# MEG II 実験液体キセノンガンマ線検出器に向けた再構成法の研究

# Development of the event reconstruction method for MEG II liquid xenon detector

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@日本物理学会 2015年秋季大会

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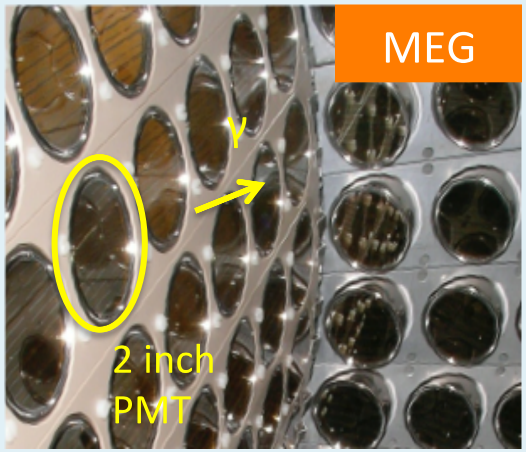
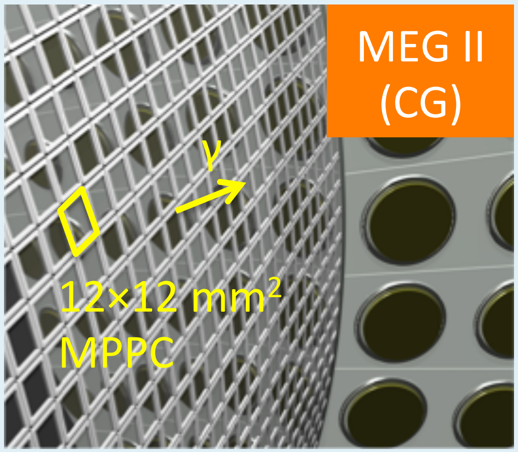
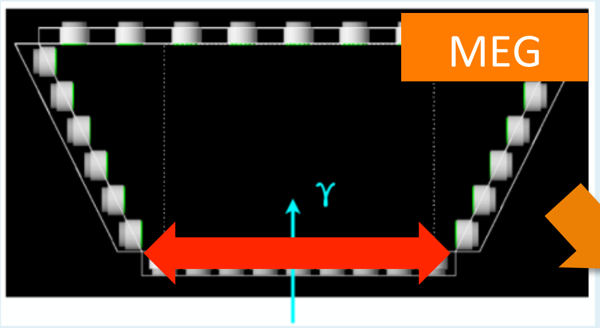
# Upgrade of LXe detector for MEG II

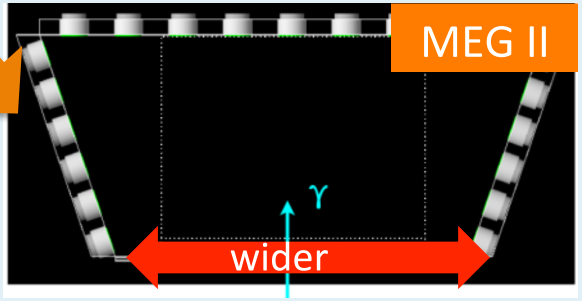
- Replace PMT of γ-entrance face to MPPC
  - Photon collection efficiency becomes uniform

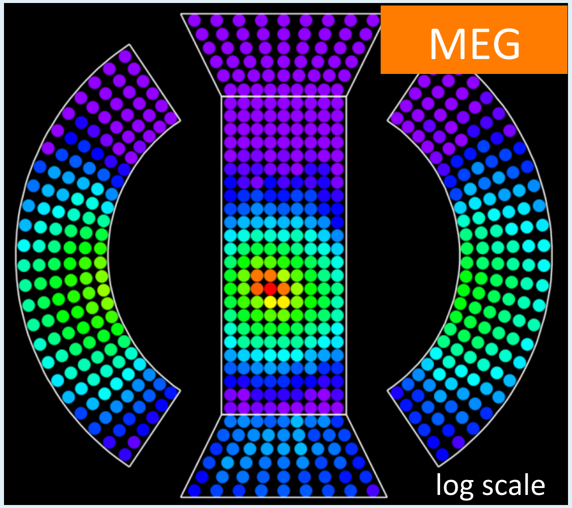


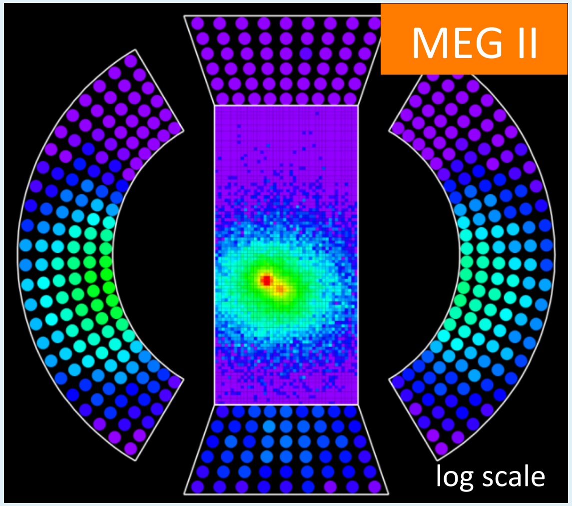

- Change PMT alignment of lateral face
  - Energy leak decreases




Imaging power improves



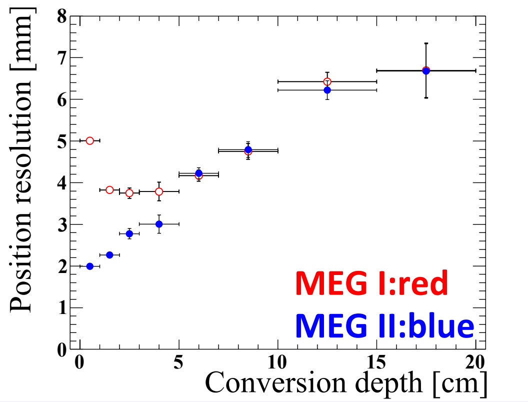
# 2. Performance of LXe detector

# Performance estimation

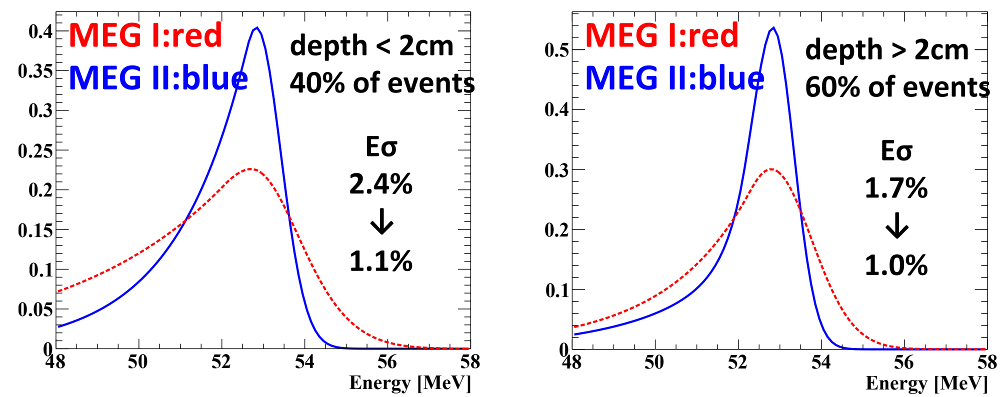


- Performance improvement of LXe detector has already been confirmed by MC simulation.
  - "MEG Upgrade Proposal (arXiv:1301.7225)"
  - 日本物理学会第70年次大会 21pDK-6

Position resolution vs. depth




Energy Distribution for signal γ




- We carried out the performance estimation again.
  - Finalized design of the detector
  - Improved and optimized analysis

# Detection efficiency

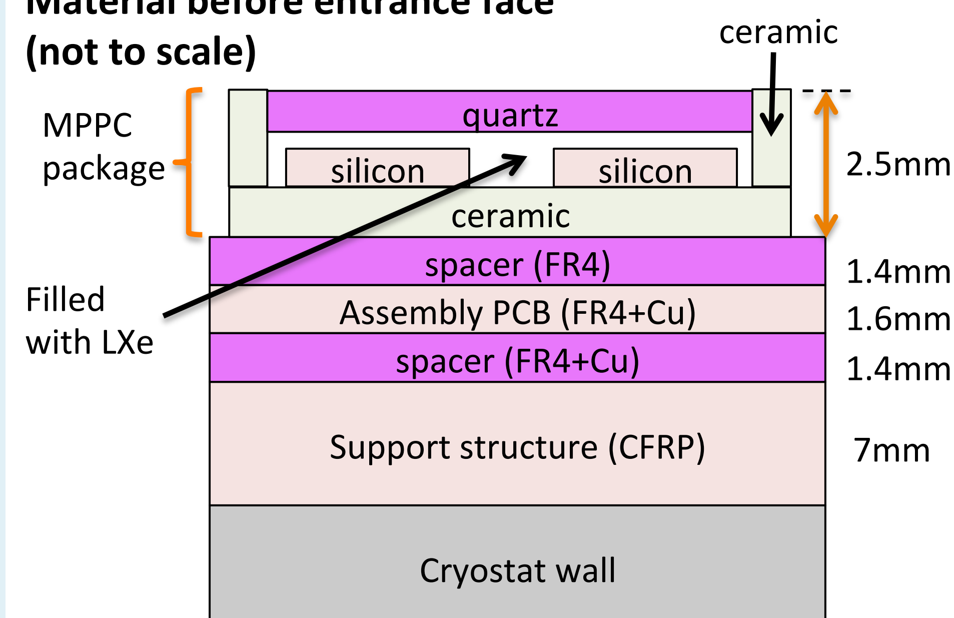
- ***Detection efficiency  for signal γ-ray*** in the detector acceptance.
  - Defined as  the fraction of events whose ***energy deposit in LXe is over 48MeV***
  - Design of the material before γ entrance face  has been finalized.

- ***Improvement by 9%*** is observed from MEG I.
  - Thanks to the ***reduced amount of material*** in the entrance face,
  - Consistent with rough estimation in previous study (69%).

| | **MEG I** | **MEG II (this study)** |
|---|---|---|
| Efficiency | 64.7% | 70.4% |

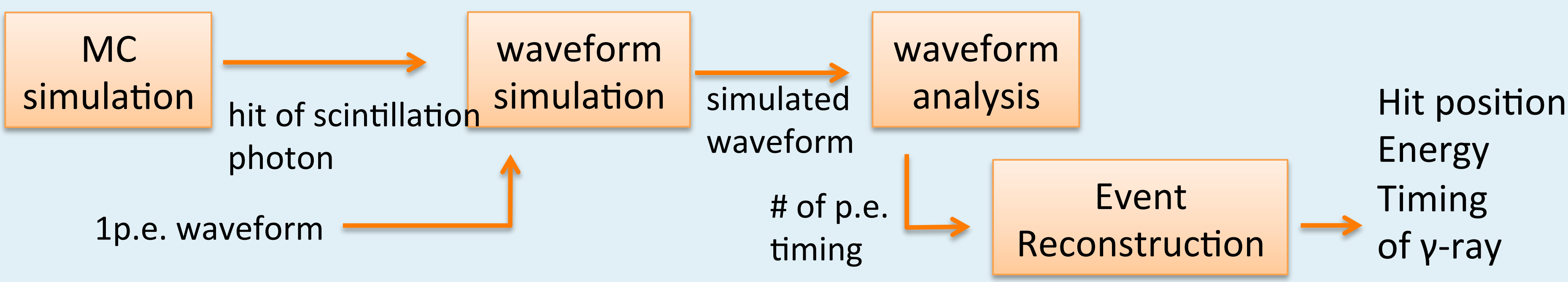
9% improvement

**Material before entrance face (not to scale)**



# Event reconstruction

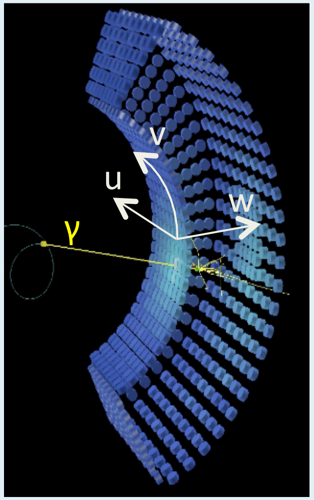
- ***Waveform simulation*** is performed for each MPPC and PMT.
  - ***Based on the measured properties*** of MPPC, PMT.
  - Crosstalk, after pulse, saturation of MPPC are simulated.
  - Same noise level with MEG I is assumed.
- Timing and # of p.e. of each MPPC, PMT are obtained by analyzing simulated waveform.
- Same reconstruction algorithm with MEG I, optimized to MEG II.
  - ***Position*** is reconstructed from the ***number of p.e. distribution on the entrance face***.
  - ***Energy*** is reconstructed from the ***summation of the photon for all channels***, taking into account of different coverage for each channel.
  - ***Timing*** is reconstructed by ***fitting the time of each channel***, considering TOF and timewalk.

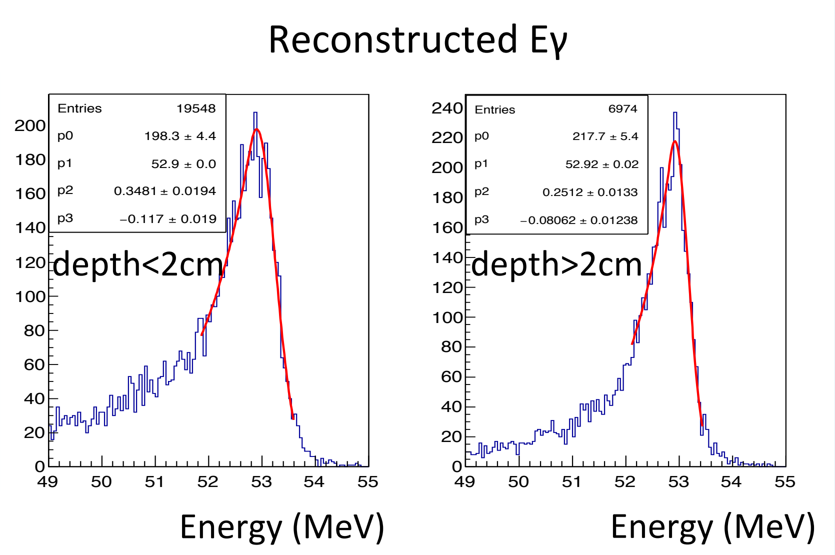


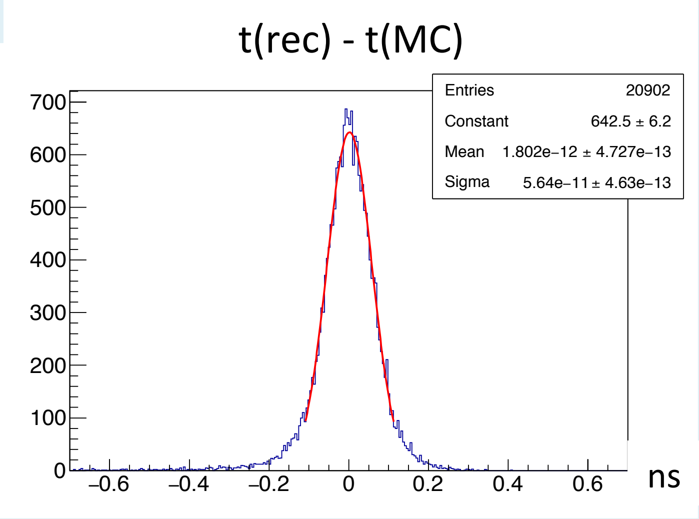
# Resolution of LXe detector

- Estimated resolution for MEG II LXe detector.
- ***Better resolution*** than previous estimation.
  - ***Thanks to the analysis optimization***

| **Resolution** | **MEG II (shown in last JPS)** | **MEG II (this study)** |
|---|---|---|
| u/v/w (mm) | 2.7/ 2.3/ 3.7 | 2.2/2.0/2.3 |
| $E_\gamma$ (w<2cm) | 0.62% | 0.65(4)% |
| $E_\gamma$ (w>2cm) | 0.53% | 0.49(2)% |
| $t_\gamma$ (ps) | 71 (preliminary) | 56(1) |



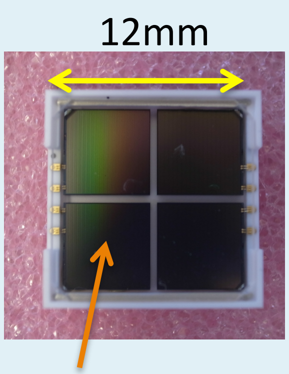



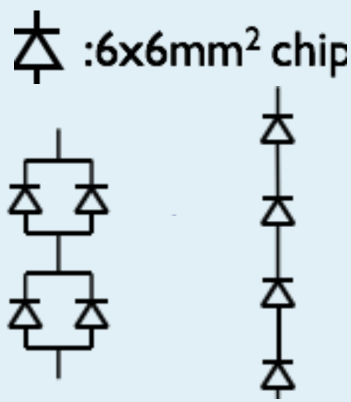
# 3. Signal readout method comparison

# Signal readout method comparison

- ***Series connection of MPPC*** will be used.
  - ***To avoid the long time constant*** caused by the large area MPPC.
  - ***Two candidates*** for signal readout method
    - 2p2s (2parallel 2series) connection
    - 4s (4series) connection
- Performance of the detector can be affected.
  - ***Different S/N ratio*** can affect position, energy, and timing resolution
  - ***Different time constant*** of waveform can affect timing resolution and pileup.




