Status of LAr simulations

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Outline: The Questions

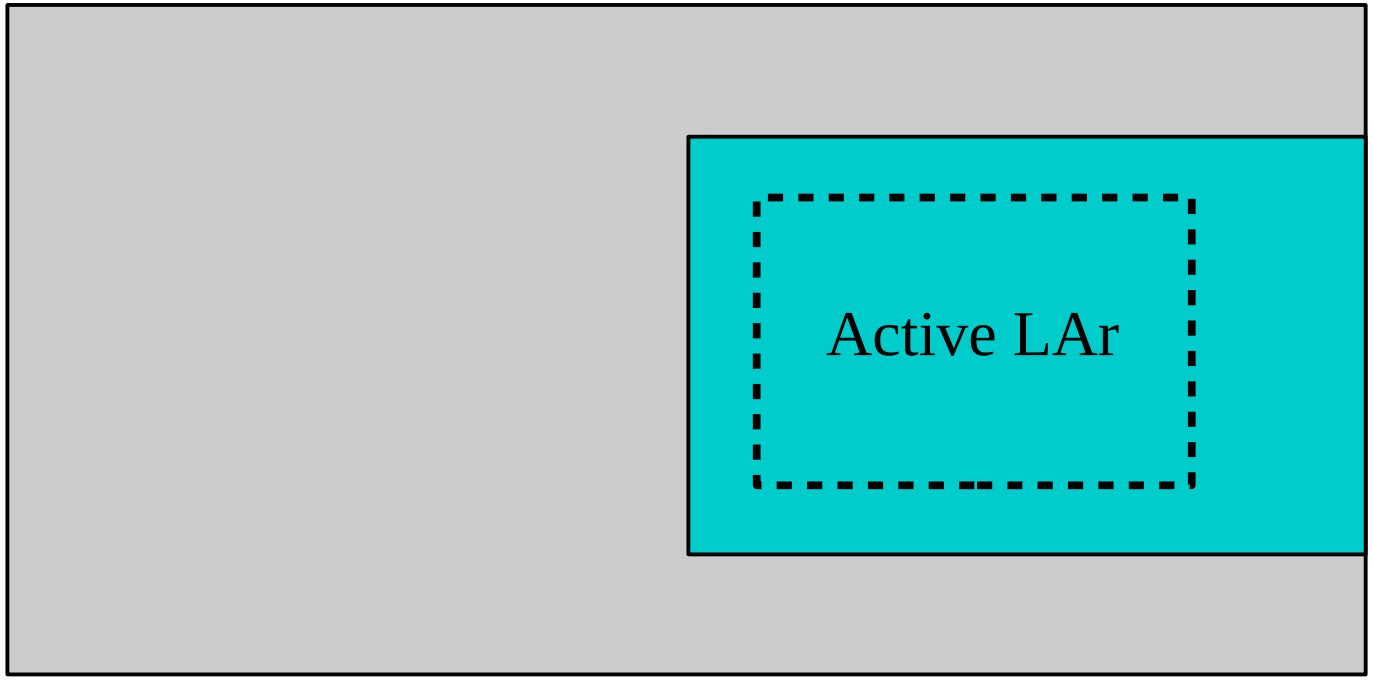
- Can LAr detector handle the high rate?
- What size is needed for hadron containment?
- What is the statistics in the fiducial volume?
- What is the muon acceptance for LAr interactions for the different tracker options?
- Is a side muon spectrometer needed?
- Can neutrino-electron scattering be measured?

Preview: The Answers

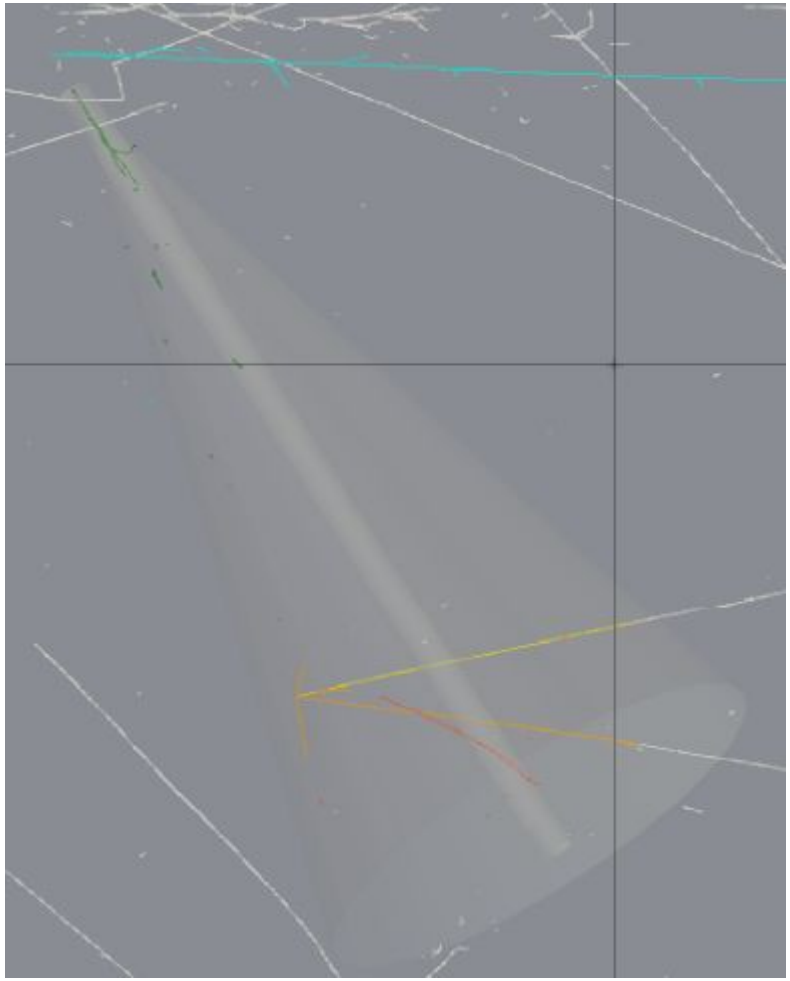
- Can LAr detector handle the high rate?
  - Tracks: yes, π^0 photons: yes, neutrons: maybe?
- What size is needed for hadron containment?
  - 4x3x5m, with 5m in ~beam direction
- What is the statistics in the fiducial volume?
  - High. For 3x2x3m F.V. (25t), 37M ν_μ CC events per year at 1.07 MW
- What is the muon acceptance for LAr interactions for the different tracker options?
  - That one is hard to answer in one bullet, but there are plots
- Is a side muon spectrometer needed?
  - Yes, otherwise the required width for muon acceptance is ~7m
- Can neutrino-electron scattering be measured?
  - Yes, with <2% normalization uncertainty and some shape power

Pile-up: LAr in high rate

- Damian Goeldi (Bern)
- Simulate interactions in 8x6x10m volume, with 4x3x5m LAr detector
- Analyze events in 3x2x3m active LAr F.V.



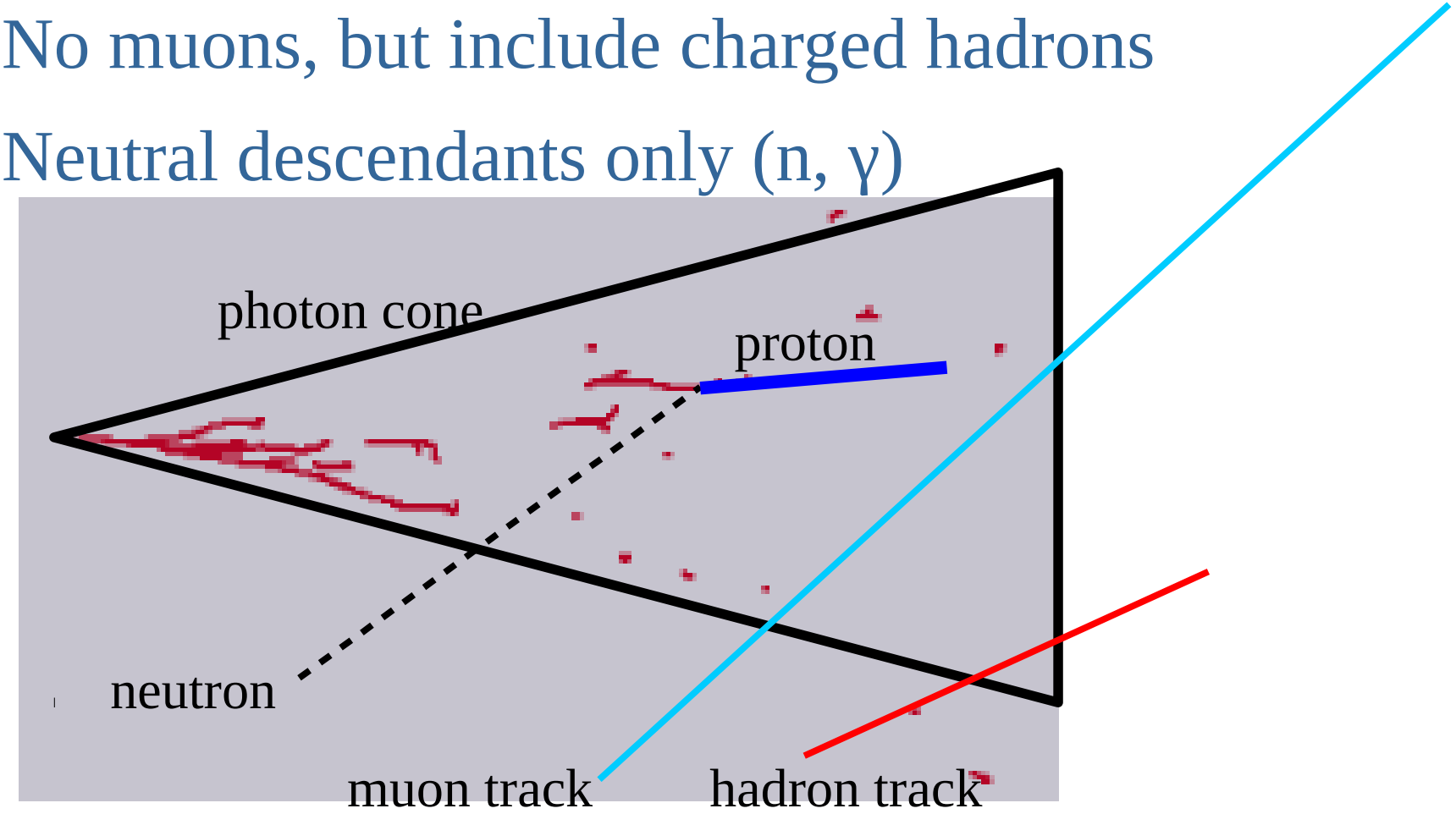
Analysis strategy



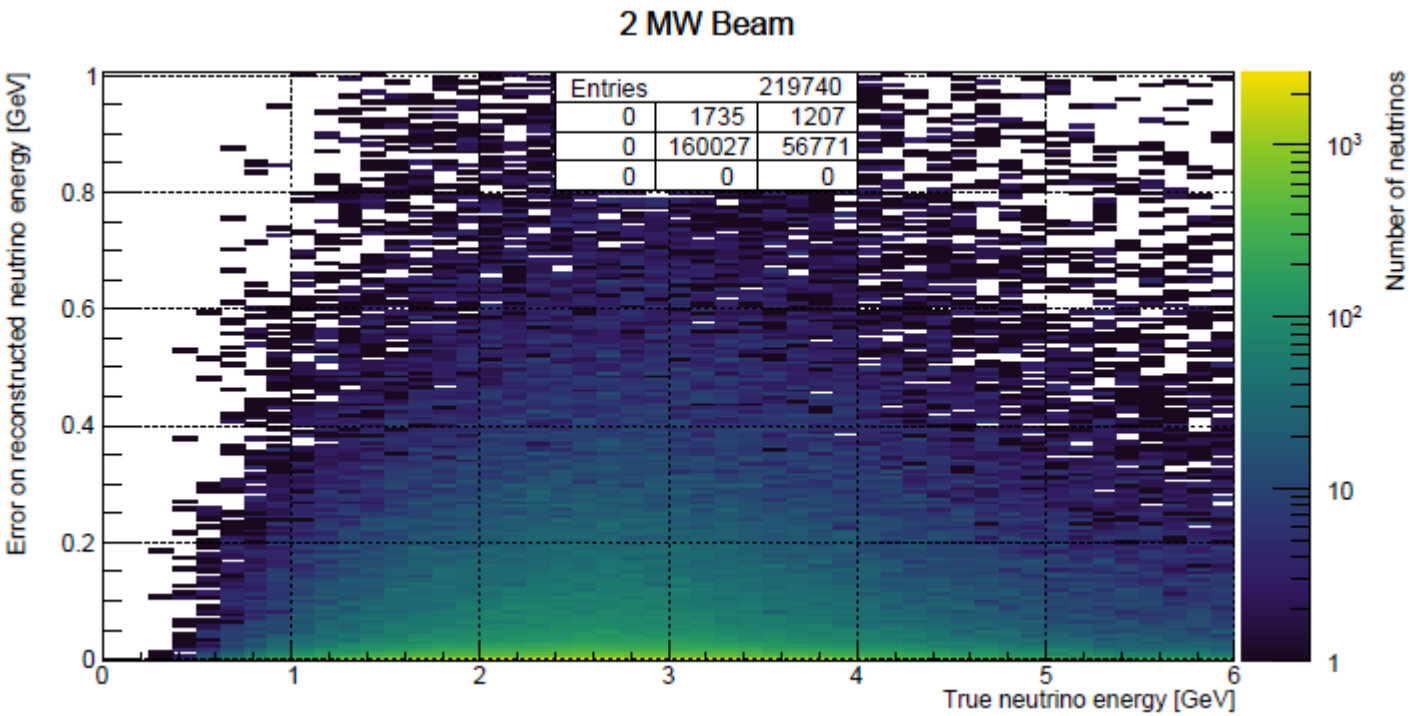
- Draw a 30°, 10 X_0 (145cm) cone around photons from π^0 decays in fiducial volume
- Measure how often hits from other neutrino interactions end up in cone
- Simulate 2MW spills (double nominal intensity) so we can see the pile-up effect

3 categories of pile-up

- Everything, including obvious muon tracks
- No muons, but include charged hadrons
- Neutral descendants only (n, γ)

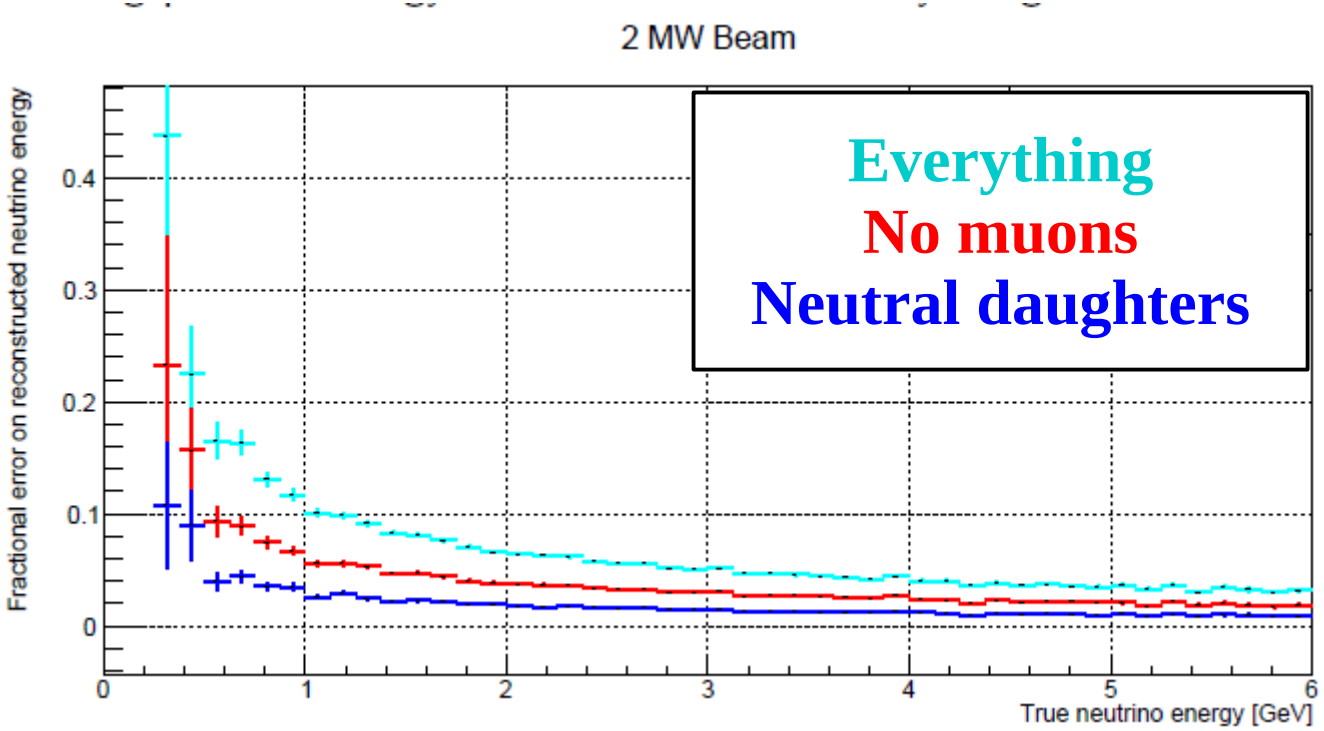


Pile-up energy in cone



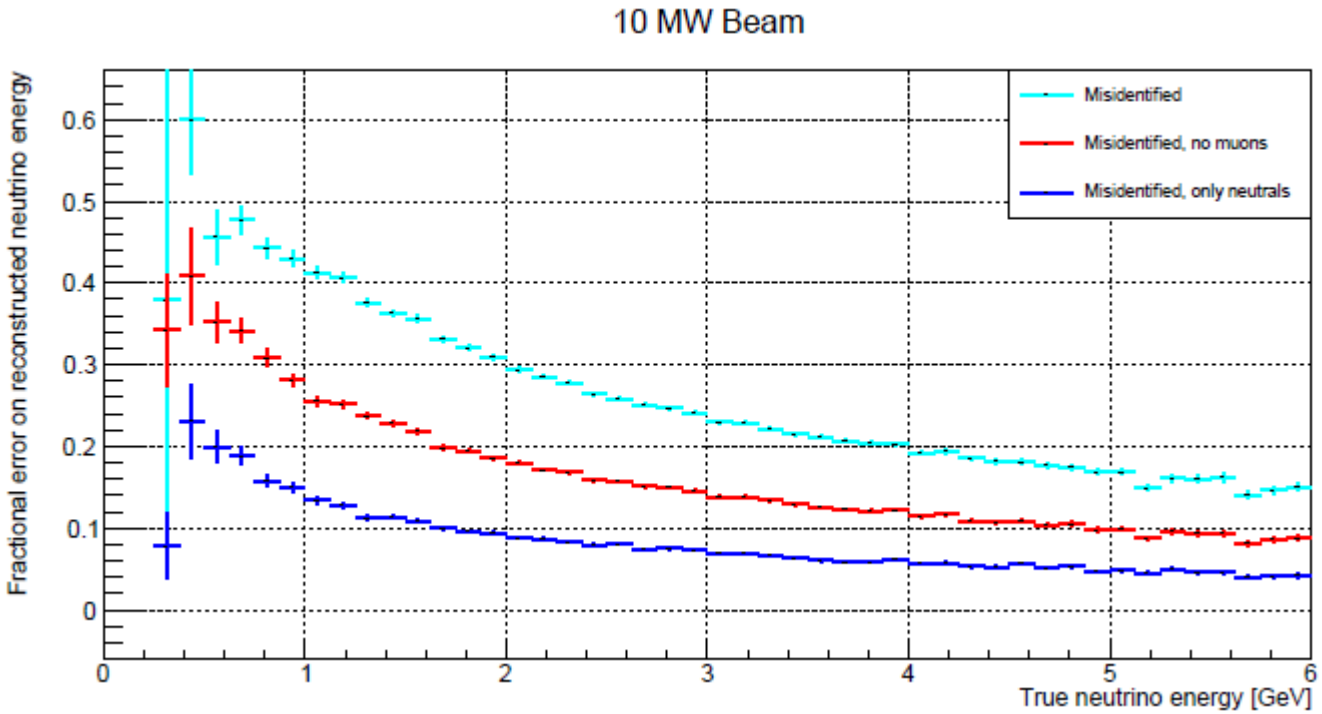
- Pile-up energy in cone as a function of neutrino energy
- Log z scale – nearly always 0, and very occasional pile-up

Pile-up energy in cone



- Fractional error on neutrino energy due to pile-up for super-naive reconstruction
- Pile-up from neutral daughters is ~1% in the flux peak

What if we had 10MW beam?

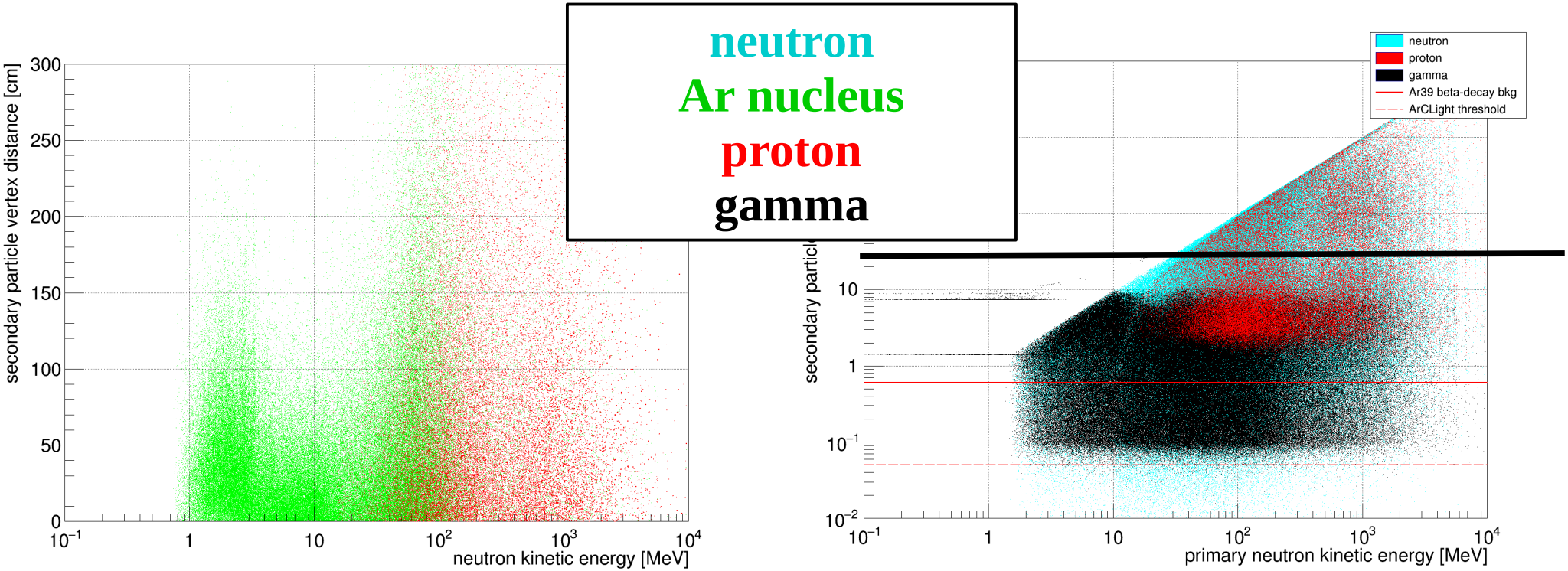


- Just for fun, same plot but with 10MW beam
- Pile-up becomes significant, 10% at 2 GeV
- LAr can handle 2MW, but not 10MW

LAr in high rate conclusions

- Even naively drawing wide cones around photon showers, and making no effort to reject things that obviously aren't photon conversions, pile-up contributes ~1% to neutrino energy
- This is at 2MW, twice the nominal intensity
- Event overlap in 2D is common, but overlap in 3D is very rare
- Neutrons are another story

Neutron-Argon interactions



- Plots from Patrick Koller (Bern)
- Left: distance to proton recoil
- Right: Recoil proton energy – black line is minimum to hit 2 pixels – typically will see energy in one voxyl

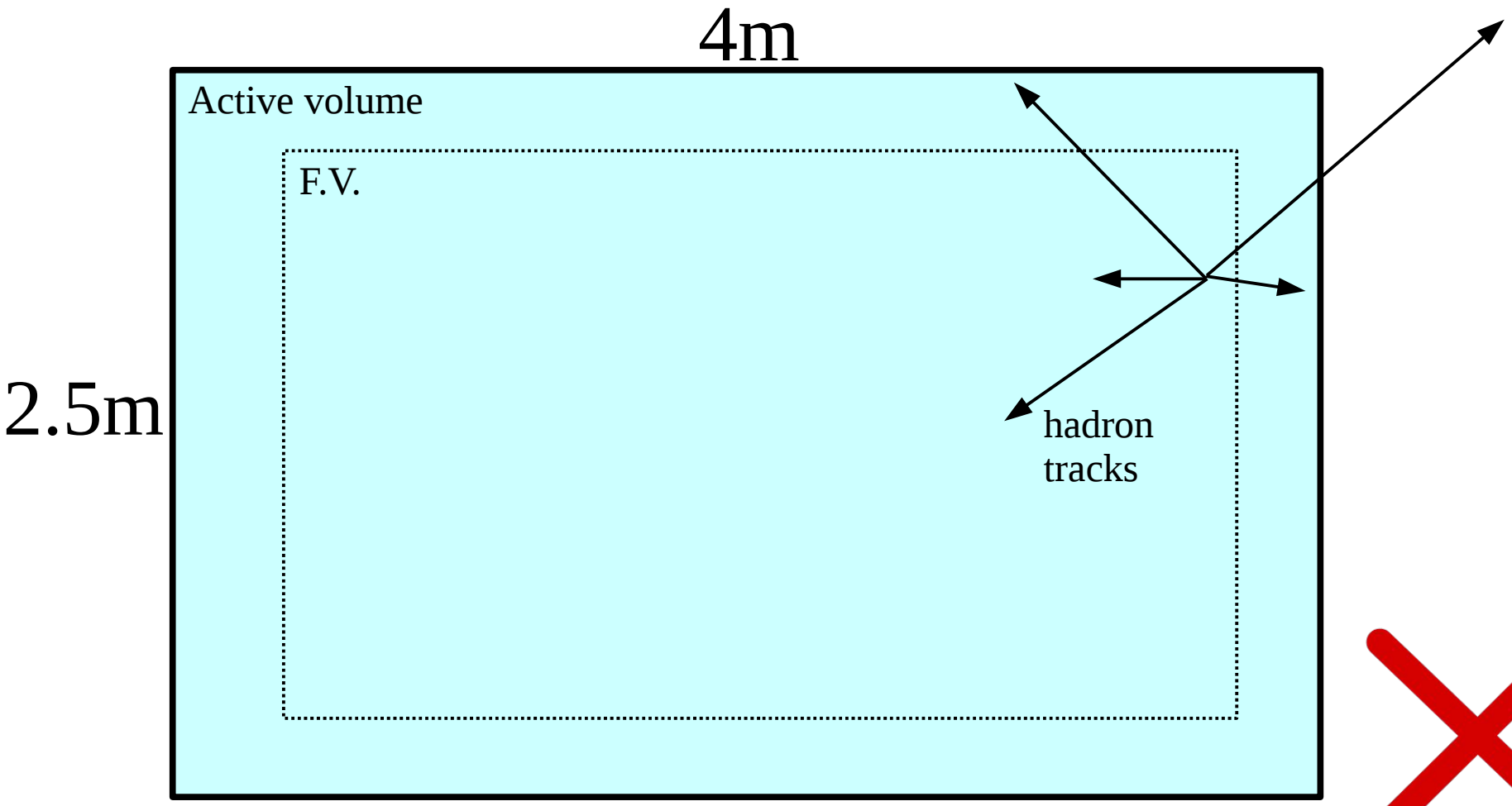
Neutrons will be tricky – maybe possible with timing

- 60t LAr has 6 interactions per spill
- Plus additional interactions in rock, cryostat, etc.
- Neutrons generally cannot be associated to a specific interaction without timing
- Ongoing work by Patrick Koller to determine if modular optical readout with ~10ns timing resolution could be used to ID timestamp neutrons, and thus associate them to specific neutrino interactions
- Without fast timing, it is not possible to associate neutrons in LAr at full intensity

