mPMT modules for the Hyper-Kamiokande detector

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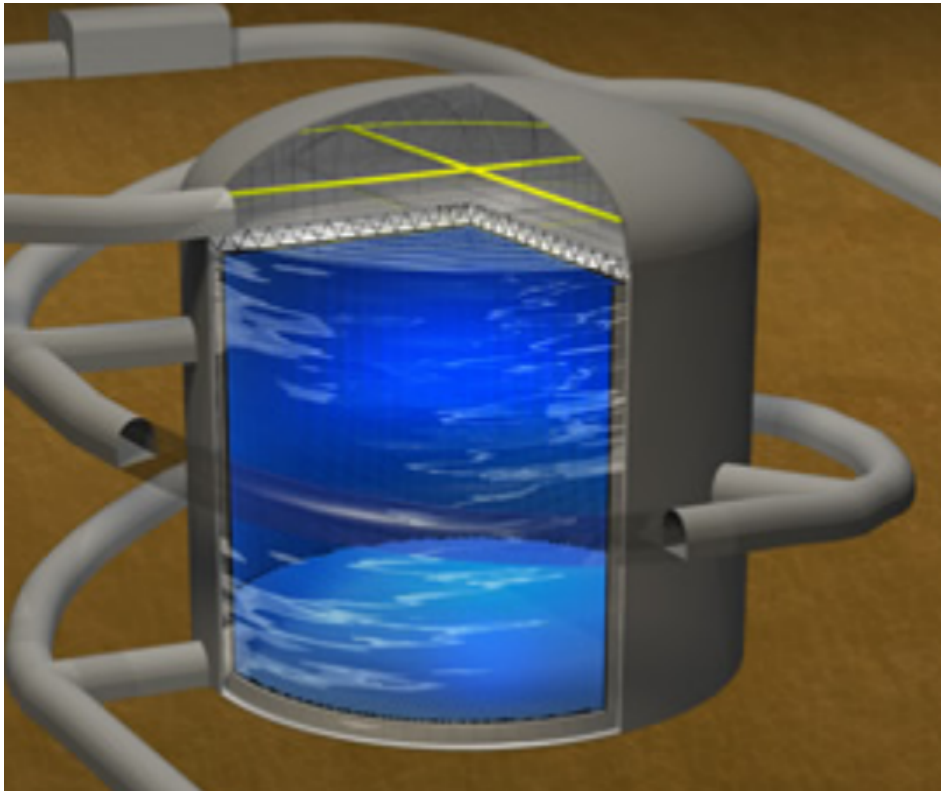
I. The Hyper-Kamiokande detector
II. mPMT simulation in Hyper-Kamiokande
III. Low energy results
IV. High energy first results

NEPTUNE conference, Napoli, 2018/08/20

Reminder : The Hyper-Kamiokande experiment

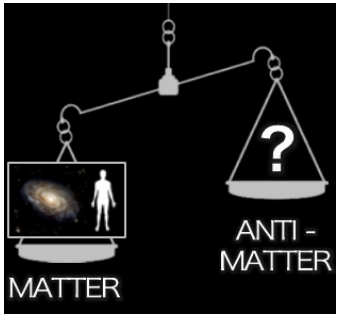


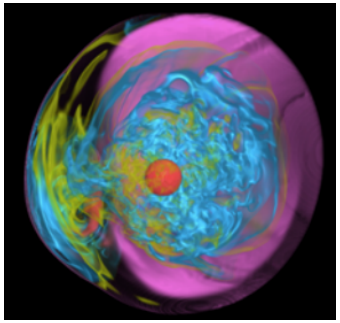
- Tank : 60 m tall x 74 m diameter
- 260 kton of ultrapure water
  → FV mass = 186 kton ~ 10 x SK
- Photo-coverage 40 %
  → 40,000 new 20" PMTs
- Rich & vast physics program :

Neutrino oscillation (High energy) :
Is CP-violated for leptons ? ν mass ordering ? etc.

Solar & astrophysics neutrino (Low energy):
MSW effect in the Sun. \
Observe ν from SN burst, relic ν from SN etc.

Proton-decay : direct verification for GUT.





How mPMTs can impact Hyper-Kamiokande physics

- 1st physics studies uses exclusively on 20" PMTs
- Can mPMTs modules (19 x 3" PMTs) improve performances synergetically w/ 20" ?
- <u>Smaller size :</u>
  Better reconstruction near wall → Increase FV.
  Better reconstruction of multi-ring events → background reduction.
- <u>Better timing resolution:</u> better vertex resolution → enhanced momentum resolution.
- @200Hz (so-far, negative HV) : S/N ratio ~ 20"
- @100Hz (if positive HV) : S/N ~ 2 x 20"
  → Can probe lower energies ?
- To find out : need a simulation first

Development of the HK simulation with mPMTs

- Final goal: Hybrid configuration of Hyper-K with e.g :
  - 20 % coverage of 20” PMTs.
  - 5 % coverage of mPMTs.

  → Proportions not fixed : depend on cost & capabilities of mPMTs.

- Intermediary goal : determine capabilities of standalone mPMTs

  → Hyper-K with 40 % coverage of mPMTs : compare with 20”.

- Simulation based on WCSim : used for E61, Hyper-K.

- We will compare the two configurations then try to reproduce basic :

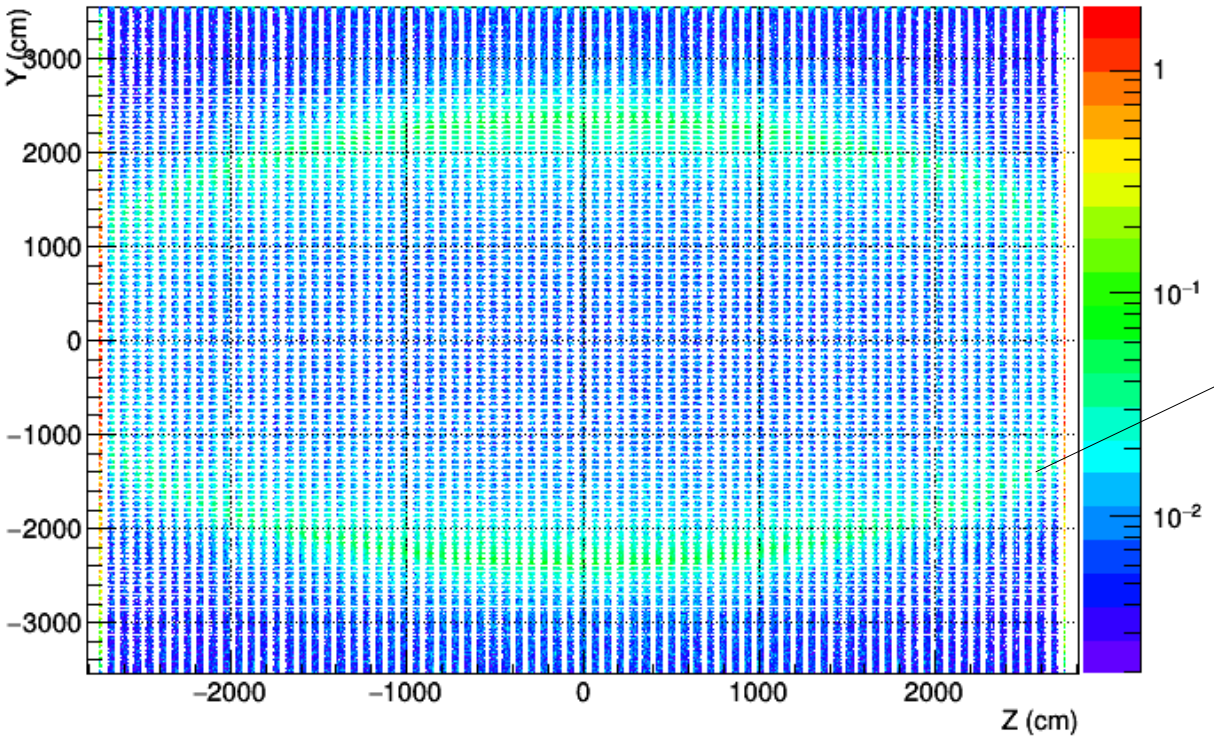
  a. Event display.

  b. Charge distribution.

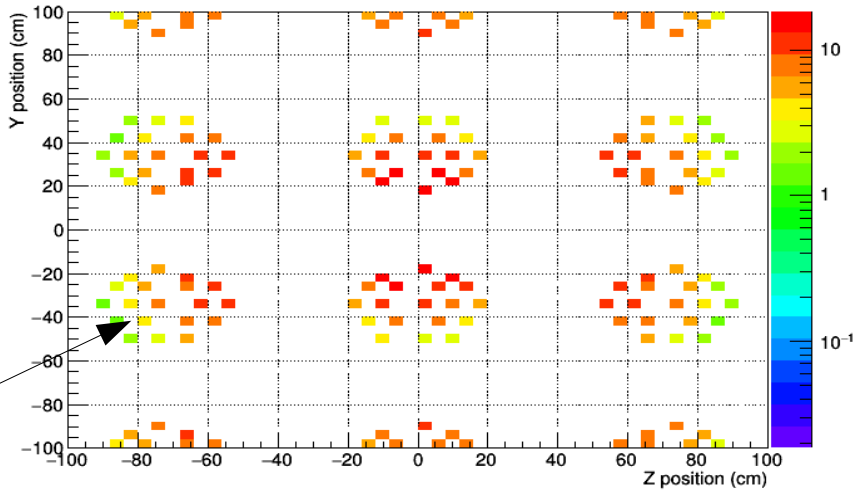
  c. Time distribution.

