LAr requirements for DUNE ND

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DUNE ND objectives

- Oscillation analysis signal samples: charged-current interactions of ν_μ, $\bar{\nu}_\mu$, and $(\nu_e + \bar{\nu}_e)$, in FHC and RHC
  - High statistics
  - High purity, full phase space coverage
  - Well understood (not necessarily high) efficiency relative to FD
  - E_{lep} and E_{had} resolutions equal to or better than FD
- High-statistics measurements of NC interactions
  - NC π^0 (background to ν_e CC)
  - NC $\pi^\pm$ (background to ν_μ CC)
- Independent measurement of neutrino flux
  - ν+e elastic scattering ($\nu e \rightarrow \nu e$)
  - Low-ν relative flux measurement

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Fully-contained events →
set requirements for size of ND LAr

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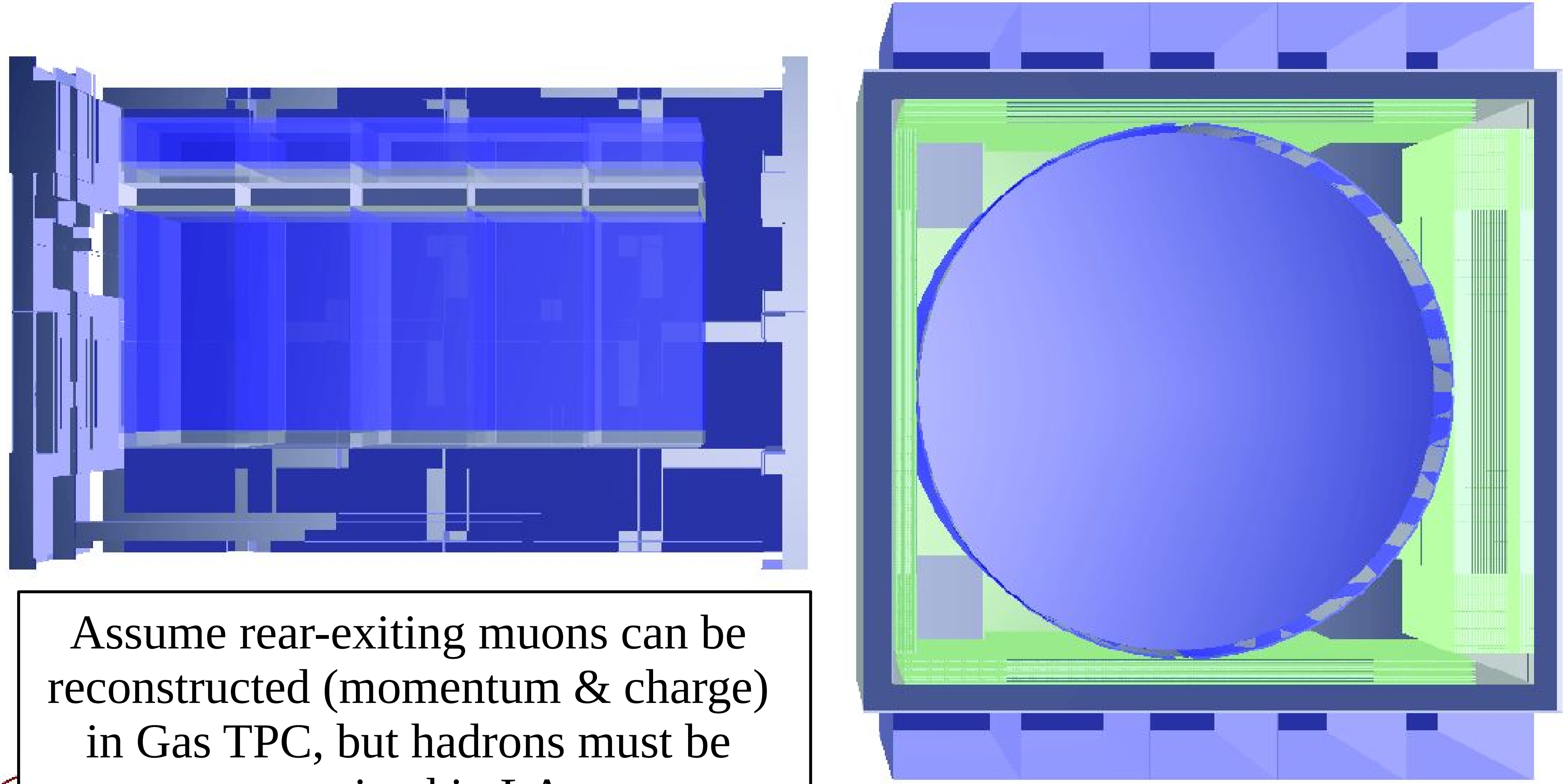
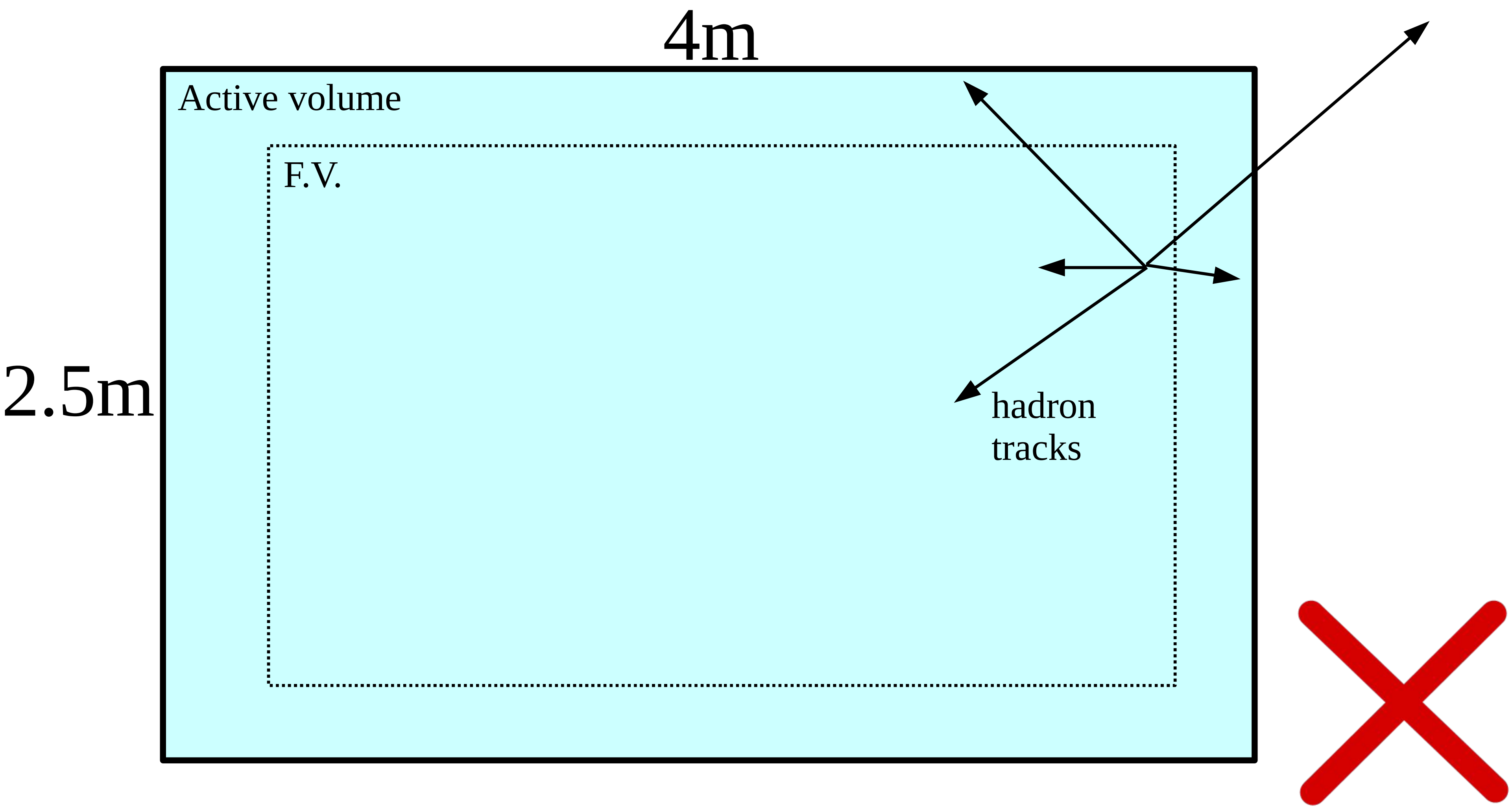
< 2% flux uncertainty →
Set requirements for energy &
angular resolution

Assumption for this talk: ArgonCube + HPGTPC in dipole

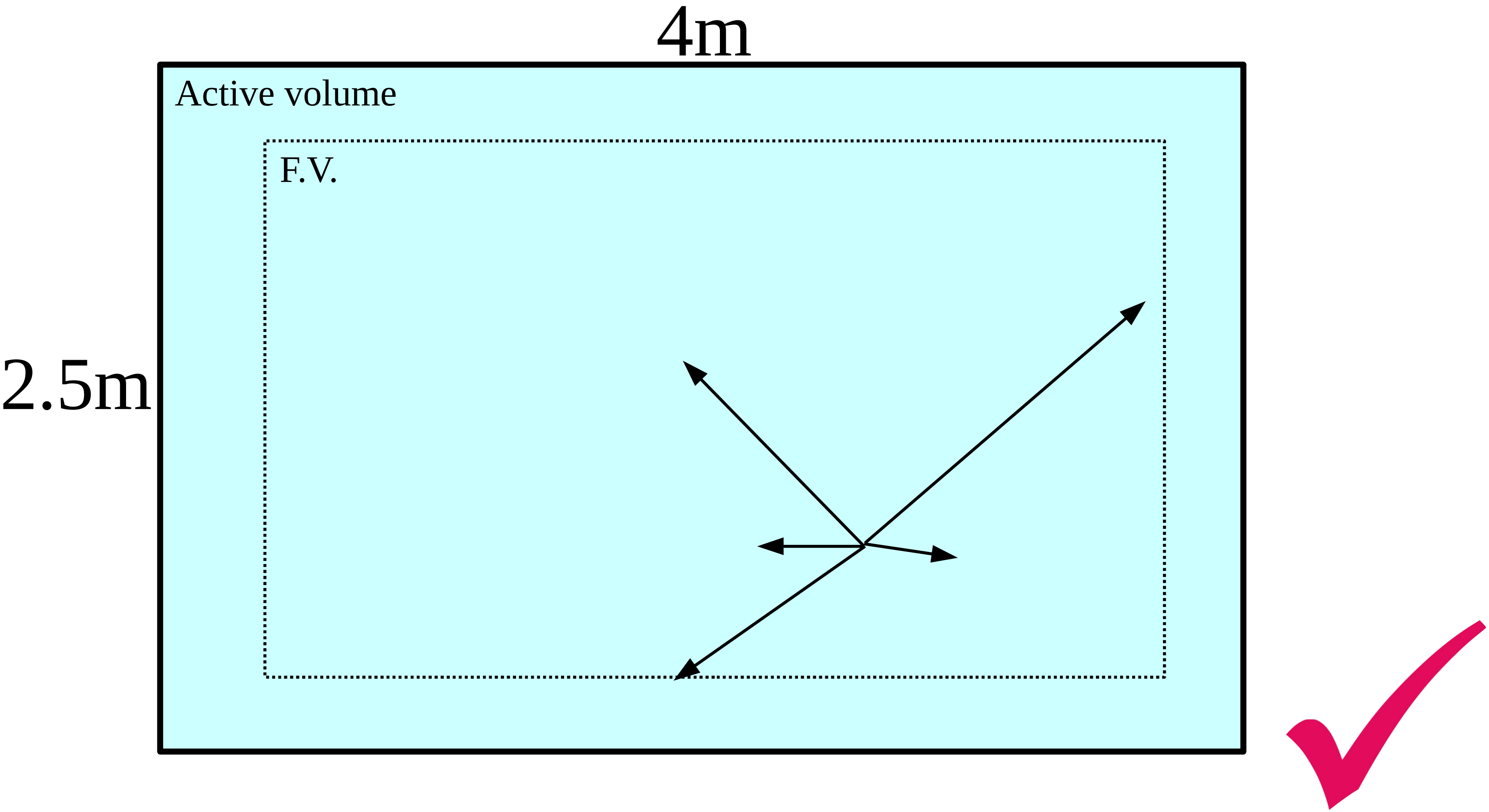


Assume rear-exiting muons can be reconstructed (momentum & charge) in Gas TPC, but hadrons must be contained in LAr

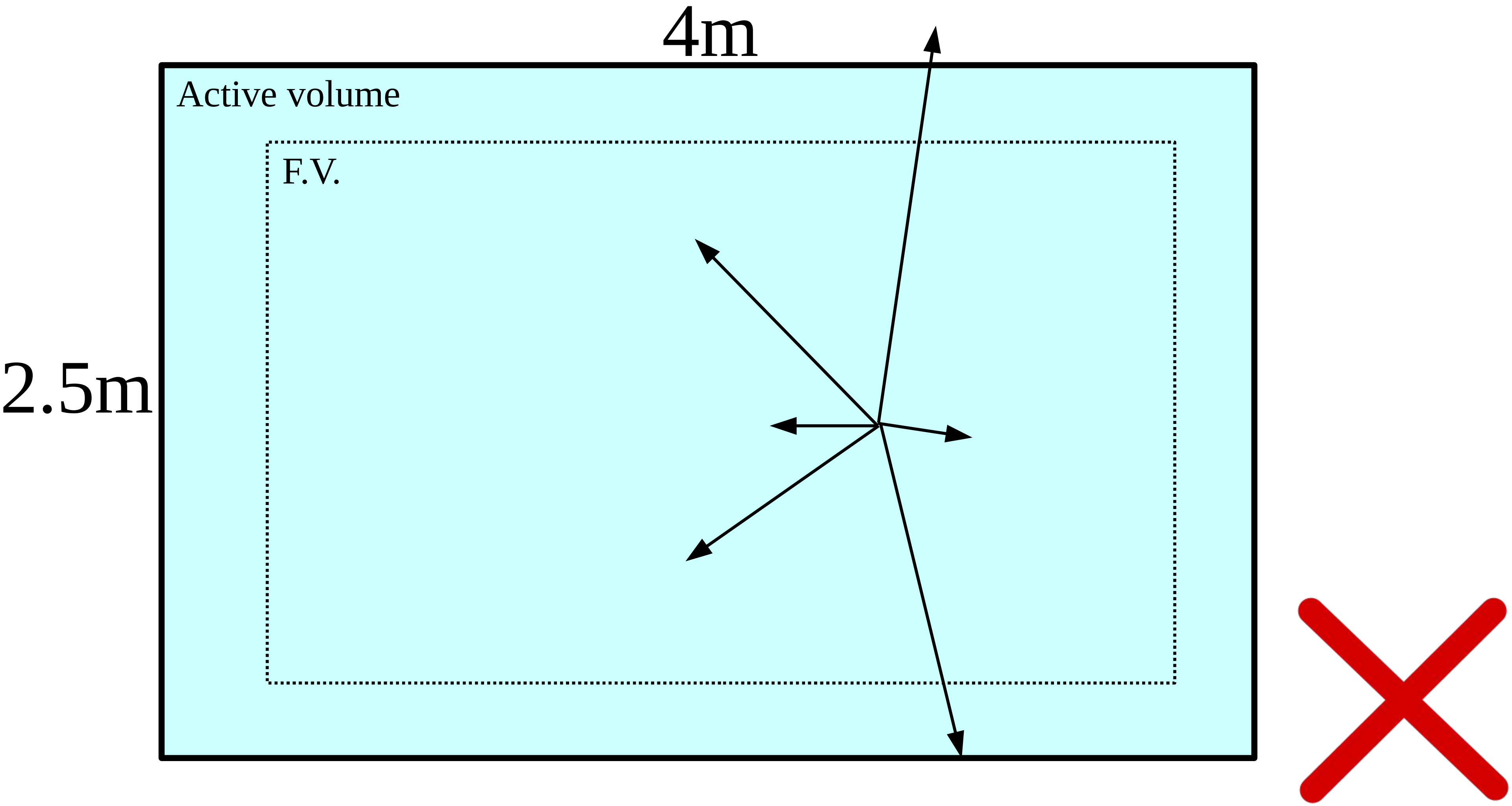
Detector as seen by ν beam (XY projection)



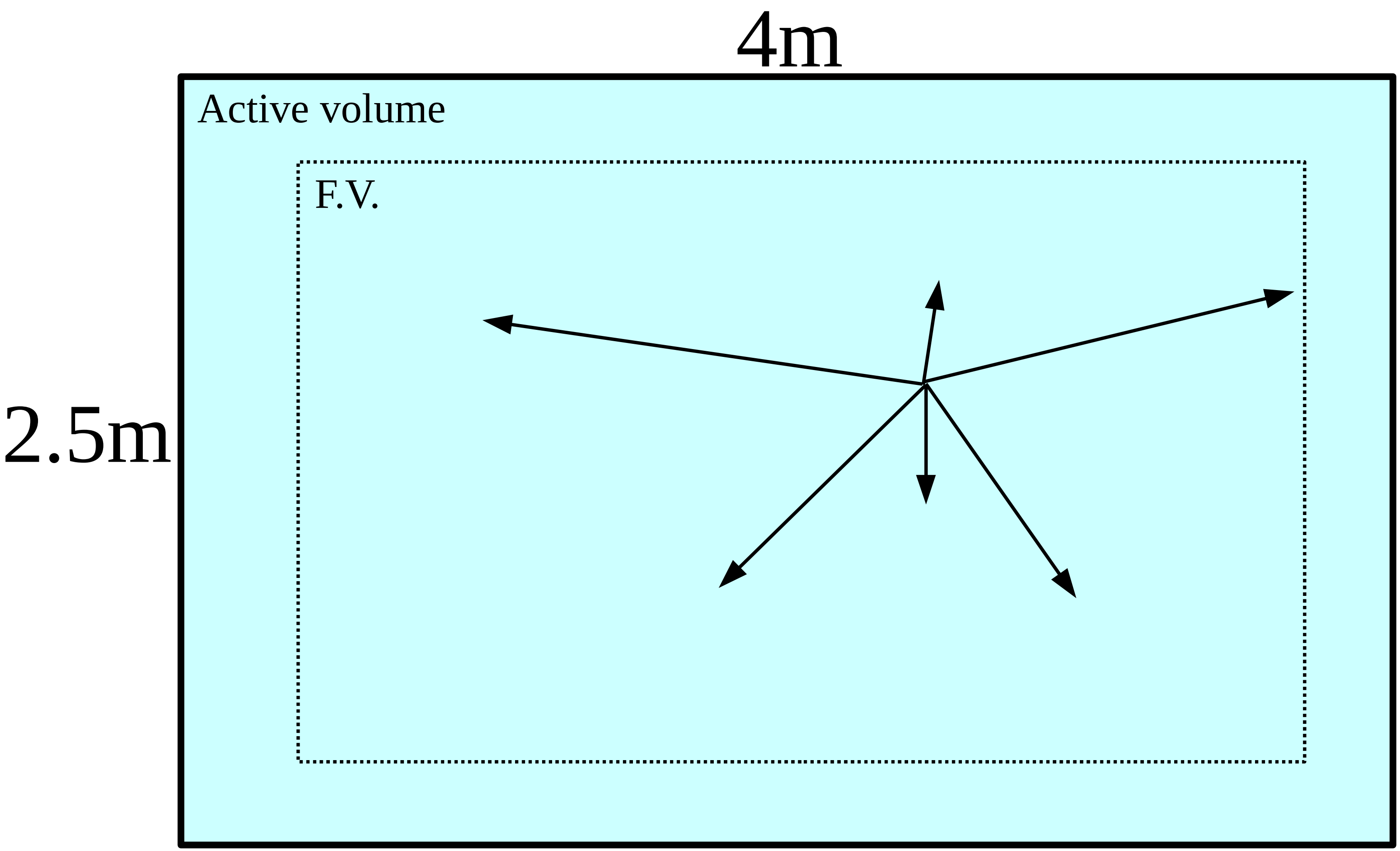
Same event, translated



Event that is not contained with any translation

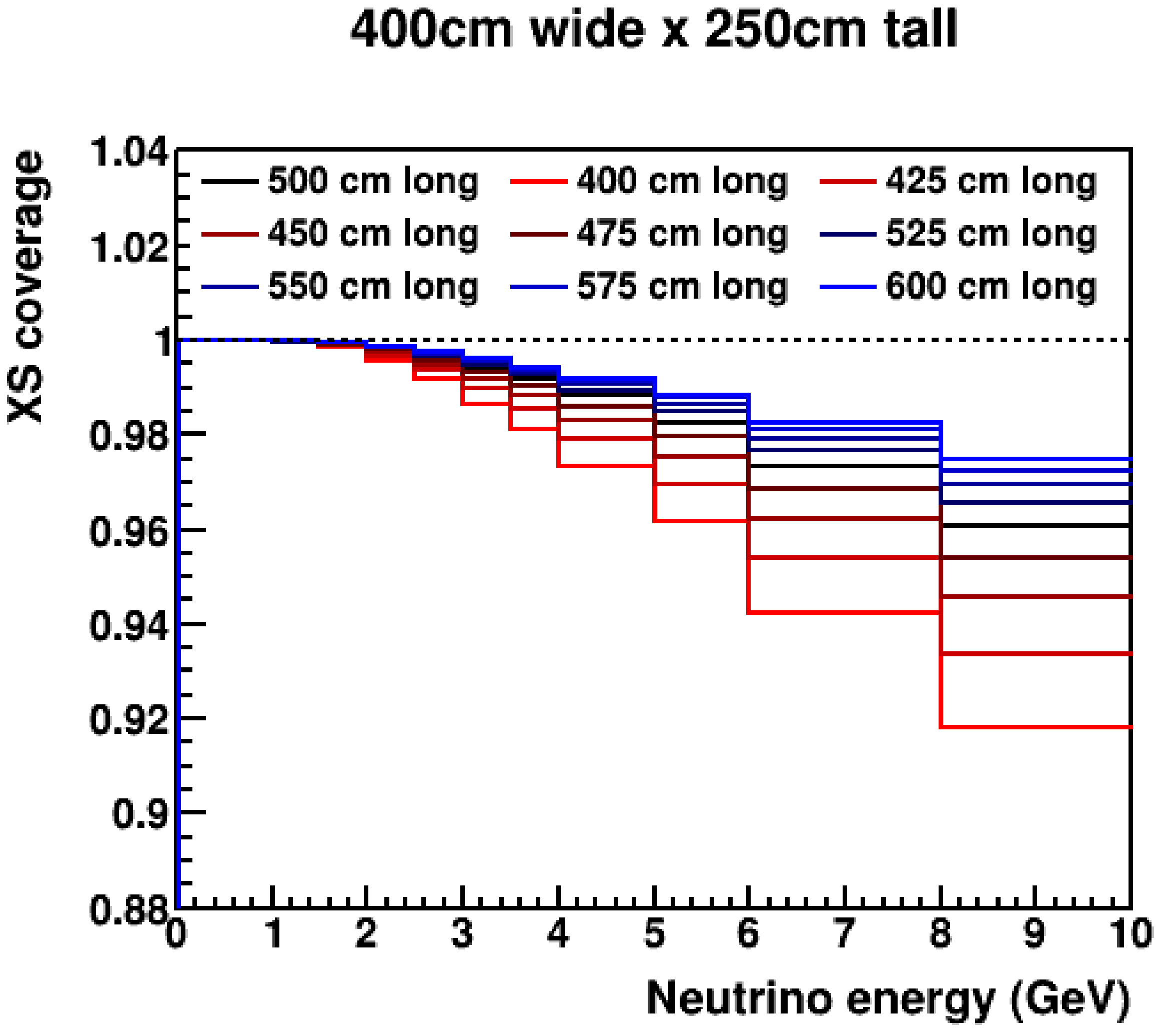


But is using phi symmetry



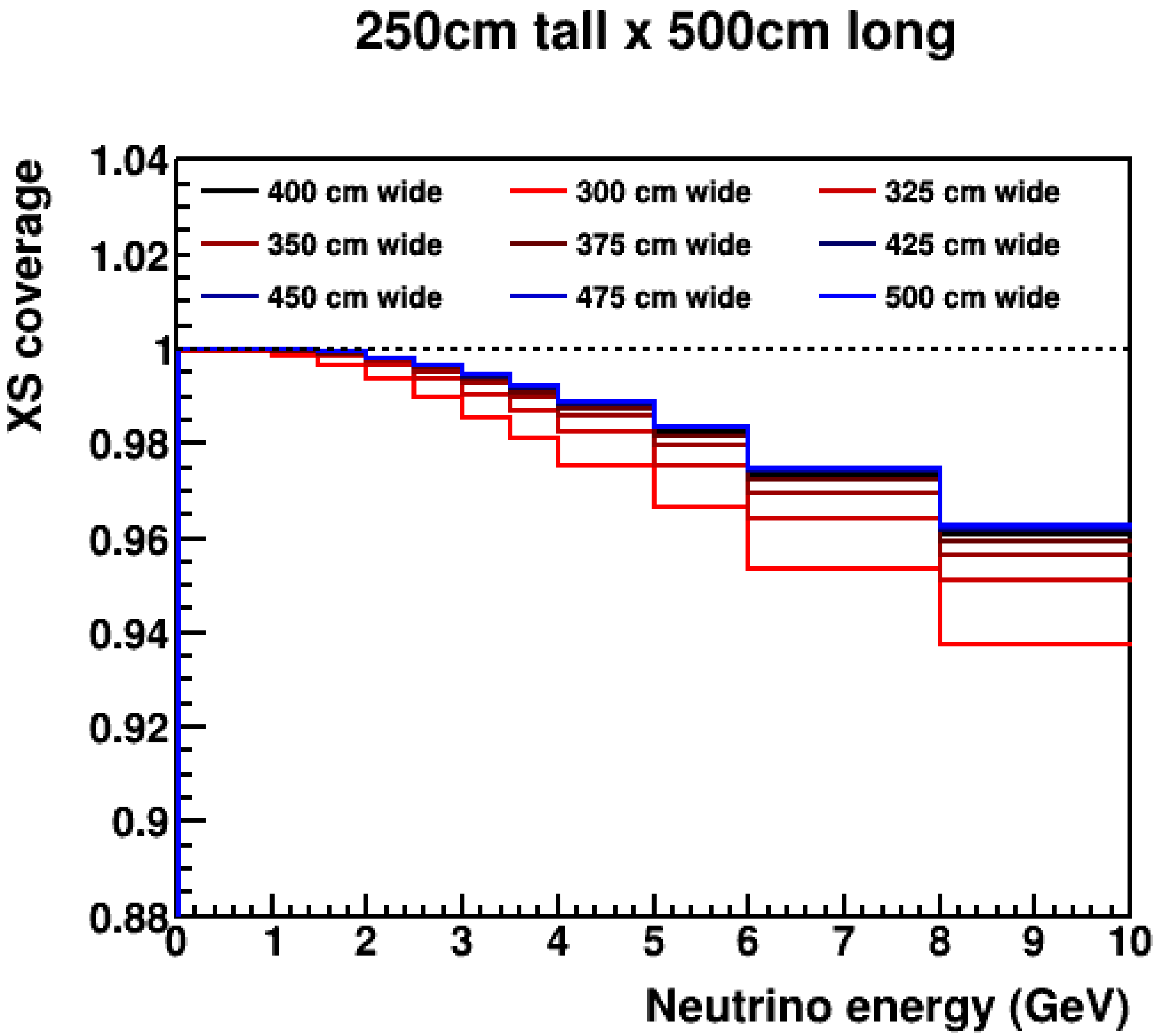
✓

XS coverage vs. Z



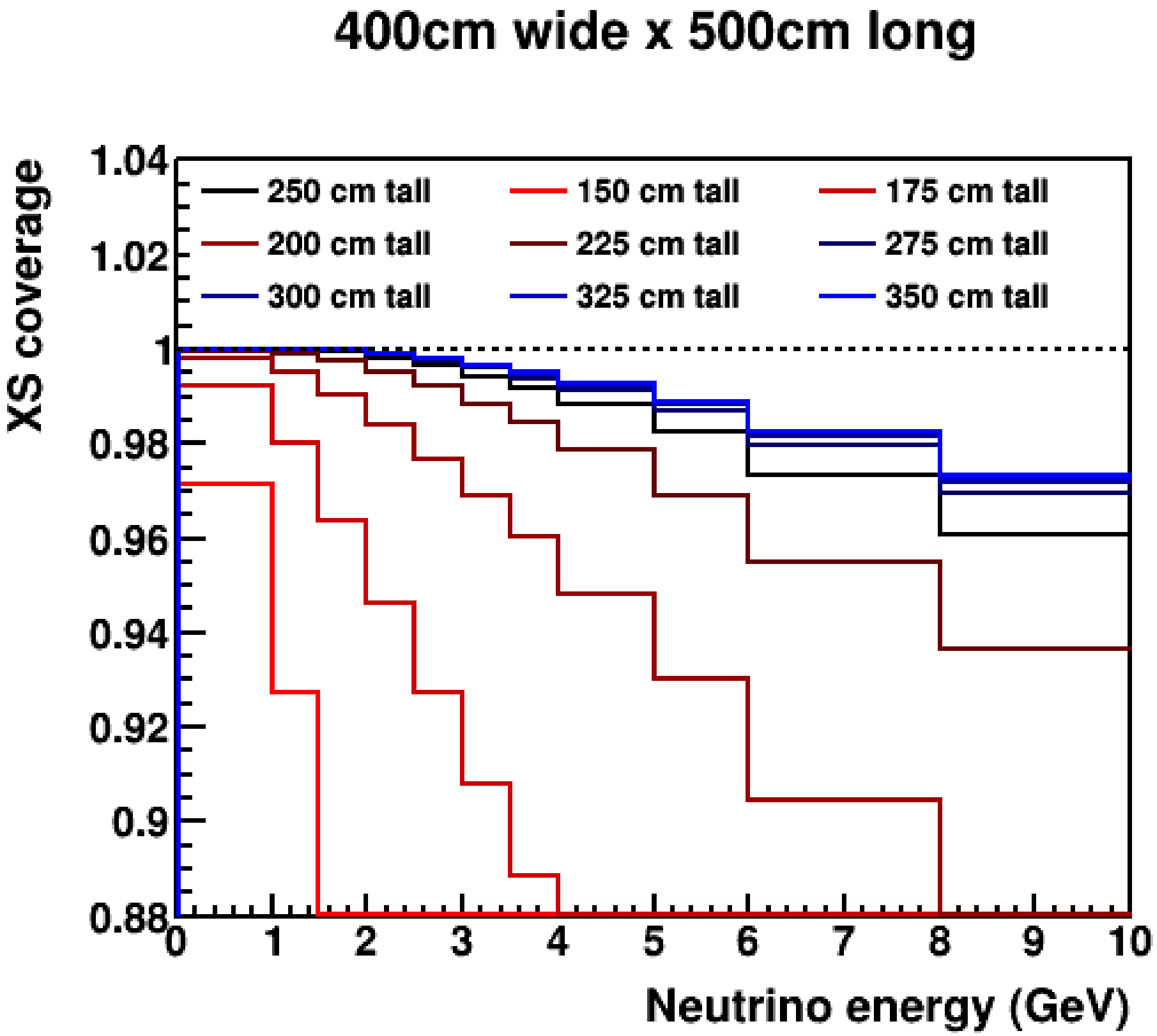
- X and Y are fixed at nominal 400cm wide x 250cm tall
- Black is nominal 500cm long, red is shorter, blue is longer

