Liquid Xenon Calorimeter Analysis

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on behalf of the MEG LXe analysis group
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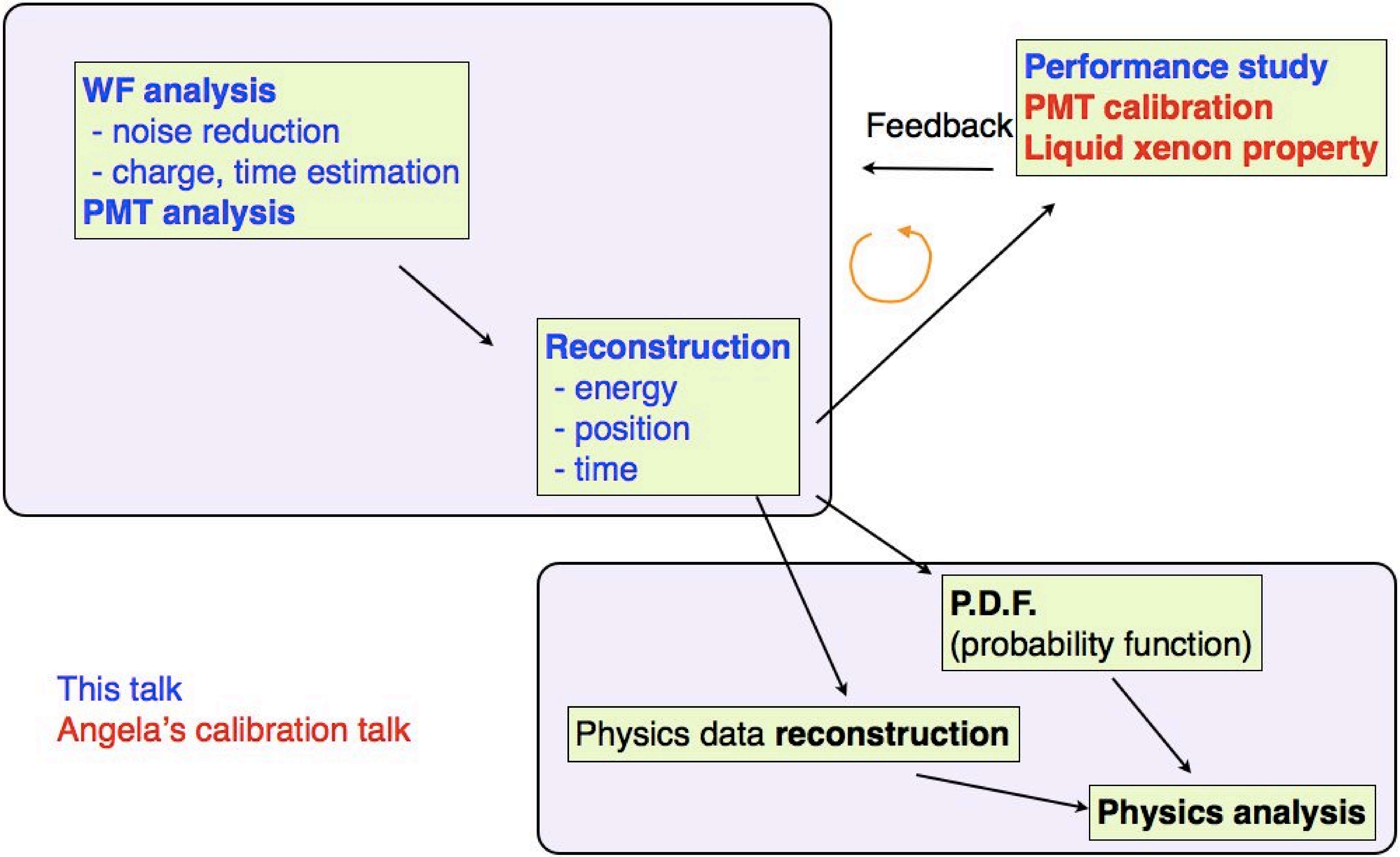
Introduction

Strategy of LXe analysis for MEG

- We develop independent two analysis lines to cross-check each other.
  - Two different waveform(WF) digitizers. DRS : PSI custom chip, fast sampling, and TRG : commercial chip, slower sampling.
  - Different reconstruction algorithms.
- Cross checking is done at lower level analyses (PMT calibration, linearity, resolution..), as well as higher level (physics) analysis.

- This strategy works well to catch problems quicker and understand better.

Strategy of LXe analysis for MEG



Status of 2009 data analysis

- At this moment, we are trying the same methods of analysis done for 2008 as the first step.
- We are preparing for further improvements.

- Alpha particle data in gas phase xenon, which was used to estimate quantum efficiencies (Q.E.) of PMT in 2008 analysis, have not been taken. So, 2009 data analyses shown in this slide were done by using Q.E. measured in 2008.

Outline

- Waveform
- Reconstruction
  - Energy
  - Time
  - Position
  - Pileup
  - Efficiency
- Summary

In each section, 2008 result and status of 2009 analysis are shown.

XEC waveform analysis for DRS

We used DRS2 in 2008, and upgraded to DRS4 in 2009

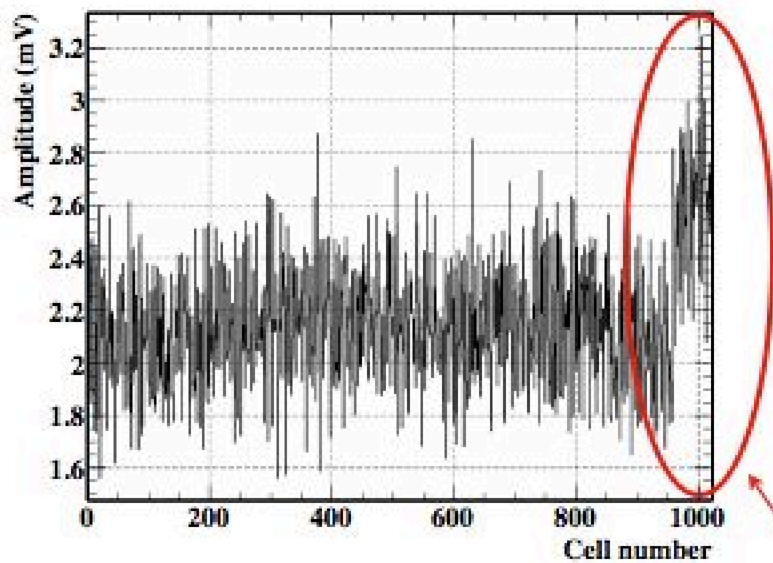
Noise reduction

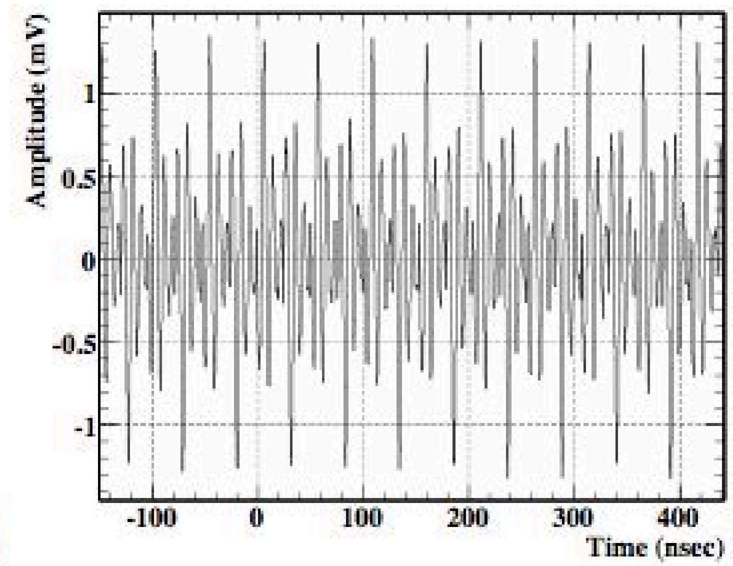
Template of noise is made for each channel by averaging many random trigger events.
The template is subtracted in analysis.

Cell pedestal
(offset voltage of sampling cells)

Noise template
Correlated with trigger

DRS2

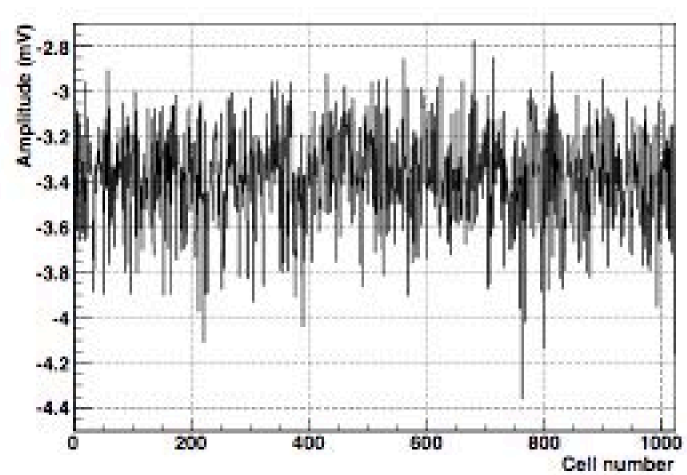


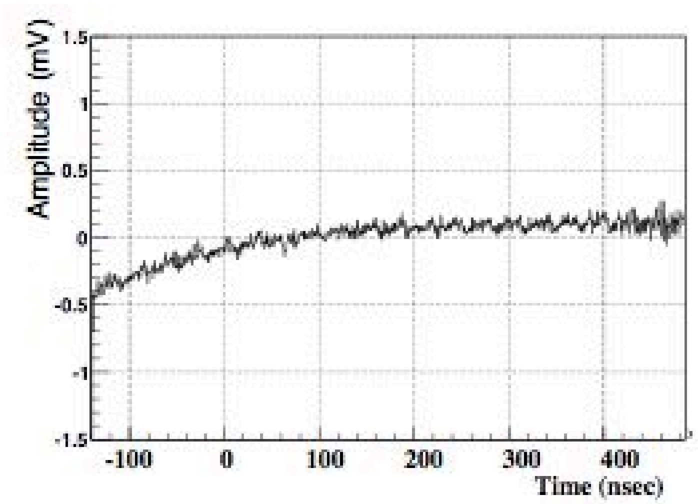


Cross talk with clock WF

Appears after several days after hardware calibration

DRS4

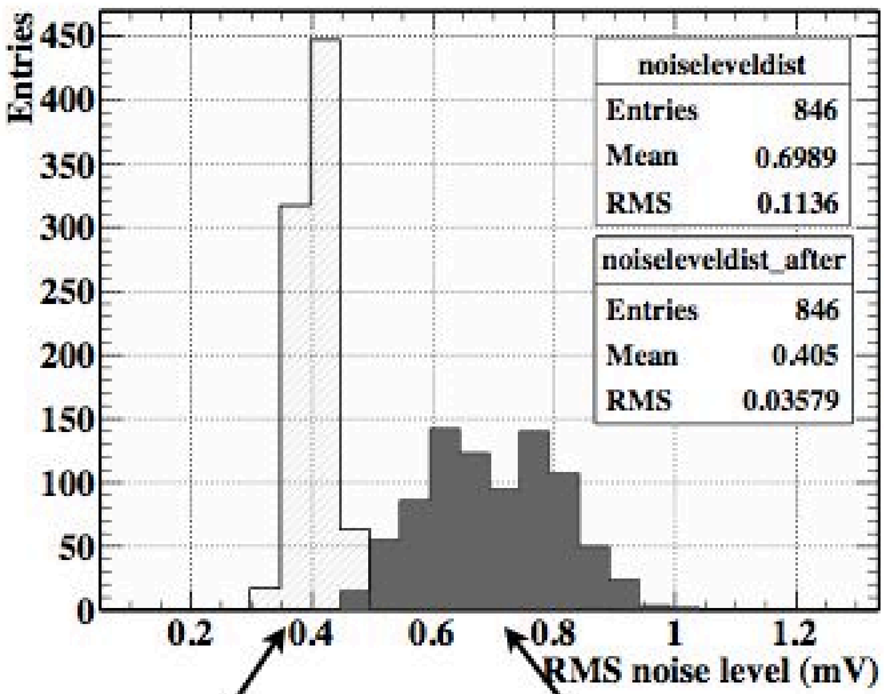




In DRS4, no step at the last 64 cells and no crosstalk of clock are seen.

Noise reduction

2008



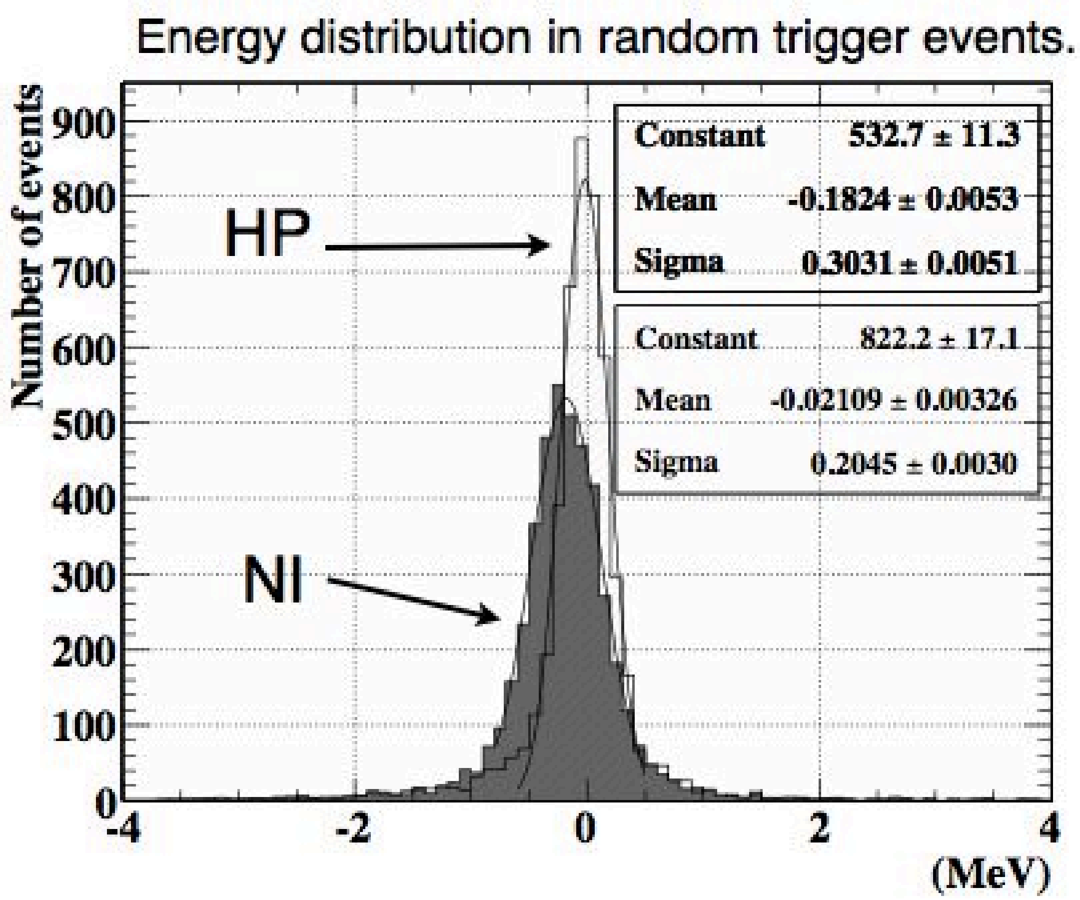
After reduction

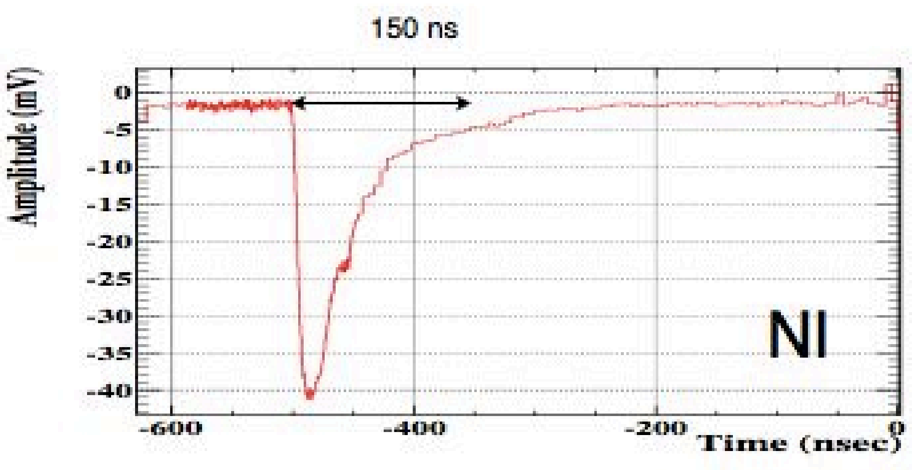
Before reduction

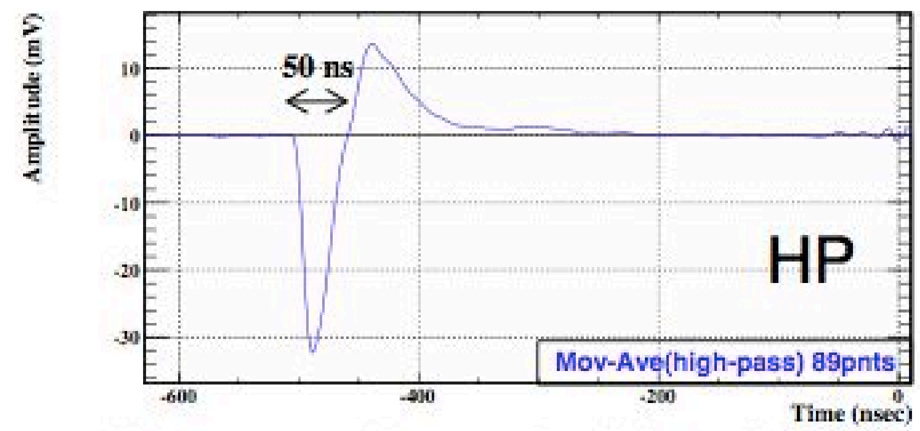
Noise is reduced by offline analysis from ~0.7 mV to 0.4 mV RMS

In 2009 (DRS4), noise level is lower (0.34 mV) after the noise reduction

Contribution to energy







We use normal integration (NI), and high pass filtered (HP) waveforms for charge integration.
Physics analysis is done with HP.

Contribution of noise to energy is small enough.

