TITUS:
A Next-Generation Near Detector for the HK Long-Baseline Programme

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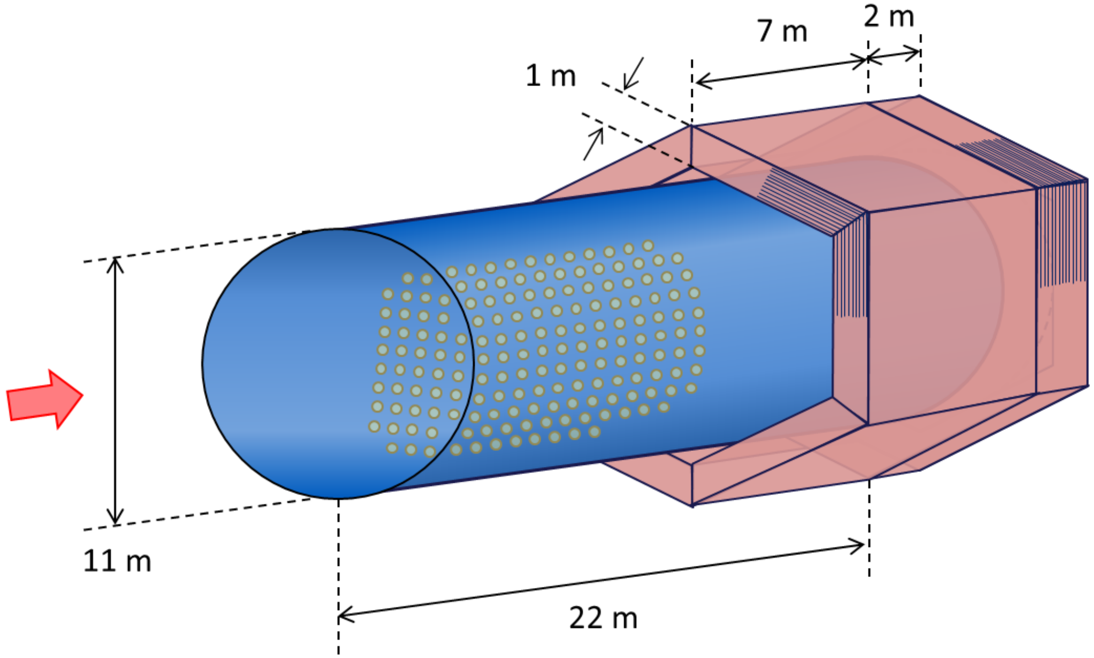
(for the TITUS Working Group)

2015 January 31
6th Open Meeting for the Hyper-Kamiokande Project

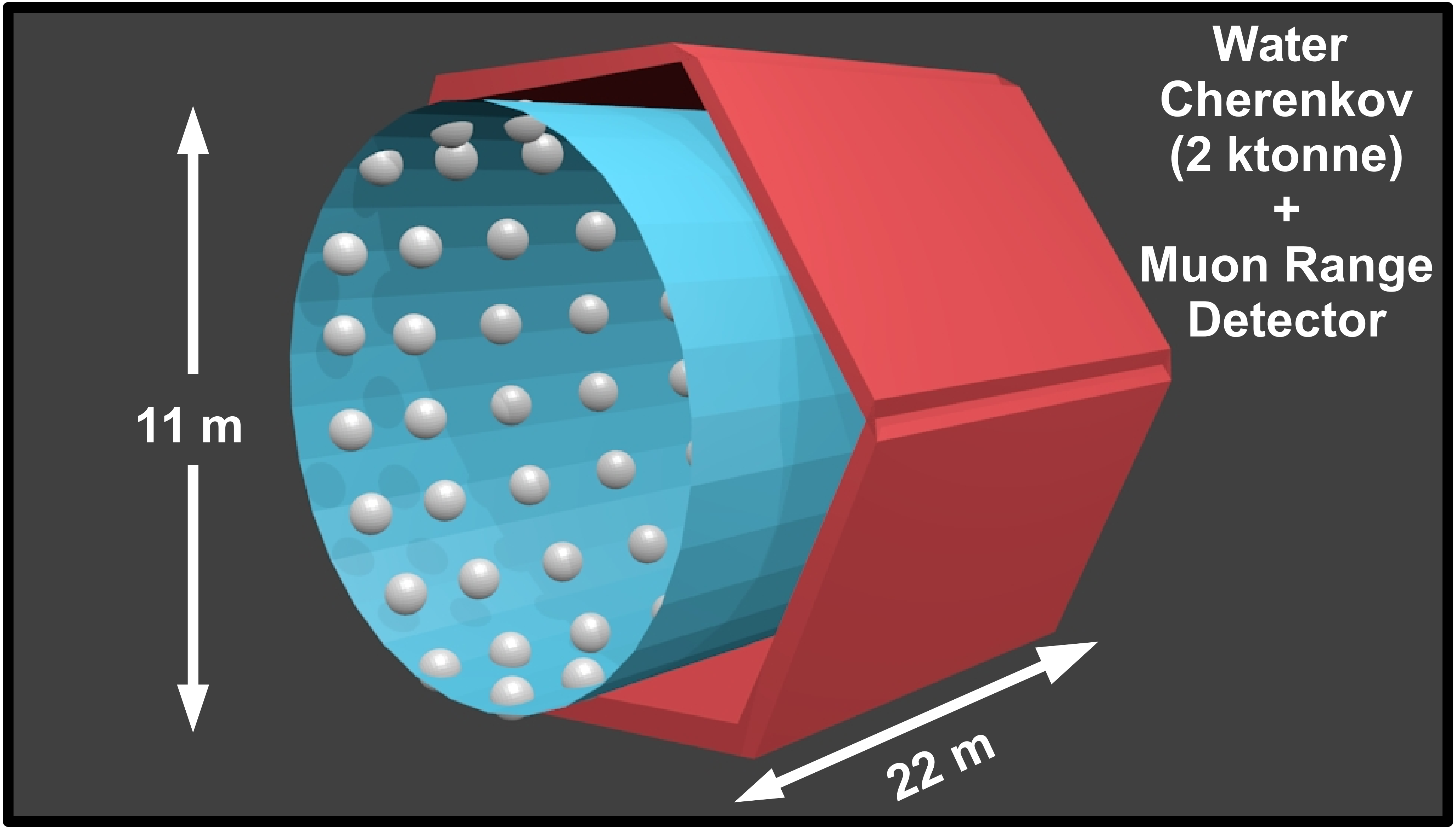
Outline

TITUS: The **T**okai **I**ntermediate **T**ank with **U**noscillated **S**pectrum

- Introduction & detector description
- Physics goals
- Software: Simulations & reconstruction
- External backgrounds
- Physics analyses:
  - Event selection
  - δ_{CP} sensitivity
  - Cross-sections
  - Sterile analyses
  - Supernova neutrinos



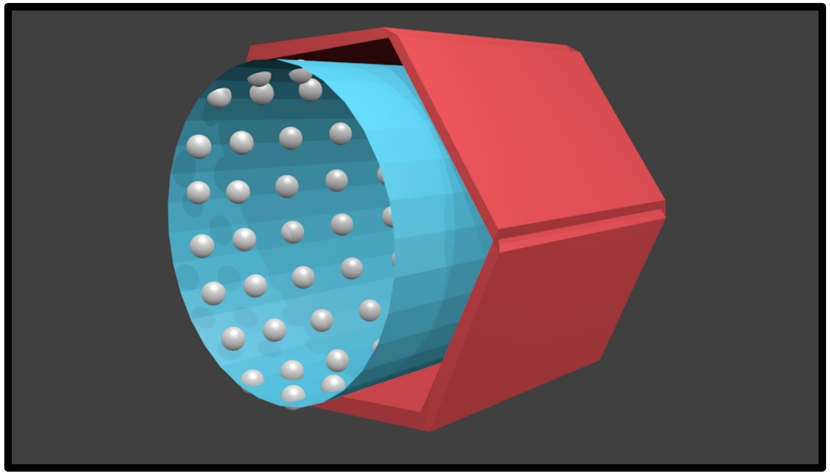
TITUS: A First Look

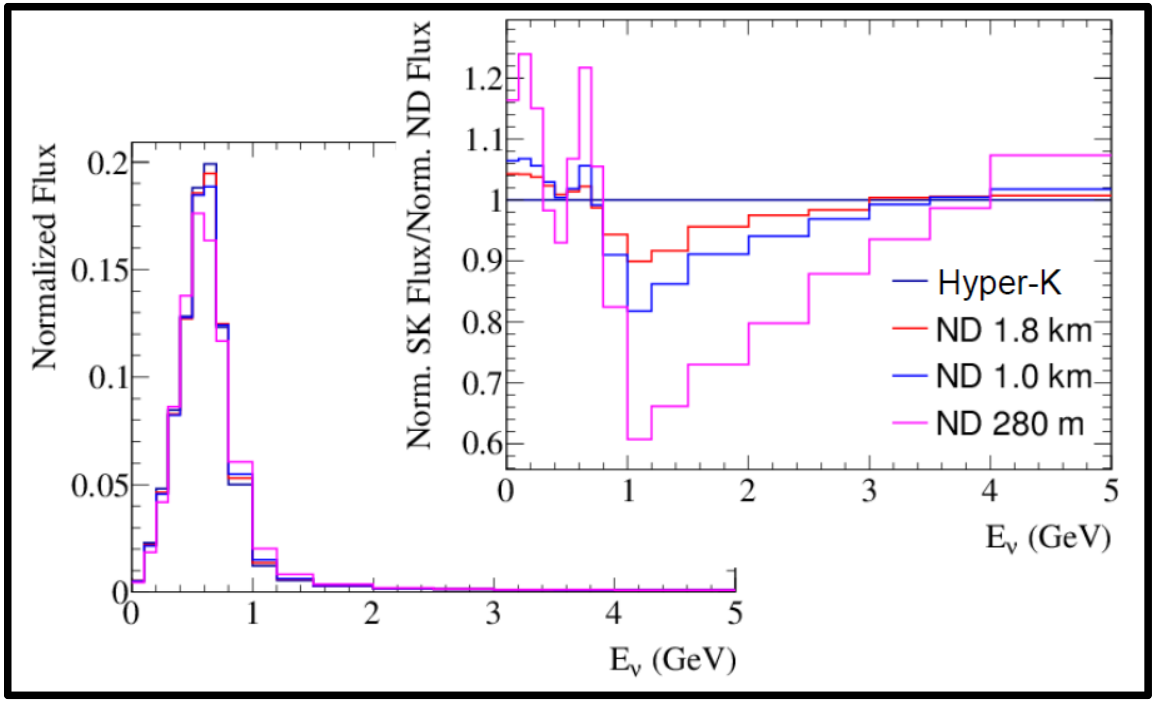


TITUS Overview

- Proposed new near detector for HK beam programme
- To be located ~2 km from J-PARC neutrino beam

- Baseline design includes:
  - ~2 ktonne water Cherenkov tank
  - 0.1% Gadolinium-doping
  - Partly enclosed by Muon Range Detector
    - See next talk by M. Rayner





- Same target nuclei as Hyper-K
  - H_2O (and maybe Gd?)

- Nearly same target angle and ν energy spectrum

- Many systematics cancel out in Far/Near ratio

TITUS Overview

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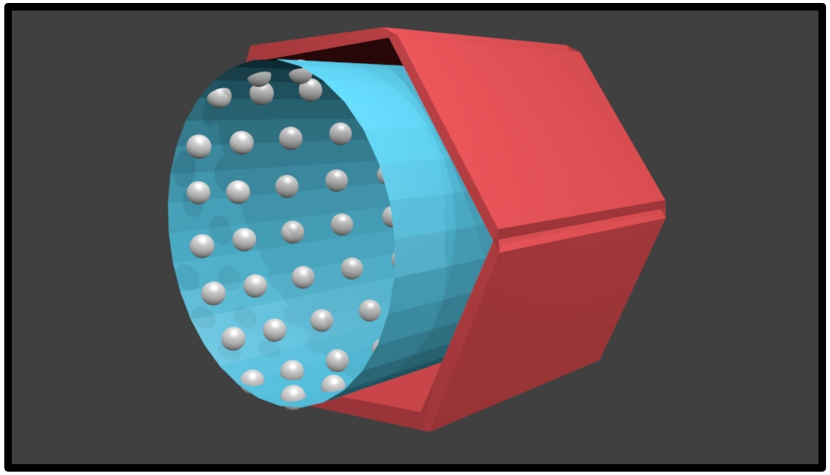
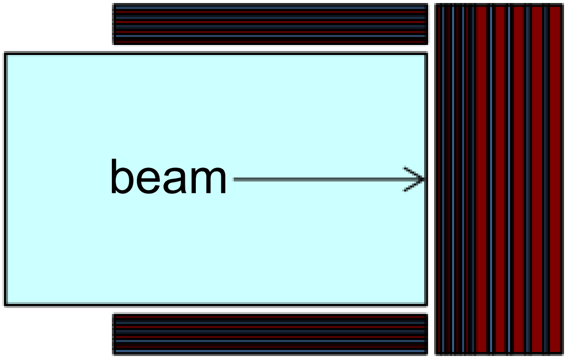


- Baseline design includes:
  - ~2 ktonne water Cherenkov tank
  - 0.1% Gadolinium-doping
  - Partly enclosed by Muon Range Detector
    - See next talk by M. Rayner

