Performance of the MEG detector

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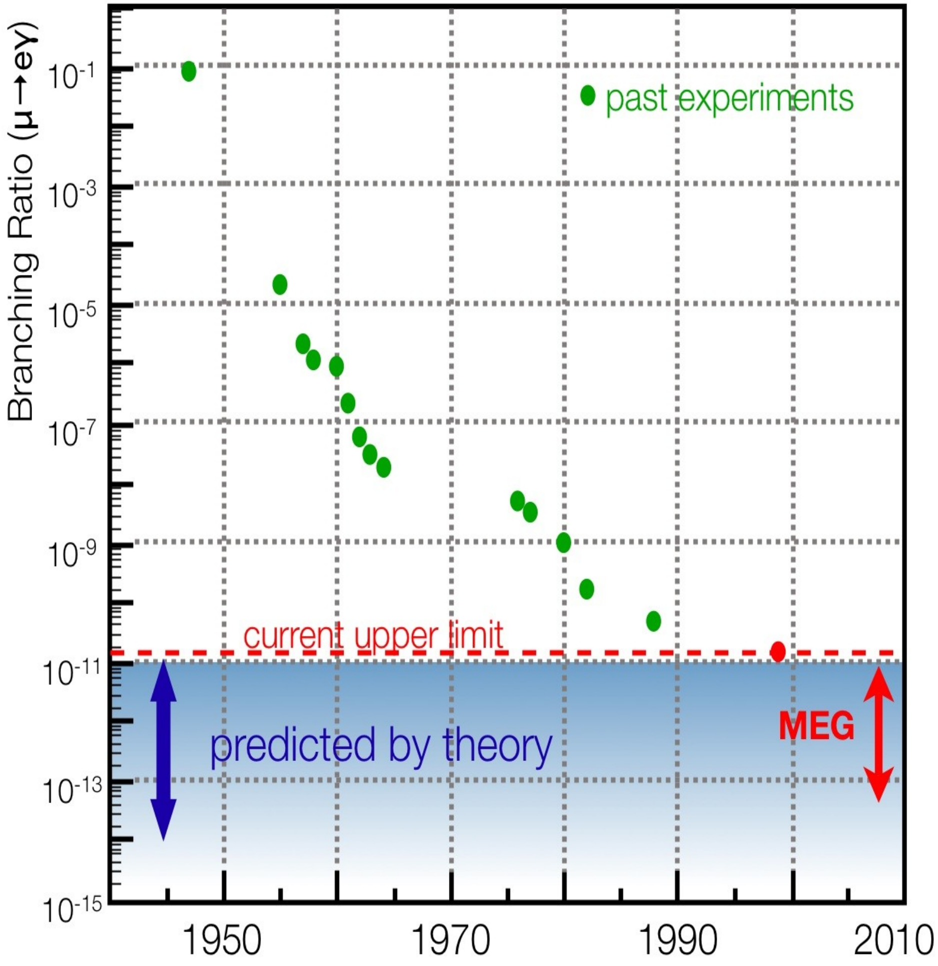
- Outline
  - Introduction
  - MEG experiment
  - MEG detector
  - Performance in 2010
  - Improvement in 2011 and later
  - Summary

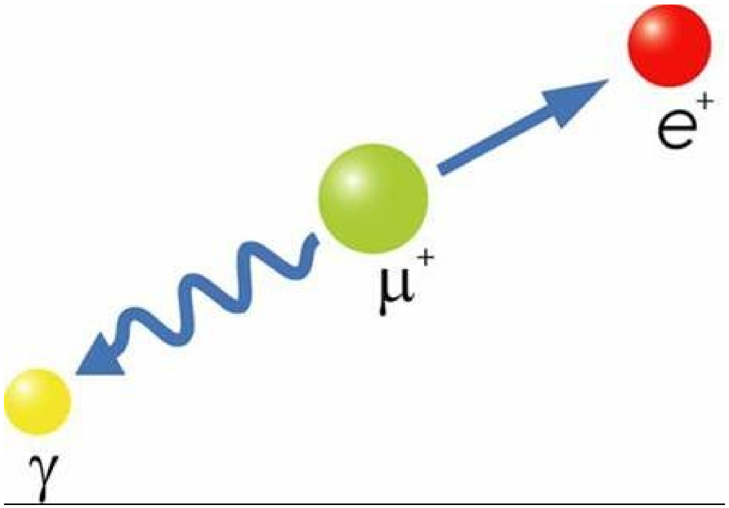
Lepton Flavor Violation

- μ -> eγ decay
  - Lepton flavor violating decay
  - In the SM with neutrino oscillation, the branching ratio is tiny($\sim 10^{-50}$)
  - Previous experimental upper limit (before MEG experiment)
    - 1.2×10^{-11} (1999, MEGA)
  - Well motivated new physics (SUSY-GUT, SUSY seesaw,...) predict the branching ratio around 10^{-11} –10^{-13} region
- MEG experiment
  - Explore down to 10^{-13} level

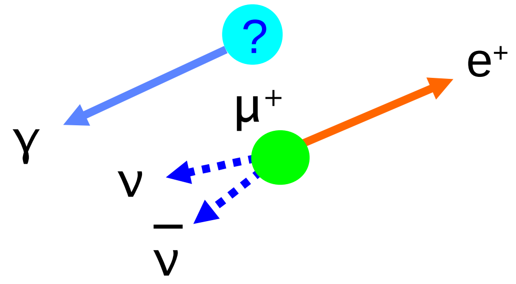


Signal & background

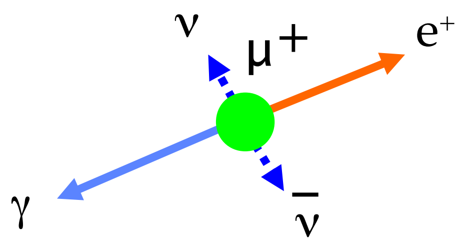
- Signal
  - μ^+ decay at rest
  - 52.8MeV (half of M_μ) (E_γ,E_e)
  - Back-to-back ($\theta_{e\gamma}$,$\varphi_{e\gamma}$)
  - Timing coincidence ($T_{e\gamma}$)



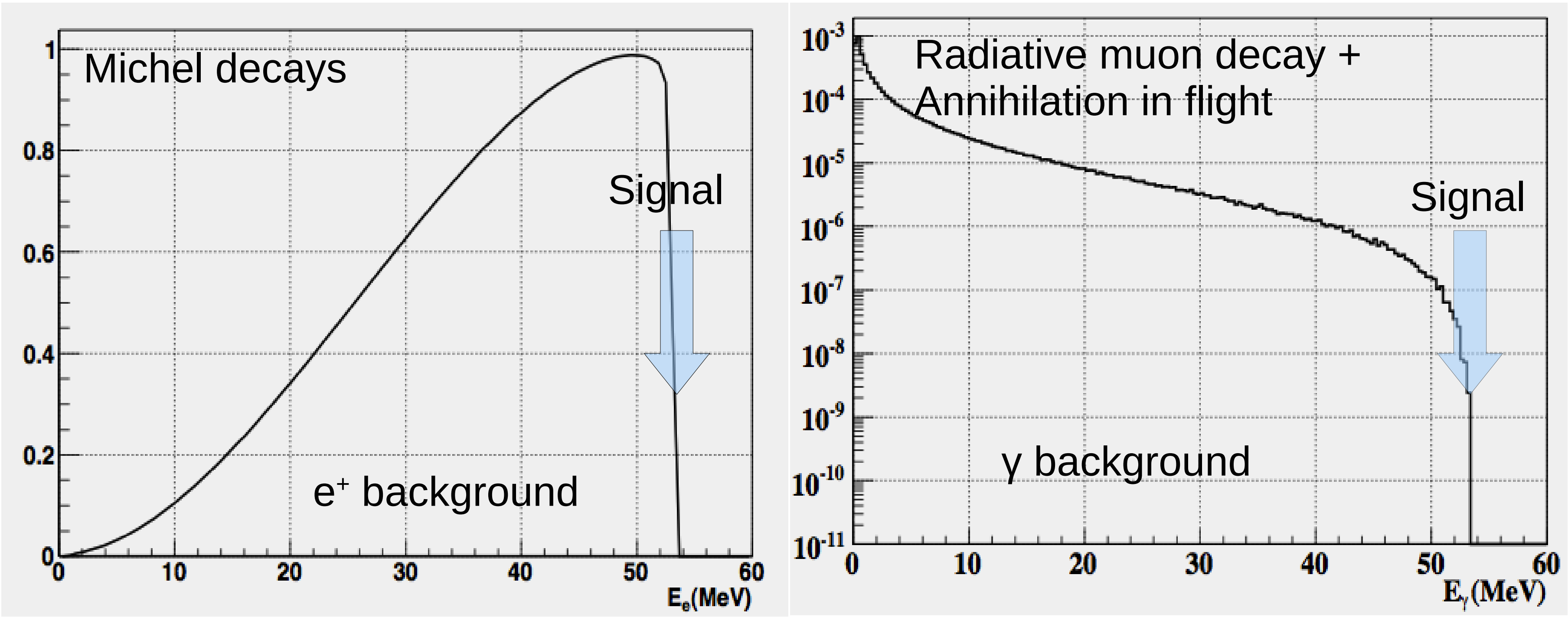
- Accidental background
  - Michel decay e^+ + random γ
  - Dominant background for us
  - Random timing, angle, <52.8MeV



- Radiative muon decay
  - $\mu \to e\nu\nu\gamma$
  - Timing coincident, not back-to back, <52.8MeV



Background spectra



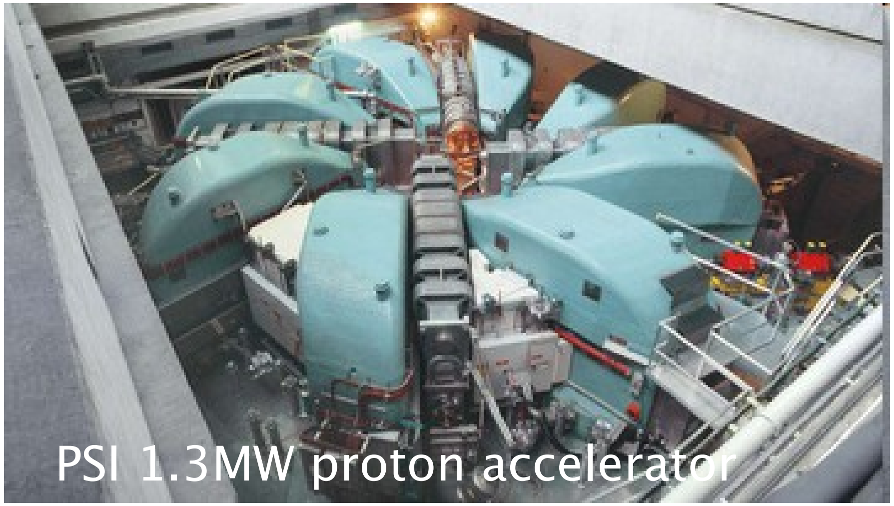
$$N_{acc} \propto R^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot (\delta \vartheta_{e\gamma})^2 \cdot \delta t_{e\gamma}$$

Good detector performance (especially E_γ)

High rate positron measurement

Pileup identification

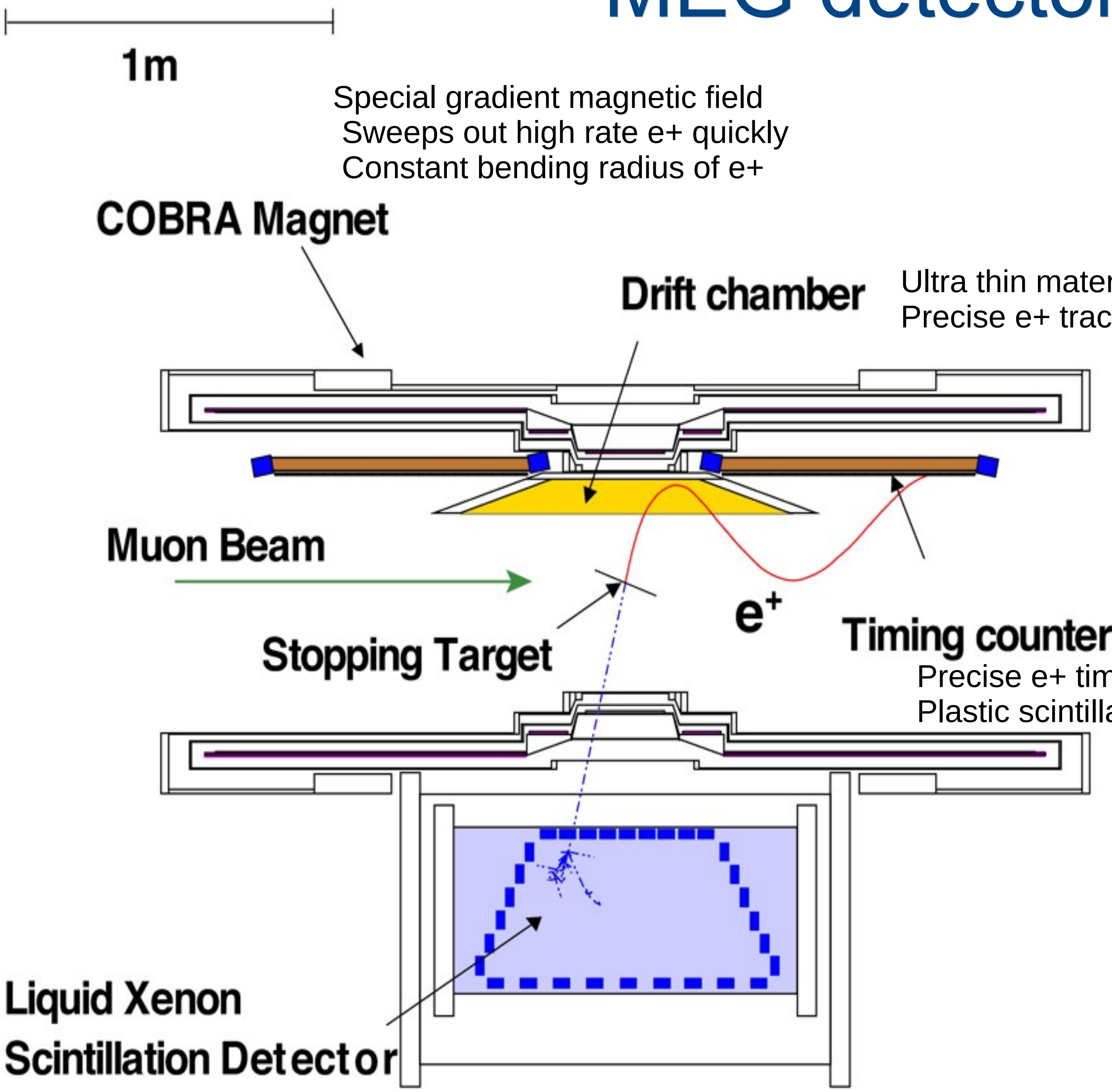
MEG experiment



Most intense DC muon beam
($>1\times10^{8}\mu^{+}/s$) possible

- Requirement:
  - Need many muon decays
  - Detectors(e^{+}) should be working in high rate environment
  - Good energy, timing, and position resolutions

MEG detector

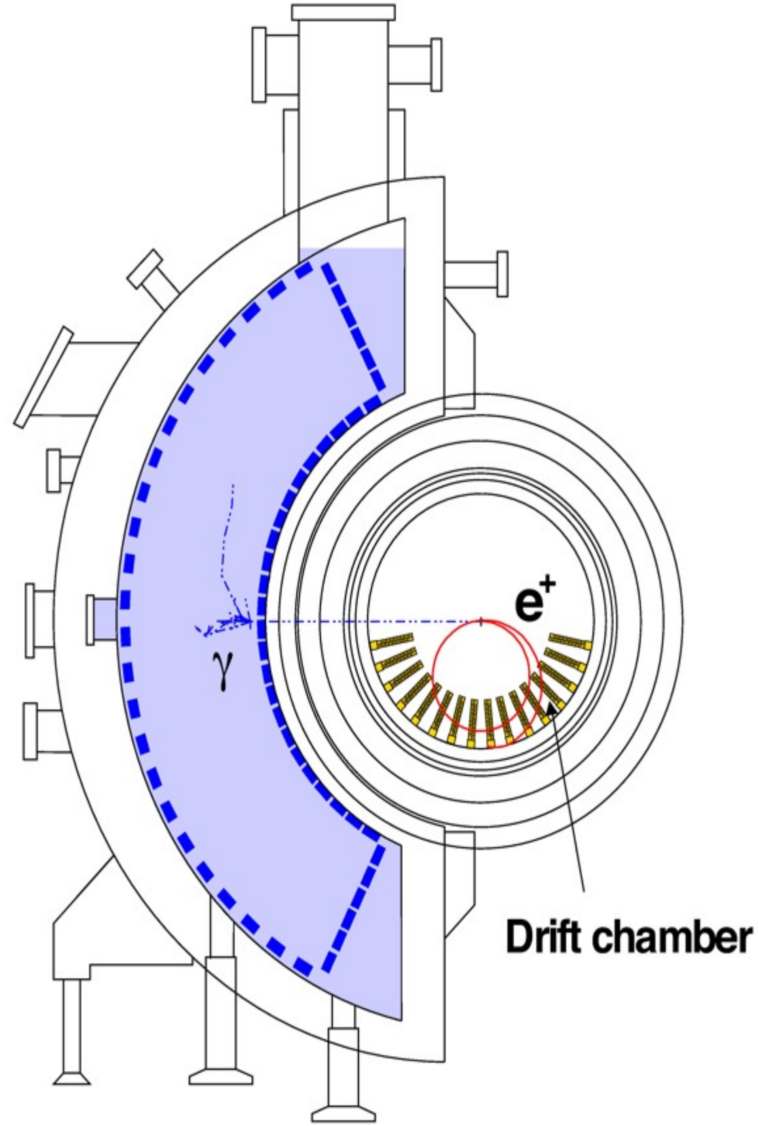


Special gradient magnetic field
Sweeps out high rate e+ quickly
Constant bending radius of e+

Ultra thin material
Precise e+ tracking

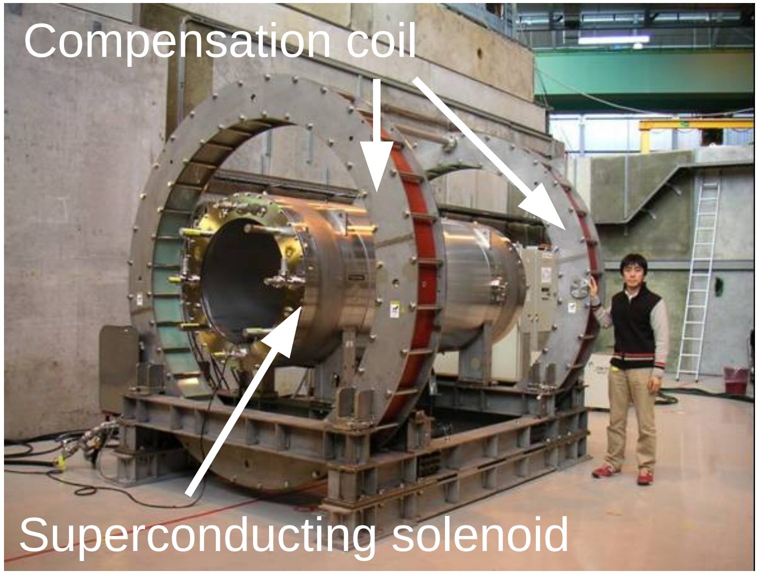
Precise e+ timing
Plastic scintillator + PMTs