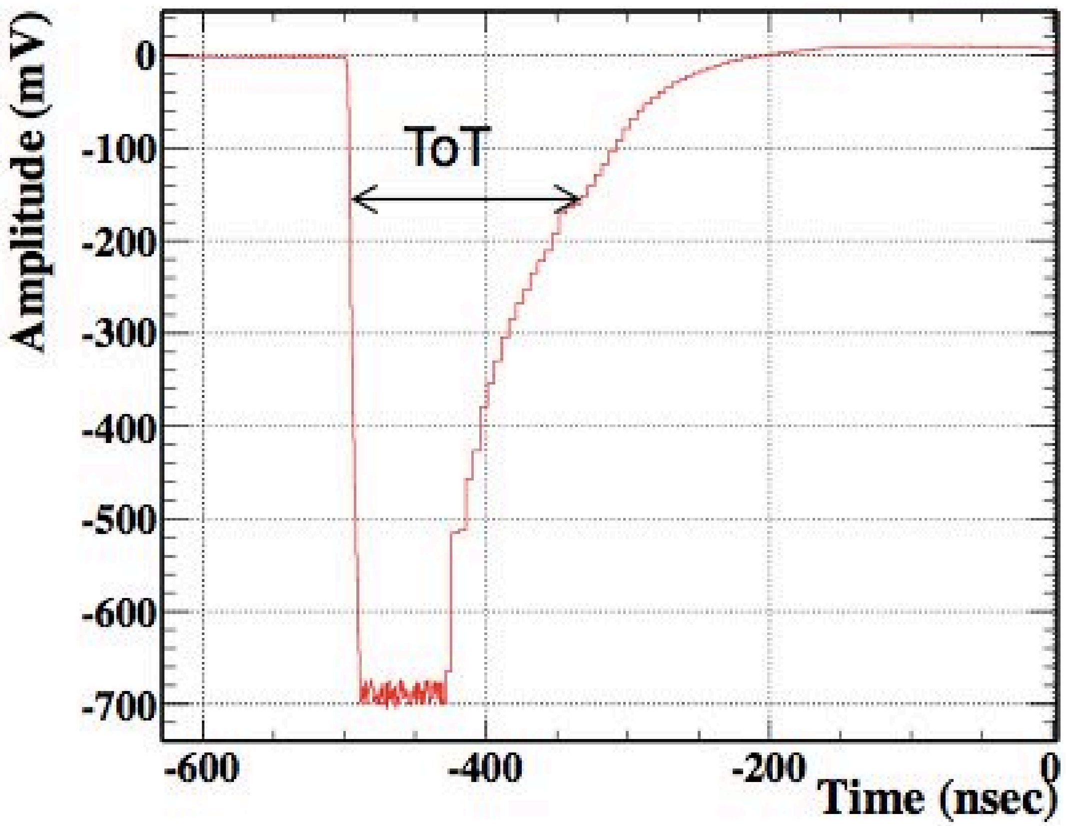
In 2008,

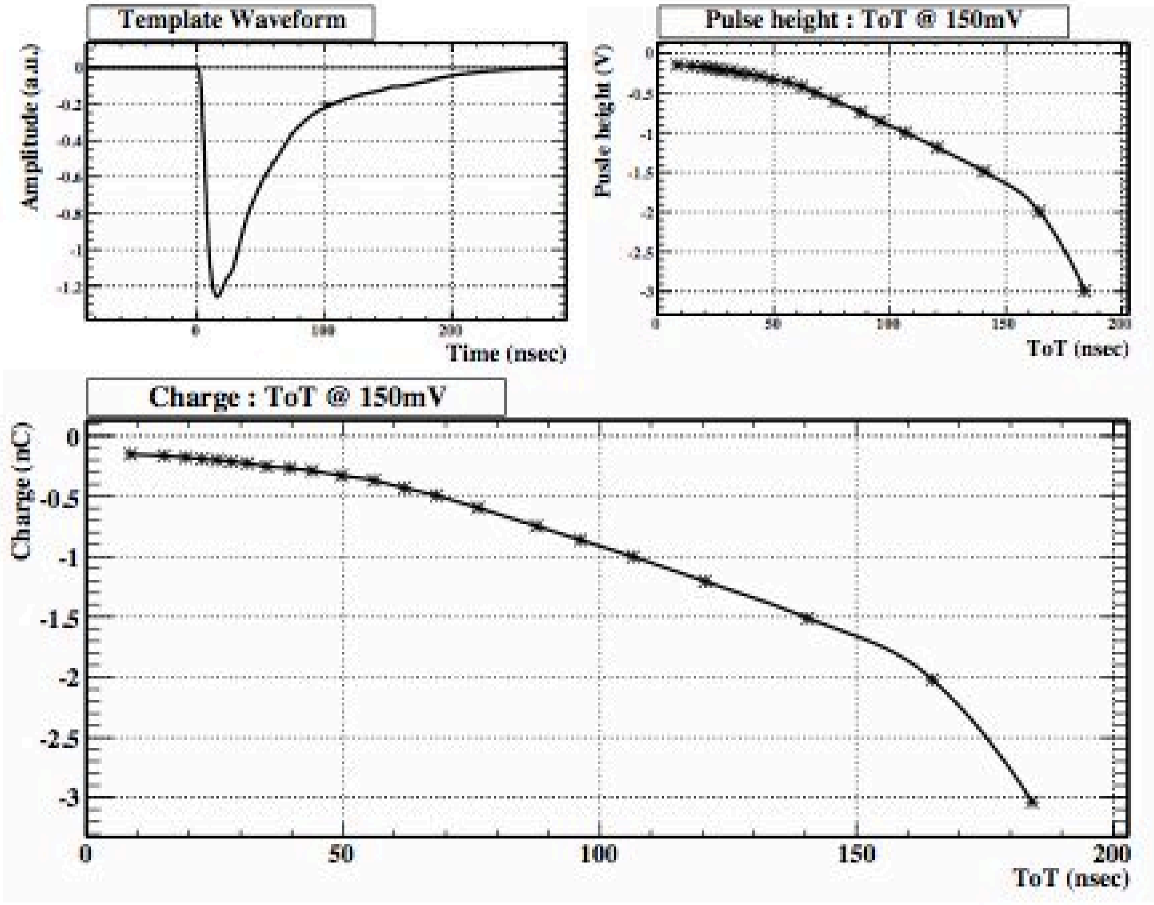
0.7 % before noise reduction

0.4 % after noise reduction

In 2009, it is **0.25 %** after noise reduction.

Thanks to lower noise level + higher light yield.





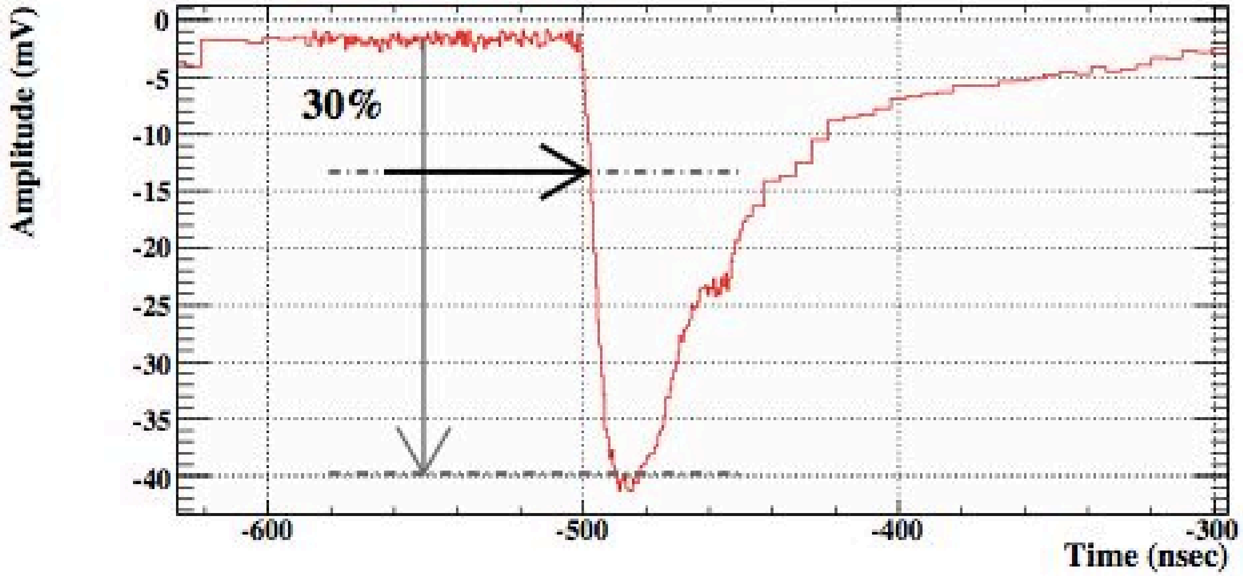
Charge of saturated PMT is estimated by using a known relation between charge and ToT (time over threshold)

2008 Saturation voltage of DRS2 are chips dependent, and can vary in time.*

2009 That of DRS4 are common in all the chips and stable.

* More accurately, baseline of splitter can change, and it affects saturation voltage.

PMT waveform



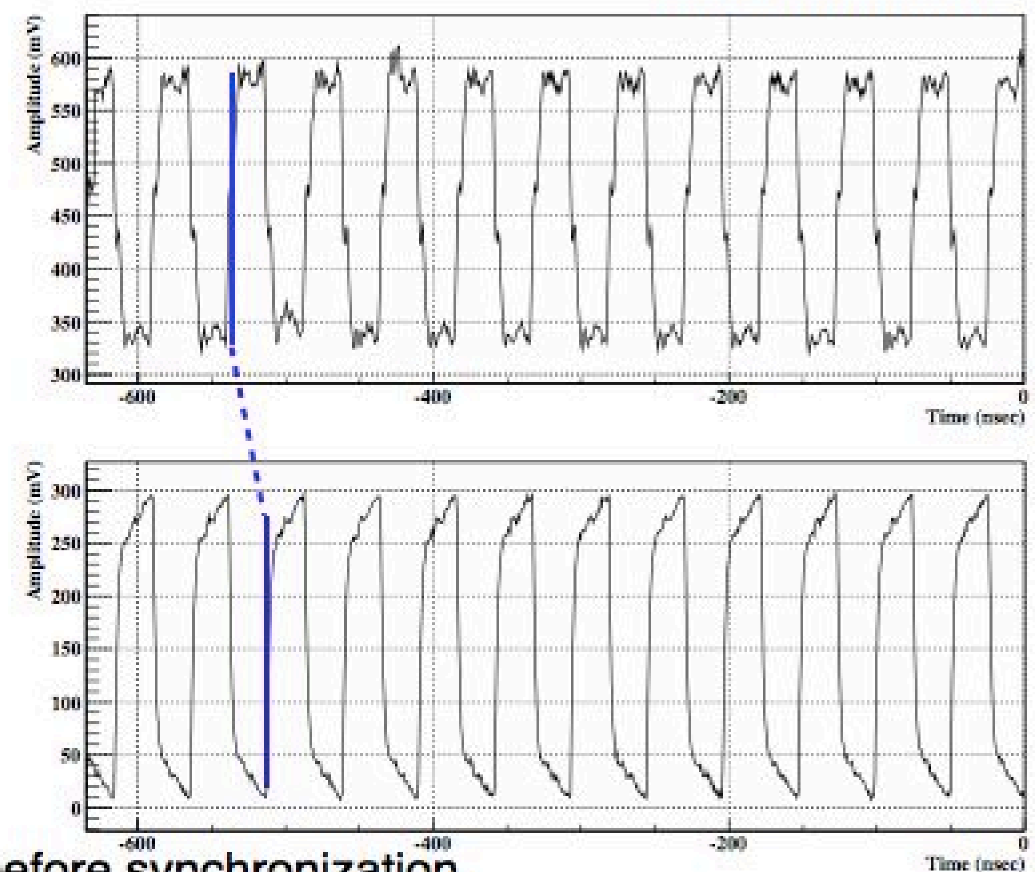
Time of each PMT is estimated by Constant-Fraction method in offline analysis.

Time of different chips are synchronized by using distributed clock waveforms.

Clock waveform

DRS2

DRS3



before synchronization

Energy

Energy reconstruction

✦**Weighted photon sum** $N = \sum Q_i/g_i/qe_i \times w_i$

charge — gain — Q.E. — correction for PMT coverage fraction (fixed)

⇩

✦**Correction** of
- Non-uniform response in the detector
- Variation of light yield

⇩

✦**Scale** to energy. (Single factor)

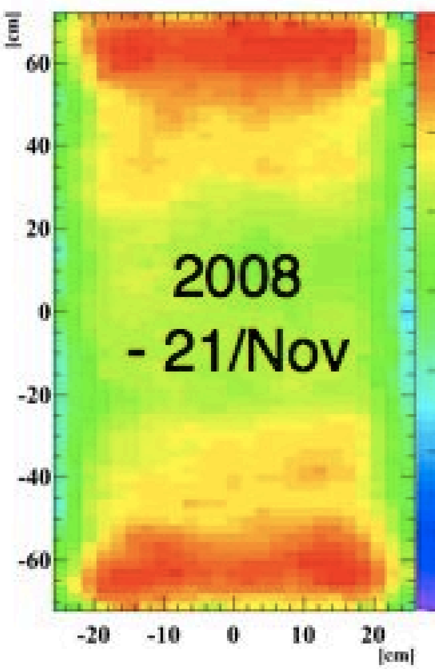
Several other methods, studies are on going

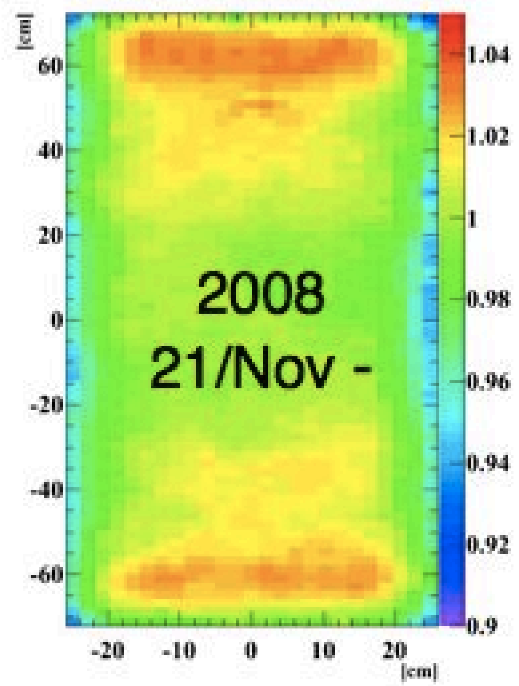
- Linear fit (estimation of the best weighting factors) works well for the large prototype. precise knowledge of optical property needed
- Gamma position dependent weighting
- Estimating energy by each PMT, then taking weighted mean

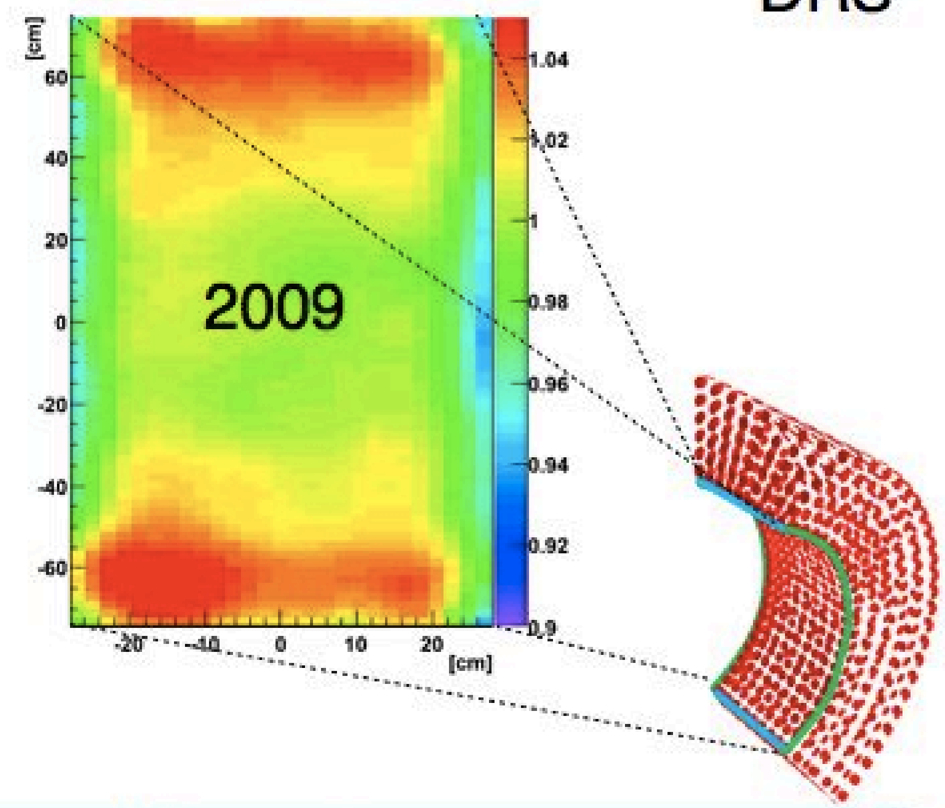
Non-uniformity and correction

Relative response map in LXe entrance window, before correction
(color code represents response.)

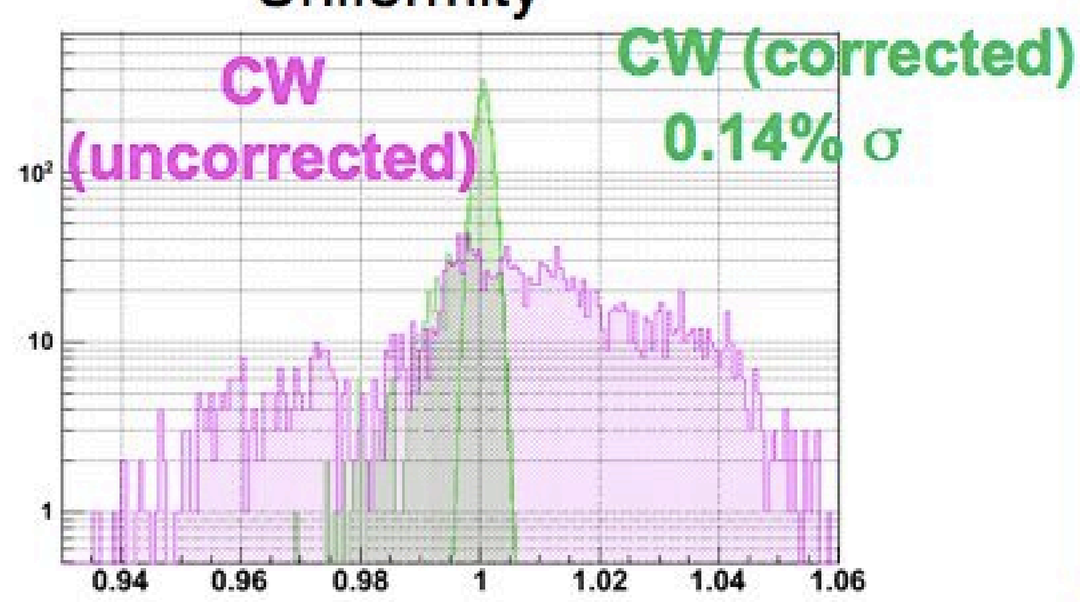
DRS





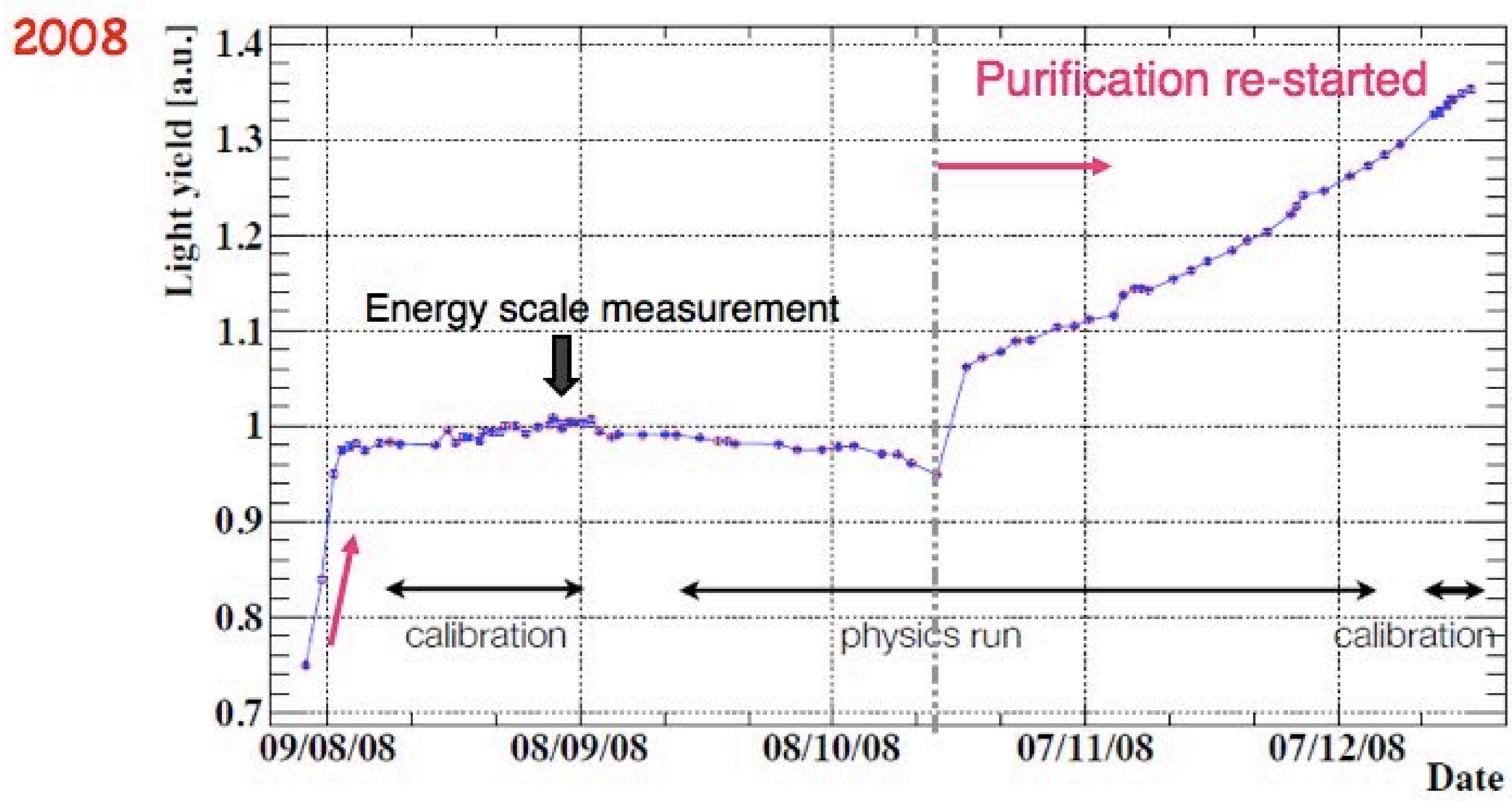


Non-uniformity is measured from **CW** data.
Response depends on purity and Q.E. estimation.



