LAr TPC ND size optimization

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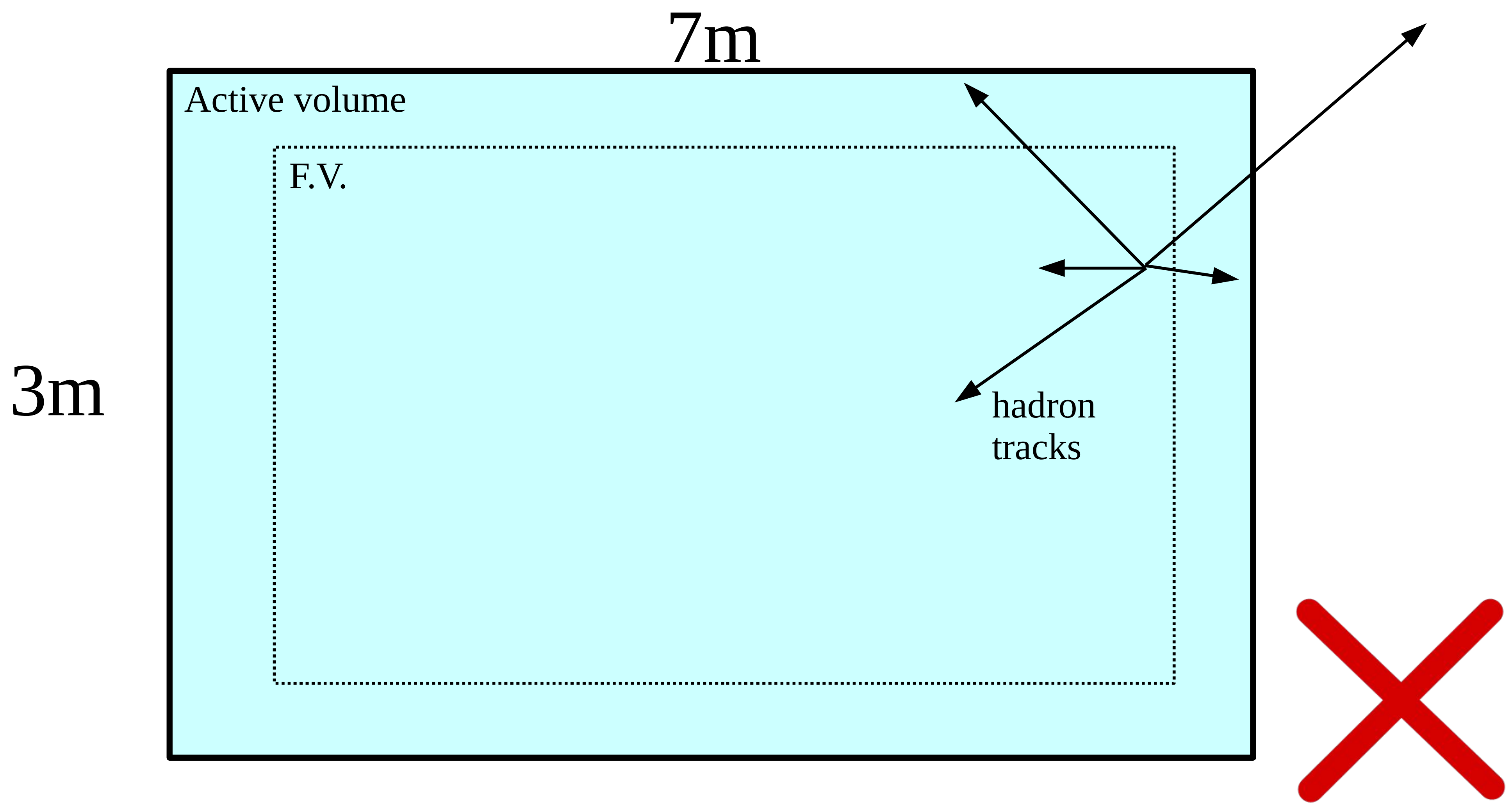
Outline

- Mostly a collection of old studies, with a renewed interest in the Z dimension of the active volume due to the hall space constraints
- Three things impact the minimum z dimension:
  - Hadronic shower containment for forward, high-energy events
  - Muon containment/matching for forward muons
  - PRISM data-driven acceptance correction

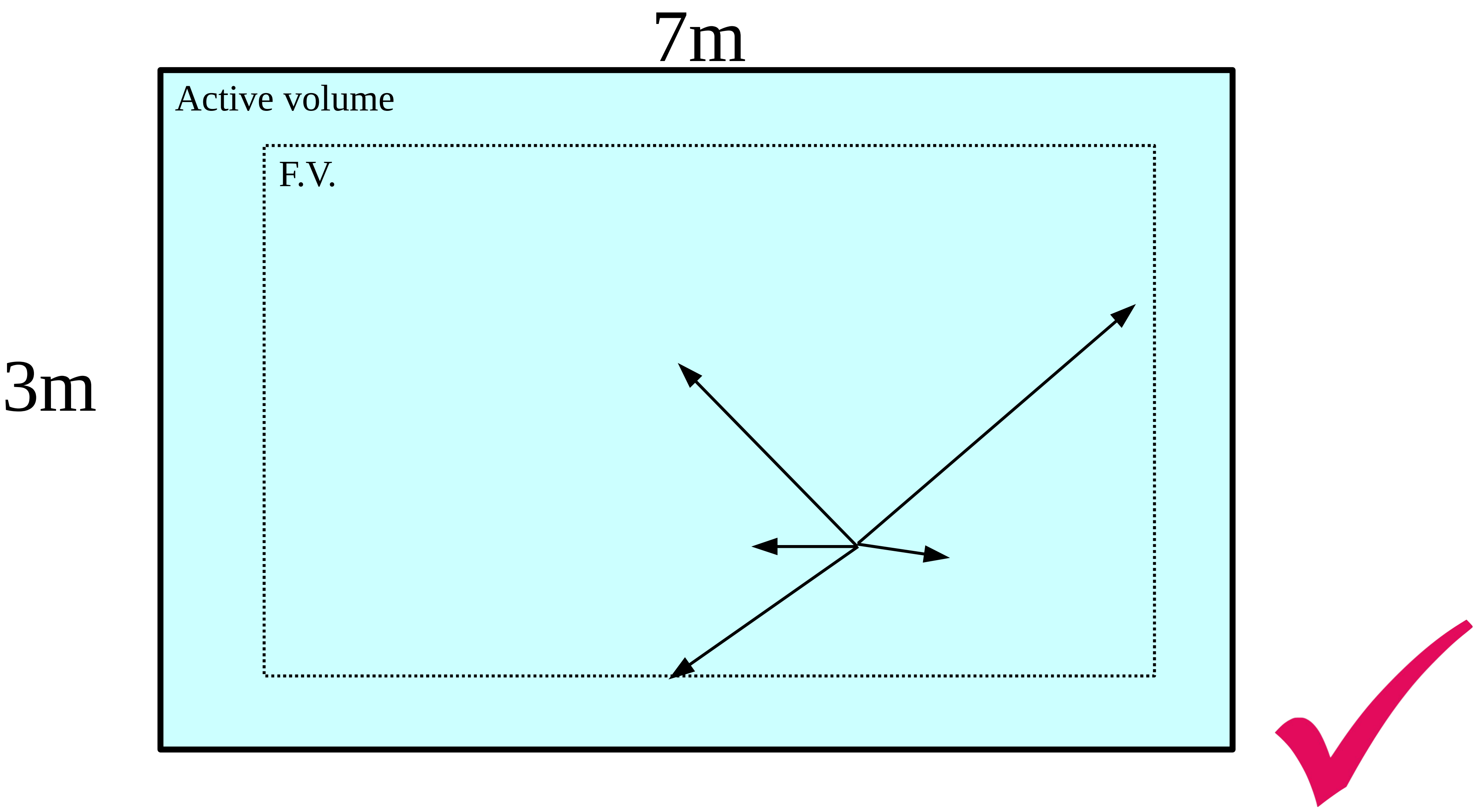
Avoiding model dependence

- Acceptance plots depend strongly on GENIE
- We don't want to build a detector that just barely contains all of the events in GENIE
- We also don't want the acceptance to be a rapidly changing function of vertex position, or of event kinematics – this will make modeling uncertainties give rise to large changes in acceptance at the ND, but small changes at the FD

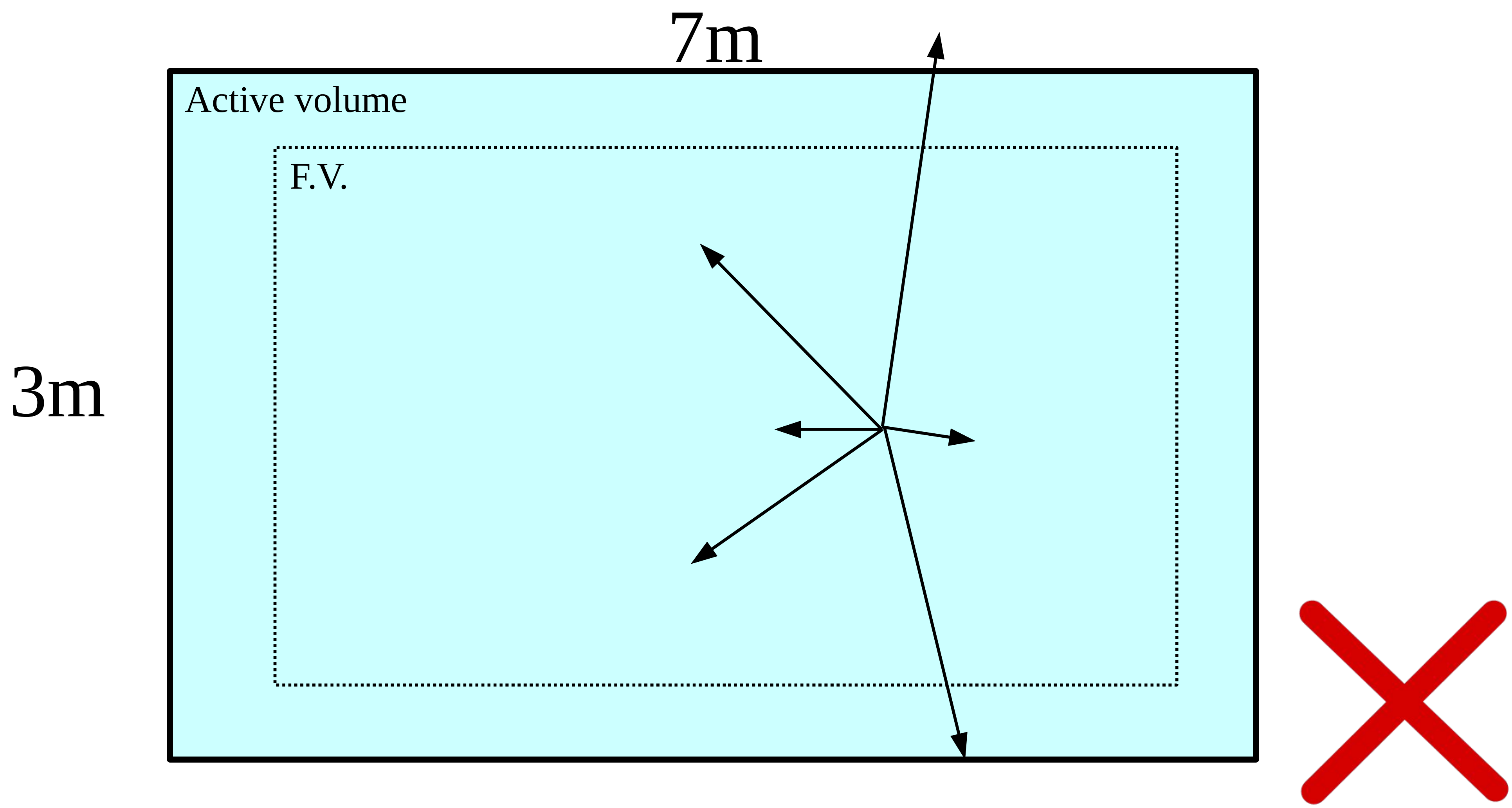
Detector as seen by ν beam (XY projection)



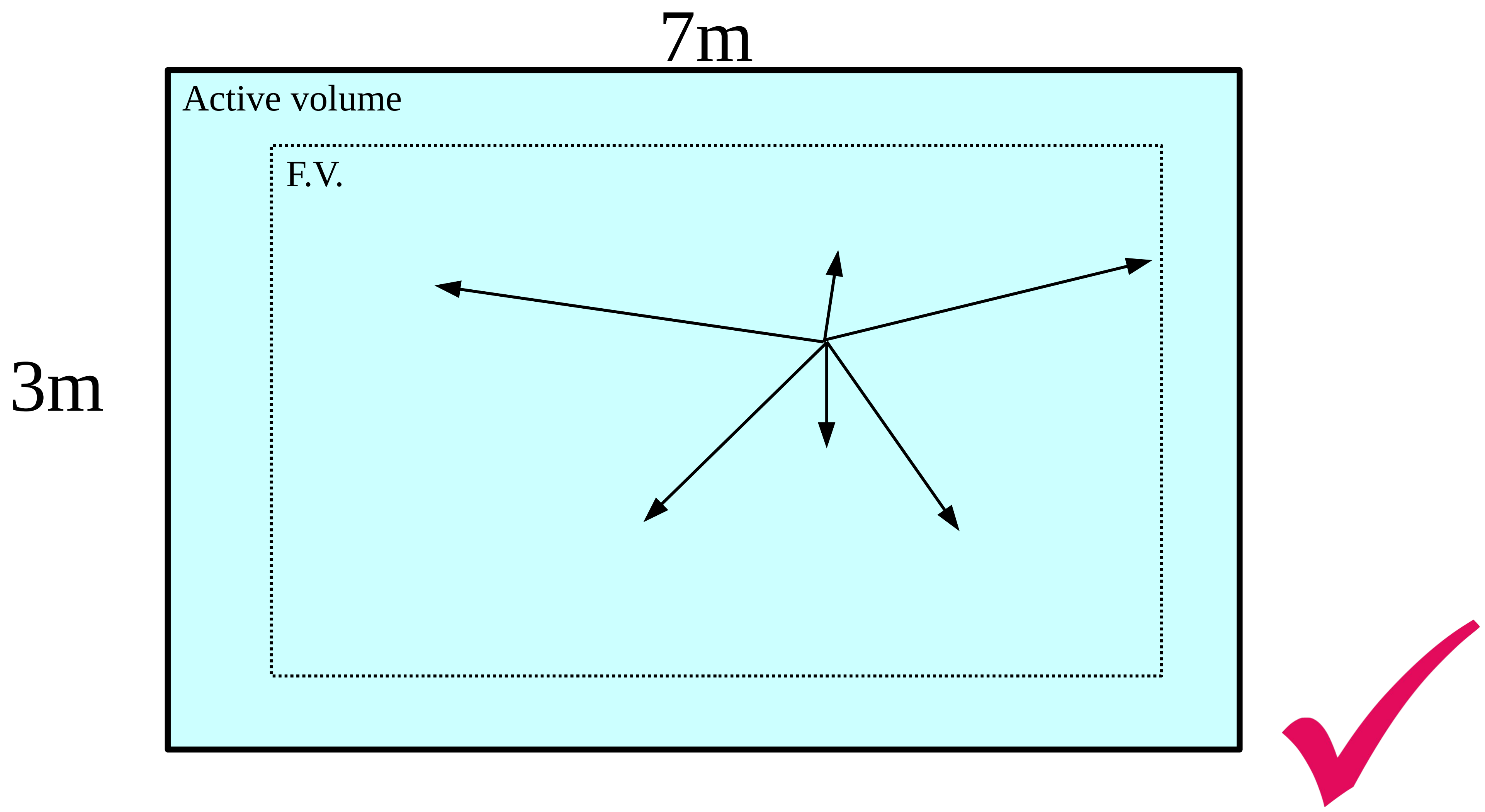
Same event, translated



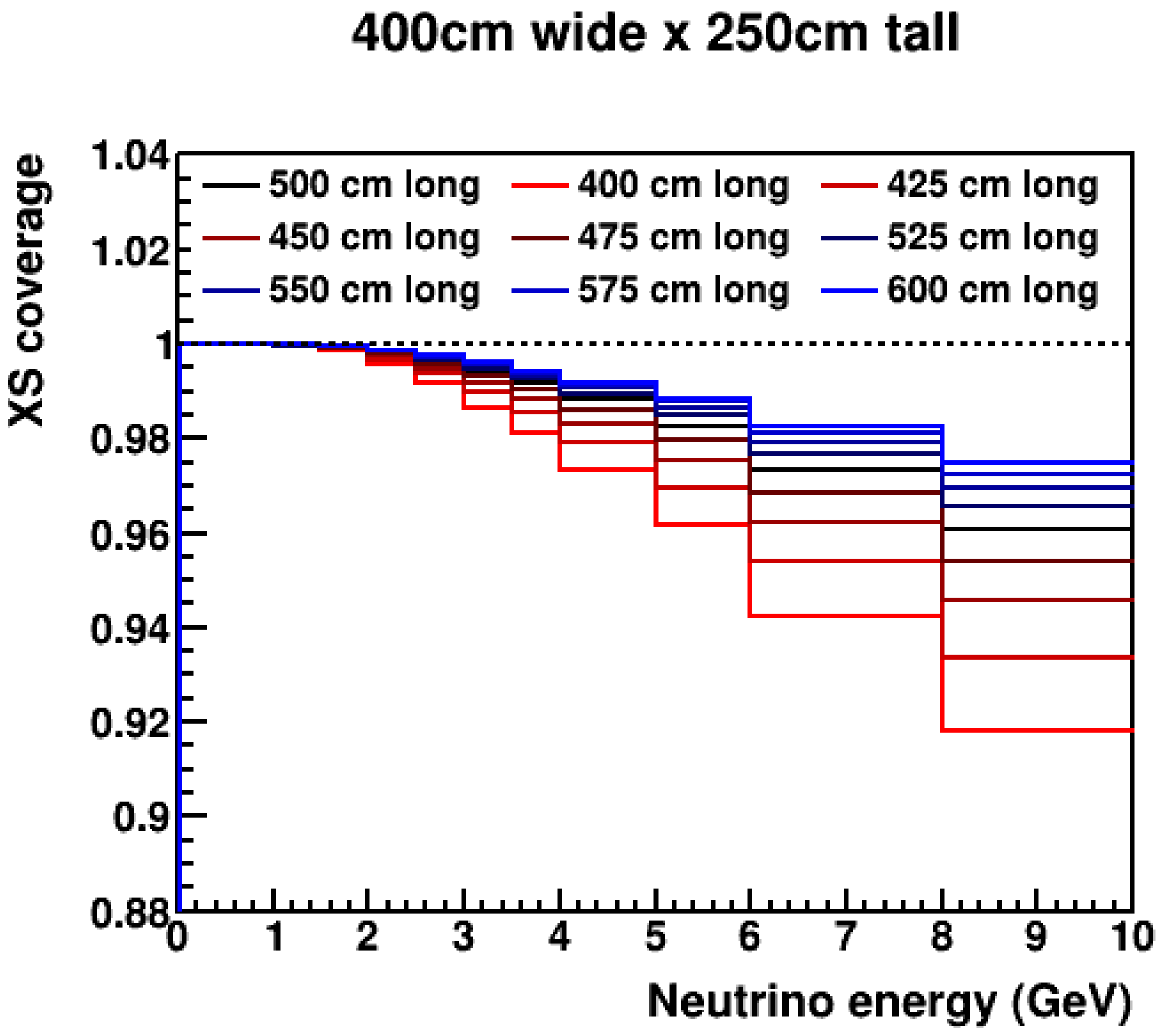
Event that is not contained with any translation



