Water Cherenkov Applications/Challenges

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Current methods of simulation

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Overview: Mostly GEANT4 based (e.g. WCSim)

- Definition of physics processes
  - Cherenkov photon profile
  - Hadronic (pion, neutron) interactions

- Accurate description of material and detector geometry for optical processes
  - Photon tracking: water attenuation/scattering, surface absorption/reflection
  - PMTs (photosensors): dimensions, reflectors & inner-structures, photocathode

- Simulation of electronic responses
  - PMT (quantum) efficiency, charge and time smearing
  - Gain/efficiency variations, effects of residual magnetic fields

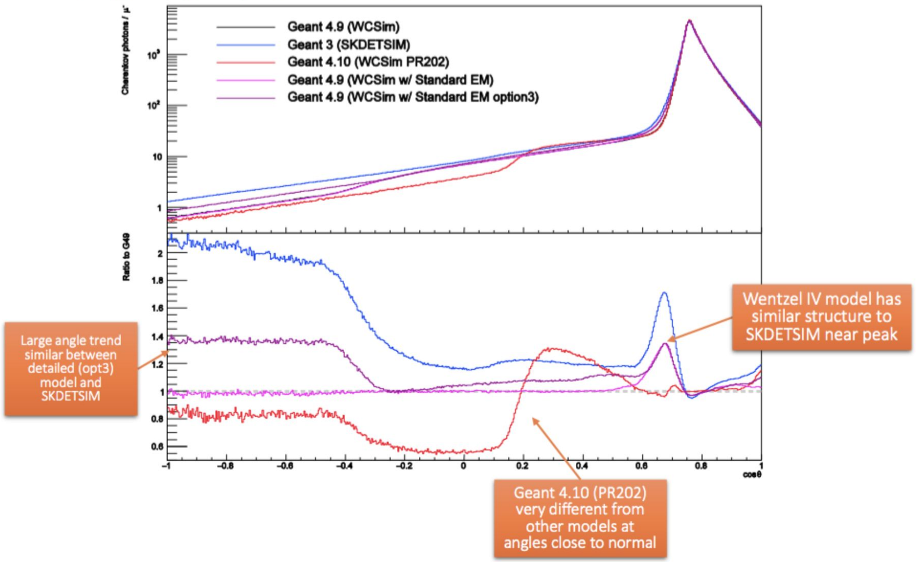
- Monte Carlo method of particle propagation
  - Stochastic method requires large computing resources

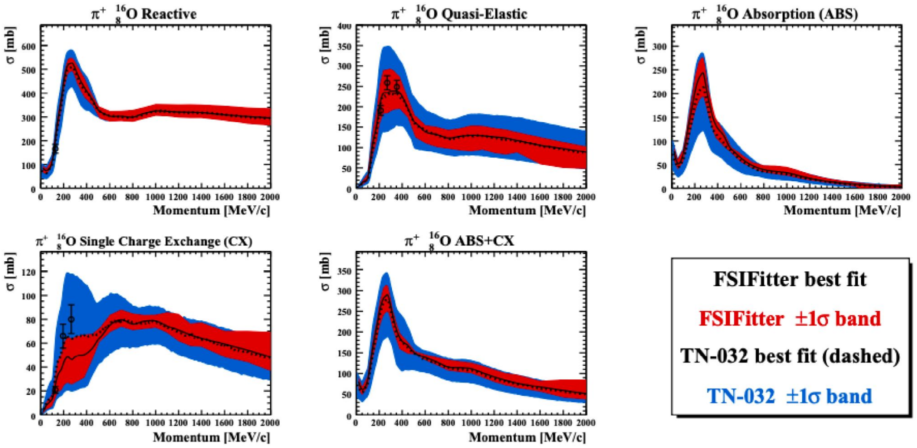
Physics Processes

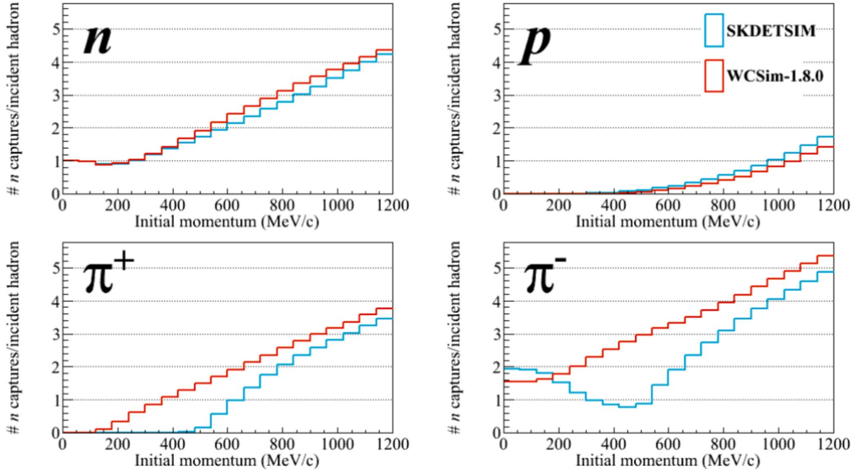
- Definition of physics processes
  - Cherenkov photon profile
  - Hadronic (pion, neutron) interactions

Cherenkov profile for 600 MeV μ^-

Using true optical photon information.

