Neutron reco in ECAL with TOF

Chris Marshall
Lawrence Berkeley National Laboratory
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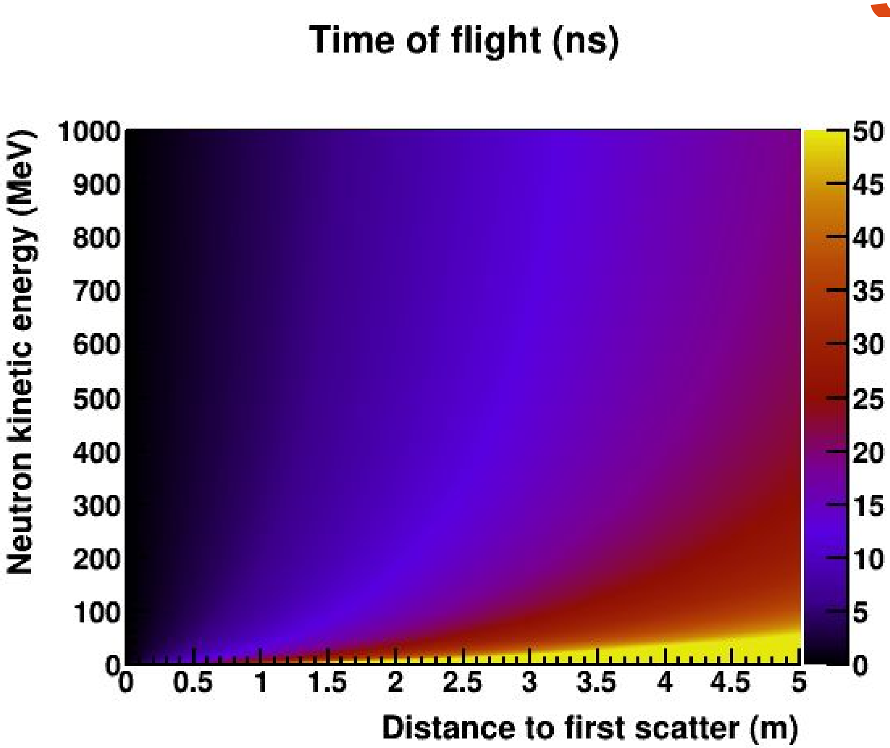
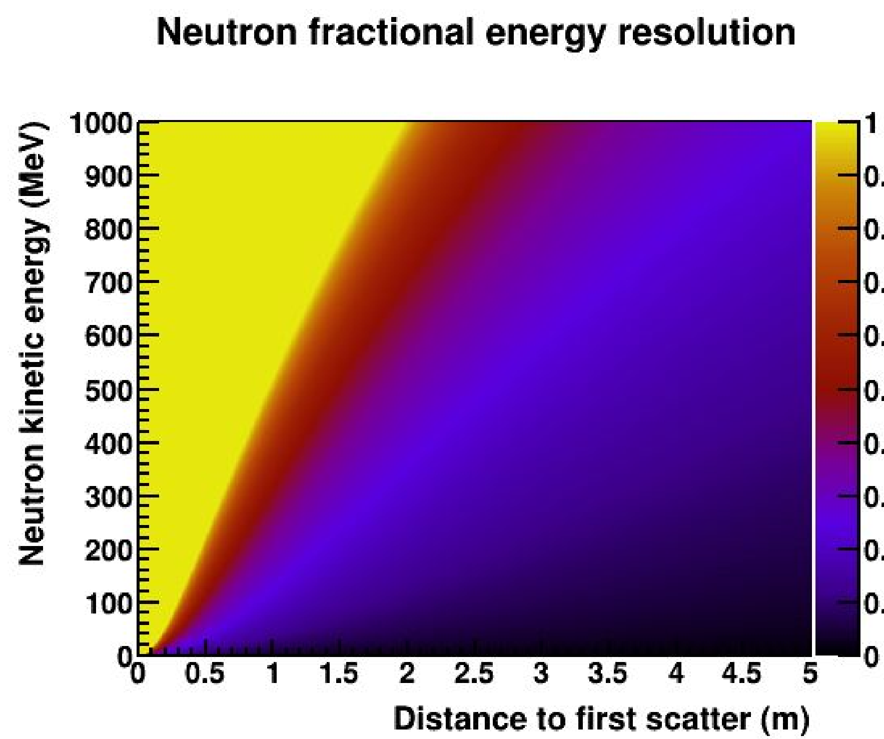
Motivation

- Neutron production by (anti)neutrinos is highly uncertain, and is a large source of neutrino energy misreconstruction
- Measuring neutron energy with TOF has been demonstrated by MINERvA, and demonstrated for DUNE by 3DST group
- Similar technique using ECAL is promising
  - Measure neutron production on Ar directly
  - Long lever arm → improved energy resolution
  - Combine HPG TPC charged particle resolution with neutron reconstruction for excellent measurement of E_ν

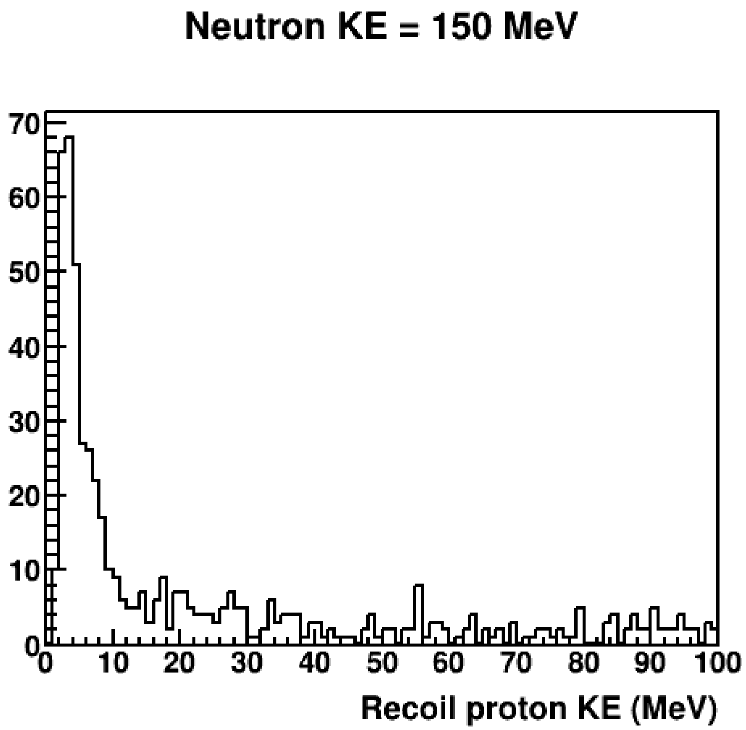
Time of flight vs. energy and energy resolution

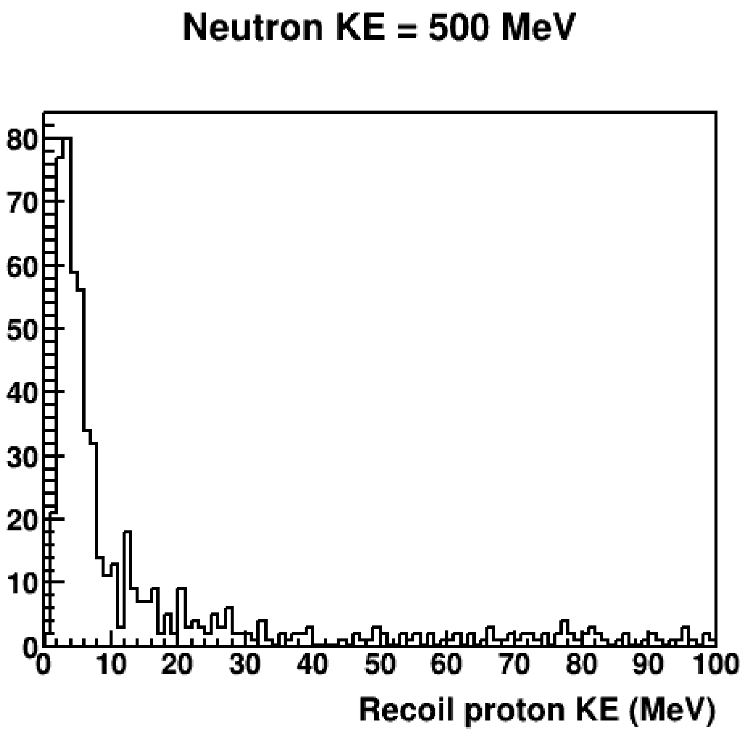




- Left: neutron time of flight as a function of lever arm, and kinetic energy
- Right: Fractional energy resolution for σ(time) = 0.7 ns on both vertex and endpoint timing, assuming you can identify the first neutron interaction (pen and paper calculation)

