Neutron reconstruction from TOF in MPD ECAL

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DESY ND workshop
22 October, 2019

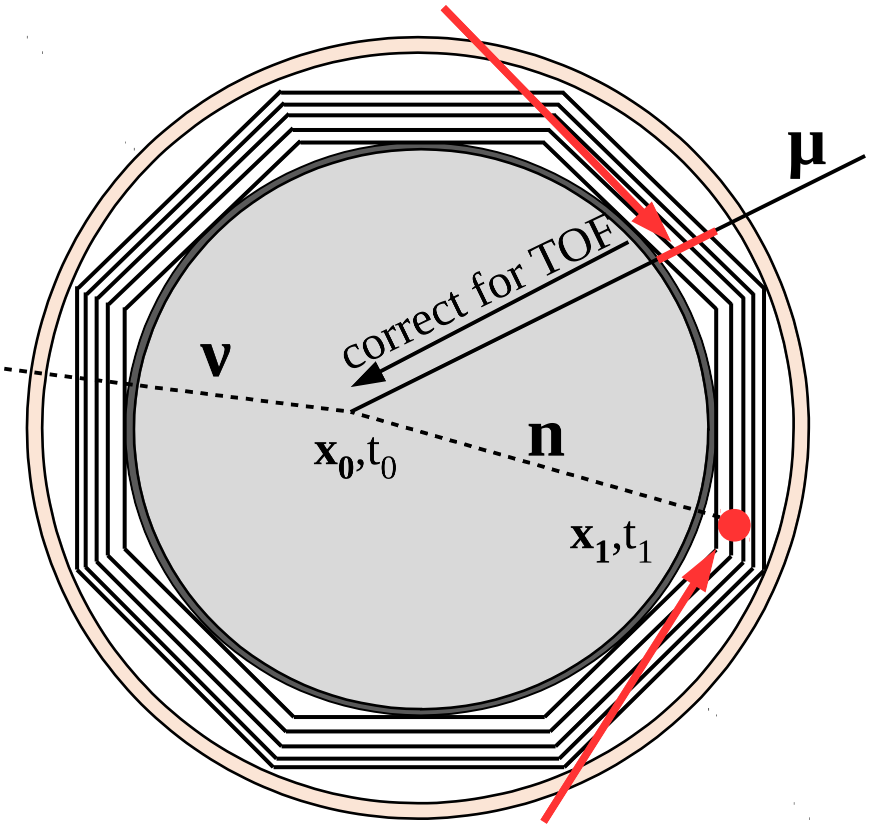
Motivation

- Neutron kinetic energy is generally not visible in LAr TPCs
  - Small (~20%) fraction of neutron KE shows up in detector via neutron re-interactions
- Neutrons in the 10s to 100s MeV are a significant source of neutrino energy misreconstruction
- Neutron production in ν-Ar scattering is highly uncertain

→ Measuring neutron energy spectrum in ND could constrain our missing energy corrections at FD

Reminder: basic premise

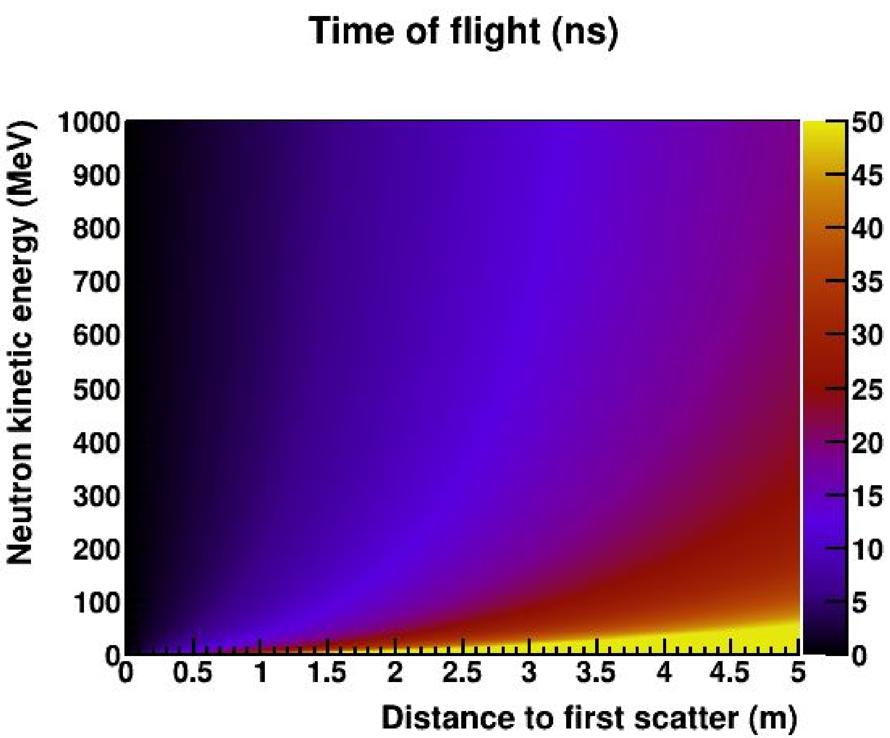
Measure interaction vertex time from muon hits in ECAL

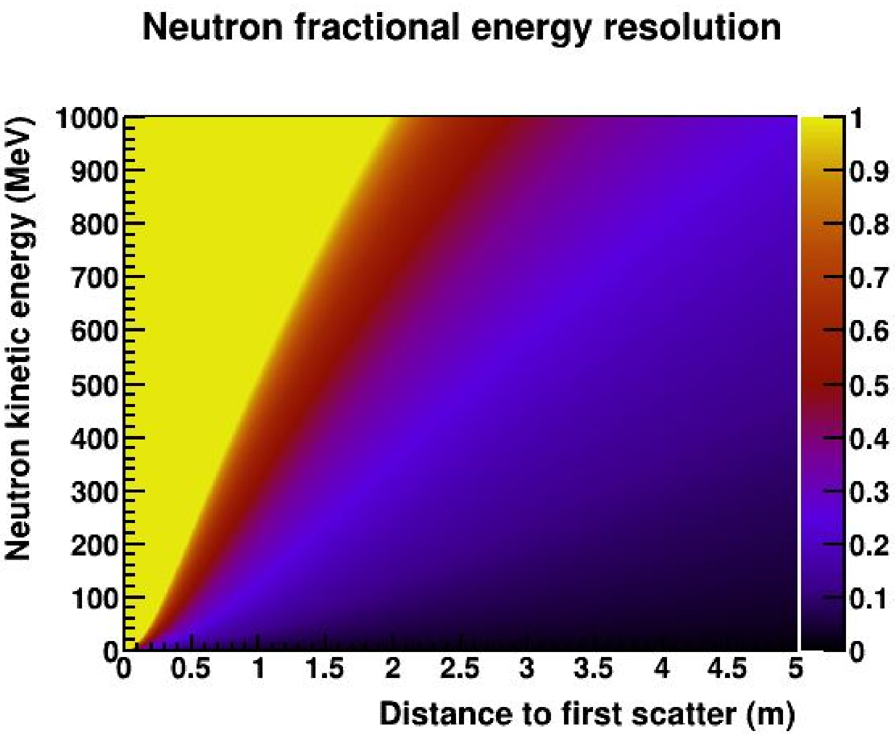


Measure neutron "endpoint" from scatter, i.e. $n + {}^{12}C \rightarrow p + X$

- Assuming neutron comes from primary vertex, start and end positions are measured
- Vertex time comes from charged particle hits in ECAL, correcting for TOF back to vertex
- Use neutron TOF to determine its momentum
- This works in any detector with fast timing and 3D position reconstruction, i.e. MPD ECAL or 3DST

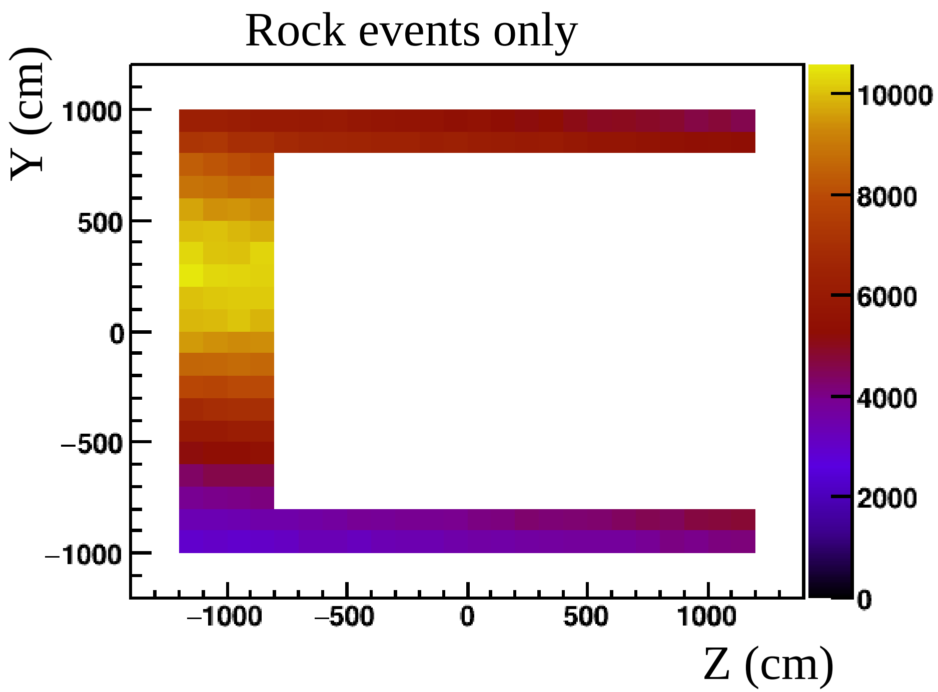
Simulation details

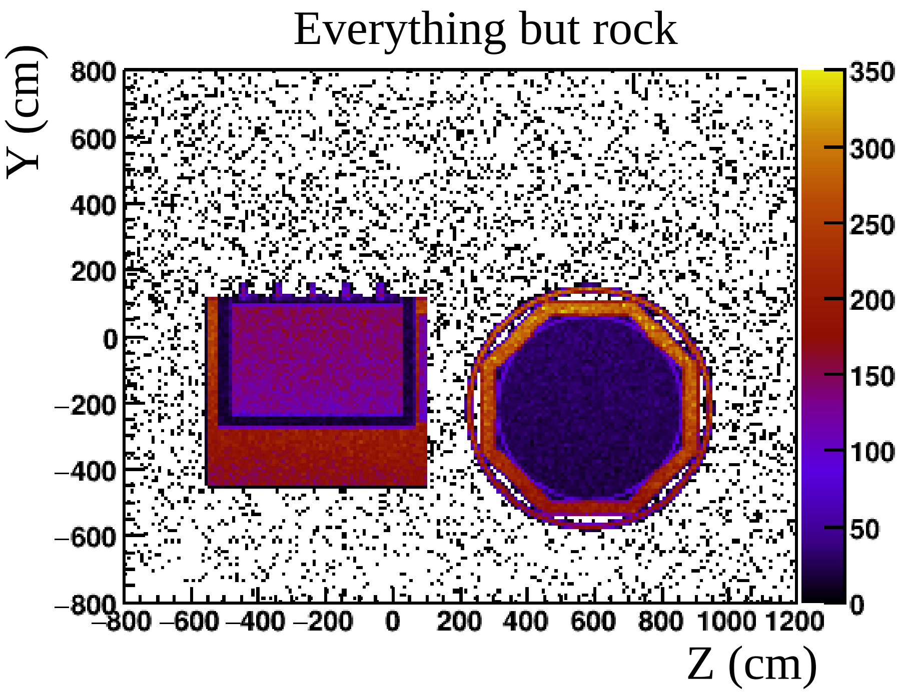




- Left: time of flight as a function of true neutron kinetic energy and lever arm
- Right: Expected neutron fractional kinetic energy resolution for 0.7ns timing resolution

Simulation details





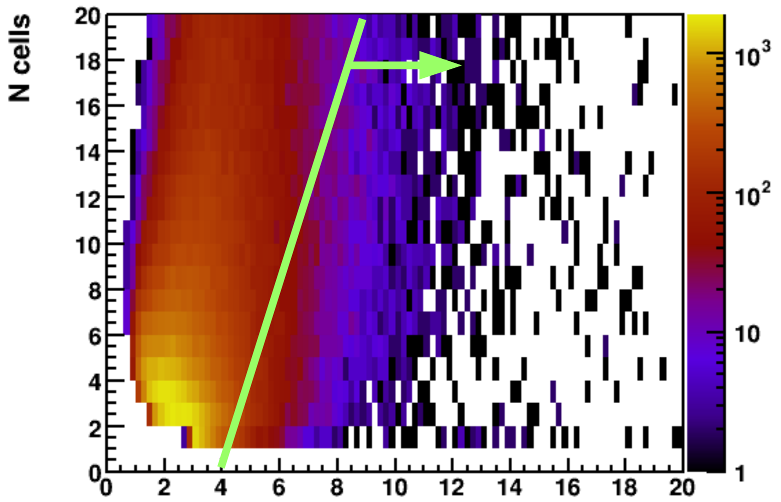
- Detector hall consists of rock, LAr TPC, Gas TPC + ~300t ECAL + 100t cylindrical magnet (geometry created by Eldwain with NDGGD)
- Includes >6kt of rock, which is enough to ensure that neutron and photon rock backgrounds are correct (see backups)

