Reconstruction in Water Cherenkov:

Using Timing

Matt Wetstein
Enrico Fermi Institute, University of Chicago
Argonne National Laboratory

on behalf of the LAPPD, LBNE collaborations, and
the Fast-Timing Reconstruction Group:
Z. Djurcic (ANL), G. Davies (Iowa State), H. Frisch (U Chicago)
M. Sanchez (Iowa/ANL), M. Wetstein (U Chicago/ANL), T. Xin (Iowa State)

Advances in Neutrino Technology - ANT 11
October 12, 2011

University of Chicago

Argonne NATIONAL LABORATORY

LAPPD

Reconstruction in Water Cherenkov:
Using Correlated Timing and Spatial Information

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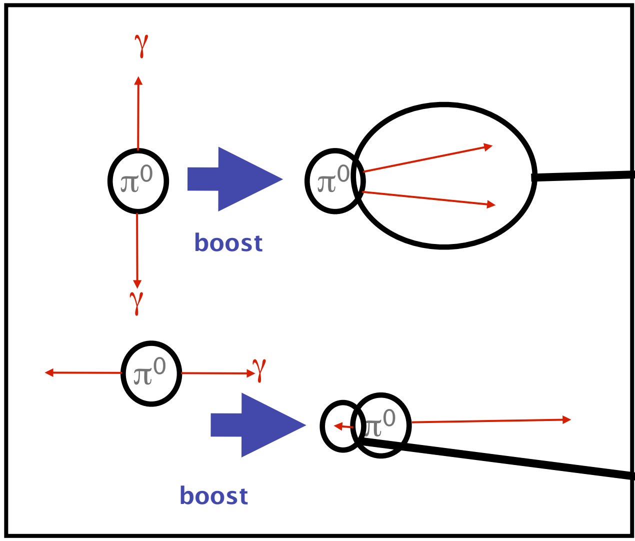
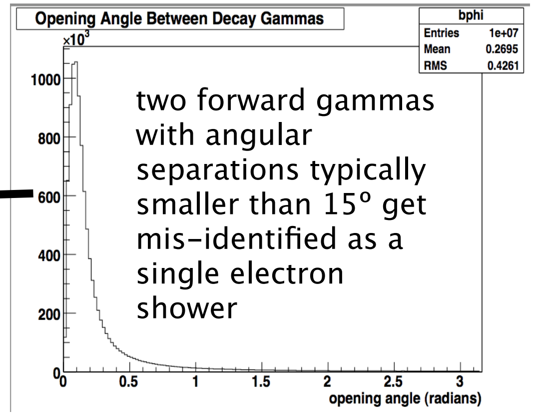
U.S. DEPARTMENT OF ENERGY

Pi0s and effects on long-baseline physics





two forward gammas with angular separations typically smaller than 15° get mis-identified as a single electron shower

after boost, the second low E gamma is too small to reconstruct

Largest reducible background. In WC, in order to achieve a pure electron sample (~1% π^0), one needs harsh quality cuts that bring signal efficiency down to 16% (28%) at 1 GeV (0.8 MeV).

This loss of events explains the factor of 3-5 larger fiducial mass necessary to match the performance of an LAr

There is still a room for significant improvement in the physics capabilities for a given mass of water.

Thinking about Full Track Reconstruction: WC as a Time Projection Chamber?

1. Signal per unit length

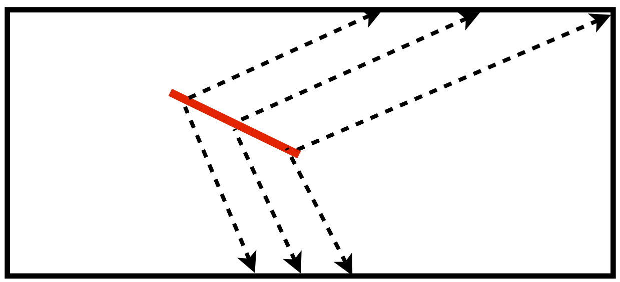
~20 photons/mm

2. Drift time

~225,000mm/microsecond

3. Topology

drift distances depend
on track parameters



Thinking about Full Track Reconstruction: WC as a Time Projection Chamber?

1. Signal per unit length

   ~20 photons/mm

Acceptance and coverage are important, especially at Low E. Is there any way we can boost this number? Scintillation?

2. Drift time

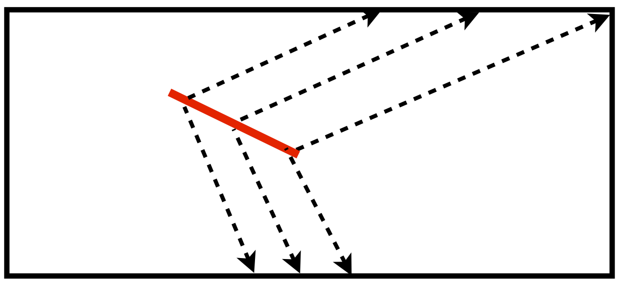
   ~225,000mm/microsecond

This necessitates **fast** photodetection. It also requires **spatial resolution commensurate with the time resolution.**

3. Topology

   drift distances depend on track parameters

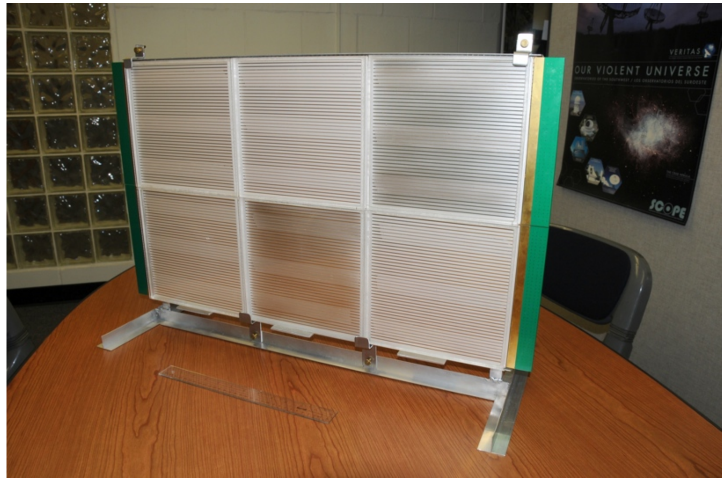
This presents some reconstruction challenges...



New Developments in Water-Based Detectors: Large Area, High Resolution MCP-PMTs

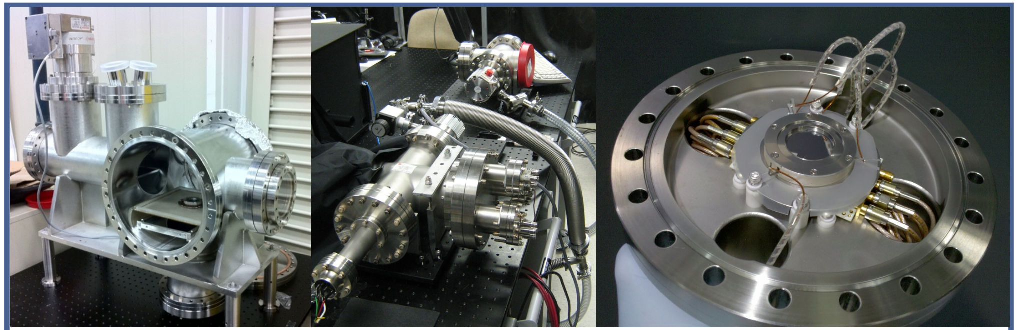
LAPPD (Large-Area Picosecond Photodetector) Project:

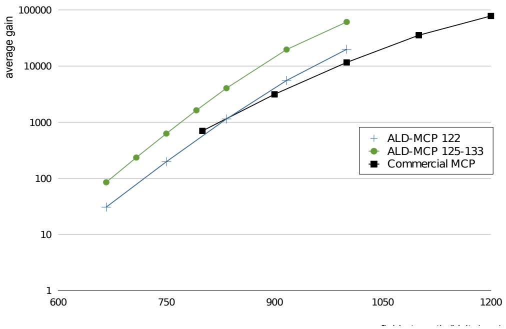
Make large-area MCPs with low-cost, bulk materials and batch industrial techniques

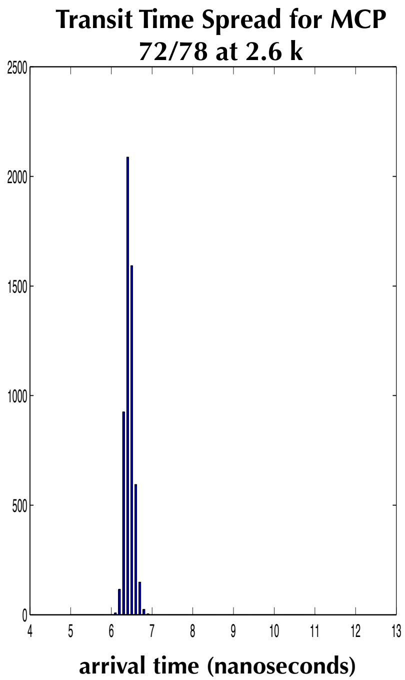


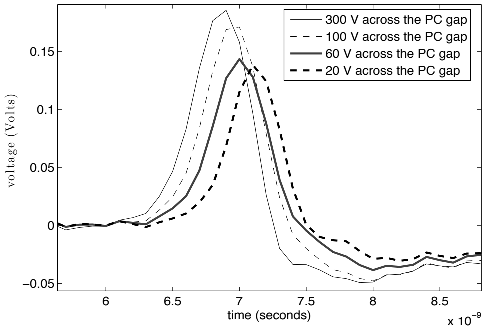
- We're attacking all aspects of this problem from the photocathode to the MCPs to vacuum sealing technology
- Goal is not just proof of principle...It's the development of a commercializable product.

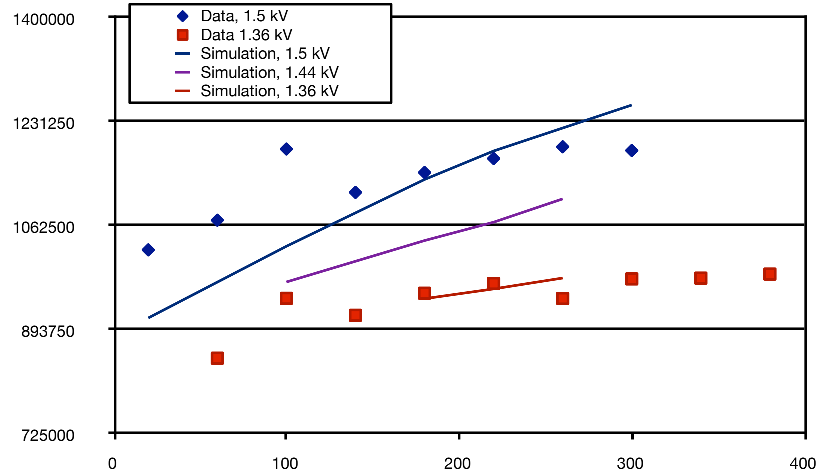
New Developments in Water-Based Detectors: Large Area, High Resolution MCP-PMTs

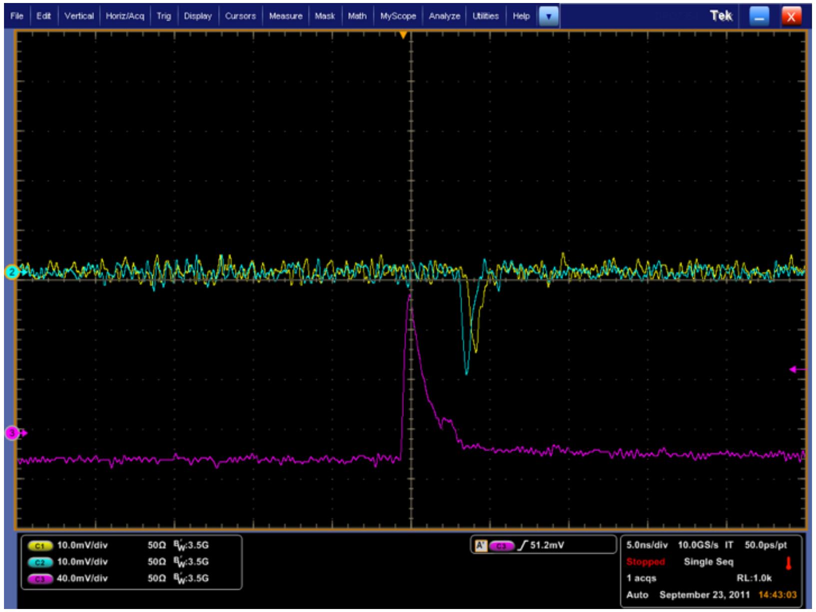










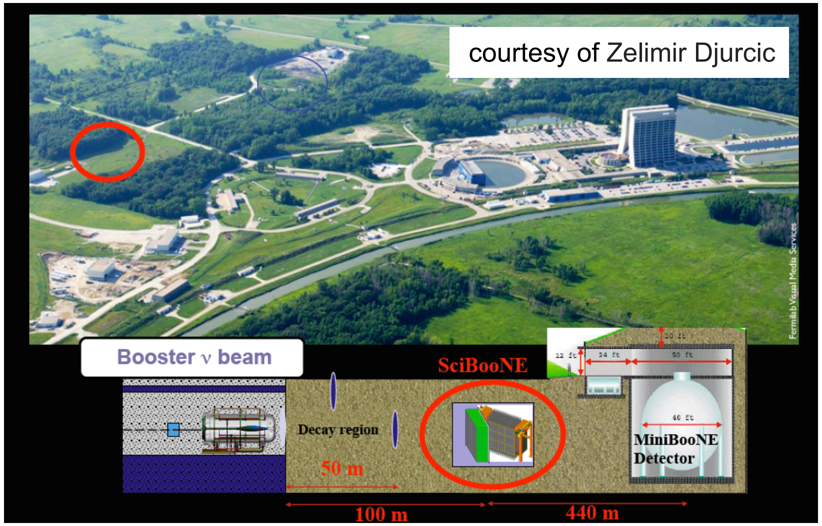


Wetstein (U Chicago/ANL-HEP), B. Adams, M. Chollet(ANL-APS)

From SciBoone to....DanielBoone?

DANIELBOONE
Next Generation Water Cherenkov Experiment

First step: to demonstrate a working, small-scale neutrino detector



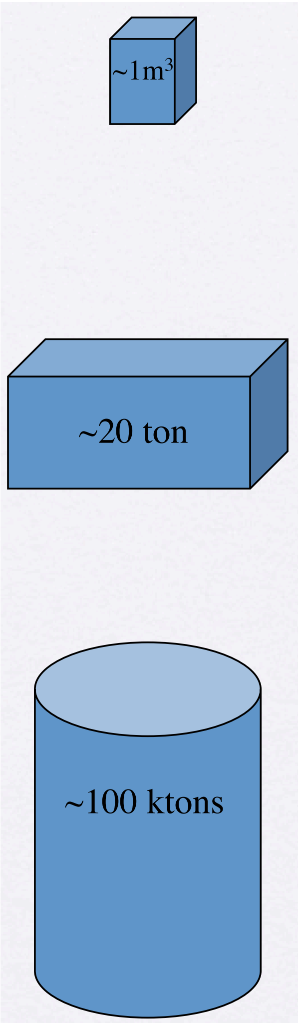
Concept and event rate calculation, courtesy of David Schmitz, FNAL

- expected rate of ~90k CC events and ~35k NC events per 1E20 POT, 10.6 ton fiducial volume
- naively scale the event rate to oxygen using a factor 8/6, then you'd expect ~12.4k CC interactions/ton/1E20 and ~4.7k NC interactions/ton/1E20
- Booster Neutrino Beam rate is ~0.5E19 POT per week on average
- ~32.2k CC interactions/ton/year, ~11k NC interactions/ton/year in a water detector BEFORE accounting for the efficiencies of such a detector.

TABLE II. The expected number and fraction of events in each neutrino interaction estimated by NEUT and NUANCE at the SciBooNE detector location with the neutrino beam exposure of 0.99×10^{20} protons on target. The 10.6 ton fiducial volume of the SciBar detector is assumed. CC and NC interactions are abbreviated as CC and NC, respectively.

	NEUT		NUANCE	
Interaction Type	# Events	Fraction(%)	# Events	Fraction(%)
CC quasi-elastic	53,038	41.5	47,573	43.6
CC single π via resonances	29,452	23.0	25,863	23.7
CC coherent π	1,760	1.4	1,736	1.6
CC multi-pion, DIS, etc	6,834	5.3	3,140	2.9
NC total	36,836	28.8	30,734	28.2
Total	127,920	100.0	109,046	100.0

Beyond DanielBoone...How do you scale this technology up?



