Energy reconstruction in CD

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Outline

- Likelihood reconstruction method (RecTimeLikeAlg);
  - Method of likelihood reconstruction;
  - Reconstruction results.
- Optical model independent likelihood reconstruction (OMILREC):
  - Motivation;
  - Method of OMILREC;
  - Reconstruction results;
  - Status in SNiPER;
- Occupancy-based energy reconstruction:
  - Motivation;
  - Methodology;
  - Preliminary performance study;
- Summary and prospects.

Method of likelihood reconstruction

- This algorithm uses the charge of each PMT to construct the charge likelihood function.

  - Minimization of charge likelihood function:

$$-\ln\mathcal{L}(E_{vis}; x_1, x_2, \ldots, x_n) = -\sum_{i=1}^{n} \ln P(x_i | E_{vis})$$

  - Probability of x_i hits at ith PMT:

$$P(x_i|E_{vis}) = \frac{v_i^{x_i} e^{-v_i}}{x_i!}$$

  - The Expected PE number:

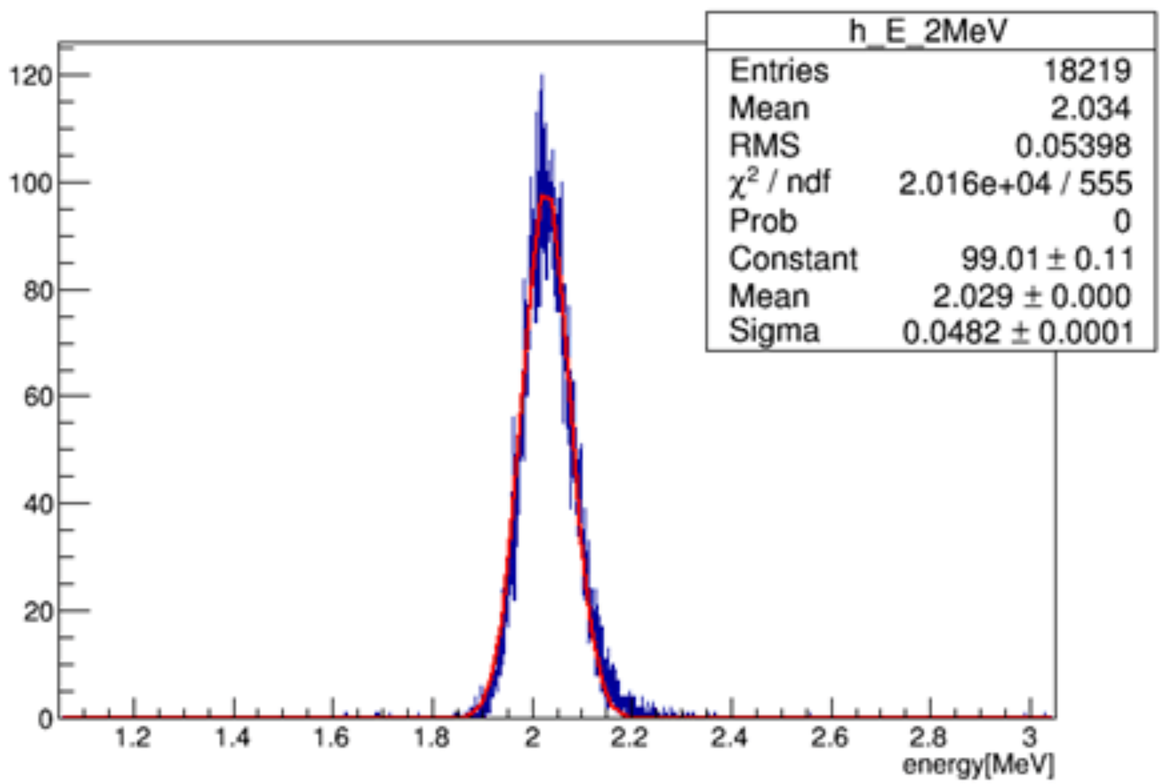
$$v_i = Y E_{vis} \frac{\Omega(\vec{r}, \overrightarrow{R_i})}{4\pi} e^{-\frac{L_{LS}(\vec{r},\overrightarrow{R_i})}{\lambda_{LS}} - \frac{L_{water}(\vec{r},\overrightarrow{R_i})}{\lambda_{water}}}$$

where $\vec{r}$ is the position of event vertex, and $\overrightarrow{R_i}$ is the position of ith PMT.

Solution to dark noise

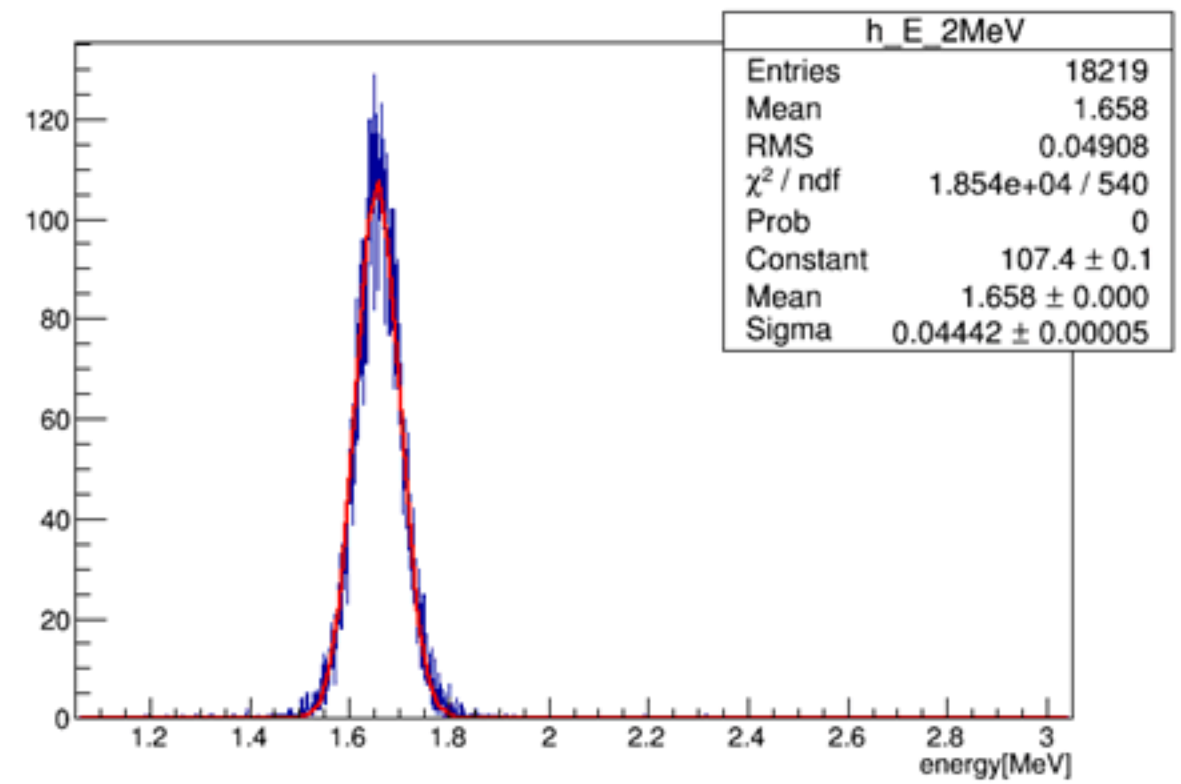
- First hit time selection approach
- Samples: 1 MeV momentum (E=1.634 MeV) positron events, uniformly generated in the detector (J17v1r1-Pre1);

w/o first hit time selection



Mean: 2.03 MeV
Sigma: 0.048

w/ first hit time selection

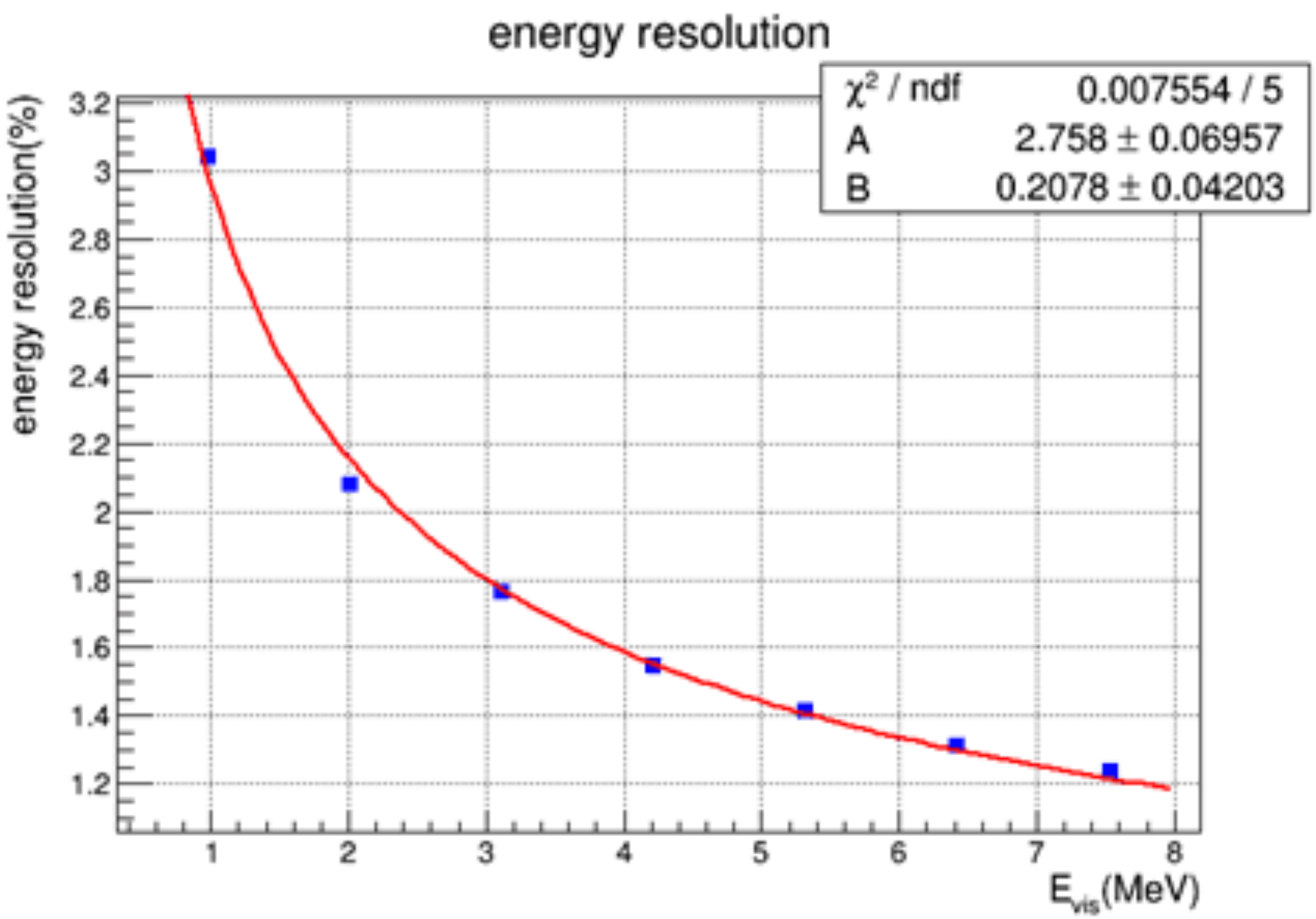


Mean: 1.66 MeV
Sigma: 0.044

- With F.H.S, bias is reduced.

