Status of MEG experiment : search for $\mu^+ \rightarrow e^+ \gamma$ decay with sensitivity to BR ~ 10^{-13}

Marco Grassi
INFN Sezione di Pisa

on behalf of the MEG collaboration

Les Rencontres de Physique de la Vallée d'Aoste

La Thuile, 1 – 7 March 2009

Outline

Physics motivation for a $\mu \rightarrow e\gamma$ experiment

The $\mu \rightarrow e\gamma$ decay and background

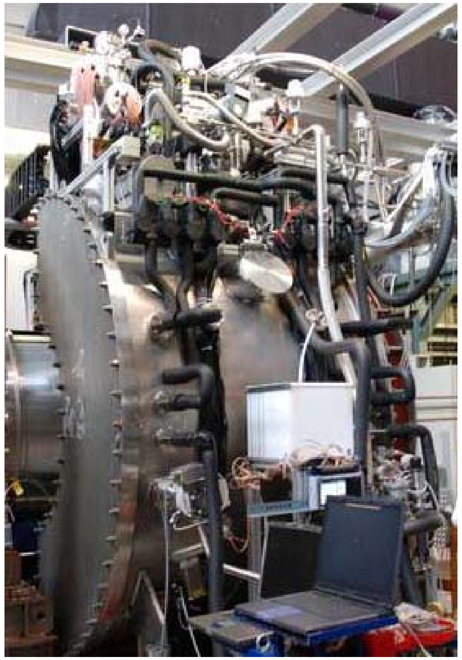
The detector

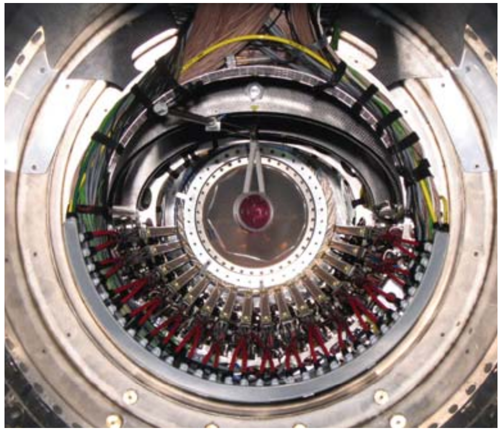
- LXe calorimeter
- Timing Counter
- Spectrometer

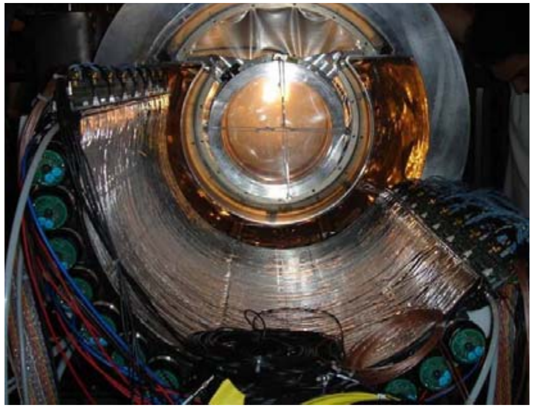
Present Status

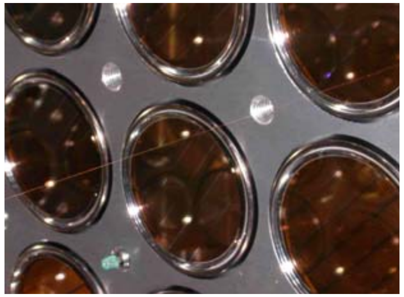
Perspectives for run 2009

Conclusions









The MEG collaboration

Tokyo U.
Waseda U.
KEK

INFN & U Pisa
INFN & U Roma
INFN & U Genova
INFN & U Pavia
INFN & U Lecce

PSI

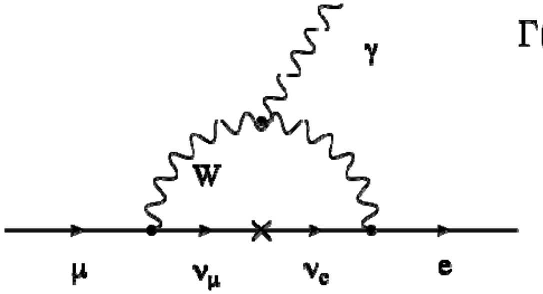
UCIrvine

JINR Dubna
BINP Novosibirsk

~65 collaborators

Physics motivation

The $\mu \to e\,\gamma$ decay is negligibly small in the extended Standard Model of elementary particles, with the introduction of neutrino masses and mixings : BR ~ 10^{-55}



$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\text{decay}} \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\text{vertex}} \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\text{oscillation}}$$

$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3}\left(\frac{\alpha}{2\pi}\right)\sin^2 2\theta_\odot \left(\frac{\Delta m^2}{M_W^2}\right)^2,$$

Super-Symmetric extensions of the SM may enhance the rate through mixing in the high energy sector of the theory

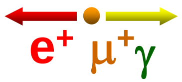
- $\mu \to e\,\gamma$ decay is a clean, no SM contaminated, evidence of new physics

(if we can talk about expectations)

- there are models in which the expected rate is close to the present experimental upper limit

Signal and Background

Signal

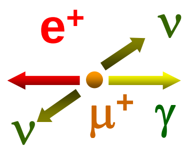


$\theta_{e\gamma} = 180°$

$E_e = E_\gamma = 52.8$ MeV

$T_e = T_\gamma$

Prompt

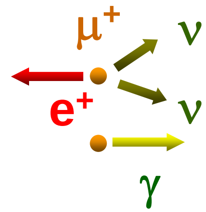


$$\mu \rightarrow e\bar{\nu}\nu\gamma$$

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

at 3x10^7^ μ–stop/s

Accidental



$$\mu \rightarrow e\bar{\nu}\nu$$

$$e^+e^- \rightarrow \gamma\gamma$$

$$\mu \rightarrow e\bar{\nu}\nu\gamma$$

$$e\mathcal{N} \rightarrow e\mathcal{N}\gamma$$

$$B_{acc} \approx R_\mu \Delta E_e \Delta E_\gamma^2 \Delta\theta^2 \Delta t$$

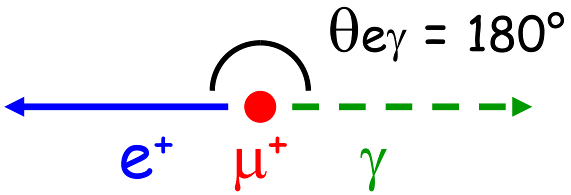
The accidental background is dominant and it is determined by the experimental resolutions

FWHM

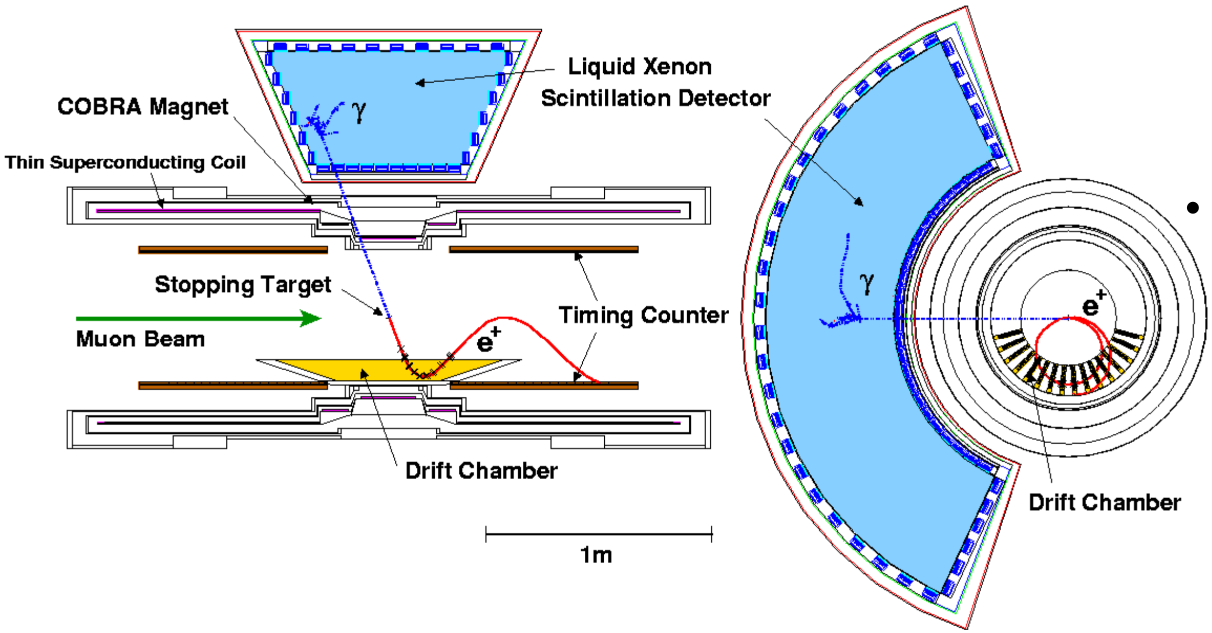
Exp./Lab	Year	ΔEe/Ee (%)	ΔEγ /Eγ (%)	Δteγ (ns)	Δθeγ (mrad)	Stop rate (s^{-1})	Duty cyc.(%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^5	(6..9)	4.9×10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5×10^8	(6..7)	1.2×10^{-11}
MEG	2008 - x	1	4.5	0.15	19	3×10^7	100	2×10^{-13}

Experimental method

Easy signal selection with μ⁺ decay at rest



$E_e = E_\gamma = 52.8$ MeV



Detector outline

- Stopped beam of $>10^7$ μ /sec in a 175 μm target
- γ detection

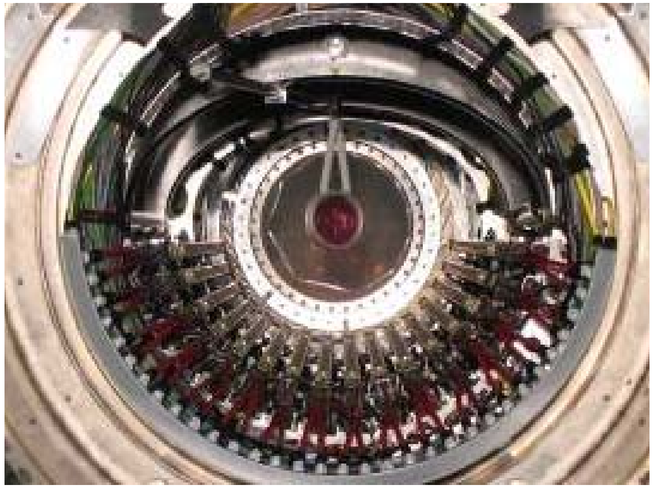
  Liquid Xenon calorimeter based on the scintillation light

  - fast: 4 / 22 / 45 ns
  - high LY: ~ 0.8 * NaI
  - short X_0: 2.77 cm
- e^+ detection

  magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum

  scintillation counters for timing

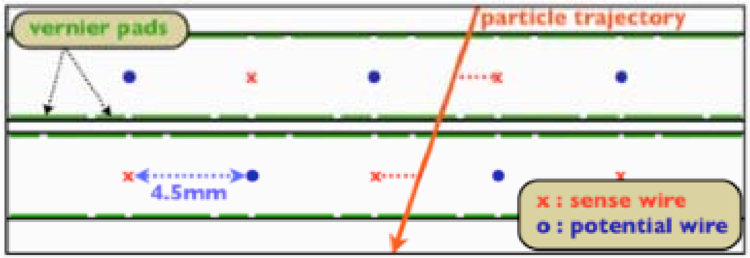
Positron Tracker

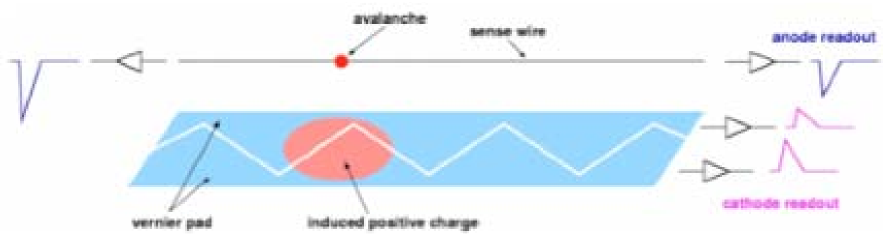


- 16 chambers radially aligned with 10°intervals
- 2 staggered arrays of drift cells
- 1 signal wire and 2 x 2 vernier cathode strips made of 15 μm kapton foils and 0.45 μm aluminum strips : total thickness 60 μm

- Within one period, the *fine structure* is given by the Vernier circle

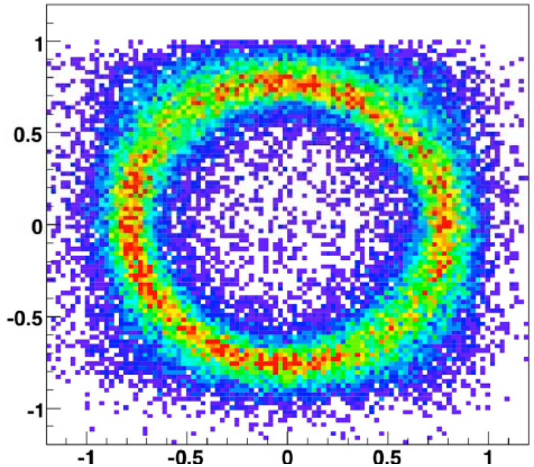
transverse coordinate (t drift)





$$\sigma_R = 100\mu m$$

$$\sigma_Z = 400\mu m$$



longitudinal coordinate (charge division + Vernier)

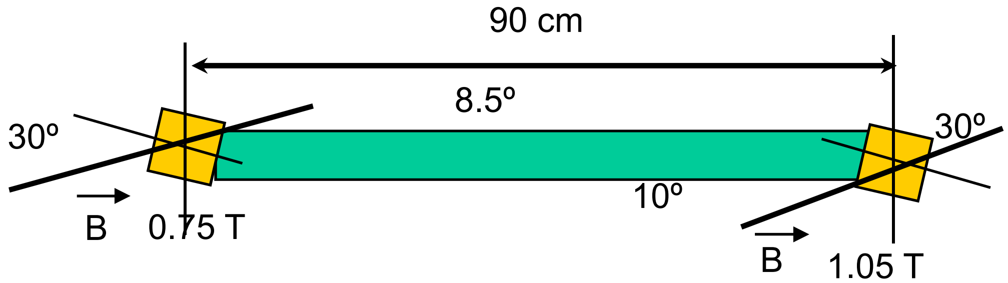
Positron timing

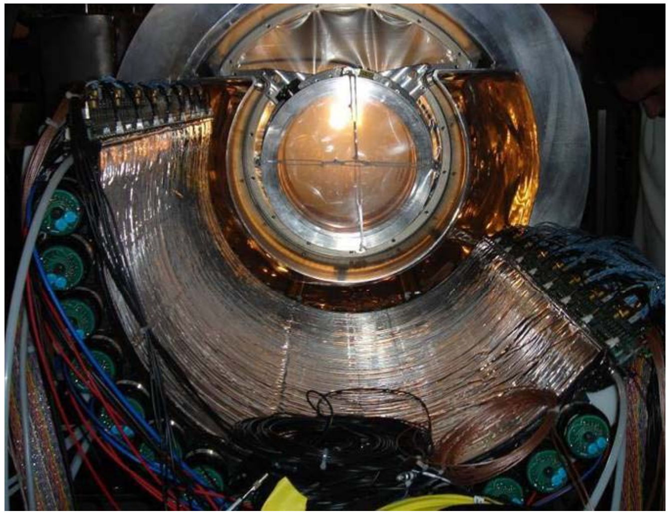
Two layers :

Outer layer, scintillator bars read out by PMTs: timing measurement

Inner layer, scintillating fibers read out with APDs: trigger and longitudinal coord.

