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New Results on the $\mu^+ \rightarrow e^+ \gamma$ decay from the MEG experiment

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Outline

- Motivations
- The event signature and backgrounds
- The MEG experiment
- The 2009 detector performances
- The new results
- LFV in the other muonic and tauonic channels

Motivations

Very sensitive tool to investigate physics beyond Standard Model

- Experimental evidence of LVF in neutral sector from neutrino oscillations

$$\mathcal{P}_{\nu_l\to\nu_{l'}} = |\langle\nu_{l'}|\nu_l\rangle|^2 = \left|\sum_i V_{li}V^*_{l'i}e^{-i(m_i^2/2E_i)/L}\right|^2 \neq 0$$

- No yet observation of LVF in charged sector, but new physics predicts observable B.R.

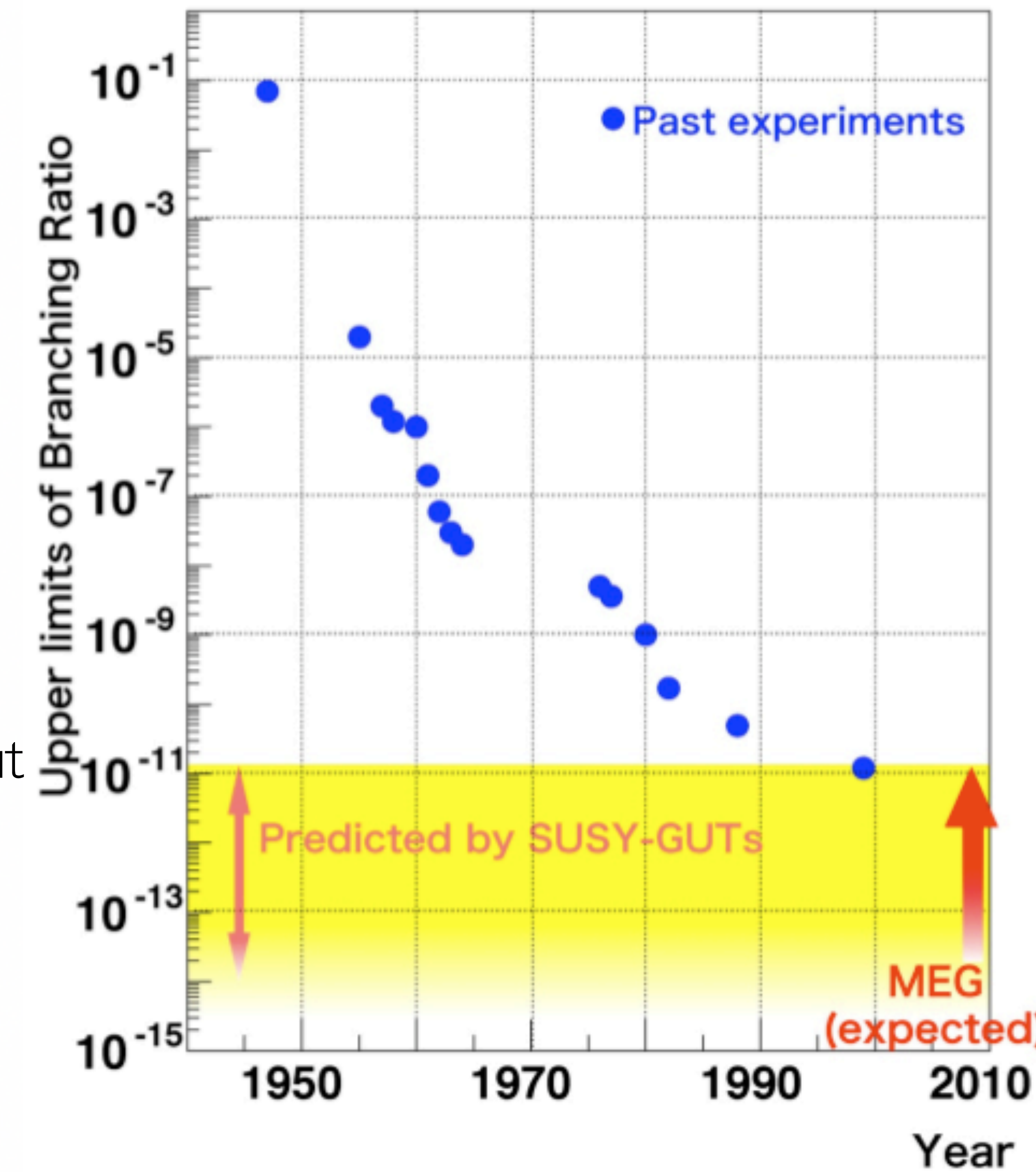
$$10^{-14} < B(\mu^+ \to e^+\gamma) < 10^{-11}$$

- The best upper limit (MEGA experiment)

$$B.R. \leq 1.2 \times 10^{-11} @ 90\% C.L.$$

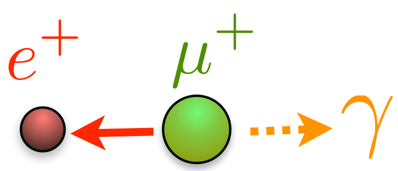
- The MEG sensitivity (goal)

$$B.R. \leq few \times 10^{-13} @ 90\% C.L.$$



Event Signature and Background

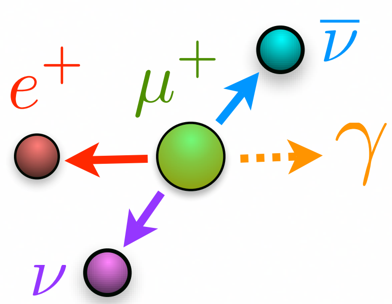
Signature of the muon at rest



Positron and gamma
in timing coincidence,
moving collinearly back-to-back,
with their energies equal to ~ 52.8 MeV

$B \sim 10^{-13}$

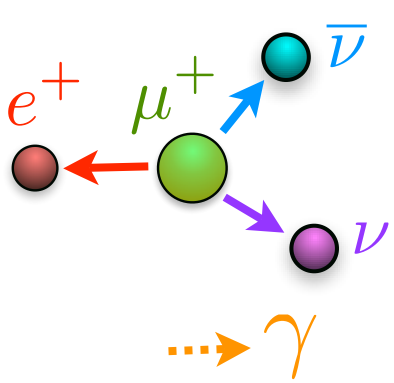
Correlated background



Positron and gamma
in opposite directions,
two neutrinos with a small amount of energy

$B \sim 10^{-15}$

Accidental background



Timing coincidence between
Michel positron and gamma from
radiative muon decay or positron
annihilation in flight