This non-uniformity also exists in MC.
Response is larger in areas close to top or bottom faces.

Light yield variation and correction



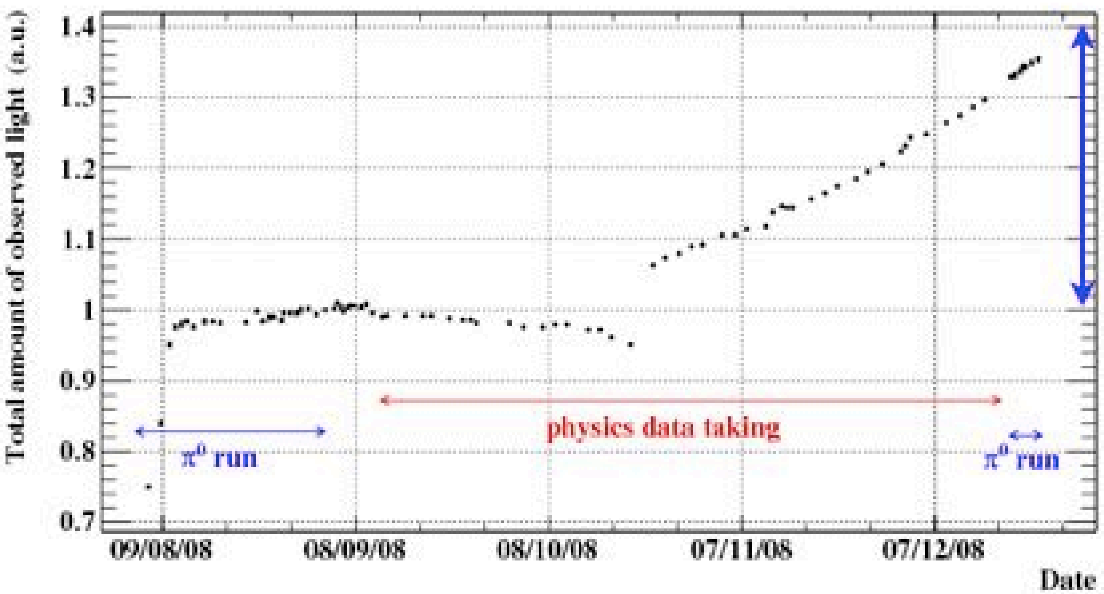
Absolute scale of energy was measured by 55 MeV gamma in Pion runs.
Variation was monitored by Pion, Cosmic ray, AmBe and CW data, and corrected.

Uncertainty of energy scale : 0.4 %

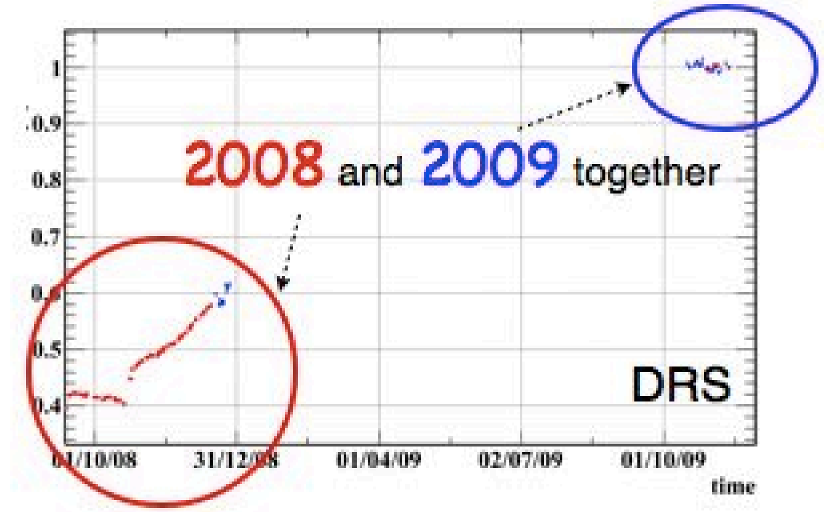
Main uncertainties from gain variation in pion runs, and peak estimation of cosmic ray data.
(In 2009, those uncertainties are not present.)

Light yield history, 2008 and 2009

2008

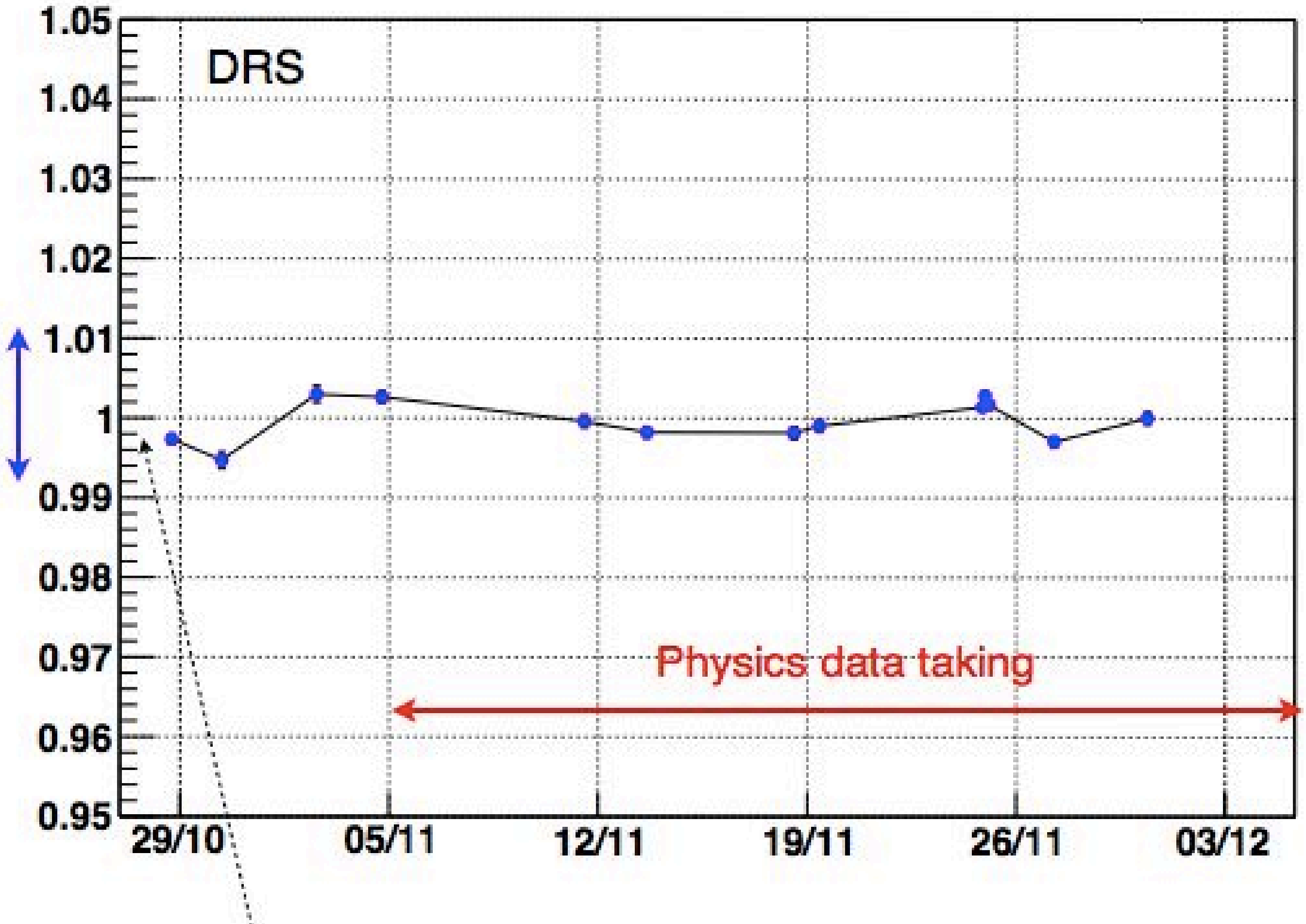


40 %



2009

± 1 %

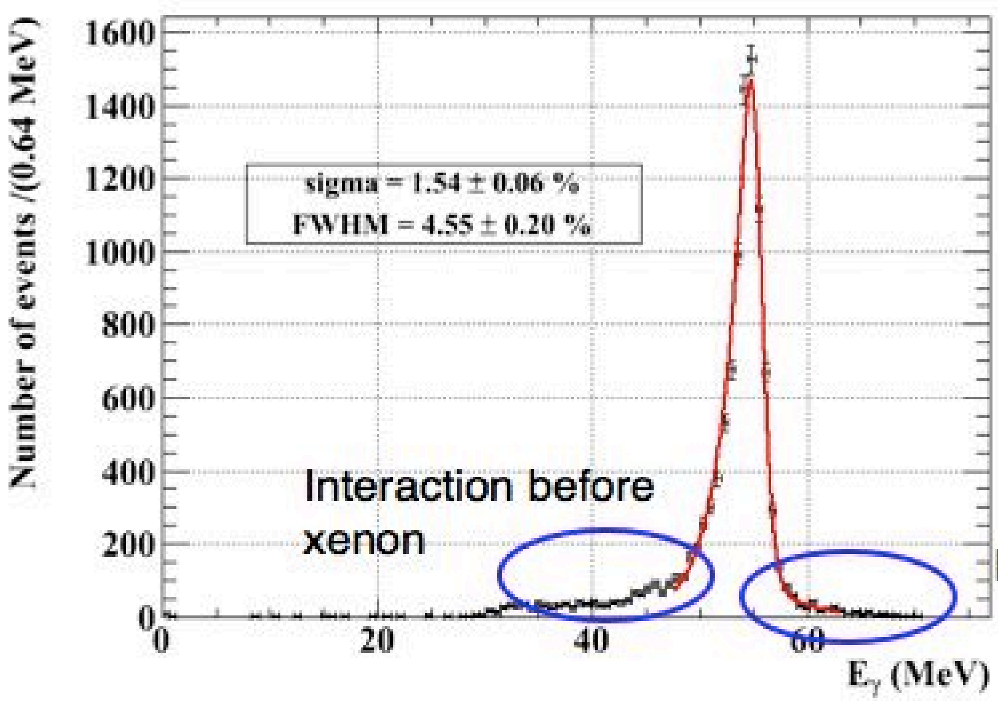


Light yield in 2009 is very stable.
No correction is needed.

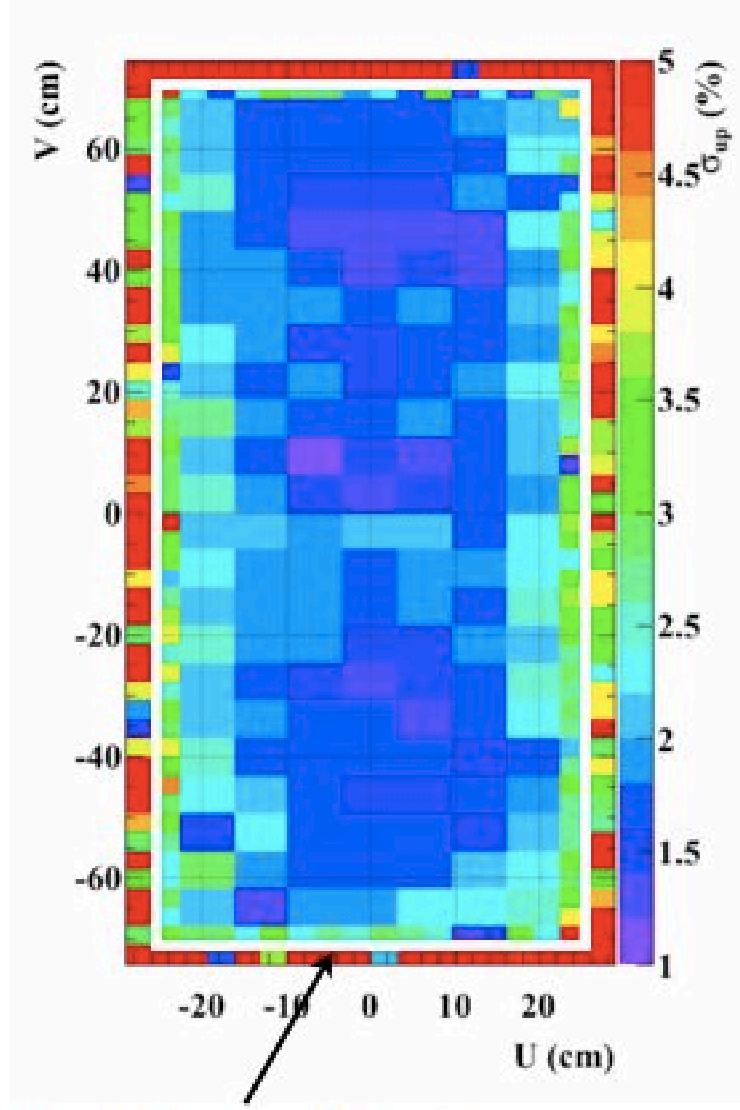
Light yield is same as the large prototype.
(i.e. maximum in our experience)

Scale of this figure is factor 2.2 larger than left top figure.
(Light yield was increased)

π^0 55MeV



Resolution map in entrance window



Fiducial volume

- Resolution is measured from 55 MeV gamma data
- Difference of pedestal distribution in pion and muon data (much more pileup gamma in pion data) is taken into account.

2008

Average resolution (sigma of higher energy side)

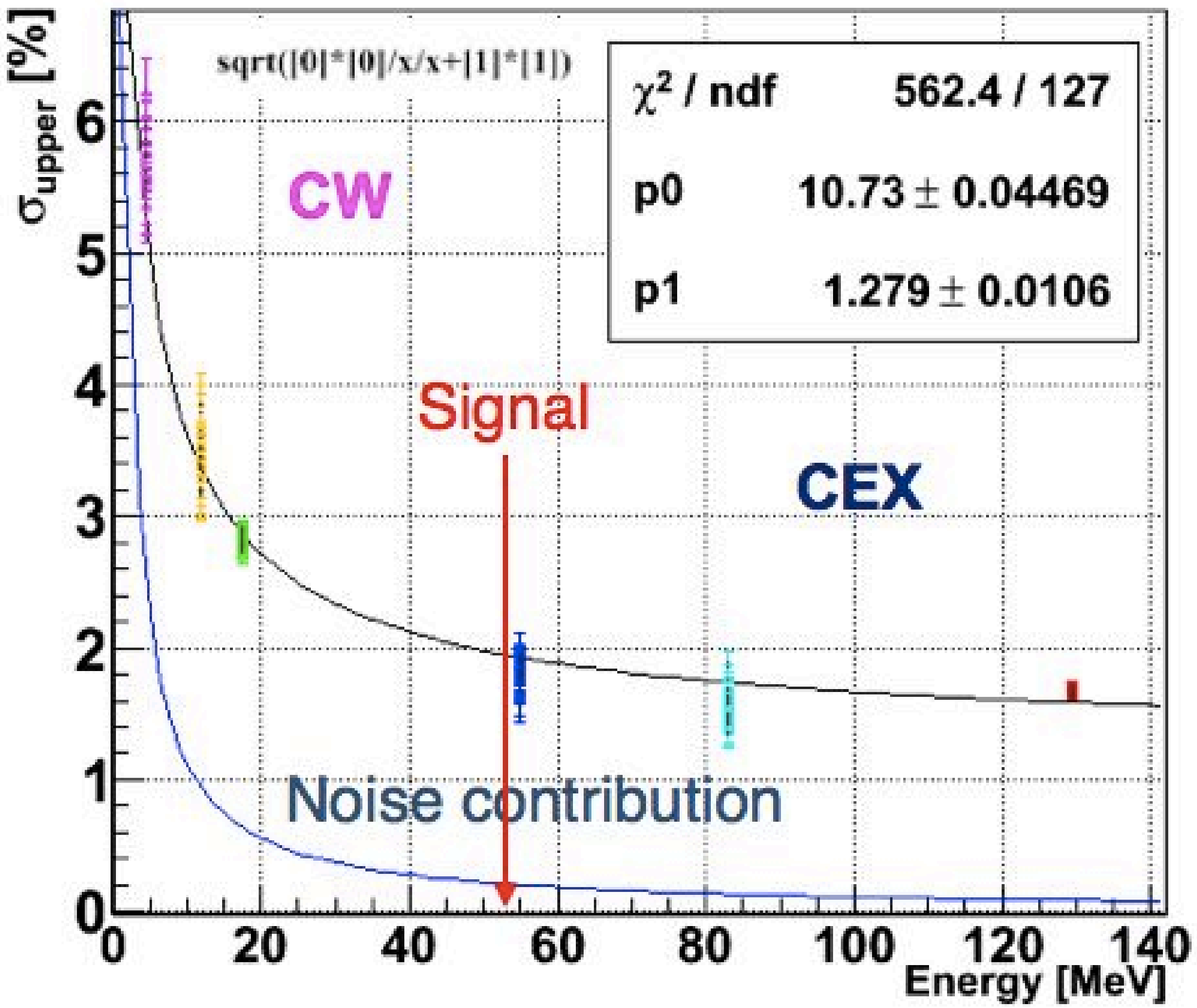
σ_{up}=2.0% for deep(>2cm), 3.0% (1~2cm), 4.2% (0~1cm)

Energy resolution is depth dependent.