XS coverage vs. X



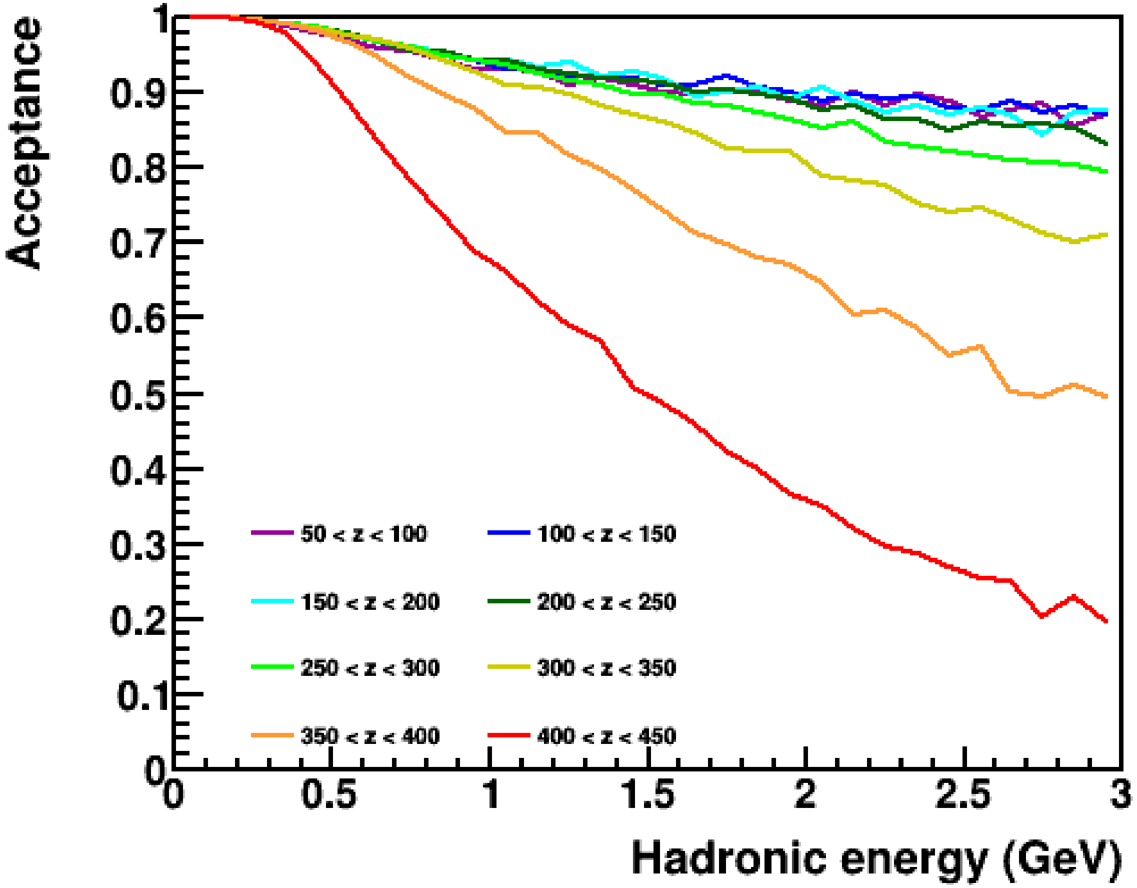
- Here, Y and Z dimensions are fixed at 250cm x 500cm
- Nominal X is 400cm, red is smaller, blue is larger
- For all sizes, 50cm buffer on all sides is assumed

XS coverage vs. Y



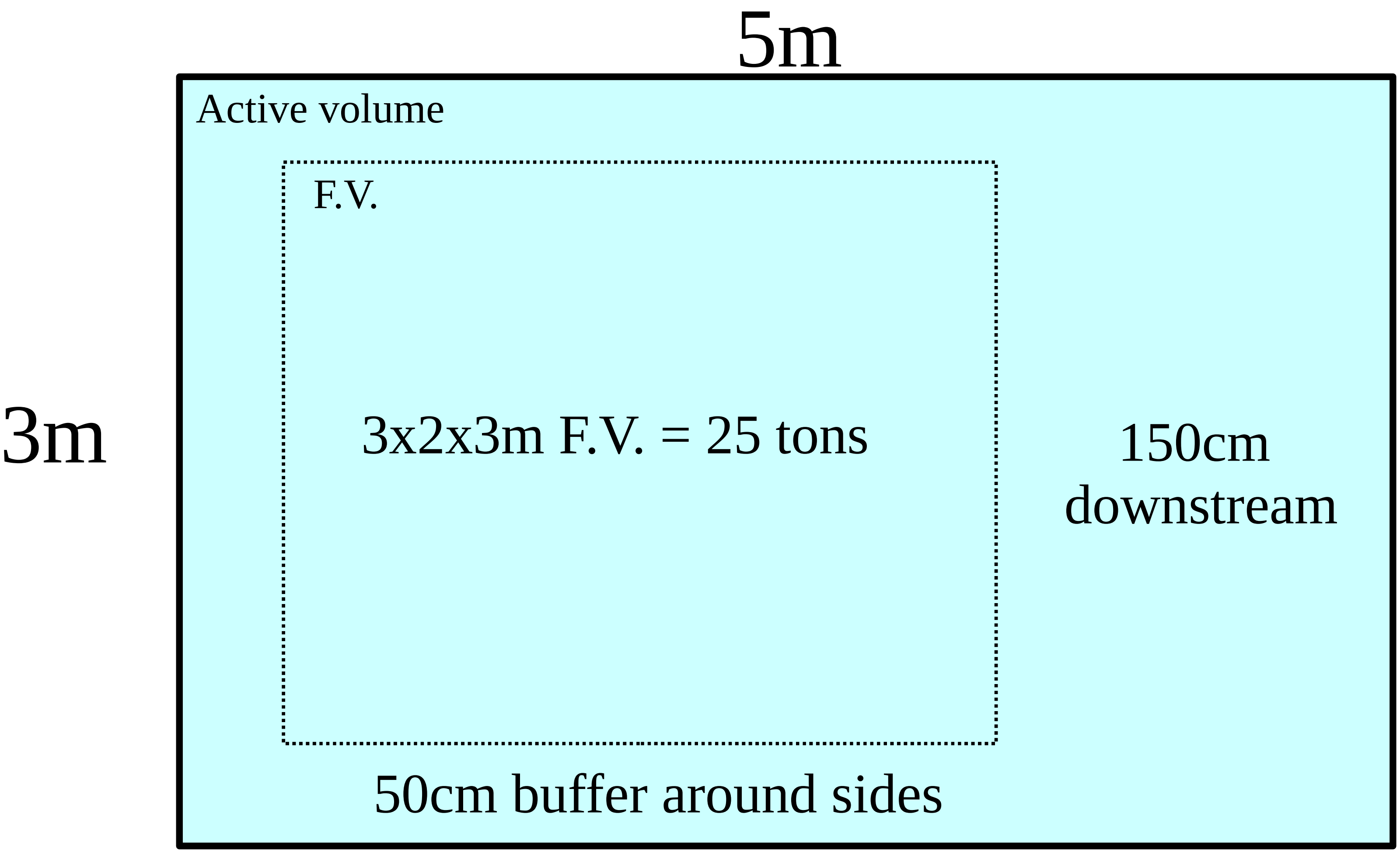
- X and Z are fixed at 400cm x 500cm
- Y (height) is varied, with black being nominal 250cm, red shorter, blue taller
- 250cm is right on the edge of significant loss of acceptance
- If Nature produces larger hadronic showers than GENIE, we could be in trouble
- 3m would be much safer

Hadron containment

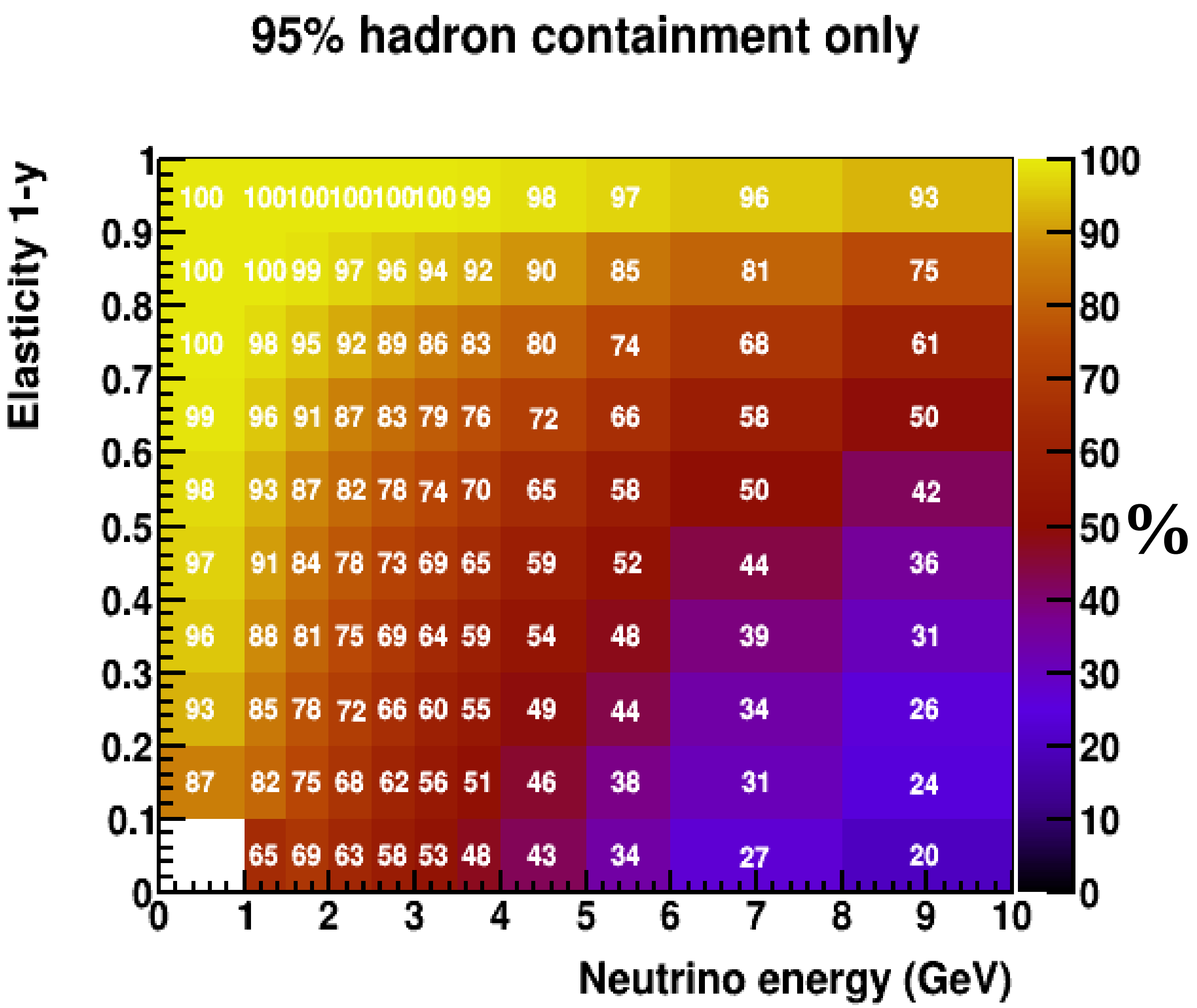


- Very downstream vertices have poor hadron acceptance, that changes with energy
- Want to avoid orange/red regions where hadron containment is poor

25t F.V. for CC samples



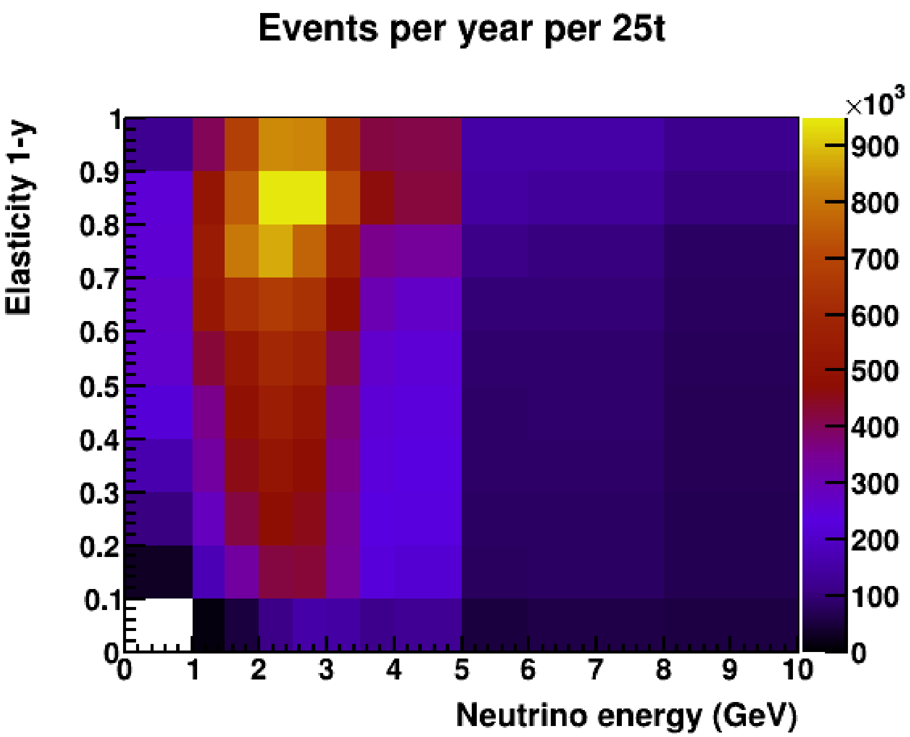
Hadronic shower acceptance

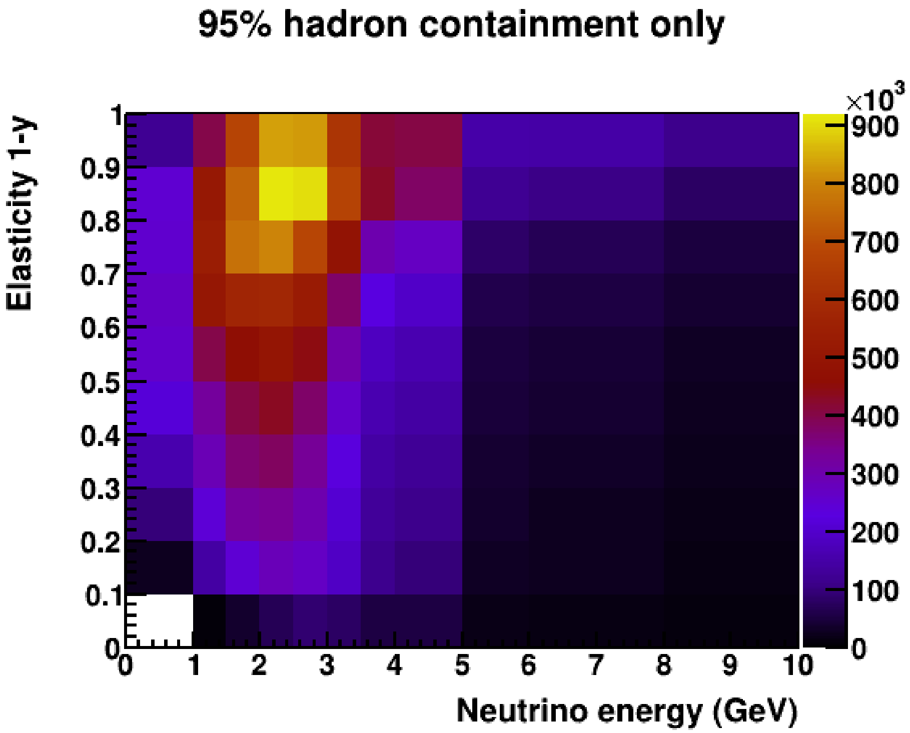


100	100	100	100	100	100	99	98	97	96	93
100	100	99	97	96	94	92	90	85	81	75
100	98	95	92	89	86	83	80	74	68	61
99	96	91	87	83	79	76	72	66	58	50
98	93	87	82	78	74	70	65	58	50	42
97	91	84	78	73	69	65	59	52	44	36
96	88	81	75	69	64	59	54	48	39	31
93	85	78	72	66	60	55	49	44	34	26
87	82	75	68	62	56	51	46	38	31	24
	65	69	63	58	53	48	43	34	27	20

- 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.

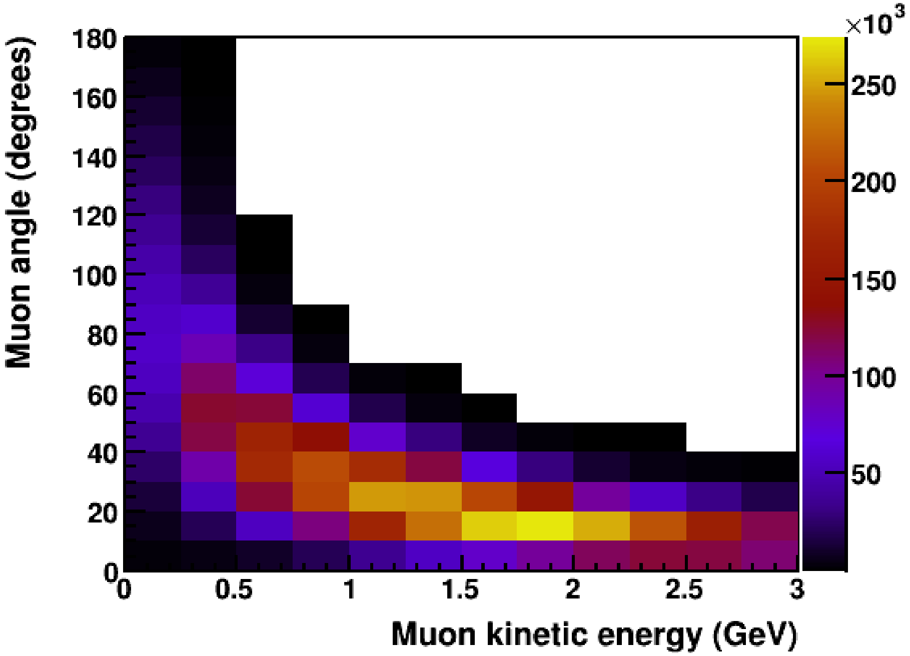

Events per year per 25t

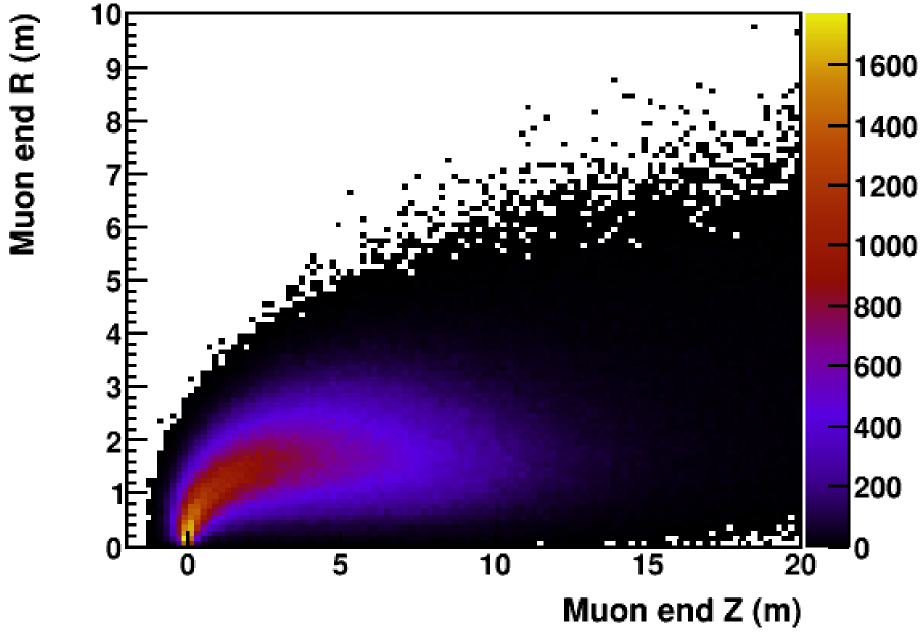

95% hadron containment only

- 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 containment in LAr

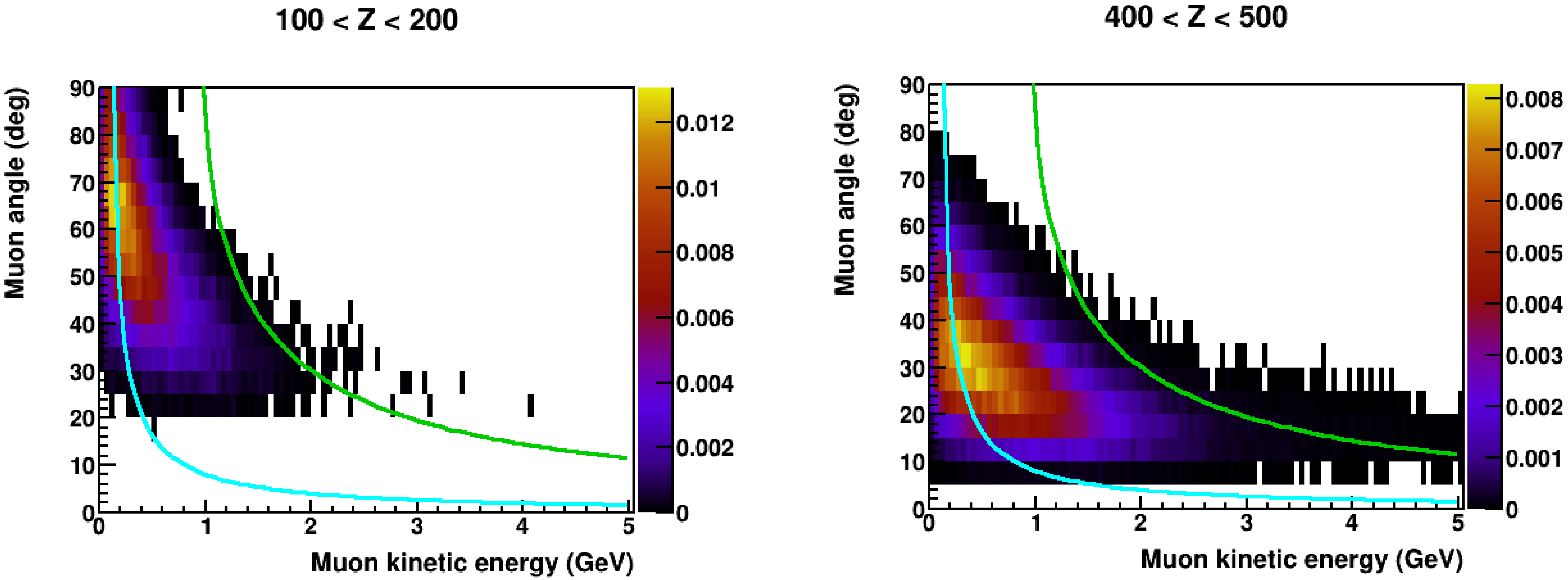
FHC CC μ^-





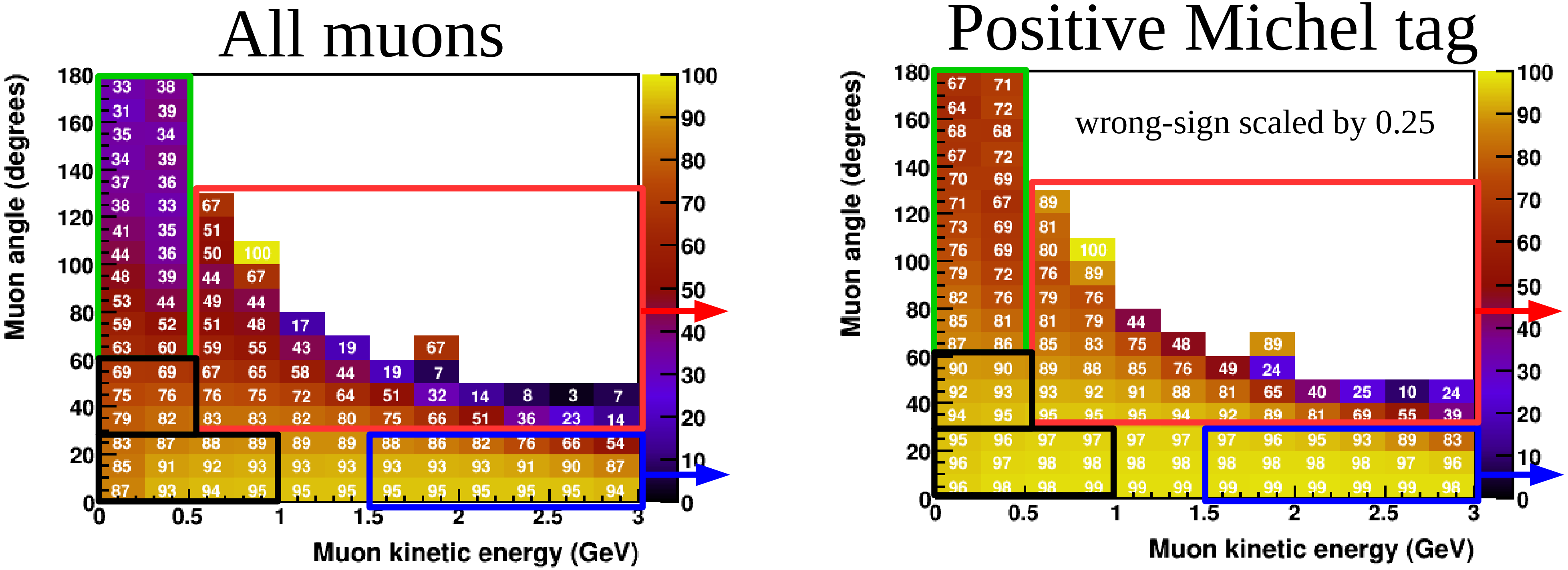
- Contained muons go ~3m in transverse direction
- Generally opposite hadronic system → muon + hadron containment in ~7m detector

