TITUS:
Introduction to Gd-based Analysis

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

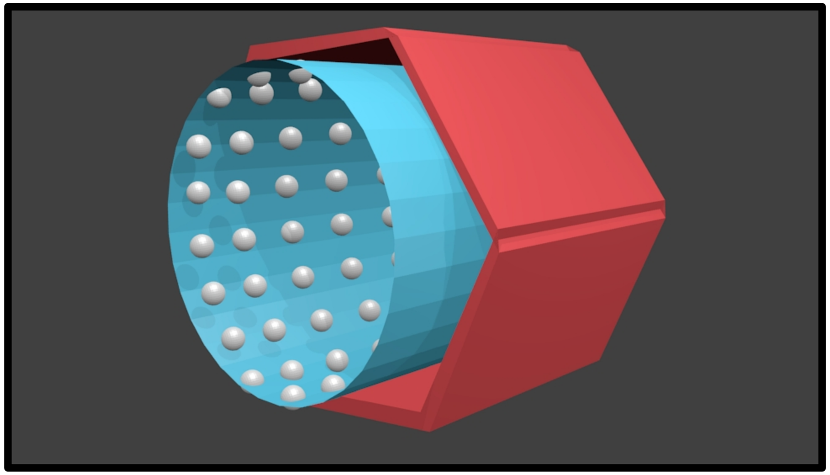
Outline

- **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

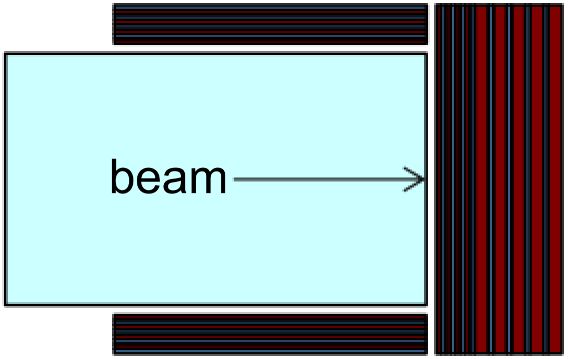


- Proposed new near detector for HK beam programme
- To be located ~2 km from J-PARC neutrino beam

- 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)

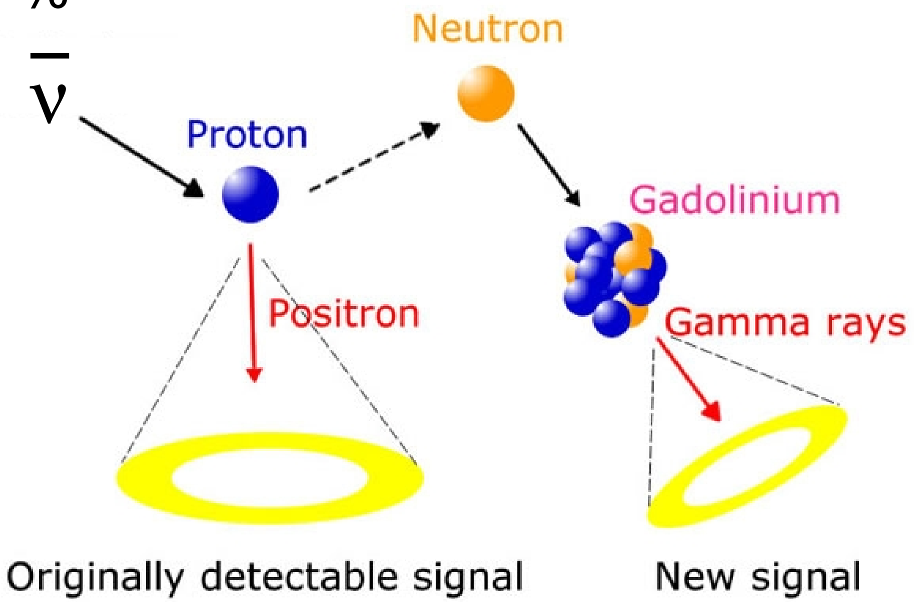
- Future possible add-ons / upgrades include:
  - Water-based liquid scintillator
  - ??? (New ideas welcome!)



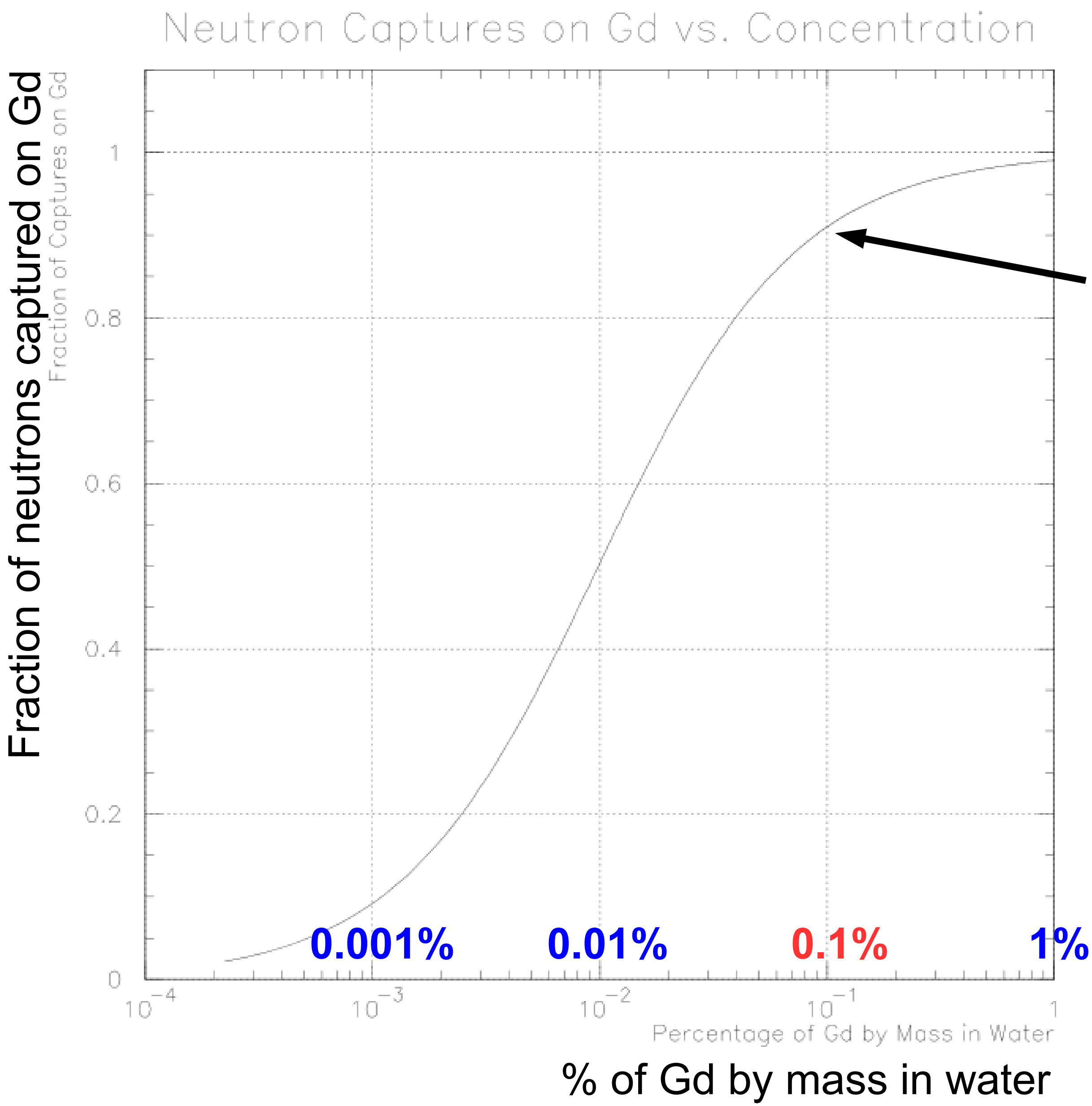
Gadolinium Doping

- **CCQE for ν:** ν + n → l^- + p (p is "invisible")