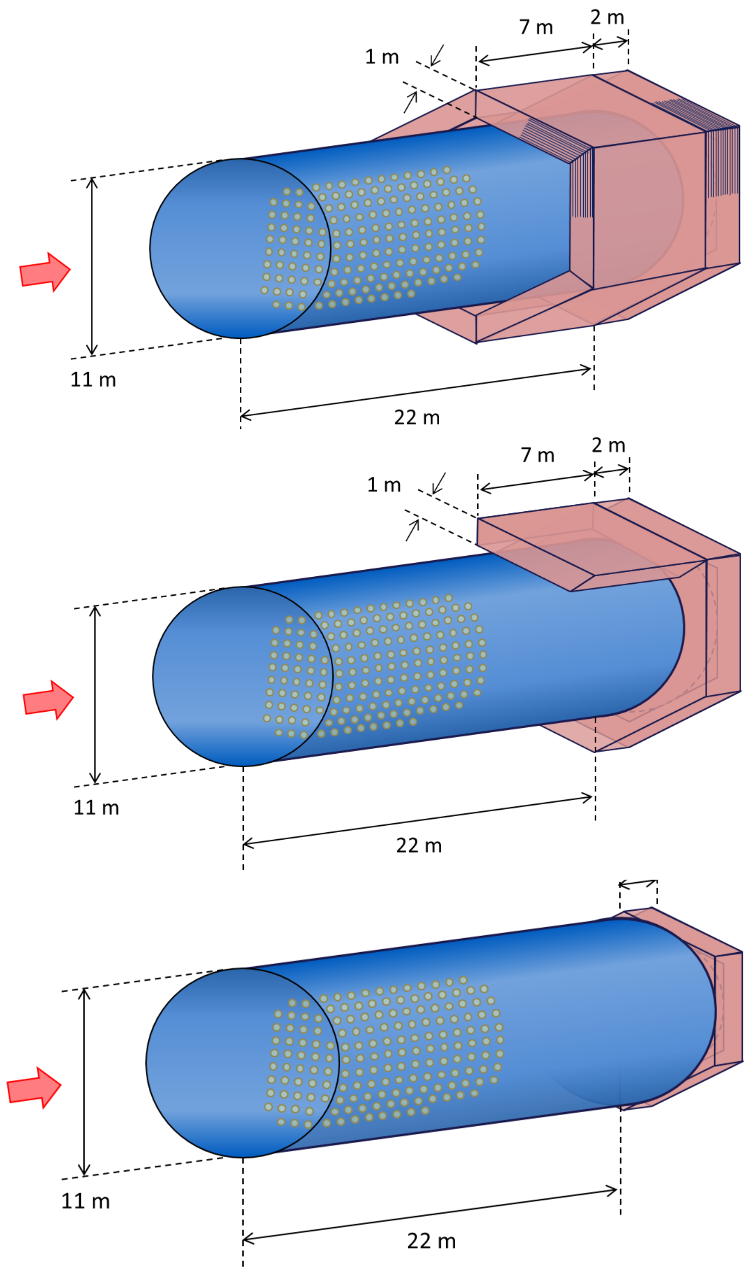
- Likely add-ons / upgrades currently being investigated include:
  - Magnetised MRD (1.5 Tesla field) for charge-sign reconstruction
  - Large Area Picosecond Photo-Detectors (LAPPDs) for high precision timing
  - High quantum efficiency PMTs (HQE PMTs)

- Future possible add-ons / upgrades include:
  - Water-based liquid scintillator
  - TPC inside an aluminium coil air core magnet
  - ??? (New ideas welcome!)



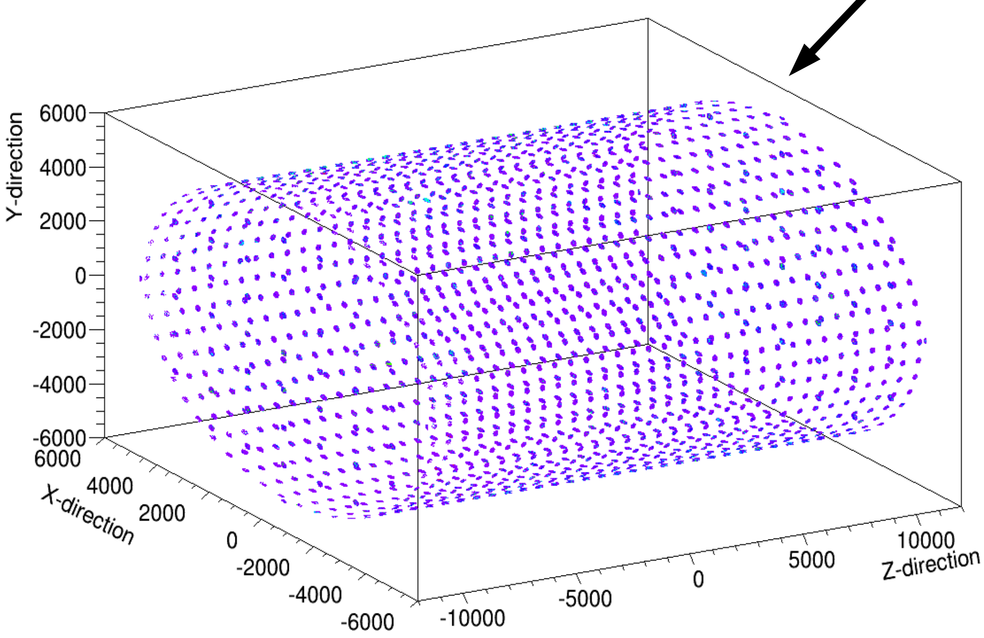
Design Optimisation

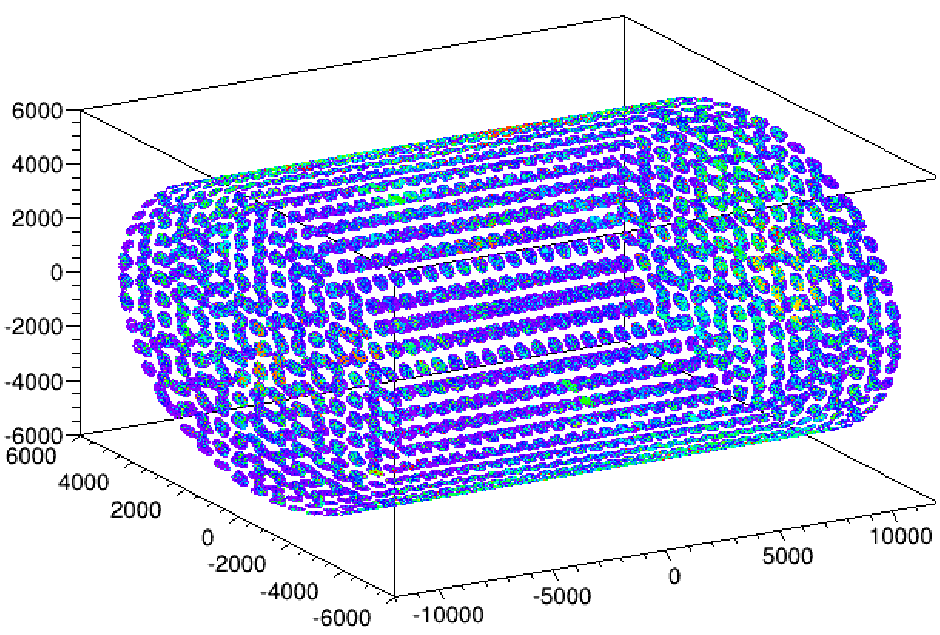
- Like Hyper-Kamiokande, TITUS design not yet final.
- Open questions include:
  - **Location**
    - 1.8 km? 2 km? Other?
    - In line with Tochibora? Mozumi?
    - Off-axis angle?
  - **Photosensors** (see next two slides)
    - Size?
    - Coverage?
    - Type? (PMTs? HQE? LAPPDs?)
  - **Muon Range Detector** (see next talk)
    - Coverage?
    - Magnetised?



TITUS Photosensors

- 12 basic configurations being tested for cost, reconstruction, etc.
  - **Four PMT sizes:** 20” PMT, 12” PMT, 10” PMT, 8” PMT
  - **Three coverages:** 20% (HK), 30%, 40% (SK)





ALSO: Option to add sparser grid of LAPPDs to any of these configurations

TITUS Photosensors

- How many PMTs do we need?
  - For base design (11 m diameter; 22 m length), TITUS surface area is ~10^7 cm^2 (1.9×10^6 cm^2 endcaps + 7.6×10^6 cm^2 barrel)

	8 inch	10 inch	12 inch	20 inch
40%	12,000	7,500	5,200	1,900
30%	9,000	5,600	3,900	1,400
20%	6,000	3,750	2,600	950

Default configuration for studies presented in this talk is:

- 40% photocathode coverage
- 20” PMTs

TITUS Physics Programme

- **Measure intrinsic ν_e component of J-PARC beam**
  - Dominant background to ν_e appearance measurement
- **Cross-section measurements**
  - Inclusive $NC\pi^0$ is sub-dominant background to ν_e appearance measurement
  - Can measure differential cross-sections as a function of neutron number
  - CCQE vs. CC-inclusive
- **Neutron multiplicity measurements**
  - Provide input to neutrino generator models
  - Use ν / $\bar{\nu}$ separation to remove contamination from "wrong-sign" neutrinos
  - Distinguish CCQE from other modes
  - Enhance Hyper-K proton decay searches via precise BG measurements
- **Sterile neutrino searches**
  - Compare NC rates at 280 m & 2 km to look for ν_{active} disappearance
- **Supernova burst neutrinos**
  - Approx. 650 events expected from SN burst (570 $\bar{\nu}_e$ IBD + 80 ν_e ES)
  - Evaluating feasibility as an independent alarm for the SNEWS network

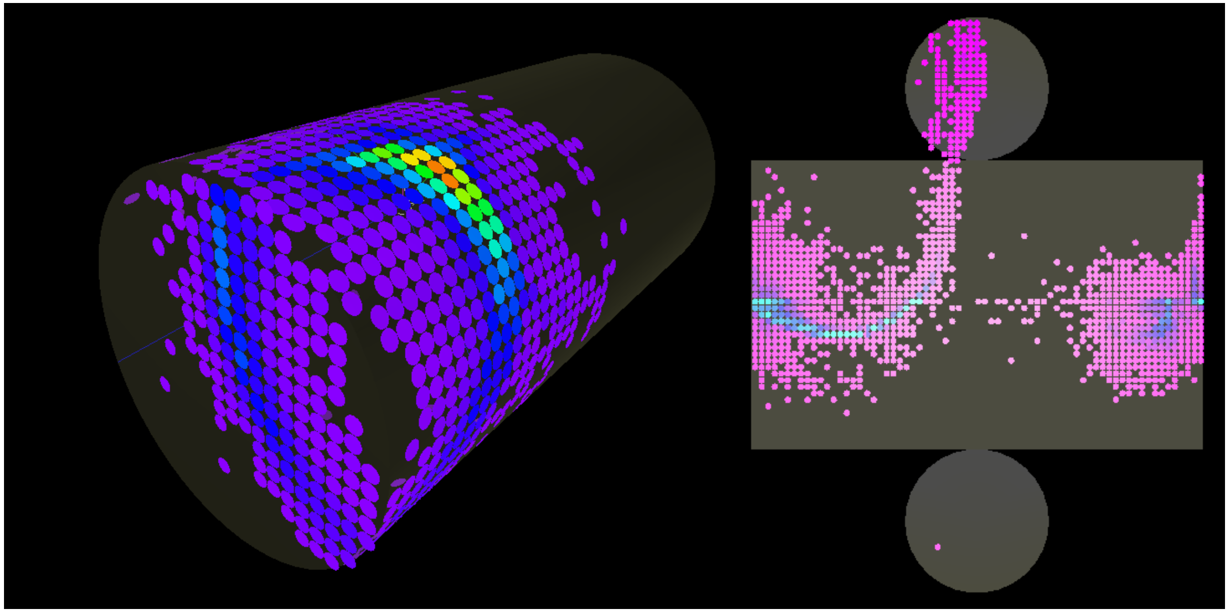
Simulation Software

Currently using TWO different simulation / reconstruction packages:

- WChSandBox is a **new** fast simulation package for WC detectors)
  - Uses native reconstruction tools (RecoLite)

- WCSim also being used with fiTQun and table-based reconstructions
  - Needs integration of Gd-capture and addition of LAPPDs

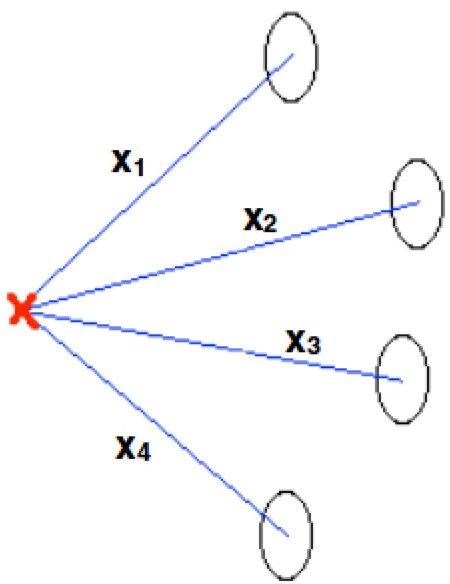
WChSandBox:
CCQE (1Rμ)