Measured resolution on all bars at the LNF test facility: σ_{time}~ 40 psec (100 ps FWHM)





Exp. application (*)	Counter size (cm) (T x W x L)	Scintillator	PMT	λ_{att} (cm)	σ_t(meas)	σ_t(exp)
G.D.Agostini	3x 15 x 100	NE114	XP2020	200	120	60
T. Tanimori	3 x 20 x 150	SCSN38	R1332	180	140	110
T. Sugitate	4 x 3.5 x 100	SCSN23	R1828	200	50	53
R.T. Gile	5 x 10 x 280	BC408	XP2020	270	110	137
TOPAZ	4.2 x 13 x 400	BC412	R1828	300	210	240
R. Stroynowski	2 x 3 x 300	SCSN38	XP2020	180	180	420
Belle	4 x 6 x 255	BC408	R6680	250	90	143
MEG	4 x 4 x 90	BC404	R5924	270	38	

One of the best existing TC

Photon calorimeter

γ energy, position, timing

Homogeneous 0.8 m^3 volume of liquid Xe
- 10 % solid angle

Only scintillation light

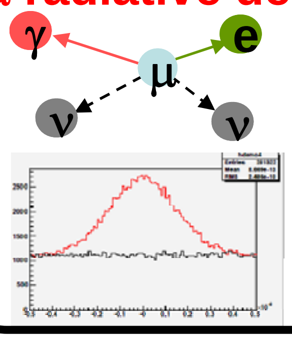
Read by 848 PMT
- Immersed in liquid Xe
- Low temperature (165 K)
- Quartz window (178 nm)

Thin entrance wall

Waveform digitization @ 1.6 GHz
- Pileup rejection

Calibration tools

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

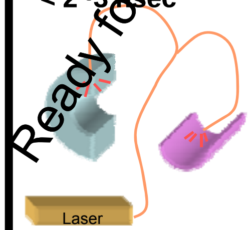
A few days ~ 1 week to get enough statistics

Laser

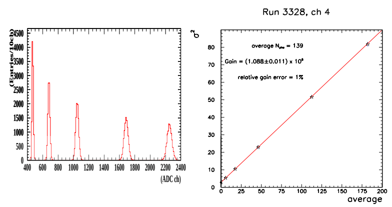
(rough) relative timing calib.

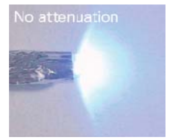
< 2~3 nsec

Ready for 2009 run



LED

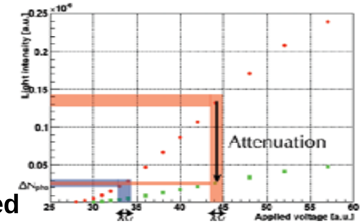


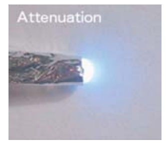


PMT Gain

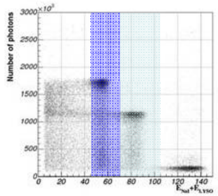
Higher V with light att.

Can be repeated frequently





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



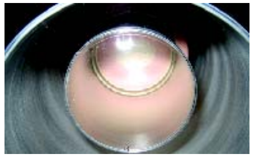
$\pi^- + p \rightarrow \pi^0 + n$

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

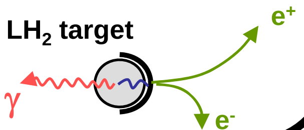
$\pi^- + p \rightarrow \gamma + n$ (129MeV)

10 days to scan all volume precisely

(faster scan possible with less points)



LH_2 target



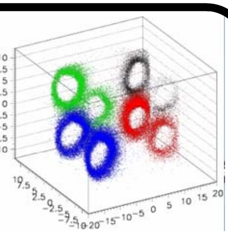
MEG Detector Standard Calibrations

alpha

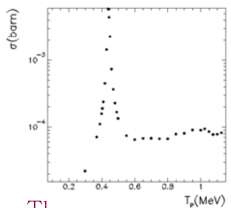
PMT QE & Att. L

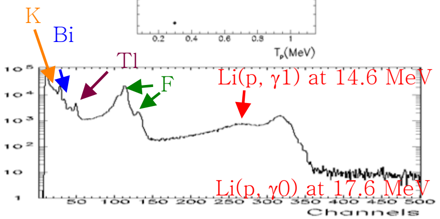
Cold GXe

LXe



Proton Acc





Li(p,γ)Be

LiF target at COBRA center

17.6MeV γ

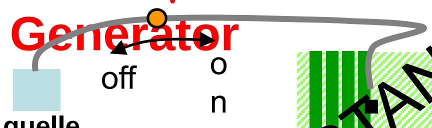
~daily calib.

+ B target →

(4.4, 11.7, 16.1 MeV) lines – Energy + Timing

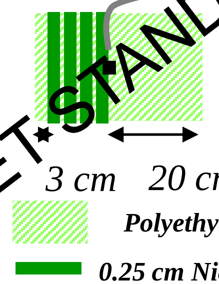
Nickel γ Generator

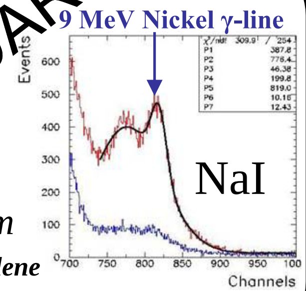
NOT YET STANDARD



Illuminate Xe from the back

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





CW accelerator

The CW accelerator is an extremely powerful tool installed to monitor and calibrate the LXe and the TC

Protons on **lithium tetraborate**

- Lithim: high rate, high energy gammas
- Boron: two photons of lower energy but coincident in time

Reaction	***Peak energy***	**σ peak**	**γ-lines**
Li(p,γ)Be	*440 keV*	5 mb	(17.6, 14.7) MeV
B(p,γ)C	*163 keV*	2 10^{-1} mb	(4.4, 11.7, 16.1) MeV

π^0 calibration

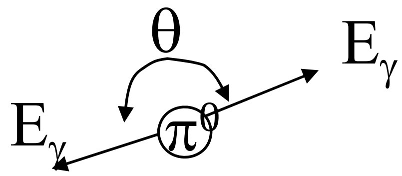
Charge exchange process

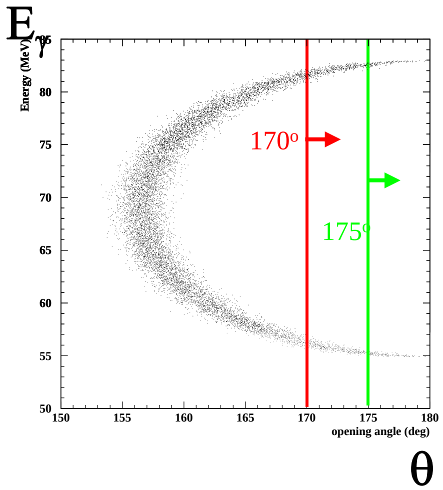
$\pi^- p \rightarrow \pi^0 n$

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

54.9 MeV < E(γ) < 82.9 MeV

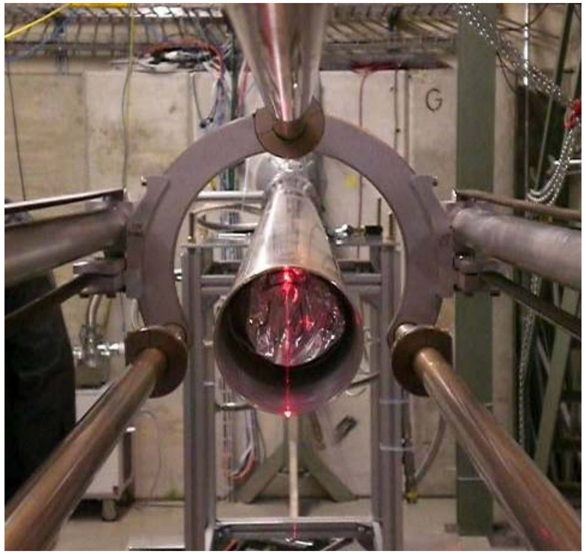
$\pi^0 \rightarrow \gamma\, e^+ e^-$





Liquid Hydrogen target of 124 cc

- Liquid helium cooling
- Stable: 1.3% RMS, 6% max
- Easy to operate: 1 dewar every 42 ore



Auxiliary calorimeter

- Segmented NaI
- Movable in the LXe acceptance solid angle

2008

First run of the experiment

(... after a short engineering run in 2007)

Time shedule

Winter - Spring

- detector dismantling
- improvement (after run 2007)
- re – installation

Summer

- LXe purification
- CW and π^0 calibration
- beam line setup

September – December

- MEG run
- short π^0 calibration

Running conditions

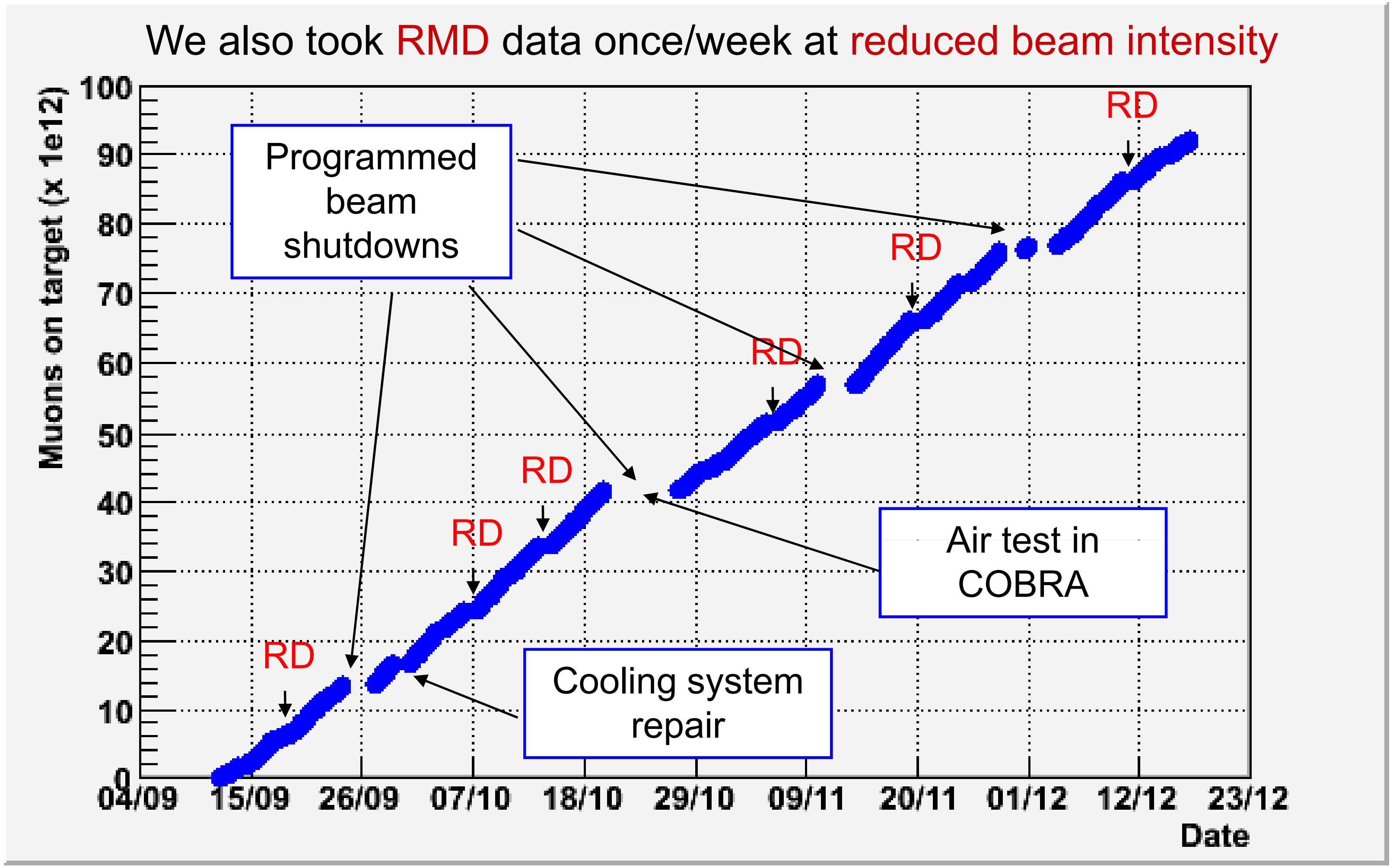
MEG run period

- Live time ~50% of total time
- Total time ~ 7×10^6 s
- μ stop rate: 3×10^7 μ/s
- Trigger rate 6.5 ev/s ; 9 MB/s

The missing 50% is composed of:

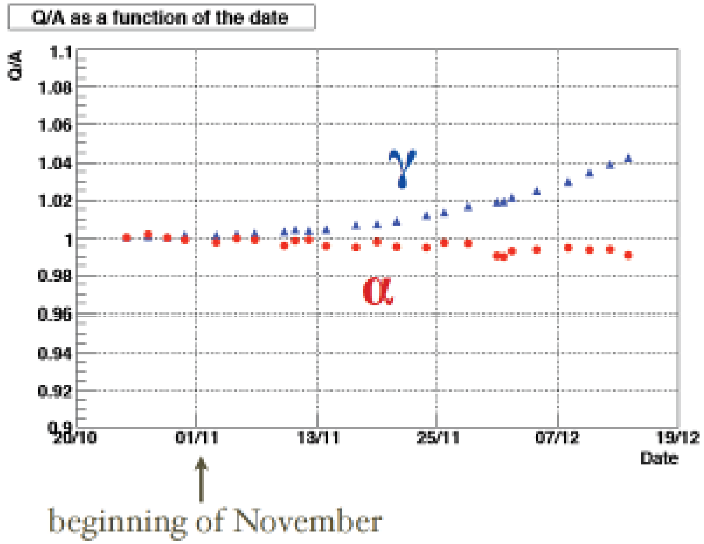
- 17% DAQ dead time
- 14% programmed beam shutdowns
- 7% low intensity Radiative muon decay runs (RMD)
- 11% calibrations
- 2% unforeseen beam stops

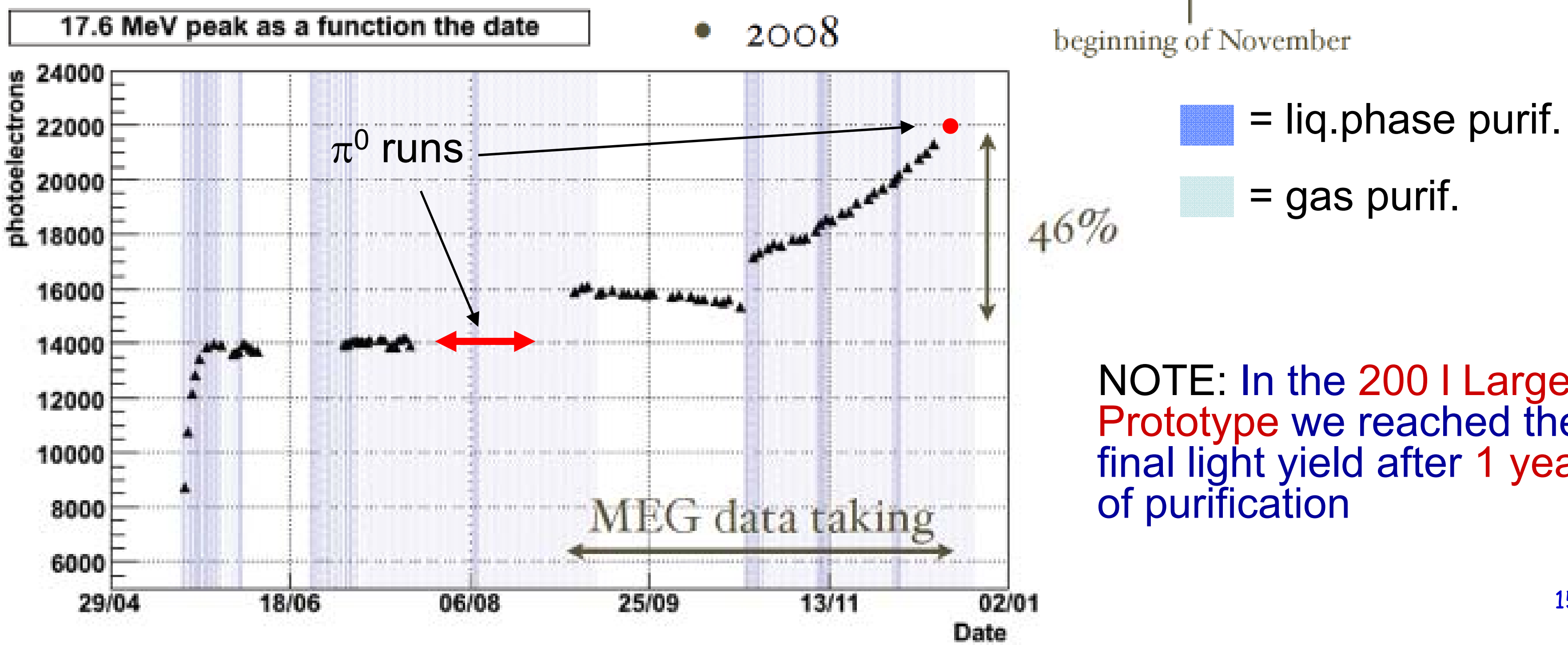
Muons on target



LXe : light yield

- Large light yield increase (46%) during MEG run
- Approaching the expected 27000 ph.el.
- LY change monitored with the calibration system
- Problems with noisy pump of liquid phase purification (solved with a new system)
- Finally we observed different time constants for α and γ scintillation pulses (as it must be)





NOTE: In the 200 l Large Prototype we reached the final light yield after 1 year of purification

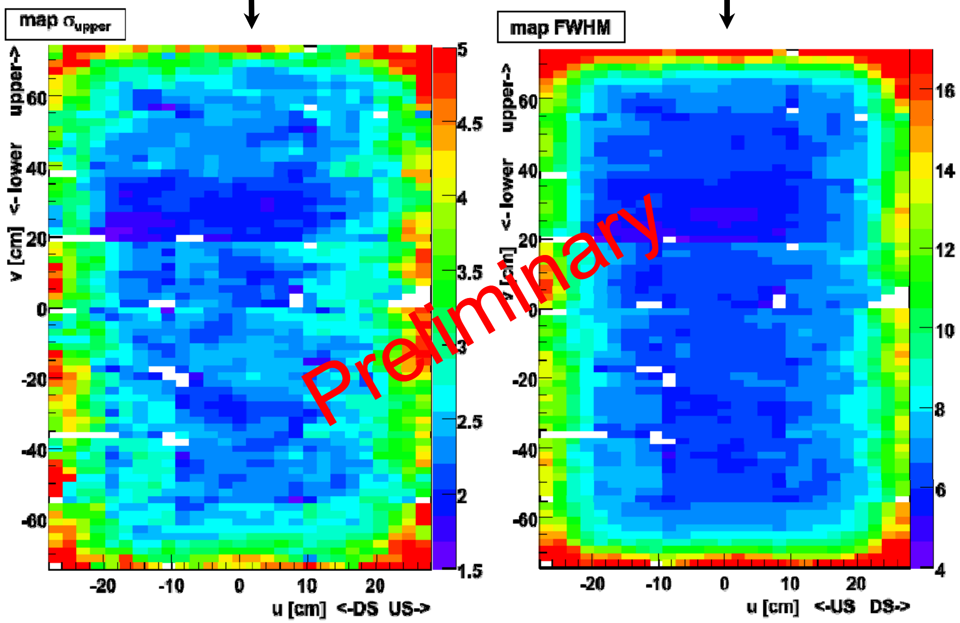
LXe Energy resolution

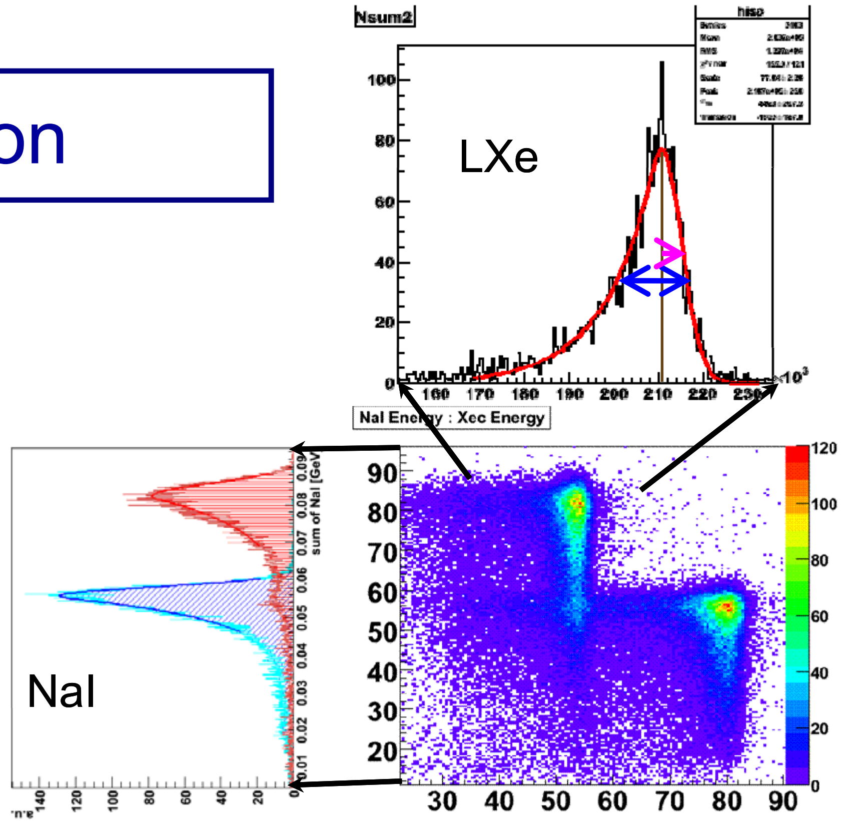
$\pi^0 \rightarrow \gamma\,\gamma$ calibration