  CCQE for $\bar{\nu}$: $\bar{\nu}$ + p → 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

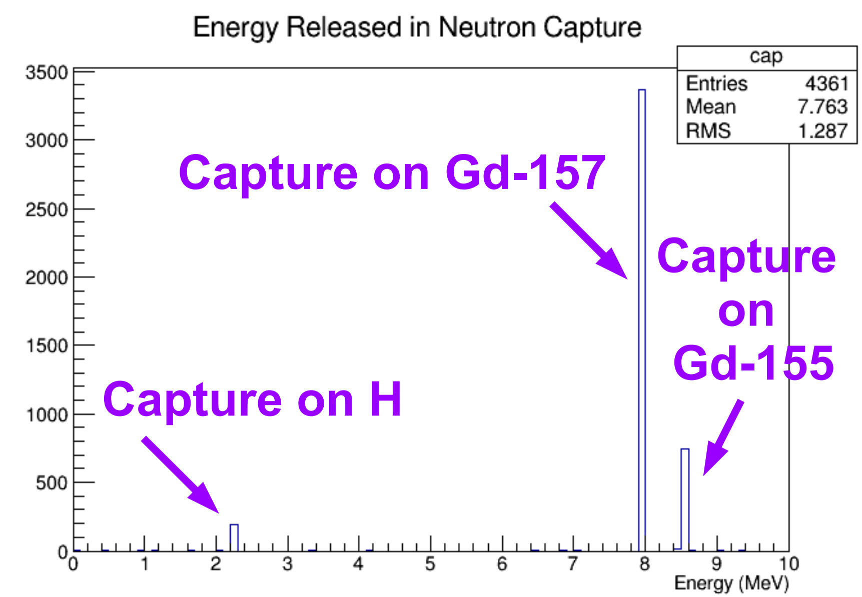


Cross-section for neutron capture is:

- ~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

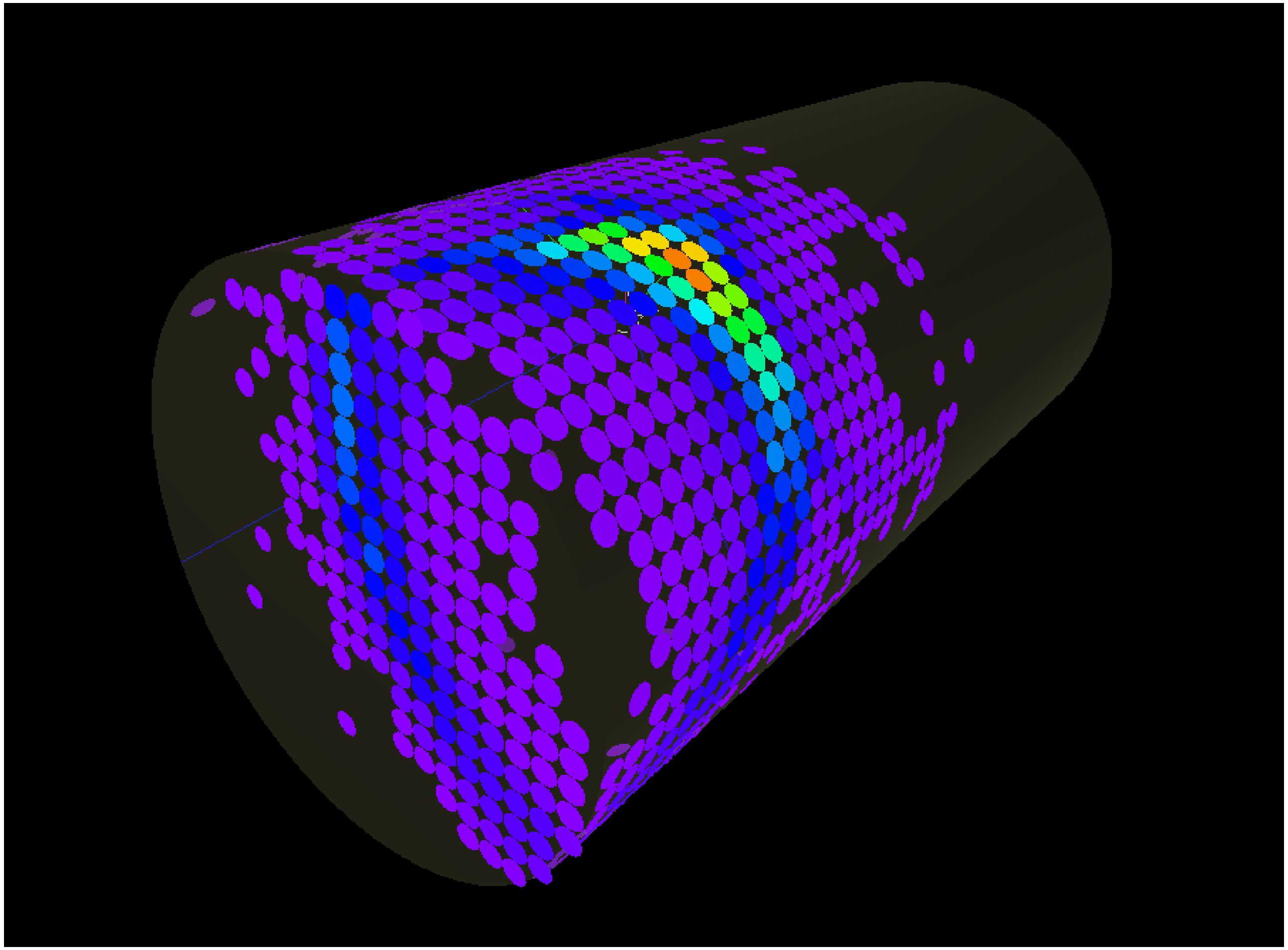
- Neutron capture can be used to separate CCQE from CC MEC and CC Other, to enhance purity of CCQE in CC0π sample:
  - ν_μ CCQE: 0 neutrons
  - ν_μ CC MEC: 0.2 neutrons (average): $\nu_\mu + (n\text{-}n) \rightarrow \mu^- + p + n$
  - $\bar{\nu}_\mu$ CCQE: 1 neutron
  - $\bar{\nu}_\mu$ CC MEC: 1.8 neutrons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