Four independent MPPC chip on one package




**2p2s connection** **4s connection**

| **@7V over voltage** | **2p2s connection** | **4s connection** |
|---|---|---|
| gain | $1.6\times10^6$ | $0.8\times10^6$ |
| leading time | 6.5ns | 2ns |
| trailing time | 49ns | 33ns |

※Definition of time constant:
[0]*(exp(-t/leading_time) - exp(-t/trainling_time))

# Signal readout method comparison



- Two kinds of noise level are assumed.
  - MEG I noise level, higher noise level.

- Same resolution for position and energy.
- ***Better timing resolution for 4s connection*** even under higher noise condition.

- ***We decided to use 4s connection***.

| MEG I noise level (0.3mV) | 4s connection | 2p2s connection |
|---|---|---|
| u/v/w (mm) | 2.4/2.2/3.1 | 2.4/2.2/3.1 |
| $E_\gamma$ (σ of upper Edge) | 0.67(2)% | 0.68(2)% |
| $t_\gamma$ (ps) | 60(1) | 69(2) |

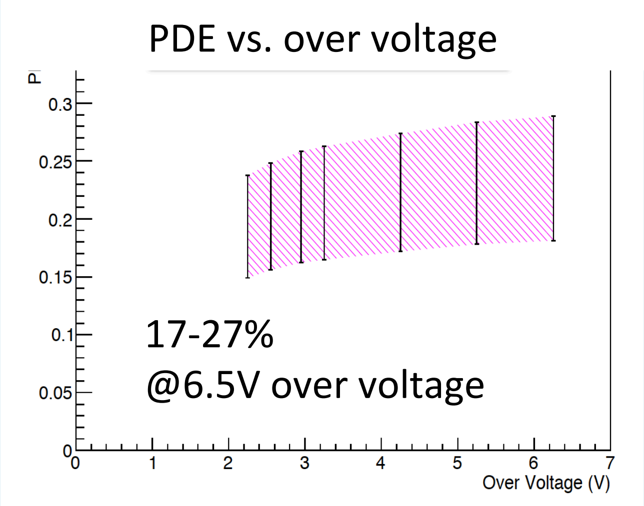
| Higher noise level (1.0mV) | 4s connection | 2p2s connection |
|---|---|---|
| u/v/w (mm) | 2.4/2.2/3.1 | 2.4/2.2/3.1 |
| $E_\gamma$ (σ of upper Edge) | 0.74(3)% | 0.79(3)% |
| $t_\gamma$ (ps) | 70(2) | 75(2) |

※These resolutions are estimated before analysis improvement.

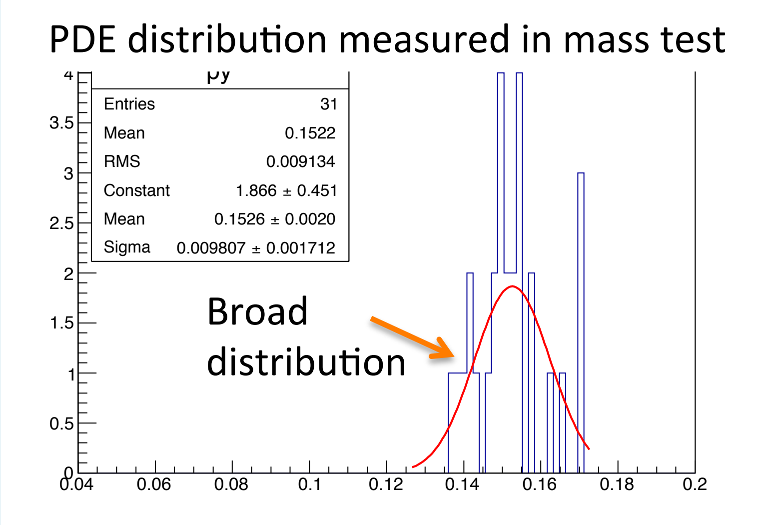
# 4. Effect from the uncertainty of PDE

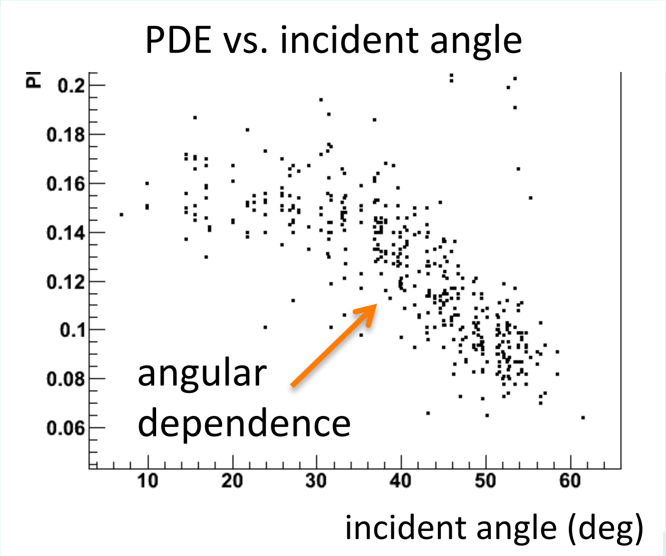
# Uncertainty of PDE

- There is the ***uncertainty of PDE of MPPC.***
  - ***Absolute PDE of MPPC*** is not well-known.
  - ***Broad distribution of PDE*** is observed in mass test. We may not be able to measure the PDE correctly for each MPPC in the final detector.
  - PDE may have an ***angular dependence*** which is not consistent with the expectation from the reflection at silicon surface.



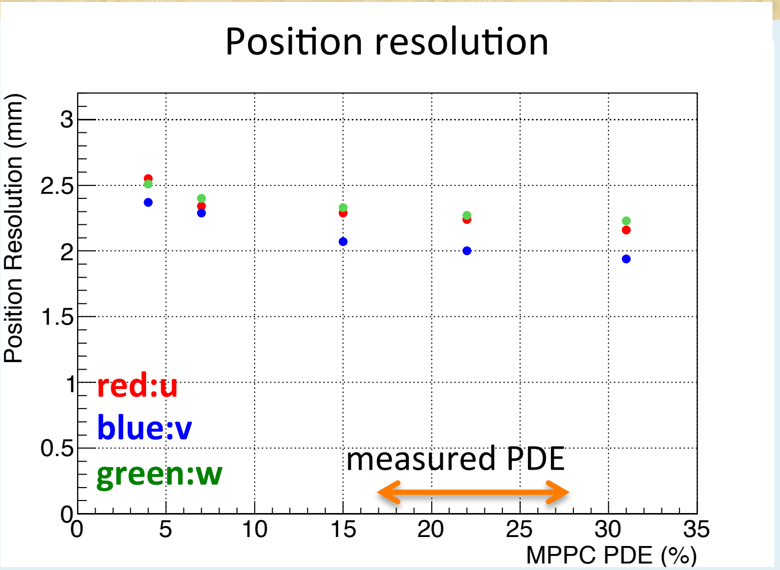

- Effects of these uncertainty to the detector performance are estimated.
  - MC truth of #of p.e. and timing for each MPPC,PMT are used for simplicity.

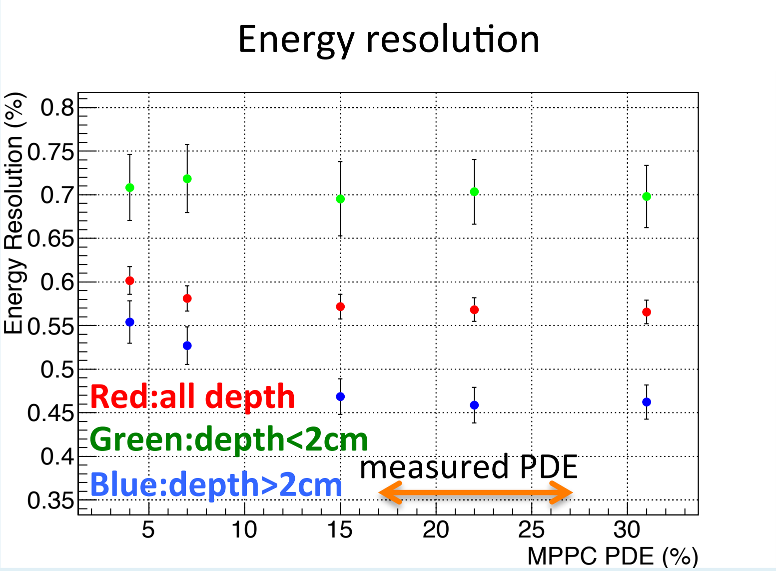


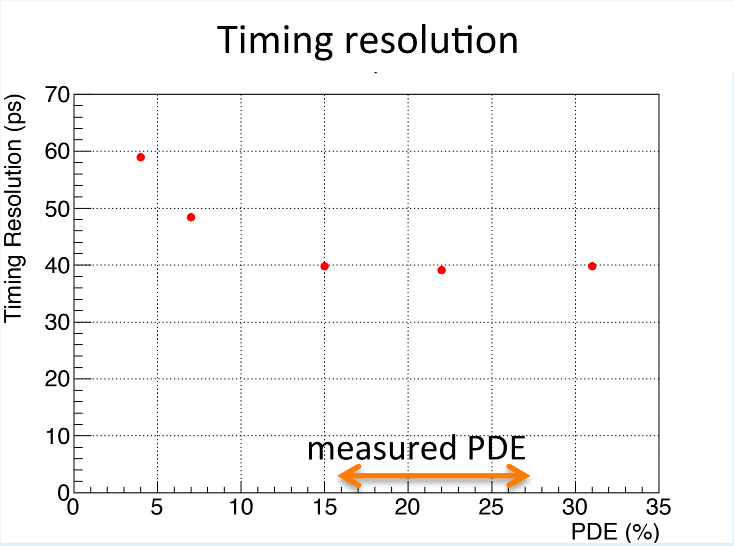



# Effect of absolute PDE

- Absolute PDE can be smaller than our previous assumption.
- We checked the degradation of resolution through statistical contribution at smaller PDE.
- We observed ***the degradation of resolution at very small PDE***, but ***effect seems negligible in the range of our measured PDE***.



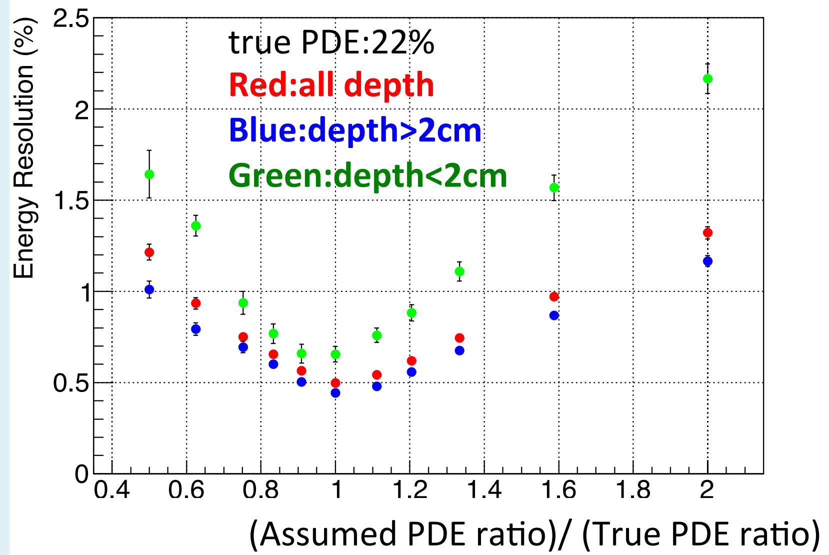

※Reconstructed from MC truth of # of p.e. and timing.
Resolution from waveform analysis result is 55ps @ PDE 22%.

# Effect of PDE ratio b/w MPPC and PMT

- We will use two kinds of sensors, MPPC and PMT.
- ***We have to estimate the ratio between PDE of MPPC and QE of PMT*** correctly for the energy reconstruction.
  - Energy is the summation of the number of the photon, and PDE (QE) is used for converting # of p.e. to # of photons.
  - ***Event by event fluctuation of the ratio of # of p.e. detected in MPPC and PMT*** can cause the degradation of energy resolution, if our assumption of the PDE ratio is wrong.

- Resolution becomes worse if assumed relative PDE ratio is wrong.
- ***We can estimate the true ratio by scanning assumed PDE in the analysis*** and finding the PDE at which energy resolution becomes best.

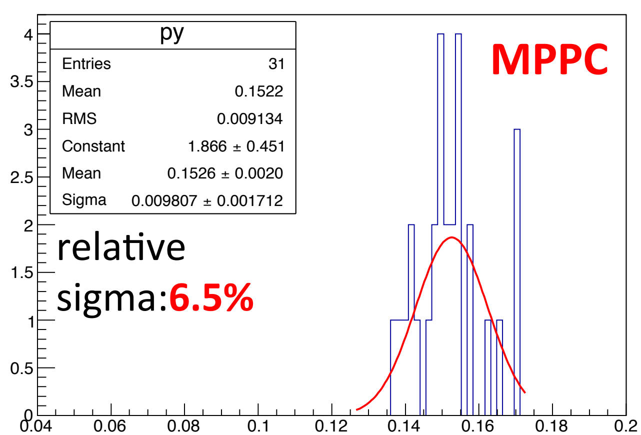
Energy resolution by assuming several PDE for MPPC



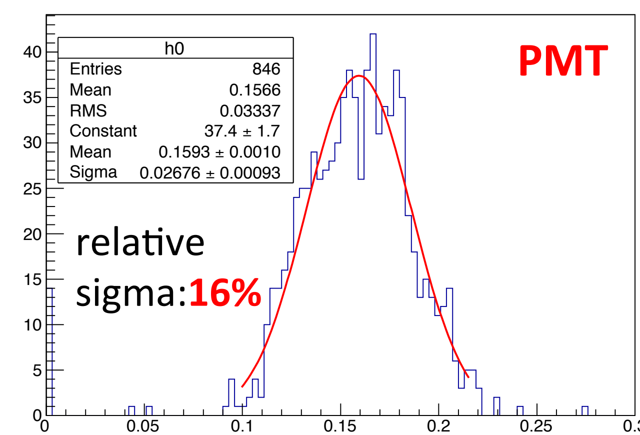
# Effect of PDE estimation error

- Broad distribution of PDE is observed in the mass test of MPPC.
- PDE(QE) of each MPPC(PMT) will be estimated by using alpha source in the final detector. ***Error of PDE(QE) estimation can cause the degradation of resolution***.
- Effect from this error to the detector resolution is estimated.
  - Error of both PMT and MPPC are taken into account.
  - Currently observed distribution is the upper limit of the estimation error.
  - Events are simulated with PDE variation and reconstructed by assuming constant PDE.

PDE measured in mass test
(at small incident angle )




QE measured in MEG I



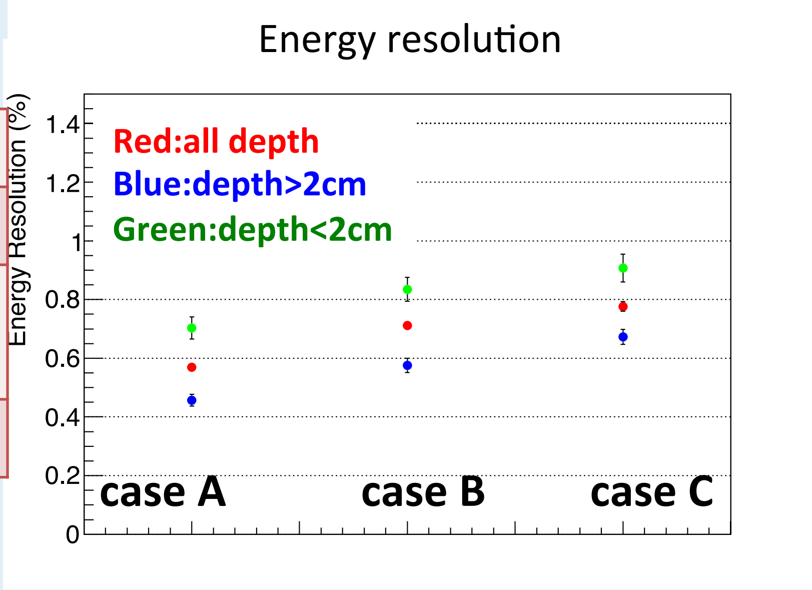
# Effect of PDE estimation error

- We compared three cases.
  - **case A**: no estimation error for both MPPC and PMT
  - **case B**: no estimation error for MPPC, 16% estimation error for PMT
  - **case C**: 6.5% estimation error for MPPC, 16% estimation error for PMT

- Degradation of the resolution is observed for the energy resolution.
- ***Correct estimation of PDE seems important***.

