Neutron Vertex Reconstruction For The Surface Detector

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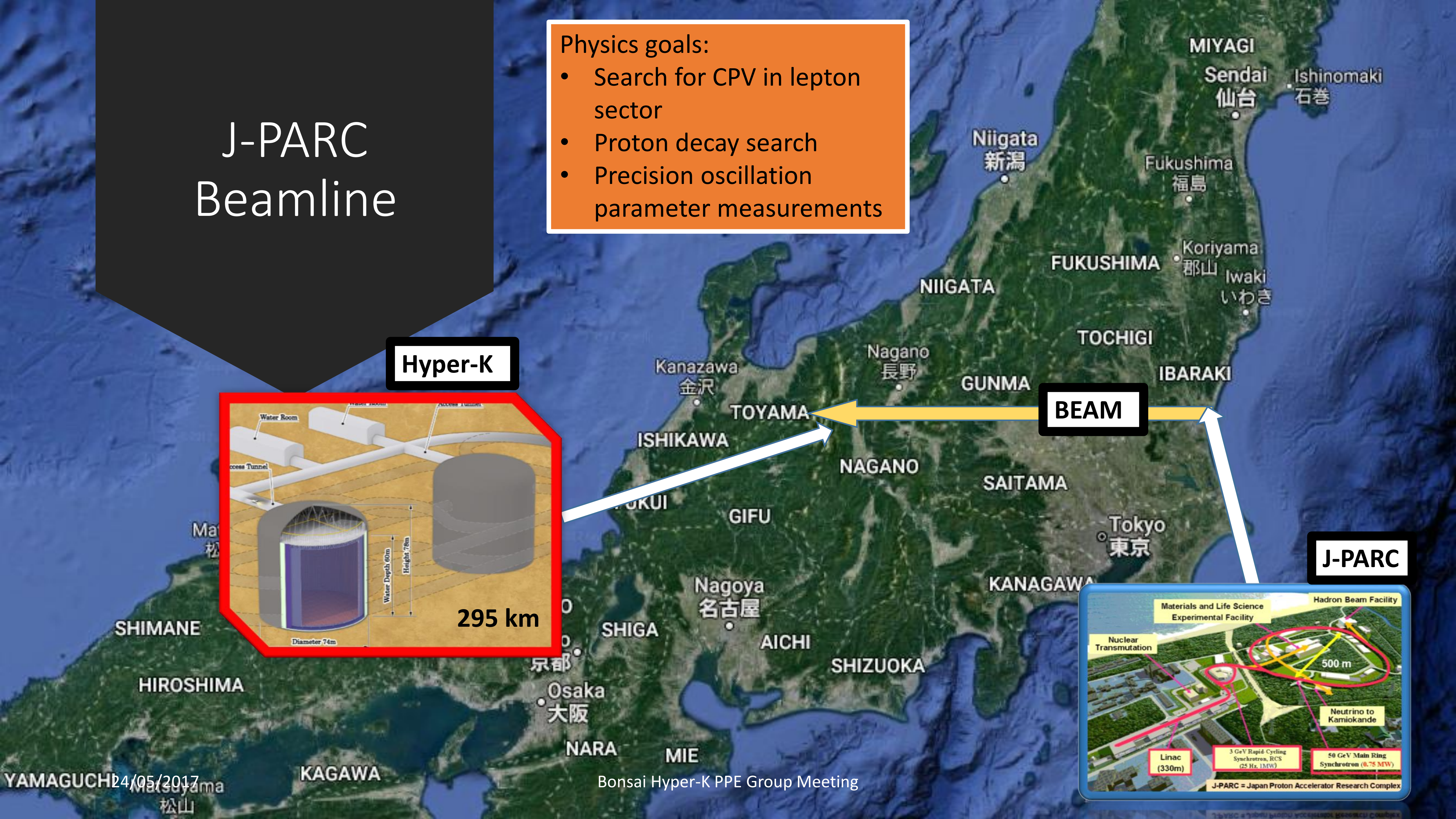
Outline

- Hyper-Kamiokande
- Intermediate detector
- BONSAI
- Neutron reconstruction results

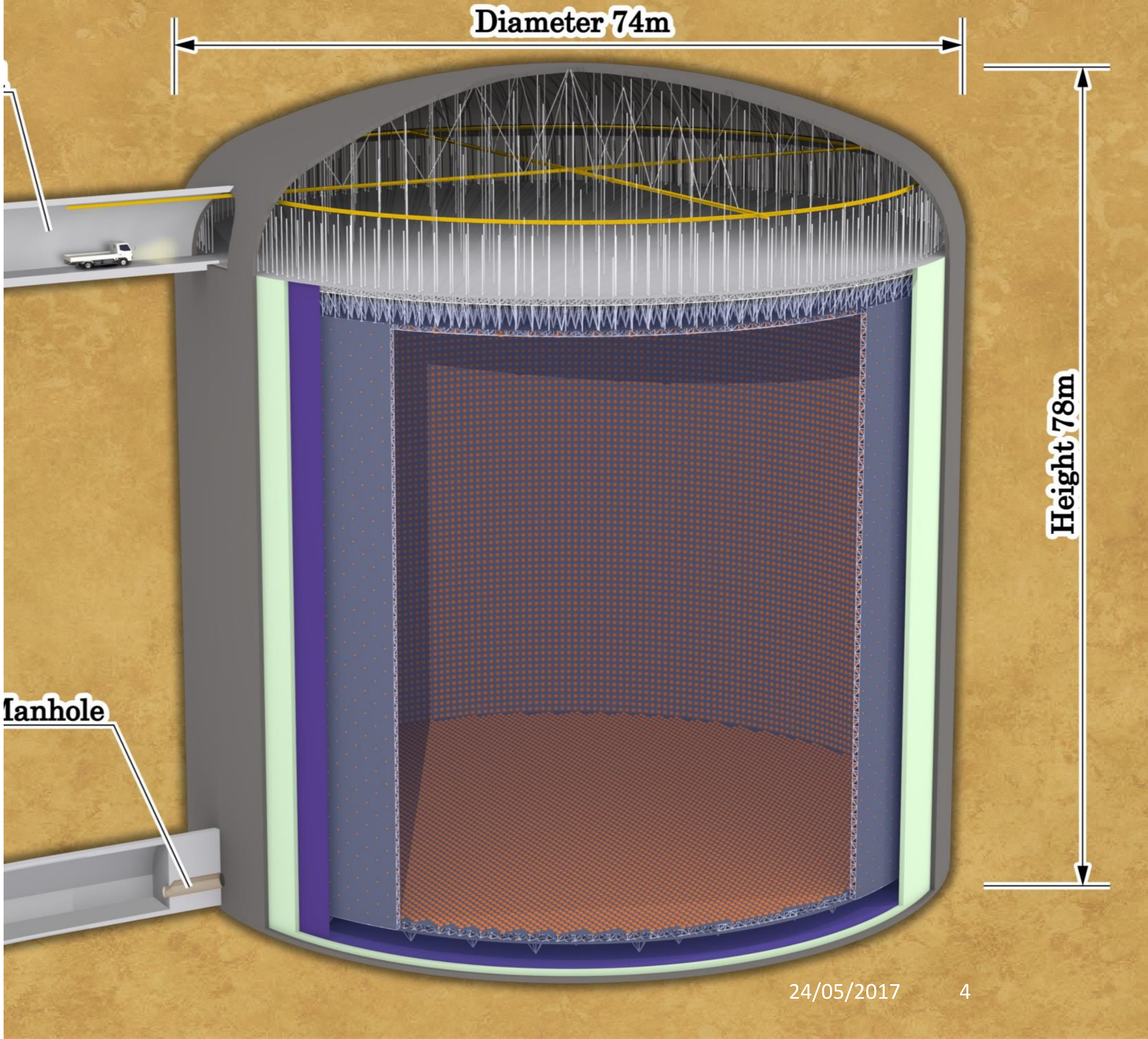
J-PARC Beamline

Physics goals:
- Search for CPV in lepton sector
- Proton decay search
- Precision oscillation parameter measurements



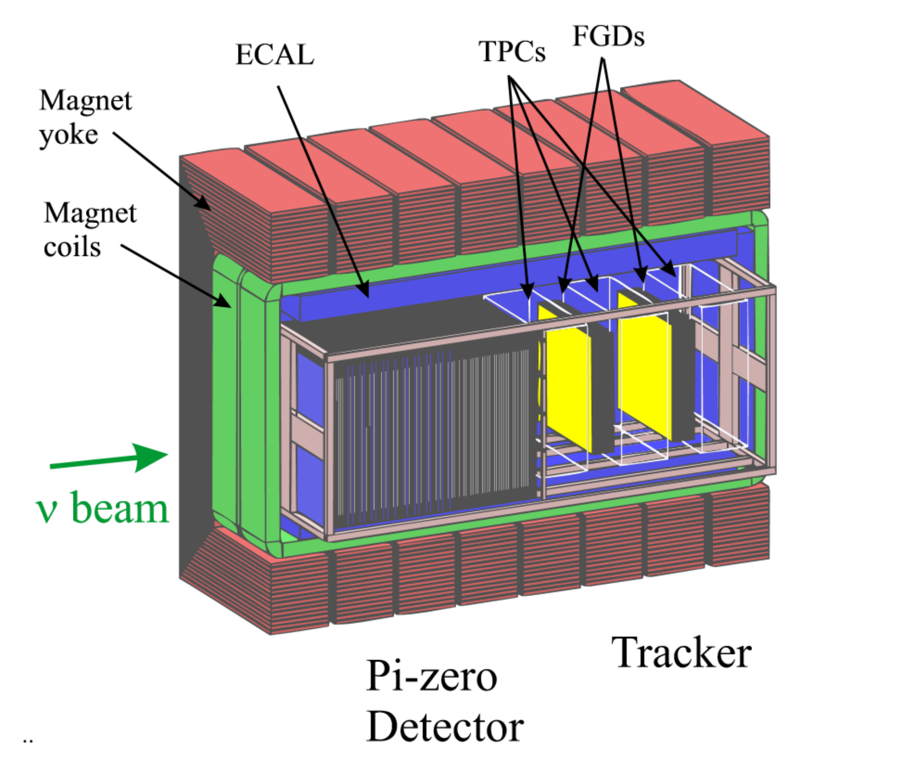
Hyper-K Detector

- Far detector for J-PARC's upgraded 1.3MW beam.
- 2.5° off-axis angle (same as Super-K).
- 40,000 20" PMTs (40% photo-coverage).
- Two cylindrical tanks. The first of which is scheduled to start operation in 2026 and the second tank to start 6 years later.
- Possibility to have the second tank in Korea.



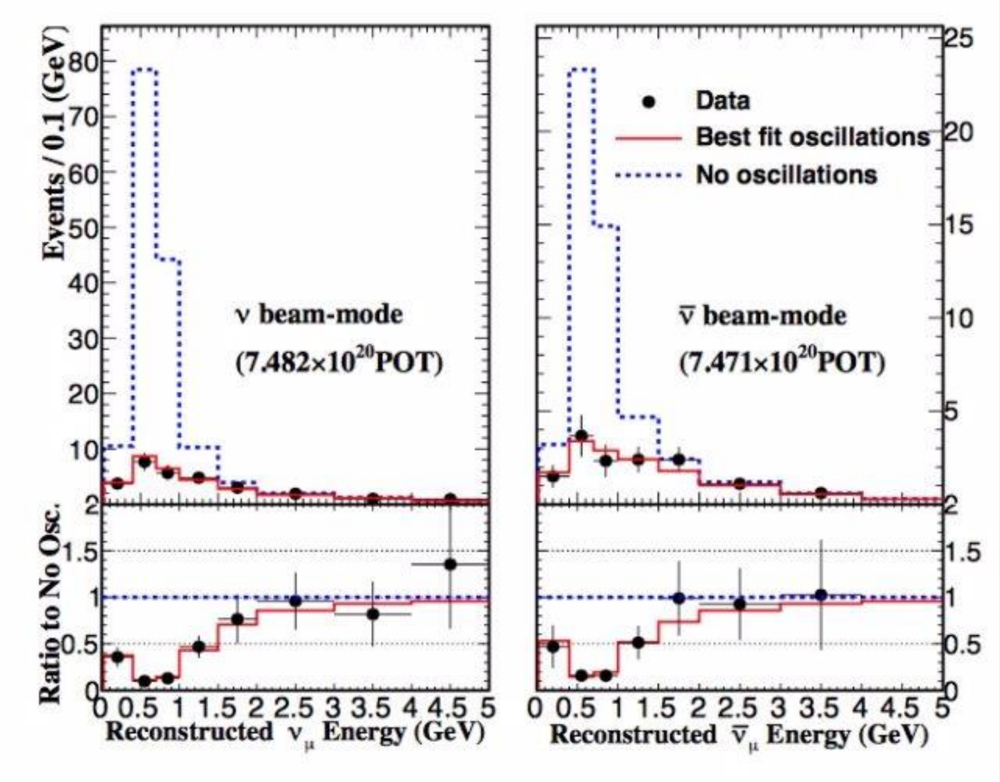
Near Detectors – ND280

- In order to measure the disappearance at the far detector we need something to compare the far detector flux to.
- T2K experiment has a suite of detectors located 280m downstream of the neutrino beam.
    - INGRID on axis detector to measure the direction of the beam.
    - 2.5° off-axis detectors to measure the properties of the neutrino beam such as energy spectrum.



Near Detectors – Problems

- Different target from far detector
- Cross sections poorly known in the few GeV region
- Flux at 280m is different from 295km (Energy spectrum changes shape)
- Can reduce errors to the levels required for Hyper-K by:
  - Placing a detector 1-2km away to know the neutrino energy spectrum (similar to far detector).
  - Using the same nuclear target (H_2O).

