Neutron TOF in the MPD ECAL

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18 September, 2019

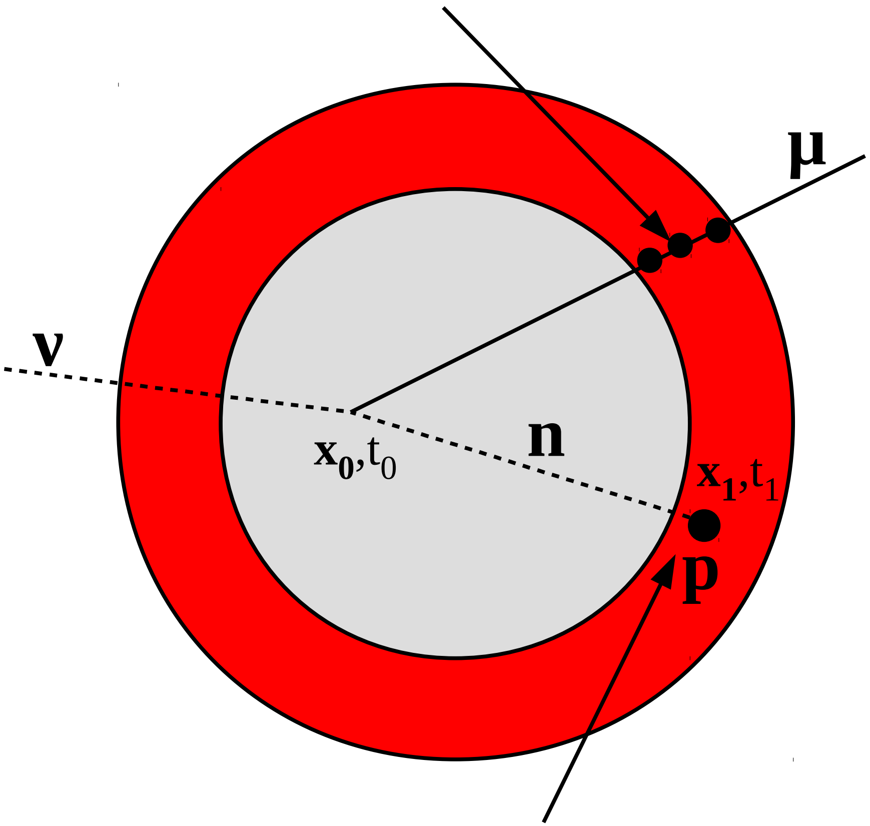
Motivation

- 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

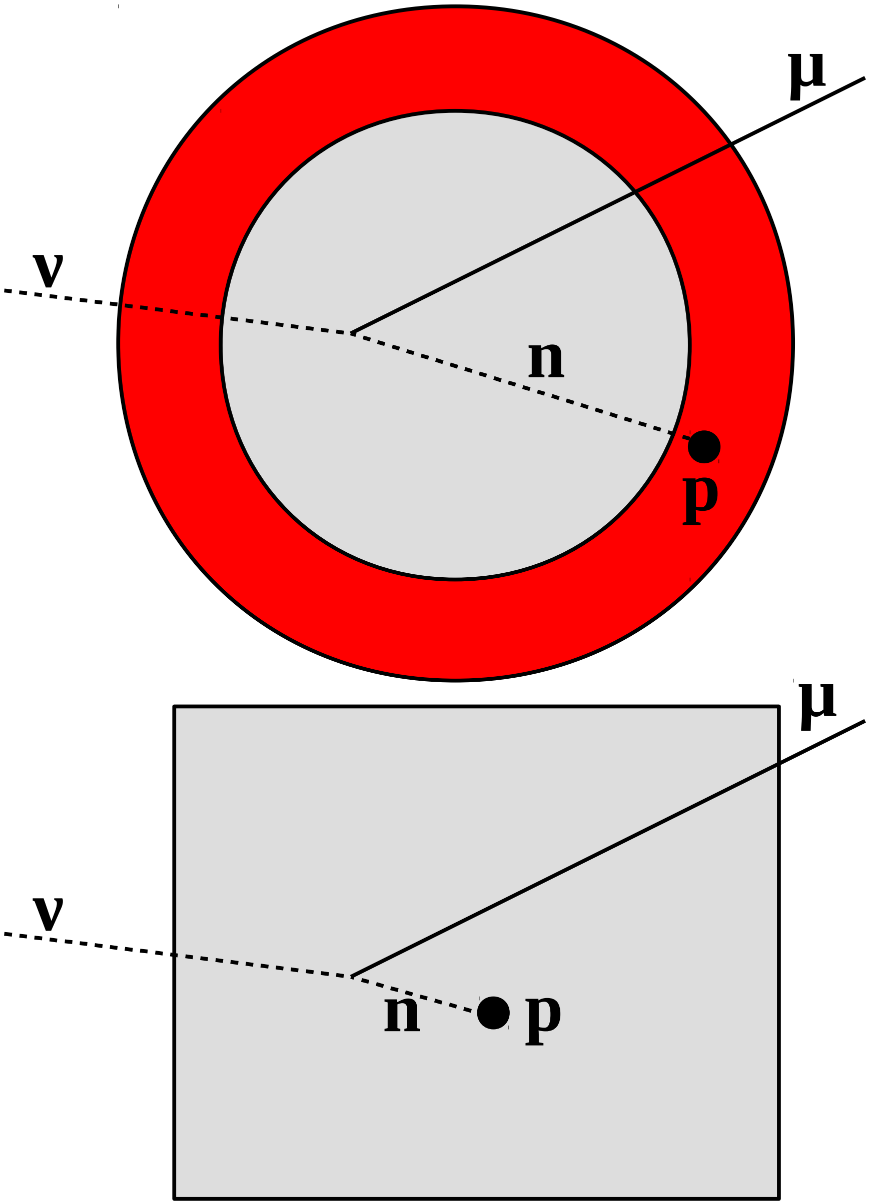
Measure interaction vertex time from muon hits in ECAL



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

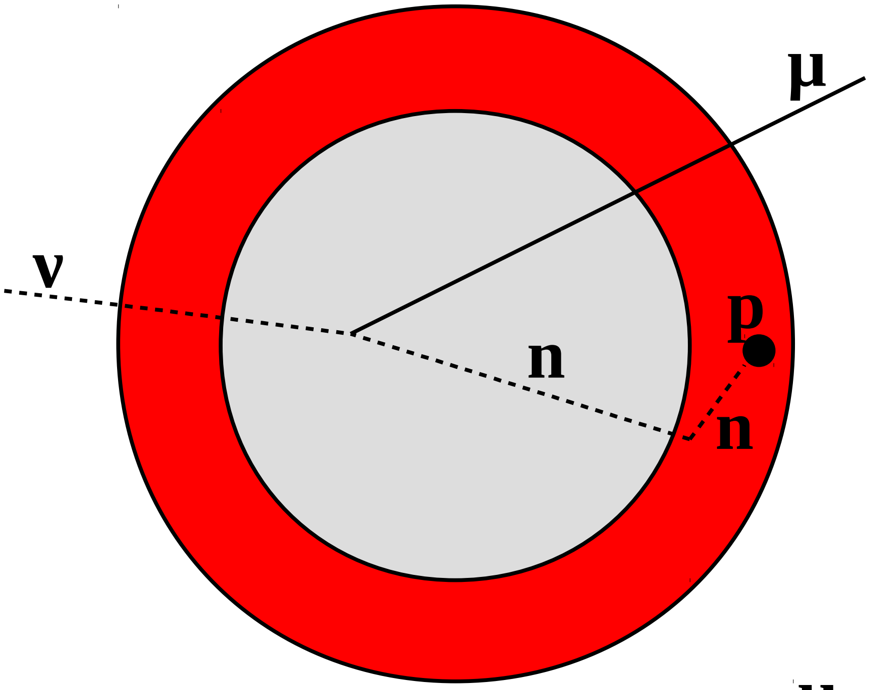
- Assuming neutron comes from primary vertex, start and end positions are measured
- Vertex time comes from charged particle hits in ECAL, correcting for TOF back to vertex
- Use neutron TOF to determine its momentum
- This works in any detector with fast timing and 3D position reconstruction, i.e. MPD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

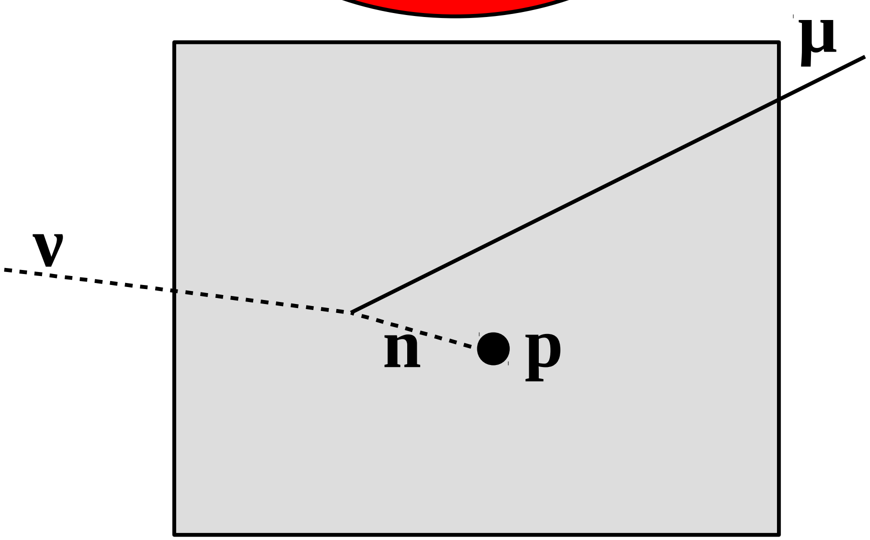
Advantages of MPD ECAL vs. 3DST

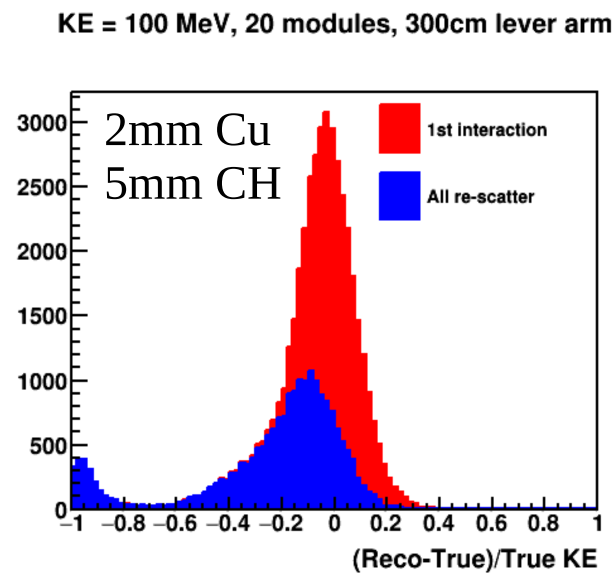


- Feasibility of neutron TOF measurement has been demonstrated in 3DST
- Two main advantages of pursuing neutron TOF using MPD ECAL
  - Neutrons produced in ν-Ar interactions → directly applicable to ν-Ar modeling of FD
  - Low density of gas TPC → lever arm of several meters, compared to O(1m) scattering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

Disadvantages of ECAL vs. 3DST

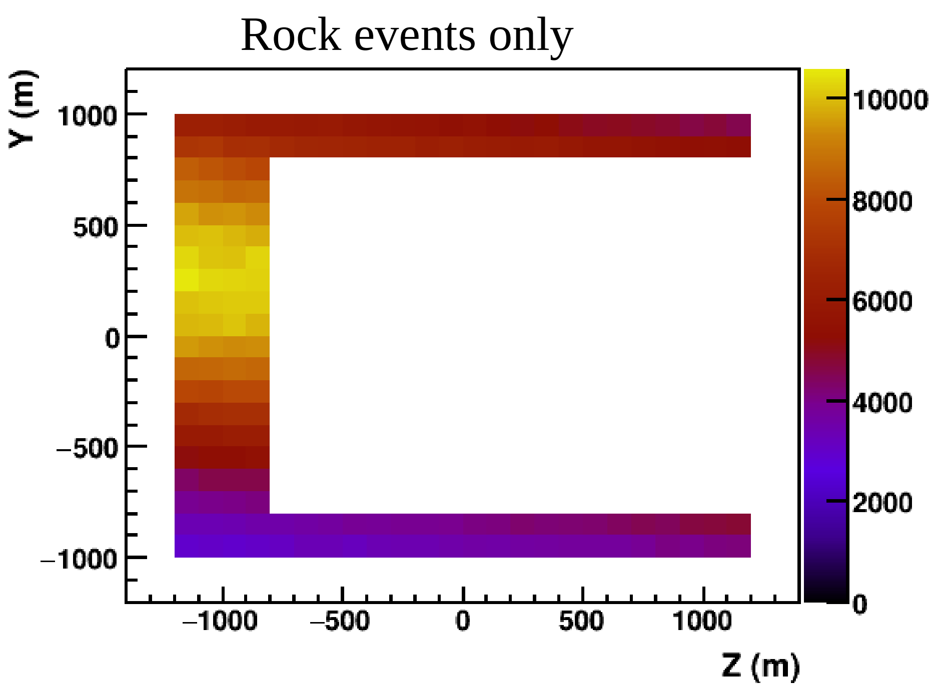


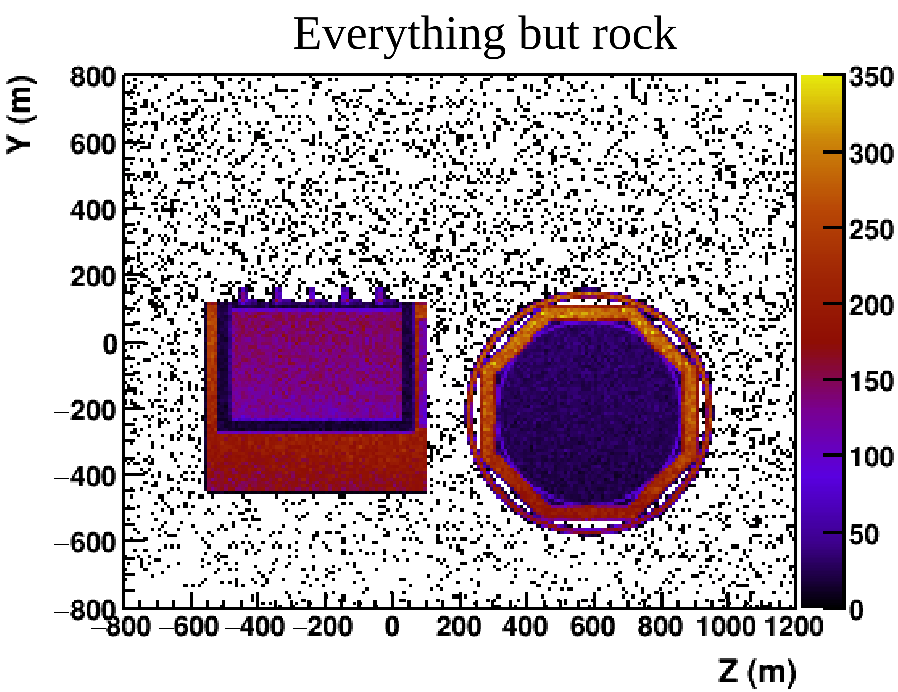




- Often miss neutron scatters that occur in passive absorber of ECAL → poor energy reco
- Long lever arm → long TOF → more beam pile-up problems

Simulation details





- Detector hall consists of rock, LAr TPC, Gas TPC + ~300t ECAL + 100t cylindrical magnet (geometry created by Eldwain with NDGGD)
- Guess on the rock location: 2m gap from rock to front of LAr TPC, rock right below and ~4m above detectors, no side rock as hall will be wide in the x dimension