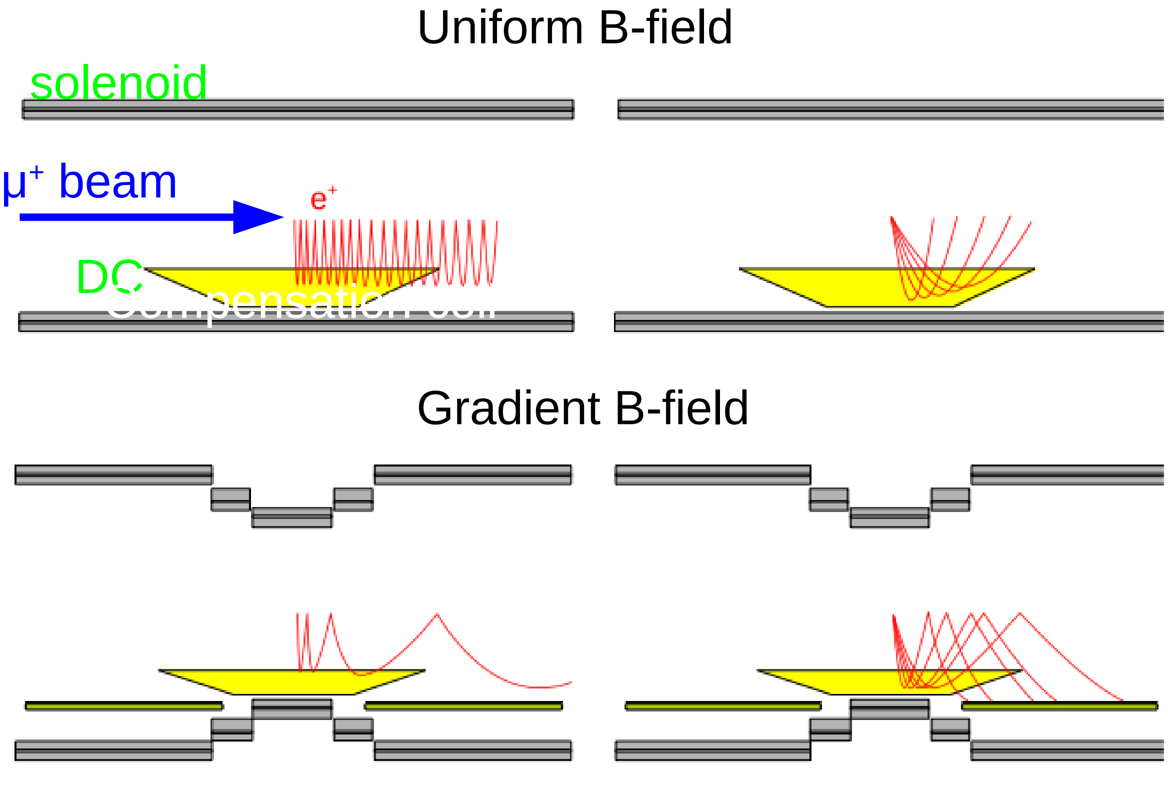
2.7 ton of liquid xenon
Homogeneous detector
Good time, position, energy resolution

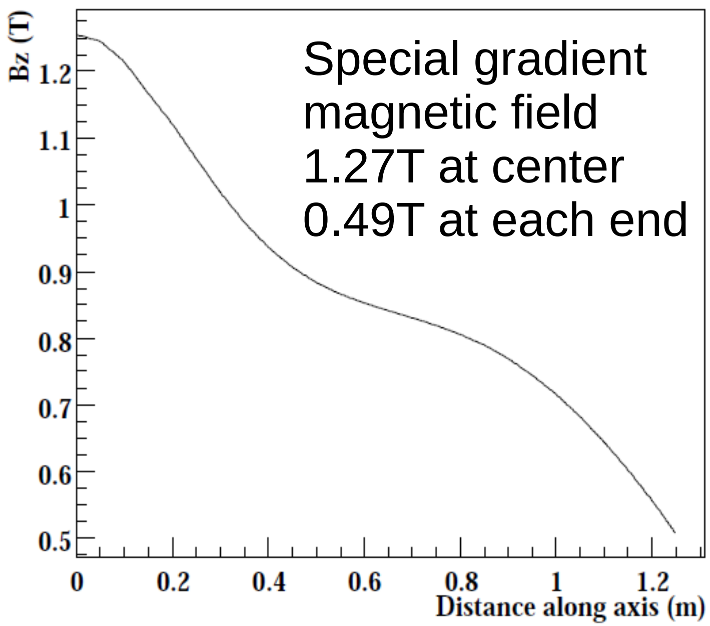


Waveform digitizer for all detectors (pileup ID)

Positron spectrometer



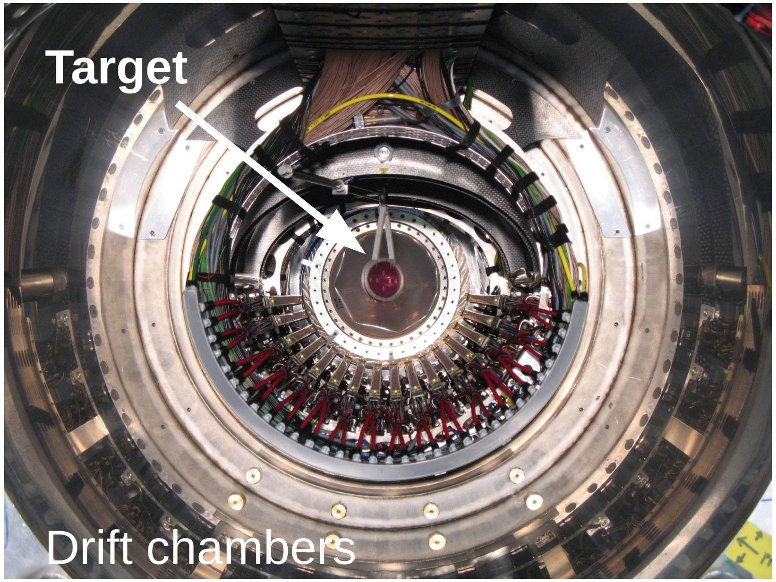


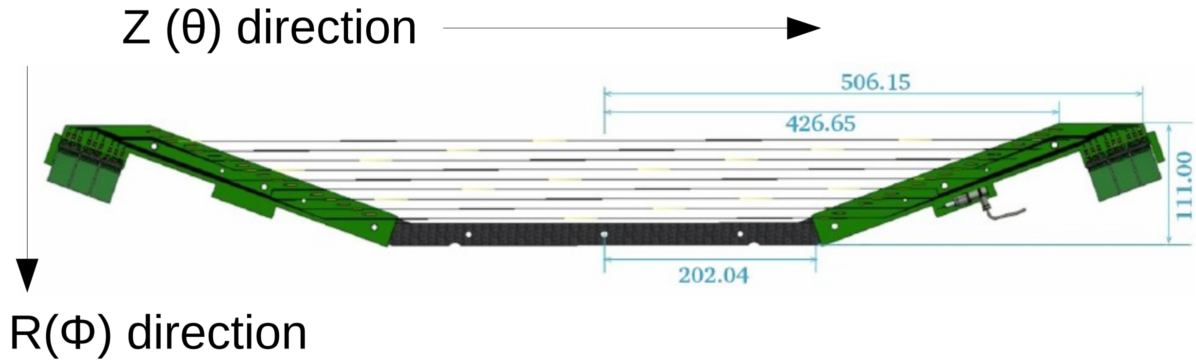


Low energy positron quickly swept away

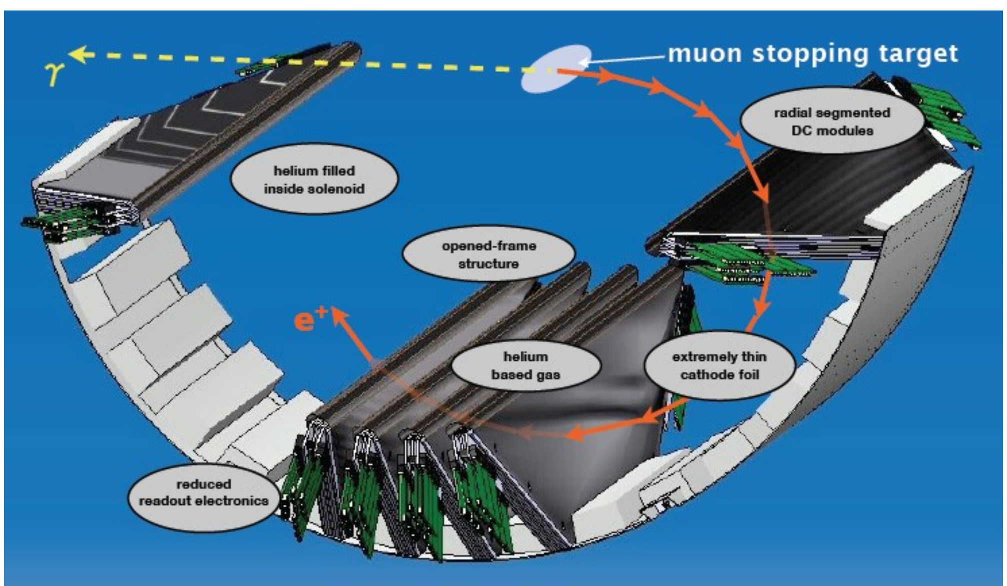
COnstant **B**ending **RA**dius independent of emission angles

Drift chambers



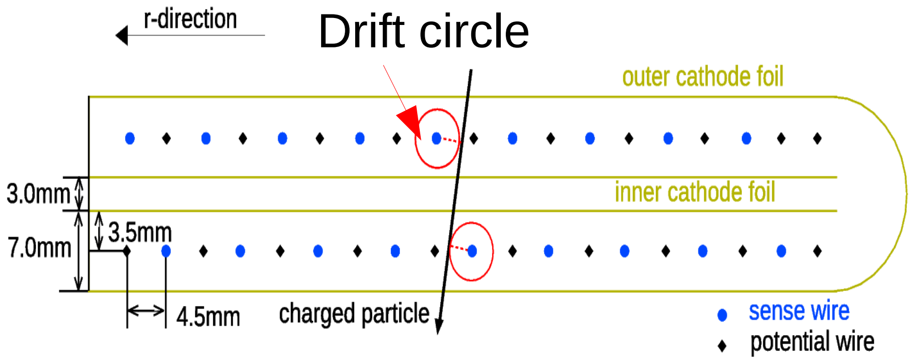


- Positron tracking
  - Momentum, emission angle (θ,φ)
- 16 radial drift chambers
  - Only high momentum e^+ (>40MeV, 19.3cm<r<27.9cm)
- Chamber gas He:C_2H_6 = 50:50
- Low material budget
  - Open frame at the target side
  - Low MS, low γ background

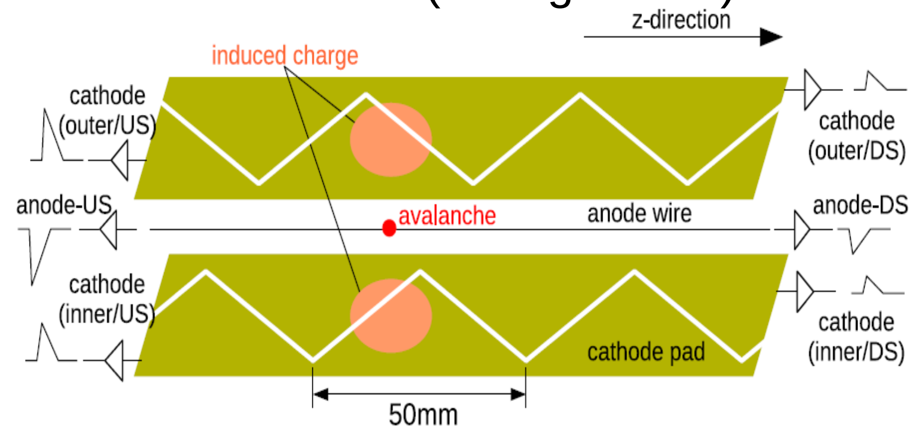


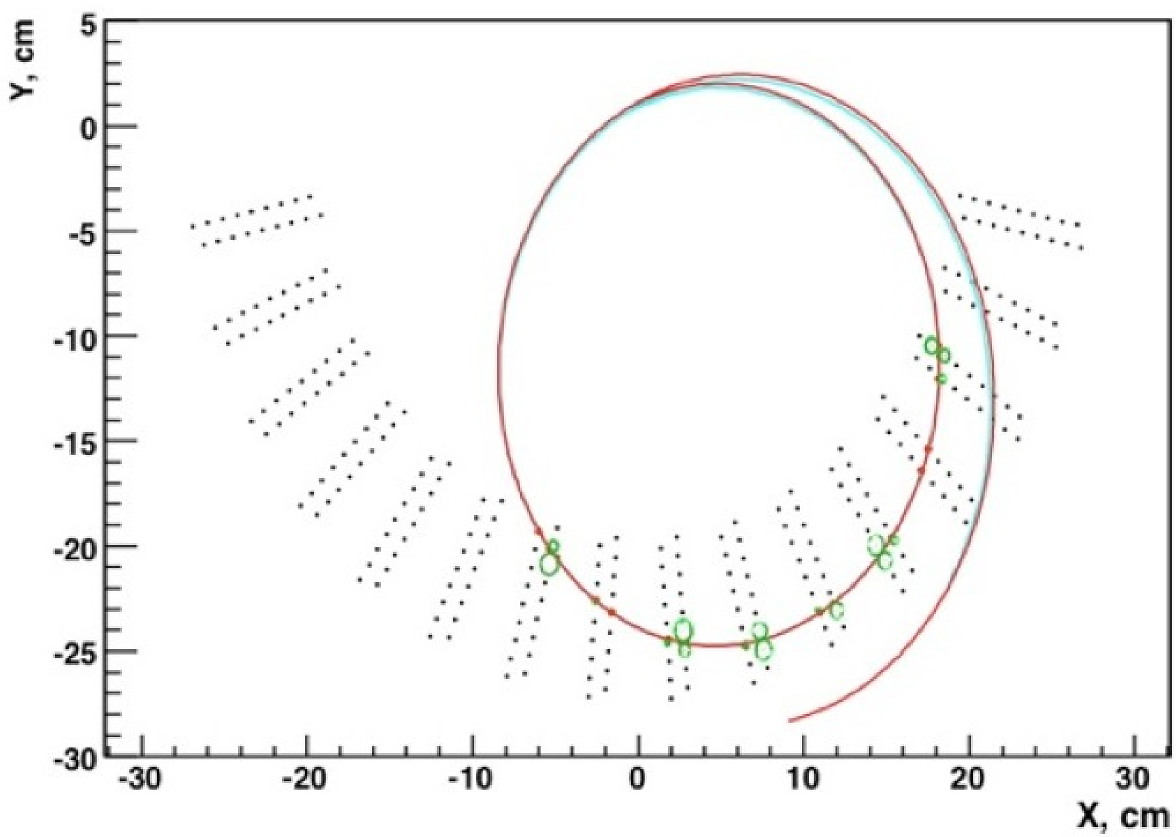
Track reconstruction

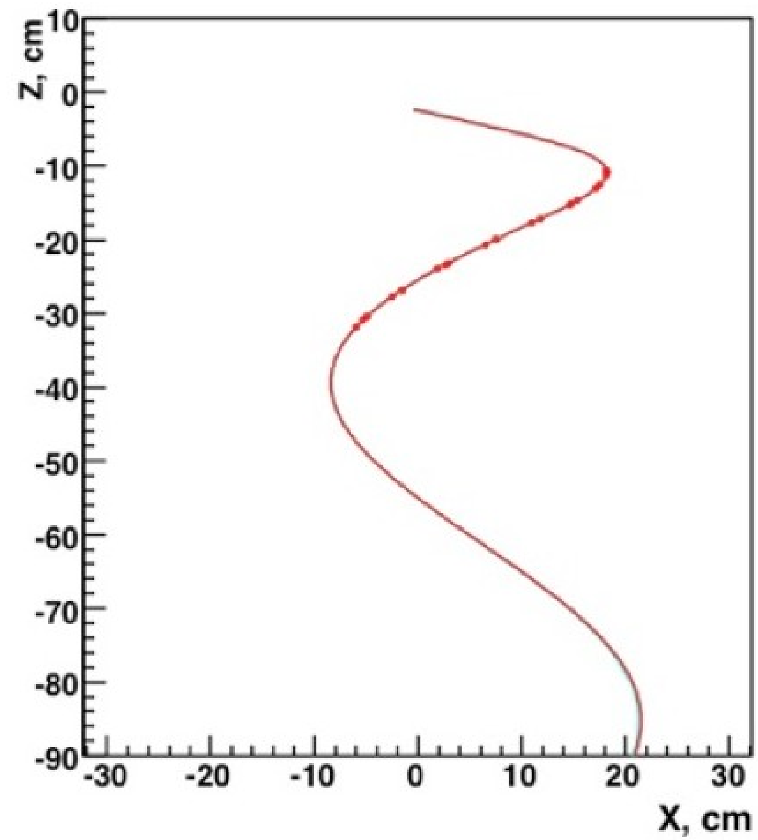
R direction (drift time)



Z direction (charge ratio)