Energy resolution in 2009

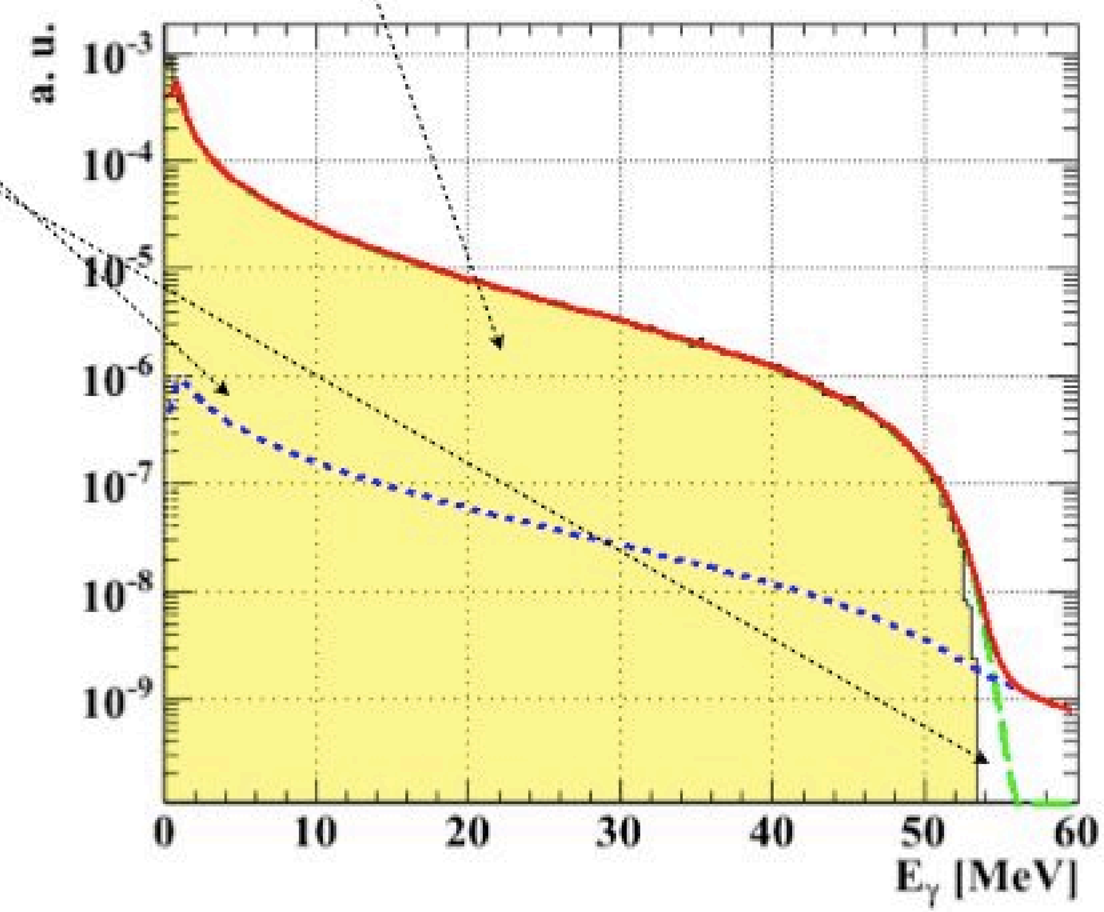
- 1.95% σ @ 52.8MeV

Energy resolution as a function of energy.

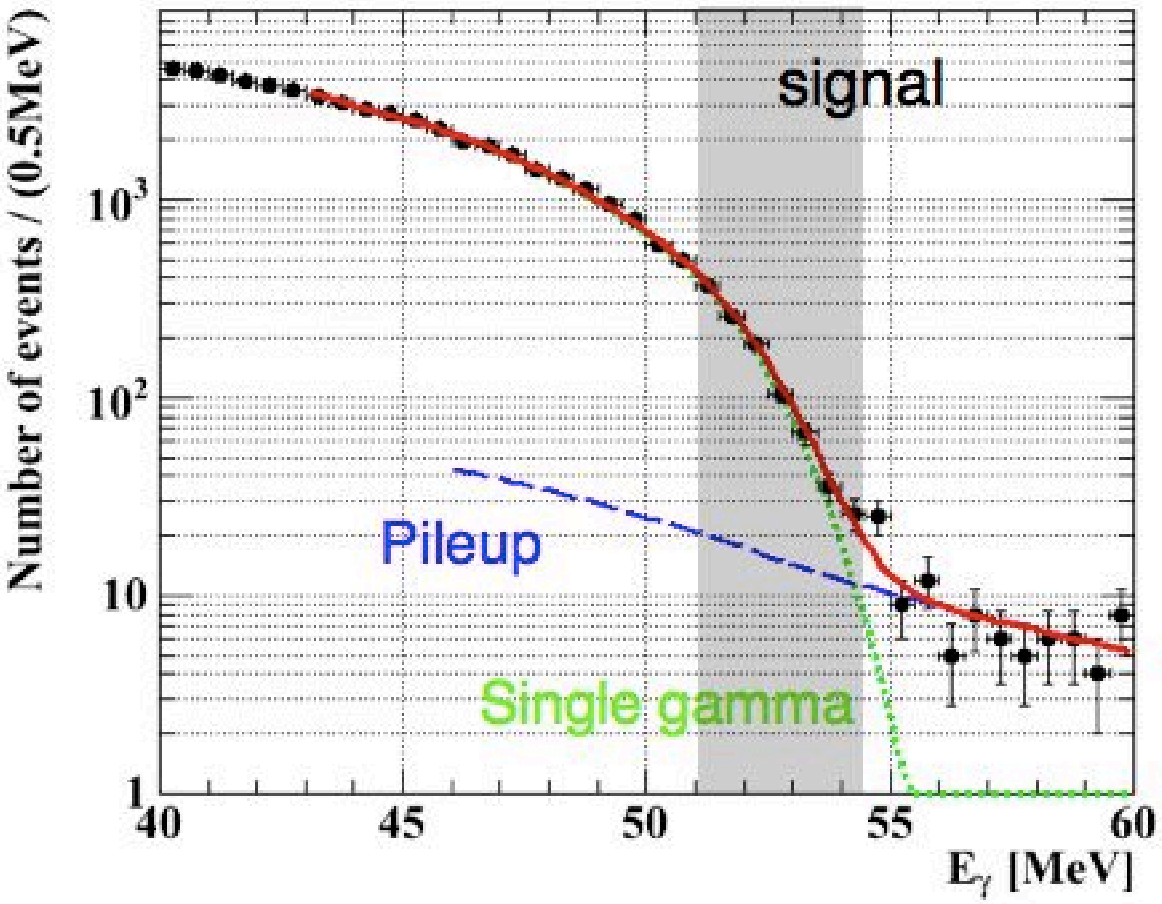


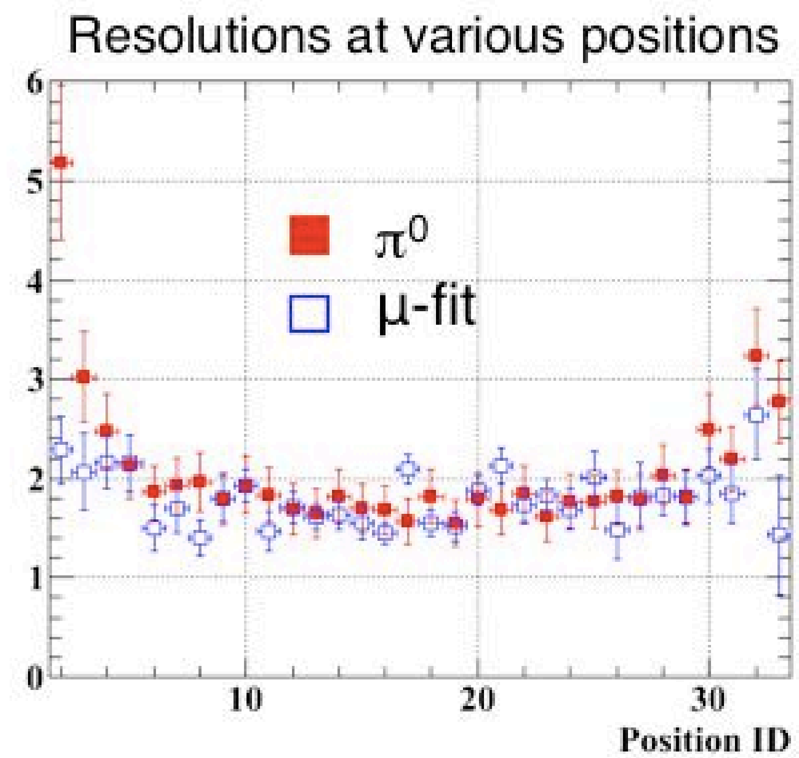
- Fitting gamma spectrum in muon runs by MC energy deposit.
- Free parameters (#RD+AIF, #pileup, energy resolution, energy scale)
- Fit result (RD + AIF + Pileup)

Energy resolution and scale can be checked by using muon data

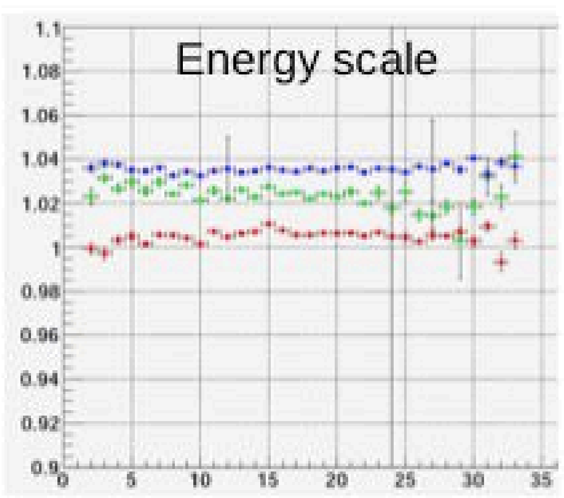


Checking by using muon data





Pion and muon data are consistent.



Scale in 2008 is **1** (i.e. consistent with pion data)

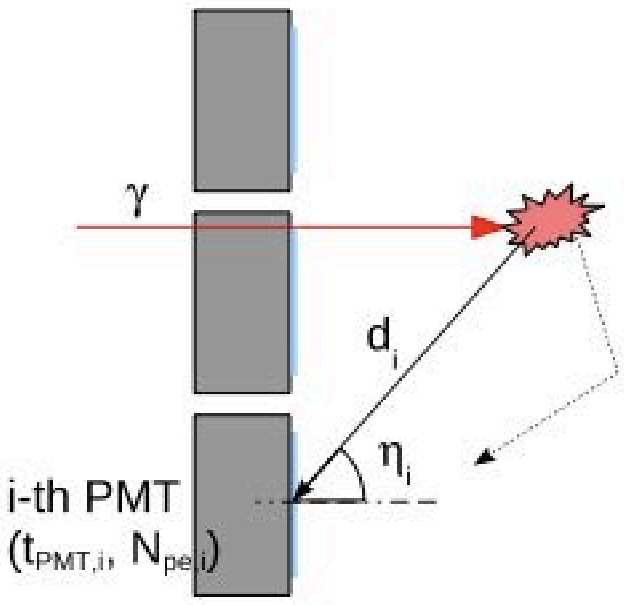
2009(200u degrader), and 2009(300u degrader) are little higher because of a mistake of configuration parameter*, to be reprocessed.

* Scale factor for NI was used, while analysis is done by HP (see page 10)

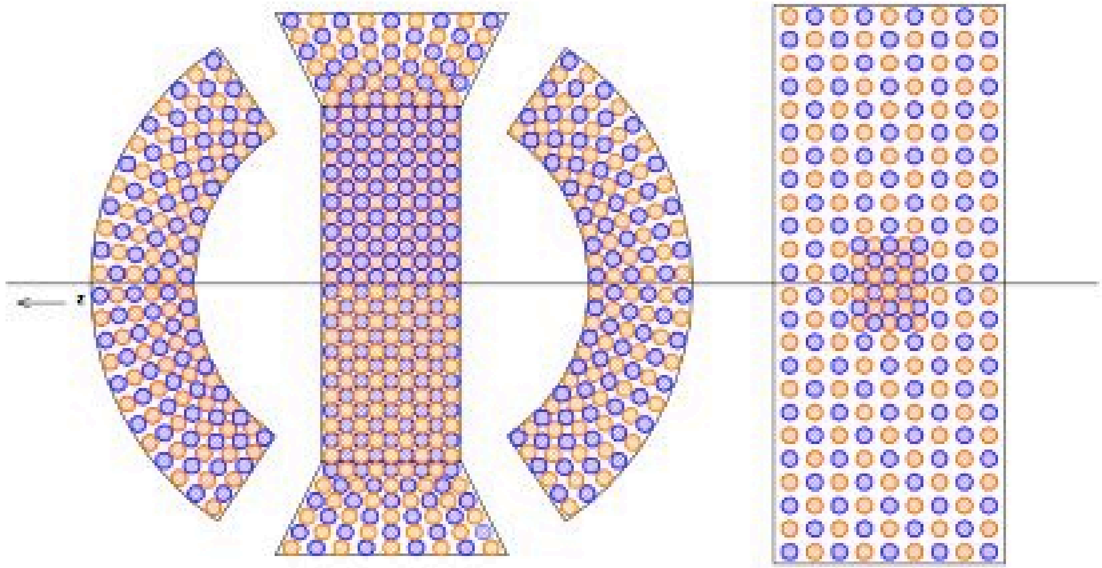
Time

Time reconstruction

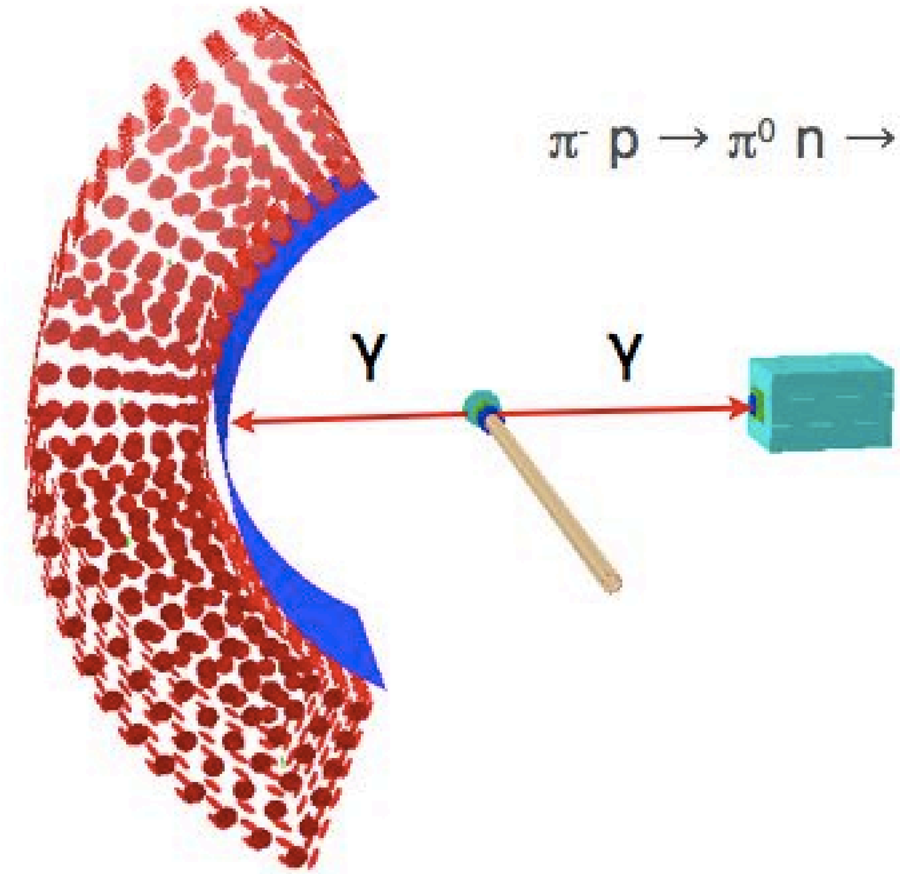
- Time reconstruction is done by fitting or averaging PMT time
- Taking into account time-walk, delay due to photon statistics, cable length, path length from gamma conversion point to each PMT and effect of indirect photons.
- Calibrations constants (PMT time offsets, time-walk correction factors...) are obtained from pion runs.