Event display of mPMT simulation

e- generated at the tank center



Zoom-in

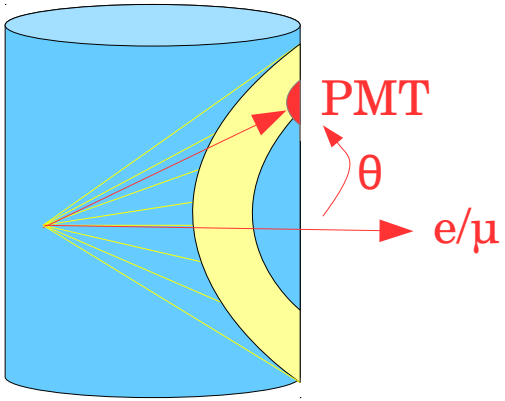


- mPMT implementation succesfully done !

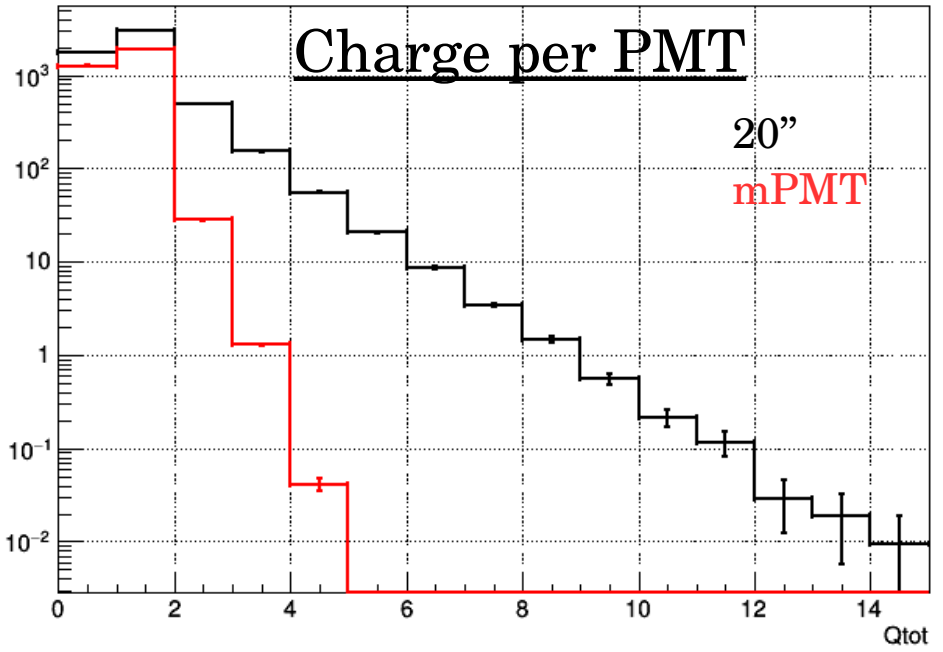
- Represents 760,000 3” PMTs.
- Same spacing between mPMTs as 20” PMT (~80 cm).
- From here, events are generated w/ uniform position&direction in tank

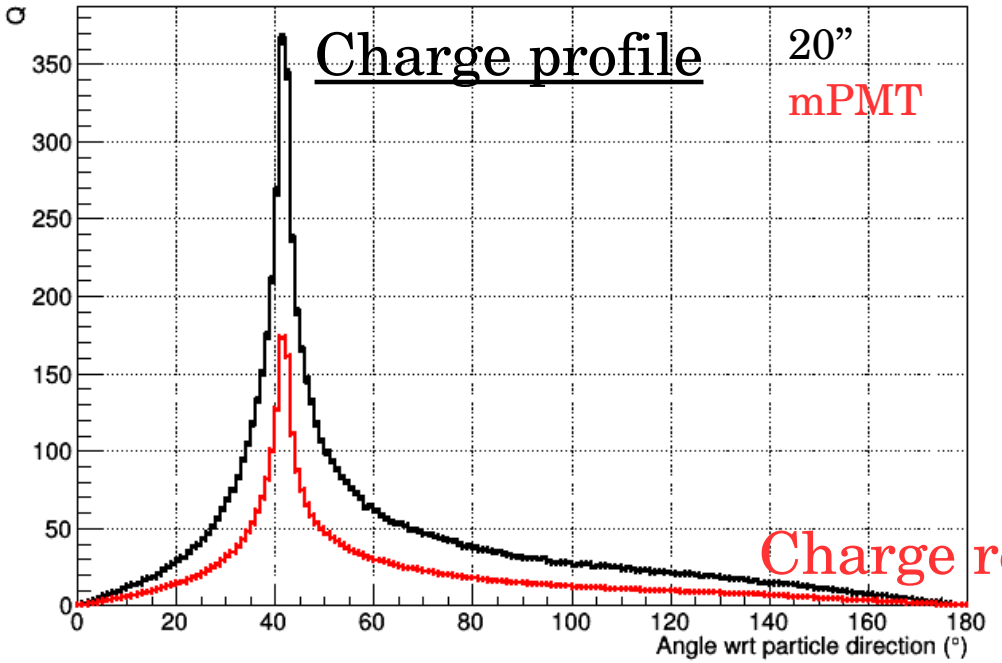
Charge response after digitization

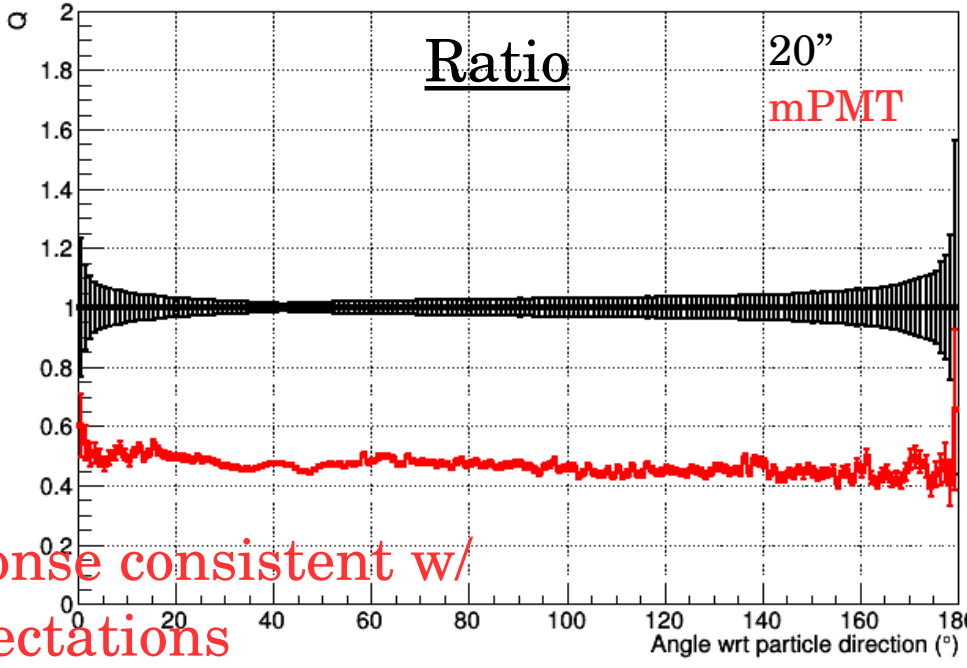
- Expect most of 3” PMTs have ≤ 1 p.e.
- Expect same charge deposition wrt PMT position in the tank



- mPMT charge / 20” = 42 %
  → 19 PMTs covers 42 % of the module





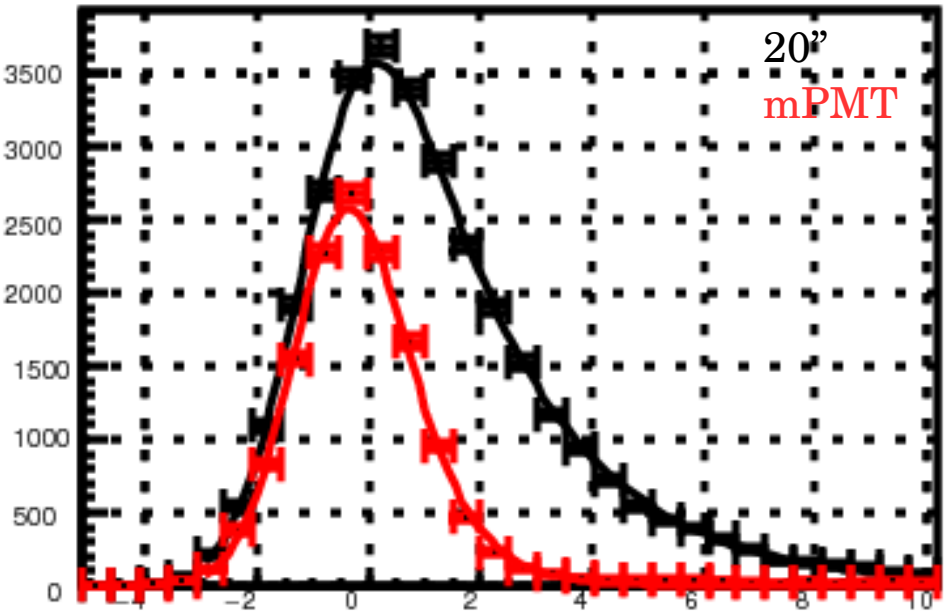


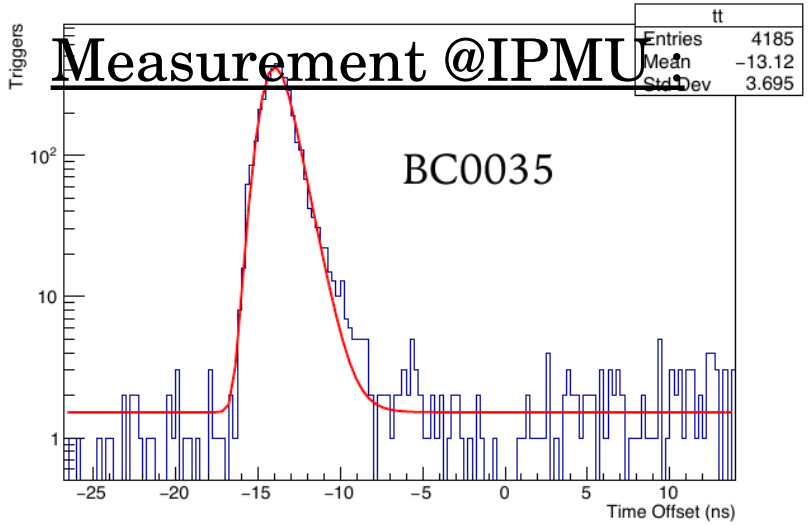
Charge response consistent w/ expectations

Digitized timing distribution

- The transit time smearing input : 2.0ns for 3” PMT, 2.6ns for B&L.

