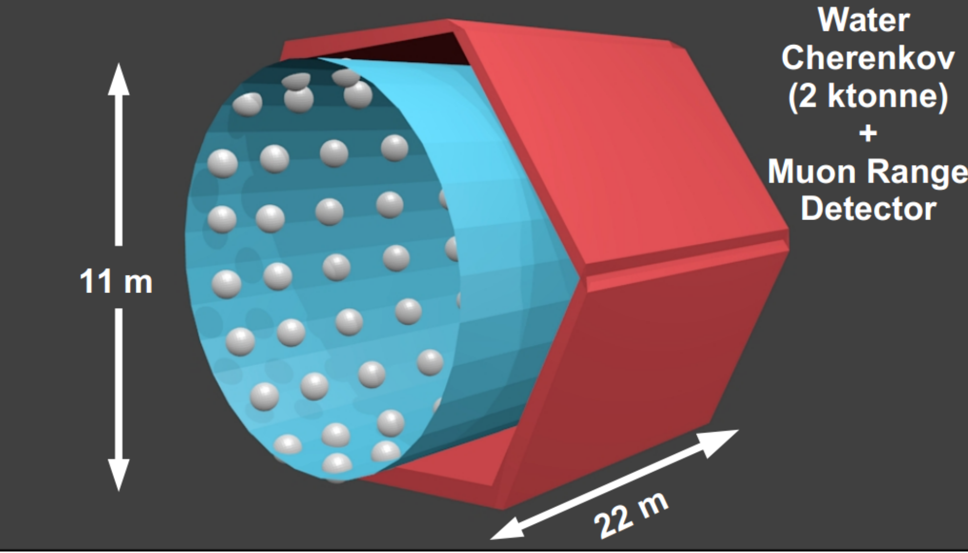


TITUS Tank

David Hadley, Francesca Di Lodovico, Matthew Malek, Ryan Terri
on behalf of the TITUS Working Group

July 2014

The TITUS Detector

- Primary goal: maximize cancellation of uncertainties in near-far ratio.
  - **Identical target nuclei** in near and far detector.
  - At ~2 km it is exposed to a **similar total flux as the far detector**
  - **Gd doping** allows neutron tagging (discriminate $\nu - \bar{\nu}$, multi-nucleon processes)
  - **Muon Range Detector** to reconstruct escaping muons, sign-selection for $\nu - \bar{\nu}$ discrimination (see talk by Mark Rayner).

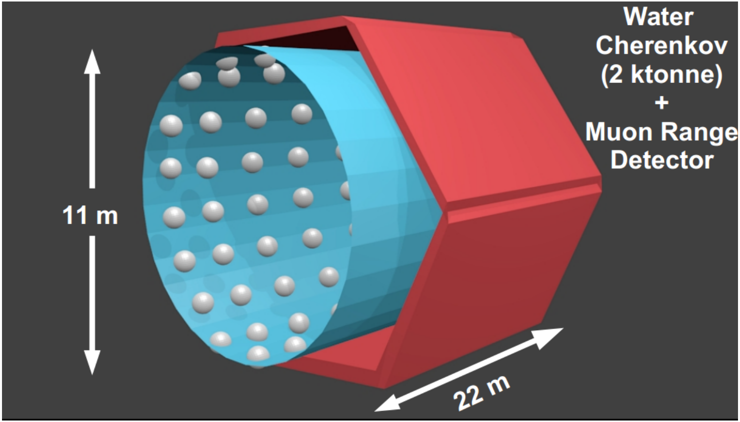
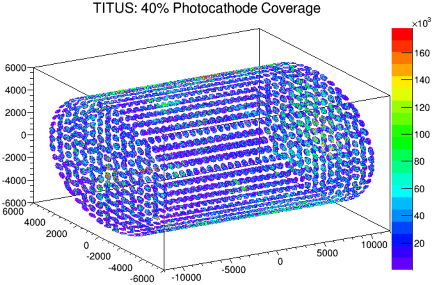


Photo-sensors

- Optimal configuration of photosensors under investigation.
- Simulation under development
- Make comparisons of:
    - 20, 12 and 8 inch PMTs
    - (HK) 20%, 30%, 40% (SK)



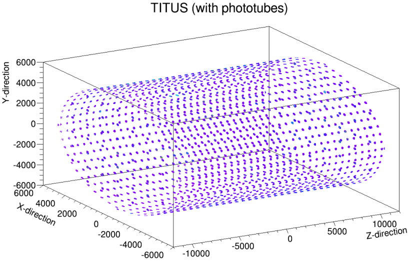
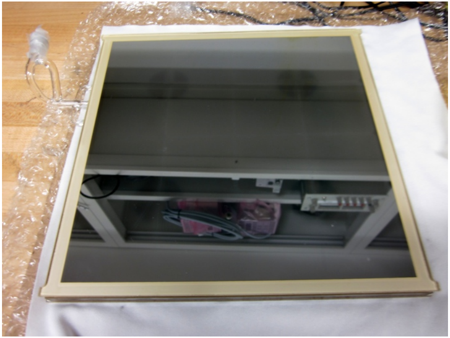
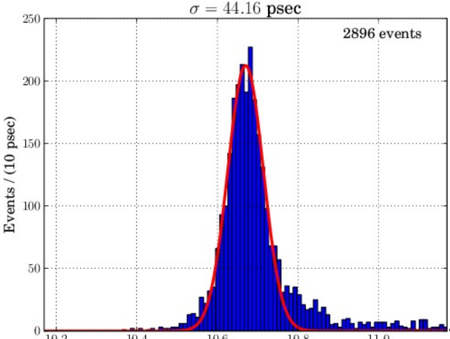


Photo-sensors

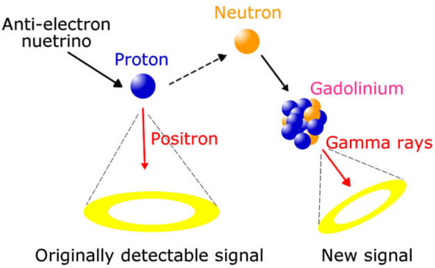
- Optimal configuration of photosensors under investigation.
- Simulation under development
- Make comparisons of:
  - 20, 12 and 8 inch PMTs
  - (HK) 20%, 30%, 40% (SK)
- Large Area Picosecond Photo Detectors (LAPPDs)
  - excellent timing and spatial resolution

