New limit on the Lepton Flavor Violating decay $\mu \rightarrow e\gamma$

Flavio Gatti - University and INFN of Genoa, Italy

FNAL, Sept. 1st , 2011

The MEG collaboration

Tokyo U.
Waseda U.
KEK

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

PSI

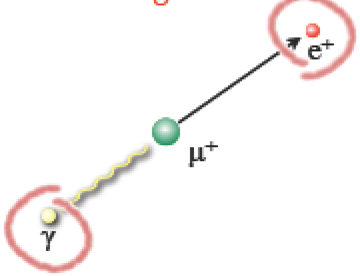
UCIrvine

JINR Dubna
BINP Novosibirsk

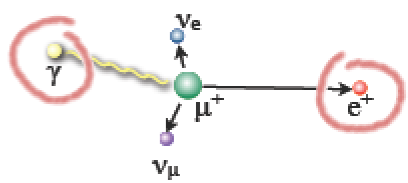
61 collaborators/5 countries

Kinematics

"Signal"

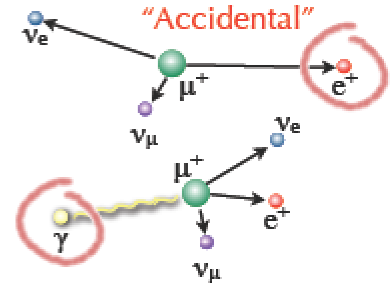


"RMD"



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

"Accidental"



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

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

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

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

$E_e = E_\gamma = 52.8$ MeV

$\theta_{e\gamma} = 180°$

$t_{e\gamma} \sim 0$

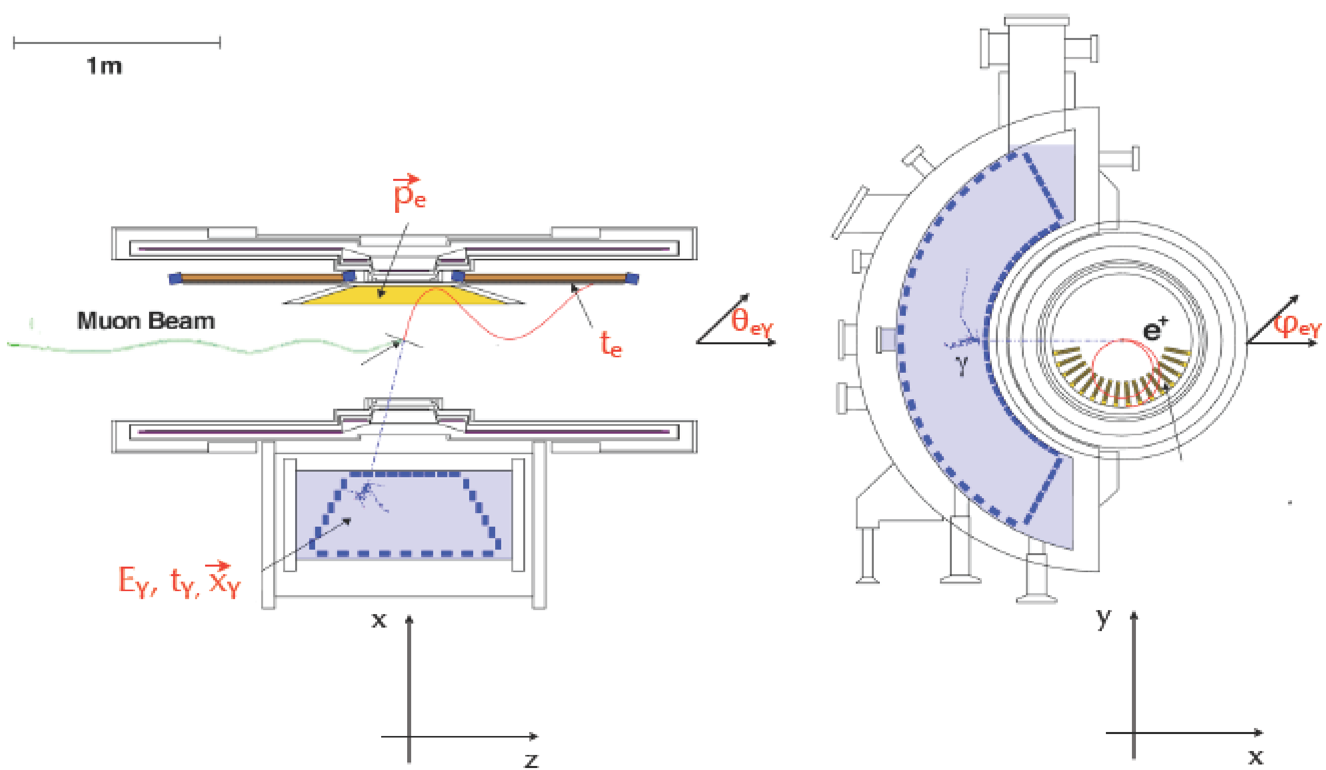
$B_{\text{prompt}} \approx 0.1 \times B_{\text{acc}}$

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

Apparatus Overview

Stopped πE5 beam of 3 10^7 μ /sec in a 150 μm target

1. Drift Chambers for e^+ momentum (DCH) in Magnetic Field
2. Scintillation counters for e^+ timing (TC) in Magnetic Field
3. Liquid Xenon calorimeter for γ energy and timing (LXe) (scintillation)



PSI muon beam

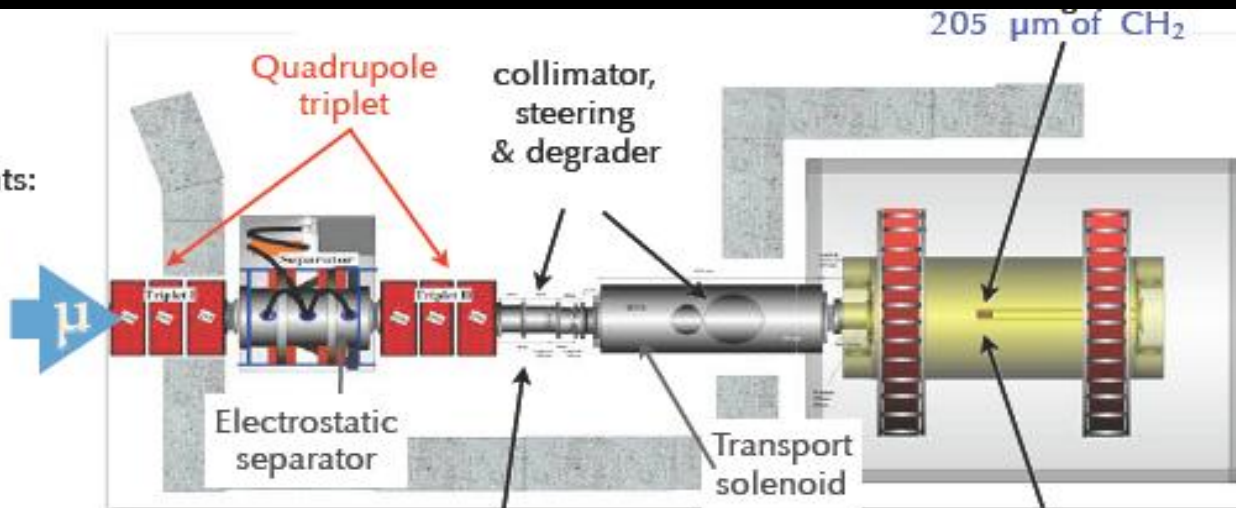
- Paul Scherrer Institut (CH)→Most intense continuous muon beam
- 1.6 MW proton accelerator
- Presently, more than 2 mA of protons (possible upgrade to 3 mA)
- Highly stable beam
- > 3 x 108 muons/sec @ 2 mA

Beam line

πE5 beam line at PSI

Optimization of the beam elements:

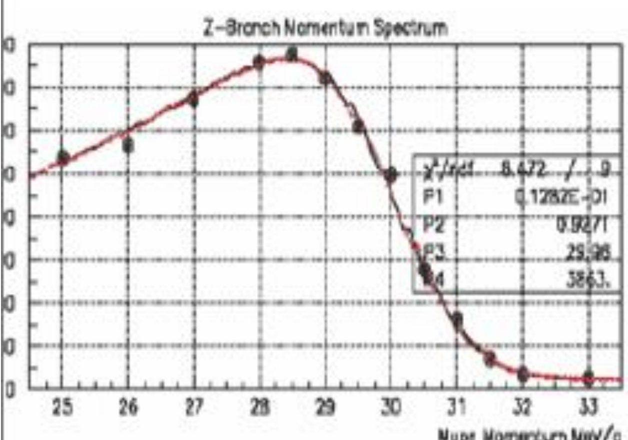
- Muon momentum ~ 29 MeV/c
- Wien filter for μ/e separation
- Solenoid to couple beam and spectrometer (BTS)
- Degrader to reduce the momentum for a 205 μm target

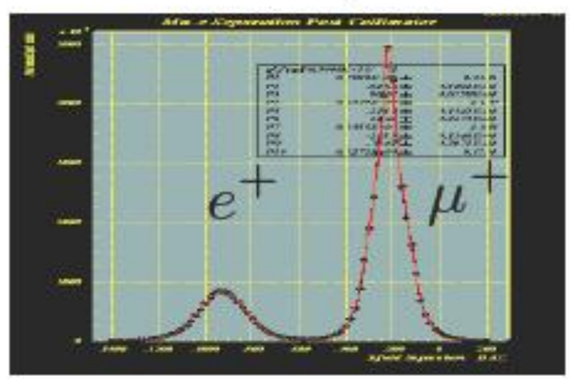


μ/e separation 11.8 cm (7.2 σ)

R_μ (exp. on target) $3 \times 10^7\ \mu^+/s$

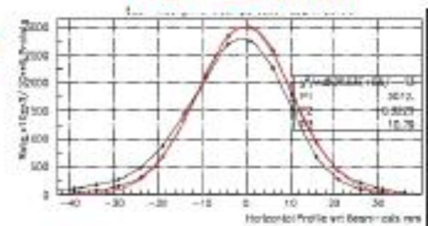
μ spot (exp. on target) $\sigma_V \approx \sigma_H \approx 11$ mm



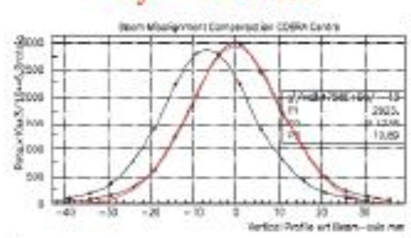


II

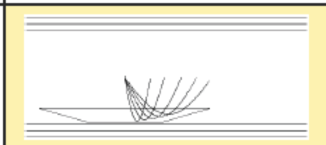
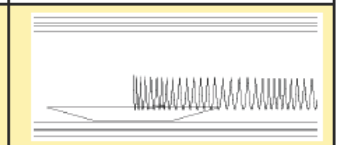
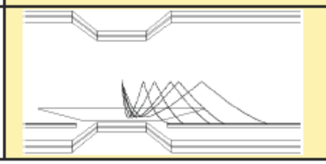
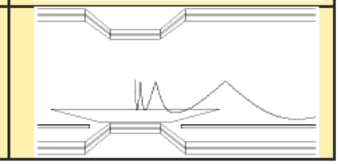
$\sigma_x = 11$ mm



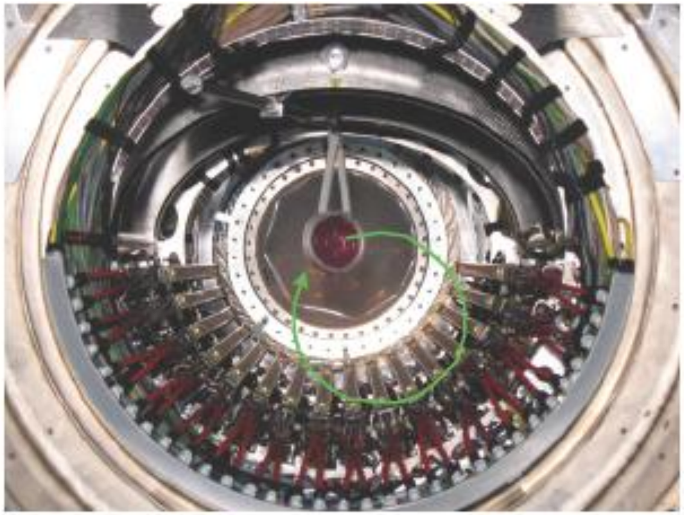
$\sigma_y = 11$ mm



Constant Bending Radius solenoid (CoBRa)

	Constant $|p|$ track	High p_T track
Uniform field		
CoBRa: Constant bending quick sweep away		

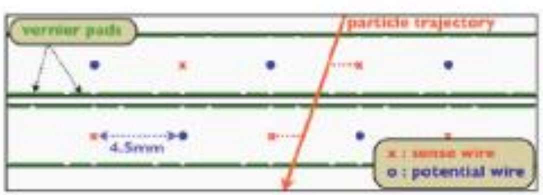
Tracking the Positrons: Drift Chambers

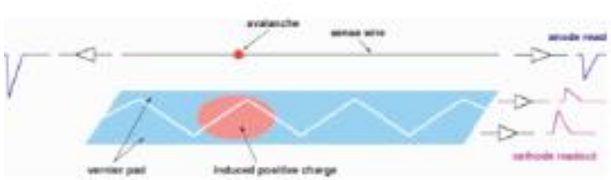


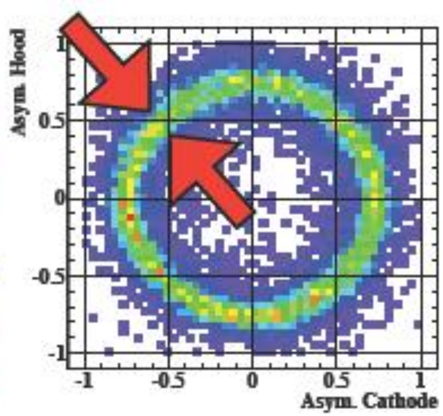
- 16 chambers radially aligned with 10° intervals
- 2 staggered arrays of drift cells
- 1 signal wire and 2 x 2 vernier cathode strips made of 15 μm kapton foils and 0.45 μm aluminum strips
- Chamber gas: He-C_2H_6 mixture
- Within one period, fine structure given by the Vernier circle

  σ_R ~ 300 μm transverse coordinate (t drift)

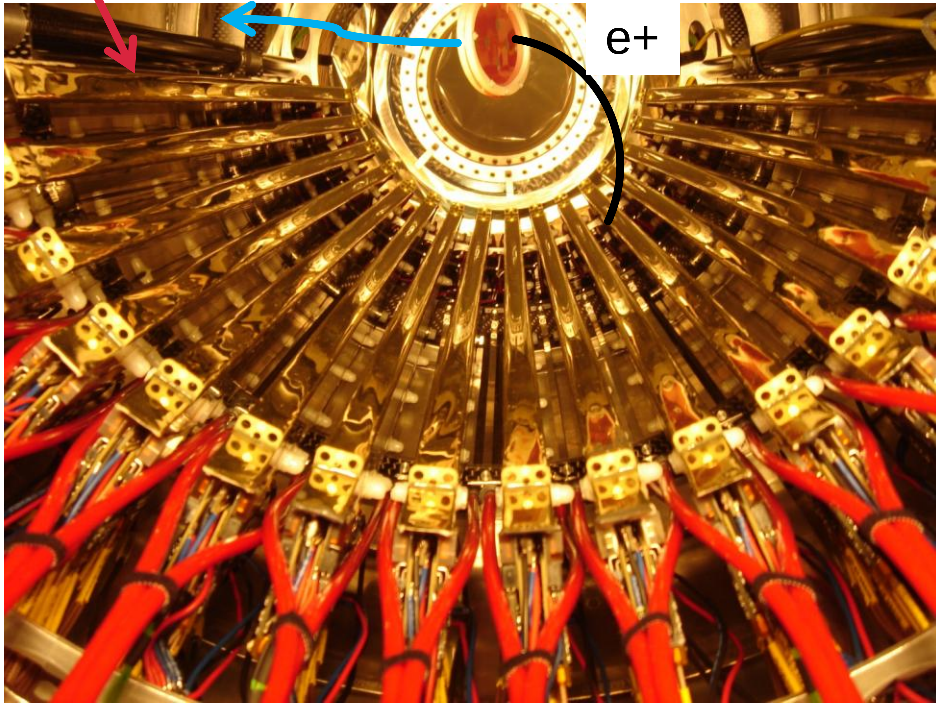
  σ_z ~ 700 μm longitudinal coordinate (Vernier)