But is using phi symmetry



“Cross section coverage”

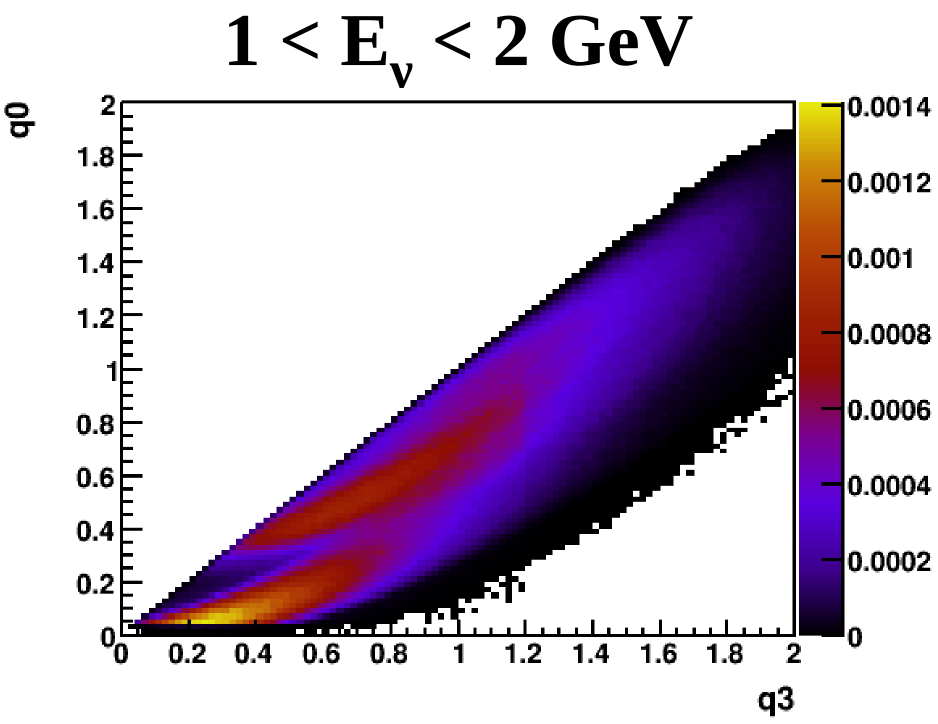


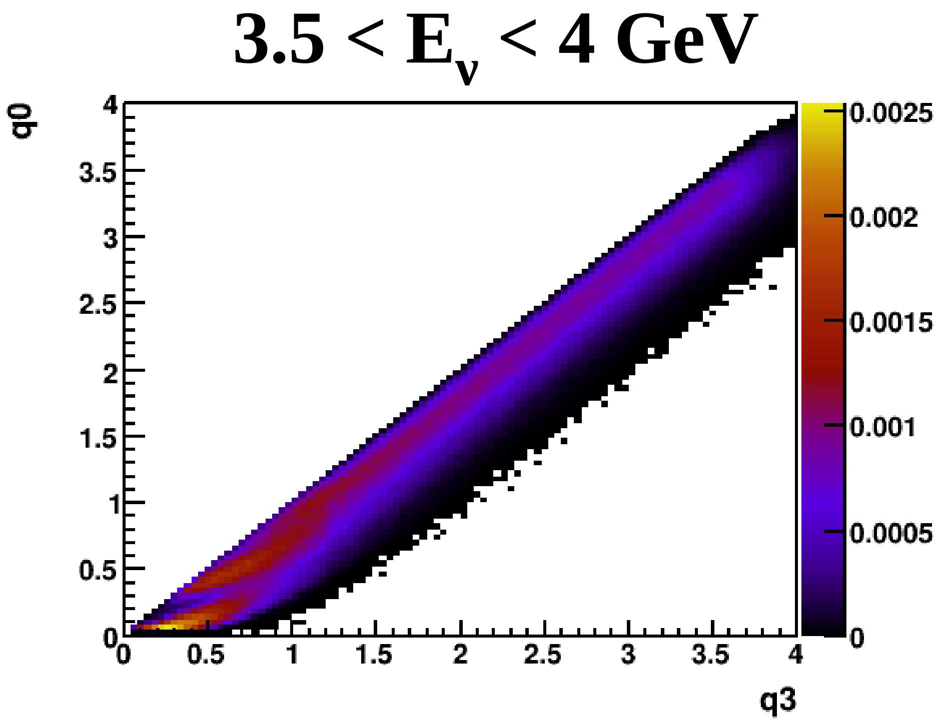
- Shows that cross section coverage is high, and slowly varying vs. neutrino energy for detectors that are >450cm long
- Implies that there are no acceptance holes in the flux peak, because >99% of cross section has non-zero acceptance

Conclusions

- 5m long detector is >98% coverage in the peak, and >95% out to 10 GeV neutrino energy
- 4m long detector is only somewhat worse, ~97% in the peak and 92% out to 10 GeV
- This doesn't tell you what the acceptance is, only that it's non-zero
- We also don't want 1% acceptance for some significant fraction of the cross section

q0-q3 distributions

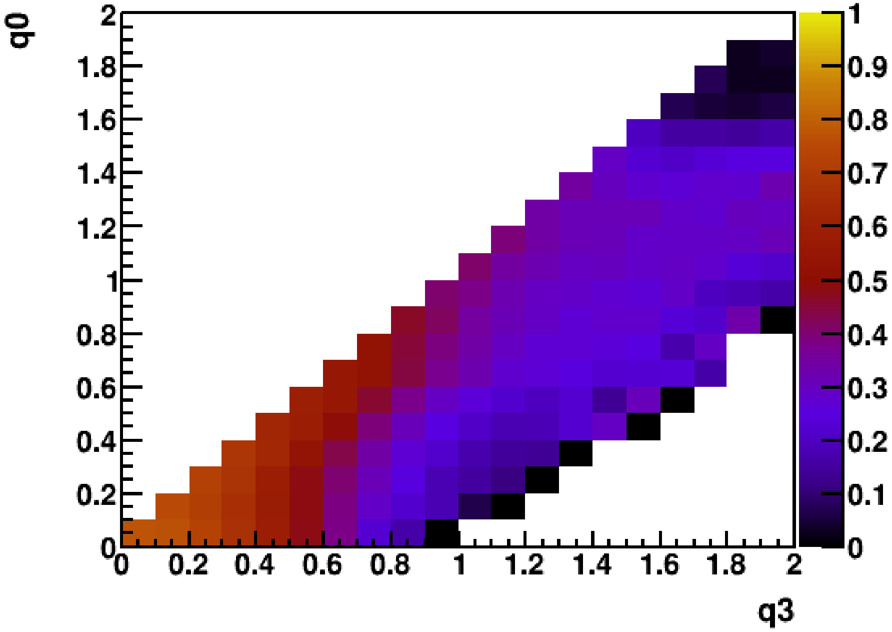




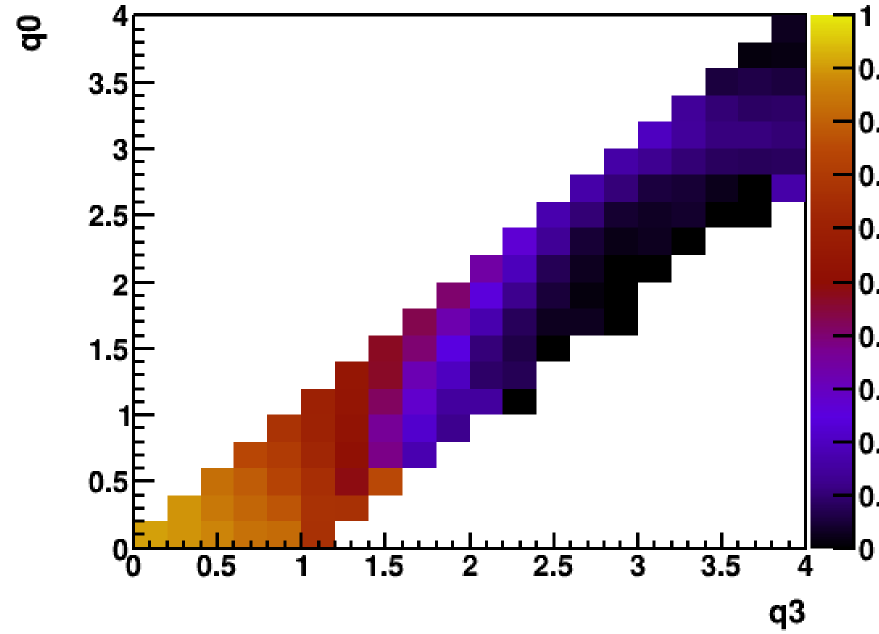
- True q0-q3 distributions in GENIE for two slices of neutrino energy
- Two populations at low momentum transfer are CCQE and Δ resonance
- q0=q3 is $Q^2 \rightarrow 0$ kinematic limit
- Lower-right corner is high muon angle

q0-q3 acceptance

$1 < E_\nu < 2$ GeV

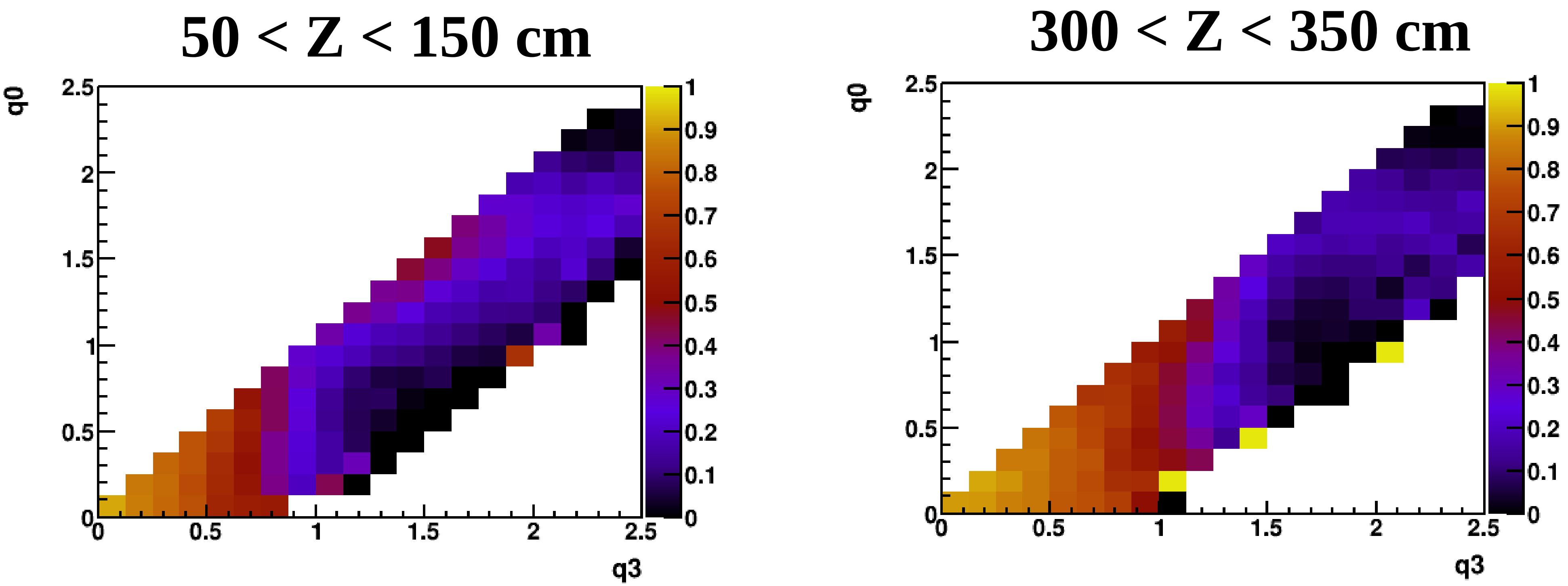


$3.5 < E_\nu < 4$ GeV



- q0 = hadronic energy, q3 ~ muon angle, q0=q3 ~ forward muon
- Bottom left = gas TPC matched, top-right = contained

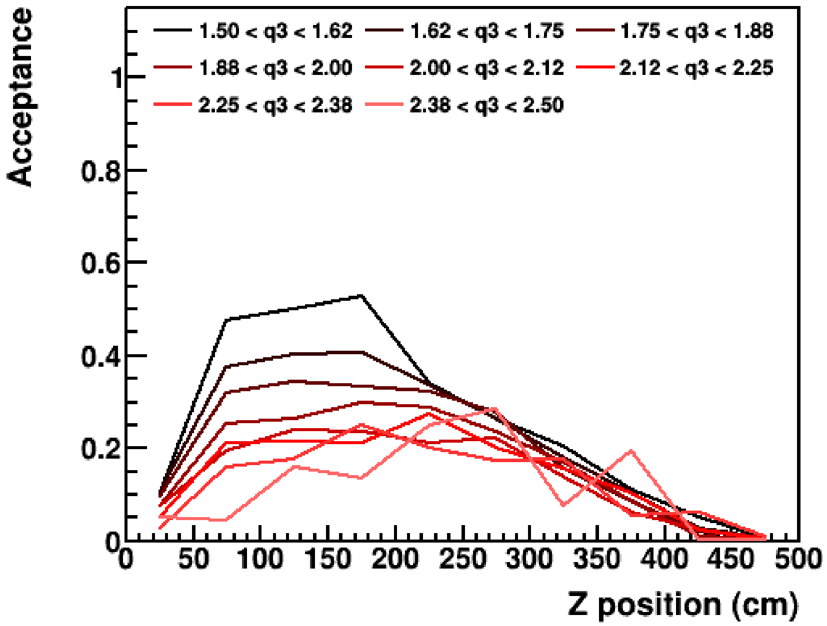
$2 < E_\nu < 2.5$ GeV, Z regions



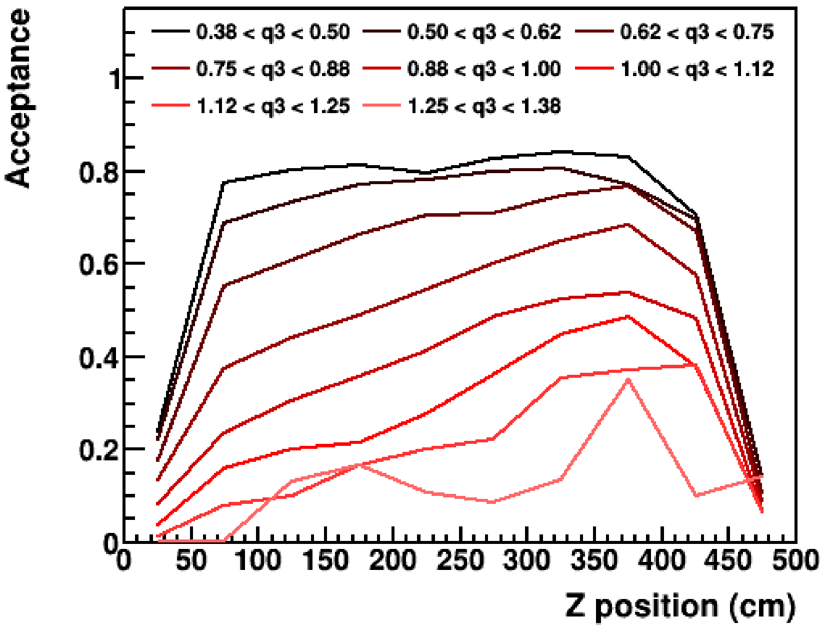
- More HPgTPC-matched muons for downstream vertices, but critical region is only reconstructed for upstream vertices with contained muon

