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
INFN & U Genova
INFN & U Pavia
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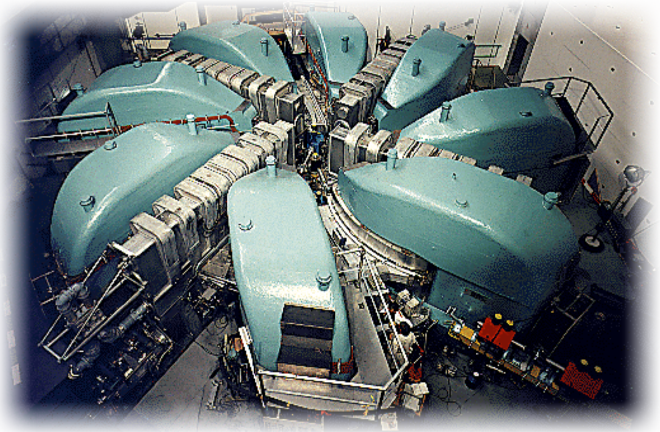
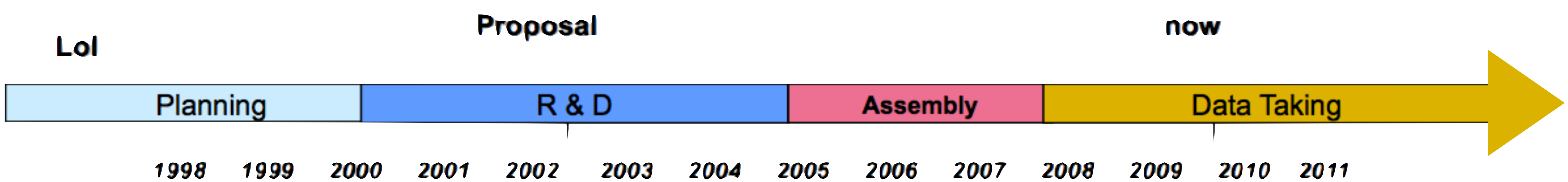
Outline

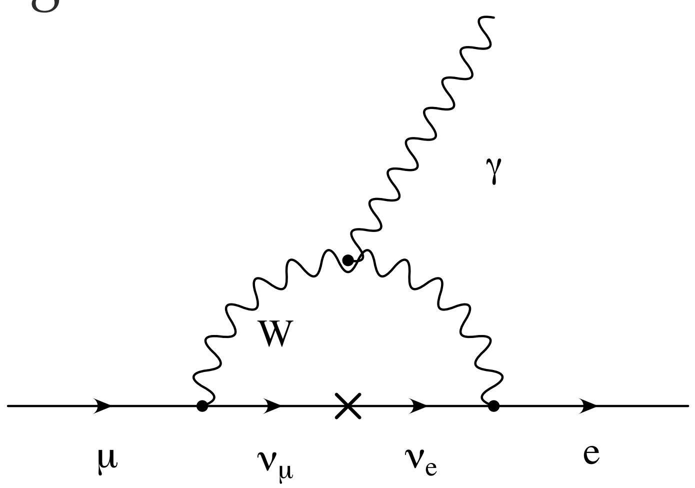
- Physics motivation for a $\mu \to e\gamma$ experiment
- The $\mu \to e\gamma$ decay
- The detector
  - Overview of sub-detectors
  - Calibration methods
- Analysis of 2008 run
- Status
  - Run 2009
- Next year(s)





The μ→eγ decay

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

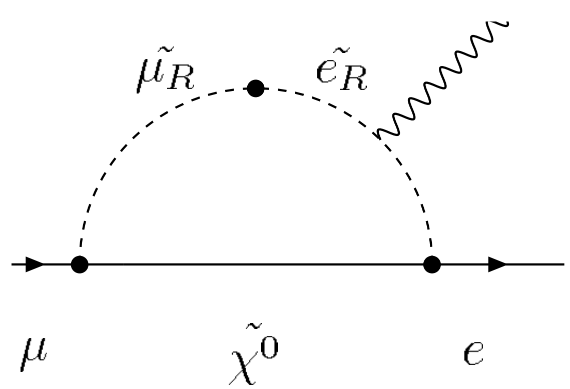


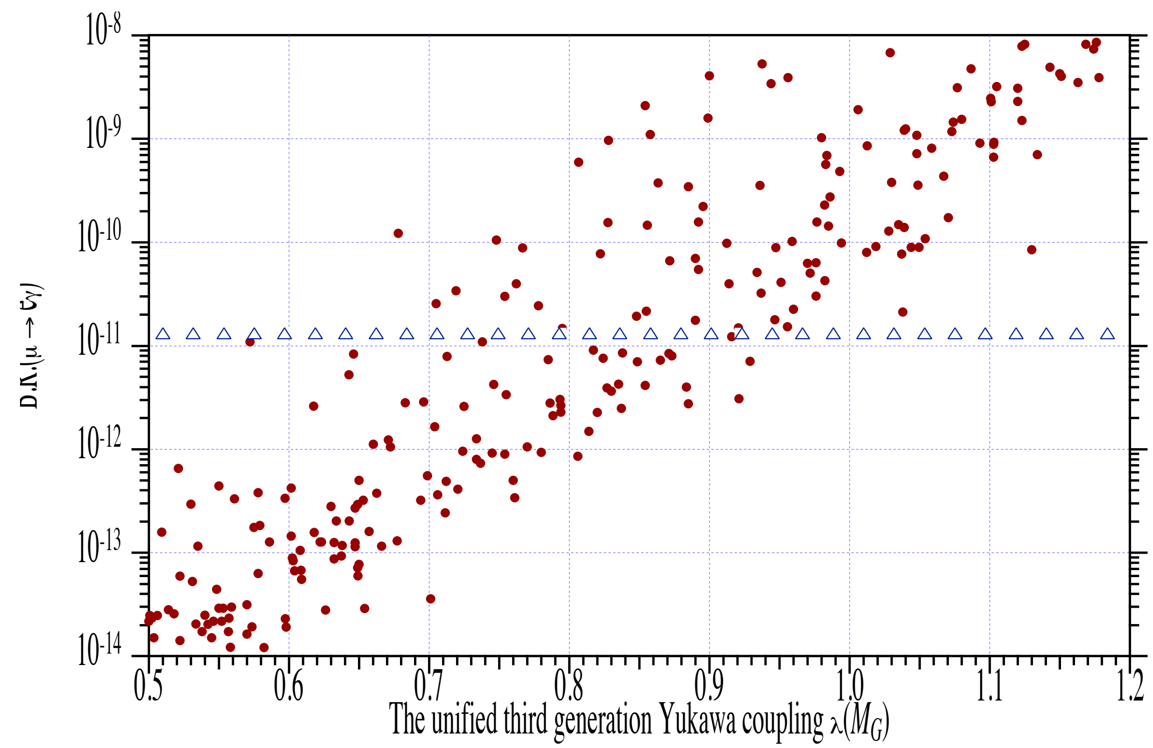
$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\text{decay}} \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\text{vertex}} \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\text{oscillation}}$$

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

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...)

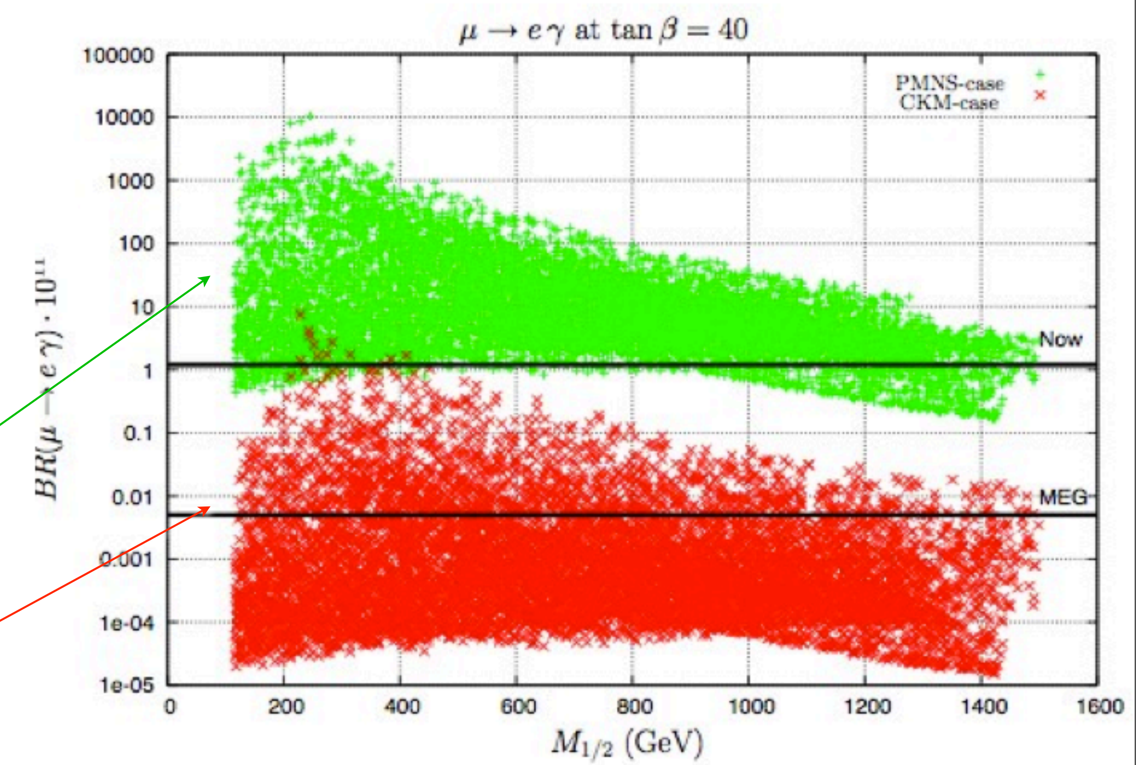




- Clear evidence for physics beyond the SM
- Restrict parameter space of SM extensions

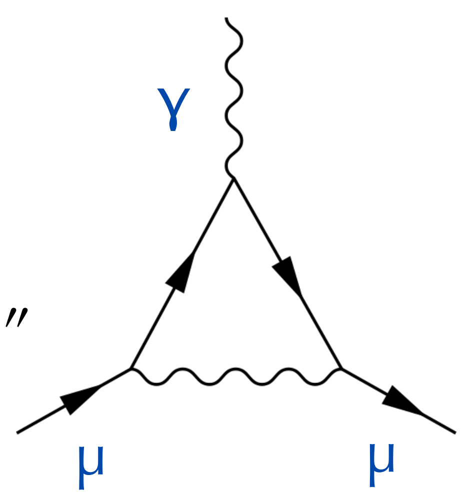
Connections

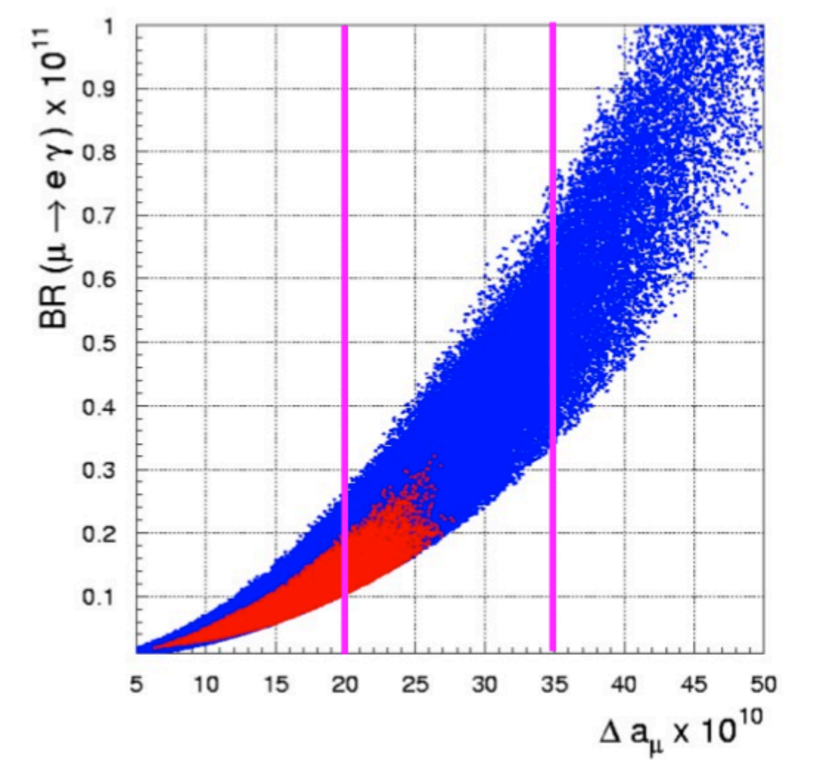
- LHC
  - it is Super Symmetry + Grand Unification that predicts new particles in the loop.
  - alternate search for (E/M_{SUSY}) suppressed effects



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

- muon g–2
  - a_μ is the "diagonal" term
  - $\mu \to e\gamma$ 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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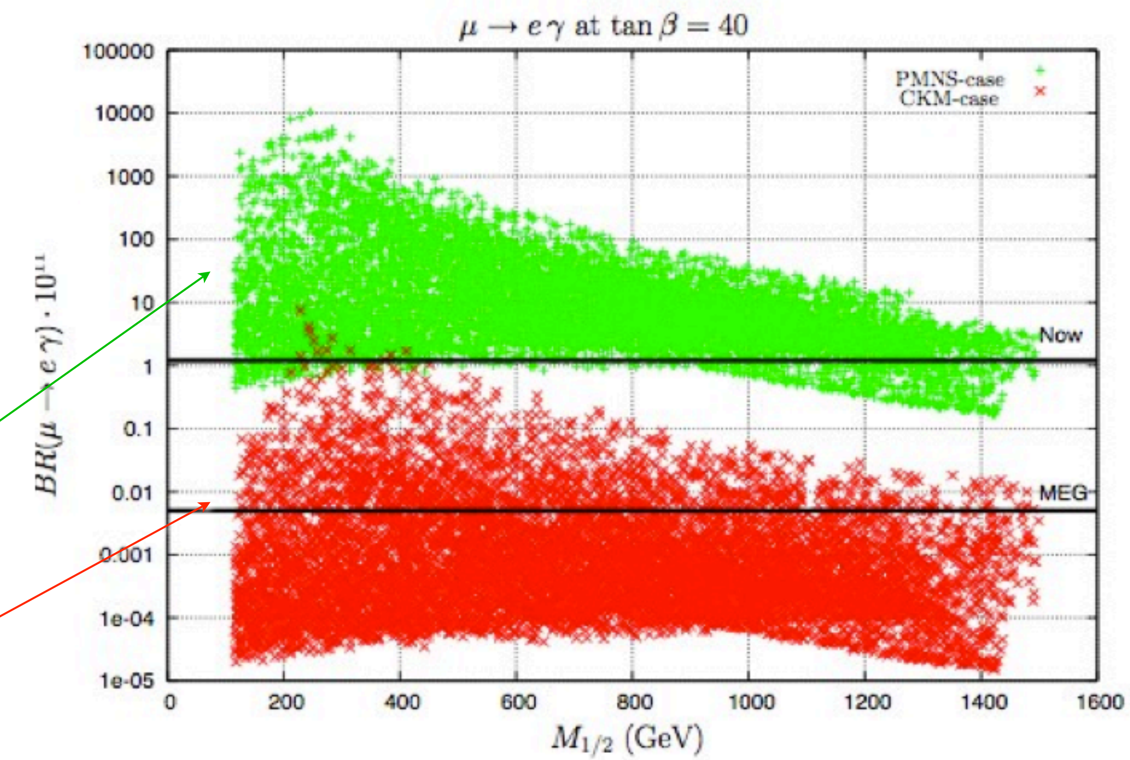

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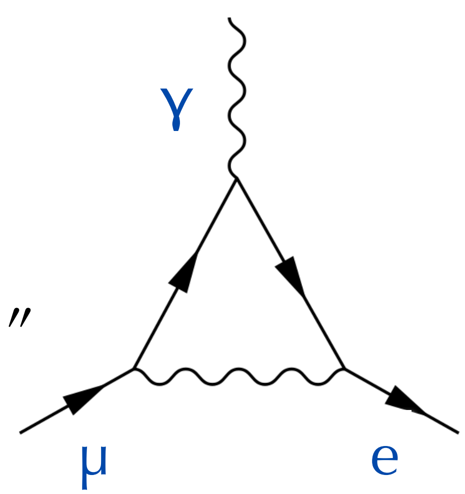

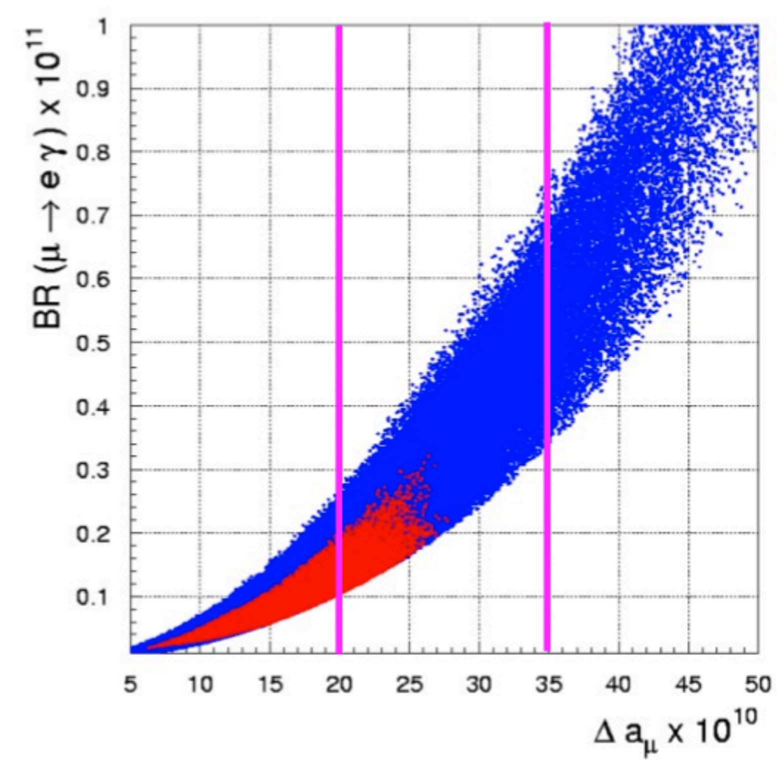

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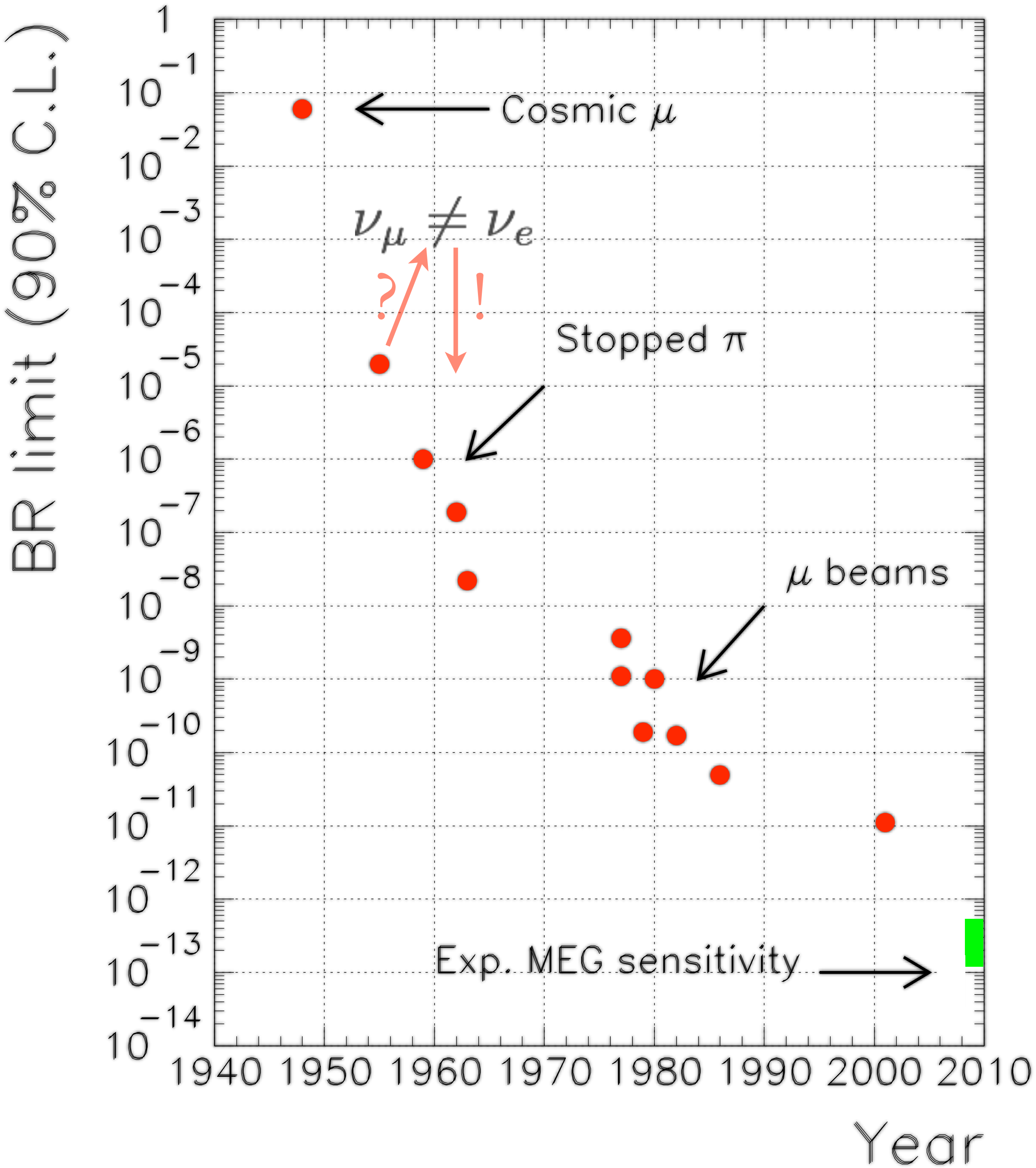
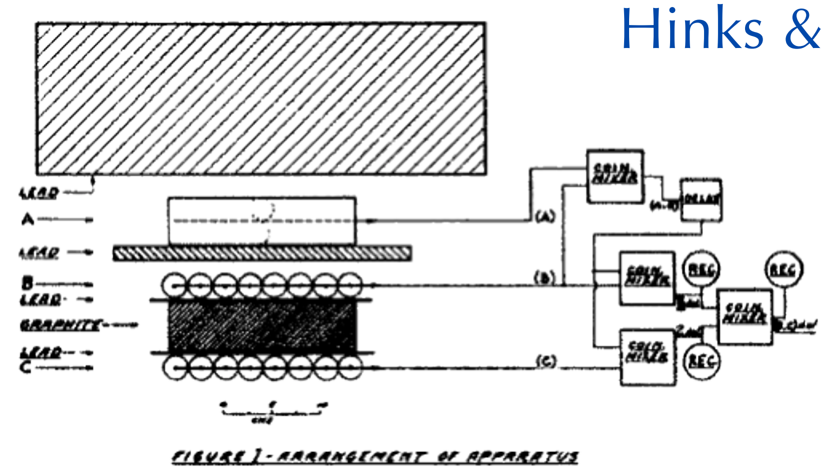
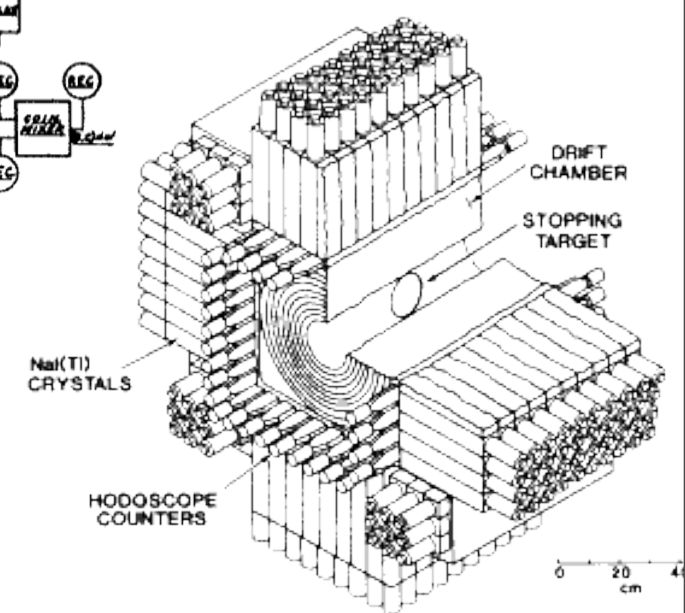
Historical perspective

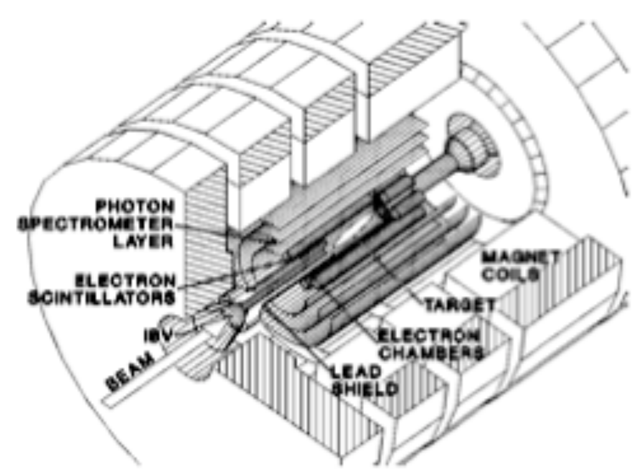


Hinks & Pontecorvo

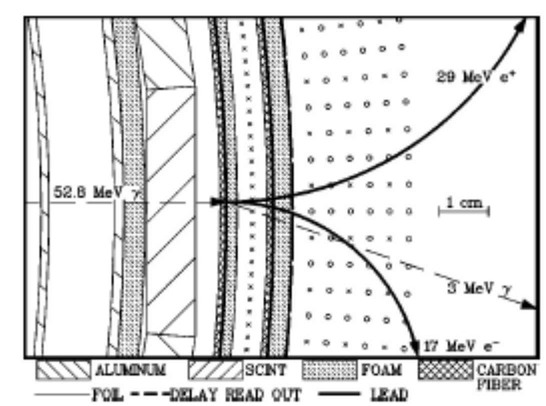




Crystal Box



MEGA

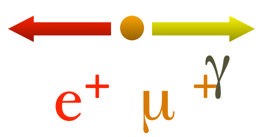


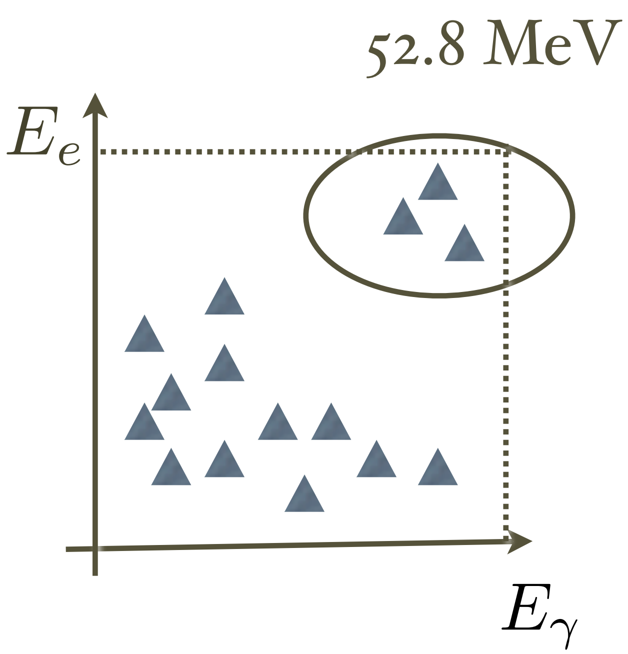
Each improvement linked to the technology either in the beam or in the detector

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

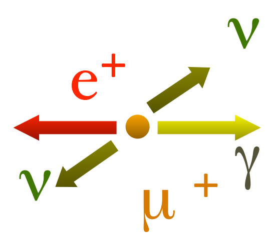
Signal and Background

"Signal"



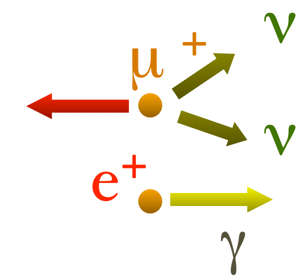


"Prompt"



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

"Accidental"



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

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

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

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

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}

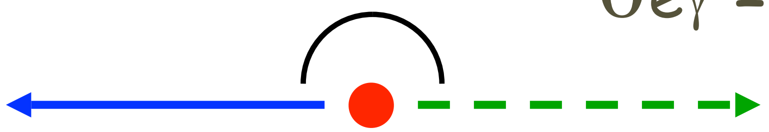
FWHM

MEG experimental method

Easy signal selection with μ^+ at rest:

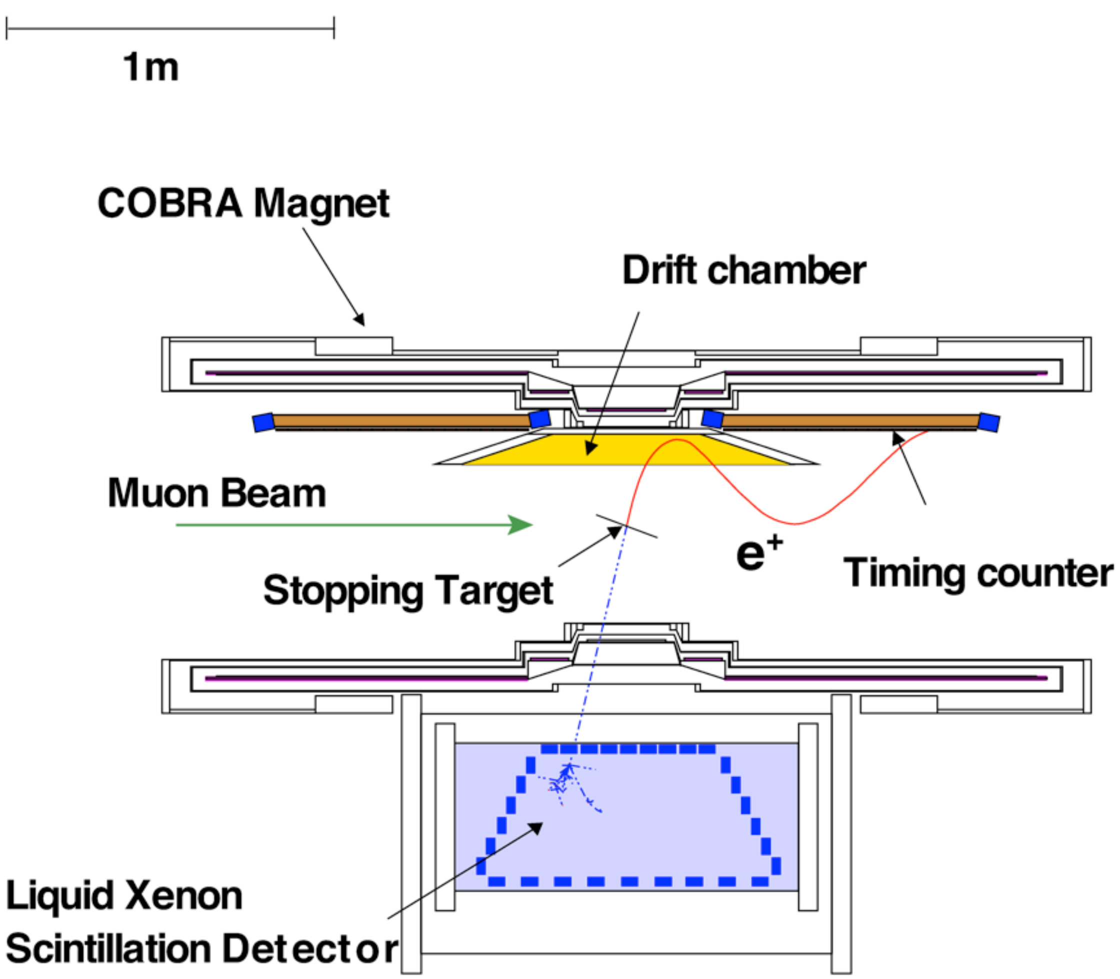
μ: stopped beam of $>10^7$ μ /sec in a 175 μm target

$\theta_{e\gamma} = 180°$



e^+ μ^+ γ

$E_e = E_\gamma = 52.8$ MeV



- e^+ detection

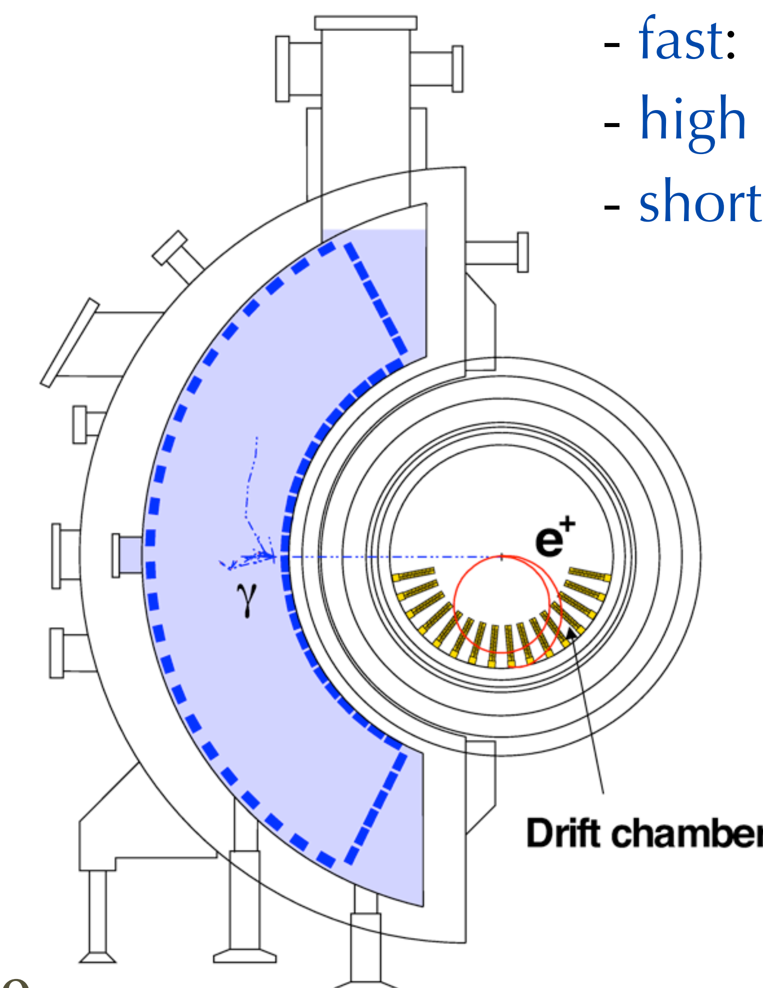
  magnetic spectrometer composed of solenoidal magnet and drift chambers for momentum

  plastic counters for timing

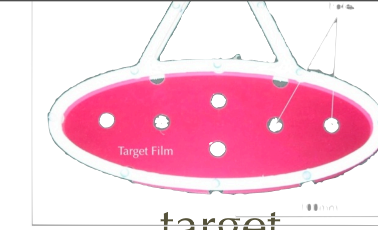
- γ detection

  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

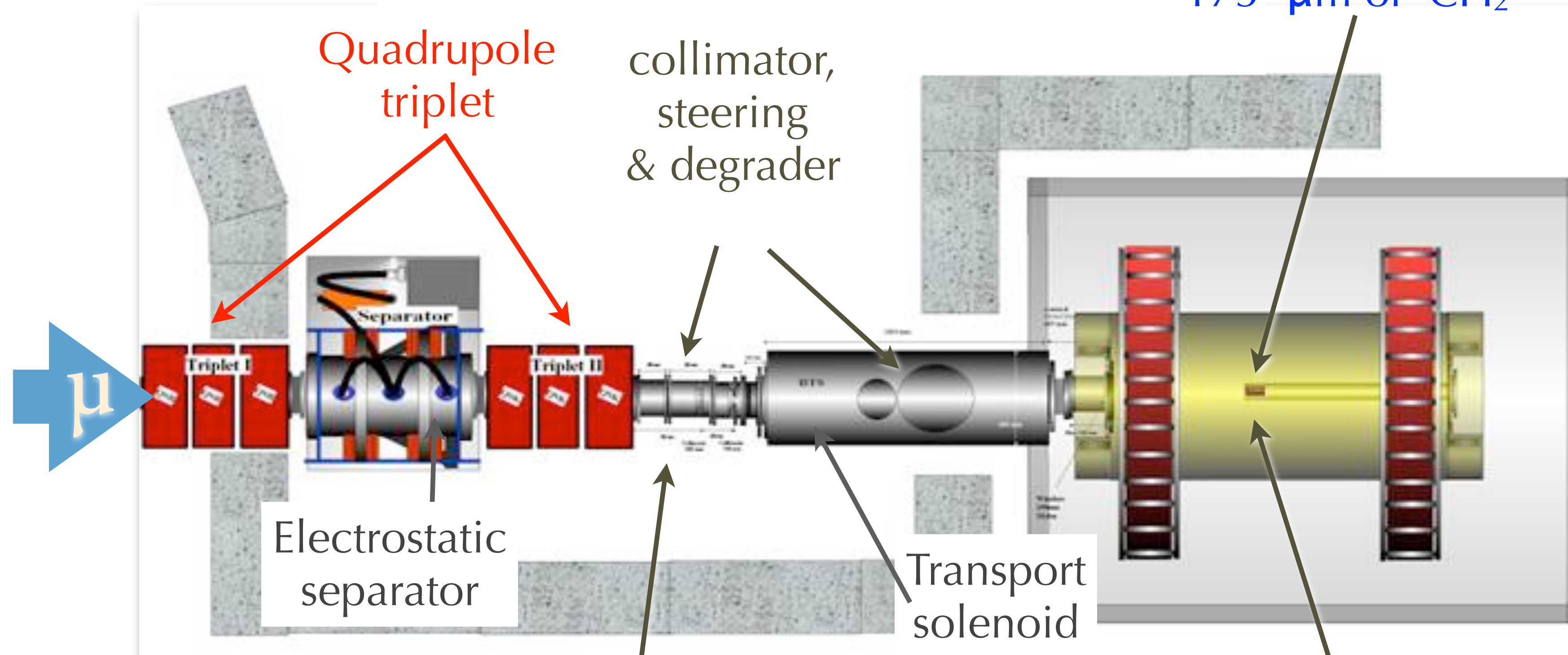


target
175 µm of CH_2

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

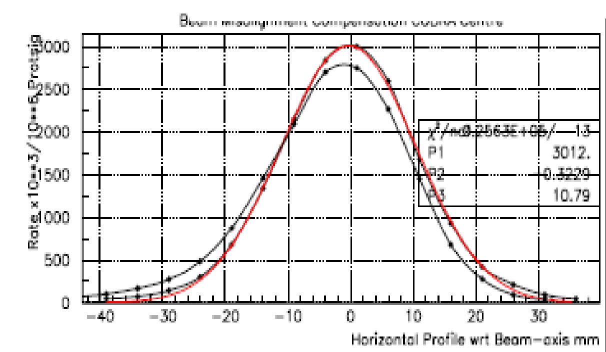


µ/e separation 11.8 cm (7.2 σ)

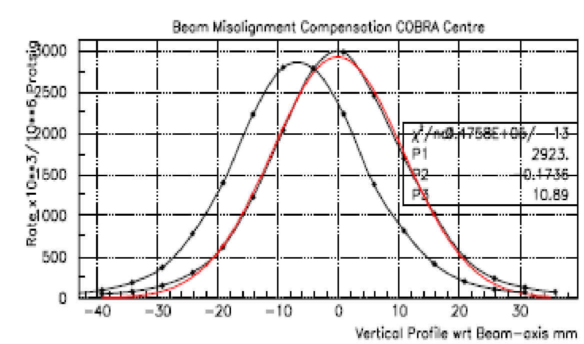
R_μ (exp. on target) >6 10^7 μ^+/s

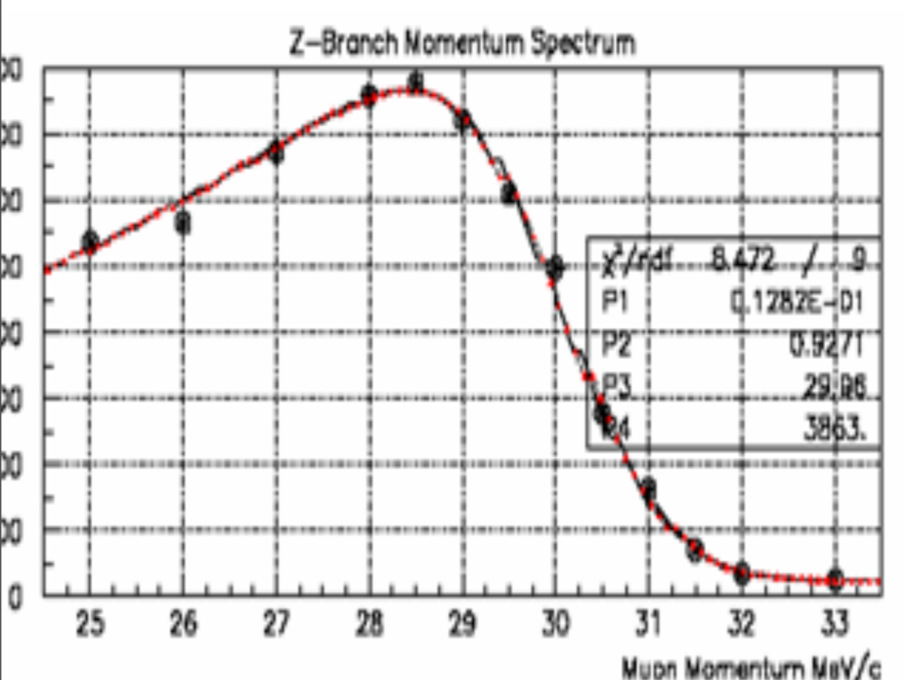
µ spot (exp. on target) $\sigma_V \approx \sigma_H \approx$ 11 mm