Side detector requirements
Or: wider LAr to contain muons



- Muon energy and angle at exit point of active LAr on sides, in two different regions of Z along TPC, for events with contained hadrons
- Lines 70 and 500 g/cm^2 penetration = 50cm and 350cm of LAr

RHC μ^+ purity with regions & percentage of total ν_μ CC

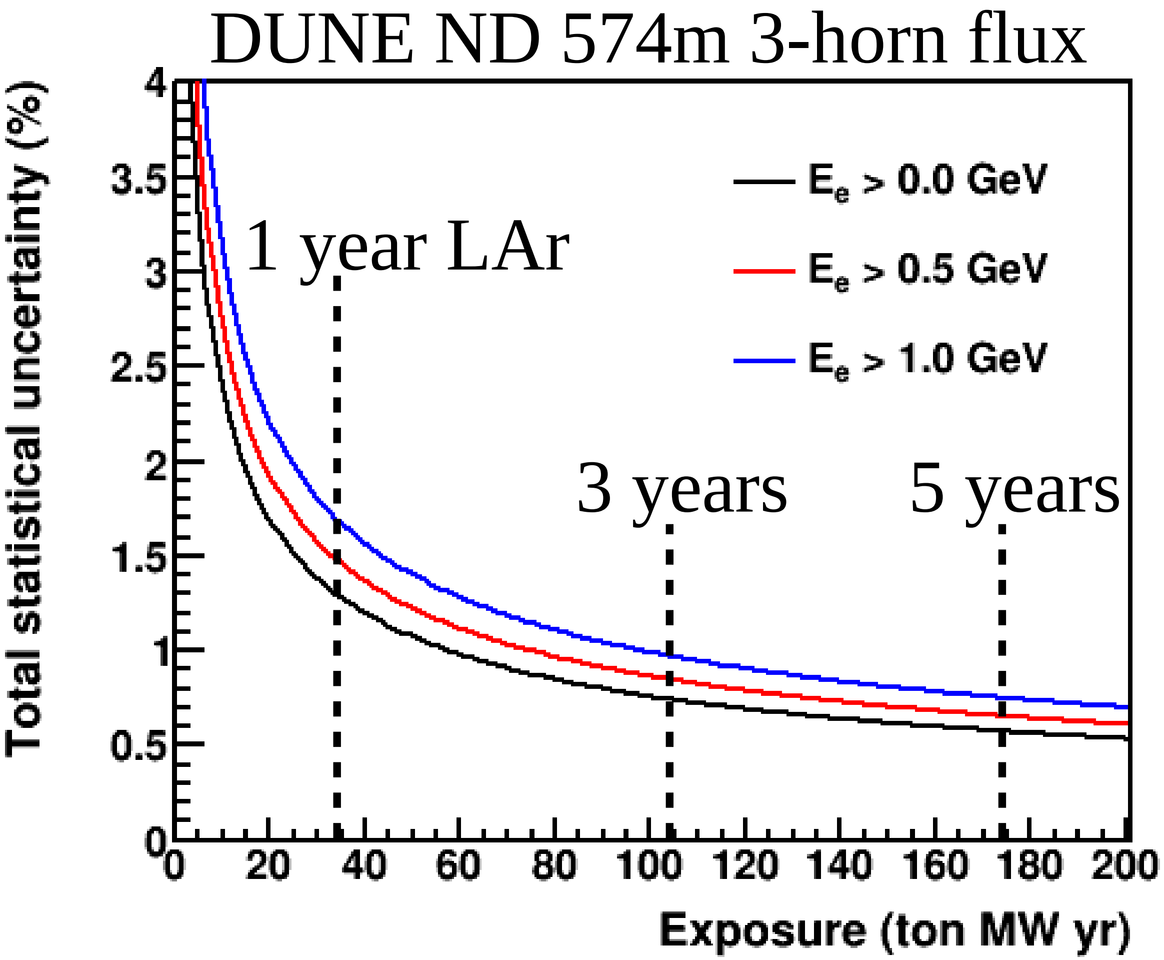


- Divide the kinematic space into regions based on how muon is primarily reconstructed:
  - Tracker-matched region, excellent μ^+ purity and momentum resolution – 62.3% of total
  - Good containment, reasonable μ^+ purity, >90% with Michel tag – 11.8% of total
  - Side-exiting region, poor μ^+ purity ~50% out of the box and ~80% with Michel tag – 9.0% of total
  - Good containment, poor μ^+ purity, only ~40% out of the box and ~70% with Michel tag – 1.4% of total
  - Dipole coil region, good μ^+ purity, also tracker-matched for downstream vertices – 15.3% of total

LAr size conclusions

- For hadronic containment: (4x3m) transverse x 5m in ~beam direction
- For hadron + muon containment: at least 7m in one transverse dimension, needs further study
- In RHC, with positive Michel tag, can get ~90% purity over ~90% of cross section
- In backups: passive material on downstream edge must be minimized, specific requirements depend on magnet technology

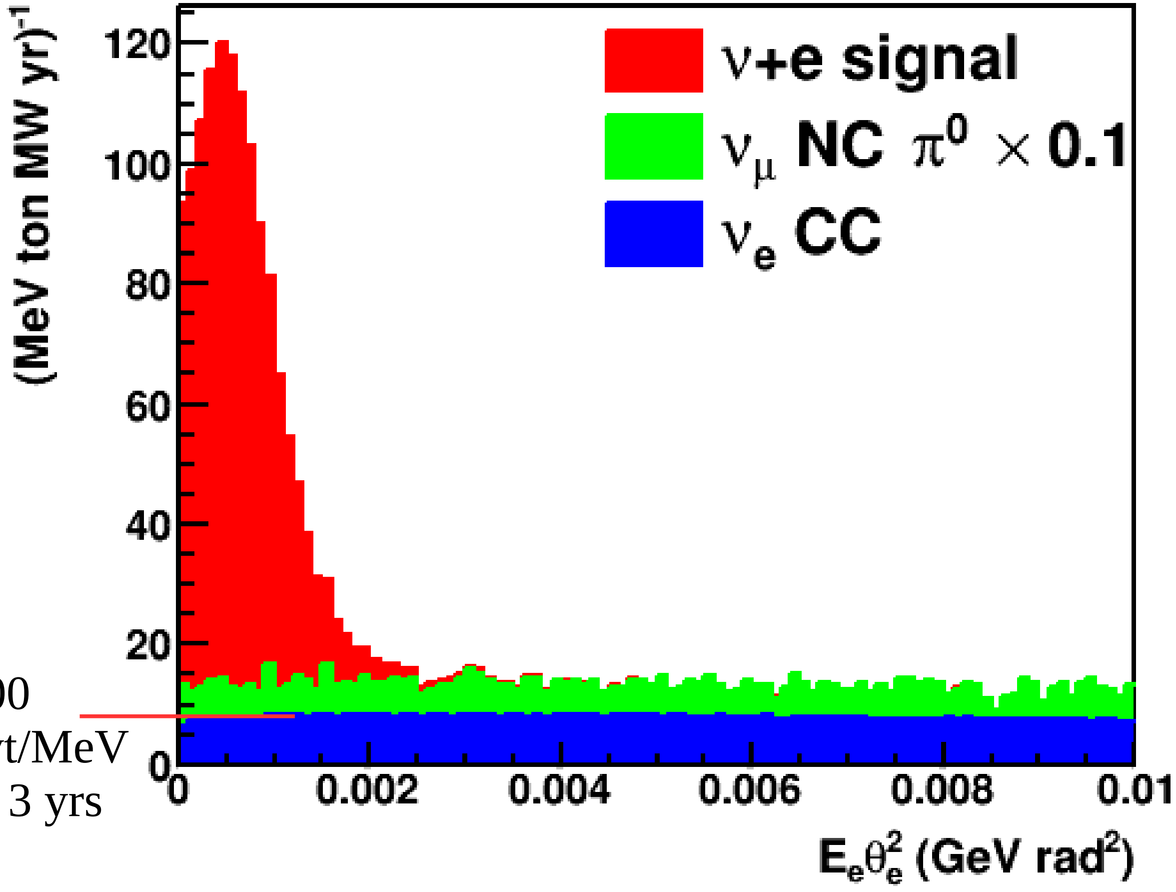
DUNE ND ν+e statistics



- 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

ν+e in ArgonCube

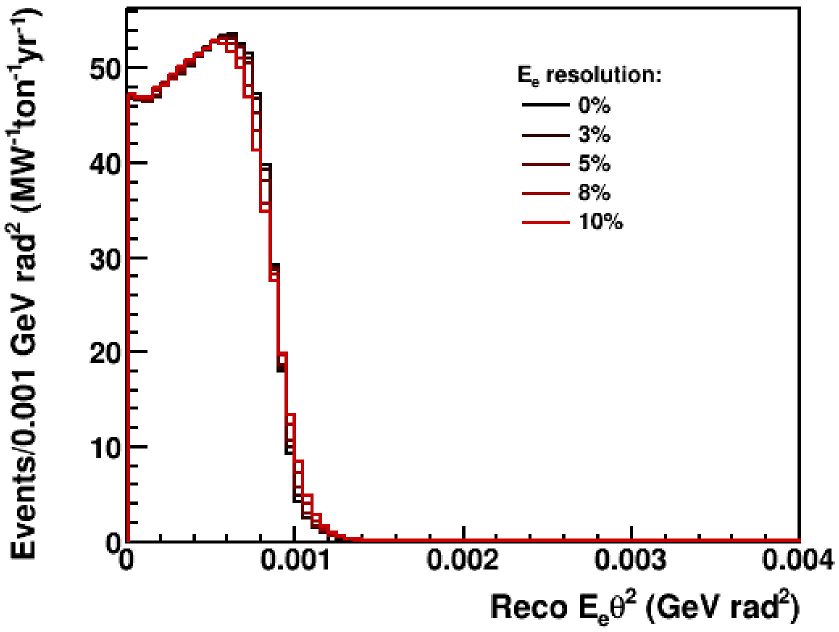
DUNE ND 574m 3-horn flux

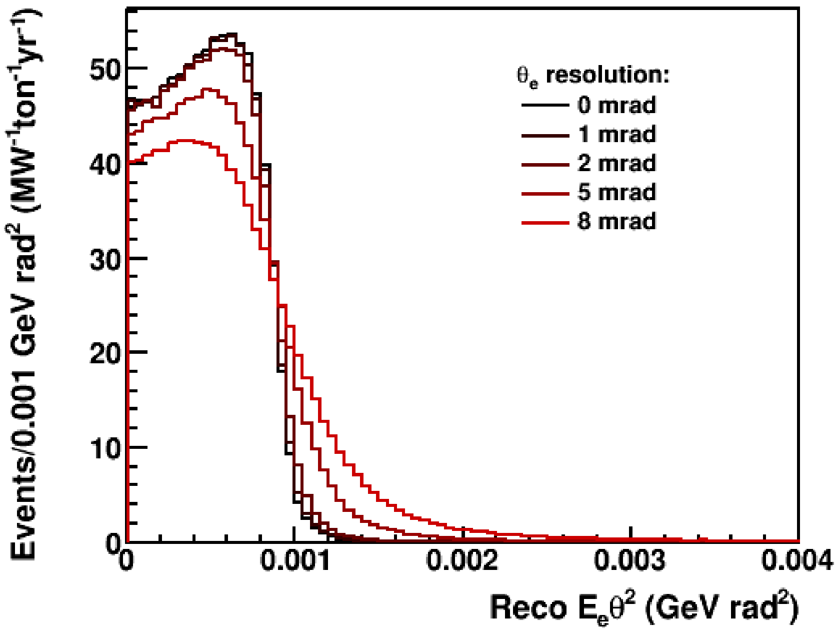


800 evt/MeV in 3 yrs

- Backgrounds are ν_e CC with very forward electron, and NC π^0 with γ misID
- Purity is ~80% if you cut at 0.003, rises to ~90% if you cut at 0.0015
- Background shape uncertainty can be reduced to ~10% with expected improvements to cross section models
- Eθ^2 resolution is key

Reco Eθ^2

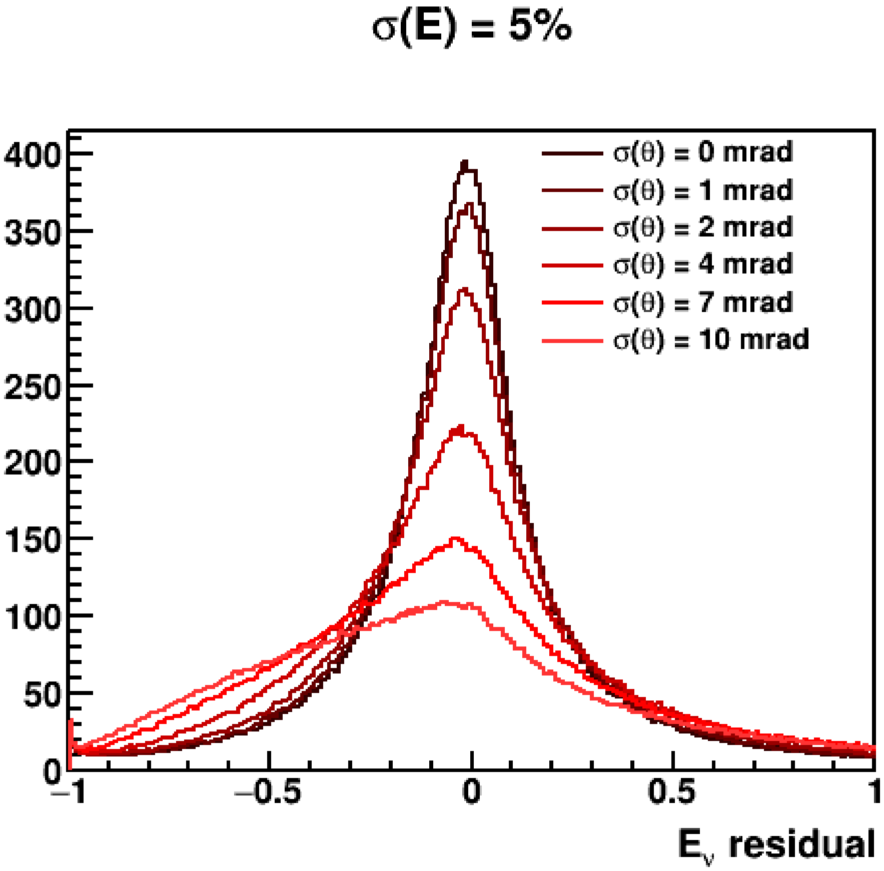




- Much more sensitive to angular resolution
- But with expected resolution purity will be ~85% in ArgonCube

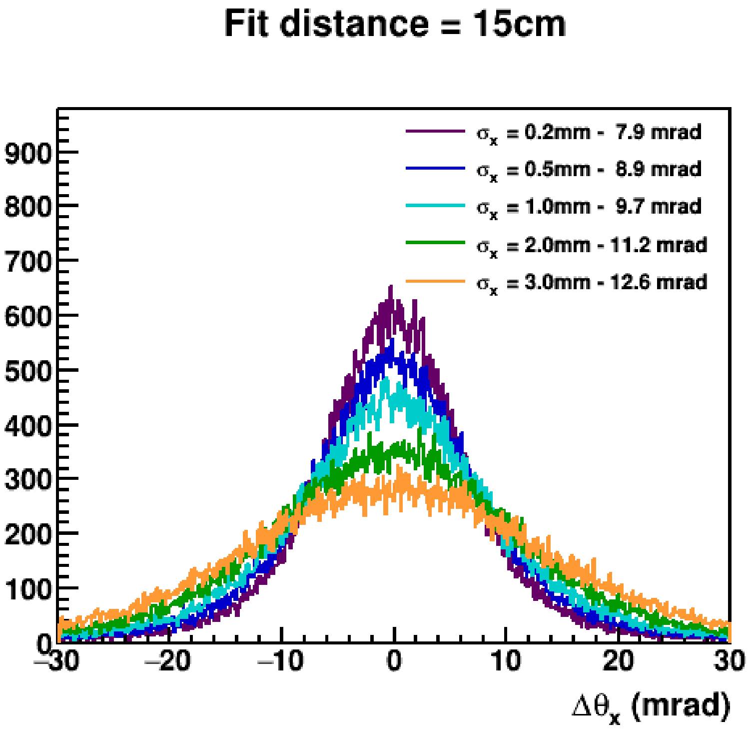
Direct neutrino energy measurement

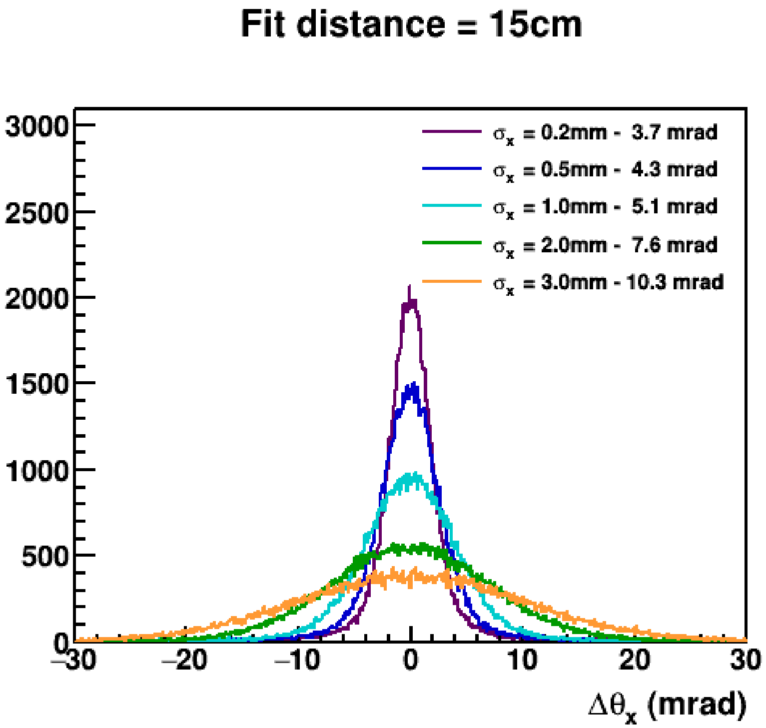
$$E_\nu = \frac{E_e}{1 - \frac{E_e(1-\cos\theta)}{m}} \approx \frac{E_e}{1 - \frac{E_e\theta^2}{2m}}$$



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

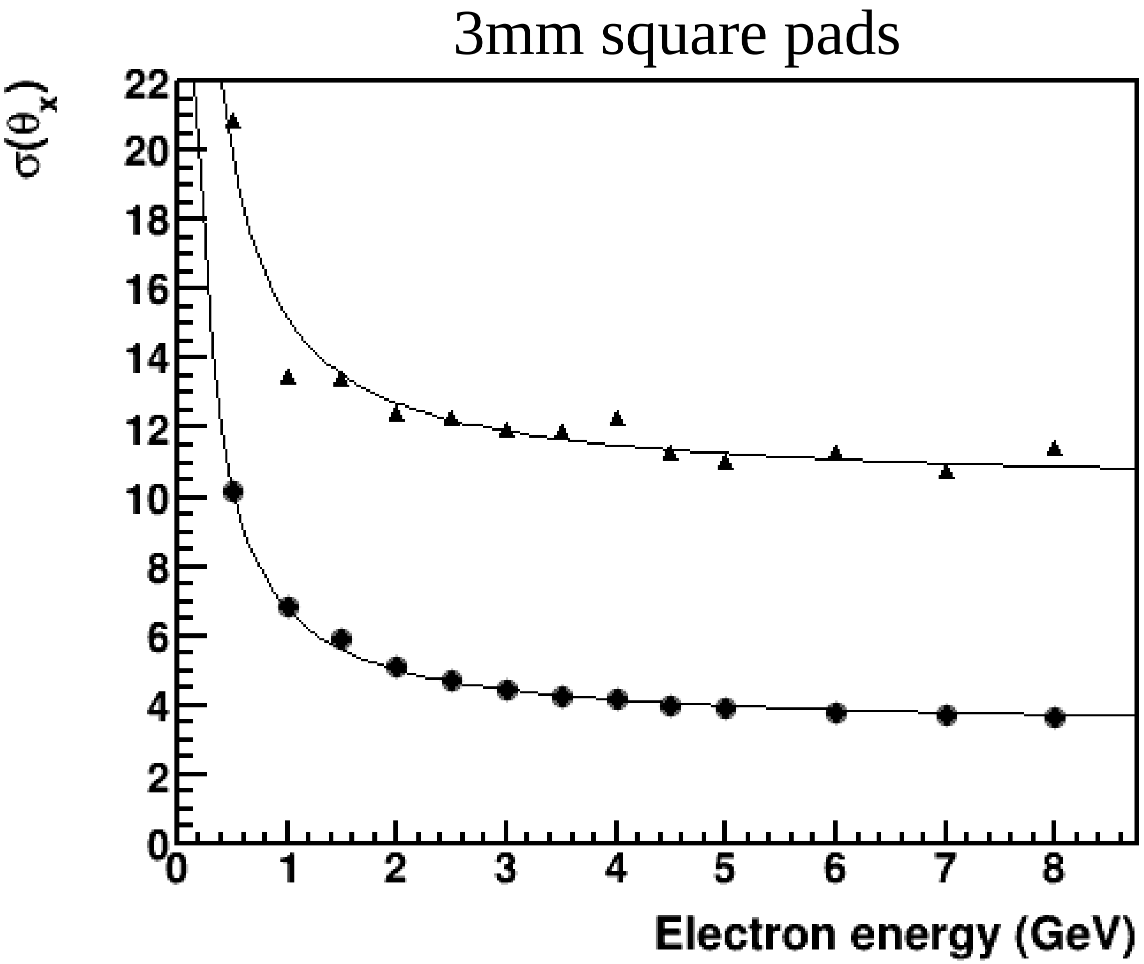
Electron angle resolution in LAr





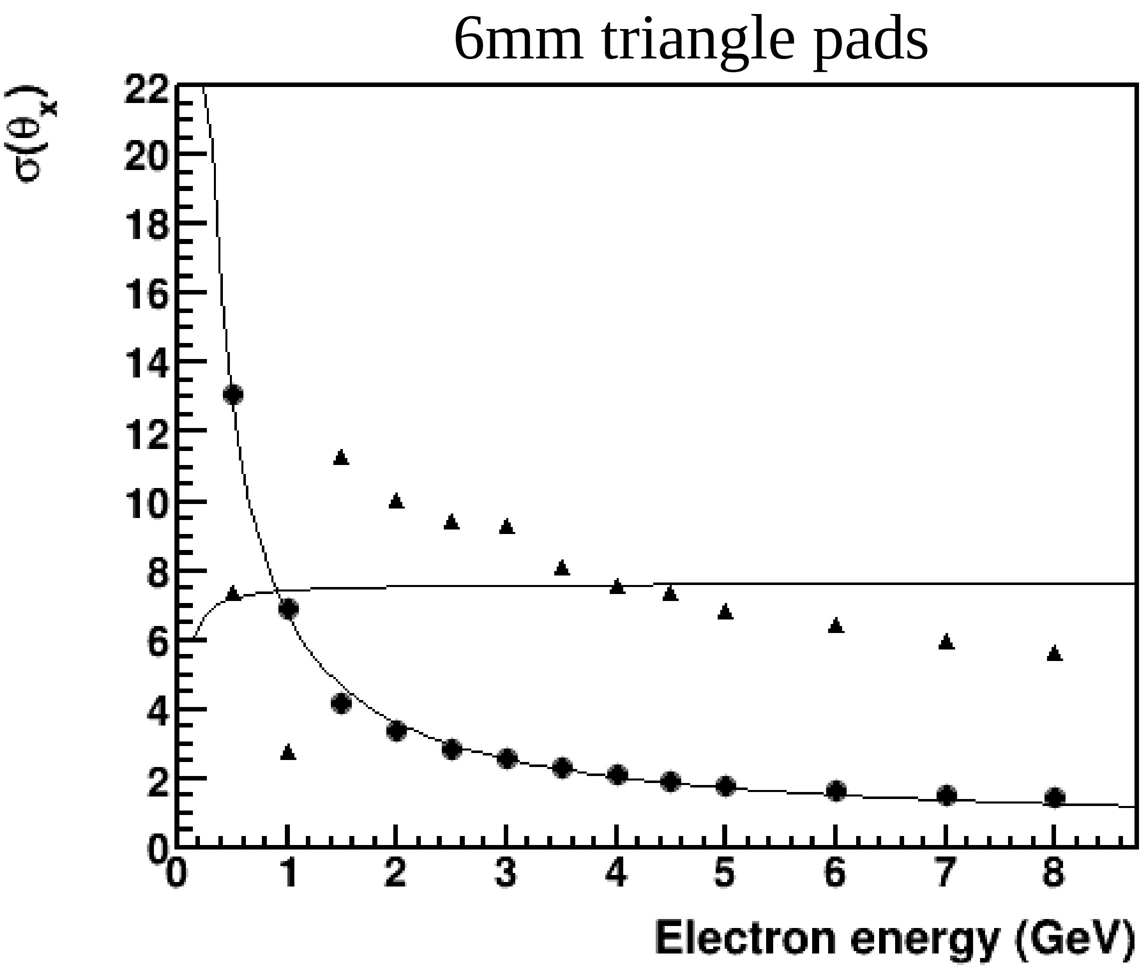
- At 1 GeV (left), and 5 GeV (right)
- Standard 3mm pads gives ~0.9mm point resolution

Electron angular resolution in ArgonCube



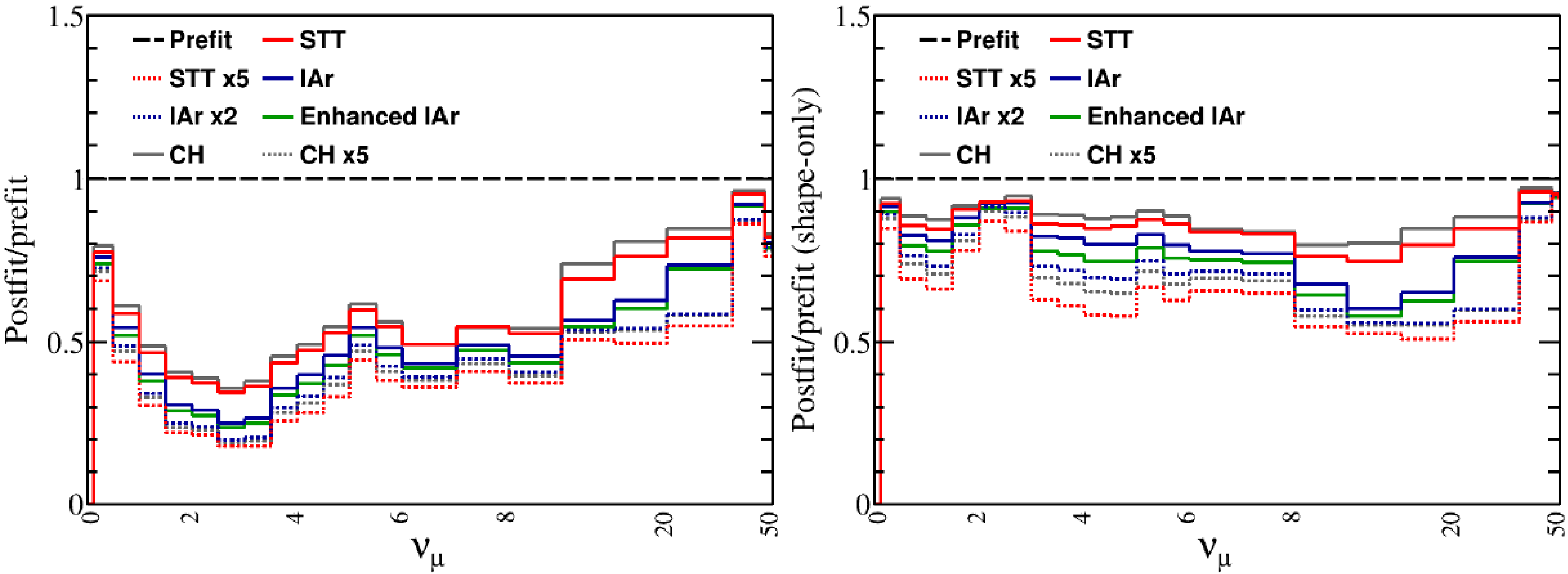
- For square pads with 3mm, point resolution is ~0.9mm
- Become measurement limited around ~4mrad at ~2 GeV

Electron angle resolution in ArgonCube with triangle pads



- 6mm triangle pads
- $\Delta q/\Delta x = 200$ keV/mm for a MIP
- 1 mV ~ 10 keV
- Potentially could get to 100µm position resolution
- Shown: 200µm

In a real analysis...