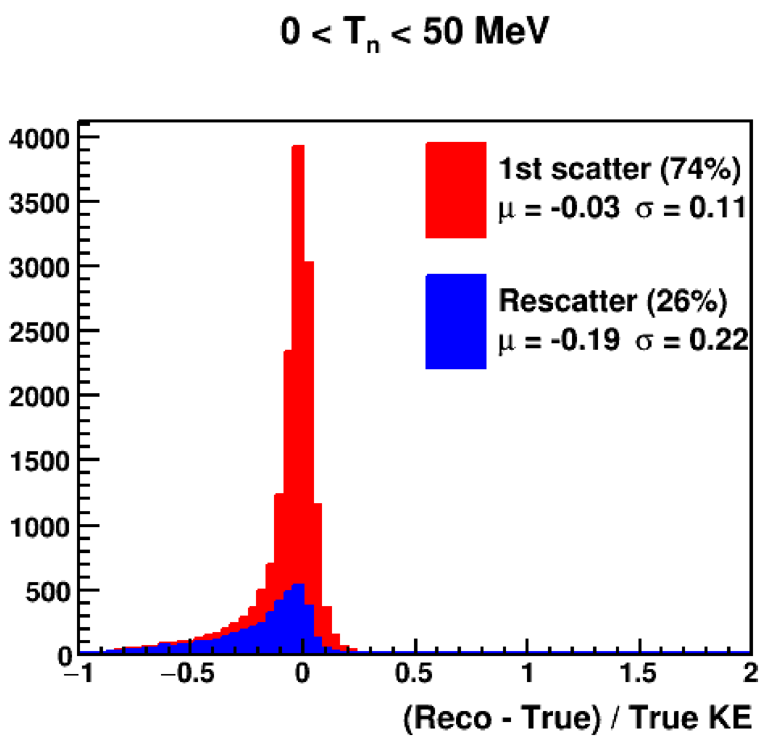
Signal and background

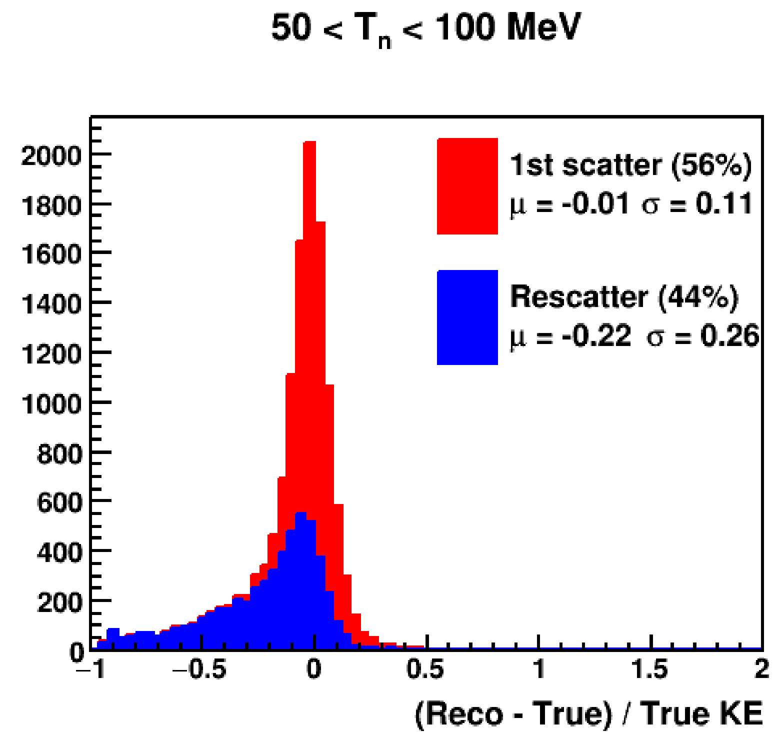
- Signal is ν_μ CC interaction in gas TPC, with a fiducial volume 50cm from the edge of the active region
- Overlay background events ±1μs from signal, and reconstruct entire spill, with hit timing resolution in the ECAL of ±0.7 ns
- 770 rock and 120 detector hall ν interactions per spill at 1.2 MW FHC,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

Almost-real reconstruction

- Hits in active ECAL elements are formed, including scintillator quenching effects
- Ionization hits from charged particles originating in gas TPC or entering the ECAL from the outside are excluded, but any hit with a neutral ancestor (neutron or photon) is considered
- Selection cut for neutrons uses both topological and energy information
  - Basically neutrons are single-cell, high-energy hits, while photons are typically multi-cell, more uniform energy

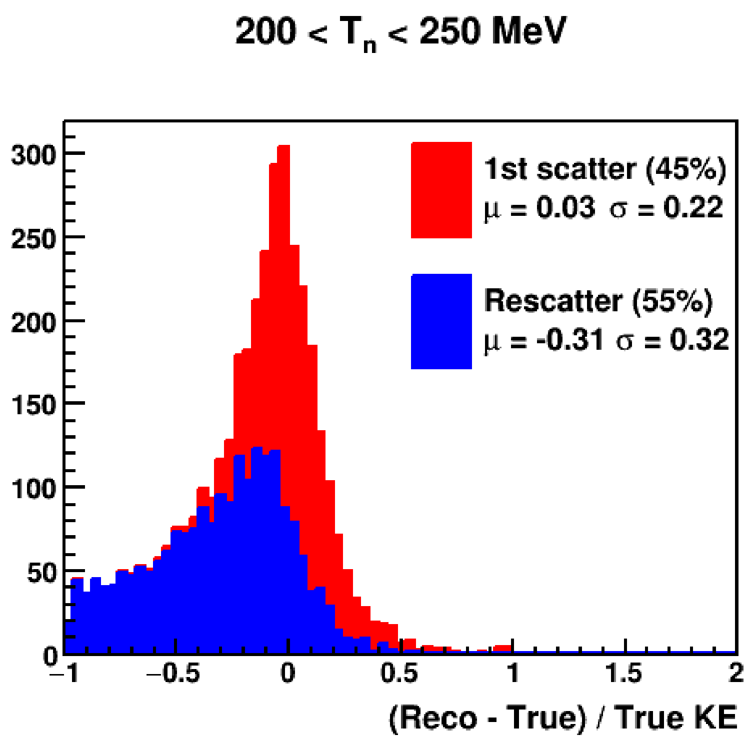
Energy resolution

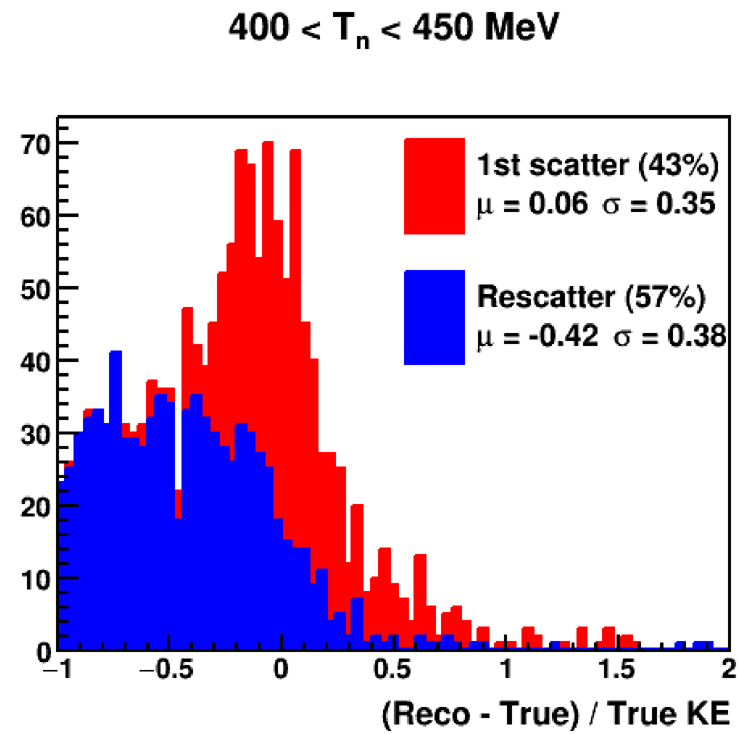




- Very good energy resolution when reconstructed neutron scatter is the first one
- But due to the high passive fraction, ~50% of the events are rescatters

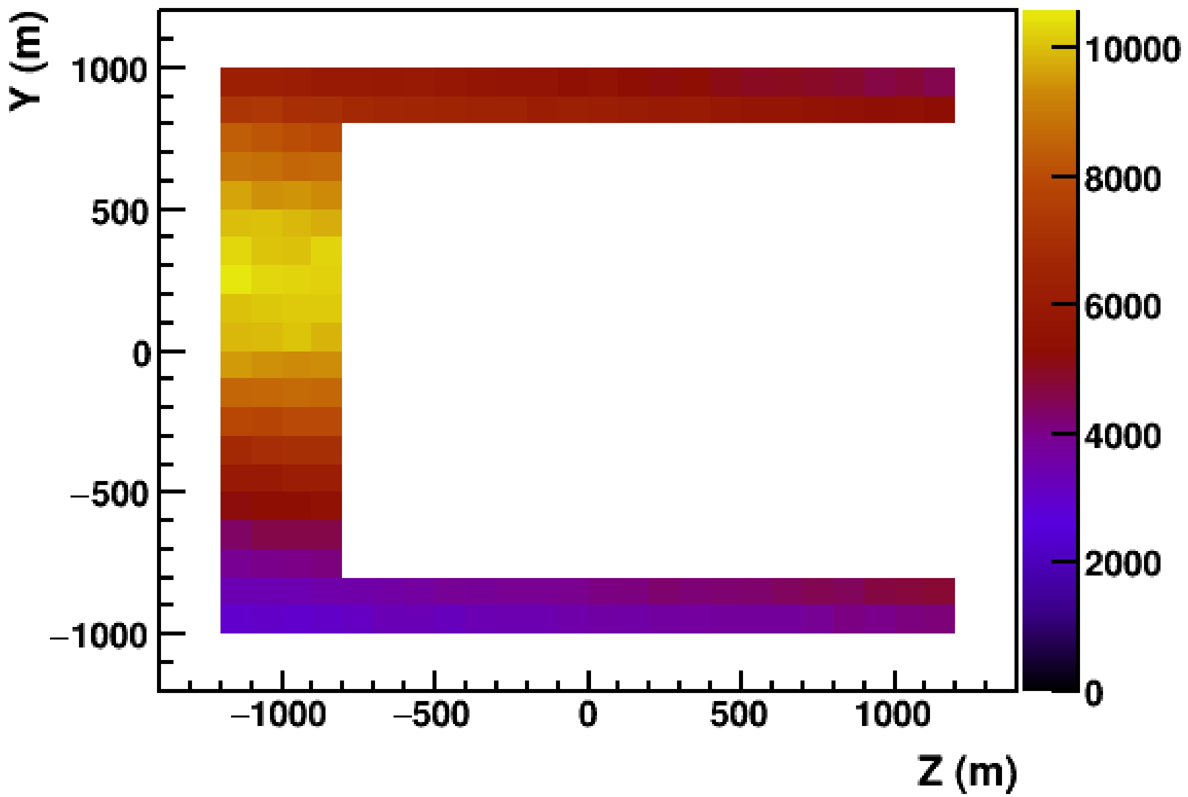
Energy resolution





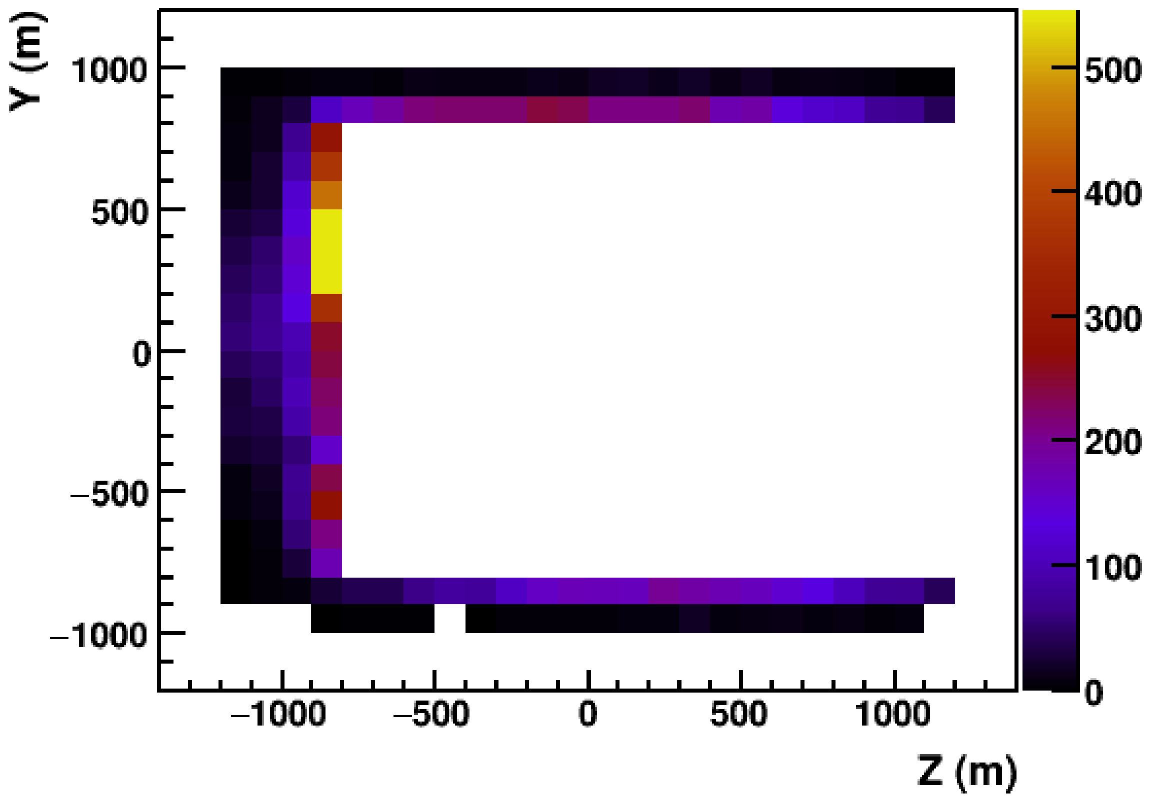
- At higher energies, resolution gets somewhat worse, up to ~40% for first scatter
- Fraction of rescatter events plateaus at ~60% at high energy
- Could be improved by increasing CH/passive ratio

Rock background: how much rock?



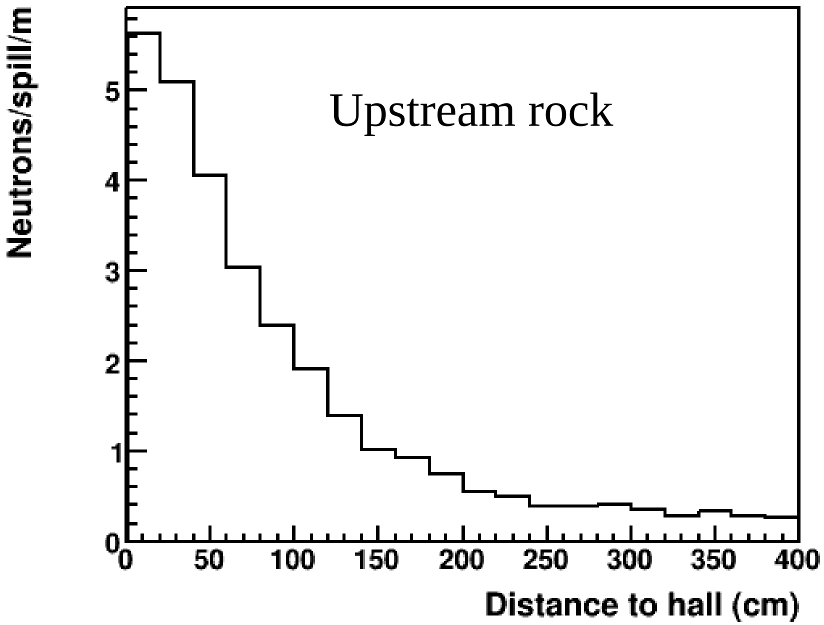
- Simulated 2m thick rock on top and bottom of hall, and 4m upstream, no downstream rock
- Plot shows all vertex positions – note the beam divergence is non-negligible over this region
- Where are the vertices that produce neutron scatters in the ECAL?

