PMT Timing Calibration with the Light Injection System

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Hyper-Kamiokande

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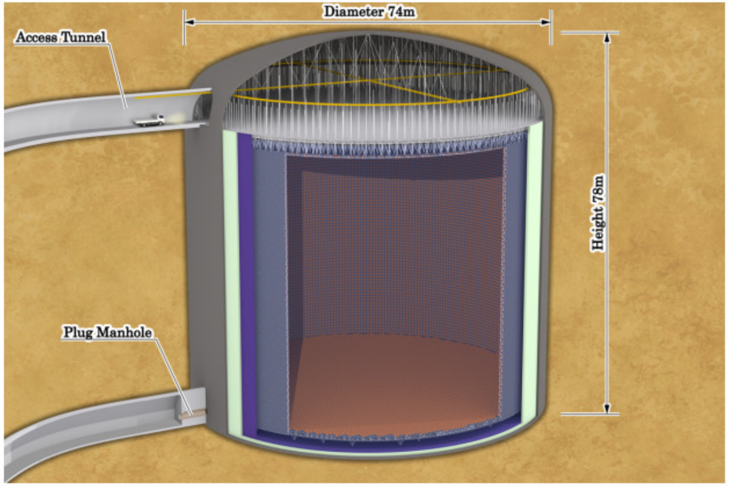
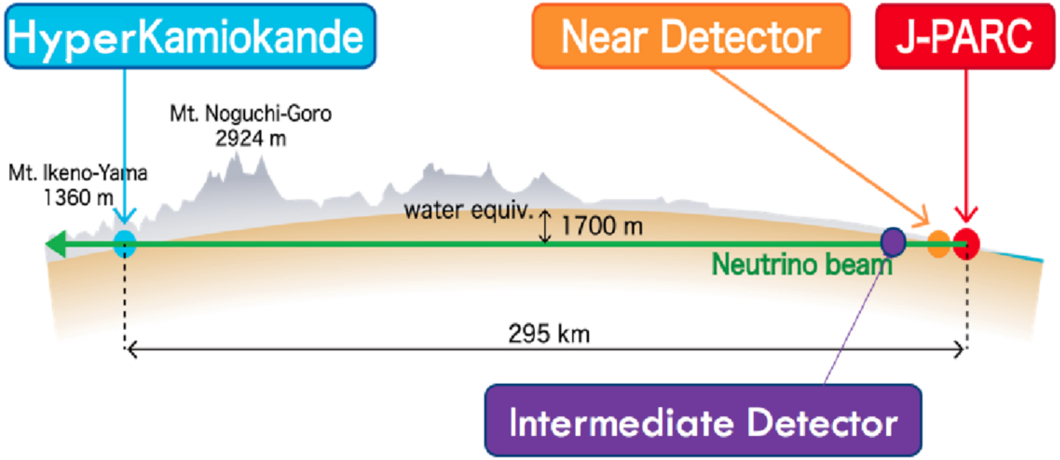
Overview