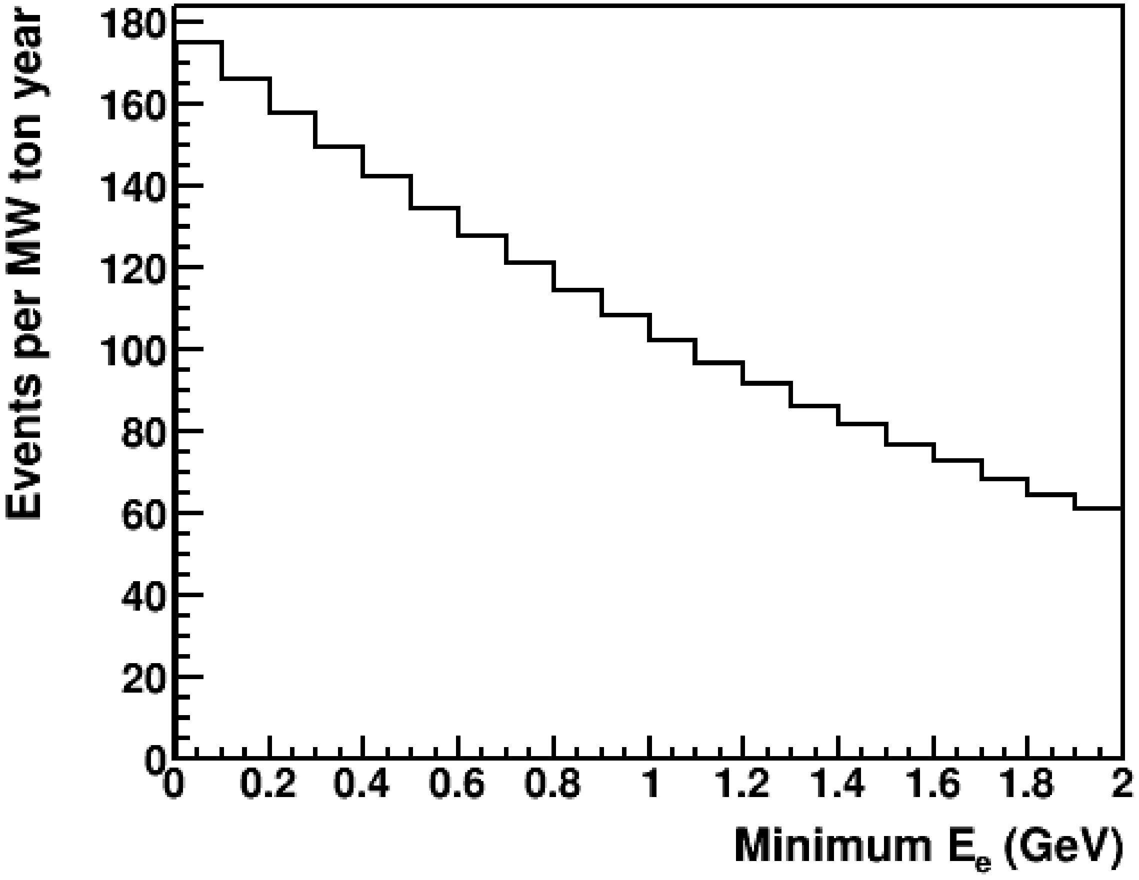


Rate+shape

Shape-only

- 2D template fits to electron energy and angle
- “lAr” is basically 3mm square pads
- “Enhanced lAr” is 6mm triangles
- But actually statistics are closer to “lAr x2” in both cases

Impact of energy scale



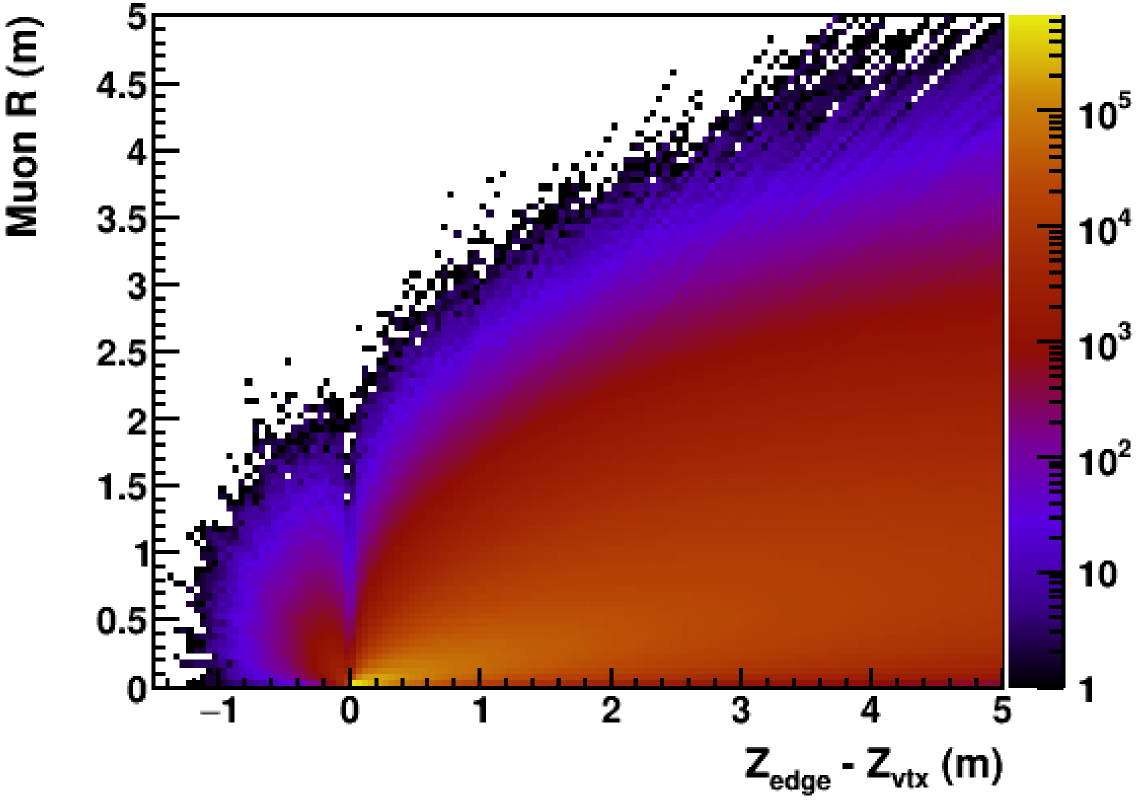
- Backgrounds in LAr will be nasty at very low electron energy
- Realistically, we will cut at some value of reconstructed E_e
- Energy scale uncertainty will affect efficiency of that cut
- Change in rate is ~0.5% per 1% change in energy scale → need EM energy scale absolute calibration to ~2%

ν+e Conclusions

- Angular resolution of ArgonCube is good enough to get ~85% purity in ν+e → ~1.5% background systematic
- Energy resolution of 10% is sufficient
- Absolute energy scale < 2% needed to reduce backgrounds at very low electron energy

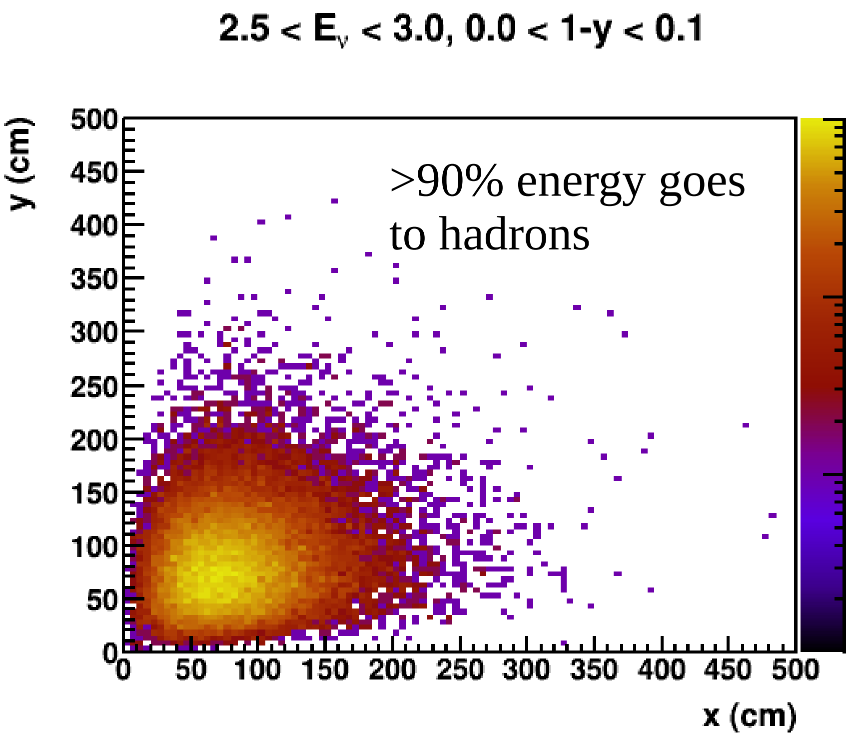
Backups

Distribution of muon transverse position vs. distance to vertex



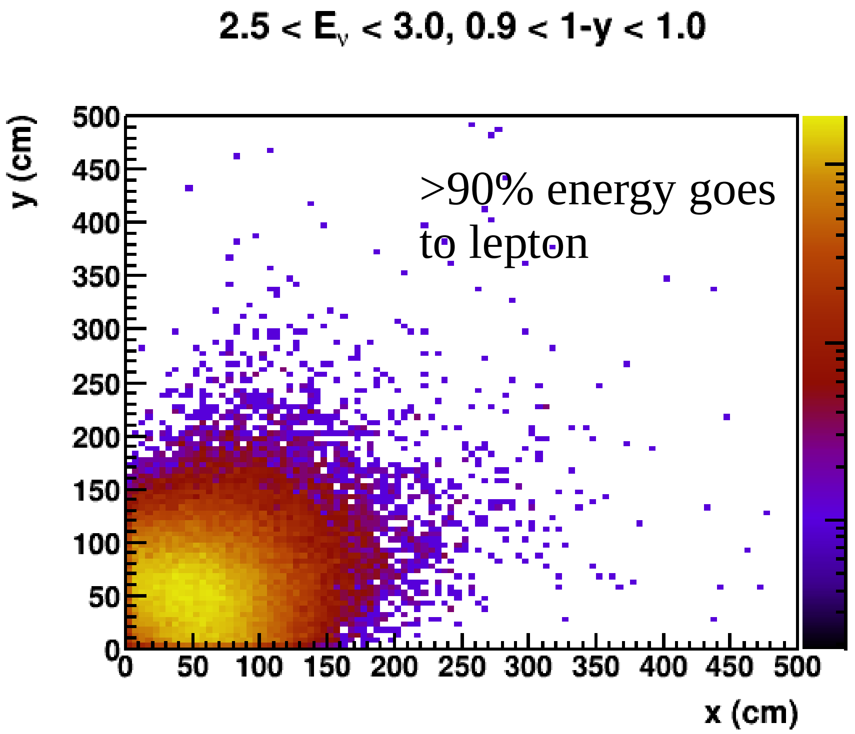
- FHC neutrino CC
- Basically muons go a maximum of ~3-4m transverse to beam axis in first ~2-5m of track
- Backscatters are always contained with ~1m, and ~2m transverse

Flux peak, highly (in)elastic



$2.5 < E_\nu < 3.0, 0.0 < 1\text{-}y < 0.1$

>90% energy goes to hadrons

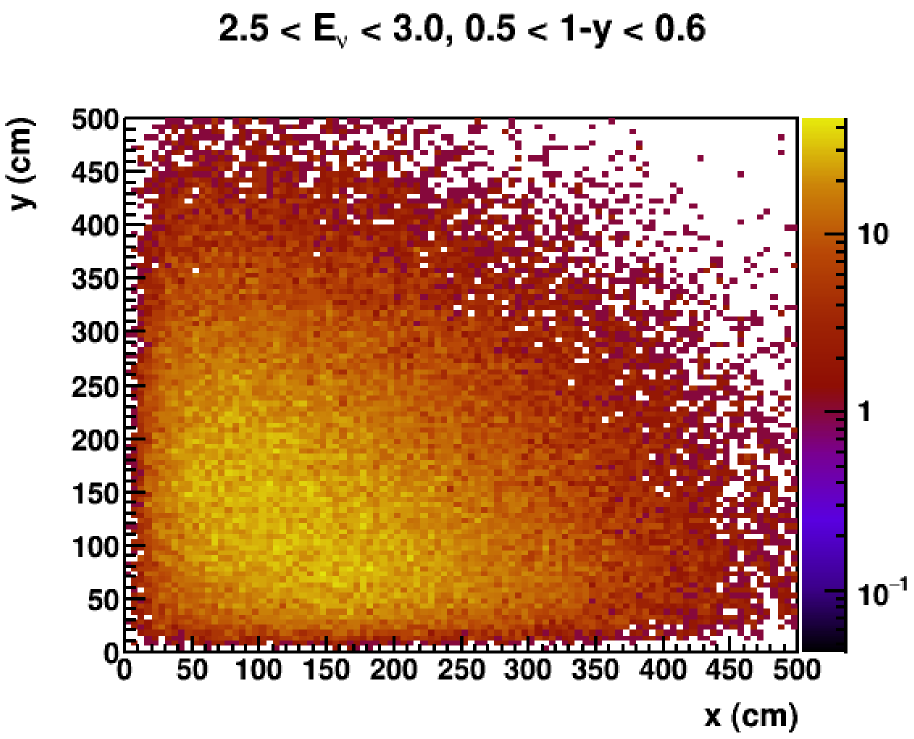


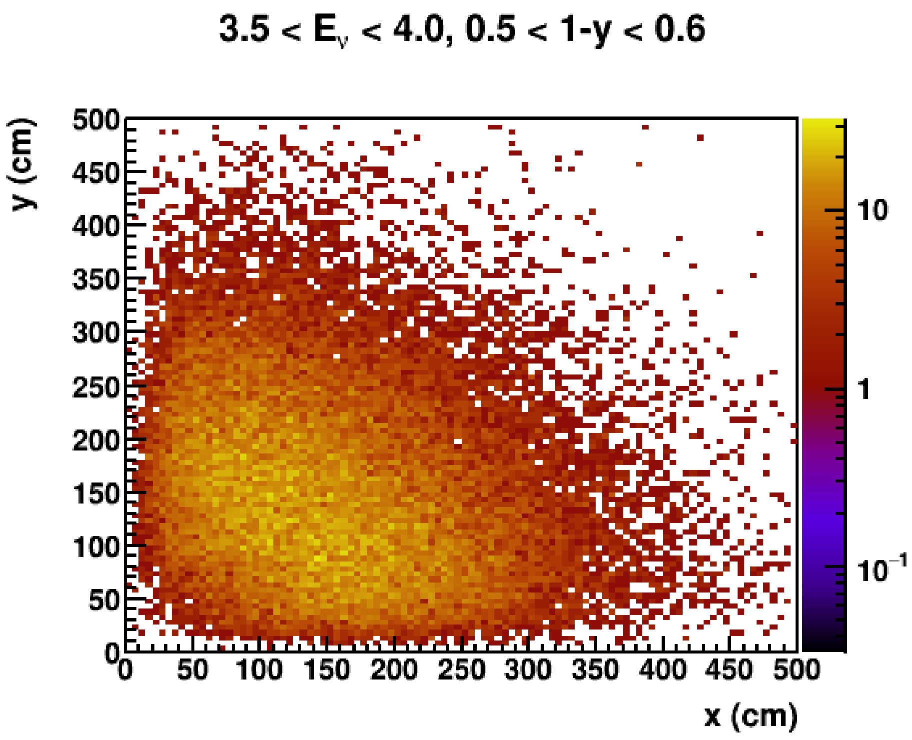
$2.5 < E_\nu < 3.0, 0.9 < 1\text{-}y < 1.0$

>90% energy goes to lepton

- Smallest transverse detector dimensions to contain muon + 95% of hadronic energy (excluding neutrons)

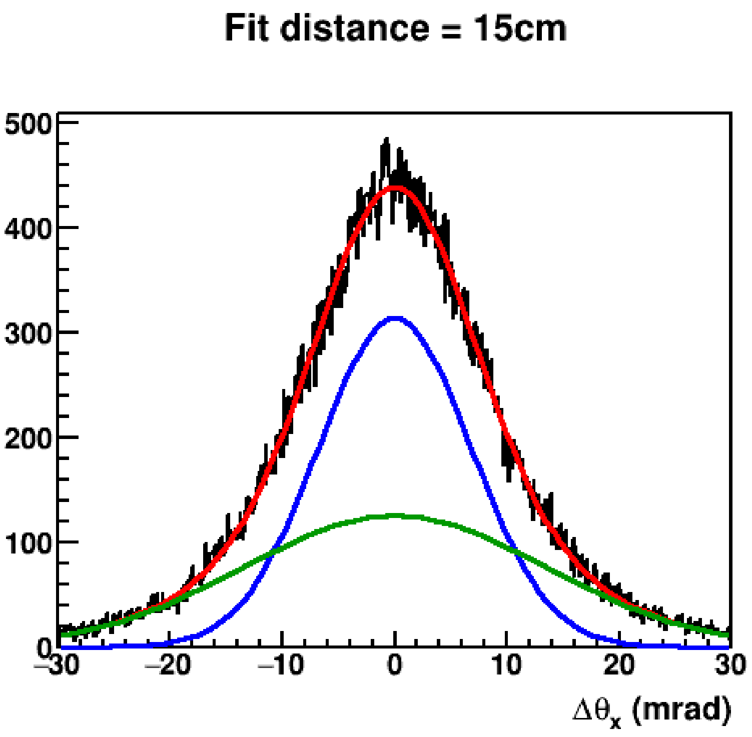
Flux peak → falling edge moderate elasticity

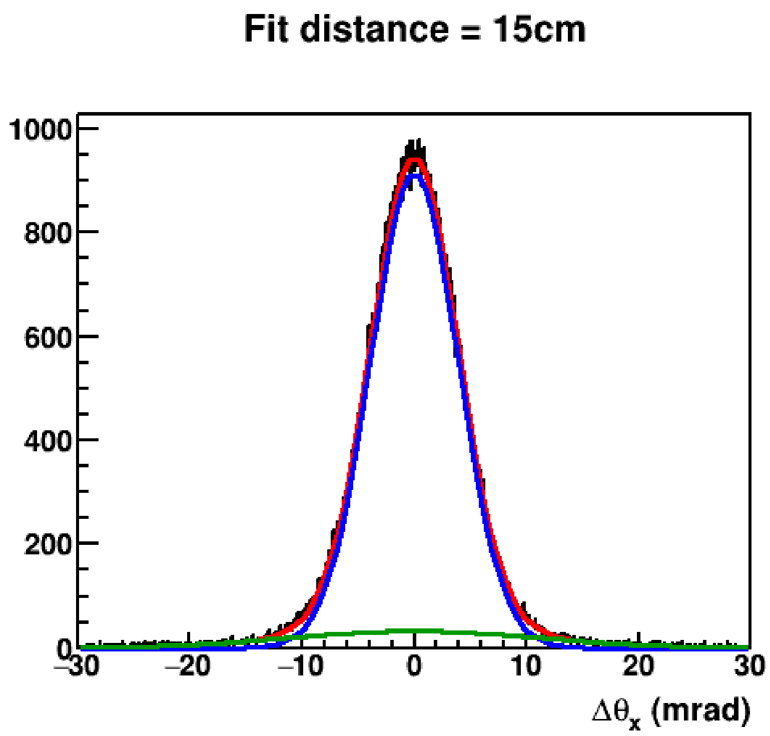

$2.5 < E_\nu < 3.0, 0.5 < 1\text{-}y < 0.6$


$3.5 < E_\nu < 4.0, 0.5 < 1\text{-}y < 0.6$

- Largest transverse events are at moderate y
- With rotational symmetry, get good coverage for detector long in one dimension
- This is event "size" only, detector needs to be >> larger than events in order to have a finite volume for vertex

