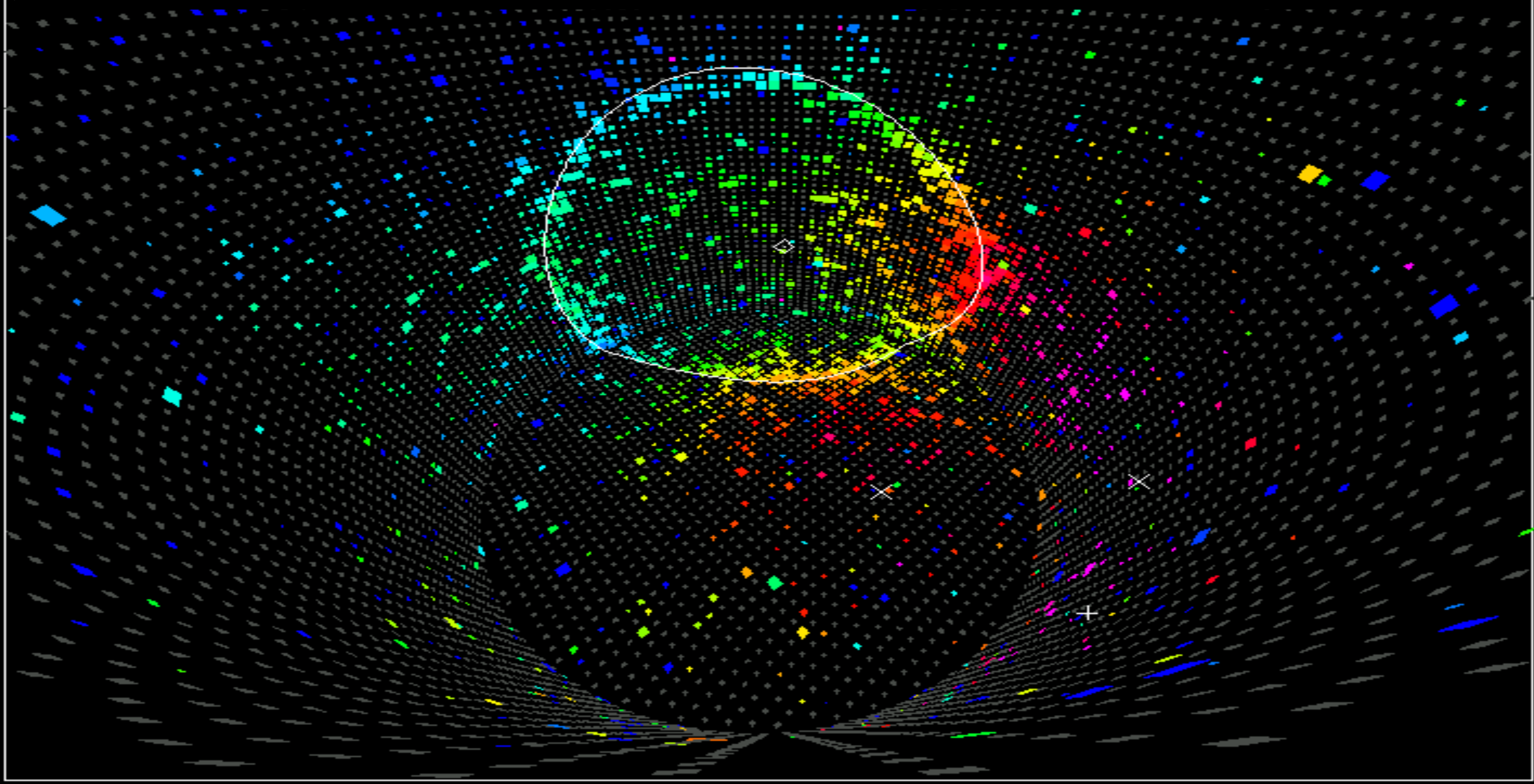
Big, Fast, and Cheap:

Precision Timing in the Next Generation of Cherenkov Detectors

RICH 2010

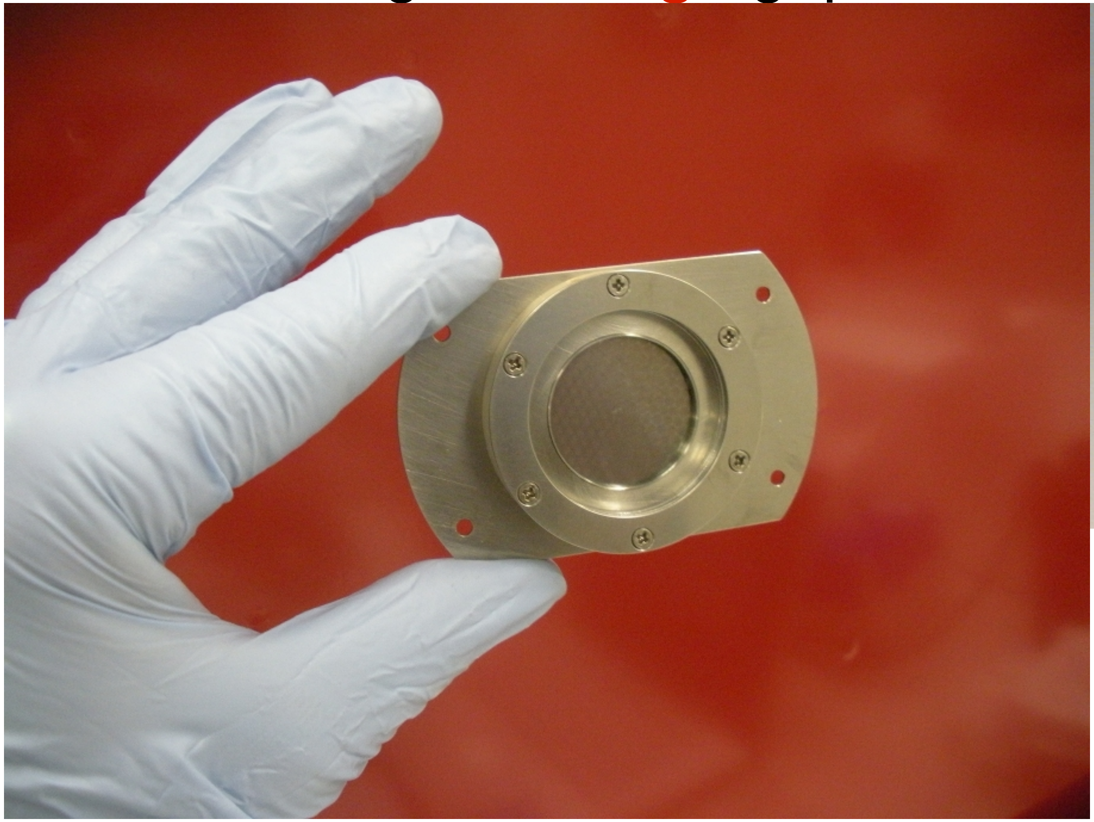


Matthew Wetstein - Enrico Fermi Institute, University of Chicago

HEP Division, Argonne National Lab

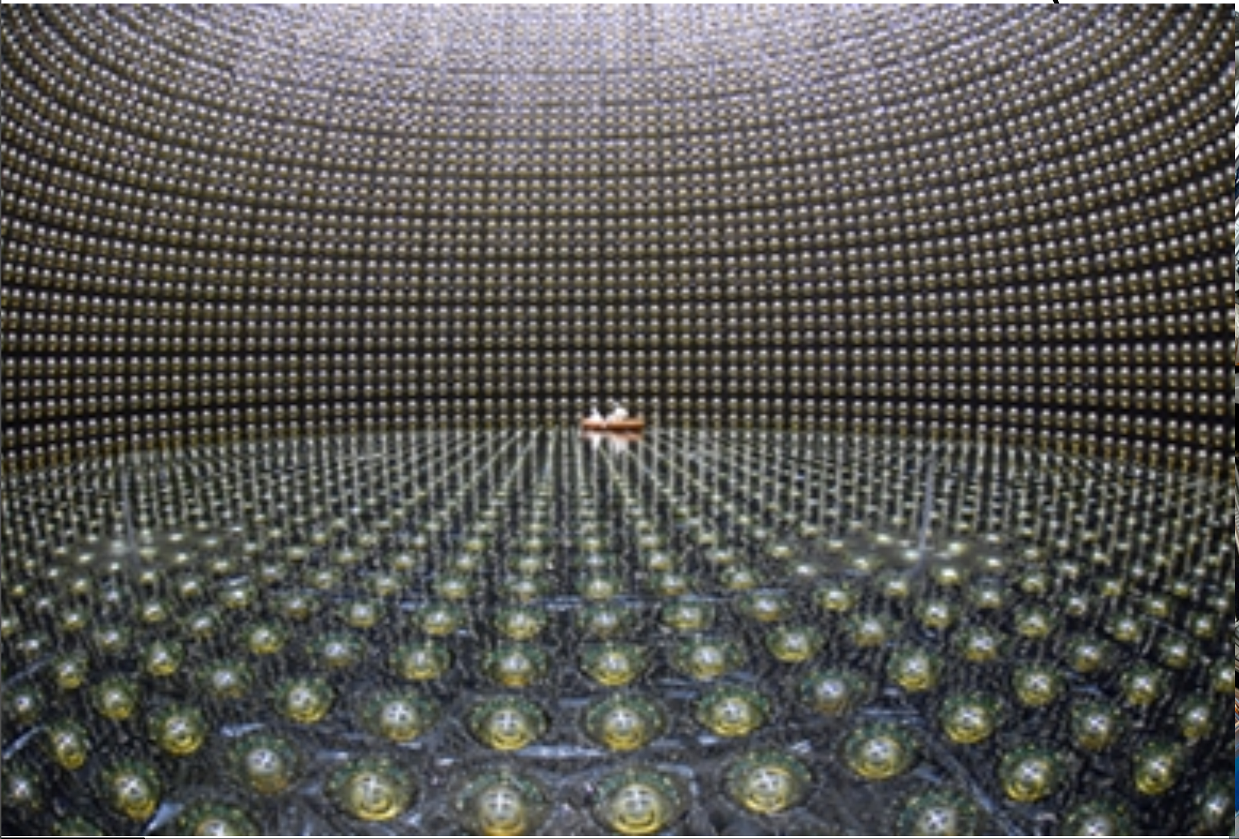
The Challenge in Designing Detectors for HEP Experiments:

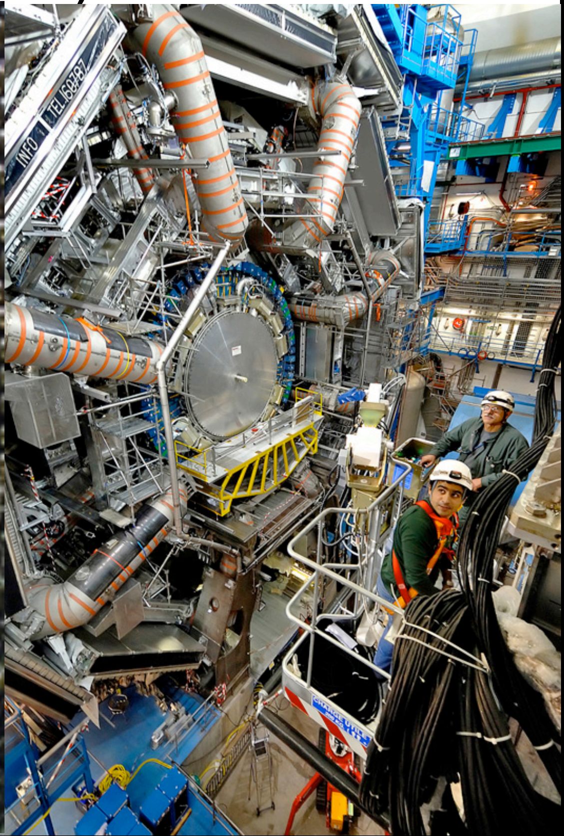
Need to bridge the ***huge*** gap between what is possible



The Challenge in Designing Detectors for HEP Experiments:

…and what is feasible (scalable)





The Good News is:

Sometimes it's worth the effort…

Georges Charpak

- If successful, we stand to greatly improve the quality of physics we can study in a given experiment.
- Because we are also forced to really understand that science behind the device, we end up
    - Making the device better
    - Enabling new possible spinoffs for other scientific or commercial applications
- In the R&D process, we are forced to imagine entirely new analysis techniques and new physics capabilities.

The LAPPD Collaboration

Large Area Picsecond Photodetector Collaboration

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Space Sciences Laboratory, University of California, Berkeley, CA

Dimitri Routkevitch

Synkera Technologies Inc., Longmont, CO

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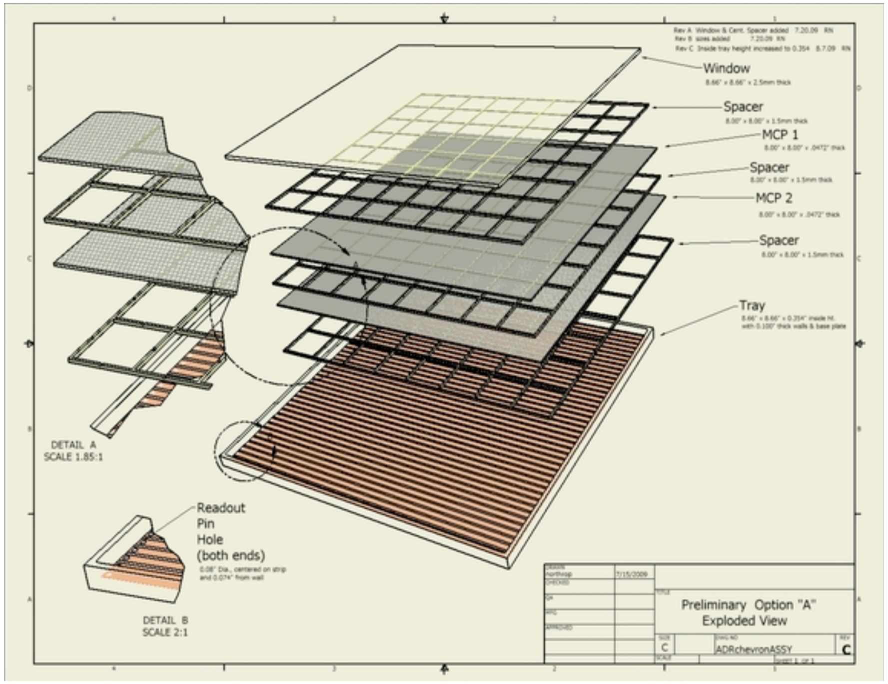
- Newly funded (end of August '09) by DOE and NSF
- 4 National Labs
- 5 Divisions at Argonne
- 3 small companies
- 5 Universities

LAPPD Collaboration:

Pushing the Limits of the Timing Frontier

Microchannel Plates are an existing photo-multiplier technology known for:

- Picosecond-level time resolution
- Micron-level spatial resolution
- Excellent photon-counting capabilities
- Being expensive



What if we could exploit advances in material science and electronics to develop new methods for fabricating:

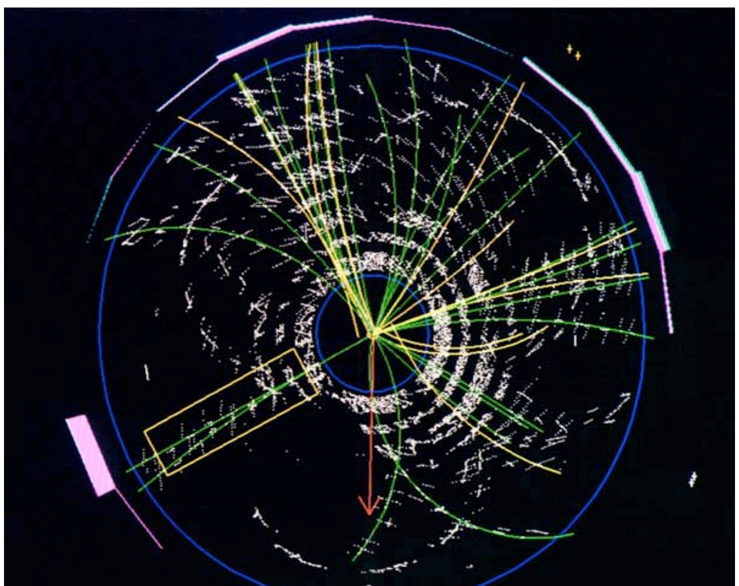
- Large area (8”x8”), flat panel MCP-PMTs **(BIG)**
- Preserving that excellent time resolution **(FAST)**
- At competitive costs for particle physics scales **(CHEAP)**

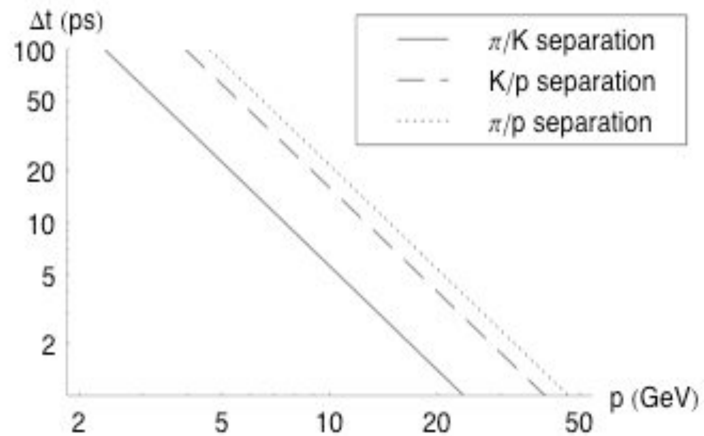
How could that change the next-generation particle Detectors?

Possible Collider Applications

Using TOF in collider experiments for better

- photon vertexing
- multiple-interaction separation
- flavor identification



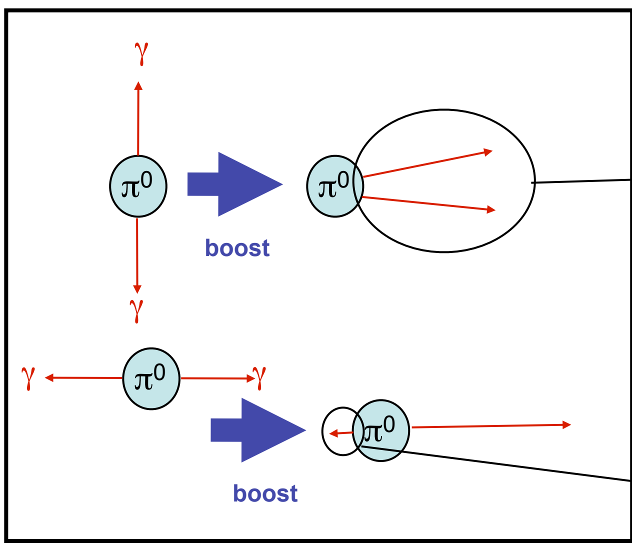


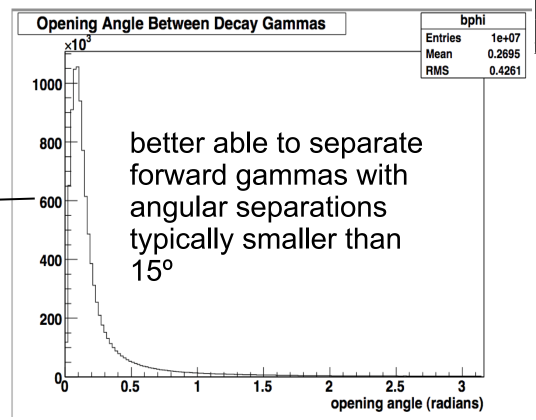
Difference in time it takes two particles with the same momentum to travel 1.5m

Possible Neutrino Applications

As a successor to photomultiplier tubes in water-Cherenkov based neutrino experiments