Signal and background

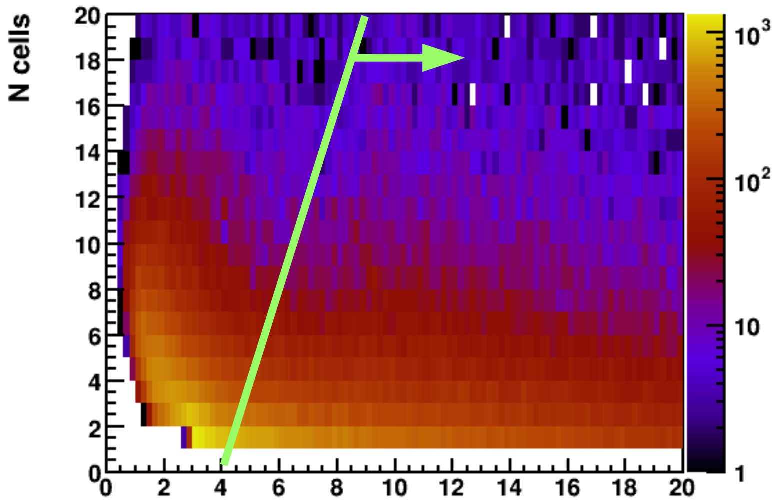
- Signal is ν_μ CC interaction in gas TPC, with a fiducial volume >50cm from the edge of the active region
- Overlay background events ±1μs from signal, and reconstruct entire spill, with hit timing resolution in the ECAL of ±0.7 ns
- 770 rock and 120 detector hall ν interactions per spill at 1.2 MW FHC, simulated separately nd overlaid
- 380 rock and 60 hall interactions at 1.2MW RHC

Reconstruction

- Voxylize ECAL energy deposits in active plastic, into 2x2cm² squares in the transverse plane (5mm layers)
- Cluster energy deposits by looking for hit voxyls that are spatially isolated (>5cm) from other hit voxyls, with at least 3 MeV visible energy per cluster

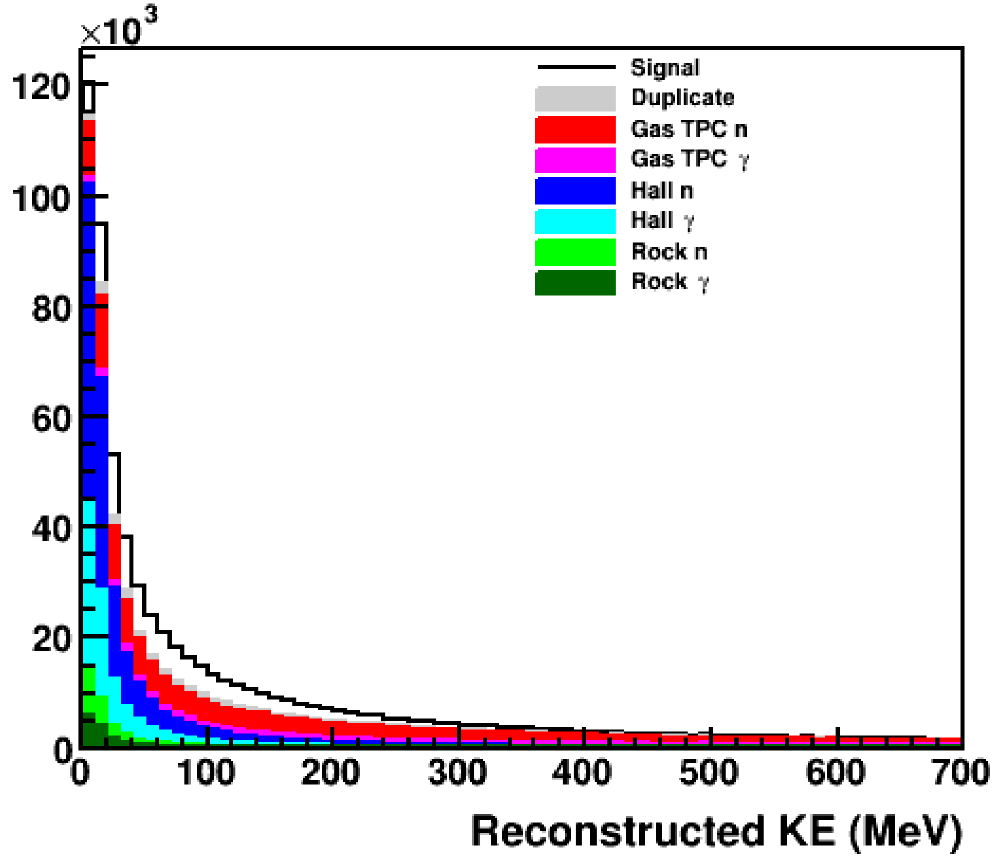


Photon-induced



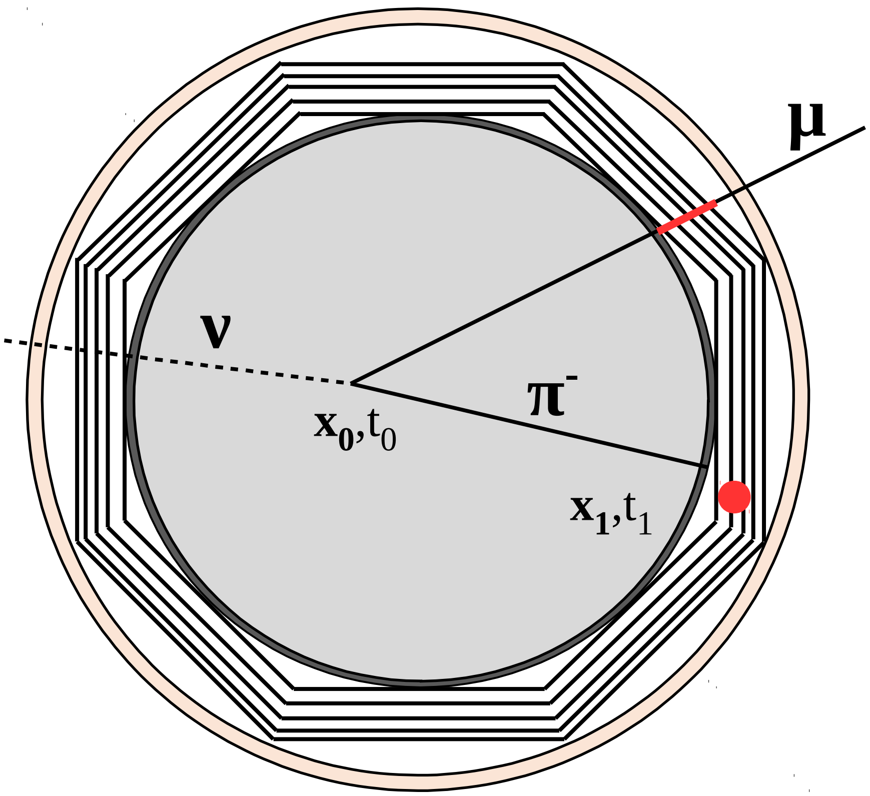
Neutron-induced

Out of the box RHC (no cuts)



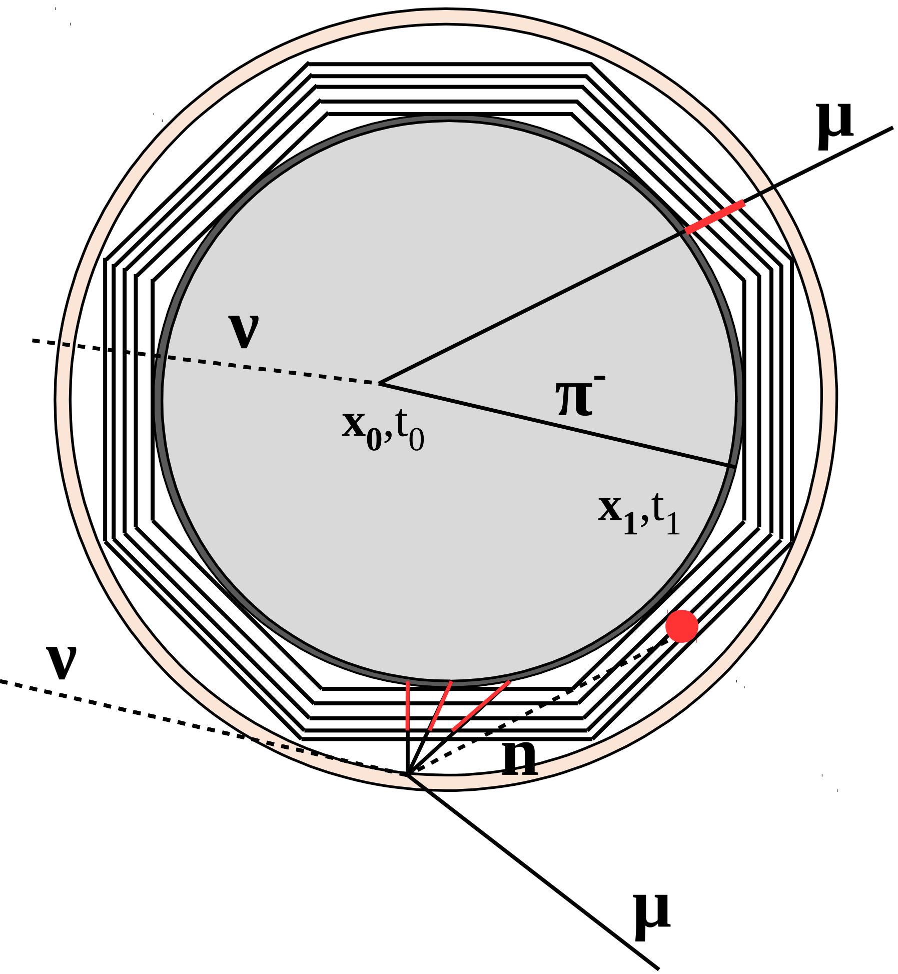
- Backgrounds are due to correlated (produced by signal neutrino interaction), and uncorrelated (produced by some other neutrino interaction that happens to be in-time) activity
- At low reconstructed energy, TOF → ∞, so the window for accidental background becomes long
- At high reconstructed energy, TOF → d/c, and backgrounds descended from $\pi^{\pm}$ dominate

Correlated backgrounds



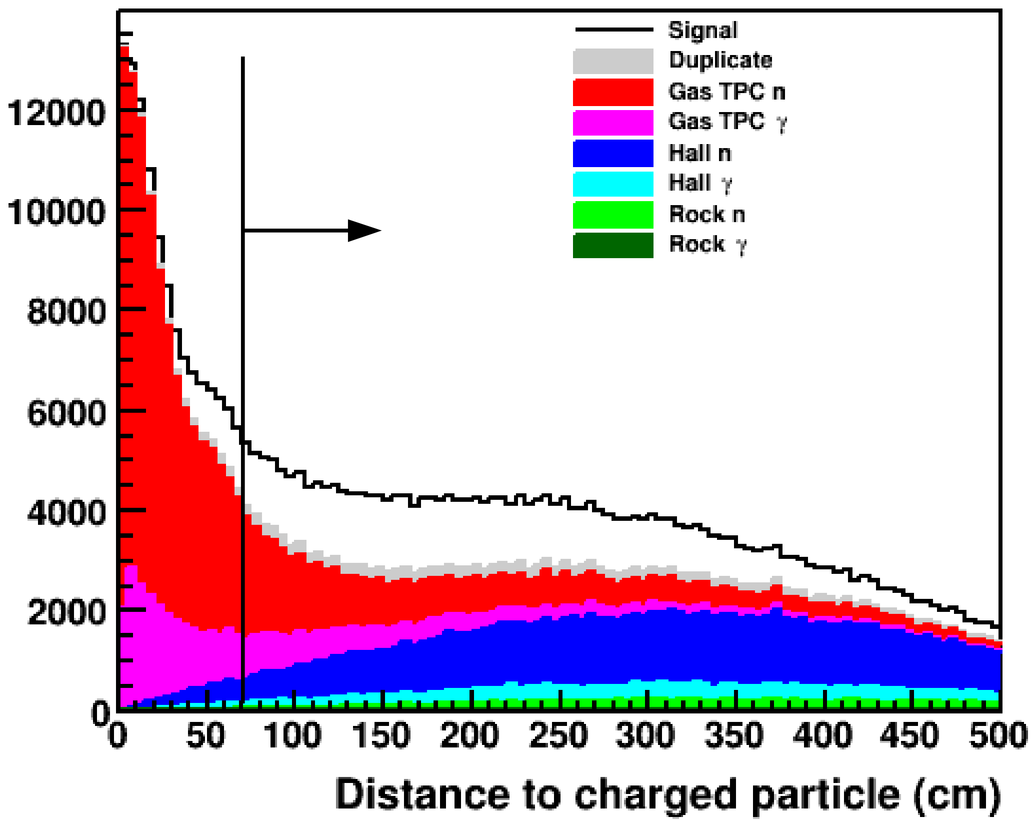
- Mostly due to charged pions produced in a gas TPC neutrino interaction that exit the gas, scatter, and knock out a neutron
- Neutron travels some distance in the ECAL, and scatters
- Cluster position can be correlated with charged track direction exiting HPgTPC

Uncorrelated backgrounds



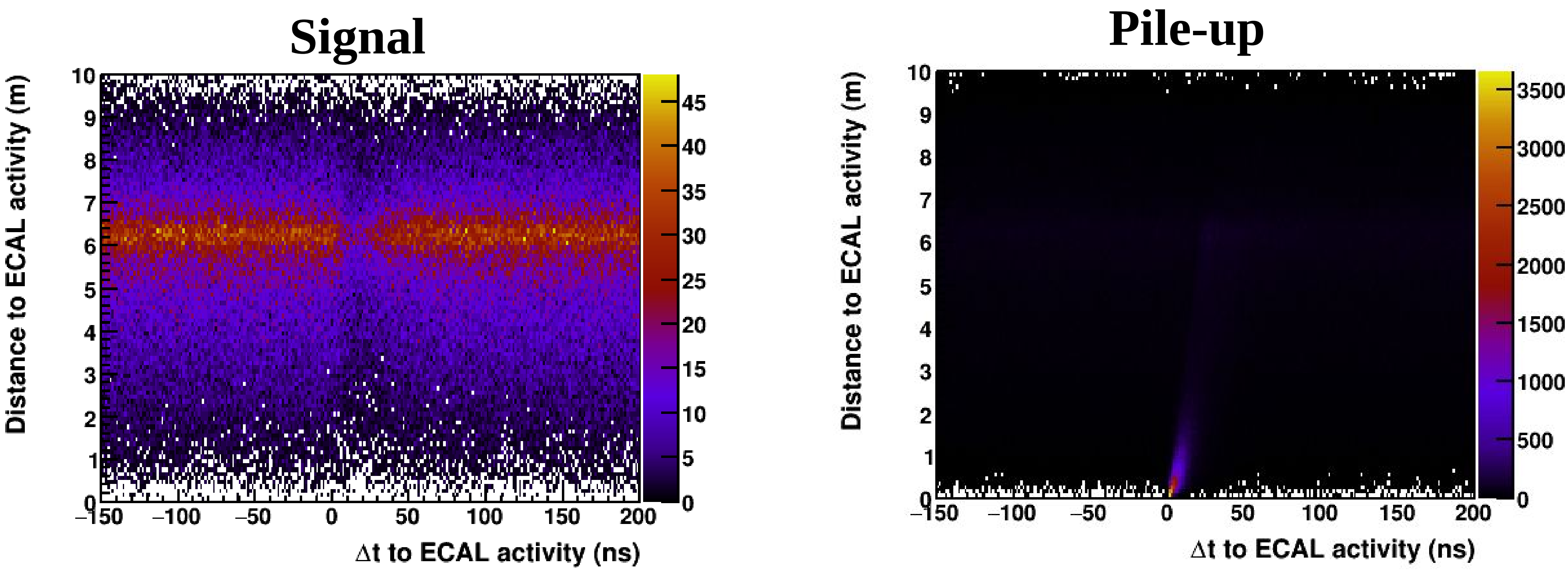
- Mostly due to in-time neutrino interactions in the ECAL itself, or in the magnet (as illustrated)
- Neutron enters ECAL, and scatters
- Cluster time can be correlated with other in-time activity in the ECAL