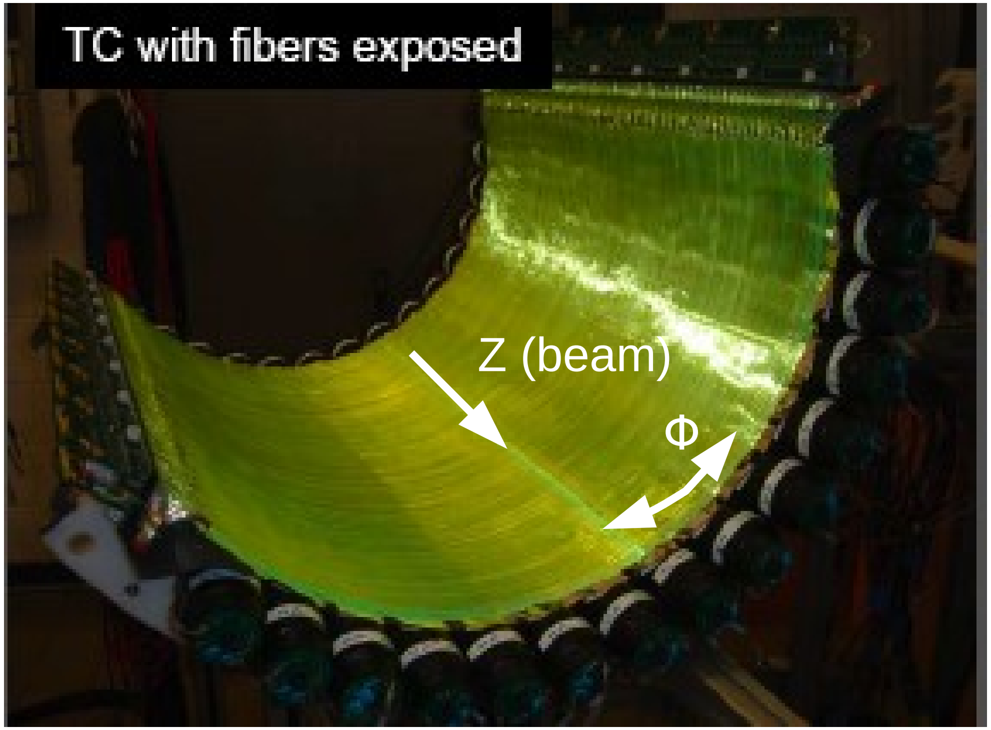


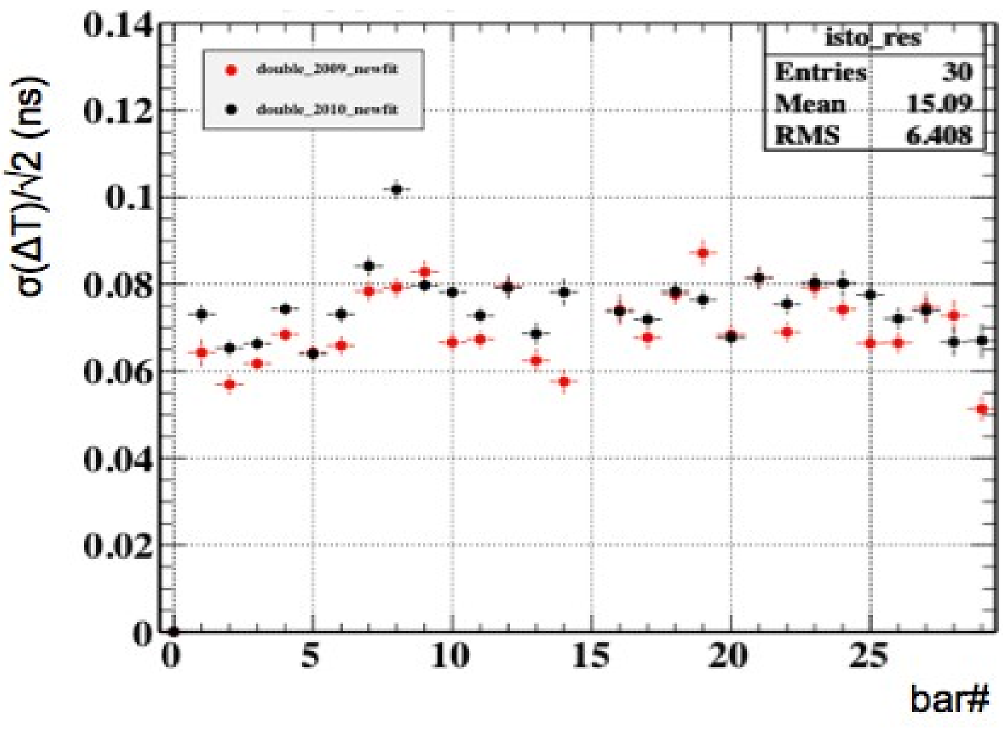




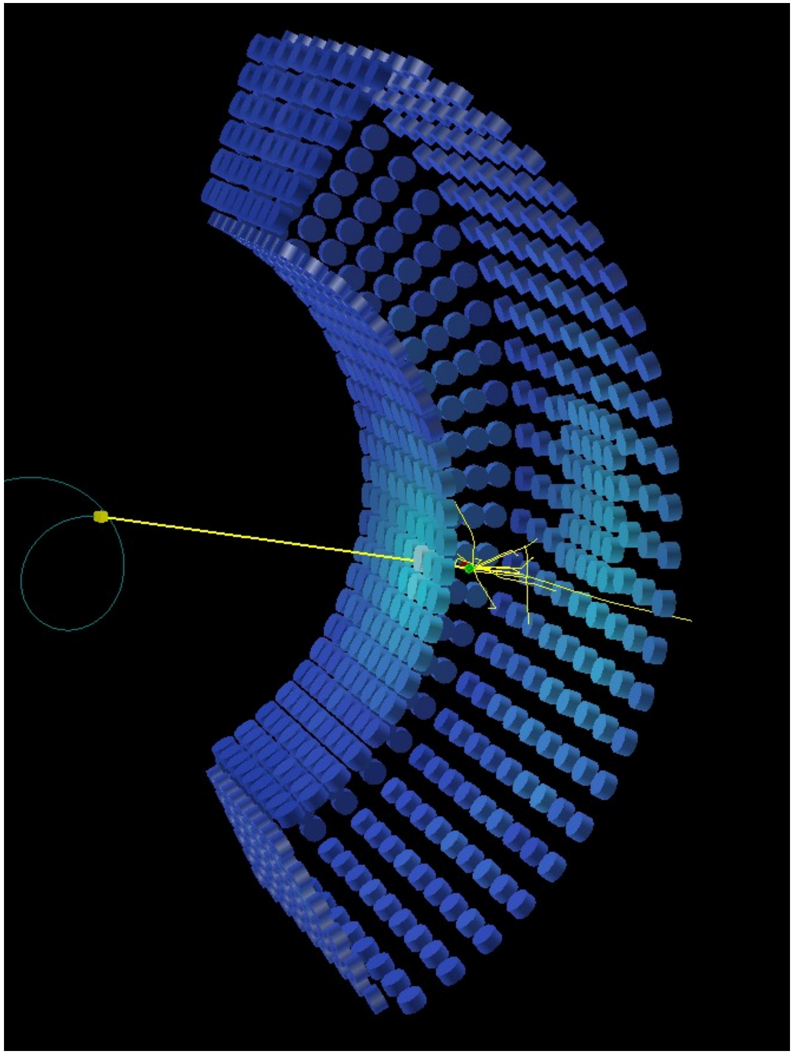
Timing counter

- 15x2(Upstream/Downstream) plastic scintillator bars ($4x4x80cm^3$)
  - Fine mesh PMTs at both ends, positron timing measurement (σ~65ps)
  - Positron φ, z position reconstruction(~5cm)
- Scintillating fibers ($6x6mm^2$) + APD
  - Precise z position measurement, fast θ emission angle information





2.7t Liquid xenon gamma-ray detector

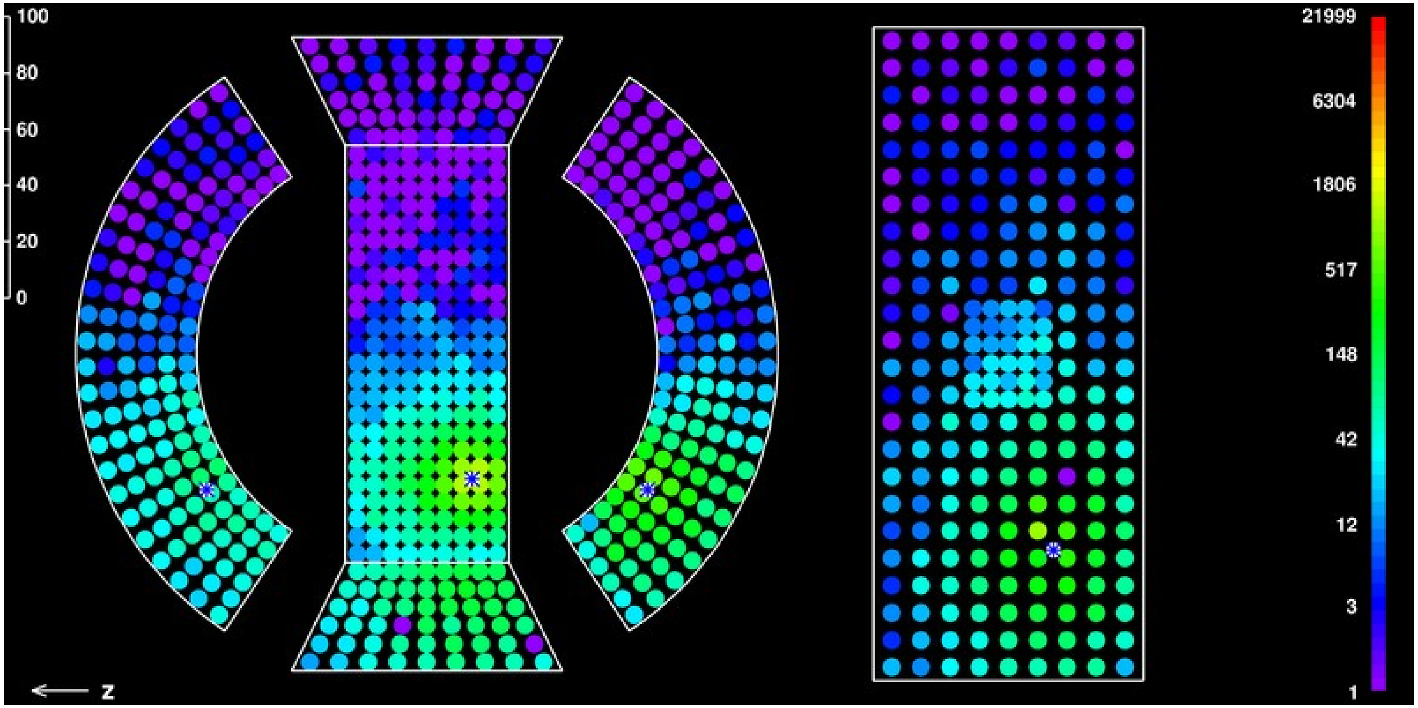


- 900L liquid xenon
- 846 2" PMTs (Hamamatsu)
  - Submerged in Liquid
- γ energy, position, and timing reconstruction
- Merits
  - High light output(80% of NaI)
  - Fast timing response(45ns)
  - Heavy($3g/cm^3$)
- Challenges
  - Low temperature(160K)
    - 200W pulse tube cryocooler
  - Short scintillation wavelength (178nm)
  - Gas/liquid purification

Reconstruction & Goal of gamma ray detector

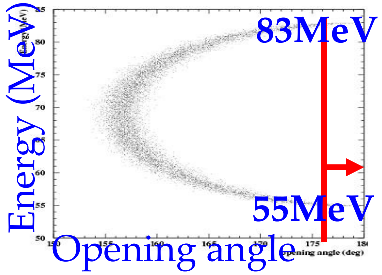
- Reconstruction
  - Energy: weighted sum of all PMTs
  - Position: peak of light distribution
  - Time: weighted average of time of PMTs
- Pileup detection
  - Waveform
  - Light distribution

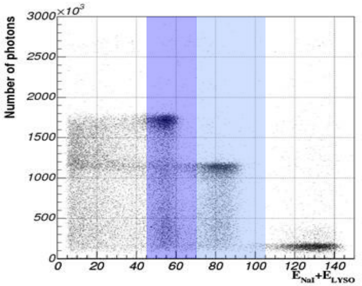
- Goal
  - Energy resolution: 1.2-1.5%
  - Vertex (Opening angle): 2-4mm
  - Time resolution: 65ps

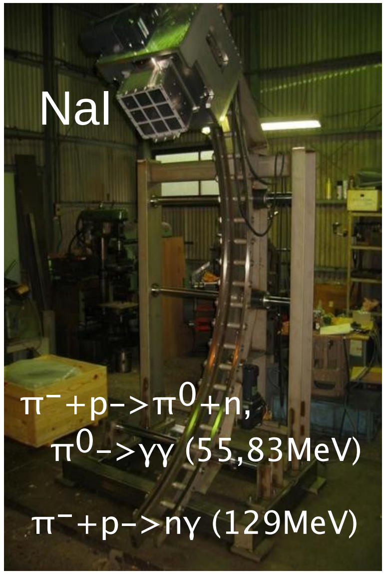


Calibration methods

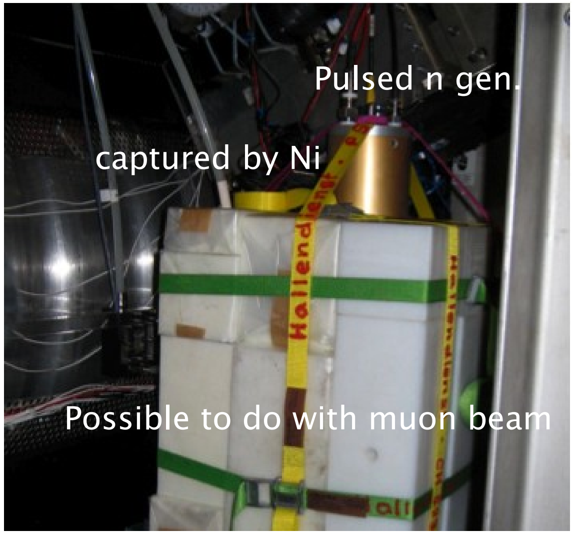
55MeV γ (CEX)



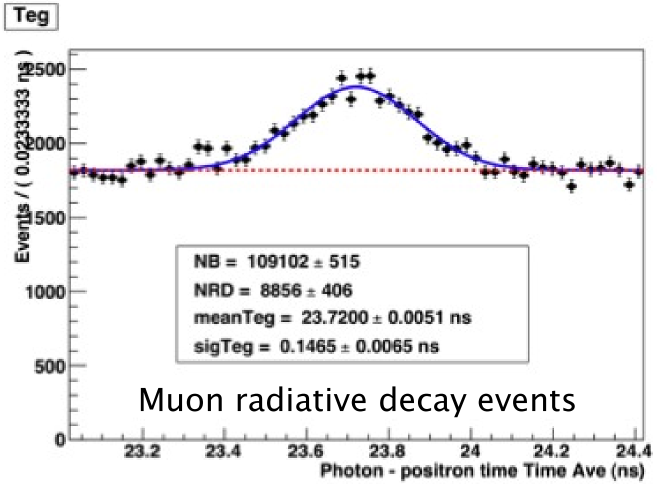




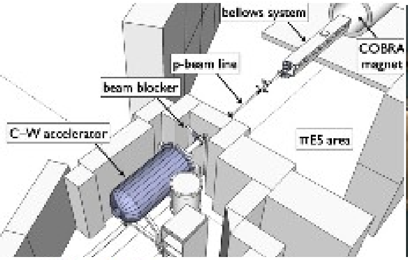
9MeV γ

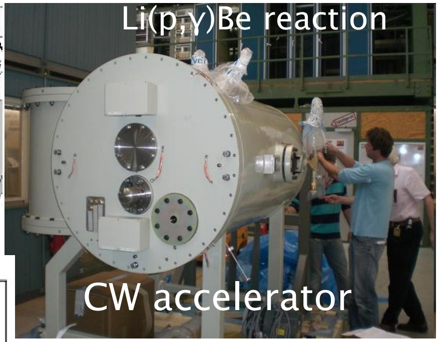


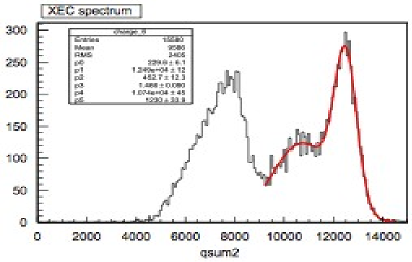
Timing resolution



17.6MeV γ







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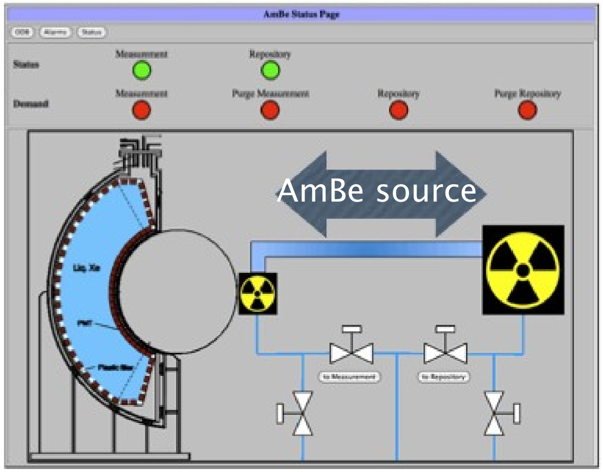
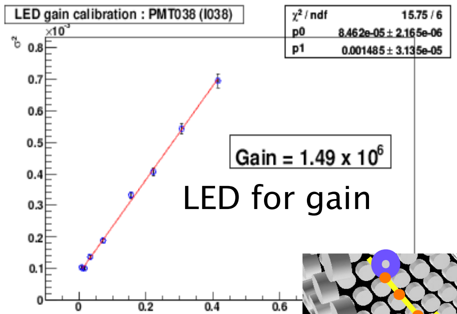
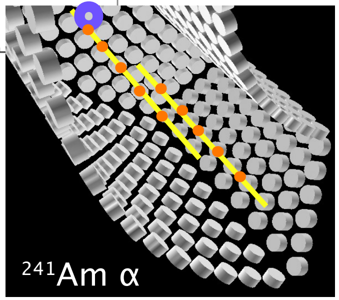
4.4MeV γ

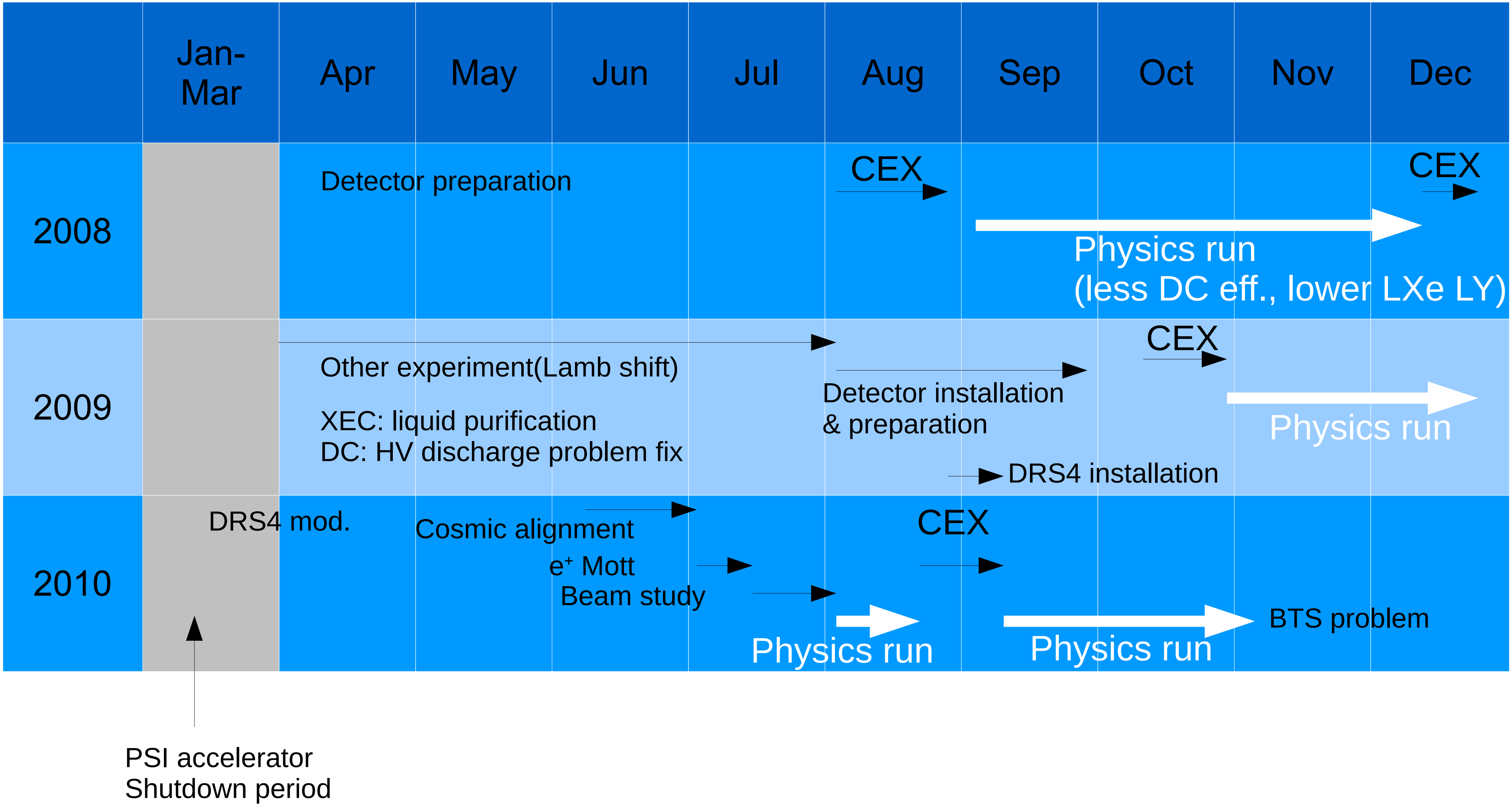


PMT calibration





MEG experiment 2008-2010



Current Status of MEG

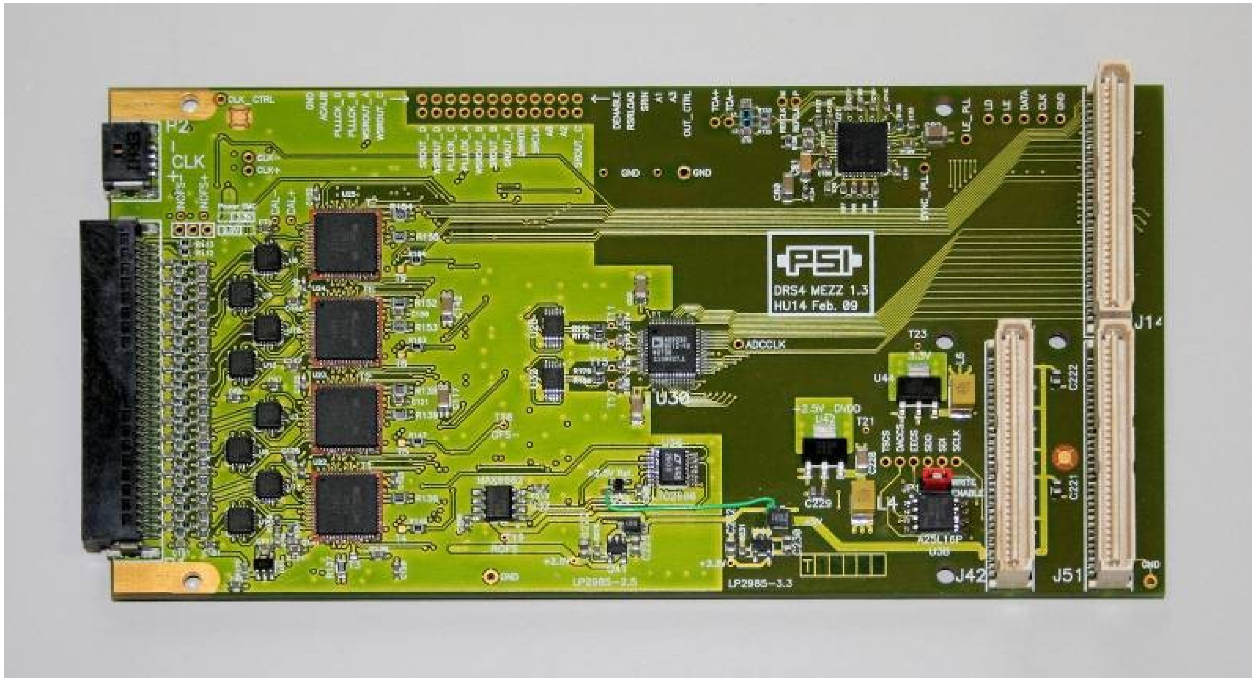
- Physics data taking started in 2008
  - 2008 data
    - $Br(\mu\to e\gamma) < 2.8\times10^{-11}$ at 90%C.L., published in Nucl.Phys.B834:1-12,2010
    - Sensitivity: 1.3×10^{-11}
  - 2009 data
    - $Br(\mu\to e\gamma) < 1.5\times10^{-11}$ at 90%C.L. (preliminary)
    - Sensitivity: 6.1×10^{-12} (preliminary)
  - 2010 data
    - 1.9x statistics of 2009
    - 2009+2010 combined analysis result was presented this year
    - $Br(\mu\to e\gamma) < 2.4\times10^{-12}$ at 90%C.L.
    - Sensitivity: 1.6×10^{-12}
- MEG Collaboration
  - ~55 Collaborators from Japan, Italy, Switzerland, Russia, and USA