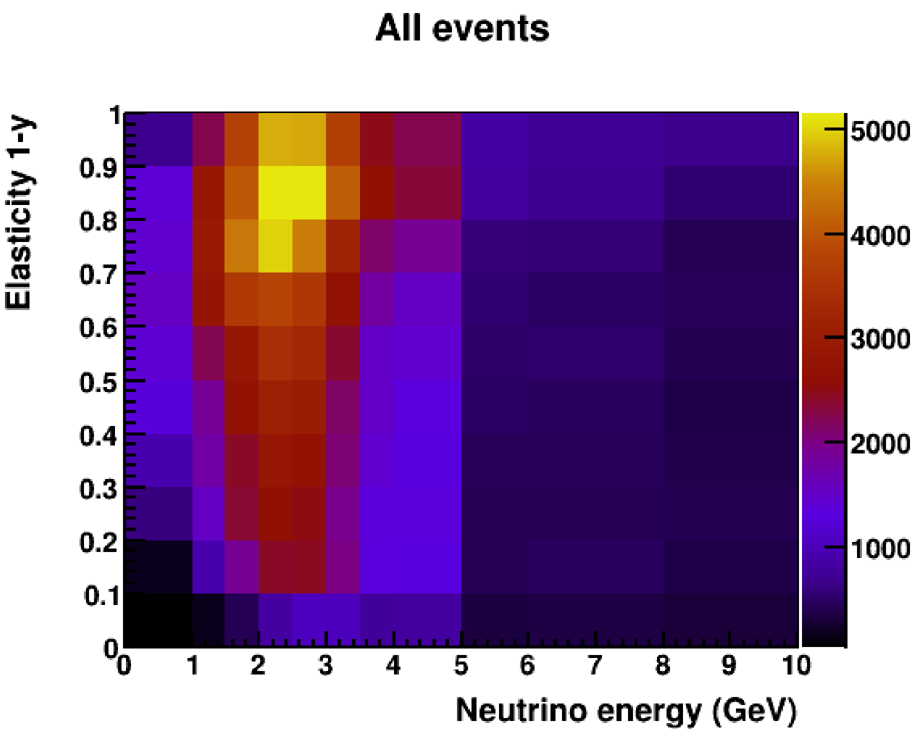
Double Gaussian fits

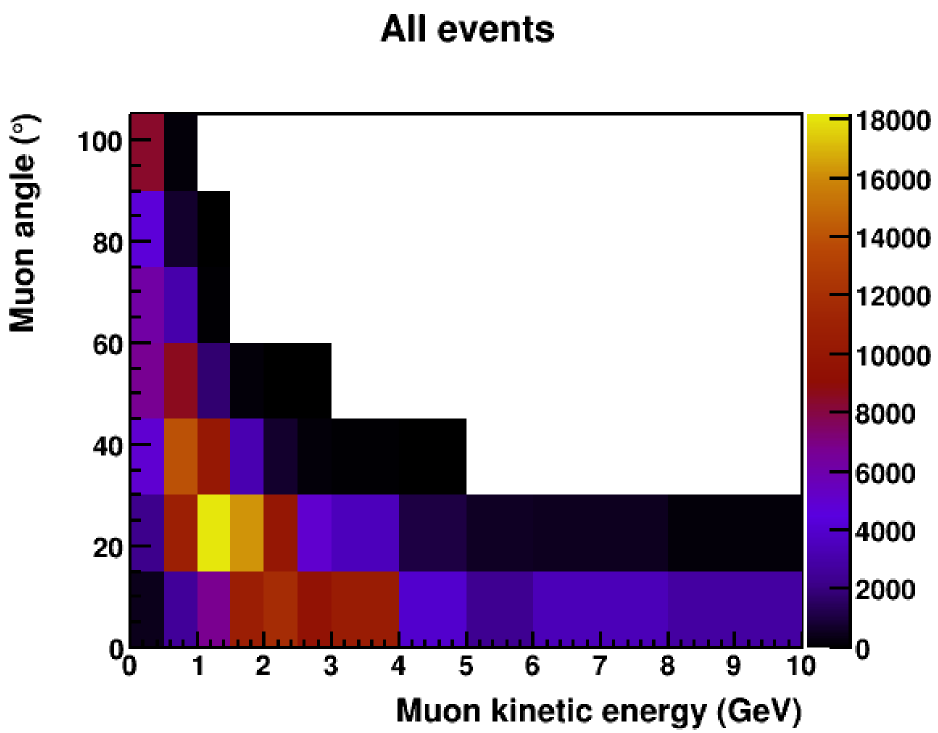




- Hard scattering is accounted for with the second, wider gaussian in the fit

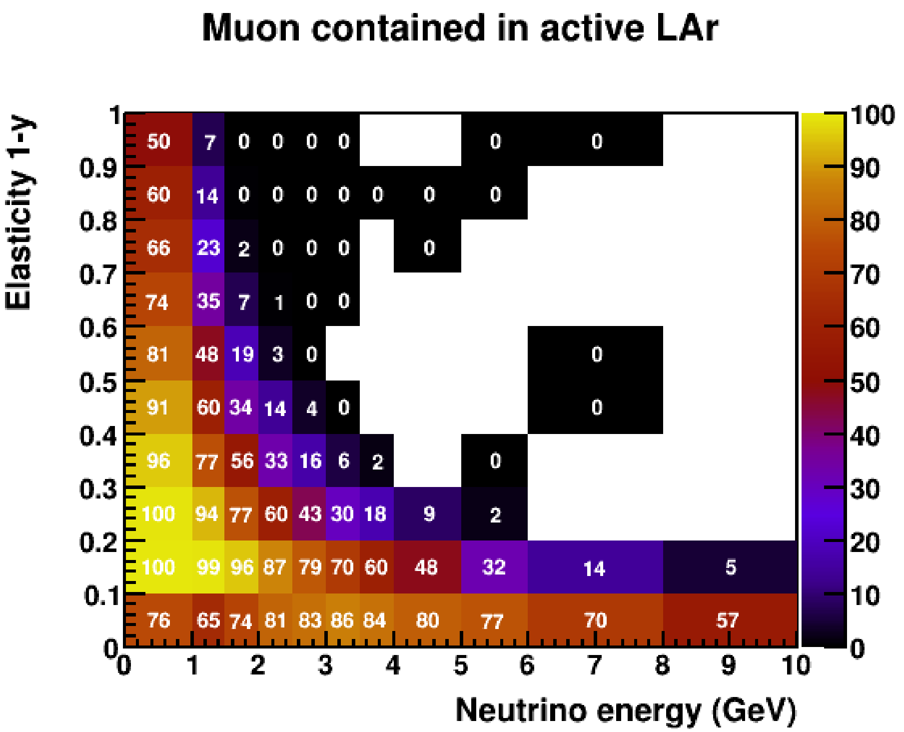
Event distributions FHC ν_μ

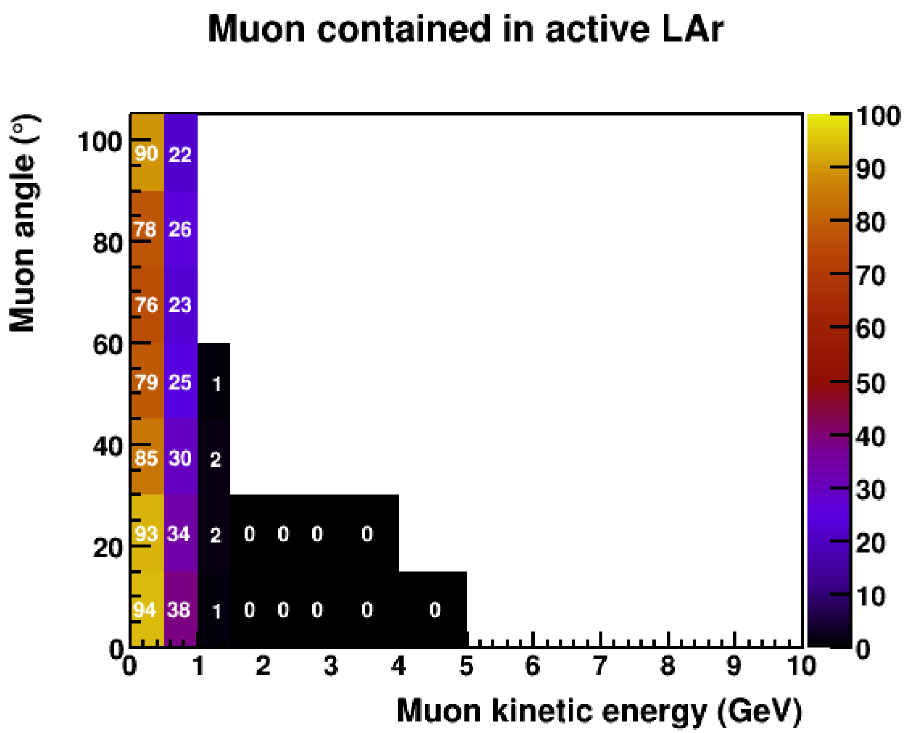

All events


All events

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

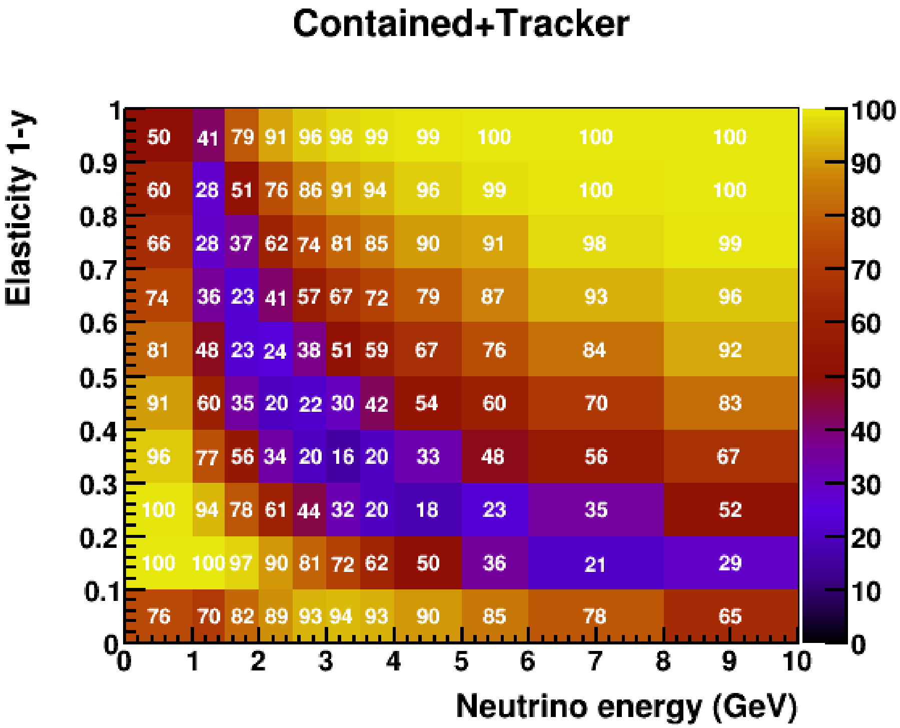
LAr-contained



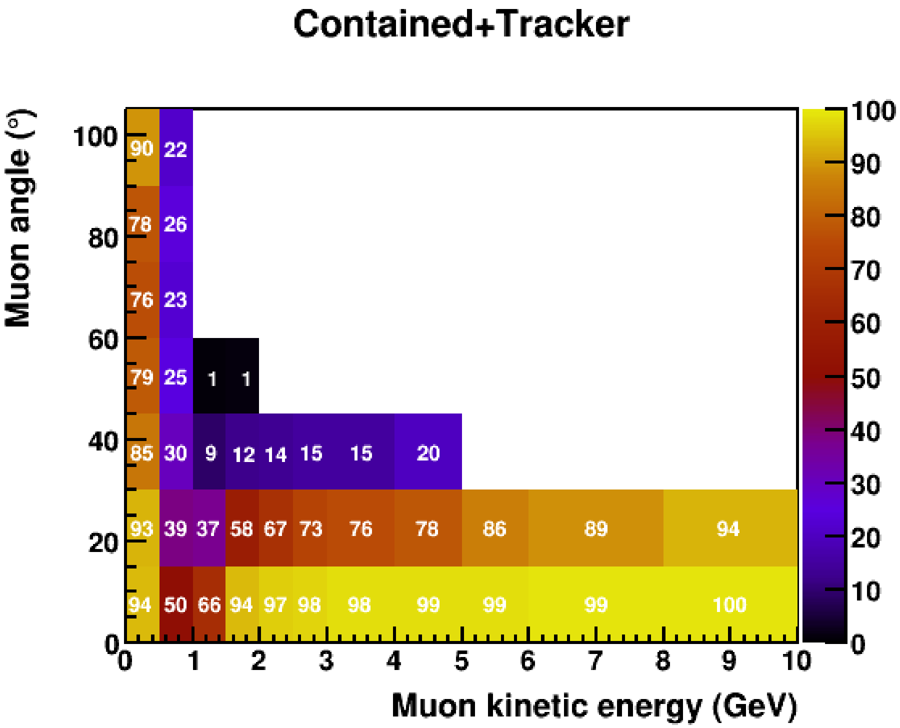


- Muons up to about 1 GeV can be contained in LAr

Contained+tracker



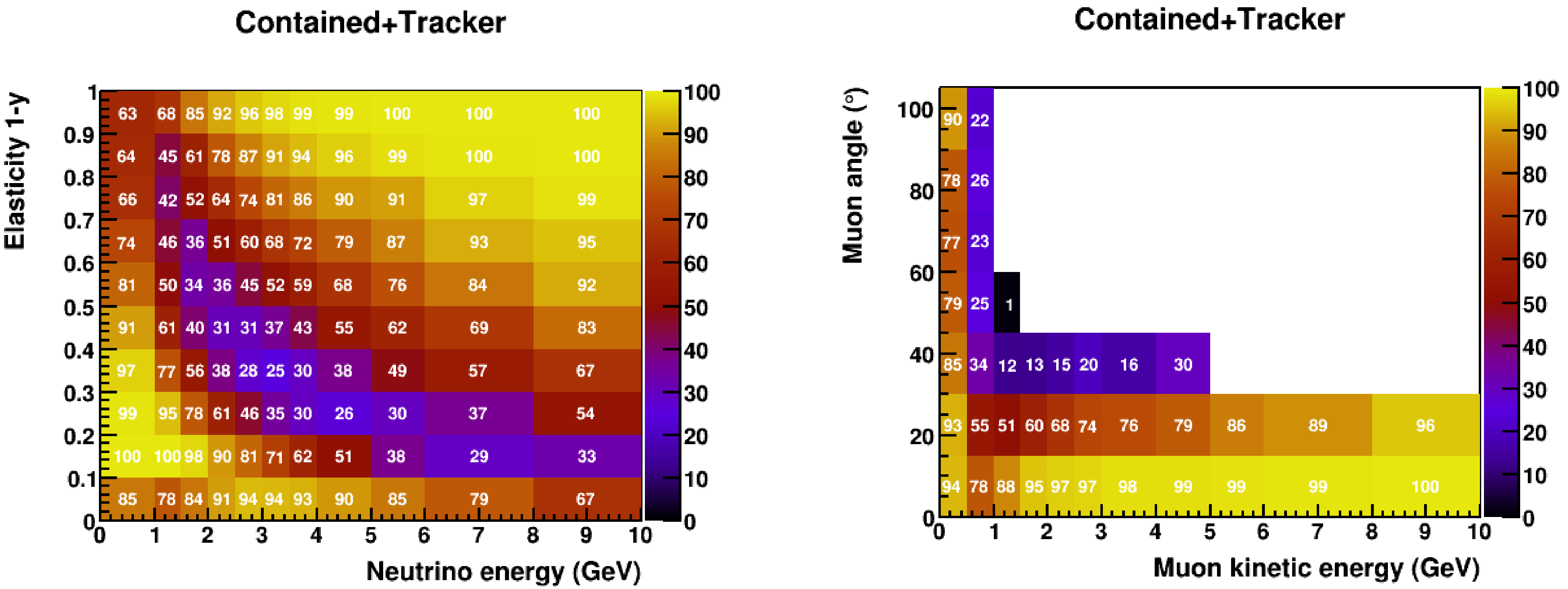
50	41	79	91	96	98	99	99	100	100	100
60	28	51	76	86	91	94	96	99	100	100
66	28	37	62	74	81	85	90	91	98	99
74	36	23	41	57	67	72	79	87	93	96
81	48	23	24	38	51	59	67	76	84	92
91	60	35	20	22	30	42	54	60	70	83
96	77	56	34	20	16	20	33	48	56	67
100	94	78	61	44	32	20	18	23	35	52
100	100	97	90	81	72	62	50	36	21	29
76	70	82	89	93	94	93	90	85	78	65



90	22									
78	26									
76	23									
79	25	1	1							
85	30	9	12	14	15	15	20			
93	39	37	58	67	73	76	78	86	89	94
94	50	66	94	97	98	98	99	99	99	100

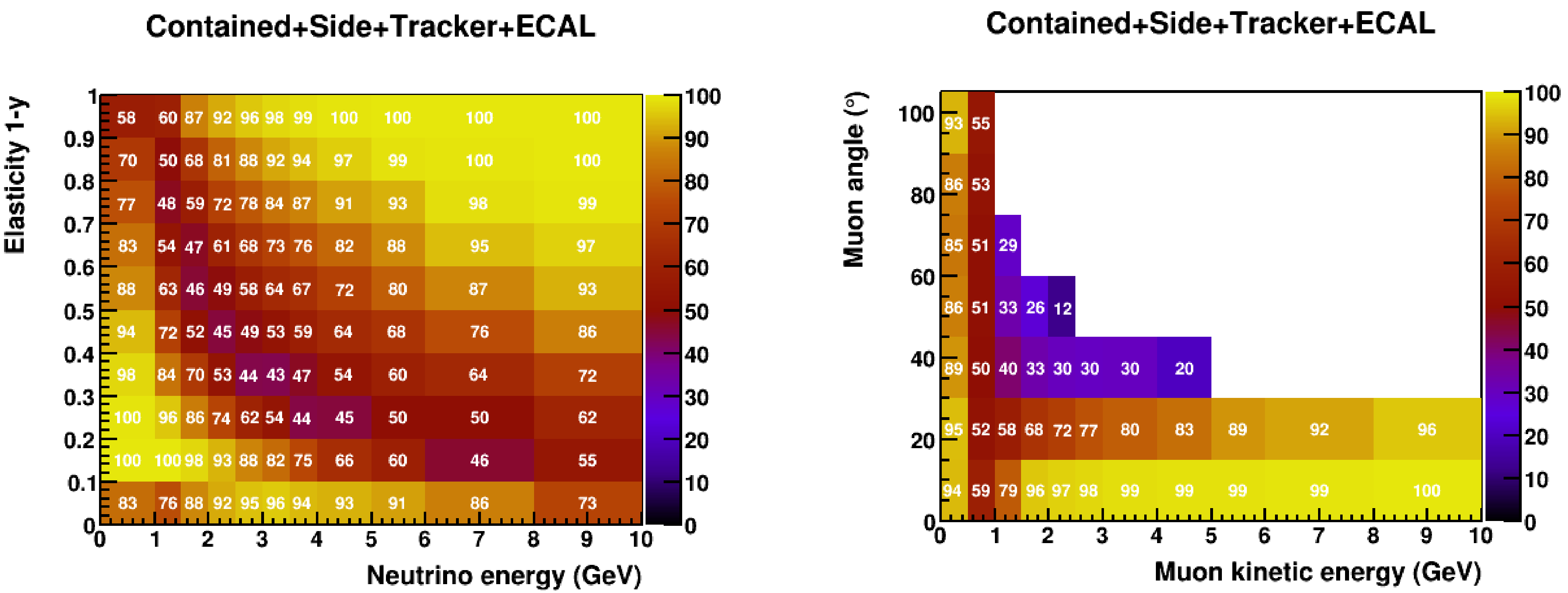
- Adding tracker-matched sample gives good acceptance for forward, high-energy muons
- Poor acceptance at high muon angles
- Acceptance dip where muons stop in dipole coil

Contained+tracker – no coil



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

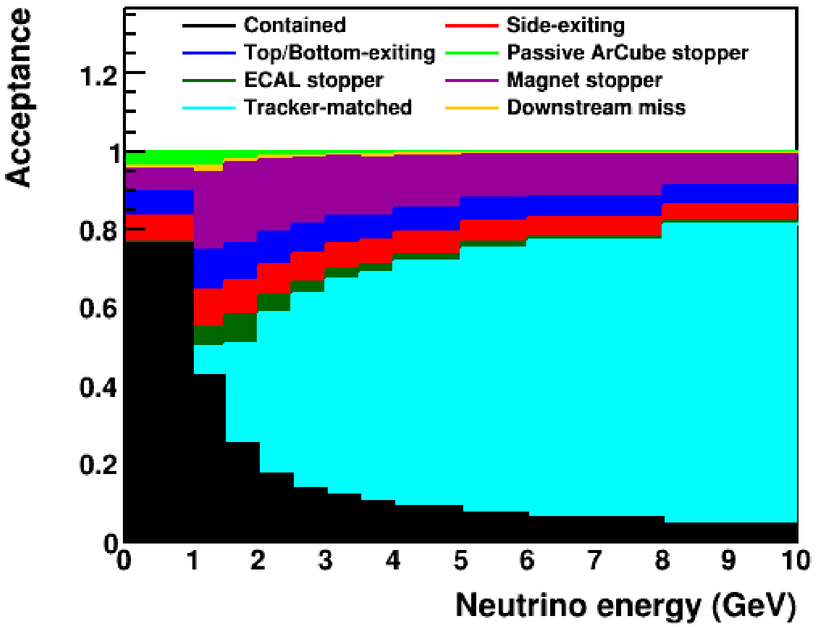
Add side events

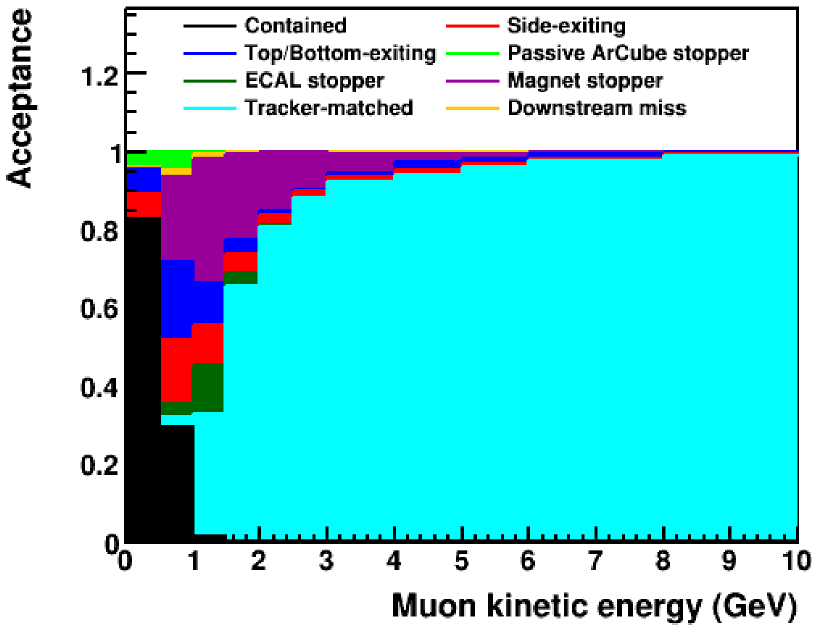

Contained+Side+Tracker+ECAL

Contained+Side+Tracker+ECAL

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

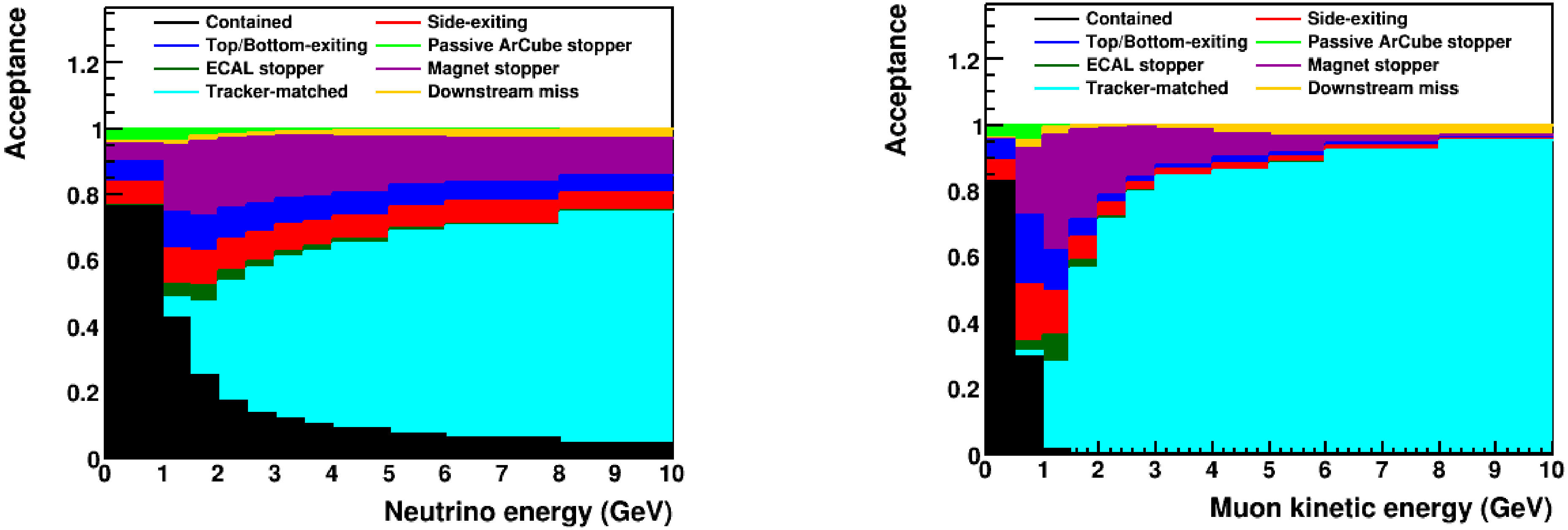
Acceptance in 1D





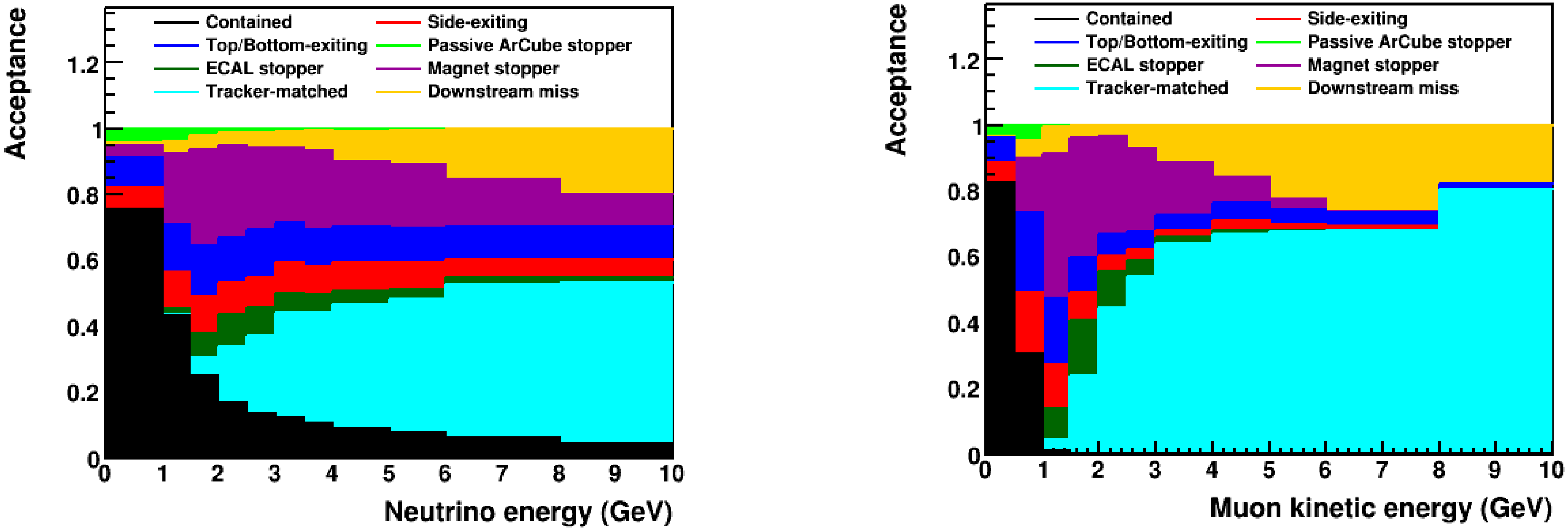
- Problematic events are purple “magnet stopper” category – 25% near peak region

Dipole+STT



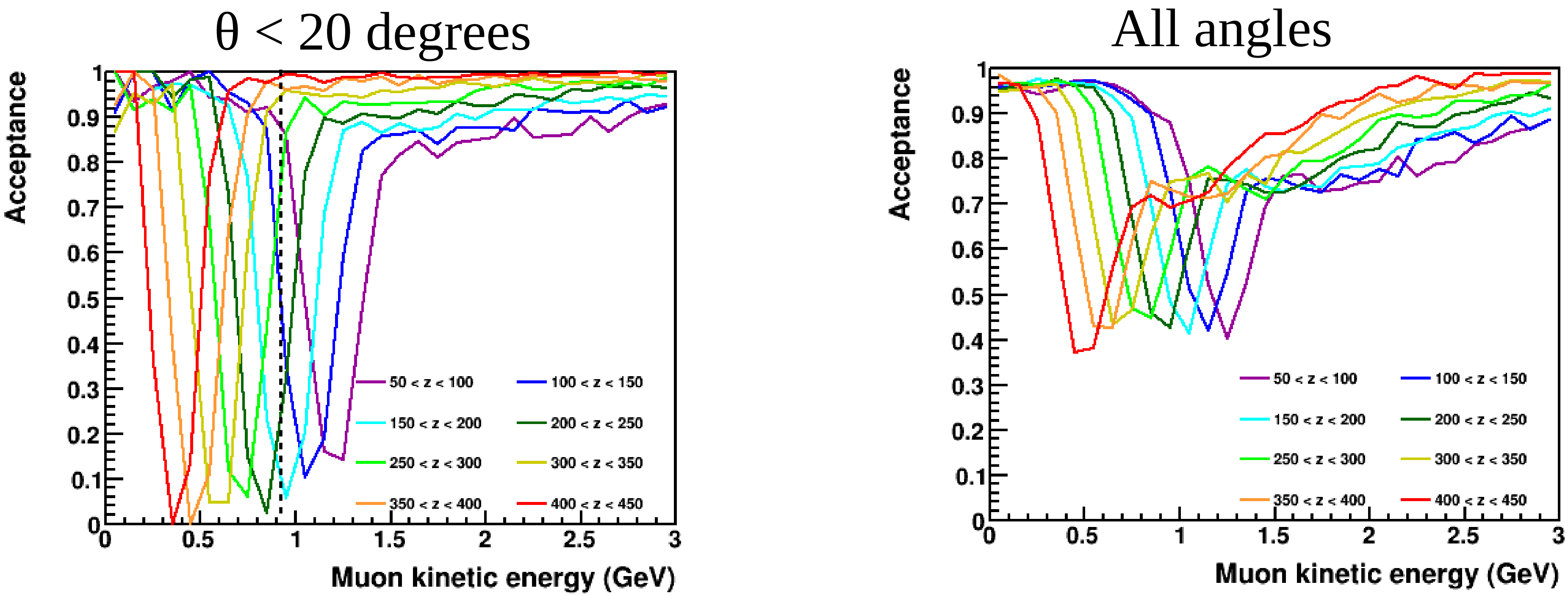
- Nearly identical – this STT geometry is not quite as wide as the LAr, so there are some events that exit the rear and miss the STT

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

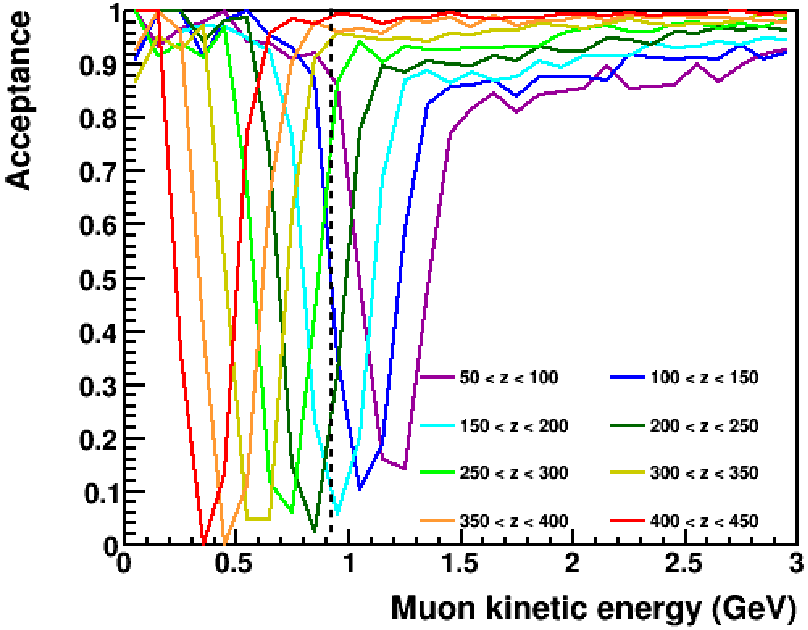
Acceptance in different Z regions

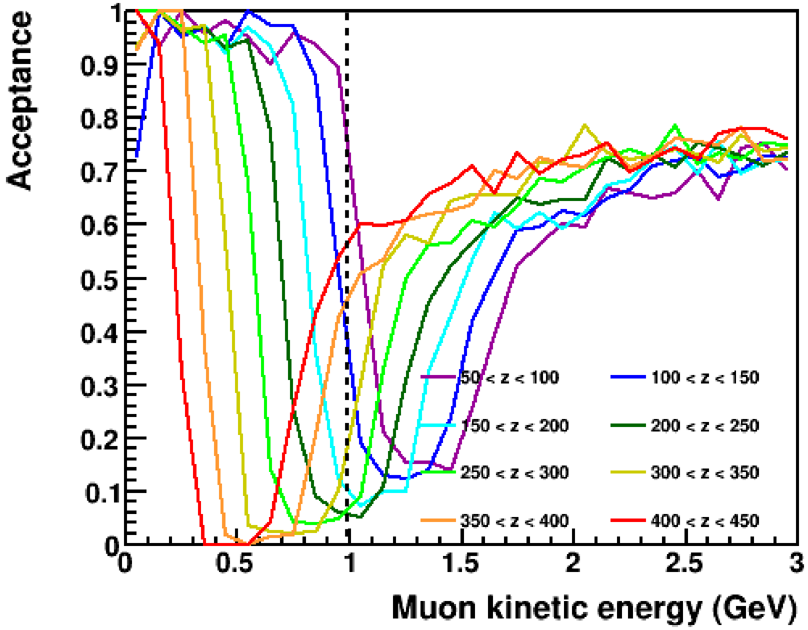

θ < 20 degrees

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

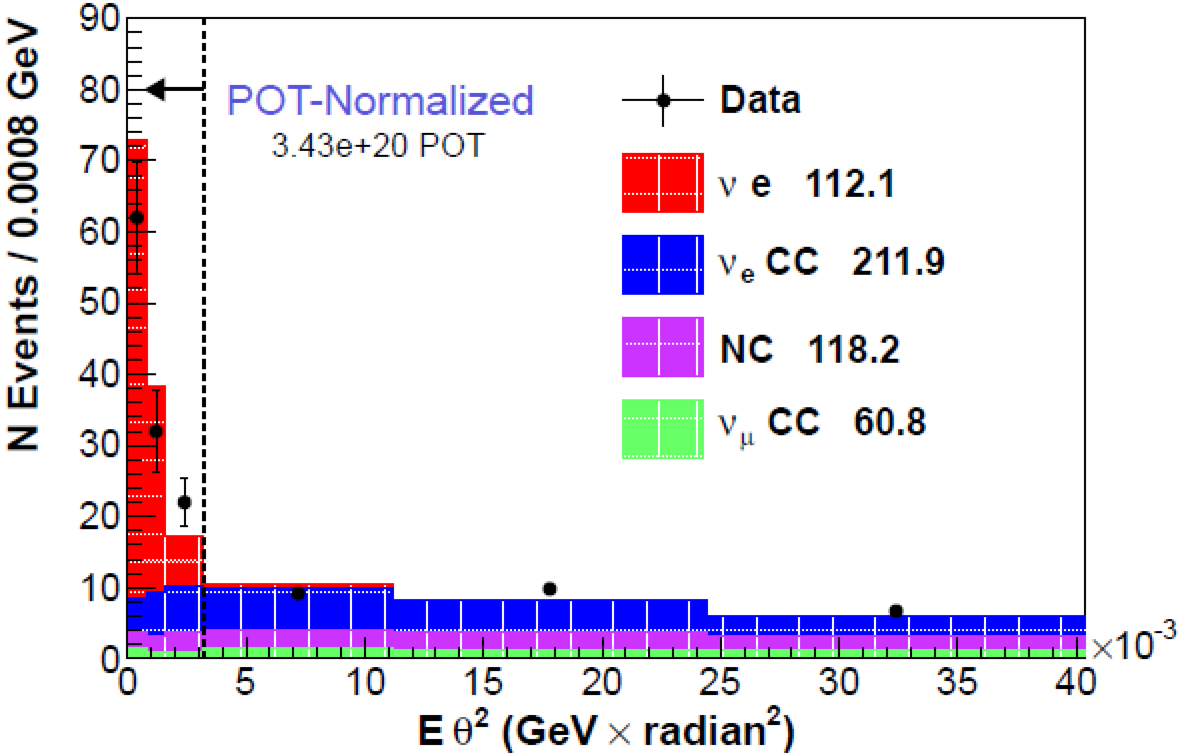

Dipole+TPC


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

MINERvA ν+e event selection

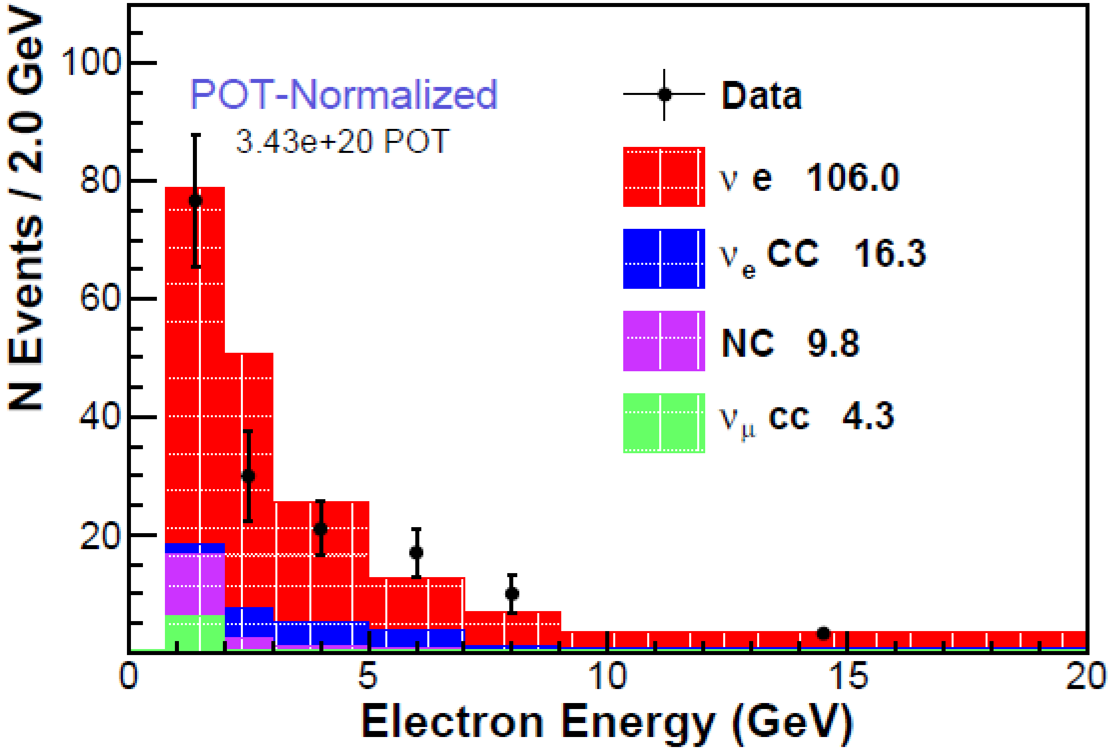
MINERvA Phys. Rev. D 93, 112007 (2016)