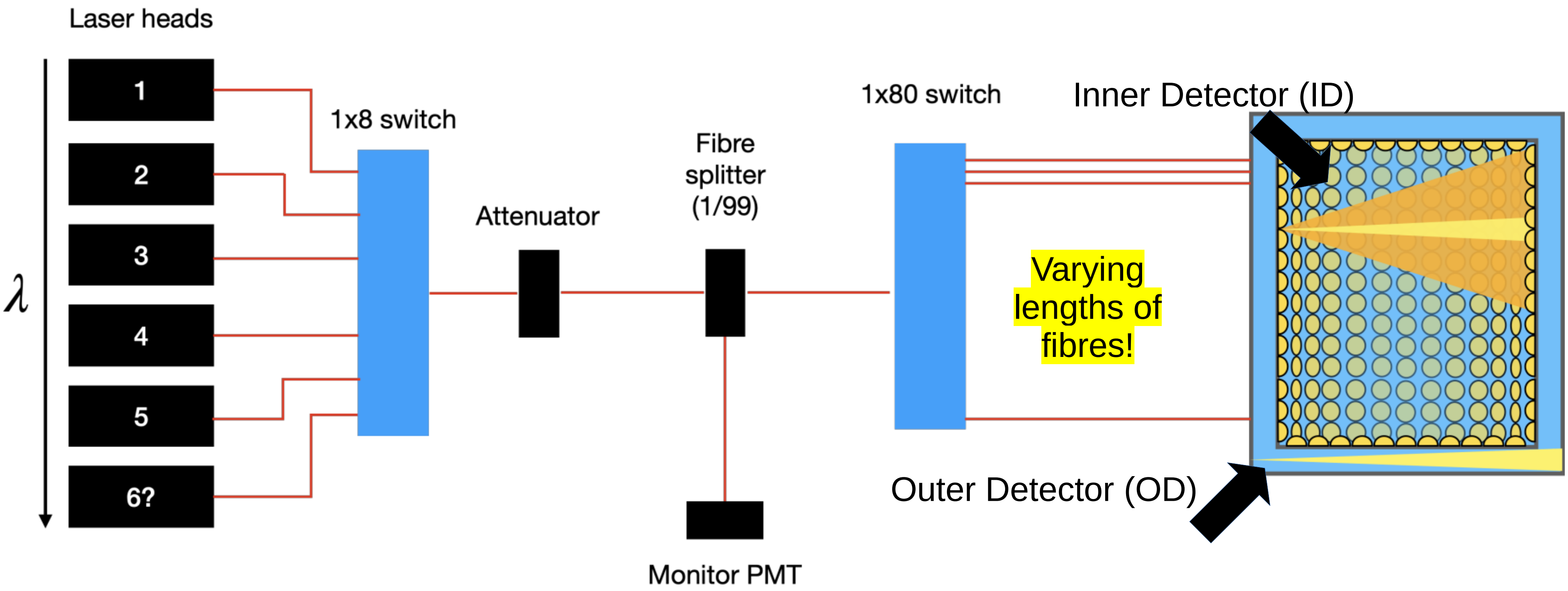
Eight times the fiducial volume of water compared to Super-Kamiokande.

Increasing beam power up to 1.3 MW and building an additional water Cherenkov intermediate detector.

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

$$A_{CP} \approx \frac{\cos\theta_{23} \sin 2\theta_{12} \sin\delta_{CP}\, \Delta m^2_{21}\, L}{4E \sin\theta_{23} \sin\theta_{13}}$$

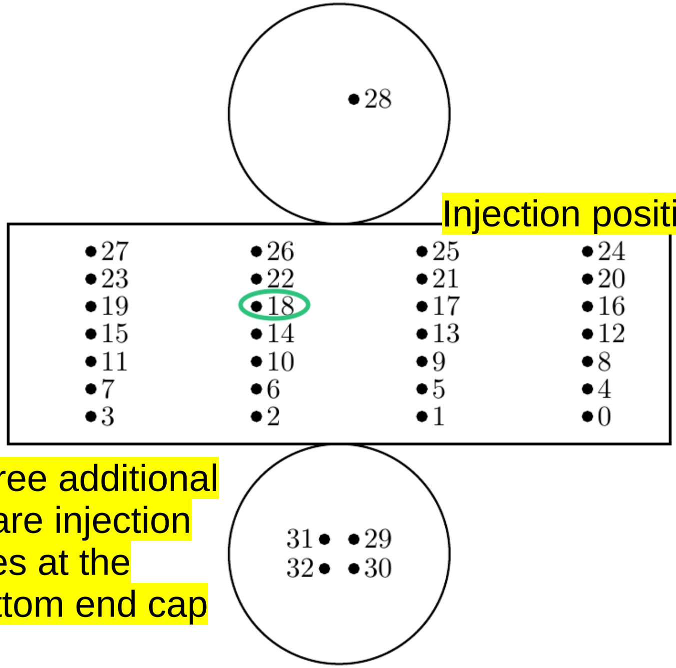
Light Injection System



Monitor and calibrate detector systematics such as the optical properties of water and PMT response properties.