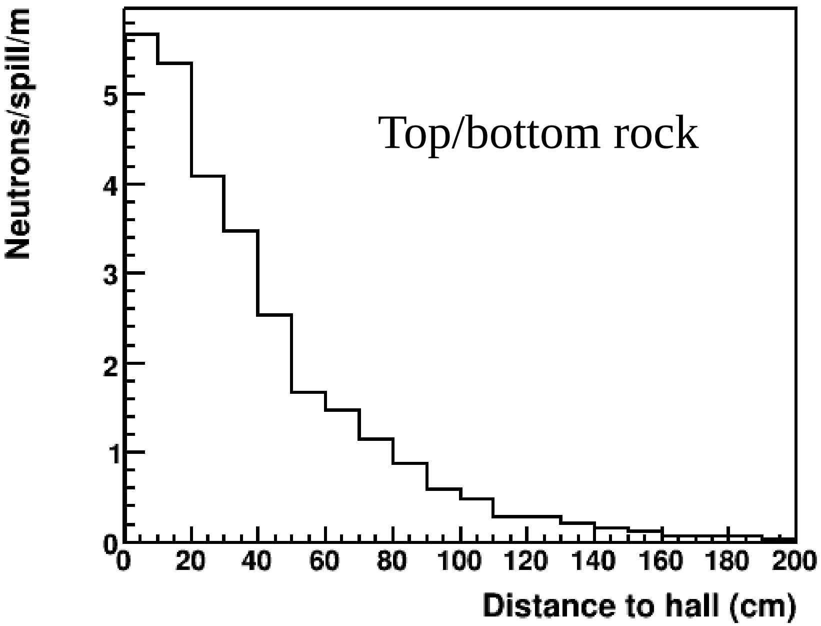
How much rock is enough? ν vertices producing ECAL activity



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

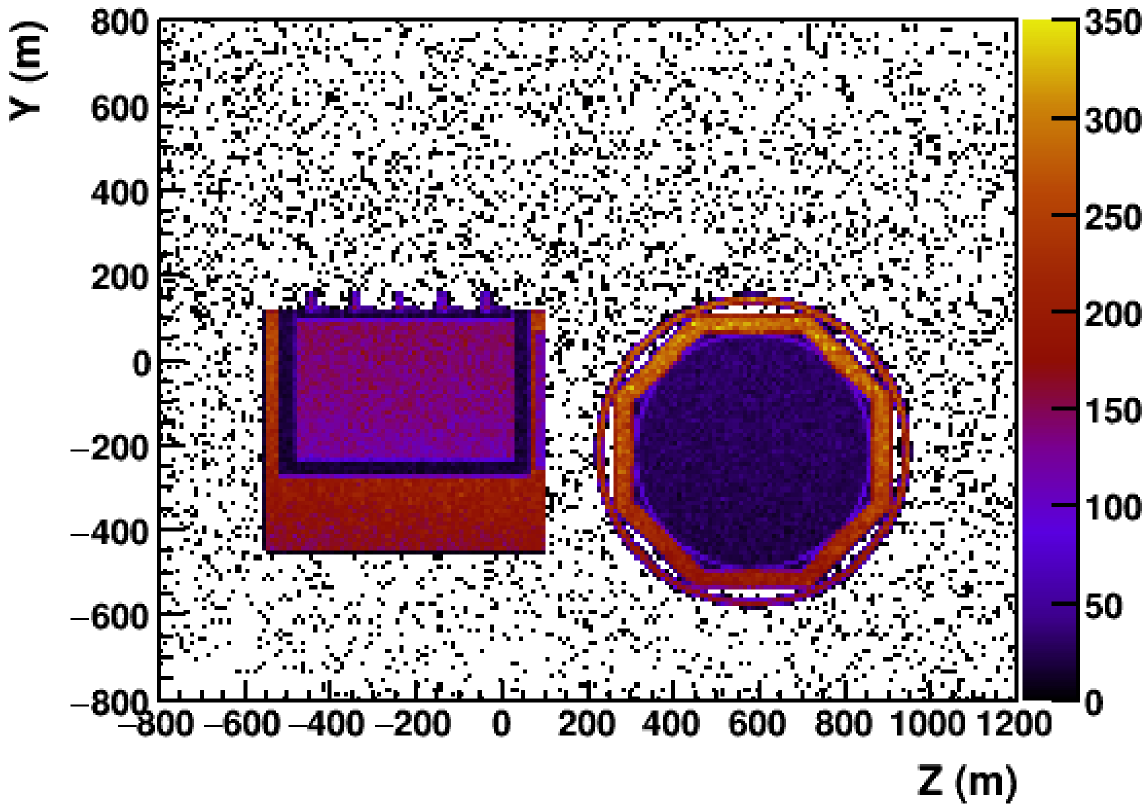
How thick rock do we need to worry about?





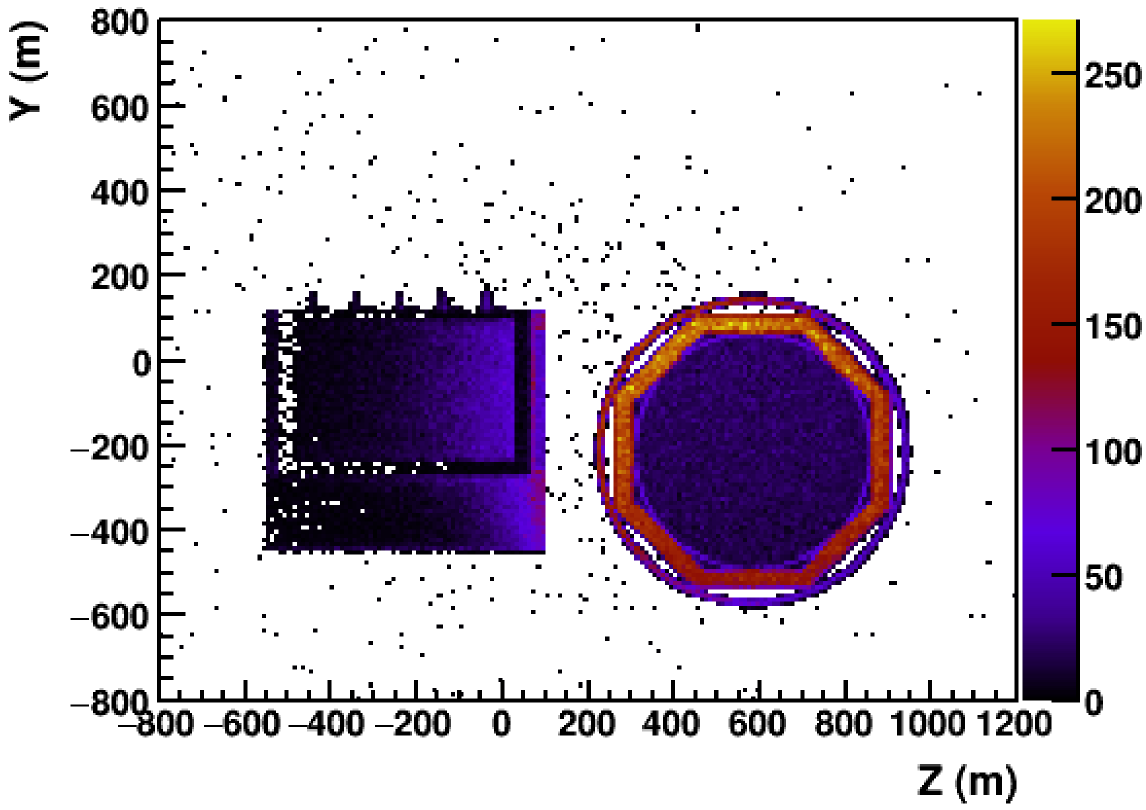
- Distance between neutrino interaction vertex that produces neutron hits in ECAL and edge of hall
- 2m on sides, and 4m upstream, is sufficient, maybe we underestimate by few %
- Integrating, we expect ~10 neutron hits in the ECAL per spill, i.e. 1 per μs – this is going to be sub-dominant

Hall-originating event vertices



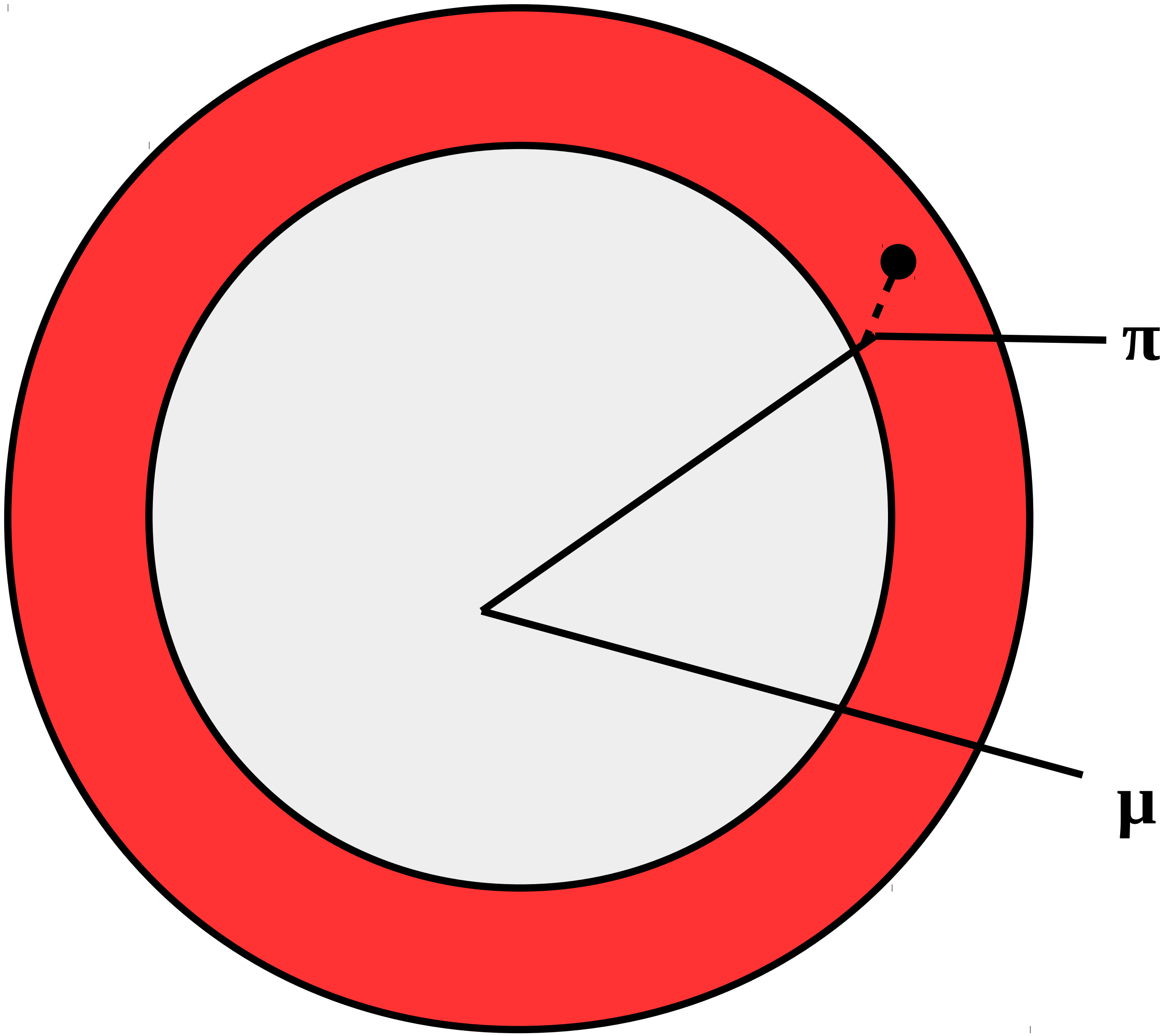
- First, position of all interactions in detector hall

Hall-originating event vertices



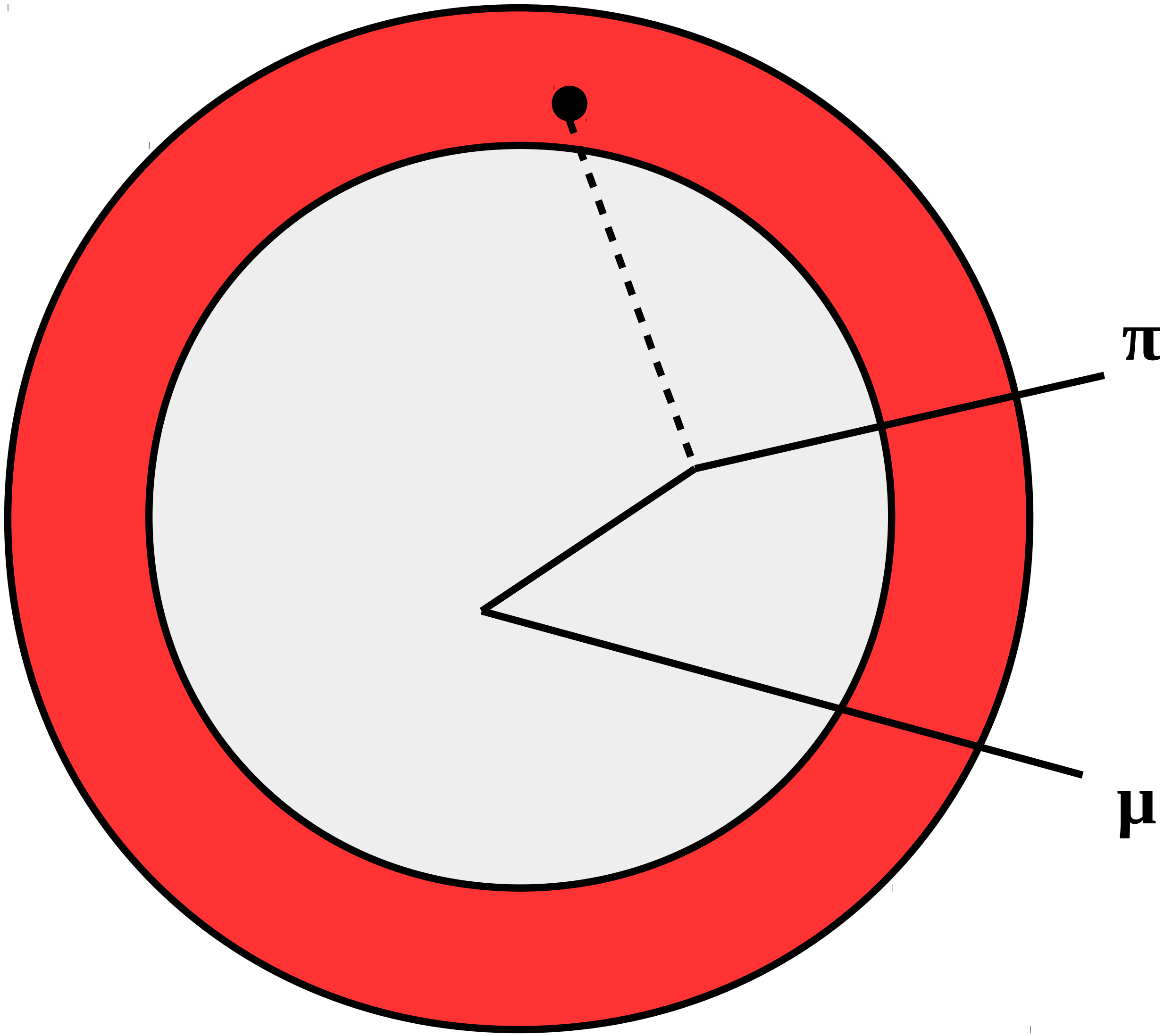
- Position of neutrino interaction for events that produce neutron candidates in ECAL
- Predominant background source is ECAL itself
- Second is the magnet, especially upstream
- Most downstream parts of LAr also contribute