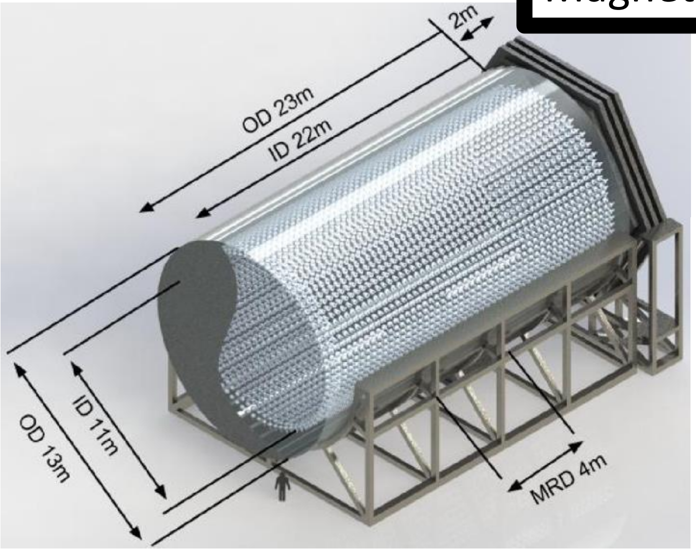


Intermediate Detector

NuPRISM arXiv:1412.3086v2
Off-axis spanning

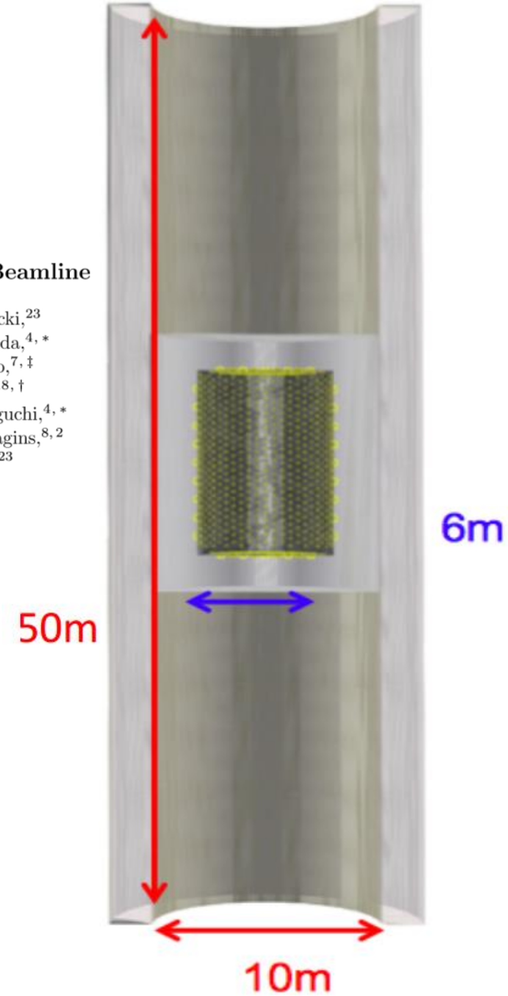
- Two proposed intermediate water Cherenkov detectors (TITUS and NuPRISM).
- Two collaborations merged into one collaboration.
- Final design will keep the off axis spanning and Gd-loading.

TITUS arXiv:1606.08114v2
Gd-loading
Magnetised MRD



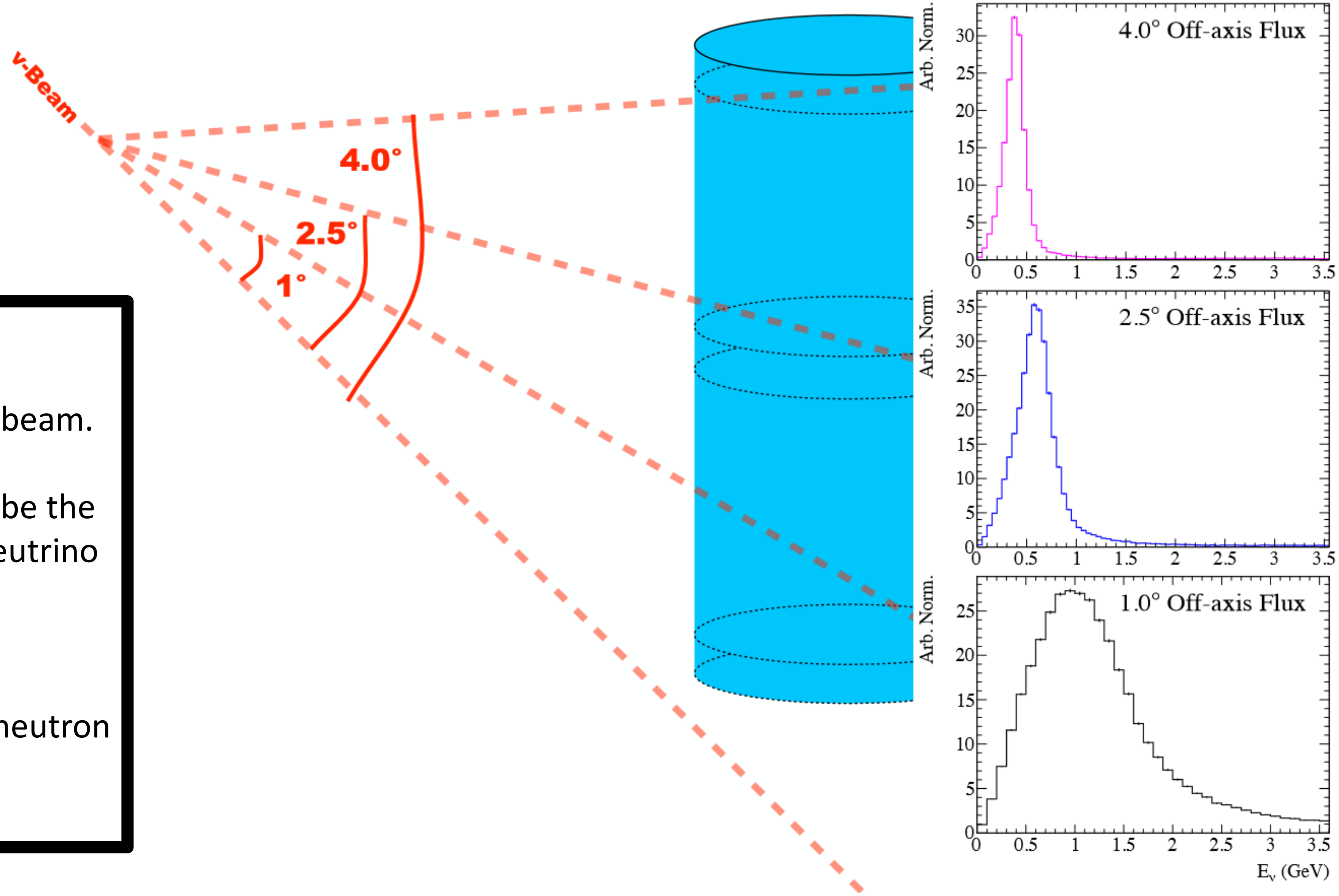
Letter of Intent to Construct a nuPRISM Detector in the J-PARC Neutrino Beamline

S. Bhadra,[24] A. Blondel,[3] S. Bordoni,[5] A. Bravar,[3] C. Bronner,[9] J. Caravaca Rodríguez,[5] M. Dziewiecki,[23] T. Feusels,[1] G.A. Fiorentini Aguirre,[24] M. Friend,[4,*] L. Haegel,[3] M. Hartz,[8,22] R. Henderson,[22] T. Ishida,[4,*] M. Ishitsuka,[20] C.K. Jung,[11,†] A.C. Kaboth,[6] H. Kakuno,[25] H. Kamano,[13] A. Konaka,[22] Y. Kudenko,[7,‡] M. Kuze,[20] T. Lindner,[22] K. Mahn,[10] J.F. Martin,[21] J. Marzec,[23] K.S. McFarland,[15] S. Nakayama,[18,†] T. Nakaya,[9,8] S. Nakamura,[12] Y. Nishimura,[19] A. Rychter,[23] F. Sánchez,[5] T. Sato,[12] M. Scott,[22] T. Sekiguchi,[4,*] M. Shiozawa,[18,8] T. Sumiyoshi,[25] R. Tacik,[14,22] H.K. Tanaka,[18,†] H.A. Tanaka,[1,§] S. Tobayama,[1] M. Vagins,[8,2] J. Vo,[5] D. Wark,[16] M.O. Wascko,[6] M.J. Wilking,[11] S. Yen,[22] M. Yokoyama,[17,†] and M. Ziembicki[23]
(The nuPRISM Collaboration)



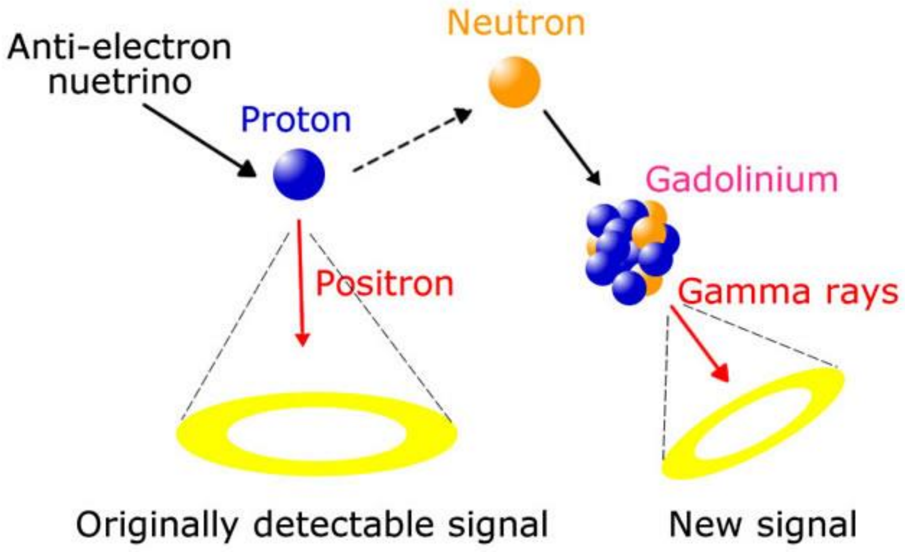
TITUS: the Tokai Intermediate Tank for the Unoscillated Spectrum

C. Andreopoulos [*15], F.C.T. Barbato[3], G. Barker[17], G. Barr[9], P. Beltrame[13], V. Berardi[2], T. Berry[11], A. Blondel[14], S. Boyd[17], A. Bravar[14], F.S. Cafagna[2], S. Cartwright[16], M.G. Catanesi[2], C. Checchia[4], A. Cole[16], G. Collazuol[4], G.A. Cowan[13], T. Davenne[12], T. Dealtry[7], C. Densham[12], G. De Rosa[3], F. Di Lodovico[10], E. Drakopoulou[13], P. Dunne[1], A. Finch[7], M. Fitton[12], D. Hadley[17], K. Hayrapetyan[10], R.A. Intonti[2], P. Jonsson[1], A. Kaboth[*11], T. Katori[10], L. Kormos[7], Y. Kudenko[6], J. Lagoda[8], J. Lasorak[10], M. Laveder[4], M. Lawe[7], P. Litchfield[1], A. Longhin[4], L. Ludovici[5], W. Ma[1], L. Magaletti[2], M. Malek[16], N. McCauley[15], M. Mezzetto[4], J. Monroe[11], T. Nicholls[12], M. Needham[13], E. Noah[14], F. Nova[12], H.M. O'Keeffe[7], A. Owen[10], V. Palladino[3], D. Payne[15], J. Perkin[16], S. Playfer[13], A. Pritchard[15], N. Prouse[10], E. Radicioni[2], M. Rayner[14], C. Riccio[3], B. Richards[10], J. Rose[15], A.C. Ruggeri[3], R. Shah[9], Y. Shitov [†11], C. Simpson [‡9], G. Sidiropoulos[13], T. Stewart[12], R. Terri[10], L. Thompson[16], M. Thorpe[12], Y. Uchida[1], D. Wark[*9], M.O. Wascko[1], A. Weber [§12], and J.R. Wilson[10]



- 1-2km distance.
- Pseudo-monoenergetic beam.
- Off-axis spanning to probe the relationship between neutrino energy and final state kinematics.
- Gd loading to measure neutron production.

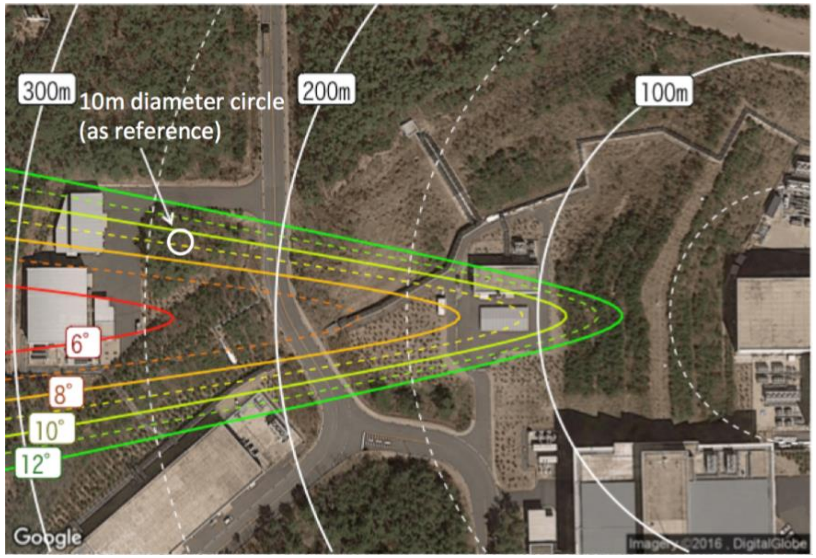
Gadolinium



- A technique gaining more popularity is using Gd to be able to see a neutron capture in a water Cherenkov detector.
- Without Gd neutrons would capture on H releasing a 2.2MeV gamma .
  - Any scattered electron would be close to the Cherenkov threshold and so it makes it difficult to see.
  - Capture of neutron takes ~200µs.
- Gd has a high neutron capture cross section (49000b) and the capture results in a ~8MeV gamma cascade (~5MeV visible).
  - Capture of neutron takes ~20µs.
- 0.1% Gd by mass allows ~90% of all neutron captures to be on Gd.