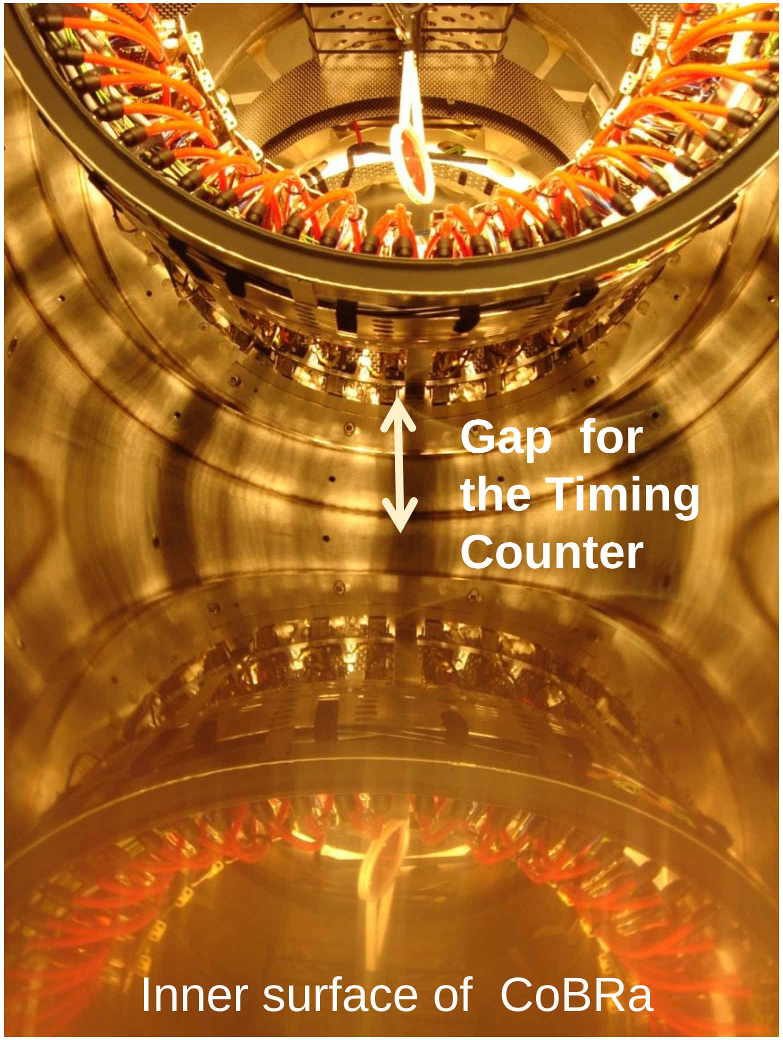




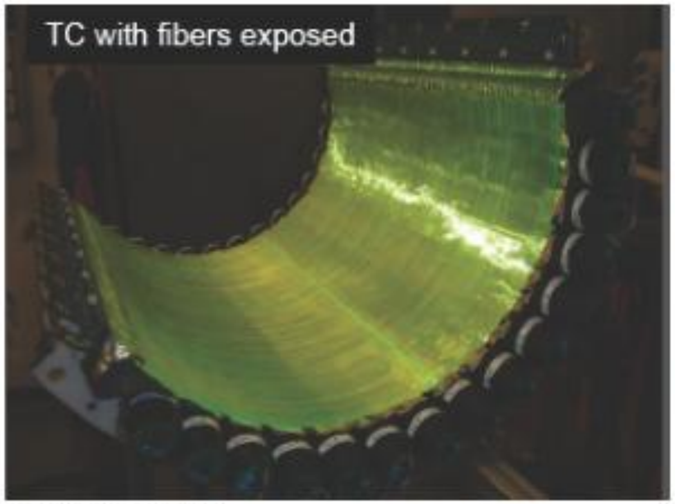


A view of Drift chambers inside the Magnet CoBra

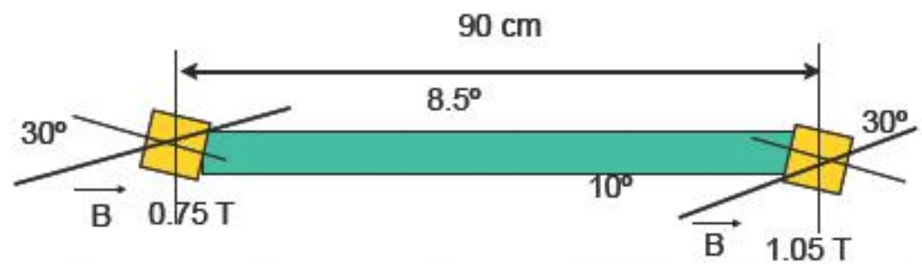


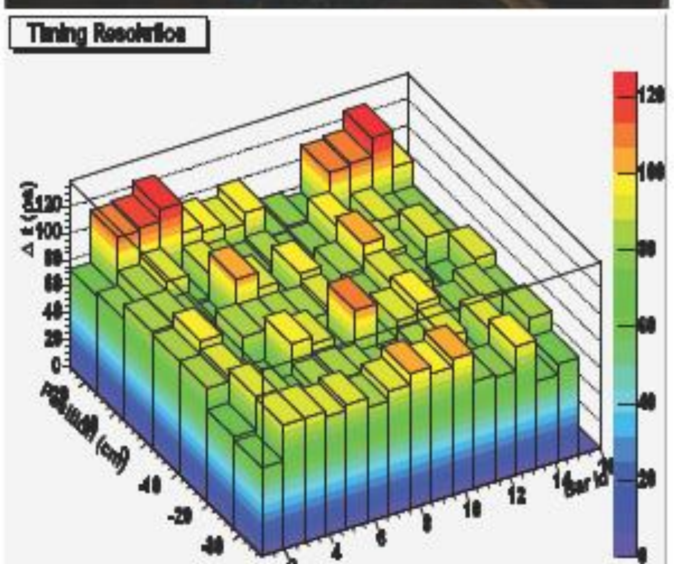


Timing (tracking) the positron



- Two layers of scintillators:
  Outer layer, read out by PMTs: timing measurement
  Inner layer, read out with APDs at 90°: z-trigger
- Resolution σ_{time}~ 40 psec (100 ps FWHM)

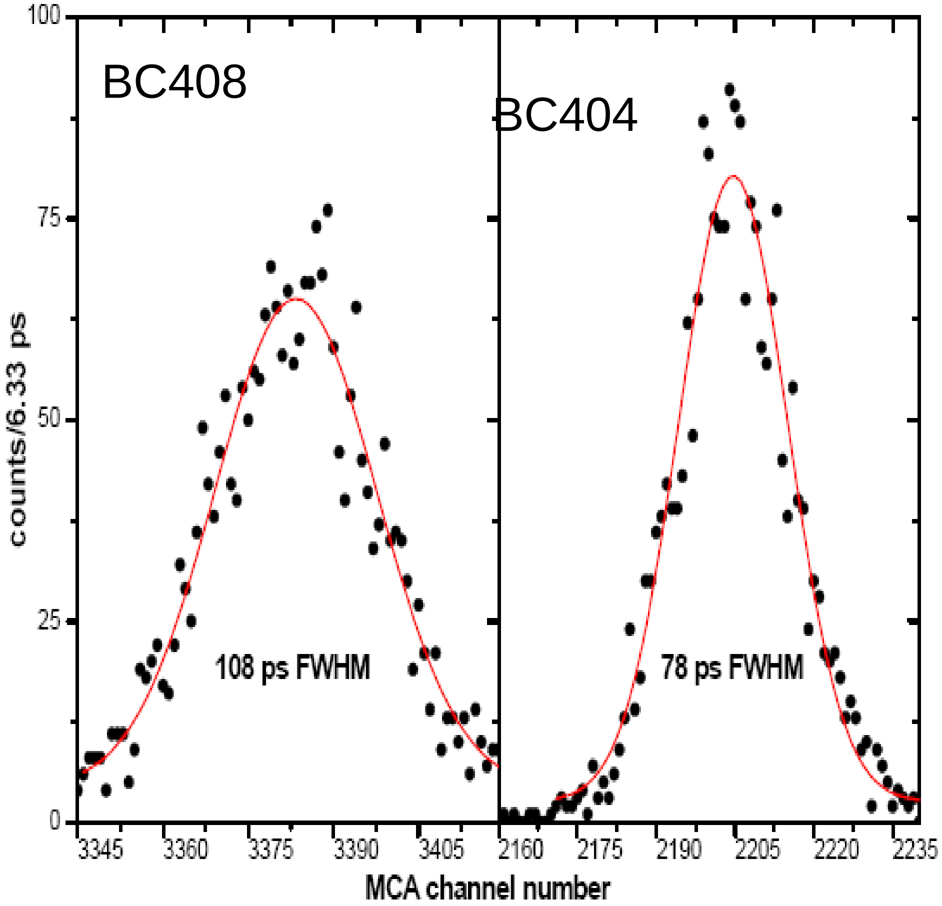




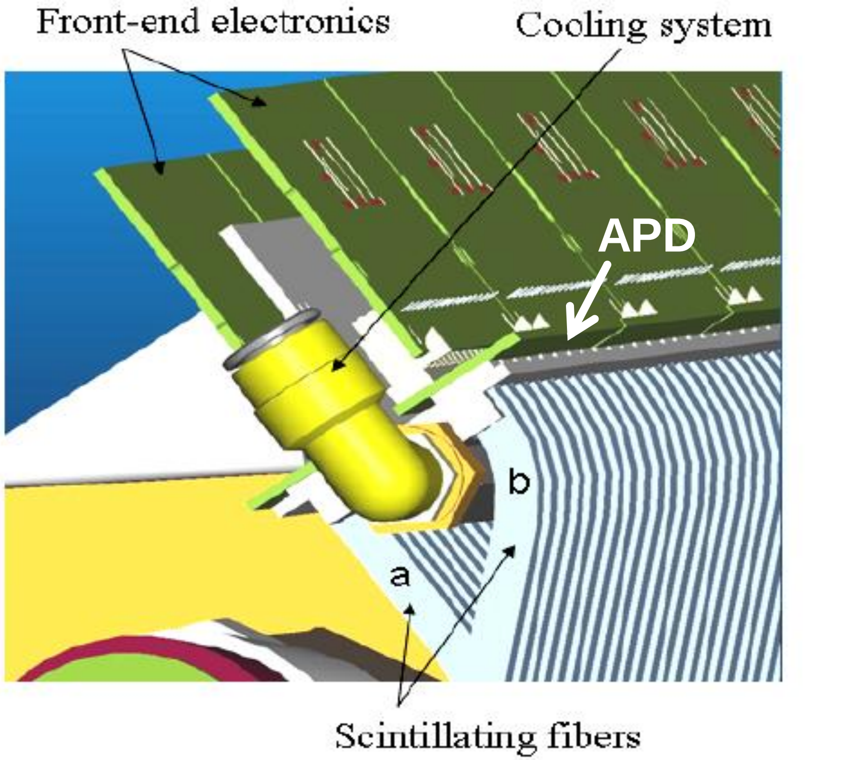
Exp. application (*)	Counter size (cm) (T x W x L)	Scintillator	PMT	λ_{att} (cm)	σ_t(meas)	σ_t(exp)
G.D.Agostini	3x 15 x 100	NE114	XP2020	200	120	60
T. Tanimori	3 x 20 x 150	SCSN38	R1332	180	140	110
T. Sugitate	4 x 3.5 x 100	SCSN23	R1828	200	50	53
R.T. Gile	5 x 10 x 280	BC408	XP2020	270	110	137
TOPAZ	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**	

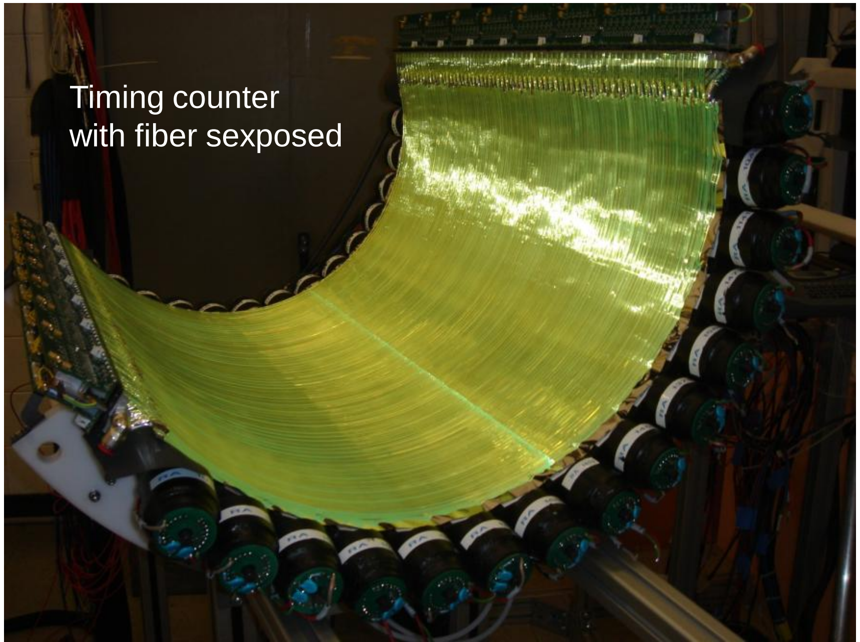
Best existing TC

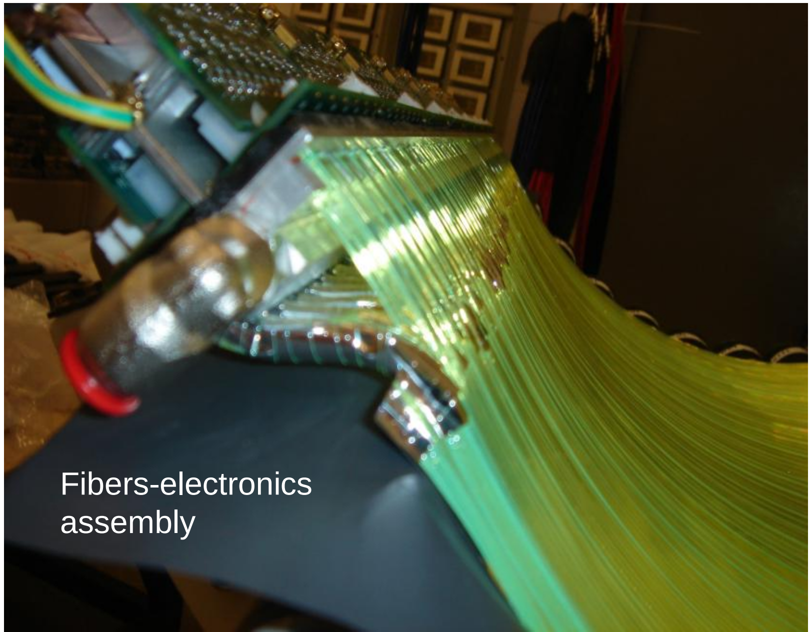
Fully Tested at BTF (LNF-ITALY)