Distance to charged track cut



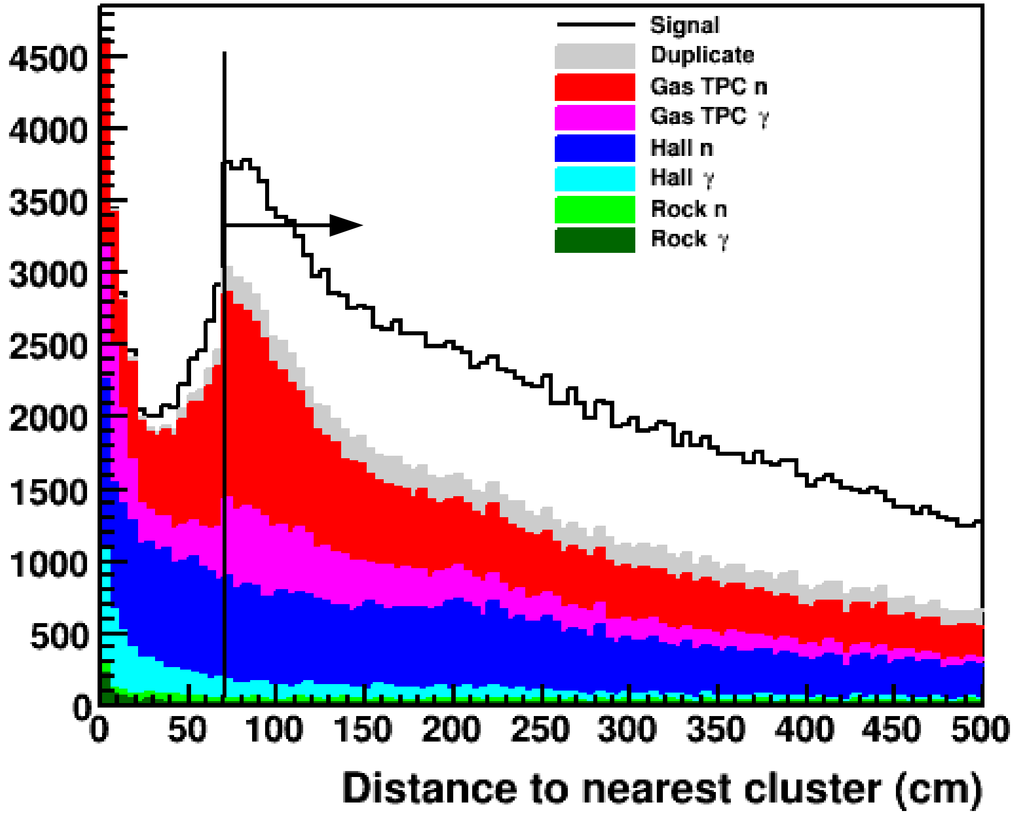
- Draw a straight line from each TPC charged track, and determine distance of closest approach to neutron candidate
- Correlated backgrounds are generally close to charged track vectors

Distance and Δt to ECAL veto cut



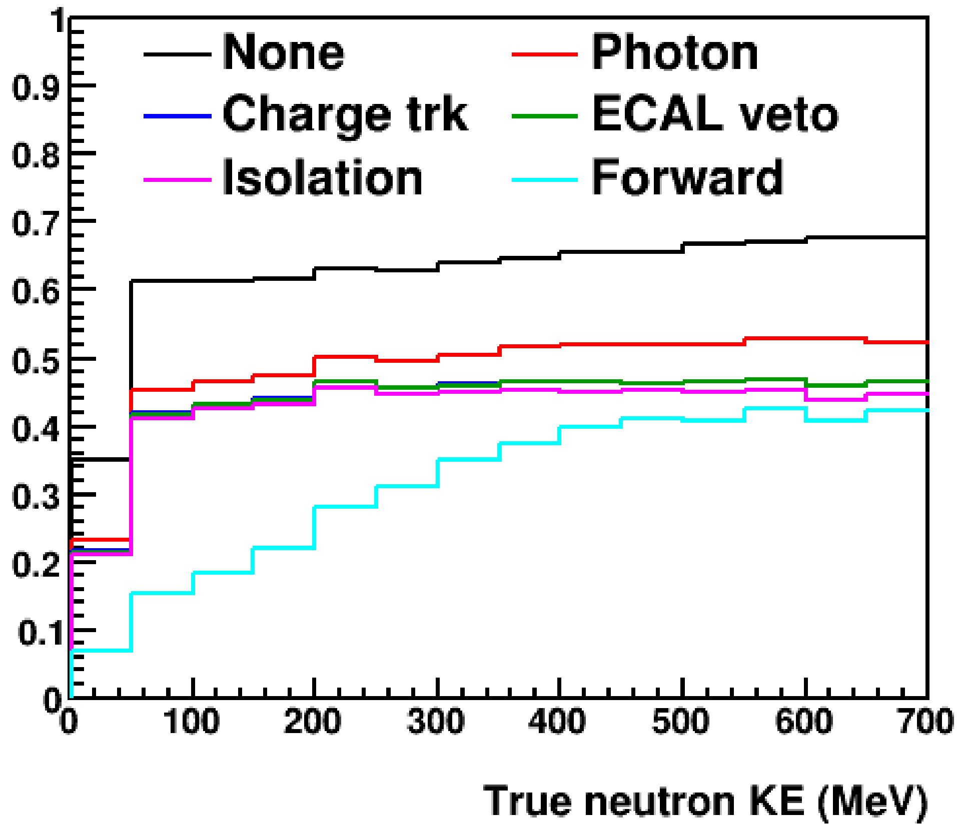
- Signal is flat in Δt to random ECAL activity, peak around 6m is because most pile-up is upstream-entering, and most signal neutrons are downstream, and thus ~6m apart
- Background is generally close in time and space to other ECAL activity and can be vetoed with almost no signal loss

Cluster isolation cut



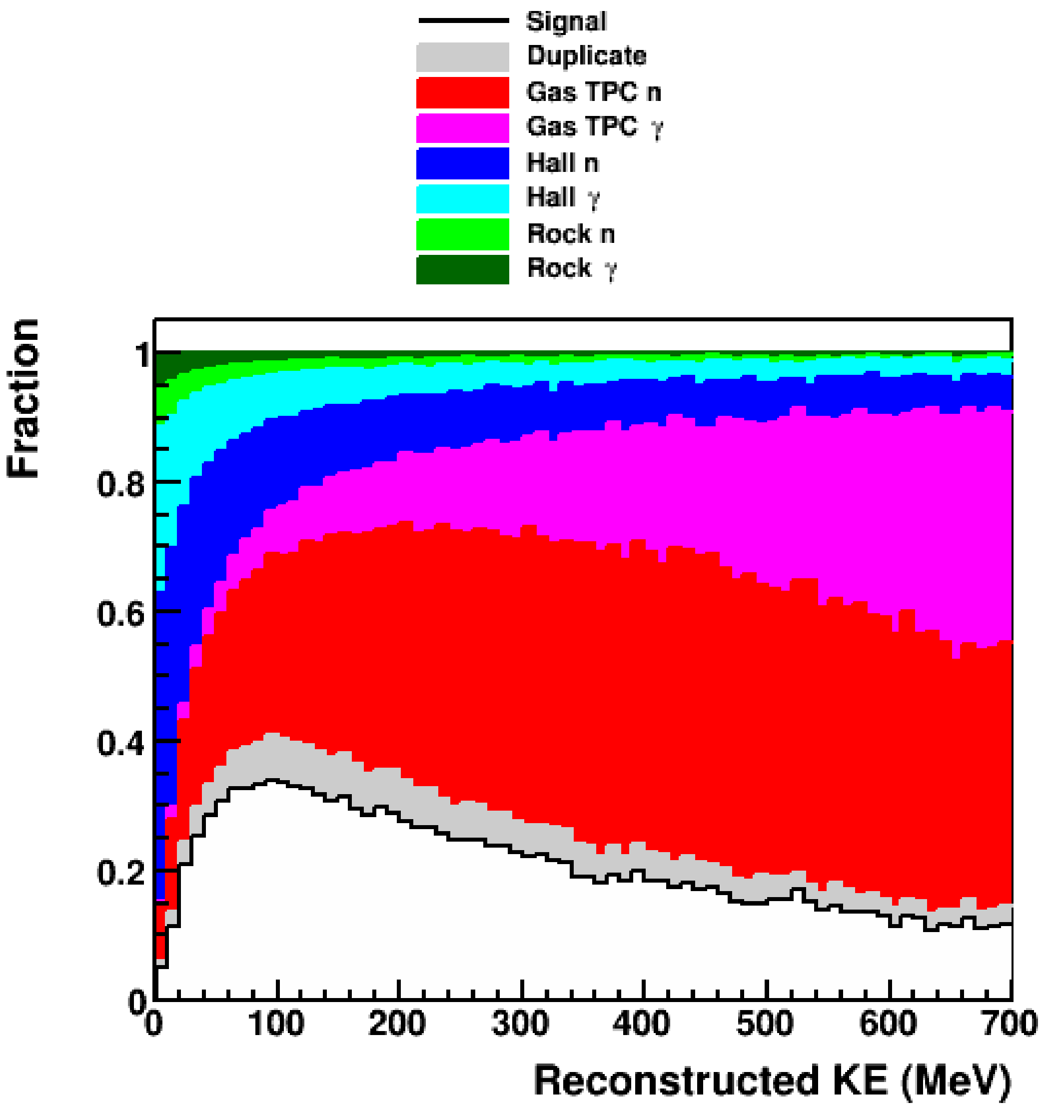
- Neutrons typically scatter multiple times
- For signal, these scatters are along the direction from the vertex to the first scatter
- For backgrounds, they are not, so cut on other clusters
- Highly correlated with charged track cut, hence the shape

Selection efficiency



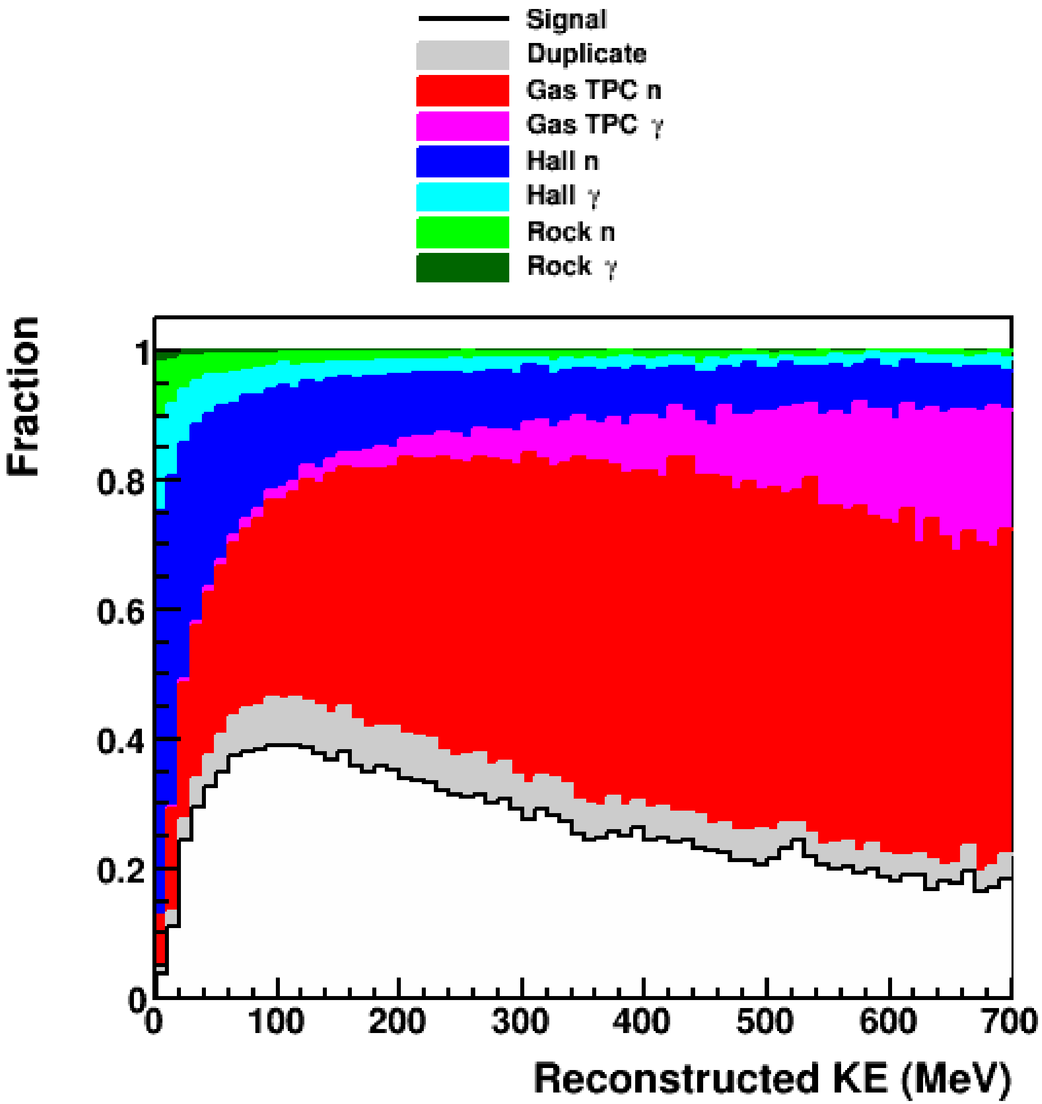
- Selection efficiency is ~40% with all cuts applied
- Photon rejection eliminates ~20% of signal, but much of this is due to de-excitation photons, which give poor energy resolution anyway
- Other cuts are very efficient
- Optional additional restriction: consider only the forward hemisphere (further reduces many backgrounds)

