Energy resolution in LArTPC reconstruction and diffusion (DUNE docdb 589)

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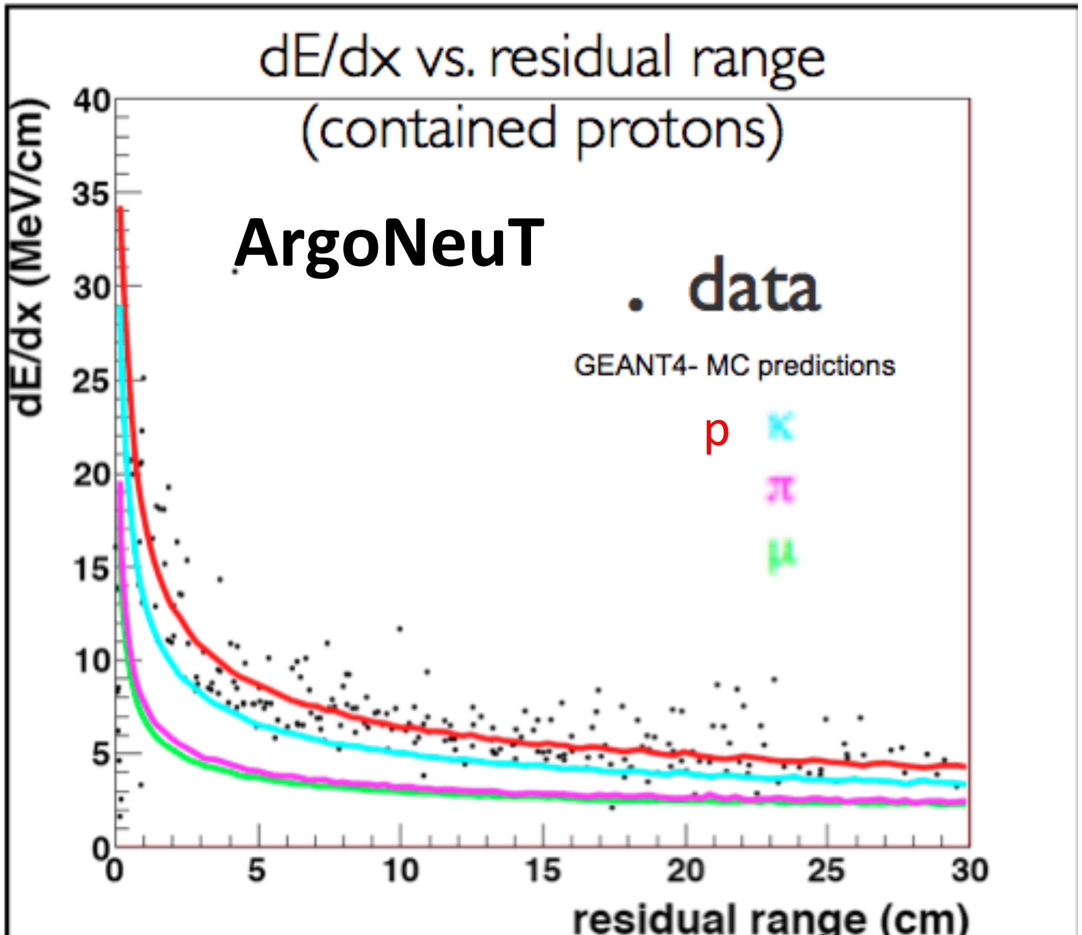
Fermilab

How does energy resolution on single wire turn into physics quantities?

Measured quantities are combinations of single wire measurements. Noise enters at the single wire level.

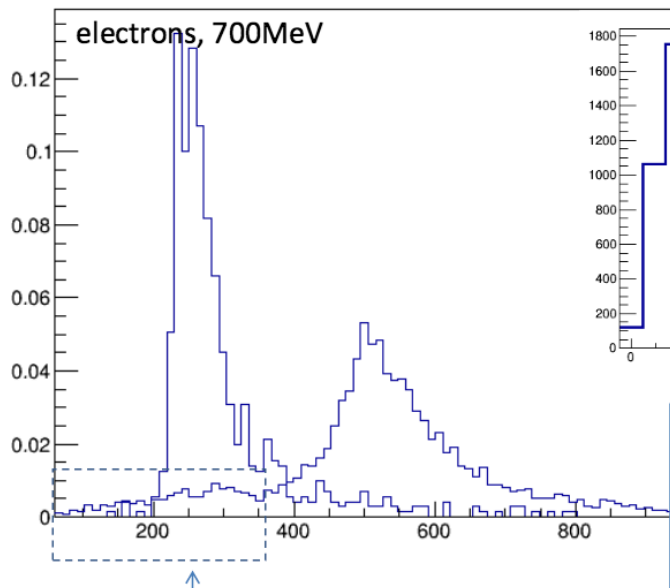
- Electron shower energy: sum over wires of charge collected on each wire.
- Particle ID: dE/dx vs residual range, single wire resolution determines band thickness?
- e/gamma/pizero separation: one component is the energy deposited in first 2.5 cm of shower, energy resolution on single wire affects overlap of 1-mip and 2-mip peaks
- ??