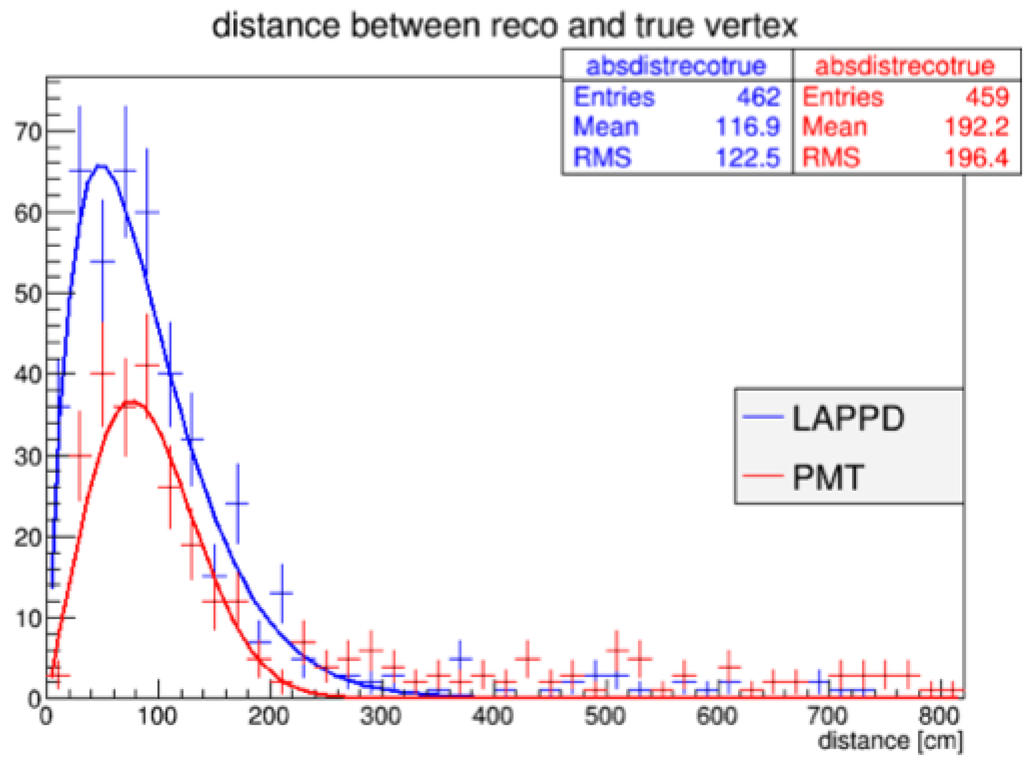
Display by
A. Finch

Reconstruction

- Low-energy reconstruction via 'RecoLite' (W. Ma & M. Malek)
  - Vertex based on 4-hit algorithm (similar to BONSAI @ SK & quad-fitter @ SNO)
  - Energy based on total number of hit PMTs



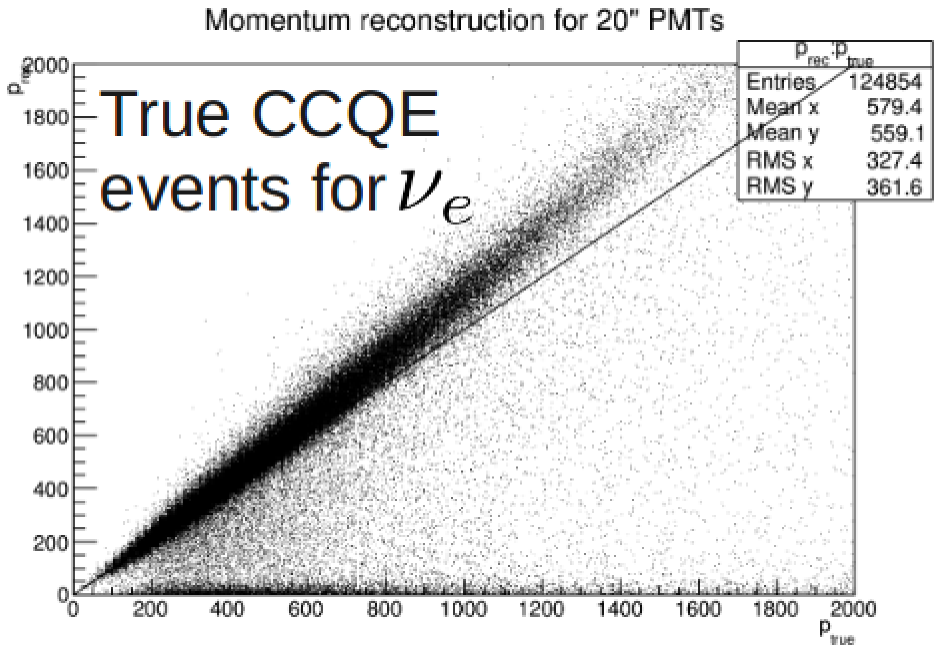
For each 4-hit combination of PMTs, calculate vertex. Evaluate relative goodness to select best vertex:



Can be run with:
- PMTs (2.5 ns resolution)
- LAPPDs (0.1 ns resolution)
- Hybrid mode (not shown)

Reconstruction

- High-energy reconstruction via fiTQun (N. Prouse)



Currently experiencing biases in vertex & momentum reconstruction.

NOT seen using fiTQun in Hyper-K.

Perhaps we need a fiTQun tuned specifically for TITUS?

Present work uses a hybrid data sample:

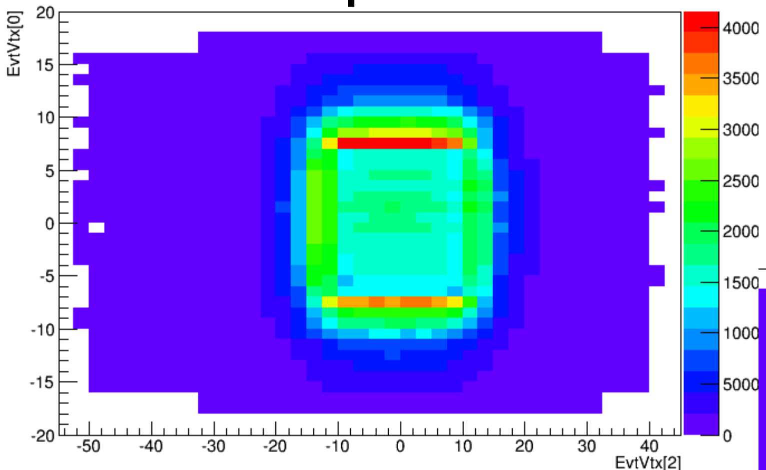
- Low energy:
  - WChSandBox simulation + RecoLite
- High energy:
  - WCSim + fiTQun table-based reconstruction
    - Provided by S. Tobayama; tables based on fiTQun at Super-K

External Backgrounds

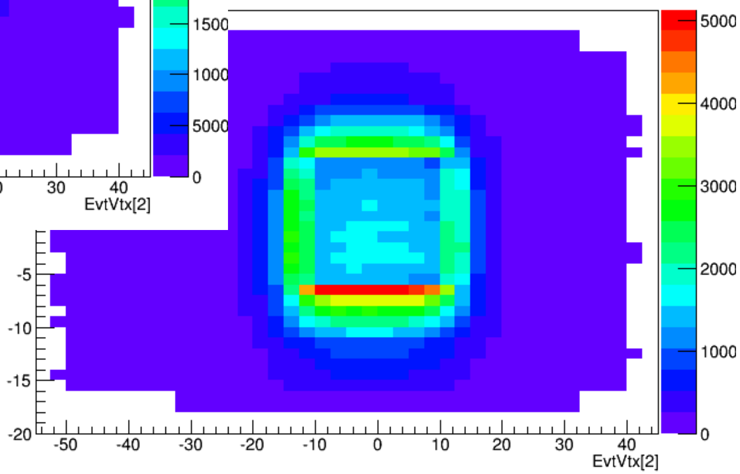
- Two main sources:
  - Cosmic ray μ
    - Can produce spallation neutrons – serious BG to Gd-based studies
    - At TITUS depth, estimated event rate of ~15 kHz for spallation n
    - Currently working on spallation cut following cosmic ray muon events
      - Need reduction power of ~10^{-2-3} (should be achievable)
  - Sand μ
    - Produced from interactions in sand & rock volume around TITUS
    - Can result in photons, neutrons, muons, electrons, pions, etc.
    - Ongoing studies by J. Łagoda & R. Terri (see next slide)

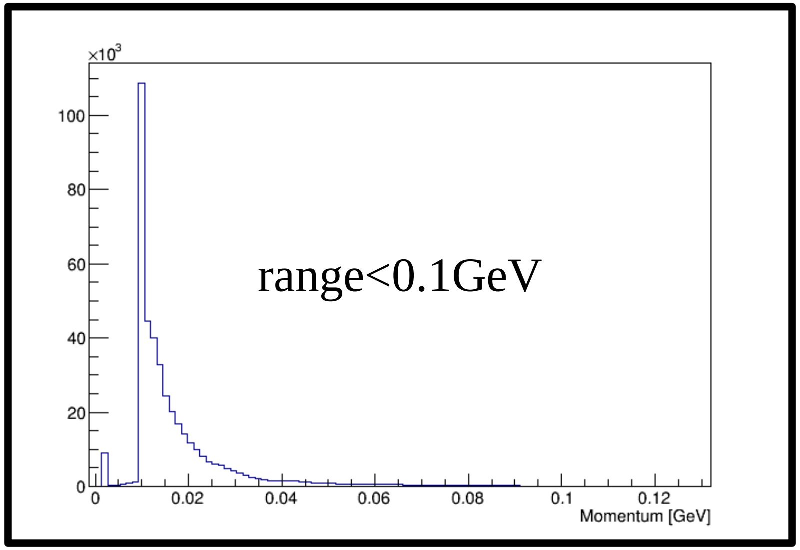
Neutrons from Sand μ

Top view

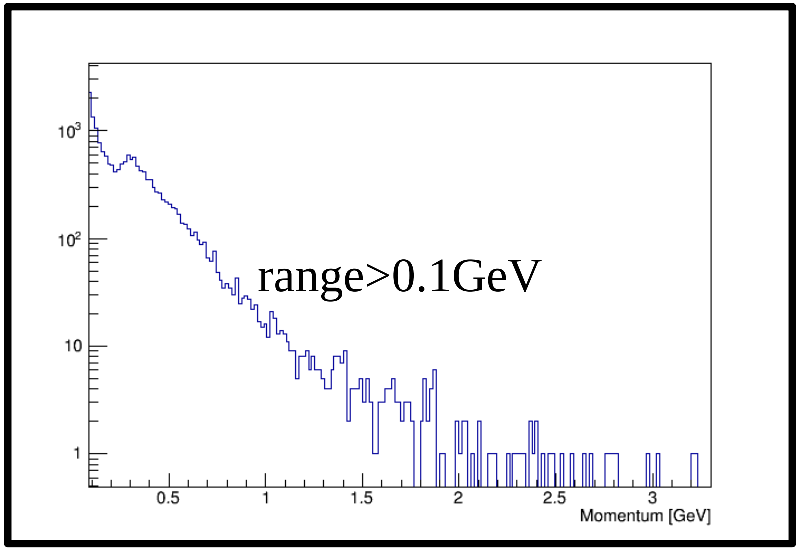


Side view





Momentum on entering detector

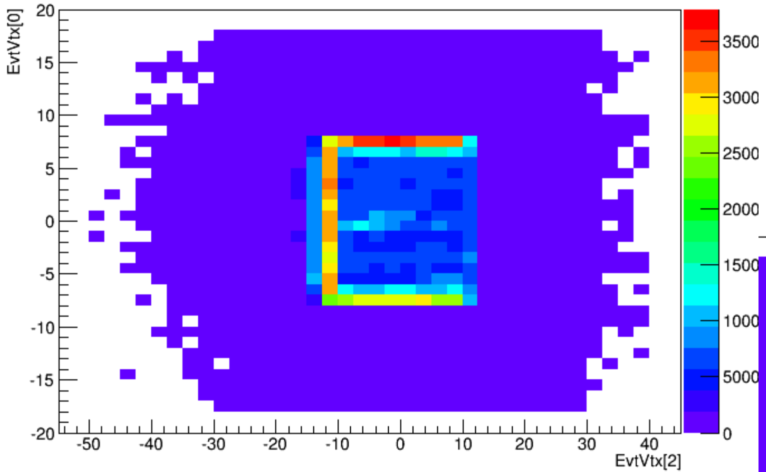


<u>N.B.:</u> Entries reflect number of incoming neutrons.

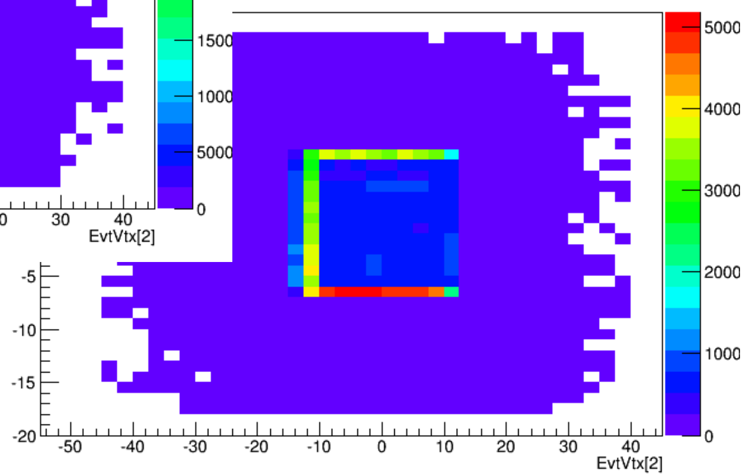
It is possible for one neutrino interaction to contribute multiple entries if it produces multiple neutrons which reach the detector volume.

