Calibration strategy and MH sensitivity

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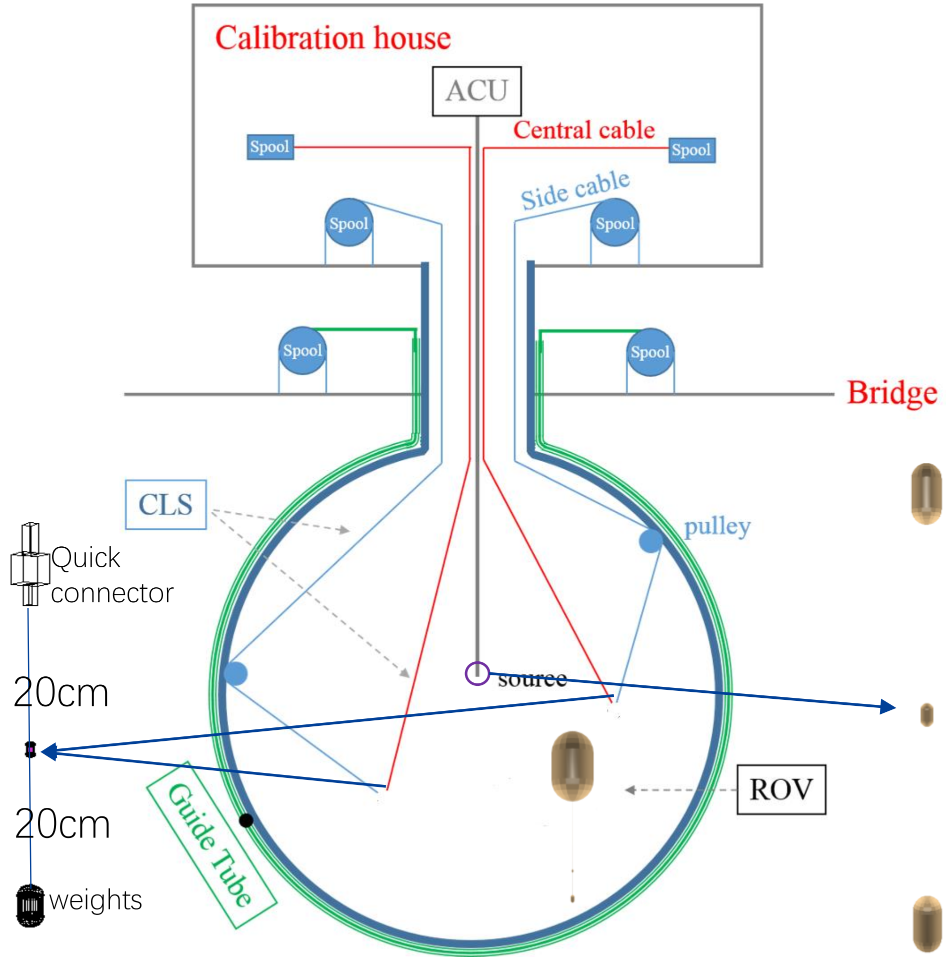
Outline

- Calibration strategy
  - Calibration status in sniper
  - Non-linearity correction
  - Non-uniformity correction
- MH sensitivity
  - Prediction of IBD spectrum
  - Observation of IBD spectrum in sniper
  - χ^2 fit and MH sensitivity
- Summary

Calibration device in sniper

- Calibration system:
  - 1-D: Automatic Calibration Unit (ACU)
  - 2-D: Cable Loop System (CLS)
  - 3-D: Remotely Operated Vehicle (ROV)
  - Outer surface: Guide Tube (GT)

- Geometry in sniper:
  - GT geometry is written into sniper as default option.
  - ROV, source enclosure, quick connector and weights are written into sniper as alternative option.
  - All these geometries can be enable or disable if necessary during simulation,



Radioactive source generator in sniper

Calibration sources

- γ: ^{68}Ge, ^{137}Cs, ^{54}Mn, ^{60}Co, ^{40}K
- e^+: ^{68}Ge, ^{22}Na
- n: ^{241}Am-Be, ^{241}Am-C or Pu-C

Usage

Use standard script "tut_detsim.py" by Lin Tao.

```
$ python tut_detsim.py --source_weight_QC  \          # enable source enclosure and quick  connector
--OffsetInX 1000 --OffsetInY 1000 --OffsetInZ 1000 \ # move source center at (1m,1m,1m)
gendecay --nuclear K40 --volume pSource              # Use 40K (you can also use 68Ge, 137Cs..)
or
hepevt --exe AmC --volume  pSource                   # Use AmC (you can also AmBe or PuC)
```

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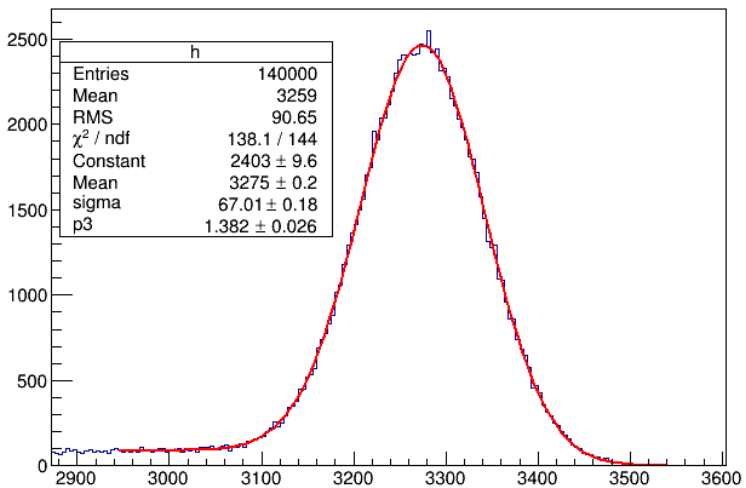
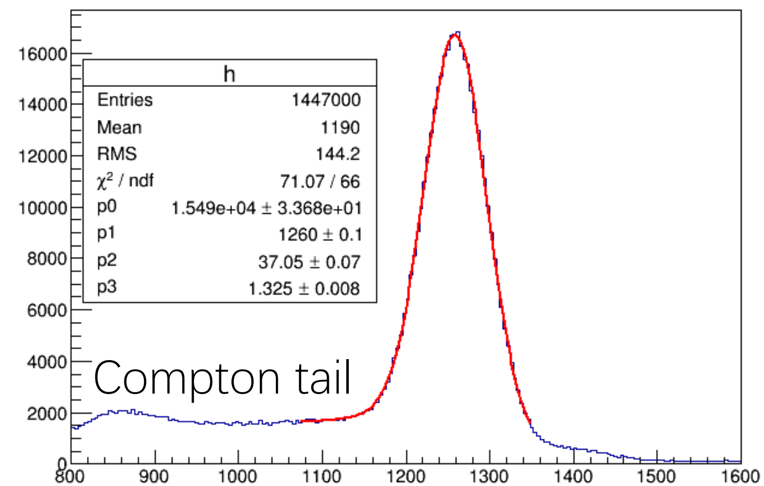
Energy scale