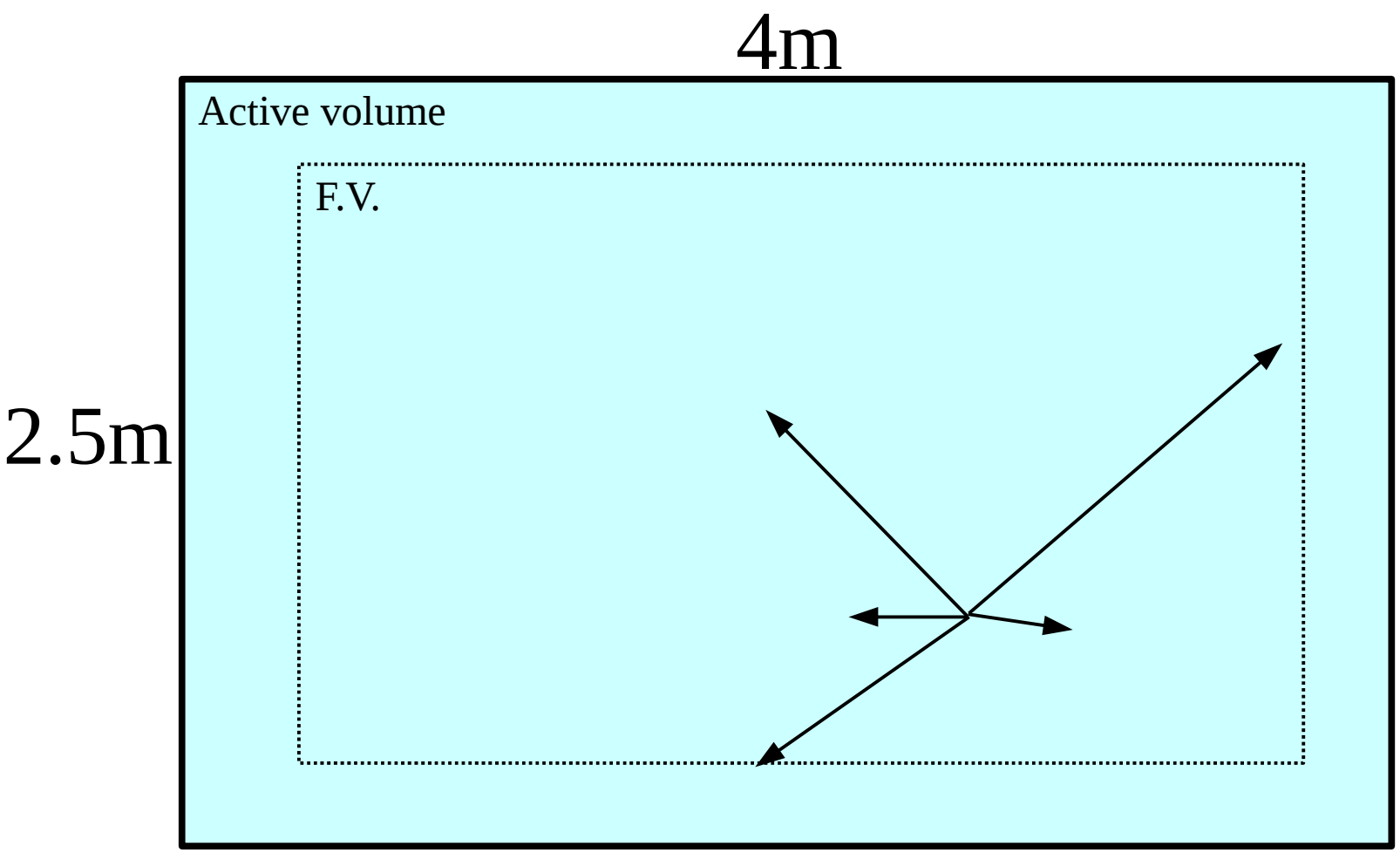
Size needed for hadron containment

- Presented at January collaboration meeting at CERN – see that talk (https://indico.fnal.gov/event/14581/session/5/contribution/86/material/slides/0.pdf) for more details
- Will show brief recap here
- Conclusion: Using translational and rotational symmetry, we can contain essentially all hadron showers in a 4x3x5m detector
- Acceptance is good in the flux peak

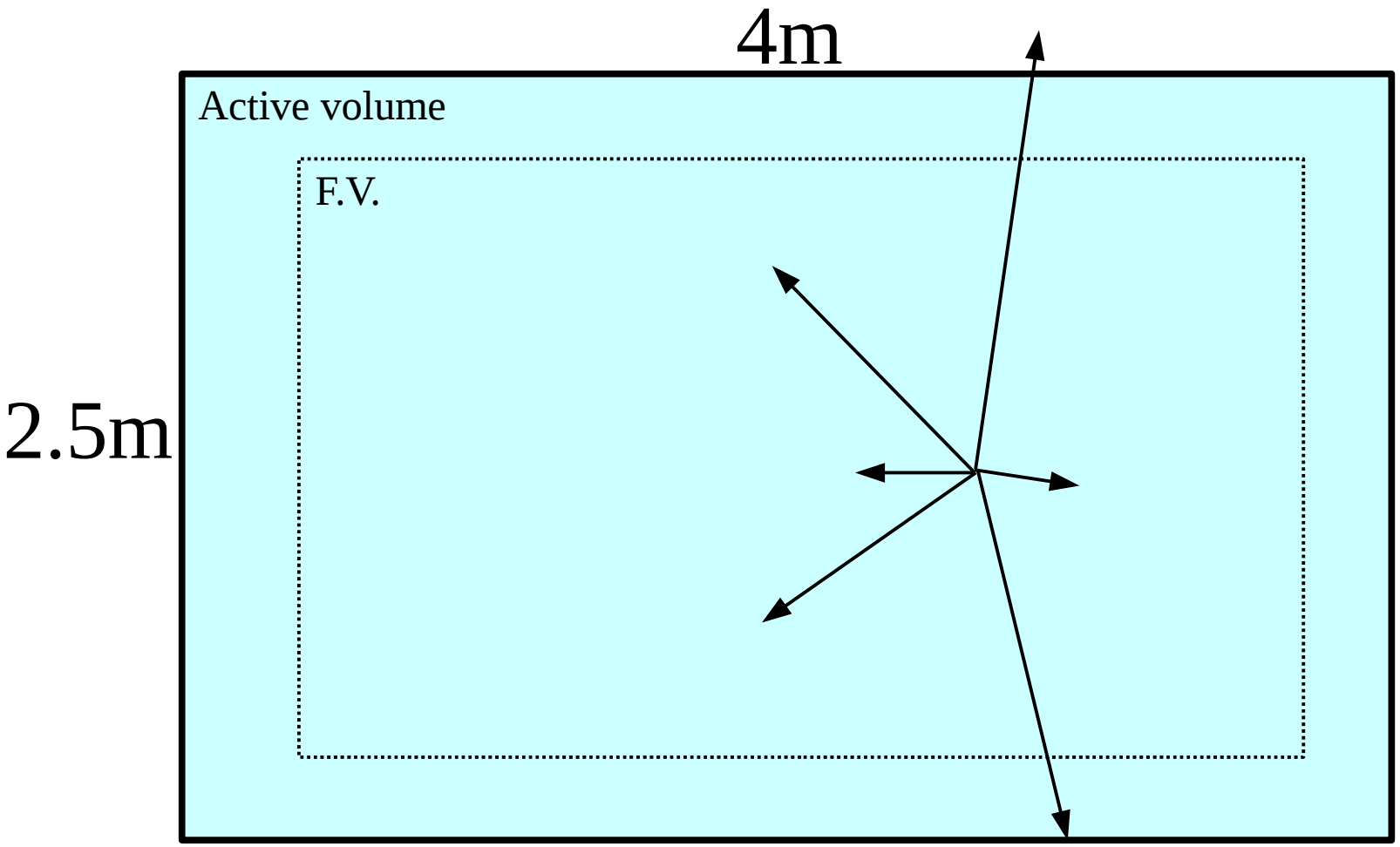
Detector as seen by ν beam (XY projection)



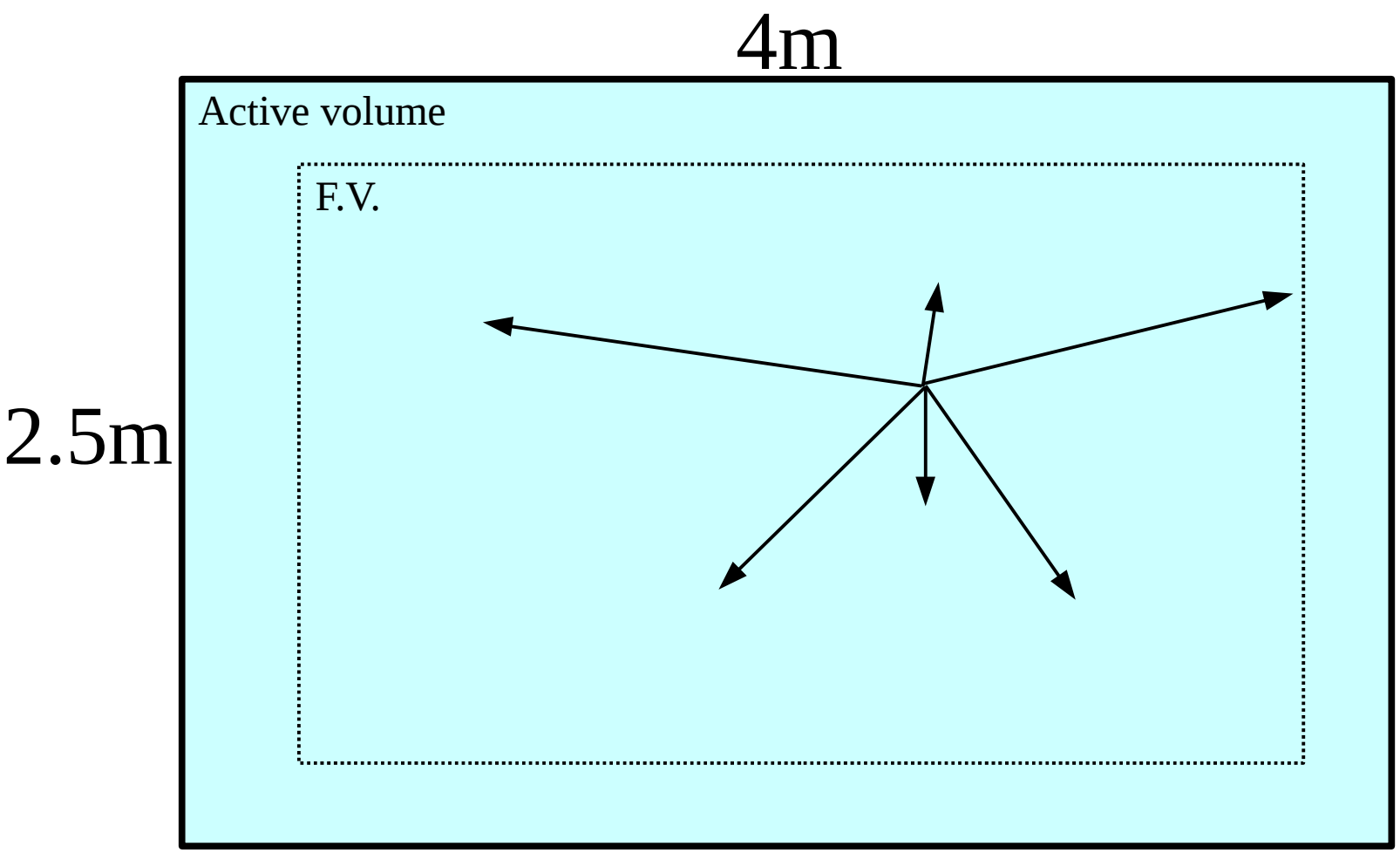
Same event, translated



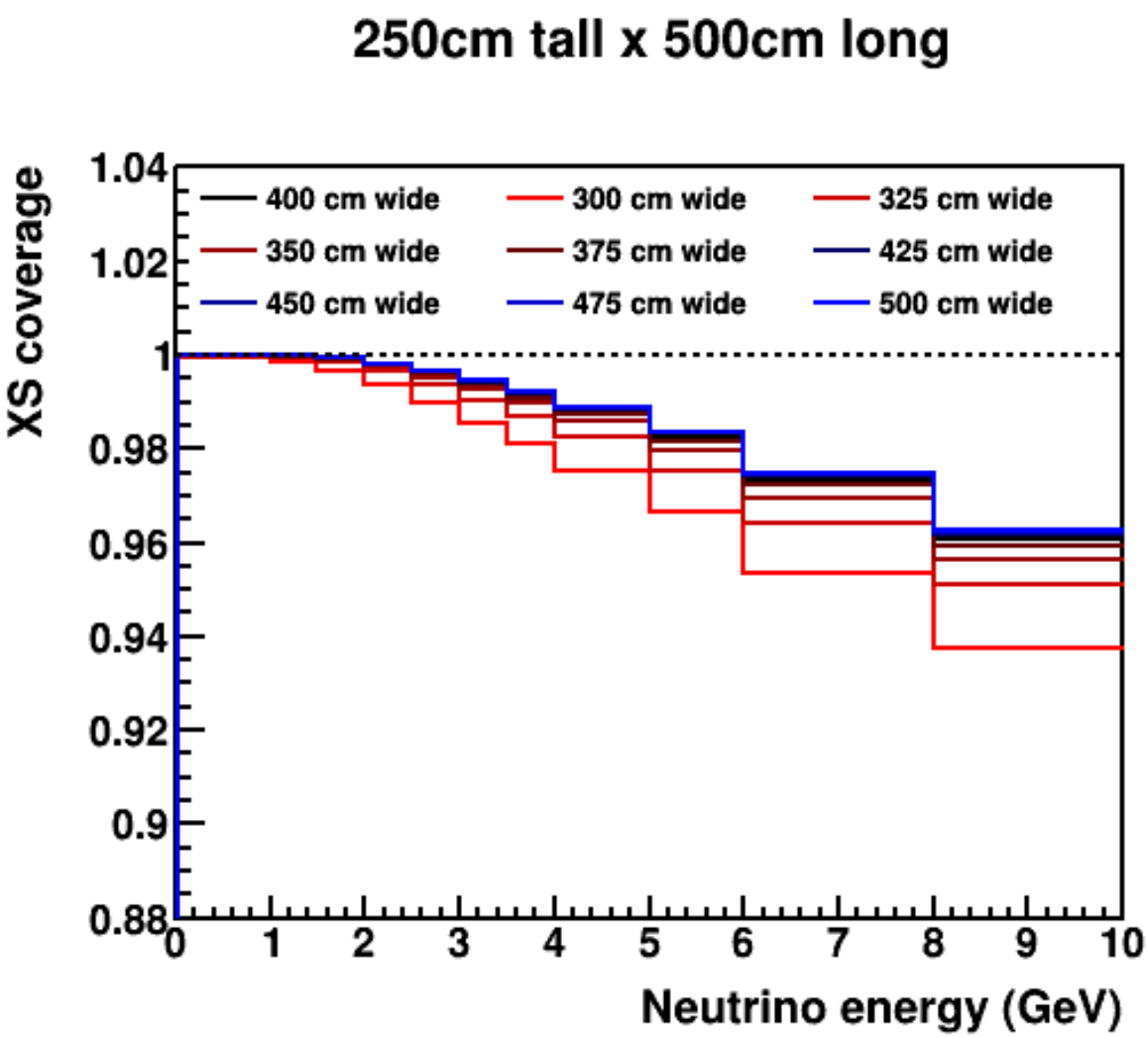
Event that is not contained with any translation



But is using phi symmetry

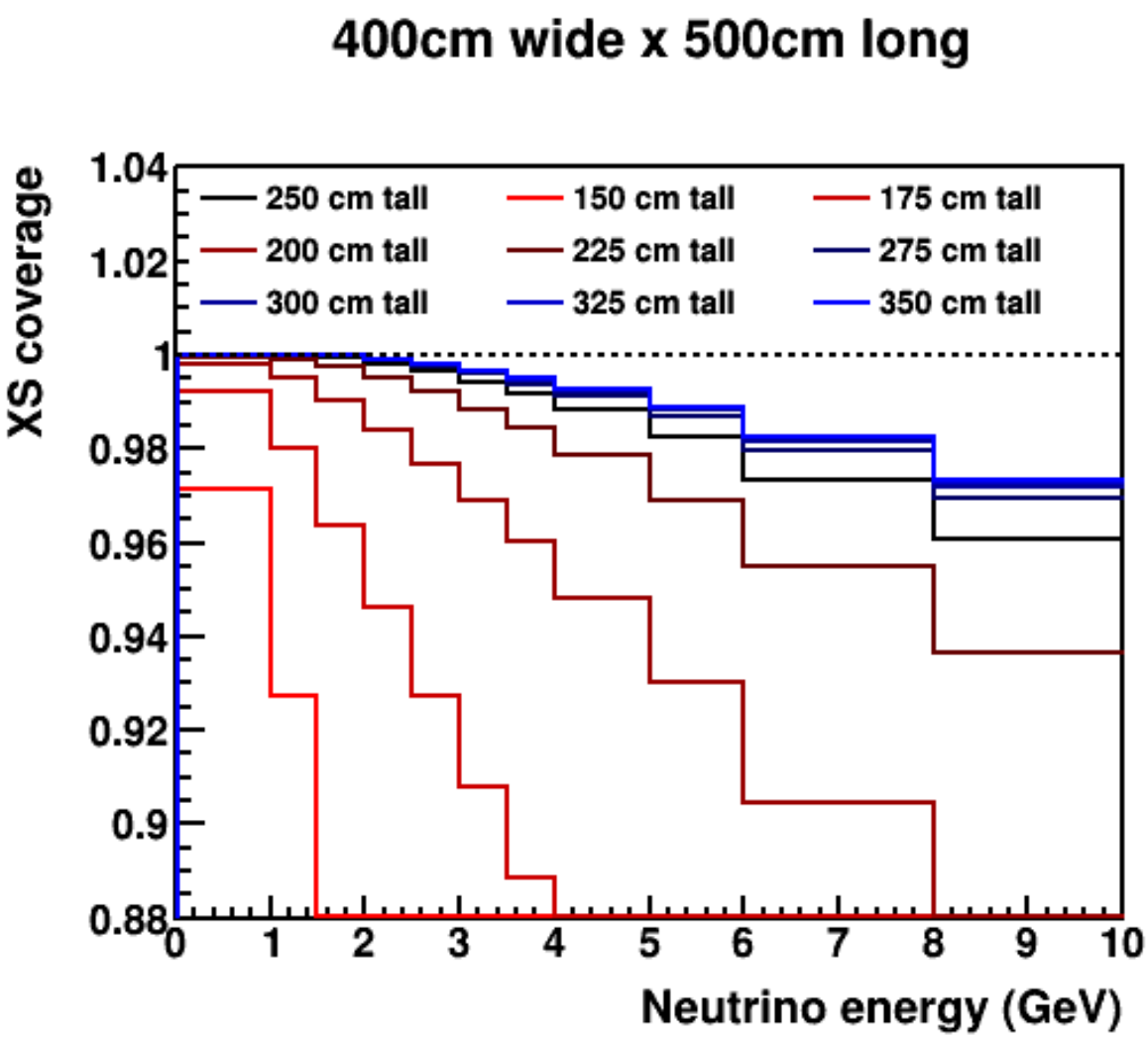


XS coverage vs. X



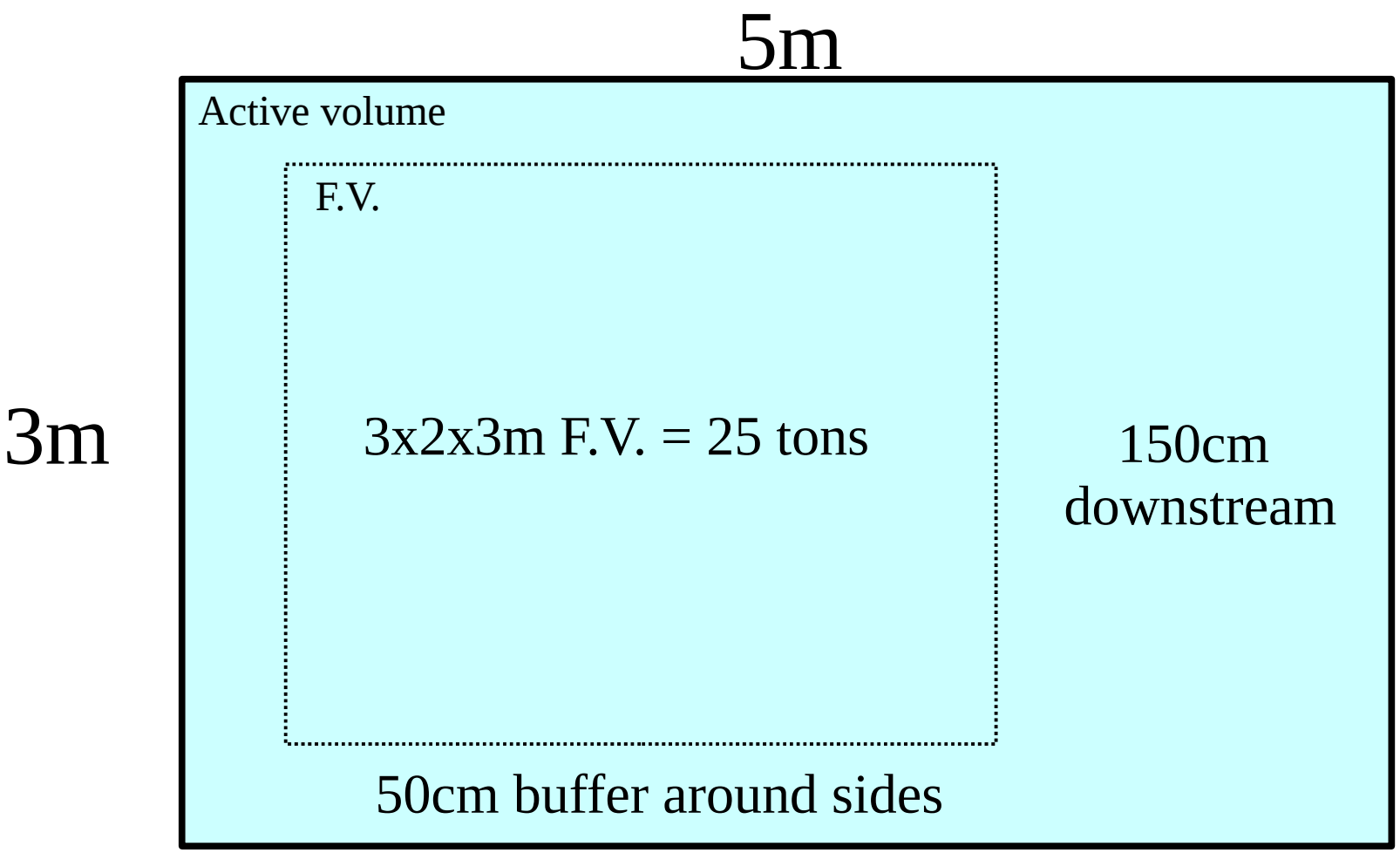
- Here, Y and Z dimensions are fixed at 250cm x 500cm
- Nominal X is 400cm, red is smaller, blue is larger
- For all sizes, 50cm buffer on all sides is assumed

XS coverage vs. Y

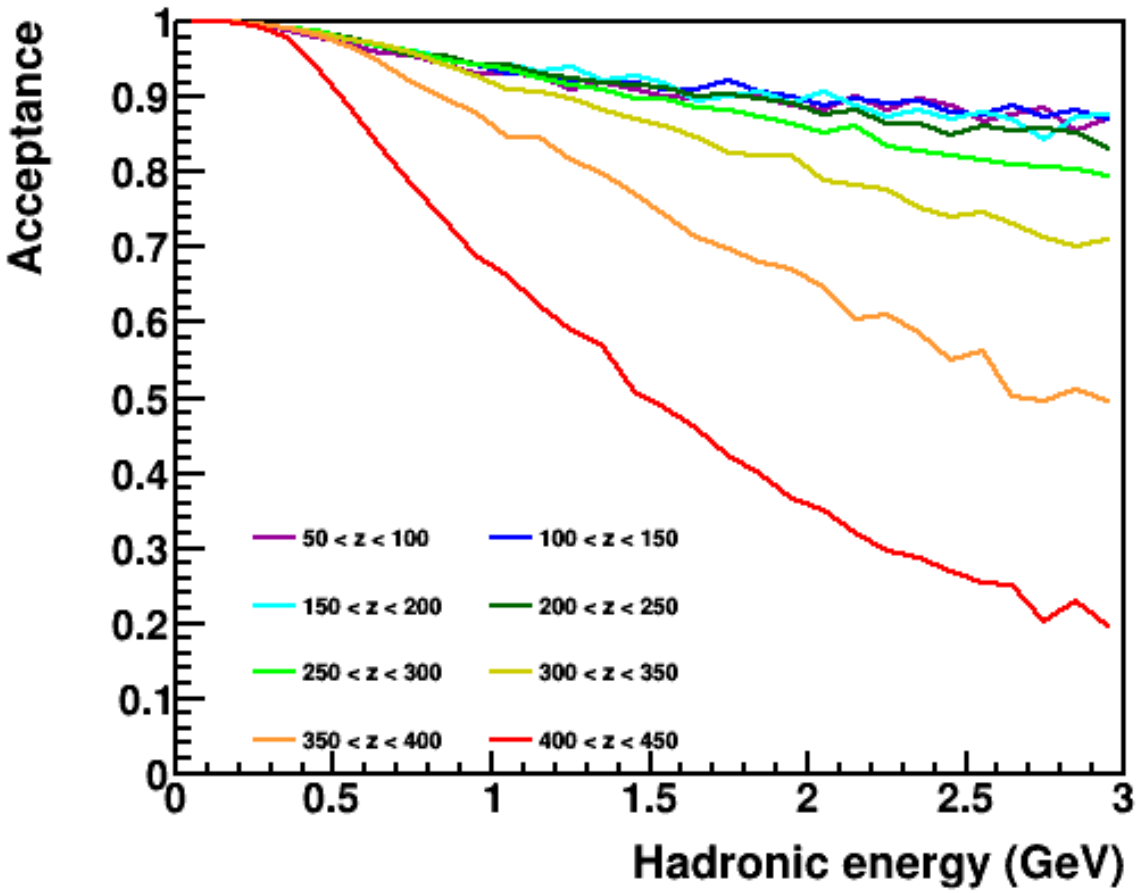


- X and Z are fixed at 400cm x 500cm
- Y (height) is varied, with black being nominal 250cm, red shorter, blue taller
- 250cm is right on the edge of significant loss of acceptance
- If Nature produces larger hadronic showers than GENIE, we could be in trouble
- 3m would be much safer

25t F.V. for CC samples

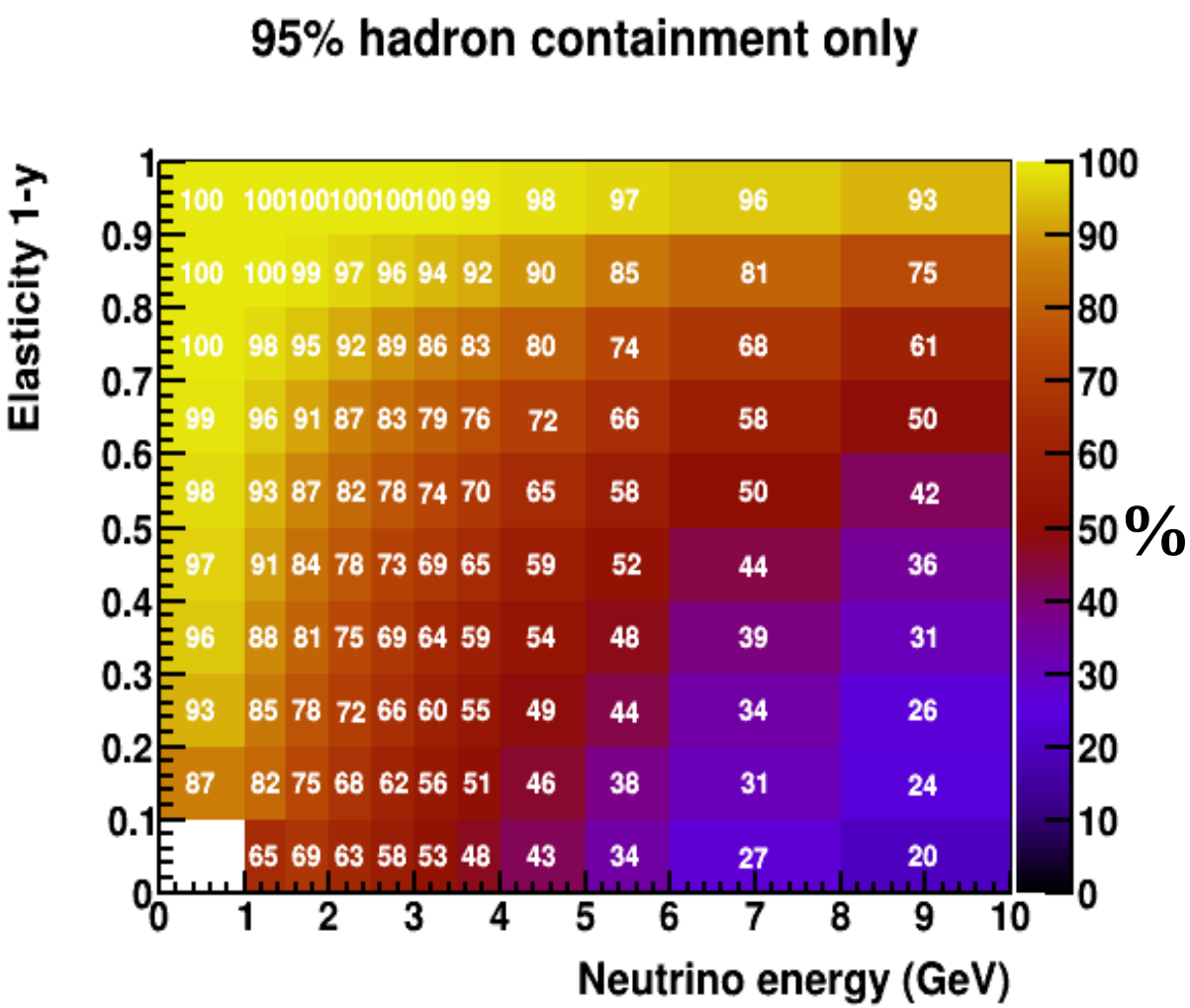


Hadron containment



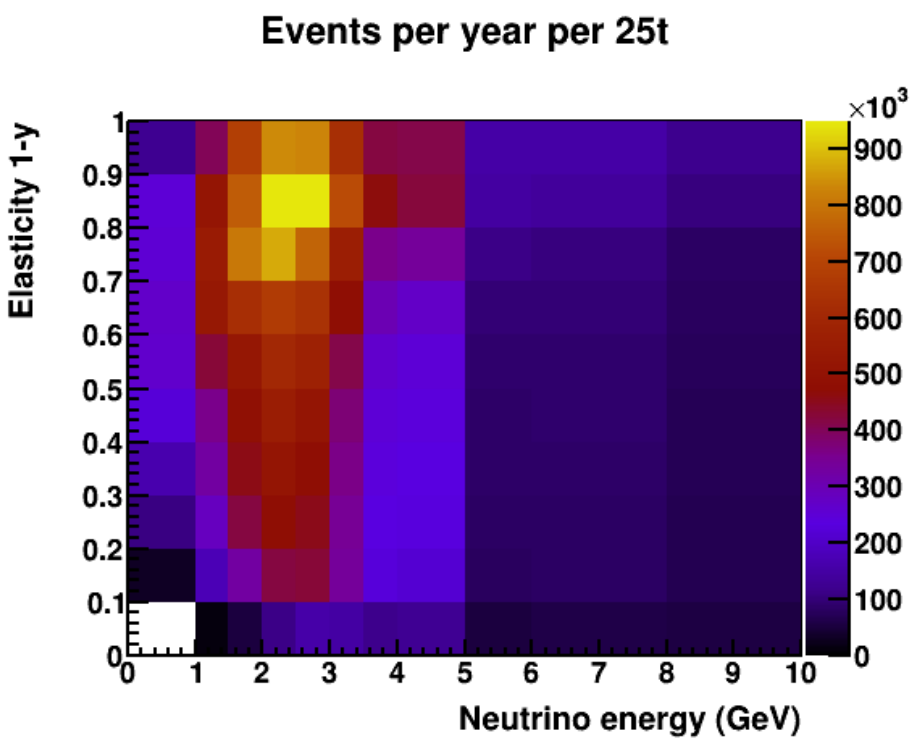
- Very downstream vertices have poor hadron acceptance, that changes with energy
- Want to avoid orange/red regions where hadron containment is poor

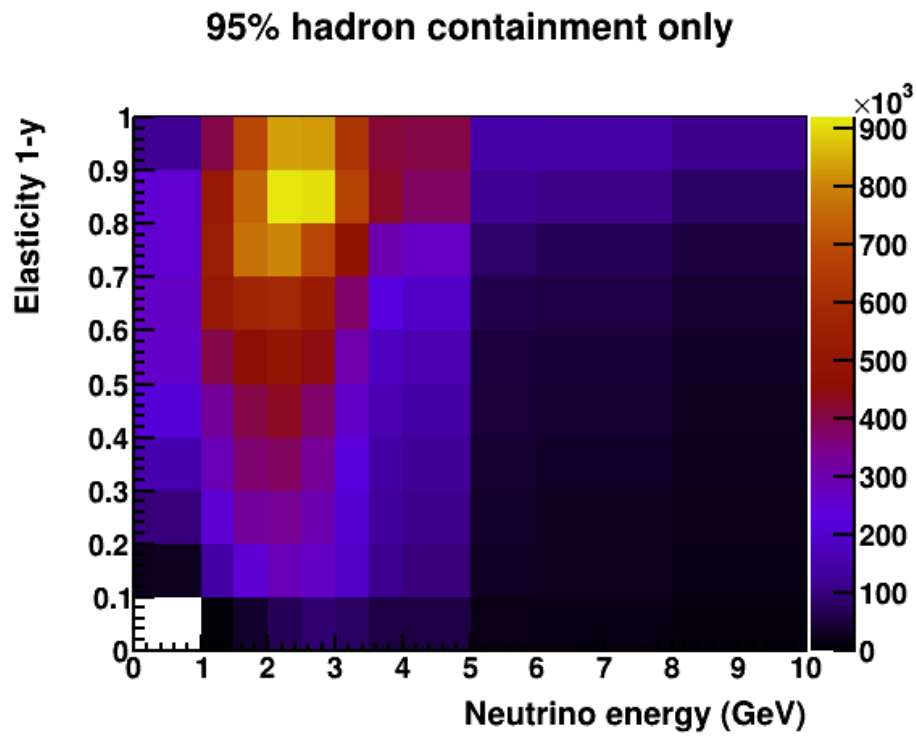
Hadronic shower acceptance



- 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 GeV per year for this F.V.



