Recent results from the MEG experiment

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(on the behalf of MEG collaboration)

Nufact 11
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Outlook

- The MEG experiment
  - The physics goal
  - Signal & background
  - Beam and detector layout
- The Run
  - Detector calibration & performance
  - Quality checks
  - Data summary
- Results
  - Analysis strategy
  - Review of results from Run 2009
  - Latest results from combined (2009+2010) data
- Perspectives for the future
  - Sensitivity plan
- Conclusions

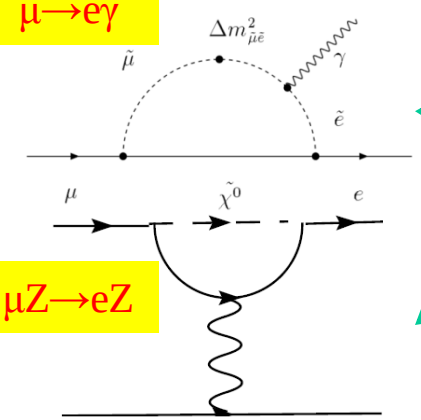
The experiment

- Physics goal
- Signature & background
- Detector layout

LFV relation to EDM, g-2

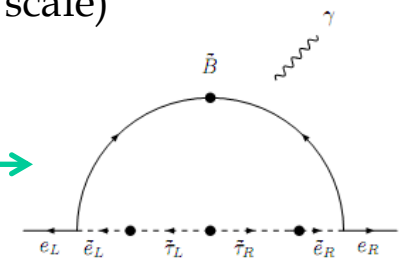
- Contribution to EDM, MDM of leptons (hadrons) from diagonal elements of the slepton (squark) mass matrix
- LFV processes induced by off-diagonal terms (depend on how SUSY breaking is generated and what kinds of LFV interactions exist at the GUT scale)

μ→eγ



μZ→eZ

$$M^2_{\tilde{l}\tilde{l}'} = \begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$



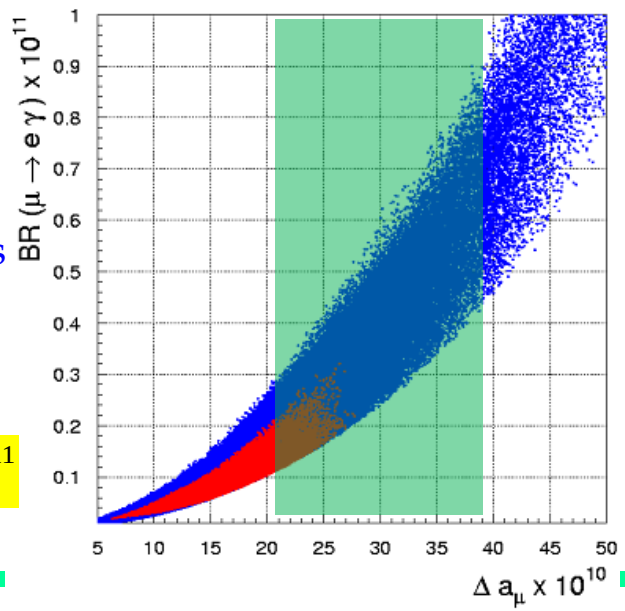
g-2 $\propto \Re(m^2_{\tilde{\mu}\tilde{\mu}})$

EDM $\propto \Im(m^2_{\tilde{\mu}\tilde{\mu}})$

- SUSY effect on g-2 ➔ deviations from SM predictions
- an experimental clue: E821 results

$$\Delta a_\mu \equiv a_\mu^{\exp} - a_\mu^{SM} = (297 \pm 79) \times 10^{-11}$$

Phys.Rev.Lett. 92(2004) 1618102



$\Delta a_\mu \neq 0$ associated with SUSY

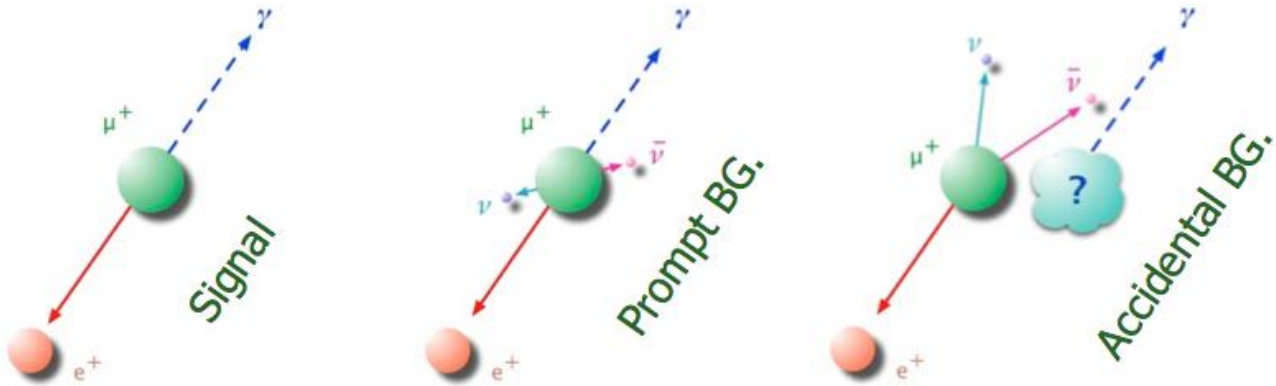
➔ $BR(\mu \to e\gamma) \geq 10^{-12}$

G.Isidori *et al.*

Phys. Rev. D75 (2007) 115019

➔ strong physics case

Signal & background



$$E_e = E_\gamma = 52.8\,\text{MeV}$$

$$\Theta_{e\gamma} = 180^\circ$$

$$\delta t_{e\gamma} = 0$$

$$B_{pro} \approx 0.1 \times B_{acc}$$

$$B_{acc} \propto R_\mu \Delta E_\gamma^2 \Delta E_e \Delta\Theta_{e\gamma}^2 \Delta t_{e\gamma}$$

Exp./Lab	Year	ΔEe/Ee (%)	ΔEγ /Eγ (%)	Δteγ (ns)	Δθeγ (mrad)	Stop rate (s^{-1})	Duty cyc. (%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^5	(6..9)	4.9×10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5×10^8	(6..7)	1.2×10^{-11}
MEG	2009	1	4.5	0.15	19	3×10^7	100	2×10^{-13}

The layout

The beam

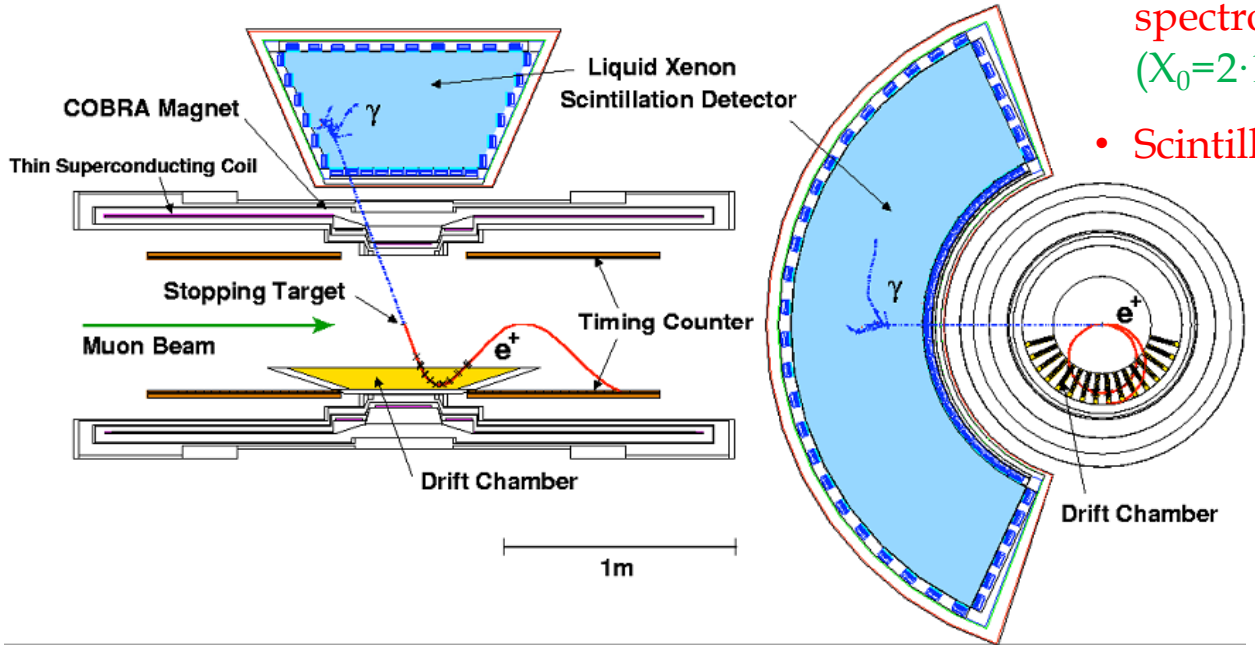
- The worldwide most intense DC beam (>10^8m/s) of surface muons (28 MeV/c)

→ stopped on a thin (100 μm) target

- Currently $R_\mu = 3\times10^7\ s^{-1}$ due to pile-up

The detector

- Liquid Xenon calorimeter for γ detection (scintillation)
  - fast (τ ~ 20÷40 ns)
  - high light yield (70% NaI)
- Thin wall quasi-solenoidal spectrometer & drift chambers ($X_0=2\cdot10^{-3}$) for e^+ momentum
- Scintillation counters for e^+ timing

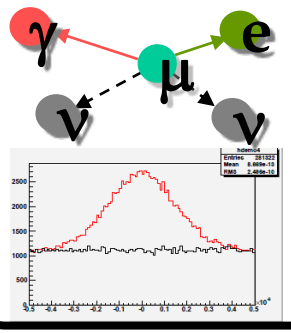


Matter effects must be minimized in order not to spoil the resolution

The Run

- Detector monitoring & calibration
- Performances
- uality checks
- Data summary

Calibration tools



Lower beam intensity $< 10^7$

Is necessary to reduce pile-ups

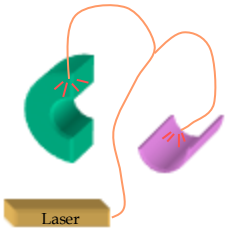
Better σ_t, makes it possible to take data with higher beam intensity

A few days ~ 1 week to get enough statistics

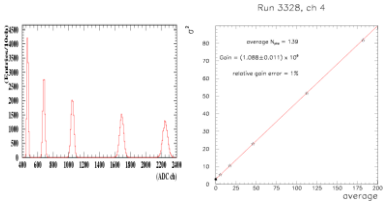
Laser

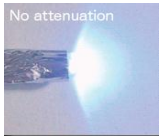
(rough) relative timing calib.

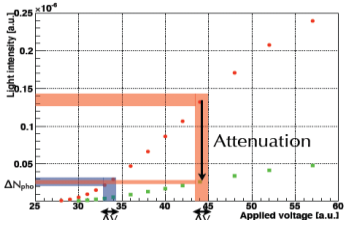
< 2~3 nsec



LED





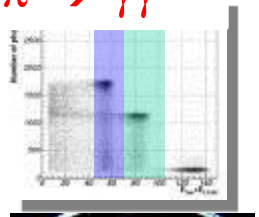


PMT Gain

Higher V with light att.

Can be repeated frequently

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



π^- + p → π^0 + n

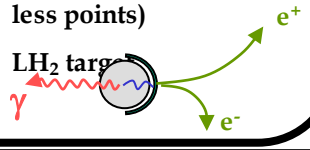
π^0 → γγ (55MeV, 83MeV)

π^- + p → γ + n (129MeV)

10 days to scan all volume precisely

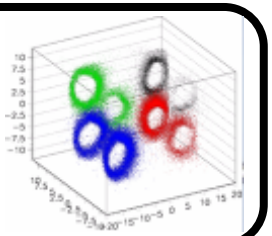
(faster scan possible with less points)

LH_2 target



MEG detector standard calibrations

alpha

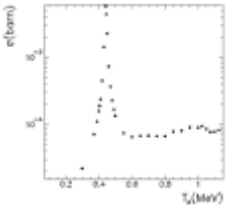


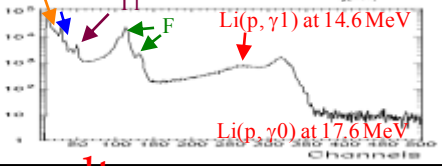
PMT QE & Att. L

Cold GXe

LXe

(p, γ) reactions





Li(p,γ)Be

LiF target at COBRA center

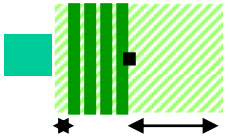
17.6MeV γ

~daily calib.

Can be used also for initial setup

(n,γ) on Ni

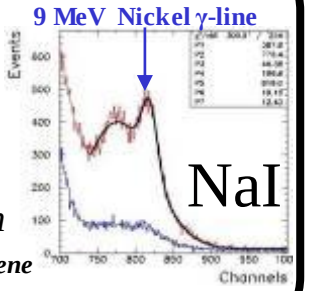
Neutron pulsed generator to induce (n, γ)



3 cm 20 cm

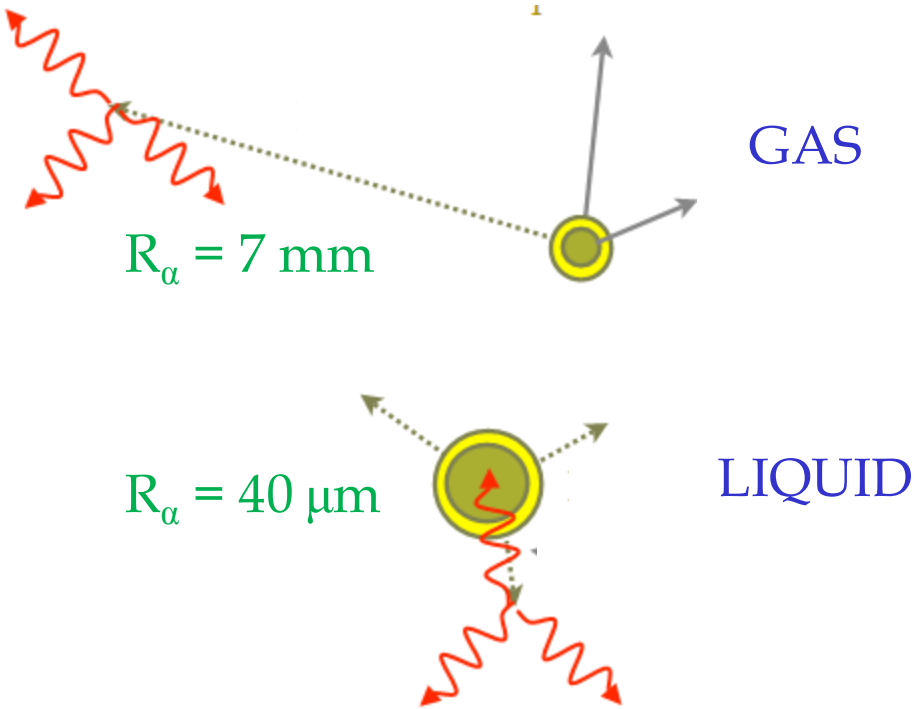
Polyethylene

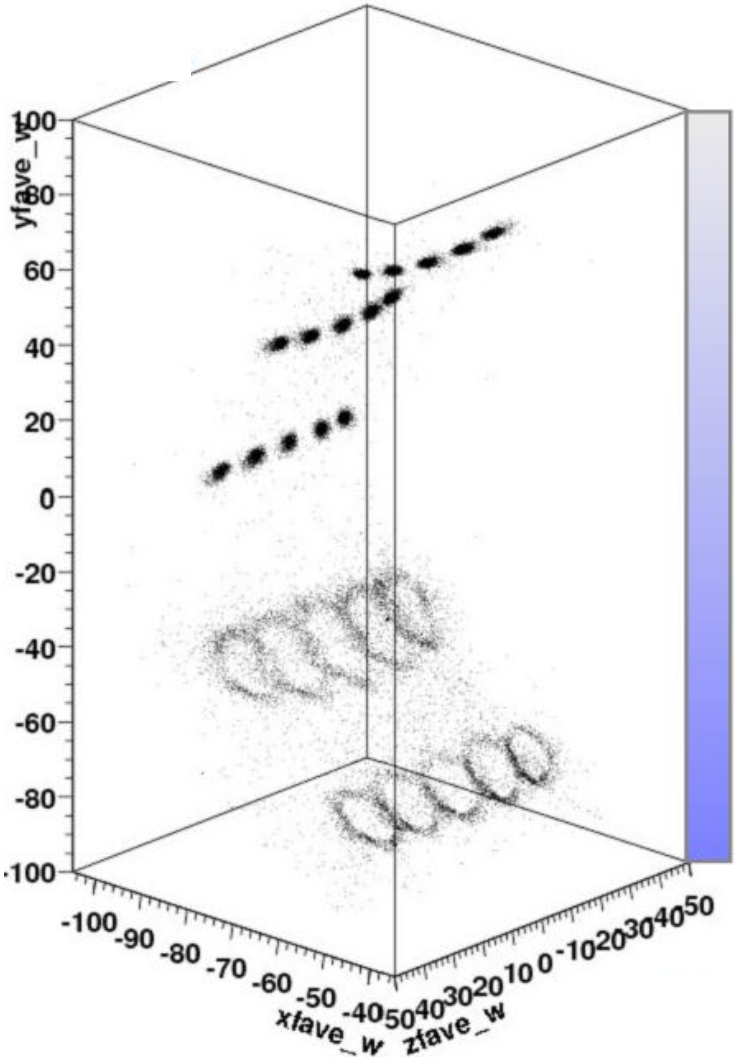
0.25 cm Nickel plate



LXe PMT monitoring

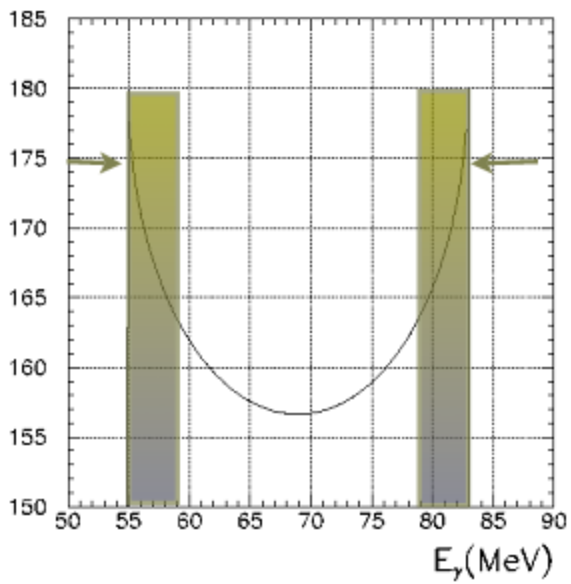
- ^{241}Am sources on ϕ=100μm wires to
  - –determine PMT QEs
  - –monitor absorption length

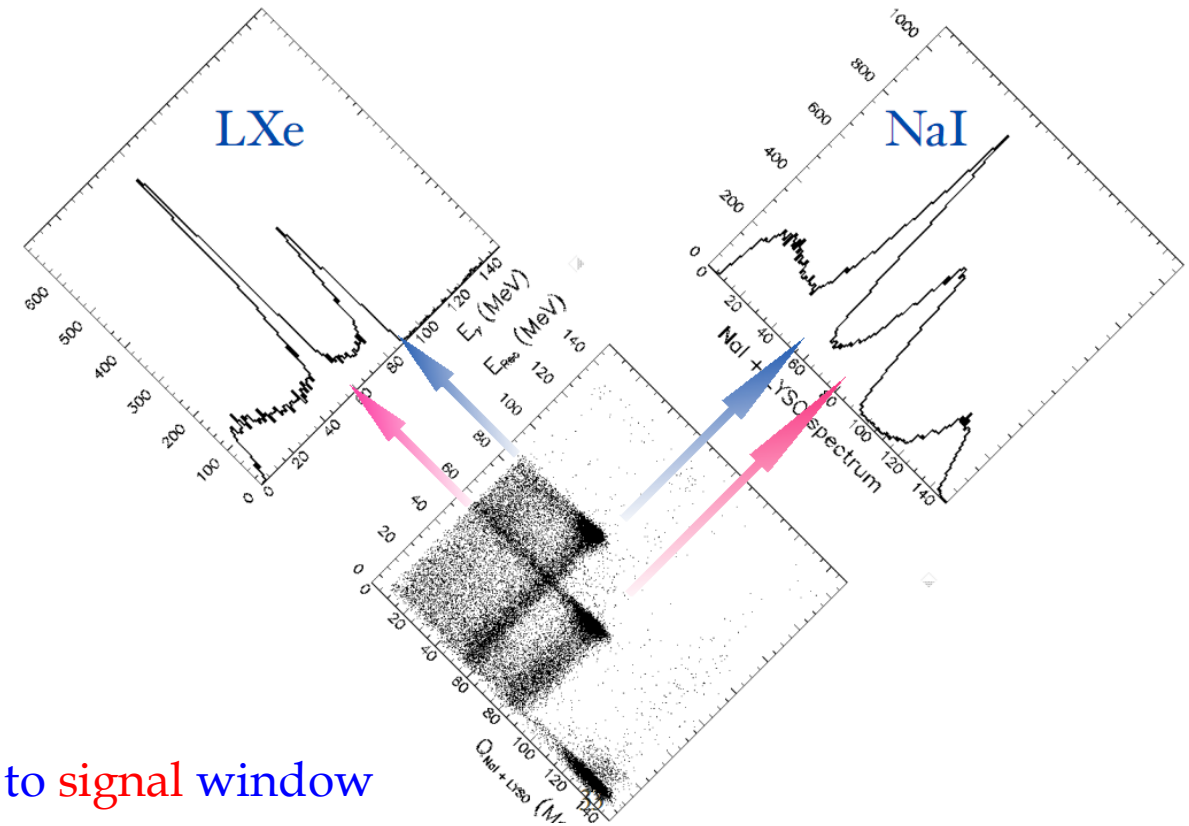




γ from π-CEX

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

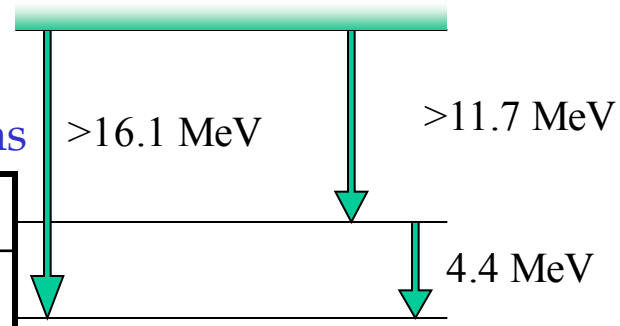




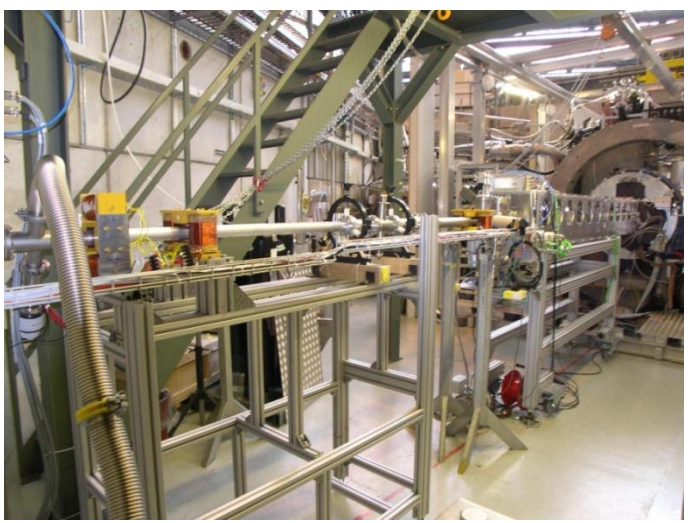
- E_γ = 55 (83) MeV ➔ close to signal window
- liquid H-target
- beam polarity and settings to be changed as well
  → to be used quite seldom (~ 1/year)