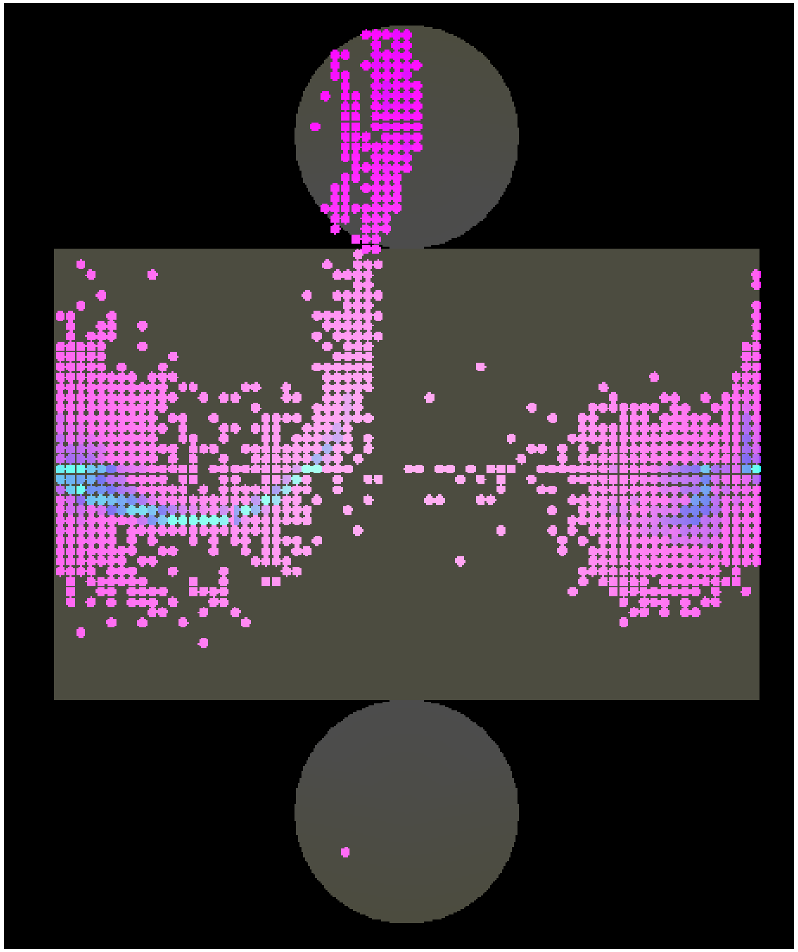
TITUS Physics Programme

- 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!



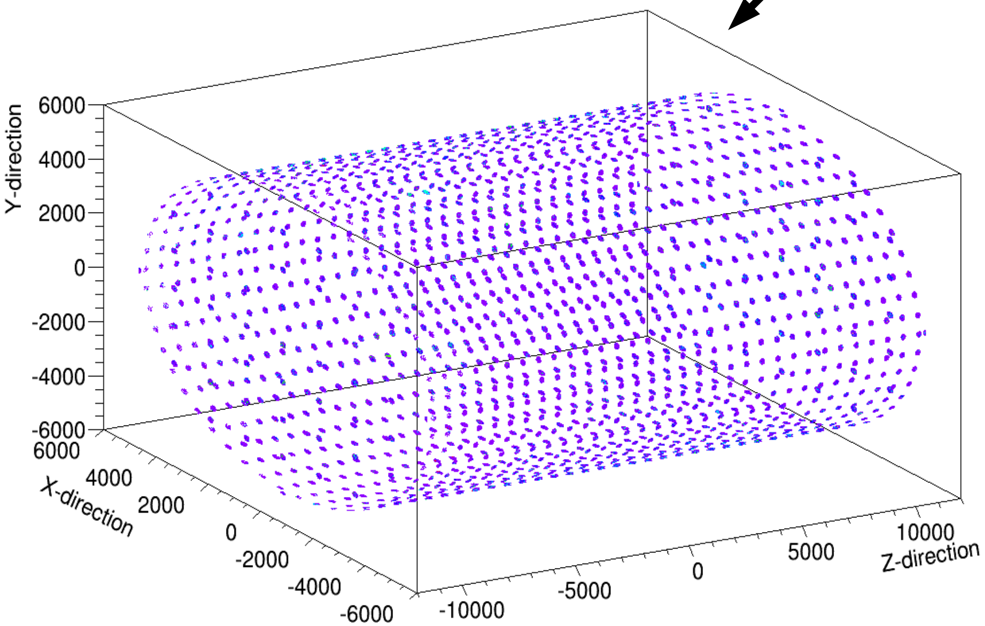


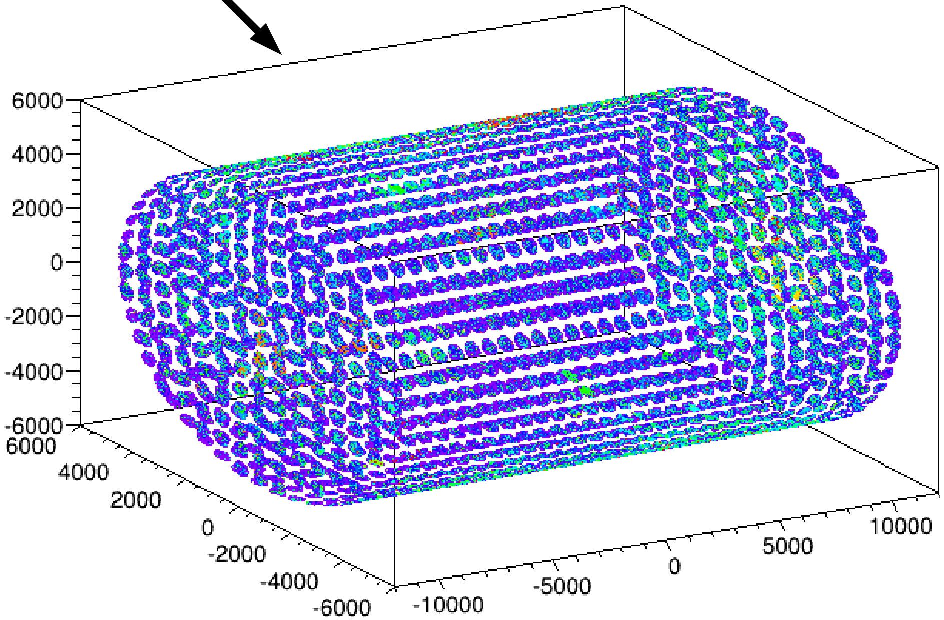
Event Display by A. Finch

CCQE (1Rμ)

