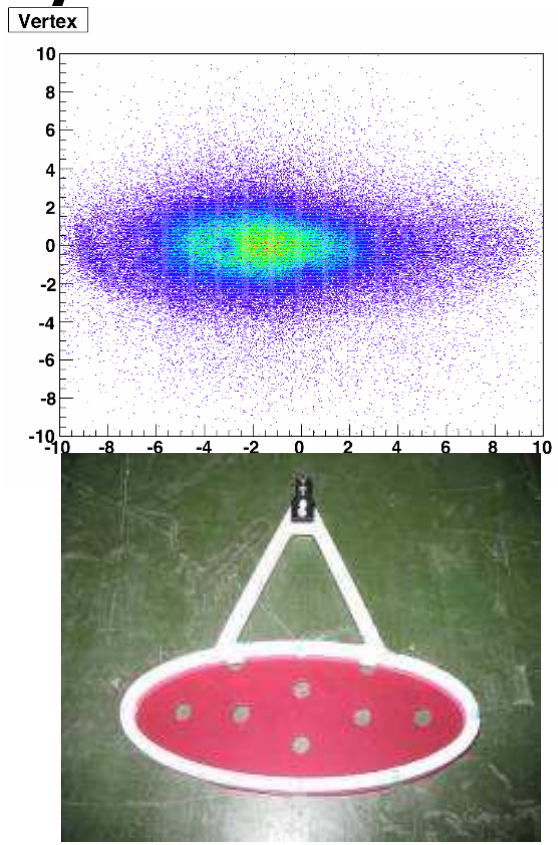
Evaluation of Probability Density Fu

- Signal PDF
  - Eγ: exponential gaussian with σ map
    - CEX data
    - Energy dependence w/o pileup tail
  - Ee: core + two tail components
    - Michel Edge
  - $\Delta\theta$: combined resolution between γ and e^+
    - $(\sigma_u \oplus \sigma_w) \oplus \sigma_{\theta e} \oplus (\sigma_x, \sigma_y)$
    - $\sigma_{\theta e}$ is evaluated to be 20mrad
  - $\Delta\phi$: combined resolution between γ and e^+
    - $\sigma_v \oplus \sigma_{\phi e} \oplus (\sigma_x, \sigma_y)$
    - $\sigma_{\phi e}$ is evaluated to be 10.6mrad
  - $t_{e\gamma}$: gaussian
    - RD and energy dependence



Positron Direction/Decay Point



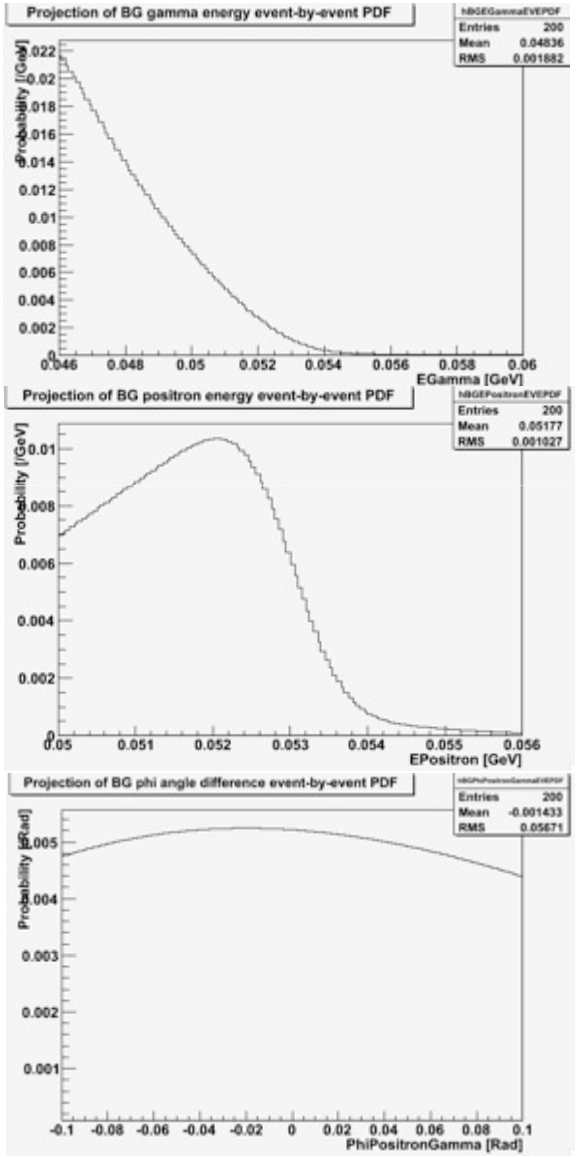


Positron Direction

- Using two turn track
- Get point between two turns closest to the spectrometer axis, R_0
- Fit each turn individually, calculate state vector at ϕ of R_0
- Calculate $\delta\phi_p$, $\delta\theta_p$ between turn 1 & turn 2, interpret this as $\sqrt{2}$ times the resolution
  - $\delta\phi_p$=10mrad, $\delta\theta_p$ =18mrad