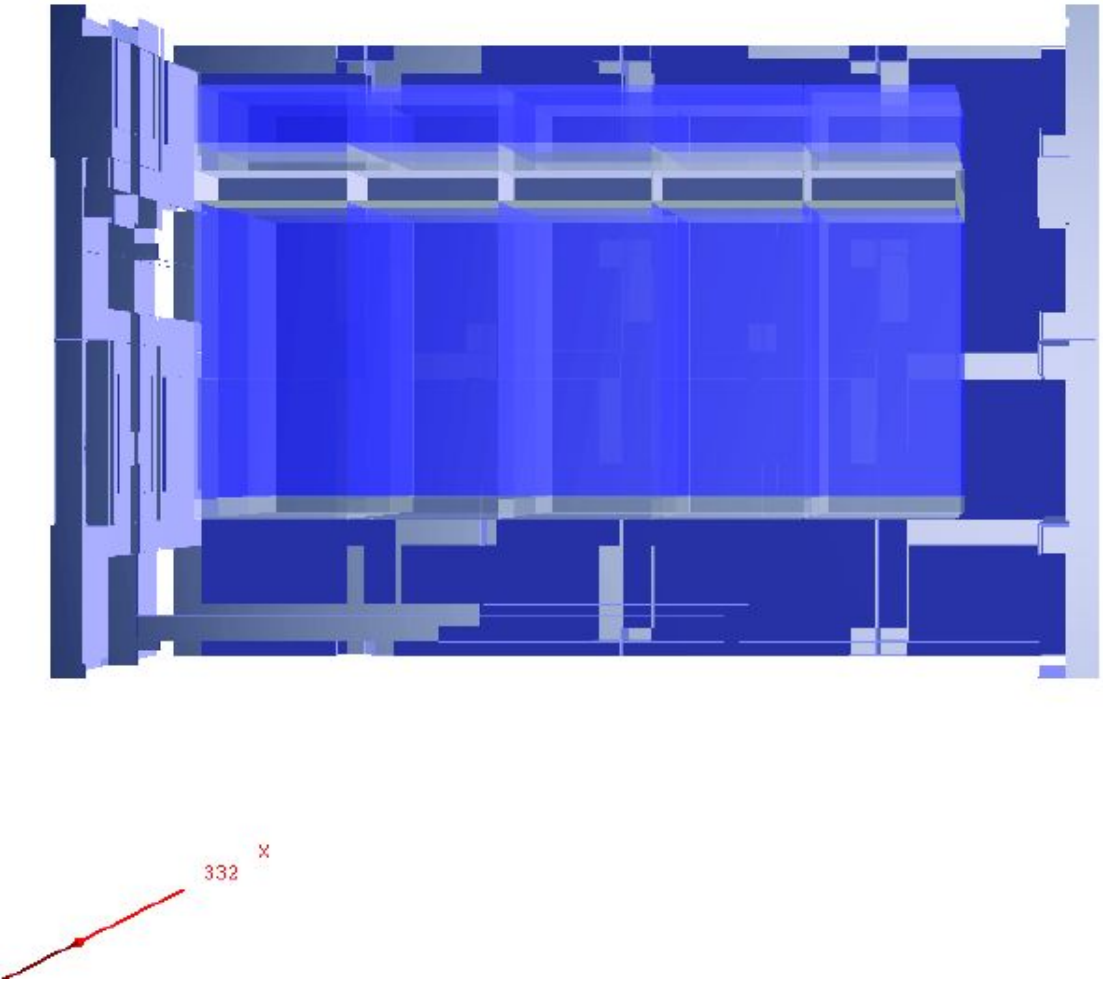


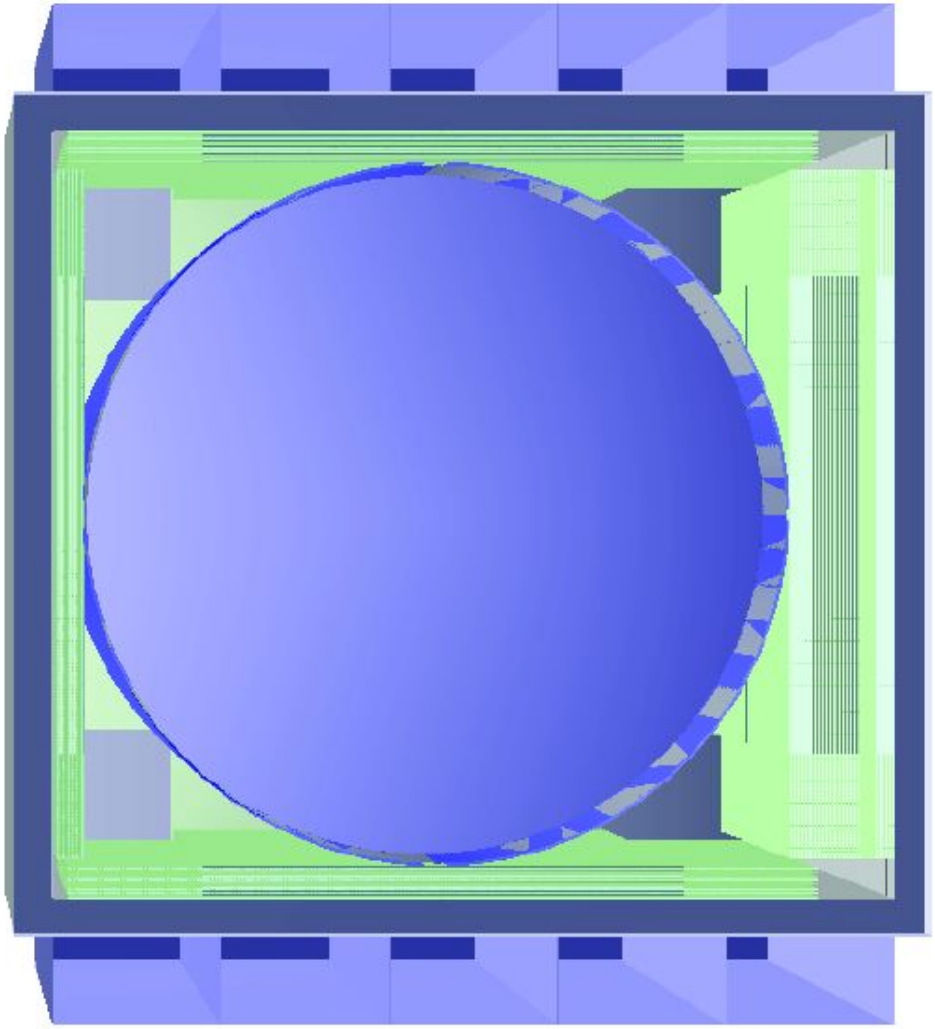
- 37M ν_μ CC interactions per year
- Right: events with contained hadrons – still very high rates in peak region, slightly worse in flux tail where hadronic energy is very high

Muon acceptance

- Discussed at length in a series of ND weekly meeting updates:
  - https://indico.fnal.gov/event/16456/contribution/0/material/slides/0.pdf
  - https://indico.fnal.gov/event/16457/contribution/0/material/slides/0.pdf
  - https://indico.fnal.gov/event/16459/contribution/0/material/slides/0.pdf
- Summary follows, along with some new stuff
- Transverse size of tracker matters, but tracking technology is irrelevant
- I'll show gas TPC in dipole magnet, but STT is similar

ArgonCube + HPGTPC in dipole





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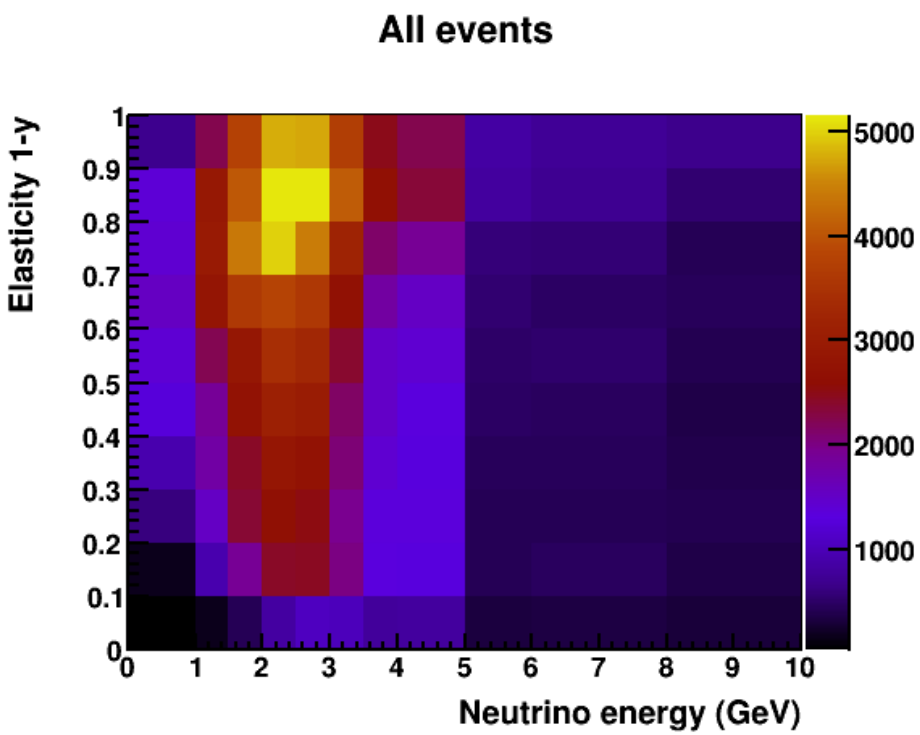
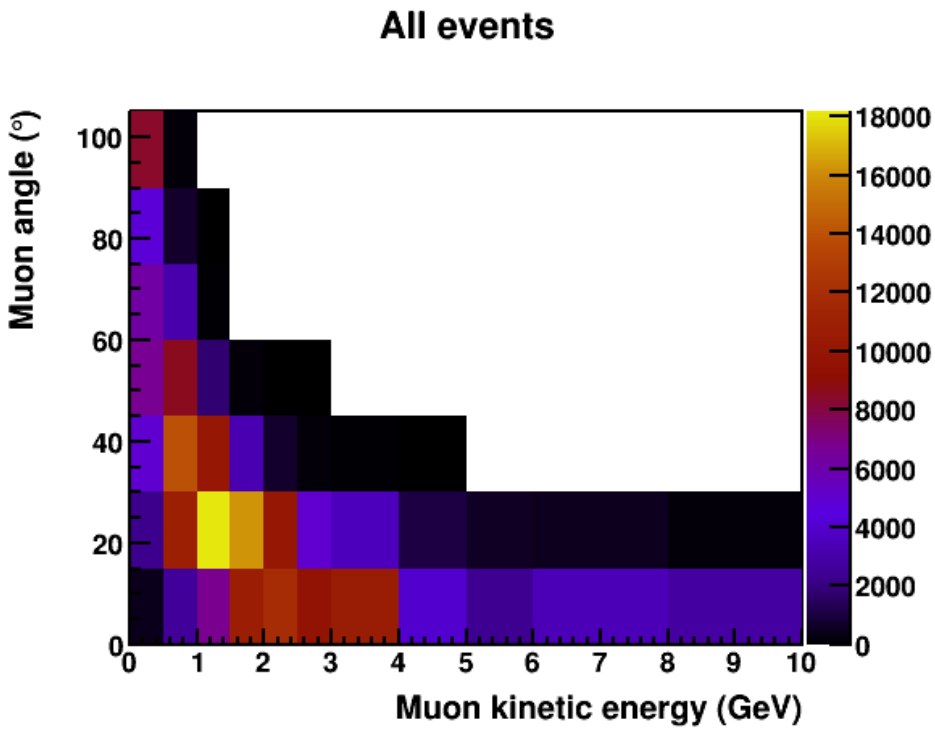
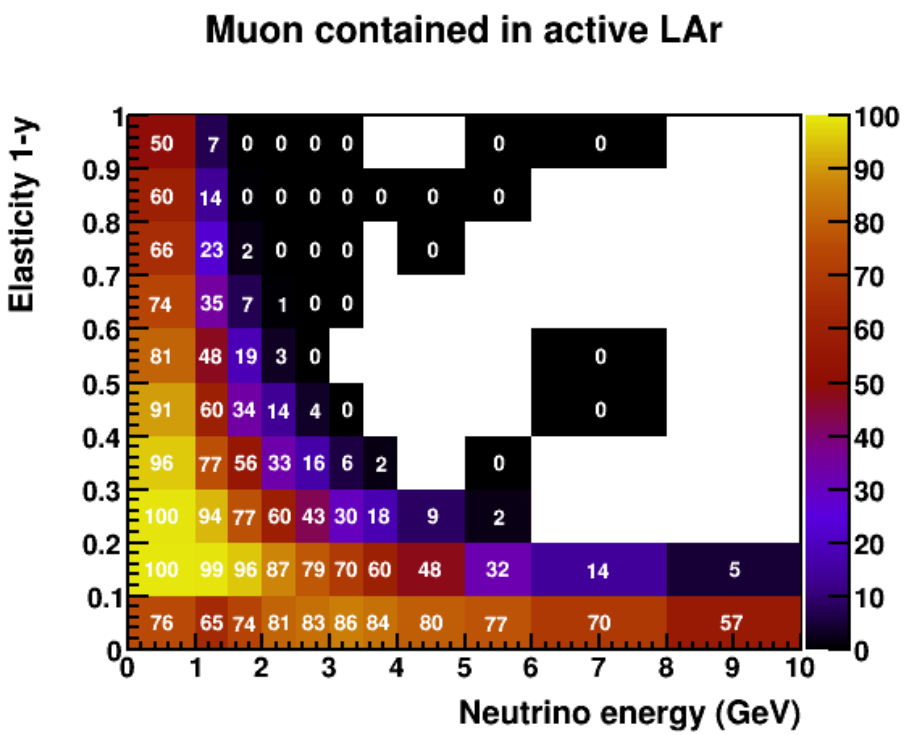
Event distributions FHC ν_μ

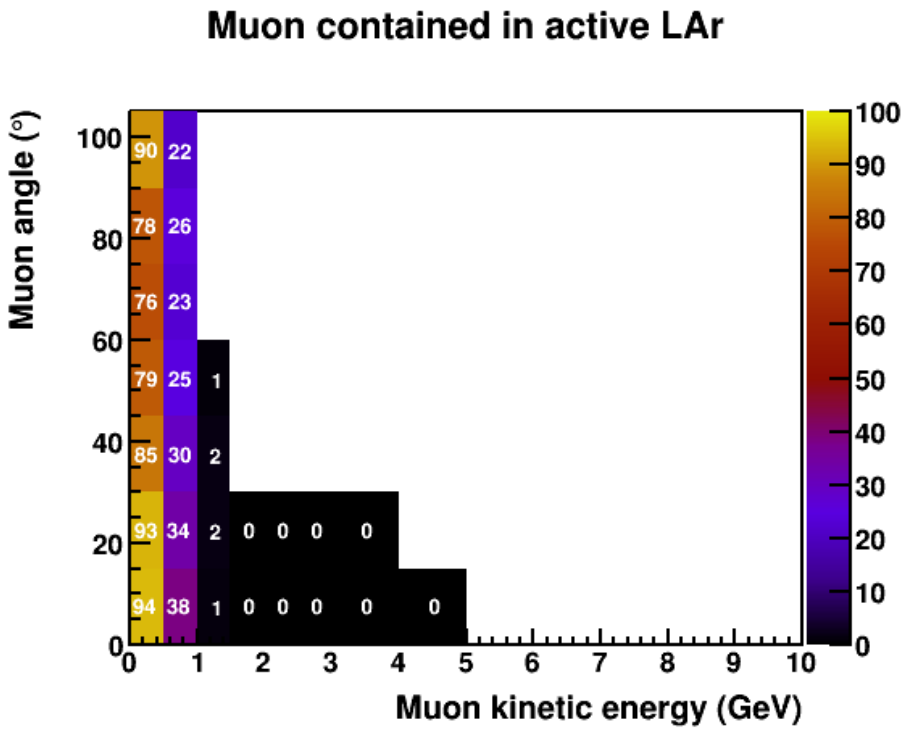




- Will show two kinematic spaces:
  - E_ν-elasticity
  - Muon energy-angle

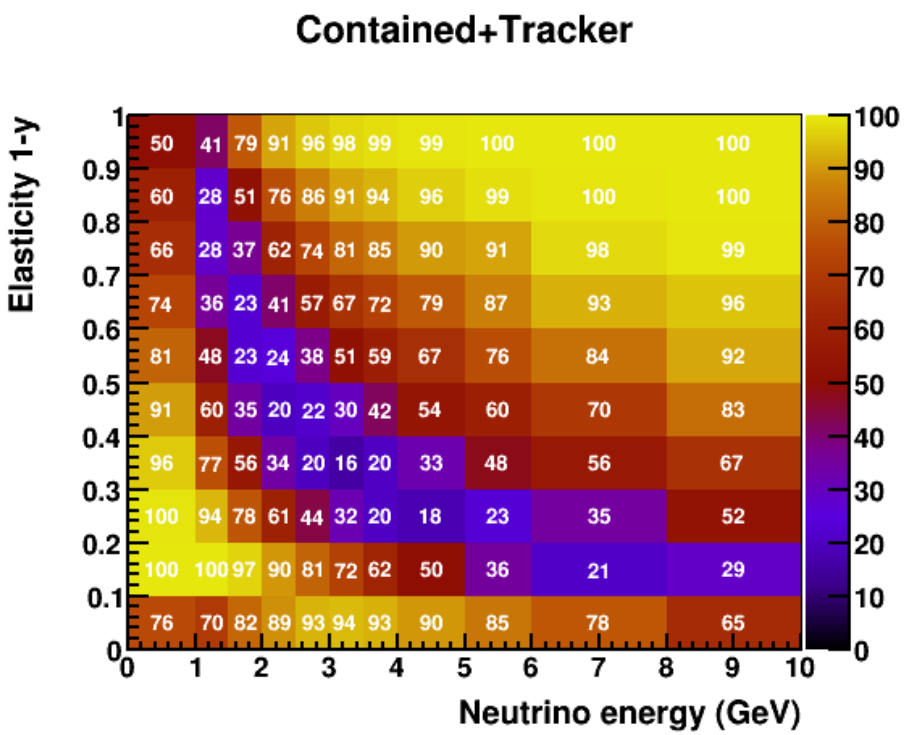
LAr-contained

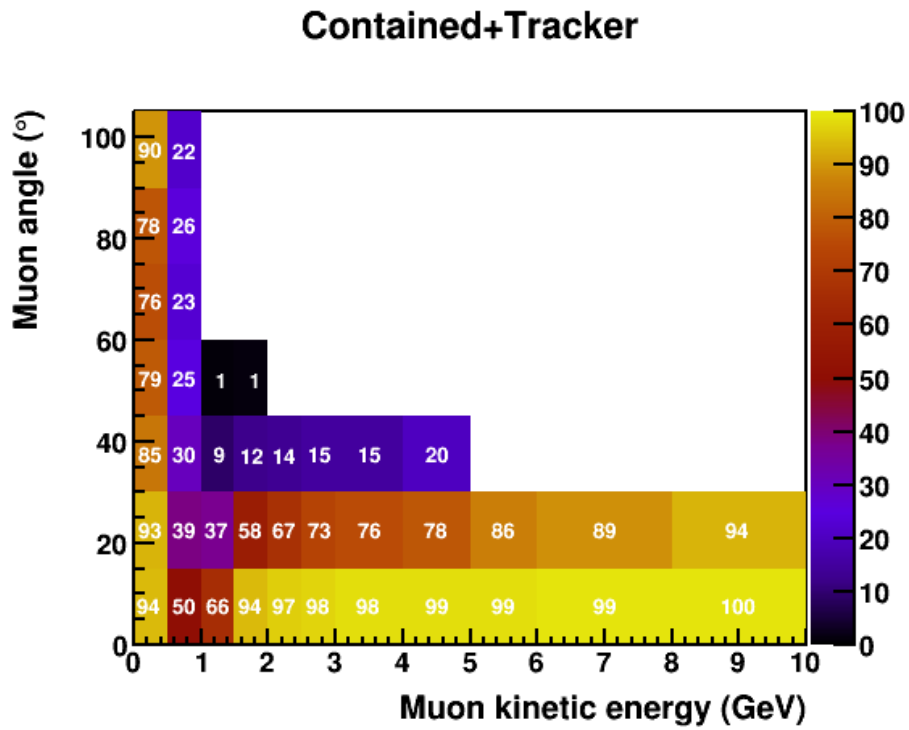




- Muons up to about 1 GeV can be contained in LAr

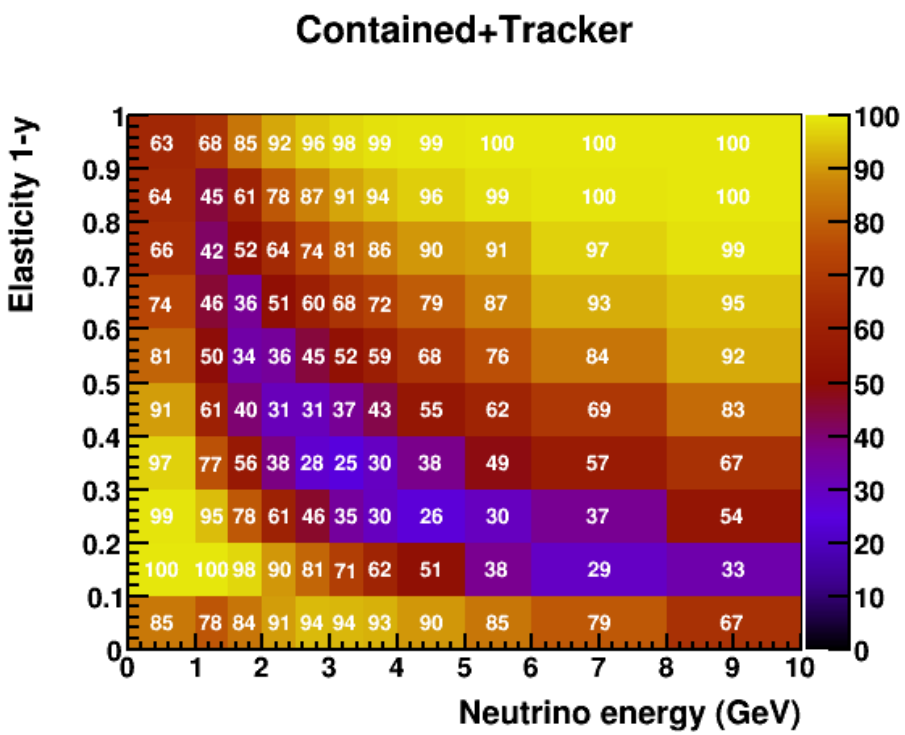
Contained+tracker

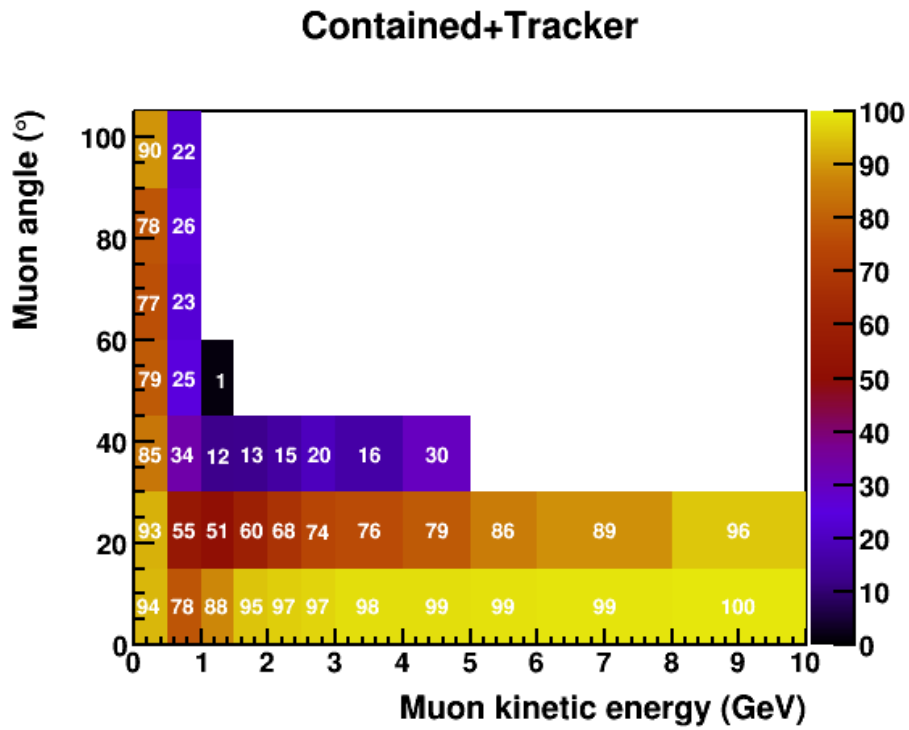




- Adding tracker-matched sample gives good acceptance for forward, high-energy muons
- Poor acceptance at high muon angles
- Acceptance dip where muons stop in dipole coil