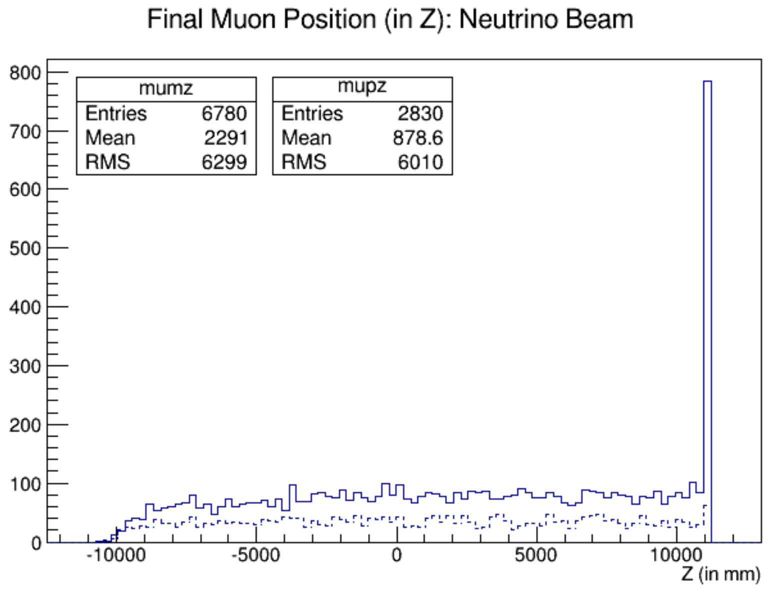
TITUS Reconstruction

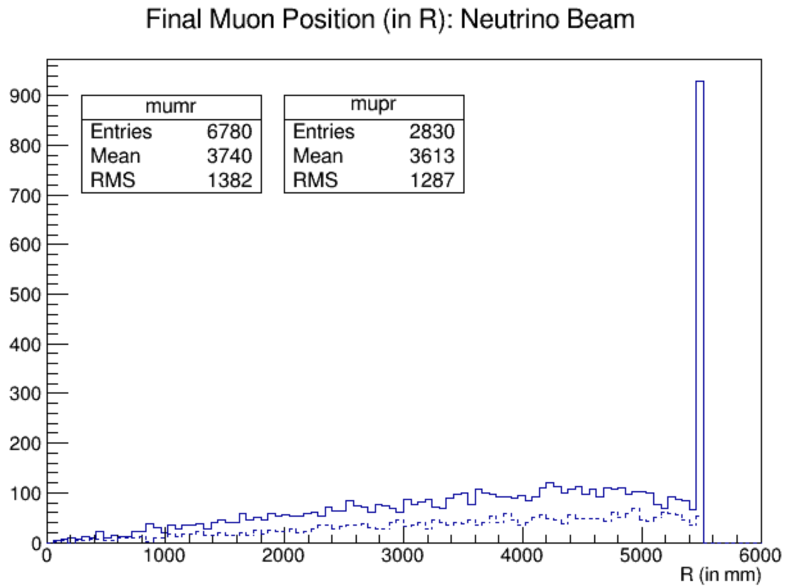
- Reconstruction:
  - Current “pseudo-reconstruction” uses smearing tables based on “fiTQun”
    - Pattern-of-light fit currently being developed for SK, T2K, HK
  - Development of both high-E and low-E (< 20 MeV) reconstruction algorithms
  - Photosensor optimisation currently underway:
    - **Six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