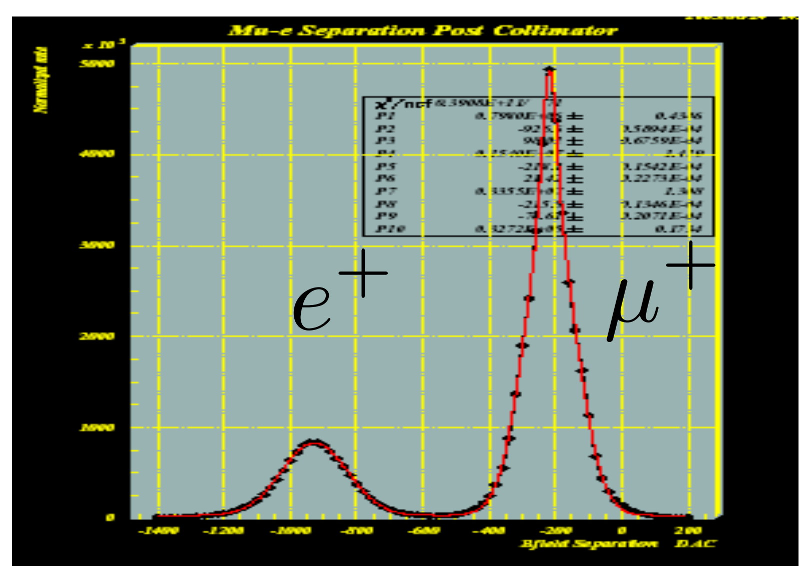
σ_x = 11 mm



σ_y = 11 mm

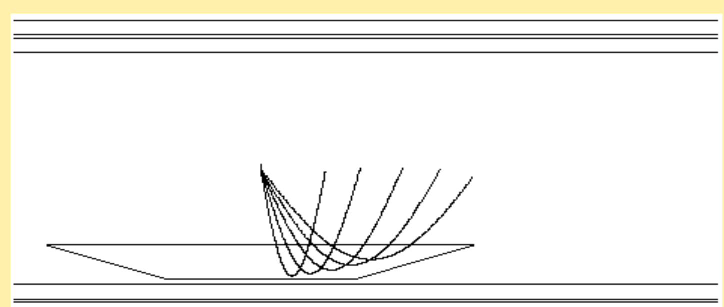
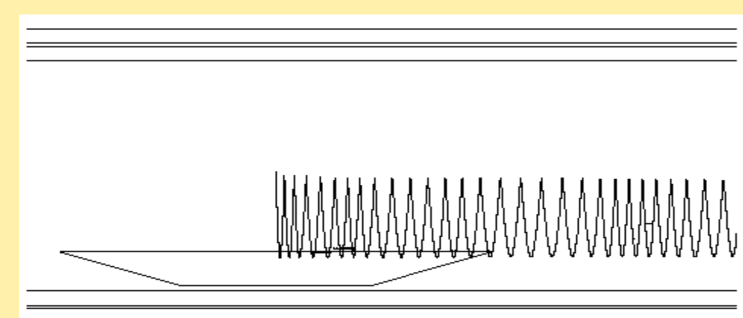
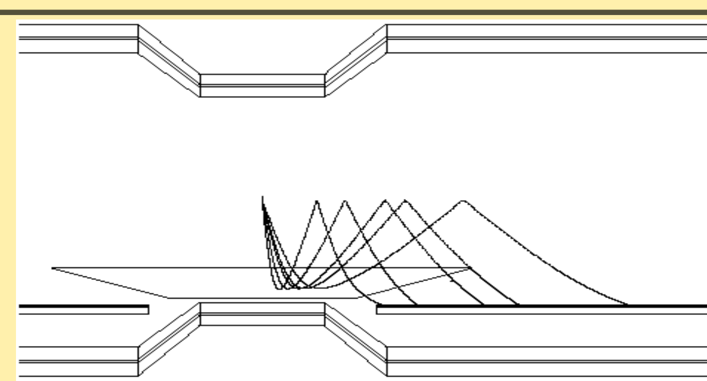
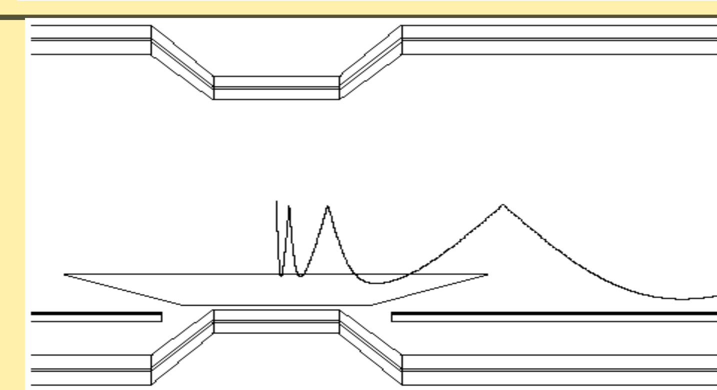






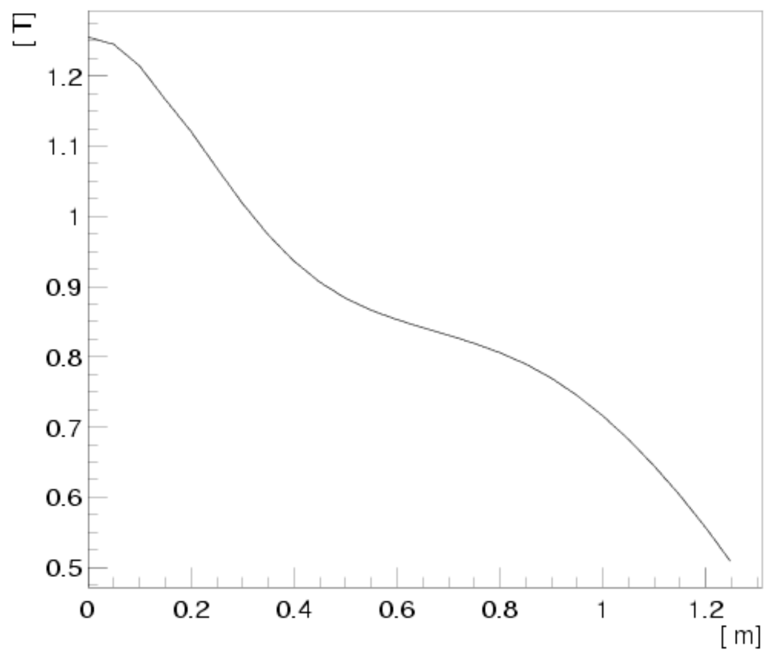
COBRA spectrometer

- 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		

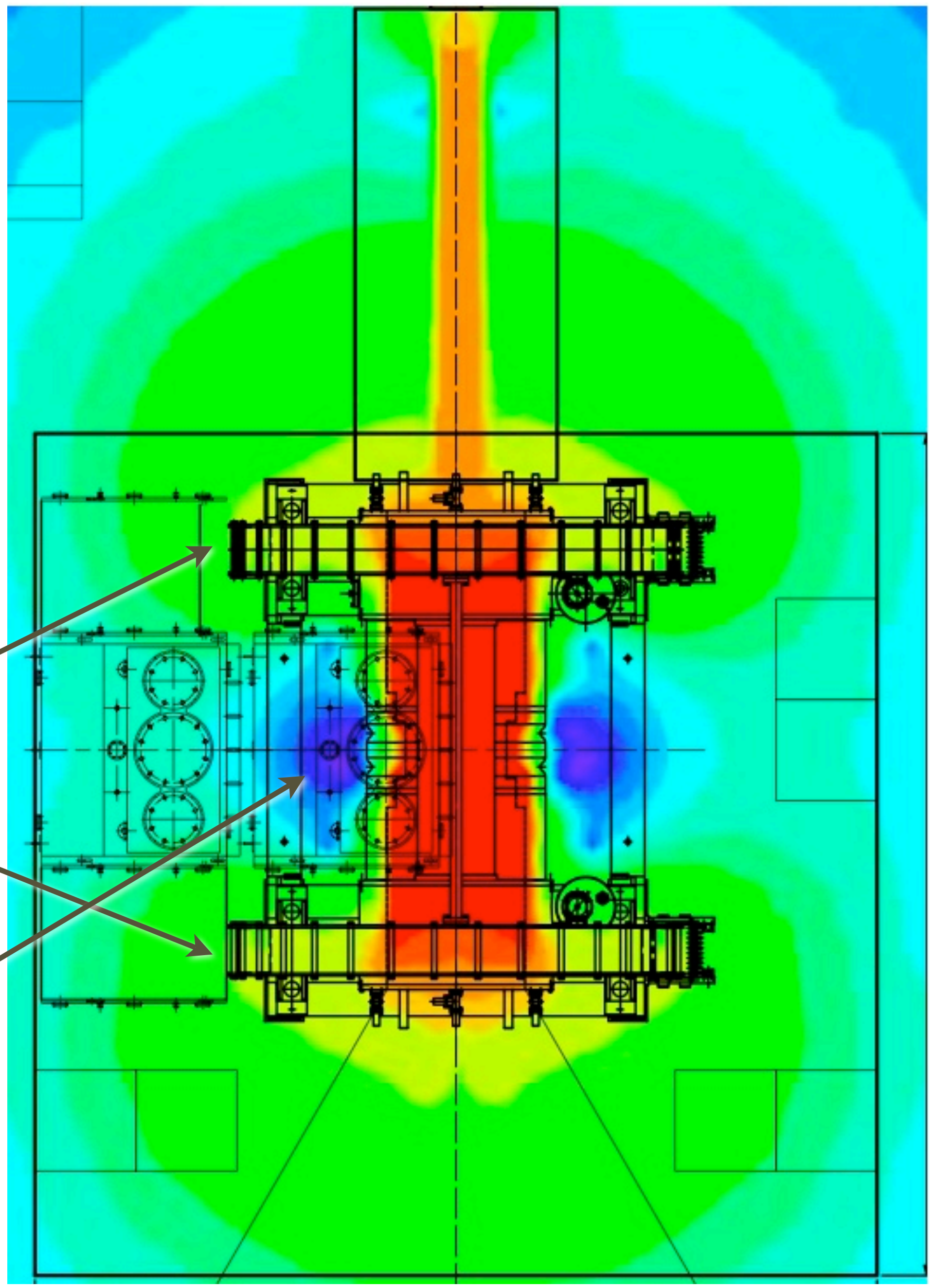
COBRA spectrometer

Non uniform magnetic field decreasing from the center to the periphery

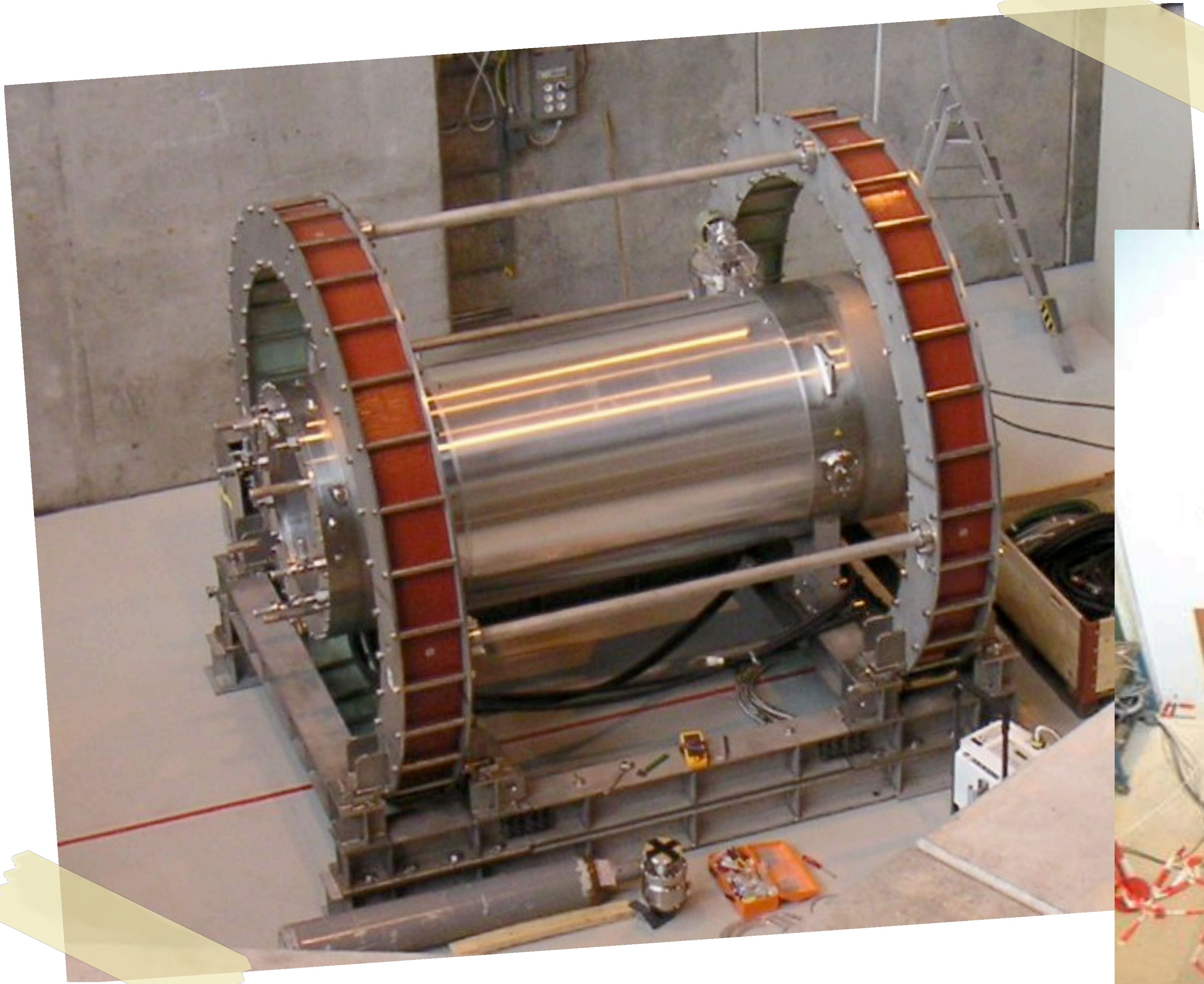


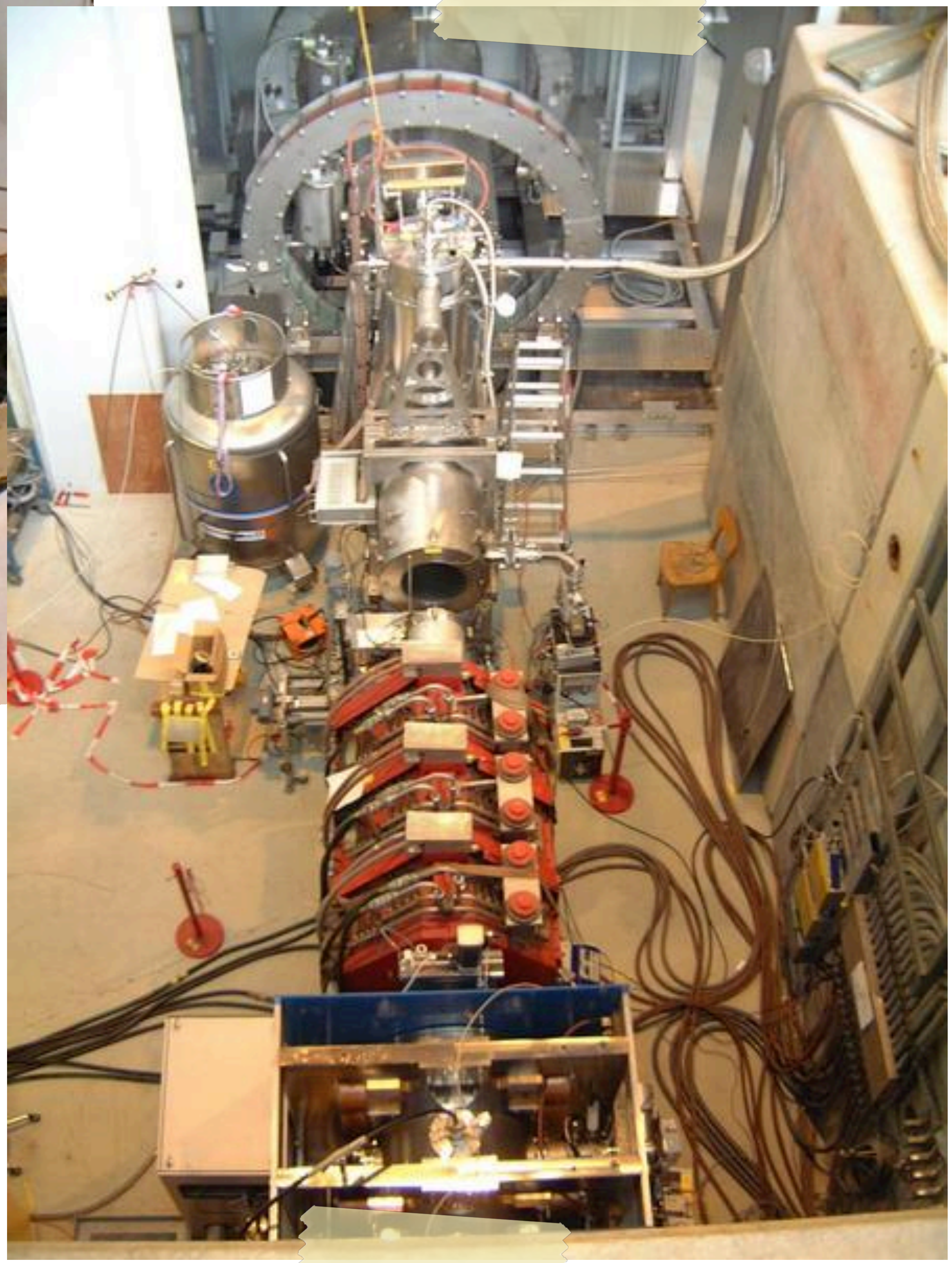
Compensation coil for LXe calorimeter

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

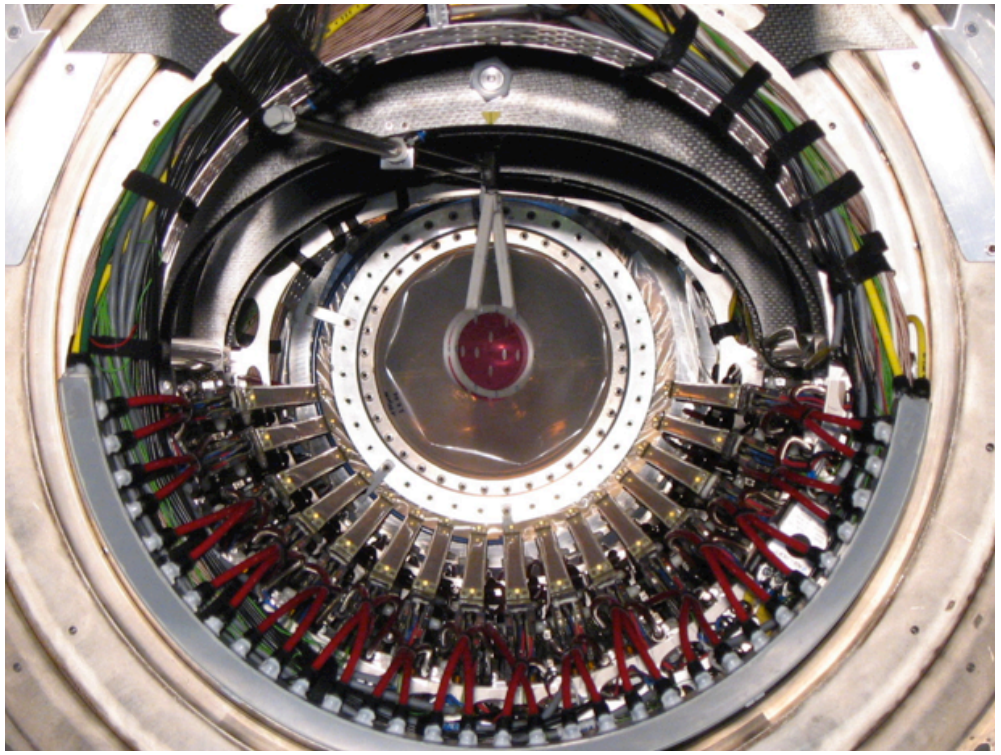


- The superconducting magnet is very thin (0.2 X_0)
- Can be kept at 4 K with GM refrigerators (no usage of liquid helium)





Positron Tracker

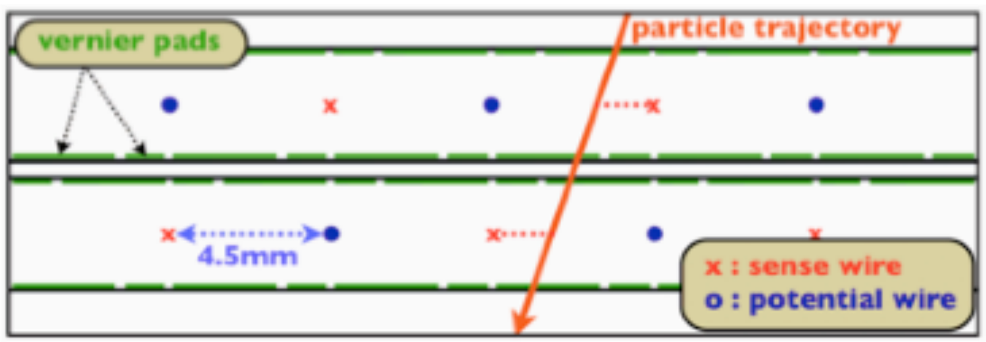


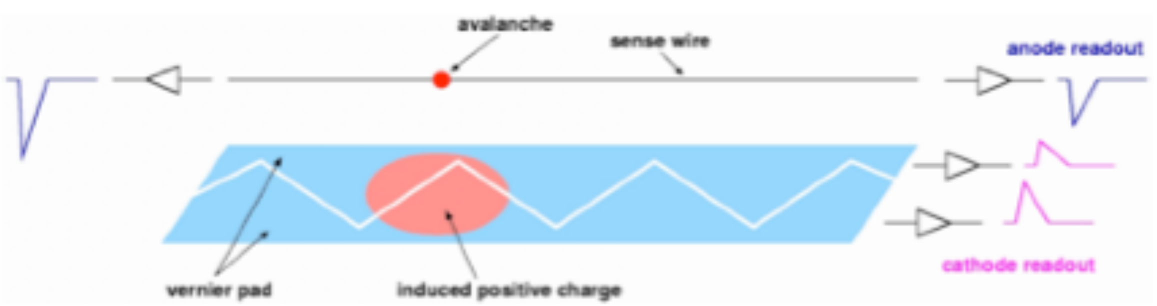
- 16 chambers radially aligned with 10° intervals
- 2 staggered arrays of drift cells
- 1 signal wire and 2 x 2 vernier cathode strips made of 15 μm kapton foils and 0.45 μm aluminum strips
- Chamber gas: He-C_2H_6 mixture
- Within one period, fine structure given by the Vernier circle

  $\sigma_R \sim 350\ \mu m$

  $\sigma_z \sim 500\ \mu m$

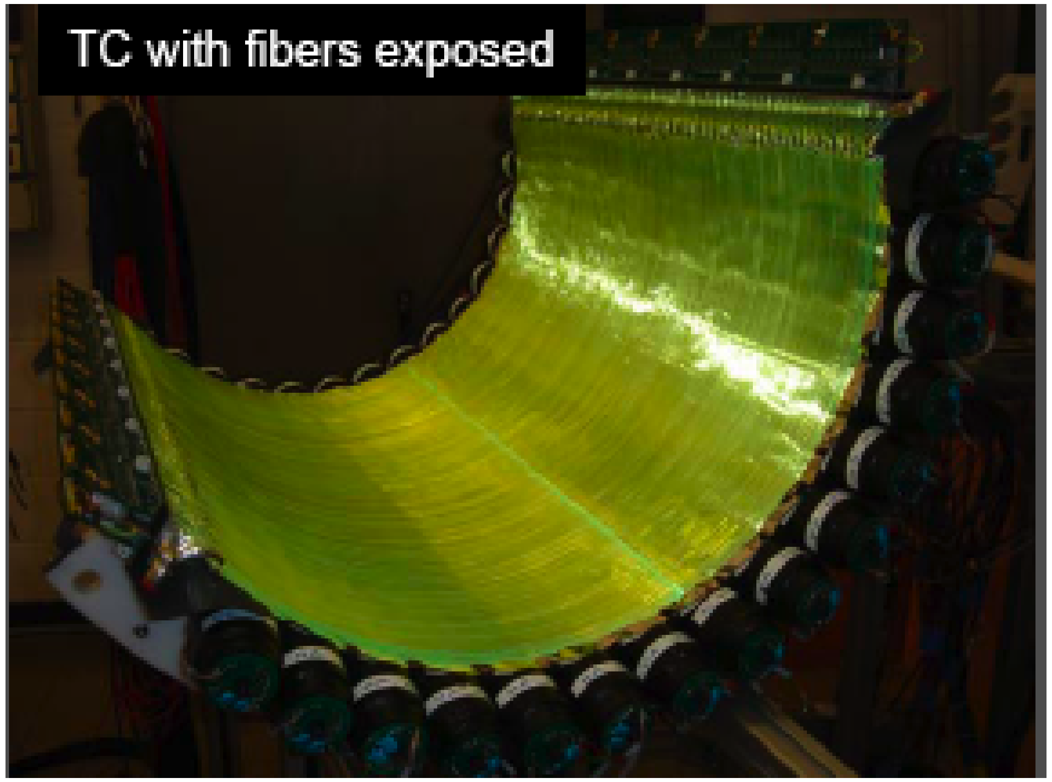
transverse coordinate (t drift)



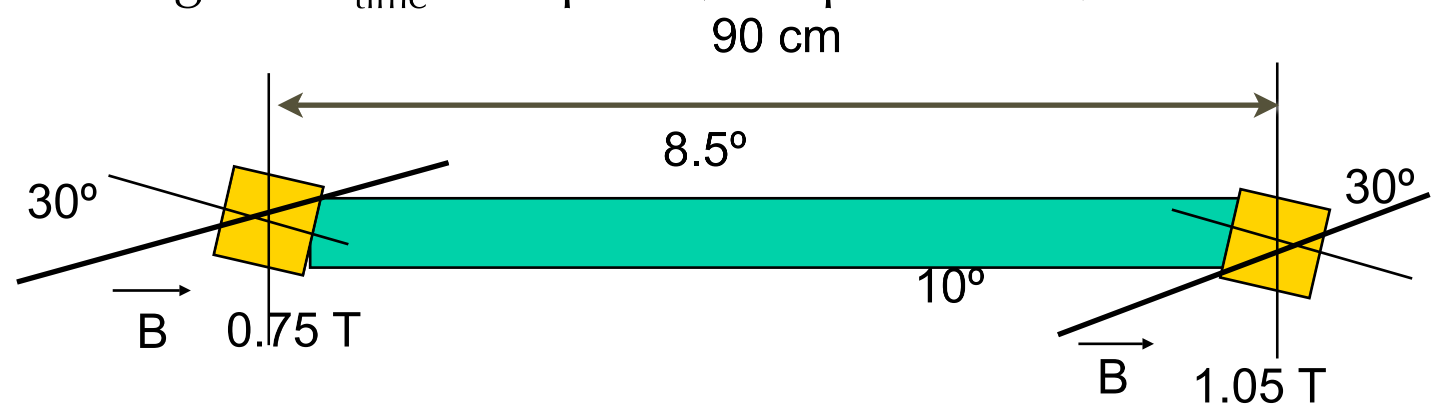


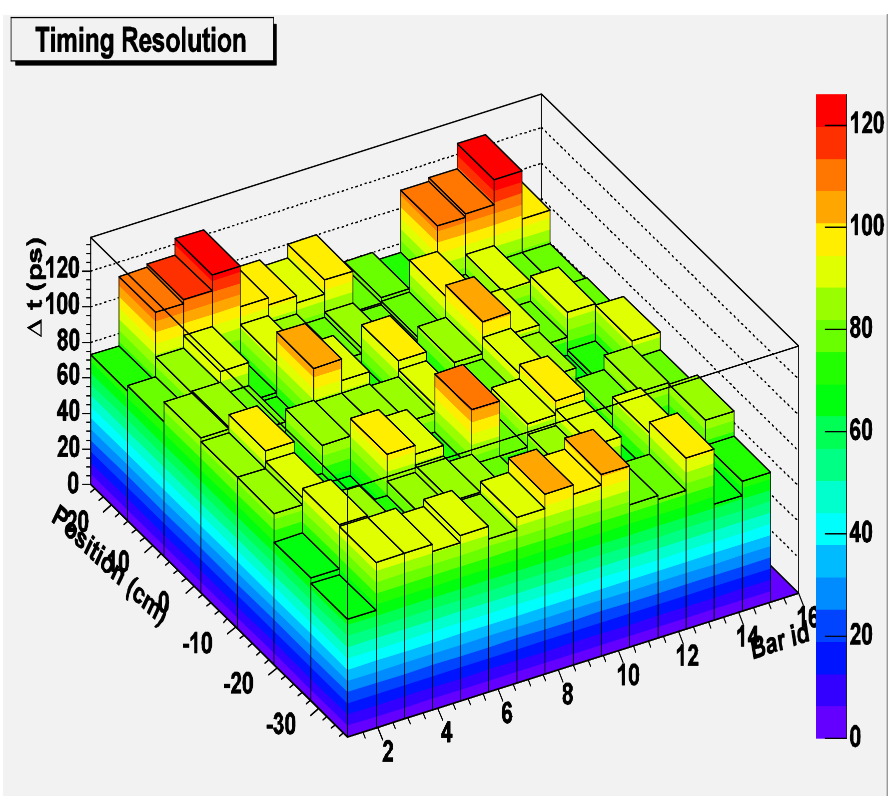
longitudinal coordinate (charge division + Vernier)

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)



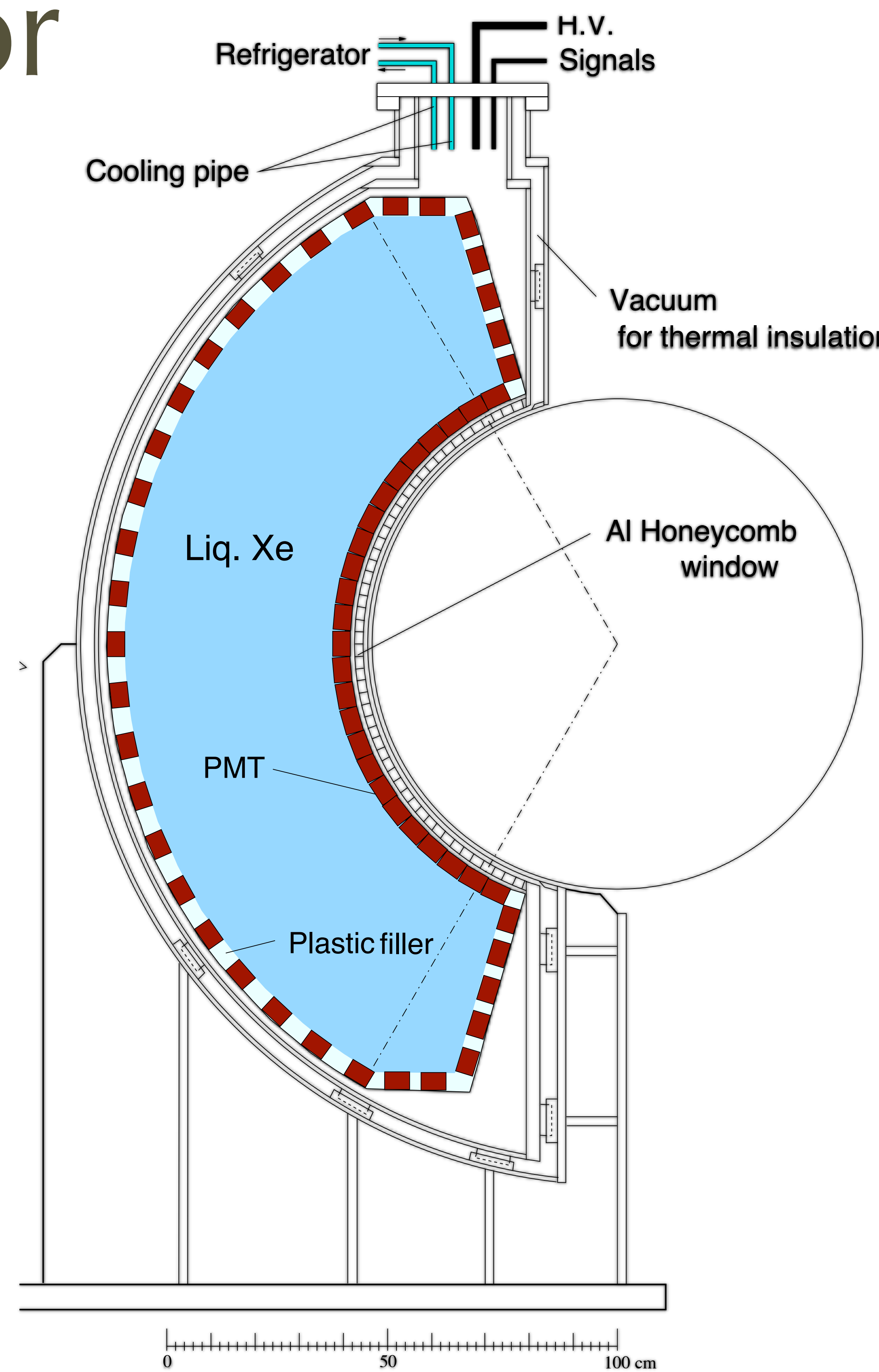


Exp. application (*)	Counter size (cm) (T x W x L)	Scintillator	PMT	λ_{att} (cm)	σ_t(meas)	σ_t(exp)
G.D.Agostini	3x 15 x 100	NE114	XP2020	200	120	60
T. Tanimori	3 x 20 x 150	SCSN38	R1332	180	140	110
T. Sugitate	4 x 3.5 x 100	SCSN23	R1828	200	50	53
R.T. Gile	5 x 10 x 280	BC408	XP2020	270	110	137
TOPAZ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

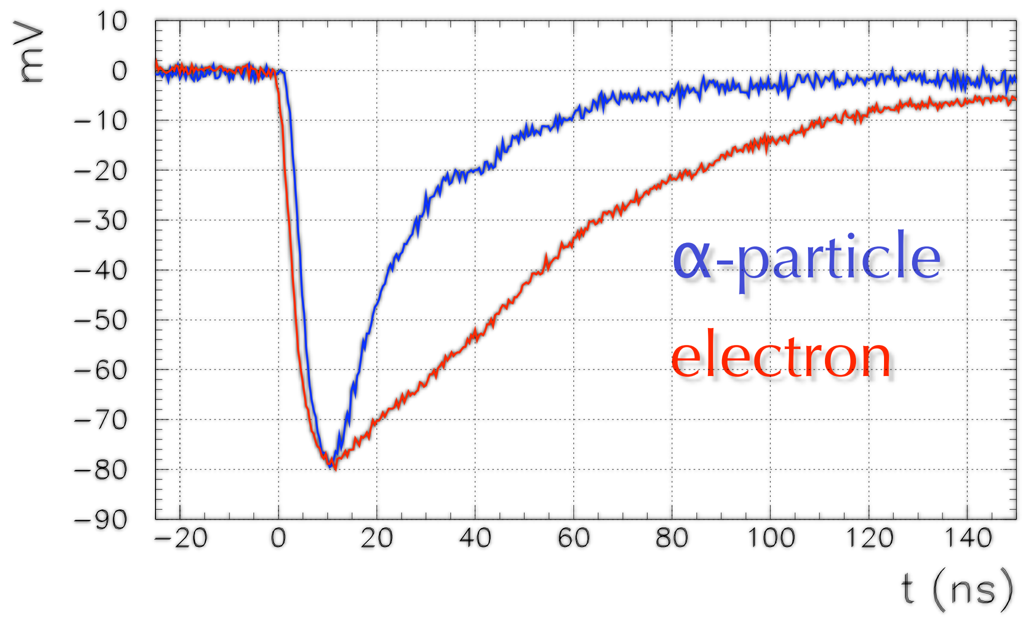
The photon detector

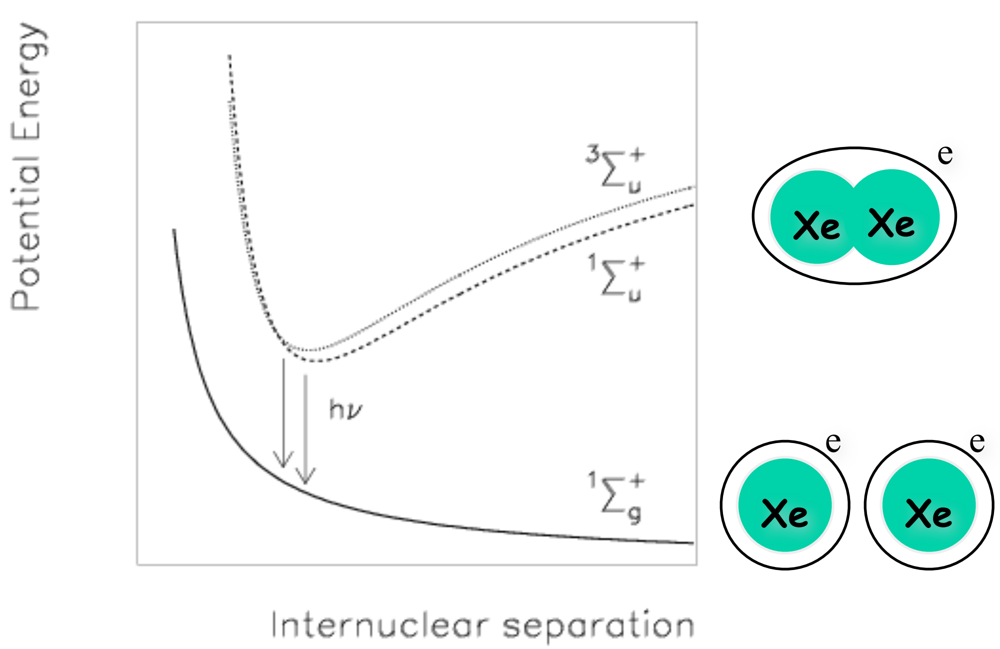
- γ Energy, position, timing
- Homogeneous 0.8 m^3 volume of liquid Xe
  - 10 % solid angle
  - $65 < r < 112$ cm
  - $|\cos\theta| < 0.35$ $|\phi| < 60^o$
- Only scintillation light
- Read by 848 PMT
  - 2″ photo-multiplier tubes
  - Maximum coverage FF (6.2 cm cell)
  - Immersed in liquid Xe
  - Low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



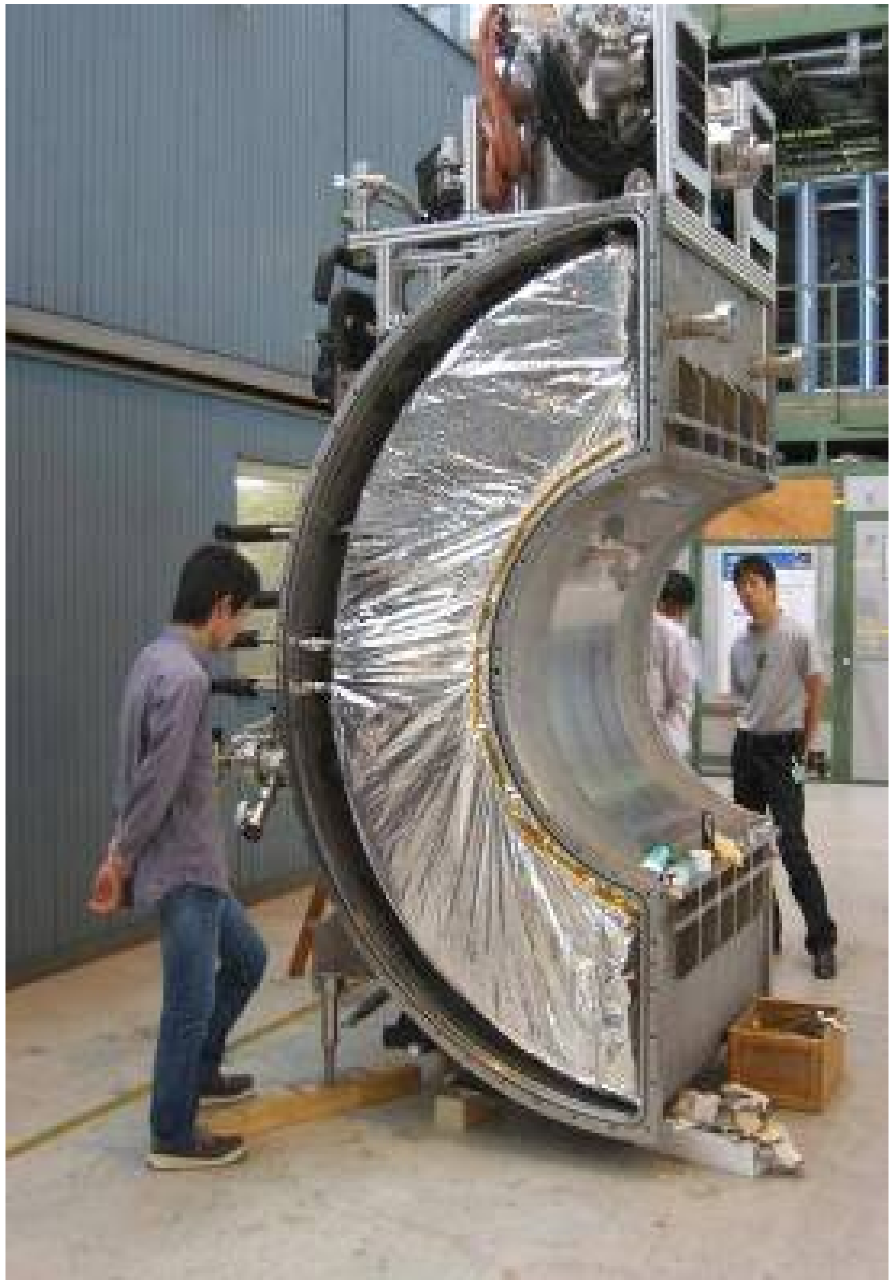
Xe properties

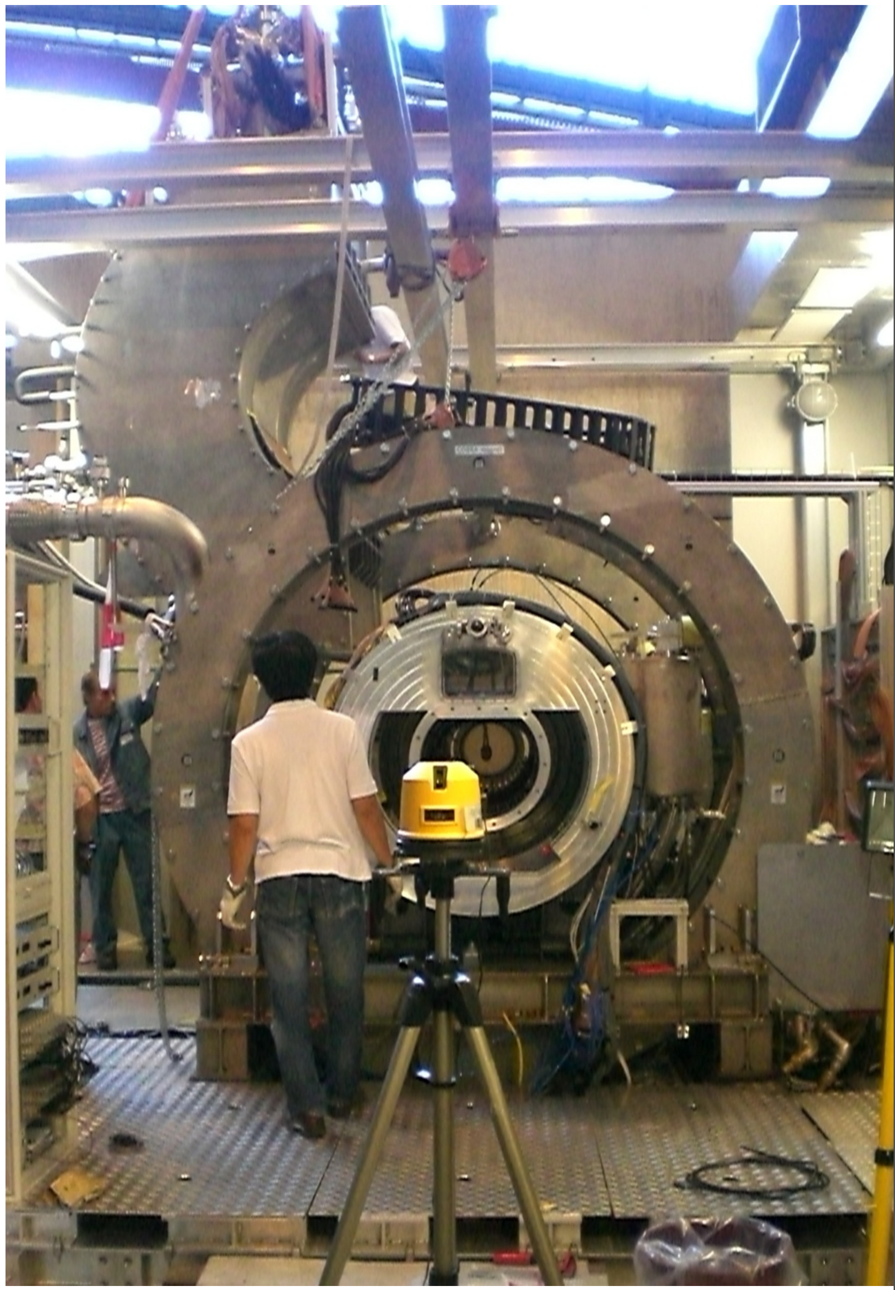
- Liquid Xenon was chosen because of its unique properties among radiation detection active media
- Z=54, ρ=2.95 g/cm^3 (X_0=2.7 cm), R_M=4.1 cm
- High light yield (similar to NaI)
  - 40000 phe/MeV
- Fast response of the scintillation decay time
  - $\tau_{singlet}$= 4.2 ns
  - $\tau_{triplet}$= 22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