PID with dE/dx

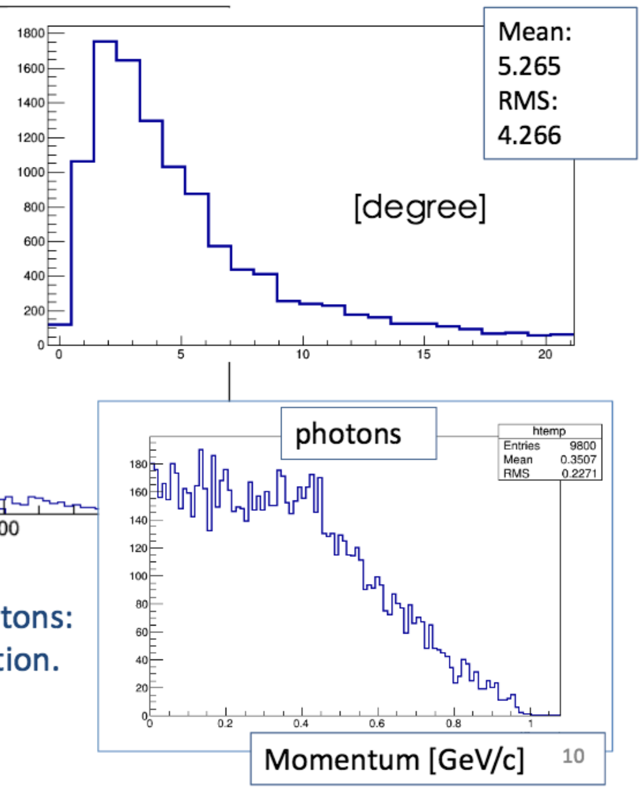


e/gamma separation

Reconstruction of dE/dx in isolated cascade



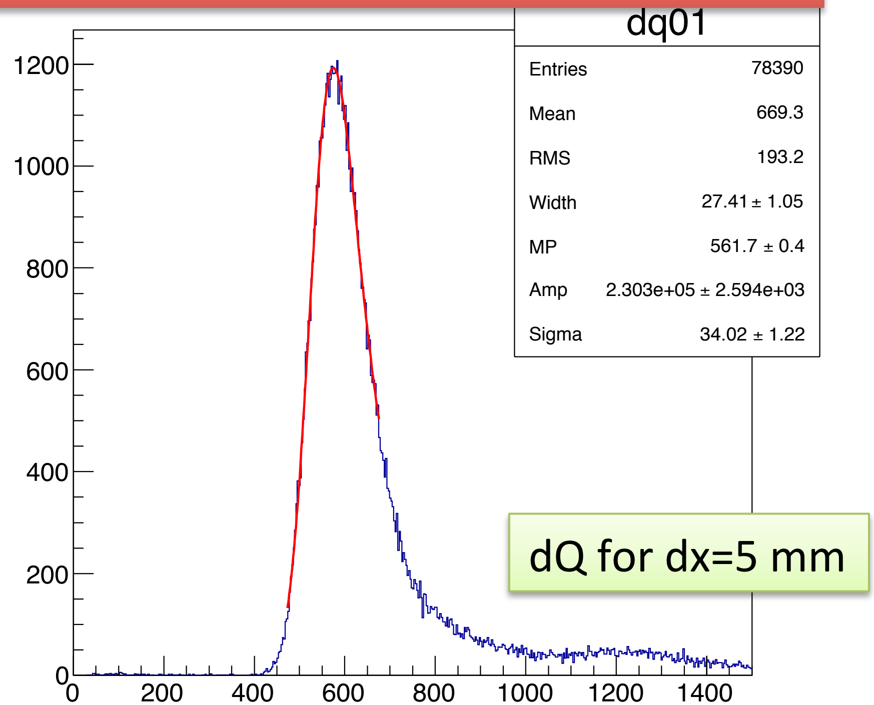
Contribution from low momentum photons: comptons and asymmetric pair production.



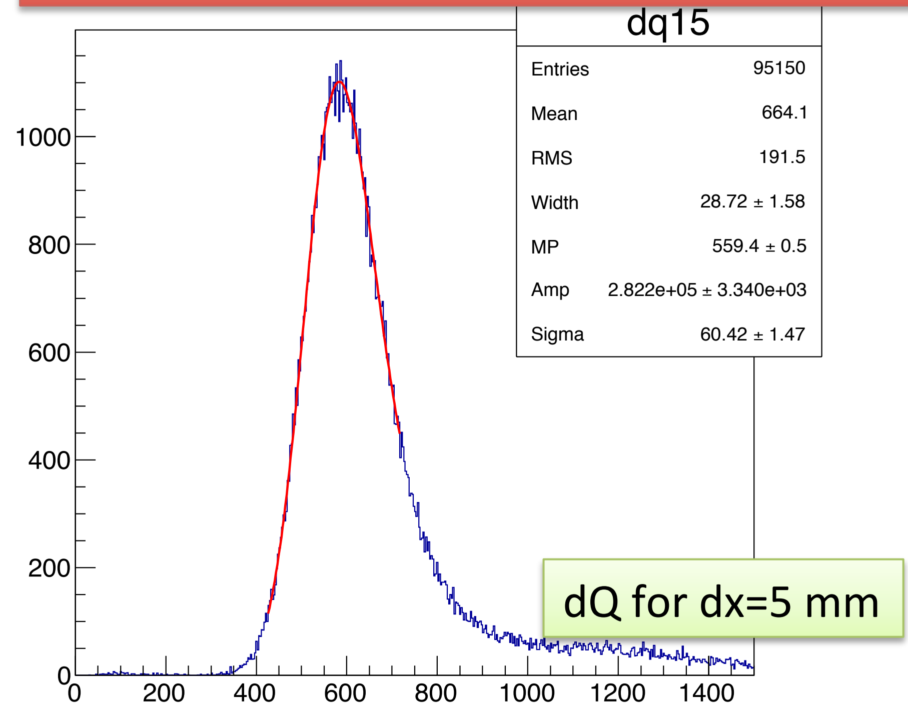
Robert Sulej, Dorota Stefan, Tingjun Yang. INDICO Sept 28, 2015

Motivation

Charge on single wire for track at 12 cm drift



Charge on single wire for track at 348 cm drift



Simulation indicates that wire-charge resolution degrades with drift distance even in the absence of charge loss to impurities

Fit function is the convolution of Landau and Gaussian

Simulation: 5mm wire spacing, 99 msec electron lifetime, 3 GeV muons

muon direction parallel to wire planes and perpendicular to collection plane wire direction

More simulation details in backup slides.

What affects measured dQ/dx on a single wire?