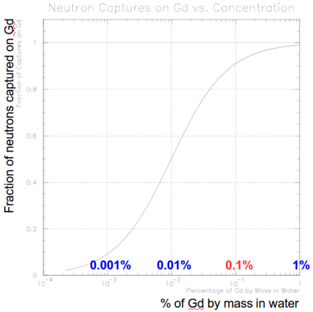




Neutron Tagging

- Expect different neutron multiplicity distribution for ν and $\bar{\nu}$ interactions.
  - ν CCQE: $\nu + n \rightarrow l^- + p$
  - $\bar{\nu}$ CCQE: $\bar{\nu} + p \rightarrow l^- + n$
- 90% of neutrons captured on Gadolinium at 0.1% Gd fraction
- $\sim$20 μs capture time.
- 8 MeV γ cascade ($\sim$ 4 MeV visible energy)

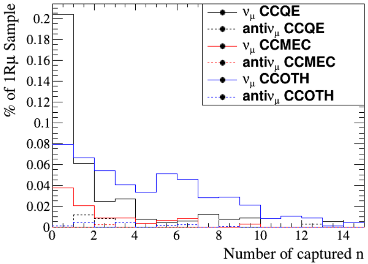




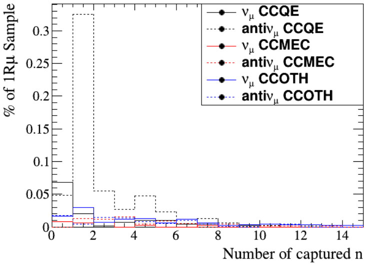
Neutron Tagging

- Neutron tagging gives ability to dicriminate between $\nu - \bar{\nu}$ and multi-nucleon interactions.
  - ν_μ CCQE : 0 neutrons
  - ν_μ CC MEC : 0.2 neutrons
  - $\bar{\nu}_\mu$ CCQE : 1 neutron
  - $\bar{\nu}_\mu$ CC MEC : 1.8 neutrons
- Enhanced purity
  - ν_μCCQE: 37% $\rightarrow$ 63% (num. neutrons = 0)
  - ν_μCCQE: 37% $\rightarrow$ 82% (num. neutrons = 1)

Forward horn current (FHC)



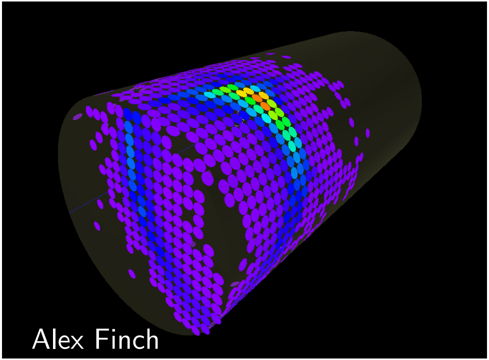
Reverse horn current (RHC)

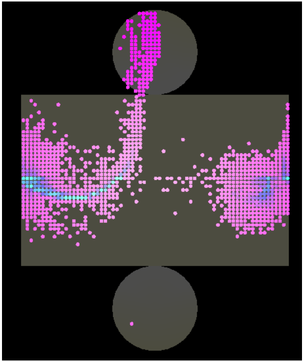


Neutron Tagging

Beam Mode & Selection	CC QE	CC MEC	CC 1π	CC Other	NC	'Wrong-Sign' CC
$\nu\mu$ all	37%	10%	28%	19%	3%	4%
$\nu\mu$ with n = 0 (CCQE-enhanced)	63%	12%	11%	13%	< 1%	< 1%
$\nu\mu$ with n > 0 (CCQE-enhanced)	20%	7%	38%	25%	5%	5%
$\bar{\nu}\mu$ all	55%	7%	5%	2%	4%	27%
$\bar{\nu}\mu$ with n = 0	30%	< 1%	2%	1%	8%	59%
$\bar{\nu}\mu$ with n = 1	82%	3%	< 1%	< 1%	1%	13%
$\bar{\nu}\mu$ with n > 1	41%	13%	11%	3%	4%	28%

Software and Reconstruction

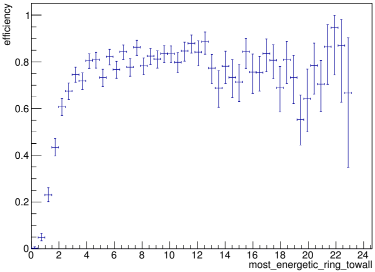




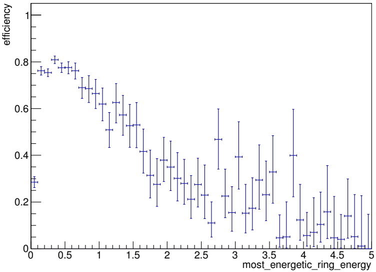
- Vectors generated with NEUT.
- GEANT4 based detector simulation (ANNIE/WCsandbox).
- Super-K based reconstruction
  - Momentum and direction smeared.
  - Efficiency of 1Rmu and 1Re selection provided by tables
    - Distance to wall
    - E_ν
    - Most energetic ring energy
    - Final state topology

Selection Efficiency

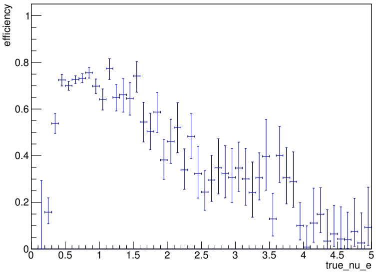
Efficiency vs towall



Efficiency vs ring energy



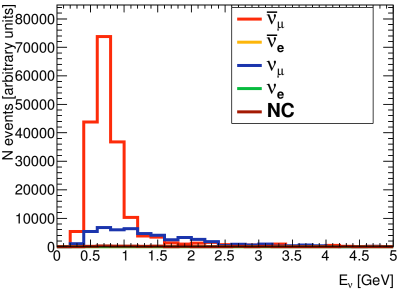
Efficiency vs E_ν



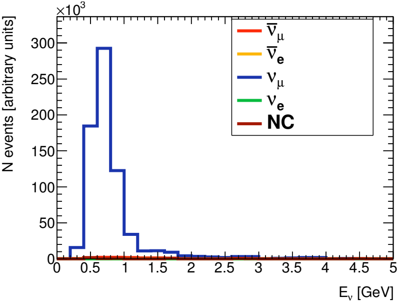
- Efficiencies for true CC$1\mu0\pi$ in TITUS.
- 80% plateau in "To wall" at 2m.
- Drop at high energy due to ranging out.

Selection

TITUS 1Rmu RHC



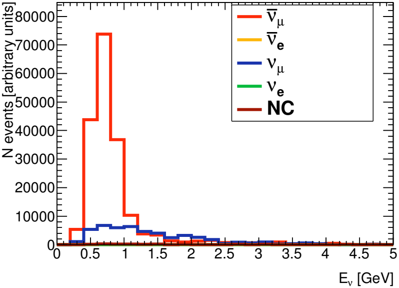
TITUS 1Rmu FHC



- RHC=Reverse Horn Current (ν dominated beam)
- FHC=Reverse Horn Current ($\bar{\nu}$ dominated beam)
- Clean ν_μ sample.
- Large ν contamination in $\bar{\nu}$ selection.