- Reduce spread due to particle travel & reflection/scattering → 10 MeV e-





- Fitting function : gaussian convoluted by exponential : G*Exp

	Gaussian σ	FWHM
20”	1.1 ns	2.6ns
3”	0.9 ns	2.1 ns

- Agrees with inputs ! → Timing response valided

PMT	HV	Gain	σ	1/λ	I(y) RMS
BC0035	-1150 V	9.80E+06	**0.65 ns**	**0.78 ns**	**0.97 ns**
BC0038	-1250 V	1.05E+07	**0.59 ns**	**0.73 ns**	**0.98 ns**

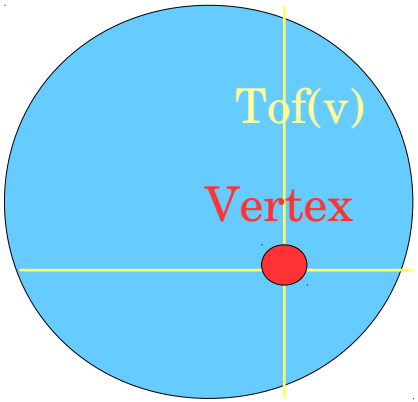
- σ = 0.6 ns → FWHM = 1.4ns
  → We can reduce TTS in simulation

The low energy fitter : BONSAI

- Relies on time residuals : $\Delta t = t - \mathrm{tof}(\vec{v}) - t_0$

- Search vertex position that maximizes likelihood of PMT hitted timing:

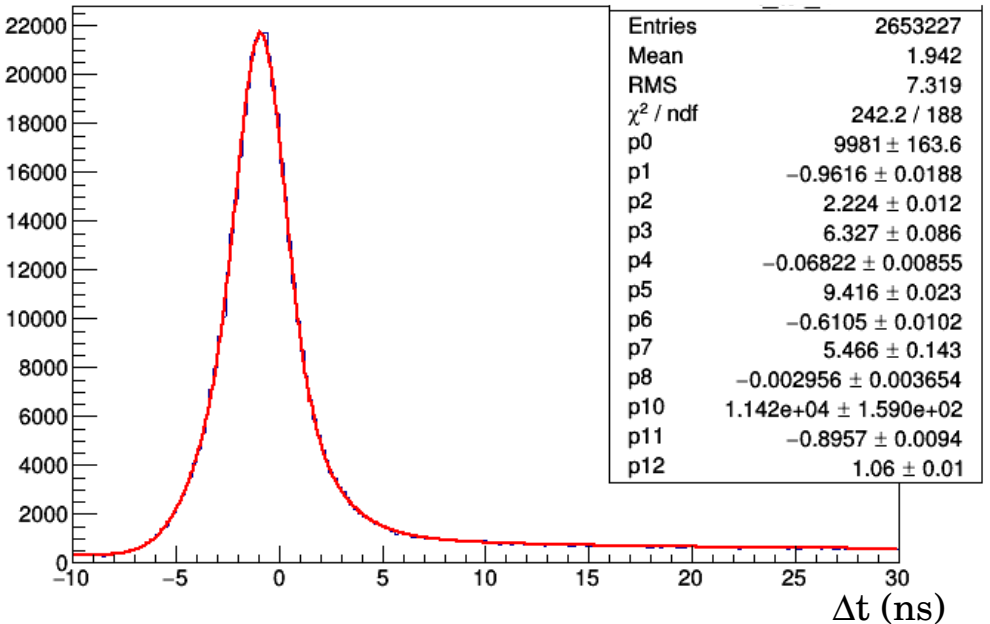
$$g(\vec{v}) = \sum_{i=1}^{N} w_i e^{-0.5(t_i - |\vec{x_i} - \vec{v}|/c)/\sigma)^2}$$



- Then, direction and energy are reconstructed
  → Crucial dependency on vertex position

- Good timing resolution is the key for vertex resolution (signal/bkg separation, directionality…)
  and E-resolution

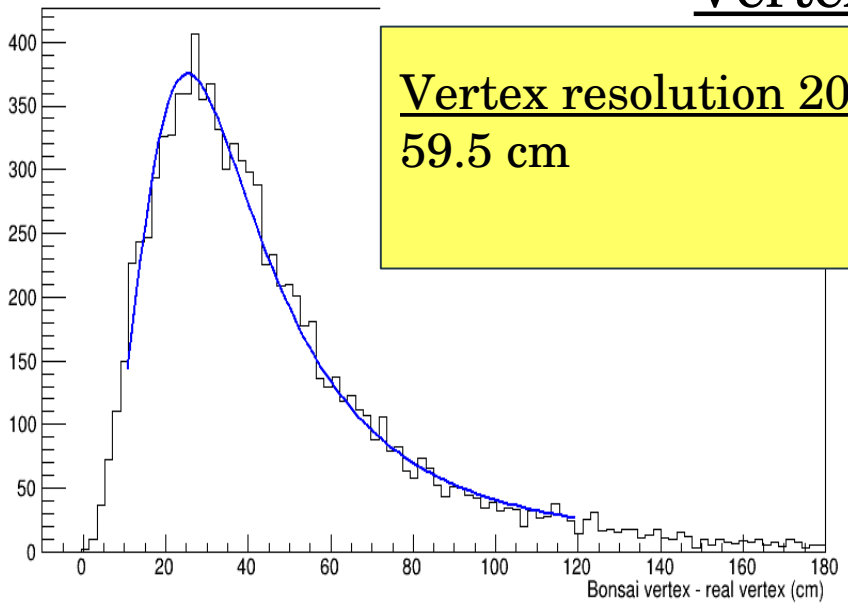
- Present performances of 3” mPMTs



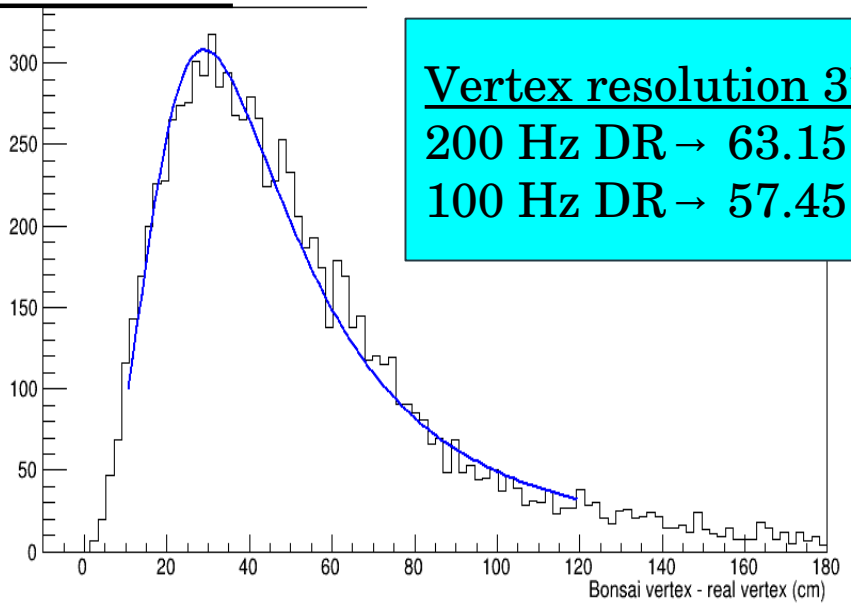
Vertex and direction resolution

- Generated 10 MeV e- uniformly in the tank.

