

Diffusion and energy resolution in LArTPC reconstruction

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Fermilab

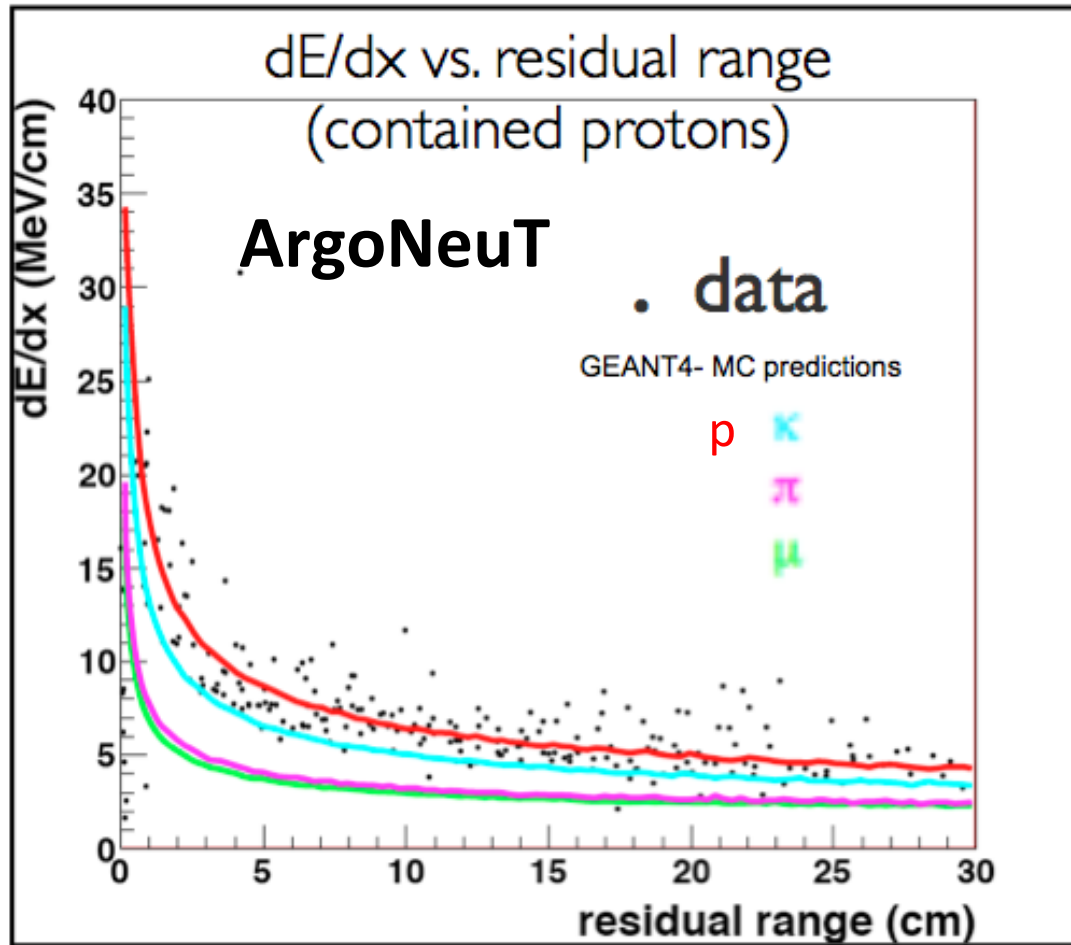
DUNE-docdb 589

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.

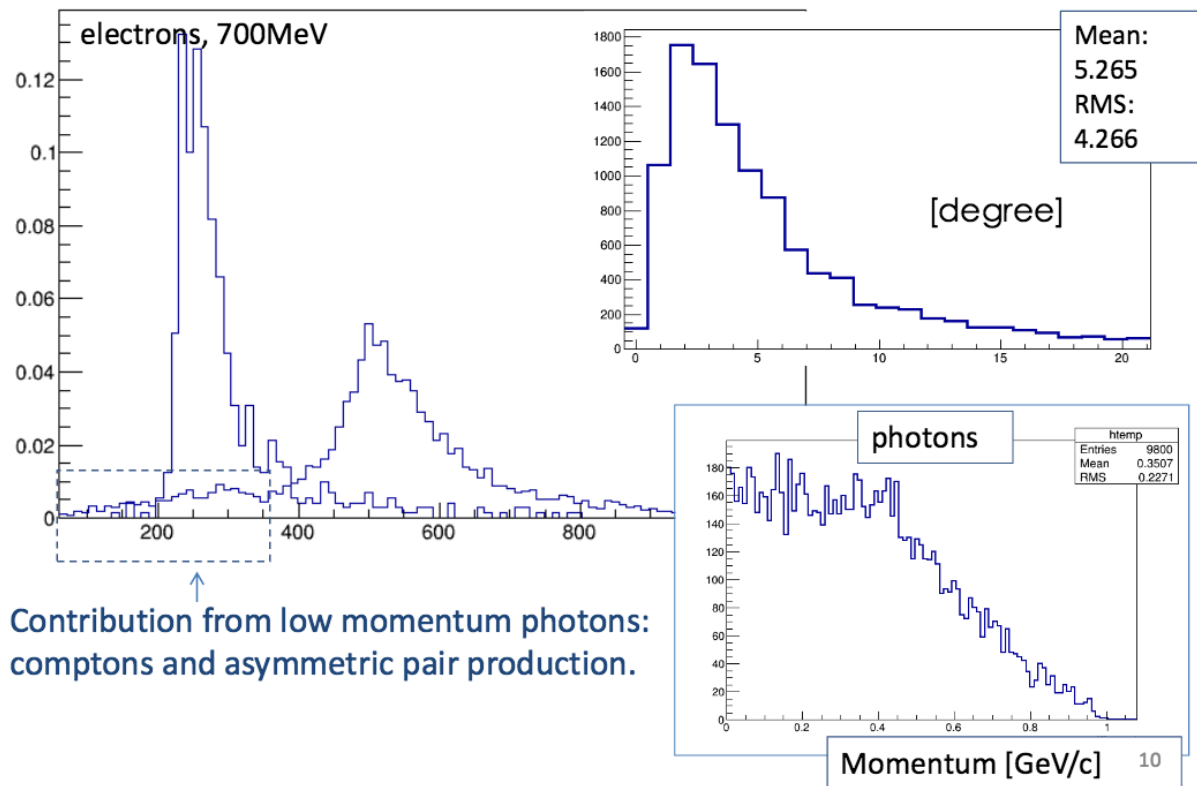
- **Electron shower energy**: sum over wires of charge collected on each wire.
- **Particle ID: dE/dx vs residual range**, single wire resolution determines band thickness?
- **e/gamma/pizero separation**: one component is the energy deposited in first 2.5 cm of shower, (first 5-10 wires) energy resolution on single wire affects overlap of 1-mip and 2-mip peaks