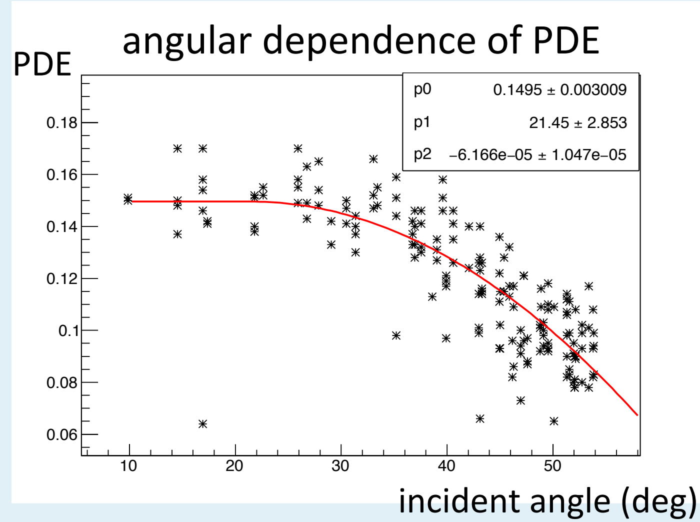
| Resolution | case A | case B | case C |
|---|---|---|---|
| u/v/w (mm) | 2.2/2.0/2.3 | 2.2/2.0/2.3 | 2.6/2.4/2.6 |
| $E_\gamma$ (σ of upper Edge) | 0.57(1)% | 0.71(2)% | 0.78(2)% |
| $t_\gamma$ (ps) | 39(1) | 38(1) | 40(1) |

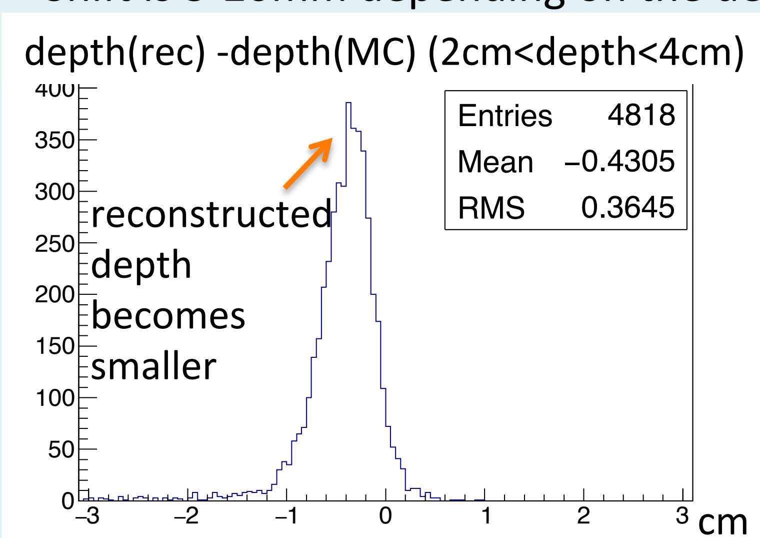
※Reconstructed from MC truth of # of p.e. and timing.
Resolution from waveform analysis result is 55ps @ PDE 22%.

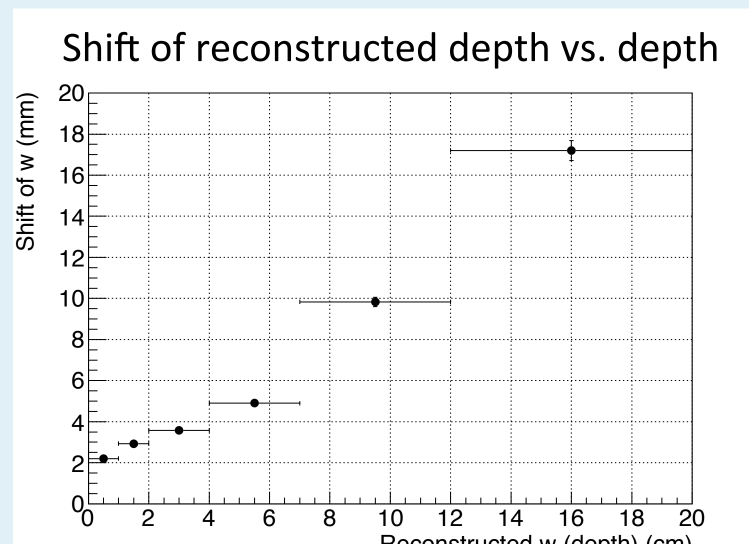


# Effect of angular dependence of PDE

- Effect of the angular dependence of PDE is estimated.
  - Angular dependence observed in the mass test is assumed in the simulation.
  - Information of angular dependence is not used in the reconstruction.
- ***Angular dependence changes the p.e. distribution on the inner face***, and ***reconstructed depth is shifted to shallower***.
  - Shift is 3-20mm depending on the depth



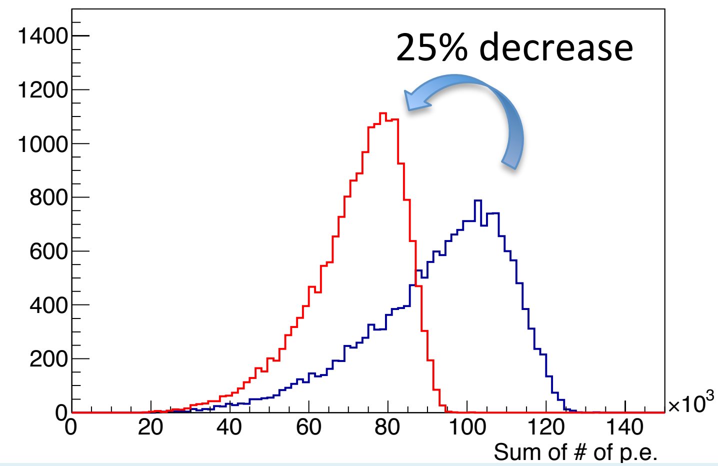



# Effect of angular dependence of PDE

- Position resolution
  - Small degradation for depth
- Timing resolution
  - Little effect to timing resolution
- Energy resolution
  - ***Decrease of the # of p.e. can be recovered*** by weighting # of p.e. detected on MPPC.
  - ***Same energy resolution can be obtained*** even with angular dependence.

**Sum of # of p.e. (all MPPCs)**
**blue: w/o angular dependence**
**red: w/ angular dependence**




| Resolution | w/o angular dependence | w/ angular dependence |
|---|---|---|
| u/v/w (mm) | 2.2/2.0/2.3 | 2.2/2.0/2.7 |
| $E_\gamma$ (σ of upper Edge) | 0.57(1)% | 0.58(2)% |
| $t_\gamma$ (ps) | 39(1) | 41(1) |

※Reconstructed from MC truth of # of p.e. and timing.
Resolution from waveform analysis result is 55ps @ PDE 22%.

# How to deal with uncertainty of PDE

- Effect of absolute PDE
  - ***Little effect*** to performance.
- Effect of relative PDE ratio btw/ MPPC and PMT
  - Relative PDE ratio is important for energy reconstruction.
  - ***Can be estimated in the calibration run***.
- Effect of PDE estimation error
  - Effect to the energy is not negligible.
  - ***PDE (QE) estimation for each MPPC and PMT is important***.
- Effect of angular dependence of PDE
  - Reconstructed depth is shifted.
  - If we can know the angular dependence, this shift can be corrected.
  - ***A new measurement of angular dependence*** is being planned (see 27aSN-9).
  - ***Method to know the angular dependence in the final detector*** will be studied.

# Summary

- Performance of MEG II LXe detector are estimated with realistic settings together with the several improvement and optimization of analysis.
- For signal readout, 4s connection will be used as it has better timing resolution.

- Effects from the uncertainty of PDE are estimated.
Some of them are not negligible (especially shift of depth by angular dependence).
- How to decrease these effects are being studied.
  - We are planning another measurement to further investigate the PDE variation and angular dependence.

| | MEG I | MEG II (in last JPS) | MEG II (this study) |
|---|---|---|---|
| efficiency | 64.7% | not estimated | 70.4% |
| u/v/w (mm) | 5/5/6 | 2.7/2.3/3.7 | 2.2/2.0/2.3 |
| $E_\gamma$ (depth<2cm) | 2.4% | 0.9% | 0.9% |
| $E_\gamma$ (depth>2cm) | 1.7% | 0.9% | 0.8% |
| $t_\gamma$ (ps) | 67 | 71 (preliminary) | 56 |

0.7% contribution are assumed for MEG II (from unsolved difference between MC and real detector in MEG I)

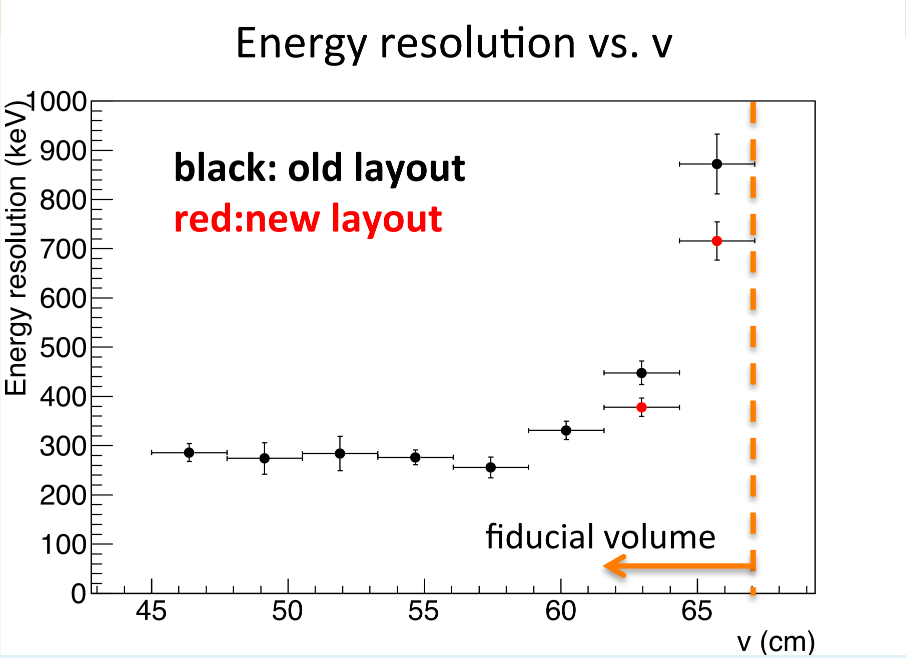
# Backup

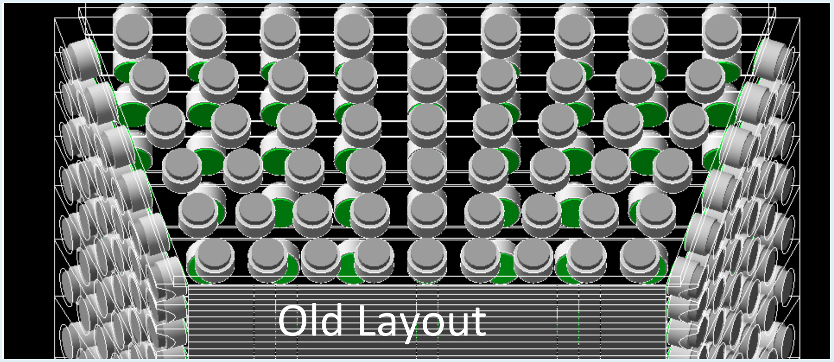
# abstract

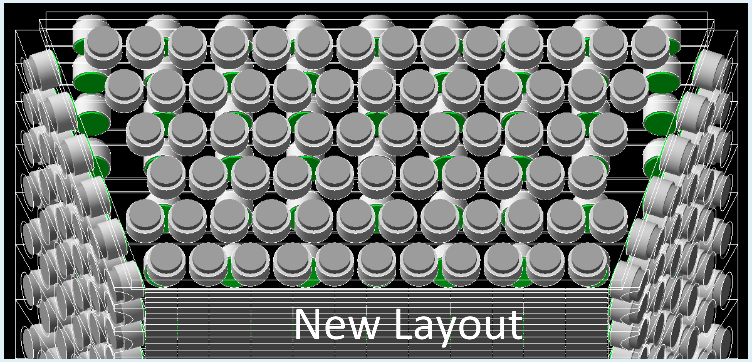

- MEG実験のアップグレードであるMEG II実験では!LaTeX$\mu \rightarrow e \gamma$ 崩壊の探索感度を一桁向上させることを目指している。
- MEG II実験では約4000個のMPPCを用いた液体キセノンガンマ線検出器を使用する予定であり、位置分解能およびエネルギー分解能の大幅な改善を見込んでいる。
- シミュレーションを用いた評価により物理目標達成に必要な分解能がすでに確認されているが、さらなる性能向上を目指して再構成法の改良および信号読み出し手法の最適化を行ってきた。
- 本講演では開発の現状および結果について報告する。

# Layout of PMT on top/bottom face

- We observed that events near top/bottom face show worse energy resolution than other events.
- We tried to improve this, by modifying the layout of PMT on top/bottom face.
  - Number of PMT increases from 54 to 73 for each face.
  - PMT is placed staggered to improve photon collection uniformity.
- Improvement of energy resolution near top/bottom can be seen. (though it is not so clear)

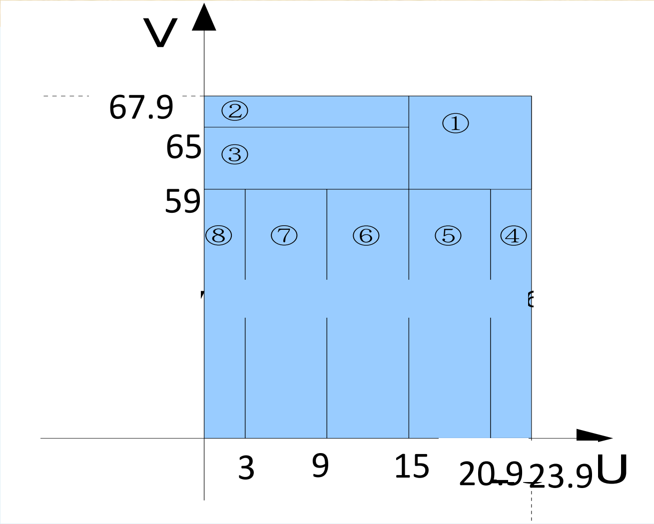


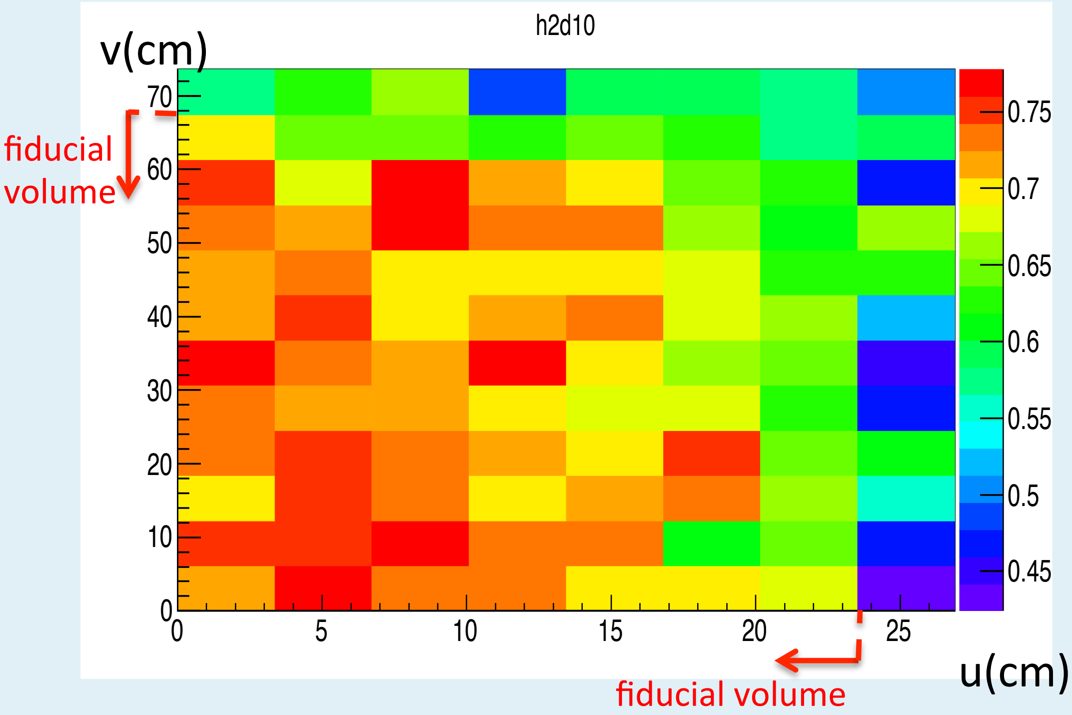



# Detection Efficiency

| Efficiency(%) | MEG I | MEG II |
|---|---|---|
| region 1 | 55.9 | 61.5 ± 1.4 |
| region 2 | 55.0 | 60.3 ± 1.8 |
| region 3 | 61.7 | 70.6 ± 1.2 |
| region 4 | 56.3 | 62.3 ± 1.0 |
| region 5 | 63.8 | 69.0 ± 0.6 |
| region 6 | 66.5 | 71.9 ± 0.6 |
| region 7 | 67.1 | 73.5 ± 0.6 |
| region 8 | 67.9 | 72.9 ± 0.8 |
| Averaged with area | 64.2 | 70.0 |
| Averaged with MEG I weight | **64.7** | **70.4** |