Intrinsic background



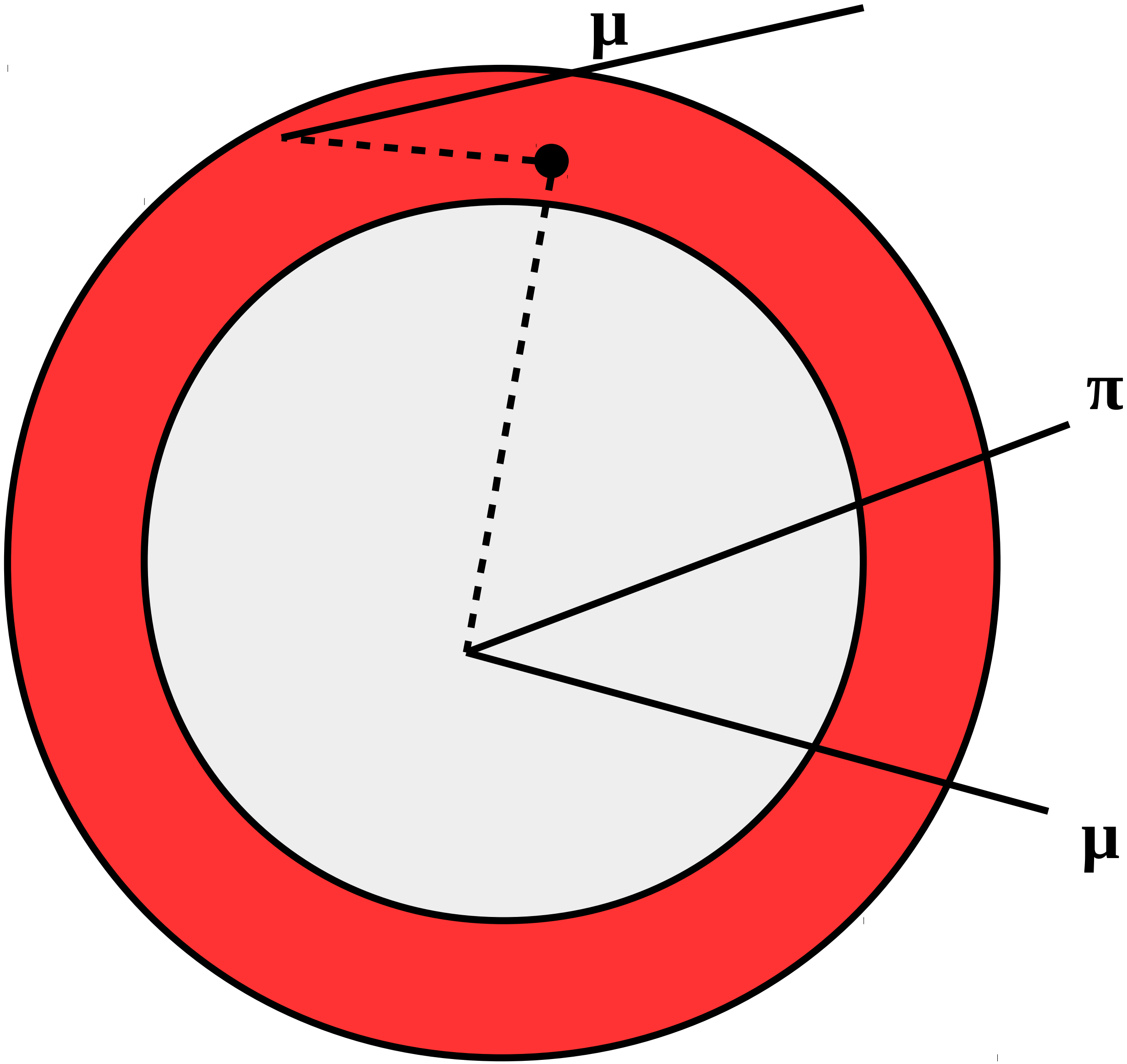
- Backgrounds can originate in gas TPC from neutrons produced by charged particle interactions
- Often, the scatter occurs in the ECAL, and the neutron is spatially near the TPC track vector, and can be rejected

Intrinsic background



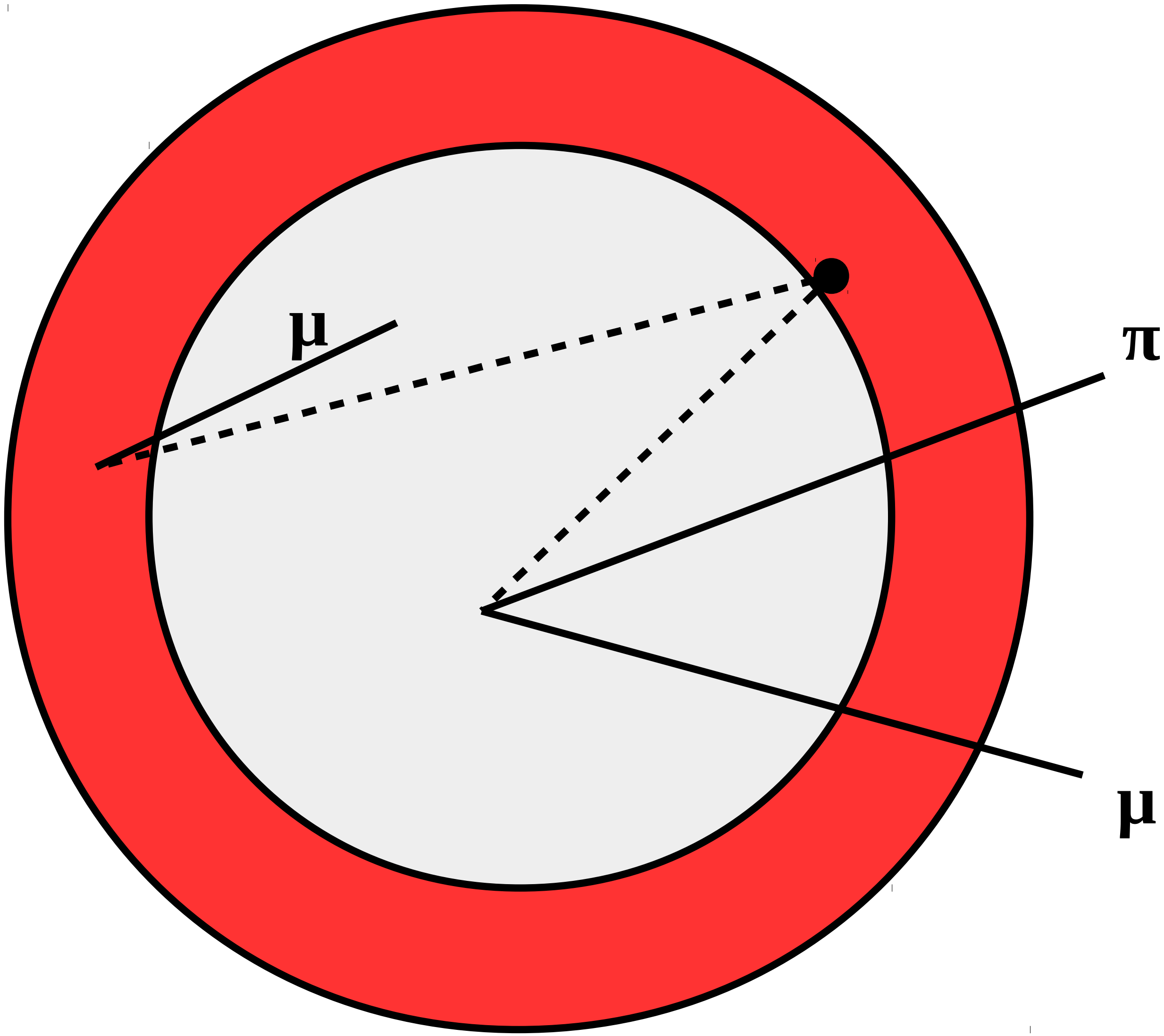
- But when interaction occurs in the TPC, it is very hard to distinguish from primary neutrons
- This is the most challenging background

External (pile-up) background



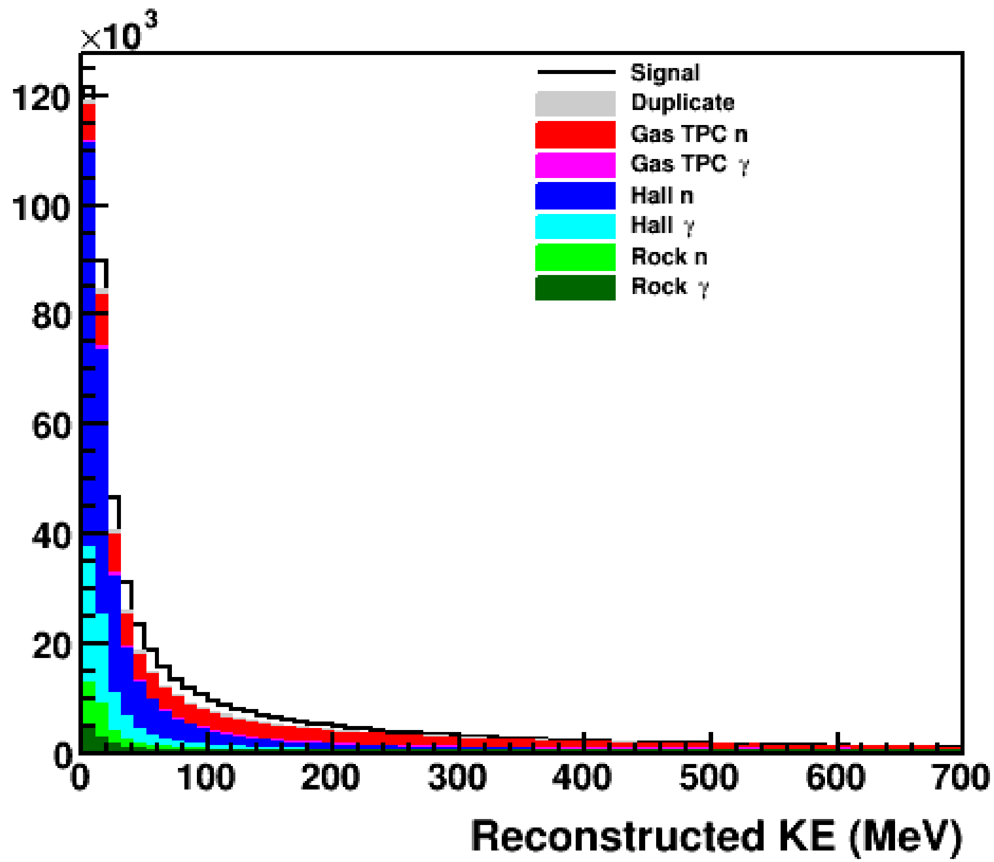
- Pile-up can produce neutrons that accidentally coincide in time with a GAr TPC event
- It is possible to apply a veto when ECAL activity is observed just before a gas TPC interaction, which may produce neutrons

External (pile-up) background



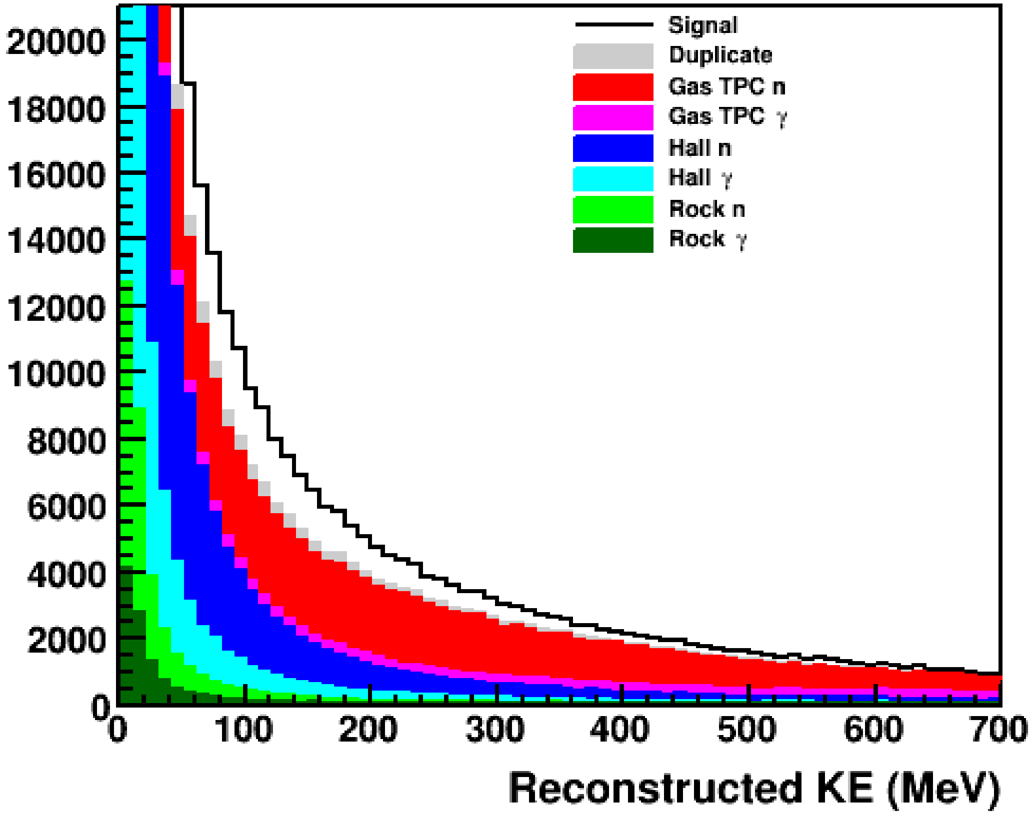
- But neutrons which traverse the GAr are hard to veto – the TOF is 10s to 100s ns, and the rate is too high to veto these events