PID with dE/dx



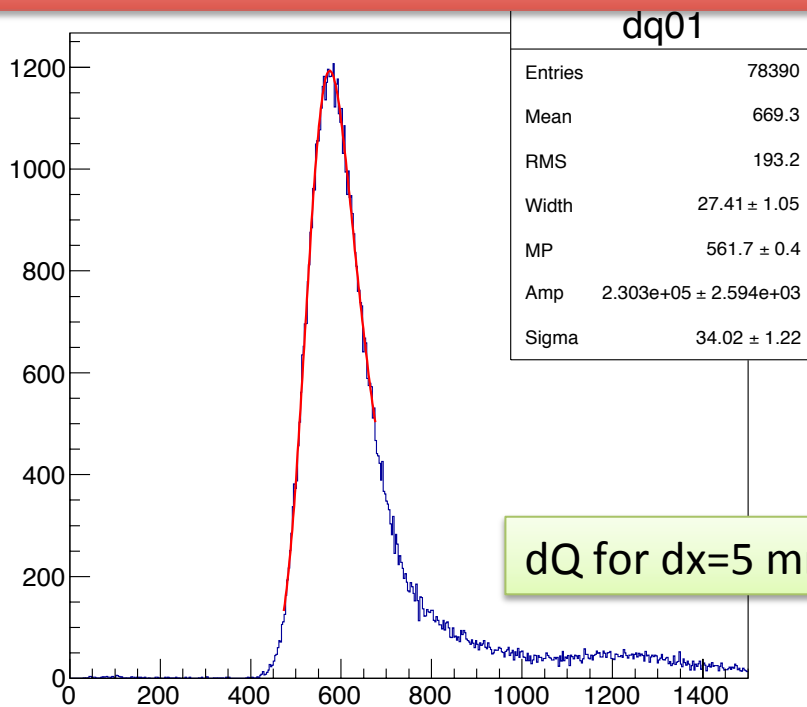
e/gamma separation

Reconstruction of dE/dx in isolated cascade

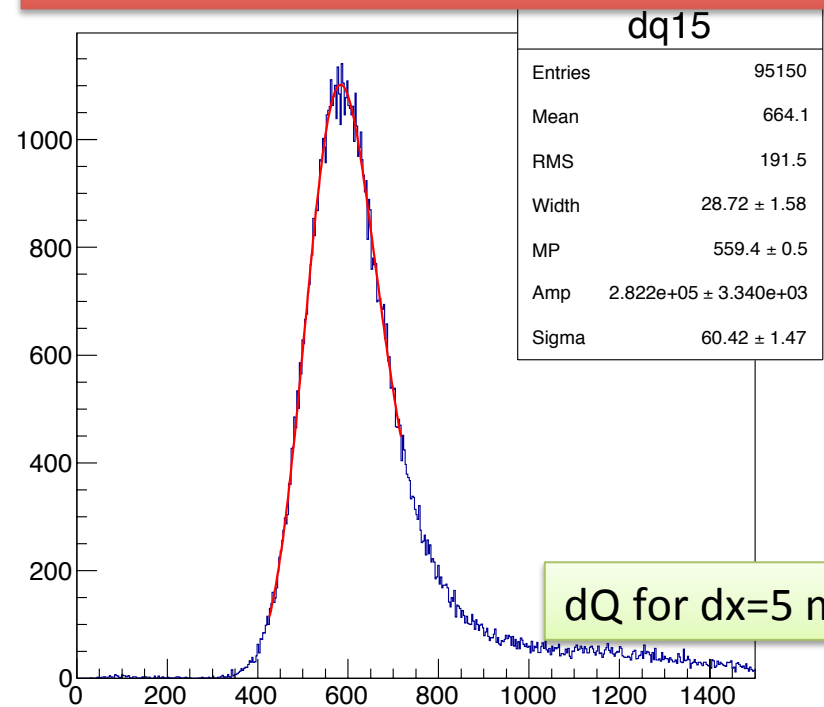


Motivation

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 $E_{drift}=500V/cm$, is that 60% subject to statistical fluctuations?
- Recombination: $\sim 1/3$ of ionization charge recombines for MIPs and $E_{drift}=500 V/cm$, (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