Resolution at different energies

w/o dark noise



Status in SNiPER

- Default reconstruction algorithm in SNiPER named as RecTimeLikeAlg ($RECTIMELIKEALGROOT);

```
BundleRecByChargeTool  Deconvolution    MuonWaveRec  PoolMuonRecTool  RecCdMuonAlg   RecTimeLikeAlg  SpmtMuonRecTool  TTTracking     WPChargeClusterRec
CMakeLists.txt         IntegralPmtRec   OMILREC      PushAndPull      RecRelease     RecWpMuonAlg    TemplateFitAlg   VertexFitAlg
ConeMuonRecTool        LsqMuonRecTool   PmtRec       QCtrRecAlg       RecSampleAlg   SmartRec        TTCalib          WaveFitAlg
```

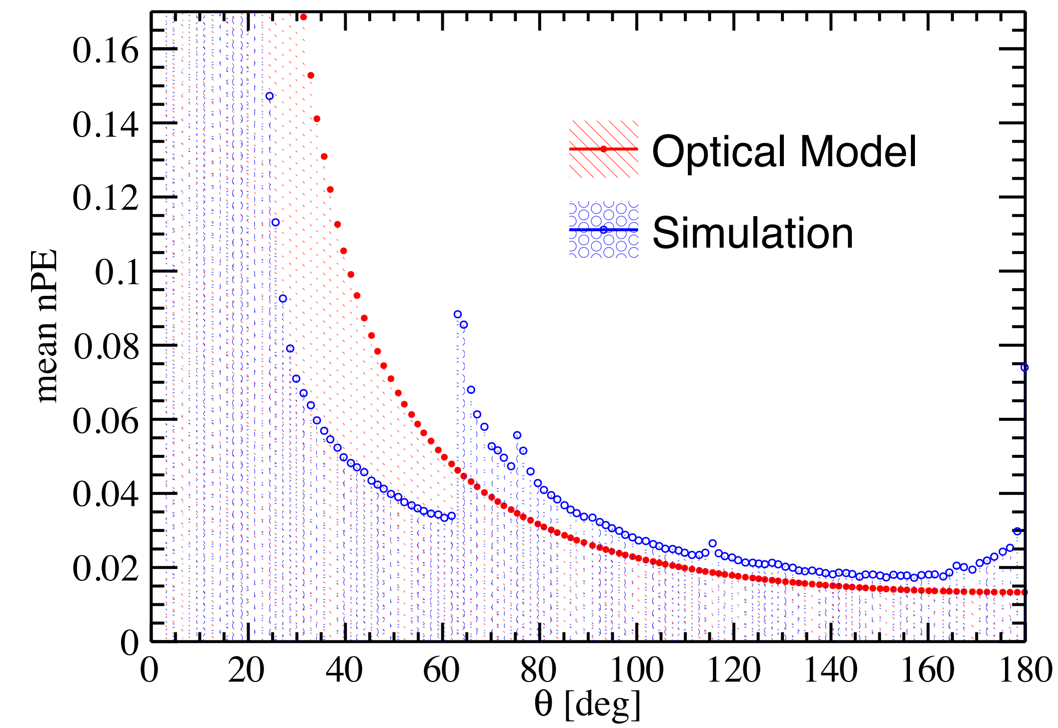
- Response functions need to be updated for a new version of offline;

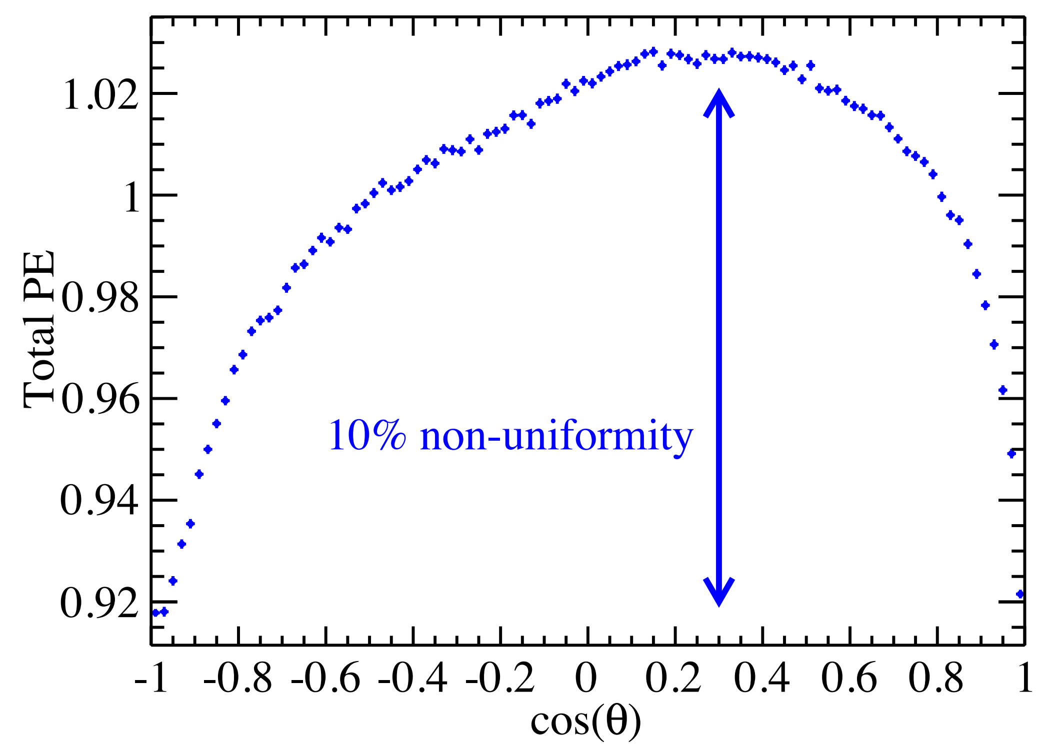
- Usage:

```
python tut_calib2rec.py --input ../elec2calib/e+_P0MeV_elec2calib.root --output e+_P0MeV_rec.root --user-output e+_P0MeV_rec_user.root --gdml --gdml-file ../detsim/sample_detsim.root --elec yes --FHS 1 --method point
```

Motivation of OMILREC

- Some propagation processes are difficult to be precisely described by a simple optical model, such as Rayleigh scattering, total reflection and so on;
- Non-uniform installation of PMTs will lead to the non-uniform response of total charge even when the event vertex is at a fixed radius R=16 m. Therefore, tremendous calibration sources are required inside the detector with precise locations.





Method of OMILREC

- $\mathbf{r}_i$: position of the ith PMT;
- $\mathbf{r}_s$: position of the source;
- θ : angle between the PMT and the source;
- Benefit from the spherical symmetry, nPE of the ith PMT depends on (r_s, θ, E) , in order to avoid the influence of non-uniform installation of PMTs, the response function can be described by:

$$\mu(r_s, \theta, E) = \overline{n_i(r_s, \theta, E)}$$

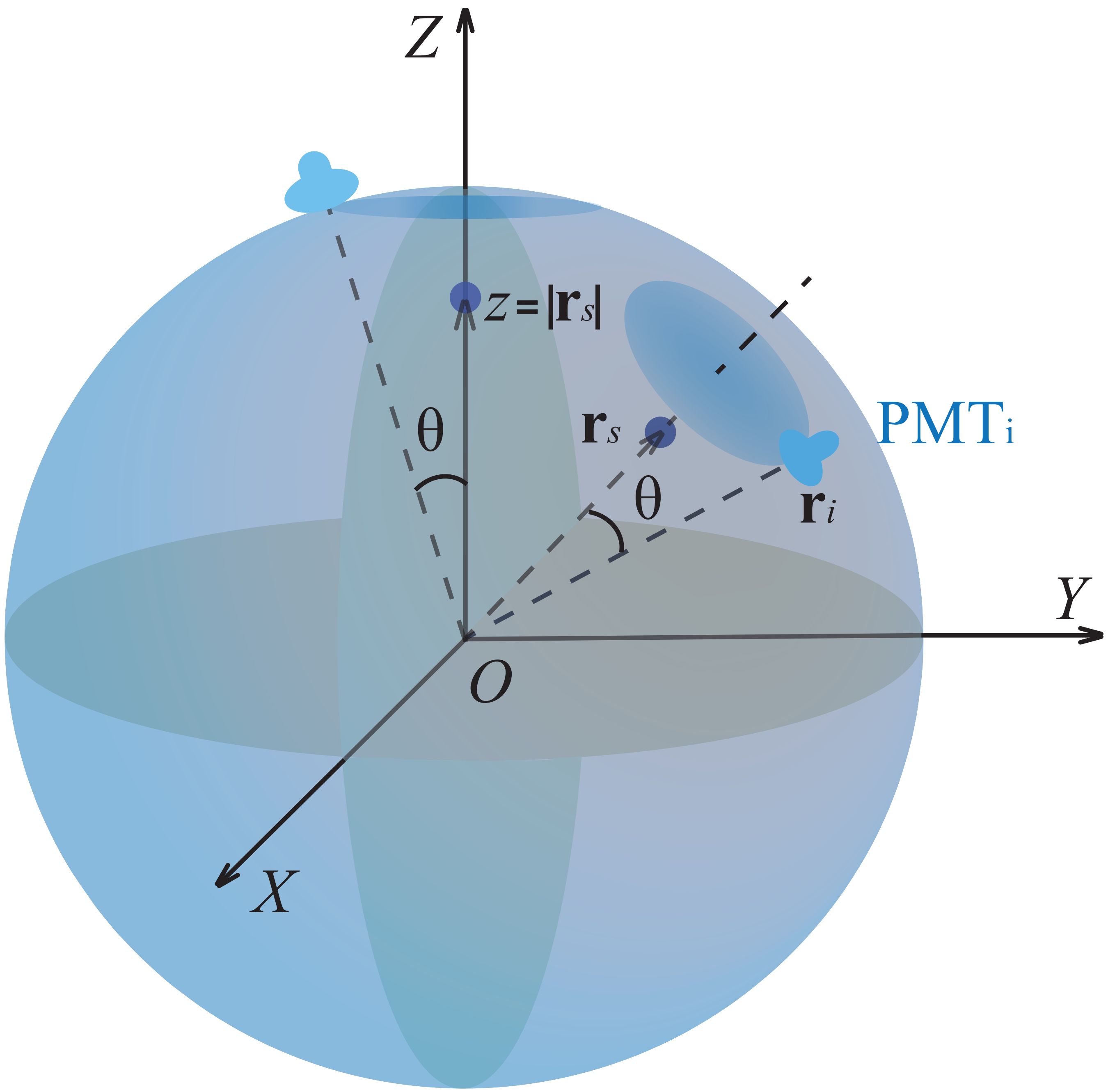
- If Z-axis is chosen to be the symmetry axis, then the response functions can be written as:

$$\mu(z, \theta, E) \equiv \overline{n_i(z, \theta, E)}$$

- Similarly, if X-axis is chosen to be the symmetry axis, the response functions can be written as:

$$\mu(x, \theta, E) \equiv \overline{n_i(x, \theta, E)}$$

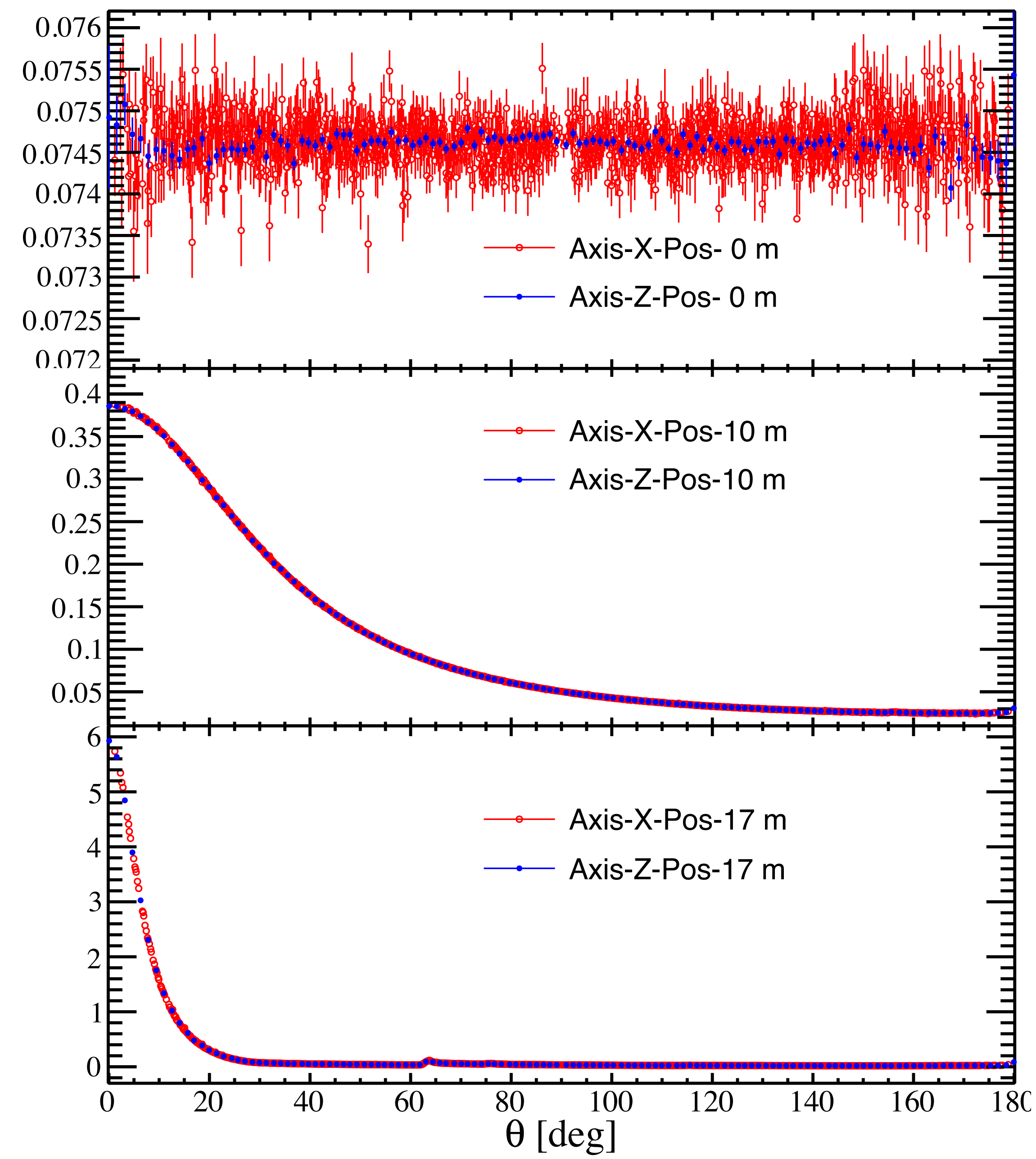
- Define a likelihood function and estimate the parameter by minimizing its minus logarithmic:



$$\mathcal{L}(k_1, k_2, \ldots, k_m|\mathbf{r}_s, E) = \prod_{i=1}^{m} P(k_i|\mathbf{r}_s, E) = \prod_{i=1}^{m} \frac{e^{-\mu_i} \cdot \mu_i^{k_i}}{k_i!} \quad (\mu_i = \mu(r_s, \theta, E))$$

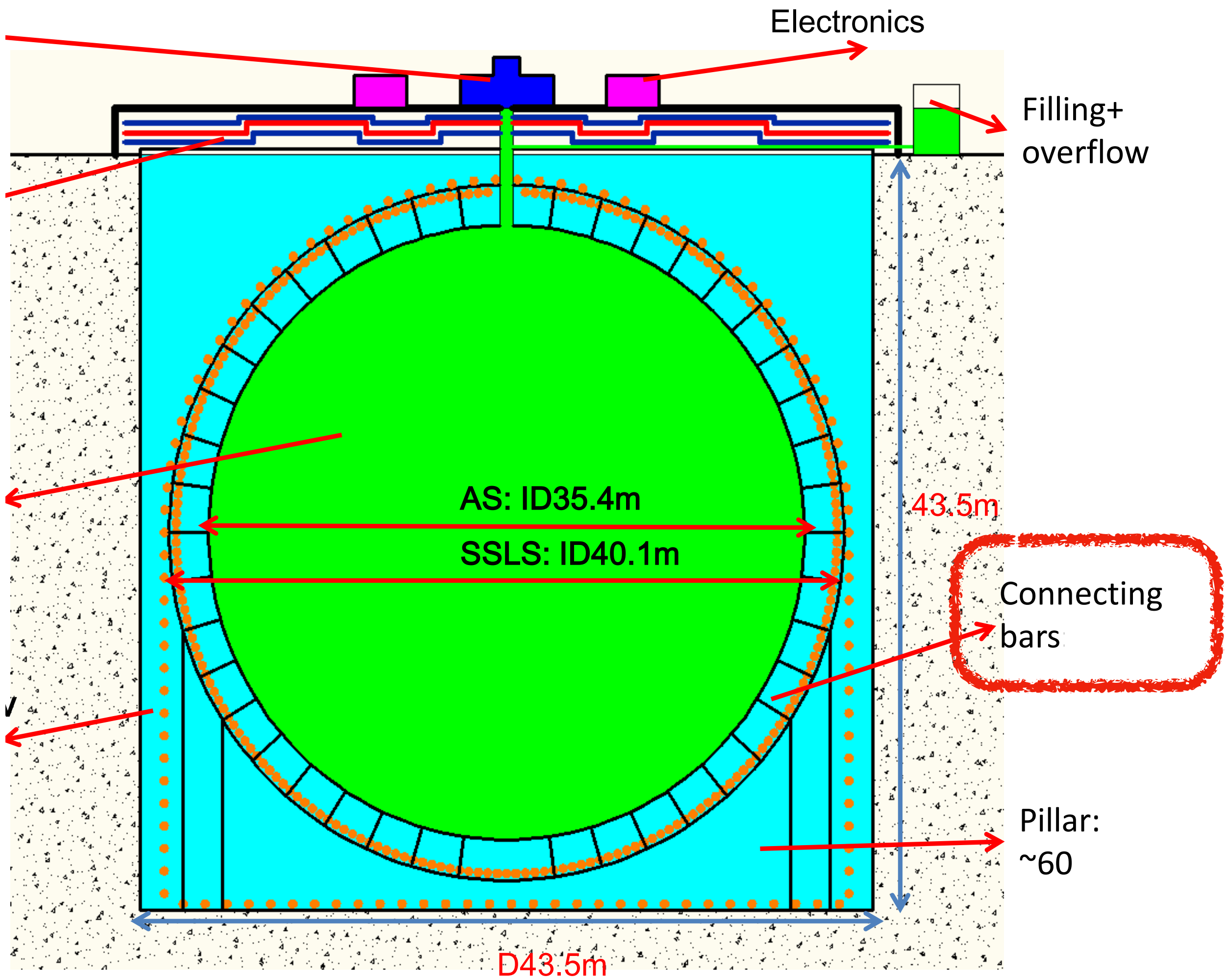
Response functions

- Connecting bars are not considered in this plot;
- Response functions from X-axis and Z-axis have the same shape;
- PMTs are arranged around the Z-axis, therefore the blue points from Z-axis are discrete. Meanwhile, the red points from X-axis are denser.

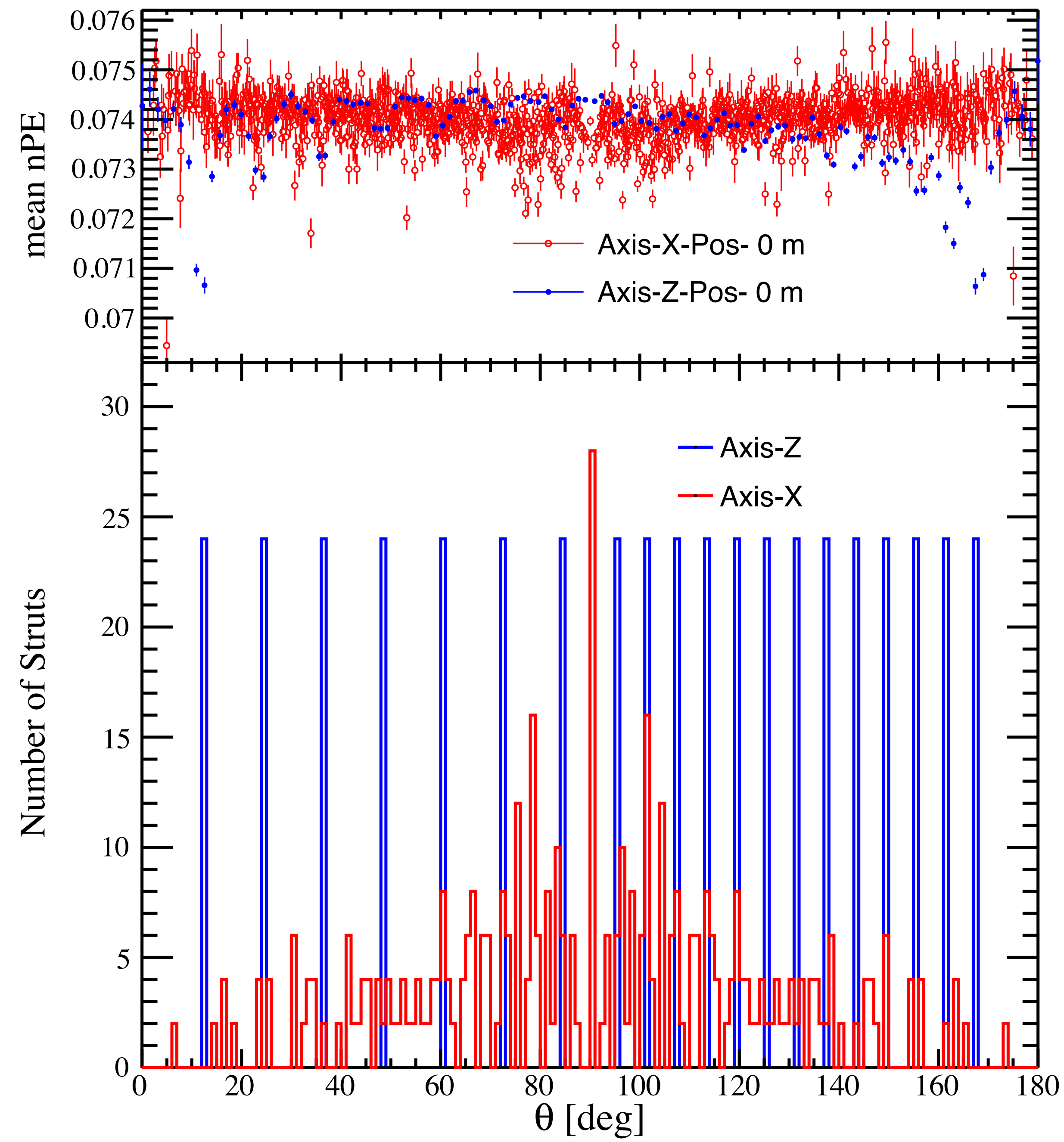


Response functions

- The existence of connecting bars has shadow effect to PMTs.

