TITUS Analysis Status

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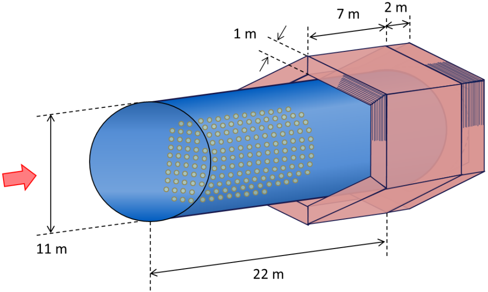
HK ND Pre-meeting, January 28, 2015

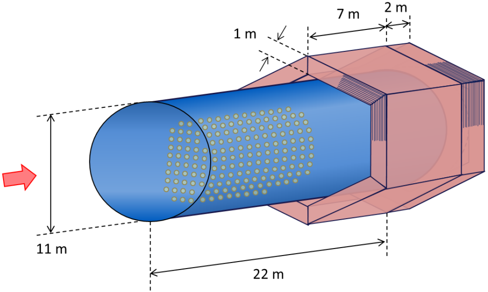
TITUS

- Primary aim of the TITUS experiment is to reduce systematics uncertainties in the measurement of δ_{CP}.
- Identical target nucleus, exposed to similar total flux at 2km
- Several advanced features available to a future TITUS analyser:
  - Neutron tagging with Gd capture
  - Magnetised MRD
  - Precision reconstruction (eg if LAPPDs used)
- Many parameters to optimise (geometry, location, photo-sensors...)



TITUS Analysis Status

- External Backgrounds (Justyna Lagoda, Ryan Terri)
- Low energy reconstruction (Wing Ma)
- High energy reconstruction (Nick Prouse)
- TITUS Selection (Dave Hadley, Nick Prouse)
- π^0 analysis (Wing Ma)
- Sterile analysis (Pierre Bartet)
- Supernova neutrinos (Matthew Lawe, Susan Cartright)



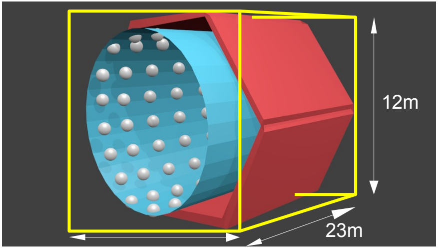
External Backgrounds

Sand Muons

How the simulation is done

Cult Polish comic book series
http://en.wikipedia.org/wiki/Tytus,_Romek_i_A%27Tomek

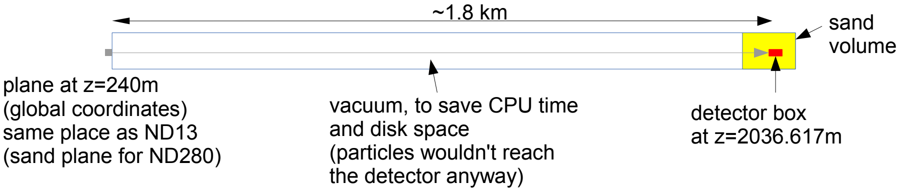
- steps:
  - produce a special flux of neutrinos (thanks, Ryan!)
  - use NEUT to generate interactions in the big volume of sand surrounding the detector
  - use GEANT to propagate the produced particles through the sand
  - save the particles which enter a box big enough to encapsulate the detector
  - export the information to format readable by detector simulation code



13.86m

Neutrino vectors and geometry

- the starting plane for neutrinos must be placed at least 30-40m upstream of the detector
  - because of problems with NEUT reported at previous meetings, we use a plane positioned at the same place as in the sand simulation for ND280
  - temporary (but working!) solution
  - huge geometry needed



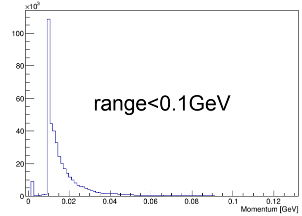
Incoming particles

	# particles entering detector box	Rate per pulse (2.2×10^{14})
muons (+ and –)	262 665	0.33
neutrons	6 426 443	8.1
photons	2 136 981	2.7
protons	32 135	0.04
pions (+ and –)	22 116	0.03
e+ and e–	150 670	0.19
other	1 401	0.002
other (ions)	3 037 250	3.8

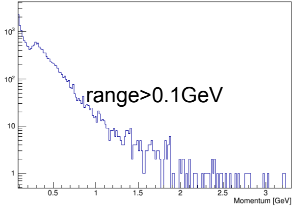
very slow, mostly deuterons (undetectable)

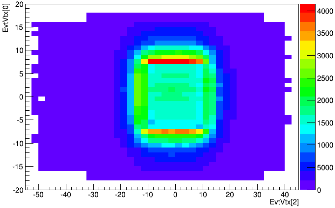
- numbers for POTs: 1.75e20
- note that not all of those particles will enter the MRD or tank – due to low energy or small incident angle

Neutrons



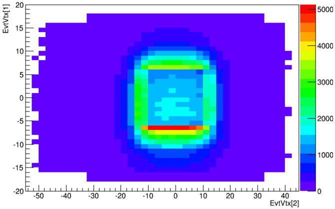
momentum
when entering
detector box





Interaction vertex

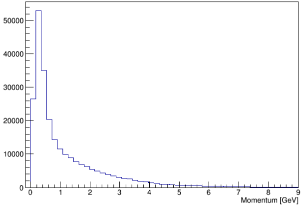
top view



side view

On all the vertex plots
the number of entries is
number of incoming partices
of given type.

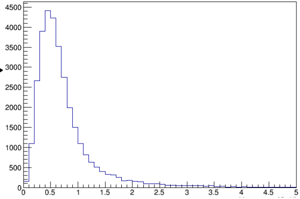
One neutrinos interaction
can be marked many times,
if many produced particles
(of the same type)
reached the detector box.

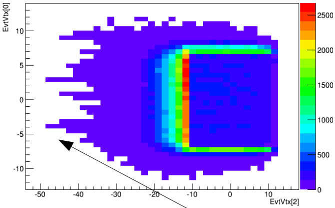


← Muons

Protons →

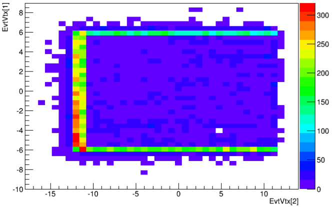
momentum when entering box

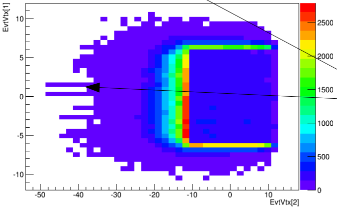




Neutrino interaction vertex

top view

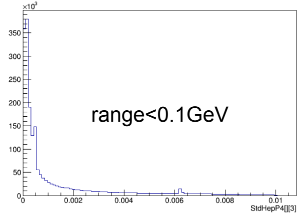


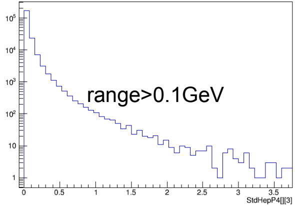


side view

Most probably the vector file is still to small.
The lines look like the same neutrino vector is used several times.

Photons

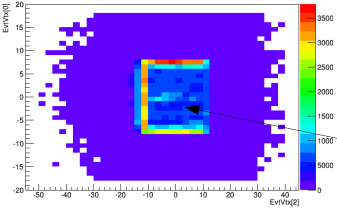




blue - initial
red – when entering detector

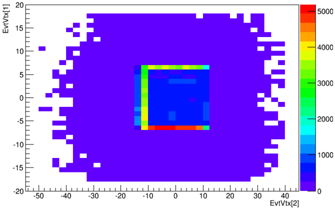
Interaction vertex

top view



same neutrino vector used? or cascade?

side view



Cosmic Sources

- Use numbers from PRC **72**, 025807 about cosmic μ & induced neutron rates
- Main numbers:
  - μ: 6×10^5 $\mu/m^2/h$
  - n: 7.2×10^6 events/kTon/day
- Scale these to per spill and per bunch values
  - Assume that μ scales with cross sectional area, neutrons with volume
- Not worried about atmν background (about 1/day based on scaling SK rate)

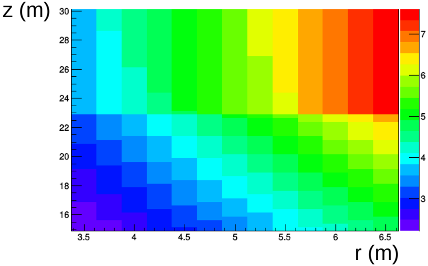
Beam-induced sources (1/2)

- Have flux histograms for both horn currents
- Calculate event rate/m^3 for interactions in water (ignore Gd) and Fe using NEUT
  - Easy to scale for various volume assumptions
  - GENIE will not largely be different
- For TITUS, calculate for various r/z
- For MIND, 3 assumptions
  - Case 1: ¾ length of TITUS + downstream, 0.5m Fe encasing TITUS
  - Case 2: downstream of TITUS, 0.5m thickness, same r
  - Case 3: non-existent

Beam-induced sources (2/2)

- Have to make a few assumptions in particle transport in MIND
- Only follow p, n, μ, e, $\pi^{\pm}$, & γ
- Assume same dE/dx for all particles
  - Not a good assumption, but will work for for muons & heavier
- To be counted as having entered TITUS, must be above Cherenkov thereshold
  - Exceptions: γ must have 30 MeV, n has no constraint
- Assume fraction of interactions entering the tank from MIND is independent of size (evaluated for nominal TITUS)
  - Not the best, but used for a quick turnaround...
- GEANT is not used, which will also affect particle multiplicities

Sand Muon Event Rate/Spill

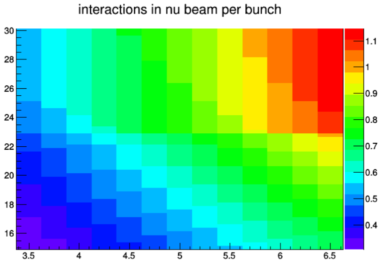


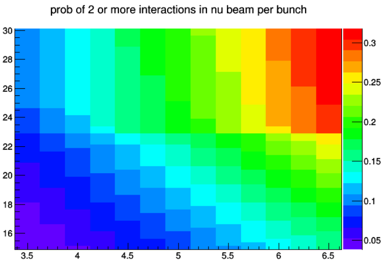
Nominal TITUS: r = 5.5m; l = 22m

- Look at event rate of sand muons on a per spill (and per bunch) basis
  - Can divide by 8 to get bunch numbers, since overall shape stays the same
- Note: weird shapes have to do with size of box used for sand muons
  - Total length is 23m, & is 6x7 m^2 in x & y

Total Interactions/Prob Per Bunch

Plots below take into account beam interactions, cosmic mus, no MIND, and sand muons



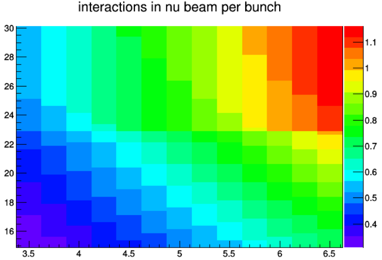


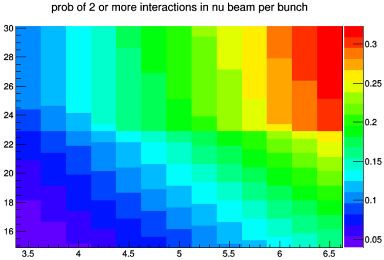
For nominal TITUS, a bunch has a probability of ~17-18% of having multiple interactions (another way to say that there should be ~8-9 interactions/spill on average)

Can the DAQ handle this much in a beam event?

Total Interactions/Prob Per Bunch

Plots below take into account beam interactions, cosmic mus, full MIND, and sand muons





For nominal TITUS, a bunch has a probability of ~18.3% of having multiple interactions (another way to say that there should be 11-12 interactions/spill on average)

Can the DAQ handle this much in a beam event?

External Backgrounds

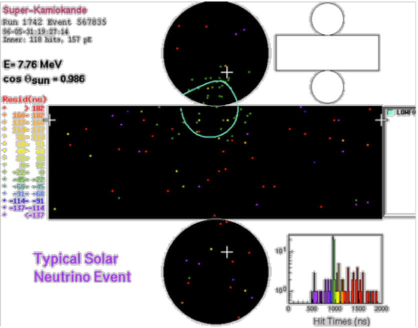
- $\sim 20\%$ chance of pile-up/sand interaction (MRD does not add much)
- Freedom to optimise these values by changing the detector size
- Can the DAQ and reconstruction handle these events?
- Can these events be vetoed?
  - upstream veto would kill most of the sand backgrounds

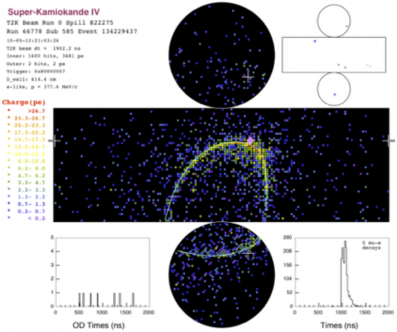
Low Energy Reconstruction

Why do we need a low-E fitter

- Neutron captures result in ~5 MeV of visible energy*, which we need to see to gain the benefit of using gadolinium

- M.Wilking says fiTQun/APFit** are not effective below 20 MeV (not enough PMT hits) , so we need a different fitter





* http://www.sciencedirect.com/science/article/pii/0168900294015201

**fitQun/ APFit are fitters used by SK

Vertex fitting

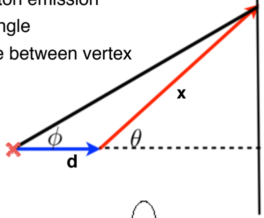
- Timing information from PMT hits used to reconstruct vertex position
- Quadruple-vertex-finding method: reconstruct one vertex candidate from 4 random PMT hits, repeated many times
- Assume all of the scintillation and Cherenkov light is emitted from a single point, as below 20 MeV the travel distance is only a few cm