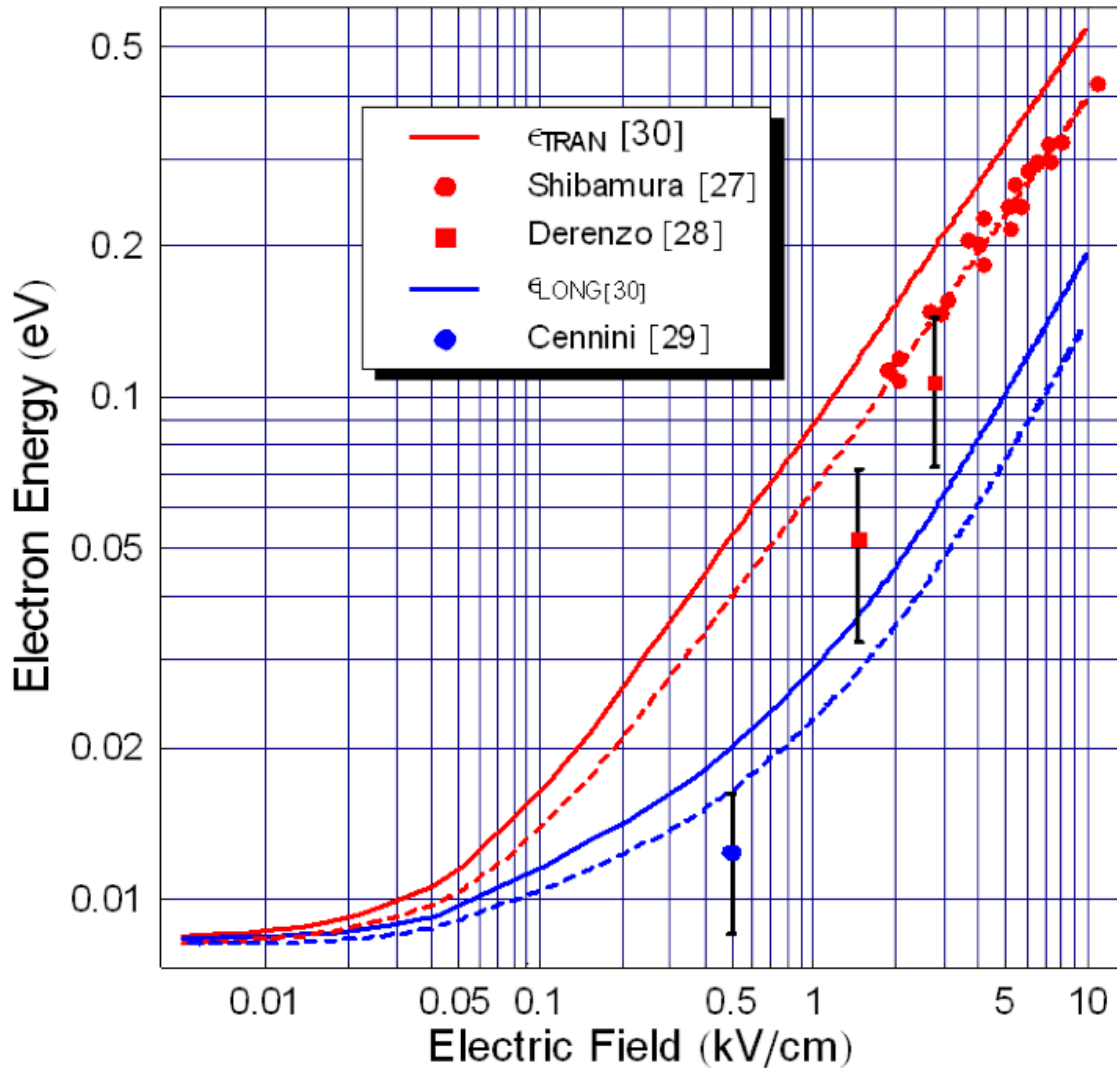
Note here that the statistical fluctuations questions above are important. The simulation does not include them for recombination or impurity losses. However, they are included for diffusion?

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
 - $\frac{1}{2}mv^2 = \frac{3}{2} kT \Rightarrow v_{th} = 6.6 \text{ m/ms}$ and $v_{drift} = 1.6 \text{ m/ms}$
- 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

Electron Energy in LAr: Data + Theory of Artazhev



$D = \mu E$, μ = electron mobility

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

$$\sigma_L = v(2D_L t)/v$$

$$\sigma_T = v(2D_T t)/v$$

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

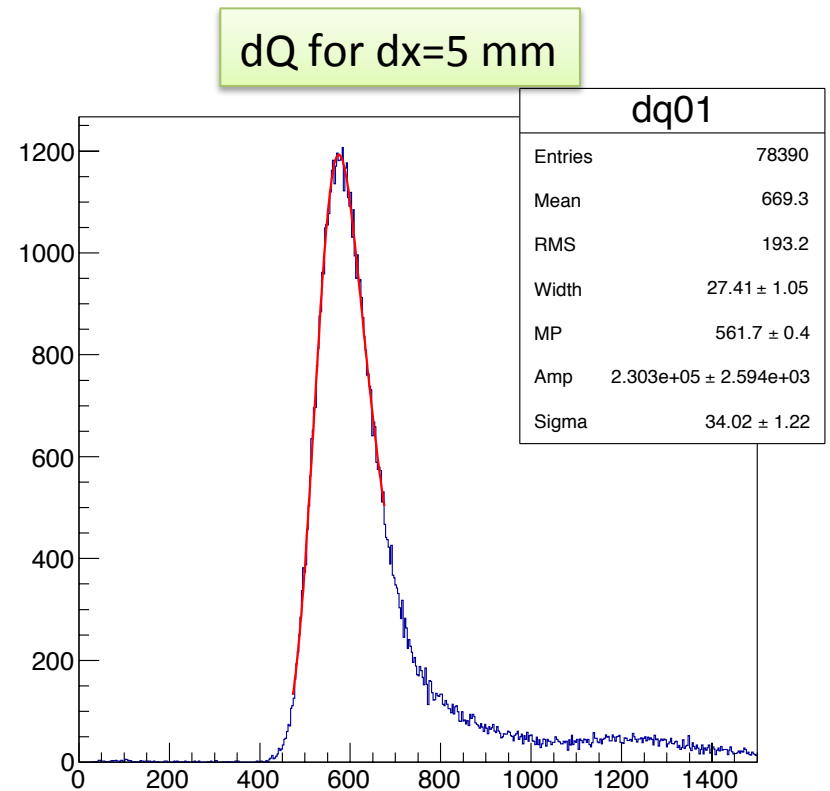
$$D_L = 6.2, D_T = 16.3 \text{ cm}^2/\text{ns}$$

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)