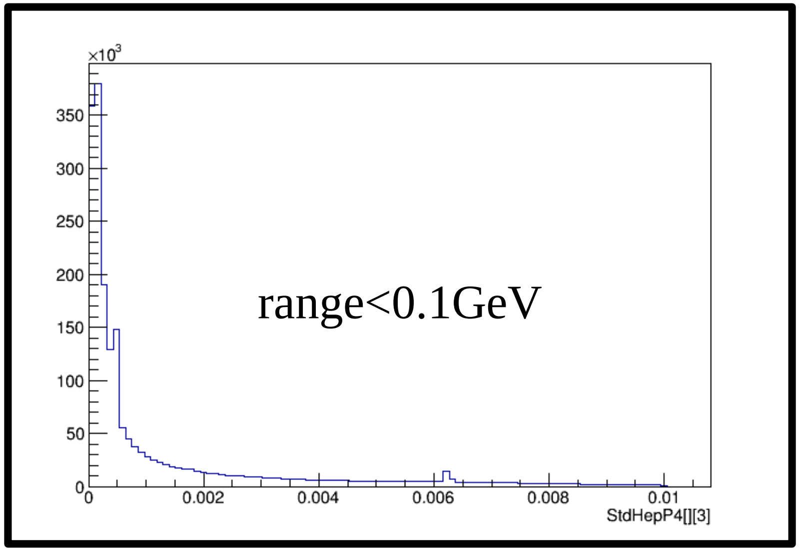
Photons from Sand μ

Top view

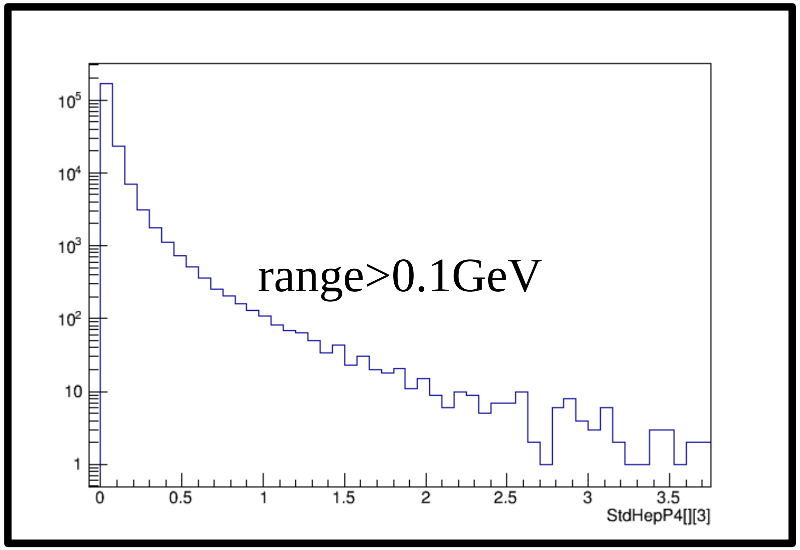


Side view





Momentum on entering detector



N.B.: Entries reflect number of incoming photons.

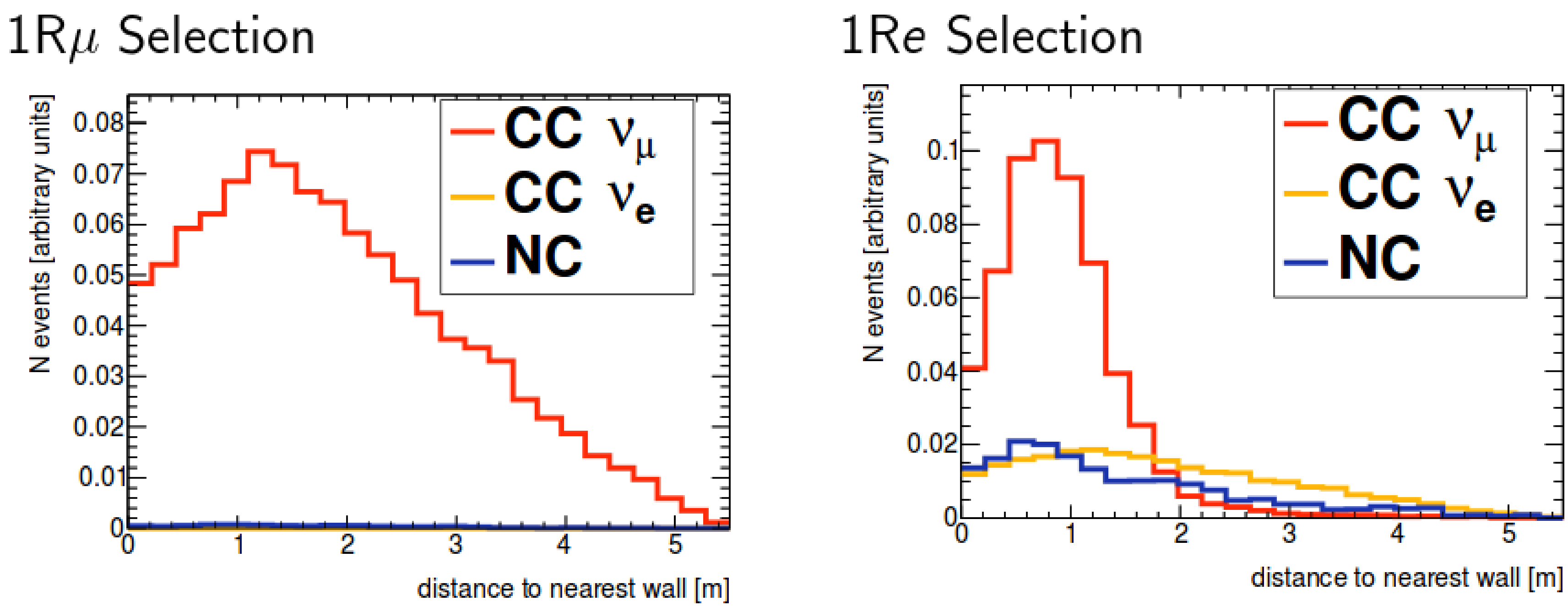
Sand interactions being added to detector MC

→ Upstream veto would remove most of sand-induced backgrounds.

TITUS Event Selection

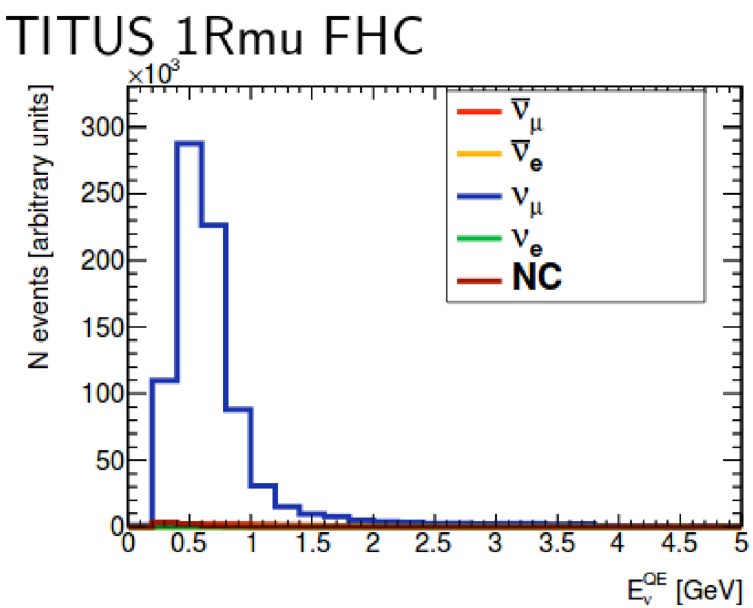
Event selection studies (D. Hadley) using table-based reconstuction:

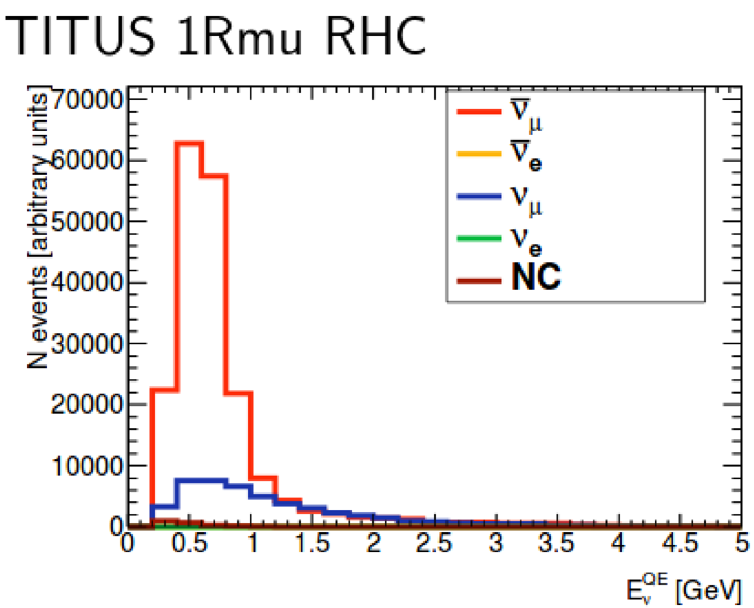
- Uses SK fiTQun efficiencies for 1Rμ & 1Re events



- Large muon contamination in electron sample at *Dwall* < 200 cm
- Low efficiency at *towall* < 200 cm
- Will need to re-optimise cuts when a real high-E reconstruction is available

1Rμ Sample


TITUS 1Rmu FHC
×10³
N events [arbitrary units]
E_ν^QE [GeV]
ν̄_μ
ν̄_e
ν_μ
ν_e
NC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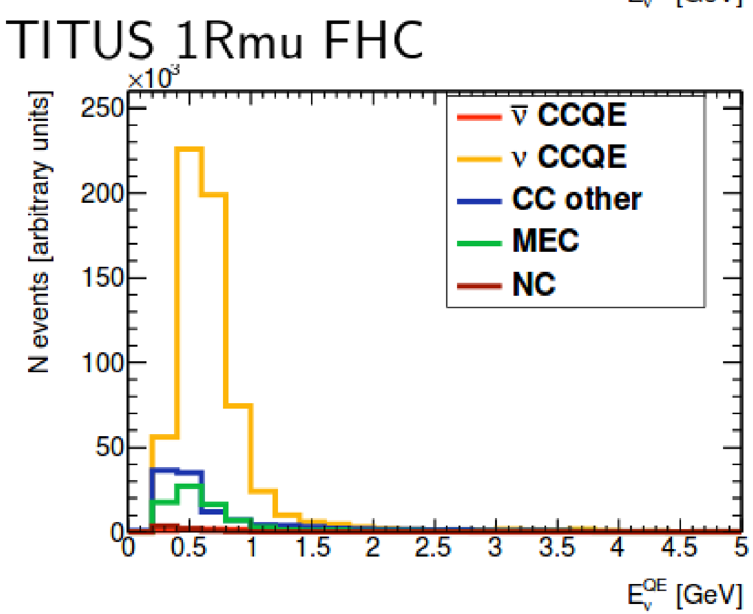
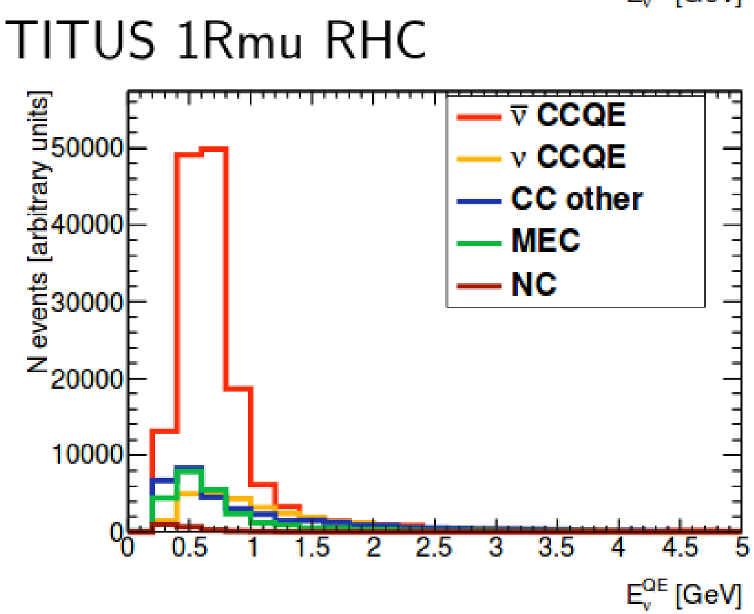
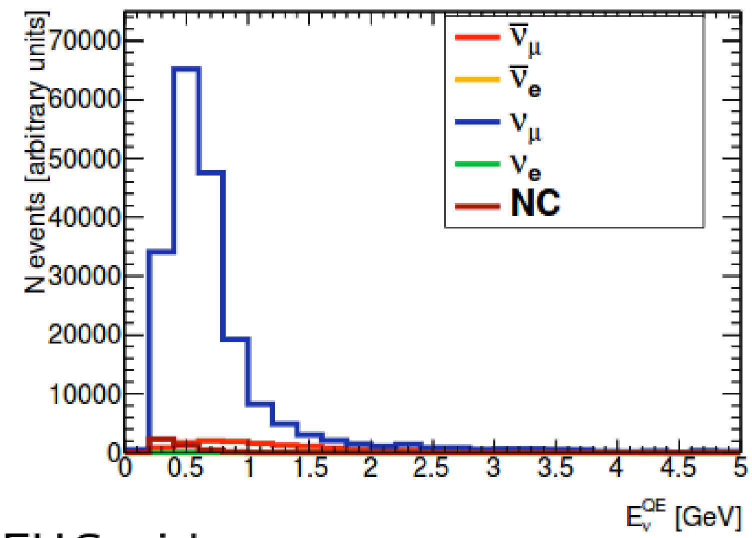
NC


TITUS 1Rmu FHC
×10³
N events [arbitrary units]
E_ν^QE [GeV]
ν̄ CCQE
ν CCQE
CC other
MEC
NC