Selection

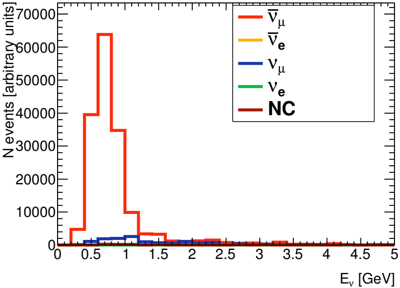
TITUS 1Rmu RHC



- RHC=Reverse Horn Current (ν dominated beam)
- FHC=Reverse Horn Current ($\bar{\nu}$ dominated beam)
- Clean ν_μ sample.
- Large ν contamination in $\bar{\nu}$ selection.

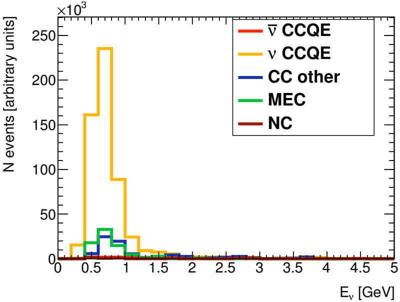
- Requiring a tagged neutron reduces the ν contamination.

RHC with tagged neutron



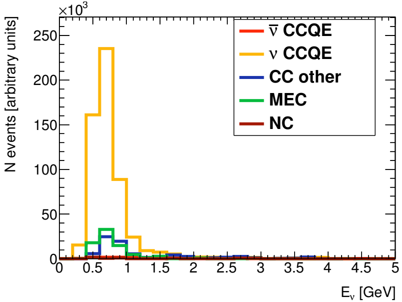
Selection

TITUS 1Rmu FHC

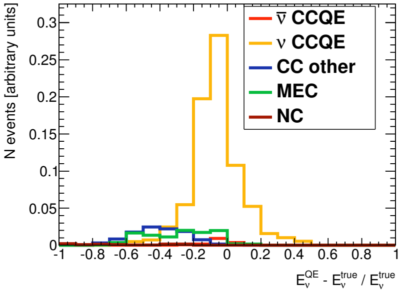


Selection

TITUS 1Rmu FHC

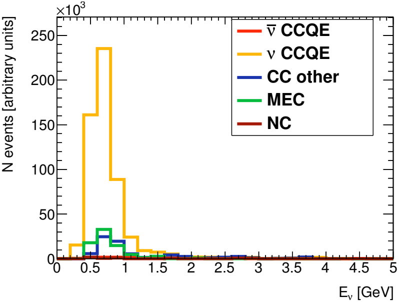


Resolution (due to QE)

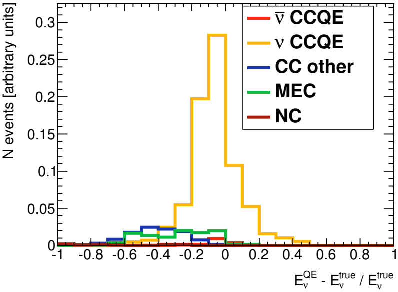


Selection

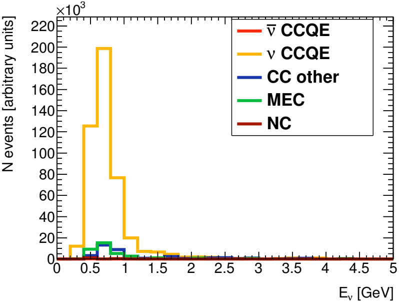
TITUS 1Rmu FHC



Resolution (due to QE)

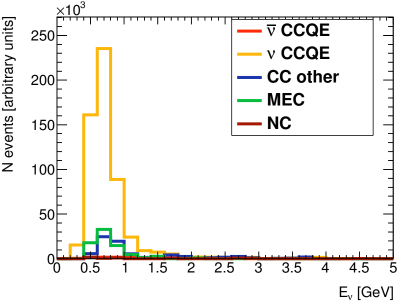


FHC no tagged neutron

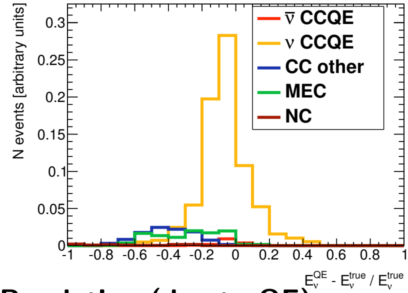


Selection

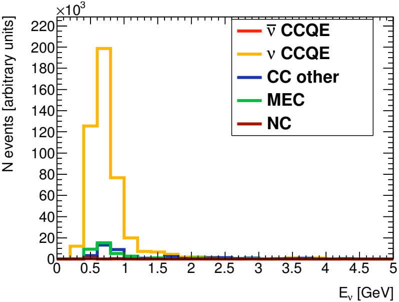
TITUS 1Rmu FHC



Resolution (due to QE)



FHC no tagged neutron



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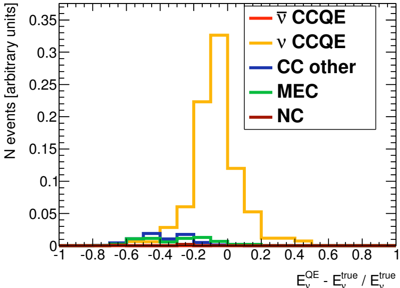
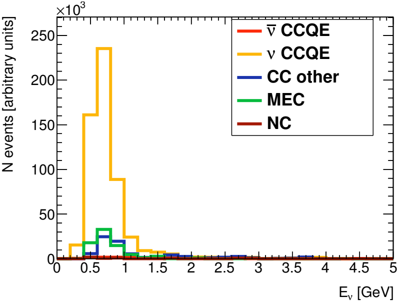
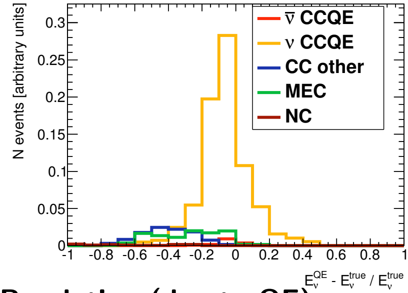