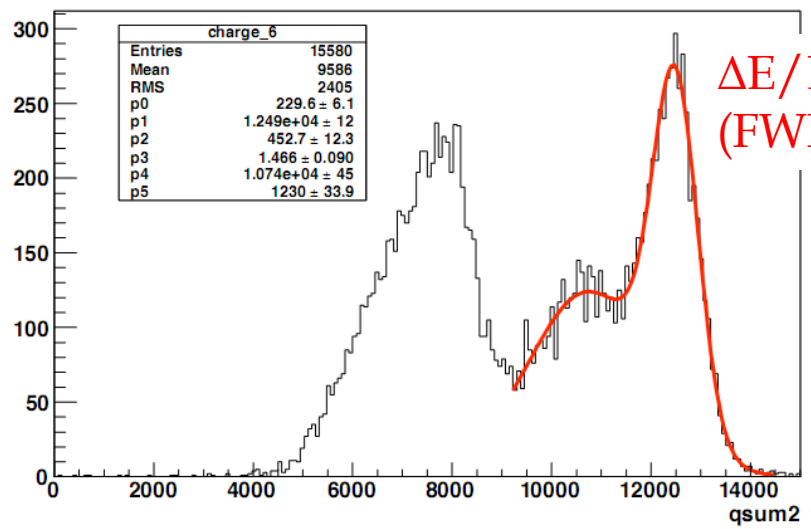
(p,γ) reactions

- 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

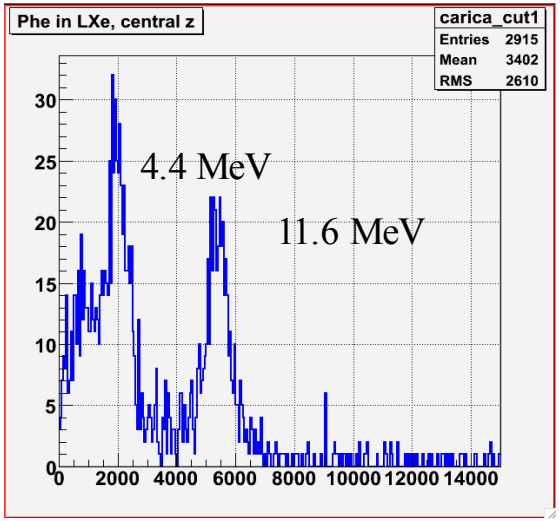


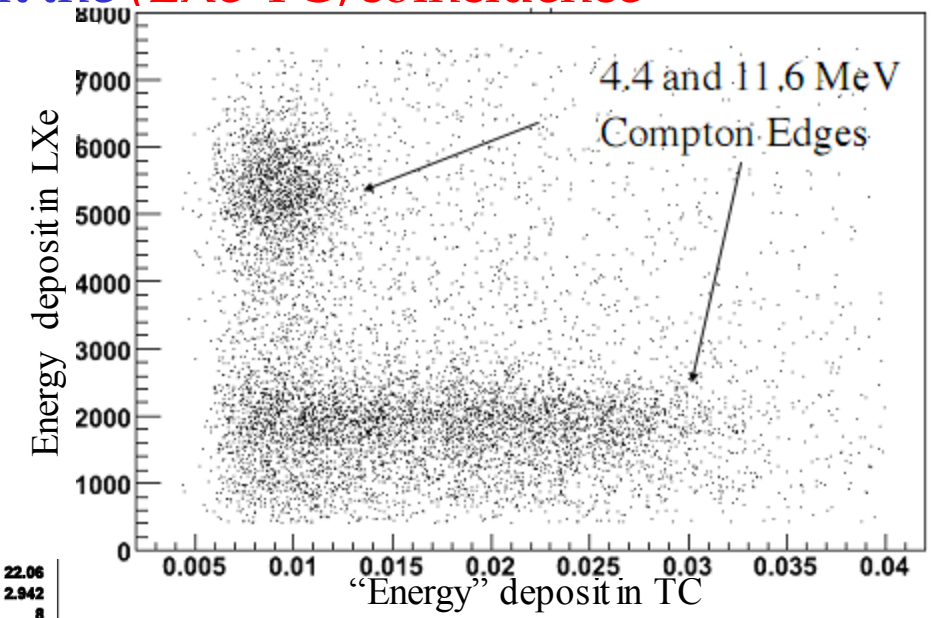


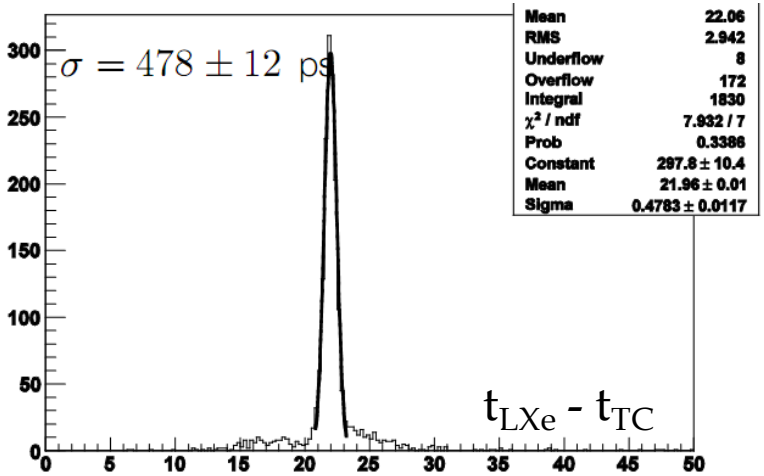
ΔE/E = 8.5% (FWHM)

B(p,γ)C reaction

- 2 simultaneous lines to exploit the (LXe-TC) coincidence

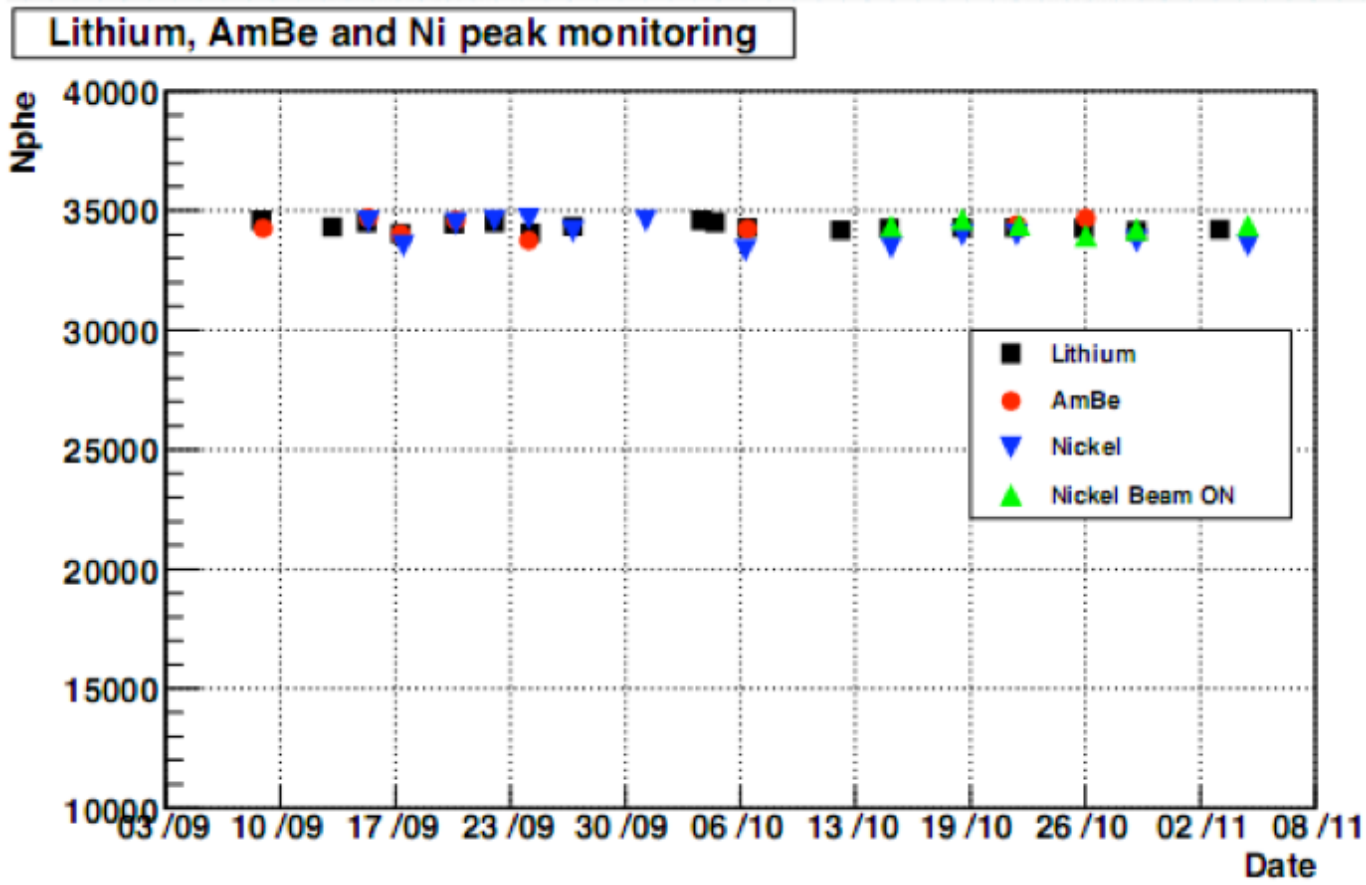




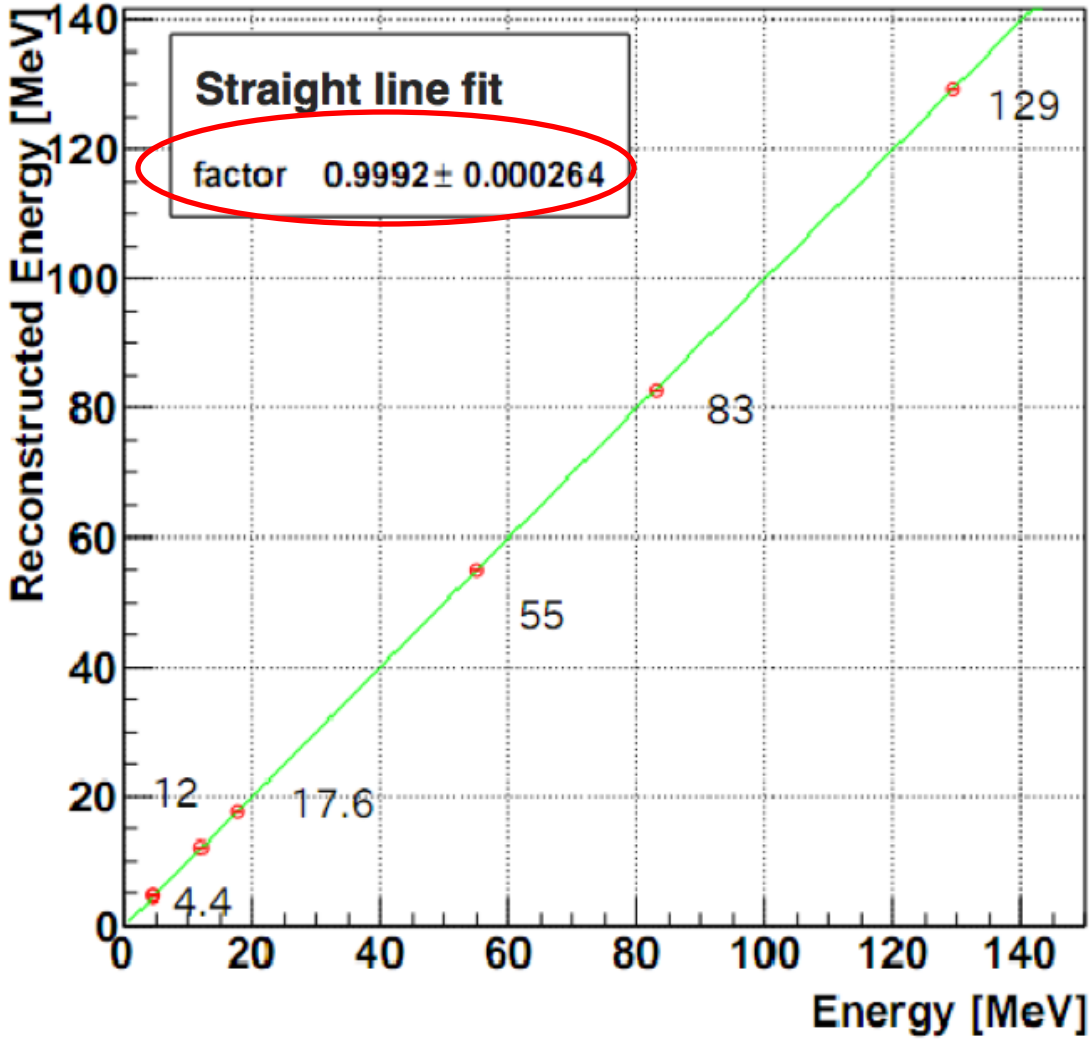


Monitoring

- All methods operational during Run 2010
- Confirm stability of the energy scale within 0.3%

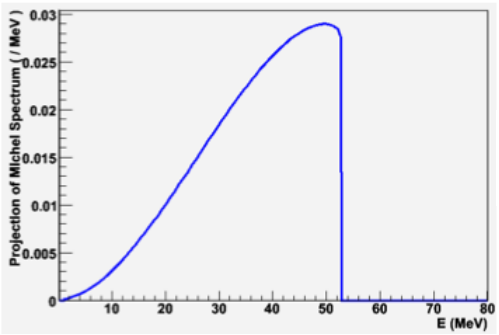


Scale linearity



Tracker performance (1)

- No decay available to produce back-to-back particles at these energy (apart from $\mu \rightarrow e\gamma$ ... if any)
- positron momentum ➔ fit of Michel edge



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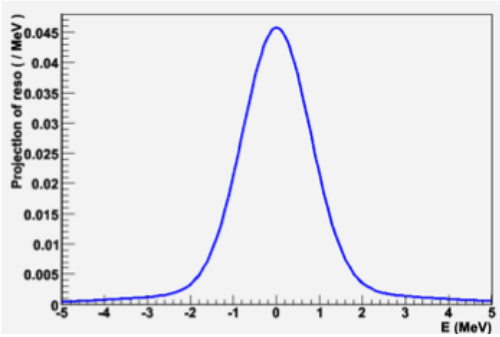

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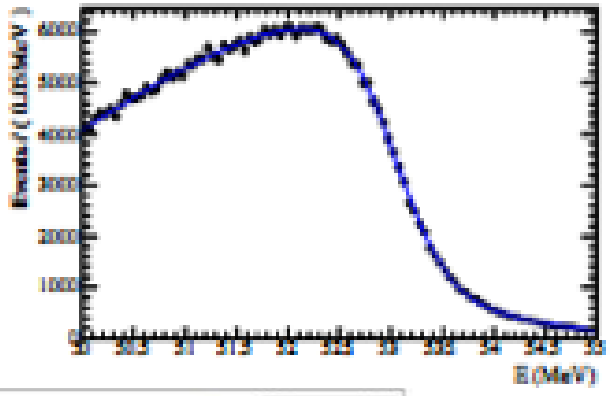
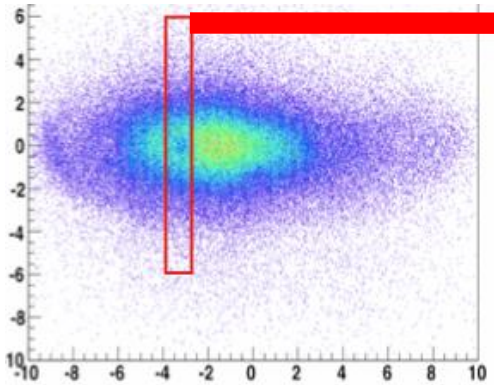
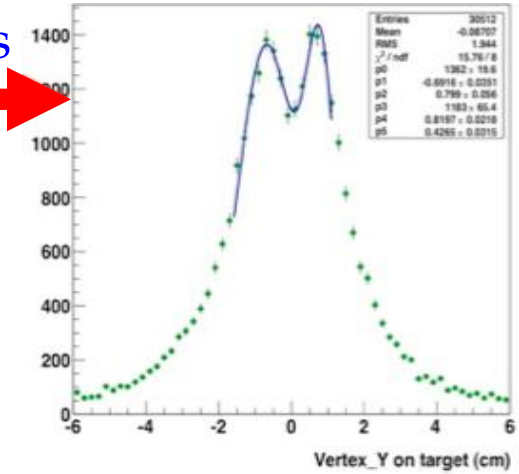


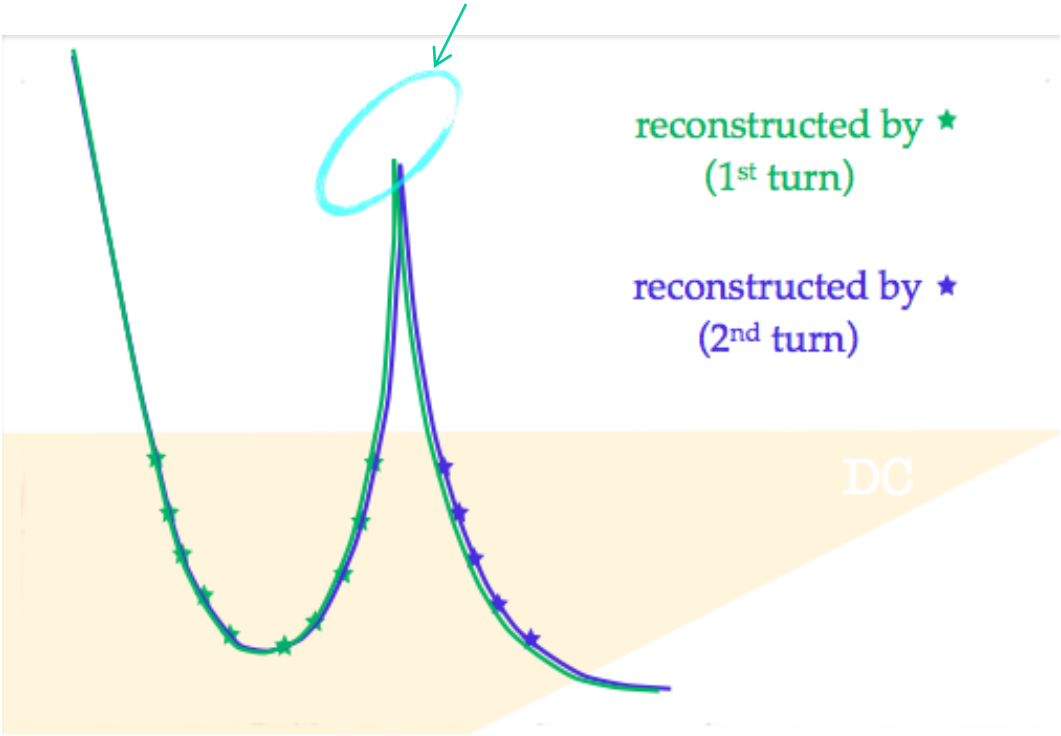
- muon decay vertex ➔ fit to target holes