"Intrinsic" resolution



$$\sigma(T_{\rm odd} - T_{\rm even}) = \sigma T_{\rm intrinsic} \times 2$$



"Practical" resolution

$$\sigma(T_{\rm LXe} - T_{\rm PreShower}) = \sigma T_{\rm LXe} \oplus \sigma T_{\rm PreShower} \oplus \sigma T_{\rm DecayPosition} \oplus \sigma T_{\rm Electronics}$$

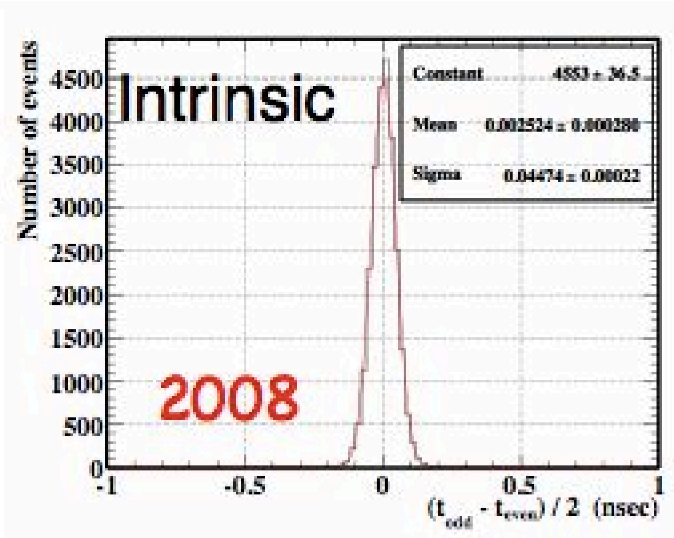
$$\sigma T_{\rm LXe} \sim \sigma T_{\rm intrinsic} \oplus \sigma D/c'$$

measurements

D : depth resolution, c' : effective speed of light

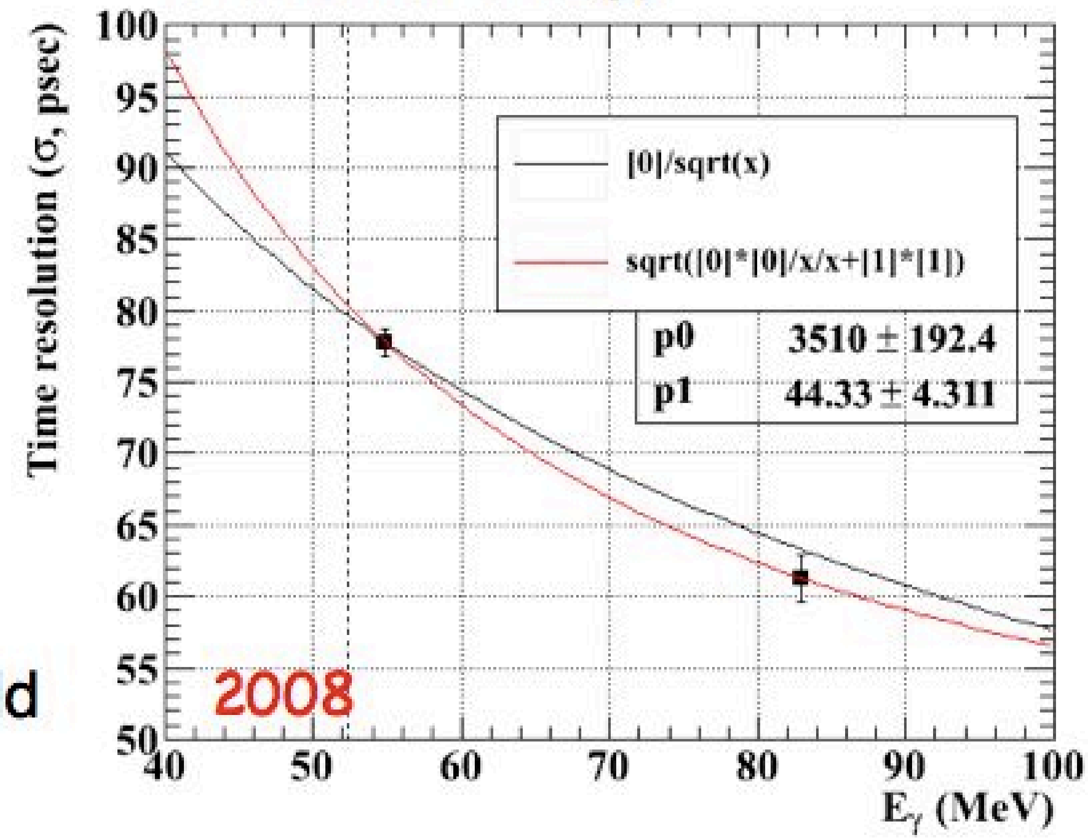
Resolution

- "Intrinsic" resolution
  - 45 psec at 55 MeV



- "Practical" resolution
  - 78ps @55MeV, 61ps @83MeV in summer 2008
  - 68ps @55MeV in winter 2008, due to higher light yield

"Practical" resolution as a function of energy

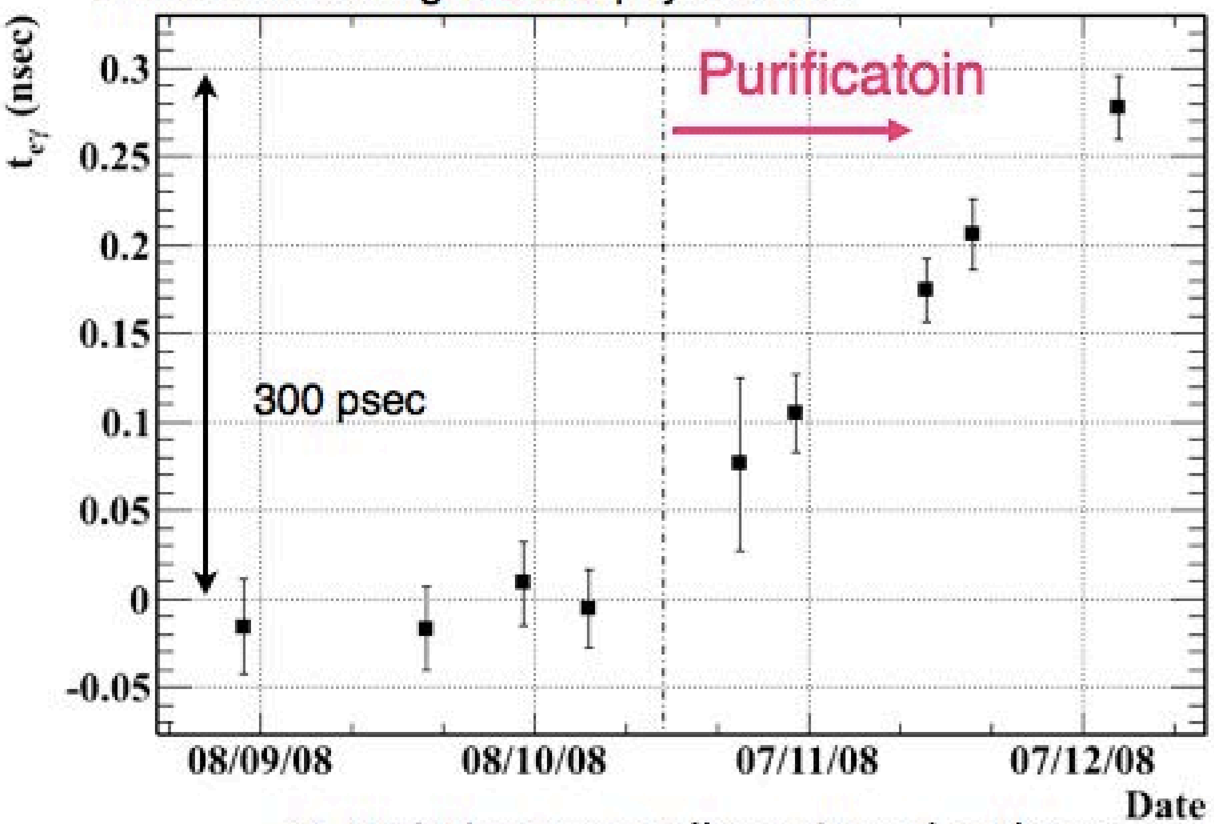


In 2009, "intrinsic" resolution is same as 2008, but "practical" is worse (169 psec); to be understood.

Possibly it is due to a jitter of electronics. The jitter is chip dependent, and it was measured to be much larger(up to 155 ps) between LXe and pre-shower chips, than that between LXe and TC chips (up to 102 ps). **Note that the effect is smaller for physics analysis.** If we subtract the jitter, LXe resolution is sqrt(169^2 - "<155"^2) = ">67" psec, which is almost same as winter 2008. See backup slide for details.

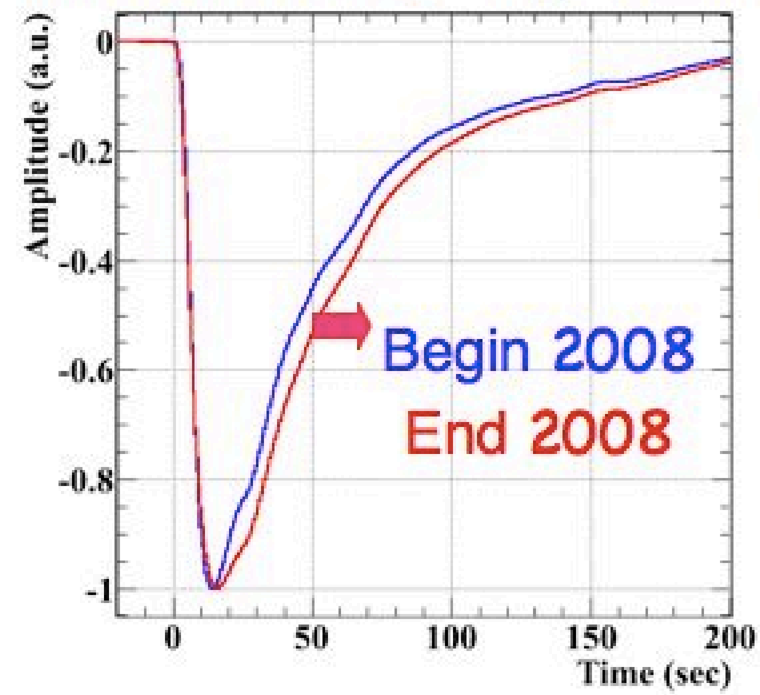
Drift of relative time to positron

Drift of time during 2008 physics runs



➔ Variation was well monitored and corrected

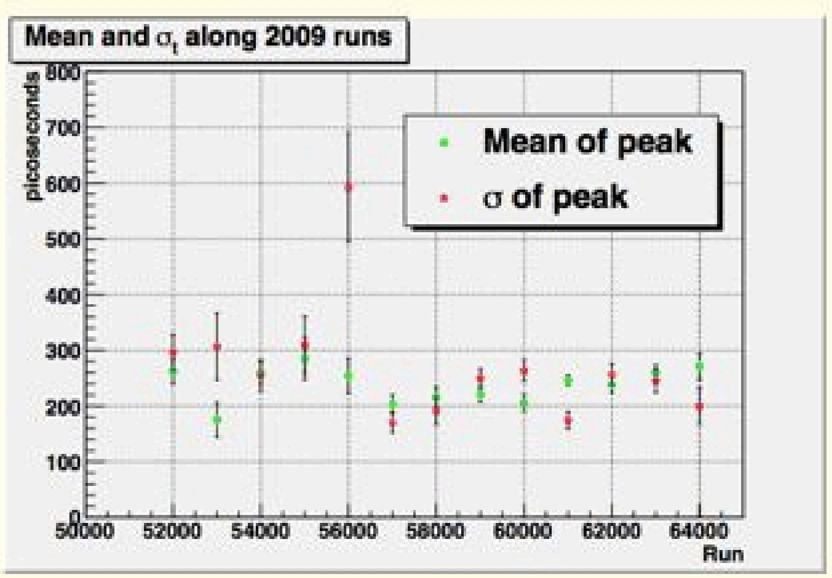
Waveform was getting wider in 2008



Constant-Fraction time depend on pulse shape

Stability after correction < 20 ps

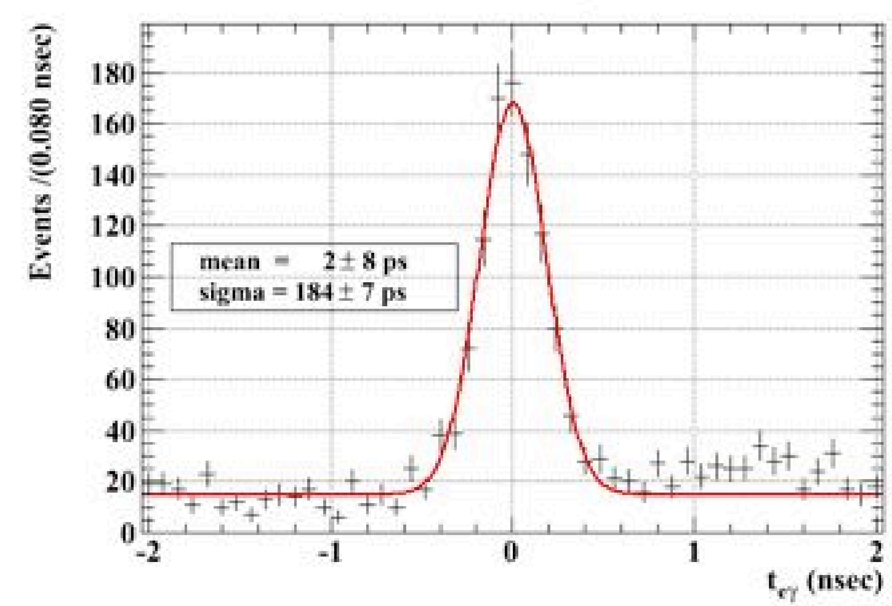
2009



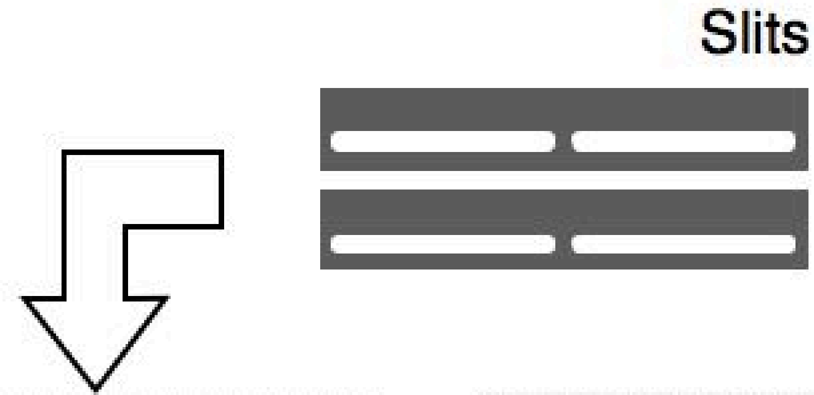
No drift is seen in 2009

2008

RD peak in low intensity muon runs



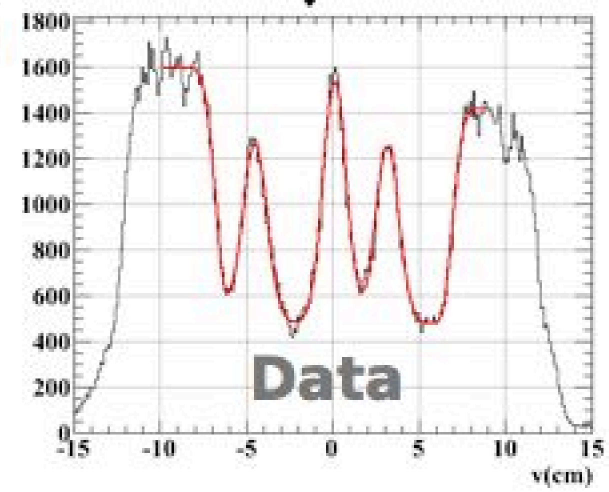
Position

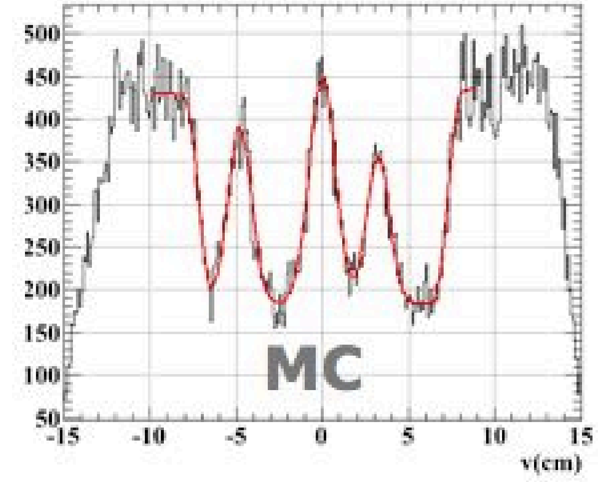


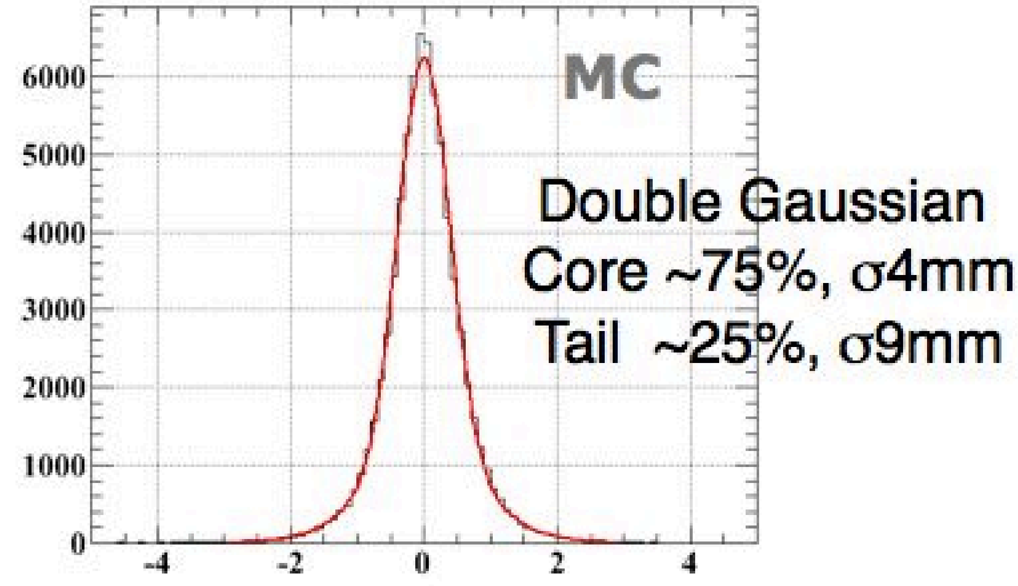
- Reconstruction : Fitting PMT output distribution on the inner face, by a sold angle function.
- Resolution measurement
  - π^0 runs with 1cm lead slits in front of the detector
  - Compare the width of shadow of slits with MC
  - Result
    - The width is 1.8 mm wider than MC (resolution is known) in quadrature