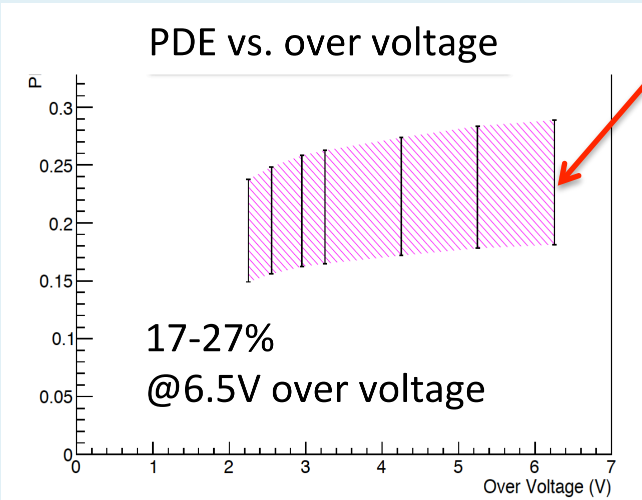



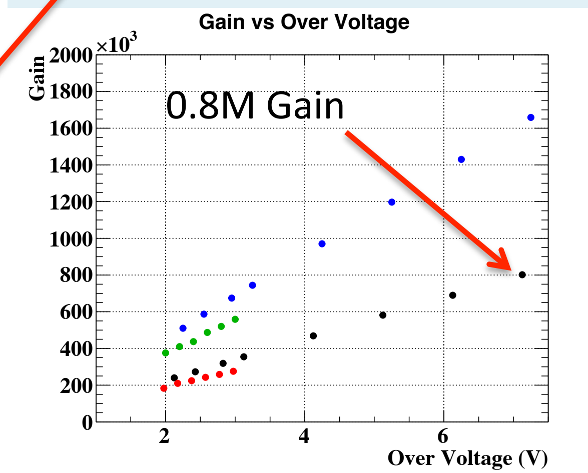
# Setting for MC

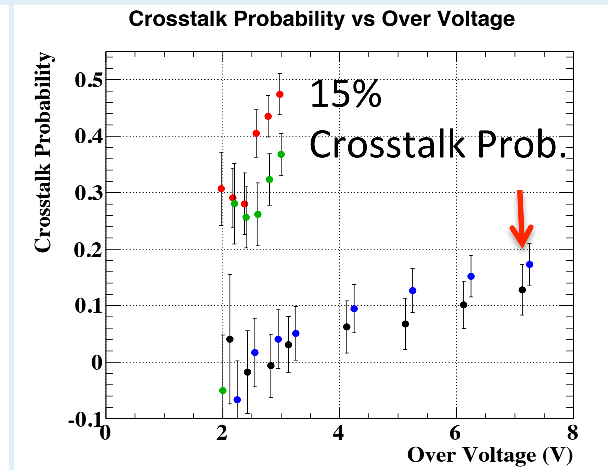
| PDE | Gain | Crosstalk Prob. | Afterpulse Prob. |
|---|---|---|---|
| 22% | $0.8 \times 10^6$ | 15% | 15% |

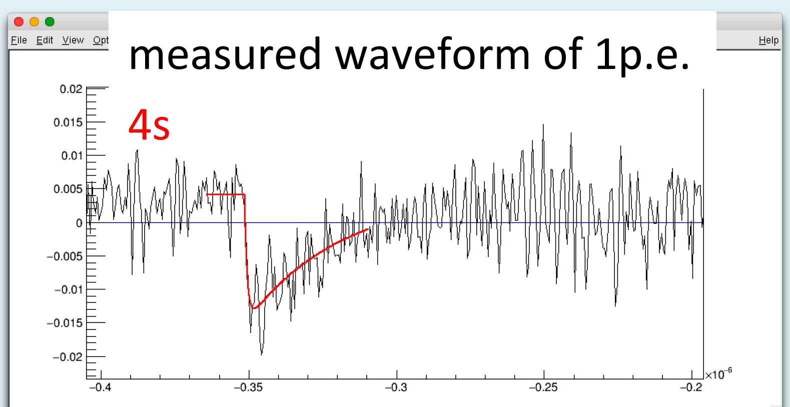
| Event by event fit | 2p2s | 4s |
|---|---|---|
| trailing time const. | 49ns | 33ns |
| leading time const. | 6.5ns | <2ns |

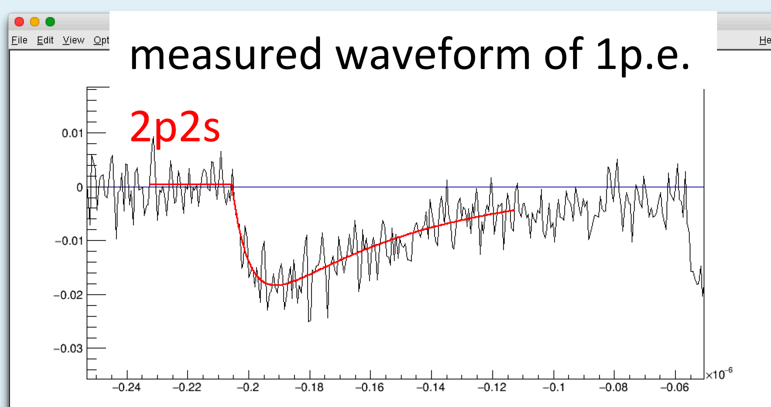
22% PDE



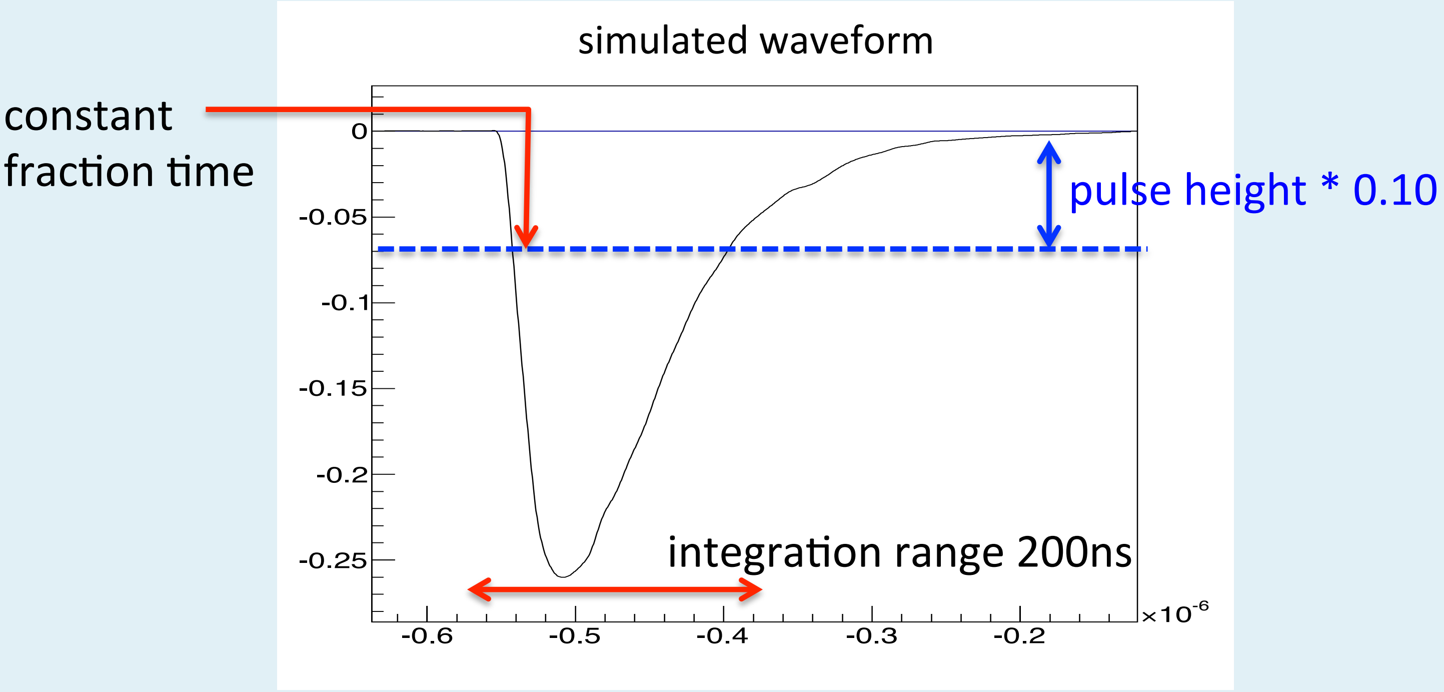



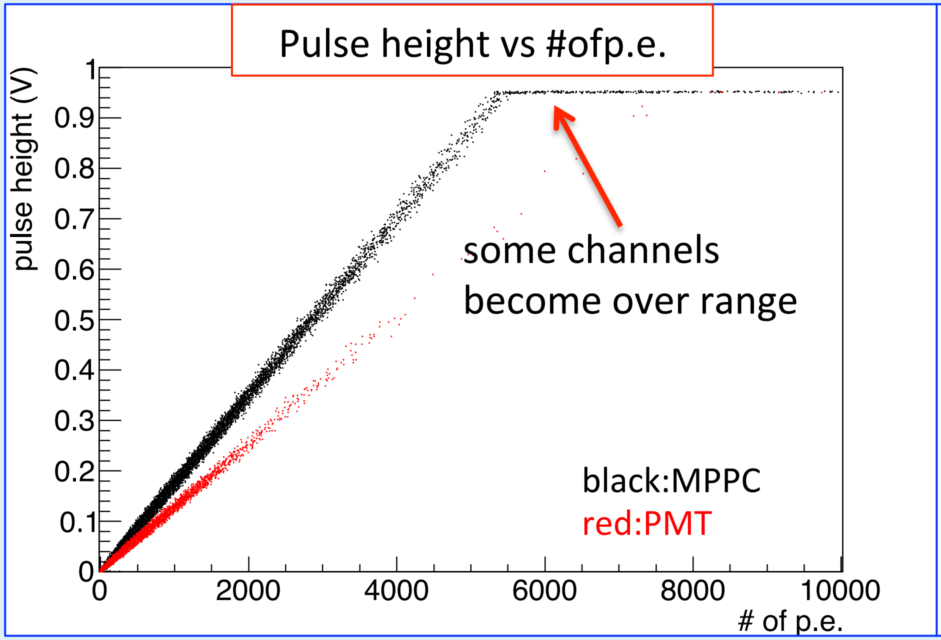
# Waveform analysis

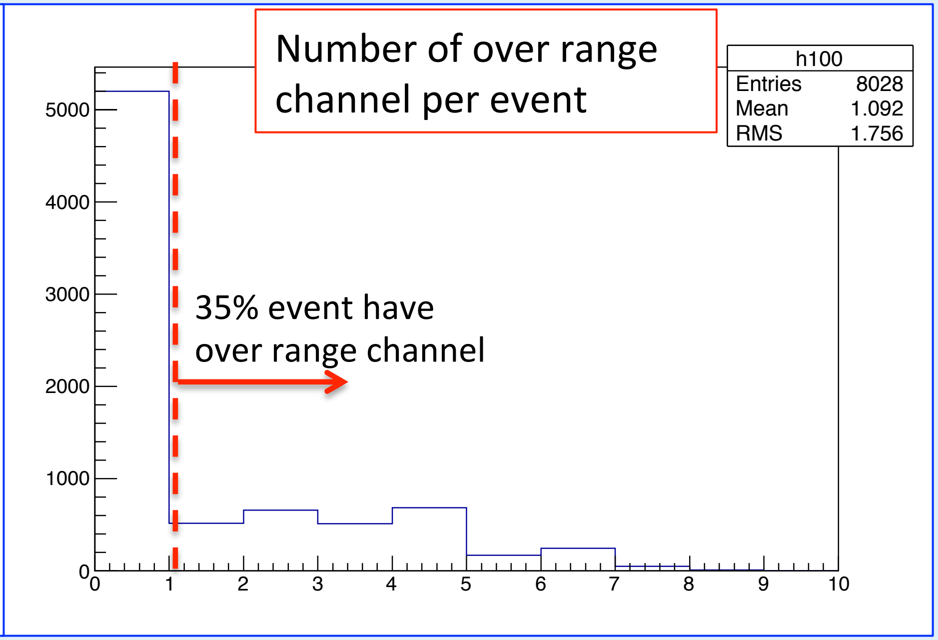
- In waveform analysis, charge (# of p.e.) and timing are calculated.
- Charge is calculated from fixed integration range.
- Constant fraction method is used for timing calculation (with 10% of pulse height threshold)



# Waveform analysis for over range channel

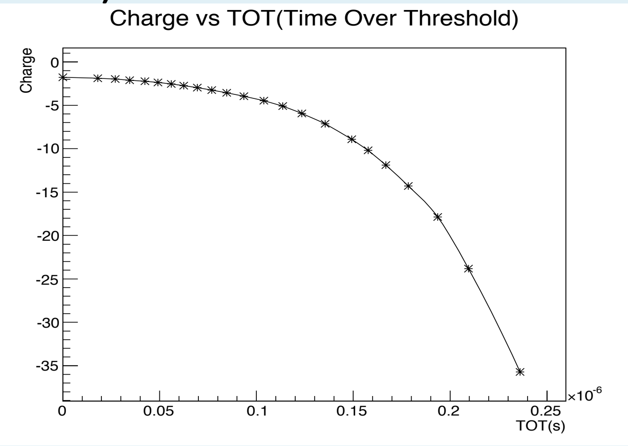
- As PDE and gain increases, 35% of event have at least one channel in which pulse height becomes higher than dynamic range of waveform digitizer (950mV).
- We can avoid over range by decreasing amp gain but it leads to worse SN ratio, and it may result in worse resolution. (Quantitative estimation has not done yet.)
- However, appropriate waveform analysis to these over range channel is important for reconstruction as they have large # of p.e.



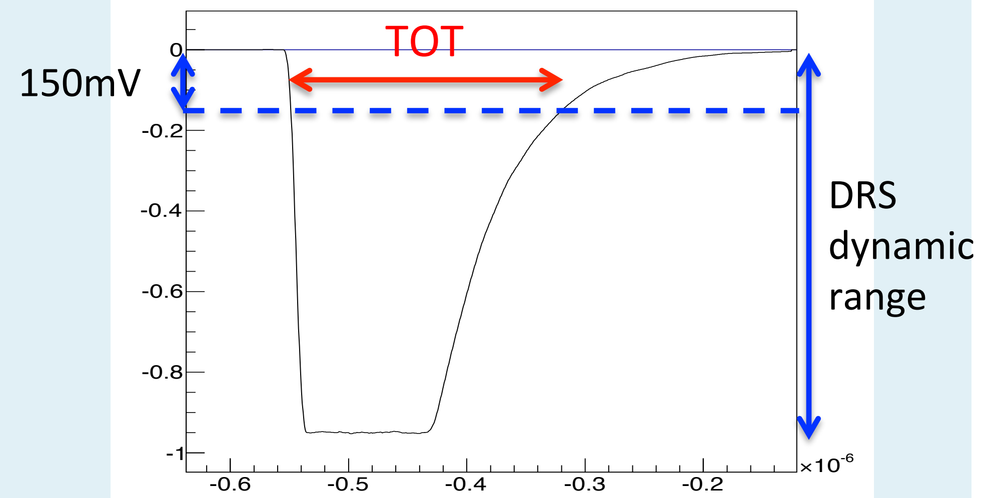



# Waveform analysis for over range channel

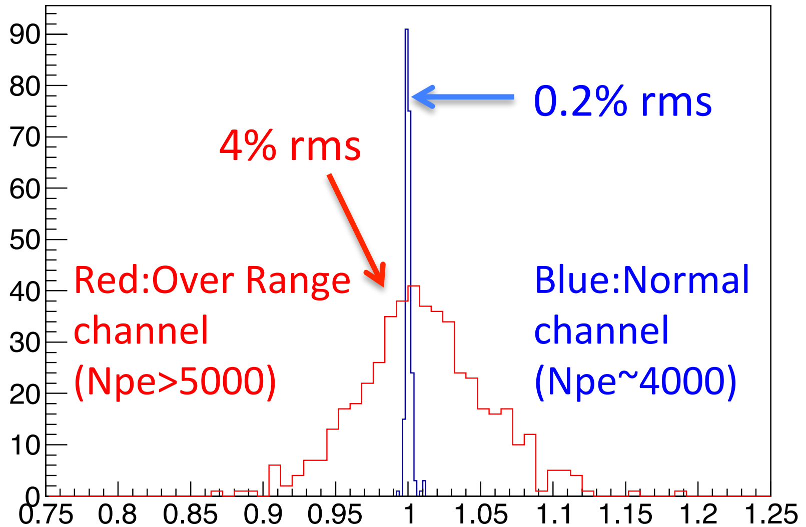
- For these over range channel, TOT (Time Over Threshold) method are used for charge calculation in MEG I.
- Same method can be used for MEG II.
- Relation between TOT and charge are calculated beforehand.
- In this study, over range channels are not used for timing calculation.




