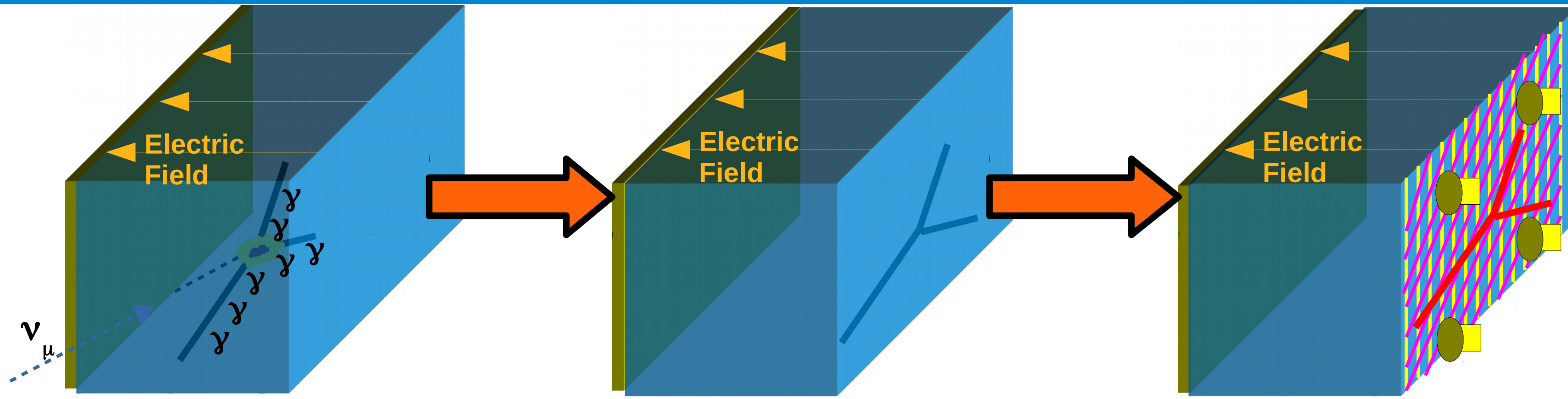
Single Phase Liquid Argon Time Projection Chambers

Jonathan Asaadi - University of Texas Arlington

International Workshop on Next Generation Nucleon Decay and Neutrino Detectors
(NNN16)

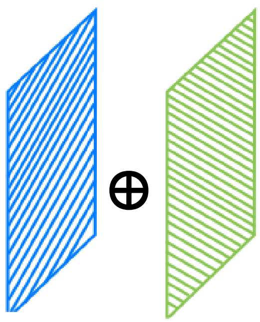
Liquid Argon Time Projection Chamber



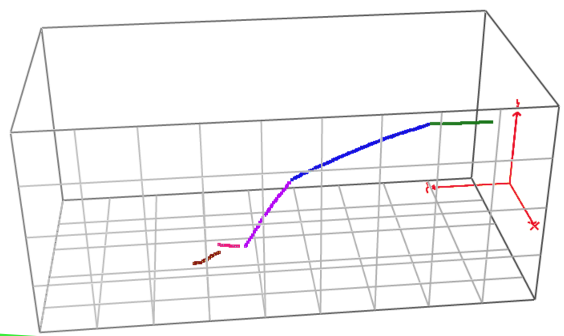
Neutrino interaction in LAr produces ionization and scintillation light

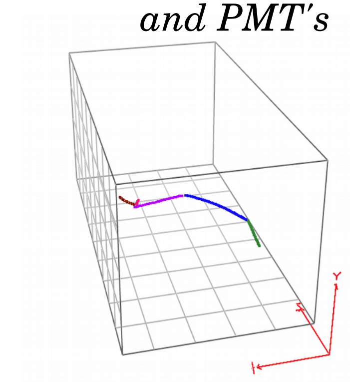
Drift the ionization charge in a uniform electric field

Read out charge and light produced using precision wires and PMT's

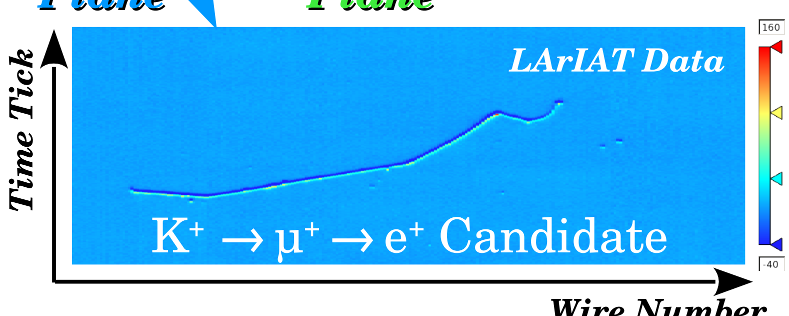


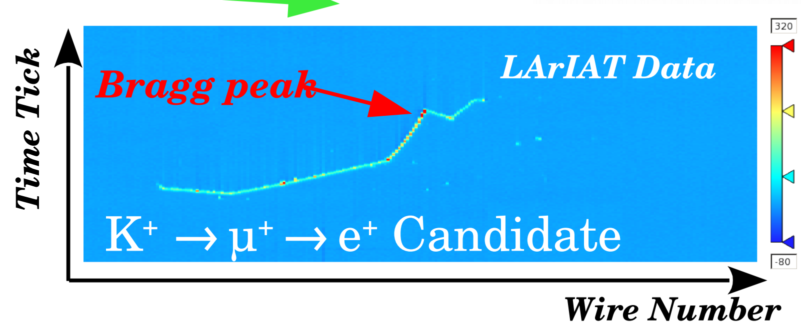
$\oplus$ $\oplus$ ***Drift Time*** =





Induction Plane ***Collection Plane***





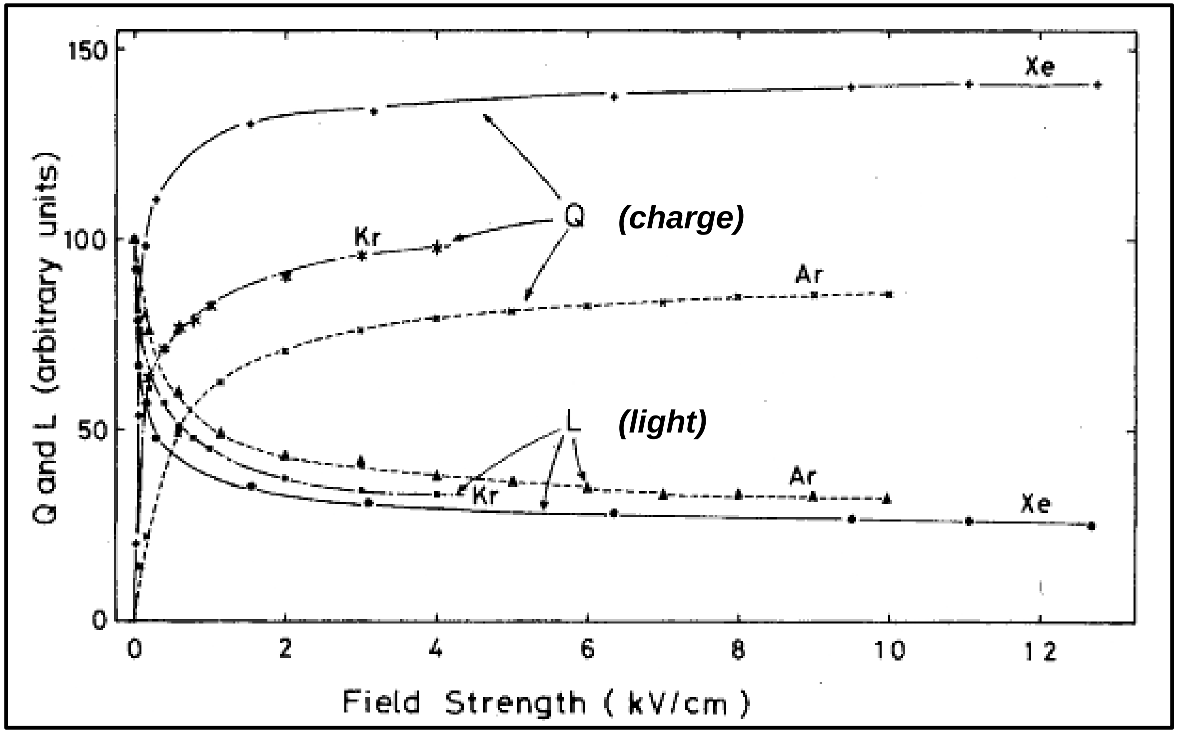
✔ *3D imaging with mm space resolution*

✔ *Calorimetry information*

✔ *PID capabilities*

Basics of LAr Scintillation Light

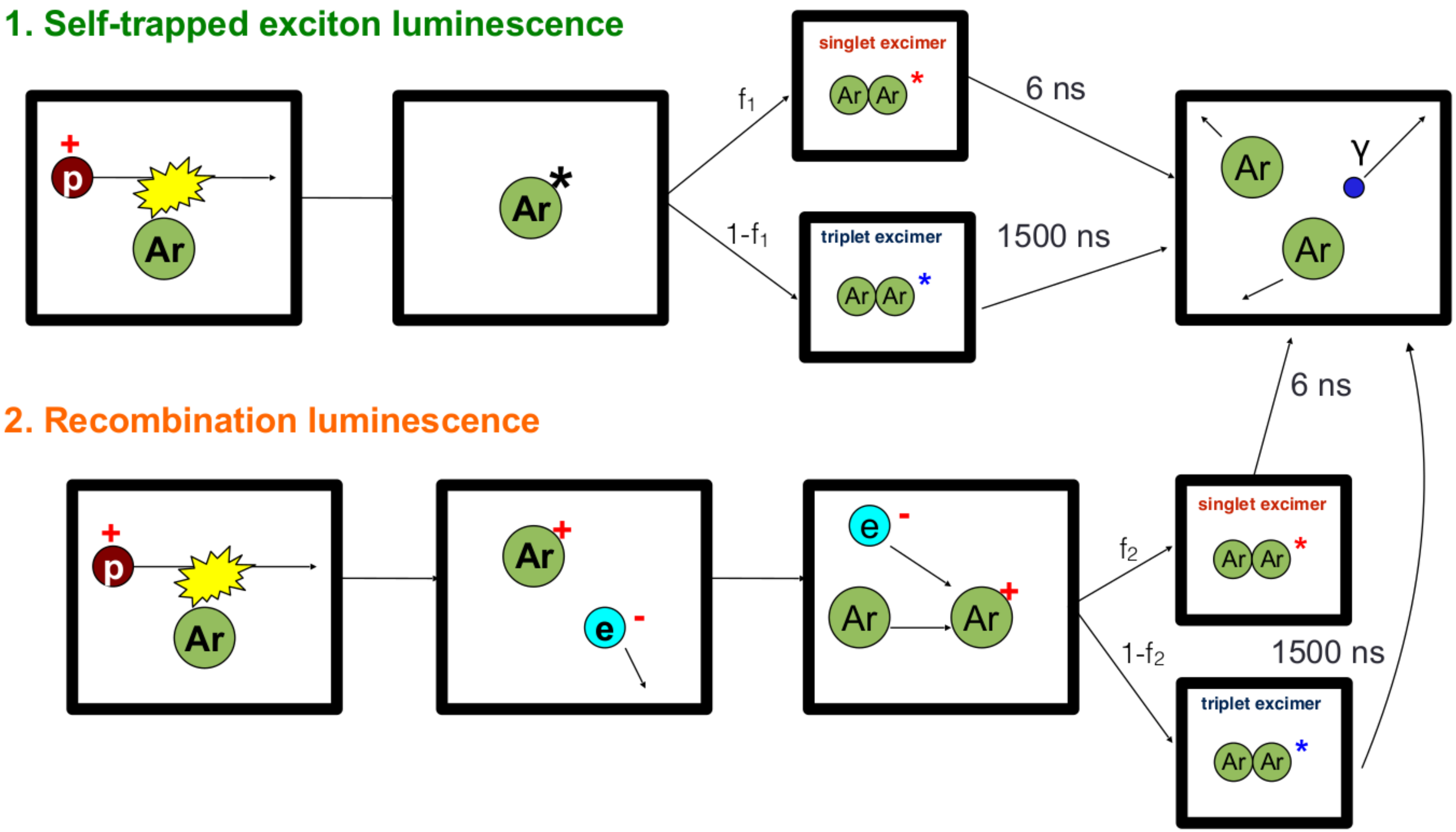
- **Overview of the basics**
  - 40,000 photons/MeV @ 0 drift field (V/cm)
    - Light yield is inversely related to the drift field (and charge yield)
  - Scintillates in the Ultraviolet (128 nm)
    - Need light detectors sensitive to UV or wavelength shift the light for detection
  - Very transparent to its own light
    - Rayleigh scattering ~$(1+\cos^2(\theta)/\lambda^4)$ = 64 cm @ λ=128nm
  - Light is emitted isotropically



40,000 γ/MeV @ 0 V/cm
29,000 γ/MeV @ 275 V/cm
24,000 γ/MeV @ 500 V/cm

Basics of LAr Scintillation Light

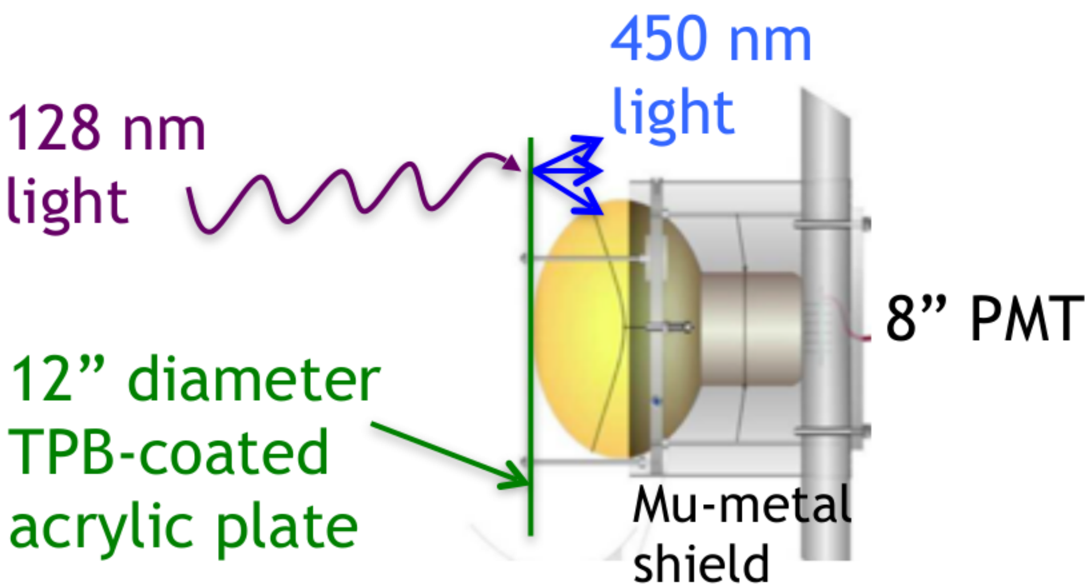
image credit: B. Jones (UTA)



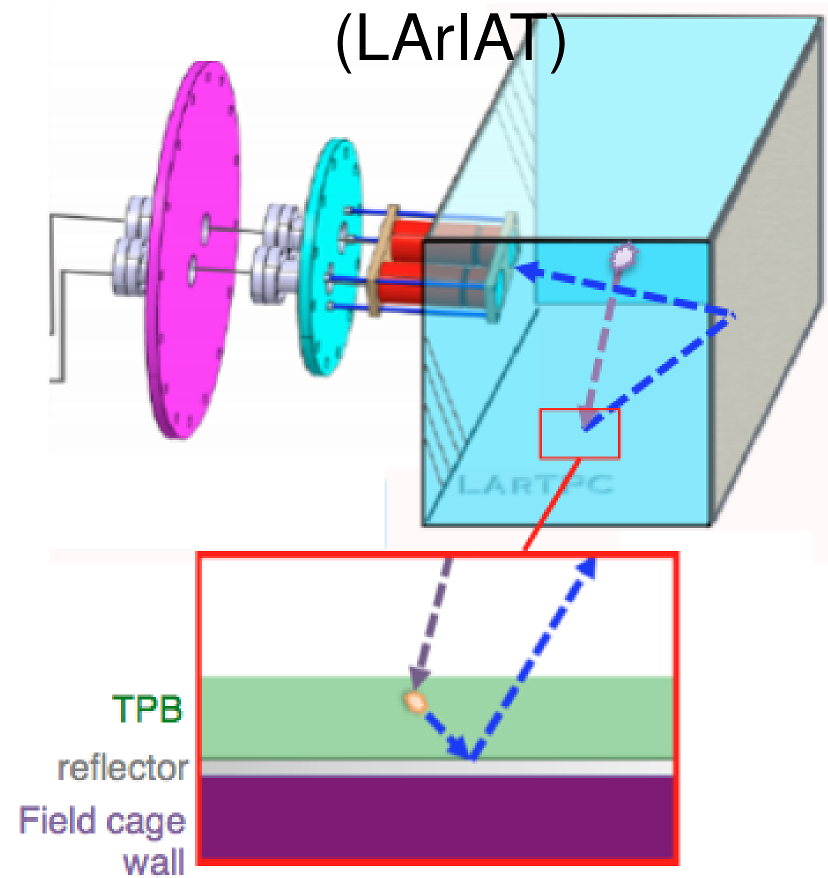
- **Two mechanisms for light production**
  - Recombination luminescence decrease with increased drift field
- **Two time components described by exponential with τ~ 6ns (fast) / 1.5 μs (slow)**
  - Different components effected by impurities differently
- **Highly ionizing particles have different recombination/light yield**
  - For a MIP: 25% fast light / 75% slow light