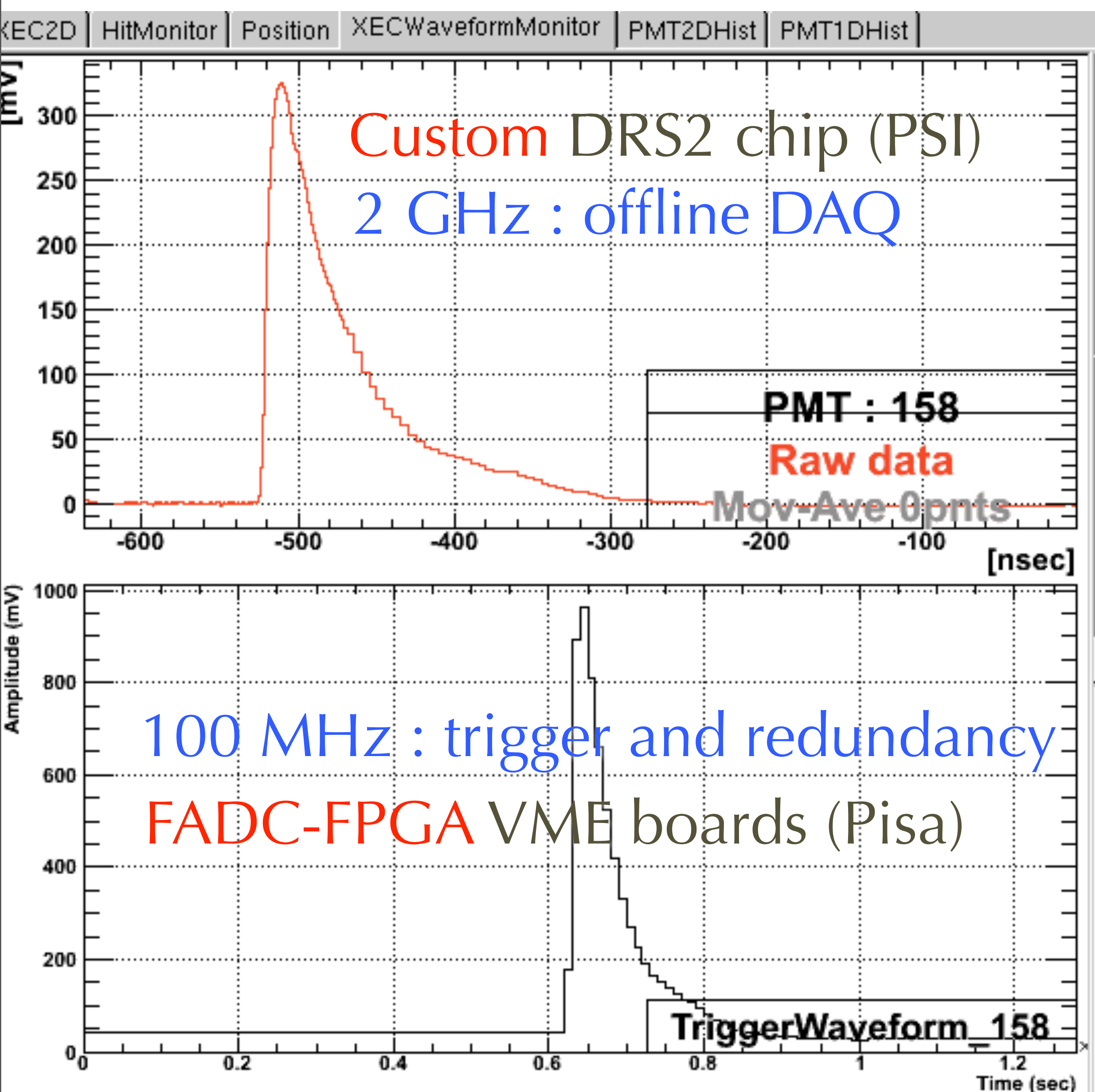
γ-detector construction





TRG + DAQ example

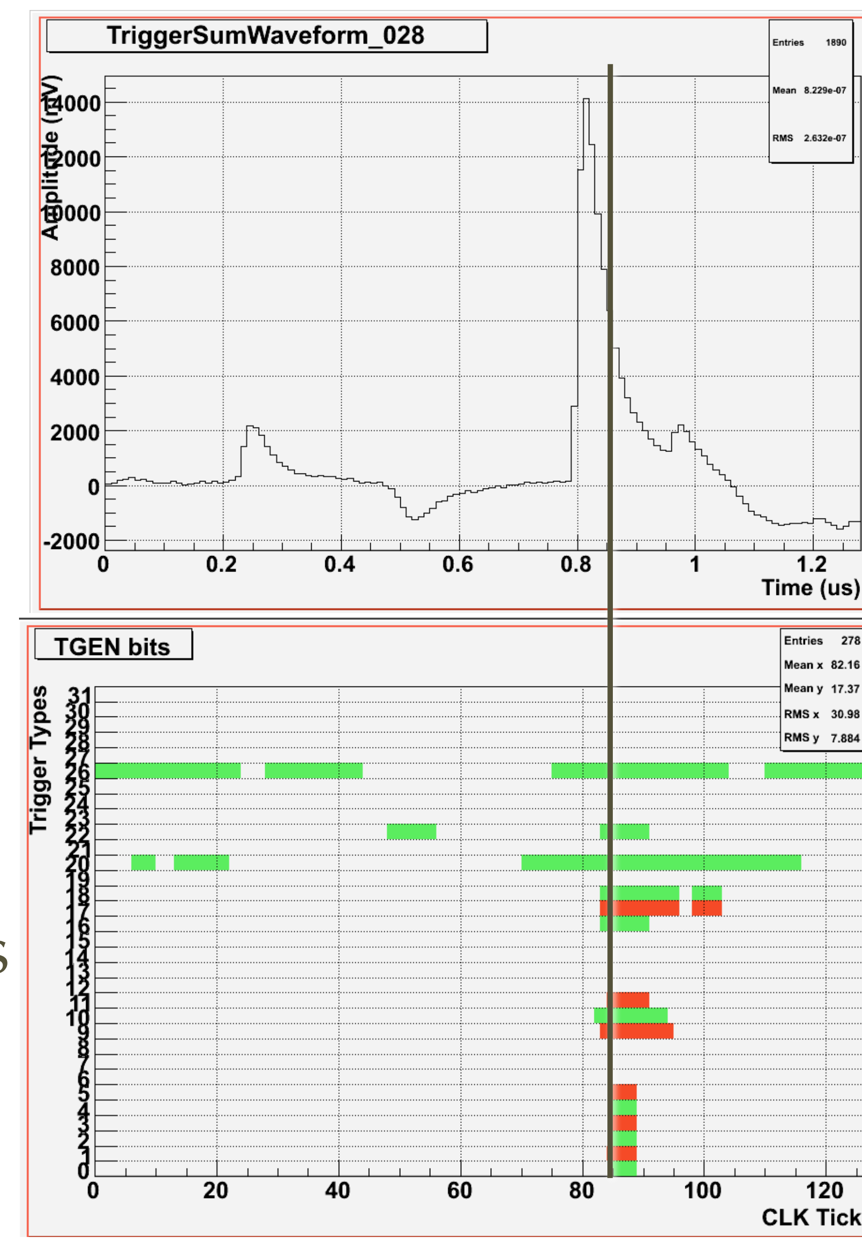
- For (almost) all channels, for each sub-detector we have two waveform digitizers with complementary characteristics



online pedestal subtraction for LXe

info from all sub-detectors is combined

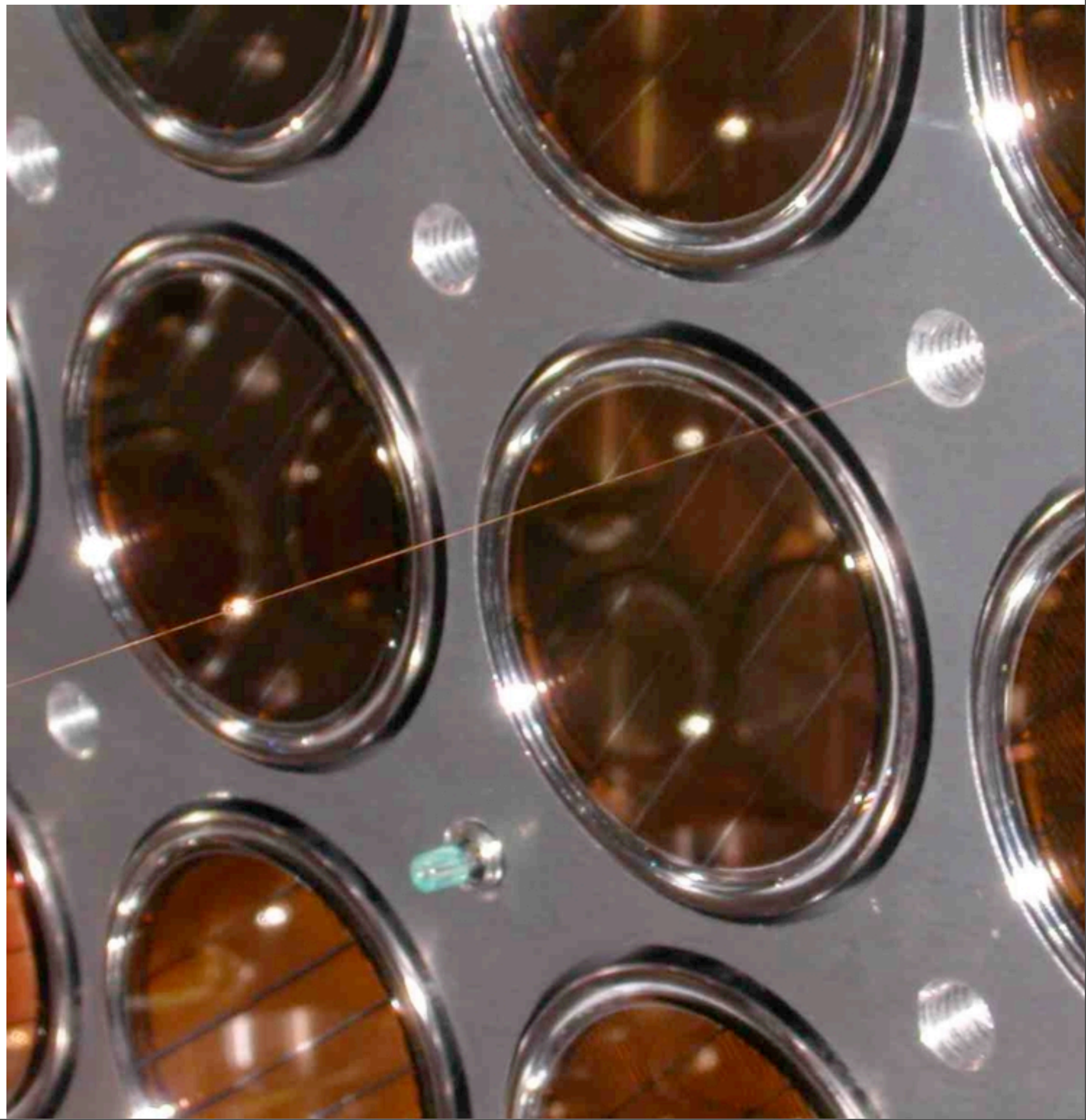
Trigger!



- ✳Beam rate ~ 3 10^7 s^{-1}
- ✳Acquisition rate 7 s^{-1}

Calibrations

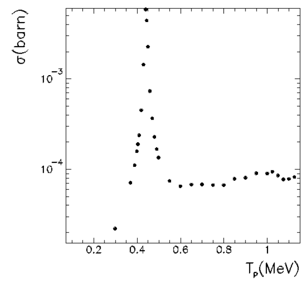
- It is understood that in such a complex detector a lot of parameters must be constantly checked
- We are prepared for redundant calibration and monitoring
- Single detector
  - PMT equalization for LXe and TIC
  - Inter-bar timing (TIC)
  - Energy scale
- Multiple detectors
  - relative timing

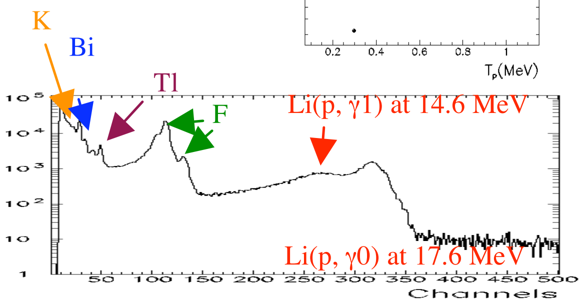


Calibrations

Xenon Calibration

Proton Accelerator



Li(p,γ)Be

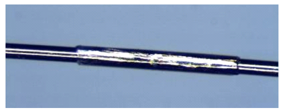
LiF target at COBRA center

17.6MeV γ

~daily calib.

also for initial setup

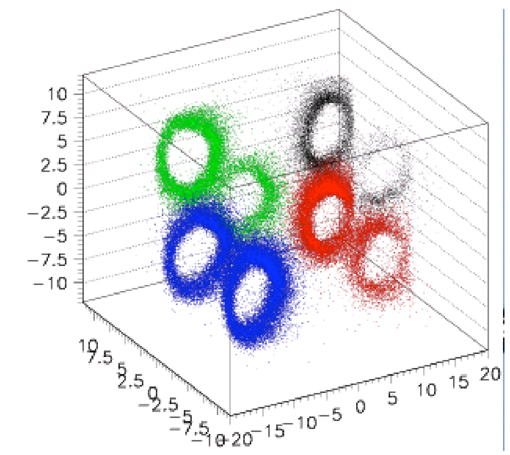
Alpha on wires



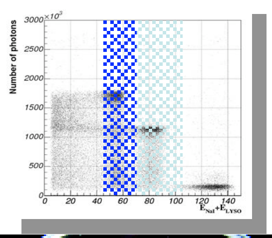
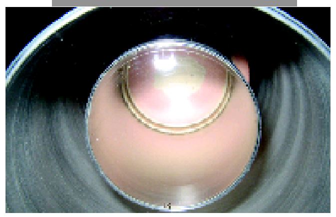
PMT QE & Att. L

Cold GXe

LXe



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

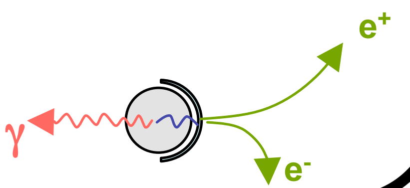



$\pi^- + p \rightarrow \pi^0 + n$

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

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

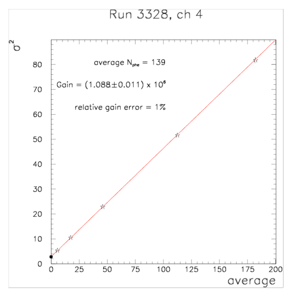
LH_2 target

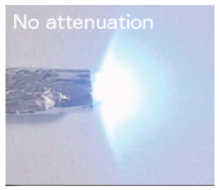


LED

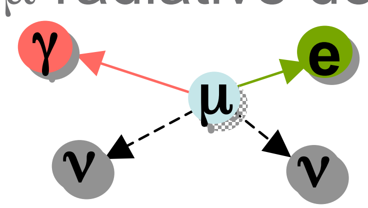
PMT Gain

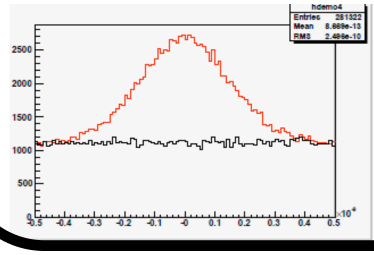
Higher V with light att.





μ radiative decay





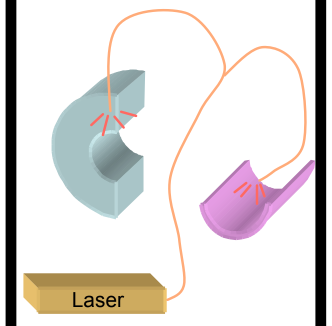
Lower beam intensity < 10^7

Is necessary to reduce pile-ups

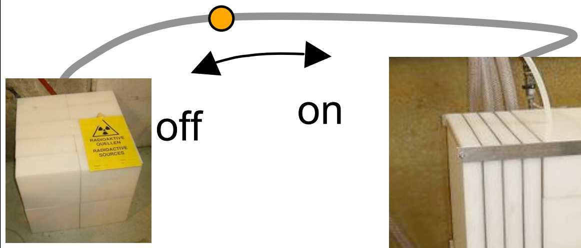
A few days ~ 1 week to get enough statistics

Laser

relative timing calib.

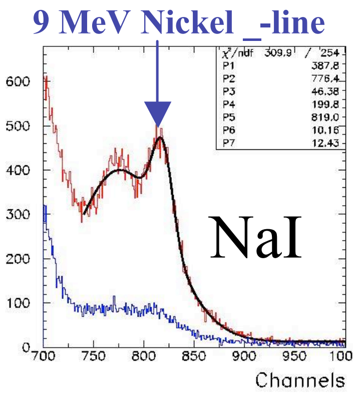


Nickel γ Generator



Illuminate Xe from the back

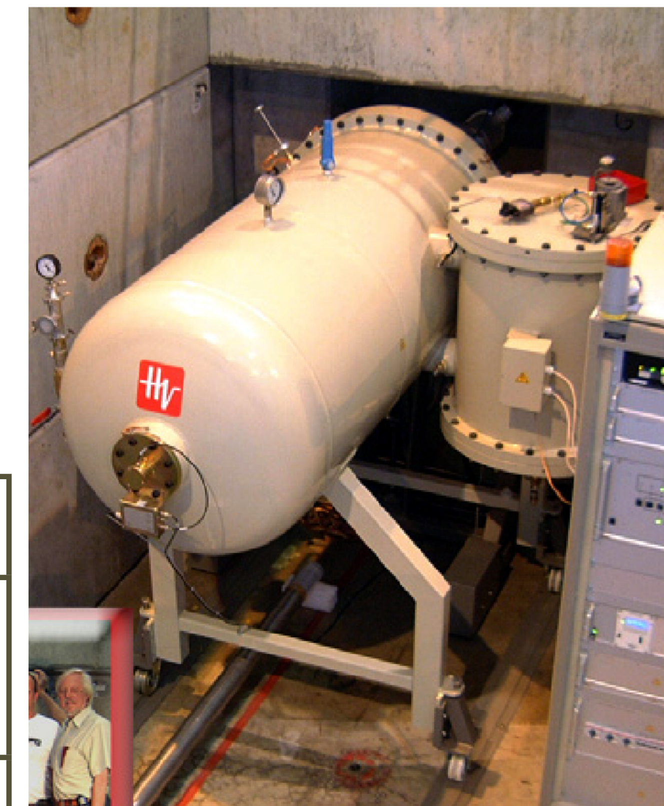
Source (Cf) transferred by comp air → on/off

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

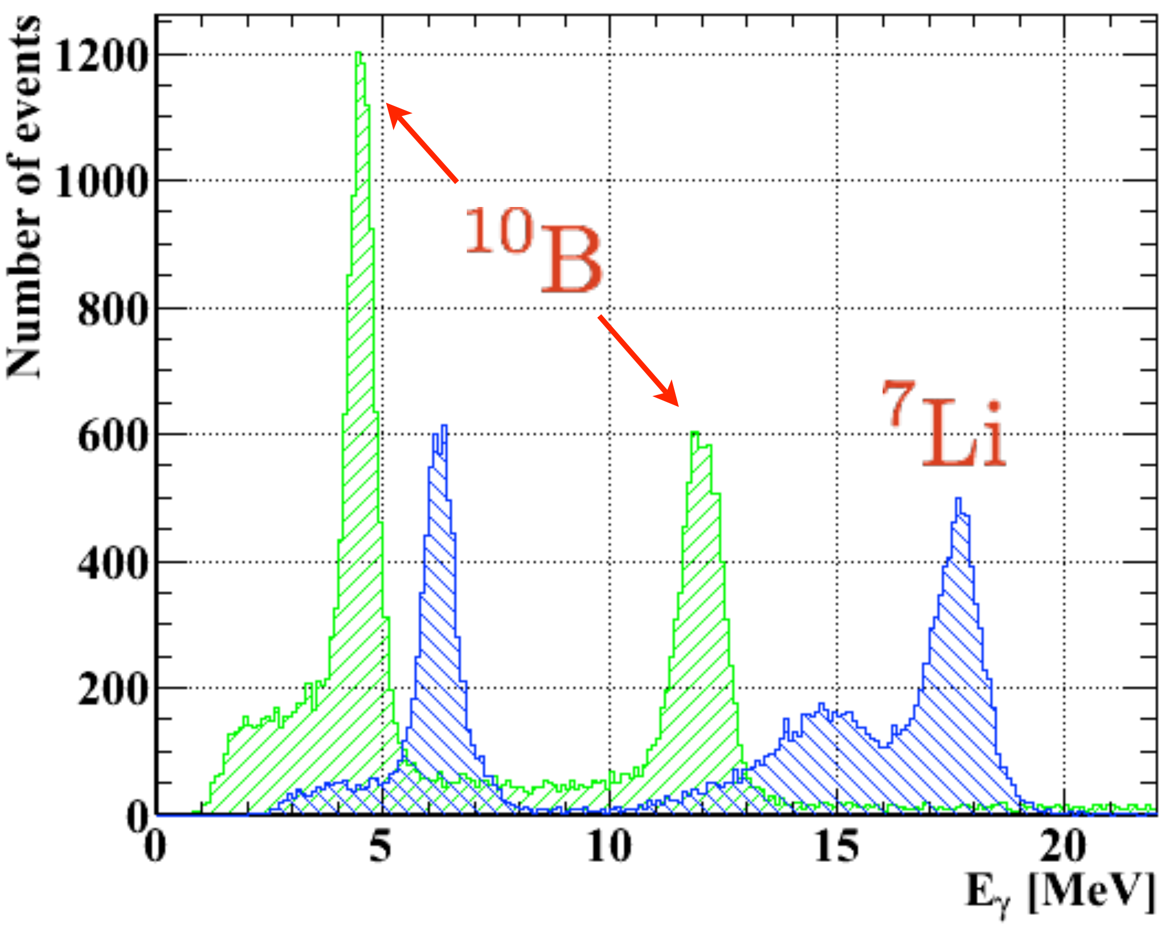
Process		Energy	Frequency
Charge exchange	$\pi^- p \to \pi^0 n$ $\pi^0 \to \gamma\gamma$	55, 83, 129 MeV	year - month
Proton accelerator	${}^7\mathrm{Li}(p, \gamma_{17.6})^8\mathrm{Be}$	14.8, 17.6 MeV	week
Nuclear reaction	${}^{58}\mathrm{Ni}(n, \gamma_9)^{59}\mathrm{Ni}$	9 MeV	daily
Radioactive source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

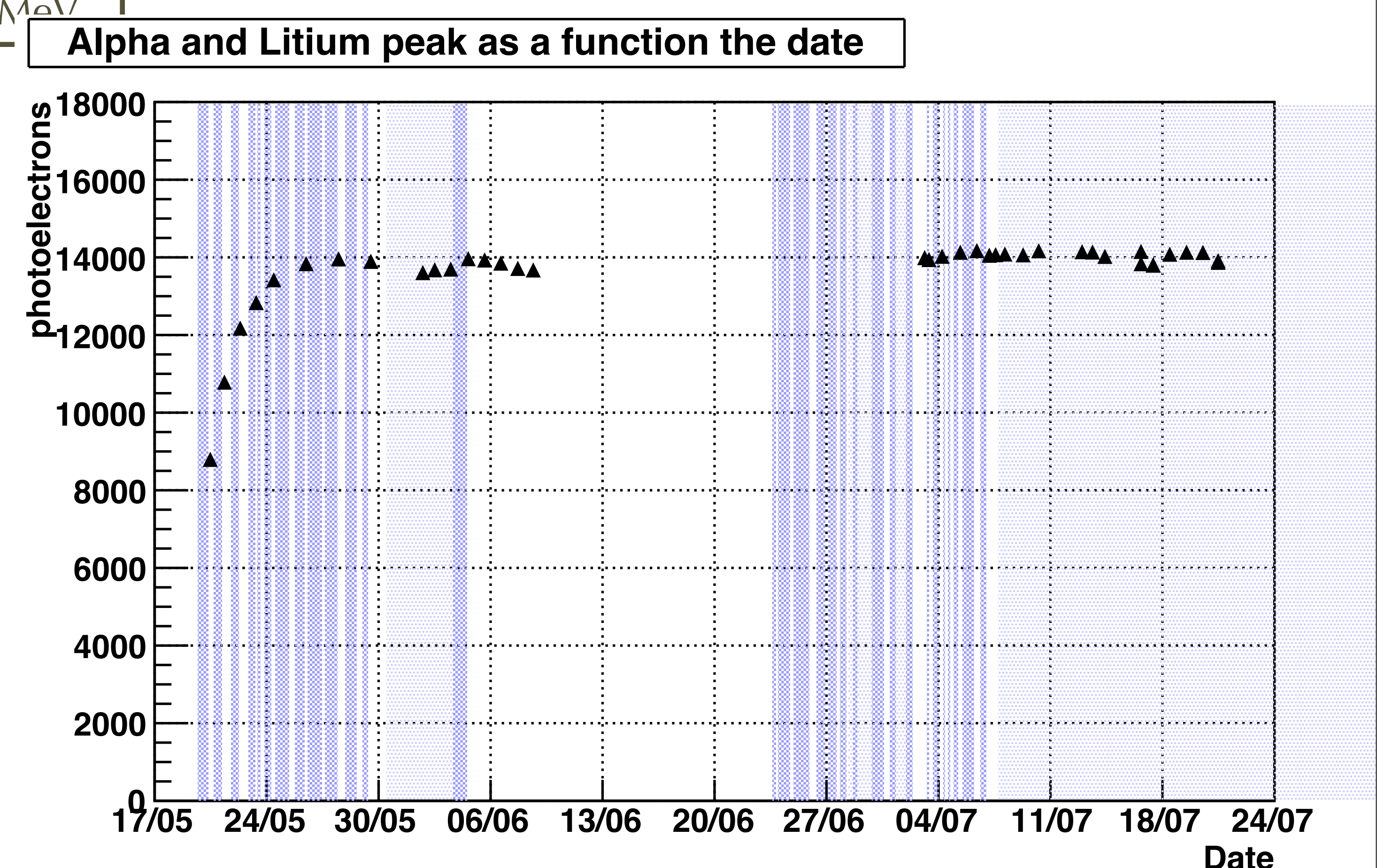


CW - daily calibration

- 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

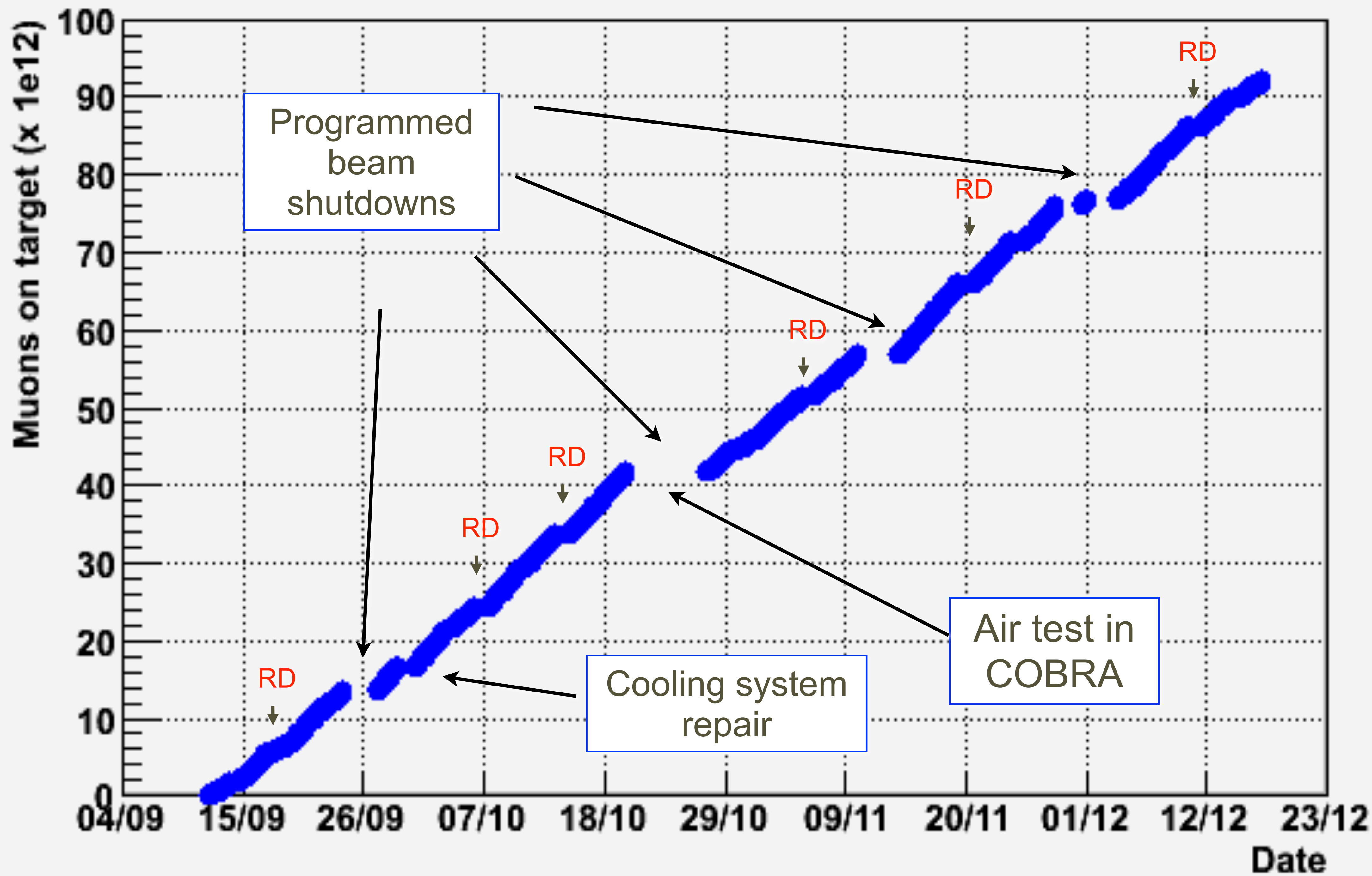
– Live time ~50% of total time
– Total time ~ 7×10^6 s
– μ stop rate: 3×10^7 μ/s
– Trigger rate 6.5 ev/s ; 9 MB/s

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



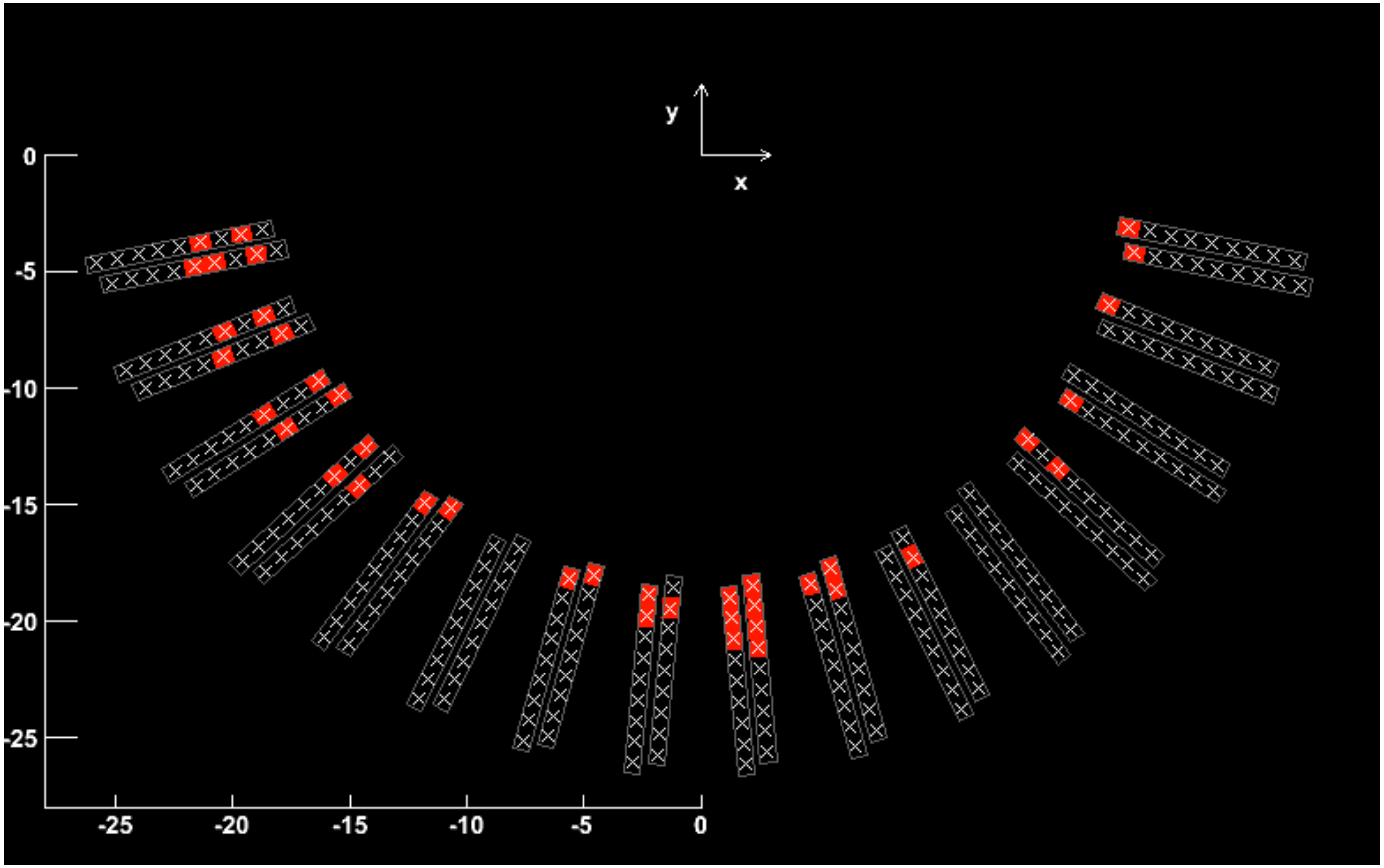
2008 run DCH instabilities

- 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

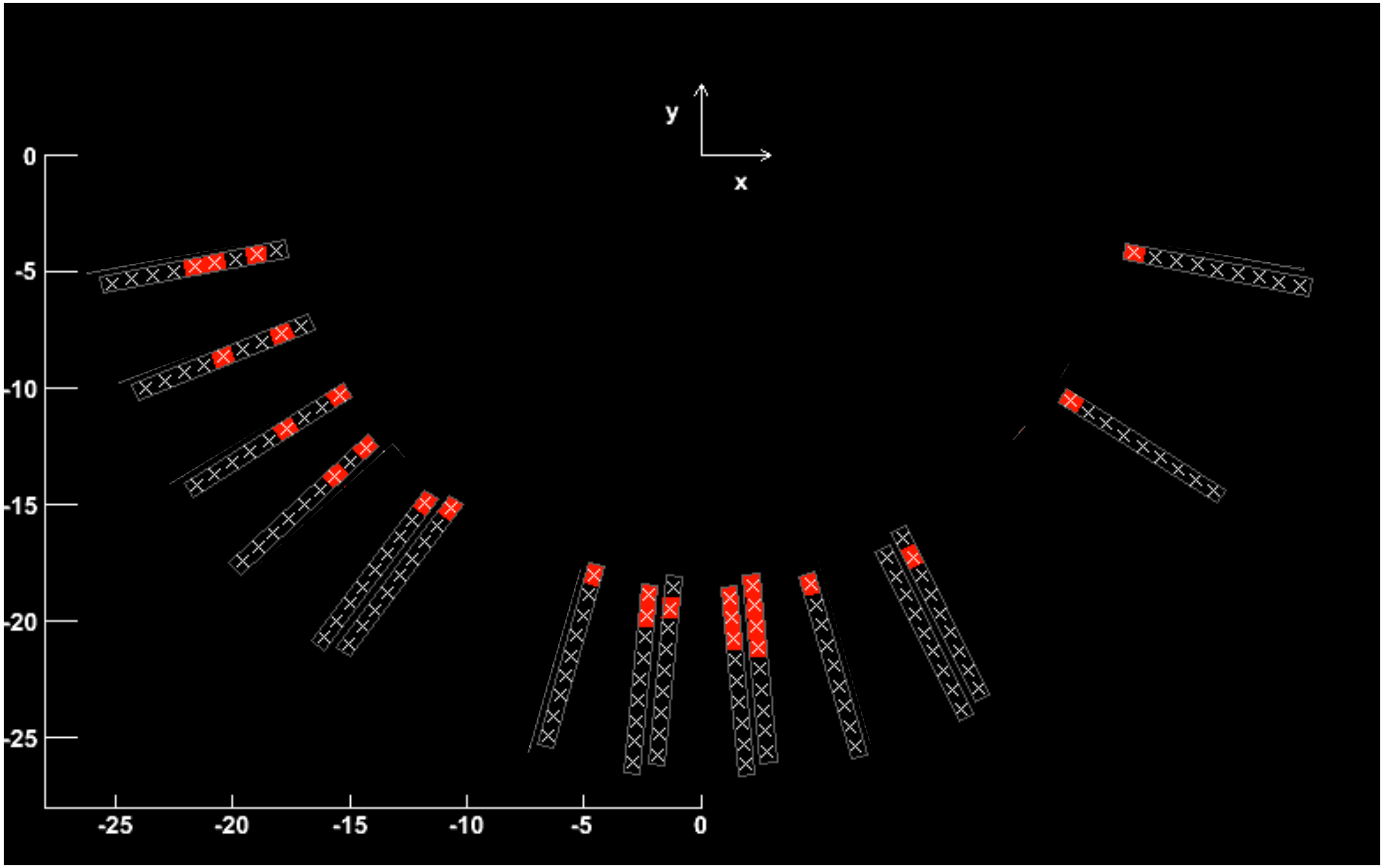
- The DCH modules have now been modified and have been successfully operated in the 2009 run