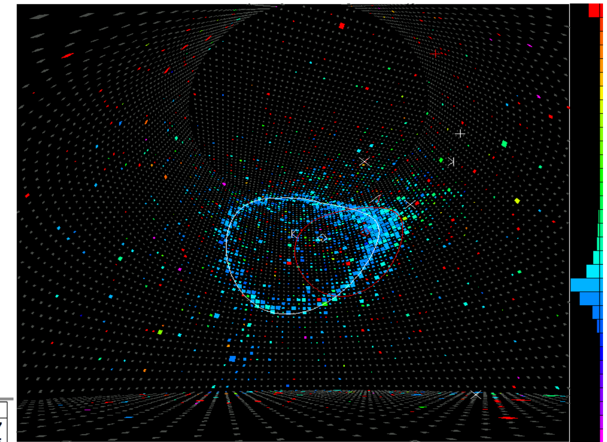
- Provide better coverage
- Use timing information to improve tracking and vertex separation
- suppress largest reducible background - neutral pion fakes an electron





better able to separate forward gammas with angular separations typically smaller than 15°

improved sensitivity to low momentum gammas with better coverage

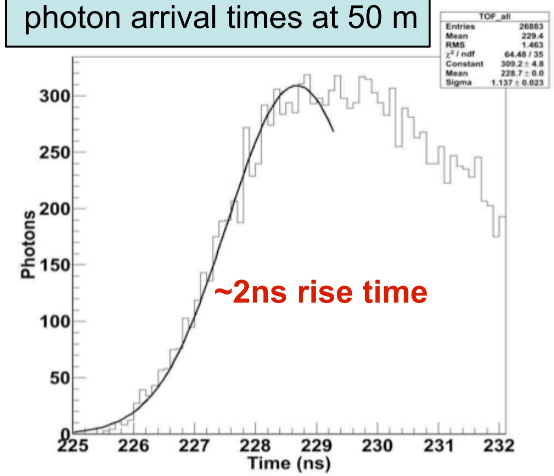


Typical vertex resolutions in Super K O(10) cm

100 psec TOF for light in water corresponds to roughly 3 cm

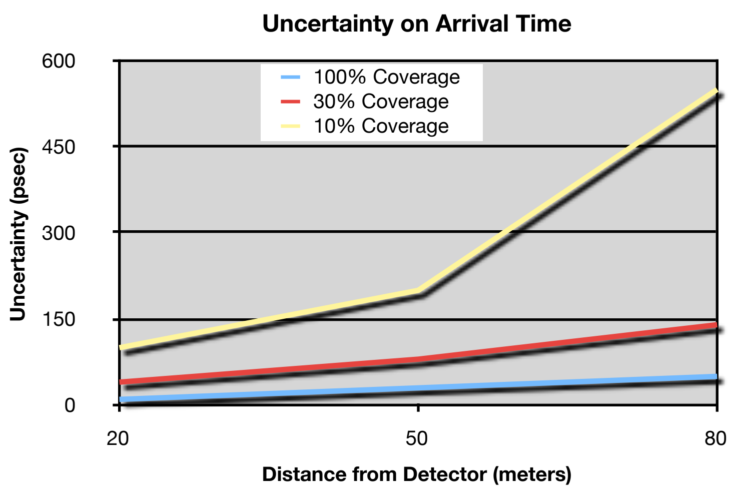
Possible Neutrino Applications

photon arrival times at 50 m



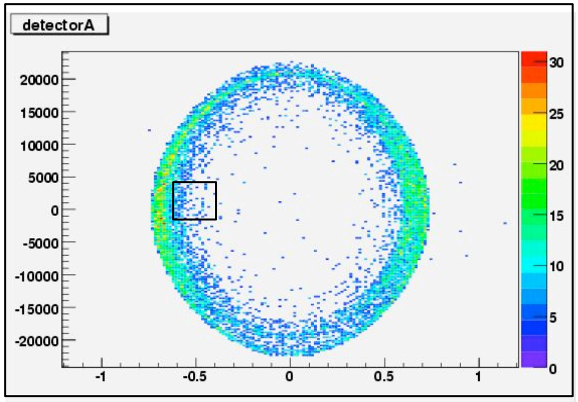
J. Felde, B. Svoboda: UC-Davis

- Chromatic dispersion/scattering/absorption present a problem
- We probably won't need the same time resolution as collider applications
- Still, even at 50 meters, we can expect to do much better than 2 nanosecond resolution in water
- Typical PMT timing resolutions > 1ns



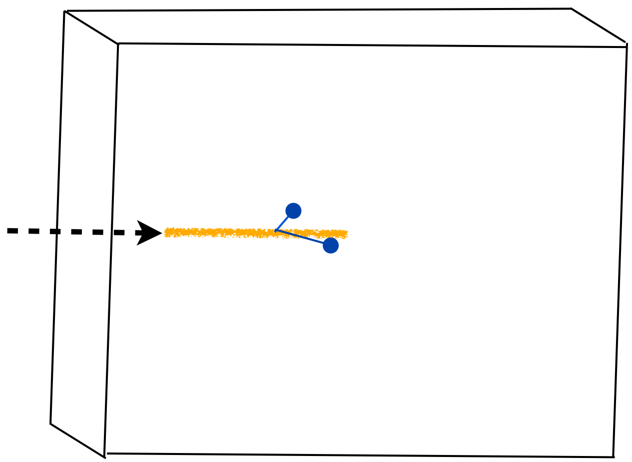
Resolution losses over large distances in water can be recovered with more coverage (photon statistics)

Possible Neutrino Applications



Finer spatial resolution =
Ability to resolve $dN_\gamma/d\Omega$ *within* a single module

- better particle ID (ability to resolve the sharpness of ring-edge)
- better able to reconstruct events close to the wall
- Could imagine new tank geometries (building walls closer together in direction orthogonal to beam?)

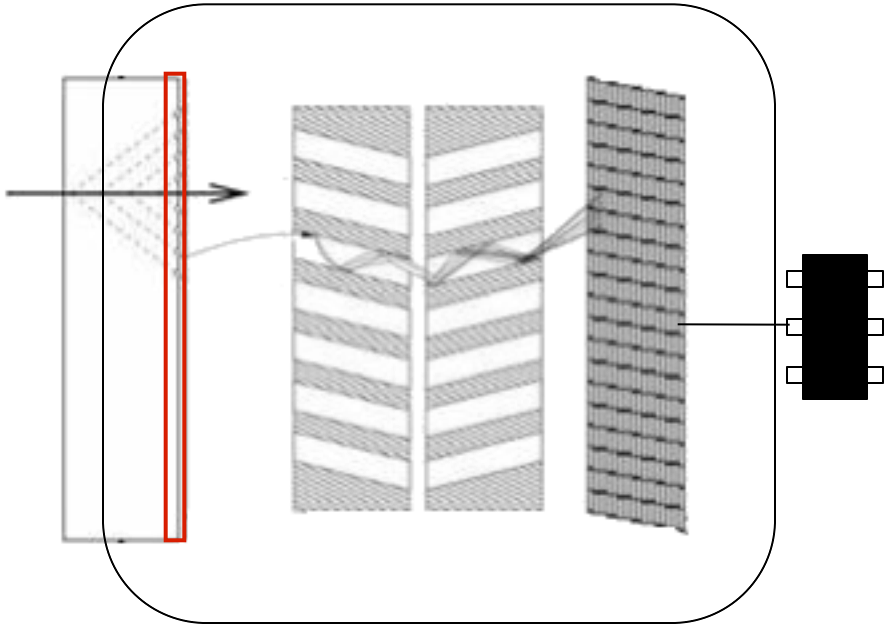


Other Possible Advantages:

- Better magnetic susceptibility (applied magnetic field?)
- Further cost reductions by
  - requiring less bulk mass for the same physics
  - cheaper excavation costs

Will require detailed simulation

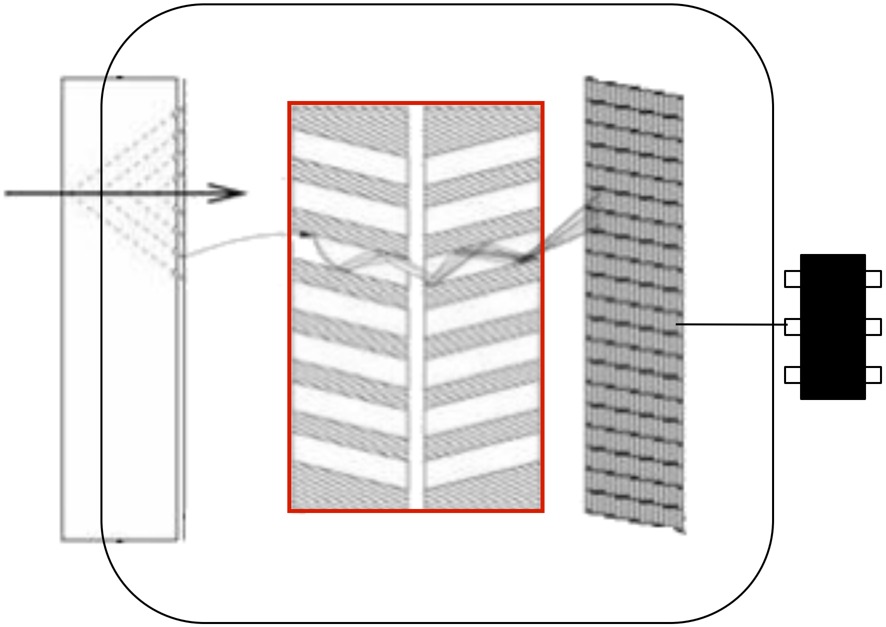
Anatomy of an MCP-PMT



1. Photocathode
2. Multichannel Plates
3. Anode (stripline) structure
4. Vacuum Assembly
5. Front-End Electronics

Conversion of photons to electrons.

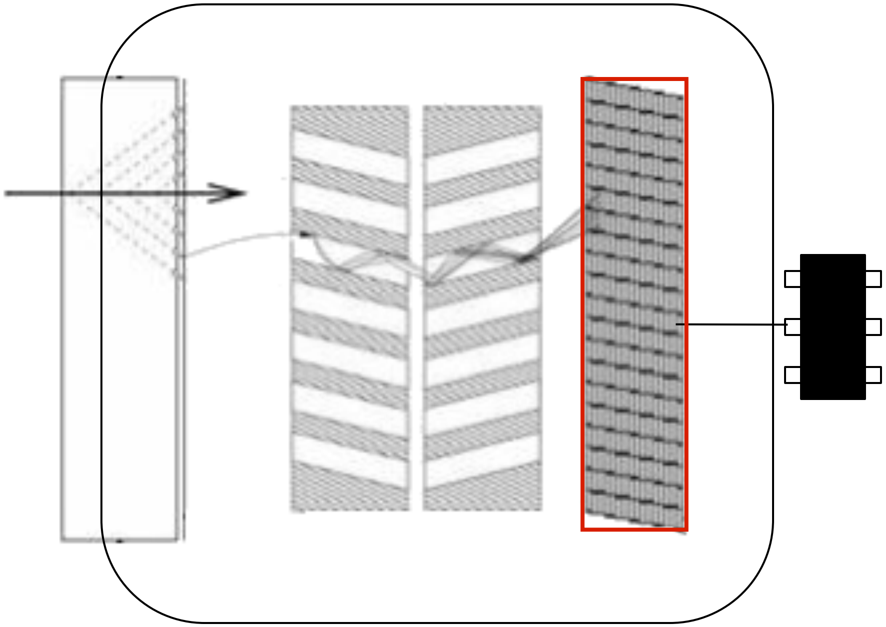
Anatomy of an MCP-PMT



1. Photocathode
2. Microchannel Plates
3. Anode (stripline) structure
4. Vacuum Assembly
5. Front-End Electronics

Amplification of signal. Consists of two plates with tiny pores, held at high potential difference. Initial electron collides with pore-walls producing an avalanche of secondary electrons. Key to our effort.

