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東京大学 THE UNIVERSITY OF TOKYO

Multi-PMTs for the Hyper-Kamiokande detectors

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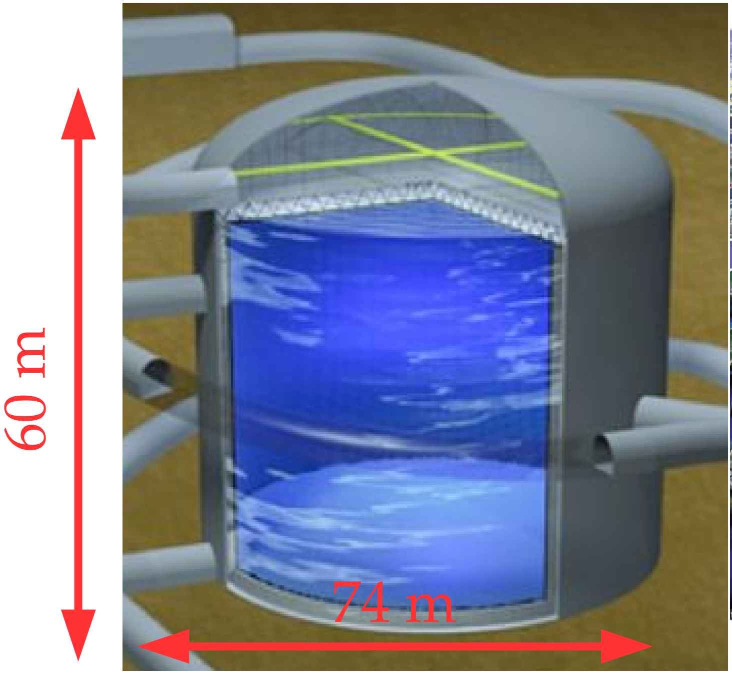
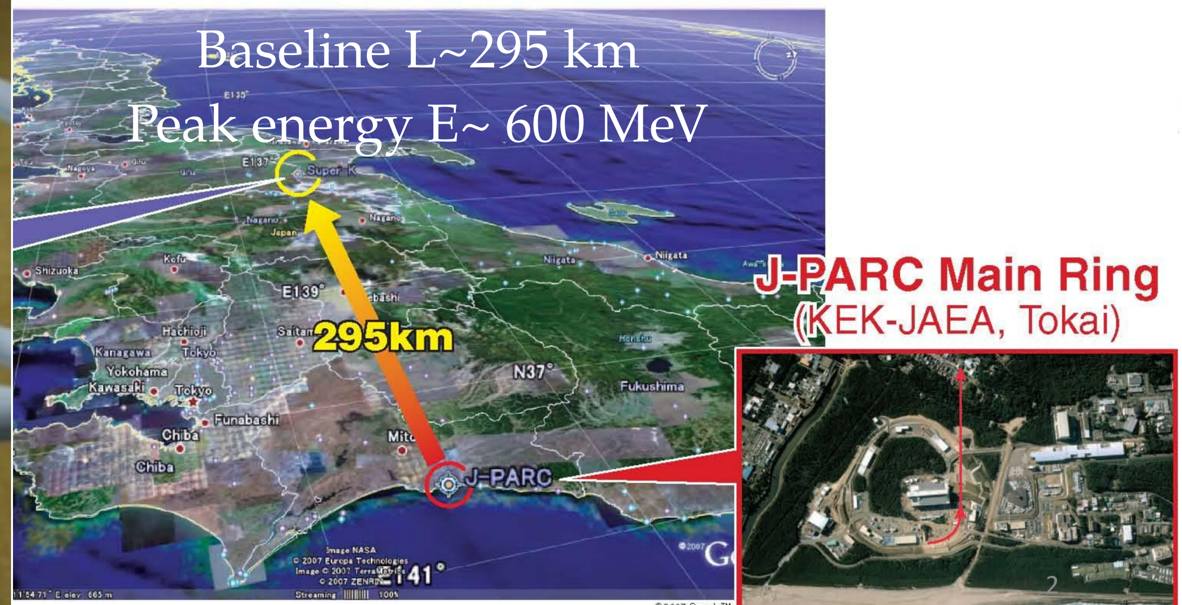
The Hyper-Kamiokande experiment

- Next generation of neutrino observatory in Japan→ construction 2020-26
  → A 260 kton water Cherenkov detector → FV mass ~ 8 x SK.



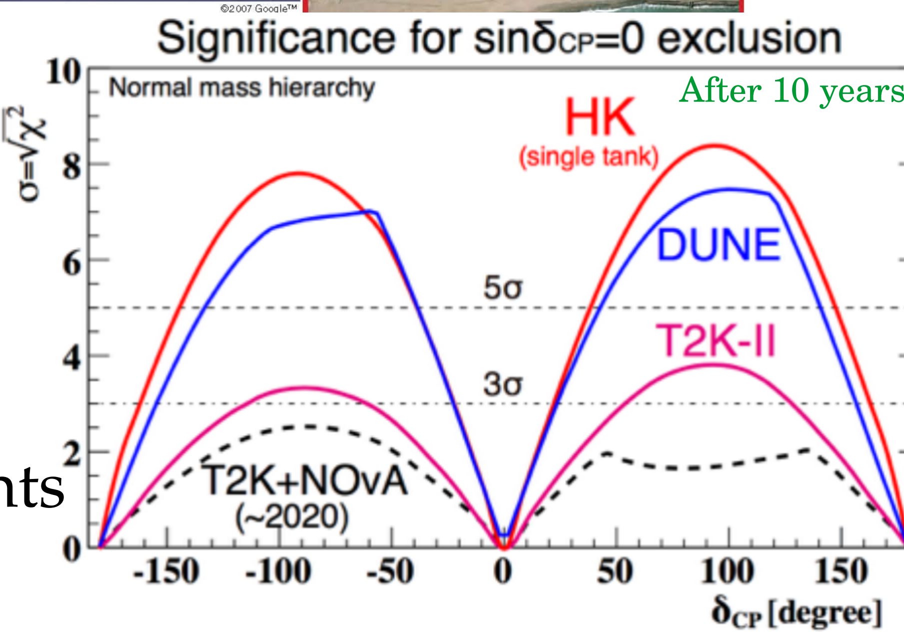


- Rich & vast physics program :

1. Observe CP violation in lepton sector
   - ν_e appearance in a ν_μ beam & compare with $\bar{\nu}$ equivalents.

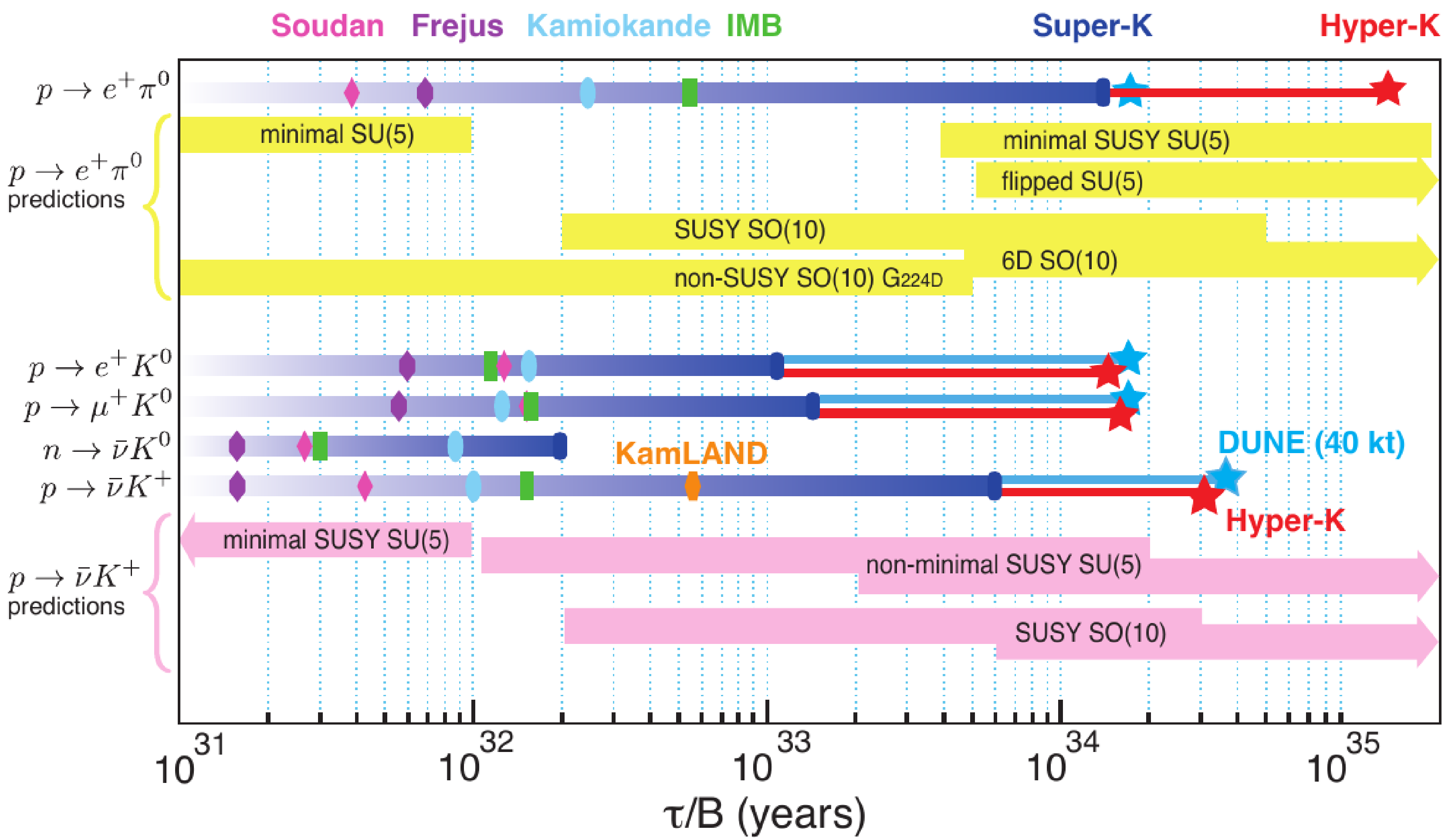
Precise measurement of δ_{CP} measurements

- Limited by E-resolution.



GUT and proton decay

2. Probe Grand Unified Theories at a new scale through proton decay.



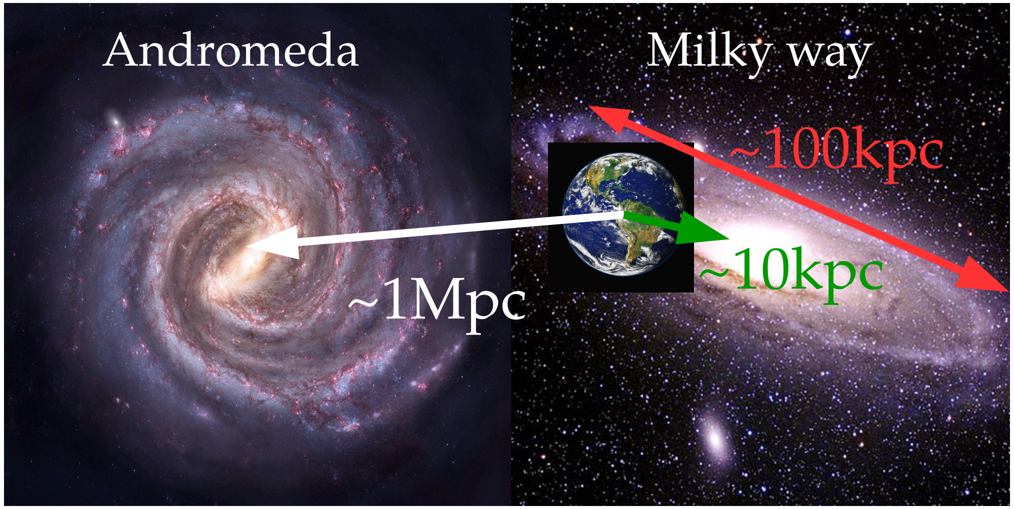
- HK will be able to probe Minimal SUSY-SU(5) & SUSY-SO(10) almost completely with the world highest sensitivity !

- This analysis is essentially limited / statistics → Crucial to increase FV.