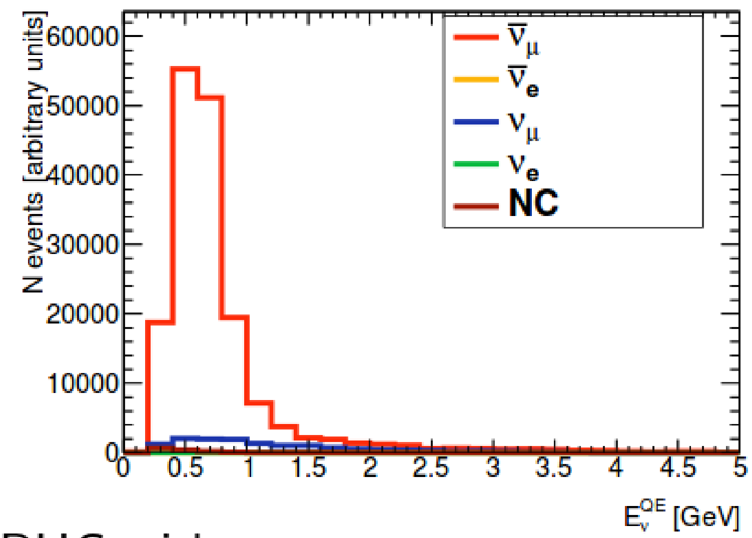

TITUS 1Rmu RHC
N events [arbitrary units]
E_ν^QE [GeV]
ν̄ CCQE
ν CCQE
CC other
MEC
NC

1Rμ Sample w/ n-tagging

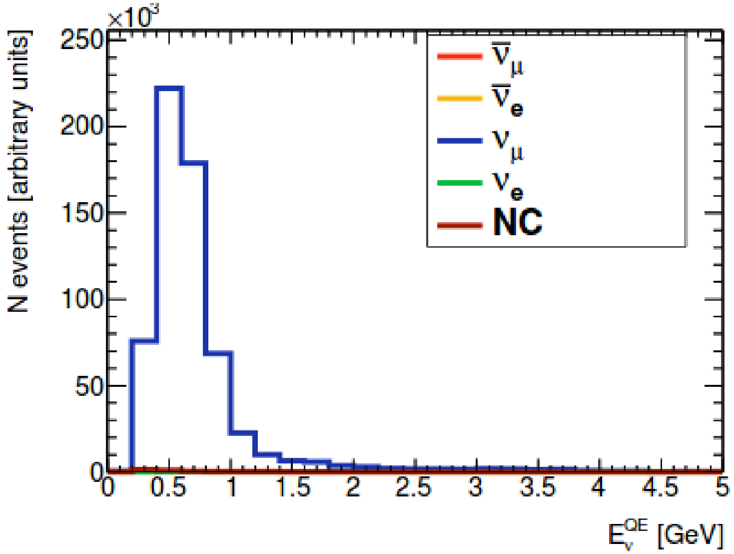
FHC with tagged neutron



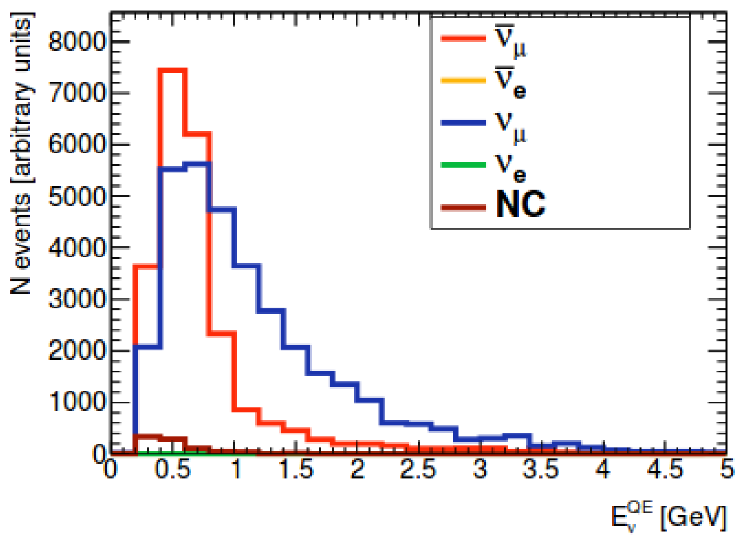
RHC with tagged neutron



FHC without neutron

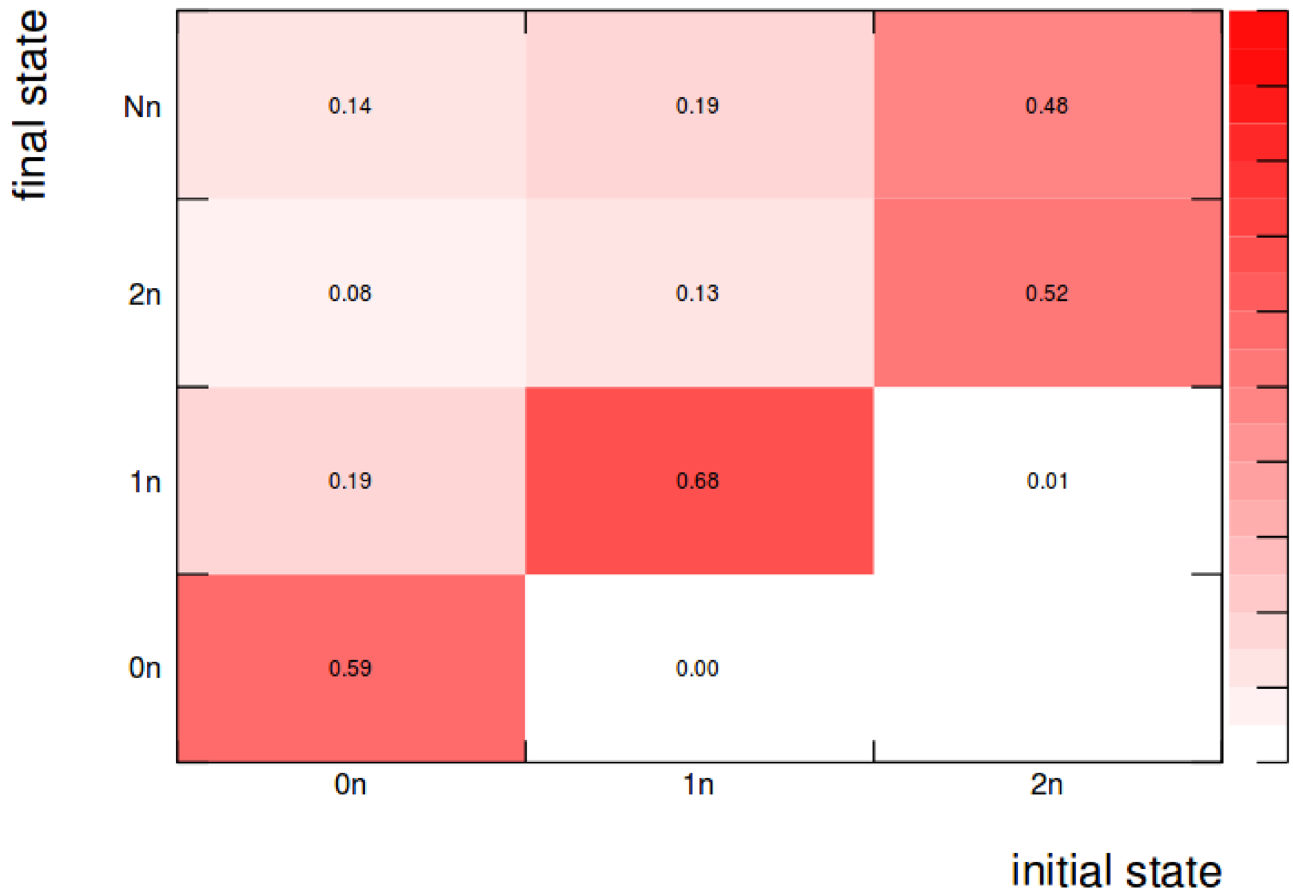


RHC without neutron



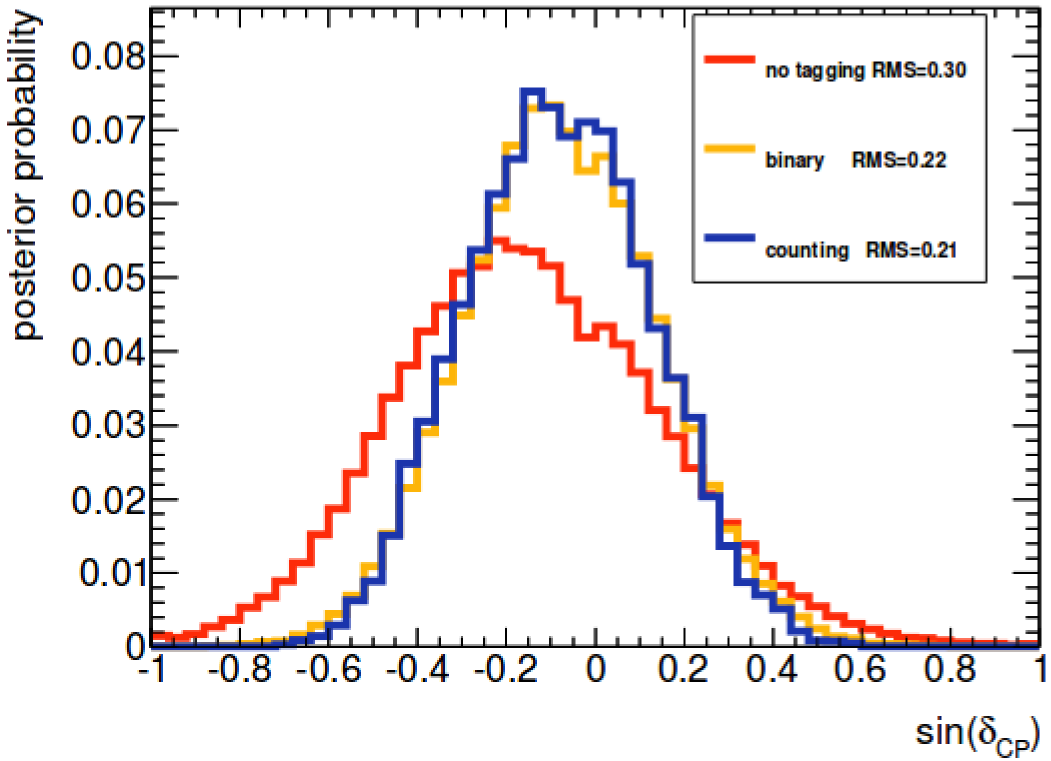
Neutron Tagging

- Including primary and secondary interactions:



- Can institute either 'binary' or 'counting' method of neutron tagging
- How does this affect δ_{CP} fits?

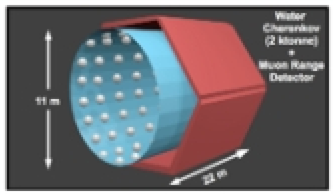
Fit Results



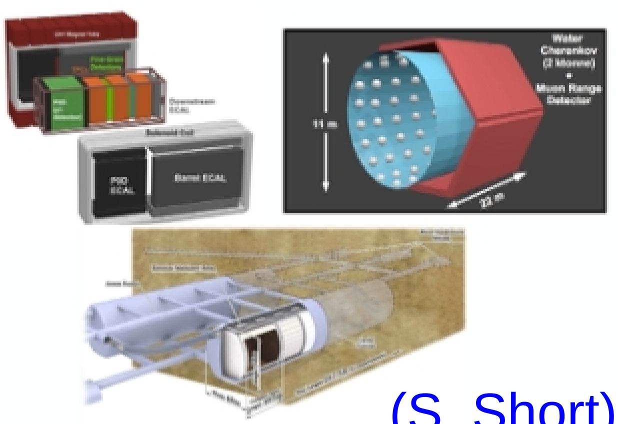
- Pseudo-experiment with **true** $\delta_{CP} = 0$
- Uncertainty in δ_{CP} evaluated with Bayesian method
- Adding binary neutron tagging gives marked improved
- Full counting of neutron multiplicity does not appear to be much more helpful.
- For full details of fit (incl. uncertainties & likelihood) see Dave's talk from pre-mtg

Oscillation Sensitivity

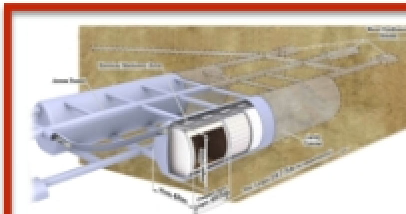
- Full oscillation sensitivity studies are currently underway
  - Uses joint fit of ND280 + TITUS + Hyper-Kamiokande:



TITUS samples + covariance
(N. Prouse)