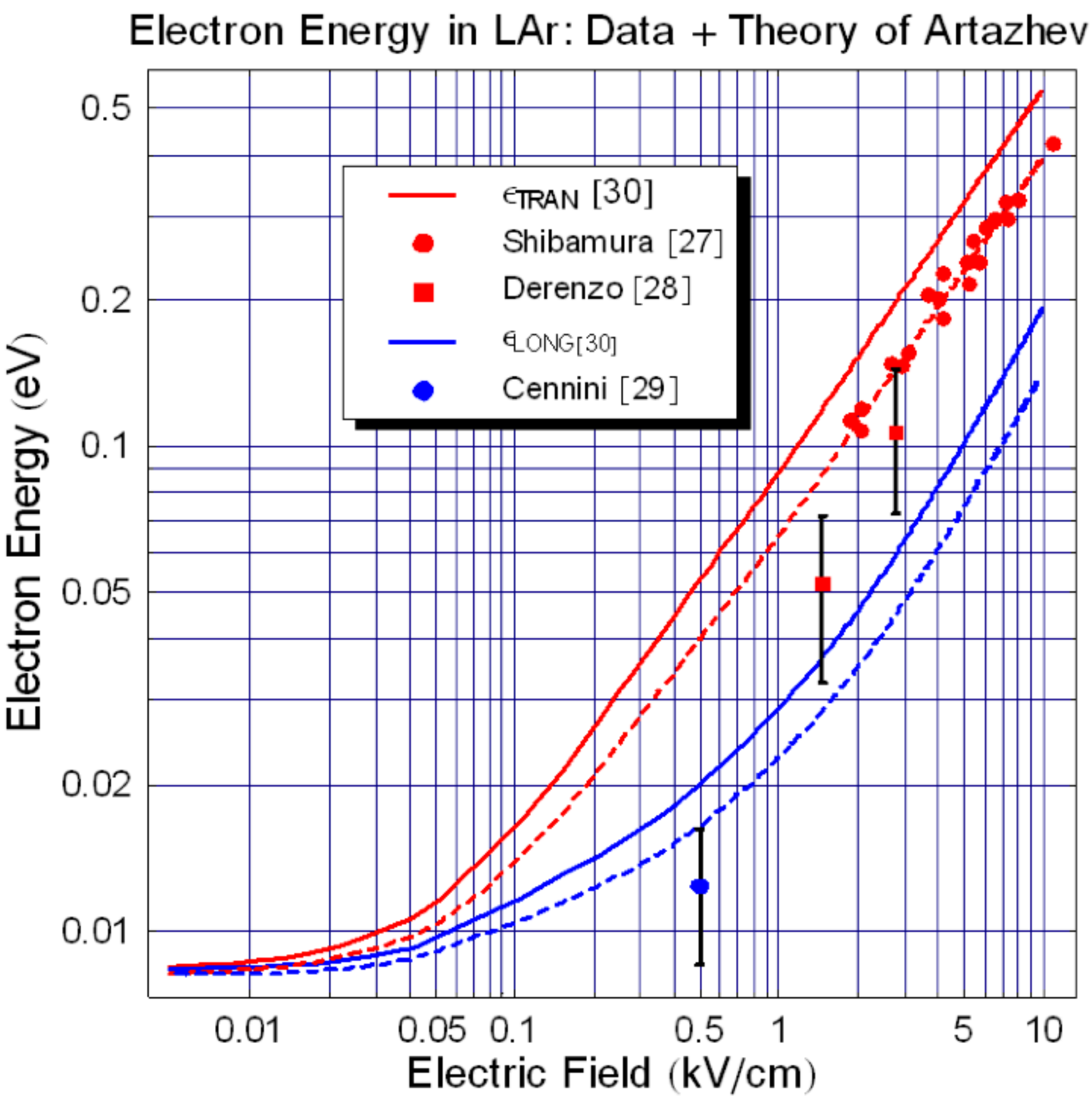
- Landau fluctuations affect how much energy is deposited (shows up as width of Landau)
- 60% of deposited energy produces ionization at Edrift=500V/cm, is that 60% subject to statistical fluctuations?
- Recombination: ~1/3 of ionization charge recombines for MIPs and Edrift=500 V/cm, (C. Thorn LBNE docdb 4482 p. 11). Is that subject to statistical fluctuations?
- Transport to wires:
  - Impurities absorb 50% of the charge for the longest drift times (spec 3 ms lifetime)
  - Transverse diffusion mixes charge among wires
- Electronics noise: S/N ratio varies from 18/1 to 7/1 with drift time (for MIPs and 3 ms lifetime)
- Track/shower reconstruction smearing
- Other complications like space charge

Note here that the statistical fluctuations questions above are important. The simulation does not include them for recombination or impurity losses. However, they are included for diffusion?

Diffusion

- Diffusion is the spreading out of drift electrons originating from the same point as they travel to the wire planes
- Remember that the thermal velocity of the drift electrons is larger than the drift velocity
  - $\frac{1}{2}mv^2 = 3/2\ kT \Rightarrow v_{th} = 6.6$ m/ms and $v_{drift} = 1.6$ m/ms
- The journey to the wire planes has a significant random walk component with many collisions along the way.
- It is 3D effect, but we measure its 2D projection on the longitudinal and transverse axes.
- The simulation models the projections in 2D also.

LBNE-docdb #4482, C. Thorn



- Typically divided into transverse and longitudinal components.
- Modeled as a Gaussian smearing of the electron position distribution

$\sigma_L = \sqrt{(2D_L t)}/v$

$\sigma_T = \sqrt{(2D_T t)}/v$

- Measured values are lower than theoretical ones?
- Theoretical values used in these results

$D=\mu E$, μ=electron mobility

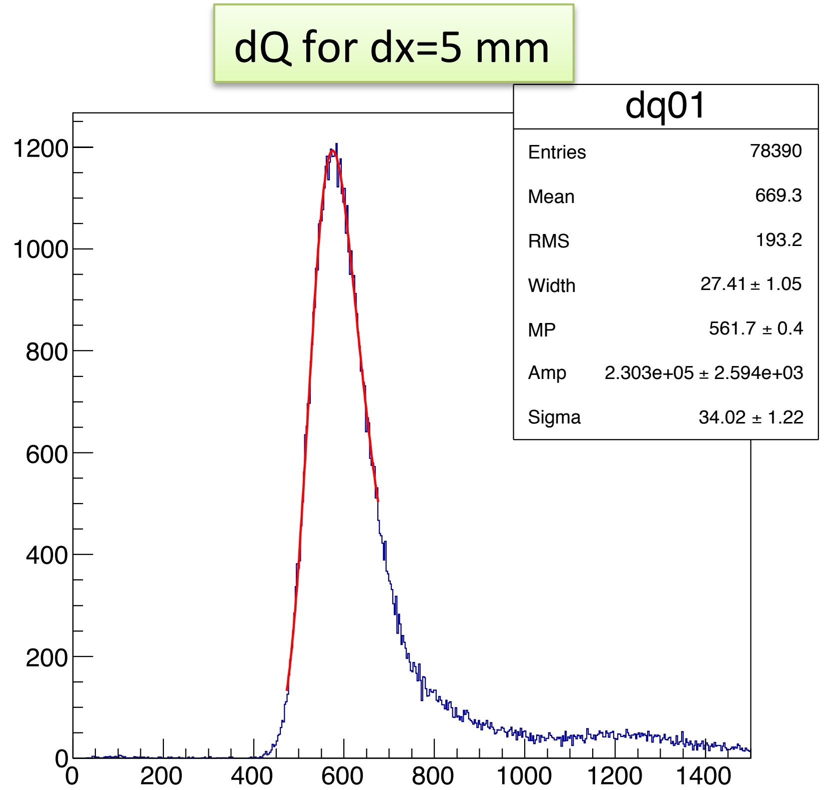
D_L=6.2, D_T=16.3 cm^2/ns

Simulation details

- FD workspace geometry 45 deg wire angle
- Particle gun: (see backup)
  - 3 GeV muons
  - fixed angle for minimum path length per wire
  - 99 msec electron lifetime
  - Random start position outside cryostat along drift direction
- No track reconstruction
- Good events/hits selected (see backup)