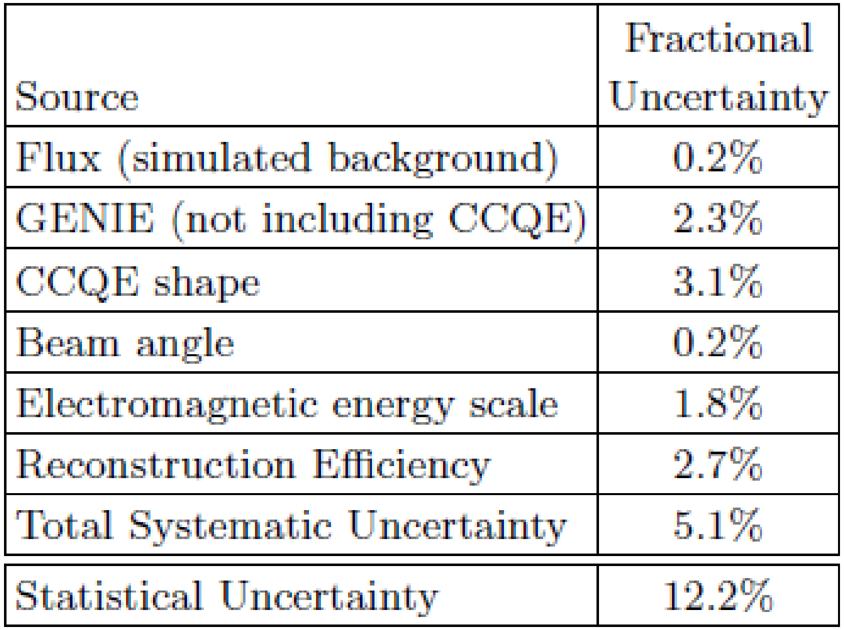


- Backgrounds are ν_e CCQE, and NC π^0
- Separated from signal by Eθ^2
- Sideband #2: moderate Eθ^2

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

Main MINERvA result: electron energy distribution

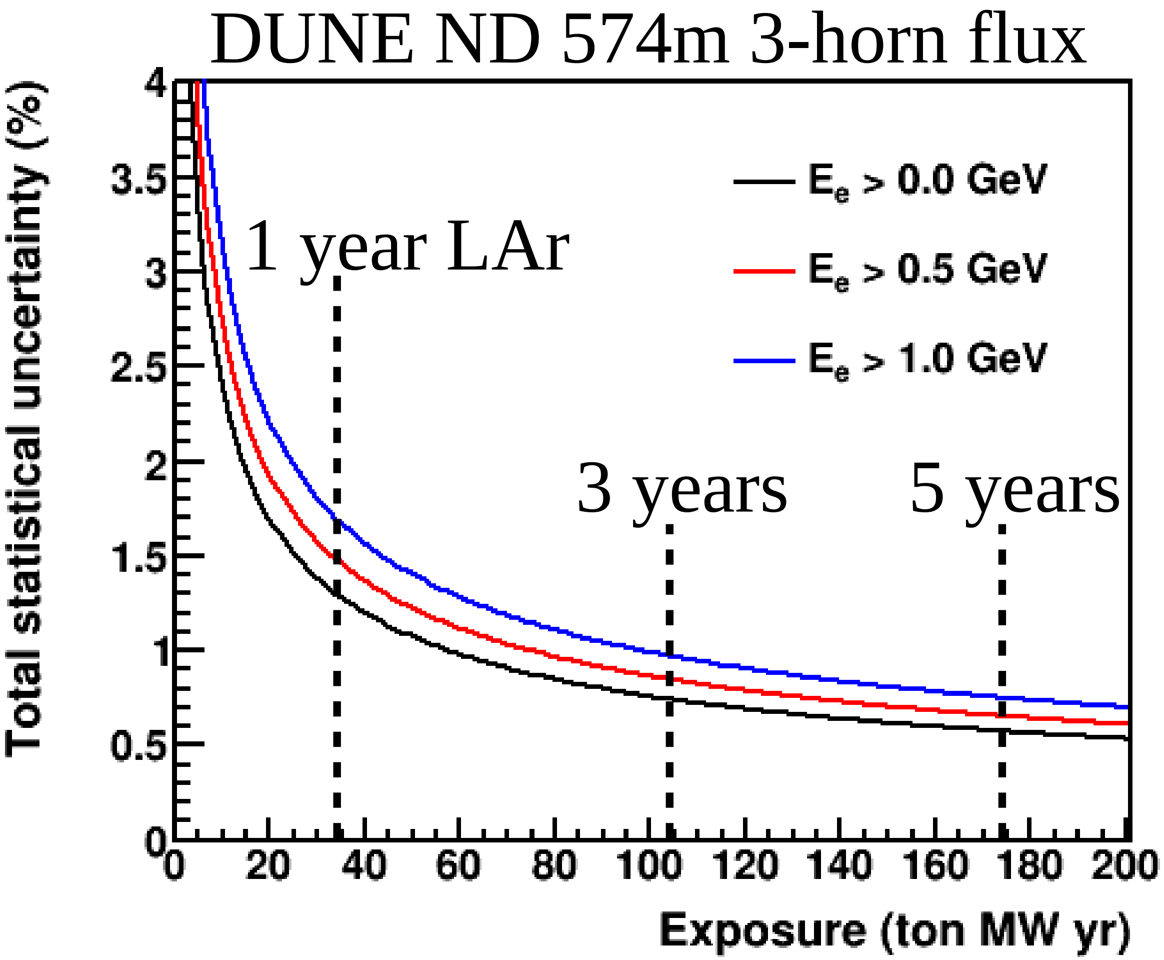




Source	Fractional Uncertainty
Flux (simulated background)	0.2%
GENIE (not including CCQE)	2.3%
CCQE shape	3.1%
Beam angle	0.2%
Electromagnetic energy scale	1.8%
Reconstruction Efficiency	2.7%
Total Systematic Uncertainty	5.1%
Statistical Uncertainty	12.2%

- 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

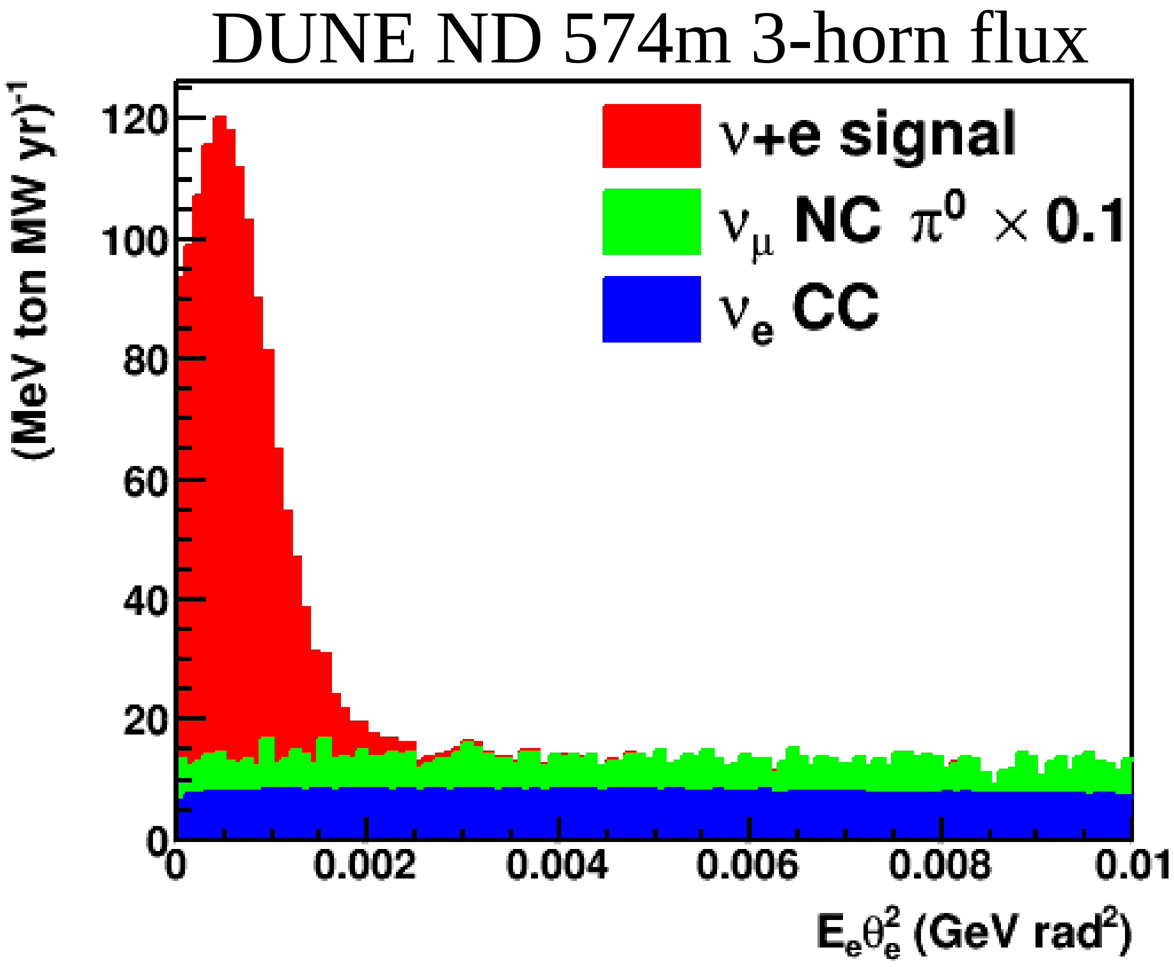
- Electron energy
  - Reconstruction efficiency will depend on electron energy
  - Cut on $E\theta^2$ is sensitive to electron energy scale
- Electron angle (or beam angle)
  - Cut on $E\theta^2$ is very sensitive to electron angle

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

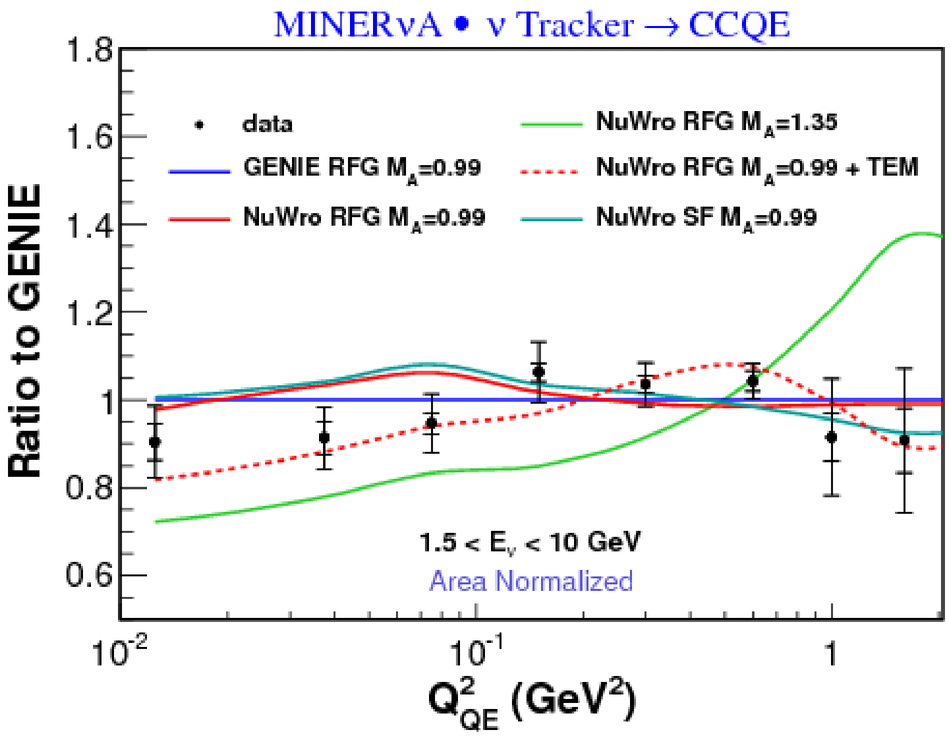
Pay a modest price in statistics, and can't escape ν_e CC background...

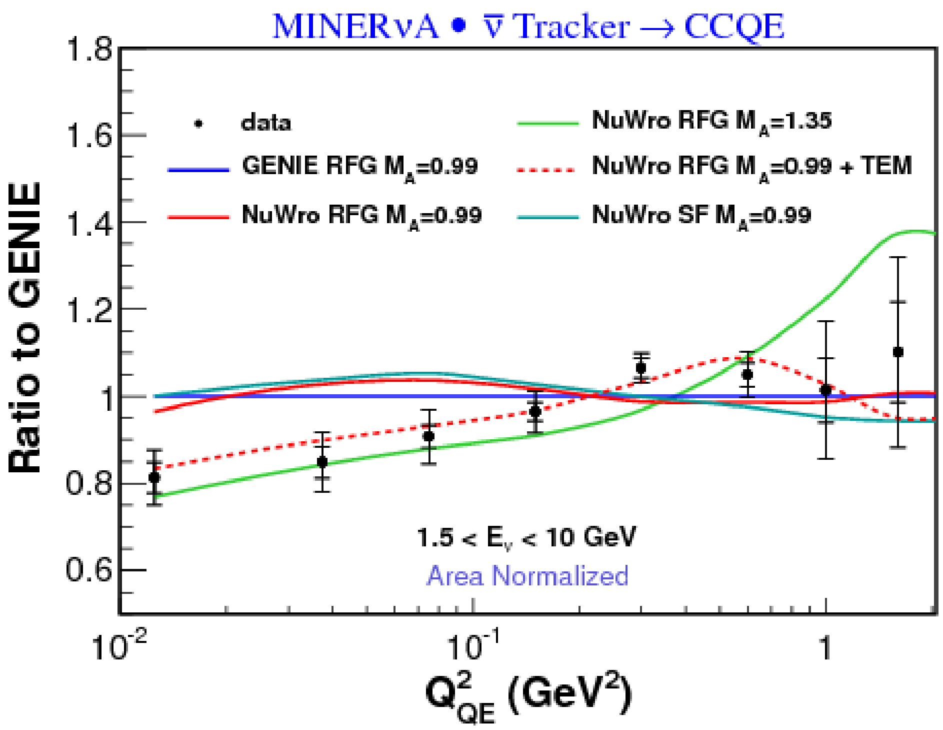
Systematics goal ~ 1%



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

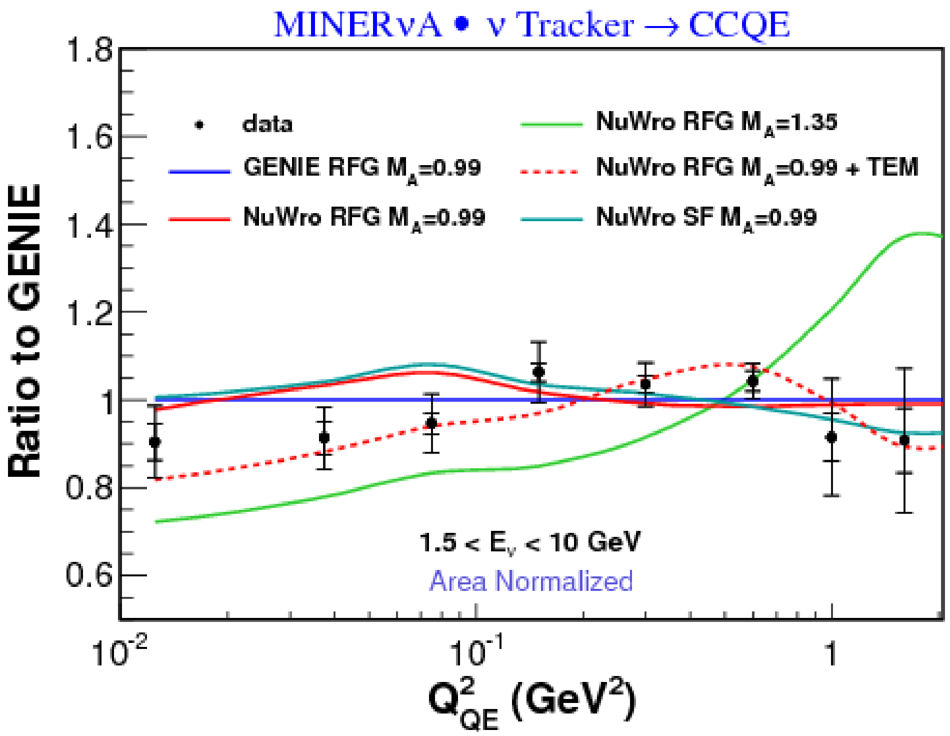
CCQE shape (ν_μ)

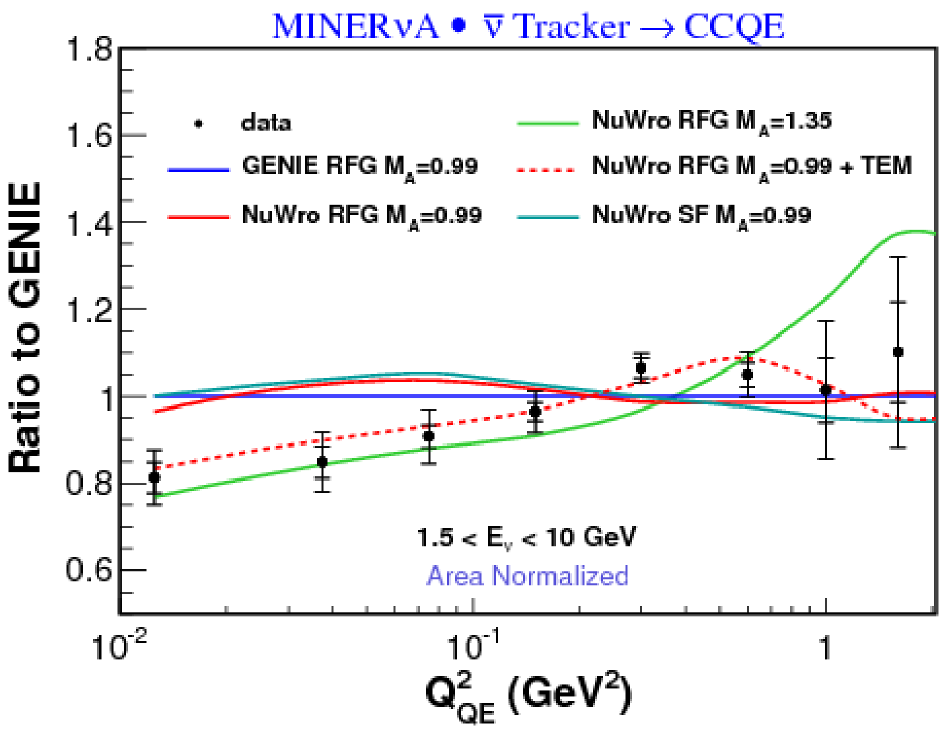




- $E\theta^2 = Q^2/E_\nu$, for 3.5 GeV E_ν MINERvA signal region of 0.0032 GeV → Q^2 ~0.01 GeV^2
- Signal region is ~half of first bin in MINERvA 2013 CCQE analysis (but for ν_e instead of ν_μ)
- Sideband is > 0.005, upper ~third of first bin and next 4 bins

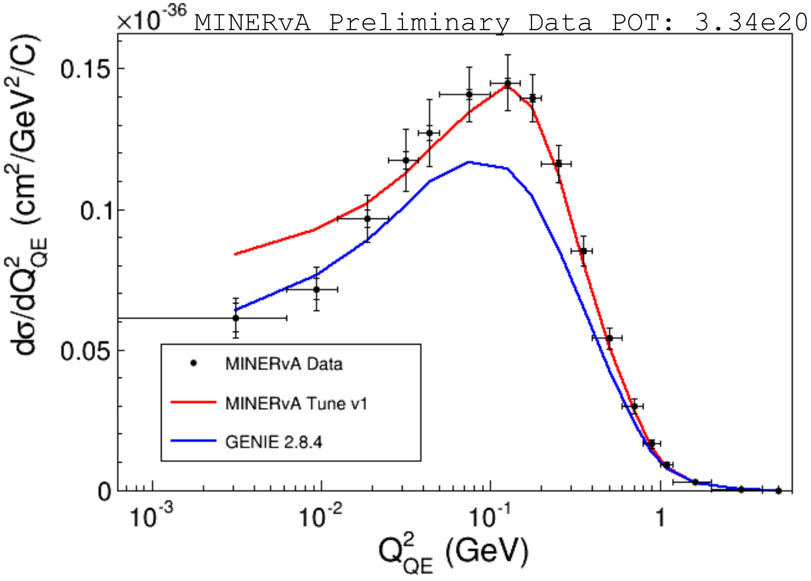
CCQE shape (ν_μ)

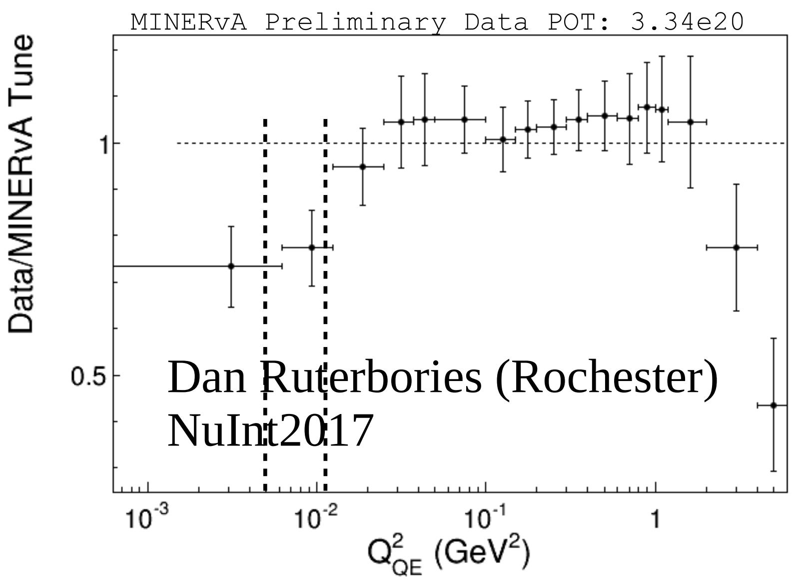




- Model used in MINERvA LE ν+e is GENIE 2.8
- CCQE model is Llewellyn Smith, dipole axial form factor with $M_A = 0.99$ GeV
- Nuclear model is Smith-Moniz, no 2p2h
- Sound theory predicts cross section is suppressed at very low momentum transfer due to long-range effects, confusingly called “RPA”

MINERvA 2018 result (ν_μ)



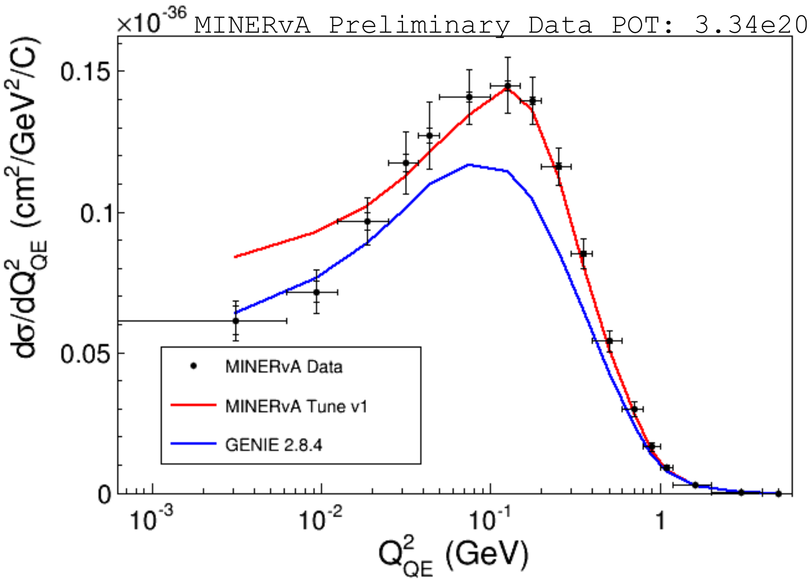


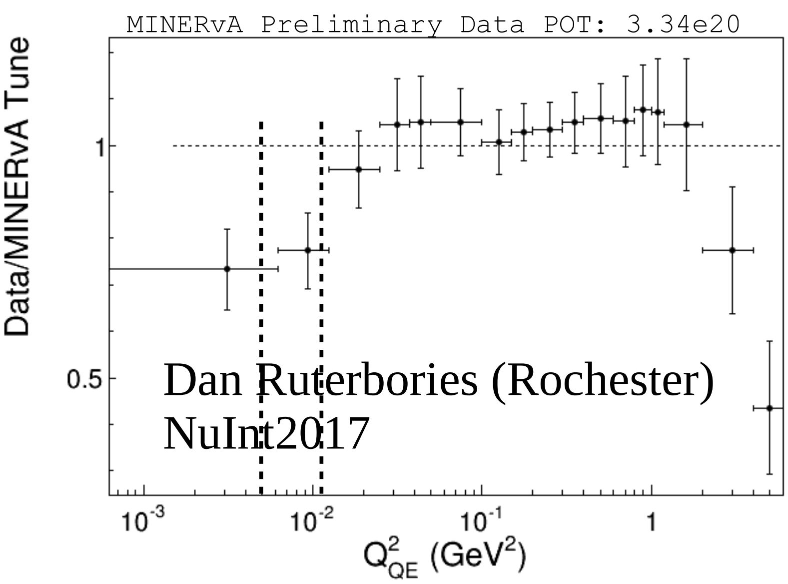
Dan Ruterbories (Rochester)
NuInt2017

lines of Eθ^2
~1.5 MeV
~3.2 MeV

- 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)