Supernovae neutrinos

3. Probe supernovae ν : 99 % of SN energy → ν.

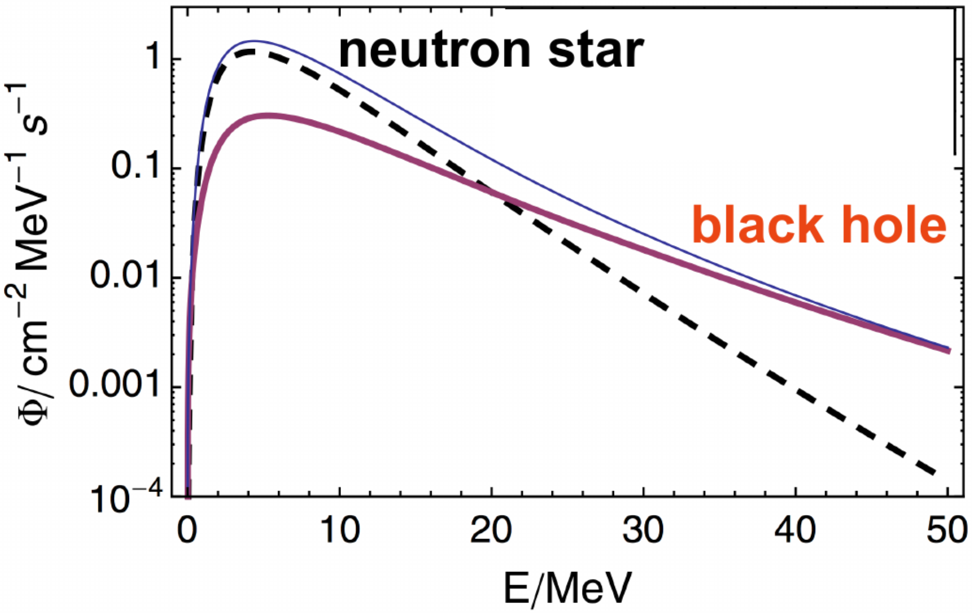
- But direct ν detection very rare.
- HK sensitive also extra-galactic SNν from Andromeda !
- Pointing directionality is crucial.

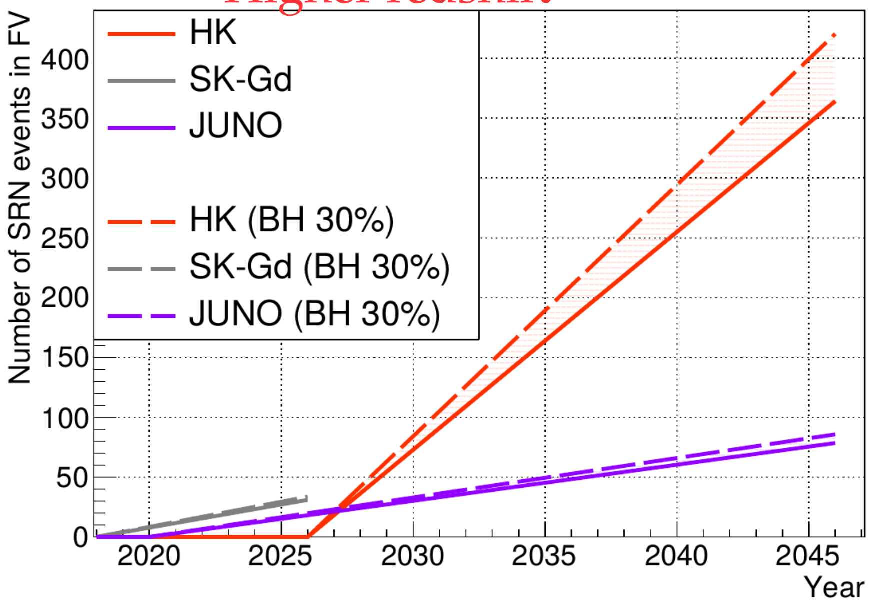


- SN-relic neutrino → new constraints on cosmic star history → May be first detected in SK-Gd.

→ The spectrum determined by HK : Low energy ↔ Probe older stars

Higher redshift

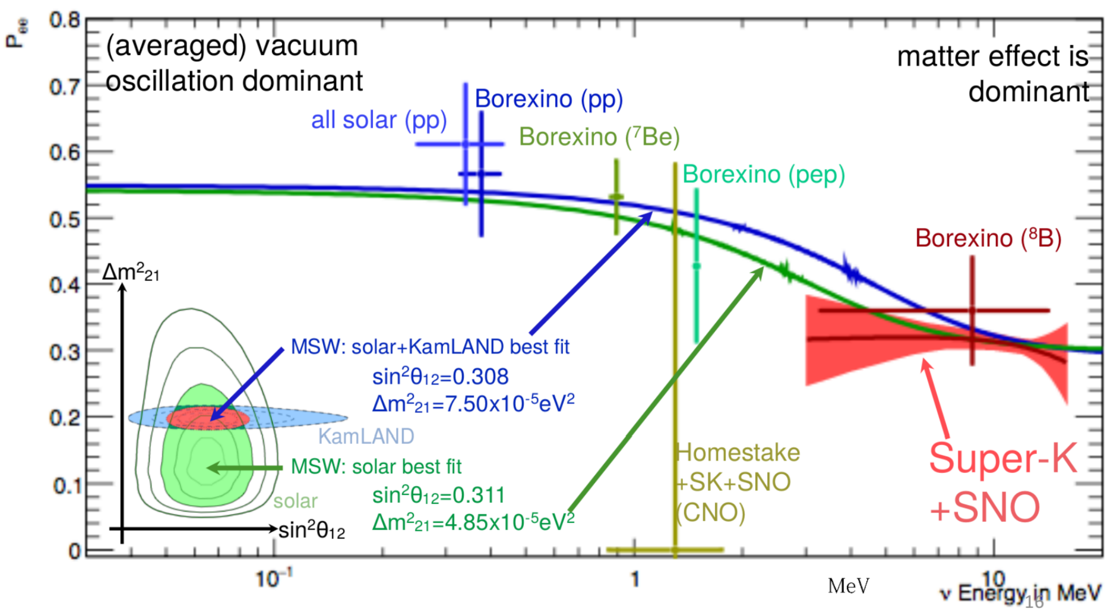


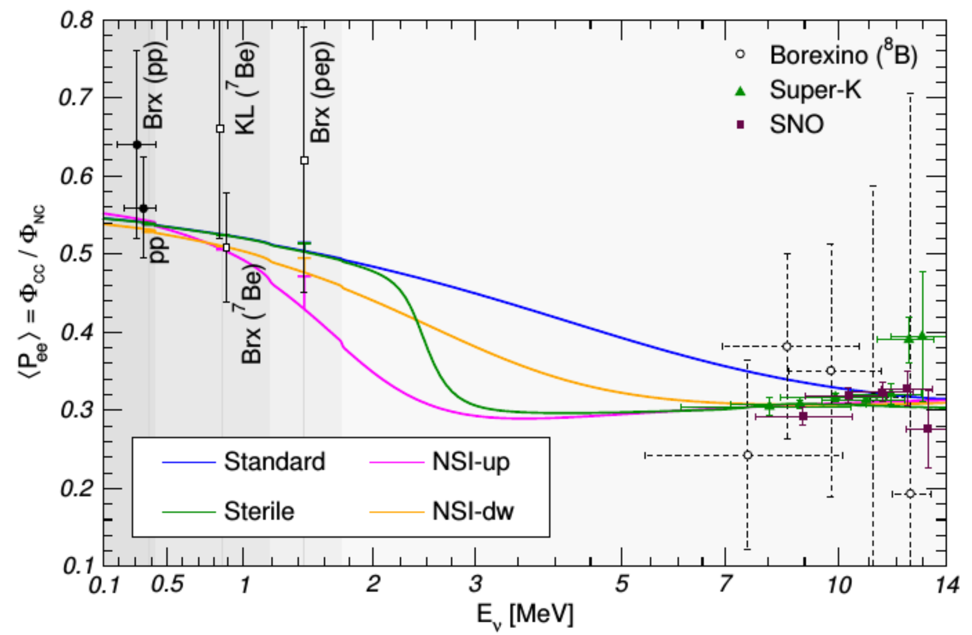


Solar neutrinos : upturn

4. Probe solar ν : SK/SNO found a high matter effect in the Sun

↔ Solar upturn shifted to lower energies



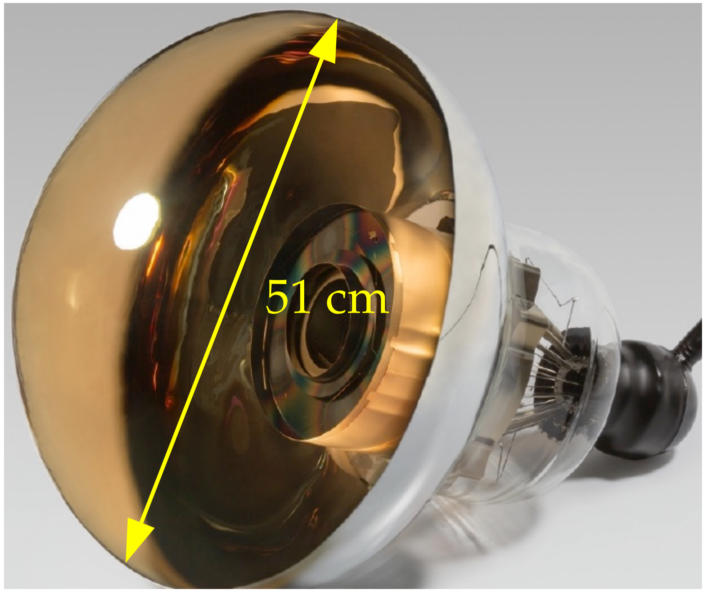


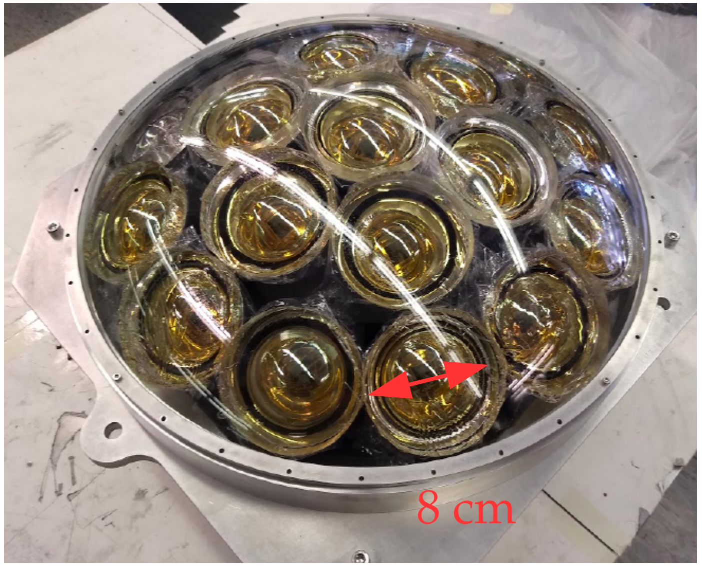
- Displacement of the upturn can be explained by :
  - Statistical fluctuation ?
  - Light sterile neutrino ?
  - Non Standard Interaction in the dense Sun ?

- Very sensitive to HK energy threshold : Can we lower E-threshold ?

Motivations for mPMT modules in Hyper-K

- To reach these goals, we rely mainly on HQE 50cm PMTs.
- Can multi-PMTs enhance HK physics as a complement of 50cm PMTs ?
- Multi-PMT : 19 PMTs of 8cm PMTs.
- Smaller size : Better reconstruction near wall
  → Increase FV e.g. for CPV or p-decay ?
- 2 x better timing resolution: ↑ vertex resolution
  → enhanced energy resolution → Decrease systematics on δ_{CP} ?
  → Better directionality for SN pointing ?
- Aim for dark rate ≤ 100Hz: S/N ~ 2 x 20″
  → Probe lower energies e.g solar upturn ?