Tracker performance (2)

- direction ➔ fit of double-turn positrons
  - track segments reconstructed as due to different particles
  - angular resolution obtained from the difference of the two reconstructions at the turning point



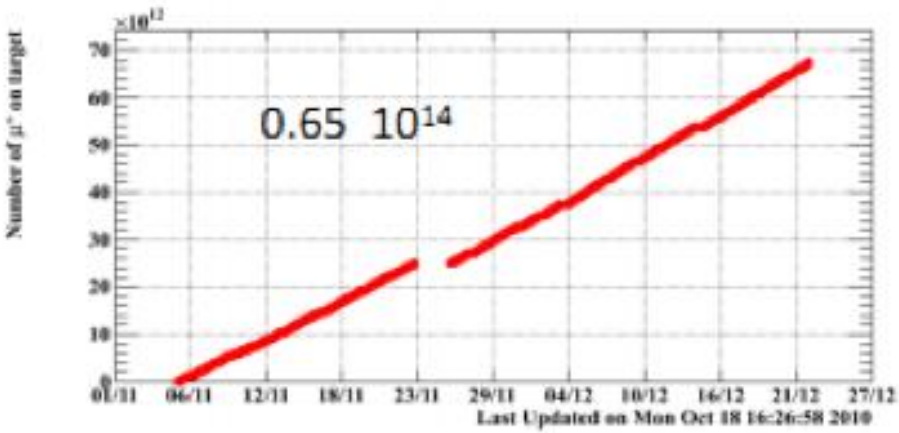
New implementations

- 2010
  - DC
    - calibrations with Mott-scatterd positrons
      (dedicated beam+target, tunable momentum byte down to 1%)
    - cosmic rays data for relative DC alignment
    - newly reconstructed magnetic field
      (measurements on a lattice + symmetry + Maxwell equation constraints)
  - XEC
    - (n,γ) reactions induced by a pulsed neutron generator
  - XEC-DC alignment
    - XEC "radiography" based on Pb-cubes in known positions w.r.t. DC
- 2011
  - DAQ+ trigger
    - multiple-buffer read-out
      ➔ trigger efficiency*livetime from 75 % (2010) to 98% (2011)
  - DC HV system (newly implemented, see later)

Data summary

muons on target

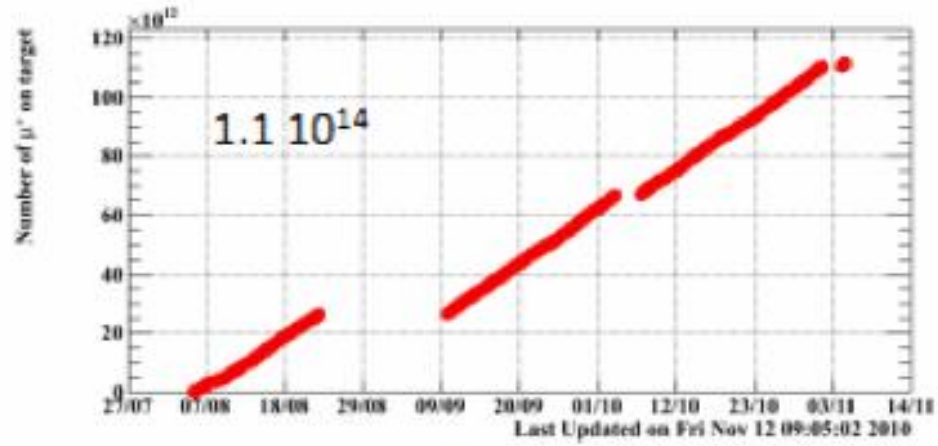
2009



DAQ time : 35 days

Fully efficient detector
Stable conditions (DCH, LXe light)

2010



DAQ time : 56 days

Optimized beam (degrader)
Improved electronics timing
Slightly worse DC noise
Conditions

Run 2010 prematurely ended due to a serious quench of the transport solenoid

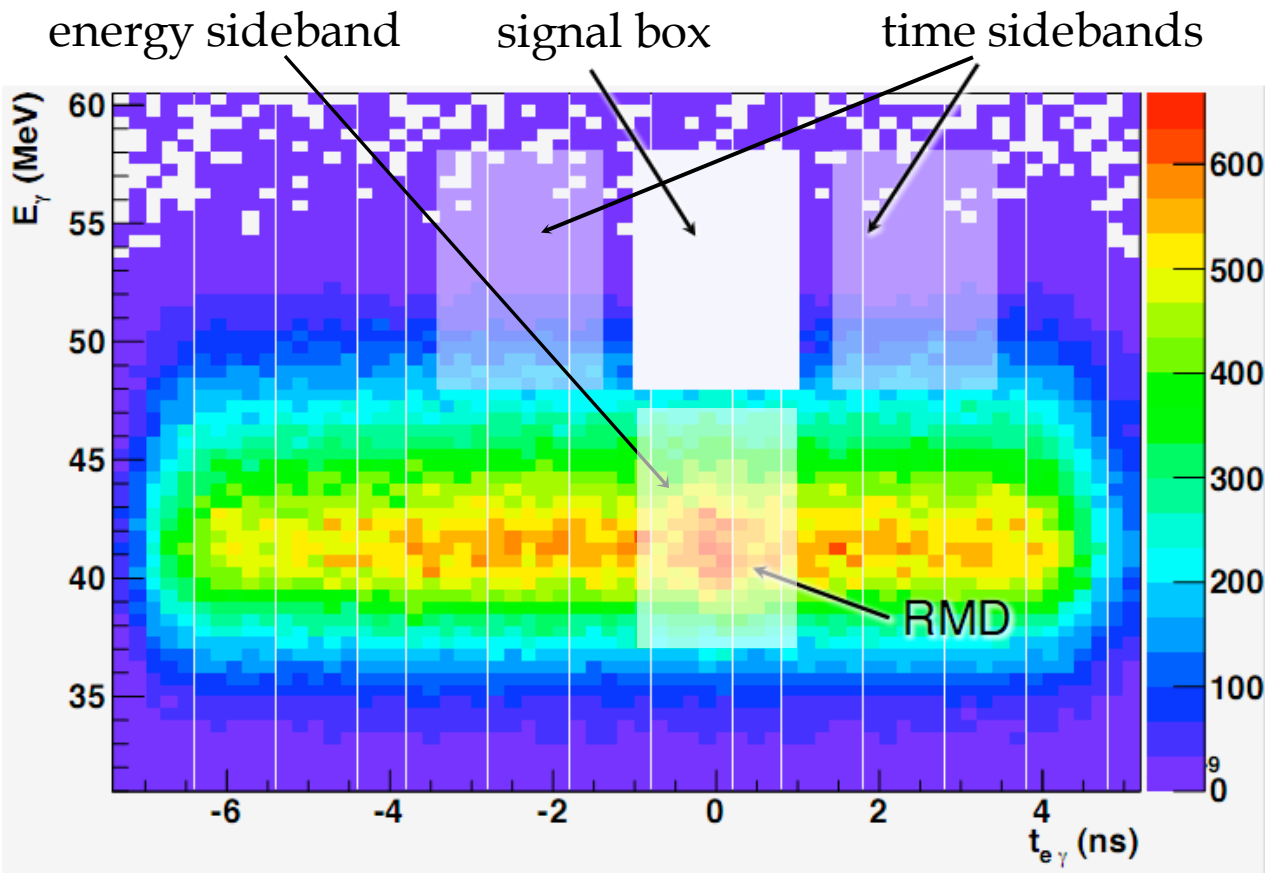
Results

- The analysis strategy
- Review of results from Run 2009
- Combination of (2009+2010) data

(see J.Adam et al. Arxiv:1107.5547)

Analysis strategy

- likelihood analysis strategy
  - blinding observables: E_γ and $\Delta t_{e\gamma}$



pdfs:

- signal: from detector response function
- accidental: from event distribution in data sidebands
- RD: from RD data distribution and trigger simulation (angular cut)

Likelihood fit

- Frequentist approach based on Feldman-Cousins prescriptions with profile likelihood ratio ordering

$$\mathcal{L}\left(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}\right) = \frac{e^{-N_{\rm obs}}}{N!} e^{-\frac{1}{2}\frac{(N_{\rm BG}-\langle N_{\rm BG}\rangle)^2}{\sigma^2_{\rm BG}}} e^{-\frac{1}{2}\frac{(N_{\rm RMD}-\langle N_{\rm RMD}\rangle)^2}{\sigma^2_{\rm RMD}}} \times \prod_{i=1}^{N_{\rm obs}} \left(N_{\rm sig} S(\vec{x}_i) + N_{\rm RMD} R(\vec{x}_i) + N_{\rm BG} B(\vec{x}_i)\right),$$

$$LR_p(N_{\rm sig}) = \frac{\max_{N_{\rm BG},N_{\rm RMD}} \mathcal{L}(N_{\rm sig}, N_{\rm BG}, N_{\rm RMD})}{\max_{N_{\rm sig},N_{\rm BG},N_{\rm RMD}} \mathcal{L}(N_{\rm sig}, N_{\rm BG}, N_{\rm RMD})}.$$

- Observables
  - kinematics $(\vec{x})$
  - event counts in the sidebands
- Parameters
  - number of signal and background events

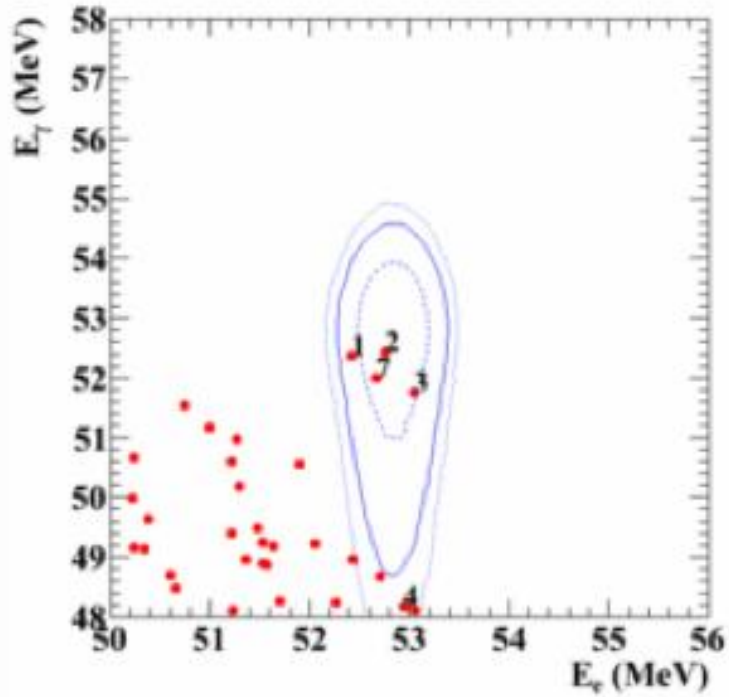
Performance summary

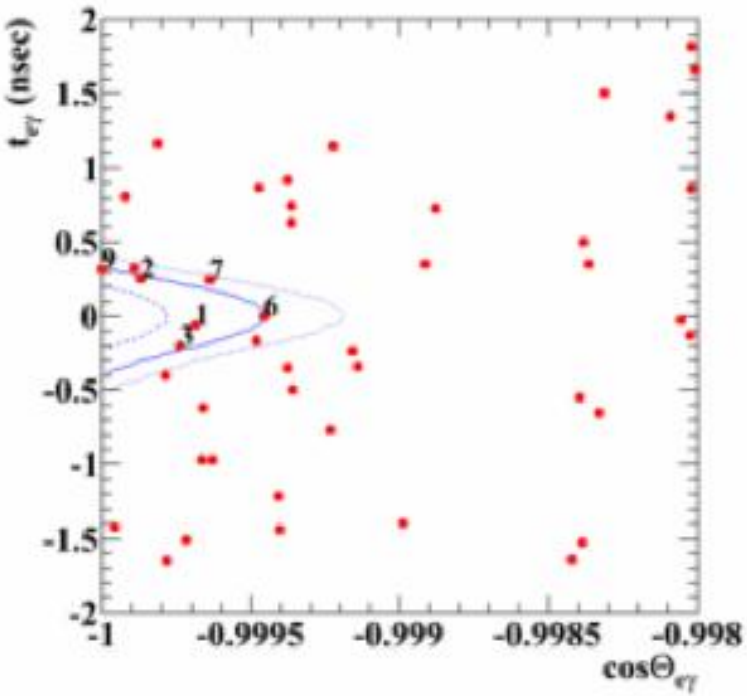
	2009	2010
Gamma E [σ_R, w>2cm – 63%]	1.9%	1.9%
Relative timing $T_{e\gamma}$ (RMD)	150ps	130ps
Positron E [Michel edge]	330 keV(82% core)	330 keV (79% core)
Positron θ	9.4 mrad	11.0 mrad
Positron ϕ [at zero]	6.7 mrad	7.2 mrad
Positron Z/Y	1.5/1.1(core) mm	2.0/1.1(core)mm
Gamma position	5(u,v)6(w) mm	5(u,v)6(w) mm
Trigger efficiency	91%	92%
Gamma efficiency	58%	59%
Positron efficiency	40%	34%
Muon stopping rate	$2.9\ 10^{7}$ s-1	$2.9\ 10^{7}$ s-1
DAQtime/real time	35/43 days	56/67 days
SES [analysis region]	$0.92\ 10^{-12}$	$0.44\ 10^{-12}$