What's new in 2010

- 2010 data = 2 x 2009 data
  - There was a problem of beam transport solenoid, and 2010 beam time finished prematurely.
- Timing improvement by waveform digitizer
- Positron tracking performance and efficiency slightly worse
  - due to noise problem and more unstable DC layers
- Better calibrations of data
  - Alignments inside/among detectors

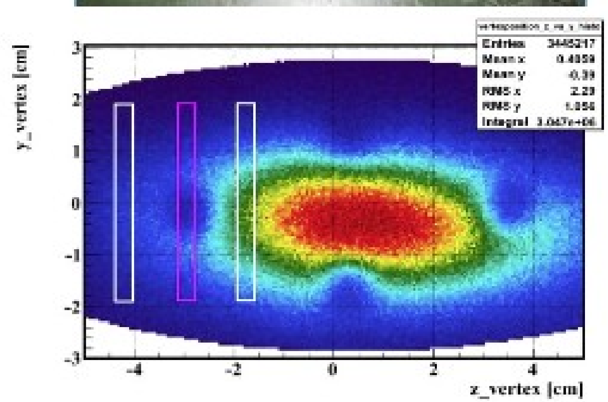
Waveform digitizer upgrade

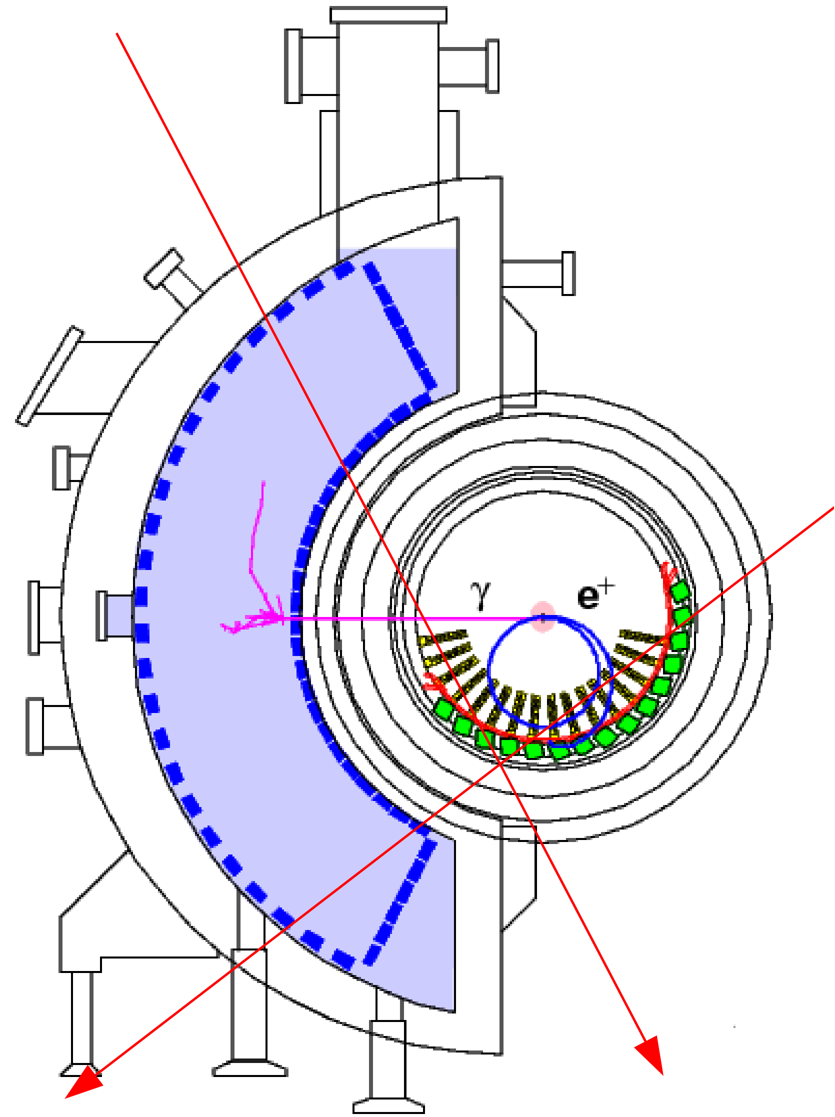
- DRS chip developed at PSI
- Fine tuning of DRS4 digitization board (introduced in 2009)
  - Noise reduction on digital board & time jitter minimization
  - Contribution of timing resolution from electronics
    - 130ps in 2009 -> 50ps in 2010



Alignment inside/among detectors

- Optical surveys
  - DC – target
  - double-checked by target hole
- Alignment by CR
  - DC – XEC
  - DC
- LXe
  - Pb collimators
  - AmBe

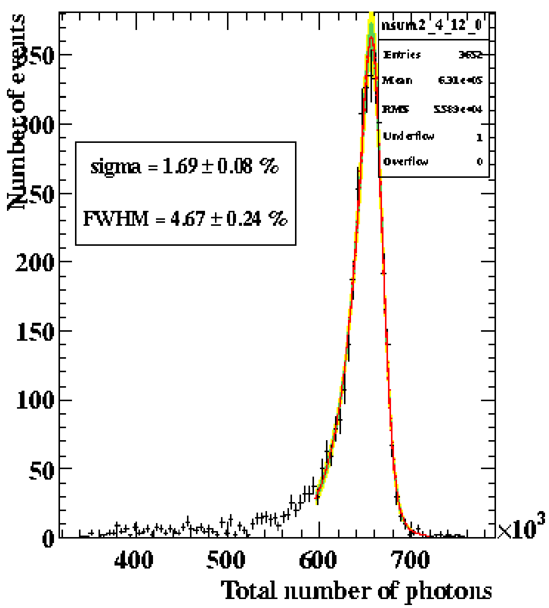


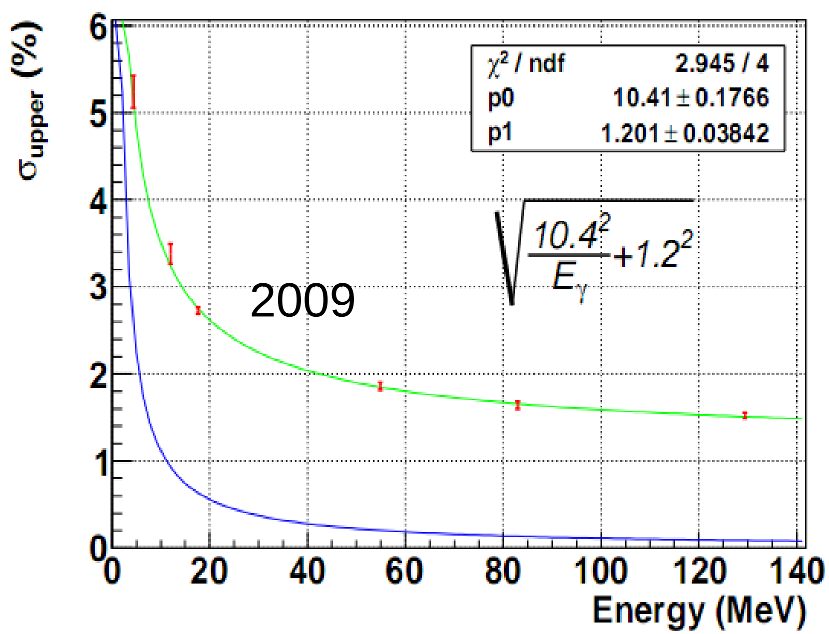


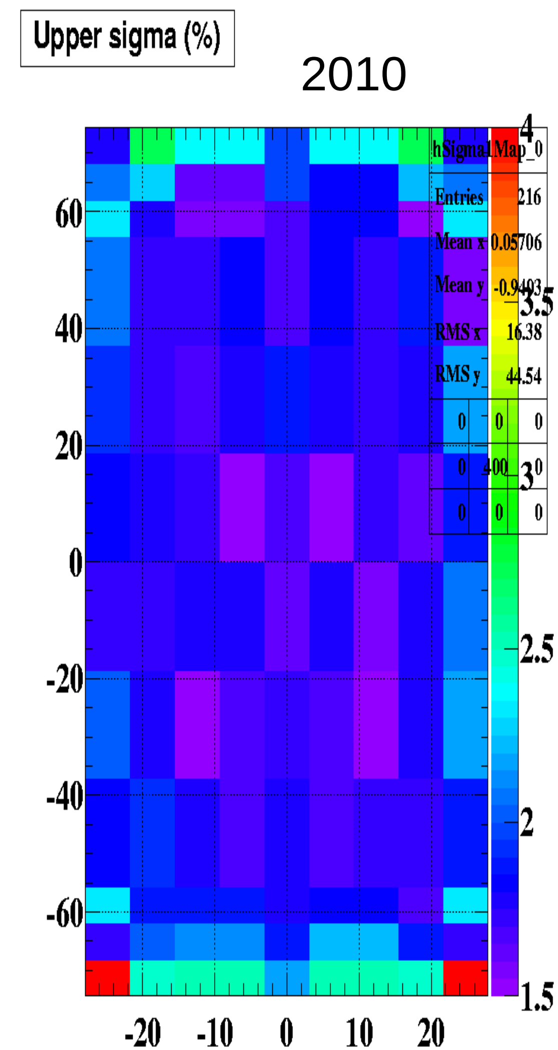
Performance

Energy resolution

- Energy resolution is evaluated with 55MeV γ in CEX data
  - $\pi^- + p \rightarrow \pi^0 + n,\ \pi^0 \rightarrow \gamma\gamma$
- Resolution map on incident position is measured by moving NaI detector

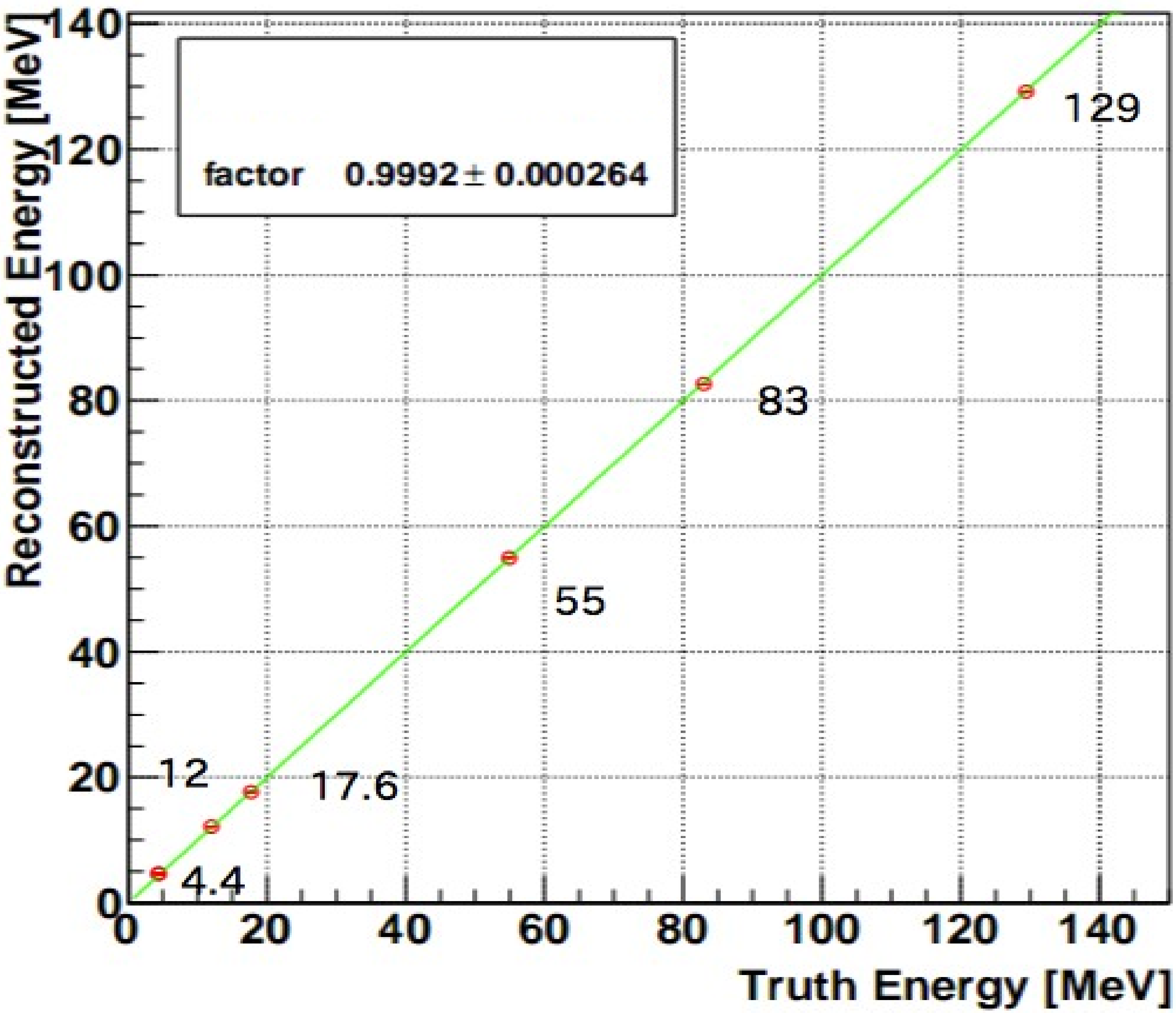






- Result of resolution in 2010
  - 1.9% (depth>2cm), 2.4% (depth<2cm)

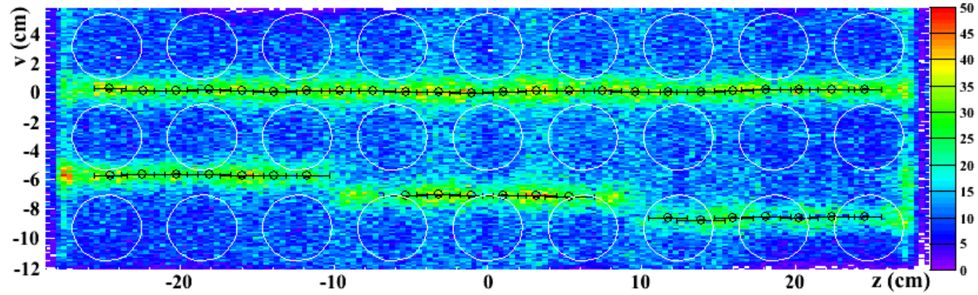
Linearity

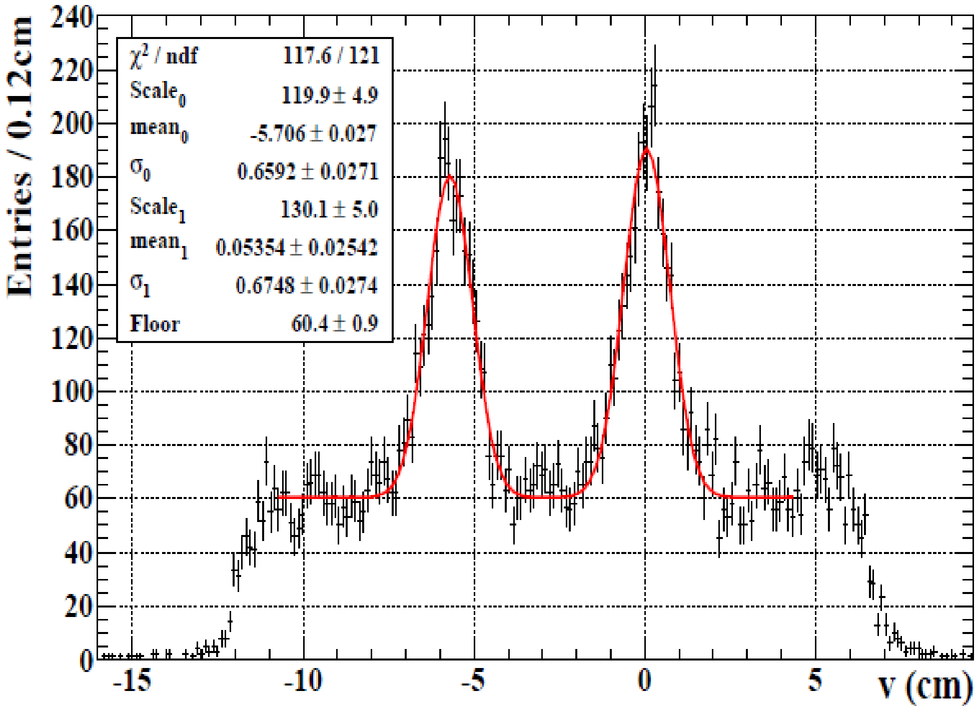


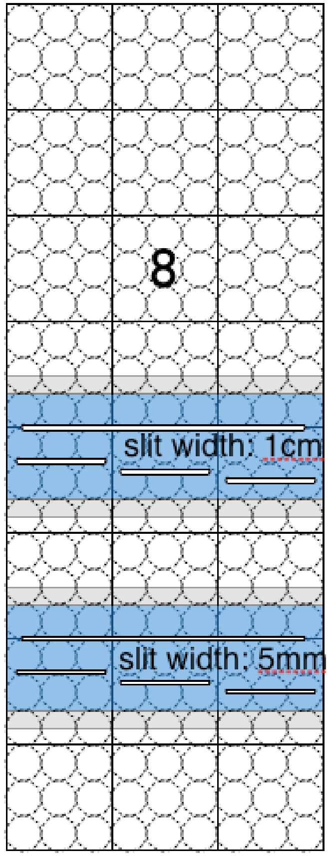
factor 0.9992 ± 0.000264
Reconstructed Energy [MeV]
Truth Energy [MeV]
0
20
40
60
80
100
120
140
129
83
55
17.6
12
4.4

Position resolution

- Position resolution is evaluated CEX data with lead collimator



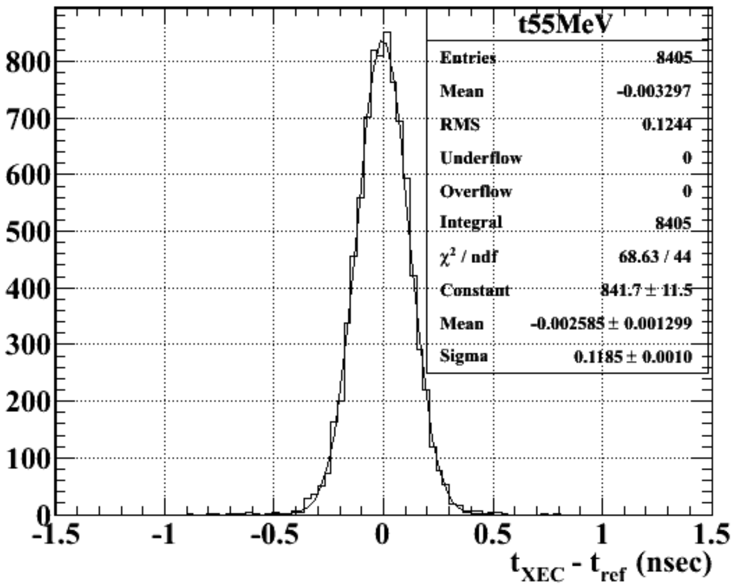


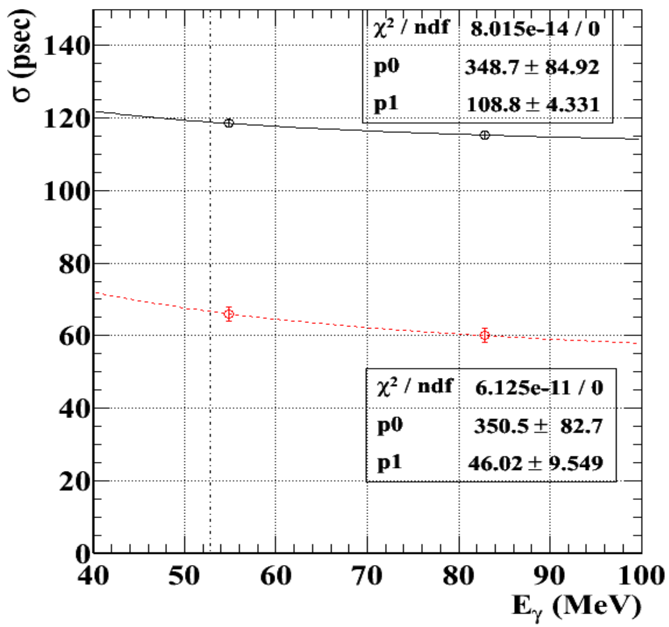


- Resolution in 2009
  - XY direction: 5mm
  - Depth: 6mm
  - MC expectation: 4.5mm (due to insufficient Q.E. Estimation?)