Vertex reconstruction

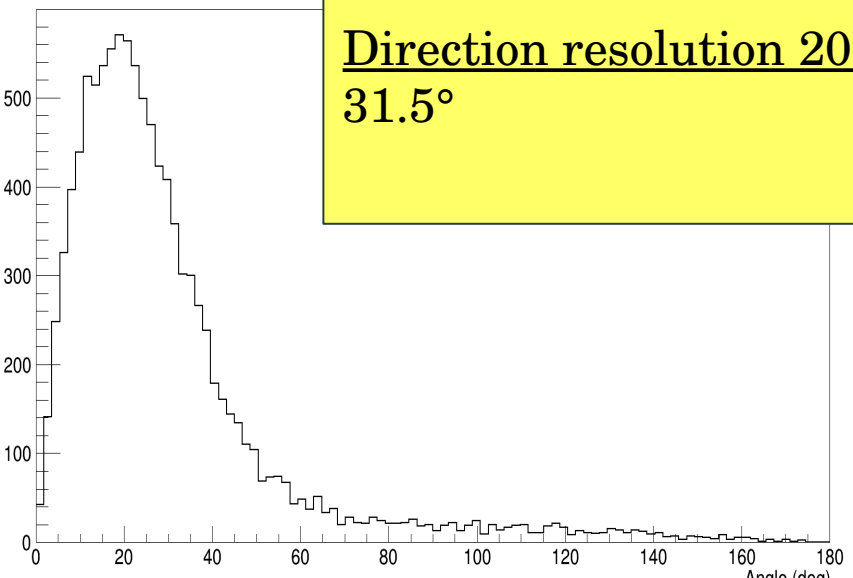


Vertex resolution 20”:
59.5 cm

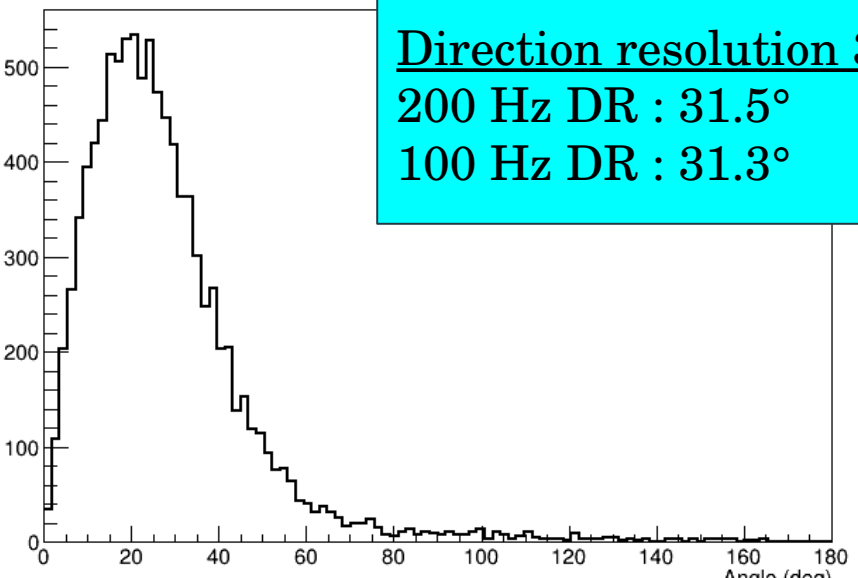


Vertex resolution 3”:
200 Hz DR → 63.15 cm
100 Hz DR → 57.45 cm

Direction reconstruction



Direction resolution 20”:
31.5°

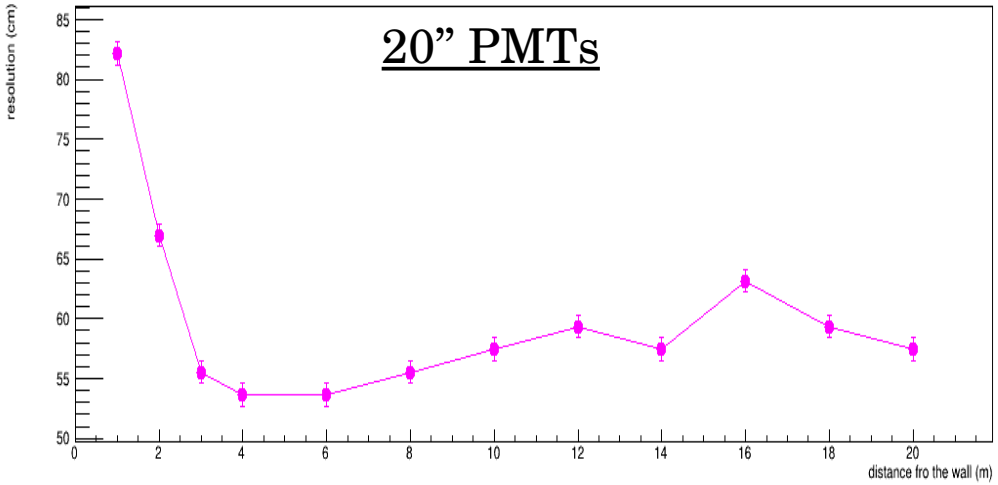


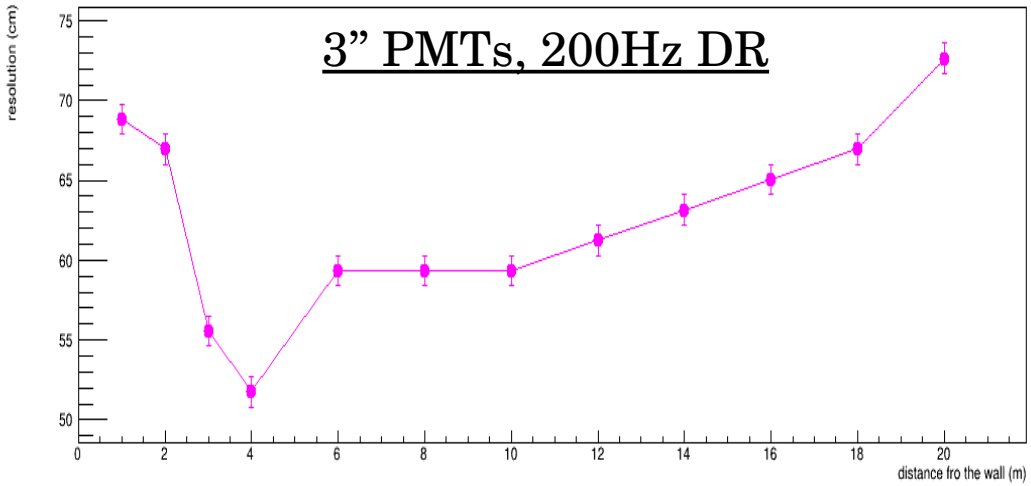
Direction resolution 3”:
200 Hz DR : 31.5°
100 Hz DR : 31.3°