Sample purity: no cuts



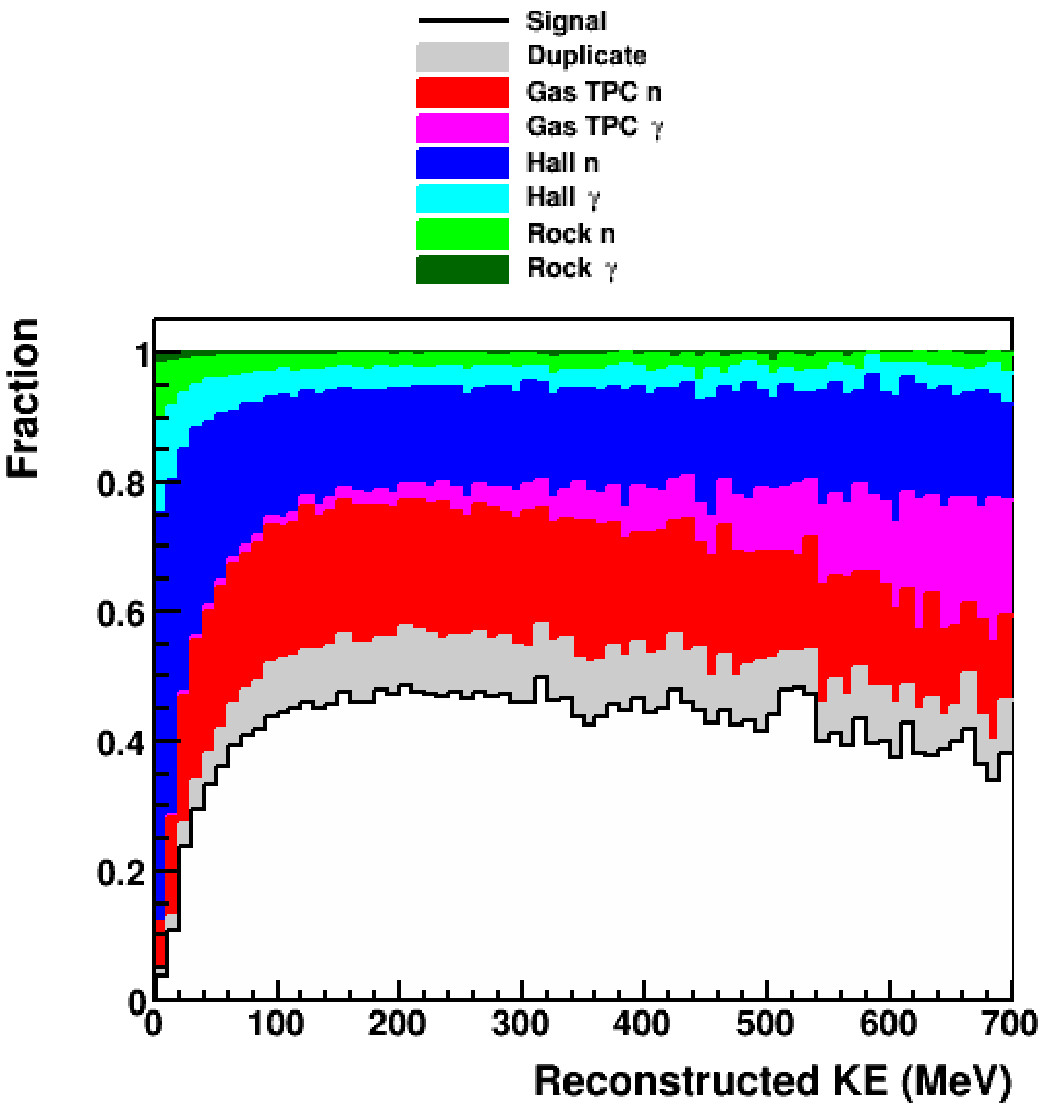
- Out of the box purity is ~10-30%
- Huge backgrounds from correlated activity, especially at high reconstructed energy
- Huge background from pile-up at low reconstructed energy

Sample purity: photon cut



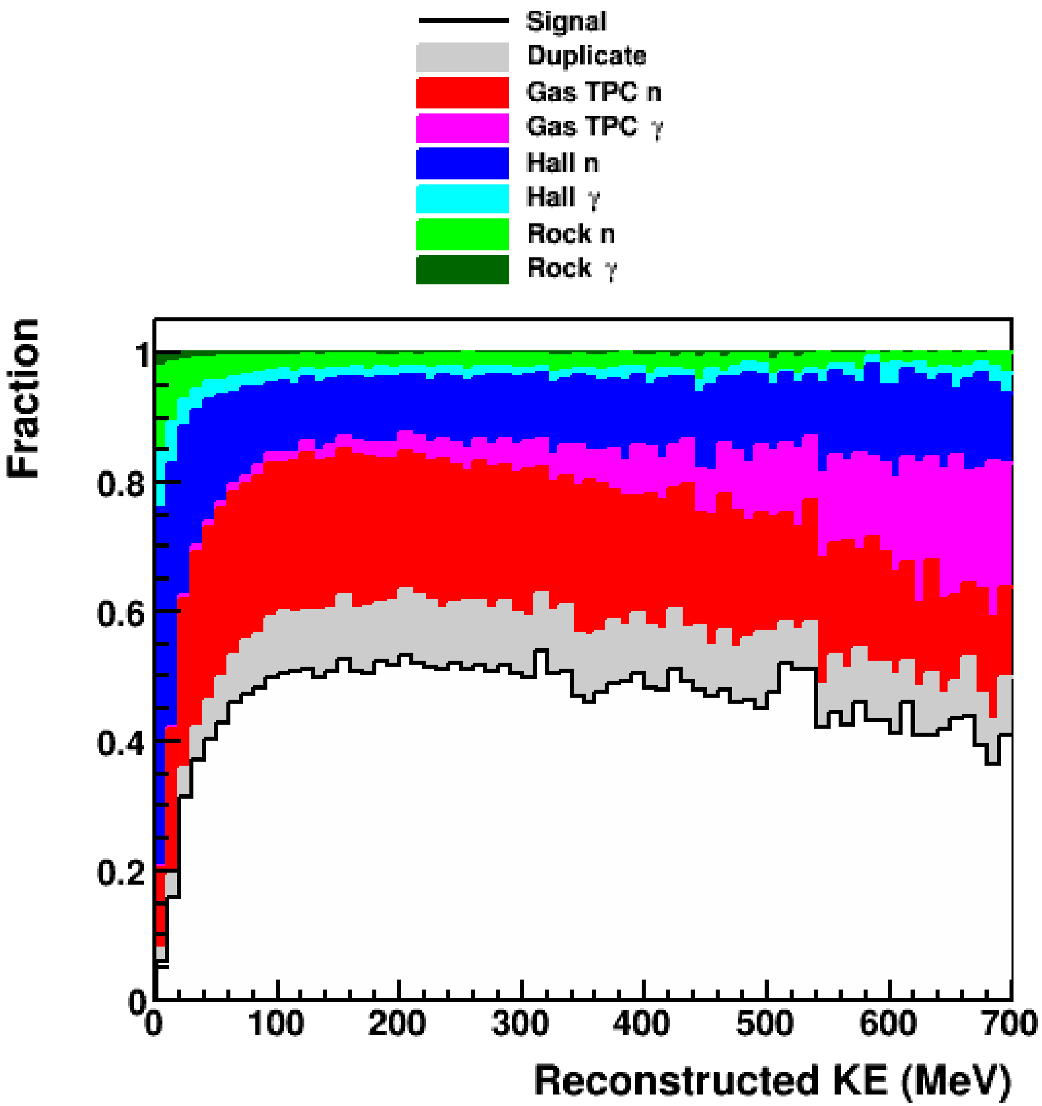
- Require proton-like cluster (rejects γs)

Sample purity: charged track cut



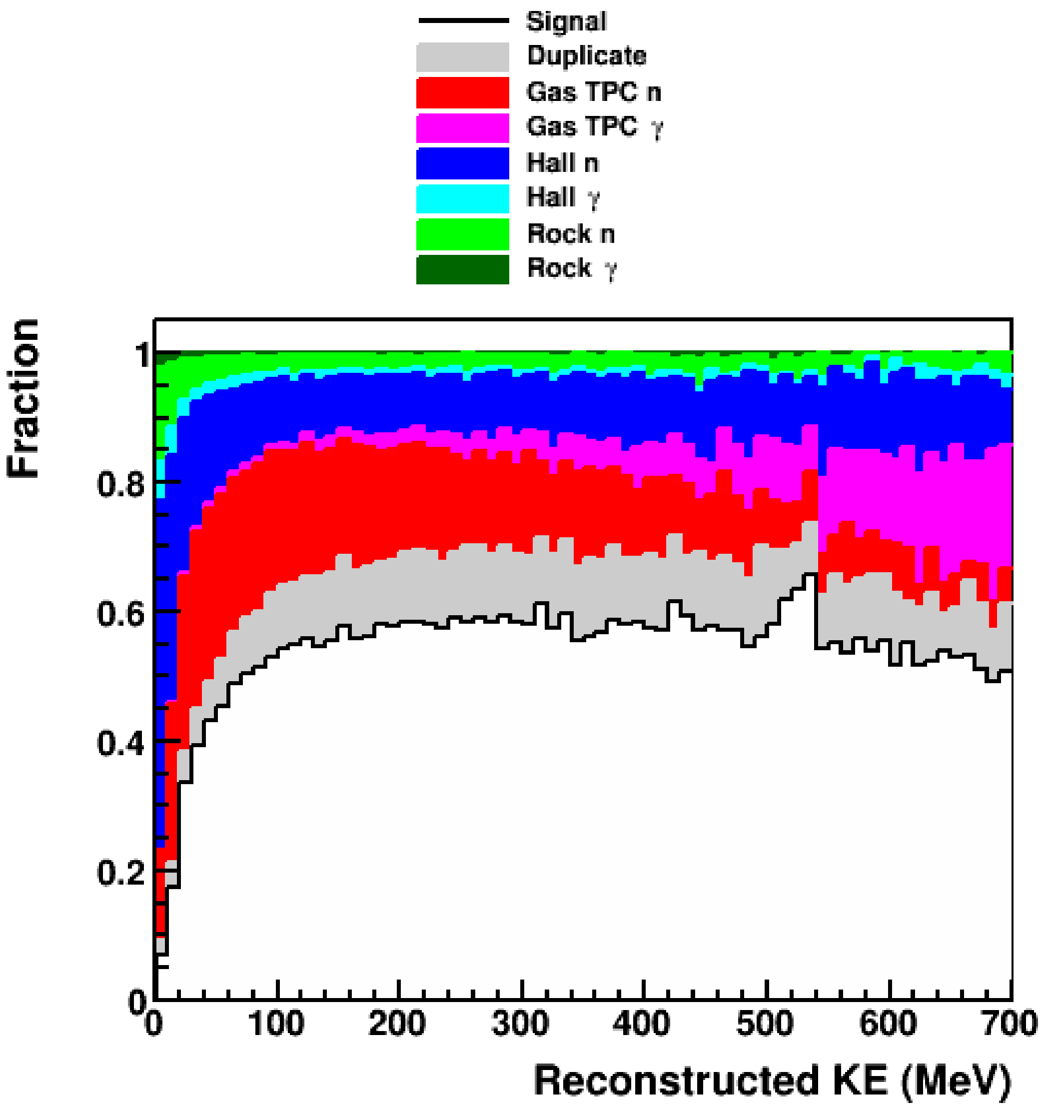
- Require proton-like cluster (rejects γs)
- Require large distance from TPC tracks (rejects correlated)