Update of 2009 analysis

Selection: $|T_{e\gamma}|<0.278$ns; $\cos\Theta_{e\gamma}<$ 0.9996

$51<E_\gamma<55$ MeV; $52.34<E_e<55$ MeV

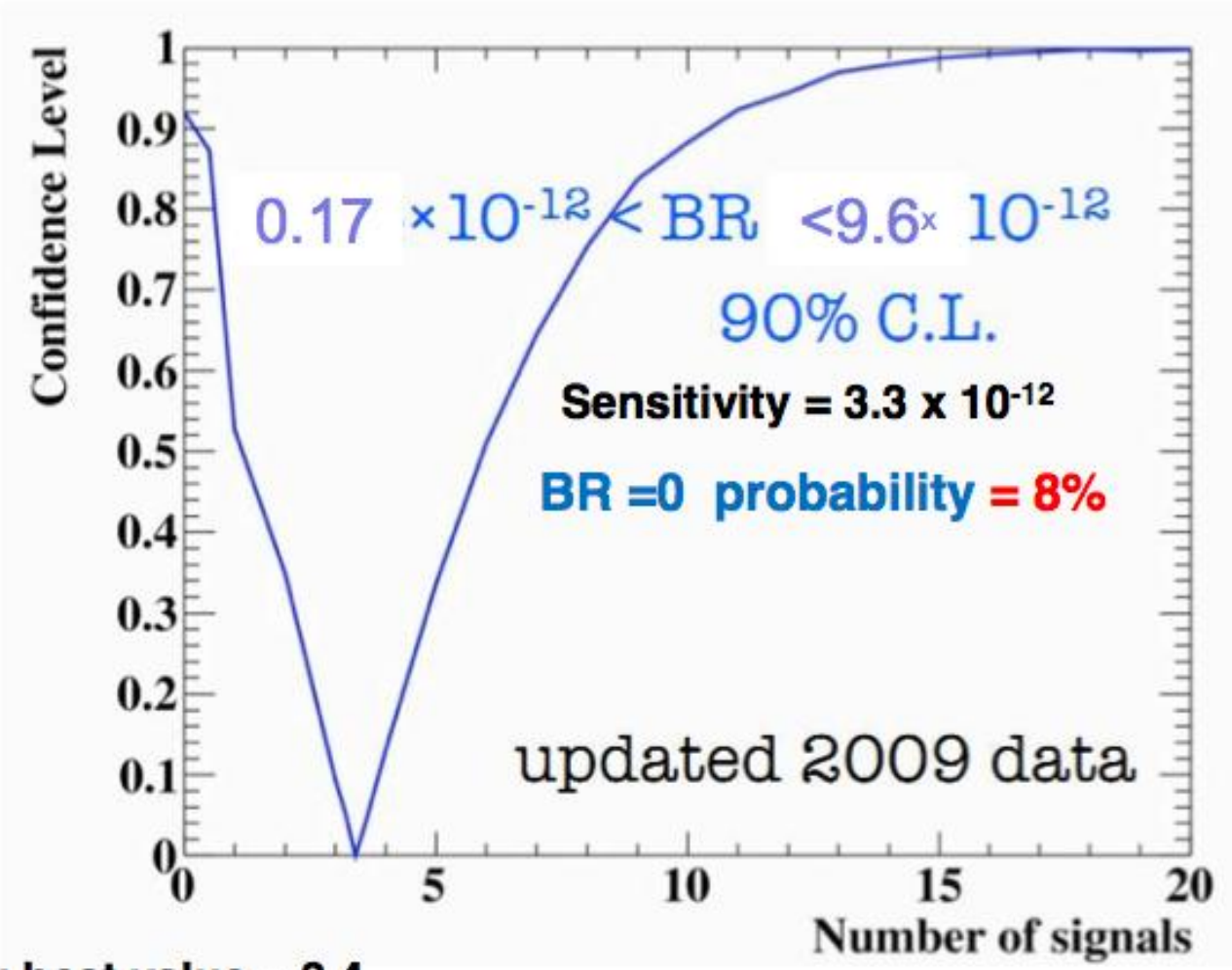




Rank of variables
In each sample

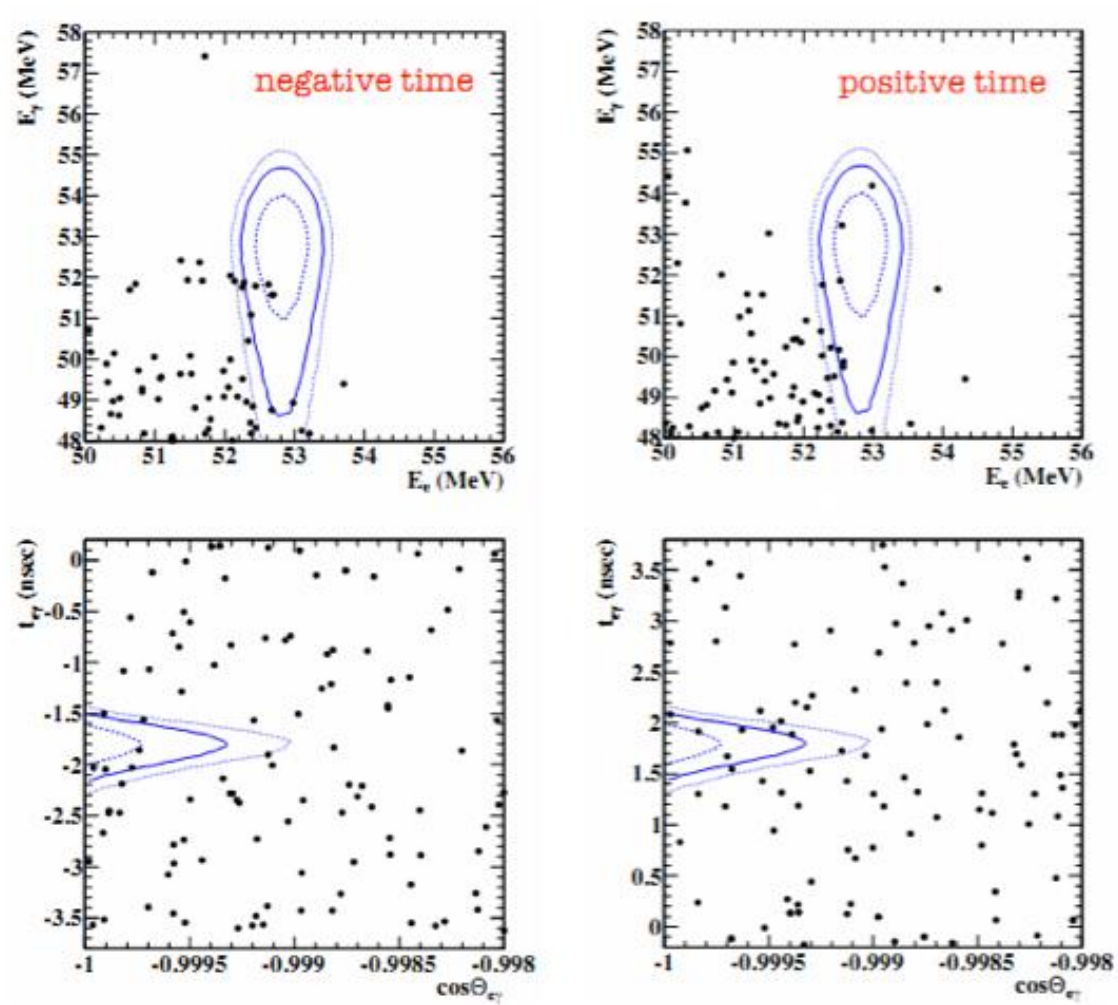
1, 1.64, 2 σ contours

Likelihood 2009

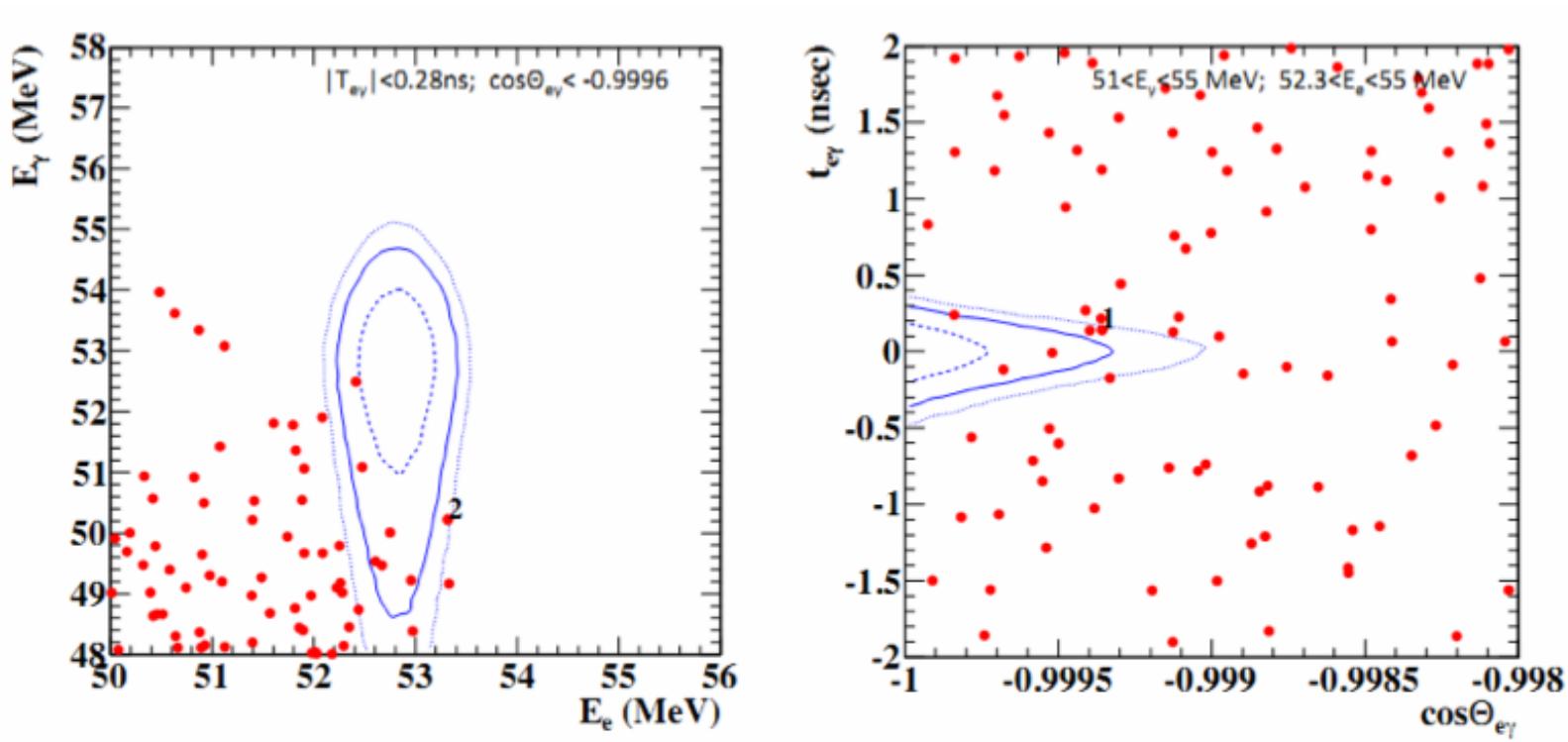


Nsig best value = 3.4

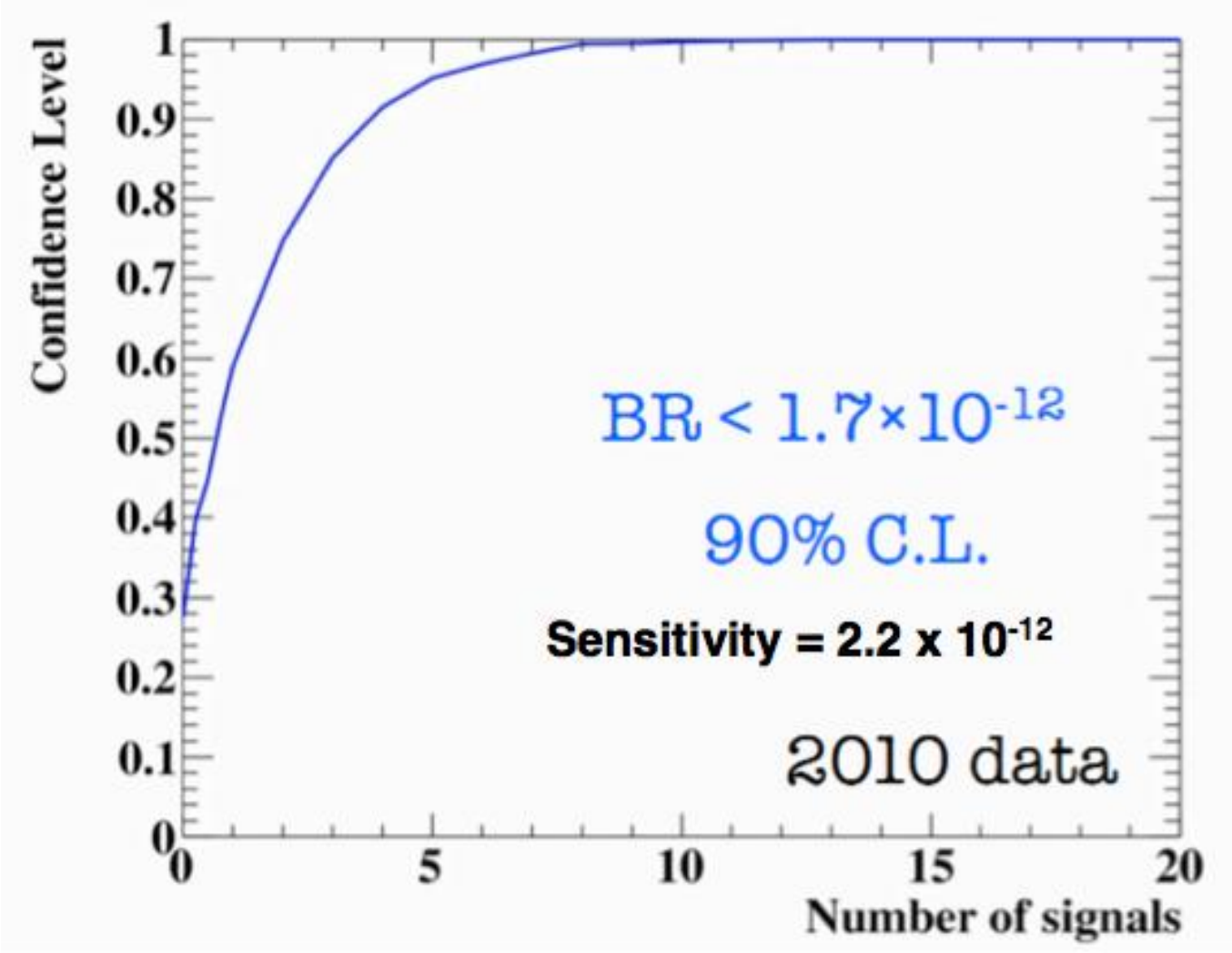
Data 2010, time sidebands



Data 2010, signal region



Fit 2010


Confidence Level
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
Number of signals
BR < 1.7×10-12
90% C.L.
Sensitivity = 2.2 x 10-12
2010 data

Combined fit

Data set	$\mathcal{B}_{\text{fit}}$	LL	UL
2009	3.2×10^{-12}	1.7×10^{-13}	$.96 \times 10^{-11}$
2010	-9.9×10^{-13}	–	1.7×10^{-12}
2009 + 2010	-1.5×10^{-13}	–	2.4×10^{-12} ← **MEG result**

Sensitivity = 1.6 x 10^{-12}

Systematic errors included (2% effect on UL)
Larger contributions from relatice angle offset, correlation in positron kinematical variables, normalization

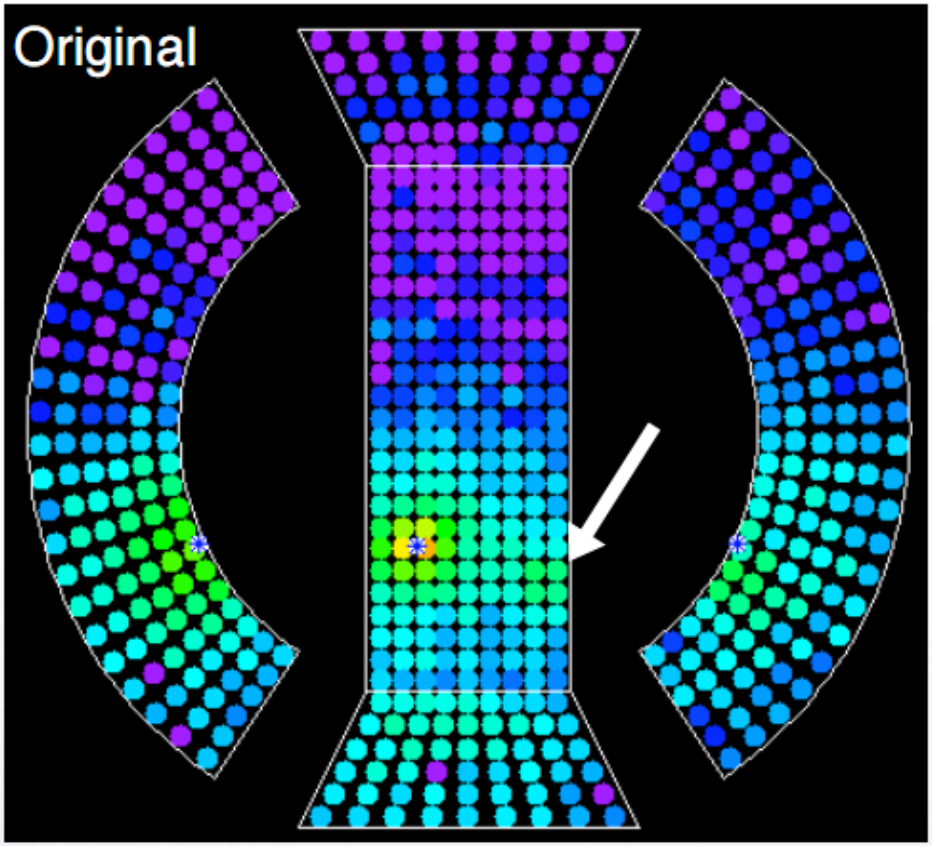
Conclusions

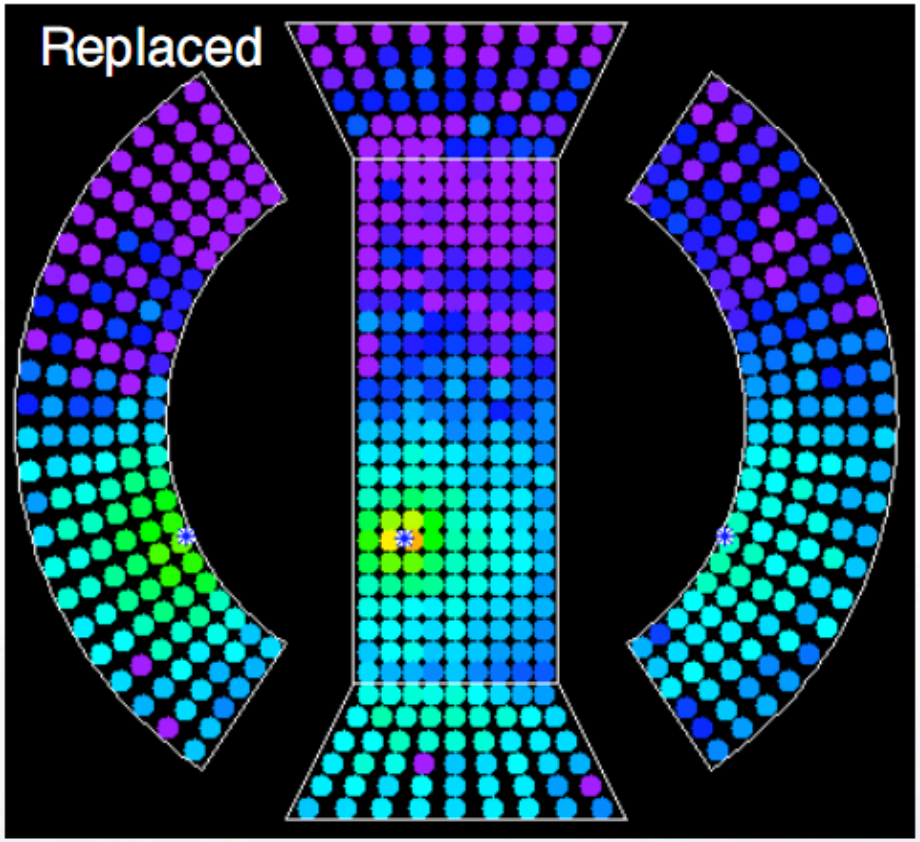
- Past
  - Data taken agree with no LFV hypothesis
  - MEGA limit improved by a factor 5
- Future
  - Sensitivity expected to achieve 5x10-13 with 2011 and 2012 data
  - Detector
  - other major improvements
    - new 2Gs digitizer (DRS4), linear in its dynamic range
    - possibility to reduce both DAQ and calibration deadtime
- need to run in stable condition until 2011 to reach the goal

Backup slides

Pile-up rejection

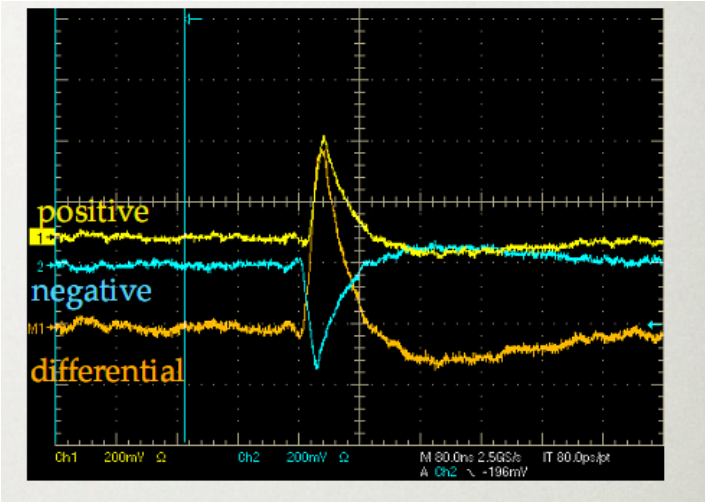
- reconstruction of the main cluster
- replacement of Npe for pile-up cluster with expected values

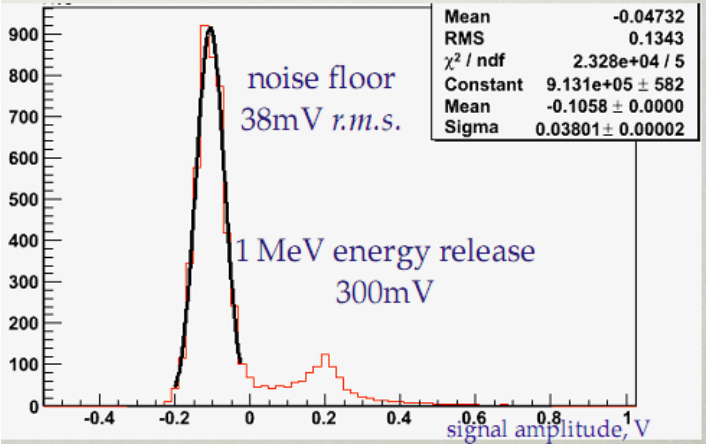




TC status

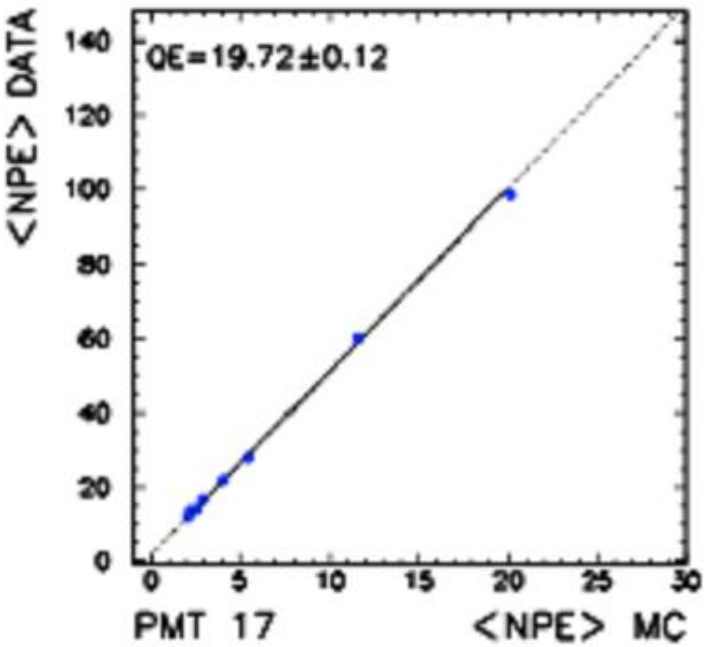
- New fast electronics for the shaping of fiber-coupled APDs
  - Stereo reconstruction of TC hit point
  - useful at both trigger and off-line stage
- Implementation of a Nd-laser
  - precise tool for LXe-TC timing