Anatomy of an MCP-PMT



1. Photocathode
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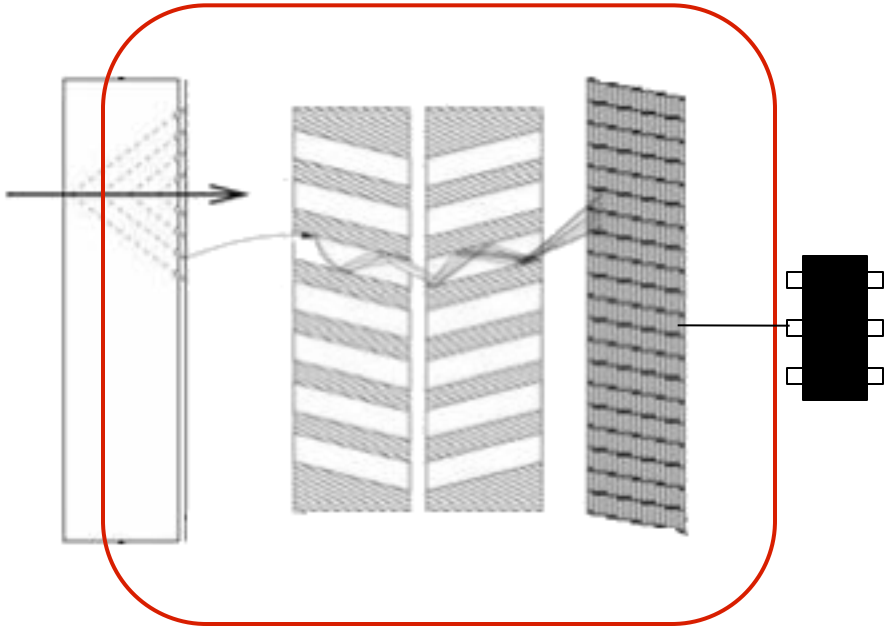
Charge collection. Brings signal out of vacuum.

Anatomy of an MCP-PMT



1. Photocathode
2. Microchannel Plates
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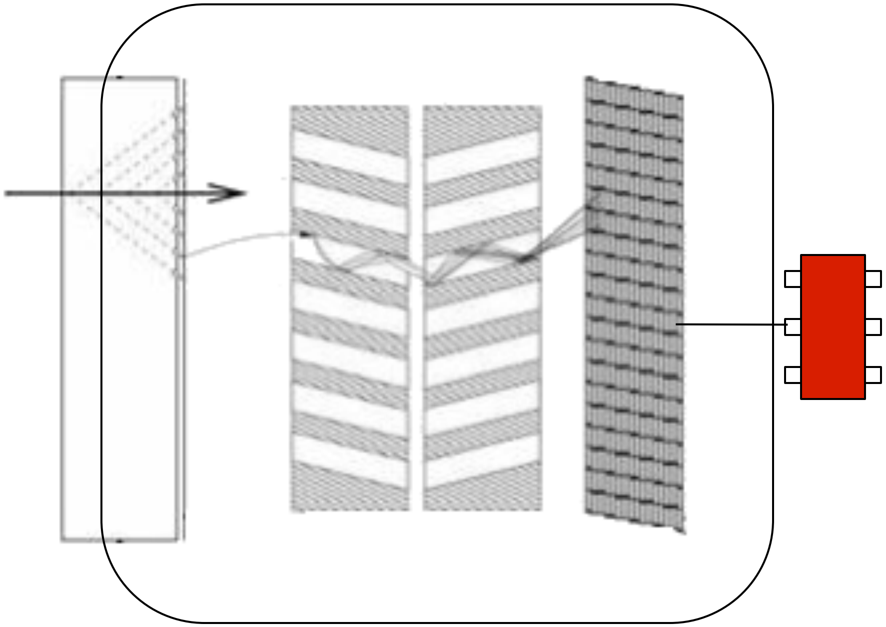
5. Front-End Electronics

Maintenance of vacuum. Provides mechanical structure and stability to the complete device.

Anatomy of an MCP-PMT



1. Photocathode
2. Microchannel Plates
3. Anode (stripline) structure
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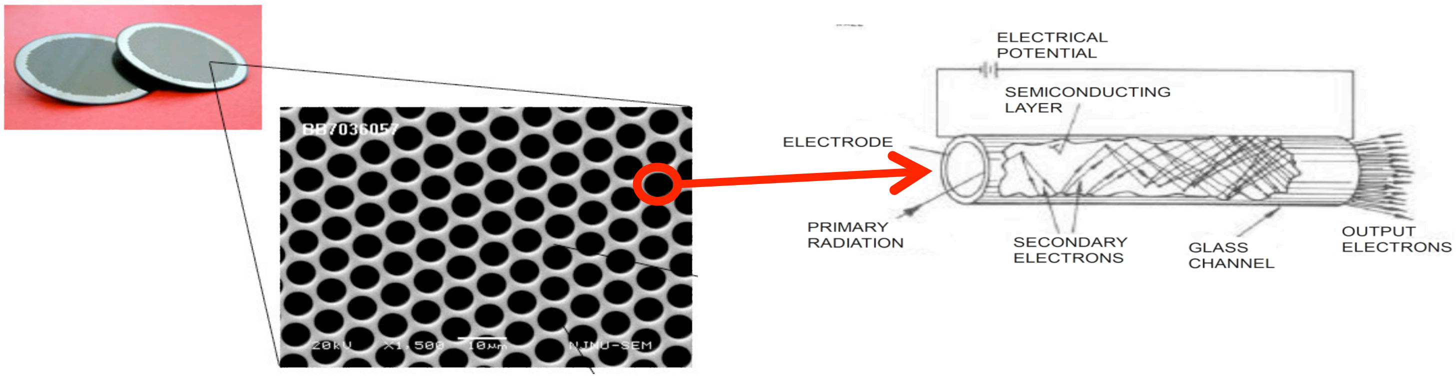
Acquisition and digitization of the signal.

Channel Plate Fabrication



Conventional MCP Fabrication

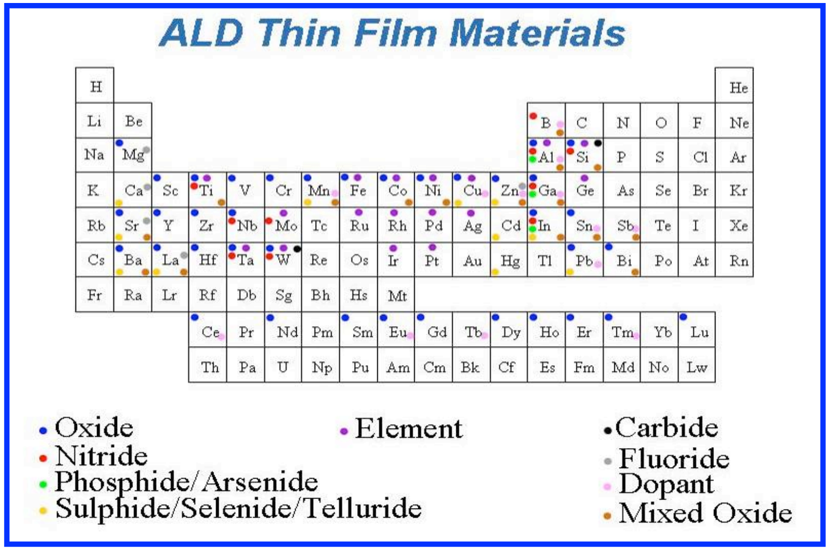
- Pore structure formed by drawing and slicing lead-glass fiber bundles. The glass also serves as the resistive material
- Chemical etching and heating in hydrogen to improve secondary emissive properties.
- Expensive, requires long conditioning, and uses the same material for geometric, resistive, and secondary emissive properties. (Problems with thermal run-away).

What we want to do differently

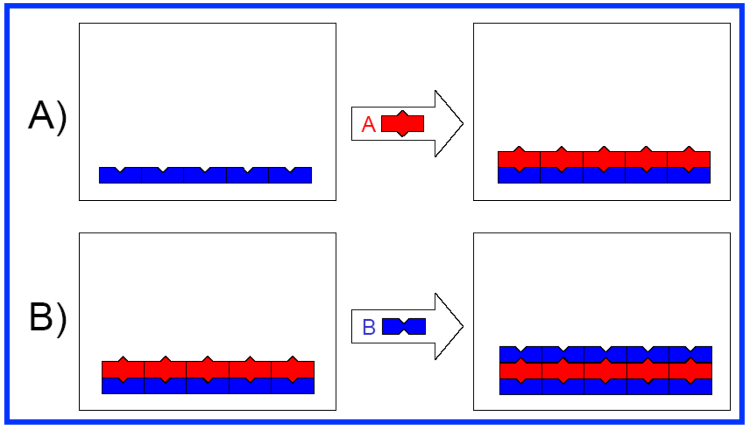
- Use Atomic Layer Deposition (ALD), a cheap industrial batch method, to deposit materials in bulk, on low-cost substrates with the appropriate pore structure.
- Could mean significantly cheaper fabrication, require less conditioning, and enable independent control over geometry, resistivity, and secondary emission properties.

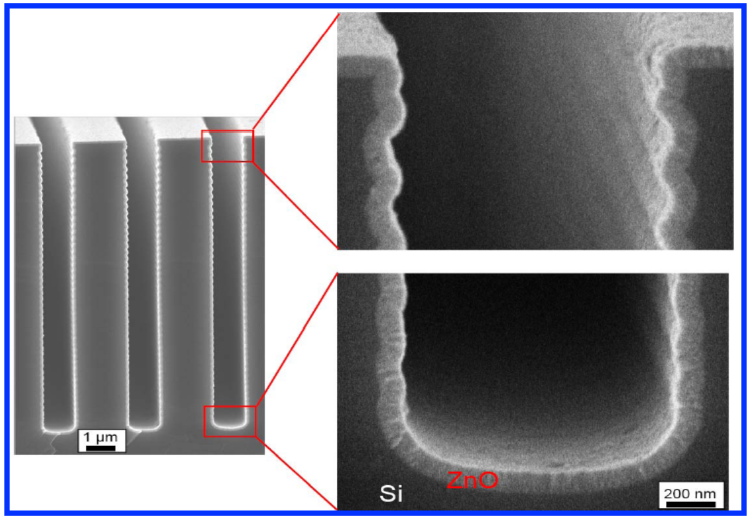
Atomic Layer Deposition

- A conformal, self-limiting process.
- Allows atomic level thickness control.
- Applicable for a large variety of materials.