Sample purity: charged track cut



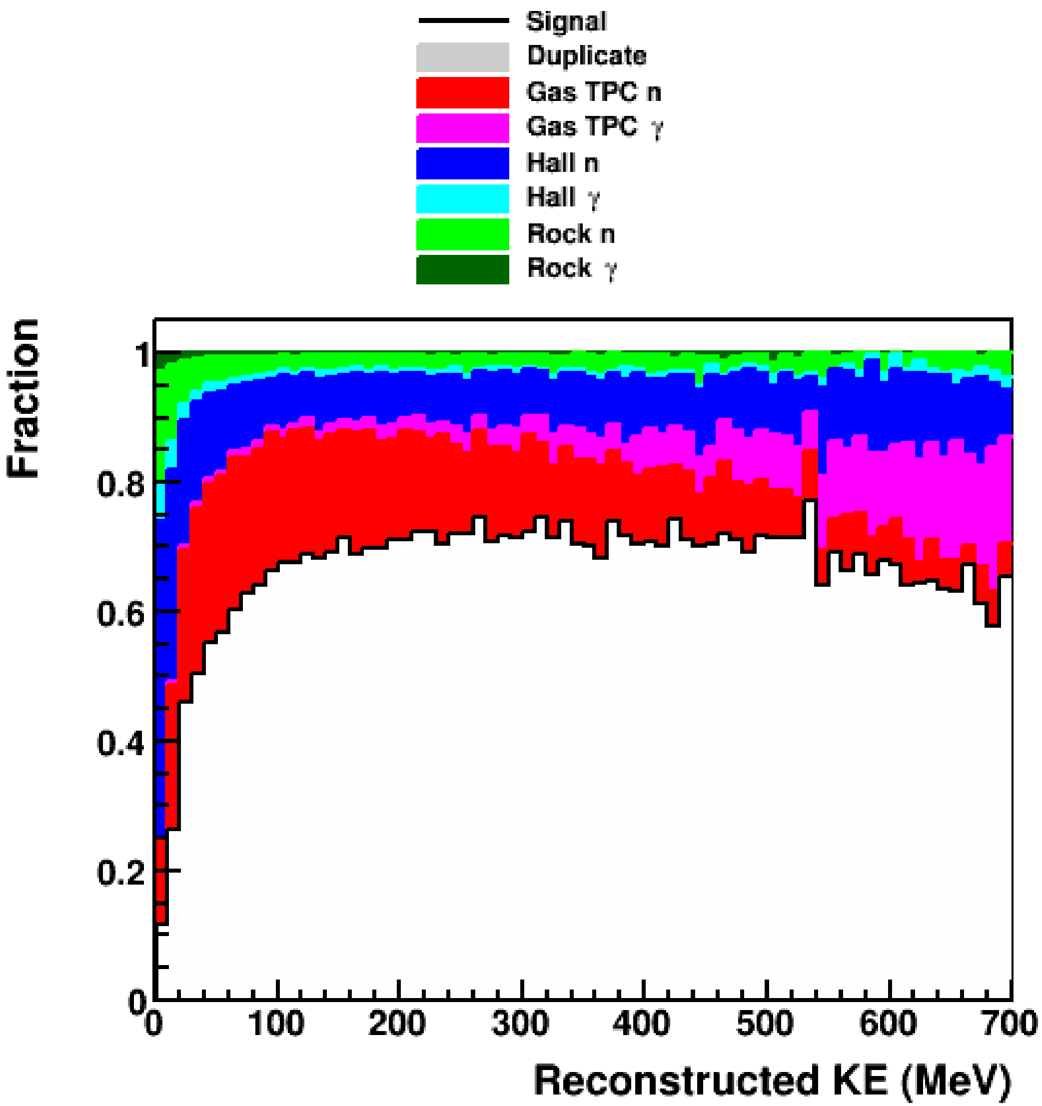
- Require proton-like cluster (rejects γs)
- Require large distance from TPC tracks (rejects correlated)
- Require no in-time ECAL activity near neutron cluster (rejects uncorrelated)

Sample purity: isolation cut



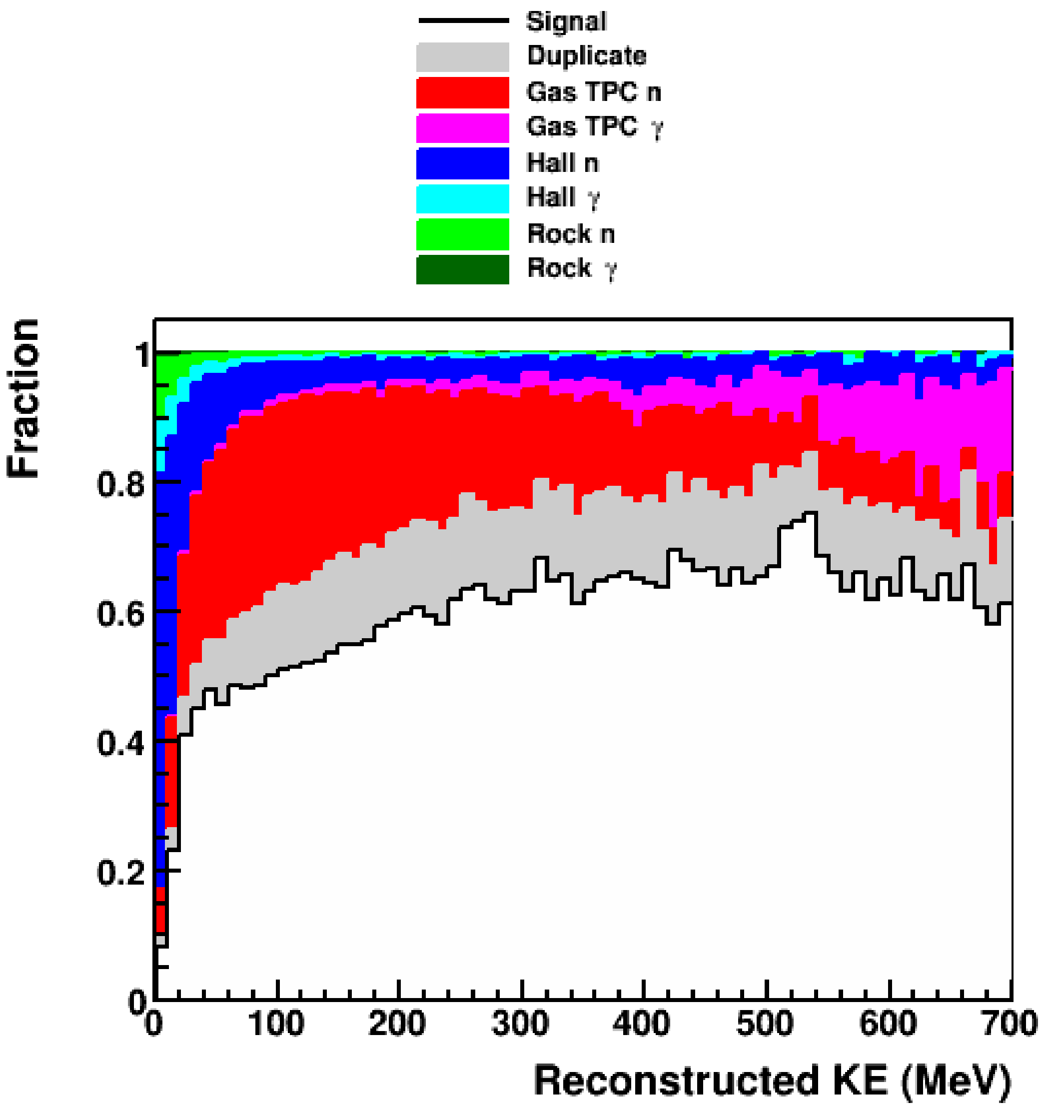
- Require proton-like cluster (rejects γs)
- Require large distance from TPC tracks (rejects correlated)
- Require no in-time ECAL activity near neutron cluster (rejects uncorrelated)
- Require isolated neutron candidate

Sample purity: leading neutron only



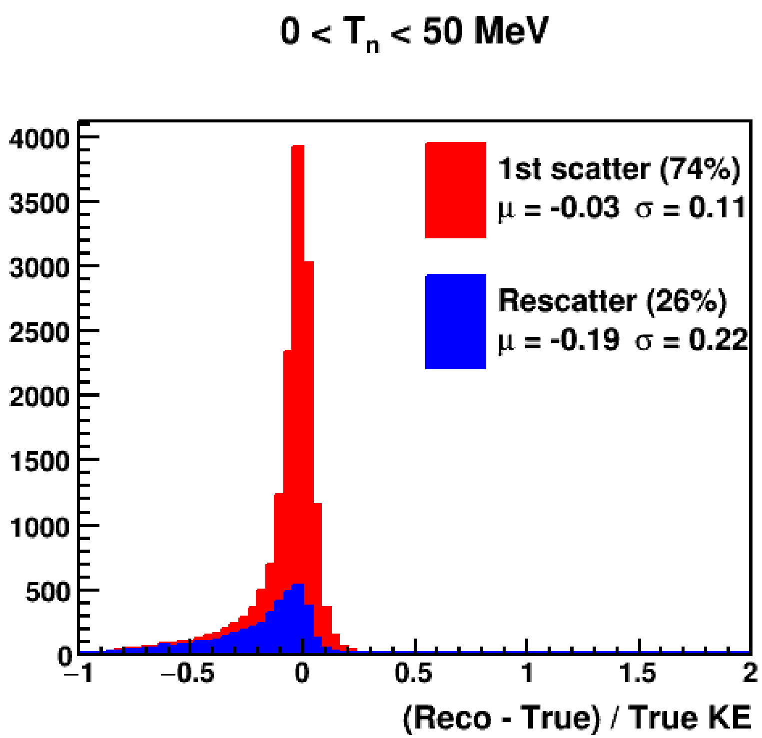
- Reconstruct only the earliest neutron scatter in each event
- Removes “duplicate” reconstruction
- Somewhat reduces correlated backgrounds, which are likelier to produce multiple candidates

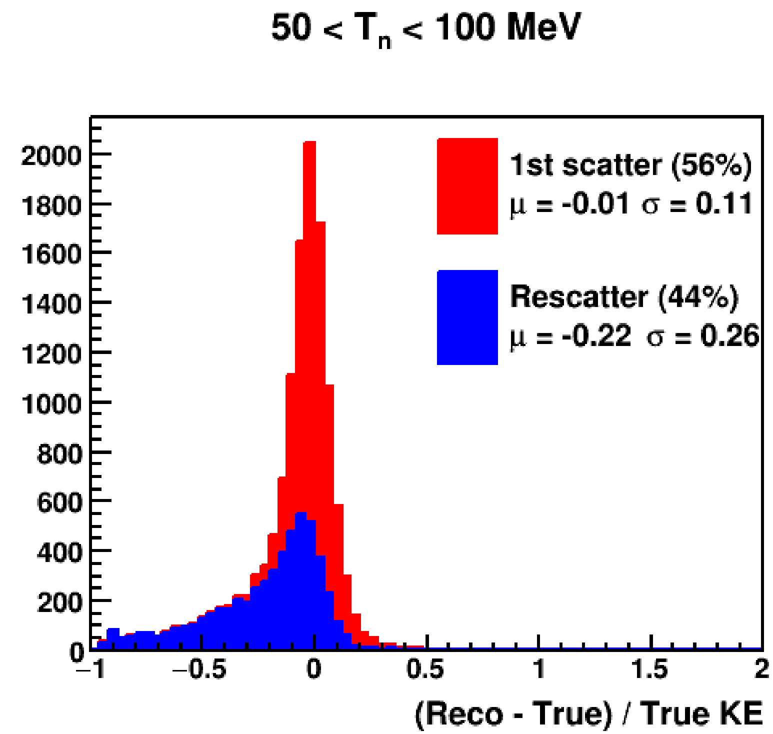
Sample purity: forward neutron only



- Suppresses uncorrelated backgrounds at low energy
- Increases purity, especially at high energy (there aren't high-energy, backward neutrons)

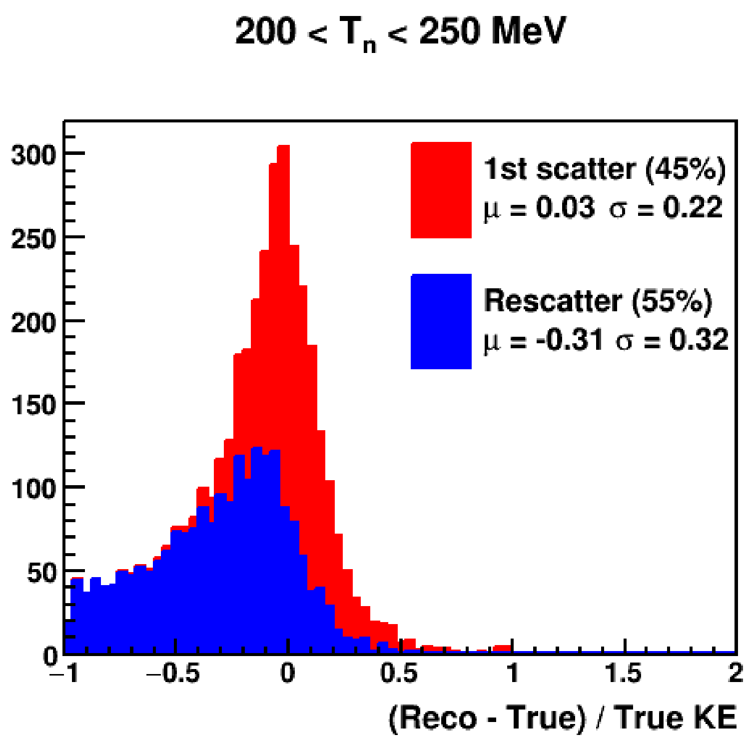
Energy resolution: low KE

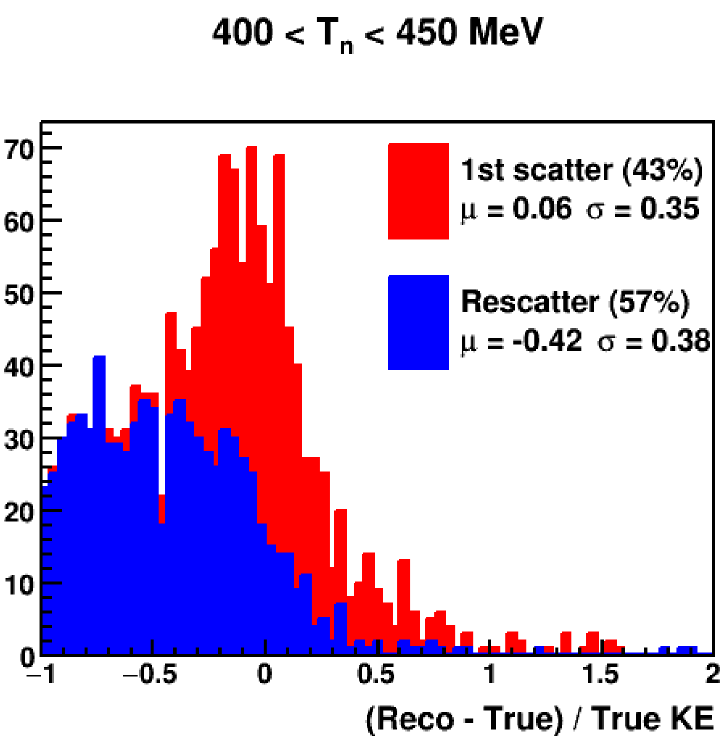




- Very good energy resolution when reconstructed neutron scatter is the first one
- But due to the high passive fraction, ~50% of the events are rescatters