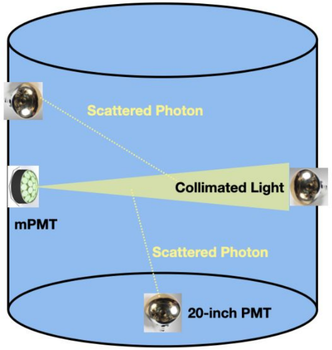


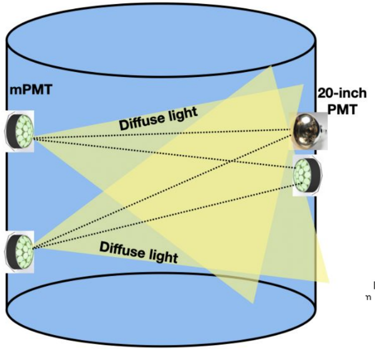


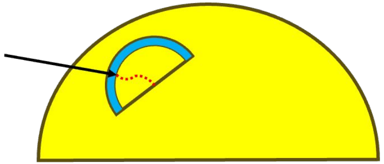


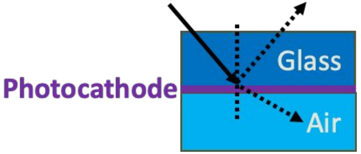
Optical Processes

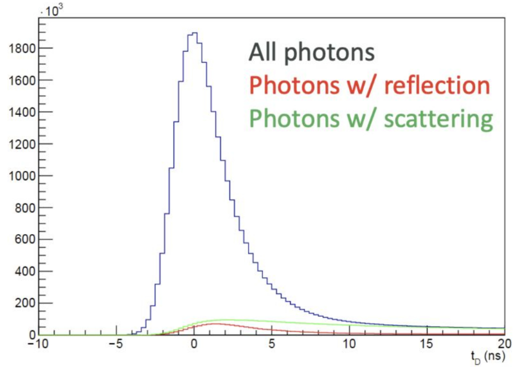
- Accurate description of material and detector geometry
  - Photon tracking: water attenuation/scattering, surface absorption/reflection
  - PMTs (photosensors): dimensions, reflectors & inner-structures, photocathode