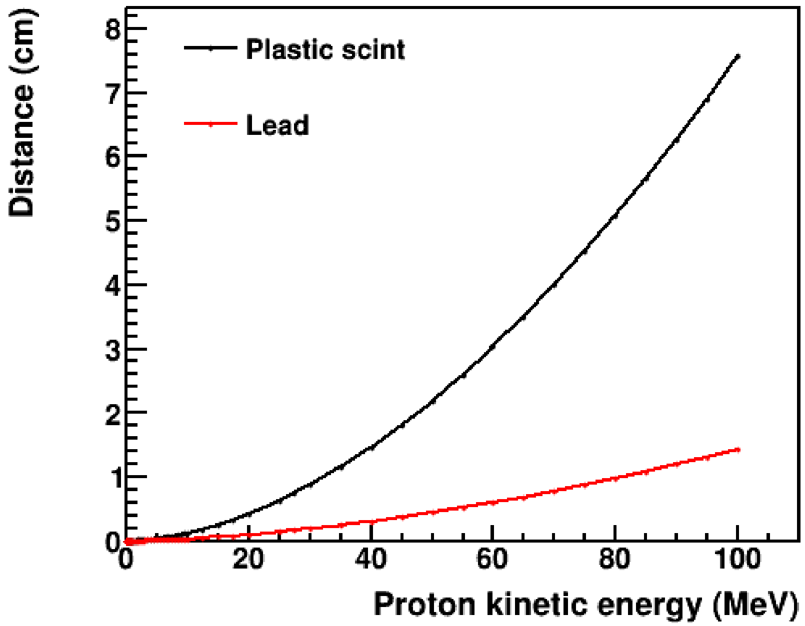
Recoil proton kinetic energy

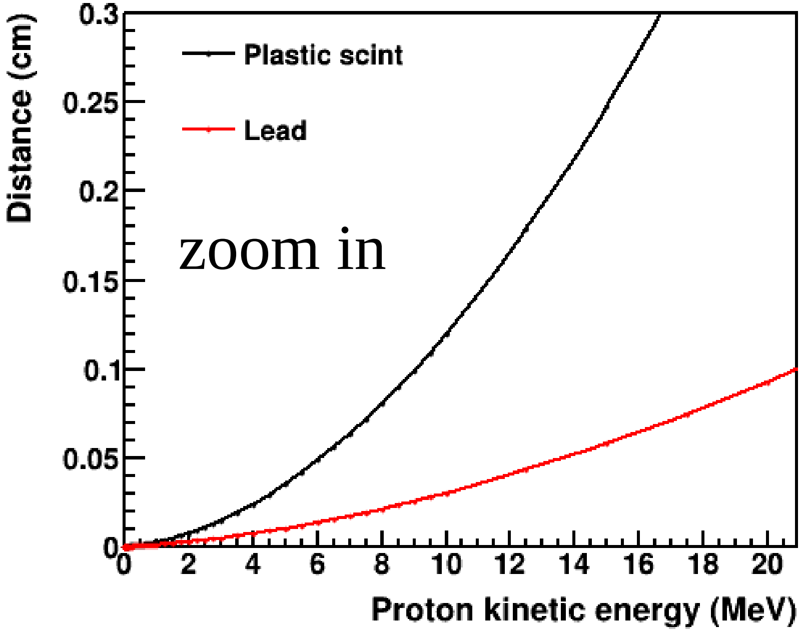




- Most recoil protons are ~3-10 MeV kinetic energy, independent of the energy of the incoming neutron
- Detector must be sensitive to isolated, few-MeV energy “blip”

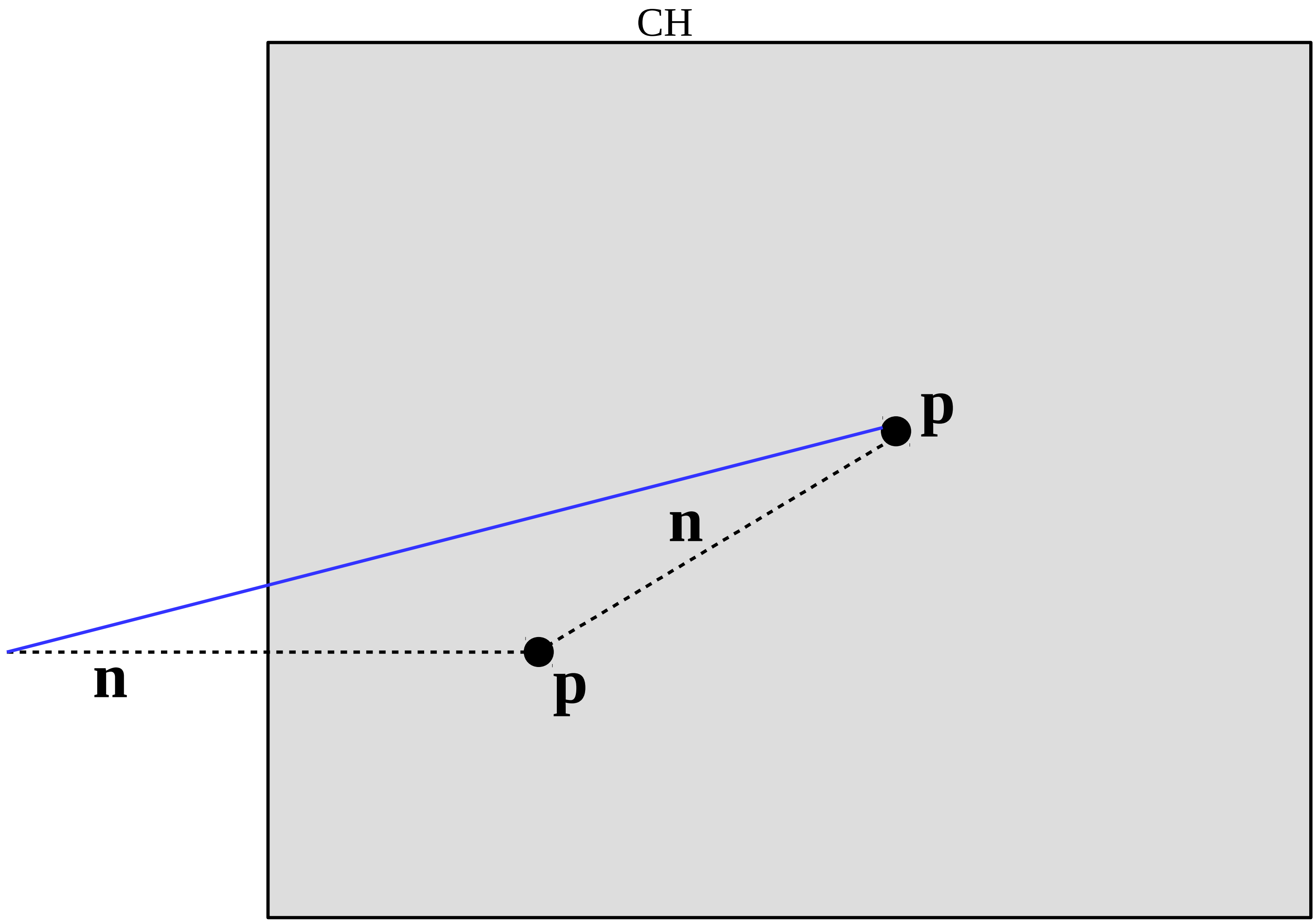
Proton stopping distance





- 10 MeV proton goes ~1mm in plastic, ~300μm in lead
- Protons will not traverse multiple detector layers unless they are sub-mm thickness, so need fully 3D readout