180º coincidence selects 55 MeV in LXe and 83 MeV in NaI

Resolution evaluated on all calorimeter surface

$\langle \sigma_R \rangle$ = 2.3%, $\langle$FWHM$\rangle$ = 6.4%





Not yet as expected (FWHM = 4.5%) but we are improving it

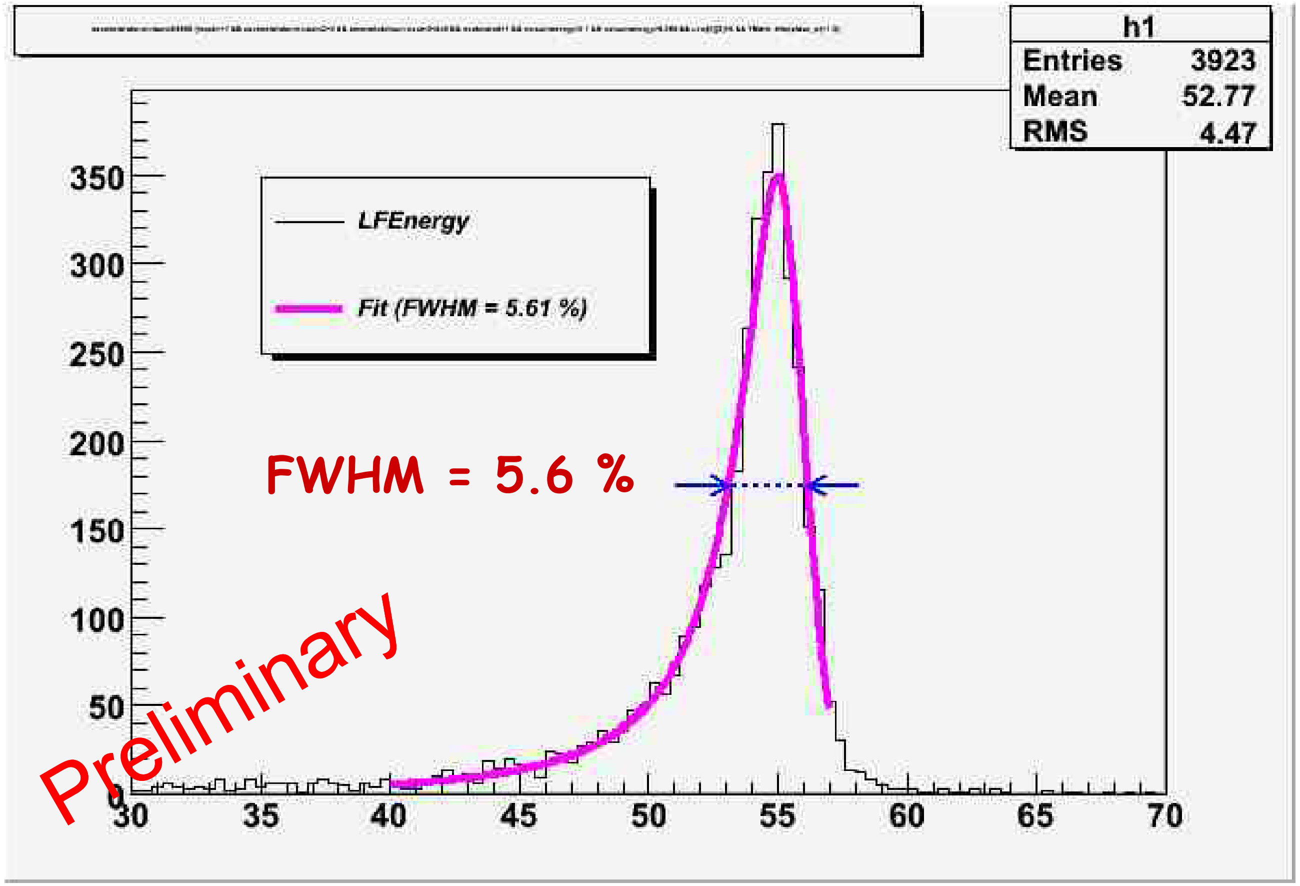
LXe Energy resolution

$\pi^0 \rightarrow \gamma\,\gamma$ calibration

PMT quantum efficiency evaluated with alphas on wires

Inner part of the acceptance region

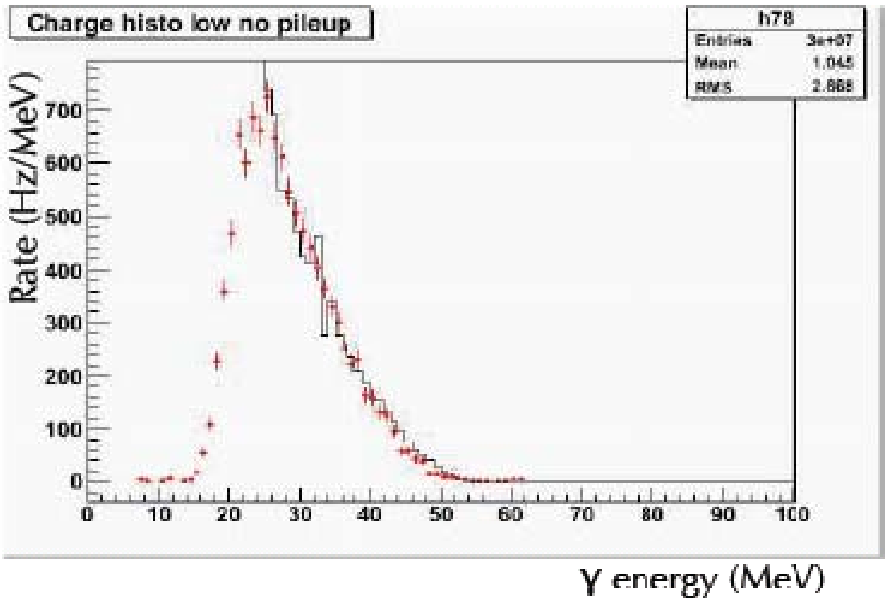
Still missing other corrections

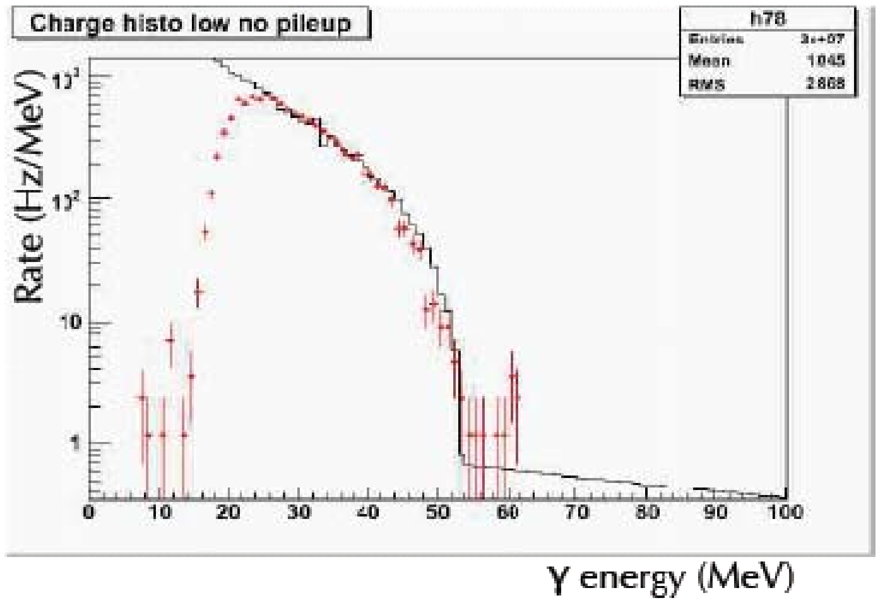


LXe energy spectrum

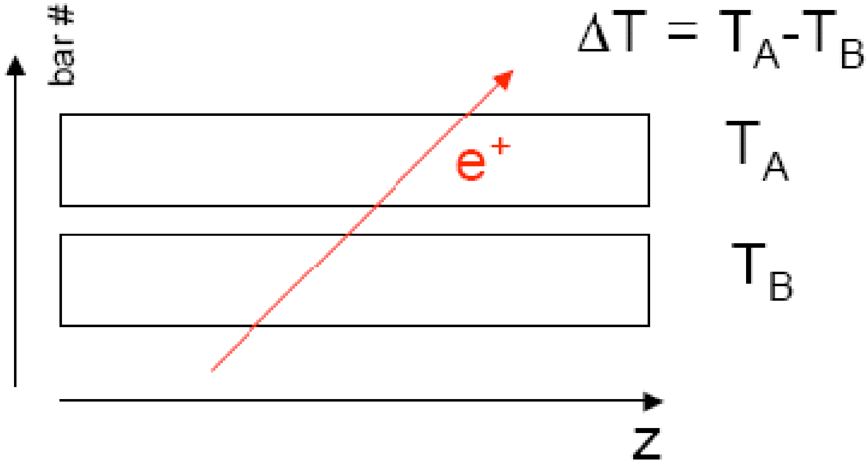
The LXe energy spectrum, both shape and rate, are correctly reproduced by the simulation

- no unforeseen background in the μ-beam
- the γ detection efficiency is understood
- cosmic muons and event pileup are under control

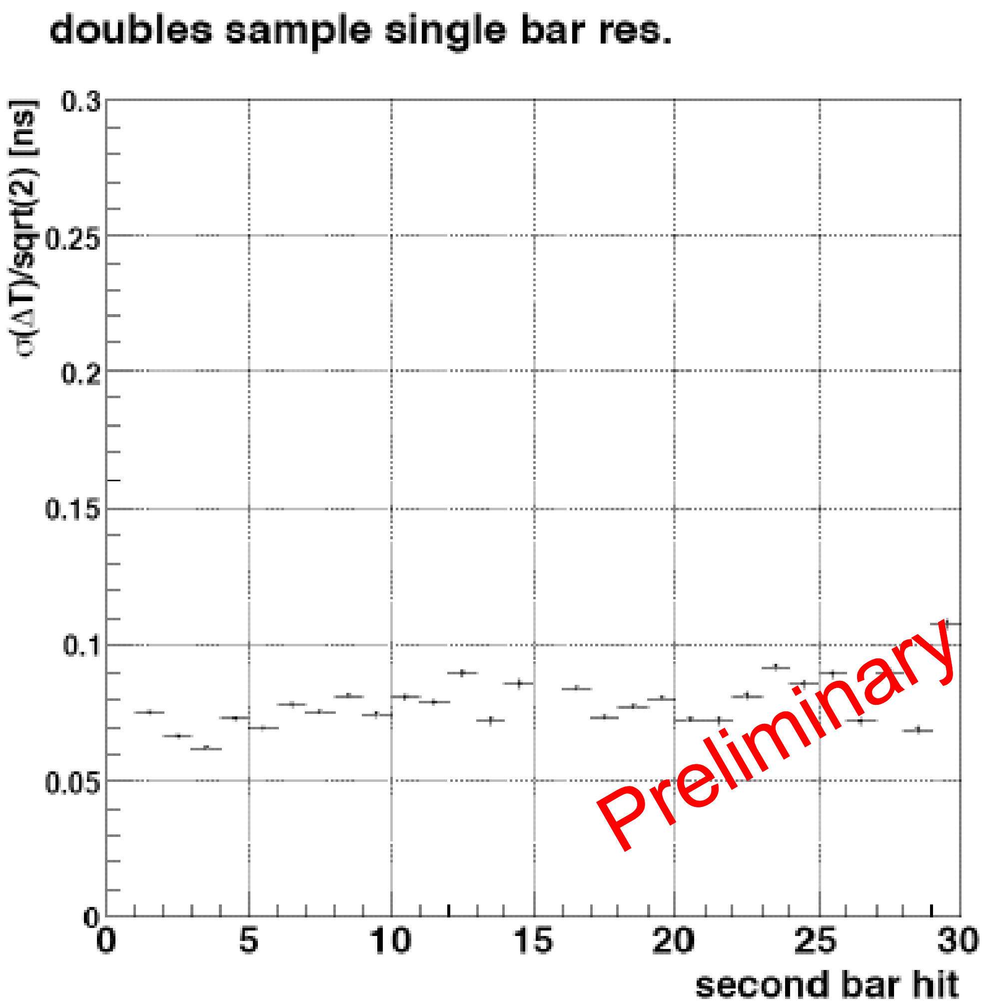




TC timing resolution



e+ from μ decay



Not yet corrected for positron track length

Upper limits on σ ~ 60-90 ps

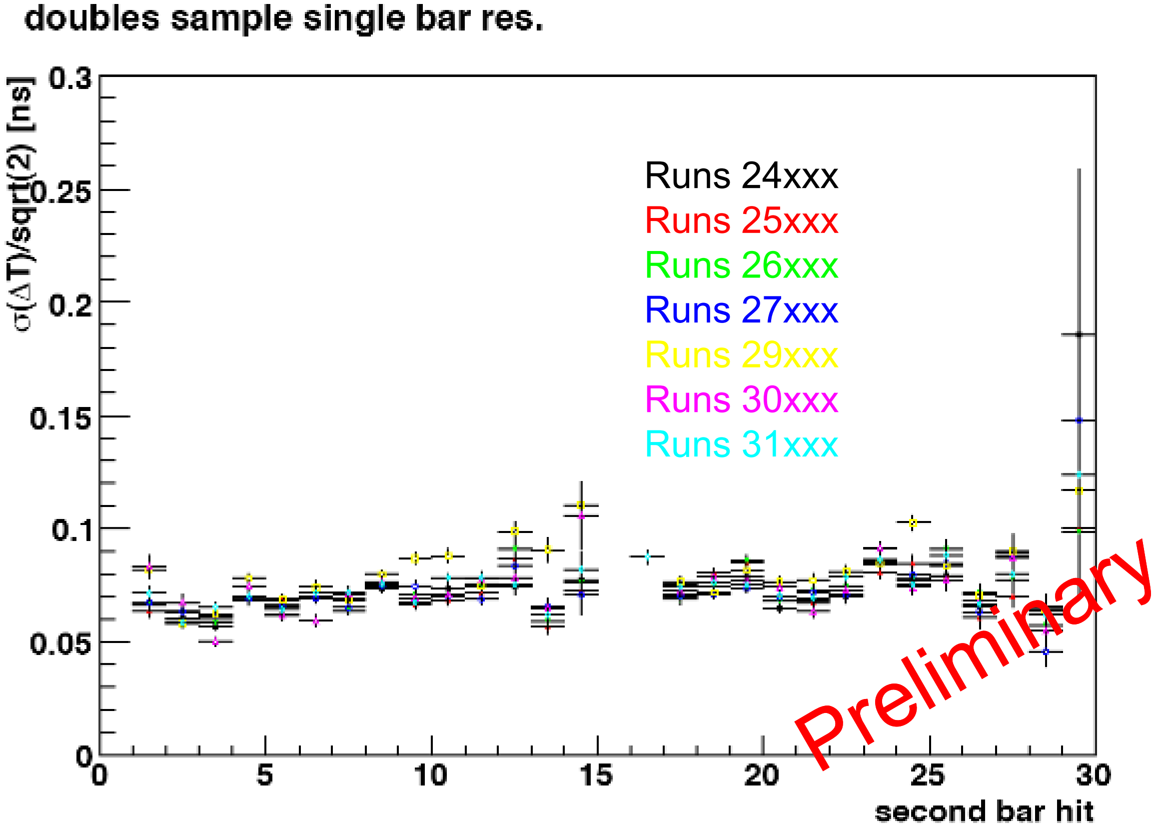
Time-walk correction applied

Further improvement in 2009 with the new digitizers (DRS4)

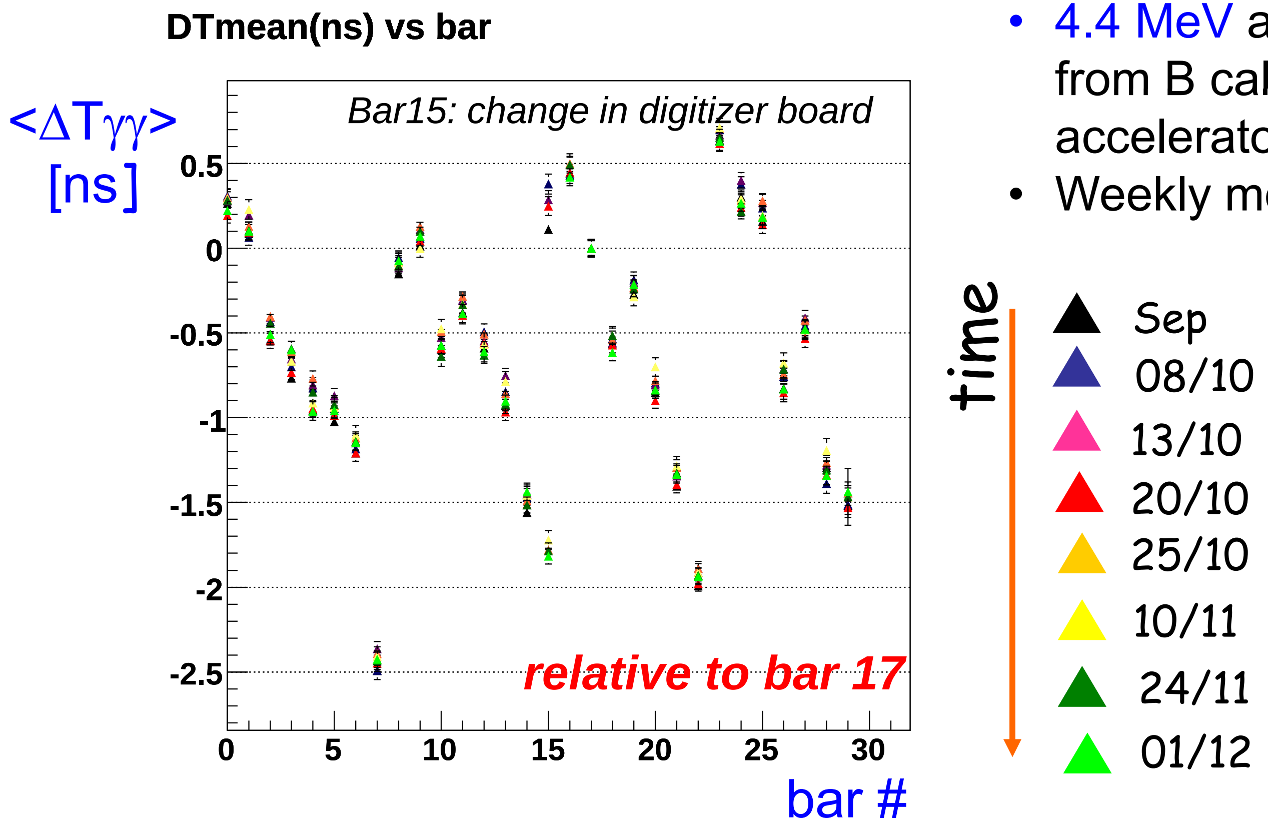
TC timing resolution stability

Stable over the MEG run period

Same Time Walk calibration constants

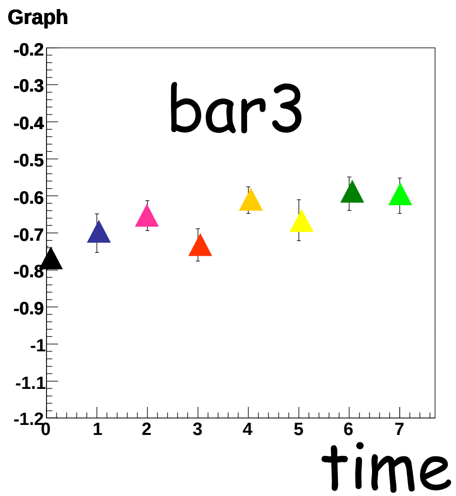


LXe-TC relative timing offsets



- 4.4 MeV and 11.7 MeV gammas from B calibration with the CW accelerator
- Weekly monitoring