Acceptance vs vertex for different kinematic regions

2 < Eν < 2.5, q0 ~ 1.5



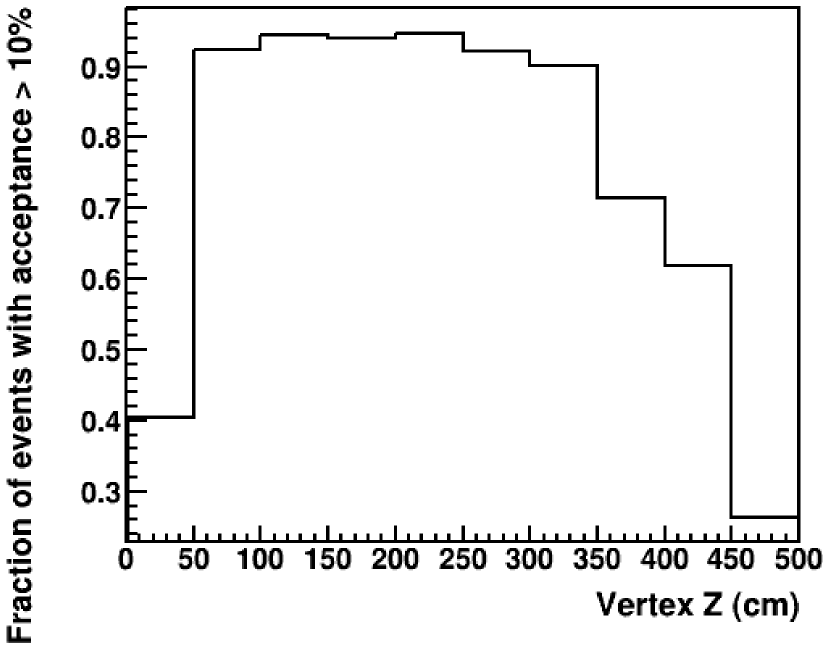
2 < Eν < 2.5, q0 ~ 0.5



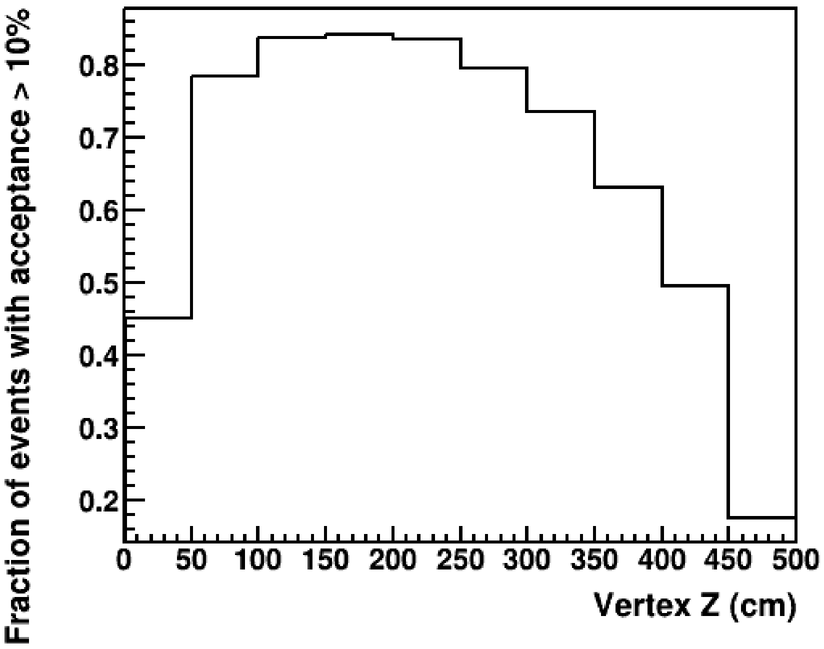
- Some kinematic regions are reconstructed well for upstream vertices, other for downstream vertices
- This is especially true right in the peak of the neutrino flux, where the muon containment drops off at y ~ 0.6

Fraction of cross section with acceptance > 10%

$2 < E\nu < 2.5$

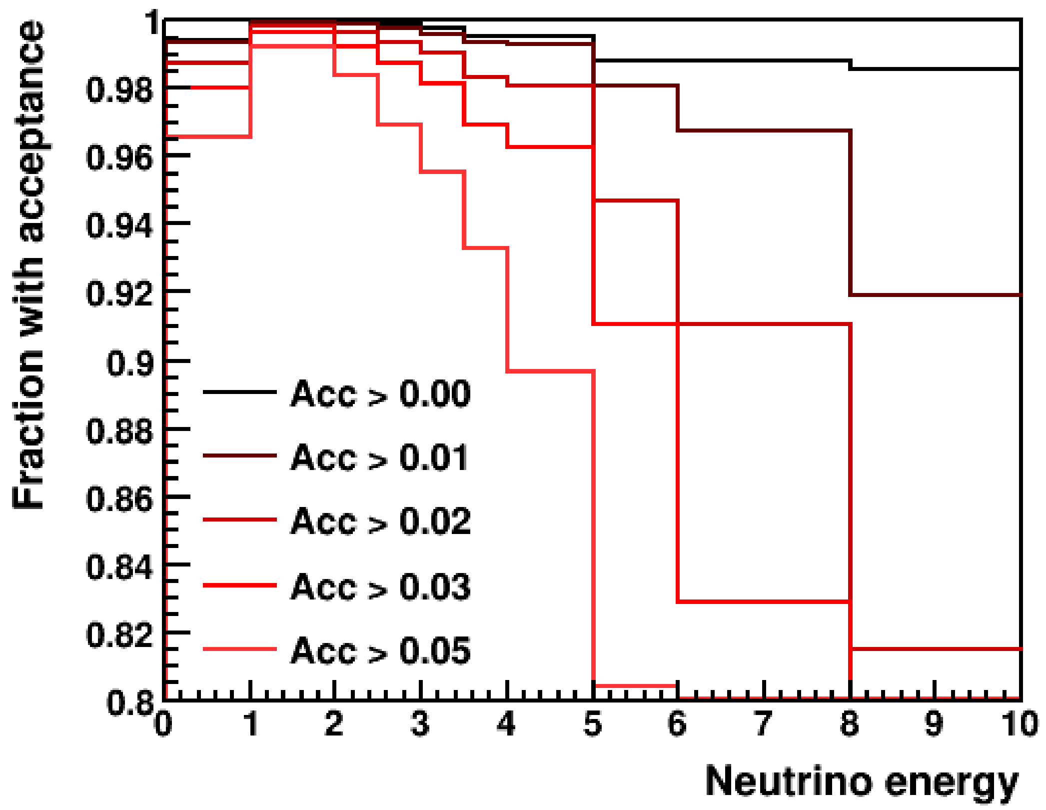


$3.5 < E\nu < 4$



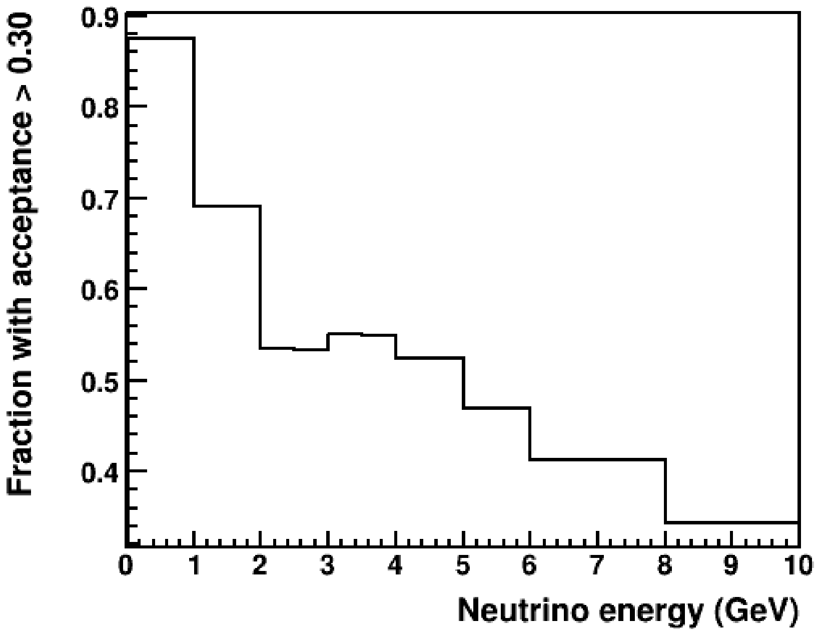
- Generally acceptance is high in the fiducial volume
- This is obviously not an accident, the fiducial volume we have been using was chosen based on this

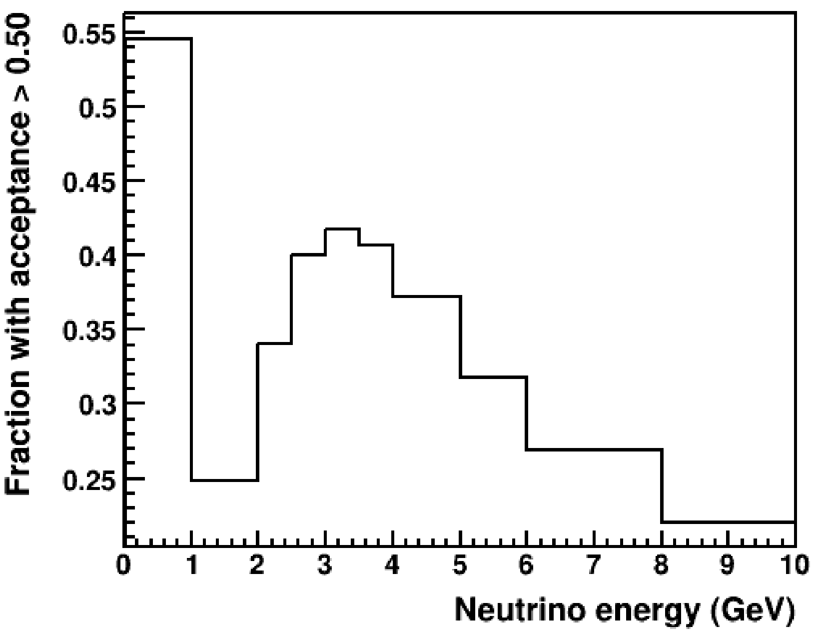
Over full F.V. for 5m long detector



- >99% have non-zero acceptance out to 10 GeV
- >98% have >2% acceptance out to 5 GeV

Acceptance is high in peak region



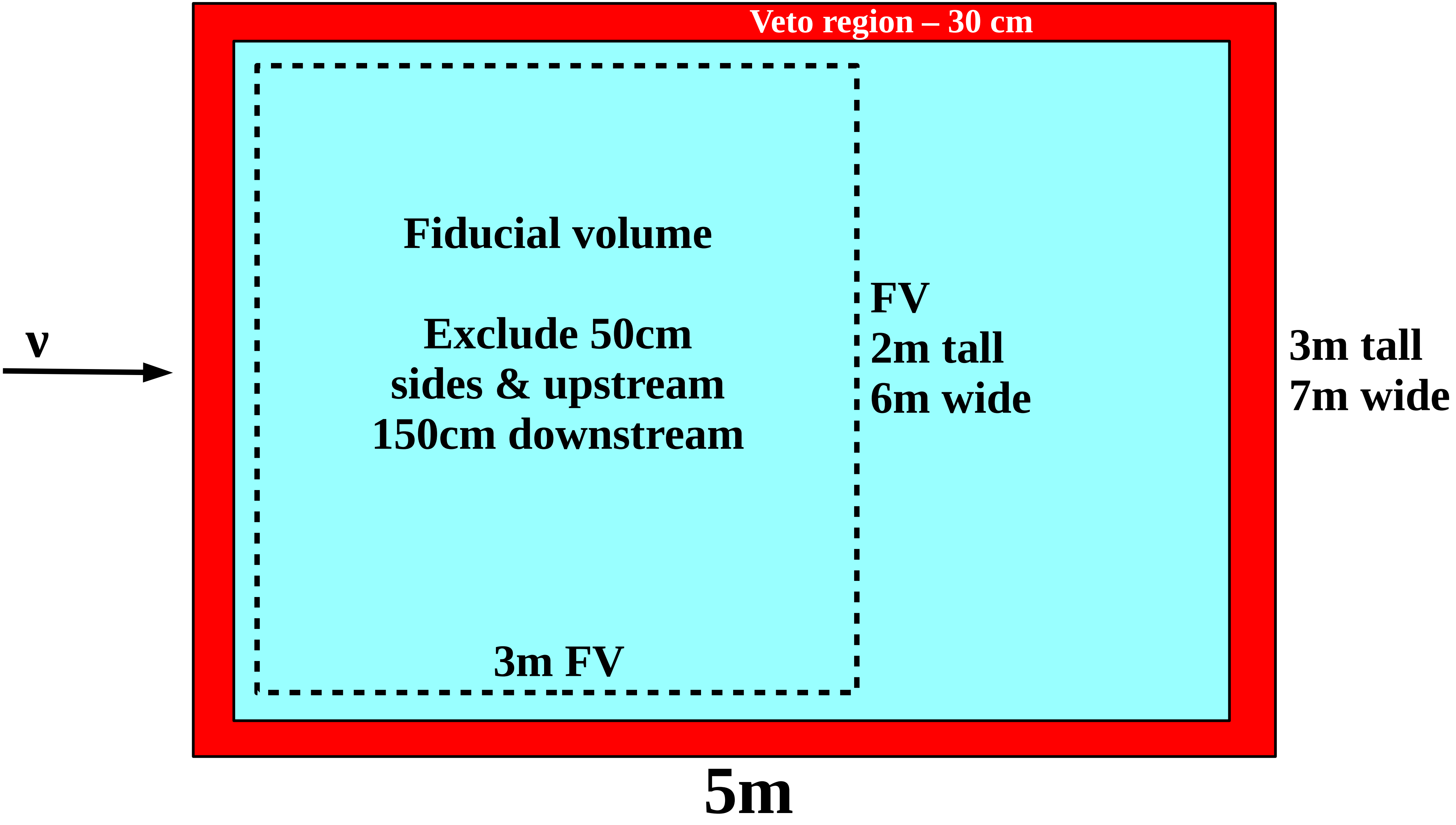


- Acceptance is >30% for most q0-q3 regions in the flux peak, and >50% for a lot of the space

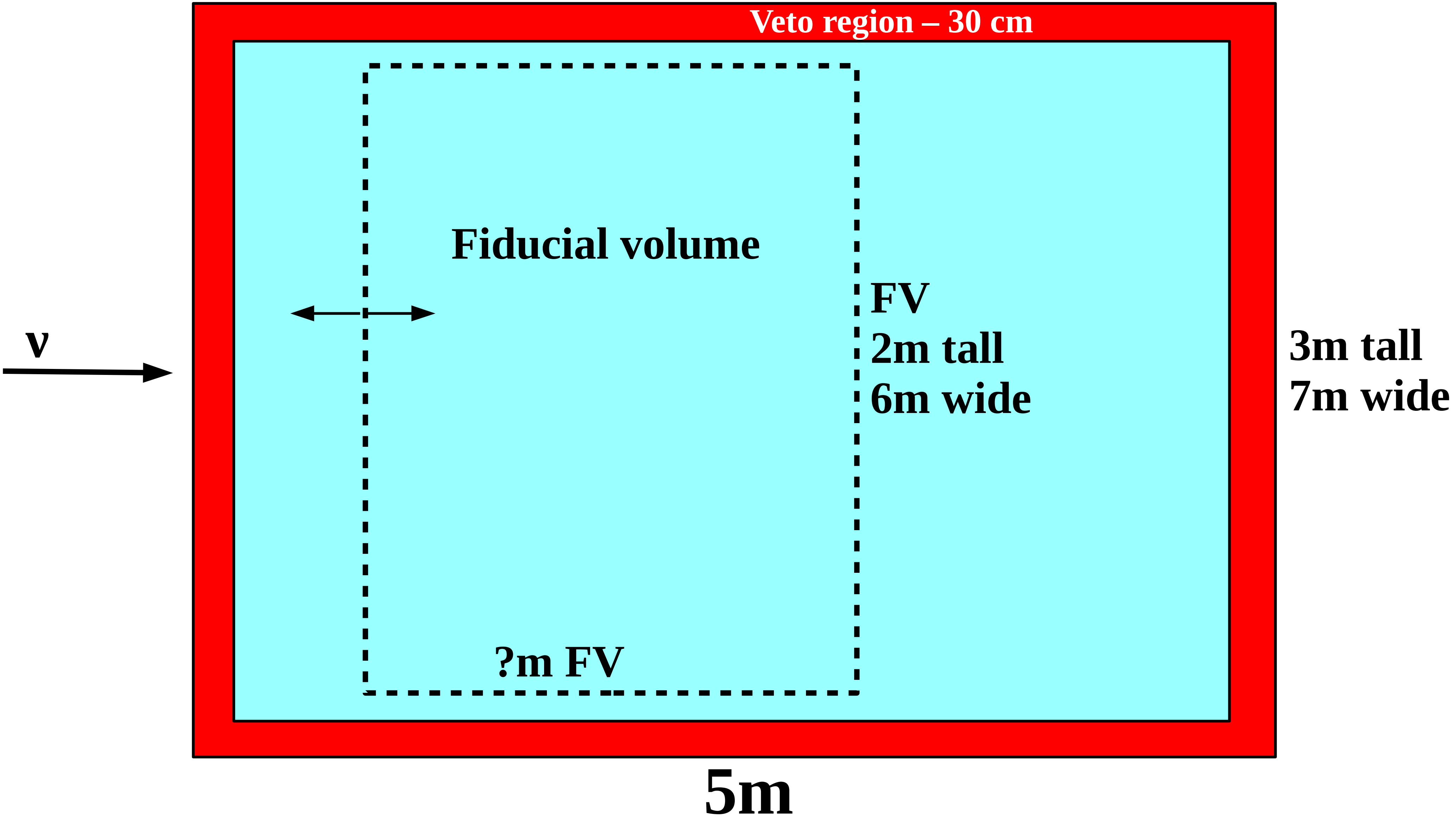
Acceptance in 50cm slices of vertex position

- Not quite the same as changing the detector dimensions, but we can look at the acceptance vs. z position to see what regions in the beam directions have good acceptance