^{60}Co at CD center with source enclosure



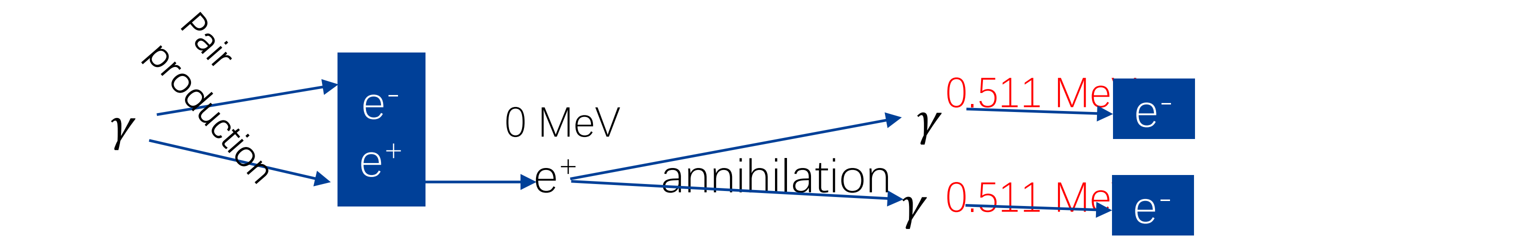
^{68}Ge at CD center with source enclosure



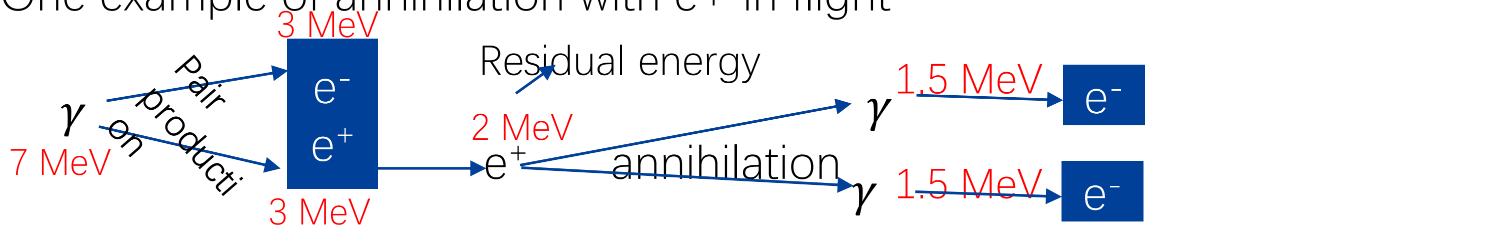
- Full absorption peak as measure.
- ^{60}Co as energy scale: $\frac{3275\ PE}{2.5057\ MeV}$=1307 PE/MeV
- Reconstructed energy for ^{68}Ge: $E_{rec} = \frac{1260\ PE}{1307\ PE/MeV}$ =0.964 MeV
- Non-linearity: $\frac{E_{rec}}{E_{true}} = \frac{0.964MeV}{1.022MeV} = 0.943$
- Reconstruct energy for ^{54}Mn, ^{137}Cs, ^{40}K, n-H, n-C, Am-C with same energy scale.

Gamma to e-/e+ converting

- Gamma convert to e-/e+:
  - Pair production
  - Compton scattering
  - Photoelectric
- Gamma energy non-linearity can be deduced from non-linearity of primary e-/e+
- The electron from annihilation gamma should also be considered.



One example of annihilation with e+ in flight



residual energy should be subtract.

Model of gamma energy non-linearity

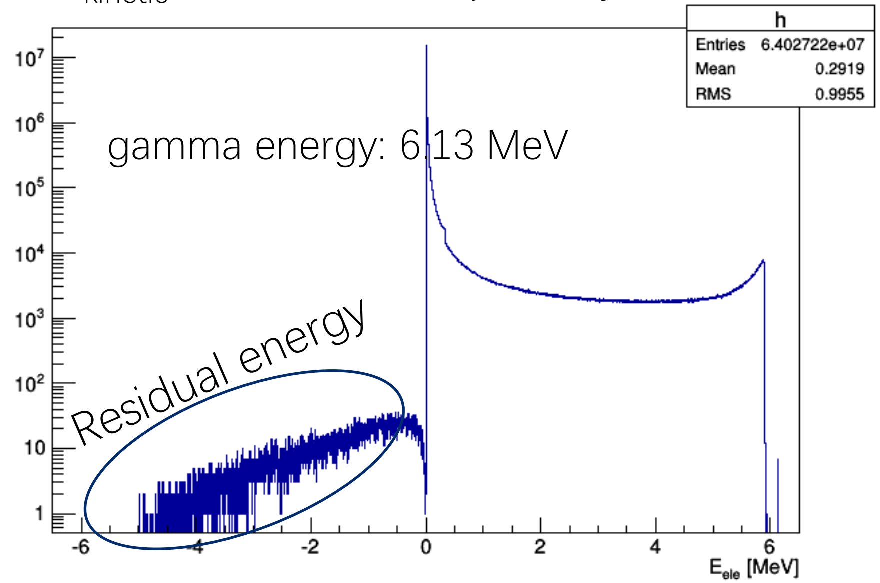
Empirical formula to describe electron non-linearity:

$$f_{nonl}(\mathrm{E}) = \frac{E_{rec}}{E_{true}} = \frac{p_0 + p_1 \cdot E + \frac{p_2}{E}}{1 + p_3 \cdot e^{-p_4 \cdot E}}$$

Construct model of gamma energy non-linearity with PDF and electron non-linearity:

$$\frac{E_{rec}}{E_{true}} = \frac{\sum E_i f(E_i) \frac{p_0 + p_1 \cdot |E_i| + \frac{p_2}{|E_i|}}{1 + p_3 \cdot e^{-p_4 \cdot |E_i|}}}{\sum E_i f(E_i)}$$