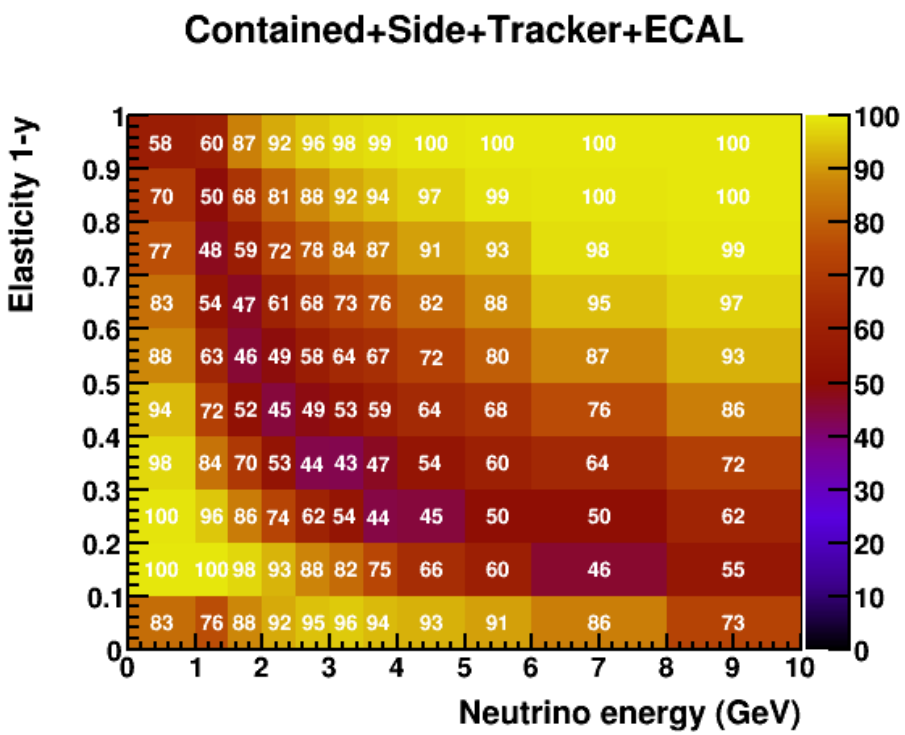
Contained+tracker – no coil

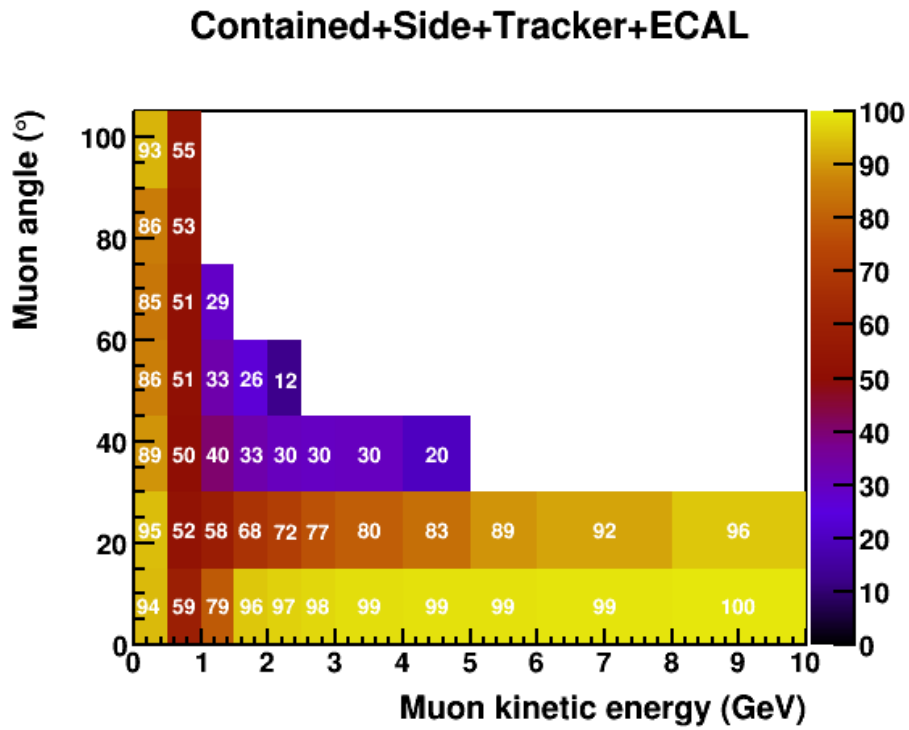




- Removing the coil fills in the dip for forward muons around 1 GeV

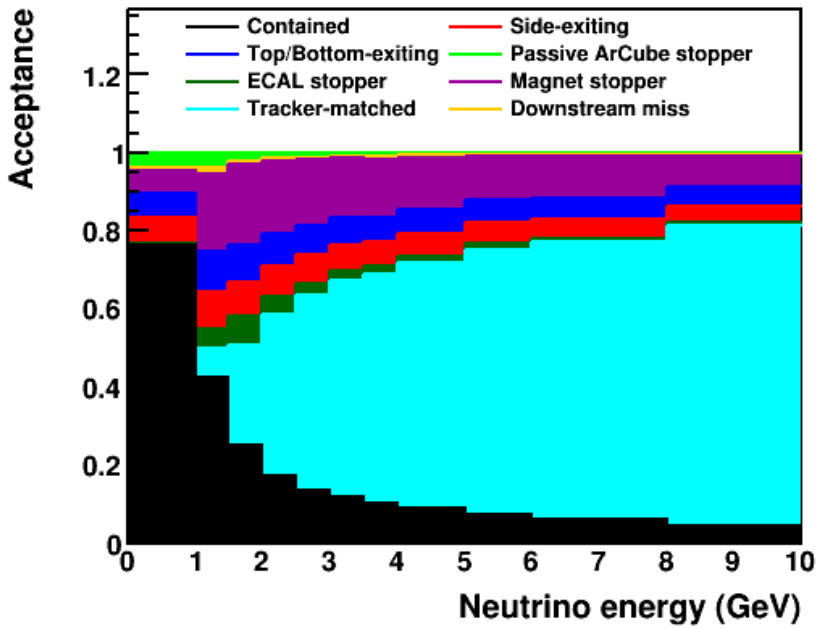
Add side events

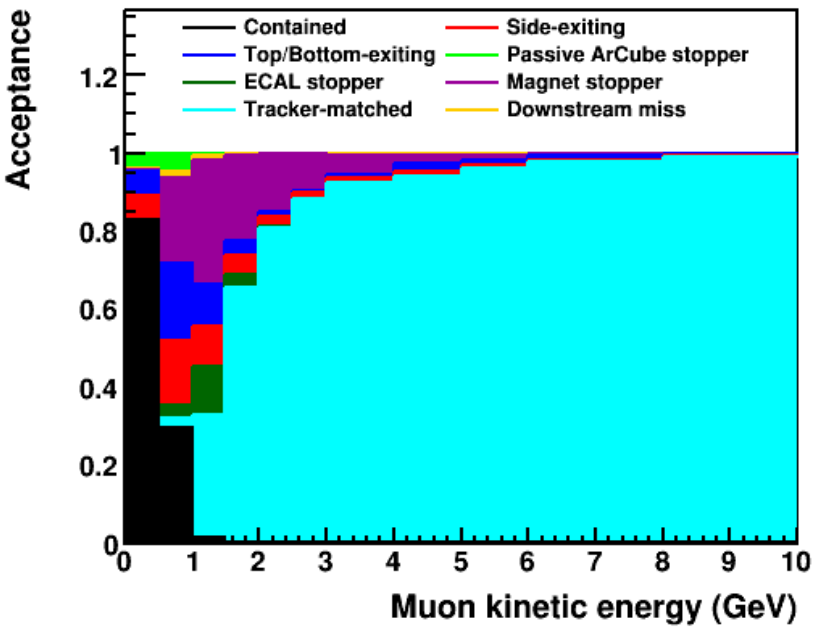




- Assuming perfect acceptance for side
- Effectively sampling – no “side” detectors on top/bottom of LAr

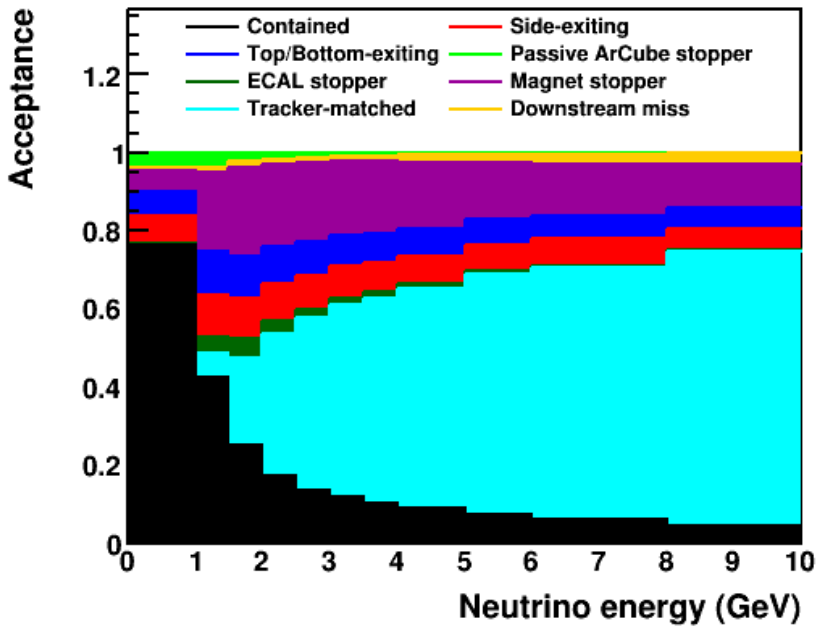
Acceptance in 1D

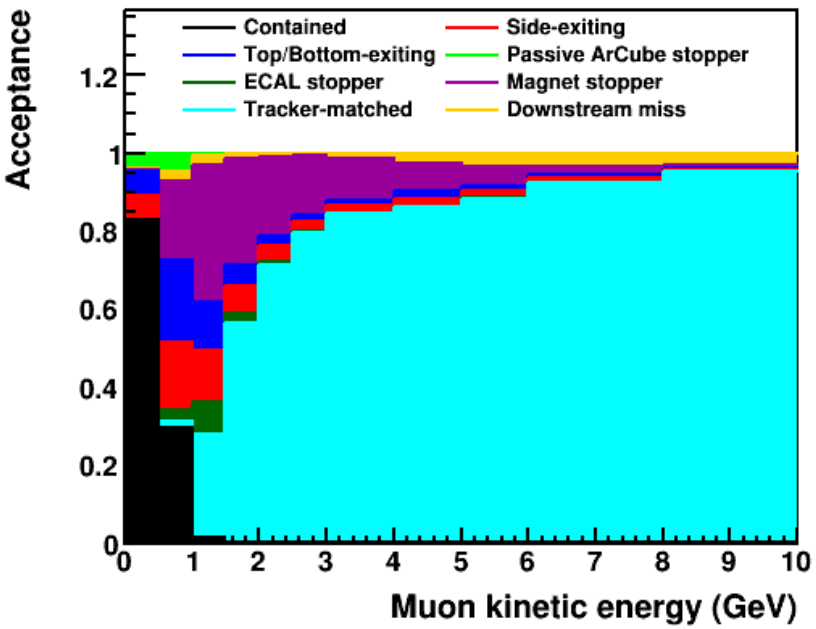




- Problematic events are purple “magnet stopper” category – 25% near peak region

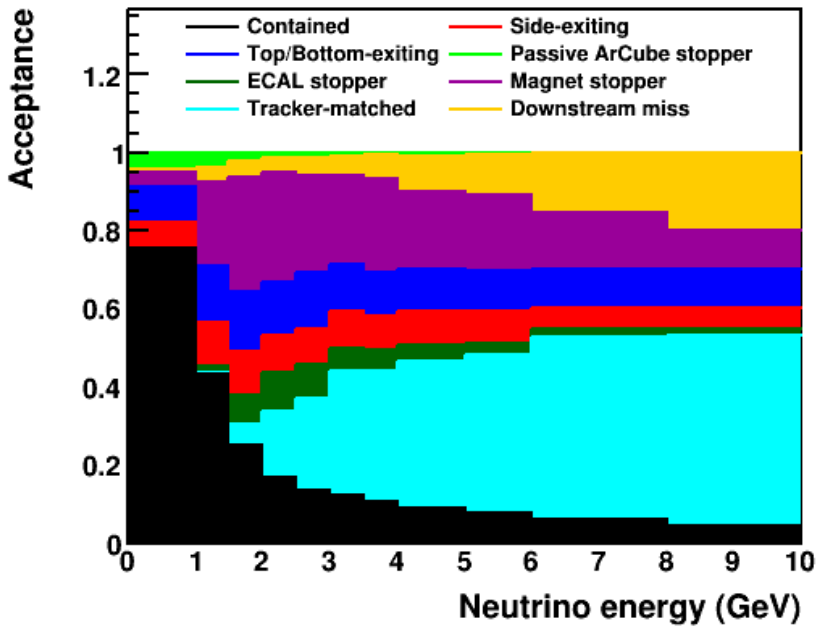
Dipole+STT

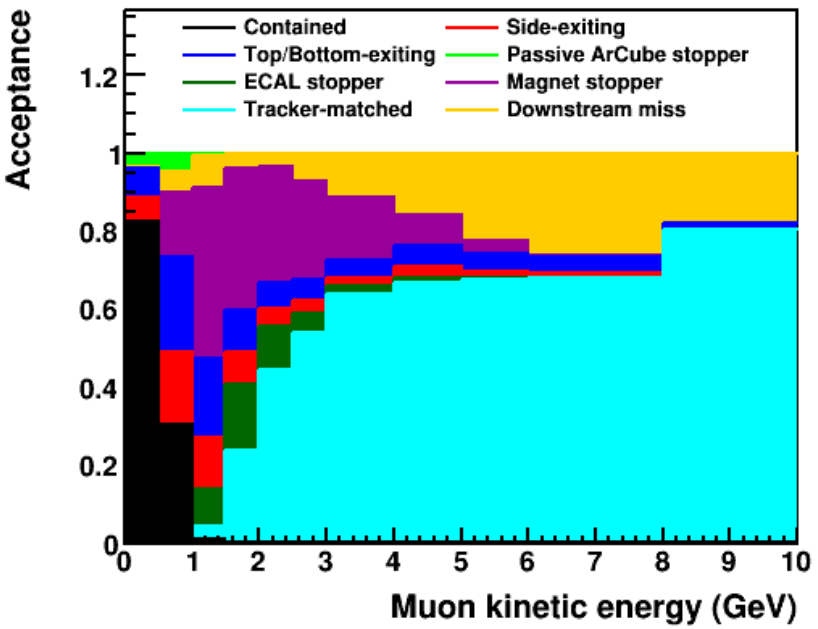




- Nearly identical – this STT geometry is not quite as wide as the LAr, so there are some events that exit the rear and miss the STT

For comparison: KLOE+STT

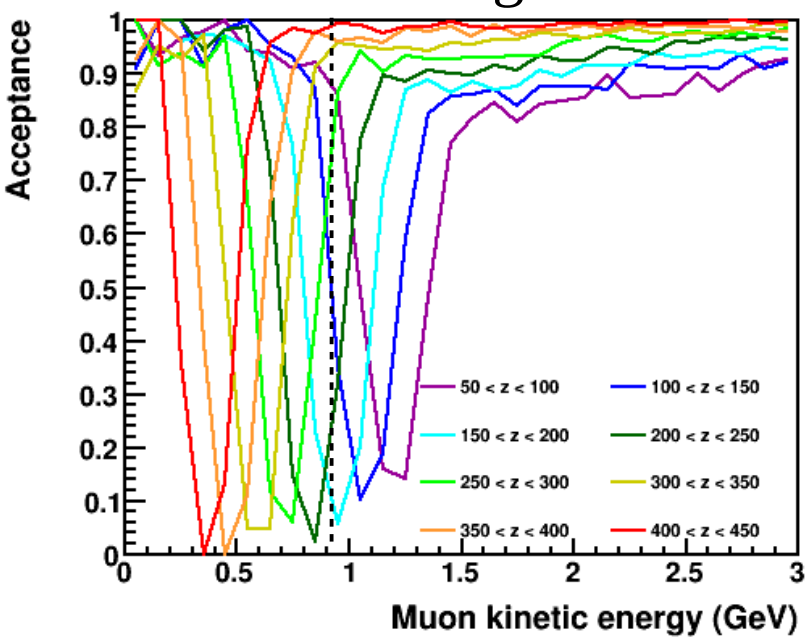




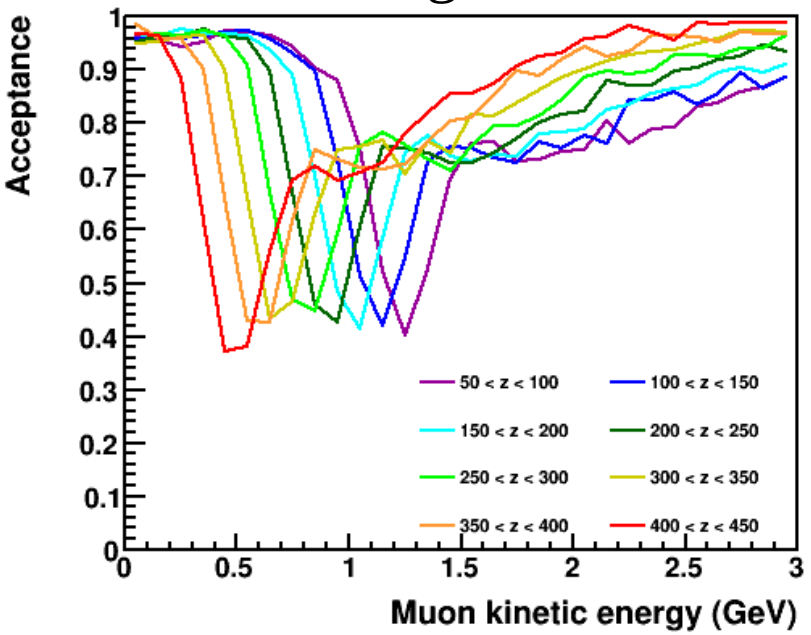
- KLOE magnet yoke is much thicker than dipole coil, and magnet stoppers are much bigger issue
- STT inside KLOE is smaller, so there are more downstream exiting events that miss STT

Acceptance in different Z regions

θ < 20 degrees



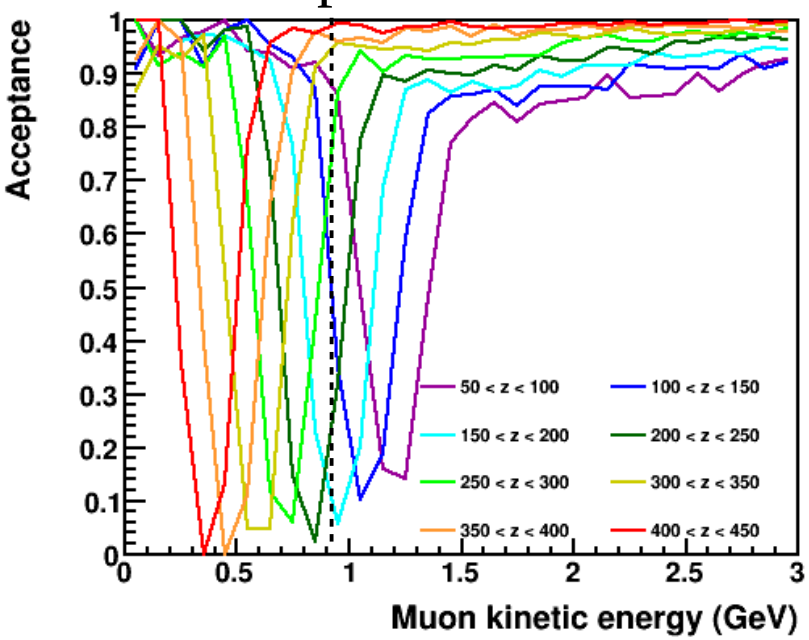
All angles



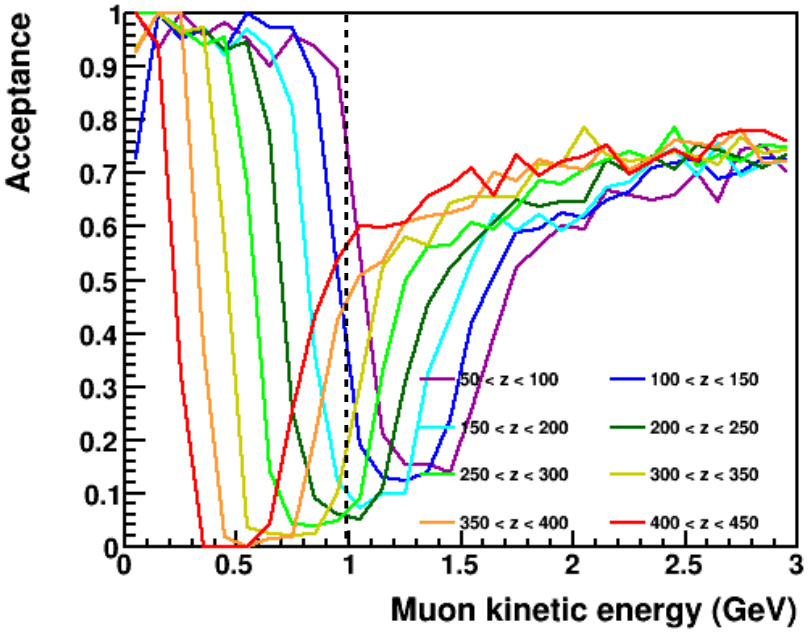
- Contained + tracker + ECAL + side detectors
- Hadron acceptance gets bad for vertices > 350 cm (orange and red curves)
- For muon around 1 GeV, can only be accepted in most upstream and most downstream regions

With KLOE, for reference

Dipole+TPC

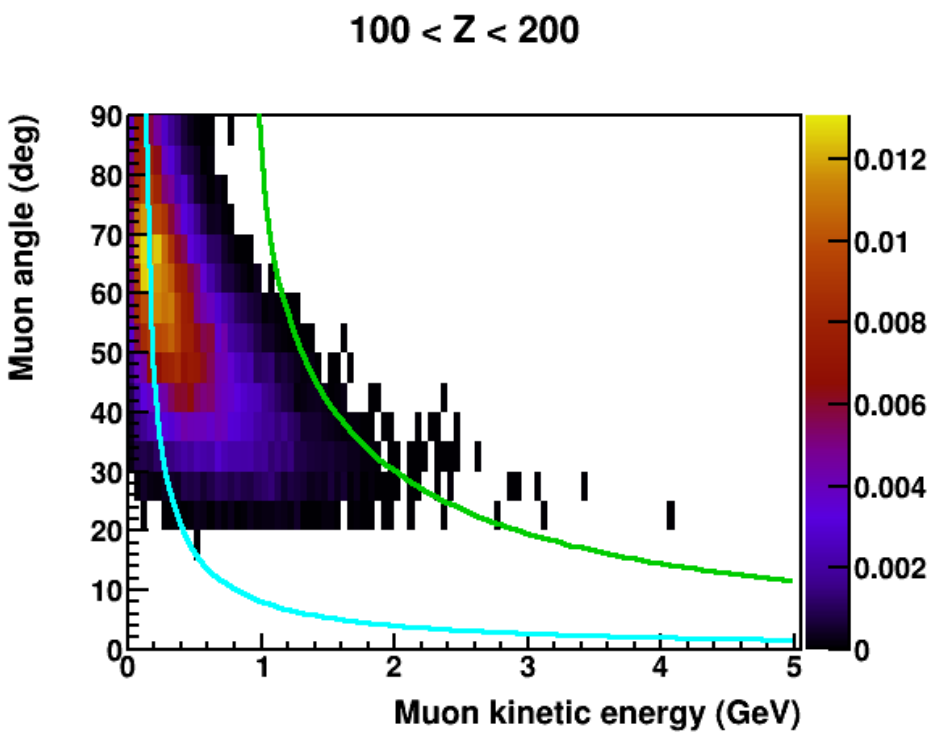


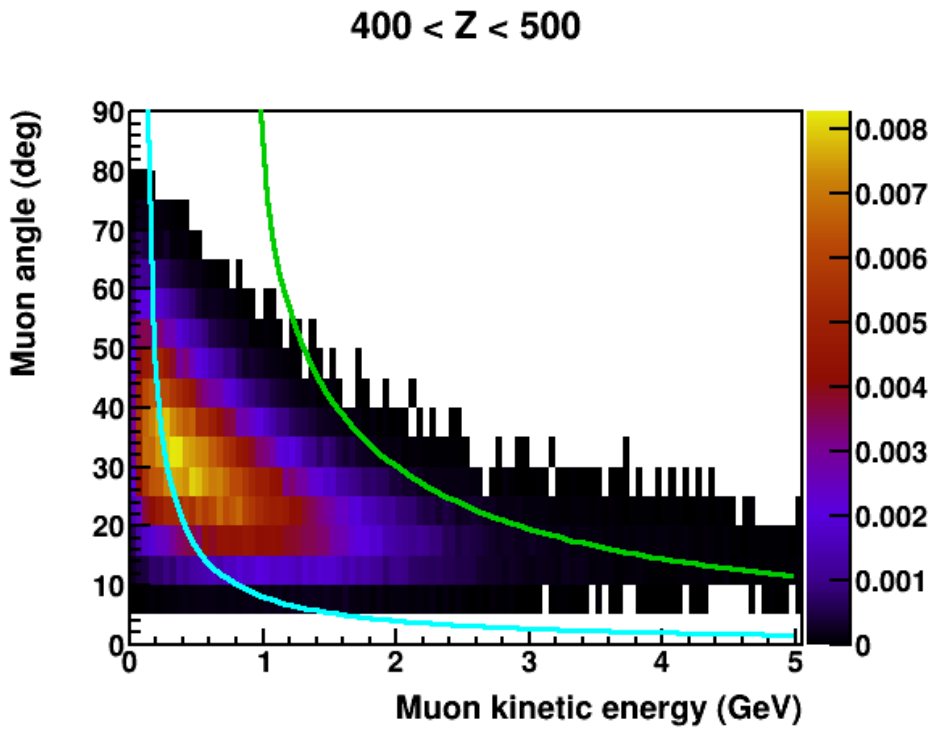
KLOE+STT



- KLOE "dip" is wider due to thickness of magnet yoke
- There is no region with good muon acceptance and good hadron acceptance for ~1 GeV muons with KLOE

Side detector requirements





- Muon energy and angle at exit point of active LAr on sides, in two different regions of Z along TPC
- Lines 70 and 500 g/cm^2 penetration
- Blue line is 50 additional cm Ar

Muon acceptance conclusions

- Dipole magnet is right at the edge of OK; it really can't get any thicker or there will be acceptance holes
- Design without coil between LAr and tracker is preferable for muon acceptance
- Side detector is required for good acceptance at high muon angle
- Not necessary to have side detectors on all 4 sides – can use rotational symmetry and only have 2

ν+e motivation

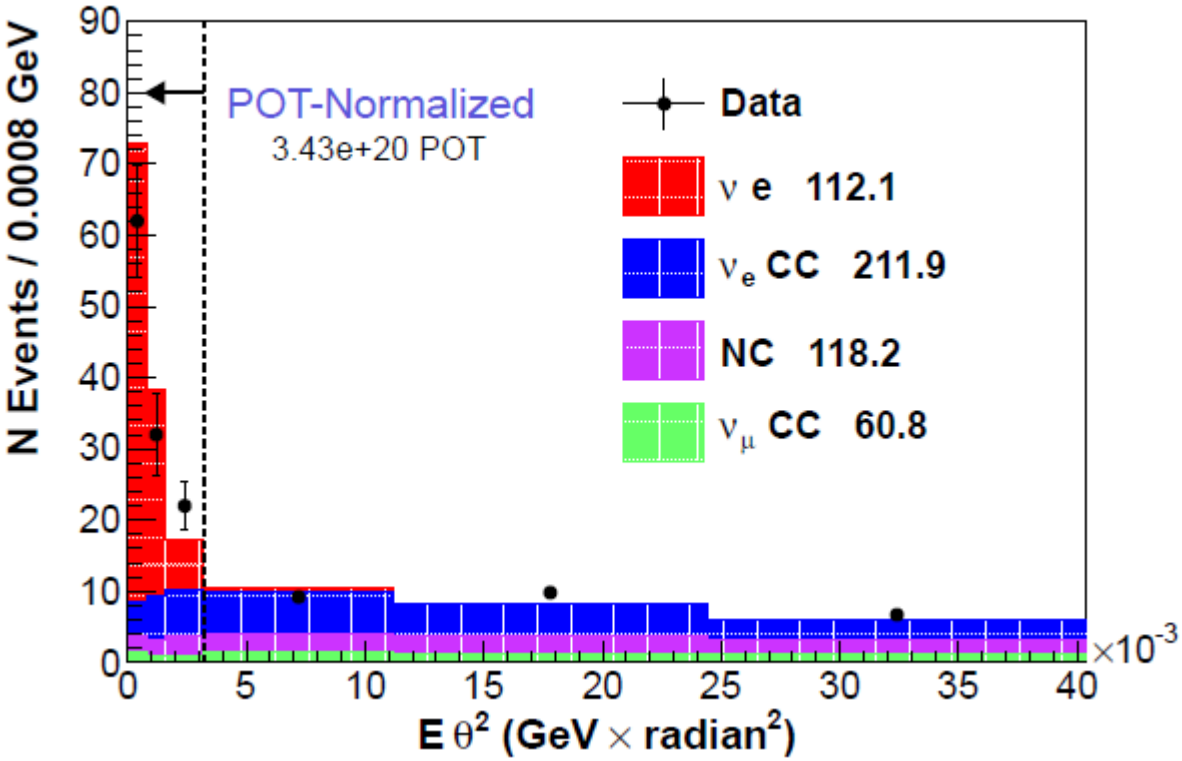
- I think we can all agree: ν+e rate measurement is very important for constraining flux normalization
- 35t LAr sees 15,000 events in 5yr → 0.8% stat error
  - Conservative assumptions: $E_e > 0.8$ with 90% efficiency
  - ν+e rate constraint will likely be systematics limited
- 5t STT sees 4,000 events in 5yr → 1.6% stat error
  - Lower threshold ~150 MeV, 100% efficiency
  - Lower backgrounds, better energy & angular resolution → percent-level systematics, likely statistics limited
- 1t gas Ar TPC sees 800 events in 5yr → 3.5% stat error
  - Probably too few events to be directly useful compared to LAr

Impact on MPT decision

- For ν+e, STT is clearly superior to gas TPC:
  - Resolutions are similar
  - Systematics likely similar and subdominant
  - STT event rate is ~5x higher
  - Different target to FD is irrelevant
- If LAr systematics are large, this could be an important factor in the MPT decision
- However, if LAr systematics are < 1.5%, then impact of adding STT to LAr ν+e measurement is minimal