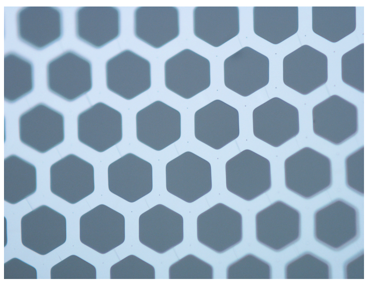
J. Elam, A. Mane, Q. Peng, T. Prolier (ANL:ESD/HEP), N. Sullivan (Arradiance), A. Tremsin (Arradiance, SSL)





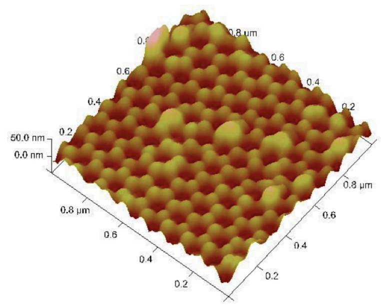
Channel Plate Fabrication w/ ALD

1. Start with a porous, insulating substrate that has appropriate channel structure.



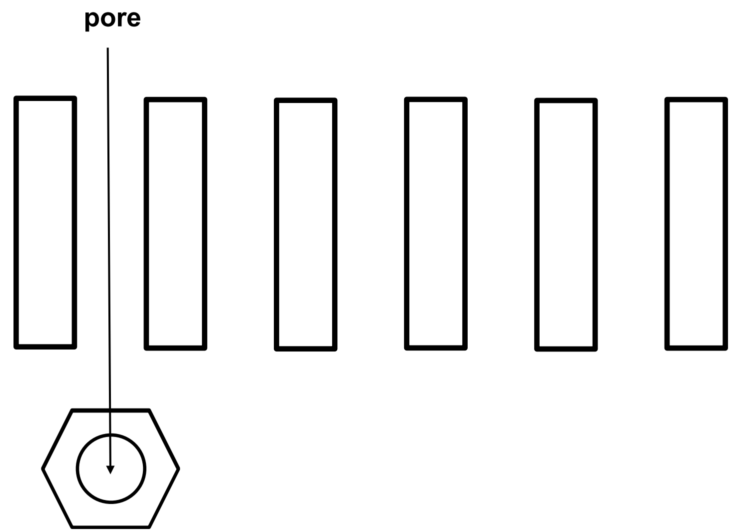
borosilicate glass filters (default)

Incom



Anodic Aluminum Oxide (AAO)

H. Wang (ANL),
S. W. Lee (ANL),
D. Routkevitch (Synkera)



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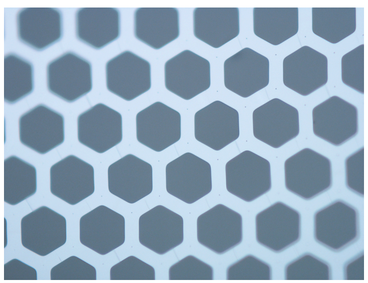
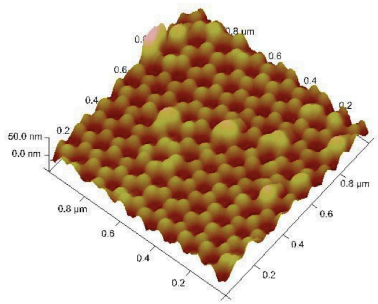


borosilicate glass filters (default)



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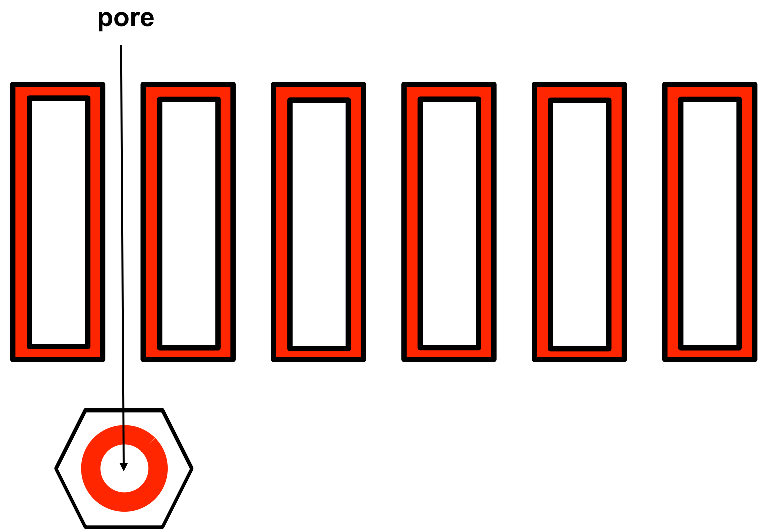
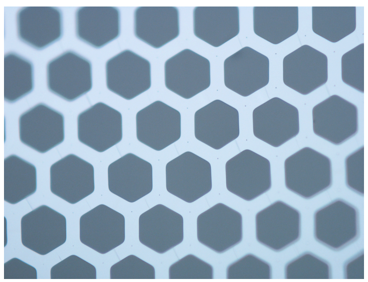


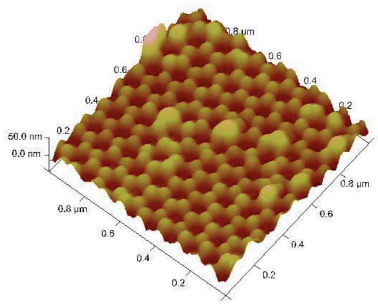
2. Apply a resistive coating (ALD)

Channel Plate Fabrication w/ ALD

1. Start with a porous, insulating substrate that has appropriate channel structure.



borosilicate glass filters (default)



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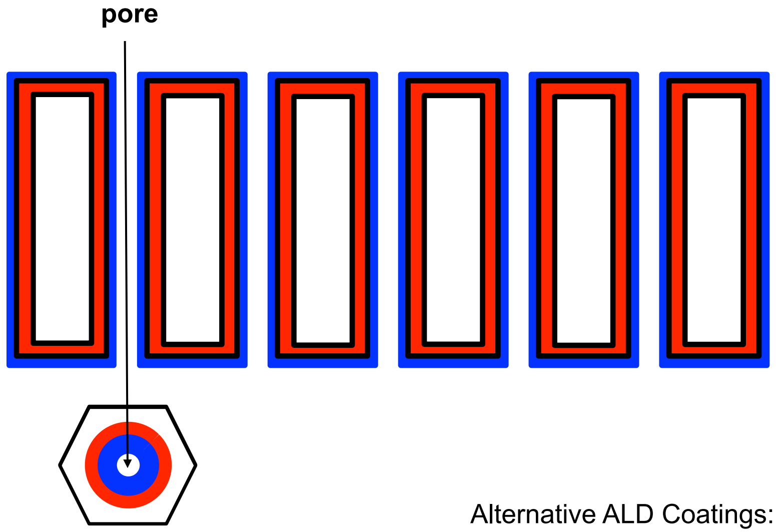
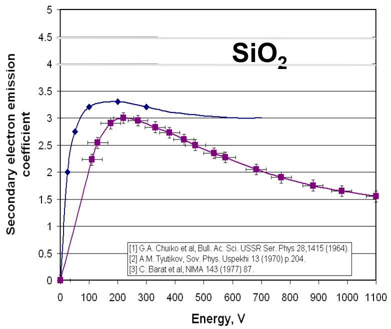
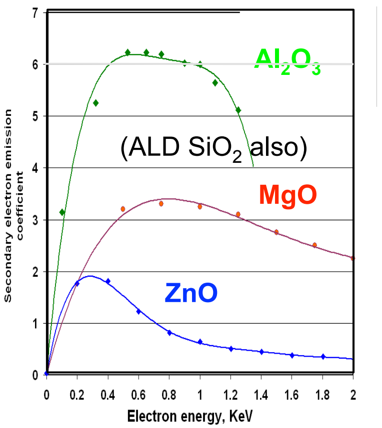


2. Apply a resistive coating (ALD)
3. Apply an emissive coating (ALD)

Conventional MCP's:

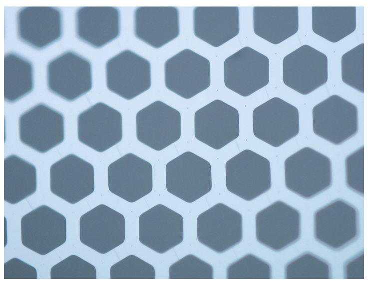


Alternative ALD Coatings:

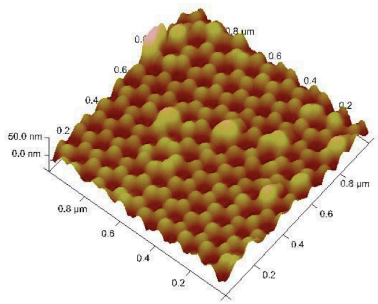


Channel Plate Fabrication w/ ALD

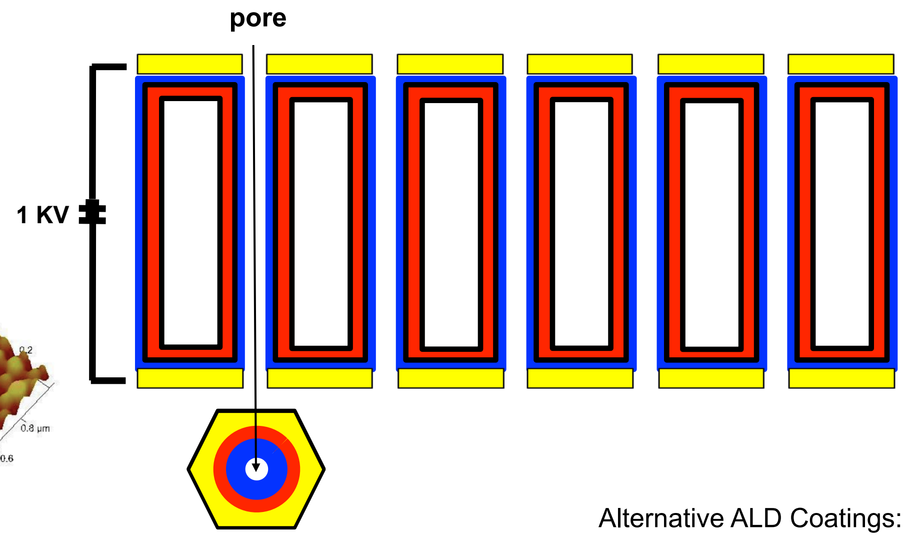
1. Start with a porous, insulating substrate that has appropriate channel structure.



borosilicate glass filters (default)

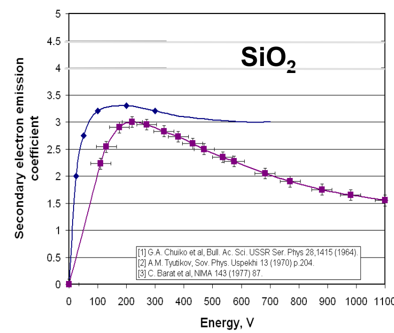


Anodic Aluminum Oxide (AAO)



2. Apply a resistive coating (ALD)
3. Apply an emissive coating (ALD)
4. Apply a conductive coating to the top and bottom (thermal evaporation or sputtering)