Building a large Water detector, based on LAPPDs is not simply a matter of building a Super K type detector with MCPs

- Different optimization of volume to length scale
- Different balance of cost per surface area
- Different physics capabilities for the same fiducial mass

Cost isn't just number of PMTs

excavation costs, magnetic shielding (not necessary for MCPs), more or better use fiducial volume, competition in the PMT market

Lower costs are important, but physics reach should be the focus

In particular, lower costs and more efficient use of target mass means leaves room for departure from conventional WC design in ways that could enhance analysis

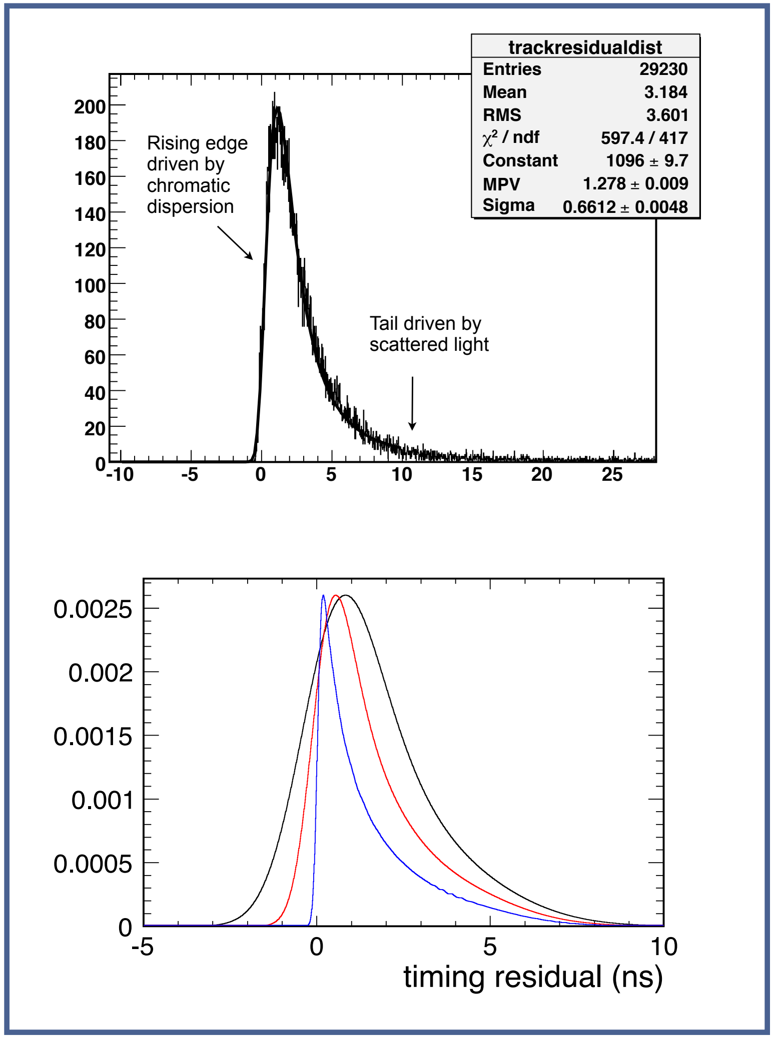
- possibility of segmentation? Less losses, scattering, dispersion...
- applied magnetic fields?

Disclaimer: This is not targeted at LBNE stage I: possible upgrade path or second detector....Or something beyond...

HiRes Water Group

Z. Djurcic (ANL), G. Davies (Iowa State), H. Frisch (U Chicago)
M. Sanchez (Iowa/ANL), M. Wetstein (U Chicago/ANL),
T. Xin (Iowa State)

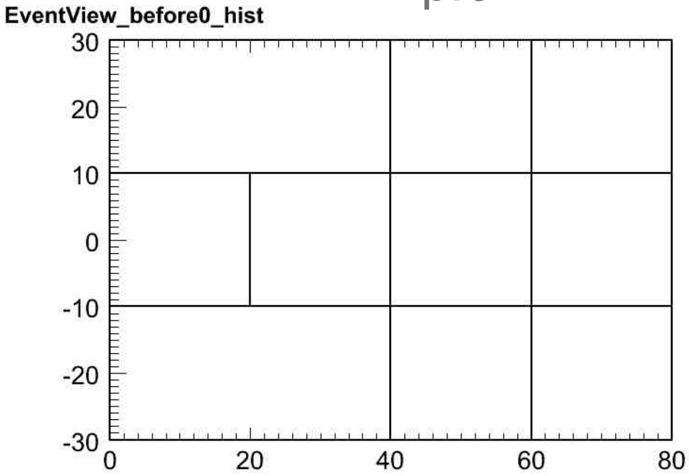
- These new capabilities and new possible optimizations necessitate a strong simulation and reconstruction program.
- Collaboration among the hi-res WCh working group has produced a new platform for testing algorithms on WCh detectors with interactively modifiable photodetector properties.
- These efforts have already identified promising features in observables, such as timing residuals, that could potentially be used to improve track reconstruction and better identify pi0 backgrounds.
- GEANT-based studies are ongoing...there is much work ahead. Plans for new post-docs and students to be starting soon.
- **These efforts are well integrated into the WC algorithms development efforts for LBNE.** Many of the tools will be useful for the nominal LBNE design.



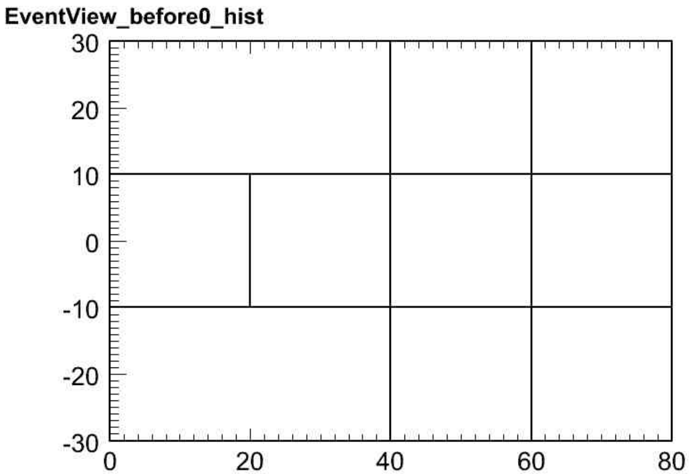
Isochrons

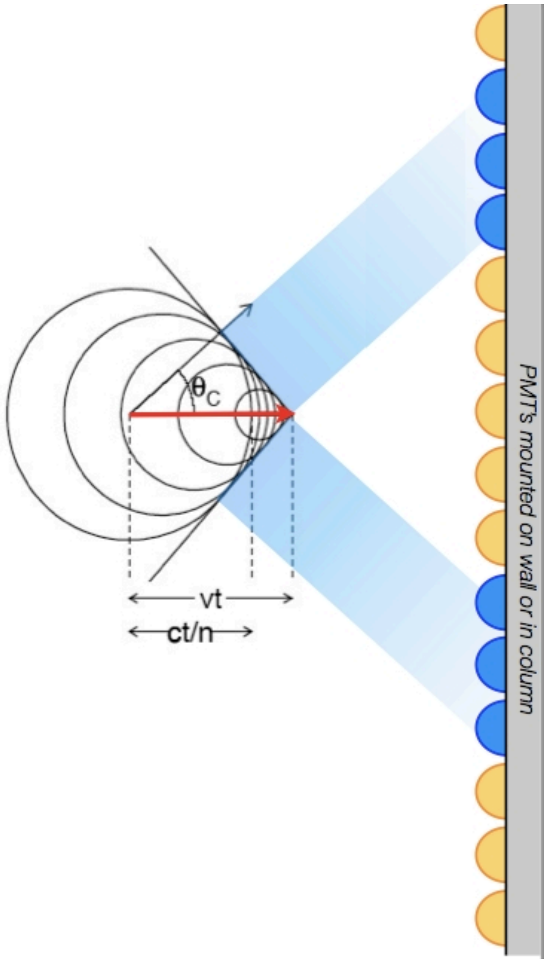
Can we use slices in constant time to fully reconstruct tracks?

pi0



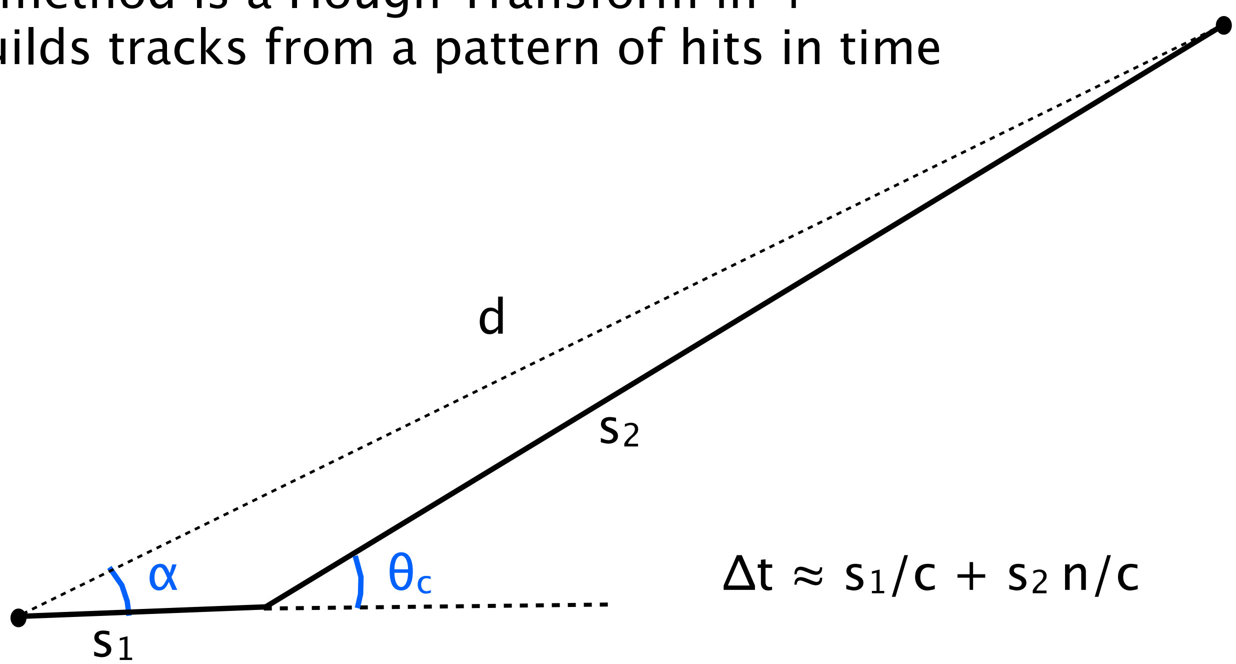
electron





Track Reconstruction Using an “Isochron Transform”

The isochron method is a Hough Transform in 4-space, that builds tracks from a pattern of hits in time and space.



$\Delta t \approx s_1/c + s_2\, n/c$

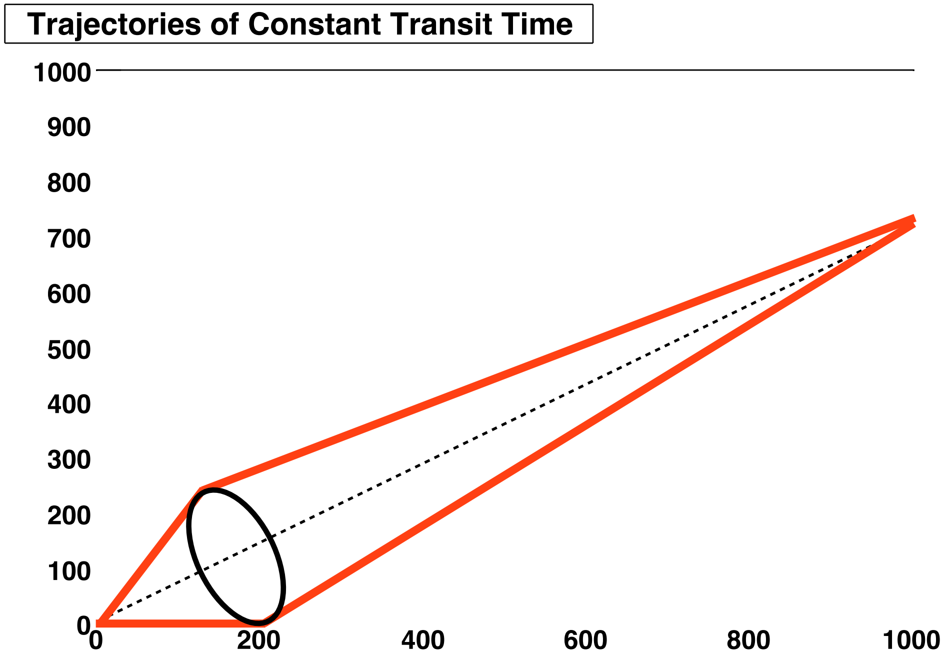
Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns:

s_1 and α

but there are two constraints:

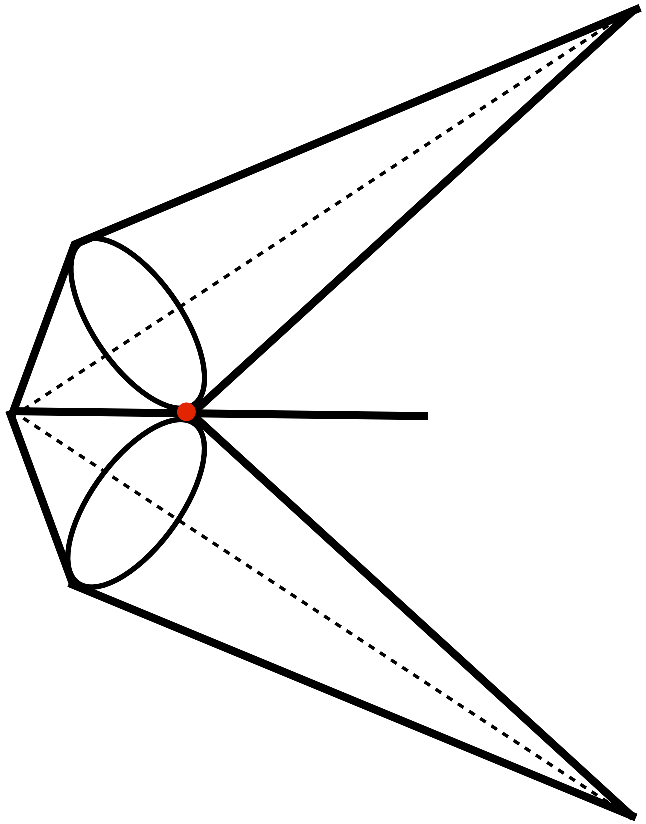
$s_1 + \; s_1 = d$ and $\Delta t\text{measured} = s_1/c + s_2\, n/c$

Track Reconstruction Using an "Isochron Transform"



And of course, there are a degenerate number of track directions, from which a photon emitted at the Cherenkov angle can hit

Track Reconstruction Using an "Isochron Transform"



However multiple hits from the same point of emission, will maximally intersect along the point of emission...This is similar to the Hough transform.