Timing Counter

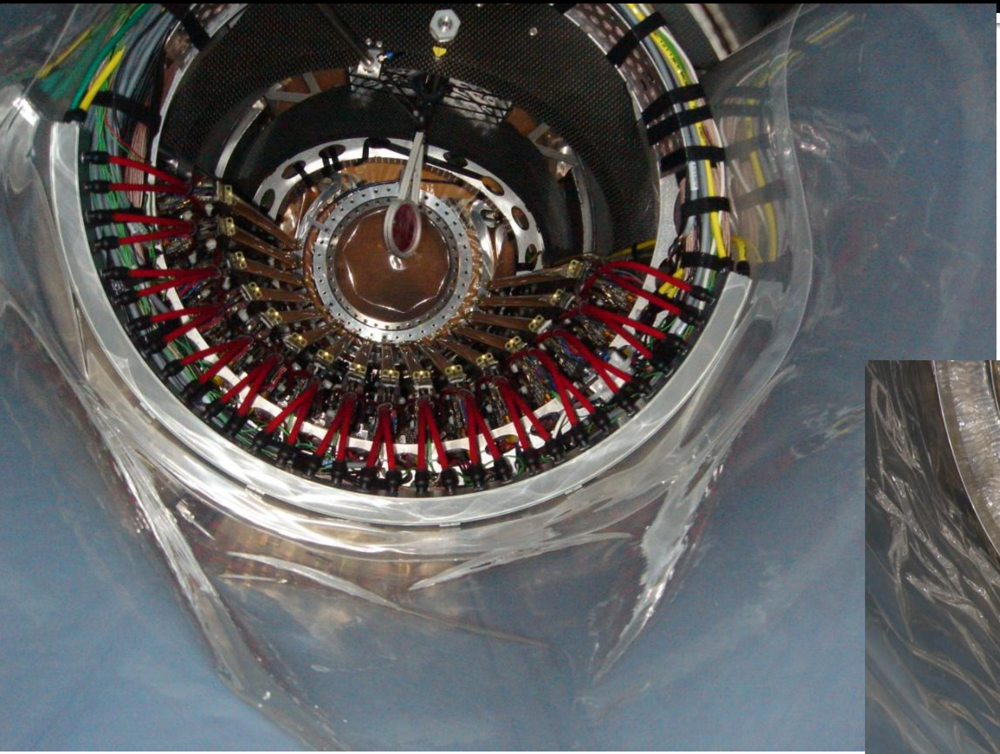






Timing Counter

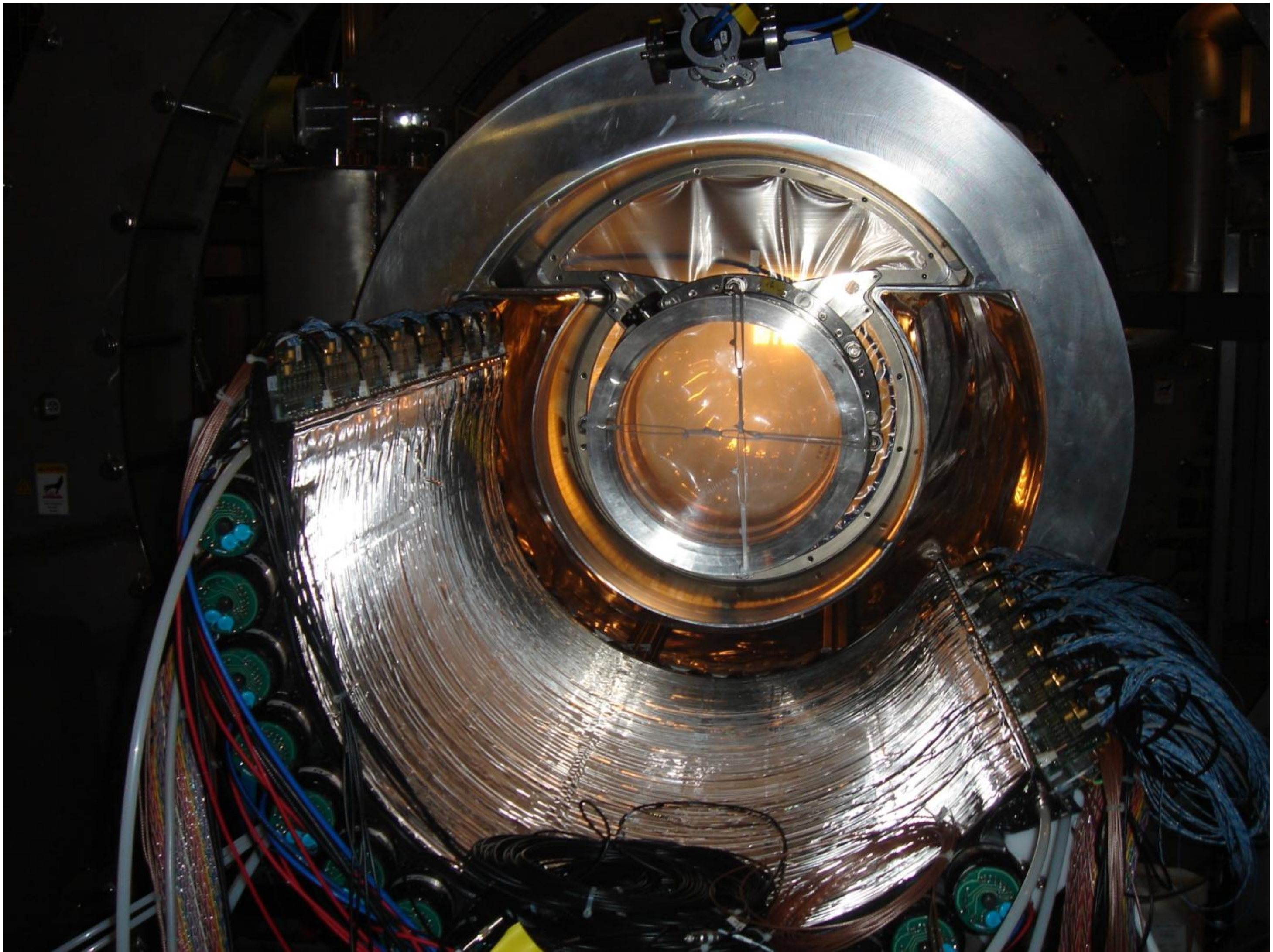
The most important thing:
a plastic Bag against the He atmosphere of CoBra



Special new plastic used for "mozzarella" 's bag (EVAL) has been produced with a thickness of 250 um (typically 25-50 um)

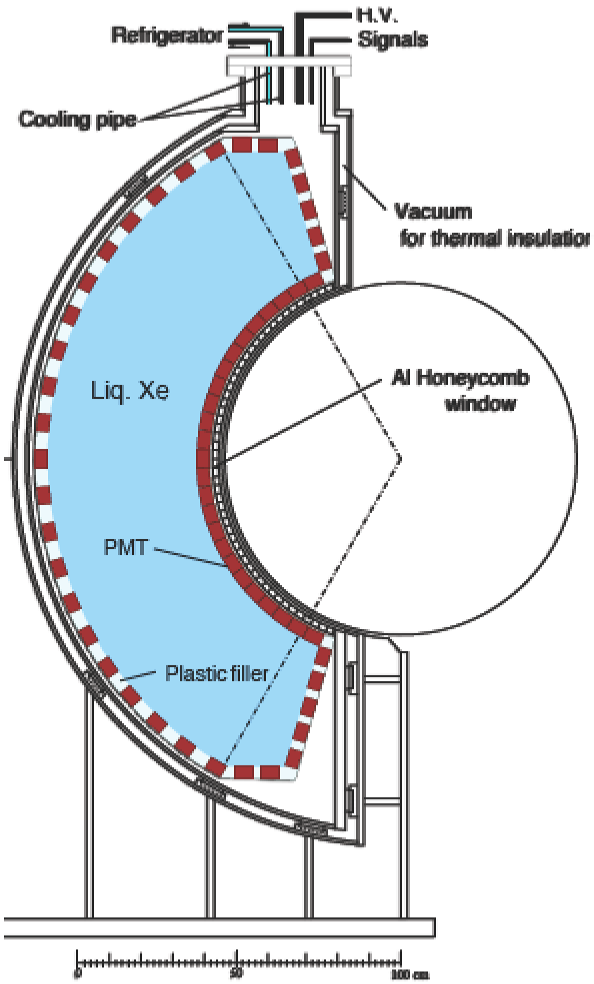
EVAL has one of the lowest He diffusivity coefficient among plastics:
With 2 m^2 surface expose to 1 atm He
We achieve 1-10 times the natural atmospheric He partial pressure

TC before insertion in the Magnet



LXe

- γ Energy, position, timing
- Homogeneous 0.8 m^3 volume of liquid Xe = 2.7 t
  - 10 % solid angle
  - 65 < r < 112 cm
  - |cosθ| < 0.35, |ϕ| < 60.0
- Only scintillation light
  - Read by 848 PMT 2" photo-multiplier tubes
  - • Maximum coverage
  - • Immersed in liquid Xe
  - • Low temperature (165 K)
  - • Quartz window (178 nm)
- Thin entrance wall
- Waveform digitizing @2 GHz
  - Pileup rejection



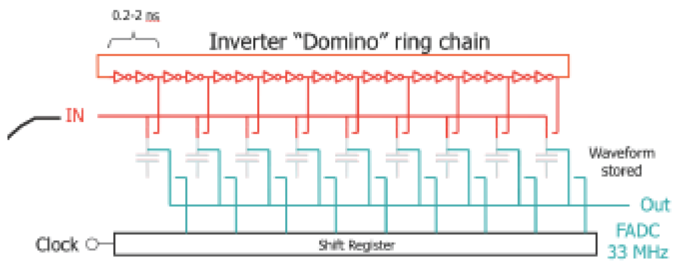
Lxe cryostat

- Inner PMT array, Cryostat, final positioning



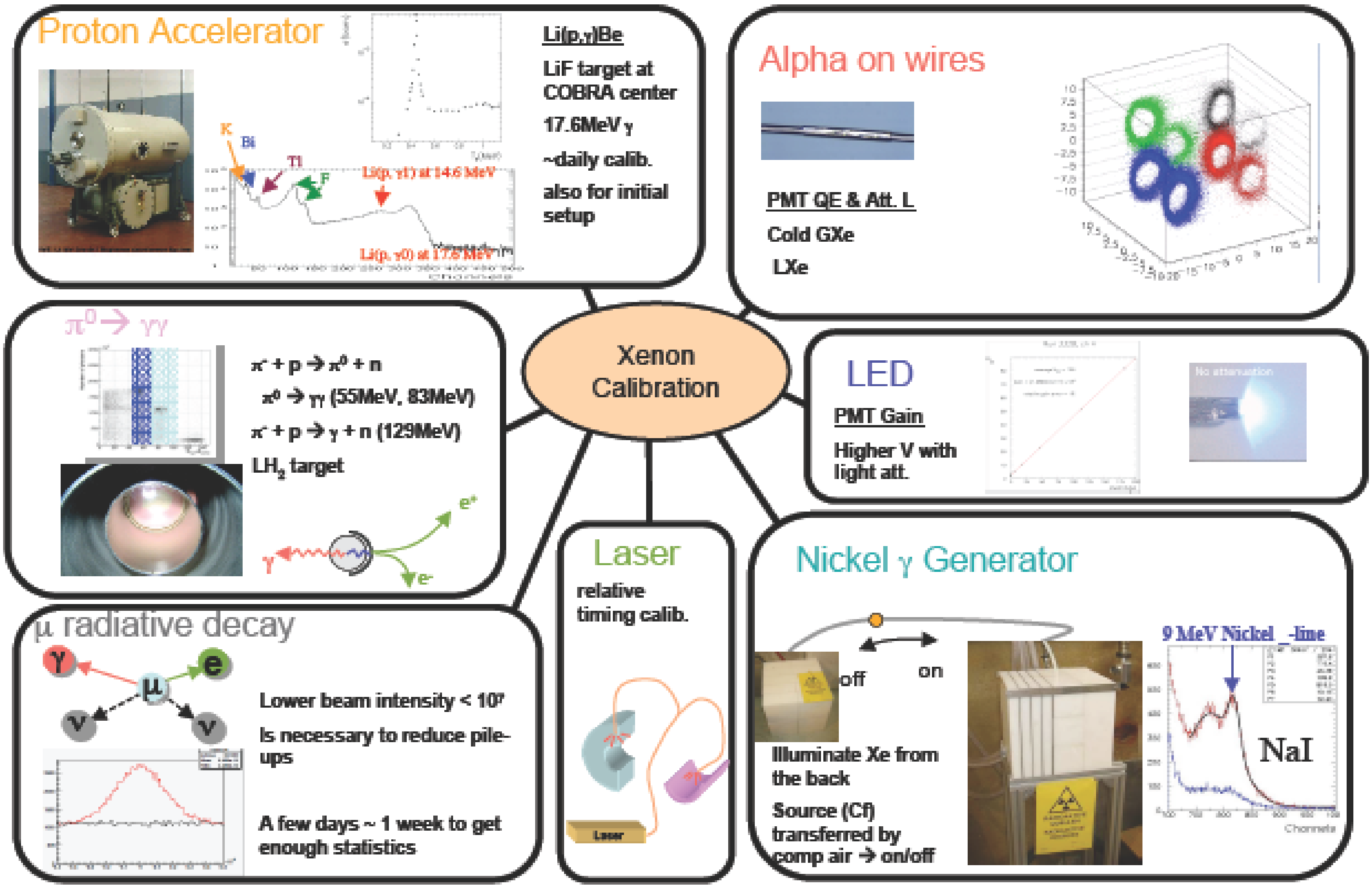
Digitizer for DAQ

- All channels are readout by a GHz WFD



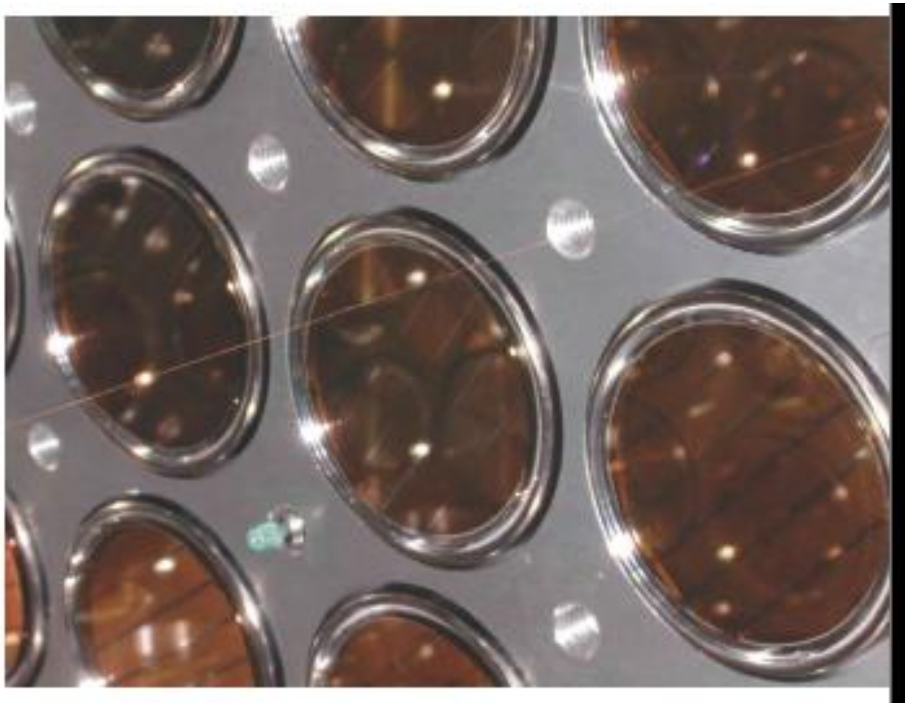
- DRS chip (Domino Ring Sampler)
  - Custom sampling chip designed at PSI (BW of 950 MHz)
  - 0.2→5GHz sampling. →40 ps timing resolution
  - Sampling depth 1024 bins for 9 channels/chip
  - Full waveform is a handle to do pile-up rejection

Calibrations and Monitoring



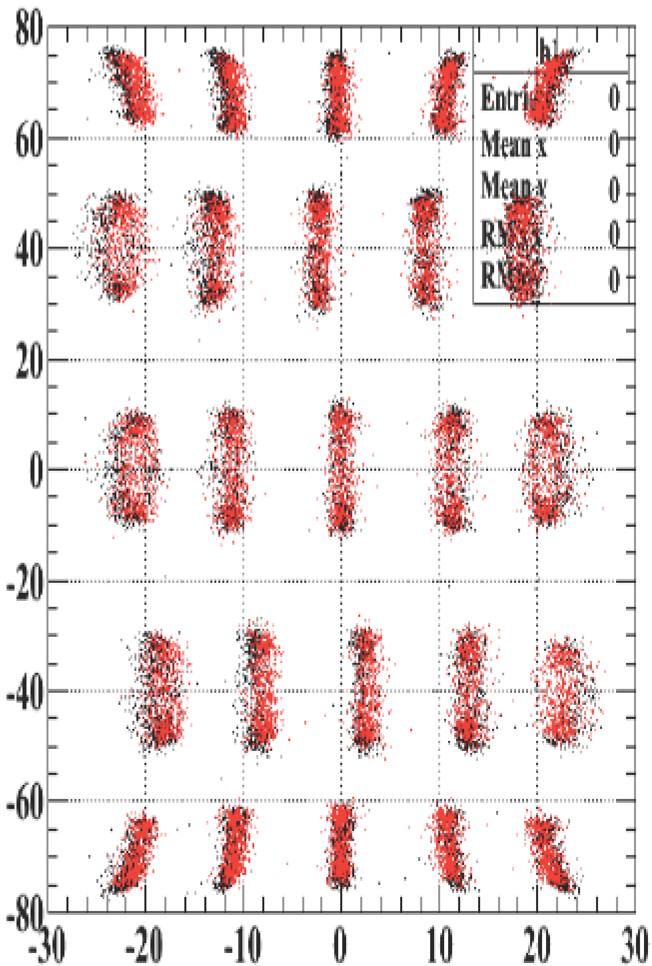
An example: the alpha sources

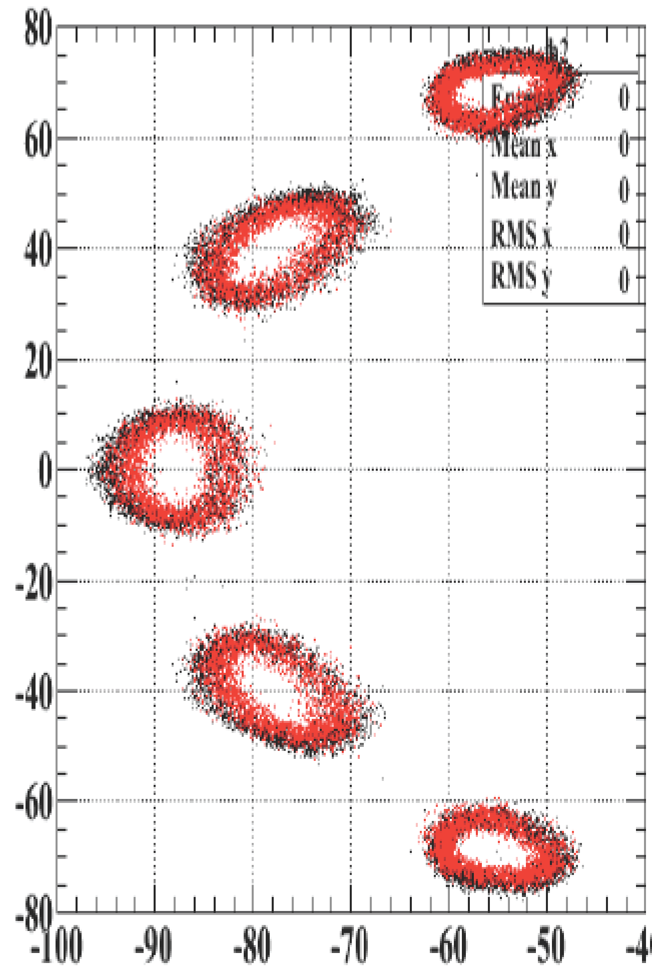
- It is understood that in such a complex detector a lot of parameters must be constantly checked
- We have prepared several and redundant calibration and monitoring tools:
  - • Single detector
  - • PMT equalization for LXe and TIC
  - • Inter-bar timing (TIC)
  - • Energy scale
  - • Multiple detectors
  - • relative timing