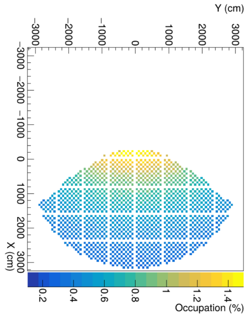
Occupancy

How often within a set of diffuser events a PMT registers a hit within a time window (±5 ns around the 'rough' arrival peak).

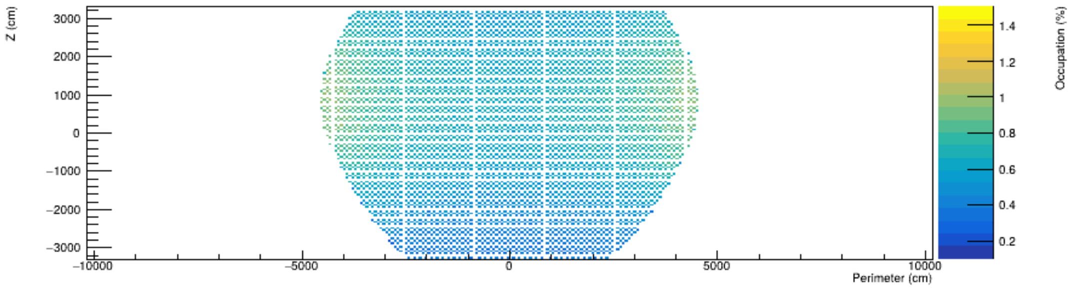


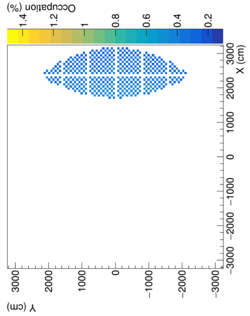
Injection positions in ID

Three additional spare injection sites at the bottom end cap



100,000 events of 1,000 photons at 400 nm wavelength

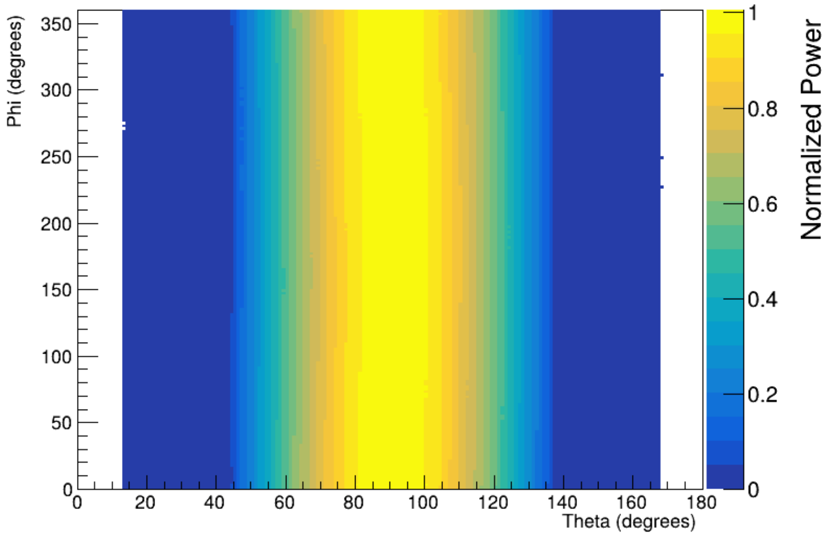


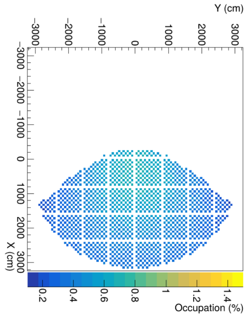


Geometric occupation profile from simulated diffuser events

Diffuser Profiles

Profile of a ID diffuser from the water tank characterisation of diffusers performed by the Sheffield Hyper-K group.