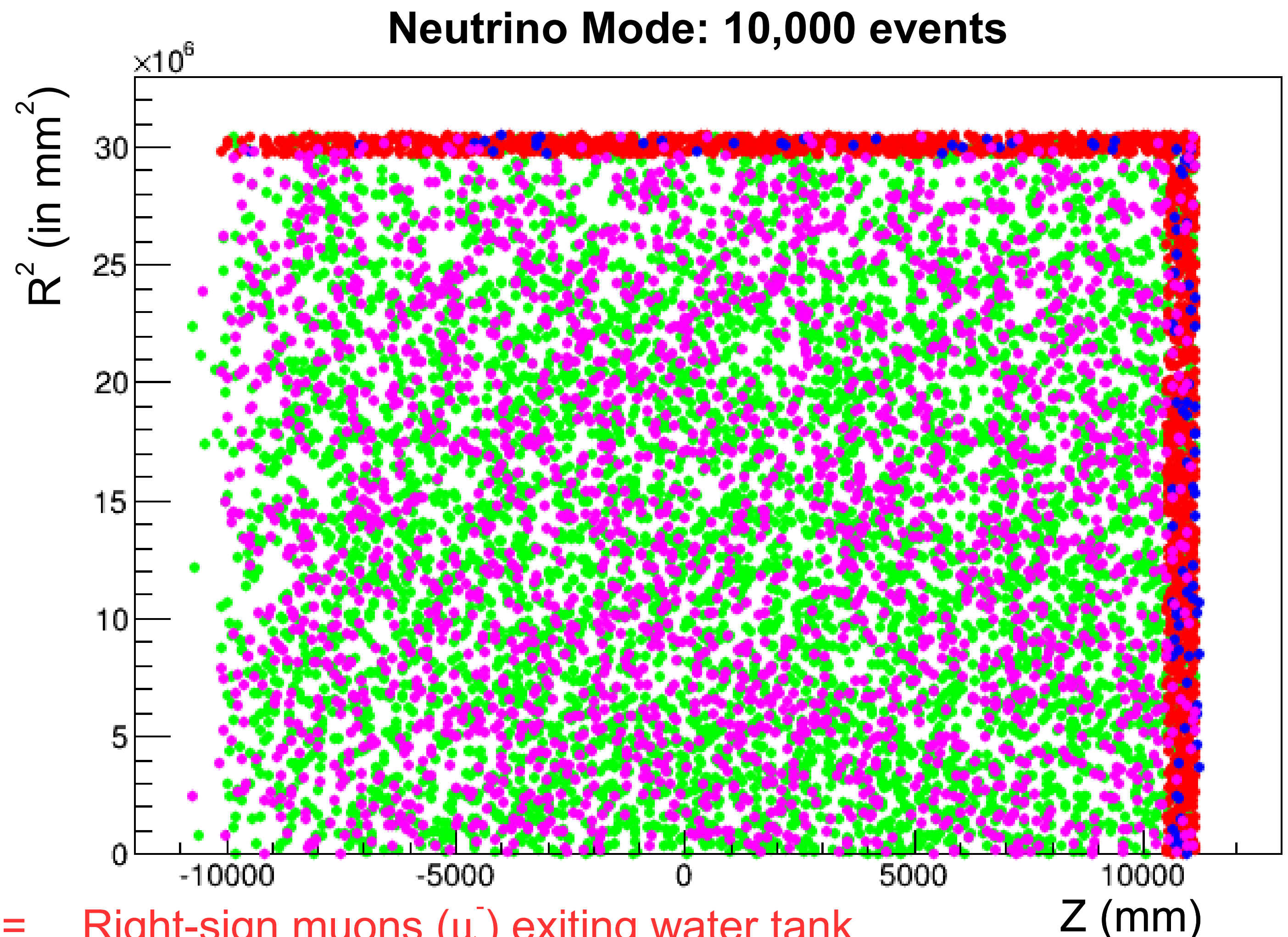
WC + MRD





- 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

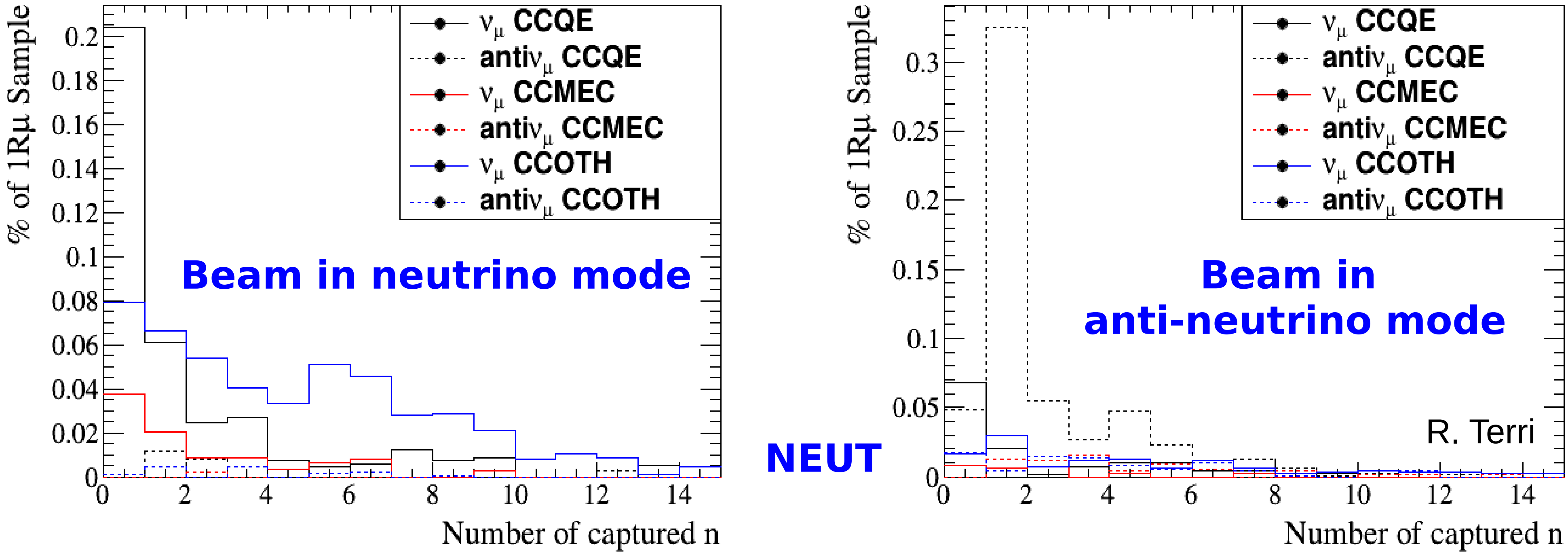
Red = Right-sign muons (μ^-) exiting water tank

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



- Studies of neutron capture demonstrate the power that gadolinium-doping adds to TITUS
- Ingredients in these figures:
  - 90% of neutrons capture on Gd
  - Neutrons from secondary interactions are included
- Clear differences can be seen between ν_μ and $\bar{\nu}_\mu$; backgrounds from CC MEC and CC Other are reduced
- Enhanced sample purities:
  - ν_μ CCQE: 37% → **63%** with n = 0 requirement
  - $\bar{\nu}_\mu$ CCQE: 55% → **82%** with n = 1 requirement

Neutron Multiplicity

NEUT

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%

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

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 NCπ^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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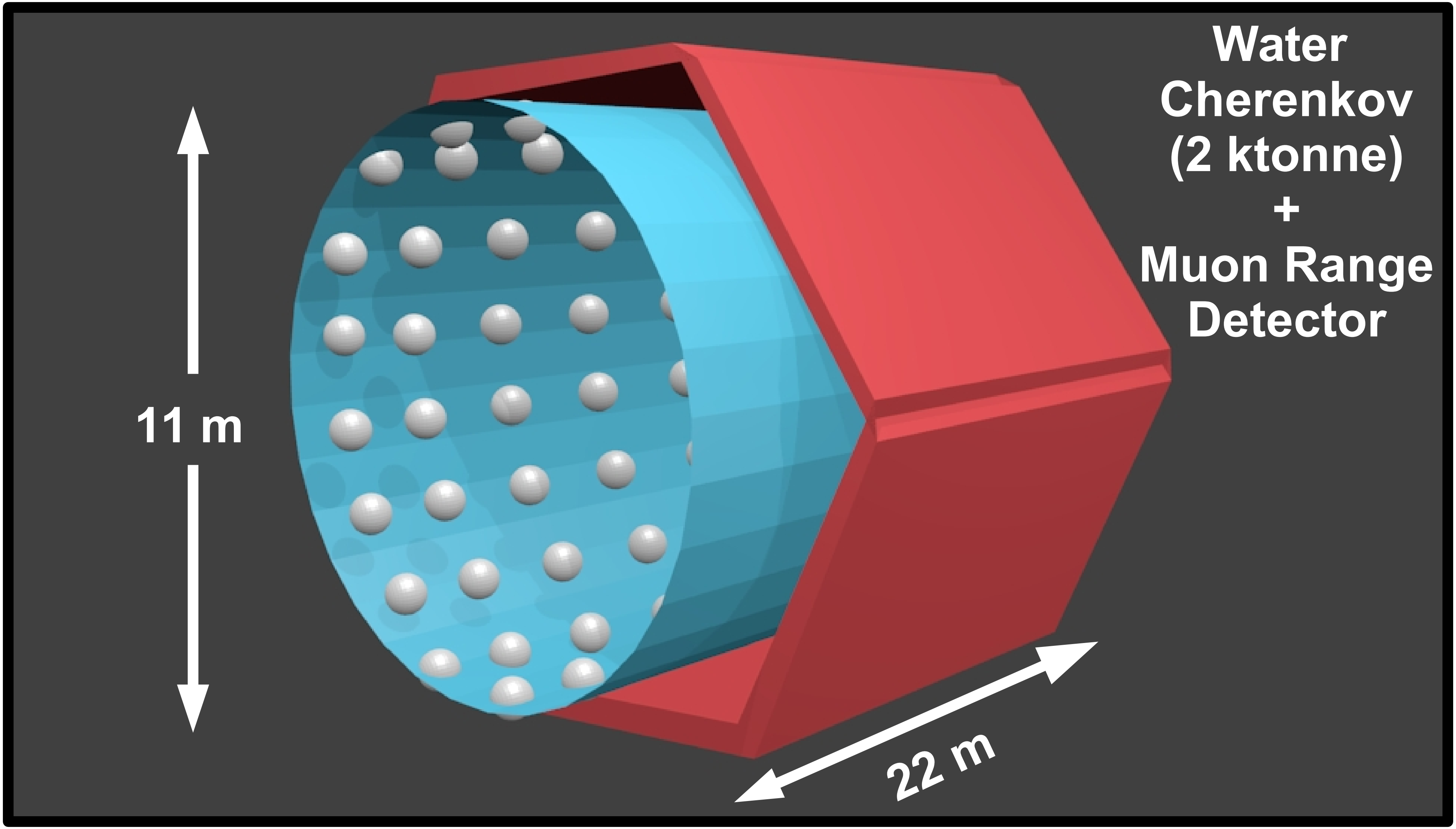
Much work to be done!