Alpha-rings,

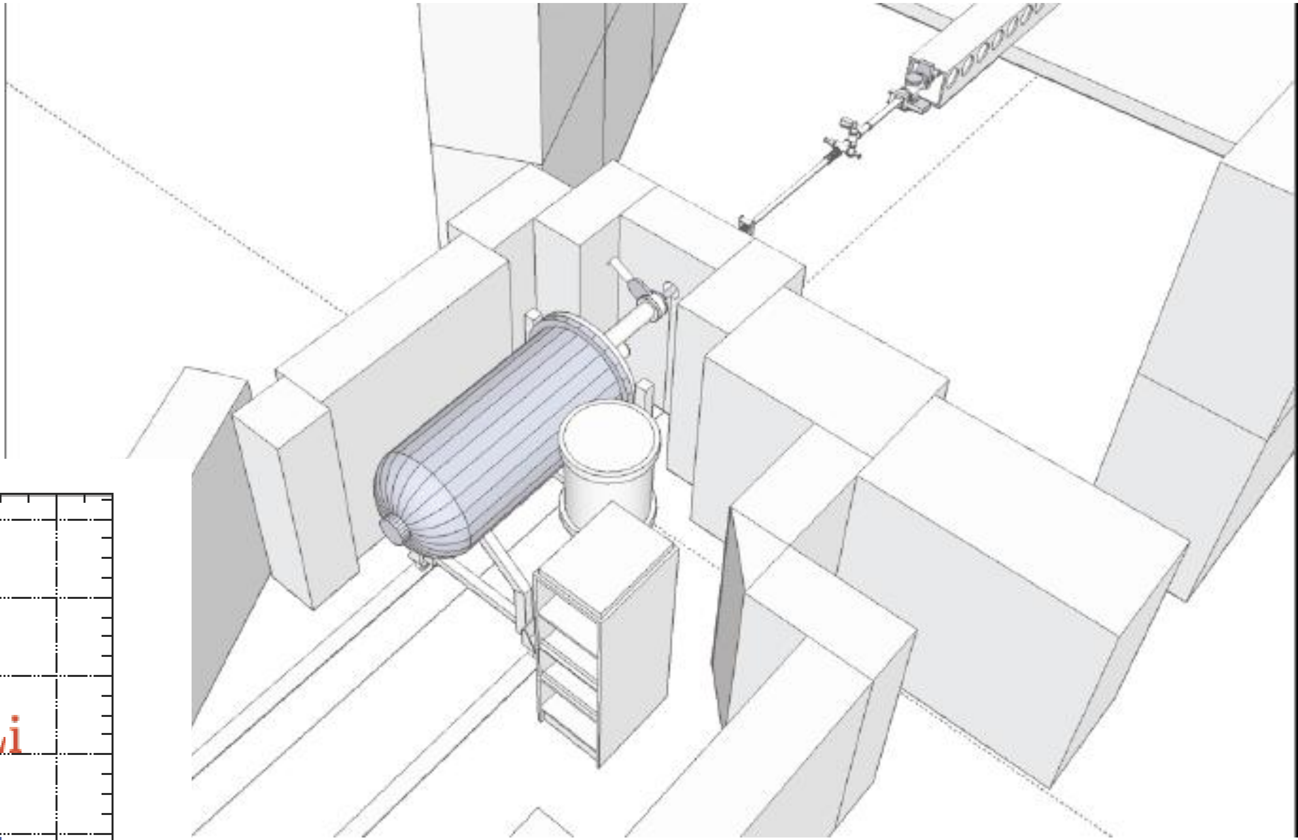
Reconstructed signal from alpha source onto thin wire in LXe

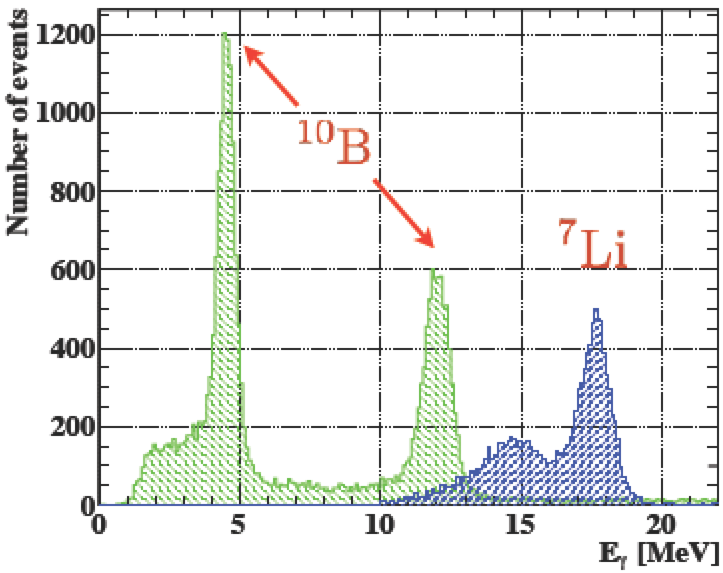




An example: the Lxe Calibration

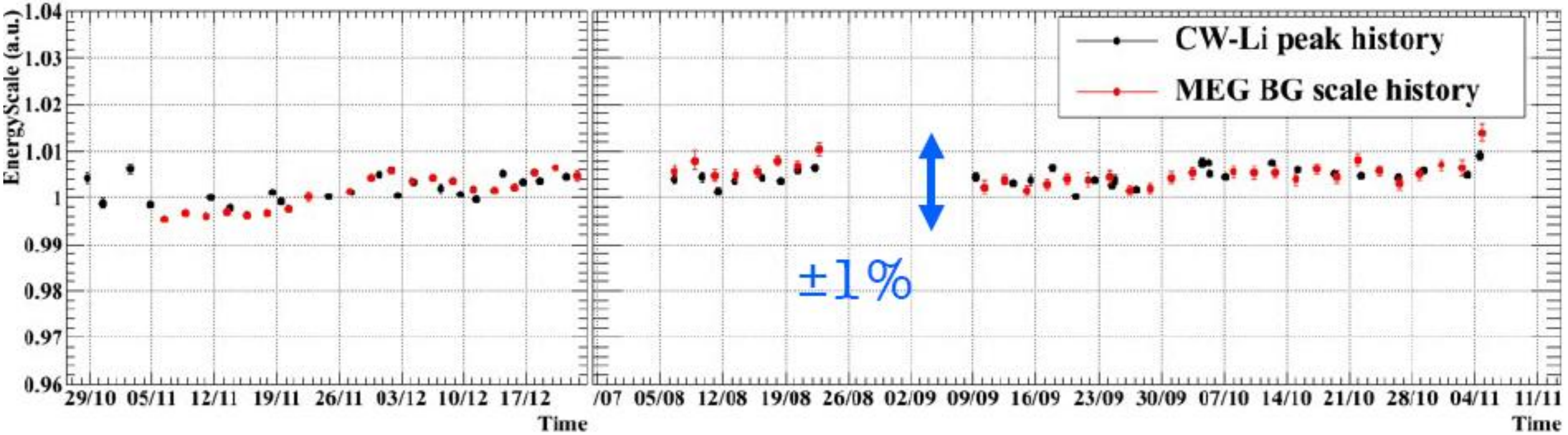
- This calibration is performed routinely
- Muon target moves away and a crystal target is inserted
- Hybrid target (Li2B4O7)
- Possibility to use the same target and select the line by
- changing proton energy





Reaction	Peak energy	σ peak	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

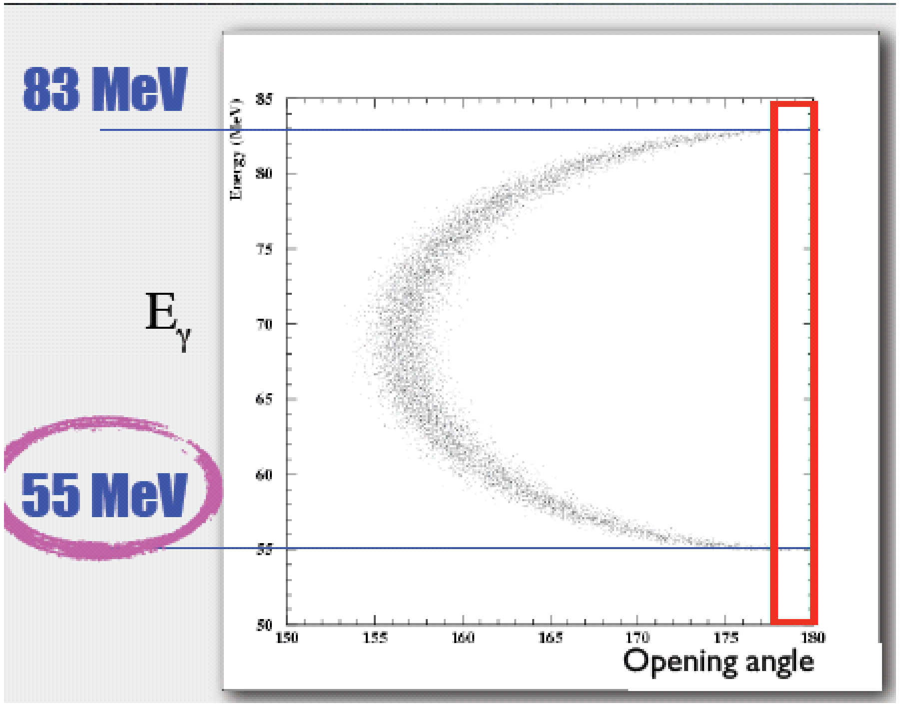
Gamma Energy stability



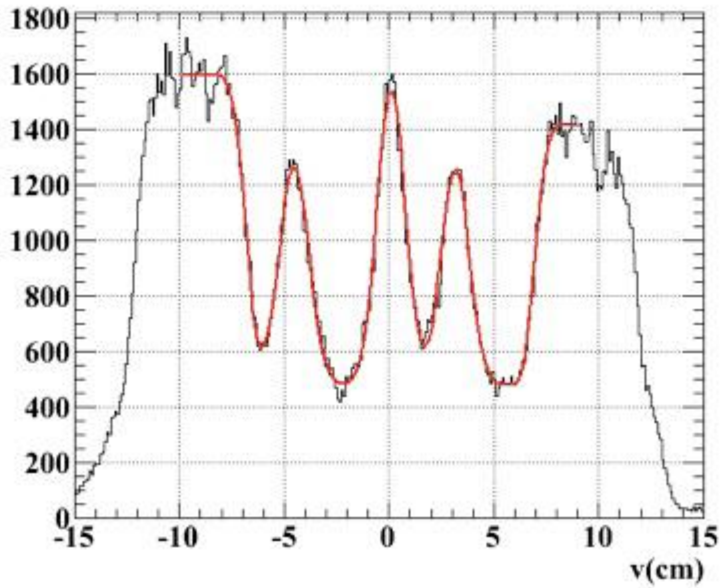
Gamma Energy Calibration

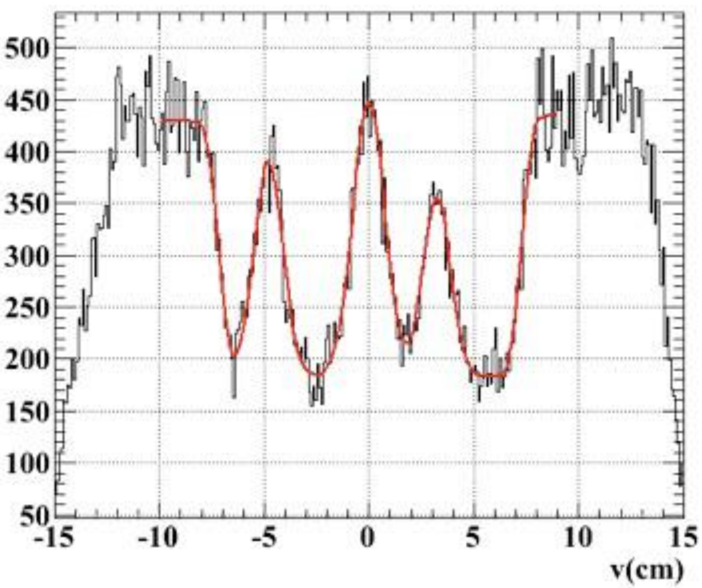
$$\pi^- p \to \pi^0 n \to \gamma\gamma n$$

- negative pions stopped in liquid hydrogen target
- Tagging the other photon at 180o provides monochromatic photons
- Dalitz decays were used to
- study positron-photon synchronization and time
- resolution: $\pi_o \longrightarrow \gamma e{+}e{-}$



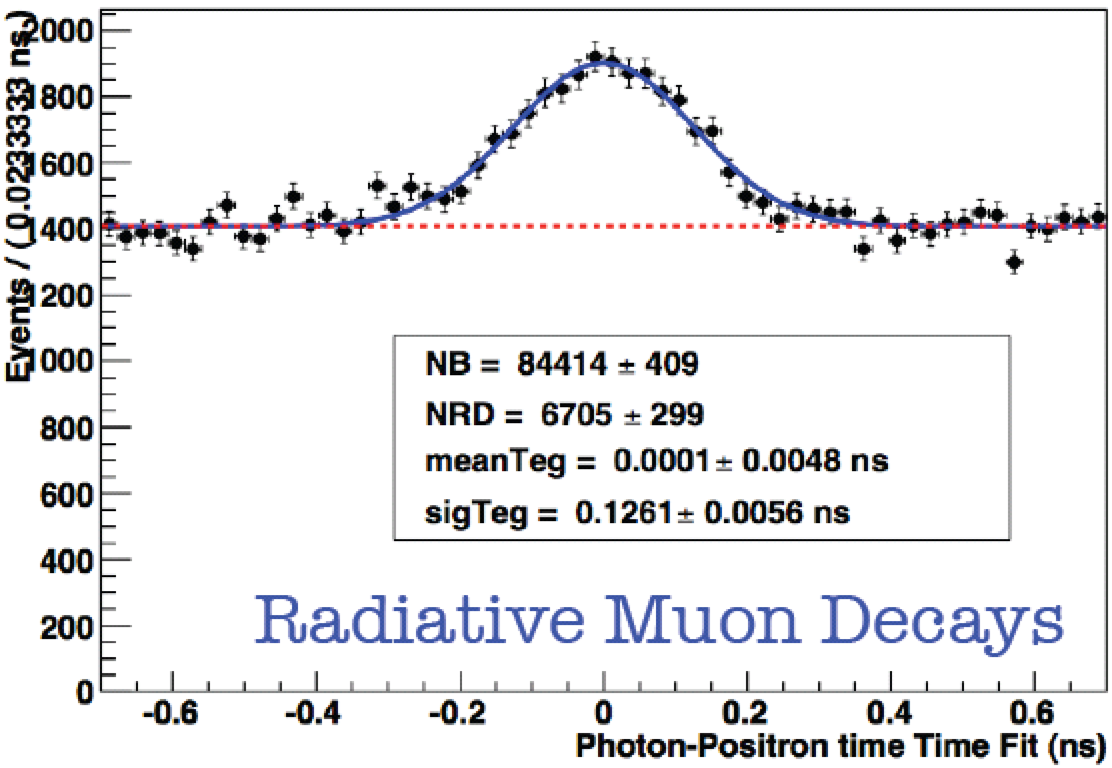
Gamma Position Resolution





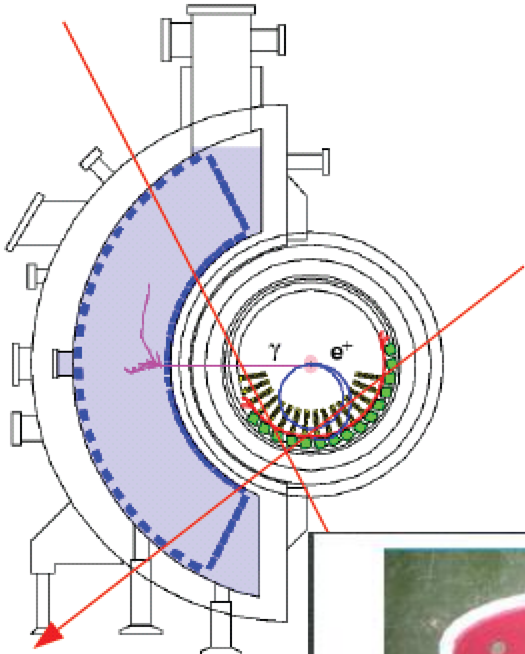
Hit point resolution for photon conversion position was evaluated by CEX run with Pb collimators ~ 5mm