$E_{kinetic}$ distribution of primary e-/e+



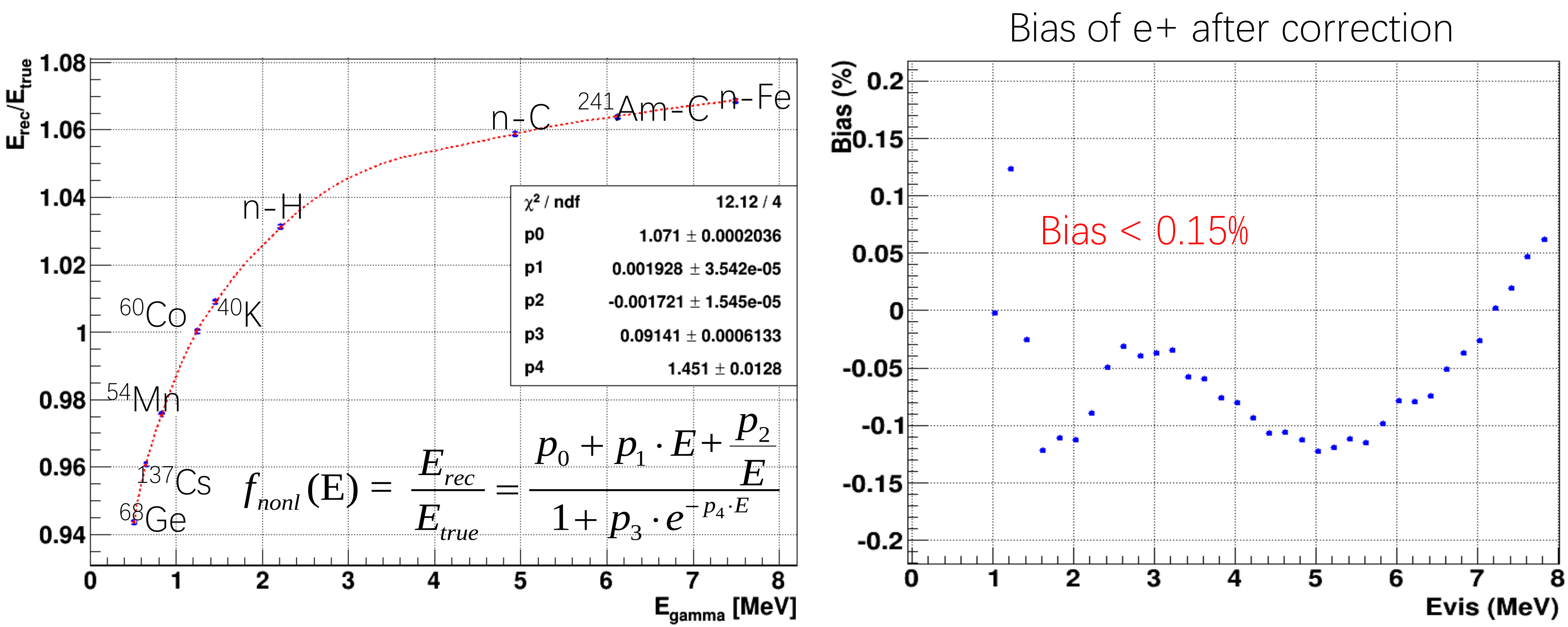
$$\sum E_i f(E_i) = 6.128 \pm 0.003 \text{ MeV}$$

Energy bias to gamma = 0.03%

Ref:

- Liangjian Wen, et al., Ref: Daya Bay DocDB 8240-v2
- Fengpeng An, et al (Daya Bay Collaboration): PRL 112, 061801(2014)

Bias of energy non-linearity correction



- Fit non-linearity of gamma to extract parameters.
- Calculate bias between true and reconstructed energy of e+ from 1 to 8 MeV based on fit result.

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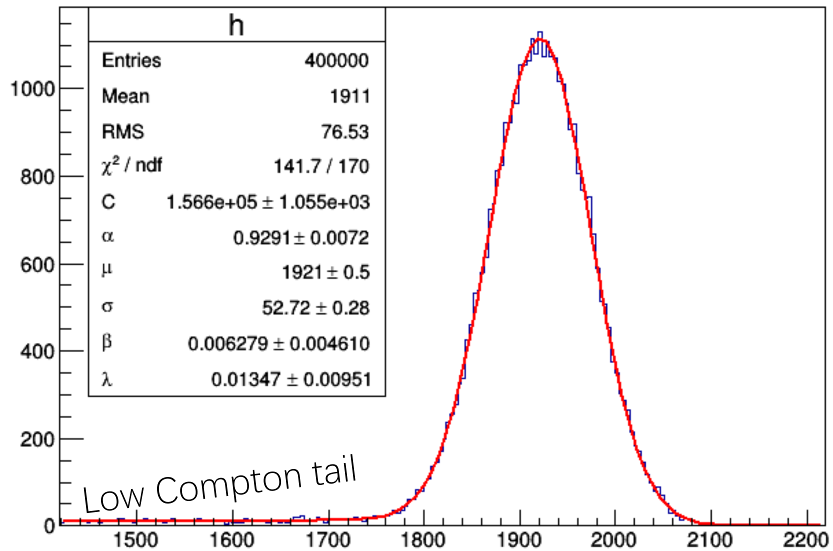
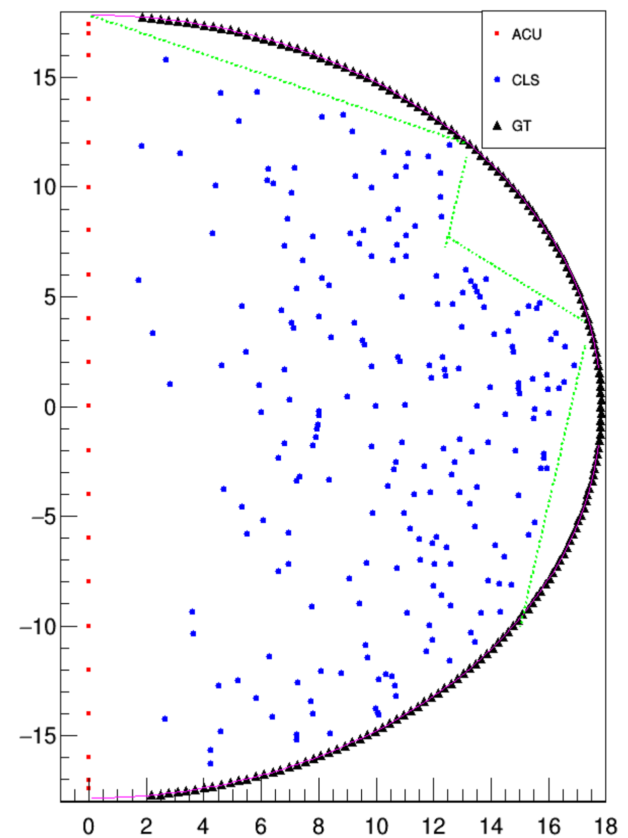
Calibration sources