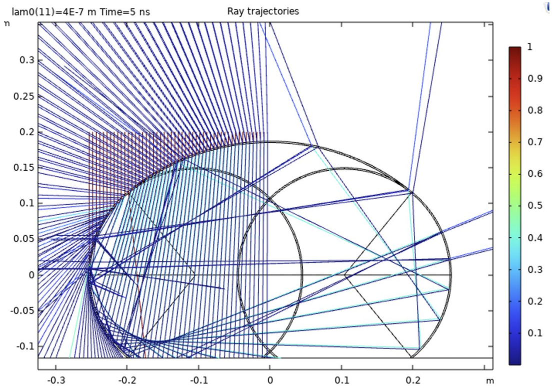


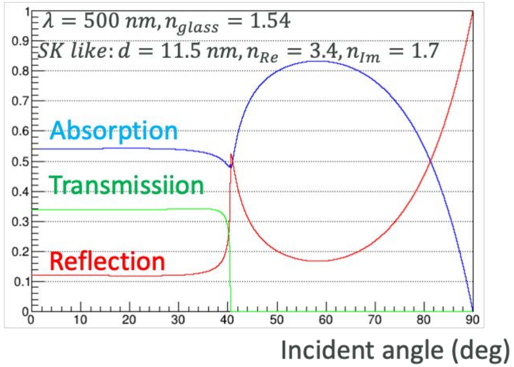






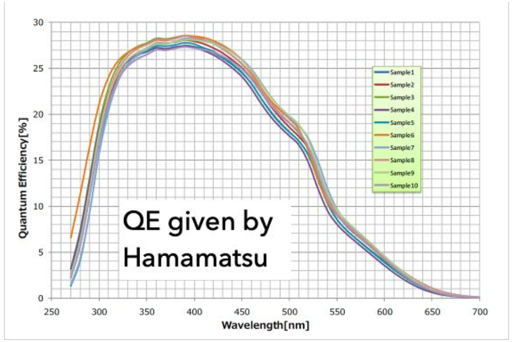


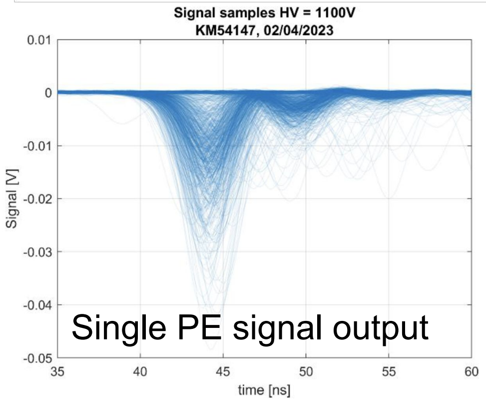




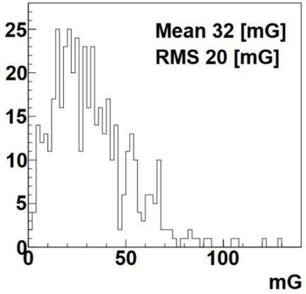
PMT and Electronics Response

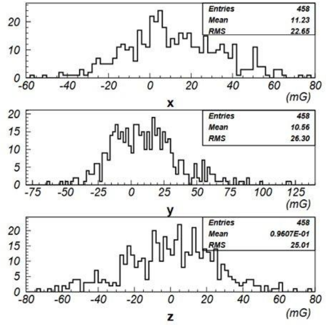
- Simulation of electronic responses
  - PMT (quantum x collection) efficiency, charge and time smearing
  - Gain/efficiency variations, effects of residual magnetic fields