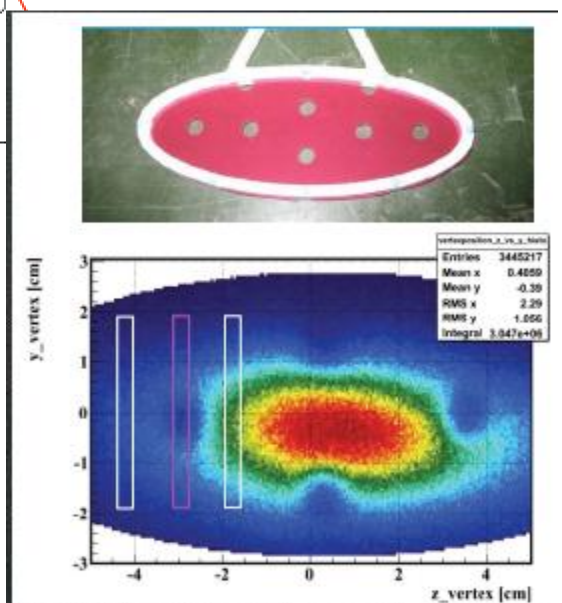
Teγ resolution



- Positron time measured by TC and corrected by ToF (DC trajectory)
- LXe time corrected by ToF to the conversion point
- RMD peak in a normal physics run corrected by small energy dependence;
- stable < 20ps

Alignements

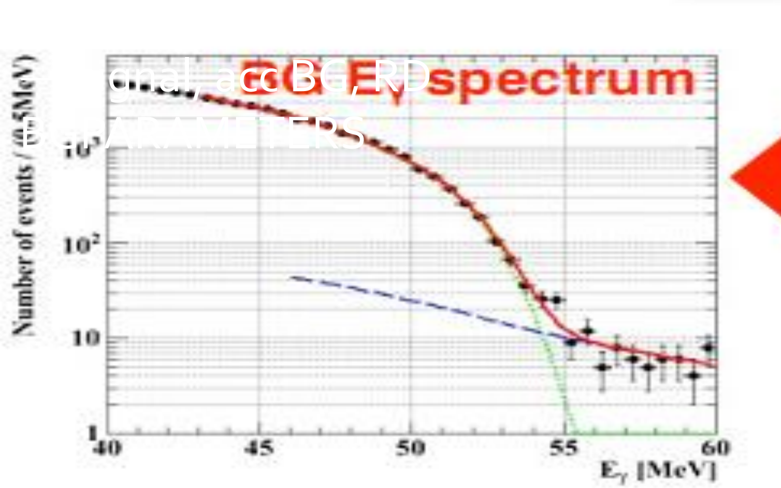


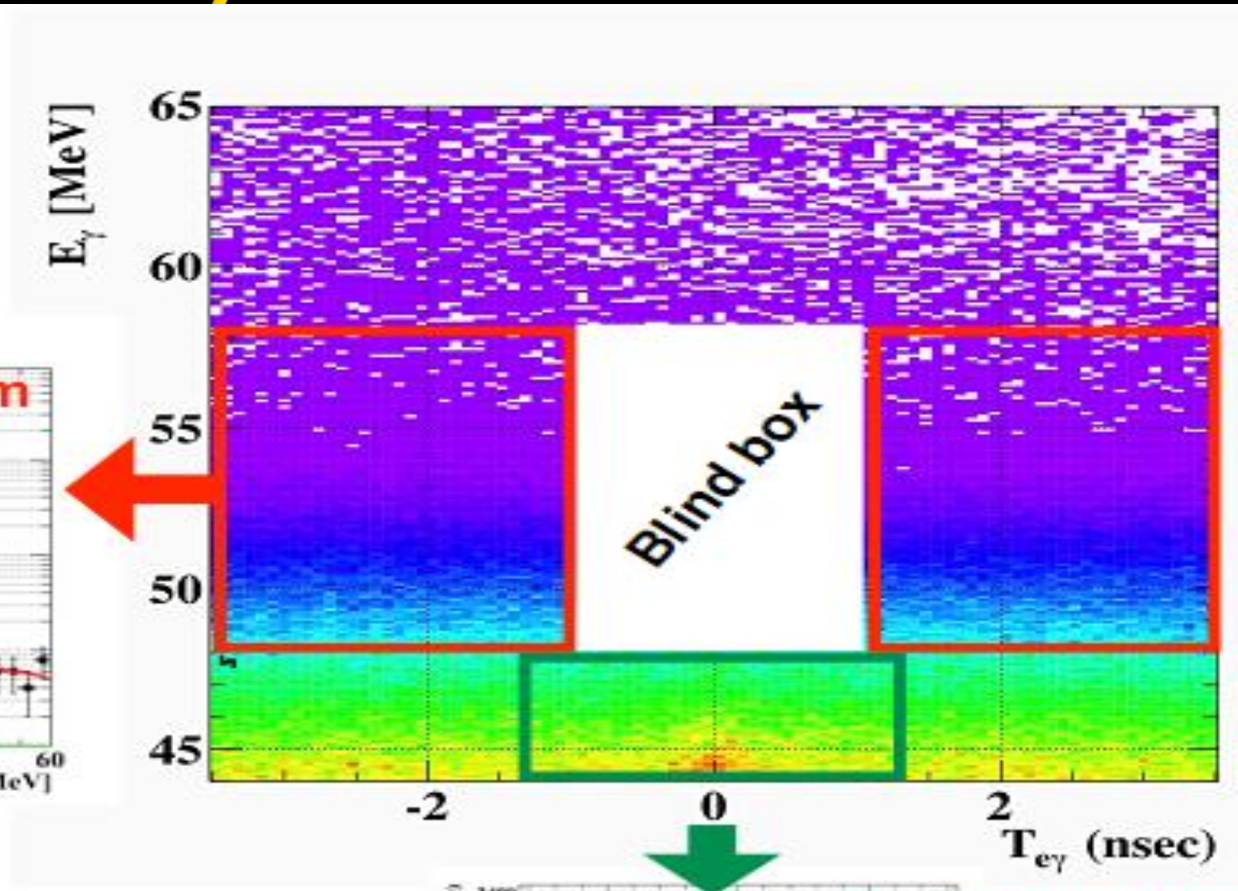


- alignment by CR & Michel e+
- DC - B field - target - LXe
- optical surveys
- DC: MILLEPEDE (like in CMS)
- target holes
- LXe: Pb collimators
- more detailed implementation of e+ correlation

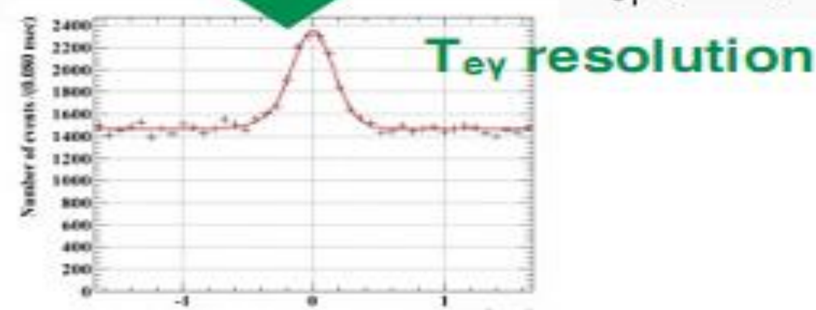
The Blind Analysis

Parameters:
(Eγ, Ee, Teγ, θeγ, φeγ)
Outputs:
signal, acc BG, RD BG





PDFs mostly from data
accidental BG: side bands
signal: measured resolution
radiative BG: theory + resolution



Analyis

Fully frequentist approach (Feldman & Cousins) with profile likelihood ratio ordering

PDF: methods of calculation

- SIGNAL

E_γ: from full signal MC (or from fit to endpoint)
E_e: 3-gaussian fit on data
$\theta_{e\gamma}$: combination of e and gamma angular resolution from data
$t_{e\gamma}$: single gaussian from MEG trigger Radiative Decay (no cut on Eg)

- RADIATIVE

$E_e, E_\gamma, \theta_{e\gamma}$: 3D histo PDF from toy MC that smears and weighs Kuno-Okada distribution taking into account resolution and acceptance
$t_{e\gamma}$: single gaussian with same resolution as signal

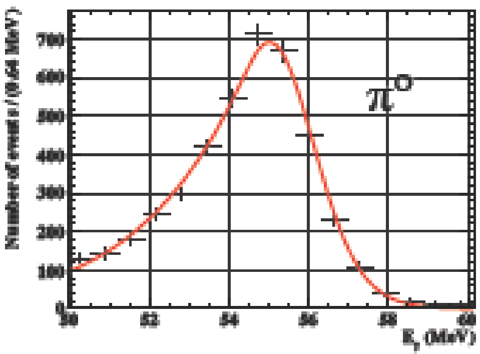
- ACCIDENTAL

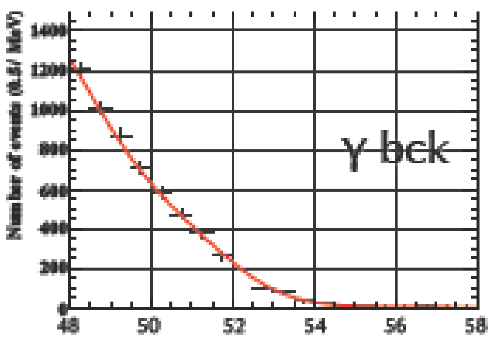
E_γ: from fit to $t_{e\gamma}$ sideband
E_e: from data
$\theta_{e\gamma}$: from fit to $t_{e\gamma}$ sideband
$t_{e\gamma}$: flat

Alternative observables definition
1) different algorithm for LXe Timing
2) Trigger LXe waveform digitizing electronics (E_γ)

PDF plots and resolutions

E_γ

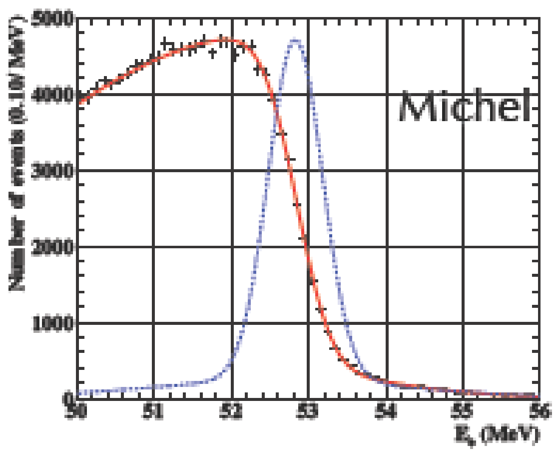




- Average upper tail for deep conversions
  - $\sigma_R = (2.1 \pm 0.15)$ %
- Systematic uncertainty on energy scale < 0.6%

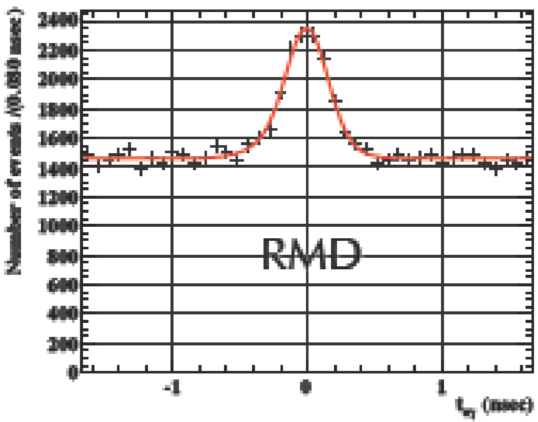
E_{e^+}

- Resolution functions of core and tail components
  - core = 390 keV (0.74%)
- Positron angle resolution measured using multi-loop tracks
  - $\sigma(\varphi) = 7.1$ mrad (core)
  - $\sigma(\vartheta) = 11.2$ mrad



- Overall angular resolution combining
  - XEC+DCH+target
    - $\sigma(\varphi) = 12.7$ mrad (core)
    - $\sigma(\vartheta) = 14.7$ mrad

$t_{e\gamma}$



- 40 MeV < E_γ < 48 MeV
- σ_t is corrected for a small energy-dependence
  - (142 ± 15) ps
  - stable within 15 ps along the run
- MEGA had on RMD
  - 700 ps resolution

The calculation of BR

- The normalization factor is obtained from the number of observed Michel positrons taken simultaneously (pre-scaled) with the μ→eγ trigger
  - Cancel at first order
  - Absolute e+ efficiency and DCH instability
  - Instantaneous beam rate variations

$$\frac{\mathcal{B}(\mu^+ \to e^+\gamma)}{\mathcal{B}(\mu^+ \to e^+\nu\bar{\nu})} = \frac{N_{\rm sig}}{N_{e\nu\bar{\nu}}} \times \frac{f^{e}_{e\nu\bar{\nu}}}{P \cdot \epsilon_{\rm pu}} \times \frac{\epsilon^{\rm trig}_{e\nu\bar{\nu}}}{\epsilon^{\rm trig}_{e\gamma}} \times \frac{\epsilon^{\rm DC}_{e\nu\bar{\nu}}}{\epsilon^{\rm DC}_{e\gamma}} \times \frac{1}{A^{\rm geo}_{e\gamma}} \times \frac{1}{\epsilon_{e\gamma}}$$

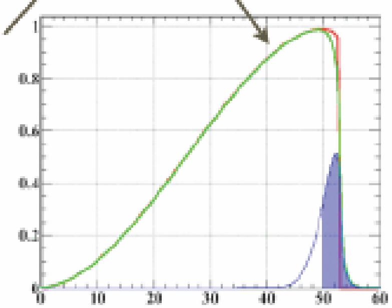
~18k

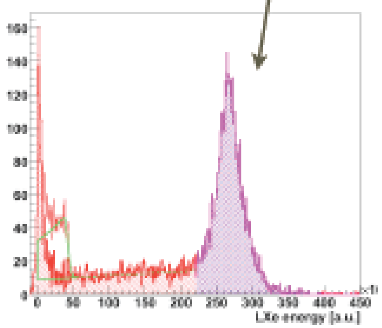
10^7

theory

resolution

acceptance





B.R. = N_{sig} x (1.01 ± 0.08) × 10^{-12}

The Likelihood

- A μ→eγ event is described by 5 kinematical variables

$$\vec{x_i} = (E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})$$

- Likelihood function is built in terms of Signal, radiative Michel decay RMD and background BG number of events and their probability density function PDFs

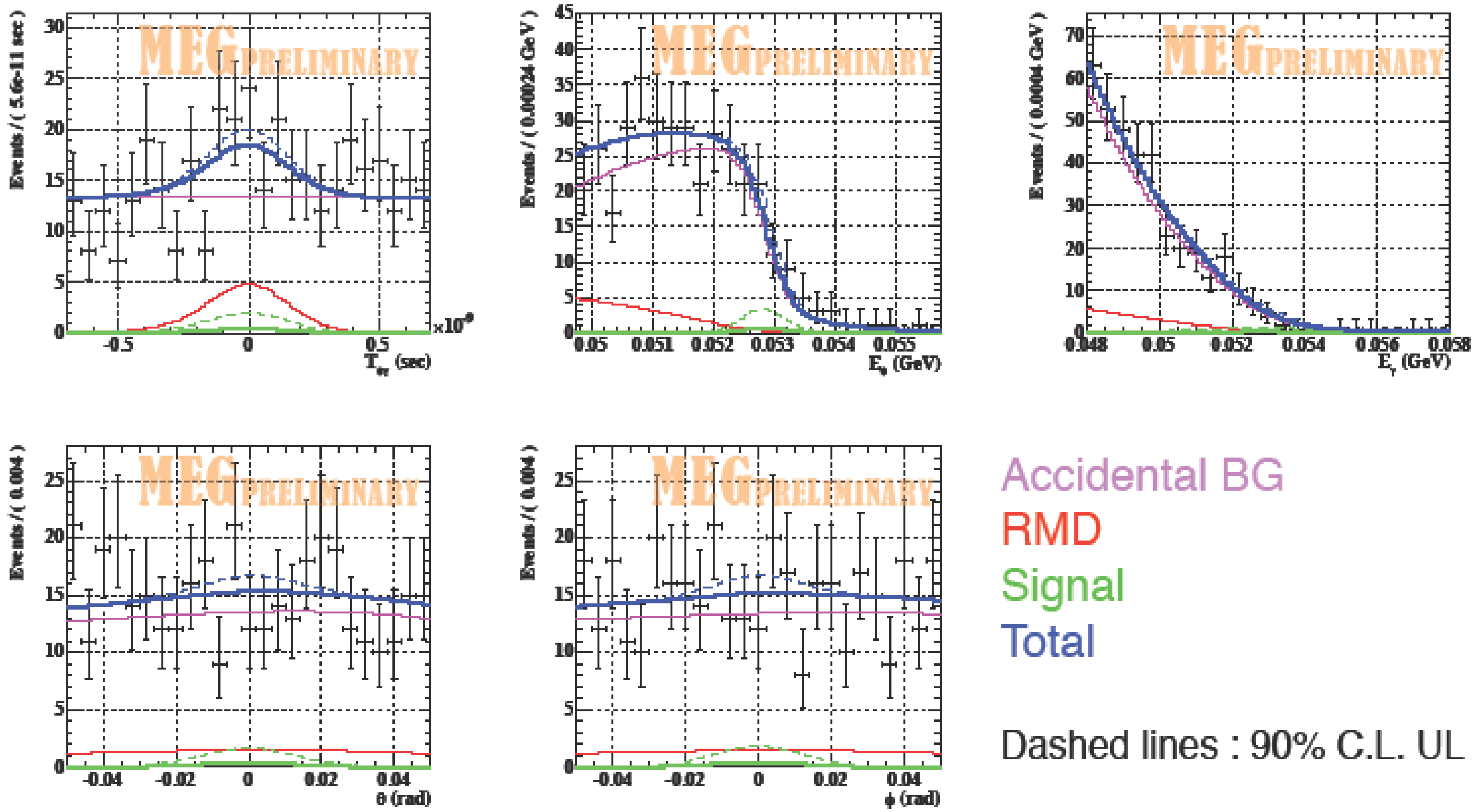
$$\begin{aligned} &-\ln \mathcal{L}\left(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{BG}}\right) \\ &\;= N_{\mathrm{exp}} - N_{\mathrm{obs}} \ln\left(N_{\mathrm{exp}}\right) \\ &\quad - \sum_{i=1}^{N_{\mathrm{obs}}} \ln\left[\frac{N_{\mathrm{sig}}}{N_{\mathrm{exp}}} S(\vec{x_i}) + \frac{N_{\mathrm{RMD}}}{N_{\mathrm{exp}}} R(\vec{x_i}) + \frac{N_{\mathrm{BG}}}{N_{\mathrm{exp}}} B(\vec{x_i})\right] \end{aligned}$$