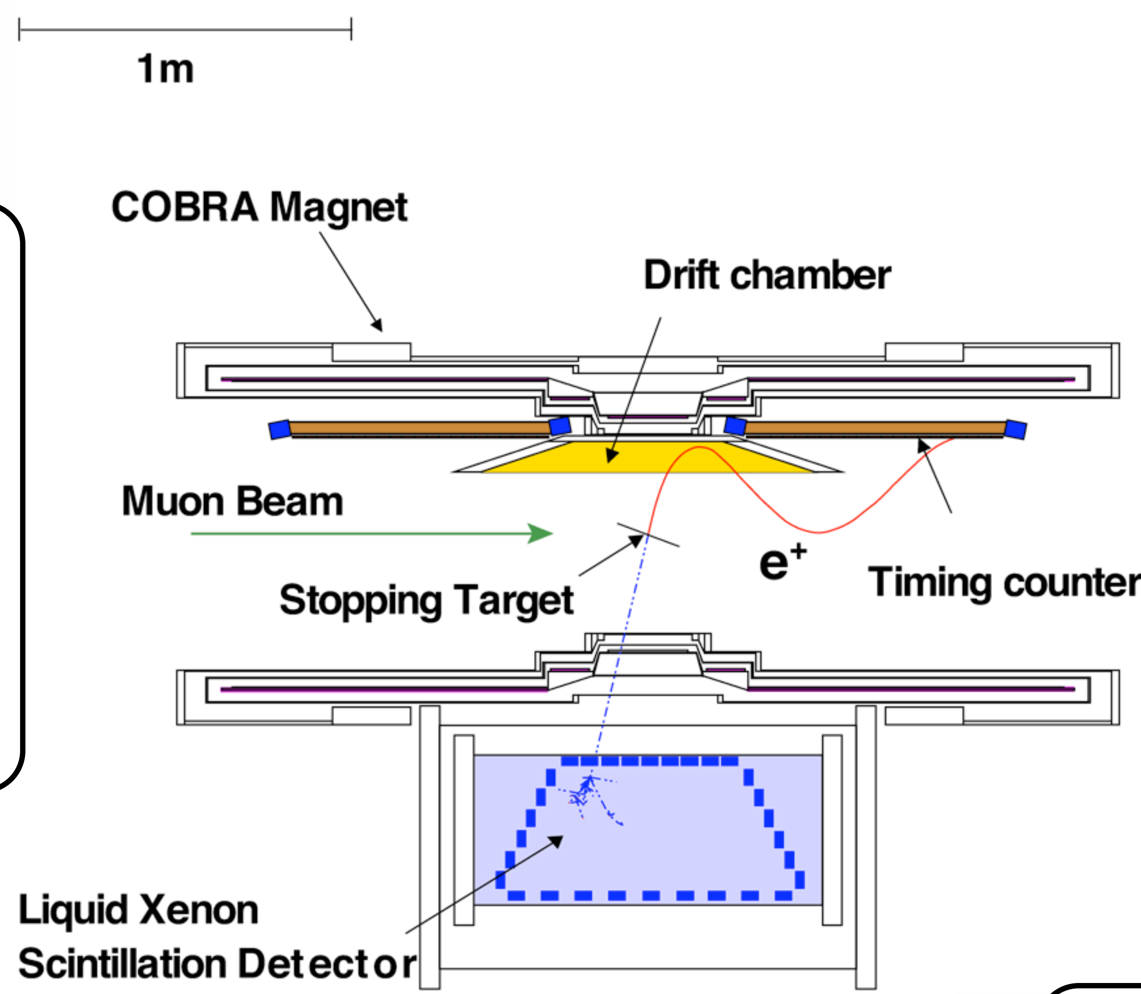
$B \sim 10^{-14}$

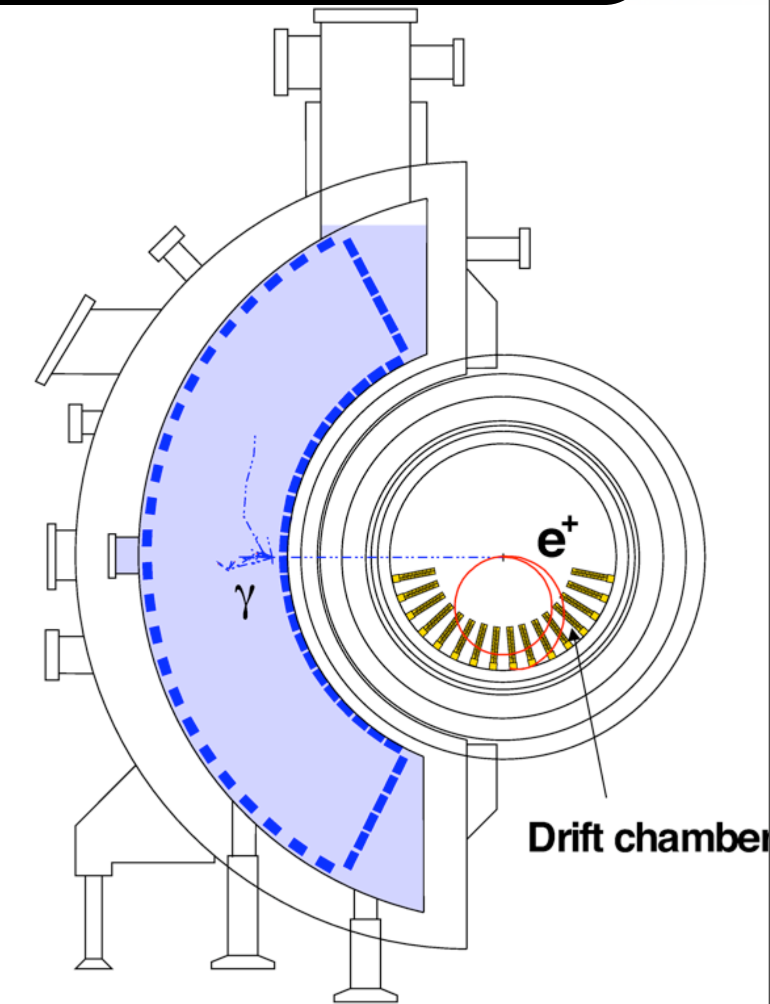
Experimental Set-up

1) The most intense muon beam

2) Gamma High energy and time resolutions

3) Positron Very precise momentum and time resolutions



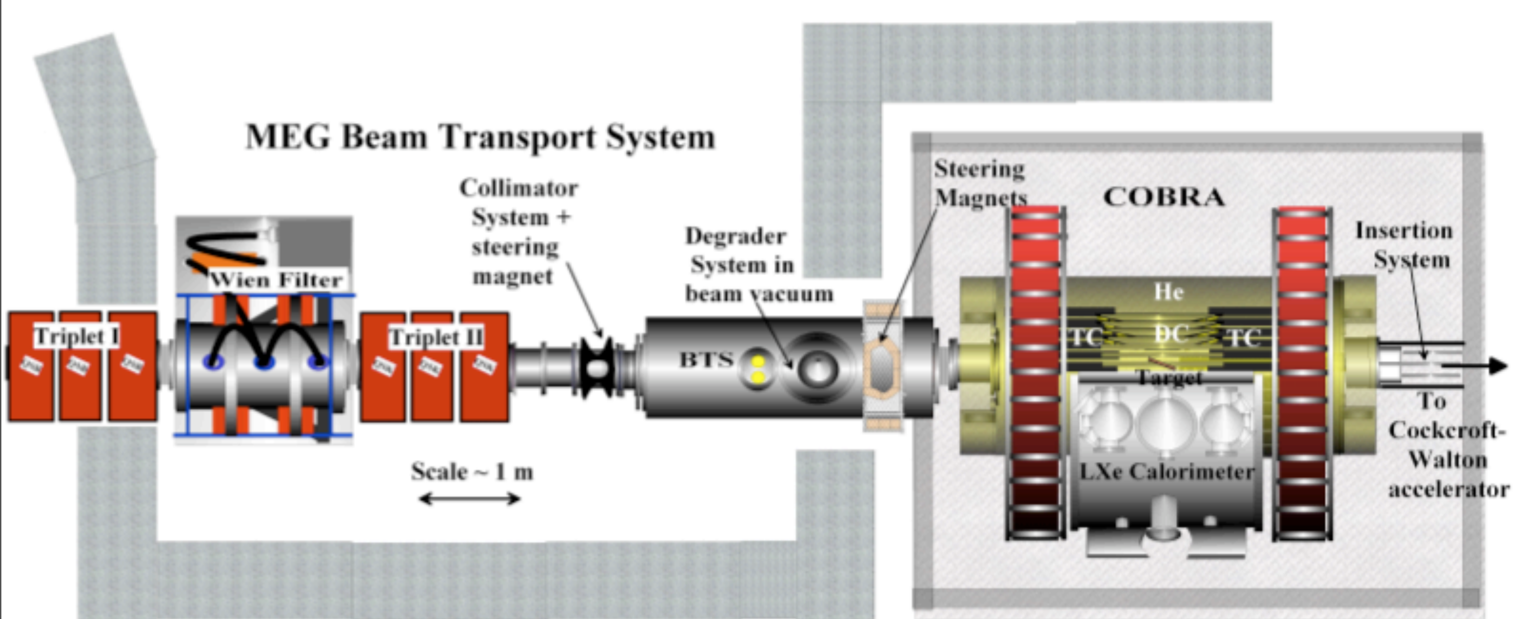


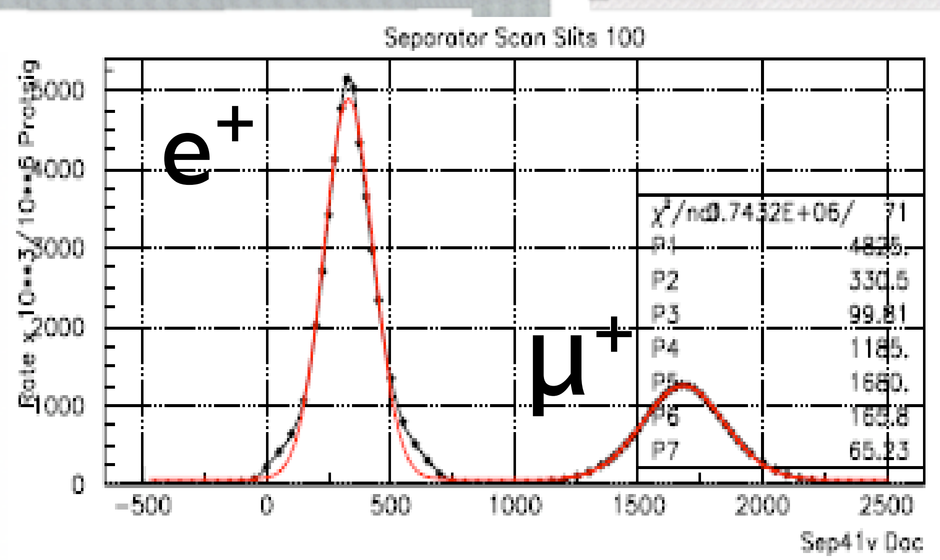
4) High efficiency event selection and frequency signal digitization

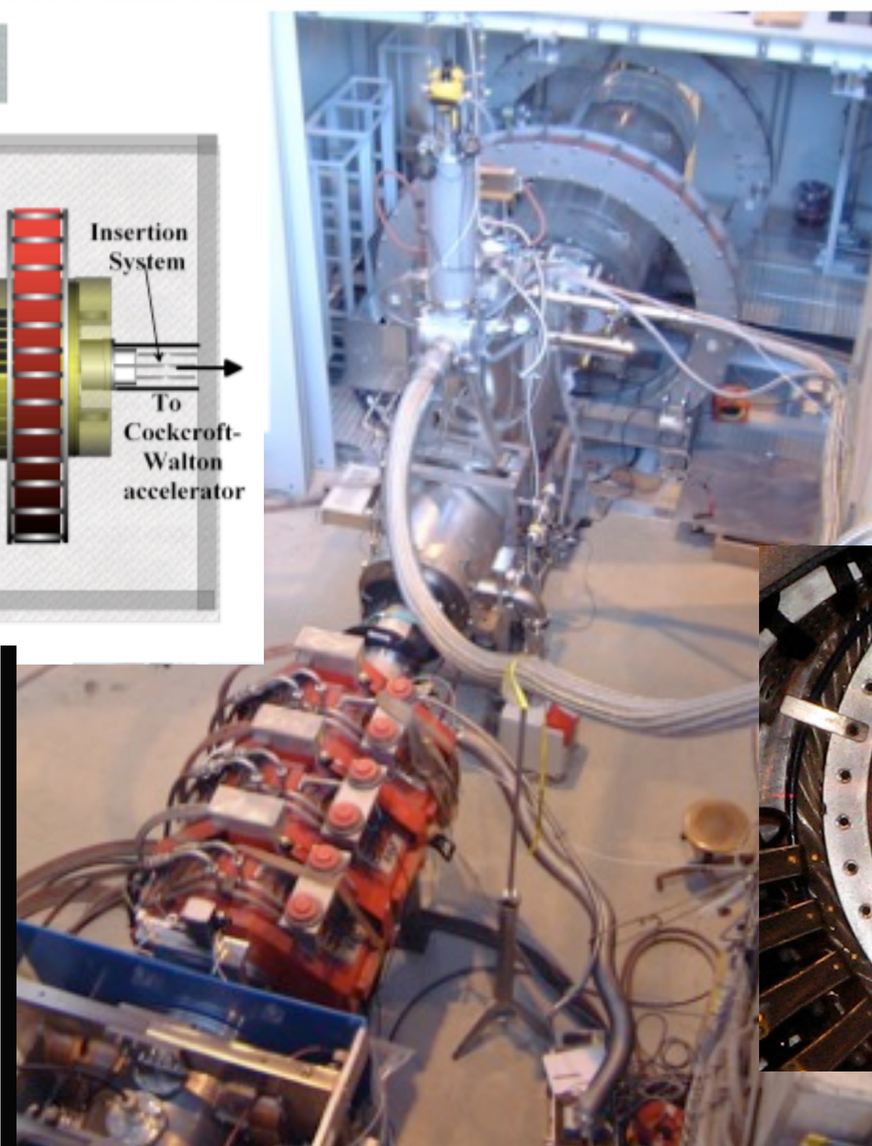
5) Complementary calibration and monitoring methods

Surface Muon Beam

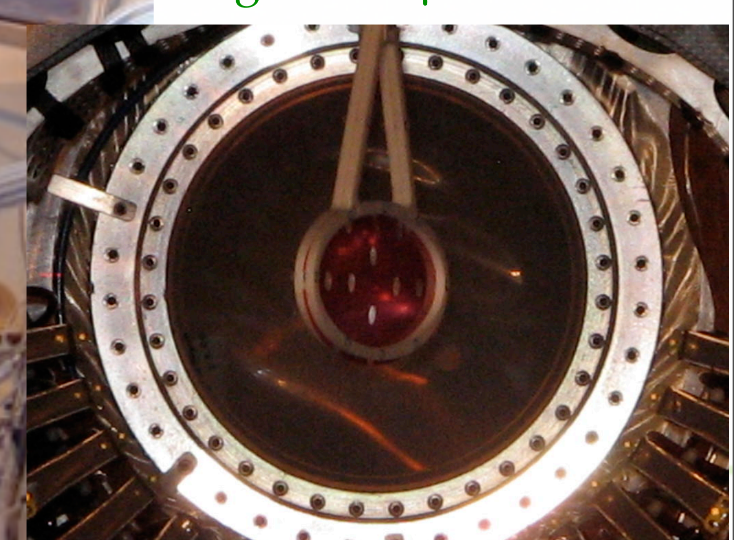
- Pure muon beam at low momentum
  - small straggling and good identification of the muon decay region
    - Reducing contaminants (beam particles other than muons)
    - Reducing the beam momentum to stop muons in a thin target