Wavelength Shifting Techniques

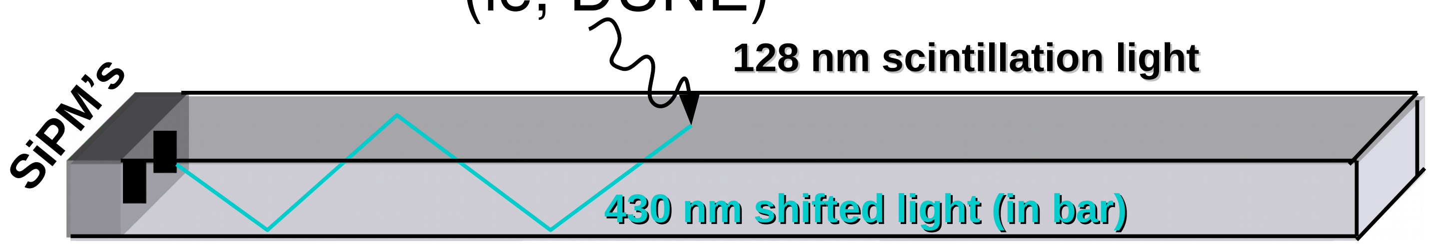
Standard LArTPC approach
(ie, ICARUS, MicroBooNE)



Reflector-based approach
(LArIAT)

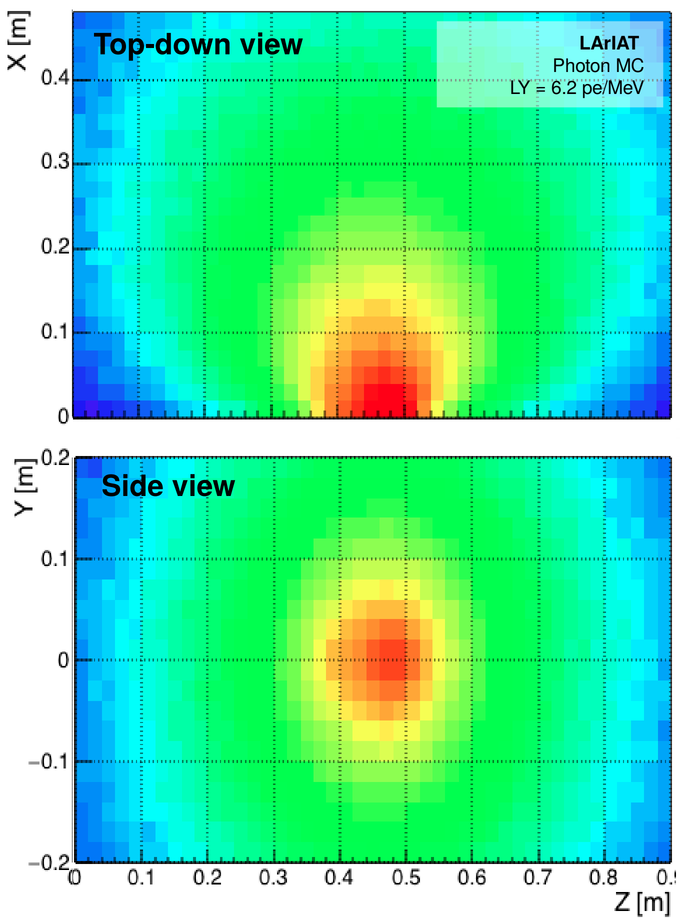


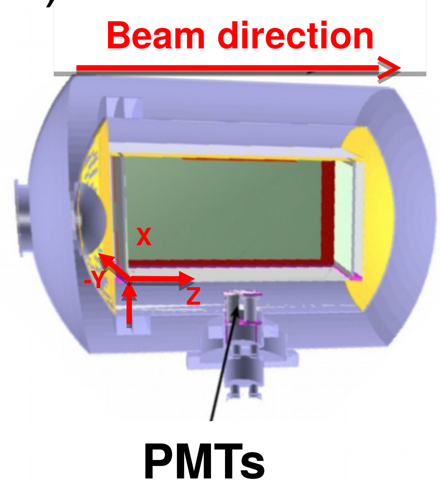
Wavelength shifting light guide approach
(ie, DUNE)



Standard LArTPC approach
(ie, ICARUS, MicroBooNE)

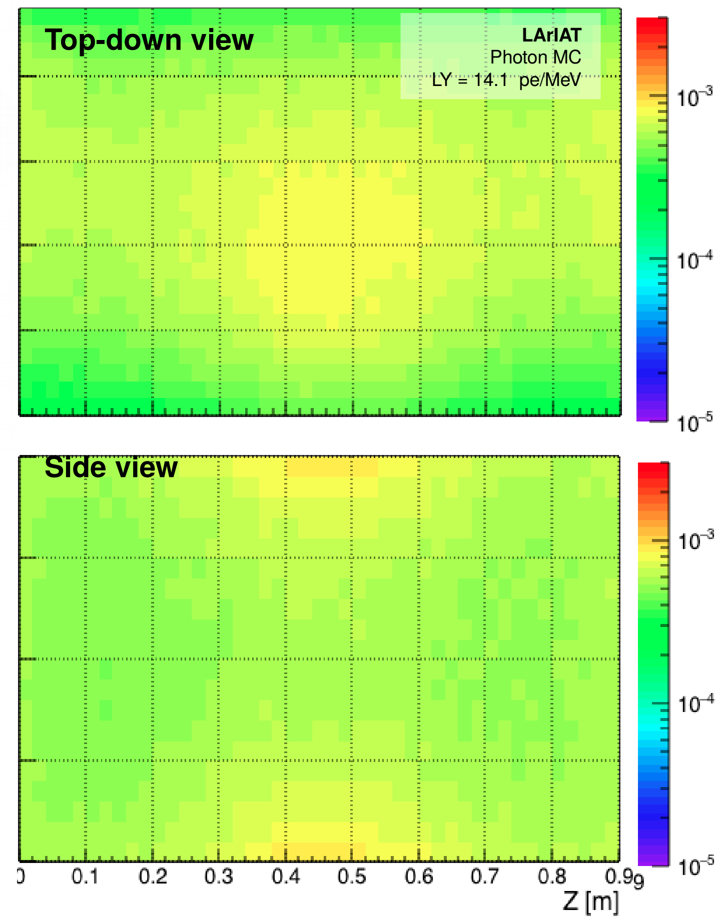
No foils, TPB-coated PMTs





Reflector-based approach
(LArIAT)

Run I

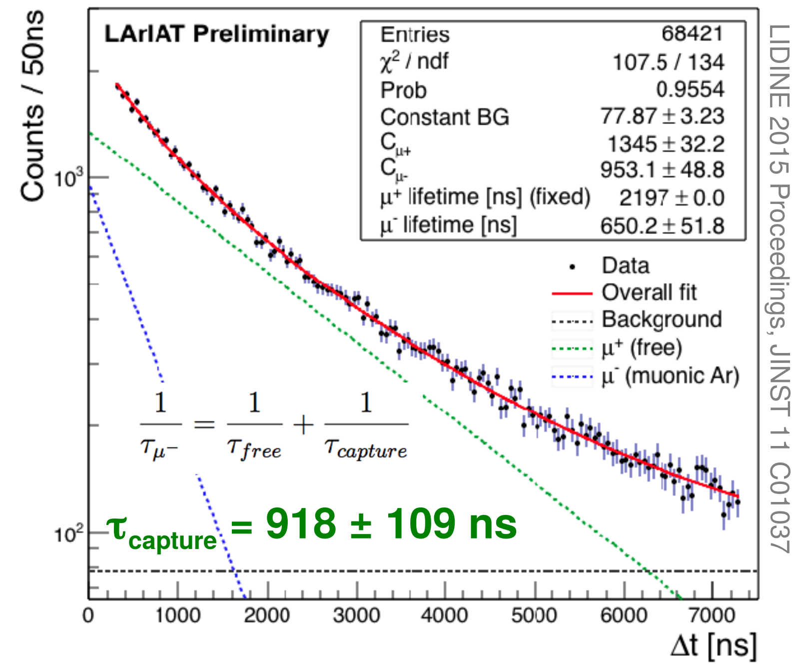


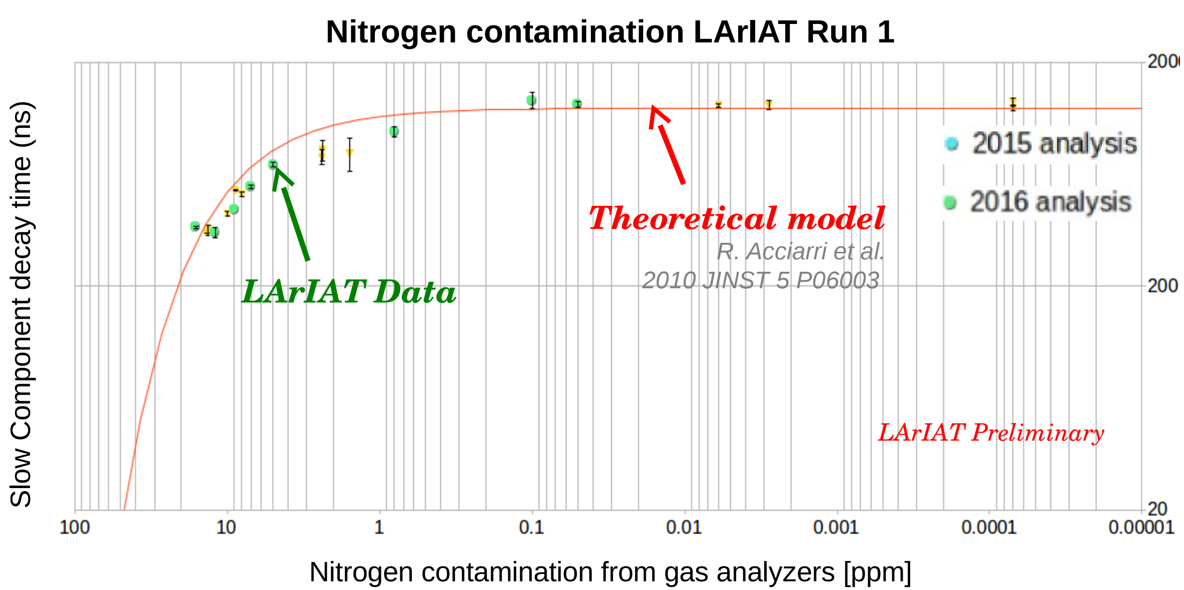
> **2x light** & **more uniform visibility** compared to case with no foils and TPB-coated PMTs

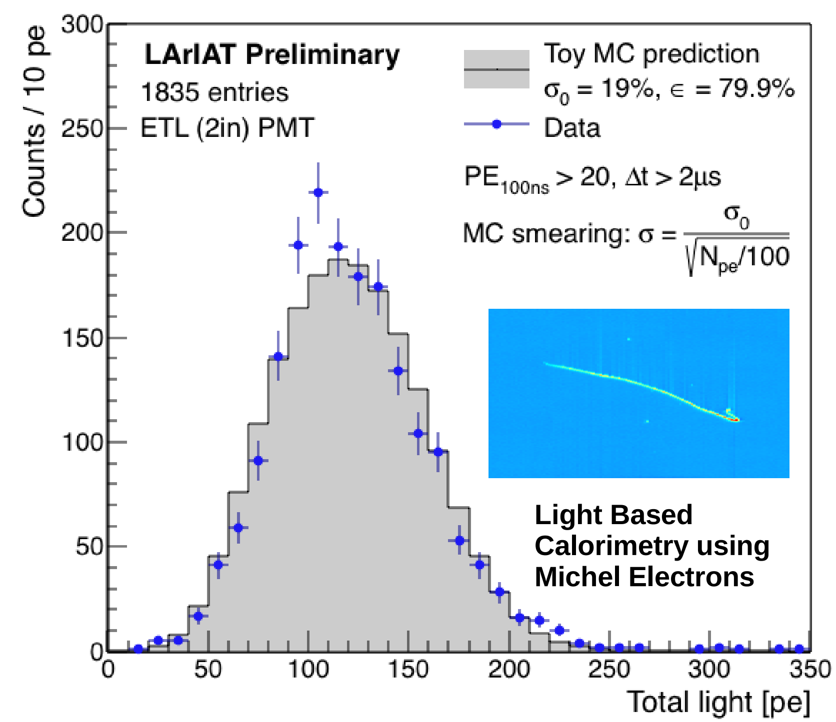
Can do calorimetry in addition to cosmic rejection using the light in the single phase detector

Physics with Scintillation Light

- **Using a sample of crossing and stopping cosmic muons LArIAT is already doing physics measurements**
  - Nitrogen Contamination from the “slow” light
  - Michel Electron energy measurements using scintillation light
  - Muon capture lifetime

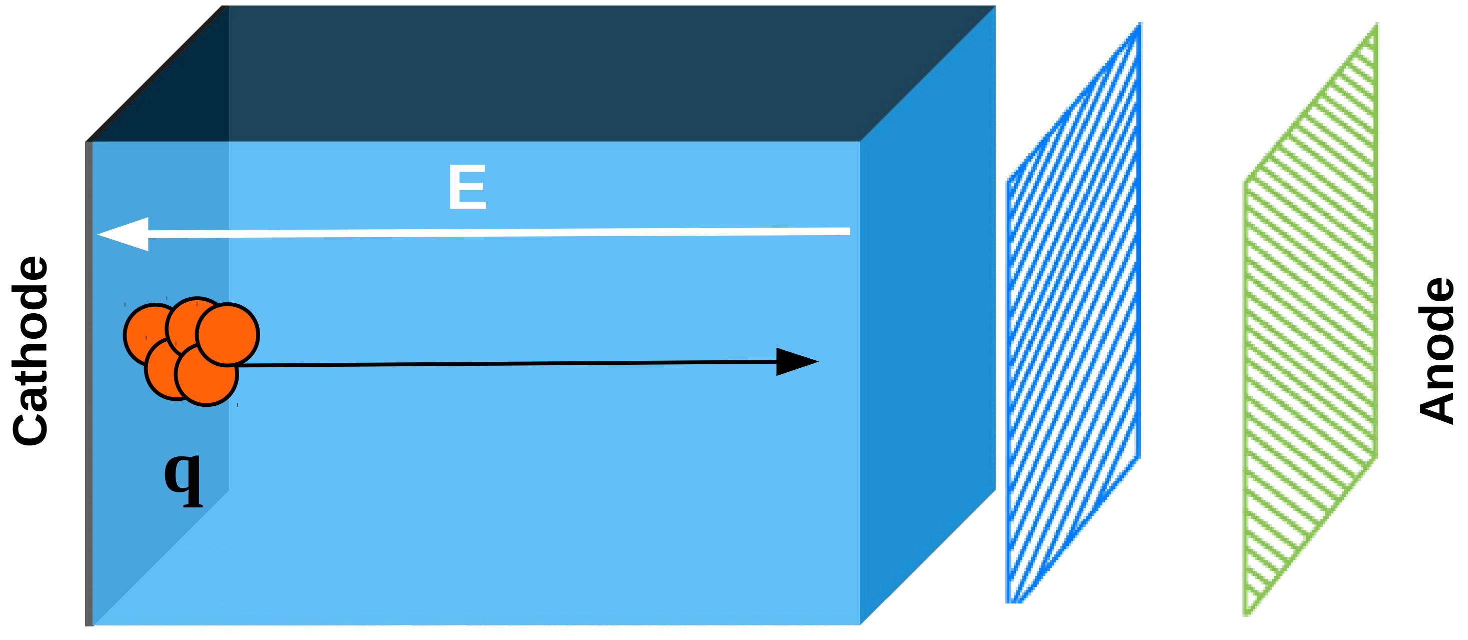






Charge Readout

When drifting your electrons through the argon you encounter a lot of interesting physics that impacts your measurement

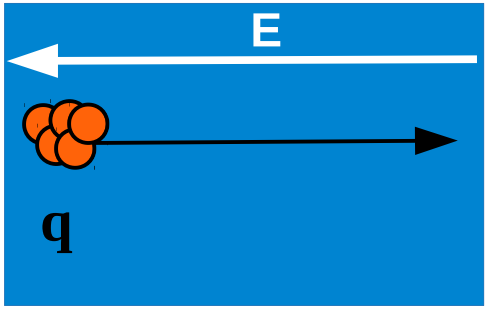


- **Ion Drift Velocity**
- **Ion Diffusion**
- **Ion Recombination**

See M.Mooney's talk for much more detail on how we cope with all these things….