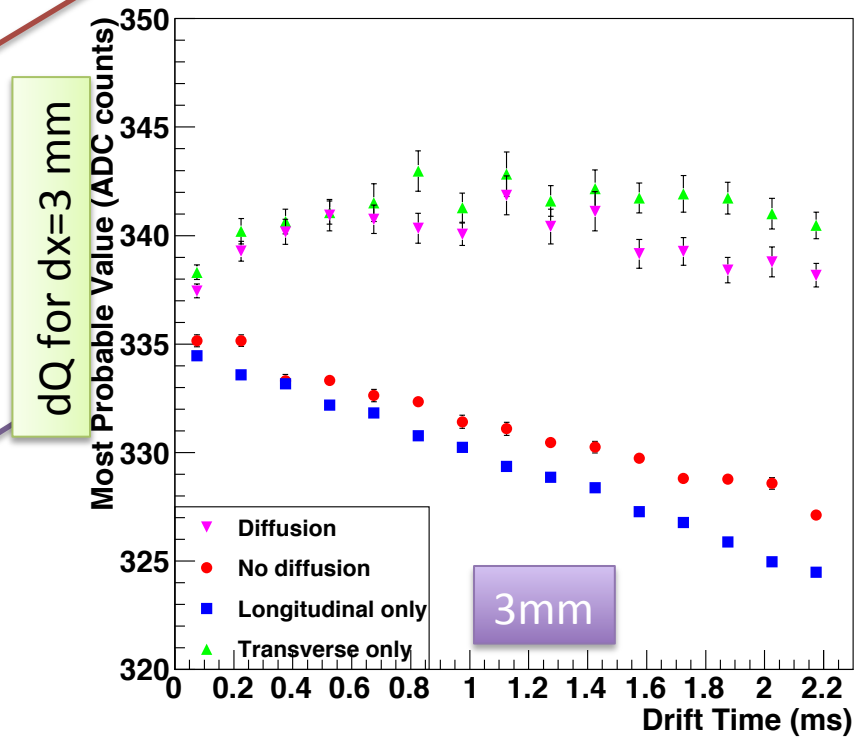
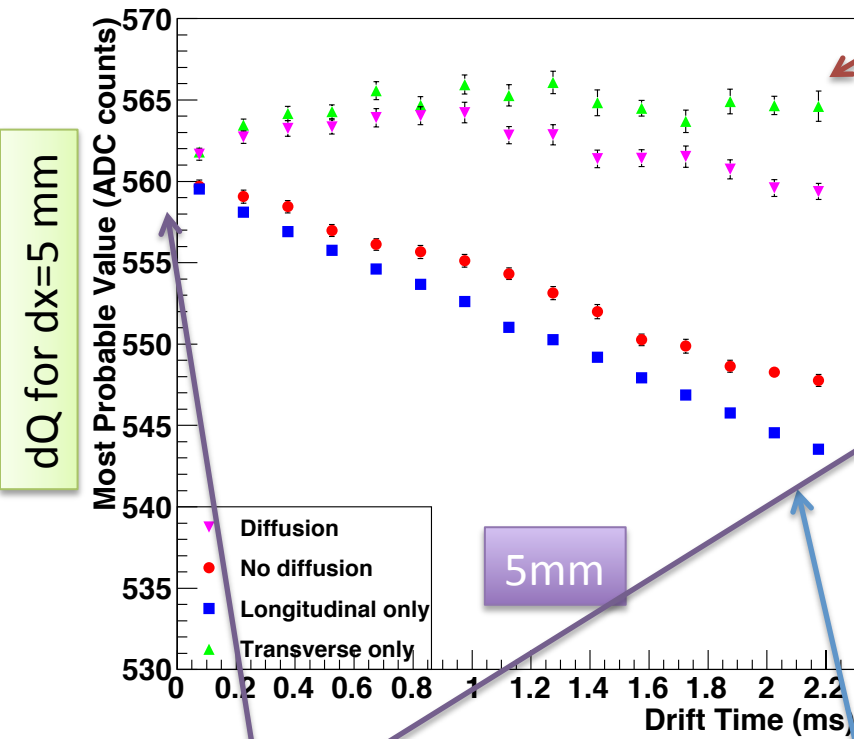
How to study diffusion?

- 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

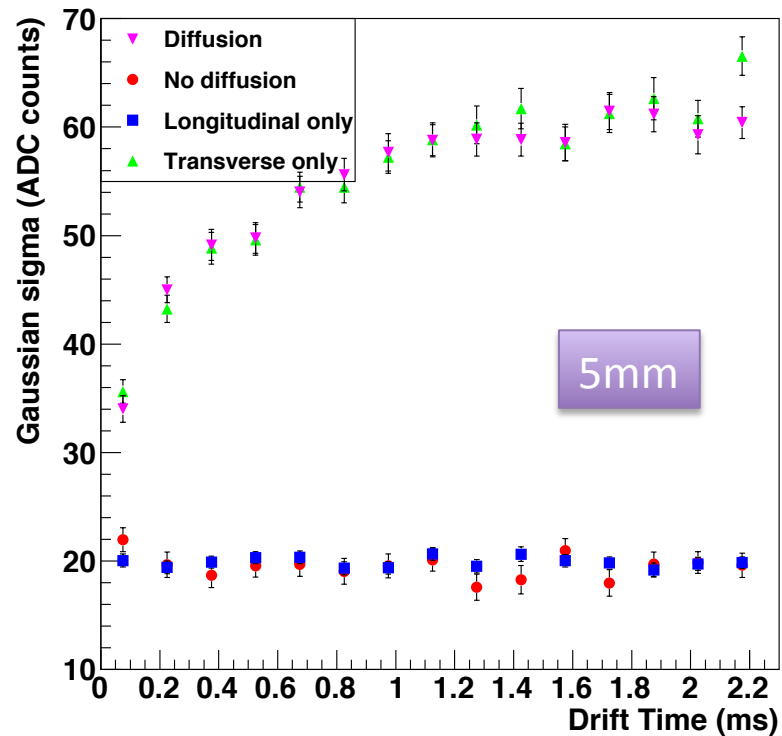
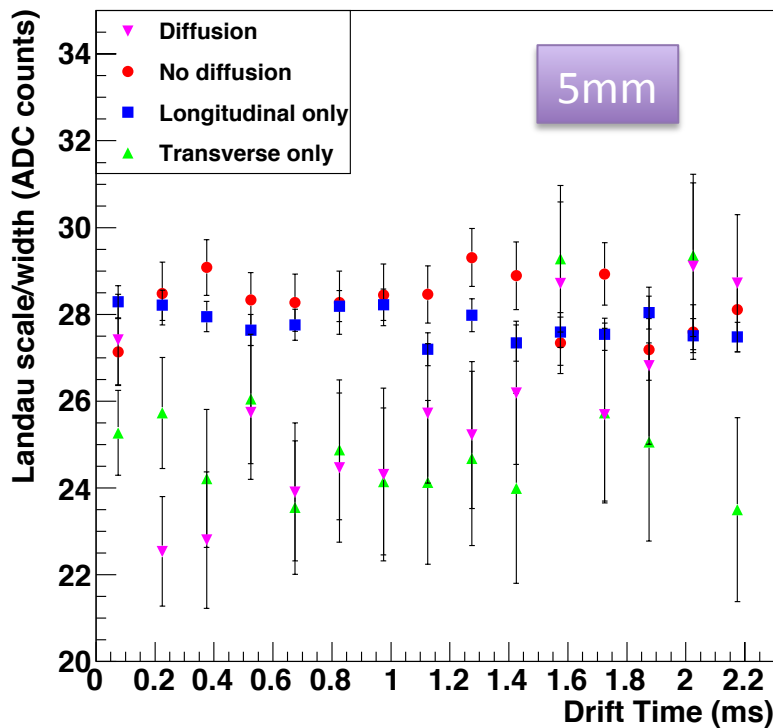


Signal for 3mm is 60% of 5mm (but noise is the same)

99 ms electron lifetime is 2% charge loss.