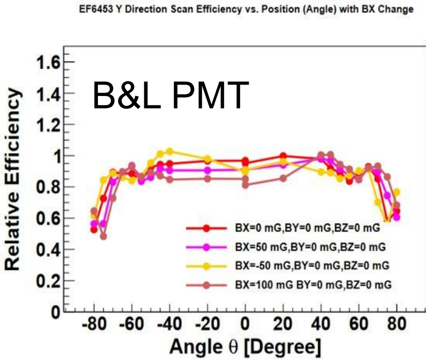


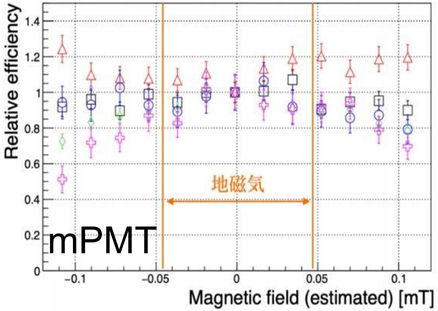


SK residual magnetic field measurements





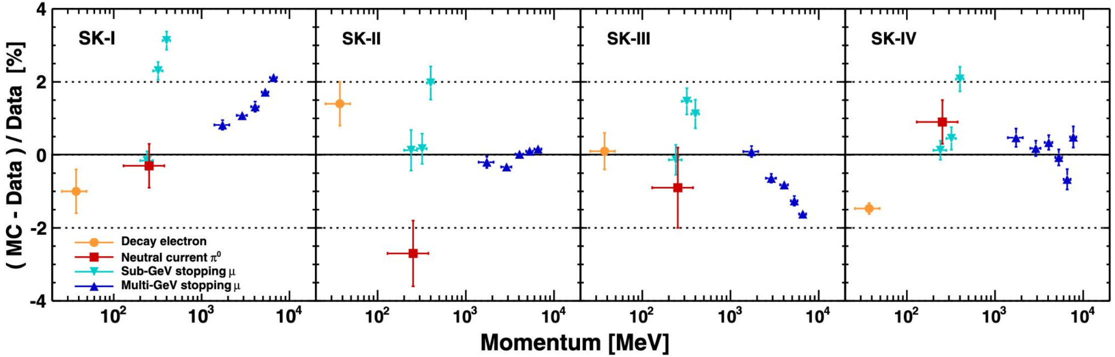




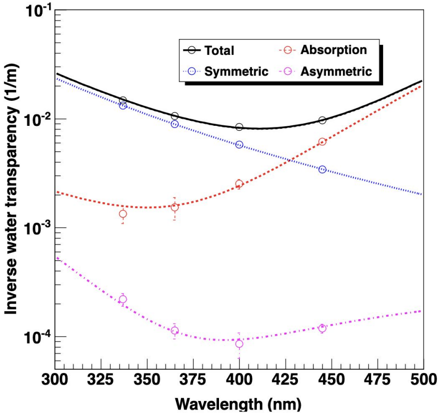
Current methods of calibration

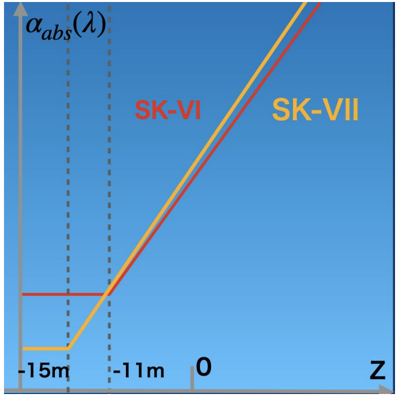
Top-down approach

- Effective parameters of energy uncertainty



- Tuning of e.g. water parameters are not properly correlated





Sequential steps

① TBA parameter tuning (1st)

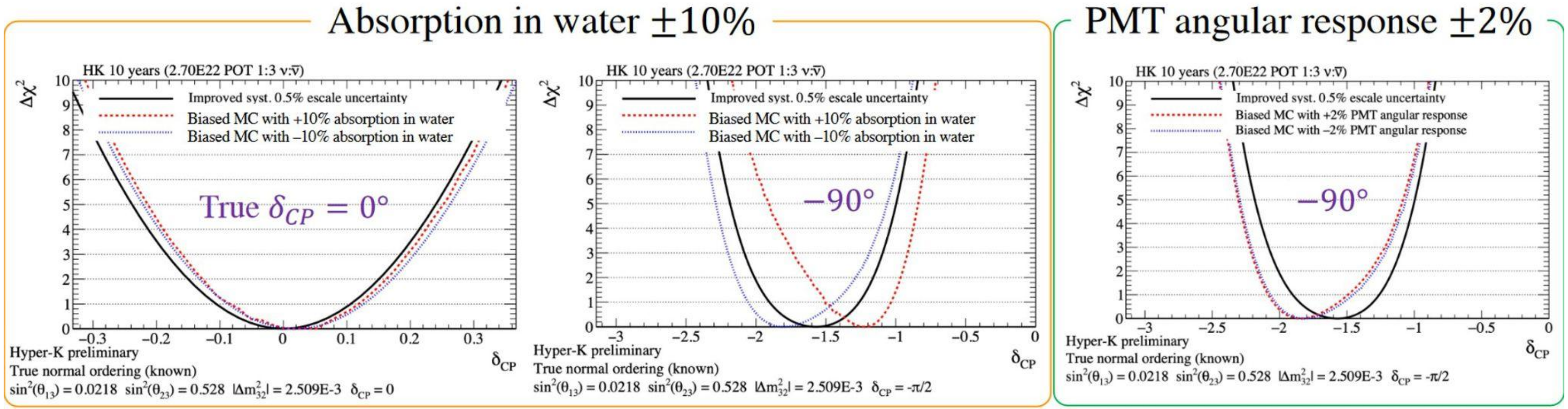
② Water parameter tuning

③ TBA parameter tuning (2nd)

④ Cross check

Bottom-up approach

- Formulate set of important detector parameters
  - Water quality, photocathode model, pe conversion factor/collection efficiency, reflectivity, etc.
- Derive prediction for diffusers, LED, radioactive source, etc.
  - Analytic + MC simulation (empirical parametrization + spline)
- Maximum likelihood fit w.r.t. Data
  - Challenges of computing time and convergence over large number of parameters and calibration samples
- Propagate uncertainties to reconstruction and oscillation analysis



Application of DDSims to e.g. WCTE

- Goal:

Photons starting at position ***r***, direction ***u***

$$p(\mu, t)_i = N_{\mathrm{ph}}(\mathbf{r}, \mathbf{u}) \left(\phi^{\mathrm{dir}}(\mathbf{r}, \mathbf{u}, i) + \phi^{\mathrm{ind}}(\mathbf{r}, \mathbf{u}, i) \right)$$

PMT hits

Direct & indirect hit prediction

- Known photon calibration sources (LEDs, diffuser ball, NiCf) to train ϕ
  - Easiest and earliest proof-of-concept from calibration runs
- Tagged particle beams to train Cherenkov yields from particles of known ID and kinematics
  - Secondary interactions and decays, etc. are included, will need more careful event selections

fiTQun -
Event Reconstruction

Ryo Matsumoto

Concept of fiTQun

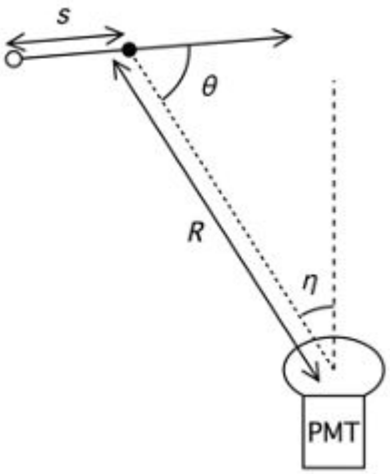
- A maximum likelihood fitter based on the look-up table of Cherenkov photons (maximized using MINUIT by ROOT).
- Likelihood function $L(x)$ uses charge and time information of the PMTs and determine the particle kinematics x:

$$L(x) = \underbrace{\prod_{j}^{unhit\ PMTs} P(unhit_j|x)}_{\text{unhit probability}} \underbrace{\prod_{i}^{hit\ PMTs} P(hit_i|x)\, f_q(q_i|x) f_t(t_i|x)}_{\text{hit probability, charge and time likelihood}}$$

- Both of the hit and unhit probabilities are taken into account.
- All parameters x (vertex, direction, momentum etc.) are fit simultaneously.
- *Need to prepare look-up tables*

Predicted charge by direct photon

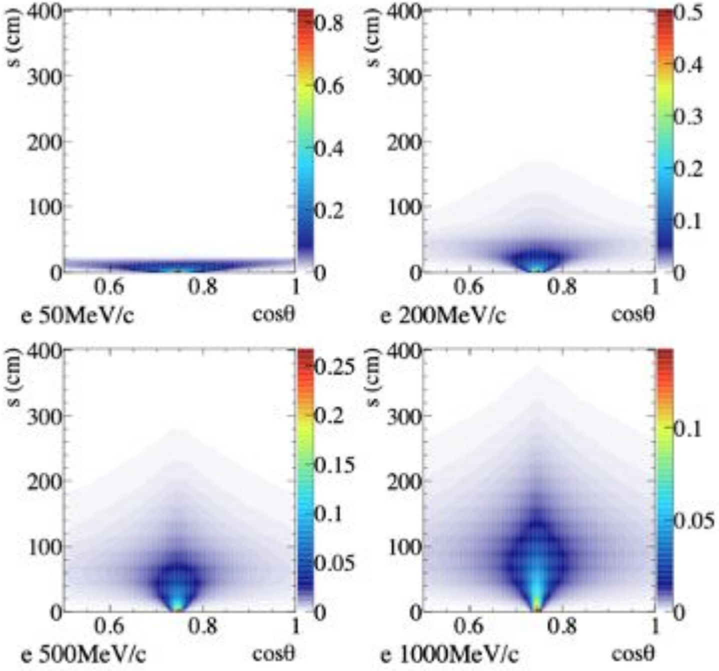
- P, fq, ft are functions of predicted PMT charge μ
- The charge is estimated from the sum of expectations from the direct and indirect light
- For direct light, predicted charge is given as an integral along the particle track length s:



$$\mu^{dir} = \Phi \int ds\, g(p, s, \cos\theta)\, \Omega(R)\, T(R)\, \epsilon(\eta)$$

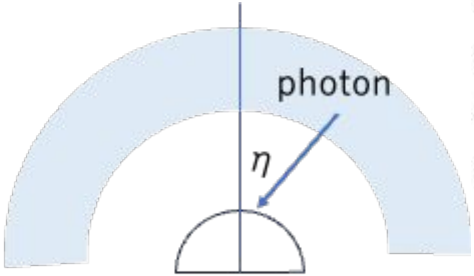
Φ: normalization factor
g: Cherenkov emission profile → using look-up table
Ω: Solid angle of PMT
T: attenuation of light
ϵ: PMT angular response → using look-up table

Cherenkov emission profile

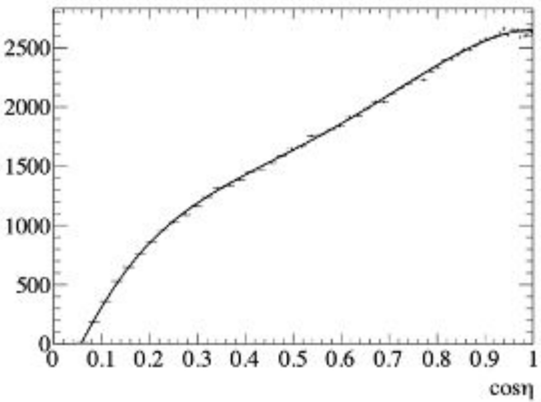


Simulate Cherenkov emission with several momentum
→ apply polynomial fit and get table for s, cos and momentum