2008

σ_{xy}~5 mm, σ_{depth}~6 mm

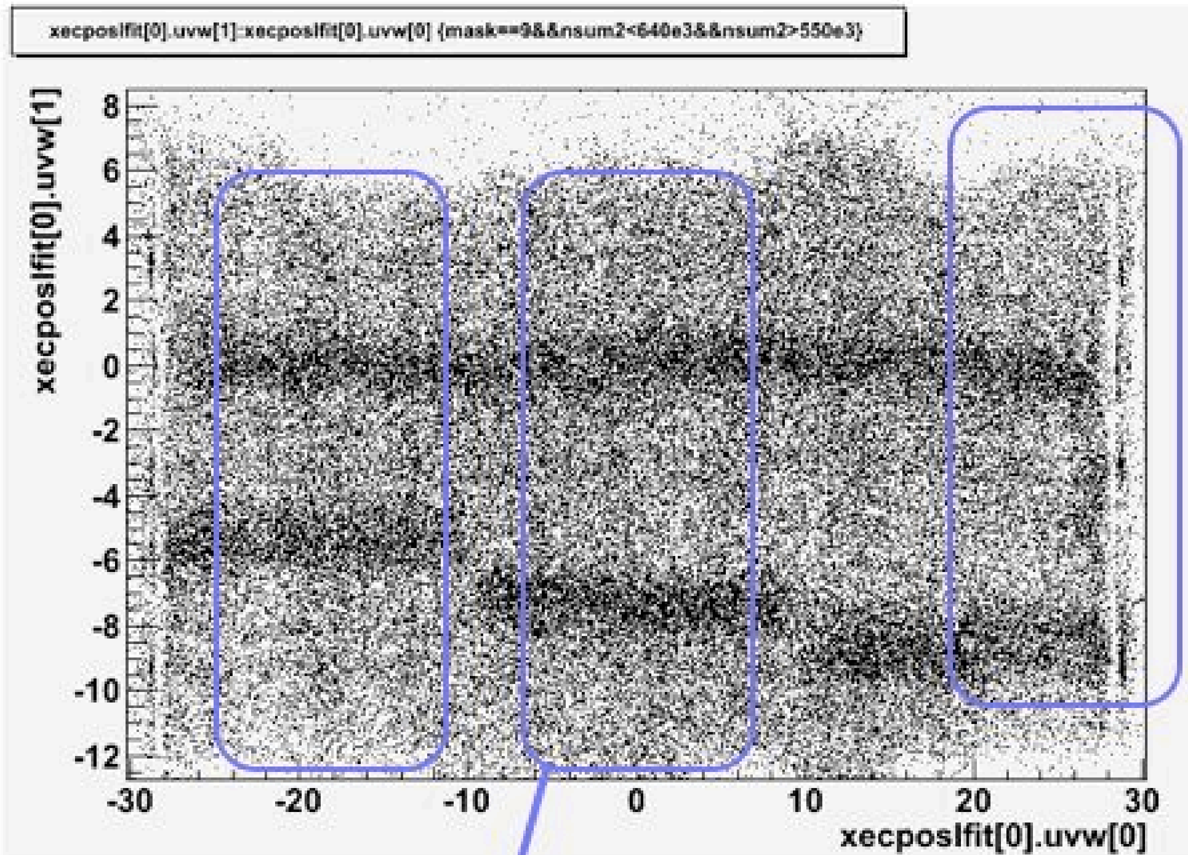


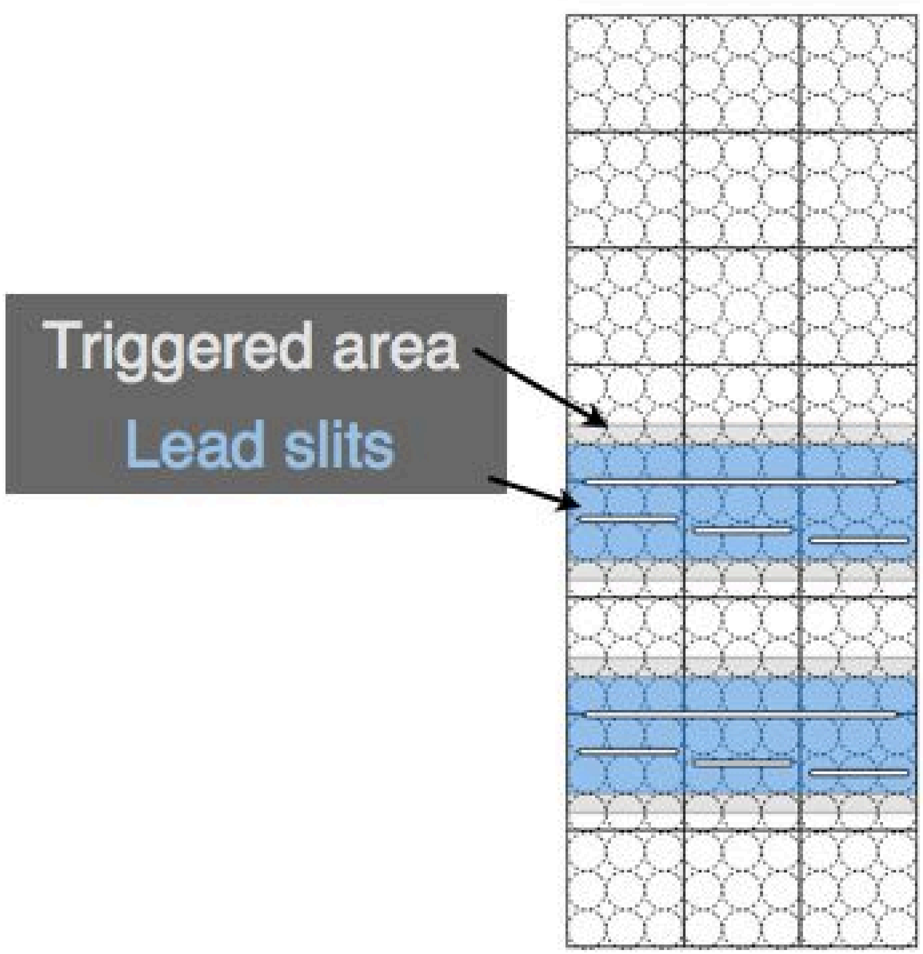


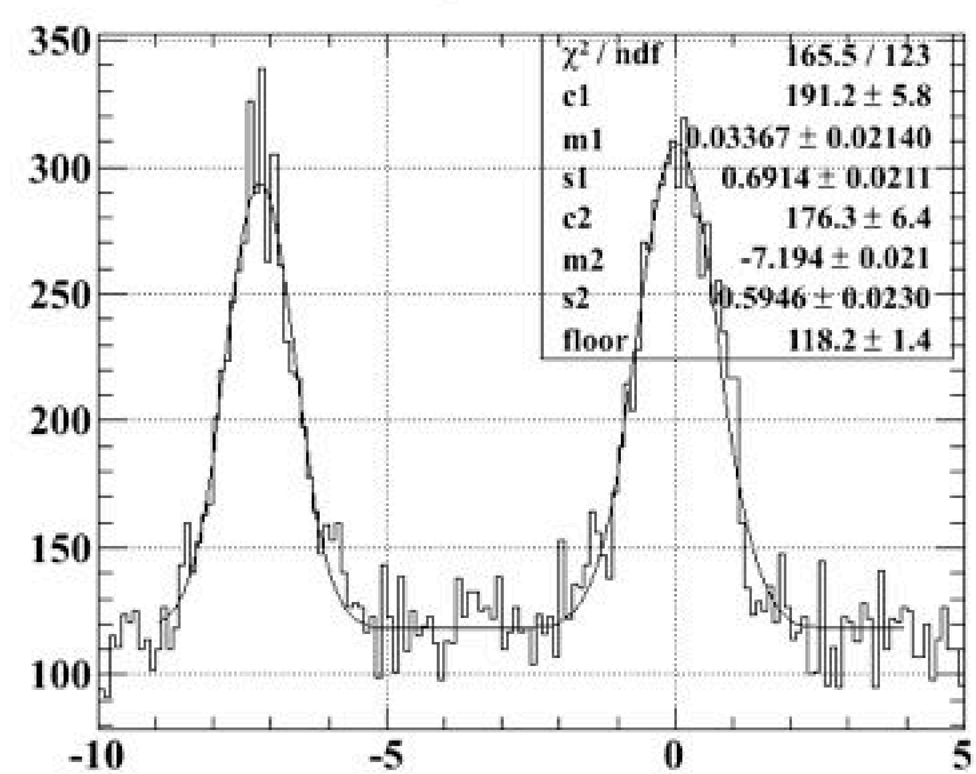


Position resolution in 2009

A similar measurement was done in 2009, and resolution is same as 2008.







Sigma : 6~7.5 (last year 6.7~7.2mm)

gas alpha data is not taken yet for 2009, so Q.E. in 2008 is used in the analysis.

Pileup analysis

Analysis for pileup events

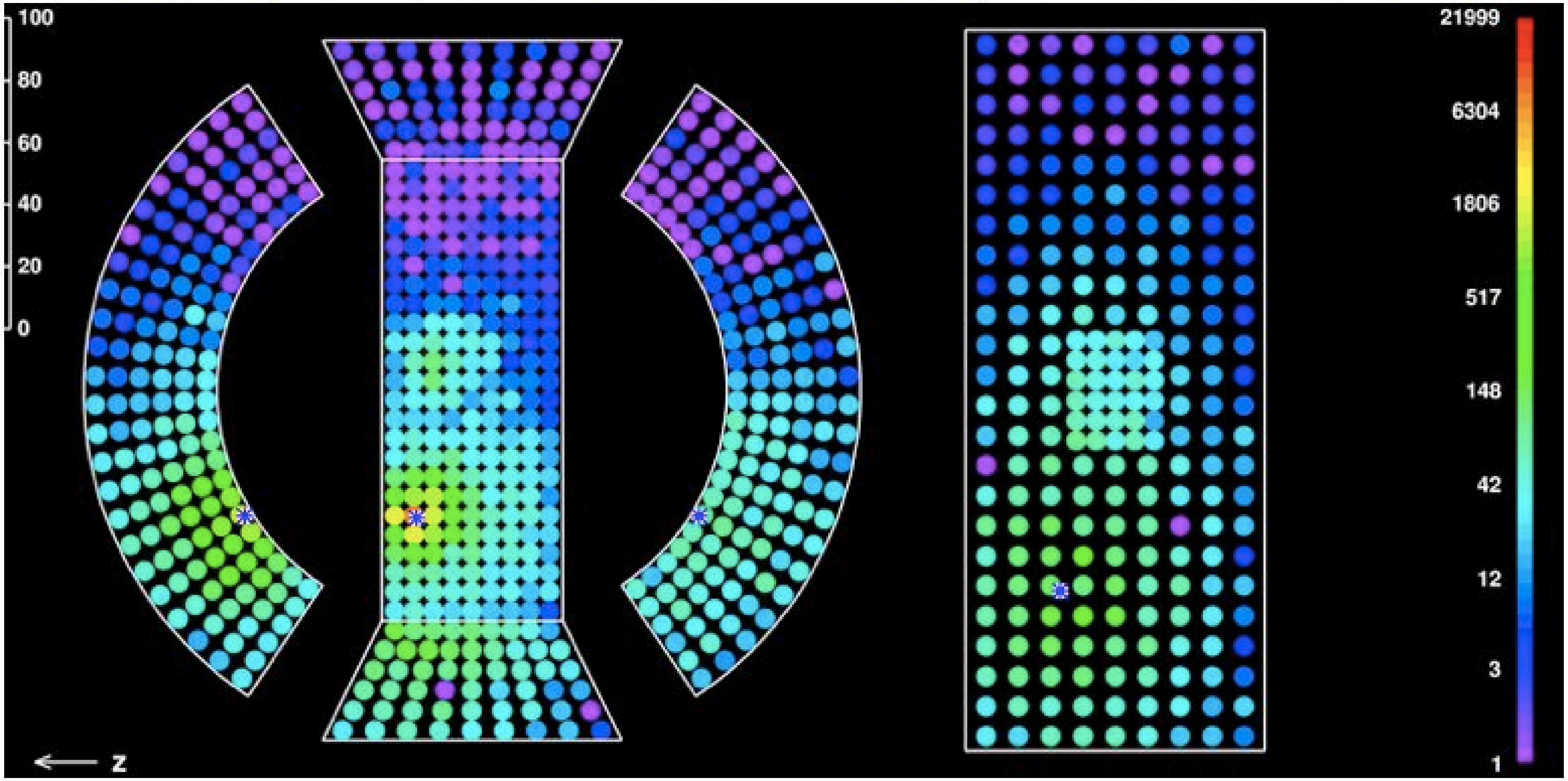
Finding pileup from light distribution pattern

→ Estimating energy without using PMTs around the pileup (resolution could be worse than usual way)

→ Replacing PMT output only around the pileup with expectation from main gamma

→ Usual reconstruction

PMT output (development view of the detector) Before replacement



We don't throw away pileup events.

Analysis for pileup events

Finding pileup from light distribution pattern

→ Estimating energy without using PMTs around the pileup (resolution could be worse than usual way)

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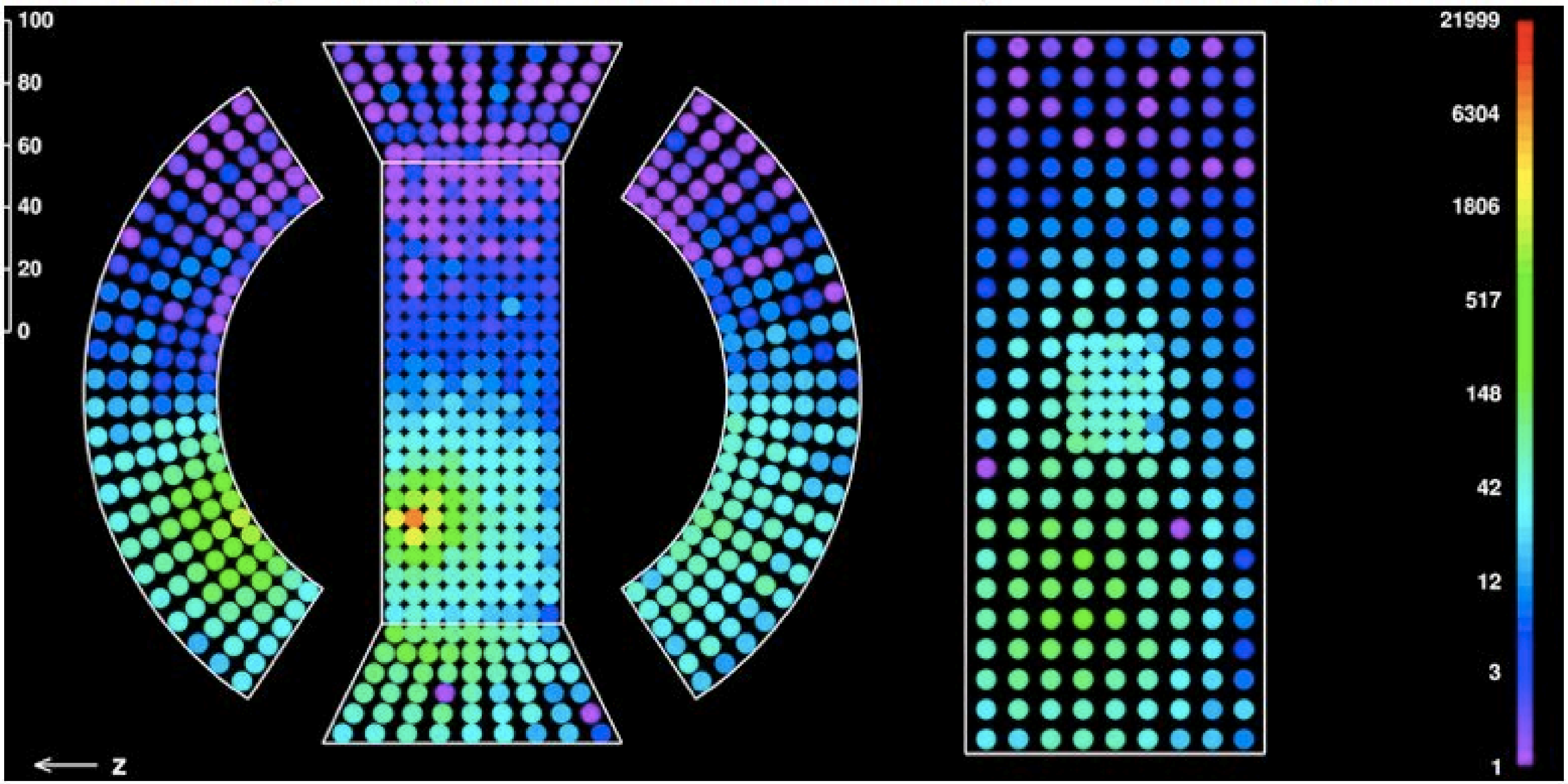
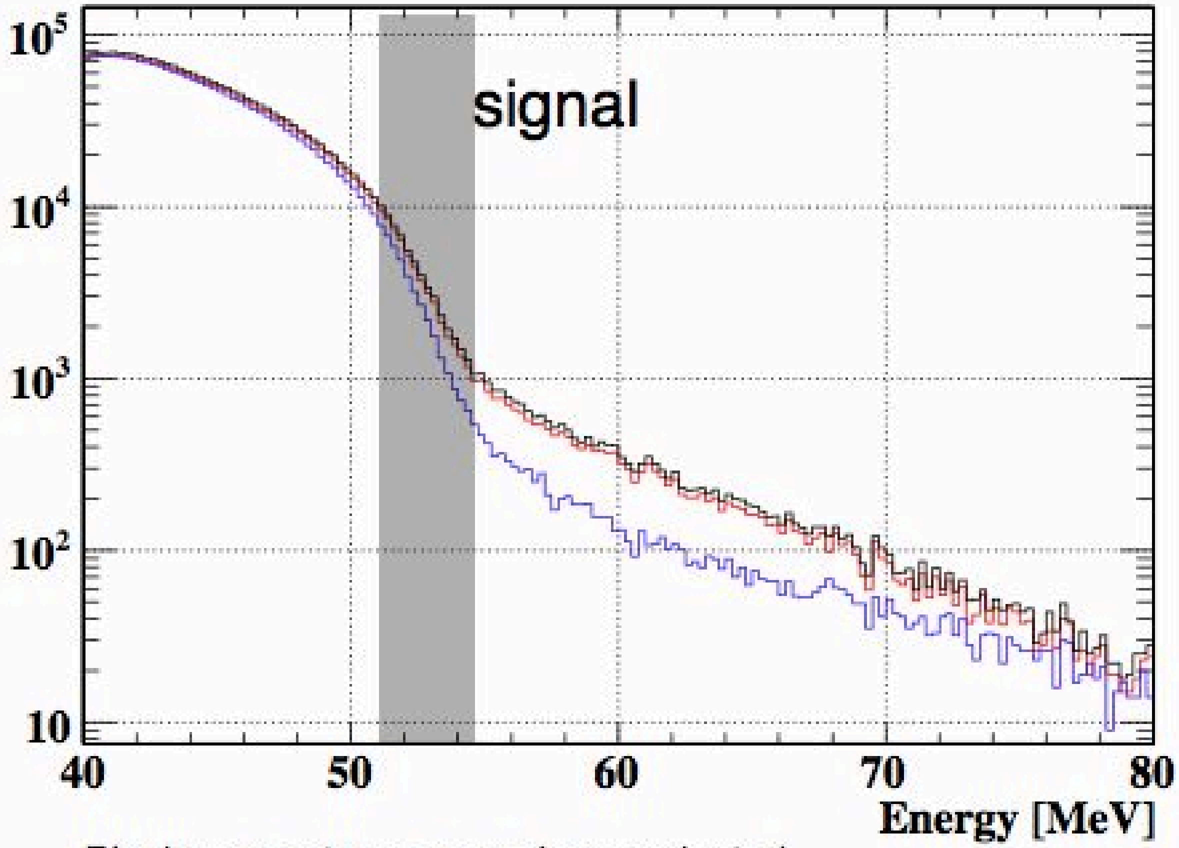


We don’t throw away pileup events.

Muon data with pileup elimination

Pileup identification is done by two methods:
time and *space* distribution of PMT outputs

2008 muon data, gamma energy spectrum



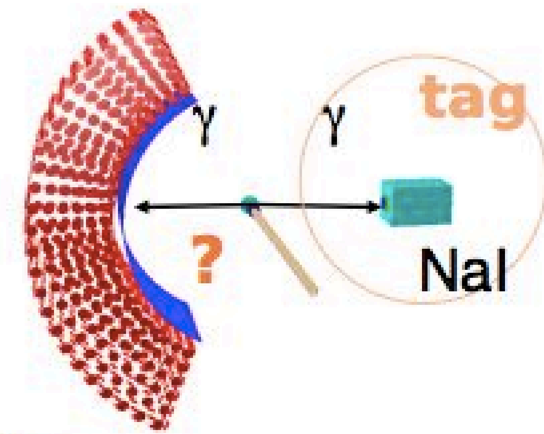
Black : acceptance, cosmic ray rejected
Red : rejected pileup events identified only by time method
Blue : After pileup contribution elimination

BG gamma rate is significantly decreased around signal energy.