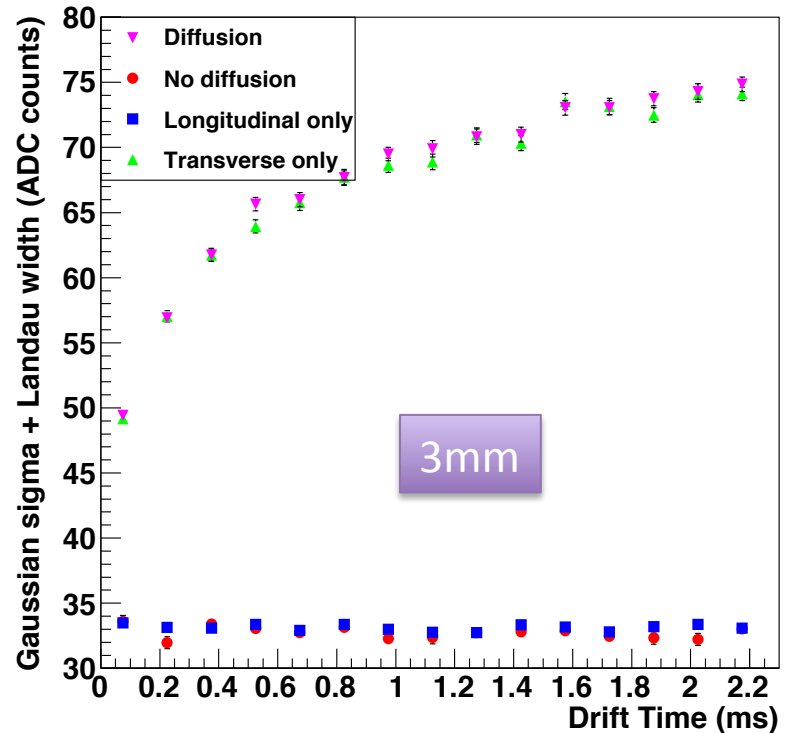
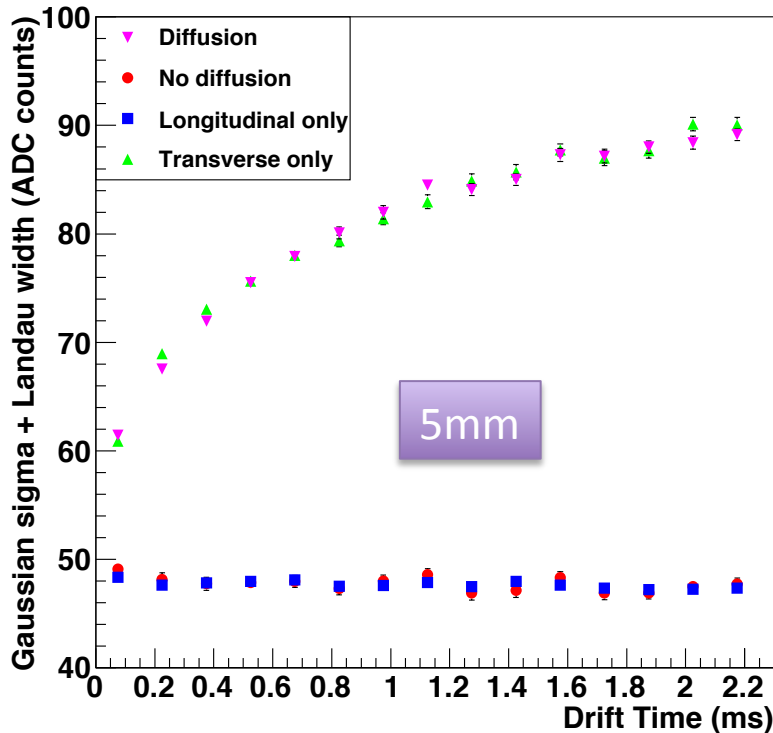
Oops, already switched to 9 seconds for future sims

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



More useful quantity is normalized to MPV

- 5mm: $\sigma=48/560=8.6\%$ at anode, 16% at cathode
- 3mm: $\sigma=32/340=9.4\%$ at anode, 22% at cathode