Misreconstruction of energy

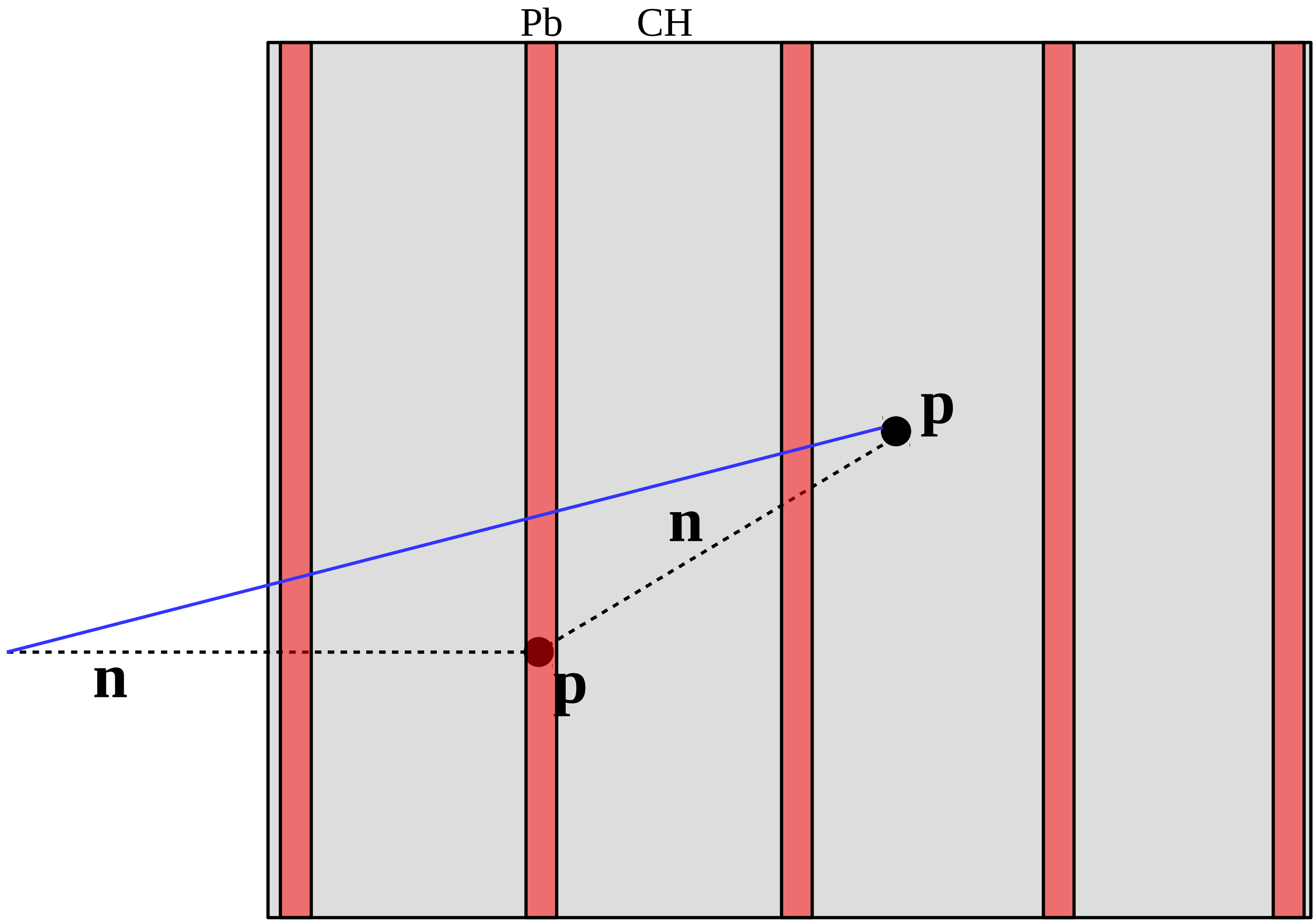


Miss first interaction → underestimate distance traveled

Second neutron is slower → TOF gives overestimate of initial neutron's energy

$\beta = d/t$ → underestimate energy

Unique challenge for ECAL



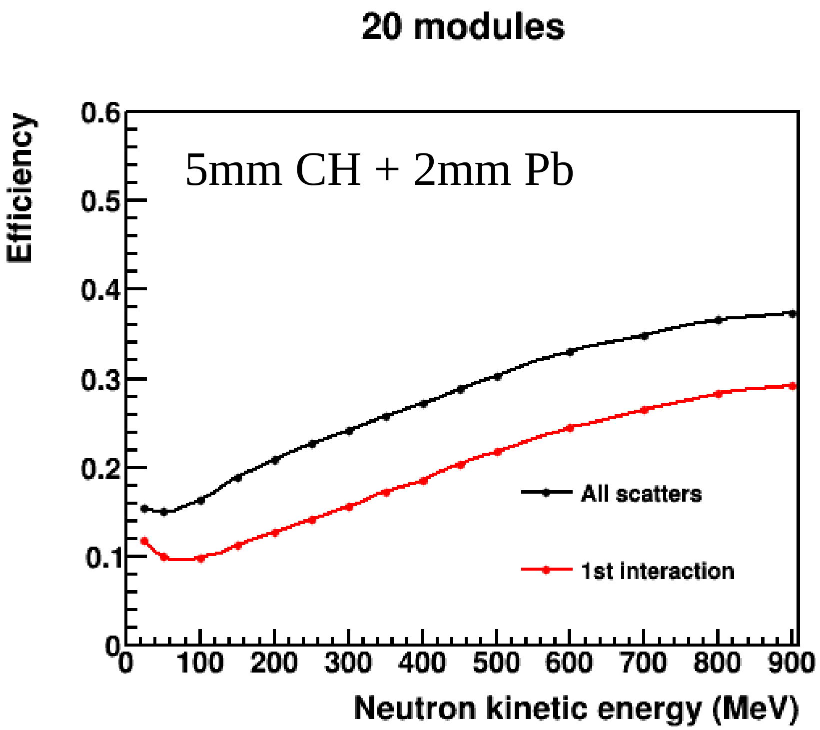
"Missed scatters" are more common because of passive absorbers

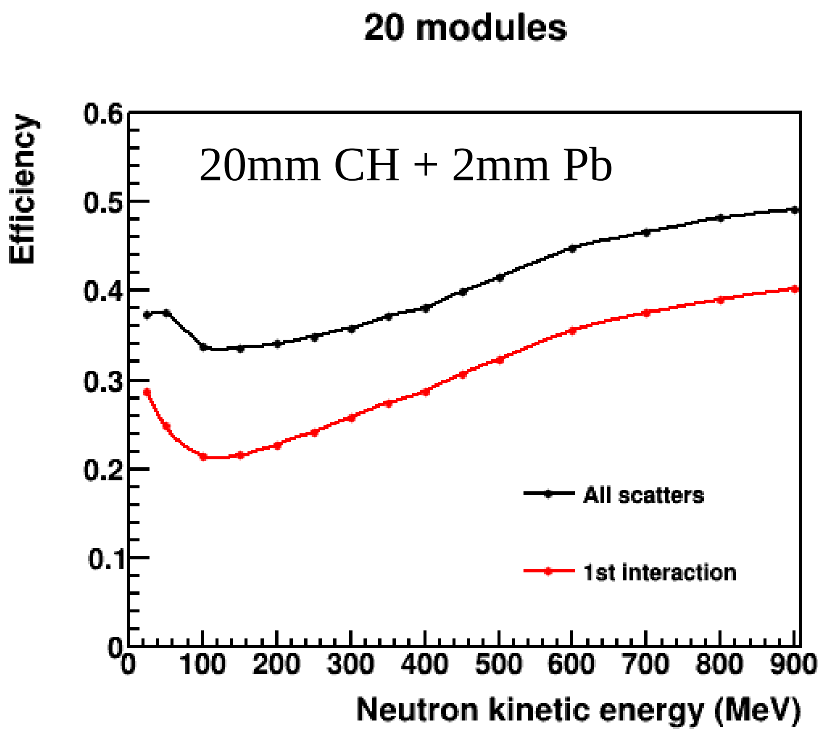
Expect low-side tails to be larger for ECAL than fully-active detector like 3DST

Optimizing ECAL parameters

- Want to minimize interactions in absorber compared to active scintillator → high-Z, short-X_0 material → lead
- Density is ~10x higher than scintillator, so to get ~equal interaction rate in CH and PB, need ~10x thicker scintillator
- We use 2mm Pb + 20mm CH to study resolution and efficiency:
  - Single neutron gun
  - Assume 0.7ns uncertainty on vertex and neutron recoil
  - Require 5 MeV true proton energy deposit (adding scintillator quenching in progress...)
  - Separate events based on "first scatter" or otherwise