Charge Readout

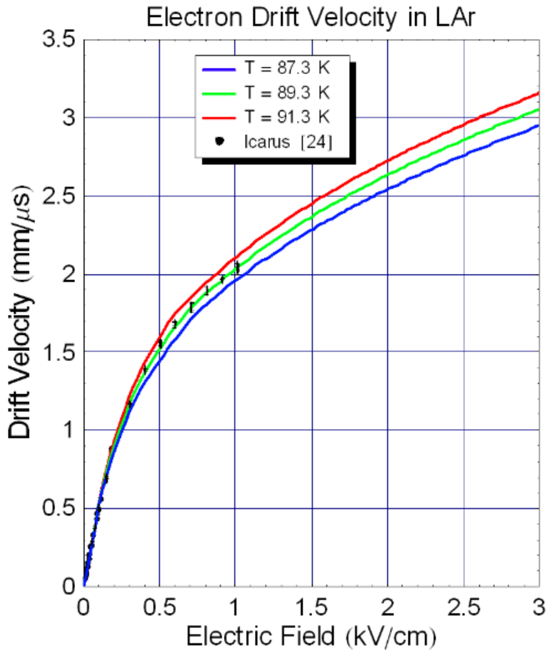
- **Ion Drift Velocity**



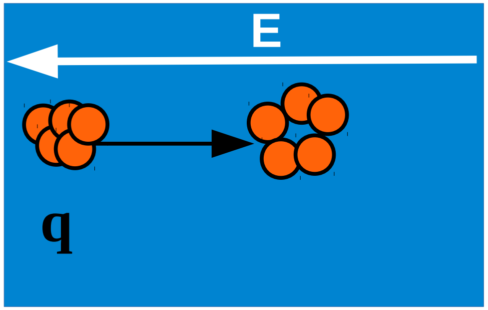
The drift velocity is an empirically modeled function depending on temperature (T) and electric field (E) in the argon

W. Walkowiak, NIM A 449 (20

$$v_d(T,|E|) = (P_1(T-T_0)+1)(P_3|E|\ln(1+P_4/|E|) + P_5|E|^{P_6}) + P_2(T-T_0)$$



- **Ion Diffusion**



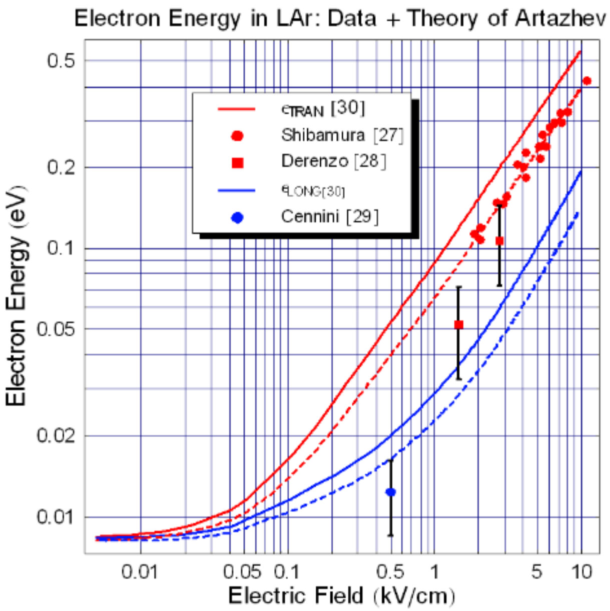
The ion diffusion (RMS spread) is related to the drift distance (Δz), the electric field (E), and the electron mobility in argon

S. Amoruso NIM **A516** (2004) 68

W. Walkowiak, NIM A449 (2000) 228

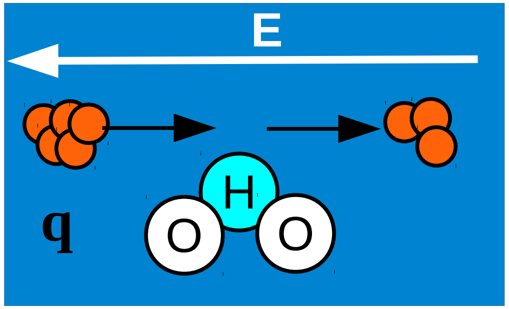
$$\sigma_{T(L)} = \sqrt{\frac{2\,\varepsilon_{T(L)}\,\Delta z}{E}}$$

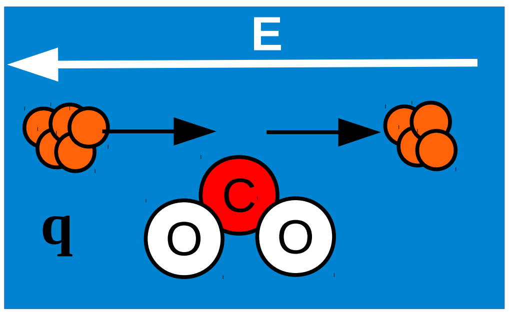
$$D = \mu\,\varepsilon$$

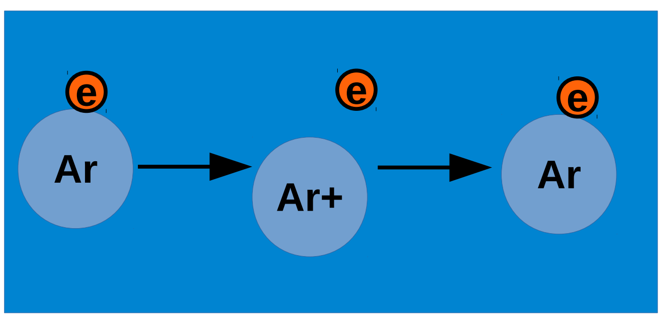


Note: What I measure is the electron energy (ε) and I get the diffusion constant using the relationship with the electron mobility

- **Ion Recombination**

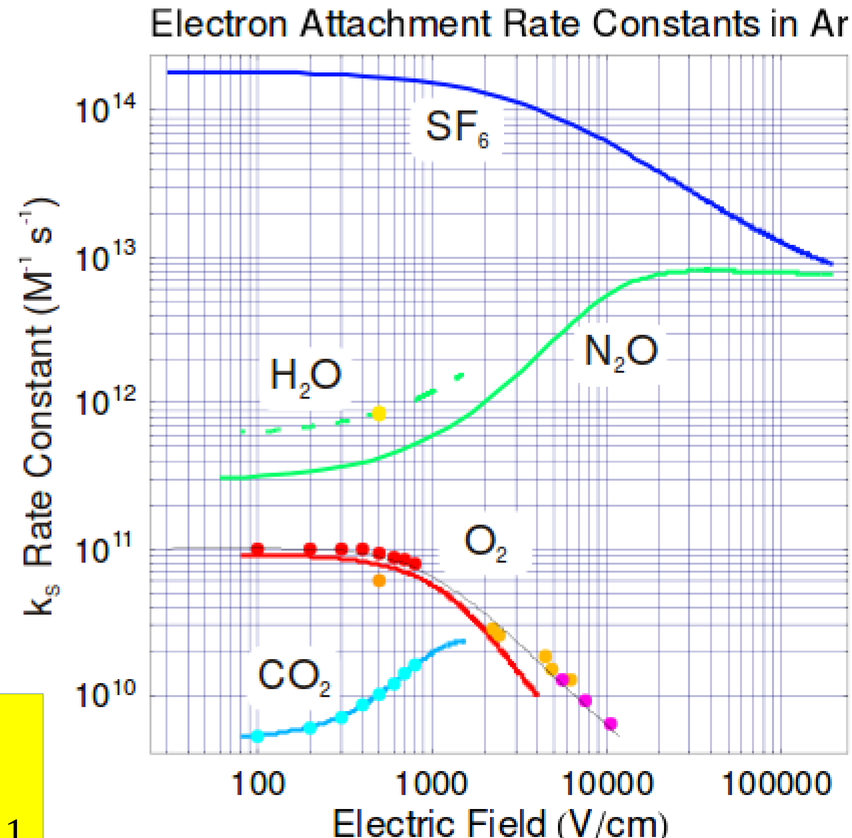






Ion recombination is also a complicated affair depending on various types of impurity, its concentration, and the electric field

$$Q(t) = Q_0 e^{t/\tau_a}$$
$$\text{where } \tau_a = (k_s n_s)^{-1}$$



Q(t) is the charge collected as a function of time
k_s is the electron attachment rate at a constant molar concentration (which itself has a dependence on the electric field)
n_s is the molar solute concentration in LAr

Charge Readout

LAr Purity

(Electro-negative impurities diminish (eat) our signal; Nitrogen quenches scintillation light)

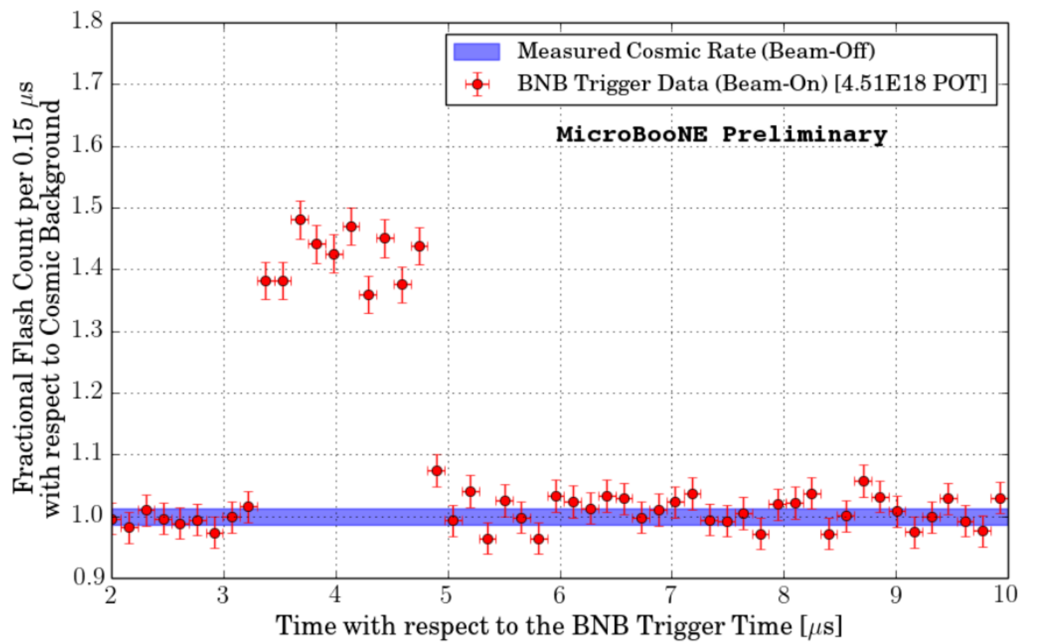
Image Credit: S. Lockwitz

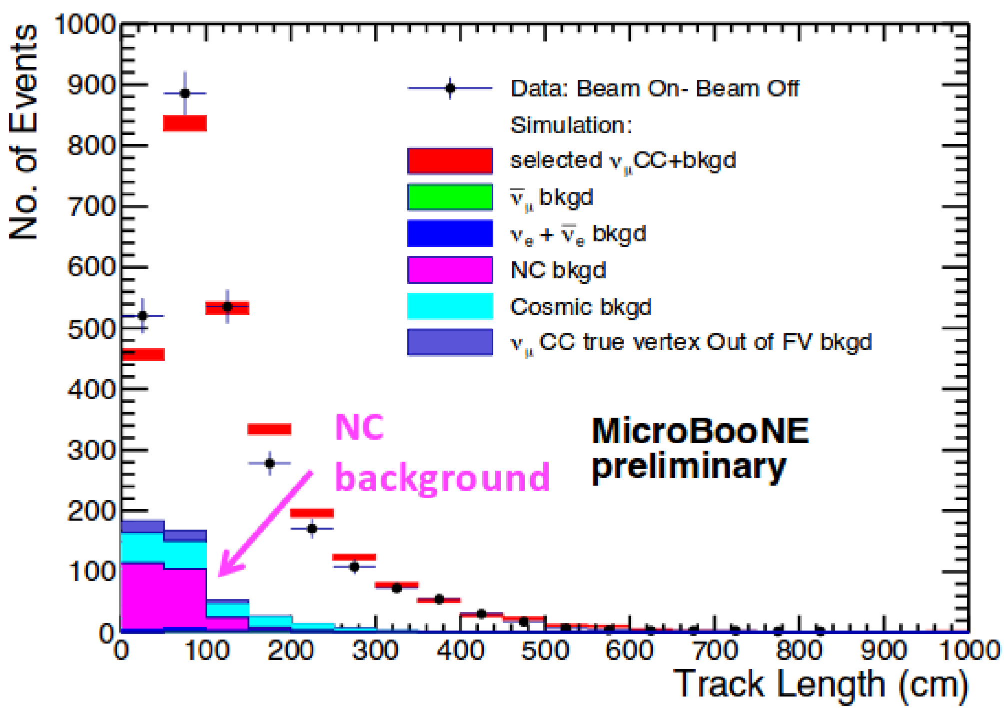
- **<100 parts per trillion (ppt) of O2 present**
  - This is so you can get the charge created by a minimum ionizing particle ~2.5 meters without the electrons being absorbed
- **< 1 part per million (ppm) of N2 present**
  - This is so the light from scintillation isn't quenched

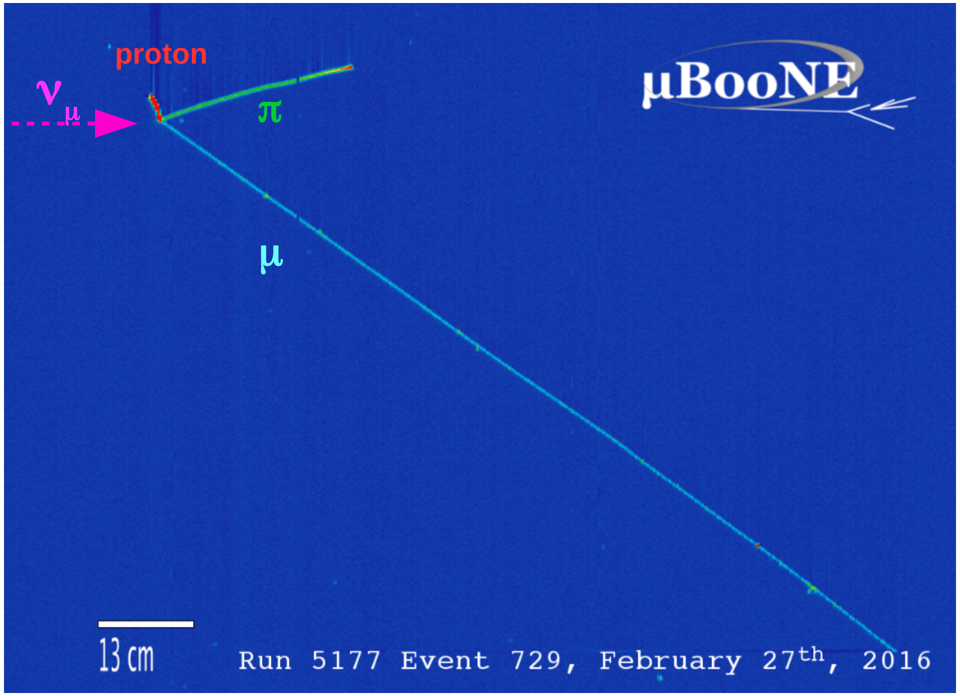
A dogs nose is sensitive at the ppt level, but they tend not to like being employed as scientists and have an adversity to -303 degrees Fahrenheit

Example of putting it all together: MicroBooNE

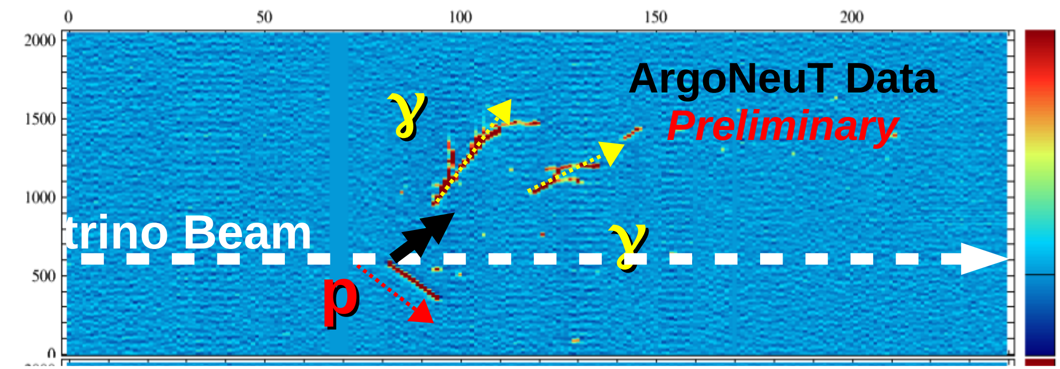
- **MicroBooNE has been successfully recording neutrino interactions since late 2015**
  - First neutrino results were announced just this year!