- Extended unbinned likelihood fit: mfit (Nsig, NRMD, NBG) in a wide region
- PDFs taken from
  - \- data
  - \- MC tuned on data
- Cuts:

• $48 \le E\gamma \le 58$ MeV • $50 \le Ee \le 56$ MeV • $|Te\gamma| \le 0.7$ ns • $|\phi e\gamma|, |\theta e\gamma| \le 50$ mrad

The Likelihood plots for 2009

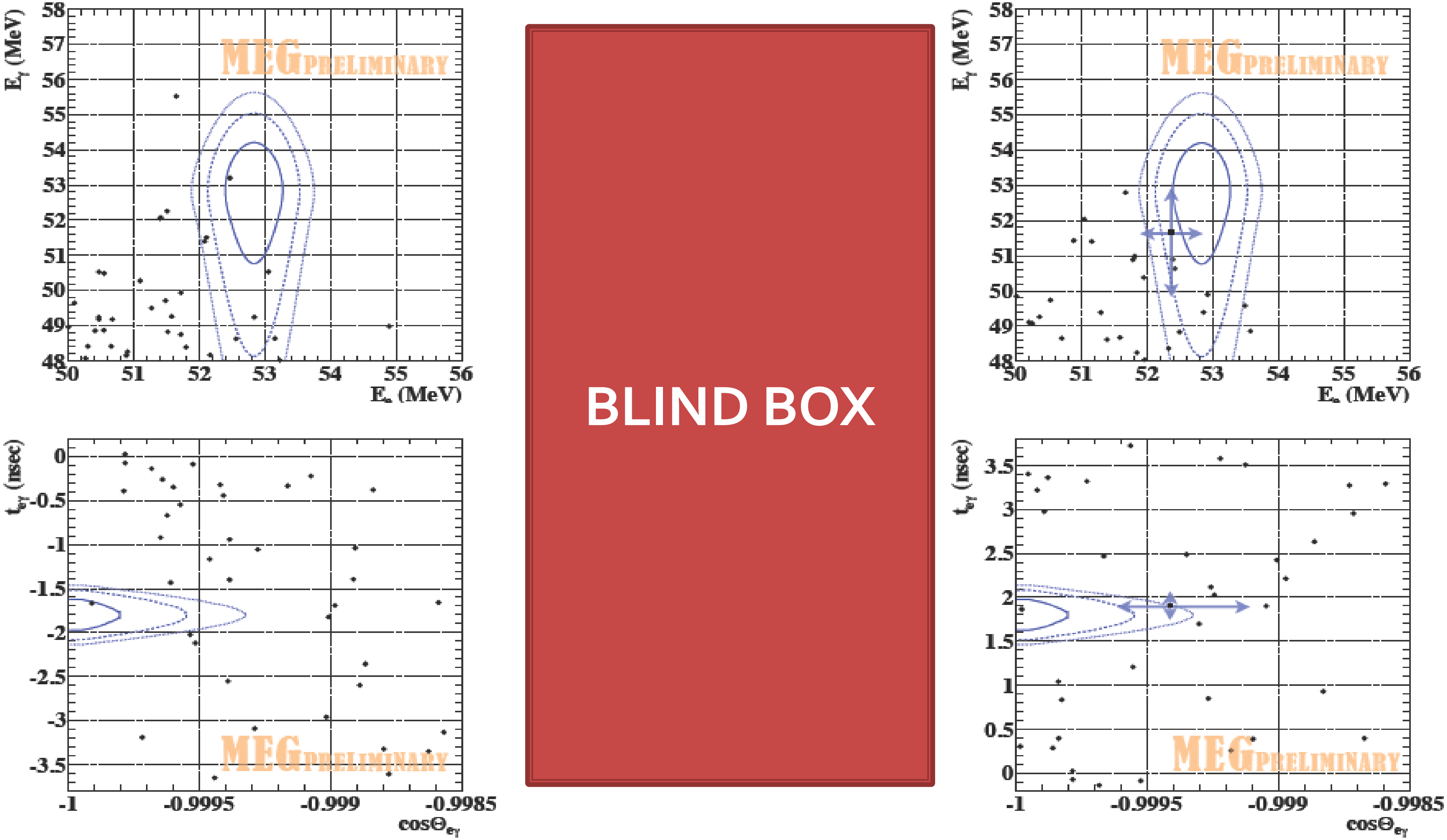
- $N_{sig} < 14.5$ @ 90% C.L., N_{sig} best–fit value = 3.0
- $N_{sig} = 0$ is in 90% confidence region
  - C.L @0: 40÷60% depending on the statistical approach



Accidental BG
RMD
Signal
Total

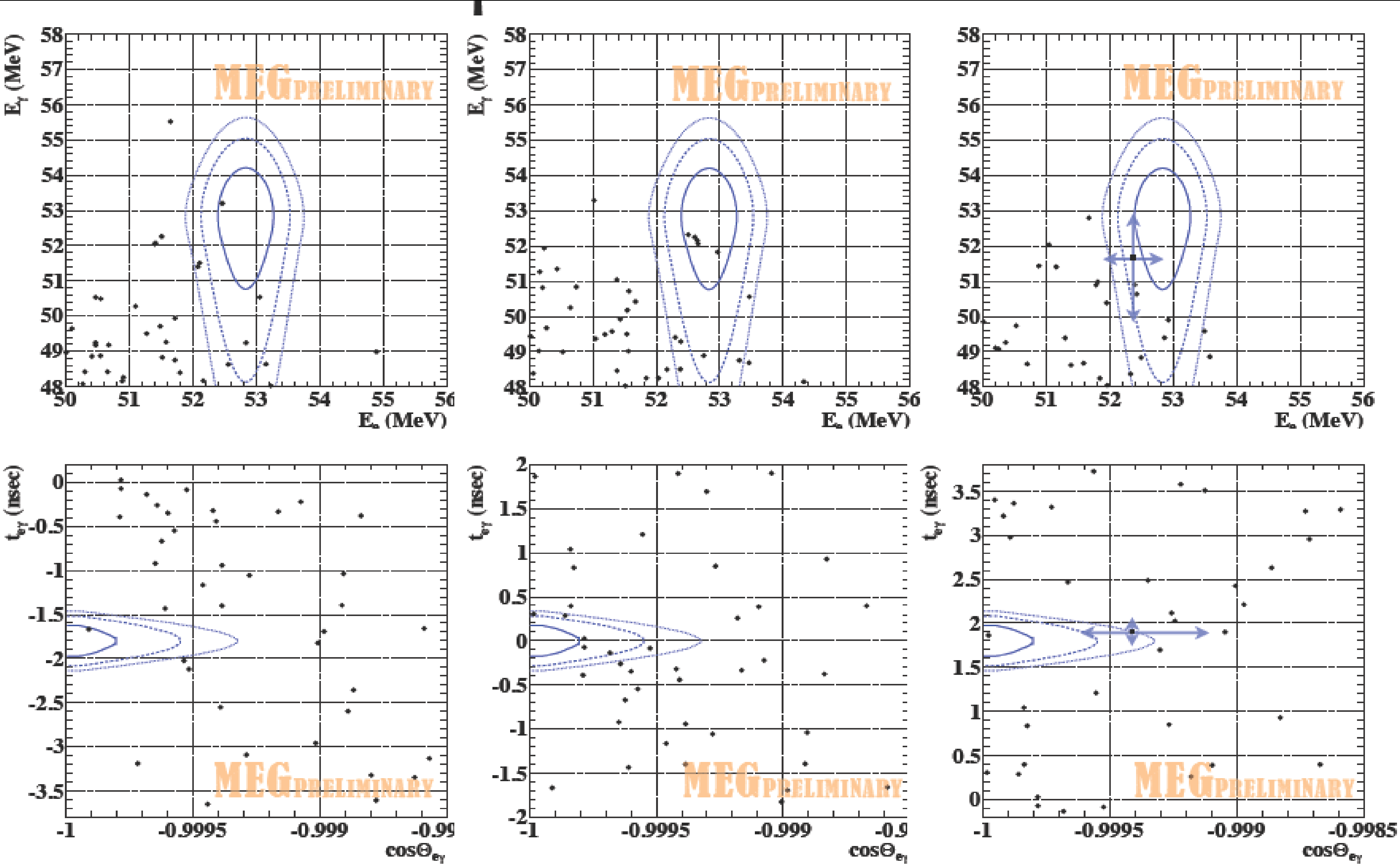
Dashed lines : 90% C.L. UL of Nsig

Sidebands for 2009 data

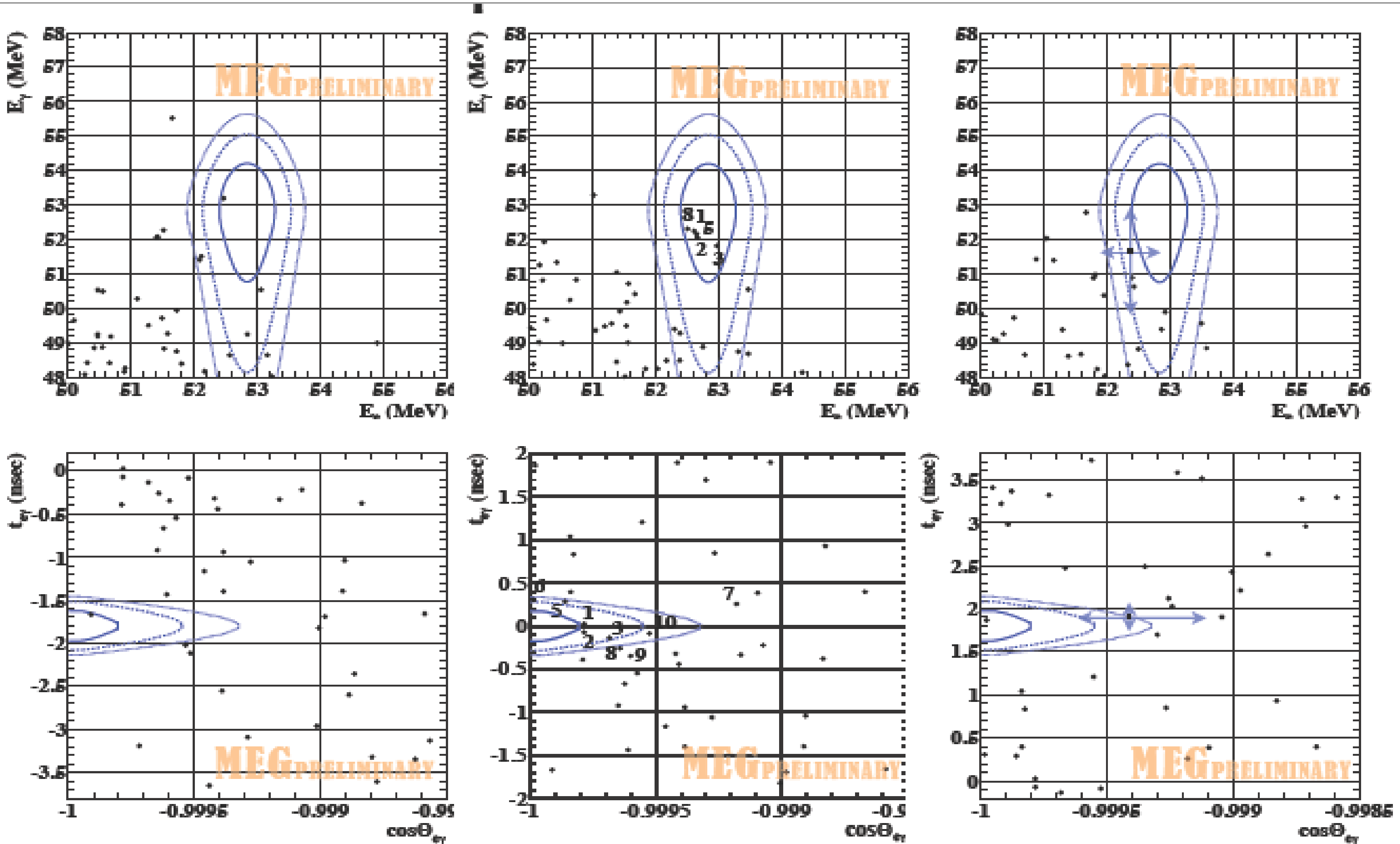


Blue lines are 1(39.3 % included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions.
For each plot, cut on other variables for roughly 90% window is applied.