MINERvA ν+e event selection

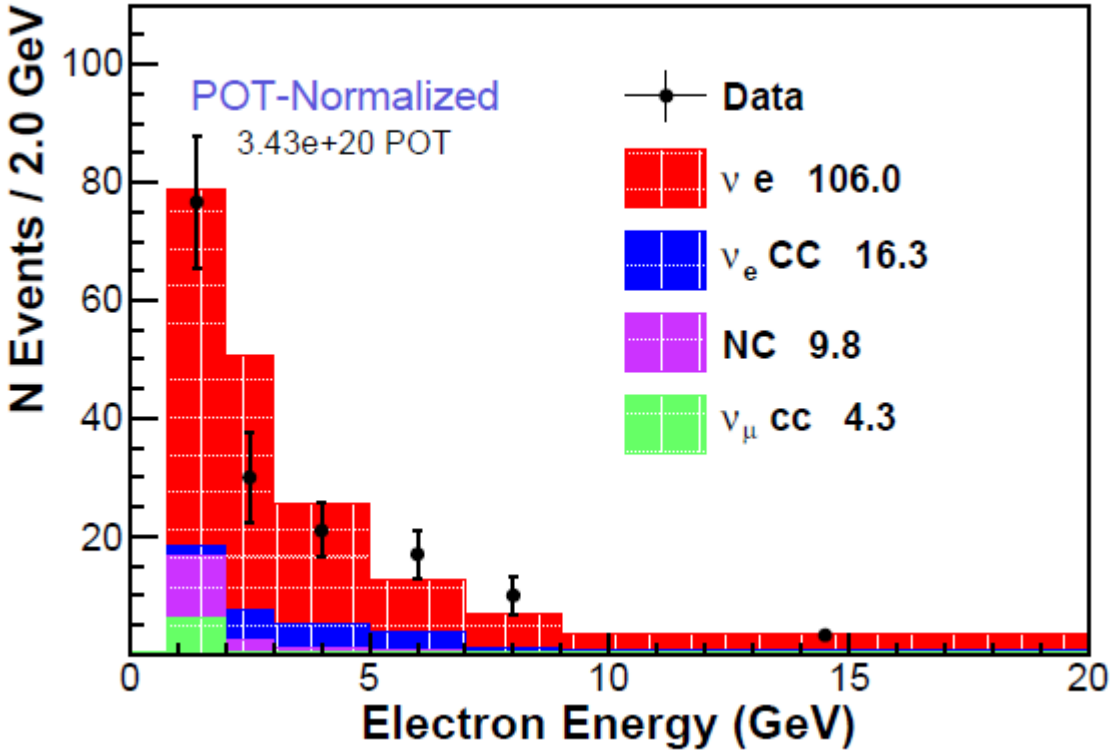
MINERvA Phys. Rev. D 93, 112007 (2016)



- Backgrounds are ν_e CCQE, and NC π^0
- Separated from signal by $E\theta^2$
- Sideband #2: moderate $E\theta^2$

- MINERvA electron energy resolution 3% ⊕ 6%/√E
- Angular resolution is ~7 mrad in each 2D projection, ~10 mrad in 3D

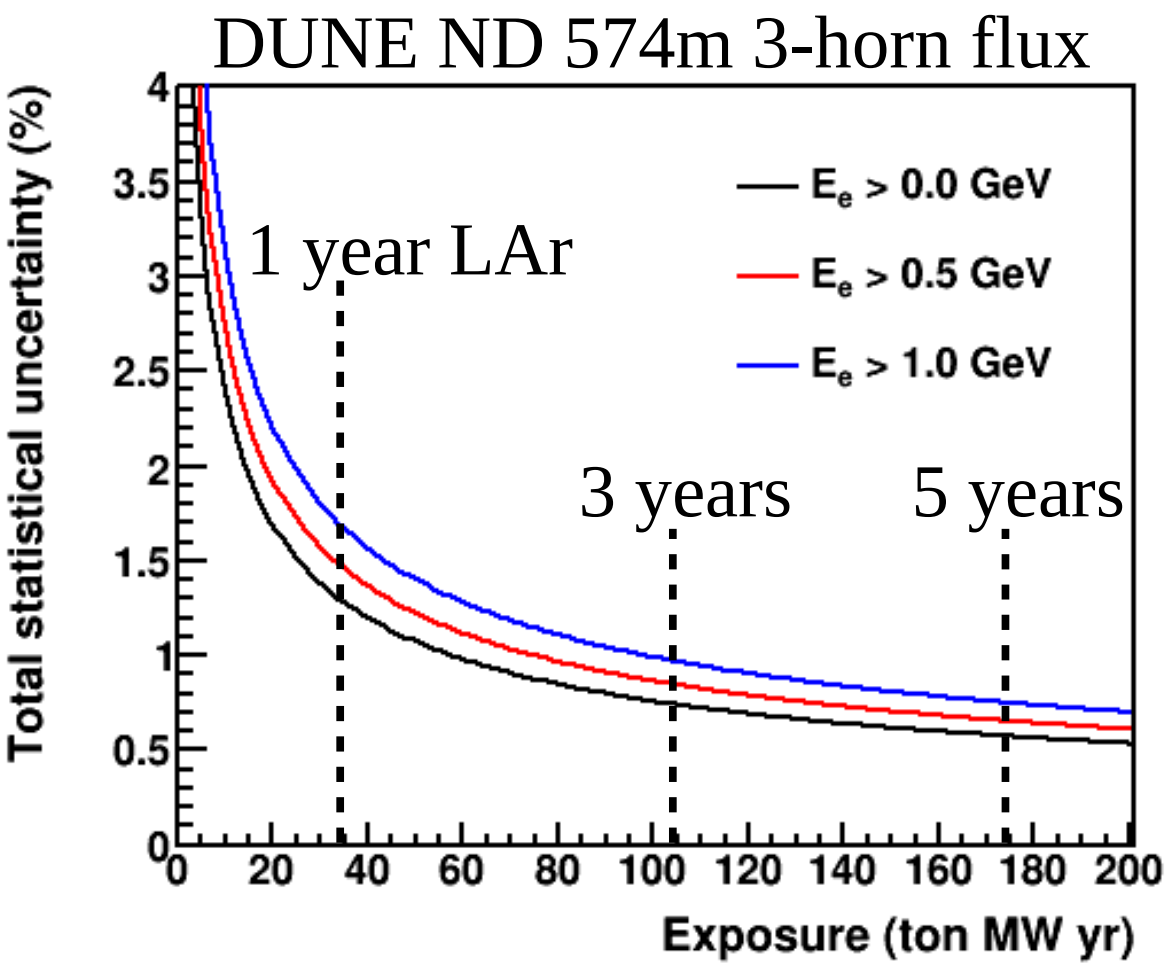
Main MINERvA result: electron energy distribution



Source	Fractional Uncertainty
Flux (simulated background)	0.2%
GENIE (not including CCQE)	2.3%
CCQE shape	3.1%
Beam angle	0.2%
Electromagnetic energy scale	1.8%
Reconstruction Efficiency	2.7%
Total Systematic Uncertainty	5.1%
Statistical Uncertainty	12.2%

- 127 selected events at 70% signal efficiency, 30 predicted background
- Energy cut > 0.8 GeV to reduce backgrounds
- Statical >> Systematic uncertainty – pushing any individual systematic beyond ~3% level has very little benefit in MINERvA LE analysis

DUNE ND ν+e statistics



- DUNE LAr ND at ~35t F.V. will have ~10k events in 3 years, even with very conservative thresholds
- ~100x more statistics than MINERvA LE analysis

Detector-related systematics

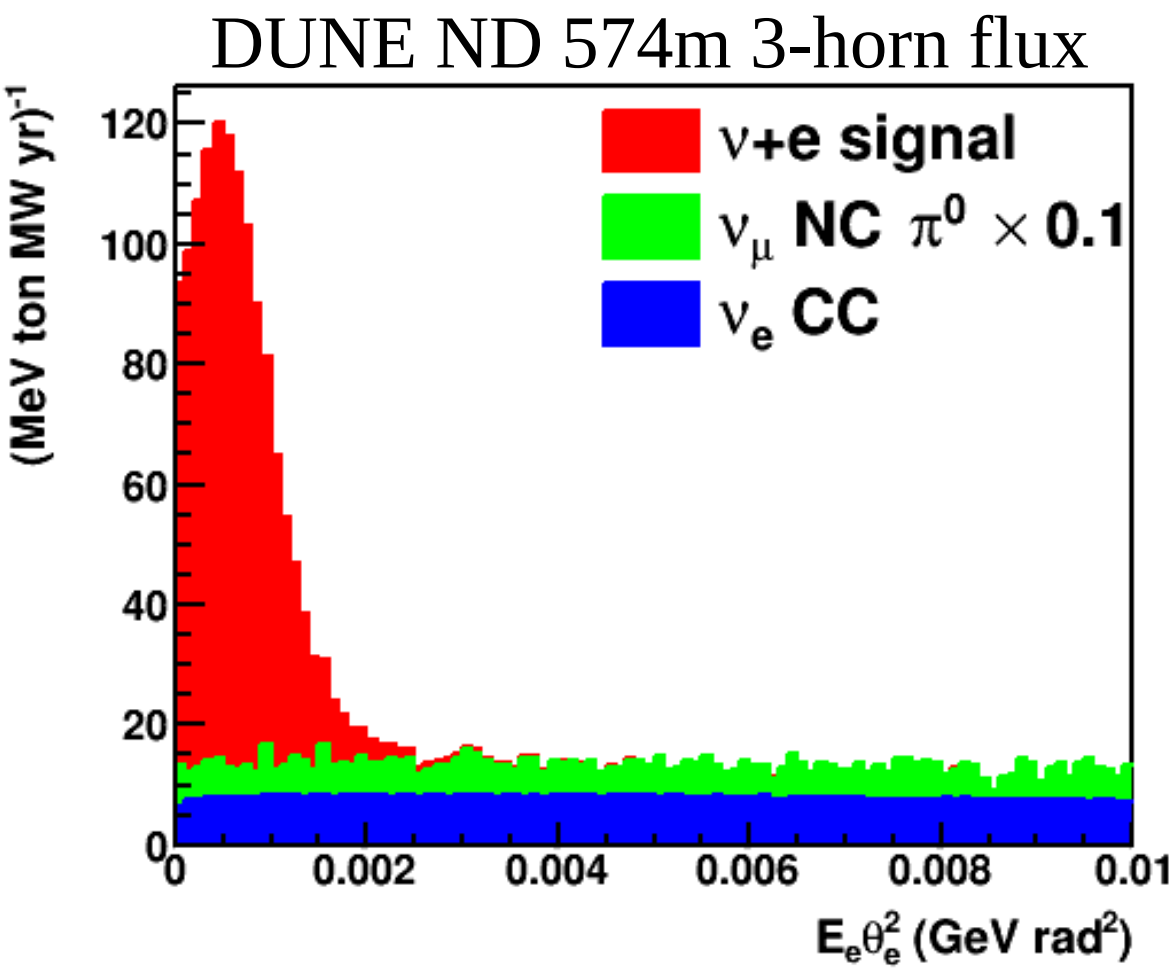
- Electron energy
  - Reconstruction efficiency will depend on electron energy
  - Cut on $E\theta^2$ is sensitive to electron energy scale
- Electron angle (or beam angle)
  - Cut on $E\theta^2$ is very sensitive to electron angle

Detector-related systematics

- Electron energy
  - Reconstruction efficiency will depend on electron energy
    - Flattens out by ~1 GeV in MINERvA, DUNE can use higher energy cut, which also reduces photon backgrounds
  - Cut on $E\theta^2$ is sensitive to electron energy scale
    - Use higher cut, where signal efficiency is ~100% and flat
- Electron angle (or beam angle)
  - Cut on $E\theta^2$ is very sensitive to electron angle
    - Use higher cut, where signal efficiency is ~100% and flat

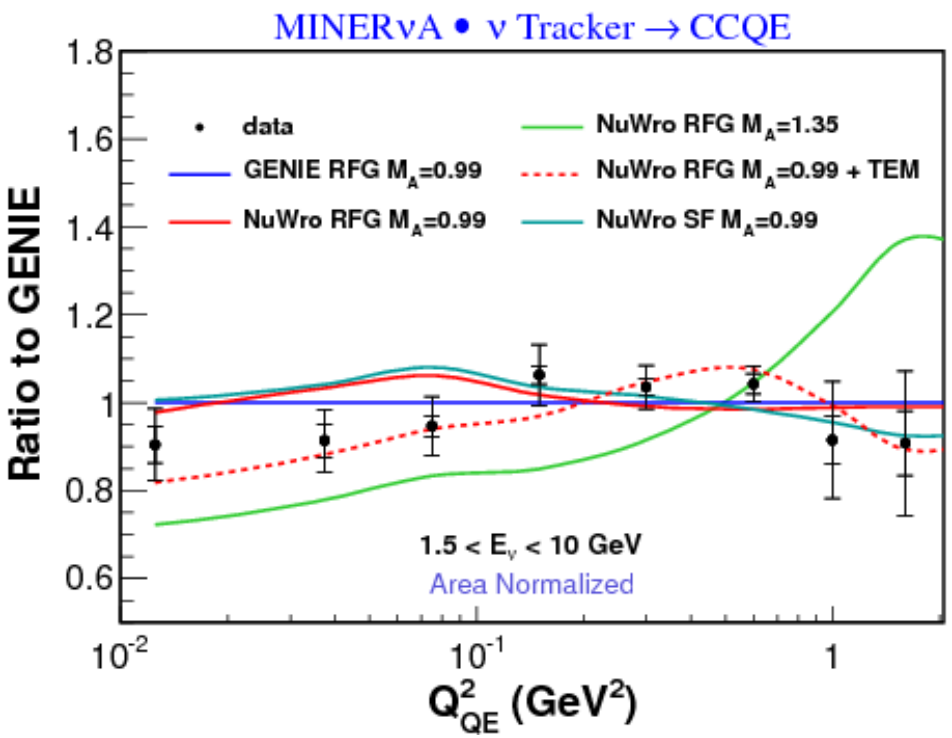
Pay a modest price in statistics, and can't escape ν_e CC background...

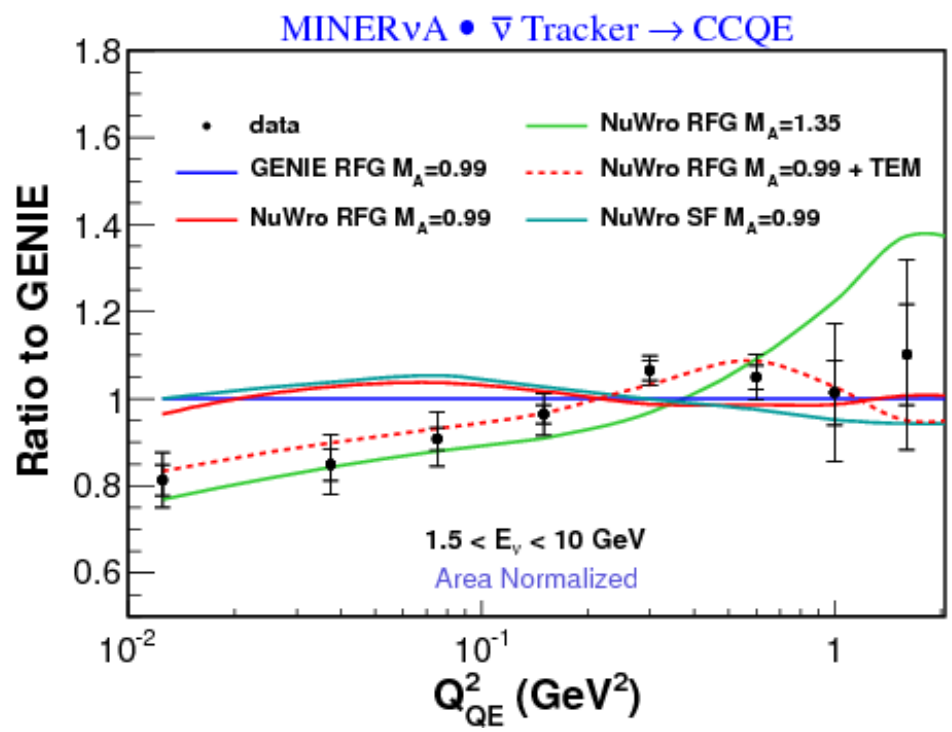
Systematics goal ~ 1%



- Sample purity will be ~88% in LAr
- It is impossible to do better than that
- Need background uncertainty to be ~10% of itself

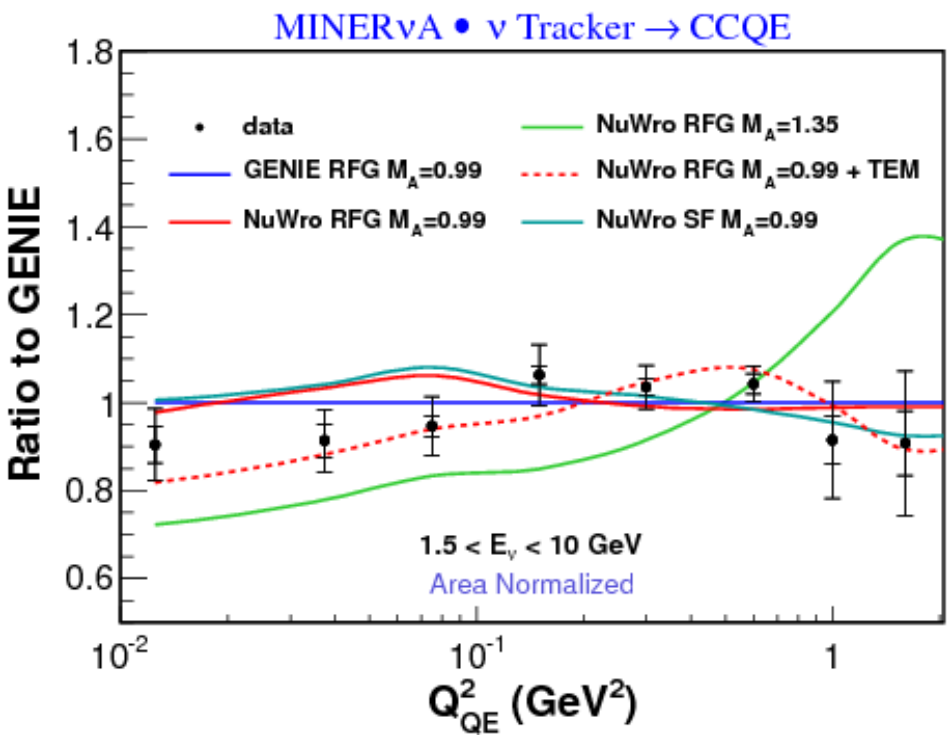
CCQE shape (ν_μ)

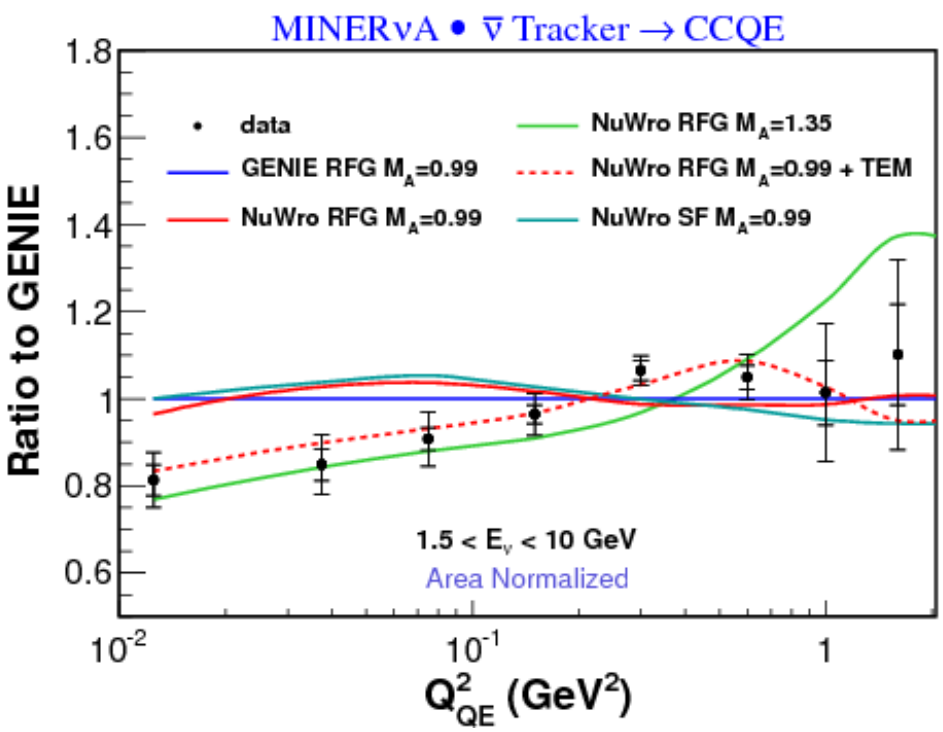




- $E\theta^2 = Q^2/E_\nu$, for 3.5 GeV E_ν MINERvA signal region of 0.0032 GeV → Q^2 ~0.01 GeV^2
- Signal region is ~half of first bin in MINERvA 2013 CCQE analysis (but for ν_e instead of ν_μ)
- Sideband is > 0.005, upper ~third of first bin and next 4 bins

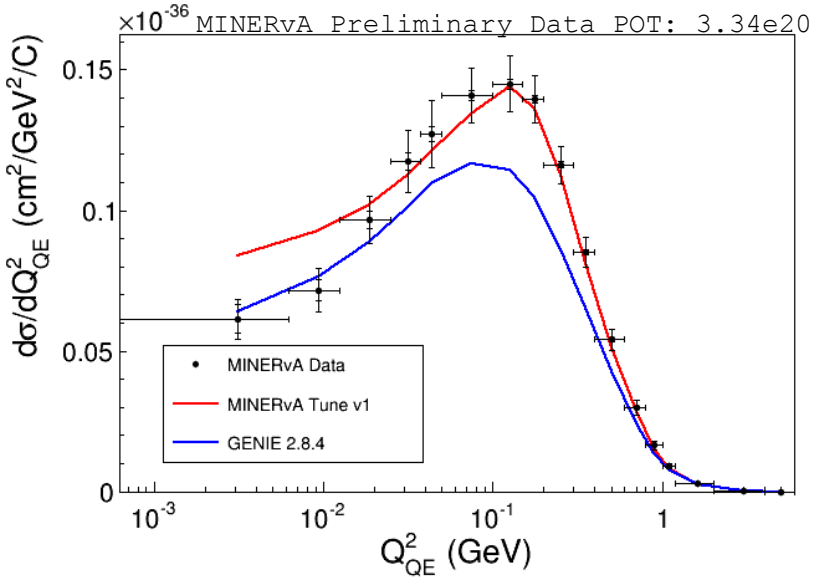
CCQE shape (ν_μ)

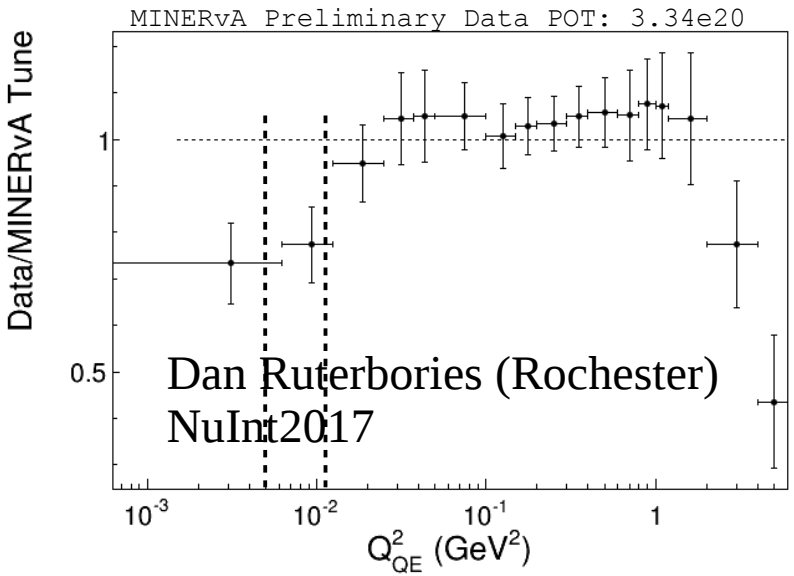




- Model used in MINERvA LE ν+e is GENIE 2.8
- CCQE model is Llewellyn Smith, dipole axial form factor with M_A = 0.99 GeV
- Nuclear model is Smith-Moniz, no 2p2h
- Sound theory predicts cross section is suppressed at very low momentum transfer due to long-range effects, confusingly called "RPA"

MINERvA 2018 result (ν_μ)



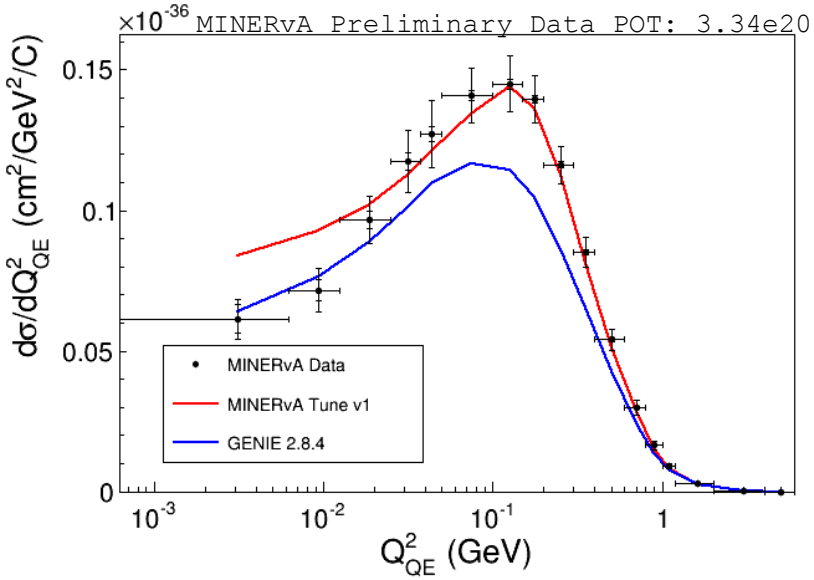


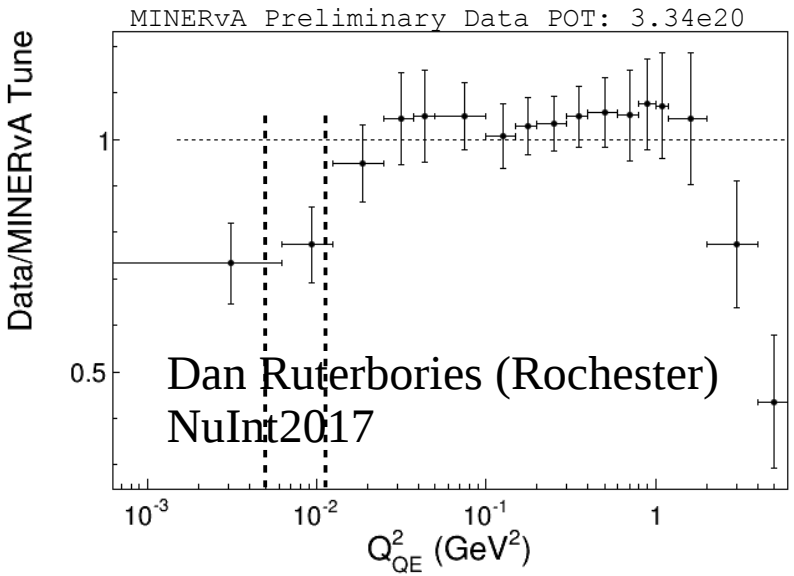
lines of $E\theta^2$
~1.5 MeV
~3.2 MeV

Dan Ruterbories (Rochester)
NuInt2017

- Current data is sensitive to effects at very low Q^2
- Models are improving – MINERvA Tune includes nonresonant pion tuning, Nieves et al. 2p2h+RPA
- But still no resonant RPA, and resonance (with pion absorption) is ~30% of the CC0π sample at very low Q2
- Expect this to improve further in next 10 years

MINERvA 2018 result (ν_μ)



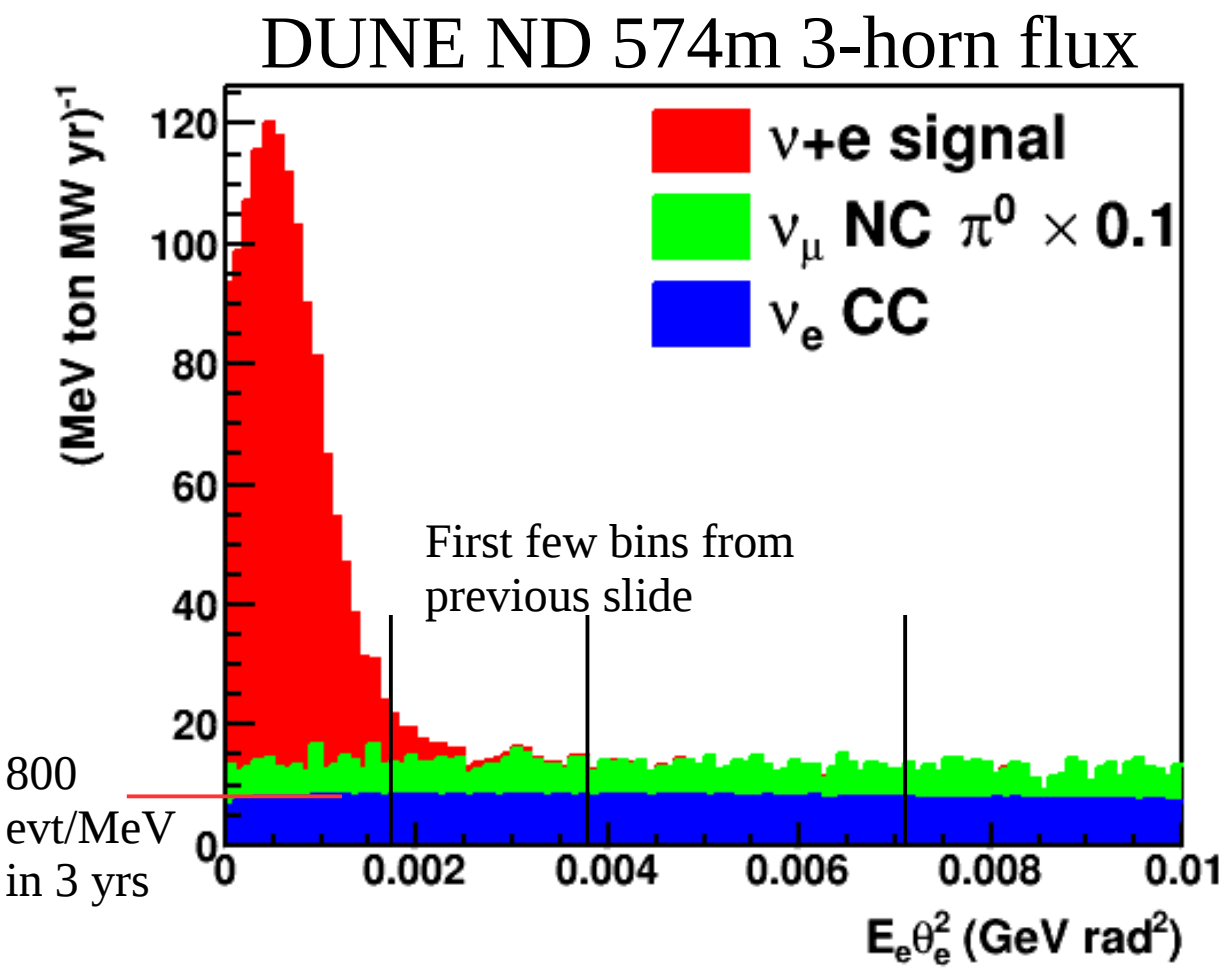


lines of $E\theta^2$
~1.5 MeV
~3.2 MeV

Dan Ruterbories (Rochester)
NuInt2017

- MINERvA ν_μ CC data shows ~25% discrepancy in shape extrapolating from MINERvA ν+e sideband to signal region, with ~10% uncertainties
- DUNE can do less extrapolating due to high sideband statistics, and can see this shape down to ~0.005