Timing resolution

- Time difference between XEC and reference counter in CEX

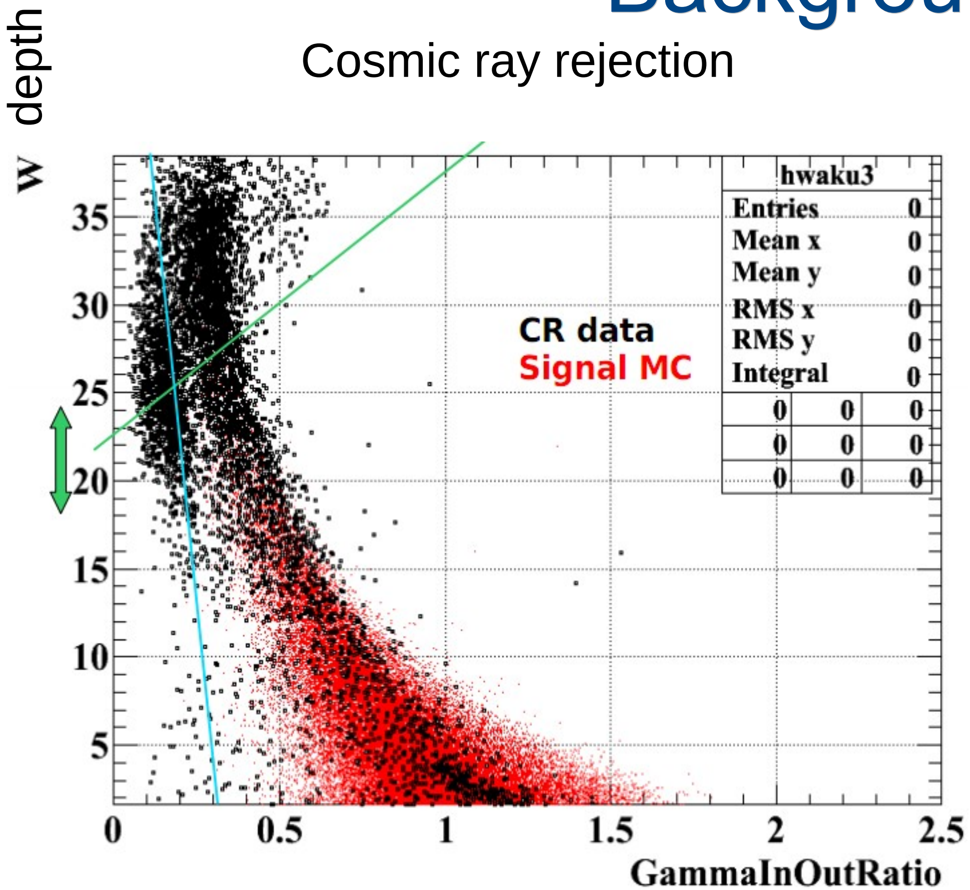




- Result
  - 119ps at 55MeV (171ps in 2009, thanks to electronics improvement)
  - XEC resolution : ~67ps
    - 119ps – beam spread(58ps) – resolution of reference counter(81ps)
    - Breakdown
      - XEC intrinsic(36ps), ToF(20ps), DRS(24ps), and 46ps
    - Further improvement only possible by new detectors
      - higher Q.E. PMT etc.

Background rejection

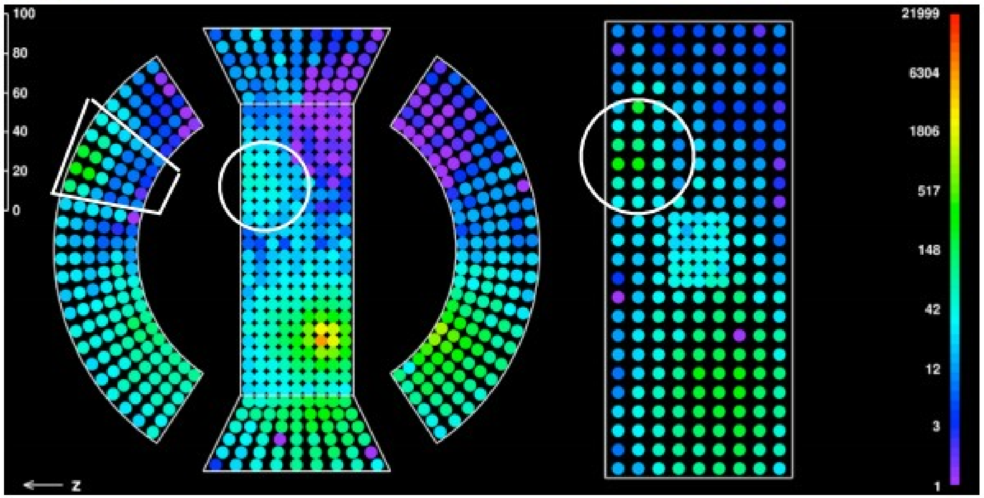
Cosmic ray rejection



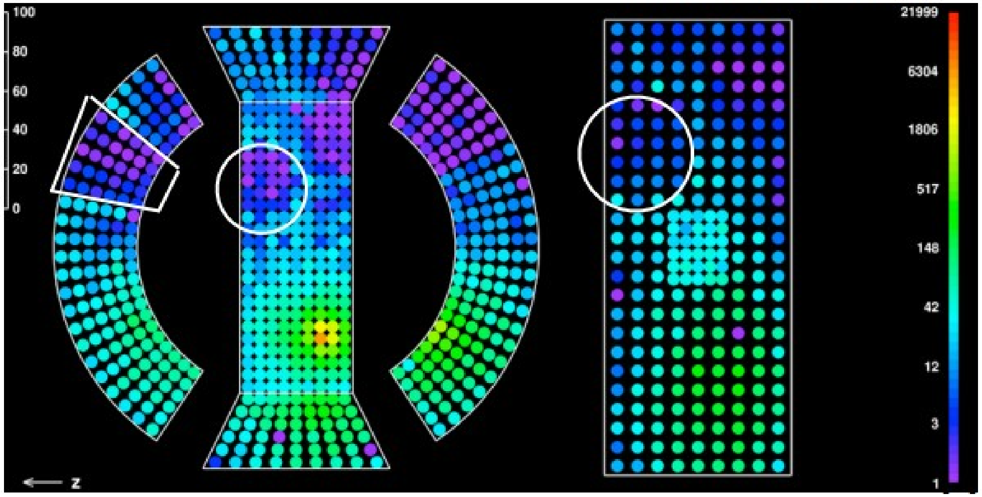
Inner/Outer charge Ratio

Pileup elimination

Original

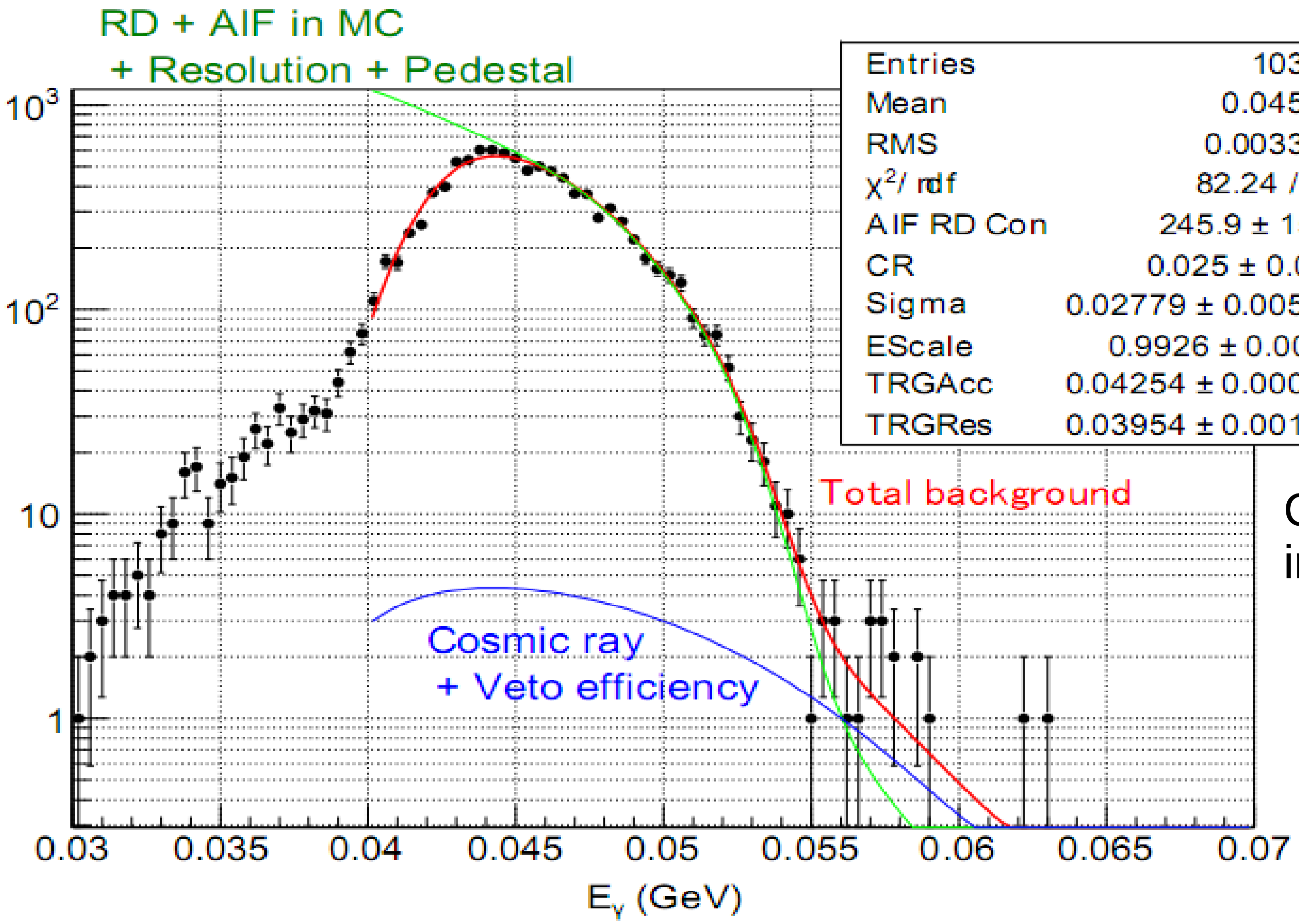


After replacement



1. Find pileup
2. Reconstruct energy w/o pileup region, calculate expected charge
3. Replace these charge

Background spectrum



Contribution of background events in signal region (51-55MeV)

RD+AIF (single gamma)	93%
Cosmic ray	1%
Remaining (pileup, tail etc.)	6%

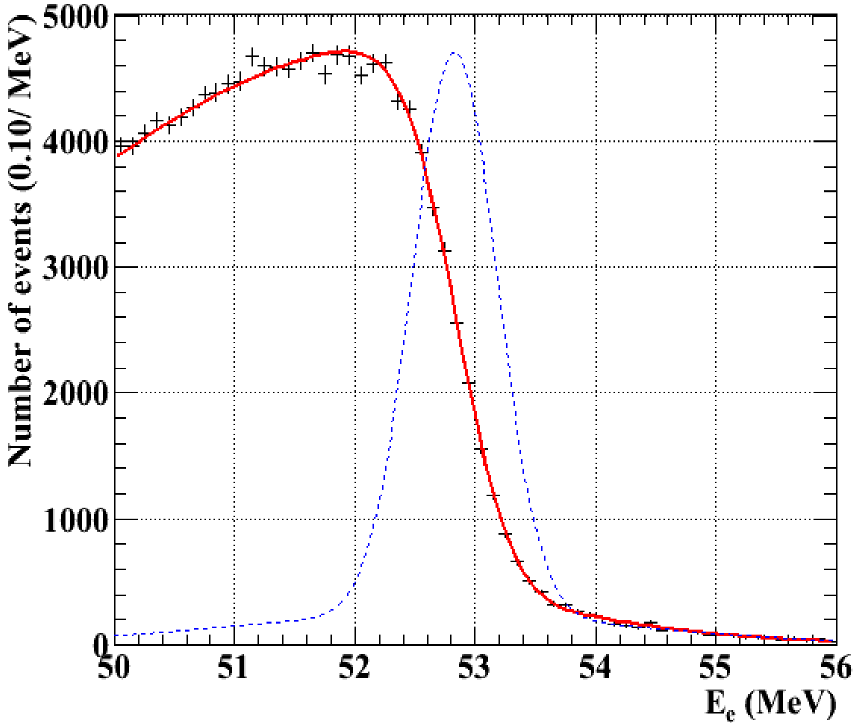
Position dependent γ background spectra --> PDF for likelihood analysis
These can be extracted directly by time sideband data
Detector response (energy resolution, energy scale) can be double checked by this,
And the result is consistent with CEX data

Positron spectrometer performance

2009 : almost all drift chamber working correctly after fixing 2008 HV discharge problem

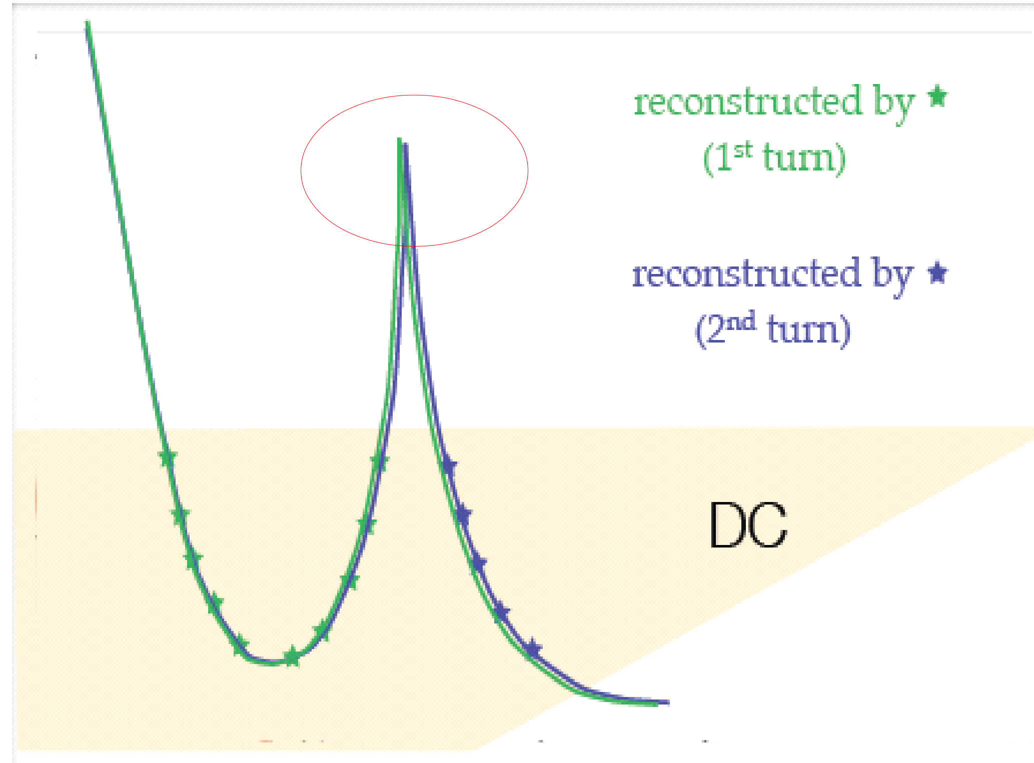
2010 : 5 DC chambers are replaced before 2010 run
more bad planes and slightly worse noise situation

- Momentum resolution is extracted from a fit to Michel edge spectrum
- Detector response
  - triple gaussian + acceptance
  - 2009
    - σ_p = 310keV (80%) + 1.0MeV(13%) + 2.0MeV(7%)
  - 2010
    - σ_p = 330keV (79%) + 1.0MeV(14%) + 2.0MeV(7%)



Positron spectrometer performance, cont.

Muon decay point, angular resolution : from tracks with two turns inside the drift chambers



2009

Vertex z/y
= 1.5/1.1mm

σ_θ = 9.4mrad

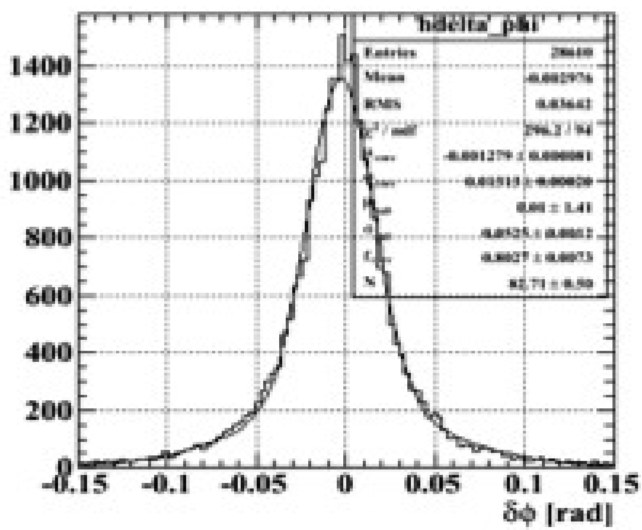
σ_φ = 6.7mrad (φ=0)