PMT angular response



ex. PMT angular response in SK

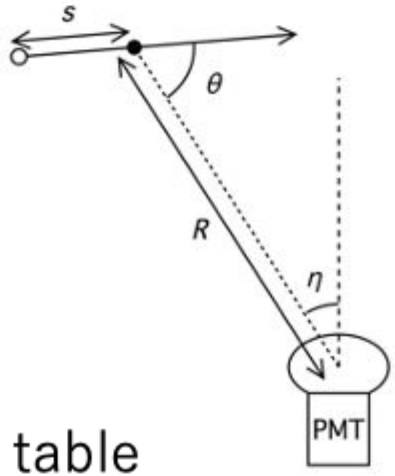


Zenith angle distribution of hits by photons around a PMT

Predicted charge by indirect photon

- The indirect photon includes the light scattered in water and detector component such as surface of PMTs.
- The predicted charge of indirect light is similar to the one of direct light:

$$\mu^{sct} = \Phi \int ds \, \frac{\rho(p,s)}{4\pi} \, A(s) \, \Omega(R) \, T(R) \, \epsilon(\eta)$$



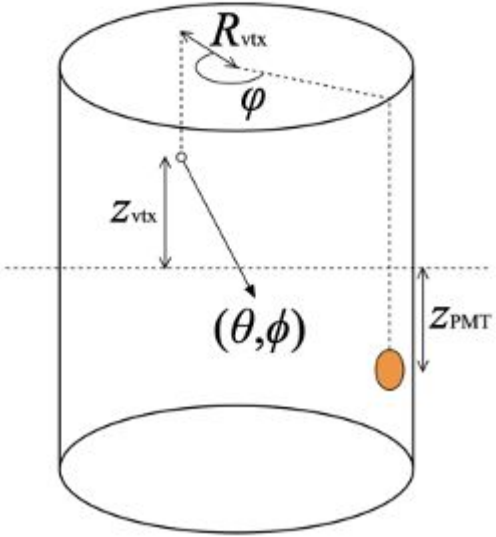
$\rho/4\pi$: integral of the Cherenkov emission profile g

$$\rho(p,s) = \int d\Omega g(p,s,\cos\theta)$$

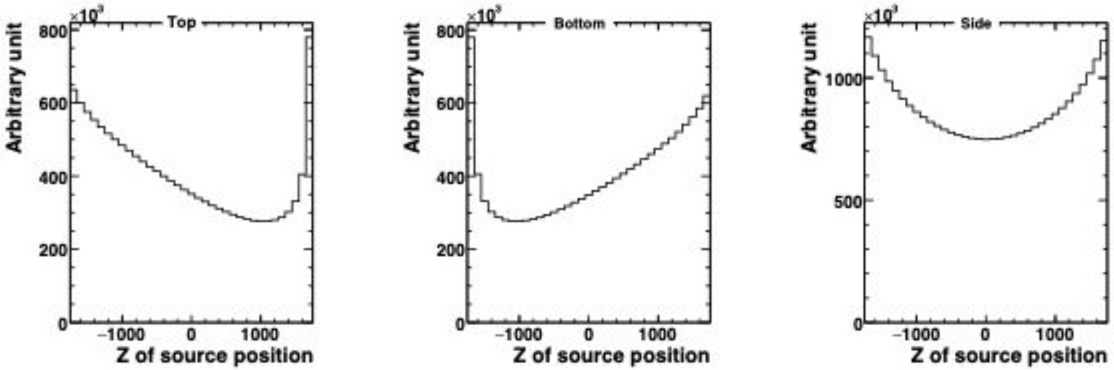
A: scattering light distribution table → using look-up table

Scattering light distribution table

- Scattering light distribution is created from 10^9 events (electron, 3MeV, uniform vertex and direction)
  - Fill 6-dimensional tables for top, bottom and barrel PMTs
- Among the tables, this requires the most events due to high dimension
  - The replacement by SIREN may contribute to computing resource and precision



ex. projected distribution to Z of source position in SK



Functions depending on charge in likelihood

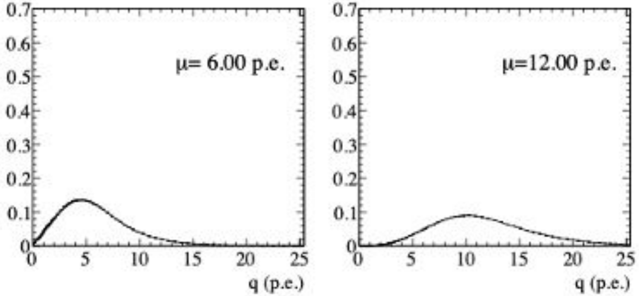
$$L(x) = \prod_{j}^{unhit\ PMTs} P(unhit_j|x) \prod_{i}^{hit\ PMTs} P(hit_i|x)\, f_q(q_i|x) f_t(t_i|x)$$