Many people getting involved recently...

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

BACK-UP SLIDES

TITUS



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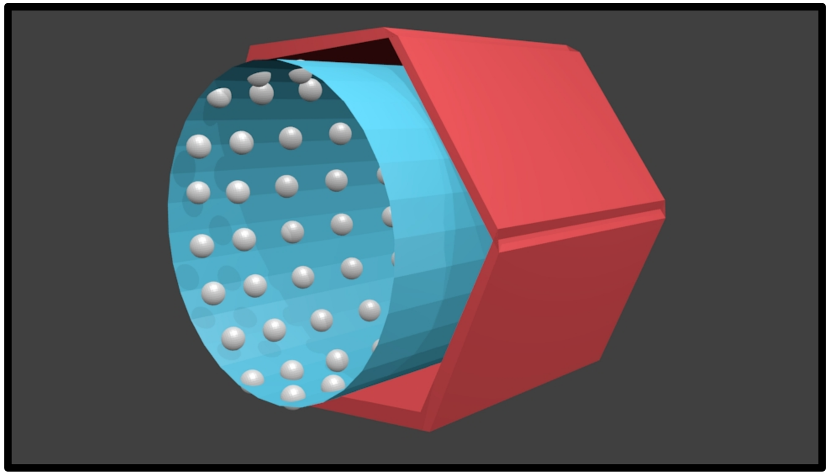

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- Baseline design includes:
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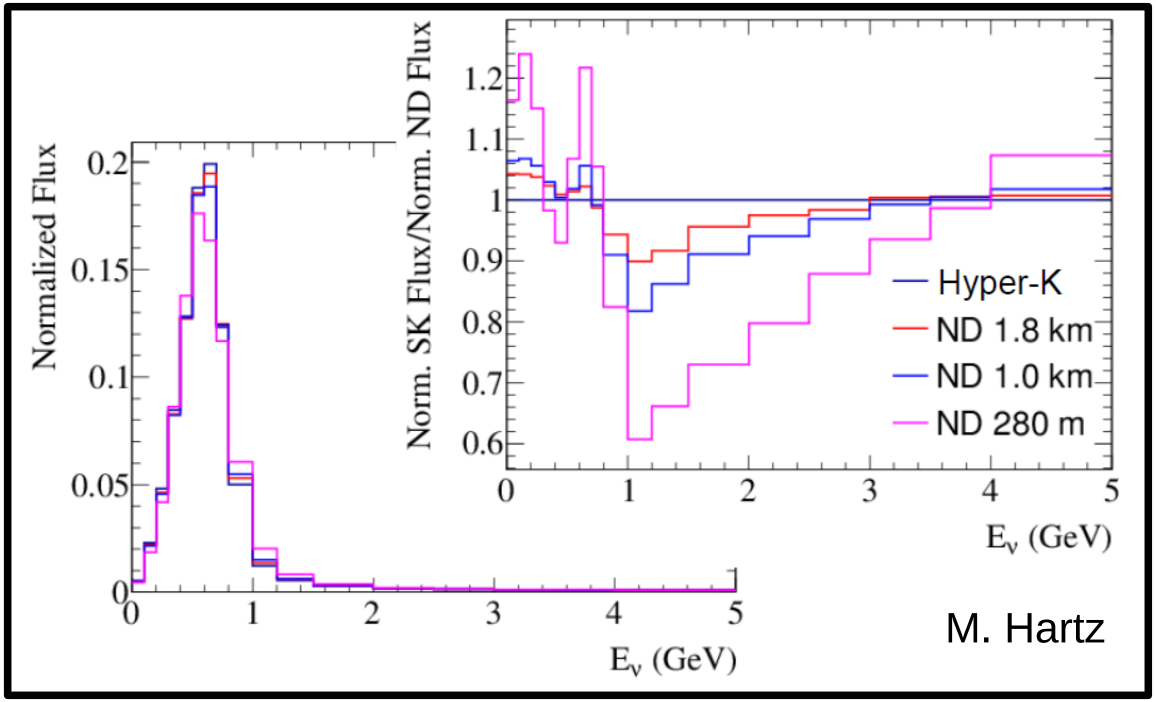
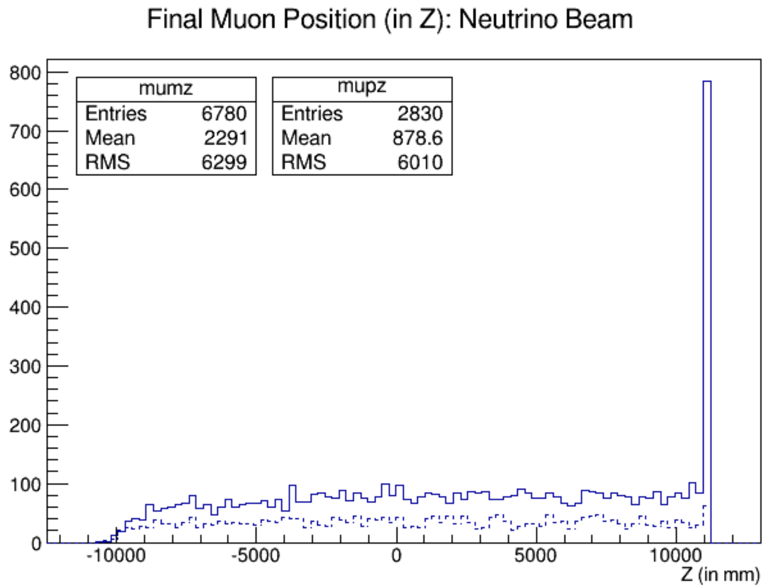
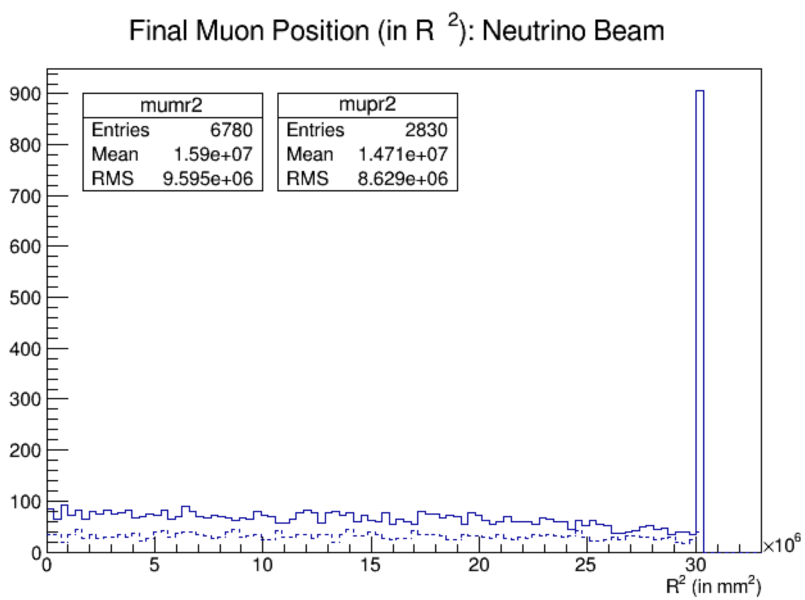
  - Partly enclosed by Muon Range Detector