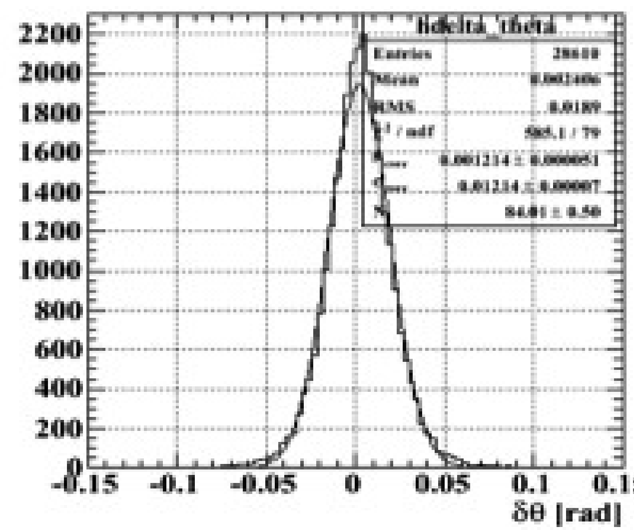
2010

Vertex z/y
= 2.0/1.1mm

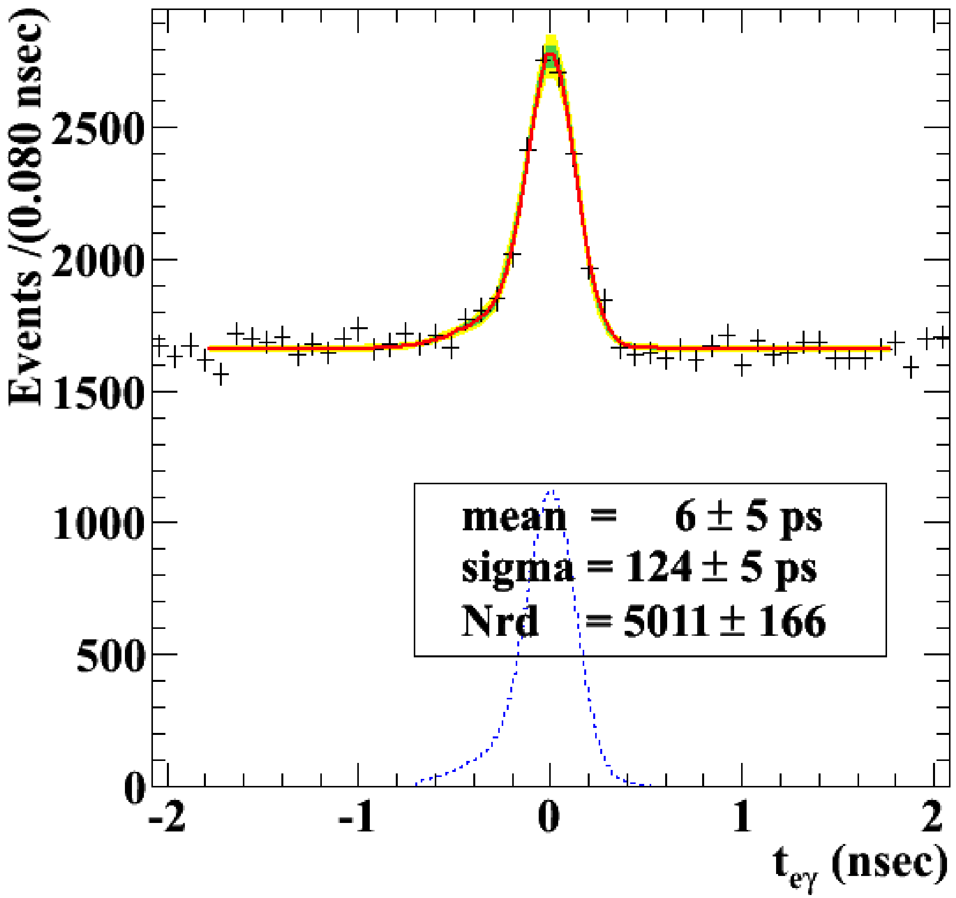
σ_θ = 11.0mrad

σ_φ = 7.2mrad (φ=0)





Positron - photon timing



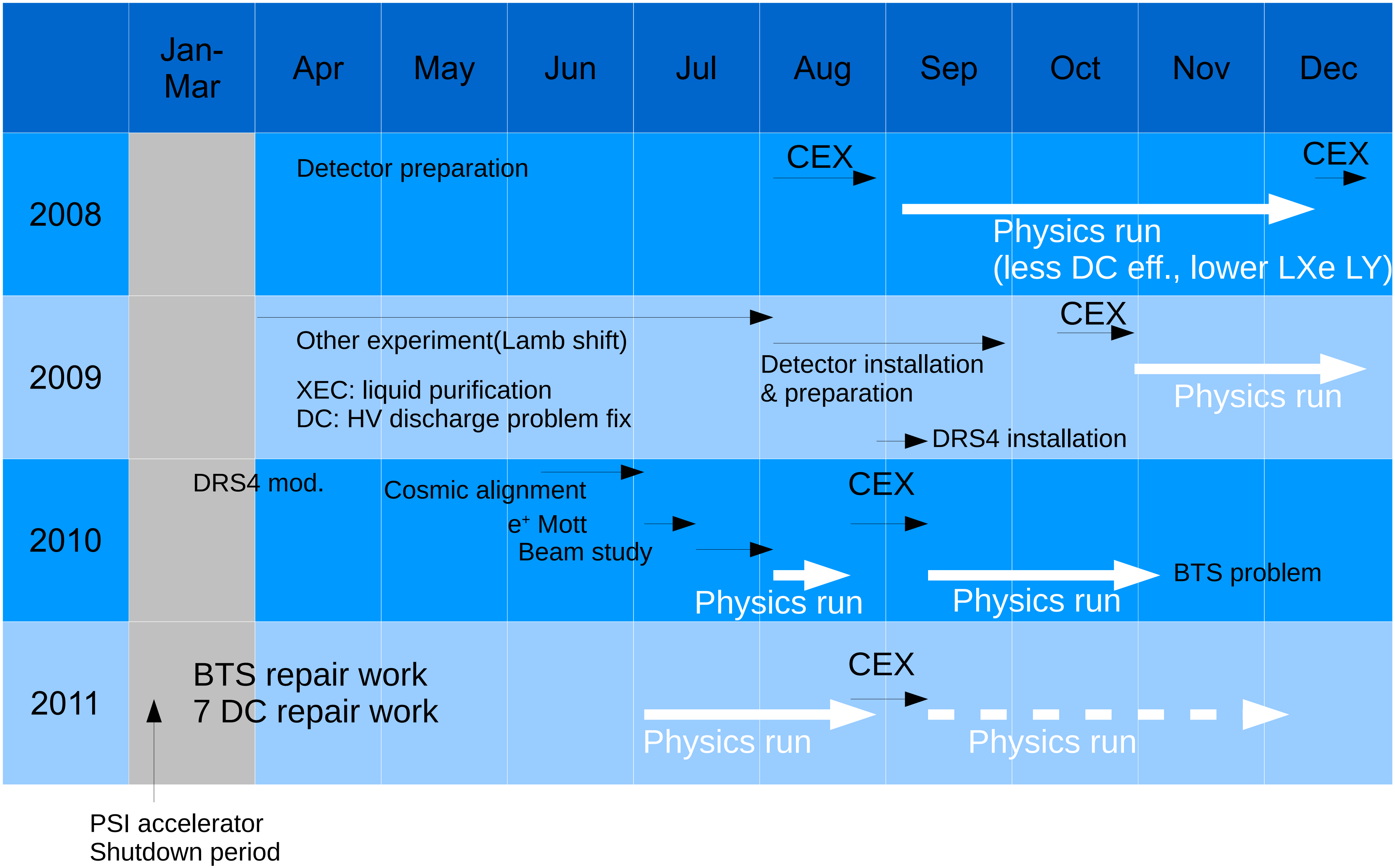
- Radiative muon decay peak
  - In a normal physics run
  - Corrected by small energy dependence
- Timing resolution of $T_{e\gamma}$
  - 122ps in 2010
  - Breakdown
    - Photon T_{γ} : 67 ps
    - T_e : 107 ps
      - T_{TC} : 65 ps (measured by double TC Michel events)
      - Le/c : 75 ps (MC scaled, x1.5)
      - TC calib: 40 ps

Performance summary

	2009	2010
Gamma energy (w>2cm)	1.9 %	1.9 %
Gamma timing	96 ps	67 ps
Gamma position	5(xy)/6(depth) mm	5(xy)/6(depth) mm
Gamma efficiency	58 %	59 %
e^+ momentum	310keV (80% core)	330keV (79% core)
e^+ φ (φ=0)	6.7 mrad	7.2 mrad
e^+ θ	9.4 mrad	11.0 mrad
e^+ vertex Z/Y	1.5/1.1 mm (core)	2.0/1.1 mm (core)
e^+ timing	107 ps	107 ps
e^+ efficiency	40 %	34 %
$T_{e\gamma}$	146 ps	122 ps
Trigger efficiency	91	92
Stopping Muon Rate	2.9×10^{7} / sec	2.9×10^{7} / sec
DAQ time/real time	35/43 days	56/67 days
Expected 90% C.L. Upper Limit	3.3×10^{-12}	2.2×10^{-12}

2009+2010 Combined
Expected 90% C.L. Upper Limit : 1.6×10^{-12}

2011 run

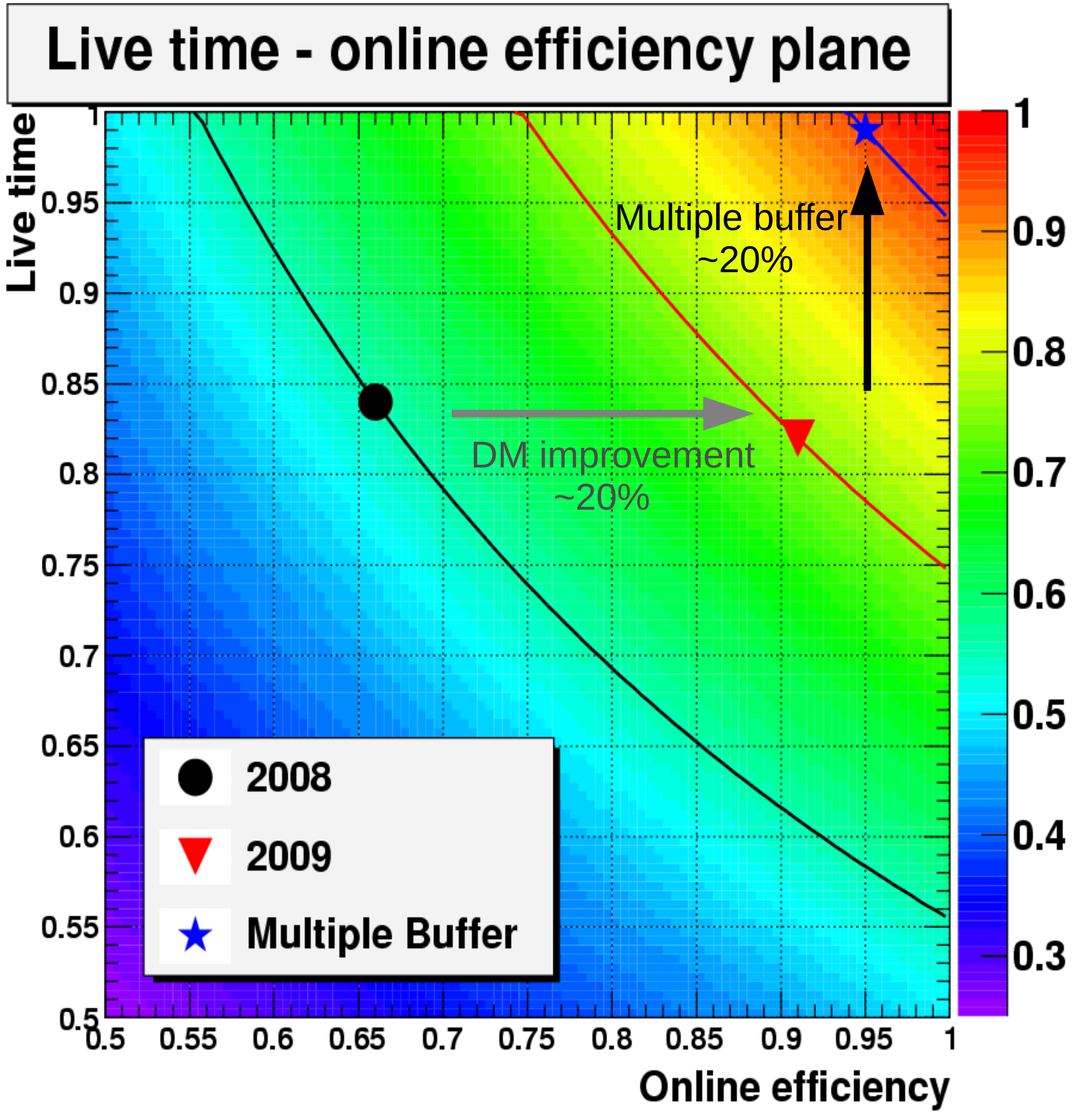

Jan-Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2008
Detector preparation
CEX
CEX
Physics run
(less DC eff., lower LXe LY)
2009
Other experiment(Lamb shift)
XEC: liquid purification
DC: HV discharge problem fix
Detector installation
& preparation
CEX
Physics run
DRS4 installation
2010
DRS4 mod.
Cosmic alignment
e+ Mott
Beam study
CEX
Physics run
Physics run
BTS problem
2011
BTS repair work
7 DC repair work
CEX
Physics run
Physics run
PSI accelerator
Shutdown period

What can improve our result?

- Statistics : still the most important thing
  - 2011 data = 2 x 2010 data (124 days expected)
  - 2012 data ≥ 2011 data
- Multi-buffer scheme for DAQ
  - Livetime improved, wider direction match table can be used
- Better e^+ resolution & detection efficiency
  - One of noise sources (HV distributor) is removed in 2011.
  - Thinner DC cables, preamplifiers, rearrangement of cable layout etc.
- Better gamma resolution & calibration
  - Stable & better quality data with new detector (BGO) for CEX
  - New reconstruction algorithm, improve Q.E. estimation etc.

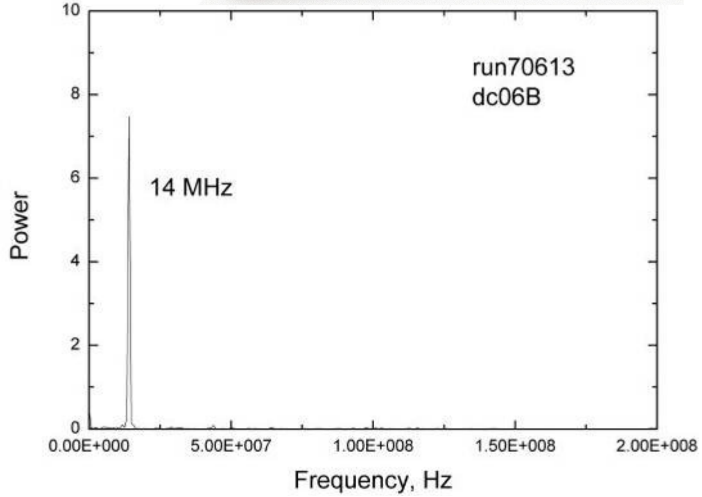
Multi buffer DAQ

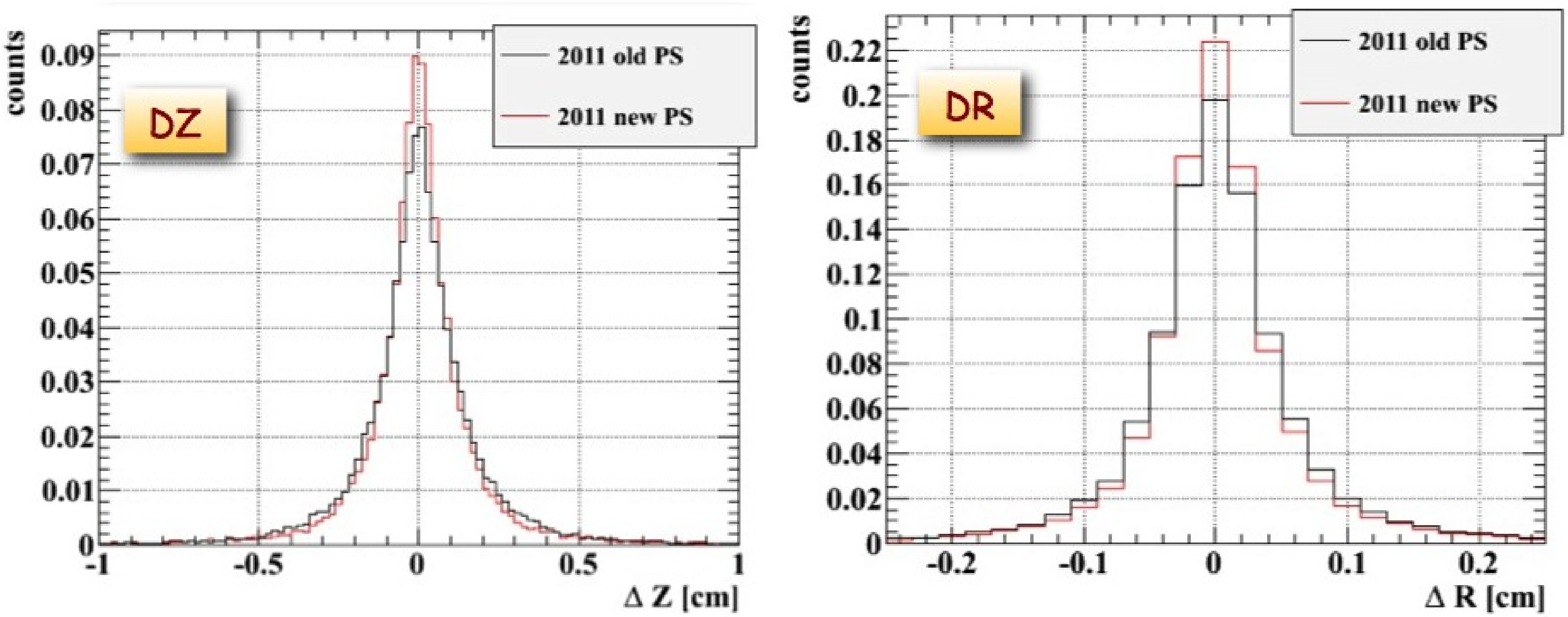
- Dead time in 2009-2010
  - 25ms/event ~ 83% livetime @ 6Hz
- Multi buffer DAQ
  - Installed at the end of 2010
  - >99% livetime @ 10Hz
  - Direction match table between positron and photon can be widen (92% -> 96%).



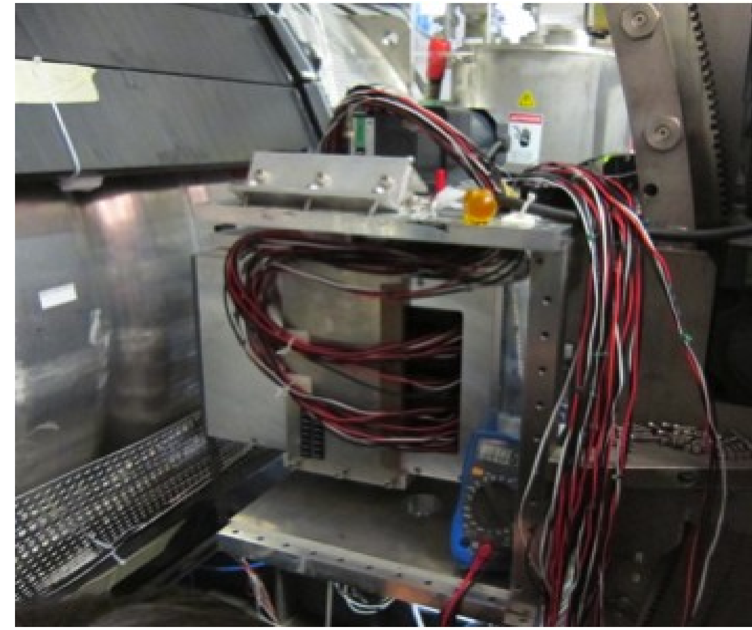
DC performance in 2011

- Found that one of noises (14MHz) coming from DC HV distribution system
  - 1 primary HV power supply(ISEG EHQ 103M) and 16 HV distribution modules with 2 ch. each (PSI)
- 2011 physics run (in a month after starting)
  - 32 different primary HV power supplies(ISEG EHS)
  - dz, dr improved before/after exchange in 2011
  - DC calibration is on-going. θ, φ resolution will be checked after that.