<u>Unhit probability with mean number of p.e.s</u> :

$$P(unhit|x) = (1 + a_1\,\mu + a_2\,\mu^2 + a_3\,\mu^3)\, e^{-\mu}$$

collection for events cannot cross PMT hit threshold × Poisson with zero expectation

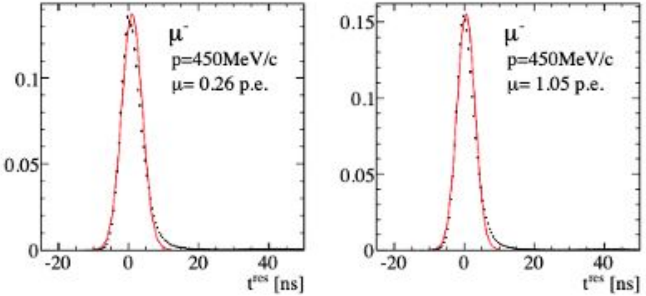
<u>Charge likelihood *f*q</u>



ex. 20-inch PMT in SK

- Charge distribution with predicted charge μ
- Look-up table obtained from simulation

<u>Time likelihood *ft*</u>

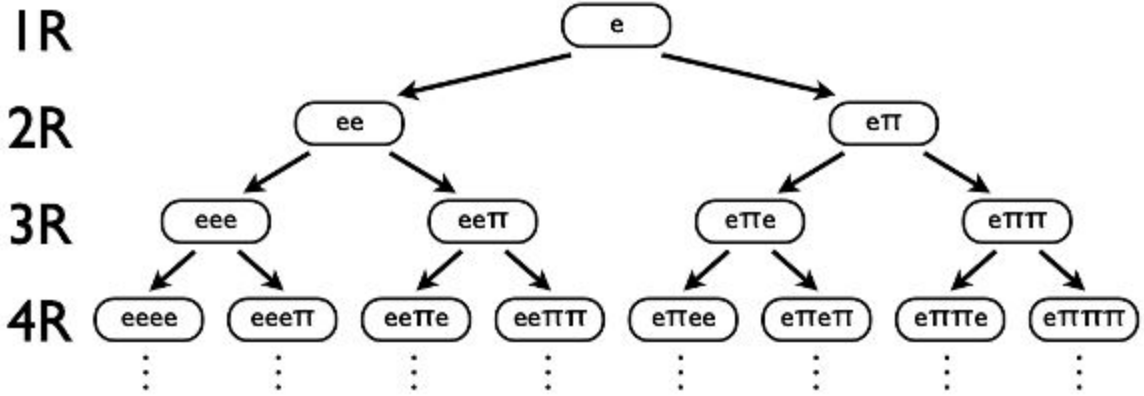


ex. residual time of direct light in SK

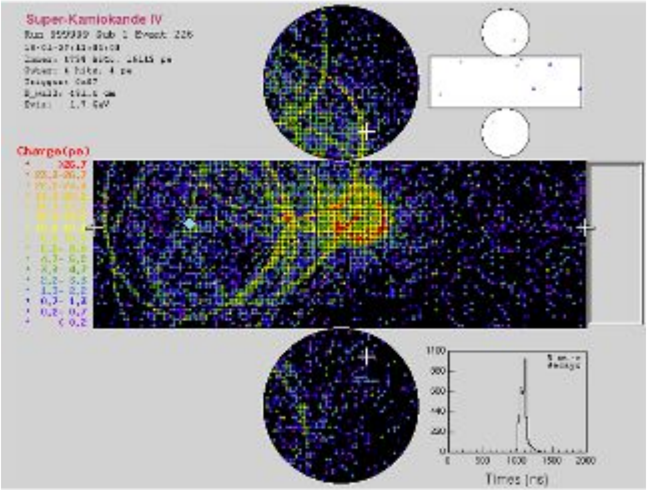
- Time distribution with predicted charge μ and momentum

Multi-ring fitter

- The algorithm searches the rings by sequentially increasing the number of rings (e or π)
- Check if likelihood is better than before the ring was added
- Since the computing time is 2^N, this process is the most time consuming among the process



Example of multi-ring event display



Outlook

- Application to fiTQun:
  - Replace generation method of current tuning files
  - Directly produce predicted charge from particle track
- Since there are many times of predicted charge calculation in fiTQun, it may contribute to reducing total computing time