simulated waveform (over range ch)




(#of p.e. from wf analysis) /(#of p.e. of MC truth)

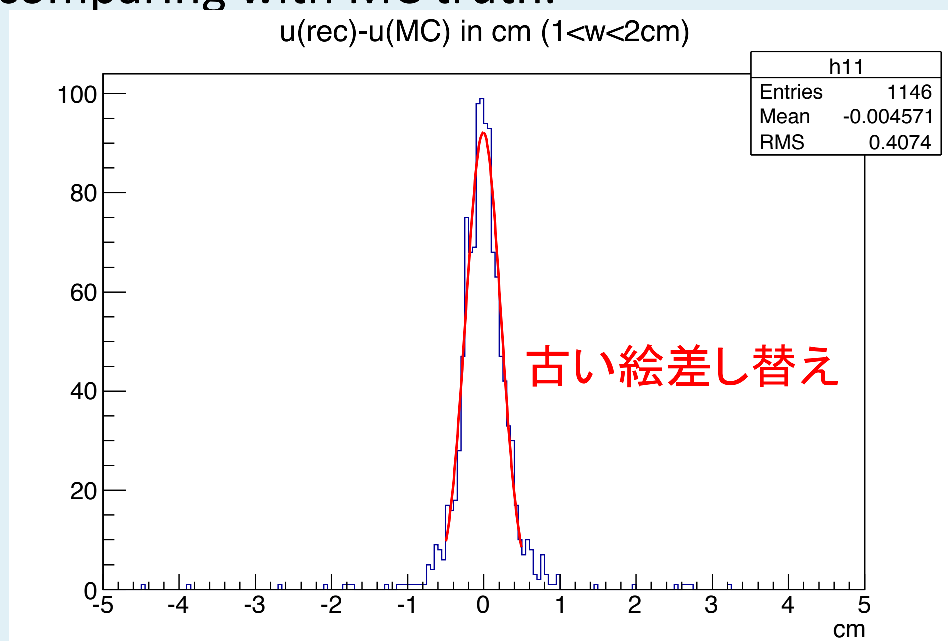


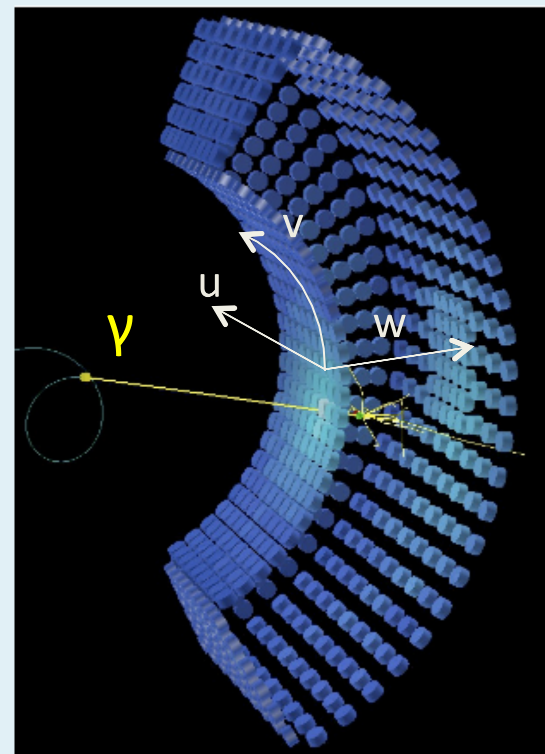
# Position reconstruction

- Position is reconstructed by fitting # of p.e. distribution of inner face with the solid angle from conversion point to each MPPCs.

$$\chi^2_{pos} = \sum_i \left( \frac{N_{pe,i} - c \times \Omega_i(u,v,w)}{\sigma(N_{pe,i})} \right)^2$$

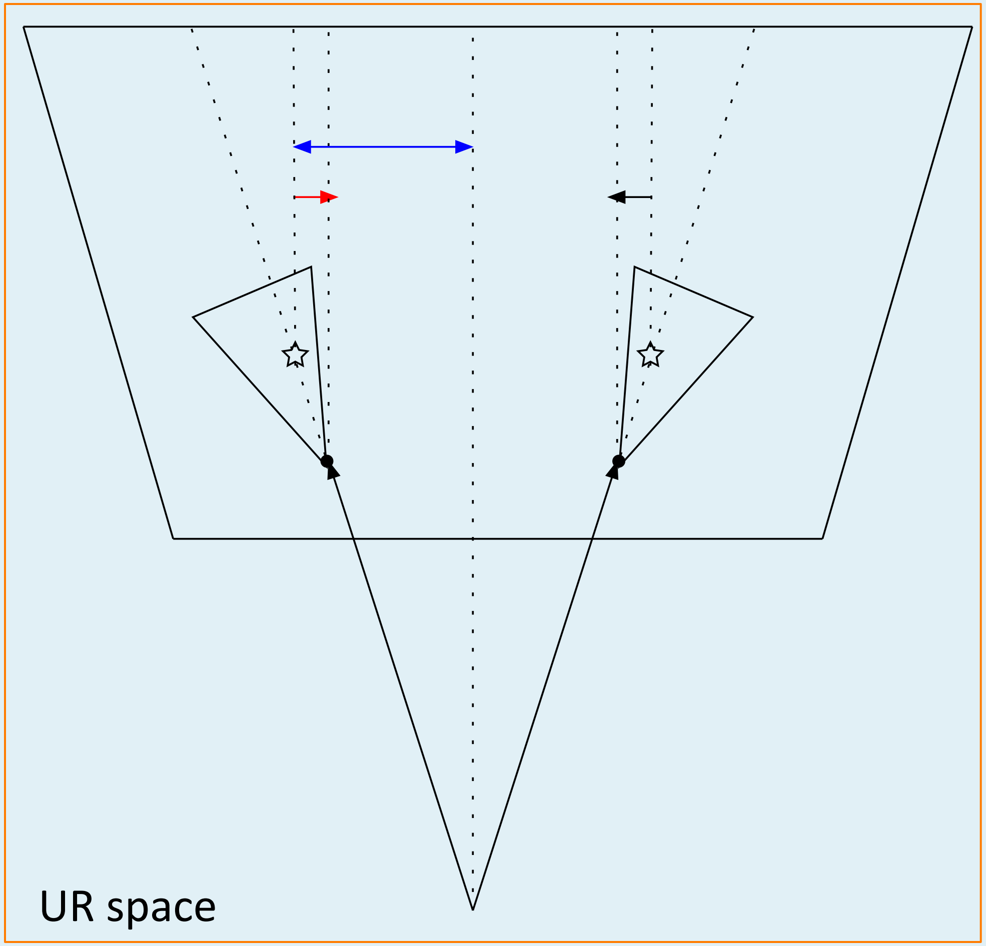
- Correction of shower direction is applied.
- We estimated position resolution by comparing with MC truth.



# Global Correction

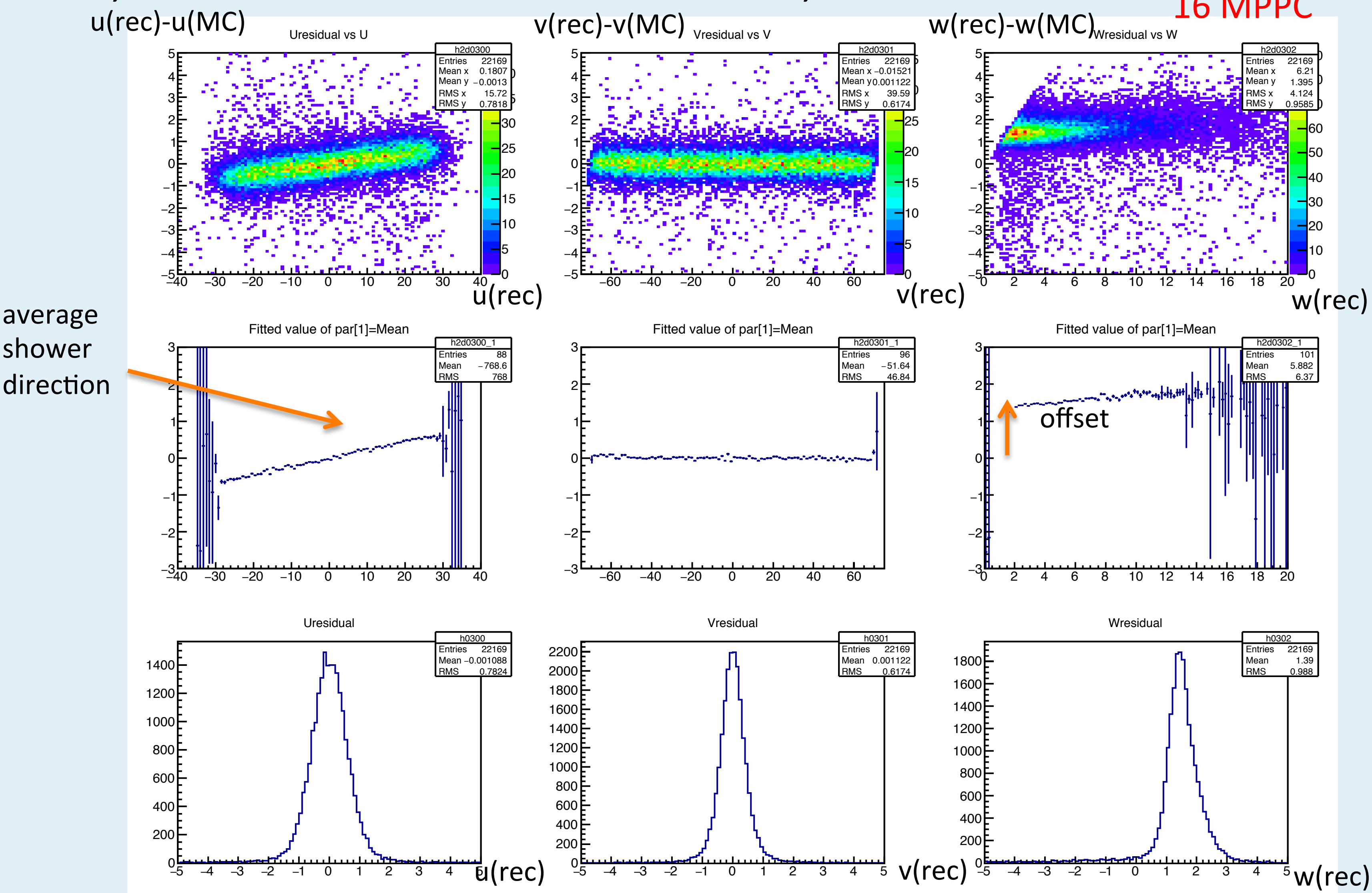
- Global correction for U is coming from average shower direction.
- Shower direction is not perpendicular to inner face in UR space.
- This is not the case for V, as inner face is perpendicular to in VR space.
- Global correction for W is basically a offset depending on FitRange.



# Global Correction

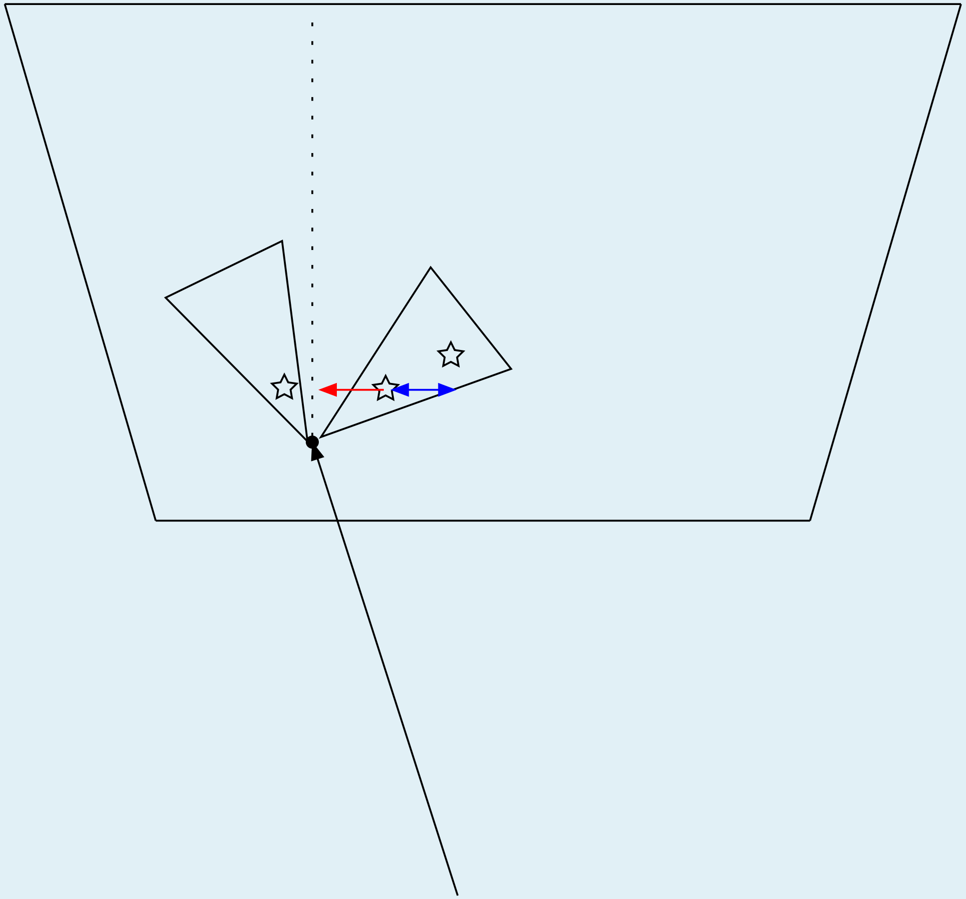
- U,W is corrected as a function of U,W

with FitRange[0]
16 MPPC



# Shower Correction

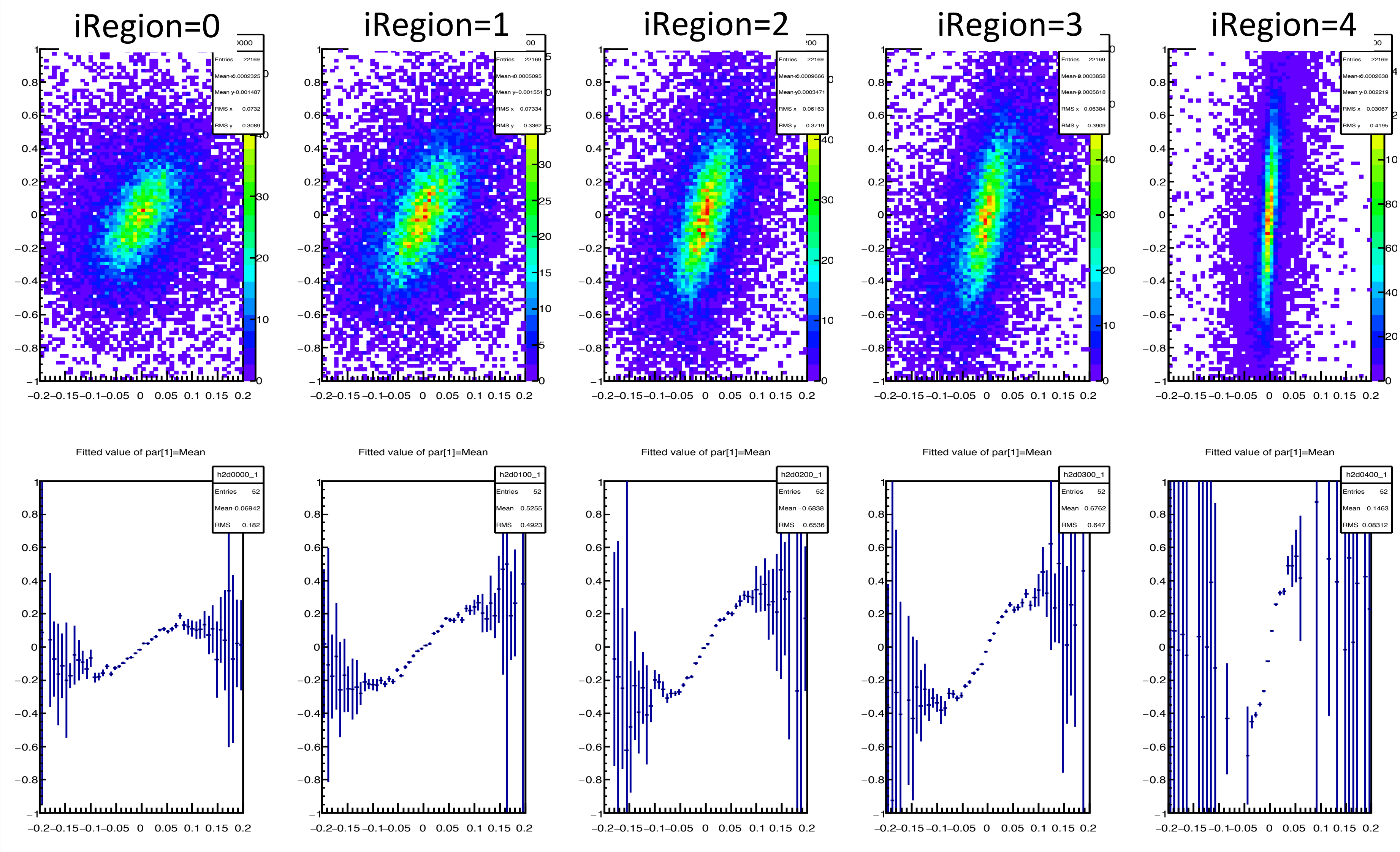
- Correction of event by event fluctuation of shower direction.
- If we use wider fit range, the effect from shower direction increases.
- Information of shower direction can be derived from difference of the fit result using different fit range.
- This correction is applied for UV.
- Dependence can be seen also for W, it is also corrected.