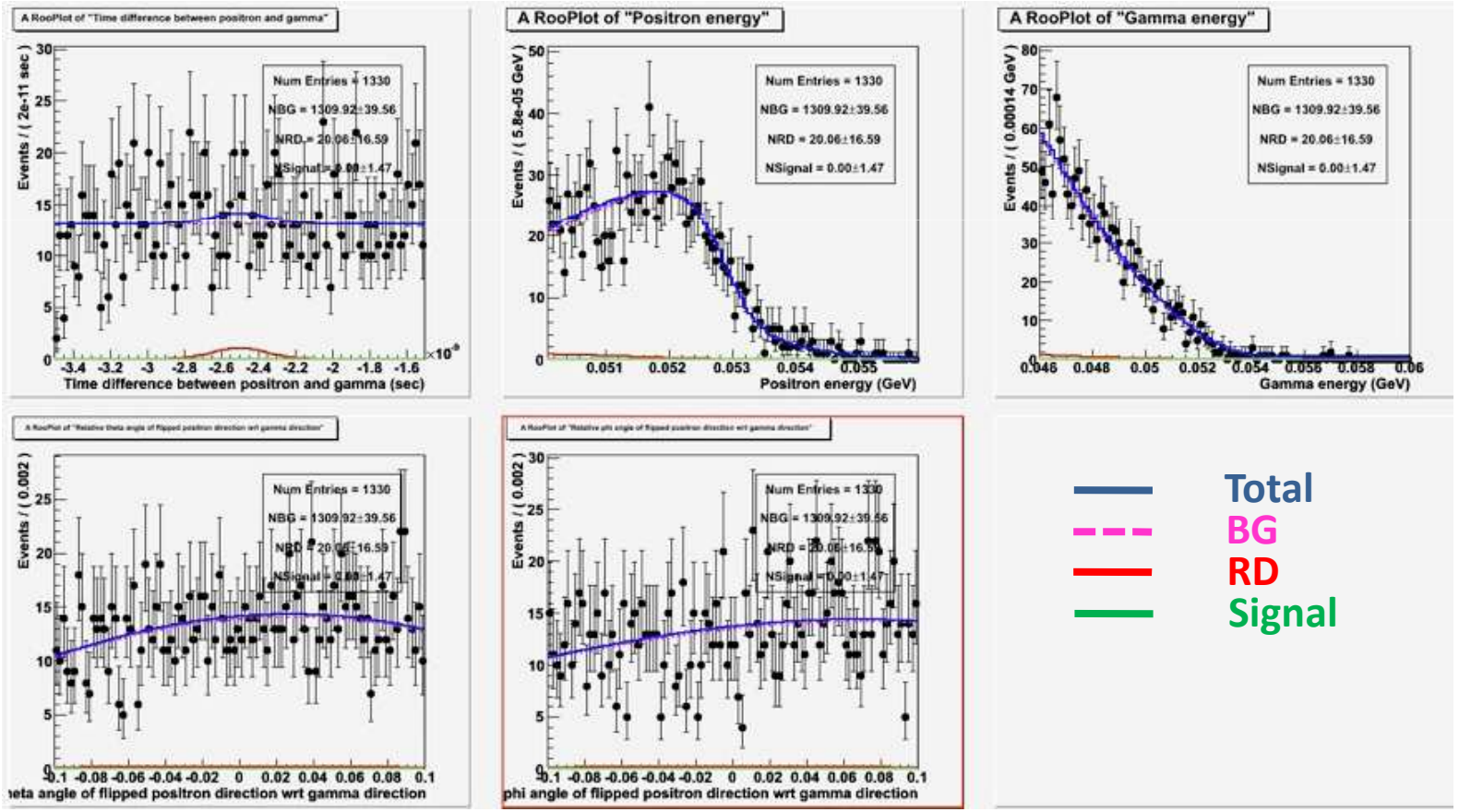
Evaluation of PDFs cont'd

- BG
  - $E\gamma$: Model of BG spectrum
    - fitted to measured spectrum
    - Pileup included
  - Ee: core + two tail components
    - Michel spectrum
  - $\Delta\theta,\Delta\phi$:
    - Measured at side-bands
  - $t_{e\gamma}$: Flat distribution
- RD
  - Theoretical spectrum convoluted with signal response functions except $t_{e\gamma}$
  - $t_{e\gamma}$
    - Same PDF as for signal



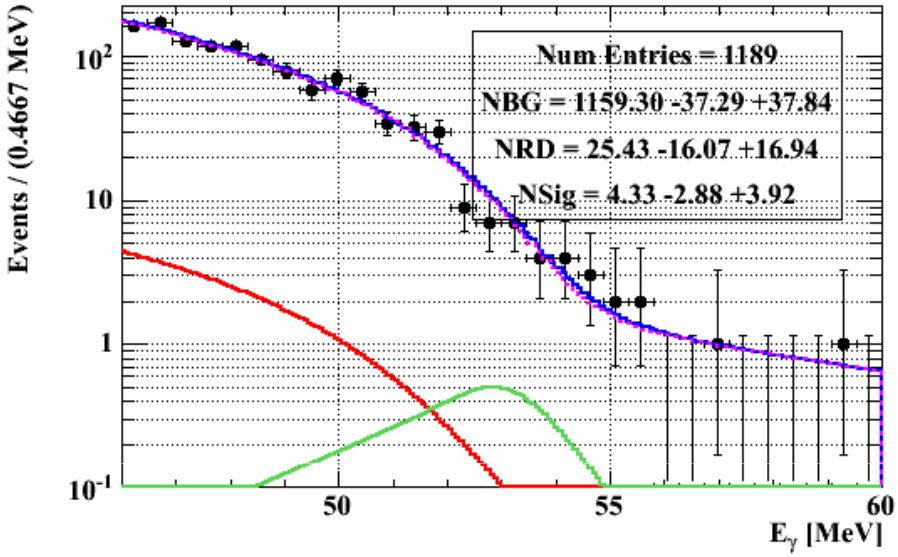
Test of Likelihood Analysis Before Opening the Box