- HV spark reproduced in lab

Sep. 2008

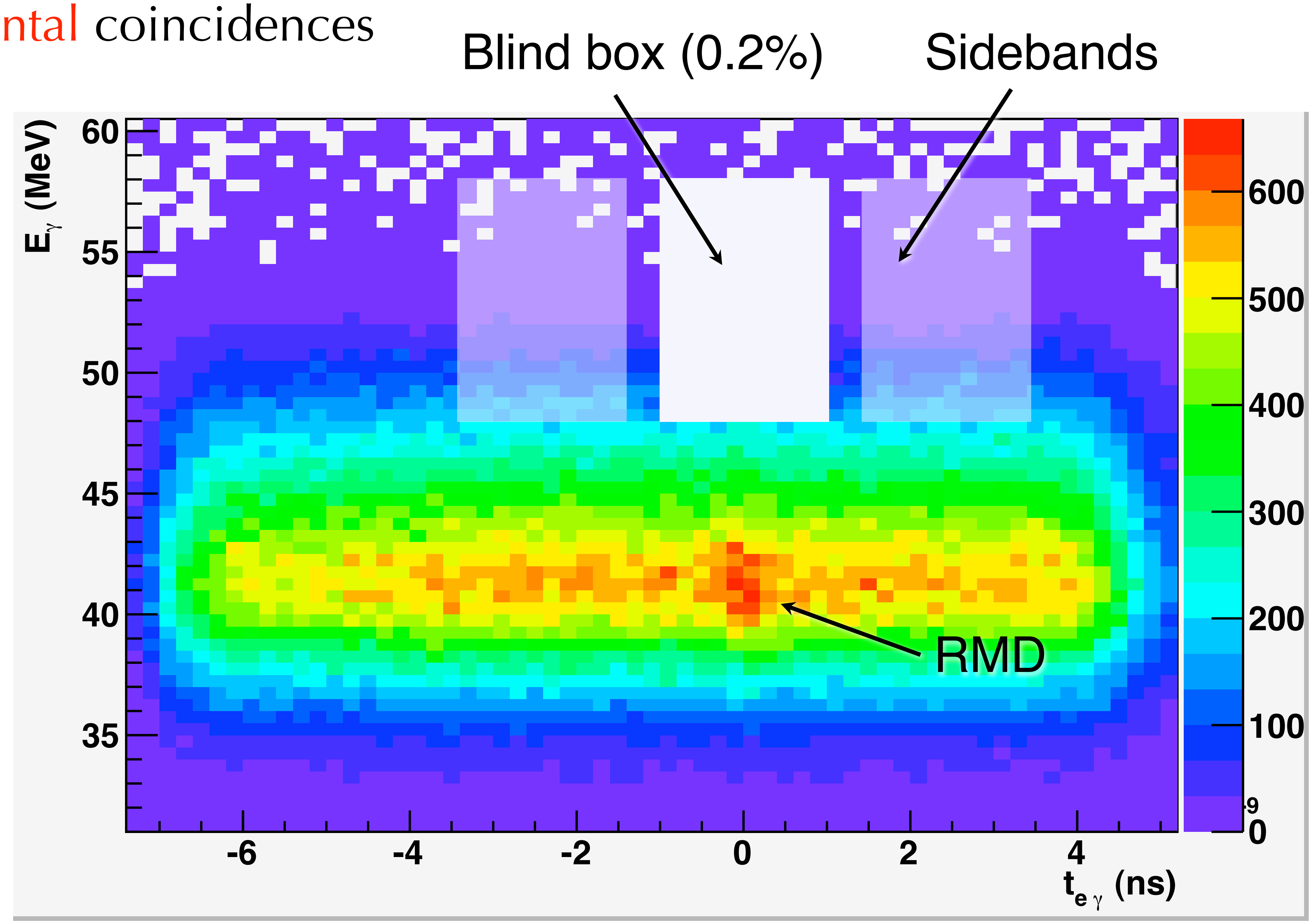


Dec. 2008



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

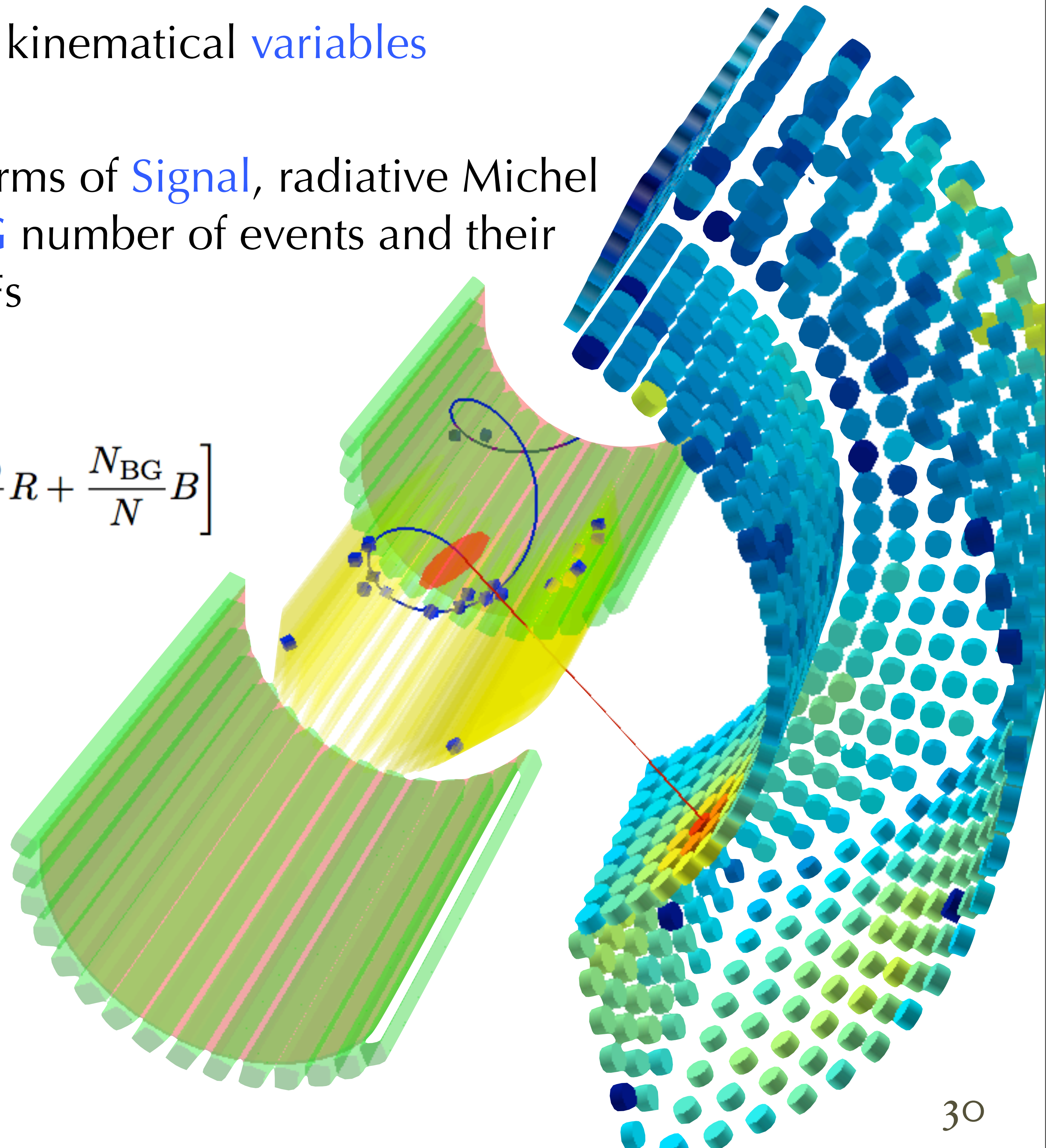


Analysis principle

- 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

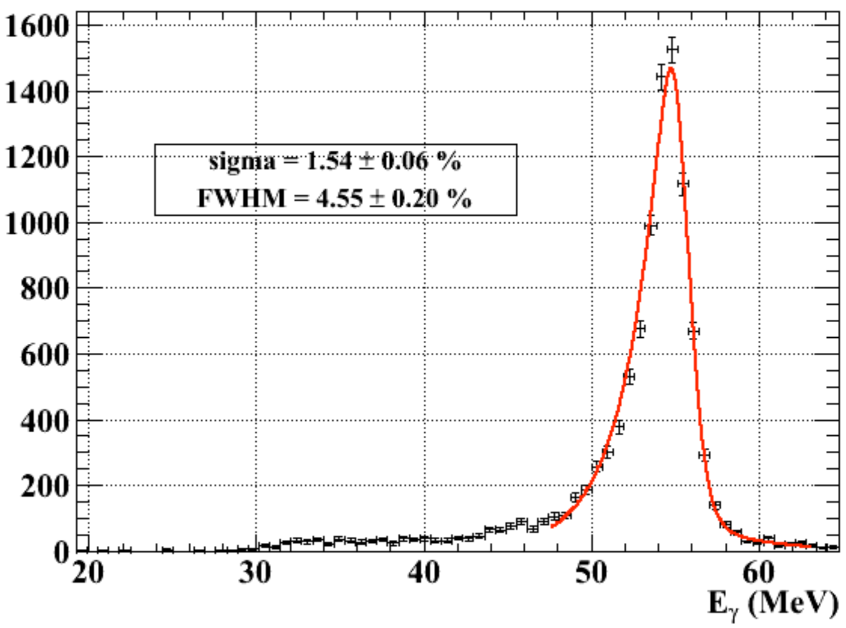
Alternative observables definition

1) different algorithm for LXe Timing

2) Trigger LXe waveform digitizing electronics (E_γ)

Some examples of *pdfs*

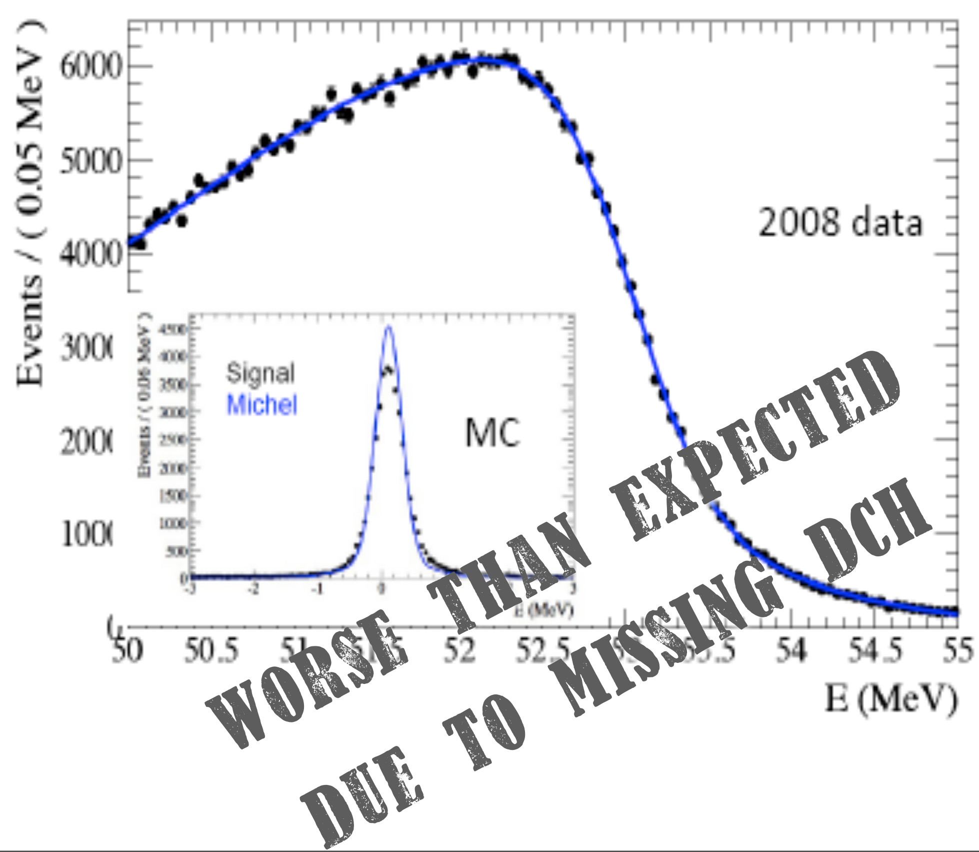
E_γ



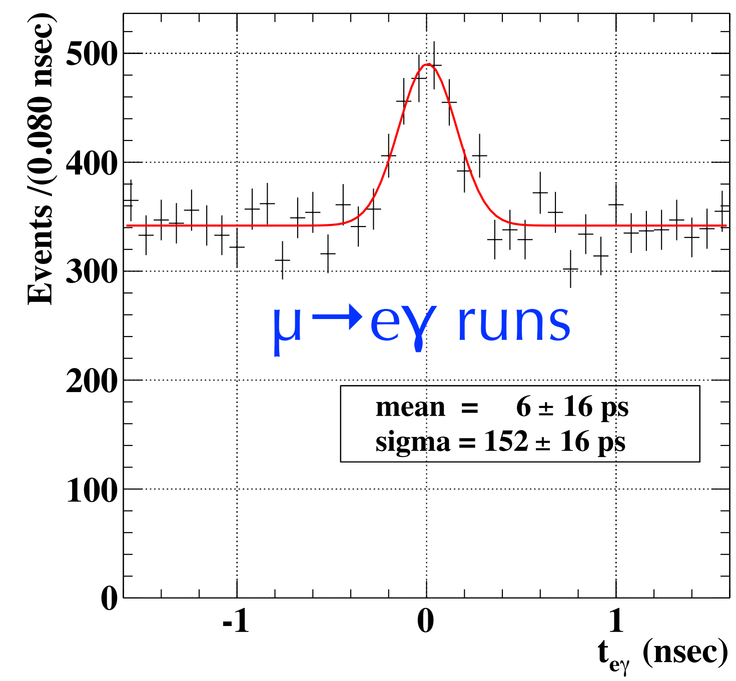
- Average upper tail for deep conversions
  - σ = 2.0 ± 0.15 %
- Systematic uncertainty on energy scale < 0.6%

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
  - σ(φ) = 10 mrad
  - σ(ϑ) = 18 mrad



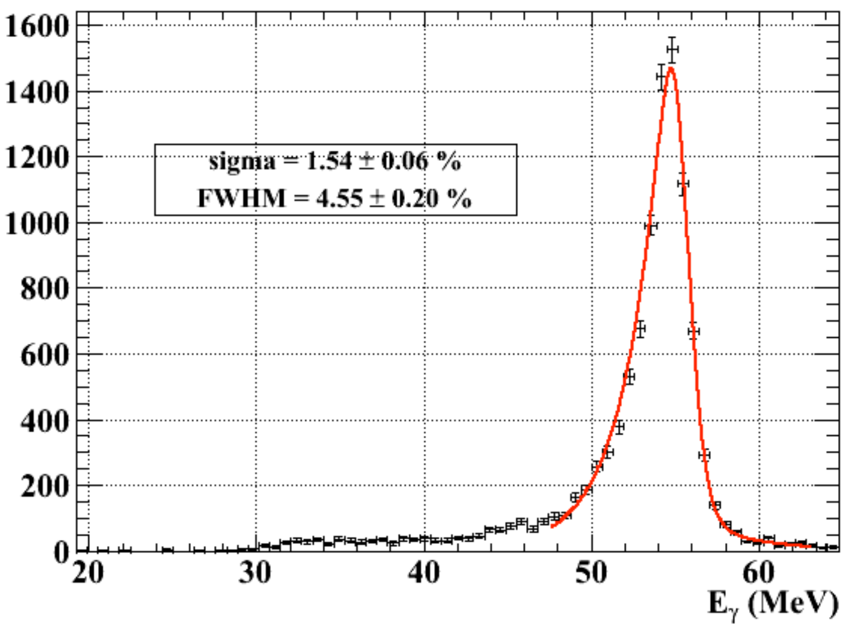
$t_{e\gamma}$



- 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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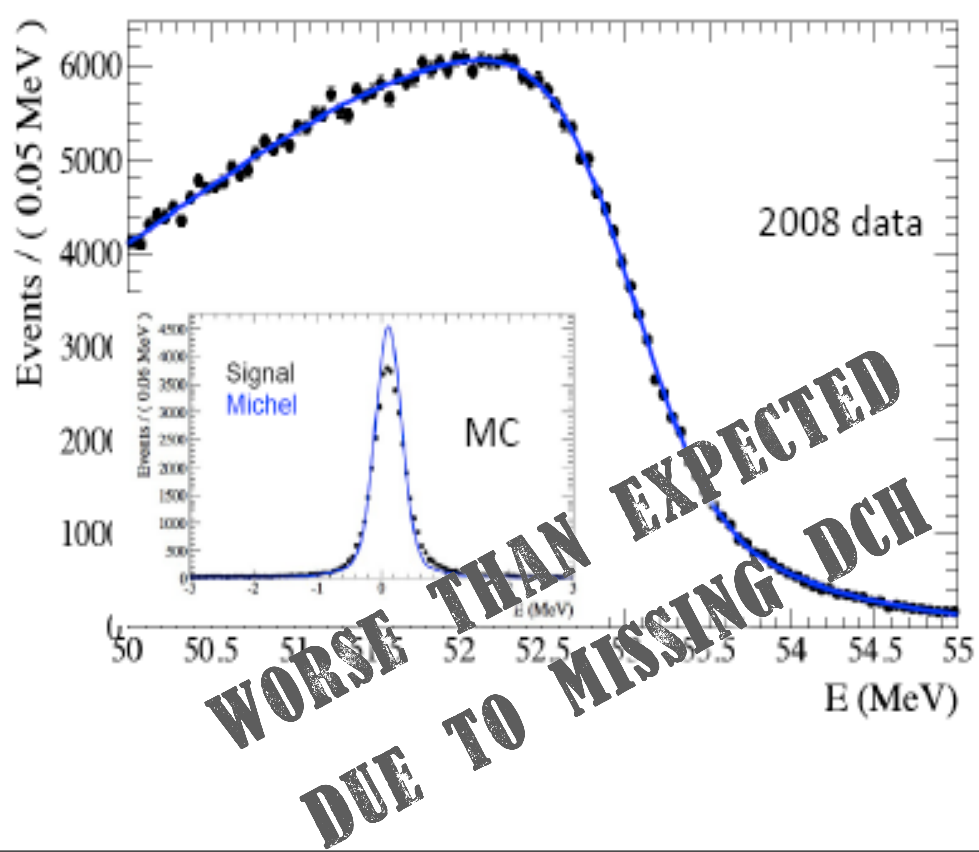
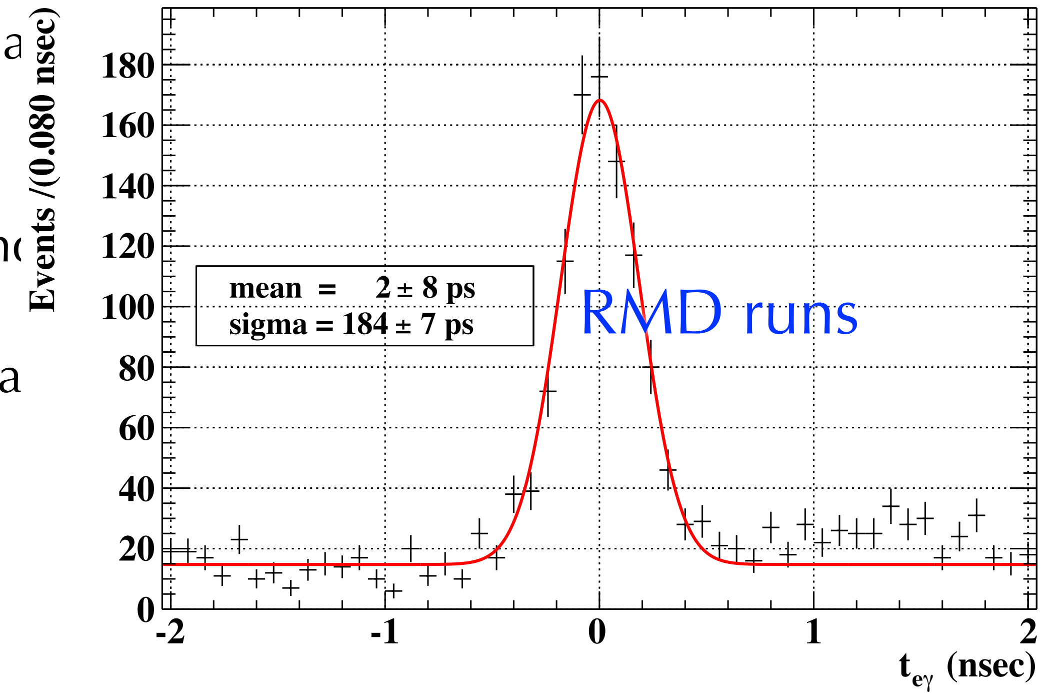
  - core = 374 keV (60%)
  - tail = 1.06 MeV (33%) anc (7%)
- Positron angle resolution mea multi-loop tracks
  - $\sigma(\varphi) = 10$ mrad
  - $\sigma(\vartheta) = 18$ mrad



$t_{e\gamma}$



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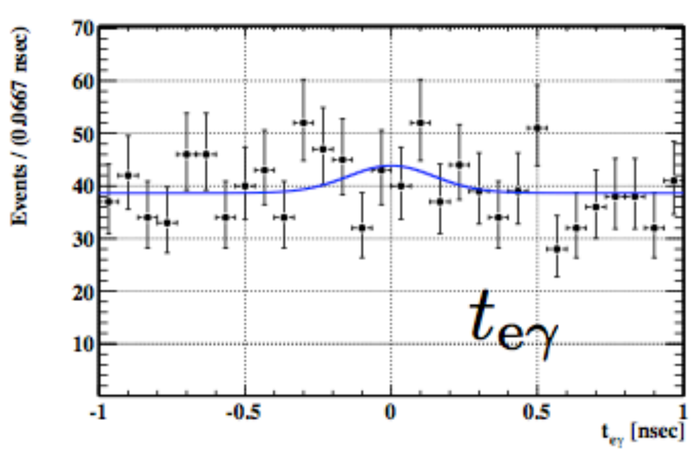
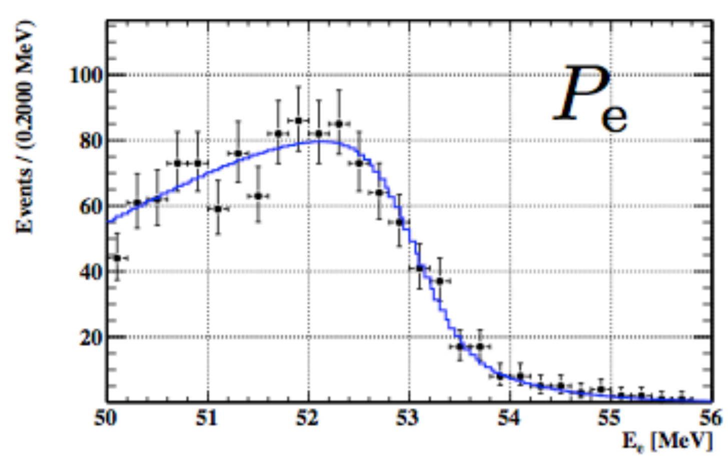
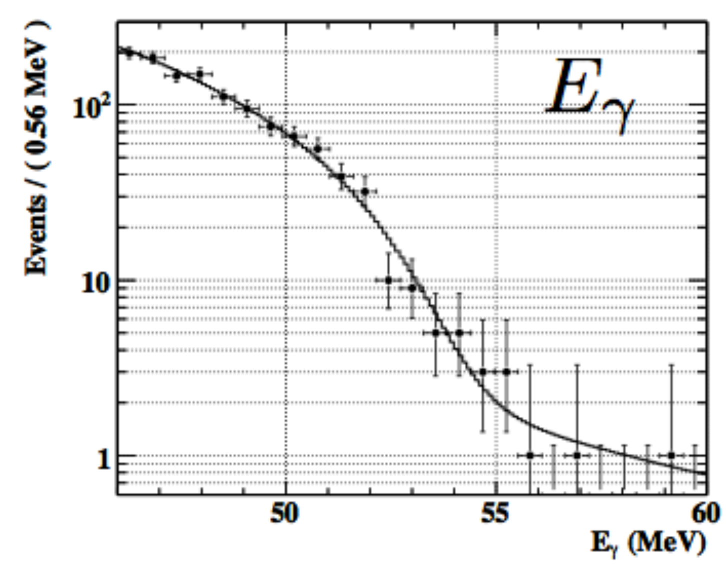
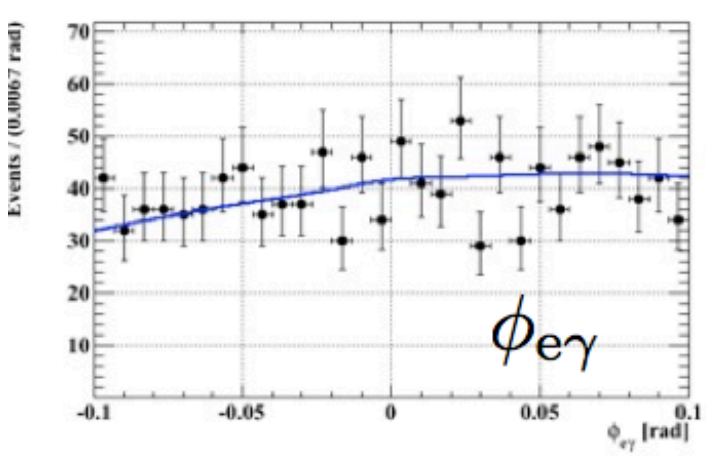
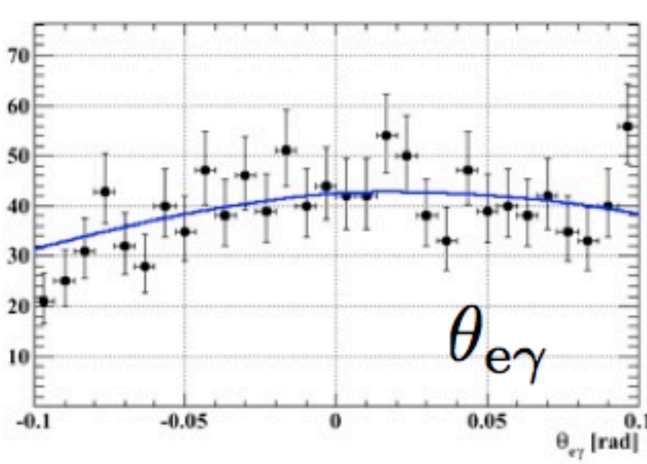










$N_{sig} < 14.7$ @90% CL

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

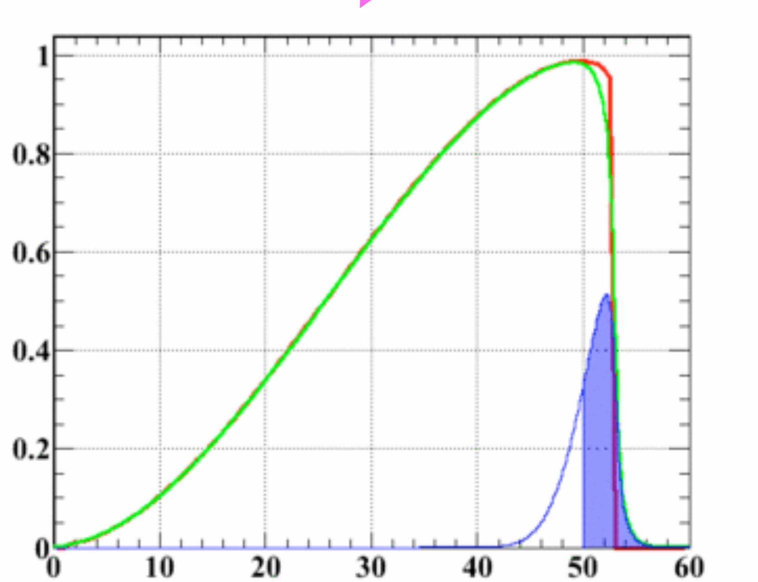
Normalization

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

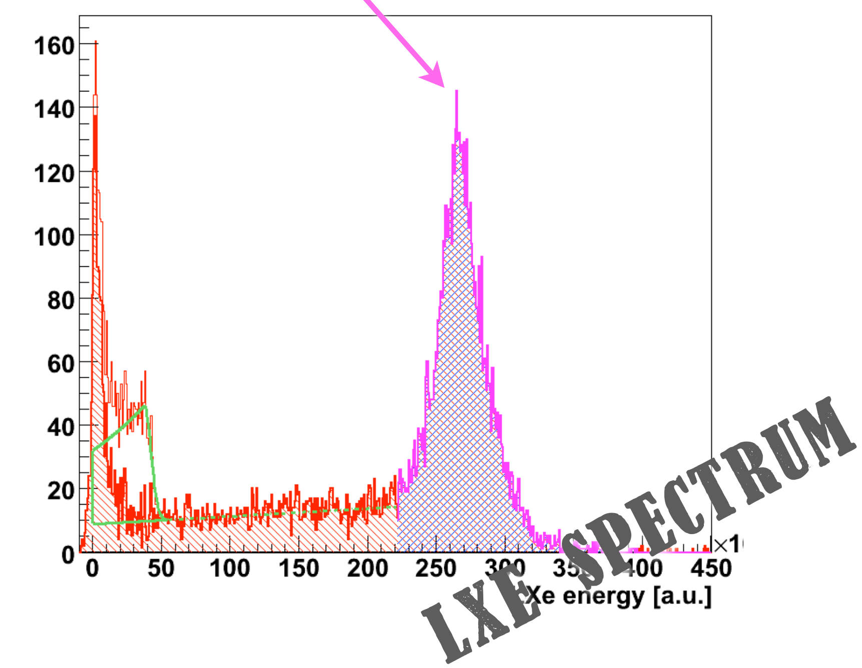
$$\mathrm{BR}(\mu^+ \to \mathrm{e}^+\gamma) = \frac{N_{\mathrm{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f^E_{e\nu\bar{\nu}}}{P} \times \frac{\epsilon^{trig}_{e\nu\bar{\nu}}}{\epsilon^{trig}_{e\gamma}} \times \frac{A^{TC}_{e\nu\bar{\nu}}}{A^{TC}_{e\gamma}} \times \frac{\epsilon^{DC}_{e\nu\bar{\nu}}}{\epsilon^{DC}_{e\gamma}}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

= ~1

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



theory
resolution
acceptance

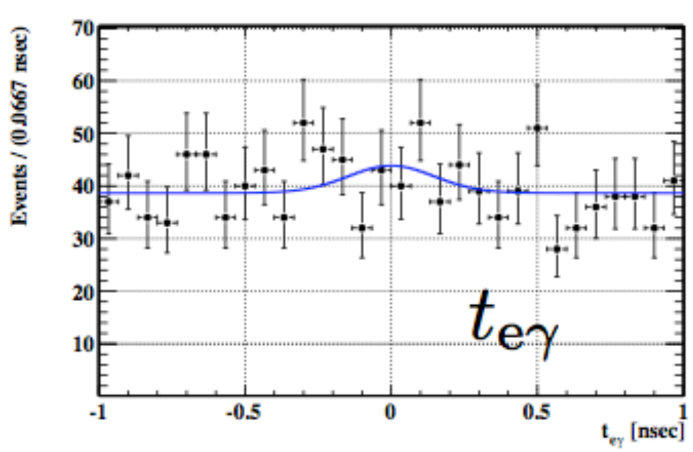


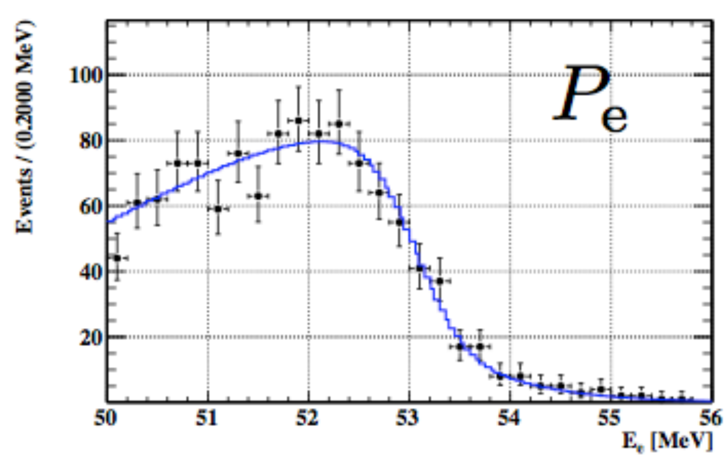
– $\varepsilon_{(\gamma)} = 0.61 \pm 0.03$, confirmed by π^o and RD spectra

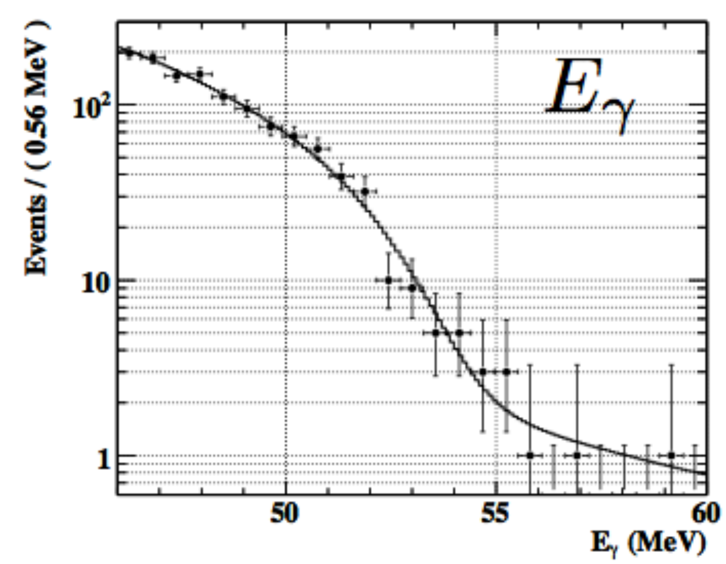
- Norm = $(2.0 \pm 0.2) \times 10^{-12}$

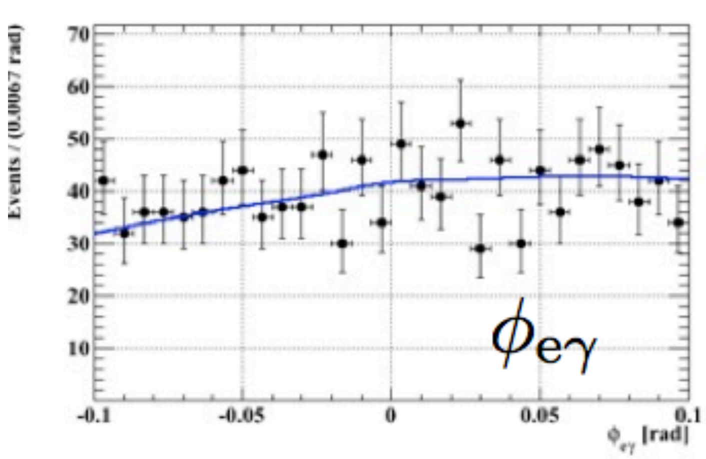
Likelihood fit

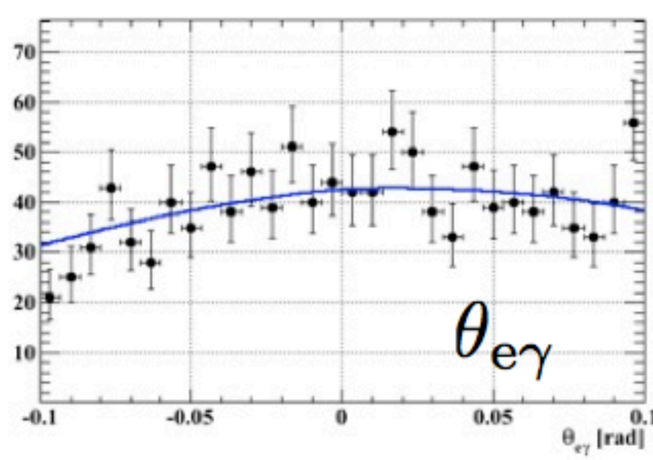
- A "Feldman-Cousins" approach was adopted for the likelihood analysis
  - The sensitivity (average expected 90% CL upper limit) on N_{sig} assuming no signal by means of toy MC:
    - BR < 1.3 x 10^{-11}
  - 90% CL upper limit from the sidebands
    - BR < (0.9 ÷ 2.1) x 10^{-11}











N_{sig} < 14.7 @90% CL

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

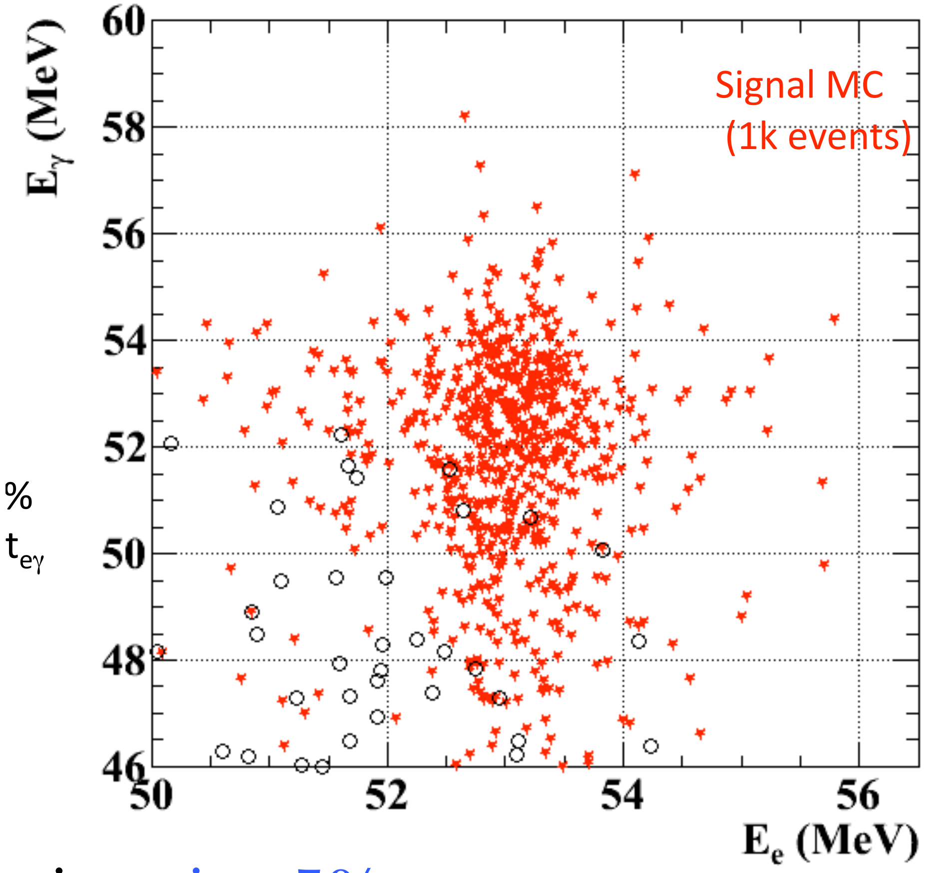
Result on BR

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

- 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)

%

$t_{e\gamma}$

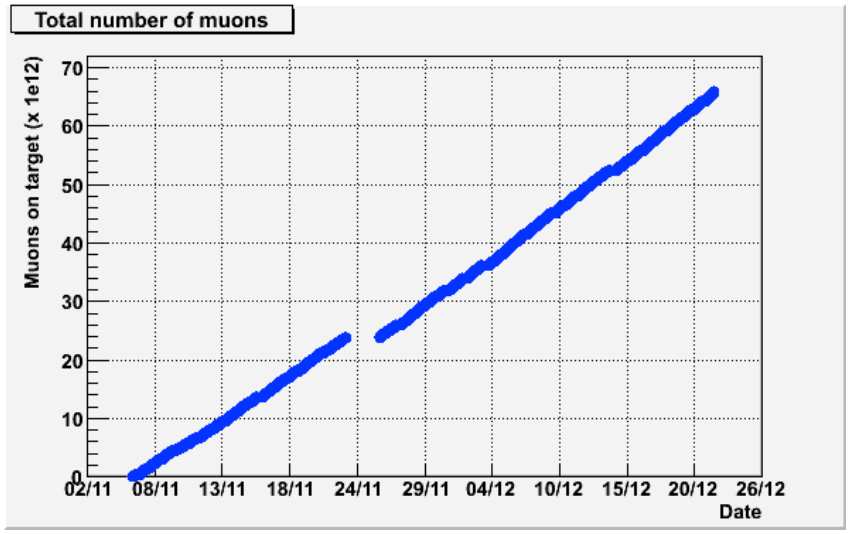


- ~2 times worse than expected sensitivity
- Probability of getting this result by statistical fluctuations is ~5%

- 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

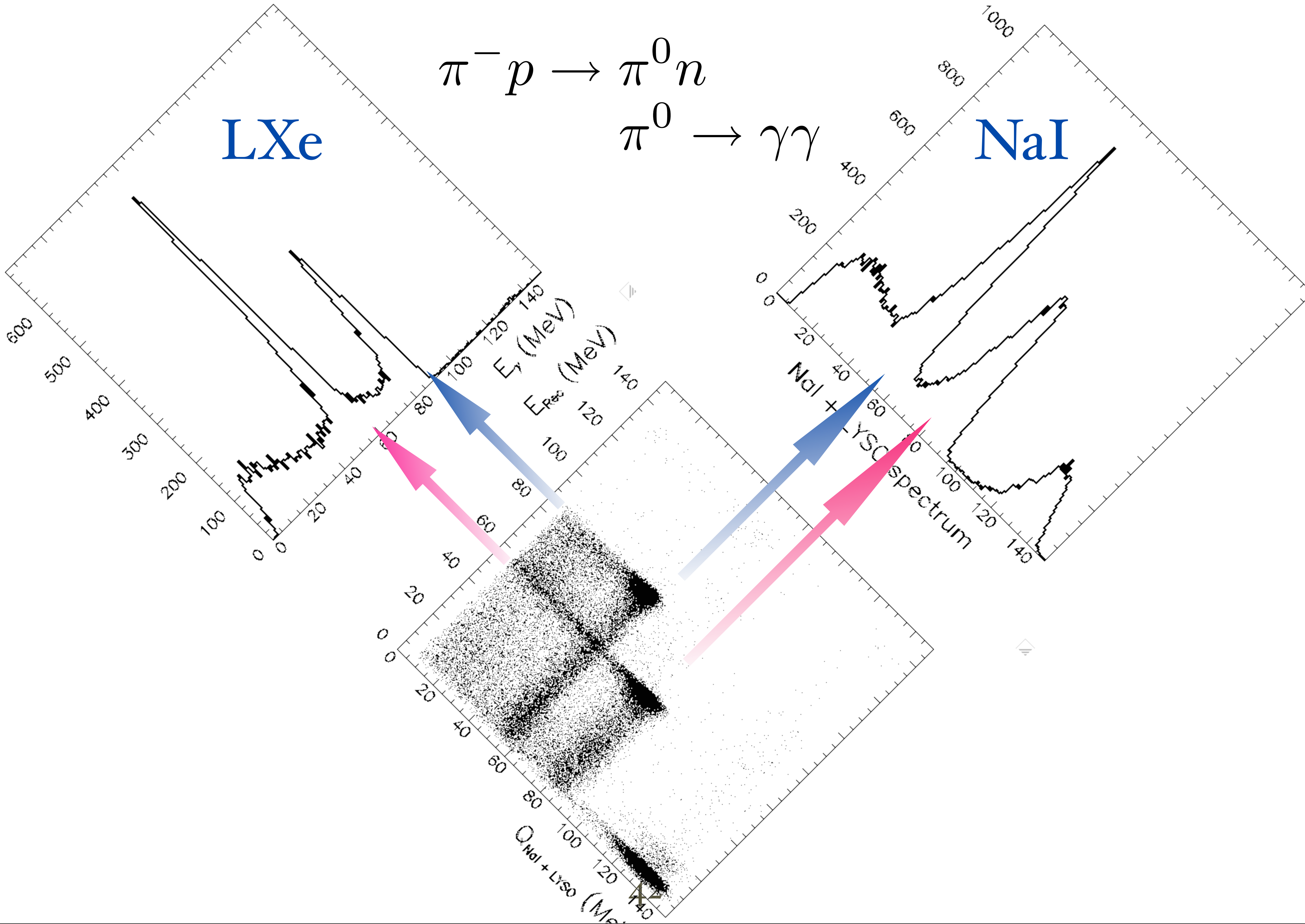
Thank you

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

Back-up slides

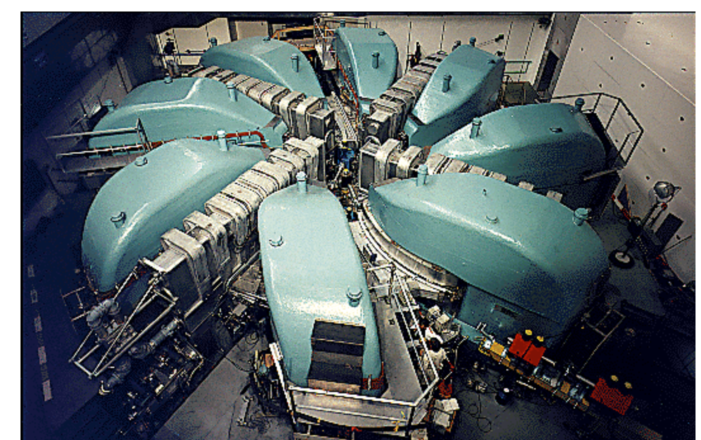
- In the back-to-back raw spectrum we see the correlation
  - 83 MeV ⇔ 55 MeV
  - The 129 MeV line is visible in the NaI because Xe is sensitive to neutrons (9 MeV)

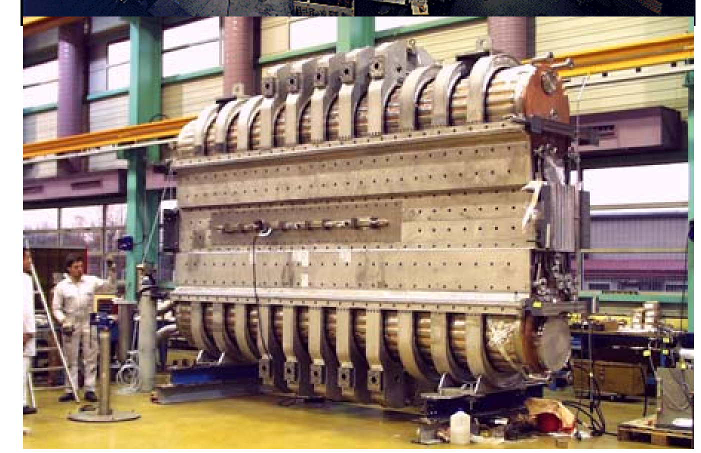
$$\pi^- p \rightarrow \pi^0 n$$
$$\pi^0 \rightarrow \gamma\gamma$$