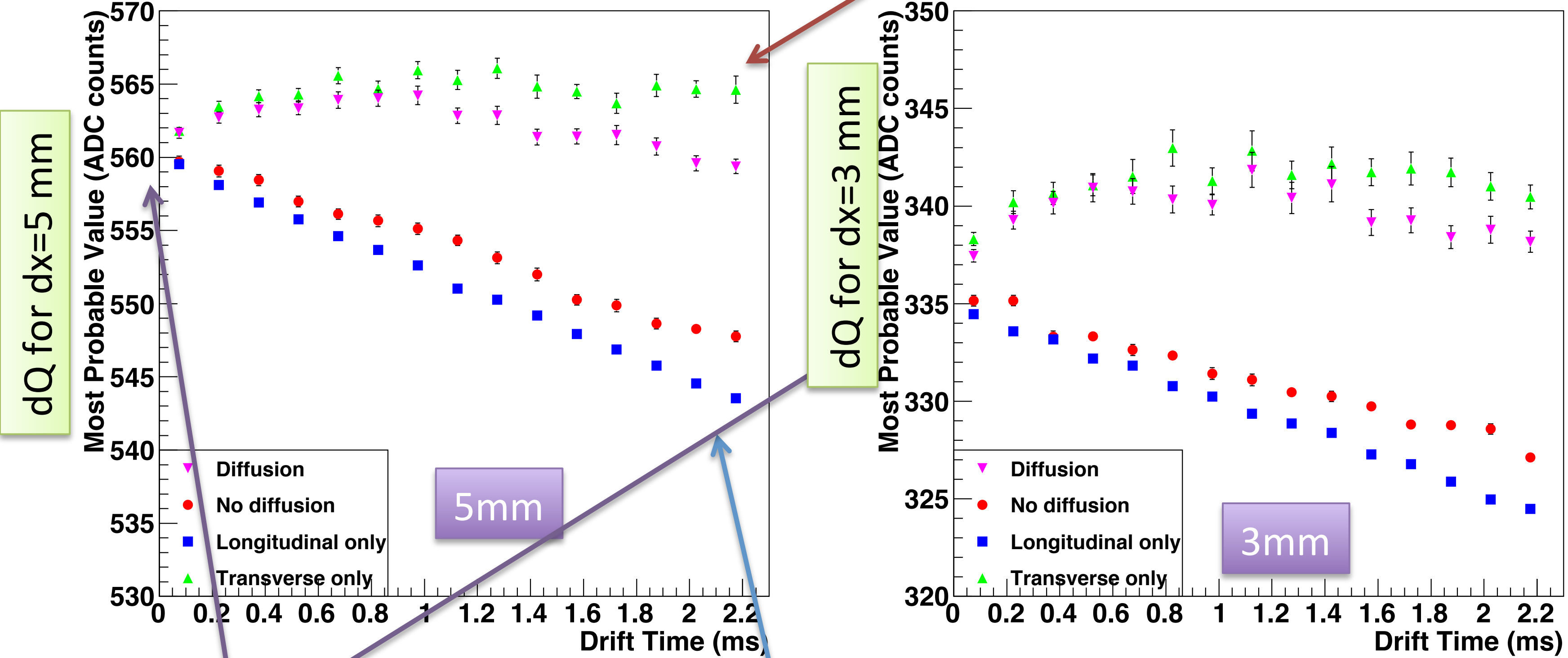
How to study diffusion?

- Slice active argon into 15 sections along drift direction
- Histogram hit charge on individual wires for each slice, about 200 tracks each
- Fit to LGconv, look at parameter dependence on drift distance



MPV of Landau

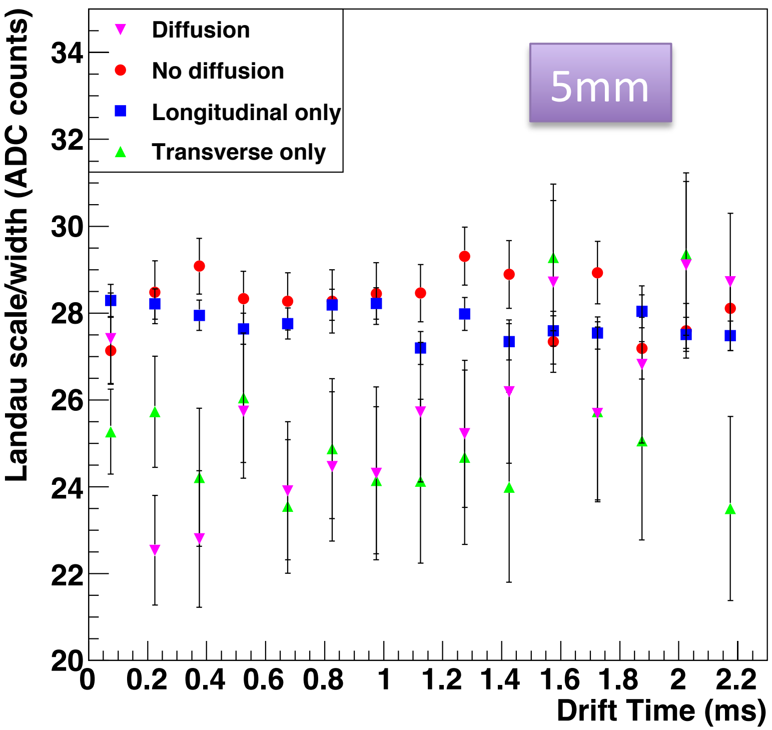
~3% systematic wandering of the MPV value

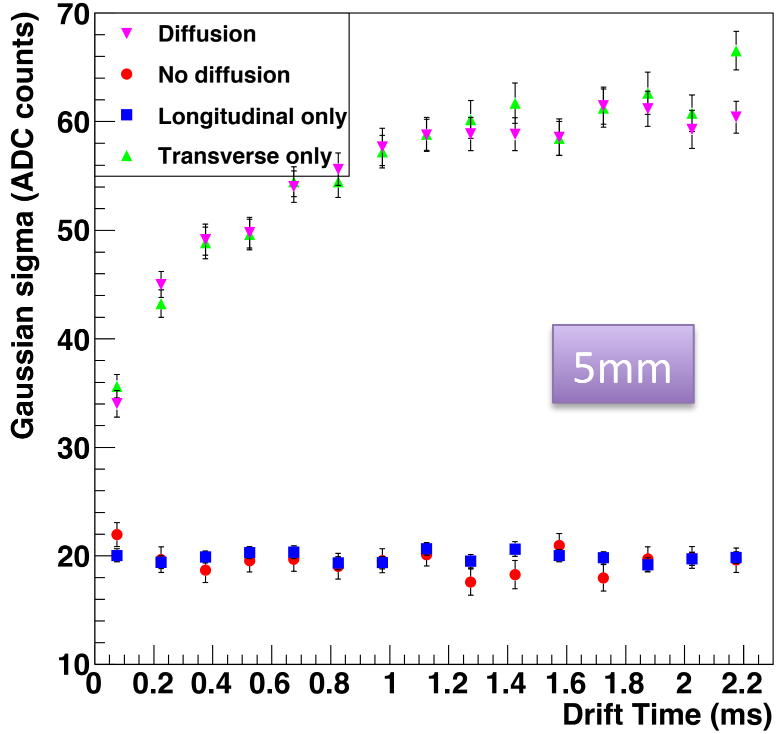


Signal for 3mm is 60% of 5mm (but noise is the same)

99 ms electron lifetime is 2% charge loss. Oops, already switched to 9 seconds for future sims