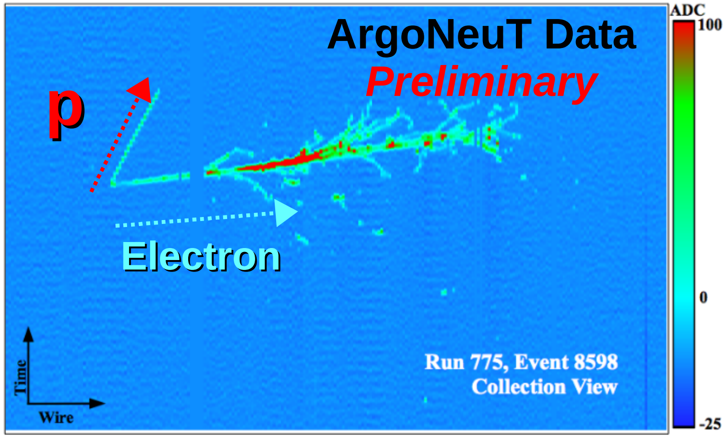


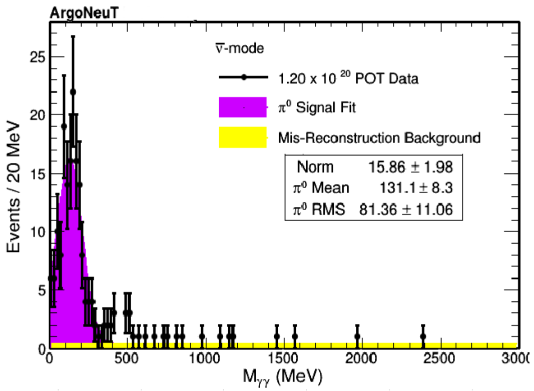


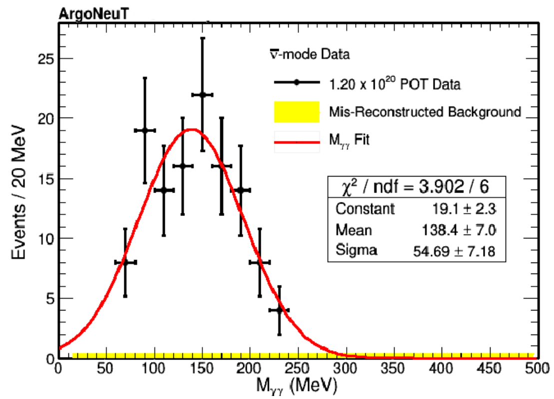


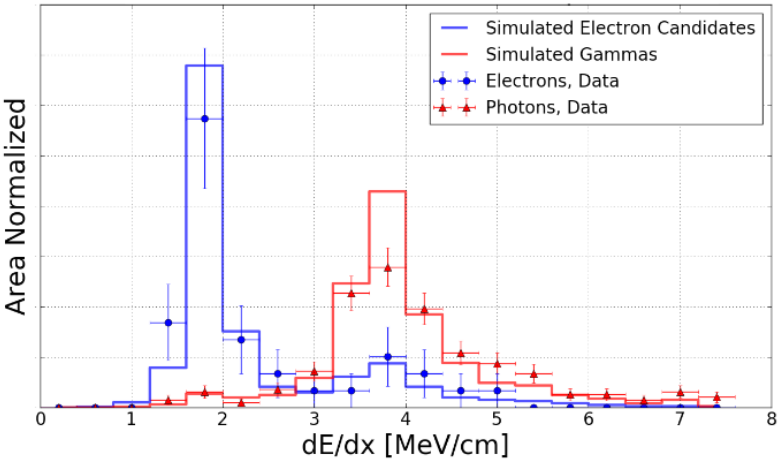
Example of putting it all together: ArgoNeuT

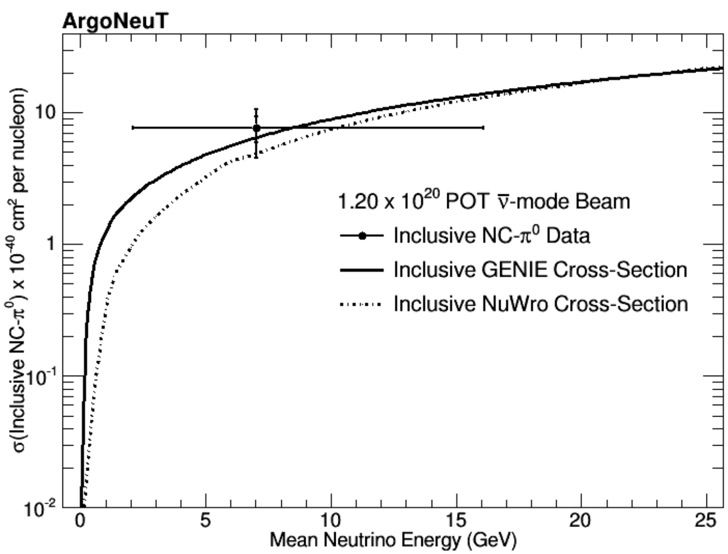








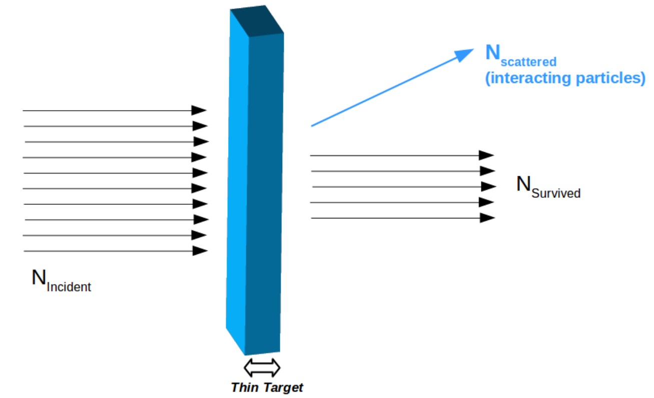




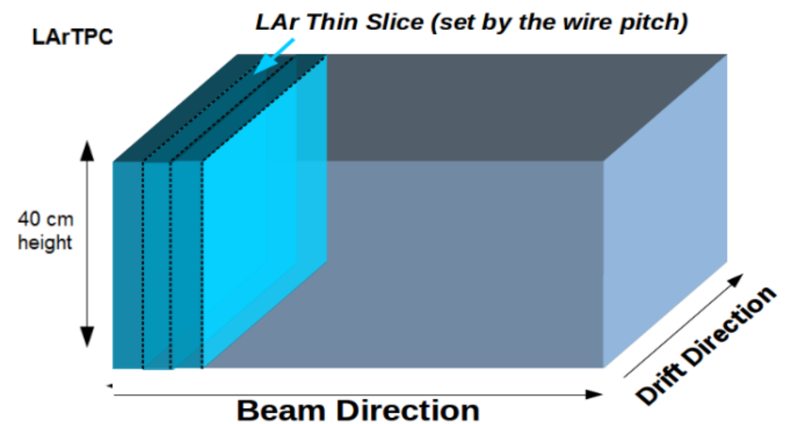
- **ArgoNeuT has recently released papers showing reconstruction of NC-π^0 neutrino interactions as well as the identification of ν_e-CC interactions using calorimetry to identify the electron showers**

Example of putting it all together: LArIAT

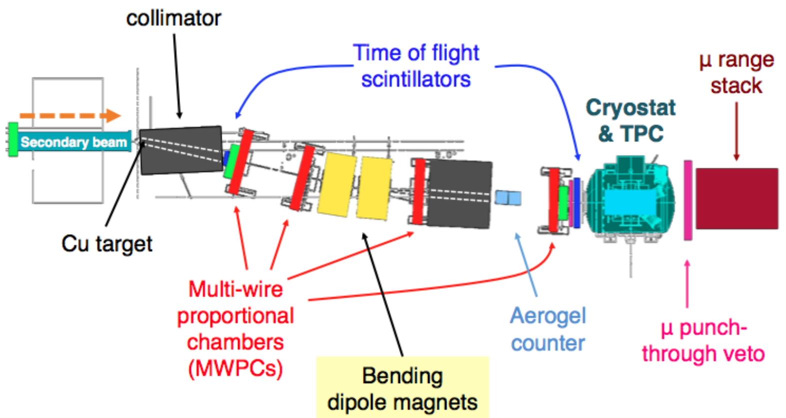
- You can calculate the probability of a particle interacting in a thin slab of argon as:



$$\frac{N_{\text{interacting}}}{N_{\text{Incident}}} = P_{\text{Interacting}} = 1 - e^{-\sigma n z}$$



- Using the granularity of the LArTPC, we can treat the wire-to-wire spacing as a series of “thin-slab” targets if we know the energy of the particle incident to that target



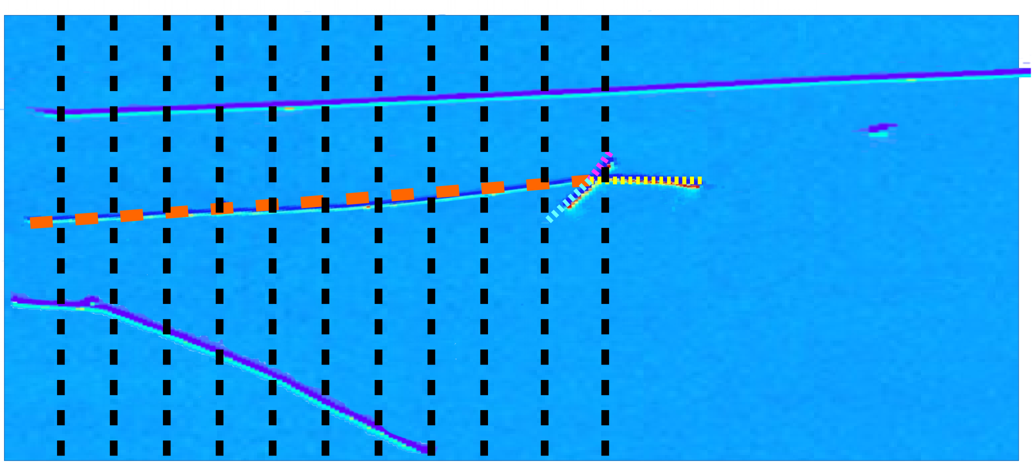
- LArIAT is a testbeam experiment where we measure the momentum of the particle prior to it entering the LArTPC

$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi - E_{\text{Flat}}$$

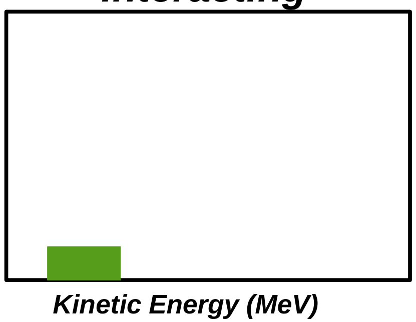
Example of putting it all together: LArIAT

- **Now that we have a wire chamber track (with an initial kinetic energy measured from the wire chambers) matched to a TPC track, we follow that TPC track in slices**
  - **The slice represents the distance between each 3D point in the track**
  - For each slice we ask: “Is this the end of the track?”
    - **NO:** Calculate the kinetic energy at this point and put that in our “non-interacting” histogram
    - **Yes:** Calculate the kinetic energy at this point and put that in both the **interacting** and **incident** histograms

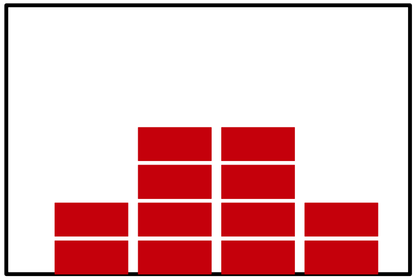
$$KE_{Interaction} = KE_i - \sum_{i=0}^{nSpts} dE/dX_i \times Pitch_i$$



Interacting

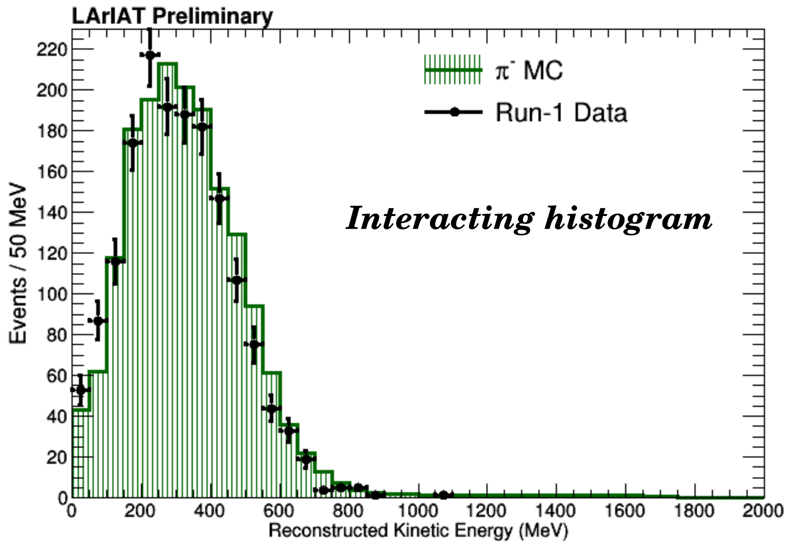


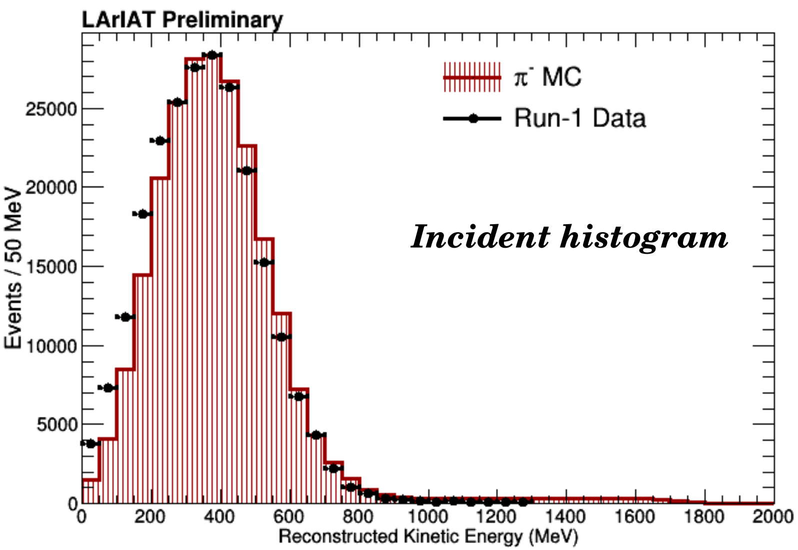
Incident



Example of putting it all together: LArIAT

- Repeat this process for your entire sample of π^-
- Use the thin slab approach and calculate the cross-section

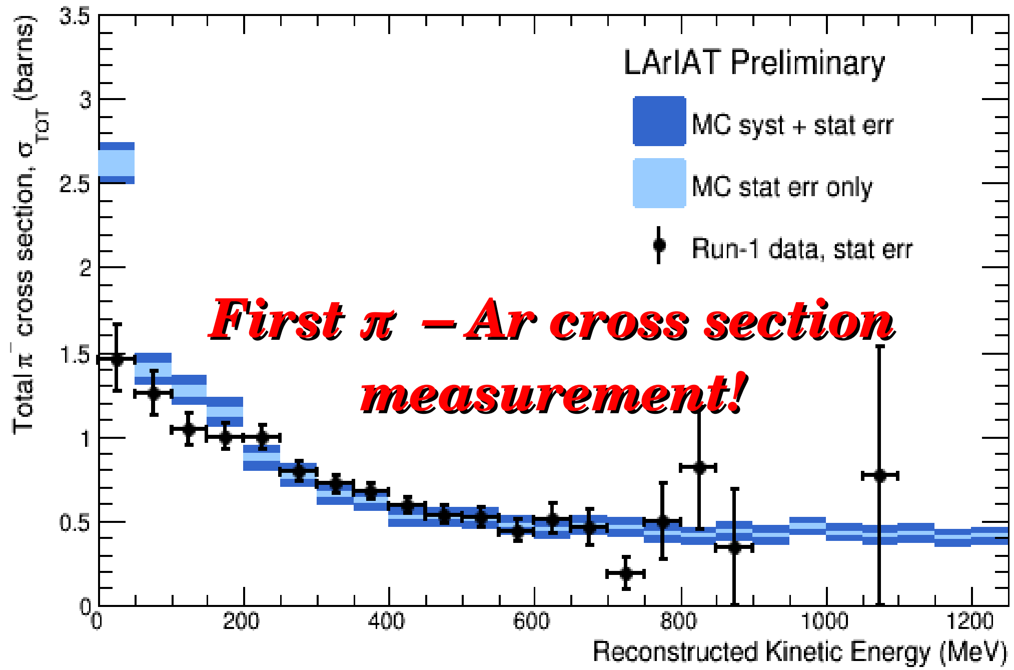




$$\sigma(E) \approx \frac{1}{nz} P_{\text{Interacting}} = \frac{1}{nz} \frac{N_{\text{interacting}}}{N_{\text{Incident}}}$$