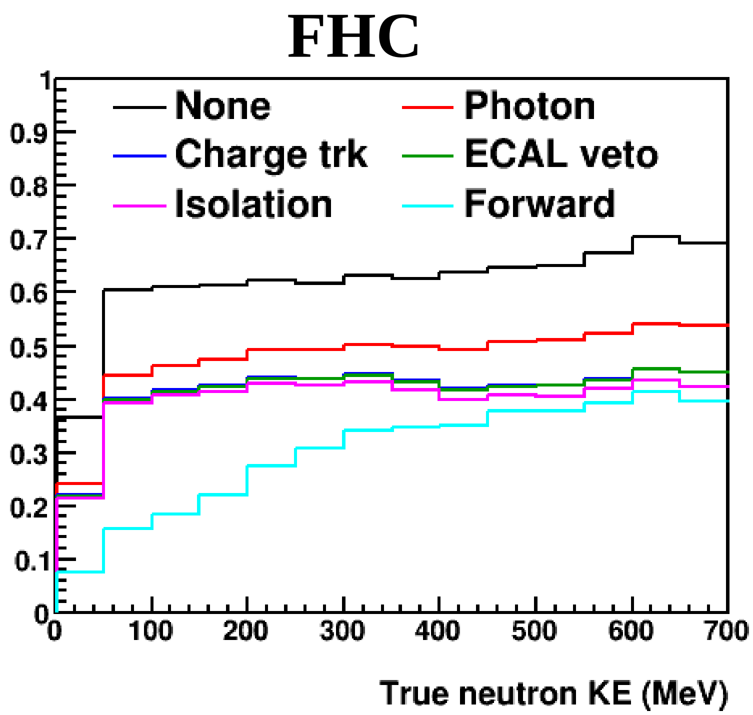
Energy resolution: high KE

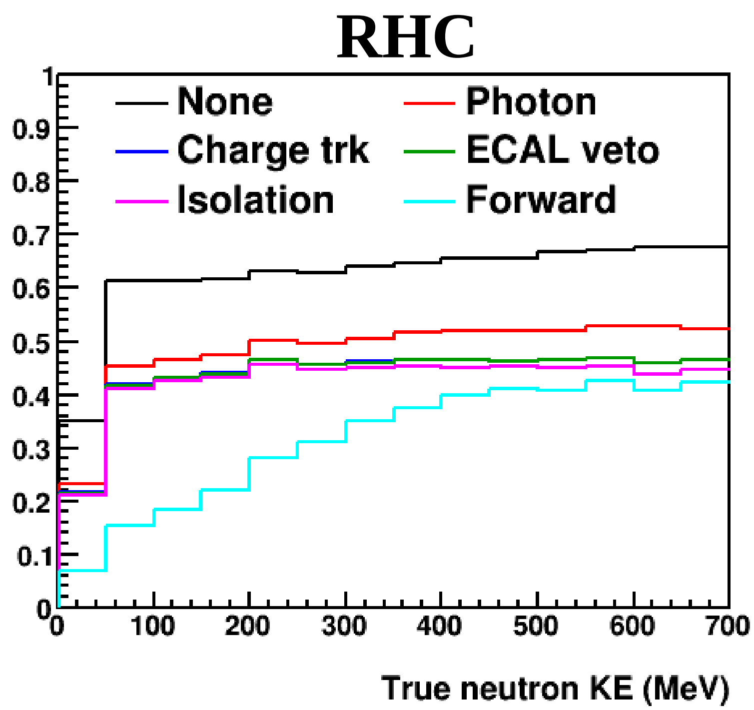




- At higher energies, resolution gets somewhat worse, up to ~40% for first scatter
- Fraction of rescatter events plateaus at ~60% at high energy
- Could be improved by increasing CH/passive ratio

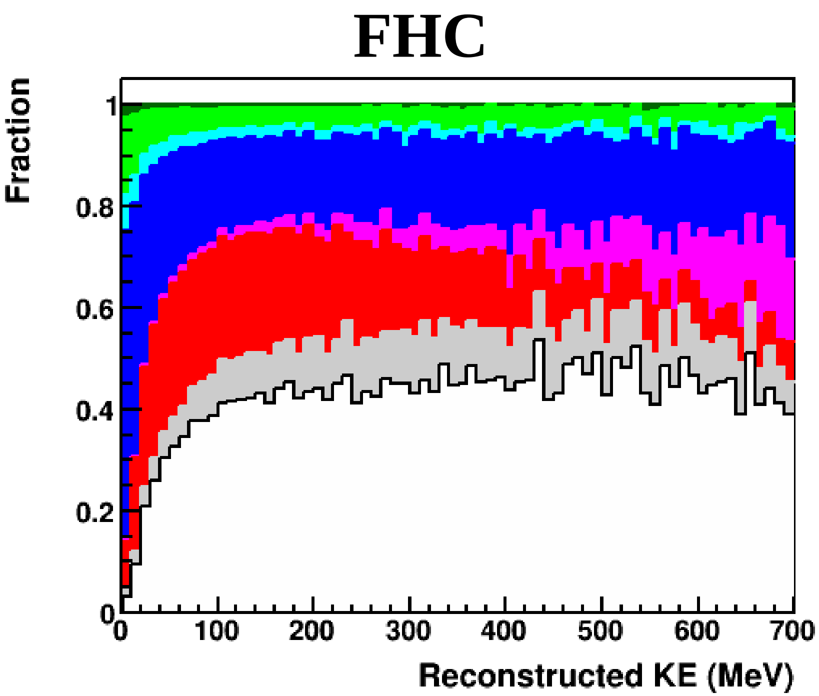
FHC vs. RHC: efficiency

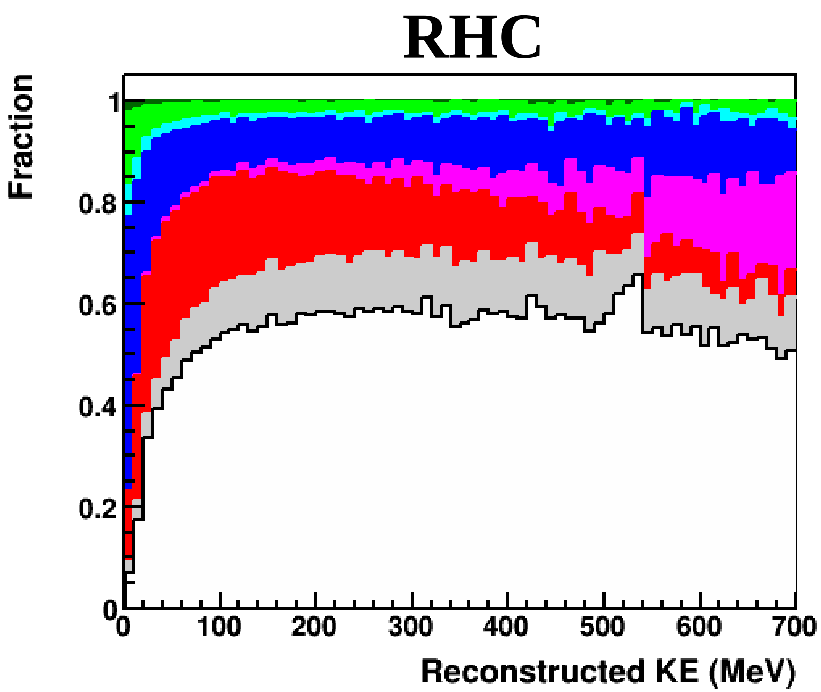




- Efficiency of each cut is basically identical in FHC and RHC

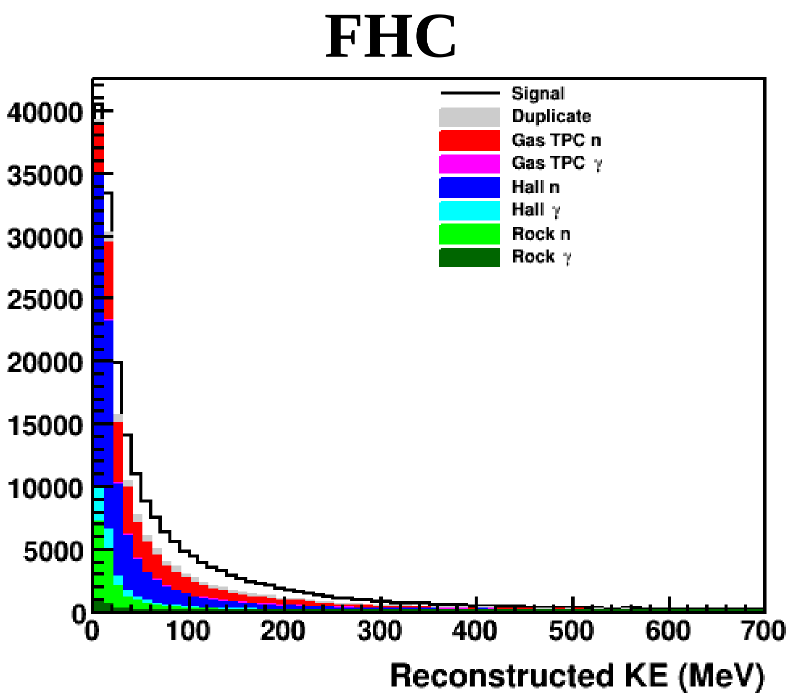
FHC vs. RHC: purity

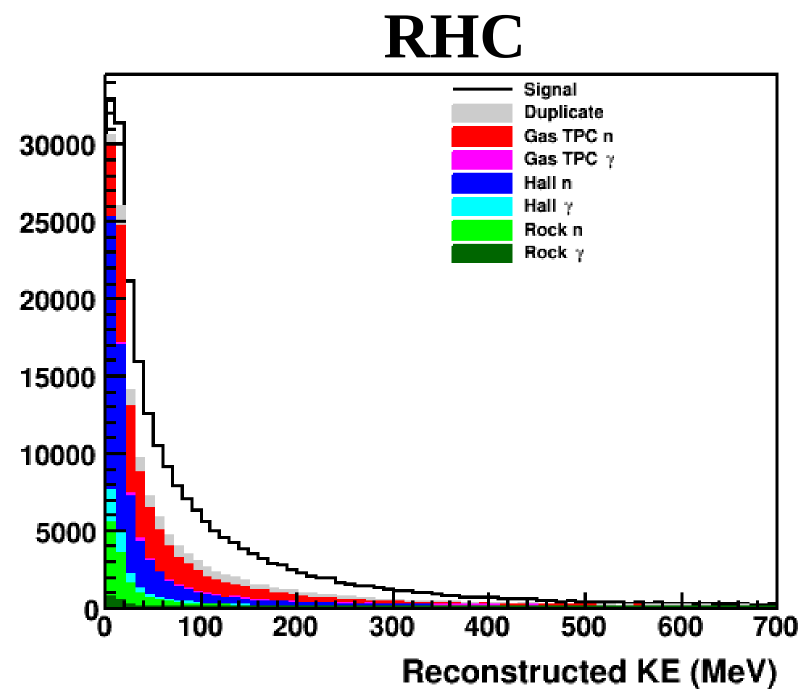




- Purity is somewhat higher in RHC, due to
  - Less pile-up due to lower antineutrino total cross section
  - Somewhat less correlated background due to fewer charged hadrons, on average, in antineutrino events

FHC vs. RHC: spectra





- More high-energy neutrons in antineutrino scattering, due largely to CCQE $\bar{\nu}p \rightarrow \mu^{+}n$

Conclusions

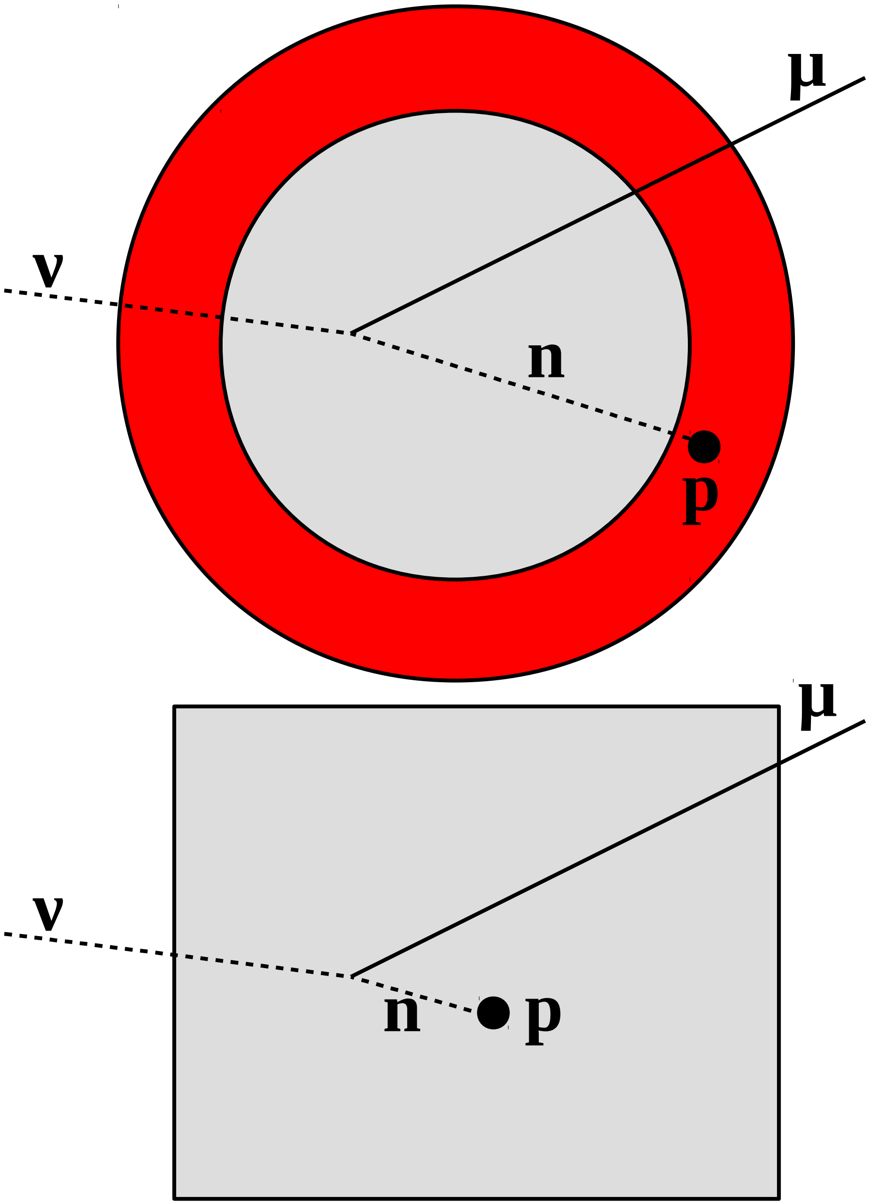
- Neutron reconstruction from TOF is possible in MPD ECAL, with ~40% efficiency and ~40% (50%) purity in FHC (RHC) mode
- Can further improve purity by looking at forward events only, or looking at leading neutron only, up to ~60-70%
- But energy resolution is poor, and biased toward low neutron KE, primarily due to missing the initial neutron interaction
  - This could be improved by reducing the passive fraction, or by adding a (10s cm) fully-active inner ECAL
- This measurement is interesting and worth pursuing as is – but is it worth re-optimizing the ECAL design to improve it?