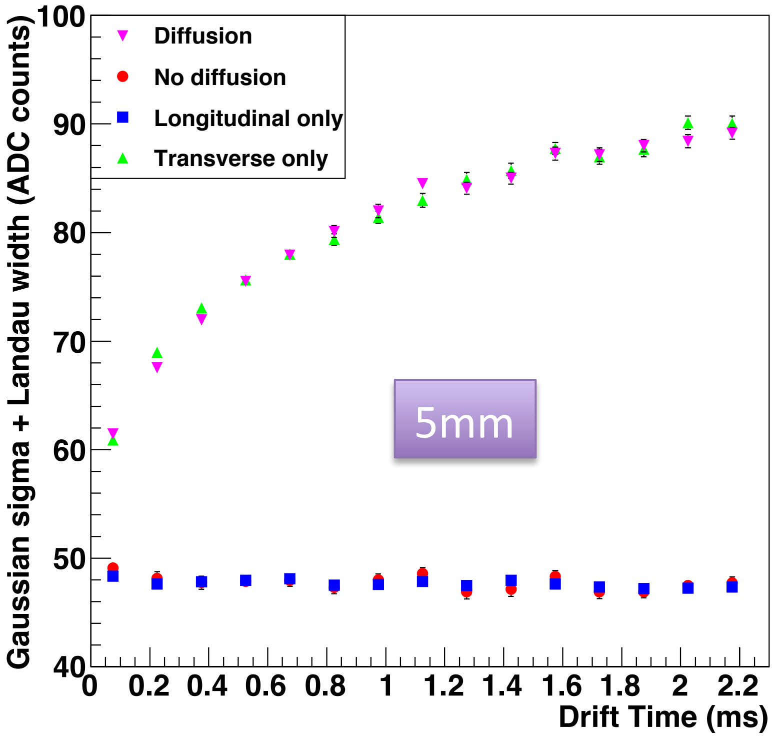
Landau Width, Gaussian Width

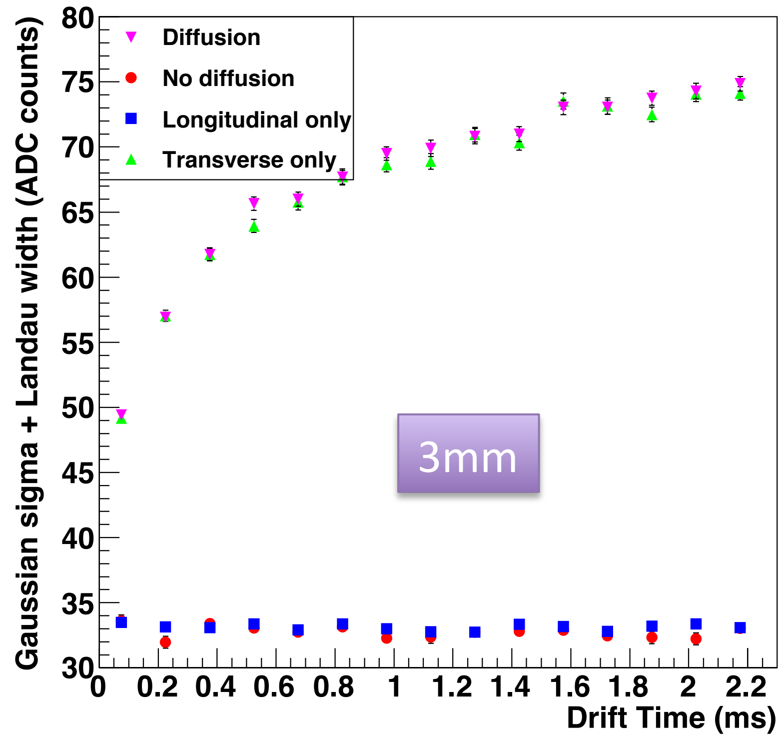




Two parameters are very correlated. Note that diffusion increases the gaussian width as expected. More useful quantity is normalized to MPV, will update slides

Total width





What is the consequence of decreasing resolution?
More useful quantity is normalized to MPV, will update slides

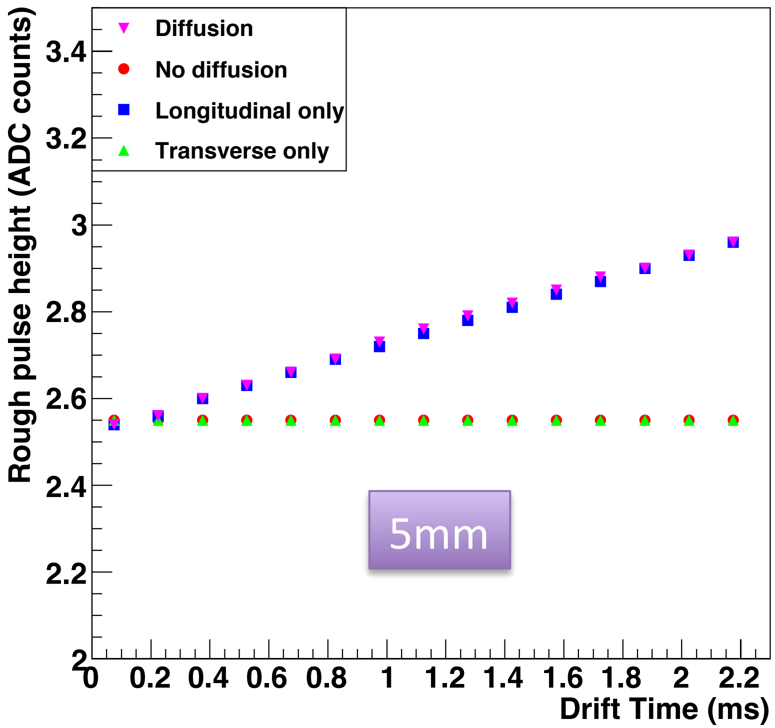
Energy Resolution?