BGO array for CEX in 2011

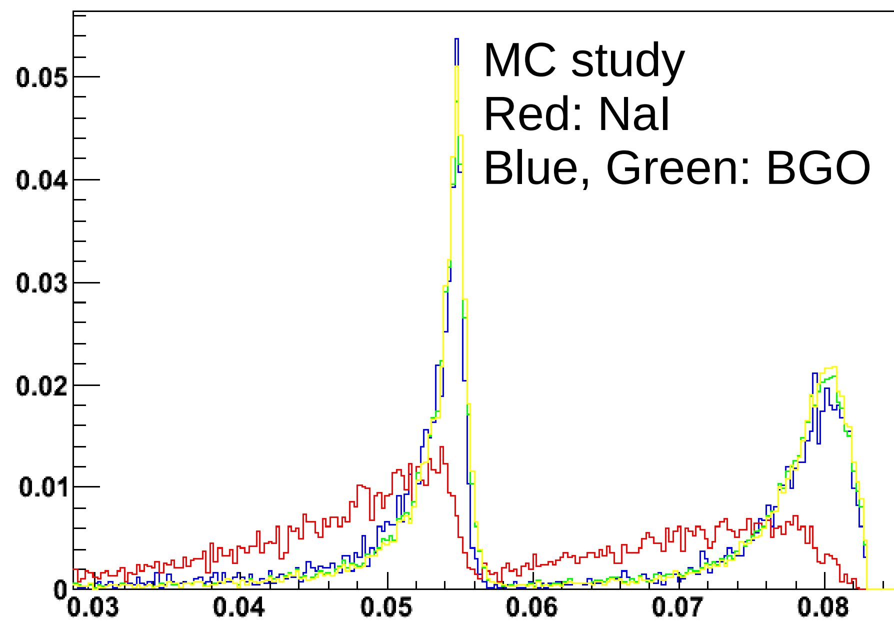


CEX two weeks for scanning all the XEC inner face, and LH_2 target setup, μ^- -> π^- beam change

Improvement of detection efficiency is important to minimize DAQ time

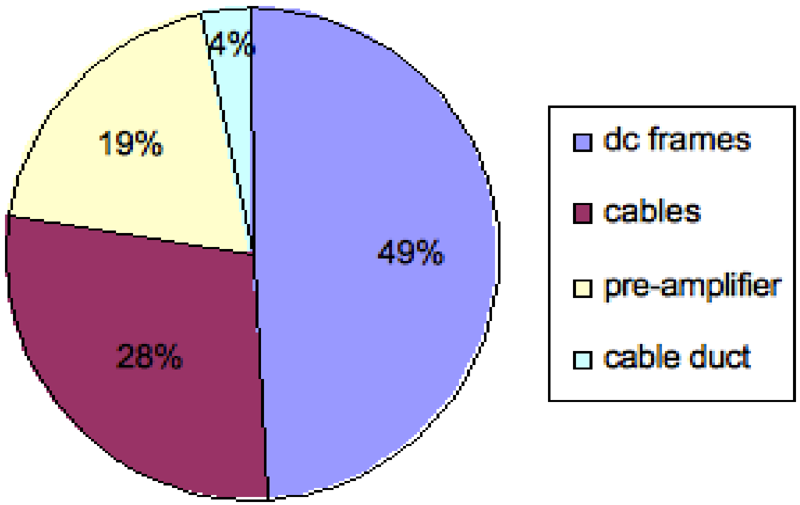
NaI (3.67g/cm3) : 3x3
(6.5x6.5x33 cm^3)

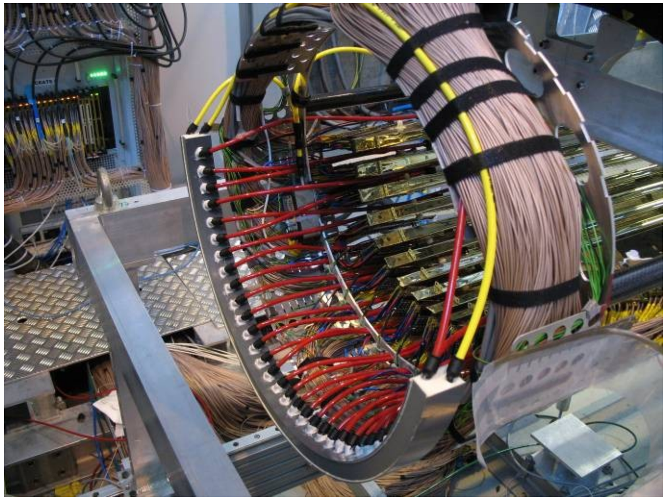
BGO (7.13g/cm^3) : 4x4
(4.6x4.6x20 cm^3)



Better detection efficiency > x2
Better position, energy resolutions
position resolution is important to know opening angle of two γs, that indicates true energy

Positron detection efficiency





- Positron efficiency ~ 40%
- New design of DC frames
  - Design of a new DC system – is a long term activity
- Feasible starting point for improvements
  - Thinner signal cables (1728ch)
  - Thinner Preamplifier PCB (576 pcb)
  - Expected: (50 +x) %

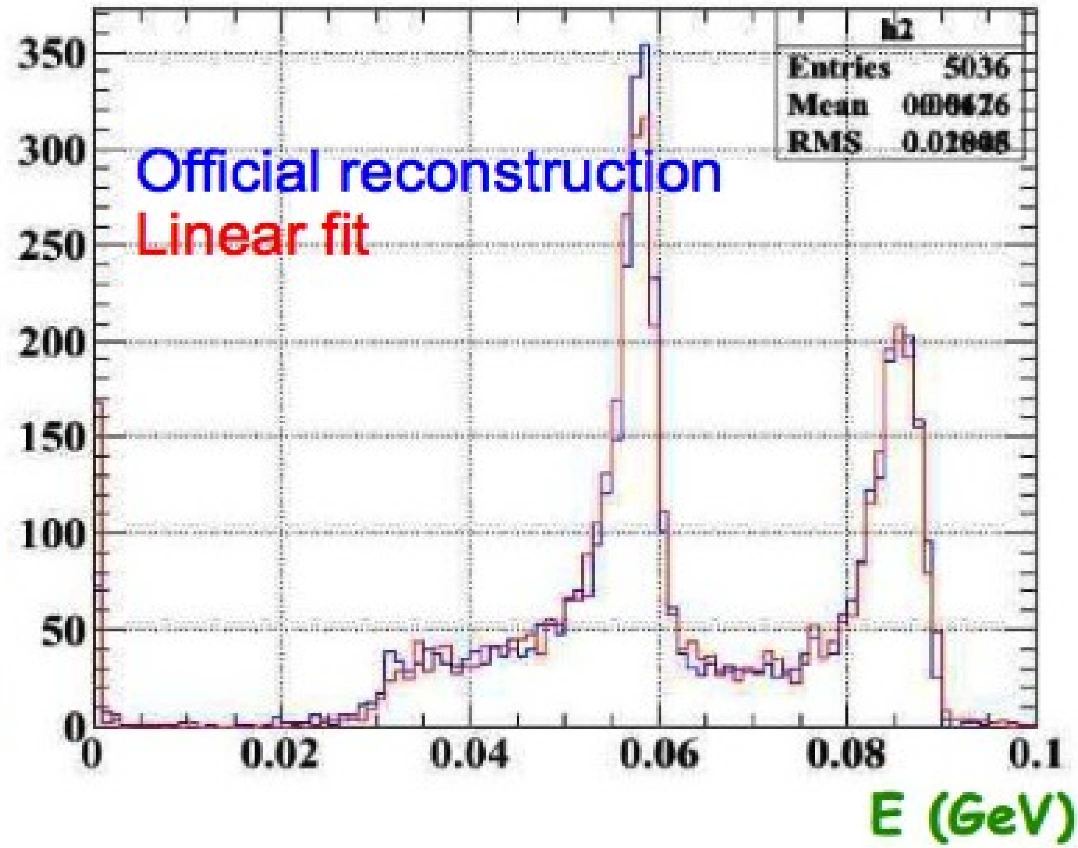
Summary

- MEG experiment has started physics run in 2008, and MEG detector has been working since then, and the performance is still being improved.
- The expected 90% C.L. upper limit with 2009+2010 data is 1.6×10^{-12}, which is already 7 times better than the previous experiment.
- MEG physics run has restarted since the end of June 2011, and MEG is accumulating more data 2011-2012 to reach $O(10^{-13})$ sensitivity.
- Possible major upgrades of experiment (sensitivity$<\sim 10^{-13}$?) are being discussed.

Linear-Fit

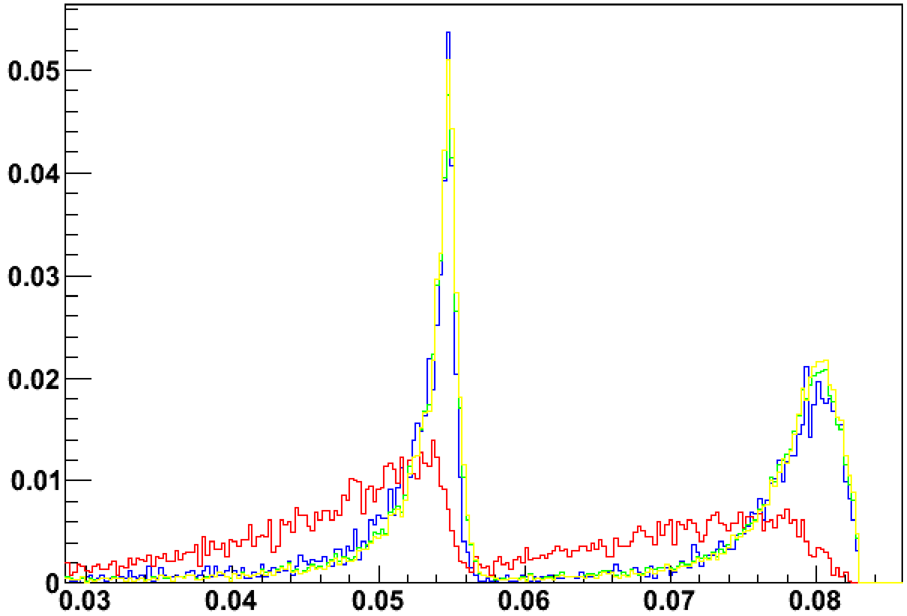
- Linear fit algorithm
  - $E = c + \Sigma c_i Q_i$
  - The weights are computed with MC
    - $\chi 2$ = distance from MC
    - Analytical minimization
- Worked well for prototype

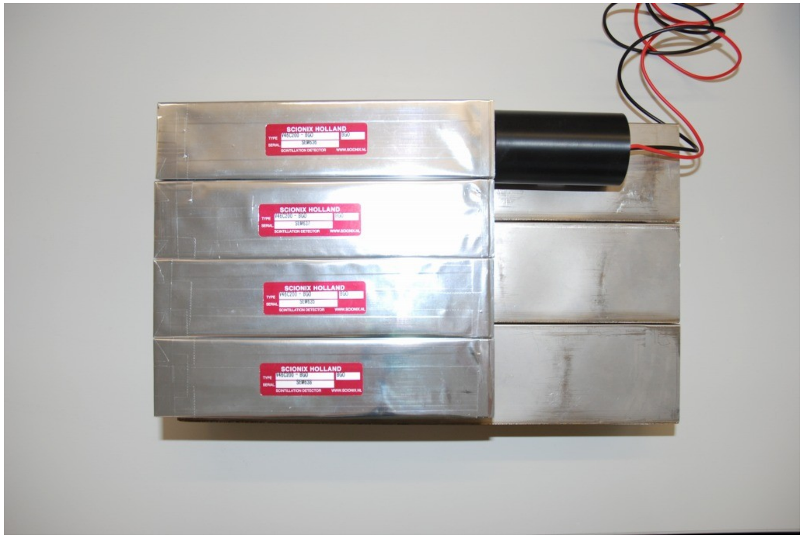
- With refinement of MC,
  - Progressing
  - Currently getting comparative to existing algorithm (still slightly worse)
  - Working further improvement of MC



BGO

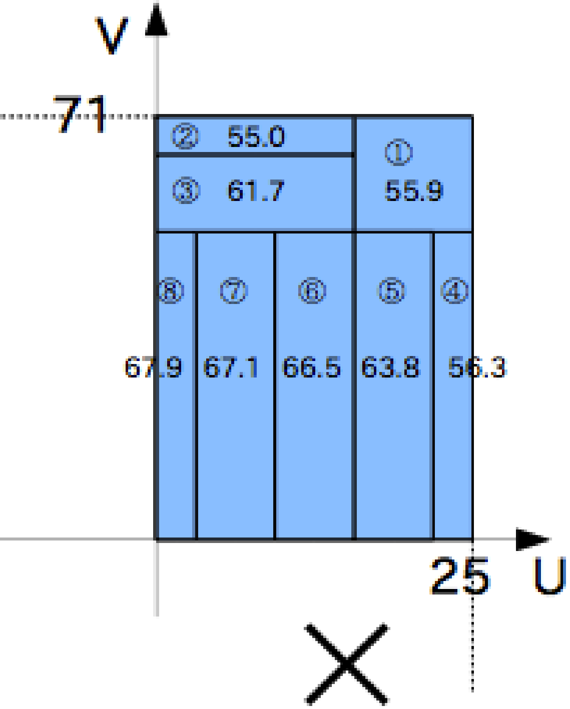
- NaI : 3x3 (6.5x6.5x33 cm³ , 3.67g/cm³)
- BGO : 4x4 (4.6x4.6x20 cm³ , 7.13g/cm³)
- Efficiency
  - 17% NaI center, 35% center 2x2 BGO
- Position reconstruction
  - NaI : 1.5cm, BGO : 1.1cm



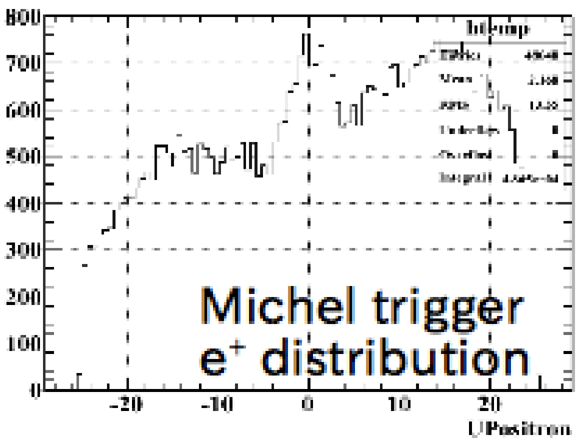


Efficiency

- For normalization, need eff conditional on the e^+ detection
  - Position-dependent efficiency from MC
  - Weighted by the e^+ distribution
- Confirmed with pi0 data (NaI-self)



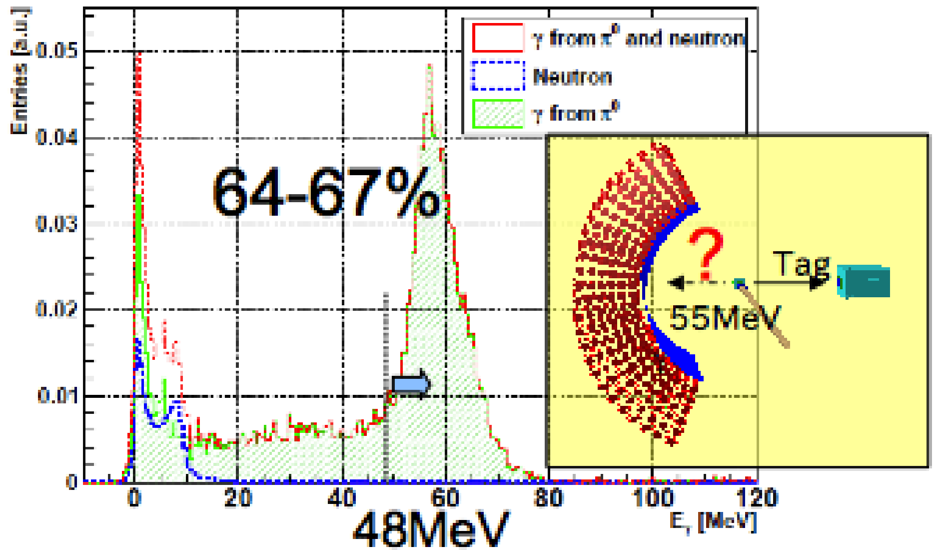
×



ε_γ (>48MeV)= ε_{det} x ε_{ana}

= 0.647 x 0.893

= 0.58 ± 0.03



9% decrease from 2008

- Change of analysis window (46→48MeV) : 5%
- Higher pileup level & higher pileup cut threshold

→ rejected events have less significance, almost no effect on sensitivity.

In 2010, pileup reduced by beam optimization

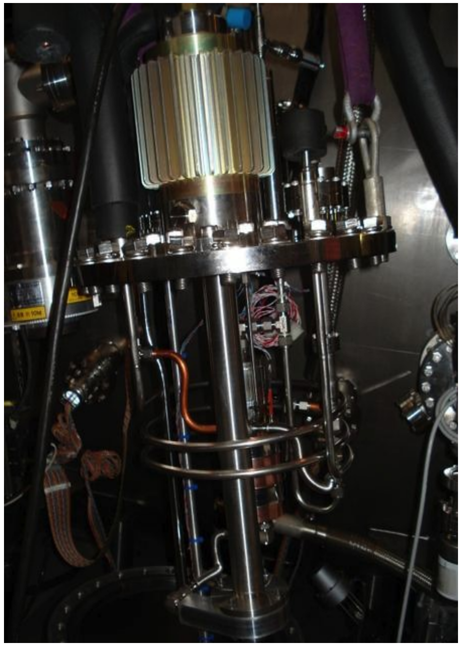
→ ε_γ (>48MeV) = 60% (expected)