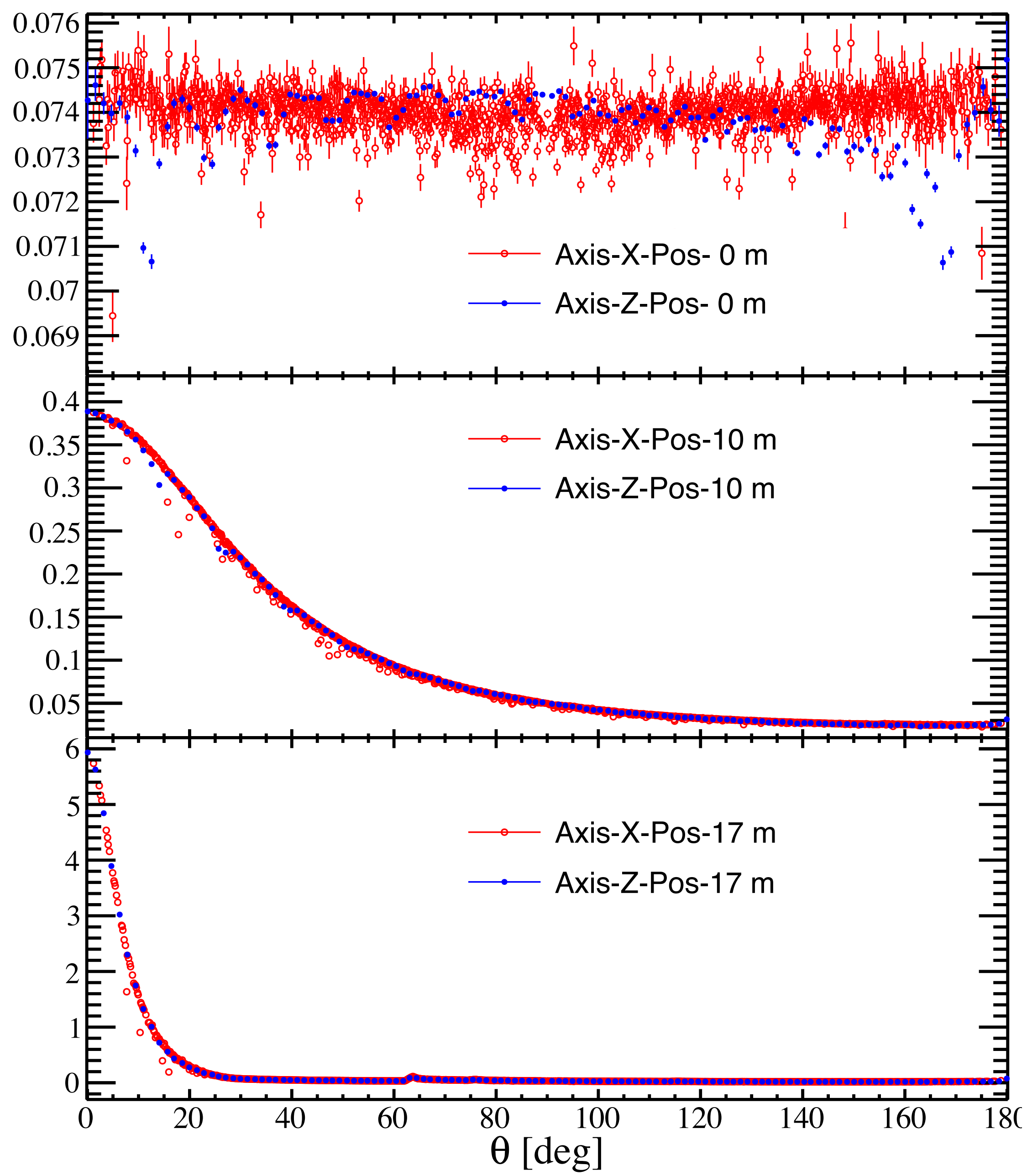


AS: Acrylic sphere; SSLS: stainless steel latticed shell

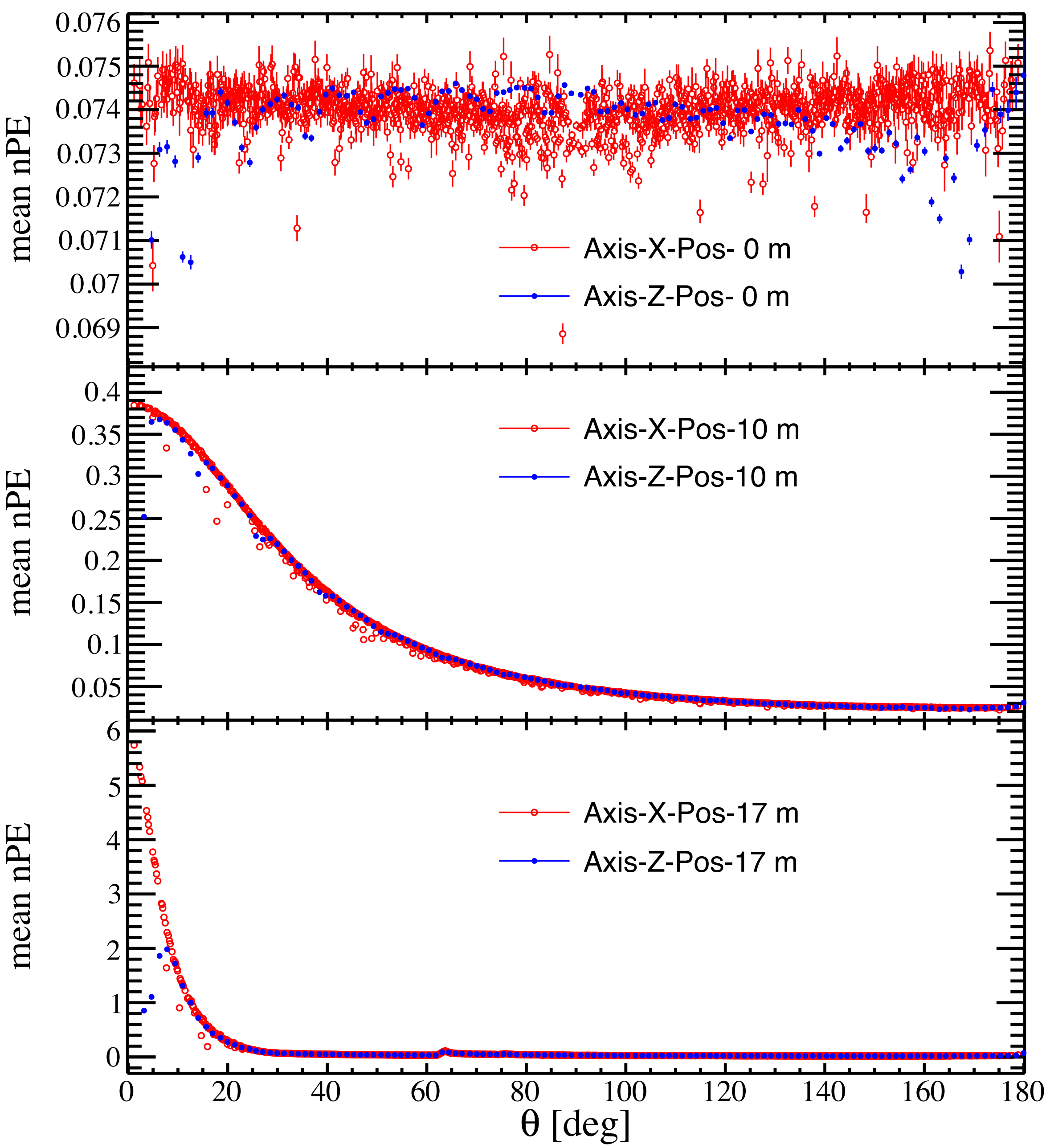


Response functions

- Connecting bars are considered in this figure



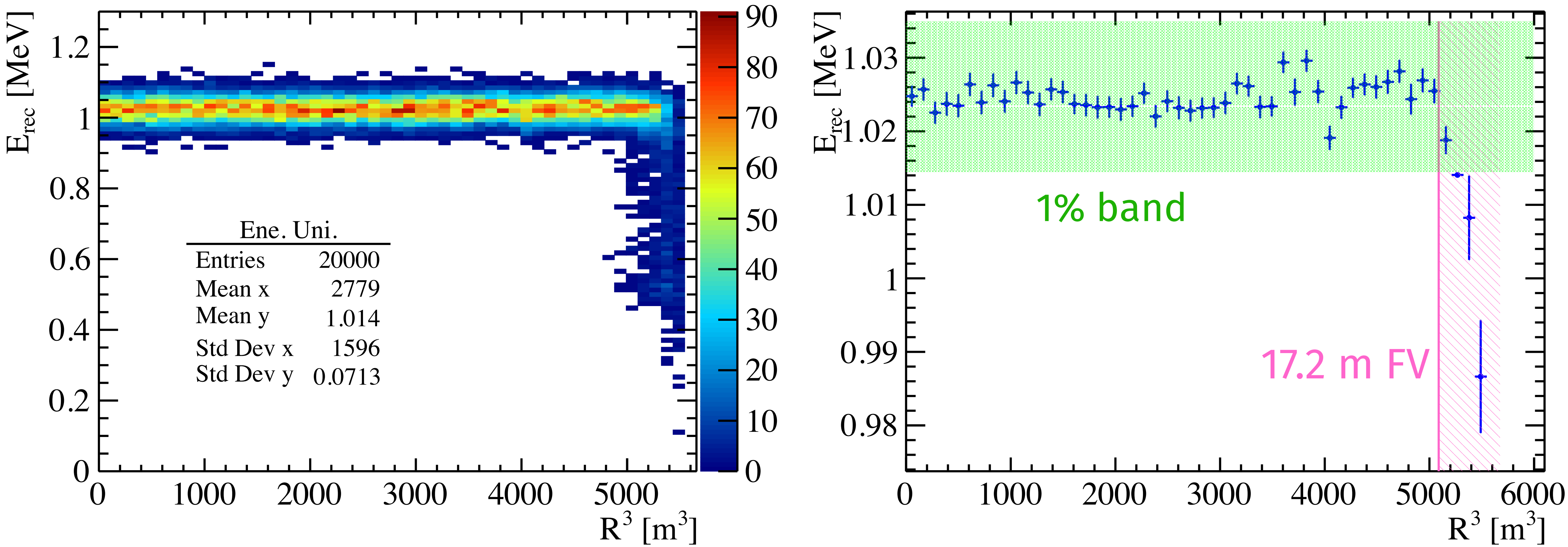
- Connecting bars and the chimney are considered in this figure



Reconstruction results

- Samples: Static positron events are uniformly generated in the detector;
- Response functions are calibrated by optical photon events.