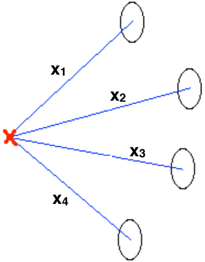
x: distance travelled by photons

d: distance between the vertex and the point of photon emission

θ: Cherenkov angle

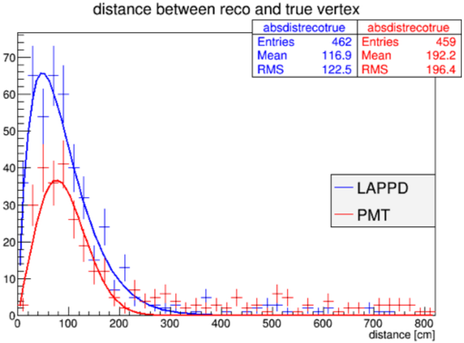
ϕ: relative angle between vertex and hit PMT





Timing resolution of photosensors

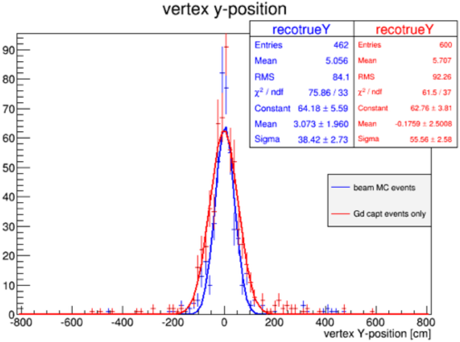
- Using 500 events with 40% coverage
- Timing res of PMTs: 2.5 ns;
  Timing res of LAPPDs: 0.1 ns
- Vertex resolution: Mean distance of the reconstructed vertices from true vertices
- Vertex resolution at ~2 m using PMTs
- Using LAPPDs improves the vertex resolution by ~1 m

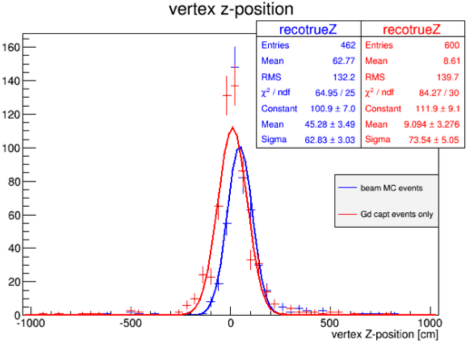


	mean [cm]
10” PMTs only	192.2
LAPPDs only	116.9

8

Single Gd capture events

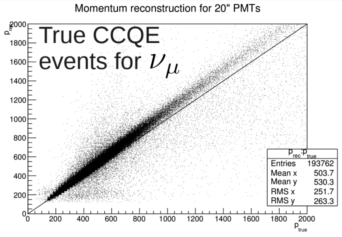


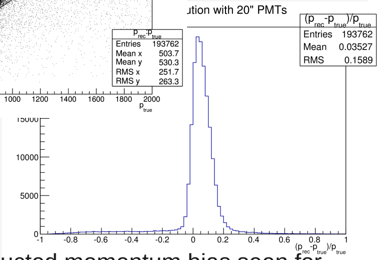


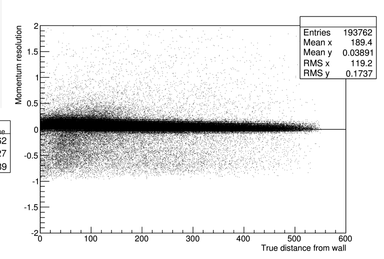
- Beam MC events: Distance between reconstructed vertex and true vertex
- Gd capture events: Distance between reconstructed vertex and neutron capture point

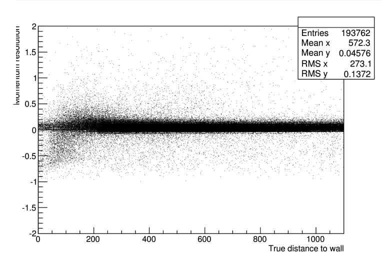
High Energy Reconstruction

Momentum resolution – muons



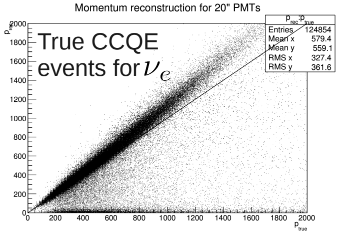


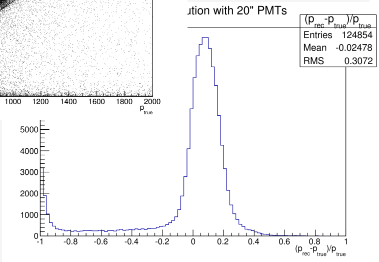


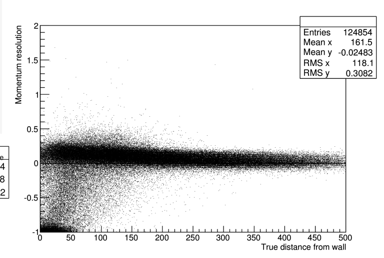


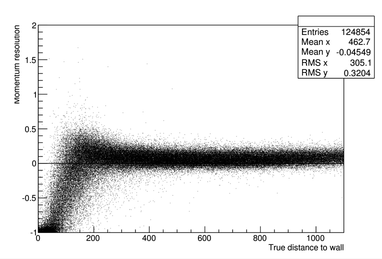
- Reconstructed momentum bias seen for true muon CCQE event in TITUS.
- Not seen for Hyper-K
- Not improved much by dwall or towall cuts
- Need fiTQun tuned for TITUS?

Momentum resolution – electrons



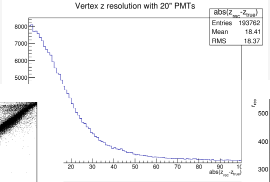




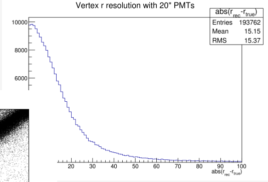


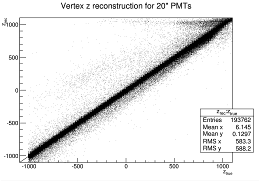
- Worse resolution again for electrons
- towall/dwall and low-E cuts partly help
- Need fiTQun tuned for TITUS?

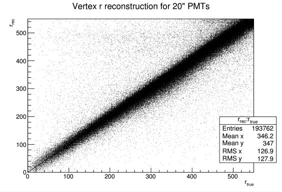
Vertex resolution - muons



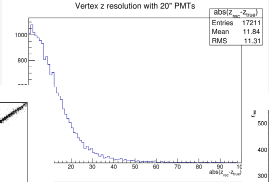
New fiTQun version



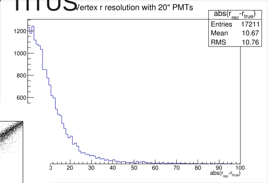


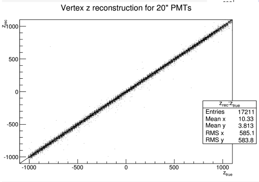


Worse vertex reconstruction for TITUS in new version
New fiTQun version fixed momentum bias for HK, doesn't for TITUS



Old fiTQun version





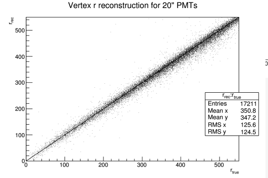
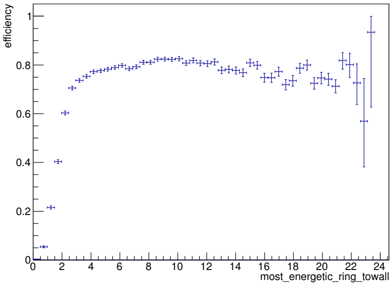
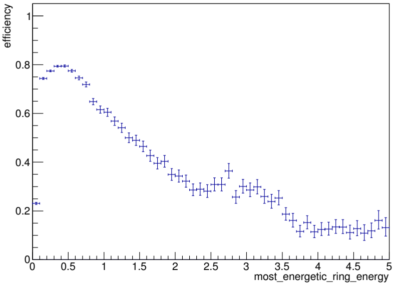


Table-based Selection Efficiency

- Using table based reconstruction.
- SK fitQun efficiencies for
  - 1 ring e-like
  - 1 ring mu-like
- Tables binned in 4 variables:
  - Final state topology
  - E_ν
  - Distance to the wall

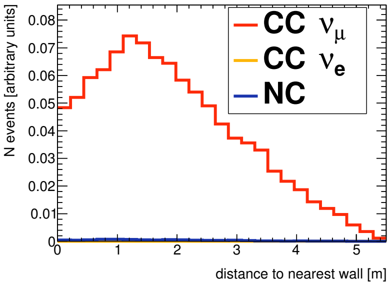




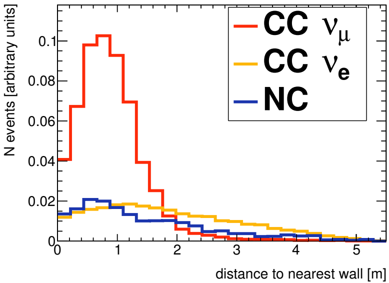
- Efficiencies for true $CC1\mu0\pi$ in TITUS.
- 80% plateau in "to wall" at 2m.
- Drop at high energy due to ranging out.

Event Selection

1Rμ Selection

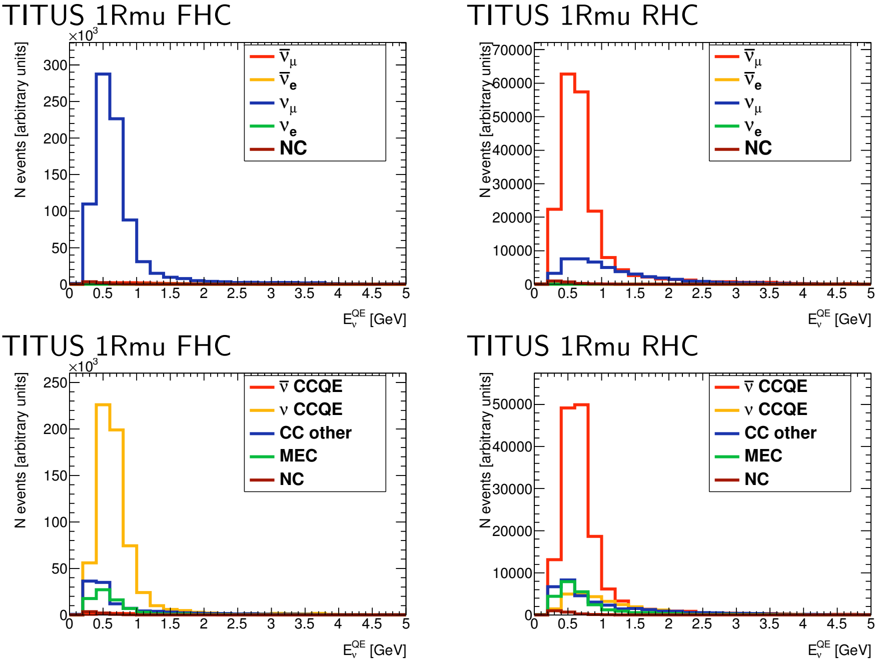


1Re Selection

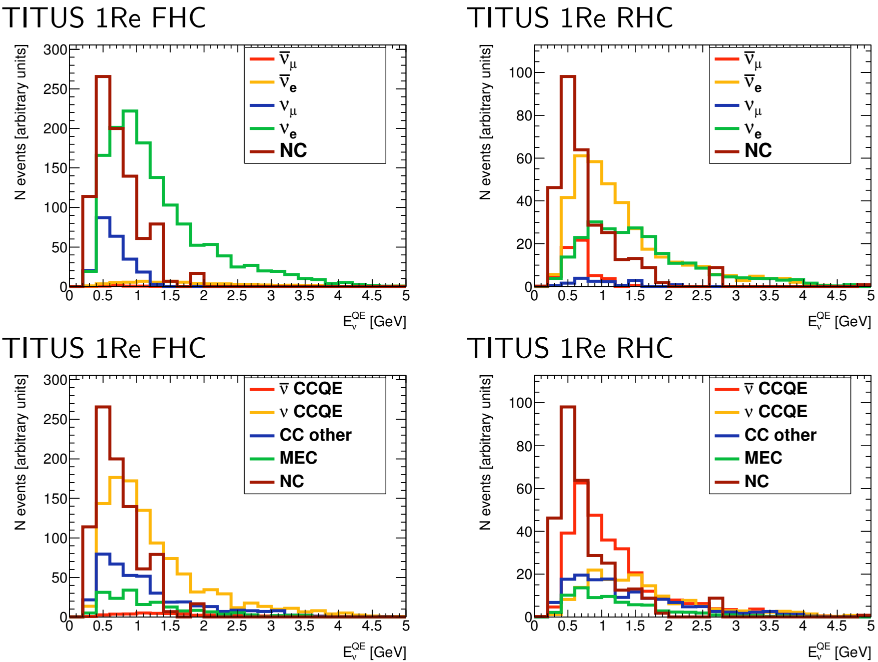


- Large muon contamination in electron sample at dwall < 2m.
- Low efficiency at towall < 2m
- Choose 2m fiducial volume.
- Cuts to be re-optimised when real reconstruction is available.