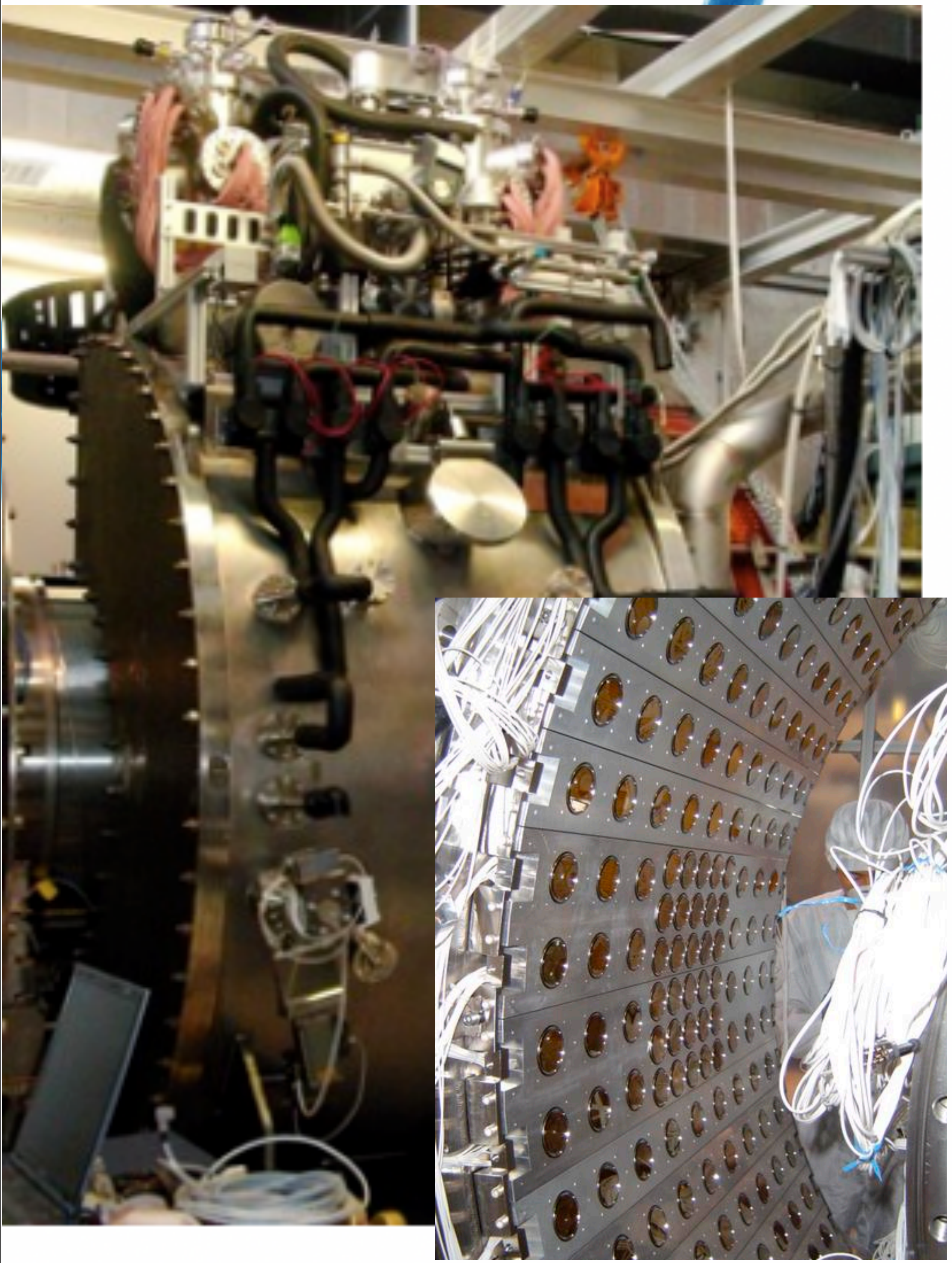


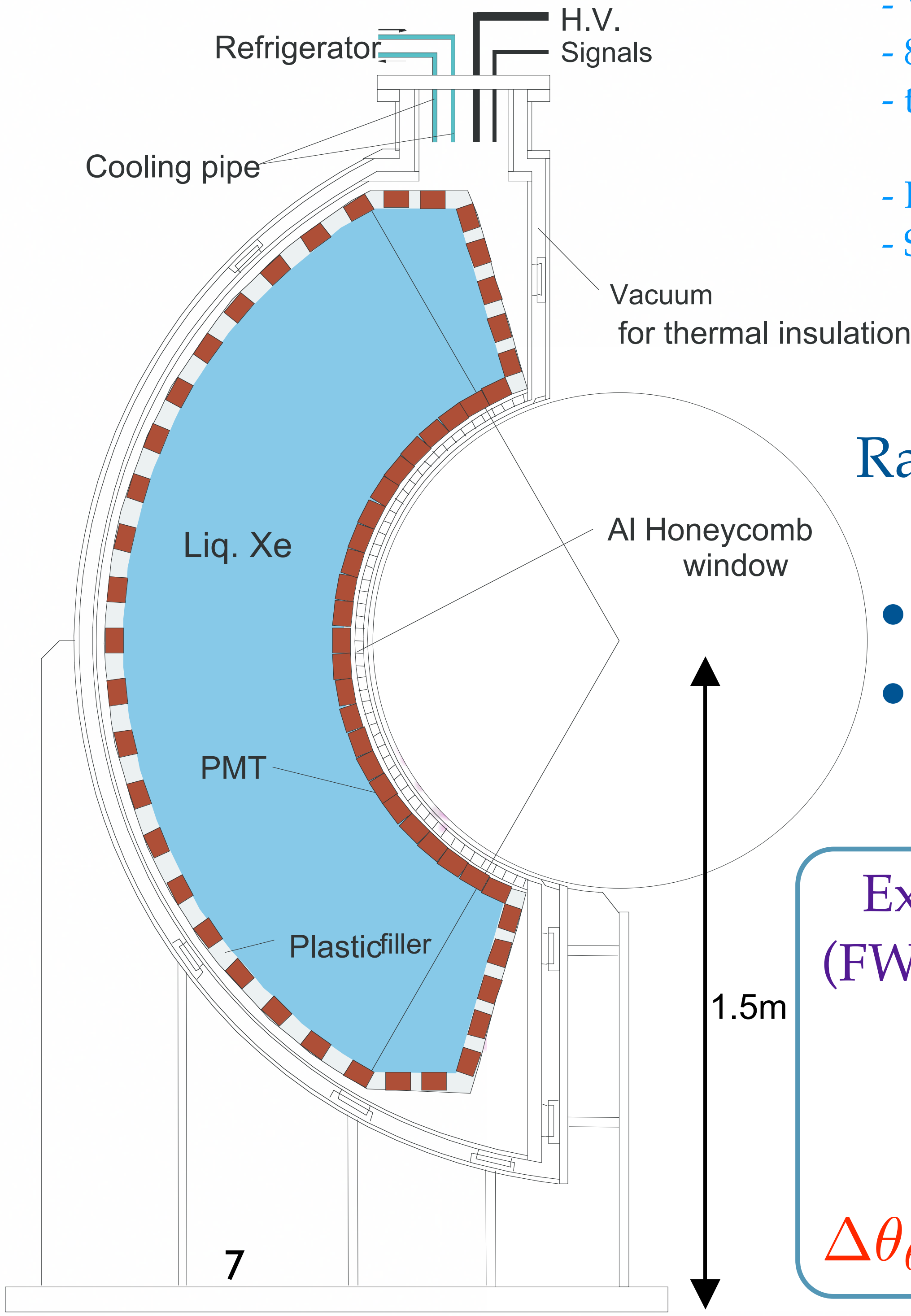
Target: 175 μm of CH_2



The LXe calorimeter

- The larger homogeneous calorimeter using only scintillation light
  - very good resolutions for photon energy, direction and time measurements





- Volume: 0.9 m^3 LXe
- 846 PMTs immersed in LXe
- thin entrance wall (honeycombe structure)
- Photocathodic coverage 40%
- Solid angle coverage 10%of 4π

Rapid and high light yield scintillator

- τ = 4, 22 and 45 ns
- ~ 40000 ph/MeV

Expected Resolutions (FWHM, MC simulation) @ 52.8 MeV

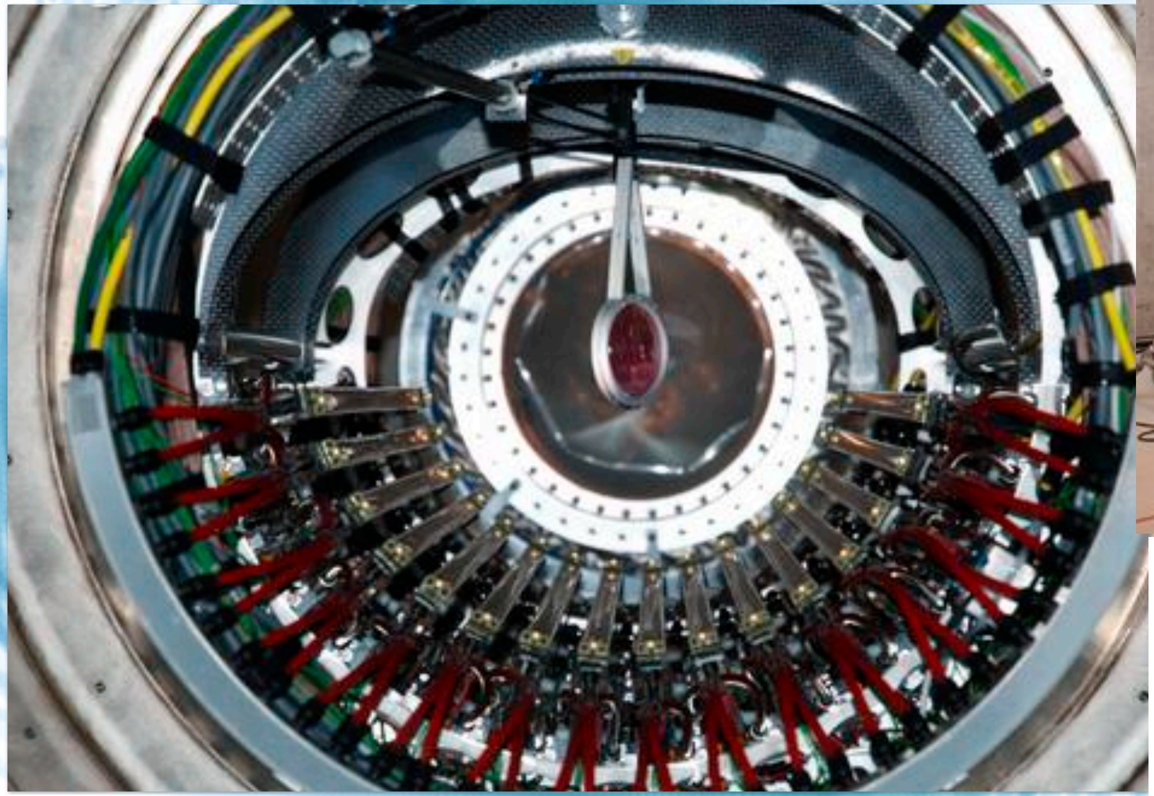
$$\Delta E_\gamma / E_\gamma = 4.5\%$$

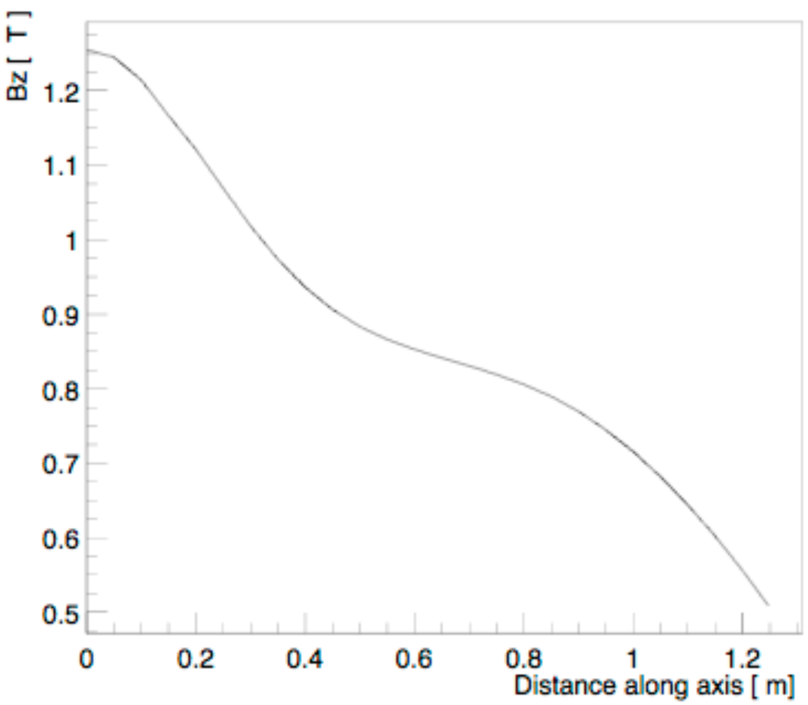
$$\Delta t_\gamma = 115 ps$$

$$\Delta\theta_{\theta,\phi} \approx 16 - 18 mrad$$

The Spectometer

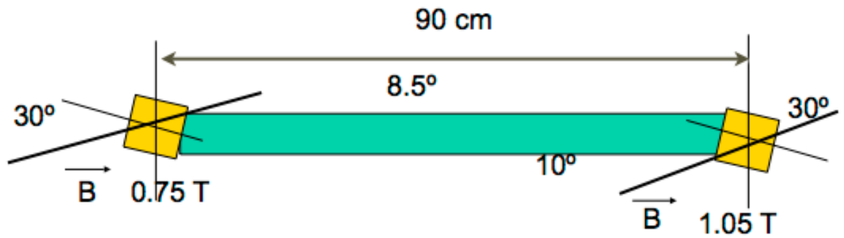
$\Delta p_{e^+}/p_{e^+} = 0.7 - 0.9\%$ (*)
$\Delta \theta_{e^+} = 9 - 12 mrad$ (*)





- Superconducting Magnet
  - Gradient B-field
    - Low momentum e^+ swept away
    - constant proected radius
- Drift chamber Array
  - 16 Sectors of 2DCHs, with staggered wire layers
    - good e^+ momentum and direction measurements
    - good time resolution (track recostruction)

The Timing Counter



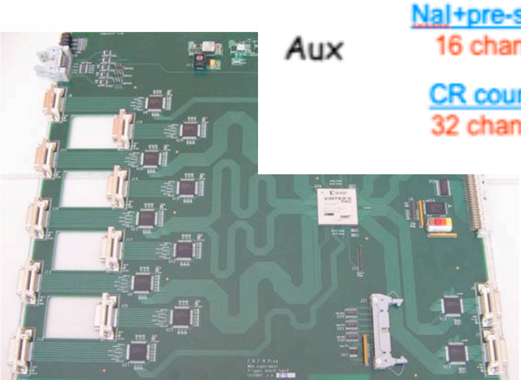
Expected Resolutions
(FWHM, MC simulation)
@ 52.8 MeV

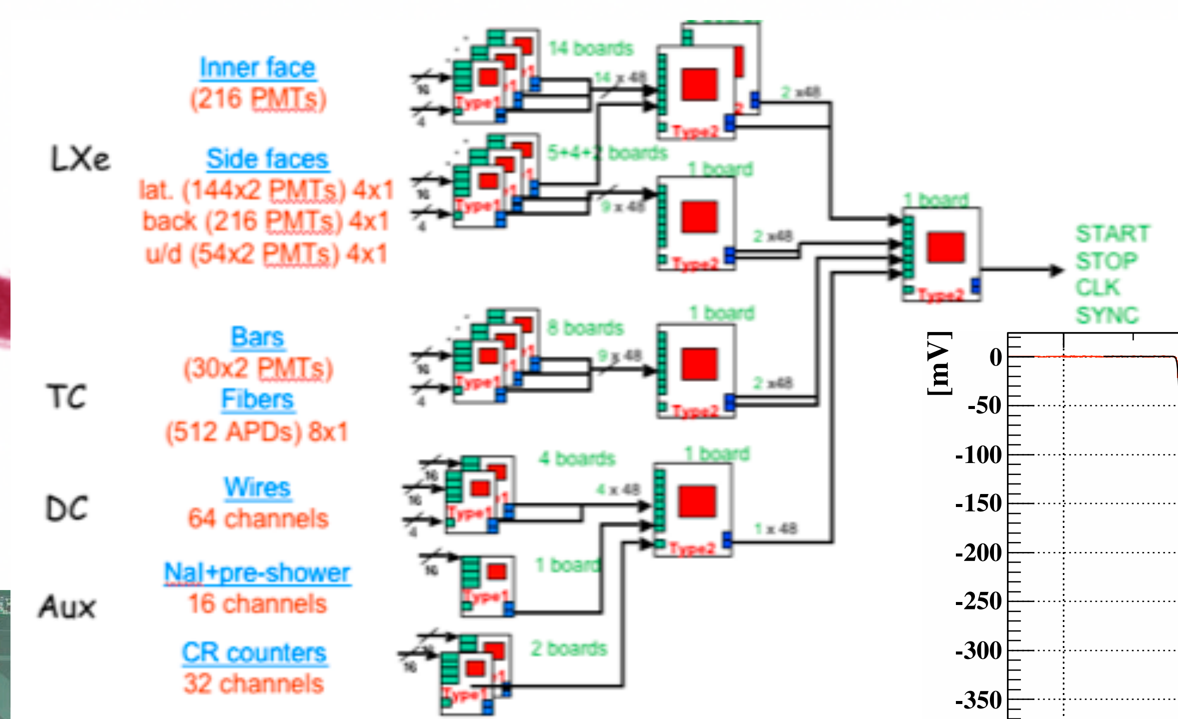
$\Delta t = 100 ps$

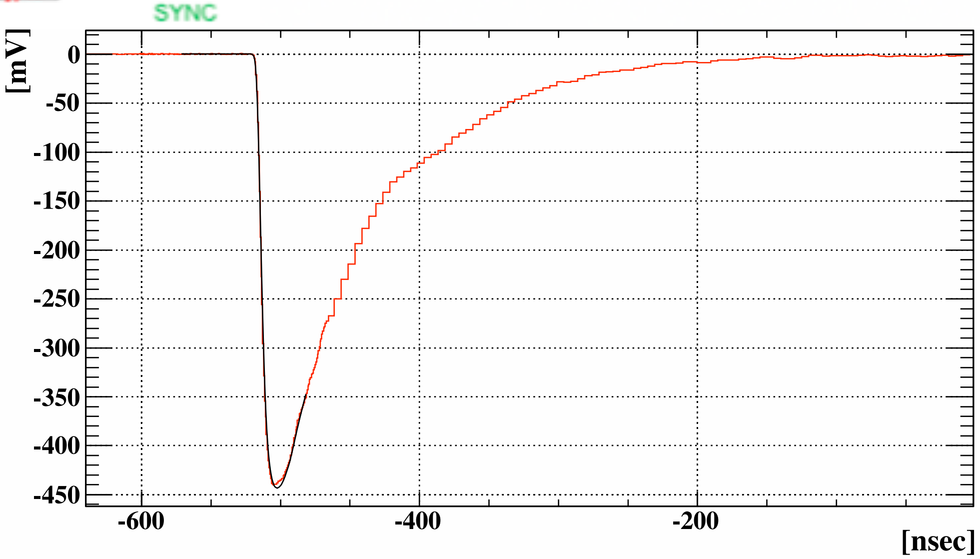
- Two sectors of 15 scintillator bars read out by PMTs, placed at each end of spectrometer
  - the best e^+ timing measurement
  - a fast estimate of the e^+ emission angle φ (for triggering)
- 256 optical fibers read out by APDs
  - a fast determination of the e^+ impact point z (for triggering)