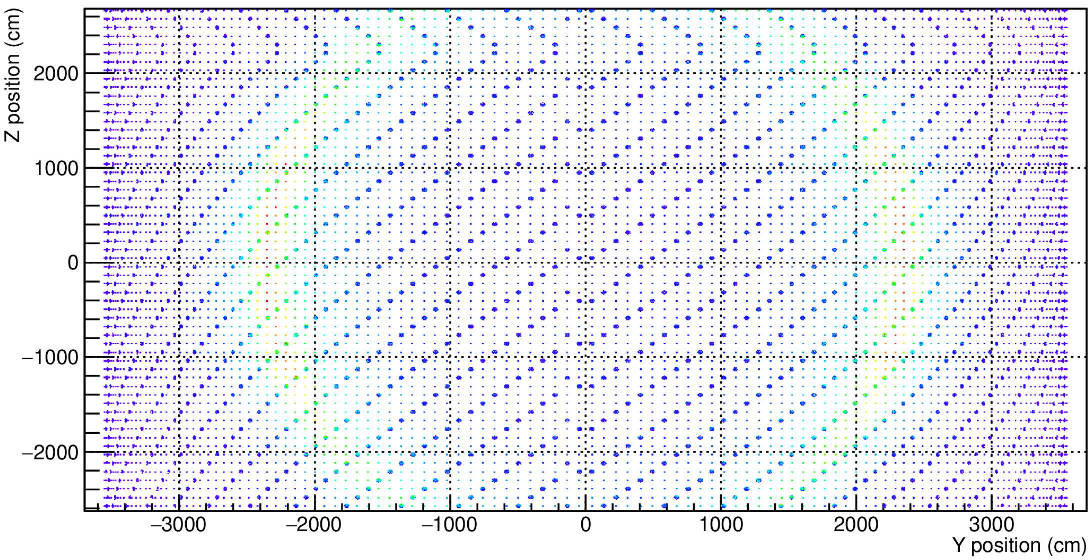


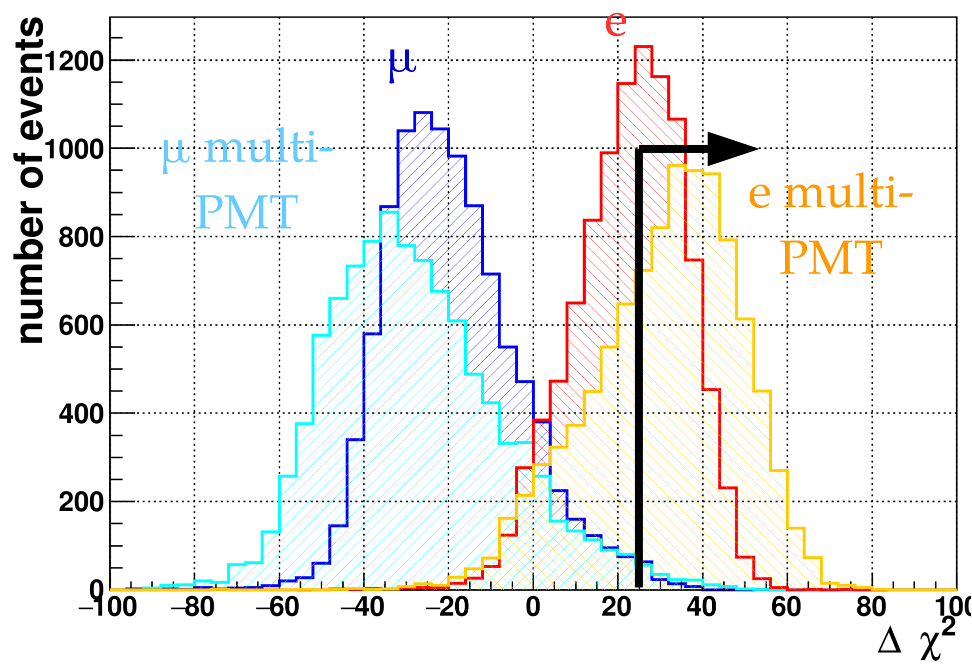


Impact of mPMTs at high energy

- <u>2 hypotheses :</u> 20 % 50cm PMT + 5 % multi-PMT or 10 % mPMT
  Today, focus on 5 % case

- <u>Event display for a 500 MeV electron :</u>

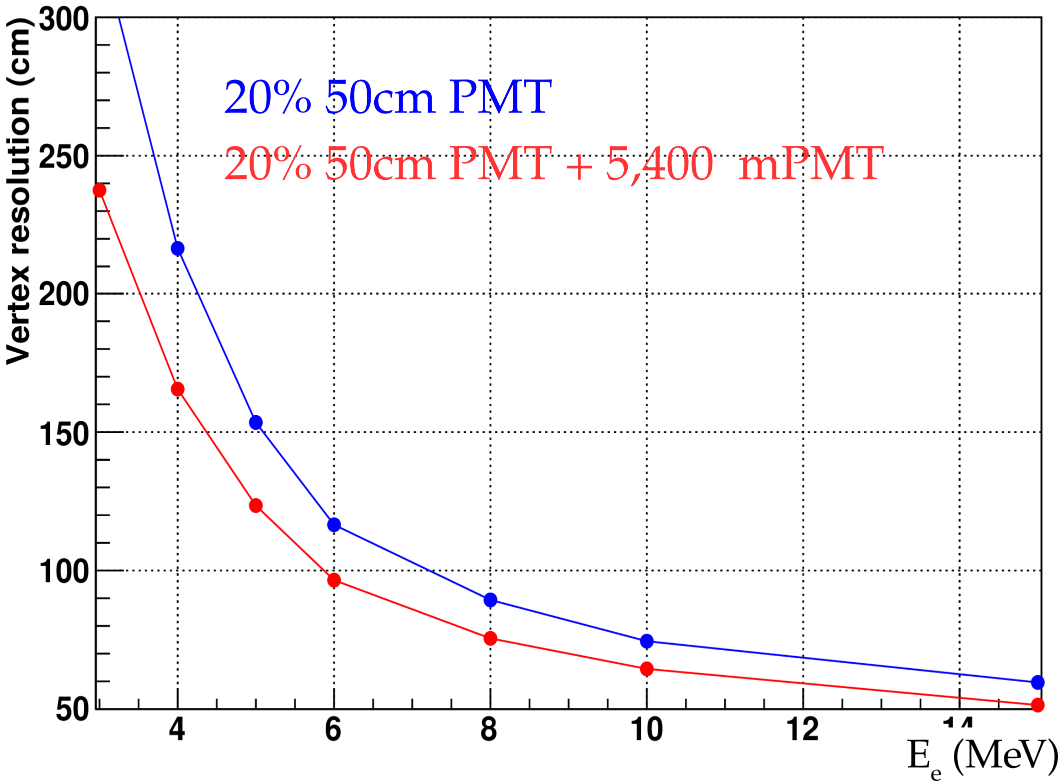




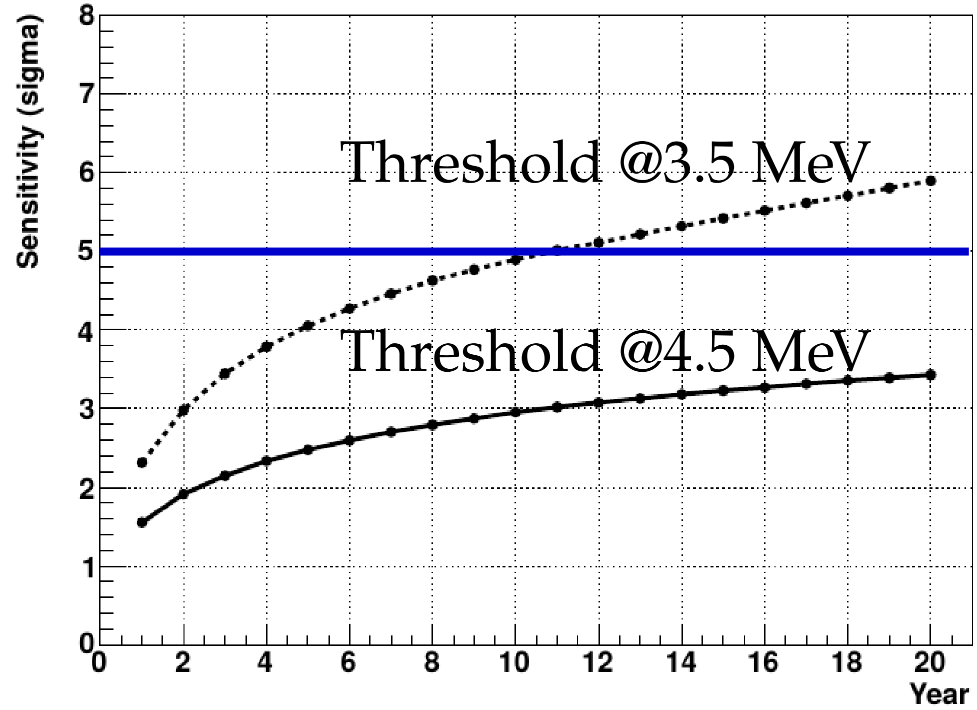
- Simplified fitter indicate possible improvement with mPMT especially for events close to wall
  → <u>+25 % statistics in e-sample</u> for a mis-ID rate of 1 %.

- <u>Our 1st goal :</u> Develop a more complete reconstruction at high energy to validate&improve these first promising results.

Impact on low energy



Up-turn sensitivity



- Improved vertex resolution, especially near the edges of the detector
  → ↑ fiducial volume +10 %.
  → May ↓ systematic uncertainties.

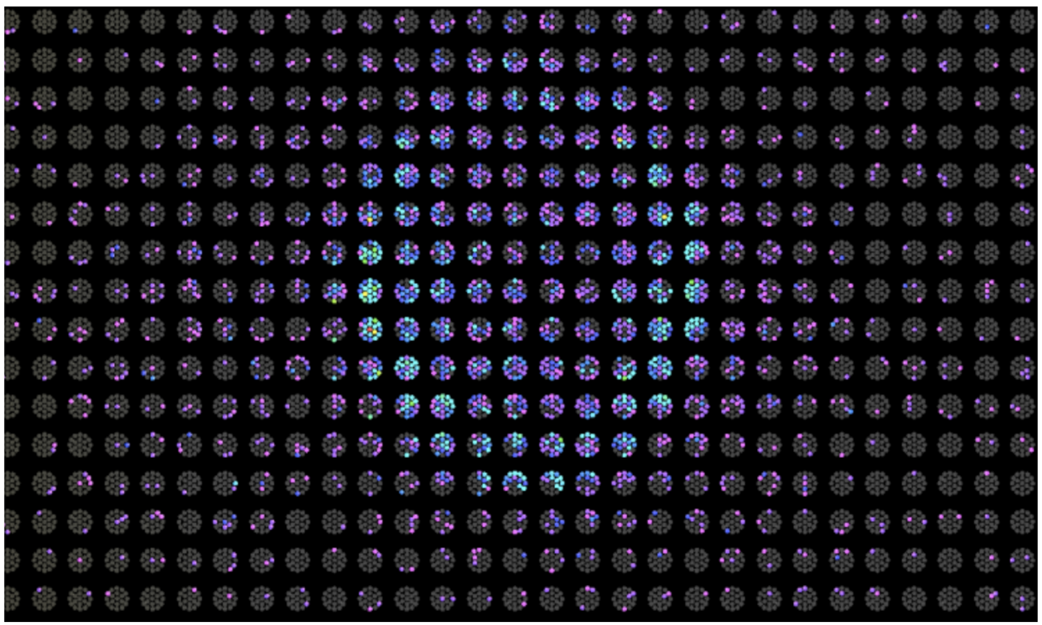
- ↓ energy theshold 4.5 → 3.5 MeV
  → May be able to probe the solar upturn with a 5σ sensitivity.

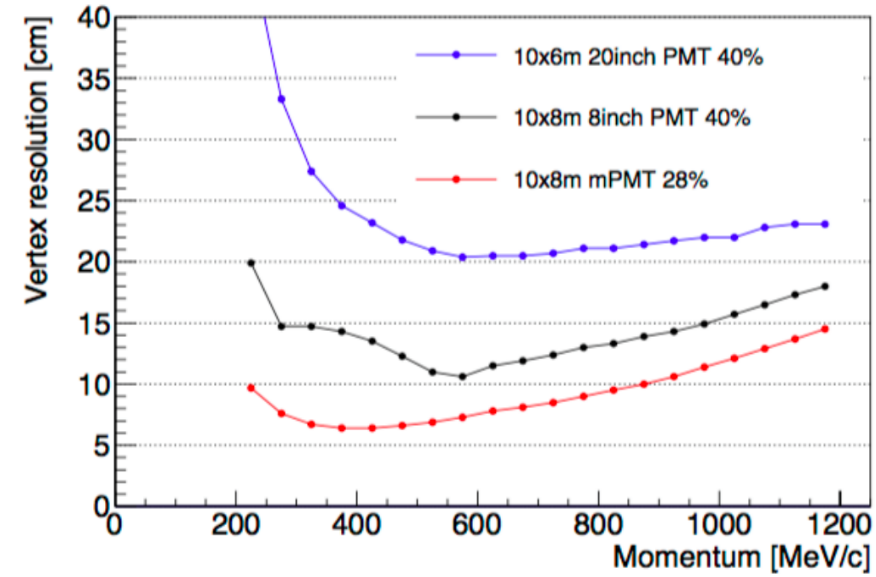
Impact on HK intermediate detector

- <u>Multi-PMT are also the primary candidates for the HK IWCD</u>

  → Located ~1-2km away from JPARC beamline.

  → Much smaller than HK → Reconstruction near the wall is crucial !

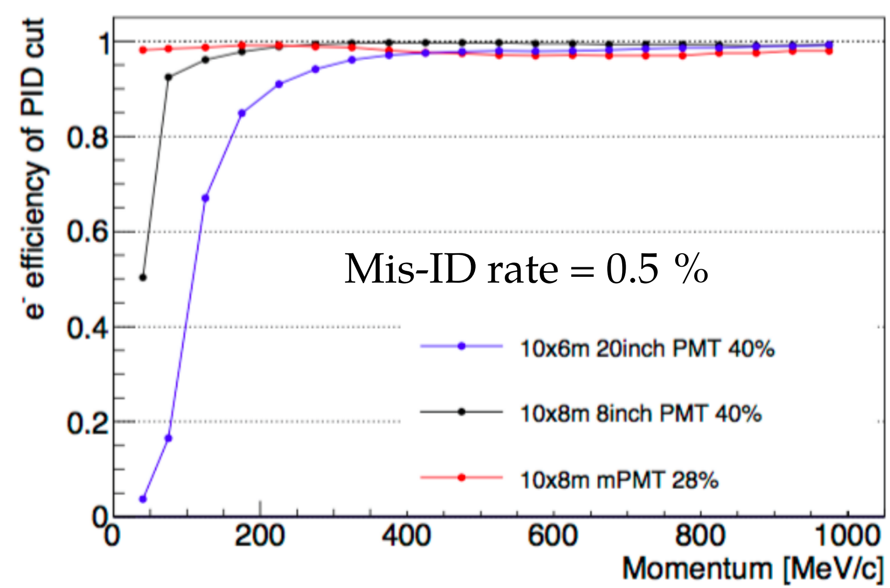




- Improved vertex resolution

  → Larger FV w/ less systematics.