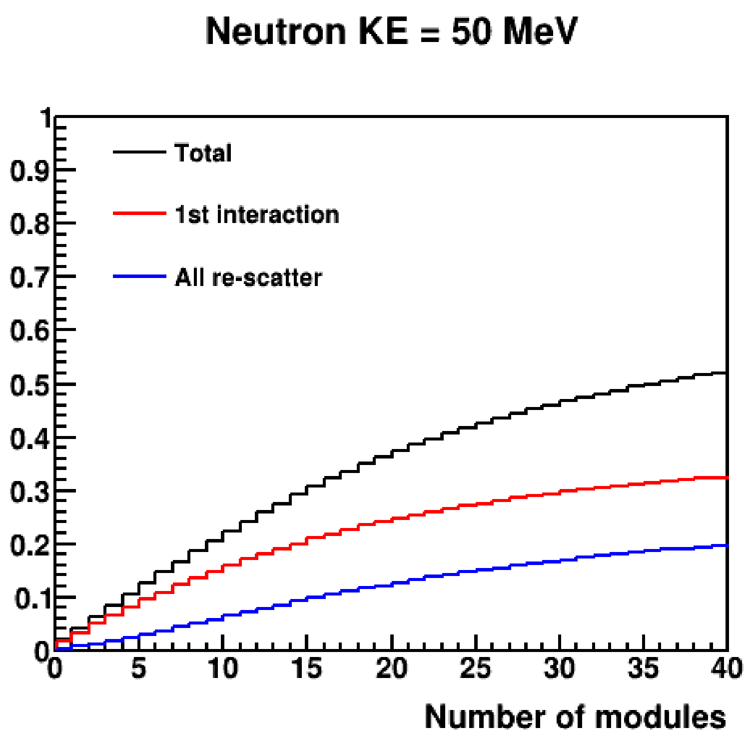
Efficiency vs energy

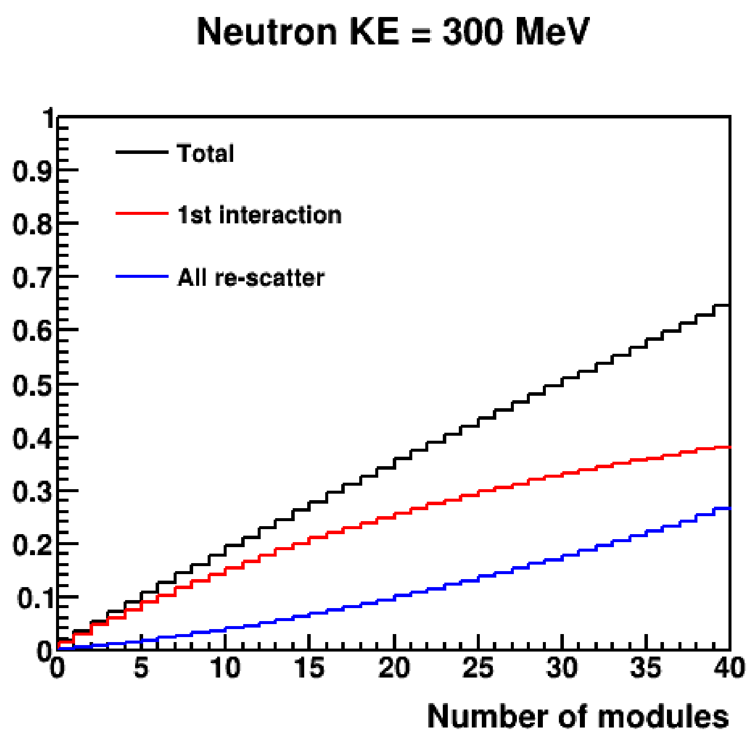




- Efficiency for ~8 X_0 ECal in two configurations
- Left: thin 5mm CH tiles
- Right: thick 2cm CH tiles → efficiency increases from ~25% to ~40%, almost entire increase is “first interaction”

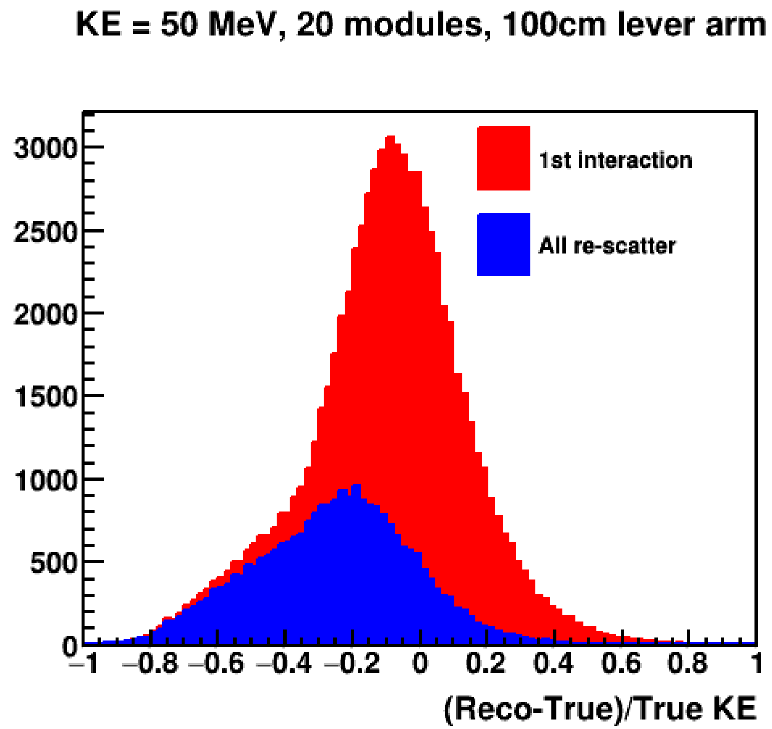
Efficiency vs ECAL thickness

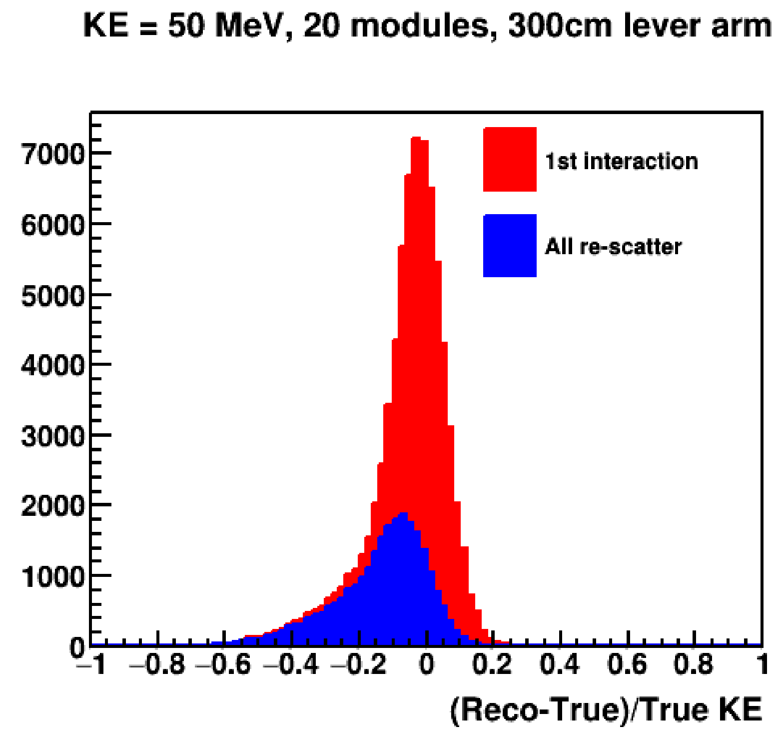




- Obviously, efficiency gets higher for thicker ECAL
- Around ~20 modules = ~44 cm thick, returns start diminishing
- Increase in efficiency is predominantly re-scatters, especially for higher energy neutrons