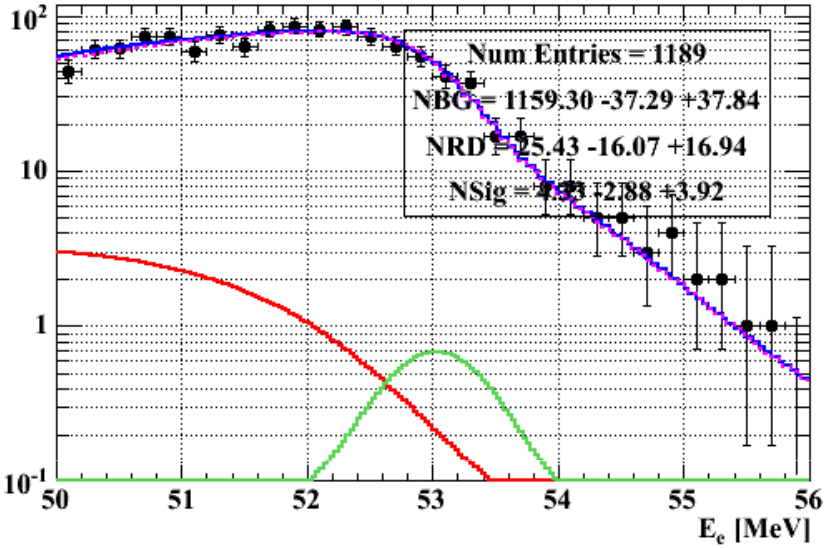
- 1330 events outside the blinding box in the analysis window
  - N_{signal} = 0+/-1.47

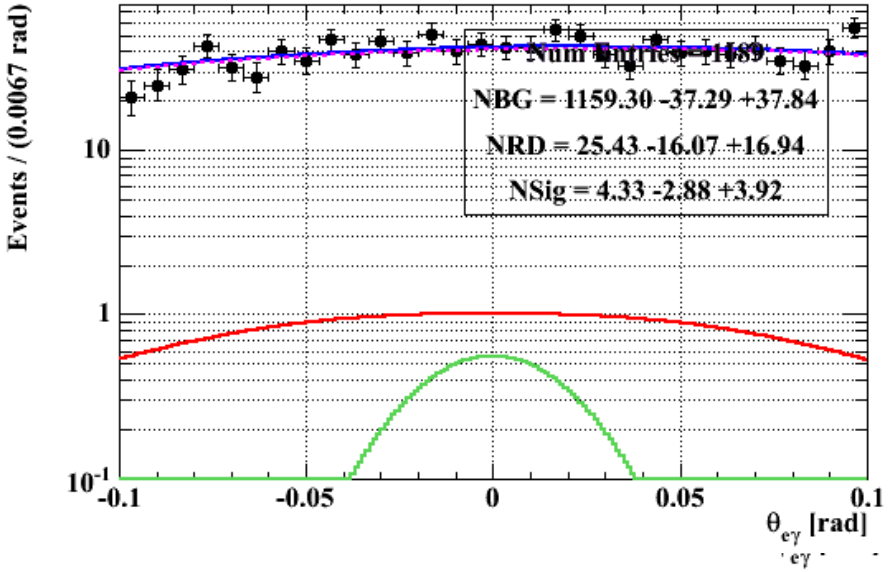


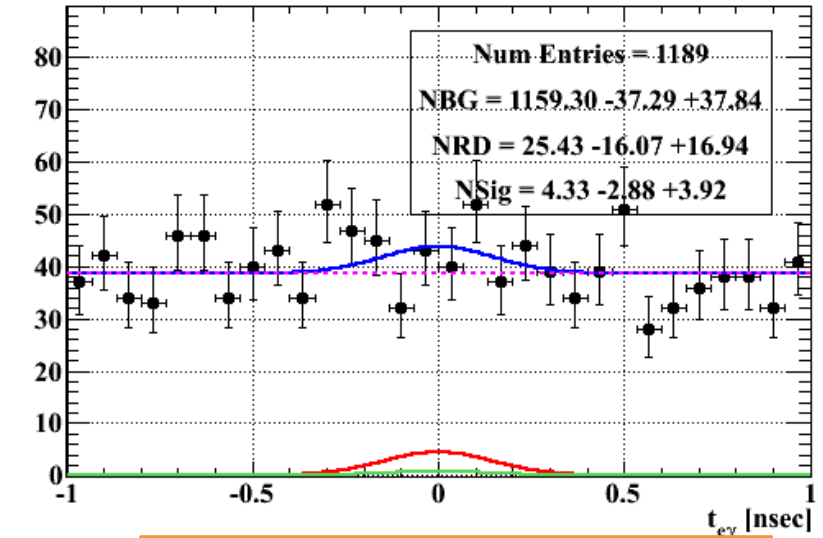

Welcome
to the
World of...

