Search of Lepton Flavour Violation with the $\mu^+ \rightarrow e^+ \gamma$ decay: first results from the MEG experiment

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Waseda U.
KEK

INFN & U Pisa
INFN & U Roma
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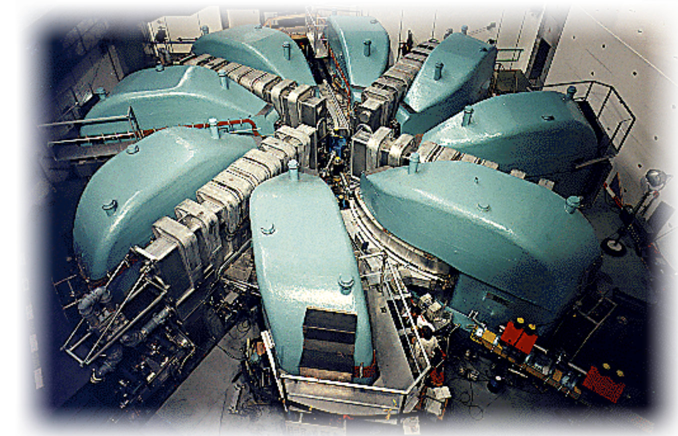
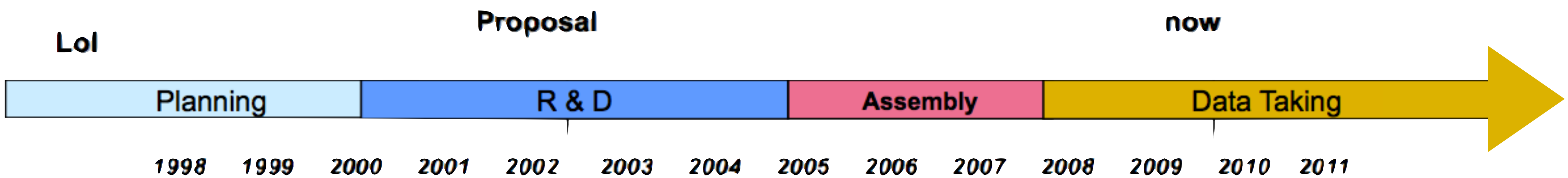
Outline

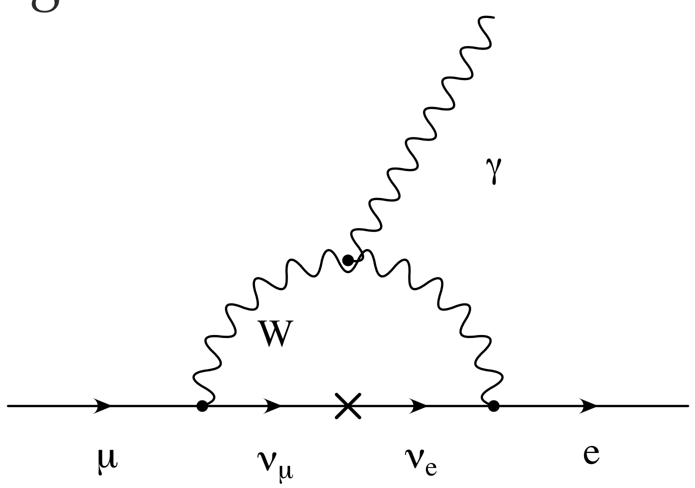
- Physics motivation for a $\mu \to e\gamma$ experiment
- The $\mu \to e\gamma$ decay
- The detector
  - Overview of sub-detectors
  - Calibration methods
- Analysis of 2008 run
- Status
  - Run 2009
- Next year(s)





The μ→eγ decay

- The μ→eγ decay in the SM is radiatively induced by neutrino masses and mixings at a negligible level

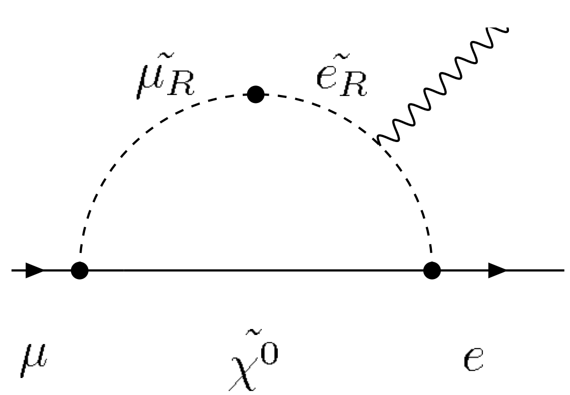


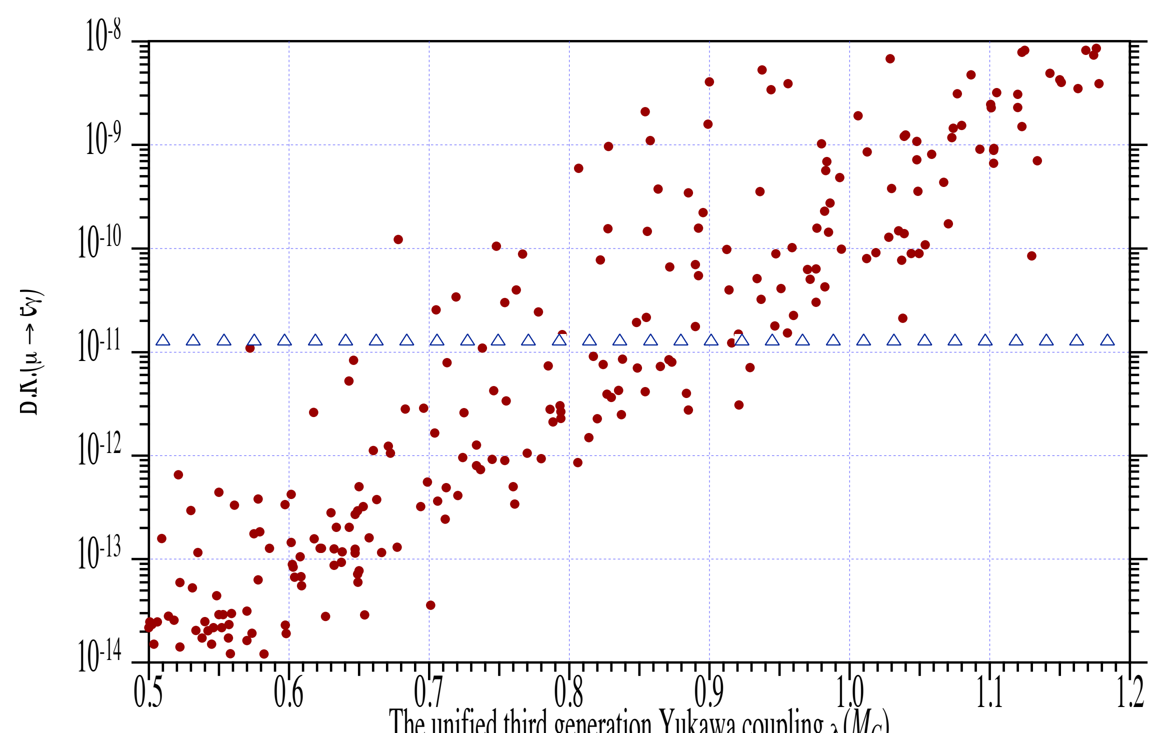
$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\text{decay}} \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\text{vertex}} \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\text{oscillation}}$$

$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{3\alpha}{32\pi} \left(\frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}}{M_W^2}\right)^2$$

Relative probability ~ 10^{-54}

- All SM extensions enhance the rate through mixing in the high energy sector of the theory (other particles in the loop...)

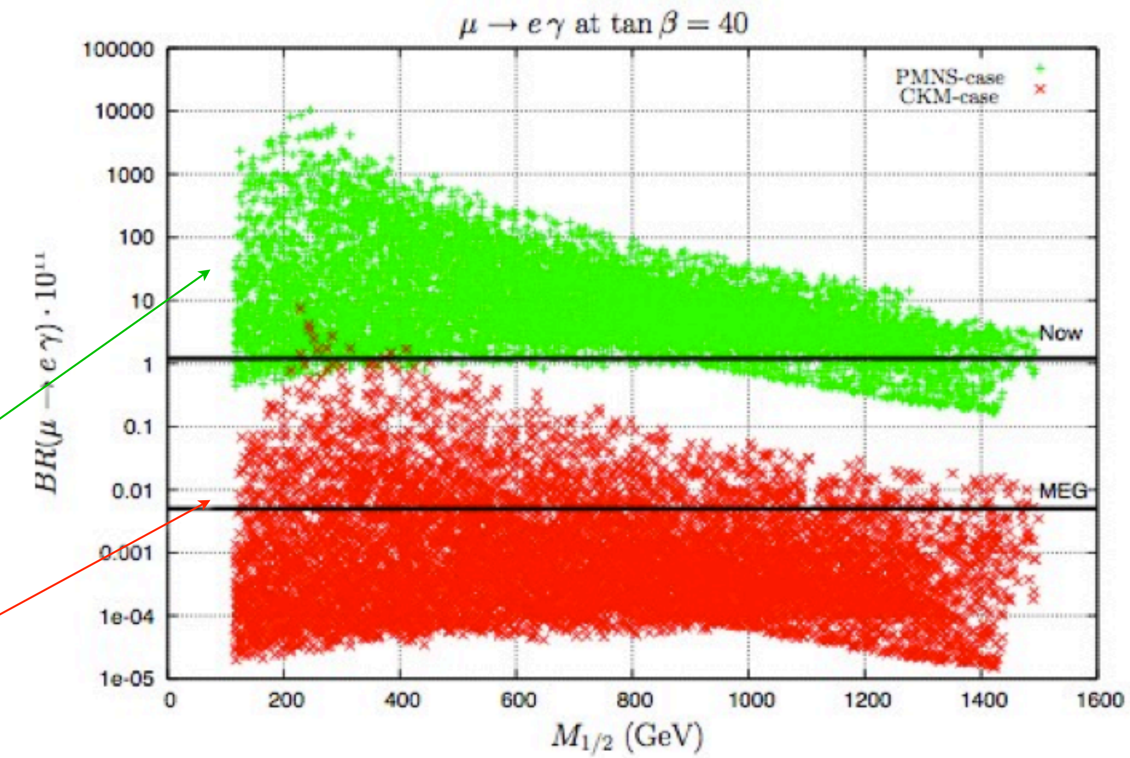




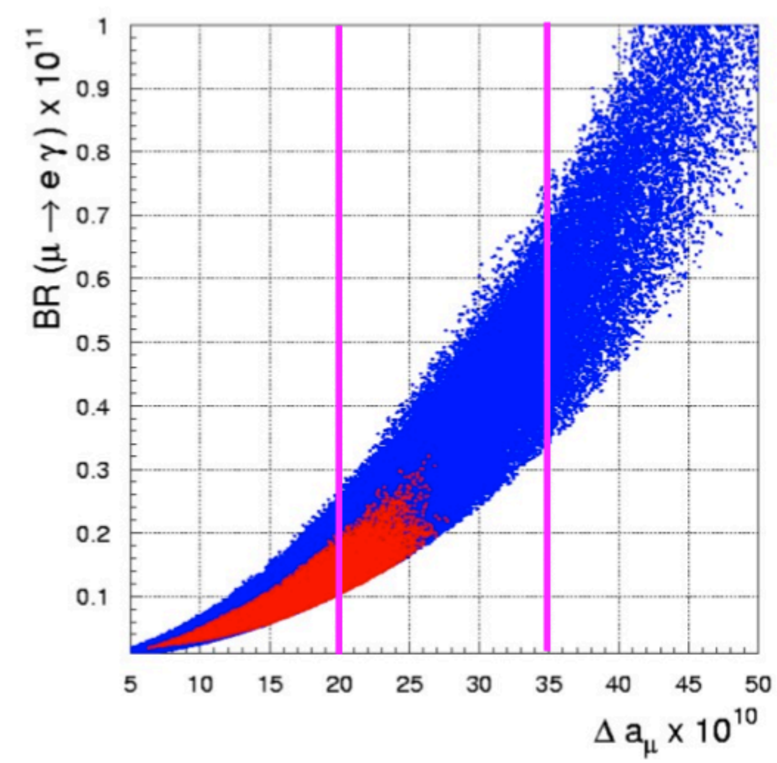
- Clear evidence for physics beyond the SM
- Restrict parameter space of SM extensions

Connections

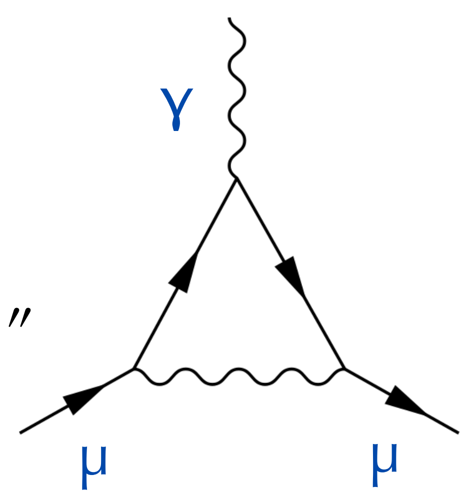
- LHC
  - it is Super Symmetry + Grand Unification that predicts new particles in the loop.
  - alternate search for (E/M_{SUSY}) suppressed effects



- neutrino oscillations
  - mixing matrix in charged sector can be proportional to
    - PMNS
    - CKM



- muon *g*–2
  - a_μ is the "diagonal" term
  - μ→eγ diagram is the "off-diagonal"



Barbieri *et al,*, Nucl. Phys B445 (1995) 225
Hisano *et al.*, Phys. Lett. B391 (1997) 341
Masiero *et al.*, Nucl. Phys. B649 (2003) 189
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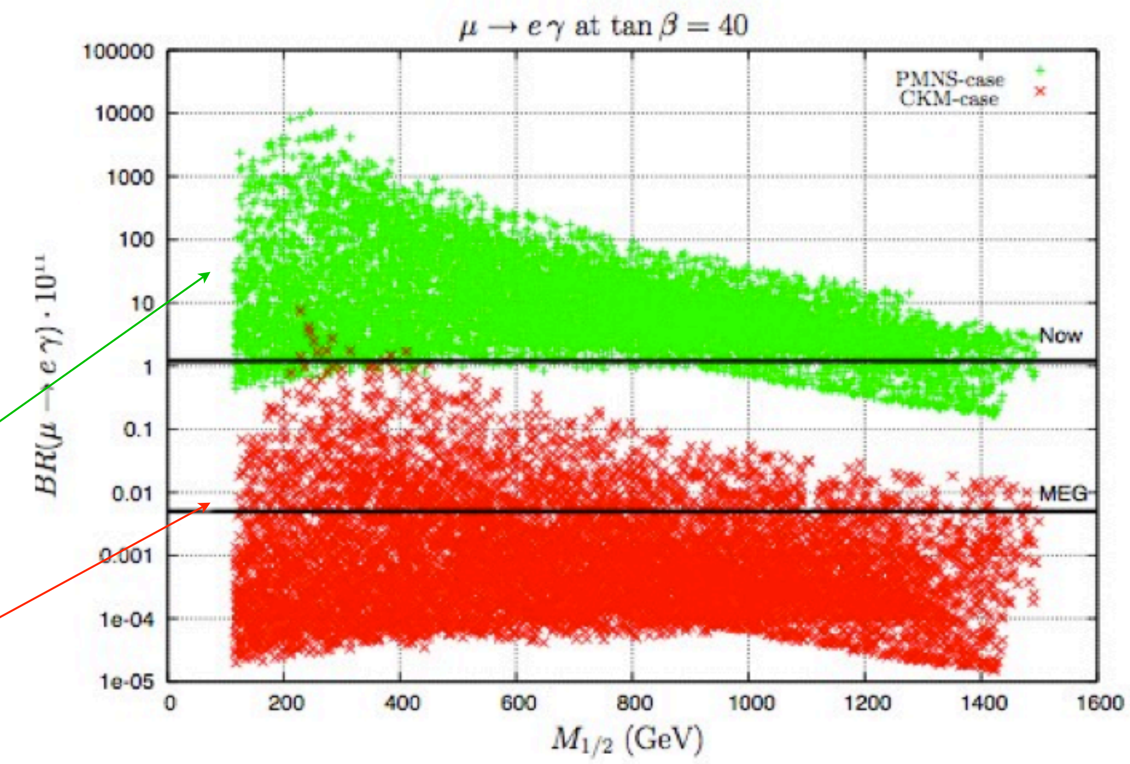

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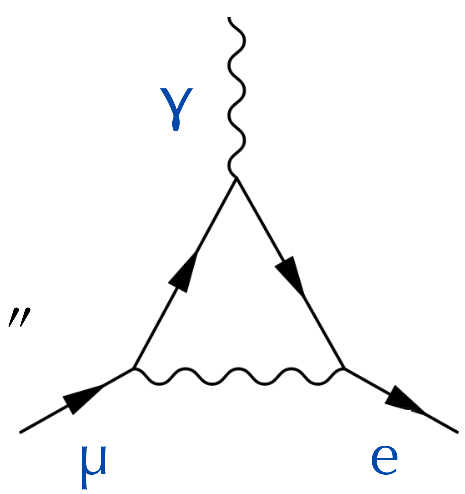