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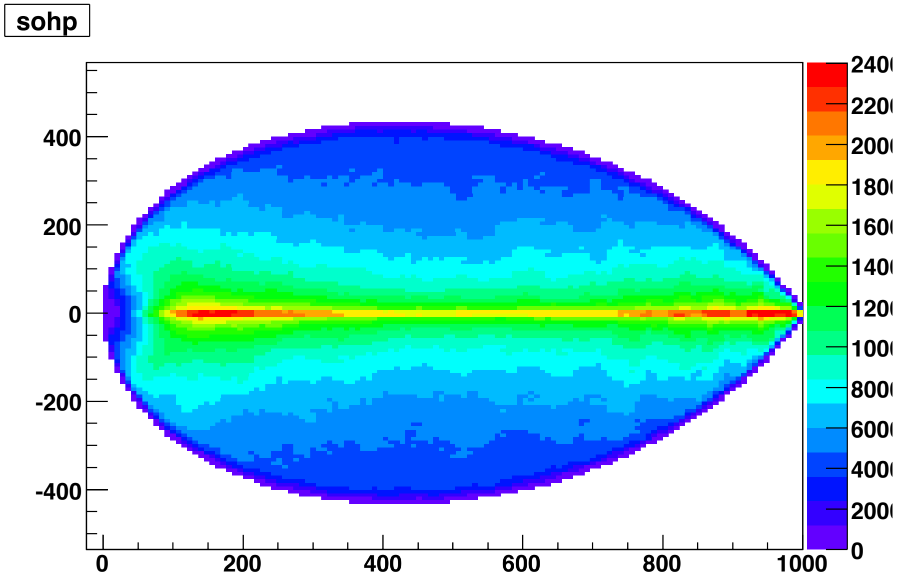
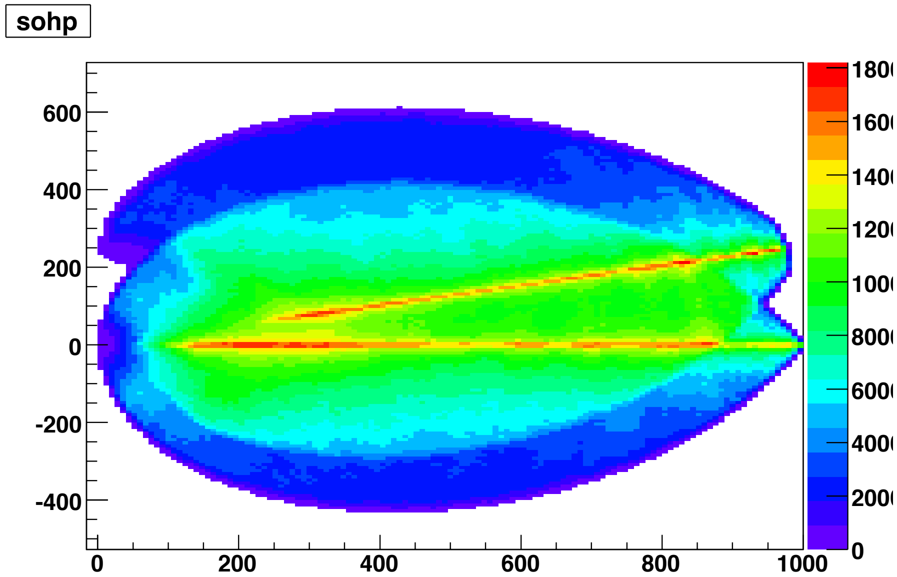
Track Reconstruction Using an "Isochron Transform"

Results of a toy Monte Carlo with perfect resolution

Color scale shows the likelihood that light on the Cherenkov ring came from a particular point in space. Concentration of red and yellow pixels cluster around likely tracks



Single track



Two tracks displaced from a common vertex

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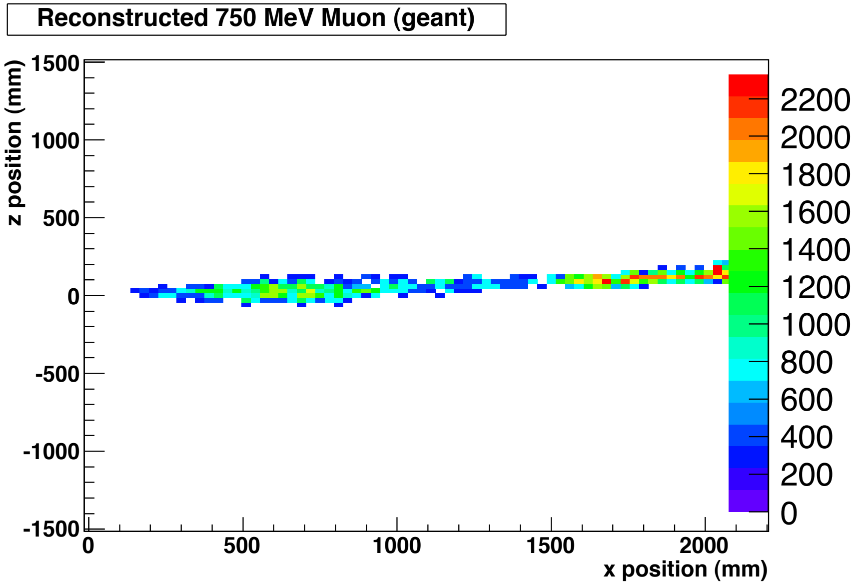
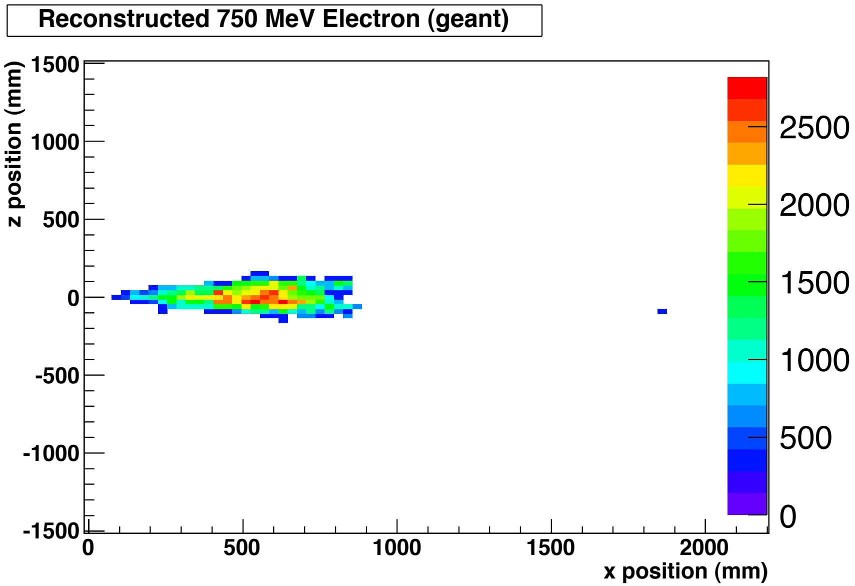
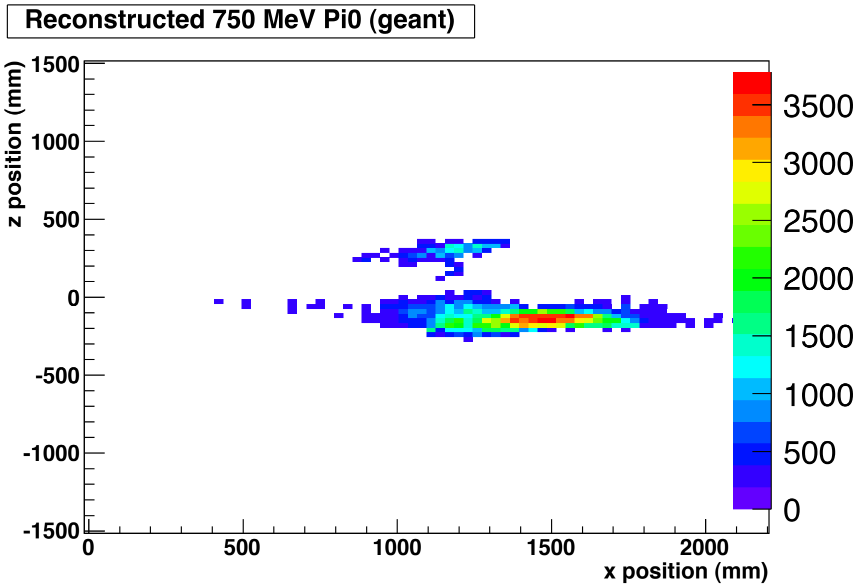
Reconstructing Geant Events

- Events were generated at the center of an 6m cube.
- These are just the crude (hand-tweeked) isochrons, constructed with respect to the primary vertex.
- Further steps could improve these transforms.
- Nonetheless, contrast between the particles, is still pretty stark.



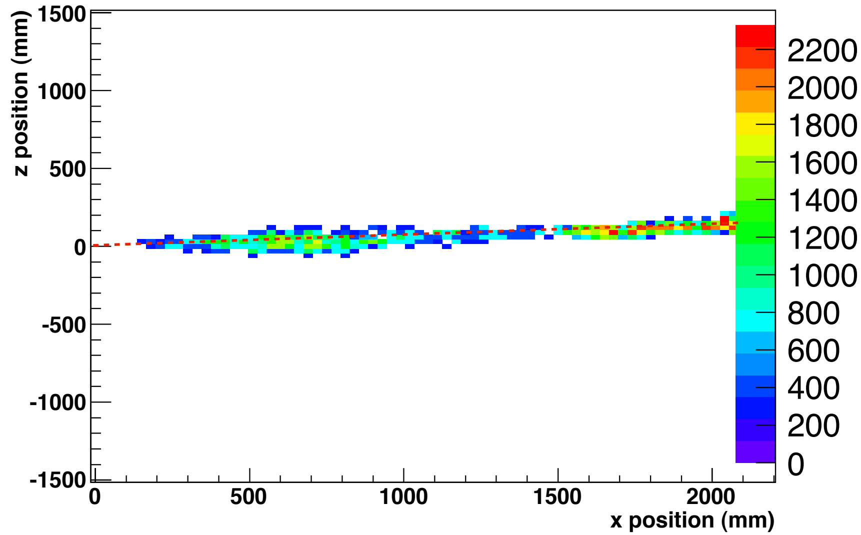




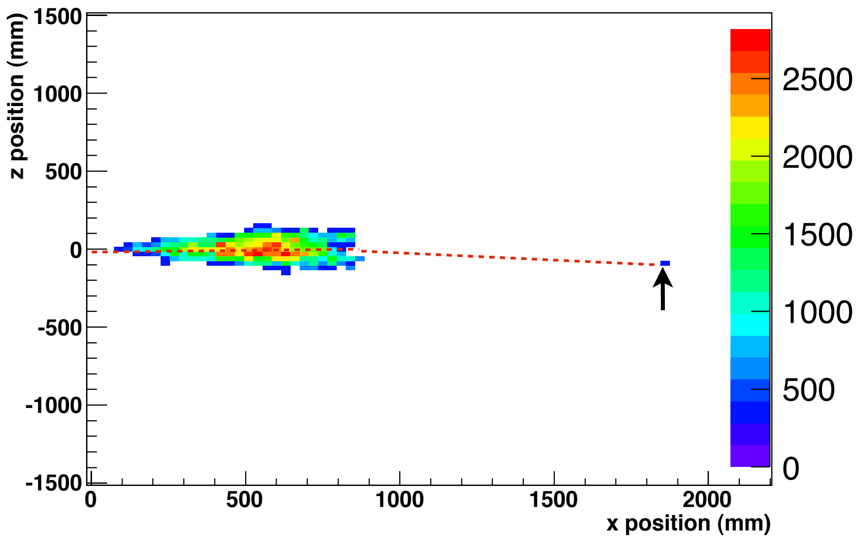
Comparing Isochron Reconstruction....

If I hand draw track hypotheses through these transforms...

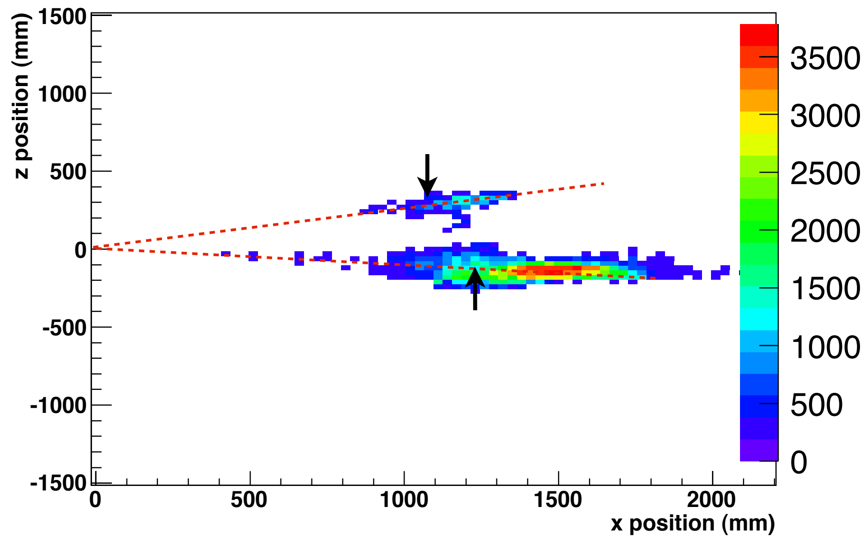
Reconstructed 750 MeV Muon (geant)



Reconstructed 750 MeV Electron (geant)

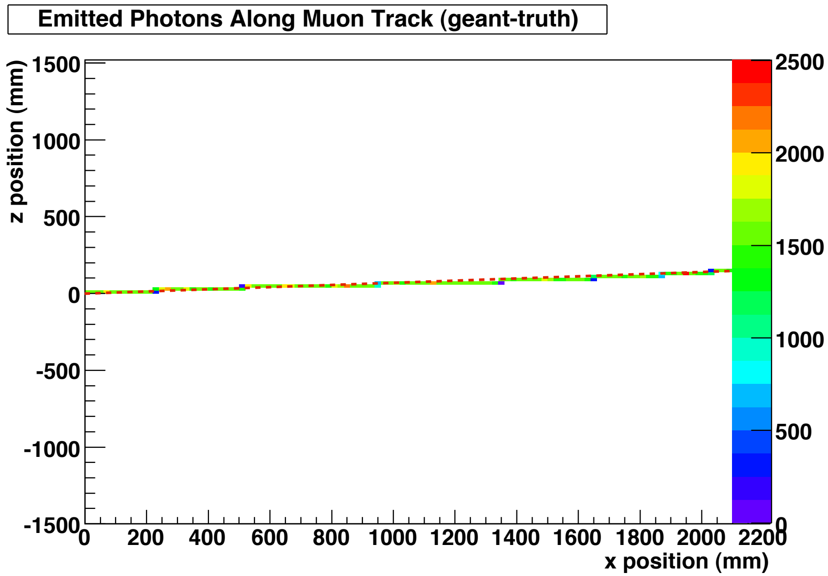


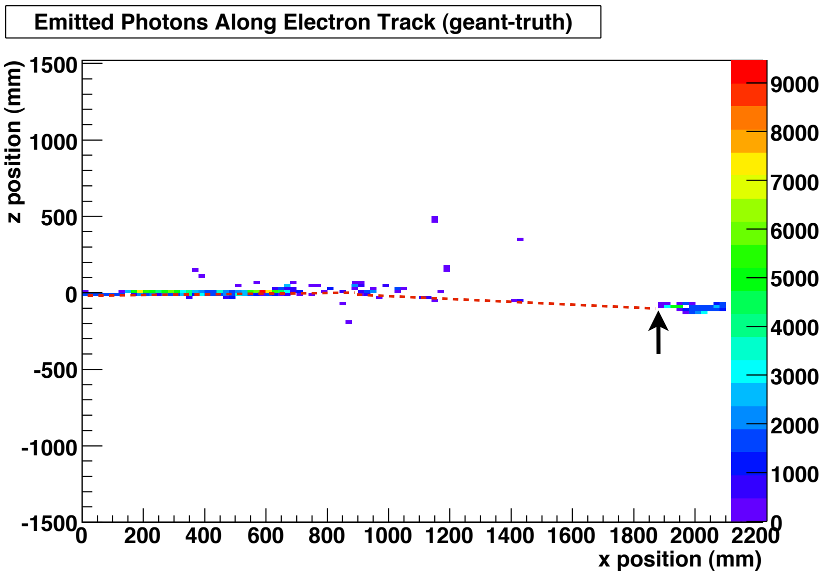
Reconstructed 750 MeV Pi0 (geant)