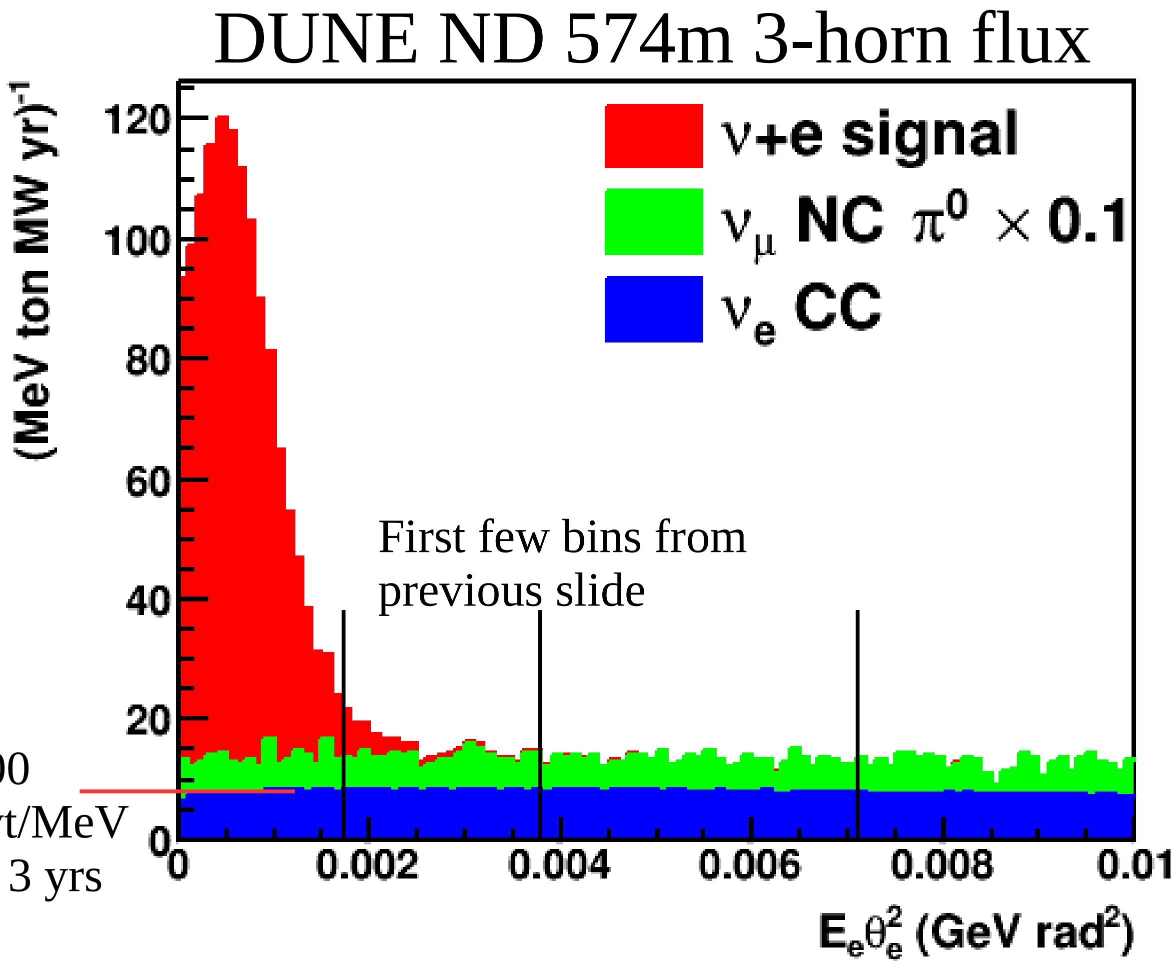


Dan Ruterbories (Rochester)
NuInt2017

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

- 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 few bins from previous slide

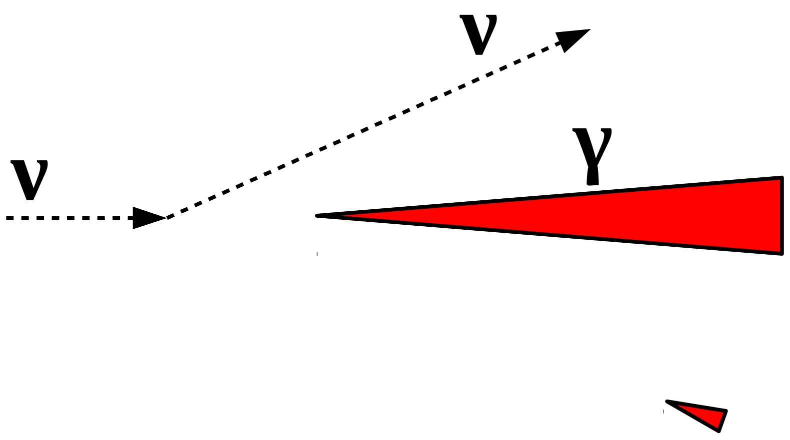
800 evt/MeV in 3 yrs

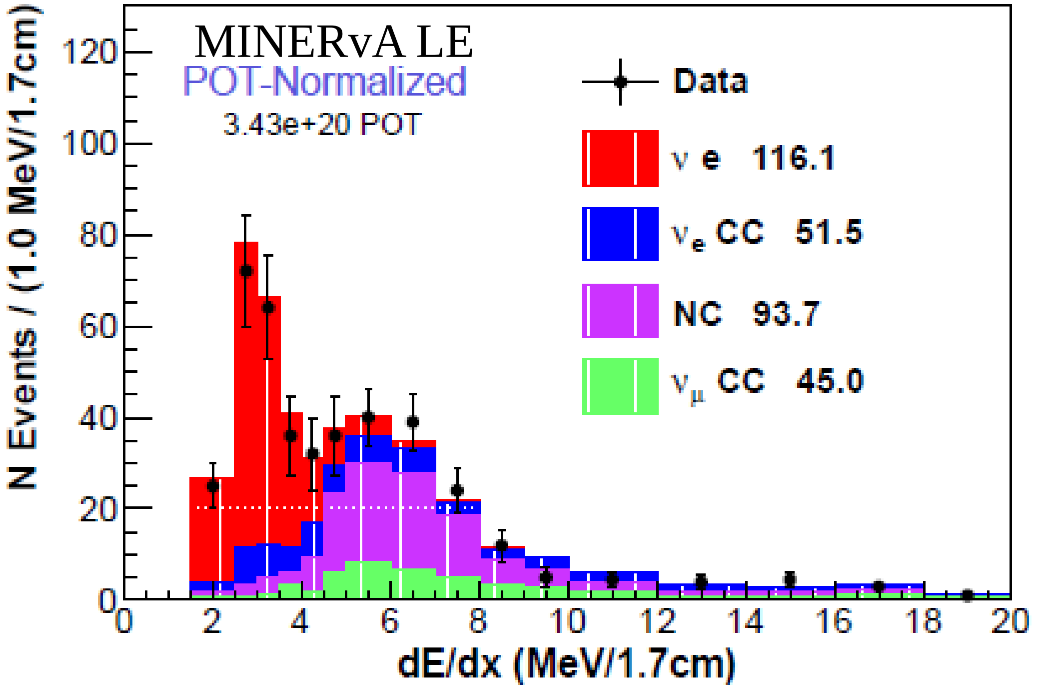
- First bin of MINERvA ν+e sideband will have ~2000 events in DUNE LAr in 3 years
- Can measure shape directly in ν_e, in addition to using ν_μ CCQE events to go down to signal region
- Limitation: lepton mass becomes important in signal region, shape below minimum Q^2 for ν_μ CC can't be measured

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





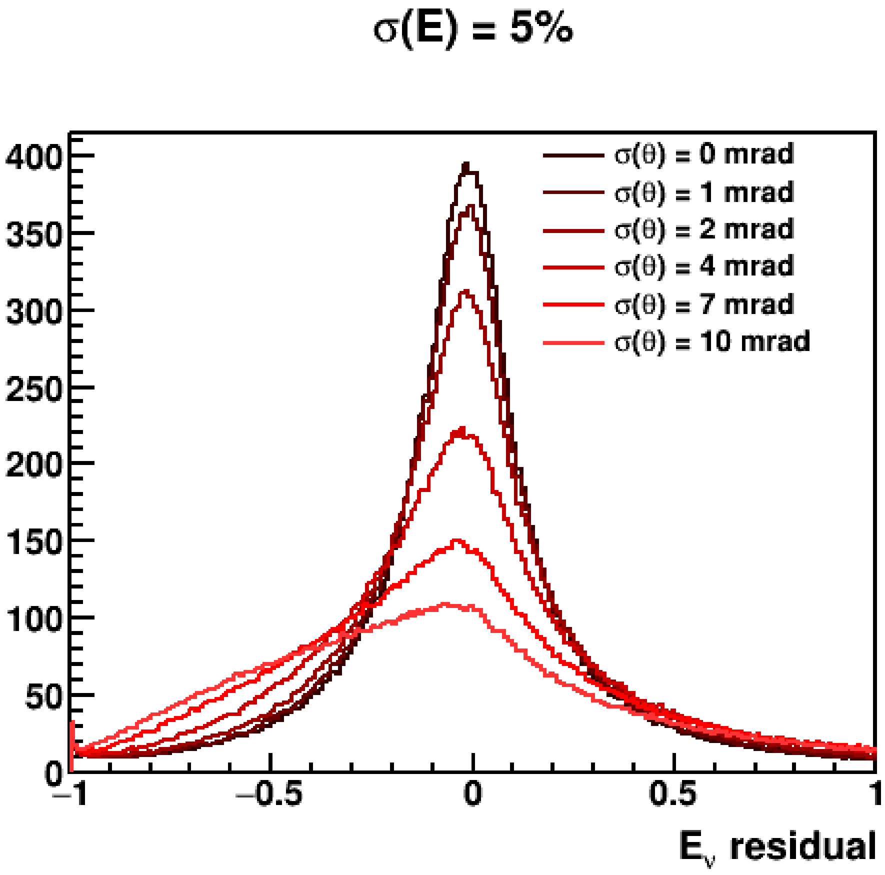
- $E\theta^2$ sideband with reversal of dE/dx cut will have huge statistics
- Unlike ν_e CC, we aren't going to $Q^2 \rightarrow 0$, as these events are typically asymmetric π^0 decays where one photon happens to point in beam direction
- “0 is not special”
- No reason to expect shape in this variable, 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 MINERνA
- LAr alone can adequately measure ν+e rate
  - Complementary STT measurement is beneficial but not required

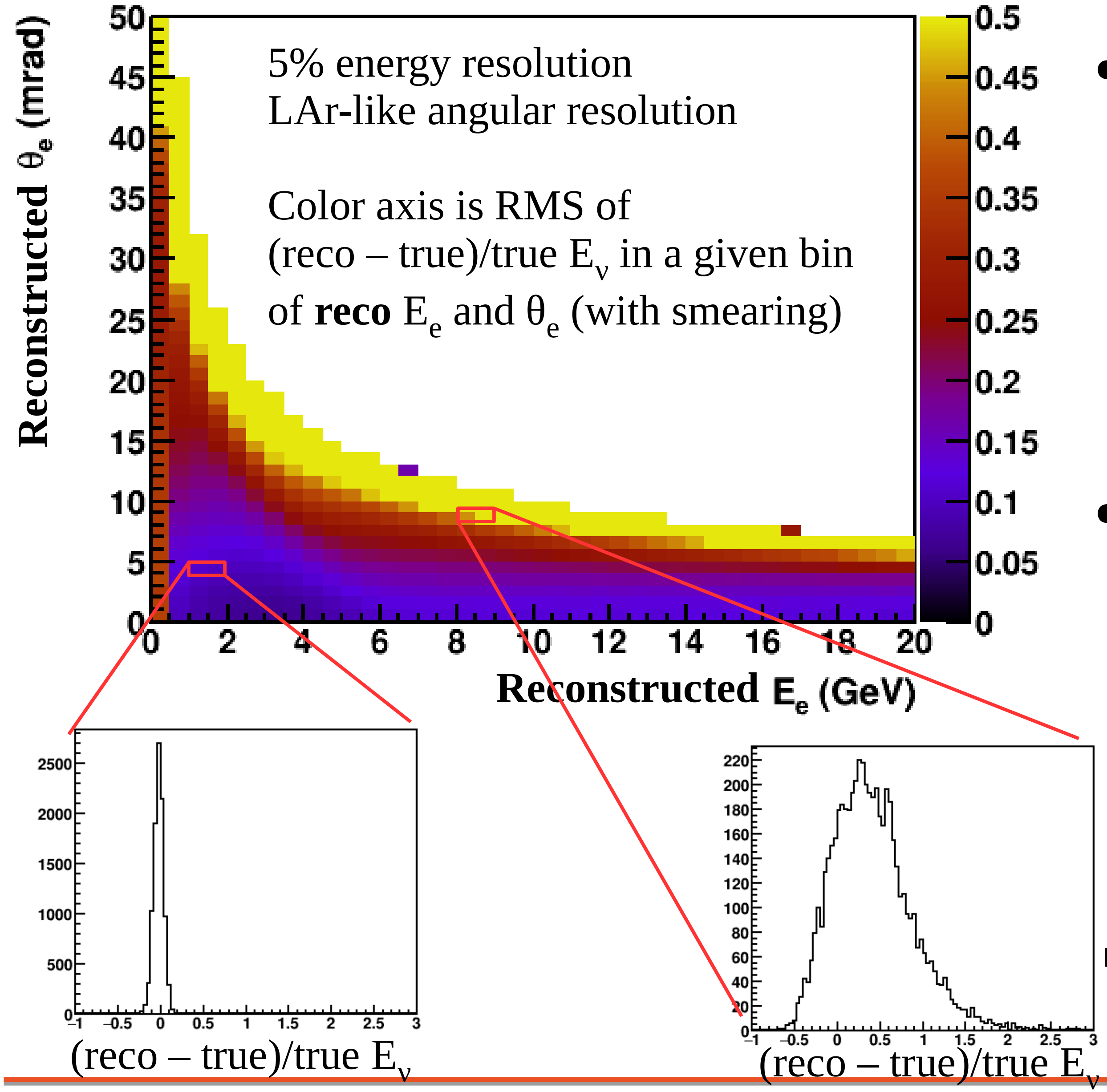
Direct neutrino energy measurement

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



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

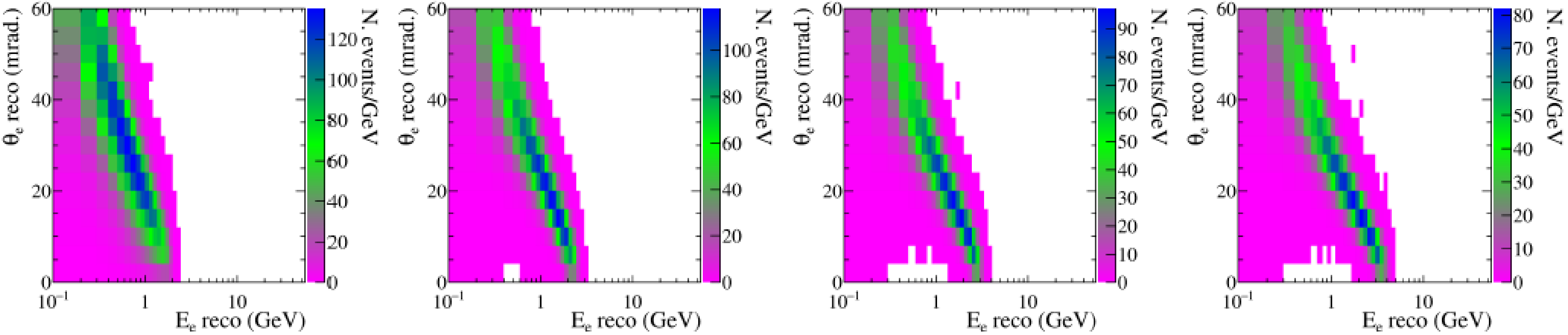
E_ν resolution vs. (E_e, θ_e)


5% energy resolution
LAr-like angular resolution

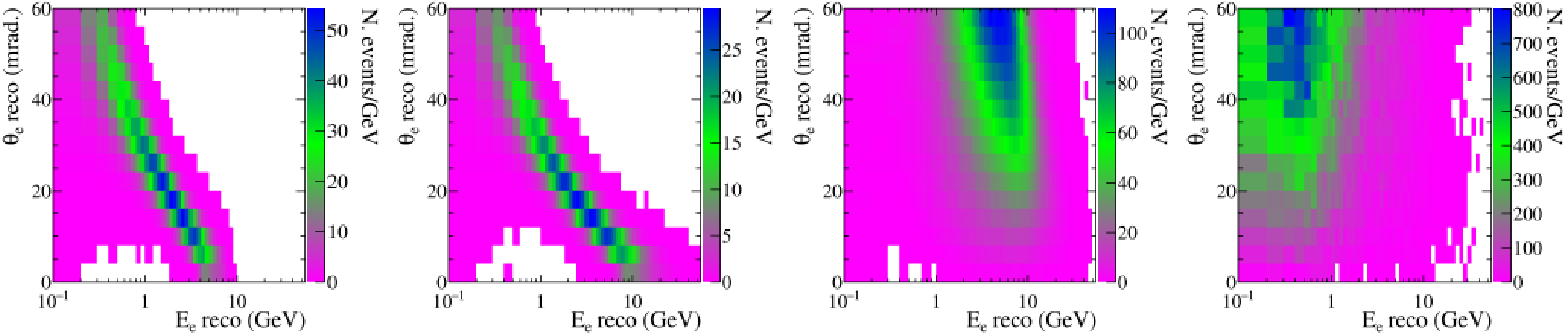
Color axis is RMS of
(reco – true)/true E_ν in a given bin
of **reco** E_e and θ_e (with smearing)

- 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



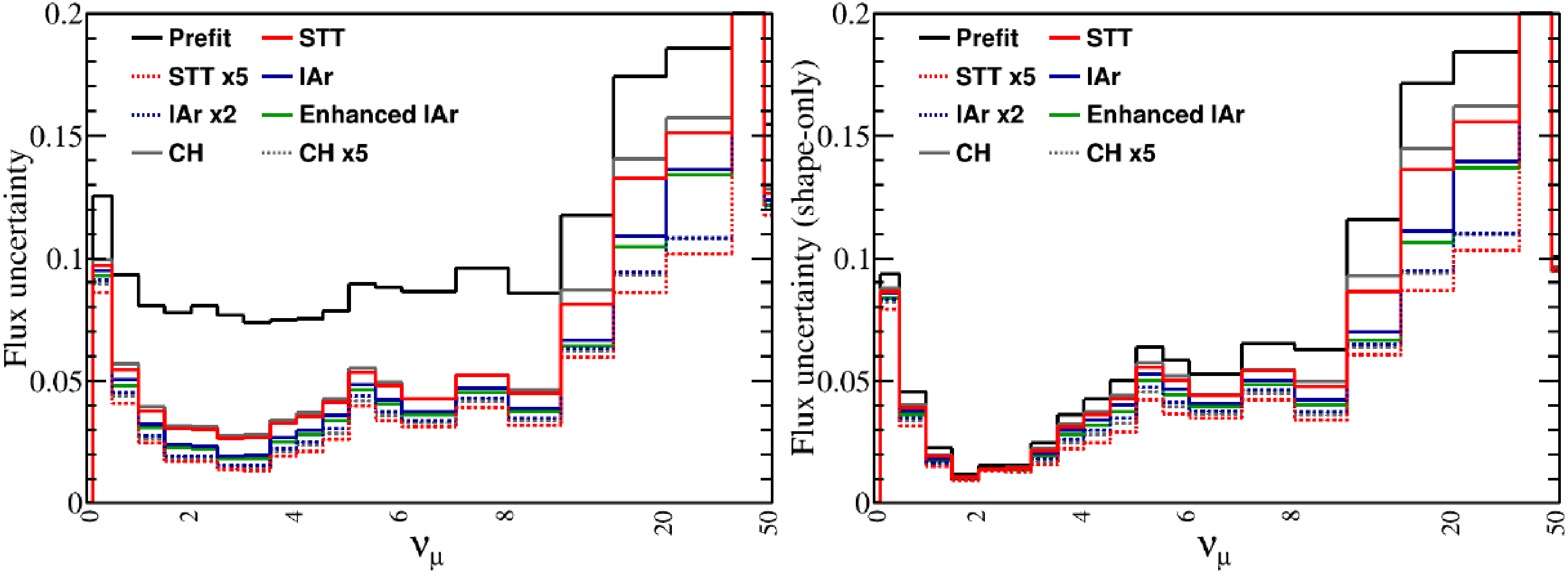
E_1 (0–2 GeV) E_2 (2–2.625 GeV) E_3 (2.625–3.25 GeV) E_4 (3.25–4.25 GeV)



E_5 (4.25–8 GeV) E_6 (>8 GeV) ν_e γ

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

Results for different ND options

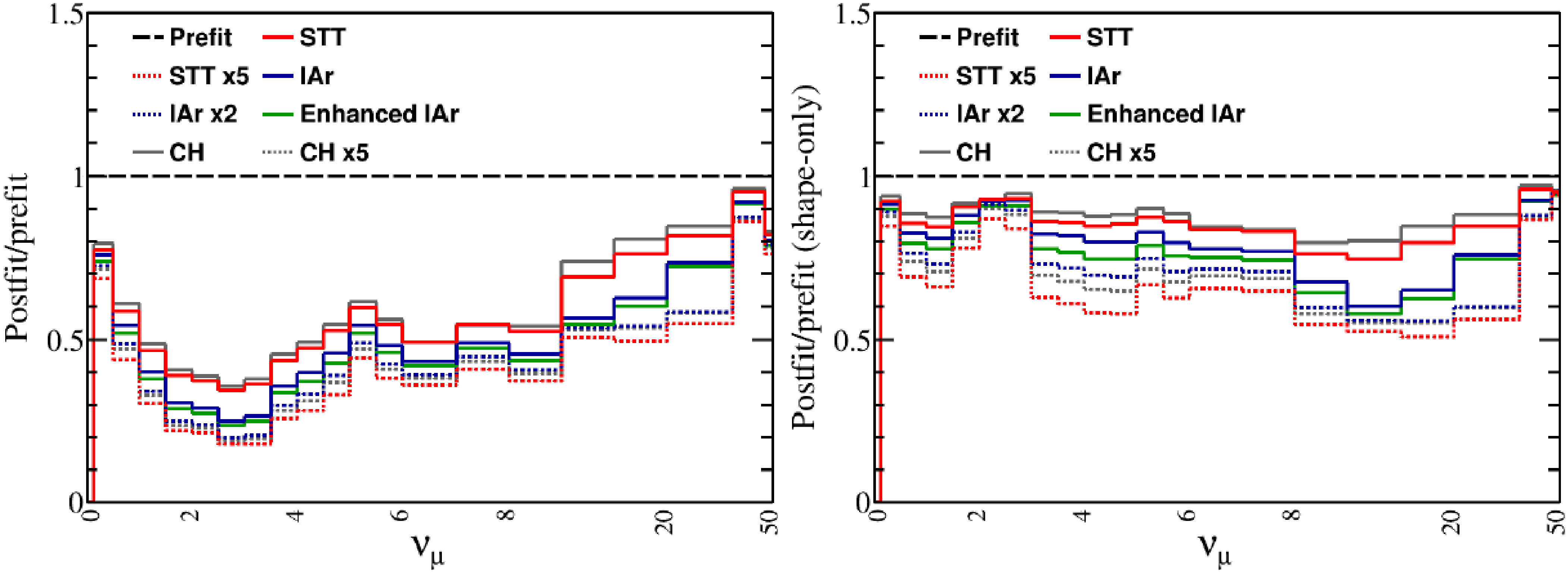


Rate+shape

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

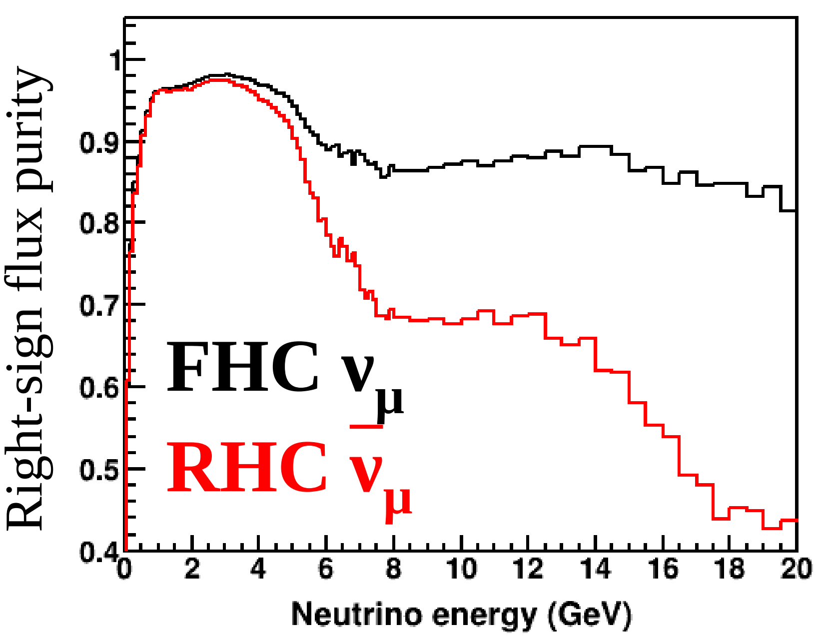
Shape-only

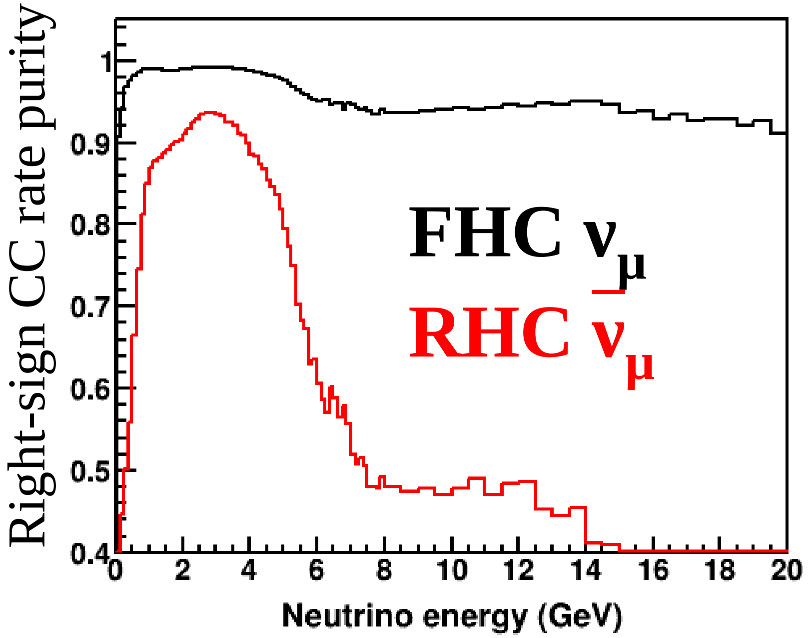
- As expected, ν+e constraint reduces flux uncertainty
- Shape uncertainties are quite small pre-fit, and improvement is modest
- LAr statistics give more power than improved resolutions from lower-mass detectors

Sign selection of muons from LAr interactions

- Plan to build non-magnetized LAr TPC at near site
- Charge will be reconstructed only for muons that exit LAr TPC and enter a magnetized detector
  - Downstream multi-purpose tracker
  - Magnetized side muon detector?
- Questions:
  - What is the wrong-sign contamination in RHC for contained muons?
  - For side-exiting muons? Must the side muon detector be magnetized?
  - What fraction of the RHC events are contained, side-exiting, etc.?

