TITUS:
An Intermediate-Baseline Detector for the Hyper-Kamiokande Neutrino Beam

Matthew Malek
Imperial College London

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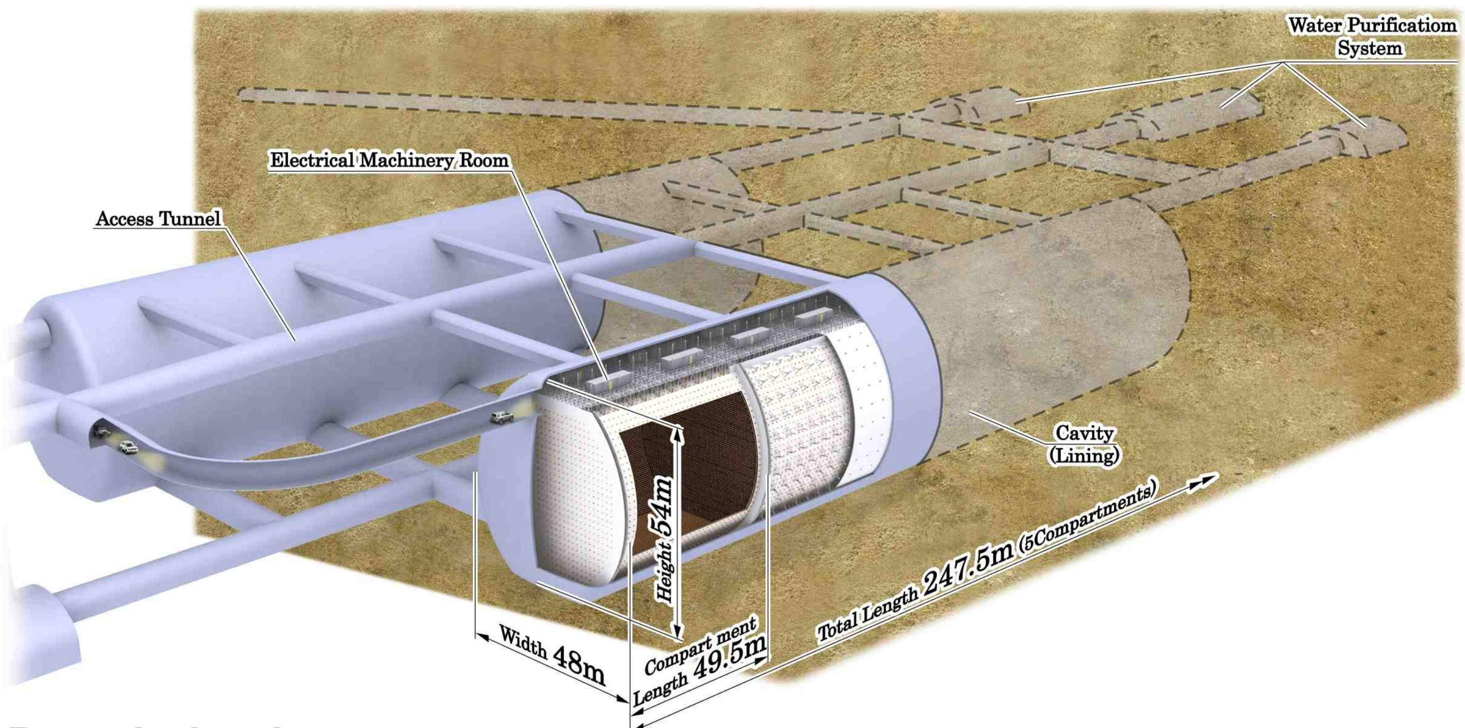
Outline

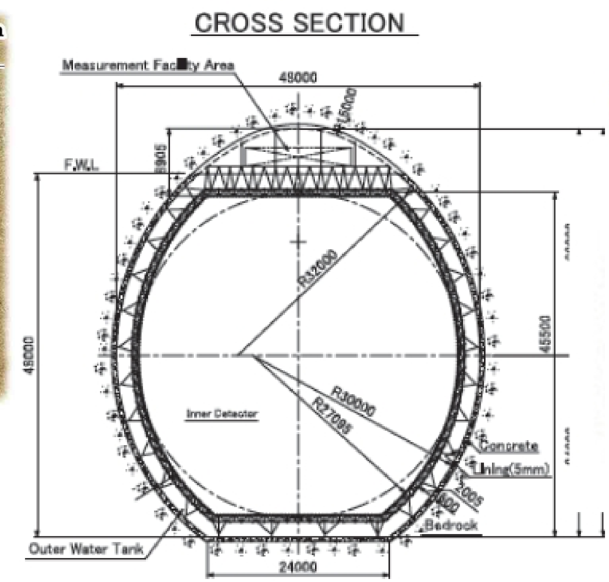
- **TITUS**: The **T**okai **I**ntermediate **T**ank w/ **U**noscillated **S**pectrum
  - Detector description
  - Physics potential
- Software development: Simulation & Reconstruction
- Synergy with MRD
- Current status:
  - $NC\pi^0$
  - Neutron multiplicity
- Future work

Titus Flavius:
Emperor of Rome (79 – 81)

Titus Andronicus:
Royal Shakespeare Company (2013)

Hyper-K Overview





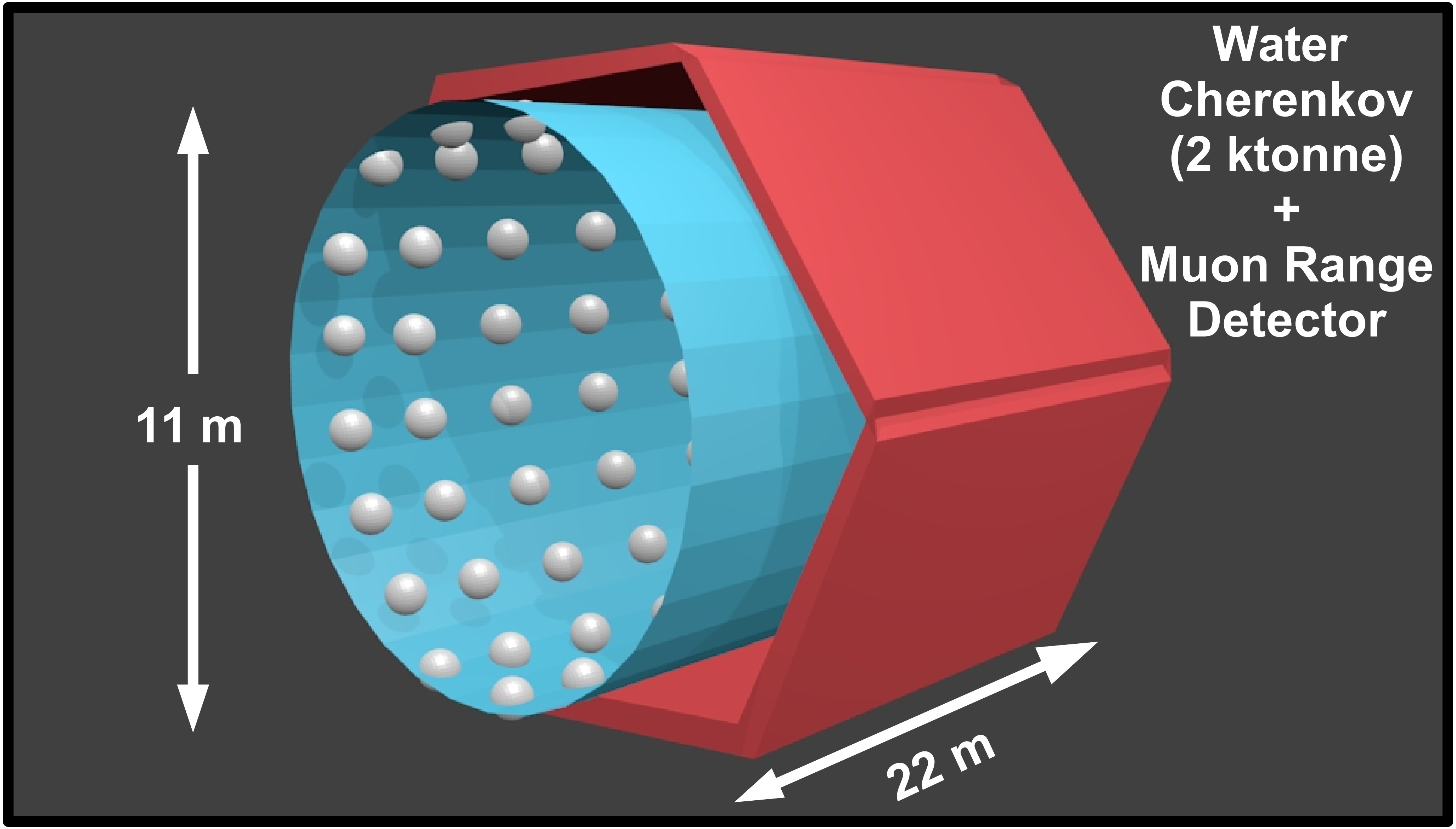
Broad physics programme:

- Neutrino oscillation:
  - Atmospheric neutrinos (still statistics limited!)
  - Solar neutrinos
  - Accelerator neutrinos
- Proton decay
- Neutrino astrophysics
  - Supernova burst (~250,000 events expected @ 10 kpc)
  - Supernova relic neutrinos
- Various other physics (indirect WIMP search, n-$\bar{n}$ osc., etc.)

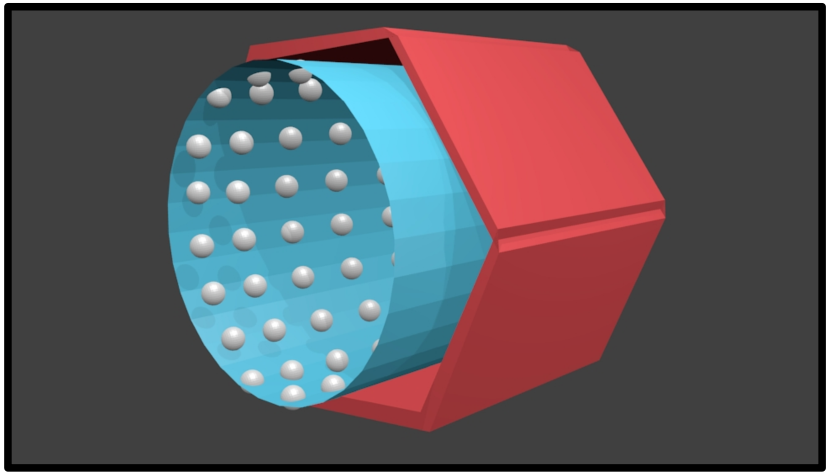
Significantly larger (x25) statistics require smaller systematics:

New near detector(s) needed!

TITUS



TITUS Overview



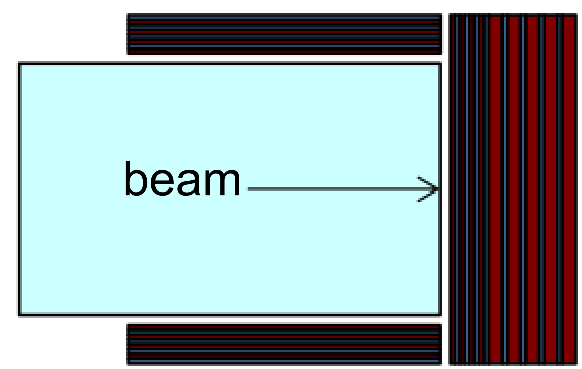
- Proposed new near detector for HK beam programme
- To be located ~2 km from J-PARC neutrino beam

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

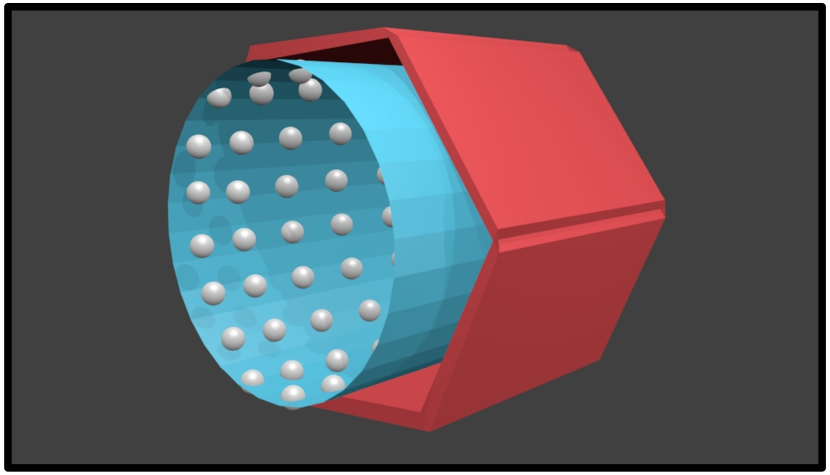
- Likely add-ons / upgrades currently being investigated include:
  - Magnetised MRD (1.5 Tesla field) for charge-sign reconstruction
  - MIND-type detector
  - Large Area Picosecond Photo-Detectors (LAPPDs) for high precision timing
  - High quantum efficiency PMTs (HQE PMTs)

See next two talks

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



TITUS Overview



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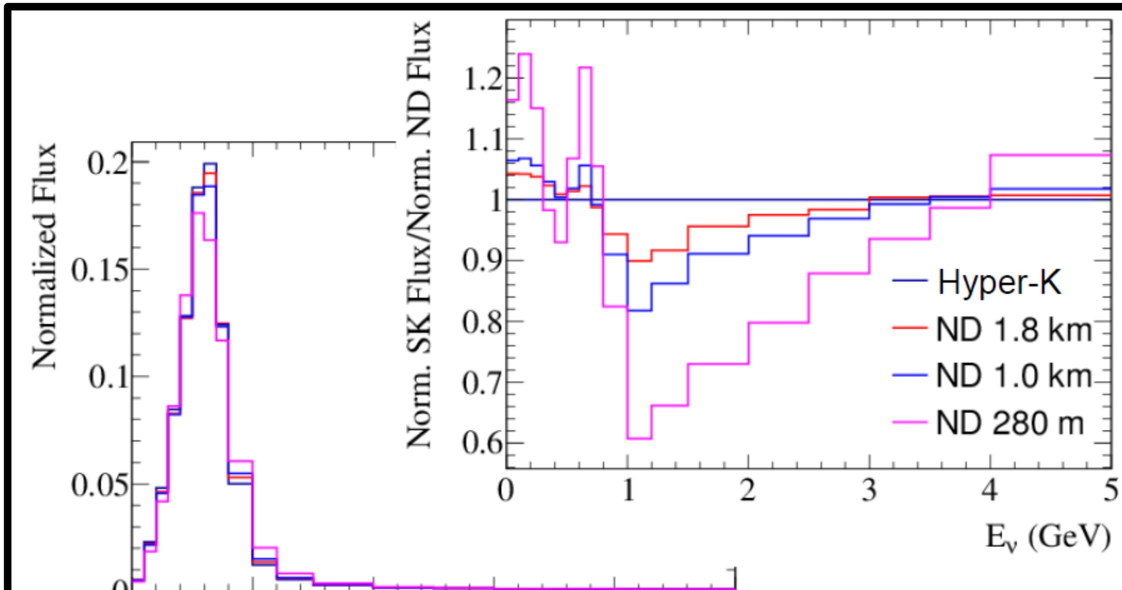
- Same target nuclei as Hyper-K
  - H_2O (and maybe Gd)