Phase 0 – Surface Detector

- The intermediate detector will proceed in a phased approach
- The instrumented portion of the detector will be built and placed near ND280.
- Will be able to test the performance of the reconstruction
- Perform a high purity measurement of σ(νe)/σ(νμ)
  - Flux ratio of νe/νμ grows with off-axis angle.
- Measure n-Gd capture from neutrino interactions.



BONSAI

- BONSAI is a low energy vertex reconstruction software that has been used for Super-K.
- Maximum likelihood fit based mostly off of PMT hit timing.
- Can reconstruct electrons as low as 3MeV.

BONSAI

- Defines a list of good hits (causality constraints: $c\Delta t<\Delta x$).

- Time order selected hits and choose a time window to achieve the desired number of 4 hit combinations.

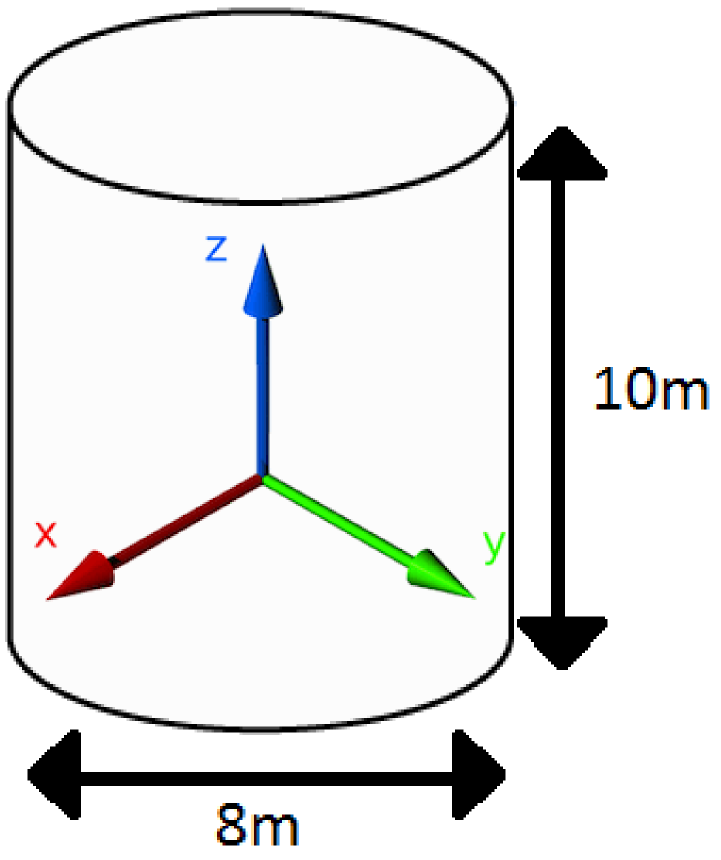
- Draws quadruples from the good hits with each quadruple defining a point in space.

- Reduce the number of points by averaging close neighbours.

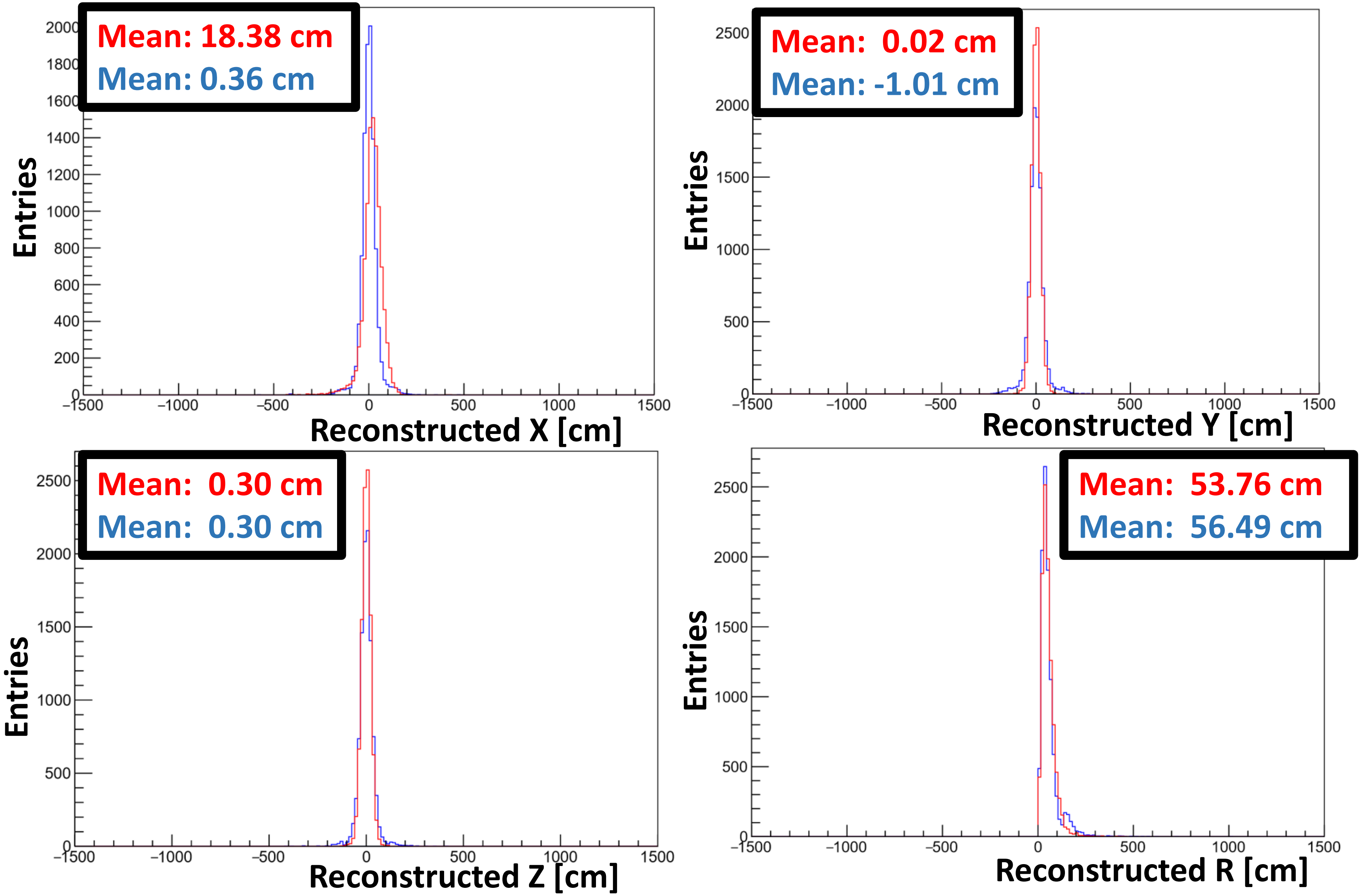
Surface Detector Geometry

Geometry
Diameter : 8m
Height : 10m
Coverage : 40%
Gd : 0.1%

PMT	Dark Rate	Number of PMTs
3 Inch	100Hz	30303
8 Inch	3kHz	4104



Vertex Reconstruction Results



10 000 electrons
10 MeV kinetic energy
8” PMT configuration

-Plots show the difference in the reconstructed vertex and the true vertex.

-Reconstructed R is the 3D difference between the true and reconstructed vertex.

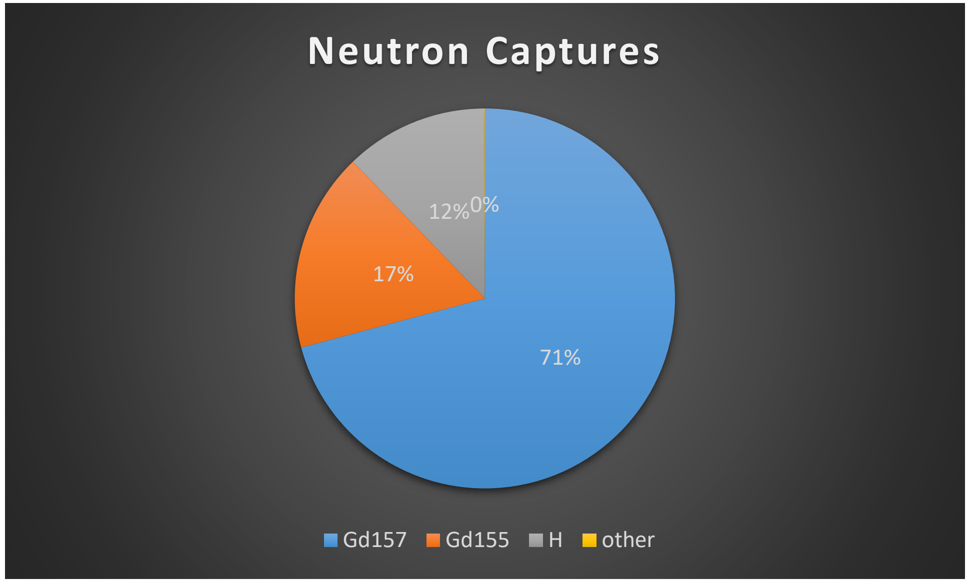
-Bias in x component as electron is moving in the x direction.

-Resolution is defined as the 68th percentile

Vertex Resolution
Dir(1,0,0)Pos(0,0,0): 60 cm
Uniform Isotropic : 57 cm

Neutron Simulation

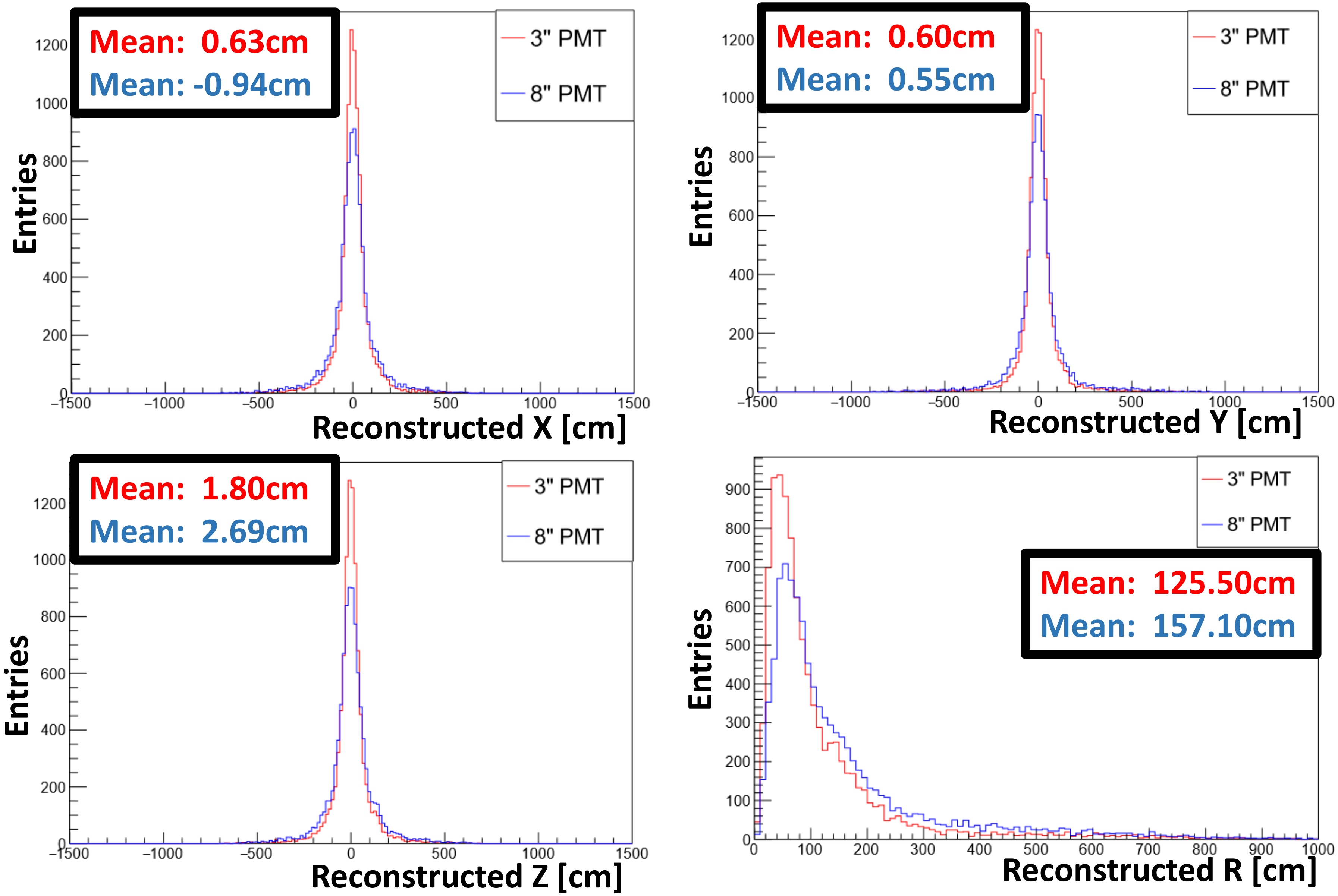
10 000 Neutrons
5 MeV kinetic energy



- 96% of Neutrons captured in tank.
- 88% of captures are on Gd.
- 12% of captures are on H.
- <0.1% of captures are on other isotopes.