- 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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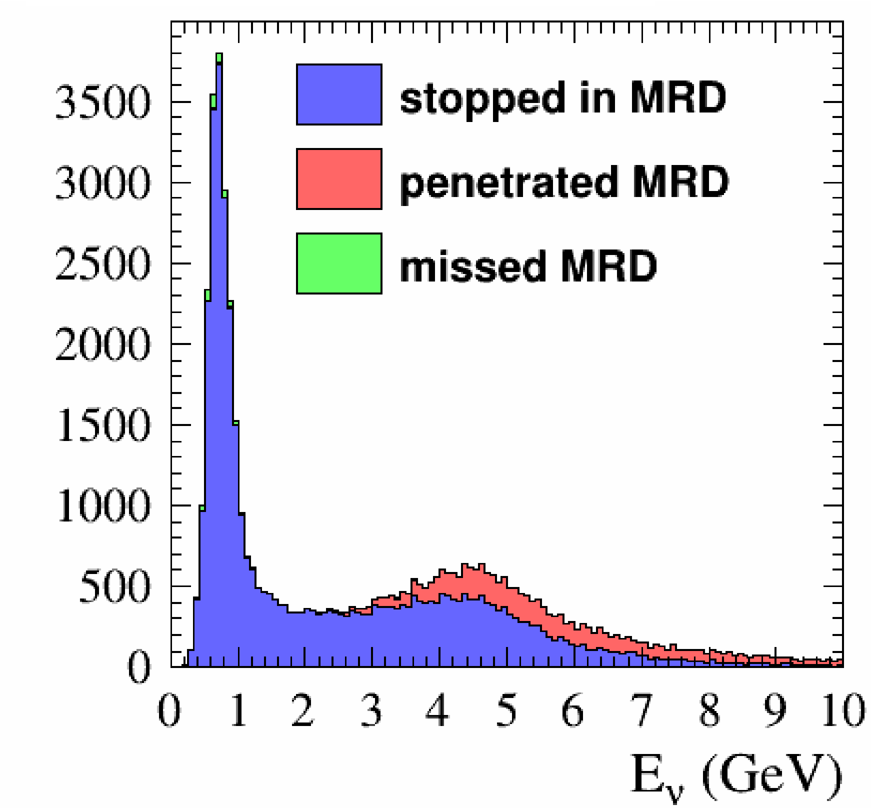
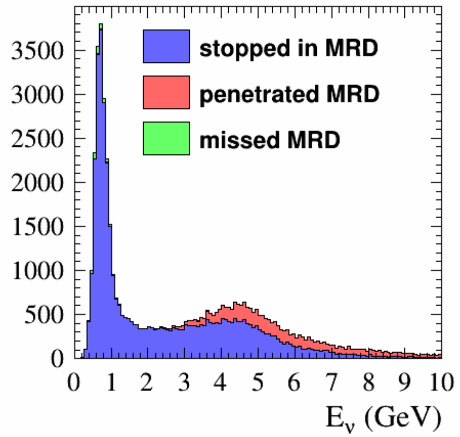
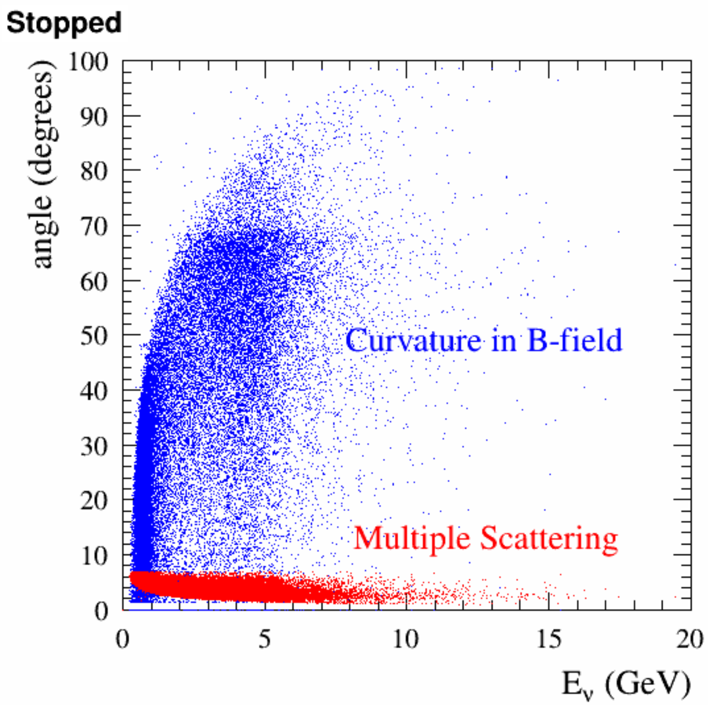
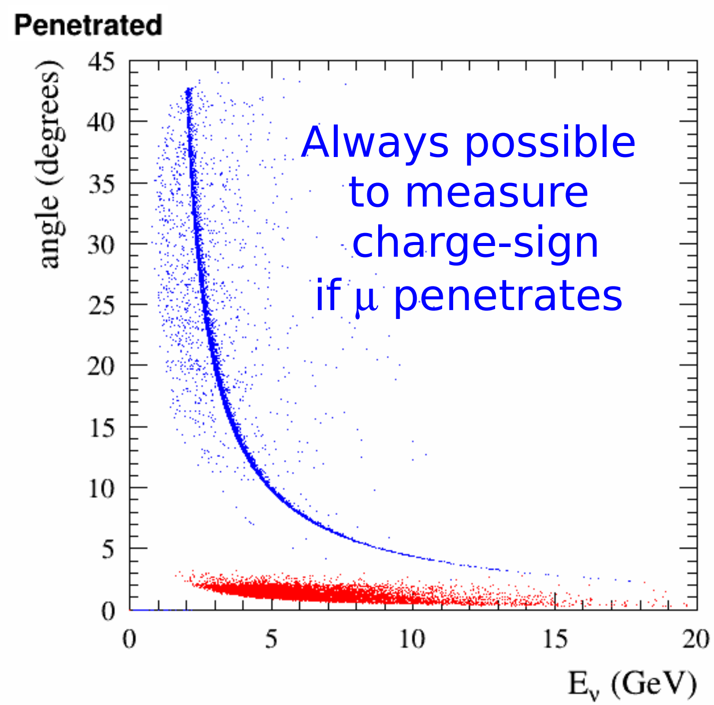