Next steps

- Rahul is preparing a technical note describing the analysis and results
  - Desired for CDR? In what form?
- Code is available on github/cmmarshall

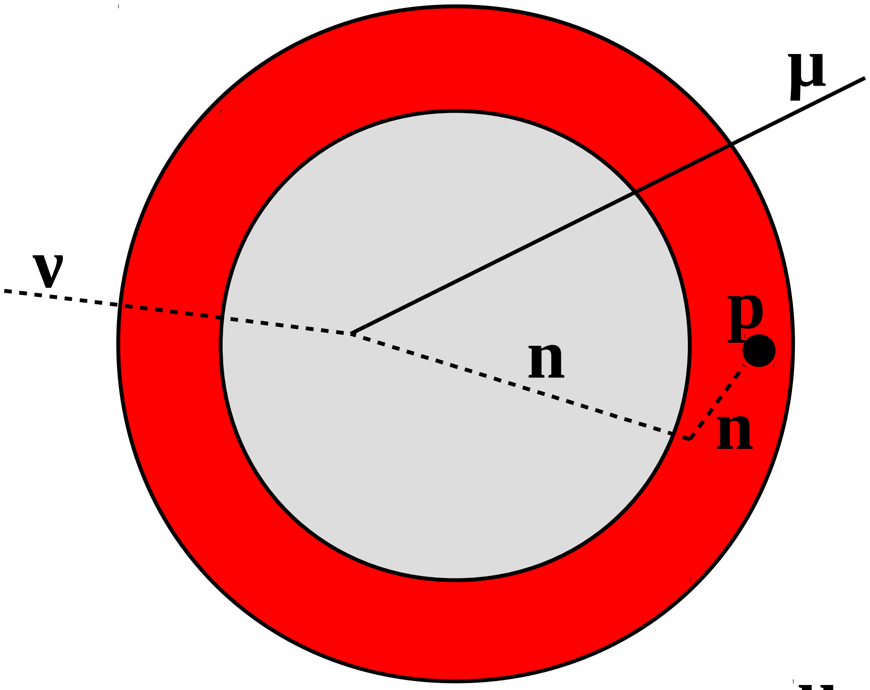
Backup

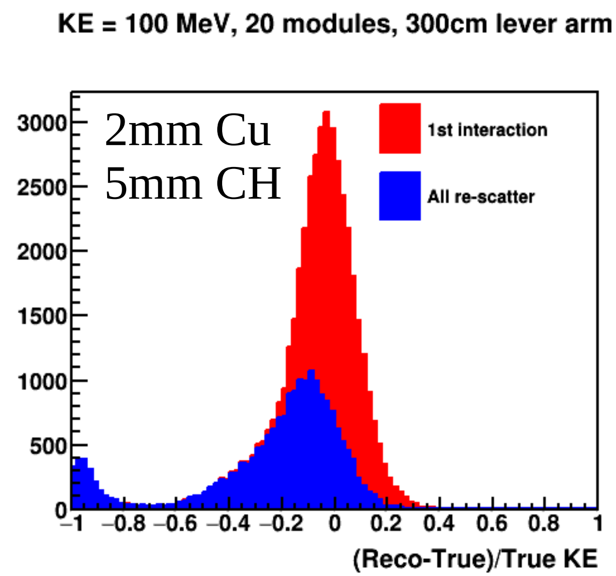
Advantages of MPD ECAL vs. 3DST

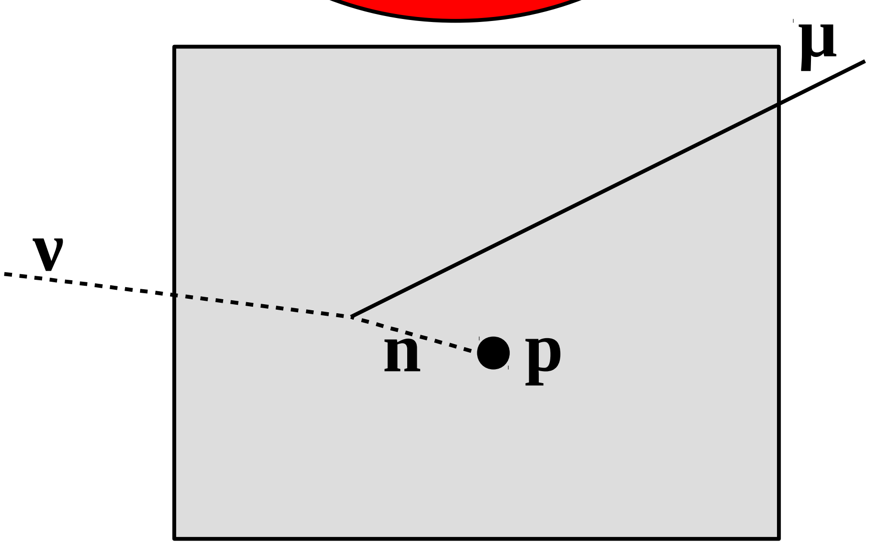


- Feasibility of neutron TOF measurement has been demonstrated in 3DST
- Two main advantages of pursuing neutron TOF using MPD ECAL
  - Neutrons produced in ν-Ar interactions → directly applicable to ν-Ar modeling of FD
  - Low density of gas TPC → lever arm of several meters, compared to O(1m) scattering length in 3DST → improved energy resolution

Disadvantages of ECAL vs. 3DST

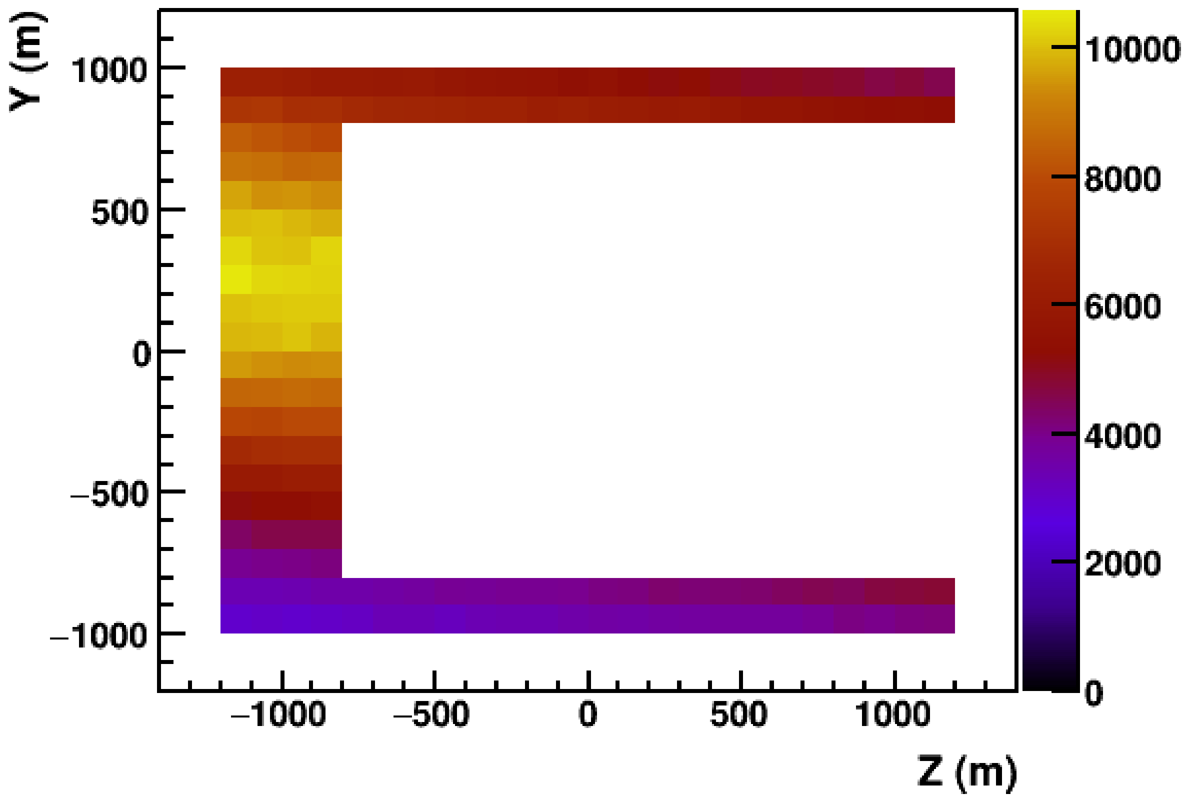






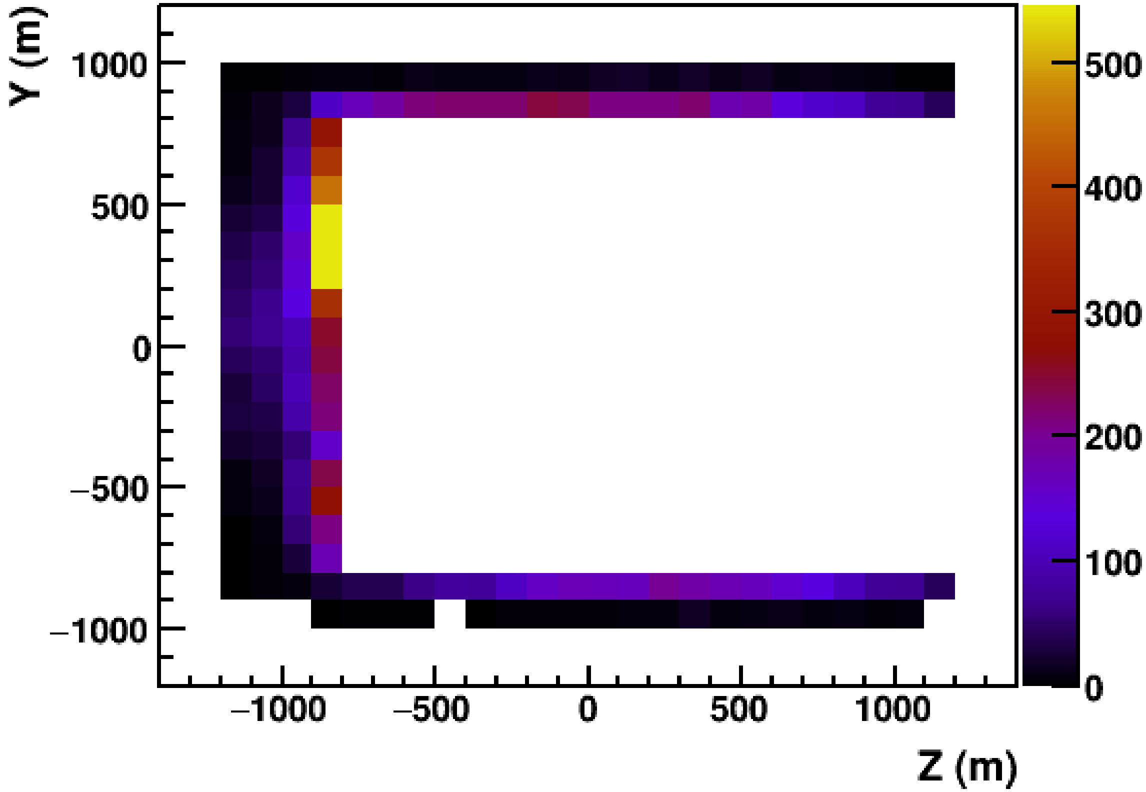
- Often miss neutron scatters that occur in passive absorber of ECAL → poor energy reco
- Long lever arm → long TOF → more beam pile-up problems

Rock background: how much rock?



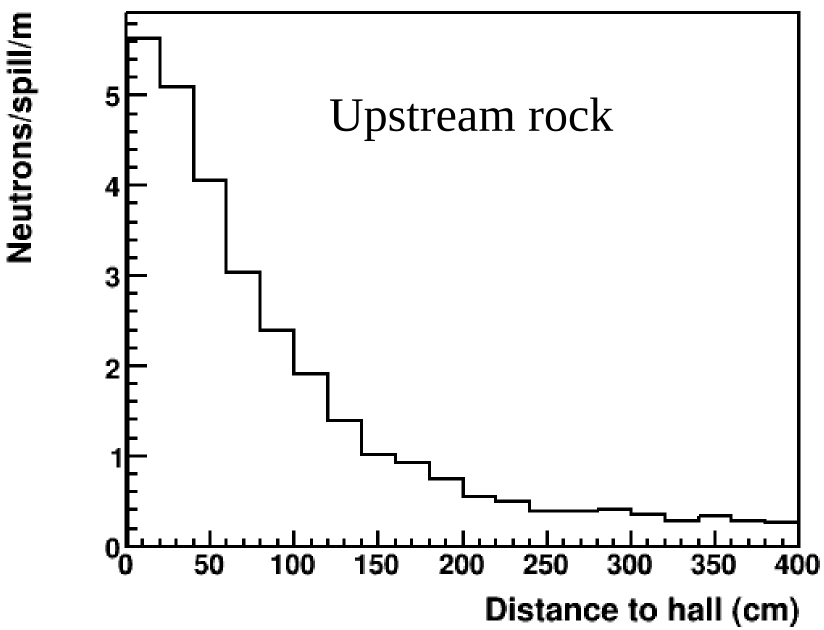
- Simulated 2m thick rock on top and bottom of hall, and 4m upstream, no downstream rock
- Plot shows all vertex positions – note the beam divergence is non-negligible over this region
- Where are the vertices that produce neutron scatters in the ECAL?