Variation of resolutions with distance to the wall

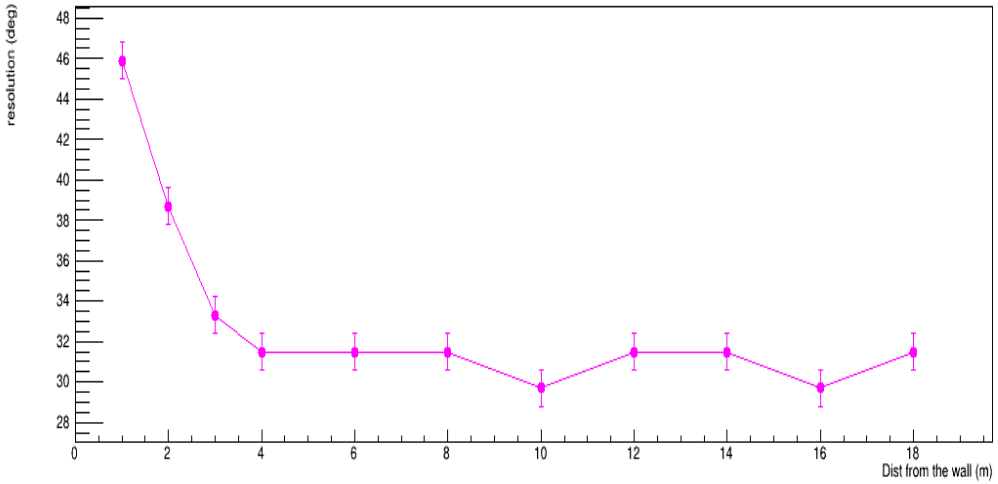
10 MeV e-

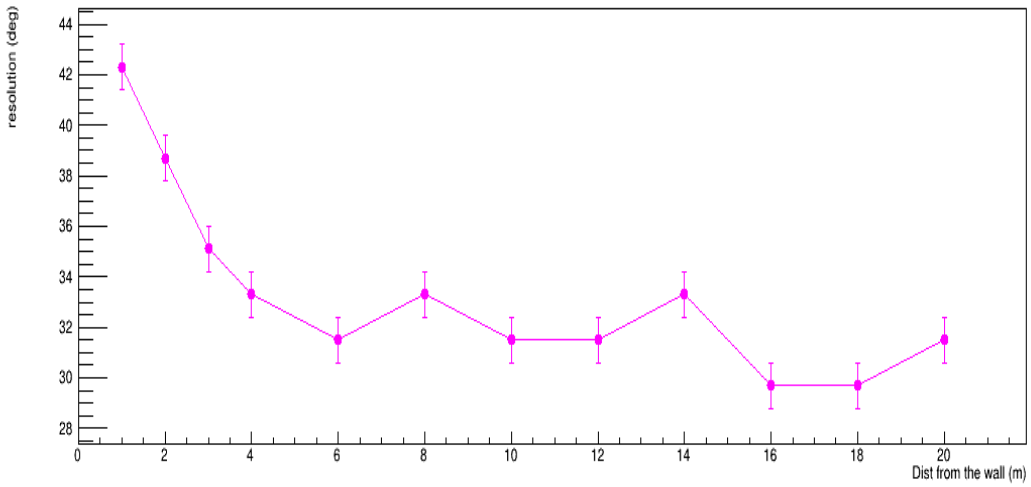
Vertex reconstruction





Direction reconstruction



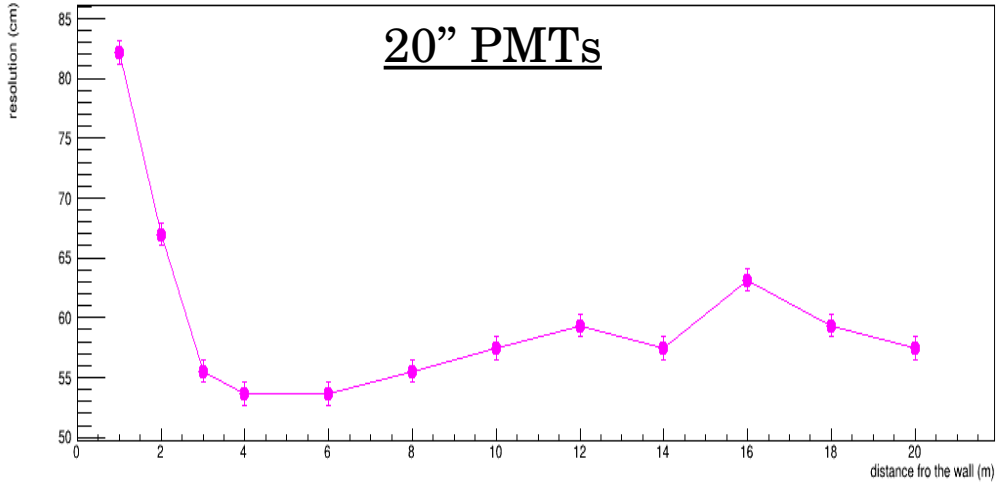


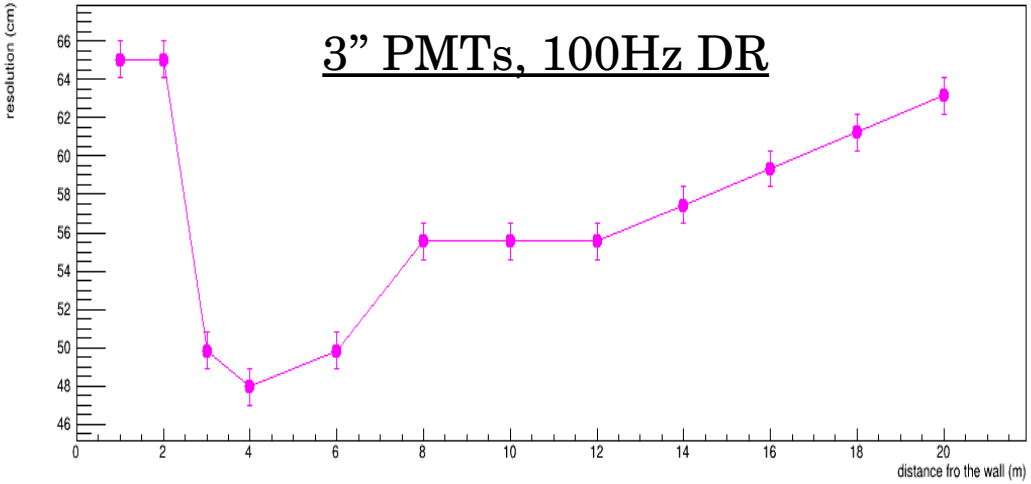
- Vertex resolution has a minimum ~4m to the wall → water absorption.
- Vertex resolution improved w/ mPMT for dWall ≤ 4m → timing effect
- Direction resolution almost flat from 4m to the wall to the tank center

Variation of resolutions with distance to the wall

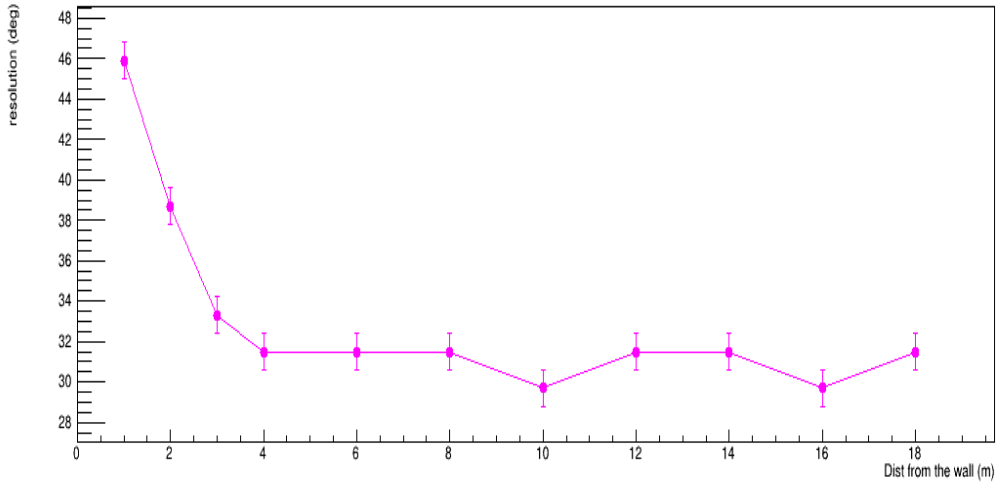
10 MeV e-

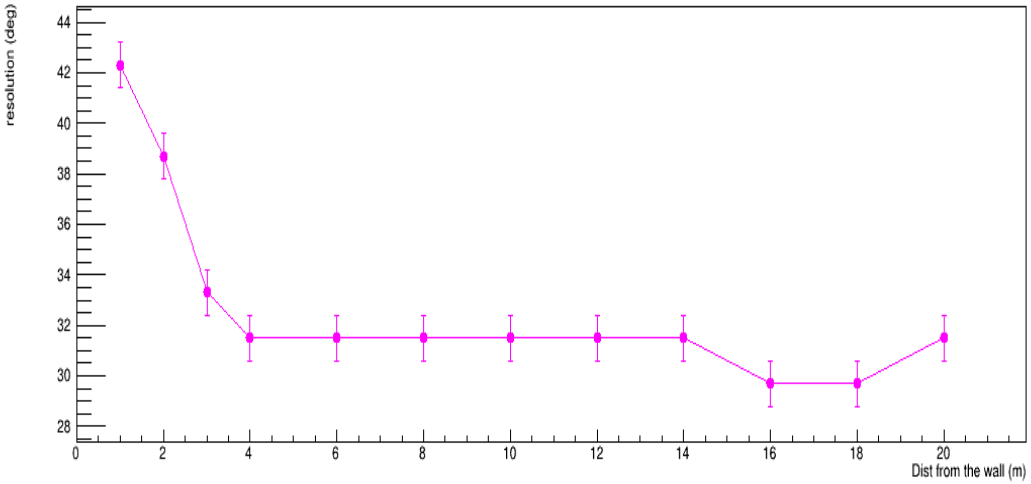
Vertex reconstruction





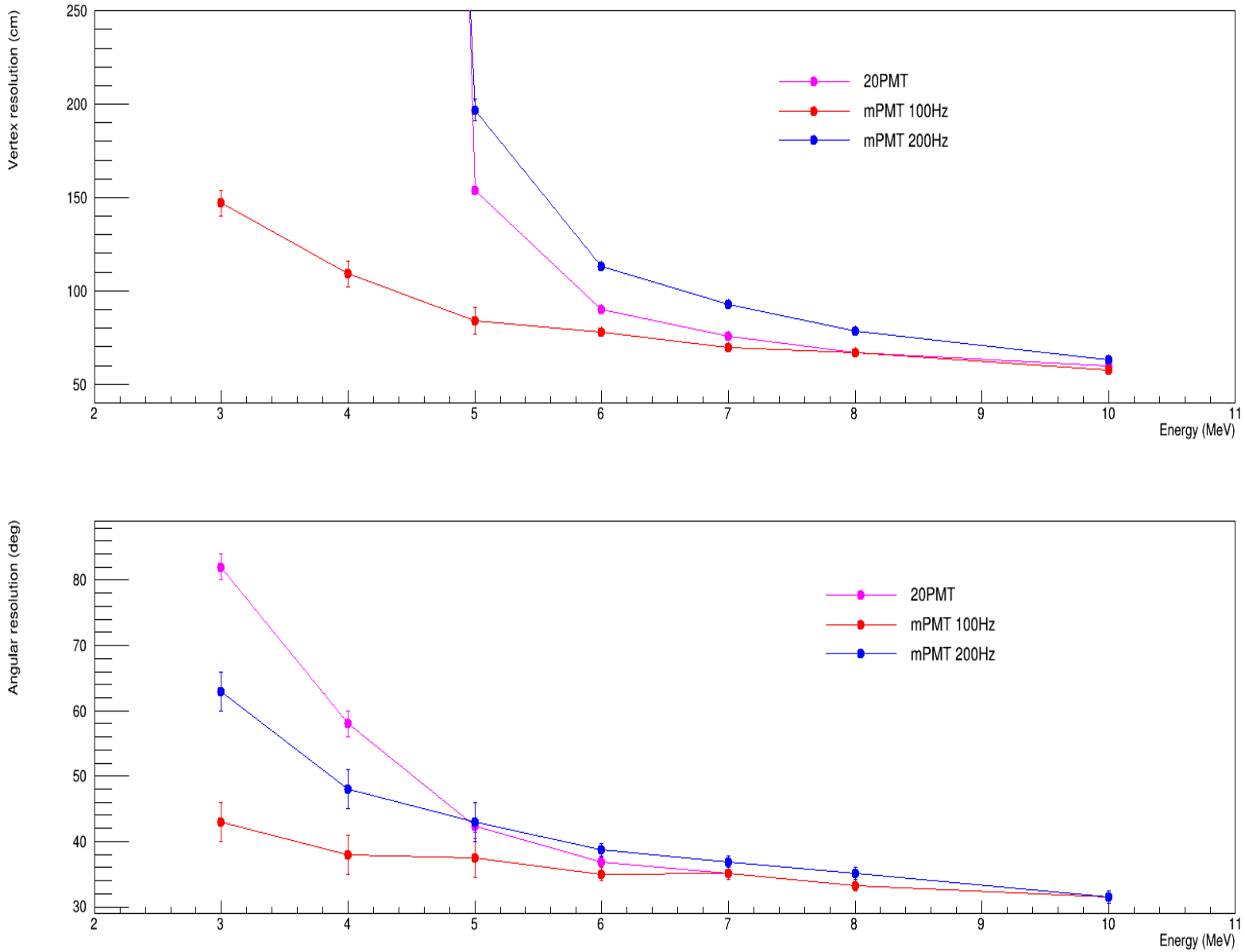
Direction reconstruction





- Vertex resolution improved w/ mPMT for dWall ≤ 8m.
- Pure DR effect : improve vertex resolution 52cm (200Hz) → 48 cm (100Hz).
- Important to reduce the Dark Rate (DR) !