Fit Result N_{obs}=1189





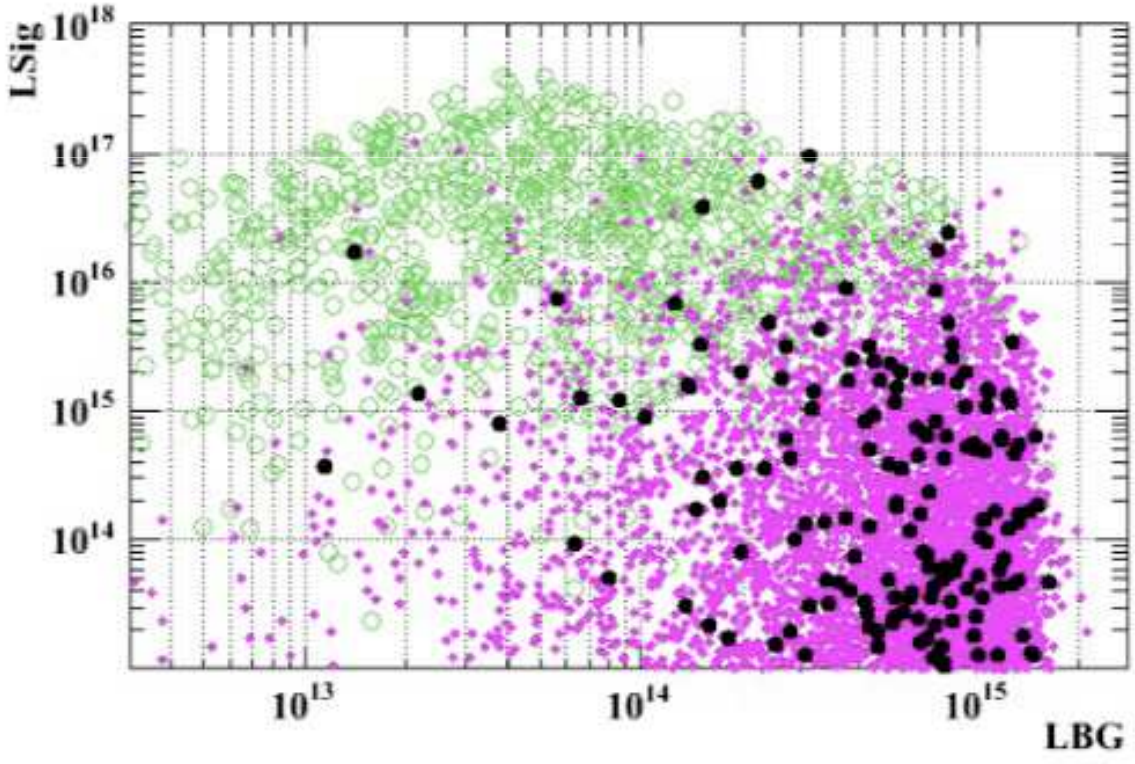




Expected RMD events: 40+/-8

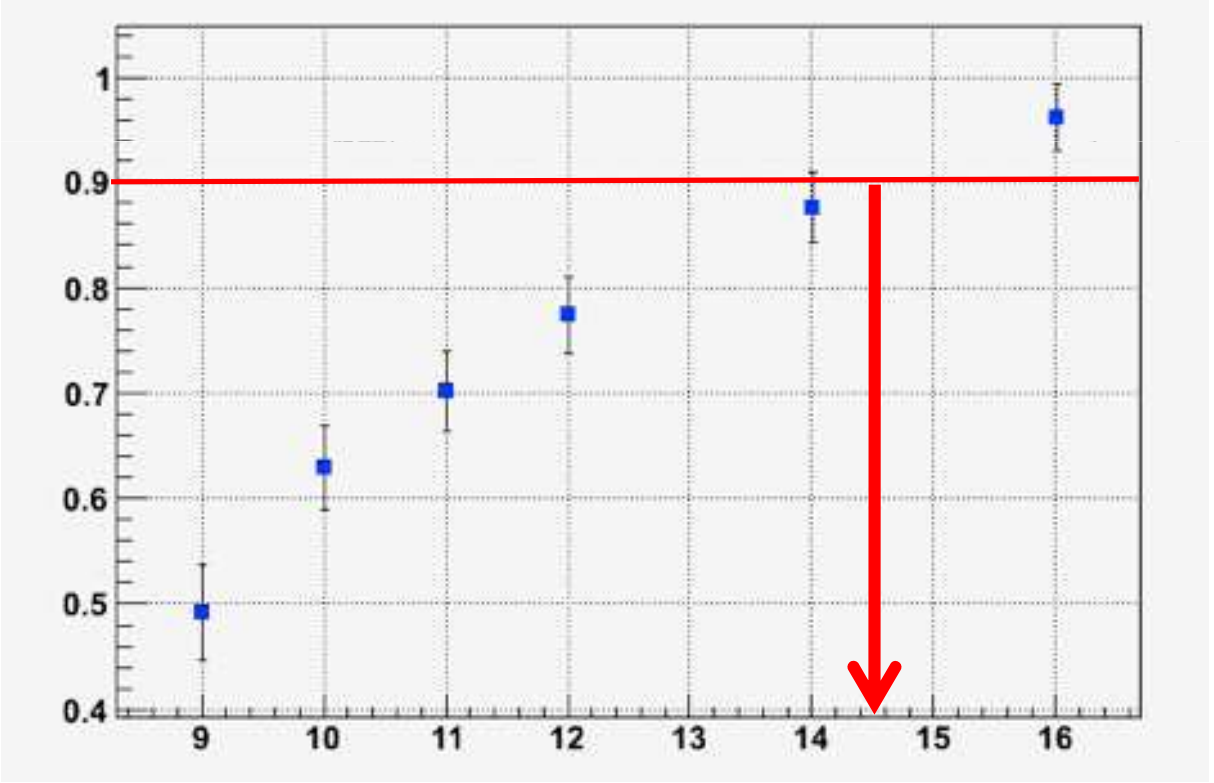
Likelihood Variable Distribution

- **Data (1189 events)**
- **BG (toy MC 40000 events)**
- **Signal (toy MC 1000 events)**



C.L. Calculation

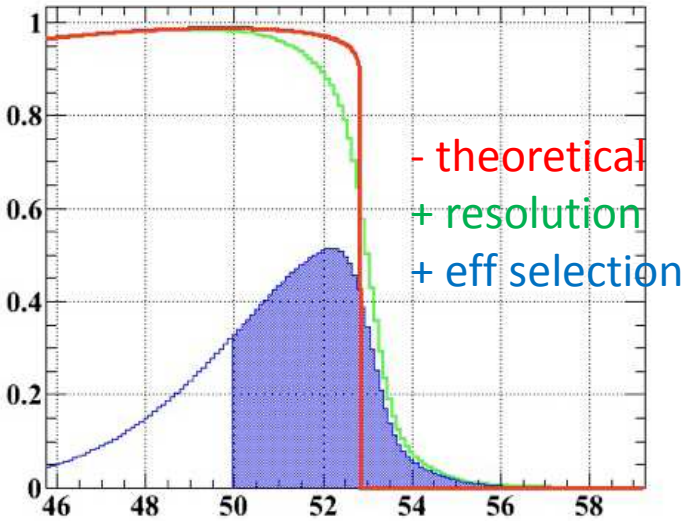
- Feldman-Cousins approach
- $N_{sig} < 14.7$ @ 90% CL
  - Systematic errors included: gamma and positron E scale



Normalization

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