Selection

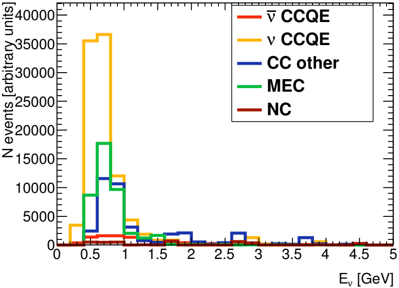
TITUS 1Rmu FHC



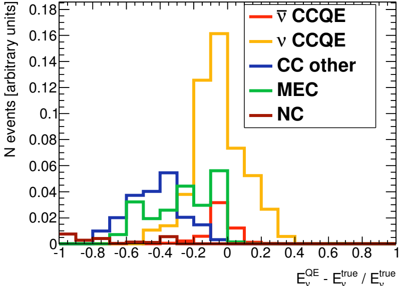
Resolution (due to QE)



FHC with tagged neutron



Resolution (due to QE)



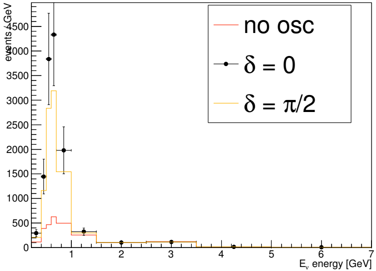
TITUS Constraint on HK Prediction

- Start with the prior constraints on flux and cross section parameters currently used by T2K.
- Maximum likelihood fit of these parameters to the predicted TITUS event rate.
- 4 input data samples
  - TITUS 1Rμ FHC
  - TITUS 1Rμ RHC
  - HK 1Re FHC
  - HK 1Re RHC
- Apply the updated prior uncertainty to the far detector prediction.
- NB fit only uses total number of selected events (without neutron tagging, no shape information).

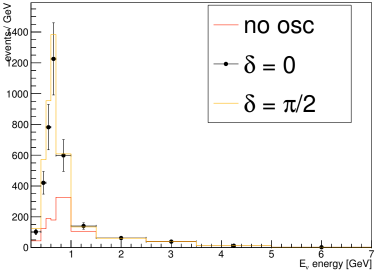
$$\begin{aligned} -2\ln\lambda(\theta) &= 2\sum_{i}^{\text{samples}}\left(E_i(\theta) - N_i + N_i \ln\frac{N_i}{E_i(\theta)}\right) \\ &\quad + \ln\frac{\pi(\theta)}{\pi(\theta_0)} \qquad (1) \\ \pi(\theta) &\propto e^{-\frac{1}{2}\Delta\theta V^{-1}\Delta\theta} \end{aligned}$$

TITUS Fit Results

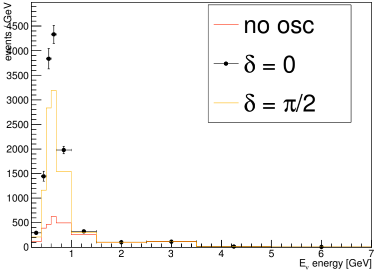
FHC before fit



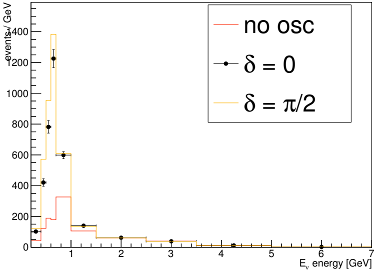
RHC before fit



FHC after fit

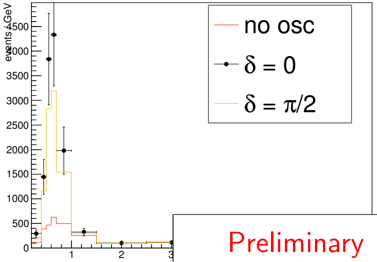


RHC after fit

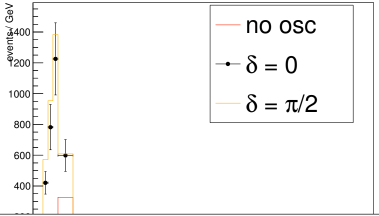


TITUS Fit Results

FHC before fit

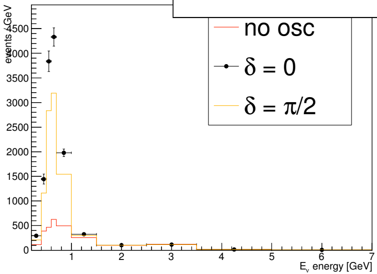


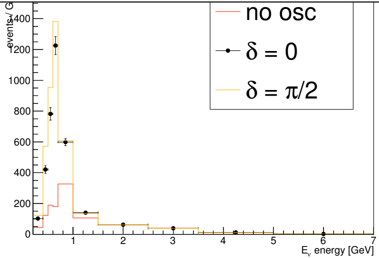
RHC before fit



Preliminary	HK FFC error	HK RHC error
No TITUS	0.253	0.164
With TITUS	0.030	0.035

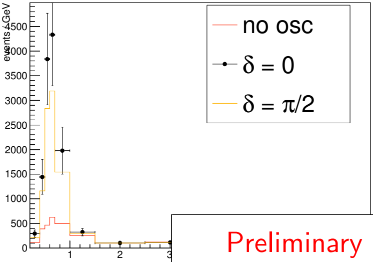
FHC after fit



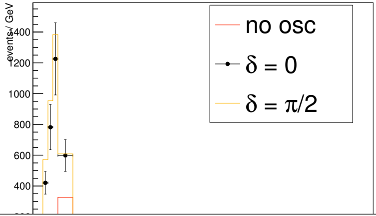


TITUS Fit Results

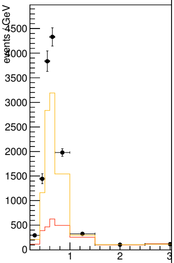
FHC before fit



RHC before fit



FHC after fit



Preliminary	HK FFC error	HK RHC error
No TITUS	0.253	0.164
With TITUS	0.030	0.035

Need to include additional selection (neutron tagging, MRD) and evaluate effect on δ_{CP}.