1Rmu sample in TITUS

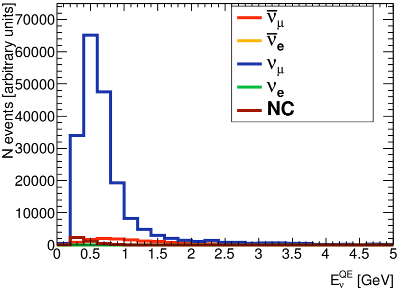


1Re sample in TITUS

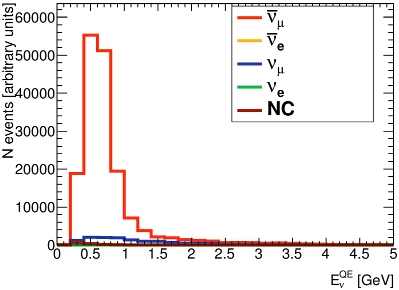


1Rmu neutron selection in TITUS

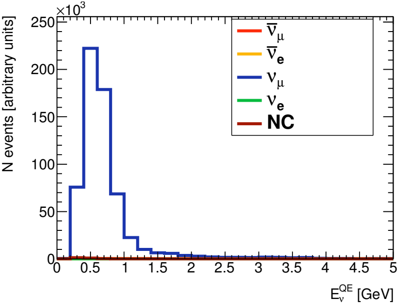
FHC with tagged neutron



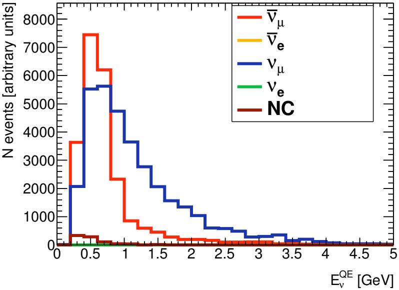
RHC with tagged neutron



FHC without neutron

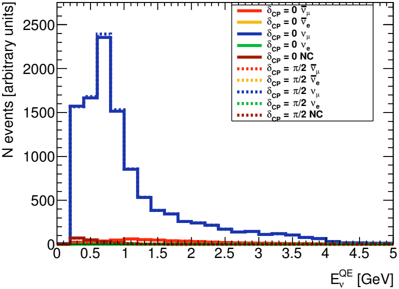


RHC without neutron

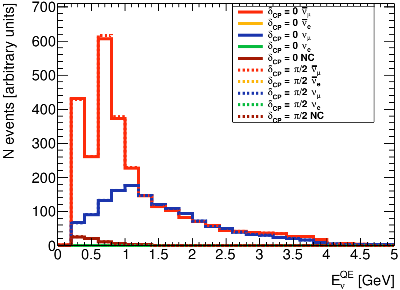


Selection in HK

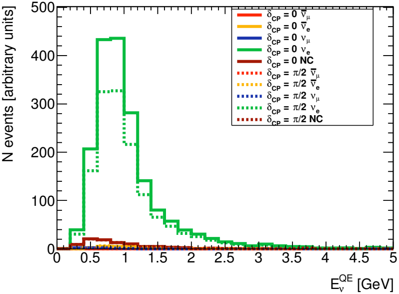
FHC 1Rmu



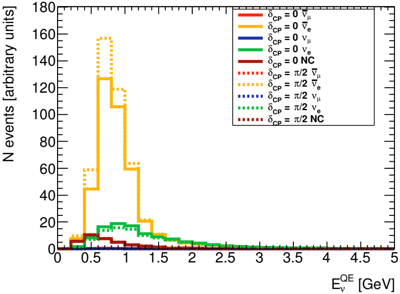
RHC 1Rmu



FHC 1Re



RHC 1Re

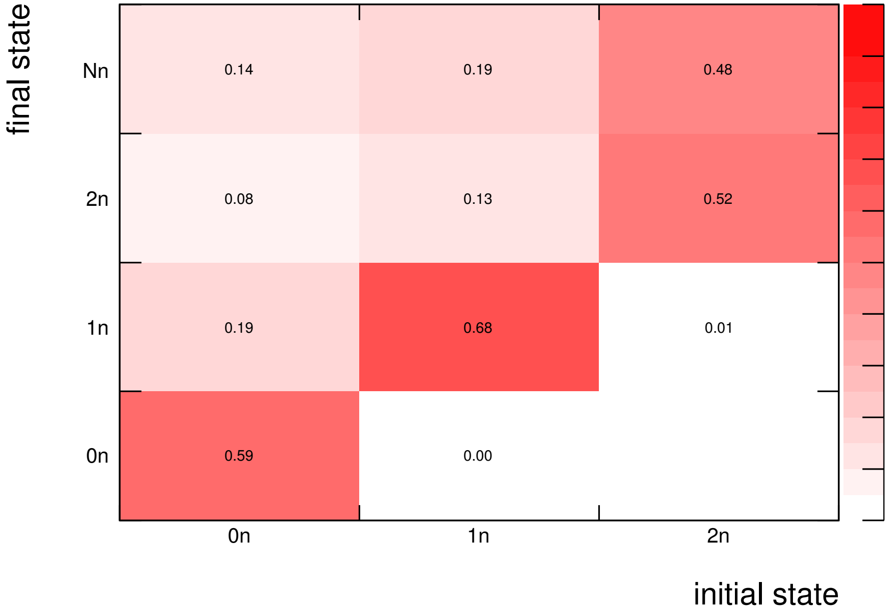


Cross Systematic Uncertainties

- Systematic uncertainties are based on T2K NIWG errors with some additions.
- MEC
  - NEUT implements NIEVES MEC model.
  - Assign a 50% normalisation uncertainty.
- $\nu - \bar{\nu}$
  - Selected 20%
- Nucleon FSI uncertainty not yet included in the fit (see later slides).

Parameter	Initial Value
CC1π E1	1.15 ± 0.43
CC1PI_E2	1.00 ± 0.40
CC coherent	1.00 ± 1.00
CCQE E1	1.00 ± 0.11
CCQE E2	1.00 ± 0.30
CCQE E3	1.00 ± 0.30
MEC	1.00 ± 0.50
NC $1\pi^0$	1.00 ± 0.30
CC other shape	0.00 ± 0.40
p_F	217.00 ± 30.00
SF	0.00 ± 1.00
M_A^{QE}	1.21 ± 0.10
M_A^{RES}	1.41 ± 0.11
$\nu - \bar{\nu}$ ratio	1.00 ± 0.20
$\nu_e - \nu_\mu$ ratio	1.00 ± 0.03

Neutrons in Initial and Final State



FSI Uncertainties in Neutron Selection

CCQE

	$\overline{\nu}_\mu$	$\overline{\nu}_e$	ν_e	ν_μ
FrAbs_N	0.033	0.028	0.024	0.057
FrCEx_N	0.016	0.017	0.246	0.155
FrElas_N	0.050	0.043	0.195	0.202
FrInel_N	0.025	0.026	0.132	0.071
FrPiProd_N	0.000	0.000	0.002	0.006
MFP_N	0.012	0.011	0.037	0.064
total	0.068	0.061	0.372	0.283

MEC

	$\overline{\nu}_\mu$	$\overline{\nu}_e$	ν_e	ν_μ
FrAbs_N	0.071	0.085	0.000	0.060
FrCEx_N	0.019	0.113	0.000	0.097
FrElas_N	0.168	0.314	0.000	0.064
FrInel_N	0.040	0.077	0.000	0.017
FrPiProd_N	0.001	0.000	0.000	0.001
MFP_N	0.022	0.022	0.000	0.013
total	0.201	0.363	0.000	0.137

- Estimates using GENIE FSI tools.
- Reverse horn current mode TITUS event sample (CCQE and MEC)
- Apply truth level selection: num FSI neutrons = 1
  - ν_μ CCQE $= 20 \pm 6\%$
  - $\bar{\nu}_\mu$ CCQE $= 76 \pm 5\%$
  - ν_μ MEC $= 29 \pm 4\%$
  - $\bar{\nu}_\mu$ MEC $= 10 \pm 2\%$

Flux Systematic Uncertainties

- As a placeholder I am using the current T2K (ND280-SK) matrix.
- Need to update to the latest version from Ryan/Mark.
- Overestimates uncertainty as ND280-T2K has a relatively large uncertainty on the near-to-far extrapolation.
  - Use the same flux covariance matrix for both FHC and RHC.
  - No FHC/RHC correlation included
    - Used independent flux parameters.
    - All off-diagonal elements in the covariance matrix correlating FHC and RHC parameters set to zero.
    - This represents the worst case scenario.

Near / Far Ratio

- A simple measure of the size of each systematic uncertainty.

$$R = \frac{\text{num. 1 ring } e\text{-like selected HK}}{\text{num. 1 ring } \mu\text{-like selected in TITUS}}$$

systematic	Ratio FHC	Ratio RHC
CCQE E1	1.149	0.648
CCQE E2	0.204	0.162
CCQE E3	0.116	0.173
M_A^{QE}	0.162	0.150
CC1PI E1	1.403	0.625
CC1PI E2	0.079	0.150
CC coherent	0.143	0.488
MEC	0.642	0.274
NC	1.247	1.169
CC other	0.140	0.047
pf	0.332	0.007
sf	0.042	0.038
$\nu - \overline{\nu}$ xsec	0.378	0.477
$\nu_e - \nu_\mu$ xsec	3.776	3.791
xsec	4.213	3.959
flux	1.938	2.278

Fit Likelihood

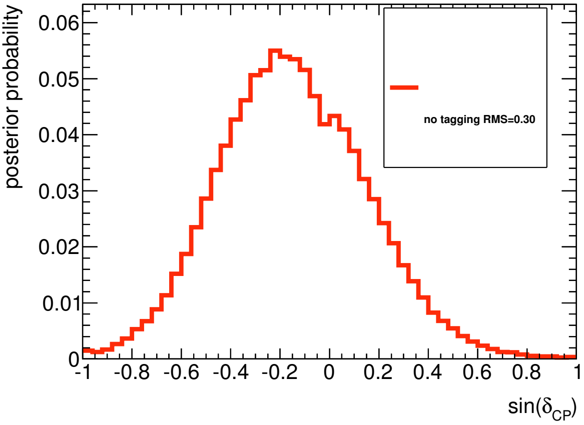
- Old fit method directly fitted the flux and cross-section nusiance parameters.
  - found this to be very slow
- New fit method generates covariance matrix (similar to T2K SimpleFitter).

$$\begin{aligned} -2\ln\lambda(\theta) &= 2\sum_{i}^{\text{reco. bins}}\left(E_i(\theta) - N_i + N_i\ln\frac{N_i}{E_i(\theta)}\right) \\ &\quad +\ln\frac{\pi(\theta)}{\pi(\theta_0)} \end{aligned} \tag{1}$$

$$\pi(\theta) \propto e^{-\frac{1}{2}\Delta\theta V^{-1}\Delta\theta}$$

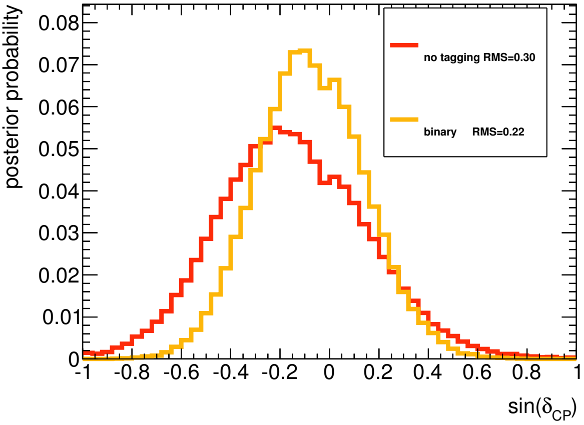
- θ are weights for each reconstructed bin.
- π is a multi-variate Gaussian constraining the θ parameters.
- For speed and simplicity, only include total number of events in each sample in the fit.
- Fit the Asimov dataset (i.e. fake data generated with all parameters set to their nominal values, and no statistical variation).

Fit Results



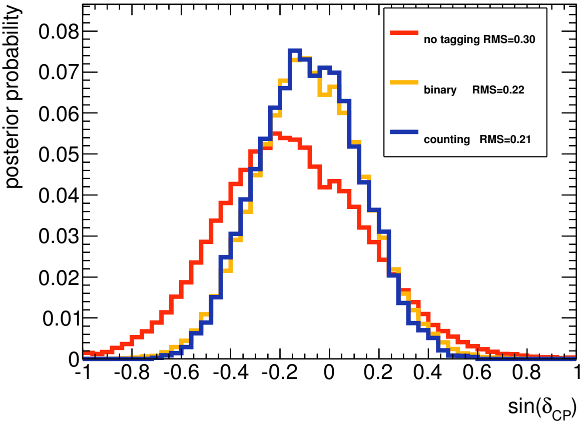
- Pseudo-experiment with true-$\delta_{CP} = 0$.
- δ_{CP} uncertainty evaluated with Bayesian method.

Fit Results



- Pseudo-experiment with true-$\delta_{CP} = 0$.
- δ_{CP} uncertainty evaluated with Bayesian method.
- Adding neutron tagging gives significant improvement.

Fit Results



- Pseudo-experiment with true-$\delta_{CP} = 0$.
- δ_{CP} uncertainty evaluated with Bayesian method.
- Adding neutron tagging gives significant improvement.
- Full multiplicity is not that helpful.

TITUS Selection

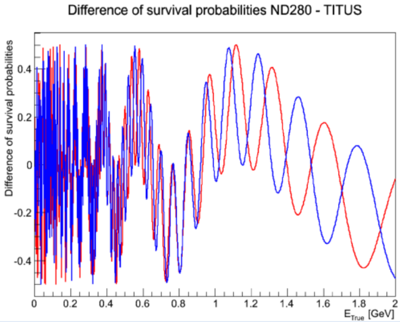
- Scope to improve TITUS electron selection (reconstruction near the wall, π^0 rejection).
- Neutron FSI errors have been evaluated (yet to be included in δ_{CP} sensitivity)
- Binary neutron tagging gives large improvement, but counting doesn't add much.

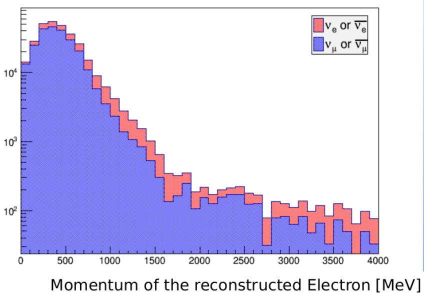
To-do

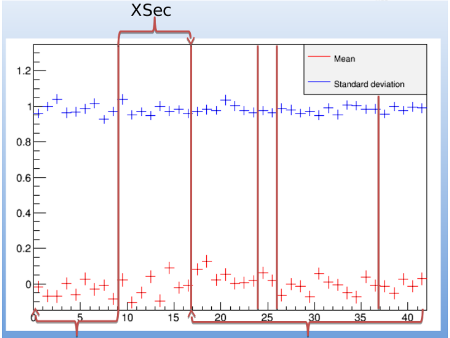
- Update all inputs to be consistent with the VALOR/MaCH3 analysis.
- Include nucleon FSI uncertainties inside the fit.
- Include MRD in selection
  - how much can neutron tagging uncertainty be reduced by using the MRD to calibrate the neutron tagging response.