(S. Short)
“BANFF”-type fit result



Hyper-K samples + covariance matrices

VaLOR

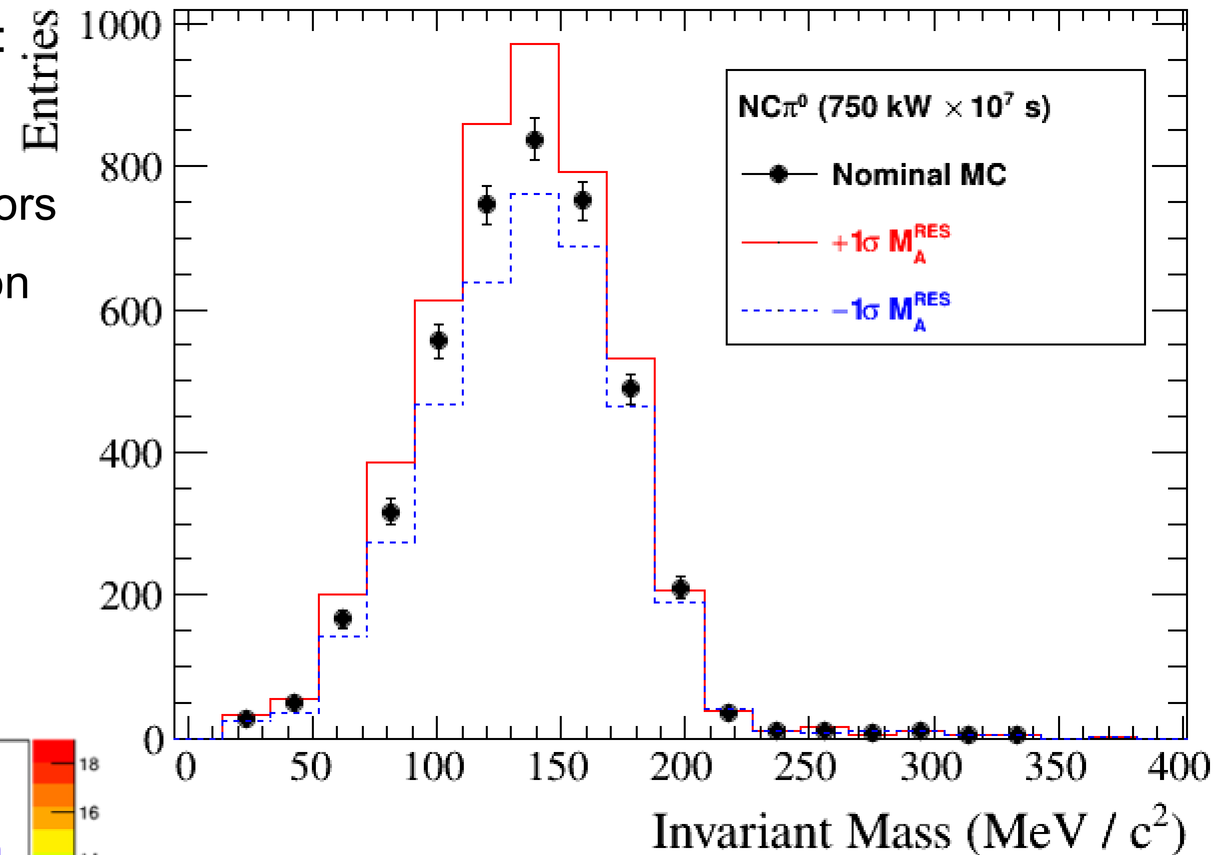
(R. Shah)

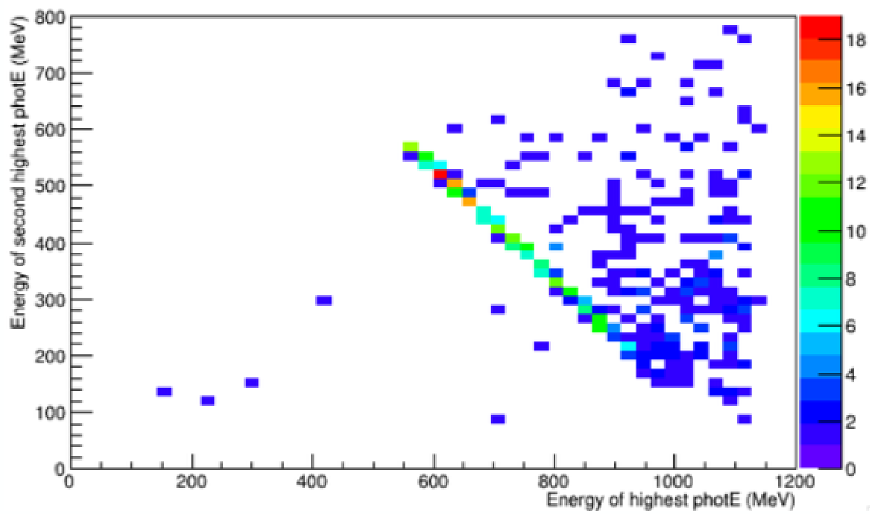
Sensitivity results

Also plans to run Simple Fitter as a cross check to VaLOR results

Cross-Sections ($NC\pi^0$)

- $\pi^0 \to \gamma\gamma$ is a significant background for:
  - ν_e appearance in HK
  - intrinsic ν_e meas. in near detectors
- Currently investigating π^0 reconstruction in TITUS tank (W. Ma & M. Malek)
- Nominal selection based on K2K-style cuts:
  - Fully contained
  - 2-ring ee-like events
  - FV: 200 t (w/ 300 cm Dwall cut)





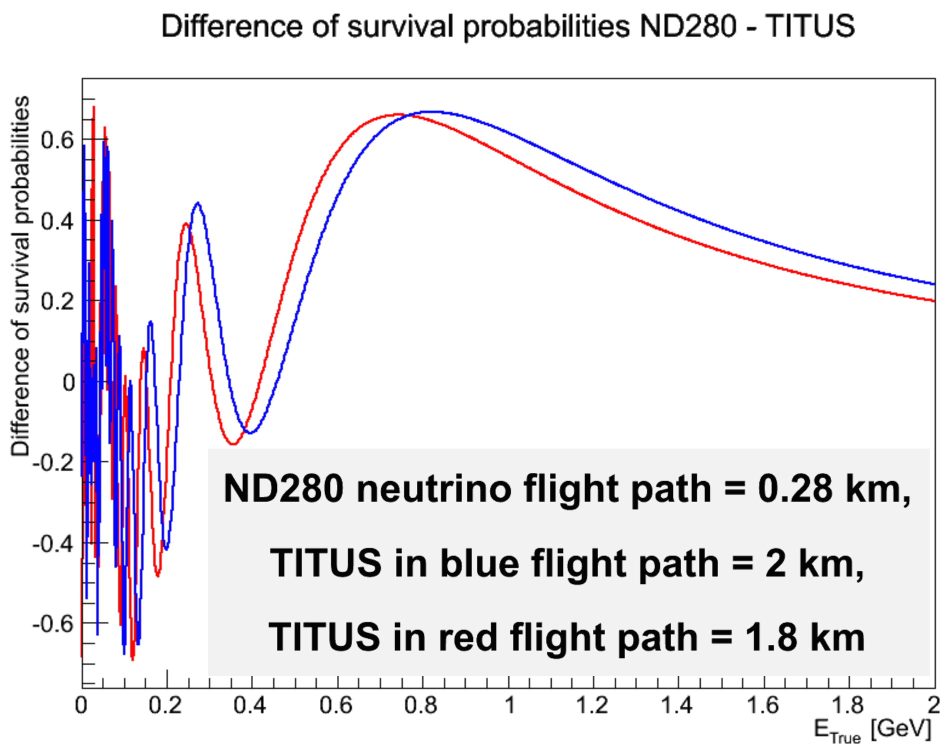
Initial studies only!

Further improvement should be possible with refined cuts, improved photon selection, etc

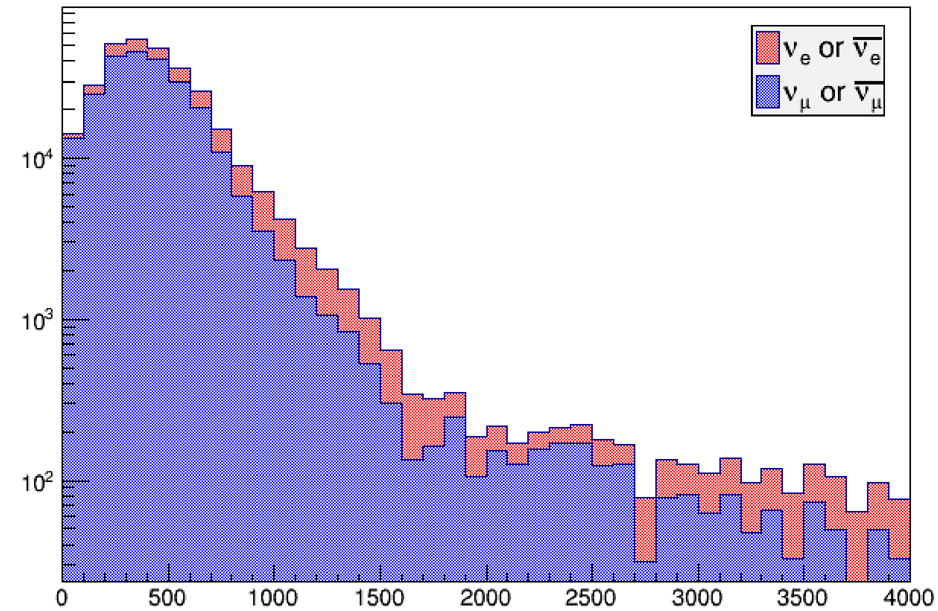
Sterile Neutrinos

- Sterile signal could manifest at TITUS via ν_e disappearance (relative to ND280)

3+1 model with $\sin^2(2\theta) = 0.7$, $\Delta m^2_{41} = 0.5\ eV^2$



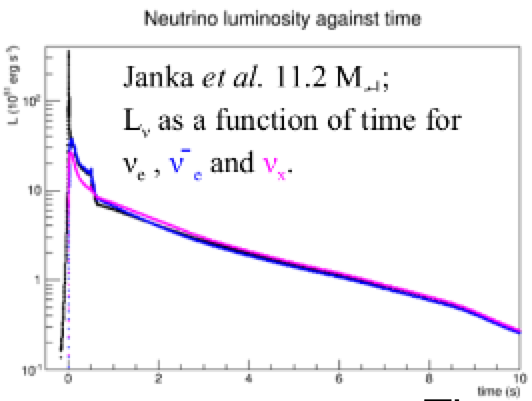
Selection criteria:
- 1Re
- P > 60 MeV
- P0 rejection
- FV: r < 450 cm & |z| < 1000 cm



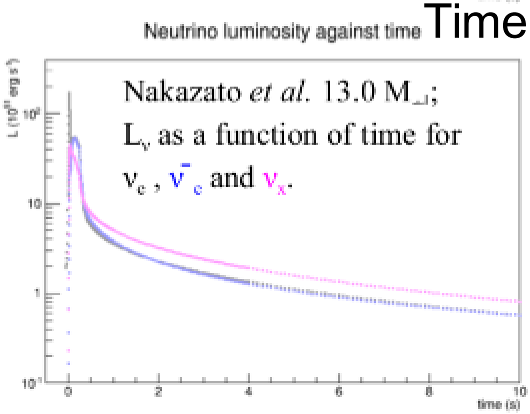
Selection being optimised by P. Lasorak;
Fit development and validation also in progress

Supernova Neutrinos

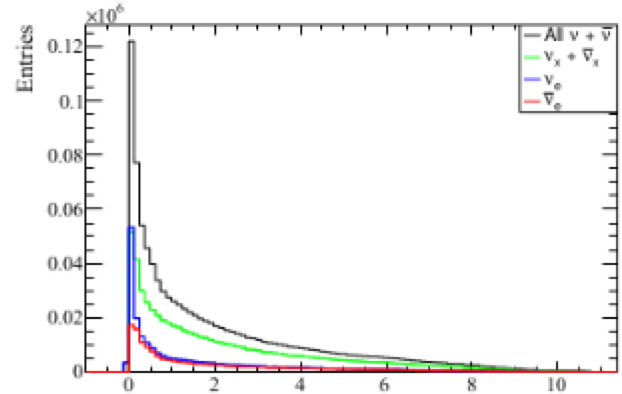
- Initial studies comparing theoretical models are underway (S. Cartright & M. Lawe)
- Interfacing with Generalised Neutrino Vector Generator developed by C. Kachulis



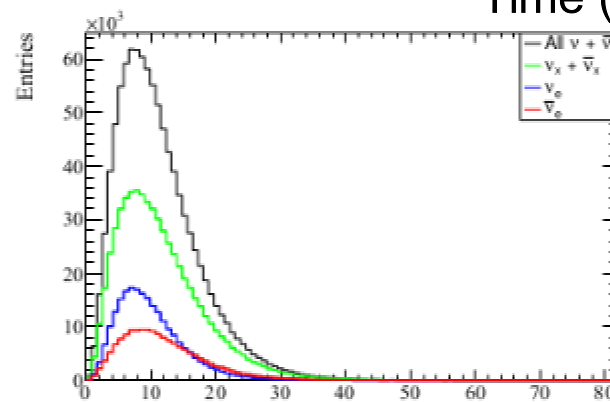
Time (s)



Time (s)



Time (s)



Energy (MeV)

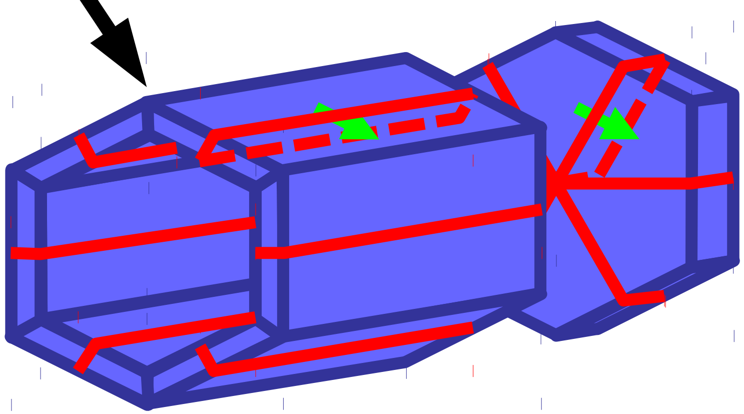
- Plan to generate vectors for both TITUS and Hyper-K
- Will simulate **full** SN events (incl. cosmic BG) to evaluate feasibility as SN alarm