Out of the box



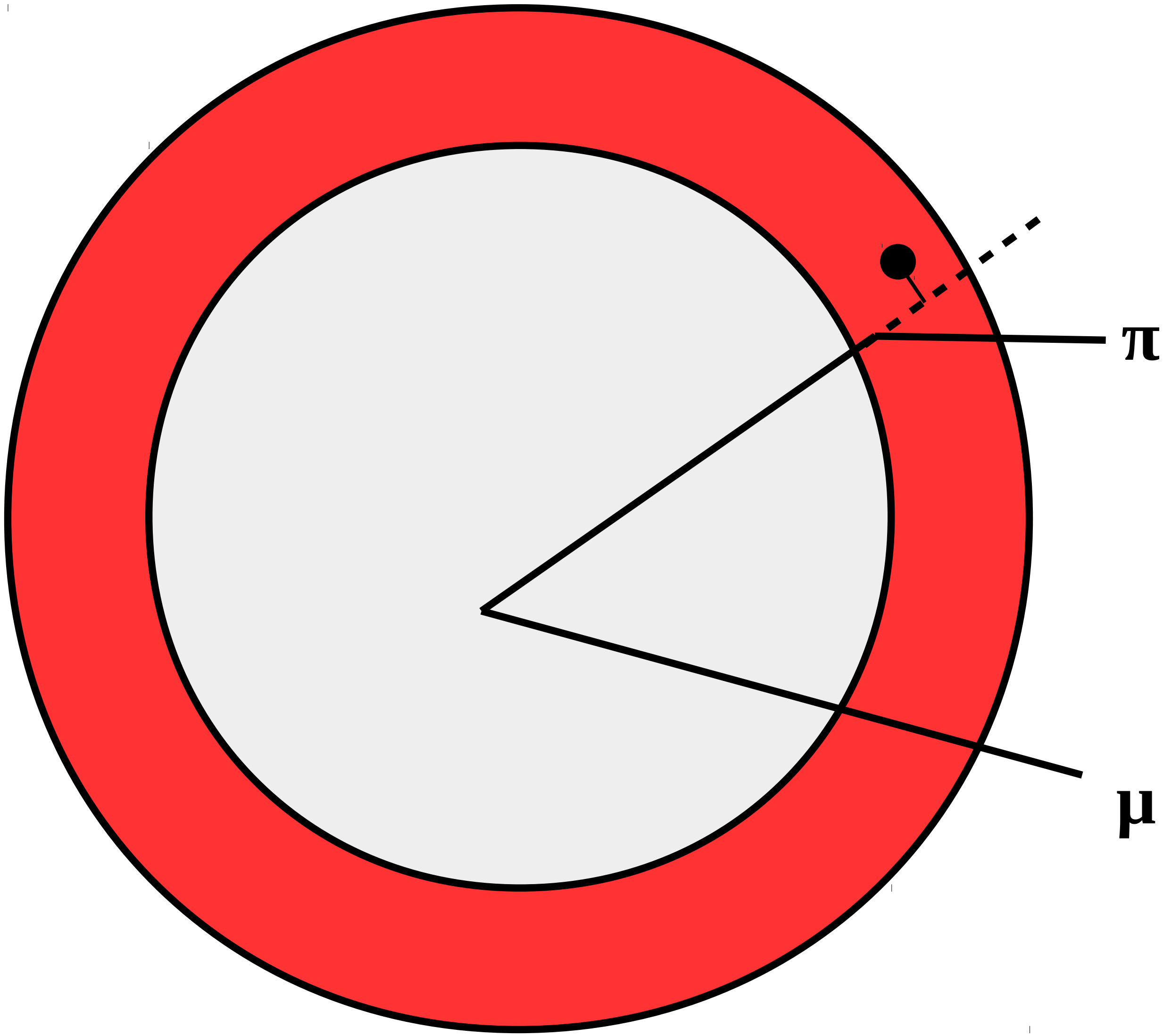
- Pile-up backgrounds are flat in Δt, so they tend to very low reco kinetic energy
- Basically we can't measure 20 MeV neutrons at full intensity because their time of flight is ~50 ns

Zoom in



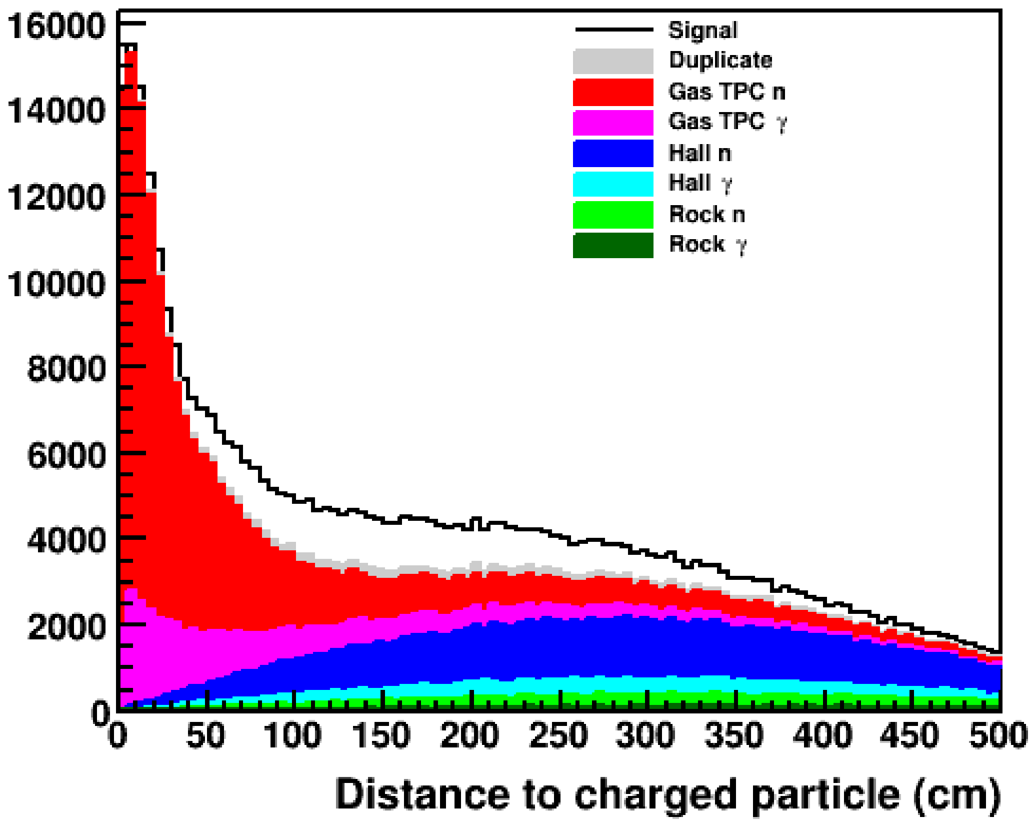
- At high energy, dominant background is from non-primary neutrons produced in the signal neutrino interaction
- At low energy, dominant background is accidental activity

Charged particle trajectory cut



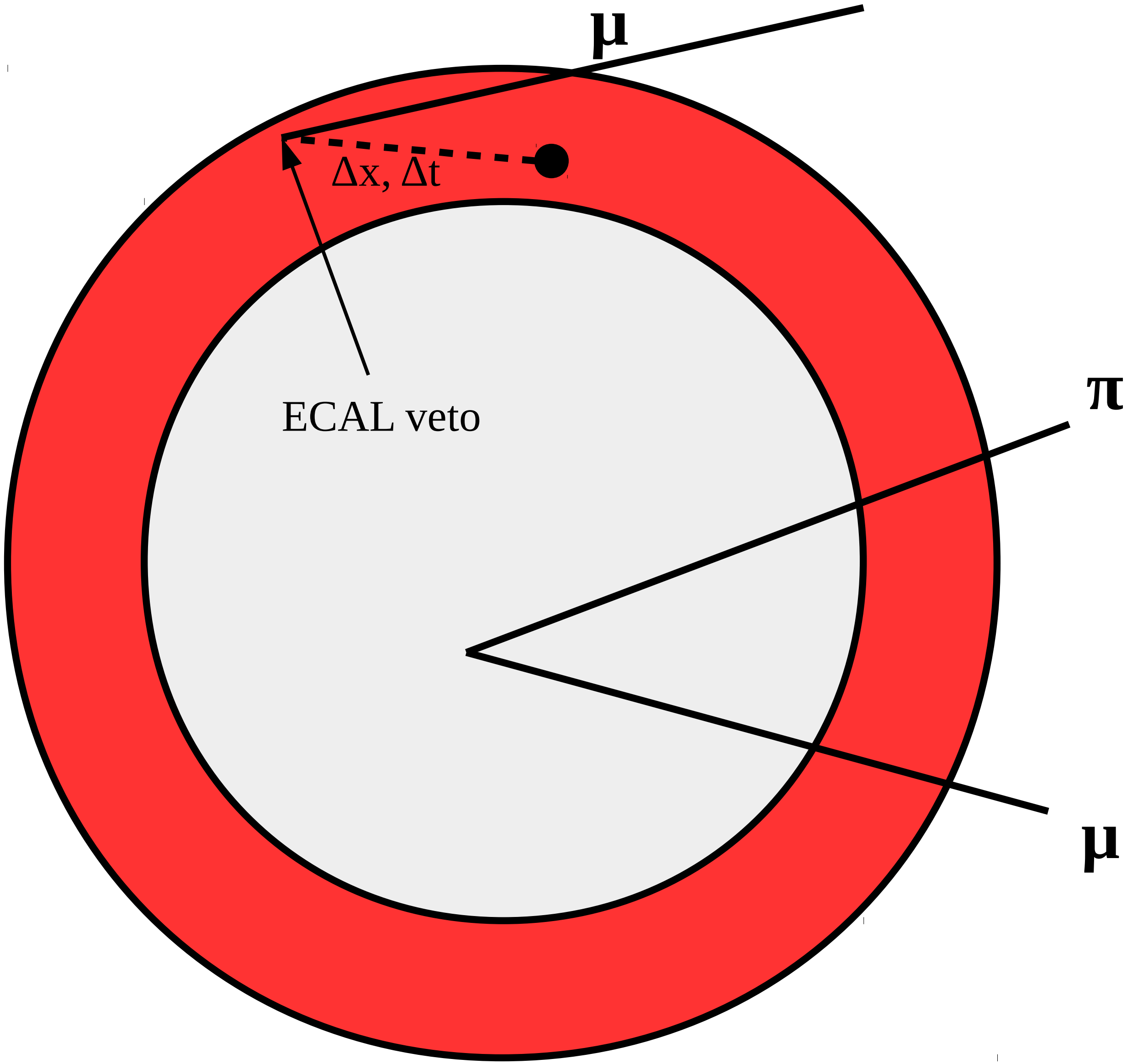
- Project charged tracks into the ECAL
- Look at the distance between a neutron candidate and the nearest charged track trajectory
- Backgrounds from charged particle interactions in the ECAL will be close

Cut #1: charged particle distance



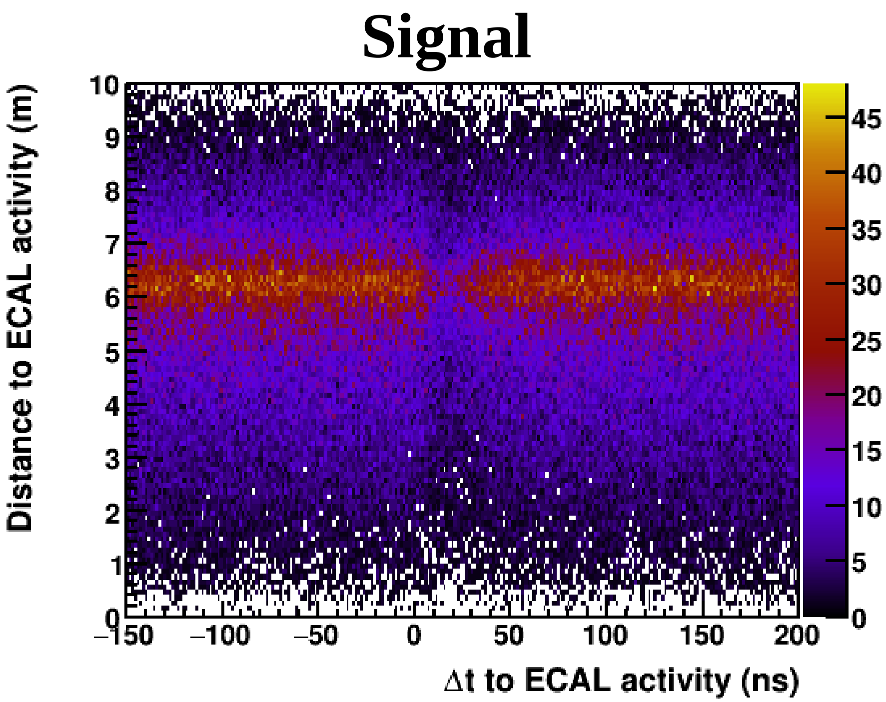
- Plot shows all candidates >5 MeV neutron energy
- Cut at 80 cm
- Rejects neutron candidates from the signal interaction
- Does not remove accidentals

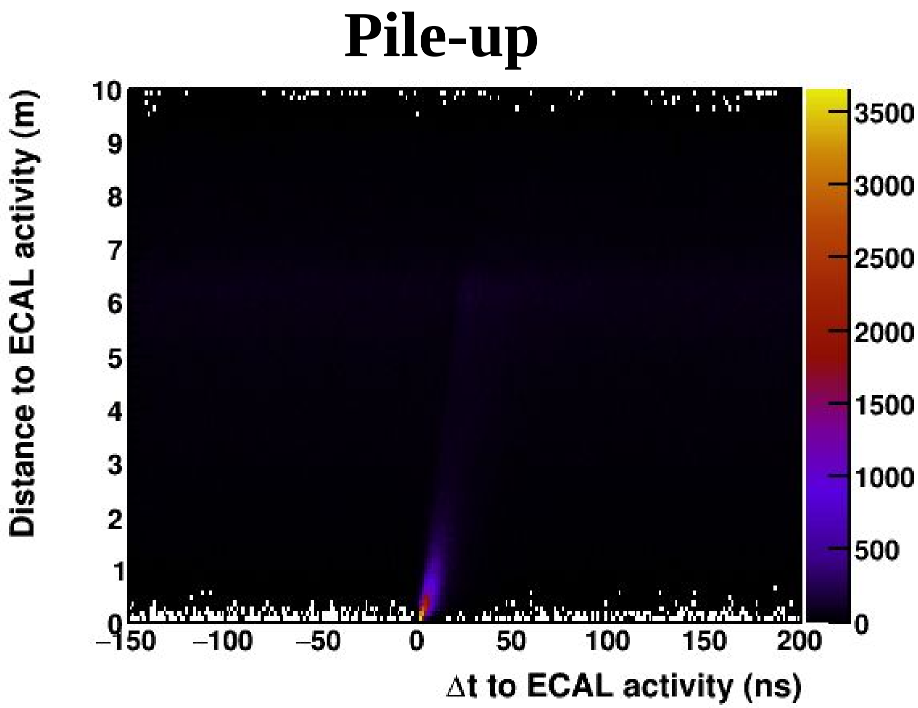
ECAL activity veto



- For each neutron candidate, determine the time and distance to other ECAL activity
- Exclude (-5, +10)ns window around GAr vertex, where ECAL activity will be due to the signal interaction