Other Analysis Topics

Sterile Neutrinos

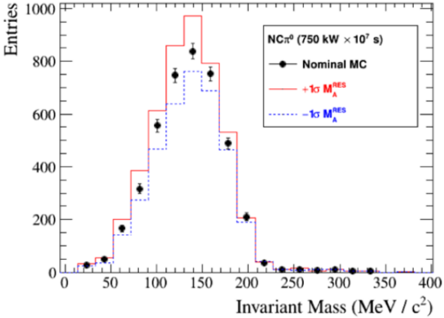






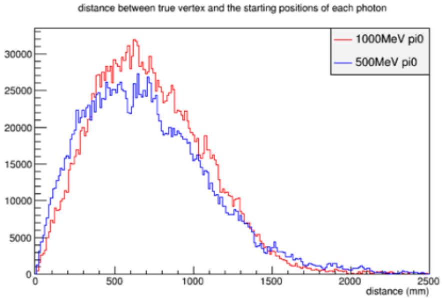
- Sterile Neutrino sensitivity analysis with ND280 + TITUS.
- ν_e selection being optimised
- Fit development and validation in progress.

π^0 reconstruction



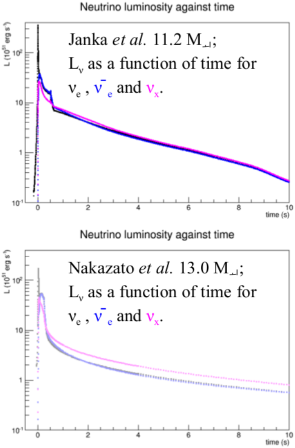
- Need charge information to reconstruct photon energy (charge proportional to number of photons)
- Selection cuts on pi0:
  - 2 rings e-like (ring cut/ PID cut)
  - FV cut 200cm
- Invariant mass cut (>105 MeV): Events without a real second ring tend to have low invariant masses

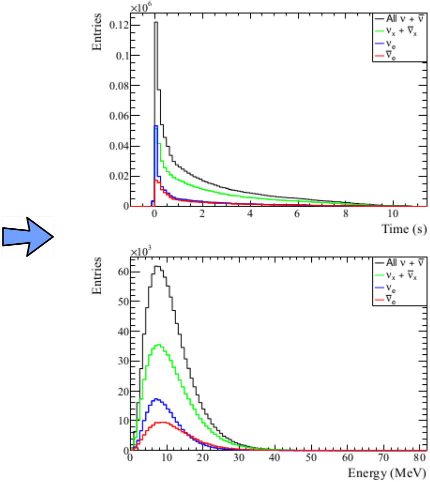
- $\pi^0 \to \gamma\gamma$ is a background to the ν_e appearance in far detector and intrinsic ν_e measurement in the near detector.
- Investigating π^0 reconstruction in TITUS tank.



Supernova Neutrinos

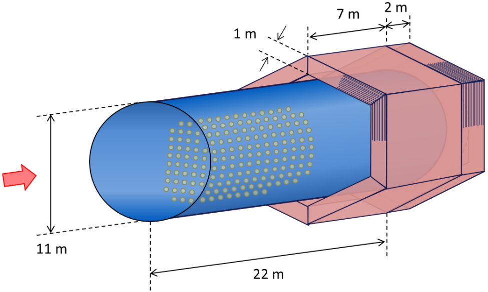
- Initial studies comparing theoretical models
- Plan to generate vectors for HK and TITUS
- Interface with Generalised Neutrino Vector Generator developed by Chris Kachulis.





TITUS Analysis

- External Backgrounds (Justyna Lagoda, Ryan Terri)
- Low energy reconstruction (Wing Ma)
- High energy reconstruction (Nick Prouse)
- TITUS Selection (Dave Hadley, Nick Prouse)
- π^0 analysis (Wing Ma)
- Sterile analysis (Pierre Bartet)
- Supernova neutrinos (Matthew Lawe, Susan Cartright)



Backup

Effect of Sand Muons on TITUS Event Rates

Ryan Terri (QMUL)
TITUS WG
28 January 2014

Motivation/Approach

- Look to see how much the event rate is affected by both the size of the detector and possible sources of interactions in the TITUS detector
  - Note: not complete, but have a reasonable way to use backgrounds
  - Current size discussed based purely on beam interactions (r: 5.5m, L = 22m)
- Contributions (used in this study):
  - Beam-induced neutrino interactions
  - Sand muons/neutrons
  - Cosmic-ray induced muons & neutrons
  - MIND
  - Radioactive backgrounds

Baseline

- Ideally, almost guarantee 1 interaction/spill, and try to get 1 interaction/bunch
  - Need to keep probability of multiple interactions/bunch low (~1%-ish)
    - Current reconstruction probably can't handle pileup
- Know that a neutron capture from a neutrino interaction should happen outside of spill
  - So worried only a bit about low E backgrounds

Beam-induced sources (1/2)

- Have flux histograms for both horn currents
- Calculate event rate/m^3 for interactions in water (ignore Gd) and Fe using NEUT
  - Easy to scale for various volume assumptions
  - GENIE will not largely be different
- For TITUS, calculate for various r/z
- For MIND, 3 assumptions
  - Case 1: ¾ length of TITUS + downstream, 0.5m Fe encasing TITUS
  - Case 2: downstream of TITUS, 0.5m thickness, same r
  - Case 3: non-existent

Beam-induced sources (2/2)

- Have to make a few assumptions in particle transport in MIND
- Only follow p, n, μ, e, $\pi^{\pm}$, & γ
- Assume same dE/dx for all particles
  - Not a good assumption, but will work for for muons & heavier
- To be counted as having entered TITUS, must be above Cherenkov thereshold
  - Exceptions: γ must have 30 MeV, n has no constraint
- Assume fraction of interactions entering the tank from MIND is independent of size (evaluated for nominal TITUS)
  - Not the best, but used for a quick turnaround...
- GEANT is not used, which will also affect particle multiplicities

Cosmic Sources

- Use numbers from PRC **72**, 025807 about cosmic μ & induced neutron rates
- Main numbers:
  - μ: 6×10^5 $\mu/m^2/h$
  - n: 7.2×10^6 events/kTon/day
- Scale these to per spill and per bunch values
  - Assume that μ scales with cross sectional area, neutrons with volume
- Not worried about atmν background (about 1/day based on scaling SK rate)

Sand Muons

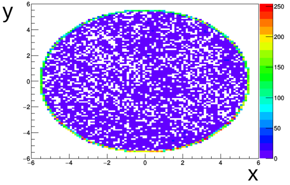
- Files produced by Justyna
  - 200 files
  - 2.5×10^{17} POT/file
  - Note: beam assumes 2.2×10^{14} protons per pulse, which is the base unit here
    - Pulse length is 5μs, bunch is assumed to be 100 ns ($\pm 2\sigma$ width)
    - Introduces scale factor of ~10^{-4}
- Particles are tracked from box until they hit side of TITUS tank

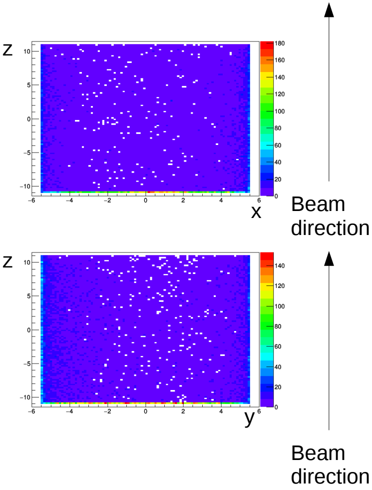
Some basic SM numbers

Particle (threshold)	Count (5×10^{20} POT); nominal TITUS
γ (1.22 MeV)	5419
e	1228
μ	1948
$\pi\pm$	166
n	45338
p	252
other	12

Photons must be able to pair produce, otherwise particles just need to enter the tank
Other category: anything w/ PDG code > 100 (and < -100)
Neutrinos and Si & O nuclei are ignored
This gives better idea of possible event rates than if Cherenkov threshold is applied since can account for multiplicities in tank when hit

Vertex distributions (nominal TITUS)





- Most particles are entering at the upstream edge of detector
  - Upstream veto?
- Also at edges, but that's a “no duh” sort of statement

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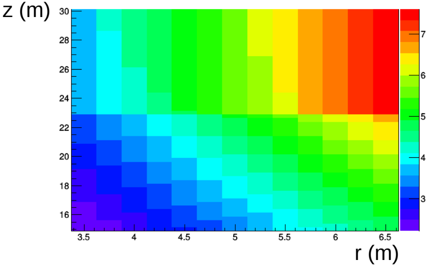
Sand Muon Event Rate/Spill

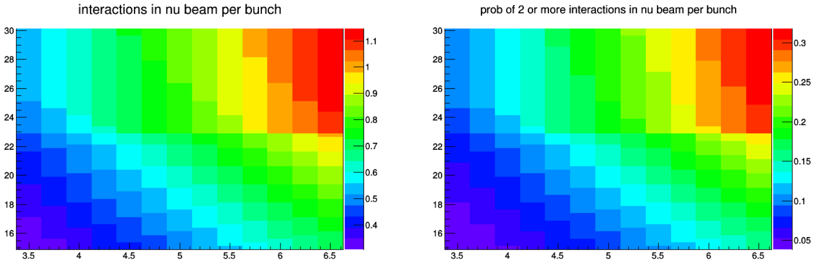


Nominal TITUS: r = 5.5m; l = 22m

- Look at event rate of sand muons on a per spill (and per bunch) basis
  - Can divide by 8 to get bunch numbers, since overall shape stays the same
- Note: weird shapes have to do with size of box used for sand muons
  - Total length is 23m, & is 6x7 m^2 in x & y

Total Interactions/Prob Per Bunch

Plots below take into account beam interactions, cosmic mus, no MIND, and sand muons

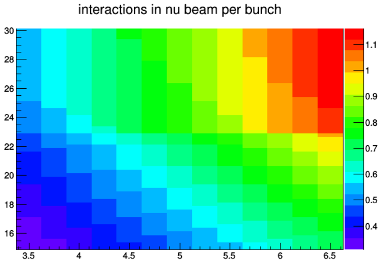


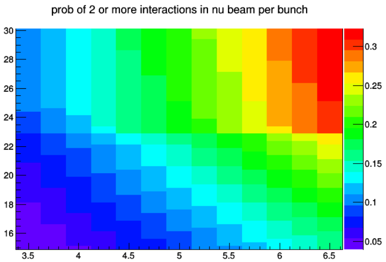
For nominal TITUS, a bunch has a probability of ~17-18% of having multiple interactions (another way to say that there should be ~8-9 interactions/spill on average)

Can the DAQ handle this much in a beam event?

Total Interactions/Prob Per Bunch

Plots below take into account beam interactions, cosmic mus, full MIND, and sand muons





For nominal TITUS, a bunch has a probability of ~18.3% of having multiple interactions (another way to say that there should be 11-12 interactions/spill on average)

Can the DAQ handle this much in a beam event?

Assumptions to play with

- Scenario 1: We have to account for all of these particles
  - Which means track them to see if the numbers get much higher and if the DAQ can handle that event rate over the course of a spill (since it will be lower for events out of spill)
    - DAQ will have to do this anyway, so this is a good idea of some numbers to be able to handle
  - For tank, means we need to push smaller size
- Scenario 2: We assume some type of veto can reduce the numbers
  - Doesn't make much of a difference in DAQ design work
  - For size optimization, means that keeping inner tank at current size
    - Would then need to optimize veto: best choice is upstream (kills most of the sand backgrounds), but can also look to SK-style tank if we've got money

cult Polish comic book series
http://en.wikipedia.org/wiki/Tytus,_Romek_i_A%27Tomek

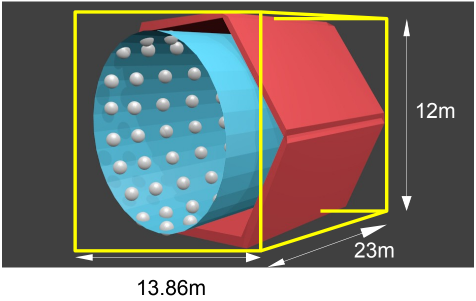
Sand muons generation for TITUS

Justyna Łagoda

NCBJ, Warsaw

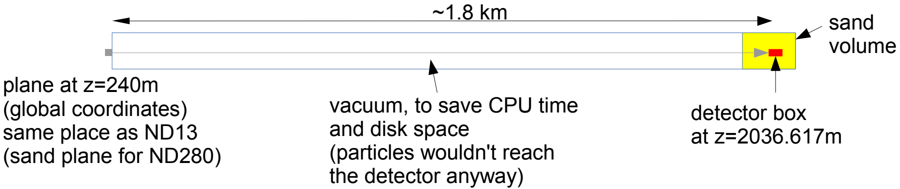
How the simulation is done

- steps:
  - produce a special flux of neutrinos (thanks, Ryan!)
  - use NEUT to generate interactions in the big volume of sand surrounding the detector
  - use GEANT to propagate the produced particles through the sand
  - save the particles which enter a box big enough to encapsulate the detector
  - export the information to format readable by detector simulation code



Neutrino vectors and geometry

- the starting plane for neutrinos must be placed at least 30-40m upstream of the detector
  - because of problems with NEUT reported at previous meetings, we use a plane positioned at the same place as in the sand simulation for ND280
  - temporary (but working!) solution
  - huge geometry needed



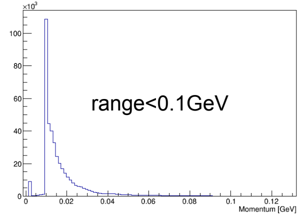
Incoming particles

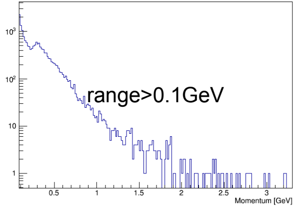
	# particles entering detector box	Rate per pulse (2.2×10^{14})
muons (+ and –)	262 665	0.33
neutrons	6 426 443	8.1
photons	2 136 981	2.7
protons	32 135	0.04
pions (+ and –)	22 116	0.03
e+ and e–	150 670	0.19
other	1 401	0.002
other (ions)	3 037 250	3.8

very slow, mostly deuterons (undetectable)

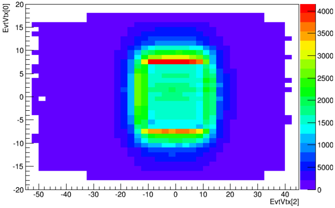
- numbers for POTs: 1.75e20
- note that not all of those particles will enter the MRD or tank – due to low energy or small incident angle

Neutrons



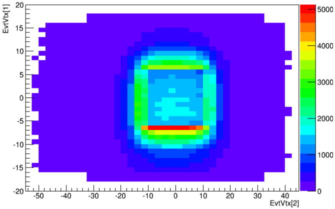


momentum
when entering
detector box



Interaction vertex

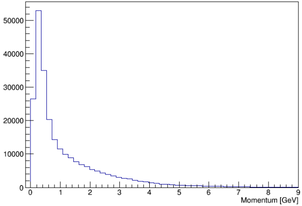
top view



side view

On all the vertex plots
the number of entries is
number of incoming partices
of given type.