On going Work

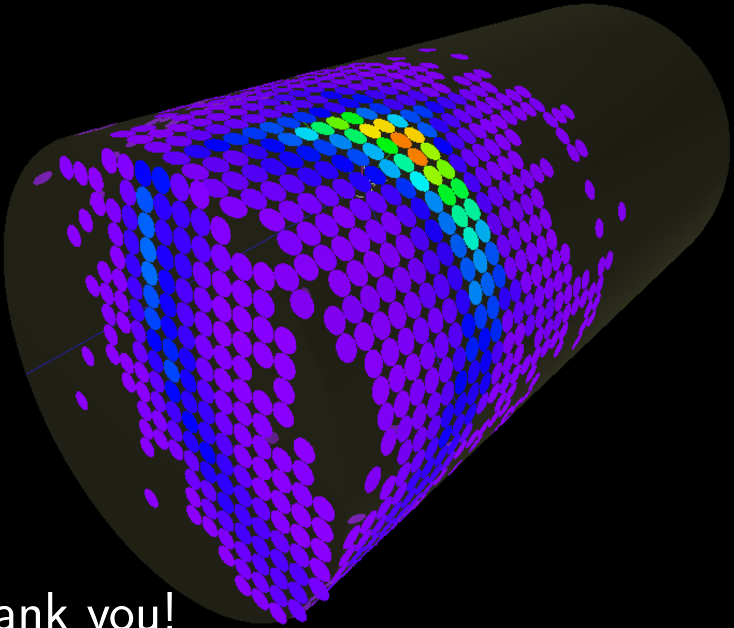
- Simulation and reconstruction
- Event selection and systematics
- Evaluate impact of full analysis on measurement of oscillation parameters
- Common software framework for tank and MRD
- Detector optimisation (PMT/LAPPD, geometry)

TITUS Other Physics

- Direct measurement of unoscillated ν_e and ν_μ flux is main goal
- Supernova neutrinos
- Cross section measurements
- Sterile neutrinos

Summary

- TITUS is Water Cherenkov-based 2 km detector for Hyper-K.
- Exploits neutron tagging to provide enhanced selections of $\nu - \bar{\nu}$ and $CCQE-$multi-nucleon processes.
- Preliminary studies to evaluate the impact on Hyper-K sensitivity are under-way.

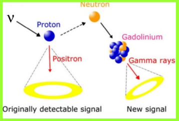


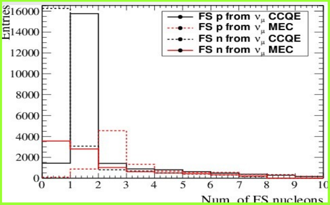
Thank you!

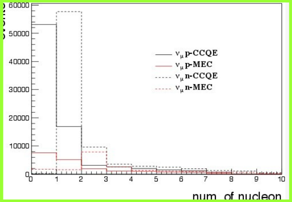
TITUS – Water Tank

Talks by M.Malek and D. Hadley

- Water → same target as Hyper-K and 4π coverage
- G_d-doped: original idea to exploit G_d for ν/anti-ν separation and use it for background reduction







$\nu + n \rightarrow l^- + p$

$\bar{\nu} + p \rightarrow l^+ + n$

Example cuts to select the signal:

- Nu-mode beam: captured neutron = 0
- Antinu-mode beam: captured neutron = 1

Cuts select CCQE and reduce CC-other, NC and anti-nu (nu) events

Main current objective is to test the procedure w/ recoed data

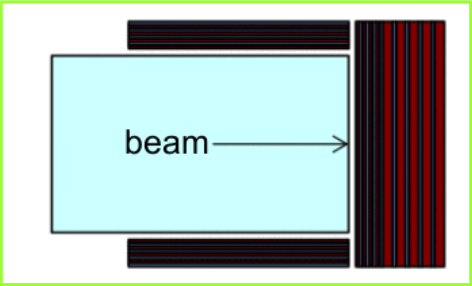
Very good initial preliminary results (to be improved w/ eg selection):

Purity ν-mode (CCQE: 37 → 63 %), $\bar{\nu}$-mode (CCQE 55 → 82%)

TITUS - MRD

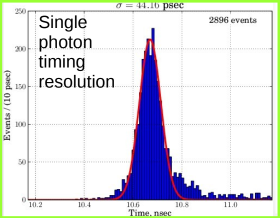
Talk by M. Rayner

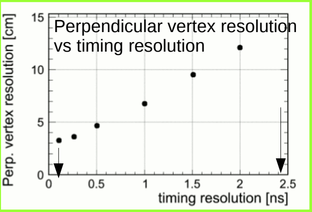
- The WC tank is surrounded by a Muon Range Detector to catch the escaping muons
- Magnetize the detector for charge identification
- Dimensions of the MRD, size and downstream, being optimized

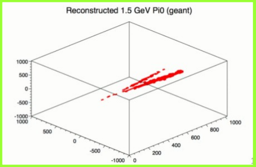


Photosensors

- Standard PMTs/HPDs and LAPPDs.
- Optimal configuration being investigated.
- LAPPDs should help reconstruction due to good timing and spatial resolution.







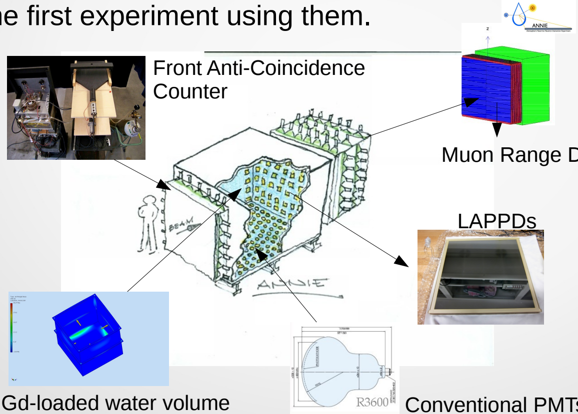
T.Xin, I. Anghel, M. Wetstein, M. Sanchez

Synergie with ANNIE

Talk on ANNIE by FDL

Similarities have been very helpful for software development so far.

ANNIE is directly involved in the LAPPD development and should be the first experiment using them.



Breath of Physics

- Main goal of the detector is to provide a 'background-free' signal for oscillation analysis.
- Several other important analyses can be addressed:
  - SN analysis, thanks to the Gd-doping.
  - Proton-decay background analysis.
  - Xsection measurements
  - Sterile neutrinos
  - ...

Status of the Code

Working on developing the simulation and soon the reconstruction for this detector.
Results shown today use:
- NEUT, Genie vector files (D. Hadley) and 2km flux (M.Hartz)
- simulation code WchSandBox by Matt Wetstein (hk-wchsandbox in HK release) and contributions from TITUS (Dave, Francesca, Matthew, Dave). MRD code being developed (M. Rayner)
- reconstruction for high energy rings based on Shimpei's fiTQun tables
- analysis developed by the TITUS team

Under way and Planned

Three main area of work:

- Software Development
  - Several studies planned to develop a simulation and reconstruction adapted for TITUS. Initial work focused on the simulation.
  - Create common software for tank and MRD.
- Detector Optimization
  - Re-optimize the detector, both the global shape of the tank and the MRD and the photosensor configuration.
- Analysis
  - Selection with captured neutrons
  - Sensitivity studies
  - Non-oscillation analysis (π^0 and xsection measurements, SN, sterile neutrinos, proton decay background etc)

Summary

- TITUS: new original detector for reaching „background-free“ signal and charge separation at 2km to minimize beam differences with Hyper-K (can work at other distances)
- Characteristics: new original use of Gd-neutron tagging (useful for SN too and to help in possible development of a Gd-doped Hyper-K) and MRD.
- Preliminary initial results show improved purity for CCQE in ν-mode (at least 37% → 63%) and $\bar{\nu}$-mode (at least 55% → 82%).