- Nearly same target angle and ν energy spectrum

- Many systematics cancel out in Far/Near ratio

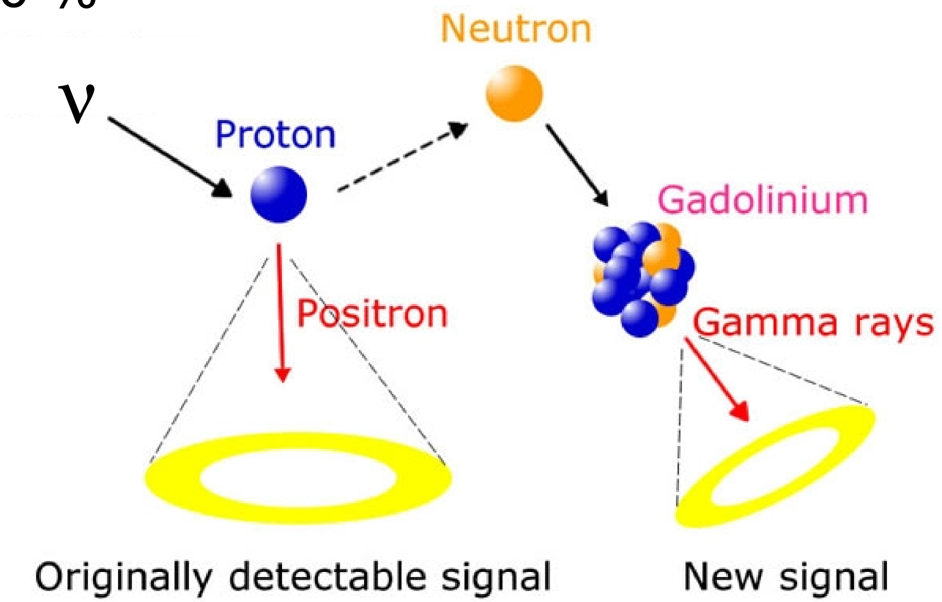


M. Hartz

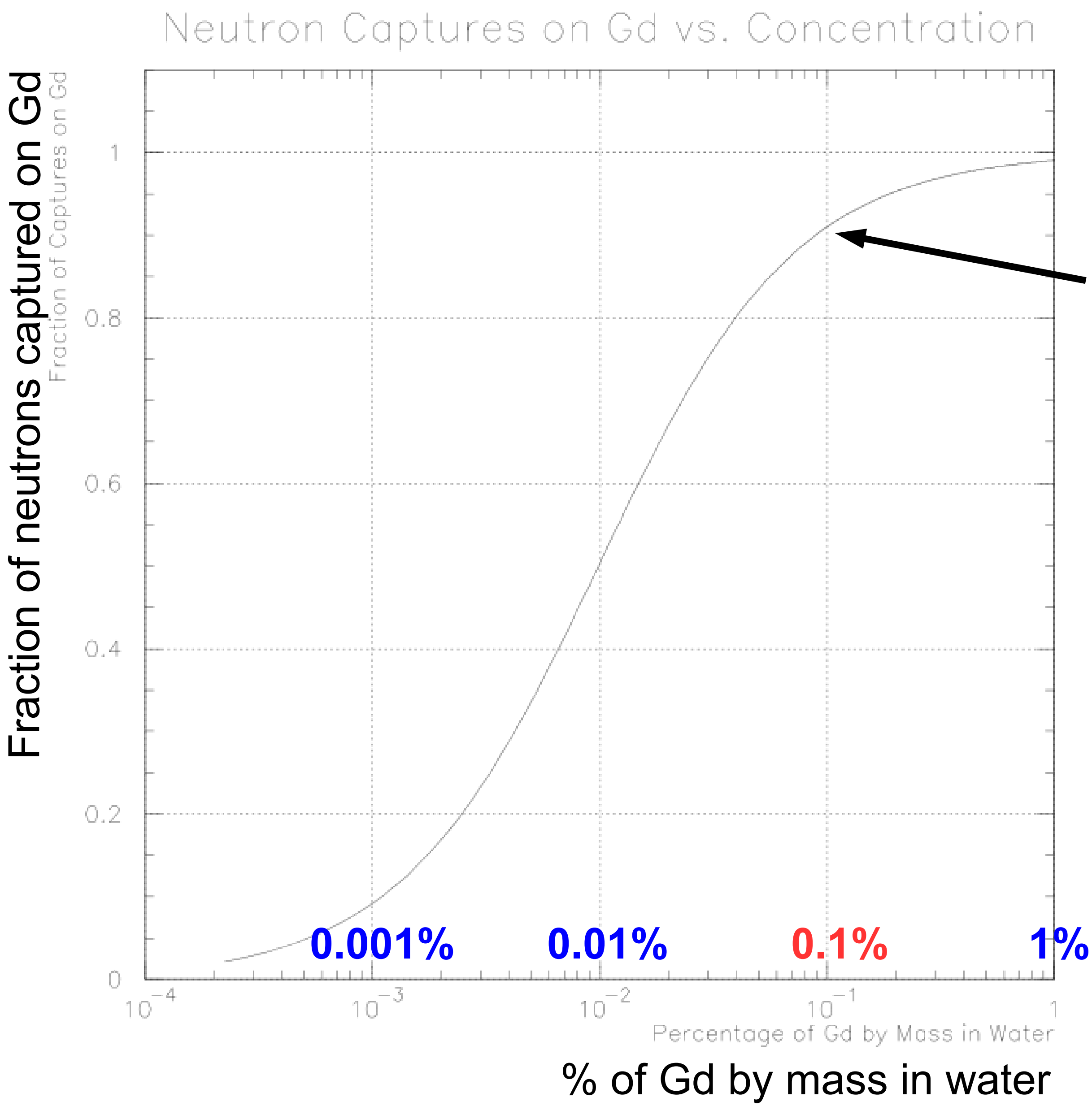
Gadolinium Doping

- **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 is captured on a free proton
  - 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

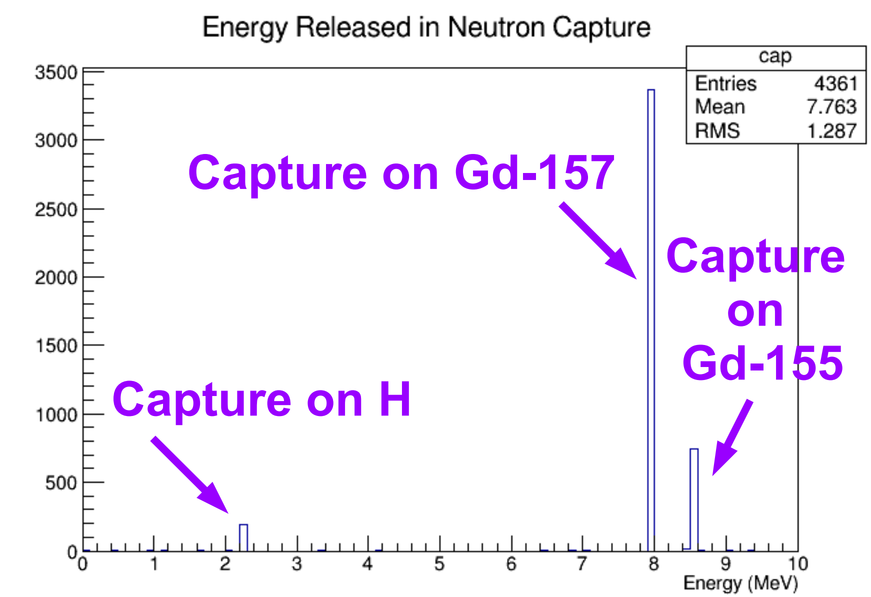


Cross-section for neutron capture is:

- ~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

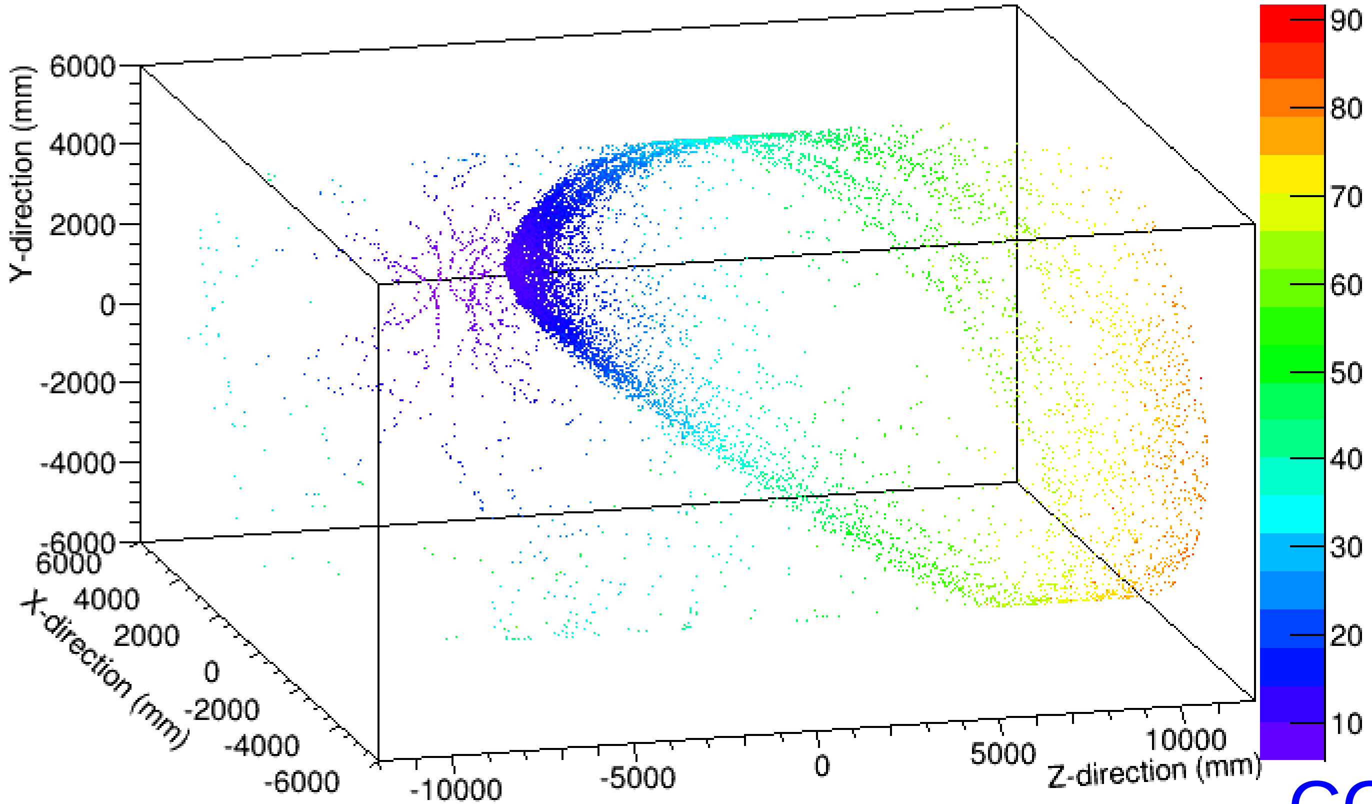
- Neutron capture can be used to separate CCQE from CC MEC and CC Other, to enhance purity of CCQE in CC0π sample:
  - ν_μ CCQE: 0 neutrons
  - ν_μ CC MEC: 0.2 neutrons (average): $\nu_\mu + (n\text{-}n) \rightarrow \mu^- + p + n$
  - $\bar{\nu}_\mu$ CCQE: 1 neutron
  - $\bar{\nu}_\mu$ CC MEC: 1.8 neutrons (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 NCπ^0 – sub-dominant ν_e appearance BG & can improve knowledge of M_A^{RES}
  - CCQE vs. CC-inclusive
- 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
- Sterile neutrino searches
  - Compare rates (NC & CC) at 280 m and 2 km to look for ν_{active} disappearance

TITUS-WC Simulation

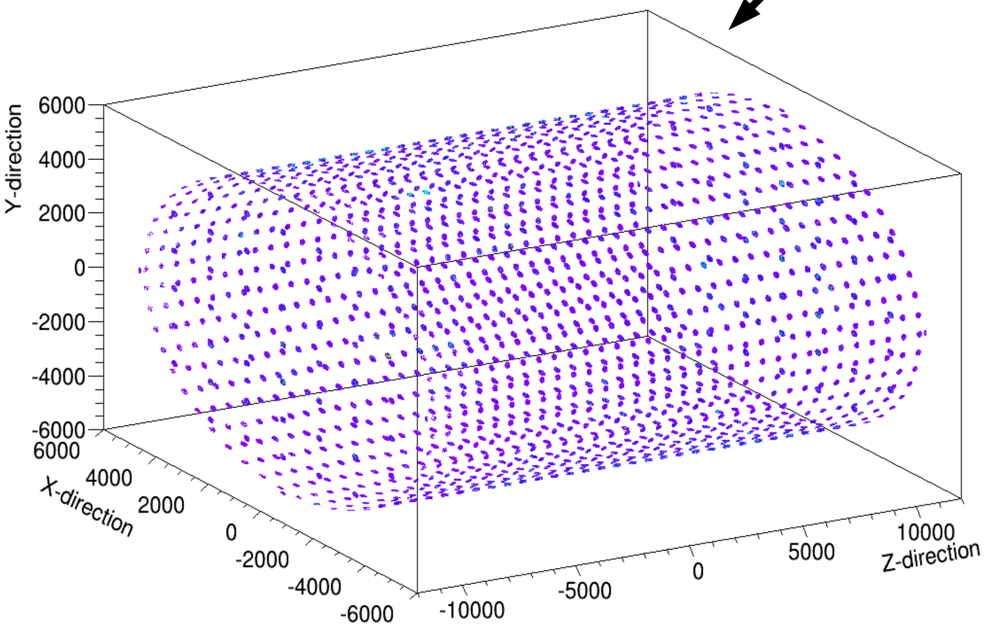
- Neutrino generation via NEUT & GENIE
- Detector simulation with WChSandBox
  - New fast simulation software package! (From March 2014)
  - Primary author is Matt Wetstein (U-Chicago)
  - HK-EU collaborators now contributing to development

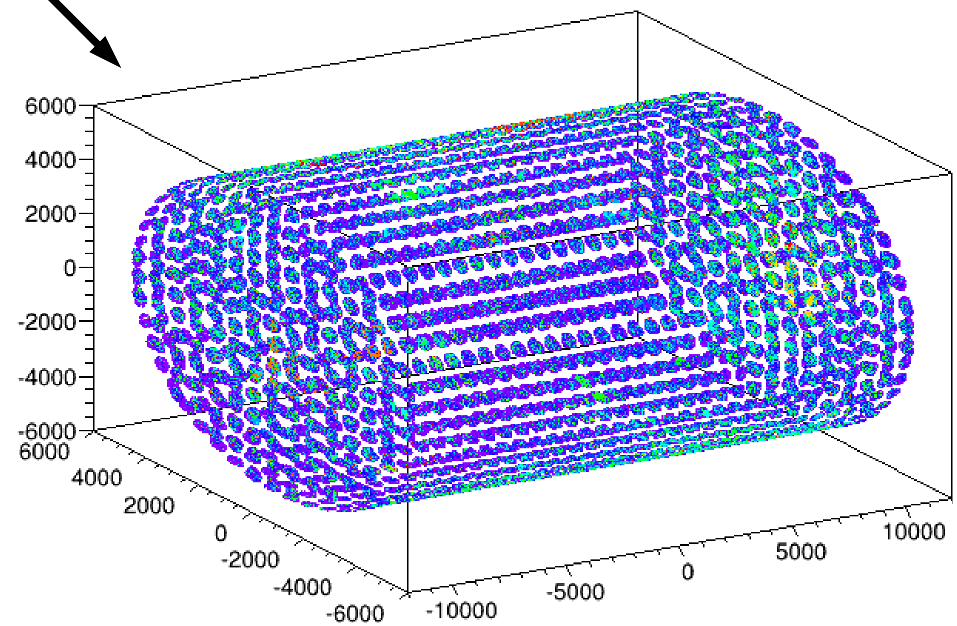


CCQE (1Rμ)