^{40}K with source enclosure

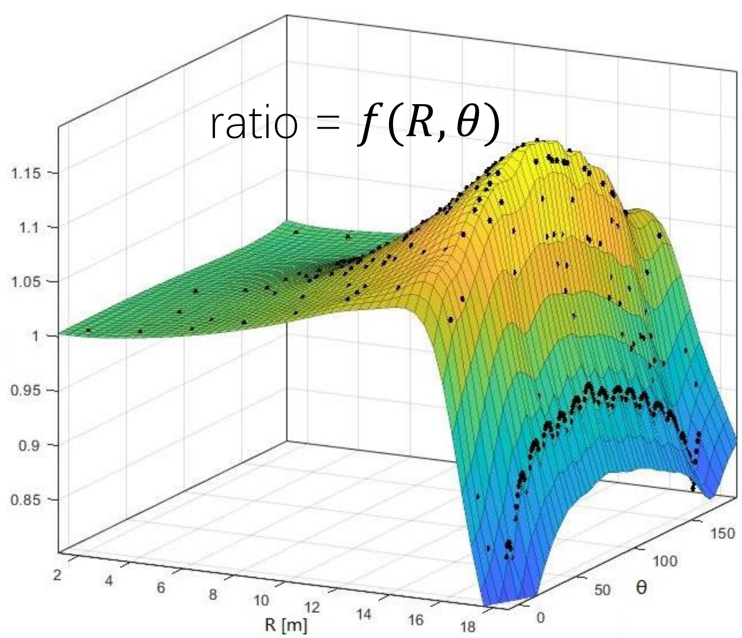


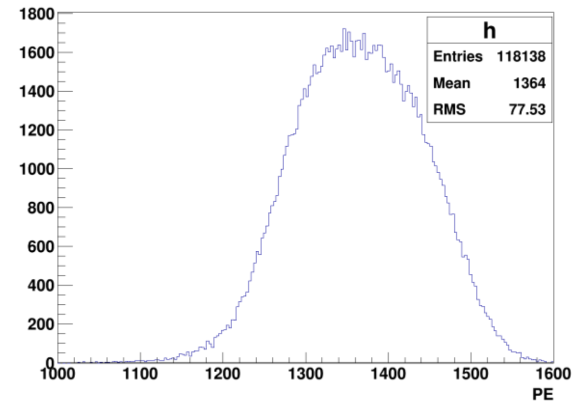
Calibration points



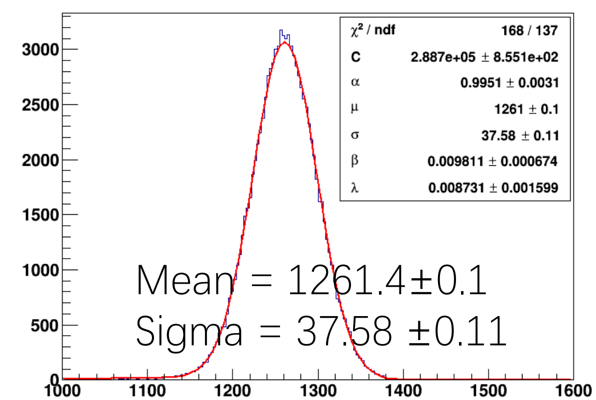
- The calibration mapping is constructed by
  - ACU(21), CLS(219), and GT(168)
- ^{40}K with source enclosure
- ~40000 events for one calibration point.
- For GT calibration:
  - Source is outer of CD surface.
  - Used as points in inner CD.

Correction mapping





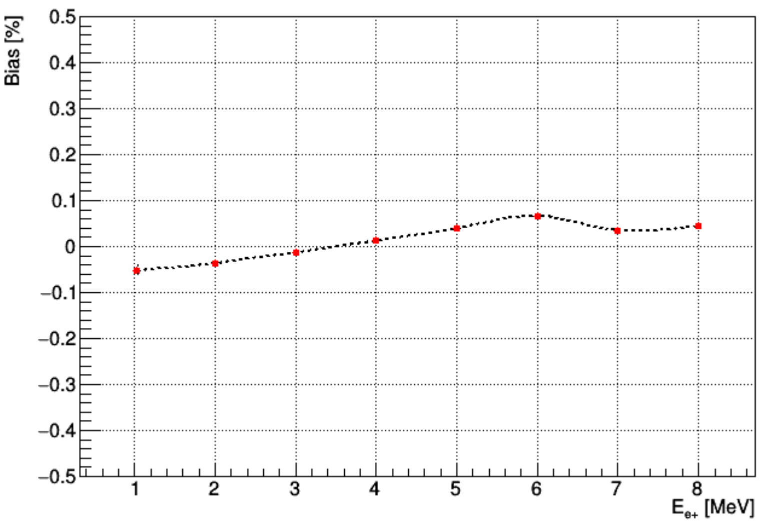
Corrected with $f(R,\theta)$



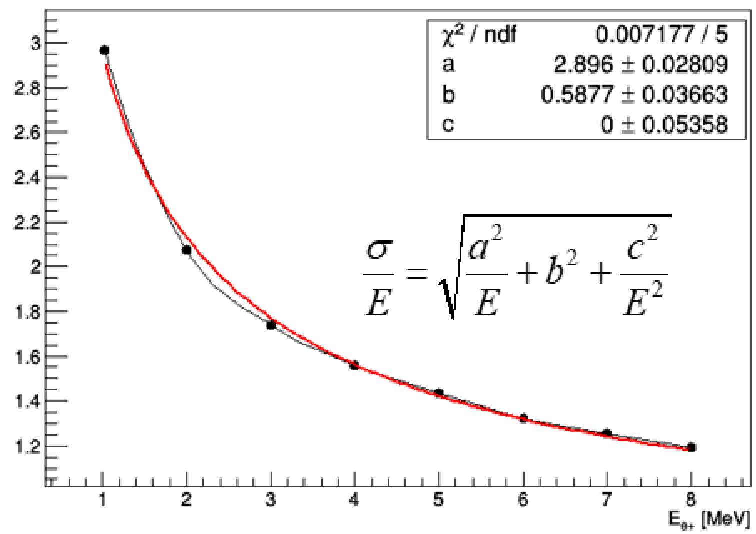
- Spline function to describe the correction mapping
- The resolution is sigma/mean = 2.98%
- Mean PE of 1 MeV e+ at CD center is 1262
- Mean bias is 0.05 % with visible energy 1 MeV of e+.