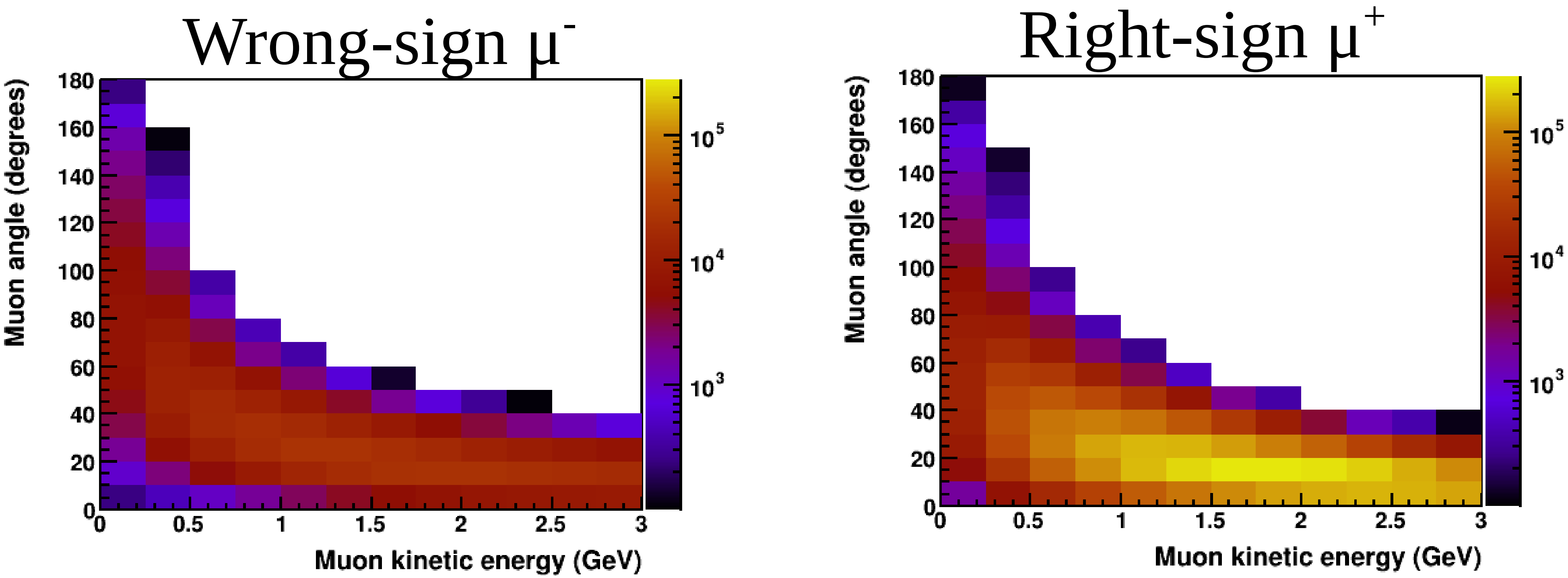
Flux purity
80GeV 3-horn optimized beam





- FHC and RHC fluxes are of similar purity in the focusing peak, but RHC purity becomes poor above ~6 GeV
- Higher CC cross section makes wrong-sign background less problematic for FHC, and more problematic for RHC
- $\bar{\nu}_\mu$ is ~1% of total FHC CC events for $E_\nu < 5$ GeV – can subtract with MC

RHC muon spectra (log z scale)



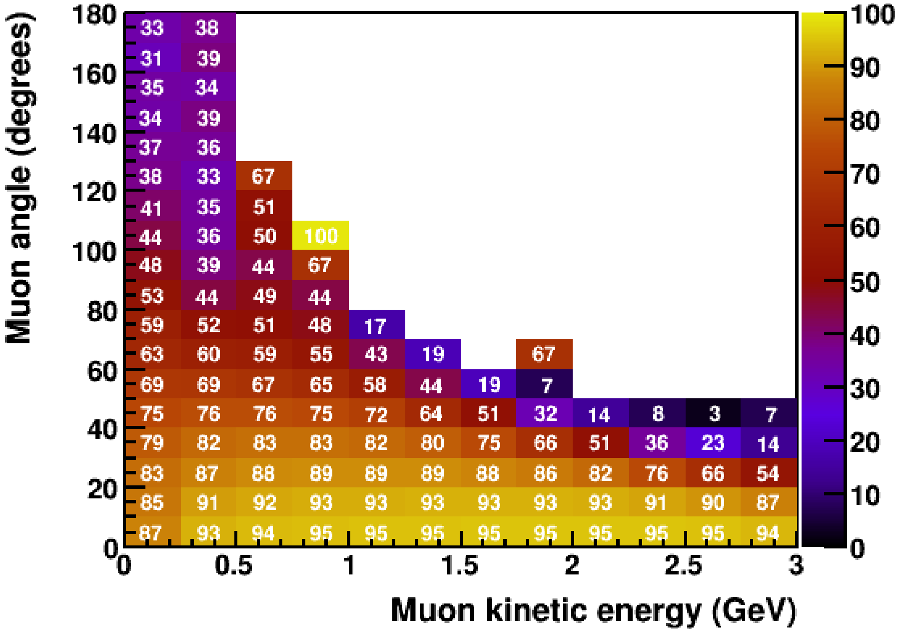
Wrong-sign μ^-

Right-sign μ^+

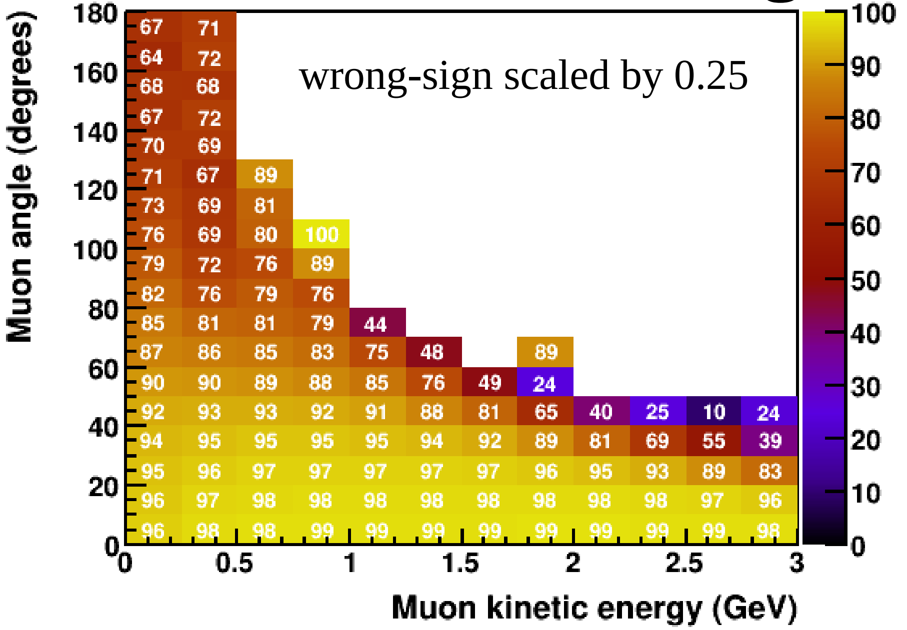
- Neutrino/antineutrino cross section is $1/(1-y)^2$, equal at $y \to 0$, which is very forward muons
- At high angles wrong-sign becomes dominant

RHC μ^+ purity (% of all CC)

All muons

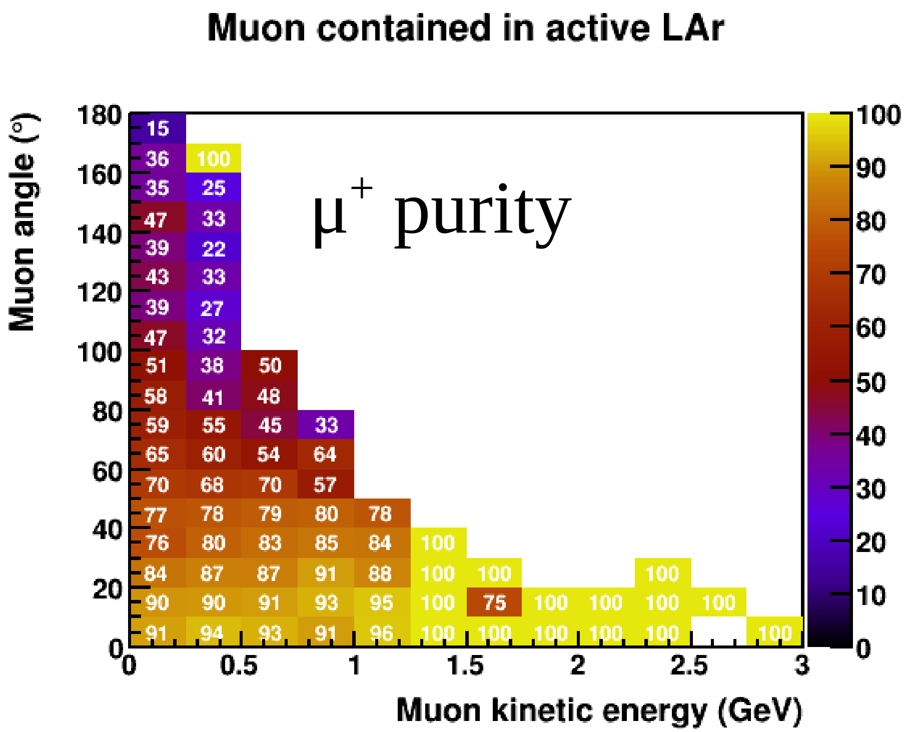


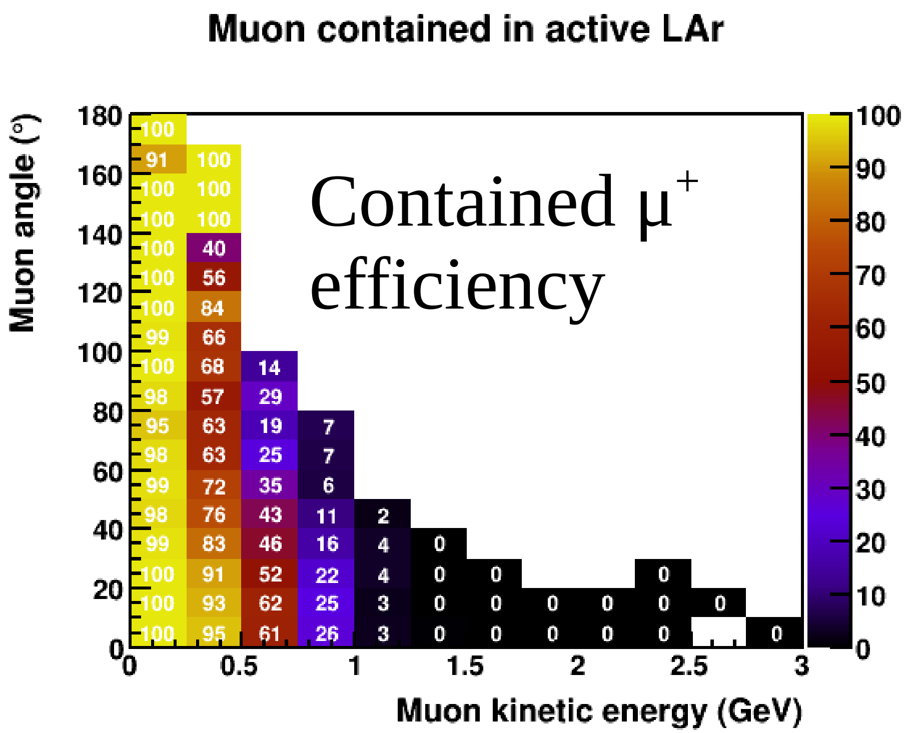
Positive Michel tag



- Out of the box, purity is ~40% for very high angles, especially backscattered muons
- Capture rate for μ^- is 75%, so the wrong-sign background can be suppressed by ~4x, with efficiency loss of Michel tagging

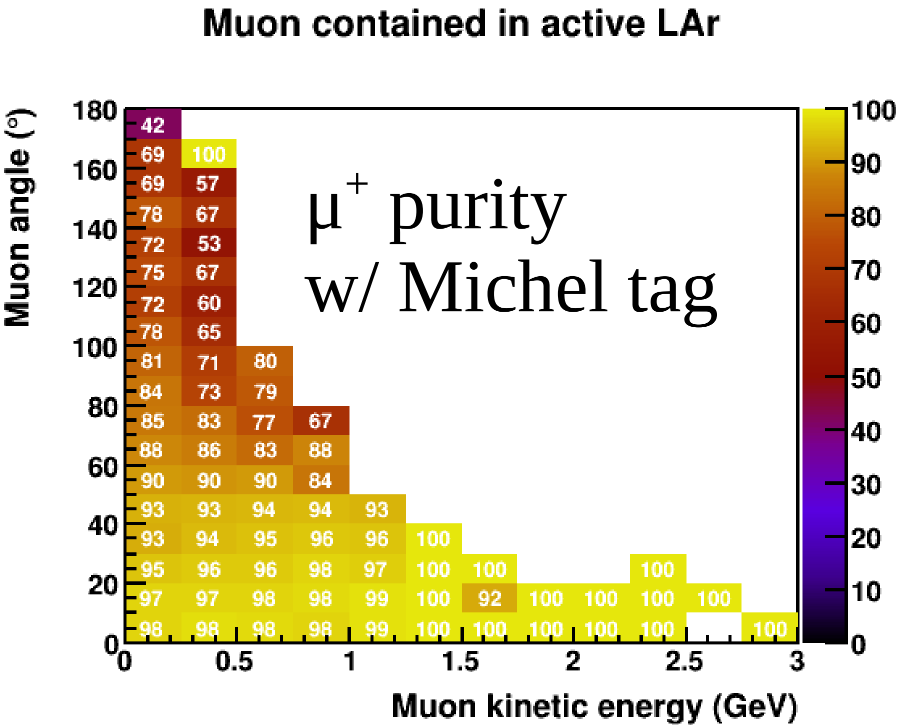
RHC contained μ⁺ purity and efficiency

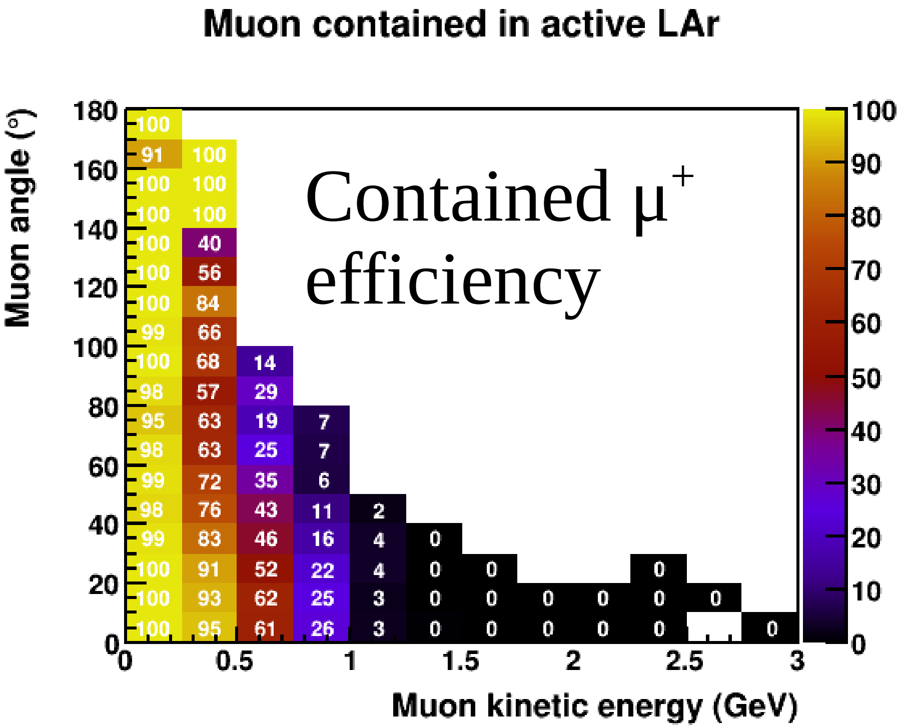




- Right plot is fraction of μ⁺ in a given bin that are contained
- Left plot is fraction of all contained muons in a given bin that are μ⁺
- Purity bad above ~20 degrees muon angle

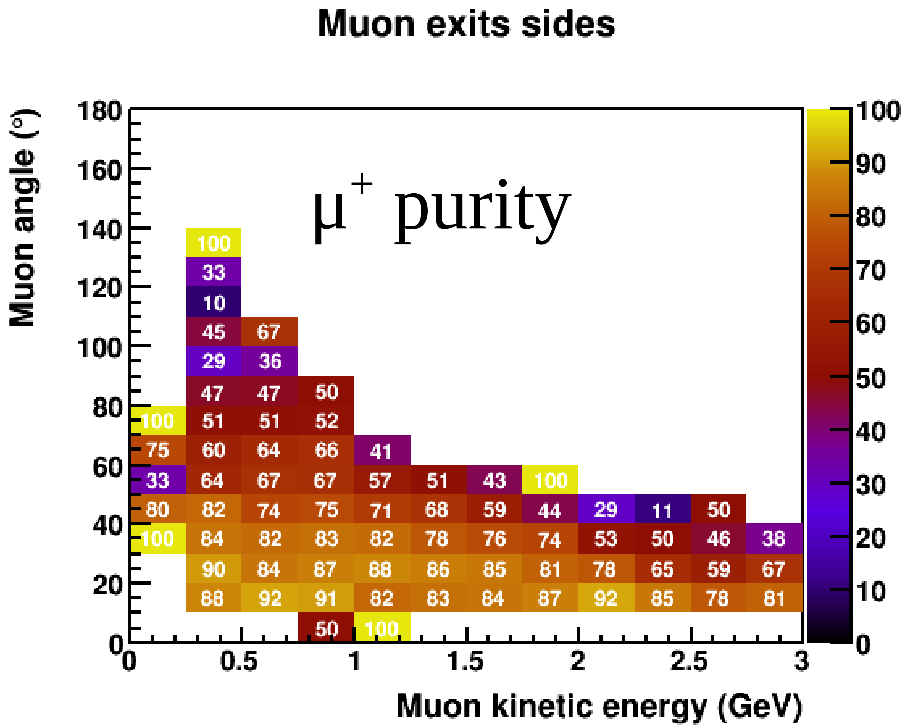
RHC contained μ^+ purity and efficiency with Michel tag

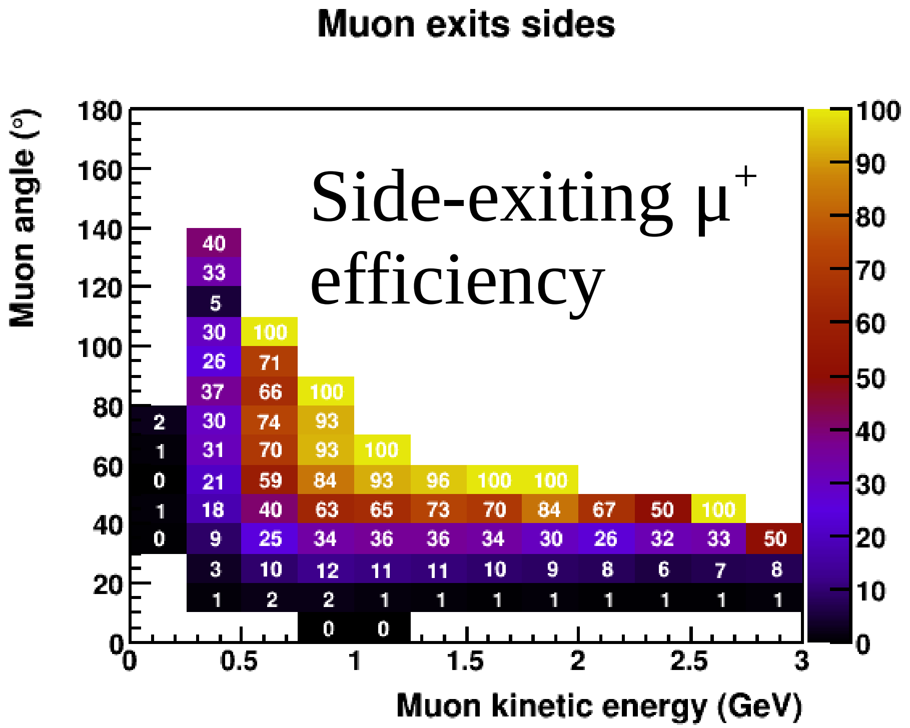




- Right plot is fraction of μ^+ in a given bin that are contained
- Left plot is fraction of all contained muons in a given bin that are μ^+
- Michel tag improves purity for contained muons to ~70% at high angles, >90% up to ~60 degrees

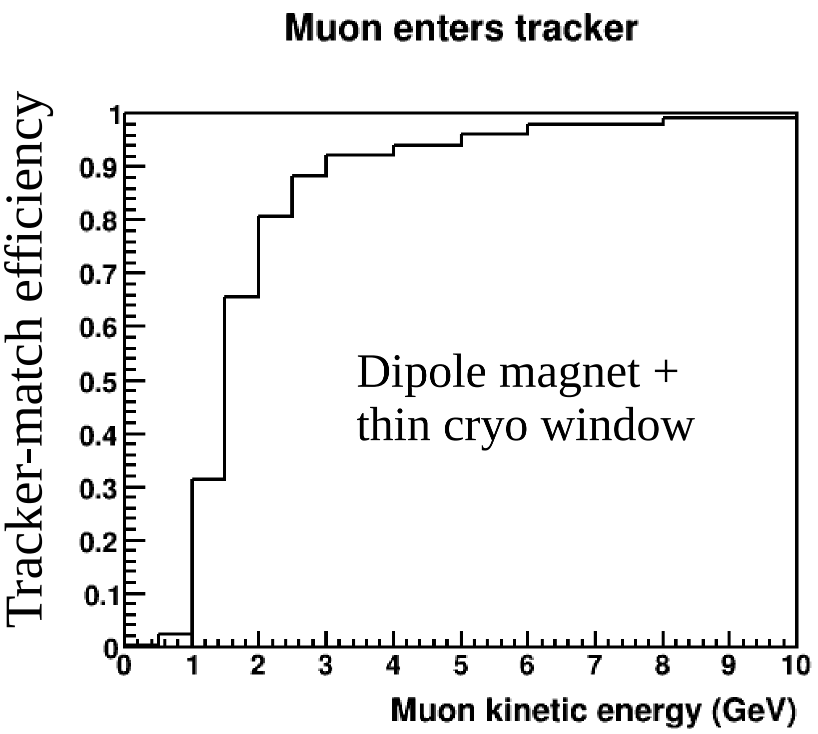
RHC side-exiting μ^+ purity and efficiency



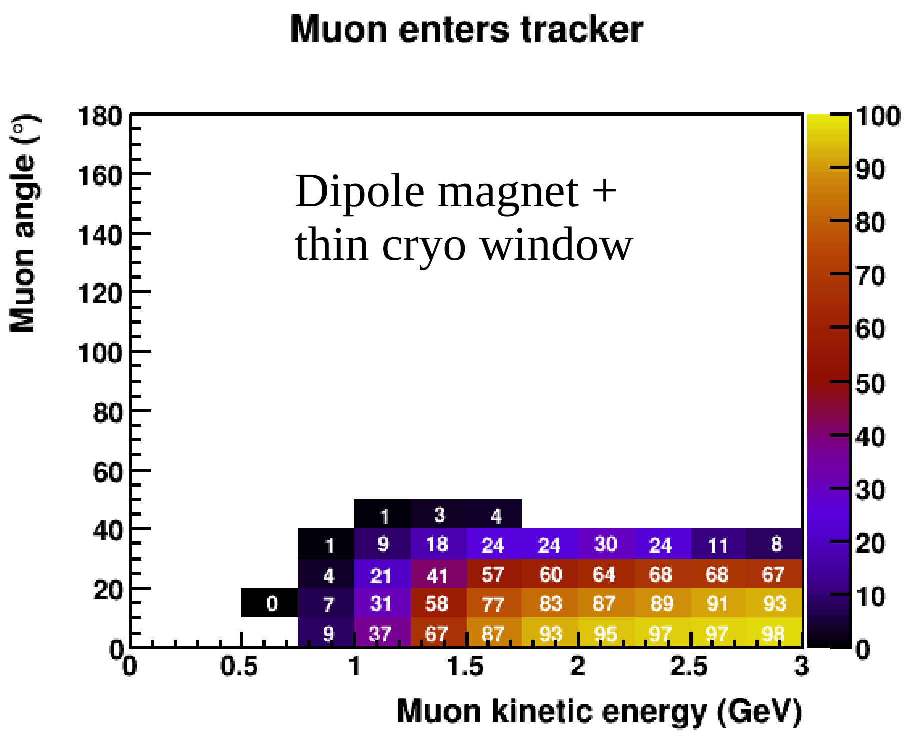


- In kinematic region where side-exiting muons are critically important, purity is only ~50% (would be ~80% if you had Michel tag but no curvature)
- These would be LAr-contained for ~7m wide active region

RHC tracker-matched sample



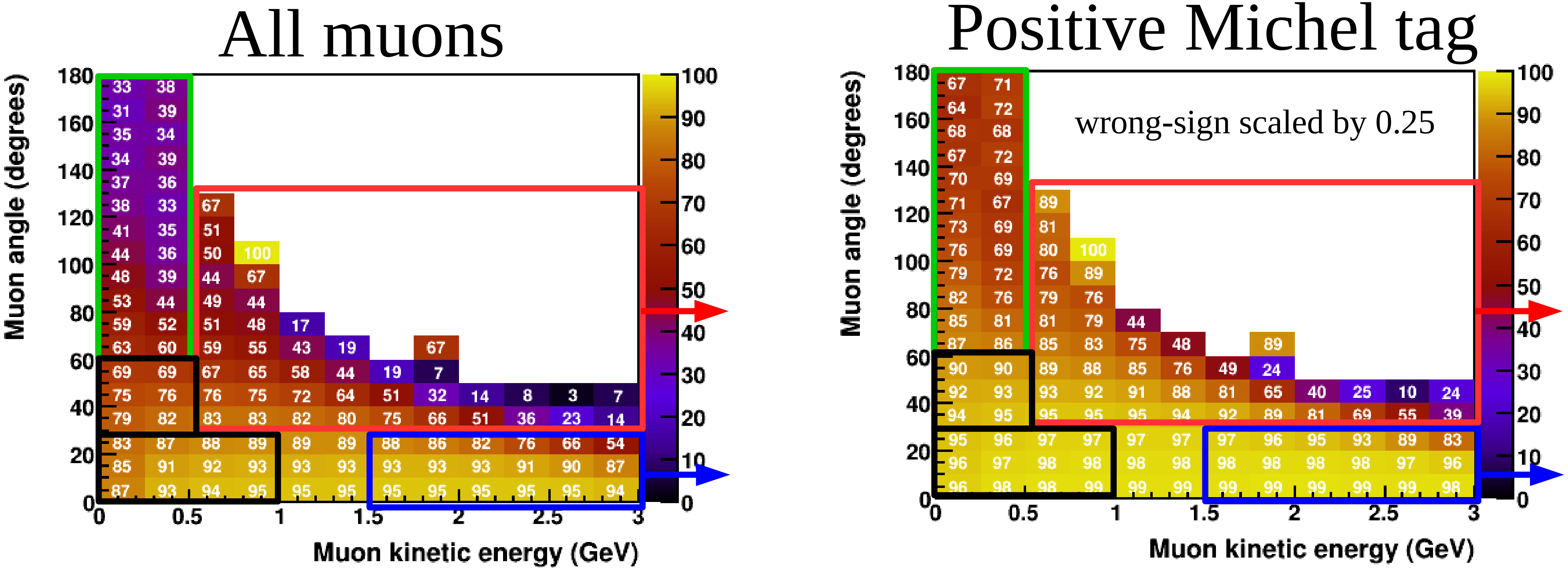
Dipole magnet +
thin cryo window



Dipole magnet +
thin cryo window

- Muons above 2 GeV will be sign-selected by curvature in MPT, but below 1.5 GeV the tracker matching is poor
- Sign purity will be ~100% from curvature in magnetic field

RHC μ^+ purity with regions & percentage of total ν_μ CC



- Divide the kinematic space into regions based on how muon is primarily reconstructed:
  - Tracker-matched region, excellent μ^+ purity and momentum resolution – 62.3% of total
  - Good containment, reasonable μ^+ purity, >90% with Michel tag – 11.8% of total
  - Side-exiting region, poor μ^+ purity ~50% out of the box and ~80% with Michel tag – 9.0% of total
  - Good containment, poor μ^+ purity, only ~40% out of the box and ~70% with Michel tag – 1.4% of total
  - Dipole coil region, good μ^+ purity, also tracker-matched for downstream vertices – 15.3% of total

Summary

- ~60% of RHC $\bar{\nu}_\mu$ CC events will be tracker-matched with good sign selection
- ~15% will be contained, 90% of which can be selected with high purity >90% – NC is likely the bigger background
- ~15% are in the “in between” region, a mix of contained, tracker-matched, and coil-death muons
- ~10% are reconstructed only with side detector (same region is 21% for FHC ν_μ CC), and would have poor purity without magnetized side detector