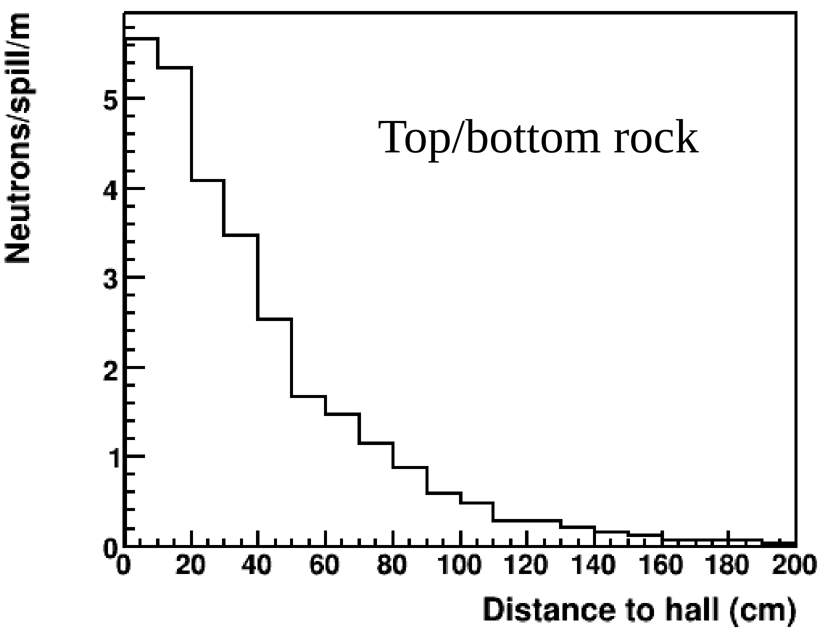
How much rock is enough? ν vertices producing ECAL activity



- Most of the vertices that produce ECAL neutrons are very near the detector hall
- Expected, as ~1m rock will attenuate neutrons

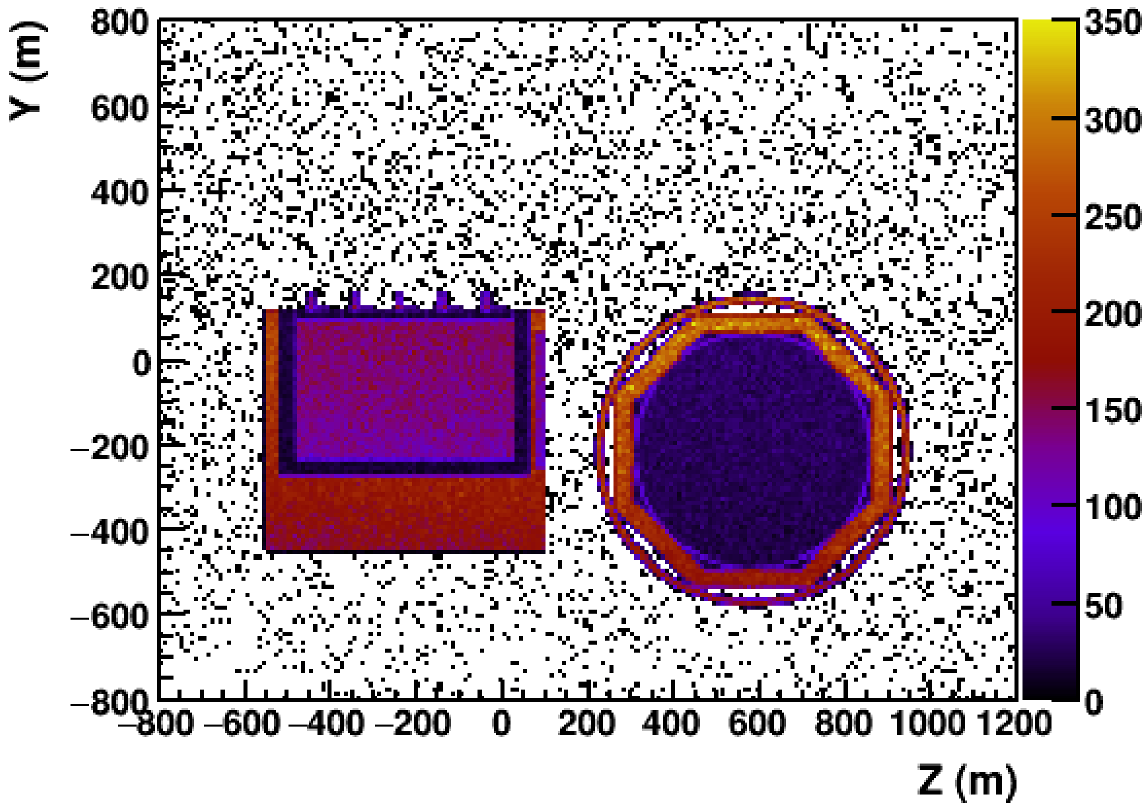
How thick rock do we need to worry about?





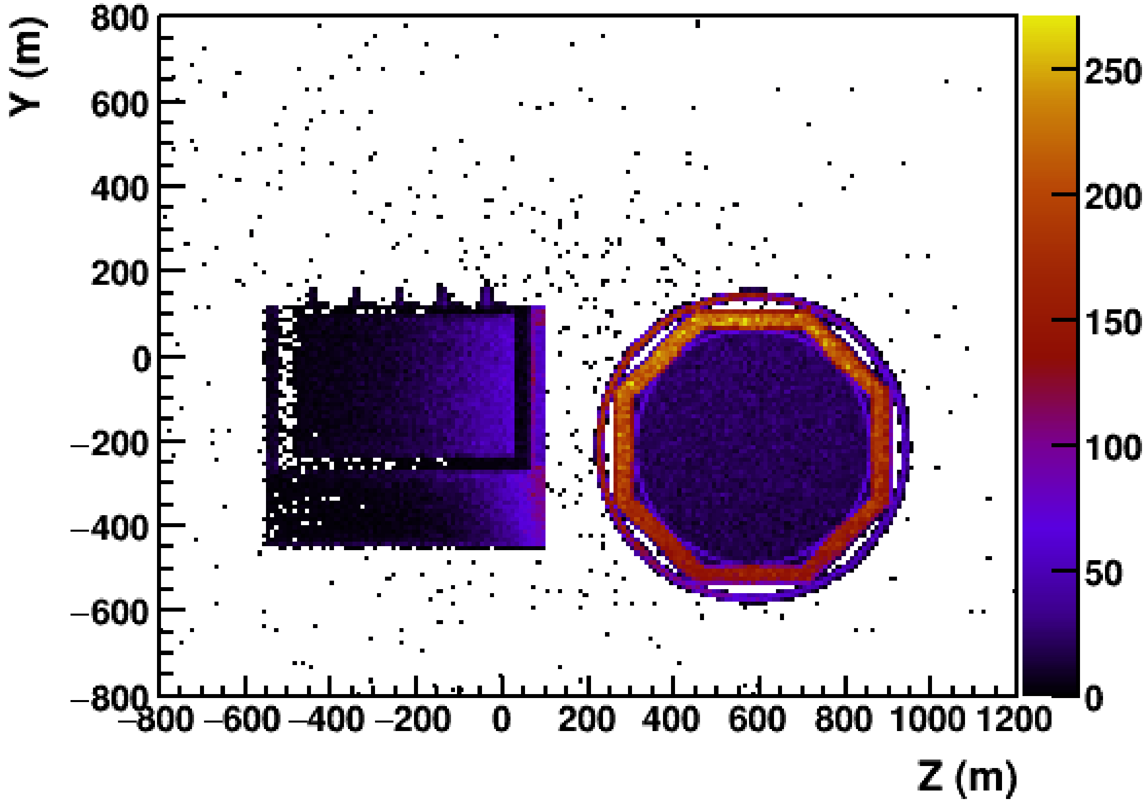
- Distance between neutrino interaction vertex that produces neutron hits in ECAL and edge of hall
- 2m on sides, and 4m upstream, is sufficient, maybe we underestimate by few %
- Integrating, we expect ~10 neutron hits in the ECAL per spill, i.e. 1 per μs – this is going to be sub-dominant

Hall-originating event vertices



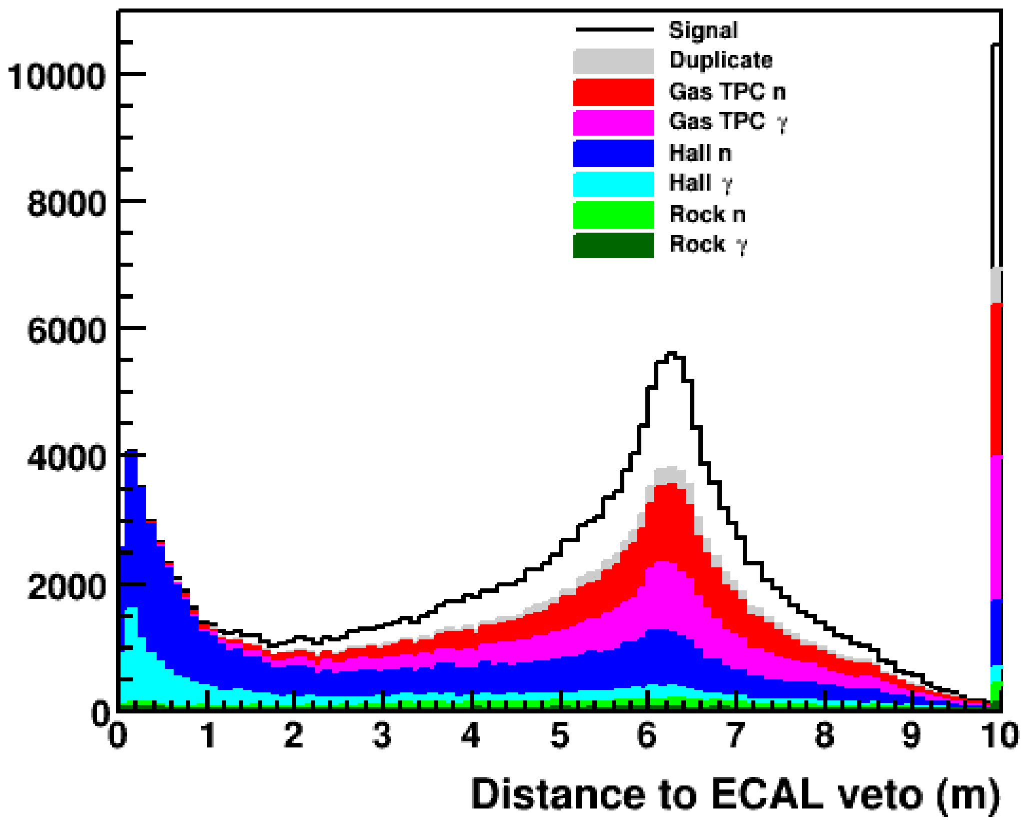
- First, position of all interactions in detector hall

Hall-originating event vertices



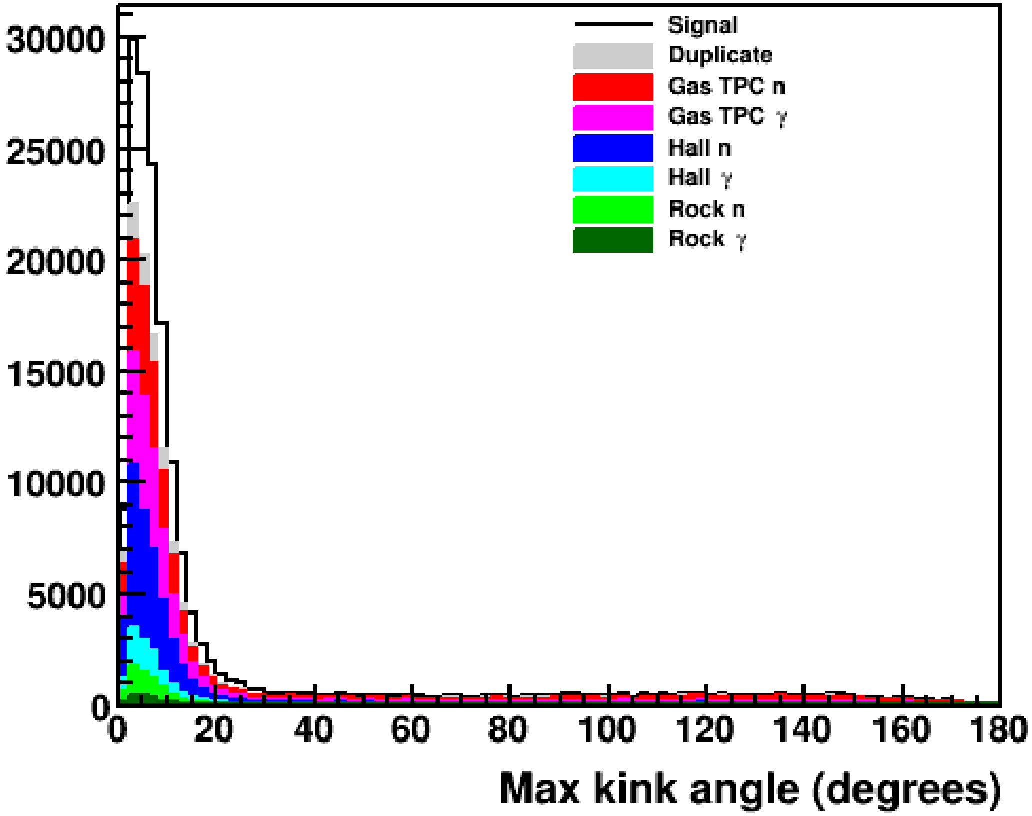
- Position of neutrino interaction for events that produce neutron candidates in ECAL
- Predominant background source is ECAL itself
- Second is the magnet, especially upstream
- Most downstream parts of LAr also contribute

Distance to ECAL activity (>50 MeV reco only)



- Most pile-up is reconstructed at very low energy

Kink track angle



- Maximum kink angle
- Some gas-induced non-primary neutrons are correlated with interactions in the TPC which produce large kinks