TITUS:
Introduction to Gd-based Analysis

Matthew Malek
Imperial College London

19 July 2014
Hyper-Kamiokande ND/Flux Pre-Meeting

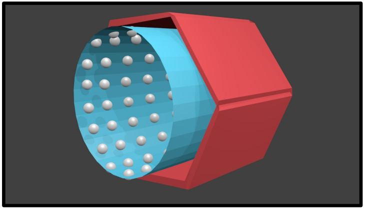
Outline

- **TITUS**: The **T**okai **I**ntermediate **T**ank w/ **U**noscillated **S**pectrum
  - Detector description
  - Physics potential
- Software development: Simulation & Reconstruction
- Interfacing WC with Muon Range Detector
- Neutron multiplicity measurements
- Future work

Titus Flavius:
Emperor of Rome (79 – 81)

"Titus Andronicus"
by William Shakespeare (1594)

TITUS Overview

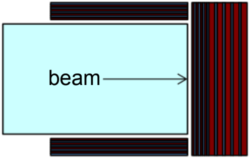


- Proposed new near detector for HK beam programme
- To be located ~2 km from J-PARC neutrino beam

- Baseline design includes:
  - 2 ktonne water Cherenkov tank
  - **0.1% Gadolinium-doping**
  - Partly enclosed by Muon Range Detector
    - Fe & plastic scintillator
      - End: 100 or 150 cm Fe
      - Side: 50 cm Fe (up to 75% coverage)

- 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)

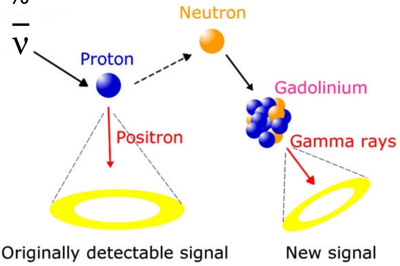
- Future possible add-ons / upgrades include:
  - Water-based liquid scintillator
  - ??? (New ideas welcome!)



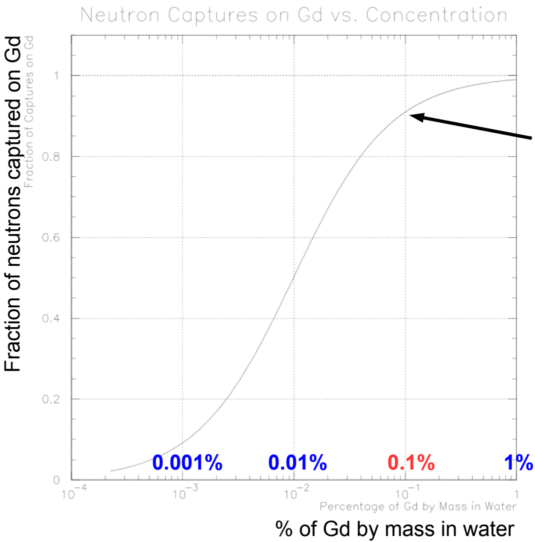
Gadolinium Doping

- **CCQE for ν:** $\nu + n \rightarrow l^- + p$ (p is "invisible")

  CCQE for $\bar{\nu}$: $\bar{\nu} + p \rightarrow l^+ + n$
- In ordinary water: n thermalizes, then captured on a free proton (H)
  - Capture time is ~200 μsec
  - 2.2 MeV gamma emitted
  - Detection efficiency @ SK is ~20 %
- When n captured on Gd:
  - Capture time ~20 μsec
  - ~8 MeV gamma cascade
  - 4 - 5 MeV visible energy
  - 100% detection efficiency



Neutron Capture w/ Gd

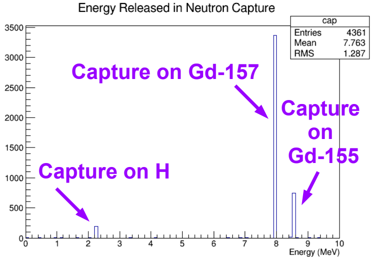


Cross-section for neutron capture is:

- ~49,000 barns for Gd
- 0.3 barns for H

0.1% Gd concentration results in ~90% of neutrons capturing on Gd

Currently, EGADS experiment is investigating feasibility of doping with gadolinium sulfate [$Gd_2(SO_4)_3$]



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

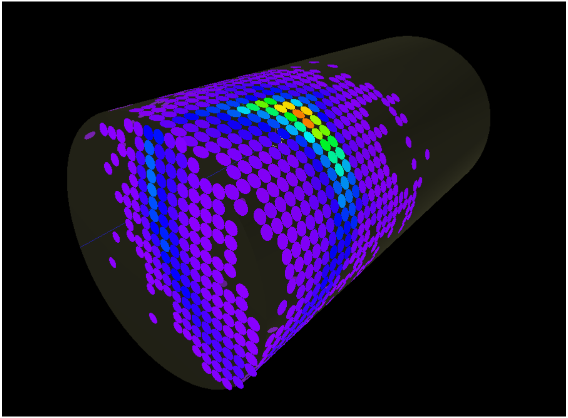
- Neutron capture can be used to separate CCQE from CC MEC and CC Other, to enhance purity of CCQE in CC0π sample:
  - ν_μ CCQE: 0 neutrons
  - ν_μ CC MEC: 0.2 neutrons (average): $\nu_\mu + (n\text{-}n) \rightarrow \mu^- + p + n$
  - $\bar{\nu}_\mu$ CCQE: 1 neutron
  - $\bar{\nu}_\mu$ CC MEC: 1.8 neutrons (average): $\bar{\nu}_\mu + (p\text{-}n) \rightarrow \mu^+ + n + n$ (~80%)
    $\bar{\nu}_\mu + (p\text{-}p) \rightarrow \mu^+ + p + n$ (~10%)

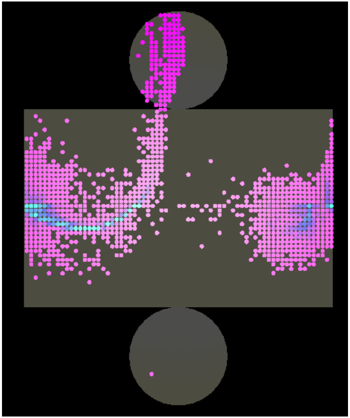
TITUS Physics Programme

- Measure intrinsic ν_e component of J-PARC beam
  - Dominant background to ν_e appearance measurement
- **Neutron multiplicity measurements**
  - **Provide input to neutrino generator models**
  - **Distinguish CCQE from other modes**
  - **Enhance Hyper-K proton decay searches (by an order of magnitude!)**
- **Cross-section measurements**
  - Inclusive $NC\pi^0$ – sub-dominant ν_e appearance BG & can improve knowledge of M_A^{RES}
  - **CCQE vs. CC-inclusive**
- Sterile neutrino searches
  - Compare CC & 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

TITUS Simulations

- Neutrino generation via NEUT & GENIE
- Detector simulation with WChSandBox: New fast simulation software package!