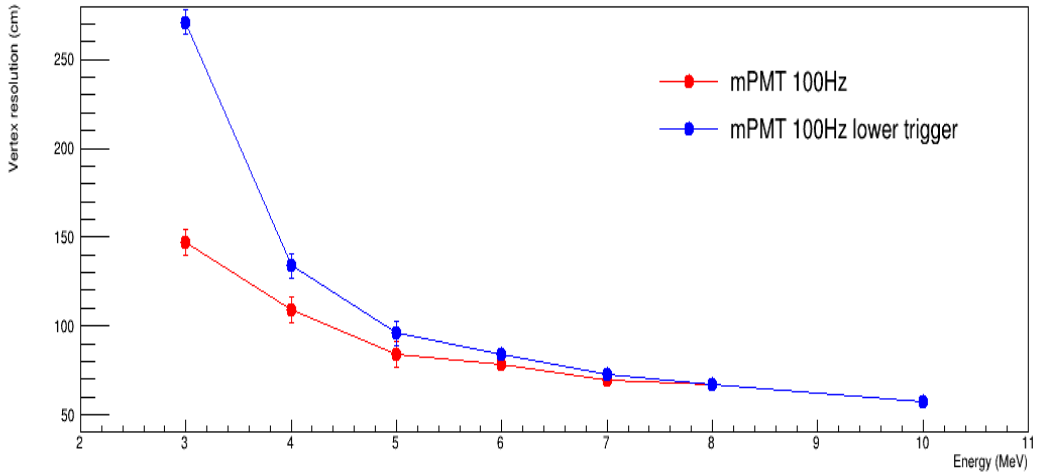
Variation of resolutions with neutrino energy

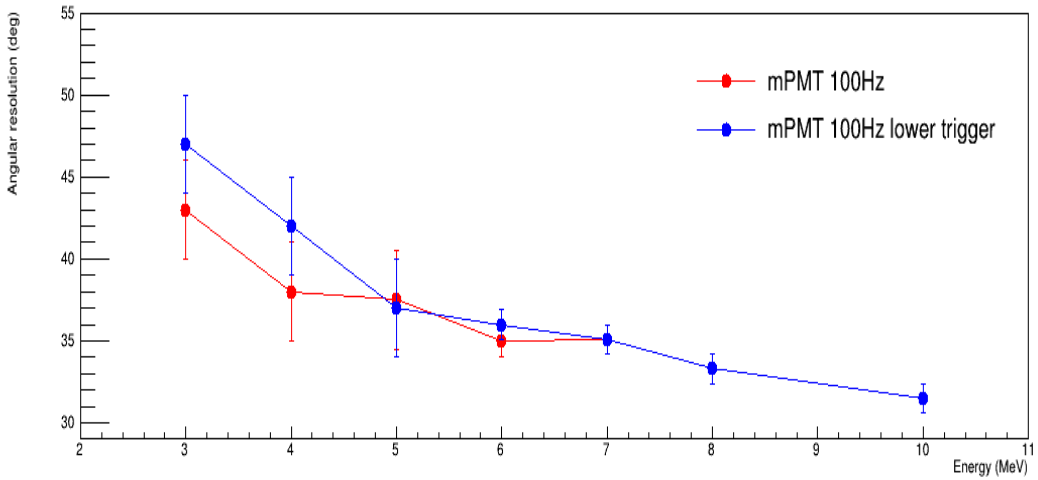


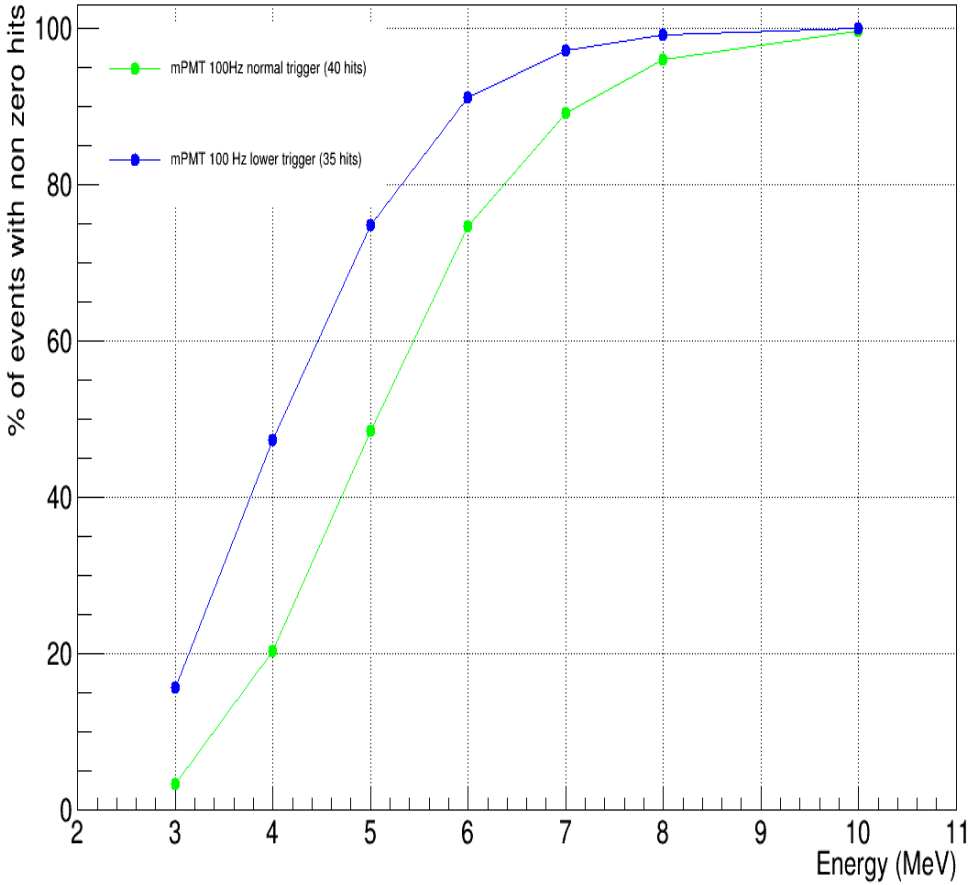
- mPMT allows to explore < 5 MeV region.
- But capital to reduce DR ≤ 100Hz → Possible e.g. if operated +HV

Lowering the energy threshold

- What happen if we lower down the data trigger : from 40 hits to 35 hits.