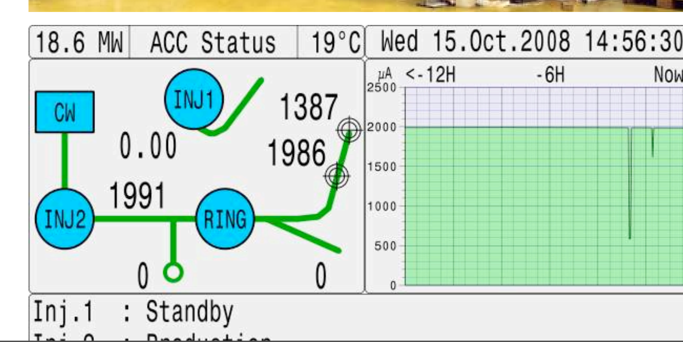


Machine

- “Sensitivity” proportional to the number of muons observed
- Find the most intense (continuous) muon beam: Paul Scherrer Institut (CH)
- 1.6 MW proton accelerator
  - 2 mA of protons - towards 3 mA (replace with new resonant cavities)!
  - extremely stable
  - > 3 x 10^8 muons/sec @ 2 mA

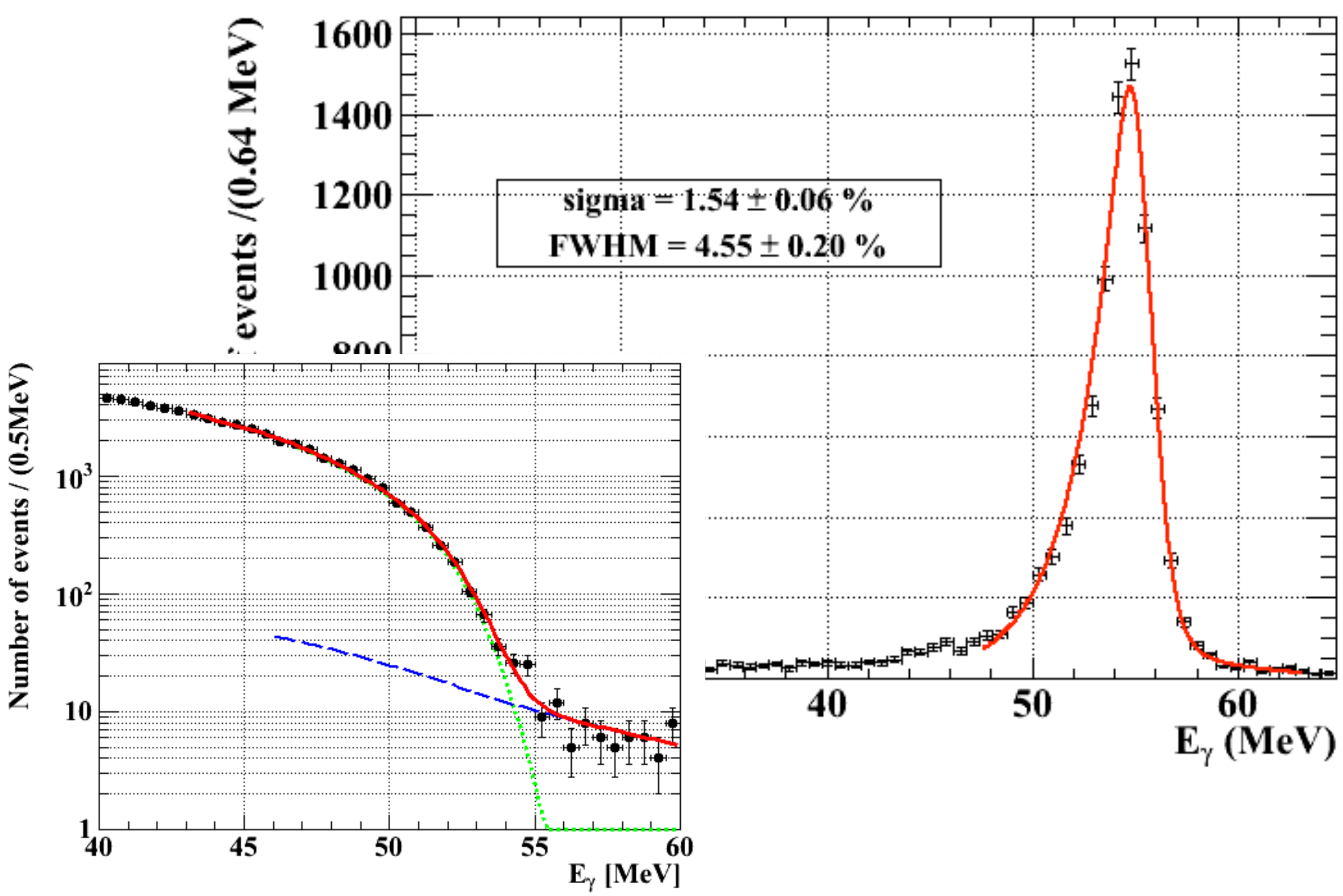


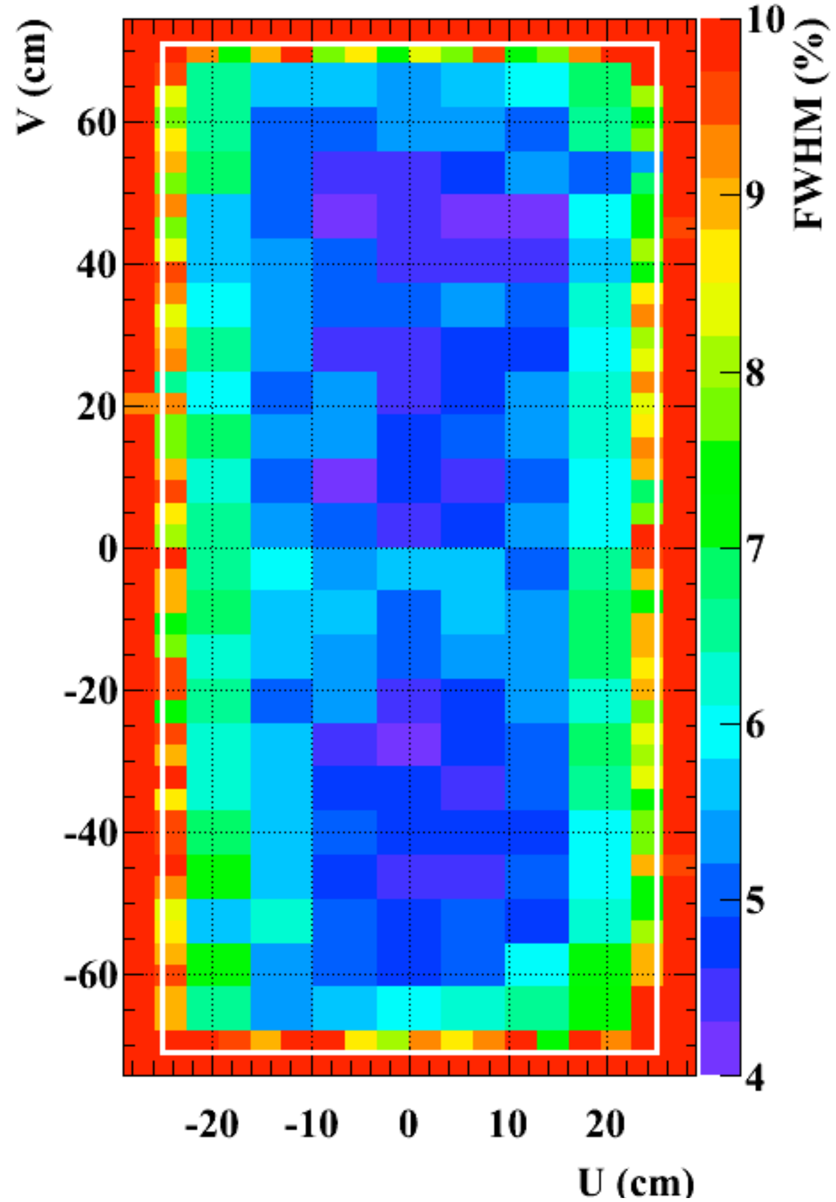




Some examples: γ-ray energy

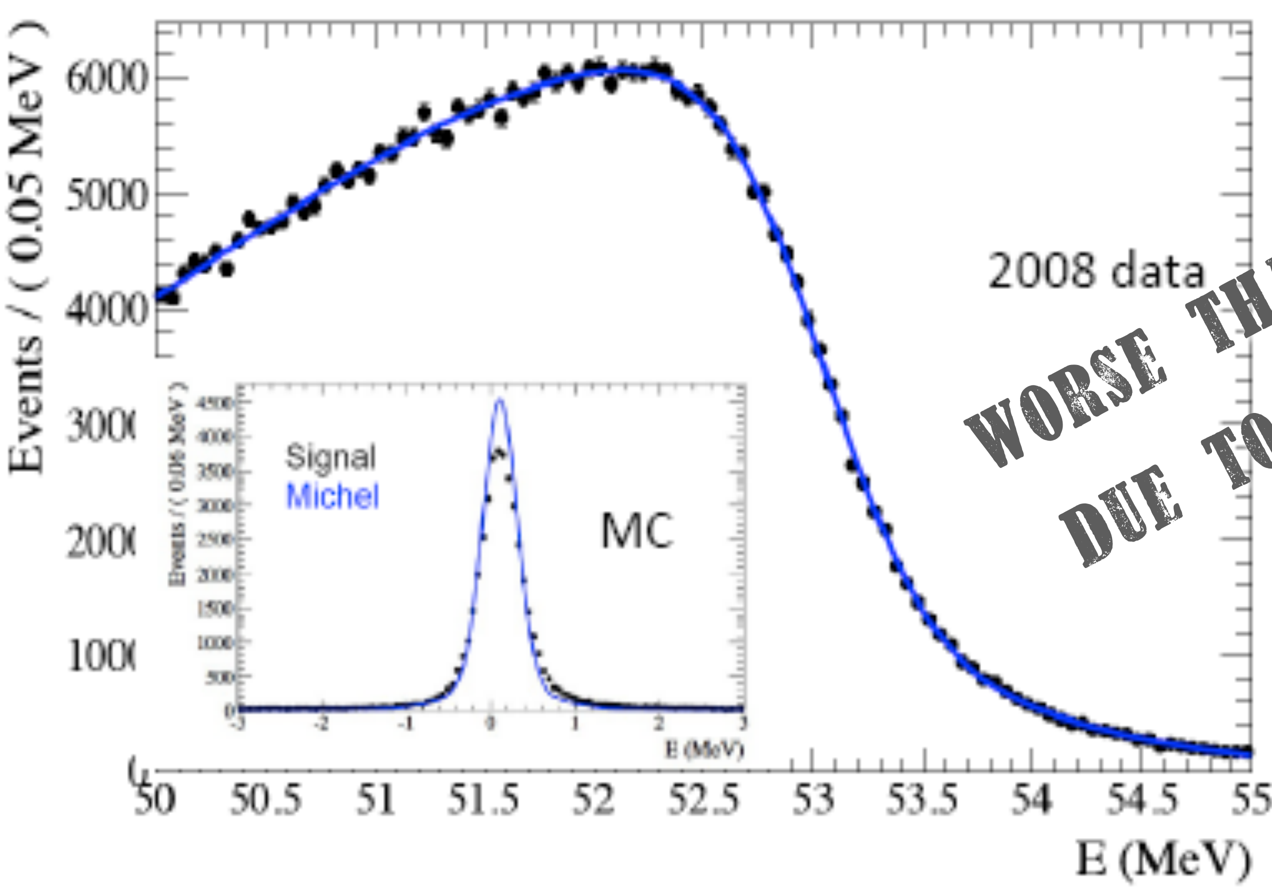
- The energy resolution and energy scale is extracted by the CEX data (55 MeV photons)
  - verified by RMD (+AIF) spectrum
- Average upper tail for deep conversions
  - σ = 2.0 ± 0.15 %
- Systematic uncertainty on energy scale < 0.6%

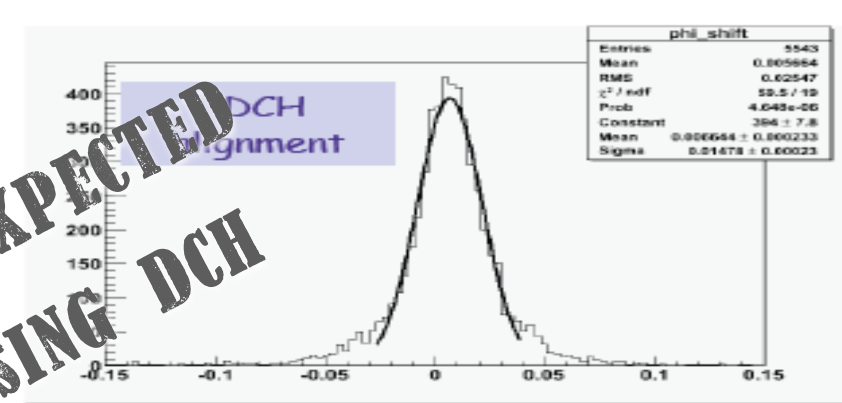


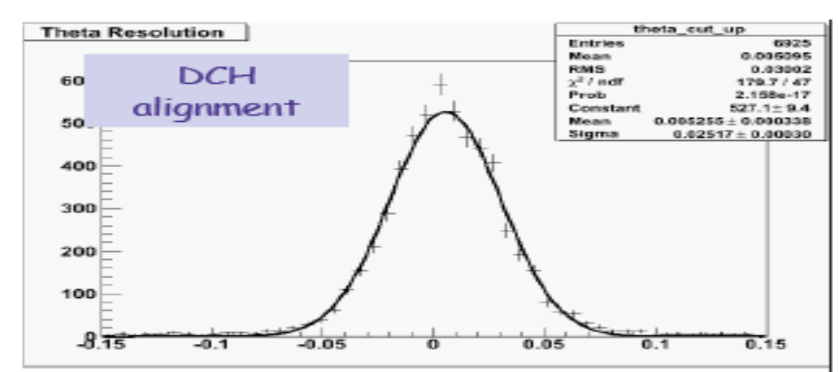


Positron momentum

- e^+ energy scale and resolution are evaluated by fitting the kinematic edge of the Michel positron spectrum at 52.8 MeV
- 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

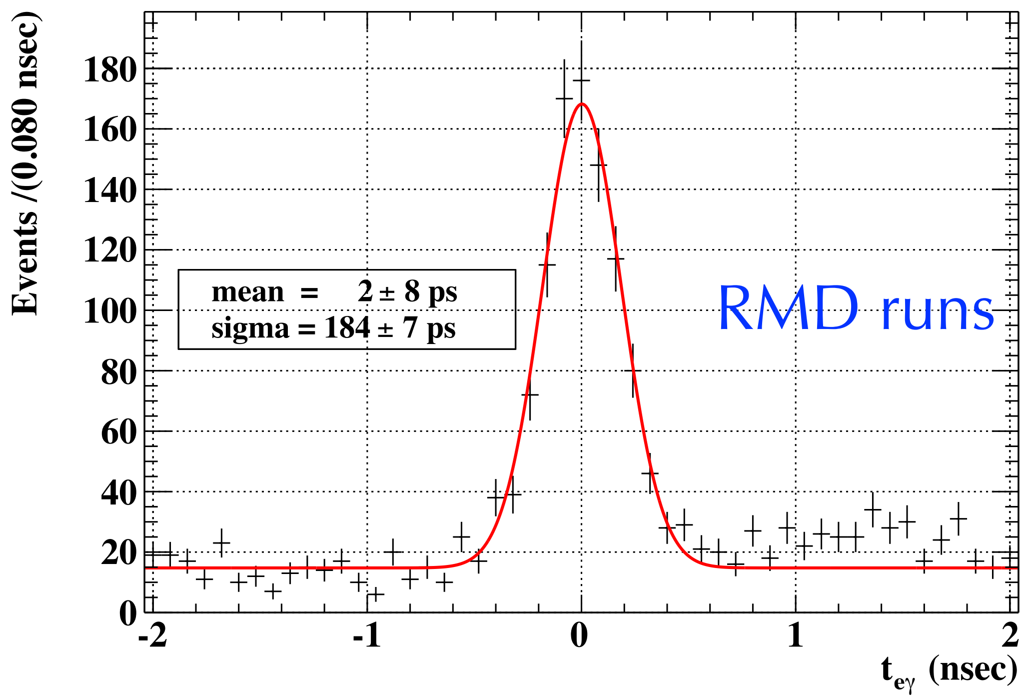


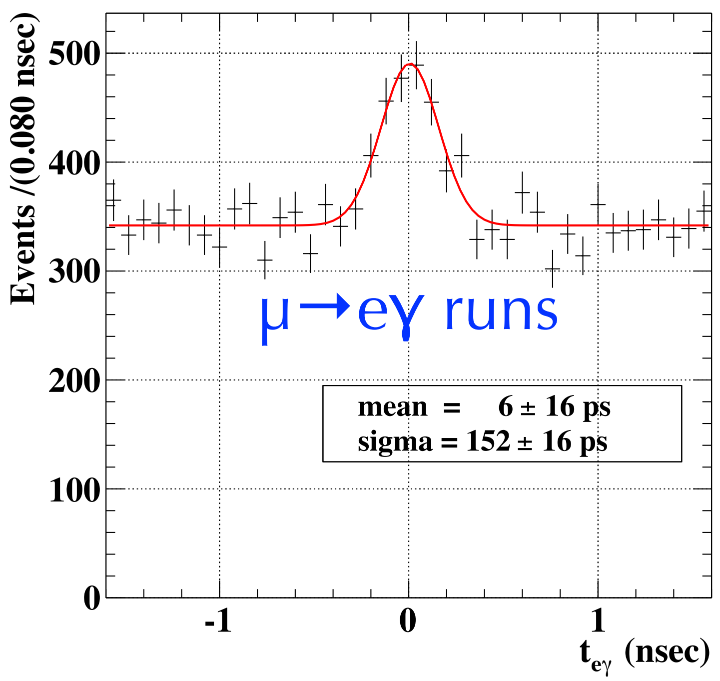




Relative time resolution

- Quote directly the $t_{e\gamma}$ from RMD resolution (recall: MEGA 700 ps) $\mu \to e\bar{\nu}\nu\gamma$
  - e^+ time from TC and corrected by ToF (DCH trajectory)
  - LXe time corrected by ToF to the conversion point
-



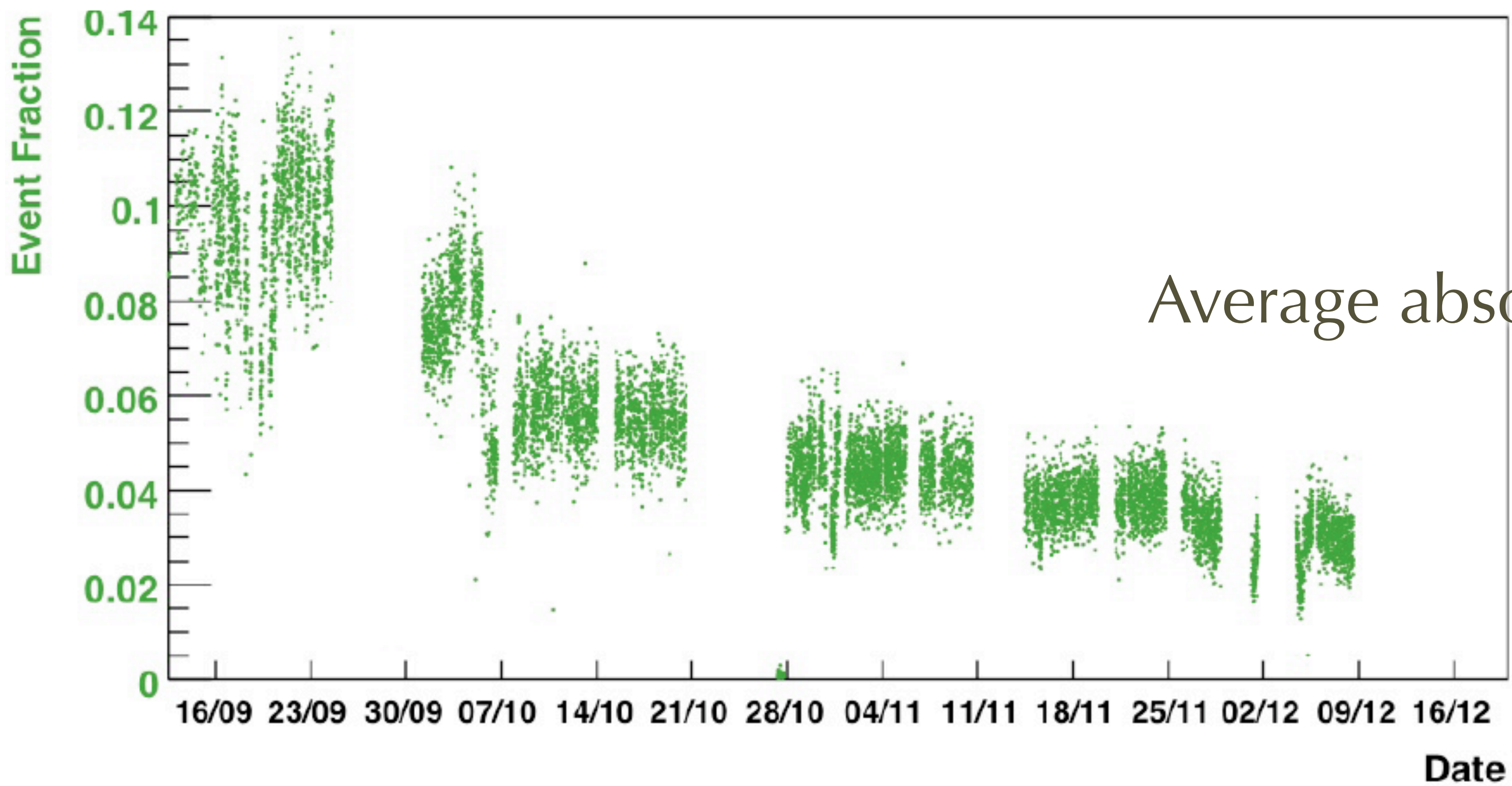


- σ_t is corrected for a small energy-dependence
  - (148 ± 17) ps
  - stable within 20 ps along the run

Normalization

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

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



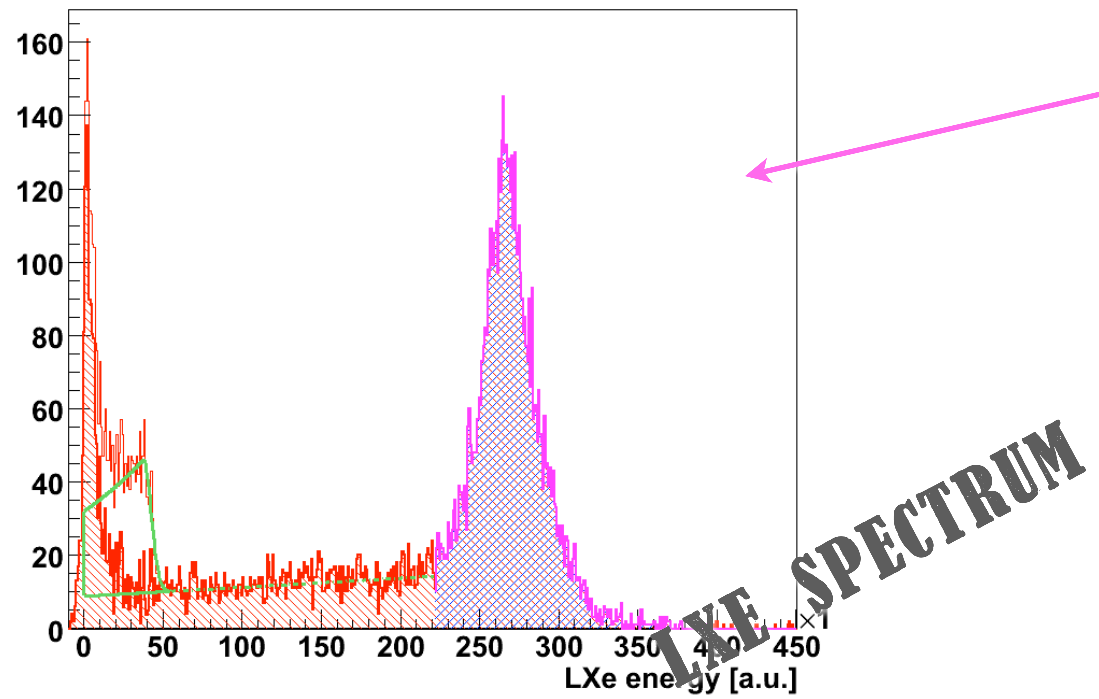
Average absolute efficiency > 30%

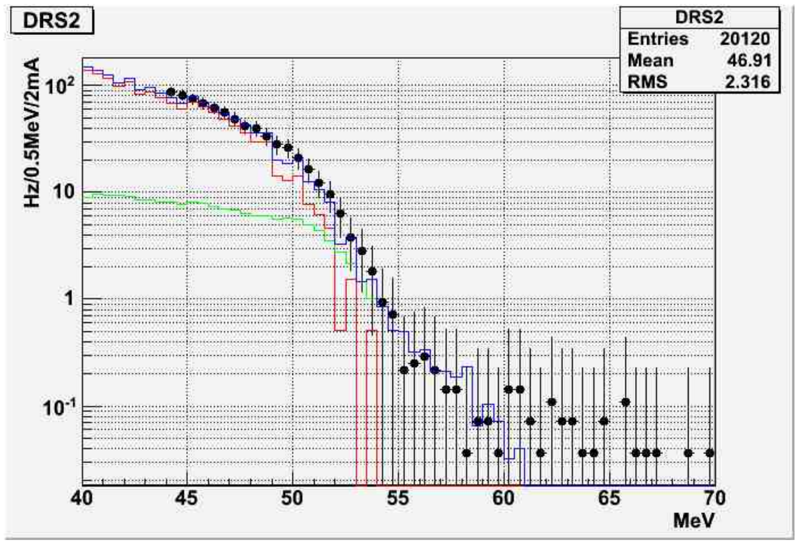
- The fraction of events with at least one reconstructed track at high momentum is a measure of relative tracking efficiency

Normalization

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

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

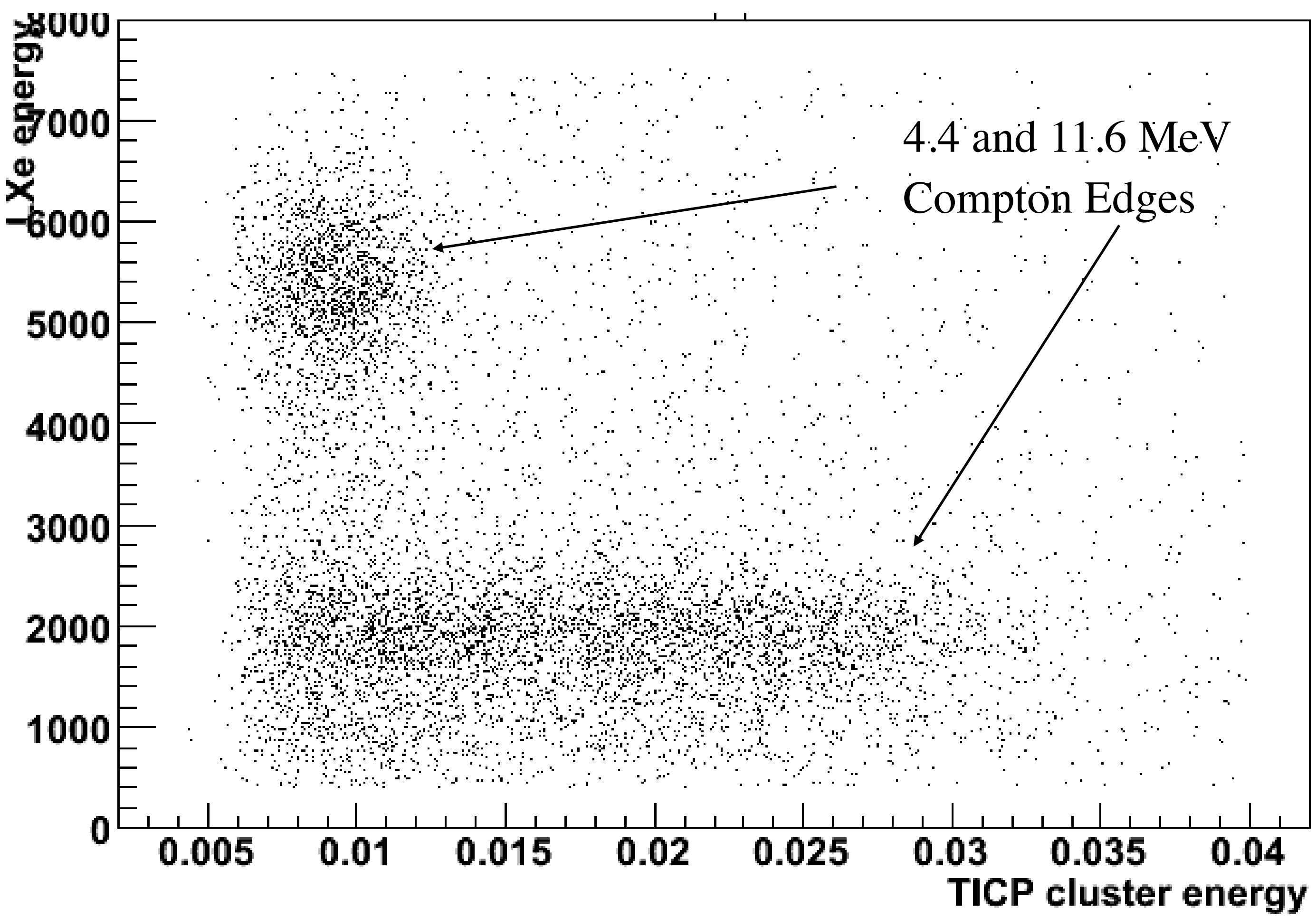


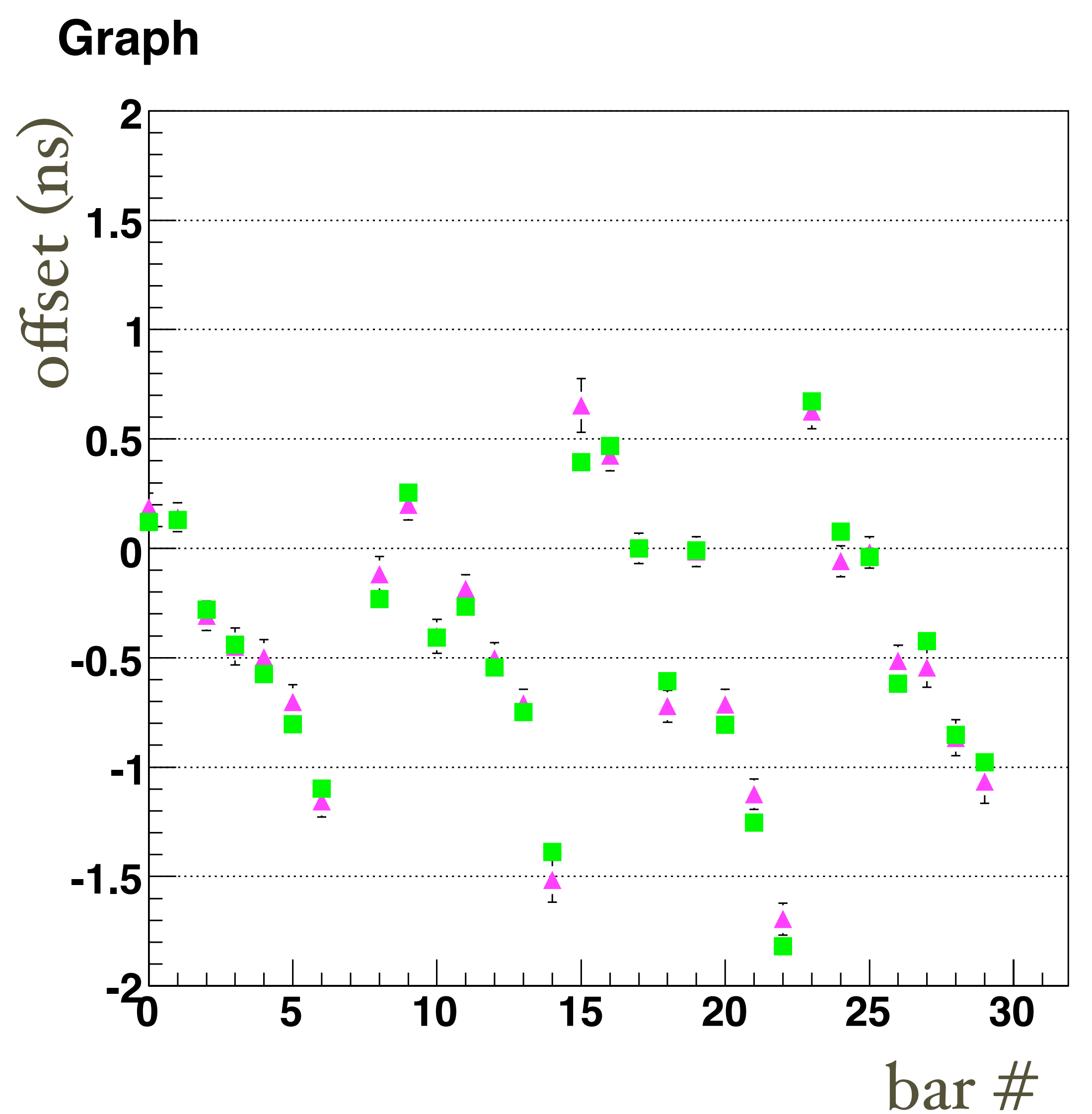


- The probability to detect a signal γ-ray computed using the MC simulation:
  - corrected for smeasing and acceptance
    - $\varepsilon_{(\gamma)} = 0.61 \pm 0.03$, confirmed by π^o and RD spectra
- Norm = $(2.0 \pm 0.2) \times 10^{-12}$

CW and timing counter

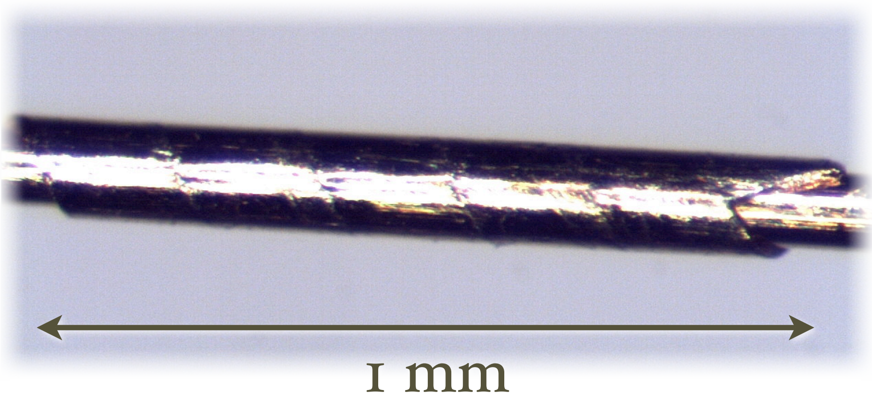
- The simultaneous emission of two photons in the Boron reaction is used to
  - determine relative timing between Xe and TIC
  - Inter-calibrate TIC bar

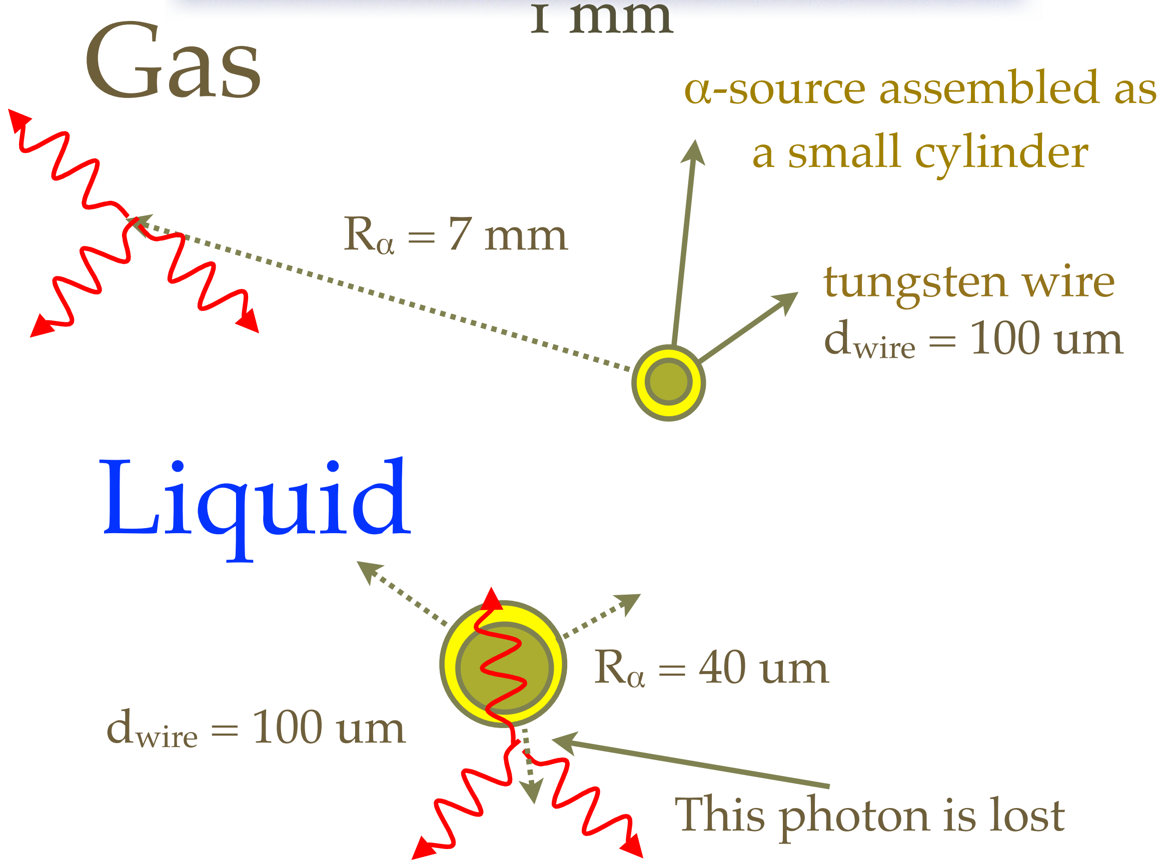


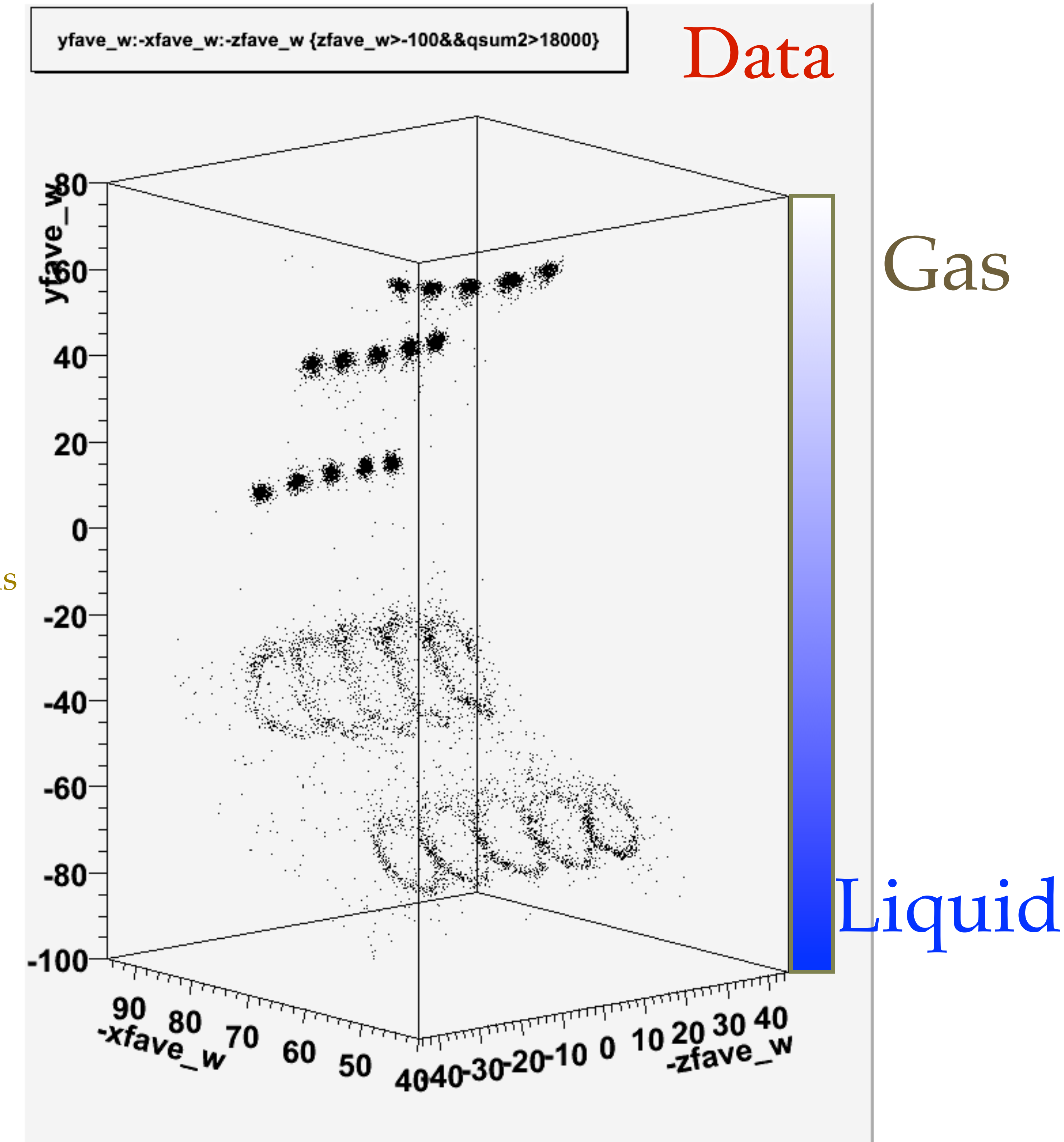


Example: α-sources in Xe

- Specially developed Am sources:
  - 5 dot-sources on thin (100 μm) tungsten wires
  - SORAD Ltd. (Czech Republic)