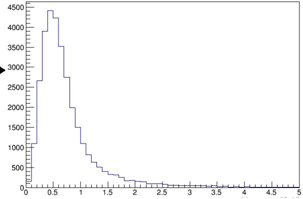
One neutrinos interaction
can be marked many times,
if many produced particles
(of the same type)
reached the detector box.

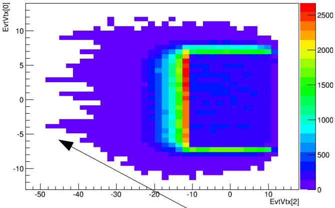


← Muons

Protons →

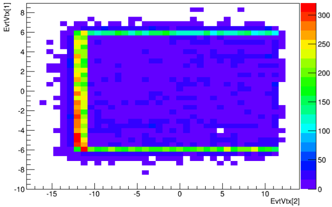
momentum when entering box

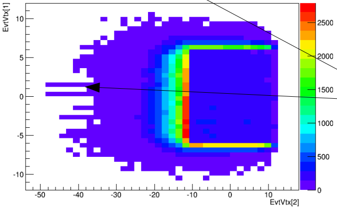




Neutrino interaction vertex

top view

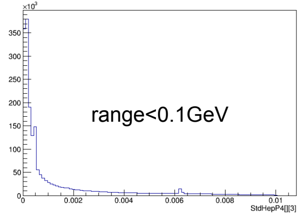


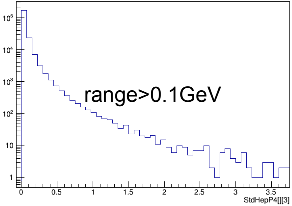


side view

Most probably the vector file is still to small. The lines look like the same neutrino vector is used several times.

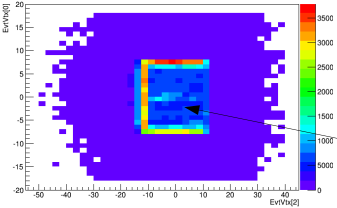
Photons





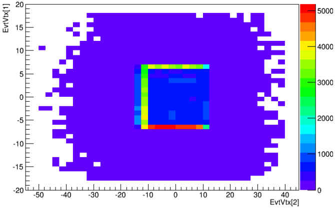
blue - initial
red – when entering detector

Interaction vertex

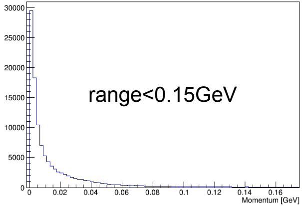


top view

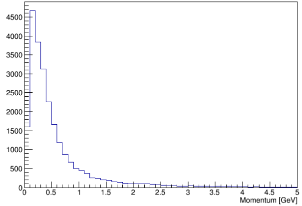
same neutrino vector used? or cascade?

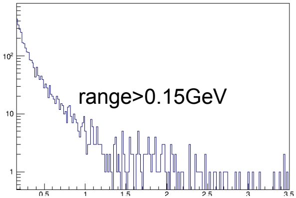


side view



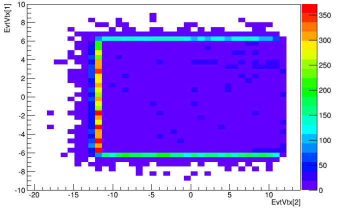
← e+e– pions +other →

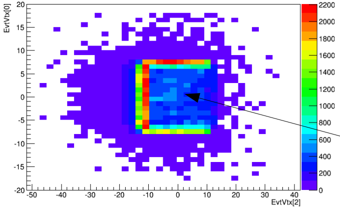




Neutrino interaction vertex

pions → side view

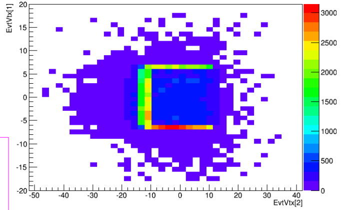




e+e–
← top view

side view →

same effect like for photons – so it is probably cascade



Summary

- temporary solution with ND13-like neutrino vectors and huge geometry seems to work
  - some vectors used > 1 time
- generation in progress:
  2e20 POT ready
- Ryan started to use the sand interactions in the detector MC

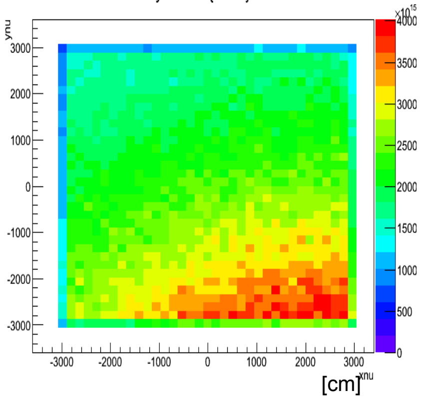
Backup slides

Problems with NEUT

- NEUT „knows” some particular planes prepared for near or far detector, identified by a number (idfd)
  - 1 – 2km detector; 5,6 – ND280 basket and magnet, 13 – ND280 sand muons
- NEUT must be changed if you want to use other planes
  - Ryan generated fluxes for idfd=1 and 2
  - I changed neutgeom to have interactions for z<-10m for this planes (by default available only for ND280 sand muons)
  - I didn't find any conditions on x and y depending on plane number, but...

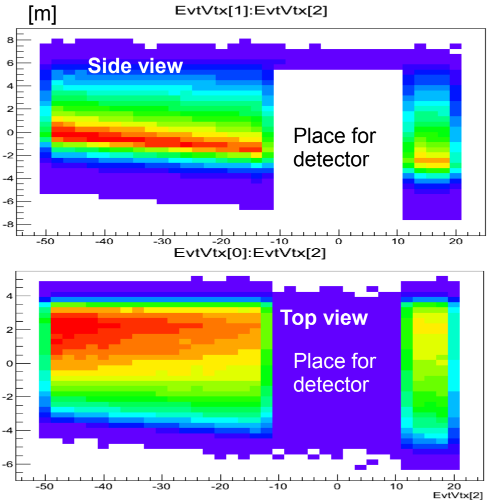
Reminder: problem with NEUT

Starting points for neutrinos (60x60m)



The flux is somehow cut to much smaller area. Problem of geometry?

Interactions vertices produced by NEUT



Possible (temporary) solution

- use a starting plane positioned as ND13 (sand muons for ND280)
- Titus is illuminated by neutrinos starting from there
- use a huge geometry (2km long) to include the plane and the detector
- fill the geometry mostly with vacuum to spare CPU time
  - for the geometry used now:
    - NEUT with 1e17 POT ~ 45h (per 1 CPU)

Low Energy Vertex Reconstruction

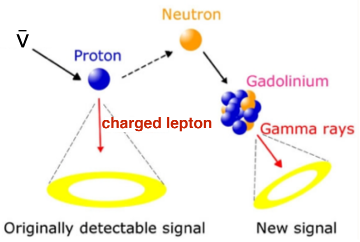
Wing Yan Ma
Imperial College London
TITUS Workshop
18/12/14

Outline

- Gd-doped water
- Need for low-E fitter
- WChRecoLite fitter
- Reconstruction algorithm
- Results
- Conclusion

Neutron tagging in Gd-doped water

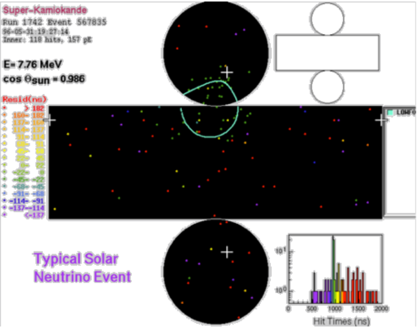
- Improve the detection efficiency of thermal neutrons
- High neutron capture cross-sections: 49,000 bn for Gd compare to 0.3 bn for free proton
  - Produce ~8 MeV gamma cascade; capture time of ~20 μs
  - Neutron capture by free protons in pure water produce 2.2 MeV gamma cascade; capture time of ~200 μs

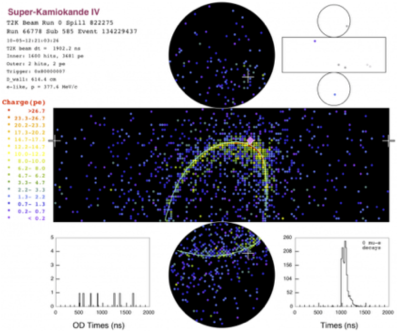


Why do we need a low-E fitter

- Neutron captures result in ~5 MeV of visible energy*, which we need to see to gain the benefit of using gadolinium

- M.Wilking says fiTQun/APFit** are not effective below 20 MeV (not enough PMT hits) , so we need a different fitter





* http://www.sciencedirect.com/science/article/pii/0168900294015201

**fitQun/ APFit are fitters used by SK

WChRecoLite fitter

- Reconstruction tool based on WCSimAnalysis, a reconstruction package for water Cherenkov detectors

- Effects from absorbed, scattered, reflected light and chromatic effects are included

Vertex fitting

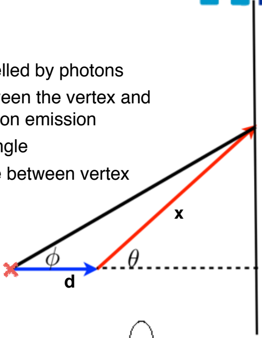
- Timing information from PMT hits used to reconstruct vertex position
- Quadruple-vertex-finding method: reconstruct one vertex candidate from 4 random PMT hits, repeated many times
- Assume all of the scintillation and Cherenkov light is emitted from a single point, as below 20 MeV the travel distance is only a few cm

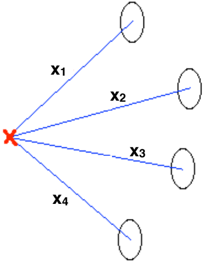
x: distance travelled by photons

d: distance between the vertex and the point of photon emission

θ: Cherenkov angle

ϕ: relative angle between vertex and hit PMT





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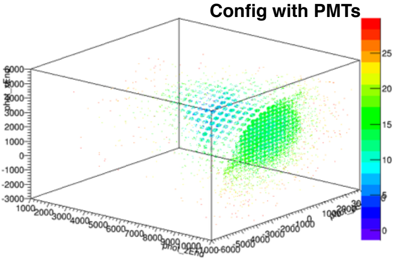
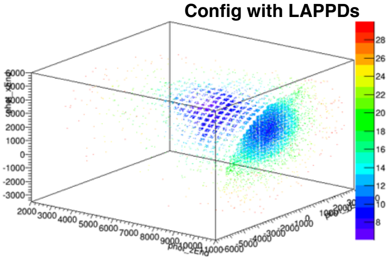
Photosensors

- Using PMTs or LAPPDs with 40% coverage
  - Hybrid configurations (PMT + LAPPD) possible; not used for this study
- Two config: 10” PMTs or 8”x 8” LAPPDs
- Assume spacial position for all photons that reach the same PMTs is the center of that PMT
- LAPPDs have much better position determination (<1 cm); can resolve individual photon hits
- Require the difference between predicted time and measured time to be less than 50 ns to exclude any random dark noise from Cherenkov light signal





7

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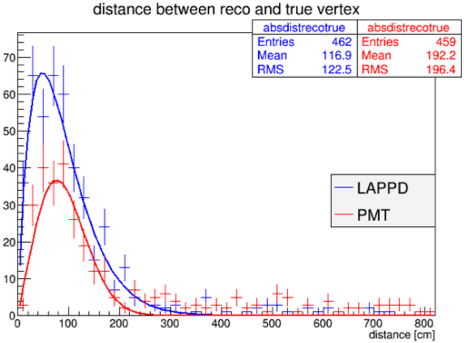
Timing resolution of photosensors

- Using 500 events with 40% coverage
- Timing res of PMTs: 2.5 ns;
  Timing res of LAPPDs: 0.1 ns
- Vertex resolution: Mean distance of the reconstructed vertices from true vertices
- Vertex resolution at ~2 m using PMTs
- Using LAPPDs improves the vertex resolution by ~1 m



	mean [cm]
10” PMTs only	192.2
LAPPDs only	116.9

Number of Photosensors

	PMTs	LAPPDs
N/front, N/back	750	920
N/row	92	102
N/column	58	64
N Total	6836	8368

40% coverage, 10” PMTs or 8”x 8” LAPPDs

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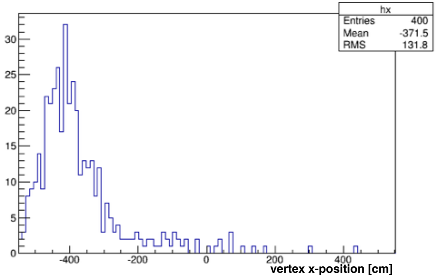
The reconstruction algorithm

- For every 4 hits, we can solve a system of 4 equations with 4 unknowns to find the seed vertex for each quadruple

- This will give an exact solution with four unscattered photons which originate from a point



- Some randomly chosen quadruplets will produce anomalous solutions due to delayed emission and effect of scattering, reflection, and dark noise

- Choose the number of quadruplets use to use reasonable computational time while having sufficient vertex resolution (see slide 17), nominal number of quadruplets used is 400.