2009 Blind Box Opening

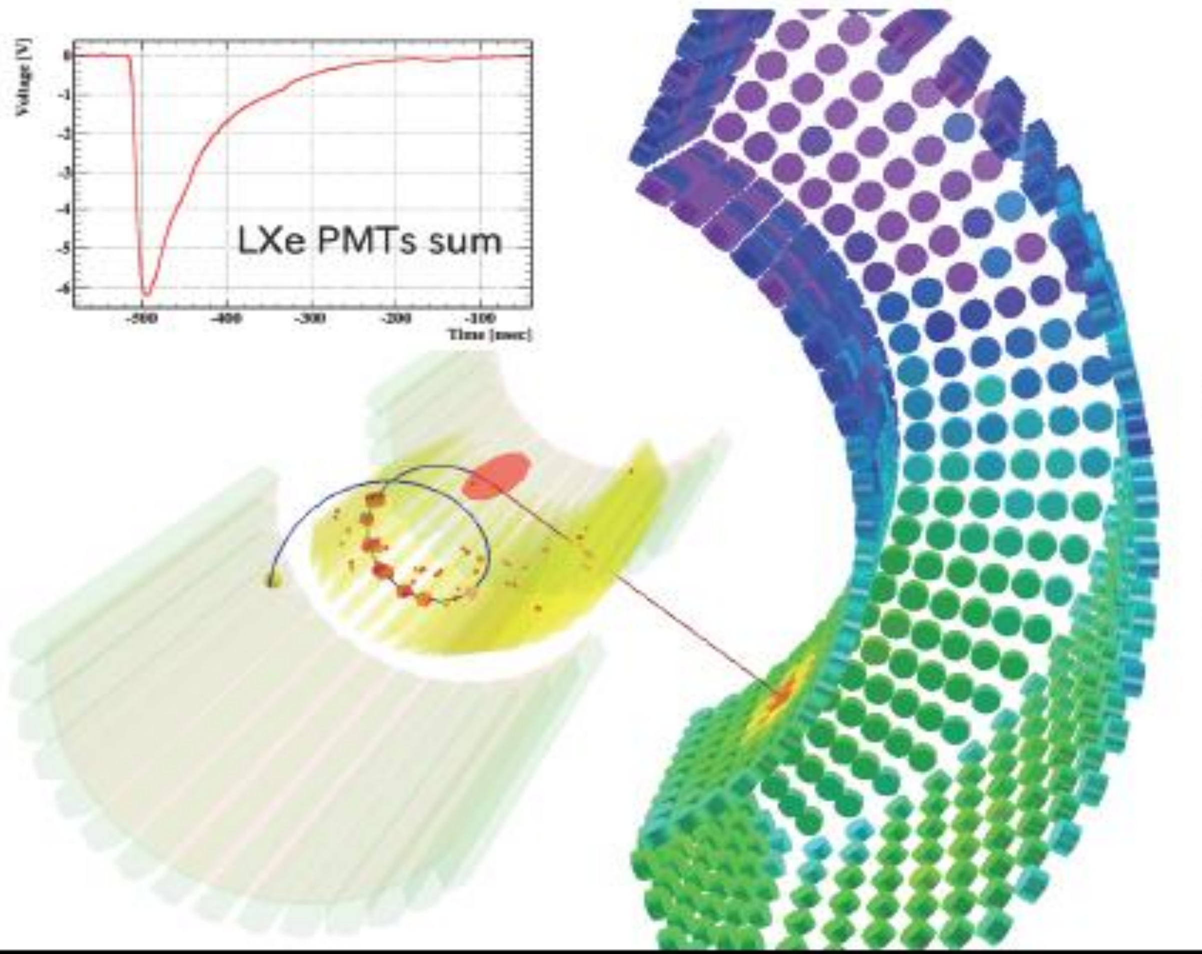


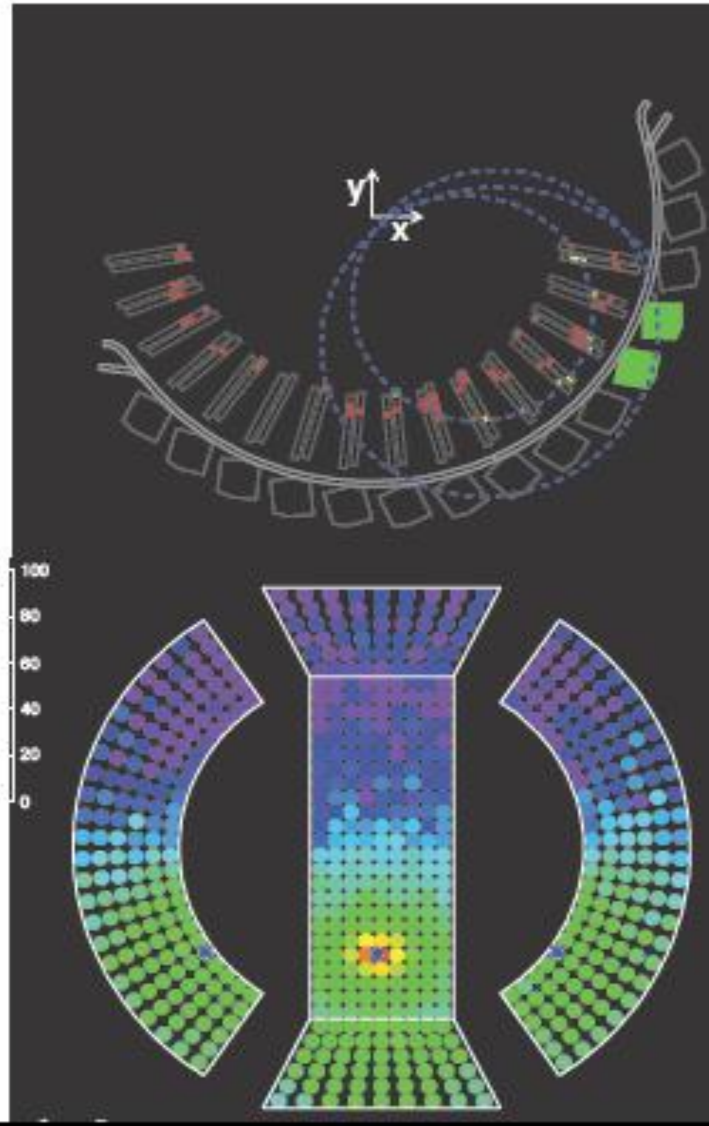
… with event ranking



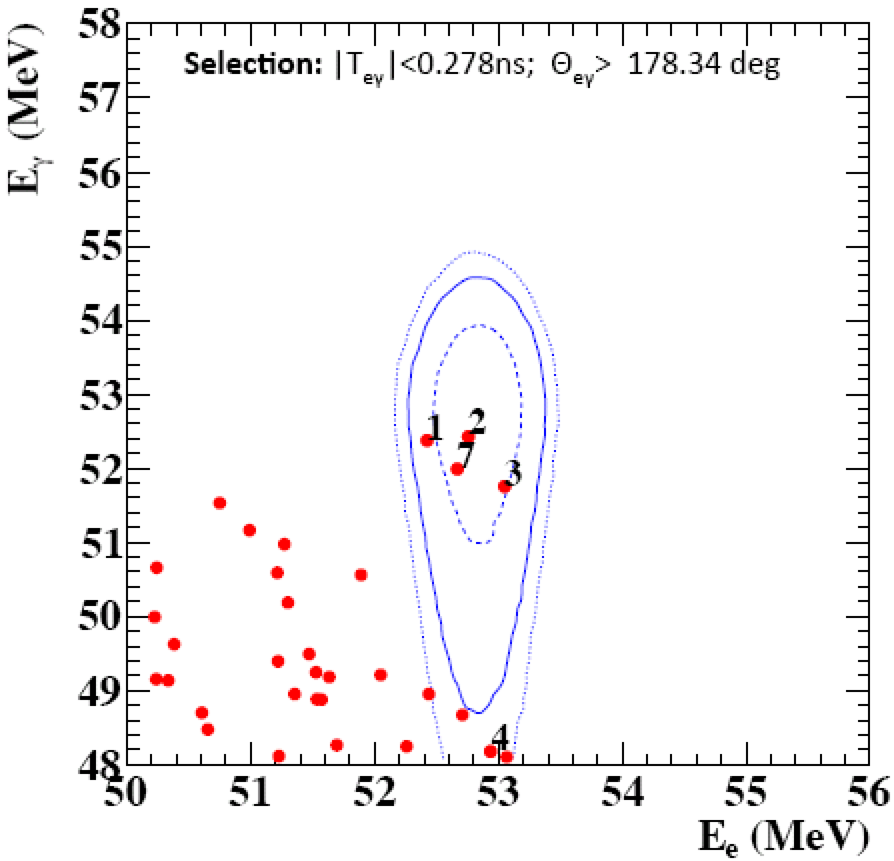
…a high ranked event…

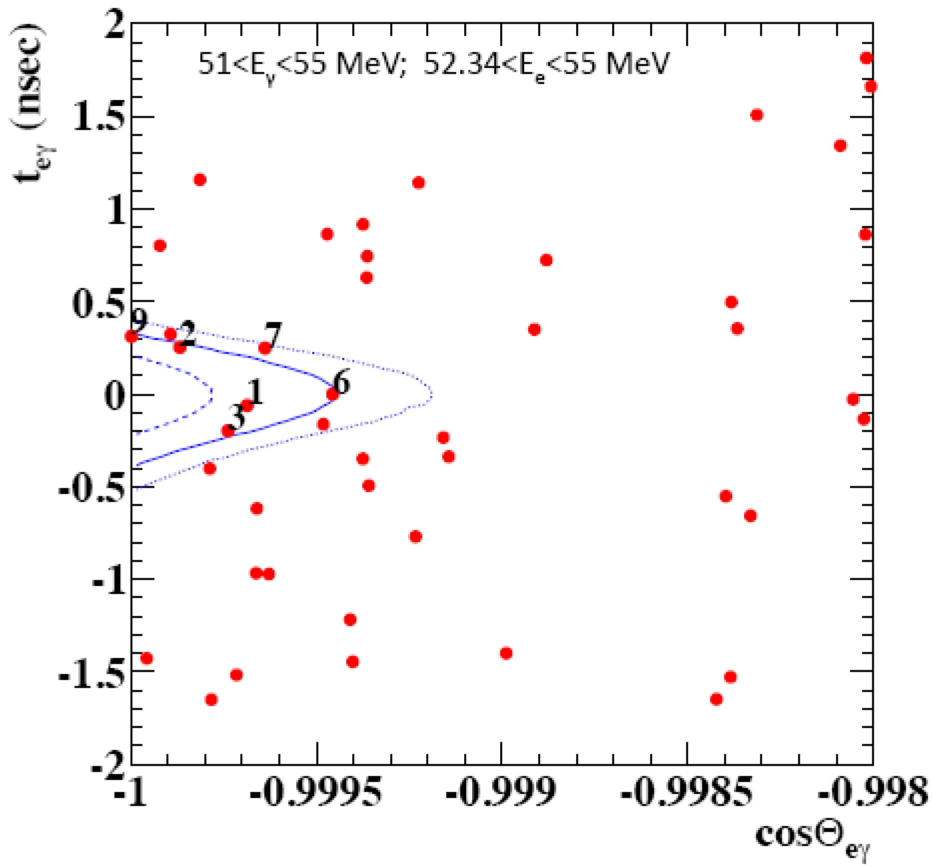
- Events in the signal region were checked carefully
- An event in the signal region