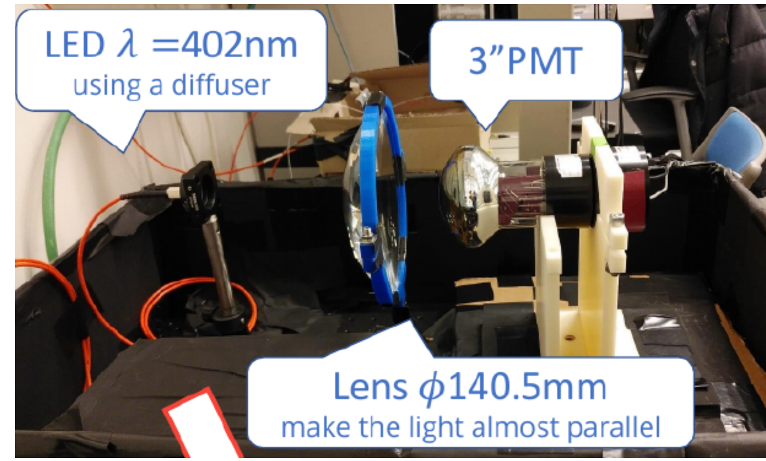
- Improved PID → Reduced systematics for $(\nu_e / \nu_\mu) / (\bar{\nu}_e / \bar{\nu}_\mu)$.

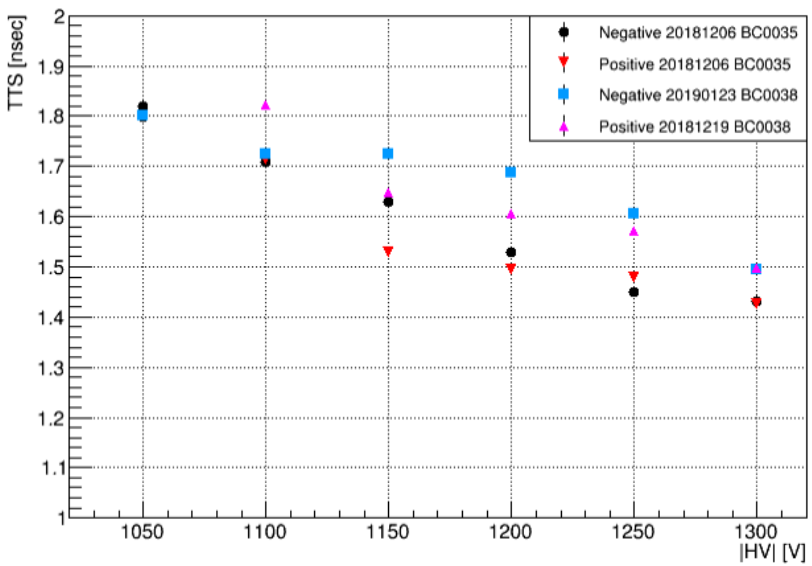


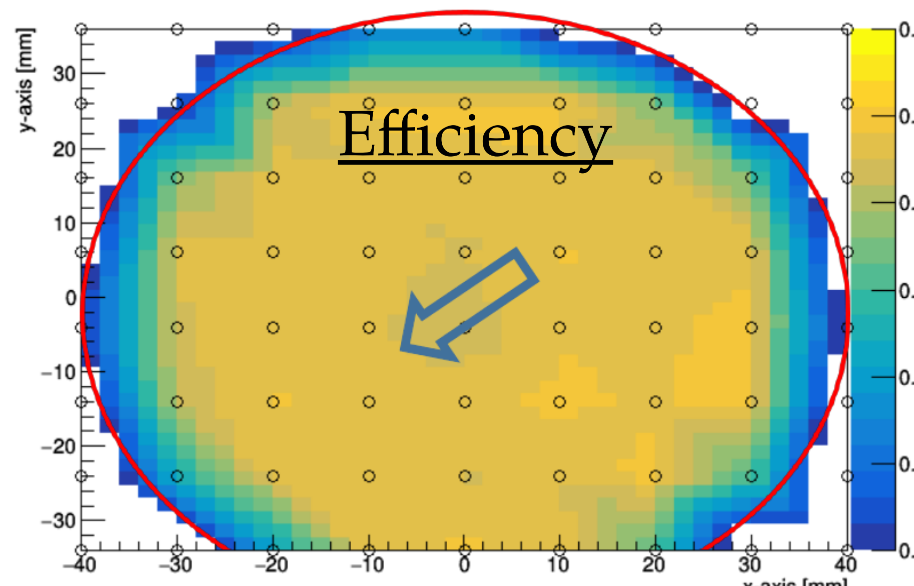
Tests of individual 3″ PMTs

- Extensive tests of the 3″ PMTs constituting mPMTs @U. Tokyo.

- <u>2 test benches allowing to measure the :</u>
  - 1. PMT time and charge response with uniform light source
  - 2. Variation of this response wrt position and angle w/ photocathode







- The individual 3″ PMT has been fully characterized (except for DR).
  → The next step is to test the whole multi-PMT module.

Enhance HK physics with mPMT

- Our project : Enhance HyperK physics capabilities with multi-PMT.

  → Joint development of the reconstruction to produce the physics sensitivities with mPMT.

  → First test of the whole mPMT in-situ.

Canadian design :
tuned for HK & flash ADC → Waveforms.

1. Why ?

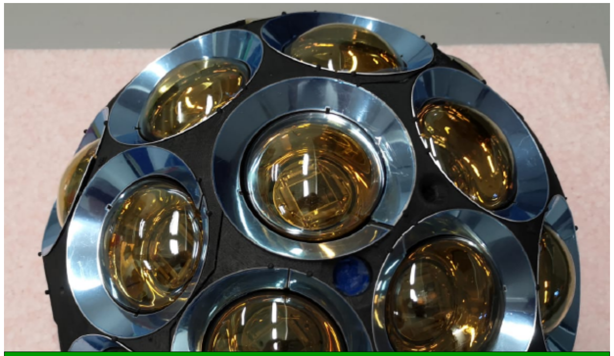
- World first test of these modules in water

  → 1st milestone towards their use in HK/E61.

  → Compare of 2 prototypes & electronics.

  → 1st measurements of 3'' w/ physics data.

  → Crucial to optimize the module & reflector.



Italian design :
half sphere
& integrated charged / timing.

- 1st dark rate measurements in-situ.

  → Crucial to determine the LE possibilities & study DR reduction (positive HV, HA-coating…)

- Development of the DAQ for HyperK.

Test the assembled mPMT in water

2. Where ? @APC in Paris → 2x2x2m³ water tank MEMPHYNO.
→ used to test KM3NeT PMTs

3. How ?

Japan

1. Test & calibrate each 3″ response

2. Assemble mPMT.

France

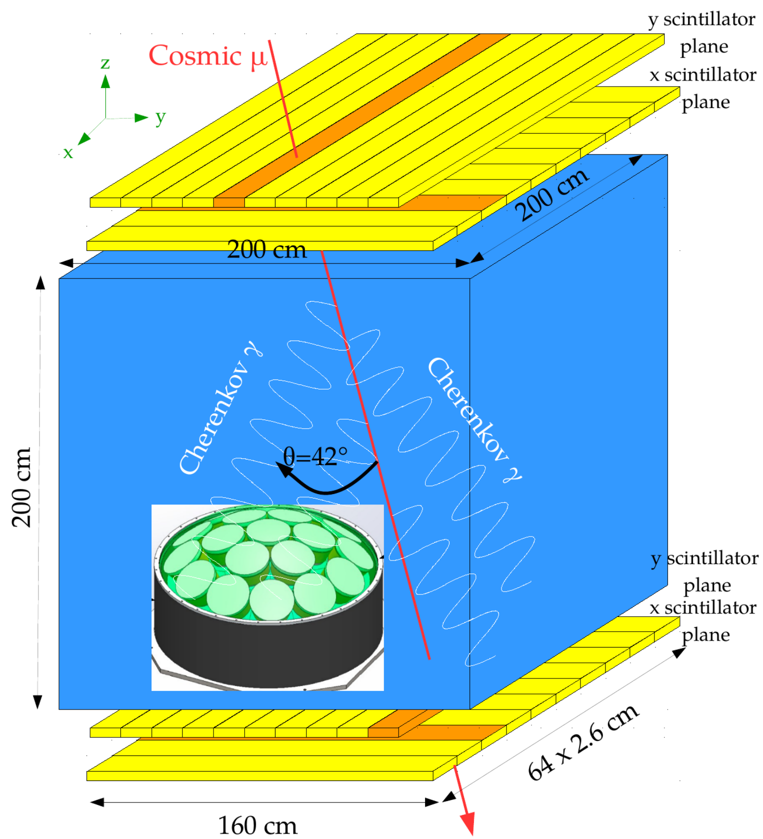
1. Develop the DAQ
→ Integrate scintillators & multiPM in same framework → LPNHE.

2. Construct a rotation support for mPMT → LPNHE & LLR.

3. Upgrade the tank w/ calibration source (LED etc.).

4. Test Italian mPMT w/ cosmics.

5. Test Japan/Canadian mPMT w/ cosmics.



Conclusions and plans

- The multi-PMTs allows to enhance HK physics capabilities in both low (solar) and high energy (CPV, p-decay etc) sectors.
  + are the primary candidates for HK intermediate detector.

- Propose a new collaboration between LPNHE/LLR/CEA & University of Tokyo/TIT/TUS in order to :
  - Develop simulation & reconstruction tools at low & high energy
    → New sensitivity studies & direct work for final HK softwares.

  - Proceed to the very first test of the mPMT in water (2019-2020)
    → 1st milestone towards their use in HK.
    → Select mPMT & electronics design.
    → Development for the HK future DAQ.

- After these successful tests → Plan to pursue them at a more ambitious scale → Install water Cherenkov w/ mPMTs @CERN in 2021.

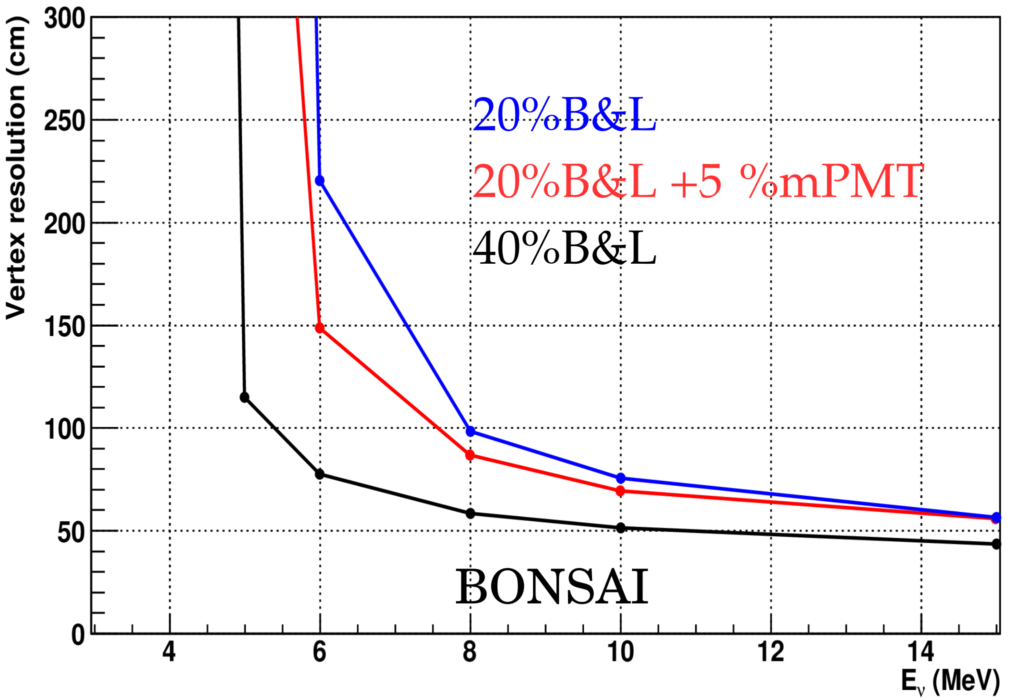
Additional slides

I. Low energy

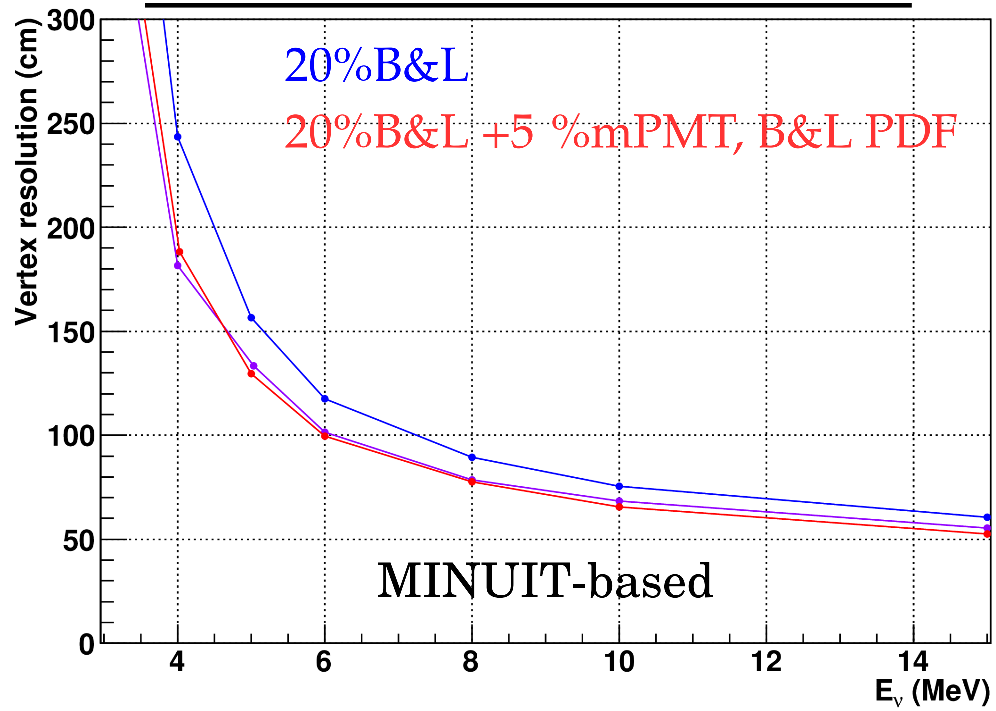
Low energy impact

- New low energy fitter to properly compare the configurations.
- Performances are increased compared to BONSAI.