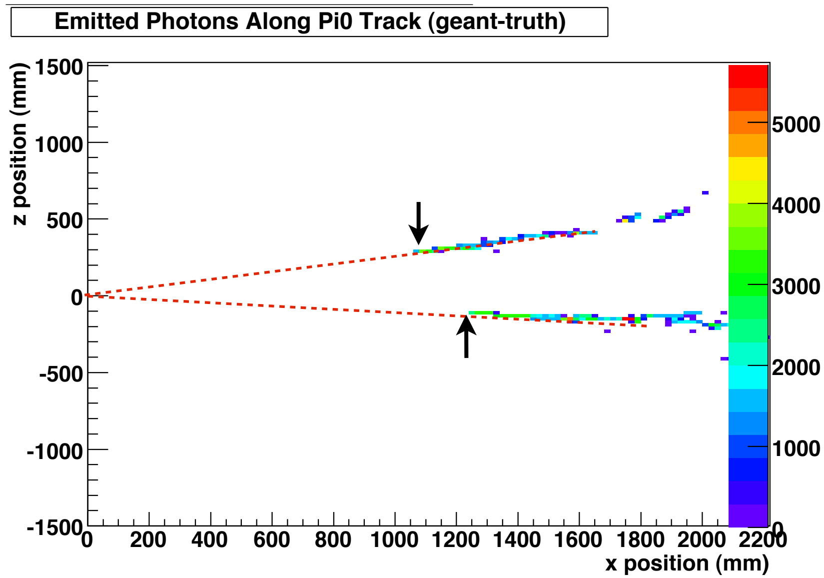


With True Tracks

They match very nicely with the truth-level tracks/shower constituents







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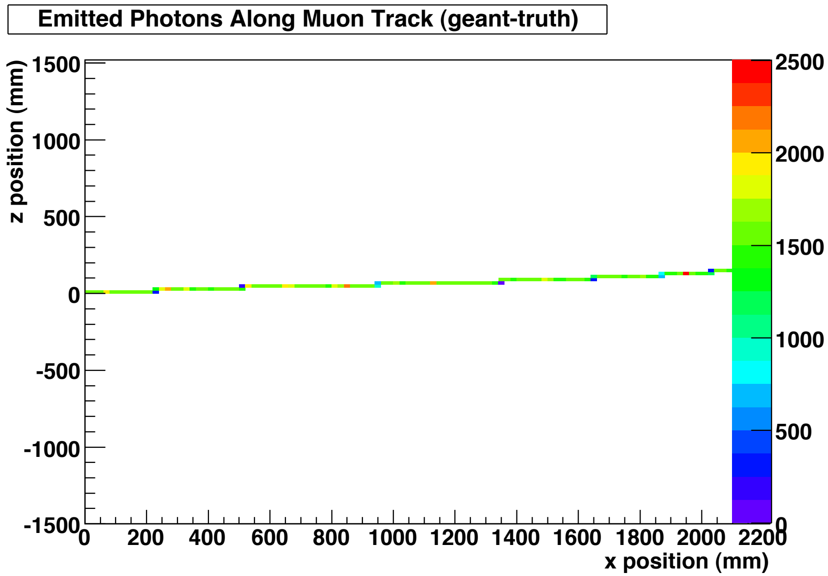
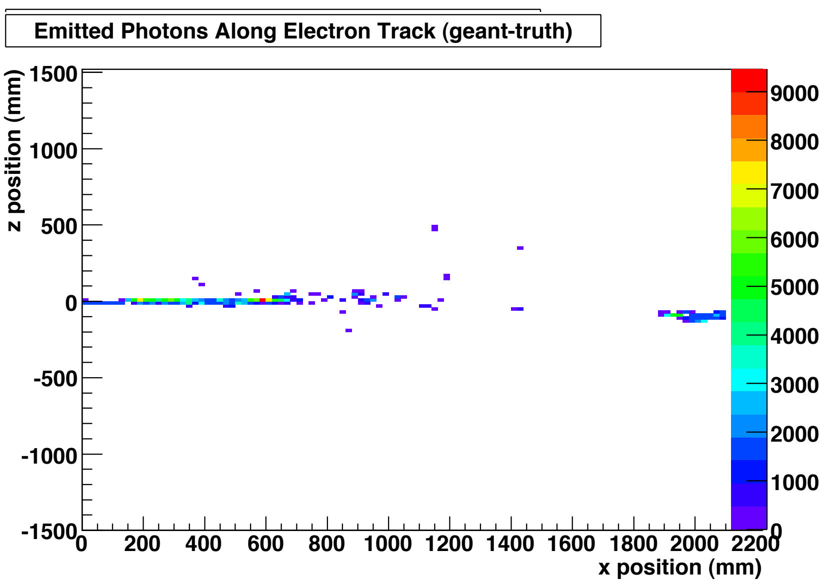
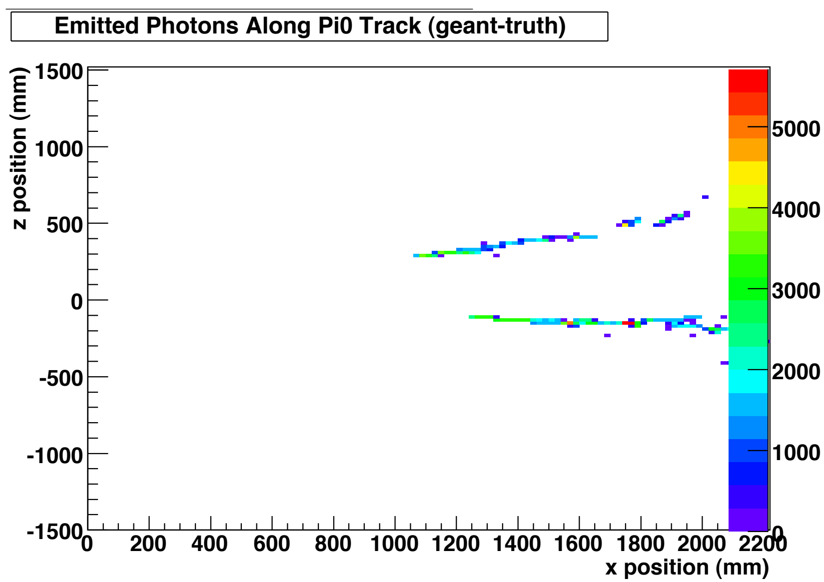






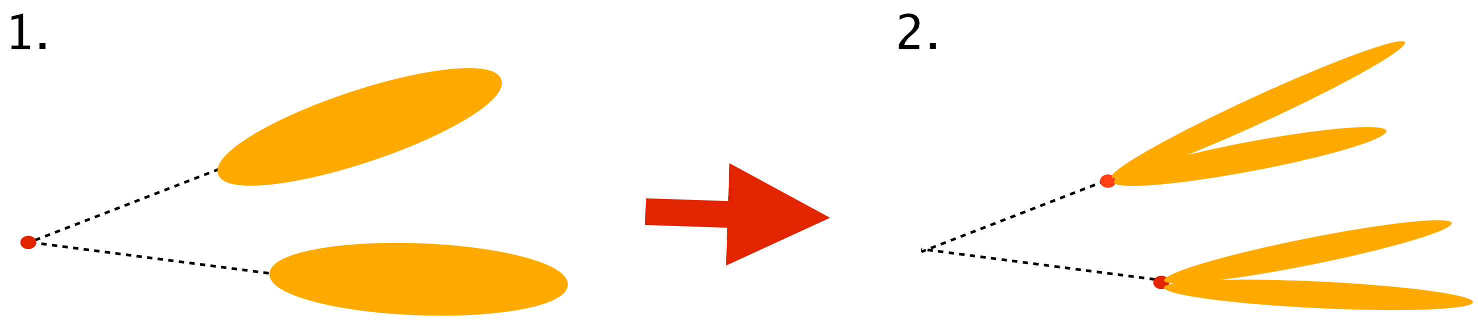
Optimizing the Transform

Once candidate showers have been identified, each stage of the shower needs to be independently transformed.

Isochron algorithm works best over one single stage of a shower. Each new branch point can be transformed iteratively, using the branch point as the new starting vertex.

Crude, first application of the isochron transform is useful to identify the original vertex, location of first light, number of shower candidates in the next stage...But, these are important particle ID handles. Can be used to make initial cuts.

In this first stage, before later applying chromatic corrections, we can very the index of refraction to look for shower candidates....



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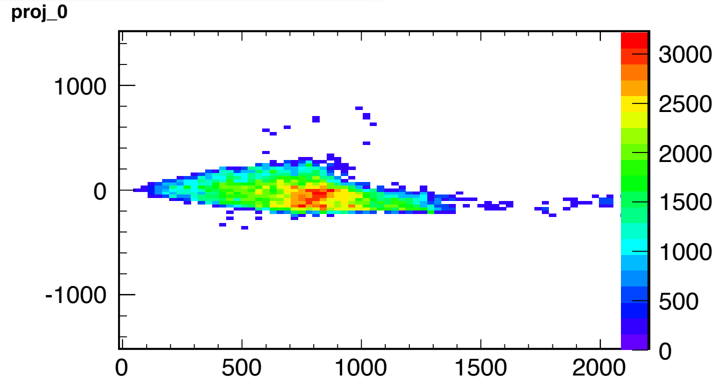
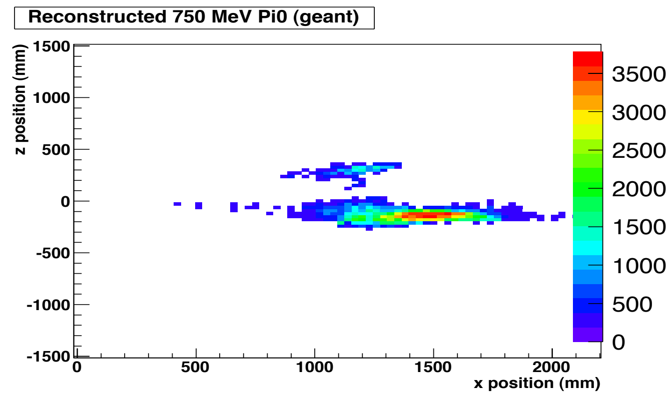
Isochron Transform Evaluated for Different Wavelengths

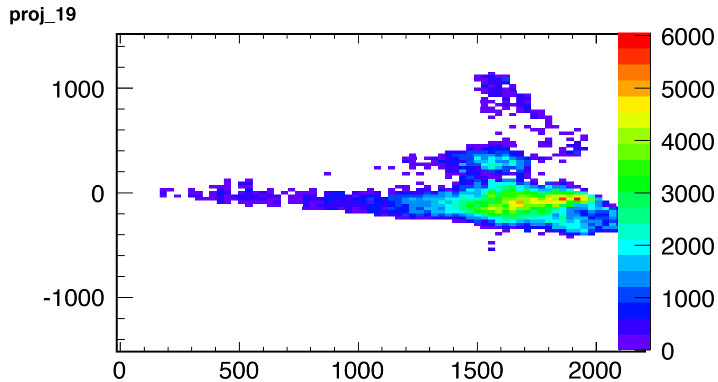
As a first pass, on can adjust the default refractive index used by the transform in order to optimize the track fit.

This is equivalent to varying the ring size in a conventional super K Hough transform...

Instead of searching for a second peak, Pi0 identification consists of searching for a second track-like object as we vary N.

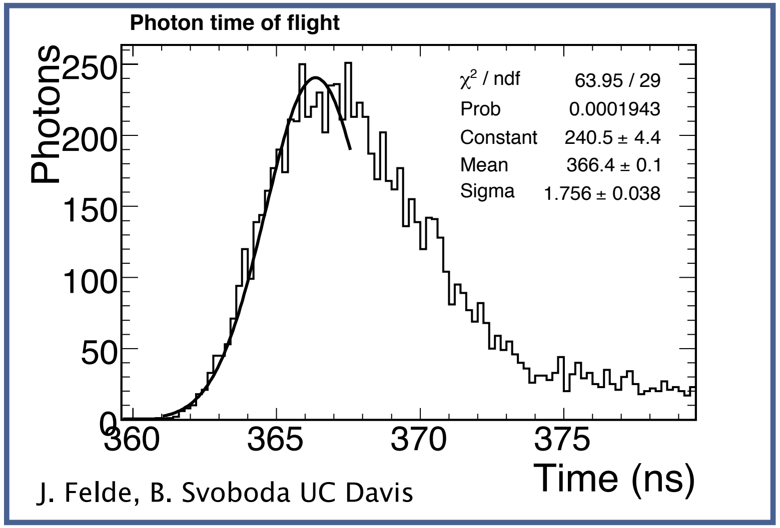


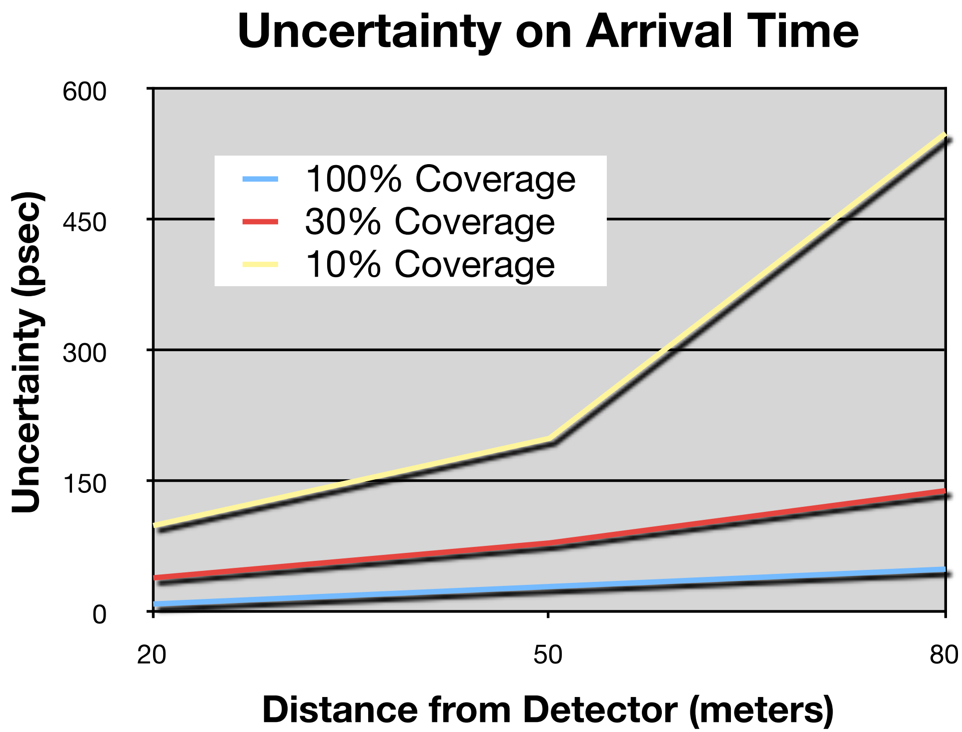




Understanding Chromatic Dispersion

- A concern in using fast timing are the effects of frequency dependent dispersion, scattering and absorption.
- Using a fast toy MC originally developed by J. Felde we study the time of arrival for photons in an spherical detector.
- For a 50m detector with 100% coverage, the rise time ($t_{90}-t_{10}$) is of the order of 2 ns which cannot be sampled with standard PMT technology.
- For a given detector size, the rise time stays constant and the uncertainty in the position of the leading edge becomes smaller if larger photodetector coverage is considered.
- A combined improvement in photodetector coverage (for reduced uncertainty in risetime) and faster timing (to better sample the risetime) allows for better use of timing information in Water Cherenkov detectors.





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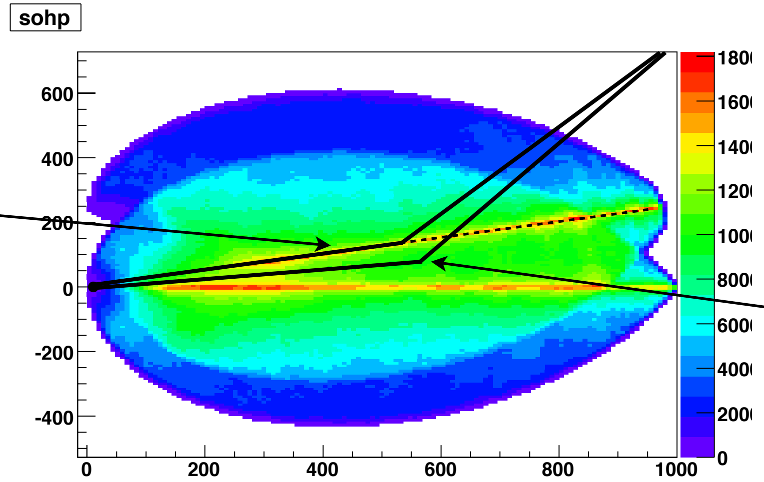
An Example Analysis

Once fit with a track, light color is fully determined.



trajectory for correct color will intersect with the track

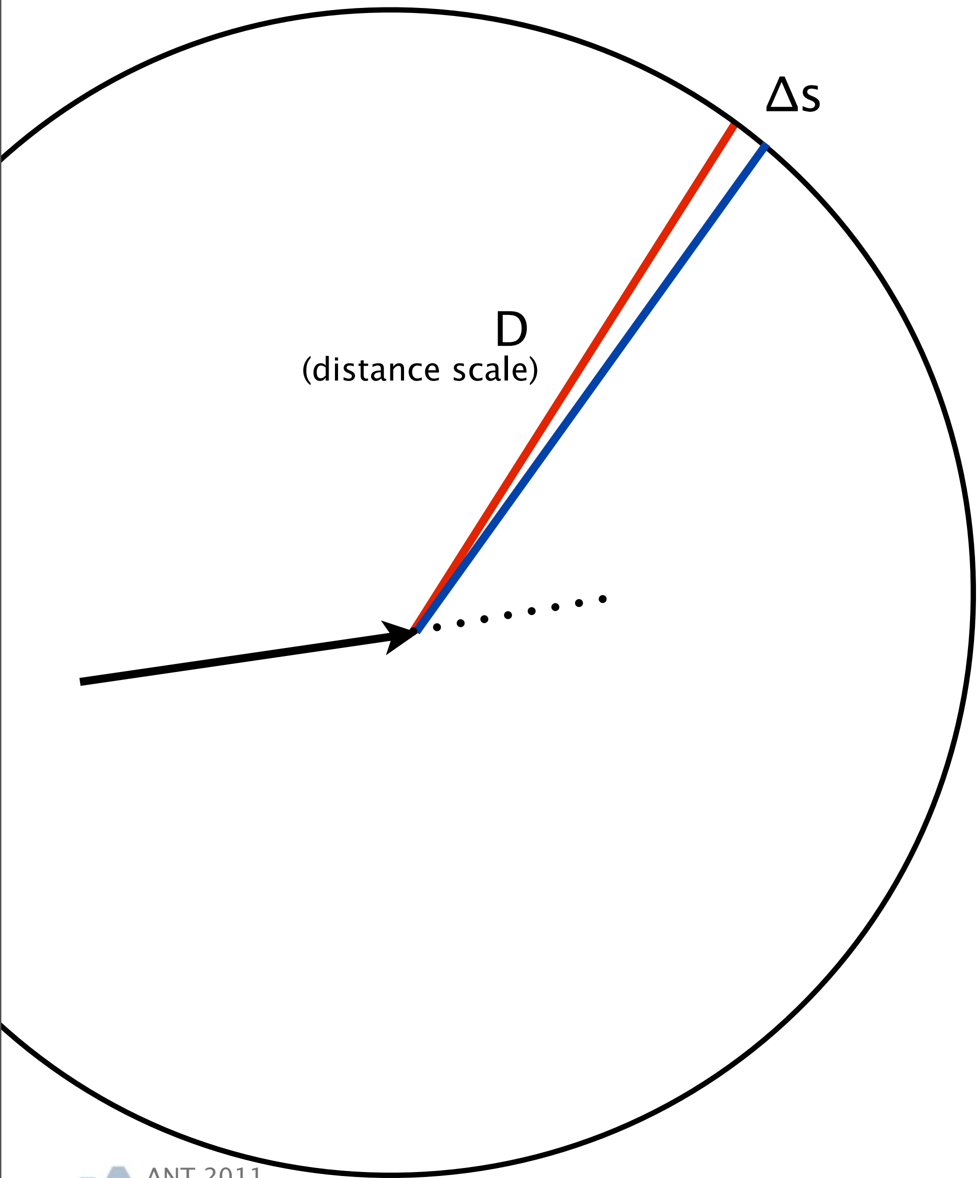
trajectory for incorrect color will not align with the rest of the track

Given known absorption properties, and Cherenkov spectra, it should also be possible to apply a Bayesian unfolding method to reverse the effects of chromatic dispersion, and sharpen the track features.