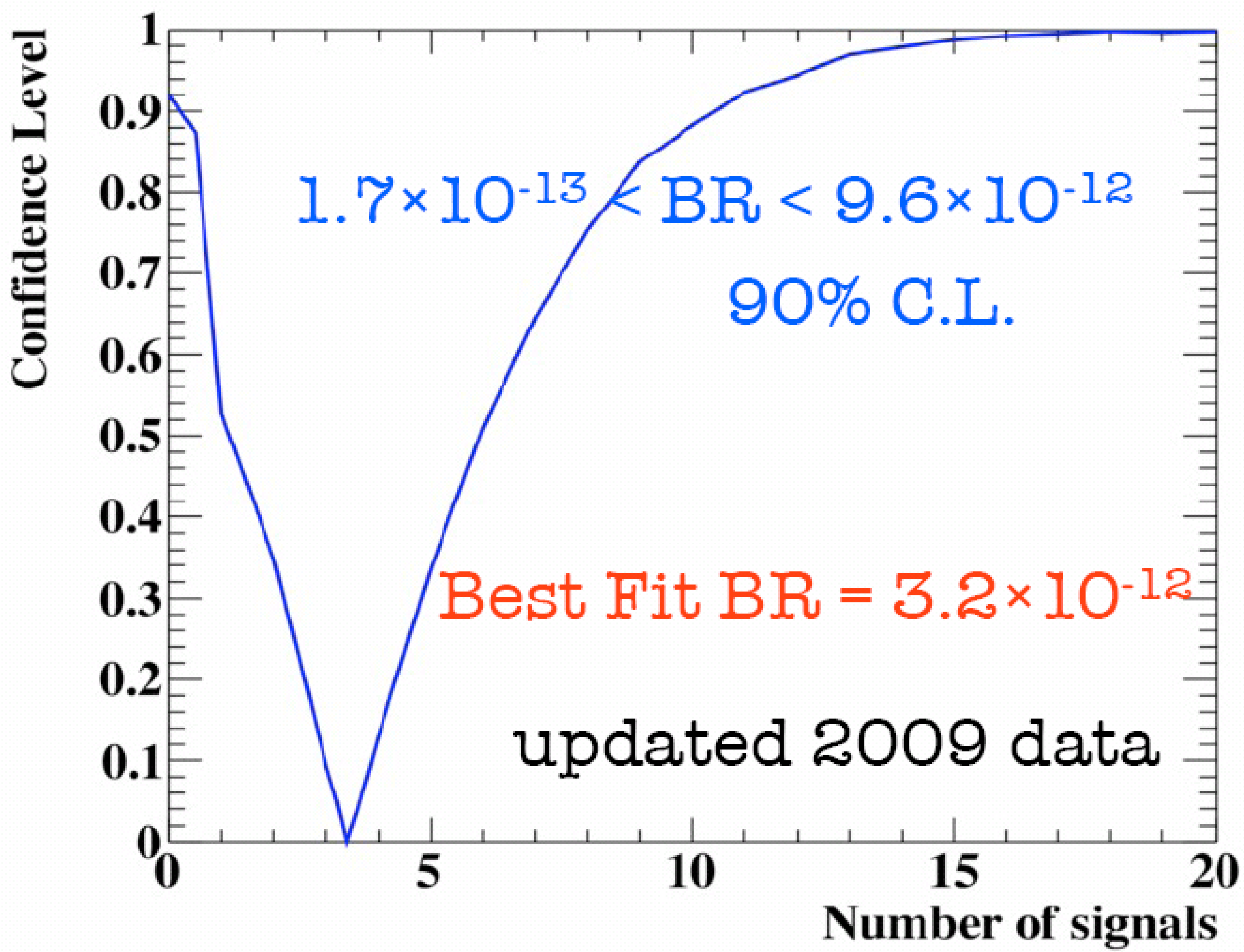
2009 data update



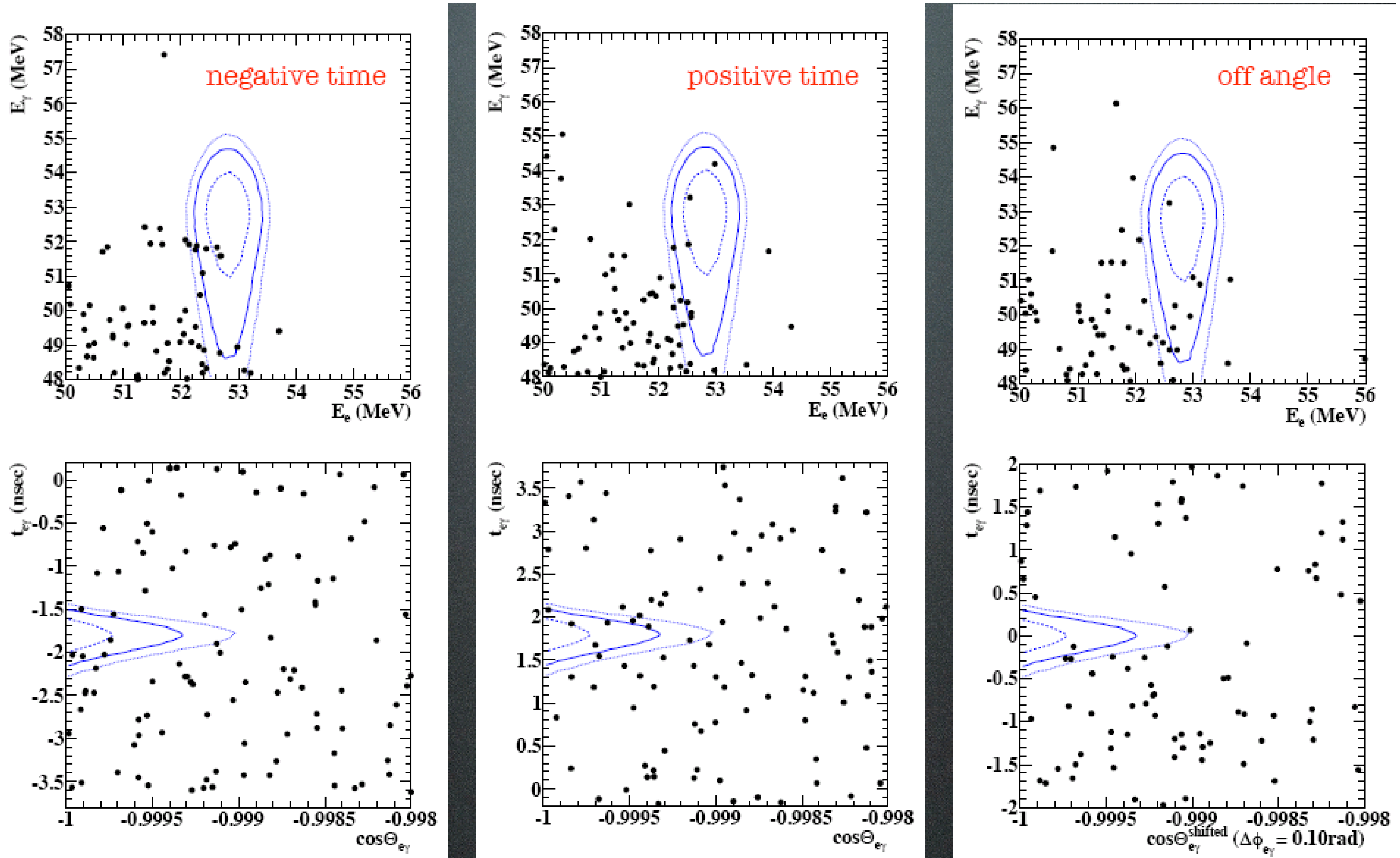


Nsig = 3.0 → Nsig = 3.4

2009 updated lakelihood analysis

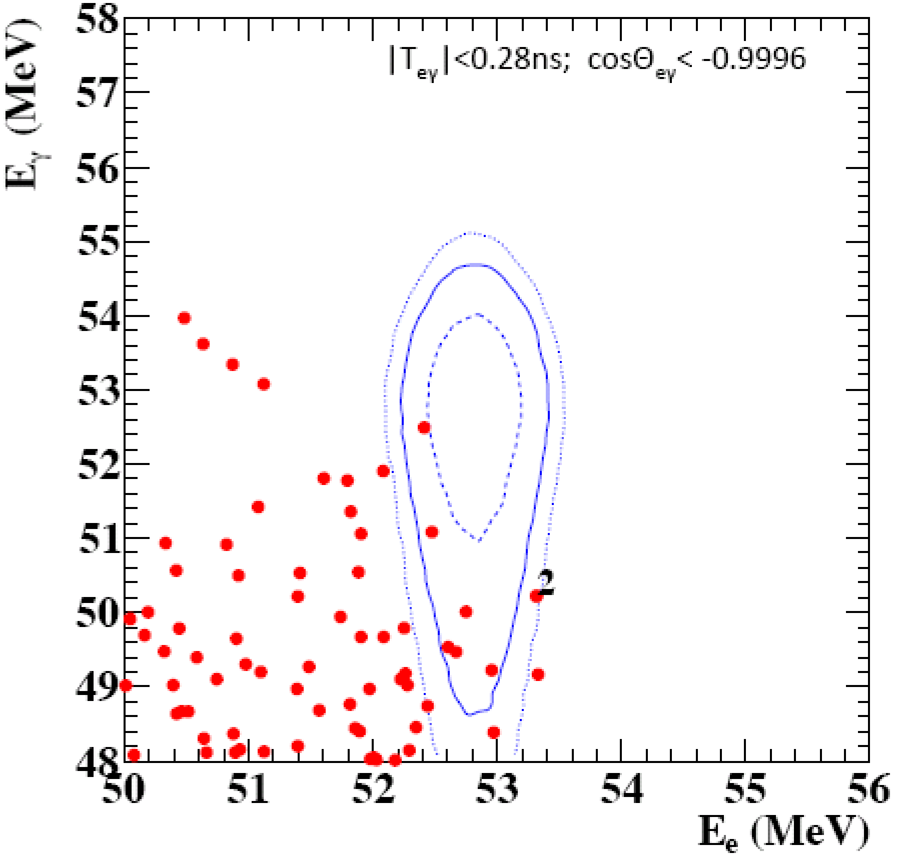


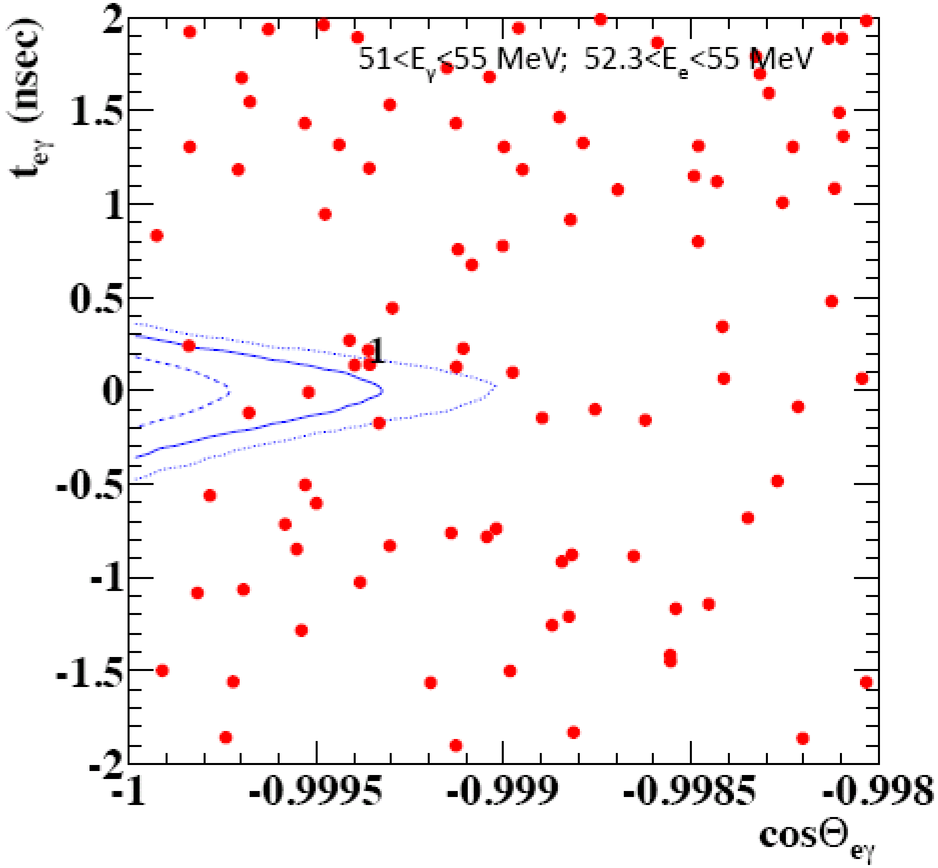
2010 analysis



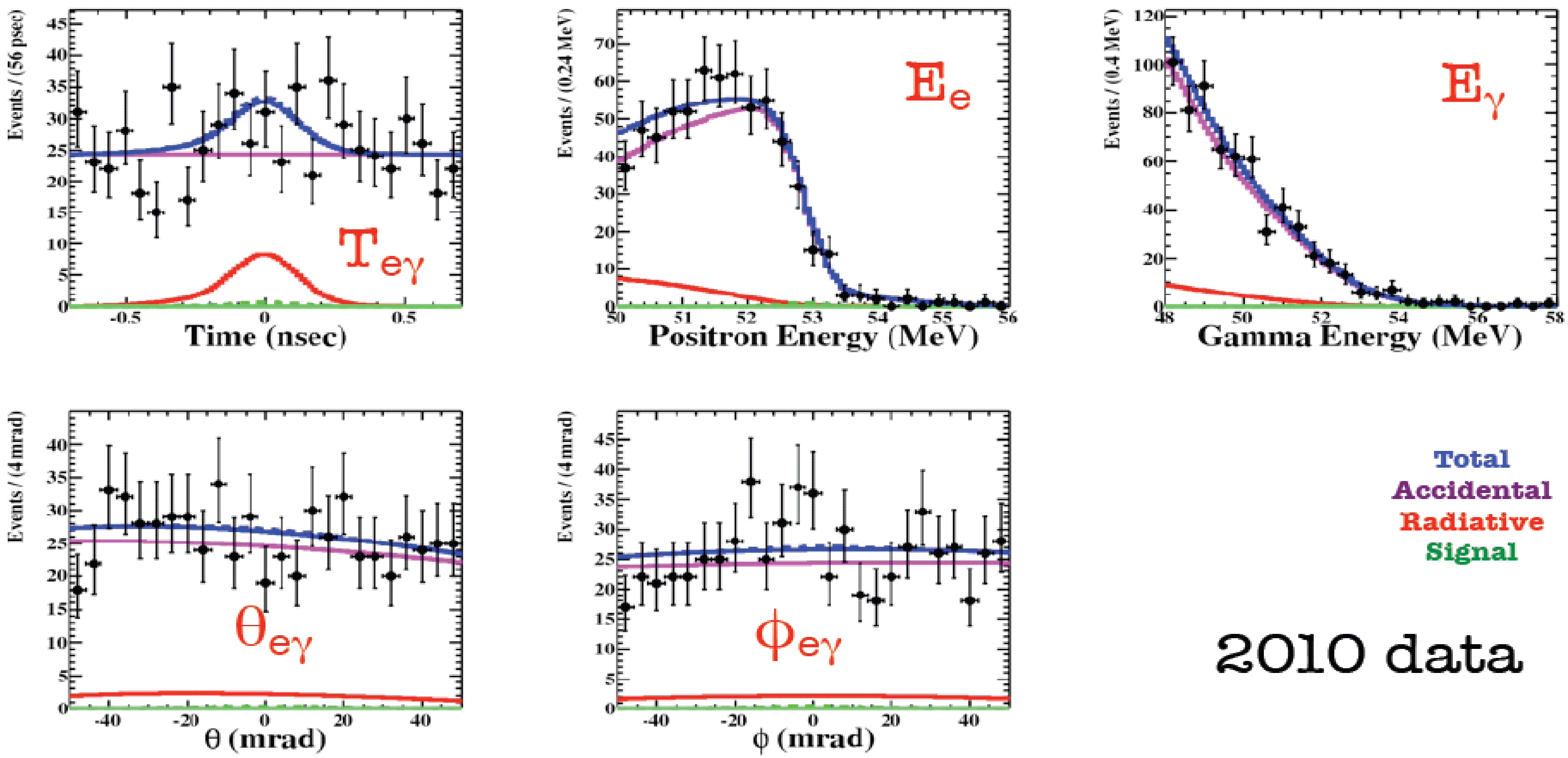
consistent with expected sensitivity = 2.2×10^{-12} @90% C.L.

2010 data after unblinding



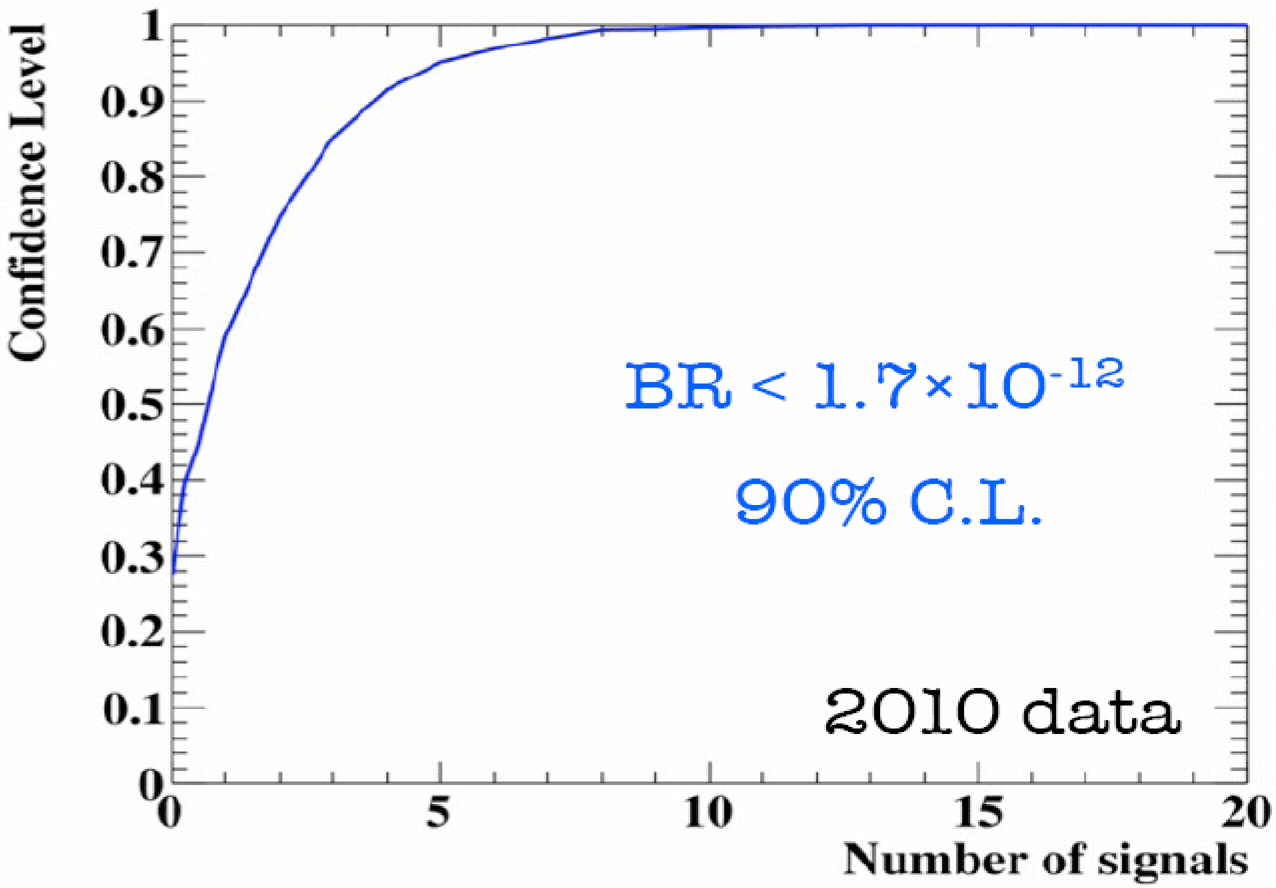


Likelihood 2010 data



2010 data

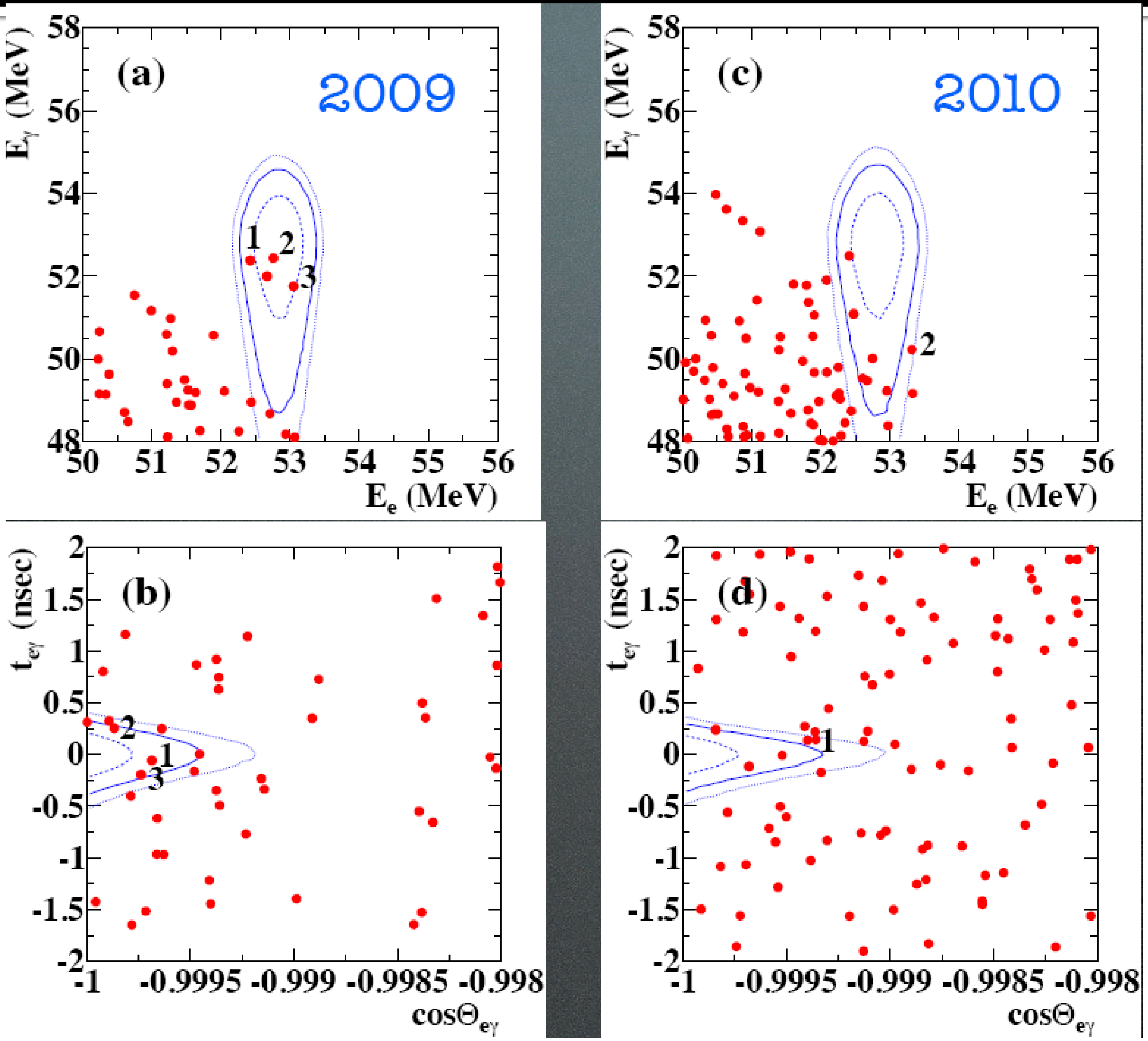
Likelihood Analysis



Performance summary

	2009	2010
Gamma Energy (%)	1.9	1.9
Gamma Timing (psec)	96	67
Gamma Position (mm)	5 (u,v), 6 (w)	5 (u,v), 6 (w)
Gamma Efficiency (%)	58	59
e^+ Timing (psec)	107	107
e^+ Momentum (keV)	310 (80% core)	330 (79% core)
e^+ θ (mrad)	9.4	11.0
e^+ ϕ (mrad)	6.7	7.2
e^+ vertex Z/Y (mm)	1.5 / 1.1 (core)	2.0 /1.1 (core)
e^+ Efficiency (%)	40	34
e^+-gamma timing (psec)	146	122
Trigger efficiency (%)	91	92
Stopping Muon Rate (sec^{-1})	2.9×10^7	2.9×10^7
DAQ time/ Real time (days)	35/43	56/67
Expected 90% C.L. Upper Limit	3.3×10^{-12}	2.2×10^{-12}

2009 and 2010 data



Results summary

	BR(fit)	LL 90%	UL 90%
2009	3.2×10^{-12}	1.7×10^{-13}	9.6×10^{-12}
2010	-9.9×10^{-13}	--	1.7×10^{-12}
2009+2010	-1.5×10^{-13}	--	2.4×10^{-12}

- systematic errors (in total 2% in UL) include:
  - relative angle offsets
  - correlations in e+ observables
  - normalizati
- (2009+2010expected UL = 1.6×10-12)

Summary

- New physics is now constrained by 5× tighter upper limit: BR < 2.4×10-12 @90% C.L.
- (Preprint available in arXiv)
- MEG is accumulating more data this and next year to reach O(10-13) sensitivity;
- Detector improvements/upgrade