# Shower Correction U

y axis: u(rec,iRegion) - u(MC)
x axis: u(rec,iRegion+1) - u(rec,iRegion)

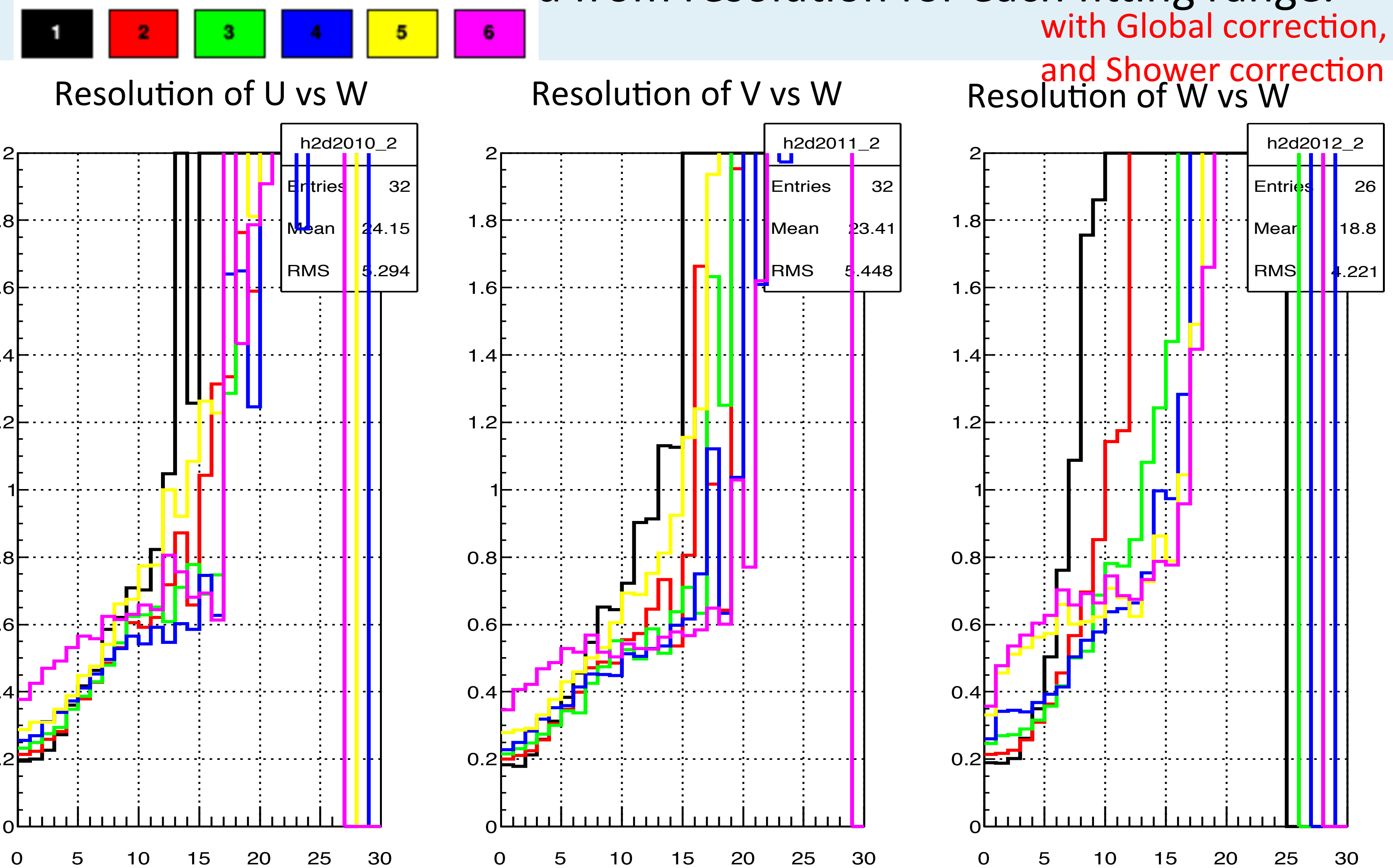
- U before correction



# W threshold optimization

- Wthreshold[6] is decided from resolution for each fitting range.

with Global correction, and Shower correction

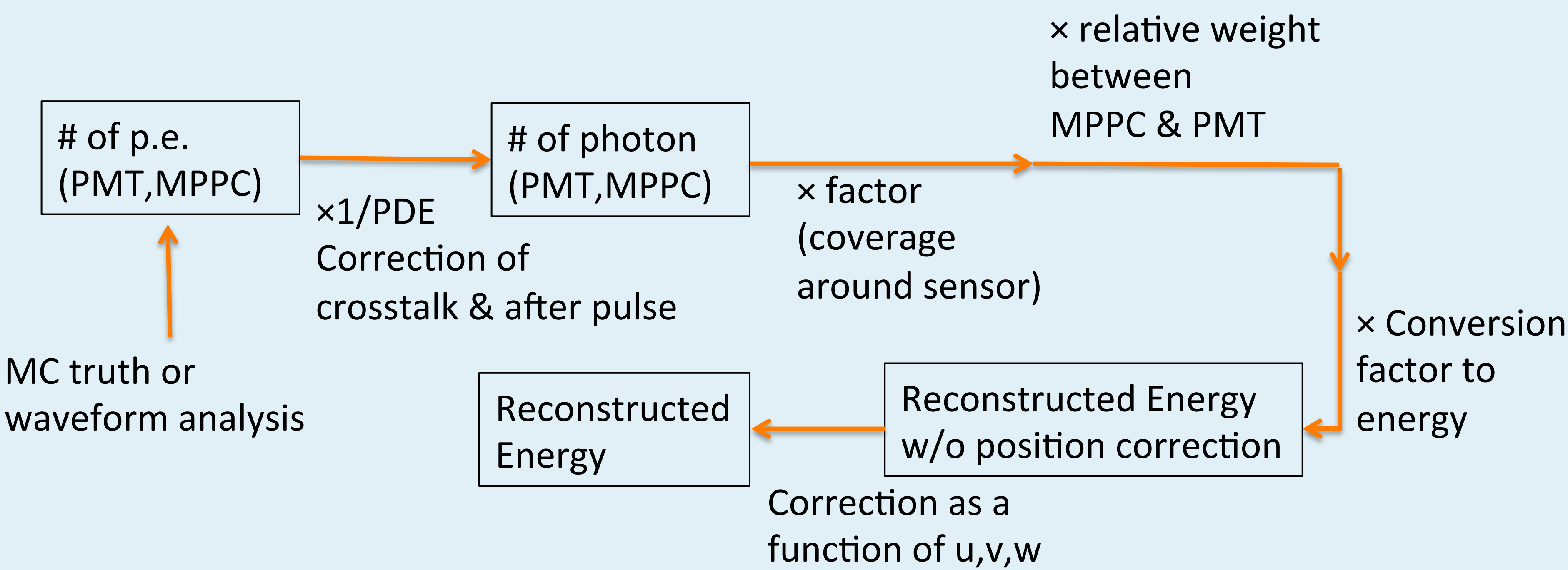



Wthreshold[6]={3,5,9,14,14,40}

# Energy reconstruction

- Energy is reconstructed by the summation of the number of photon (not photoelectron) from all channels taking into account of different coverage for each channel.
- Correction as a function of position is applied.

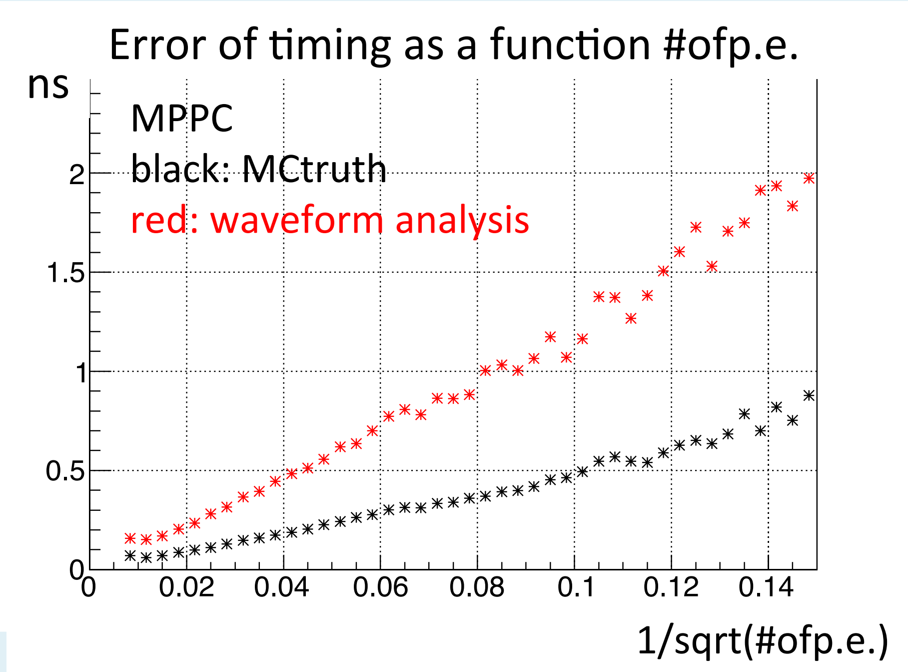
$$E_\gamma = F(u, v, w) \times C \times \sum_i (N_{pe,i} \times W_i)$$

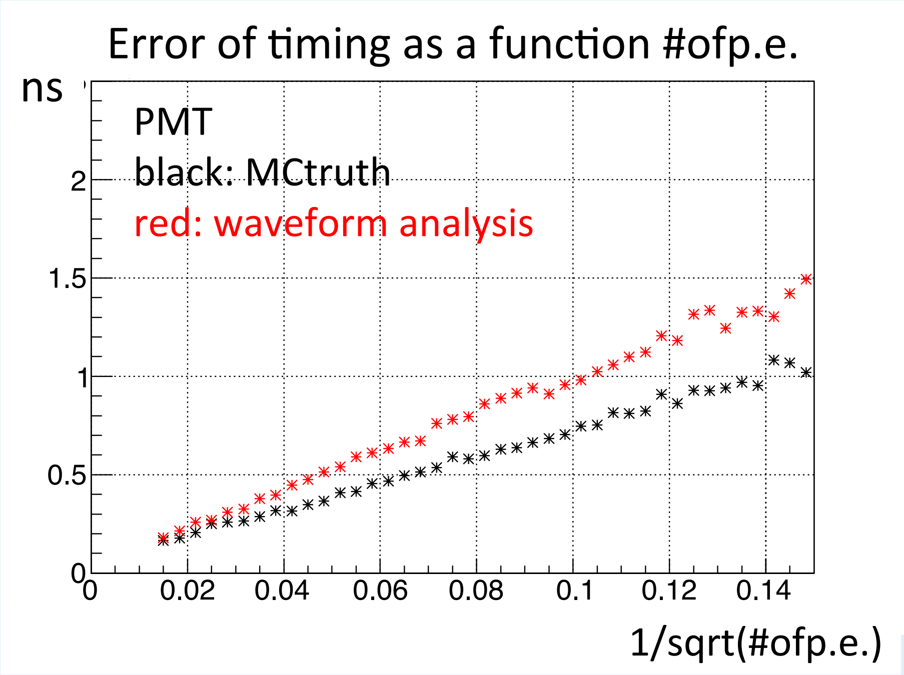


# Timing reconstruction

- Timing is reconstructed by fitting the time at each sensor, taking into account of TOF from the reconstructed conversion point.
- Error of the timing is a function of # of p.e.
- Calibrations of timewalk effect and calibration with position are done.

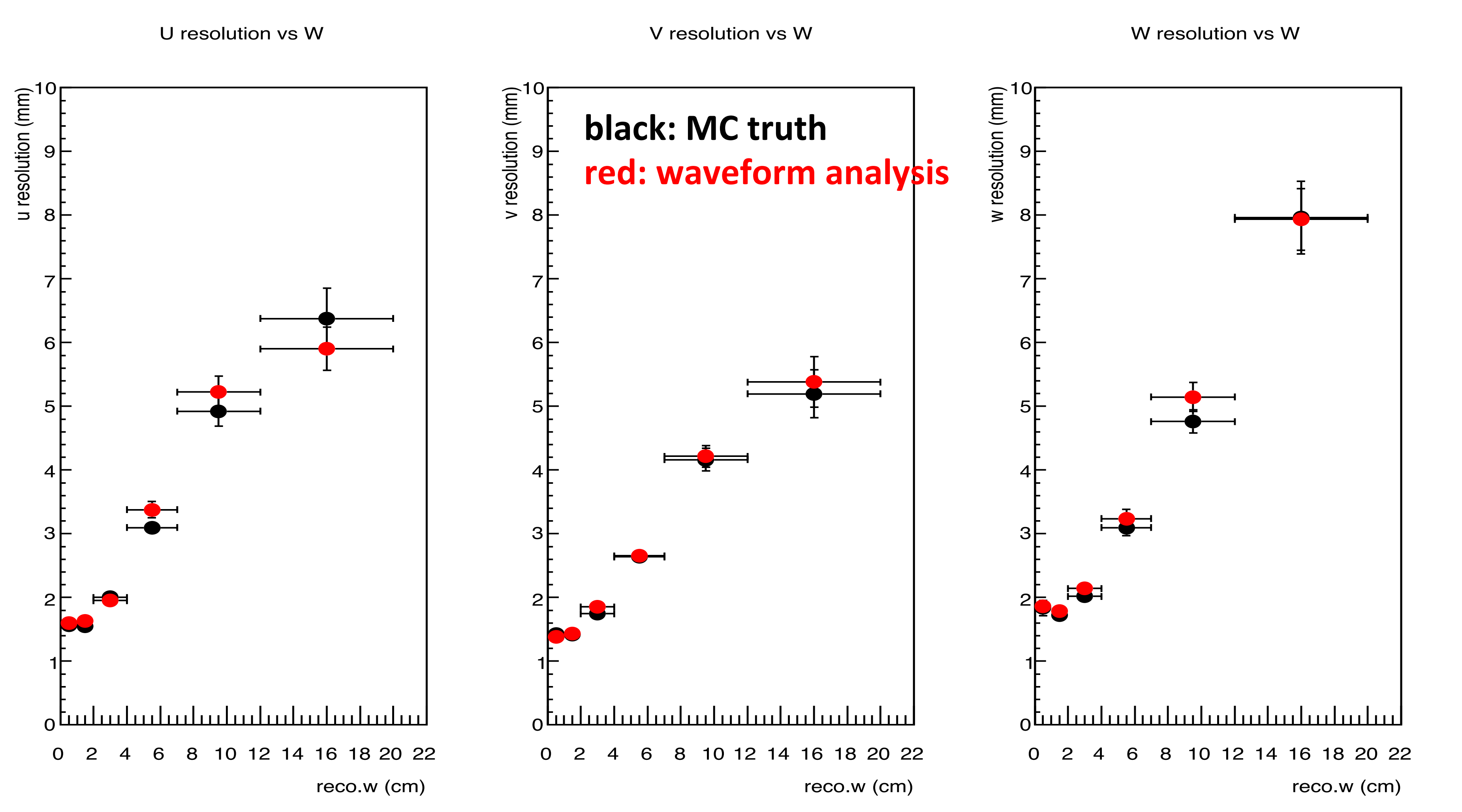
$$\chi^2_{time} = \sum_i \left( \frac{t_{hit,i} - t_\gamma}{\sigma(N_{pe,i})} \right)^2, t_{hit,i} := t_{pm,i} - t_{TOF,i} - t_{calib,i}$$