- To minimize DC instability effect on normalization
- Use ratios to cancel ambiguity in the 1st-order approximation
- 50 MeV < E_e < 56 MeV



E_e[MeV]

$f^E_{e\nu\bar{\nu}}$ = 0.101 ± 0.006, fraction of Michel positron spectrum above 50MeV

$\frac{\epsilon^{trig}_{e\nu\bar{\nu}}}{\epsilon^{trig}_{e\gamma}}$ = 0.66 ± 0.03, Ratio of signal-to-Michel trigger efficiencies

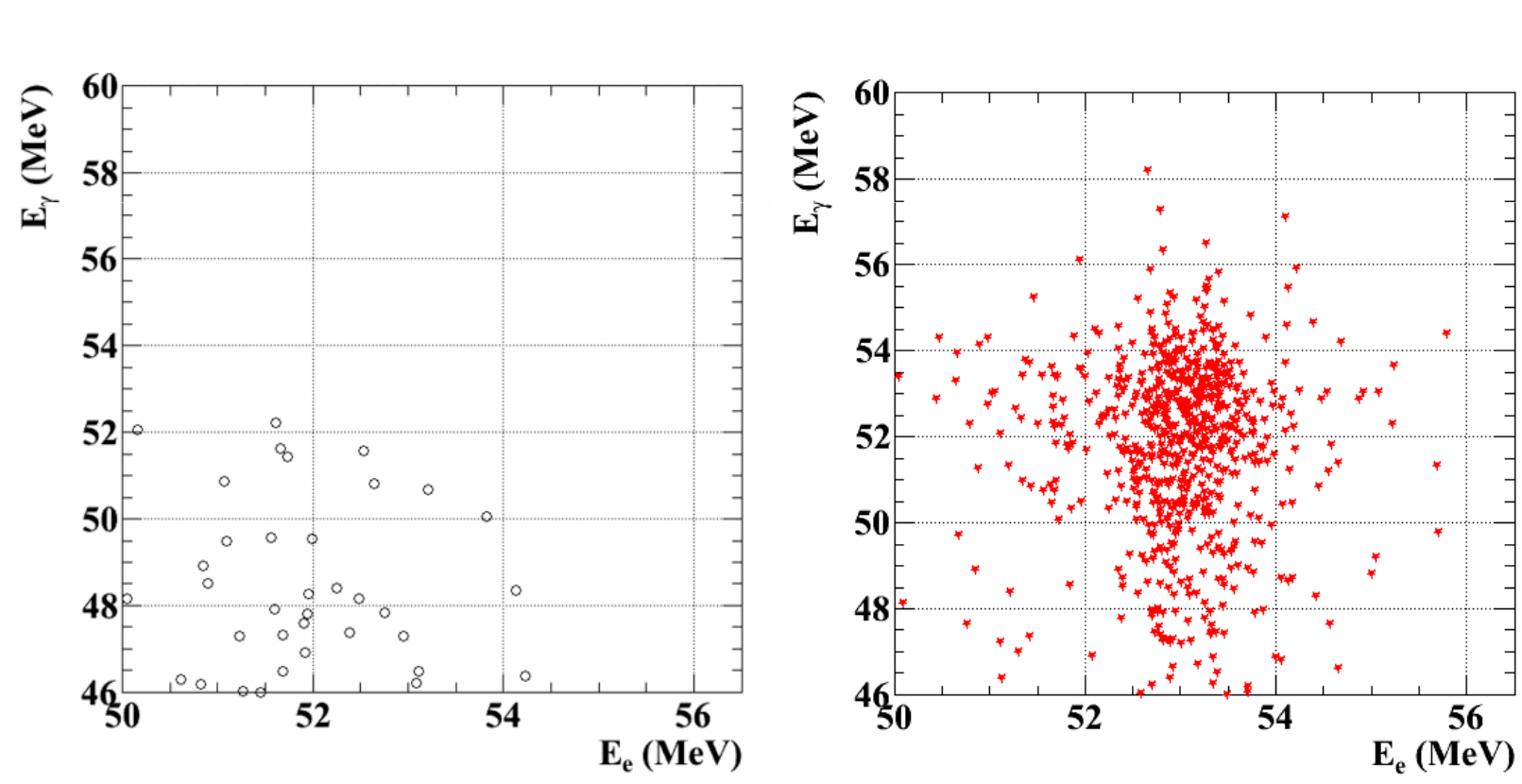
$\frac{A^{TC}_{e\nu\bar{\nu}}}{A^{TC}_{e\gamma}}$ = 1.11 ± 0.02, Ratio of signal-to-Michel DCH-TC matching efficiency