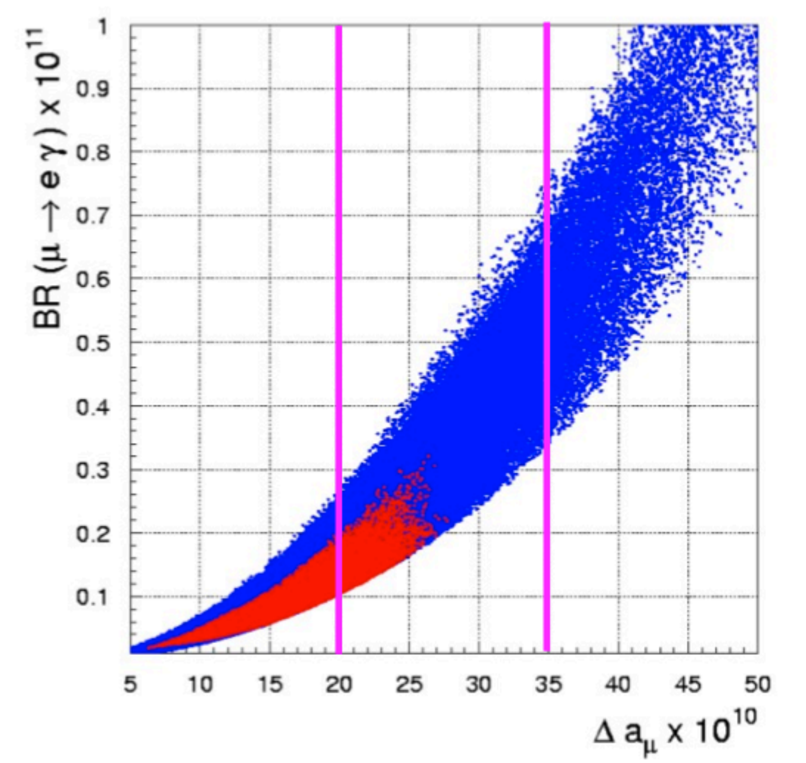

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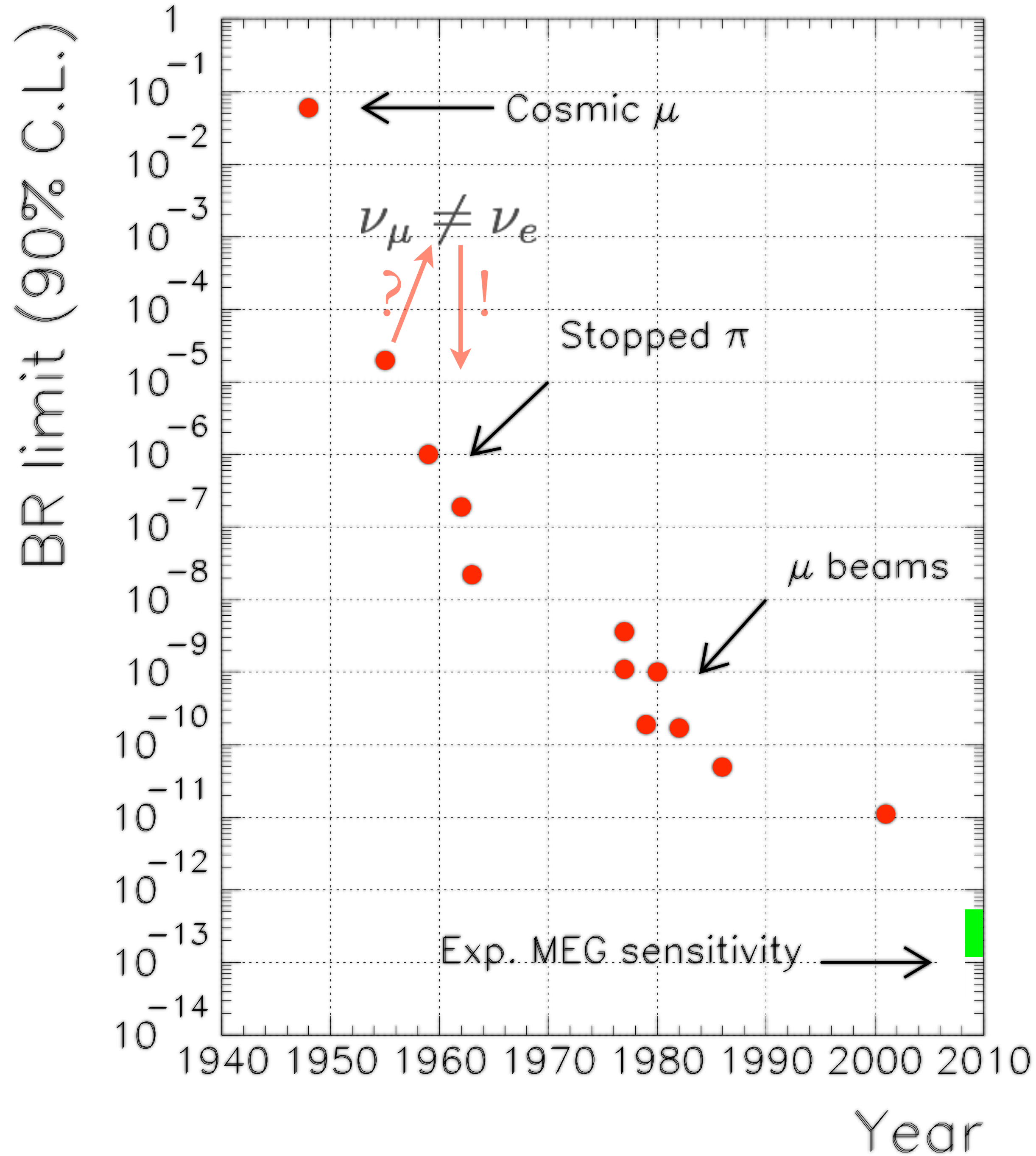
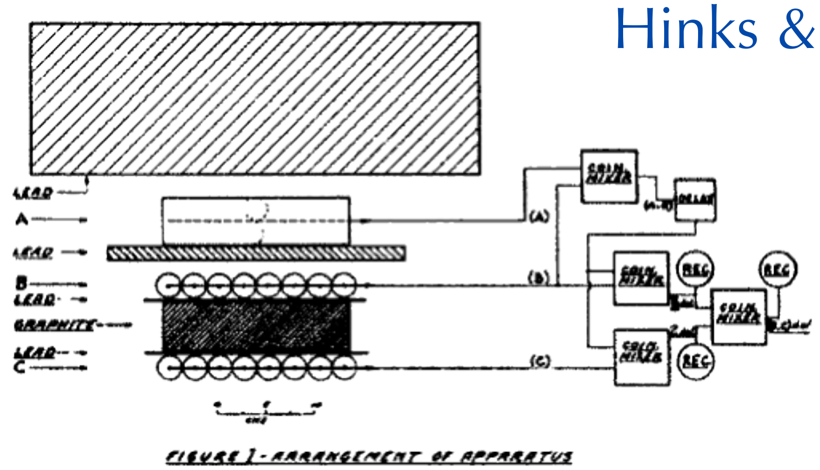
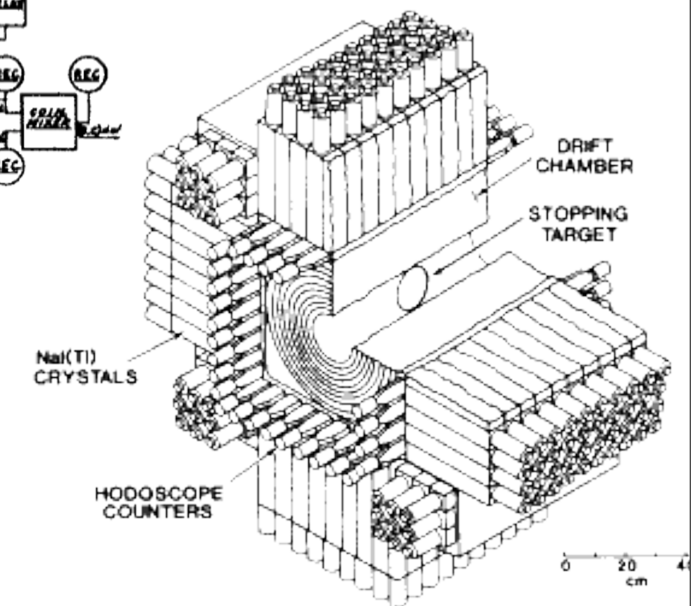
Historical perspective

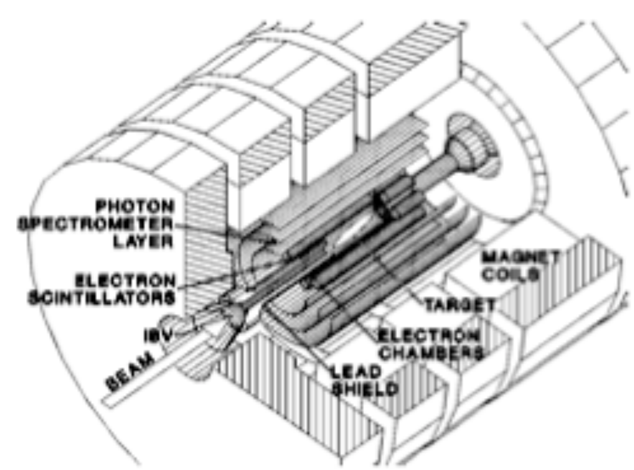


Hinks & Pontecorvo

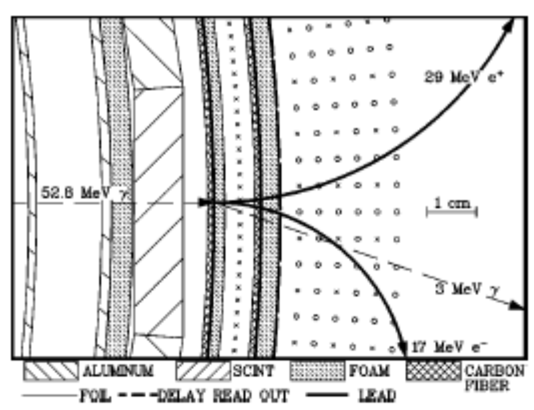


Crystal Box





MEGA

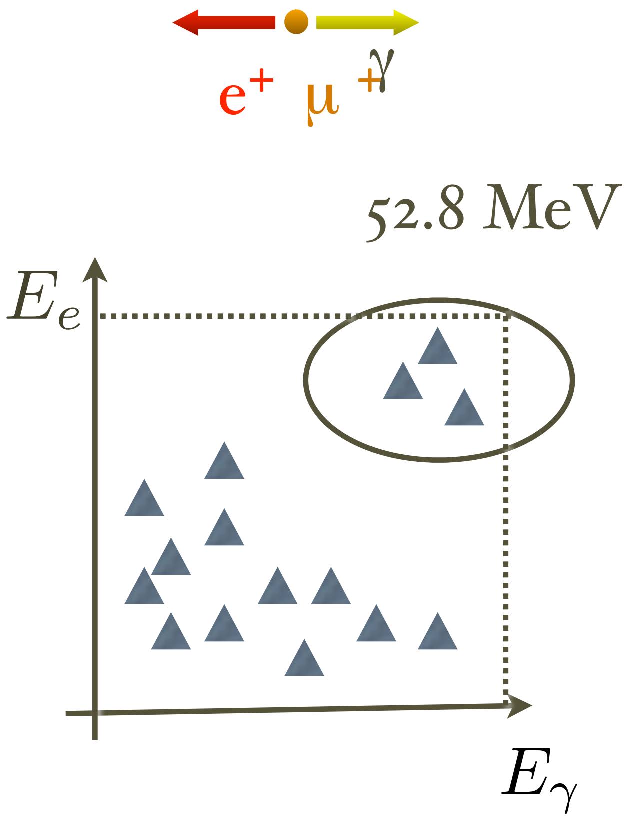


Each improvement linked to the technology either in the beam or in the detector

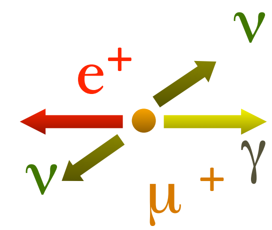
Always a trade-off between various elements of the detector to achieve the best "sensitivity"

Signal and Background

"Signal"

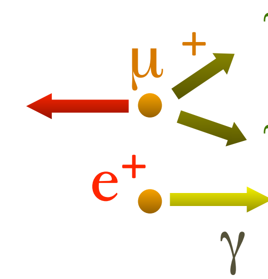


"Prompt"



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

"Accidental"



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

$$e^+e^- \rightarrow \gamma\gamma$$
$$\mu \rightarrow e\bar{\nu}\nu\gamma$$
$$e\mathcal{N} \rightarrow e\mathcal{N}\gamma$$

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

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

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

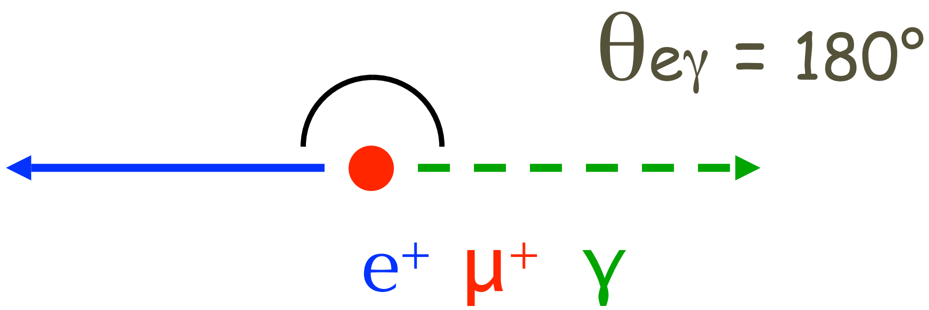
Exp./Lab	Year	ΔEe/Ee (%)	ΔEγ /Eγ (%)	Δteγ (ns)	Δθeγ (mrad)	Stop rate (s^{-1})	Duty cyc. (%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^5	(6..9)	4.9×10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5×10^8	(6..7)	1.2×10^{-11}
MEG	2010	1	4.5	0.15	19	3×10^7	100	2×10^{-13}

FWHM

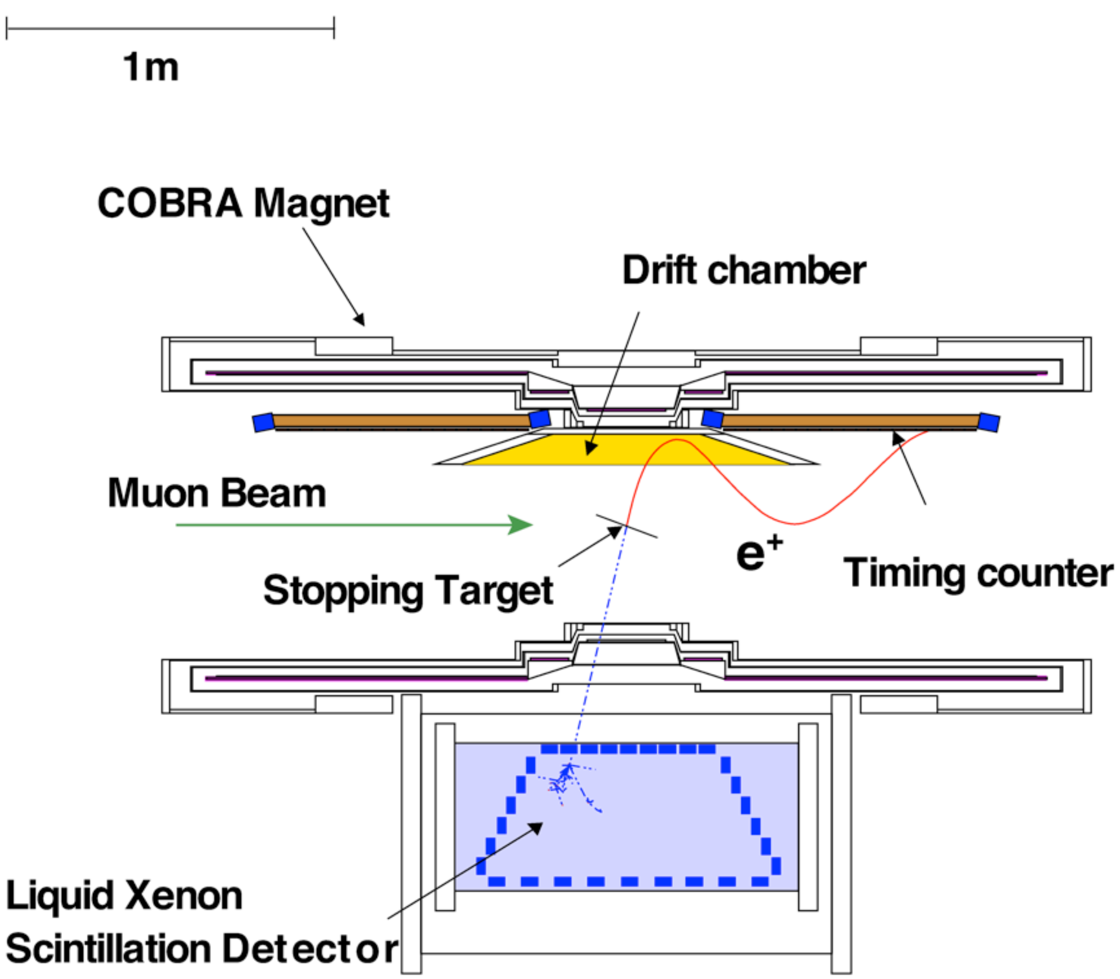
MEG experimental method

Easy signal selection with μ+ at rest:

μ: stopped beam of >10^7 μ /sec in a 175 μm target



Ee = Eγ = 52.8 MeV



- e+ detection

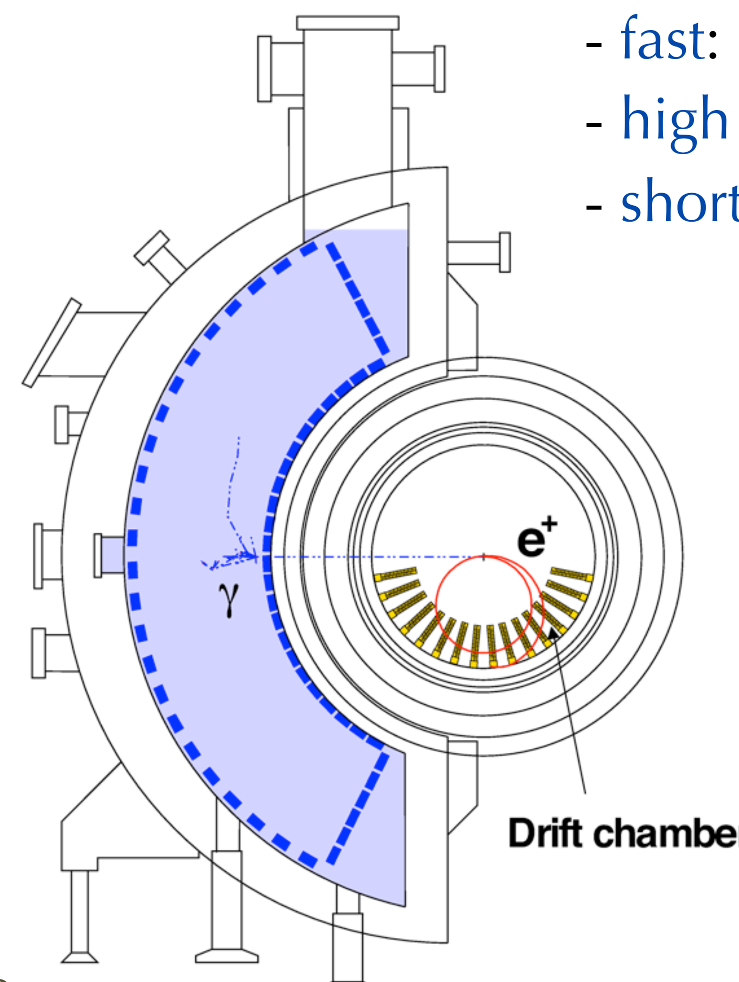
  magnetic spectrometer composed of solenoidal magnet and drift chambers for momentum

  plastic counters for timing

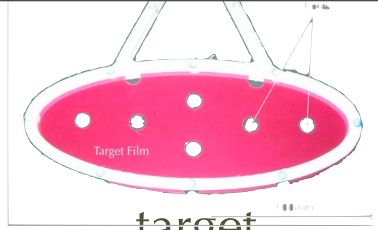
- γ detection

  Liquid Xenon calorimeter based on the scintillation light

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



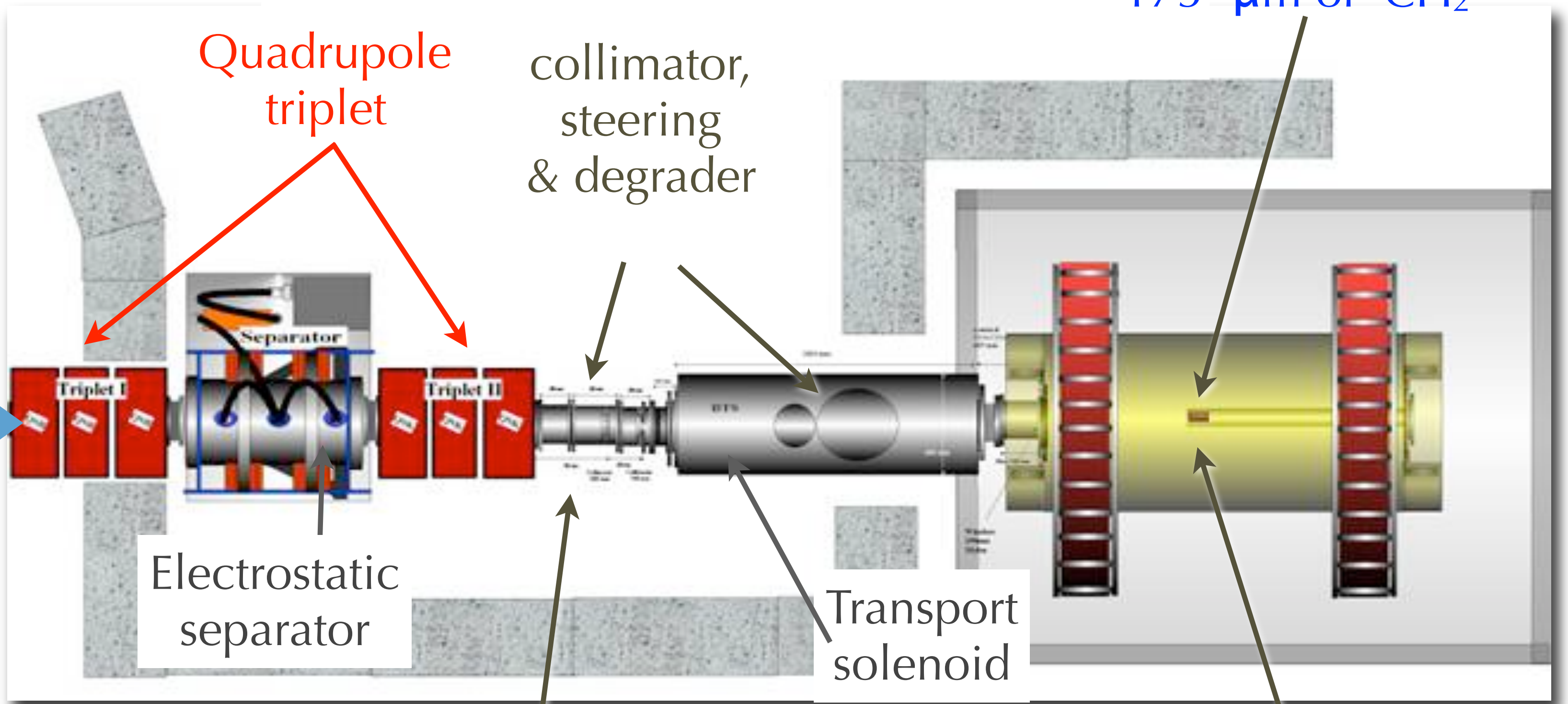
Beam line



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 175 μm target

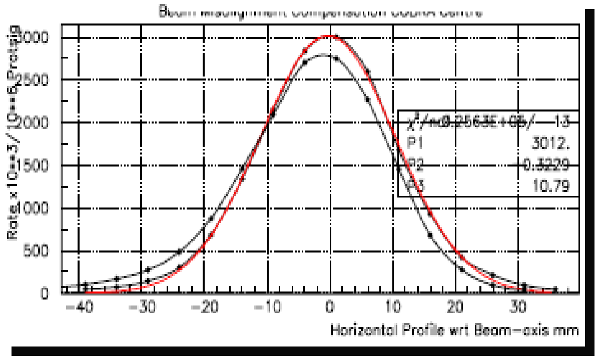


μ/e separation 11.8 cm (7.2 σ)

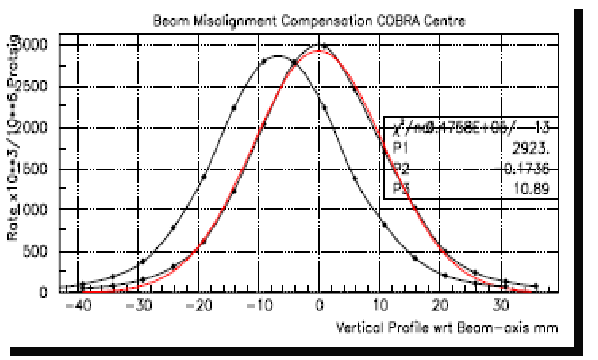
R_μ (exp. on target) $>6\ 10^7\ \mu^+/s$