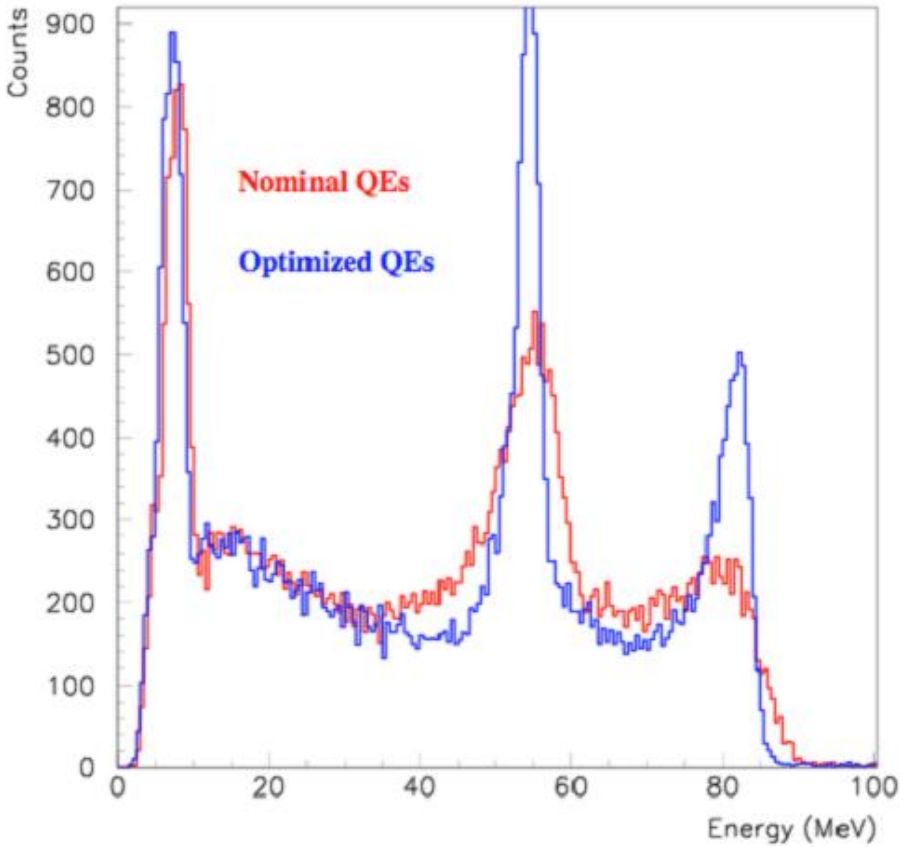




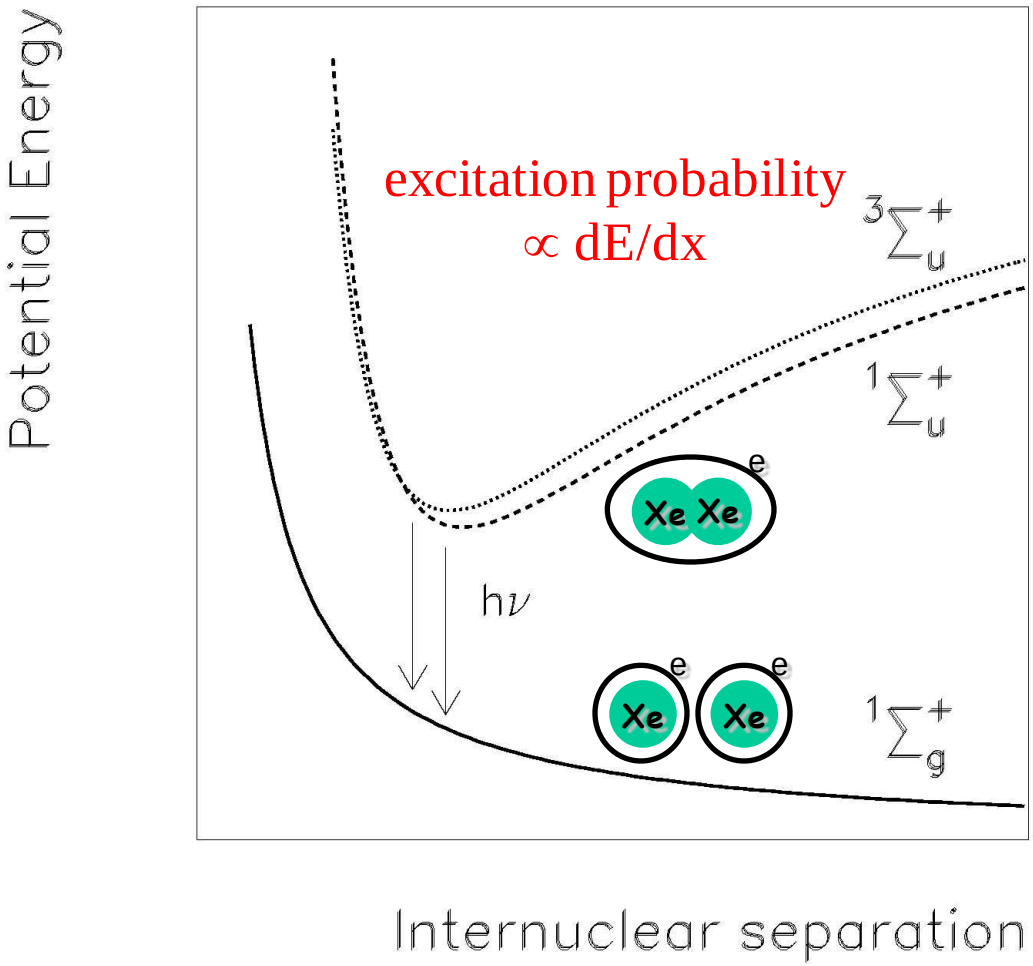
QE measurement

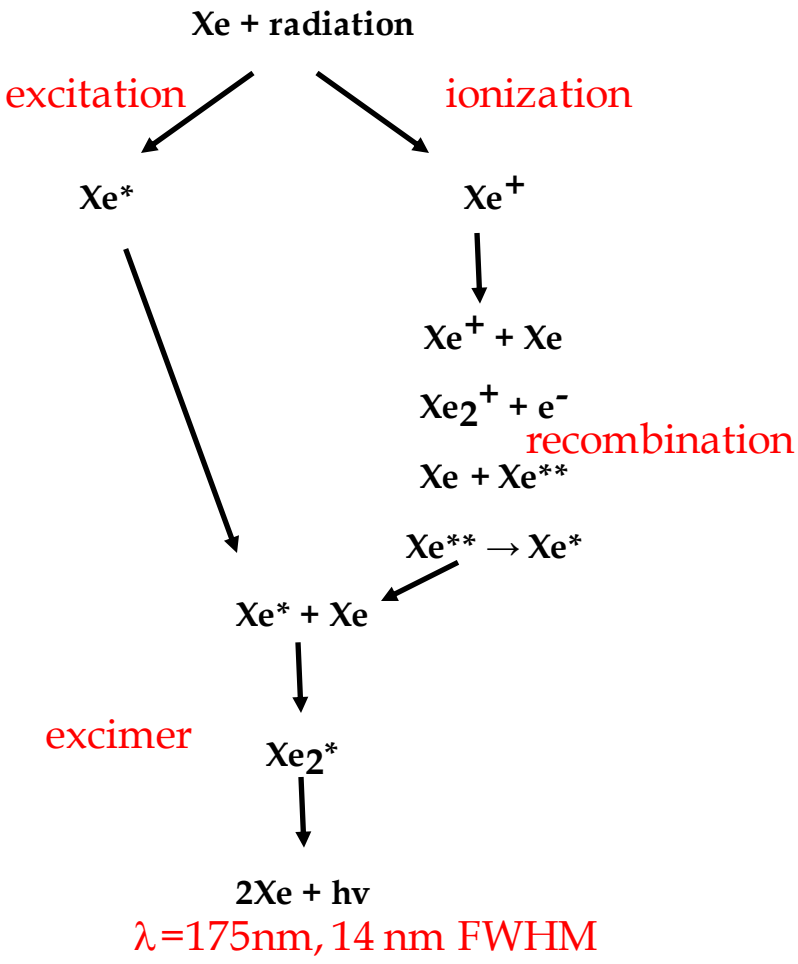
Obtained by comparison of measured vs. expected number of photoelectrons from each α-source





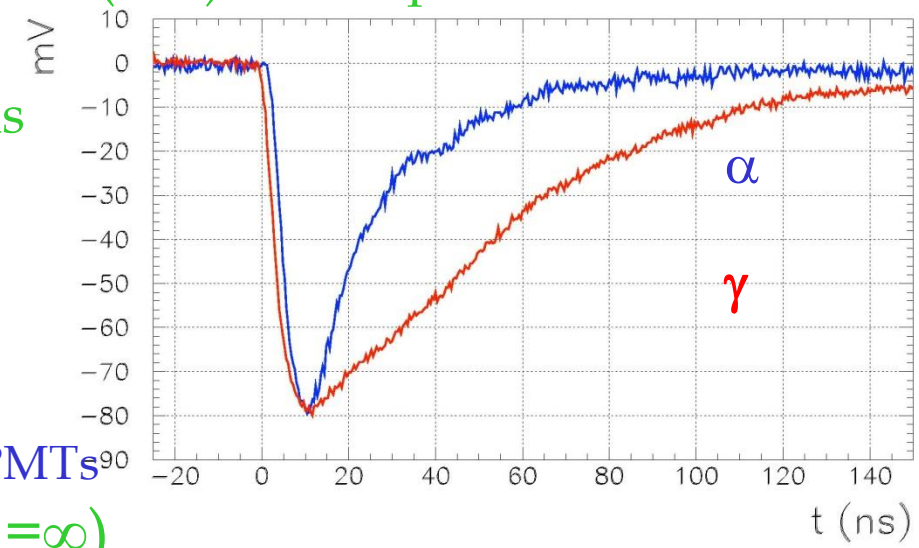
Scintillation mechanism





Features

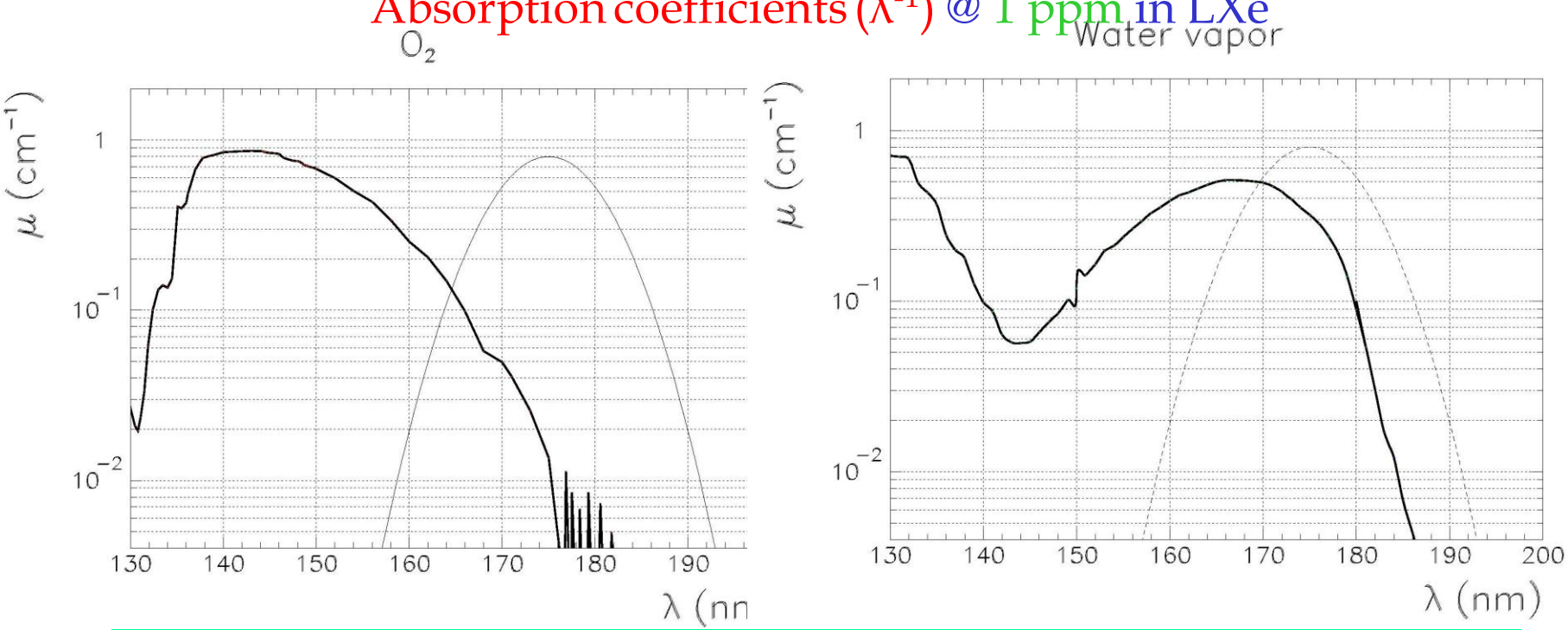
- Compact
  - $Z=54$, $\rho=2.95\ g/cm^3$ ($X_0=2.7$ cm), $R_M=4.1$ cm @ T=165 K
- High light yield
  - LY=42000 phe/MeV ≈ 0.7 LY(NaI) for m.i.p.'s
- Fast
  - $\tau_1=4ns$, $\tau_3=22ns$, $\tau_{rec}=45ns$
- Particle ID
  - $\tau_\gamma \approx 2\ \tau_\alpha$
  - $LY_\alpha = 1.2 \times LY_{mip}$
- n = 1.65 ($\approx n_{quartz}$)
  - ➔ good optical coupling with PMTs
- No self-absorption ($\lambda_{Abs}=\infty$)
  - ➔ position-independent energy response
  - ➔ homogeneous calorimeter



Light absorption

- Due to the presence of contaminants
  (mainly oxygen and water moisture in the VUV region)
- measurements of optical properties available in the literature
  often contradictory

Absorption coefficients (λ^{-1}) @ 1 ppm in LXe



Additional quenching factors

- Ionization quenching

  e-capture by electro-negative impurities (namely O_2)

  (WARP collaboration, submitted to NIM A, and references therein)

- Non-radiative collitional reactions

  $\mathbf{Xe_2^* + N_2 \rightarrow 2\,Xe + N_2}$

  $1/t'_j = 1/\tau_j + k[N_2]$ (shorter decay-time)

  $A'_j = A_j/(1 + \tau_j k[N_2])$ (lower light intensity)

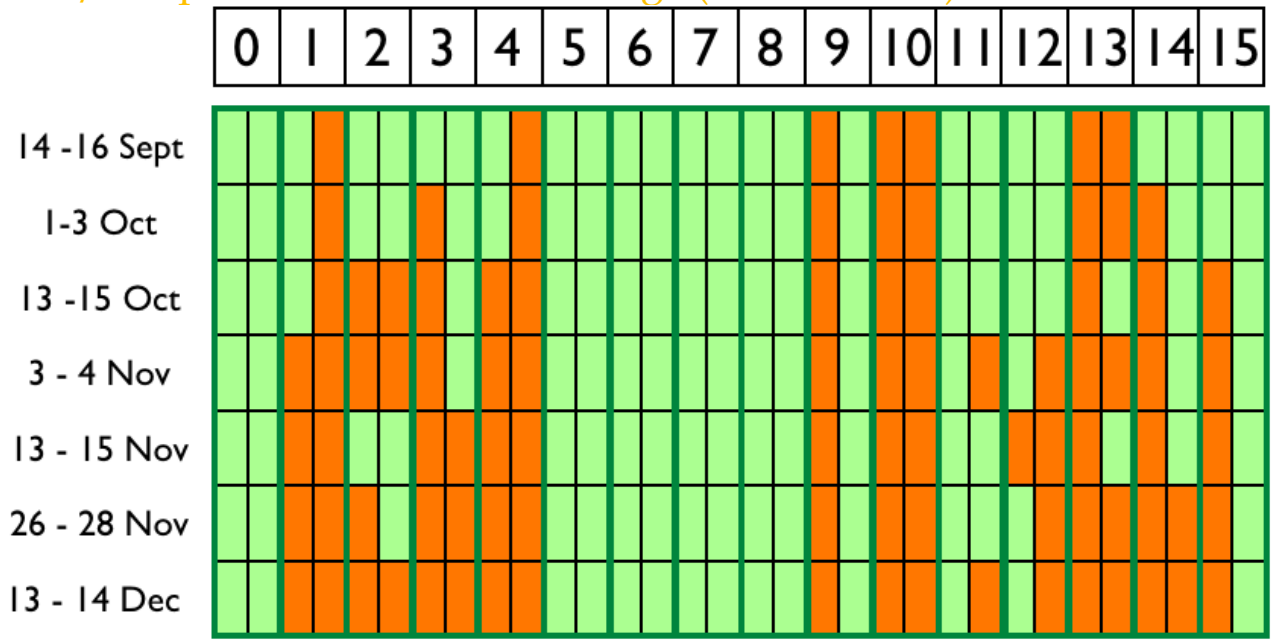
  used in LAr to shorten the long decay-time component

  (WARP collaboration, arXiv:0804.1217v1 [nucl-ex])

  In both cases, quenching of scintillation light is expected,
  More significant in the case of lightly ionizing particles

DC operation in Run 2008

- operated in He+ethane 50%/50% mixture and immersed in He-atm
- at turn-on (July 08) the system was fine 30/32 planes OK (@1850 V)
- HV deterioration observed during the Run; at the end
  - 11/32 planes OK (@1850 V)
  - 7/32 planes off-nominal voltage (1700÷1800 V)

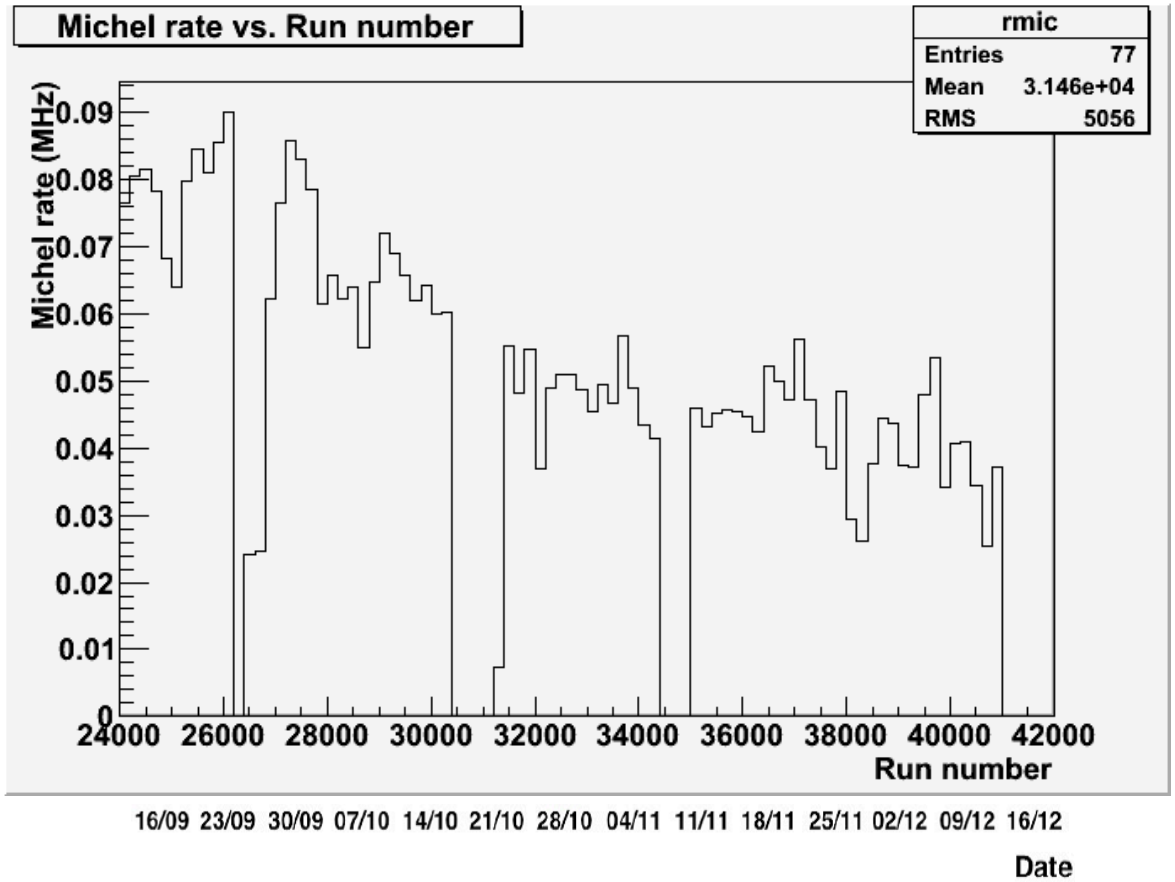


RUN
24000
27000
29000
33000
35000
37500
40000

- body of evidence for He-diffusion inside the HV distribution frame

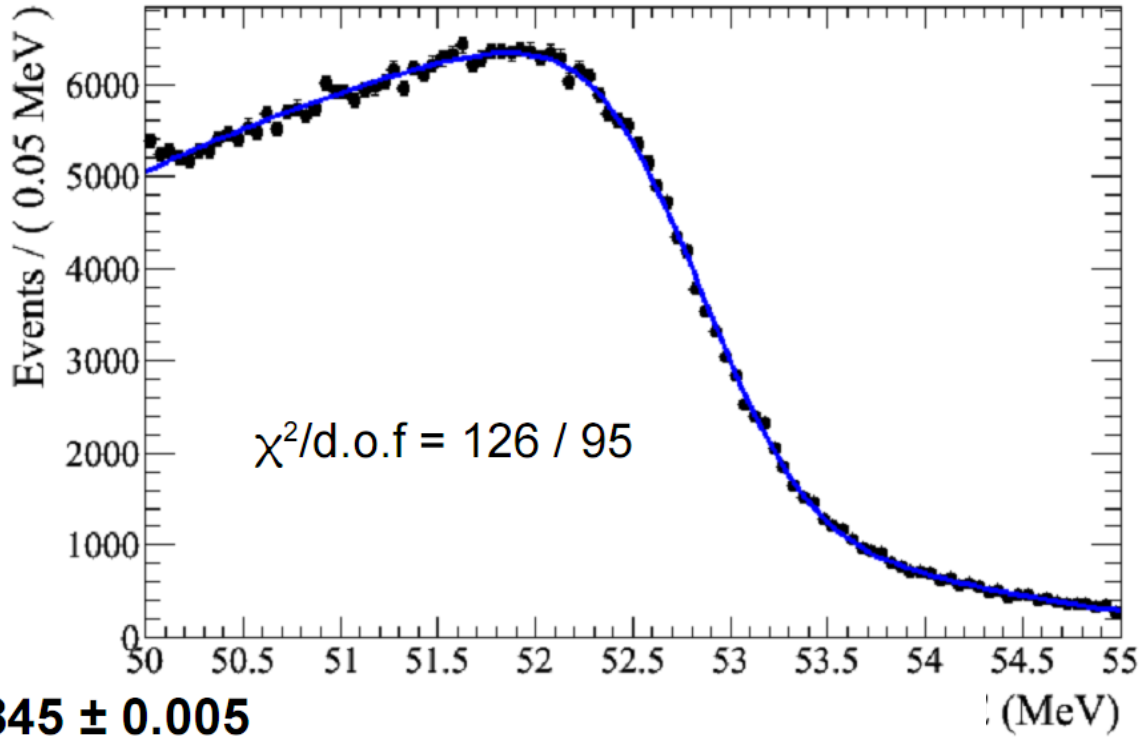
DC performance

The rate of events with a reconstructed track decreases with the Run going on ➔ absolute e+-efficiency getting lower and lower



e^+-momentum resolution

obtained from a fit of the edge of Michel spectrum
(with a slight dependence on the emission angle)



f_{core} = 0.845 ± 0.005

μ_{core} = 0 (fixed)

σ_{core} = 0.431 ± 0.007 MeV

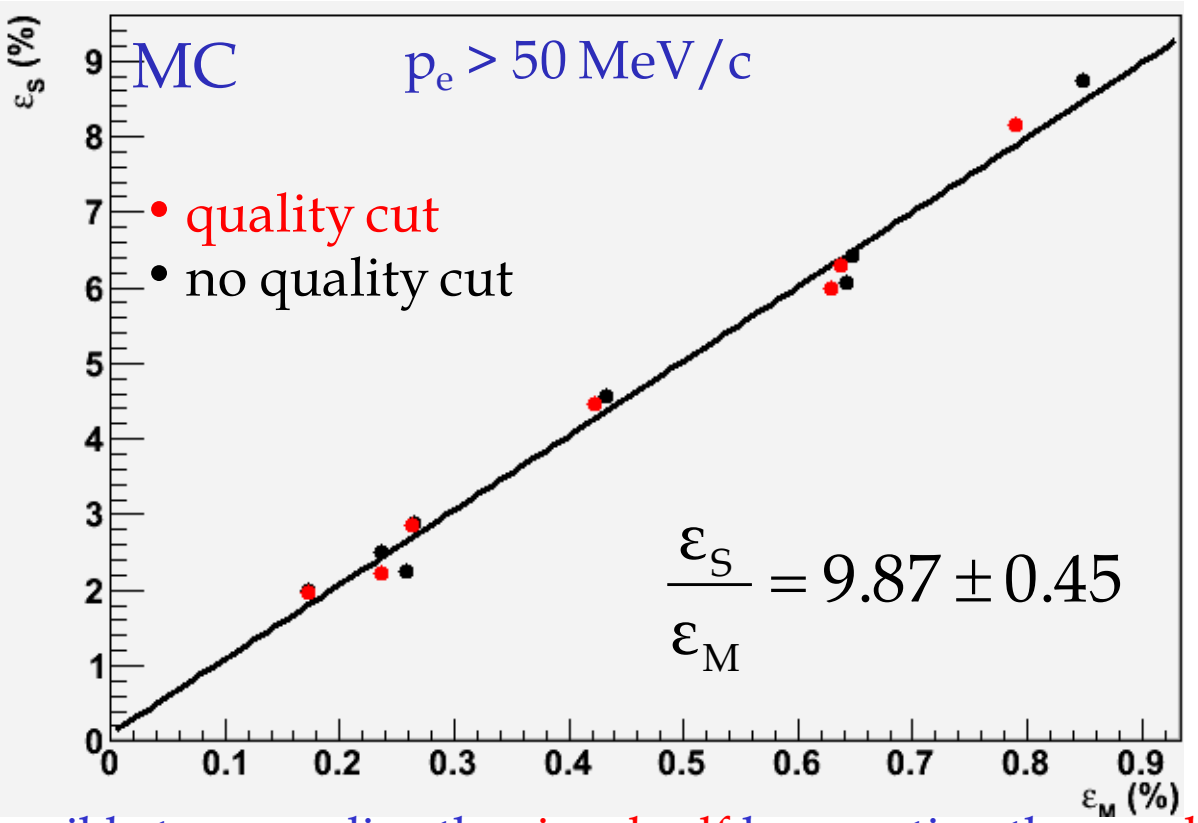
μ_{tail} = -0.51 ± 0.05 MeV

σ_{tail} = 1.89 ± 0.06 MeV

twice worse than expected

DC relative efficiency

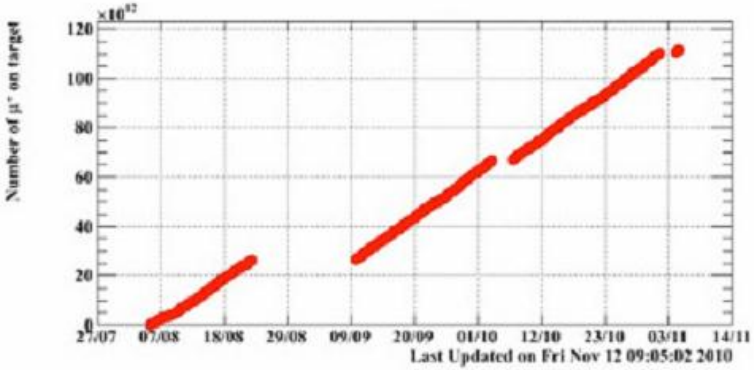
- Relative efficiency (i.e. fraction of signal/Michel events) is almost constant during the run (in spite of DC deterioration)
- average ratio agrees with the expected fraction of e^+ with p>50 MeV



➔ it is possible to normalize the signal pdf by counting the number of Michel

Il Run 2010

Summary of Run 2010



- Aug-Oct, 2009 (DAQ time: **56 days**)
- μ-stop rate: **2.9×10^{7} s^{-1}**
- Total μ-stop in target: **1.1×10^{14}**

- Optimized μ-stop distribution in target
- Improved electronics timing accuracy (DRS4)
- Smooth and efficient DAQ had to be stopped on Nov. 5th due to the problem of the BTS.
  - Resultant data statistics: **×1.9 higher** w.r.t. run 2009
  - Normalization factor: ***k* = 2.1×10^{12} (preliminary)**
- Calibration and optimization of the analysis are still in progress.