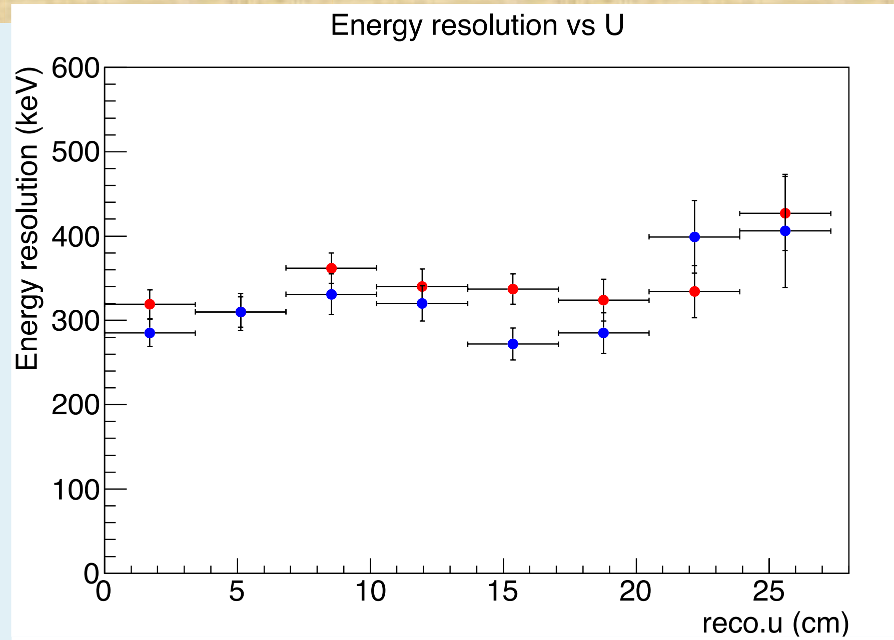
# Position resolution

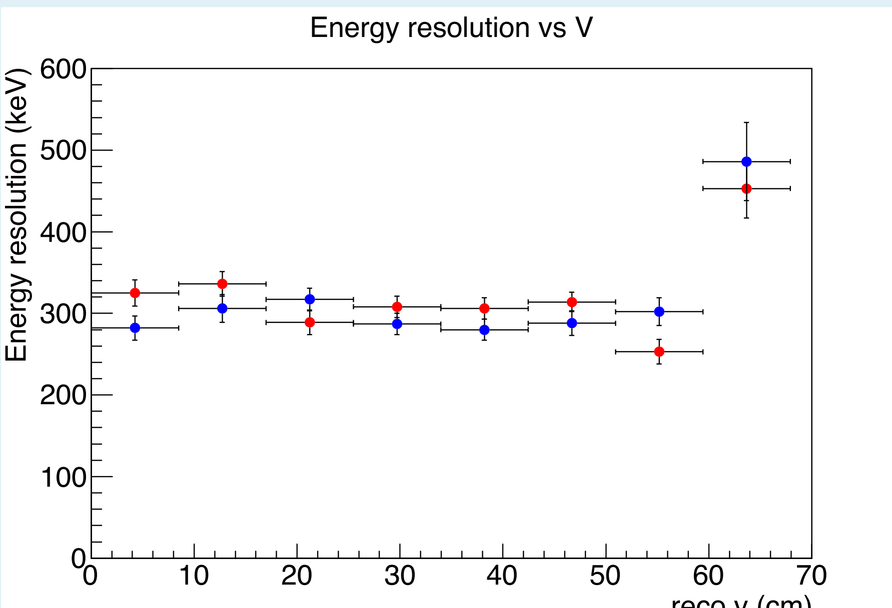
- Improvement of position resolution for shallow event from MEG I can be seen as we expected in proposal.

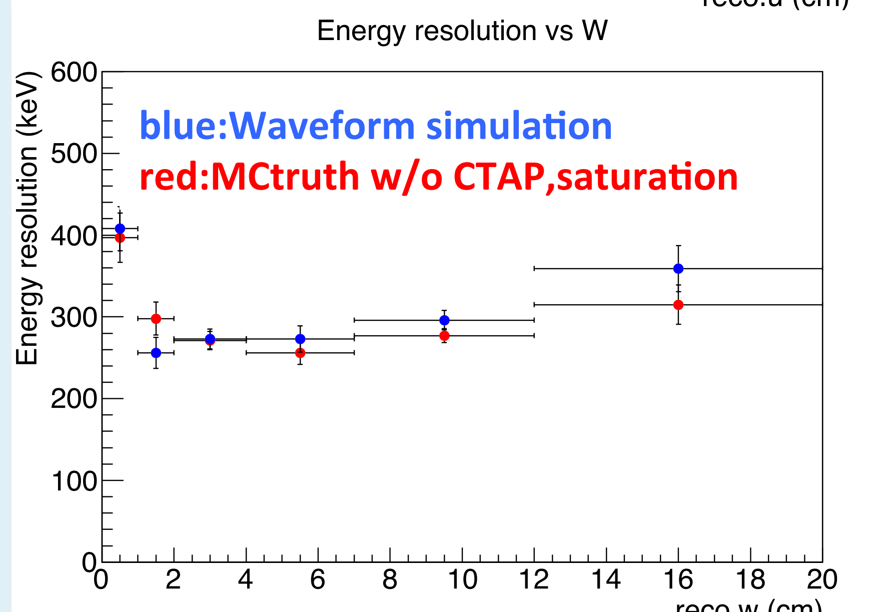


# Energy resolution vs position

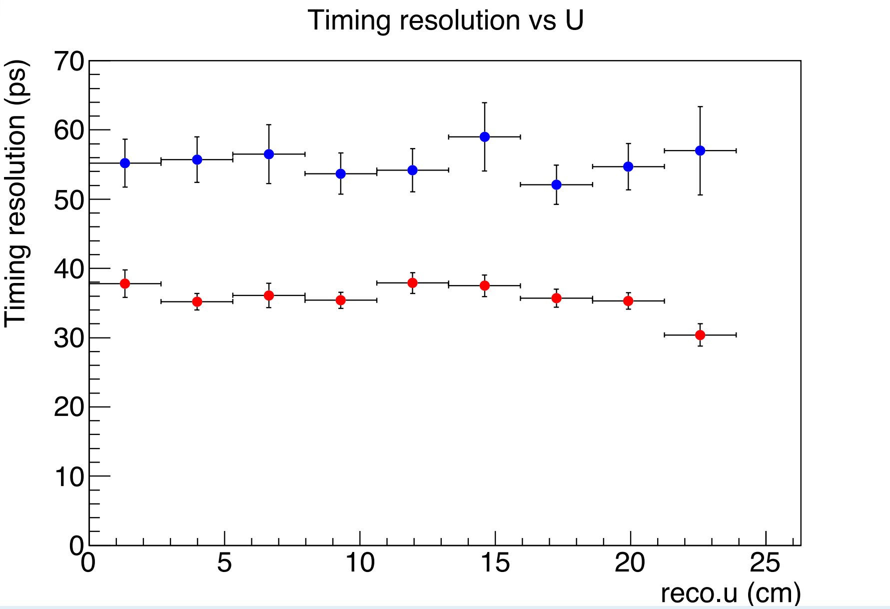
- Same resolution for all position with MC truth.

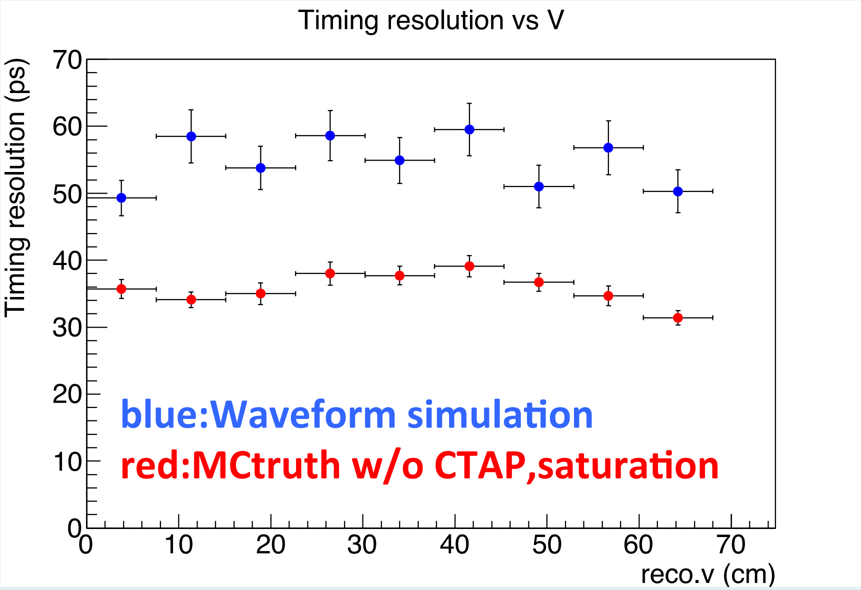


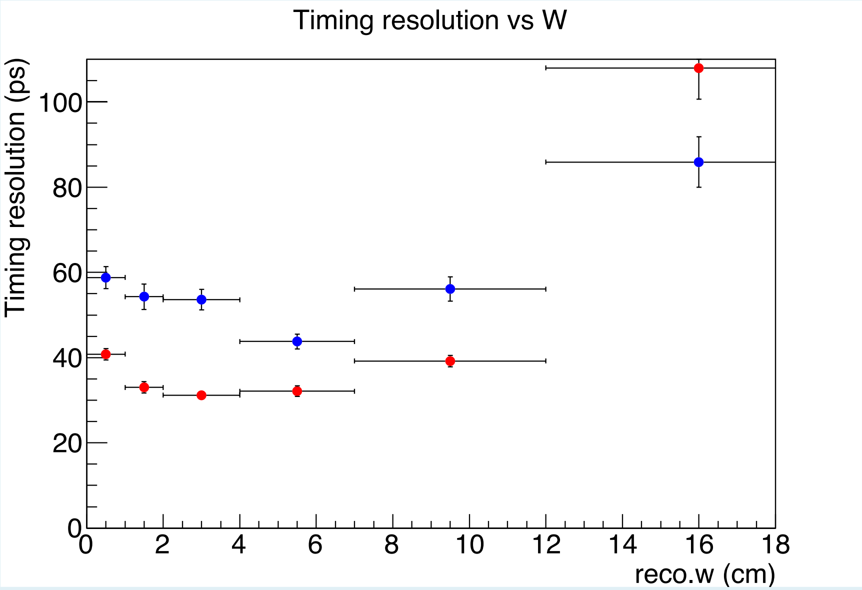



# Timing resolution vs. position



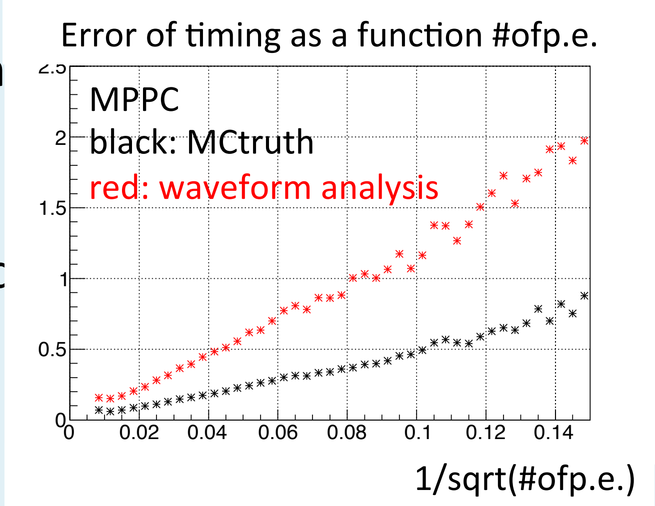



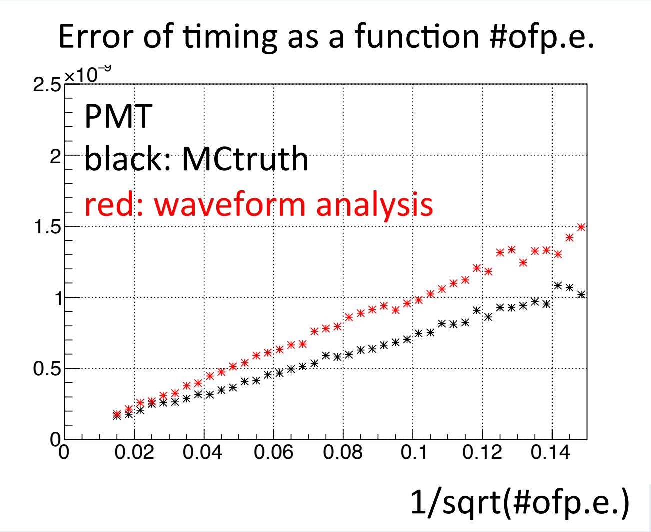



# Comparison with reconstruction from MCtruth



- We also tried reconstruction using MCtruth of # of p.e. and timing for each MPPC,PMT for comparison
  - Effect from crosstalk, after pulse, saturation, noise can be seen.
- Almost same resolution is obtained for position and energy.
- Different timing resolution is observed.
  - This can be coming from the error of timing in the waveform analysis.
  - There is the room for the improvement in the waveform analysis.



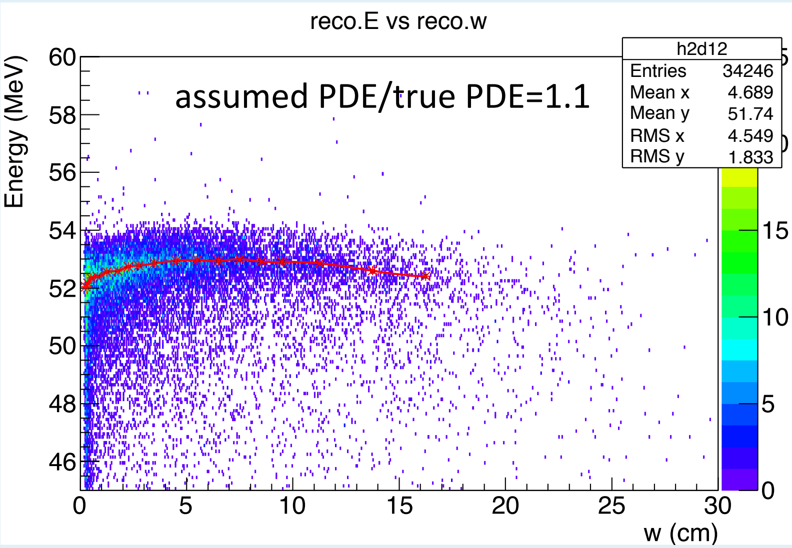



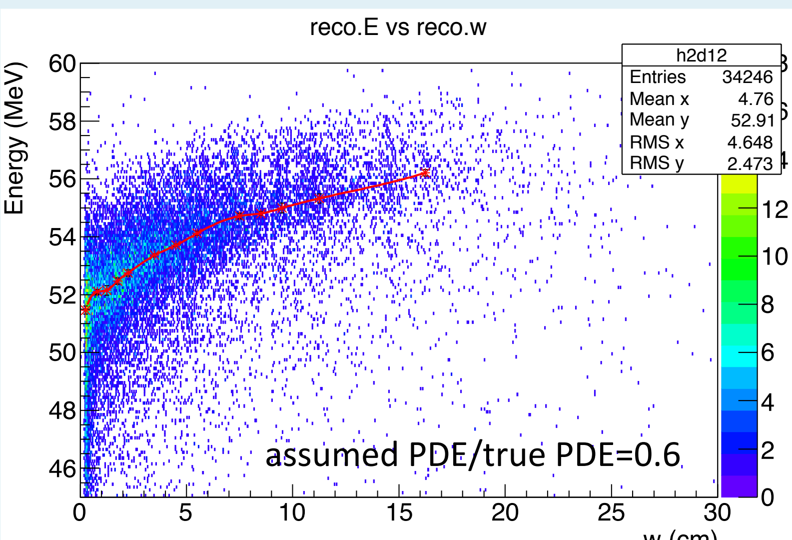

| **Resolution** | **MC truth** | **waveform analysis** |
|---|---|---|
| u/v/w (mm) | 2.2/2.0/2.3 | 2.3/2.0/2.4 |
| $E_\gamma$ (w<2cm) | 0.70(4)% | 0.65(4)% |
| $E_\gamma$ (w>2cm) | 0.45(2)% | 0.49(2)% |
| $t_\gamma$ (ps) | **39**(1) | **56**(1) |