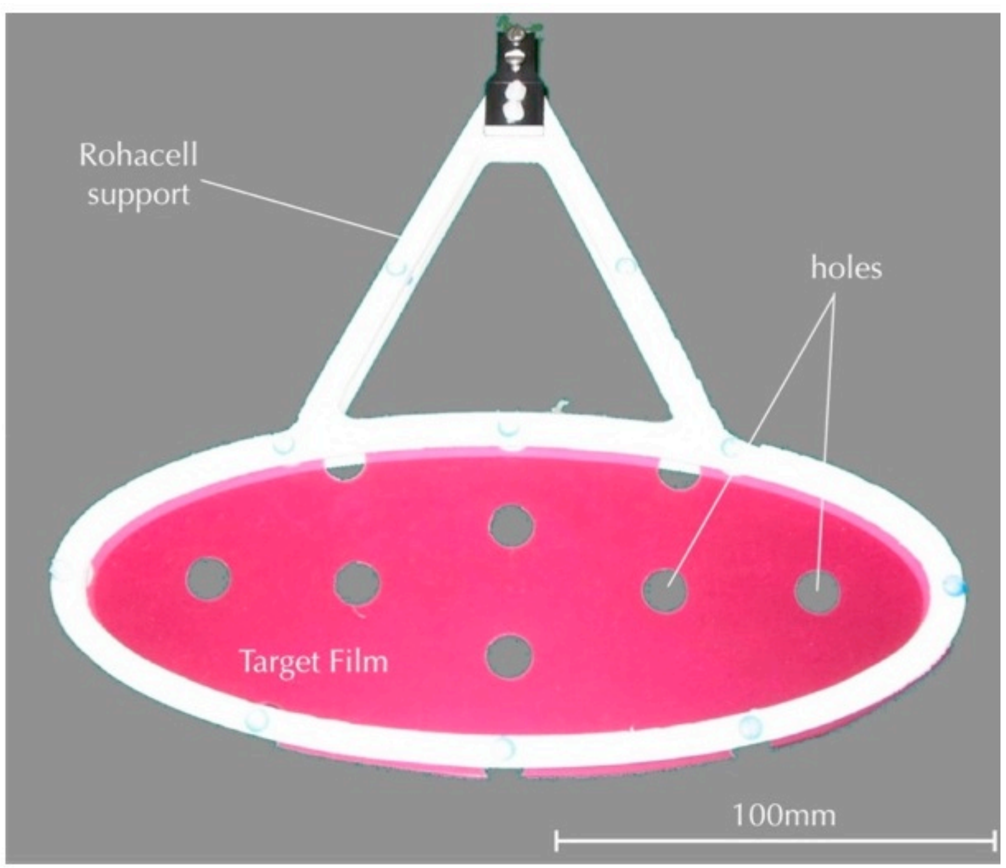






Target

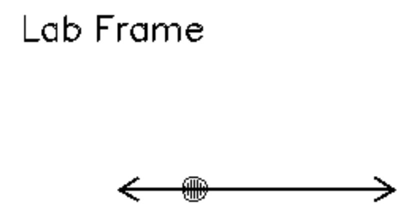
- Stop muons on the thinnest possible target 175 μm CH_2:
  - need low energy muons (lots of multiple scattering) but...
  - the MS of the decaying positron is minimized: precise direction/ timing
  - bremsstrahlung reduced
  - the conversion probability of the photon in the target is negligible

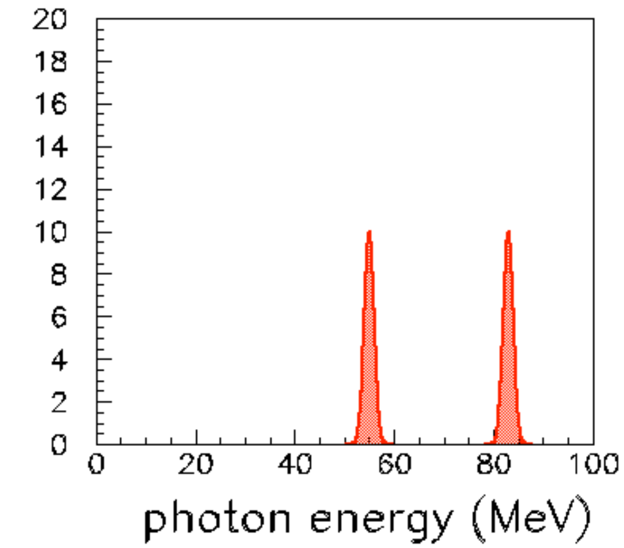


Holes to study position reconstruction resolution

CEX measurement

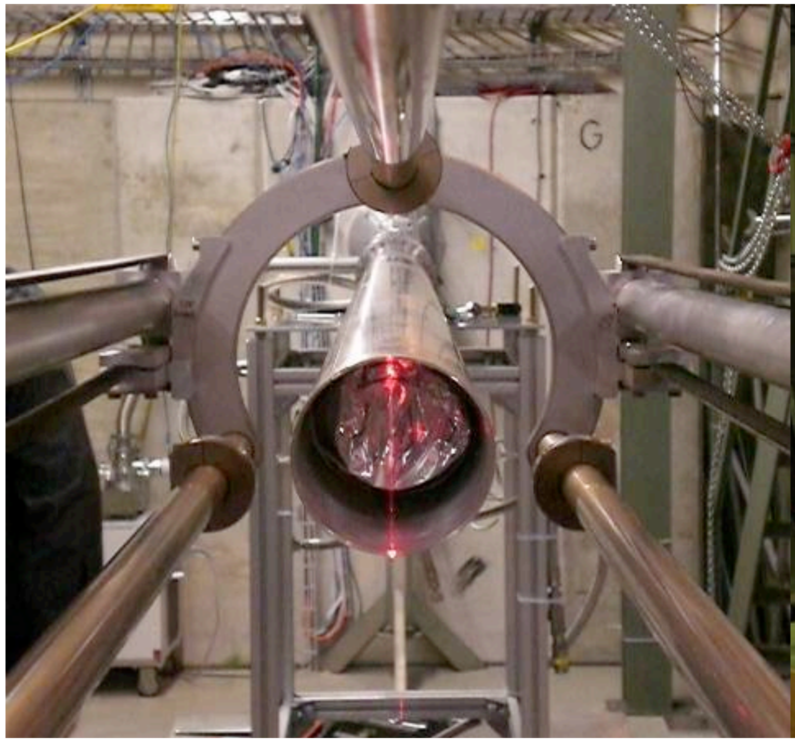
$$\pi^- p \to \pi^0 n$$
$$\pi^0 \to \gamma\gamma$$



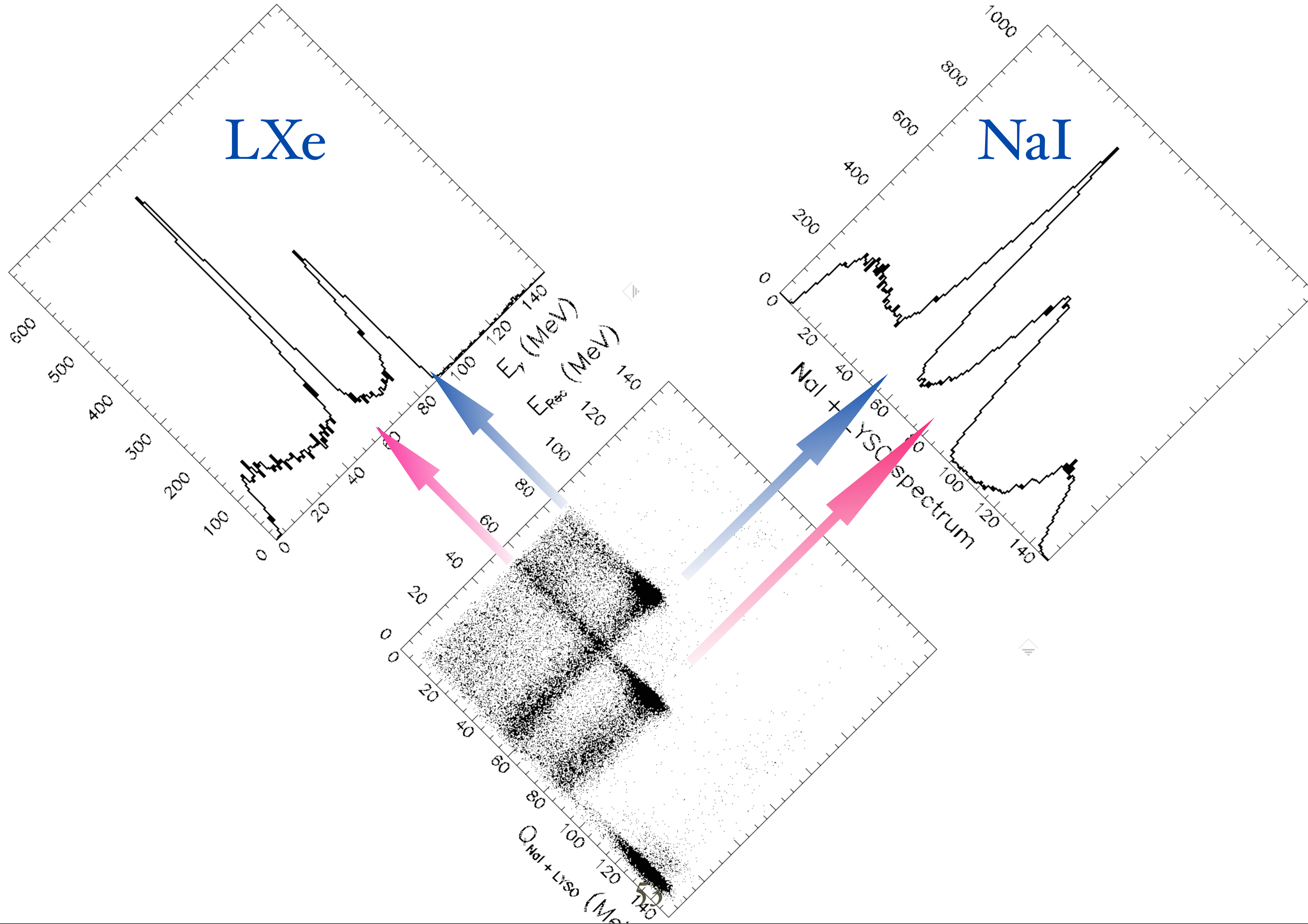


- The monochromatic spectrum in the pi-zero rest frame becomes flat in the Lab
- In the back-to-back configuration the energies are 55 MeV and 83 MeV

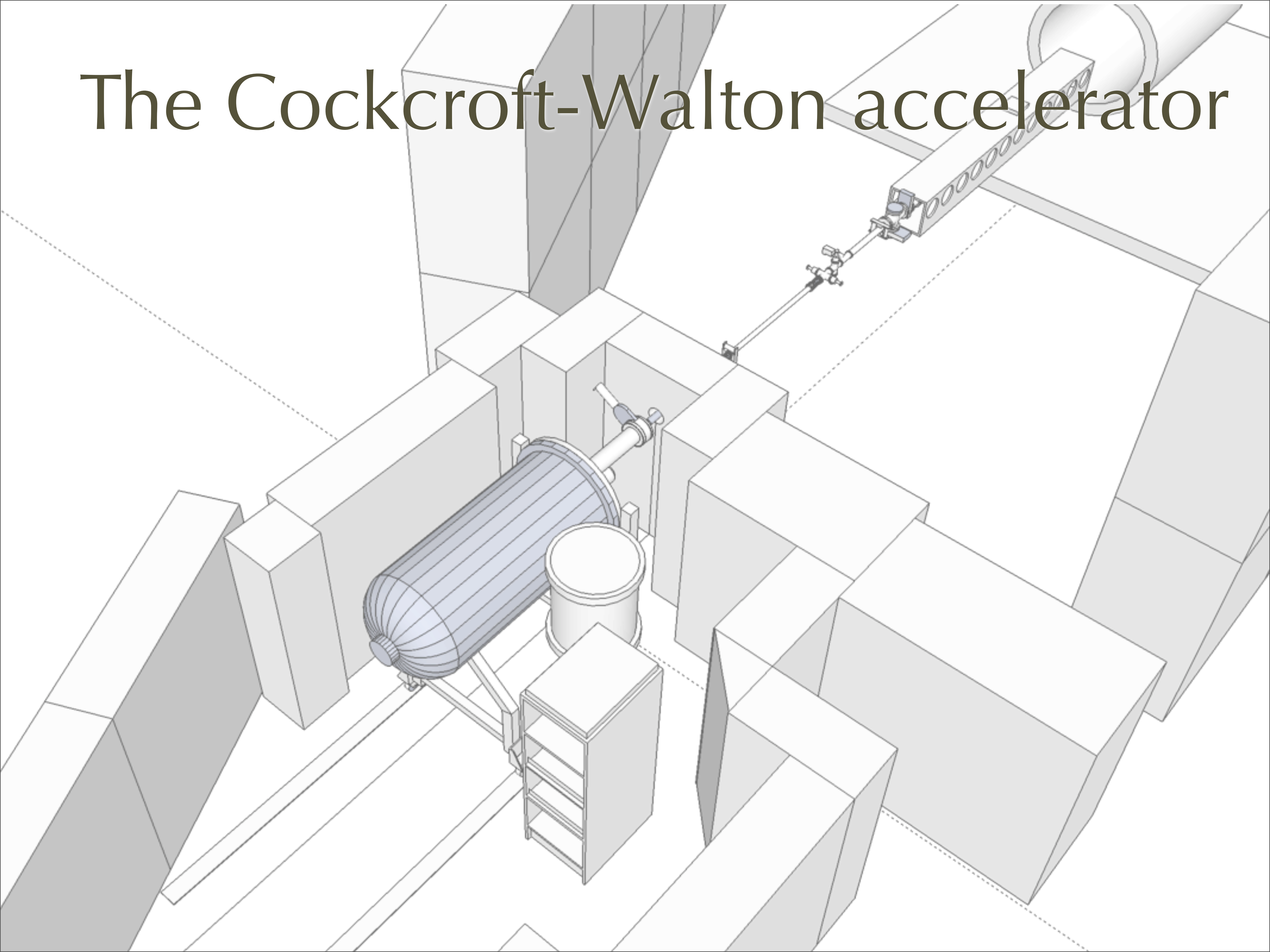
- Even a modest collimation guarantees a sufficient monochromaticity
- Liquid hydrogen target to maximize photon flux
- An "opposite side detector" is needed (NaI array)



- In the back-to-back raw spectrum we see the correlation
  - 83 MeV ⇔ 55 MeV
  - The 129 MeV line is visible in the NaI because Xe is sensitive to neutrons (9 MeV)



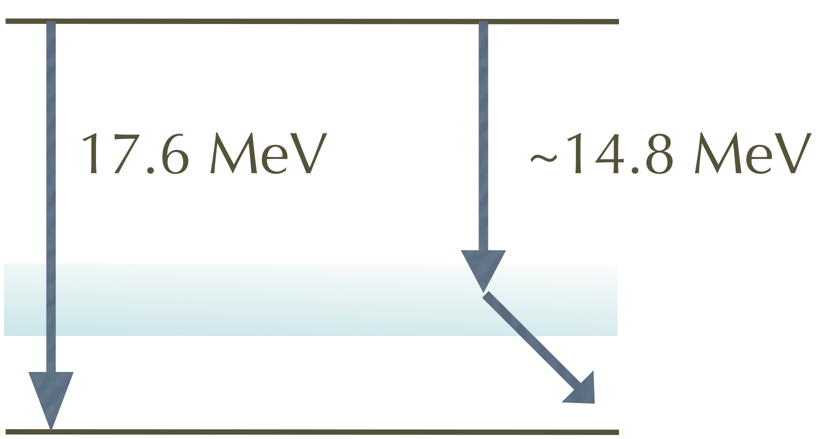
The Cockcroft-Walton accelerator

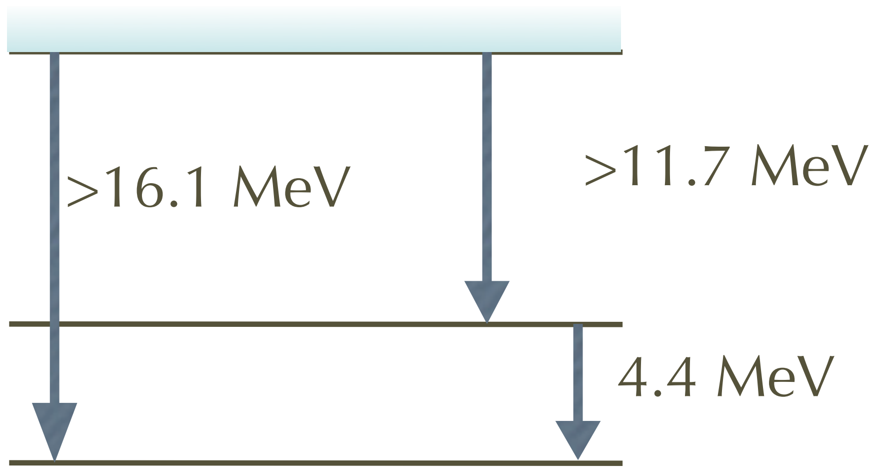


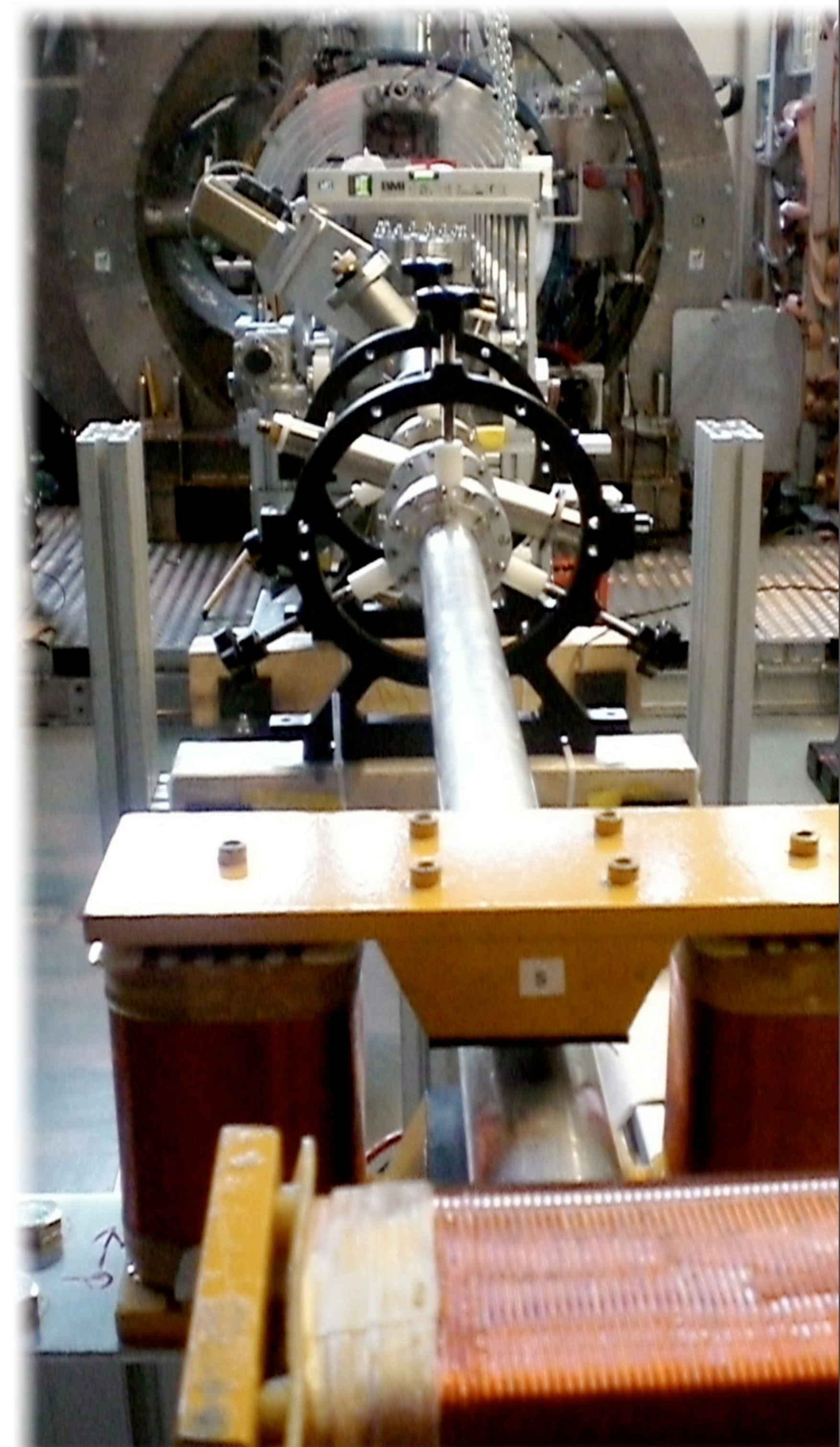
Reactions

- The Cockcroft-Walton is an extremely powerful tool, installed for monitoring and calibrating *all* the MEG experiment
- Protons of up to 1 MeV on Li or B
  - Li: high rate, higher energy photon
  - B: two (lower energy) time-coincident photons

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

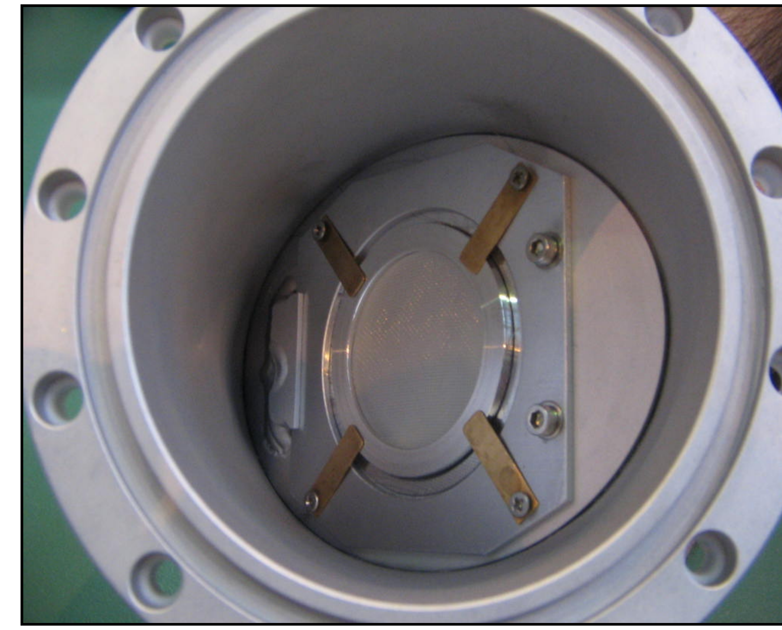


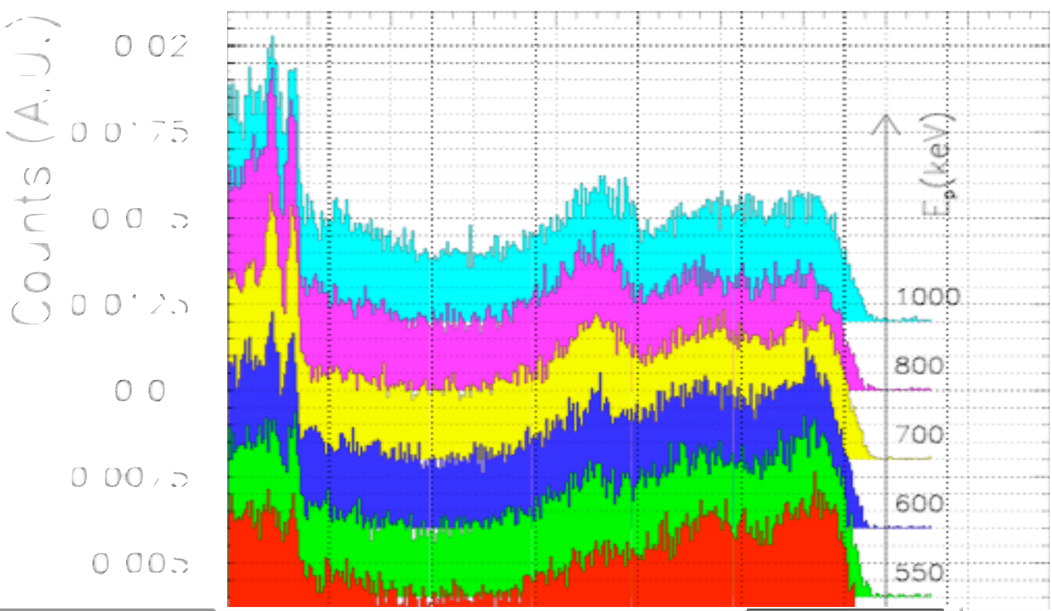




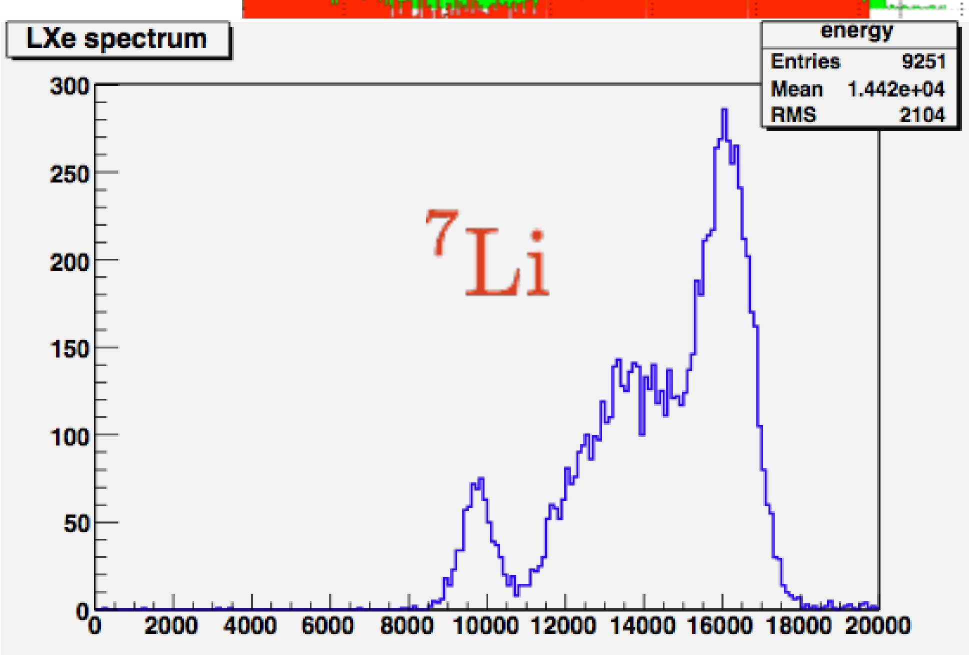
CW - daily calibration

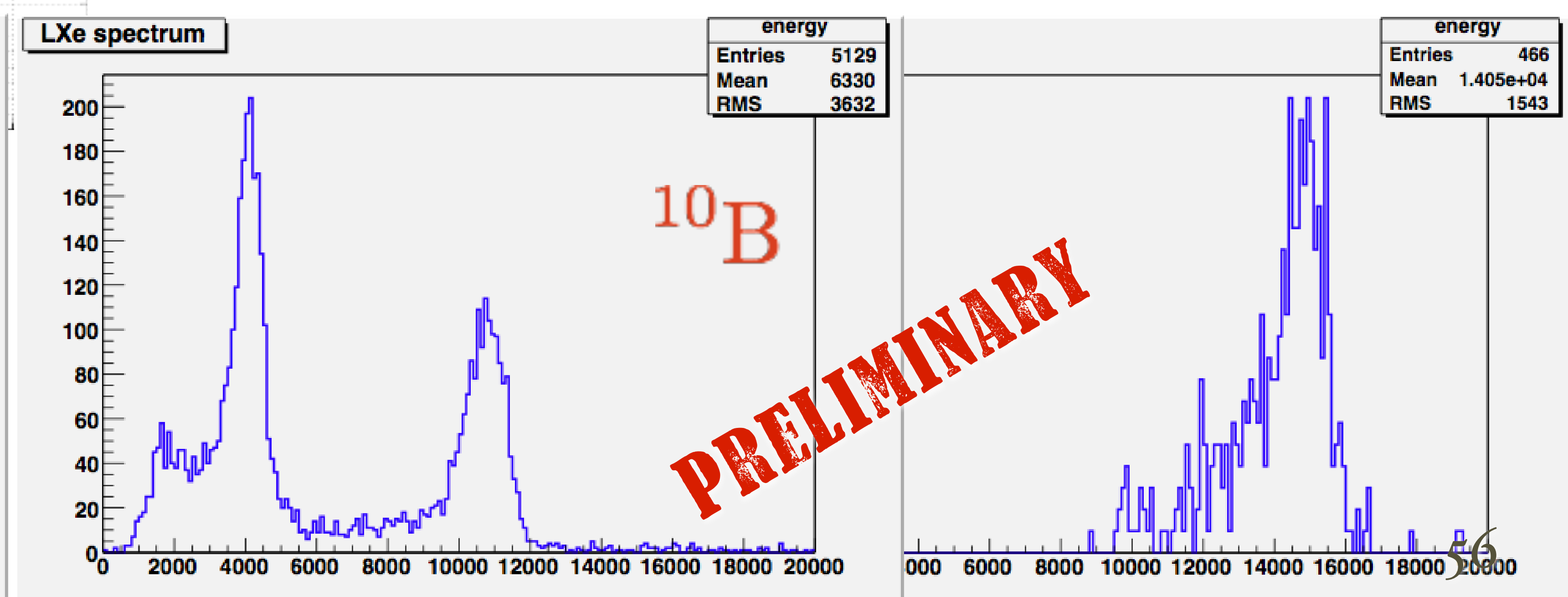
- This calibration is performed every other day
  - Muon target moves away and a crystal target is inserted
- Hybrid target ($Li_2B_4O_7$)
  - Possibility to use the same target and select the line by changing proton energy





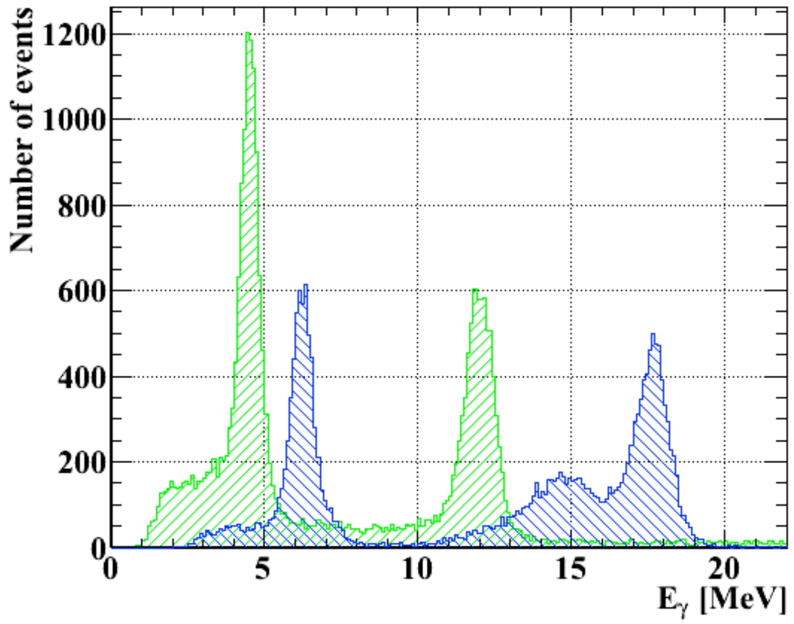
When p energy increases B lines appear

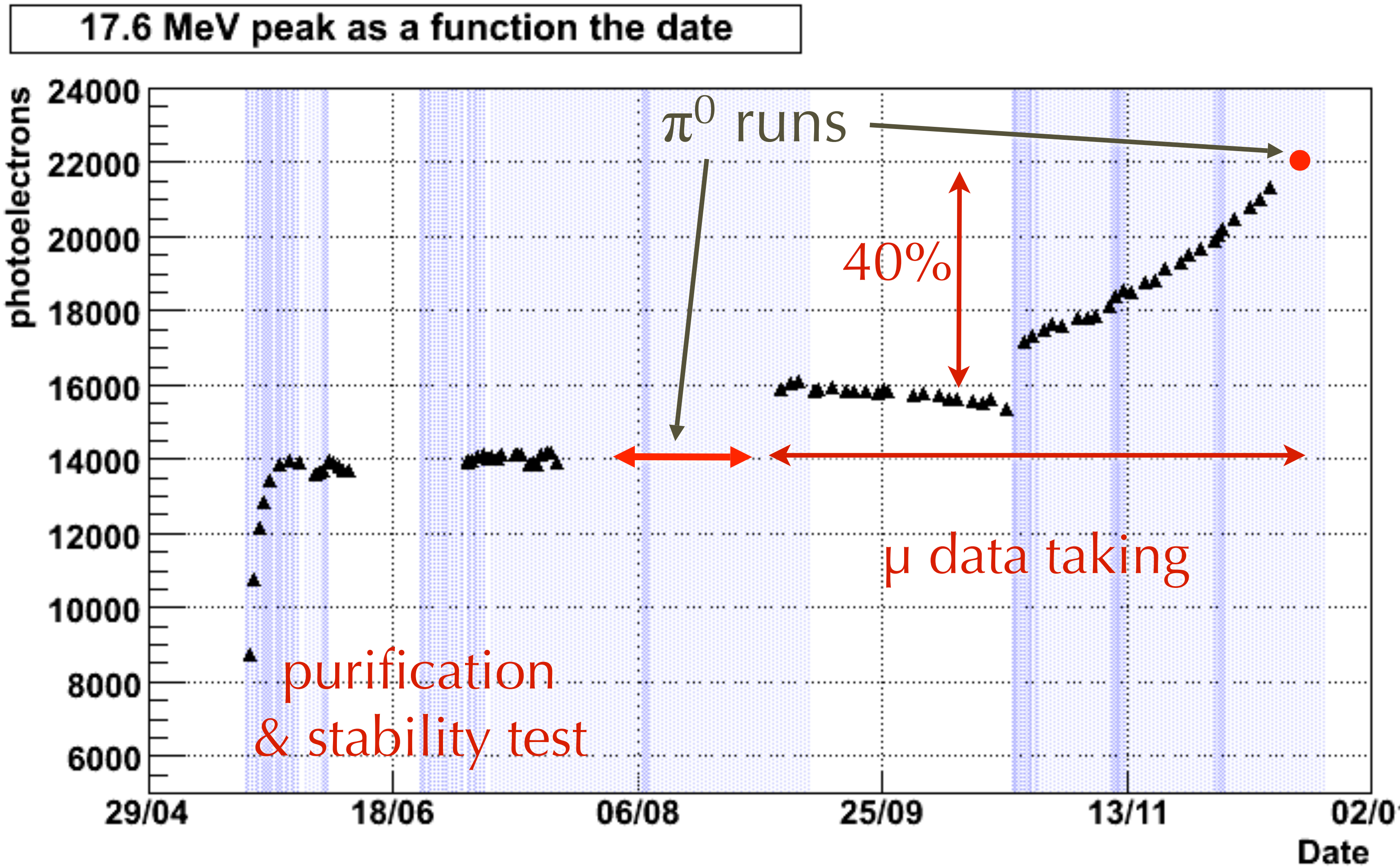


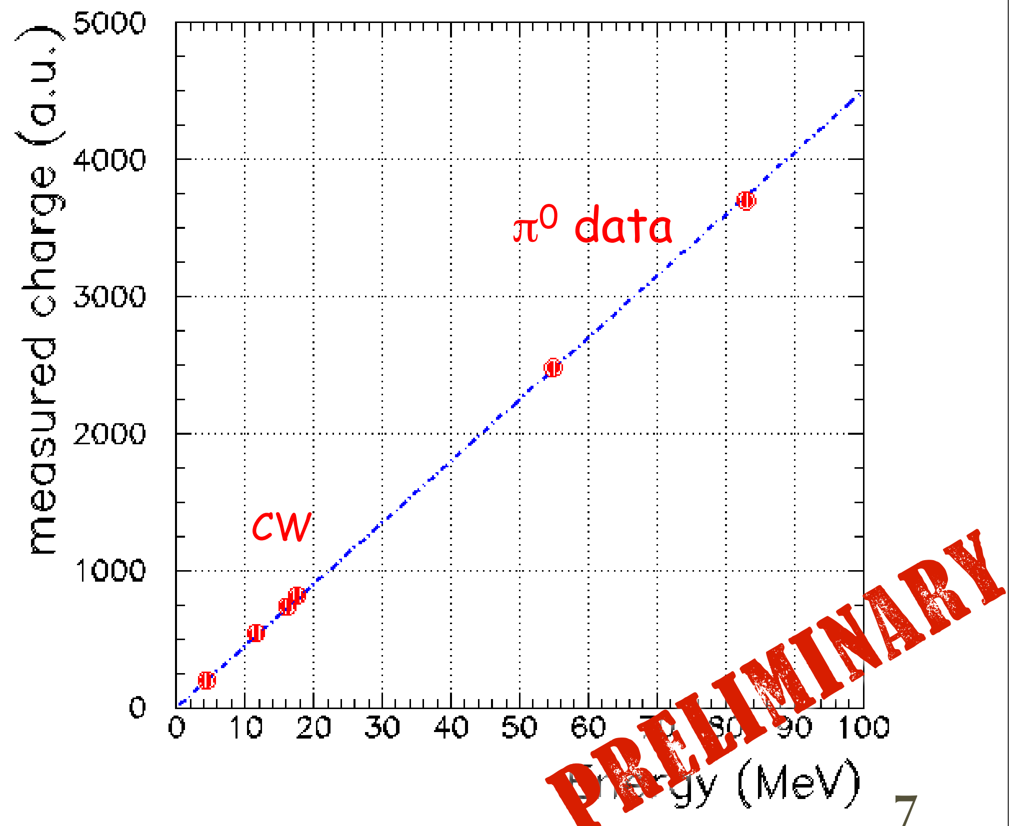


Xe light yield

- Large light yield increase (40%) during MEG run
- LY change monitored with the calibration system
  - three times per week @ 4.4, 11.6 and 17.6 MeV





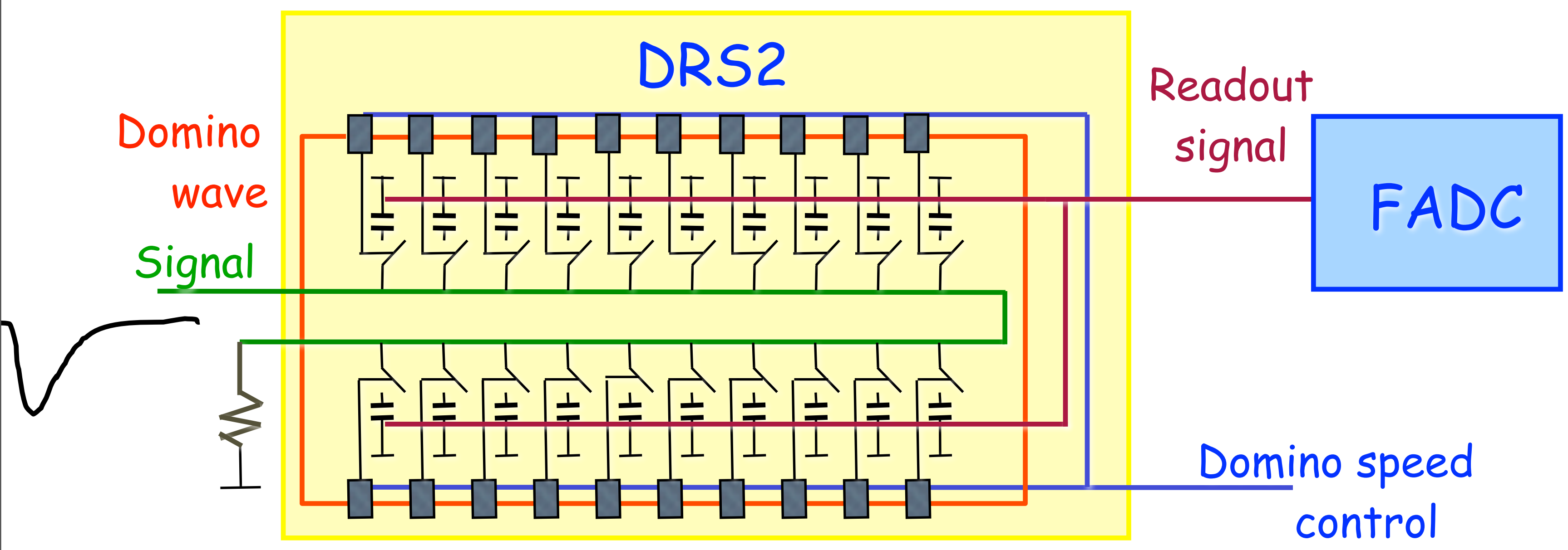


Signal and Background

- To better understand why MEG was designed the way it is we have to understand exactly:
  - what are we searching for? signal
  - in which environment? background
- which handles can we use for discrimination?