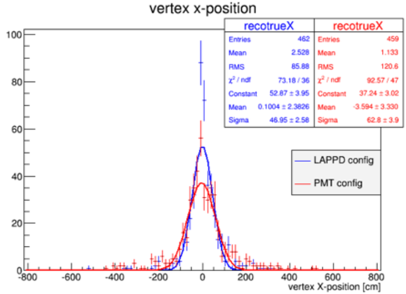
The reconstruction algorithm (2)

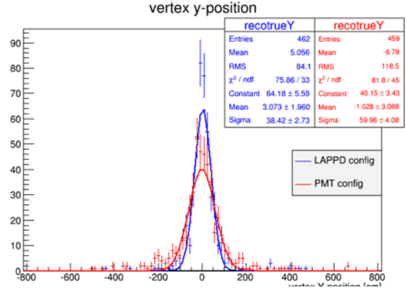
- The goodness of each vertex is tested for each vertex candidates
- The goodness of fit is determined based on the distribution of "time residual", which is difference between PMT hit time and time of flight of each photon, assuming a single effective speed of light in water $\frac{c}{n}$

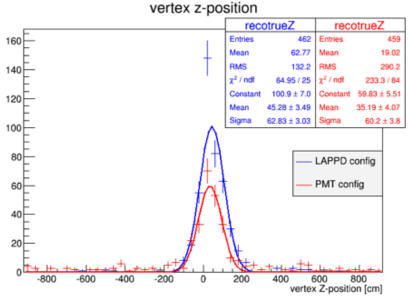
$$G(x_{reco}, t_0) = \sum \exp\left(-\frac{1}{2}(T^i_{res}/\sigma)^2\right) \qquad T^i_{res} = t^i_{hit} - t_0 - \frac{|x^i - x_{reco}|}{c/n}$$

- Choose the best vertex from the candidates by selecting the largest value of goodness of fit

Comparing different configuration of photosensors

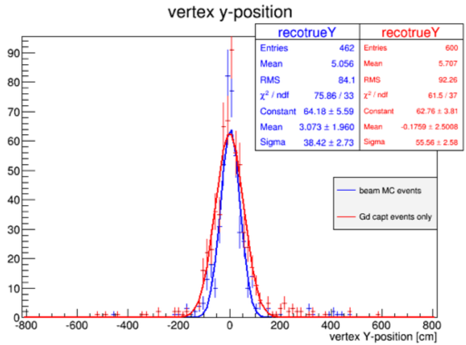


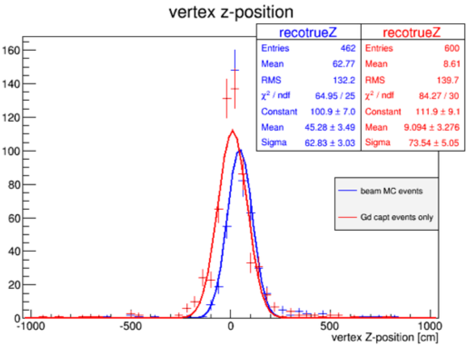




- Comparing the two configurations of photosensors
- Two config: 10” PMTs or 8”x 8” LAPPDs
- Vertex reconstruction is more sensitive in the plane transverse to the track direction

Single Gd capture events



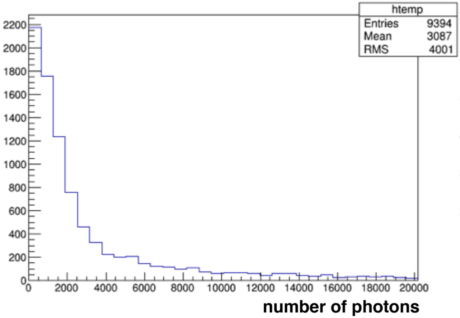


- Beam MC events: Distance between reconstructed vertex and true vertex
- Gd capture events: Distance between reconstructed vertex and neutron capture point

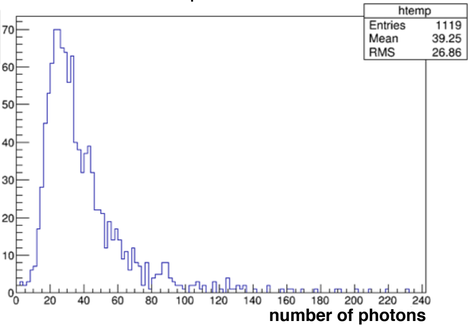
Single Gd capture events

- Some Gd capture events don't produce many photons -> don't have enough hits to reconstruct vertex

All beam MC events



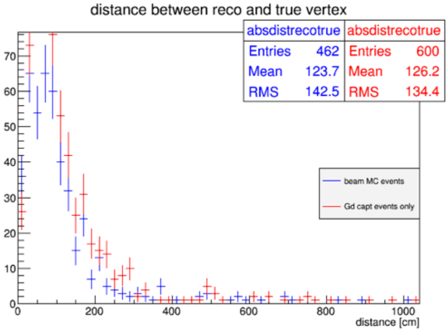
Gd capture events



Single Gd capture events

RMS [cm]	PMTs		LAPPDs	
	beam MC	Gd capt	beam MC	Gd capt
X	120.6	126.7	85.88	100.2
Y	118.5	127.4	84.1	92.26
Z	290.2	299.3	132.2	139.7

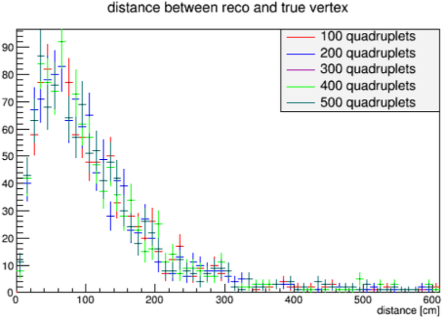
Single Gd capture events



Mean [cm]	PMTs		LAPPDs	
	beam MC	Gd capt	beam MC	Gd capt
absdist	234.1	258.7	123.7	126.2

- Vertex resolution not as good for Gd capture events (less photons to reconstruct vertex)

Number of quadruplets



- Gd capture events only: Distance between reconstructed vertex and n capture point
- Doubling the number of quadruplets increases the computational time by more than twice

Number of quadruplets	Mean [cm]
100	131.4
200	129.8
300	128.0
400	126.5
500	128.0

Number of quadruplets	Computational time [hrs]/ 500 events
100	<1
200	2.5
300	4
400	7
500	9.5

Summary

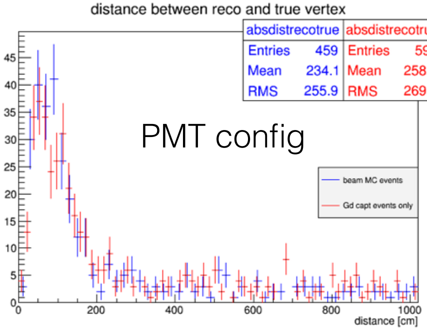
- Vertex resolution ~2 m using 10” PMTs, ~1 m for LAPPDs
- Vertex resolution not as good for Gd capture events (less photons to reconstruct vertex)-> Could use less number of quadruplets
- Ways to improve the algorithm, especially for Gd capture events
    - Look at vertex candidates near the true vertex
- Other FOM need to consider?
- Next: Directional/ Energy/ Ring /PID reconstruction

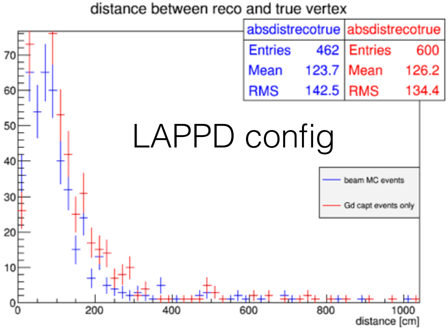
Backup

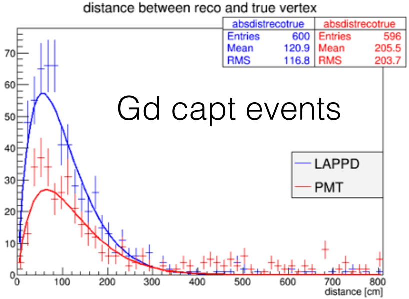
Other photosensor coverage

all with 12" PMTs	mean [cm]
2.0 ns w/o LAPPDs	124.9
2.5 ns w/o LAPPDs	130
2.5 ns w/ LAPPDs	120.6

- Testing with hybrid photosensor configurations: PMTs + LAPPDs


distance between reco and true vertex
absdistrecotrue
Entries 459
Mean 234.1
RMS 255.9
absdistrecotrue
Entries 596
Mean 258.7
RMS 269.3
PMT config
beam MC events
Gd capt events only
distance [cm]


distance between reco and true vertex
absdistrecotrue
Entries 462
Mean 123.7
RMS 142.5
absdistrecotrue
Entries 600
Mean 126.2
RMS 134.4
LAPPD config
beam MC events
Gd capt events only
distance [cm]


distance between reco and true vertex
absdistrecotrue
Entries 600
Mean 120.9
RMS 116.8
absdistrecotrue
Entries 596
Mean 205.5
RMS 203.7
Gd capt events
LAPPD
PMT
distance [cm]

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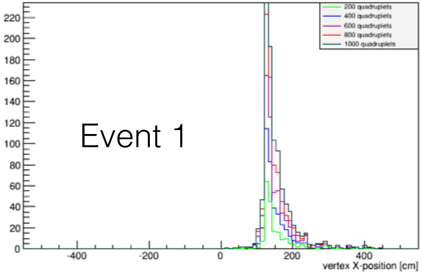
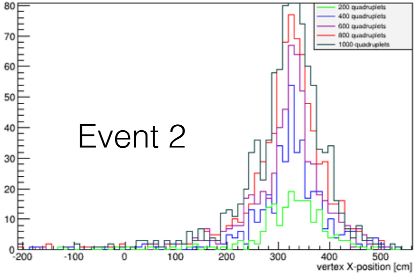
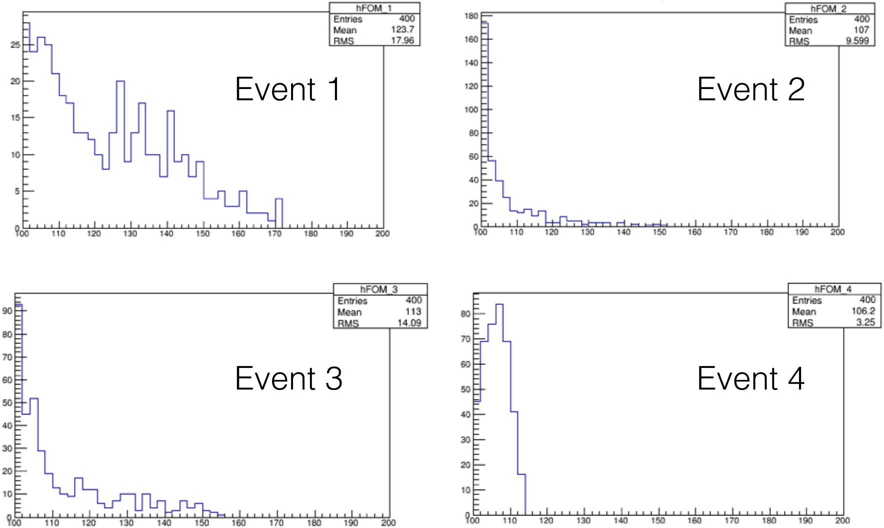
Number of quadruplets





number of quadruplets	mean [cm]
200	129.8
400	126.5
600	130.9
800	125.6
1000	126.6

Goodness distribution



Plan

- Produce selections for
  1 ring e-like, 0 neutrons
  1 ring e-like, 1 neutron
  1 ring e-like, 2 neutrons
  1 ring μ-like, 0 neutrons
  1 ring μ-like, 1 neutron
  1 ring μ-like, 2 neutrons
- For now, just focusing on CCQE selections, no neutron tagging
  1 ring e-like
  1 ring μ-like

Simulation & Reconstruction

- Length 22m, radius 5.5m, 20” PMTs, 40% coverage
- WCSim with no Gd
  →no neutron capture
- Reconstruction using fiTQun
- Need new fiTQun scattering tables for final detector size, PMT type, etc

Selection Cuts

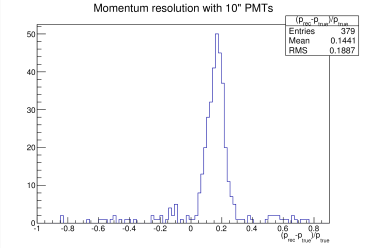
- Standard fiTQun PID cut
  - $-\ln L_e + \ln L_\mu - 0.2 p_e^{\mathrm{rec}}$
    >0 for electrons, <0 for muons
  - 1 sub event for electrons, at most 2 for muons

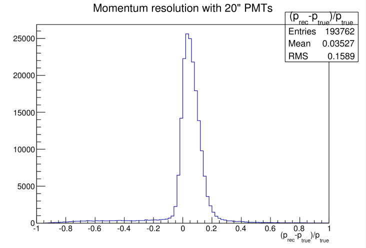
- Reconstructed vertex distance from wall

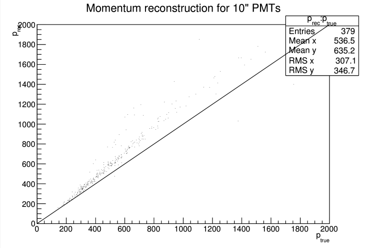
- Reconstructed distance to wall

Reconstruction

fiTQun scattering tables used 20” PMTs - worse reconstruction with 10” PMTs



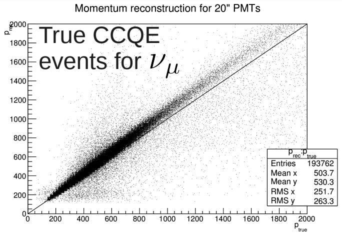


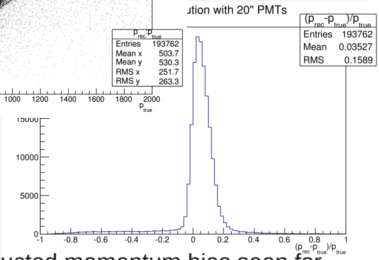


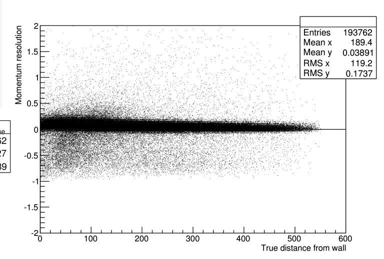
Possibly fixed by new fiTQun scattering tables or other tuning for TITUS

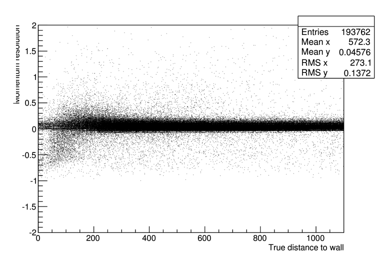
For now, use 20” PMTs

Momentum resolution – muons



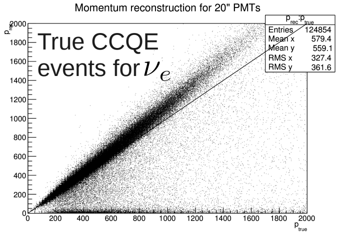


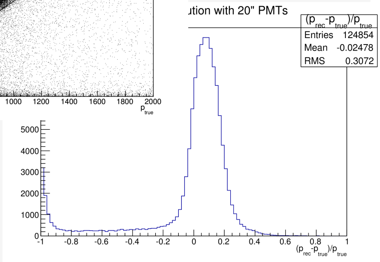


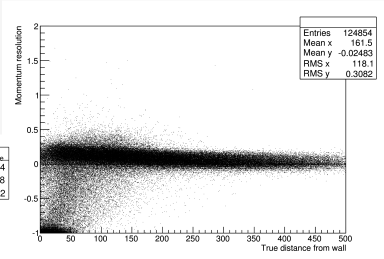


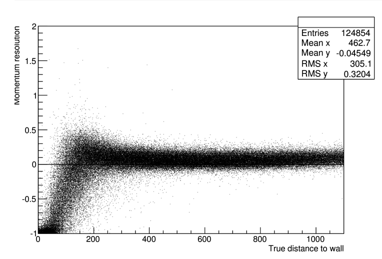
- Reconstructed momentum bias seen for true muon CCQE event in TITUS.
- Not seen for Hyper-K
- Not improved much by dwall or towall cuts
- Need fiTQun tuned for TITUS?