- Bonsai reconstructs 98% of captured neutrons.

Vertex Reconstruction Results



10 000 Neutrons
5 MeV kinetic energy

-Plots show the difference in the reconstructed vertex and the true vertex.

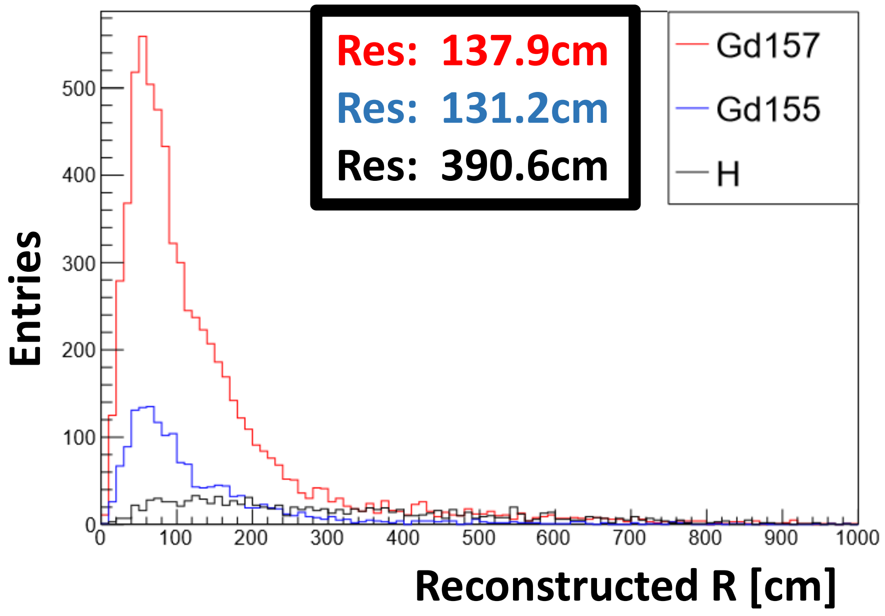
-Reconstructed R is the 3D difference between the true and reconstructed vertex.

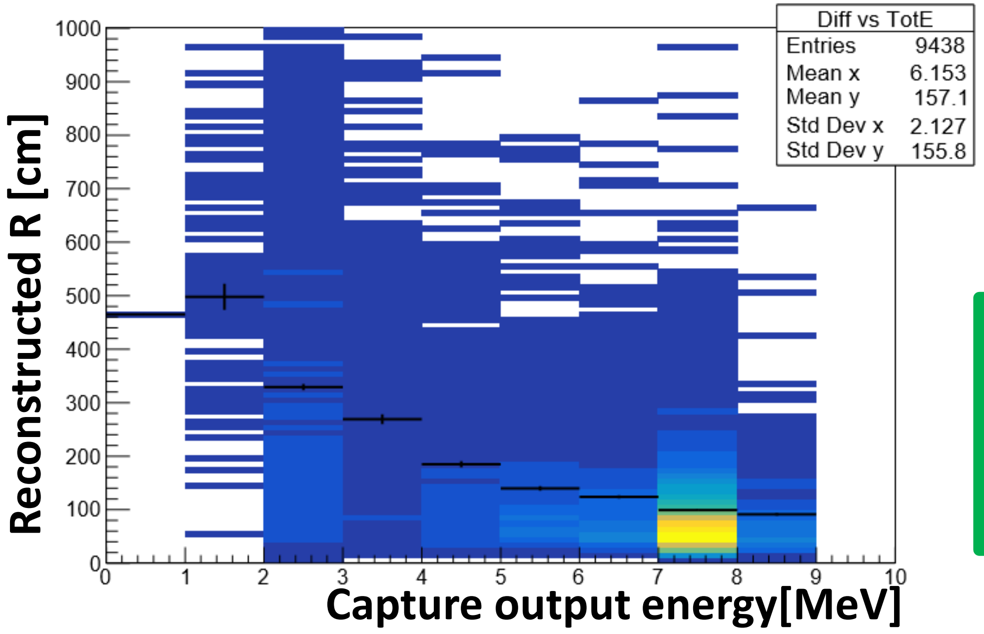
-Results for 3" PMTs are better than 8" PMTs.

-Resolution is defined as the 68th percentile

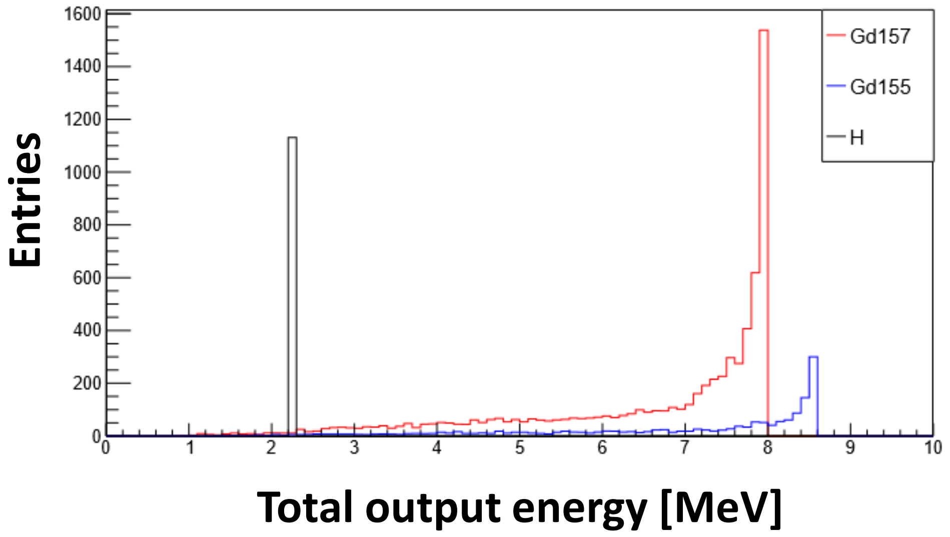
Vertex Resolution
3inch : 109.7 cm
8inch : 155.1 cm

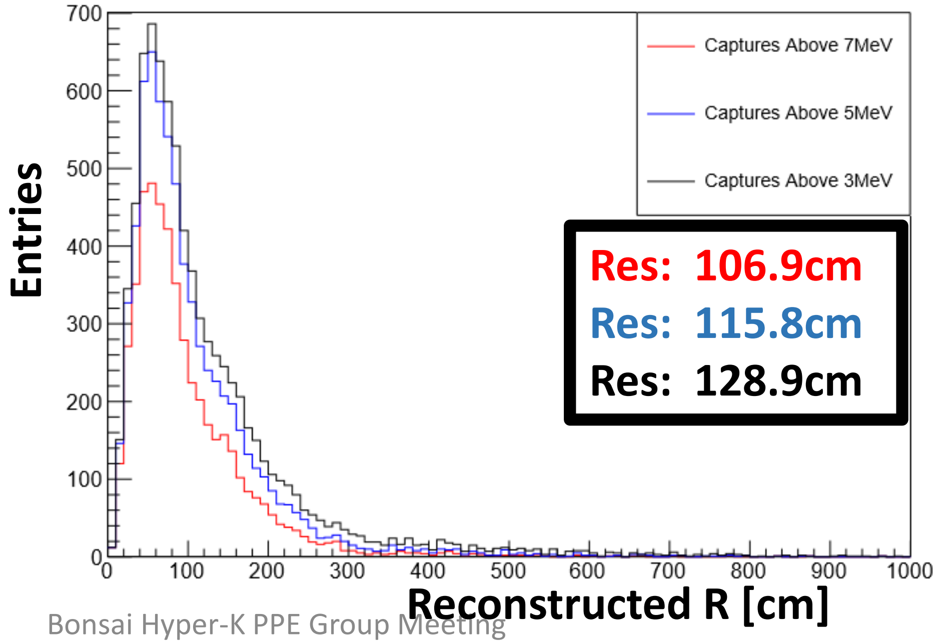
Reconstruction Results Vs Energy



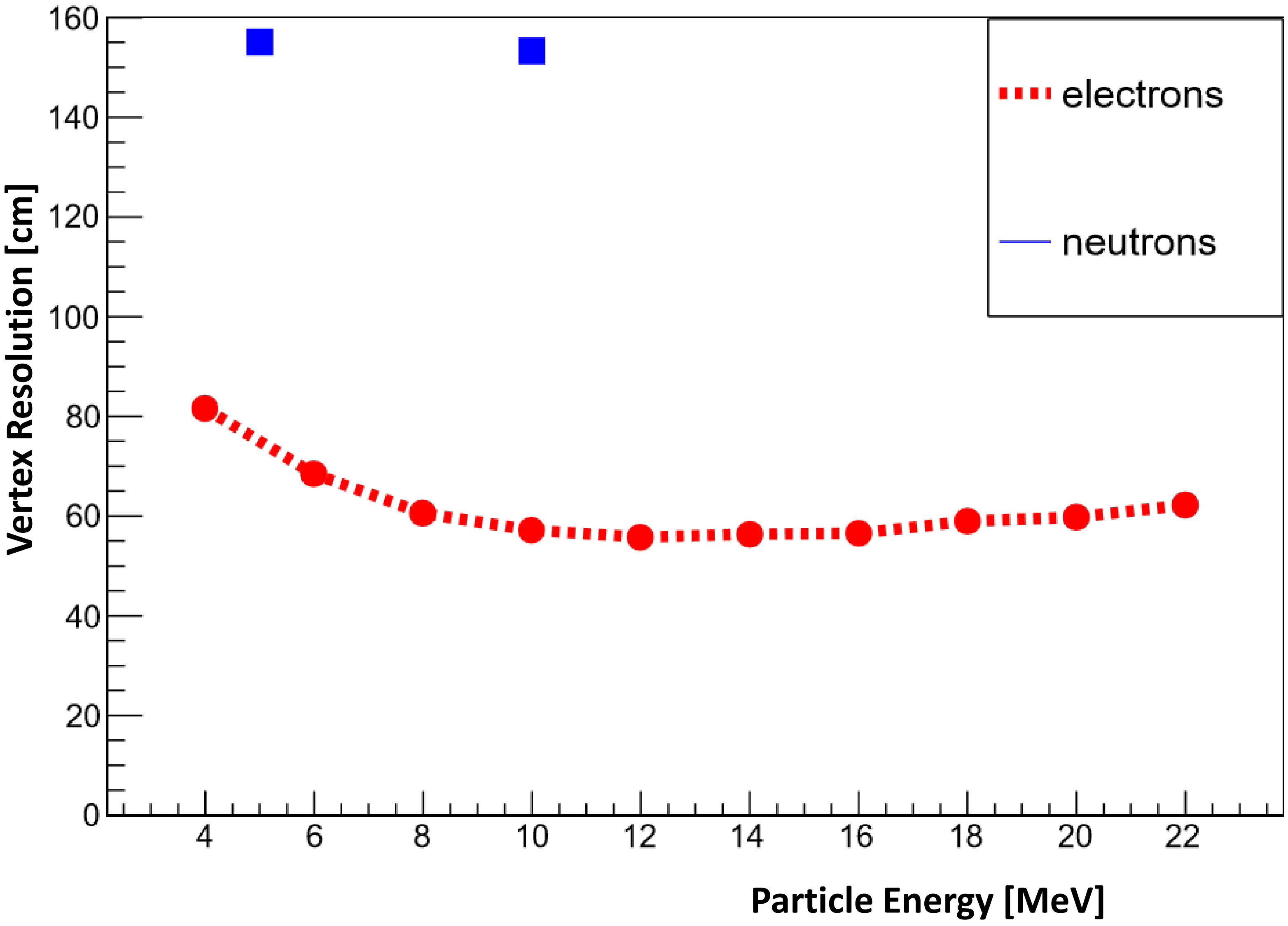


8 inch reconstruction results, 3inch shows the same shapes with better resolutions.





Resolution Vs Energy



Neutron vertex resolution worse than electron vertex resolution.