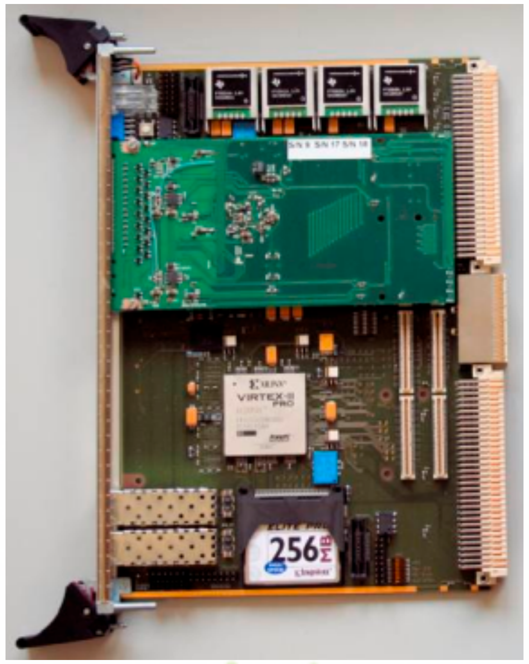
Trigger and DAQ

- Flexible and efficient trigger system, to select the candidate events, using fast detectors only
  - FADC digitization at 100 MHz
  - online selection algorithms implemented into FPGAs
- Domino Ring Sampler (DRS) chip for excellent pile-up rejection with a full waveform digitization
  - all 1000 PMTs signals (LXe and TC) digitize at 1.6 GHz
  - all 3000 DC channels (anodes and cathodes) digitize at 800 MHz



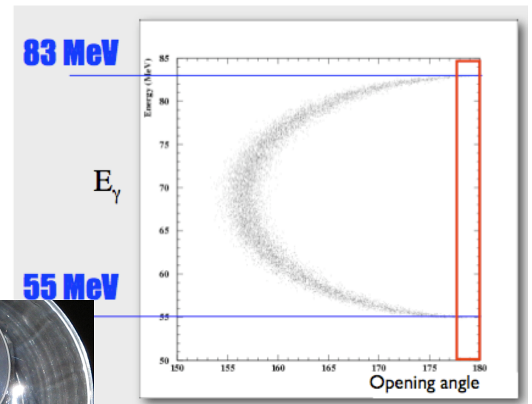


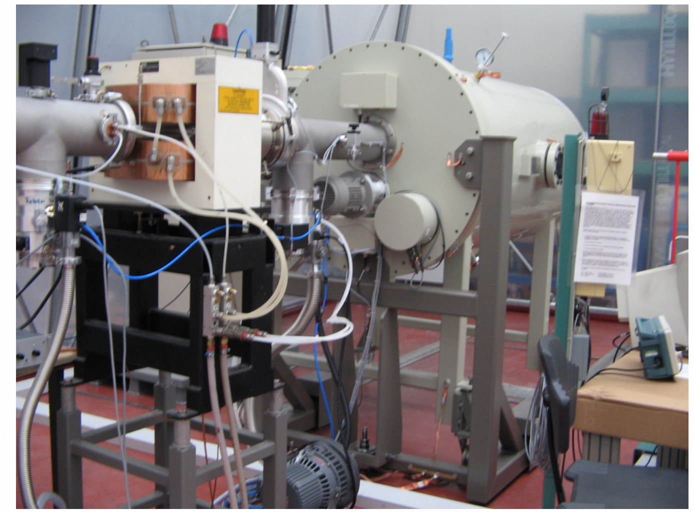


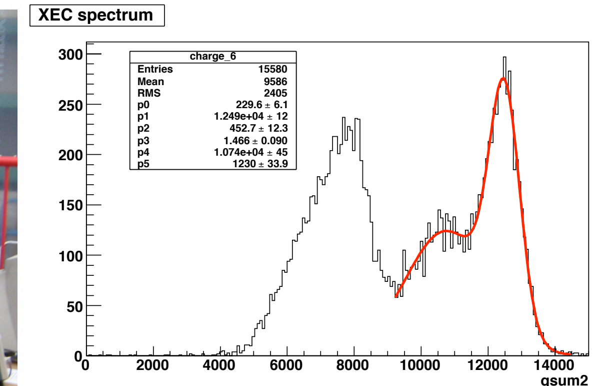


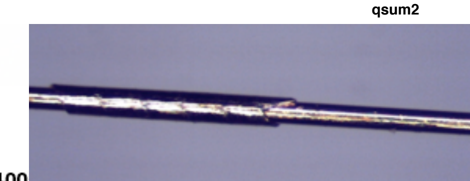
Calibration methods

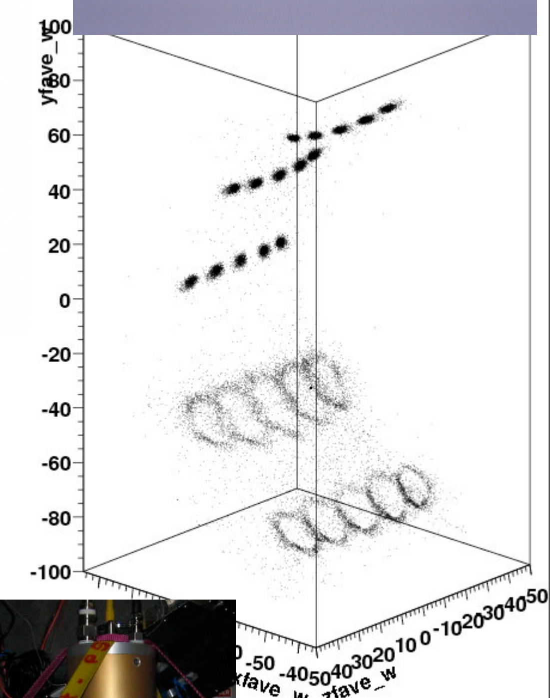
- The only way to unsure that the required performances are reached and maintained during the time



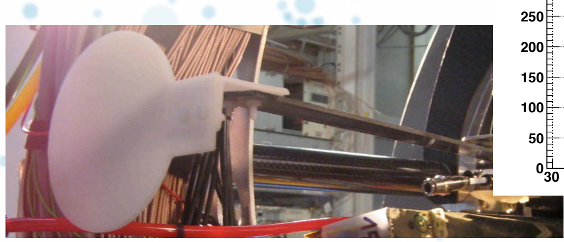


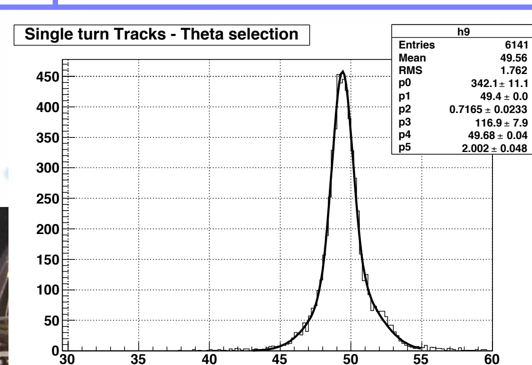


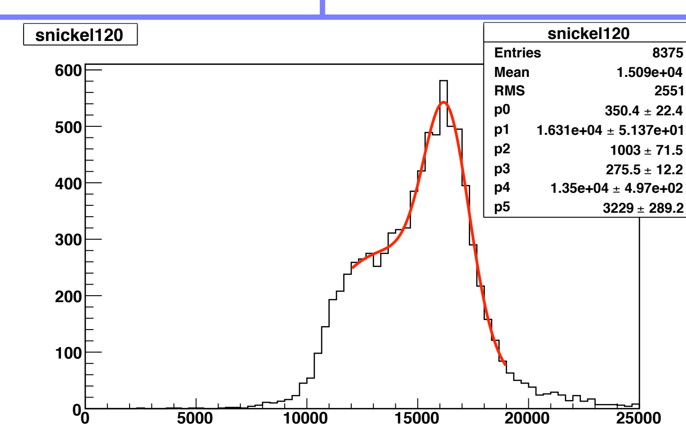


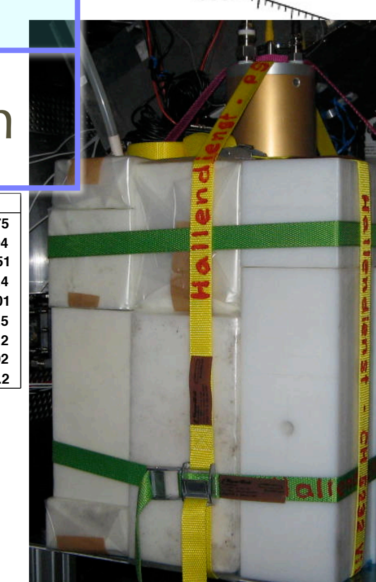


Physical process		Particle/energy (MeV)	Frequence
CEX	p (π^-,π^0) n $\pi^0 \rightarrow \gamma\ \gamma$ $\pi^0 \rightarrow \gamma\ e^+\ e^-$	e/γ = 55, 83	year -month
C-W accelerator	${}_3^7$Li (p,γ)${}_4^8$Be ${}_5^{11}$B (p,γ)${}_6^{12}$C	γ = 4.4, 11.7, 17.6	week
Neutron generator	n(Ni,Ni)γ	γ = 8.9	day
Radioactive sources	Am-Am/Be	γ = 4.4; α = 5.4	day
e^+ Mott scattering	p (e^+,e^+) p	e = 50, 55, 60	year -month







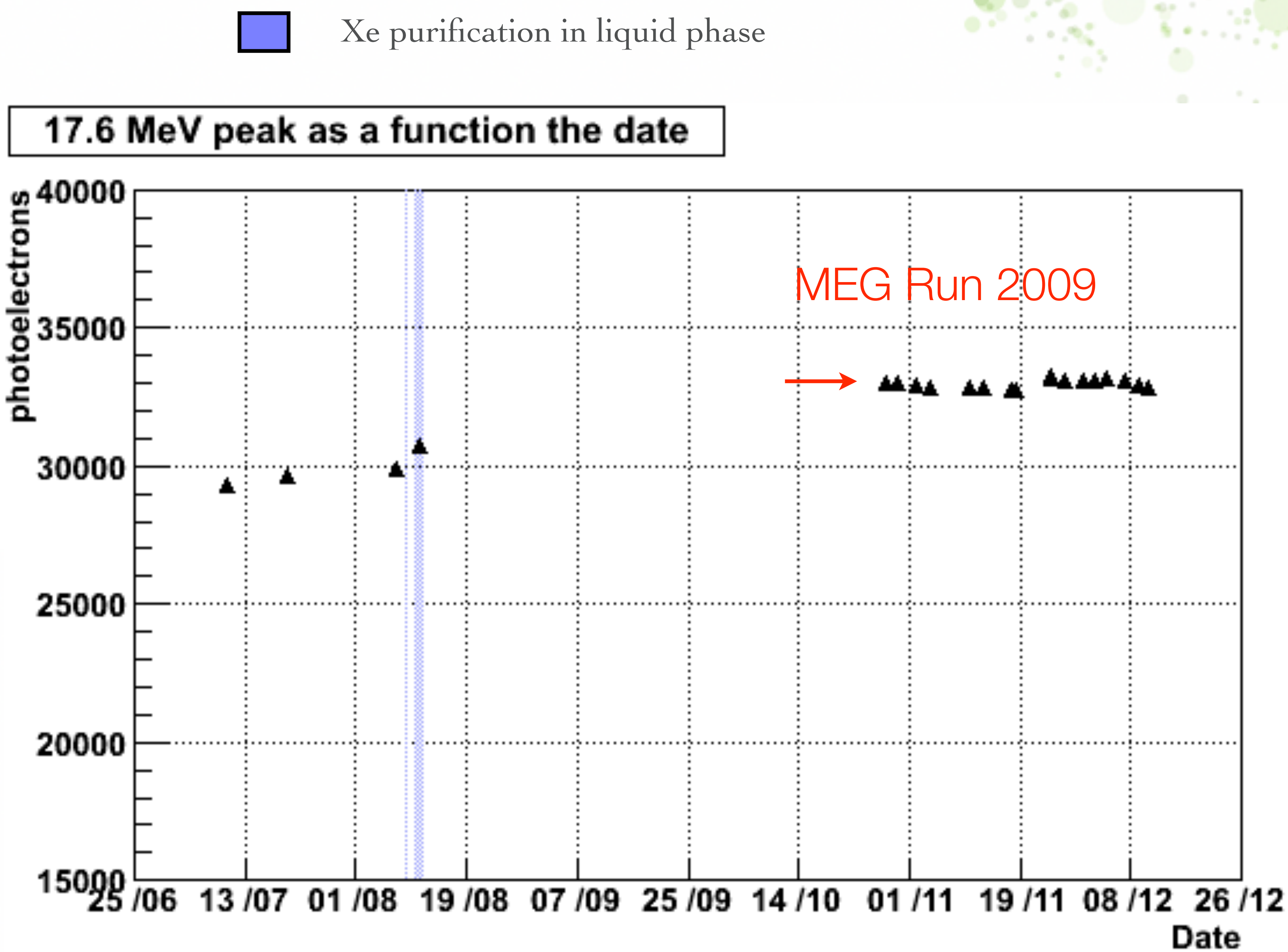


Detector Performances

Variable (σ)	2008	2009
Gamma Energy (%)	2.0 (w>2cm)	←
Gamma Timing (psec)	80	> 67
Gamma Position (mm)	5 (u,v) - 6 (w)	←
Gamma Efficiency (%)	63	58
Positron Momentum (%)	1.6	0.74 (core)
Positron Timing (psec)	<125	←
Positron Angle (mrad)	10 (φ) - 18 (ϑ)	7.4 (φ) - 11.2 (ϑ)
Positron Efficiency (%)	14	40
Gamma-Positron Timing (psec)	148	142 (core)
Muon decay point (mm)	3.2 (R) - 4.5 (Z)	2.3 (R) - 2.8 (Z)
Trigger efficiency (%)	66	84
DAQ time/Real time (days)	48/78	35/43
Stopping Muon Rate (sec^{-1})	3×10^7	2.9×10^7
Sensitivity	1.3×10^{-11}	-
B.R. upper limit	2.8×10^{-11}	-