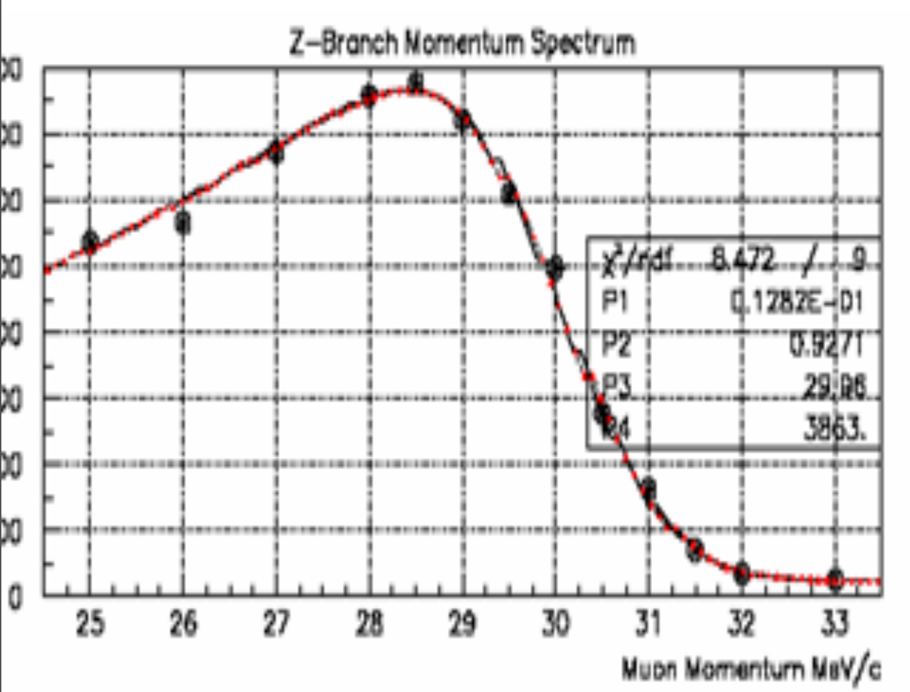
μ spot (exp. on target) $\sigma_V \approx \sigma_H \approx 11$ mm

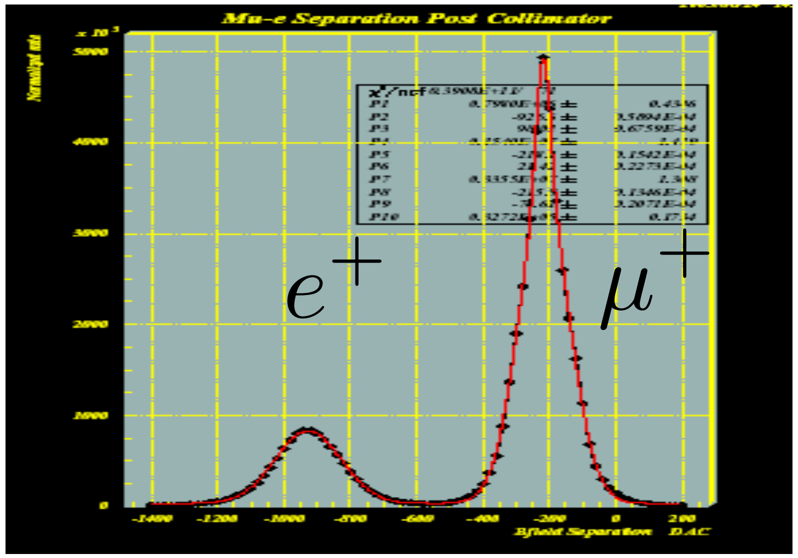
$\sigma_x = 11$ mm



$\sigma_y = 11$ mm

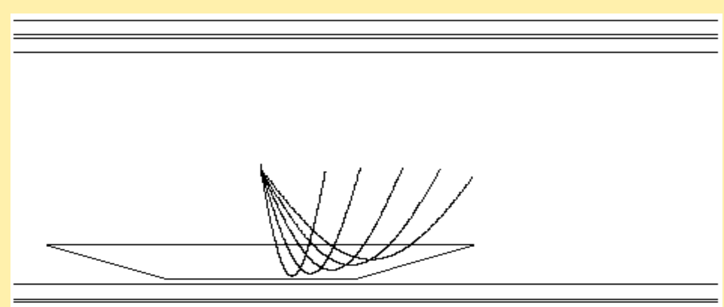
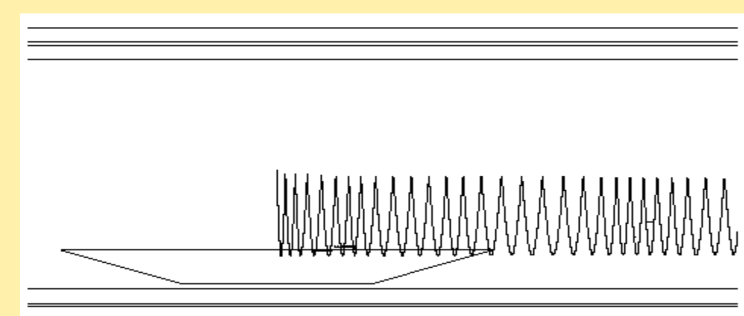
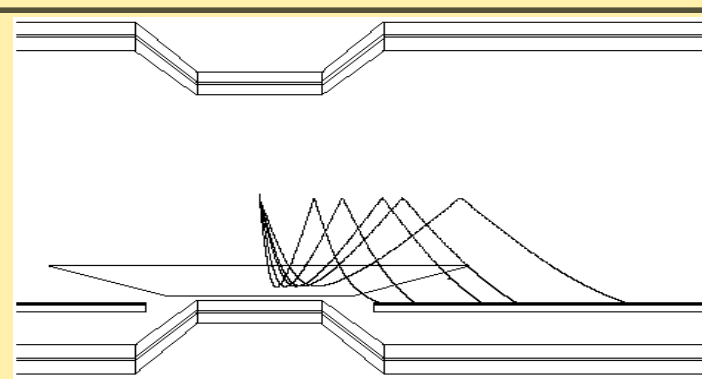
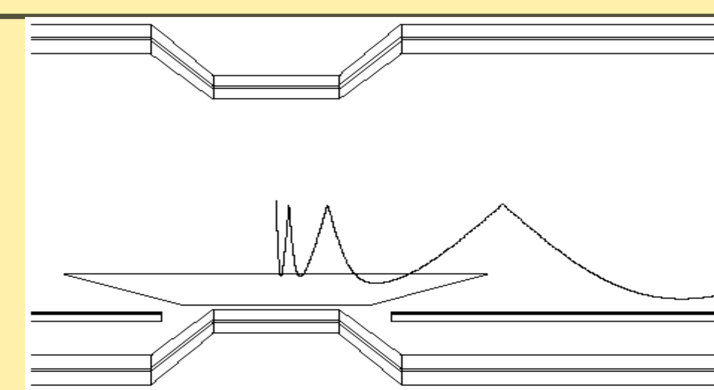






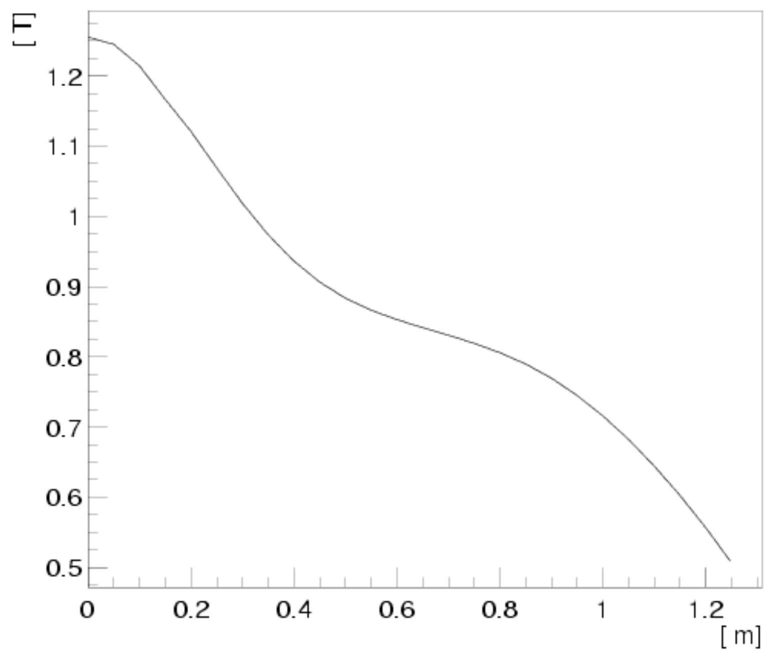
COBRA spectrometer

- The emitted positrons tend to wind in a uniform magnetic field
  - the tracking detector becomes easily “blind” at the high rate required to observe many muons
- A non uniform magnetic field solves the rate problem
- As a bonus: COnstant Bending RAdius

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

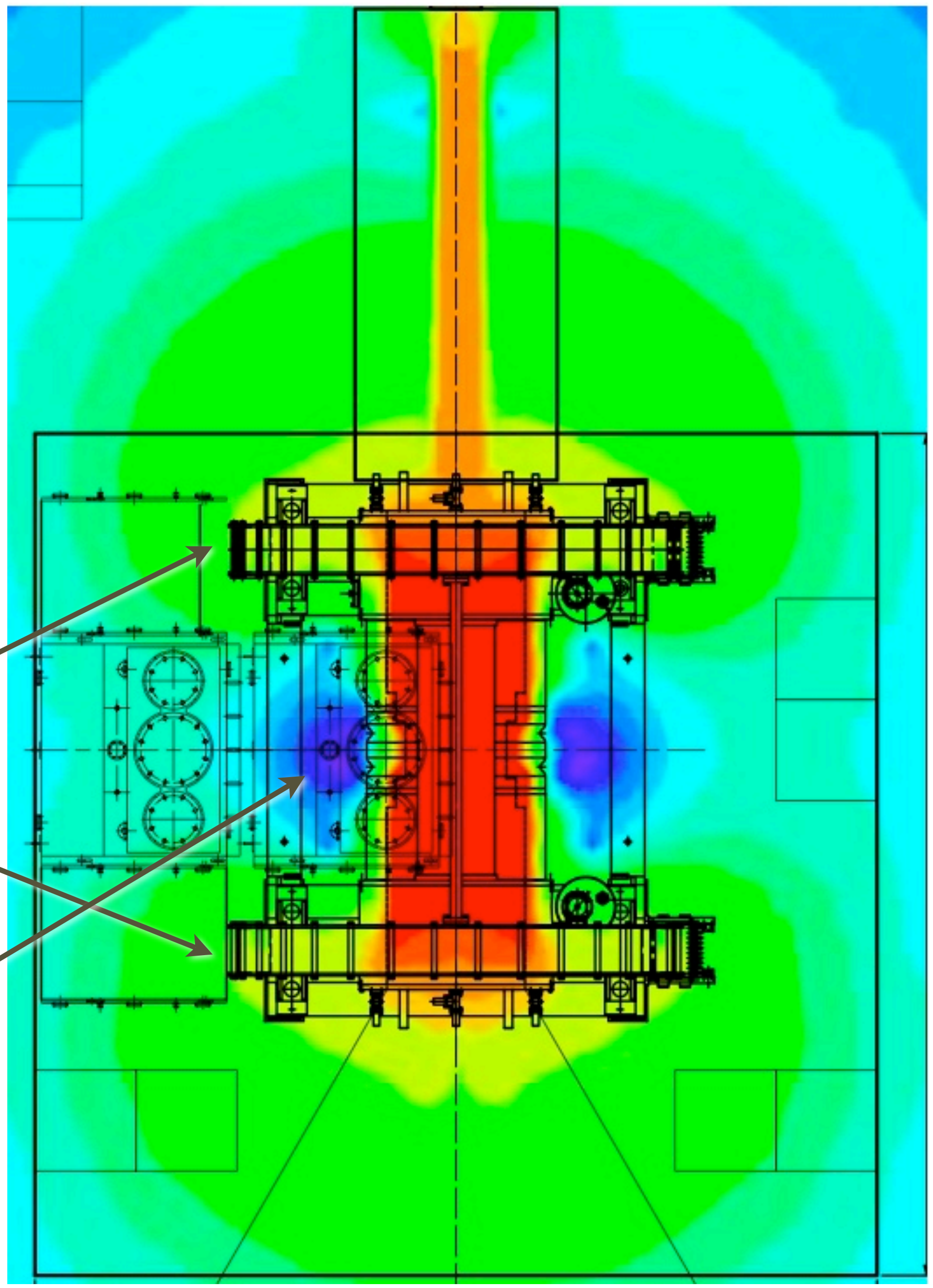
COBRA spectrometer

Non uniform magnetic field decreasing from the center to the periphery

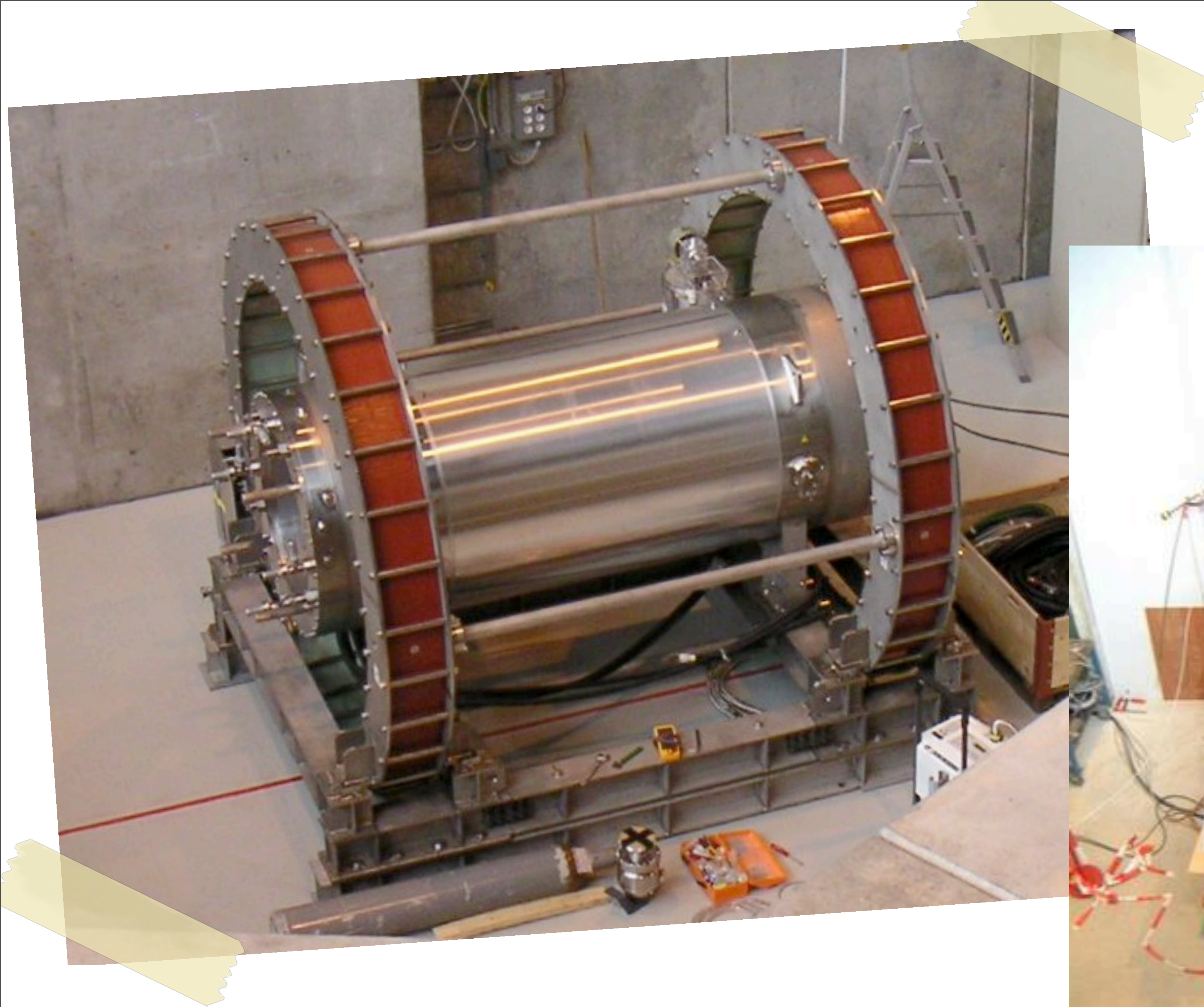


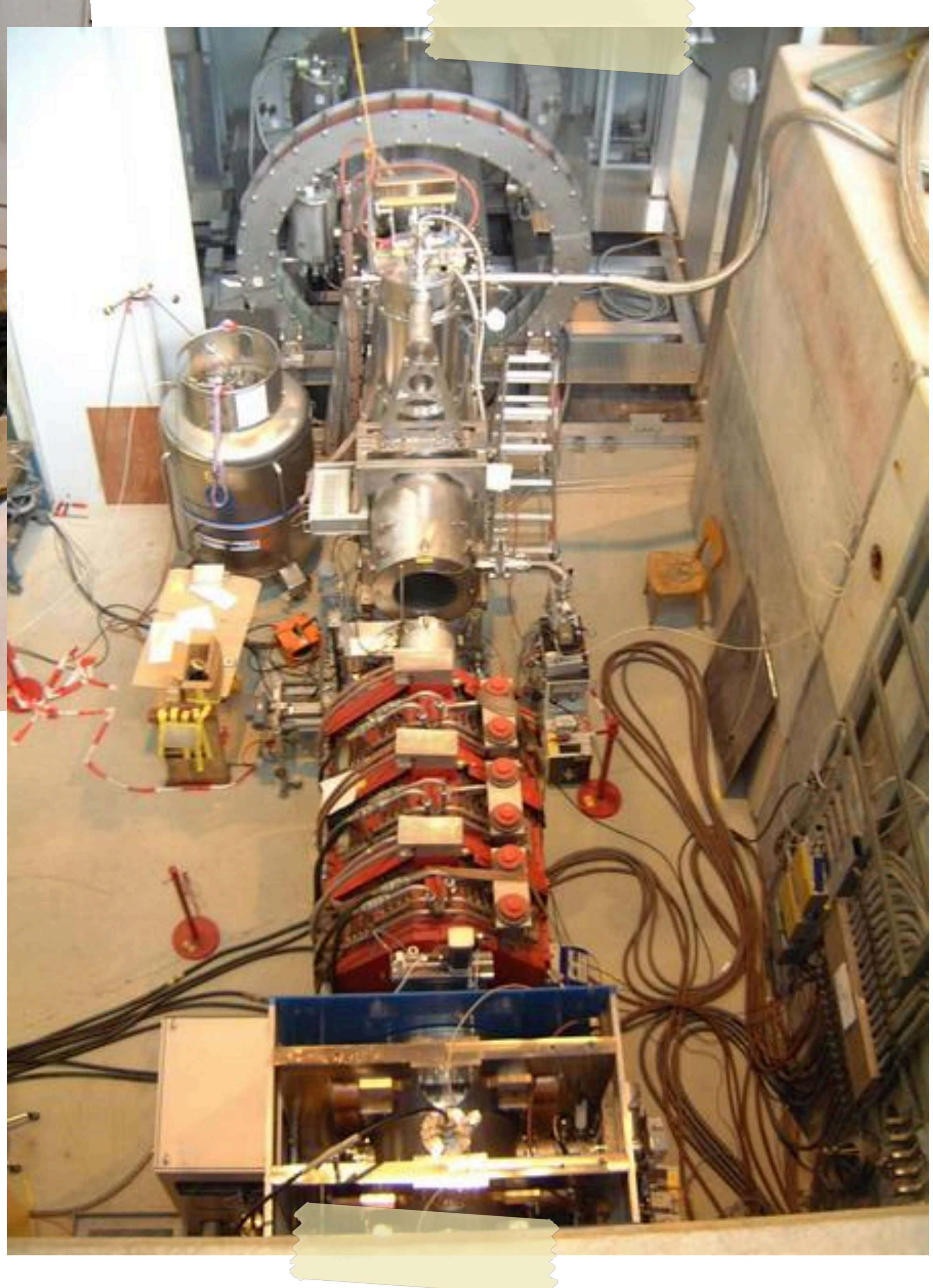
Compensation coil for LXe calorimeter

$|\vec{B}| < 50\ G$

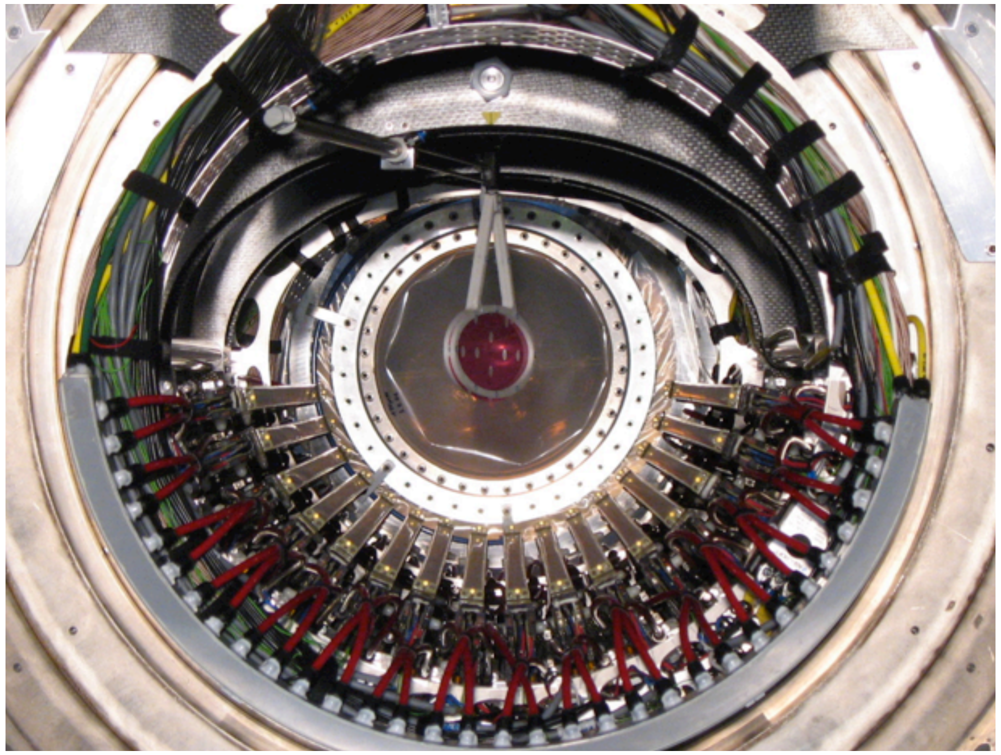


- The superconducting magnet is very thin (0.2 X_0)
- Can be kept at 4 K with GM refrigerators (no usage of liquid helium)