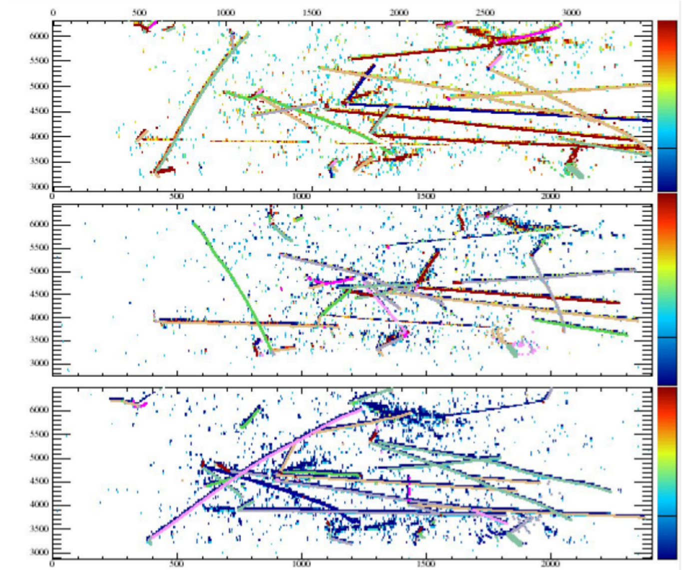
Where $n = \rho N_A / A$
Z = slab depth

=

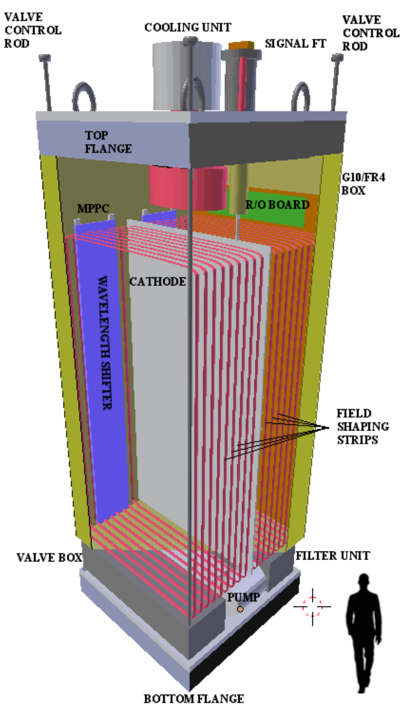


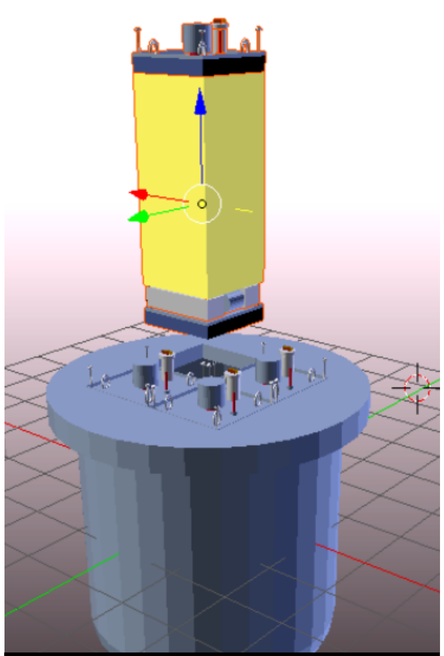
Single Phase LArTPC Challenges

- **One place where it would be advantageous to have a single phase liquid argon neutrino detector is to serve as the DUNE near detector**
  - Target Nuclei the same between near/far
  - High density target (lots of statistics!)
  - Fine grain tracking and calorimetry broad energy range of neutrino cross-section measurements
- **However, this is a tough environment for a SP-LArTPC!**
  - “Slow” drift time leads to large event pileup
  - High energy beam means high multiplicity events
    - Wire ambiguities are going to be present
- **A proposed solution is ArgonCube**
  - Modular LArTPC with short drift lengths (small drift times)
  - Accessibility to the TPC to allow for in-situ servicing and upgrades
  - Being designed with Pixel readout in mind



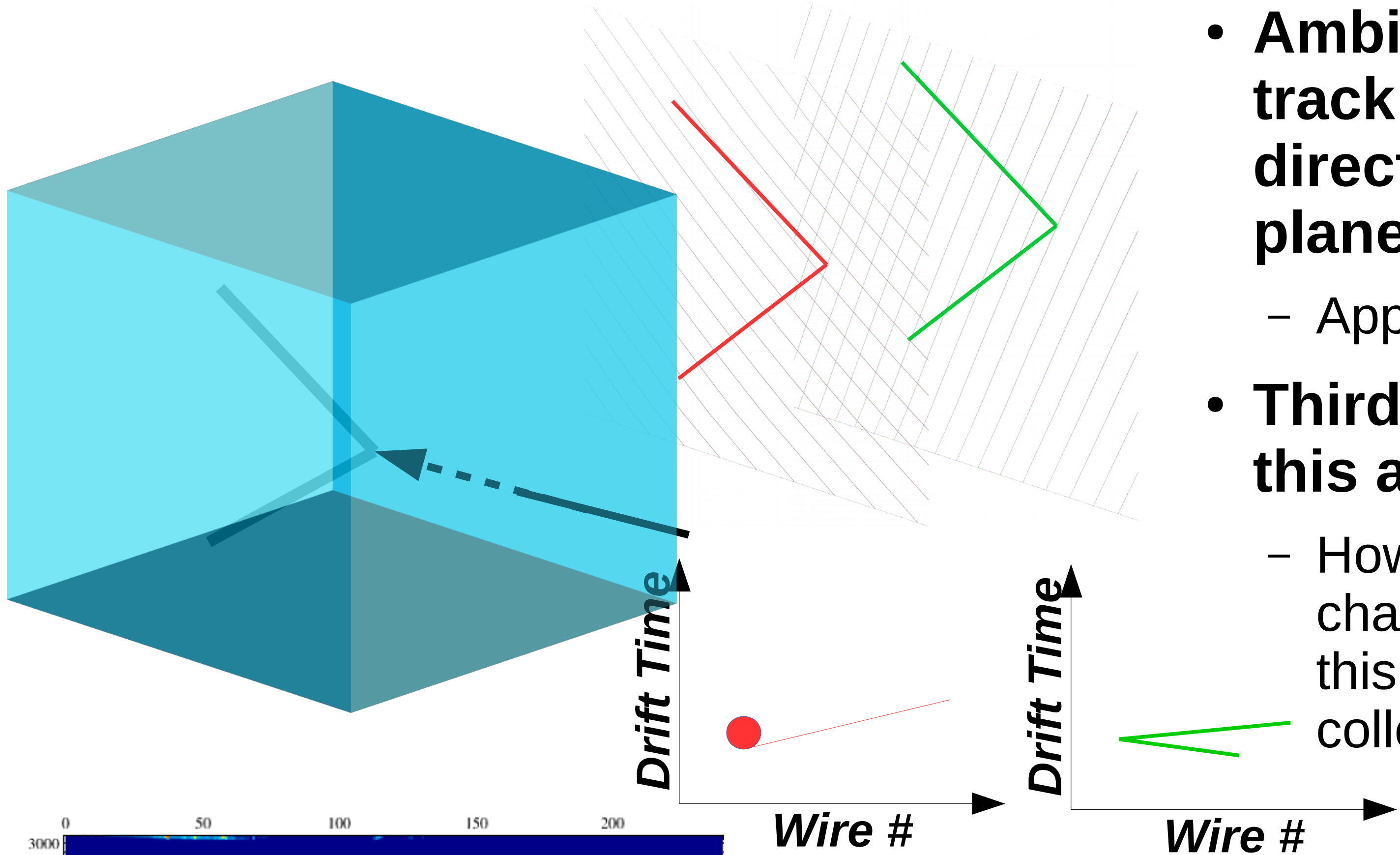
MicroBooNE size detector in the DUNE Near Detector Beamline *(credit S. Lockwitz)*



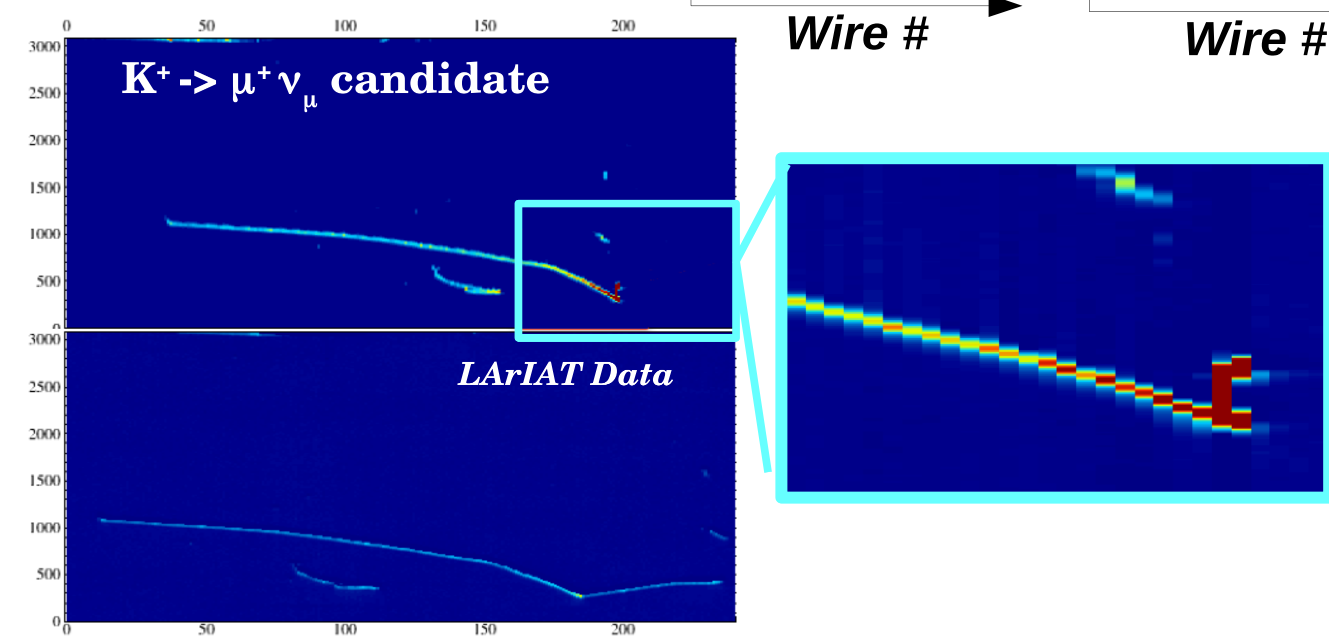


0.6 m x 0.6 m x 1.8 m^3 ArgonCube Prototype

Why Pixel Readout?

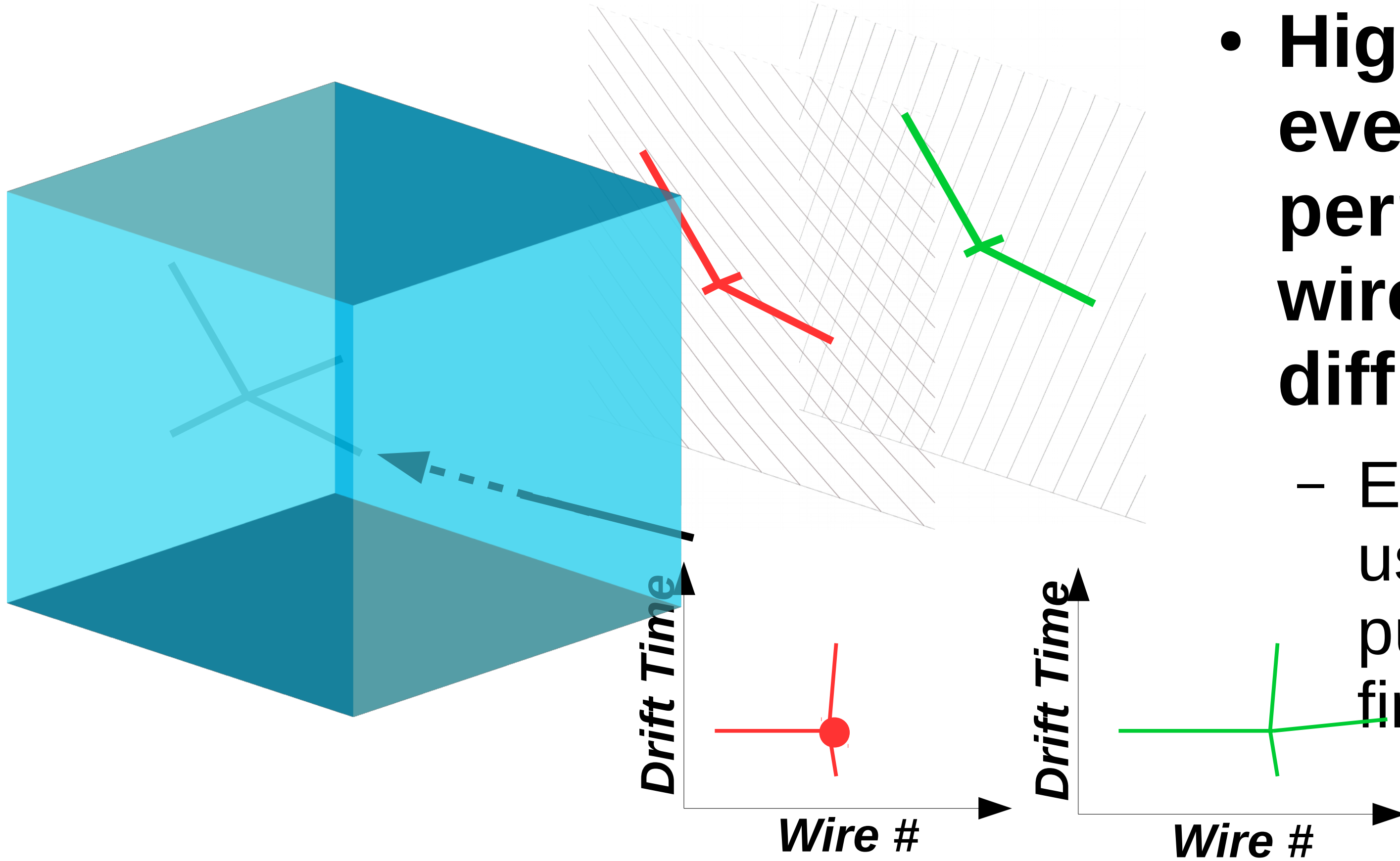


- **Ambiguities arrive when a track ionizes along the direction of one of your wire planes**
  - Appears as a “blob” of charge
- **Third wire plane helps break this ambiguity**
  - However, this can add challenges to the calorimetry if this happens to be your collection plane

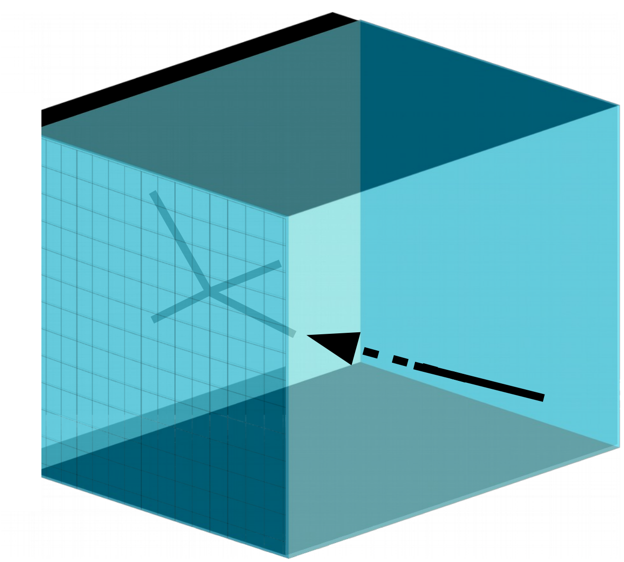


Pixel style detectors don’t suffer from this same type of ambiguity

Why Pixel Readout?