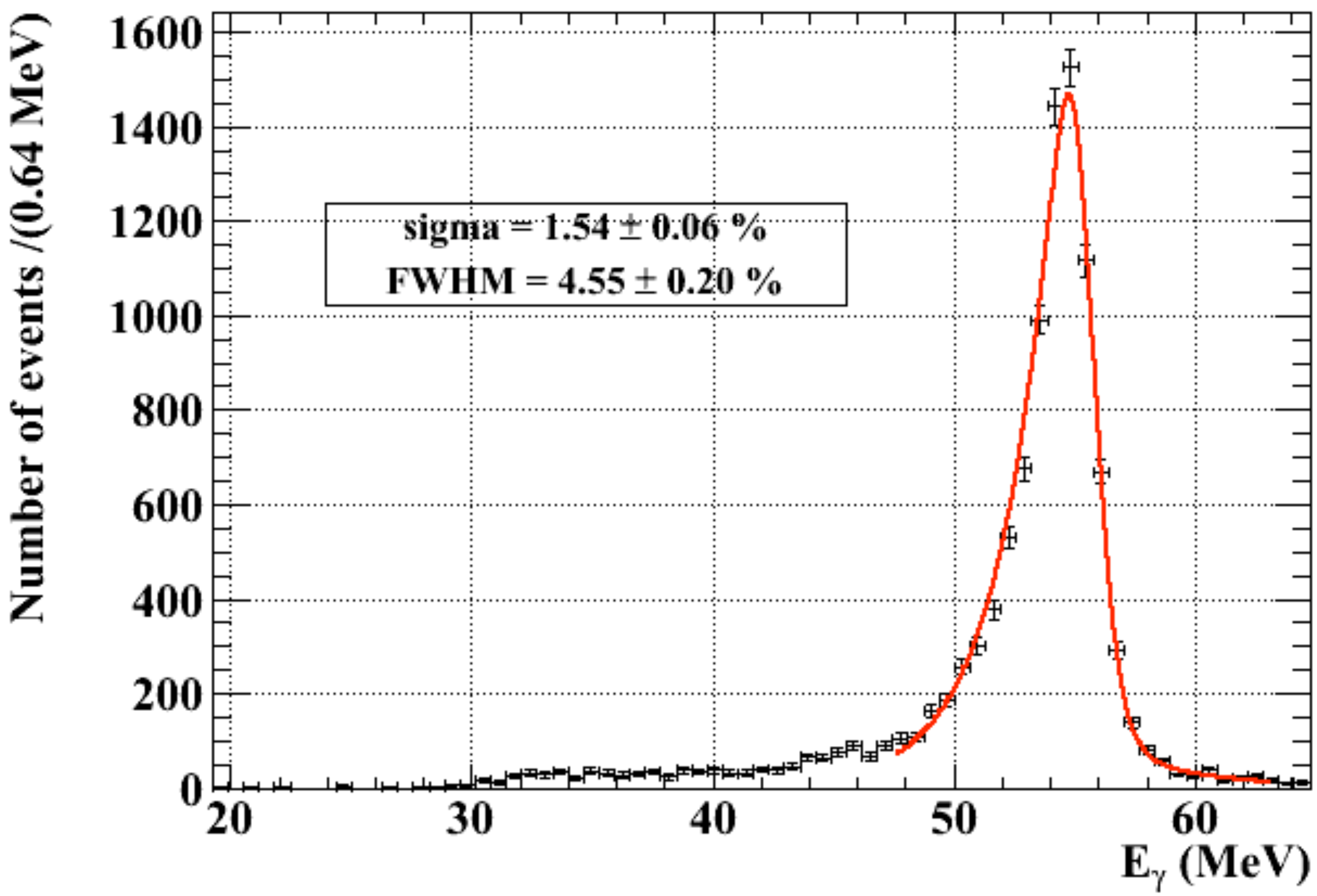
LXe Light monitoring

- LY stable at the 1% level during data taking period 2009



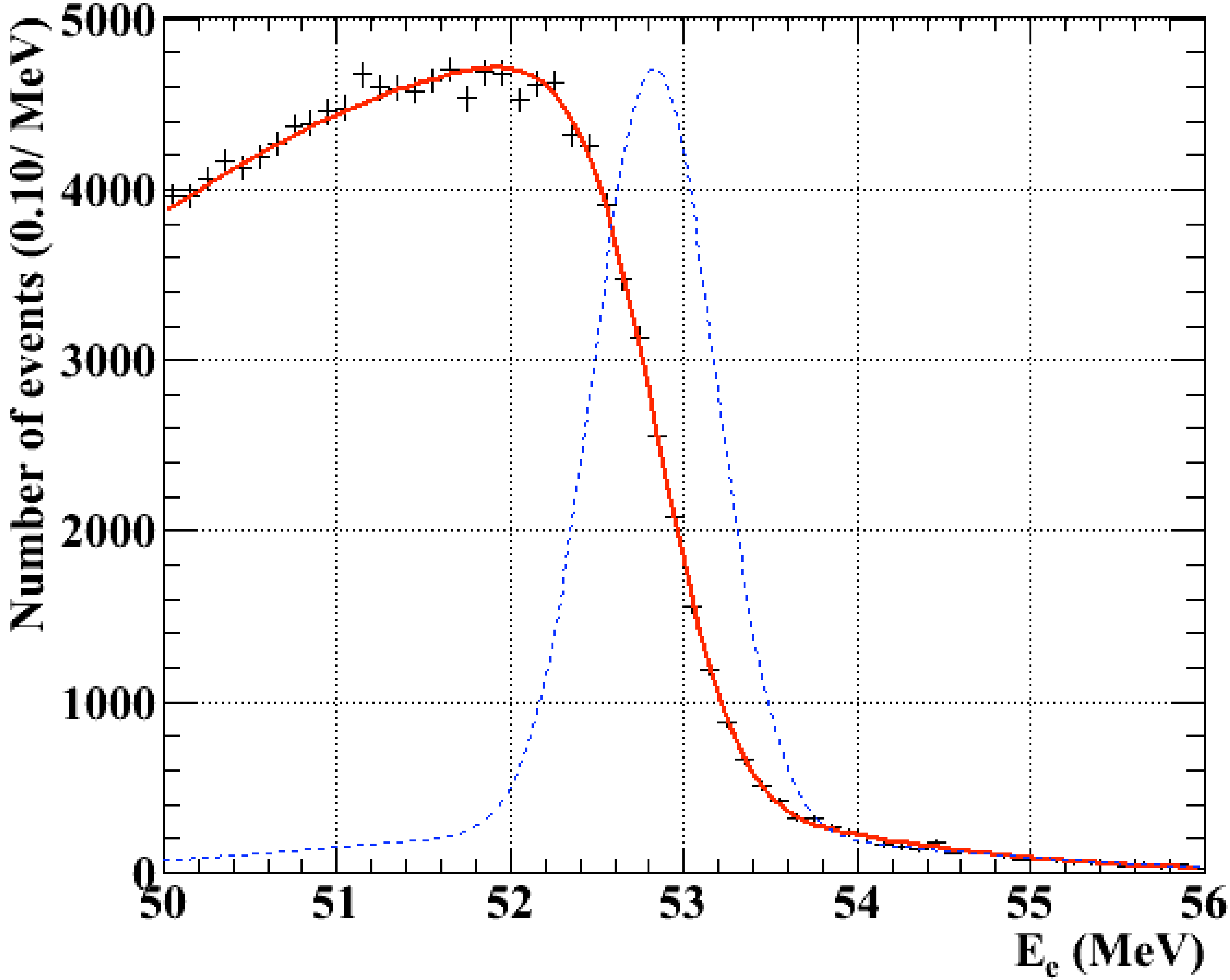
LXe energy resolution

Measured by CEX reaction at 54.9 MeV
σ/E at 52.8 MeV = 1.95 %



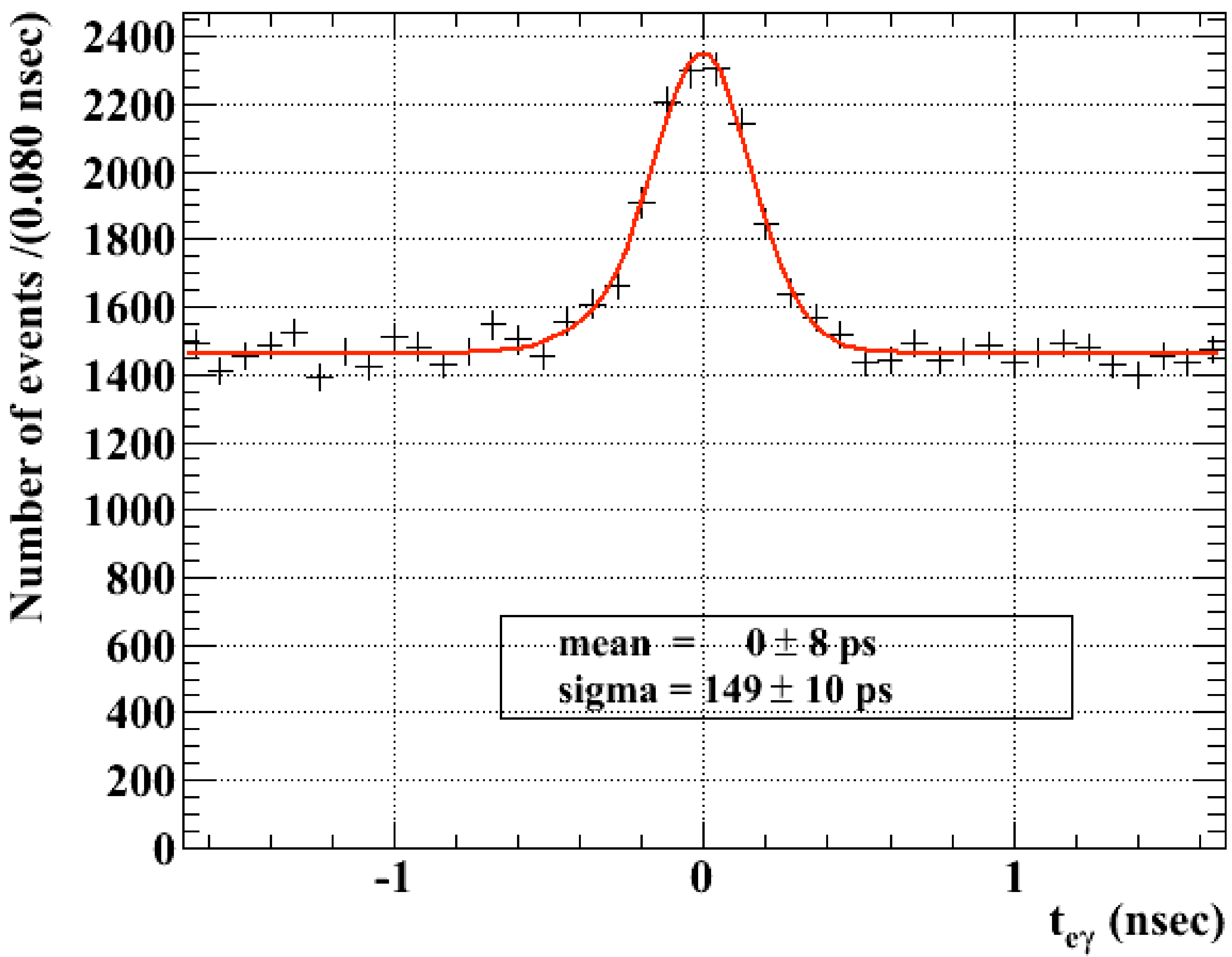
DCH Momentum resolution

Measured by Michel energy spectrum edge
σ/E at 52.8 MeV = 0.74% (core)