Positron Tracker

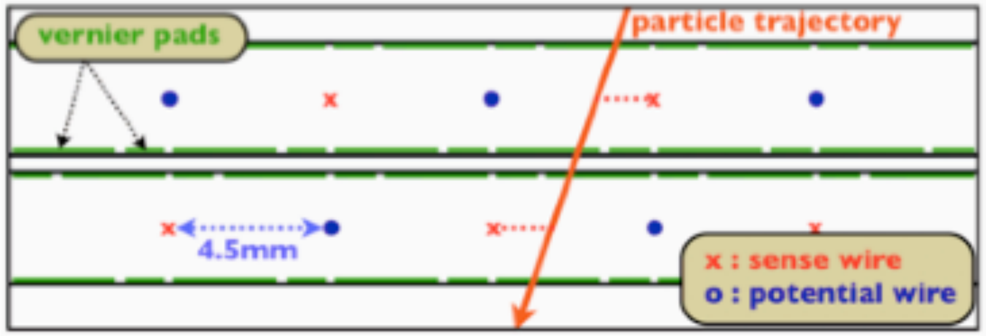


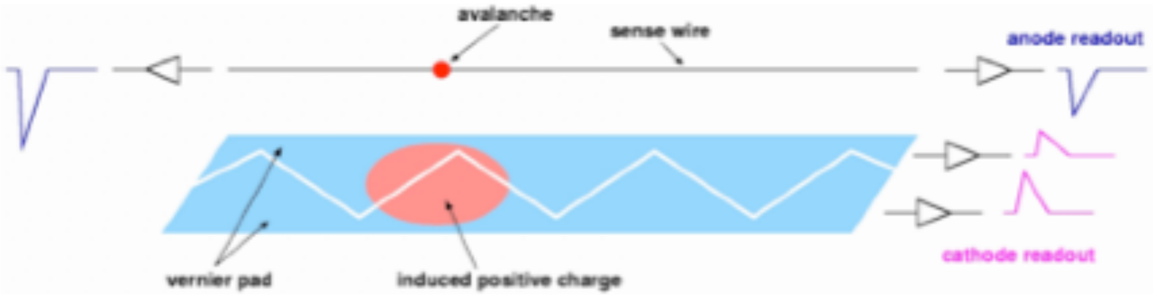
- 16 chambers radially aligned with 10° intervals
- 2 staggered arrays of drift cells
- 1 signal wire and 2 x 2 vernier cathode strips made of 15 μm kapton foils and 0.45 μm aluminum strips
- Chamber gas: He-C_2H_6 mixture
- Within one period, fine structure given by the Vernier circle

  $\sigma_R \sim 350\ \mu m$

  $\sigma_z \sim 500\ \mu m$

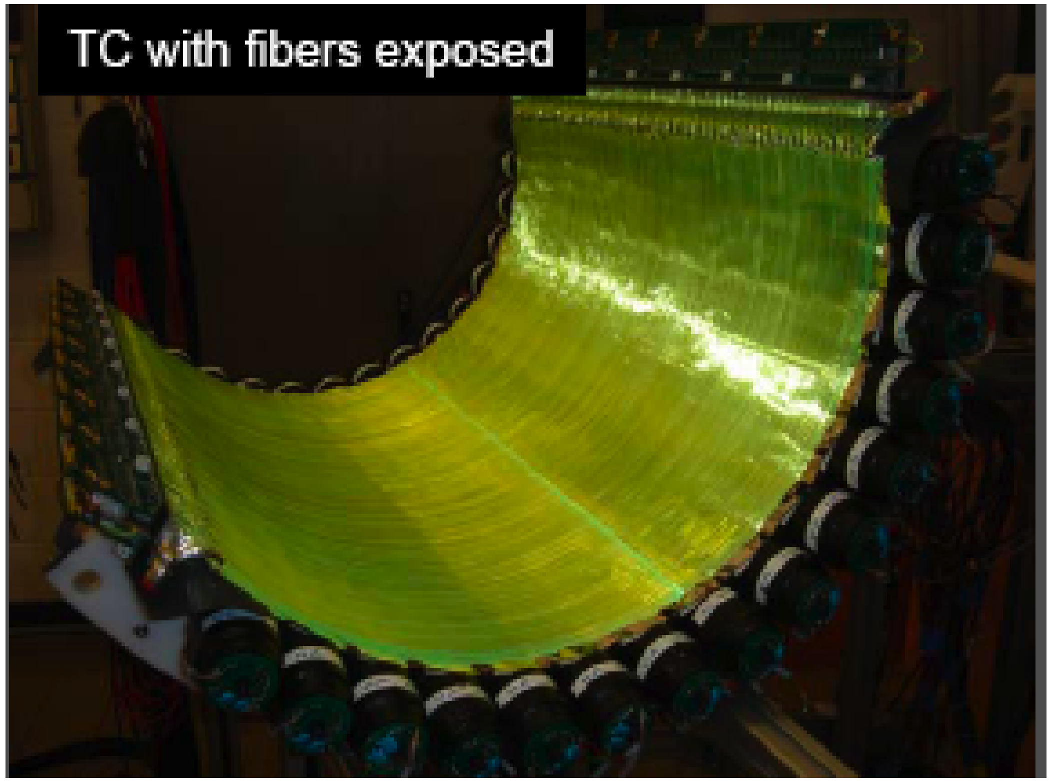
transverse coordinate (t drift)



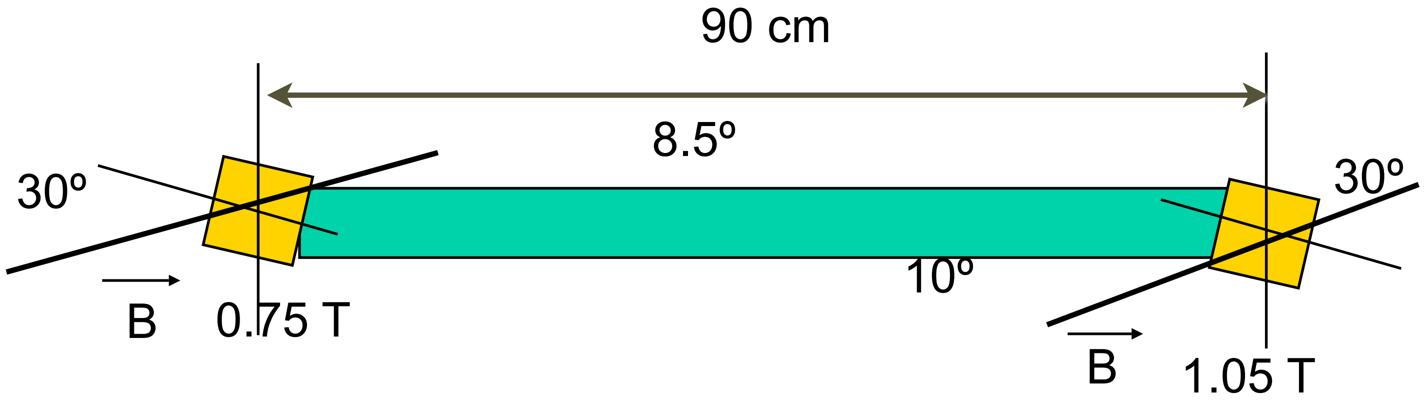


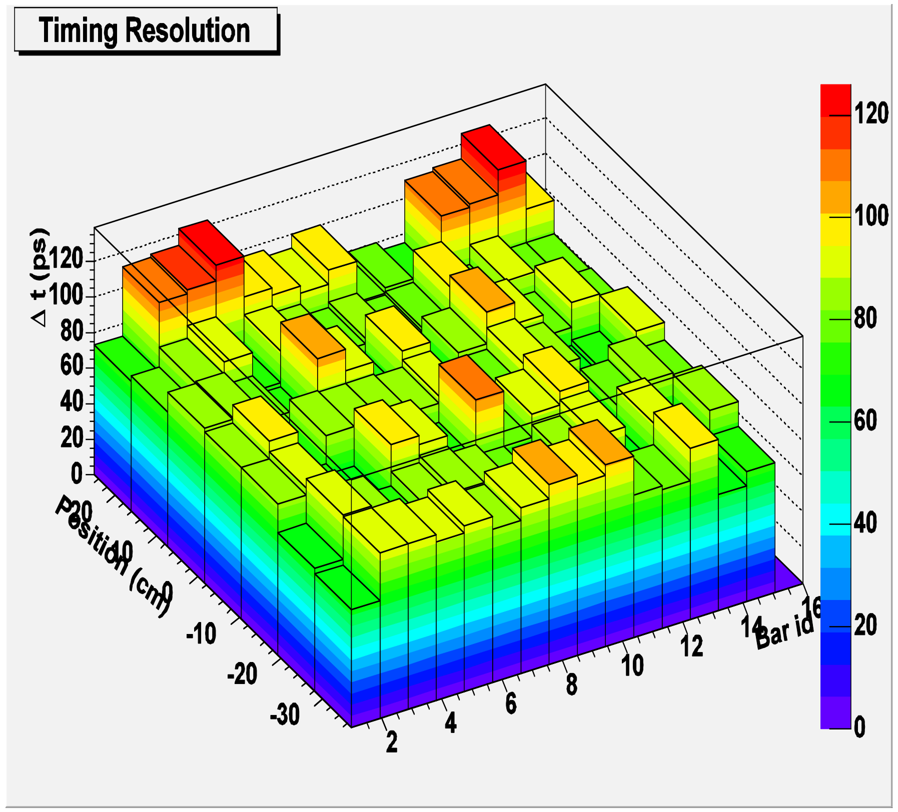
longitudinal coordinate (charge division + Vernier)

Timing Counter



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



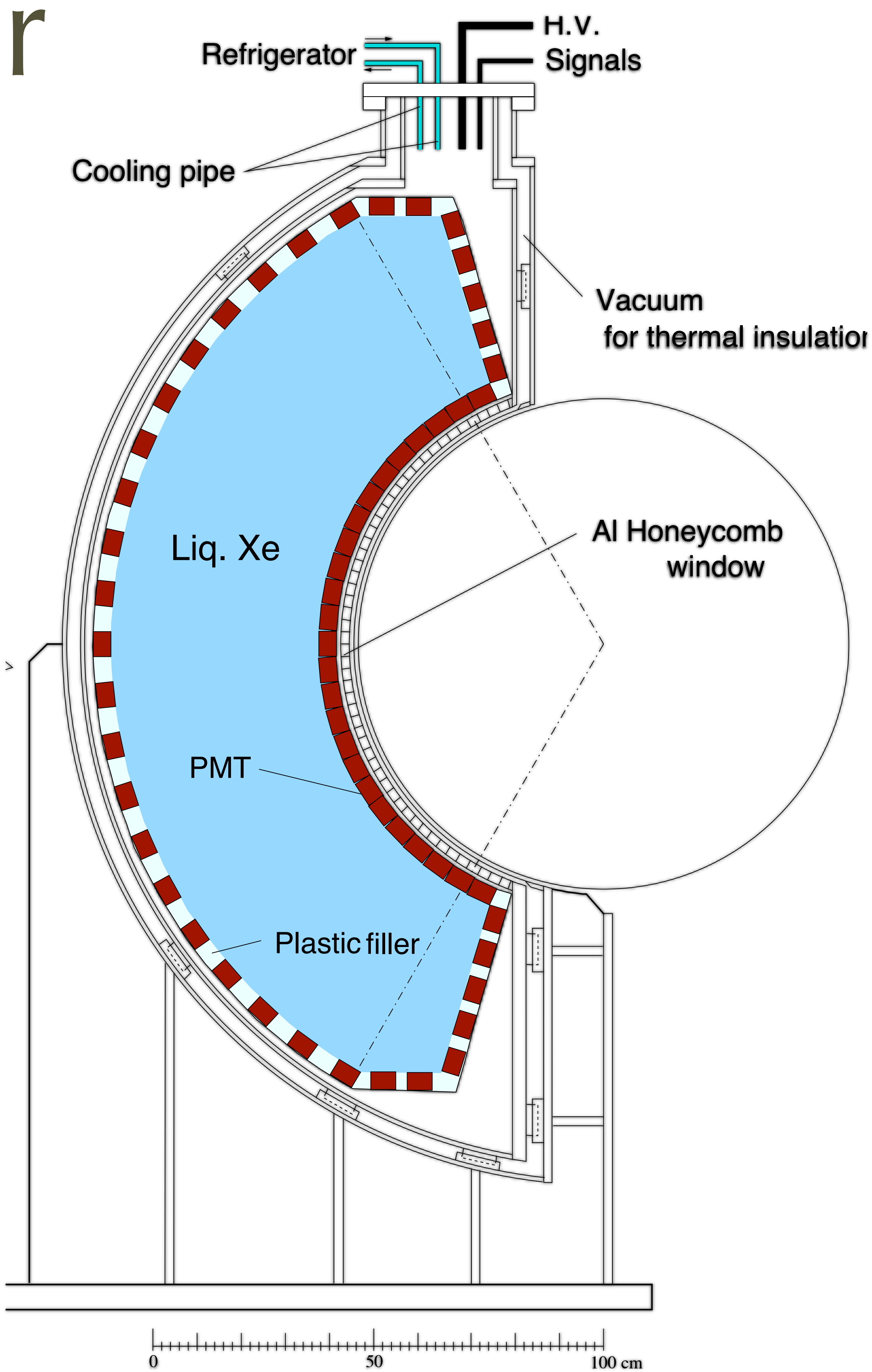


Exp. application (*)	Counter size (cm) (T x W x L)	Scintillator	PMT	λ_{att} (cm)	σ_t(meas)	σ_t(exp)
G.D.Agostini	3x 15 x 100	NE114	XP2020	200	120	60
T. Tanimori	3 x 20 x 150	SCSN38	R1332	180	140	110
T. Sugitate	4 x 3.5 x 100	SCSN23	R1828	200	50	53
R.T. Gile	5 x 10 x 280	BC408	XP2020	270	110	137
TOPAZ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

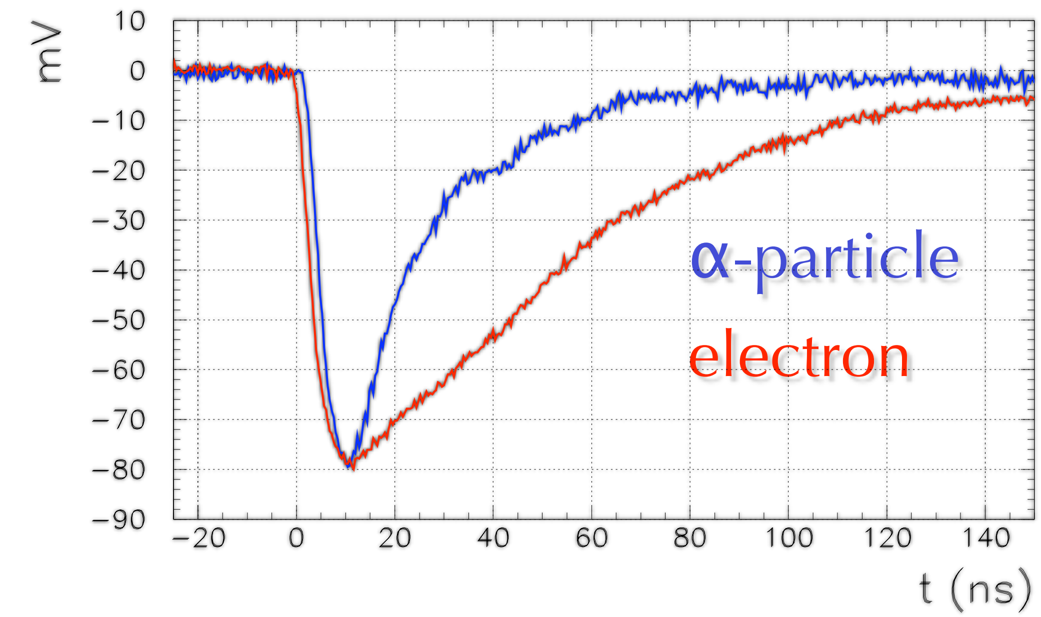
The photon detector

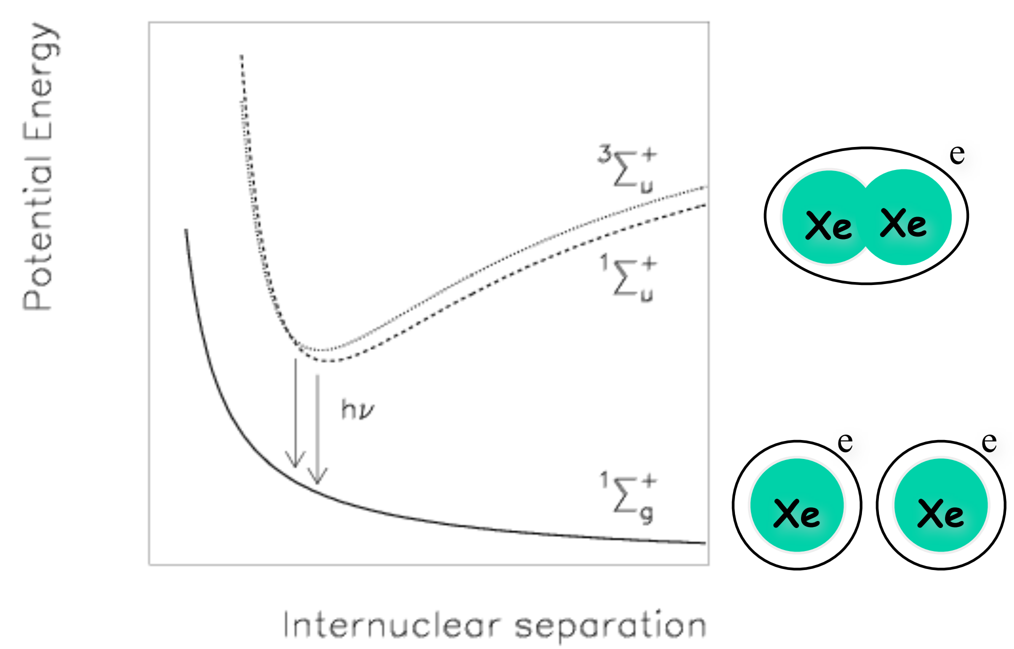
- γ Energy, position, timing
- Homogeneous 0.8 m^3 volume of liquid Xe
    - 10 % solid angle
    - $65 < r < 112$ cm
    - $|\cos\theta| < 0.35$ $|\phi| < 60^o$
- Only scintillation light
- Read by 848 PMT
    - 2″ photo-multiplier tubes
    - Maximum coverage FF (6.2 cm cell)
    - Immersed in liquid Xe
    - Low temperature (165 K)
    - Quartz window (178 nm)
- Thin entrance wall
- Singularly applied HV
- Waveform digitizing @2 GHz
    - Pileup rejection