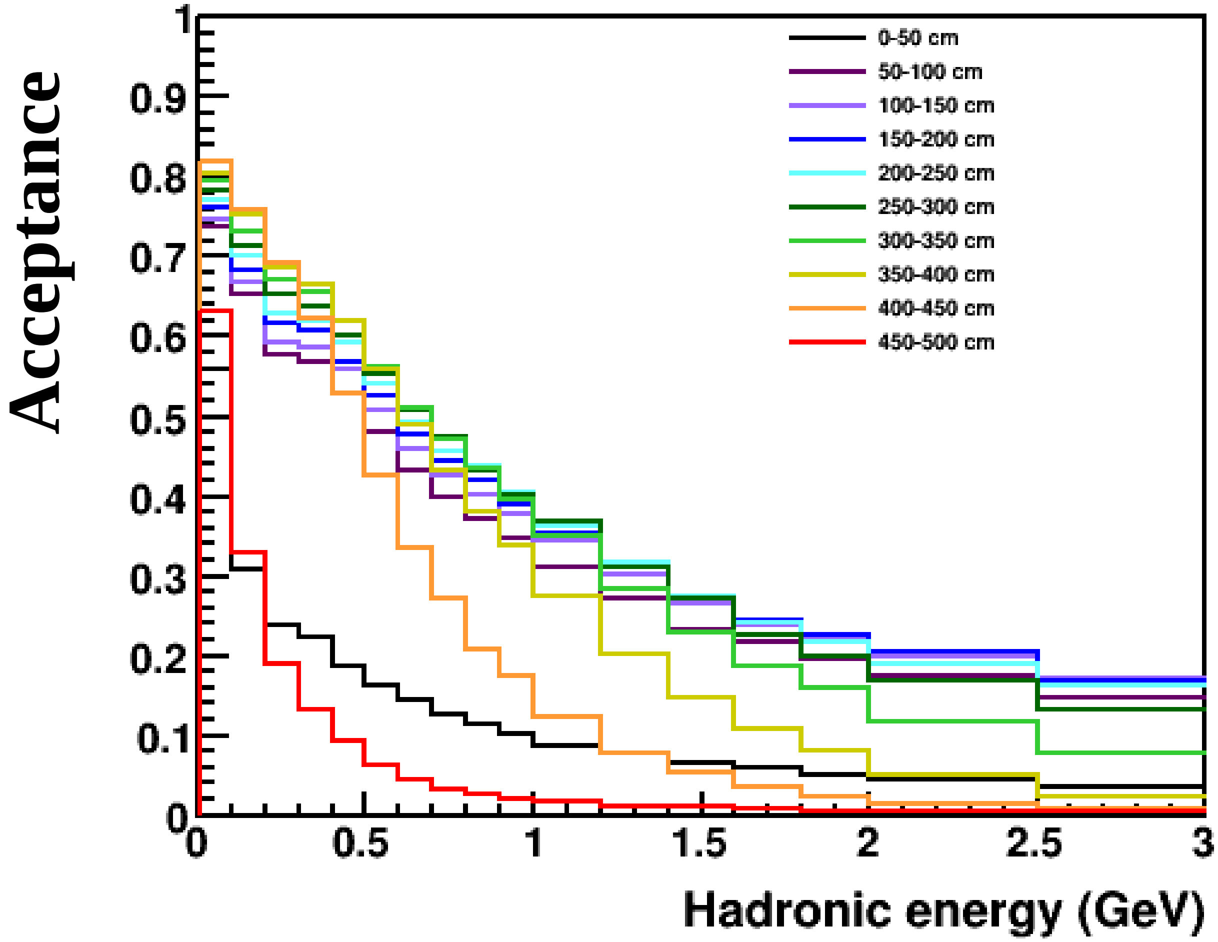
Fiducial, veto definitions



Acceptance vs. detector size



Hadronic acceptance



- In 50cm slices of vertex position
- Not quite the same as shortening the detector due to backscatter, which can be seen at very low hadronic energy
- Stable vs. hadronic energy up to 2m from downstream edge

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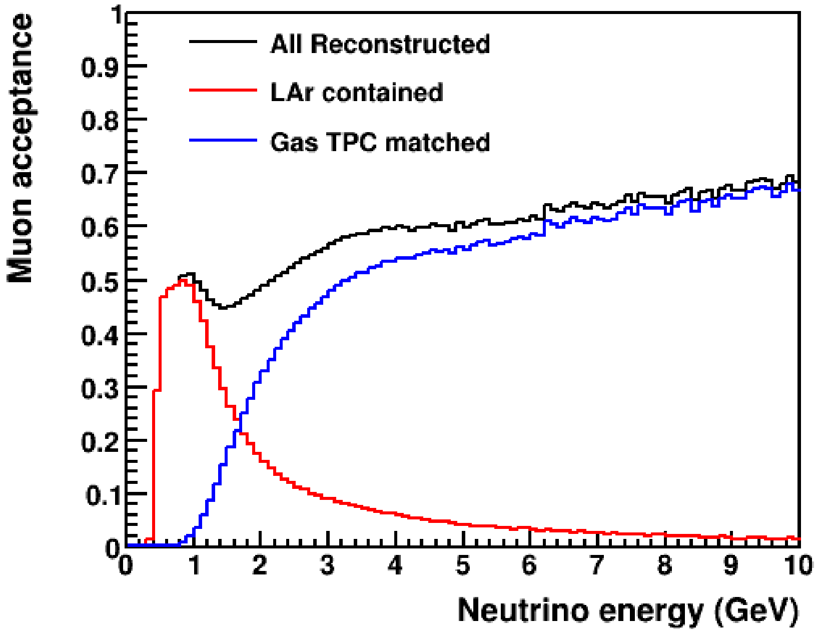
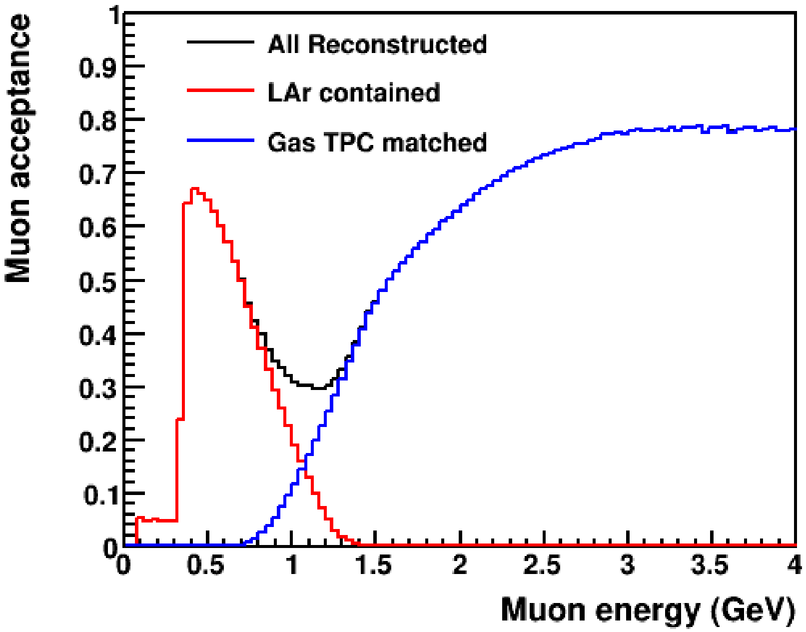
Comments

- “Awesome region” where acceptance is not changing as a function of Z position is between 50cm from upstream end and 2m from downstream end
- This is all dependent on GENIE, detector model, etc.
- It is critical to be able to study rates in different slices as a data-driven cross check of the acceptance estimate
- Detector must be significantly longer than this
- Since acceptance gets worse for more downstream vertices, shortening F.V. by X% reduces the well-reconstructed event rate by >X%

Muon acceptance

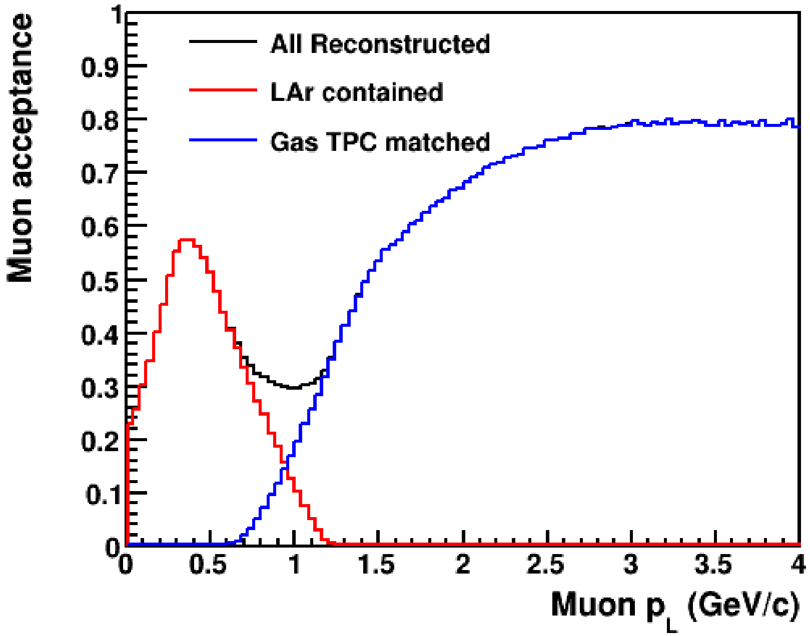




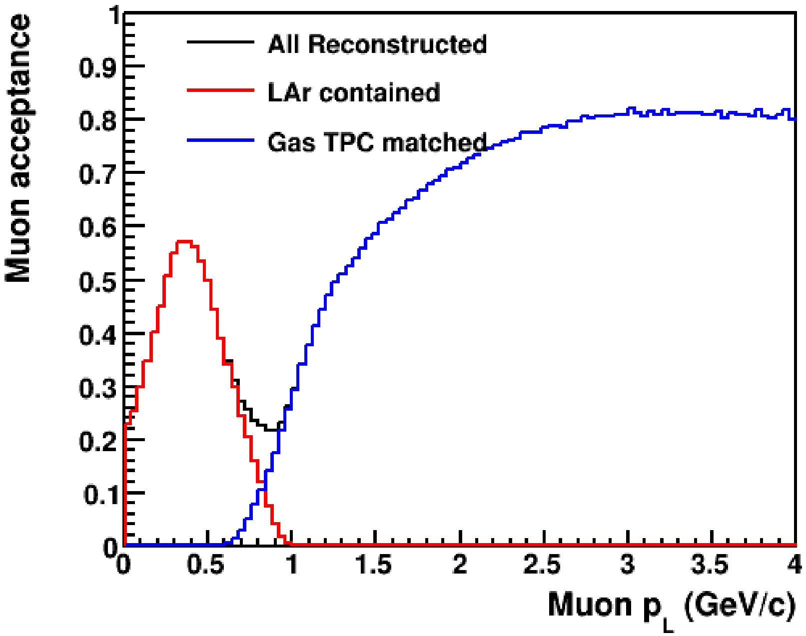
- “Dip” in muon acceptance is strongly dependent on the dead material between LAr & GAr
- This plot is for the “FD TDR geometry” with a magnet that is nothing like what we're planning to build

Muon acceptance vs. LAr size

5m long



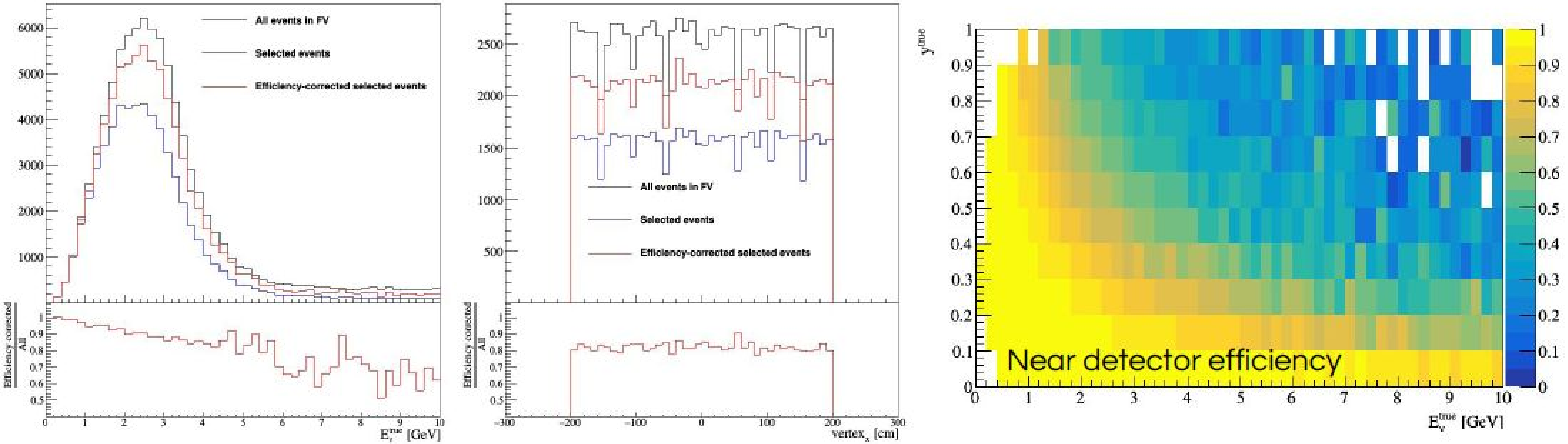
4m long



- Shortening the active LAr squeezes the contained muon distribution, which causes the dip to be deeper
- This is just an illustration of the effect of shortening the active region by 1m, with the same caveats about the dead material

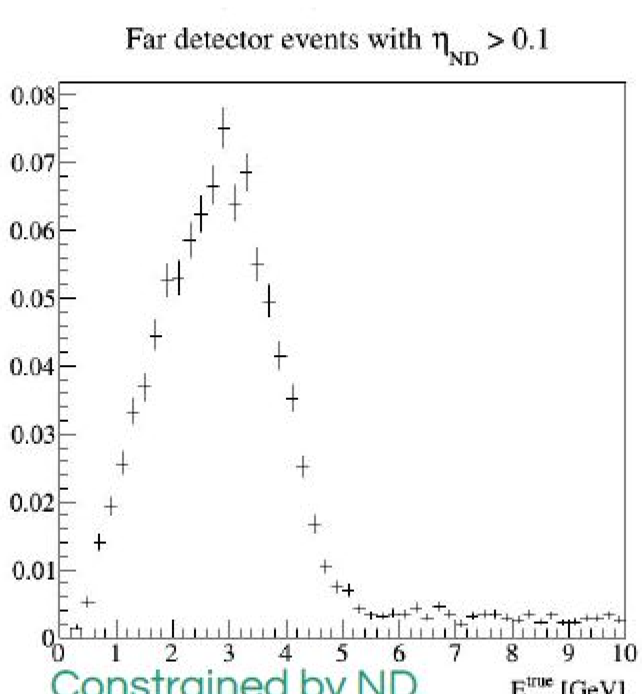
PRISM data-driven correction

- PRISM analysis is mostly concerned with uniformity of efficiency vs. X, but there is also an MC-based correction for events with very low acceptance in ND, which also depends on Z
- Work by Cris Vilela



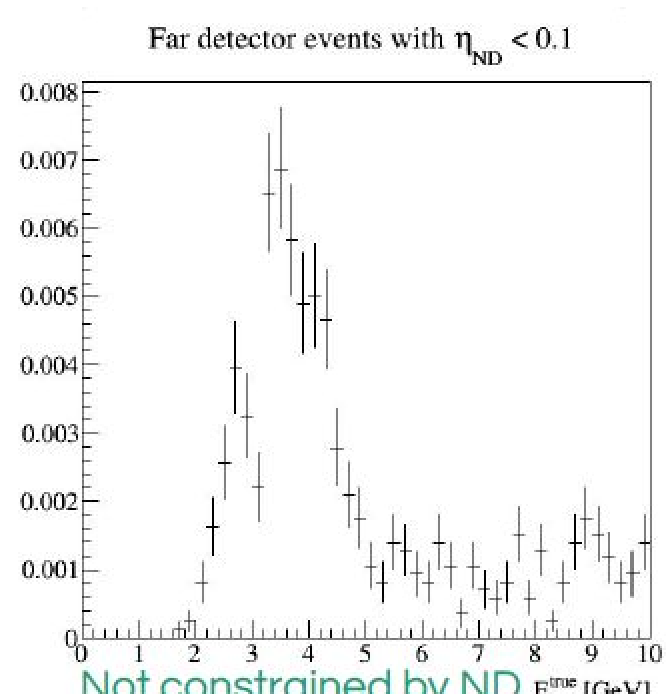
PRISM data-driven correction

- 5m detector has ~98% data-driven in the peak, ~90% in falling edge, but only ~50% in the tail > 6 GeV
- Large regions of (E_ν, y) with >0% but <10% acceptance