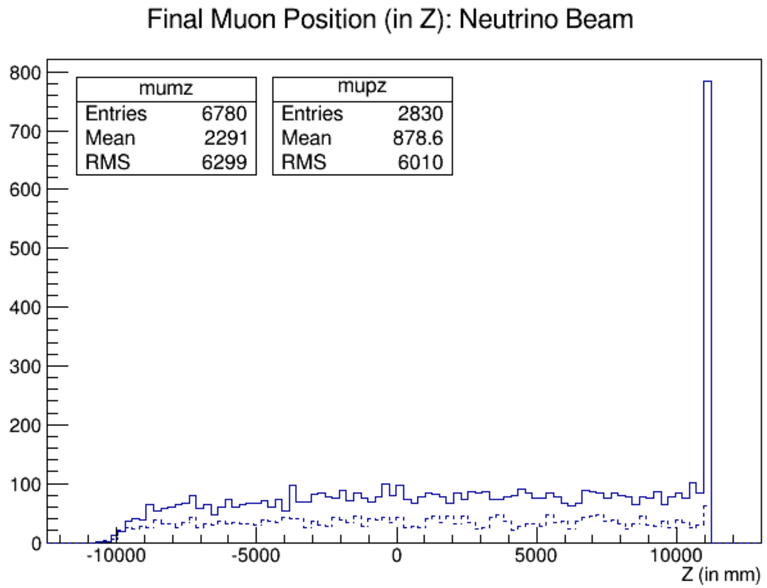
TITUS-WC Reconstruction

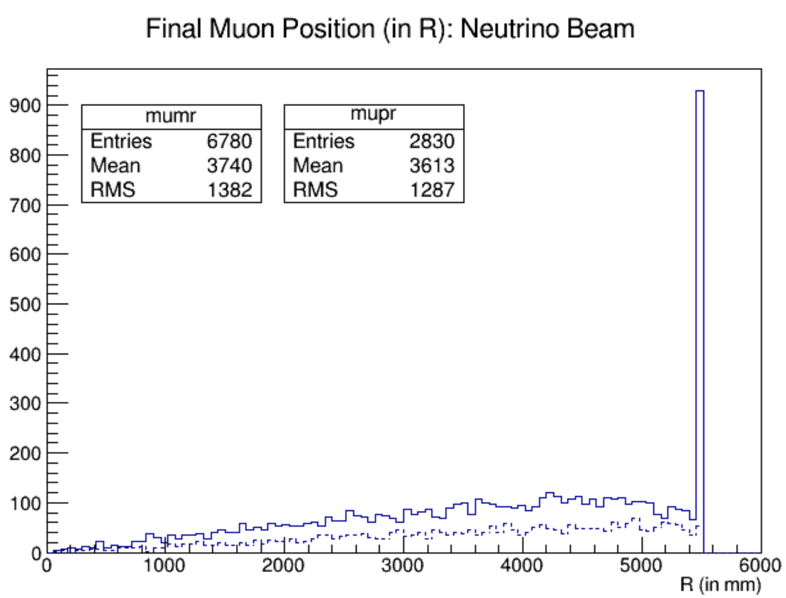
- Reconstruction:
  - Current “pseudo-reconstruction” uses smearing tables based on fiTQun
    - Pattern-of-light fit currently being developed for SK, T2K, HK
  - Development of both high-E and low-E (< 20 MeV) reconstruction algorithms
  - Photosensor optimisation currently underway:
    - **Four arrangements:** 20” PMT, 12” PMT, 8” PMT, 8” PMT + LAPPD
    - **Two coverages:** 20% (HK), 40% (SK)