Inefficiency to the signal : 5.5 ± 2.5 %

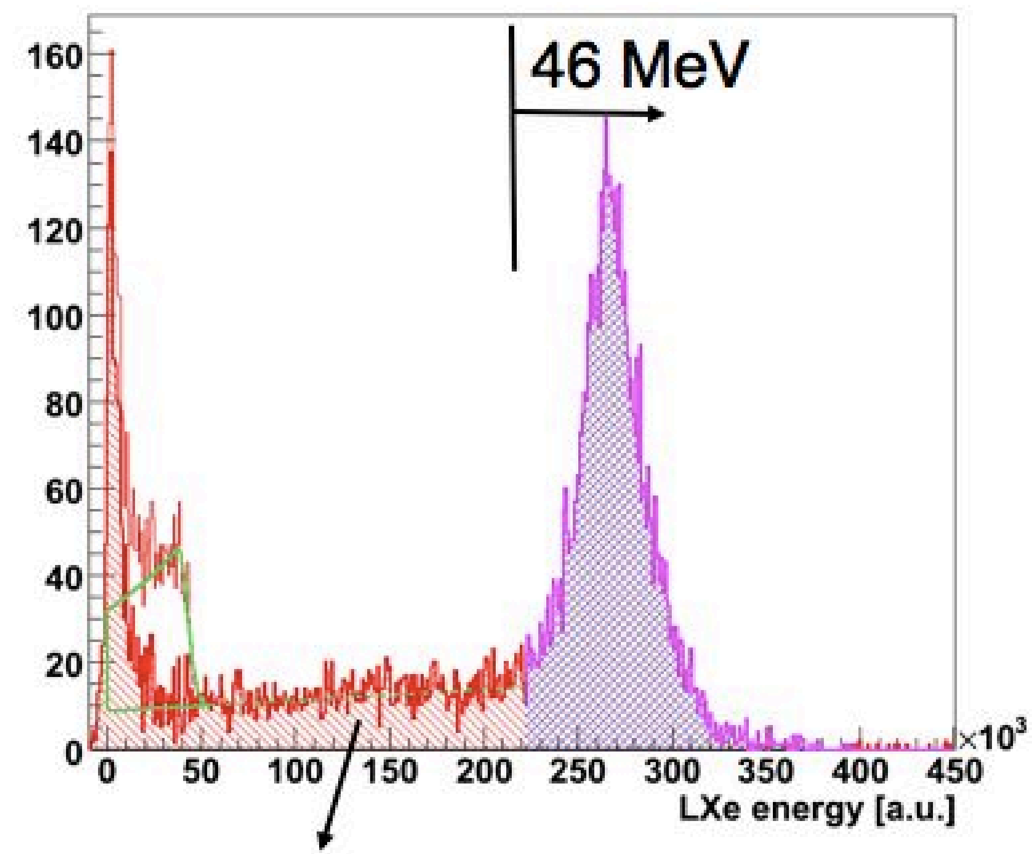
- Detection efficiency
  - Three methods to measure efficiency
    - signal MC
    - π^0 2 gamma rate, at NaI single trigger
    - muon runs, gamma rate

    } consistent in 5 % (rel.)



  - Position dependence, and event distribution in muon data are taken into account
  - ε_{det} = 66 % ([46, 60] MeV)

Energy spectrum of NaI trigger data



Interaction before xenon = inefficiency

- Analysis efficiency (Pileup, and cosmic ray cut)

ε_γ = (63 ± 4) %

Performance

	2008	2009 (Tentative)
Gamma Energy (%)	2.0/3.0/4.2 *	2.0/NA/NA**
Gamma Timing (psec)	80	> 67
Gamma Position (mm)	5-6 (~7.5 mrad)	5-6 (~7.5 mrad)
Gamma Efficiency (%)	63	NA**

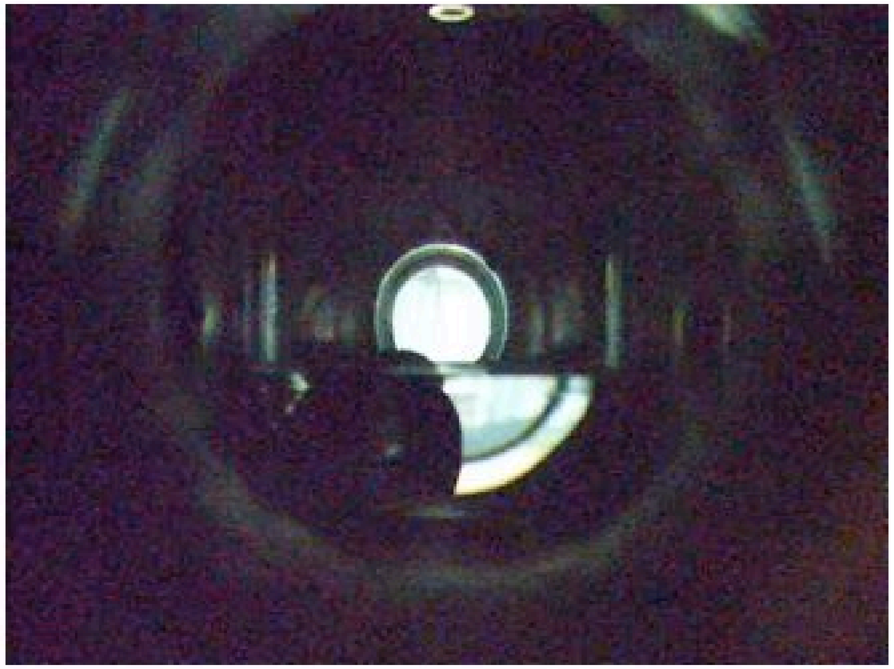
Tentative performance in 2009 is already similar to 2008.

* For different depth, 2>cm / 1-2 cm / 0-1 cm

** To be estimated

Future improvements

- Purity of xenon(i.e. optical property) was stable in 2009
  - Optimization of analysis for a single set of optical parameters must work.
  - Even more **detailed study on optical properties.** ➔ The better Q.E. estimation ➔ The better position, time and energy estimation.
- Improvements of **energy reconstruction**
  - Better equalization of PMT output to obtain uniform response before a posterior correction.
  - Better weight for summing PMT output (LinearFit method worked very well for the large prototype)
  - New algorithms to decrease fluctuation from low output PMTs. (energy estimation by each PMT)
- Ideas to improve **timing performance of DRS** (➔ Stefan's talk)
- More stable operation of the detector by more **powerful cooling.** The large prototype was operated 100% by a refrigerator during the measurement, while we use also LN_2 for the final detector. Effect of convection to resolutions is not known: Convection may look like position and time dependent scattering.



LXe convection seen in a glass cryostat at KEK

Summary

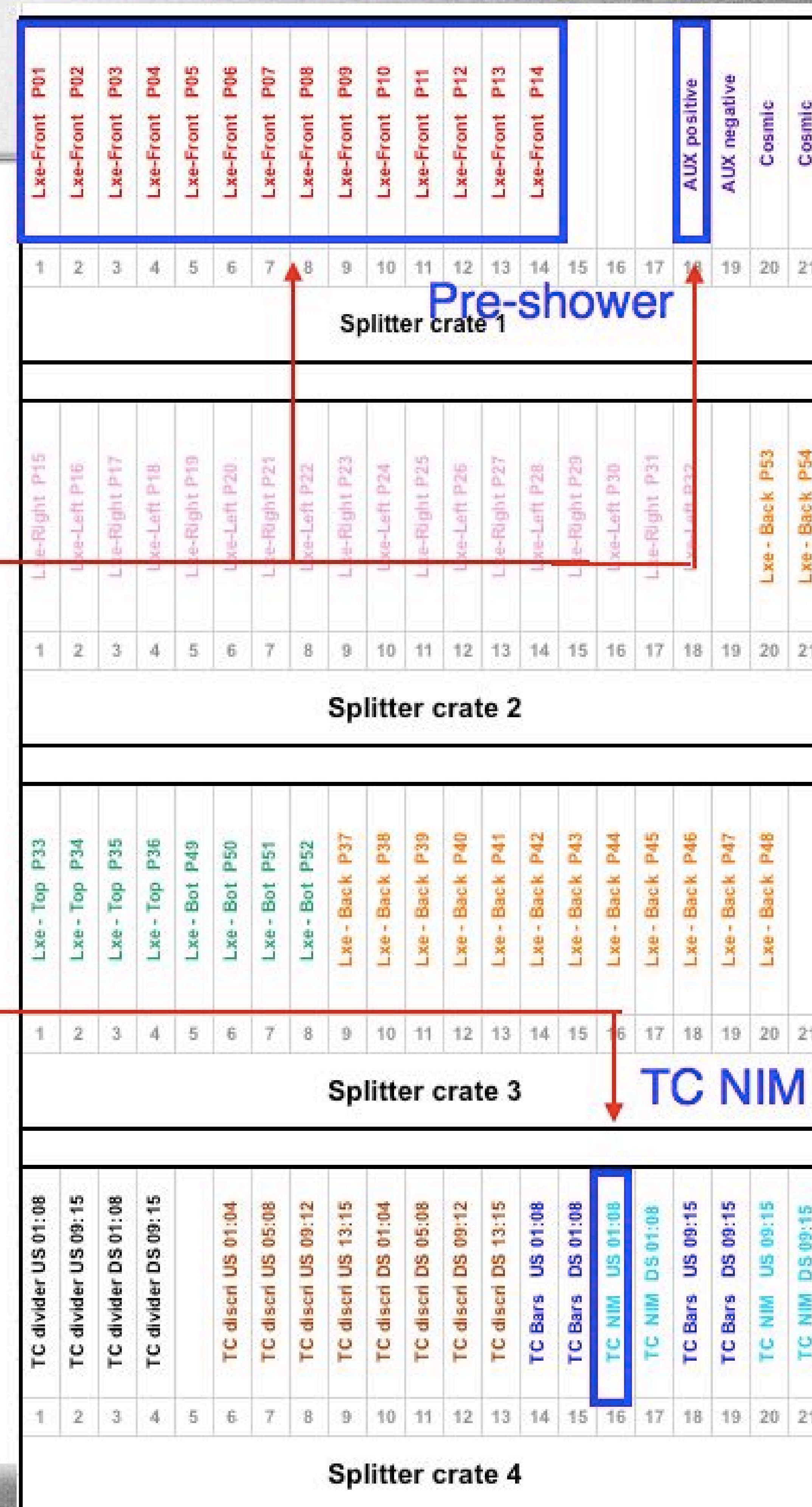
- Good performance was achieved for 2008 data analysis.
  - Noise level of WF is low enough.
  - Time and position resolutions are good.
  - A few % non-uniformity of energy, and 40% change of light yield are well monitored and corrected. 2 % energy resolution was achieved.
  - BG gamma rate was decreased by eliminating pileup contribution, instead of just throwing away events.
- 2009 performance is estimated by using the same method with 2008. Performance is almost same as 2008. Further improvements will be tried.
- Hardware modifications (Cooling, DRS4) are planed.
- Several ideas to improve analysis, to be developed and verified.

Backup

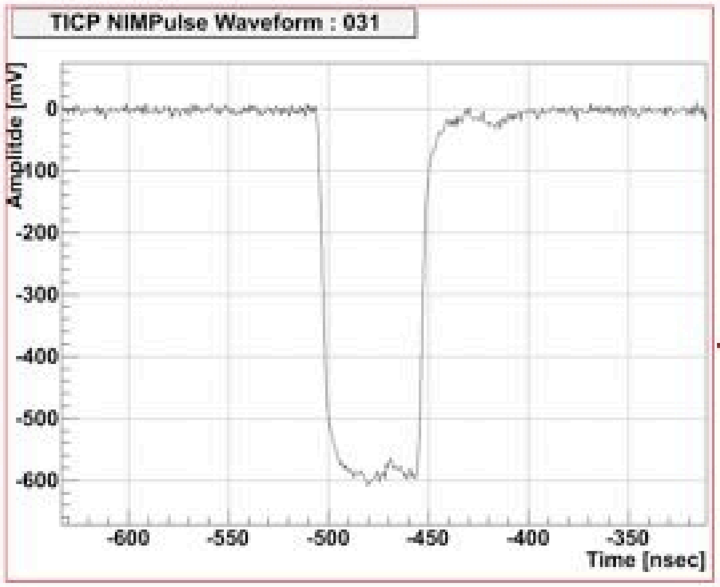
Effect of electronics for 2009 time resolution measurement

Measurement electronics contribution

xenon inner



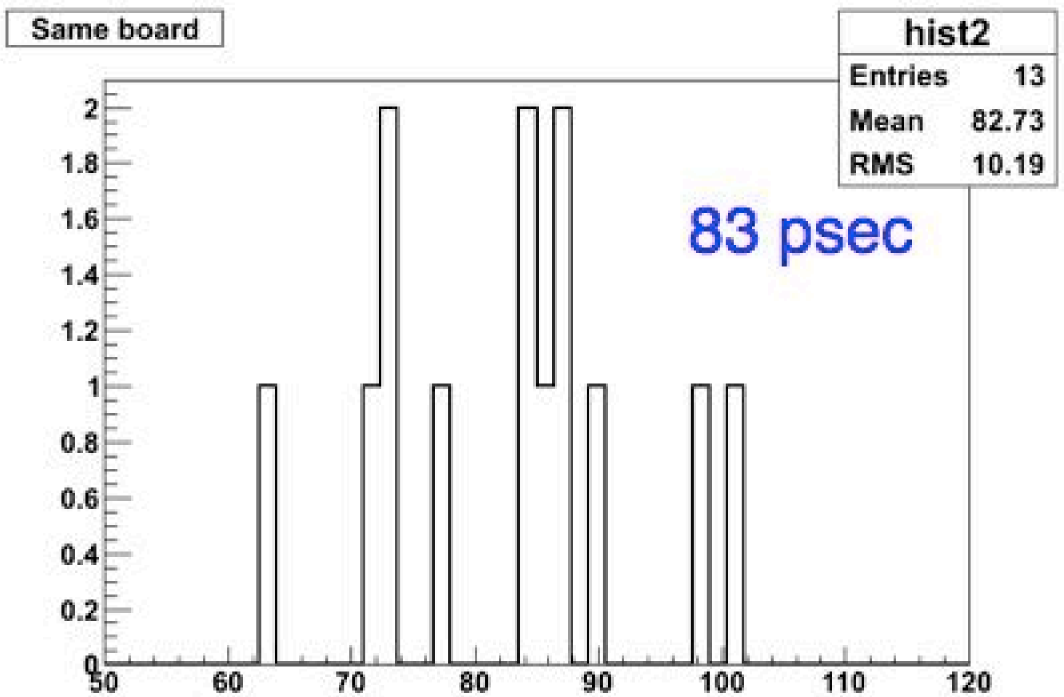
Pulse generator



- Square pulse into inputs of splitters, going to “Xenon inner”, “Pre-Shower”.
- One pair (two chips) is used at each run.
- Similar measurement was done between Xenon and TC (in Backup slides)

One entry is a pair of a XEC and pre-shower chip

Leading edge time

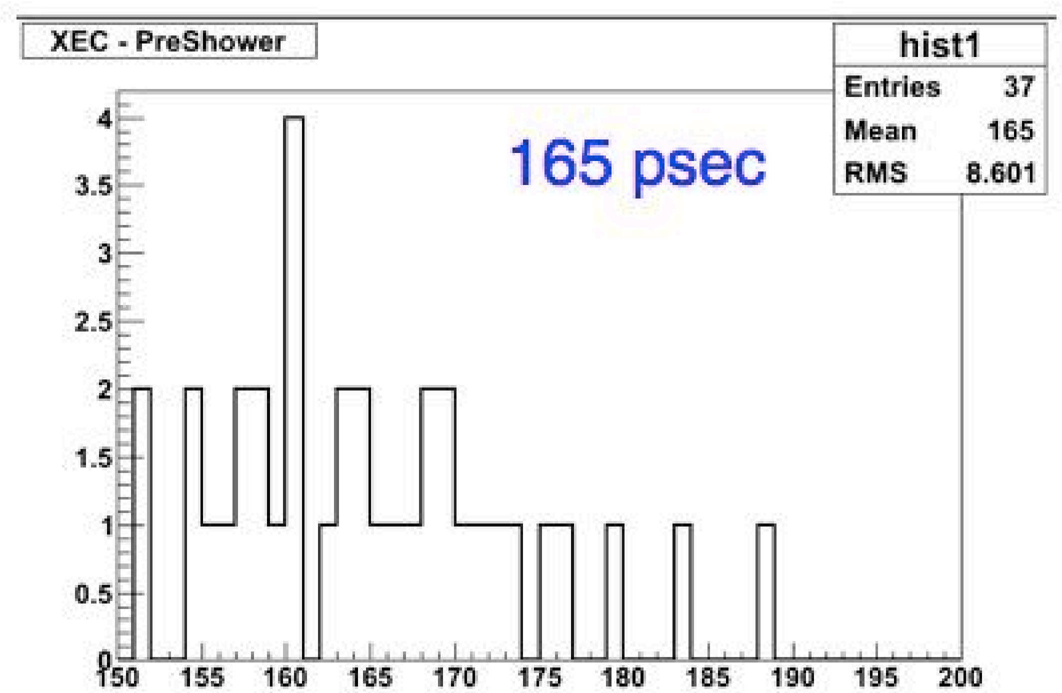


On the same chip : 30 psec
On same pre-shower board : 104

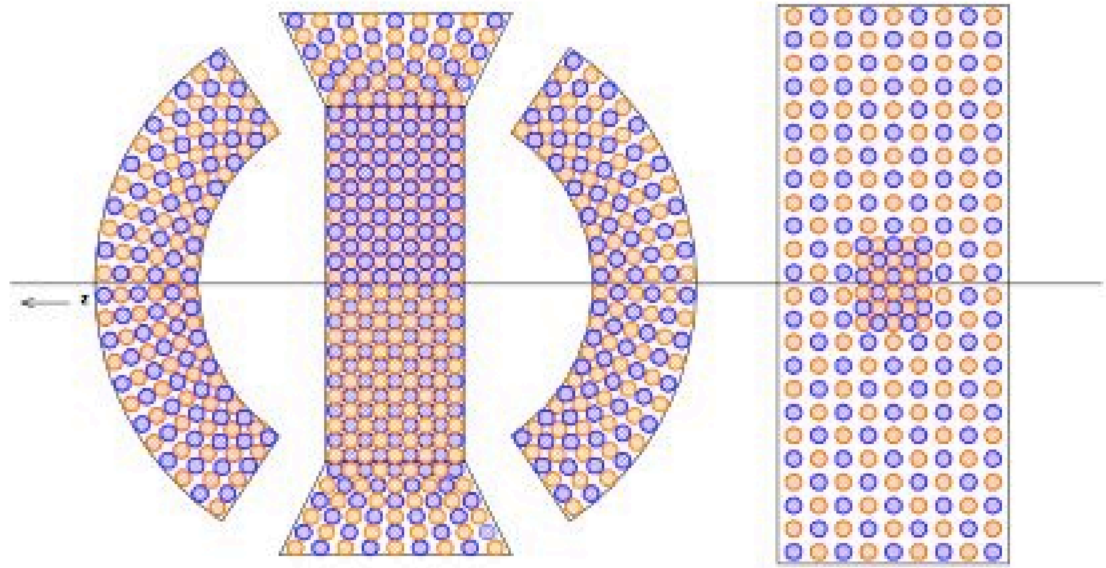
XEC Inner chips

$\sigma T_{\mathrm{Electronics}}$ < 155 psec

(This jitter is specific to the pi0 data. Not same as physics data)