Delayed start: DCHs construction, MEG target accidentally broken
Premature end: BTS solenoid magnet problem on beginning of november

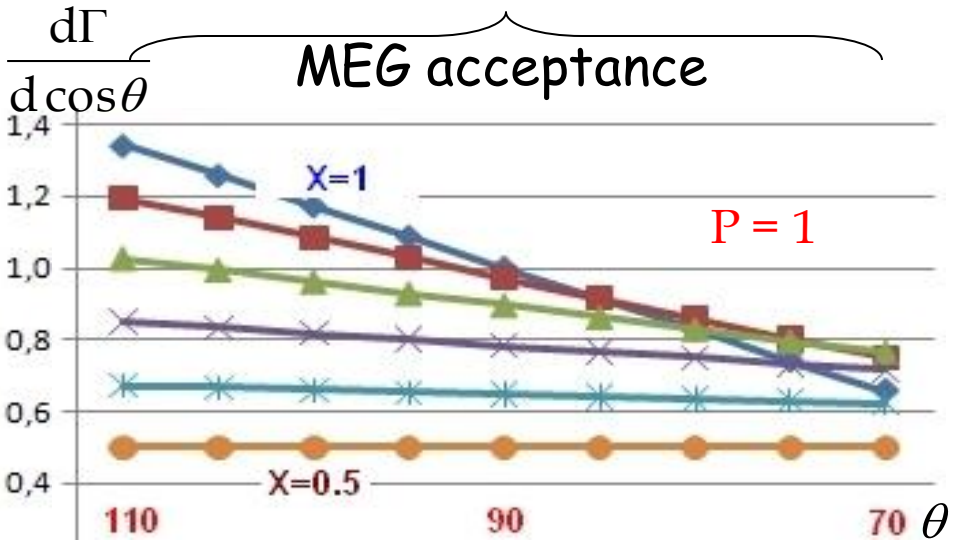
Polarizzazione dei muoni

- Fascio costituito da "surface muons" ➔ P = 1
- Possibili effetti di depolarizzazione
  - contaminazione da "cluod muons"
    (i.e. muoni da decadimenti di pioni non a riposo) ➔ $\Delta P = 4\%$
  - rotazione di spin ➔ $\Delta P < 0.7\%$
  - multiplo scattering nel bersaglio ➔ $\Delta P < 0.3\%$
  - divergenza del fascio ➔ $\Delta P = 4\%$

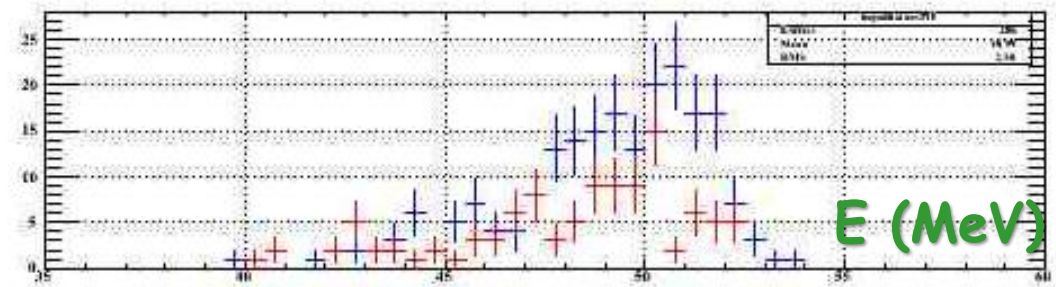
➔ $\langle P_z \rangle = 0.92 \pm 0.03$

- Misura della polarizzazione
  - distribuzione angolare
    dei decadimenti di Michel

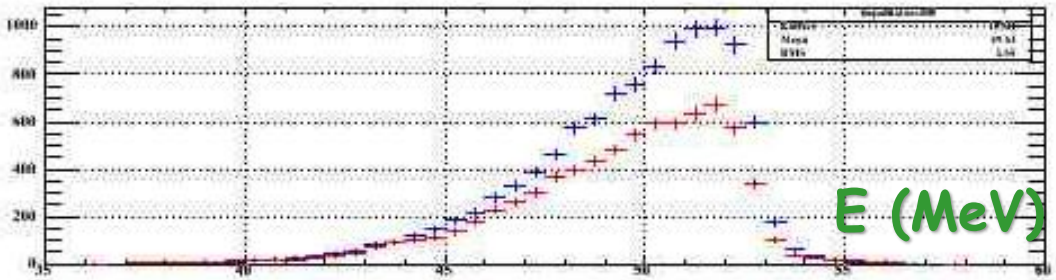
    (tanto più asimmetrica
    all'end-point)



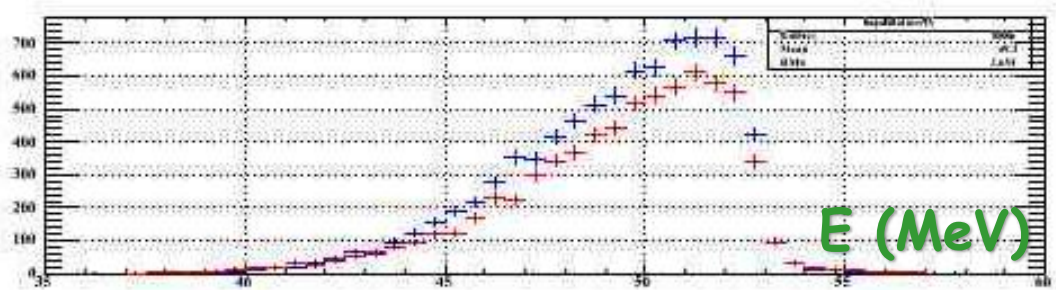
Dati 2009



$$\left.\begin{array}{l}\vartheta_1 = 20\\ \vartheta_2 = 30\end{array}\right\}$$



$$\left.\begin{array}{l}\vartheta_1 = 10\\ \vartheta_2 = 20\end{array}\right\}$$



$$\left.\begin{array}{l}\vartheta_1 = 0\\ \vartheta_2 = 10\end{array}\right\}$$

Blue: US

Red: DS

US

$$\int_{90+\vartheta_1}^{90+\vartheta_2} \frac{dN}{dEd\cos\vartheta} d\cos\vartheta$$

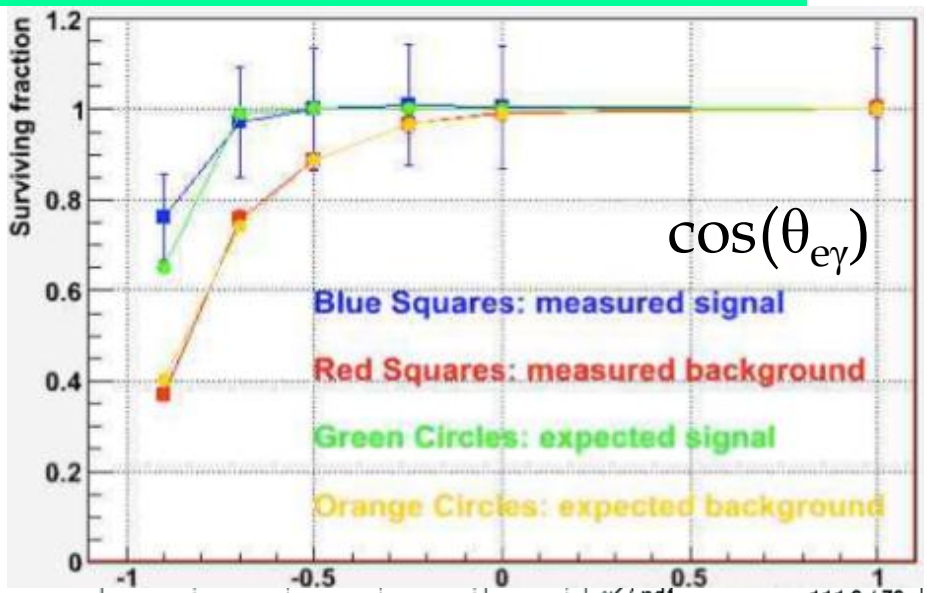
DS

$$\int_{90-\vartheta_2}^{90-\vartheta_1} \frac{dN}{dEd\cos\vartheta} d\cos\vartheta$$

< P > = 0.89 ± 0.04
(only statistical error)

Radiative decays

- The number of observed events is compatible with estimated efficiencies
- also the angular distribution agrees with expectations

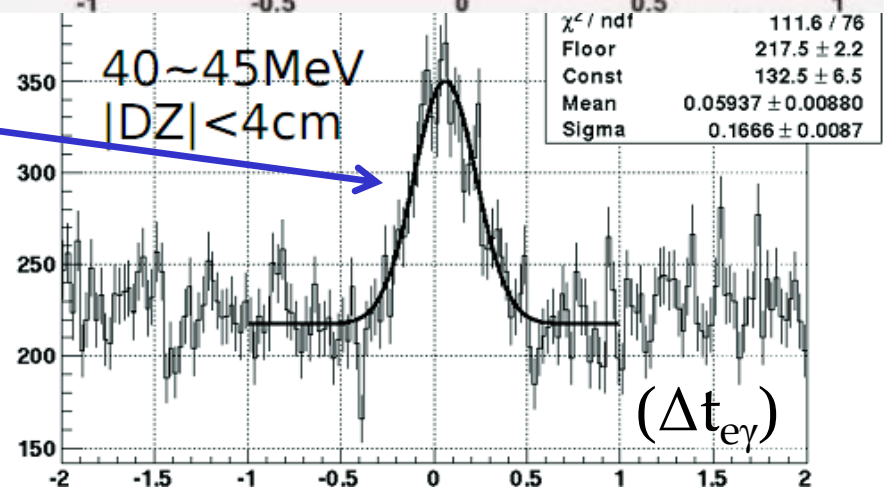


- also seen in normal data (with kinematical cuts applied)

  $\sigma(\Delta t_{e\gamma})$ = (159±9) ps

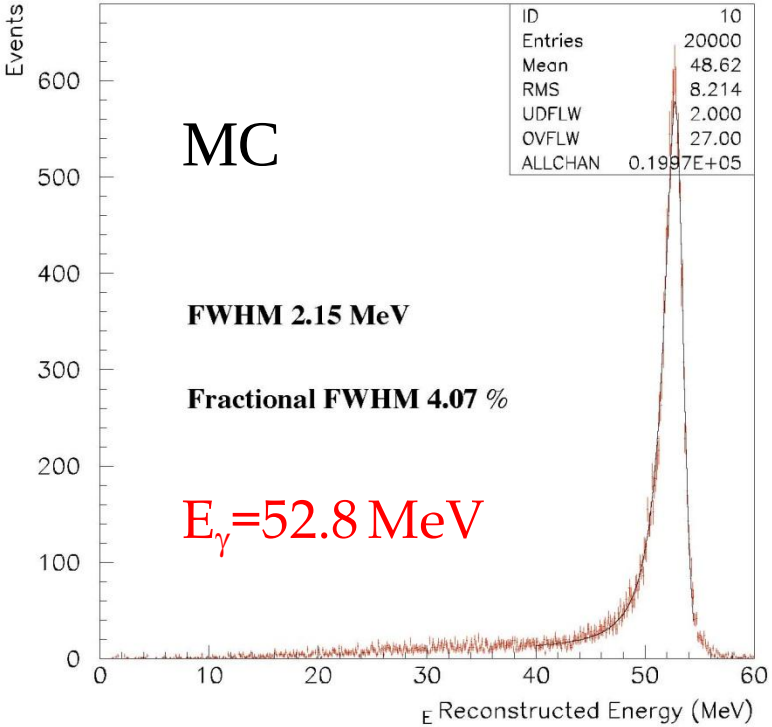
  (extrapolated to 143 ps @52.8 MeV)
- contribution from tracking

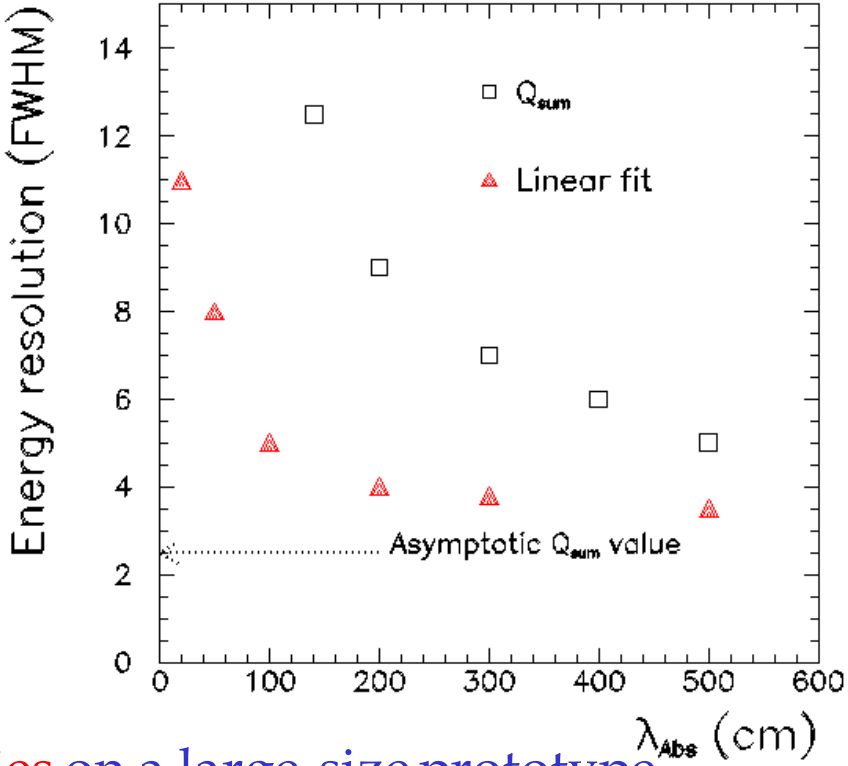
  ➔ e^+ time-of-flight uncertainty



σ_E vs λ_{abs}

- Absorption ⇒ R(E) position-dependent
- Energy resolution dominated by shower-fluctuations





➔ need to verify optical properties on a large-size prototype

The “Large Prototype”

Design

- 40 x 40 x 50 cm^3, 100 l LXe

(same depth, 1/10 of the final volume)

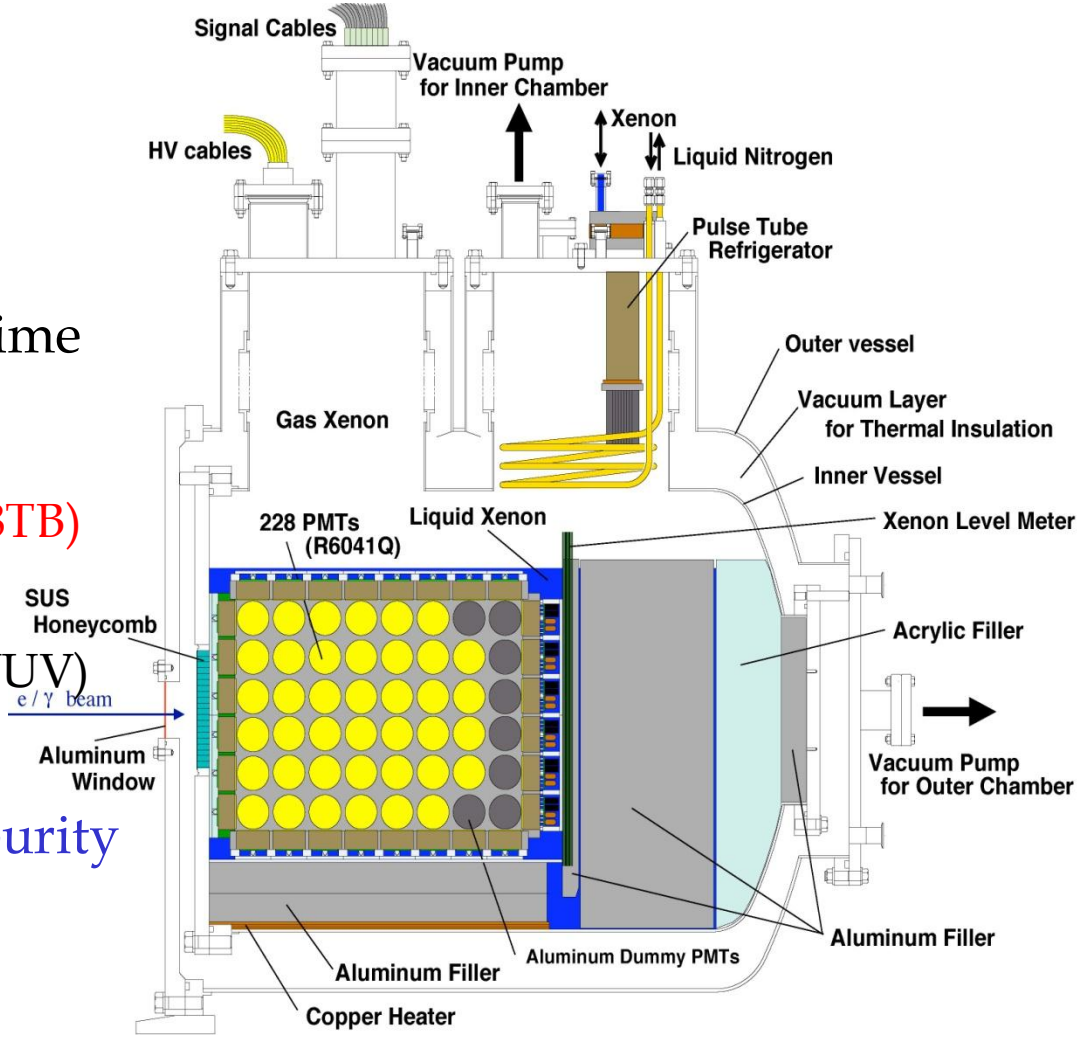
the world-wide largest at that time

- Equipped with 240 PMTs

  (HAMAMATSU R6041+R9288TB)

  - K-Cs-Sb photocathode
  - Quartz window (suited for VUV)