Readout electronics

2 GHz waveform digitization for all channels



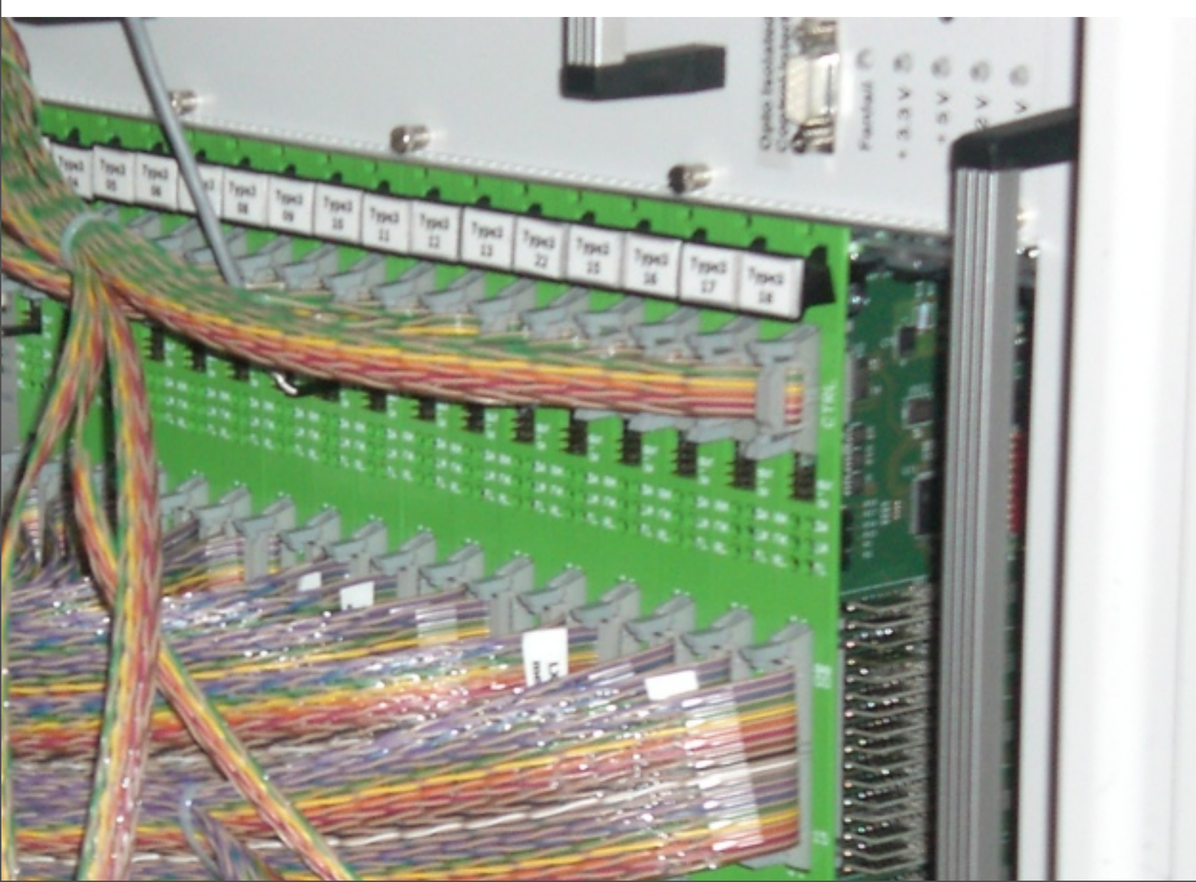
DRS chip (Domino Ring Sampler)

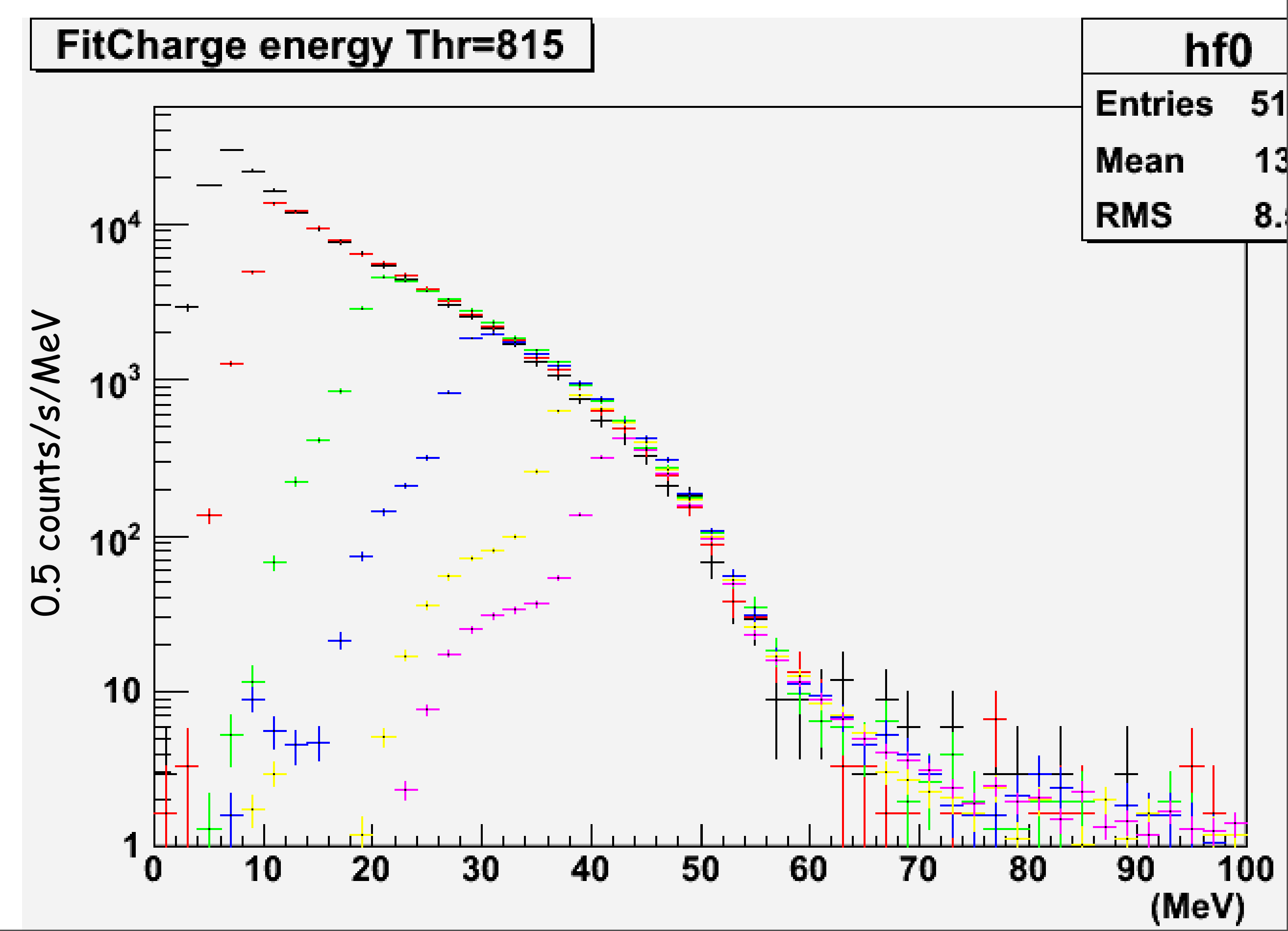
- Custom sampling chip designed at PSI
- 2 GHz sampling speed @ 40 ps timing resolution
- Sampling depth 1024 bins for 8 channels/chip
- Full waveform is a unvaluable handle to do pile-up rejection

Trigger

- 100 MHz waveform digitizer on VME boards that perform online pedestal subtraction
- Uses :
  - γ energy
  - e^+ - γ time coincidence
  - e^+ - γ collinearity
- Built on a FADC-FPGA architecture
- More performing algorithms could be implemented

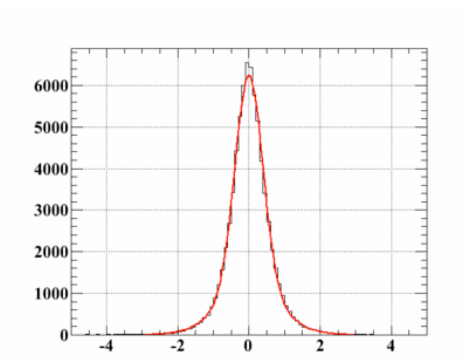
✳Beam rate ~ $3\ 10^7\ s^{-1}$
✳Fast LXe energy sum > 45MeV $2\times10^3\ s^{-1}$
  ✳gamma interaction point (PMT charge)
  ✳e^+ hit point in timing counter
✳time correlation γ – e^+ $100\ s^{-1}$
✳angular correlation γ – e^+ $10\ s^{-1}$

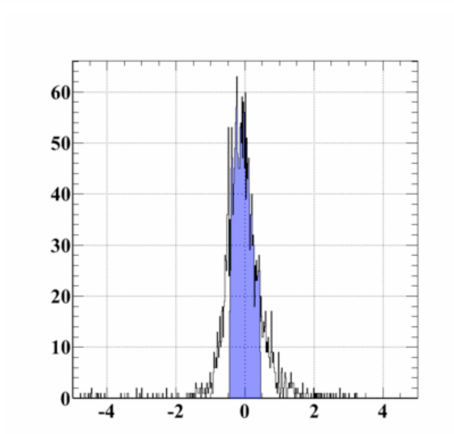


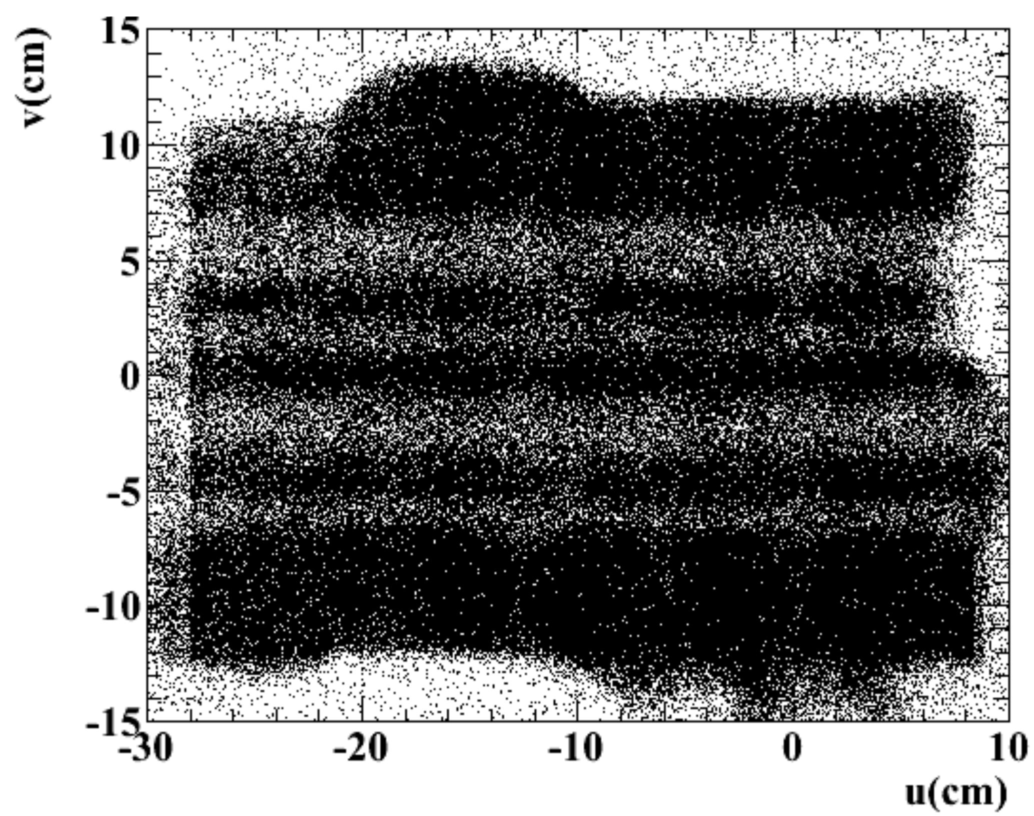


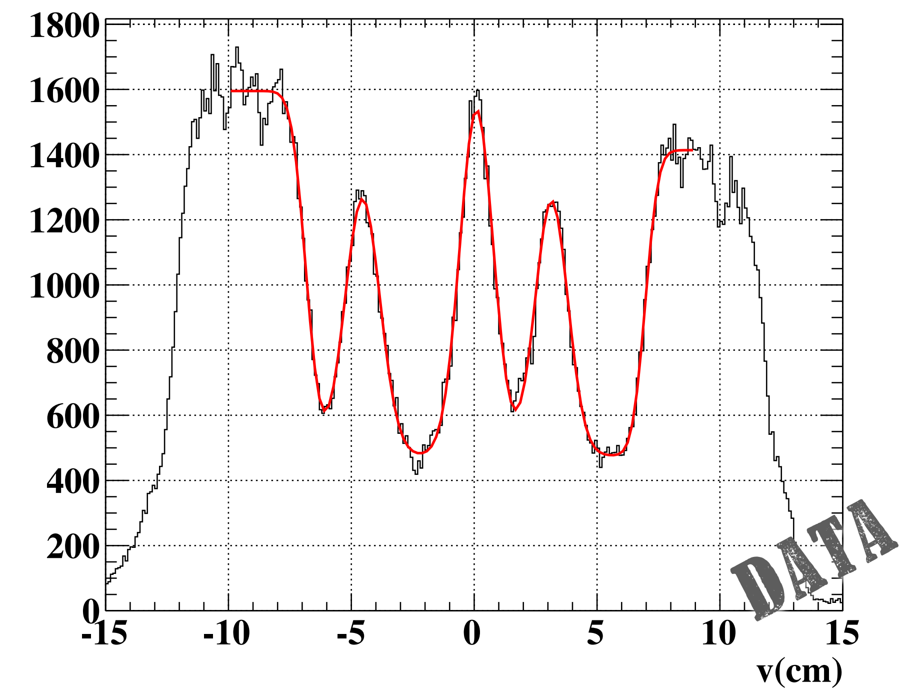
γ hit resolution

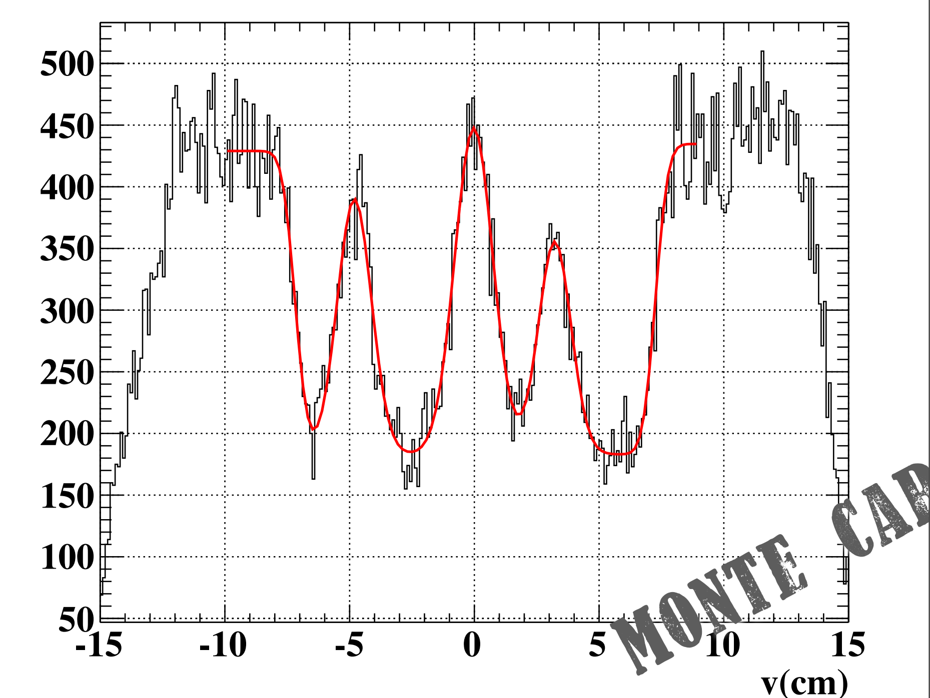
- We use the response shape from the Monte Carlo folded with an additional component estimated from data using a lead collimator









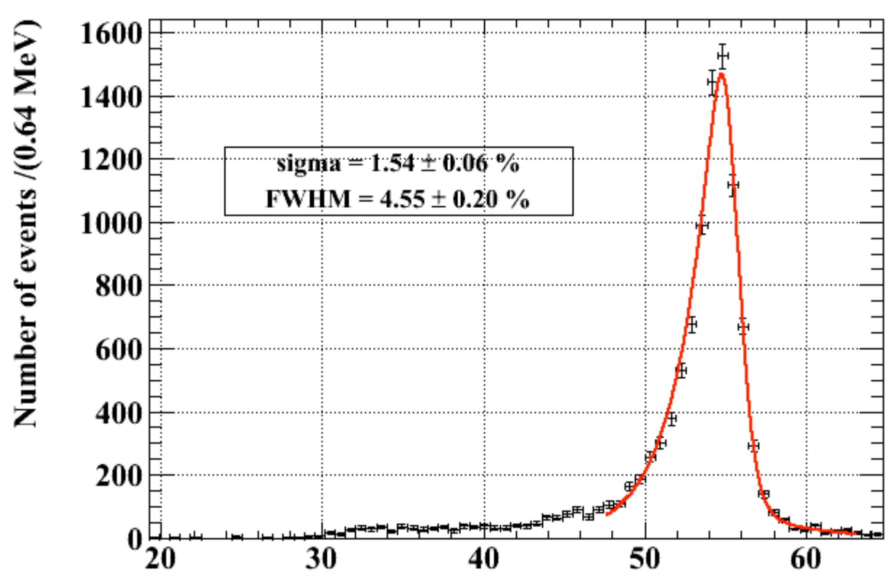


- $\sigma(u,v)$ ~ 5.0 mm
- $\sigma(w)$ ~ 6.0 mm

Typical resolutions and eff

- are summarized in this table

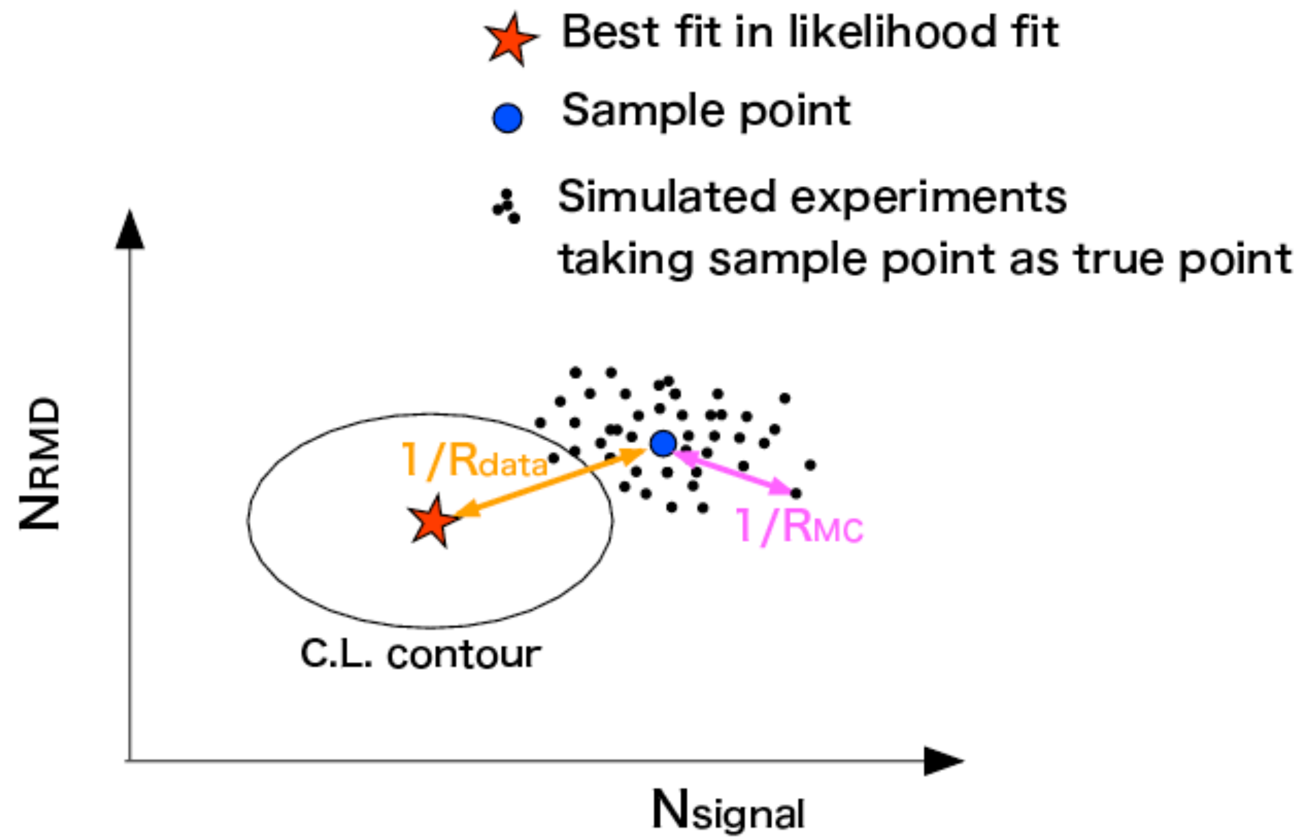
	peak	error	spread
σ_E (%)	2.0	0.15	0.4
$\sigma_{(u,v)}$ (mm)	5.0	0.5	0.3
$\sigma_{te\gamma}$ (ps)	148	17	20
Energy scale		0.6%	
Efficiency	61%	3%	



$$= \frac{3\alpha}{32\pi}\left(\frac{\Delta m^2_{23} s_{13} c_{13} s_{23}}{M_W^2}\right)^2$$

Normalization numbers

$N_{e\nu\nu}$	11414
Prescale	10^7
Michel fraction	1/0.1008
ε_{e+} ratio	1.14
ε_γ	0.98 x 0.66
$\varepsilon_{trigger}$	0.66
$\varepsilon_{selection}$	0.99 x 0.91
SES	$(2 \pm 0.2) \times 10^{-12}$



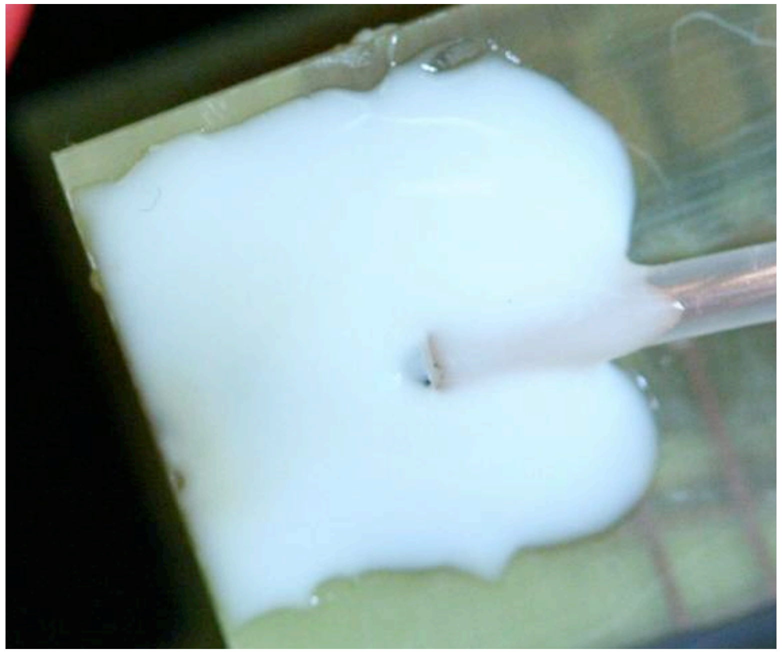
$\Omega/4\pi$	0.09	4.6×10^{-3} (from BG rate, E_γ>45MeV, E_e>50MeV)	280/250 (RD sideband data, E_e<48MeV, #expected / #observed)
γ	0.66 x 0.91 ($E\gamma$>46MeV)x(pileup, CR)		
e^+	0.15 (DCH x DC-TC match)		
Trigger	0.66 (DM)		
Selection	0.99 x 0.98 (DCH x γ acc.)		
$N\mu$	9.4×10^{13} μ stops ($3.0\times10^7 \mu$/s/2mA·6290C)		
SES	2.0×10^{-12}	2.2×10^{-12}	2.2×10^{-12}

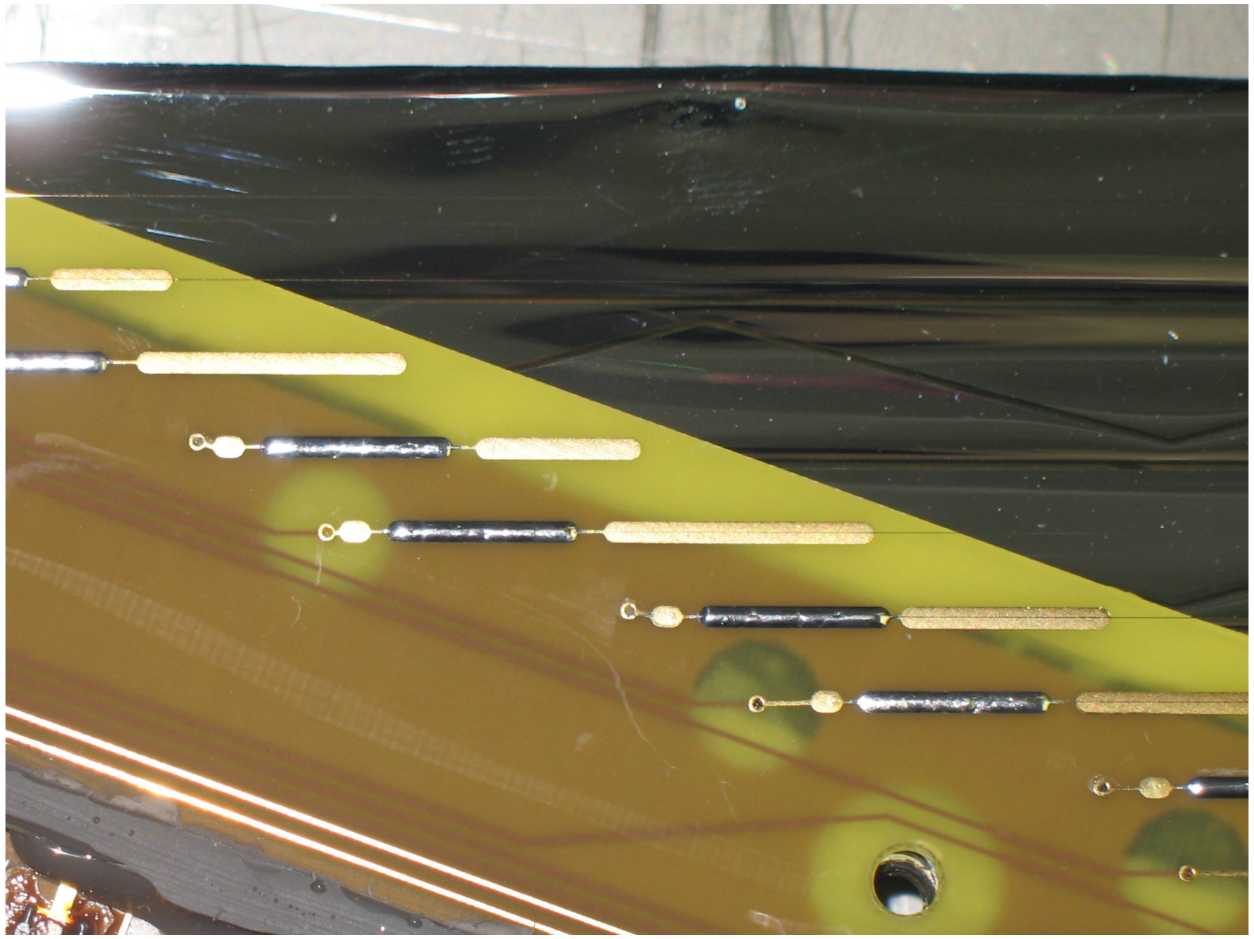
DCH repair

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





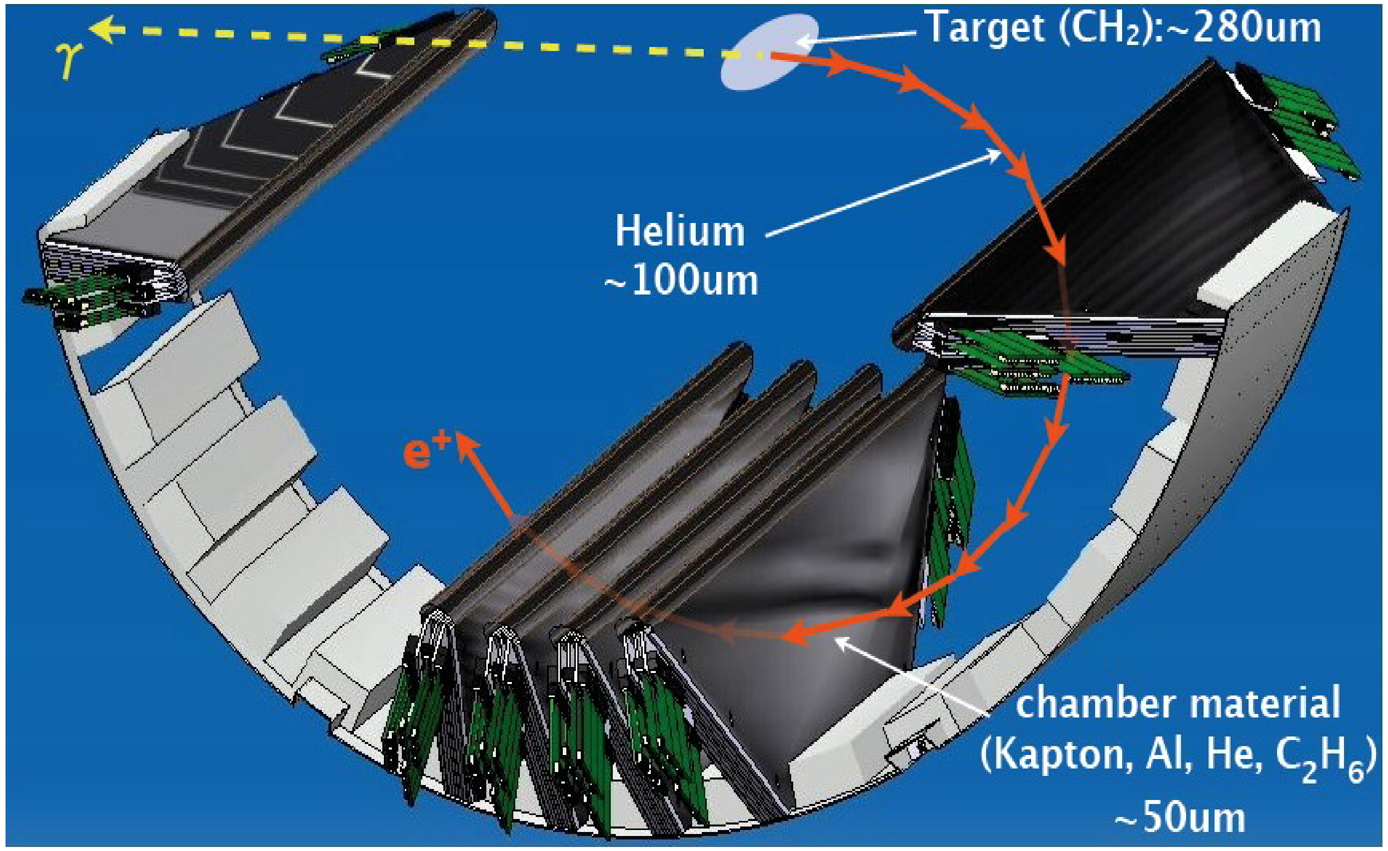
4) Open all chambers, replace the PCB and the wires, saving the cathodes

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

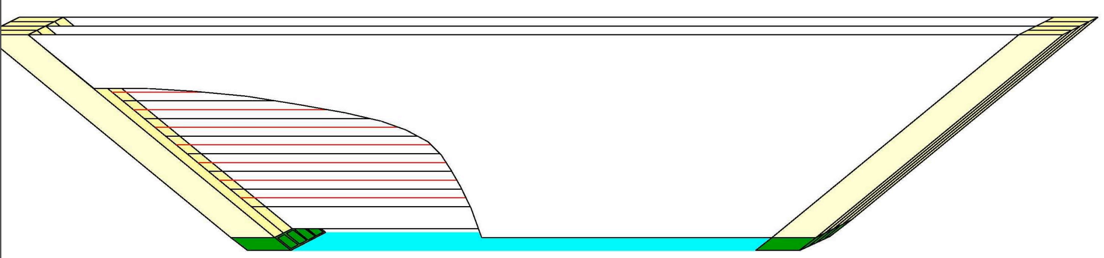
Estimated time: ready to mount in August

Positron tracker

- Excellent momentum resolution at ~50 MeV
- The energy is very low hence the multiple scattering is important
  - we tend to loose position/energy resolution
  - MS ~ σ
- The volumes of the chambers are independent
  - too much high-Z gas otherwise (He/C_2H_6 vs He)
  - find a clever way for a good *z*-reconstruction

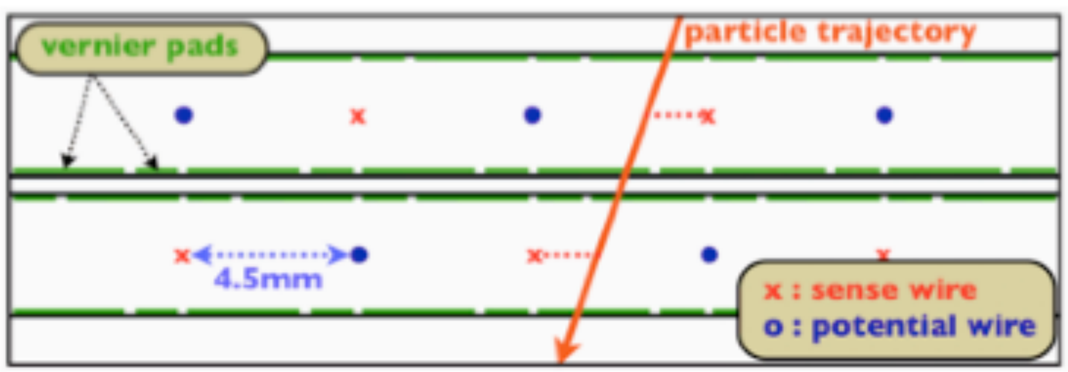


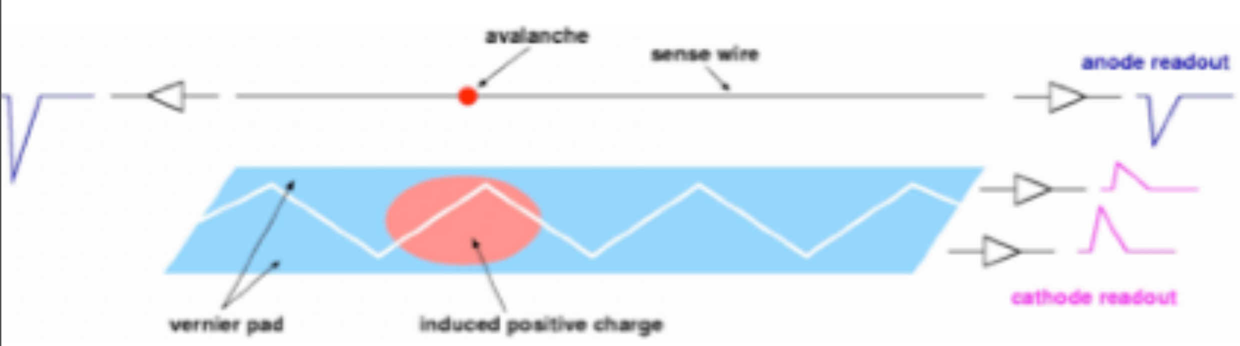
Positron Tracker



- 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

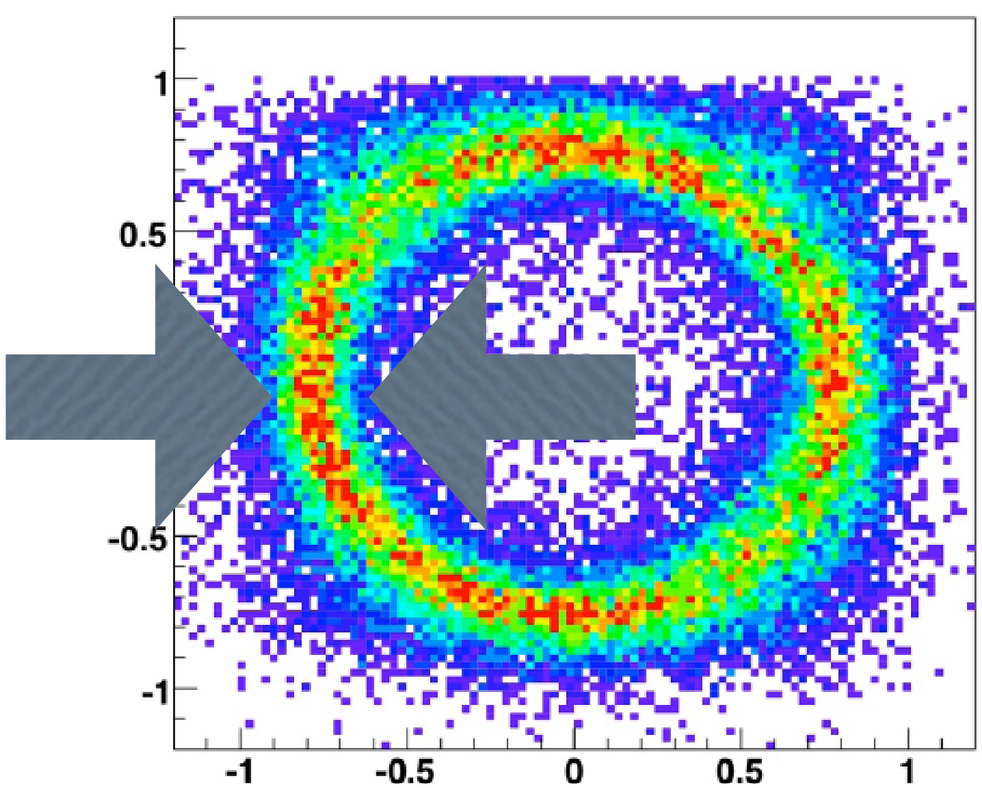
transverse coordinate (t drift)



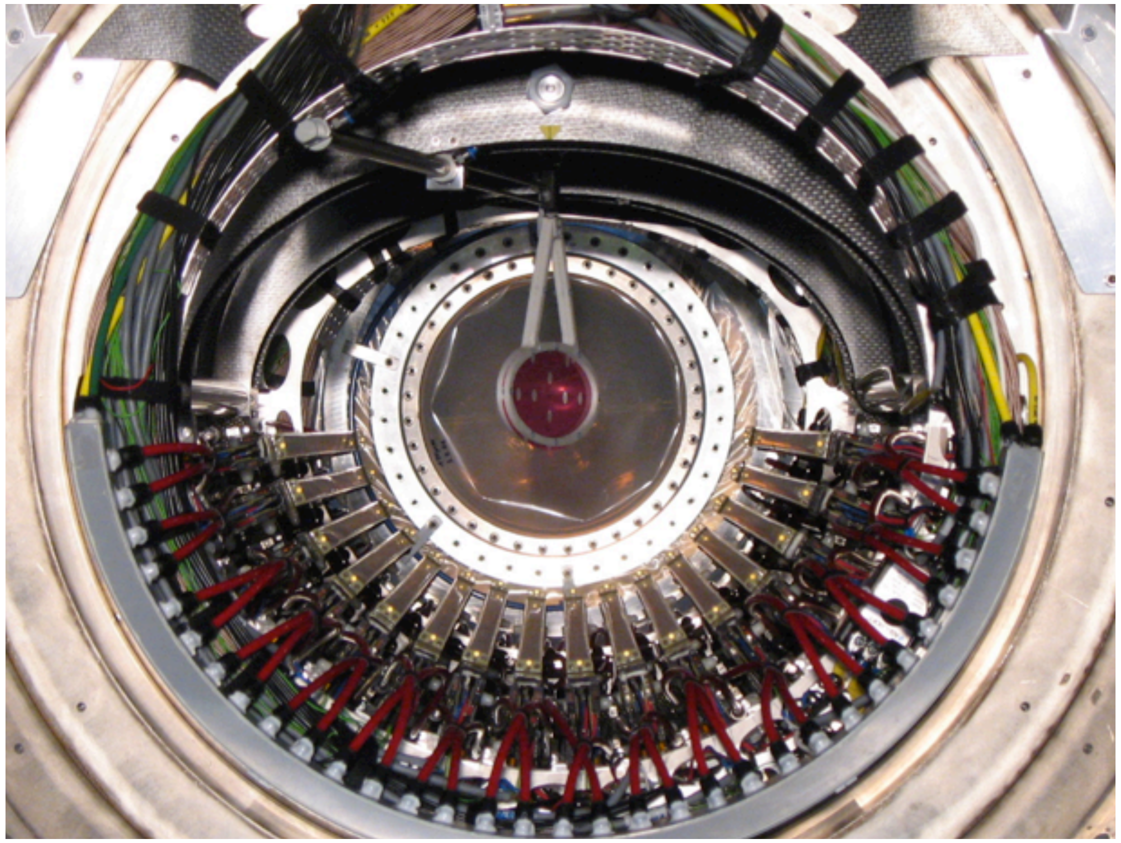


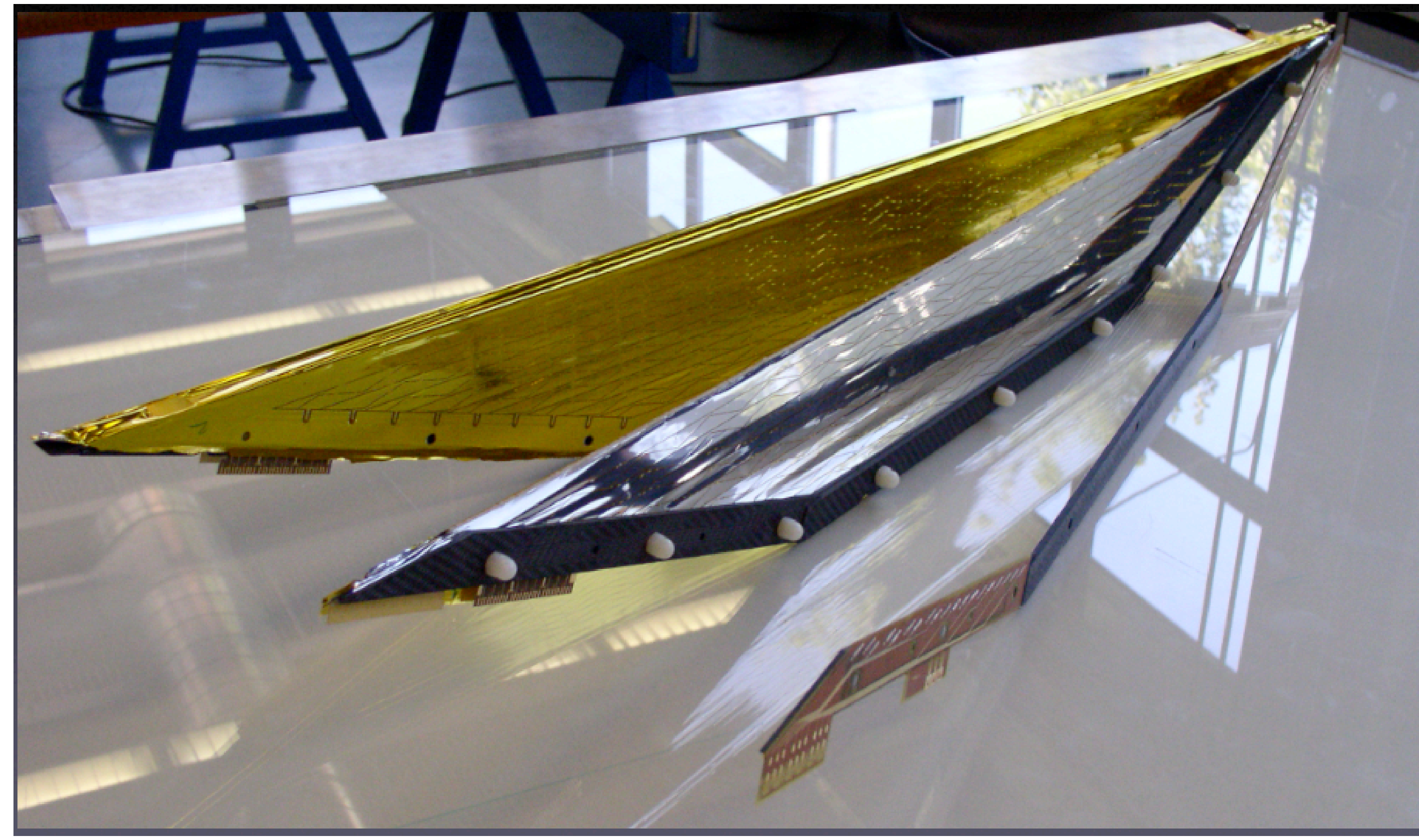
longitudinal coordinate (charge division + Vernier)