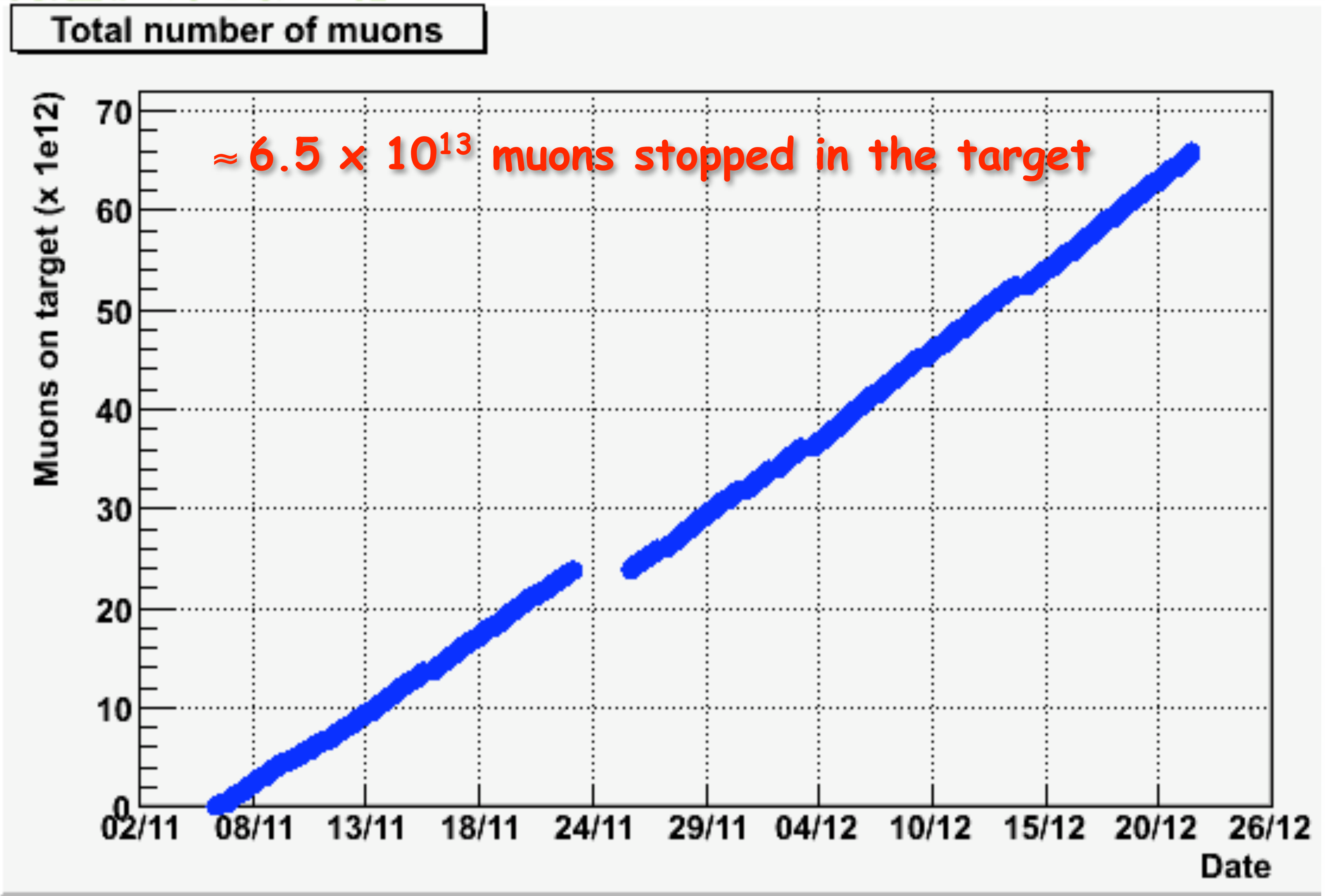
LXe-TC timing resolution

Measured by Radiative muon decay



Data sample 2009

- Short run, but good detector performances and quality data



MEG event selection

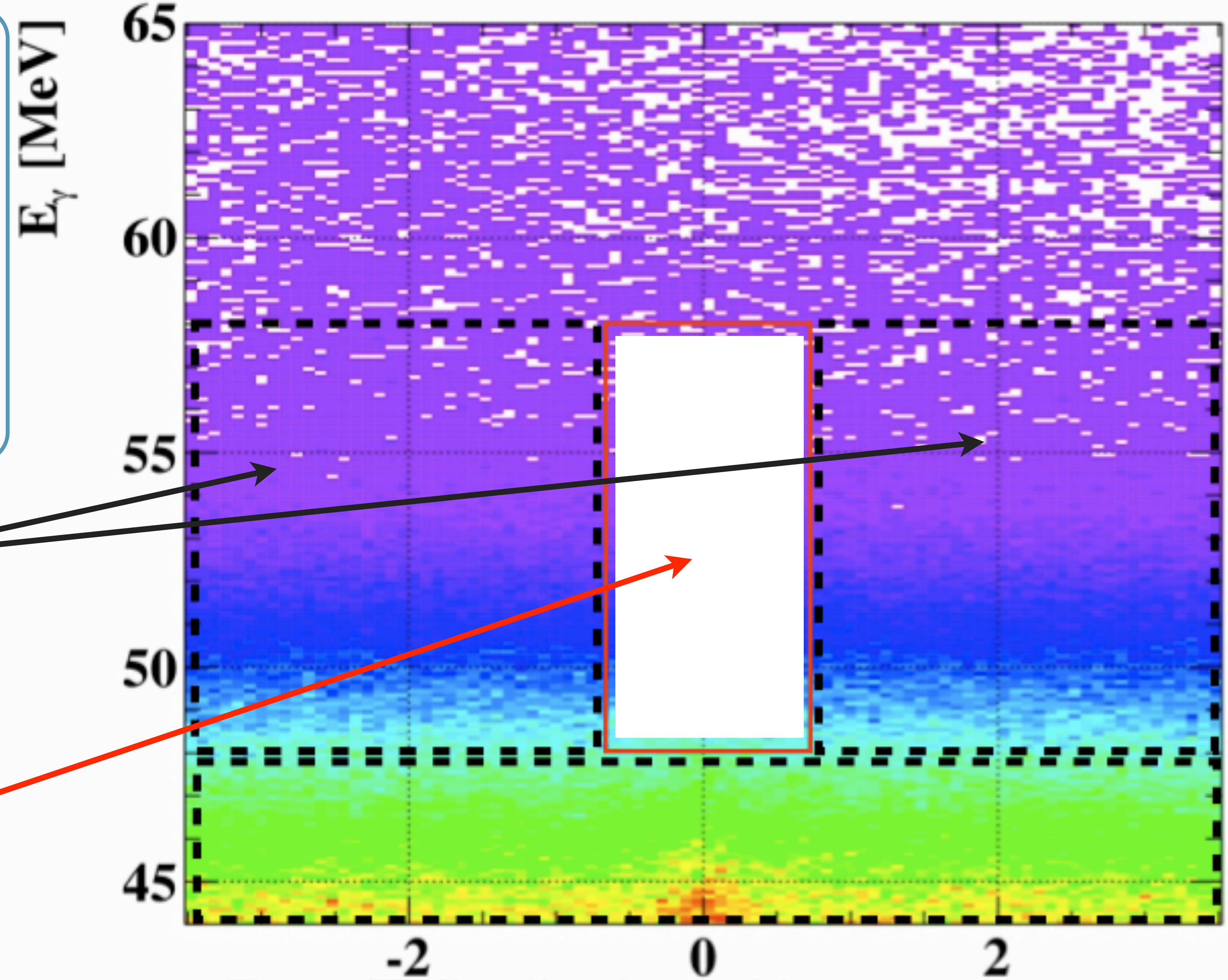
- ☐ Analysis box (~10 σ)
  - ☐ $48 < E_\gamma$ (MeV) < 58
  - ☐ $50 < E_e$ (MeV) < 56
  - ☐ $|T_{e\gamma}| < 0.7$ ns
  - ☐ $|\Phi_{e\gamma}|, |\theta_{e\gamma}| < 50$ mrad

Side-boxes

Events used for optimizing algorithms and background studies

Blinding box

Events saved in separated hidden files



E_γ vs T distribution without any selection.

Analysis strategies

- A candidate μ→eγ event is characterized by 5 kinematical variables: E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}

- Three indipendent likelihood analyses were performed to check possible systematic effects

- Likelihood function is built in terms of Signal S, radiative Michel decay RMD and background BG number of events and their probability density function PDFs (S,R and B):

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

Signal PDF:
is the product of the PDFs for the 5 kinematical variables E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}

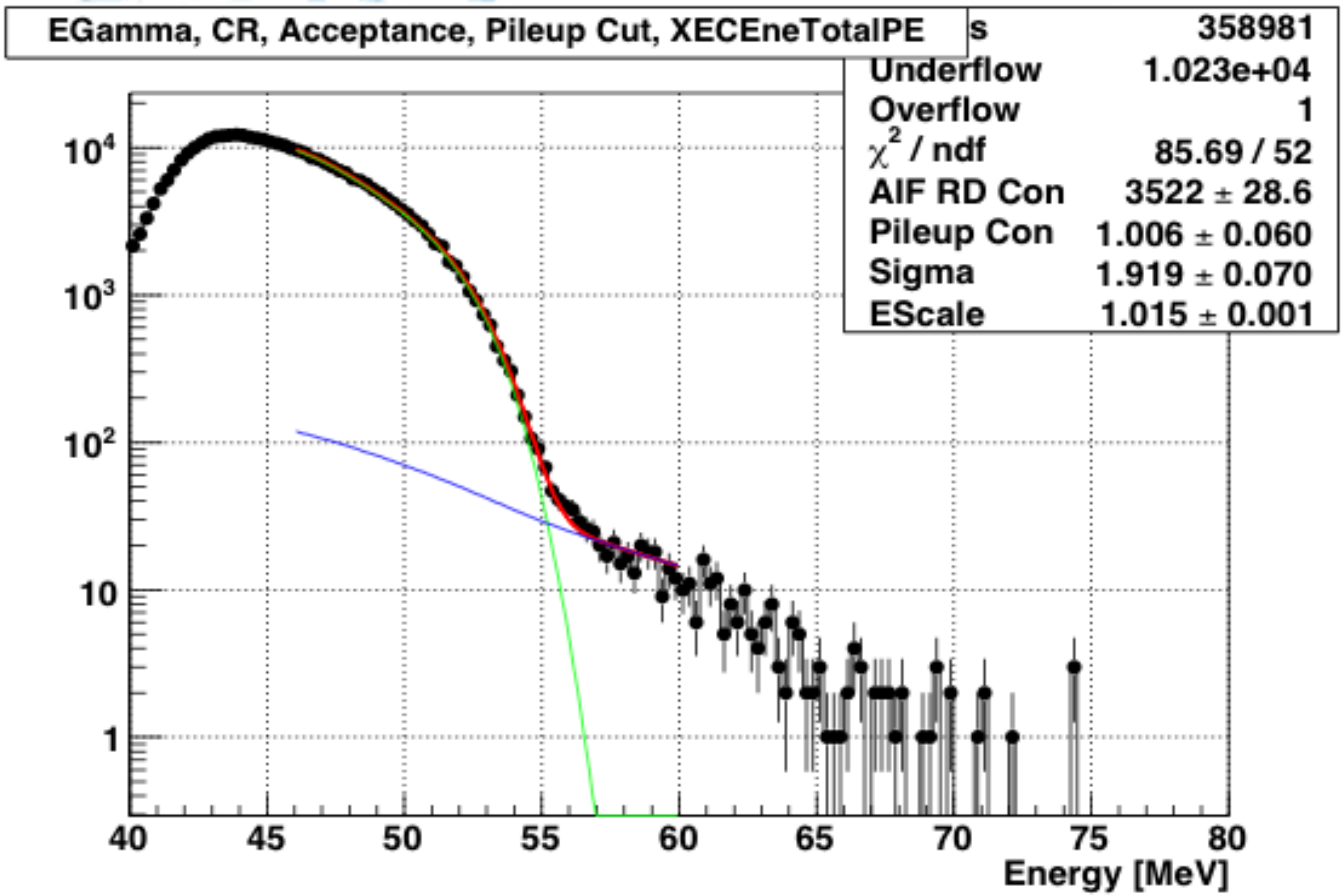
RMD PDF:
is the product of the theoretical PDF (correlated E_g, E_e, ϑ_{eg}, ϕ_{eg}) folded with detector response, and the measured t_{eg} PDF (same of signal one)

BG PDF:
is the product of the background spectra of the 5 kinematical variables E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}, precise measured in the side-bands