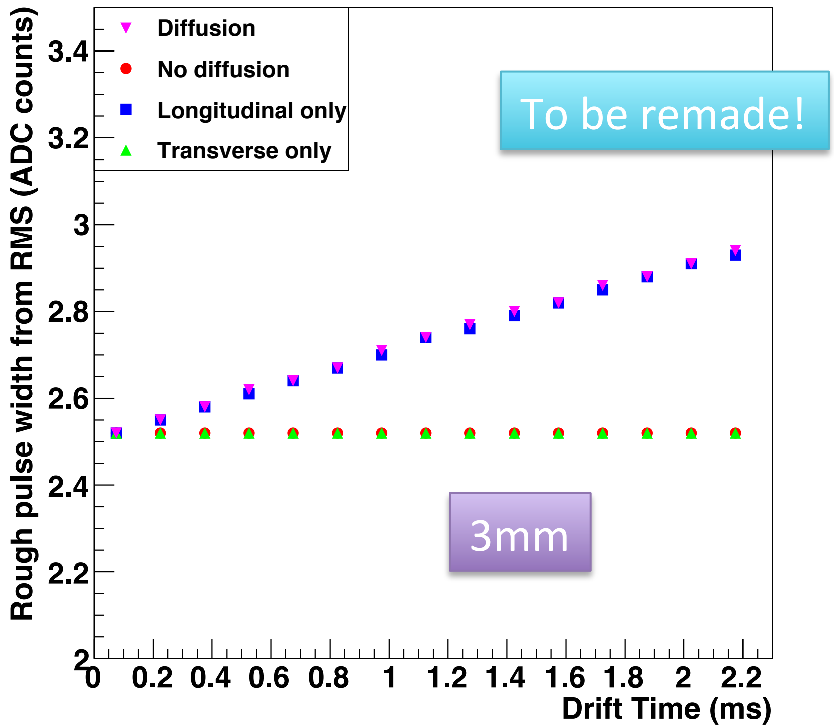
5mm: σ_Q/Q~90/562=16% at cathode, 8.5% at anode

3mm: σ_Q/Q~74/340=22% at cathode, 10% at anode

- Directly affects widths of dQ/dx bands for PID?
- e/gamma separation is the sum of first 2.5 cm of shower, 5-10 wires
- Shower is sum of all wires, but correlated errors. (more terms in the sum, each with larger uncertainty)
  - Best case (all correlated) is that $\sigma_{E3mm} = 1.8\sigma_{E5mm}$ at cathode, $\sigma_{E3mm} = 1.5\sigma_{E5mm}$ at anode
  - However, the shower energy resolution is likely dominated by other effects such as shower reconstruction.

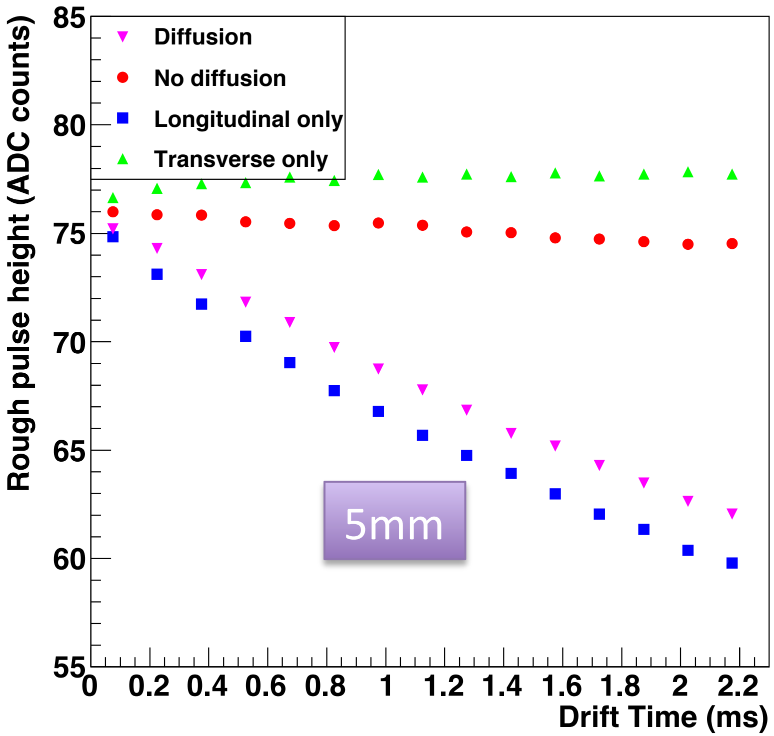
Pulse "width"

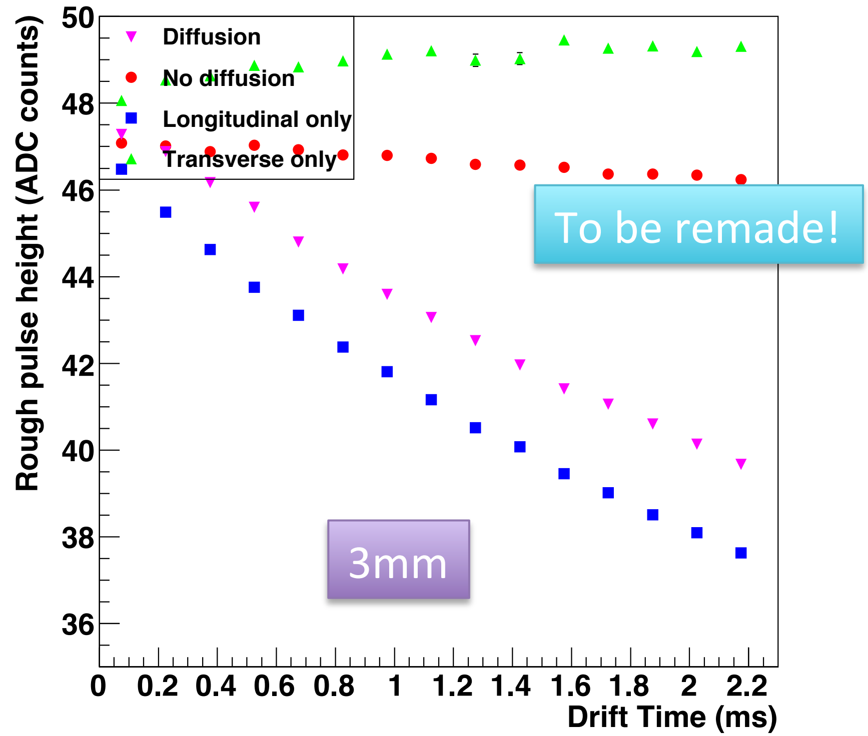




Dominant effect of longitudinal diffusion is to widen the pulses on each wire.
Direct experimental access to longitudinal diffusion through pulse height and width, but complicated by impurities.