Constrained by ND

DUNE-PRISM LC analysis

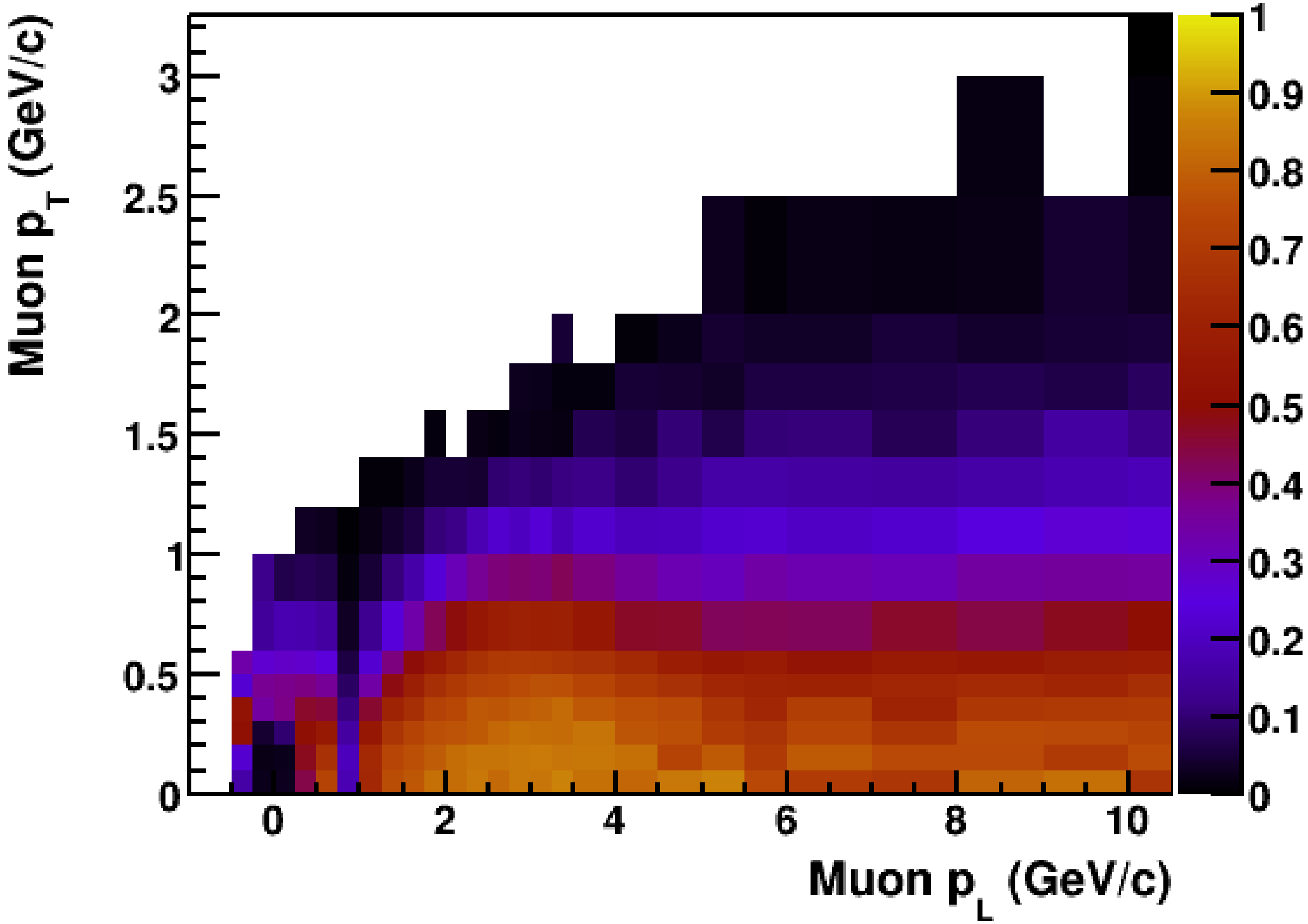


Not constrained by ND

MC-based analysis

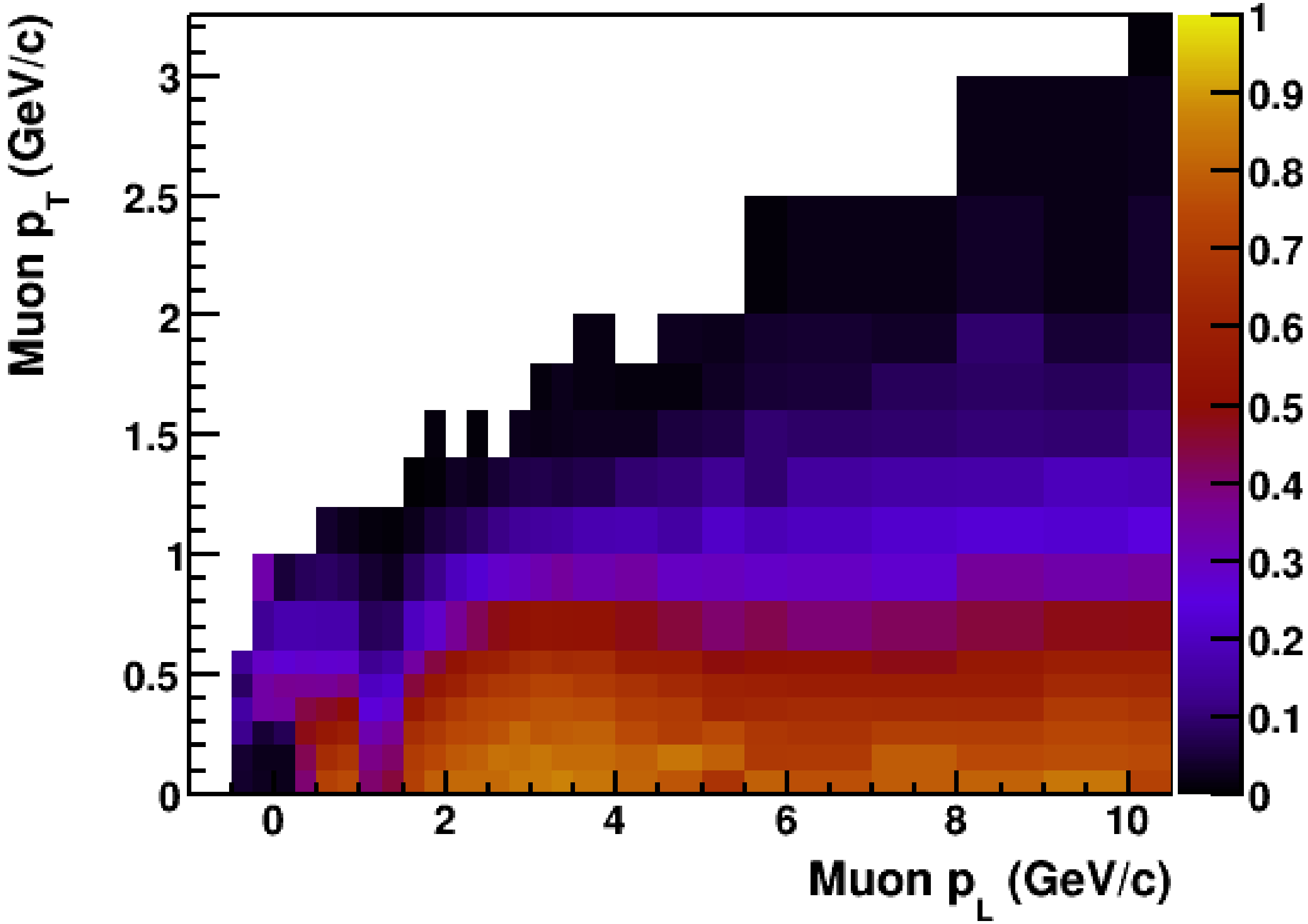
Backups/more slides

Acceptance vs. muon kinematics 200 < vertex z < 250cm



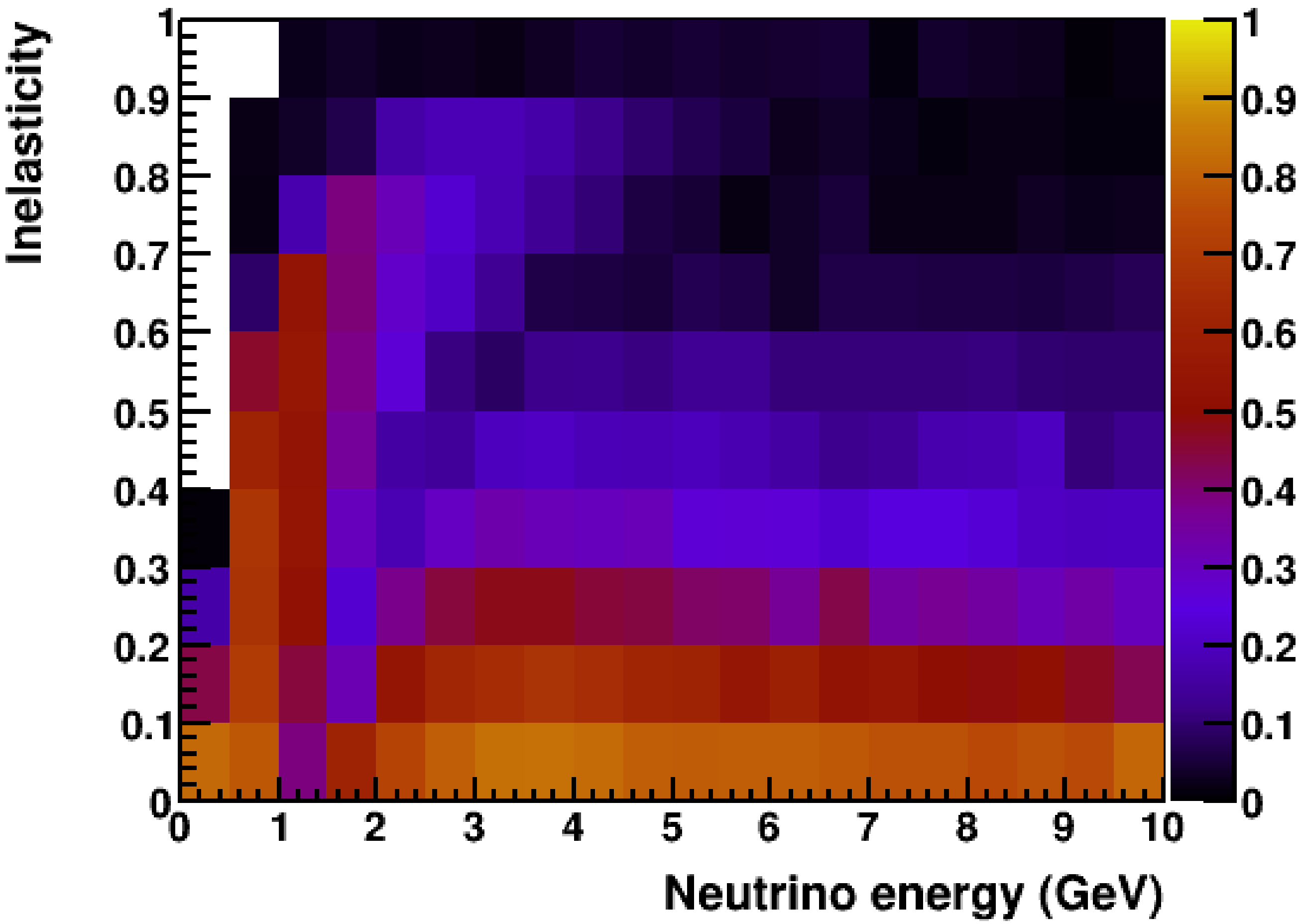
- For a given vertex position, there is an acceptance hole due to passive material between LAr and gas TPC

Acceptance vs. muon kinematics 50 < vertex z < 100cm



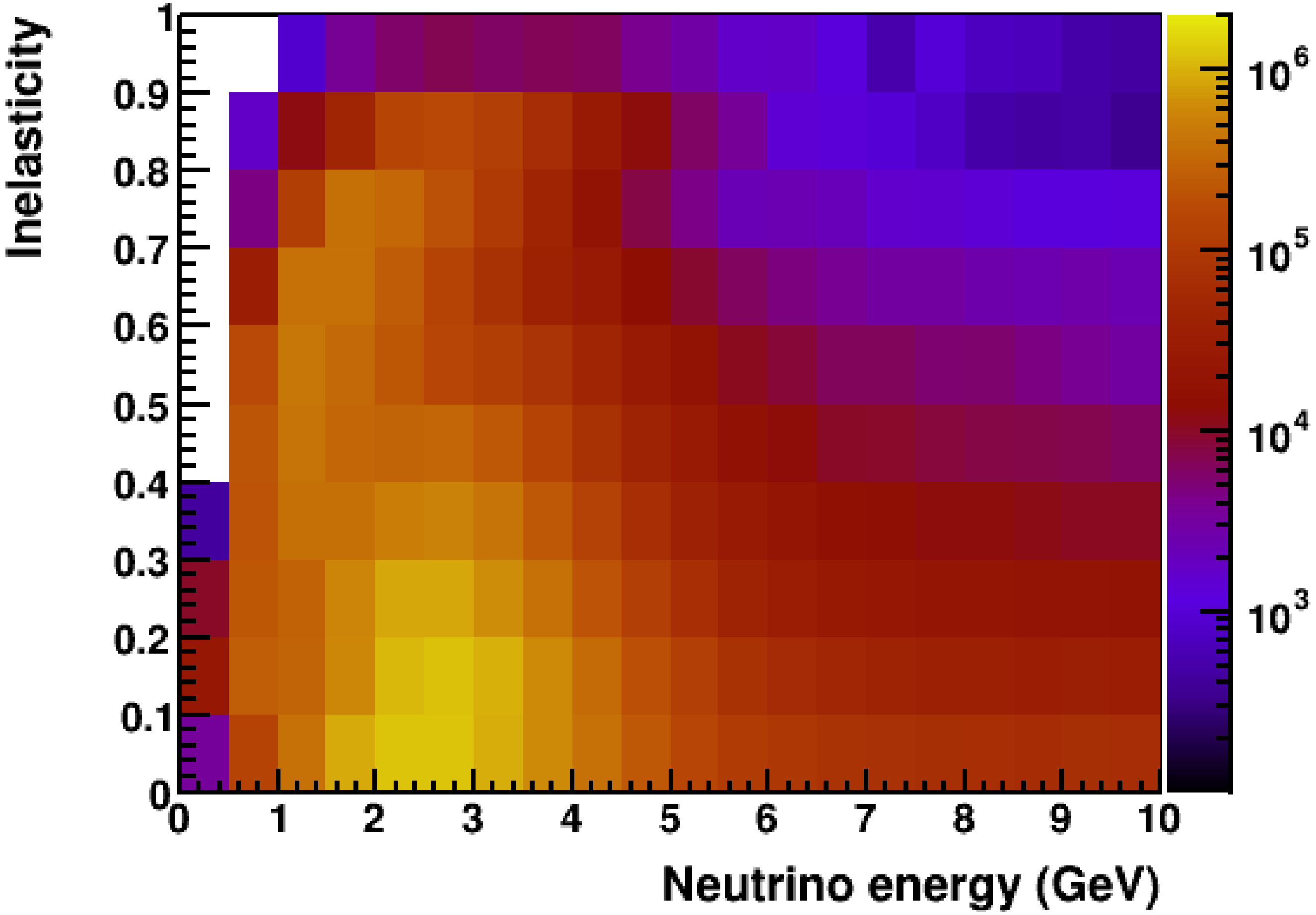
- Location of hole moves with vertex position
- It is critical that the LAr fiducial volume is much longer than the width of the gap
- Shorter LAr → more important to minimize dead material

Acceptance vs. neutrino energy 50 < vertex z < 100cm



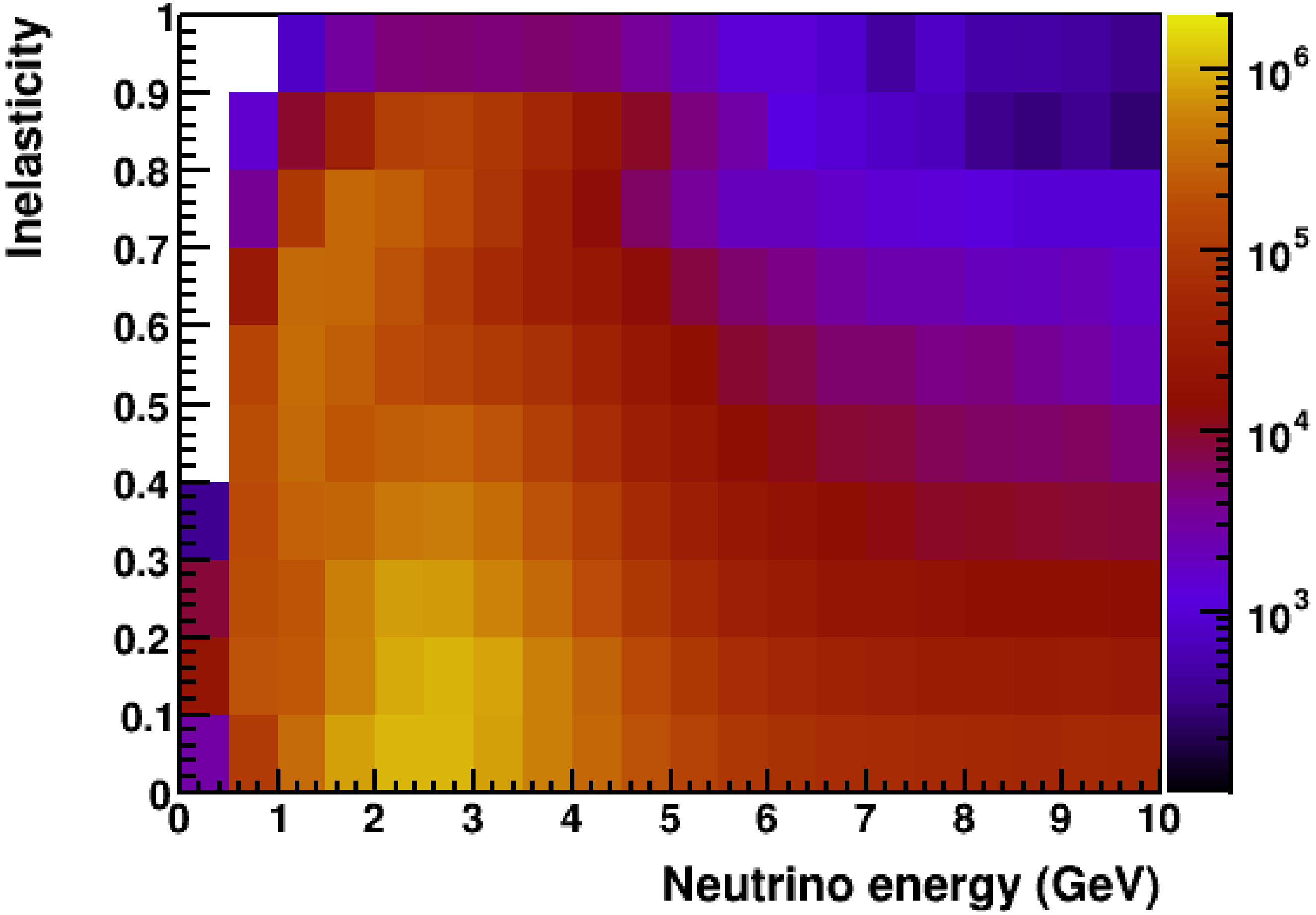
- Second oscillation maximum = 0.8 GeV is always contained for upstream vertex
- For shorter detector, muons at low y will always exit