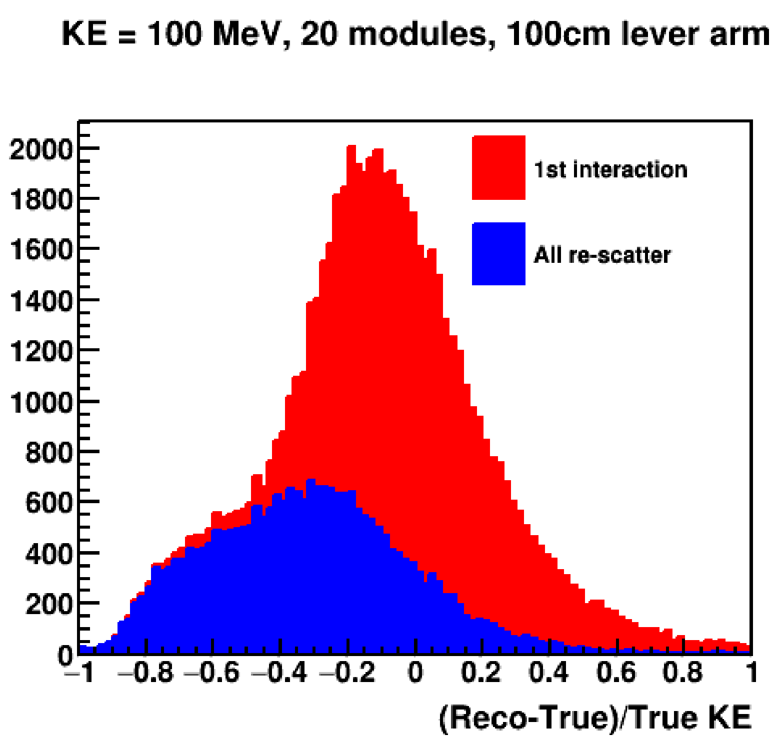
Energy residual 50 MeV neutron

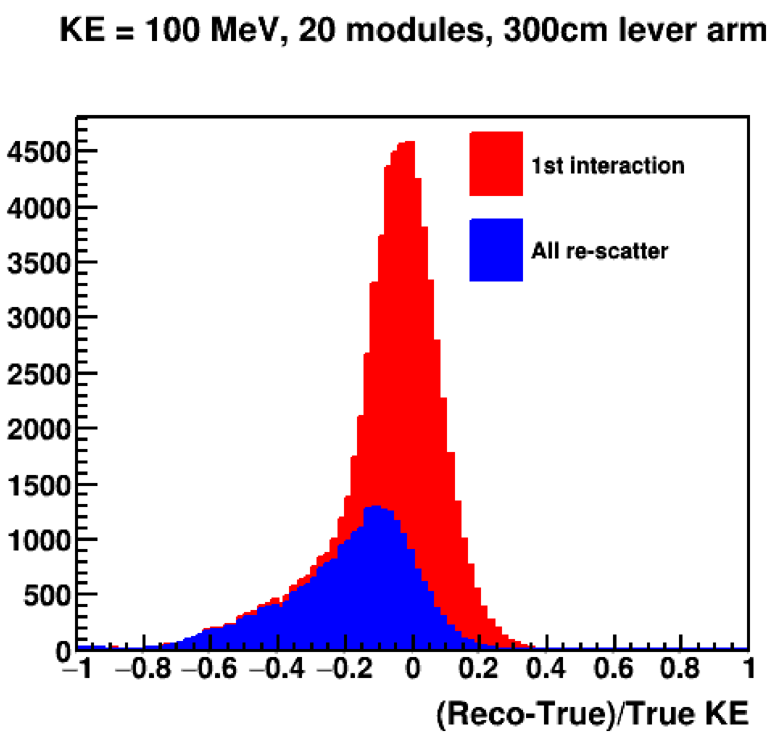




- 100cm lever arm (left) is about the shortest F.V. distance you would get for gas TPC, 300cm (right) is closer to the middle of the TPC

Energy residual 100 MeV neutron





- Energy resolution gets worse at higher energy due to reduced time of flight
- Re-scattering becomes more pronounced

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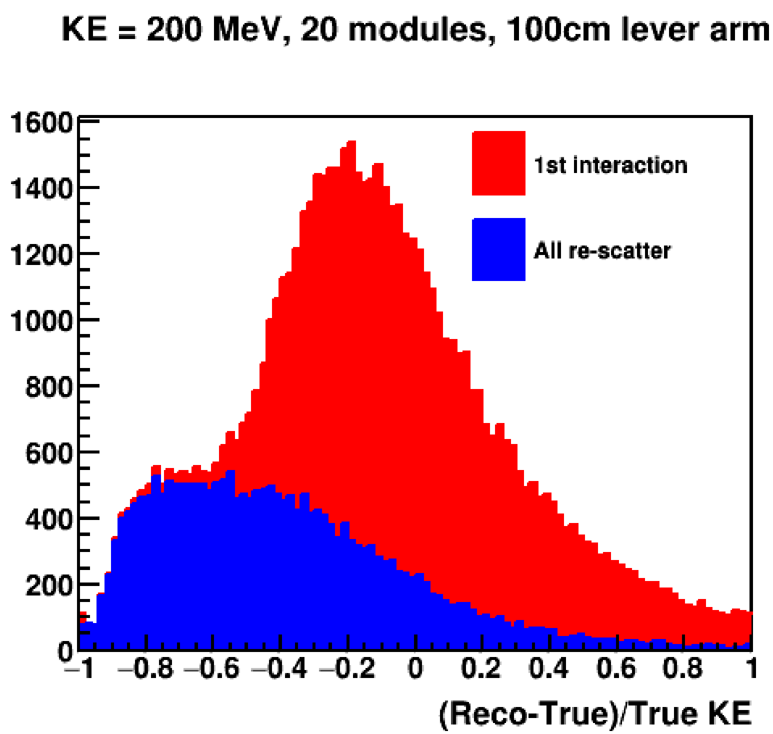