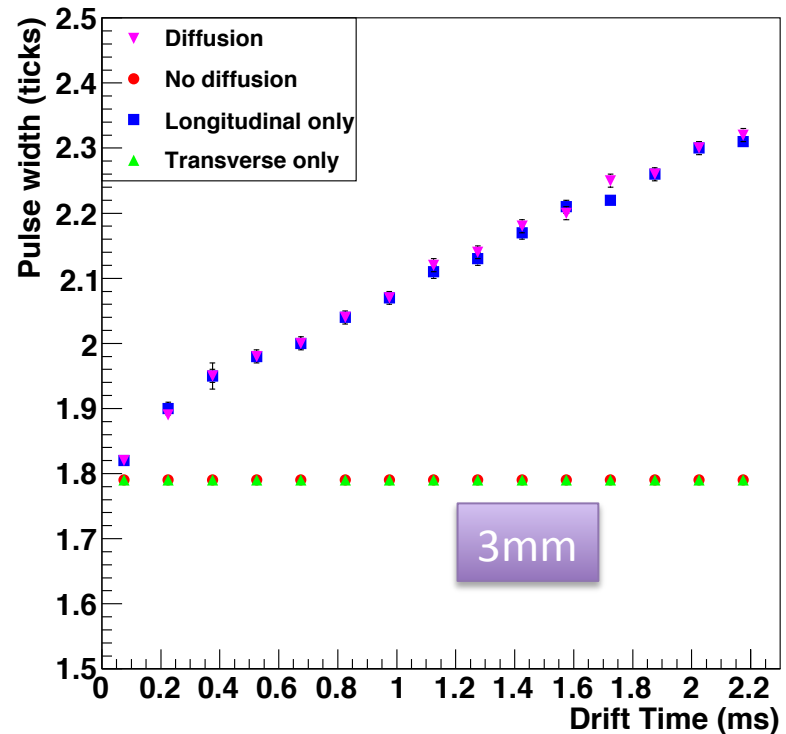
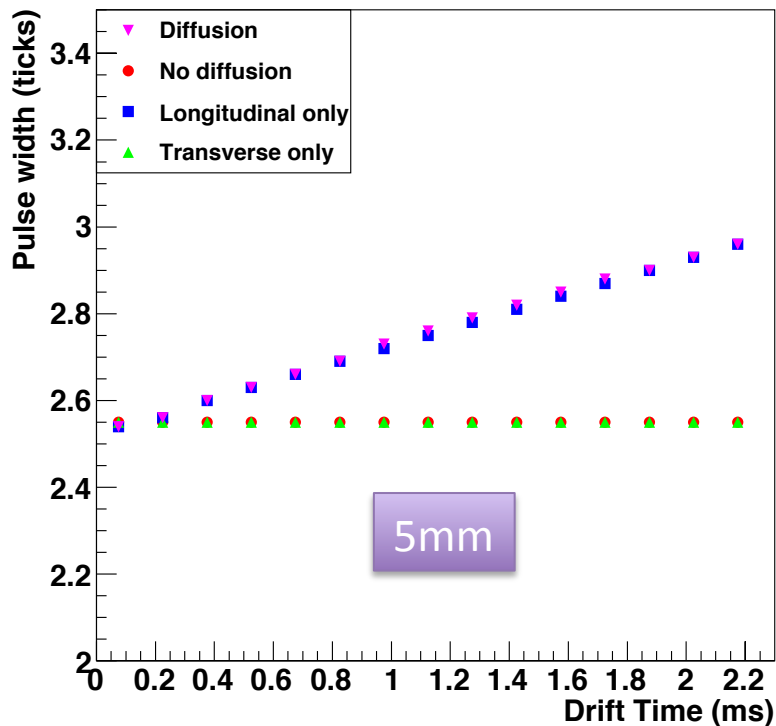
Energy Resolution?

5mm: $\sigma_Q/Q \sim 89/562 = 16\%$ at cathode, 8.6% at anode

3mm: $\sigma_Q/Q \sim 75/340 = 22\%$ at cathode, 9.4% at anode

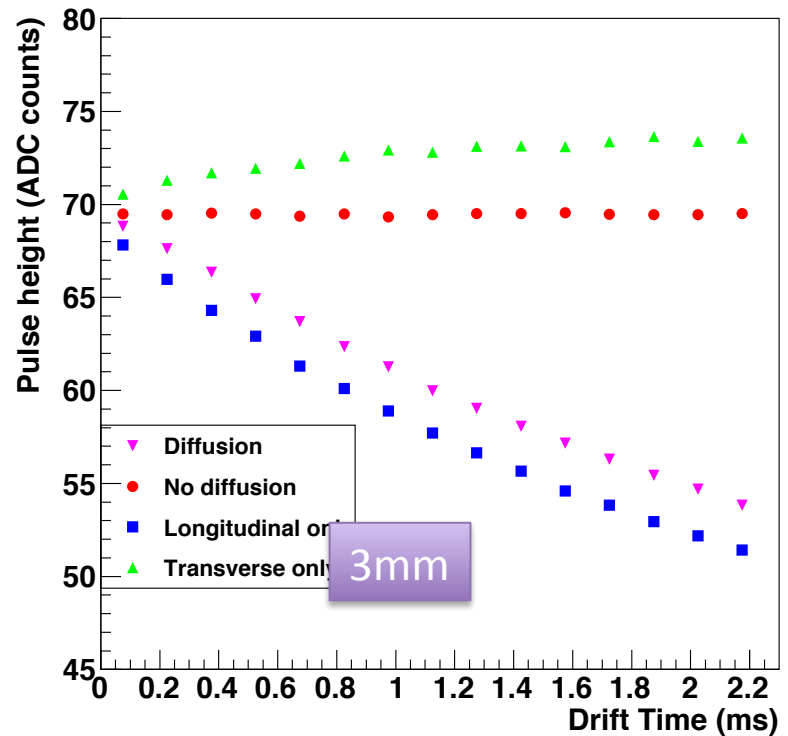
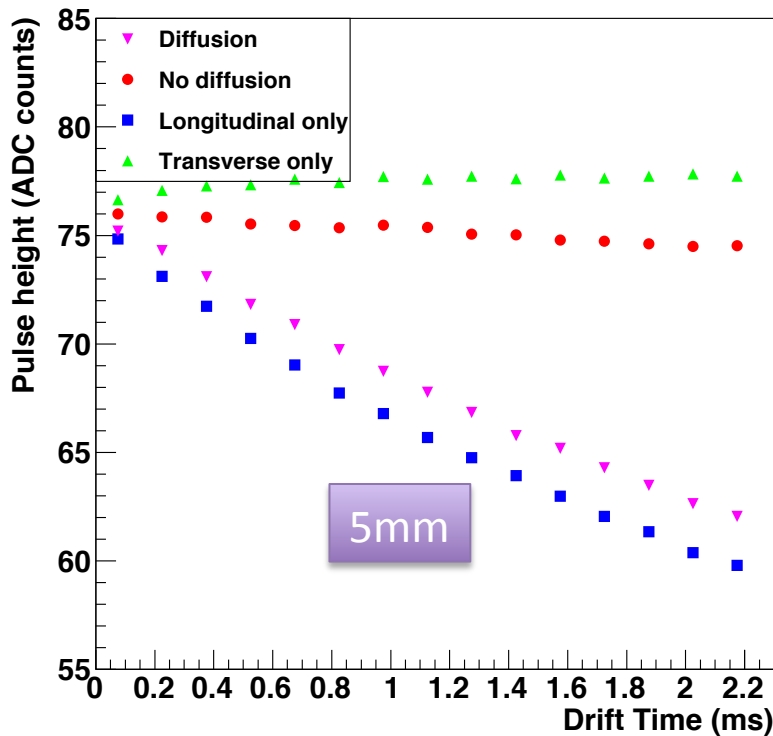
- Directly affects widths of dQ/dx bands for PID
- e/gamma separation is the sum of first 2.5 cm of shower, 5-10 wires, some influence
- Shower is sum of all wires, but correlated errors.
(more terms in the sum, each with larger uncertainty)
 - Best case (all correlated) is that $\sigma_{E3mm} = 1.8\sigma_{E5mm}$ 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