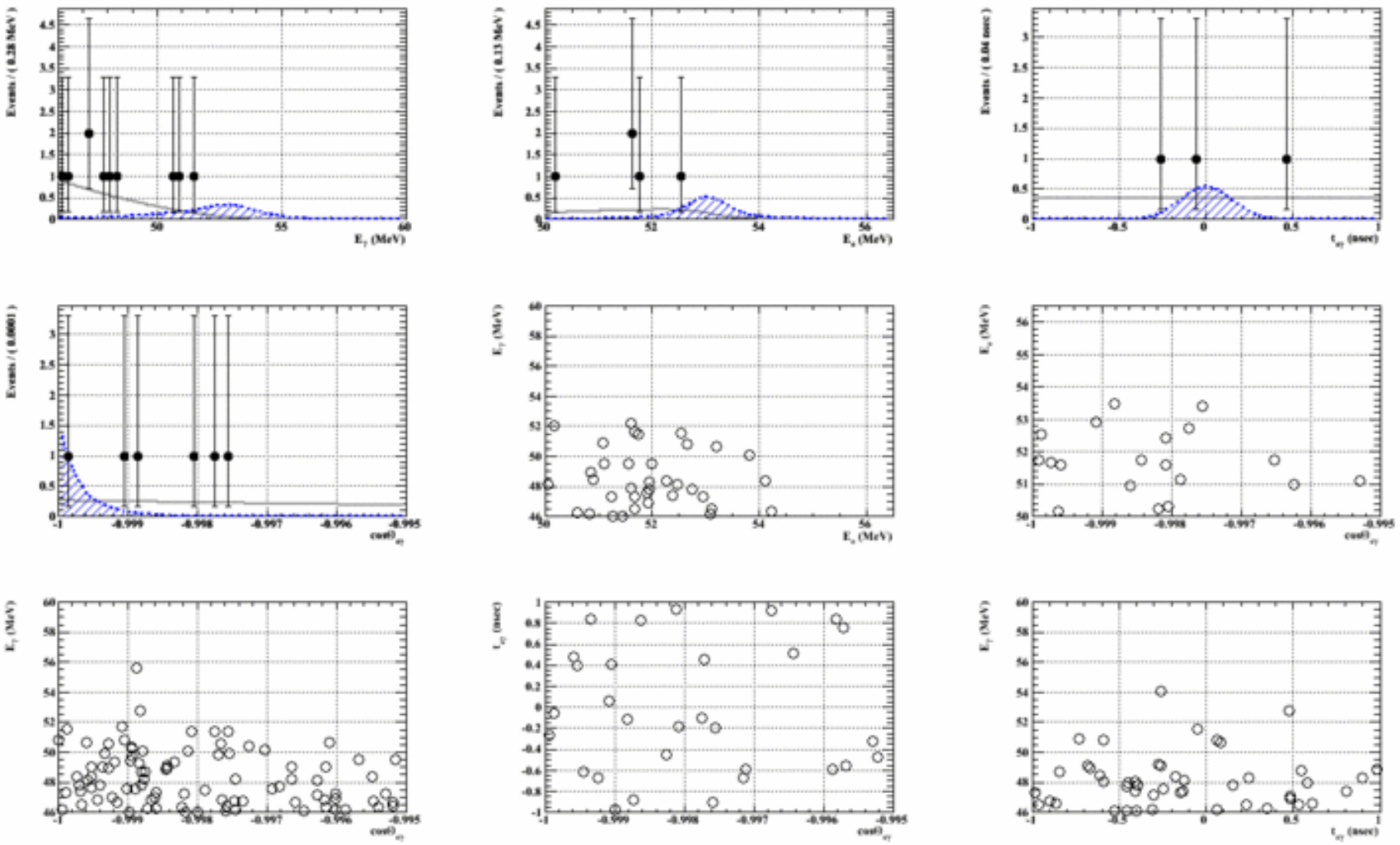
$\frac{\epsilon^{DC}_{e\nu\bar{\nu}}}{\epsilon^{DC}_{e\gamma}}$ = 1.02±0.005, Ratio of signal-to-Michel DCH reconstruction efficiency and acceptance