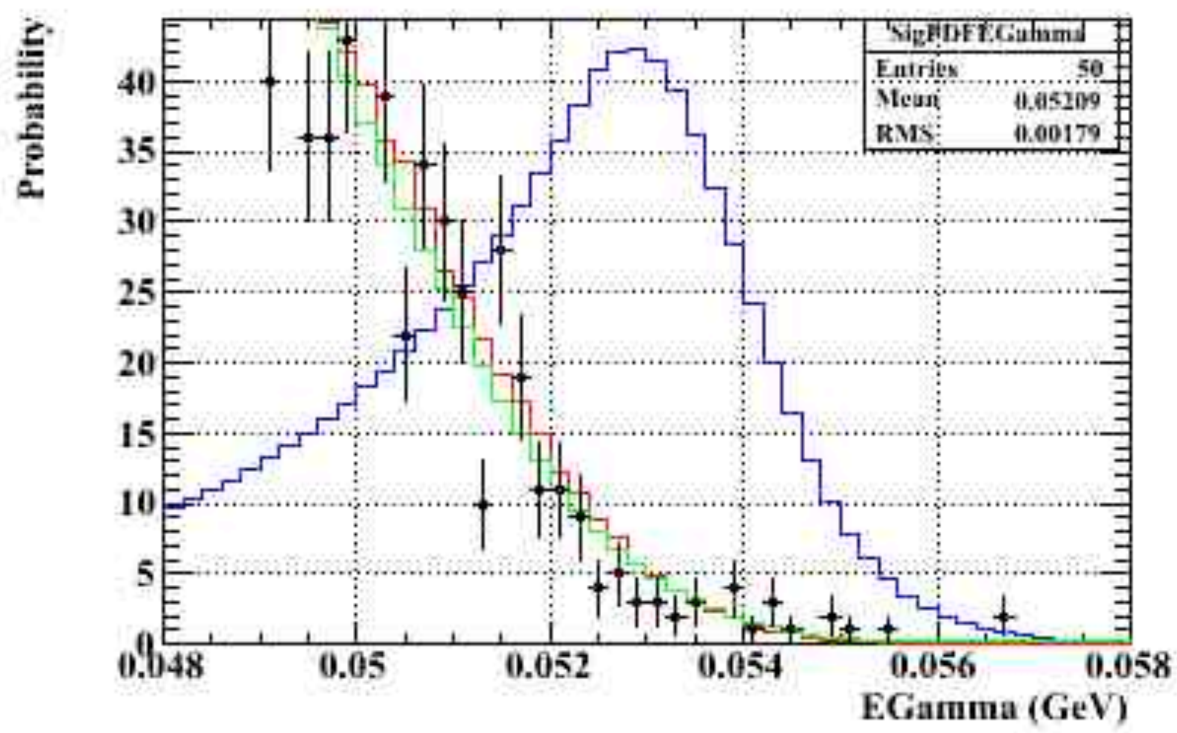
PDF... one more example

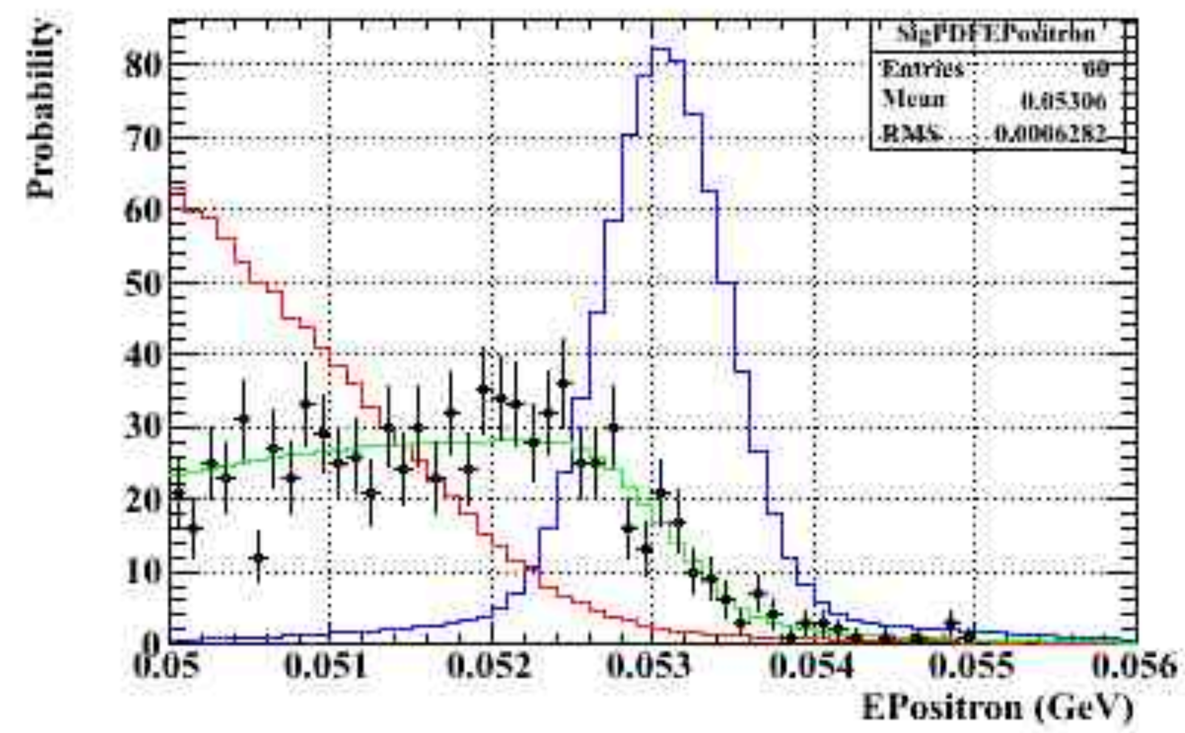
E_g BG PDF from side-band events

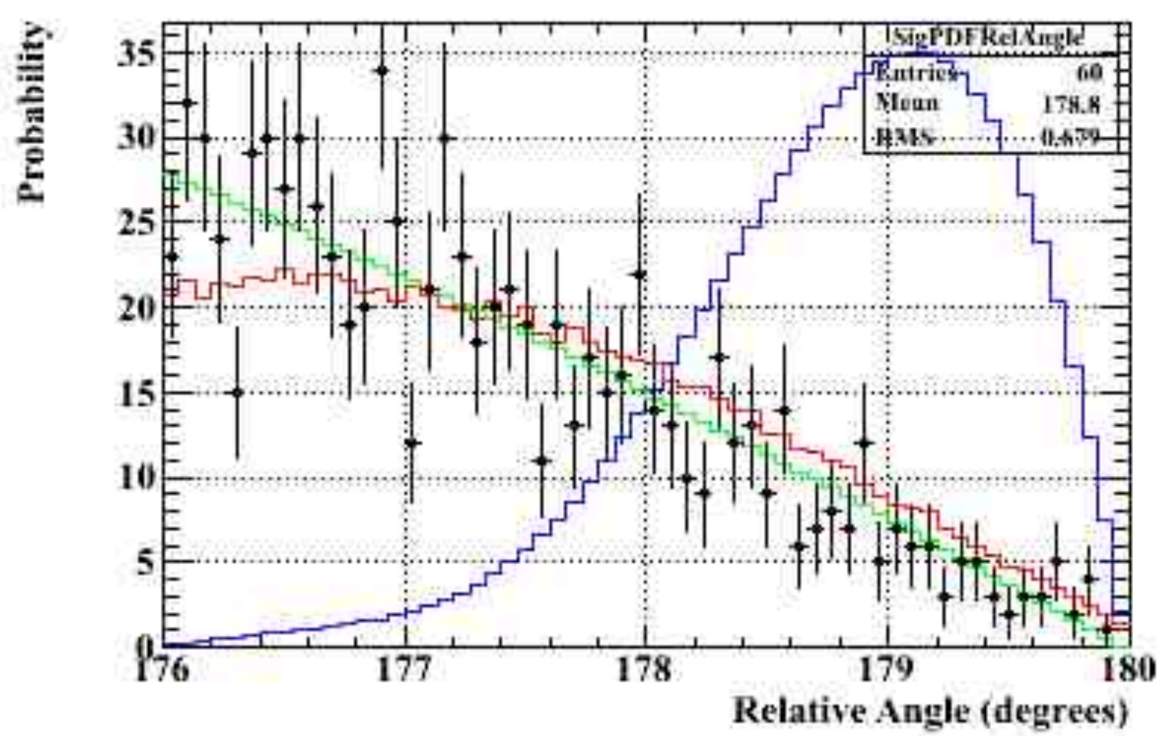
black: data
green: RMD
blue: AIF
(+ resolution+pile up)



Events in sidebands vs PDF



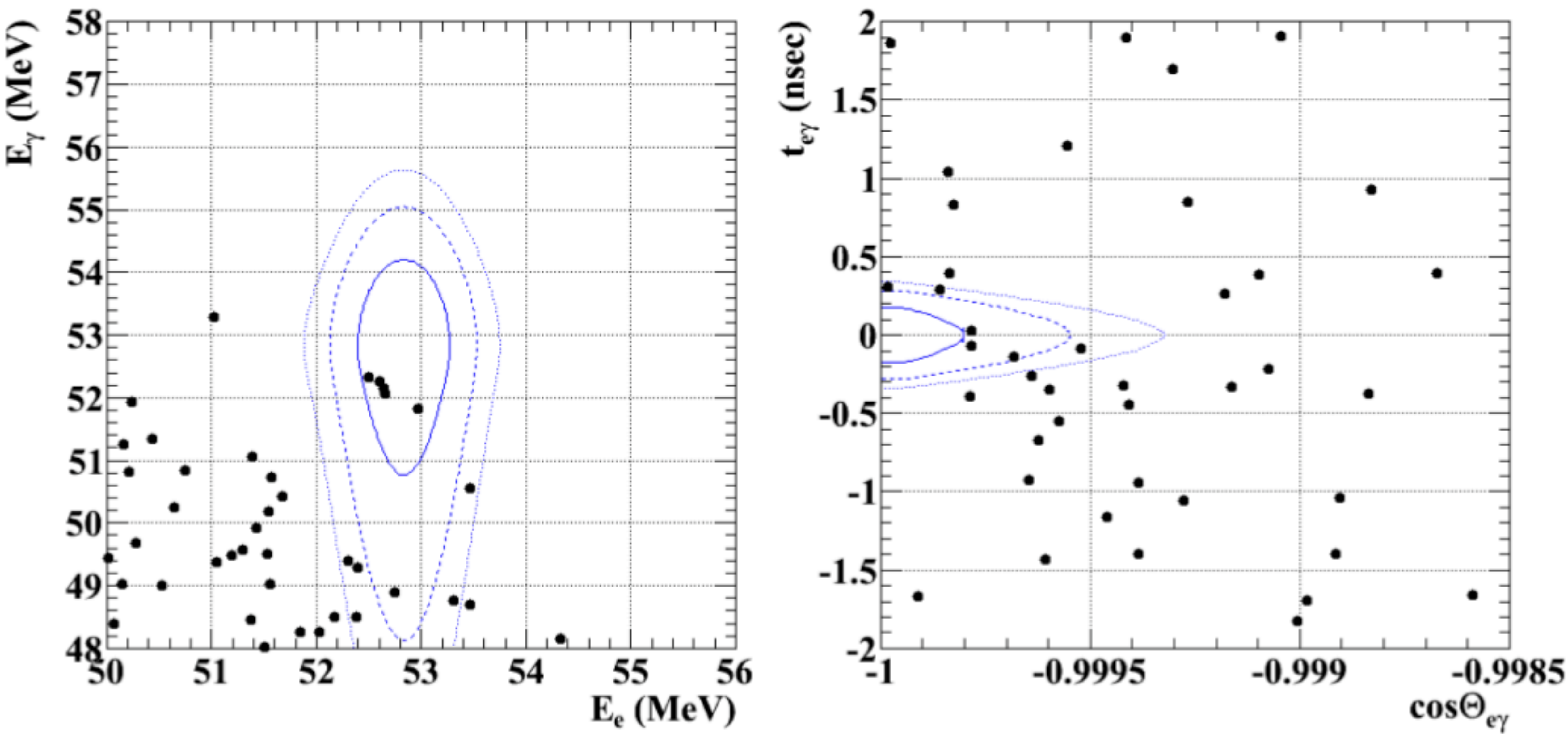




Black dots: Data
Red: RMD
Green: BCK
Blue: Signal

Event distribution after unblinding

- Blue lines are at 1 (39.3%), 1.64 (74.2%) and 2 (86.5%) sigma
- For each plot cut in the other variables for roughly 90% window is applied



Normalization

- $\mathrm{BR}(\mu^+ \to \mathrm{e}^+\gamma)$ is calculated by the 90% C.L. normalizing the upper limit in N_S to the Michel positrons (same cuts) assuming $\mathrm{BR}(\mu^+ \to e^+\nu_e\overline{\nu}_\mu) \approx 1$

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

$$k \equiv N_{e\nu\nu} \times \left[\frac{f_S}{f_M}\right] \times \left[\frac{\varepsilon(TRG=0 \mid e^+\gamma)}{\varepsilon(TRG=22 \mid track \cap e^+_m \cap TC)}\right] \times A(\gamma \mid track)\cdot\varepsilon(\gamma)\cdot Psc(22)$$

$$f_S \equiv A(DC)\cdot\varepsilon(track, p_e > 50\mathrm{MeV} \mid DC)\cdot\varepsilon(TC \mid p_e > 50\mathrm{MeV})\big|_S$$

$$f_M \equiv \ldots\big|_M$$

Signal to Michel relative efficiency (data/MC)

TRG = 0 : MEG Trigger
TRG =22: Special Trigger fo Michel positrons

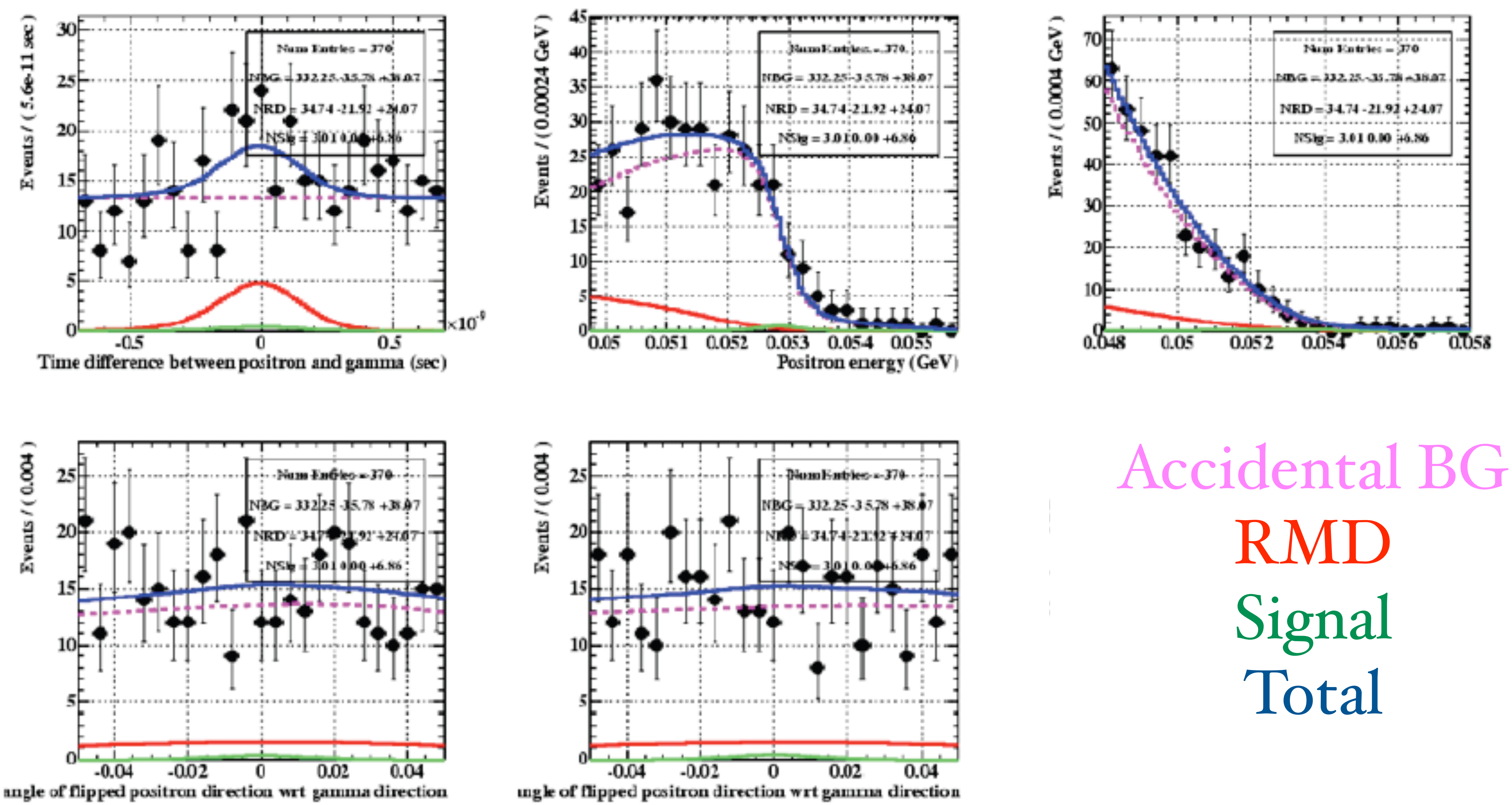
Prescaling factor = 10^7

k = 1.0 x 10^{12} (+- 10%)