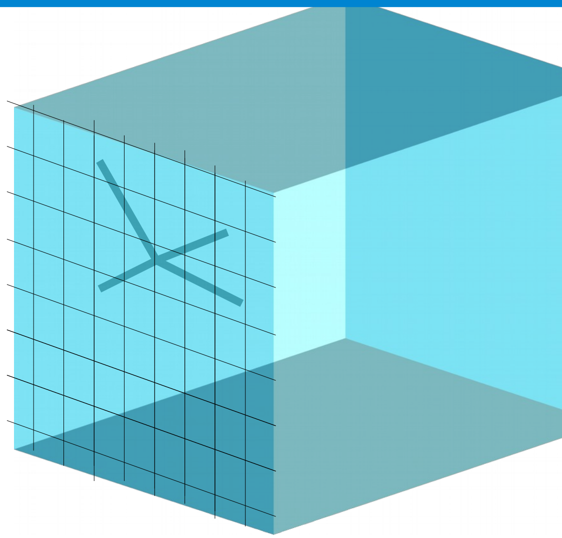
- **High multiplicity events with tracks perpendicular to the wire plane become difficult to disentangle**
  - Especially when trying to us the same charge pulse identification ("hit finding") algorithms

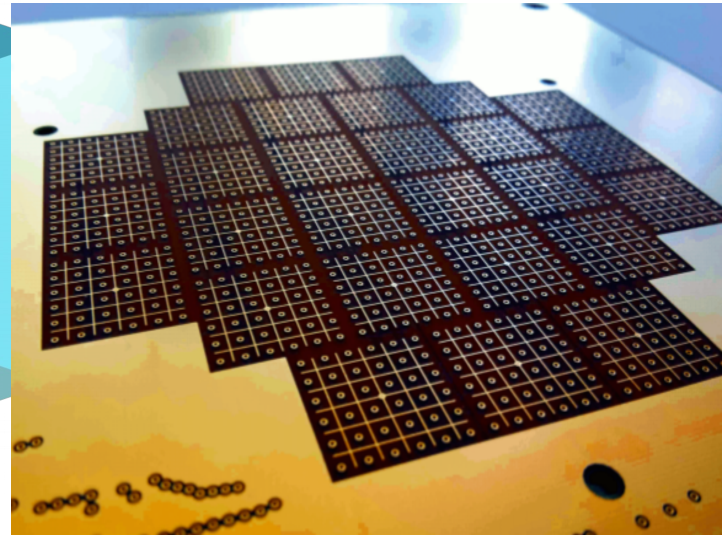


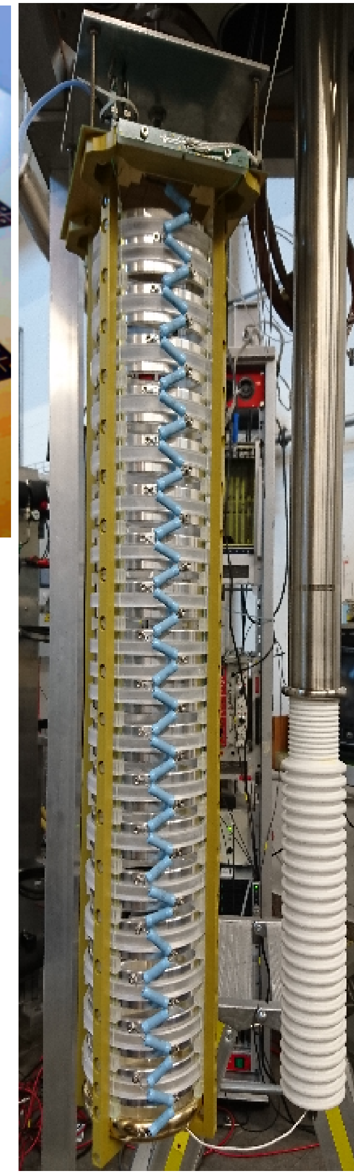
By treating all pixel deposits at a given drift time the same, a pixel readout can avoid some of these challenges

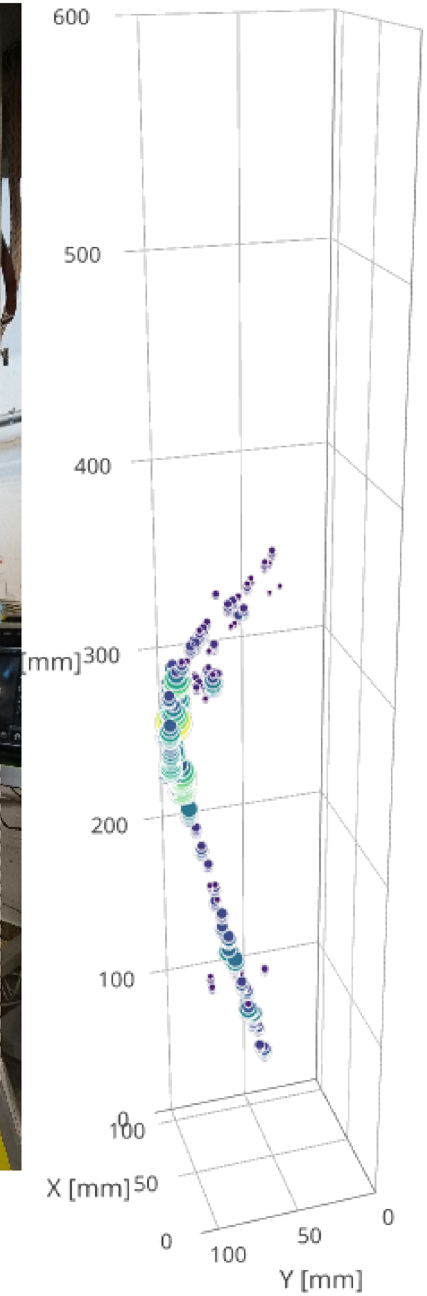
(For sure, it will come with its own set of challenges...but might be a "better" battle)

Why Pixel Readout?





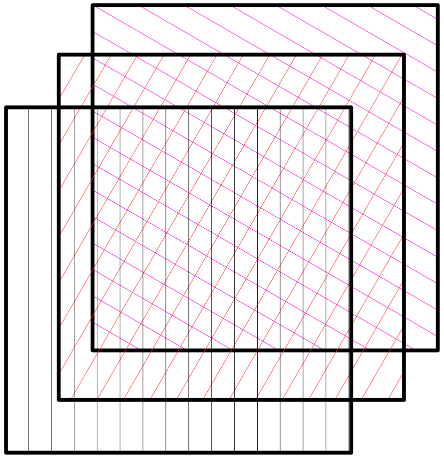




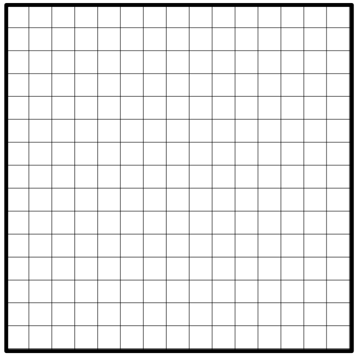
- **Pixel readout allows you to “go straight to 3d” with each readout**
- **Nearby pixels arrays can be analyzed by an FPGA to do rudimentary reconstruction and look for topologies of interest**
  - This claim obviously still needs to be demonstrated

What are the challenges?

- **Requires a large number of pixels to cover the entire area with the same separation as the wire pitch**
  - Example: 2 meter tall by 2 meter long volume w/ 3mm wire pitch
    - # of wires
      - ~650 collection plane wires
      - ~1800 induction plane wires
    - # of pixels
      - ~422,000 pixels

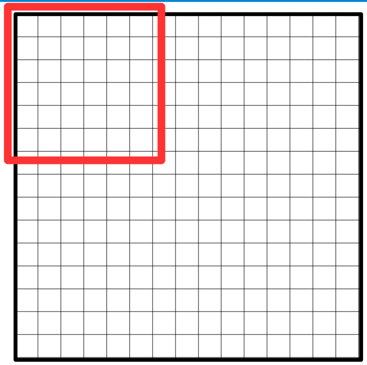


- **Large channel count requires new ideas in readout**
  - Can't bring out every pixel as a channel!
  - Need to take power consumption of your electronics channel is the liquid argon into consideration

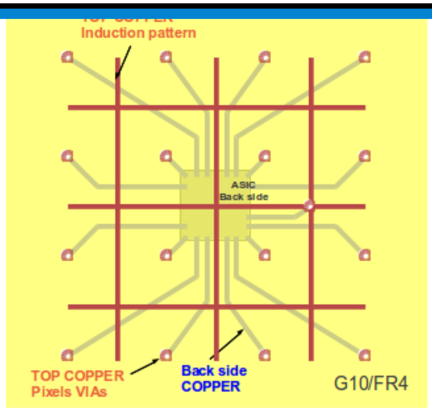


- **With the large channel count, heat loads due to the electronics start to become a concern**
  - The current analog front end ASIC (LARASIC4) is ~ 6-10 mW per channel
  - Current ADC ASIC ~200 mW per channel
    - Liquid Argon's heat capacity 22.6 J/(mol K)
    - Liquid Argon has a liquid range of ~ 3 K

Some ideas being worked on

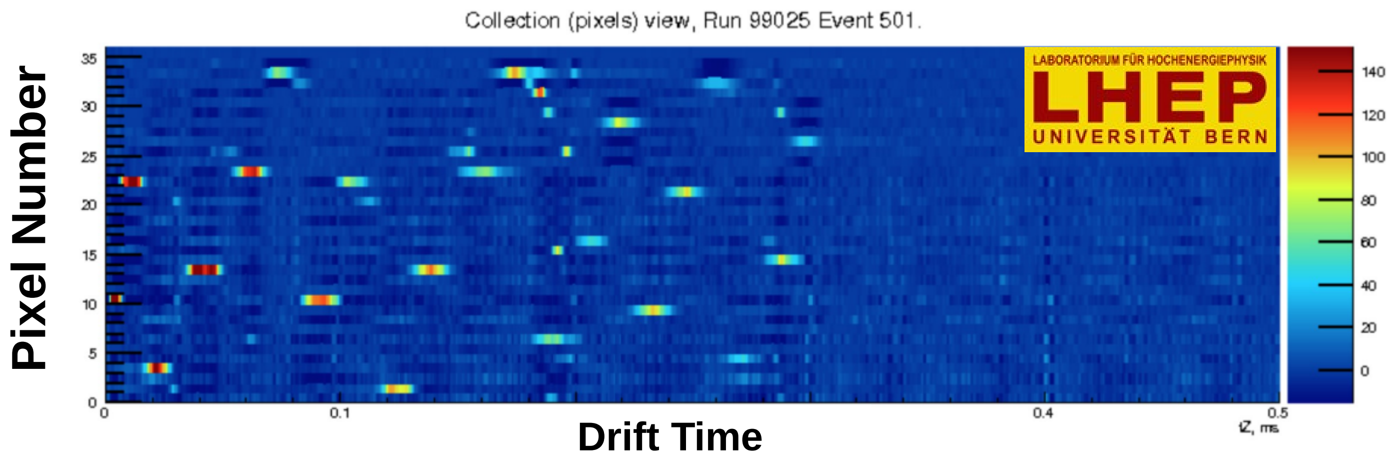


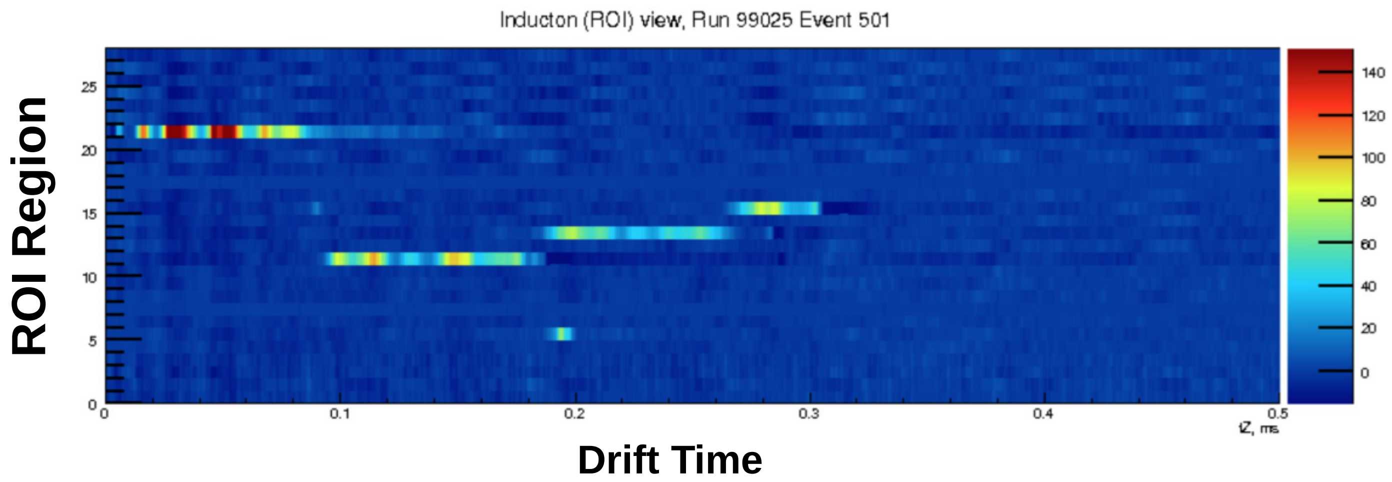
A	1	2	3	1	2	3	B
	4	5	6	4	5	6	
	7	8	9	7	8	9	
C	1	2	3	1	2	3	D
	4	5	6	4	5	6	
	7	8	9	7	8	9	



- **Using the existing front end ASIC you break up your channels by having Regions of Interest (ROI's A, B, C, D…) which are identified by an inductive trace and then you duplicate the same channel in each ROI (e.g. 1→9)**
- **Now one region can be readout by one 16 channel ASIC**
  - This allows you to readout your **N** pixels with **2 x sqrt(N)** DAQ channels (where N is the number of pixels)
    - How the current implementation of 1008 pixels is readout with 64 channels
    - Number of ASICS is just # of DAQ channels / 16
      - E.g. BERN Pixel TPC has just 4 ASICS