However, this is computation-intensive and should only be applied as a second step.

We're working on the best way to do this....

Understanding Chromatic Dispersion



Light of different colors arrives at different times, but also at different Cherenkov angles.

At 10 meters distance, 250nm light arrives ~6.5 nsec later than 550 nm.

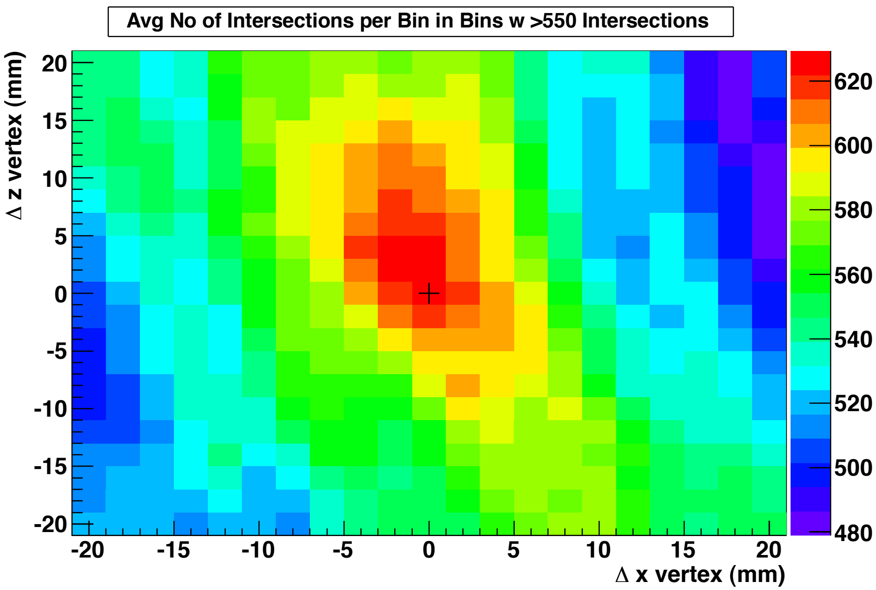
Given the difference in θ_c for the two colors (0.885 versus 0.747 radians), the spatial separation between the red and blue light at 10 meters is ~1.4 meters

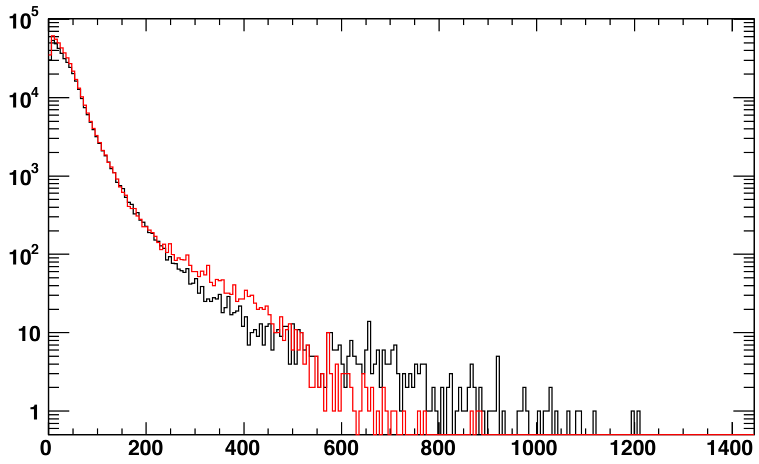
with resolution on Δt approaching 100 picoseconds, one can distinguish between colors much closer on the spectrum, but only if one can also resolve the corresponding Δs which is 2.4 cm

in LBNE, granularity of PMTs is 10" (25.4 cm) with more the 1 meter separation between phototubes.

An Example Analysis

Sharpness of intersection points can be used as a figure-of-merit for fitting vertices



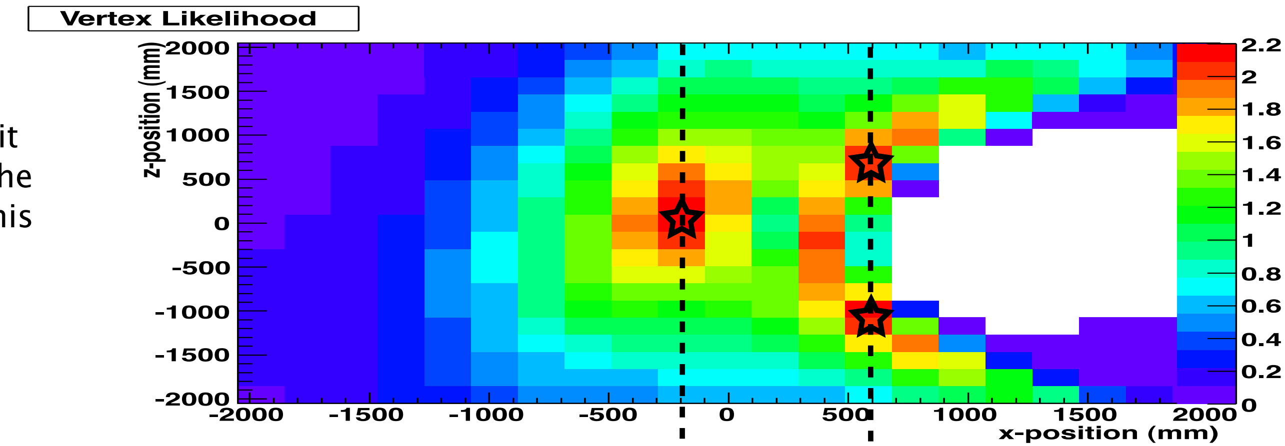


This allows you to work back to the original vertex that causally unites all of the detector hits...even if that common vertex proceeds the onset of Cherenkov light...

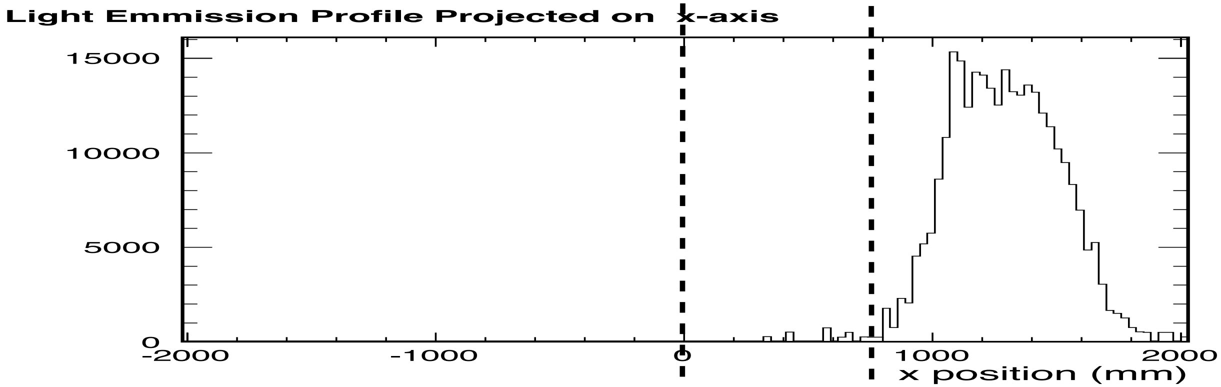
Later branch-points in the EM shower will appear as local minima....

Vertex Separation As A Handle on PID

Pi0

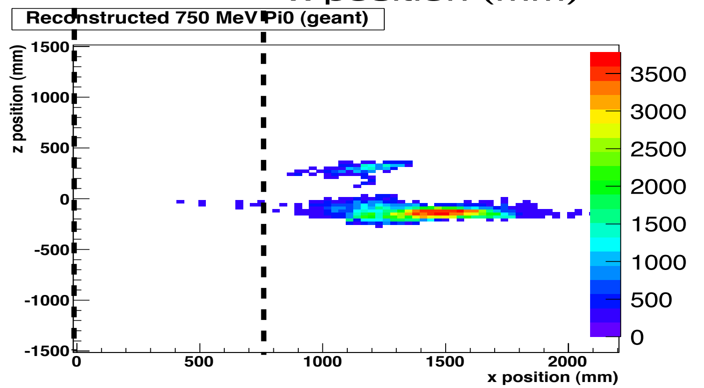


We have one strong vertex that causally connects the hit pattern, located far before the onset of Cherenkov light. This is followed by two vertex candidates, corresponding roughly with first light.



Location of the candidate vertices do not correspond perfectly to true vertices, probably due to an inappropriate choice of refractive index.

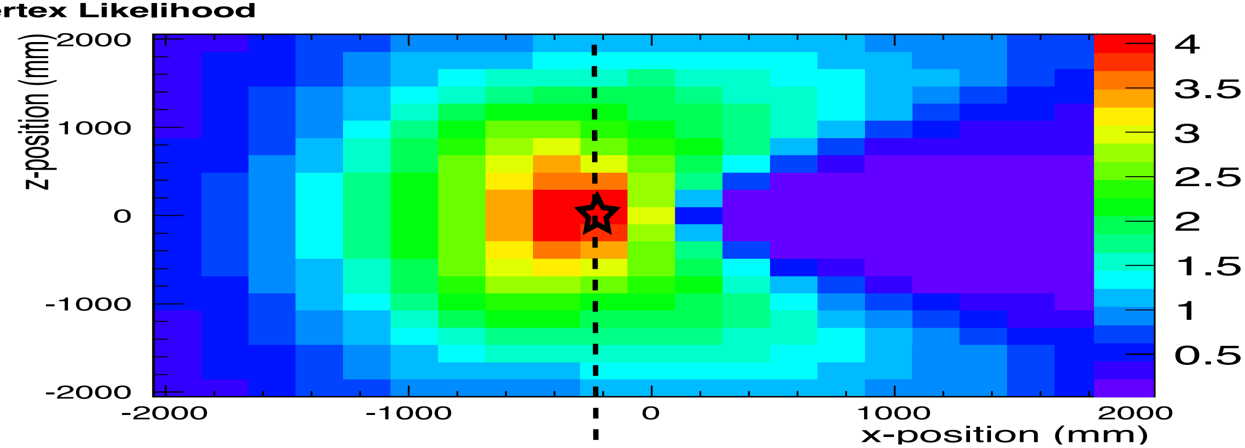
First light and vertex candidates correspond nicely with the two shower candidates reconstructed by the isochron method



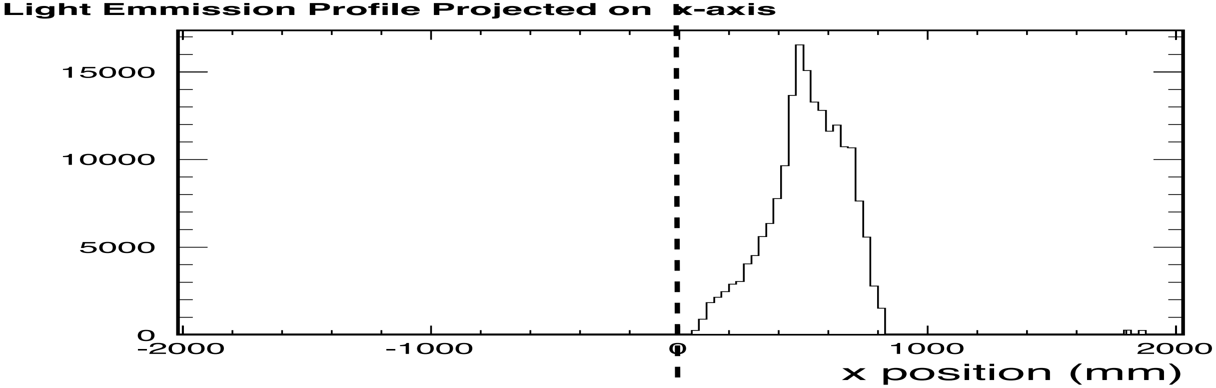
Vertex Separation As A Handle on PID

Electron

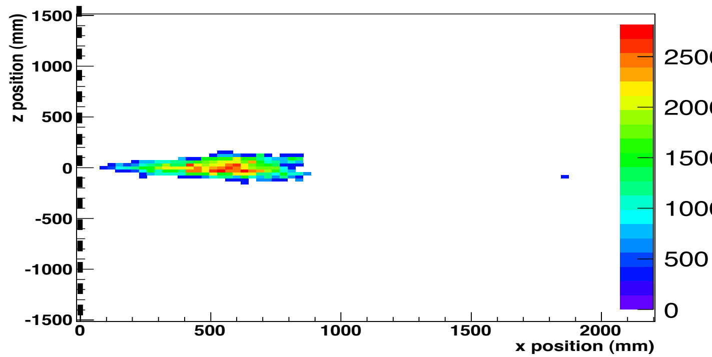
We have one strong vertex that causally connects the hit pattern, located far before the onset of Cherenkov light. This is followed by two vertex candidates, corresponding roughly with first light.



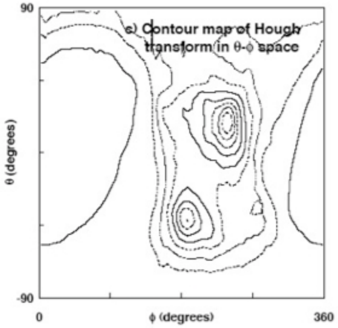
Location of the candidate vertices do not correspond perfectly to true vertex, probably due to an inappropriate choice of refractive index (I used the wrong value).