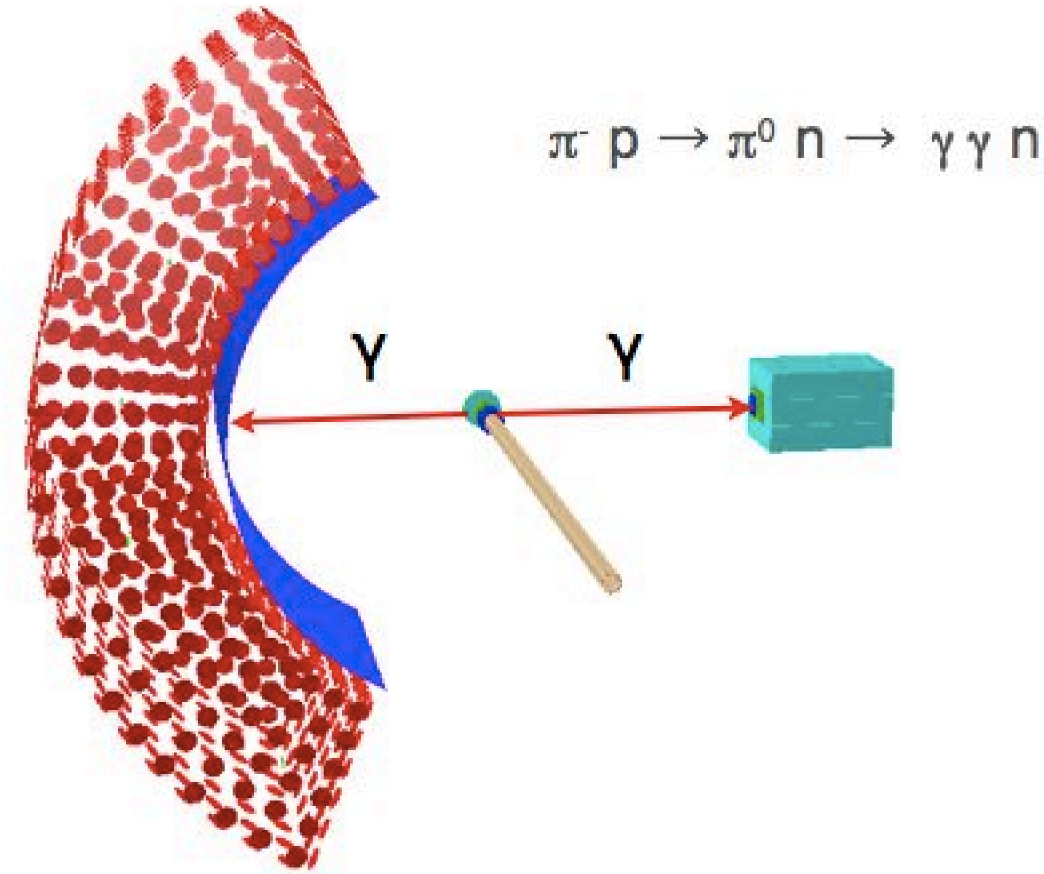


Time resolution measurement (55 MeV)



43 psec

$\sigma(T_{\rm odd} - T_{\rm even}) = \sigma T_{\rm intrinsic}$ x 2



202 psec | >68 psec | 93 psec | 60 psec | <155 psec

$$\sigma(T_{\rm LXe} - T_{\rm PreShower}) = \sigma T_{\rm LXe} \oplus \sigma T_{\rm PreShower} \oplus \sigma T_{\rm DecayPosition} \oplus \sigma T_{\rm Electronics}$$

$$\sigma T_{\rm LXe} \sim \sigma T_{\rm intrinsic} \oplus \sigma D/c'$$

43 psec | >53 psec

~60 psec (MC)

measurements

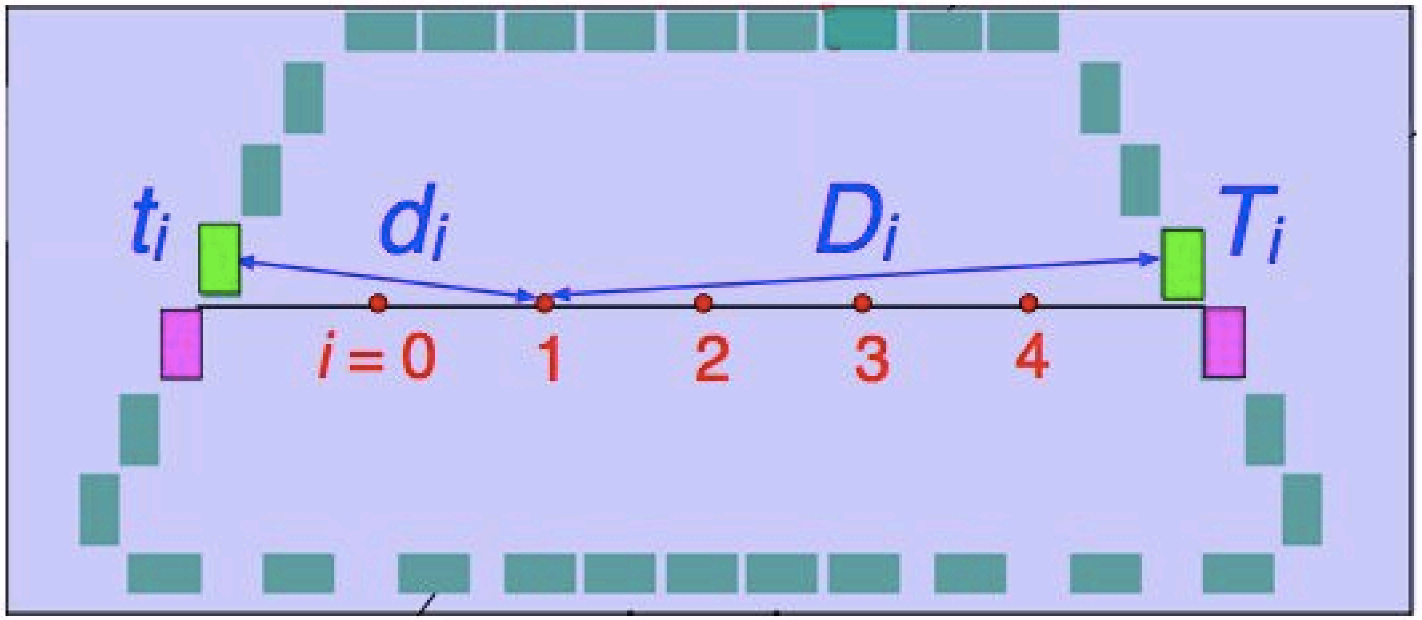
$\sigma T_{\rm LXe}$ is same as 2008

D : depth resolution, c' : effective speed of light

Speed of scintillation light in LXe

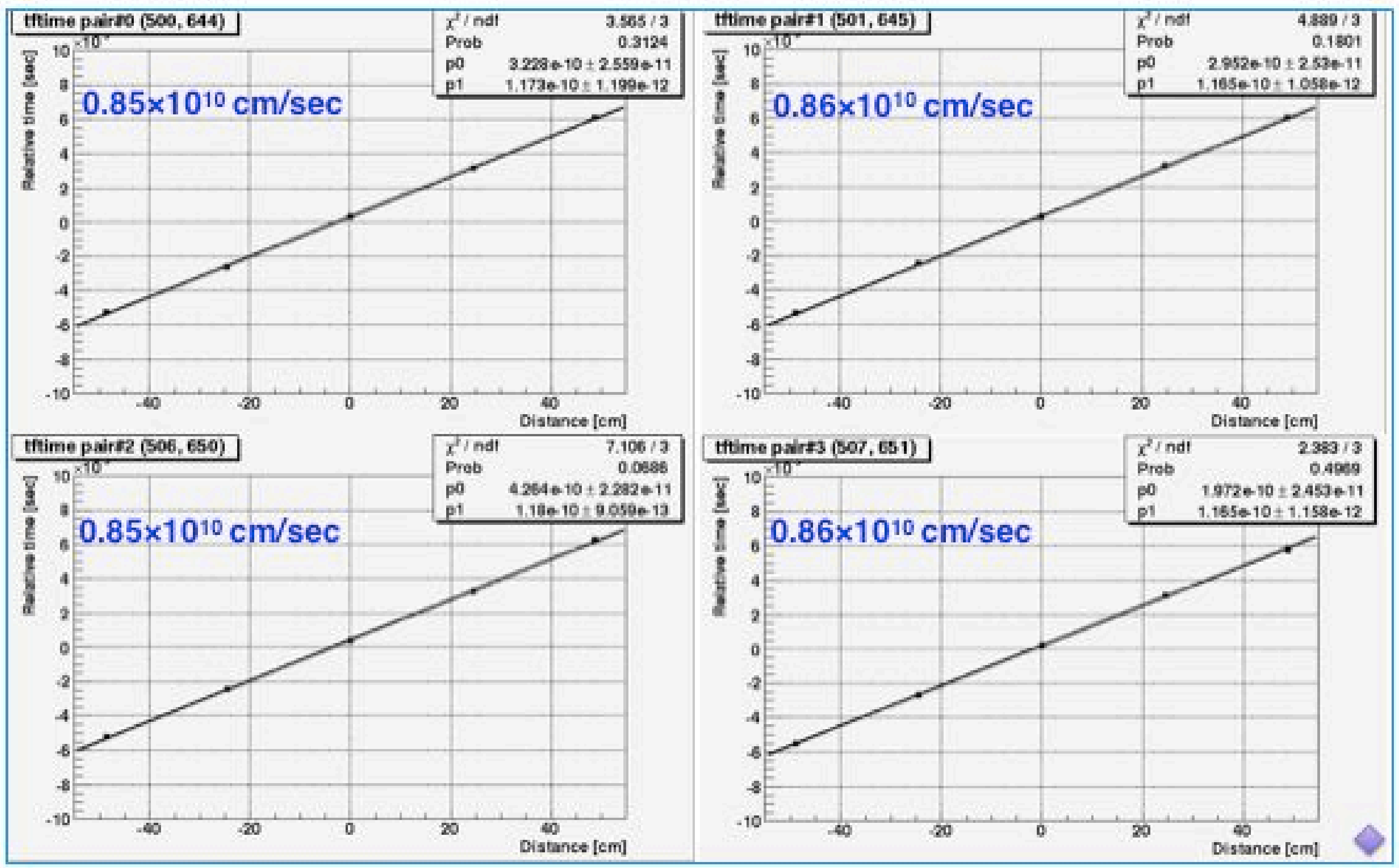
Measurement by using alpha data

- Vary alpha source position to obtain different distances.
- Use only PMTs around the end of the wire to minimize the systematic effect due to reflection and scattering.
- Wide distance range [0, 48.7]cm



$$V = (D_i - d_i) / (T_i - t_i) \quad i = 0,..4$$

- Clear linear relation bw/ distance and time difference
- Small time offset depending on pairs.



0.85×10^{10}cm/sec (averaged over 4 PMT pairs)

→23% lower than expected (peak speed)

Result

- Different data samples are analyzed.

Data sample	Speed [cm/s]	Ratio to expectation
Oct. 2008 (DRS2)	0.91×10^{10}	0.83
Dec. 2008 (DRS2)	0.89×10^{10}	0.81
Dec. 2008 (DRS2, high gain)	0.85×10^{10}	0.77
Dec. 2009 (DRS4)	0.99×10^{10}	0.90
MC	1.08×10^{10}	0.98
MC w/o scattering and reflection	1.14×10^{10}	1.04

$V_{expected} \sim V_{MC} > V_{2009} > V_{2008}$

How can the difference (2008 vs 2009) be interpreted?

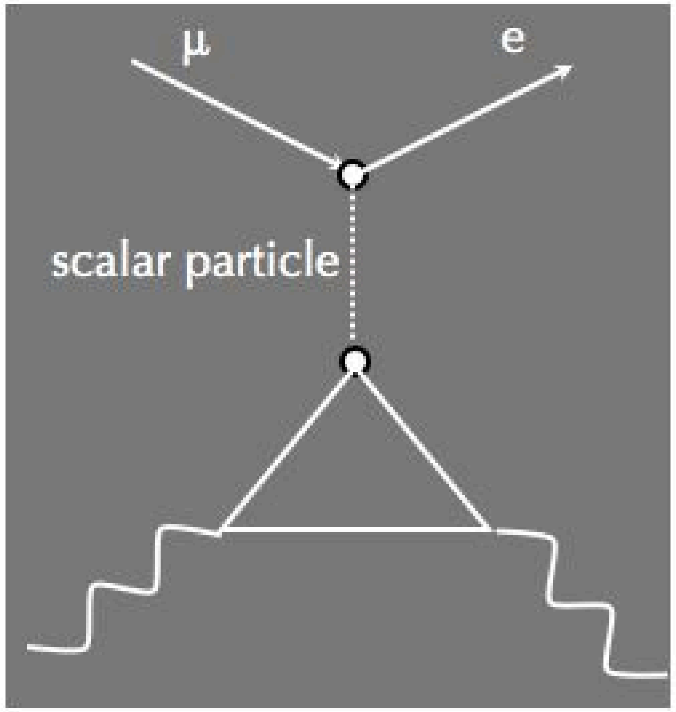
- Systematics in the measurement?
  - Scattering/reflection
  - Fluctuation due to low photon statistics
  - DRS2 vs. DRS4
  - Discrepancy seems too large to explain with systematics. (systematic uncertainty ~5%)
- Speed is really changed?
  - Effect of impurities
    - Refractive index
    - Wavelength

- Speed of scintillation light in LXe is measured
- Measurements in data give lower speed than expected, while MC measurement shows a good agreement with expectation.
  - **~20% lower in run2008**
  - **~10% lower in run2009**
- The difference seems too large to explain with the systematics of the measurement.
- Theoretical mechanism to change the speed is not understood yet.

The world largest xenon detector allows to measure scintillation light.
The study is on going.

Analysis of 2 gamma event

$\mu \rightarrow e \gamma \gamma$ decay



- $\mu \rightarrow e \gamma \gamma < 7.2 \times 10^{-11}$ (Crystal Box Phys.Rev.D38 2077(1988))
- In some models $\mu \rightarrow e \gamma \gamma$ decay is much larger than $\mu \rightarrow e \gamma$
  - Example : R-parity-violating (RPV) SUSY (Phys. Rev. D67 115012 (2003))
- One RPV SUSY model says $BR(\mu \rightarrow e \gamma \gamma) = 1.3 \times 10^{-8} \times |\lambda\lambda'|^2$
- If we lower the limit, we can set the limit on RPV coupling products

$\mu \rightarrow e\,\gamma\,\gamma$ event property

Most probable event :

Both photons are around 26 MeV

Sum energy of photons is a bit higher than 52.8 MeV

Angle between photons is small

positron energy is a bit smaller than 52.8 MeV

positron is around back to back to the photons

Photons and positron are on the same plane

Efficiency ~ $3.8 \times 10^{-2} \times \Omega/4\pi = 3.4 \times 10^{-3}$

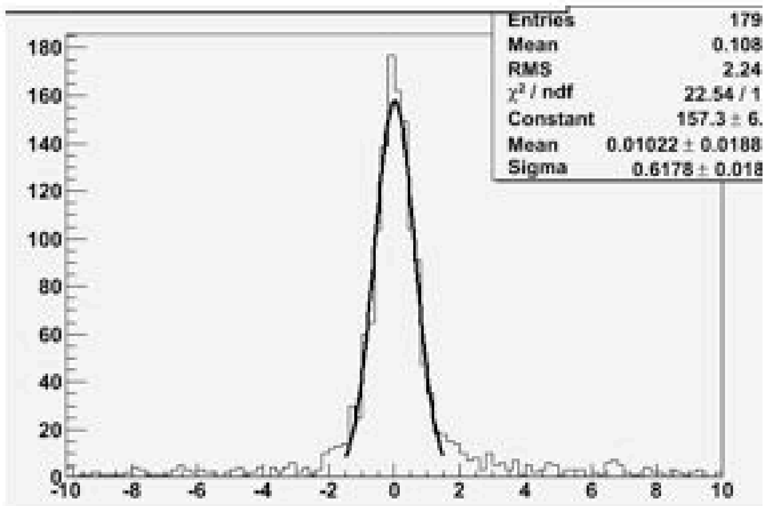
single event sensitivity for 2008 (Preliminary) :

$1/N\mu/\text{eff.} = 1/9.13\text{x}10^{13}/3.4\text{x}10^{-3}$/trig.eff./reconstruction eff. = $3.2\text{x}10^{-12}$/trig.eff./ reconstruction eff.

Sum energy of most of events < CR veto, almost back to back, photons positron at the same time → trig. eff. should not be too small

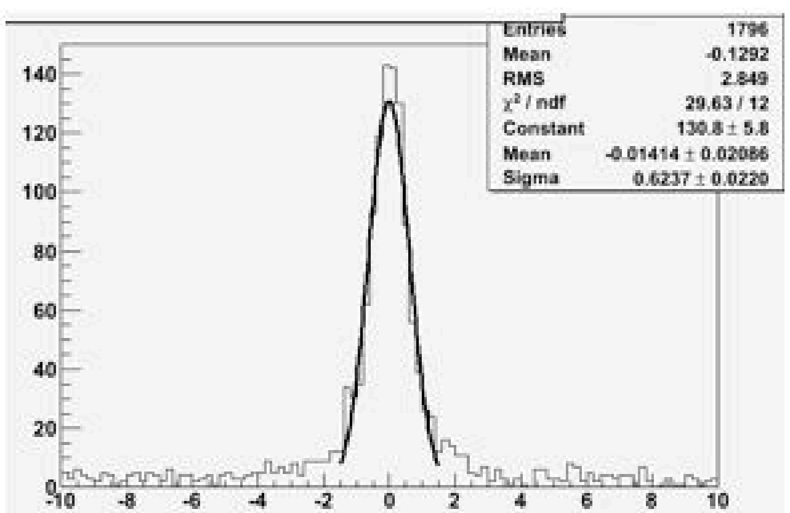
Position reconstruction of 2 photons (Preliminary, no shower correction)

higher energy gamma

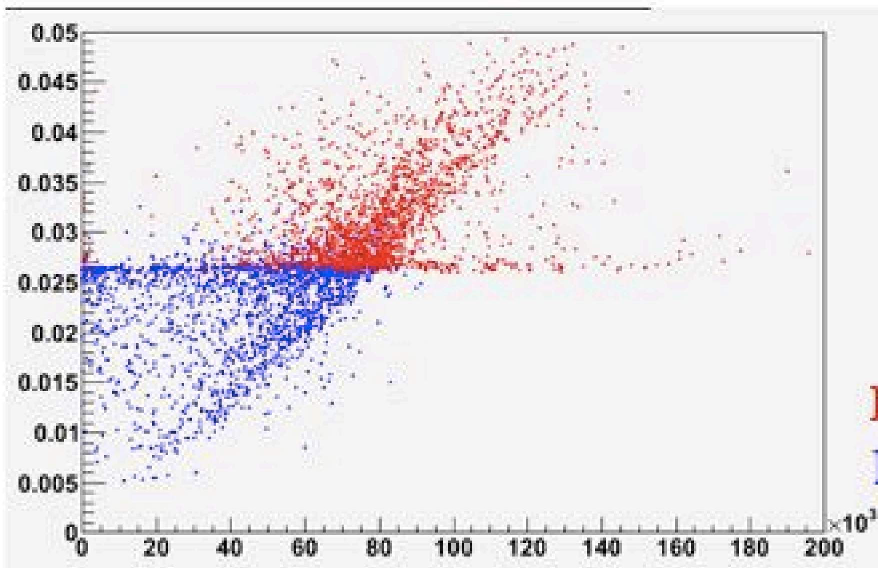


u, $\sigma = 6.2$ mm

lower energy gamma



u, $\sigma = 6.2$ mm



Red: higher energy gamma
Blue: lower energy gamma

Usual pileup rejection from time distribution can be used to reject accidental two gamma events.

Development of analysis for $\mu \to e \gamma \gamma$ was just started.

There are still a lot of things to check possibility of the analysis.

- Estimation of trigger efficiency by MEG trigger (w/ and w/o APD)
- To use 2008 data
    - Reconstruction of positron timing and angle by TC hit
- Timing reconstruction for 2 photons with better quality
- Estimation of resolution and reconstruction efficiency
- Background estimation
    - 1 radiative decay + 1 photon from radiative, AIF, bremsstrahlung
    - michel + 2 photons from radiative decays, AIF, bremsstrahlung