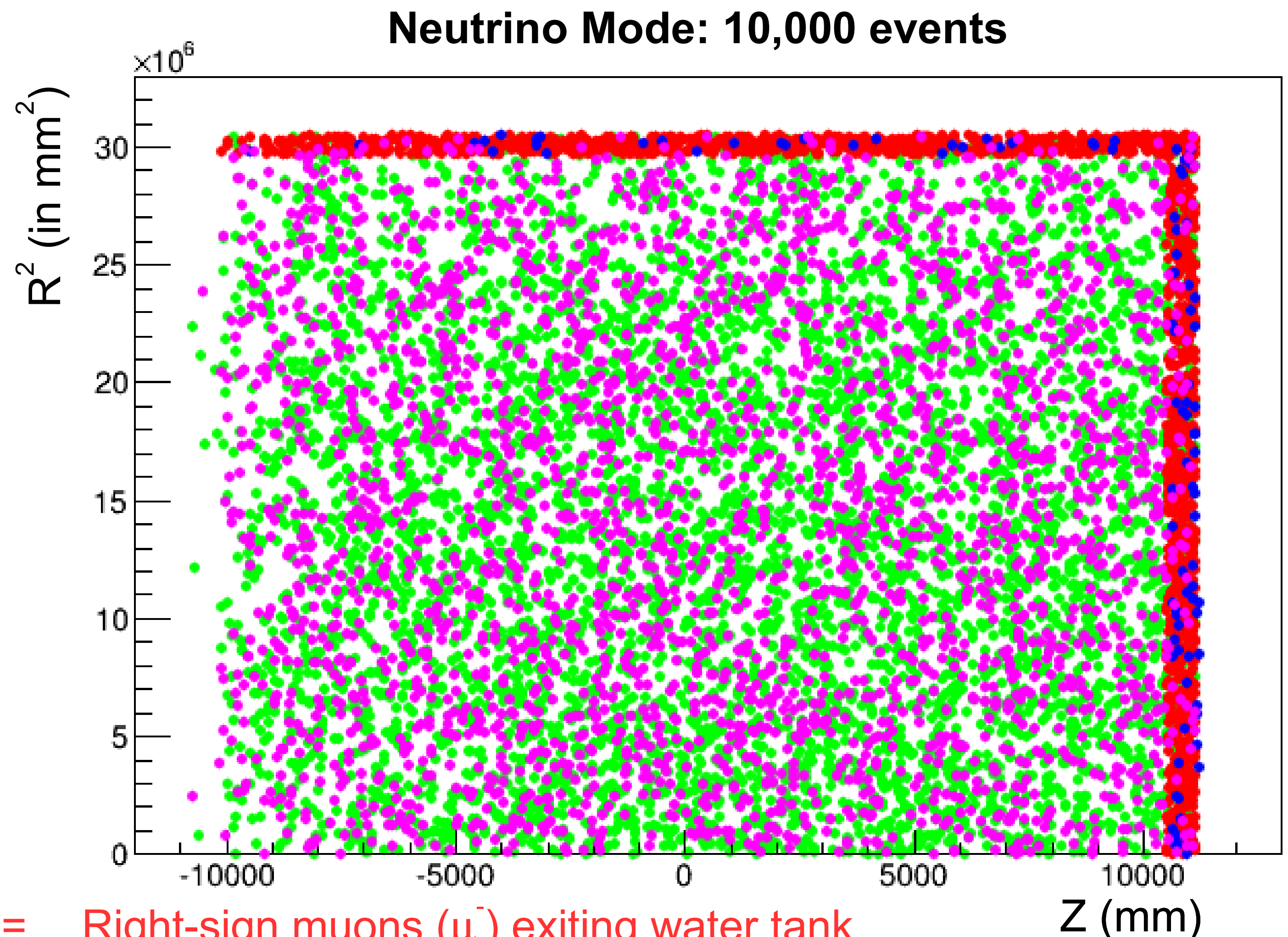
WC + MRD





- 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

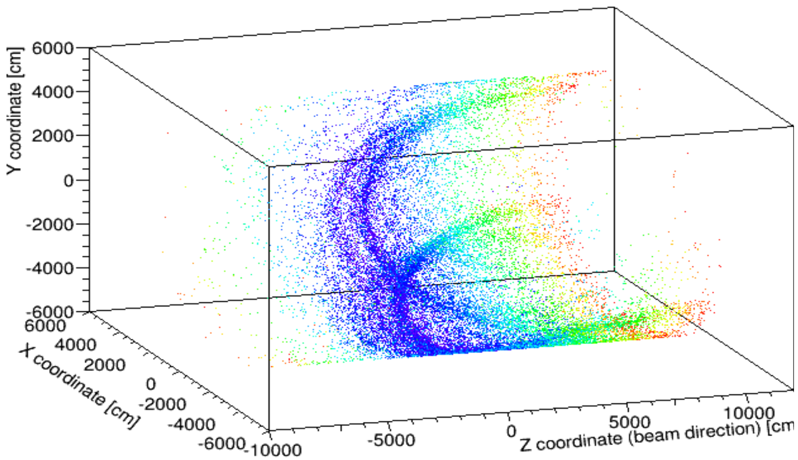
Red = Right-sign muons (μ^-) exiting water tank

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

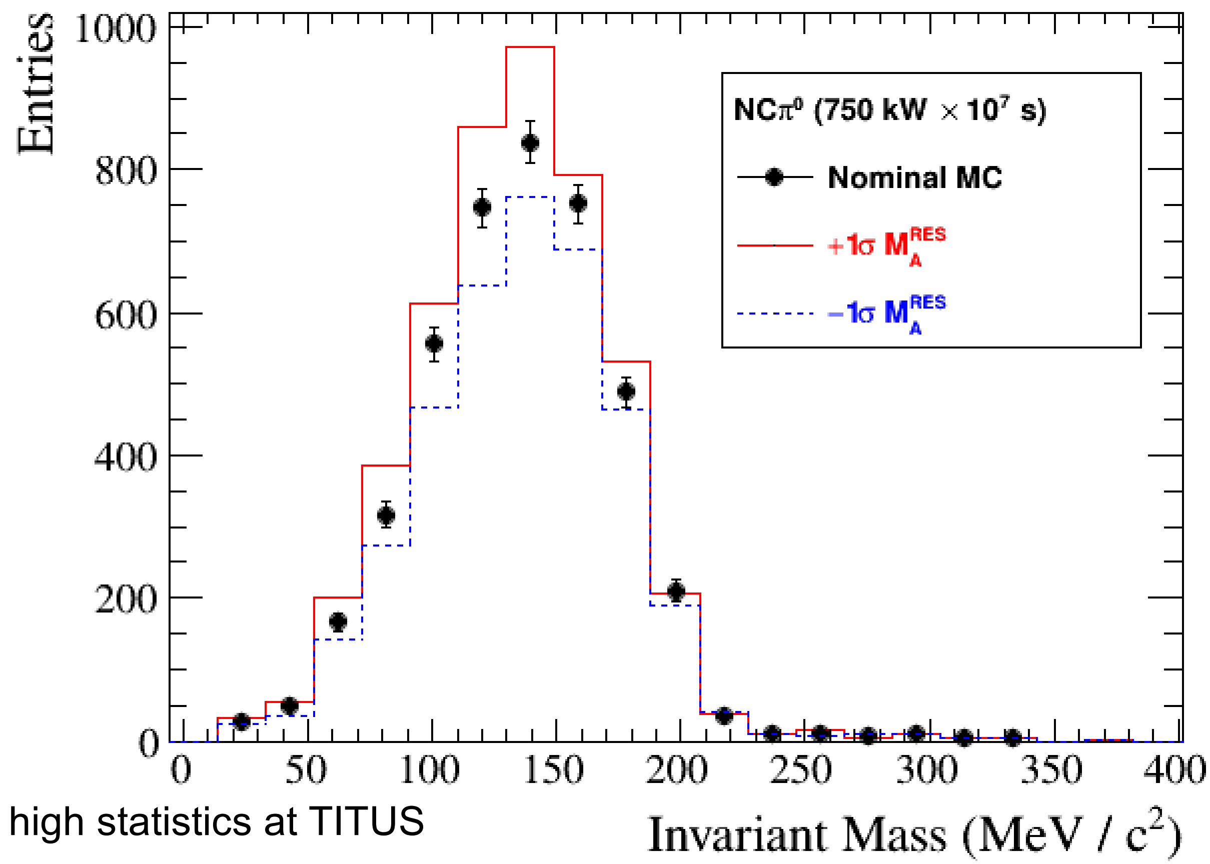
Green = Right-sign muons (μ^-) contained within water tank