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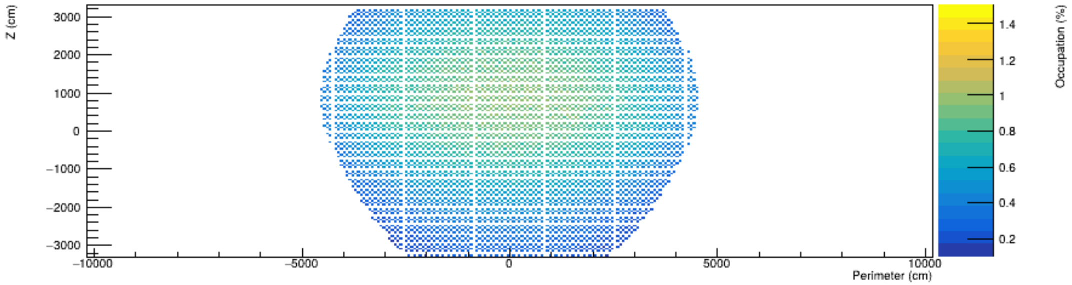
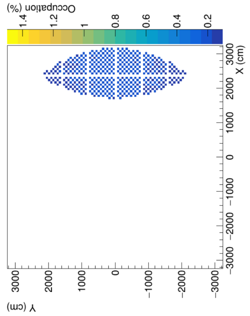
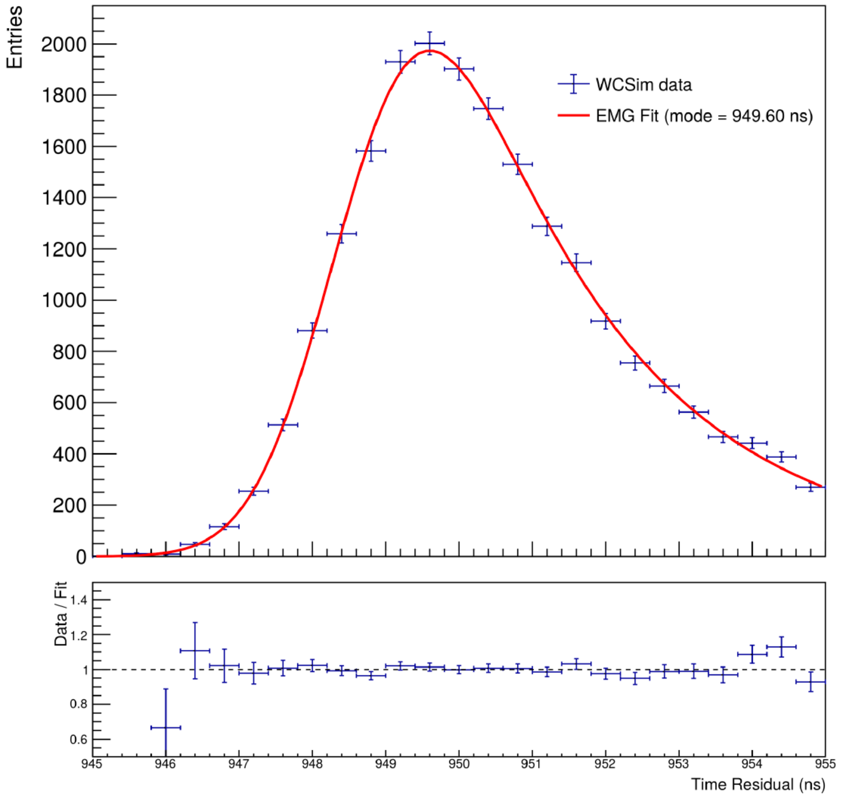




Additionally, this implementation has the diffused photons have timing width of 1 ns

Arrival Timing



Time residuals of hits from a million diffuser events for a PMT from a specific diffuser