Accepted CC ν_μ event rate per year



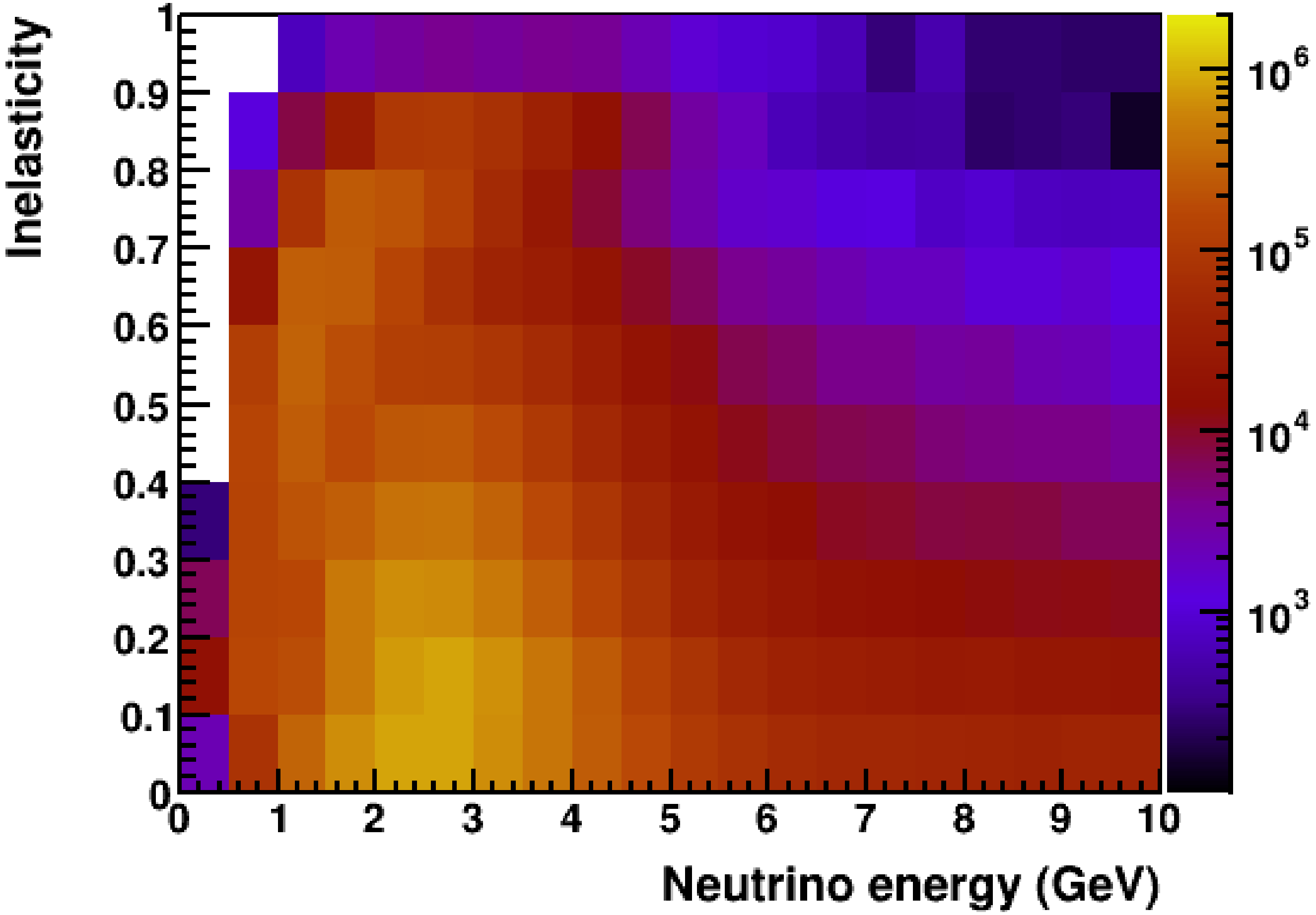
- Nominal 3x7x5 detector
- Shown is rate per bin per year at 1 MW
- 28M events total

Accepted CC ν_μ event rate per year



- Shortened 3x7x4.5
- Shown is rate per bin per year at 1 MW
- 24M events total

Accepted CC ν_μ event rate per year



- Shortened 3x7x4 detector
- Shown is rate per bin per year at 1 MW
- 19M events total

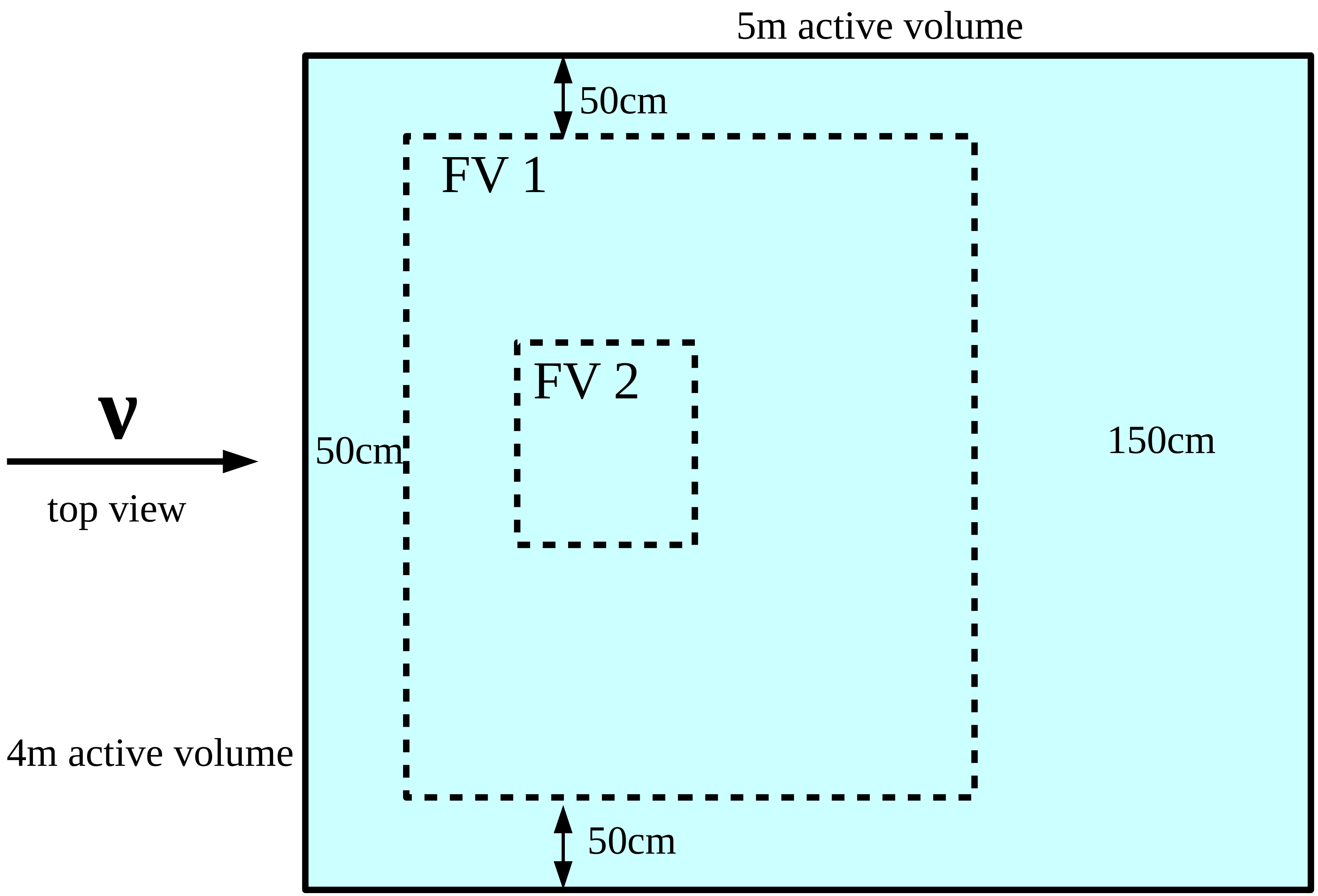
ν+e elastic rate

- ~100 events per year per ton Ar assuming 90% efficiency and threshold of 800 MeV
- 2 meters along beam direction cannot be used
  - Upstream 50cm required to avoid backgrounds from photons produced in upstream material
  - Downstream 150cm (11 radiation lengths) required for energy reconstruction
- ~3000/yr for 3x4x5, ~6000/yr for 3x7x5
- Shortening from 5m → 4m reduces ν+e rate by 33%

Conclusions

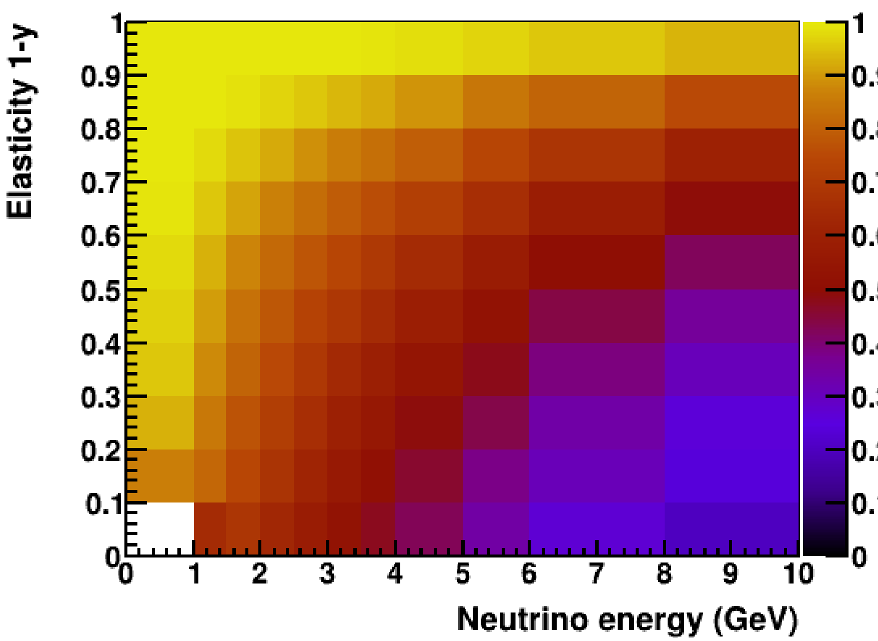
- Shortening ArgonCubeND to ~4.5m does not obviously break physics capability, but carries significant risk
  - Worse hadronic containment
  - Smaller volume over which containment is stable → increased dependence on interaction & detector models
  - More stringent requirements on passive material between detectors
- Reduction in rate is not problematic, rate is still high
- Reduction in ν+e rate is not ideal, could be compensated with additional detector width

2 different fiducial volumes

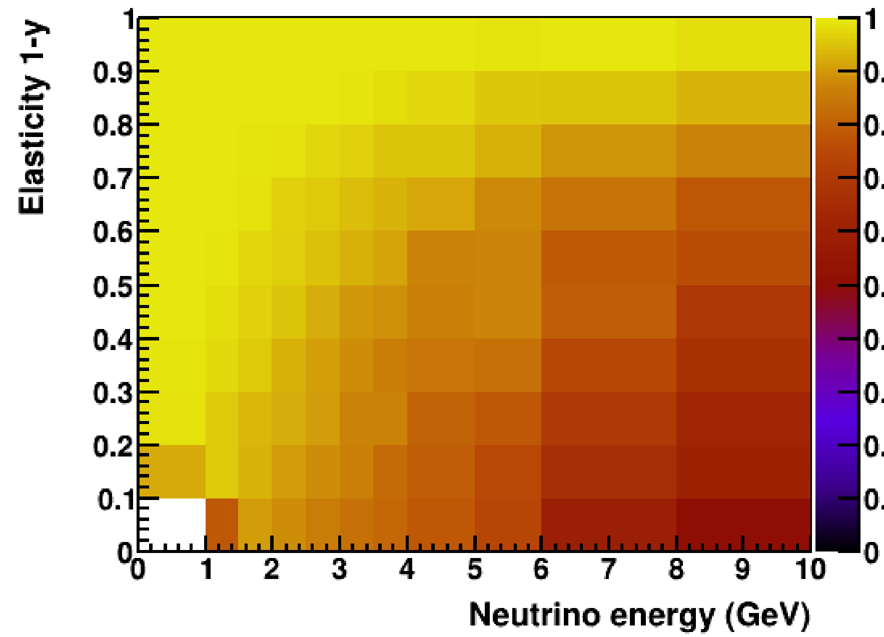


Acceptance for 4x3x5m LAr detector for different F.V.

Acceptance for 3x2x3m F.V.



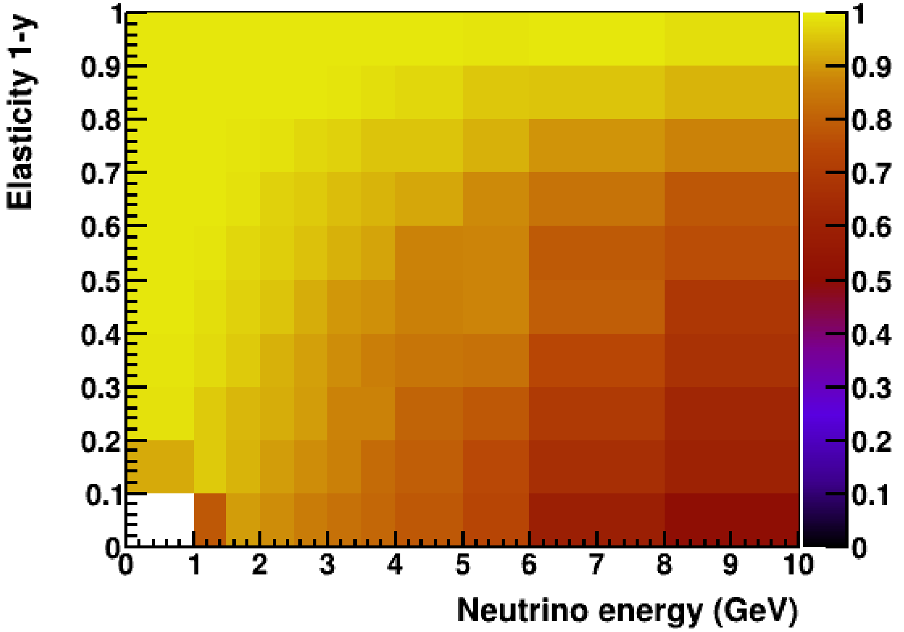
Acceptance for central 1x1x1m region



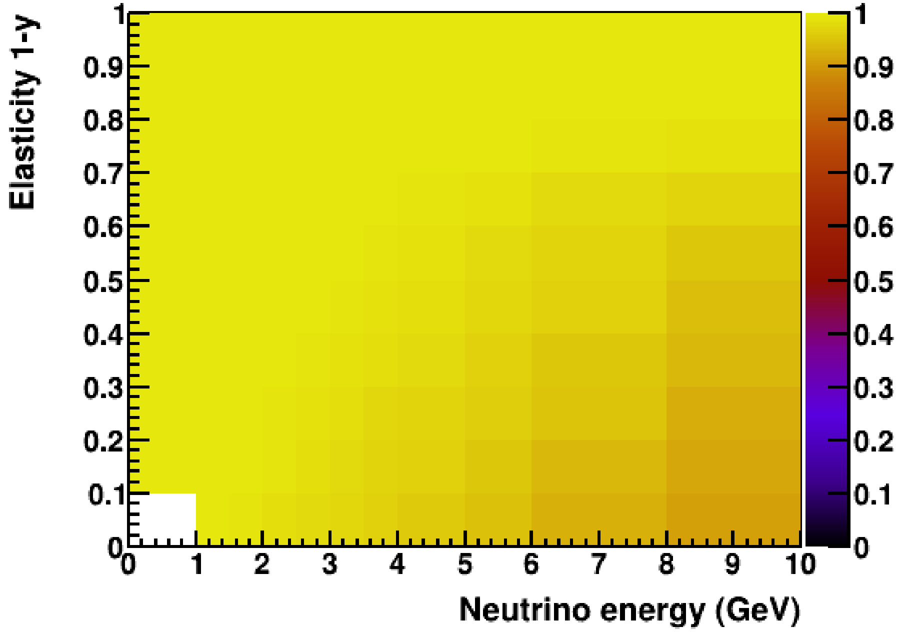
- ν_μ CC events only, y axis is $1\text{-}y = E_\mu/E_\nu$
- When hadronic energy is large, only ~20% of fiducial events are contained, but that goes up to ~50% if you restrict to a 1x1x1m volume in the very center

Acceptance vs. XS coverage

Acceptance for central 1x1x1m F.V.