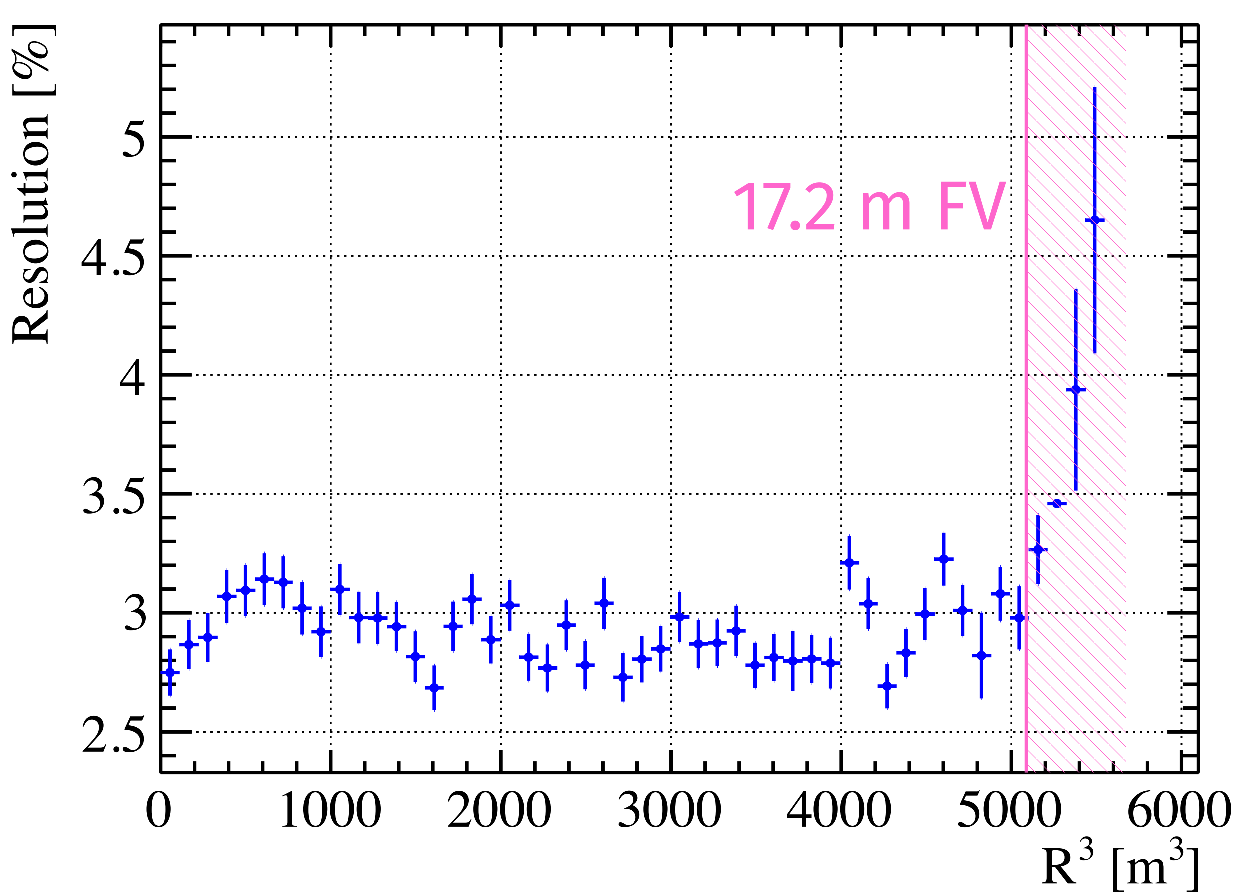
When connecting bars and the chimney are not considered

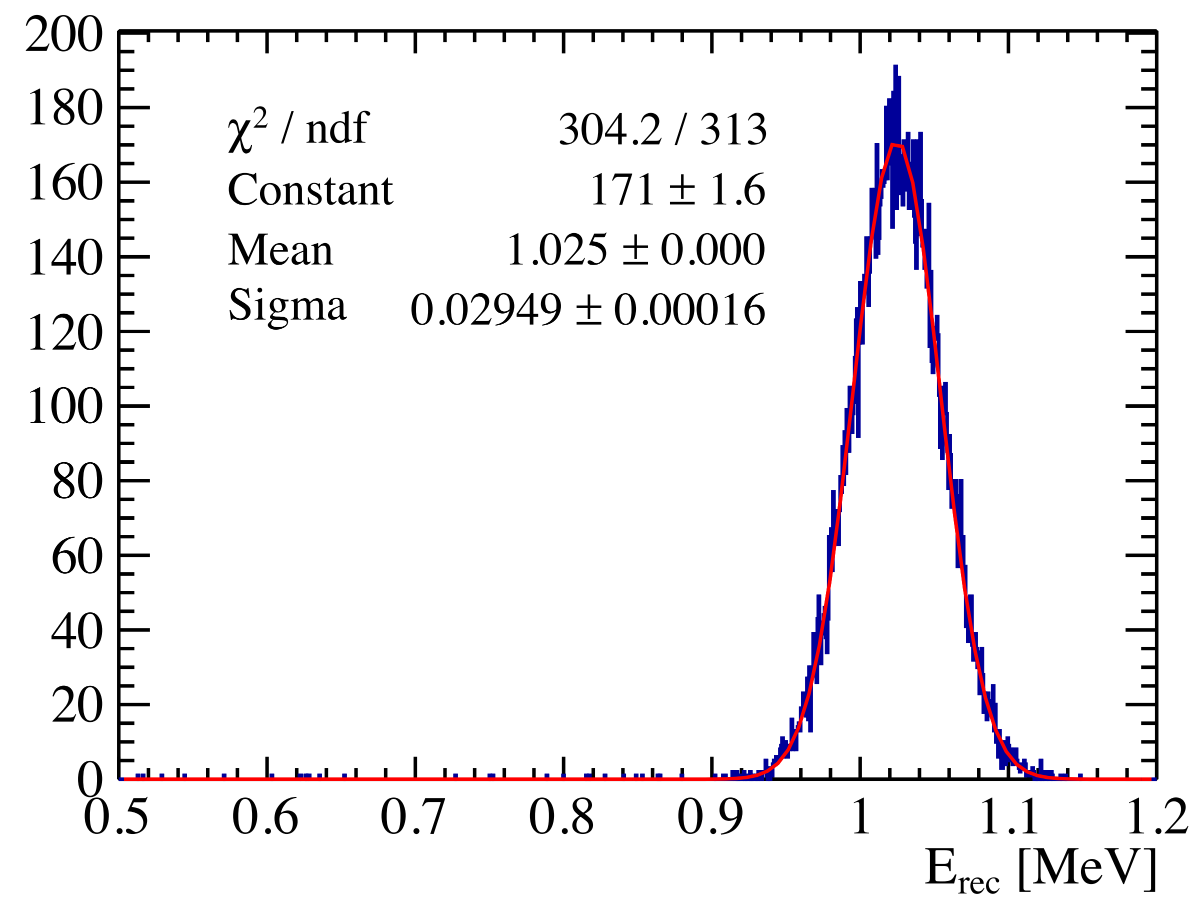


Reconstruction results

- Samples: Static positron events are uniformly generated in the detector (J16v1r4);
- Response functions are calibrated by optical photon events.