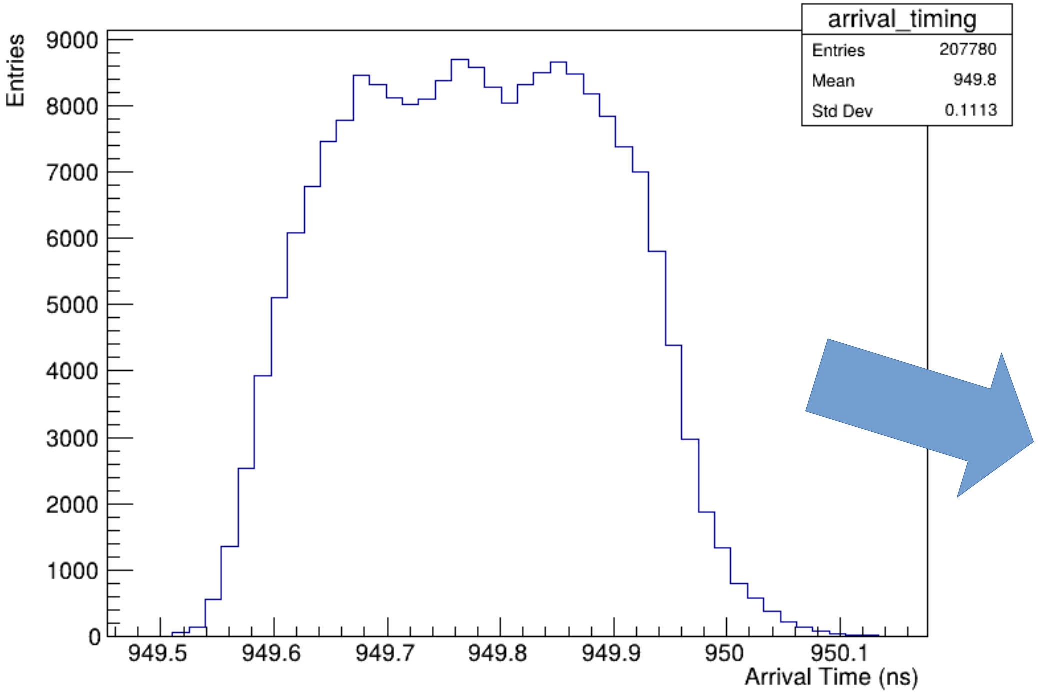
Characterise arrival time using the modal value of exponentially modified Gaussian fit to hits recorded in a specific PMT from light injected by a given diffuser.

$$\text{Time Residual} = t_{\text{measured}} - \frac{\text{distance}}{v_{\text{group}}} + t_{\text{offset}} + t_{\text{trigger}}$$

$$f(x) = A \cdot \frac{\lambda}{2} \cdot \exp\left(\frac{\lambda}{2}(2\mu + \lambda\sigma^2 - 2x)\right) \cdot \text{Erfc}\left(\frac{x - \mu - \lambda\sigma^2}{\sqrt{2}\sigma}\right)$$

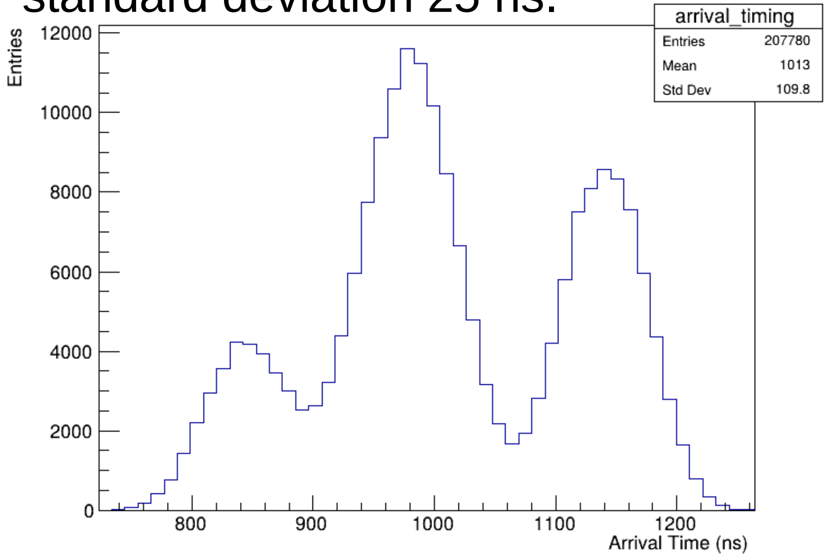
Exponentially modified Gaussian function

Timing Offsets



Arrival timings of all PMTs from every diffuser for a million diffuser events.