Muon Range Detector

- All results presented so far use **only** the TITUS WC tank!
- For nominal TITUS design, 18% of μ are **not** fully contained
  - Momentum can be measured if they stop in the MRD [Fe + scintillator layers]
  - Adding a magnetic field (1.5 Tesla) allows us to measure curvature to get:
    - Momentum for μ that penetrate MRD
    - Charge sign reconstruction for all events, based on direction of curvature

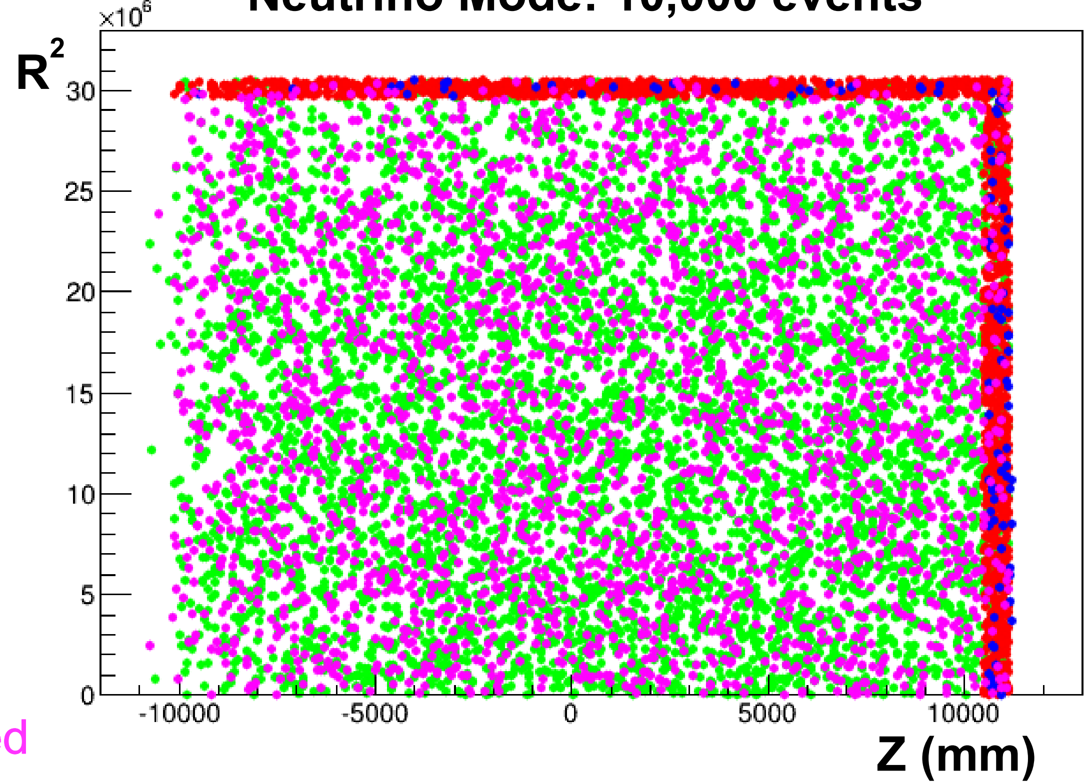
See next talk (M. Rayner)

Toroidal **B** field to prevent leakage into WC tank



Red = Right-sign muons exiting
Blue = Wrong-sign muons exiting
Green = Right-sign muons contained
Purple = Wrong-sign muons contained

Neutrino Mode: 10,000 events



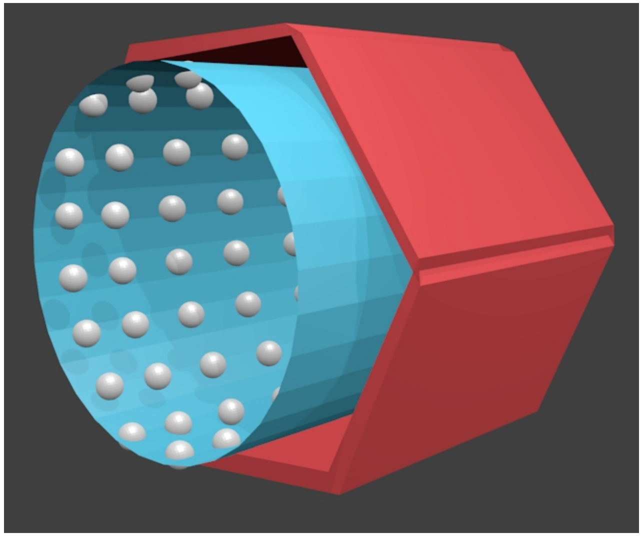
Conclusions

- **Hyper-Kamiokande's increased statistics require smaller systematics**
  - New near detector(s) necessary for HK beam programme
- **TITUS is new proposal for an HK near detector**
  - Uses elements of older proposals (e.g., WC tank at 2 km distance)
  - Incorporates new ideas:
    - Gd-loaded water
    - First magnetised MRD to be used with WC
    - Enhanced photosenors (LAPPDs)
- **Initial simulation studies look promising**
  - ν / $\bar{\nu}$ separation via neutron tagging
  - Enhanced CCQE sample using neutron multiplicity
  - NCπ^0 measurement
  - Intrinsic νe measurement
  - Oscillation sensitivity studies in progress; improvements look likely
- **Other physics studies underway**
  - Sterile neutrinos: Compare NC & CC rates at 280 m & 2 km to look for ν_{active} disappearance
  - Supernova burst simulations to evaluate feasibility of using TITUS as an independent SN alarm

Thank you for listening!

Titus Flavius:
Emperor of Rome
(79 – 81)

Titus Andronicus:
A Play by William Shakespeare
(1594)

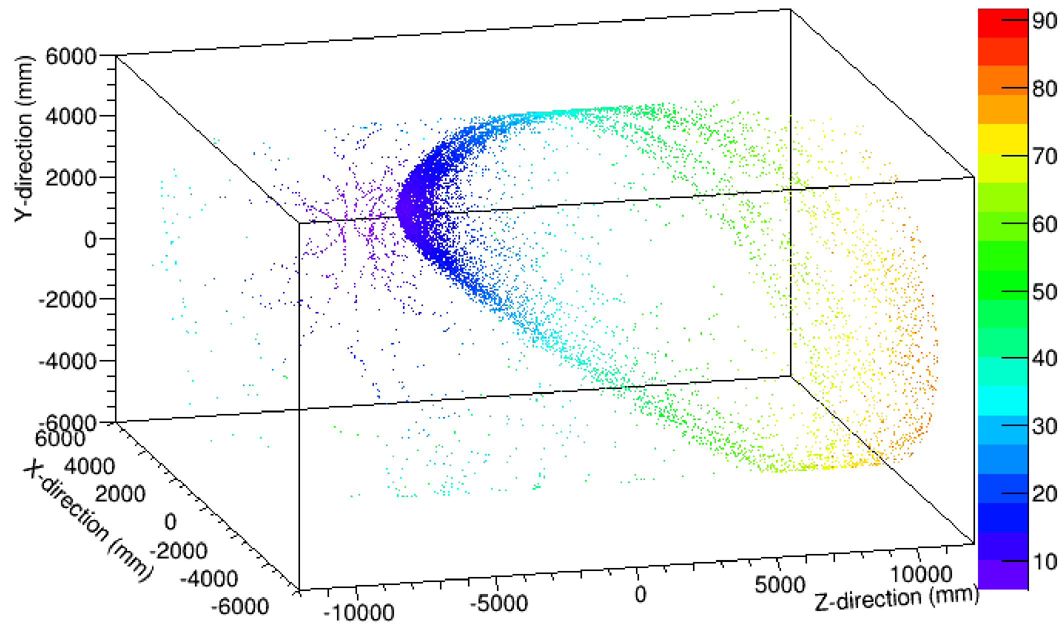


TITUS:
Gd-doped WC + MRD
(2020?)

BACK-UP SLIDES

WChSandBox Basics

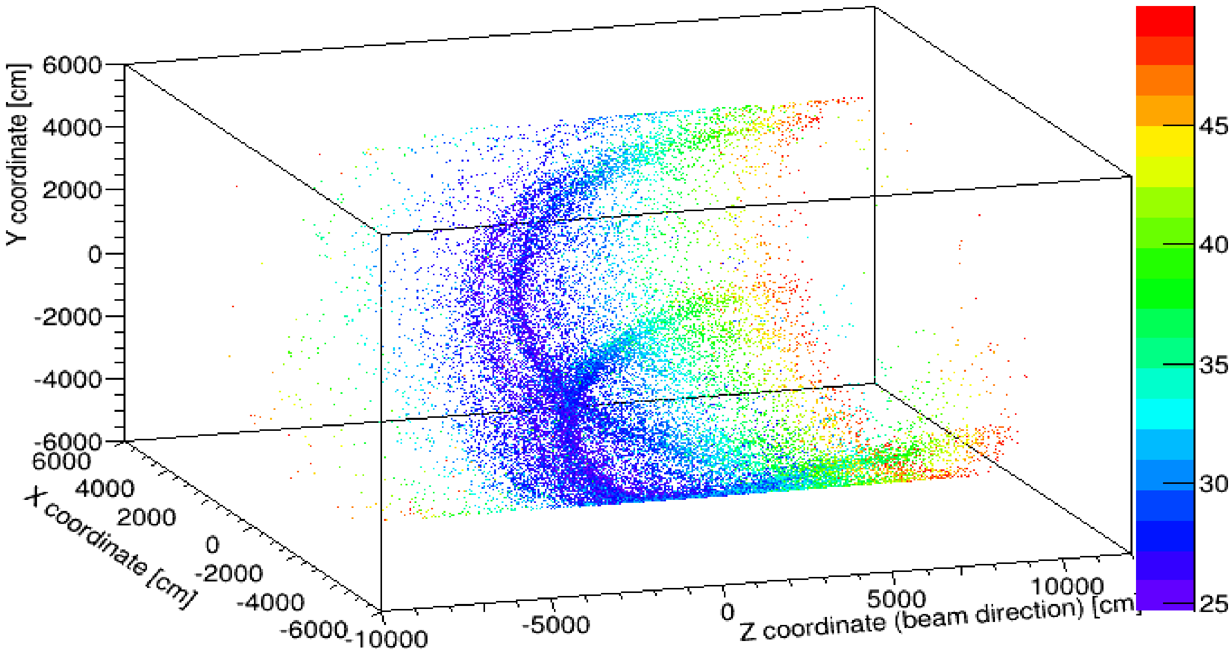
- WChSandBox is a **new** fast simulation package for WC detectors
- Beta version released in April 2014
- Primary package developers are M. Wetstein (University of Chicago) and M. Malek (Imperial)
- Significant contributions from also from:
  - R. Terri (Queen Mary)
  - T. Gregoire (Imperial)
  - W. Ma (Imperial)



CCQE

WChSandBox Basics

- WChSandBox is a **new** fast simulation package for WC detectors
- Uses basic Geant detector objects
- Inherits water model (*i.e.*, scattering, absorption, etc.) from WCSim (which inherited in turn from Super-Kamiokande)
- Neutron simulations being developed in collaboration with other experiments:
  - ANNIE
  - WATCHMAN
- Native reconstruction tools (high & low E) being developed
  - RecoLite

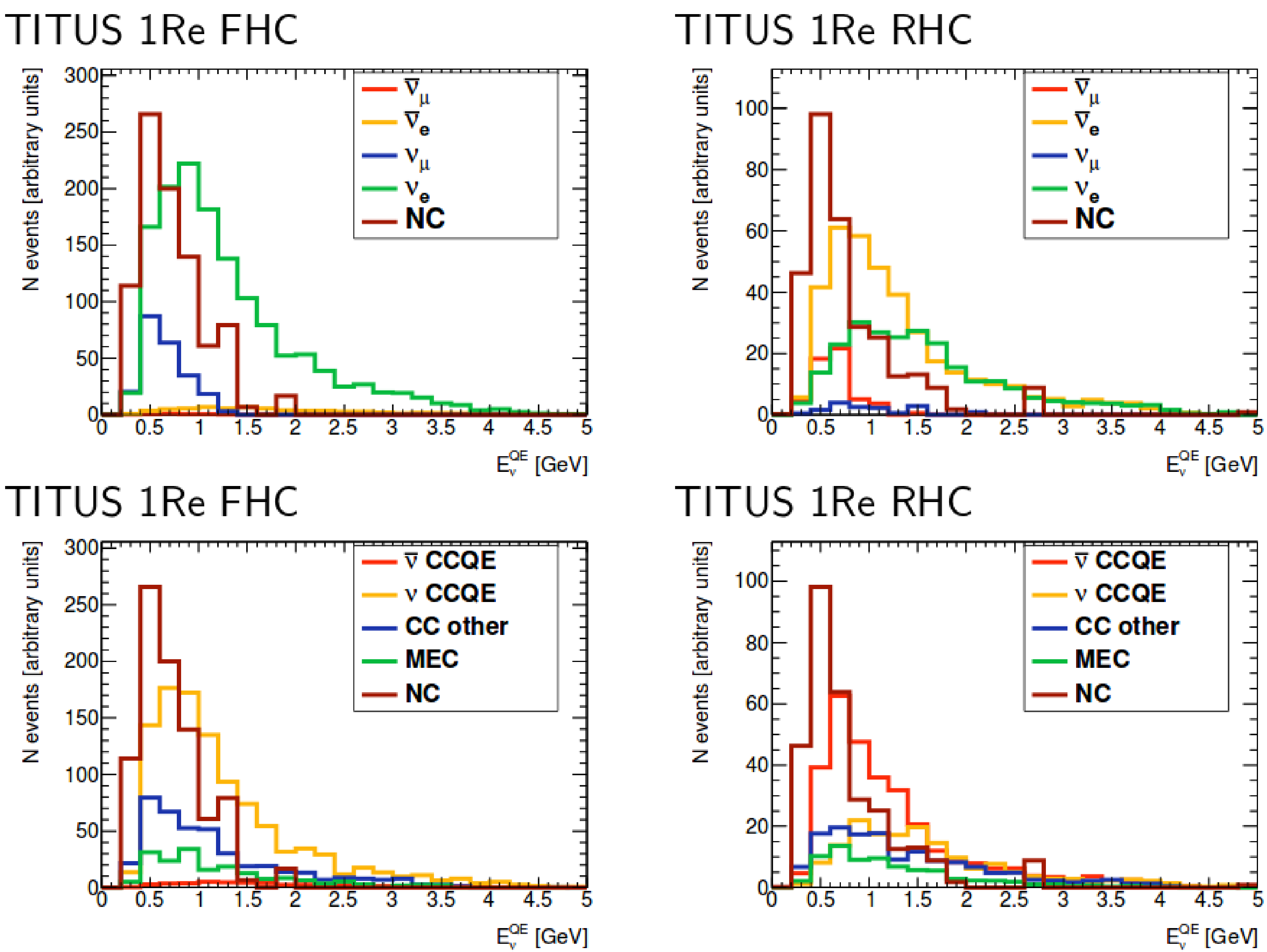


$NC\pi^0$

Cosmic BG Sources

- Use numbers from PRC **72**, 025807 for the cosmic ray muon flux (and induced neutrino rates)
- Primary numbers:
  - μ: 6 x 10^5 μ / m^2 / h
  - n: 7.2 x 10^6 events / ktonne / day
- Scale these numbers to per spill & per bunch values
  - Assume that:
    - μ scales with cross-sectional area
    - n scales with volume
- Can ignore atmospheric neutrino background
  - Approx. 1 / day, based on scaling Super-Kamiokande rate