When connecting bars and the chimney are not considered

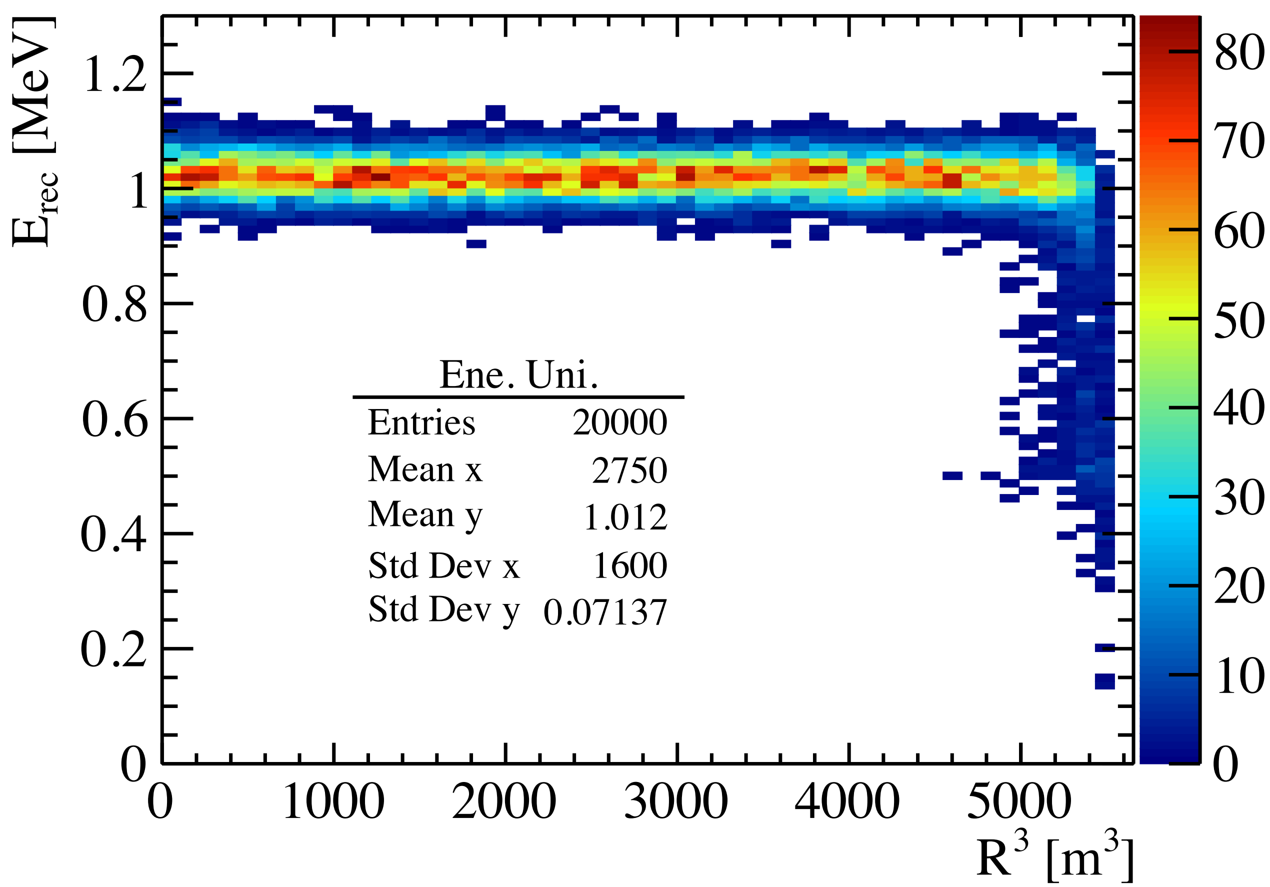


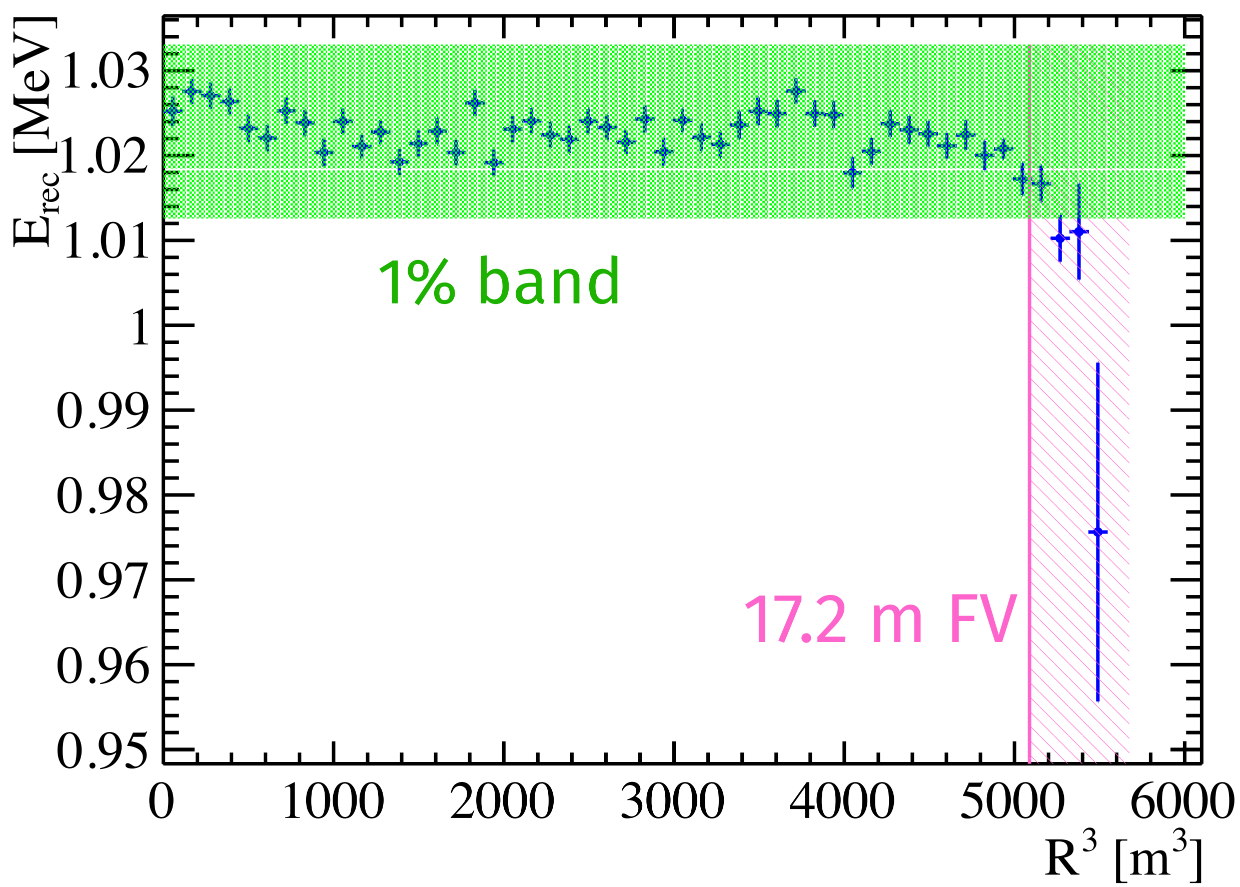


$$\sigma = \frac{\sigma_{E_{\rm rec}}}{\overline{E_{\rm rec}}} = (2.88 \pm 0.02)\%$$

Reconstruction results

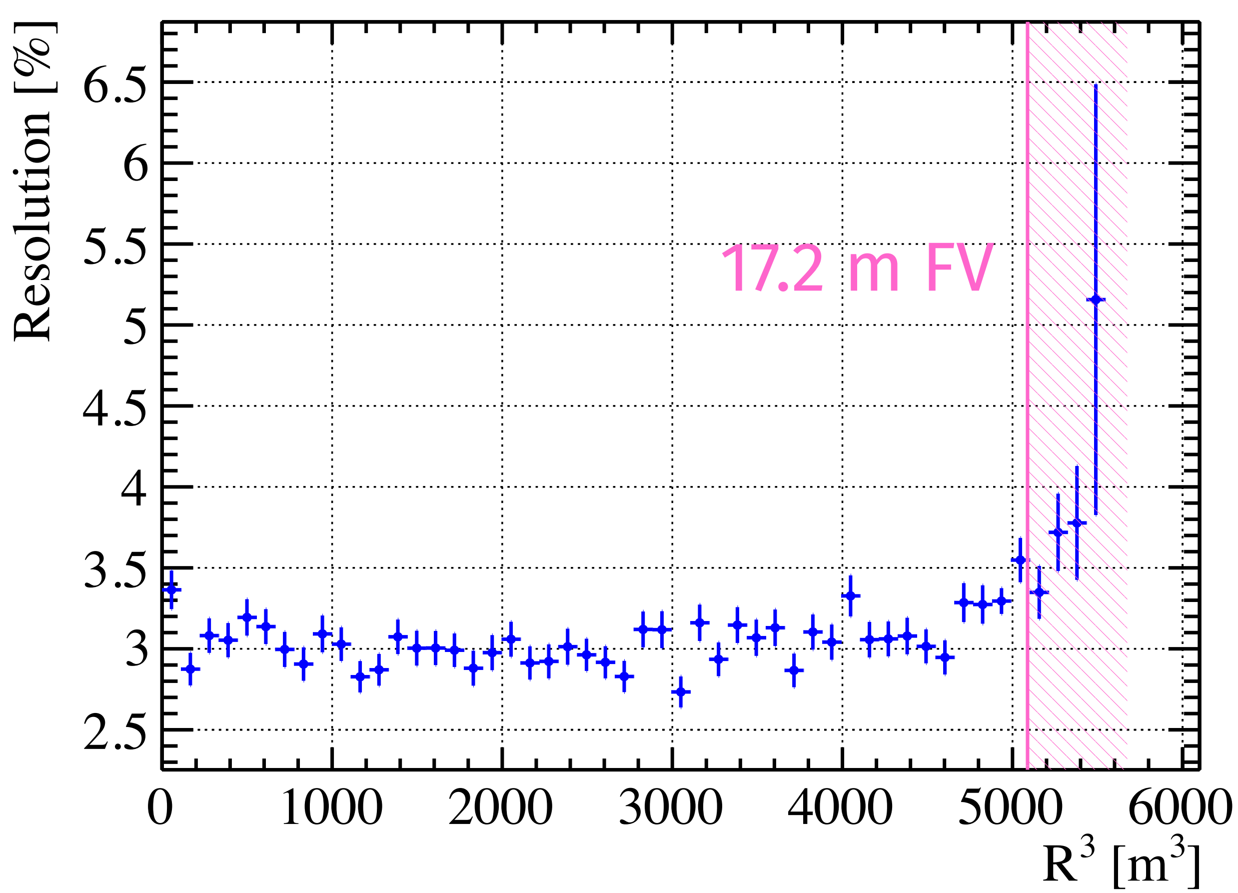
When connecting bars and the chimney are considered