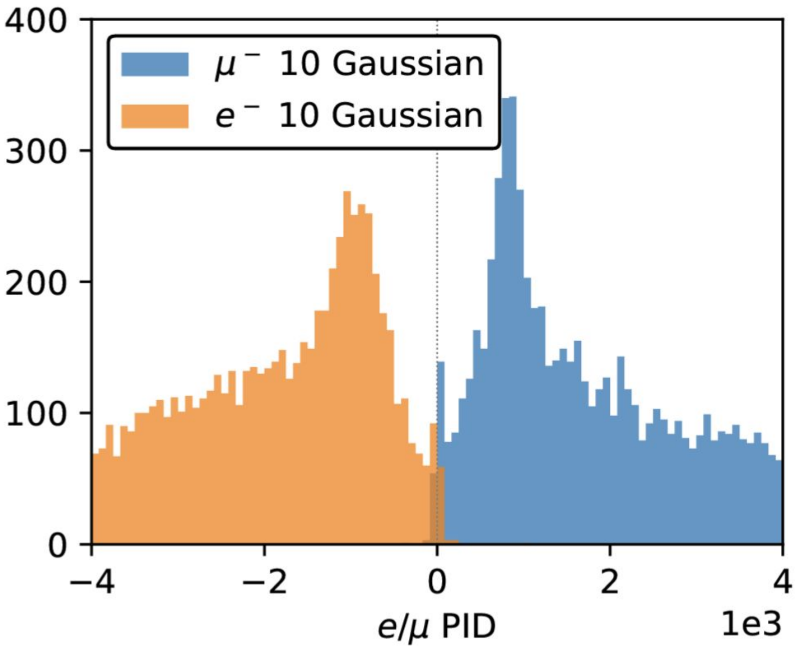
- Application to detector simulation:
  - E.g. Can the same SIREN for fiTQun indirect light table be used instead of G4 photon propagation?
    - Systematics (e.g. water parameters) directly tuned/optimized from calibration data
  - Include other parts of simulation, like QExCE of each PMT?

Appendix

NN-based Reconstruction

A working example

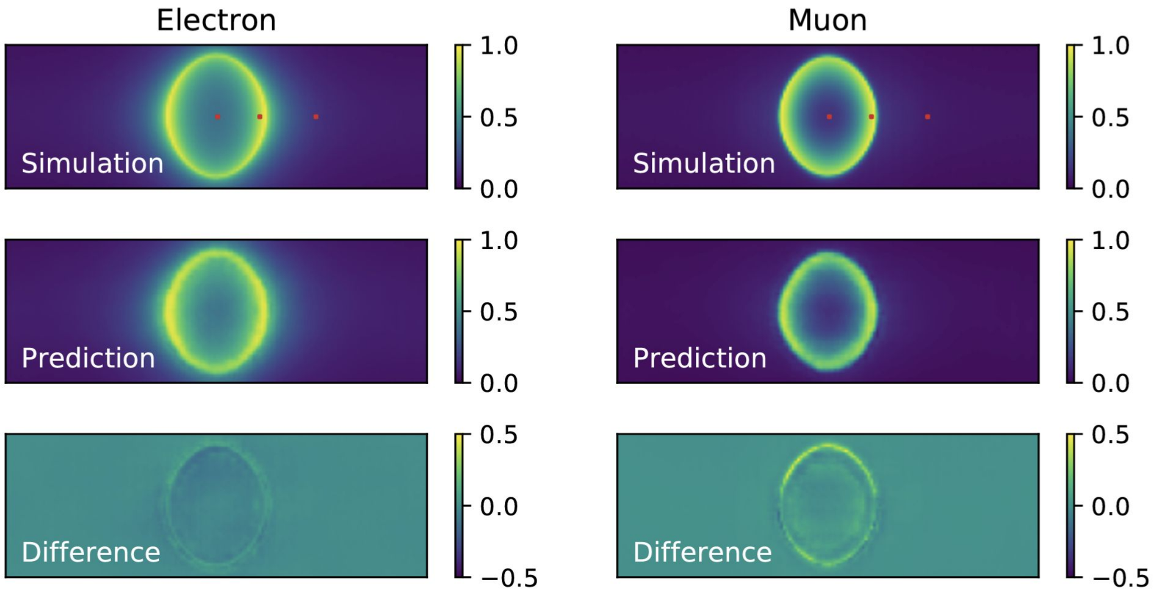
- A deep convolutional NN to generate WC detector responses to a particle of given particle type, energy, position, and direction.
- Loss designed based on the fiTQun likelihood function on p.17, optimized by ADAM and can be trained on the "physics MC".
- Enabled finer details in each individual photodetector responses by multi-gaussian distributions, and the correlation between charge and timing.



Demonstration of the PID likelihoods given by a trained CNN for single ring events uniformly generated inside the WC detector. Pile-up of events around the boundary comes from the events near detector walls.

A working example

- In this example, the CNN-generated WC events show some extents of “smearing effect”, which might have be originated from the use of ReLU.



- To solve this “smearing effect”, the use of periodic activation functions, e.g. ideas from SIREN and NeRF, is under study.