Apply two random offsets for both PMT and diffuser from a Gaussian distribution with standard deviation 25 ns.



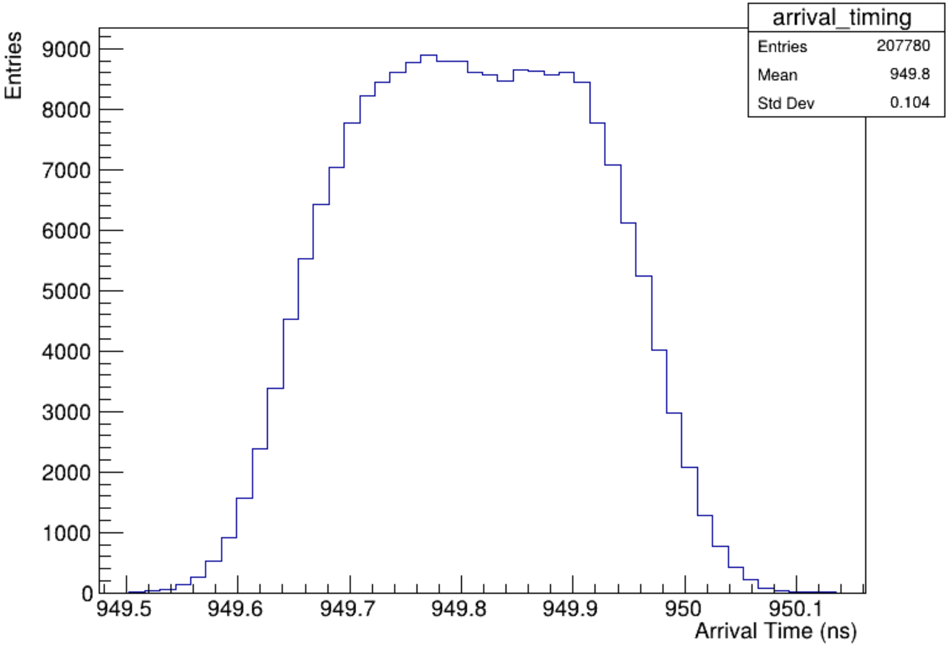
Additionally, apply an offset for just PMTs based on where they are in the detector.

Calibration Method

Chi-squared fit of injector offset based on mean timing differences of common PMTs between two diffusers.

$$\chi^2 = \sum_{\substack{0 \leq i,j \leq 29 \\ i \neq j}} \frac{(V_i - V_j - D_{ij})^2}{\sigma_{ij}^2}$$

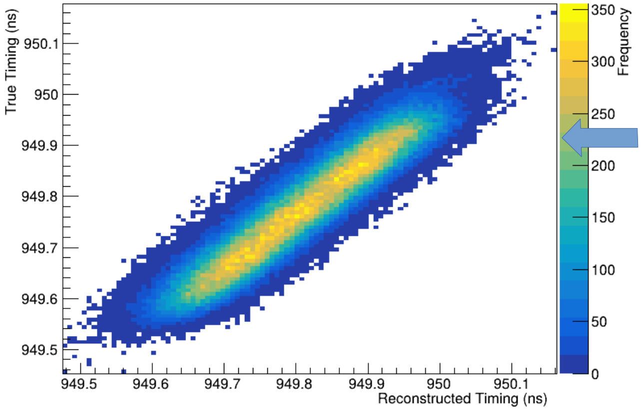
With injector timing differences found, ideally all that should remain is arrival timings for every diffuser the PMT is illuminated by. From this the PMT timing offset can be found.