- Br ($\mu \rightarrow e\,\gamma$) < 3.0×10^{-11} at 90% C.L.
  - including systematic uncertainty on the normalization
  - Probability to obtain this limit given the average expected limit of 1.3×10^{-11} is 5%

Event Distribution in 90% Box

- Event selection with 1.64σ on all variables





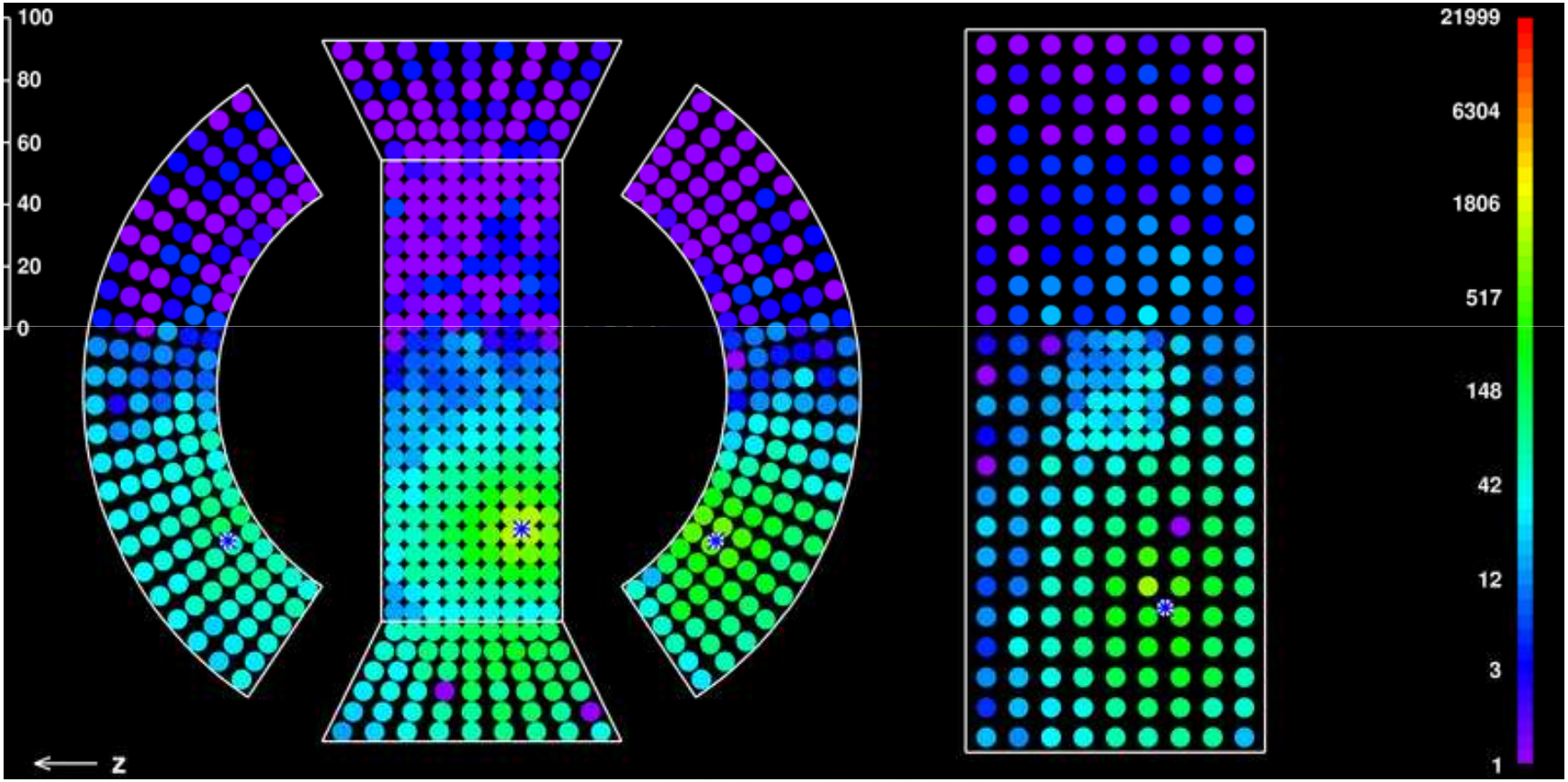
BoxSize = 1.64σ

TimeWindow (-0.242228, 0.242228)