1Re Sample


TITUS 1Re FHC
N events [arbitrary units]
$\bar{\nu}_\mu$
$\bar{\nu}_e$
ν_μ
ν_e
NC
E_ν^{QE} [GeV]
TITUS 1Re RHC
N events [arbitrary units]
$\bar{\nu}_\mu$
$\bar{\nu}_e$
ν_μ
ν_e
NC
E_ν^{QE} [GeV]
TITUS 1Re FHC
N events [arbitrary units]
$\bar{\nu}$ CCQE
ν CCQE
CC other
MEC
NC
E_ν^{QE} [GeV]
TITUS 1Re RHC
N events [arbitrary units]
$\bar{\nu}$ CCQE
ν CCQE
CC other
MEC
NC
E_ν^{QE} [GeV]

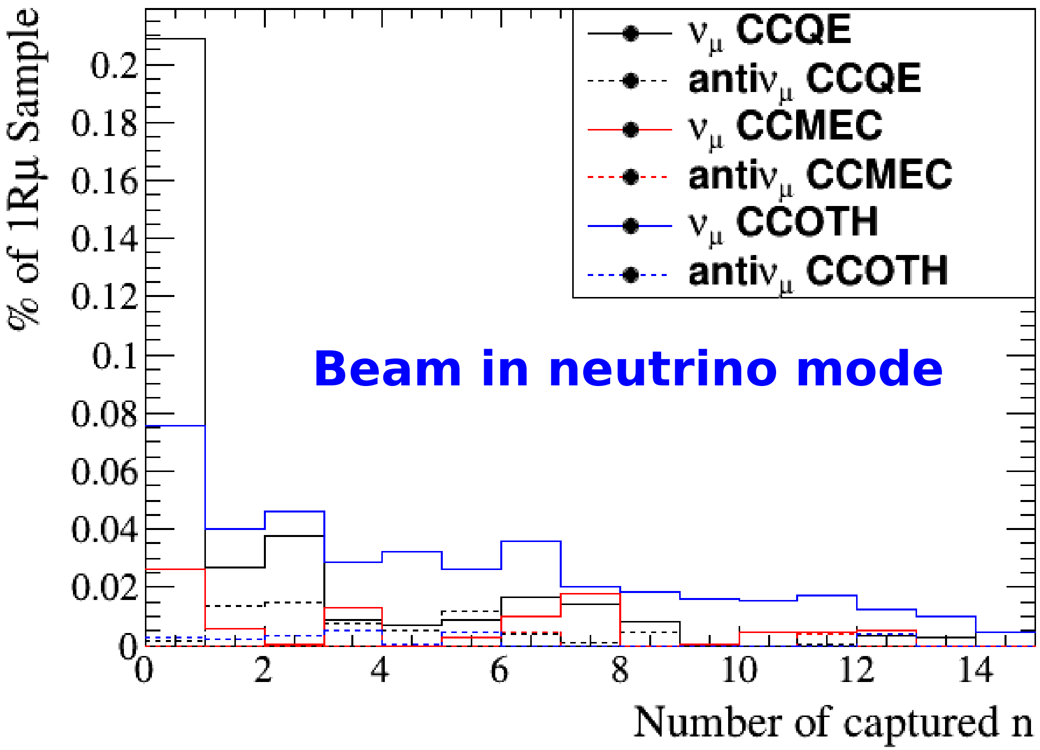
Physics Benefits of Gd

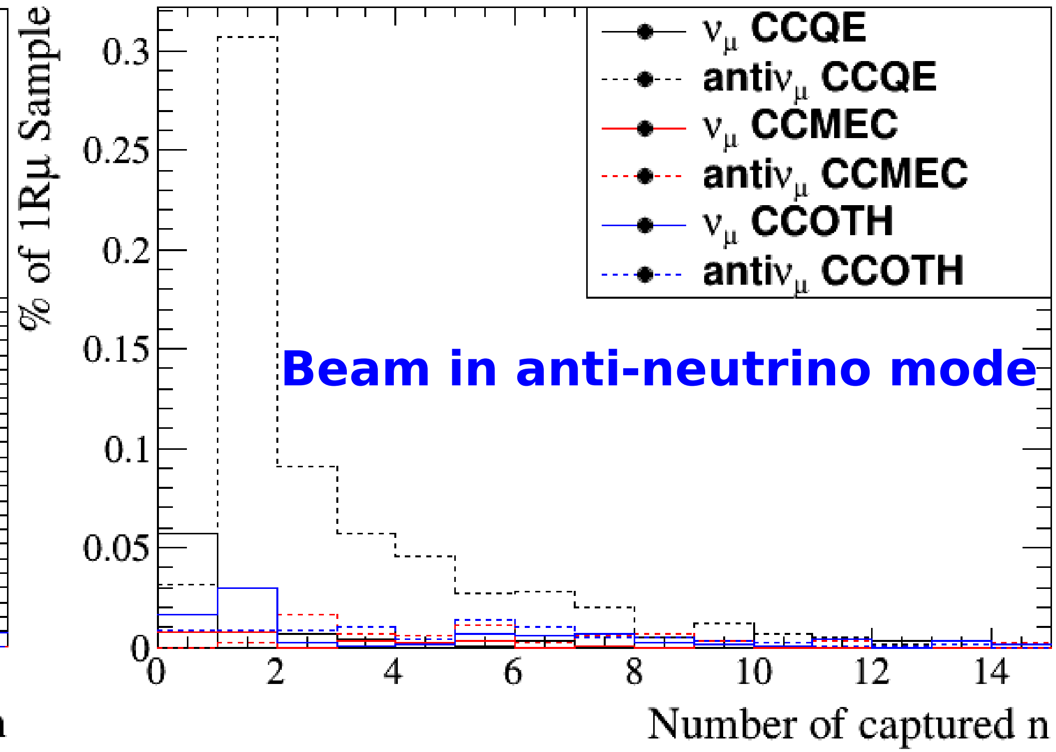
- "Wrong sign" neutrino discrimination
  - From T2K sensitivity studies, we know that running a mix of neutrino mode & antineutrino mode enhances δ_{CP} sensitivity
  - Antineutrino mode has greater contamination from neutrinos
  - With Gd-doping, can separate ν from $\bar{\nu}$ in TITUS to understand contamination, characterize beam, and reduce systematics for Hyper-K

- Neutron capture can be used to separate CCQE from CC MEC and CC Other, to enhance purity of CCQE in CC0π sample:
  - ν_μ CCQE: 0 neutrons
  - ν_μ CC MEC: 0.2 neutrons (average): $\nu_\mu + (n\text{-}n) \rightarrow \mu^- + p + n$
  - $\bar{\nu}_\mu$ CCQE: 1 neutron
  - $\bar{\nu}_\mu$ CC MEC: 1.8 neutrons (average): $\bar{\nu}_\mu + (p\text{-}n) \rightarrow \mu^+ + n + n$ (~80%)

    $\bar{\nu}_\mu + (p\text{-}p) \rightarrow \mu^+ + p + n$ (~10%)

Neutron Multiplicity





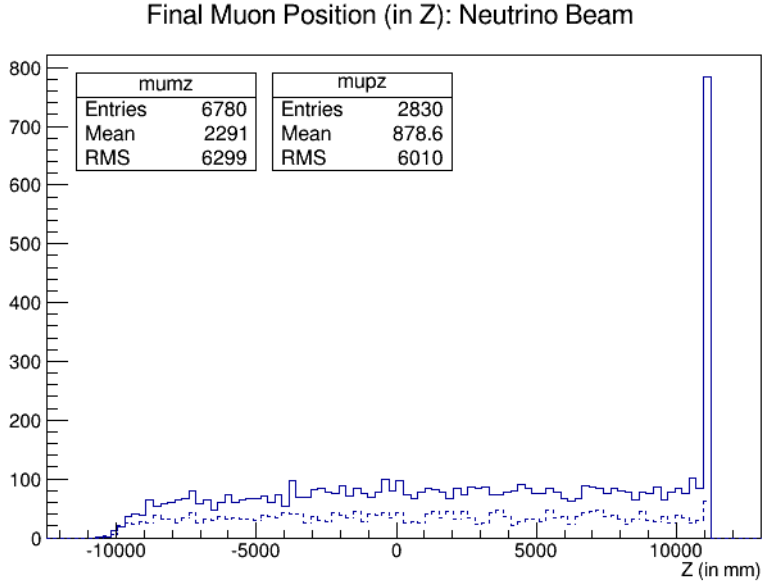
- Studies of neutron capture demonstrate the power that gadolinium-doping adds to TITUS
- Ingredients in these figures:
  - 90% of neutrons capture on Gd
  - Neutrons from secondary interactions are included
- Clear differences can be seen between ν_μ and $\bar{\nu}_\mu$; backgrounds from CC MEC and CC Other are reduced
- Enhanced sample purities:
  - ν_μ CCQE: 36% → **67%** with n = 0 requirement
  - $\bar{\nu}_\mu$ CCQE: 63% → **88%** with n = 1 requirement

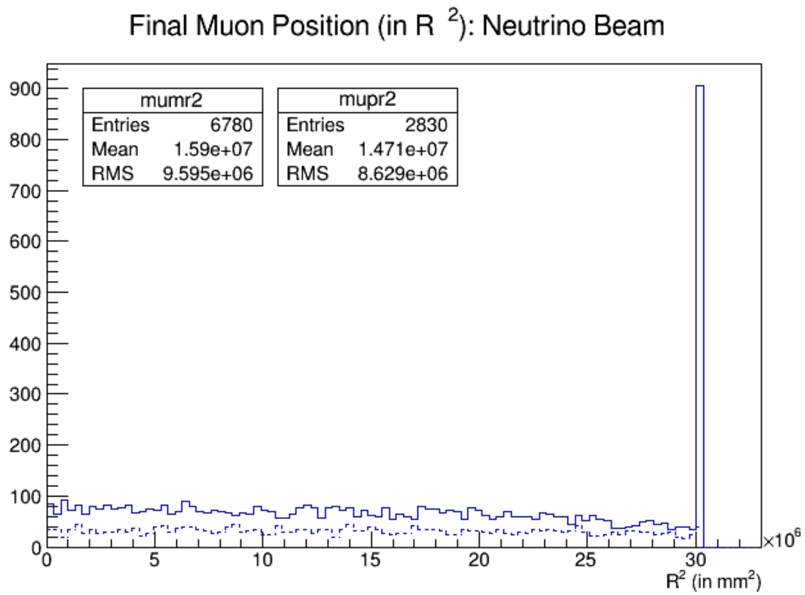
Neutron Multiplicity

Beam Mode & Selection	CC QE	CC MEC	CC 1π	CC Other	NC	'Wrong-Sign' CC
$\nu\mu$ all	36%	10%	25%	18%	4%	7%
$\nu\mu$ with n = 0 (CCQE-enhanced)	67%	8%	9%	14%	2%	< 1%
$\nu\mu$ with n > 0 (CCQE-enhanced)	22%	10%	32%	20%	6%	10%
$\bar{\nu}\mu$ all	63%	7%	5%	2%	3%	20%
$\bar{\nu}\mu$ with n = 0	27%	< 1%	< 1%	< 1%	10%	63%
$\bar{\nu}\mu$ with n = 1	88%	< 1%	1%	2%	< 1%	8%
$\bar{\nu}\mu$ with n > 1	57%	13%	8%	2%	2%	18%

N.B. Each sample (row) sums to 100%

Muons in the MRD





- Muons that escape the water tank enter the MRD
- Range within MRD provides μ momentum
- Example shown is 10,000 event sample in ν-mode
  - Nearly no backwards exiting events
  - Most wrong-sign muons contained