BONSAI :Vertex resolution



MINUIT :Vertex resolution



- Vertex resolution clearly improved with mPMTs.

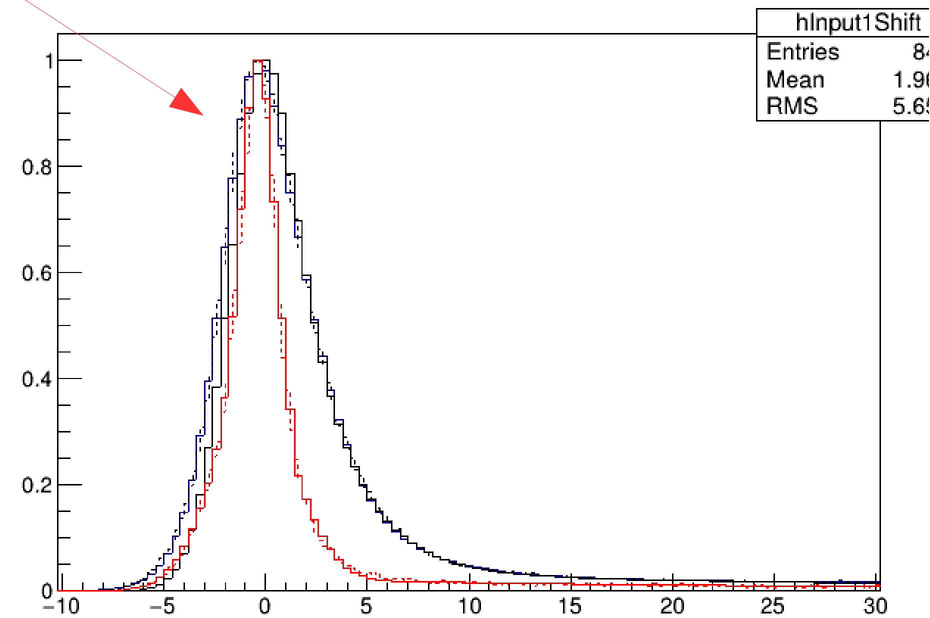
New fitter

- <u>Maximize :</u> $L(\text{vertex at } t, \tilde{X}) = \Pi_{i=hits} P(\text{ time} - \text{tof} - t_{vertex} \mid \text{vertex at } t, \tilde{X})$.

- <u>Principles :</u>

1. A coarse GRID search in the tank using 3m / 12 ns steps.

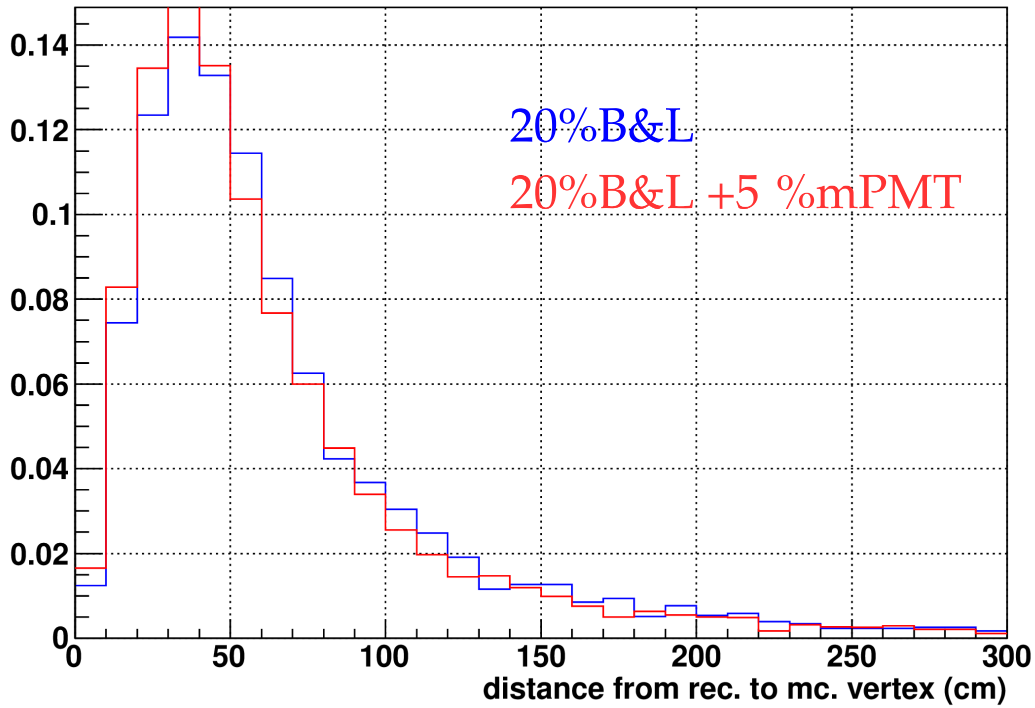
2. A minimization using MINUIT in a 3m / 12ns radius sphere around the candidate.



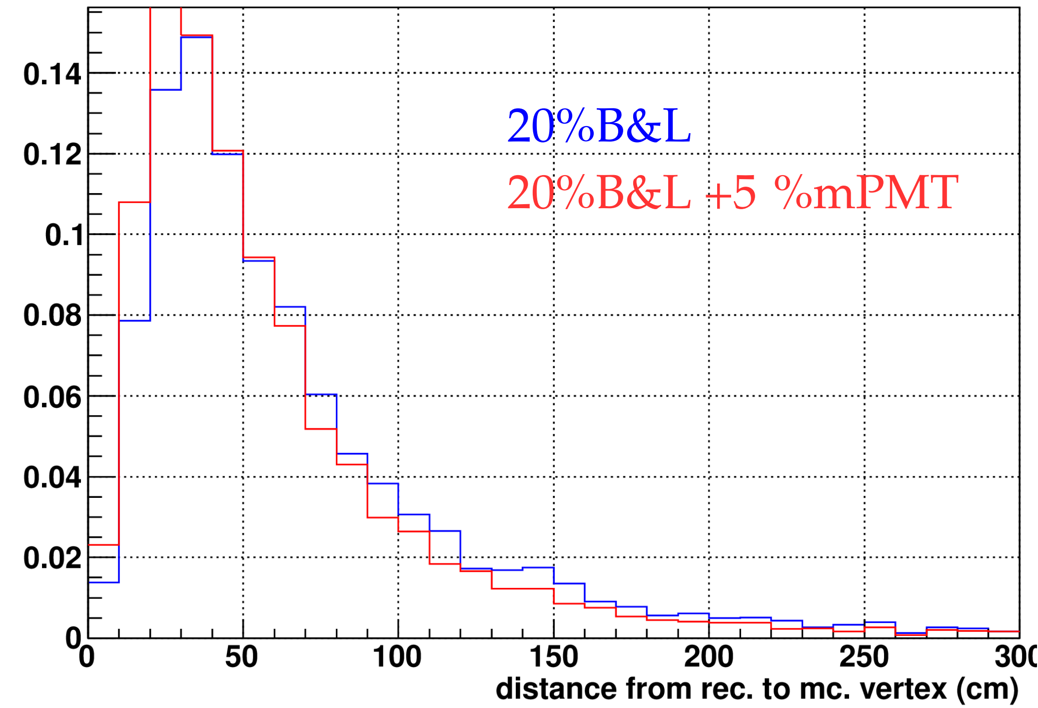
→ Details provided in last week software meeting + back-up slides

Results for 10 MeV electrons

Vertex resolution, 10 MeV, BONSAI



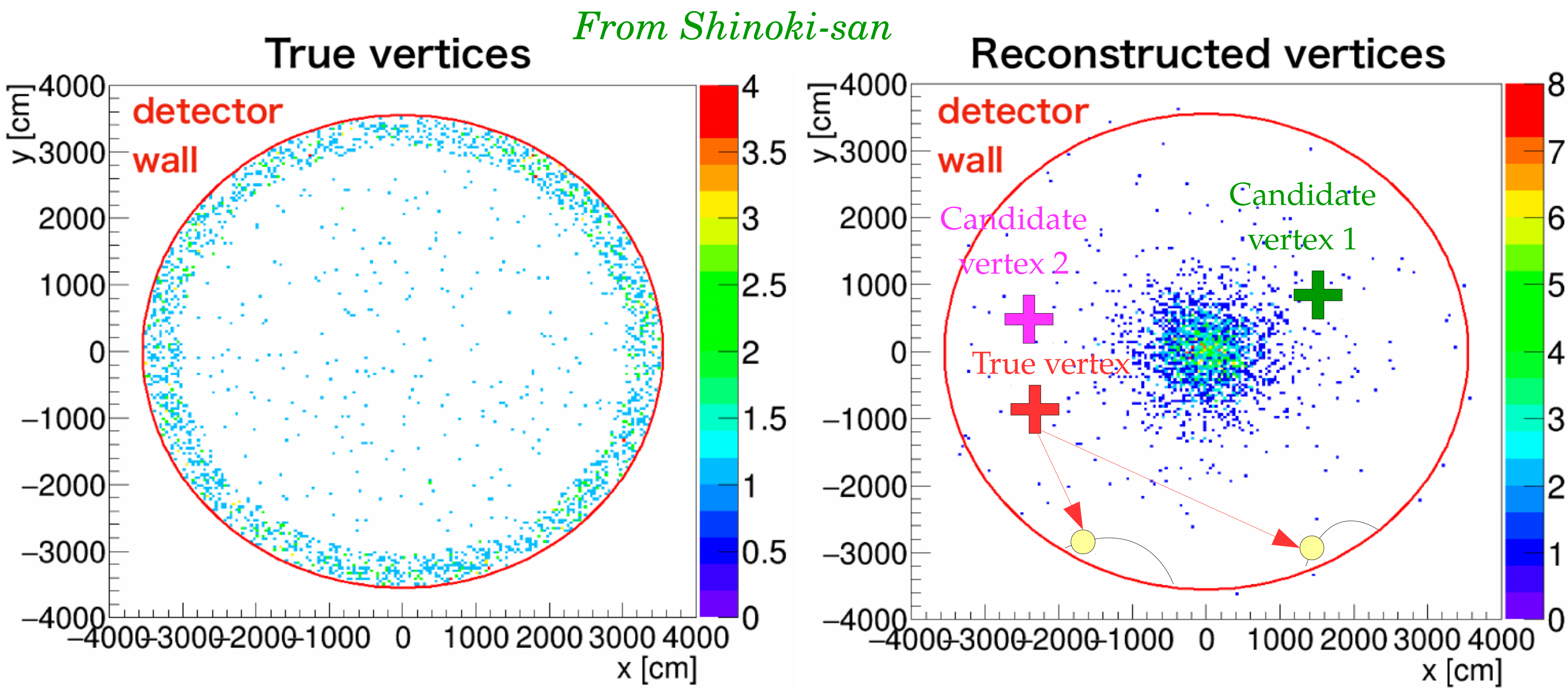
Vertex resolution, 10 MeV, MINUIT



	Vertex resolution (cm)	Direction resolution (°)
20%B&L	77 cm → 77 cm	33.3°
20%B&L +5 %mPMT	70 cm → 65 cm	31.5°

- Results same as BONSAI ! → Show both that new algorithm works well, and that both algorithms uses well all information of time PDF (otherwise, unlikely to find exactly same result)