- Gas purification system (getter+Oxysorb) to keep impurity content < 1ppb

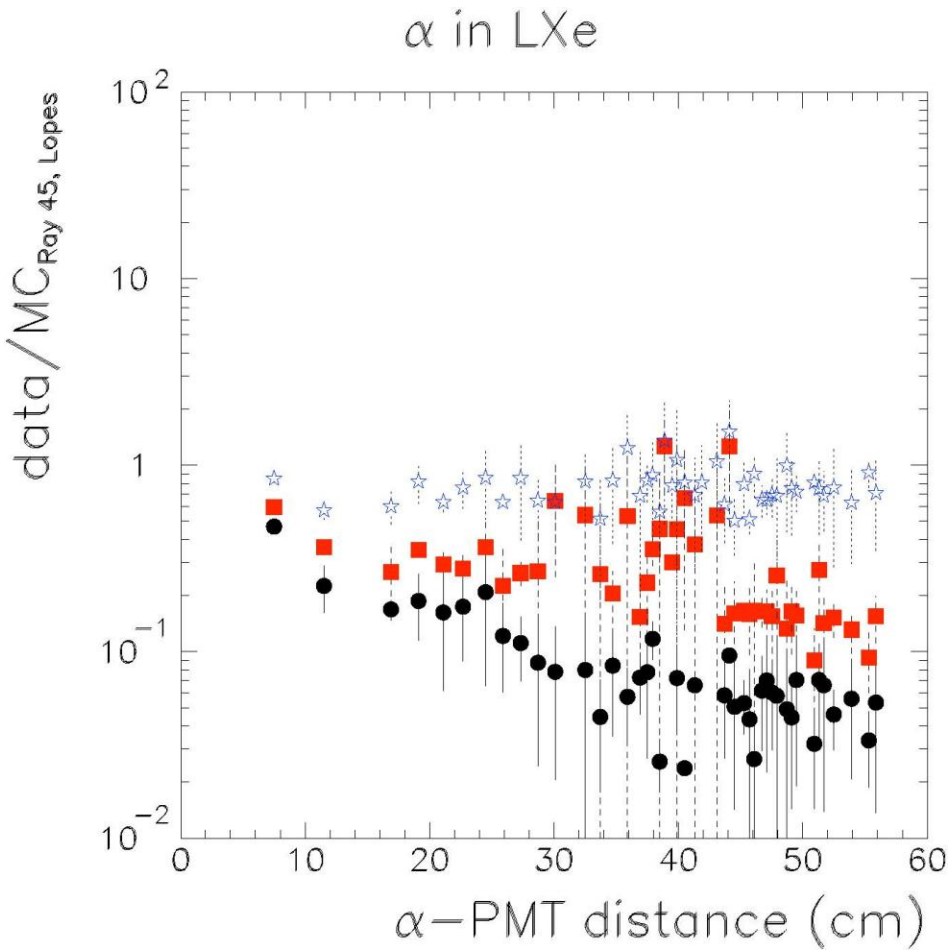


Absorption measurement

- Use of α-sources

  N_{phe} vs distance
- Increase of both light yield and absorption length observed during the purification cycle

➔ removal of water



λ_{abs} > 125 cm (68% CL) o λ_{abs} > 95 cm (95 % CL)

σ_E @ signal window

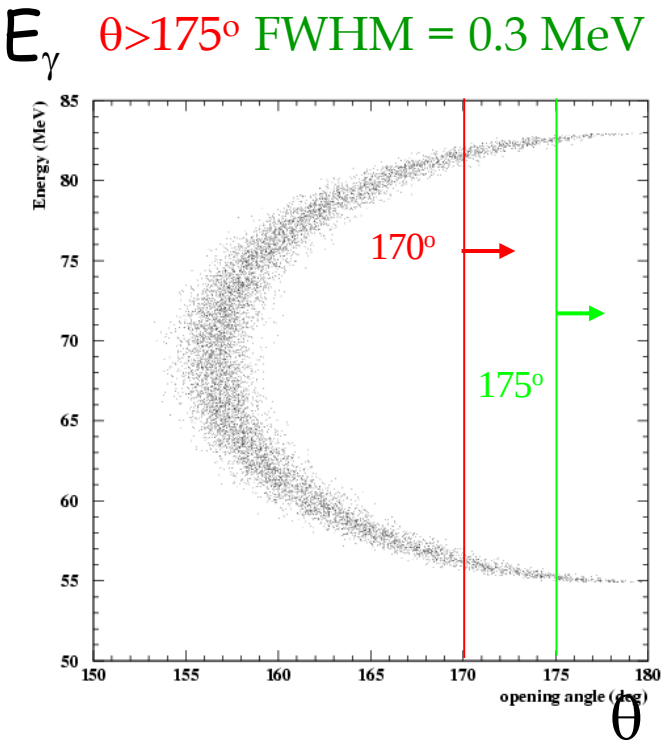
$\pi^- p \rightarrow \pi^0 n$,

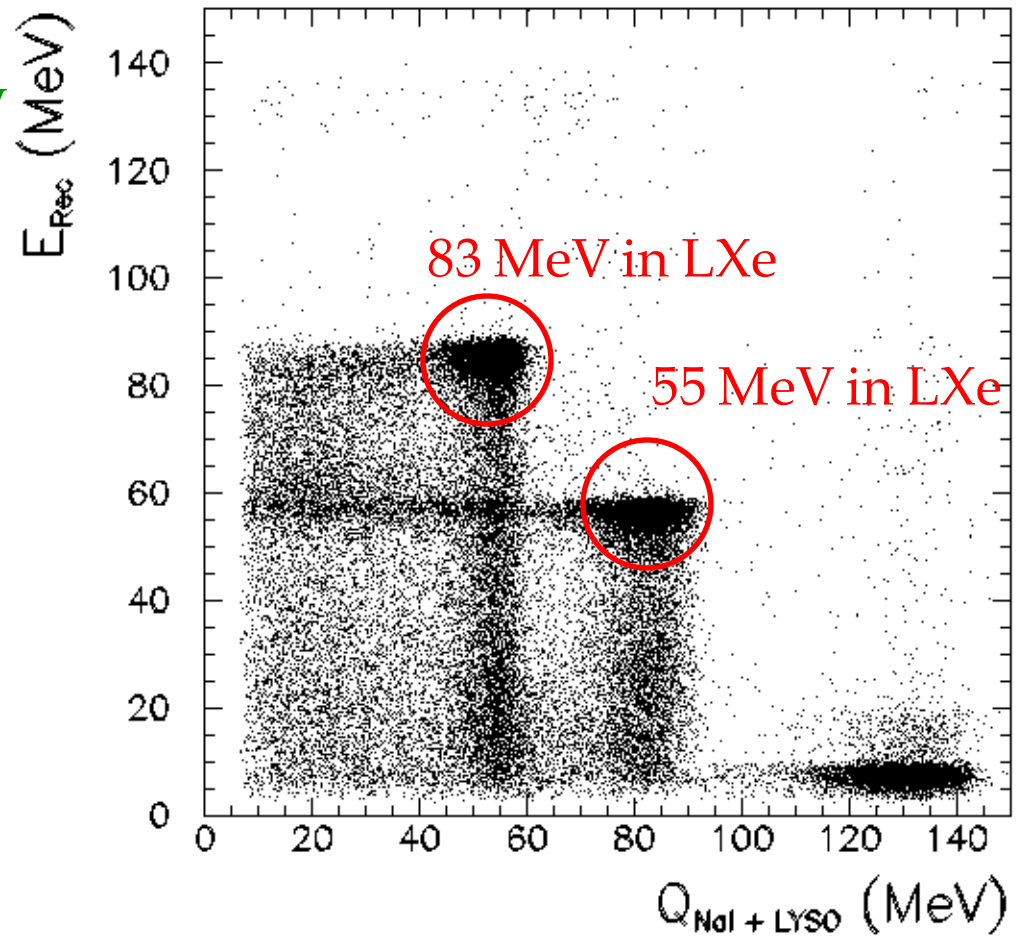
$\pi^0 \rightarrow \gamma\gamma$

54.9 MeV < E(γ) < 82.9 MeV

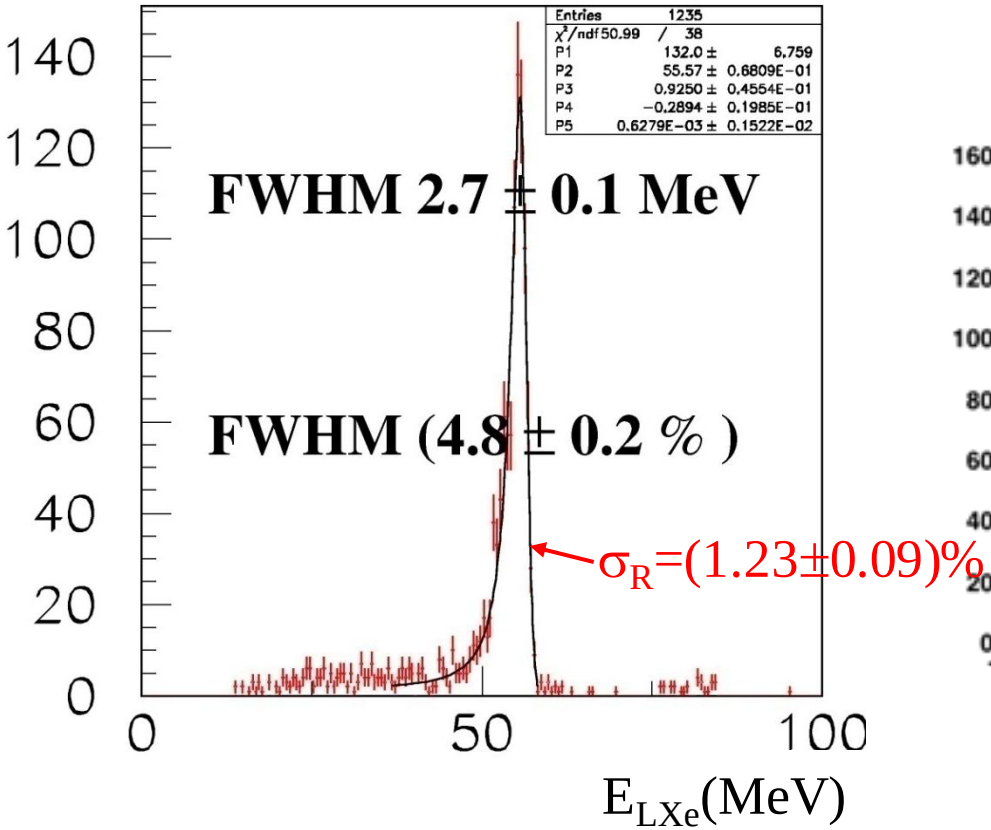
θ>170° FWHM = 1.3 MeV

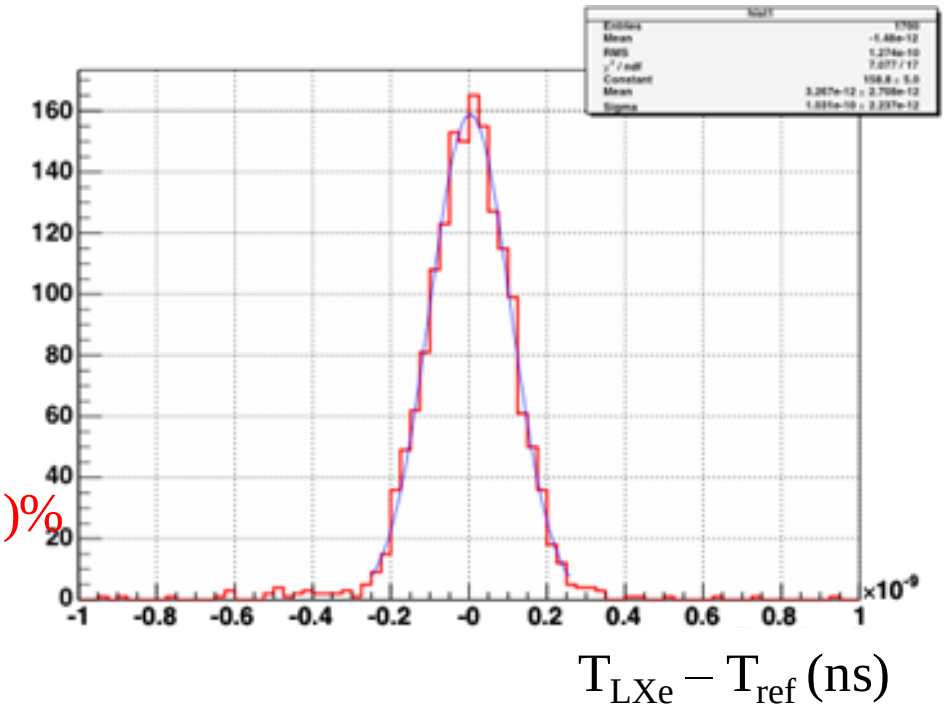
θ>175° FWHM = 0.3 MeV





Performances





$\sigma(E_\gamma)/E_\gamma = 4.8\%$

$\sigma(T_\gamma) = 125$ ps

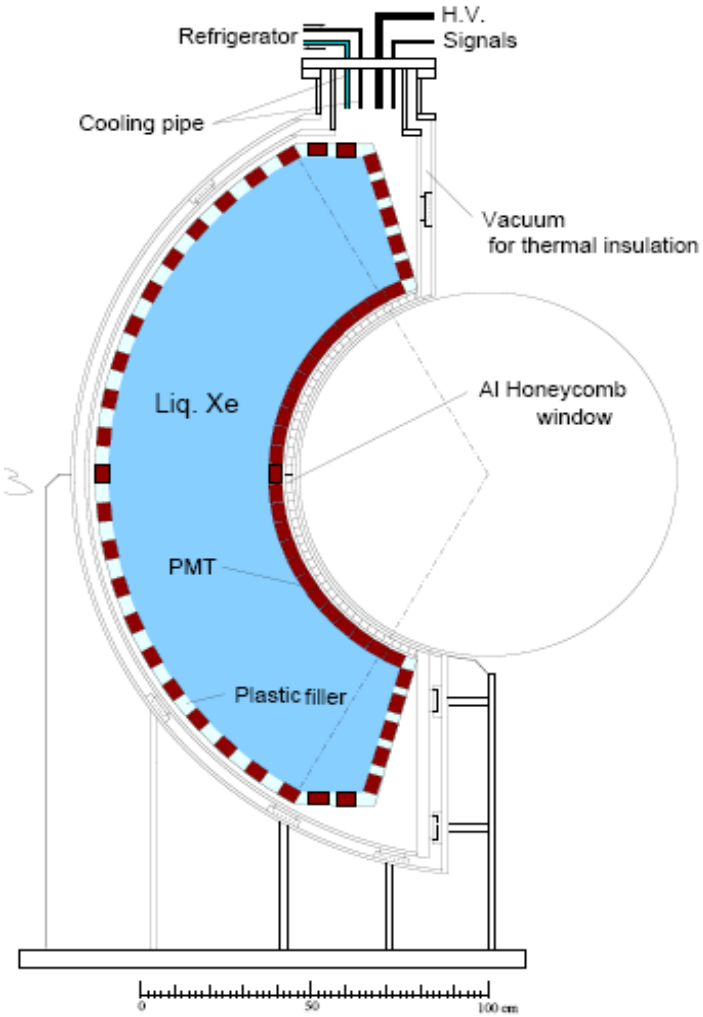
unprecedented at these energies!

The final detector

Conceptual view

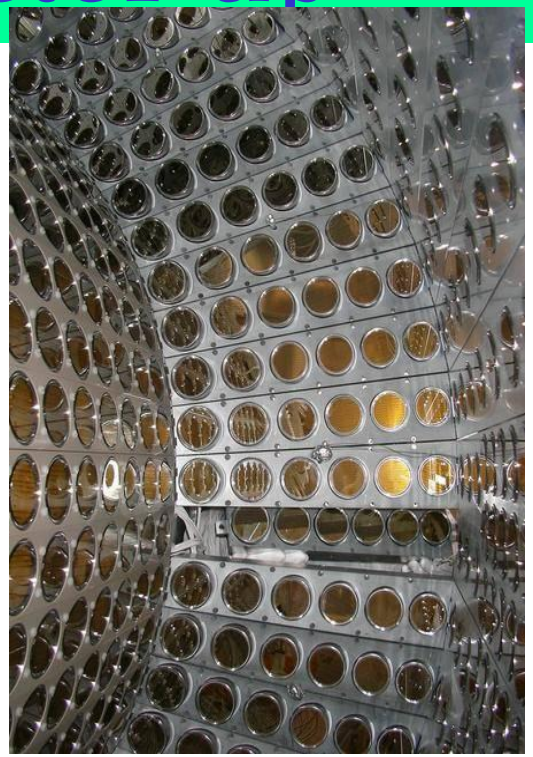
- 4π, single-vessel detector consisting in
  - 800 l LXe
  - viewed by 848 PMTs
  - C-shaped, $\Omega/4\pi = 9\%$
  - located out of the spectrometer field (B < 100 G)
  - 19 X_0 depth (containment > 99%)
  - 0.4 X_0 front material

(see R.Valle's talk for further details on the overall detector)

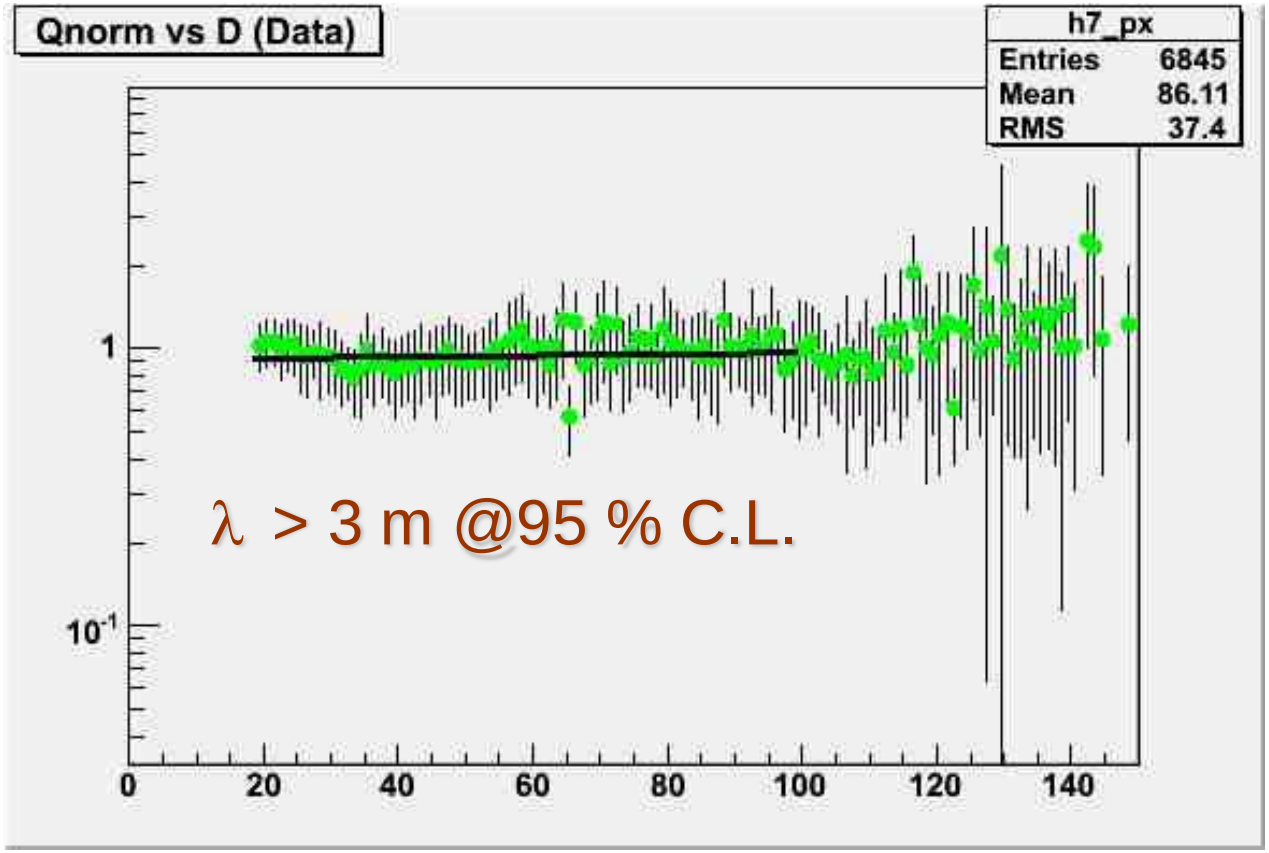


Setting the detector up

- Detector instrumentation
  - completed in Aug 2007
  - all PMTs mounted
  - sources
    - α-wires
    - LEDs
    - Laser fibers
  - sensors
    - PT100 temperature sensors
    - Surface level meter
- LXe transfer
  - completed by 20 September
  - 15 days needed (10 l/h speed)
- Purification system
  - Liquid-phase circulation
  - dedicated pump, 70 l/h
  - molecular sieves (>25 g water absorption)