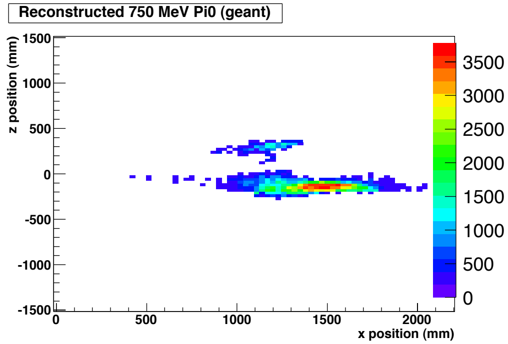


First light and vertex candidates correspond nicely with the two shower candidates reconstructed by the isochron method



Conclusions



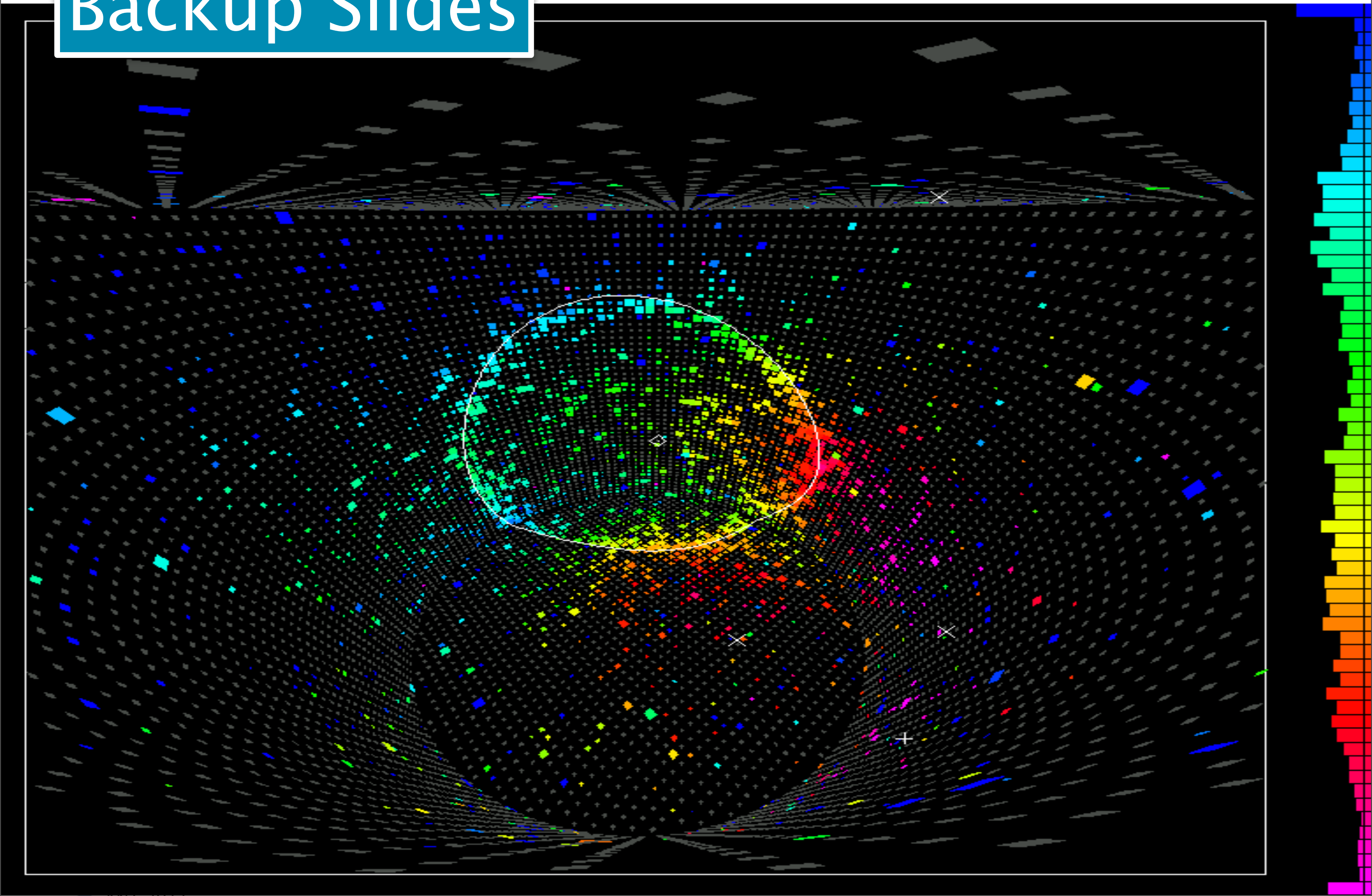


- Discrimination between pi0s and electrons at higher energies (>1 GeV) in WC is a difficult task, but with high pay off for long baseline neutrino physics: We have a factor of ~5 loss we can recover...
- Advances in photodetection technology provide us with a new opportunity re-imagine water-based neutrino detectors.
- Simultaneous use of fine binned timing **and** high spatial resolution can provide enough information to think about close-to-full event reconstruction in water, but necessitate new analysis techniques.
- Chromatic dispersion is a confounding factor, making analysis more difficult..but it can be corrected for.
- Attenuation and scattering losses (as well as low light yield) are the biggest challenges for a large detector. These could be optimized (novel design) or mitigated (water-based scintillator- M. Yeh, BNL).
- This talk focused on accelerator neutrinos, but there are countless other applications. We need your help imagining applications for these tools.

Thank you

Thanks to Conference Organizers for making ANT happen
to all of my LBNE and LAPPD colleagues for all of the work presented in this talk
to Henry Frisch and Mayly Sanchez for their help with the talk

Backup Slides



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Next Steps

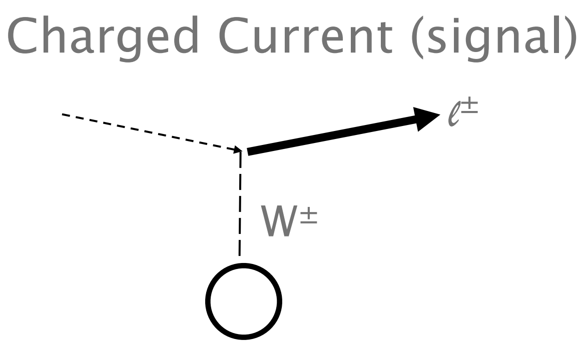
- Developing an effective reconstruction recipe.
- Implement explicit track and vertex fitting based on isochron transforms.
- Development of tools for correcting chromatic dispersion
- Develop metrics for particle ID. Test those metrics.
- Studying algorithm performance over variations in drift distance
- Apply isochron algorithm on LBNE (WCSim) simulations.
- Make the code fast and efficient.

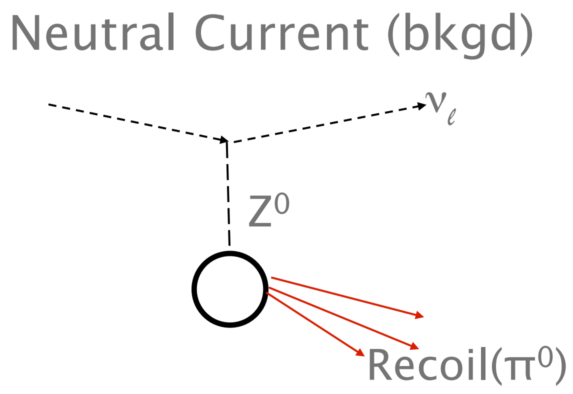
Neutrino Interactions with Matter

Typical neutrino oscillation experiments detect neutrinos through their interactions with matter.

Specifically neutrino flavor can be determined by charged-current interactions, which produce charged leptons of like flavor.

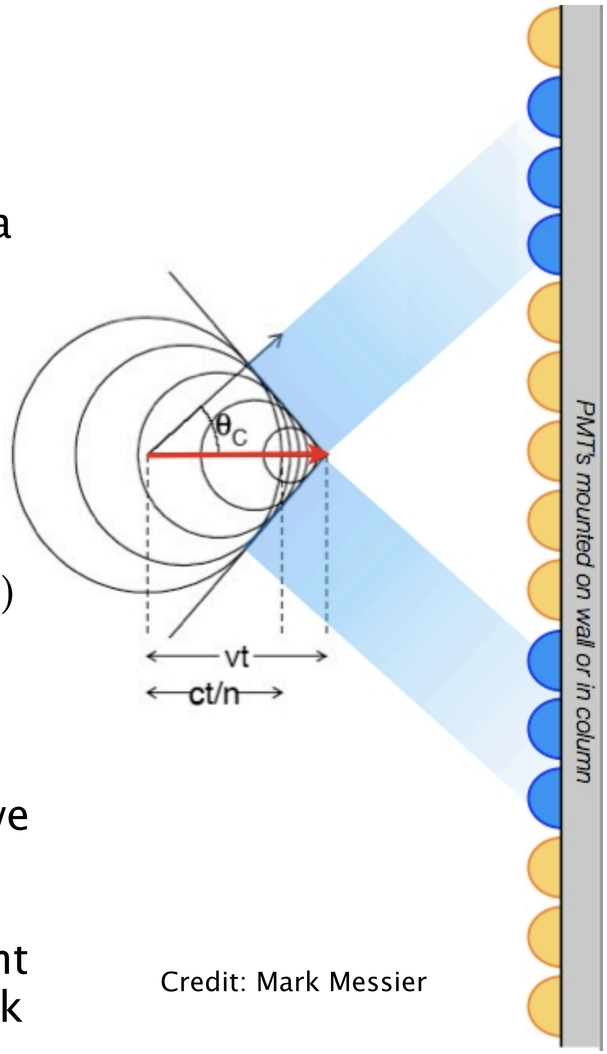
The ability to discriminate between types of neutrinos is then limited by the ability of a detector paradigm to discriminate between high energy particles in the fiducial volume.



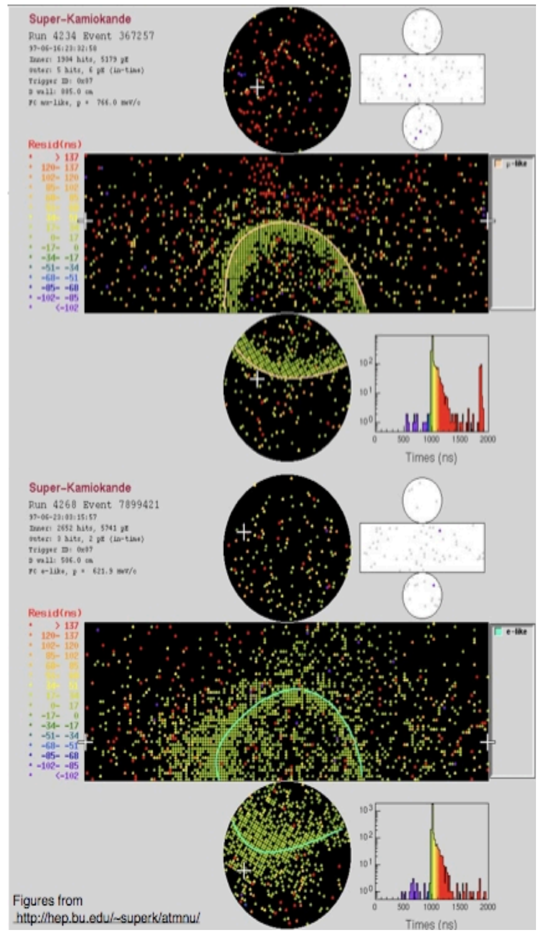


Intro to WC Detectors

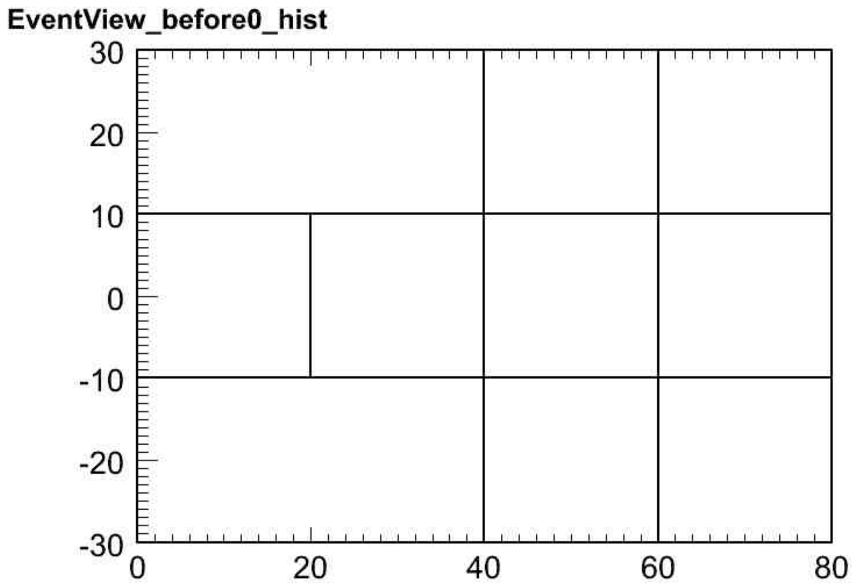
- An shockwave of optical light is produced when a charged particle travels through a dielectric medium faster than the speed of light in that medium: c/n
- This light propagates at an angle $\theta_C = \mathrm{acos}(1/n\beta)$ with respect to the direction of the charged particle…
- Using photodetectors, we can measure the positions and arrival times of the emitted light and reconstruct the track



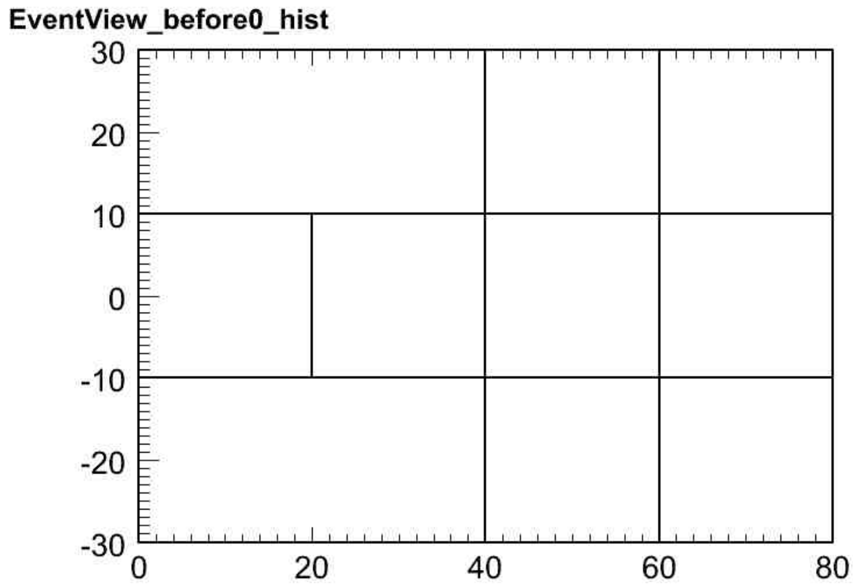
Credit: Mark Messier



electron



pi0



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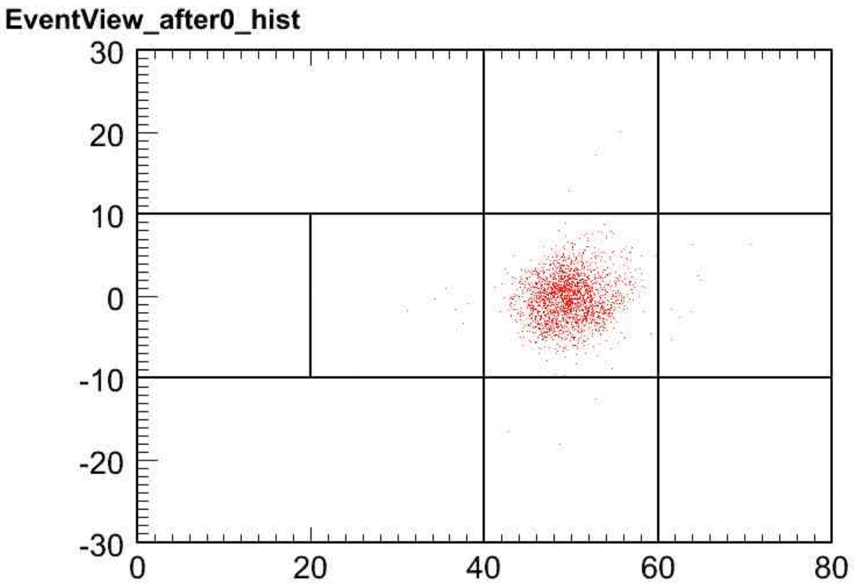
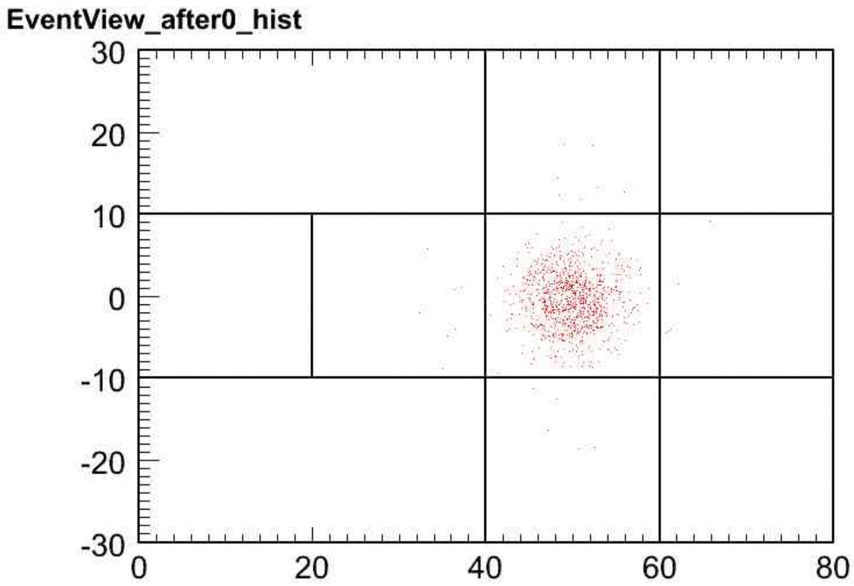
electron



pi0



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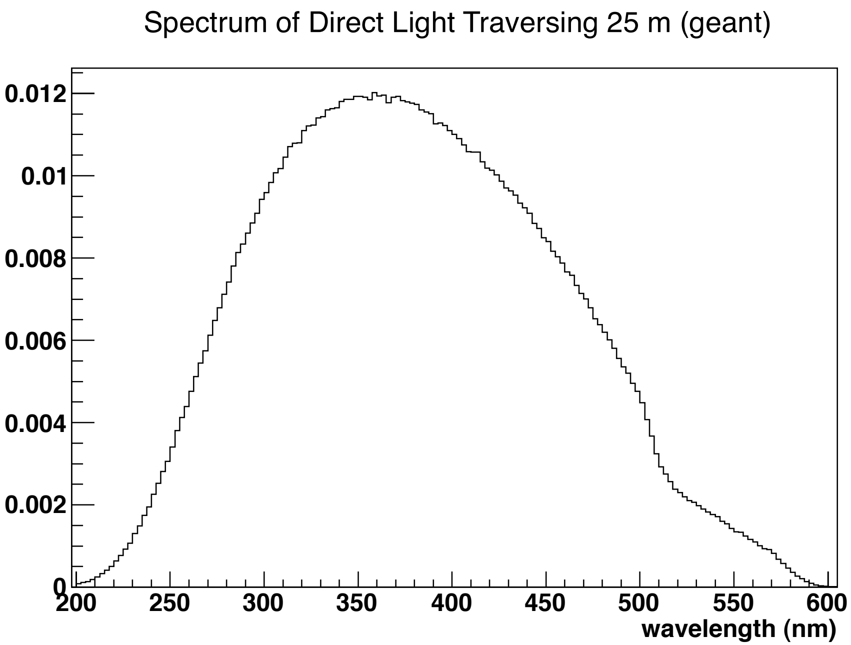