Conventional MCP's:



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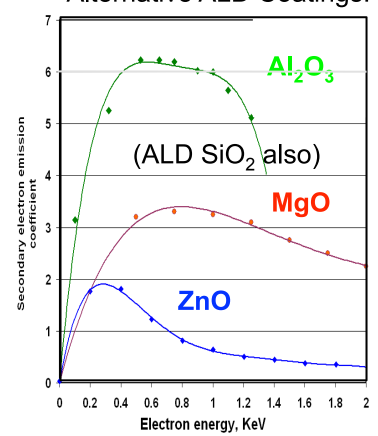
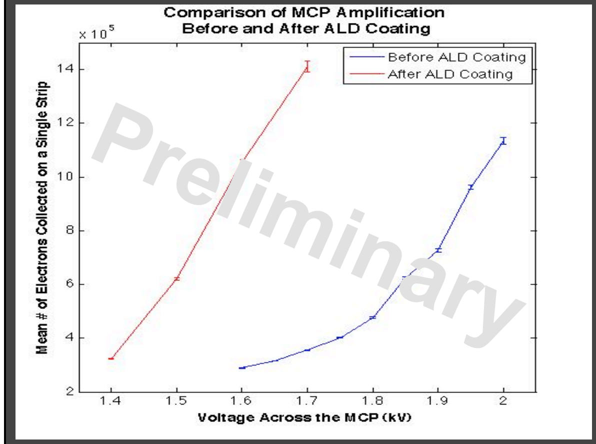
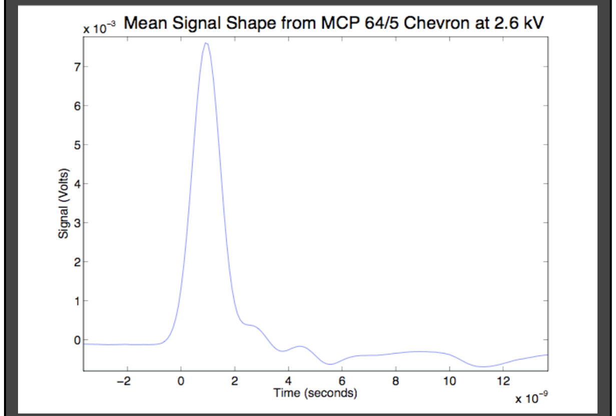


Early Achievements





B. Adams, M. Chollet (ANL/APS), M. Wetstein (UC, ANL/HEP)

Demonstrated enhanced amplification in commercial microchannel plates, coated with ALD layer.

- After characterizing the Photonis MCP, we coat the plates with 10 nm Al_2O_3.
- The “after-ALD” measurements have been taken without scrubbing.
- These measurements are ongoing.

Demonstrated process of MCP fabrication by atomic layer deposition on a 33mm glass filter.

- Able to control resistance of the plates for several different chemistries

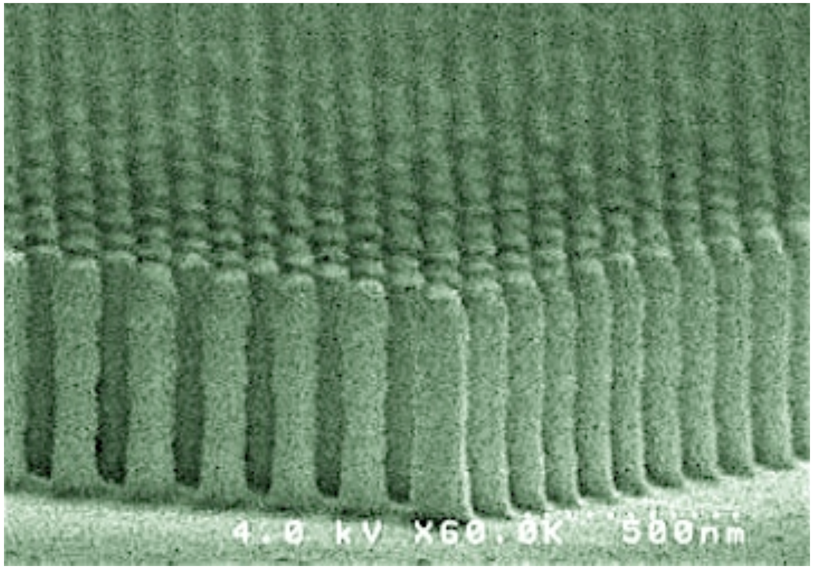
Demonstrated >10^5 amplification on ALD-functionalized glass plates.

Photocathode Fabrication

Two parallel efforts:

- Work at UC Berkeley (SSL) to scale conventional multi-alkali photocathodes to large-area, flat geometries.

- Work at Argonne to develop a fabrication and testing chamber
  - to complement Berkeley's multi-alkali work
  - further the fundamental understanding of photocathode materials
  - look into novel photocathode designs (advanced materials, nano-structures...)



K. Broughton, E. Indacochea (UIC), X. Li, R. Dowdy (UIUC), B. Adams, M. Chollet, Z. Insepov, S. Jokela, A. Mane, Q. Peng, T. Prolier, M. Wetstein, I. Veryovkin, Z. Yusof, A. Zinovov (ANL), O. Siegmund, J. McPhate, S. Jelensky, A. S. Tremsin, J. V. Vllerga (Berkeley, SSL), V. Ivonov (Muons Inc)

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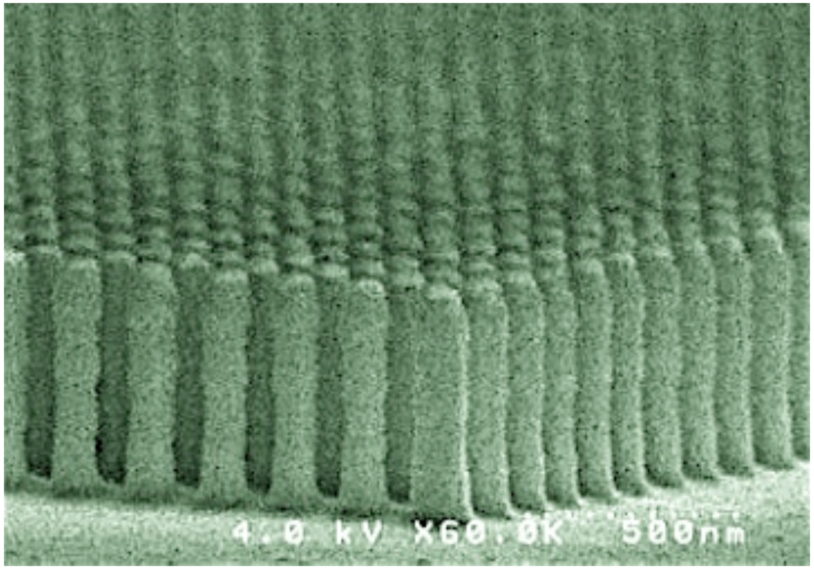
Possible long-term photocathode center at ANL



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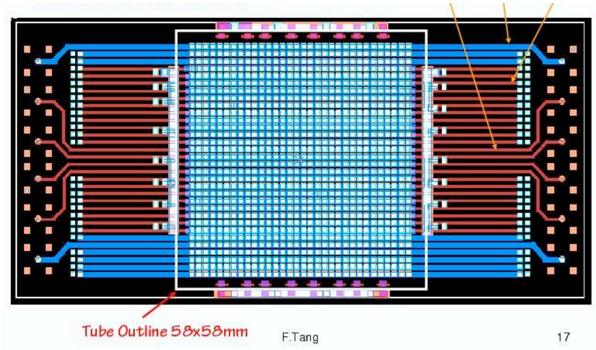
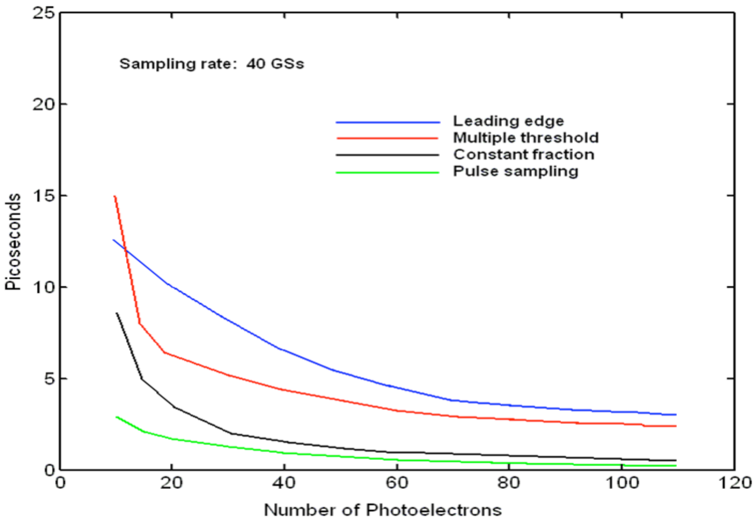
Front End Electronics

- Resolution depends on # photoelectrons, analog bandwidth, and signal-to-noise.
- Transmission Line: readout both ends → position and time
- Cover large areas with much reduced channel count.
- Simulations indicate that these transmission lines could be scalable to large detectors without severe degradation of resolution.

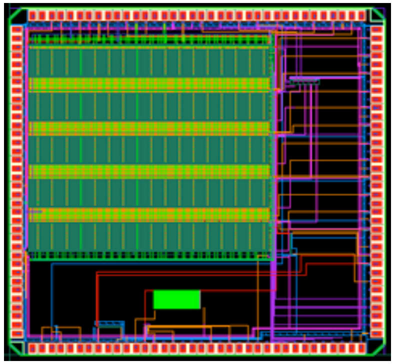


Differential time resolution between two ends of a strip line



Wave-form sampling is best, and can be implemented in low-power widely available CMOS processes at low cost per channel.

Currently testing first prototype chip. Next iteration soon to follow.