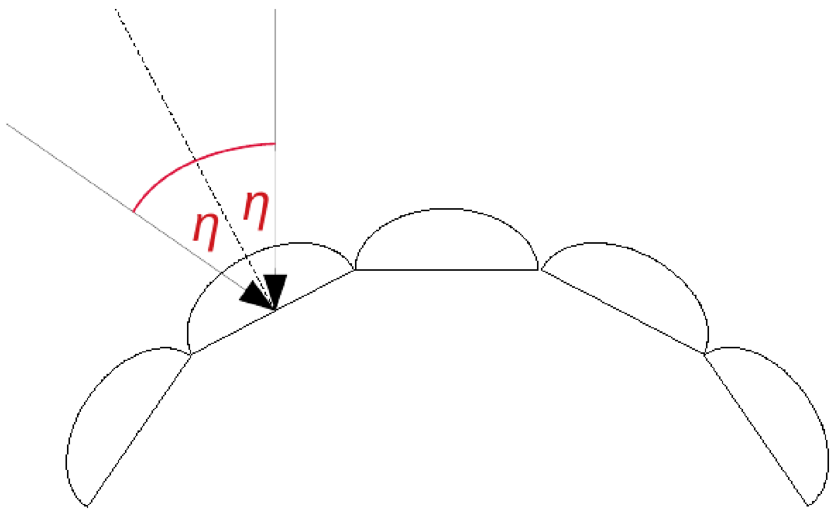
mPMT directionality

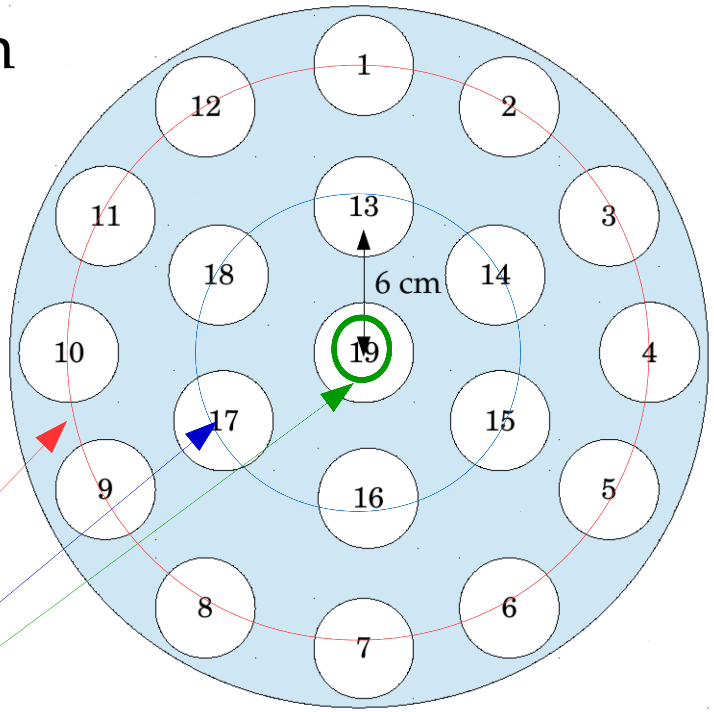


- The mPMT hit should point in average towards the true vertex (almost no dark rate hits for 3'' PMTs)
  → Help to discriminate candidate vertices from B&L PMTs that are degenerate due to dark rate.

mPMT directionality

- Effect of directionality is not the same for each PMT on the mPMT.



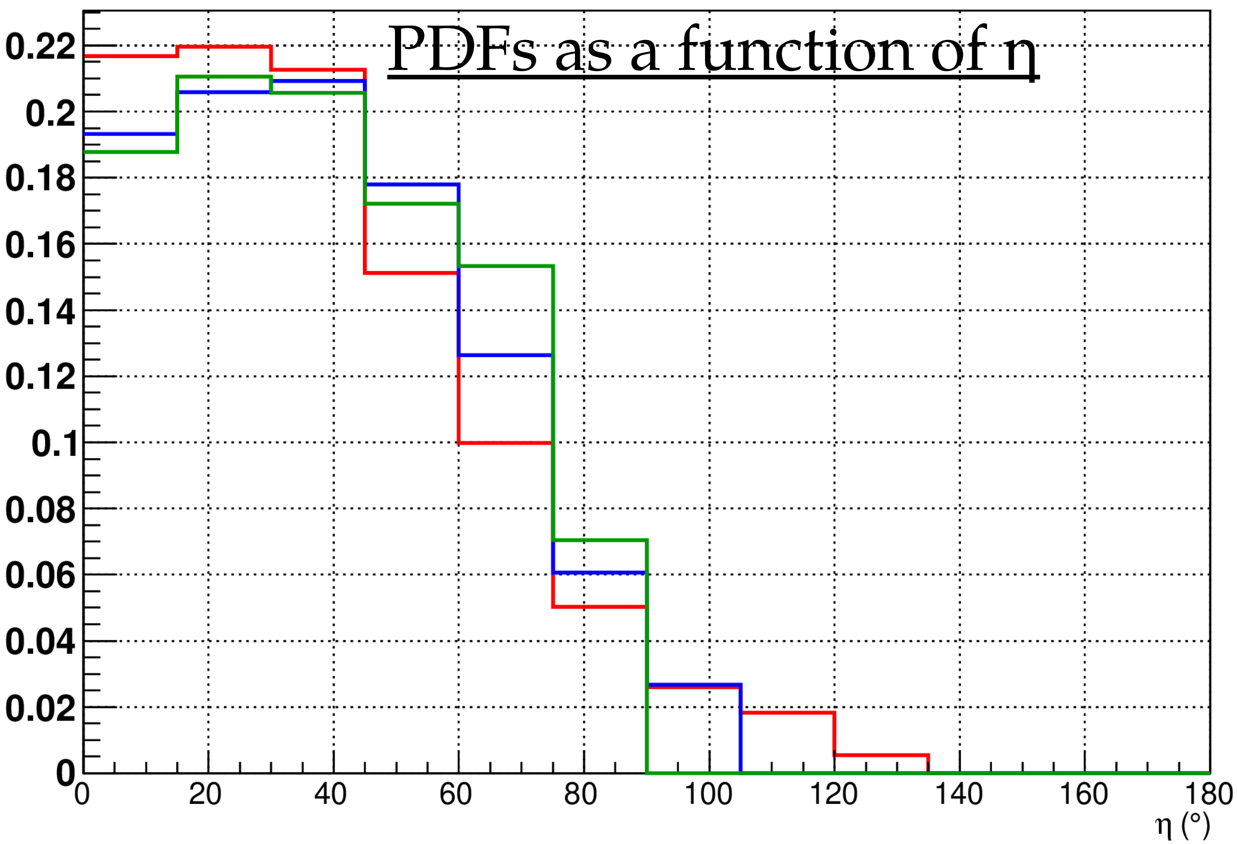


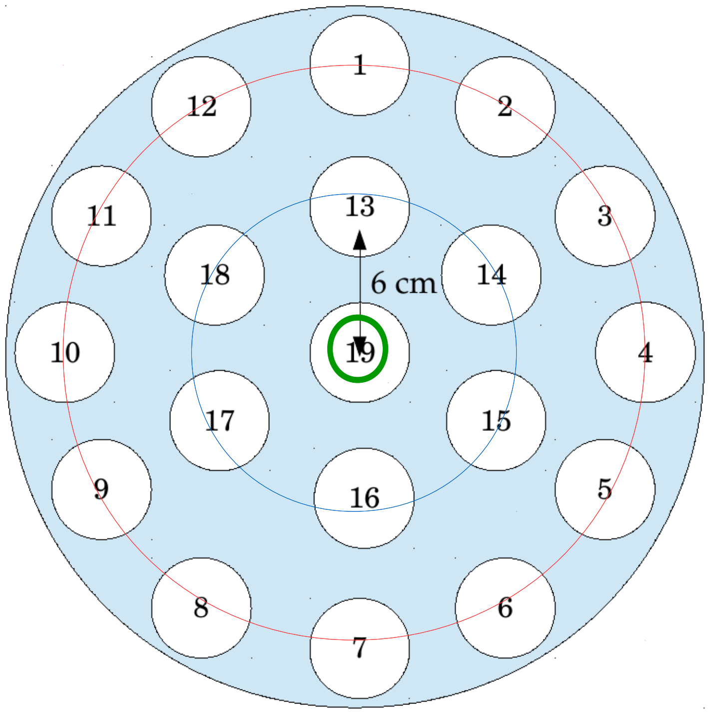
- It dominantly affect the PMTs on the edges of the mPMT.

- Basically 3 groups of PMTs.

- <u>Note :</u> there is also a little dependency within these 3 groups → I put it in the code but did not used it for today (processing time is long!)

mPMT directionality



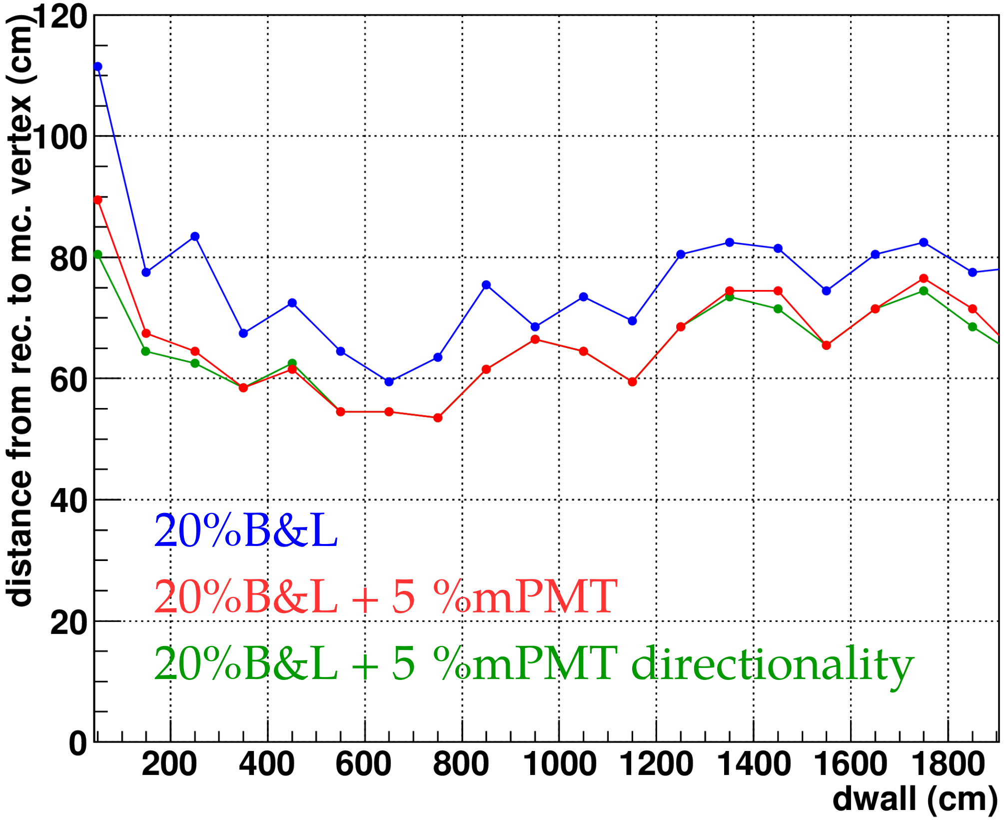


- Efficiency should fall > 90°, apart from scattering / reflection.
  → ≠ between groups > 90° due to non total cover of vertices in FV.

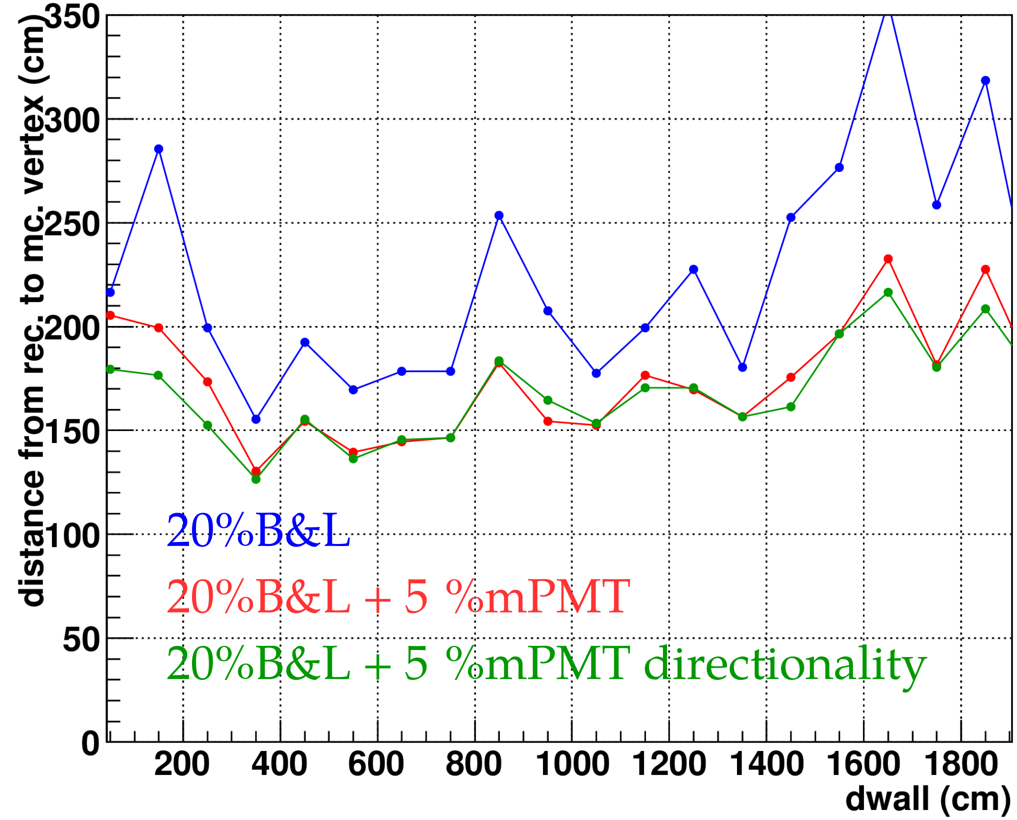
- The more on the edge, the more the efficiency can fall as light can be screened by other PMTs on the same module.