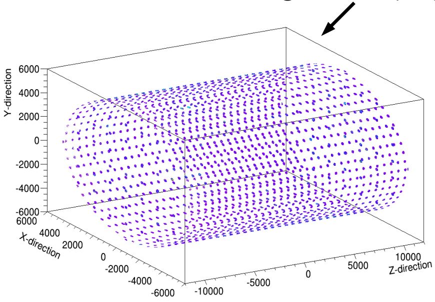


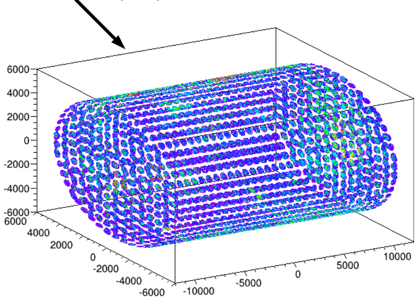


CCQE (1Rμ)

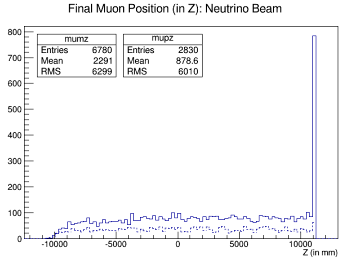
TITUS Reconstruction

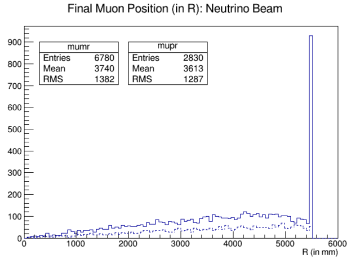
- Reconstruction:
  - Current “pseudo-reconstruction” uses smearing tables based on “fiTQun”
    - Pattern-of-light fit currently being developed for SK, T2K, HK
  - Development of both high-E and low-E (< 20 MeV) reconstruction algorithms
  - Photosensor optimisation currently underway:
    - **Six arrangements:** 20” PMT, 12” PMT, 8” PMT (with & without LAPPDs)
    - **Three coverages:** 20% (HK), 30%, 40% (SK)





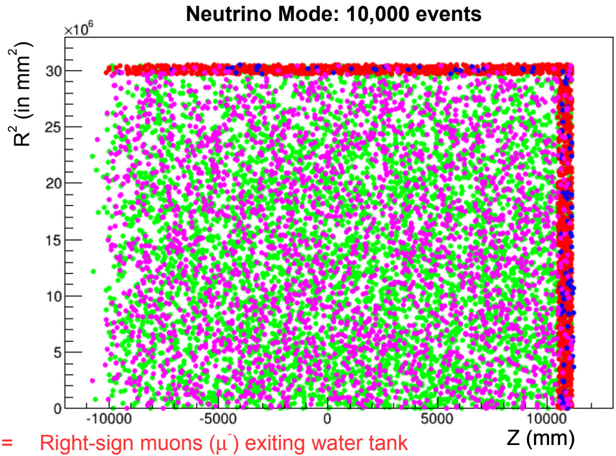
WC + MRD





- 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
- **Magnetized MRD offers complementary information to neutron tagging with gadolinium**
- At high-Eν, μ escapes MRD
  - Charge-sign easy to determine
  - Can be used to calibrate and validate ν / $\bar{\nu}$ discrimination via Gd
- At lower energies (*i.e.*, oscillation region), charge reconstruction less efficient
- Curvature in MRD is **complementary** information to neutron multiplicity
  - **Combination of WC + MRD can give very accurate particle / antiparticle separation!**

Muon Positions in 2D



Final position in WC tank shown for all muons

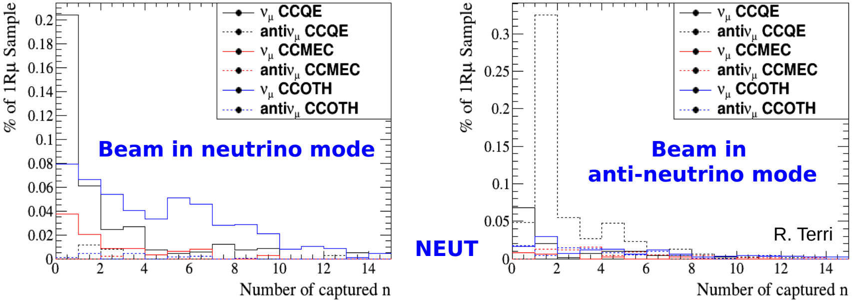
Red = Right-sign muons (μ^-) exiting water tank

Blue = Wrong-sign muons (μ^+) exiting water tank

Green = Right-sign muons (μ^-) contained within water tank

Purple = Wrong-sign muons (μ^+) contained within water tank

Neutron Multiplicity



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- 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: 37% → **63%** with n = 0 requirement
  - $\bar{\nu}_\mu$ CCQE: 55% → **81%** with n = 1 requirement

Ongoing Work

- **TITUS efforts are still ramping up → LOTS of recent work!**
  - Event generation
  - Software development
    - Photosensor implementation and optimisation
    - Water Cherenkov + MRD joint analysis
    - High energy reconstruction
    - Low energy reconstruction (< 20 MeV)
  - Event selection
    - Selection criteria (esp. CCQE)
    - Fiducial volume optimisation
  - Detector and beam studies
    - Neutron capture & multiplicity
    - Intrinsic beam ν_e measurements
    - Separation of ν / $\bar{\nu}$
    - Intrinsic $NC\pi^0$ studies
  - Physics analyses
    - Oscillation sensitivity at Hyper-Kamiokande
    - Sterile neutrino search
    - Supernova burst evaluation
    - Proton decay background reduction