DUNE ND backgrounds & sideband

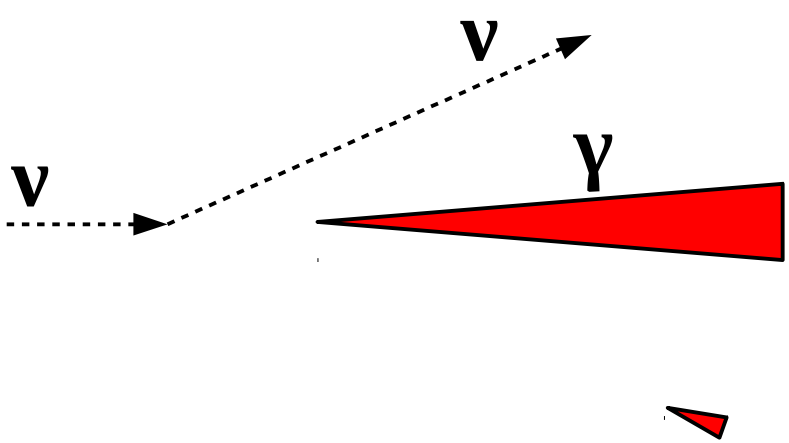


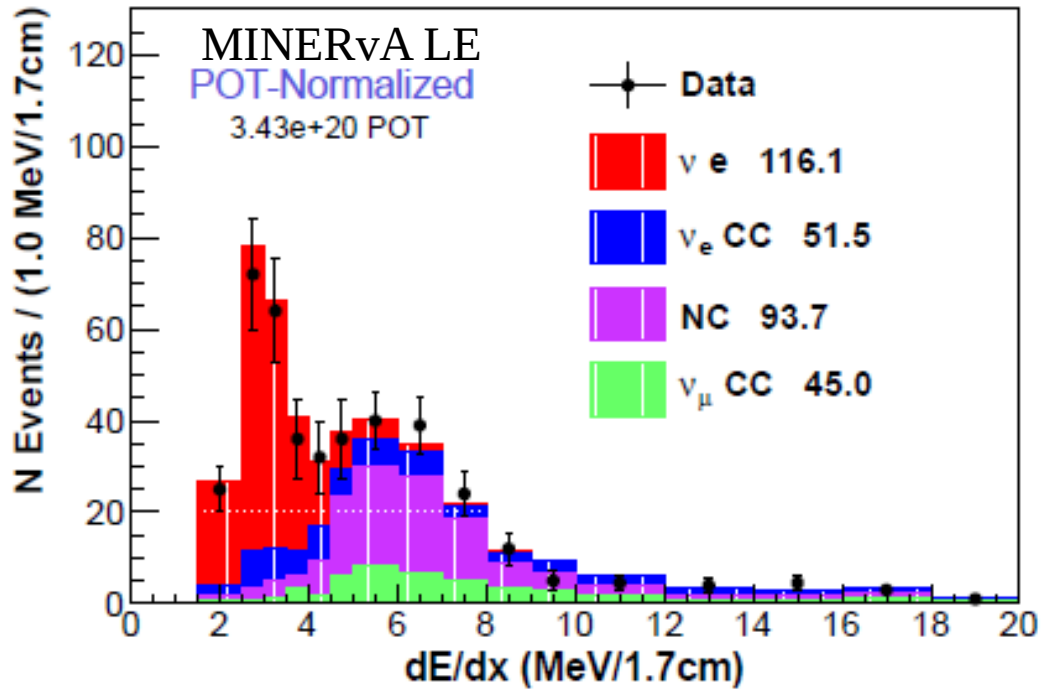
- First bin of MINERvA ν+e sideband will have ~2000 events in DUNE LAr in 3 years
- Can measure shape directly in ν_e, in addition to using ν_μ CCQE events to go down to signal region
- Limitation: lepton mass becomes important in signal region, shape below minimum Q^2 for ν_μ CC can't be measured

CCQE shape conclusions

- Data/MC discrepancy using current, un-tuned models would give ~25% uncertainty
- Data is already good enough to get to ~10% uncertainties at Q^2 relevant for ν+e
- DUNE's own LAr ND sidebands will be sensitive to shape discrepancies
- 10% shape uncertainty is an ambitious but achievable goal for DUNE
- Given expected purity in LAr, that is ~1% systematic on flux normalization from background

NC photon background





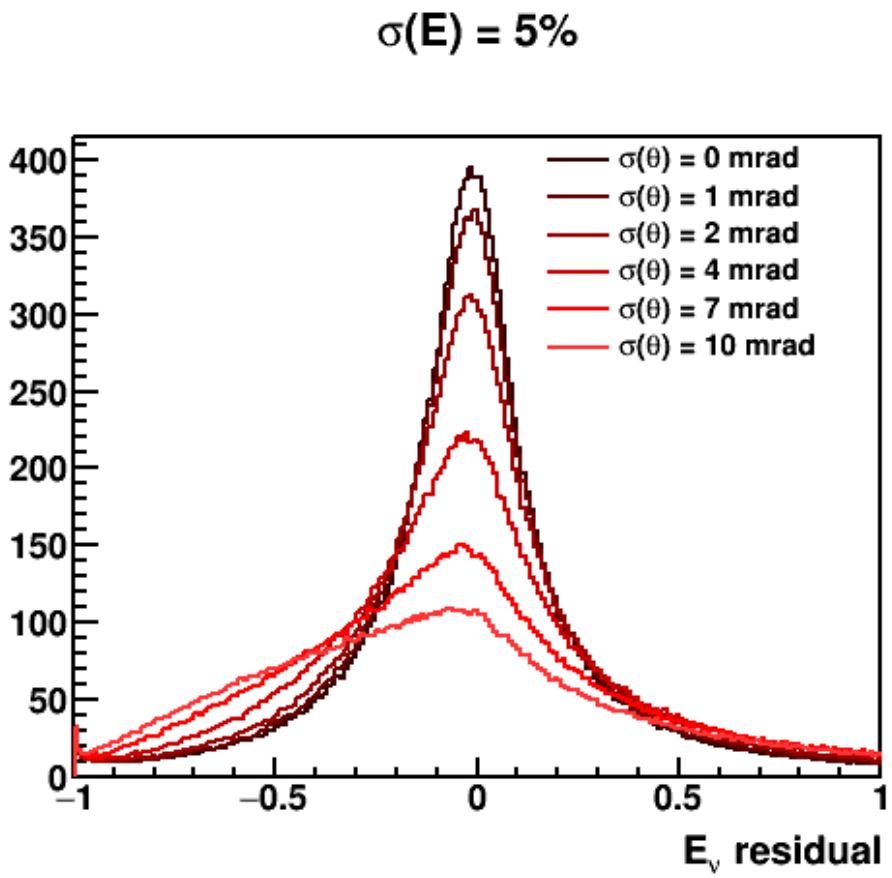
- $E\theta^2$ sideband with reversal of dE/dx cut will have huge statistics
- Unlike ν_e CC, we aren't going to $Q^2 \rightarrow 0$, as these events are typically asymmetric π^0 decays where one photon happens to point in beam direction
- "0 is not special"
- No reason to expect shape in this variable, and sideband constraints will be very powerful

Systematics conclusions

- 10% uncertainty on background extrapolation is possible in LAr, with improved CCQE and CCΔ modeling, and use of high-statistics control samples
  - → 1% uncertainty on ν+e normalization
- Detector systematics will be important, especially electron energy scale and beam angle
  - Reducing impact will lower statistics or increase backgrounds
- Other uncertainties are small using a technique similar to MINERvA
- LAr alone can adequately measure ν+e rate
  - Complementary STT measurement is beneficial but not required

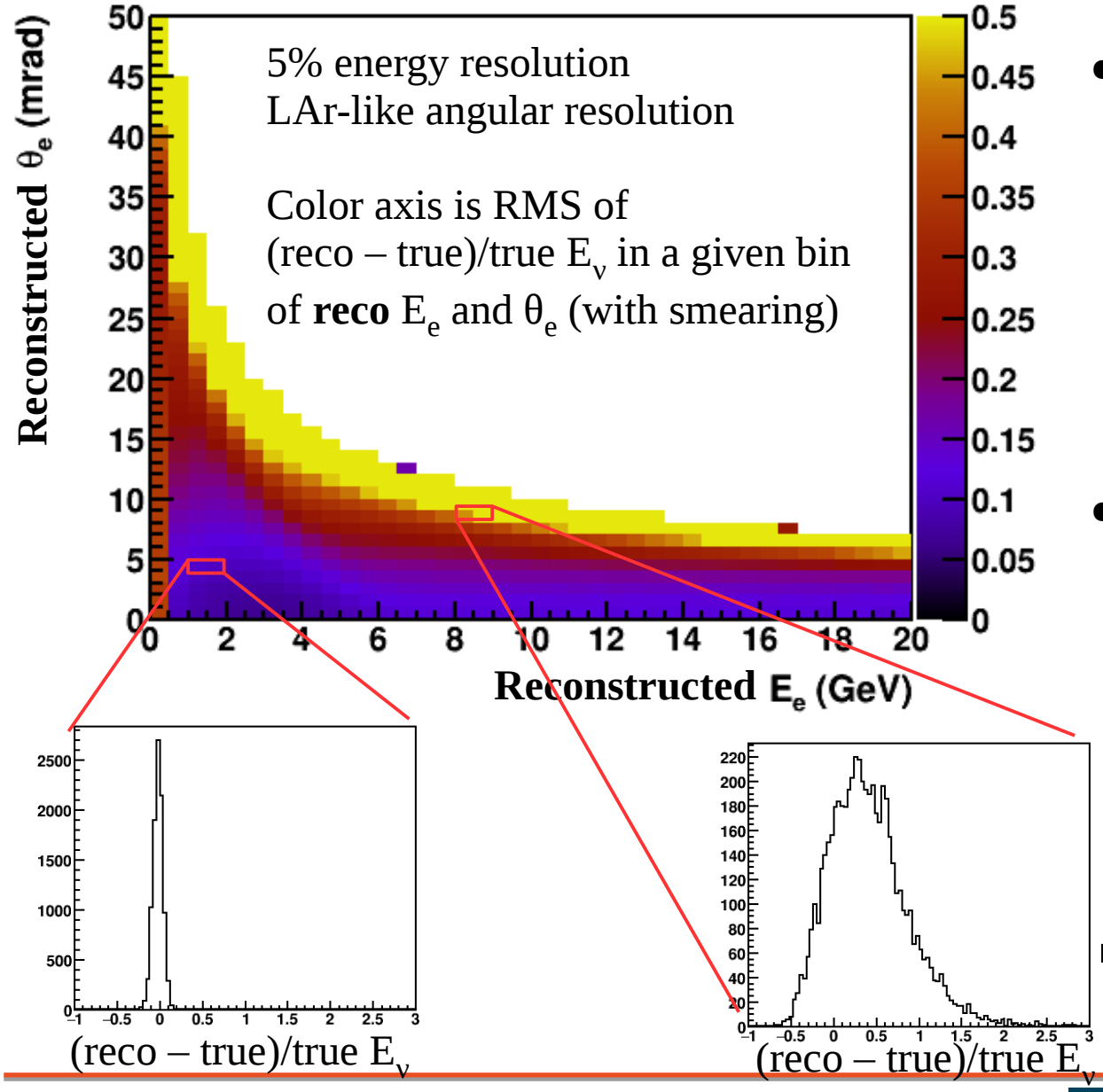
Direct neutrino energy measurement

$$E_\nu = \frac{E_e}{1 - \frac{E_e(1-\cos\theta)}{m}} \approx \frac{E_e}{1 - \frac{E_e\theta^2}{2m}}$$



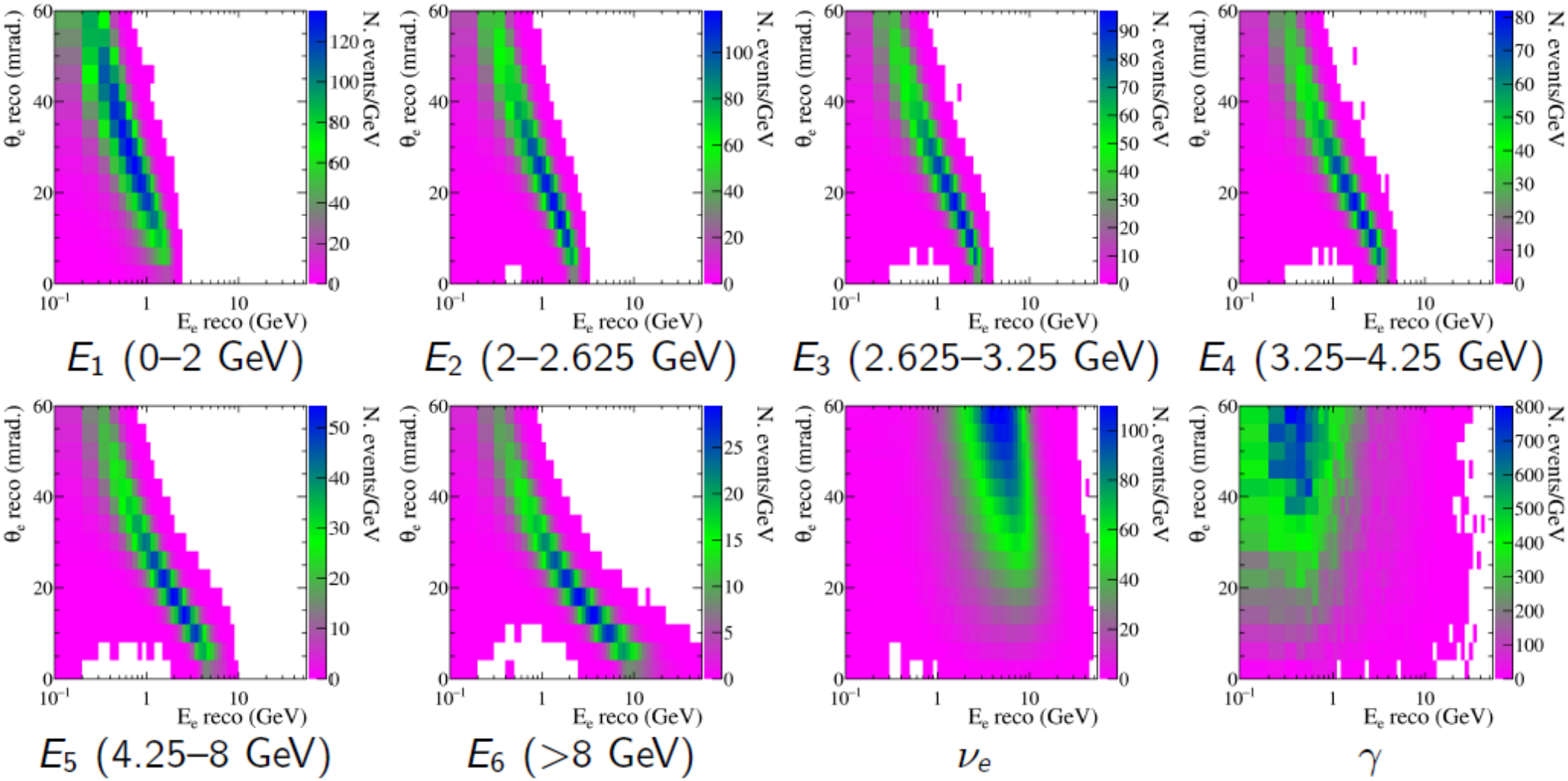
- In principle, one can measure neutrino energy event by event
- Extremely sensitive to electron kinematics, especially angle
- Beam divergence alone gives ~20% resolution

E_ν resolution vs. (E_e, θ_e)



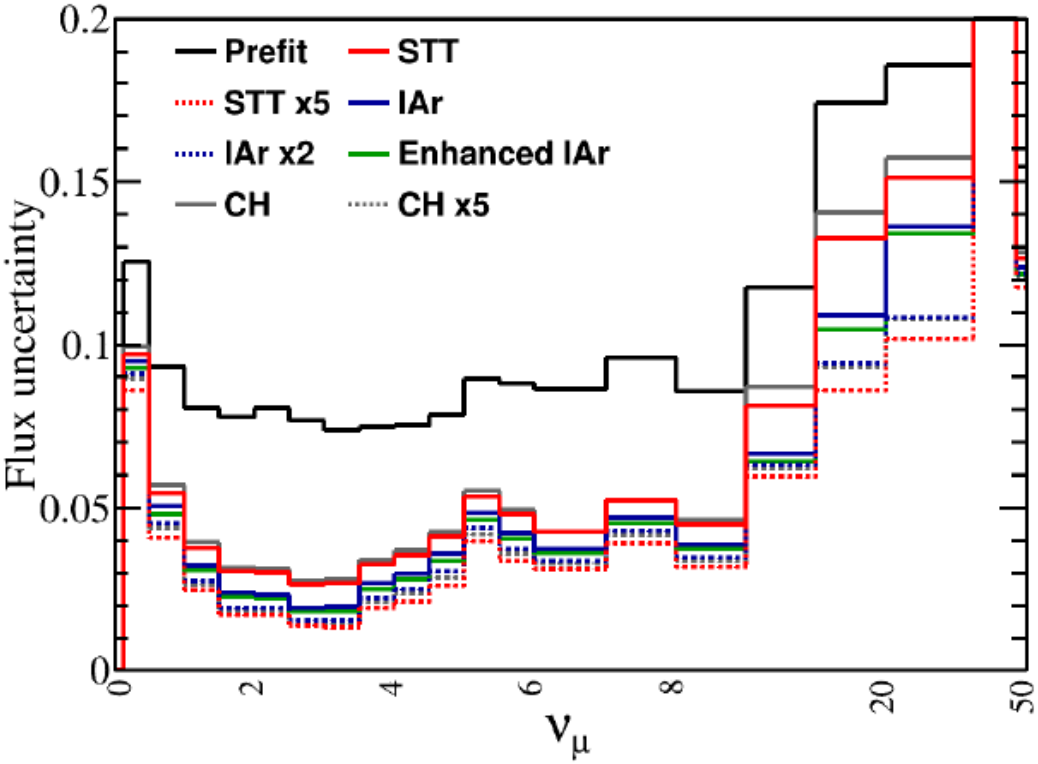
- Energy resolution is quite good in a region of (E,θ), basically where $E\theta^2$ is very small
- Effectively, select a subsample of good, and unbiased energy resolution and measure shape from it
- Requires very high statistics

2D template fit

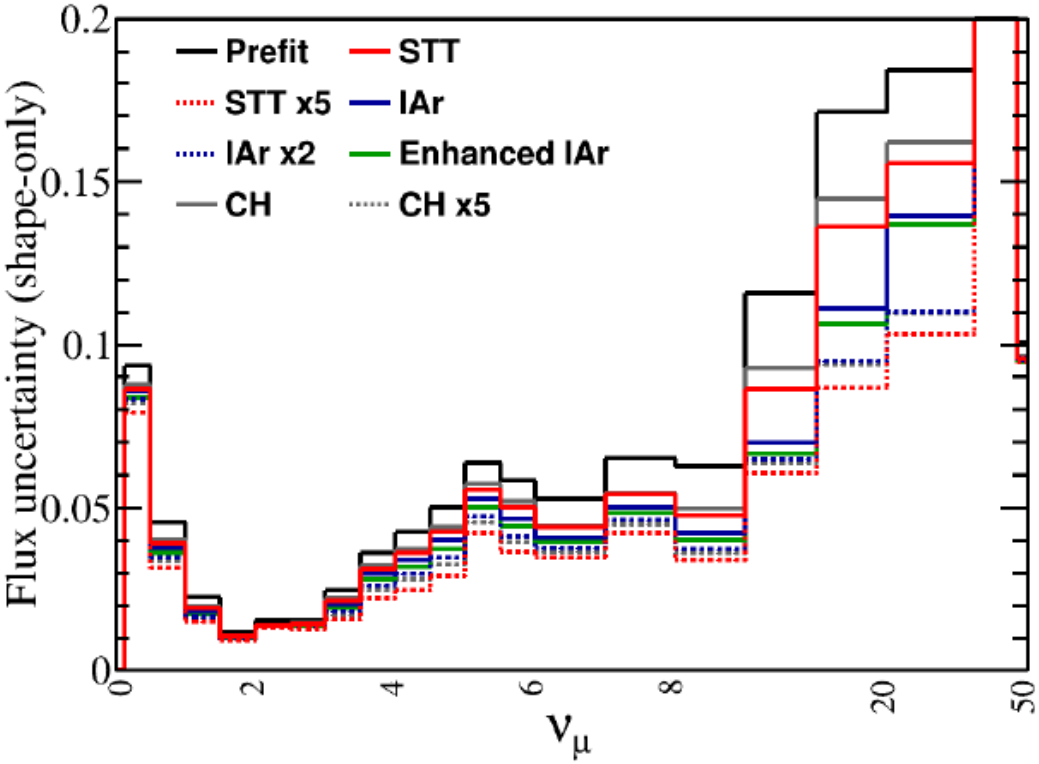


- Each template is a bin of neutrino energy, and adds events in (E,θ)

Results for different ND options



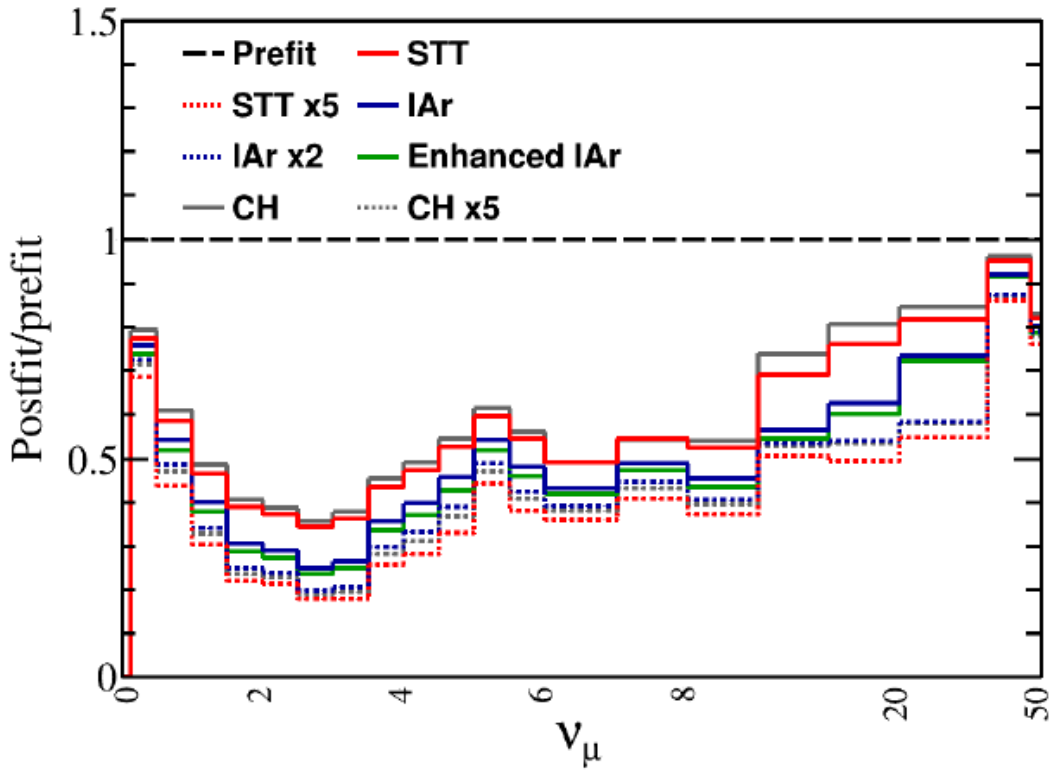
Rate+shape



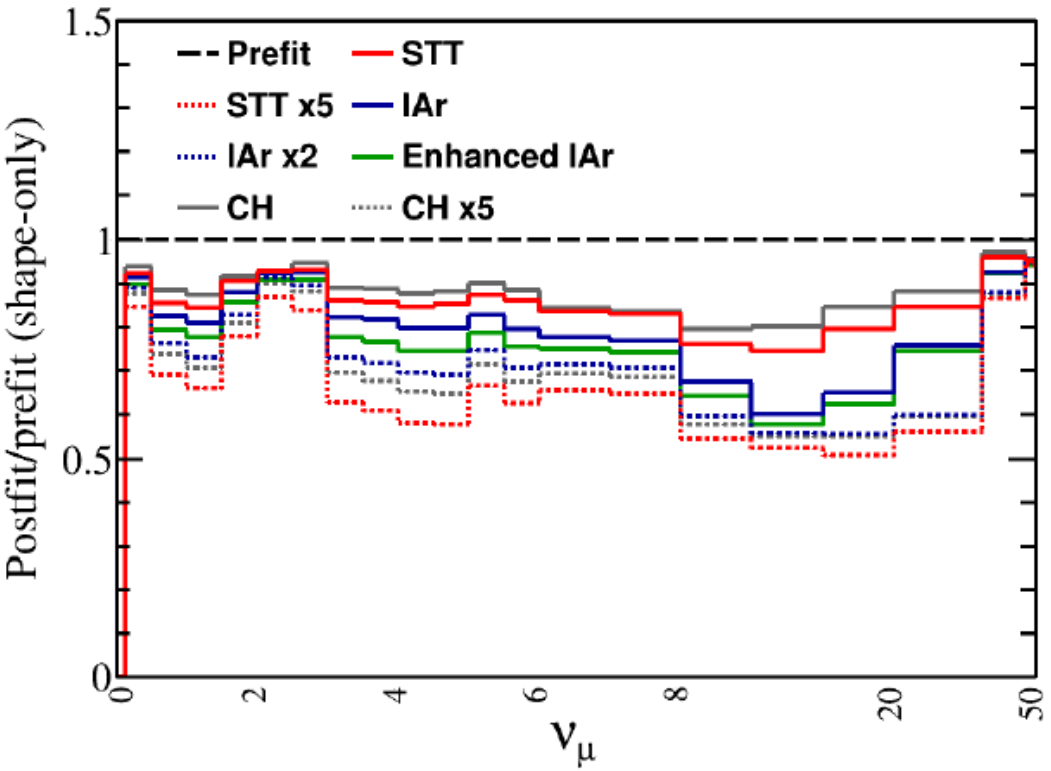
Shape-only

- As expected, ν+e constraint reduces flux uncertainty
- Shape uncertainties are quite small pre-fit, and improvement is modest

Ratios to pre-fit uncertainties



Rate+shape



Shape-only

- As expected, ν+e constraint reduces flux uncertainty
- Shape uncertainties are quite small pre-fit, and improvement is modest
- LAr statistics give more power than improved resolutions from lower-mass detectors