Pulse Height





The S/N ratio at the cathode is 80% of that at the wires just due to diffusion (pulses get shorter and fatter). For a 3 ms electron lifetime, 50% are lost to impurities. Combined, **the S/N ratio at the cathode is 40% of that at the anode.**

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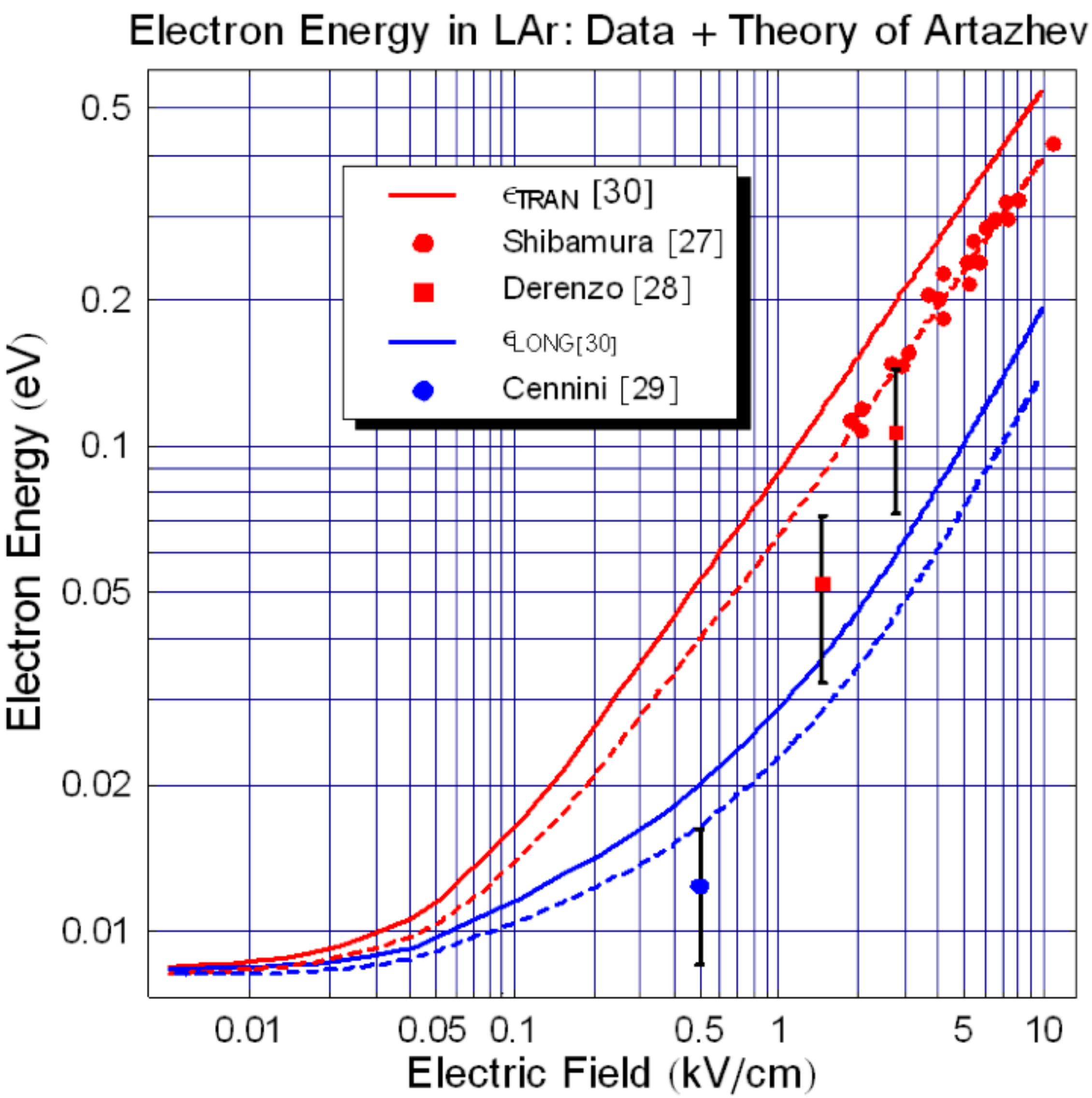