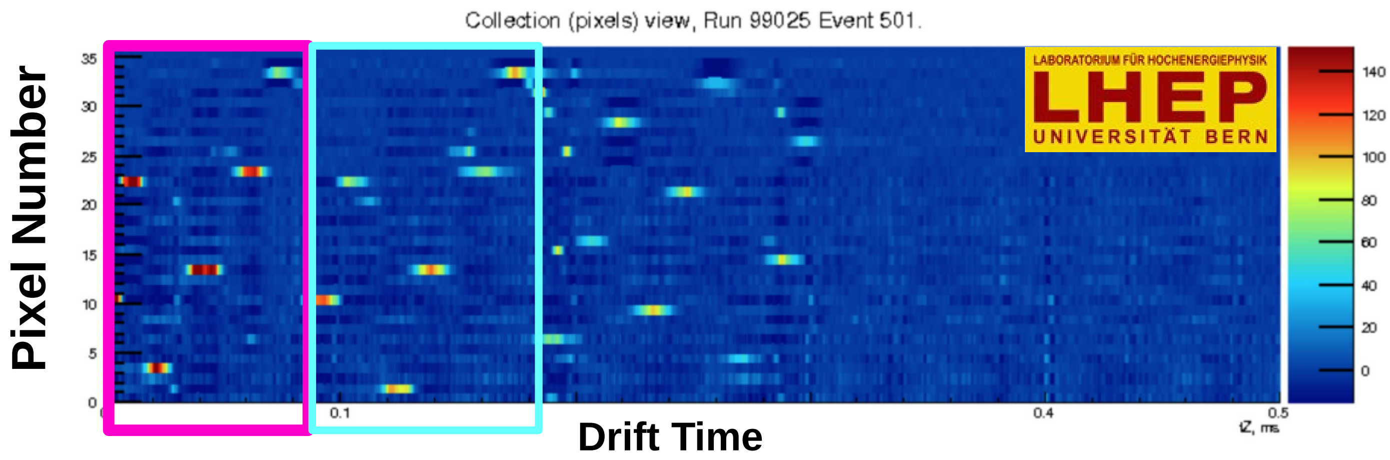
Some ideas being worked on

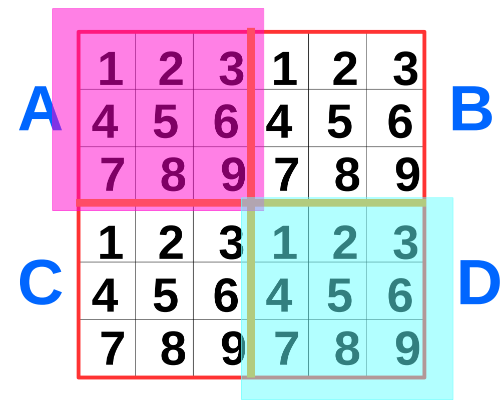


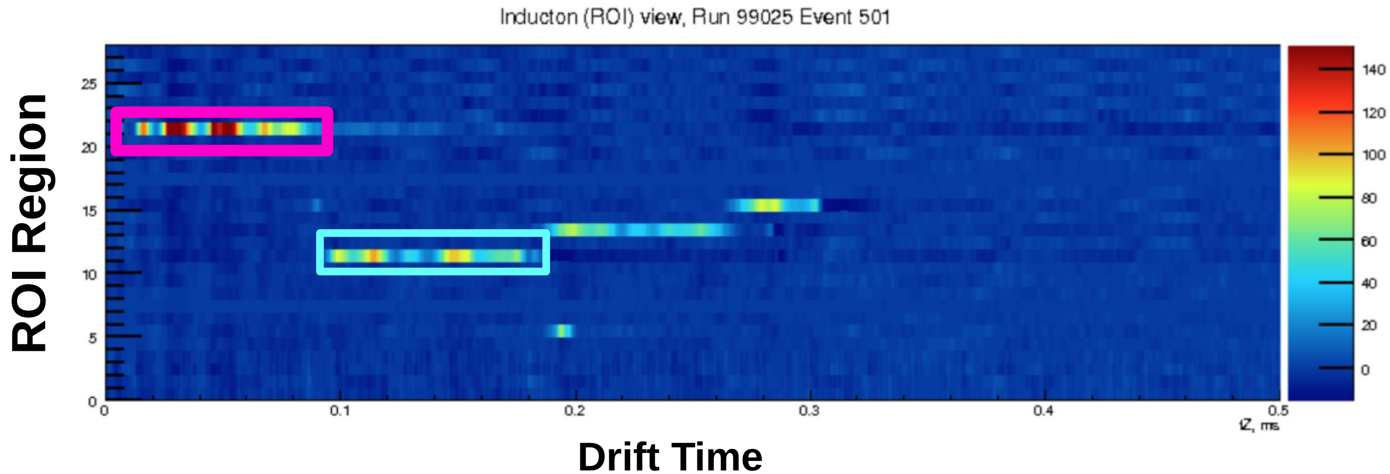


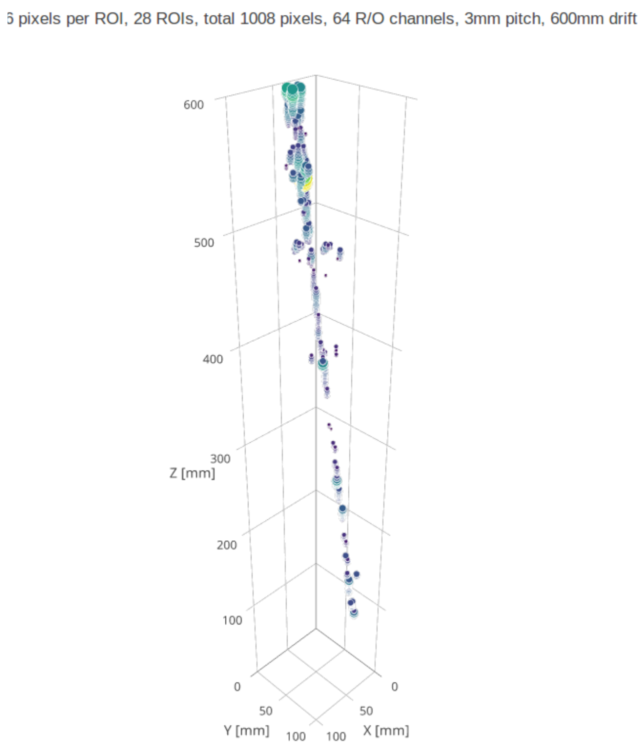
- An idea currently being worked on is to take this approach and test it with a large number of pixels in a test beam envioronment
  - The Liquid Argon in A Testbeam (LArIAT) experiment is currently upgrading for a Run-III with ~600 channels available using the LARASIC4 chip

Some ideas being worked on





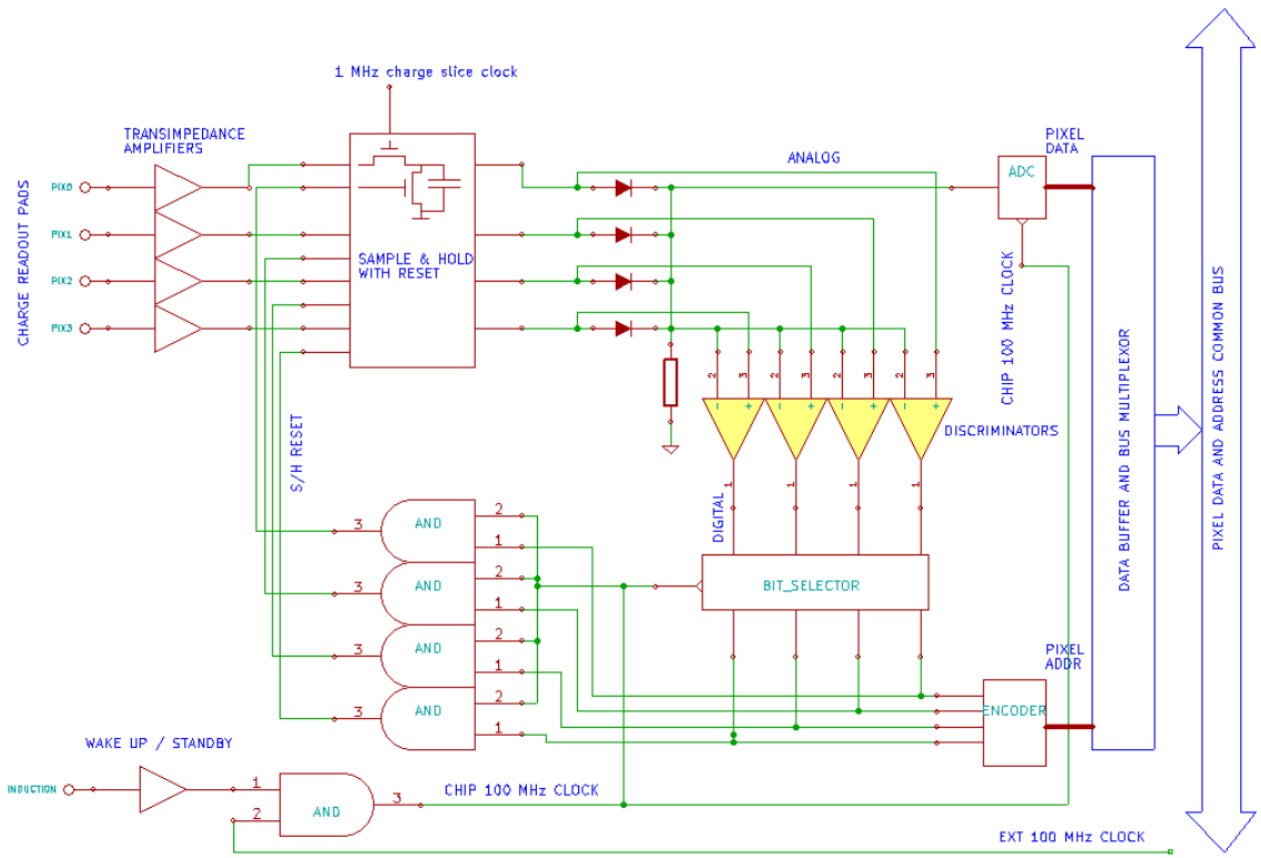




- **An idea currently being worked on is to take this approach and test it with a large number of pixels in a test beam environment**
  - The Liquid Argon in A Testbeam (LArIAT) experiment is currently upgrading for a Run-III with ~600 channels available using the LARASIC4 chip

Other ideas being worked on

- **Try to do a “smart token” zero suppression**
  - The readout is in a low power “sleep” state and is “woken” by the induction pulse
  - ADC could get a ~5μS “warning” from the induction signal
  - Use this to lower the power consumption



Credit: I. Kreslo (Bern)

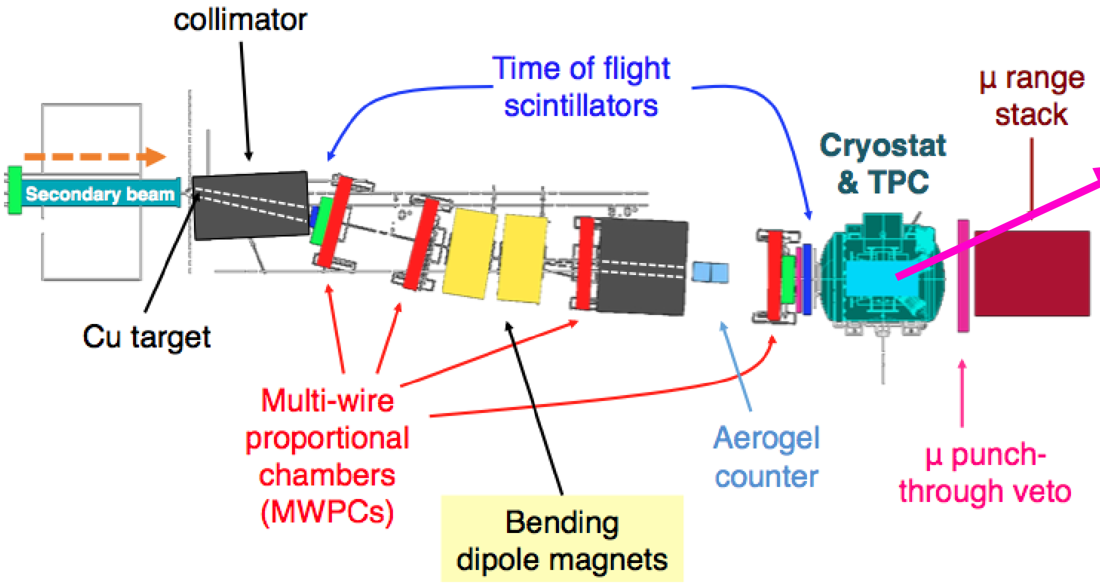
Summary

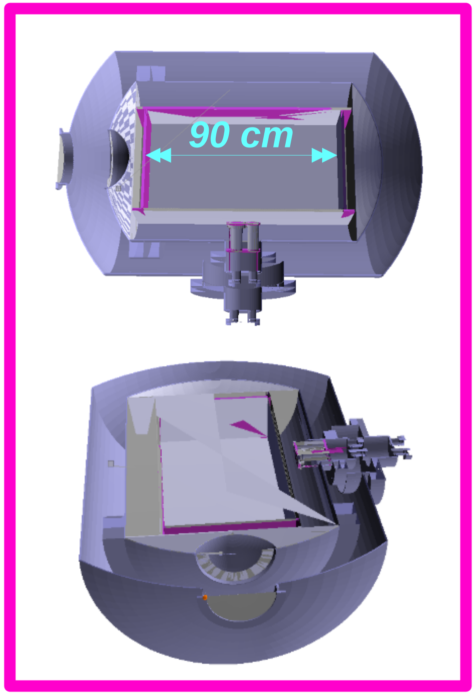
- ***Full Disclosure:***
  There was no way to cover all the aspects and R&D going on in Single Phase LArTPC
  – If I missed your favorite project or your piece of R&D I apologize
  – There are lots of talks in the parallel session highlighting this work
- **There is a solid foundation demonstrating the power of single phase LArTPC's**
  – Lots of successful physics results from ν-Argon interactions
  – Lots more work ongoing for current and future LArTPC detectors
- **The next generation experiments will continue to push the boundaries and address the many challenges to scale this detector to the multi-kiloton neutrino detector**

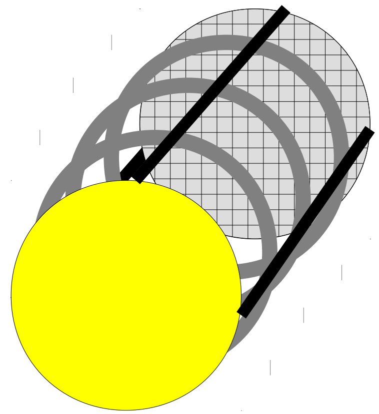

TODAY'S MENU
Backup Slides $1.50
Questions $ 5.35
Coffee $ 1.00
Special
Applause free!!!!

Back-up Slides

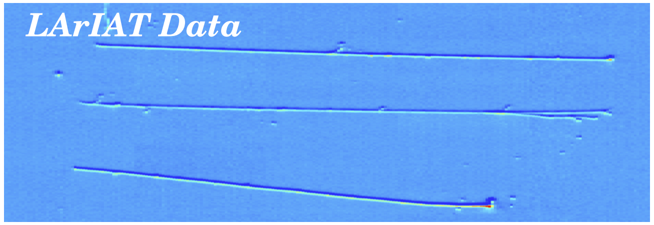
Pixel Detector in LArIAT



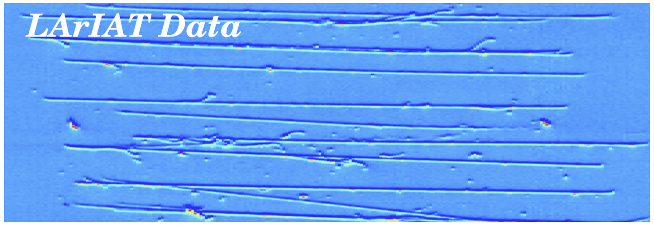




- **The idea would be to replace the existing TPC (90 cm x 47 cm x 40 cm) with a larger version of the Bern Pixel TPC with a large number of pixels readout in this ROI method**
  - For a ~45 cm diameter readout plane and 1.3 mm pitch that is ~92,000 pixels using all available channels
- **Can orient the TPC so the pixels are perpendicular and or parallel to the beam direction**
  - Longer drift if the pixels are perpendicular to the beam
  - Shorter drift if the pixels are parallel to the beam
- **The test beam is well understood and configurable to test high and low occupancy events**



Low Occupancy Beam Events



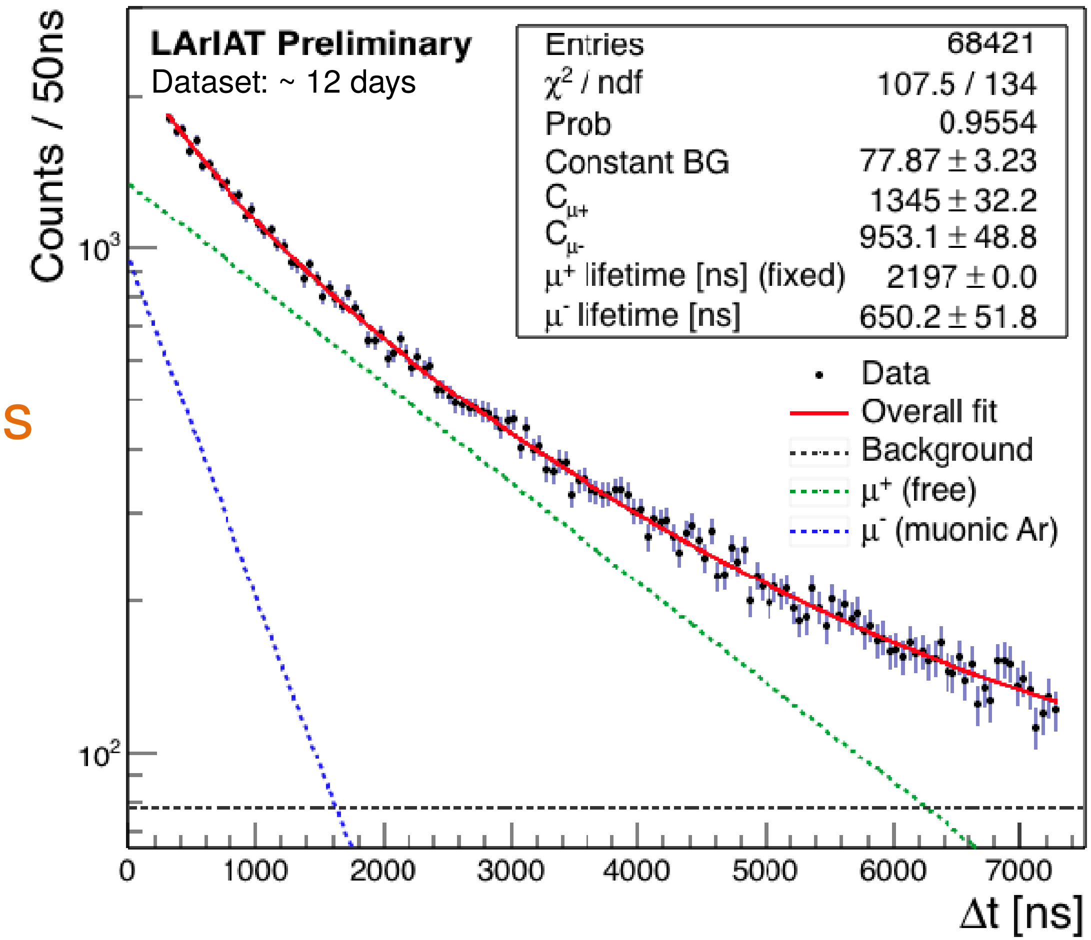
High Occupancy Beam Events

$$\boxed{\tau_{\mu-}} = \left(\frac{1}{\tau_c} + \frac{Q}{\boxed{\tau_{free}}} \right)^{-1}$$