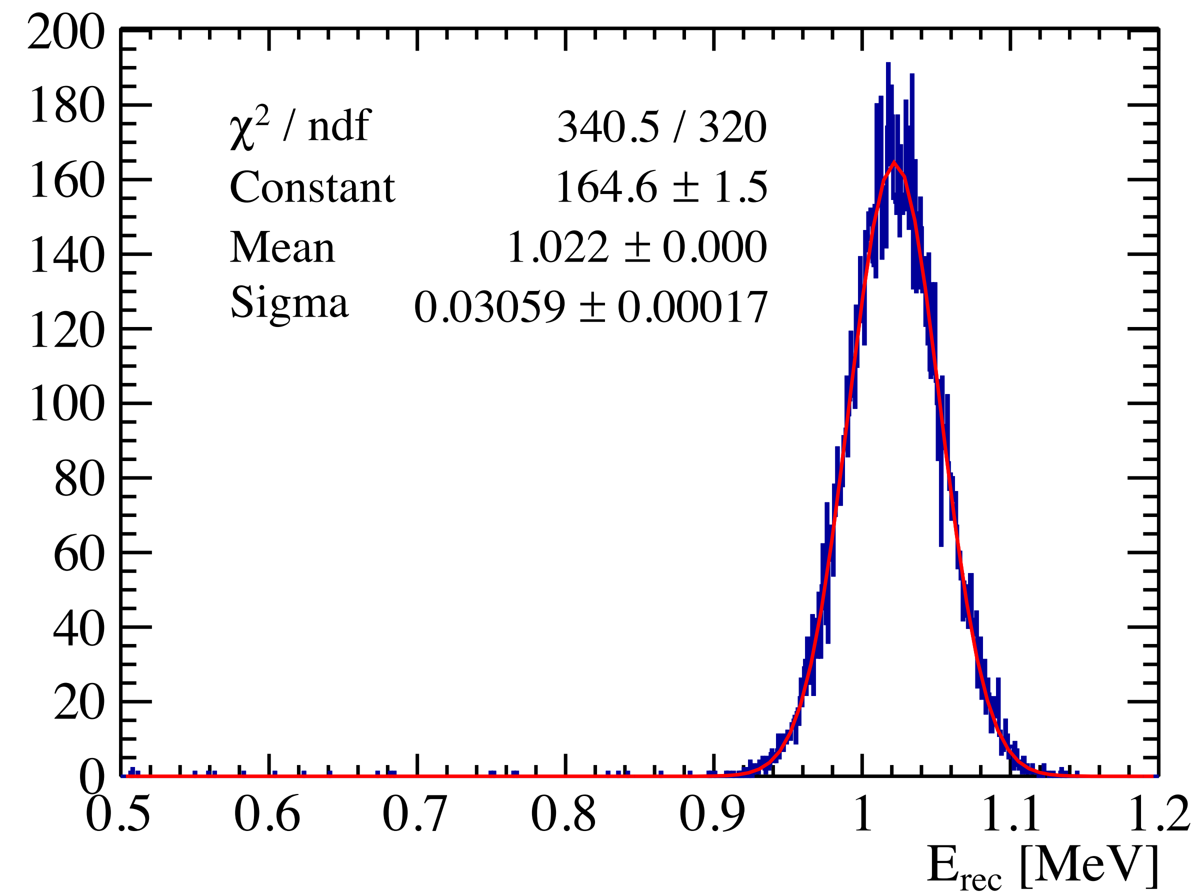




Reconstruction results

When connecting bars and the chimney are considered





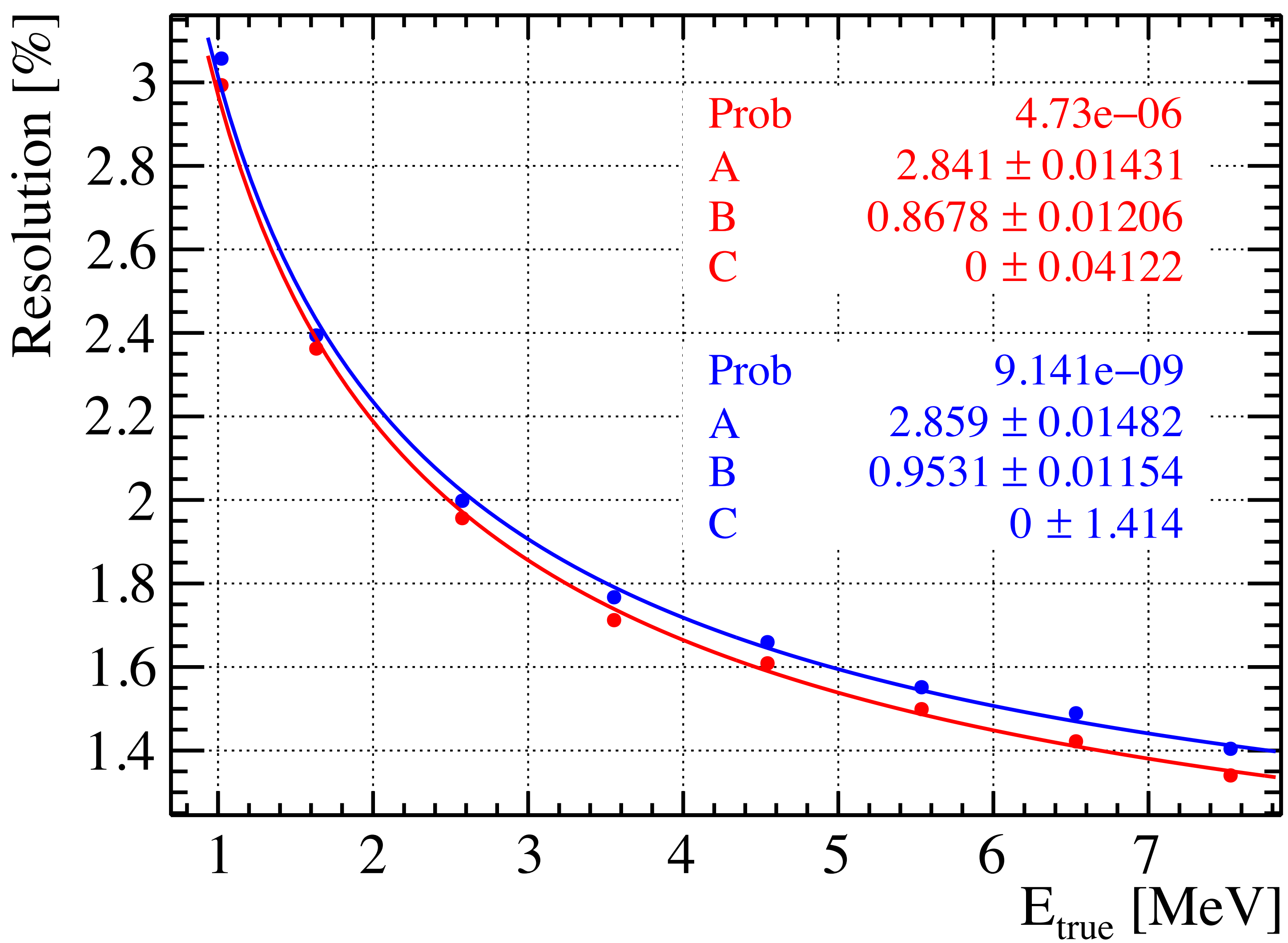
$$\sigma = \frac{\sigma_{E_{\rm rec}}}{\overline{E}_{\rm rec}} = (2.99 \pm 0.02)\%$$

Resolution at different energies

Samples: uniformly generated positron events
Momentum: 0/1/2/3/4/5/6/7 MeV

$$\sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2} \simeq \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{1.6\,b}{\sqrt{E}}\right)^2 + \left(\frac{c}{1.6\,\sqrt{E}}\right)^2}, \quad (2.12)$$

Ref: An, et al. "Neutrino Physics with JUNO."



Effective resolution: 3.16%
calibrated by optical photon events

Effective resolution: 3.24%
calibrated by Co60 (2.5 MeV γ)

More about the connection bars

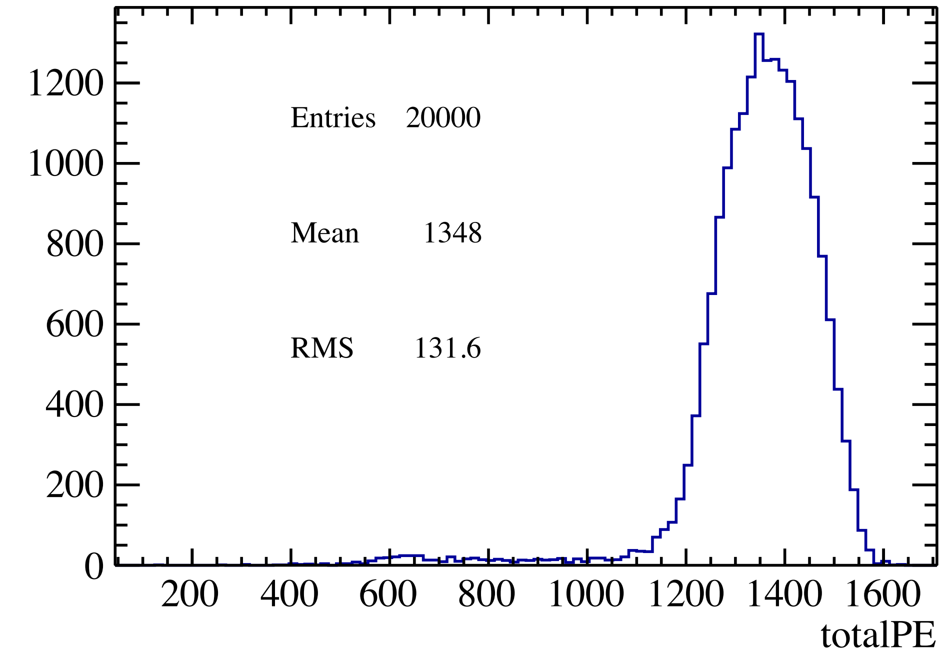
Samples: uniformly generated static positron events

When connecting bars and the chimney are not considered

$$\sigma = \frac{\sigma_{E_{\rm rec}}}{\overline{E}_{\rm rec}} = (2.88 \pm 0.02)\%$$

Total PE: $N = 1348$

Simulation w/o connecting bars

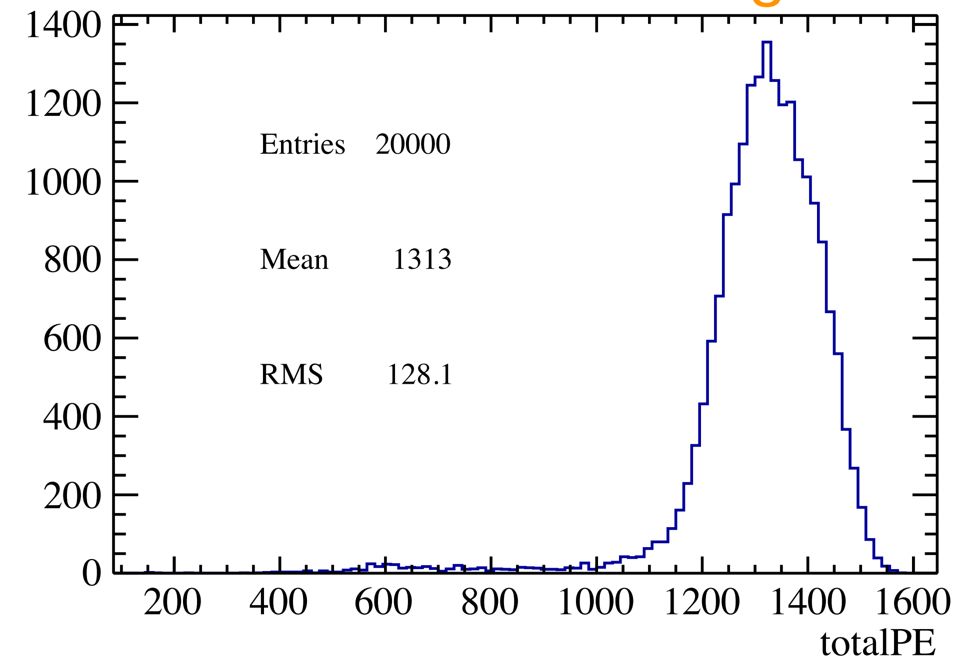


When connecting bars and the chimney are considered

$$\sigma = \frac{\sigma_{E_{\rm rec}}}{\overline{E}_{\rm rec}} = (2.99 \pm 0.02)\%$$

Total PE: $N = 1313$

Simulation w/ connecting bars



- Connecting bars worsen the resolution by 3.8%;
- On one hand, connecting bars have shadow effects on PMTs which cause the decrease of total PE by 2.6%;
- On the other hand, connecting bars affect the performance of the energy reconstruction because they break the spherical symmetry of the detector.

Requirements to calibration

- Calibration source: take Co60 as an example.
- Calibration positions (x-coordinate):
    - From 0 m to 16 m per 1 m;
    - From 16.2 m to 17 m per 0.2 m;
    - From 17.1 m to 17.7 m per 0.1 m;
    - Totally 29 positions.
- Statistics: 50000 events for each position to reduce statistical uncertainty. For 100Hz emission frequency of Co60, 8.3 minutes are necessary to finish one calibration point and 4 hours are needed to finish the whole calibration procedure.

Status in SNiPER

- Already implemented in SNiPER named as OMILREC ($OMILRECROOT);

```
BundleRecByChargeTool  Deconvolution     MuonWaveRec  PoolMuonRecTool  RecCdMuonAlg   RecTimeLikeAlg  SpmtMuonRecTool  TTTracking     WPChargeClusterRec
CMakeLists.txt         IntegralPmtRec    OMILREC      PushAndPull      RecRelease     RecWpMuonAlg    TemplateFitAlg   VertexFitAlg
ConeMuonRecTool        LsqMuonRecTool    PmtRec       QCtrRecAlg       RecSampleAlg   SmartRec        TTCalib          WaveFitAlg
```

- Response functions need to be updated for a new version of offline;

- Usage:

```
python tut_calib2rec.py --input ../elec2calib/e+_P0MeV_elec2calib.root --output e+_P0MeV_rec.root --user-output e+_P0MeV_rec_user.root --gdml --gdml-file ../detsim/sample_detsim.root --elec yes --method energy-point
```

Occupancy-based Ene. Rec.

- Motivation
  - OMILREC is based on that accurate nPE can be obtained once a PMT is fired;
  - What we actually got in a real experiment is the pulse of each fired PMT;
  - More or less, there will always be an efficiency from pulse to reconstruct nPE, which means that the input of OMILREC is biased and the output of the algorithm would be correspondingly biased.
  - Occupancy-based energy reconstruction doesn't rely on the accurate nPE information, which may be a better way in case nPE info. is lost.
- Methodology
  - The calibration process is the same as OMILREC;
  - The likelihood function is constructed based on the occupancy of one PMT, instead of the nPE of one PMT:

    1. if $(c_i = 0), P(c_i|r_s, E) = e^{-\mu_0^i}$

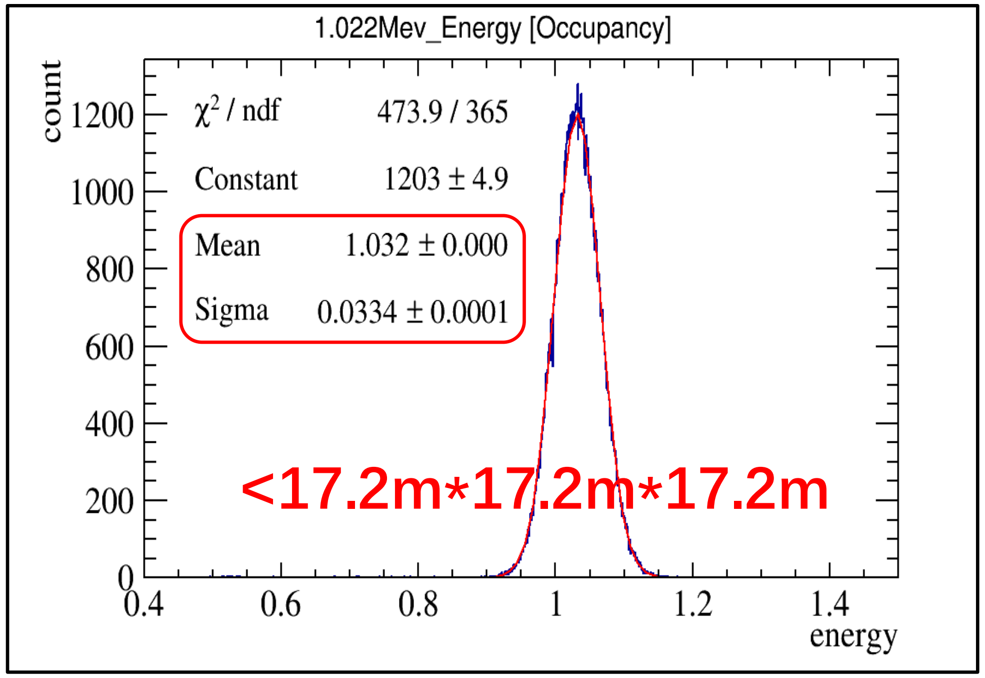
    2. if $(c_i = 1), P(c_i|r_s, E) = 1 - e^{-\mu_0^i}$