Neutron loses energy before getting captured so we do not expect to see a difference in resolution at different energies

Summary

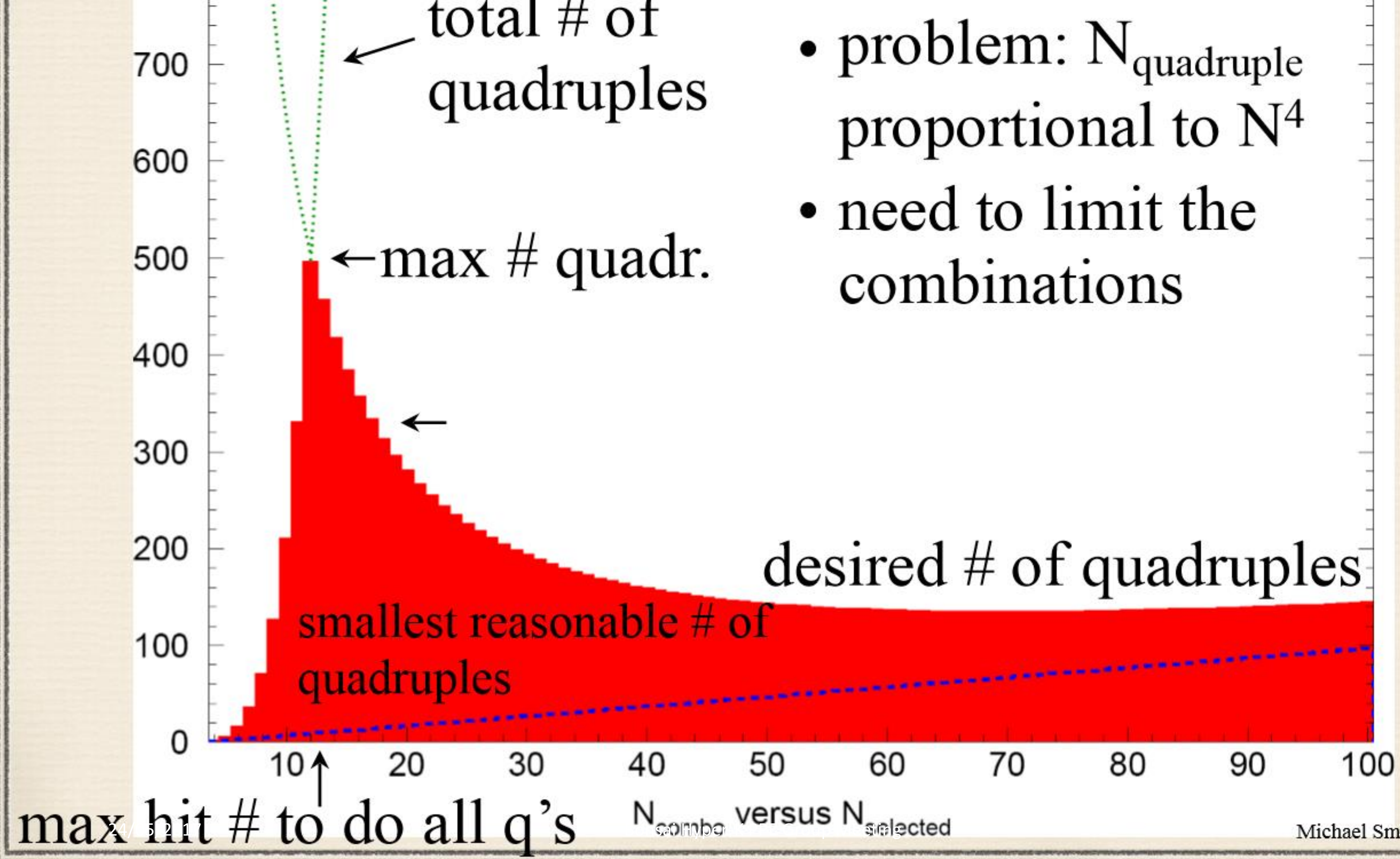
- NuPRISM and TITUS collaborations merged to form one intermediate water Cherenkov collaboration in J-PARC beamline.
- Prototype detector (Phase-0) will be placed on the surface.
  - Demonstrate detector performance.
- Bonsai performs better with the 3” PMT setup, compared to 8” PMTs for neutron capture reconstruction.
- Reconstruction for captures on Hydrogen not very good.
- Overall neutron resolution is worse than the resolutions of reconstructed electrons.

Thank You

Backup

Intermediate Detector

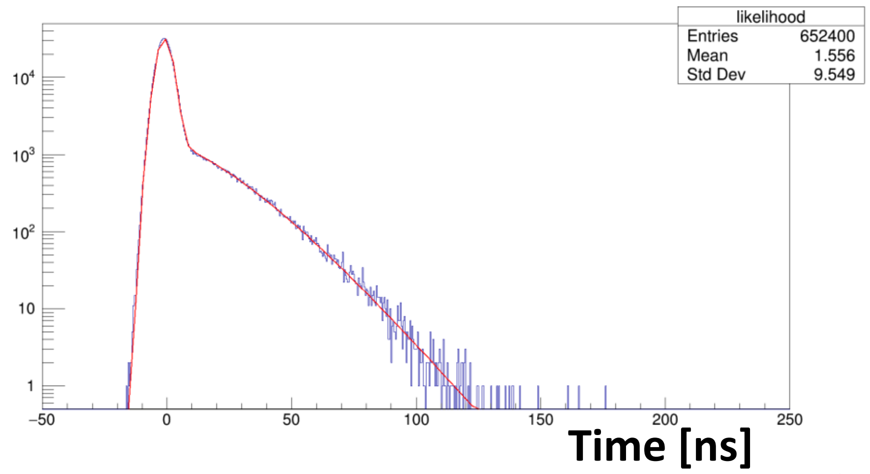
- Goal of the intermediate detector is to constrain the relationship between the reconstructed and true energies.
- Current energy reconstruction formula assumes a single nucleon knockout but ~20-30% of interactions eject multiple nucleons
- Constrain $\sigma(\nu e)/\sigma(\nu\mu)$



- problem: $N_{quadruple}$ proportional to N^4
- need to limit the combinations

BONSAI

- BONSAI is a low energy vertex reconstruction software that has been used for Super-K.
- Works by maximising a likelihood function based off of timing residuals.
- Tuning BONSAI:
  - Like.bin (generated from hit time - time of flight distribution)
  - Fit_param.dat (grid constants, minimum wall distance etc.)



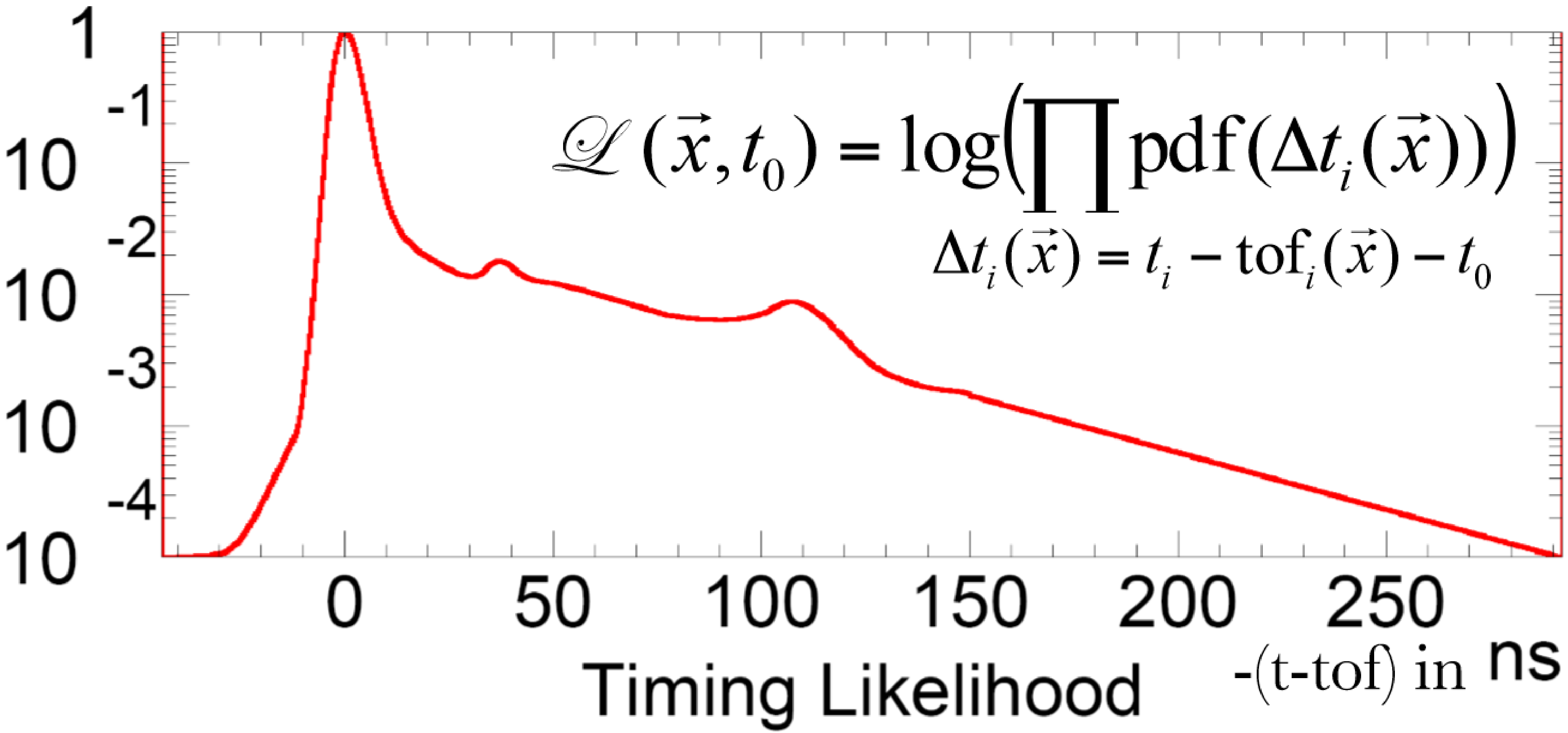
Parameter	Value
Initial grid constant:	25.00 cm
Minimum wall distance for 4-hit vertices:	-75.00 cm
Clusfit grid constant:	50.00 cm
BONSAI grid constant:	25.00 cm

```
BONSAI and Clusfit Shared Parameters
-------------------------------------------------------
PMT time resolution: 3.00 ns
PMT coincidence time difference: 3.00 ns
PMT pair maximal distance fraction: 0.1785
PMT pair maximal time difference fraction: 0.1079
Maximum # of hits to do all 4-hit combin.: 10
Initial grid constant: 60.00 cm
Minimum wall distance for 4-hit vertices: -300.00 cm
BONSAI Parameters
-------------------------------------------------------
BONSAI grid constant: 150.00 cm
Minimum wall distance for BONSAI vertex: -100.00 cm
Wall distance to invoke fine search: 50.00 cm
Initial Cherenkov cone opening angle: 44.75 deg
Initial Cherenkov angle positive deviation: 8.00 deg
Initial Cherenkov angle negative deviation: 19.12 deg
Final minimum likelihood difference to skim: 0.01
Final likelihood skim fraction: 0.08
Coarse Search Parameters------------------------------
Coarse search Cherenkov cone opening angle: 44.75 deg
Coarse search positive angle deviation: 8.00 deg
Coarse search negative angle deviation: 19.12 deg
Coarse search minimum likelihood diff to skim: 0.04
Coarse search likelihood skim fraction: 0.08
Coarse search start radius: 200.00 cm
Coarse search stop radius: 100.00 cm
Fine Search Parameters--------------------------------
Fine search Cherenkov cone opening angle: 44.75 deg
Fine search positive angle deviation: 8.00 deg
Fine search negative angle deviation: 21.18 deg
Fine search minimum likelihood diff to skim: 0.05
Fine search likelihood skim fraction: 0.10
Fine search search minimum radius: 100.00 cm
Fine search search stop radius: 10.00 cm
```

```
Clusfit Parameters
-------------------------------------------------------
Clusfit grid constant: 400.00 cm
Minimum wall distance for Clusfit vertex: -100.00 cm
Initial Clusfit Cherenkov cone opening angle: 23.00 deg
Initial Clusfit angle positive deviation: none
Initial Clusfit angle negative deviation: none
Initial Clusfit angle goodness weight: 0.02
Number of Clusfit passes: 3
First minimum goodness difference to skim: 0.05
Second minimum goodness difference to skim: 0.02
Third minimum goodness difference to skim: 0.01
Final minimum goodness difference to skim: 0.01
First goodness skim fraction: 0.10
Second goodness skim fraction: 0.10
Third goodness skim fraction: 0.10
Final goodness skim fraction: 0.10
Grid search goodness time window: 8.00 ns
First search goodness time window: 6.00 ns
Second search goodness time window: 5.00 ns
Third search goodness time window: 4.00 ns
First search Clusfit minimum radius: 200.00 cm
Second search Clusfit minimum radius: 20.00 cm
Third search Clusfit minimum radius: 5.00 cm
First search Clusfit stop radius: 100.00 cm
Second search Clusfit stop radius: 14.00 cm
Third search Clusfit stop radius: 8.00 cm
First Clusfit Cherenkov cone opening angle: 45.17 deg
First Clusfit angle positive deviation: none
First Clusfit angle negative deviation: none
First Clusfit angle goodness weight: 0.05
Second Clusfit Cherenkov cone opening angle: 45.17 deg
Second Clusfit angle positive deviation: 7.60 deg
Second Clusfit angle negative deviation: 5.08 deg
Second Clusfit angle goodness weight: 0.20
Third Clusfit Cherenkov cone opening angle: 45.17 deg
Third Clusfit angle positive deviation: 7.60 deg
Third Clusfit angle negative deviation: 5.08 deg
Third Clusfit angle goodness weight: 0.20
```

BONSAI

The timing residual probability density function measured by LINAC calibration data.