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

NCπ^0 Measurement

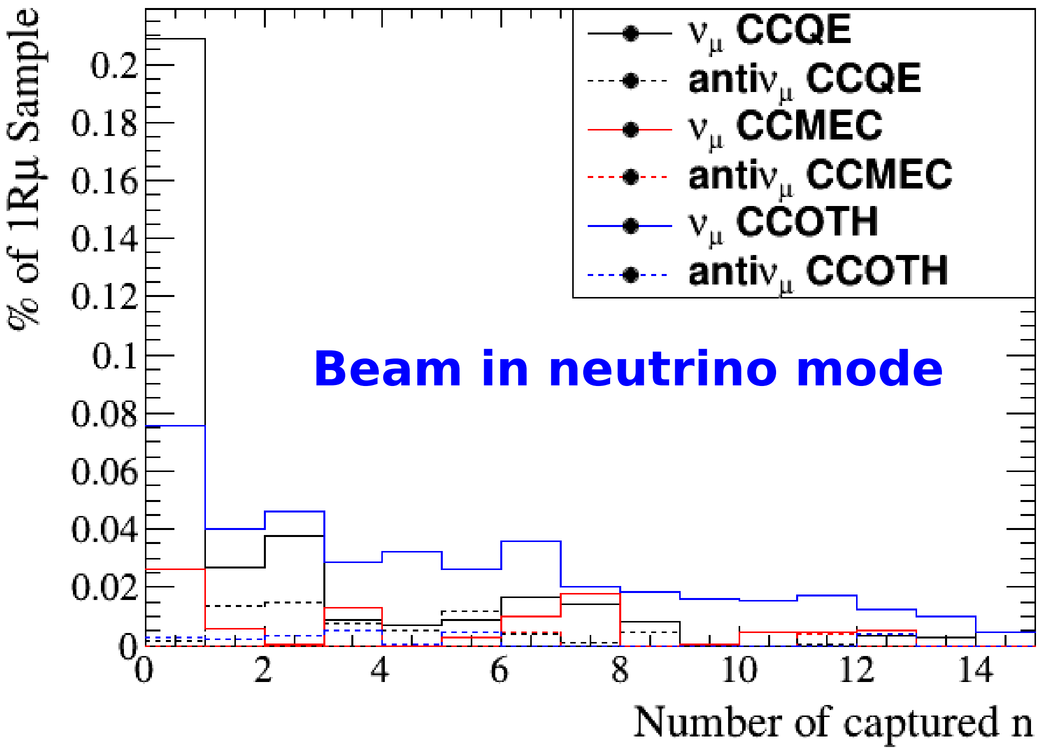


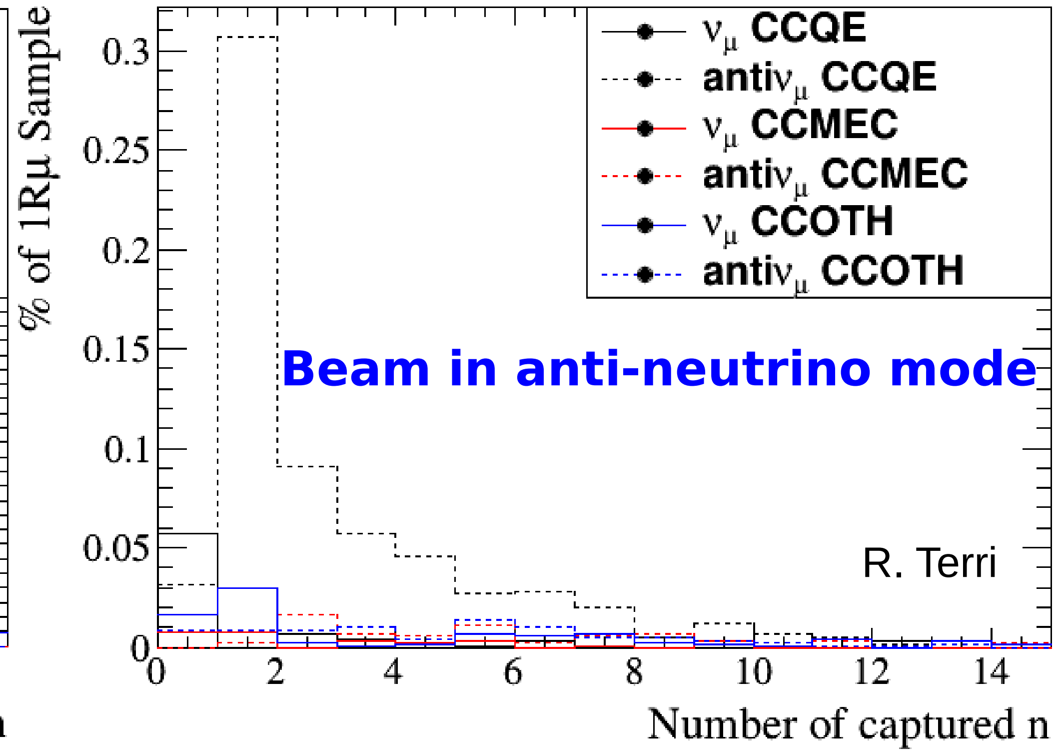
NCπ^0



- Inclusive NCπ^0 measurement possible with high statistics at TITUS
- Can use same selection criteria as Super-K and Hyper-K
- Figure shows one year of nominal running at TITUS with K2K-style cuts:
  - Fully contained
  - 2-ring ee-like events
  - Fiducial cut: 300 cm from walls (200 tonne FV)
- Already possible to constrain better than theoretical uncertainty in M_A^{RES}

Neutron Multiplicity





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

Future Work

- **EU effort on TITUS-WC is ramping up → LOTS of recent work!**
  - **Event generation [F. di Lodovico, D. Hadley, R. Terri]**
  - **Software development**
    - Photosensor implementation and optimisation [T. Gregoire, M. Malek]
    - Water Cherenkov + MRD joint analysis [M. Malek, M. Rayner]
    - High energy reconstruction [F. di Lodovico]
    - Low energy reconstruction (< 20 MeV) [F. di Lodovico, M, Malek]
  - **Event selection**
    - Selection criteria (esp. CCQE) [D. Hadley]
    - Fiducial volume optimisation [M. Malek, R. Terri]
  - **Detector and beam studies**
    - Neutron capture & multiplicity [P. Beltrame, T. Katori, M. Malek, R. Terri]
    - Intrinsic beam ν_e measurements [G. Cowan, P. Beltrame]
    - Separation of ν / $\bar{\nu}$ [M. Malek, R. Terri]
    - Intrinsic NCπ^0 studies [W. Ma, M. Malek]
  - **Physics analyses**
    - Oscillation sensitivity at Hyper-Kamiokande [L. Cremonesi, R. Shah, S. Short]
    - Sterile neutrino search [T. Gregoire, W. Ma, M. Malek]
    - Supernova burst evaluation [S. Cartwright, M. Malek]
    - Proton decay background reduction [???]