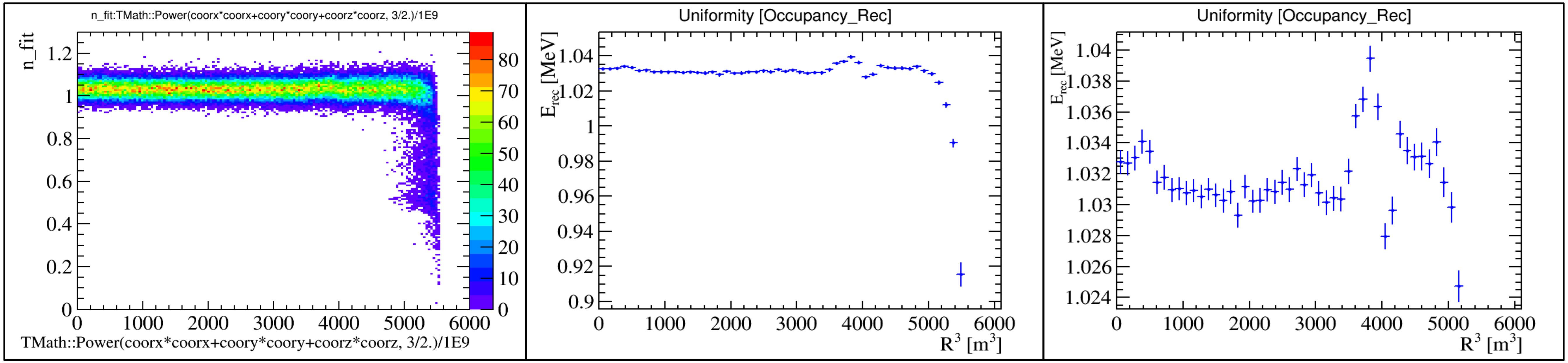
    3. $\mathcal{L}(c_1, c_2, \cdots, c_m|r_s, E) = \prod_{i=1}^{m} P(c_i|r_s, E)$

Resolution and uniformity

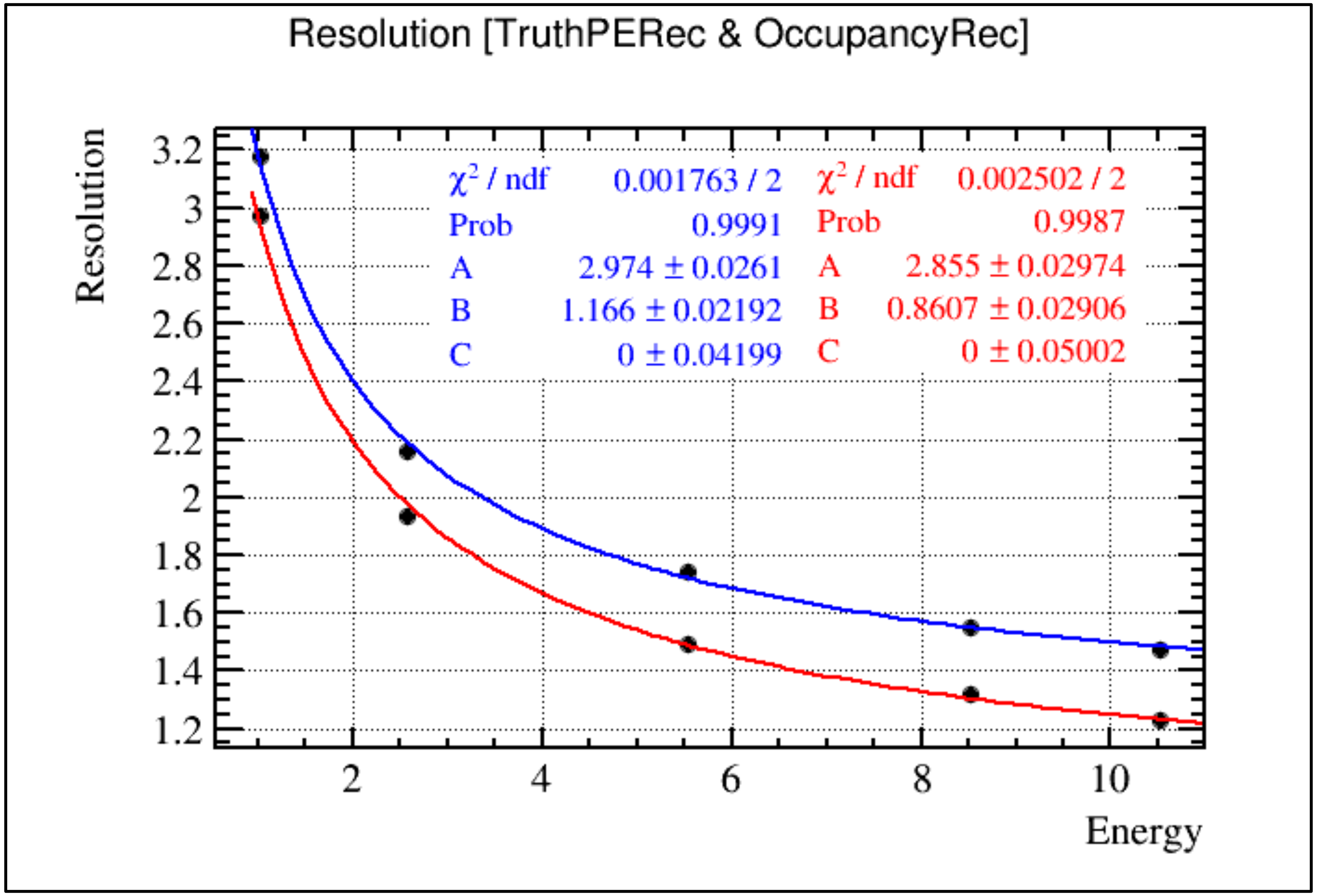
- Resolution≈3.24%
- Non-Uniformity < 1%

- Compared to TruthPE-based reconstruction, energy resolution decreased 0.2%.
- There is no significant change in Uniformity.





Resolution at different energies

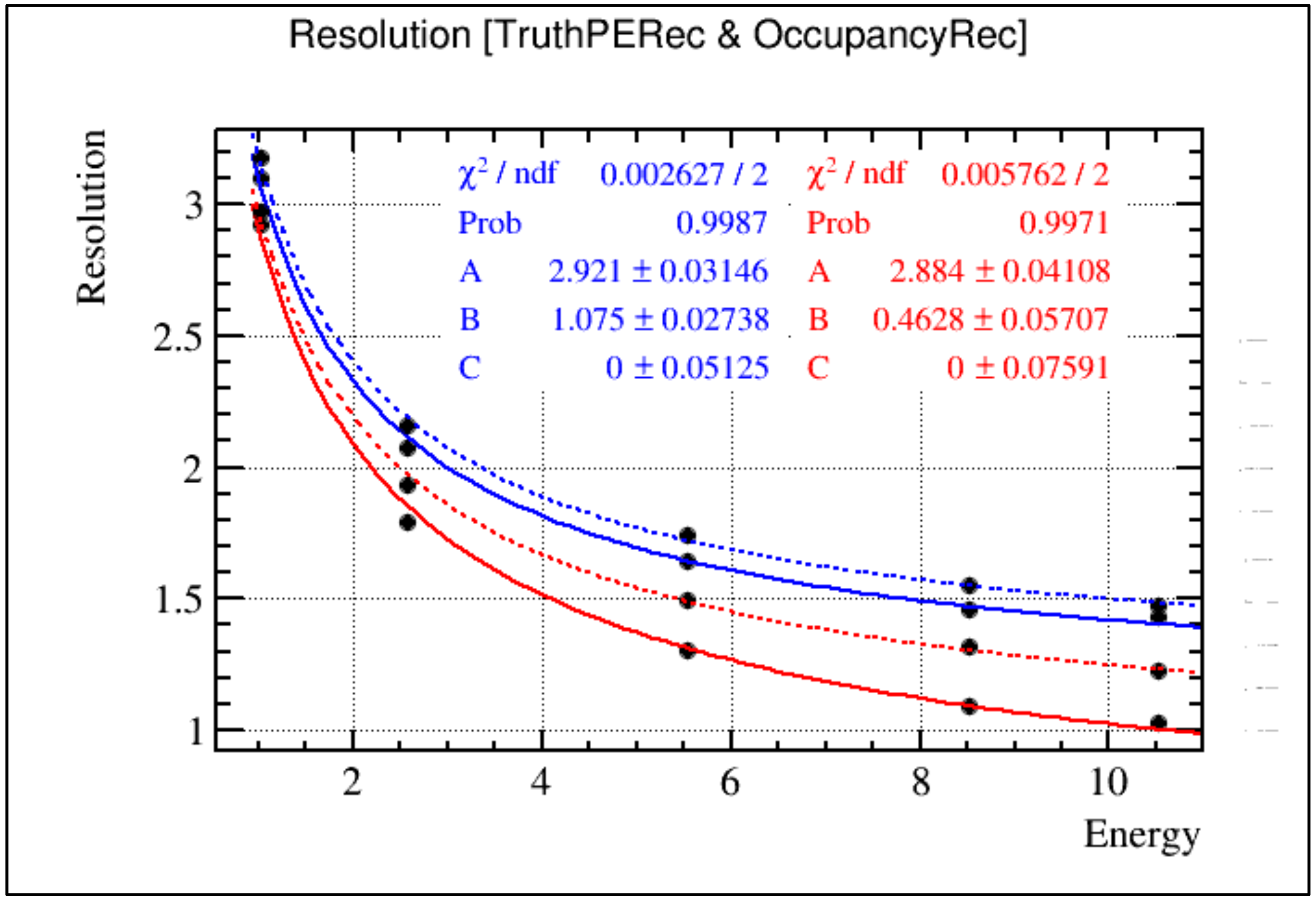


Effective resolution: 3.17%
TruthPE-based

Effective resolution: 3.51%
Occupancy-based

Geometrical effect from connection bars

- W/O connecting bars, the energy resolution is better;
- Connecting bars have visible effects on the TruthPE-based Reconstruction;
- Connecting bars have significant effects on Constant-term;
- It is worth to try correct the shielding effect caused by connecting bars when constructing the response functions.



solid line: W/O Acrylic nodes
dash line: W/ Acrylic nodes

Occupancy-based
TruthPE-based

Summary and prospects

- Conclusions
  - Approximately uniform arrangement of PMTs and connecting bars along X-axis lead to better reconstruction results than discrete arrangement along Z-axis. The axis and number of points used to deploy calibration source need to be optimized;
  - Connecting bars have two kinds of side effects, the shadow effect and the symmetry breaking. They can worsen the resolution for both OMILREC and occupancy-based reconstruction;
  - Two reconstruction methods have similar performance in the uniformity. Occupancy-based reconstruction has a 0.2% drop in the resolution for the ideal case.

- Next to do
  - The correction of connecting bars will be implemented in the construction of response functions;
  - Electronic simulation will be added to compare the performance of two reconstruction methods in this case.


Thanks for your attention