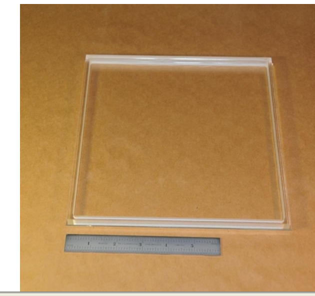


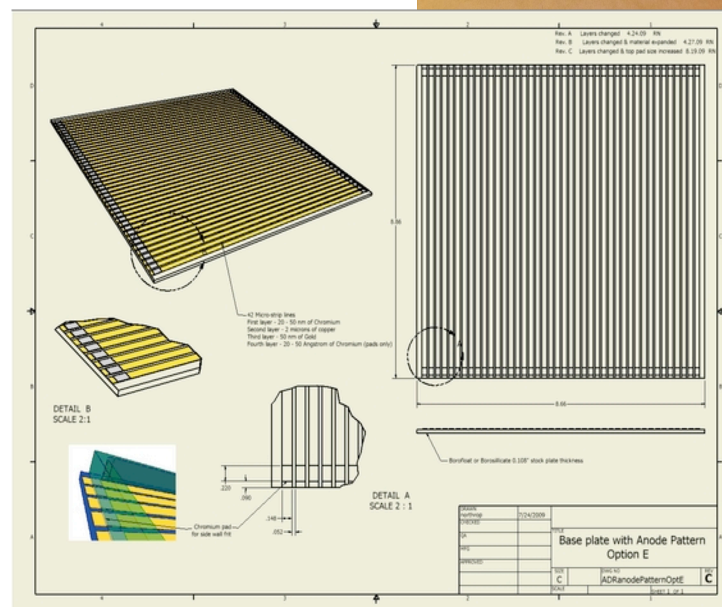
J-F. Genat, G. Varner, M. Bogdan, M. Baumer, M. Cooney, Z. Dai, H. Grabas, M. Heintz, J. Kennedy, S. Meehan, K. Nishimura, E. Oberla, L.Ruckman, F. Tang

Device Assembly

Device construction must maintain:

- a vacuum-tight seal
- mechanical integrity under high pressure and stress
- high bandwidth of the read-outs through vacuum seal
- low cost design goals





Pursuing two main directions:

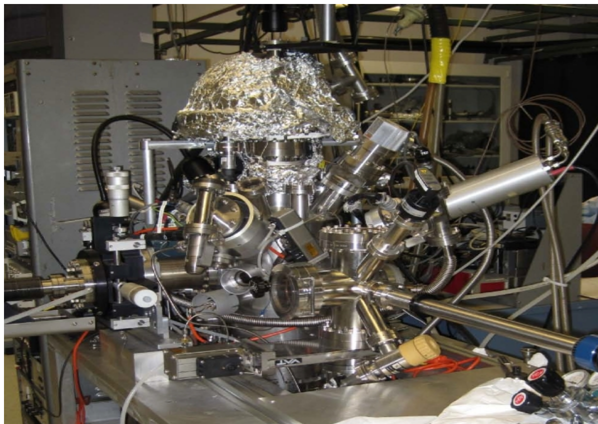
- Ceramic assemblies, similar to those used in conventional MCP designs (Berkeley, SSL)
- Flat-panel sealed glass technologies (ANL, Chicago)

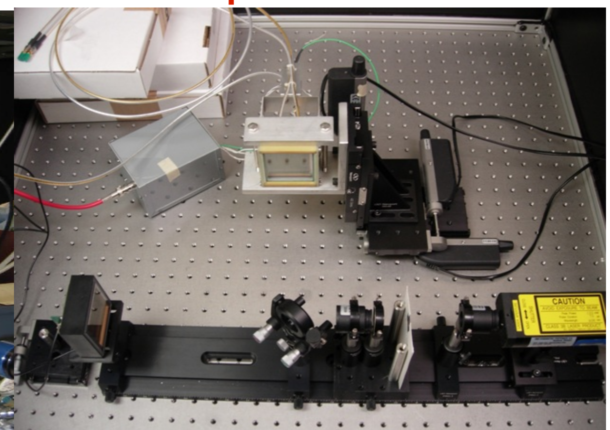
R. Northrop, H. Frisch, S. Asare (UC), M. Minot (Minotech Eng.), G. Sellberg (Fermilab), J. McPhate, O. Siegmund (SSL), A. Tremsin (SSL/Arradiance), R. Barwhani (UCB) , D. Walters (NE/ANL), R. Wagner (HEP/ANL), J. Greggor (ANL)

Testing and Characterization

Microscopic/Materials-Level | **Macroscopic/Device-Level**

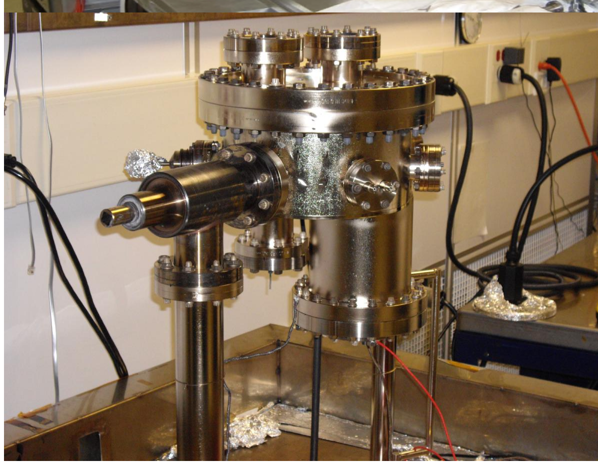
Material Science Division, ANL

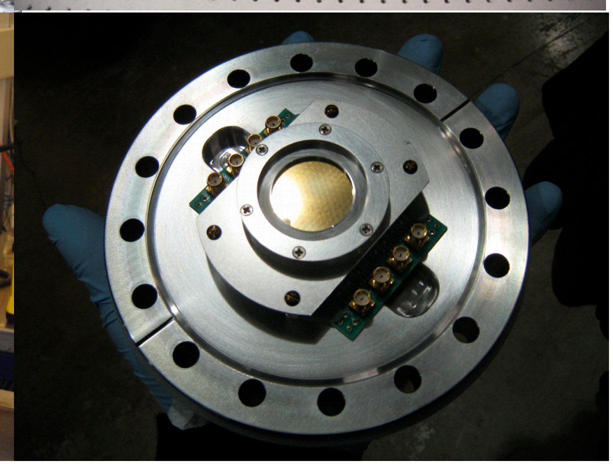




HEP laser test stand

Berkeley SSL





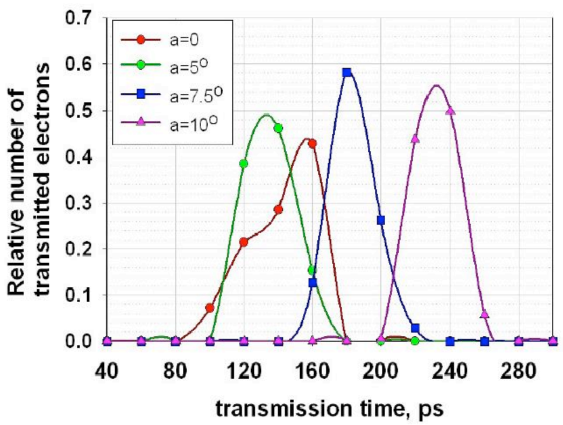
Advanced Photon Source, ANL

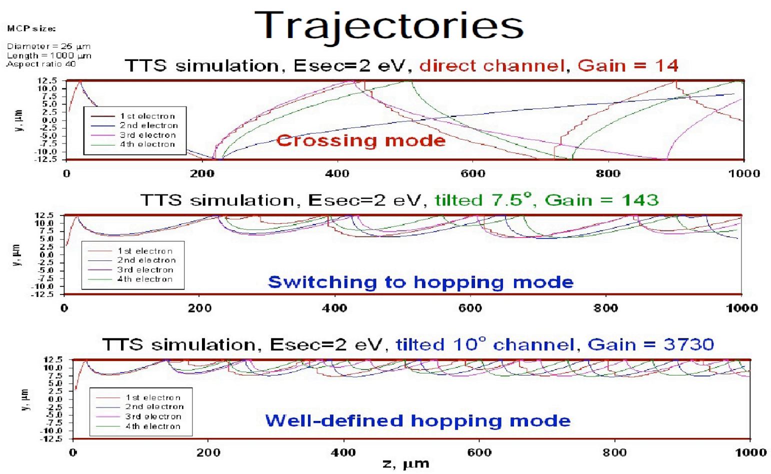
Component-Level | **System Integration-Level**

Simulation

- Working to develop a first-principles models to predict MCP behavior, at device-level, based on microscopic parameters.
- Will use these models to understand and optimize our MCP designs.

Transit Time Spread (TTS)





Z. Yusov, S. Antipov, Z. Insepov (ANL),

V. Ivanov (Muons,Inc), A. Tremsin (SSL/Arradiance), N. Sullivan (Arradiance)

Conclusions

- Funding arrived in August and we're on a 3 year time table. Lots of work ahead. Preliminary achievements are encouraging.
- May make photo-detection significantly cheaper.
  - Reduce bottom-line manufacturing costs.
  - Economic impacts of new vendor/alternative in the market.
- If successful, this project presents potential opportunities for future Cherenkov Detectors.
  - New set of optimizations for analysis using better spatial and timing resolution.
  - Variations in overall detector design.
  - Direct analysis-driven feedback to guide photodetector design.
  - Will require detailed simulations.

Thanks

- The organizers of RICH 2010
- LAPPD collaboration for their help and hard work.
- Ossy Siegmund, Jason McPhate, Mayly Sanchez, Henry Frisch, Bob Svoboda for their feedback and guidance.

Backup Slides

How Much Would These Cost?

Too soon to tell…

But, keeping cost down is a major objective:

- Made from inexpensive materials.
- Use industrial batch processes.
- Inexpensive electronics, trying to reduce number of necessary readout channels.

In addition to the bottom-line cost of the detectors are secondary effects.

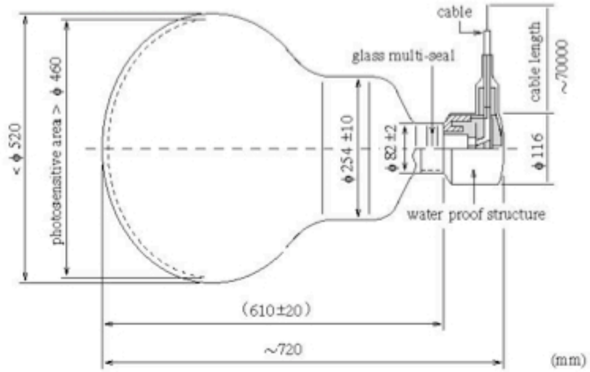
- Market impact.
- Possible savings on civil construction. Detector can be built closer to walls.

Cost/unit area is not the only relevant factor. Physics gains could be worth a little more.