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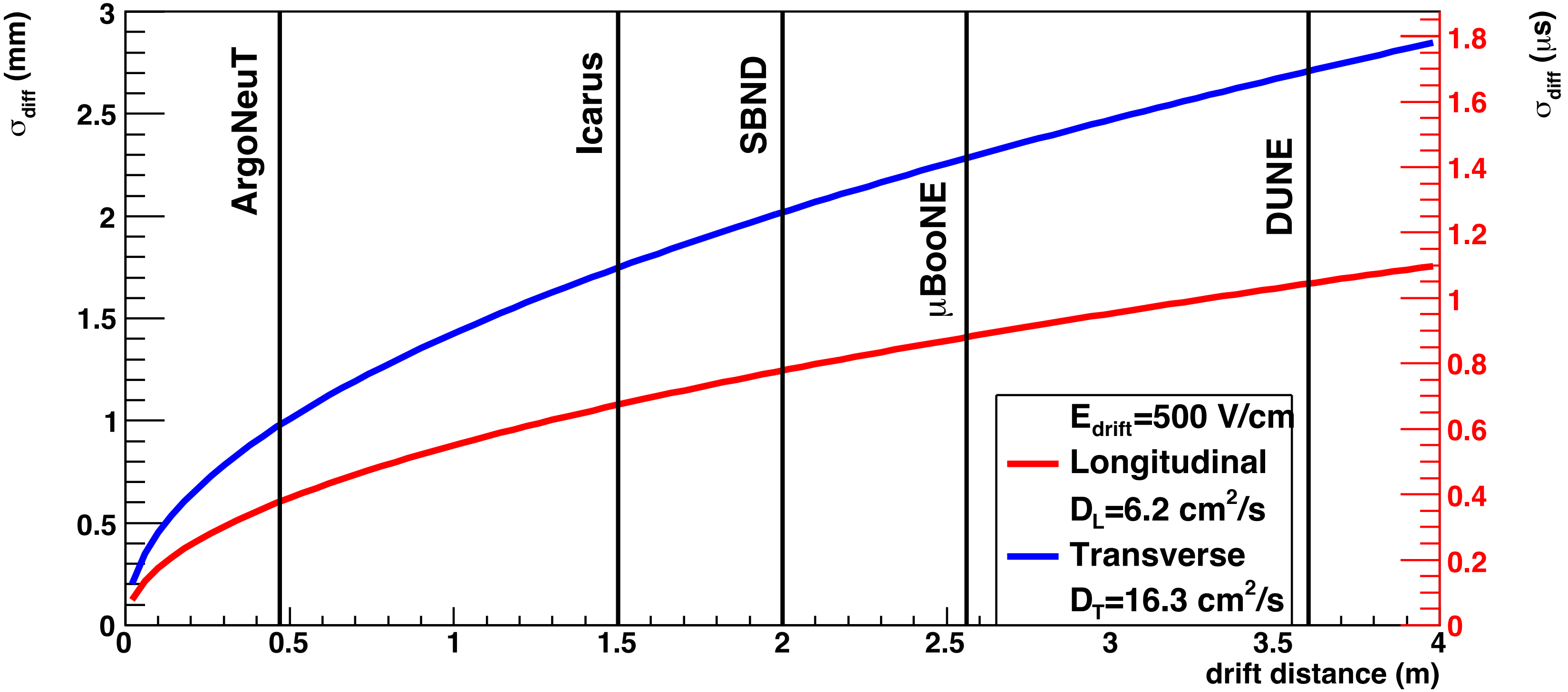
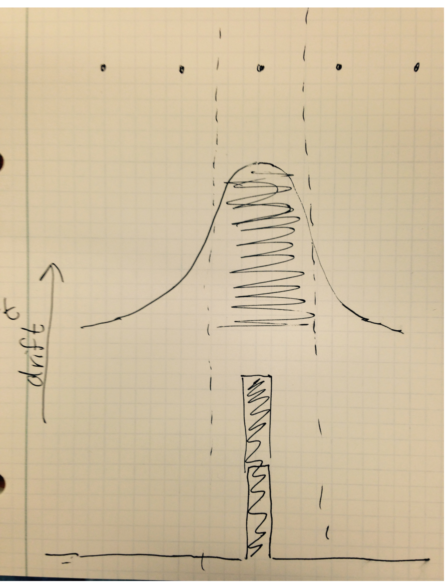
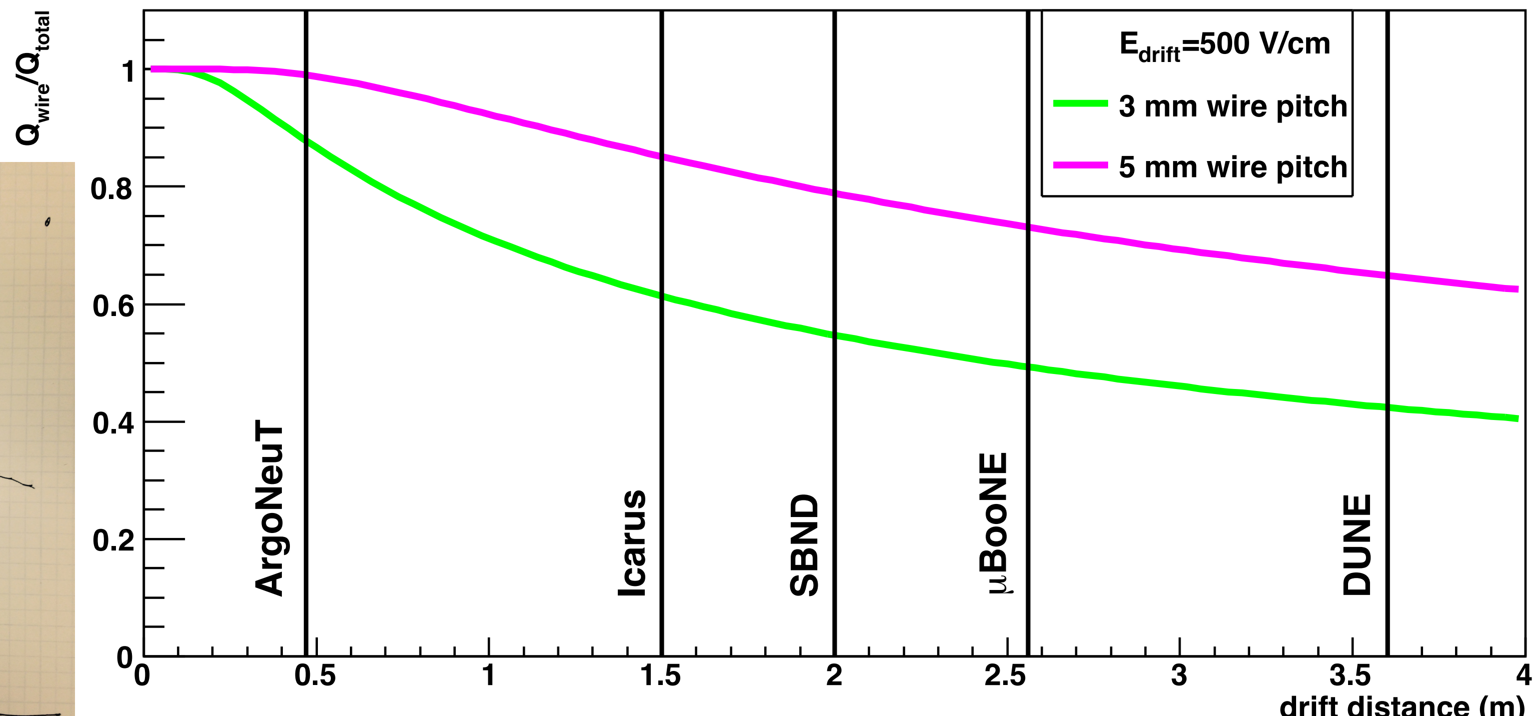
How big is the smearing? How does DUNE compare with other detectors?



How much charge moves from wire to another?





To Do list

- Update plots with new simulations (improved 3mm signal simulation and 9 second electron lifetime)
- Dom Brailsford and myself are planning the 35ton measurement with realistic data sample and track reconstruction, stay tuned.

Summary

Predictions of detector performance are only as accurate as the simulation inputs. In particular, energy resolution, PID and e-gamma are sensitive to noise and diffusion.

- There is a noise model in the LArSoft simulation. Noise is difficult to predict, need a special case study for “unexpected large amounts of noise”
- There is a diffusion model in the LArSoft simulation. This model can be tested/refined with microboone and 35ton data.

Performance and sensitivity should be studied as a function of drift distance

- The detector performance is very drift distance dependent (diffusion+impurities) – the 1/3 of the detector close to the wire planes will perform much better than the other 2/3.

Backup

Simulation/reco details

- Used latest 3mm/5mm signal simulations
- Used workspace geometry, default noise simulation
- Hits from RawHitFinder, hit charge is sum of ADC counts above threshold (5 counts)
- Hit time
- Peak height is max ADC
- Pulse width is charge weighted RMS of tick values above threshold.

Event/hit selection details

- Assume all tracks have the same dx per wire and can thus be combined in the same histogram (they were generated this way)
- Reject events if the distribution of hit times for an event exceeds 400 ticks (1 tick = 500 ns)
- Only collection plane hits
- Reject hits on wires at edge of APA
- Reject all hits on any wire with more than one hit
- Reject hits with RMS>4 ticks
- Reject hits with time more than 50 ticks away from the average hit time for the track.

- SigmaE3 propto sqrt(N3)sigma3i
- SigmaE3=shower energy resolution, N3 is number of wires, sigma3i is charge resolution on a given wire
- SigmaE5 propto sqrt(N5)sigma5i
- sigmaE3/sigmaE5 = sqrt(N3/N5)(sigma3i/sigma5i) = sqrt(5/3)(22/16) = 1.77

Simulation of transport effects

- Charge deposited is sampled from Landau (GEANT) on voxel-by-voxel basis, 300 μm step size
- Charge is reduced by recombination by a constant value, no fluctuations
- Total charge that arrives at the wire plane is reduced by impurity loss factor, no fluctuations
- The charge is translated to the wire plane, along the drift axis. The arrival time is smeared with the longitudinal diffusion distribution. The transverse position is smeared with the transverse diffusion distribution.
- It's a numerical smearing – divide the voxel charge into 100 pieces, sample the diffusion distribution for each piece. After shifting the transverse position and time, find the nearest wire for that transverse position, and add this fraction of the voxel charge to that wire.
- It adds signal shape distributions, not just numbers.