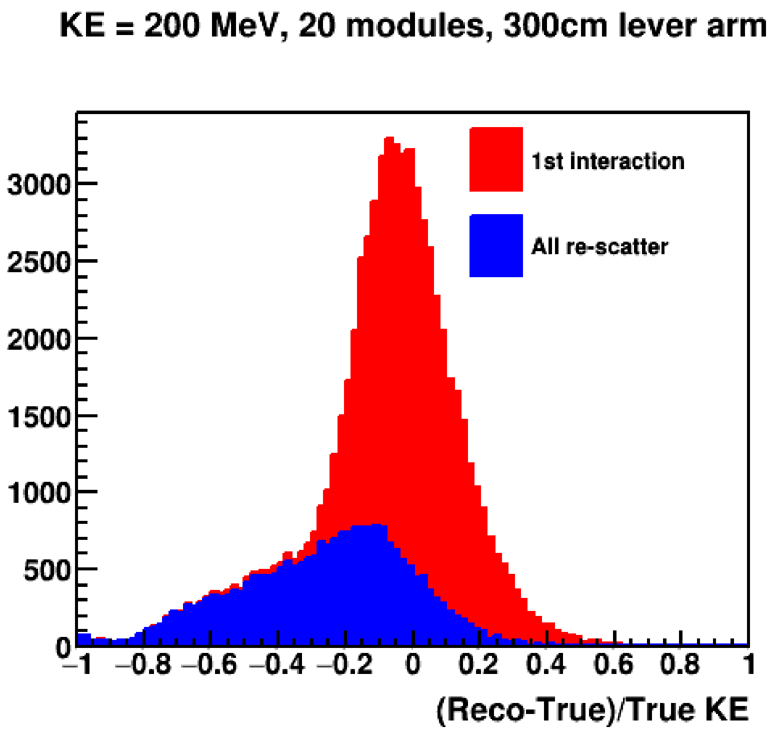

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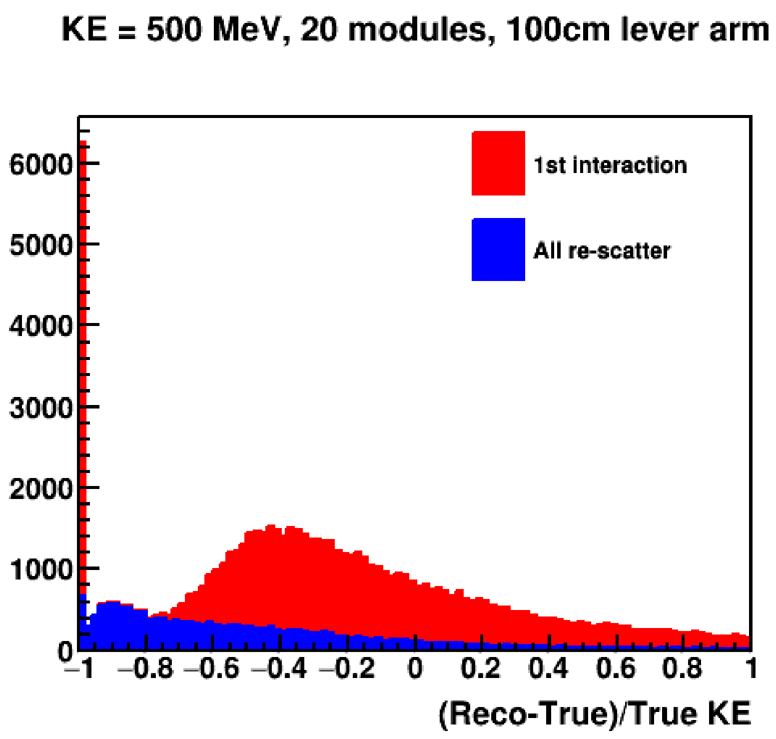
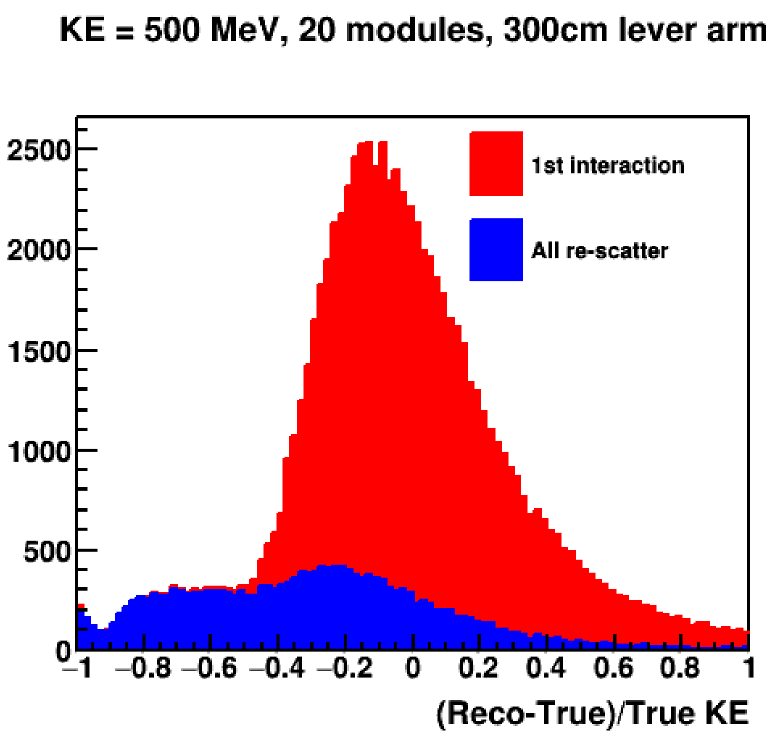
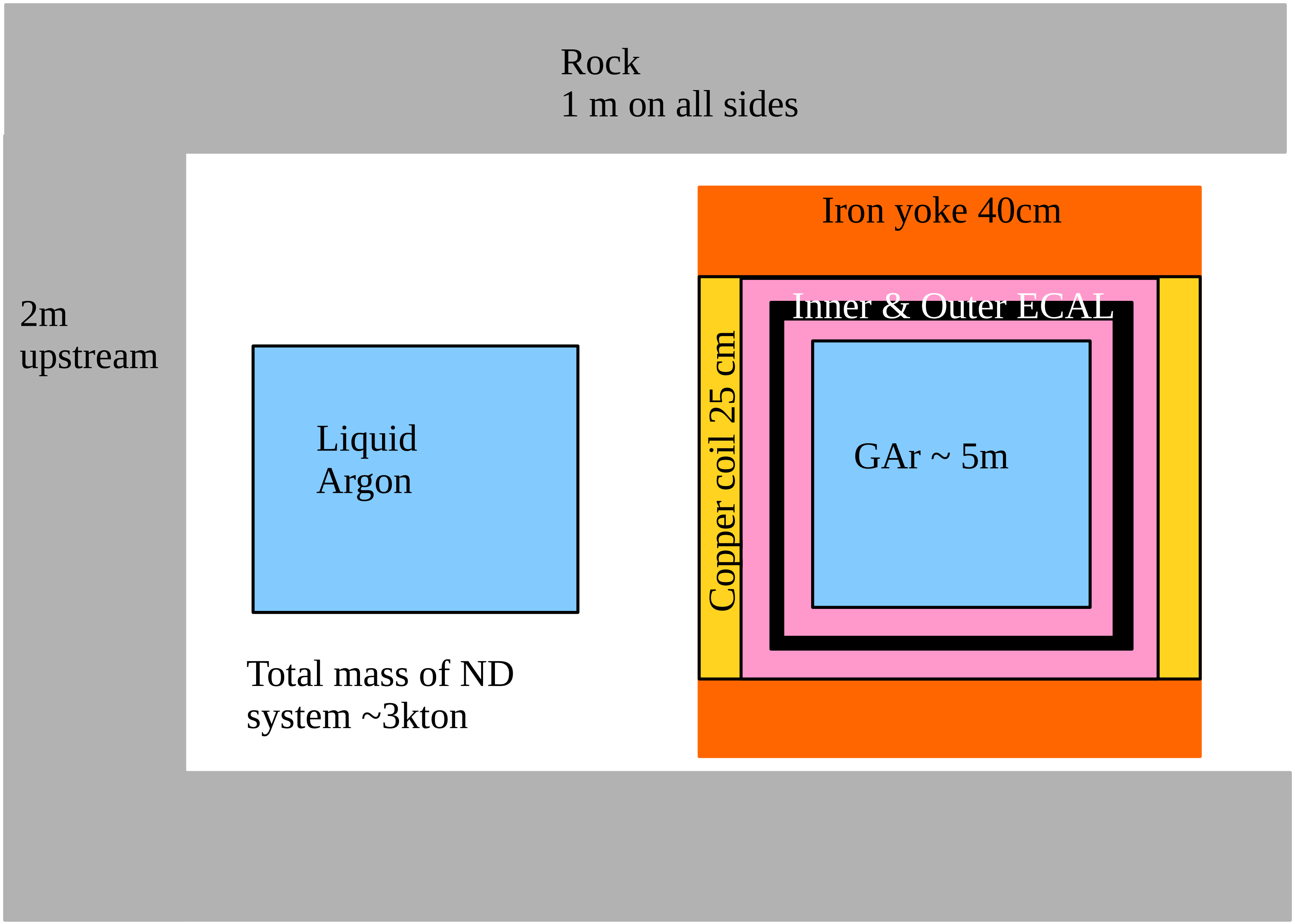




- Bin at -1 is neutrons that reconstruct super-luminal, which is often at 100cm but non-existant at 300cm
- Resolution is still ~30% for long lever arm even at 500 MeV, but with shelf due to missing first interaction

Full spill simulation



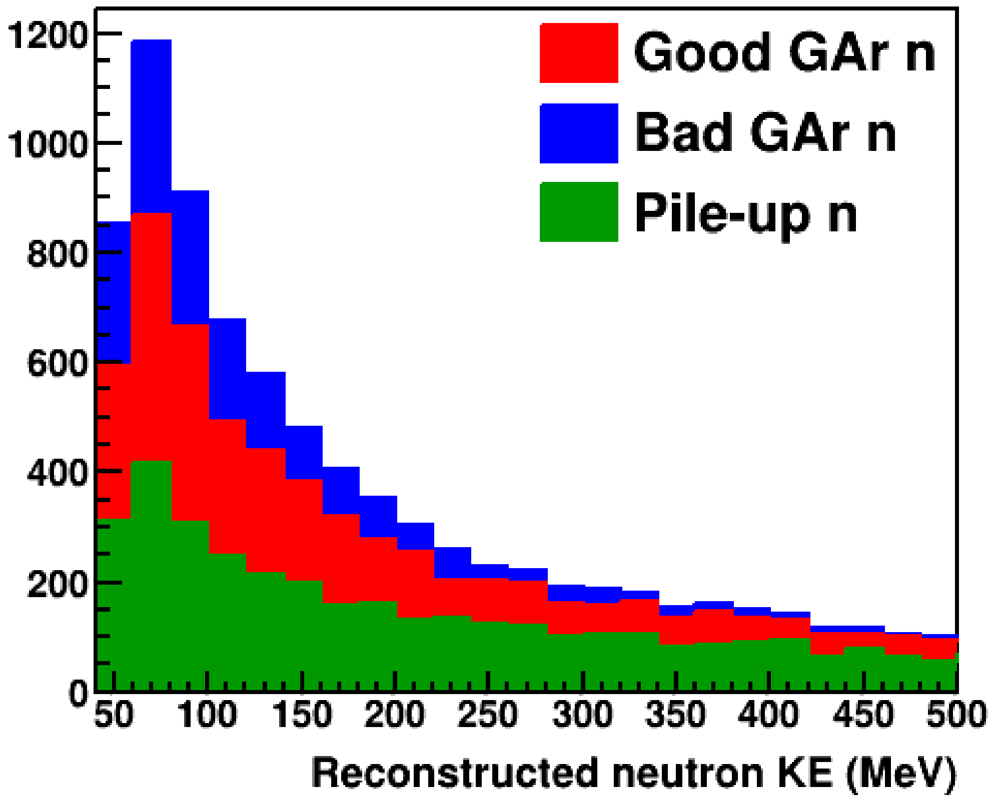
Analysis strategy

- “Neutron candidate” = >5 MeV knock-out proton (or deuteron) in CH of ECAL
- For each gas TPC vertex, determine distance to inner-most neutron candidate
  - Draw 30^{o} cone, with axis along straight line from vertex to knock-out proton
  - Collect any other in-time neutron candidates inside cone, and remove them (almost always due to re-scatters)
  - Repeat
- For each neutron candidate, determine distance to vertex
- Determine “search window”, starting with time at speed of light and ending with TOF for 50 MeV neutron
- Accept neutron candidate if it's in the time window