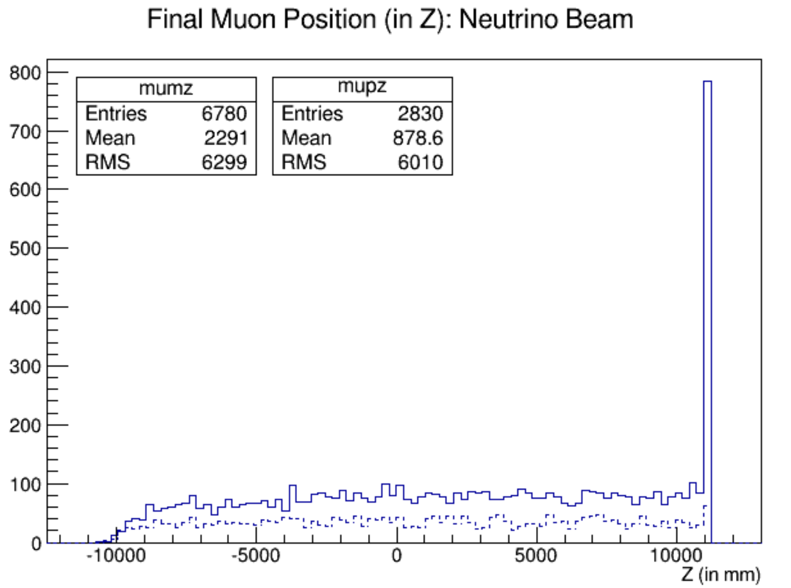
BACK-UP SLIDES

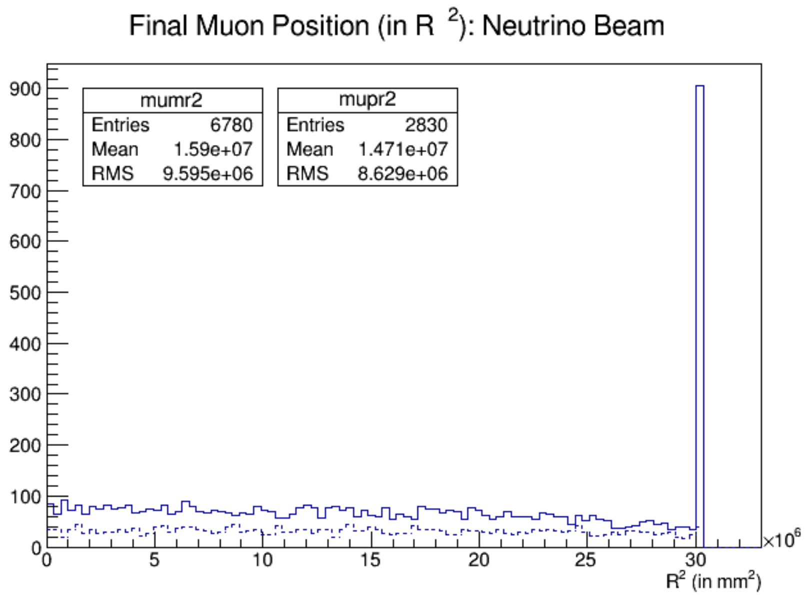
Neutron Multiplicity

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

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

Muon Positions by R^2





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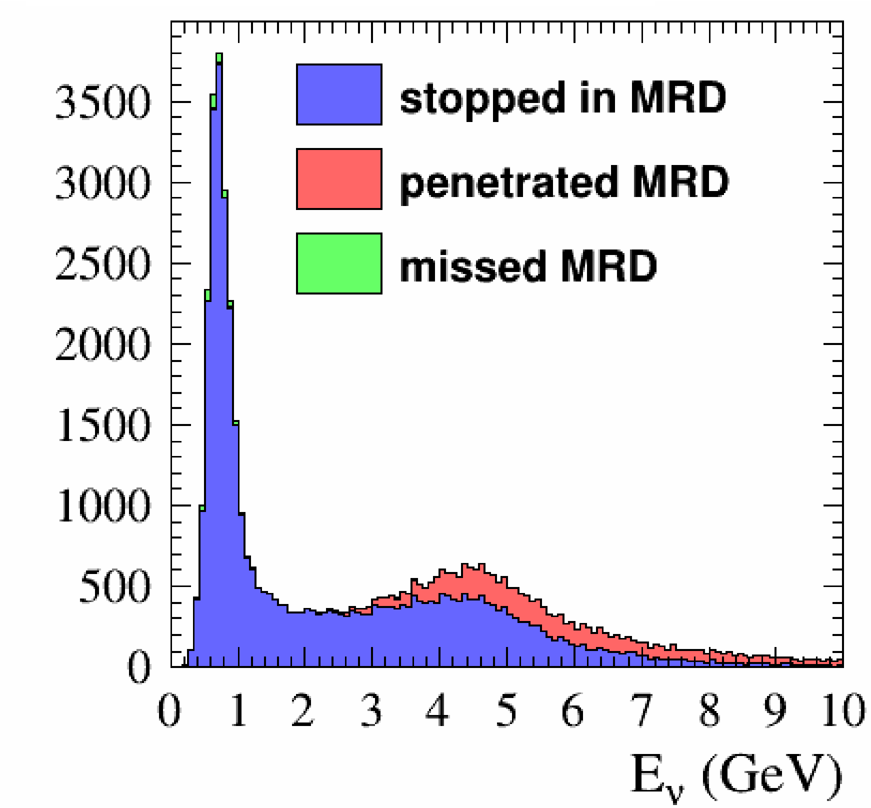
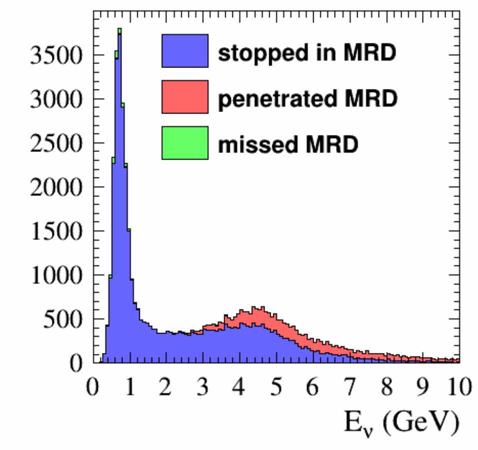
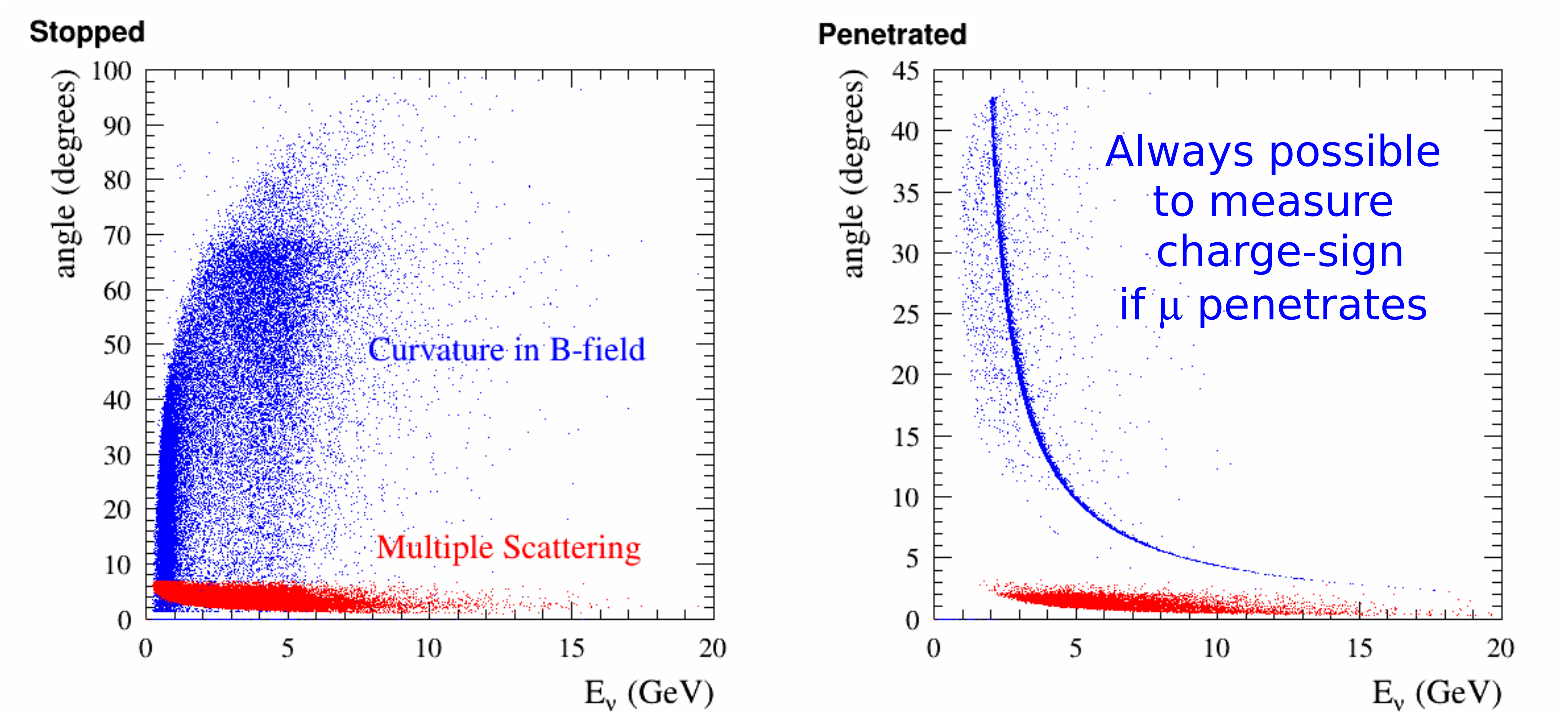


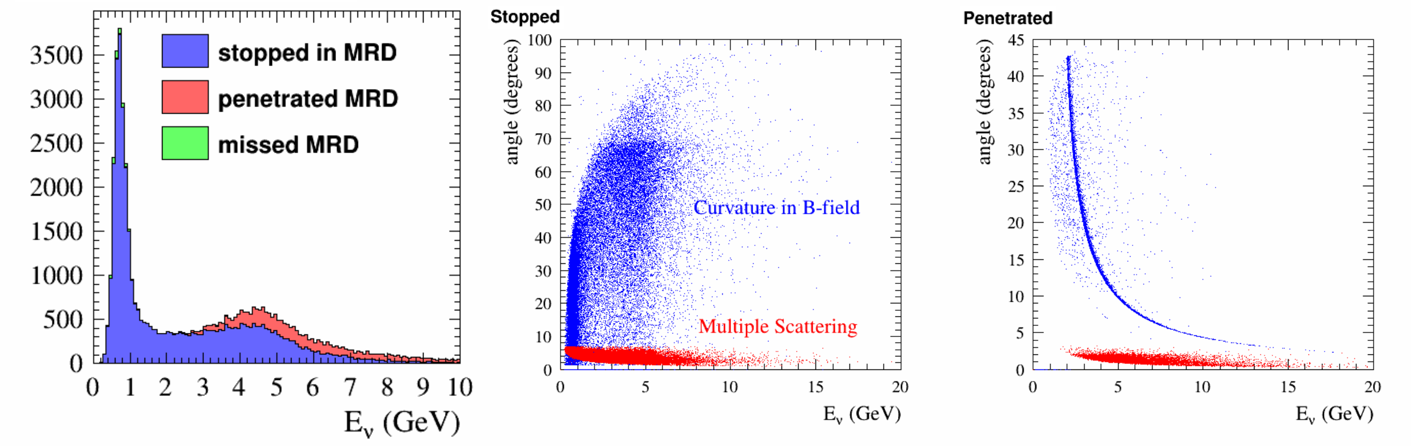
Magnetizing the MRD



- 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



All plots on this slide from M. Rayner

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