Shape measurement conclusions

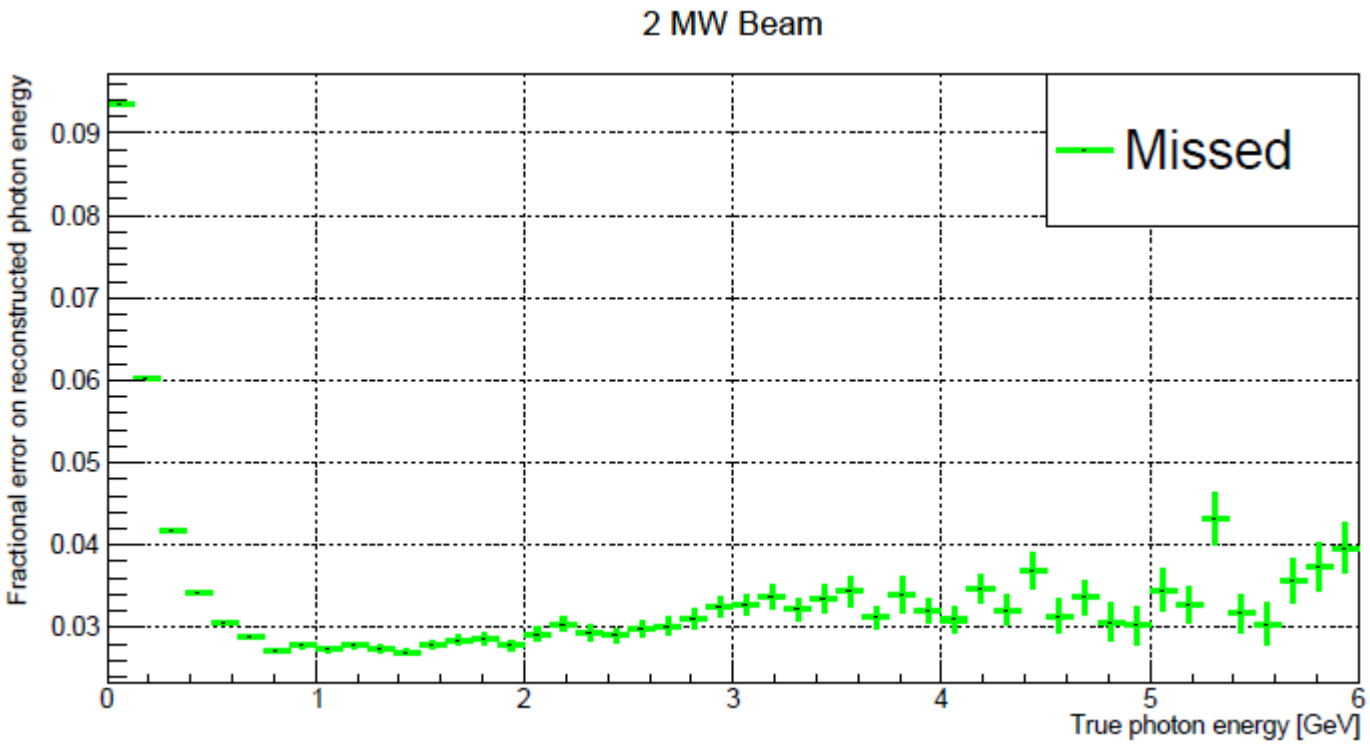
- Sensitivity to flux shape requires very large statistics
- Neither STT nor gas TPC is likely to add much to this, even with fantastic resolutions

The Answers

- Can LAr detector handle the high rate?
  - Tracks: yes, π^0 photons: yes, neutrons: maybe?
- What size is needed for hadron containment?
  - 4x3x5m, with 5m in ~beam direction
- What is the statistics in the fiducial volume?
  - High. For 3x2x3m F.V. (25t), 37M ν_μ CC events per year at 1.07 MW
- What is the muon acceptance for LAr interactions for the different tracker options?
  - That one is hard to answer in one bullet, but there are plots
- Is a side muon spectrometer needed?
  - Yes, otherwise the required width for muon acceptance is ~7m
- Can neutrino-electron scattering be measured?
  - Yes, with <2% normalization uncertainty and some shape power

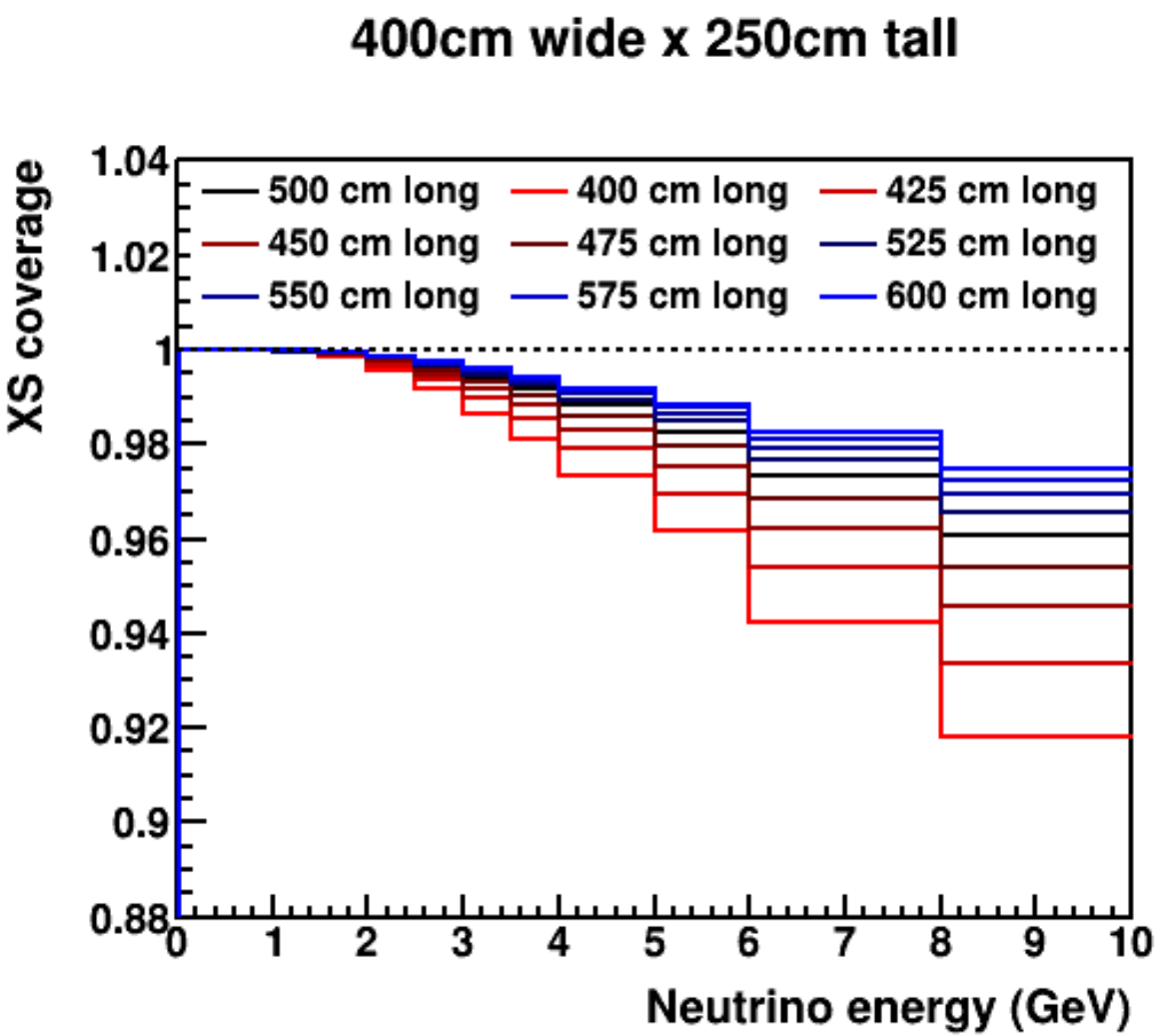
Backups

Cone contains ~97% of photon



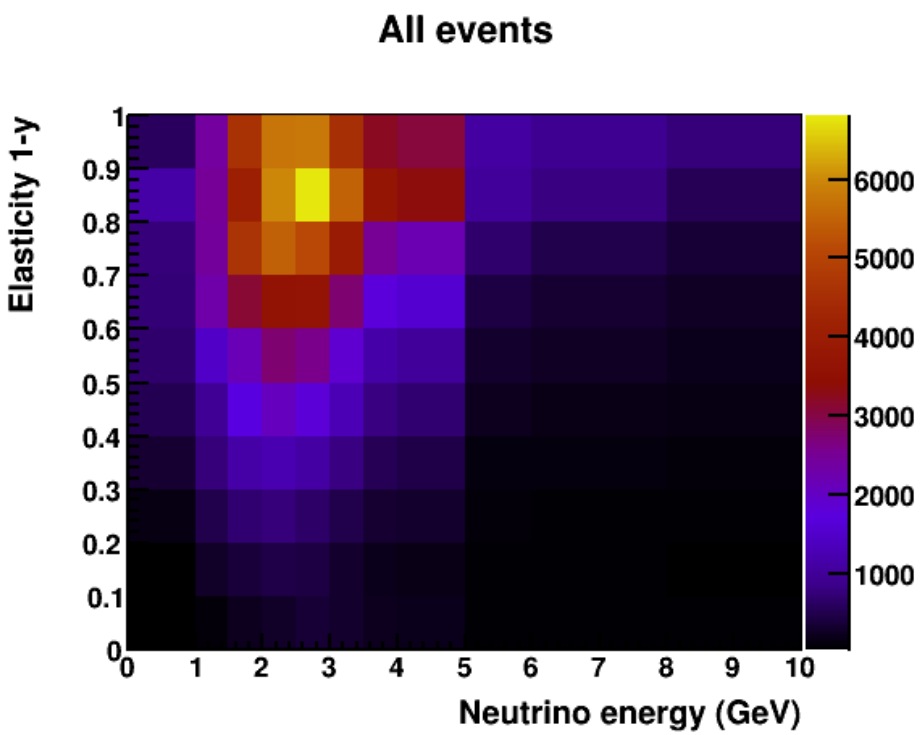
- Place cone vertex at true conversion point, with axis along true photon direction
- Cone contains 97% of photon energy above ~400 MeV

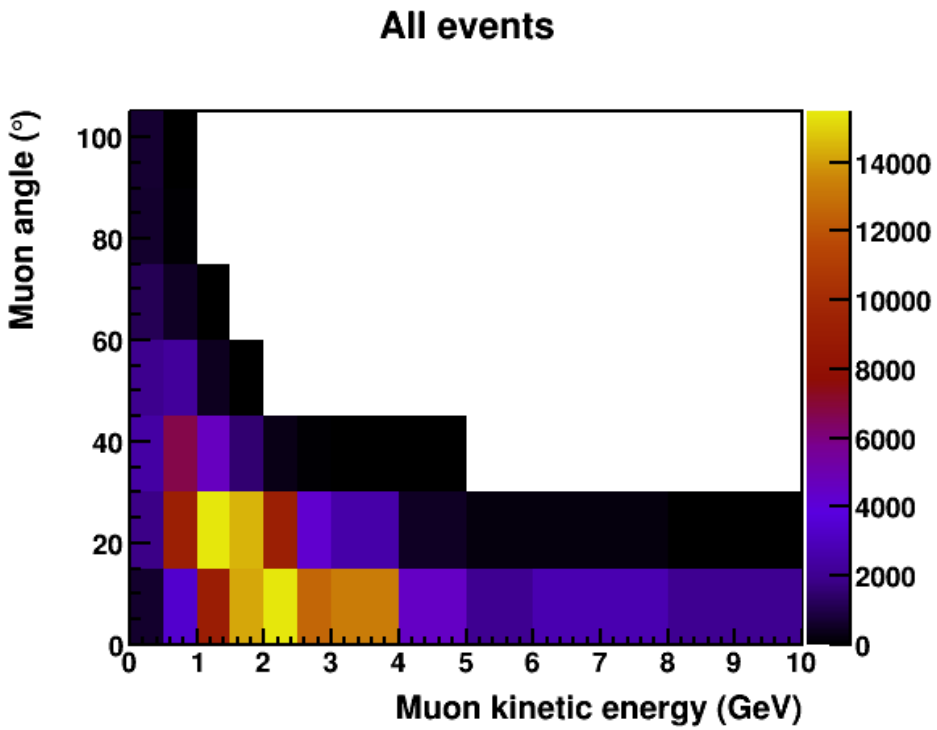
XS coverage vs. Z



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

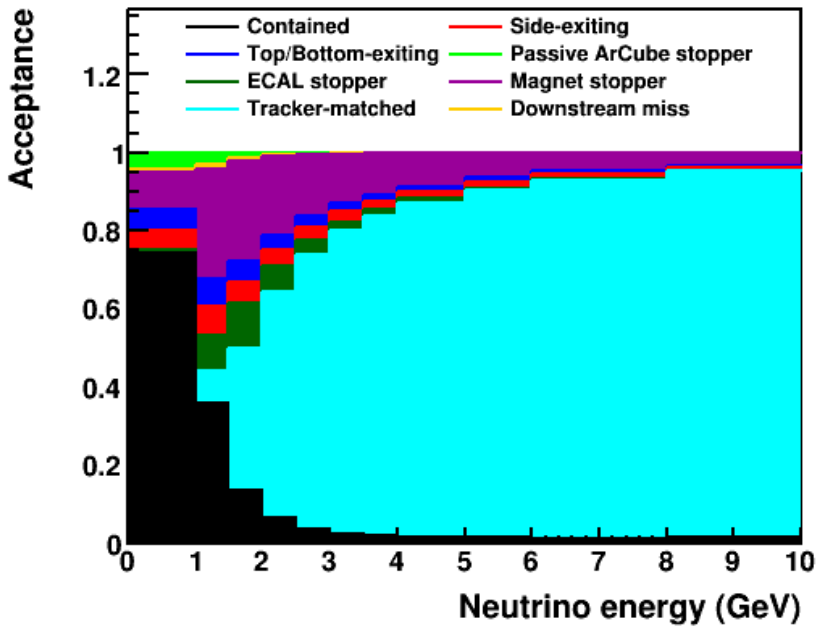
RHC $\bar{\nu}_\mu$ acceptance

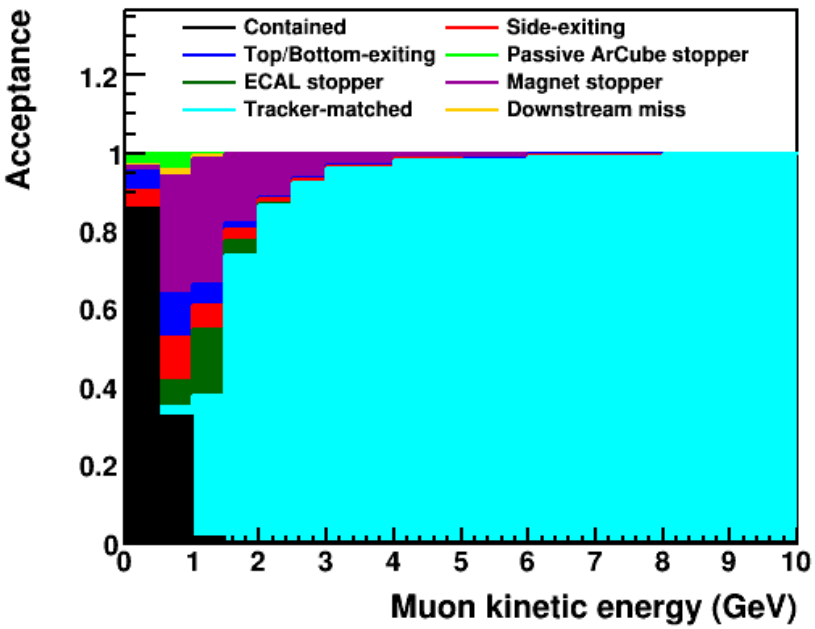




- Events are more elastic
- Muons are more energetic and more forward

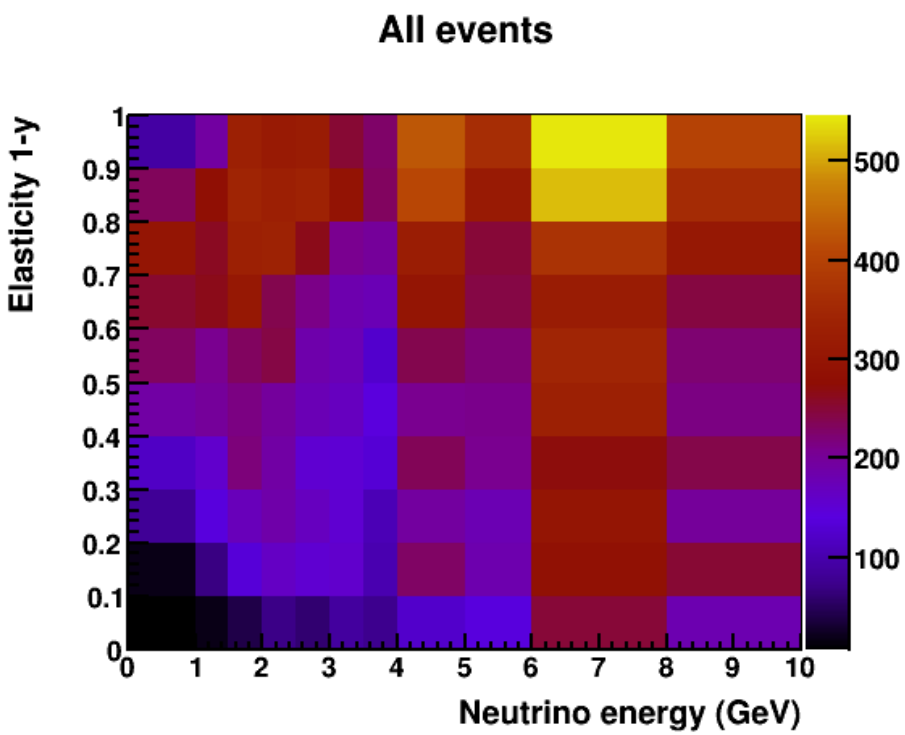
RHC $\bar{\nu}_\mu$ acceptance

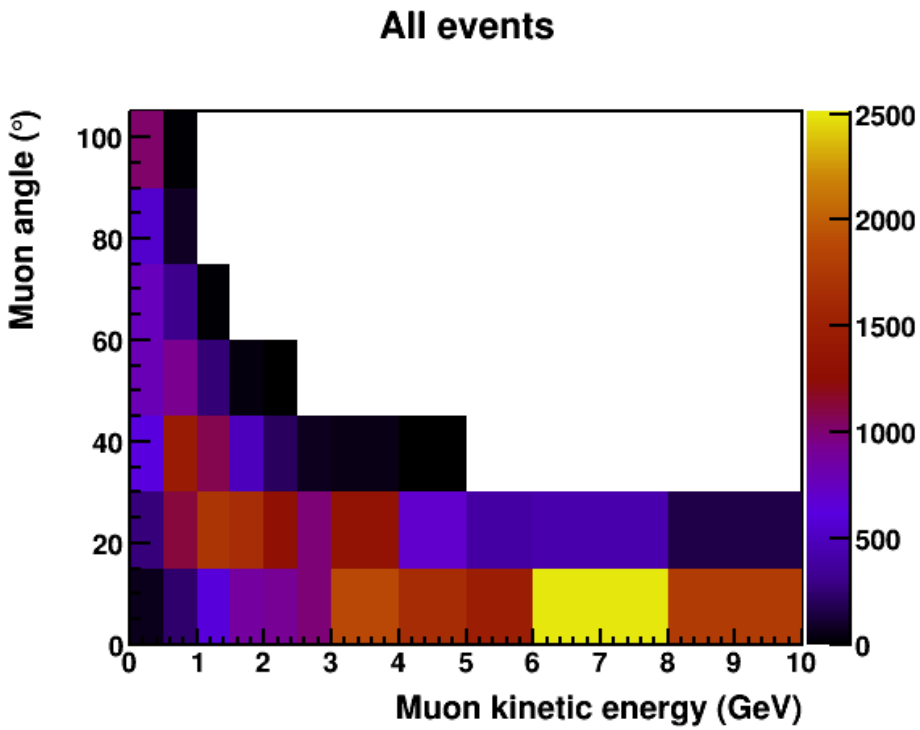




- Dipole + gas TPC
- Similar to neutrino for muon energy
- Better at high neutrino energy due to higher elasticity

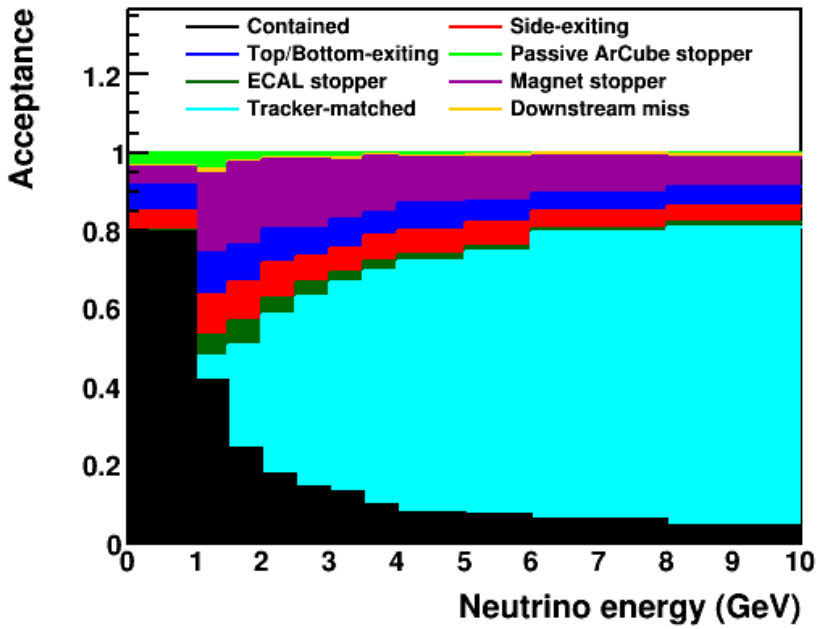
RHC ν_μ acceptance (wrong sign)

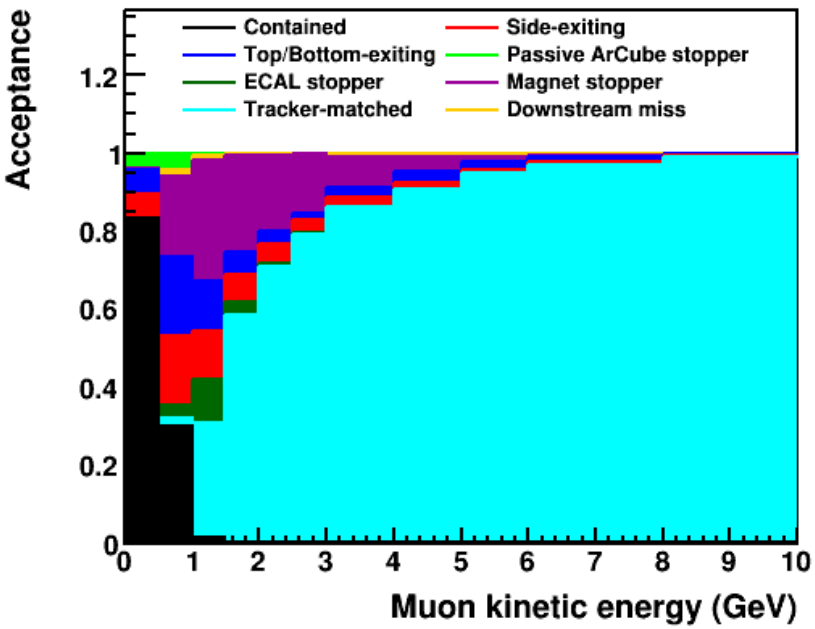




- Flux is very different obviously
- Higher energy

RHC ν_μ acceptance (wrong sign)

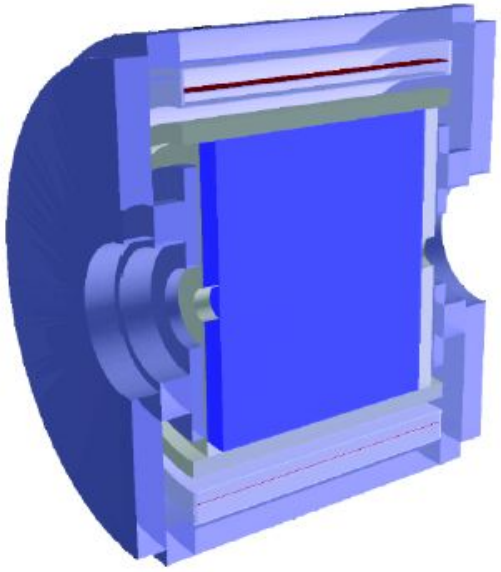


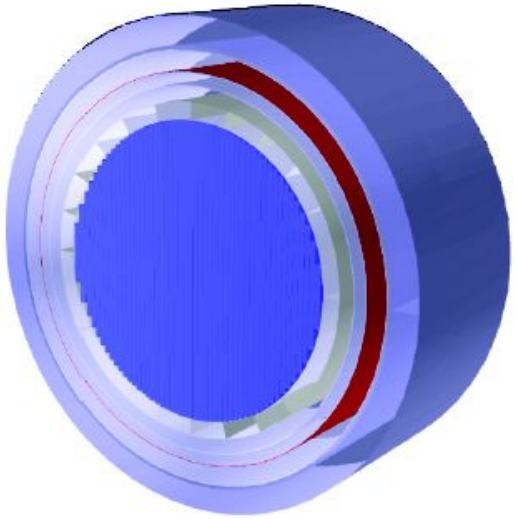


- Acceptance is similar
- To do: look at rates for different muon fates in RHC for neutrino and antineutrino

KLOE+STT geometry

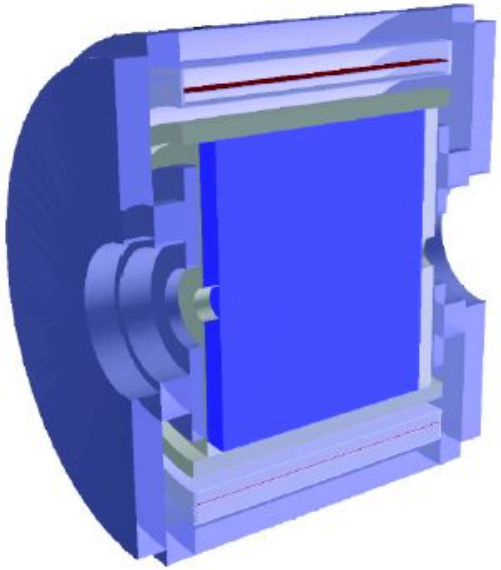
- Inner STT tracker (radius 0-200 cm)
- Lead/scintillator ECAL (200-223)
  - Considered ACTIVE volume
  - Average density 5.3 g/cm^3
- Solenoid cryostat (244-288)
  - 2x1.5cm Al walls, 1cm Al shell
  - 1cm Cu coil
  - Filled with air – low mean density
- Magnet yoke (293-330)
  - Iron ρ = 7.87 g/cm^3

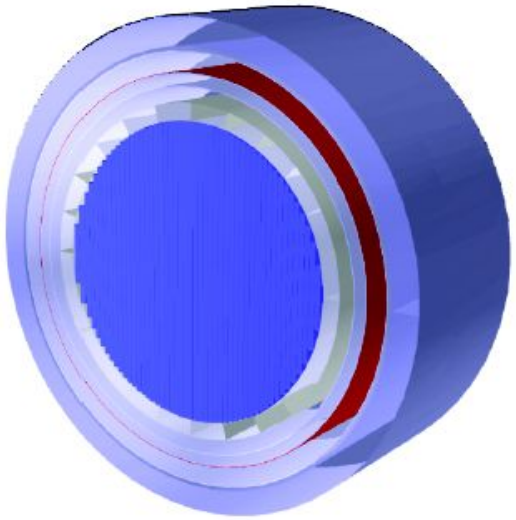




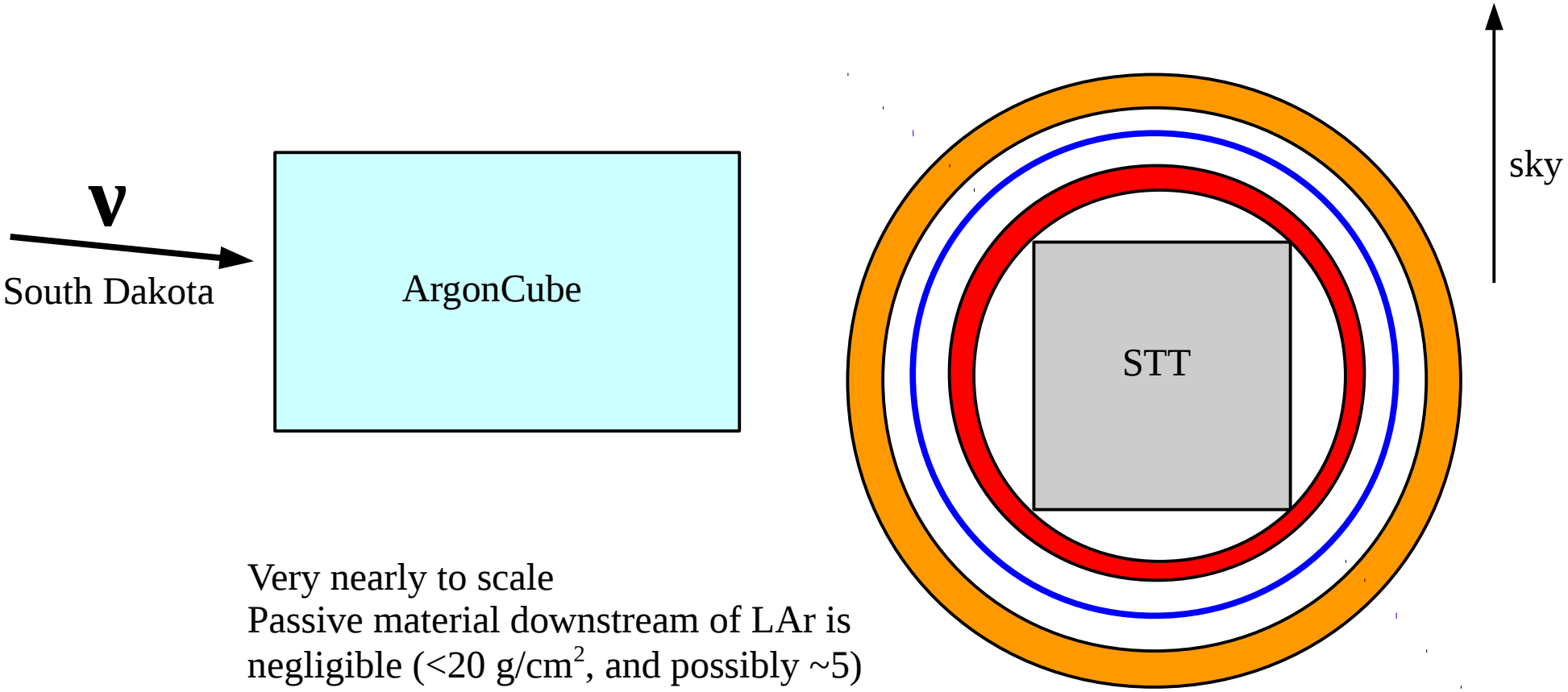
KLOE material thickness

- 37-cm iron yoke = 291 g/cm^2
- 44-cm cryostat+coil = 20 g/cm^2
- 23-cm ECAL = 122 g/cm^2
- Total to ECAL
  - 311 g/cm^2
  - ~620 MeV μ stopping power
- Total to STT
  - 433 g/cm^2
  - ~860 MeV μ stopping power
- LAr ~280 MeV per meter