Momentum resolution – electrons





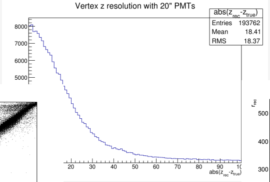


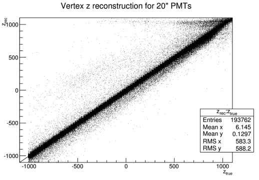


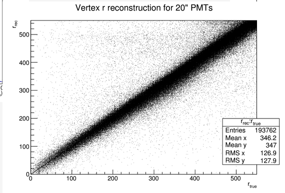
- Worse resolution again for electrons
- towall/dwall and low-E cuts partly help
- Need fiTQun tuned for TITUS?

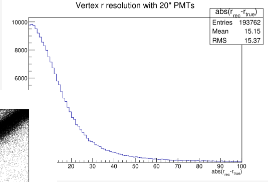
Vertex resolution - muons

New fiTQun version





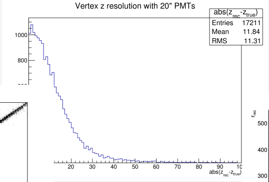


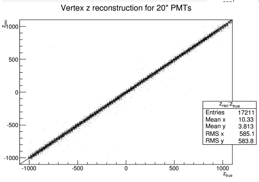


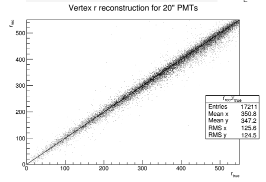
Worse vertex reconstruction for TITUS in new version

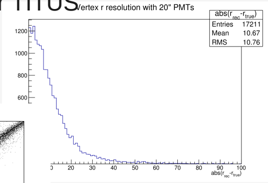
New fiTQun version fixed momentum bias for HK, doesn't for TITUS

Old fiTQun version









Next steps

- **Need better reconstruction – tune fiTQun for TITUS?**
- Need to add gadolinium and neutron capture simulation and reconstruction (WChSandbox or WCSim & fiTQun?)
- Optimize volume cuts and look at other possible variables

Preliminary π^0 studies

Wing Yan Ma
Imperial College London
TITUS Workshop
19/12/14

Outline

- π^0 particle gun with WChSandBox
- Preliminary plots:
  - Distance from π^0 decay point to photon conversion point for each photon
  - Energy of each photon
  - Angle of each photon wrt π^0 momentum direction

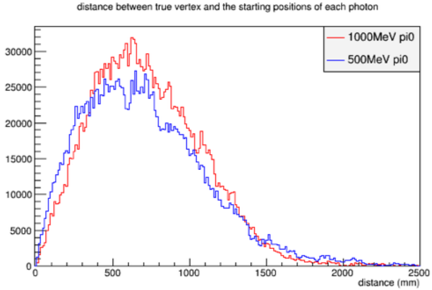
π^0 particle gun with WChSandBox

- π^0 decay to two photons, which can look e-like if one of the photons is not reconstructed; background to ν_e appearance search which is sensitive to CPV

- Other main background for ν_e appearance search is from the intrinsic ν_e component of the beam

π^0 particle gun with WChSandBox

- Distance from π^0 decay point to photon conversion point for each photon
- Distance travelled by decay products (electrons)



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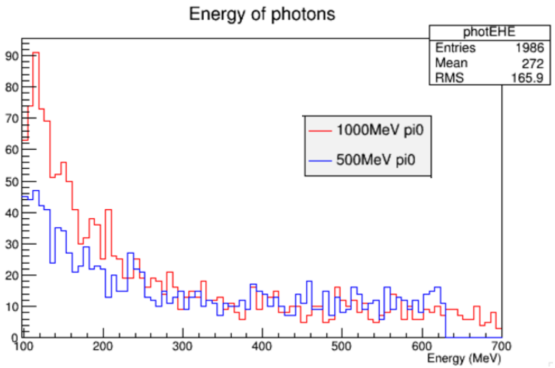
π^0 particle gun with WChSandBox

- Separating high energy photons from Cherenkov photons
- Distribution of photon energy > 100 MeV



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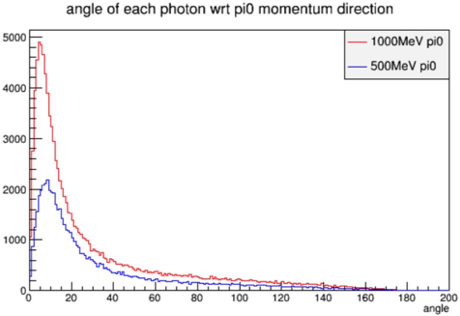
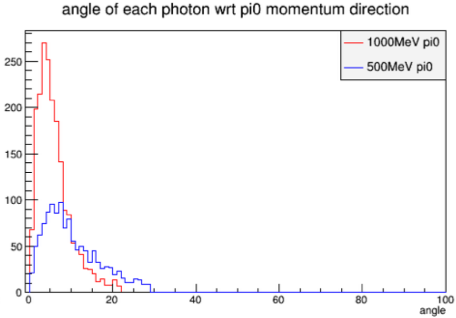
π^0 particle gun with WChSandBox



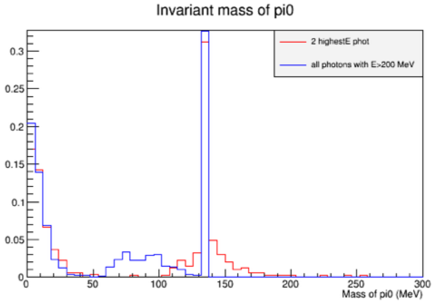
Low E

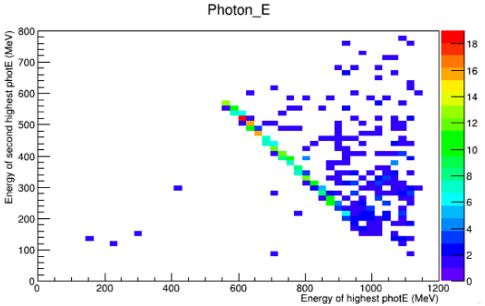


High E

6

Invariant mass of π^0





- Reconstruct invariant mass of π^0 from: 2 photons with highest energy (red), and all photons with energy > 200 MeV (blue)

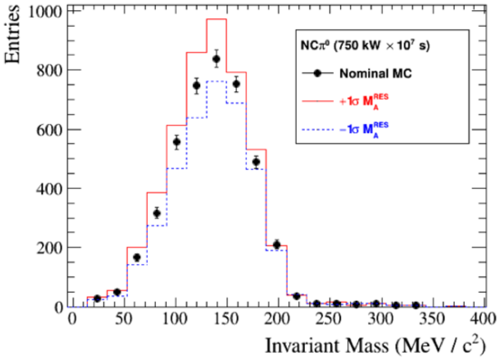
- Plot of second highest energy photon against highest energy photon.

Reconstructing π^0

- Need charge information to reconstruct photon energy (charge proportional to number of photons)
- Selection cuts on pi0:
  - 2 rings e-like (ring cut/ PID cut)
  - FV cut 200cm
- Invariant mass cut (>105 MeV): Events without a real second ring tend to have low invariant masses

π^0 invariant mass

- π^0 invariant mass plot using SK reconstruction tool
- Aim: reproduce this using WChSandBox



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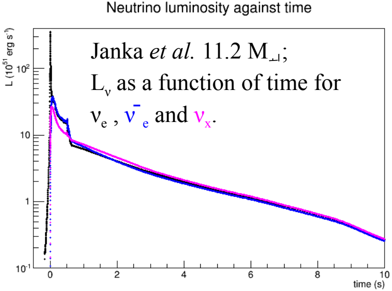
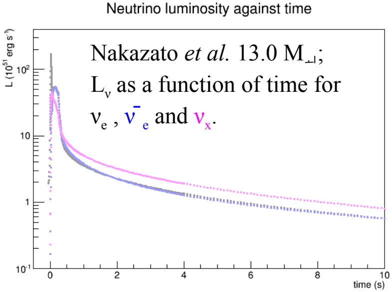
SN ν for TITUS and HK

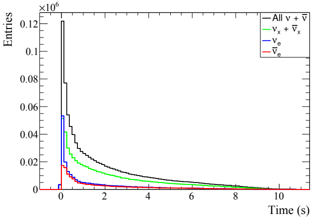
- Initial studies compared Nakazato *et al.* and Janka *et al.* model databases.
  - Both contain a range of theoretical assumptions and progenitor masses.
- For the moment pursuing the Janka *et al.* model.
  - Will return to Nakazato *et al.* model in the future.
- Looking to begin producing SN ν vectors now for TITUS and HK detectors.

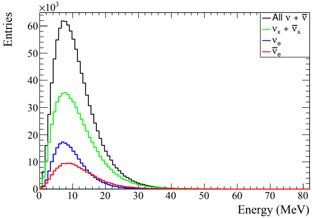


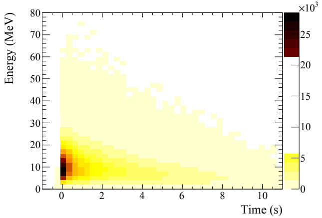


SN ν for TITUS and HK

- Have taken database inputs and produced ν flux as a function of energy, time and flavour.
  - Neutrino time and flavour are randomised within each period cover by the input tables.
- Plan moving forward is to interface our ν flux with the Generalised Neutrino Vector Generator being developed by Chris Kachulis.



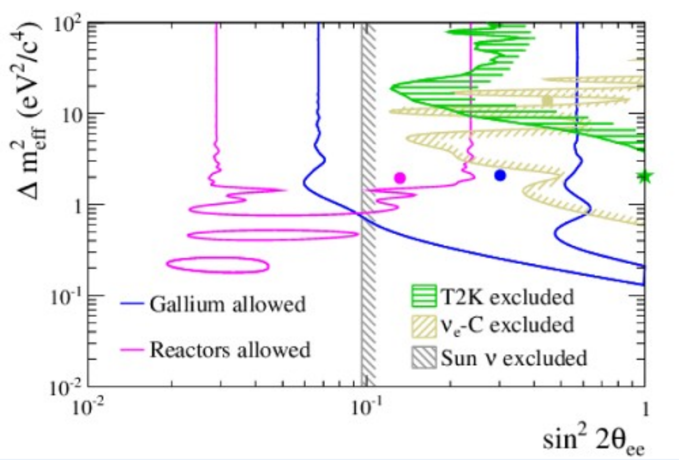




TITUS and sterile neutrinos

Sensitivity to ν_e disappearance
3+1 model

T2K ν_e disappearance



http://arxiv.org/abs/1410.8811

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Sterile in TITUS

- In the case of TITUS, a sterile neutrino could manifest by disappearance of ν_e.
- Survival probability is given by:

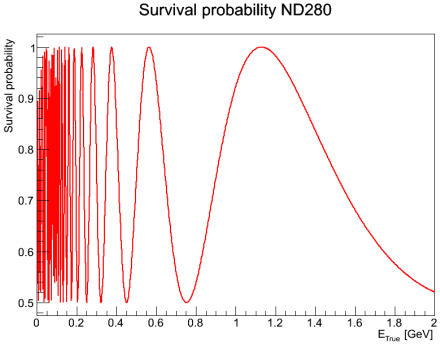
$$P_{surv} = 1 - \sin^2 2\theta_{ee} \cdot \sin^2 \left(\frac{1.267 \Delta m^2_{41} L_\nu}{E} \frac{GeV}{eV^2 km} \right)$$

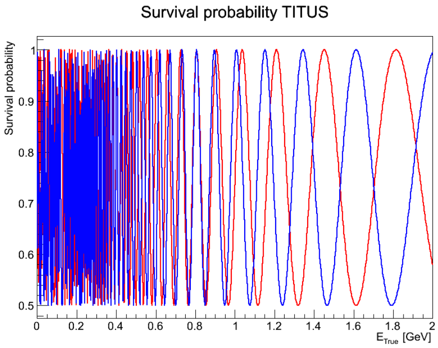
ND280/TITUS

ND280 neutrino flight path = 0.28 km,

TITUS in blue flight path = 2 km,

TITUS in red flight path = 1.8 km





3+1 model with $\sin^2(2\theta) = 0.5$, $\Delta m^2_{41} = 10\ \text{eV}^2$

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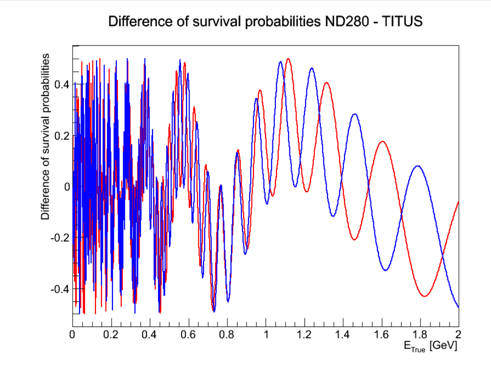
Difference P_{surv}(@ND280) - P_{surv}(@TITUS)



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TITUS in red flight path = 1.8 km

3+1 model with $\sin^2(2\theta) = 0.5$, $\Delta m^2_{41} = 10\ \mathrm{eV}^2$

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TITUS is...