Bias and energy resolution

Mean bias after correction

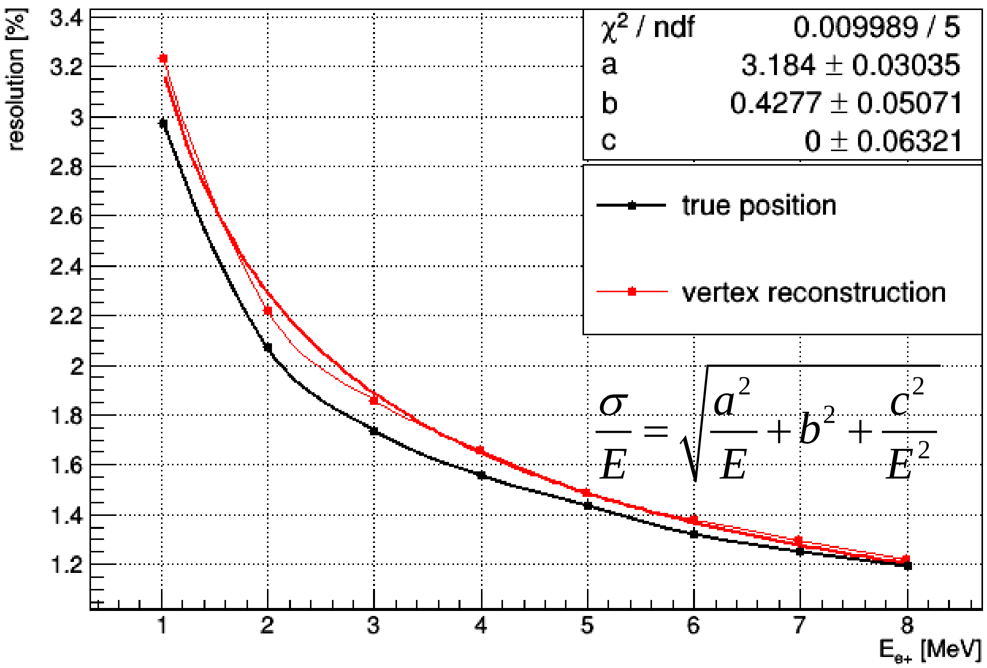


Energy resolution after correction



- Mono energy e+ (1-8 MeV) uniformly distribution in CD.
- Corrected it with non-uniformity correction mapping.
- Use true position of event in MC simulation.
- The overall bias is less than 0.1% from 1 to 8 MeV for e+.
- Energy resolution: $\sqrt{a^2 + (1.6b)^2} = 3.04\%$
  $(requirement\ in\ Yellow\ book: < 3\%)$

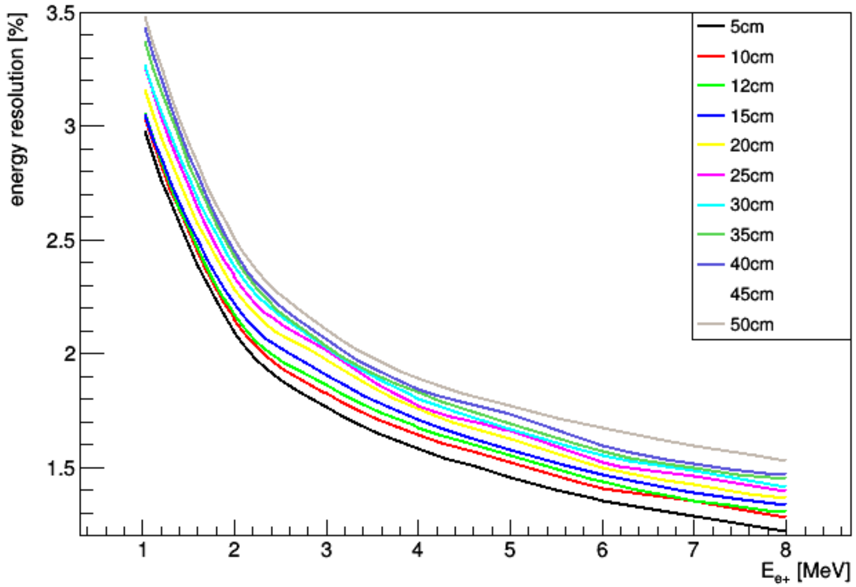
Combined with Vertex reconstruction



- *Energy resolution:*
  - *3.25% @ 1MeV*
  - $\sqrt{a^2 + (1.6b)^2} = 3.26\%.$
- We need better vertex reconstruction

Assumption of vertex reconstruction

Energy resolution



Resolution (cm)	a (%)	b(%)	$\sqrt{a^2 + (1.6b)^2}$
5	2.89	0.65	3.07
10	2.94	0.74	3.17
12	2.95	0.78	3.20
15	2.95	0.84	3.24
20	3.07	0.83	3.34
25	3.16	0.82	3.43
30	3.18	0.86	3.46
35	3.27	0.83	3.53
40	3.32	0.84	3.58
45	3.36	0.87	3.64
50	3.35	0.94	3.67

- Assume resolution of vertex reconstruction: 5,10,12,15,20,25,30,35,40,45,50 cm
- Non-uniformity correction with the assumption, and calculate corresponding resolution.
- Fit with $\sqrt{a^2/E + b^2}$ to get parameter a and b.
- Energy resolution is sensitive to vertex reconstruction.

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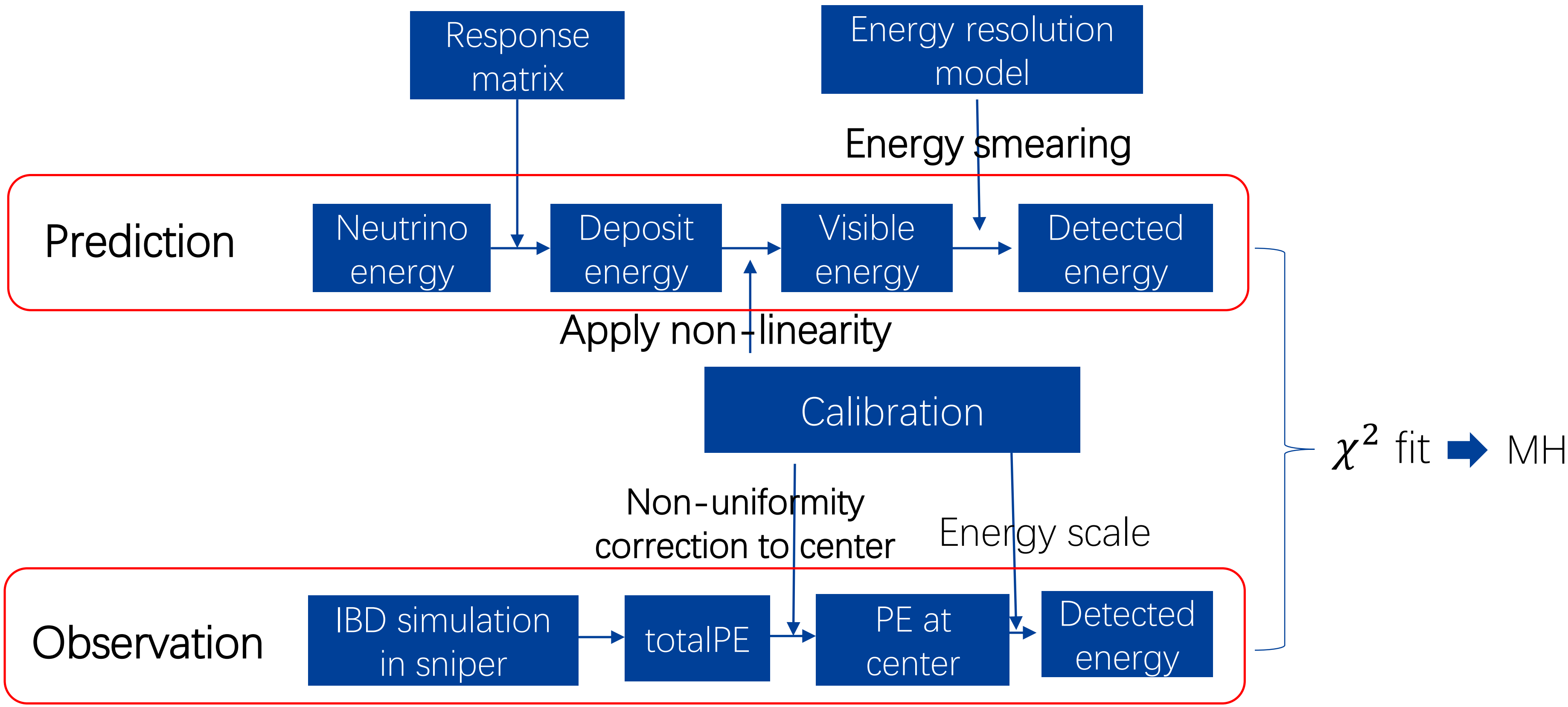
Procedure of study