Impact of mPMT on FV

10 MeV electrons



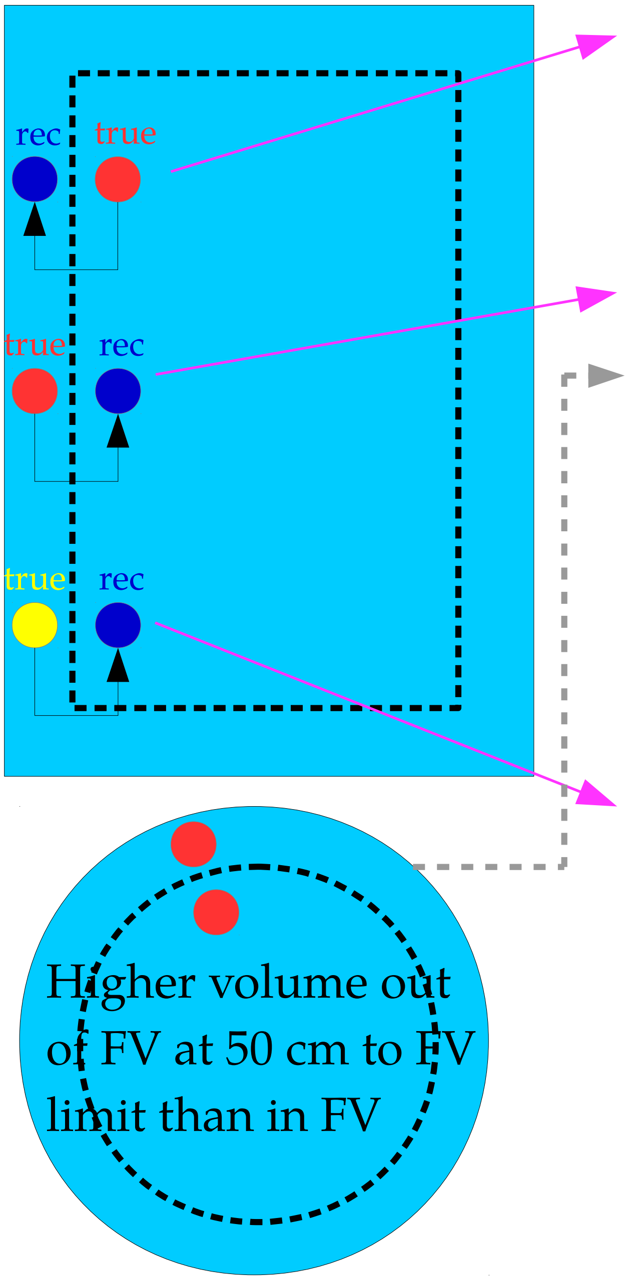
4 MeV electrons



- For 10 Mev electrons, ~10cm difference in vertex resolution in average.
  → Difference rise to 32 cm at 100 cm from the wall.

- Clear impact of directionality near the wall → Expected, but confirm implementation generally works.

Increasing the Fiducial Volume



Case 1 : Signal migration in → out FV

Case 2 : Signal migration out → in FV

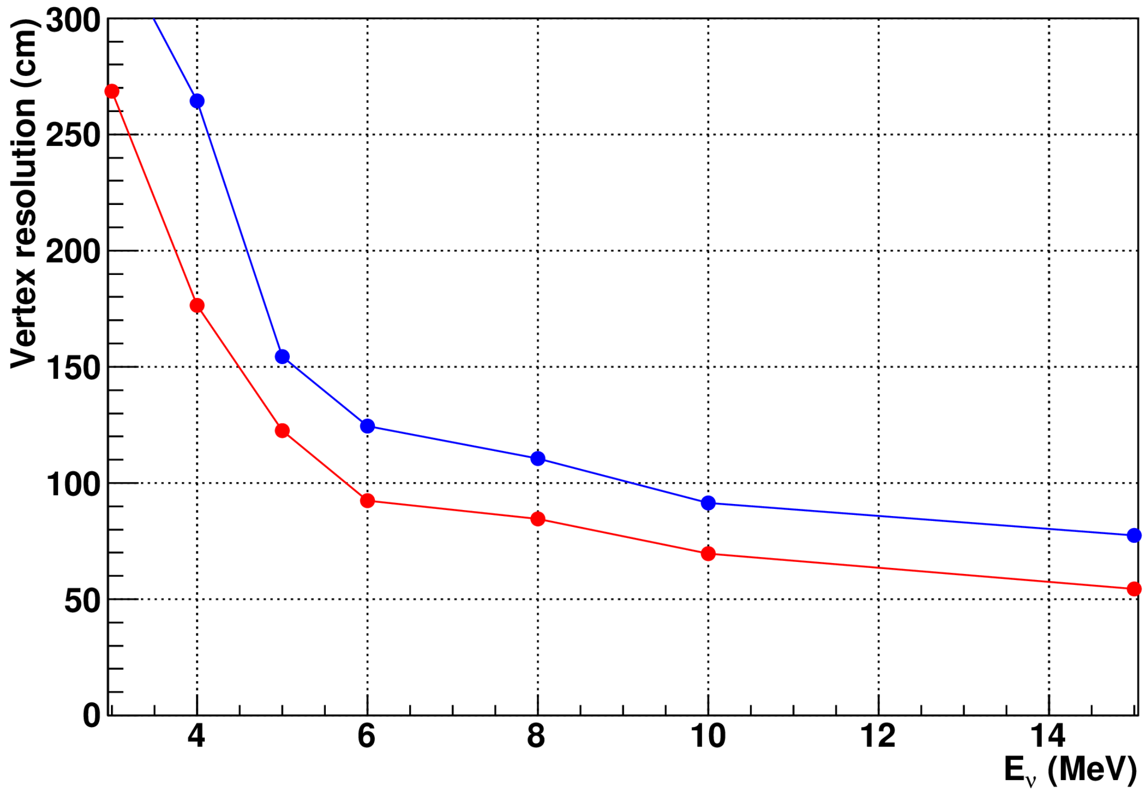
- Not equal to in → out migration
- Number of events in FV is increased.
- But, this increase can be corrected by MC

Case 3 : background migration out → in FV.

- Not compensated for bkg from PMT or rock.
- Partially compensated for bkg in water, but not perfectly (same as case 1 vs 2).
- As background simulation is poor → large systematics that is propagated in FV.

Increasing the Fiducial Volume

- FV in SK for LE is defined as dWall ≥ 2m. How many events out of FV can migrate ?



- ≥ 5 MeV : Increase of FV by 30-40cm → 3-4 % gain in statistics.

- But background comes ≤ 5 MeV → Increase of 90 cm at 3 and 4MeV.
  <u>→ 10 % increase in statistics in total.</u>

II. High energy

Event display for 20 % B&L + 5k mPMT

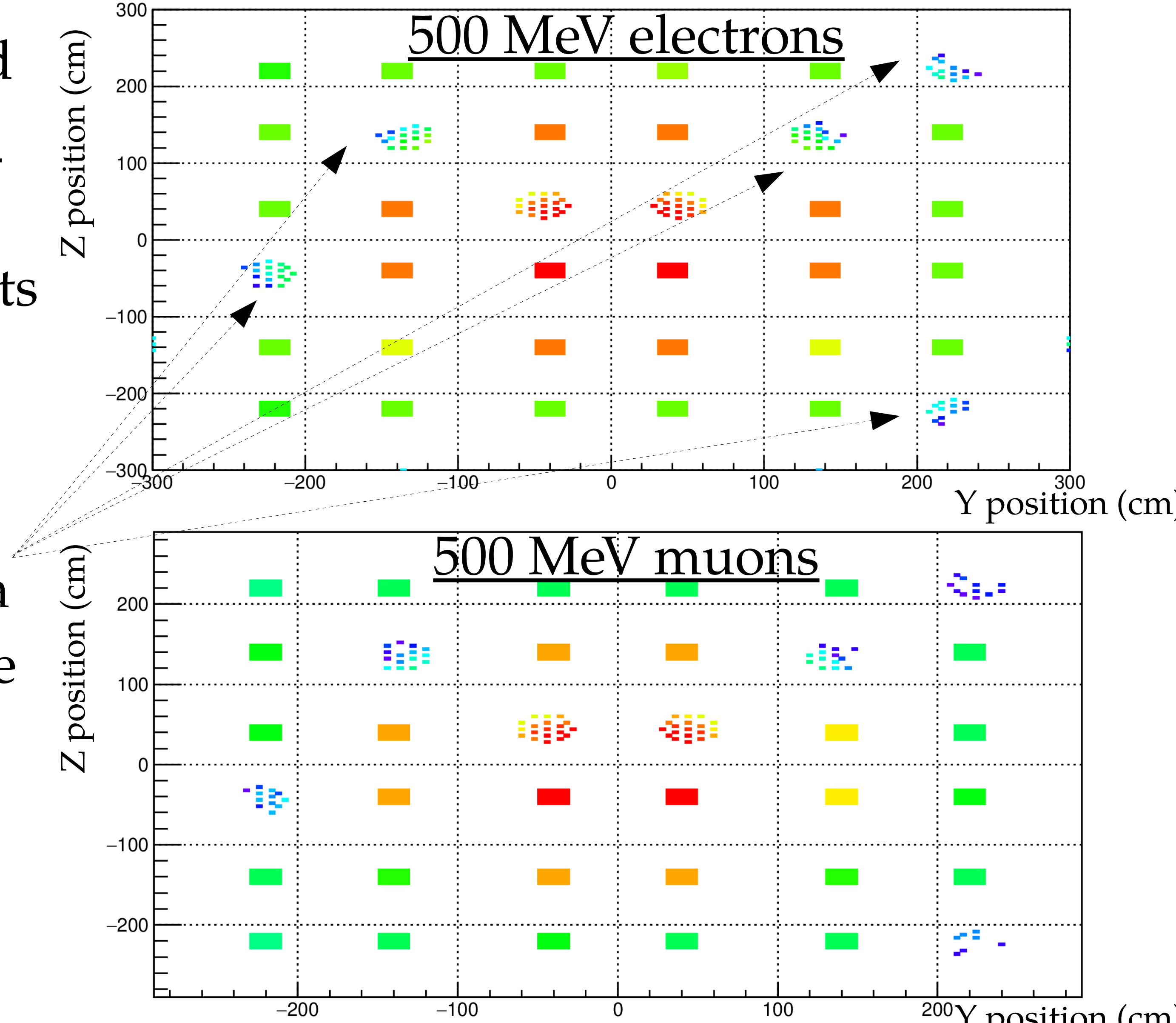
- Can we improve PID and Fiducial volume using multi-PMT ?

- μ & e events generated at 1.5 m from the wall.

- Can identify μ/e events here w/o mPMT?
  → Limited to 2 hits.

- Adding mPMT helps a lot in separation by eye

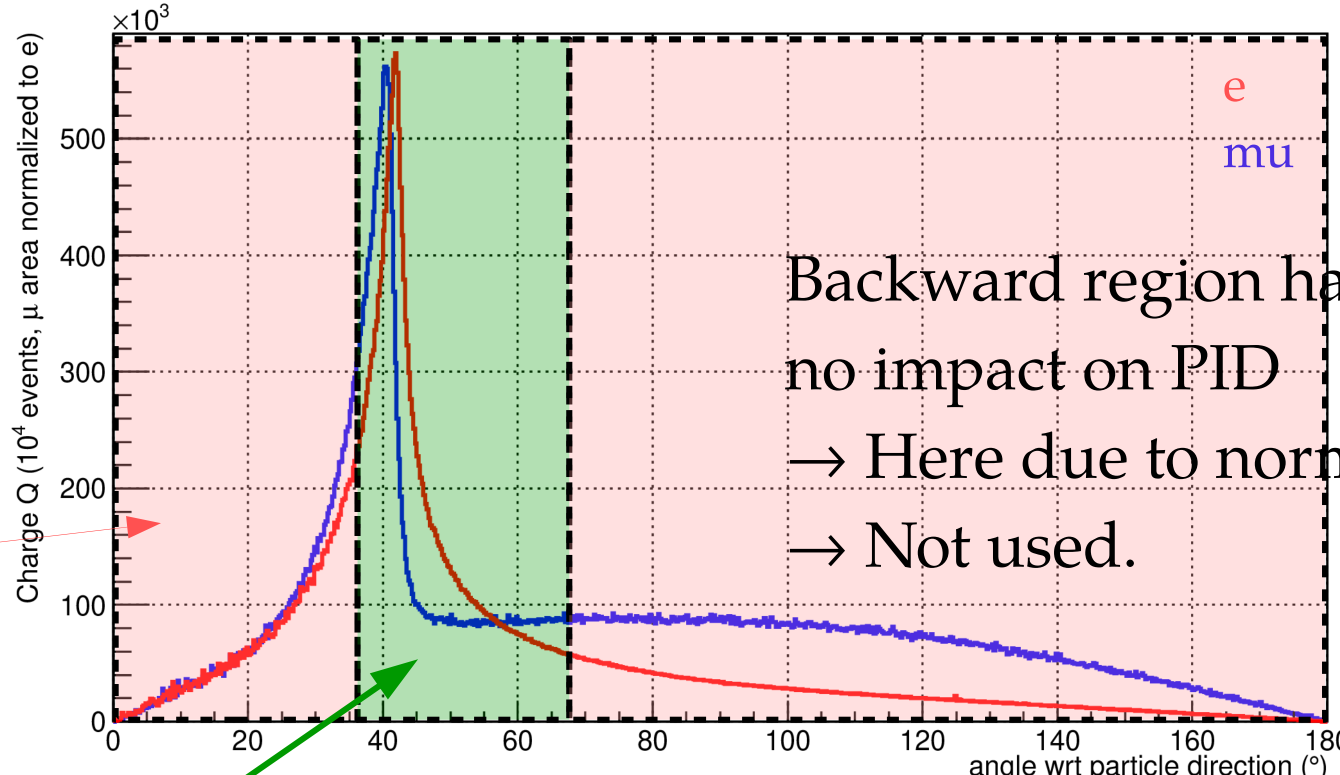
- How much is the quantative impact ?