- Small trend vs time, mainly due to the LXe Light variation
- Enough calibration data to correct the effect



DC HV Performance

- The chambers are operated in He/ethane 50%/50% mixture
- They are immersed in He atmosphere

In June-July the situation was ok:

- 30 / 32 planes >1800 V
- 2 planes showed problems right from beginning

In **September,** after the p0 calibration, the situation started to deteriorate but we decided to start anyhow data taking (September 12th)

During MEG run (Sep – Dec):

- further deterioration of HV performance

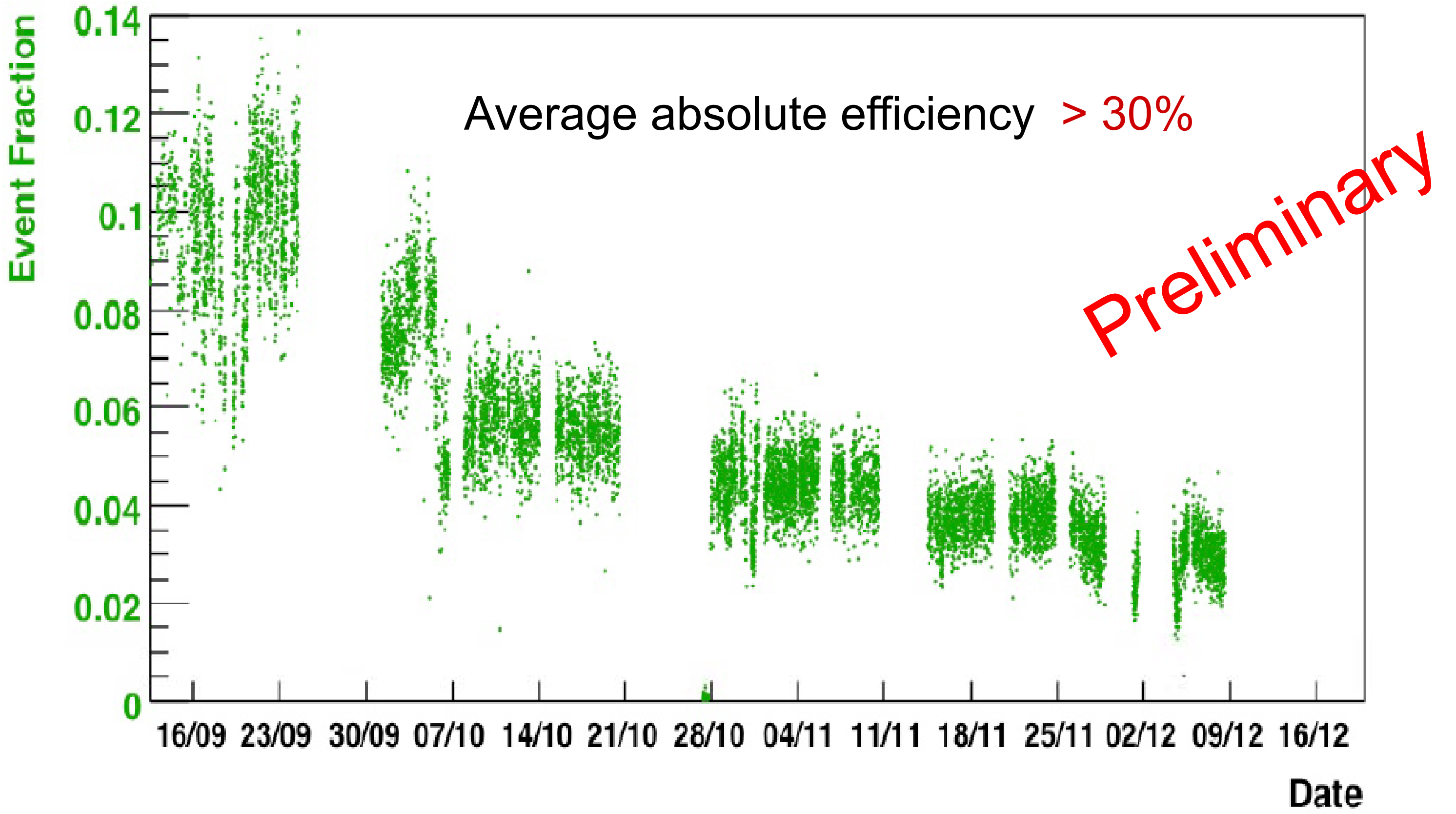
At the end of MEG run

- 11 / 32 planes >1800 V
- 7 / 32 planes 1700-1800 V

The problem is tricky because it does not show up immediately but only after some time: helium penetration in HV distribution

DC efficiency

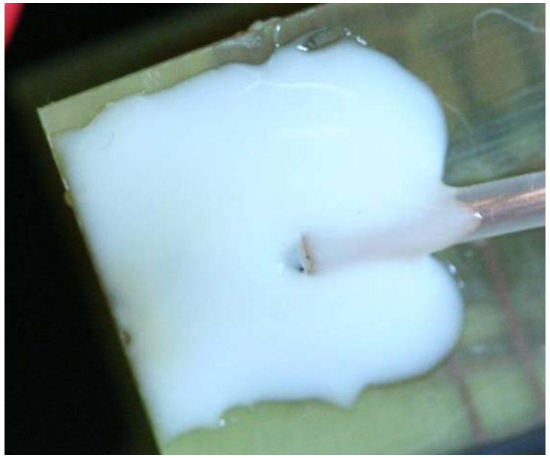
Namely the fraction of events with at least one reconstructed track at high momentum is a measure of relative (not absolute) tracking efficiency



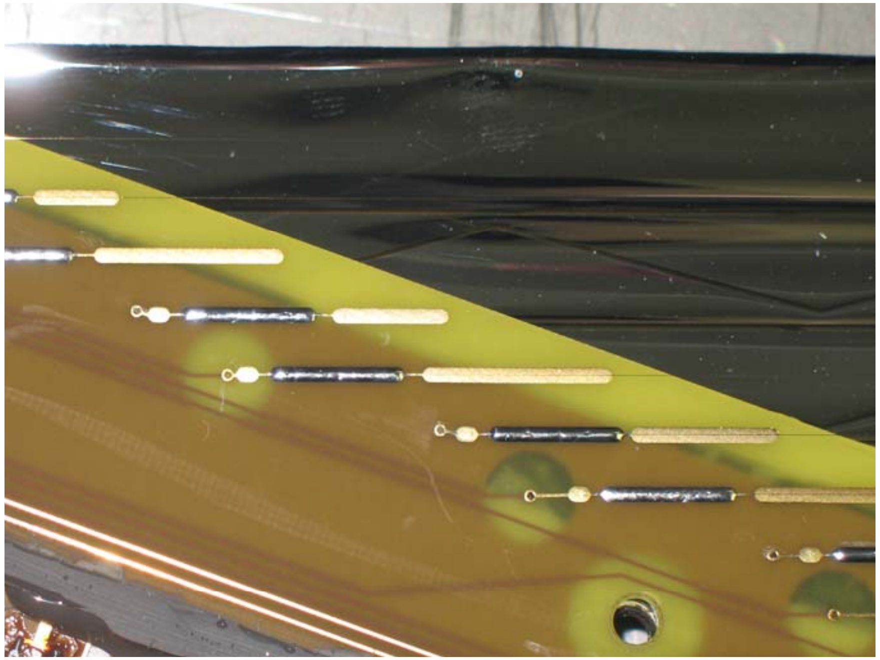
DC repair

1) The chambers are dismounted and operated in laboratory in He atmosphere

2) The potting glue for the HV protection was inadequate: change on all chamber to epoxy glue



3) The PCB has vias close to ground plane, partially filled with araldite to fix PCB to the Carbon fiber frame: new PCB design



4) Open all chambers, replace the PCB and the wires, saving the cathodes

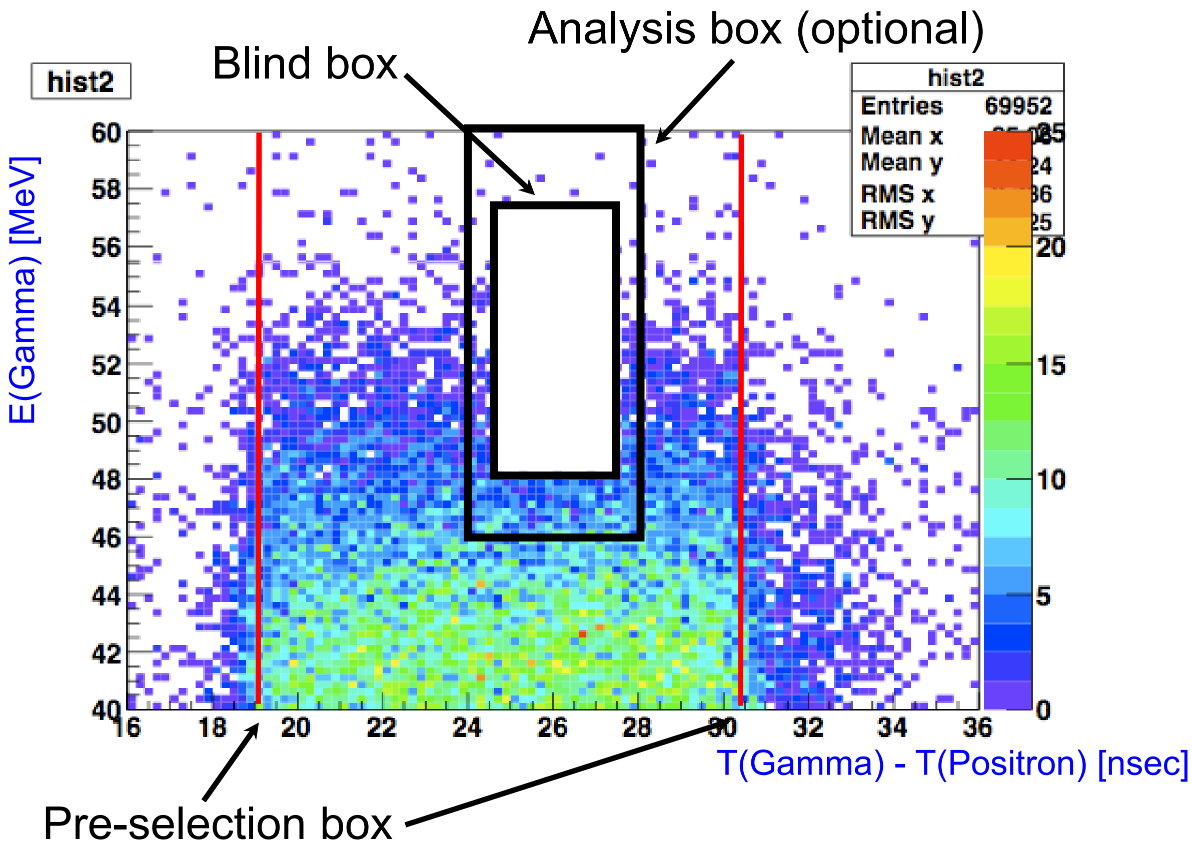
5) Test of the chambers in laboratory as soon as they are ready

Estimated time: ready to mount in August

Analysis

We decided to adopt a blind-box likelihood analysis strategy

The blinding variables are $E\gamma$ and $\Delta te\gamma$



PDF

Signal: from detector resolutions

Accidental background: from data

Prompt background: from simulation and from RMD data sample

Radiative μ-decay signal

The radiative μ-decay events are:

- good sample to check the LXe-TC timing
- good sample to control the efficiencies
- the second source of background: we want to validate our pdf

Search in dedicated low μ-beam intensity runs

Event selection

1) Reject cosmic muons
2) Reconstructed track matching the TC
3) LXe energy >30 MeV

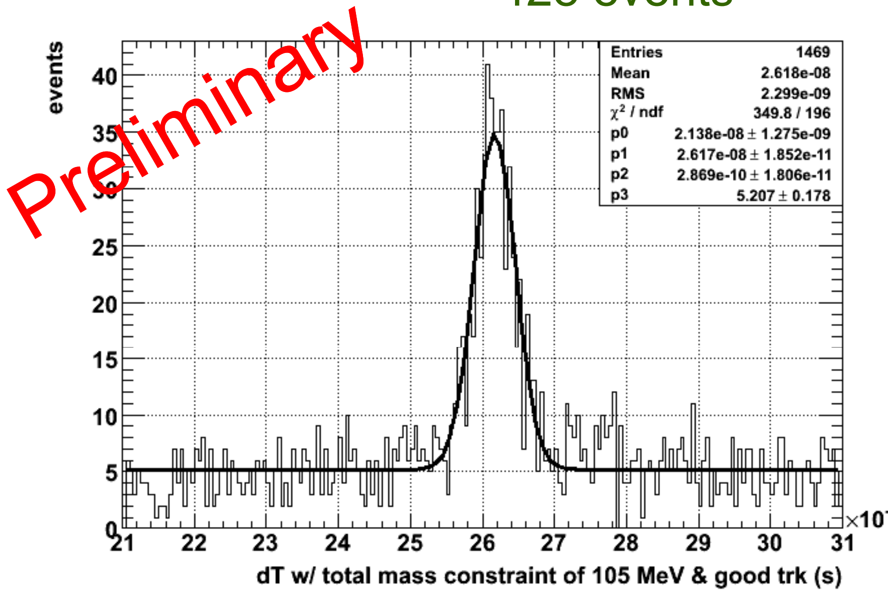
S/N ratio = 0.8

4) Kinematical constraint

S/N ratio = 2.8

$$M_{2\nu}^2 = E_{2\nu}^2 - \vec{p}_{2\nu}^{\,2} = (M_\mu - E_e - E_\gamma)^2 - (\vec{p}_e + \vec{p}_\gamma)^2$$
$$\approx M_\mu^2 - 2(E_e + E_\gamma)M_\mu + 2E_e E_\gamma \sin^2(\vartheta/2) \geq 0$$
$$\Rightarrow xy\sin^2(\vartheta/2) \geq x + y - 1$$