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Probability of neutrino

Oscillation probability

Parameter	best-fit	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.97
$\|\Delta m^2\|$ [10^{-3} eV ^{2}]	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248

$$P_{osc}(E,\Delta m^2) = 1 - \sin^2 2\theta_{13}\cos^2\theta_{12}\sin^2\frac{1.267\Delta m^2_{31}L}{E} - \sin^2 2\theta_{13}\sin^2\theta_{12}\sin^2\frac{1.267\Delta m^2_{32}L}{E} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{1.267\Delta m^2_{21}L}{E}$$

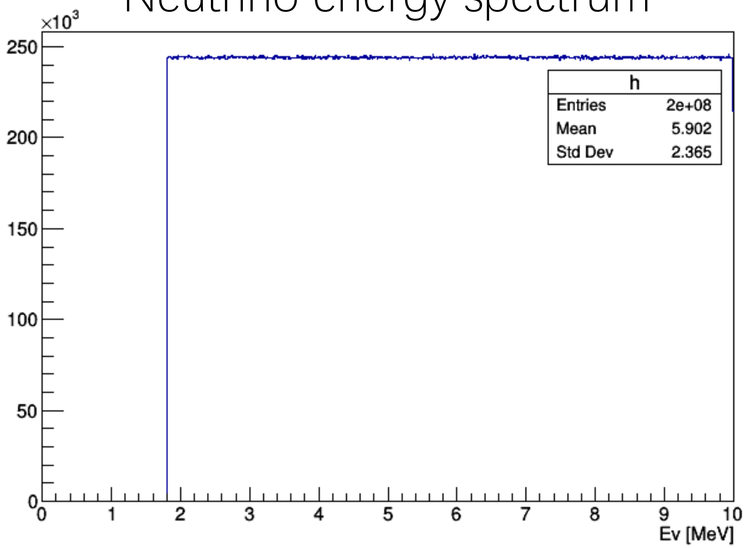
$$L = 52.5Km$$

$$P(E_\nu) = Flux(E_\nu)\cdot\sigma(E_\nu)\cdot P_{osc}(E_\nu)$$

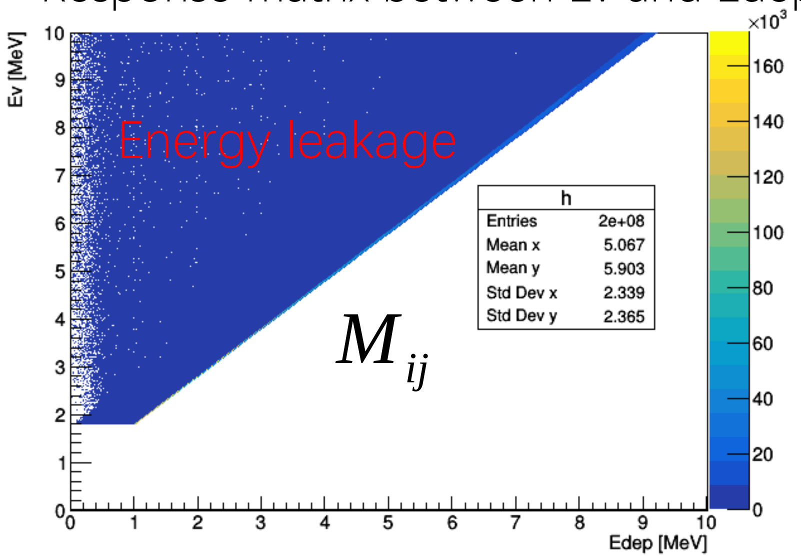
Cross section

Neutrino energy to deposit Energy

Neutrino energy spectrum



Response matrix between Ev and Edep

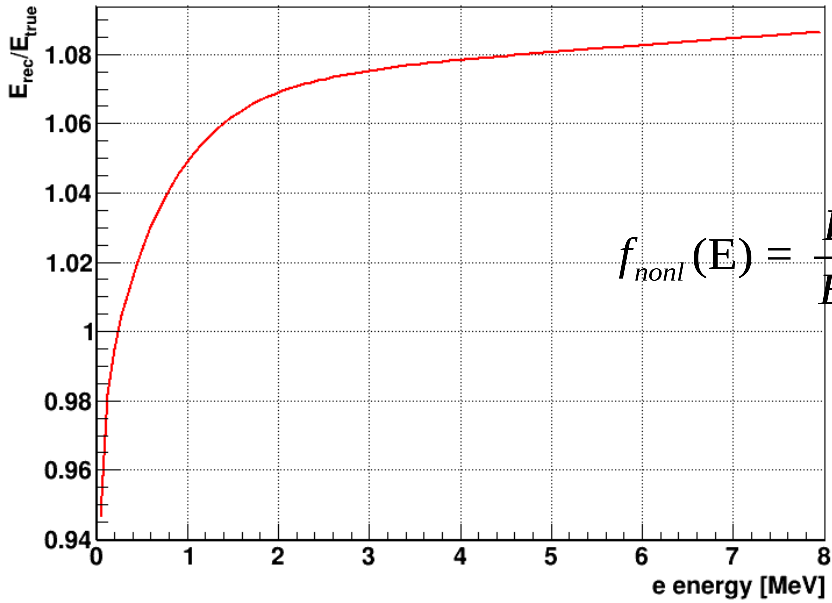


- Neutrino events uniformly distribute in CD.
- Get the corresponding deposit energy for every event.
- Construct response matrix between neutrino energy and deposit energy.
- Bins of matrix are 4000×4000.