650 ± 52 ns

(from fit result, preliminary)

918 ± 109 ns

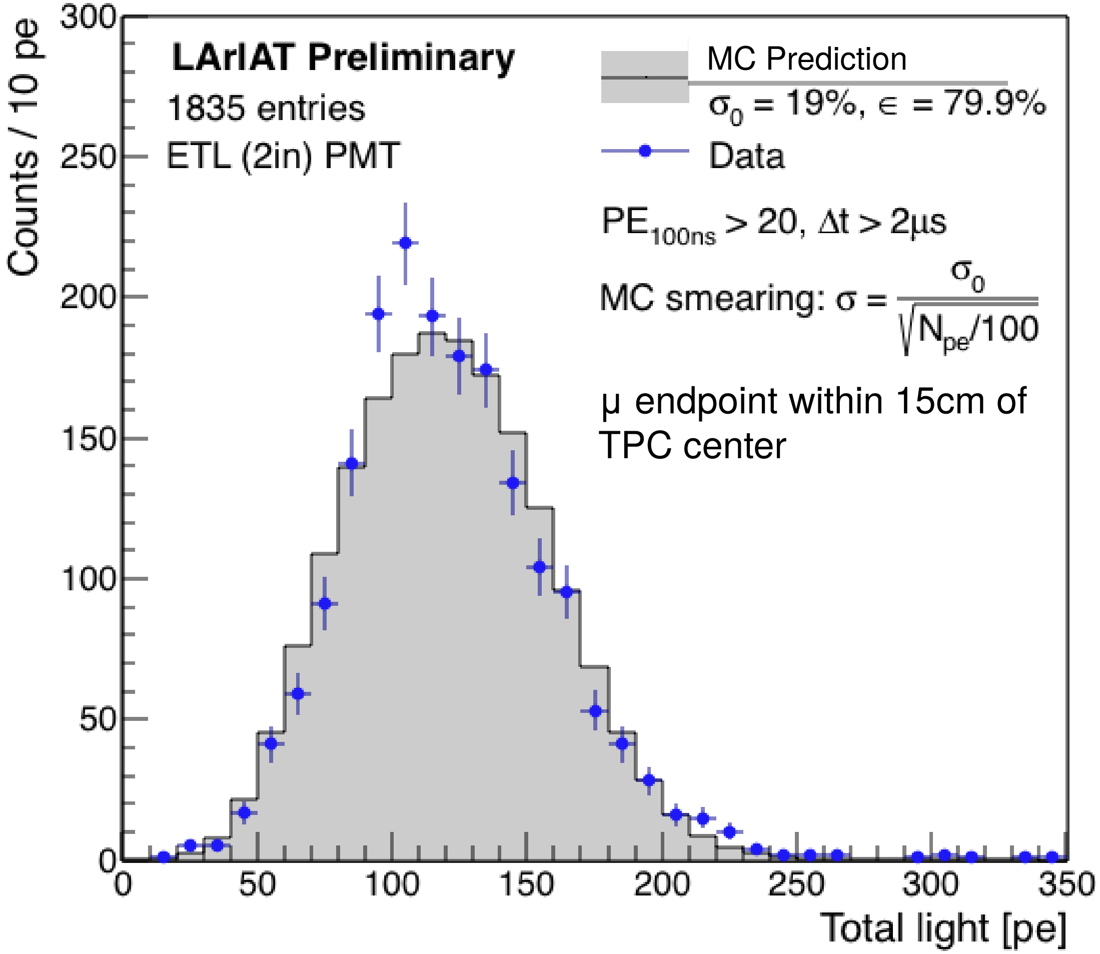


LIDINE 2015 Proceedings, JINST 11 C01037

Early results agree w/ recent measurement[1] (854 ± 13 ns) and theory prediction[2] (851ns)

[1](Klinskih et al., 2008)

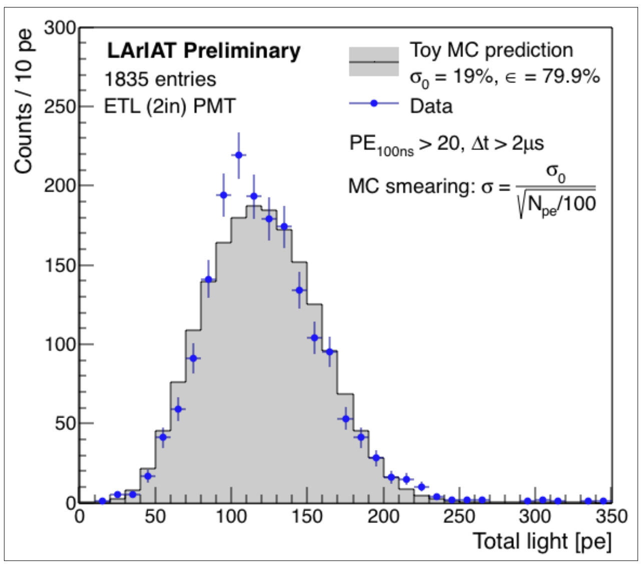
[2](Suzuki & Measday, 1987)

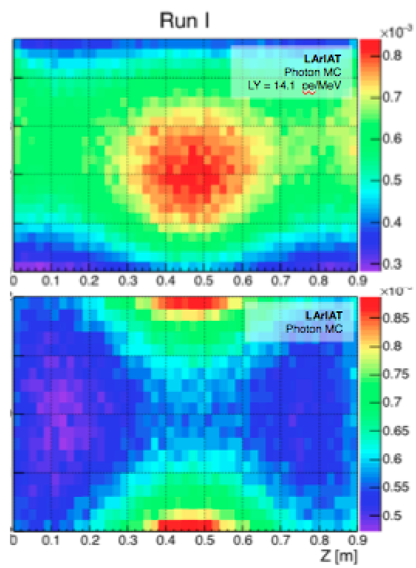


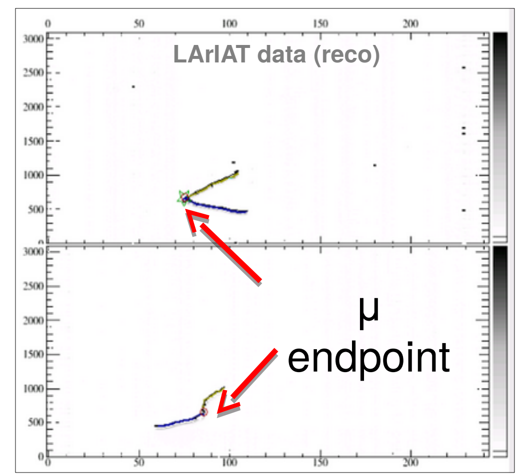
- Michel-candidate signals integrated to get PE spectrum
- Data in approximate agreement with preliminary MC
  - Gives confidence in MC-predicted LY: 2.4 pe/MeV for 2” ETL PMT (Run I)

GOAL: Scaling from **light (γ)** to **energy (MeV)**

Raw PE spectrum + MC photon visibility (& γ/MeV yield) + Reconstructed $e^{+/-}$ position (or μ endpoint)

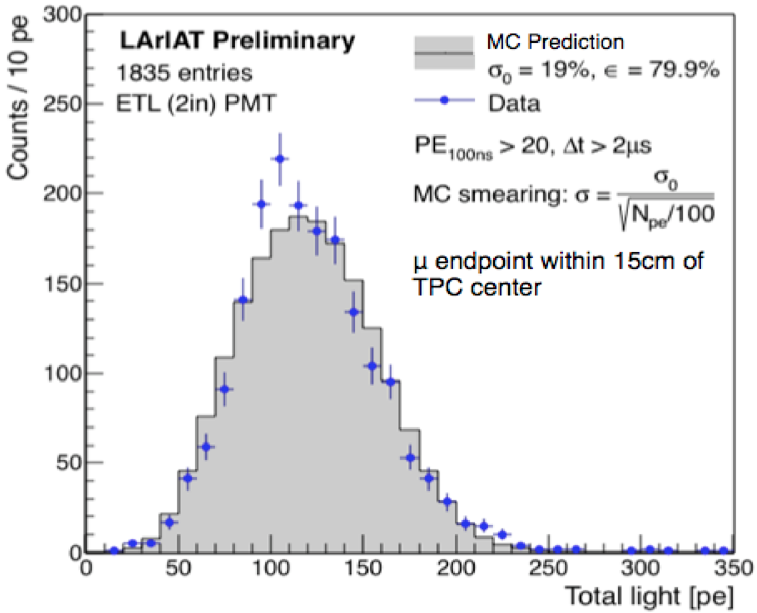


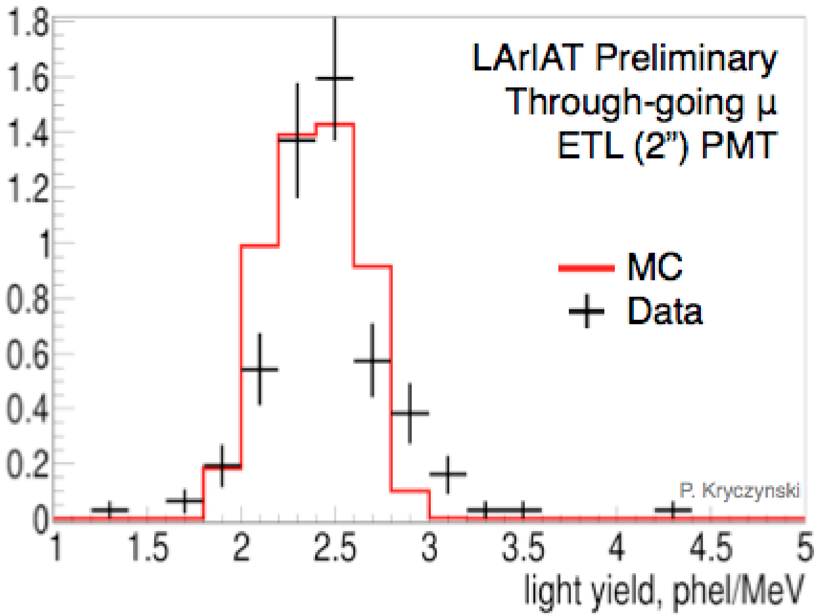




μ endpoint

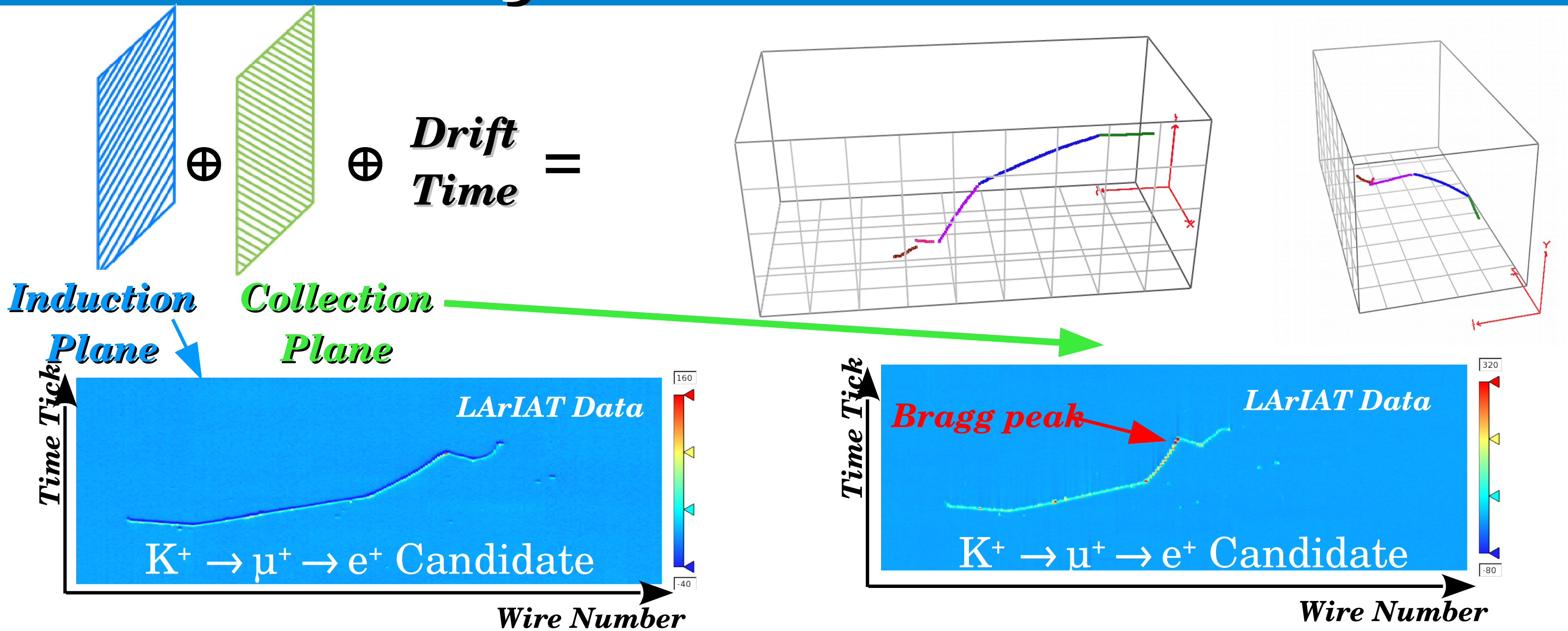
3D track/shower reconstruction actively under development!



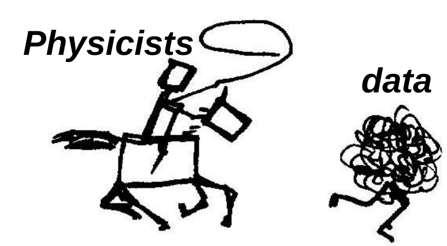


Agreement between data and MC seen in two independent analyses (using two different simulation techniques)

Why Pixel Readout?



- **In order to do 3d reconstruction and calorimetry, wire readouts require you to bring together information from multiple wire planes to reconstruct the the event**
- **For rare event searches (supernova neutrino identification, proton decay, n/$\bar{n}$ oscillation searches, etc…) this requires quite a bit of “data wrangling”**
  - TPC signals from wires on different planes are readout meters apart, into separate crates, which then need to be assembled by an event builder before a decisions can be made
  - Ongoing work to find solutions is promising….but challenging



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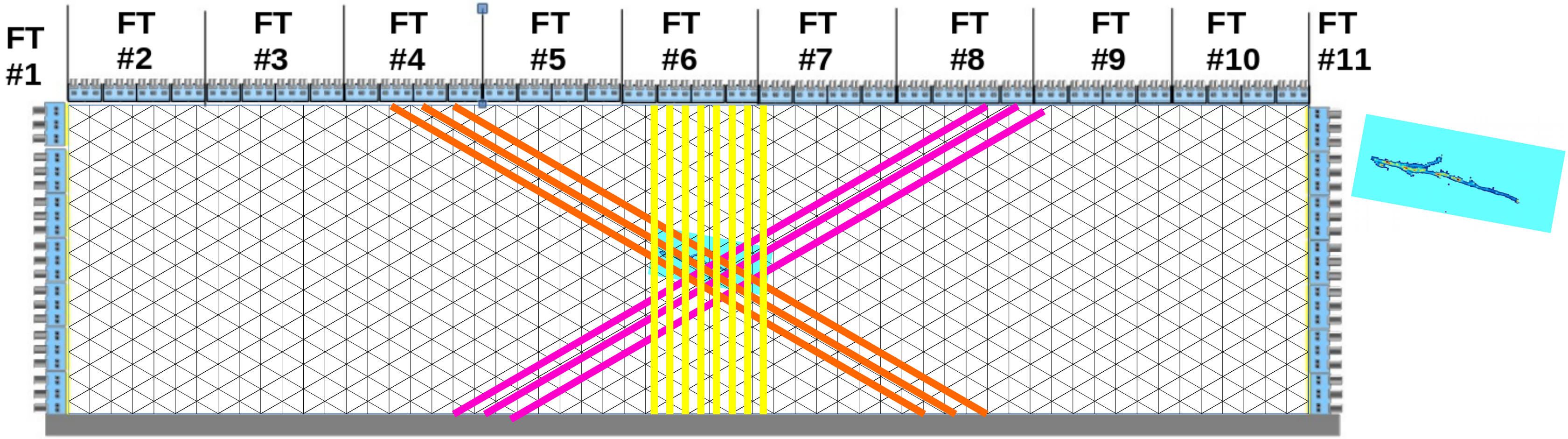

- **Imagine some low energy event in (ala supernova neutrino) where the activity is somewhere in your detector and small**
  - In a “MicroBooNE” size TPC, you need to gather together information across O(20) ASICS spread across O(10) motherboards which live on 3 different feedthroughs and that are routed to different racks/eventbuilders/etc….

    Before you can say this is a an interesting event!
  - On a “pixel” version of the same detector….this could be done on O(1) chips!
  - Better yet….you could then send a warning out that something of interest has happened and the rest of the detector should readout too