Purification system

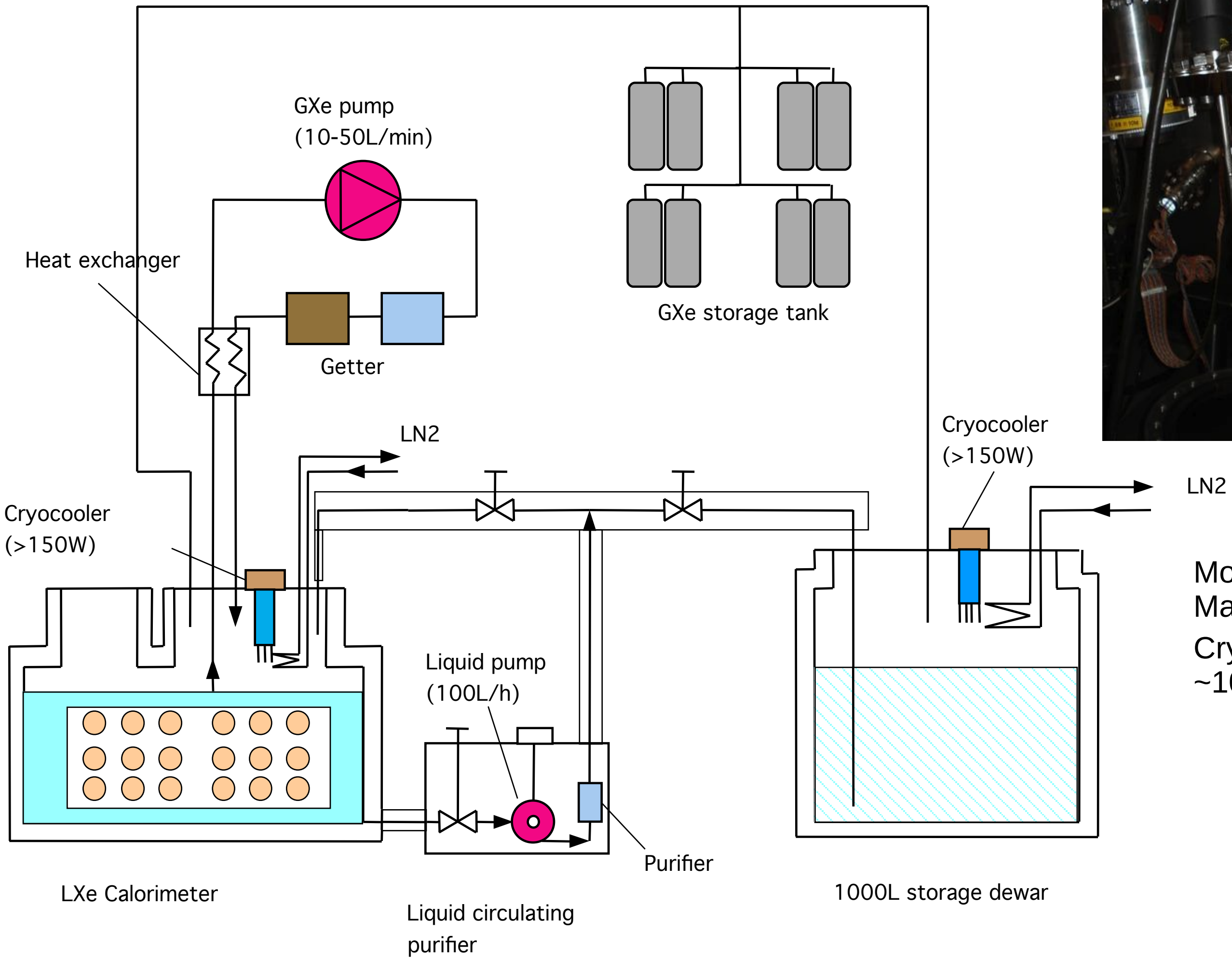
Gaseous purification

Metal heated getter
H_2O, O_2, N_2,...
Diaphragm pump
~1L/h

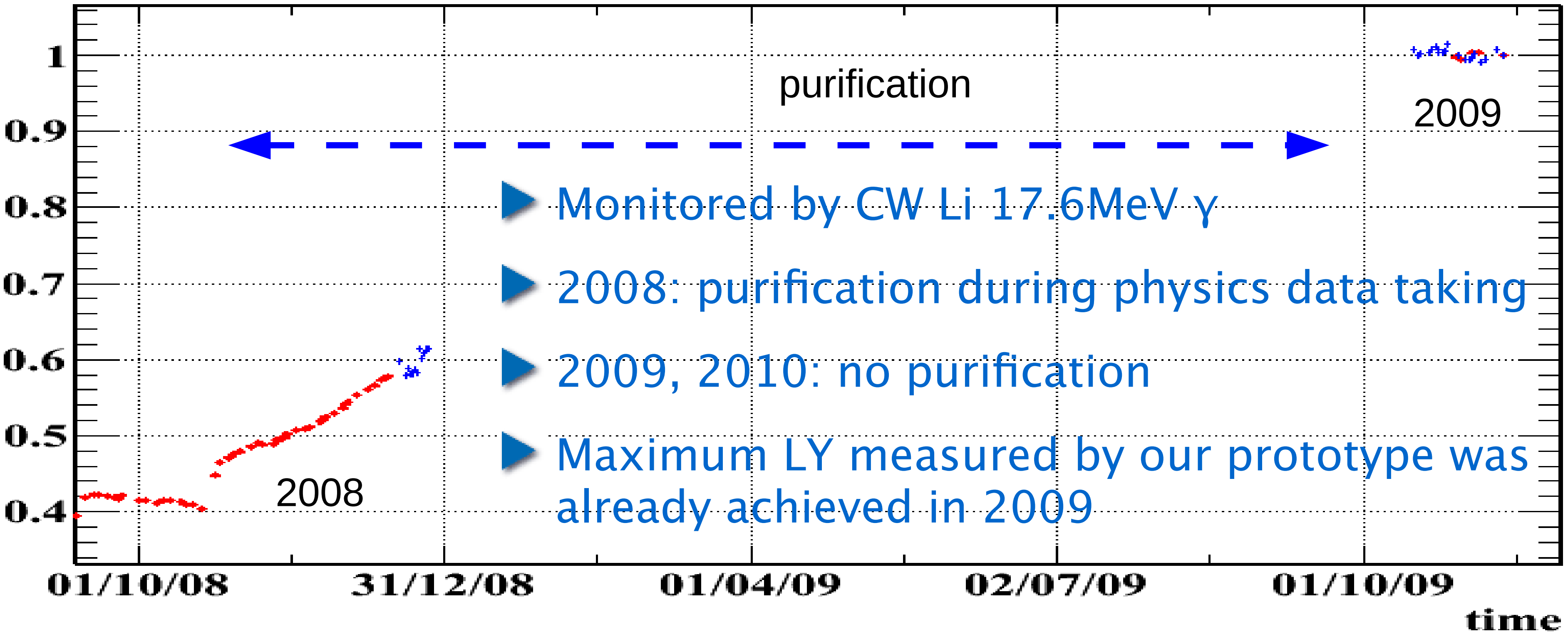
Liquid purification



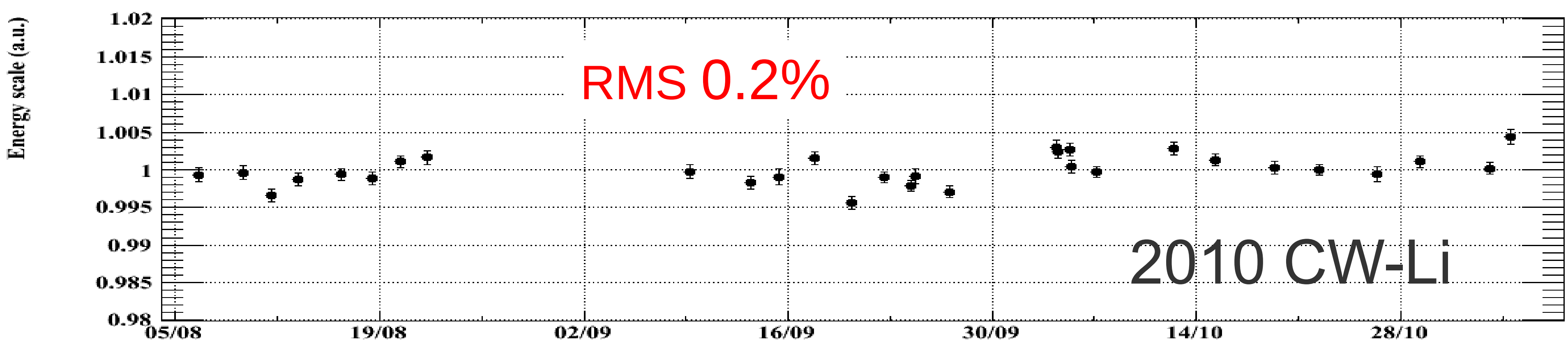
Molecular sieves
Mainly H_2O rejection
Cryogenic centrifugal pump
~100L/h



Light yield

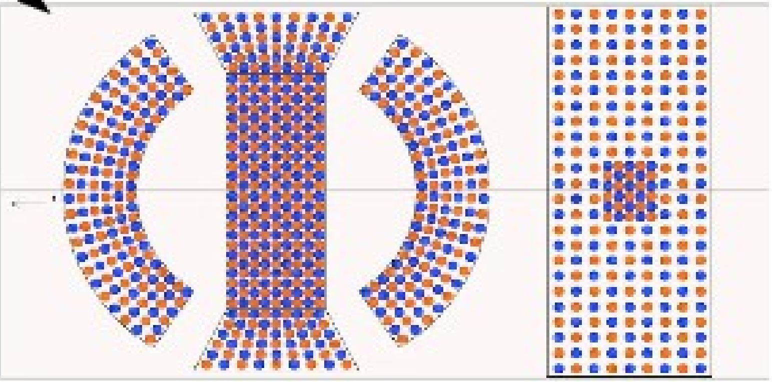


- Monitored by CW Li 17.6MeV γ
- 2008: purification during physics data taking
- 2009, 2010: no purification
- Maximum LY measured by our prototype was already achieved in 2009

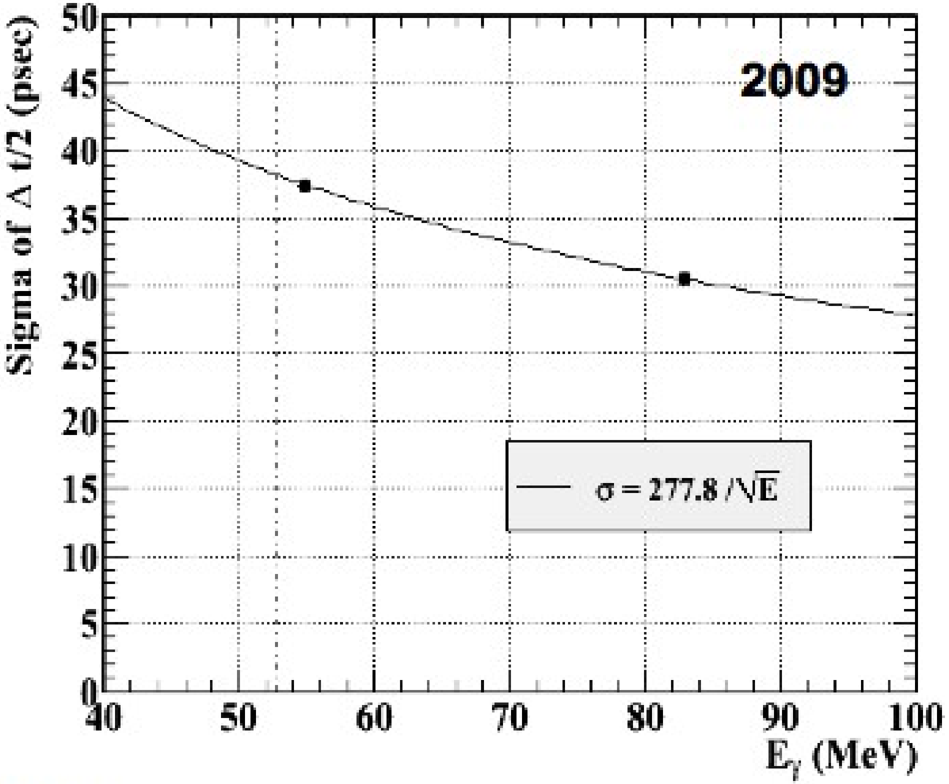


Intrinsic resolution

- PMTs are divided into 2 groups (odd, even)
- See difference of rec. time by the two
  - Electronics contribution canceled out
  - $\sigma((T_{odd} - T_{even})/2)$



	55 MeV	83 MeV
2008	44.7	36.0
2009	37.5	30.5
2010	36.4	28.4



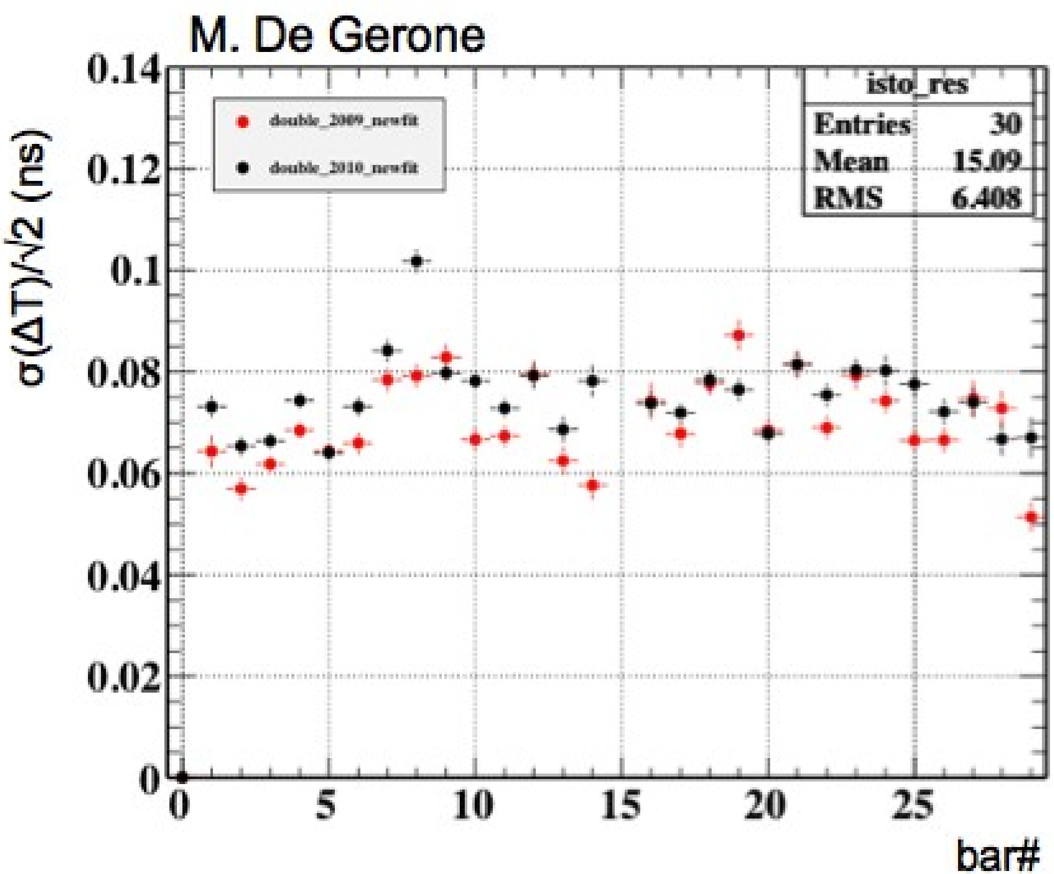
Intrinsic time resolution is dominated by p.e. statistics

16/Feb/2011 Yusuke UCHIYAMA

TC resolution: intrinsic+DRS

- $\sigma(\Delta T)/\sqrt{2}$ in double bar Michel events ⇒upper limit on TC intrinsic resolution +DRS

$$\Delta T = T_A - T_B$$

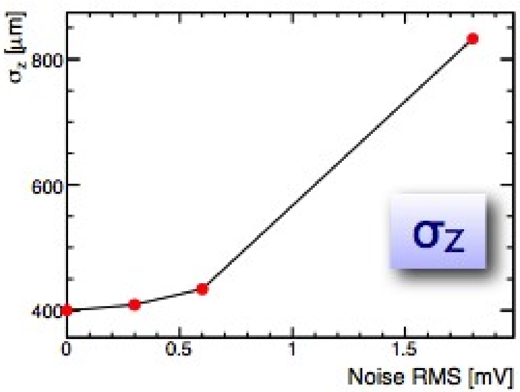


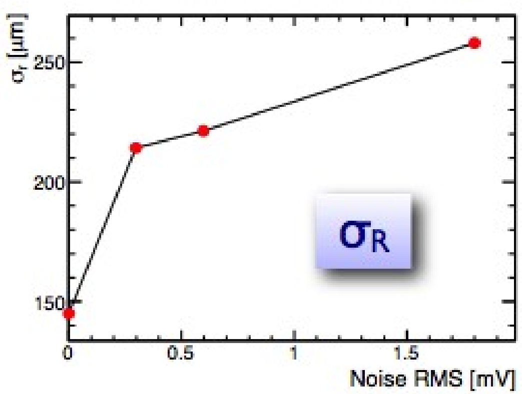
Estimate of resolution on positron impact point at TC: $\sigma(T_{TC})$~65 ps

Resolution on average ~5 ps worse in 2010 with respect to 2009

The Future

single hit resolutions vs noise RMS from MC

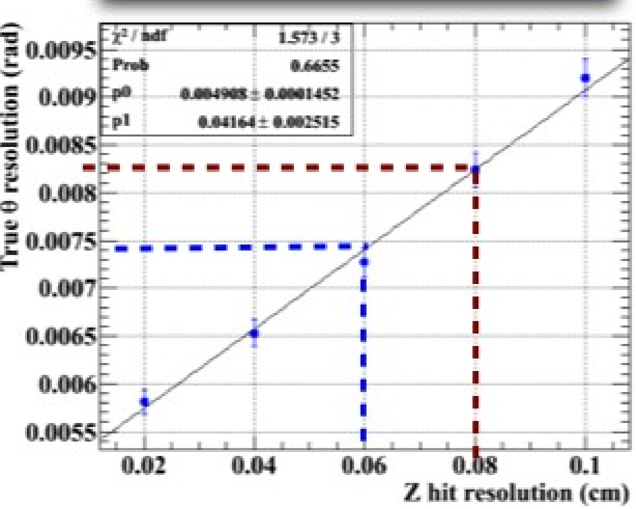




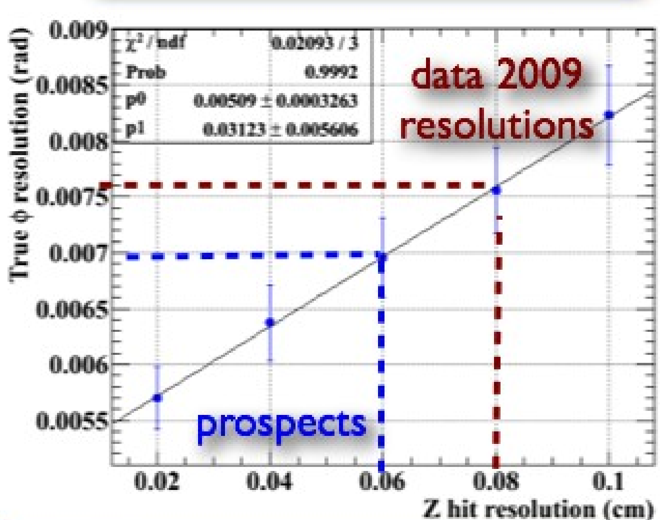
- Assuming for 2011 the expected noise RMS from the test on the new HV modules (see M.Hildebrandt's talk), we should be able to reach ~600 μm resolution in Z single hit position and ~230 μm in R

Moreover, with reduced noise, subleading contributions to resolution clearer (and easier to correct for)

θ resolution vs z resolution

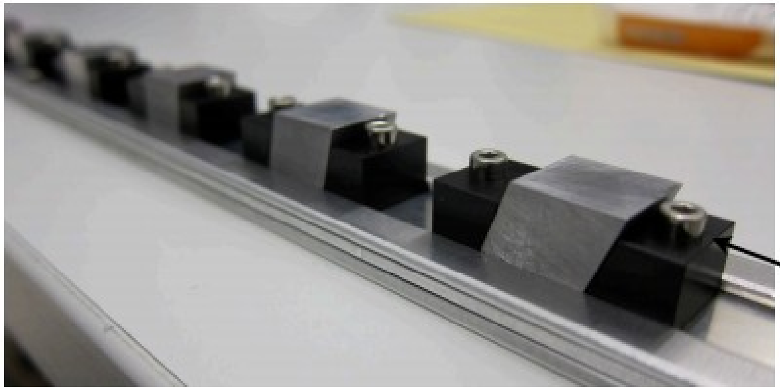


φ resolution vs z resolution



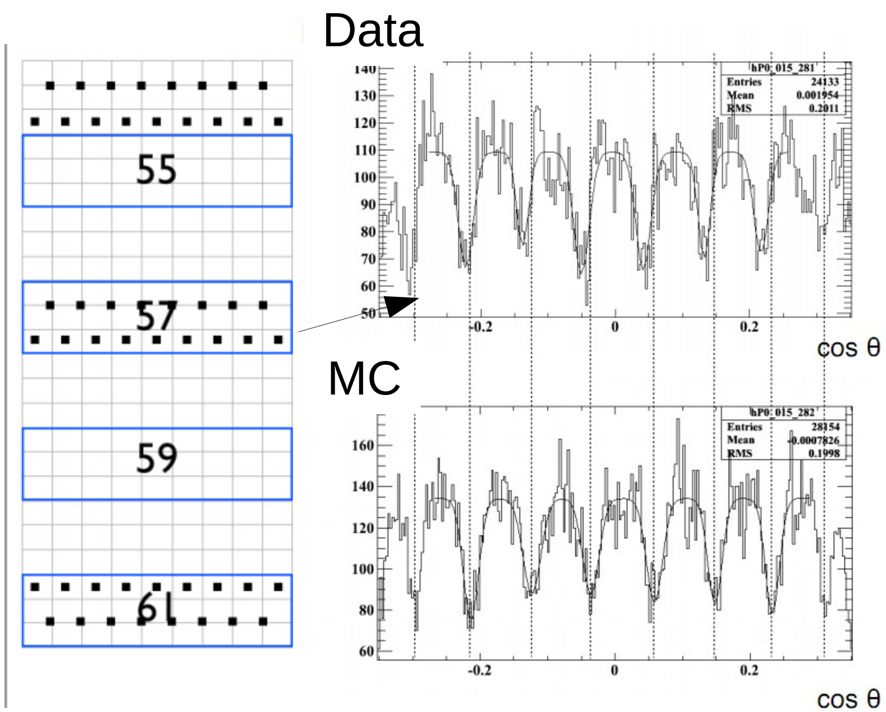
- From MC studies (not taking into account all the other possible improvements described in previous slides) we expected an improvement of
  - ~15 % in θ
  - ~<5% in φ
  - ~10% in momentum (but bigger data/MC discrepancy not yet explained)

Alignment



About 15 x 15 x 13 mm

These screws were replaced by plastics



Systematics

MEG Mu-E-Gamma Collaboration

- Systematic effects are taken into account in the calculation of confidence interval by profiling on (N_{RD}, N_{BG}) and by fluctuating PDFs according to the uncertainty values
  - all the results shown so far already contain systematic effect.
- Size of effect of systematic uncertainty is in total 2% on the UL.
  - $2.3\times10^{-12} \rightarrow 2.4\times10^{-12}$ for combined result

Contribution of each item was studied with toy-experiment by comparing the result with nominal PDF and that with fluctuated one.

Relative contributions on UL

Center of $\theta_{e\gamma}$ and $\phi_{e\gamma}$	0.18
Positron correlations	0.16
Normalization	0.13
E_γ scale	0.07
E_e bias, core and tail	0.06
$t_{e\gamma}$ center	0.06
E_γ BG shape	0.04
E_γ signal shape	0.03
Positron angle resolutions (θ_e, ϕ_e, z_e, y_e)	0.02
γ angle resolution (u_γ, v_γ, w_γ)	0.02
E_e BG shape	0.02
E_e signal shape	0.01

Alternative Energy Reconstruction

- Treat each PMT as a detector and fit energy for each PMT
- Calculate event energy from tube energies
    - weighted mean energy of truncated distribution
- Correction table for gain×QE is prepared from output of PMT for each event
- Potential advantages:
    - can optimize PMT selection
    - insensitive to vast variations in solid angles subtended by nearby PMTs