Developing a simplified PID

- PID based on the charge profile

Charge profile highly vary depending if particle stops in or out of HK
→ Not used



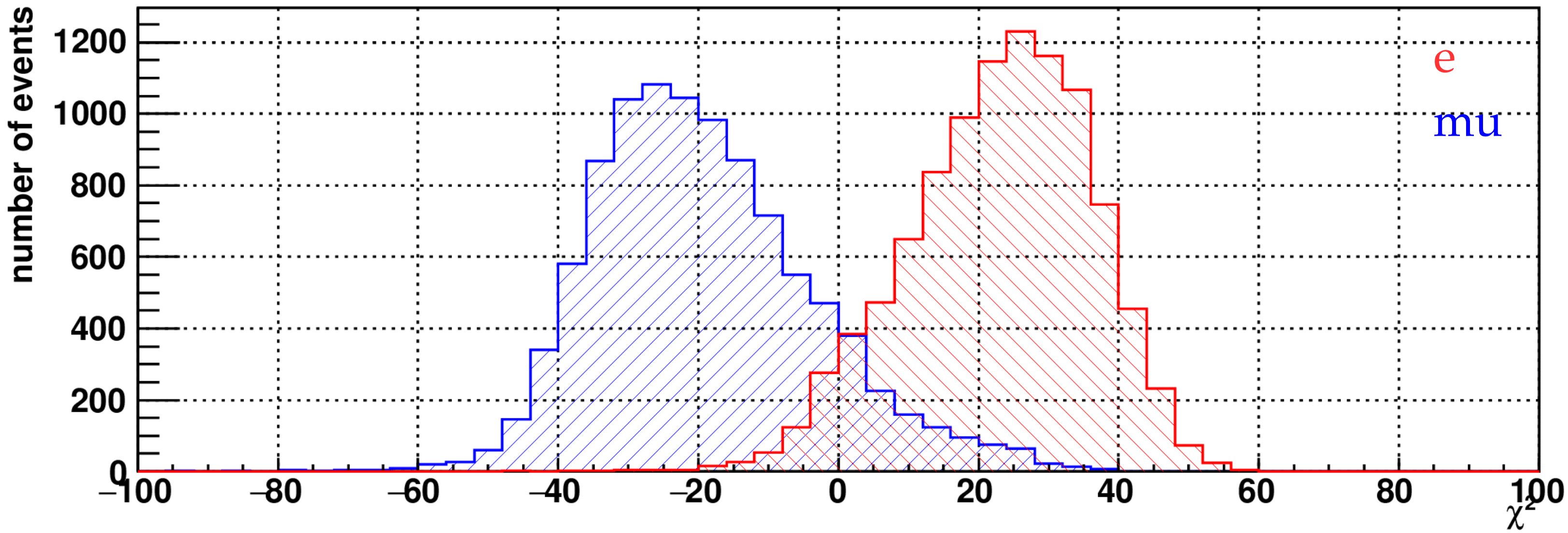
Backward region has almost no impact on PID
→ Here due to normalization
→ Not used.

- Build a χ^2 in the 38-65° region.

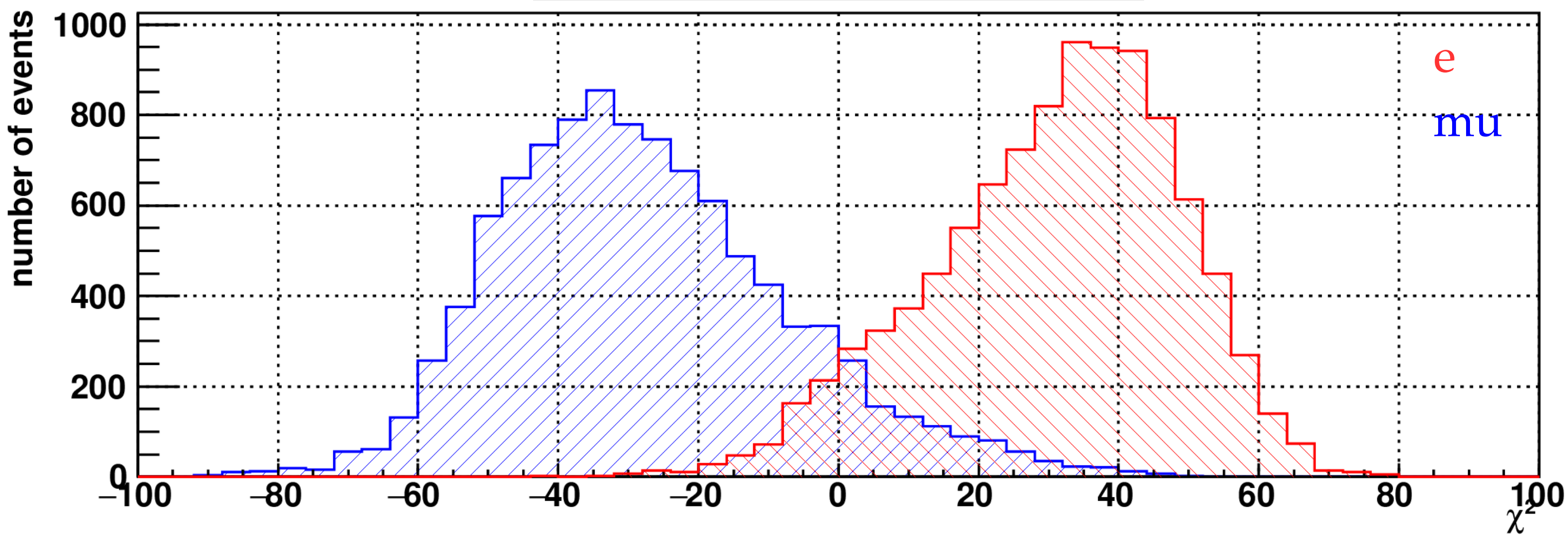
- Region has been chosen to contain the peaks of muon / electron. It can be extended over 65° region without damaging the PID.

Separation power of the PID

20 % B&L

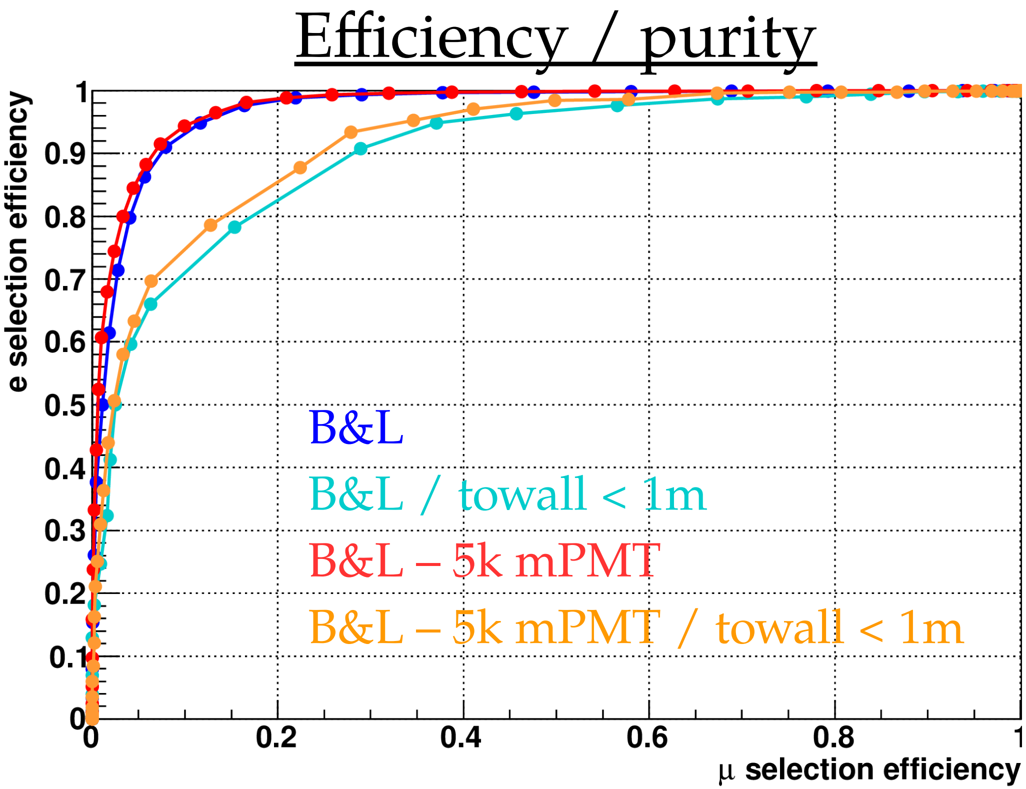


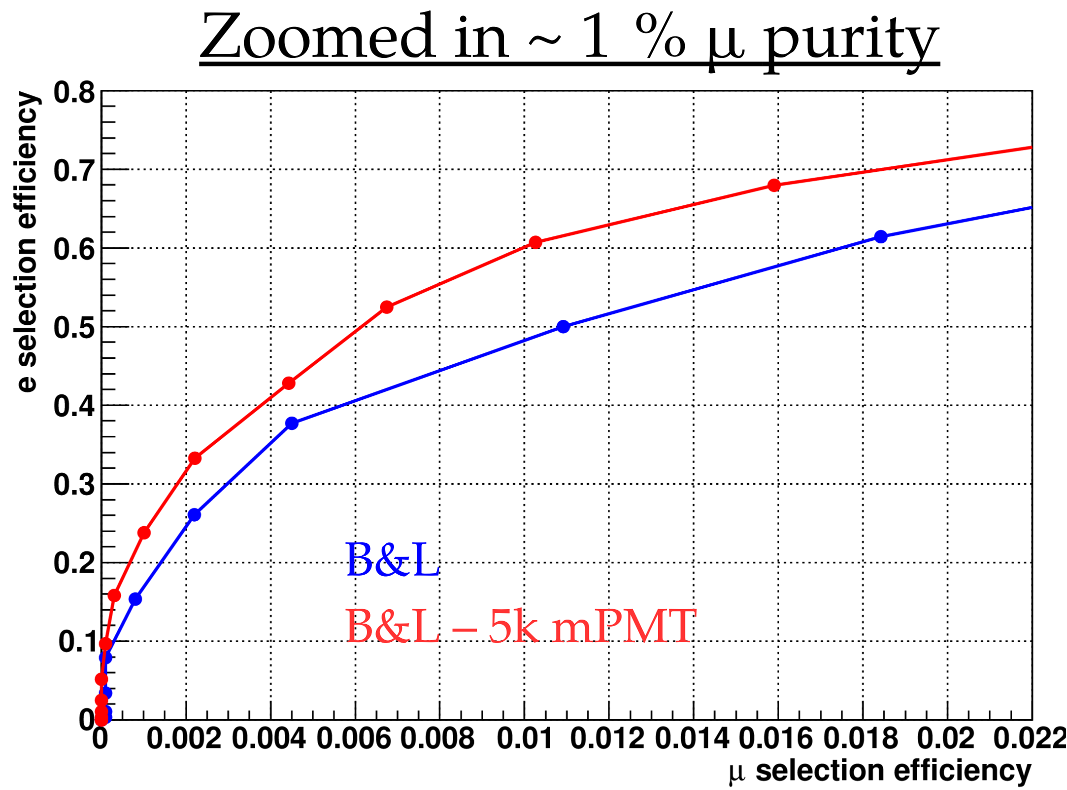
20 % B&L + 5k mPMT



Separation power of the PID

- Build an efficiency / purity curve based on the PID.





- mPMT improves performances, main impact close to the wall.

- At 1 % μ purity, efficiency is 48 % for B&L-only and 60 % for hybrid
→ Increase statistics by 25 % through FV enlargement.