2.10%,0.96%,18.2mrad,148ps

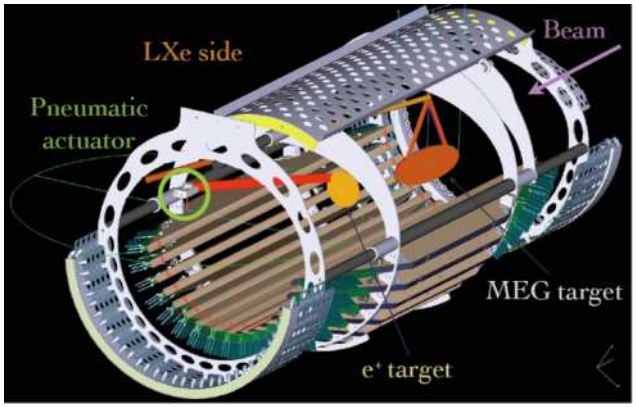
NBG = 1

Observed Event



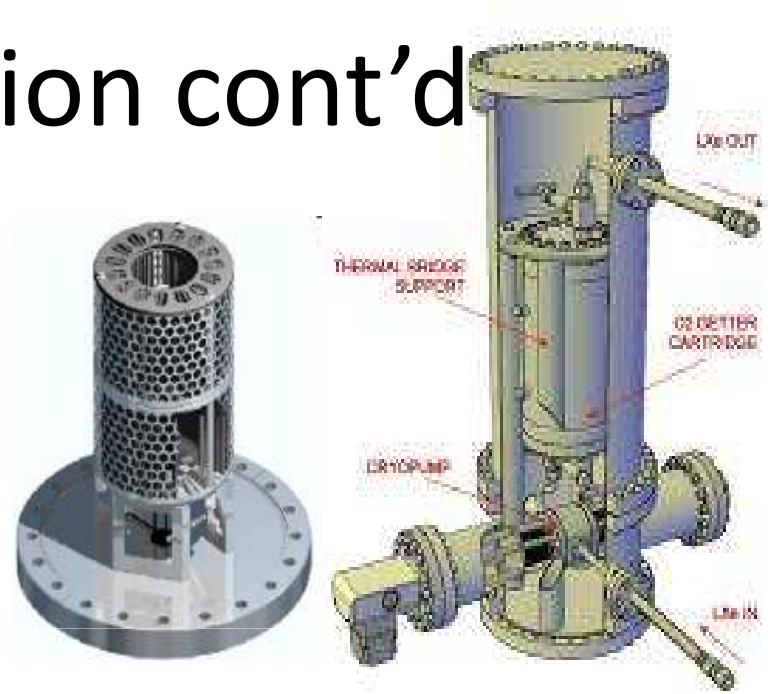
Detector Preparation toward 2009 Run

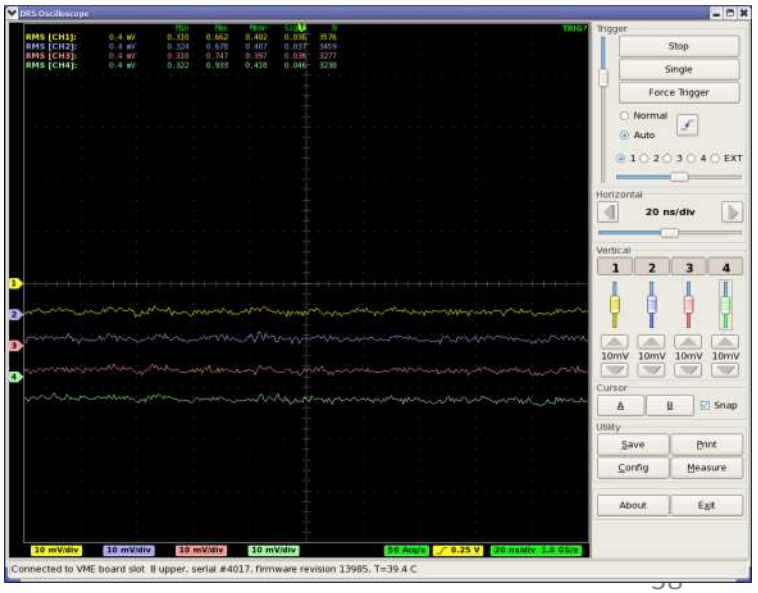
- DC
  - Overhaul of all modules
  - Long term test in helium atmosphere
  - Installation in the magnet on 1/Sep completed
- TC
  - New calibration source on each bar
  - Fiber counter



Detector Preparation cont'd

- Lxe
  - Installation of a new getter pump
  - Installation of a new Liquid Pump/Purifier
    - 180 L/hour circulation
    - No electric noise
  - Higher Light yield is confirmed (x1.4)
    - Better time resolution is expected
- DAQ
  - New waveform digitizer, DRS4
    - Better linearity and stability, lower noise
    - Better time/energy resolutions





Summary

- Br ($\mu \rightarrow e\,\gamma$) < 3.0×10^{-11} at 90% C.L.
  - Suffered from larger background than expected
    - Tails in positron measurements & gamma pile-up
  - …
- More data in 2009 and also in 2010
  - Detector overhaul and modification
  - 8.6 weeks in 2009
    - longer in 2010