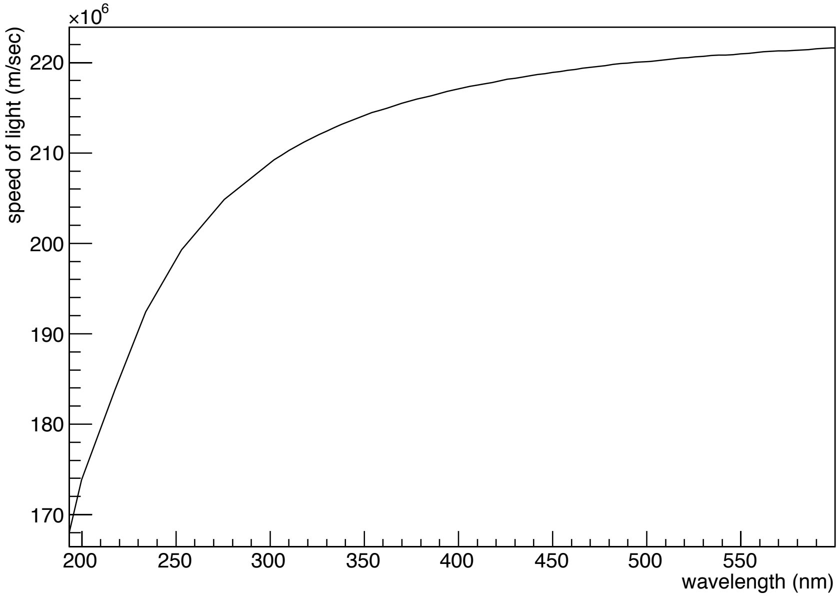

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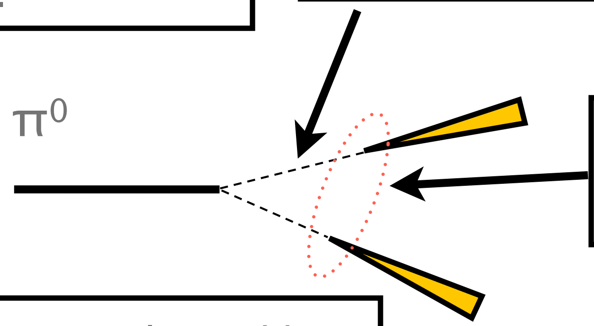
Timing Information:

On average, this amounts to separating the two vertices from which the Cherenkov cones radiate...

~1 radiation length
~37 cm



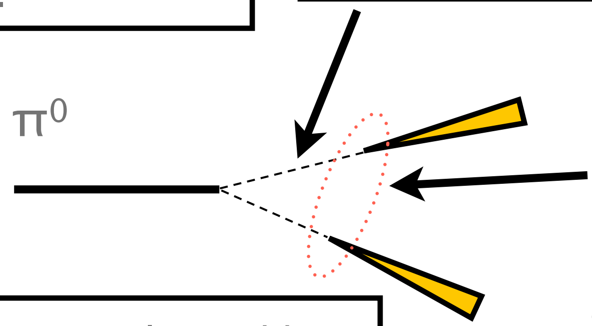
vertices are separated:
at 7 degrees: ~4.5 cm
at 15 degrees: ~9.7 cm

- Finding a single event vertex is limited by our ignorance of T_0.
- Vertex separation is not...

Timing Information:

On average, this amounts to separating the two vertices from which the Cherenkov cones radiate...

~1 radiation length
~1.64 nsec



in term of time:
at 7 degrees: ~200 psec
at 15 degrees: ~425 psec

speed of light in water: ~44 psec/cm

- Finding a single event vertex is limited by our ignorance of T_0.
- Vertex separation is not...

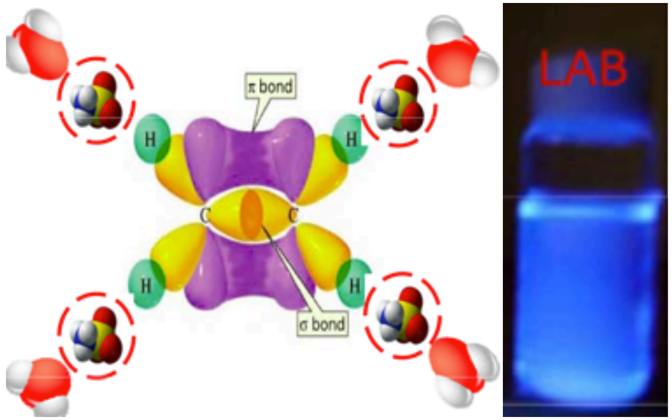
New Developments in Water-Based Detectors: Possibility of Water-Based Scintillator

Minfang Yeh et al, Brookhaven National Lab

Linear Alkylbenzene (LAB) - Industrial detergent

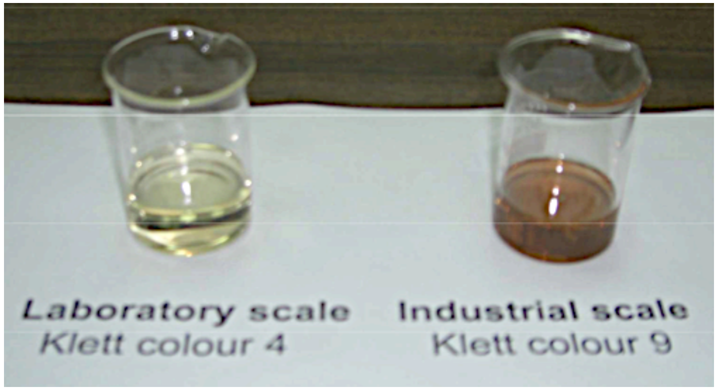
Key innovations:

- ability to create stable solutions
- purification to achieve longer attenuation lengths



Ideal for large scale experiments

- Non-toxic
- Non-flammable
- Stable
- Cheap



The scintillation light might be difficult to resolve with timing, but...

- It may be possible to have both Cherenkov and scintillation light, separated in time
- The spatial/statistical gains would be considerable.

This slide is courtesy of M. Yeh. Special thanks also to Howard Nicholson.

Several Approaches To WC reconstruction

- Use pure timing of hits
- Use pattern-of-light fitting, based on Geant simulations of light yields and transmission
- Use geometric properties of Cherenkov light, combined with timing

Several Approaches To WC reconstruction

- Use pure timing of hits

Need to solve systems of equations for 7 degrees of freedom for septuplets of hits. Combinatorics become hairy...but worth pursuing

- Use pattern-of-light fitting, based on Geant simulations of light yields and transmission

Best way to do things with brute force computing, not the focus of this talk but will be a major part of this effort.

- Use geometric properties of Cherenkov light, combined with timing

Best way to conceptually understand the problem, focus of this talk...

Track Reconstruction

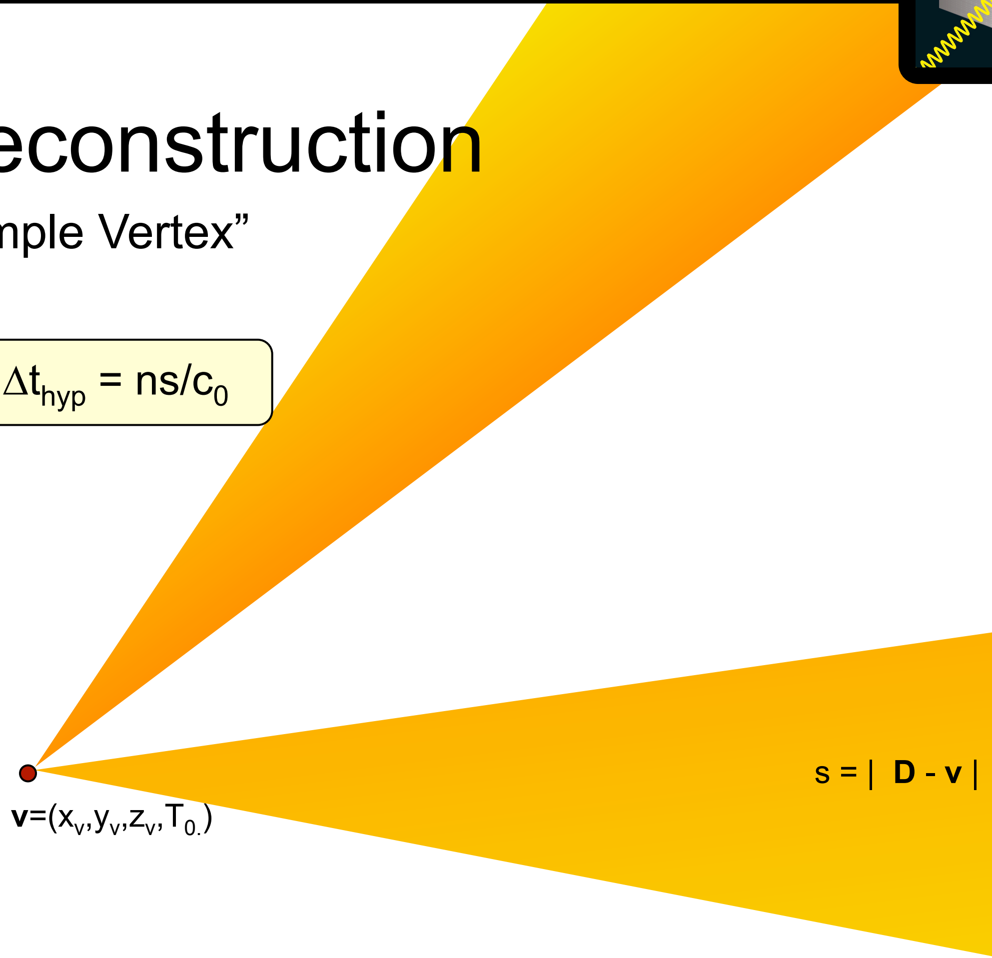
"Simple Vertex"

Step 1:

Conceptualize Cherenkov light as coming from a point source…

- For different hypothesized point-source locations compute the distance (s) between the point and the detector hits.
- Calculate the hypothesized time (Δt_{hyp}) it would take the light to reach each detector from the point source.
- Adjust the location of the point source to minimize the width of the $(\Delta t_{hyp}-t_D)^2/\sigma_t$ distribution for all hits.

$\Delta t_{hyp} = ns/c_0$



Fit pameters: x_v,y_v,z_v,T_0

Track Reconstruction

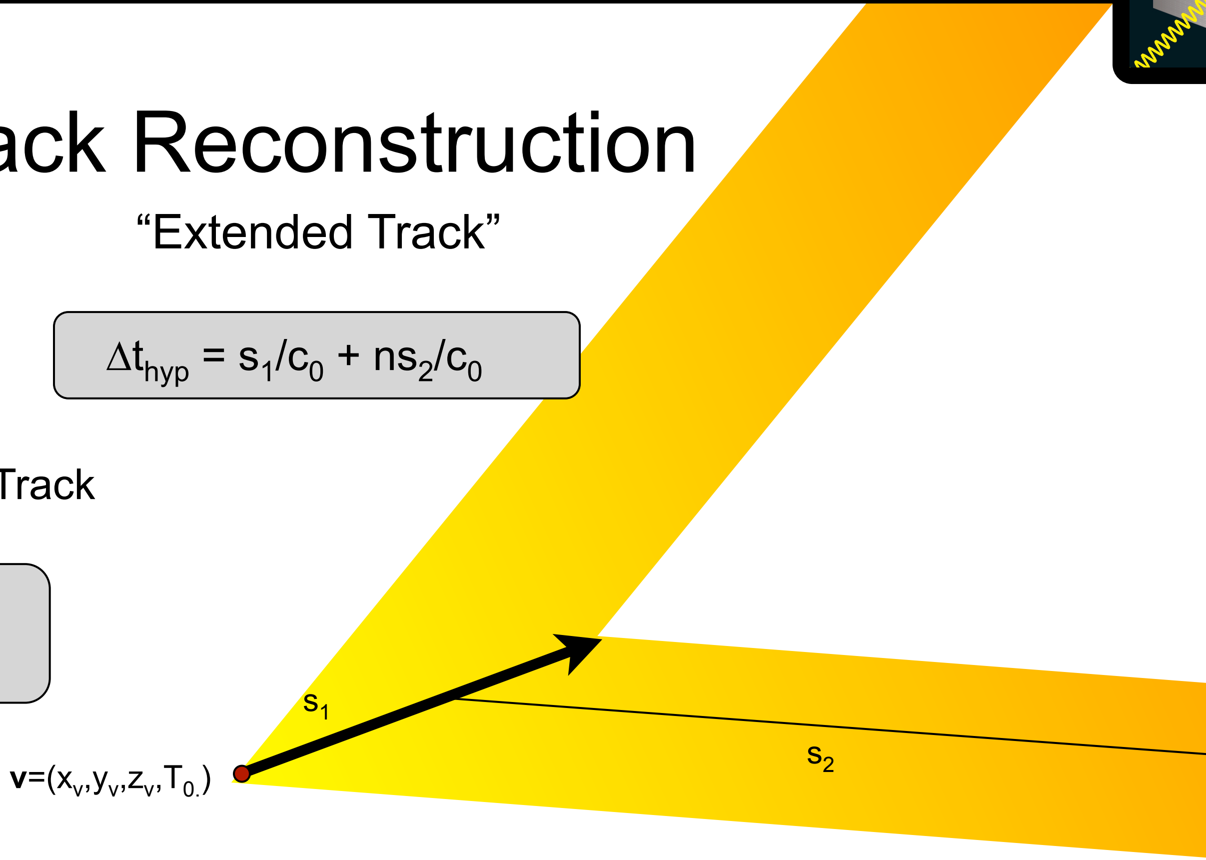
"Extended Track"