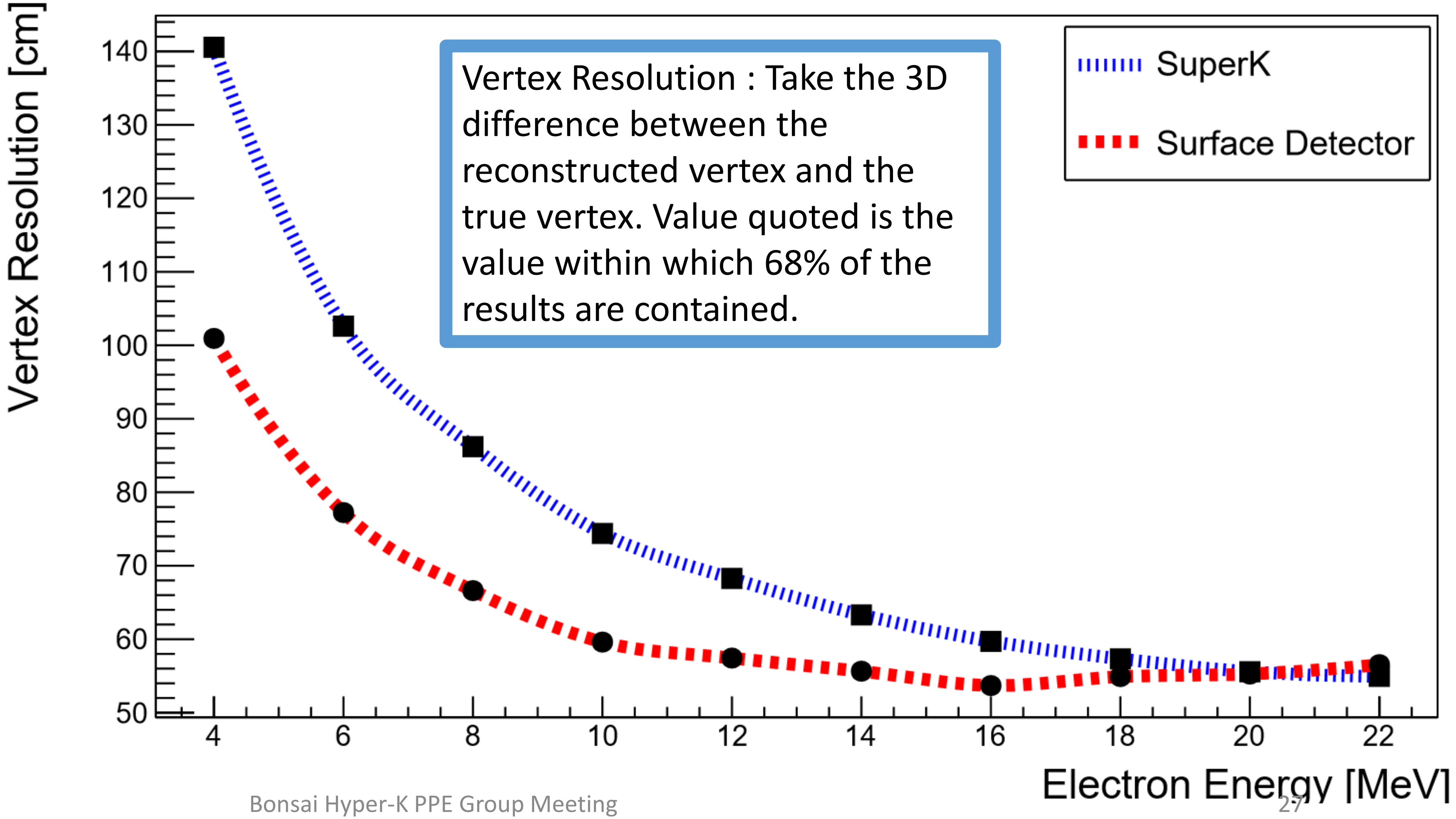


Super-K

10 000 events
10 MeV electrons
Pos (0,0,0)
Dir (1,0,0)

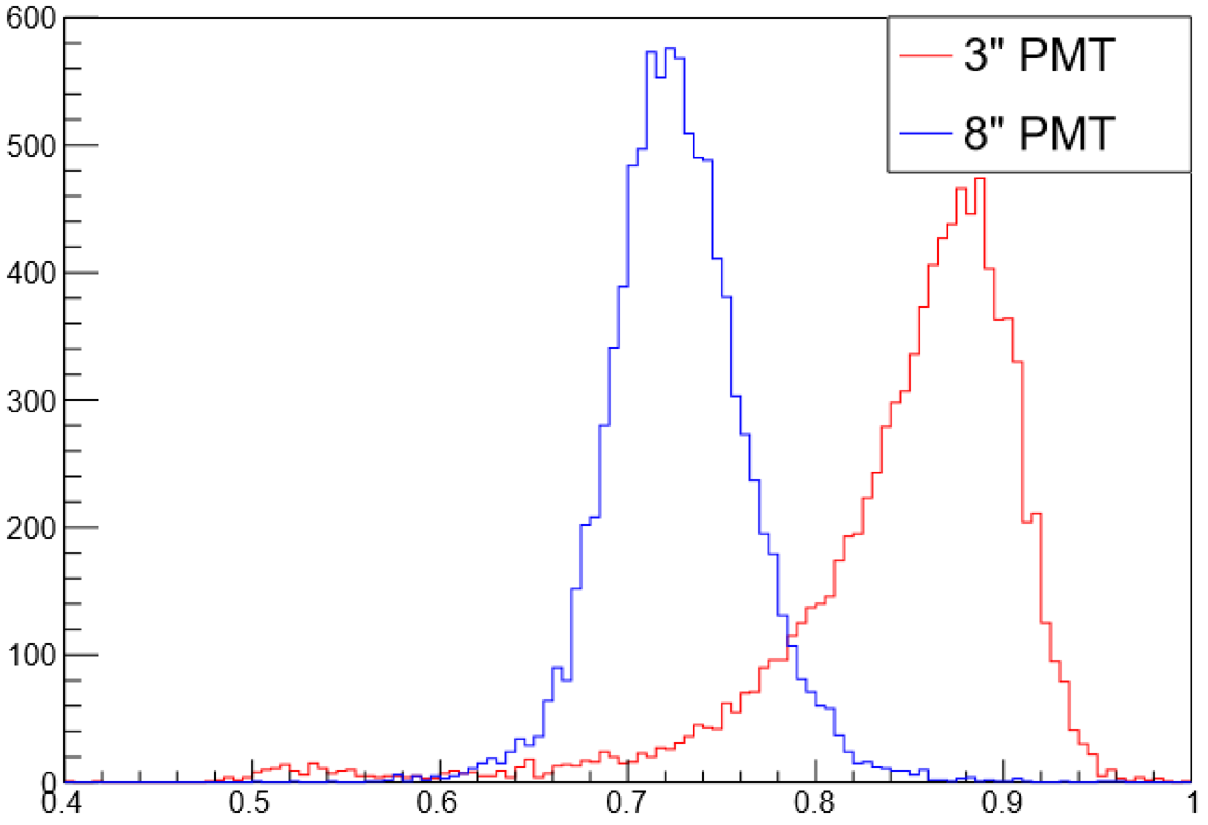
Surface detector DR : 3kHz
SuperK DR : 4.2kHz

-Generally, resolutions for the surface detector are better than those for SuperK.



Vertex Resolution : Take the 3D difference between the reconstructed vertex and the true vertex. Value quoted is the value within which 68% of the results are contained.

Bonsai Goodness



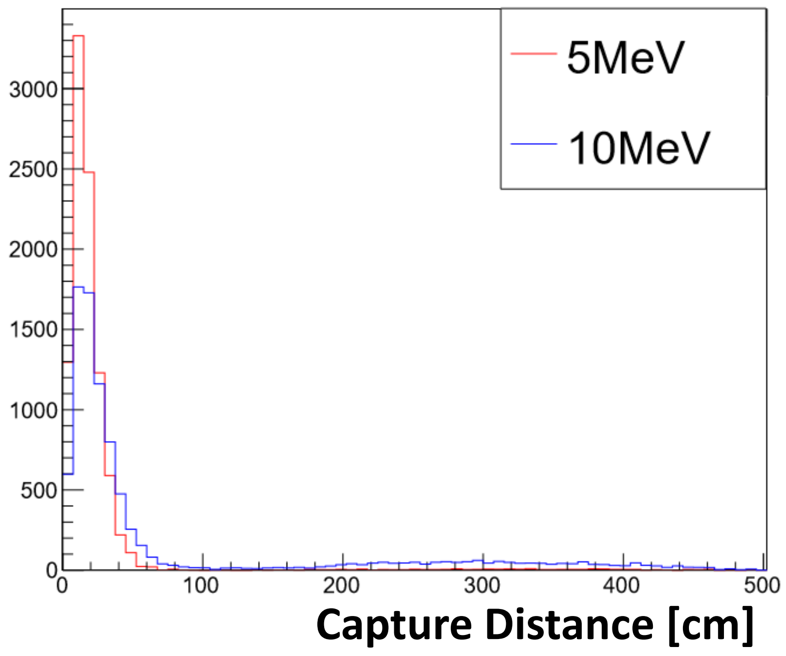
Bonsai Goodness

Goodness value is calculated by bonsai to show confidence in the fit.

1 is the best value.

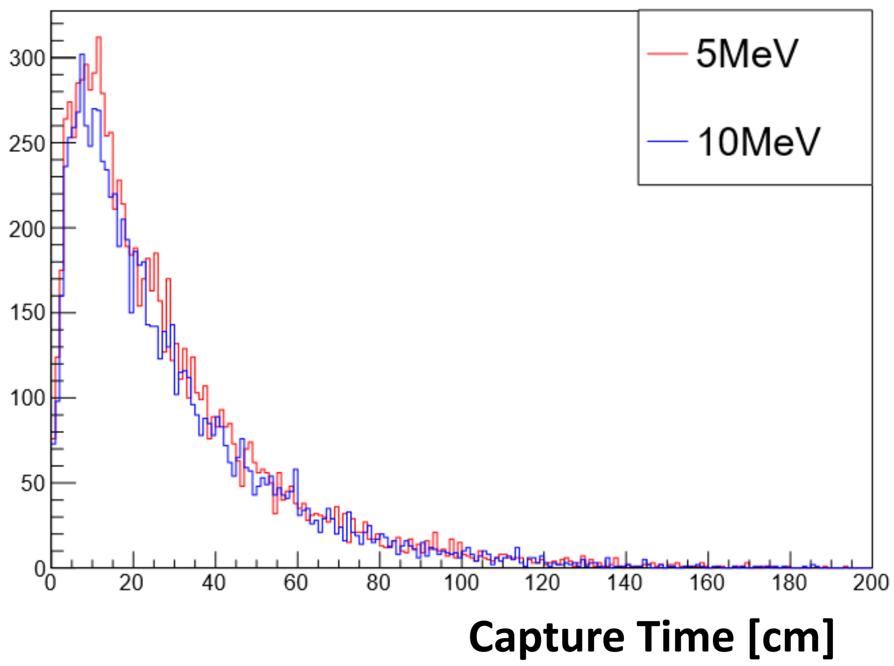
Bonsai Goodness values are higher for the 3" PMTs.

Neutron Energies

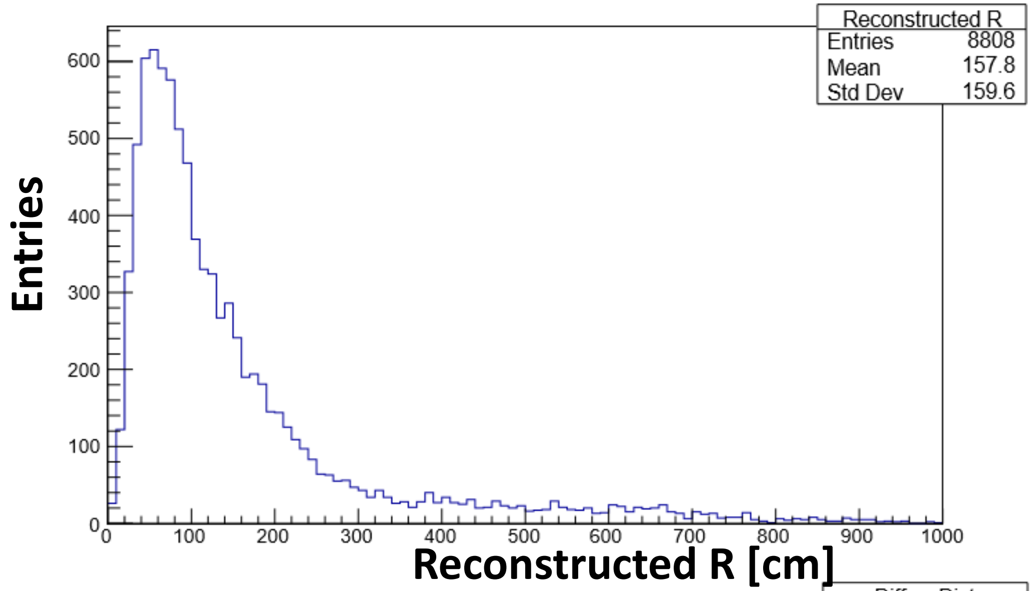


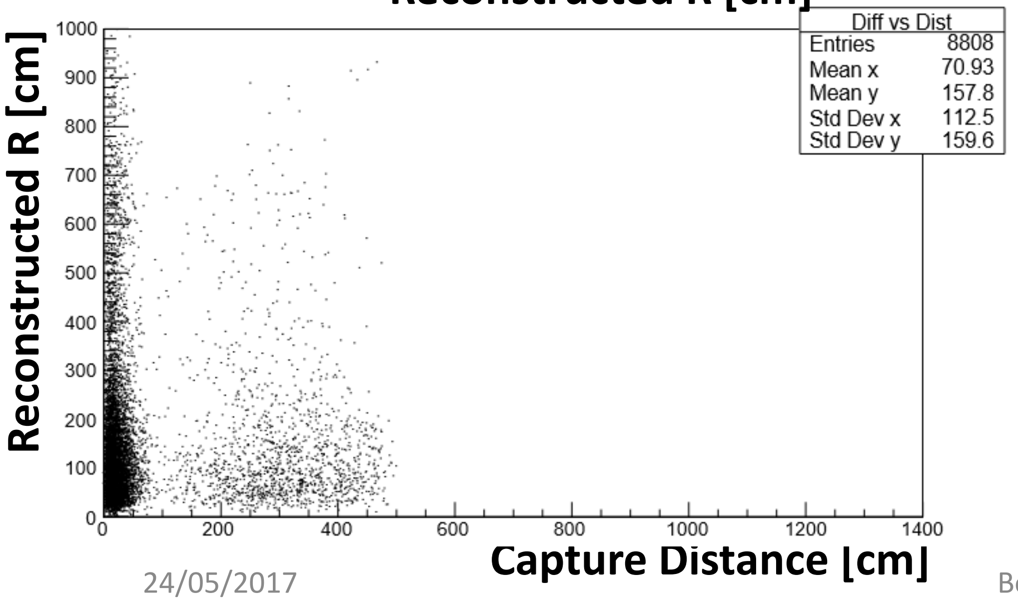
The capture time does not vary with different neutron energies

At higher energies, the neutron may travel further in the tank before eventually getting captured.