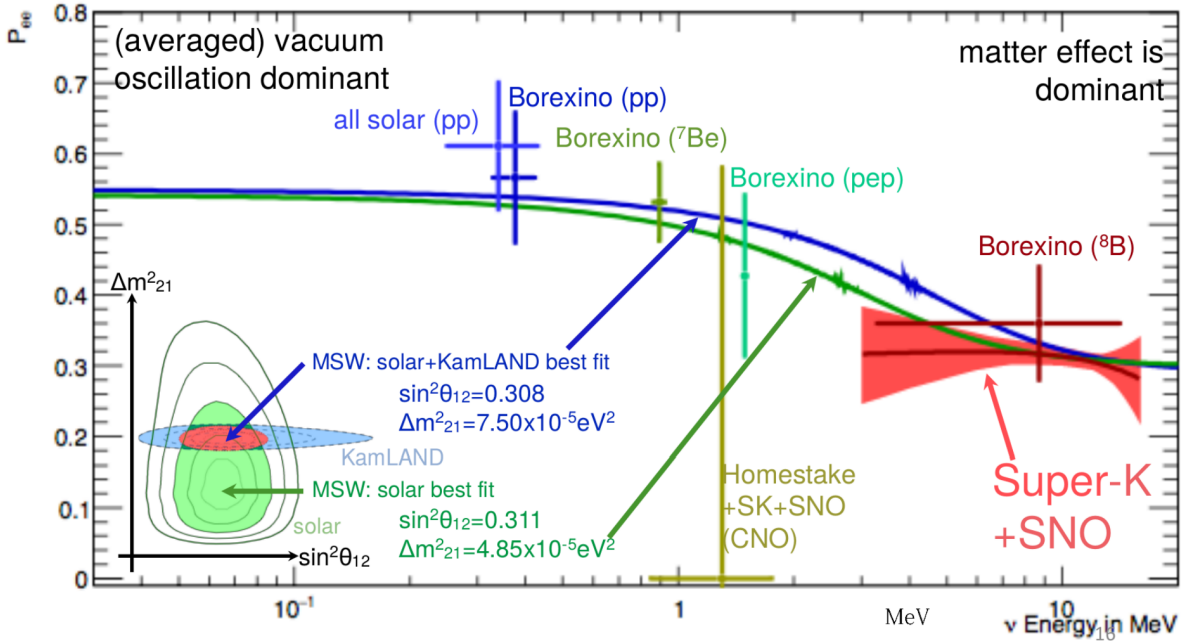


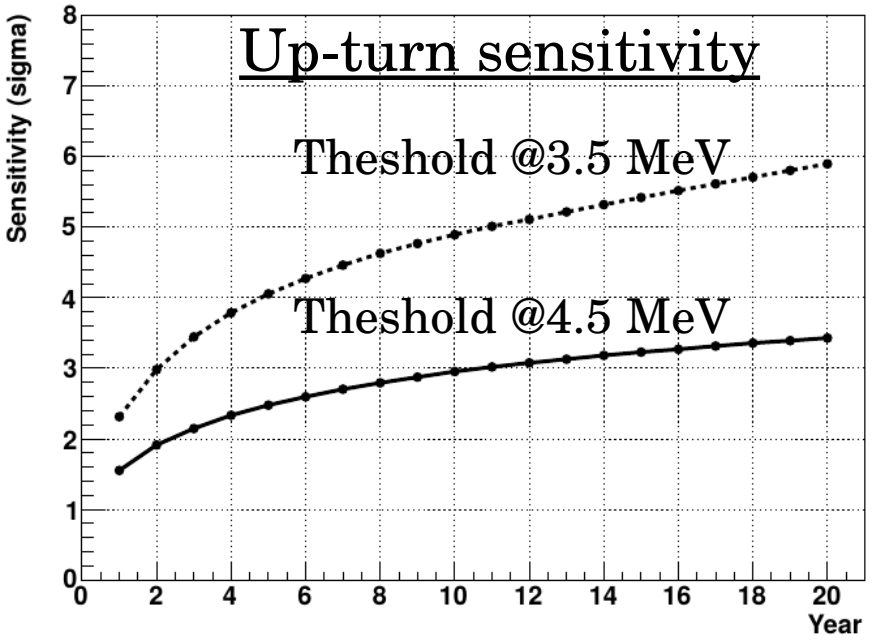
- 15 % trigger efficiency @3MeV (x4 times higher statistics) w/ dropback of a 2.7m vertex resolution

Impact at on the low energy physics

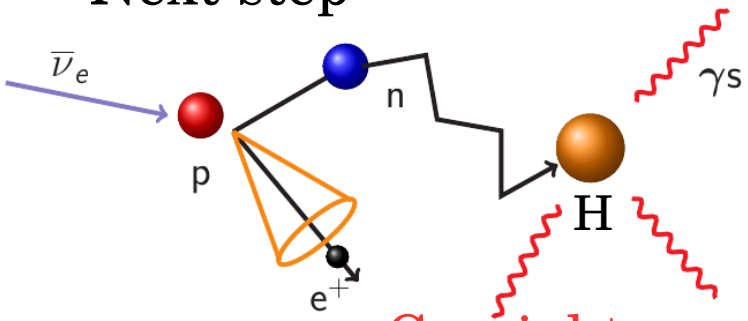
- Improved vertex resolution => Higher FV, improved E-resolution…

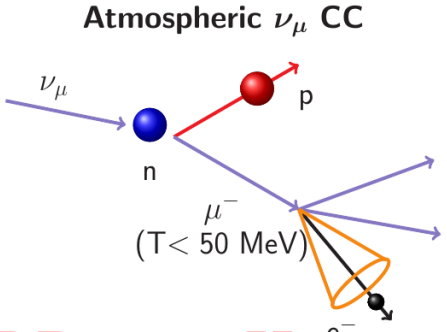
- Improved S/N : allows to probe low energy (3 MeV) → detect Solar up-turn ?



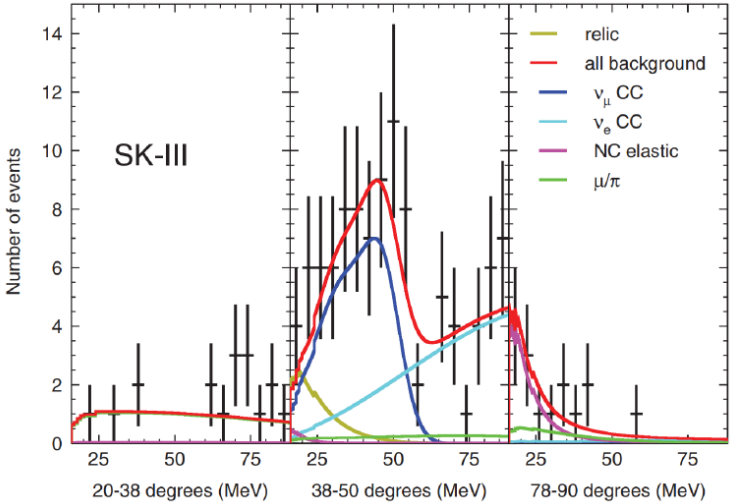


- Higher n tagging efficiency/purity on H?
  → Next step



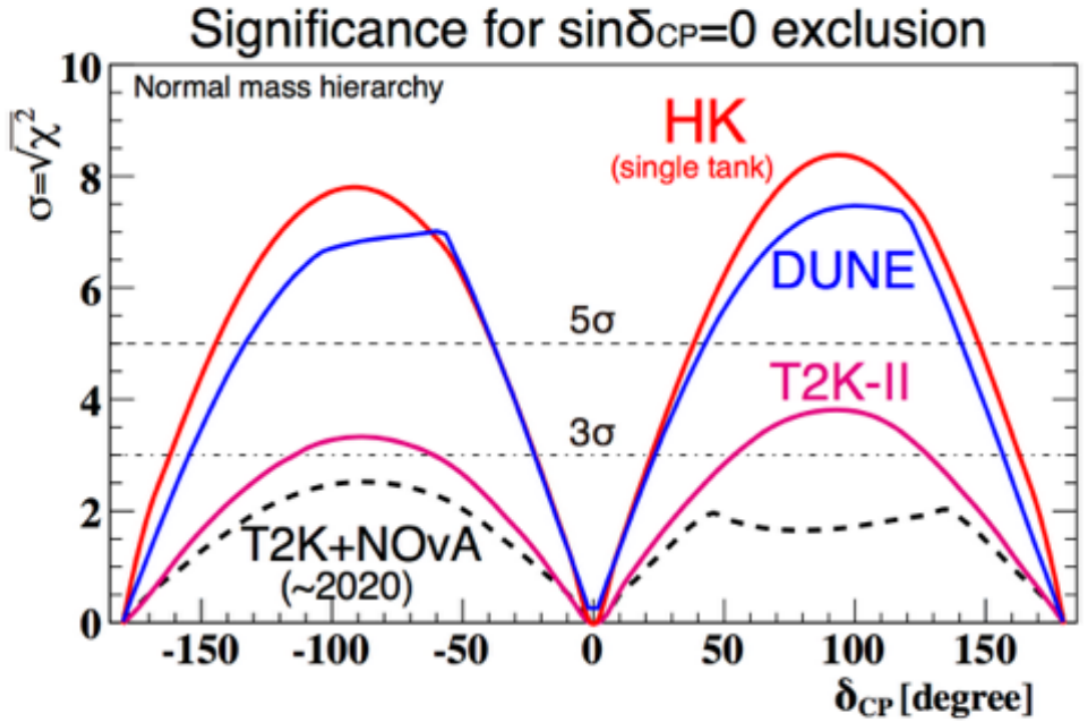


Crucial to reach DR ≤ 100Hz



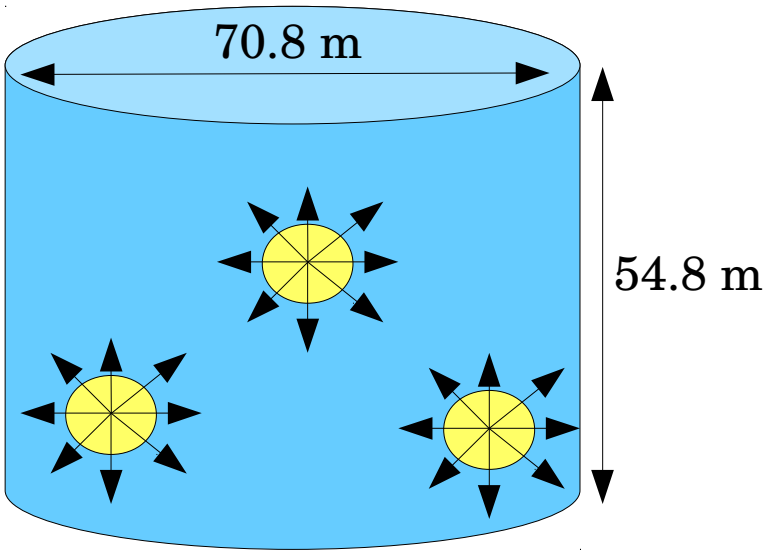
Impact at high energy

- Better ring separation → multi-ring events, e/pi0 separation….