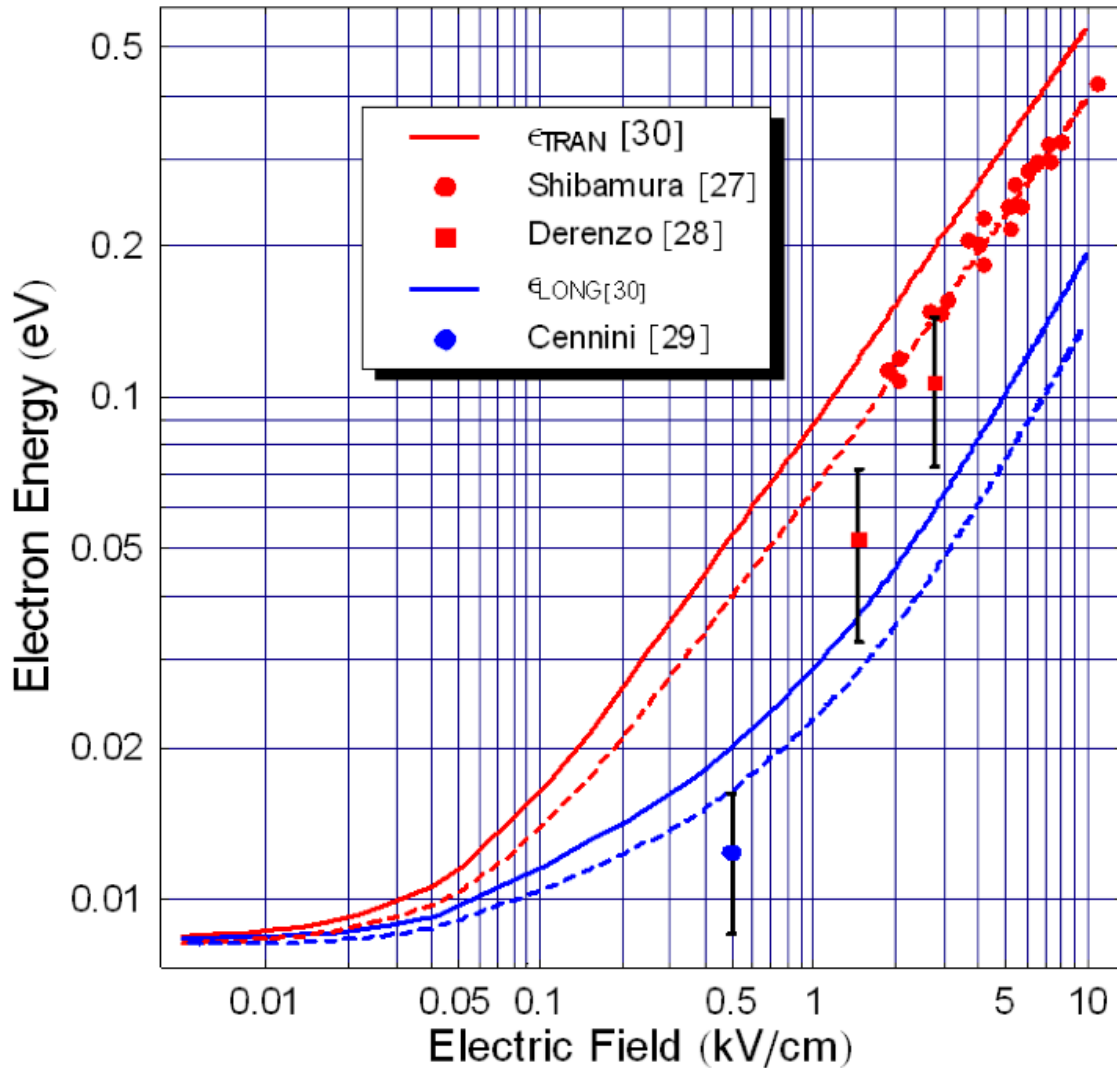
Dominant effect of longitudinal diffusion is to widen the pulses on each wire.
Direct experimental access to longitudinal diffusion through pulse height and width,
but complicated by impurities.