Neutron Energies



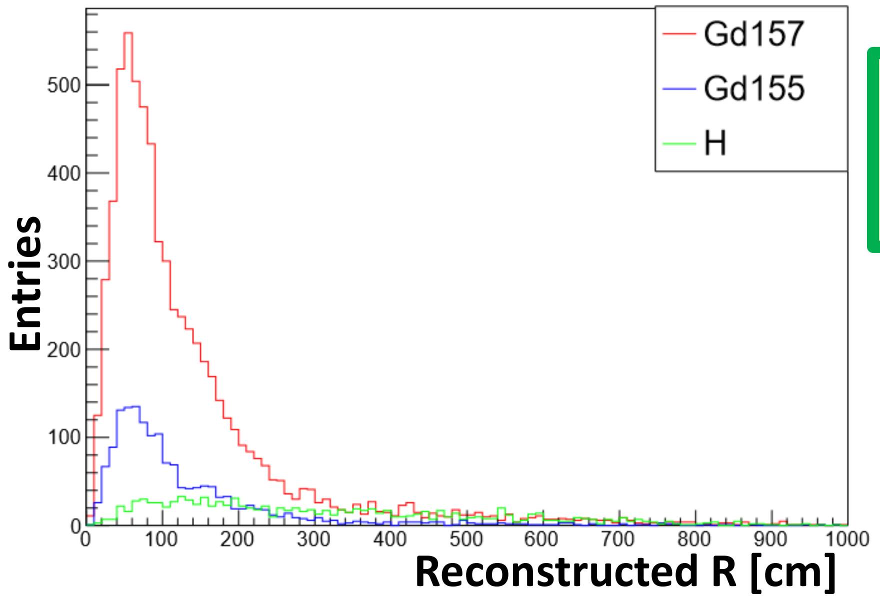


At higher energies, the neutron may travel further in the tank before eventually getting captured.

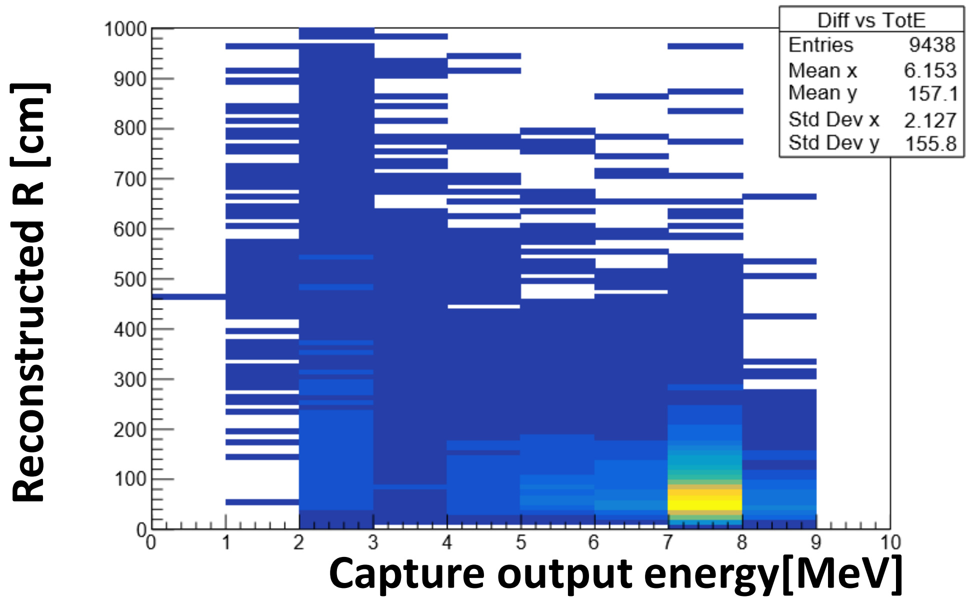
The resolution for 10MeV neutrons is 153cm

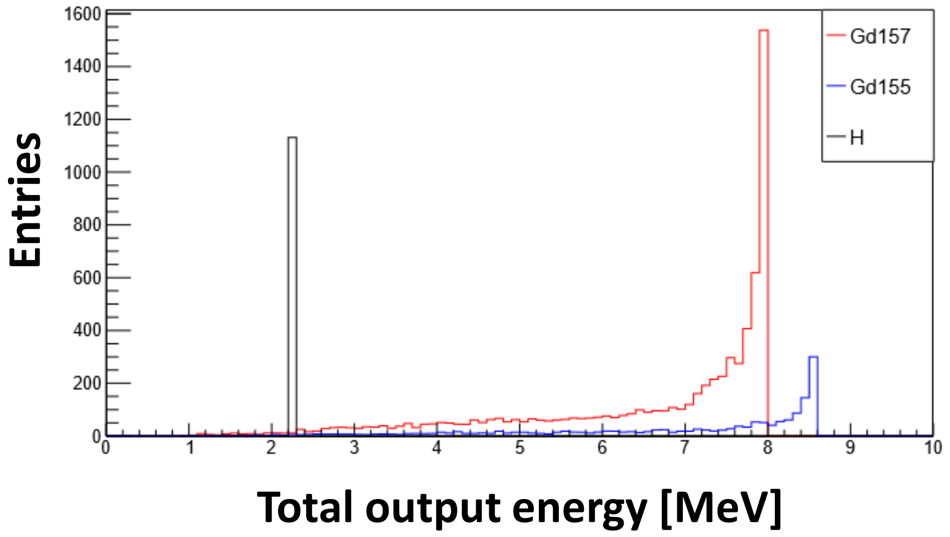
The resolution for 5MeV neutrons is 155cm

Reconstruction Results Vs Energy



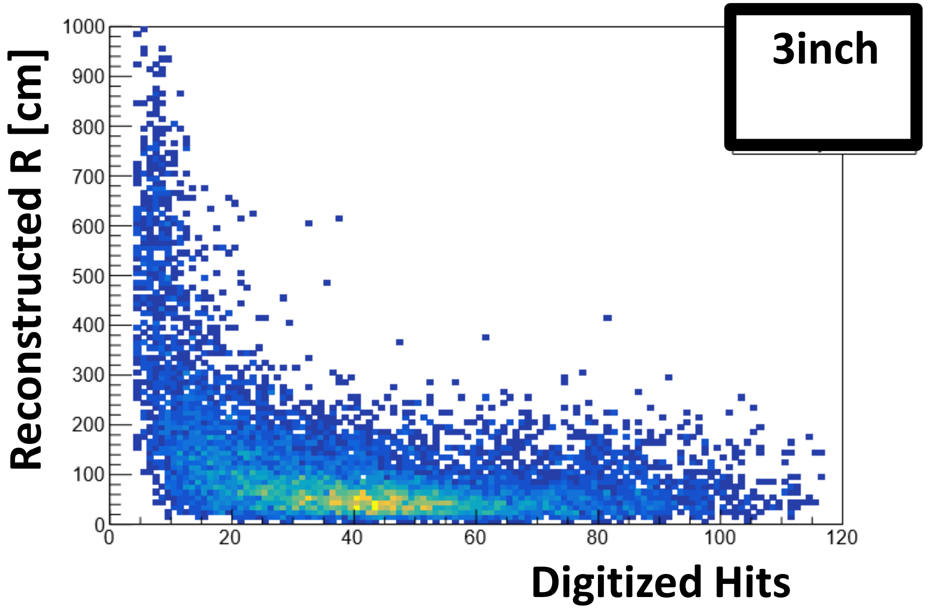
8 inch reconstruction results, 3inch shows the same shapes with better resolutions.

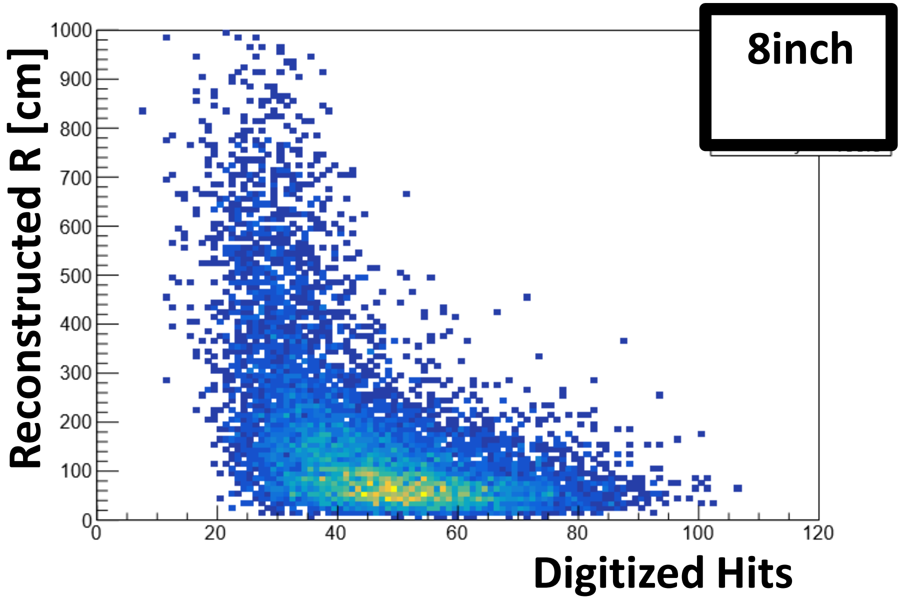




3" PMT	Captures [%]	ResTot [cm]	ResEnergy [cm]
7MeV+	53%	109.7	80.64
5MeV+	72%	"	84.45
3MeV+	84%	"	91.83
8" PMT	**Captures [%]**	**ResTot [cm]**	**ResEnergy [cm]**
7MeV+	53%	155.1	106.9
5MeV+	72%	"	115.8
3MeV+	84%	"	128.9

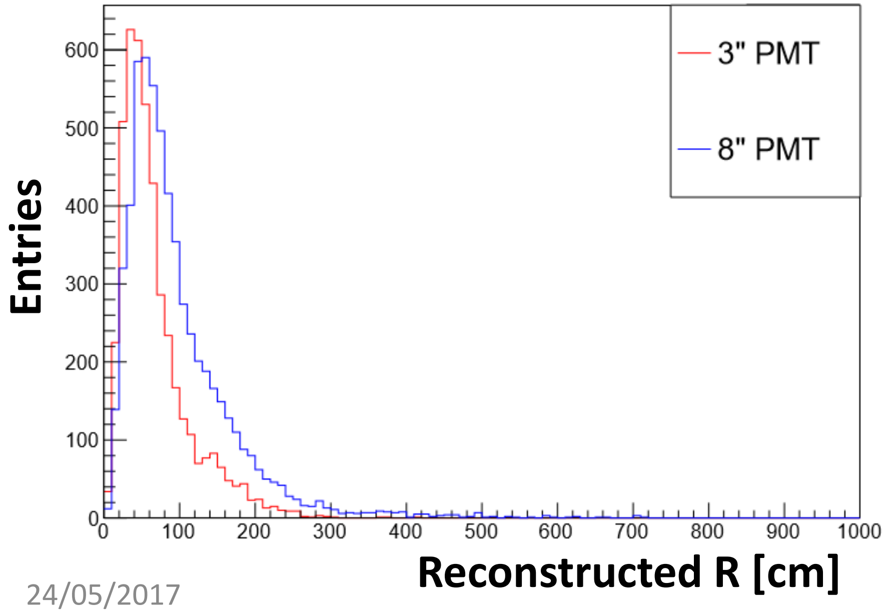
Reconstruction Results Vs Hits





3” PMT configuration shows many events with less than 20 hits, whereas 8” configuration rarely has less than 20 hits.

Larger reconstructed vertex differences with less than 40 hits

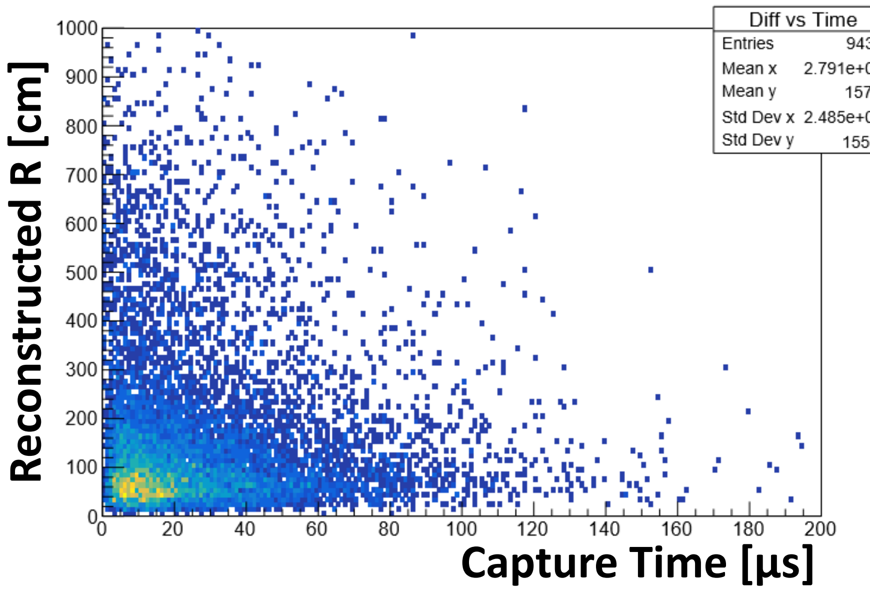


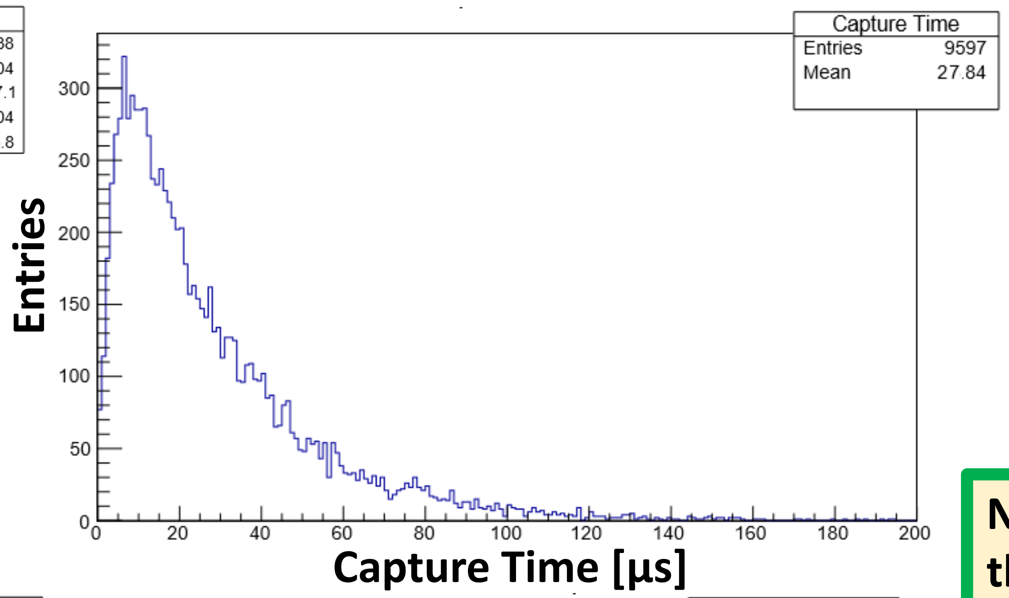
	Captures>40hits	Res	Res40 [cm]
3inch PMT	46%	109.7	71.37
8inch PMT	63%	155.1	105.8