Reconstructed arrival timings of all PMTs from every diffuser.

Performance

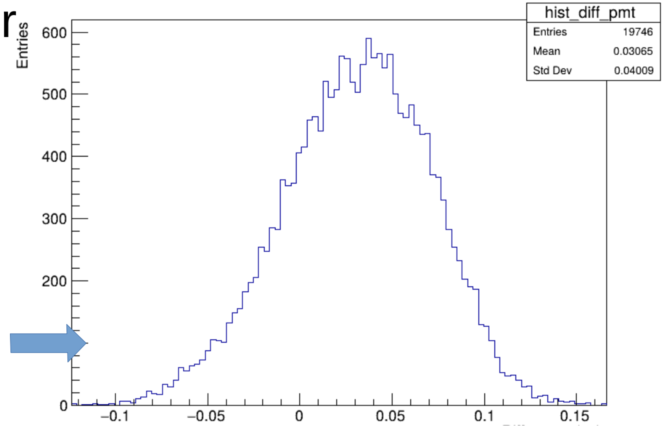
Hyper-Kamiokande

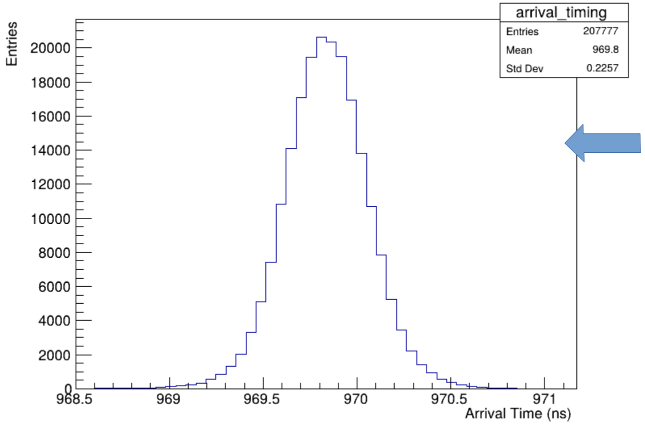


High Statistics – Uniform diffuser

Comparison between initial arrival timings and reconstructed arrival timings through this method.

Difference between actual PMT offset and reconstructed PMT offset. Injector differences have around 10 ps width and are effectively zero.

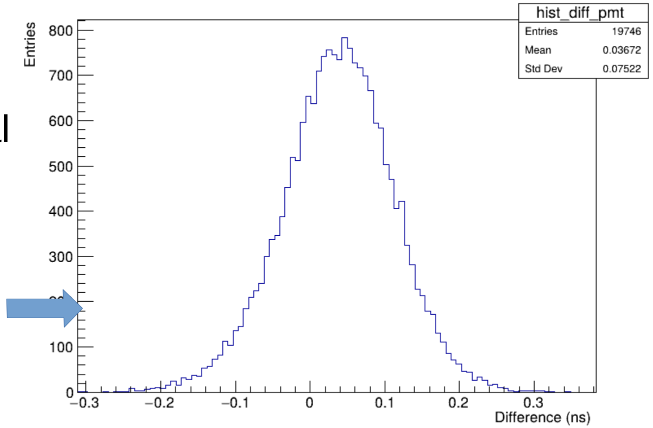




Low Statistics – Sheffield diffuser

With a hundred thousand events, all arrival times of PMTs for all diffusers.

Difference between actual PMT offset and reconstructed PMT offset. Injector differences have around 20 ps width and are effectively zero.



Summary and Future Work

- Differences in fibre path length can be resolved in any timing calibration undertaken with the LI.
- Foundation for a broader PMT calibration, with further work continuing with access to PMT pre-calibration data, specifically charge vs. time.
- The systematics related to this calibration of PMTs, will be one of the inputs into probing machine learning reconstruction.