KLOE magnet + ArCube side view

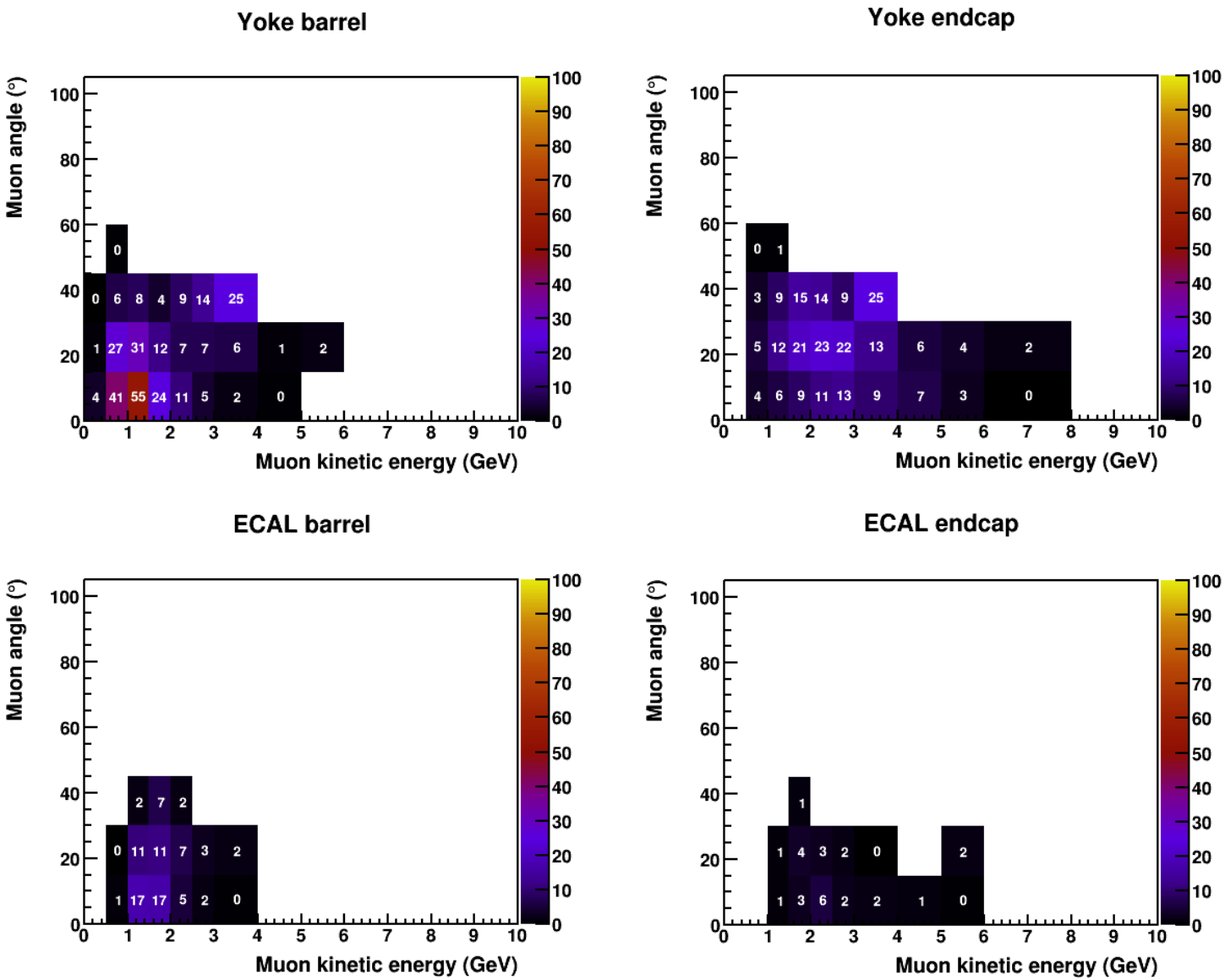


Very nearly to scale
Passive material downstream of LAr is negligible (<20 g/cm^2, and possibly ~5)
KLOE ECAL
Magnet coil (inside cryostat)
KLOE yoke

ArCube + KLOE stopping power

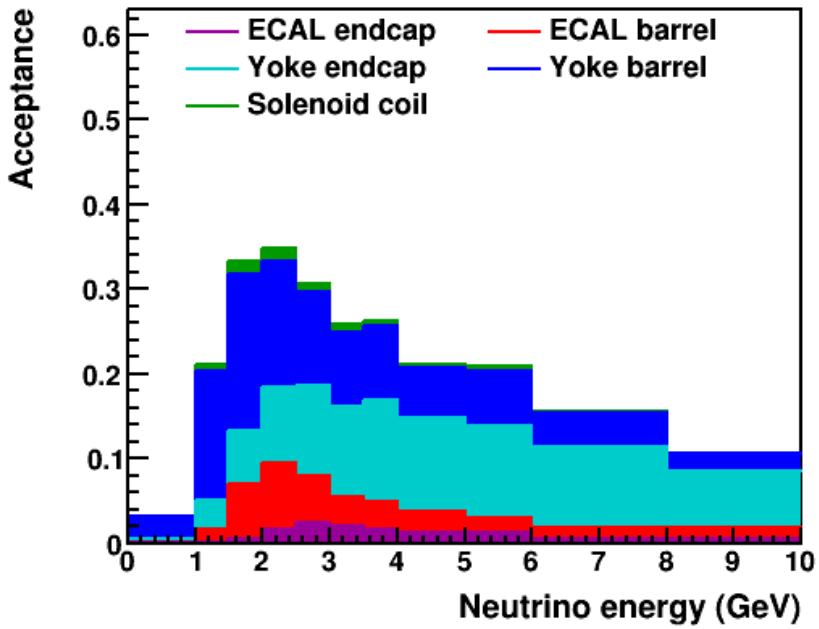
- Bar below is to scale in areal density, assuming a forward-going track intersecting barrel elements head-on
- Dark blue are cryostats, assuming 10 g/cm² passive material in ArgonCube, and including the solenoid coil
- Black bars are basically the shortest muon that can't reasonably be contained in LAr (about 1.2 GeV)
- Trackable in ECAL for vertices >300cm into LAr
- Trackable in STT for vertices >360cm into LAr

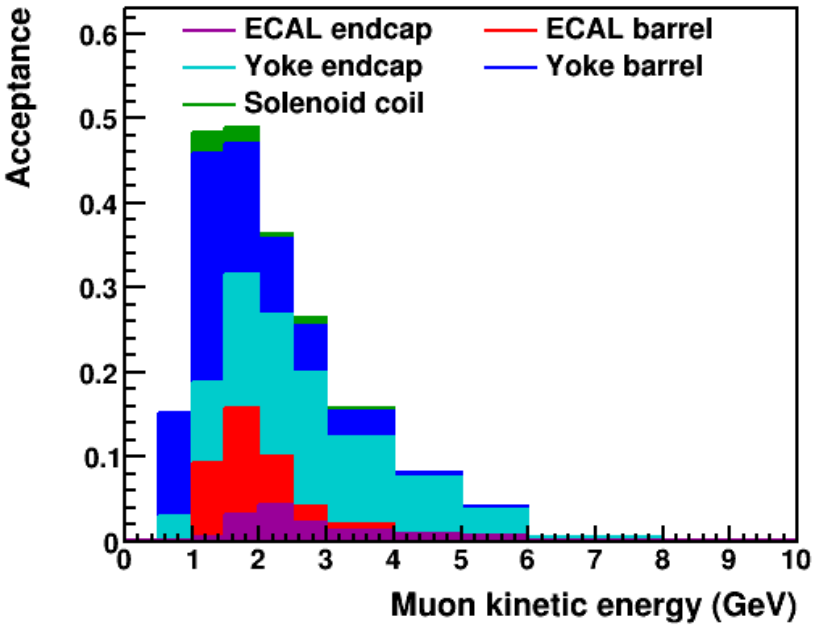
Breakdown of KLOE stoppers



- Denominator is still all events, not just KLOE stoppers
- Yoke (top)
- ECal (bottom)
- Barrel (left)
- Endcap (right)

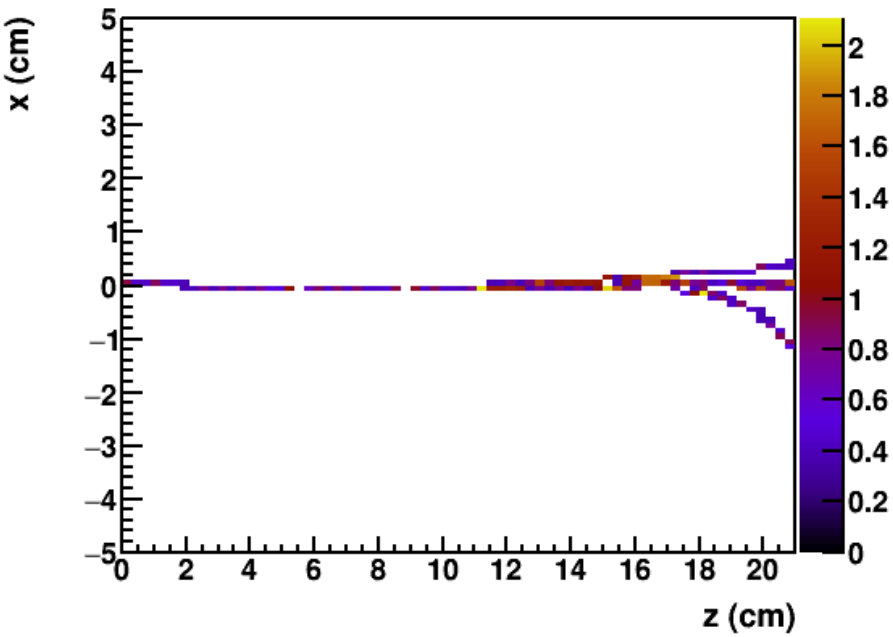
Breakdown of KLOE stoppers 1D

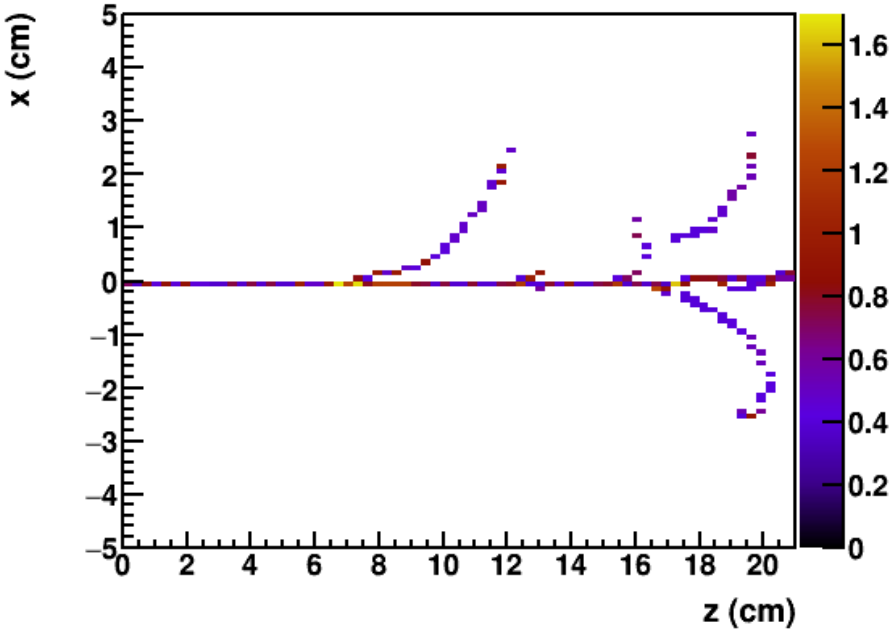




- Red/Magenta are ECal muons which could be reconstructed by range based on the stopping point
- “Coil” includes cryostat walls, but there isn't a lot of material (not shown on previous slide as there are so few events)

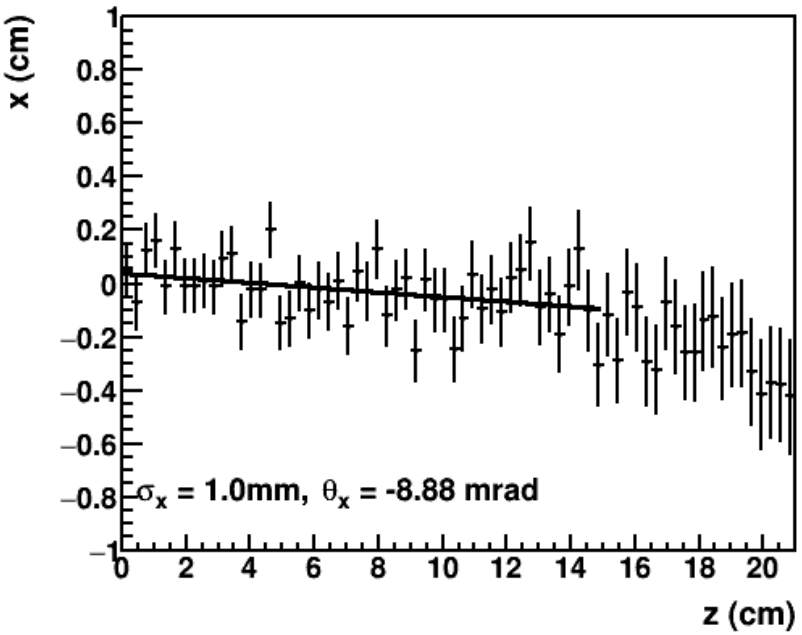
Improved LAr angular resolution from Geant4 simulation

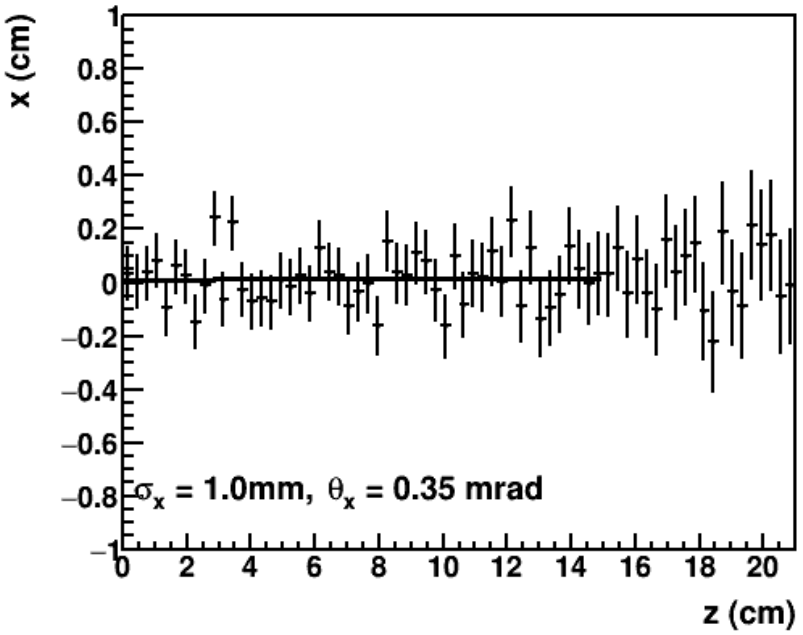




- Simulate forward electrons in LAr, with measurement every 3mm
- At each 3mm plane, track position is whichever is closer to 0 of:
  - The true electron trajectory
  - The charge-weighted centroid of the shower

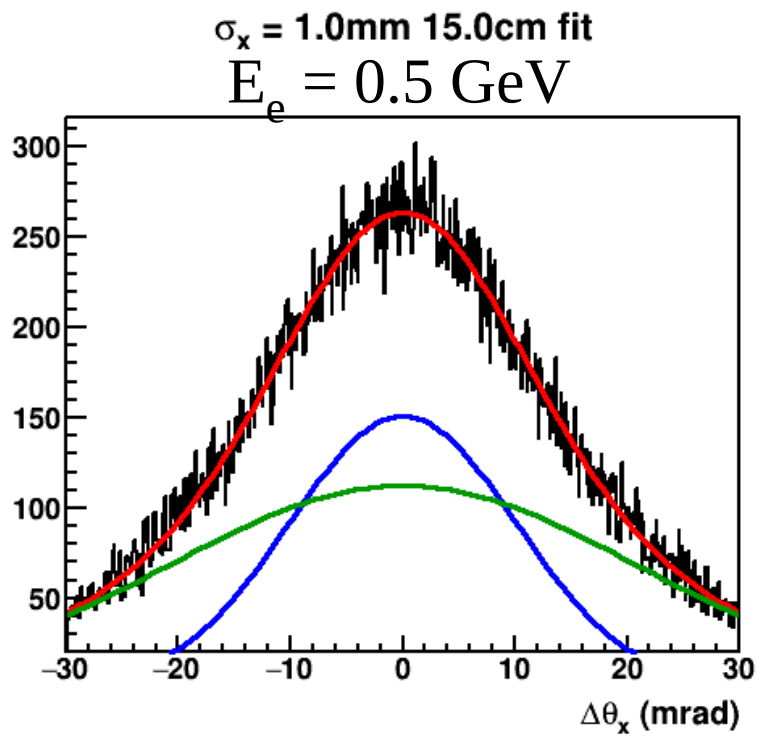
Straight-line fit to tracks

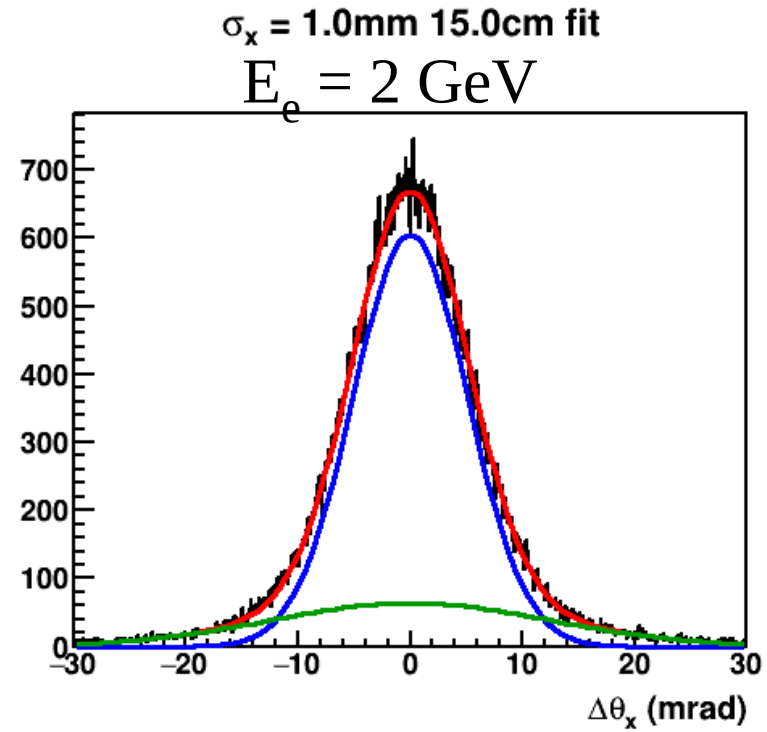




- Smear the measurement at each 3mm point by a Gaussian with some σ_x, shown here 1mm
- Uncertainty at each point is σ_x + expected multiple scattering, in quadrature
- Fit each event to a straight line to determine θ_x

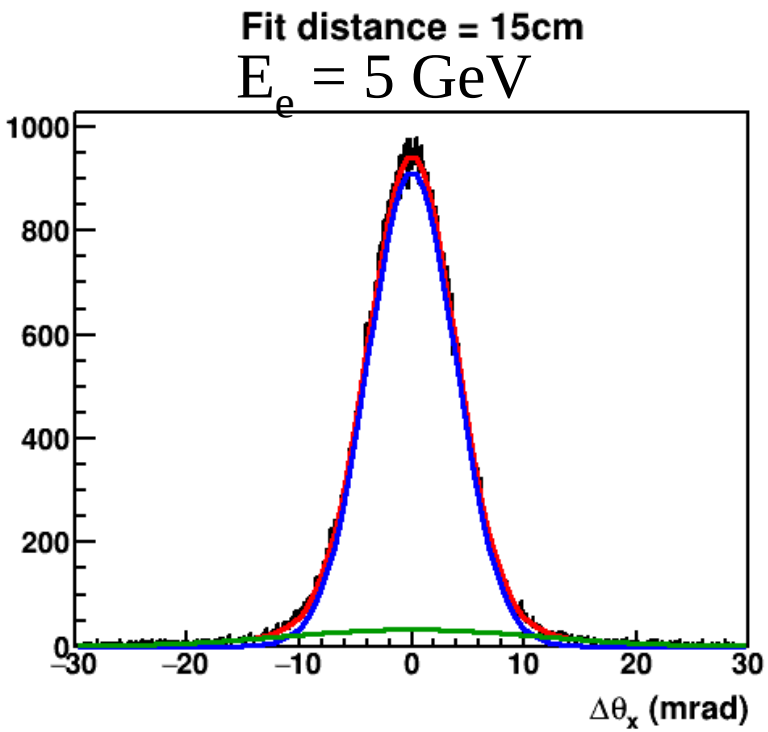
Fit resulting $\Delta\theta_x$ distributions to double gaussians

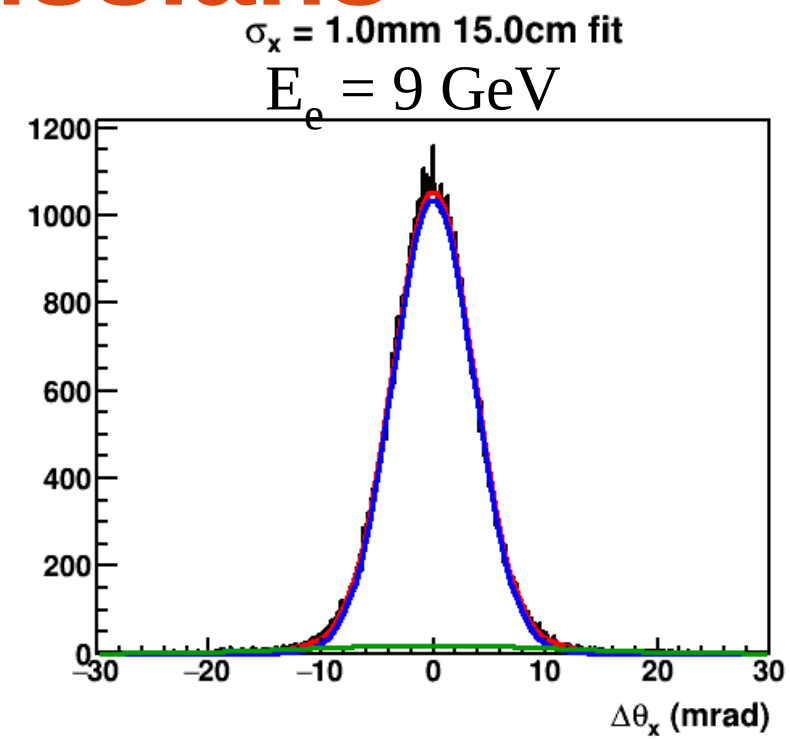




- Wide Gaussian takes into account non-Gaussian multiple scattering tail
- Width of central peaks follow expected $1/E_e$ form

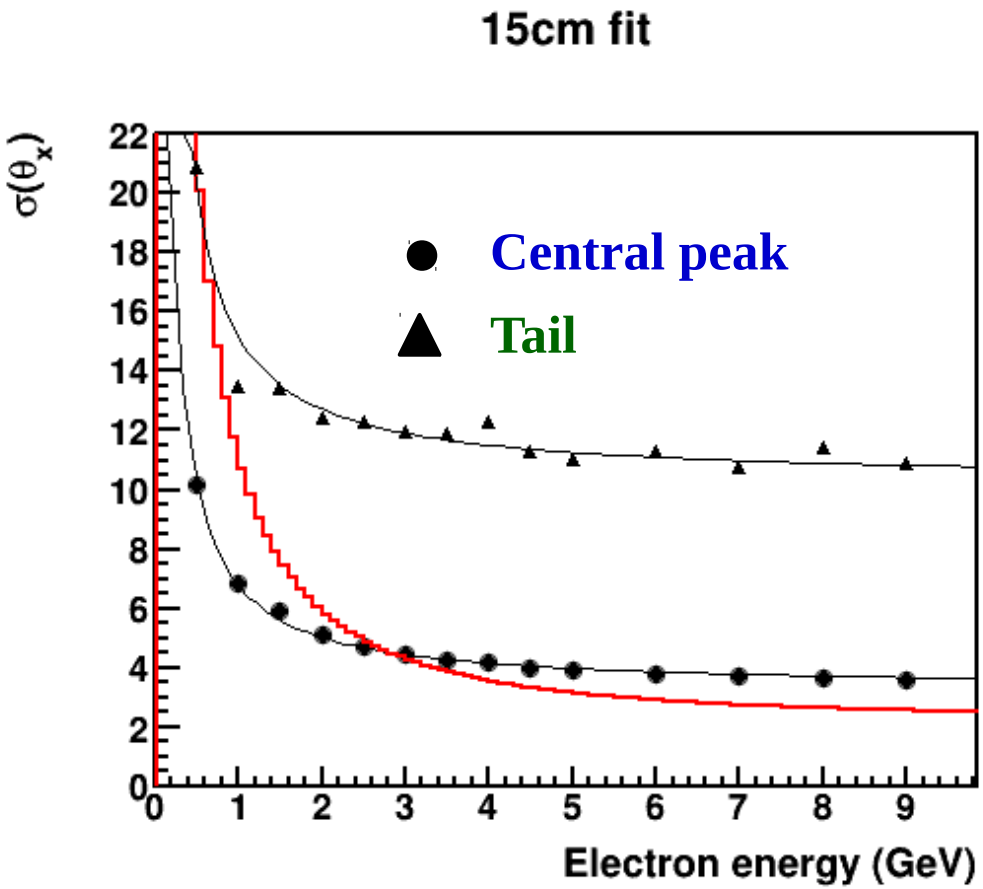
Fit resulting $\Delta\theta_x$ distributions to double gaussians





- Width of multiple scattering decreases as 1/p
- Normalization of Moliere component also falls with electron energy

Double gaussian sigmas

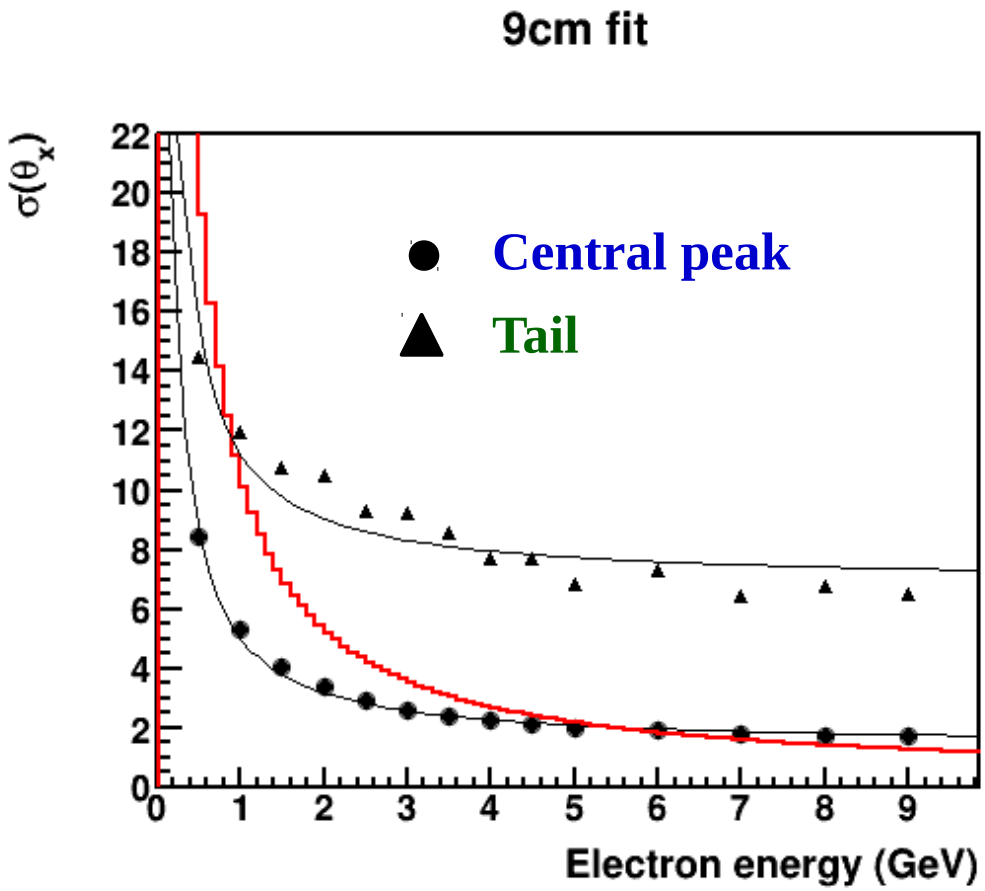


- y axis is fitted σ for angle in XZ plane only, in mrad
- Red line is what is expected from equation, assuming same measurement uncertainty on every point, and neglecting tails

$$\sigma_{samp} = \sqrt{\frac{\sigma_x^2}{(N+1)L^2}\frac{12N}{N+2}}$$

$$\sigma_{MS} = \frac{0.015GeV}{p}\sqrt{\frac{L}{X_0}}$$

If σ_x = 200μm



- If you reduce the uncertainty on each track point measurement to 200μm
- For example, by using triangular pads with charge sharing
- No change to multiple scattering