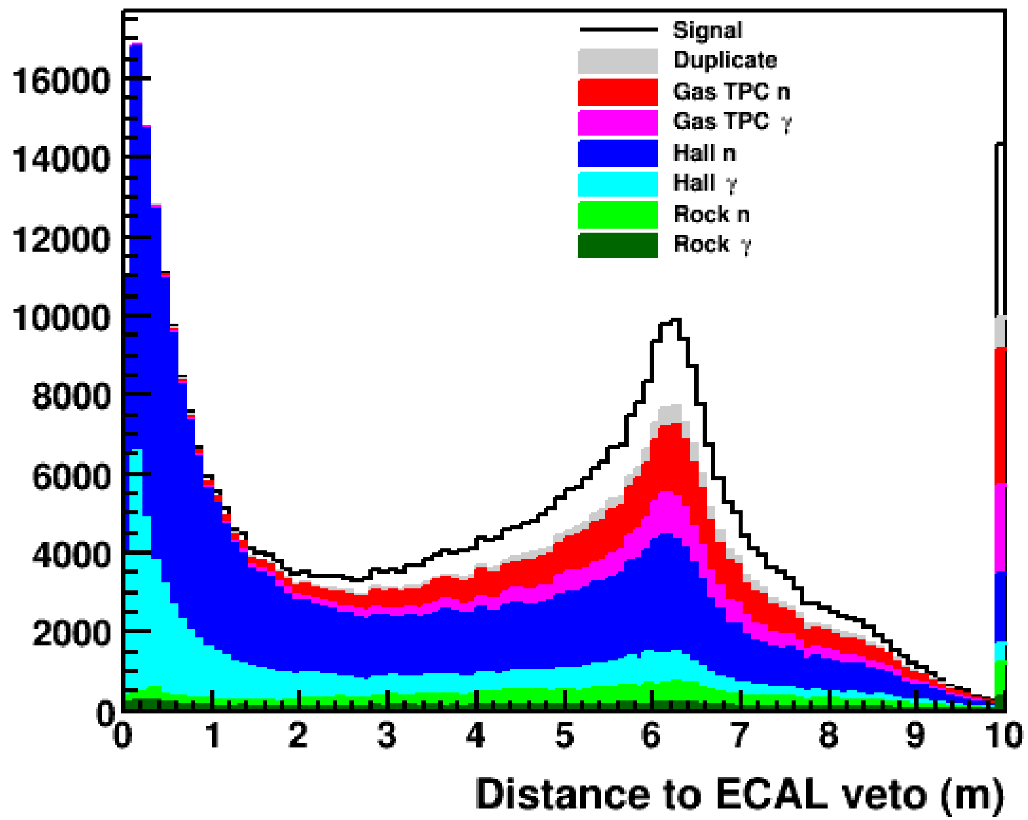
Distance and Δt to ECAL veto





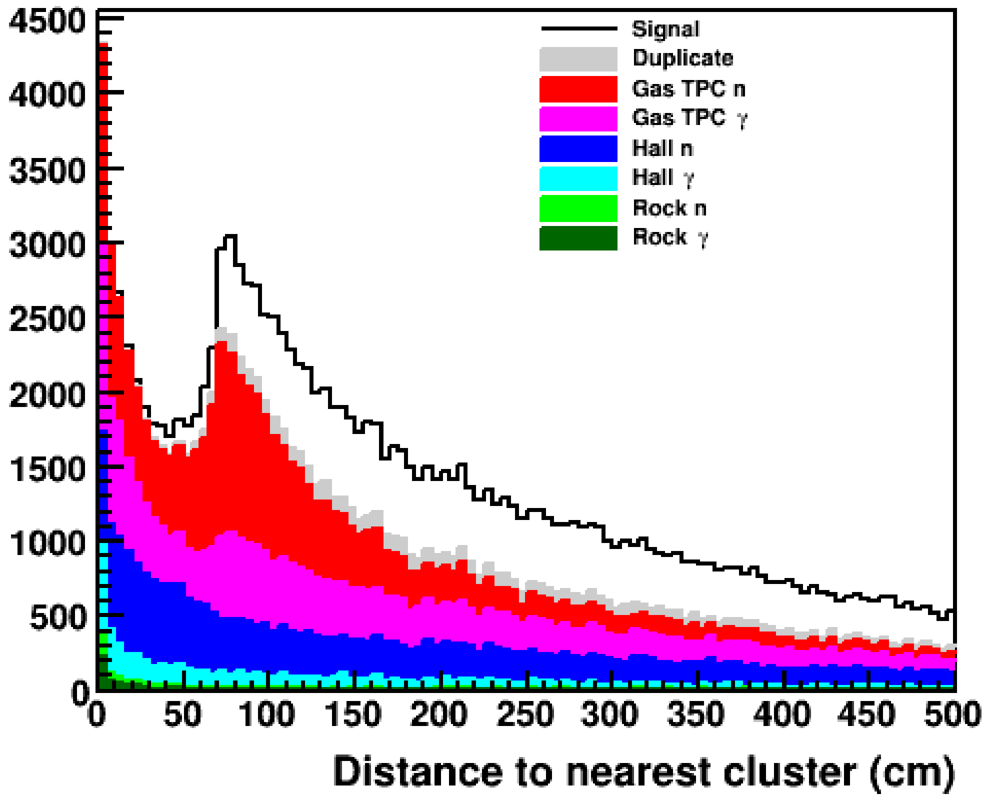
- Signal is flat in Δt to random ECAL activity, peak around 6m is because most pile-up is upstream-entering, and most signal neutrons are downstream, and thus ~6m apart
- Background is generally close in time and space to other ECAL activity and can be vetoed with almost no signal loss

Projected onto distance axis



- Pile-up neutrons that don't go all the way through gas TPC are easily rejected by cut at 2m
- Pile-up for neutrons that scatter far from where they are produced is not rejected – the veto is too long and would reject too much signal

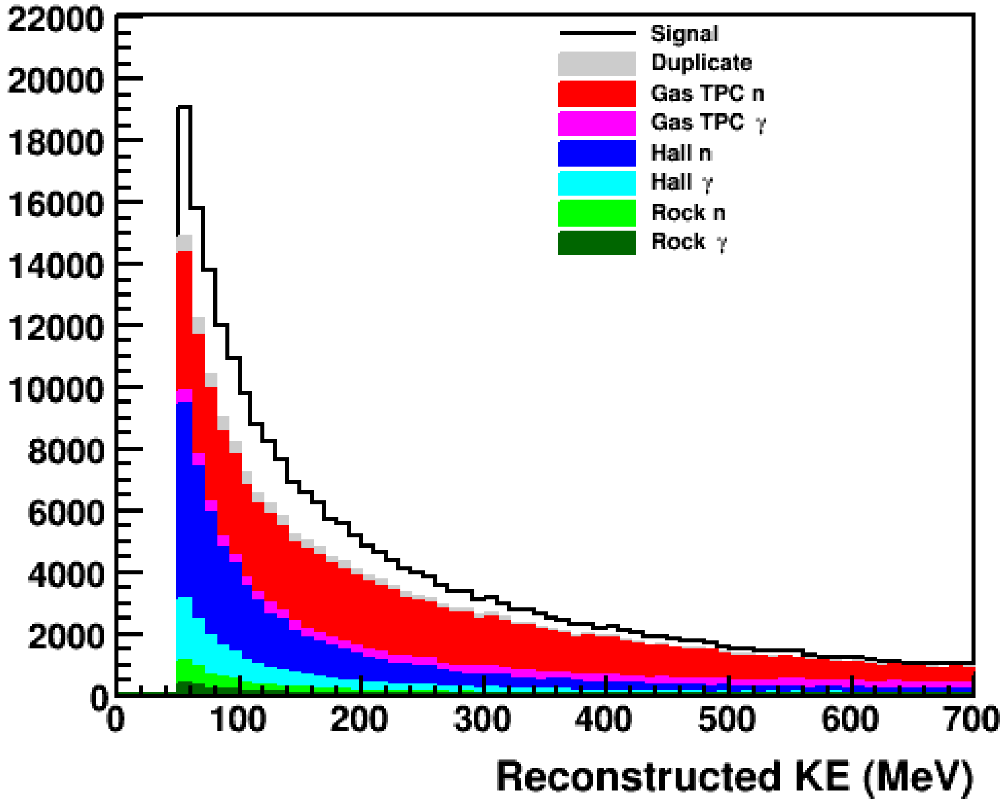
Isolation from other ECAL clusters



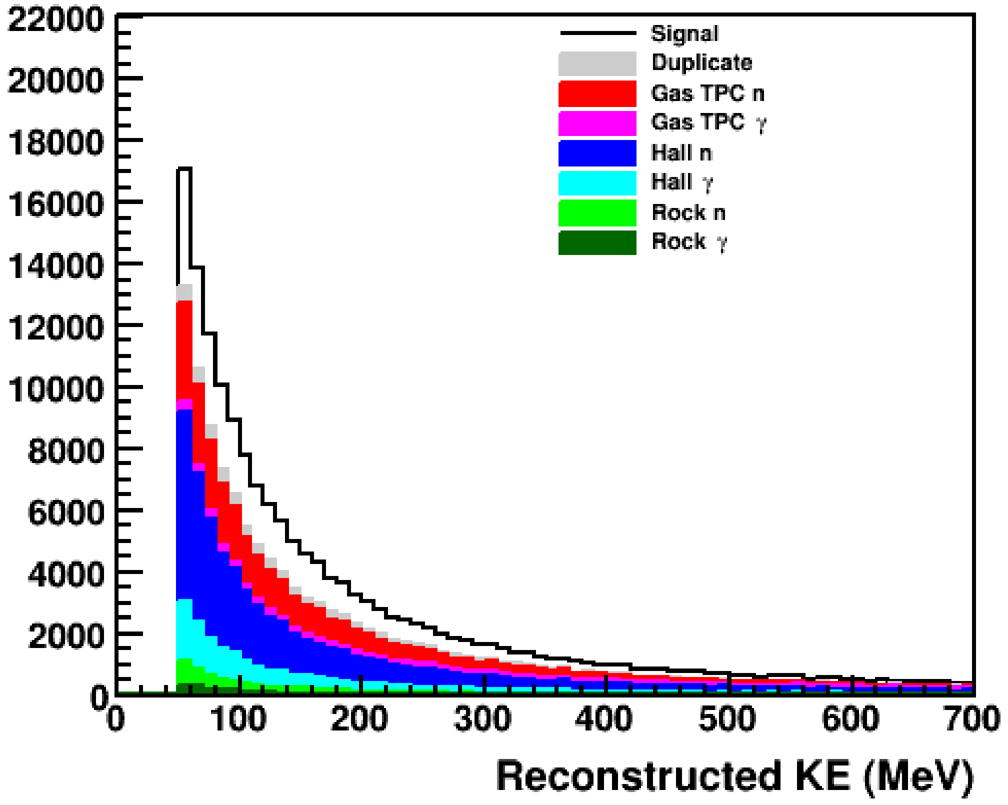
- Largely redundant with cut on entering charged tracks
- But can remove some additional background where track does not come from gas TPC

Reco KE distribution

- No cuts

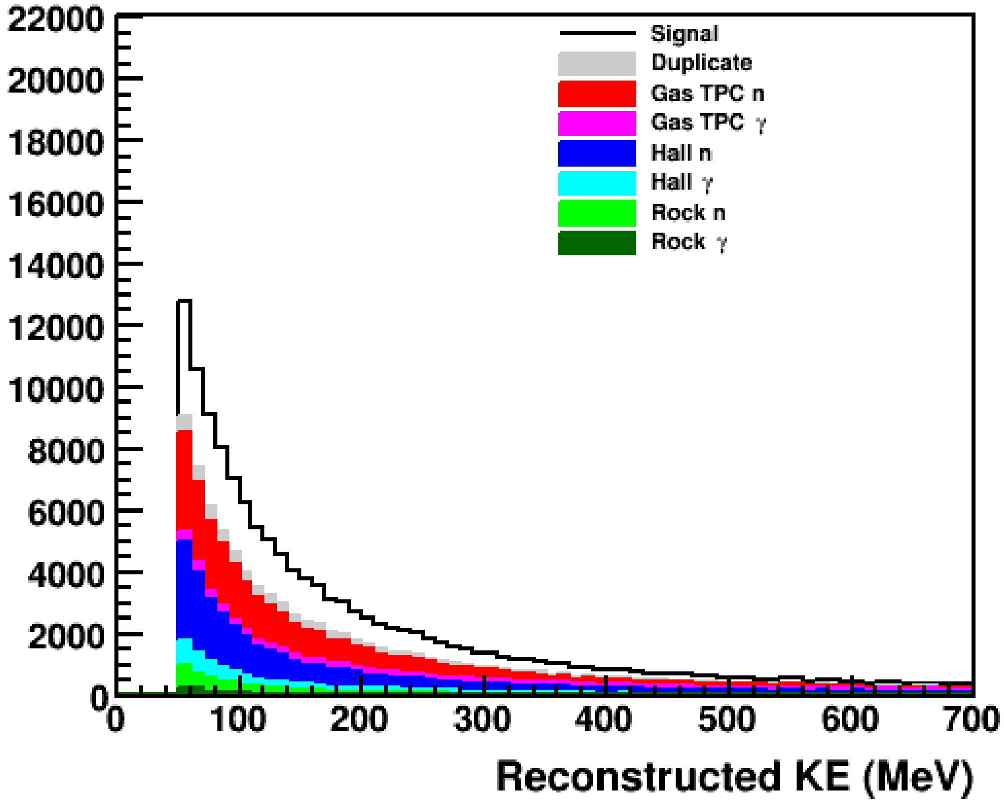


Reco KE distribution



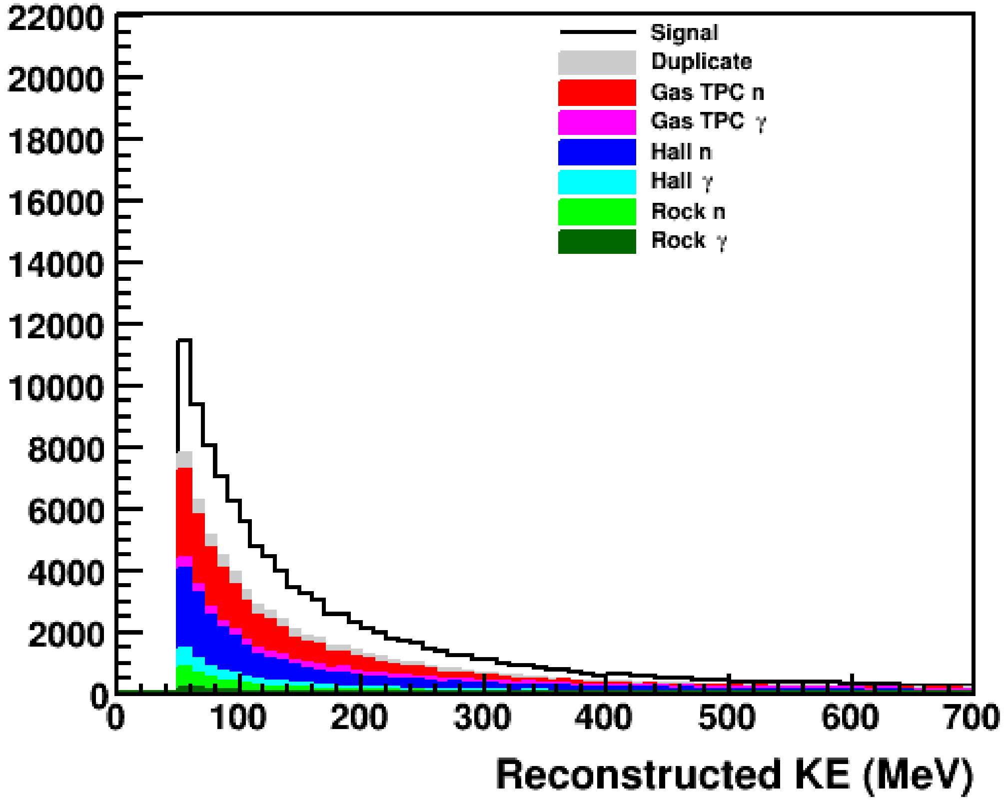
- Charged TPC track cut

Reco KE distribution



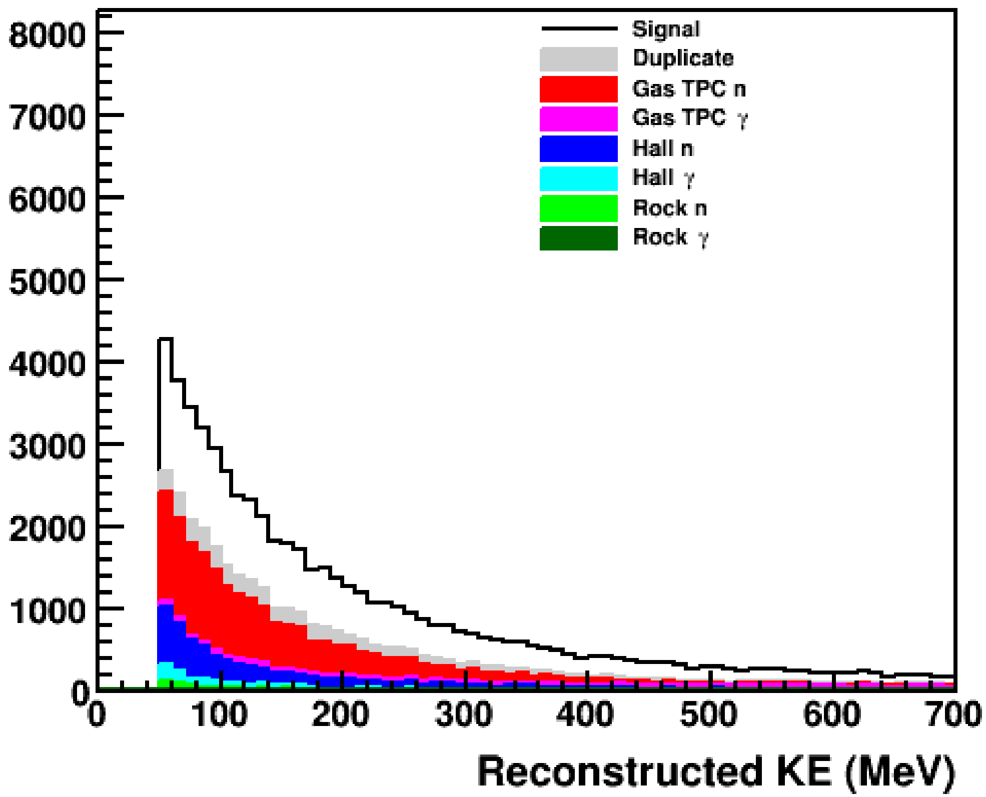
- Charged TPC track cut
- ECAL activity veto