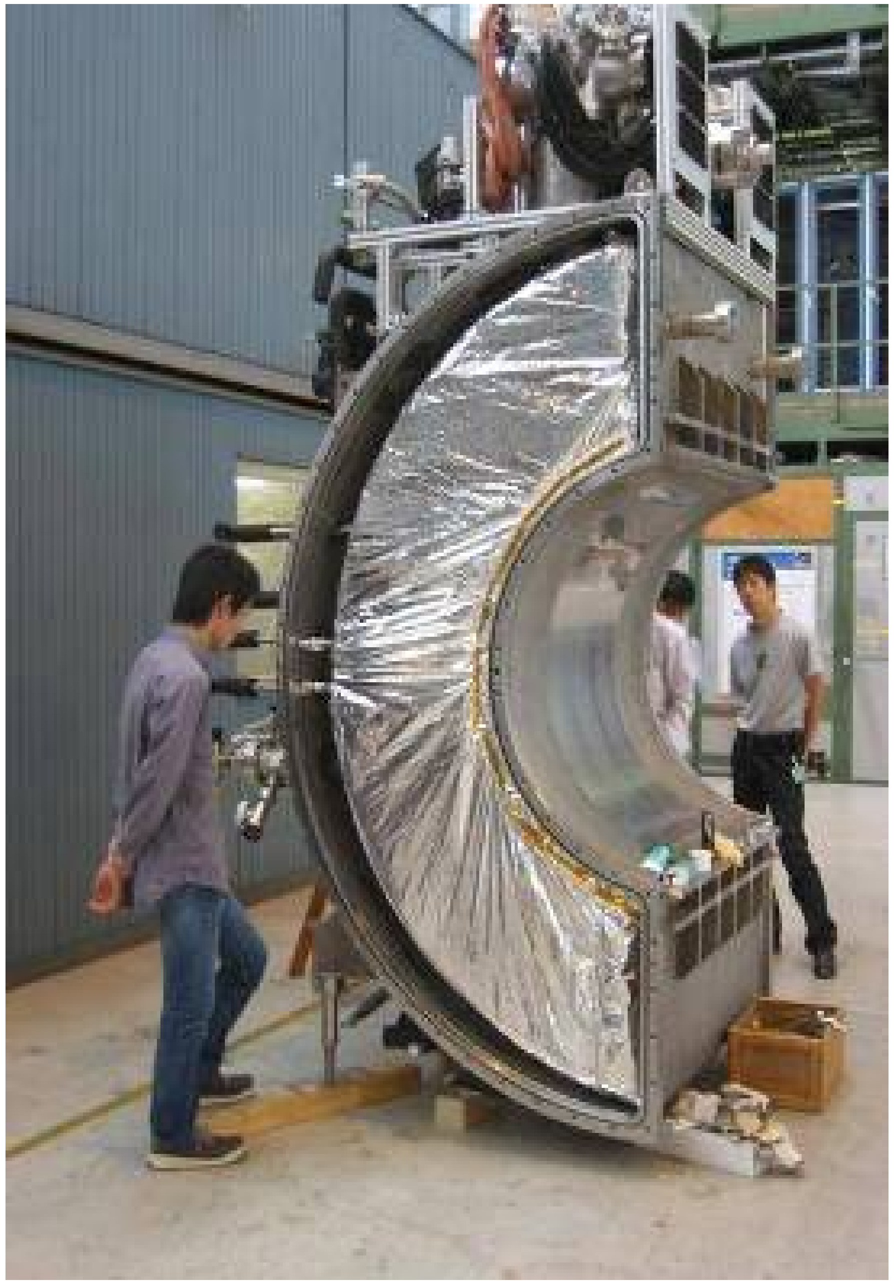
Xe properties

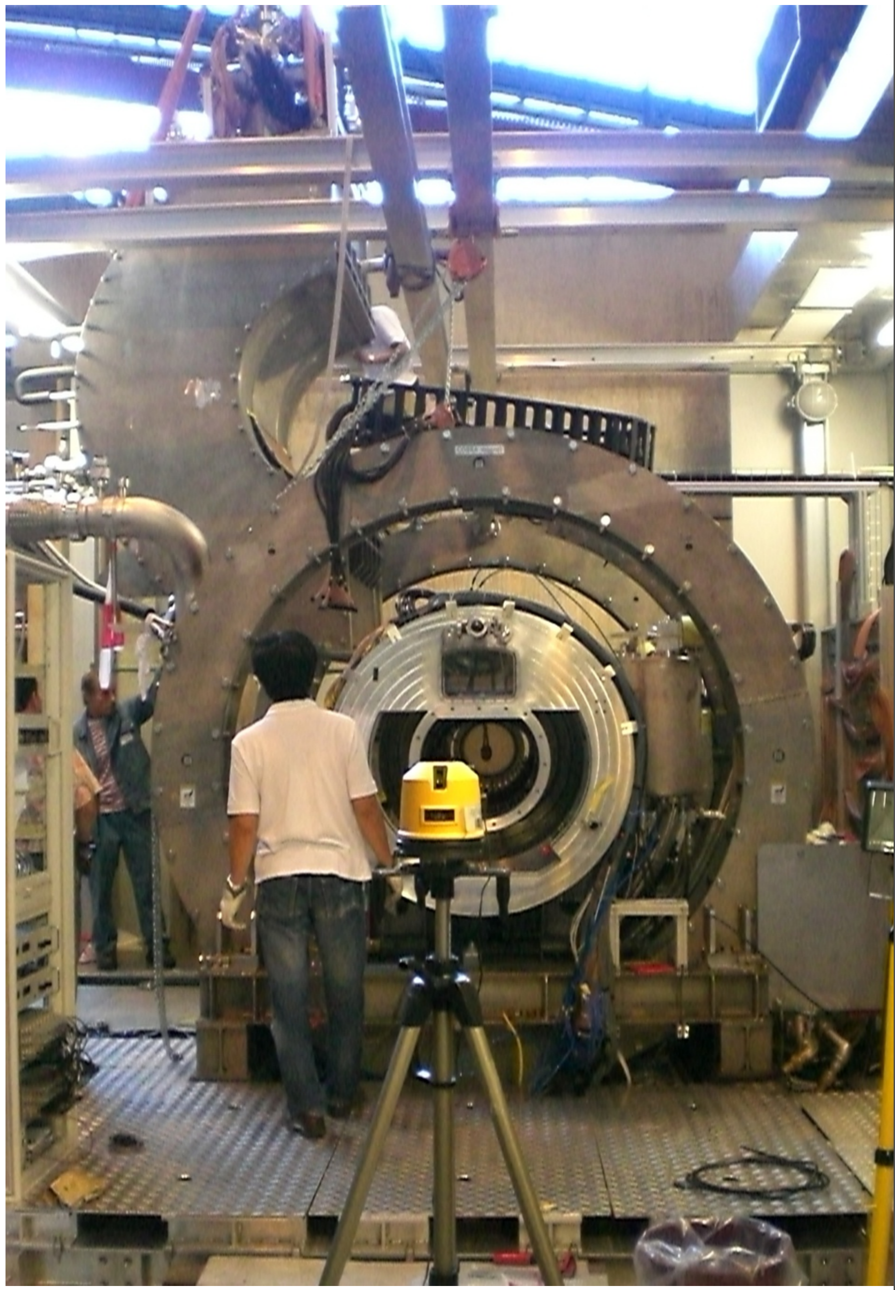
- Liquid Xenon was chosen because of its unique properties among radiation detection active media
- Z=54, ρ=2.95 g/cm^3 (X_0=2.7 cm), R_M=4.1 cm
- High light yield (similar to NaI)
  - 40000 phe/MeV
- Fast response of the scintillation decay time
  - $\tau_{singlet}$= 4.2 ns
  - $\tau_{triplet}$= 22 ns
  - τ_{recomb}= 45 ns
- Particle ID is possible
  - α ~ singlet+triplet, γ ~ recombination
- Large refractive index n = 1.65
- No self-absorption (λ_{Abs}=∞)





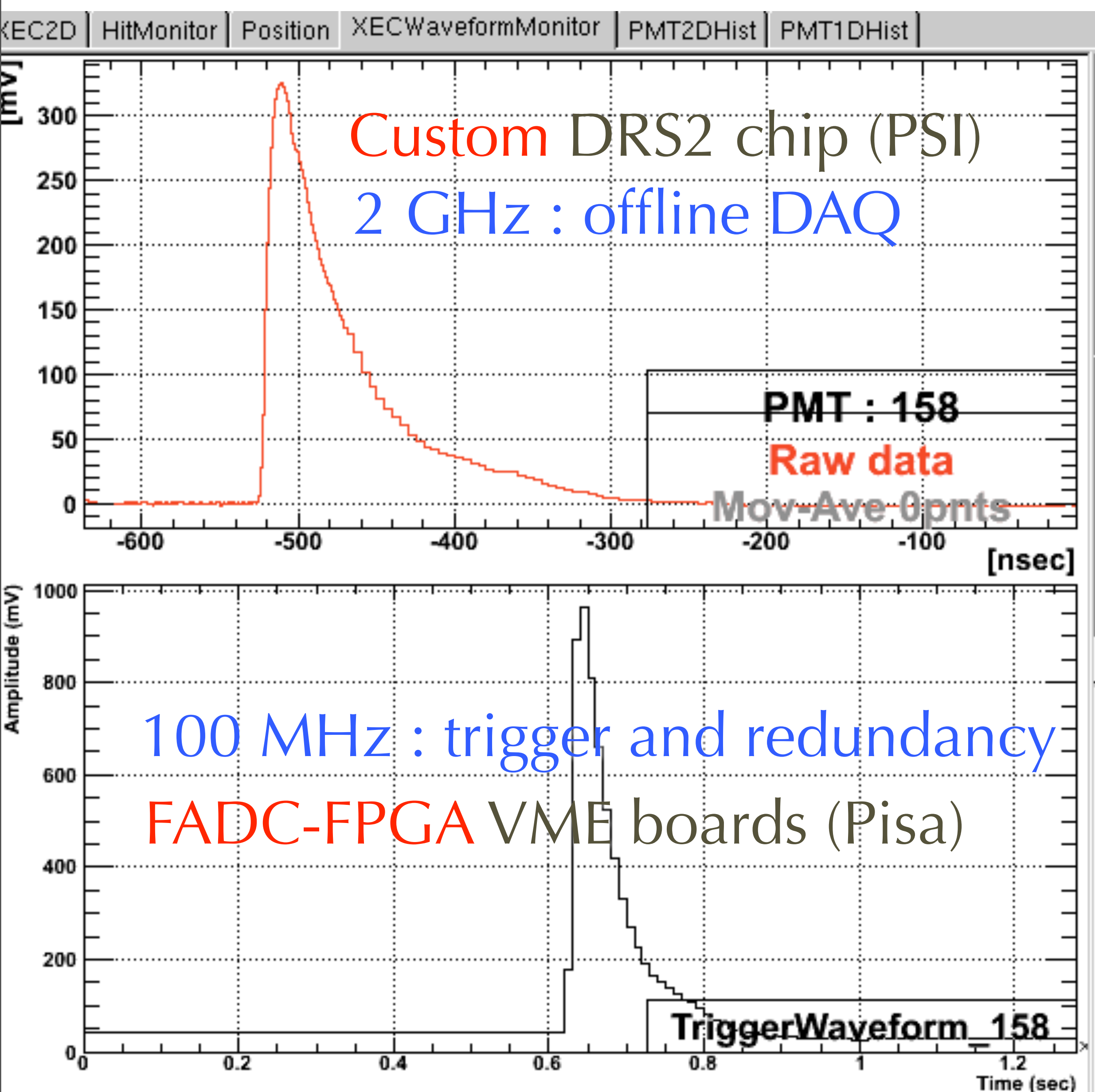
γ-detector construction





TRG + DAQ example

- For (almost) all channels, for each sub-detector we have two waveform digitizers with complementary characteristics



Custom DRS2 chip (PSI)

2 GHz : offline DAQ

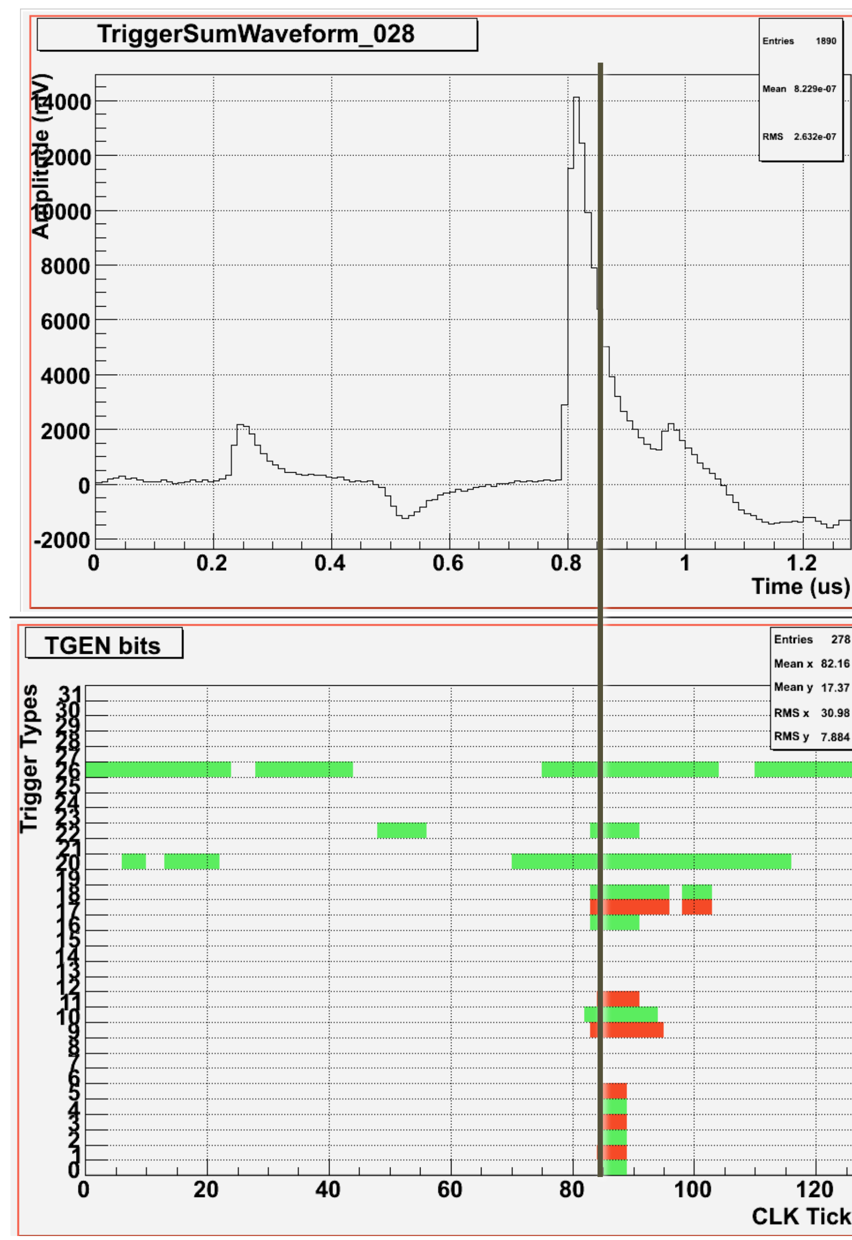
100 MHz : trigger and redundancy

FADC-FPGA VME boards (Pisa)

online pedestal subtraction for LXe

info from all sub-detectors is combined

Trigger!

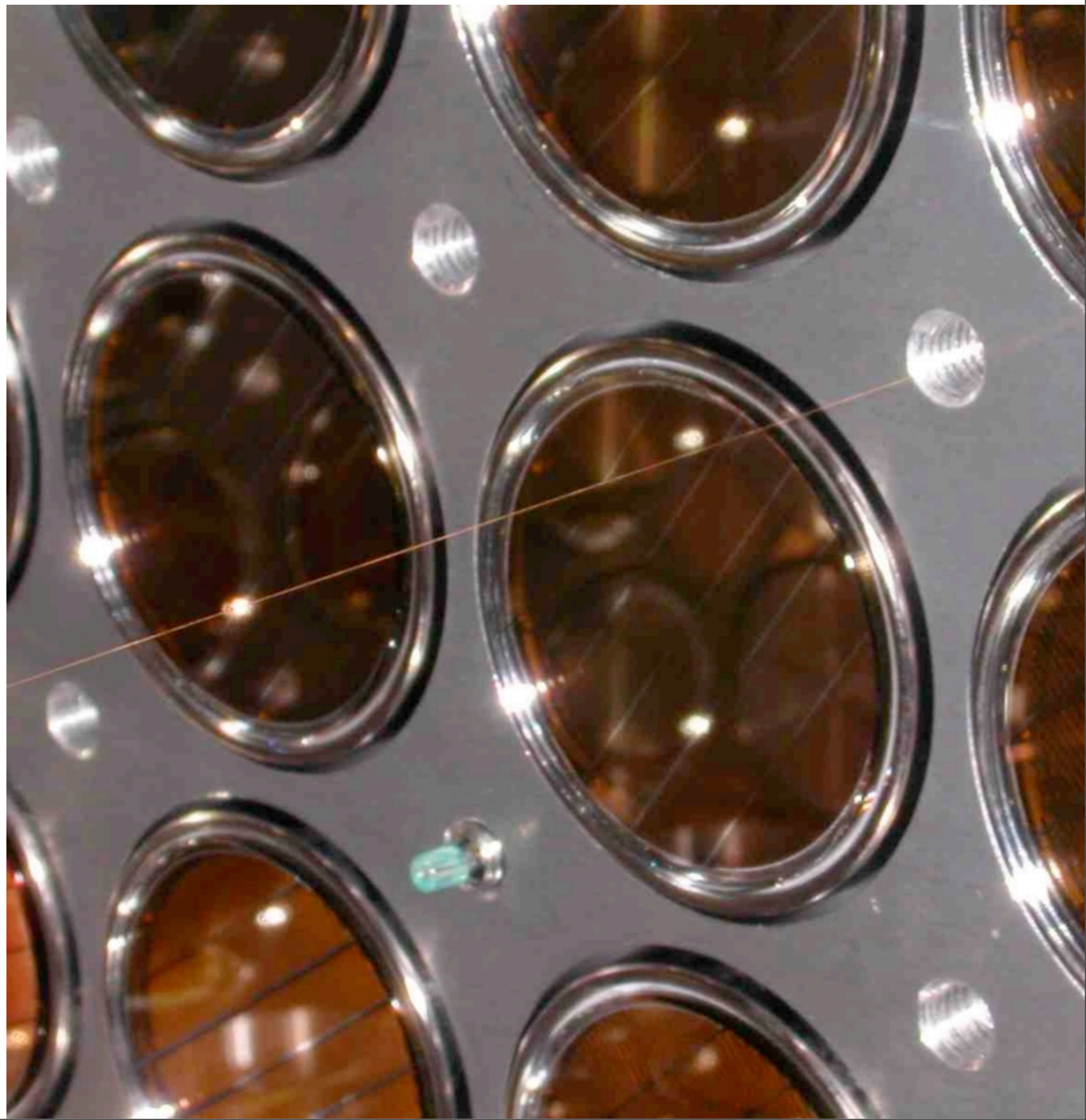


✴Beam rate ~ 3 10^7 s^{-1}

✴Acquisition rate 7 s^{-1}

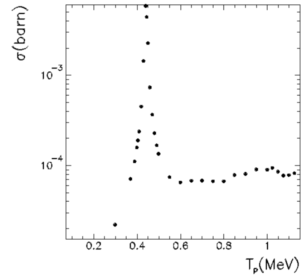
Calibrations

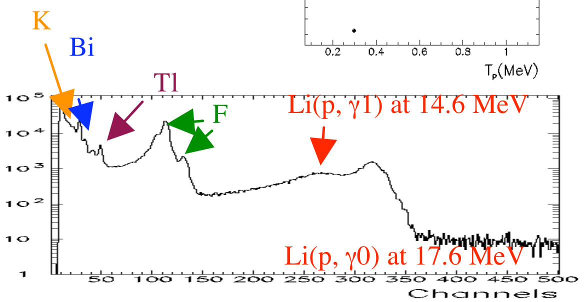
- It is understood that in such a complex detector a lot of parameters must be constantly checked
- We are prepared for redundant calibration and monitoring
- Single detector
  - PMT equalization for LXe and TIC
  - Inter-bar timing (TIC)
  - Energy scale
- Multiple detectors
  - relative timing



Calibrations

Proton Accelerator





Li(p,γ)Be

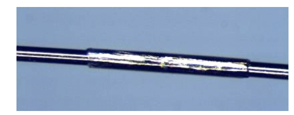
LiF target at COBRA center

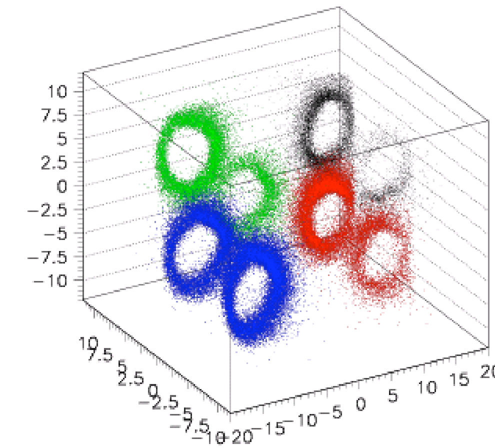
17.6MeV γ

~daily calib.

also for initial setup

Alpha on wires





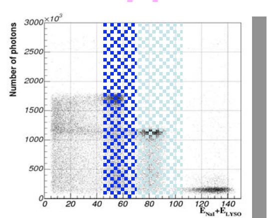
PMT QE & Att. L

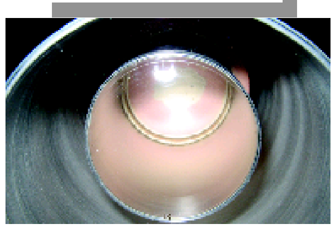
Cold GXe

LXe

Xenon Calibration

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



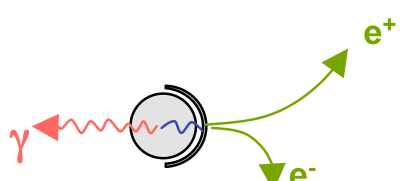


$\pi^- + p \rightarrow \pi^0 + n$

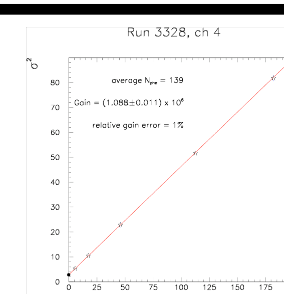
$\pi^0 \rightarrow \gamma\gamma$ (55MeV, 83MeV)

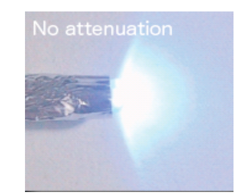
$\pi^- + p \rightarrow \gamma + n$ (129MeV)

LH_2 target



LED

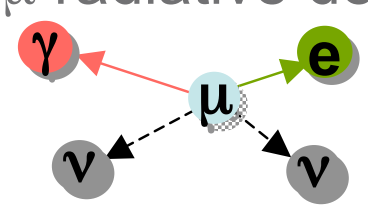


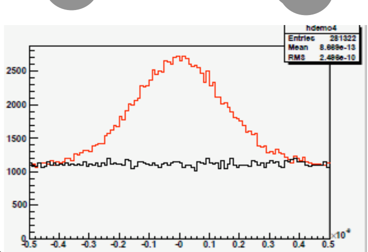


PMT Gain

Higher V with light att.

μ radiative decay





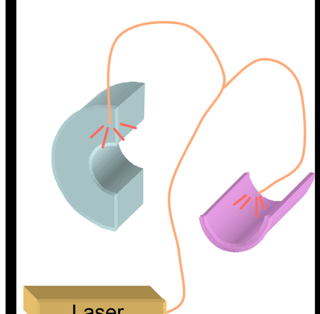
Lower beam intensity < 10^7

Is necessary to reduce pile-ups

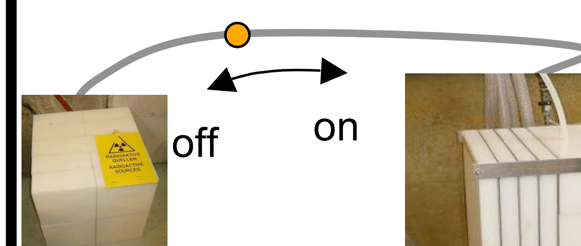
A few days ~ 1 week to get enough statistics

Laser

relative timing calib.