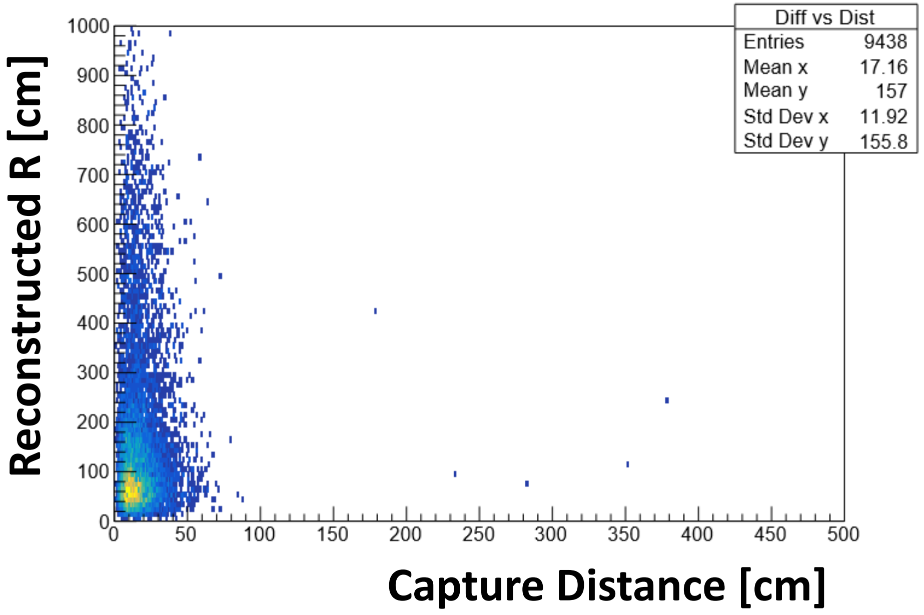
	Captures>20hits	Res	Res20 [cm]
3inch PMT	78%	109.7	84.52
8inch PMT	99%	155.1	152.9

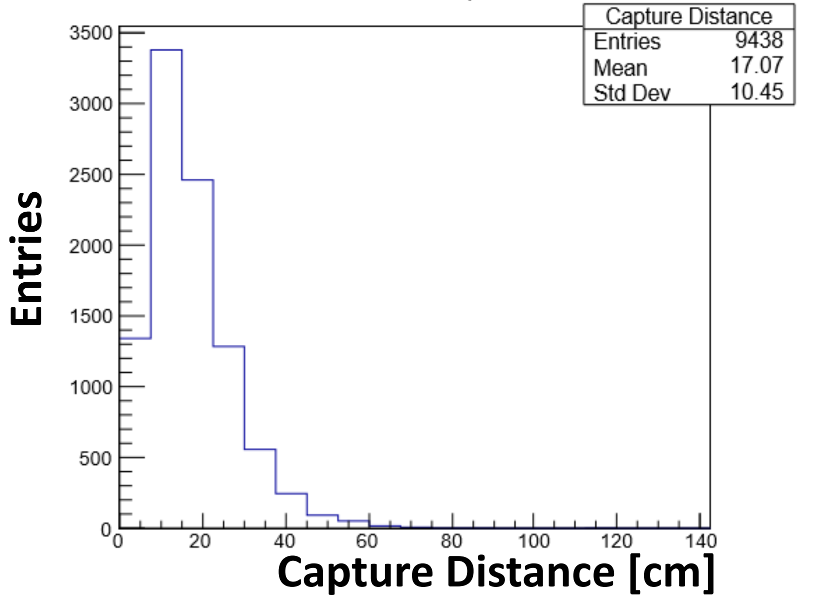
Reconstruction Results Vs Capture Info

8 inch





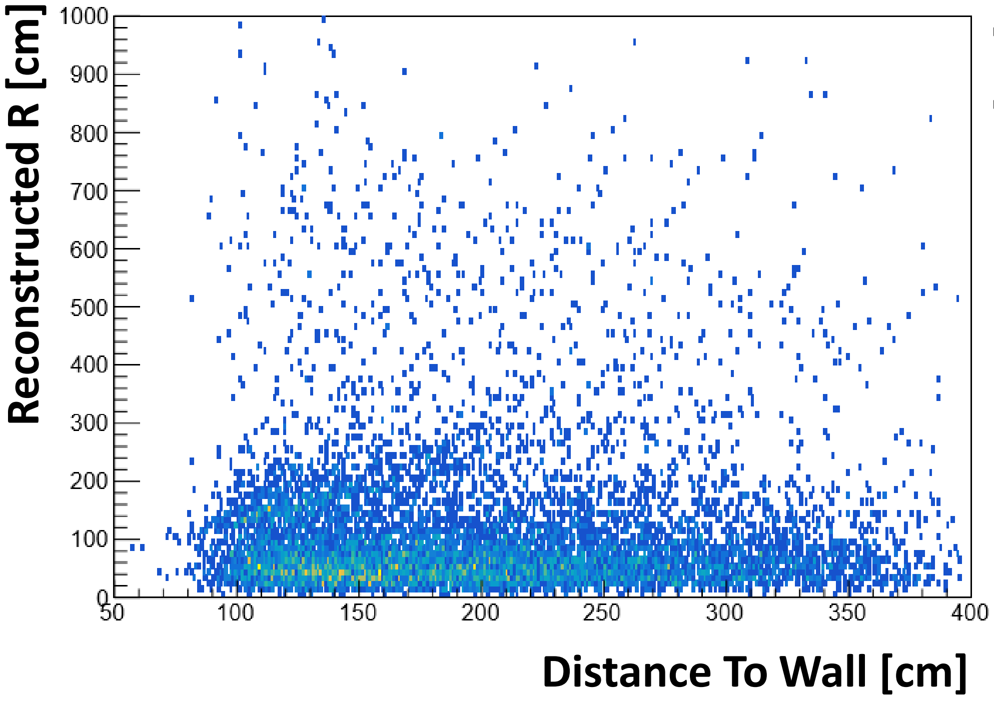


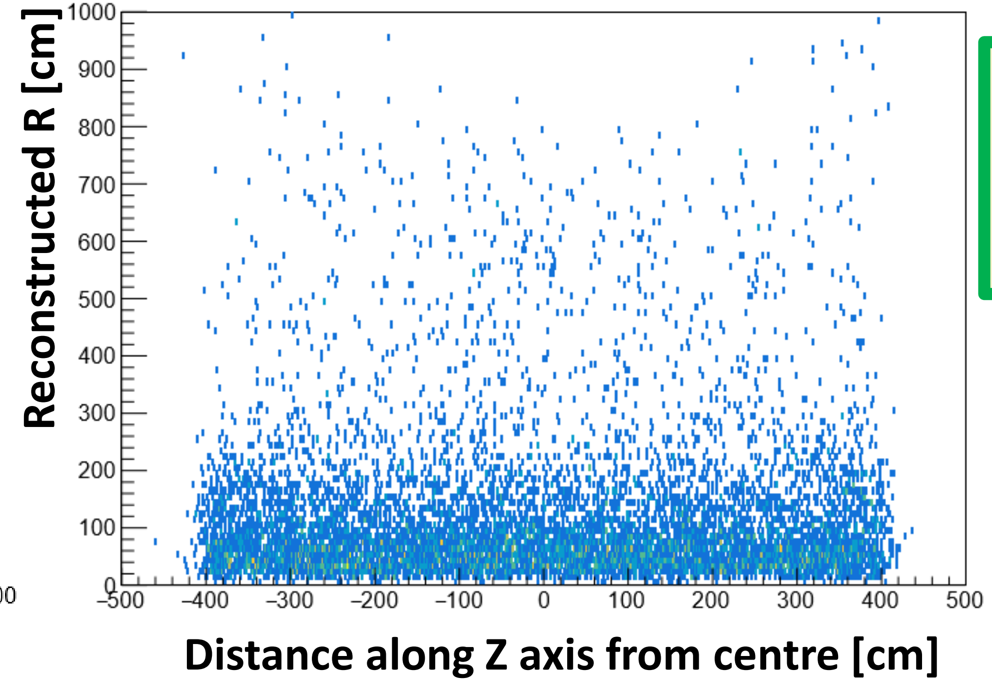


No correlation between these parameters and the reconstruction result.

Reconstruction Results Vs Position of Capture

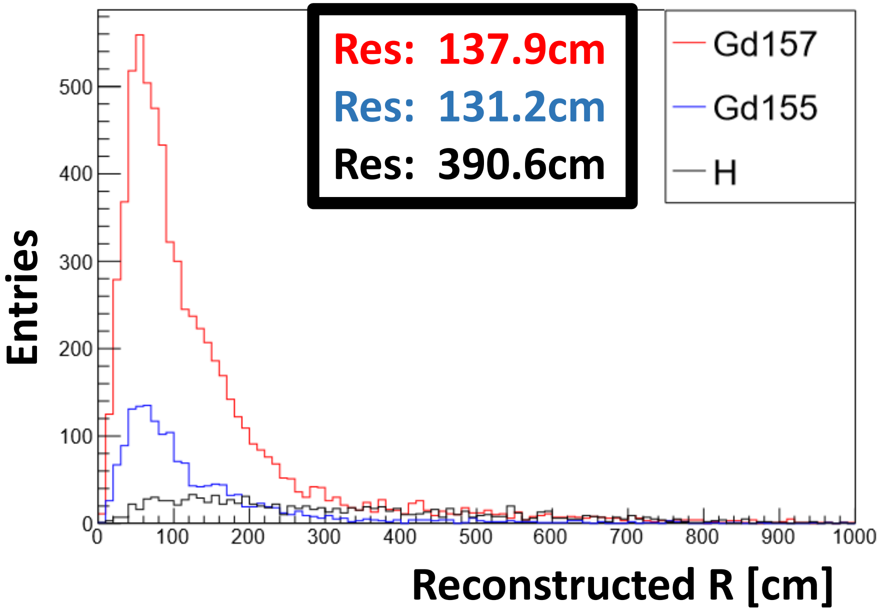
8 inch

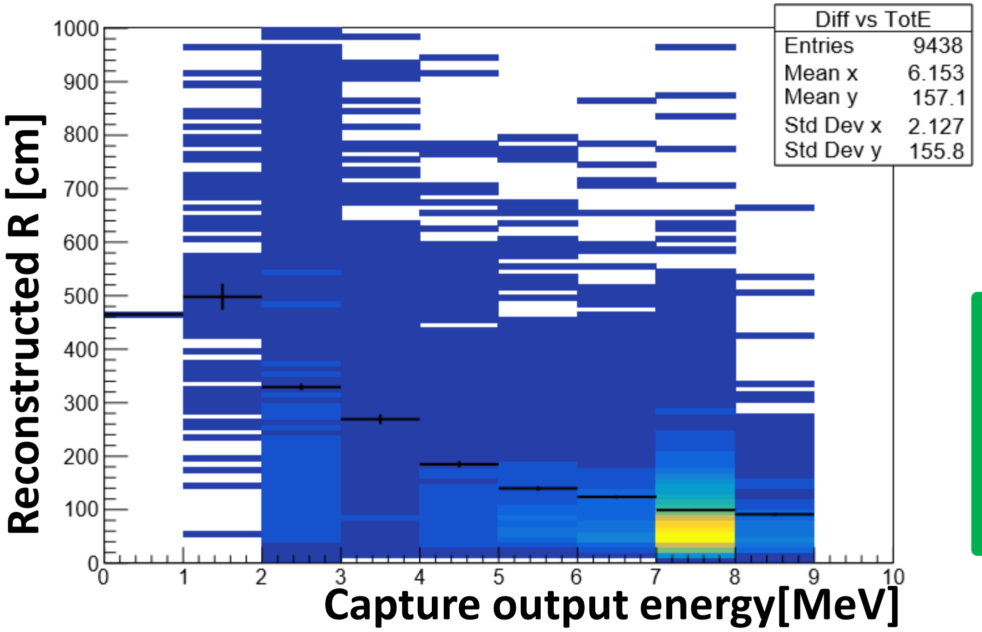




No correlation between the reconstructed values and the position of the capture

Reconstruction Results Vs Energy





8 inch reconstruction results, 3inch shows the same shapes with better resolutions.