Pile-up

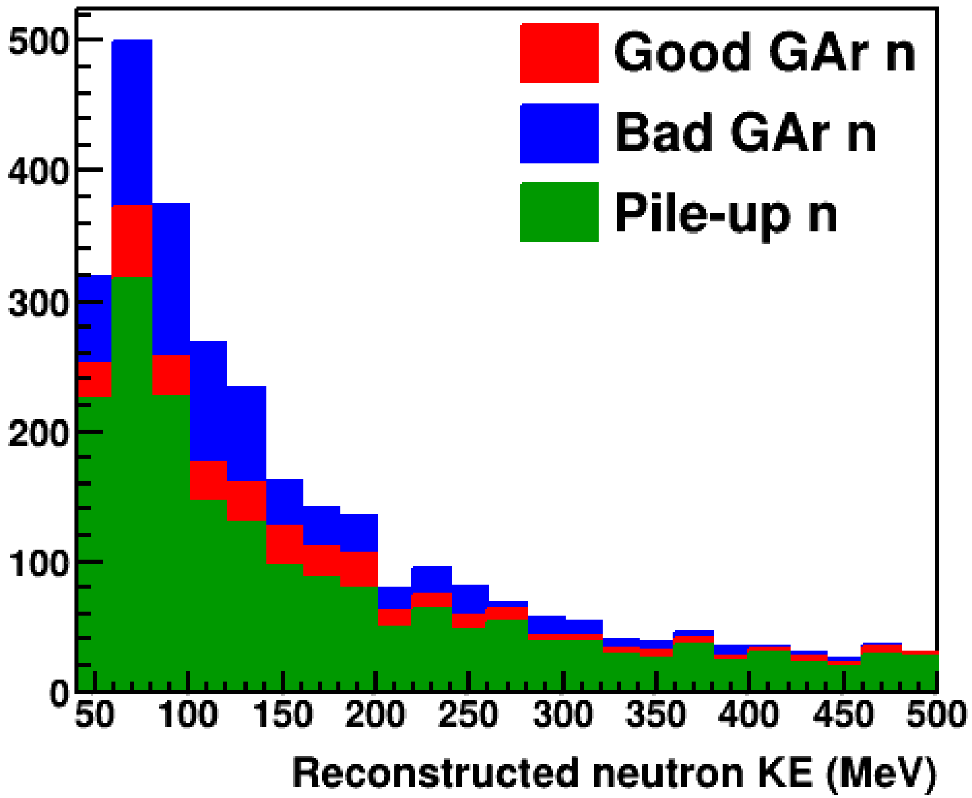
- DUNE beam generates 1 neutrino interaction per spill per ~10 tons
- Long lever arm → long “search window” → increased pile-up from neutrons produced outside gas TPC
- 3DST analysis has shown that pile-up is small for short lever arm, i.e. few ns search window, but for gas TPC search window is often few 10s of ns
- Following plots assume no rejection, which is conservative
  - Could veto on other activity in ECAL and reject background

Neutron energy distribution Inner ECal 20 modules



- This is 20 modules, so efficiency ~35% for signal neutrons
- Purity is ~70% at 50-100 MeV
- Low purity at high reconstructed energy because pile-up is flat in Δt, and there are few signal events at very high energies

Neutron energy distribution
Side outer ECal



- Outer side ECal contains almost no signal
- The little signal that does make it out there is poorly reconstructed
- So we definitely don't want to analyze these events

Conclusions

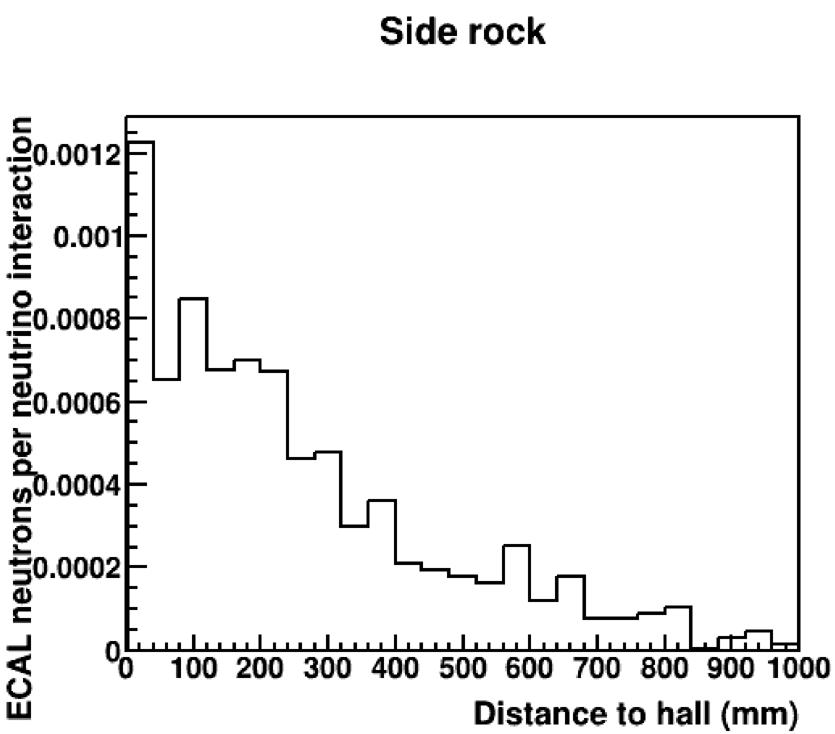
- Neutron energy resolution from gas TPC + ECAL is excellent when first interaction can be identified, but ~30% of sample will be misreconstructed due to first interaction in passive absorber
- Efficiency is ~40% for 40cm of CH
- Pile-up is important – need to repeat study with detailed design including superconducting magnet
- Demonstrating ability to veto background is crucial

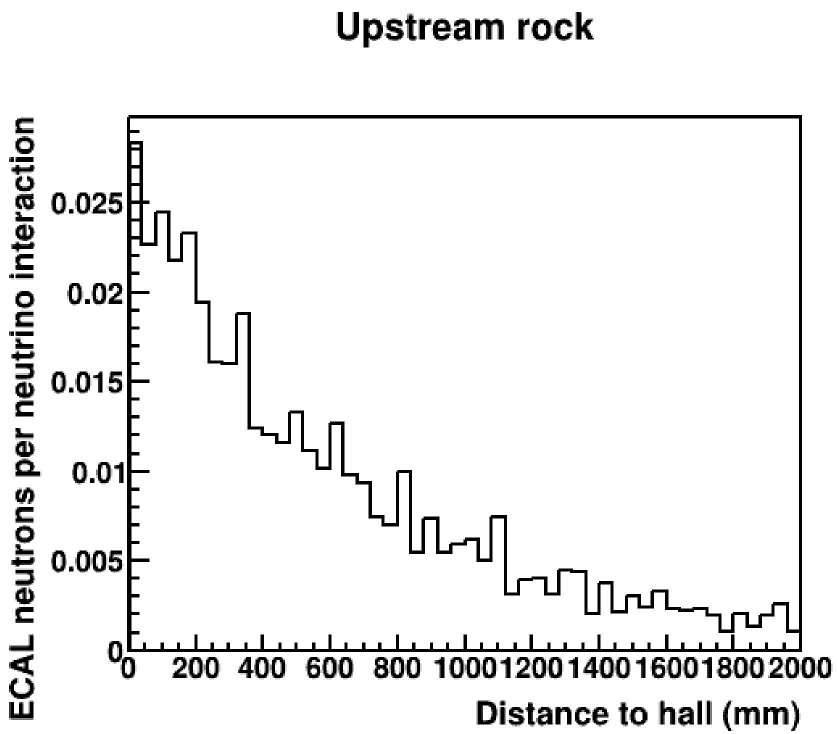
Backup

Why does it cut off at 50 MeV

- For 3m lever arm, high-energy neutron TOF is 10 ns
  - 50 MeV neutron is 31ns
  - 25 MeV neutron is 44ns
  - 10 MeV neutron is 69ns
- Arbitrarily choose 50 MeV as the cut-off velocity
- To go down to 25 MeV, window goes from 21ns to 34ns, and pile-up increases by 65%