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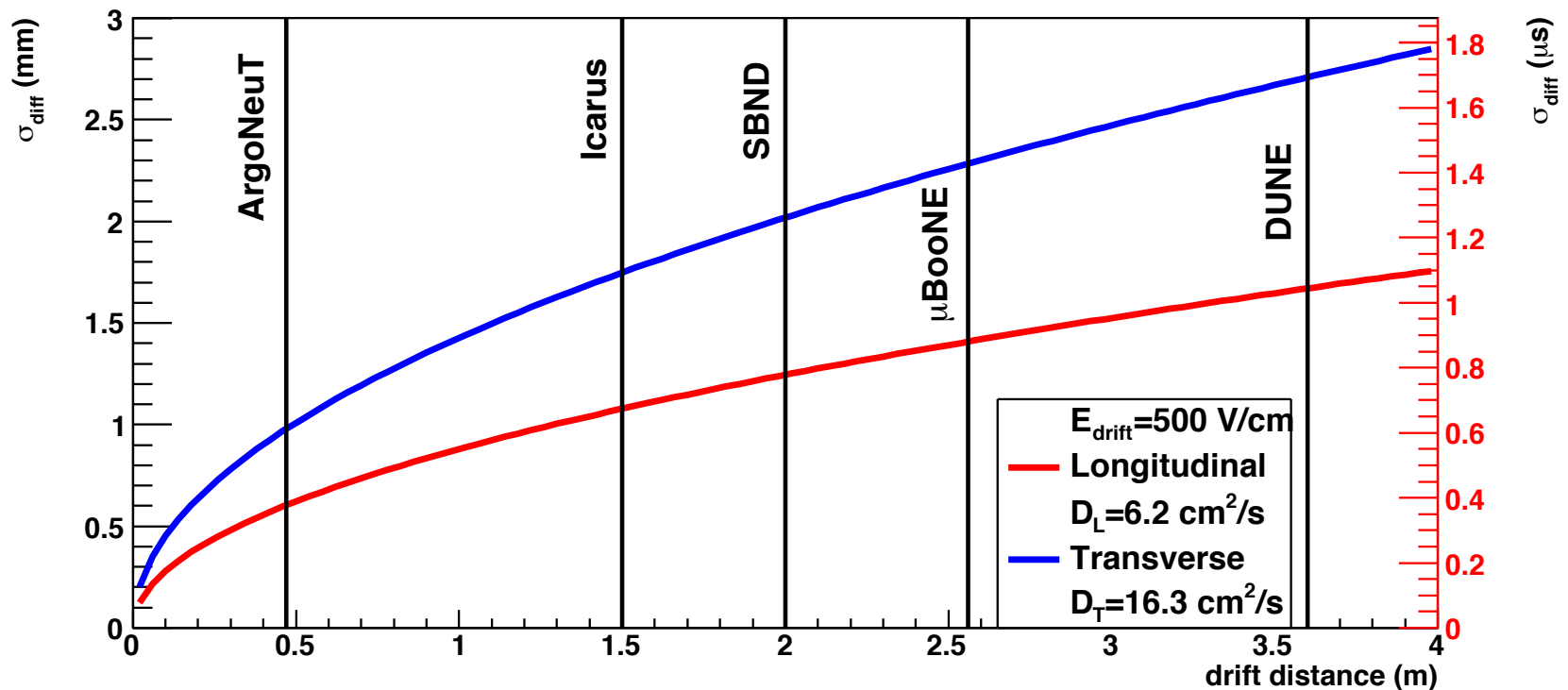
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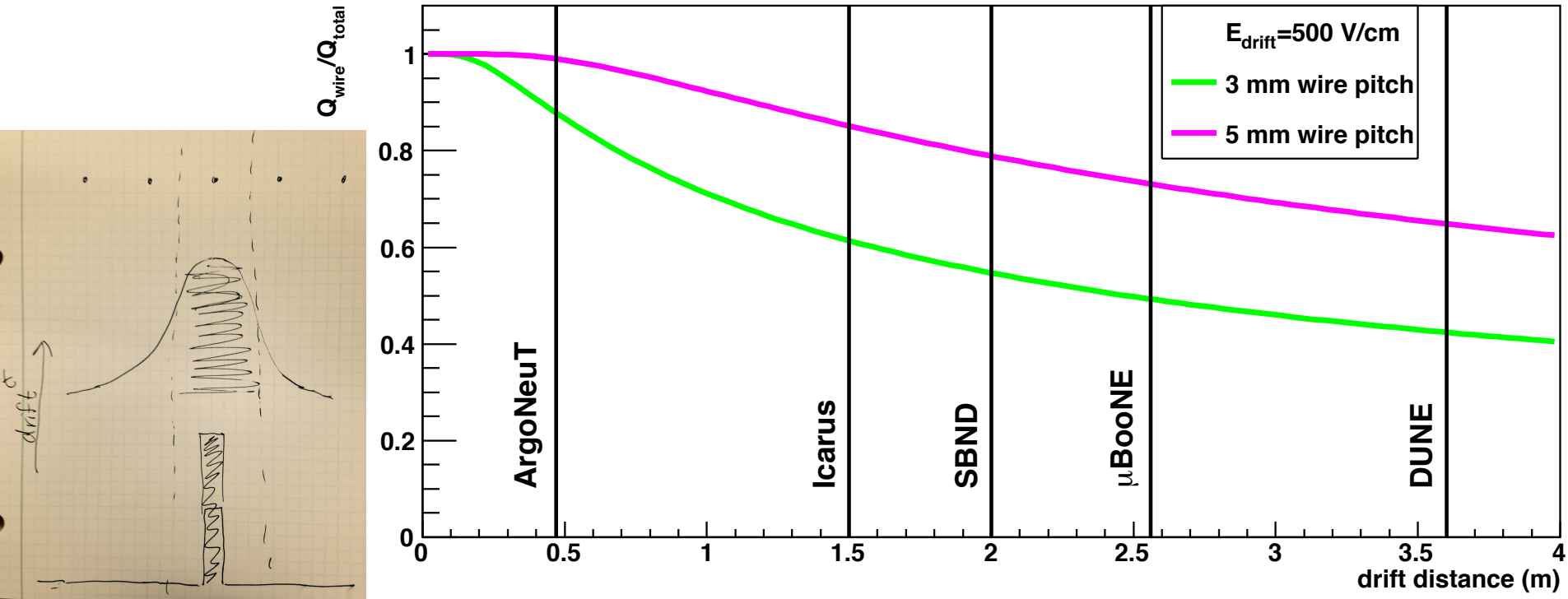
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How big is the smearing? How does DUNE compare with other detectors?



***Note that Microboone is not running at 500 V/cm

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). Pulse height and width plots already updated for new 3mm signal simulation, others will be updated in docdb 589 by October 15.
- Dom Brailsford and myself are planning the 35ton measurement with realistic data sample and track reconstruction, stay tuned.

DISCLAIMER: this is not a comprehensive study (straight muon tracks at one angle only). Samples were to chosen to investigate a 35ton diffusion measurement

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, and we need a special case study for “unexpected large amounts of noise”
- There is a diffusion model in the LArSoft simulation, results in a large enhancement of single wire charge uncertainty. 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.
- Use ArgoNeuT, LArIAT and ICARUS performance numbers with care

Backup

Simulation/reco details

- Will update with 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 is time of max ADC
- Pulse 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)
- Use 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.

math

- $\sigma_{E3} \propto \sqrt{N3} \sigma_{3i}$
- σ_{E3} = shower energy resolution, $N3$ is number of wires, σ_{3i} is charge resolution on a given wire
- $\sigma_{E5} \propto \sqrt{N5} \sigma_{5i}$
- $\sigma_{E3}/\sigma_{E5} = \sqrt{N3/N5} (\sigma_{3i}/\sigma_{5i}) = \sqrt{5/3} (22/16) = 1.77$

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.