Magnetizing the MRD

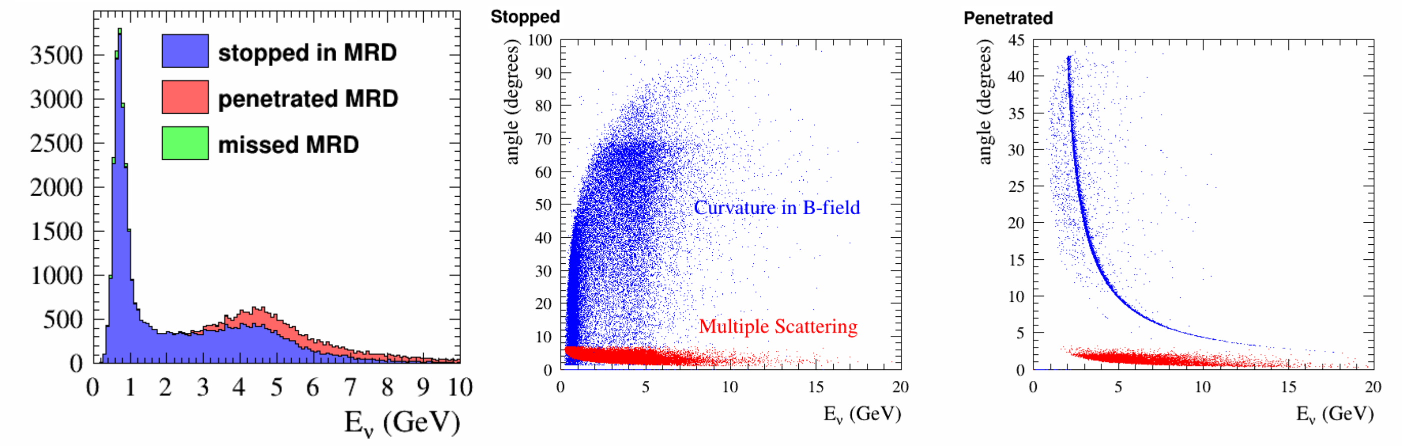


- A 1.5 Tesla magnetic field enables:
  - Momentum reco. for μ that penetrate MRD (magnitude of curvature)
  - Charge-sign reconstruction (direction of curvature)
- For μ that stop in MRD, multiple scattering may inhibit curvature measurement
- For μ that penetrate MRD, always possible to separate curvature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





PID with MRD



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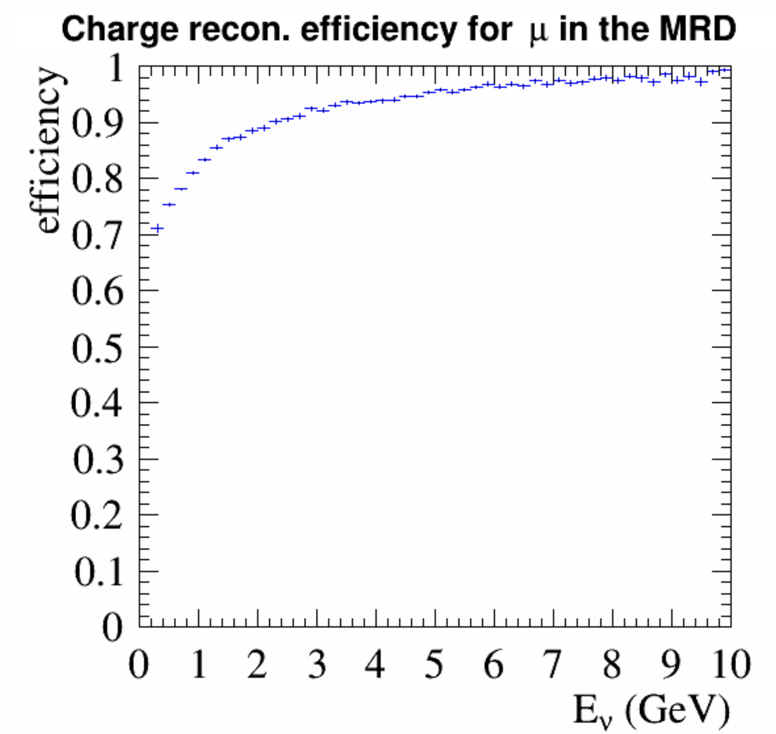

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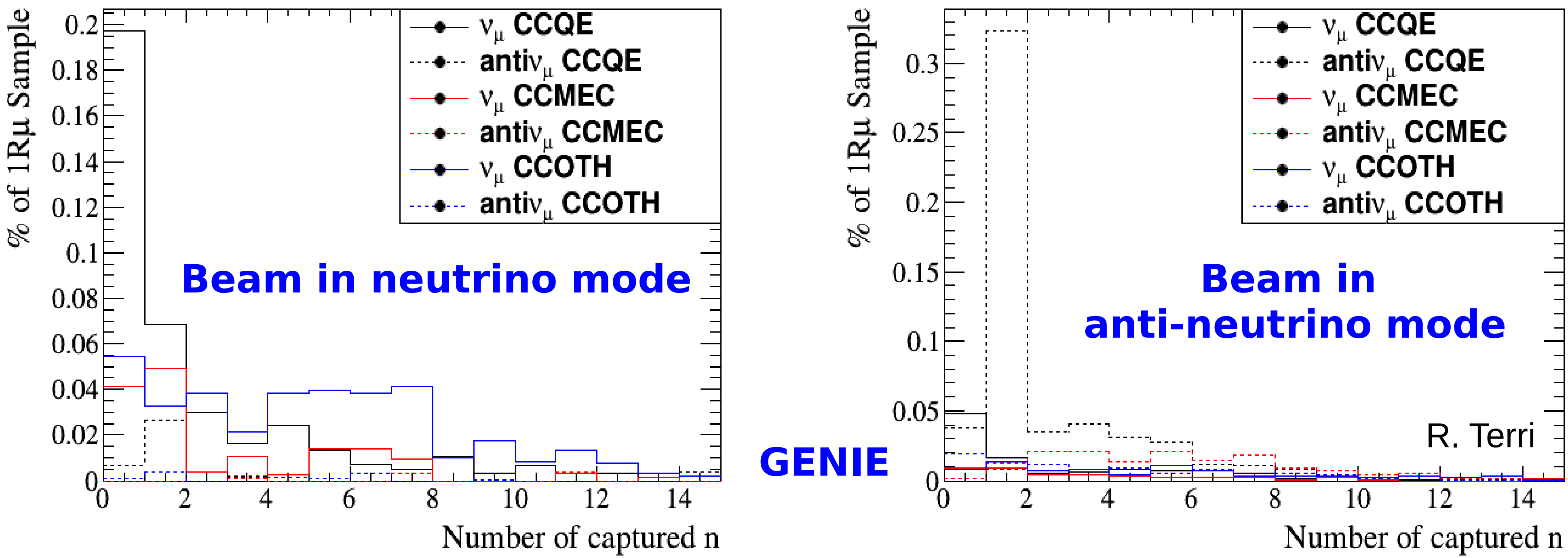

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