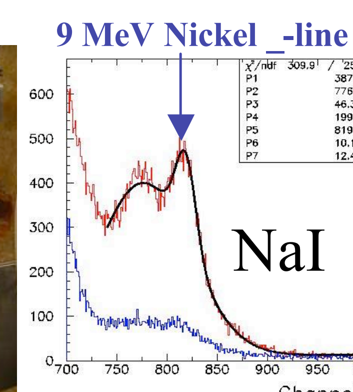


Nickel γ Generator



Illuminate Xe from the back

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



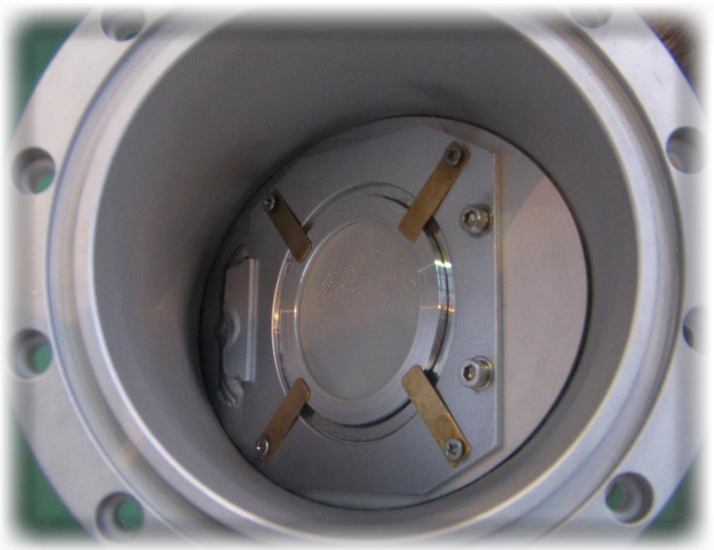
γ-energy scale calibration

- A reliable result depend on a constant calibration and monitoring of the apparatus
- We are prepared for continuous and redundant checks
  - different energies
  - different frequency

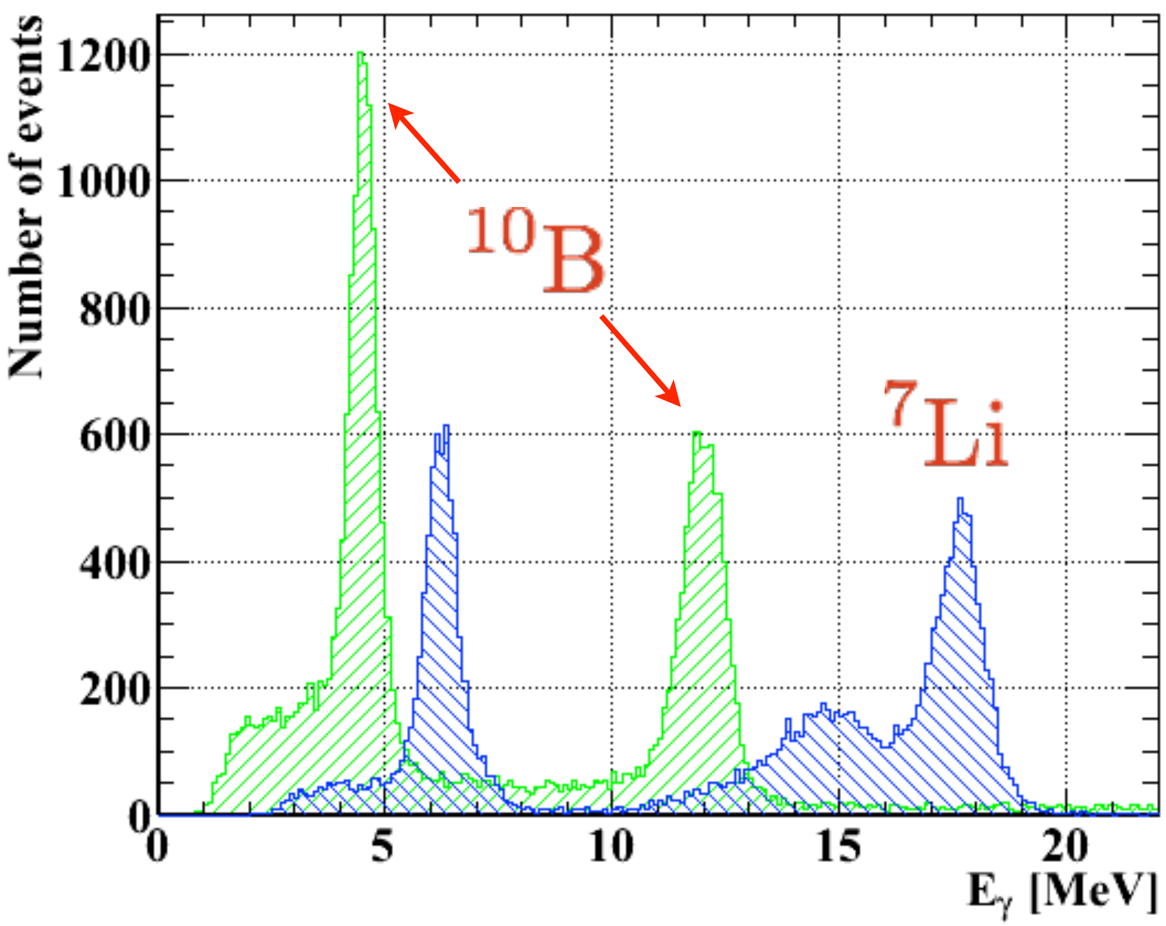
Process		Energy	Frequency
Charge exchange	$\pi^- p \to \pi^0 n$ $\pi^0 \to \gamma\gamma$	55, 83, 129 MeV	year - month
Proton accelerator	$^7\mathrm{Li}(p, \gamma_{17.6})^8\mathrm{Be}$	14.8, 17.6 MeV	week
Nuclear reaction	$^{58}\mathrm{Ni}(n, \gamma_9)^{59}\mathrm{Ni}$	9 MeV	daily
Radioactive source	$^{60}\mathrm{Co}$, AmBe	1.1 -4.4 MeV	daily

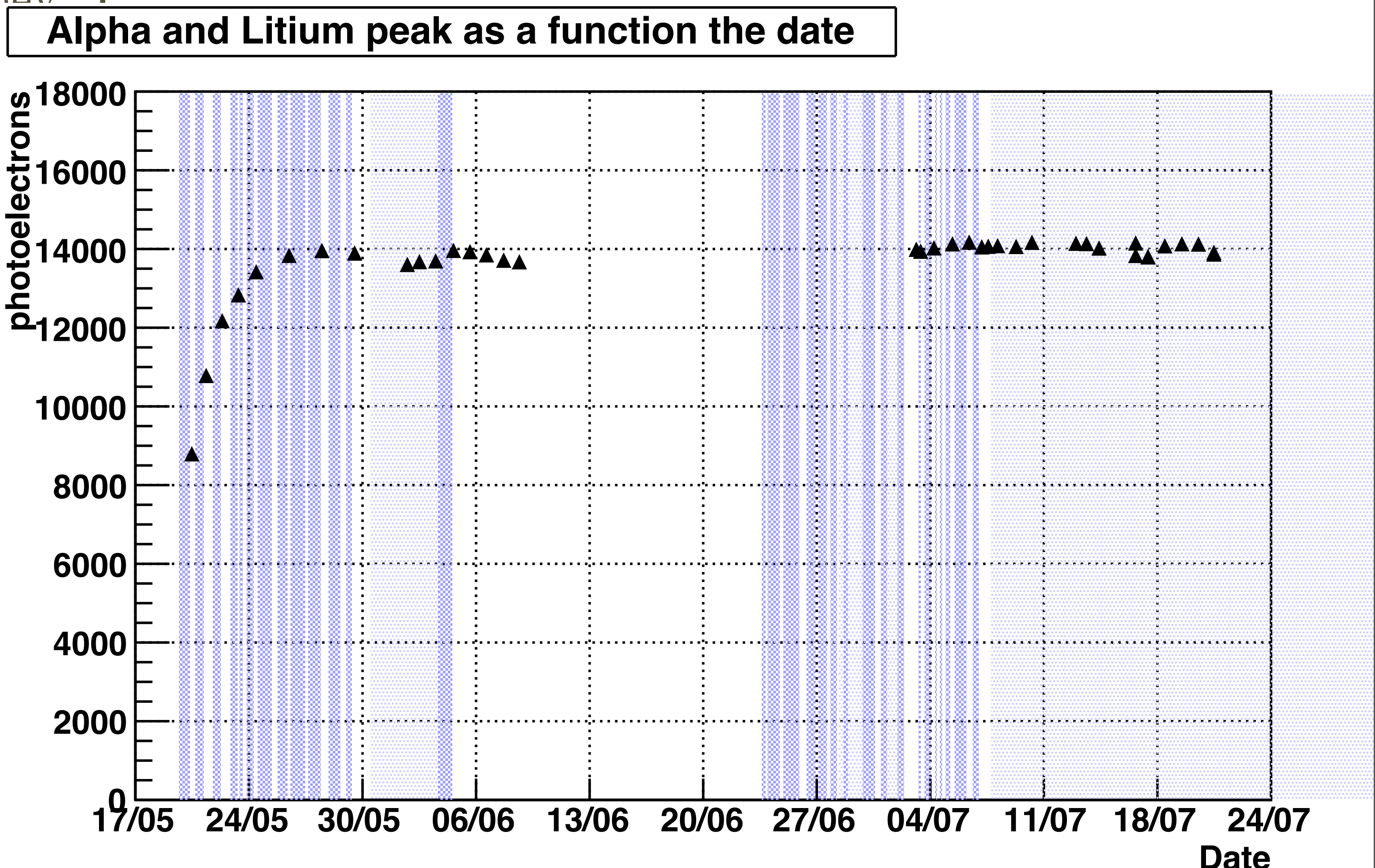
CW - daily calibration

- This calibration is performed every other day
  - Muon target moves away and a crystal target is inserted
- Hybrid target ($Li_2B_4O_7$)
  - 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





liquid phase purification

gas phase purification

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

Spring - Summer

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

September – December

- MEG run
- short π^0 calibration

Running conditions
MEG run period

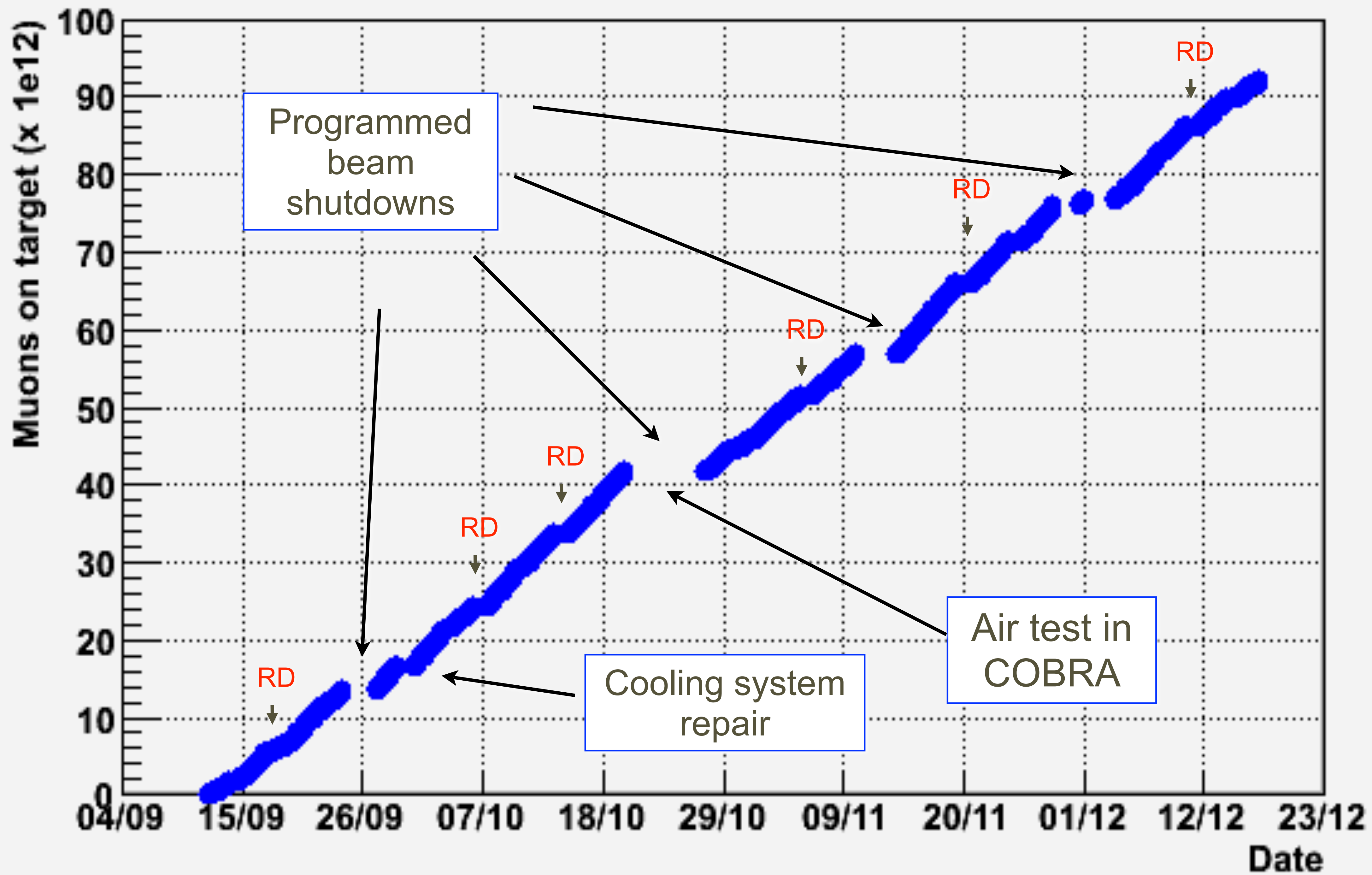
– Live time ~50% of total time
– Total time ~ 7×10^6 s
– μ stop rate: 3×10^7 μ/s
– Trigger rate 6.5 ev/s ; 9 MB/s

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

We also took RMD data once/week at reduced beam intensity



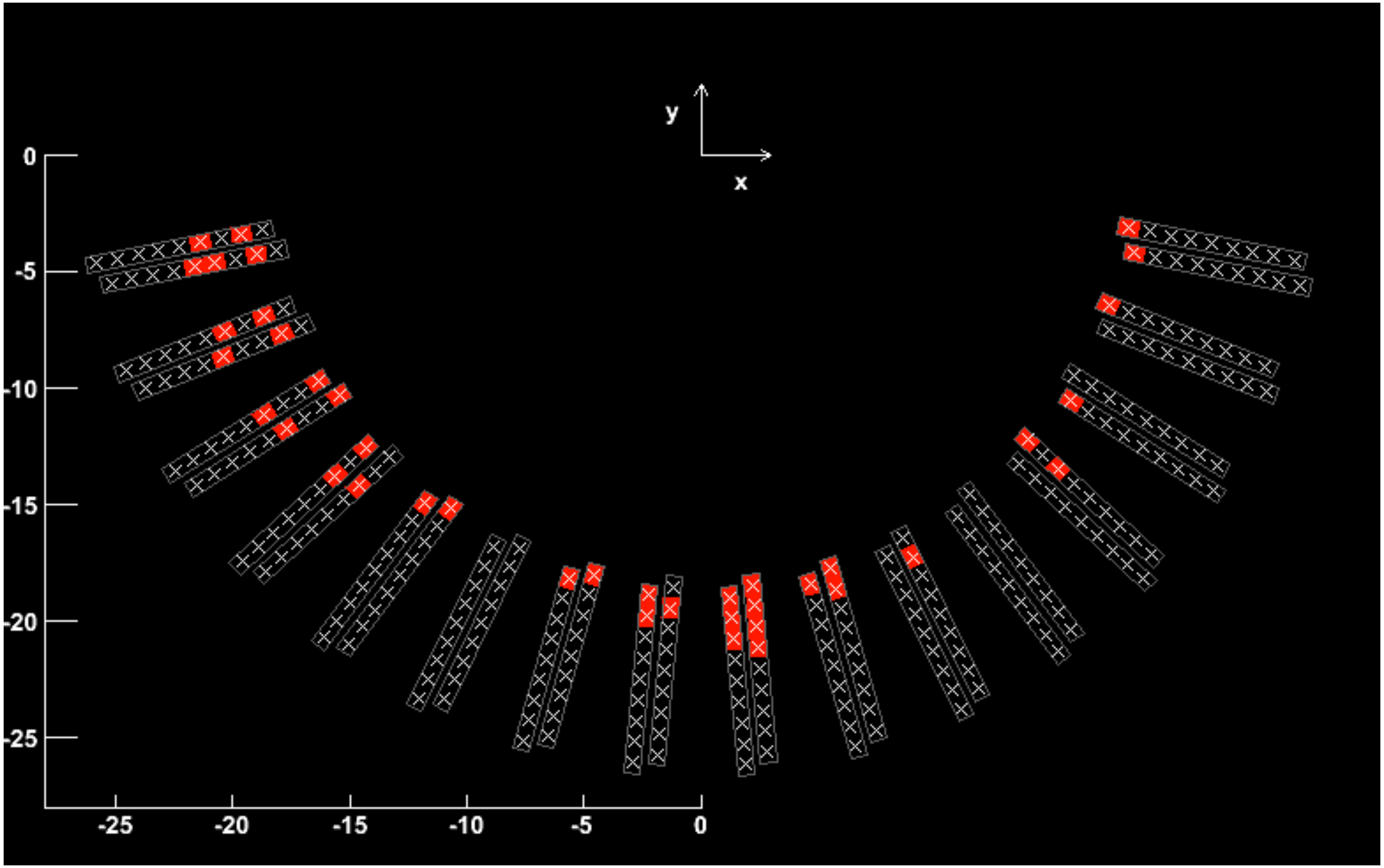
2008 run DCH instabilities

- DCH started to show frequent HV trips after 2–3 months of operation
  - an increasing number of DCH had to be operated with reduced HV settings
    - reduced efficiency and resolution
    - problem due to long-term exposure to helium
  - the DC instability cancels out in the evaluation of the branching ratio
    - normalized to Michel decays

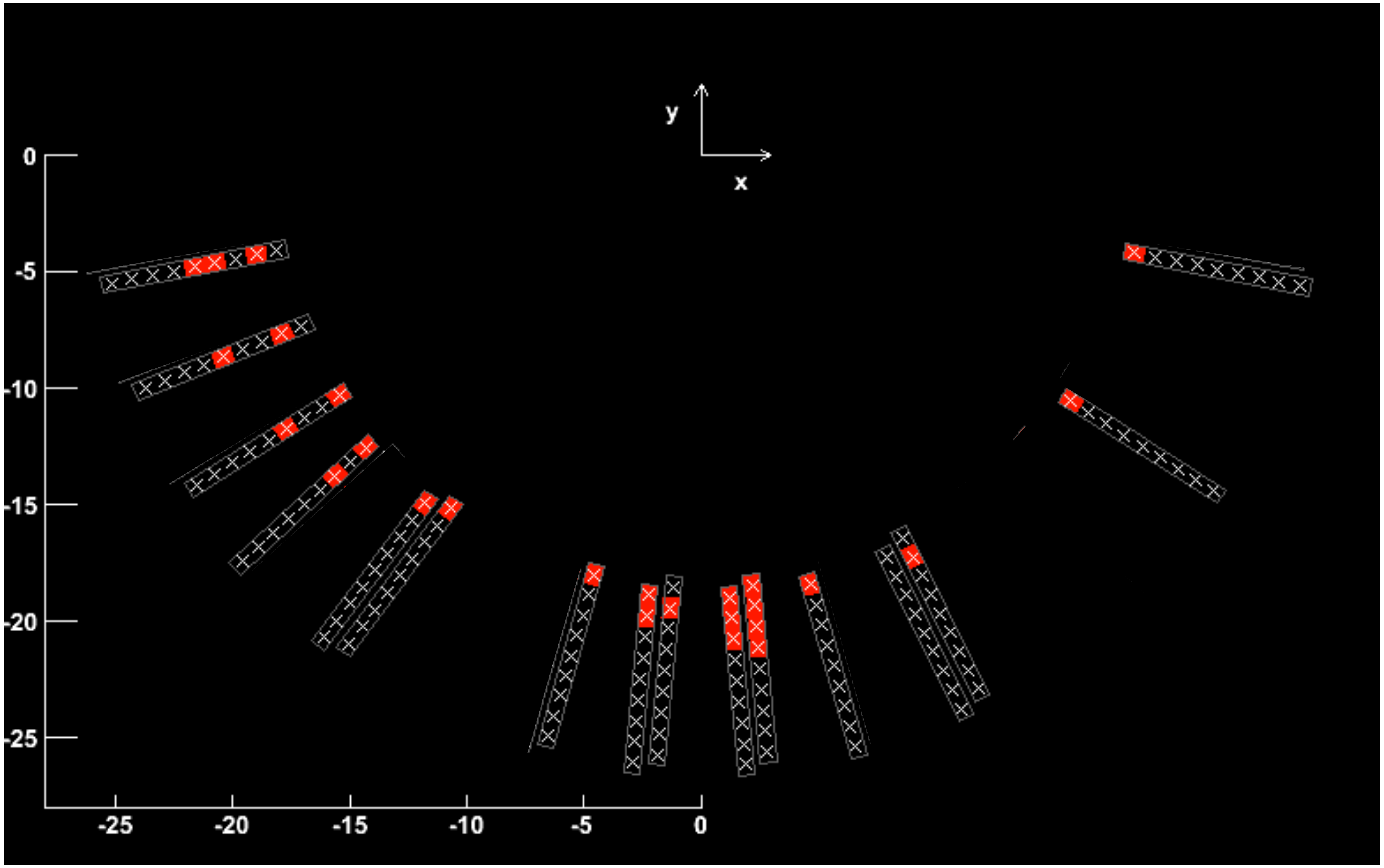
- The DCH modules have now been modified and have been successfully operated in the 2009 run