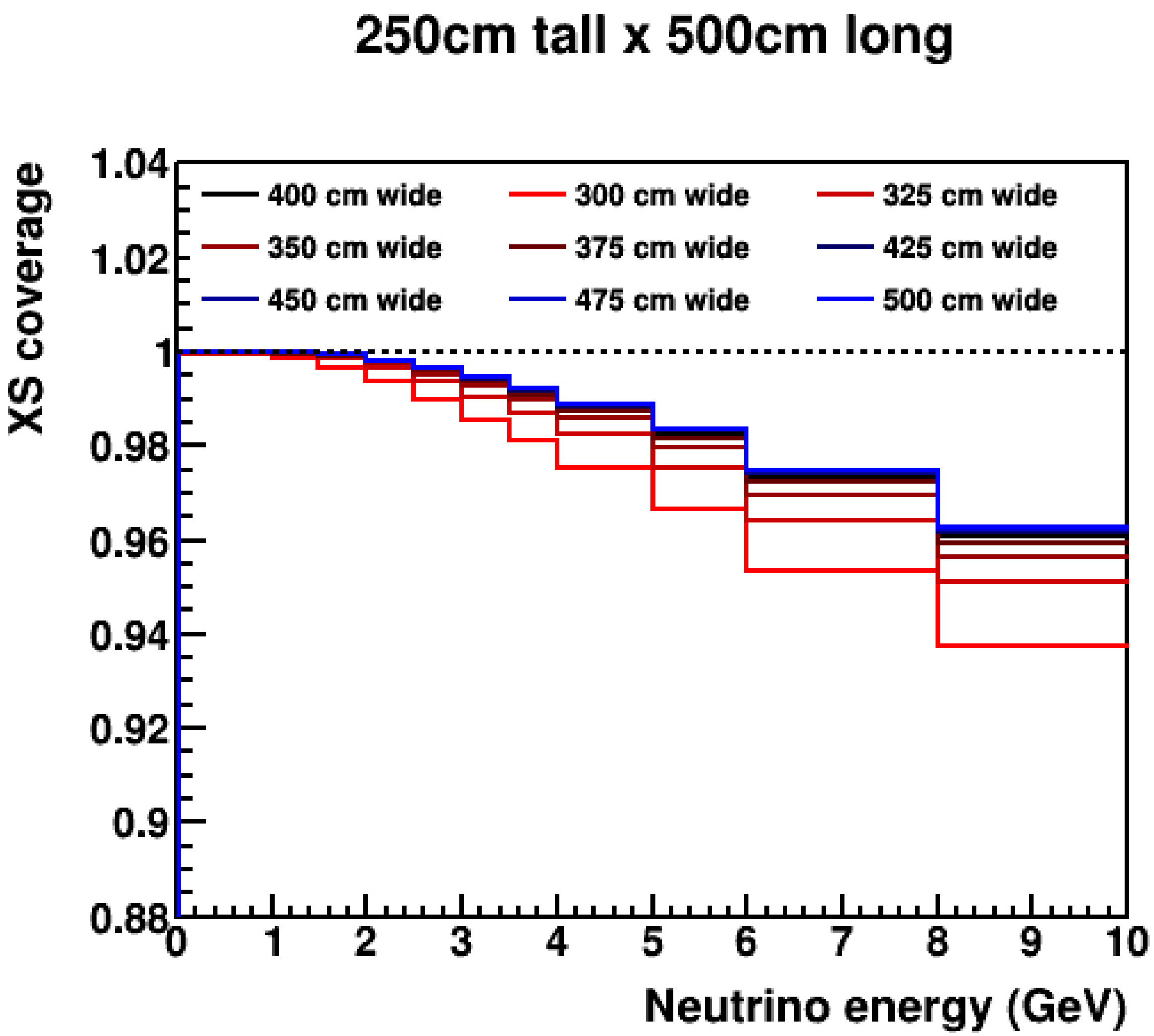


XS coverage for 3x2x4 region



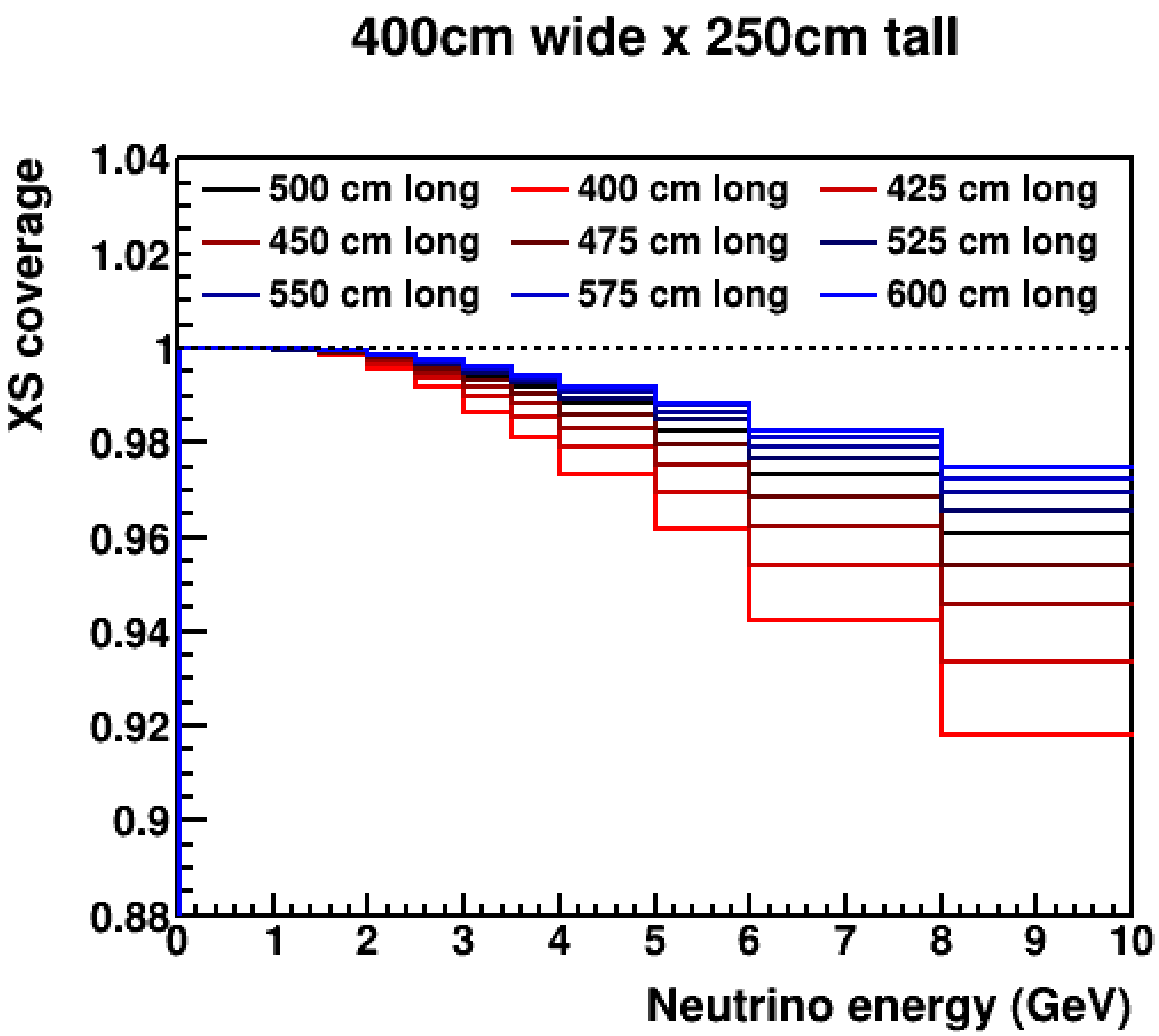
- "XS coverage" includes translation and phi symmetry, in a region 1m smaller than detector size in each dimension (i.e. 50cm buffer around the edge)

XS coverage vs. X



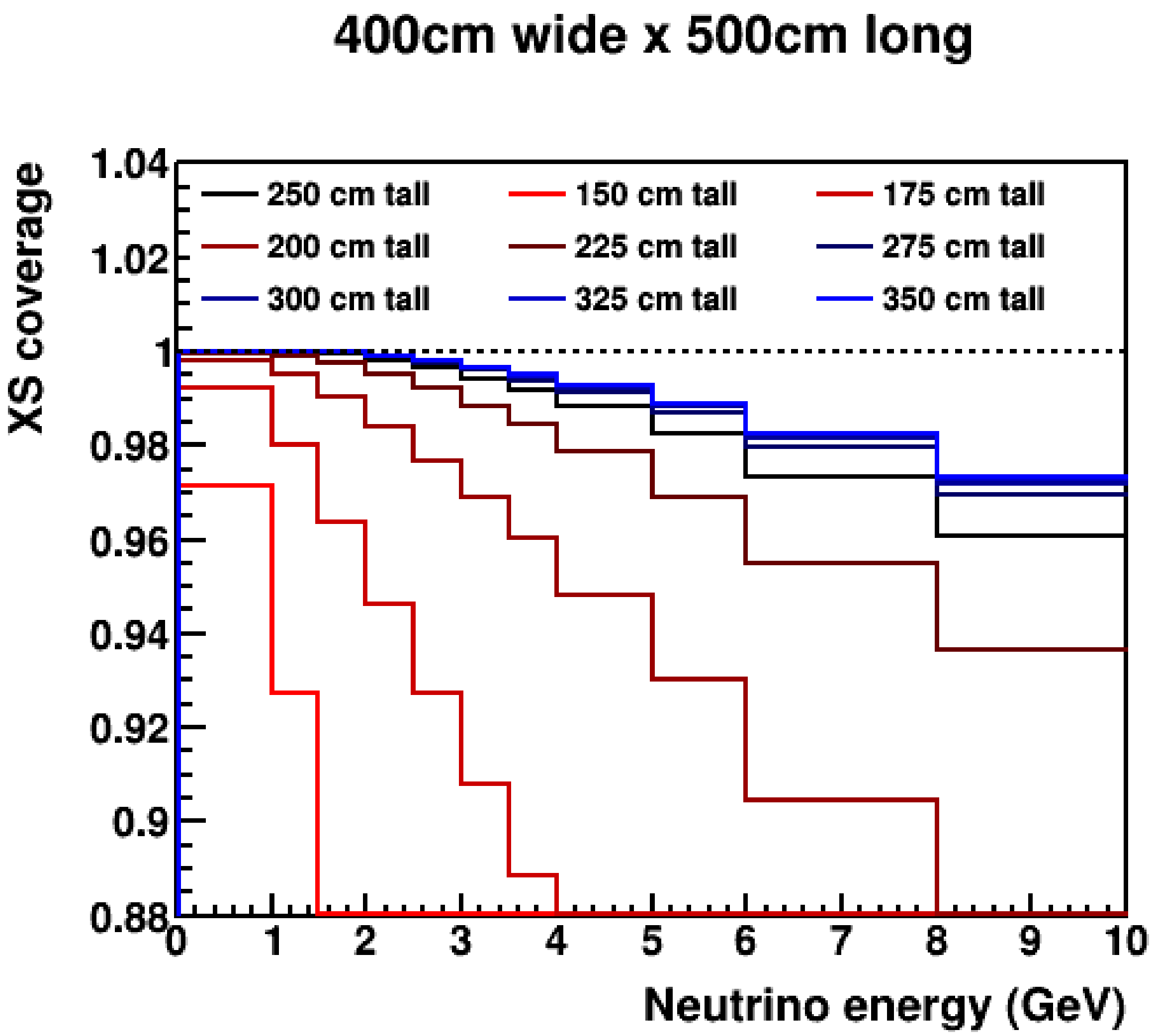
- Integrating out the 1-y variable, plot XS coverage for different size detectors
- Here, Y and Z dimensions are fixed at 250cm x 500cm
- Nominal X is 400cm, red is smaller, blue is larger
- For all sizes, 50cm buffer on all sides is assumed

XS coverage vs. Z



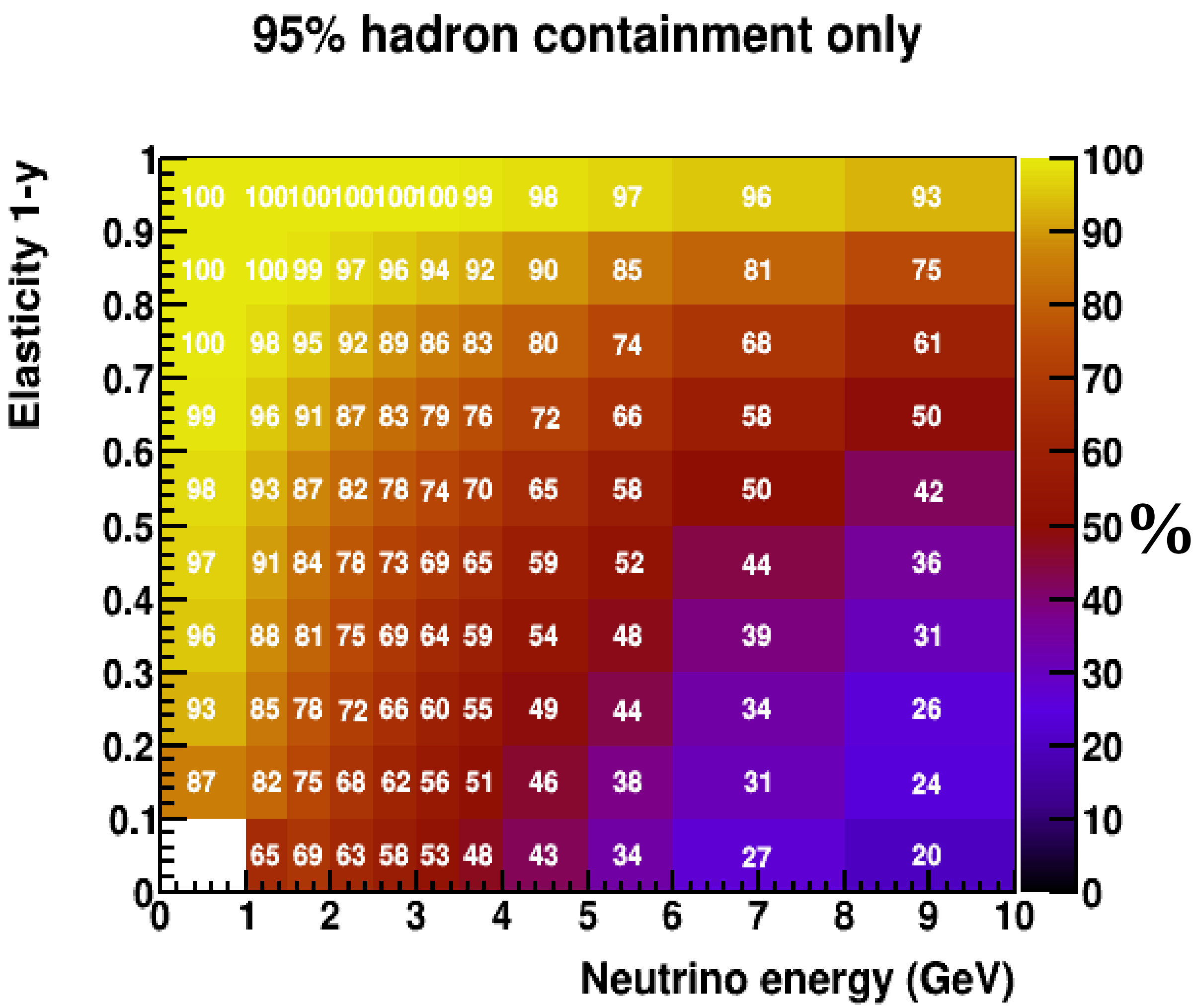
- X and Y are fixed at nominal 400cm wide x 250cm tall
- Black is nominal 500cm long, red is shorter, blue is longer

XS coverage vs. Y



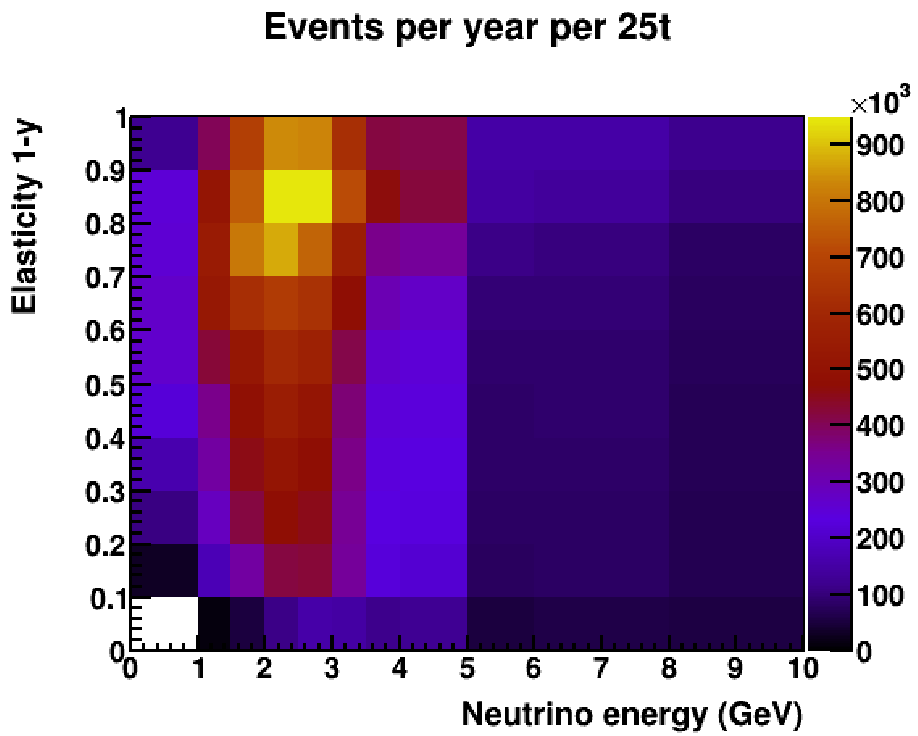
- X and Z are fixed at 400cm x 500cm
- Y (height) is varied, with black being nominal 250cm, red shorter, blue taller
- 250cm is right on the edge of significant loss of acceptance
- If Nature produces larger hadronic showers than GENIE, we could be in trouble
- 3m would be much safer

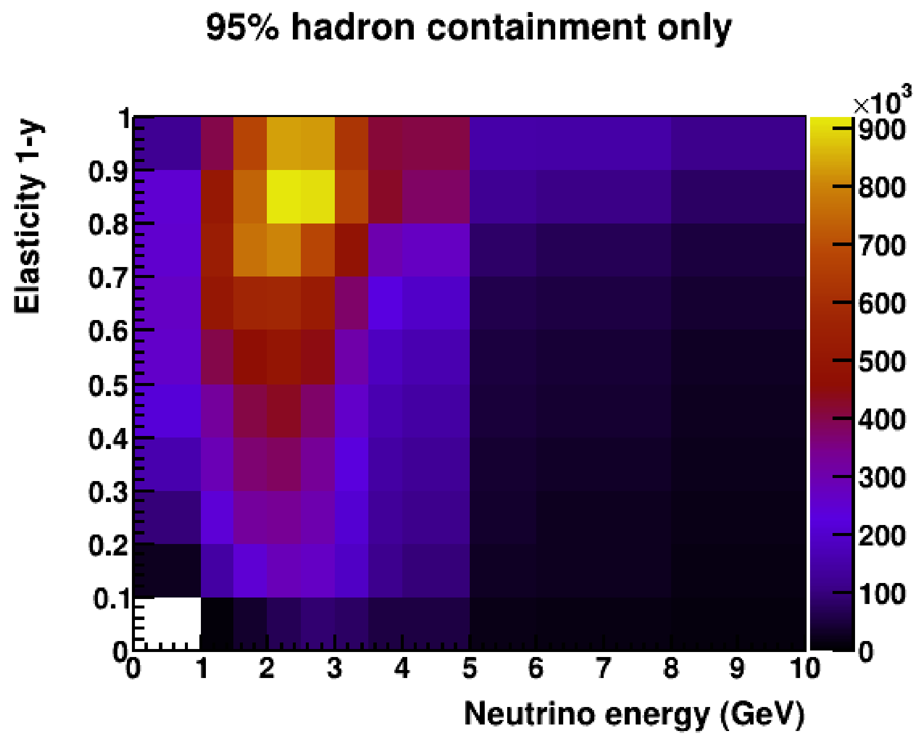
Hadronic shower acceptance



- 4x3x5m detector
- Fiducial volume is 3x2x3m
- 50cm upstream and side buffer
- 150cm downstream side
- Reject events with >20MeV in outer 30cm of detector