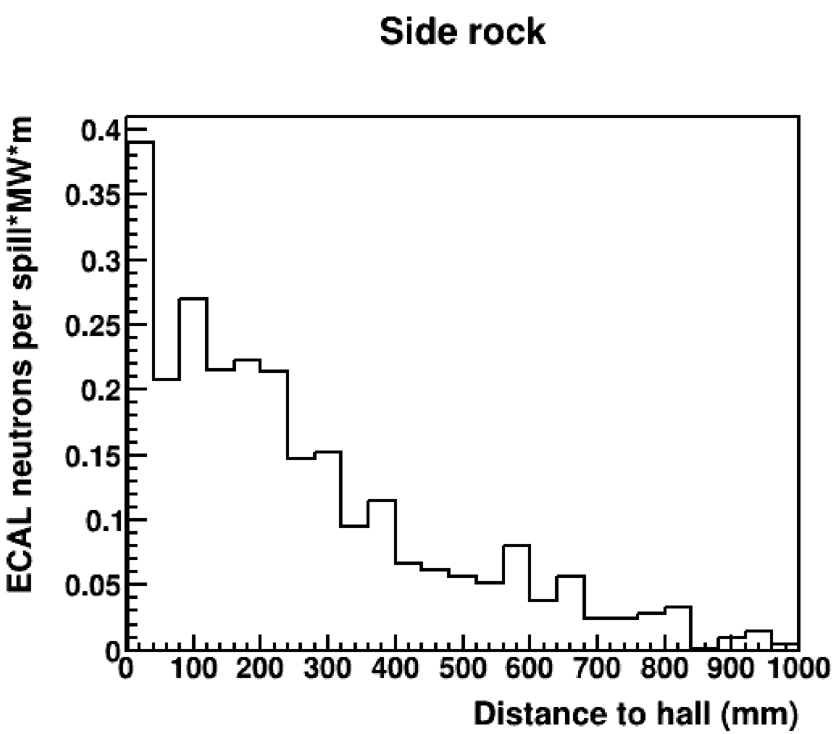
ECAL neutrons from rock neutrinos

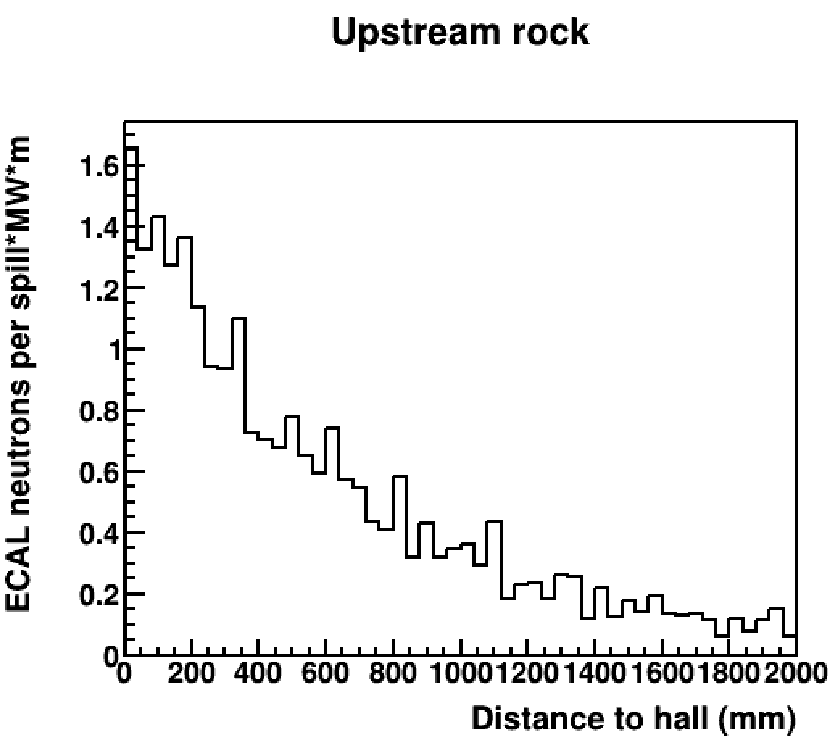




- Look for >5 MeV knock-out protons in ECal CH
- Plot distance from neutrino interaction to hall-rock boundary → probability for a neutrino interaction to produce a neutron that is then reconstructed in the ECal

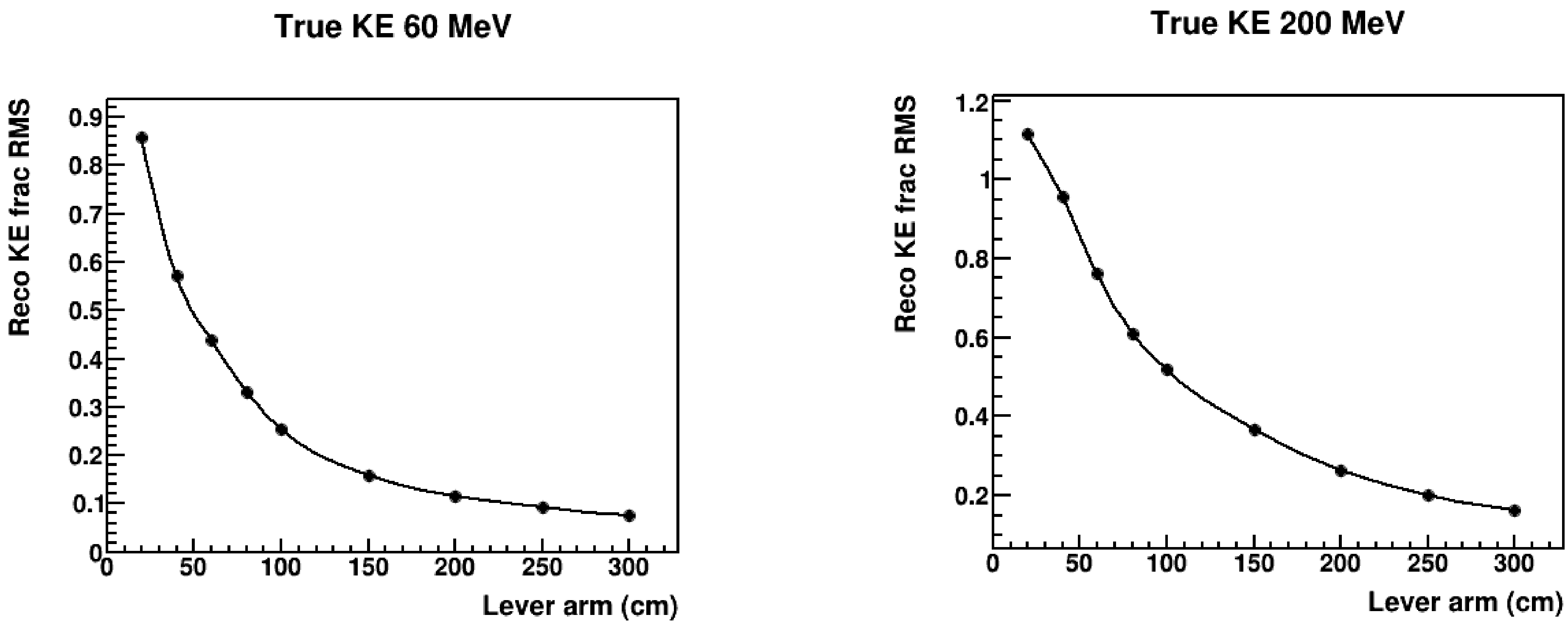
ECAL neutrons from rock neutrinos





- Normalize to neutrons per spill*MW per linear meter of rock
- Total ~1 rock neutron per spill
- Many neutrons come into the hall, but few make it through the magnet
- Most of the rock→ECal neutrons are actually charged particles interacting in the magnet and producing neutrons

Energy resolution vs lever arm



- For 60 MeV (left) and 200 MeV (right) neutrons
- Becomes very good for lever arm > 1m