Important for Gadolinium-based analyses

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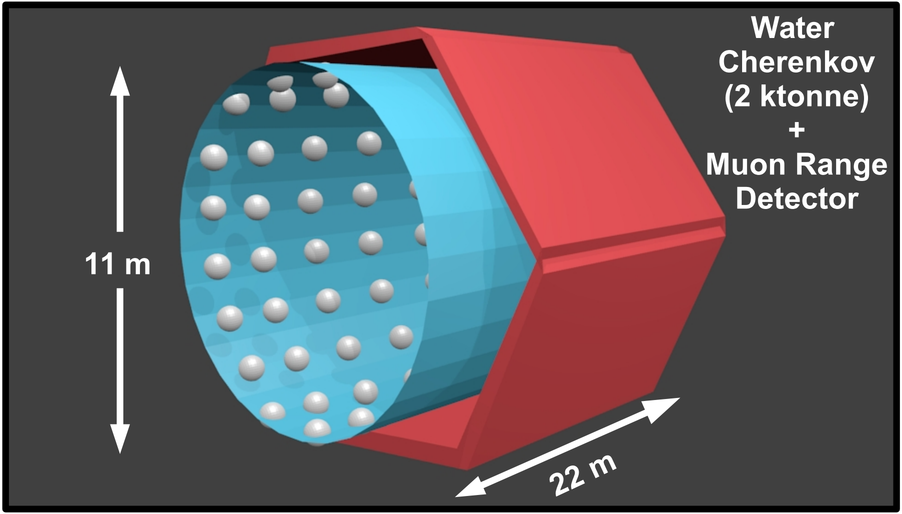
Much work to be done!

Many people getting involved recently...

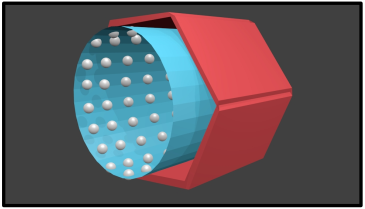
...let us know if you want to join!

BACK-UP SLIDES

TITUS



TITUS Overview



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- Baseline design includes:
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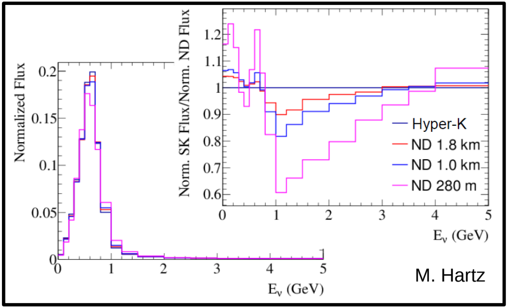
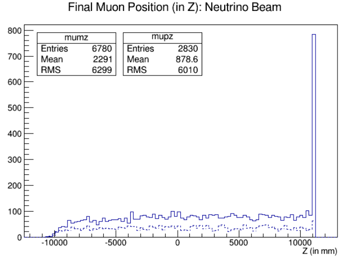
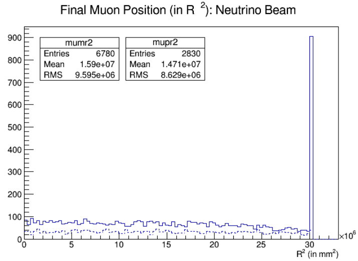
  - 0.1% Gadolinium-doping
  - Partly enclosed by Muon Range Detector

- 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



Muon Positions by R^2





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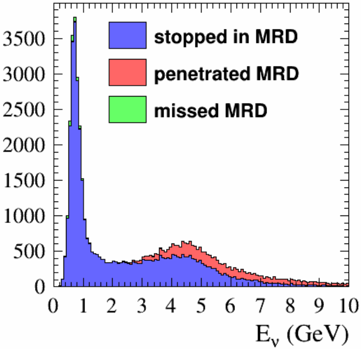
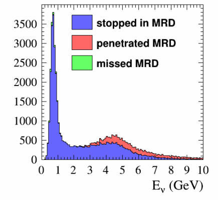
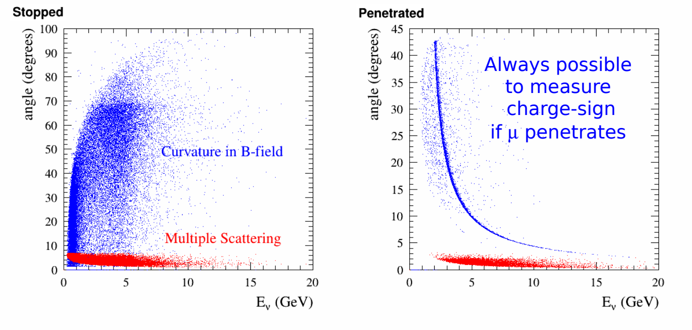


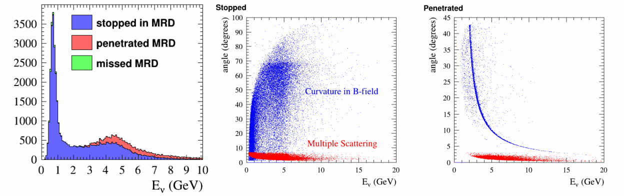
Magnetizing the MRD



- A 1.5 Tesla magnetic field enables:
  - Momentum reco. for μ that penetrate MRD (magnitude of curvature)
  - Charge-sign reconstruction (direction of curvature)
- For μ that stop in MRD, multiple scattering may inhibit curvature measurement
- For μ that penetrate MRD, always possible to separate curvature from multiple scatters



PID with MRD



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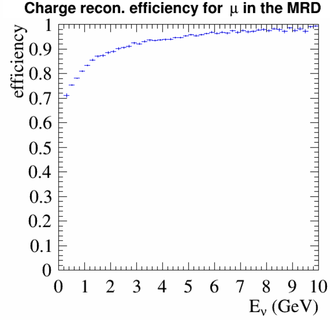
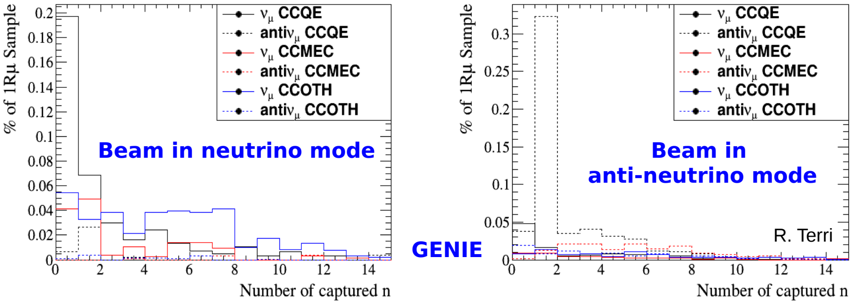


Neutron Multiplicity



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Neutron Multiplicity

Beam Mode & Selection	CC QE	CC MEC	CC 1π	CC Other	NC	'Wrong-Sign' CC
ν_μ all	37%	10%	28%	19%	3%	4%
ν_μ with n = 0 (CCQE-enhanced)	67%	8%	9%	14%	2%	< 1%
ν_μ 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%