428 events

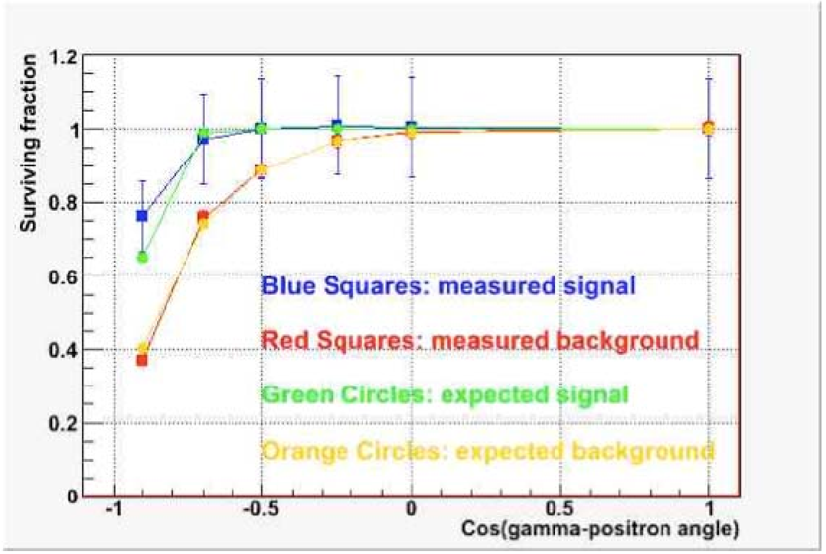


Radiative μ-decay

Comparison with expectation

The observed number is compatible with the estimated detectors efficiencies

The measured angular dependence of e+ γ pair is in agreement with the expectations



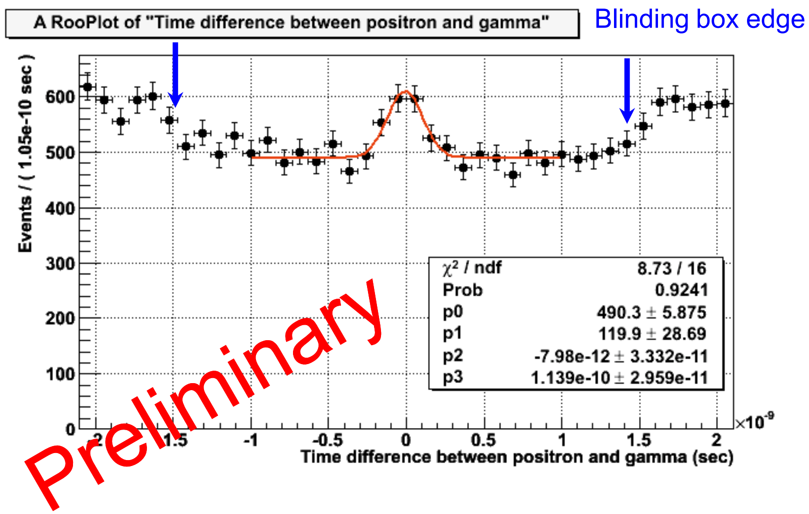
Search in normal MEG runs

1) Reject cosmic muons
2) Reconstructed track matching the TC
3) Kinematical constraint
4) LXe energy >30 MeV

$\sigma(\Delta t)$ = 178±29 ps

LXe energy >40 MeV

$\sigma(\Delta t)$ = 114±30 ps



Single Event Sensitivity for RUN 2008

CAUTION: All 2008 numbers are provisional

Still lots of things to learn from the data

Efficiencies

- Blue numbers likely to change - Grey numbers may vanish

(%)	"Goal"	2008 Provisional Lower Limits	2009 Provisional Prospects
Gamma	> 40	(depth, pileup) > 50 x (65 x 85)	> 50 x 90
e+	65	(DC, DC-TC) 30 x 40	85 x 50
Trigger	100	(energy, time, direction) 100 x 99 x 80	> 99
Selection	$90^4 = 66$	$90^3 \times 95 = 69$	69
DAQ	(> 90)	(live, run transition) > 80 x 93	> 90 x 99
Calibration Run etc	(> 95)	~70	90
Running Time (week)	100*	11.5**	11.5
Single Event Sensitivity (10^{-13})	0.5	< 30 - 50	< 3 - 5

* 1 week = 4×10^5 sec (66%) ** CEX runs not included

Resolutions for RUN 2008

CAUTION: All 2008 numbers are provisional

Resolutions

Resolutions are improving as we understand the detectors better.

(in sigma)	"Goal"	2008 Provisional	2009 Provisional Prospects
Gamma Energy (%)	1.2 - 1.5	< 2.3	< 1.7
Gamma Timing (ps)	65	< 100*	< 80
Gamma Position (mm)	2 - 4	5 - 6.5	5
e+ Momentum (%)	0.35	1.5 - 2.0	0.7 - 0.8
e+ Timing (ps)	45	< 60 - 90	60
e+ Angle (mrad)	4.5	9 - 18	11
mu Decay Point (mm)	0.9	3 - 4	2
Gamma - e+ Timing (ps)	80	150	100
Background (10^{-13})	0.1 - 0.3	-	< 0.6 - 3

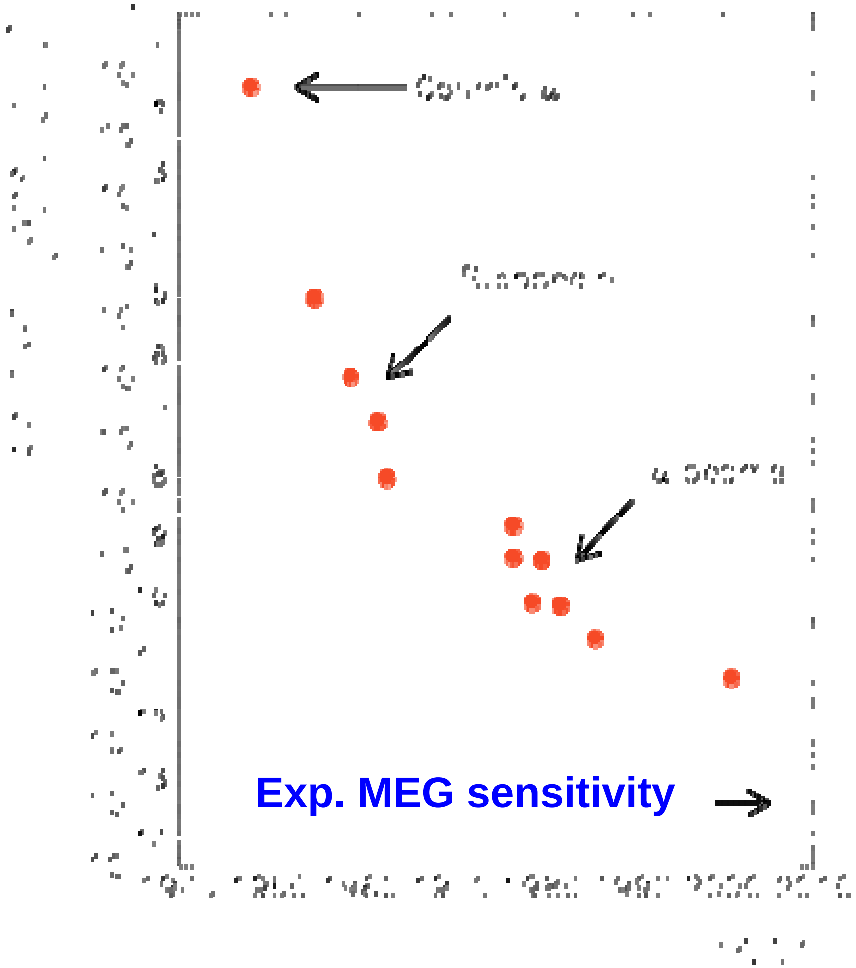
* clock error of ~60ps included

Conclusions

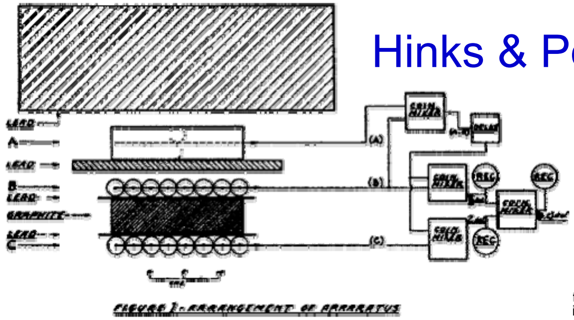
- Despite 2008 run suffered from detector instabilities we demonstrated our ability in seeing $\mu \to e\,\gamma$ events (RMD process observed in normal data taking)
- We are gaining better knowledge of our detectors systematics: resolutions are (almost daily) improving
- We are working to have analysis results on 2008 data ready by this summer
- We are making all efforts to reach stable DC operation for the 2009 run: we believe the strategy presented will eliminate HV discharges
- We will need to run until the end of 2011 for reaching the target sensitivity

Spare

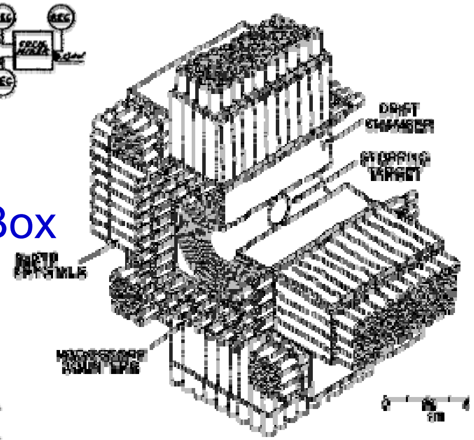
Historical perspective

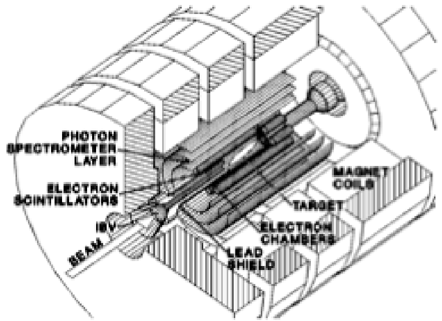


Hinks & Pontecorvo

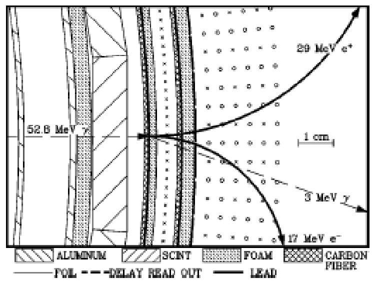


Crystal Box





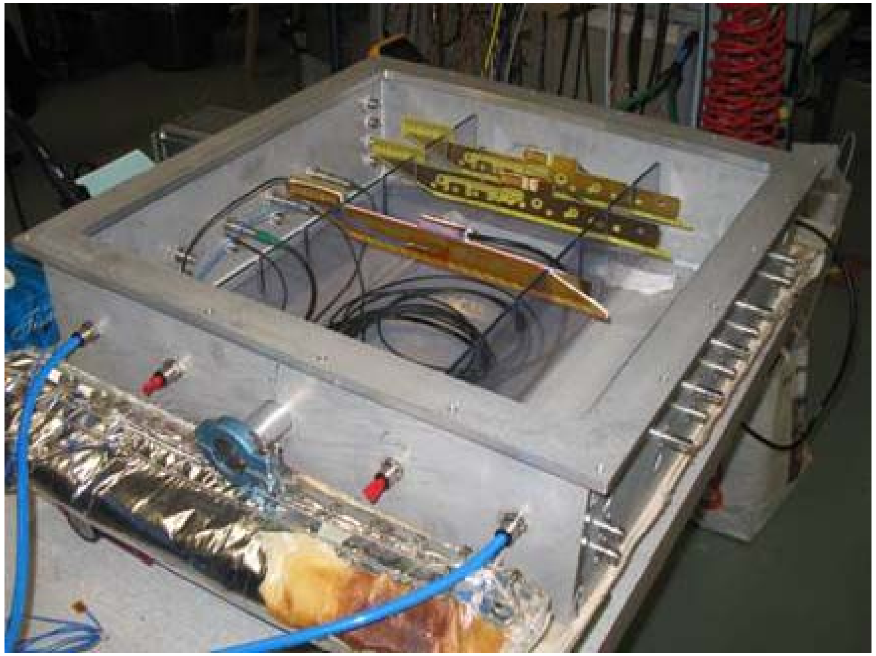
MEGA

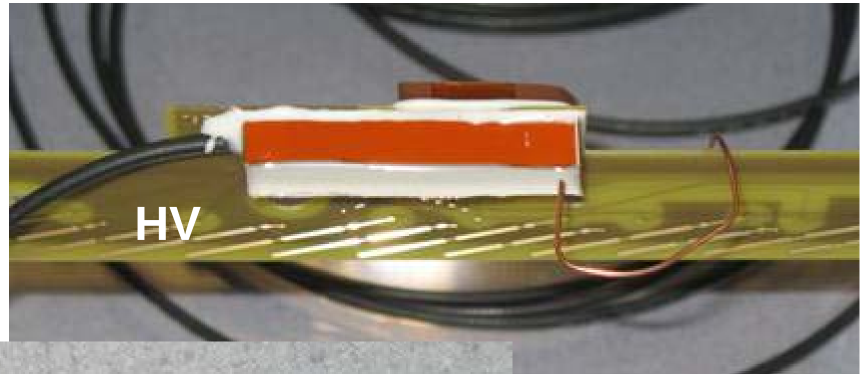


Each BR improvement linked to improvements in technology either in the beam or in the detector

DC: PCB nella testbox

since Fri nov 7th: HV in helium atmosphere (~99% from reading O_2 sensors)