$$\Delta t_{hyp} = s_1/c_0 + ns_2/c_0$$

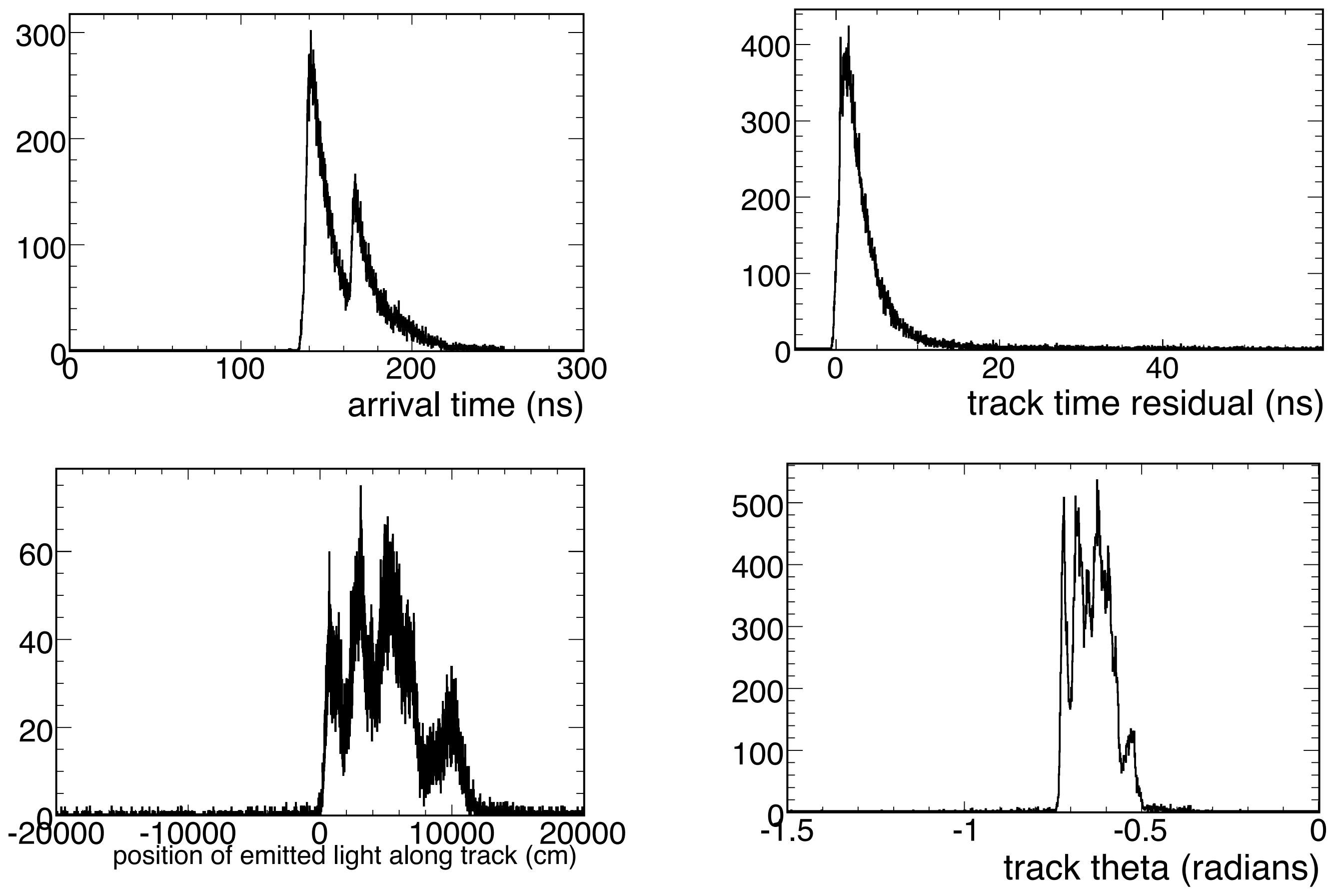
0-D Point Source → 1-D Track

7 Fit pameters:

$x_v, y_v, z_v, T_0, \theta_{track}, \phi_{track}, \beta$



Basic Observables Used in Fits



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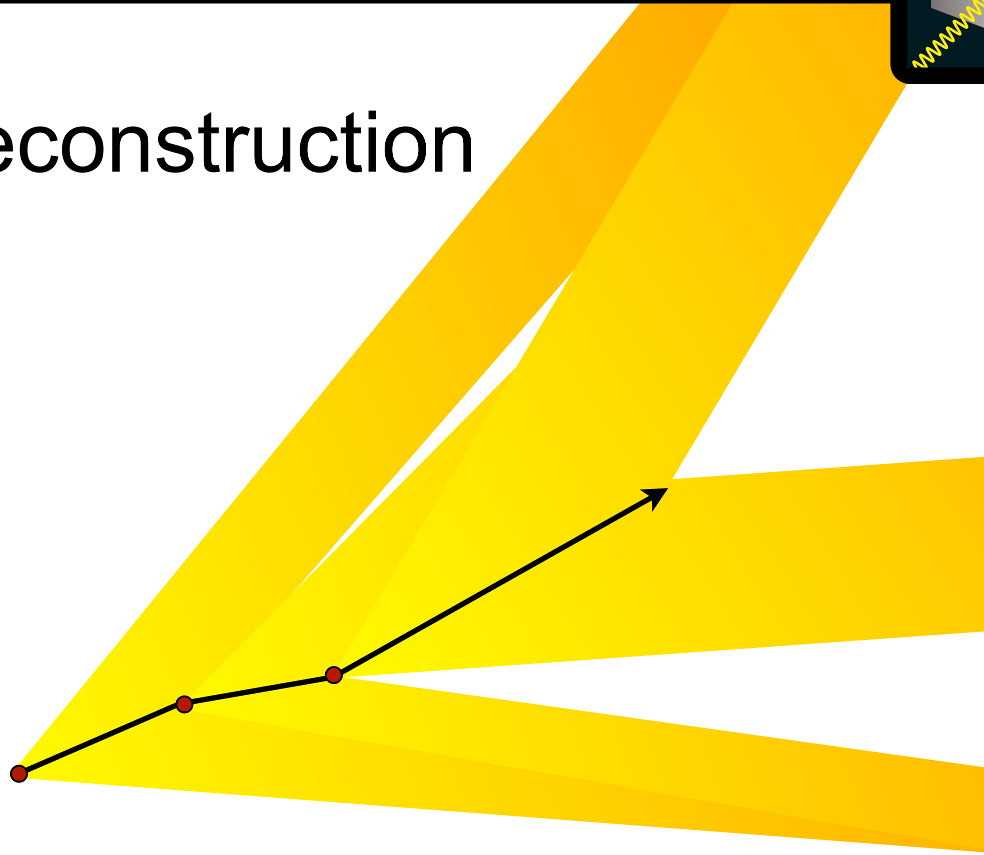
Track Reconstruction

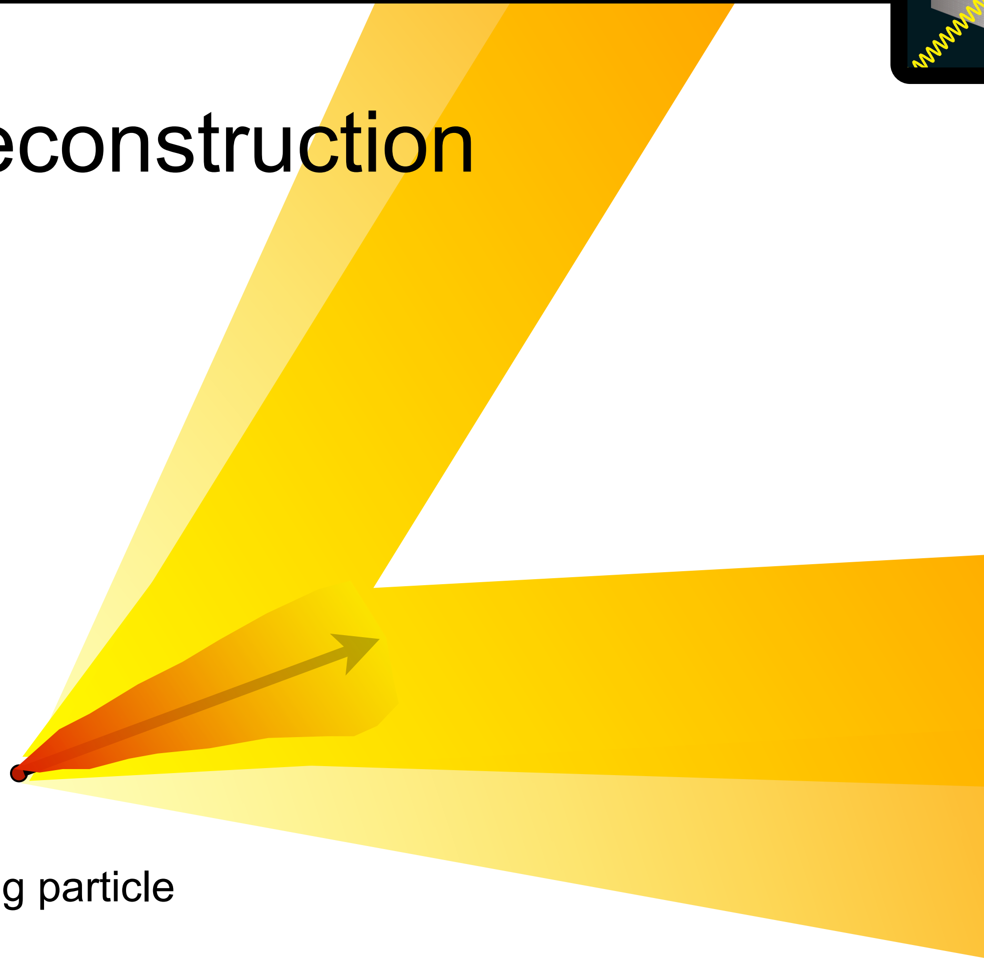
1-D Track → richer structure



multi-scattered muon

Track Reconstruction

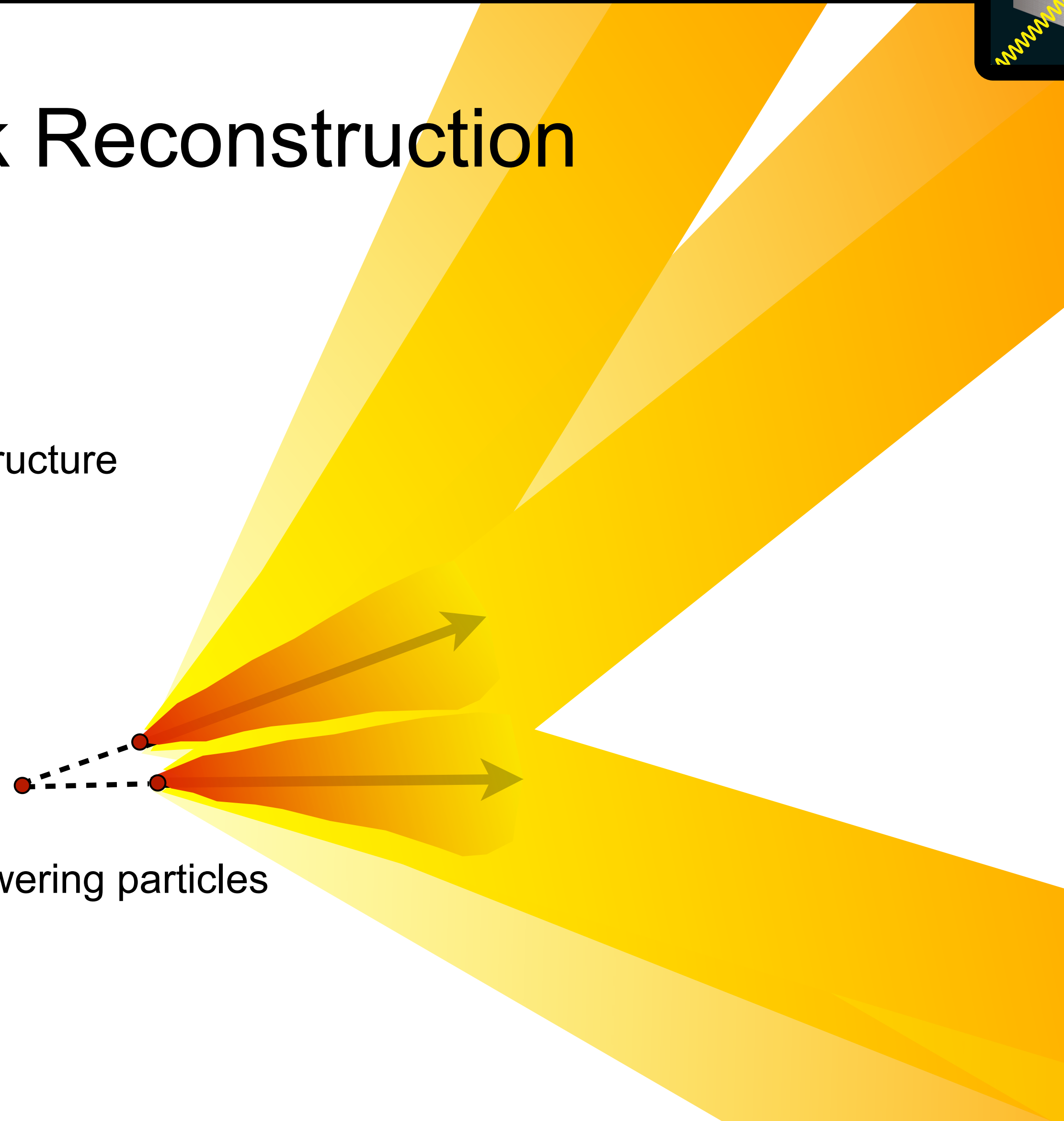
1-D Track → richer structure



a showering particle

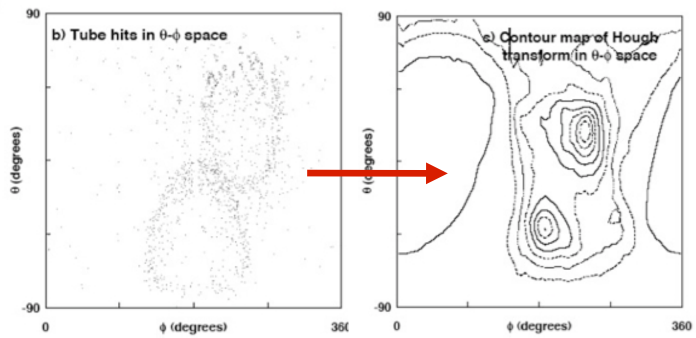
Track Reconstruction

1-D Track → richer structure

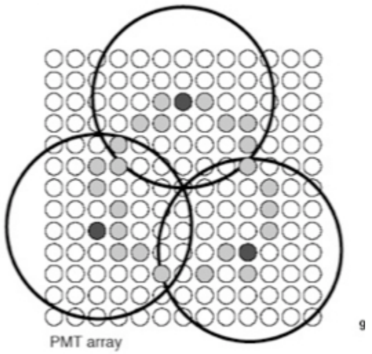


two showering particles

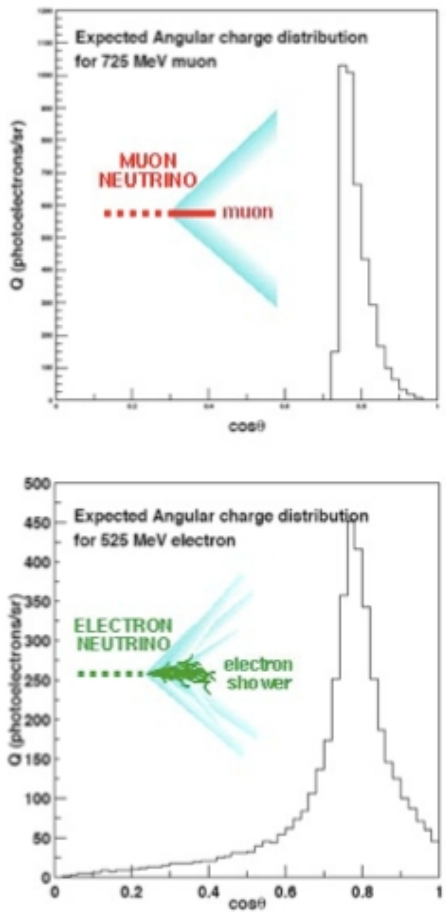
Ring Counting



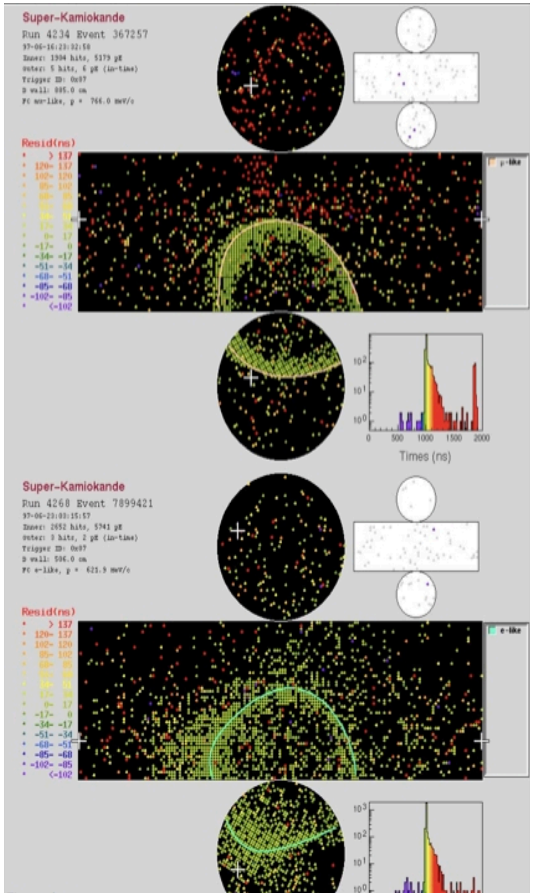
Hough transformation converts ring counting into peak counting



Particle ID



Figures from M. Earl's PhD Thesis



Figures from http://hep.bu.edu/~superk/atmnu/