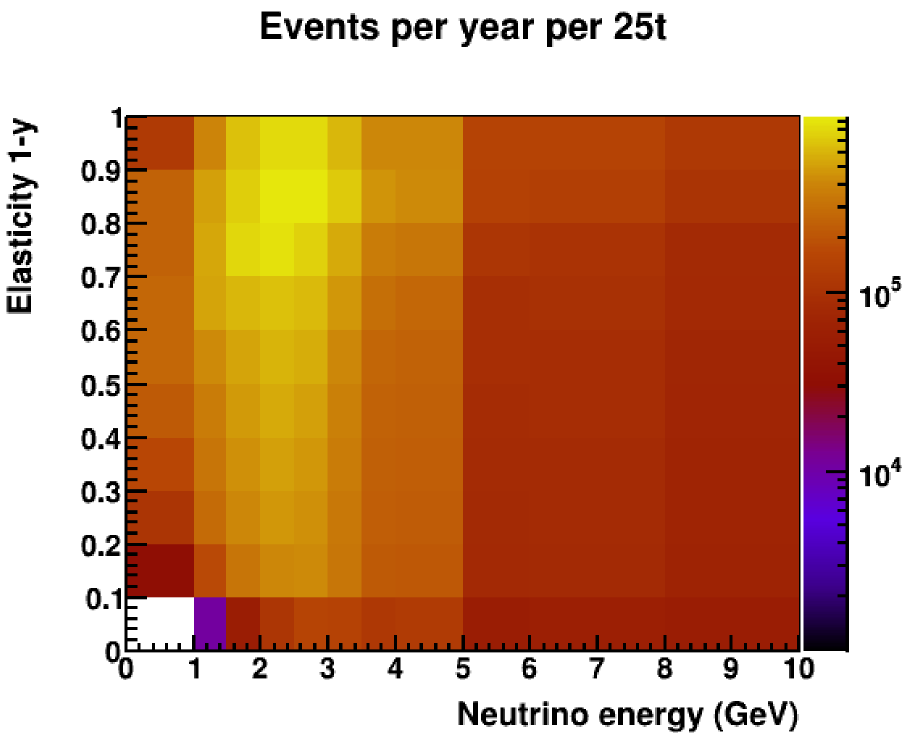
Event rates per bin per year for this F.V.

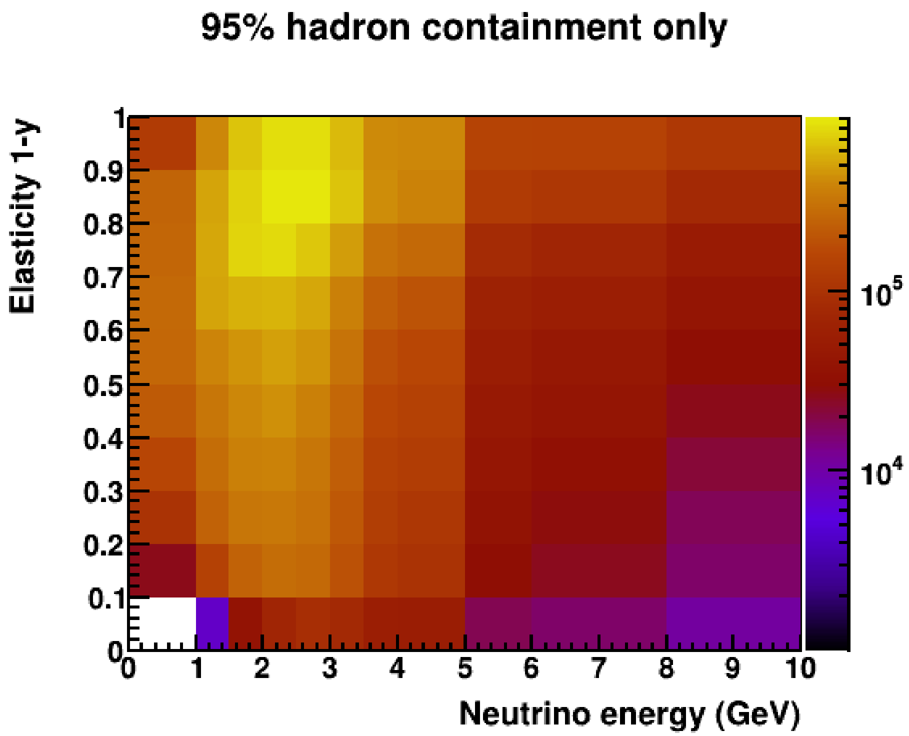




- ~1M per bin in the peak
- 10,000s events per bin in the worst bins of the tail

Event rates per bin per year for this F.V.



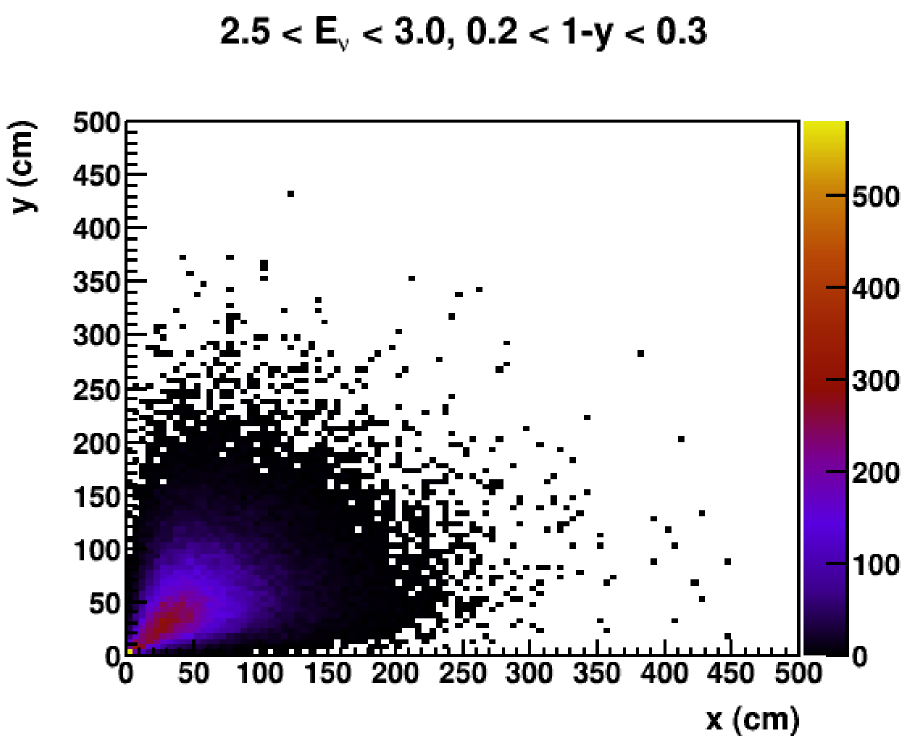


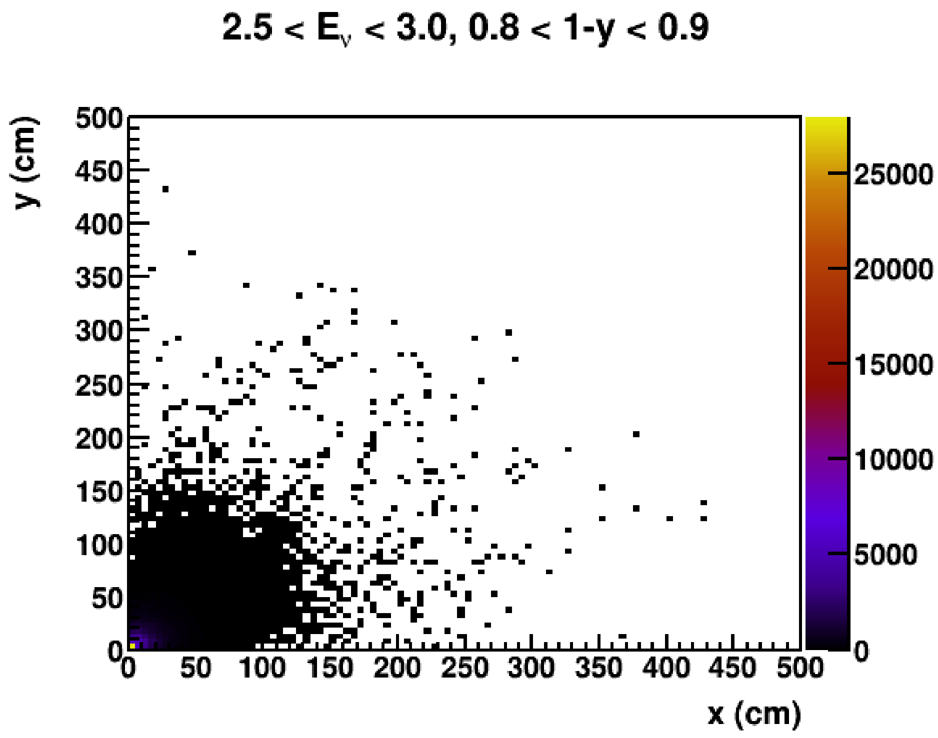
- ~1M per bin in the peak
- 10,000s events per bin in the worst bins of the tail

Conclusions

- 4m in longer transverse dimension is fine
- 5m in ~beam direction is fine
- 2.5m in shorter transverse dimension requires faith
- Extra 50cm is very beneficial – puts us in a regime where the acceptance is not rapidly changing with detector size

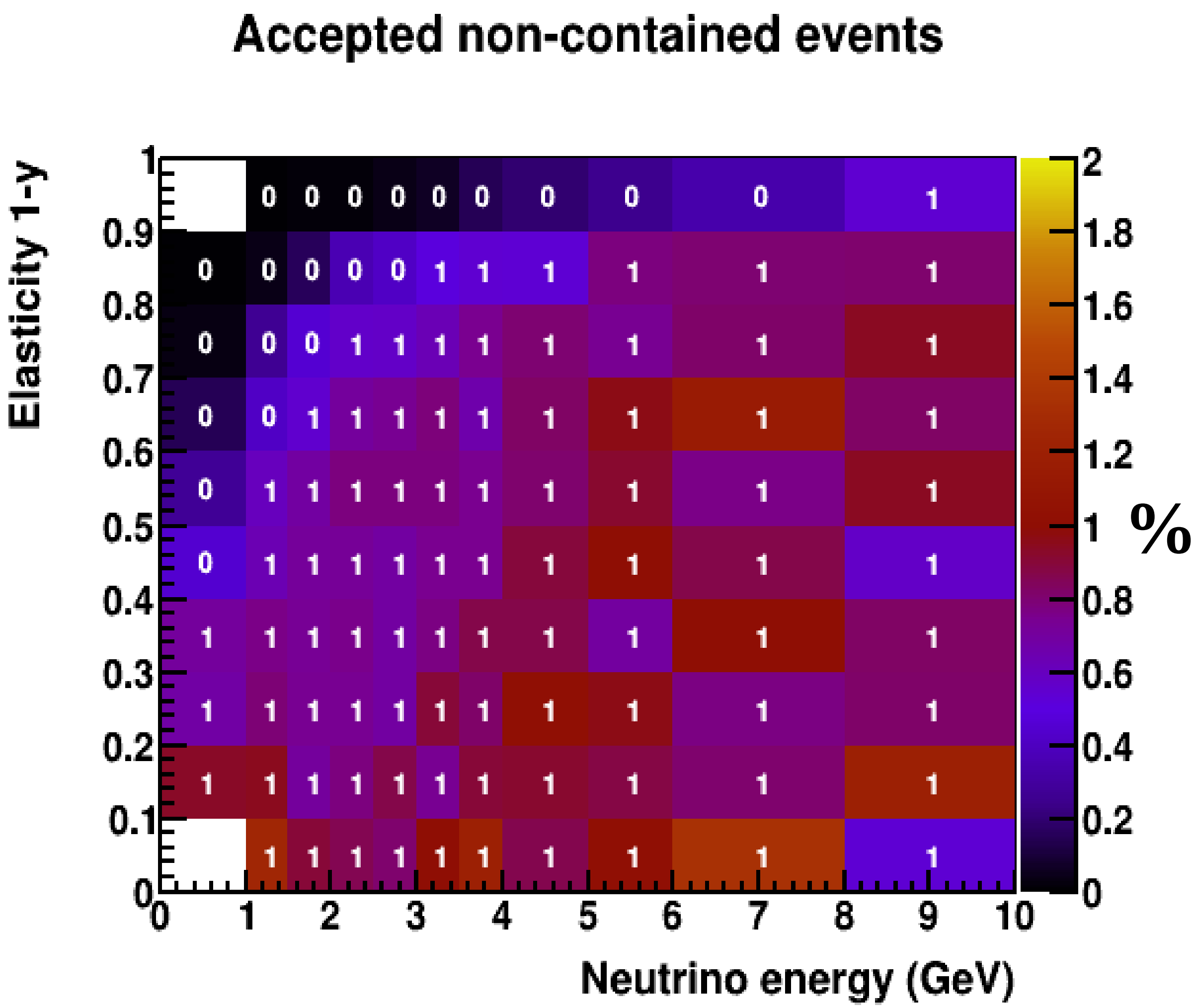
Size of hadronic showers simulated in G4





- In each E_ν-y bin, take distribution of size of hadronic shower in XYZ simulated in thousands of events
- Use this distribution as a proxy for the cross section, which depends on many variables (Q^2, N_π, E_π, N_p, N_n, etc.)

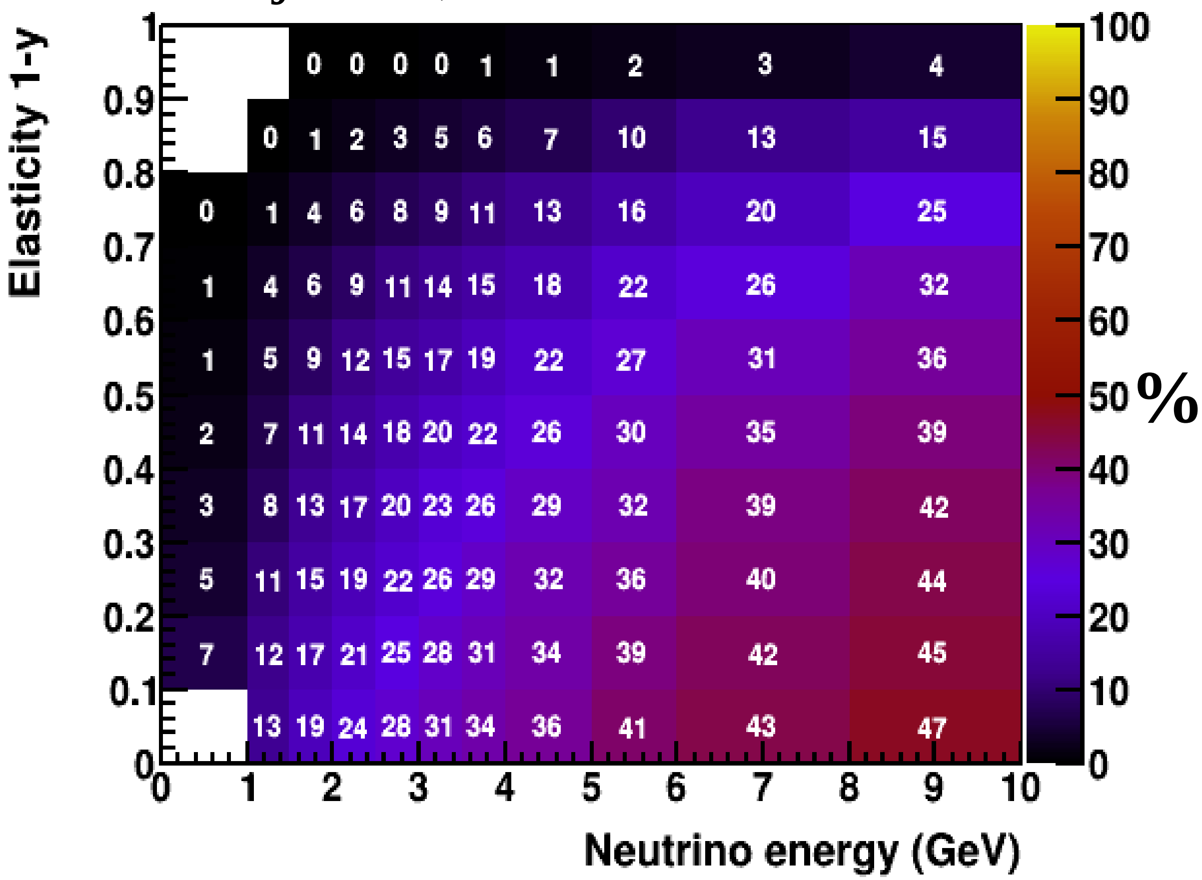
Containment cut purity



- Percent of events which have <20MeV in outer 30cm region, but have <95% hadronic energy contained in detector
- ~1% at high hadronic energy
- Not very sensitive to choice of 20MeV or 30cm
- Also looked at making this fractional to the visible energy in detector, negligible differences

Containment cut inefficiency

Rejected, but >95% contained



- Percent of events which have >95% hadronic energy contained, but >20MeV in outer 30cm region
- Significant losses in very high hadronic energy, where events frequently “end” near the edge