- HV spark reproduced in lab

Sep. 2008

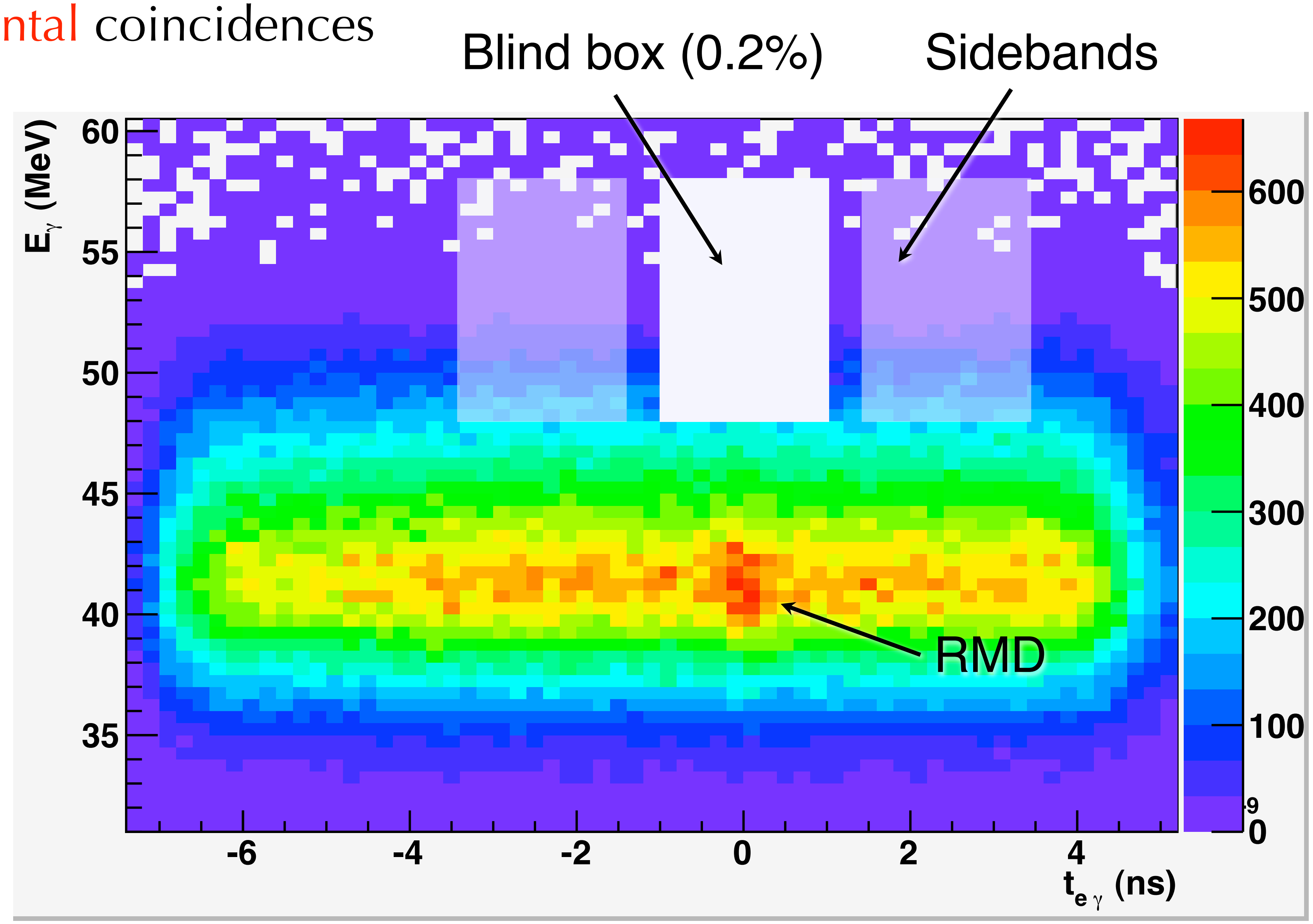


Dec. 2008



Analysis

- We decided to adopt a blind-box likelihood analysis strategy
  - Three independent blind likelihood analyses
- The blinding variables are E_γ and $t_{e\gamma}$
- Use of the sidebands justified by the fact that our main background comes from accidental coincidences

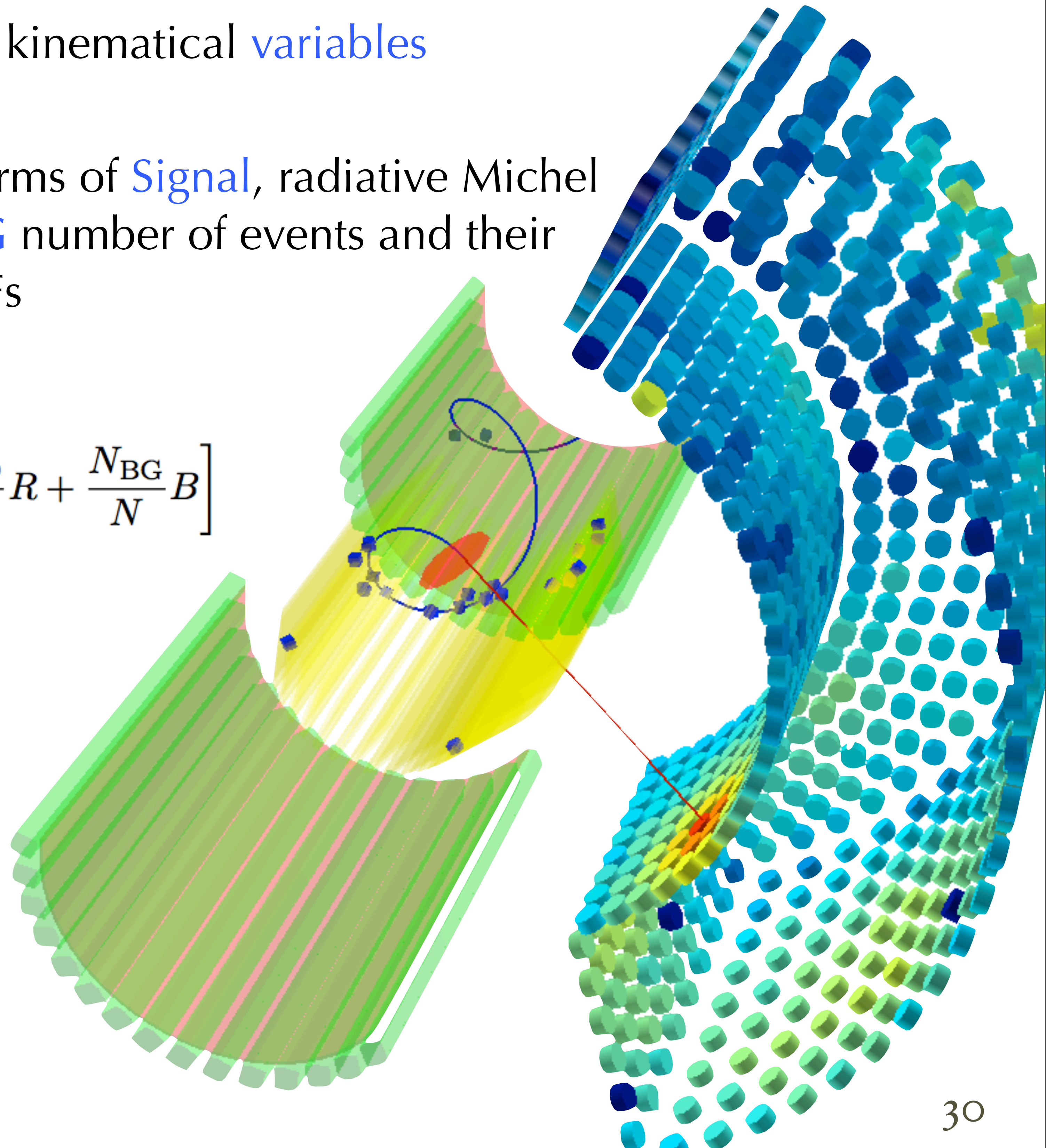


Analysis principle

- A μ→eγ event is described by 5 kinematical variables
  - E_e, E_γ, ($\Delta\vartheta$, $\Delta\varphi$), $t_{e\gamma}$
- Likelihood function is built in terms of Signal, radiative Michel decay RMD and background BG number of events and their probability density function PDFs

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

- PDFs taken from
  - data
  - MC tuned on data



Probability Density Functions

- 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)

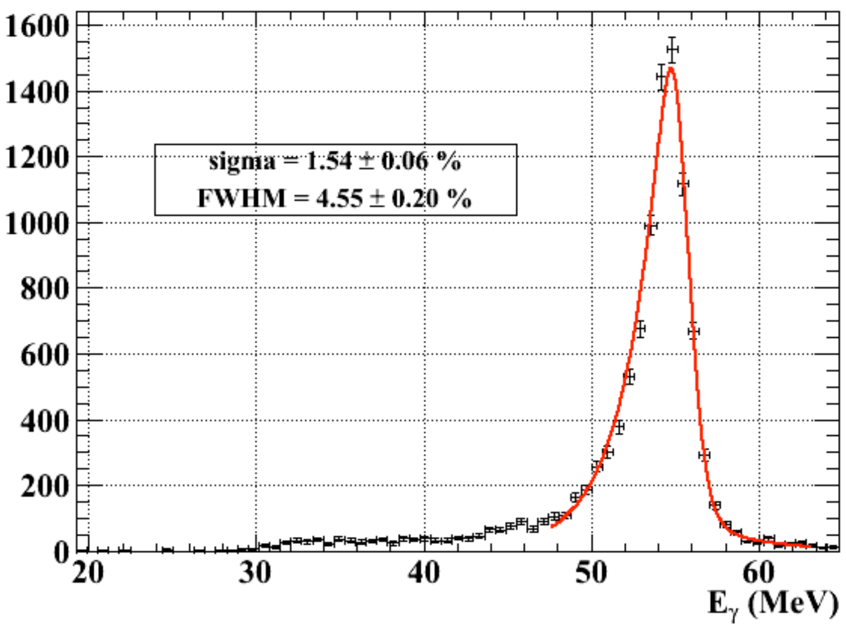
- RADIATIVE
  $E_e, E_\gamma, \theta_{e\gamma}$: 3D histo PDF from toy MC that smears and weighs Kuno-Okada distribution taking into account resolution and acceptance
  $t_{e\gamma}$: single gaussian with same resolution as signal

- 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)

Some examples of *pdfs*

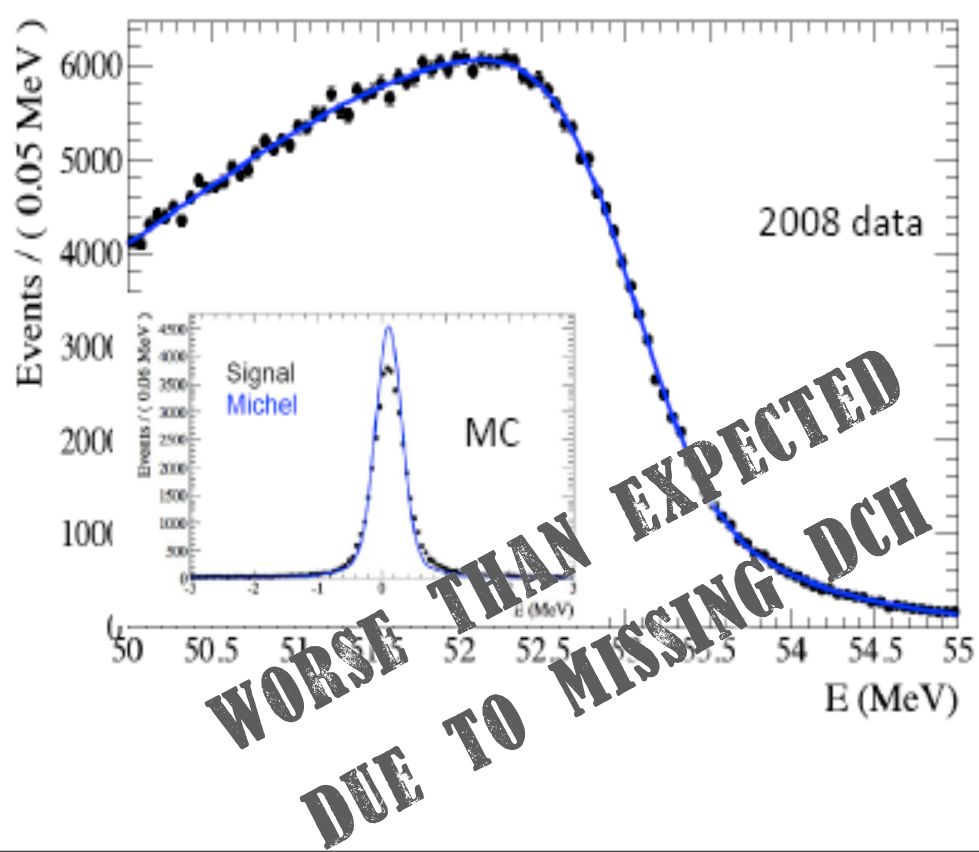
E_γ



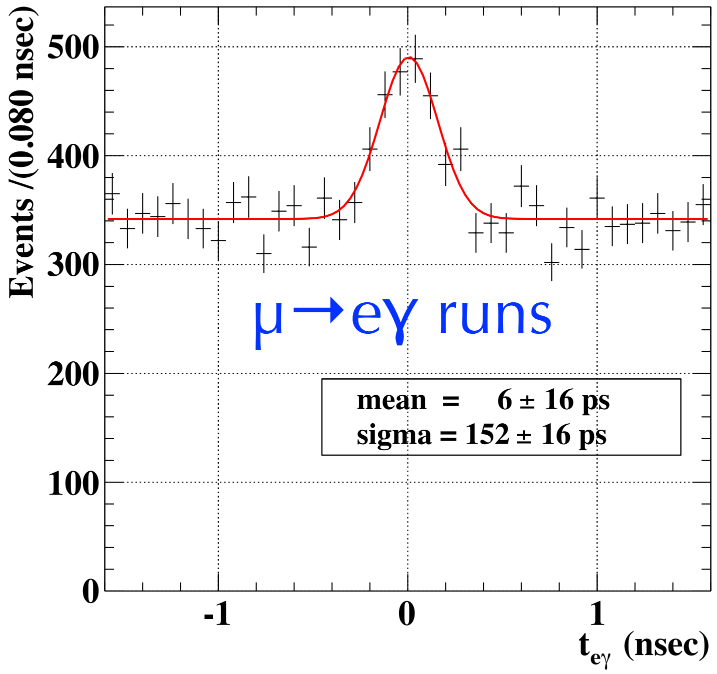
- Average upper tail for deep conversions
  - $\sigma = 2.0 \pm 0.15$ %
- Systematic uncertainty on energy scale < 0.6%

E_{e^+}

- Resolution functions of core and tail components
  - core = 374 keV (60%)
  - tail = 1.06 MeV (33%) and 2.0 MeV (7%)
- Positron angle resolution measured using multi-loop tracks
  - $\sigma(\varphi)$ = 10 mrad
  - $\sigma(\vartheta)$ = 18 mrad



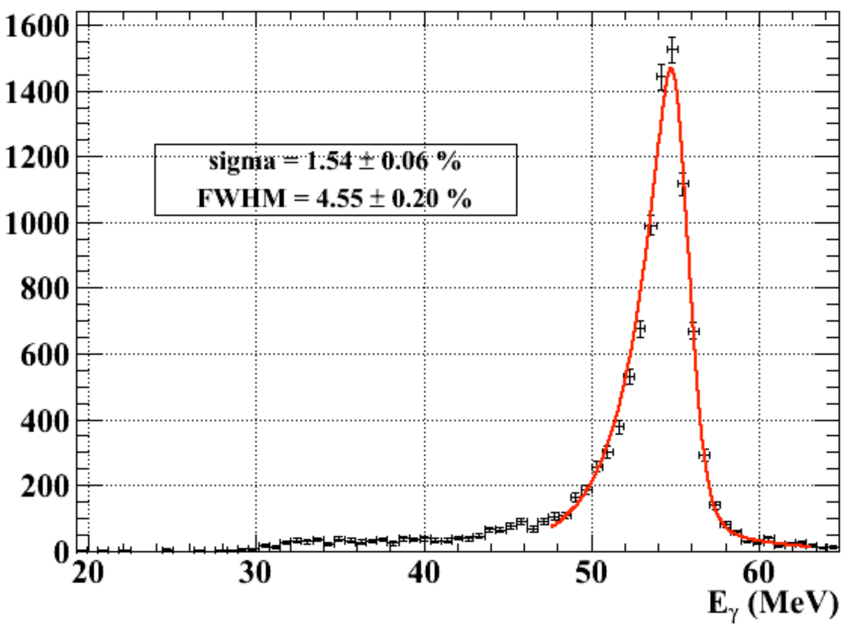
$t_{e\gamma}$



- σ_t is corrected for a small energy-dependence
  - (148 ± 17) ps
  - stable within 20 ps along the run

Some examples of *pdfs*

E_γ



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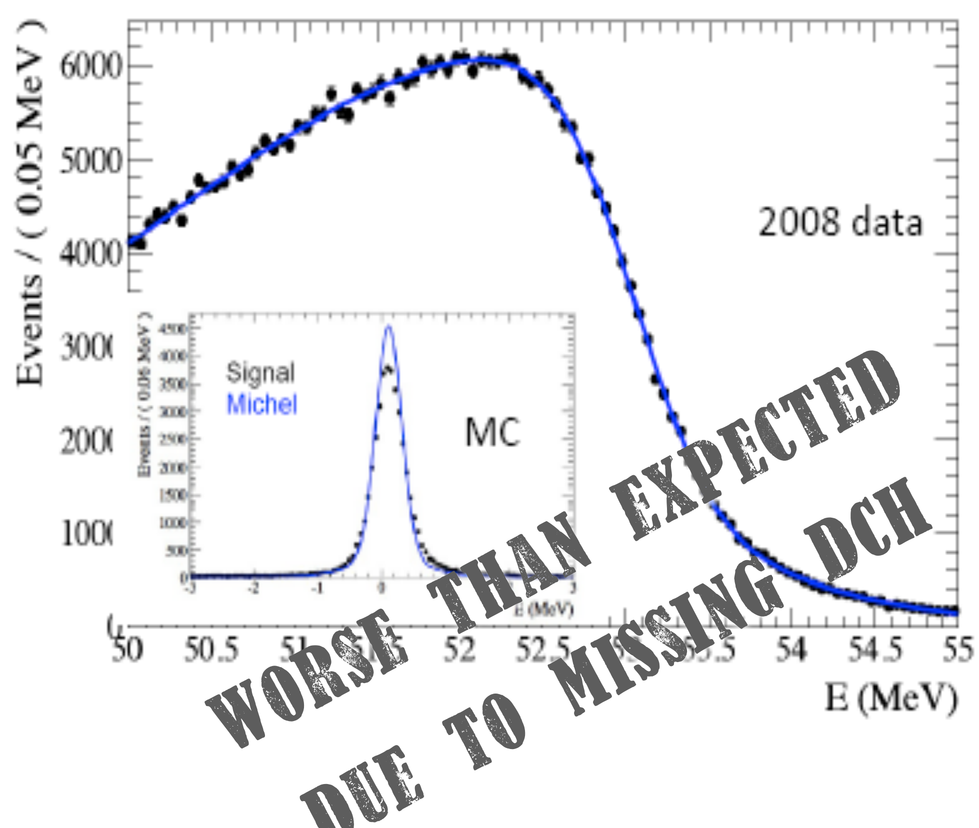
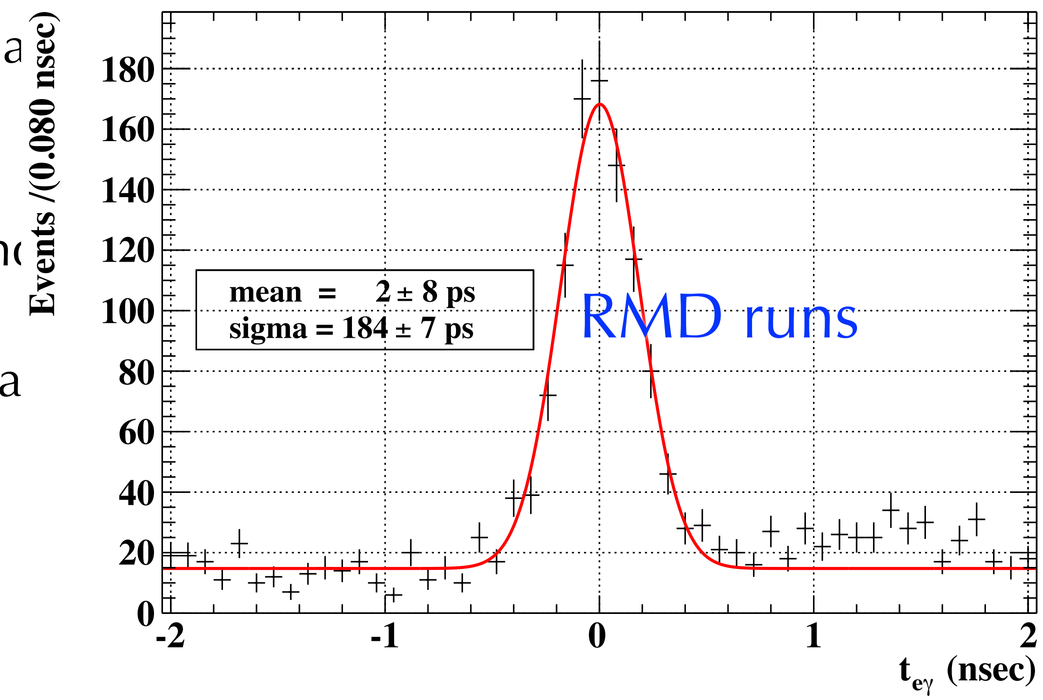