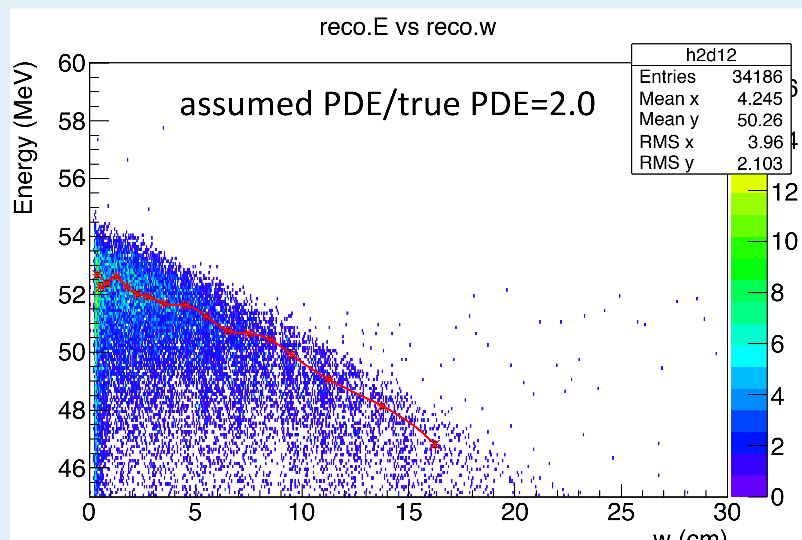
# Wrong PDE ratio b/w MPPC and PMT



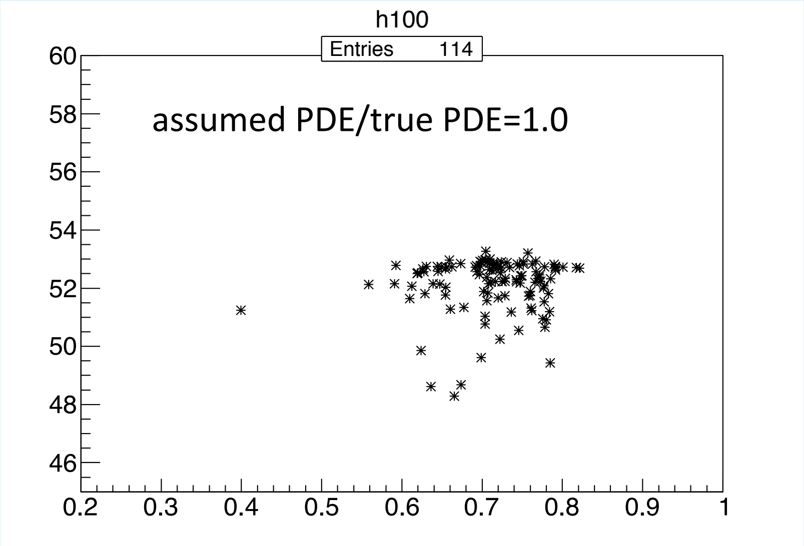
wrong ratio changes reco.E vs. w
This change can be calibrated in the calibration run



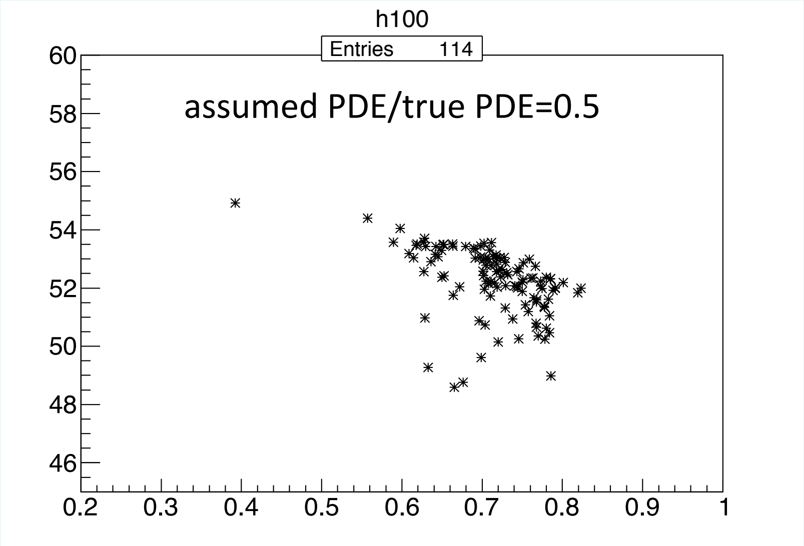



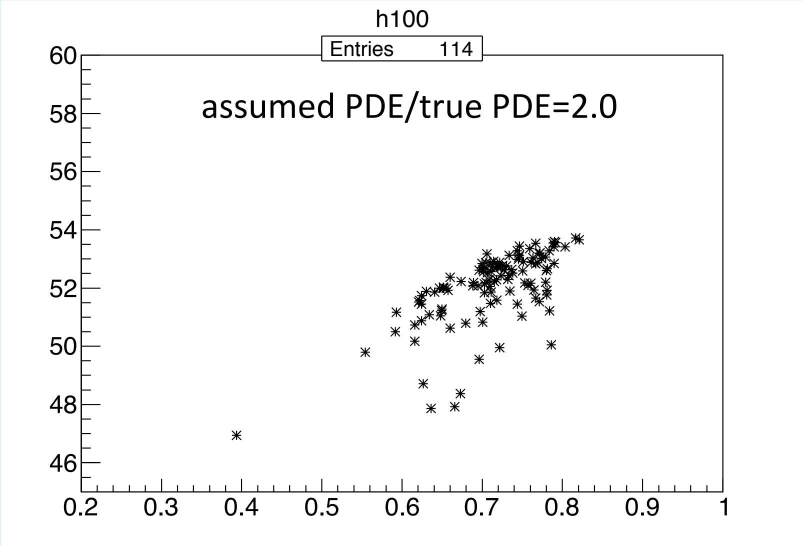
# Wrong PDE ratio b/w MPPC and PMT




Event by event fluctuation of detected # of p.e. for MPPC and PMT causes degradation of resolution with wrong PDE ratio.

x-axis: # of p.e.(MPPC) / # of p.e. (PMT) taking into account different coverage
y-axis: reconstructed Energy
selecting events in abs(u)<5 && abs(v)<15 && 3<w<4

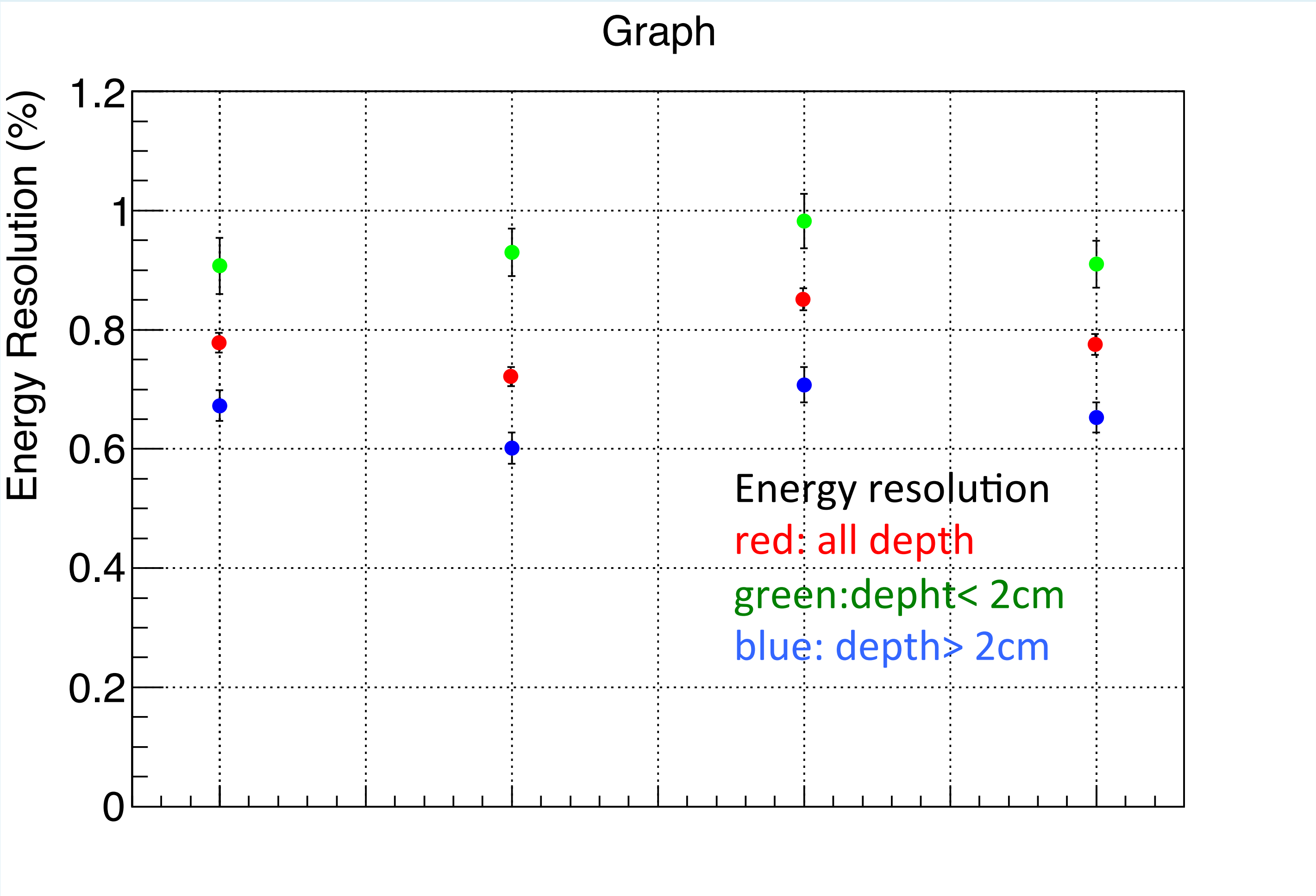


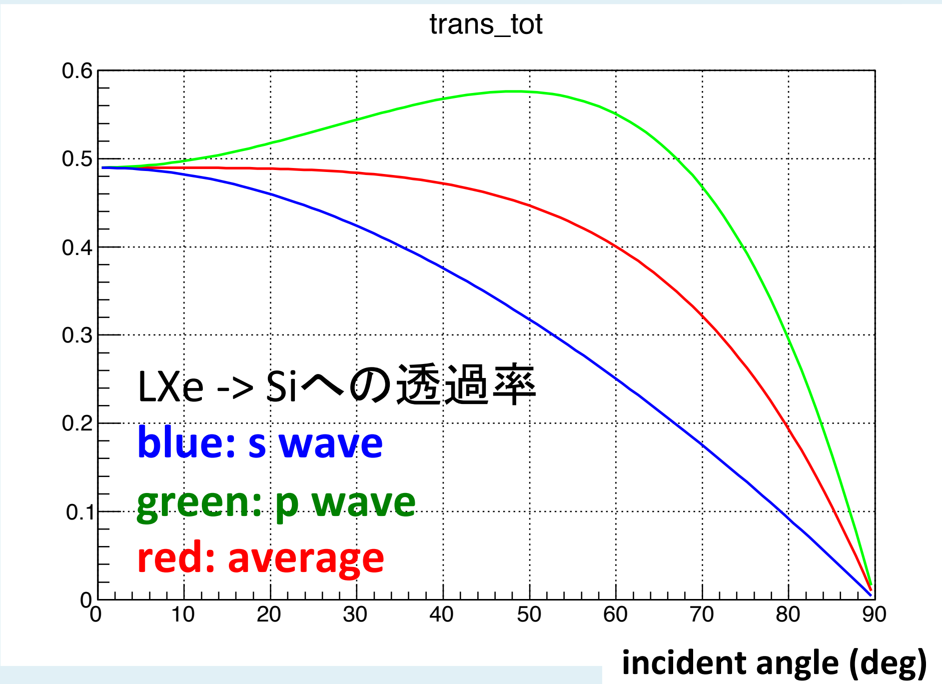
# Reproducibility of PDE fluctuation



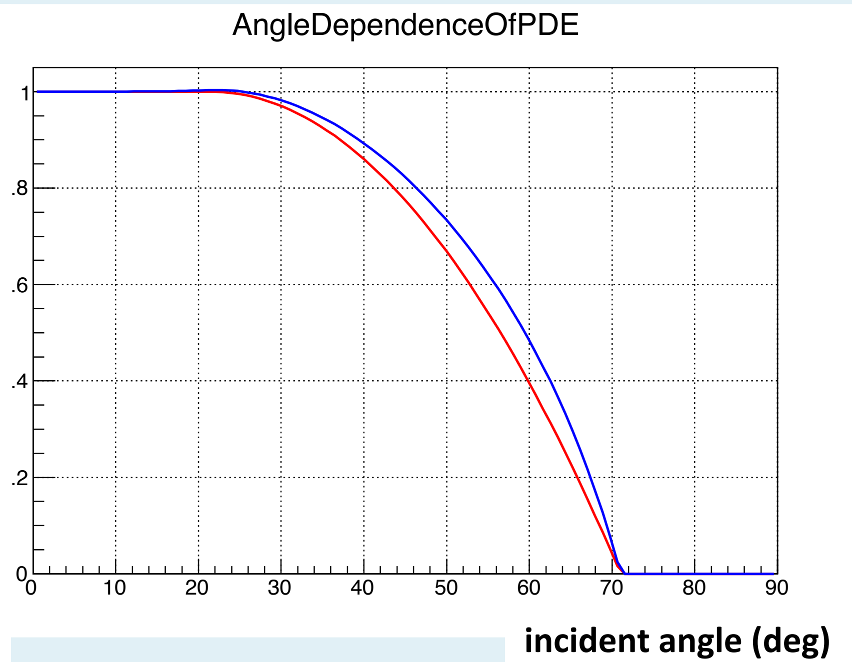
- **Case C**(PMT QE distribution 16% + MPPC PDE distribution 6.5%)
- Reproducibility of the result is confirmed with different seed value.



# angular dependence




calculated from
complex refractive index
LXe: 1.61
Si: 0.8+2.2i

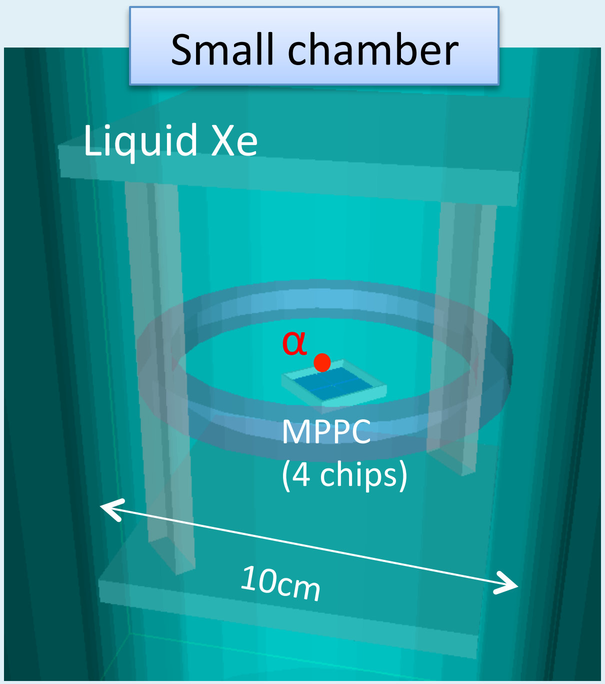



**red: angular dependence measured in mass test**

**blue: angular dependence measured in mass test (w/o LXe to Si reflection)**

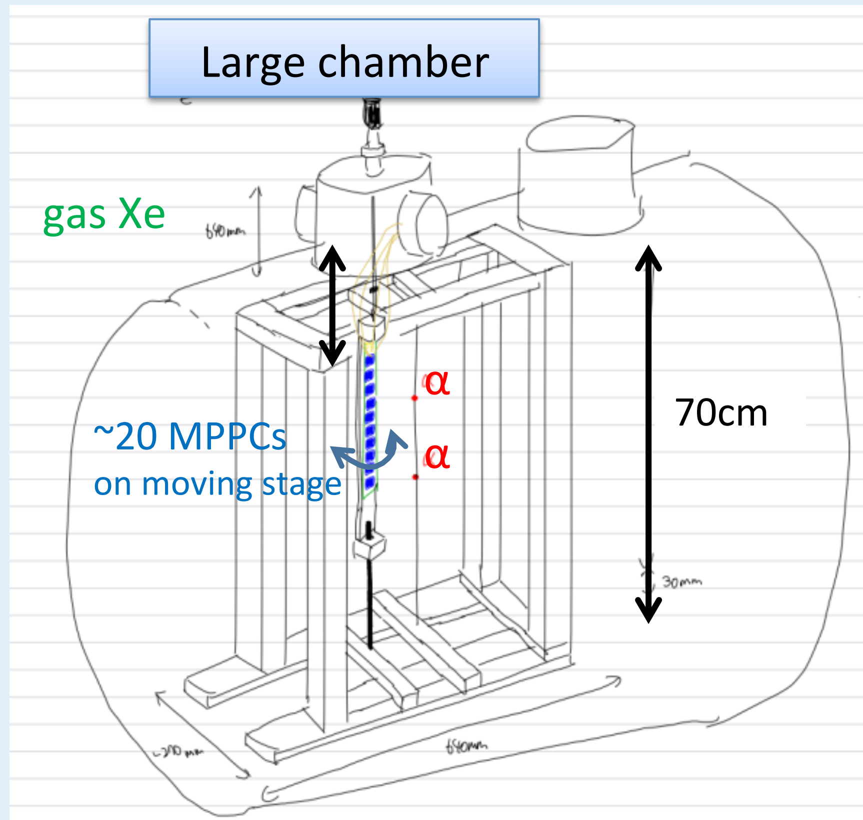
# Additional angular dependence meas.

We plan to do two different type of tests.




- Quick setup, only 4 chips
- Confirm angular dependence

↑ Today's topic




- Movable stage, 20~30 MPPCs.
- Check the angular dependence and MPPC by MPPC variation of PDE

# Energy reconstruction (w/ angular dependence)



**Sum of # of p.e. (all MPPCs)**
**blue: w/o angular dependence**
**red: w/ angular dependence**