Reco KE distribution



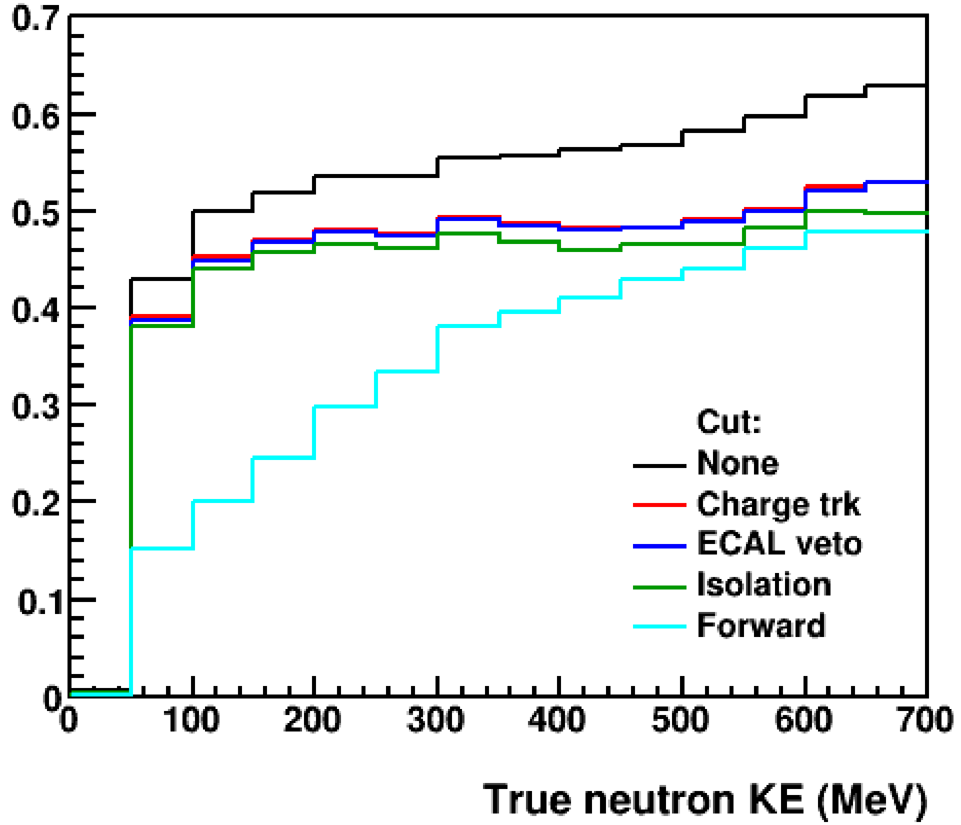
- Charged TPC track cut
- ECAL activity veto
- Isolation from other clusters

Reco KE distribution



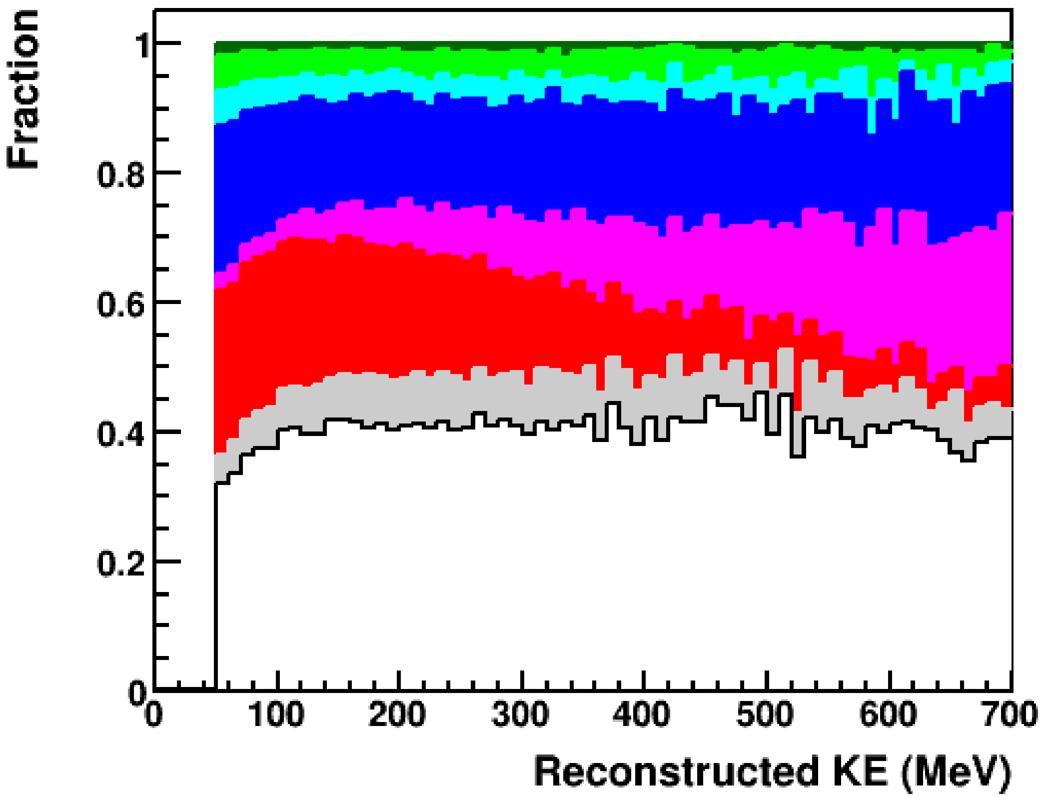
- Charged TPC track cut
- ECAL activity veto
- Isolation from other clusters
- Forward neutrons only

Selection efficiency



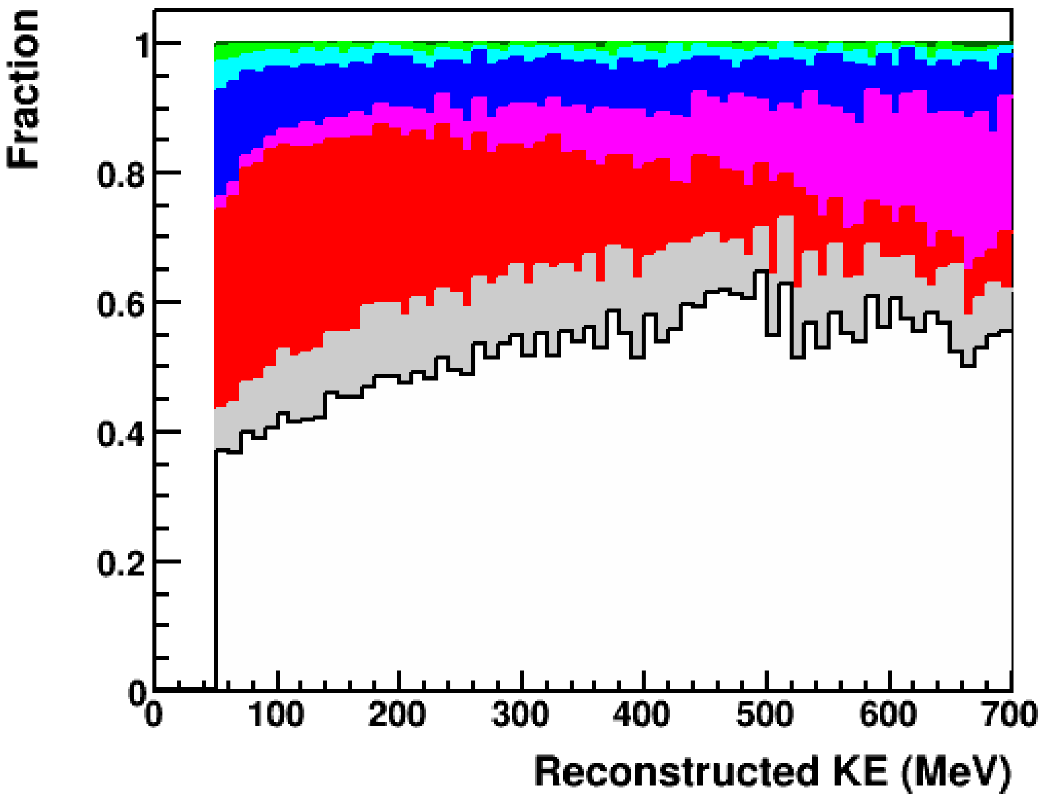
- Efficiency for all neutrons is ~40-50% with loose selection cuts

Sample purity



- But purity for all neutrons is only ~40%
- ~20% due to pile-up background, the rest due to neutrons (or photons) from the gas TPC event
- Better photon rejection in progress, should help purity at high reconstructed KE

Sample purity (forward)



- Slightly better at high energy when you only consider forward neutrons

Conclusions

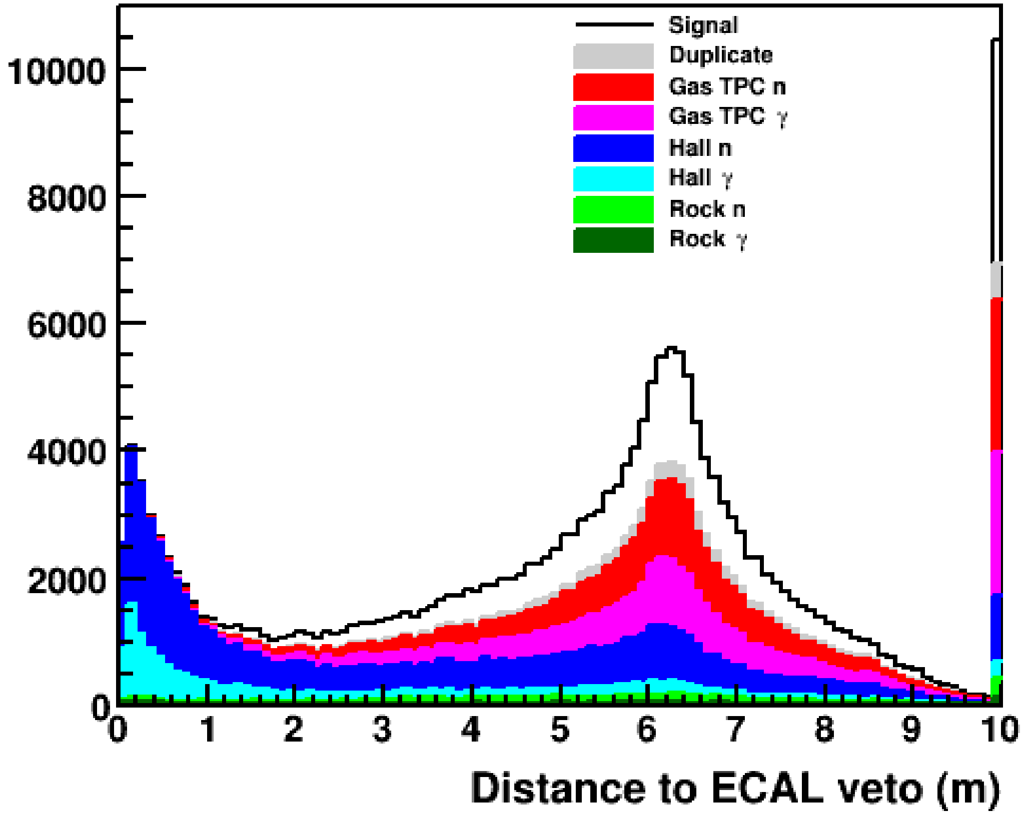
- Neutron reconstruction in MPD is challenging
- Can achieve ~50% efficiency with ~50% purity for forward neutrons
- Energy resolution is poor and biased above ~100 MeV due to missing the initial scatter, could be improved by optimizing active fraction (more CH)
- Non-primary neutrons are a major background
- Backgrounds from rock are minimal – magnet, ECAL, and LAr TPC are major sources

Next steps

- Improve n/γ cut by voxylizing hits in each layer and looking at transverse quantities
- Look at RHC
  - Less pile-up background
  - Less non-primary background on average due to lower energy hadrons
  - More energetic primary neutrons

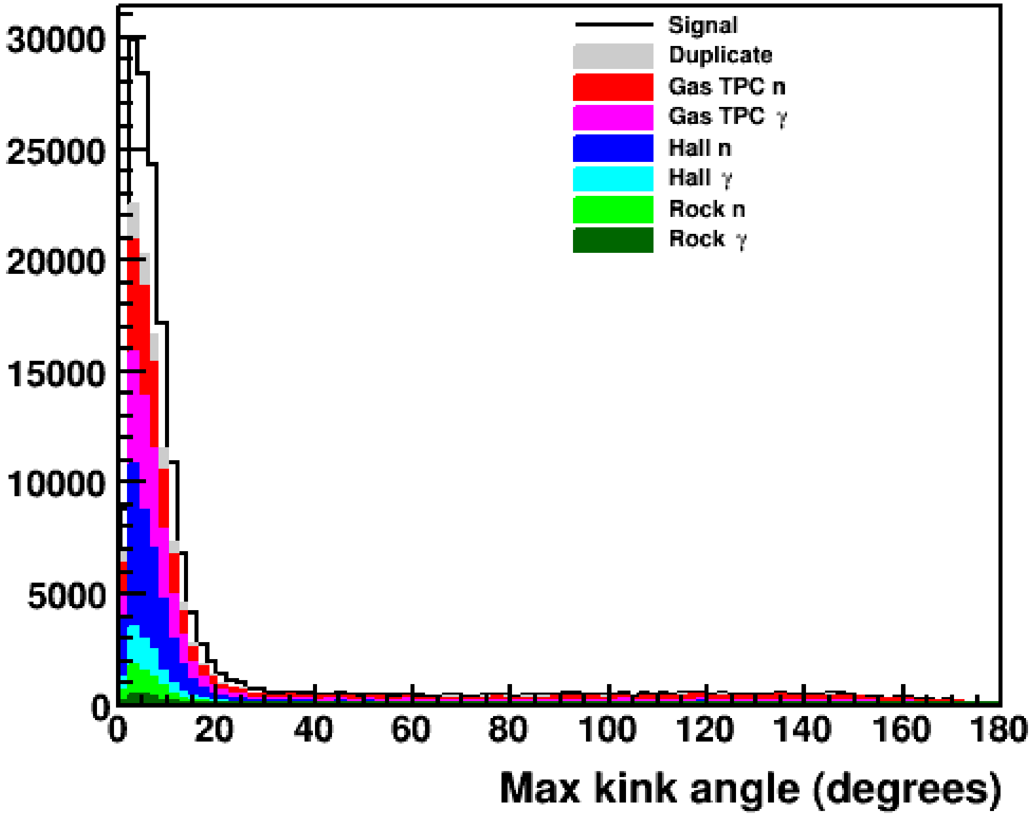
Backup

Distance to ECAL activity (>50 MeV reco only)