$$P(E^{i}_{dep}) = \sum_{j=0}^{4000} M_{ij} \cdot P(E_{\nu}^{\ j})$$

Deposit energy to visible energy

Energy non-linearity obtained from calibration.



$$f_{nonl}(E) = \frac{E_{rec}}{E_{true}} = \frac{p_0 + p_1 \cdot E + \frac{p_2}{E}}{1 + p_3 \cdot e^{-p_4 \cdot E}}$$

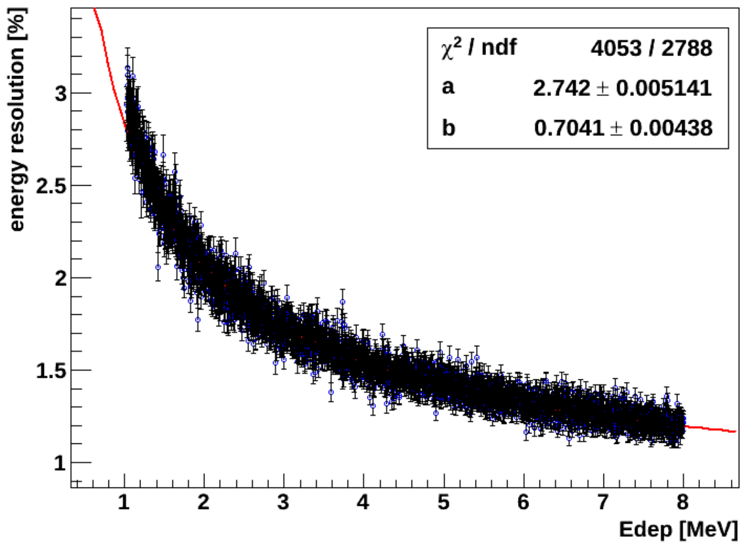
Non-linearity exists between deposit energy and Visible energy.

$$E_{vis} = f_{NL}(E_{dep})E_{dep}$$

$$P(E_{vis}) = \frac{\partial E_{dep}}{\partial E_{vis}} P(E_{dep})$$

Visible energy to detected energy

- Construction of energy resolution model:
  - e+ uniformly distribute in CD, with continuous energy from 1 to 8 MeV.
  - Non-uniformity correction.
  - Energy resolution as function of deposit energy.
  - Fit it with $\sqrt{a^2 / E + b^2}$ to get "a" and "b"
- "a" and "b" will be used to construct energy resolution model.



$$\sigma / E = \sqrt{a^2 / E + b^2}$$

$$P(E_{\det}) = \int_0^{60MeV} P(E_{vis}) dE_{vis} \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(E_{vis} - E_{\det})^2}{2\sigma^2}\right)$$

This method can only be used simulation.
Should try to obtain model of energy resolution from calibration in real experiment.

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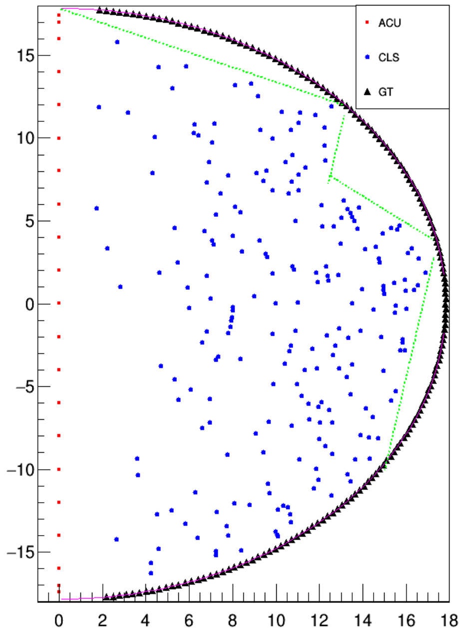
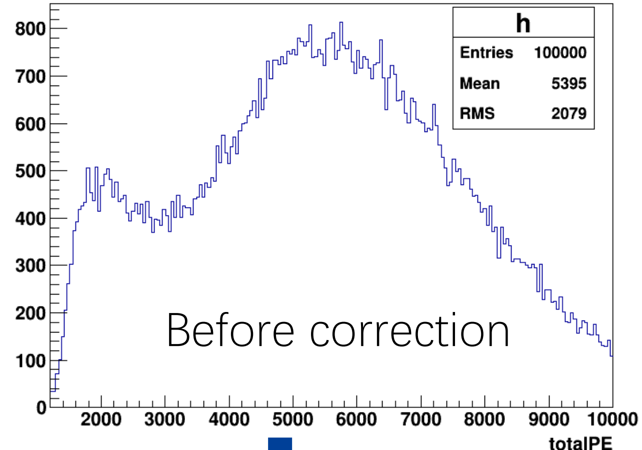
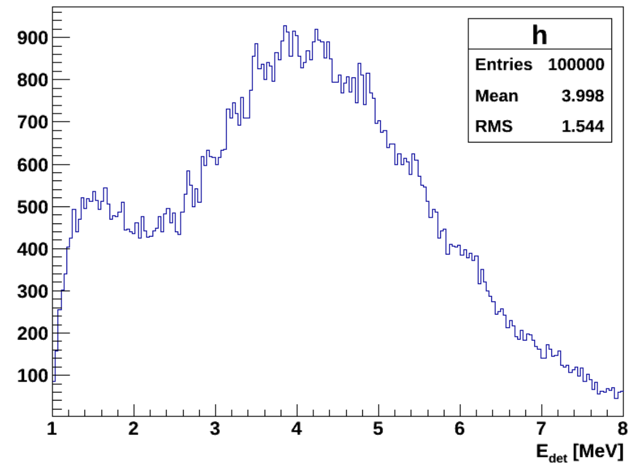
Observation of IBD spectrum

Correction mapping





PE / energy scale



- Simulation: IBD events uniformly distribute in CD.
- 100,000 events (~6 years data)for one experiment.
- Correct them with correction mapping
- Energy scale: 1307 PE/MeV (^{60}Co)

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Definition of χ^2 and $\Delta\chi^2$

χ^2 is constructed to qualify the consistent of data and prediction:

$$\chi^2 = \chi^2_{stat} + \chi^2_{penalty} = \sum \frac{(M_i - T_i)^2}{M_i} + \frac{(\Delta m^2 - \Delta m^2{}_{pdg})^2}{\sigma_{pdg}{}^2}$$