- π^0 is 2nd dominant background → asymmetric decays

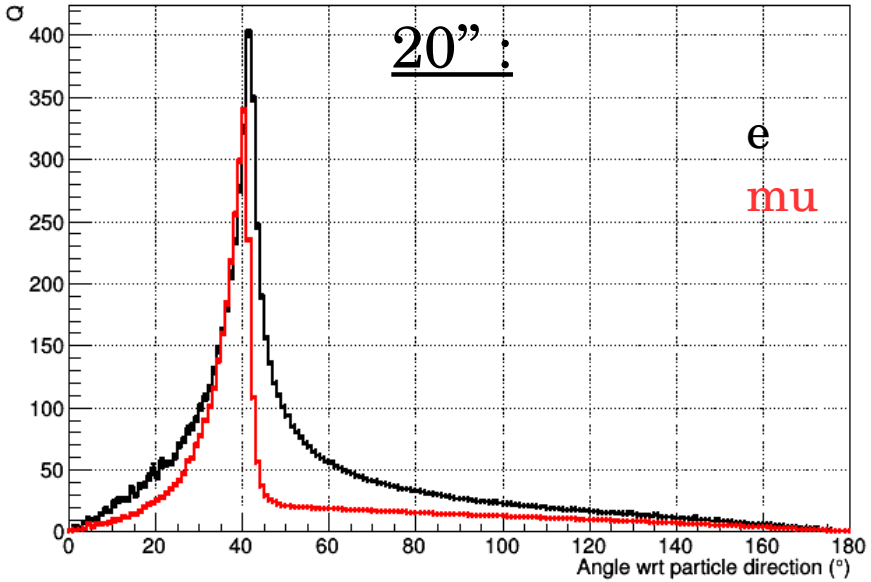
- Add multi-ring events → Increased statistics



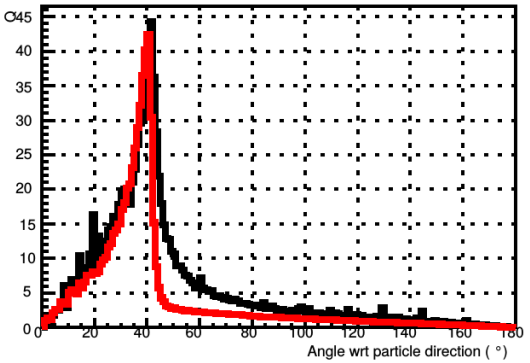
- <u>1. e/γ separation :</u> 500 MeV e^- and e^-e^+ pair generated at the same vertex.
- <u>2. e/μ separation :</u> Compare 500MeV e and mu event wrt distance to wall.

Impact at high energy

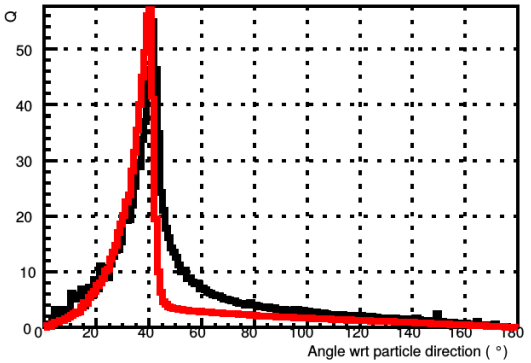
- Muon has a clear narrower peak (reduced scattering of mu)

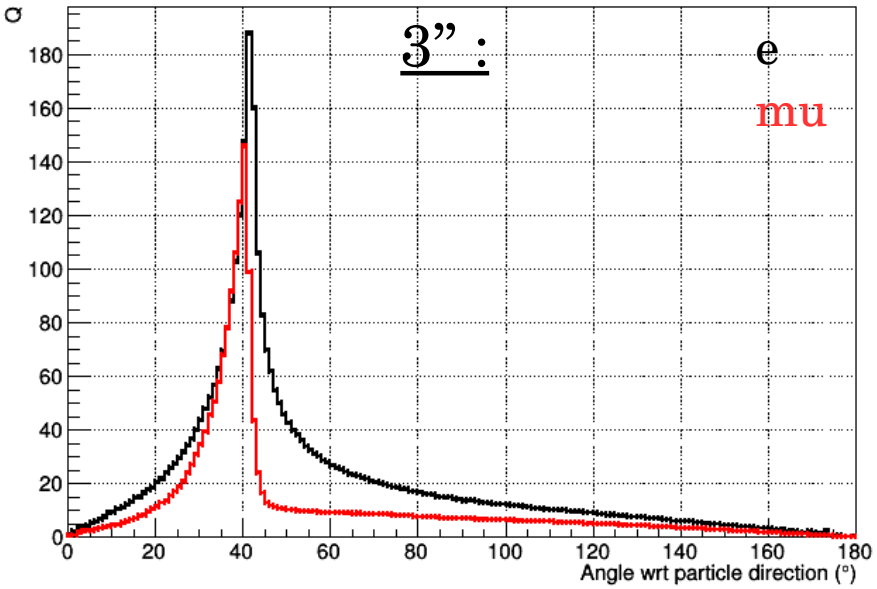


Dwall < 2m :

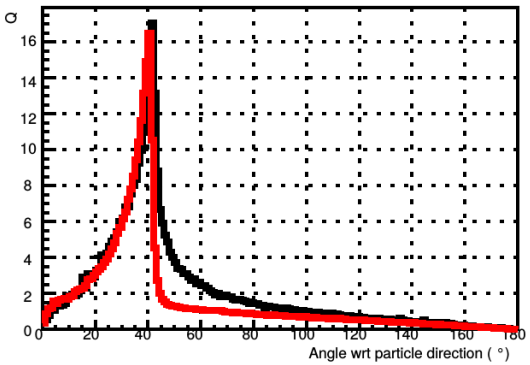


2m < Dwall < 4m :

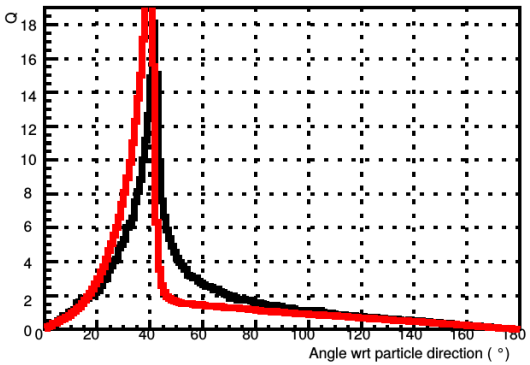




Dwall < 2m :



2m < Dwall < 4m :



- Less fluctuation of the profile
- Clearer separation in inner&outer peak

Results using the high energy fitter

- SK / HK fitter relies on fiTQun high energy fitter

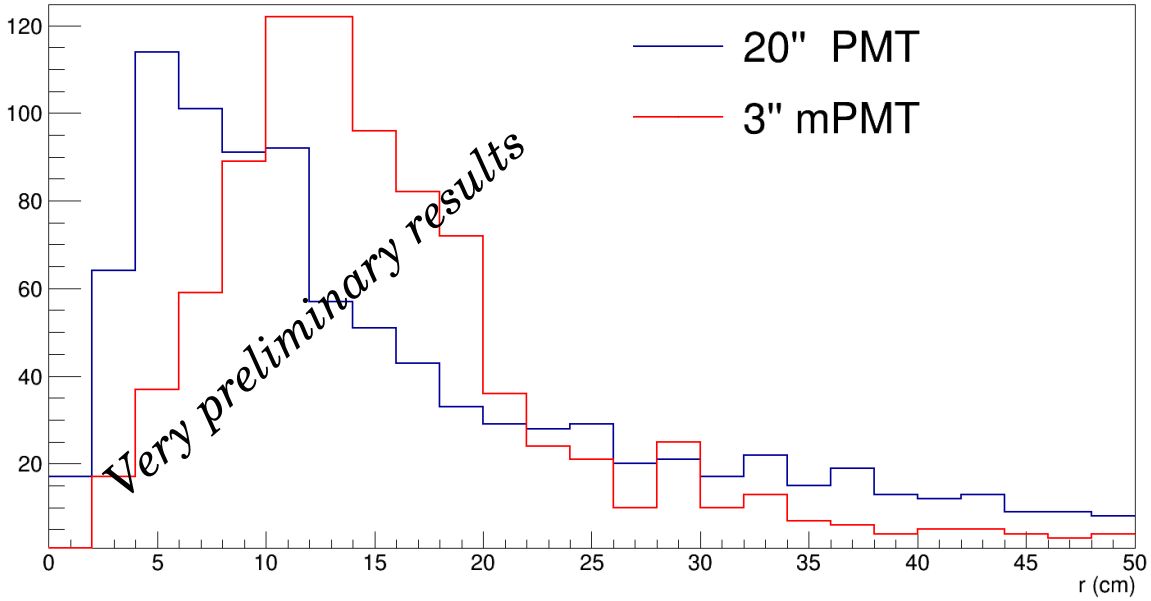
PMT unhit probability PMT hit probability PMT charge pdf

$$L(\mathbf{x}) = \prod_{j}^{\text{unhit}} P_j(\text{unhit}|\mu_j) \prod_{i}^{\text{hit}} \{1 - P_i(\text{unhit}|\mu_i)\} f_q(q_i|\mu_i) f_t(t_i|\mathbf{x})$$

PMT timing pdf

→ Relies on charge / time tables of hits → See T. Yoshida talk's

- Re-generated the tables for mPMT HK :



	20" PMT	3" PMT
Vertex resolution (cm)	21 cm	19 cm

Conclusions

- 3” mPMTs can be a very powerful complement to 20” to enrich Hyper-K physics.
- Implementation in the Hyper-K simulation is done and validated.
- At low energy : improved vertex resolution near the wall
- If operate 100Hz : improved vertex resolution and lower down the Energy threshold from 5 to 3 MeV → Access to low energy neutrino physics !
  → Crucial to operate ≤ 100Hz.
- At high energy : muon/electron separation seems improved near the wall.
- First results on vertex resolution → show improved resolution for 3”.

Thank you very much !

Additional slides

Additional slides