LXe : light yield

Number of Ph. El. for different sources and conditions

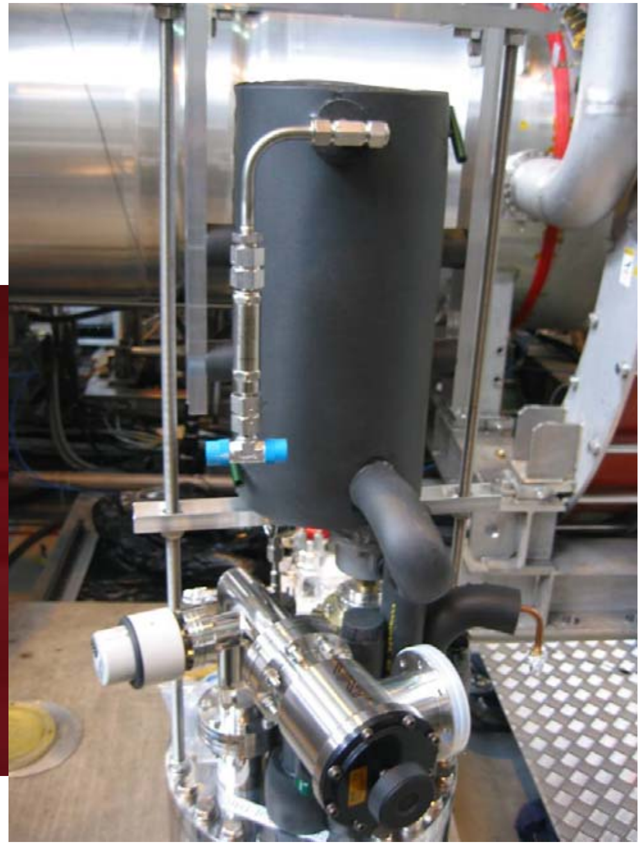
measured simulated estrapoletae

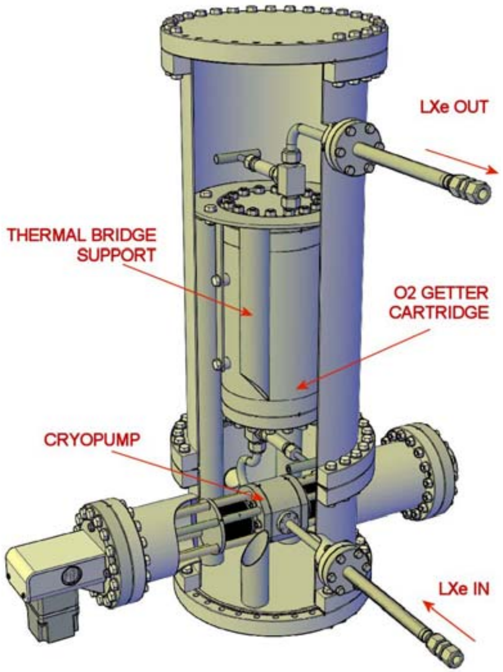
	ALPHA	17.6 MeV	54.9 MeV
LXe simulation	5500	27000	90000
LXe 2008	7500	13000	42000
LXe 2007	5200	8100	22000
LP 2004	7000	30000	90000
LP simulation	7000	32000	100000

LXe: electronegative impurities

Electronegative impurities change the light emission mechanism

An O_2 getter is added to the liquid phase purification system



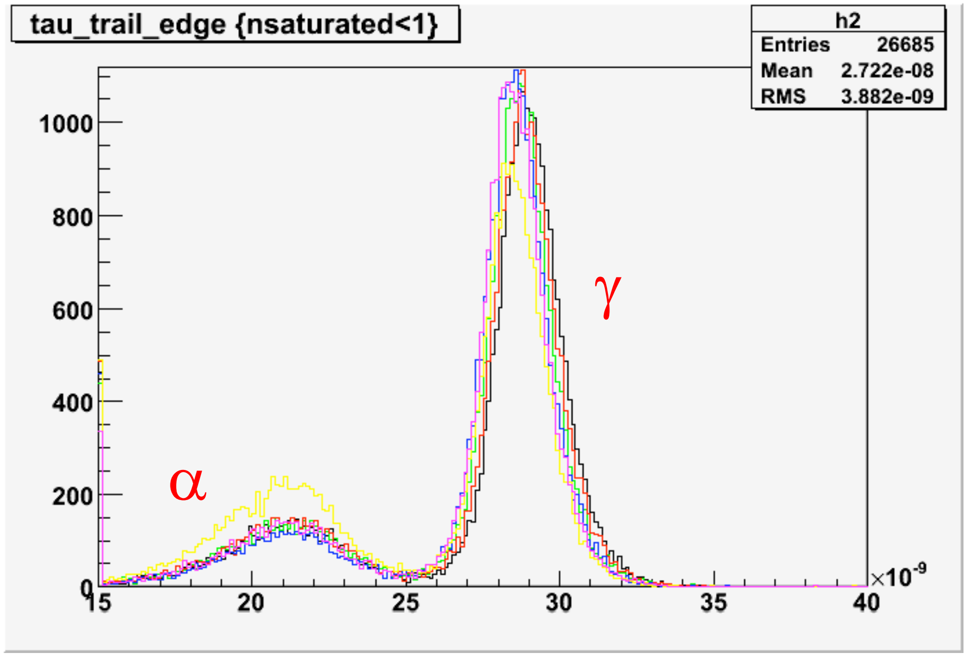


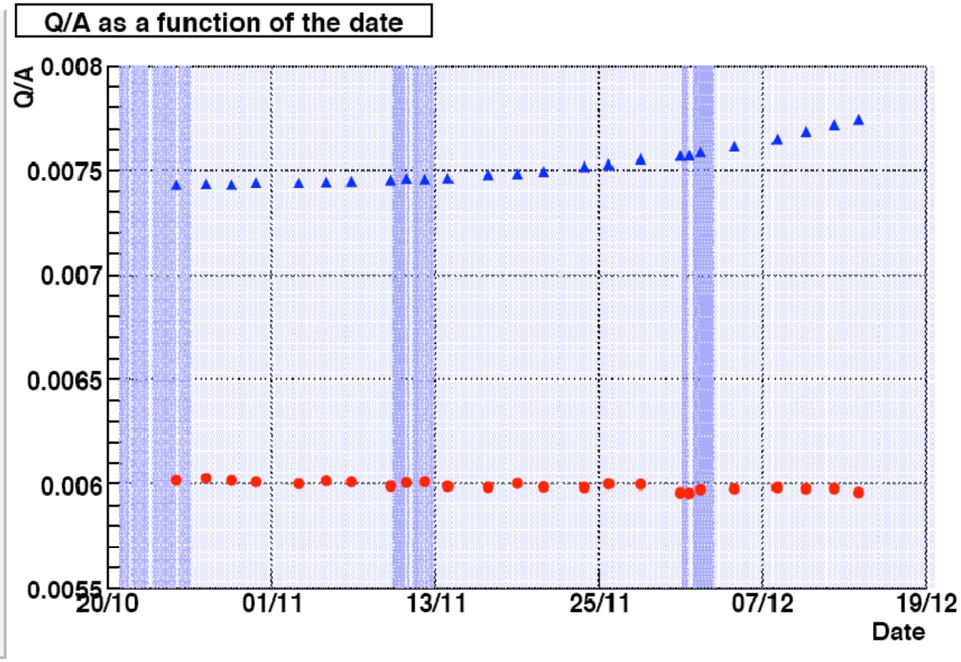
New cryogenic pump that doesn't induce electronic noise

LXe: Q/A ratio

The Q/A ratio is a measure of τ_{scint}

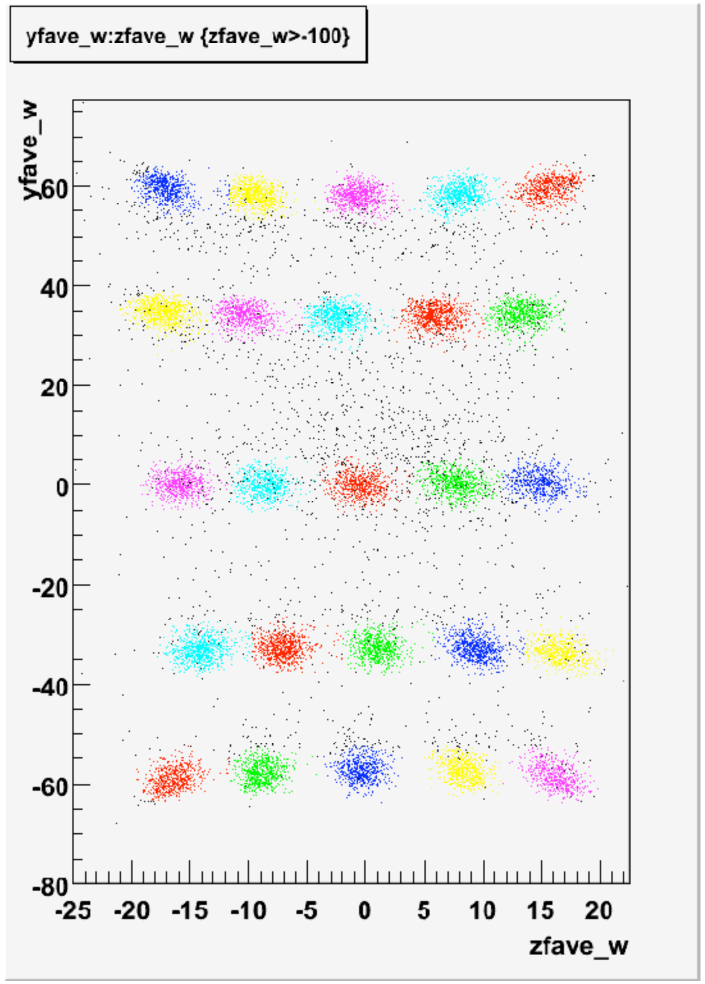
We expect a very good separation, we measured a factor $(Q/A)_\gamma / (Q/A)_\alpha \sim 2$