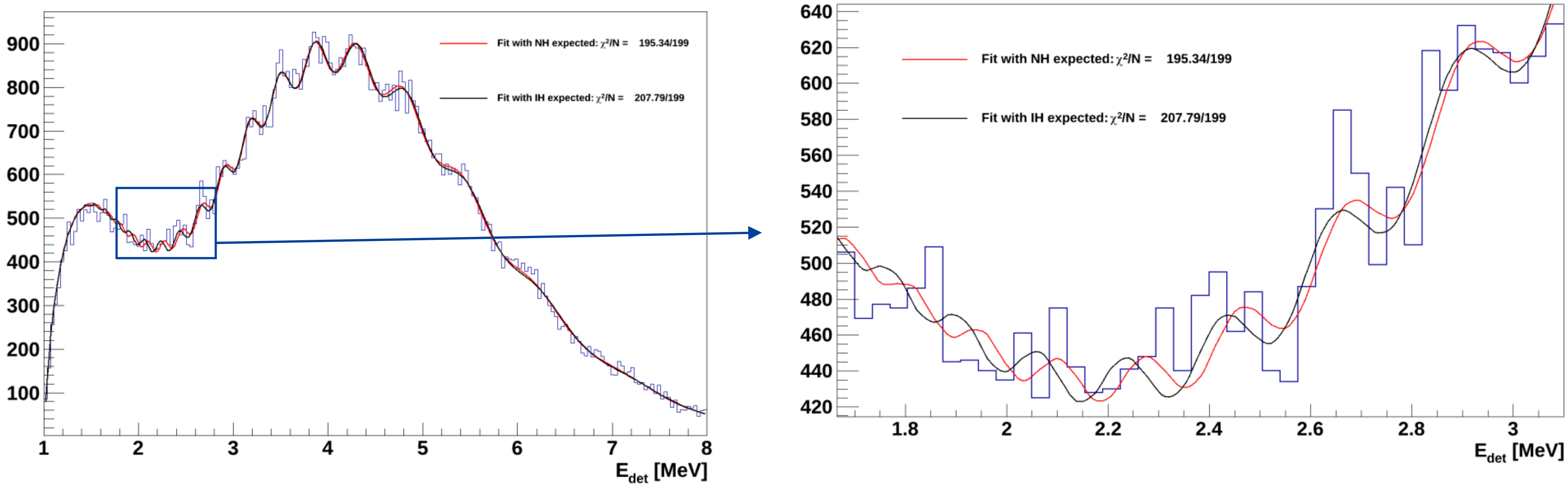
Fit the IBD detected energy spectrum with normal hierarchy(NH) or inverted hierarchy(IH) predicted.

MH discriminator is defined as:

$$\Delta\chi^2 = \chi^2(NH) - \chi^2(IH)$$

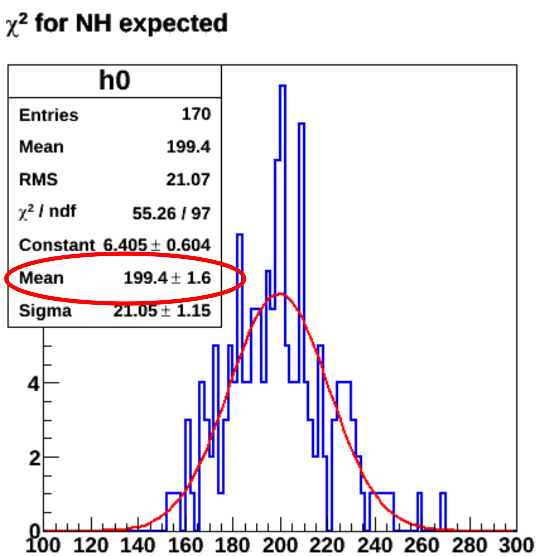
Fit the IBD detected energy spectrum

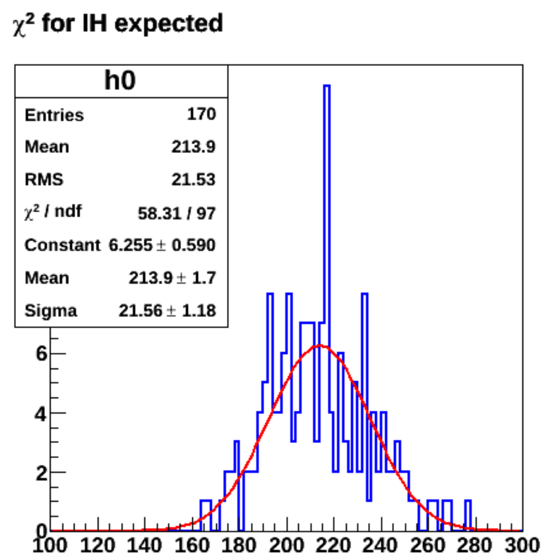
NH is true

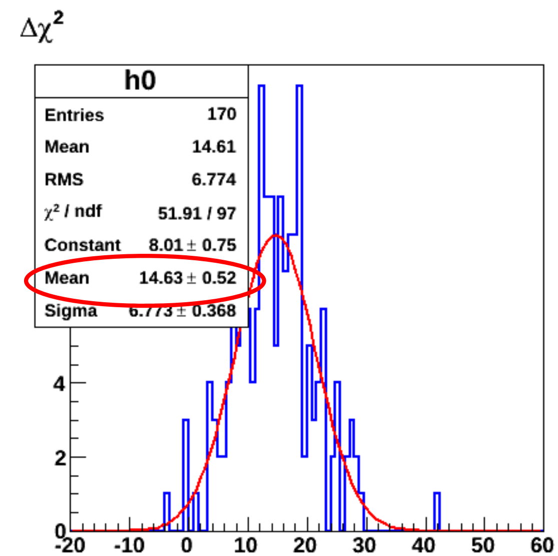


- Fit the IBD spectrum with prediction.
- Number of bins is 200. So NDF = 200 -1 = 199.
- χ^2 for NH expected: 195 and χ^2 for IH expected: 208.
- $\Delta\chi^2$ is 13.
- There is only one experiment (100,000 events for ~6 years data)
- Simulate multiple times of experiment, and get the distribution of $\boldsymbol{\chi^2}$ and $\Delta\chi^2$.

χ^2 and $\Delta\chi^2$ distribution







- *Simulate times of experiment: 170.*
- χ^2 *is 199.4 with right MH predicted , which seems good since the NDF is 199.*
- And $\Delta\chi^2$=14.63
- MH sensitivity is $\sqrt{\Delta\chi^2}\sigma$=3.82$\sigma$ refer to standard sensitivity definition in Yellow book.

Summary

- With Daya bay's model of energy non-linearity, it's promising to make the bias less than 0.2%.
- Combining ACU, CLS and GT, we can construct a correction mapping of non-uniformity. But this correction rely on vertex reconstruction, and we need better vertex reconstruction.
- Considering non-linearity and non-uniformity correction, the MH sensitivity can reach to 3~4 σ.
- But We need energy resolution model from calibration for prediction of IBD energy spectrum. That's what we will consider for next step.

Thank you！