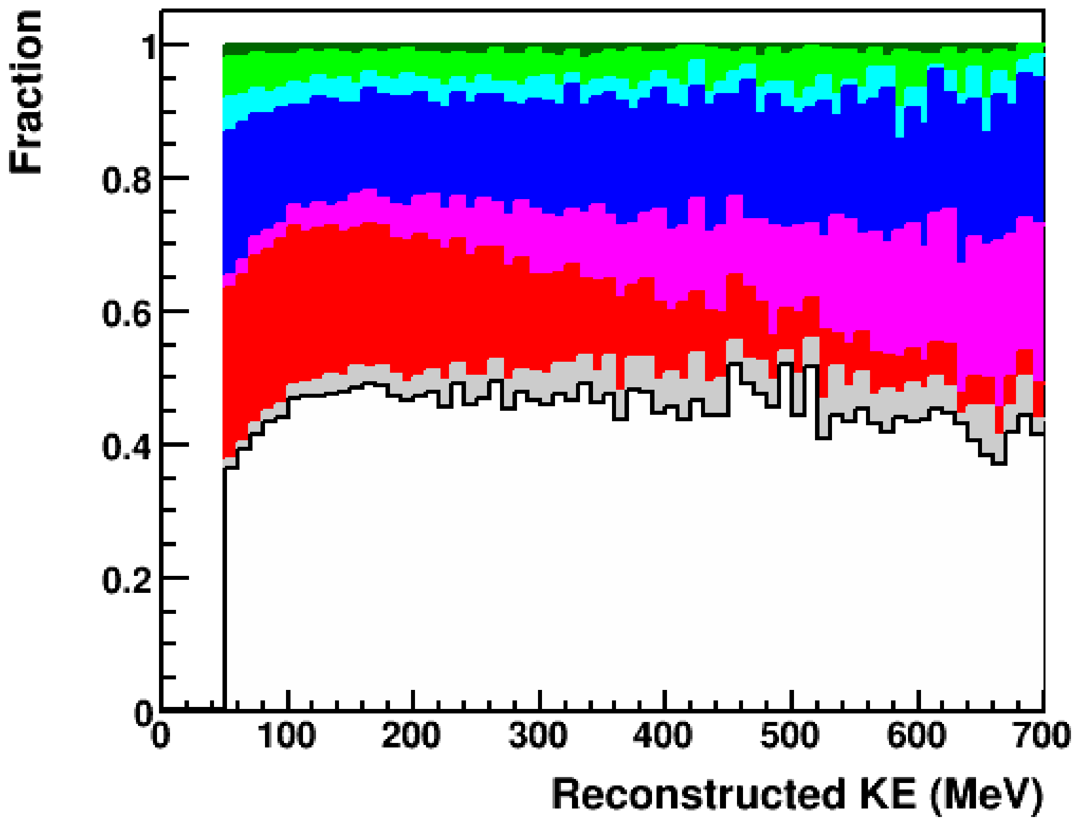
- Most pile-up is reconstructed at very low energy

Kink track angle



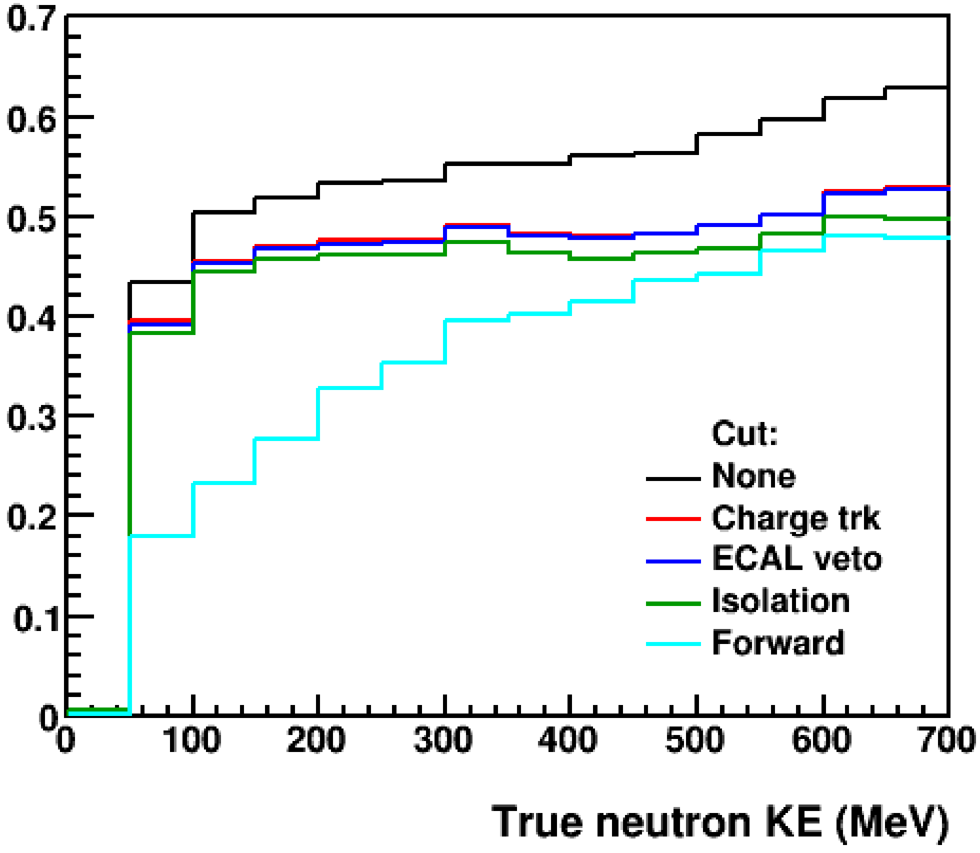
- Maximum kink angle
- Some gas-induced non-primary neutrons are correlated with interactions in the TPC which produce large kinks

Purity for leading neutron only



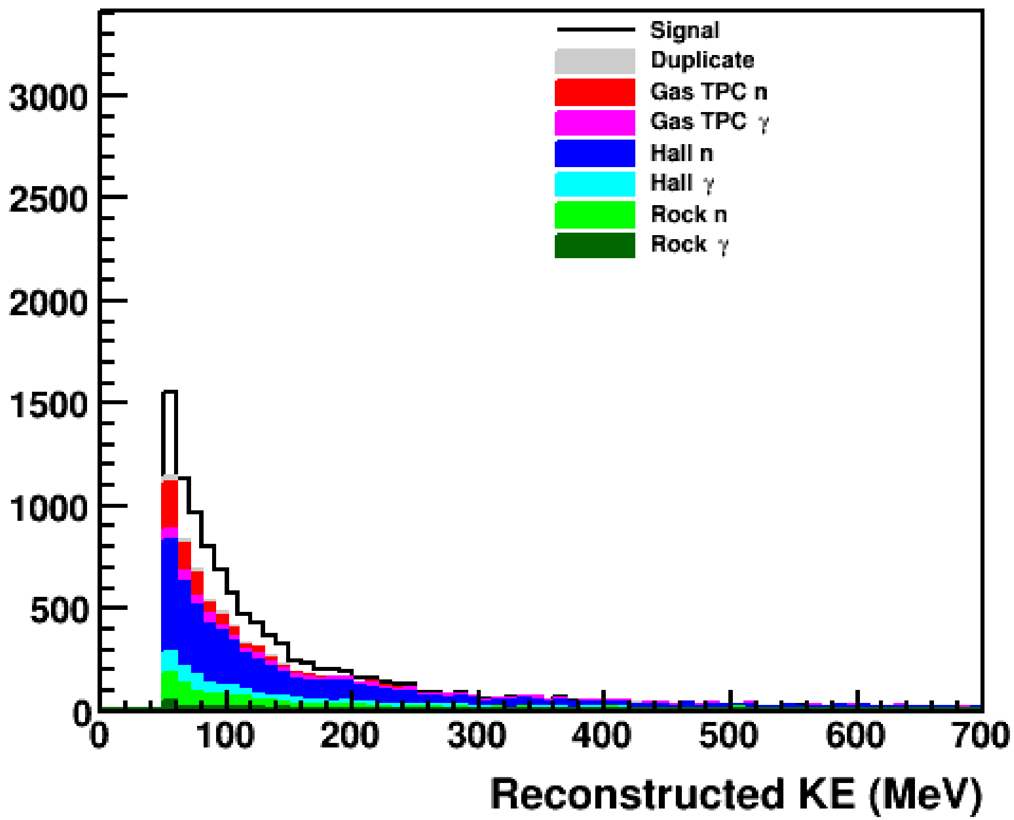
- All angles
- Slightly higher purity

Eff for leading neutron only



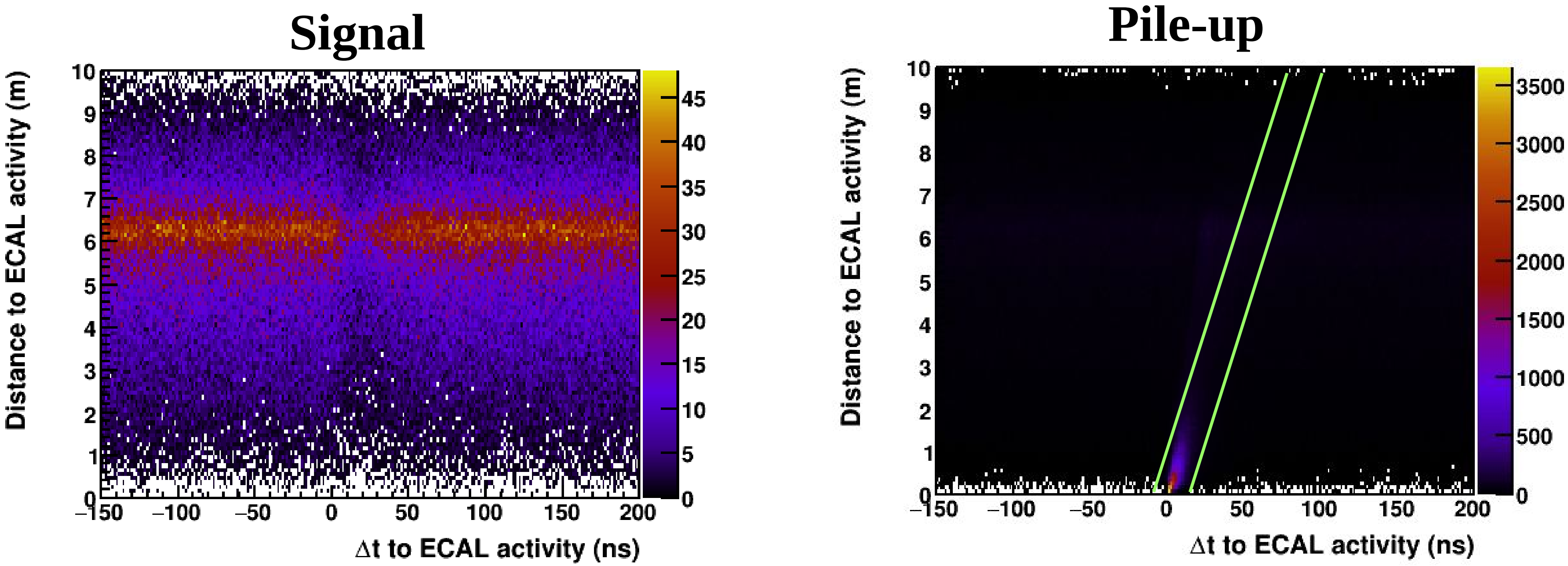
- All angles
- Similar efficiency to considering all neutrons

Backward neutrons



- More pile-up, less signal

Tighter pile-up cut



- Nominal cut only excludes neutrons within 2m of ECAL activity
- But can also exclude entire ECAL for fast-coincident activity

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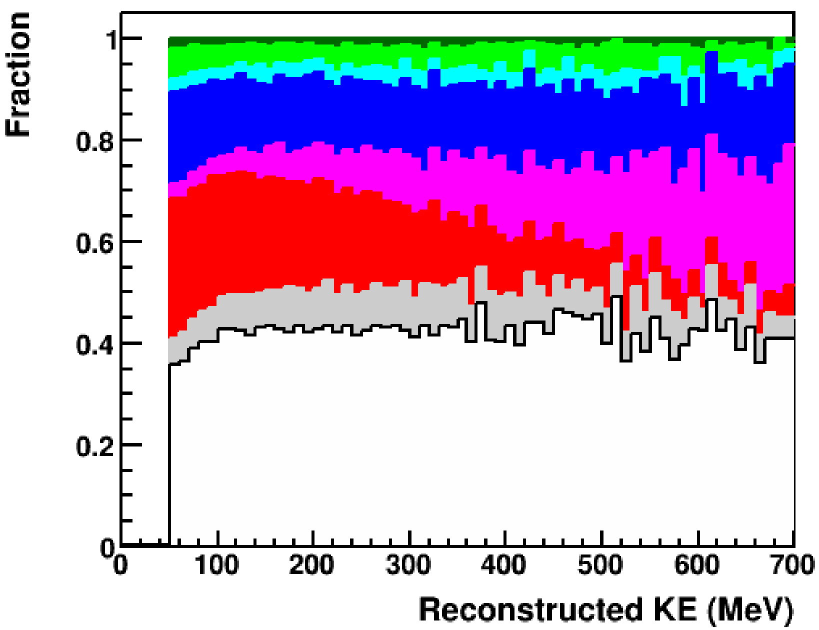
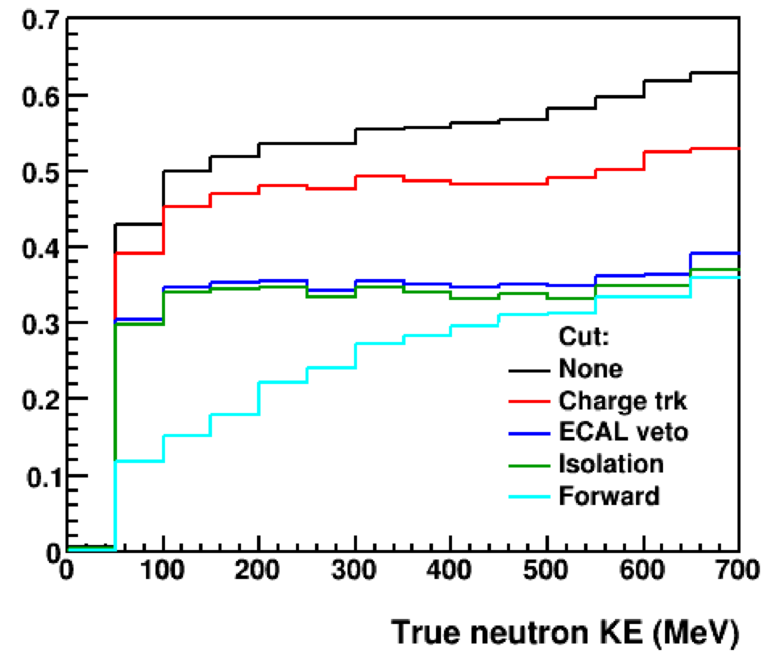
Tighter pile-up cut





- Reduced efficiency, but only slightly improved purity
- Not a good cut – vetoing on activity far away from the neutron candidate removes too much signal