$t_{e\gamma}$



- σ_t is corrected for a small energy-dependence
  - (148 ± 17) ps
  - stable within 20 ps along the run
- MEGA had on RMD
  - 700 ps resolution

Likelihood fit

- A "Feldman-Cousins" approach was adopted for the likelihood analysis
  - The sensitivity (average expected 90% CL upper limit) on N_{sig} assuming no signal by means of toy MC:
    - $N_{sig} < 6$
  - 90% CL upper limit from the sidebands
    - $N_{sig} < (4.2 \div 9.7)$

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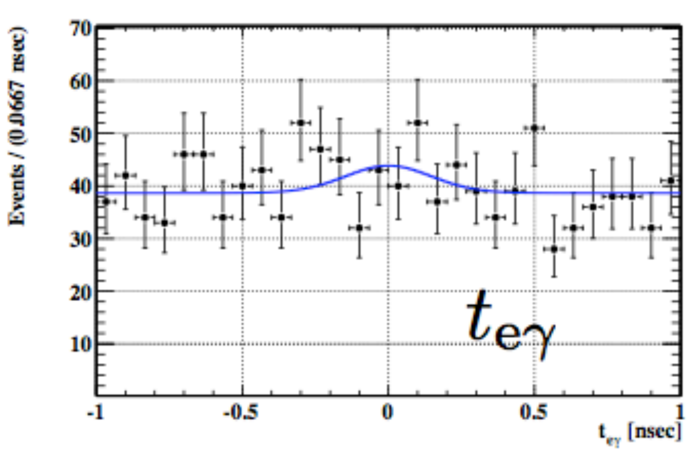
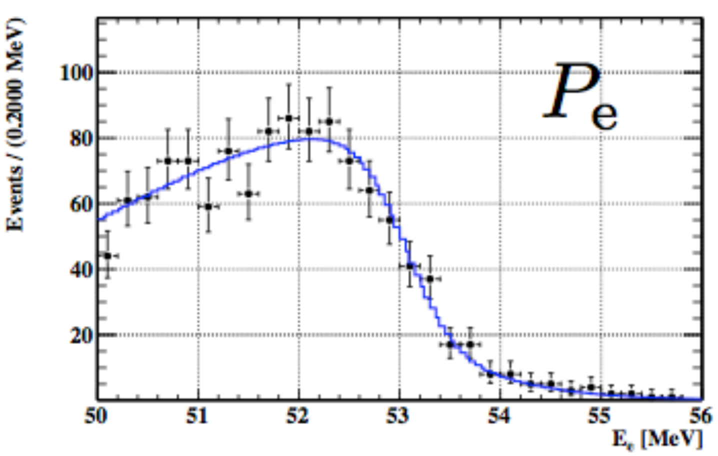
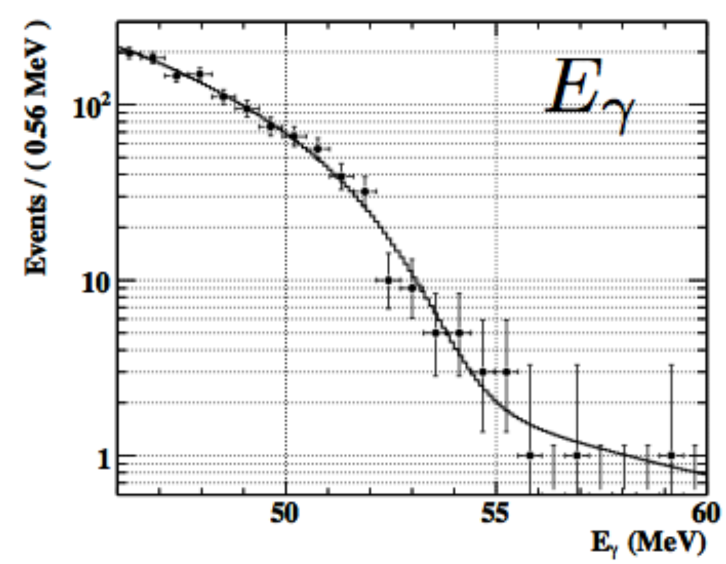
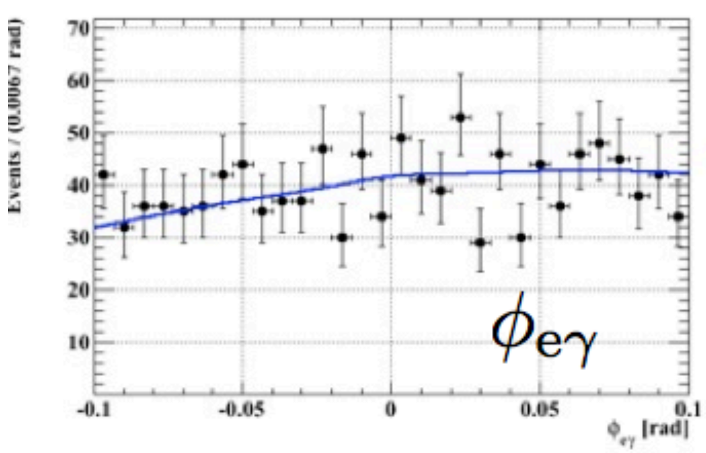
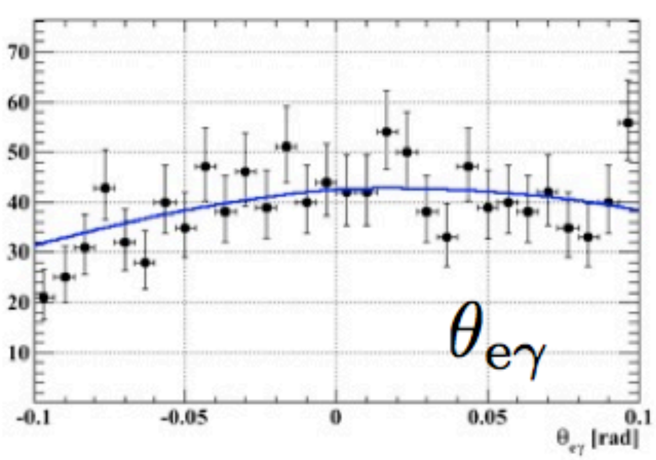










$N_{sig} < 14.7$ @90% CL

N_{RMD} consistent with sideband estimate: 25^{+17}_{-16}

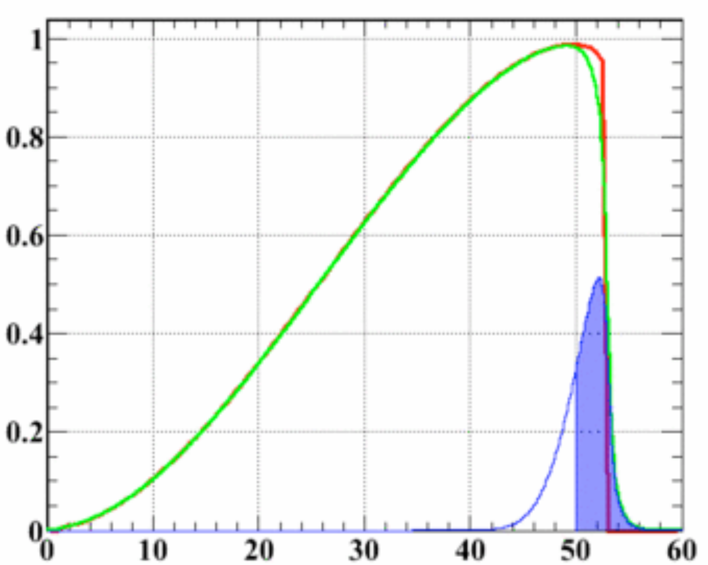
Normalization

- The N_{sig} are normalized to the detected Michel positrons

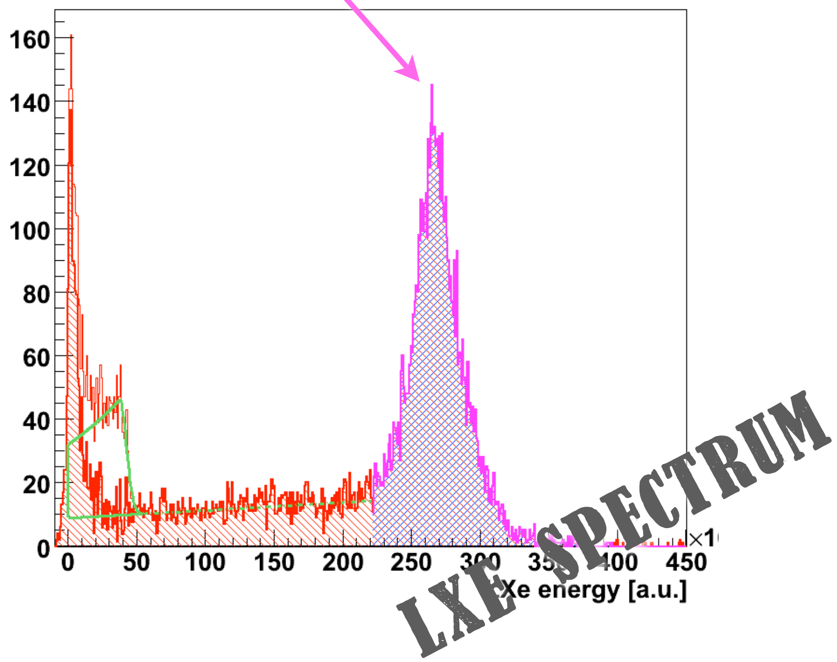
$$BR(\mu^+ \to e^+\gamma) = \frac{N_{sig}}{N_{e\nu\bar{\nu}}} \times \frac{f^E_{e\nu\bar{\nu}}}{P} \times \frac{\epsilon^{trig}_{e\nu\bar{\nu}}}{\epsilon^{trig}_{e\gamma}} \times \frac{A^{TC}_{e\nu\bar{\nu}}}{A^{TC}_{e\gamma}} \times \frac{\epsilon^{DC}_{e\nu\bar{\nu}}}{\epsilon^{DC}_{e\gamma}} \times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

= ~1

count # of Michel decays in the analysis window with a pre-scaled trigger



theory
resolution
acceptance

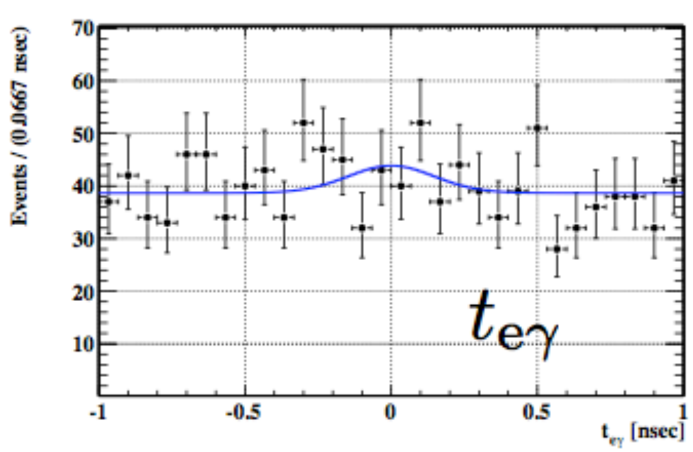


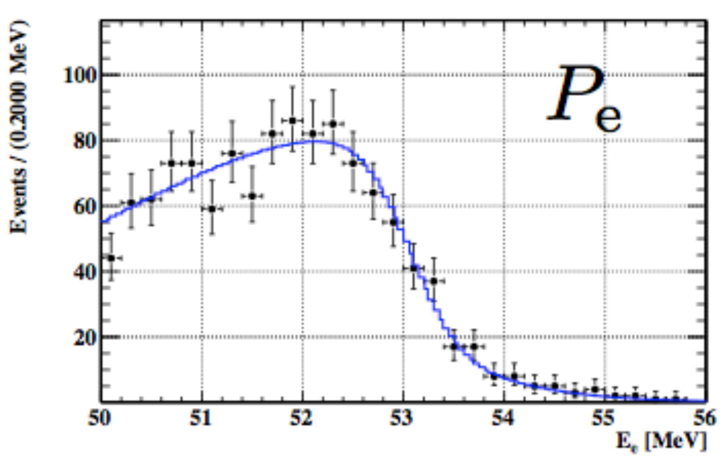
- $\varepsilon_{(\gamma)} = 0.61 \pm 0.03$, confirmed by π^0 and RD spectra

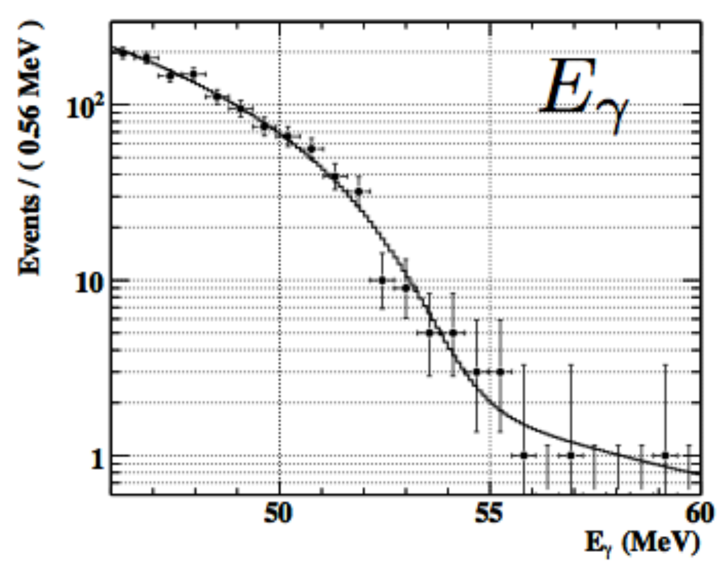
- Norm = $(2.0 \pm 0.2) \times 10^{-12}$

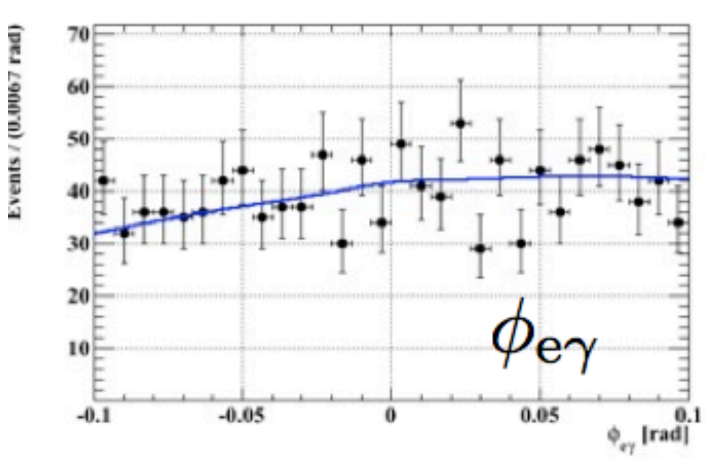
Likelihood fit

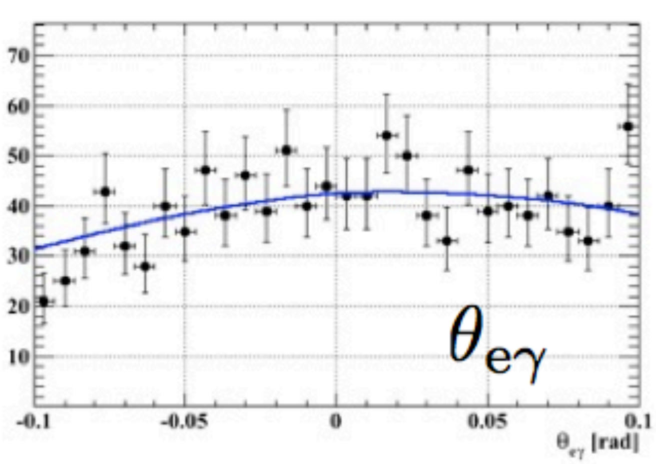
- A "Feldman-Cousins" approach was adopted for the likelihood analysis
  - The sensitivity (average expected 90% CL upper limit) on N_{sig} assuming no signal by means of toy MC:
    - BR < 1.3 x 10^{-11}
  - 90% CL upper limit from the sidebands
    - BR < (0.9 ÷ 2.1) x 10^{-11}











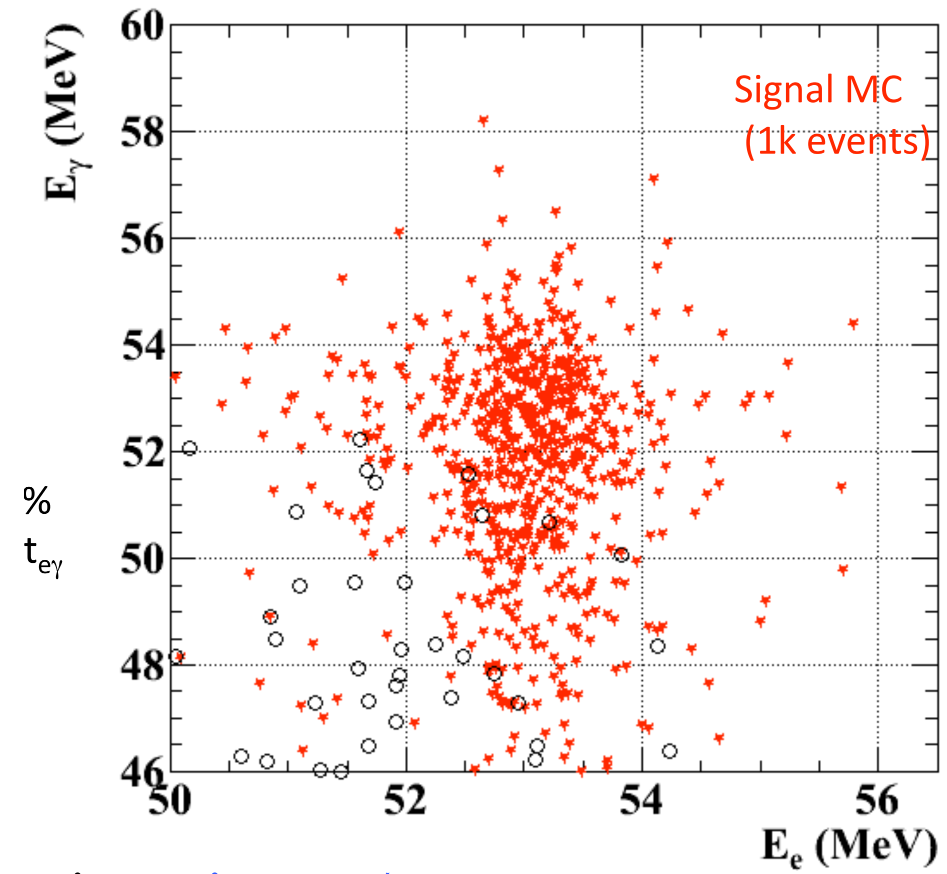
N_{sig} < 14.7 @90% CL

N_{RMD} consistent with sideband estimate: 25^{+17}_{-16}

Result on BR

$$\mathrm{BR}(\mu^+ \to \mathrm{e}^+\gamma) < 3.0 \times 10^{-11}$$

- Effect of systematics on evaluation of limit on N_{sig}
  - E_γ energy scale (~0.6)
  - e^+ angle (~0.35)
  - e^+ energy spectrum (~1.18)

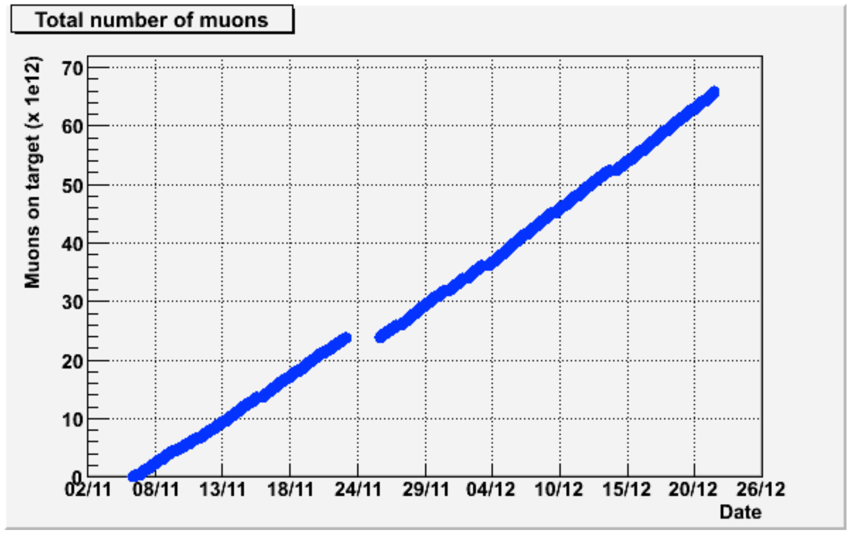


- ~2 times worse than expected sensitivity
- Probability of getting this result by statistical fluctuations is ~5%

- see arXiv:0908.2594v1 [hep-ex]

Conclusion

- Data from the first three months of operation of the MEG experiment give a result competitive with the previous limit
  - 2008 run suffered from detector instabilities
- During 2009 shutdown the problem with the DCH instability was solved
  - DCH operated for all the 2009 run with no degradation
- Data taking in Nov-Dec/2009
  - improved efficiency
  - improved electronics (DRS2 → DRS4)
  - improved resolutions (track, time...)



- Confident in a sensitivity ~5 x 10^{-12} for this year's data
- We will need to run until the end of 2011 for reaching the target sensitivity

Thank you

- Visit us on http://meg.psi.ch

Back-up slides