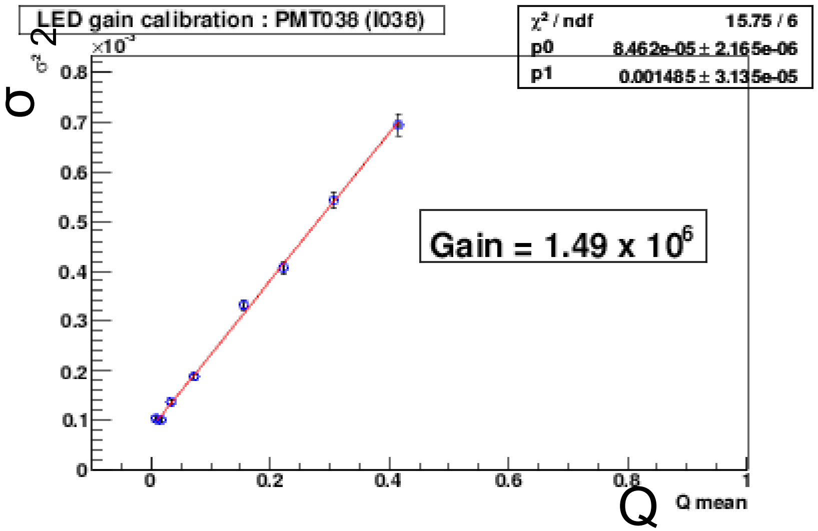




LXe: PMT calibration

Alpha quantum efficiencies
(both in liquid and in gas)
attenuation length

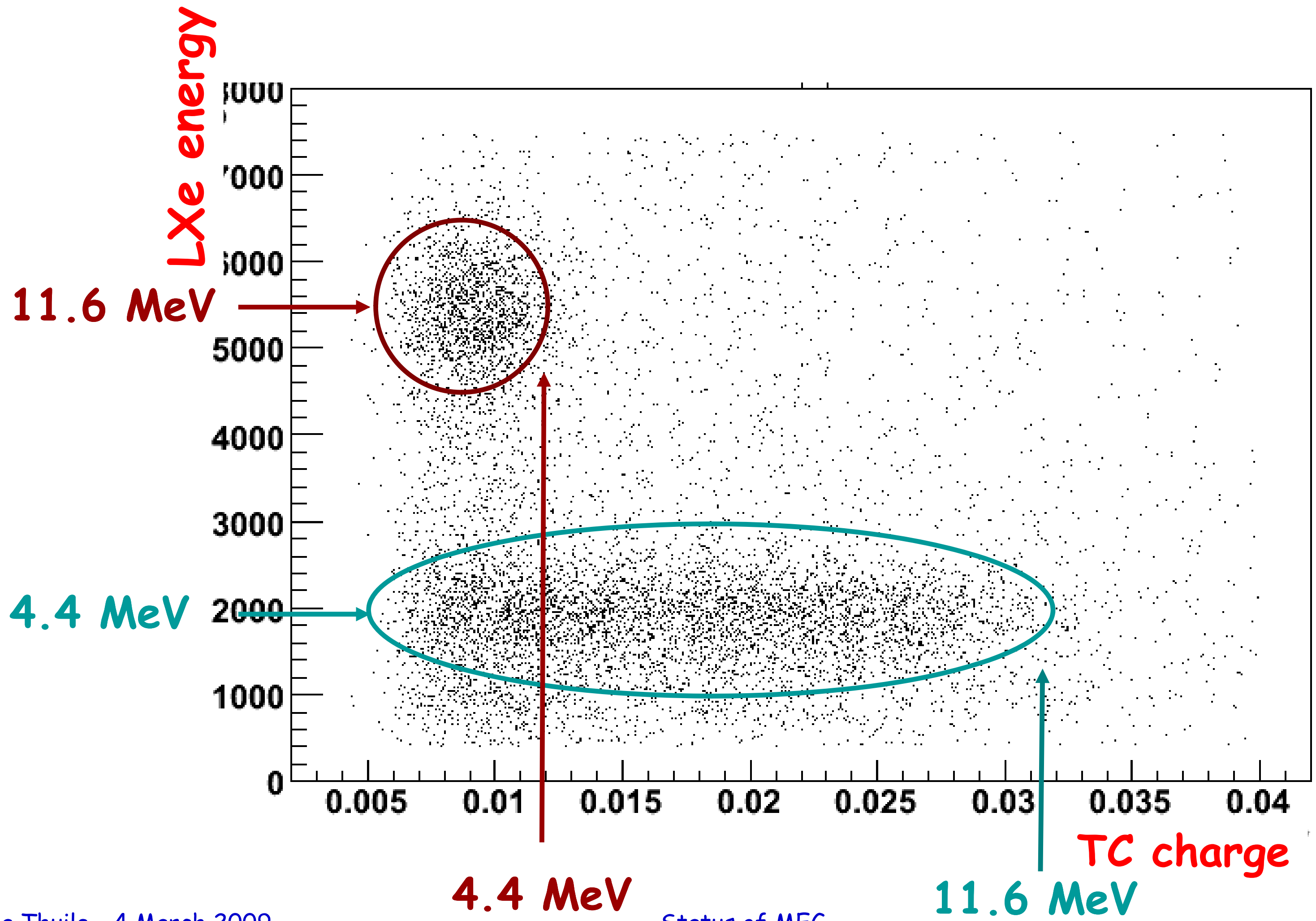




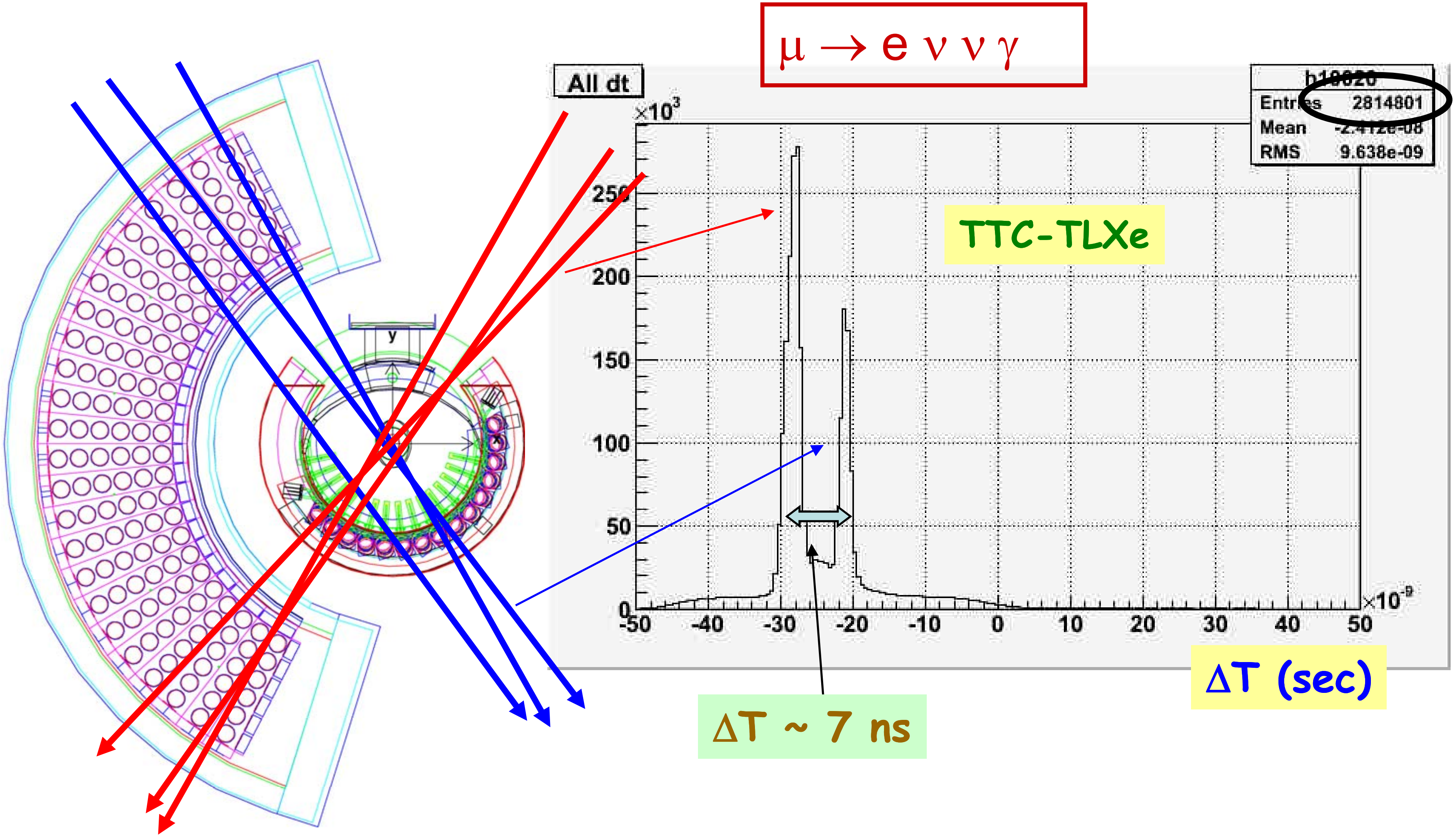
LED PMT gain

- LED signals at different intensities
- $N_{pe} \sim \sigma^2$

TC: timing LXe - TC



RD: all triggers



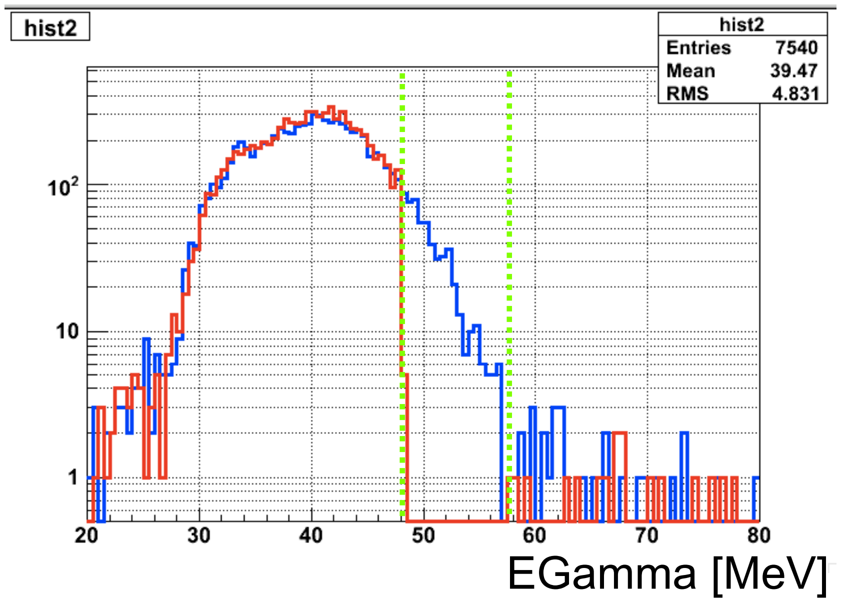
Analysis check

Check of Eγ

#24002-#24212 (physics runs)

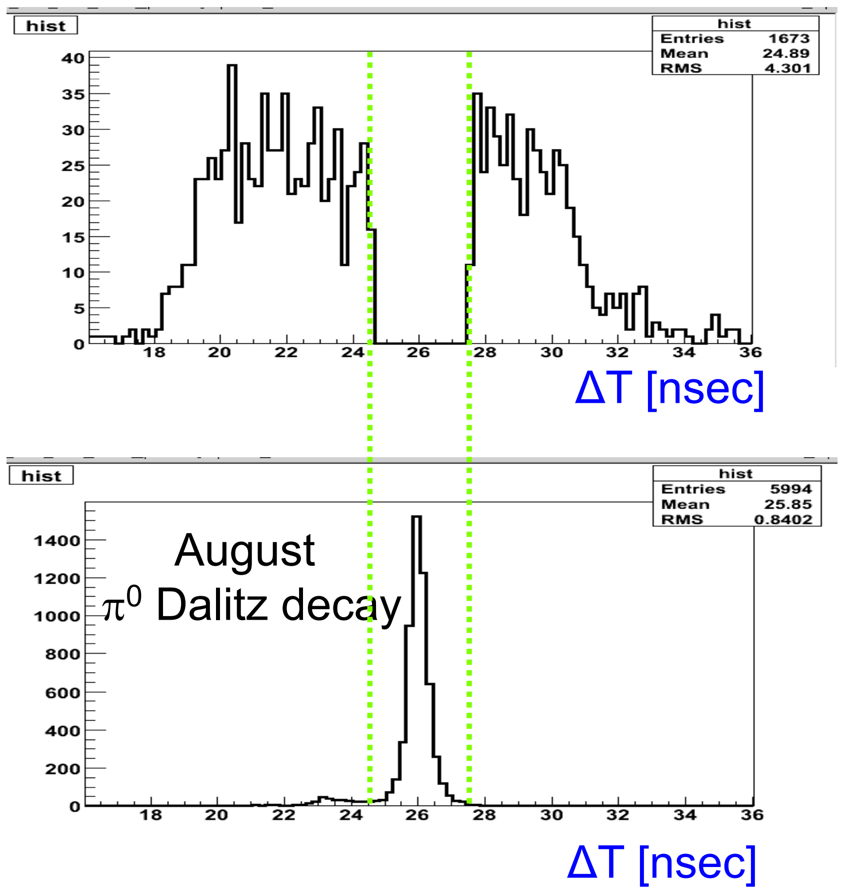
| ΔT | < 1.5 nsec

| ΔT - 1.5 | < 1.5 nsec (side band)

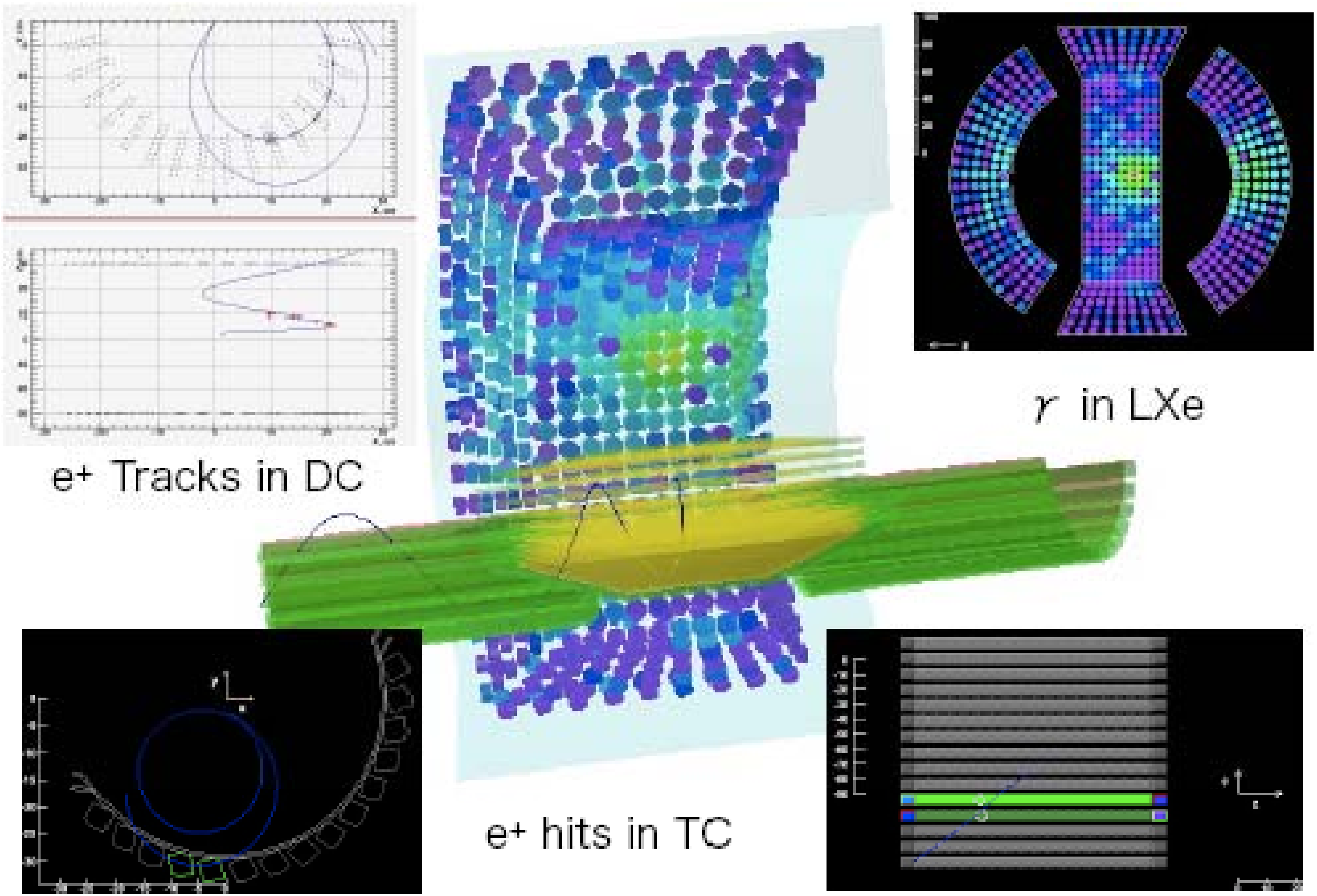


Check of T

| EGamma-52.8 | < 4.8 MeV

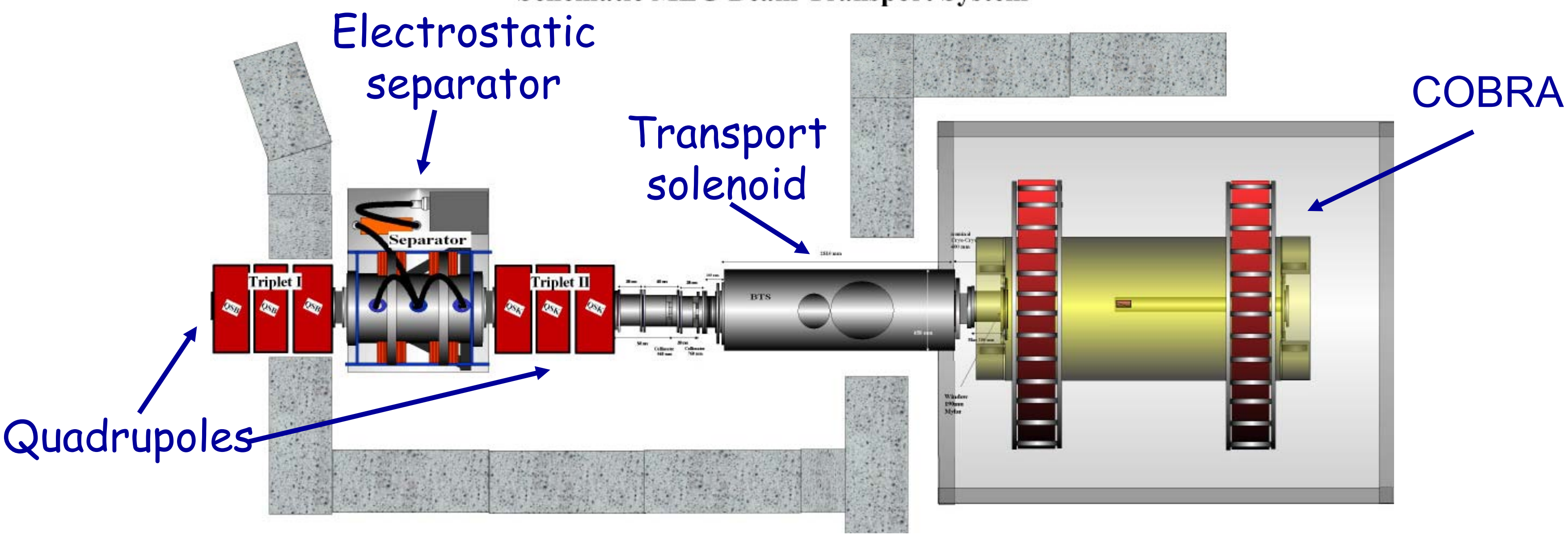


RD event display



μ beam

Schematic MEG Beam Transport System



Intensity' (μ-stop/s)

- Low 2.5 x 10^6
- Normal 3.2 x 10^7
- High 8.6 x 10^7

characteristics

- P = 27.7 MeV/c
- ΔP = 0.3 MeV/c
- σ_X = 9.5 mm
- σ_Y = 10. mm