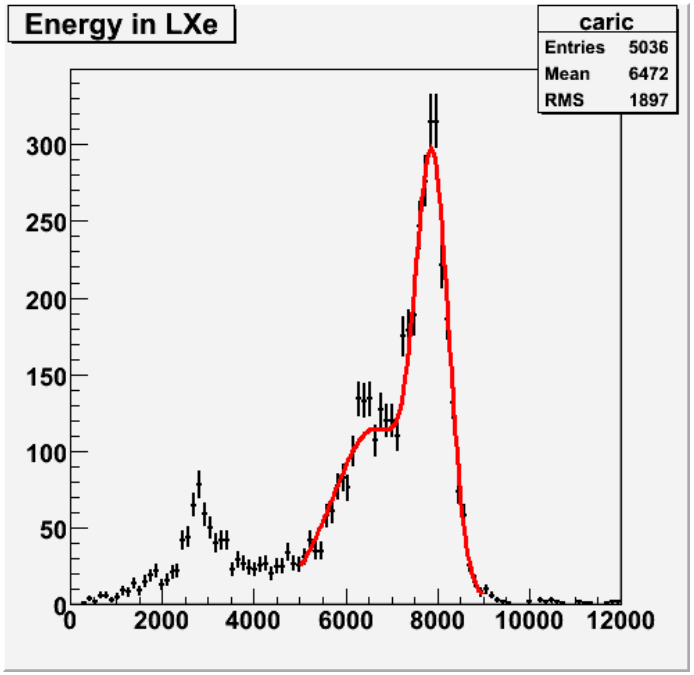
Absorption Length

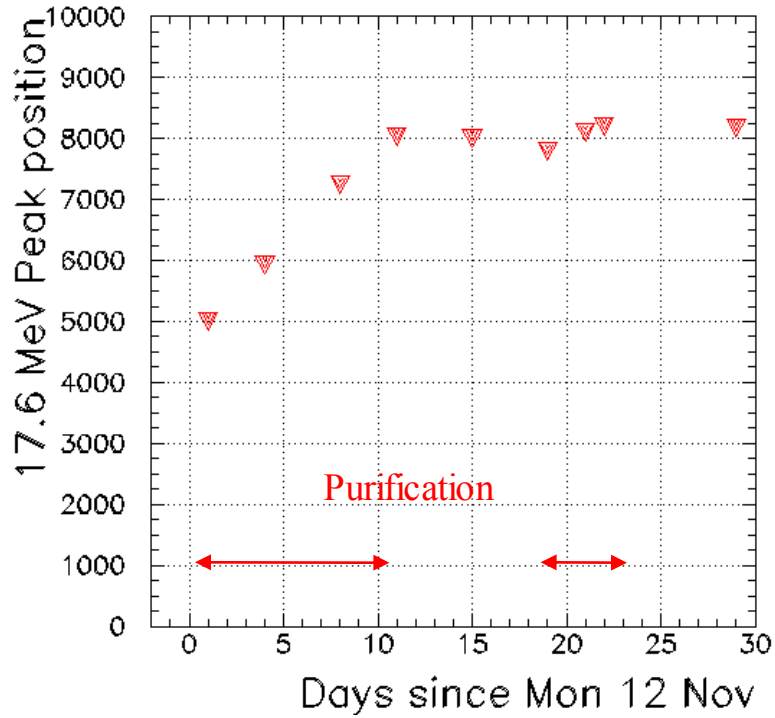


- Data/MC ratio vs distance fitted with an exponential curve
- Slope compatible with no absorption
- Obtained on 25 Nov (after 180h purification)

Li(p,γ)Be reaction

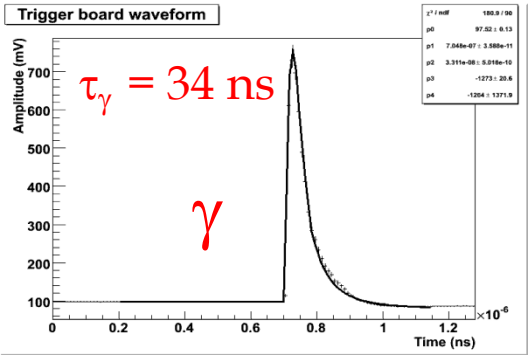
- 1-morning data taking twice a week with a LiF target
- Clear 17.6 MeV peak on the 14.8 MeV broad resonance
- Improvement of light yield
- Consistent with absorption length measurement with α-sources

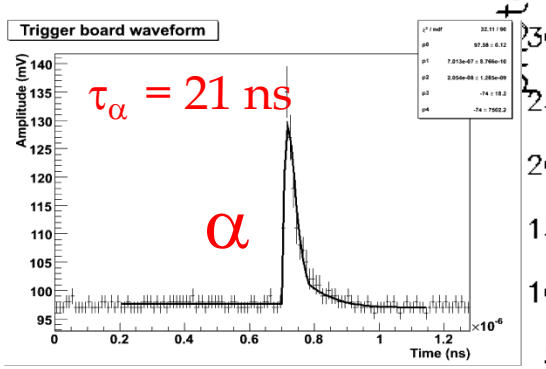


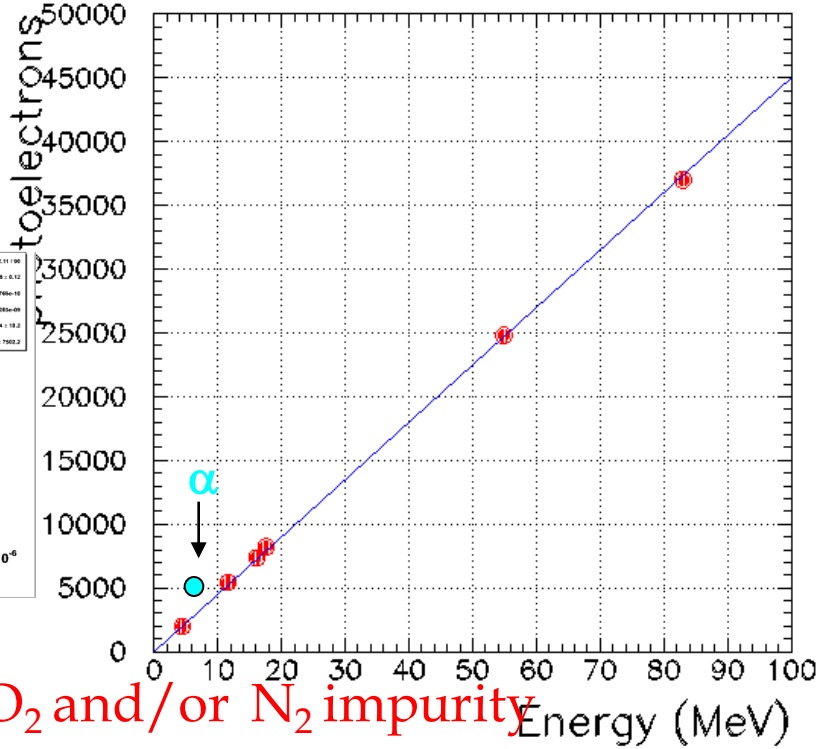


Troubles in 2007 run

- Light yield
  - smaller than expected (~ ½) in the case of γ-events
  - in agreement with expectations in the case of α-events
- Scintillation decay time
  - shorter in the case of γ-events
  - OK in the case of α-events



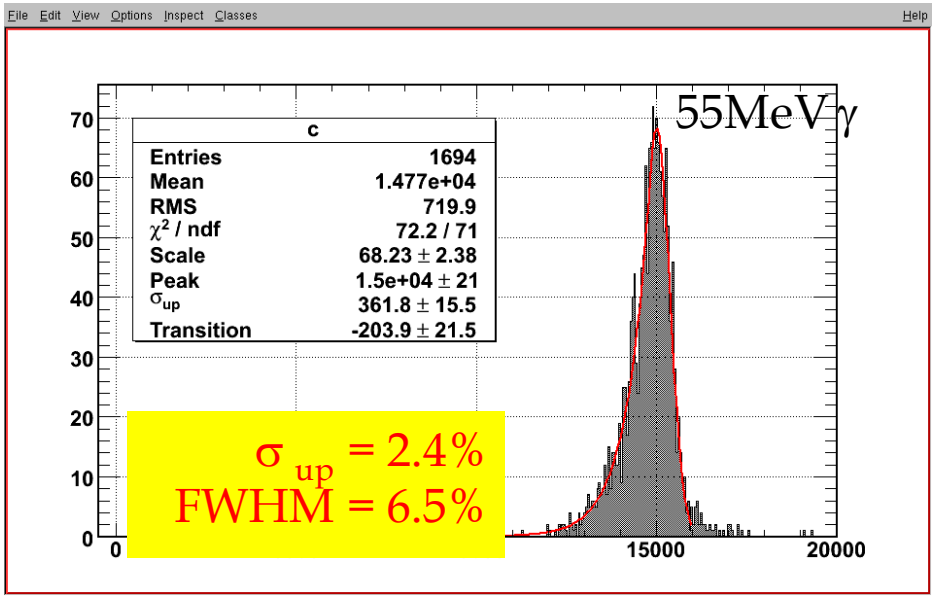


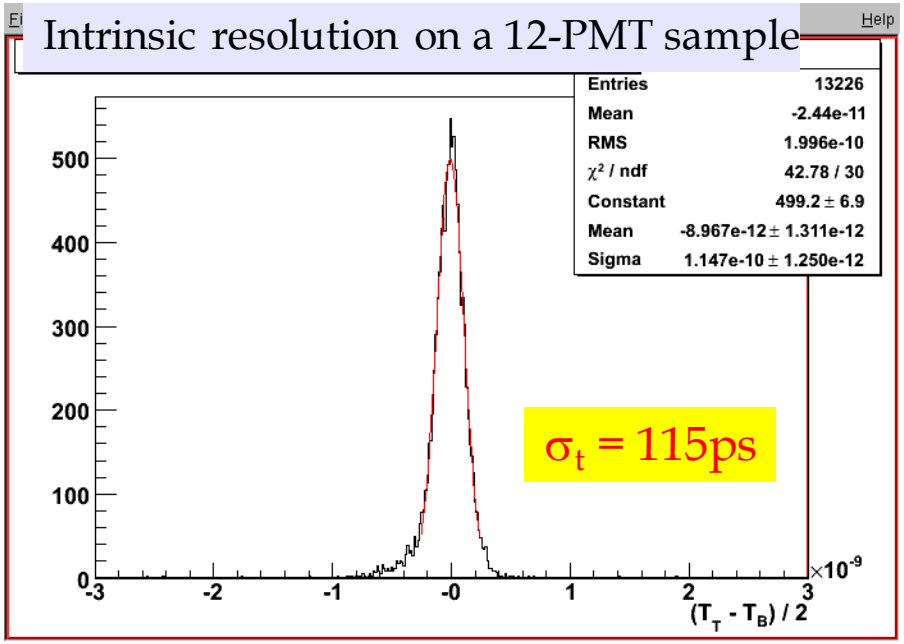


➔ possible contamination from O_2 and/or N_2 impurity

Performances in 2007 Run

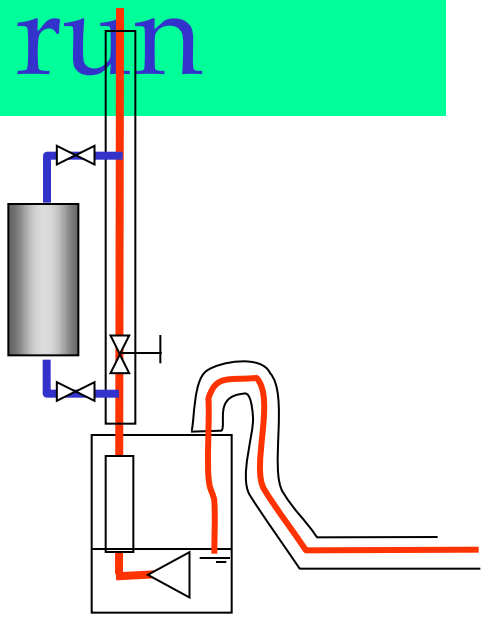
- From π^0-decay events

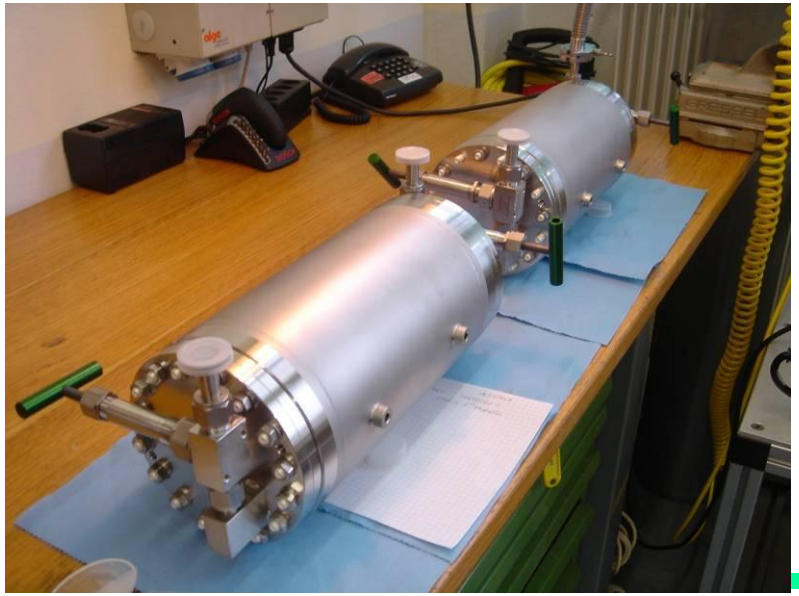


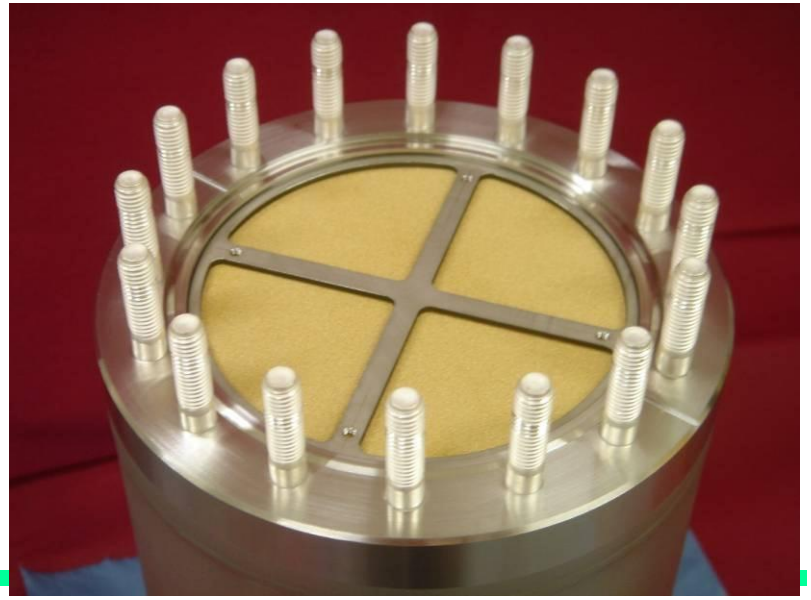


Solutions for 2008 run

- Impurity removal
  - use of a O_2-getter cartridge
  - developed for LAr use at CERN
  - mounted at the outlet of the liquid-phase purifier with by-pass valves
  - (in parallel) restoring of gas-phase circulation through a Zr-getter
- Avoid to use inner Nitrogen cooling pipe







Perspectives for 2008 run

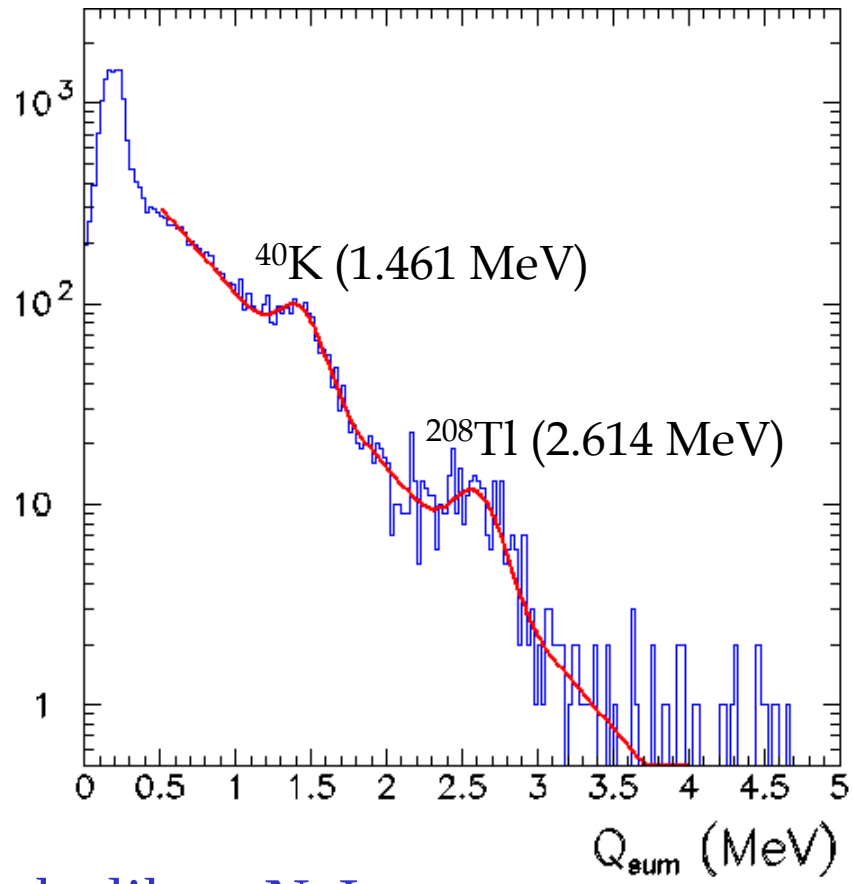
	"Goal" Measured	"Goal" Simulation	2007 Measured	2008 Prospects
Gamma Energy (%)	4.5-5.0		6.5	5.0
Gamma Timing (nsec)	0.15		0.27*	0.15*
Gamma Position (mm)	4.5-9.0		15.	9.0
Gamma Efficiency (%)	>40		>40	>40
e+ Timing (nsec)	0.1		0.12*	0.12*
e+ Momentum (%)		0.8	2.1	1.1
e+ Angle (mrad)		10.5	[17.]	[17.]**
e+ Efficiency (%)		65	65	65
Muon Decay Point (mm)		2.1	3.	3.**
Muon Rate (10^8/sec)	0.3		0.3***	0.3***
Running Time (week*)	100		8	24
Single Event Sens (10^{-13})	0.5		6.7	2.2
Accidental Rate (10^{-13})	0.1-0.3		6.0*	1.0*
# Accidental Events	0.2-0.5		0.9	0.5
90% CL Limit (10^{-13})	1.7		23.	6.9

Conclusions

- LXe scintillation is an established technique for e.m. calorimetry with unprecedented performances @ 50 MeV
- Validation by test on a 100l prototype
- Main concerns on the final detector experienced on 2007 Run are related to O_2, N_2 contamination
- Standard solutions adopted to fix that problem
- We are confident to reach goal resolutions by 2008 Run

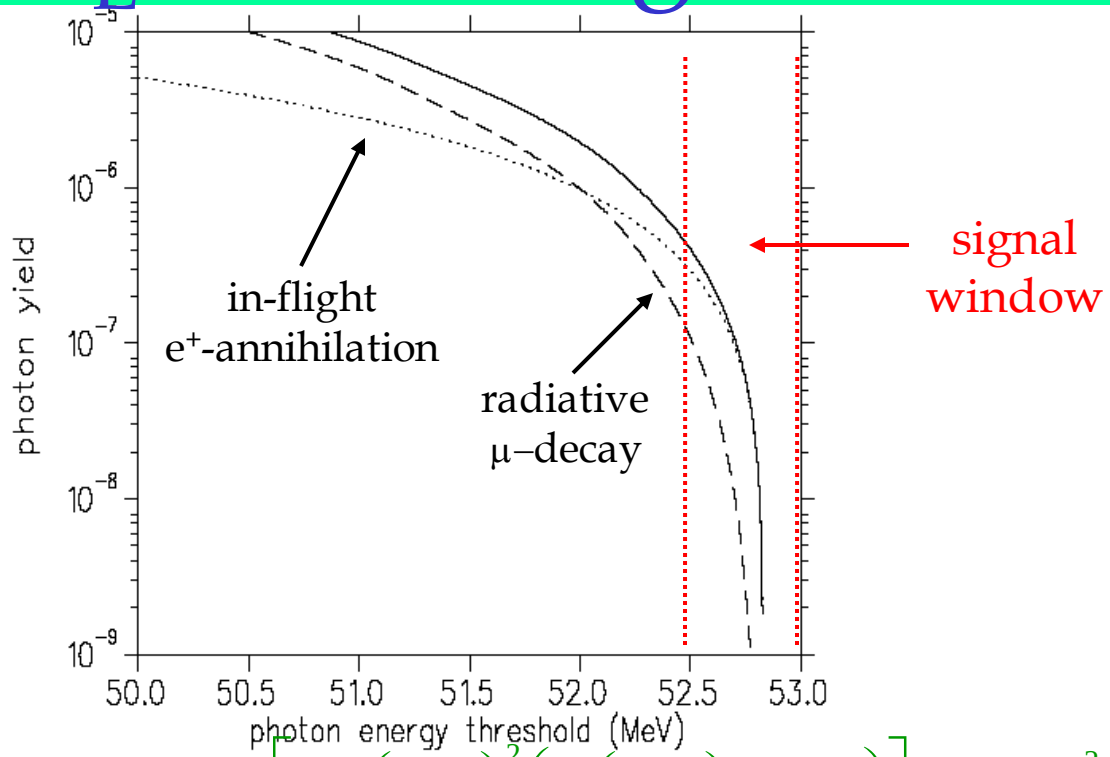
σ_E @ low energy

- Event selection of environmental radioactivity (non-dedicated trigger) ➔topological cuts to exclude α-induced events
- Identified lines
  - ^{208}Tl (2.59±0.06) MeV
  - ^{40}K (1.42 ± 0.06) MeV
- Low energy calibration



looks like a NaI ...

σ_E and background



$$BR_{acc} \equiv \frac{N_{acc}}{N_\mu} = R_\mu \cdot \left(2\frac{\delta E_e}{E_e}\right) \cdot \left[\frac{\alpha}{2\pi}\left(\frac{\delta E_\gamma}{E_\gamma}\right)^2 \left(\ln\left(\frac{\delta E_\gamma}{E_\gamma}\right) + 7.33\right)\right] \cdot \left(\frac{\delta\theta_{e\gamma}}{4}\right)^2 \cdot (2\delta t)$$

μ-rate e⁺-energy γ– energy back-to-back timing

Background suppression ➔ improvements of detector performances

(in particular for E_γ)

α-sources, a closer view