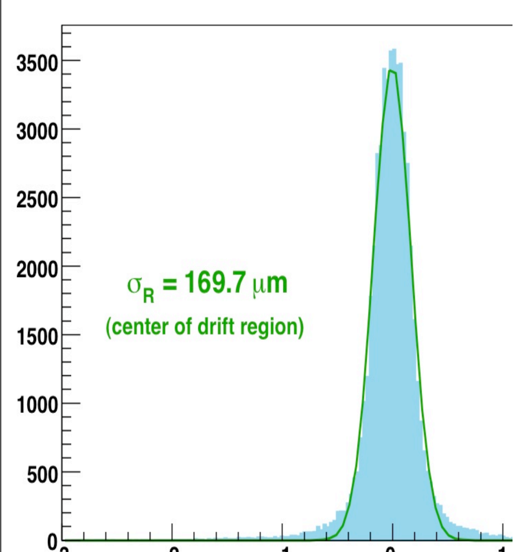
- Within one period, fine structure given by the Vernier circle

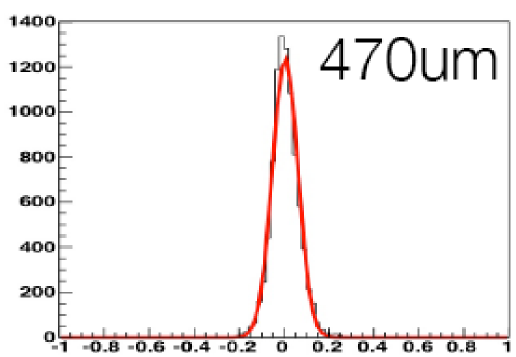


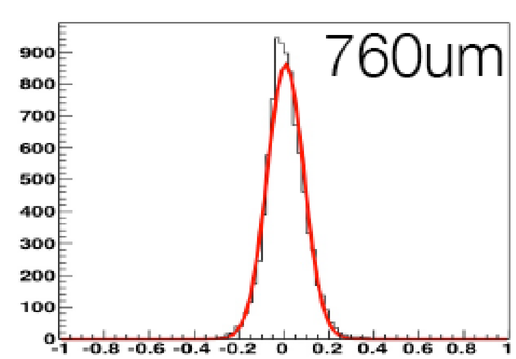
Drift chambers

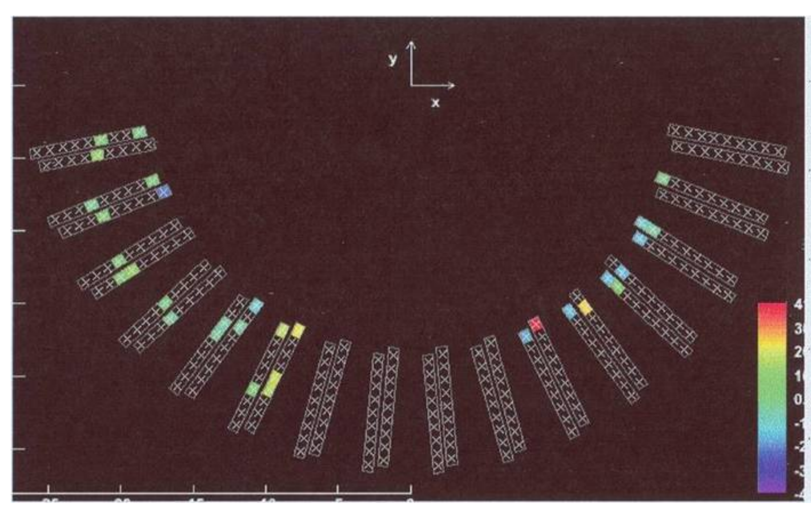


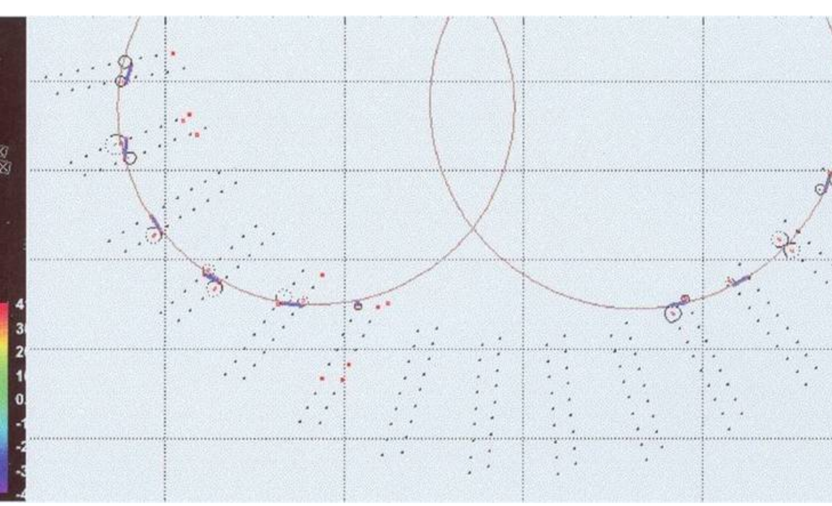










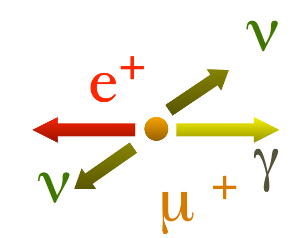


Radiative decay signal

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



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

Event selection

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

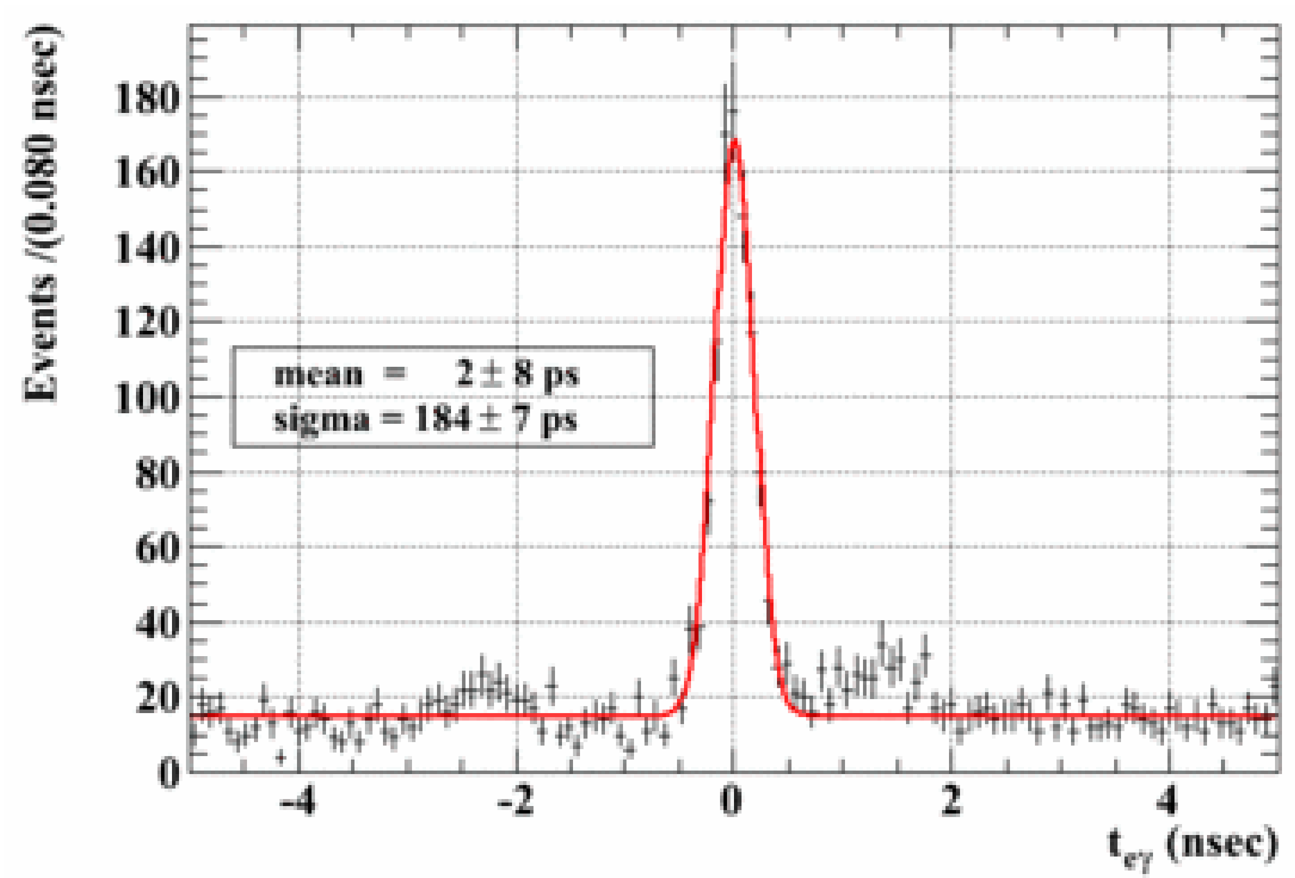
S/N ratio = 0.8

4. Kinematical constraint

S/N ratio = 2.8

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

428 events



Analysis schemes

(*) Phys. Rev. D57(1998) 3873

- The 90% confidence levels are calculated by 3 indipendent likelihood fitting tools, all based on the Feldman-Cousins approach (*)
- All results are consistent

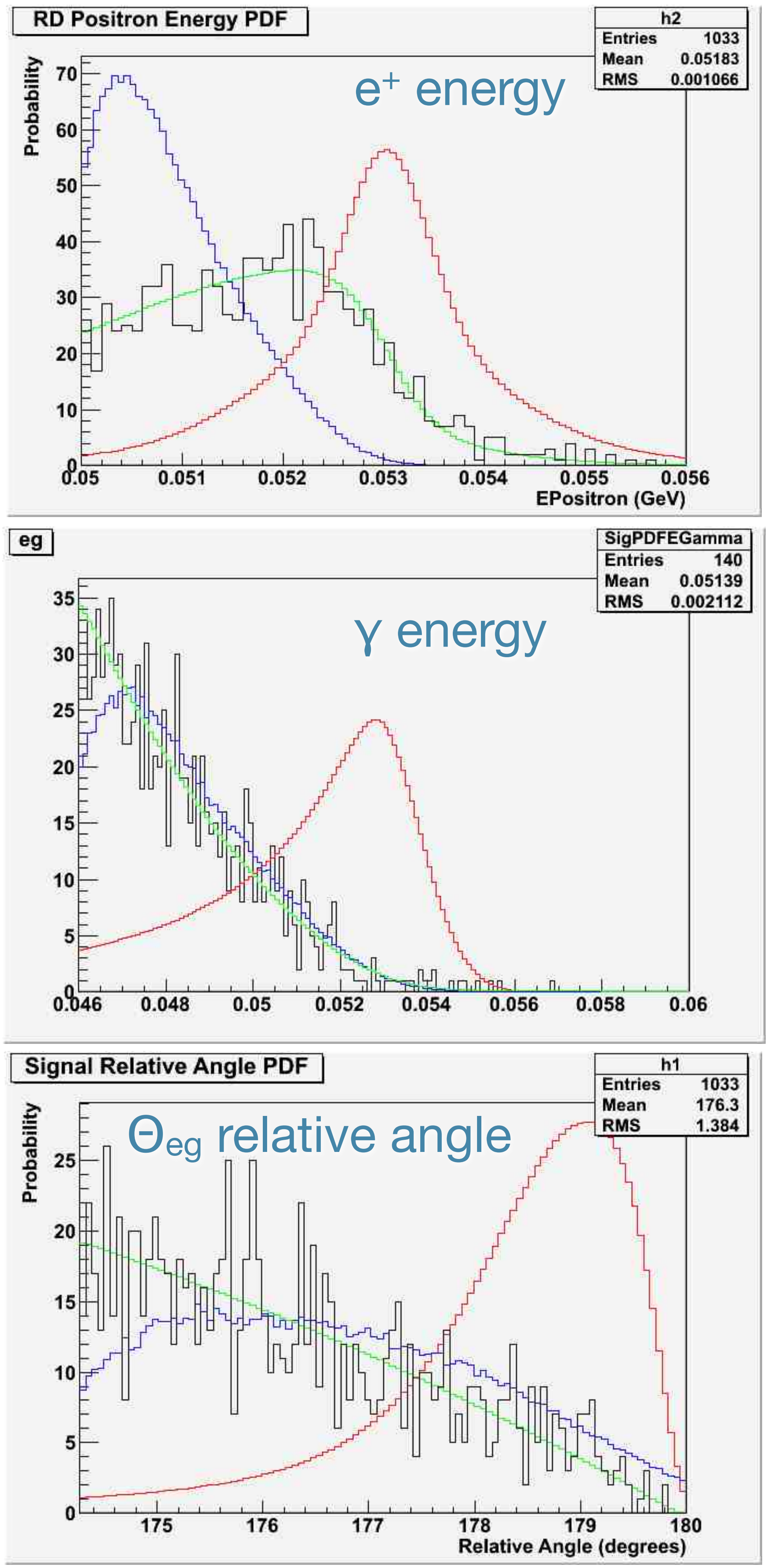
1st scheme

- uses an a-priori estimates of N_{RMD} and N_{BG}
- A likelihood ratio LR table is built as a function of N_{sig}
- The 90% confidence level for BR comes from the LR for experimental data vs tabulated values

2ND-3rD scheme

- extract N_S, N_{RMD} and N_{BG} by likelihood fit on the observed events in the signal region, with two independent algorithms
- 90% confidence level of N_S comes from (N_S N_{RMD})-plane, with N_{BG} fixed
- BR from the LR ordering technique

Signal region vs PDFs:



Legend (*):

Black: data

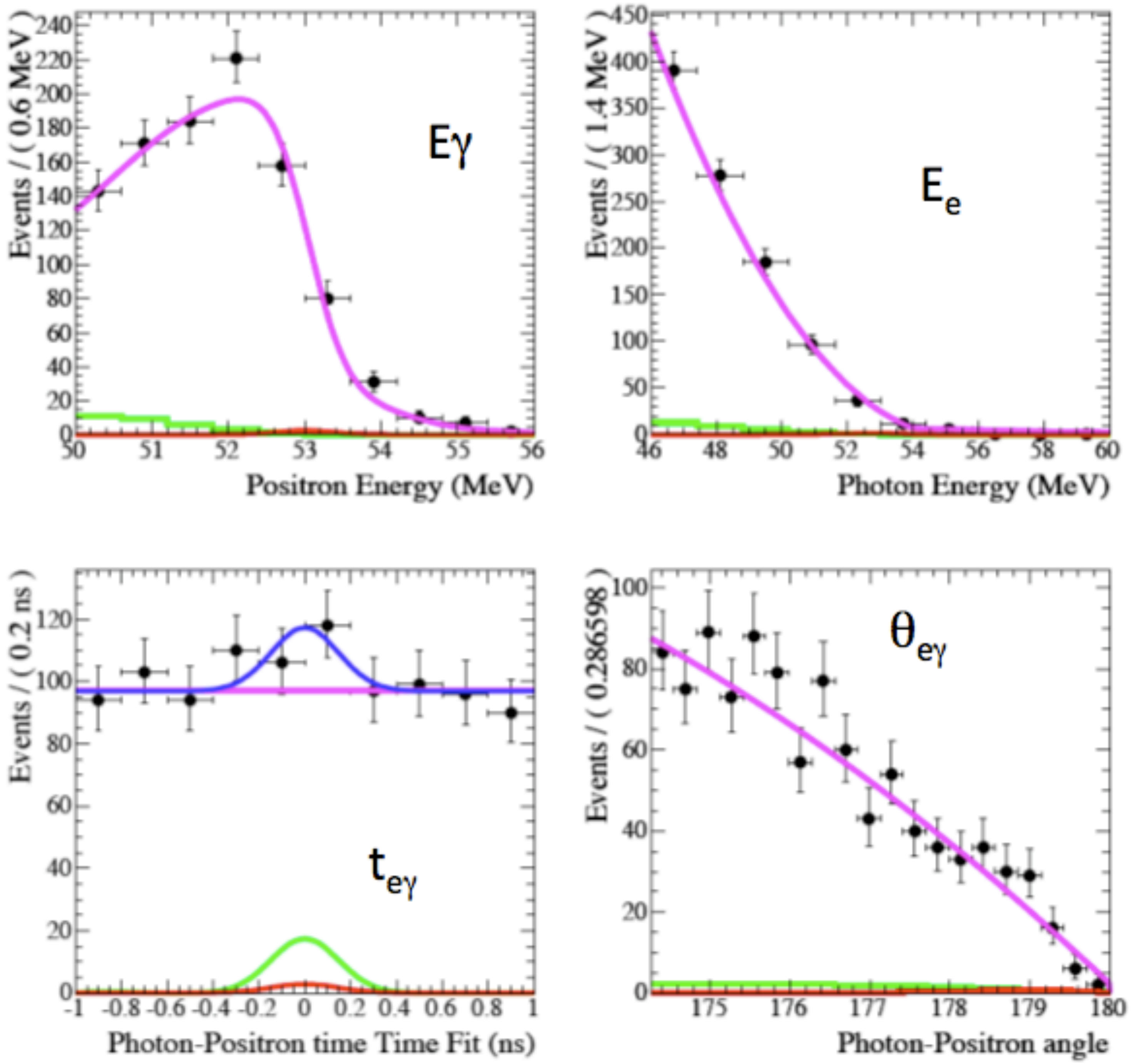
Red: Signal PDF

Blue: RMD PDF

Green: BG PDF

(*)Note:

All curves normalized to the event number



ACC BKG

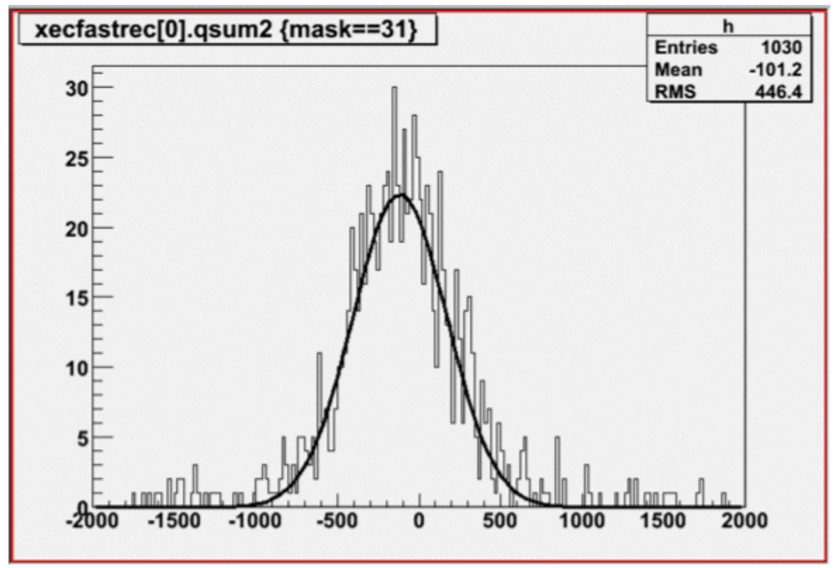
Rad Muon Decay

SIG

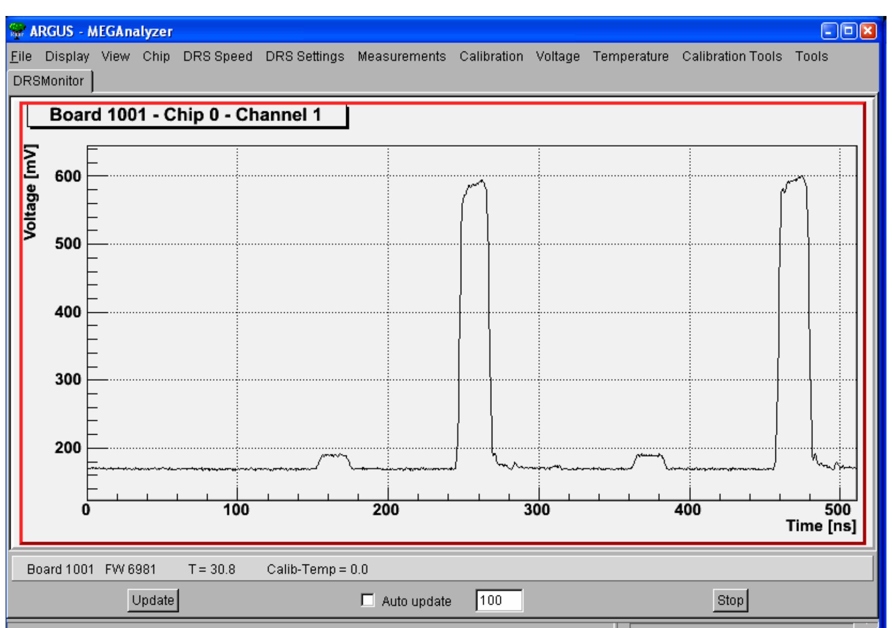
Fit with alternative observable definition gives very compatible results

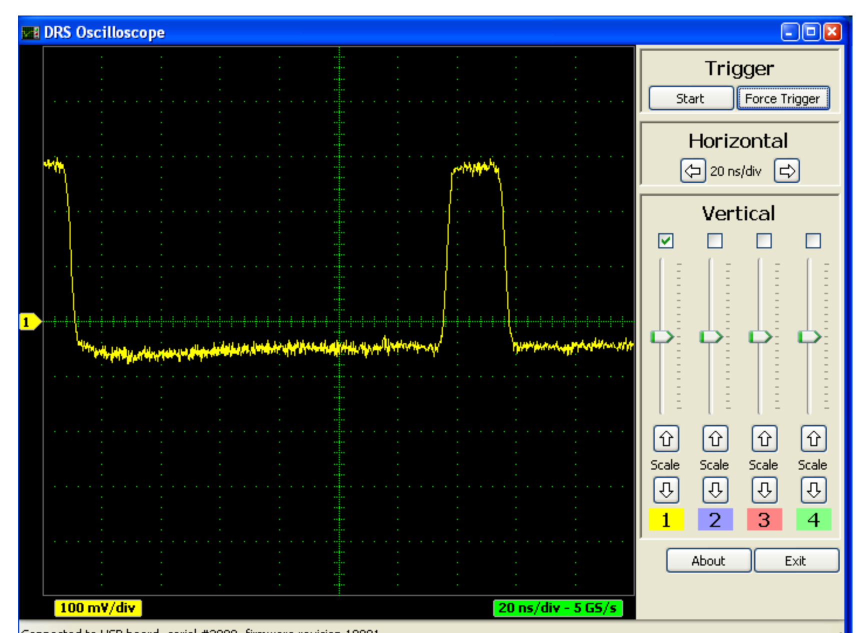
Pedestal

- Residual large (2%) contribution of pedestal due to ghost pulses in DRS2



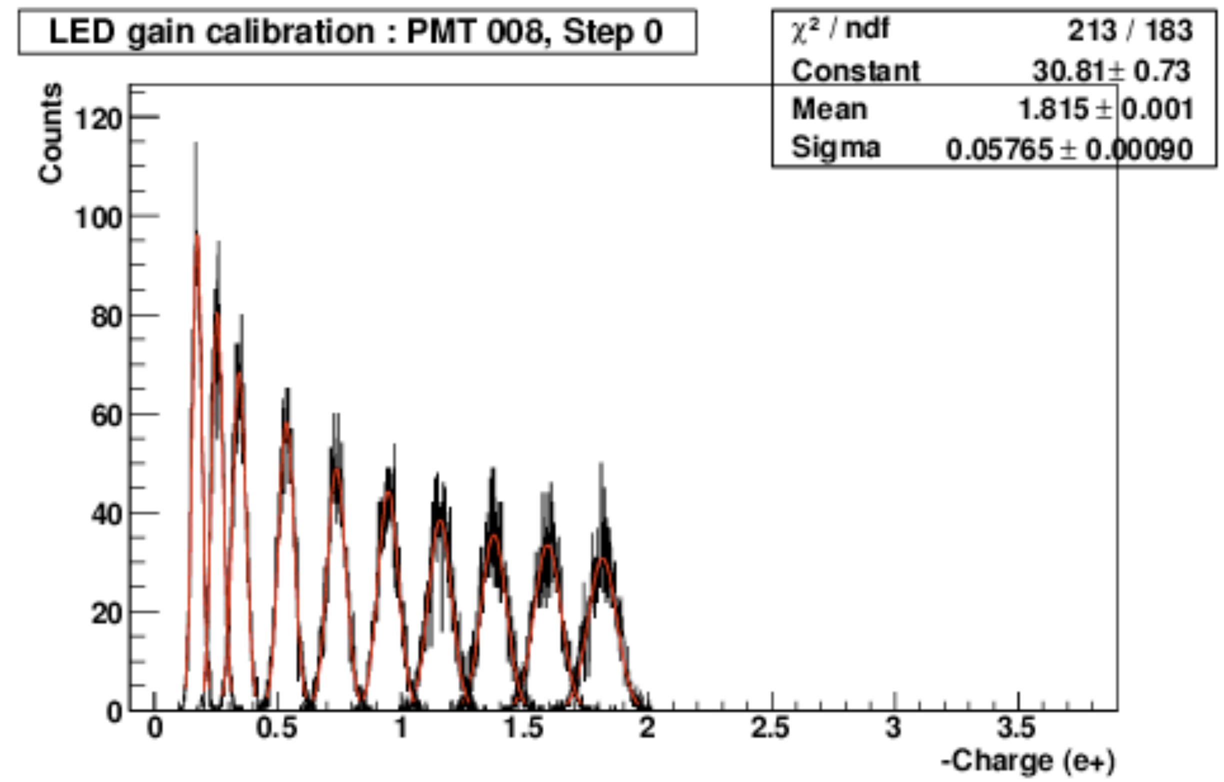
- Solved with new version of chip (installed in 2009)

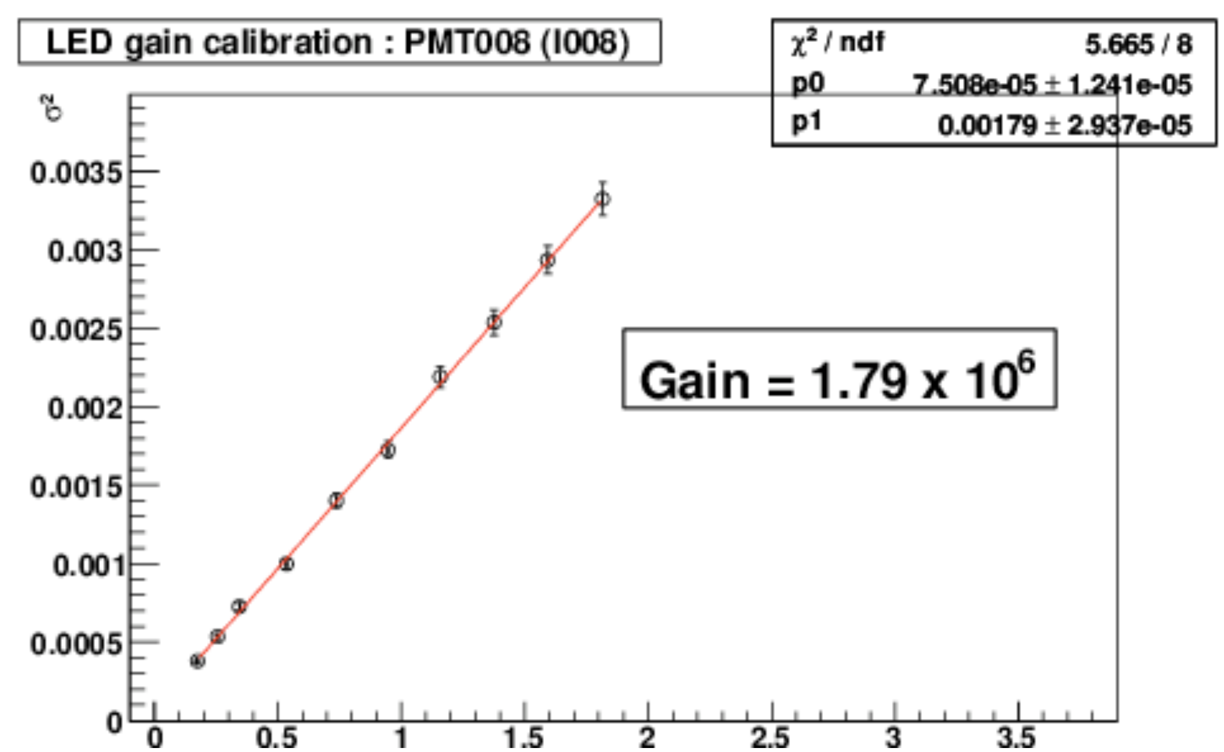


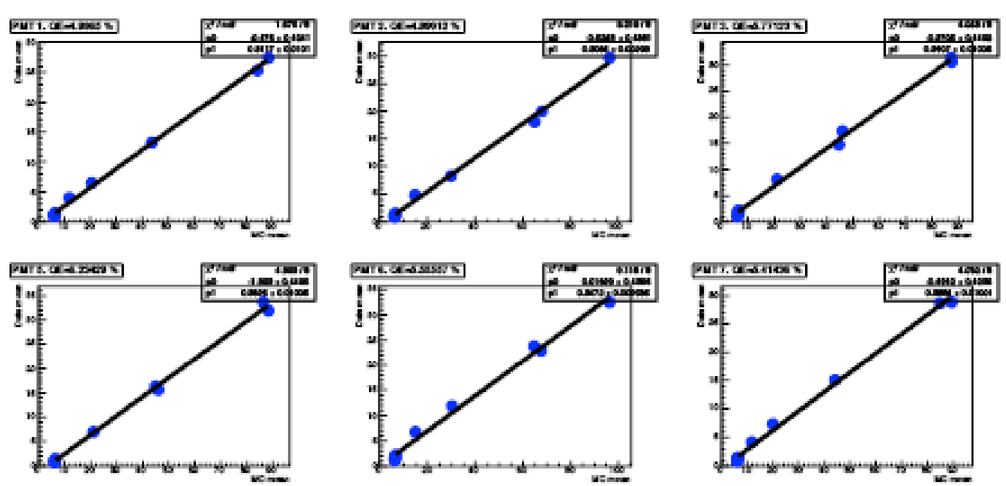


LXe: *g* and QE

- The calorimeter is equipped with blue LEDs and alpha sources
- Measurements of light from LEDs:
  - $\sigma^2 = g\,(q - q_0) + \sigma_0^{\,2}$
  - Absolute knowledge of the GAIN of ALL PMTs within few percents
  - $g = 10^6$ for a typical HV of 800 V
- QEs determined by comparison of alpha source signal in cold gaseous xenon and MC determined at a 10% level

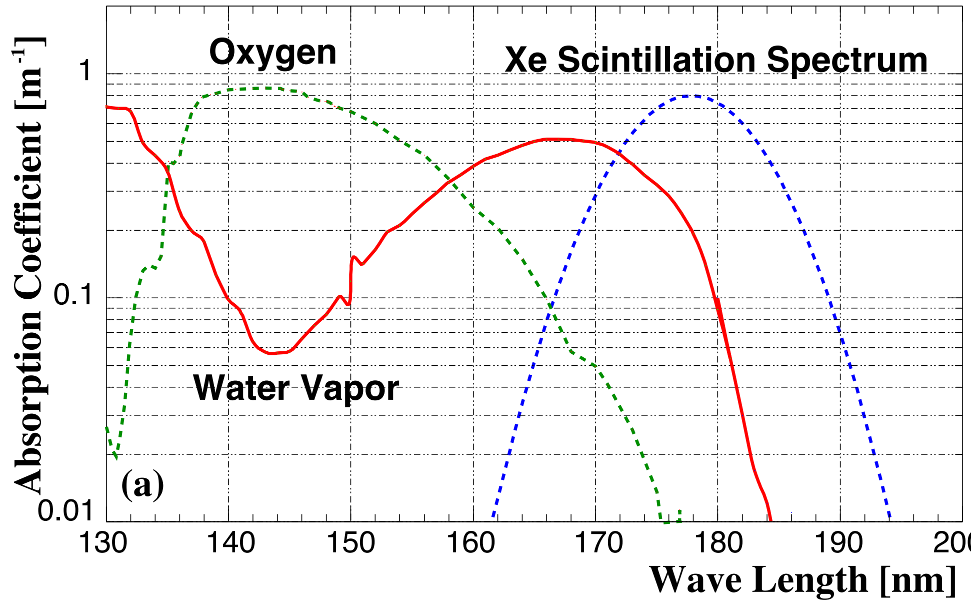


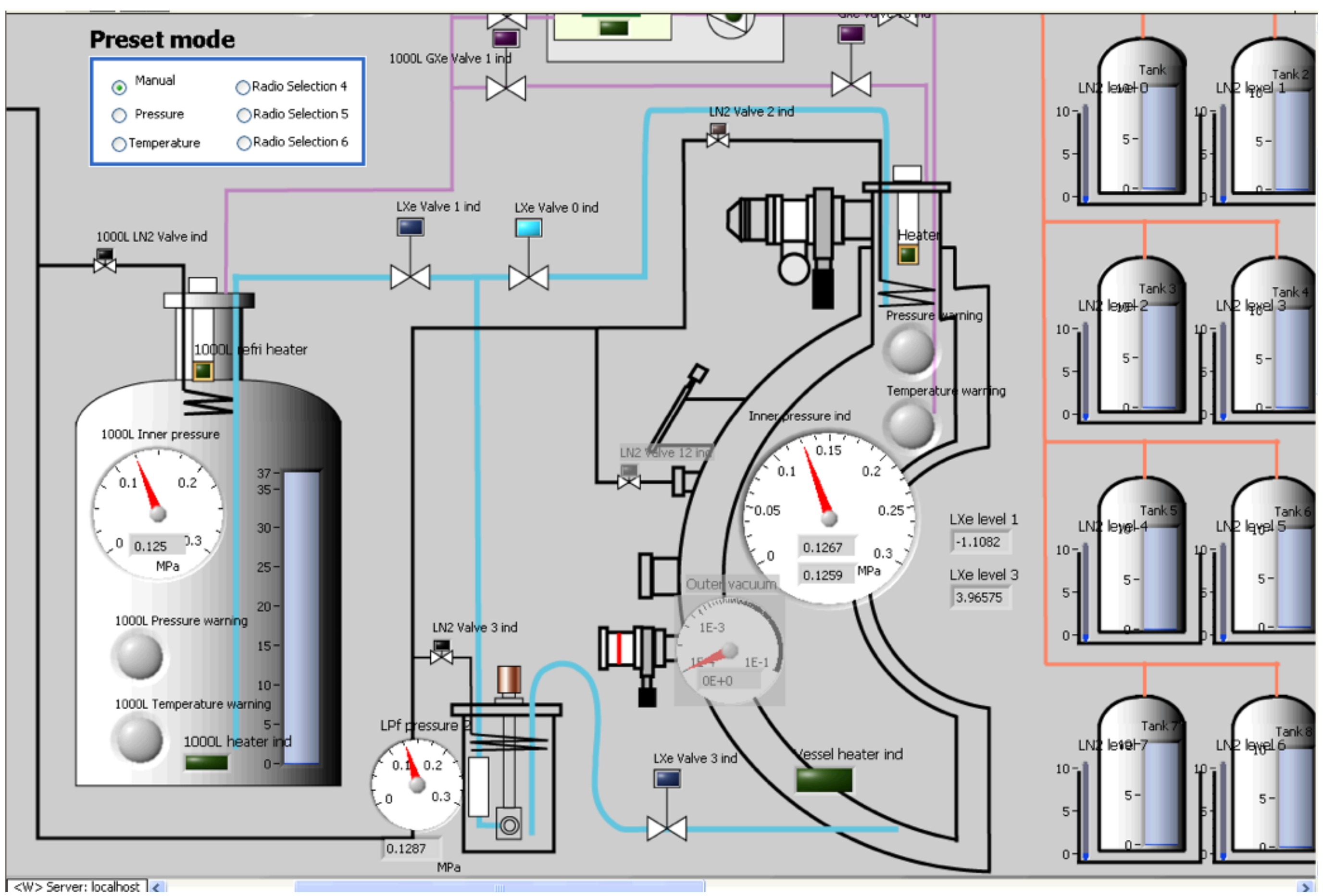


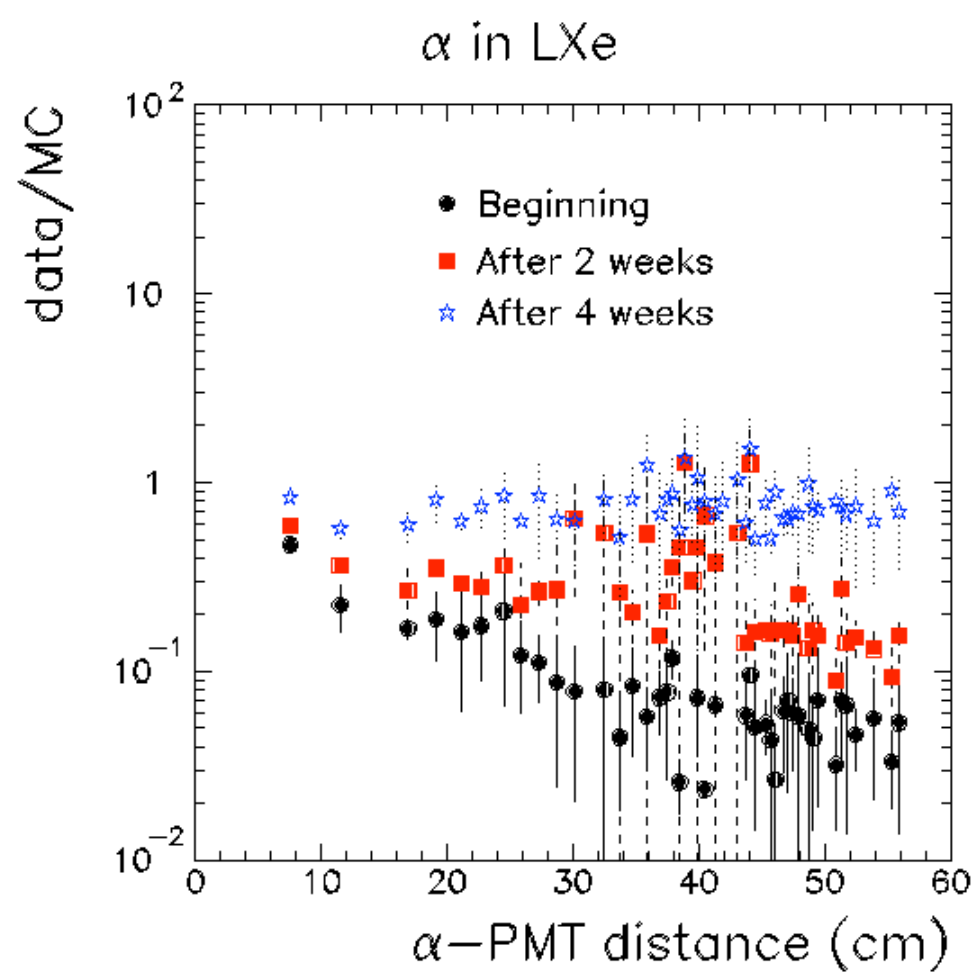


Xenon purity

- Energy resolution strongly depends on absorption
- We developed a method to measure the absorption length with alpha sources
- We added a liquid and gas purification system (molecular sieve + gas getter) to reduce impurities below ppb

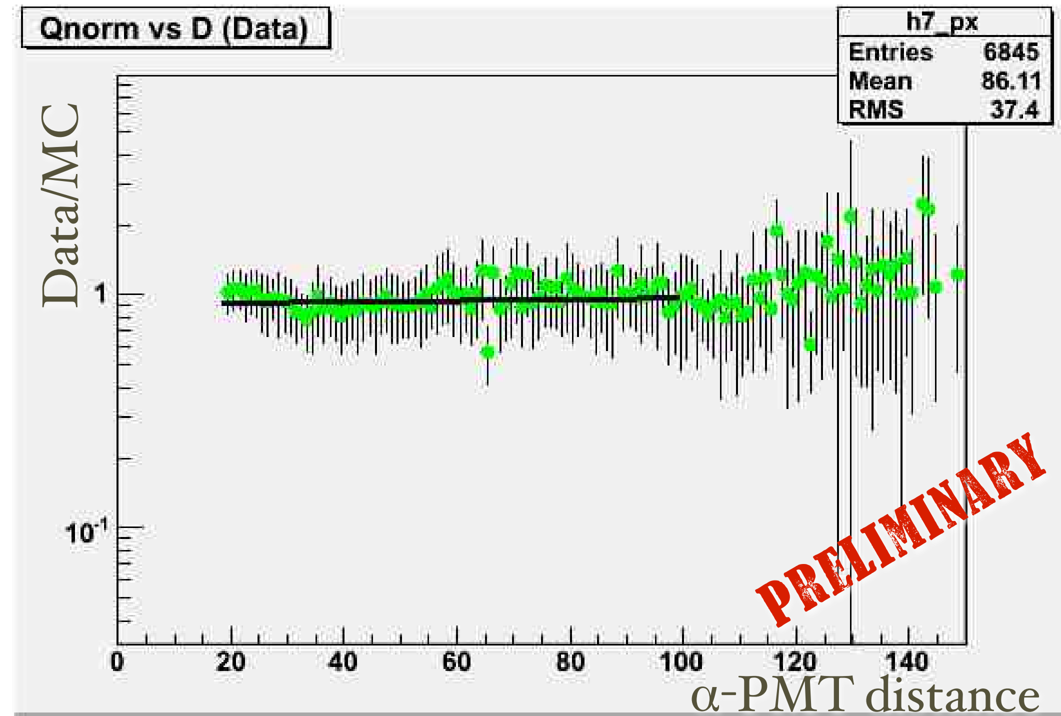






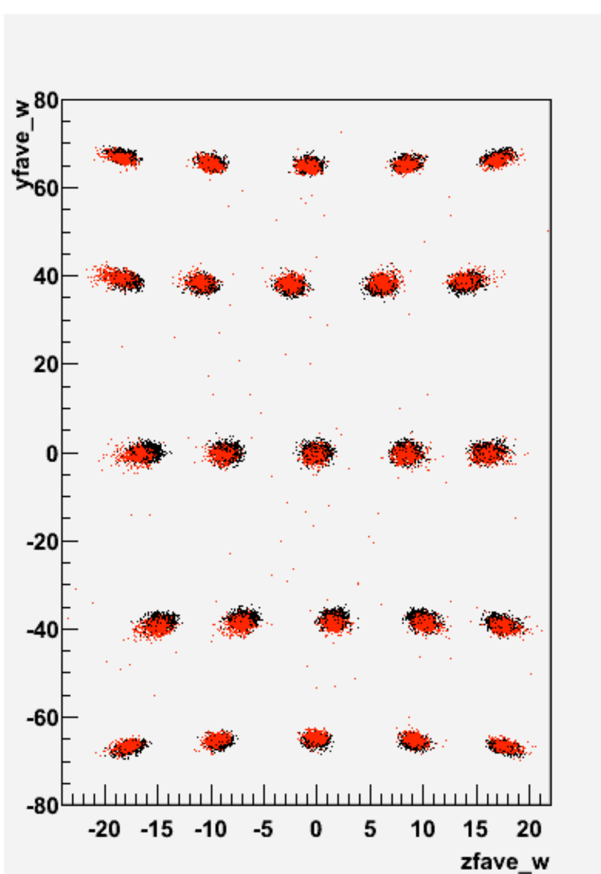
α-sources in Xe

- Used to
  - QE determination
  - Monitor Xe stability
  - Measure absorption
  - Measure Rayleigh scattering



$\lambda_{Abs} > 300$ cm

GXe: MC & data



LXe: MC & data