Results

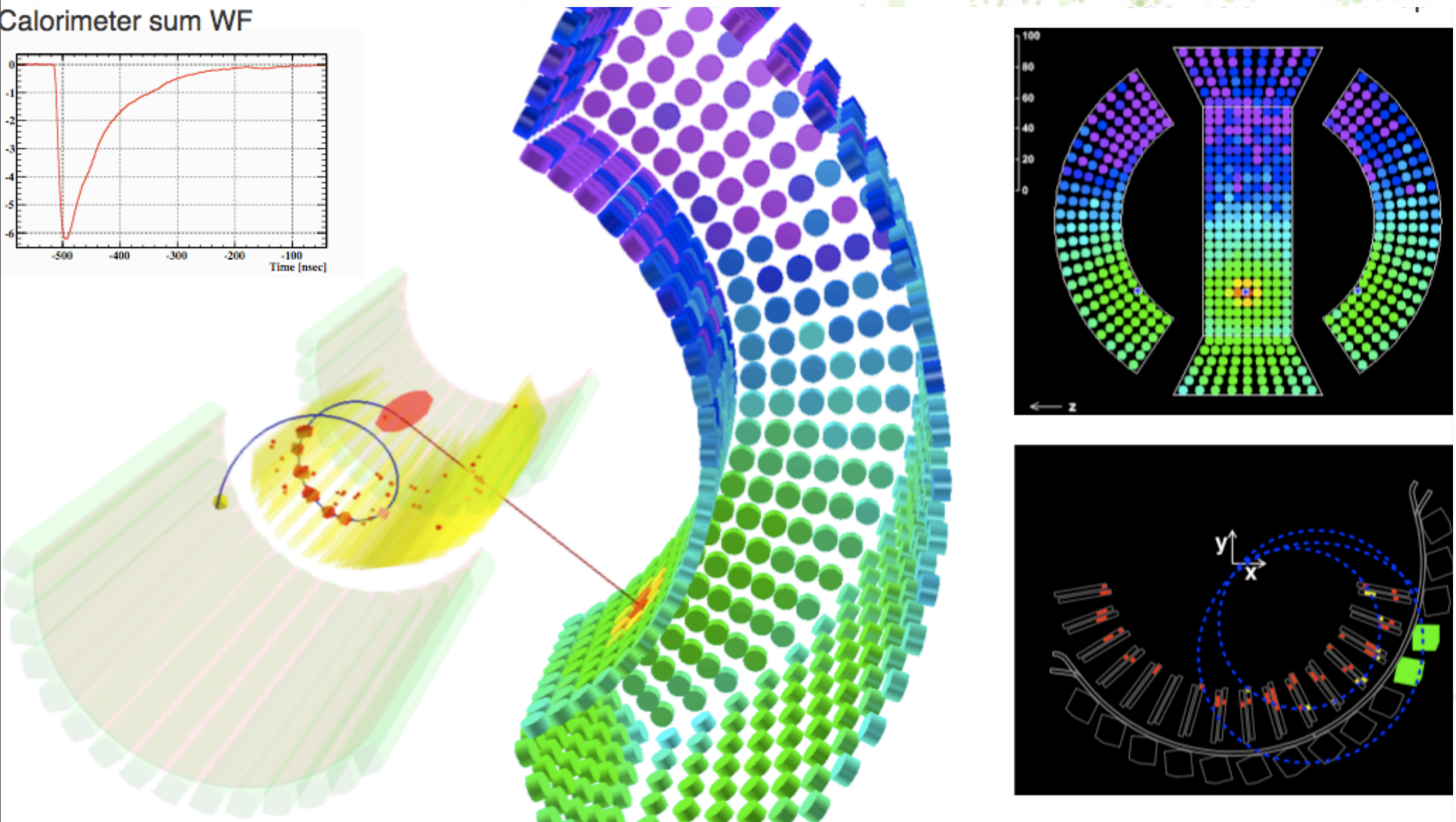
- Nsig < 14.5 @ 90% C.L.
- Nsig = 0 is in 90% confidence region
- Nsig best fit = 3

BR($\mu \rightarrow e\gamma$) @90% C.L. ≤ 1.5 × 10^{-11}



A candidate event

- Each highly ranked event was checked carefully



Summary and future prospects

Variable (in sigma)	2008	2009	2010 (preliminary estimate)
Gamma Energy (%)	2.0 (w>2cm)	←	1.5 (w>2cm)
Gamma Timing (psec)	80	> 67	68
Gamma Position (mm)	5 (u,v) - 6 (w)	←	←
Gamma Efficiency (%)	63	58	←
Positron Momentum (%)	1.6	0.74 (core)	0.7
Positron Timing (psec)	<125	←	←
Positron Angle (mrad)	10 (φ) - 18 (ϑ)	7.4 (φ) - 11.2 (ϑ)	8 (φ) - 8 (ϑ)
Positron Efficiency (%)	14	40	←
Gamma-Positron Timing (psec)	148	142 (core)	120
Muon decay point (mm)	3.2 (R) - 4.5 (Z)	2.3 (R) - 2.8 (Z)	1.4 (R) - 2.5 (Z)
Trigger efficiency (%)	66	84	94
DAQ time/Real time (days)	48/78	35/43	95/117
Stopping Muon Rate (sec^{-1})	3×10^7	2.9×10^7	3×10^7
Sensitivity	1.3×10^{-11}	6.1×10^{-12}	2.0×10^{-12}
B.R. upper limit	2.8×10^{-11}	1.5×10^{-11}	

LFV in the other muonic channels

$\mu^+ \rightarrow e^+ e^+ e^-$

- Best Upper Limit: BR($\mu \rightarrow 3e$)< 10^{-12} (SINDRIUM Experiment, $I_\mu \sim 10^6$ μ/s)
- Signature: 3 charged leptons
- Main background source: Accidental coincidences
- Positive and DC Muon Beam
- Possible improvements by using present muon beam intensity (10^8 μ/s): a sensitivity two orders of magnitude better respect last U.L. can be reached
- Desiderable sensitivity to be competitive with $\mu \rightarrow e\,\gamma$: 10^{-16}

$\mu^- N \rightarrow e^- N$

- Best Upper Limit: BR($\mu\, N \rightarrow e\, N$)< 7×10^{-13} (SINDRIUM II Experiment)
- Signature: monochromatic electron
- Main background sources: e^- from muon decay in orbit and beam related background
- Negative Muon Beam
- Possible improvements: push on towards very high muon beam intensity $I_\mu \sim 10^{10}$-10^{11} μ/s
- Desiderable sensitivity to be competitive with $\mu \rightarrow e\,\gamma$: 10^{-16}

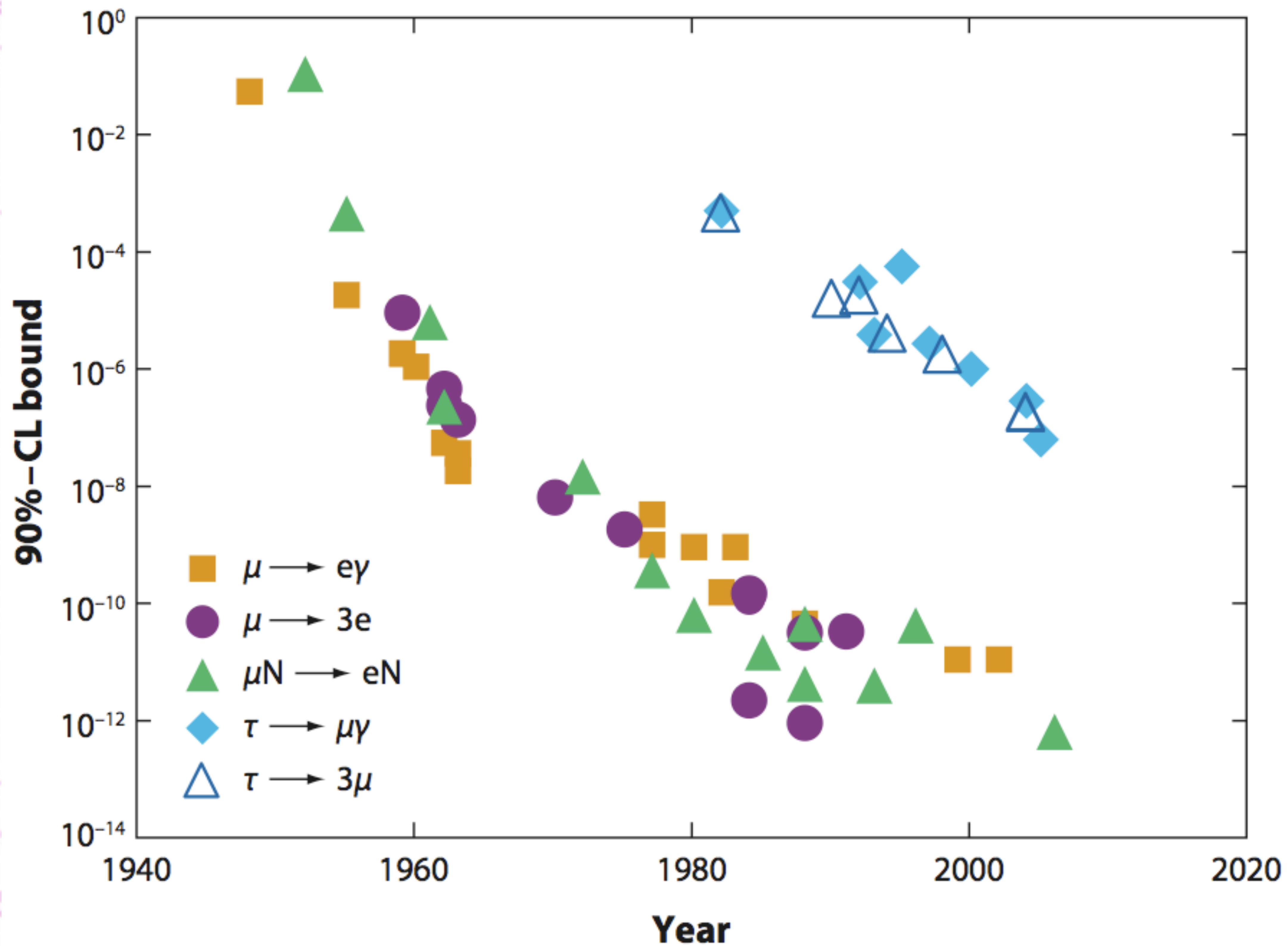
LFV in the tauonic channels

$\tau^{\pm} \to l^{\pm} \gamma$ $\tau^{\pm} \to l^{\pm} l^{+} l^{-}$ $\tau^{\pm} \to l^{\pm} h^{0}$

- More open decay channels
- Best Upper Limit: BR($\tau \to 3l$)< few $\times 10^{-8}$ (BELLE and BaBar Experiment)
- B-factories are in fact τ-factories
- Possible improvements: higher luminosity $e^{+} e^{-}$ collider (KEKB upgrade and new project as SuperB factory)
- Desiderable sensitivity to be competitive with $\mu \to e \gamma$: 10^{-9} - 10^{-10}

	Belle[b]		BaBar[c]		Combined BF	
Channel	N_{obs} (N_{bkg}) events	BF (10^{-8})	N_{obs} (N_{bkg}) events	BF (10^{-8})	Frequentist (10^{-8})	Bayesian (10^{-8})
$\tau \to \mu\gamma$	10 ($13.9^{+6.0}_{-4.8}$)	4.5	4 (6.2 ± 0.5)	6.8	2.3	5.9
$\tau \to e\gamma$	5 ($5.14^{+3.86}_{-2.81}$)	12	1 (1.9 ± 0.4)	11	7.2	8.5
$\tau \to \mu e^{+}e^{-}$	0 (0.04 ± 0.04)	2.7	2 (0.89 ± 0.27)	8.0	3.0	3.0
$\tau \to \mu\mu^{+}\mu^{-}$	0 (0.07 ± 0.05)	3.2	0 (0.33 ± 0.19)	5.3	1.7	2.0
$\tau \to e\mu^{+}\mu^{-}$	0 (0.05 ± 0.03)	4.1	0 (0.81 ± 0.31)	3.7	1.4	2.2
$\tau \to ee^{+}e^{-}$	0 (0.40 ± 0.30)	3.6	1 (1.33 ± 0.25)	4.3	1.8	2.6

Muonic and tauonic LVF searches



Conclusions

- During the 2009 data taking a sensitivity two time lower than the actual B.R.($\mu \rightarrow e\, \gamma$) limit was reached ($6.1 \times 10^{-12}$)
- A B.R. ($\mu \rightarrow e\, \gamma$) $\leq 1.5 \times 10^{-11}$ was set by using only ~ 1.5 months of data taking
- The MEG experiment has started a long data taking period
- A sensitivity "a few $\times 10^{-13}$" is expected to be reached in the next 3 years