- Length = 22m
- Radius = 5.5m
- At 2km
- 40% coverage of 20PMTs
- 0% LAPPD
- no Gd
- No SMRD for the mu-PiD

Cuts for the electron sample (SK-like)

From the output of fiTQun:

- 1 “CCQE-like” subevent (1 track),
- PiD electron-like
- Momentum higher than 60MeV
- Pi0 rejected
- FV cut: r < 450cm and |z| < 1000cm

Likelihood definition

$$-2\log L_{\nu_e}(\sin^2 2\theta, \Delta m^2, \vec{f}) = 2\sum_{i=0}^{31}\left(n_{\text{exp}}^{\nu_e,i} - n_{\text{data}}^{\nu_e,i} + n_{\text{data}}^{\nu_e,i} \times \log\left(\frac{n_{\text{data}}^{\nu_e,i}}{n_{\text{exp}}^{\nu_e,i}}\right)\right) + (\vec{f}-\vec{f}_0)^T V^{-1}(\vec{f}-\vec{f}_0)$$

- Likelihood (+ penalty term for the systematics)
- Calculated from the reconstructed energy:

$$E_{Rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e\cos\theta_e)}$$

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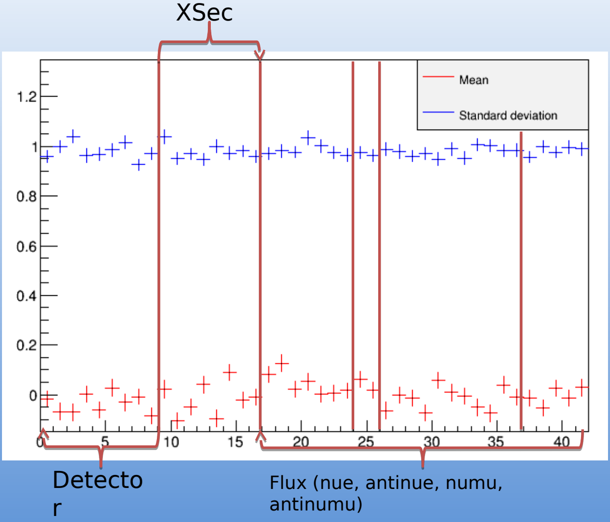
Fit validation



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Back up

Systematics 1/3

- Detector systematics:
  - SK-like (TN157)

Type	Standard deviation
Nue CC single electron	0.031
Nue CC other	0.141
Numu CC	1.259
Numu CC 1pi0 other	0.30
NC gamma	0.017
NC 1pi0	0.242
NC 1pi0 other	1.001
NC 1pi+/-	1.729
NC other	1.733

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Systematics 2/3

- Cross section systematics:
  - TN108
  - Only “normalisation factors”
- List:
  - CCQE (3), CC 1pi res (2), CC Coh (1), NC other (1), NC 1pi0(1)

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Systematics 3/3

- Flux systematics
  - Assuming ND280 ▭ TN166
- 25 in total:
  - numu (11), nue (7), numubar (5), nuebar(2)

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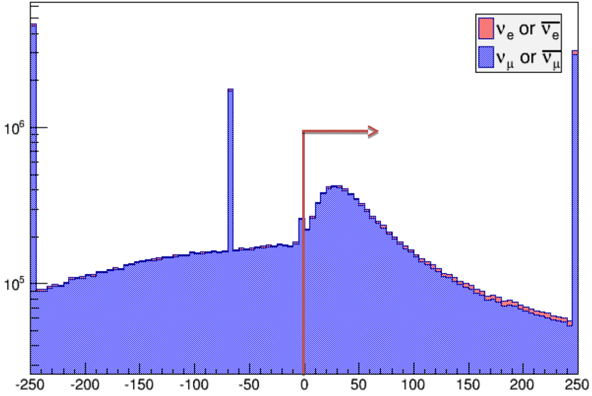
Cuts: Electron-like PID



PiD (m_llhd – e_llhd + 0.2 mom_m)

Purity:
0.03 – 0.04

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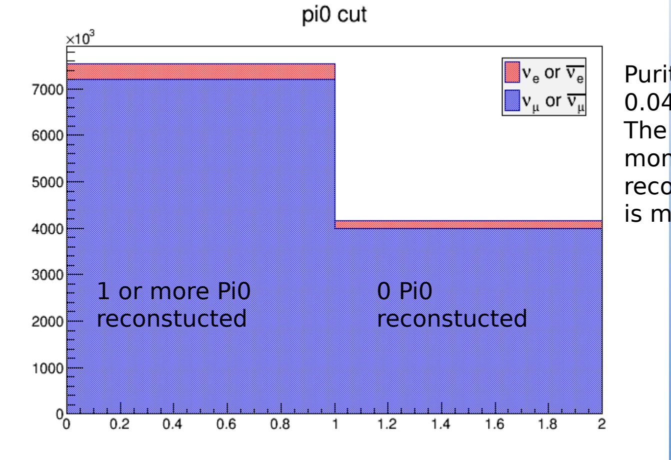
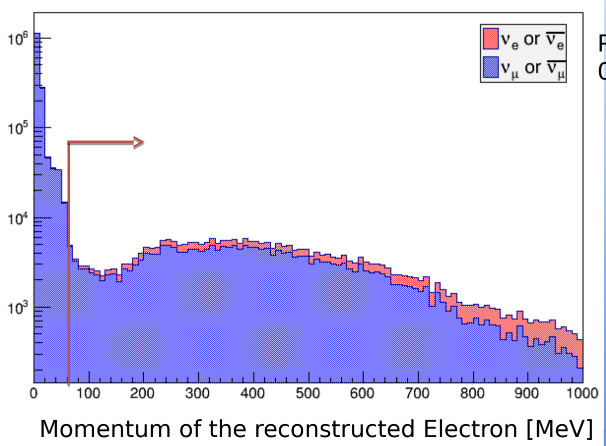
Cuts: Pi0 rejection



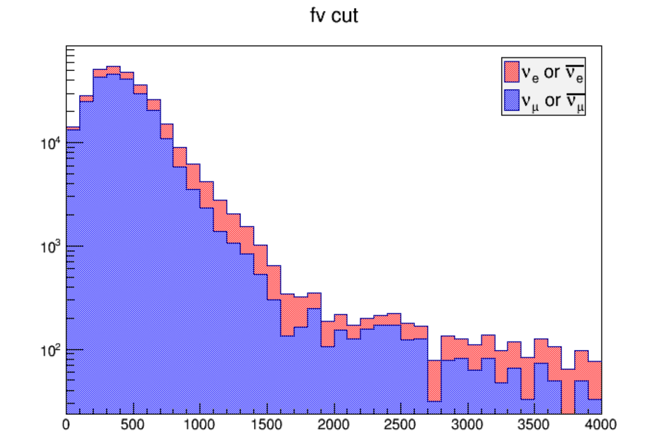
Purity:
0.042 ▭ 0.040
The momentum reconstruction is much better

Cuts: FV



Purity:
0.049 0.19

Final selection



Momentum of the reconstructed Electron [MeV]

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ND280/TITUS

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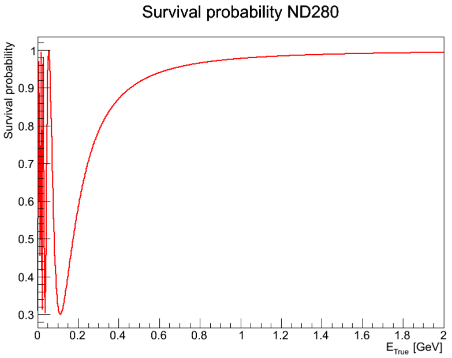

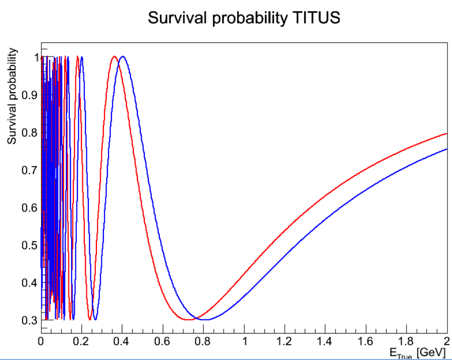

3+1 model with $\sin^2(2\theta) = 0.7$, $\Delta m^2_{41} = 0.5\ \mathrm{eV}^2$

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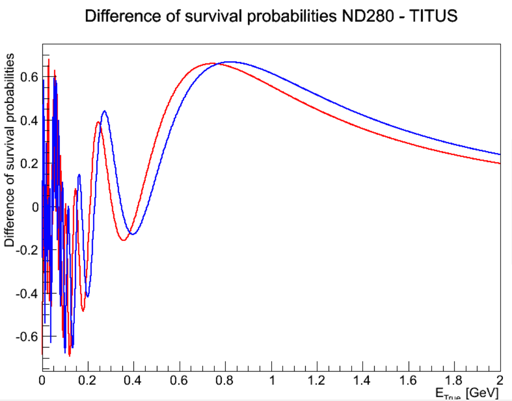
Difference P_{surv}(@ND280) - P_{surv}(@TITUS)



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TITUS in red flight path = 1.8 km

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

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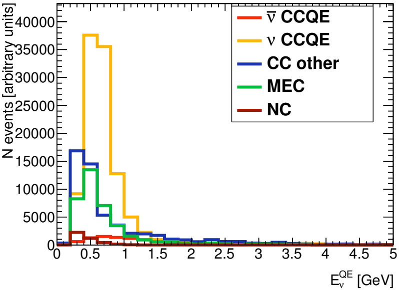
Toys

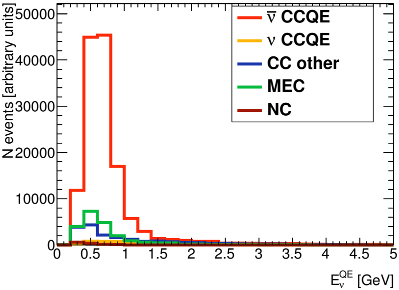
- To get the toys:
  - The covariance matrices from the systematics diagonalized
  - Some systematic parameters thrown in the non correlated basis
  - The matrix in the correlated basis is recovered ($M_{corr} = V \times M_{non\ corr} \times V^{-1}$)
  - The reconstructed energy histogram is filled according to the oscillation parameters and the systematics
    - If a bin is negative ⇒ throw another toy
  - A bin by bin Poisson fluctuation is added on top of that

1Rmu neutron selection in TITUS

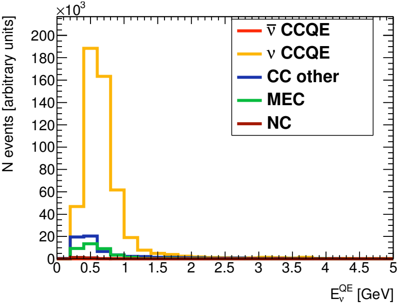
FHC with tagged neutron



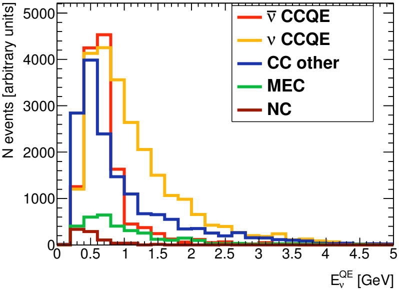
RHC with tagged neutron



FHC without neutron



RHC without neutron



1Rmu neutron selection in TITUS

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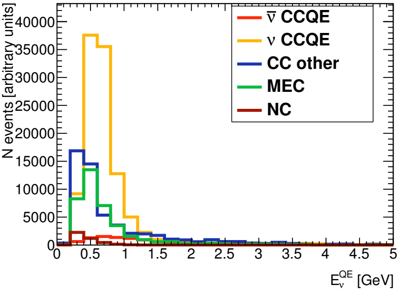
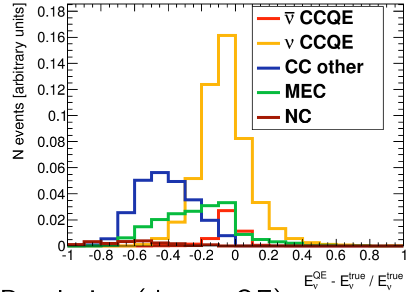
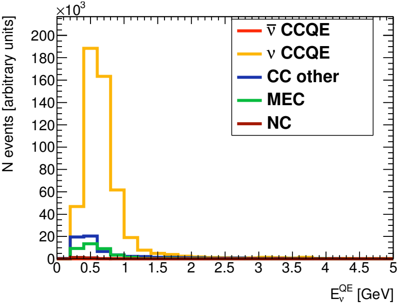


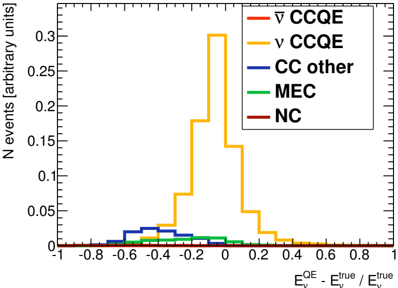
Resolution (due to QE)



FHC without neutron

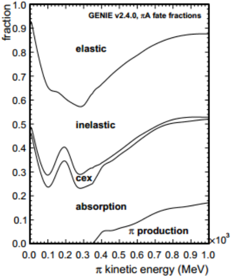


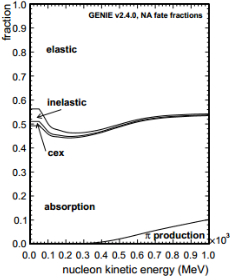
Resolution (due to QE)



Nucleon FSI Uncertainties

- Effectiveness of neutron tagging depends on precision of FSI model.
- Nucleon FSI uncertainties missing from 2012 NIWG model.
- GENIE provides tools for estimating FSI uncertainties.
- Nucleon interactions simulated:
  - Mean Free Path (MFP_N) [20%]
  - Elastic Scattering (FrElas_N) [30%]
  - Multi-nucleon KO (FrAbs_N) [20%]
  - Inelastic scattering (FrInel_N) [40%]
  - Pion Production (FrInel_pi) [20%]
  - Charge exchange (FrCEx_N) [50%]





Effect of FSI Uncertainties