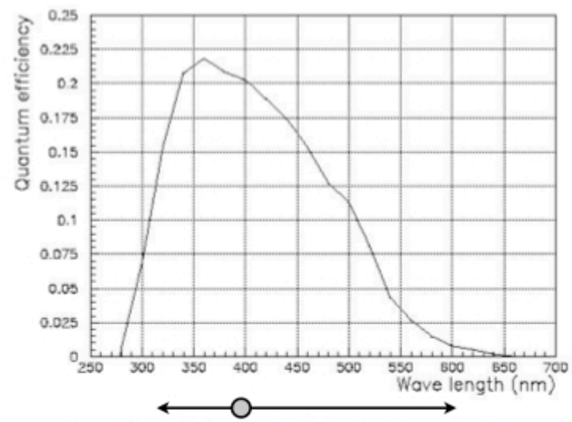
Photomultiplier Tubes

Phototubes:

- ~2-3 nsec time resolution
- Spatial resolution cannot exceed tube radius
- Total coverage offered is typically less than 40%
- Typical photocathode efficiency ~25%



100 ns transit time, 2.2 ns time resolution

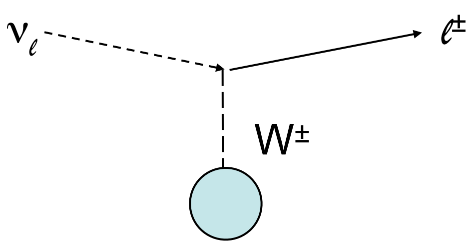


wavelength of Cherenkov photons in water

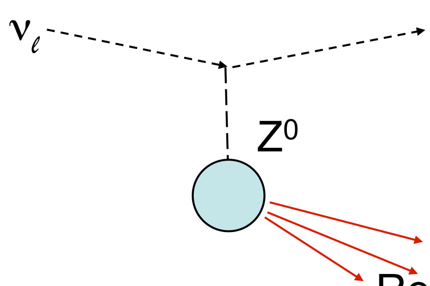
Water Cherenkov Basics

Main Neutrino Interactions:

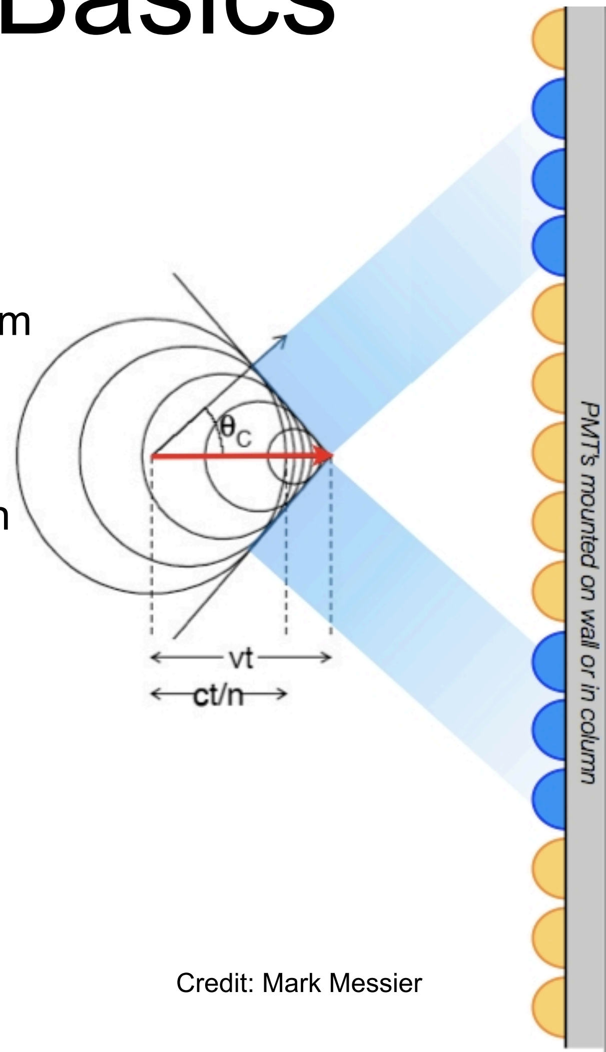
Charged Current (signal)



Neutral Current (bkgd)

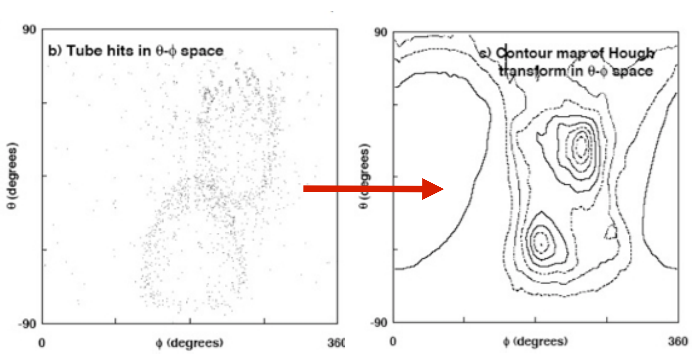


- An shockwave of optical light is produced when a charged particle travels through a dielectric medium faster than the speed of light in that medium: c/n
- This light propagates at an angle $\theta_C = 1/n\beta$ with respect to the direction of the charged particle…
- Using photodetectors, we can measure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

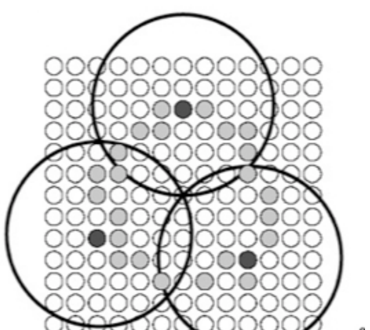


Credit: Mark Messier

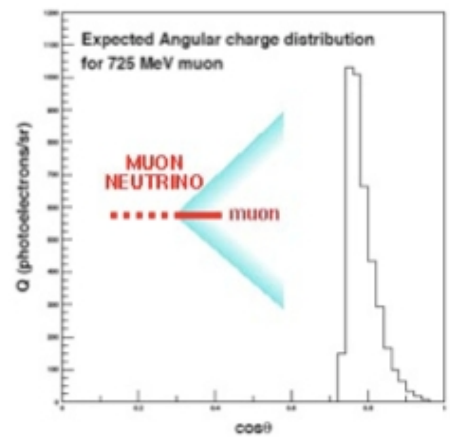
Ring Counting

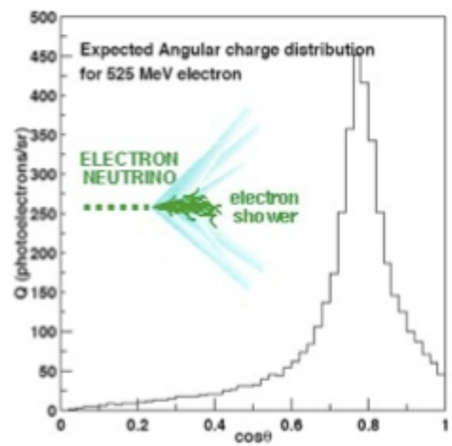


Hough transformation converts ring counting into peak counting

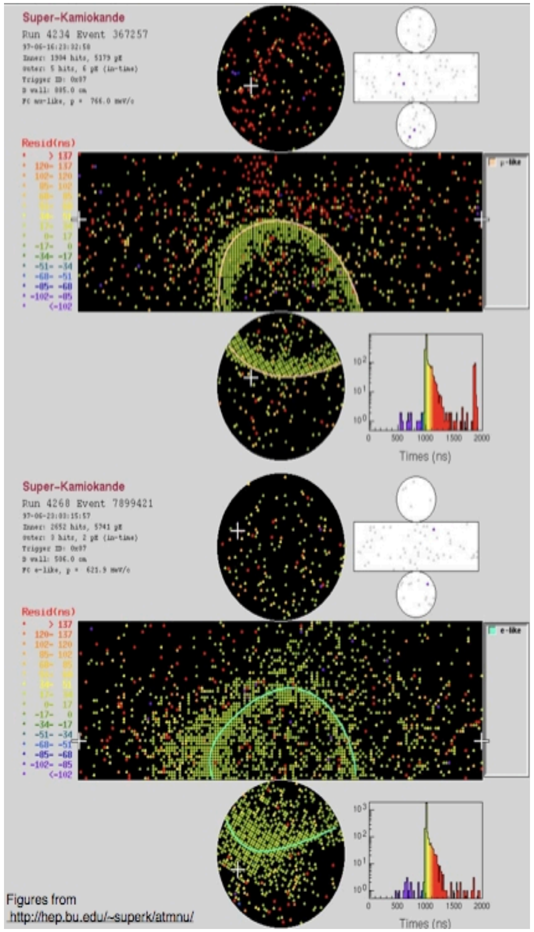


Particle ID





Figures from M. Earl's PhD Thesis



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

Tracking in Water Cherenkov

1-D Track → Multiple Tracks/ Showers

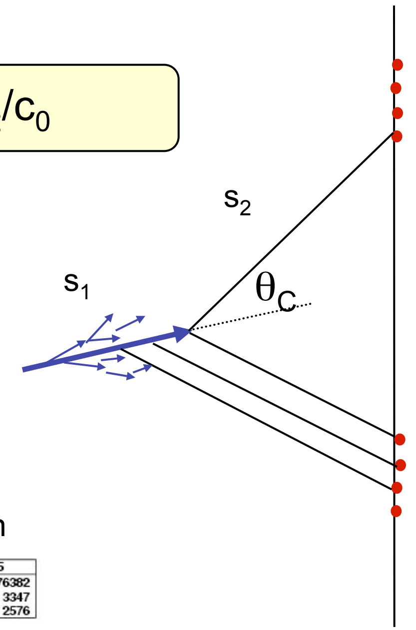
$\Delta t_{hyp} = s_1/c_0 + ns_2/c_0$

7 Fit pameters:

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

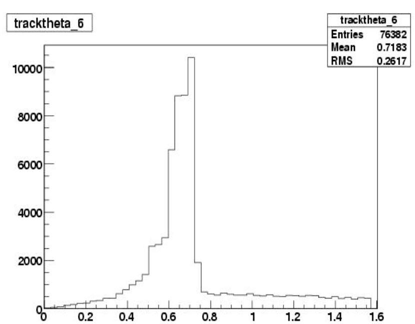
Also: Particle ID? How many tracks?

$\mathbf{v}=(x_v, y_v, z_v, T_{0.})$

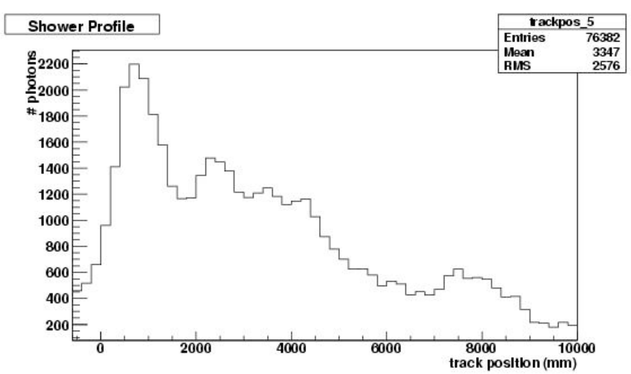


In addition to Δt_{hyp}, we can also use information from:

Light intensity VS $\Delta\theta_{track}$



Intensity of emitted light VS track position

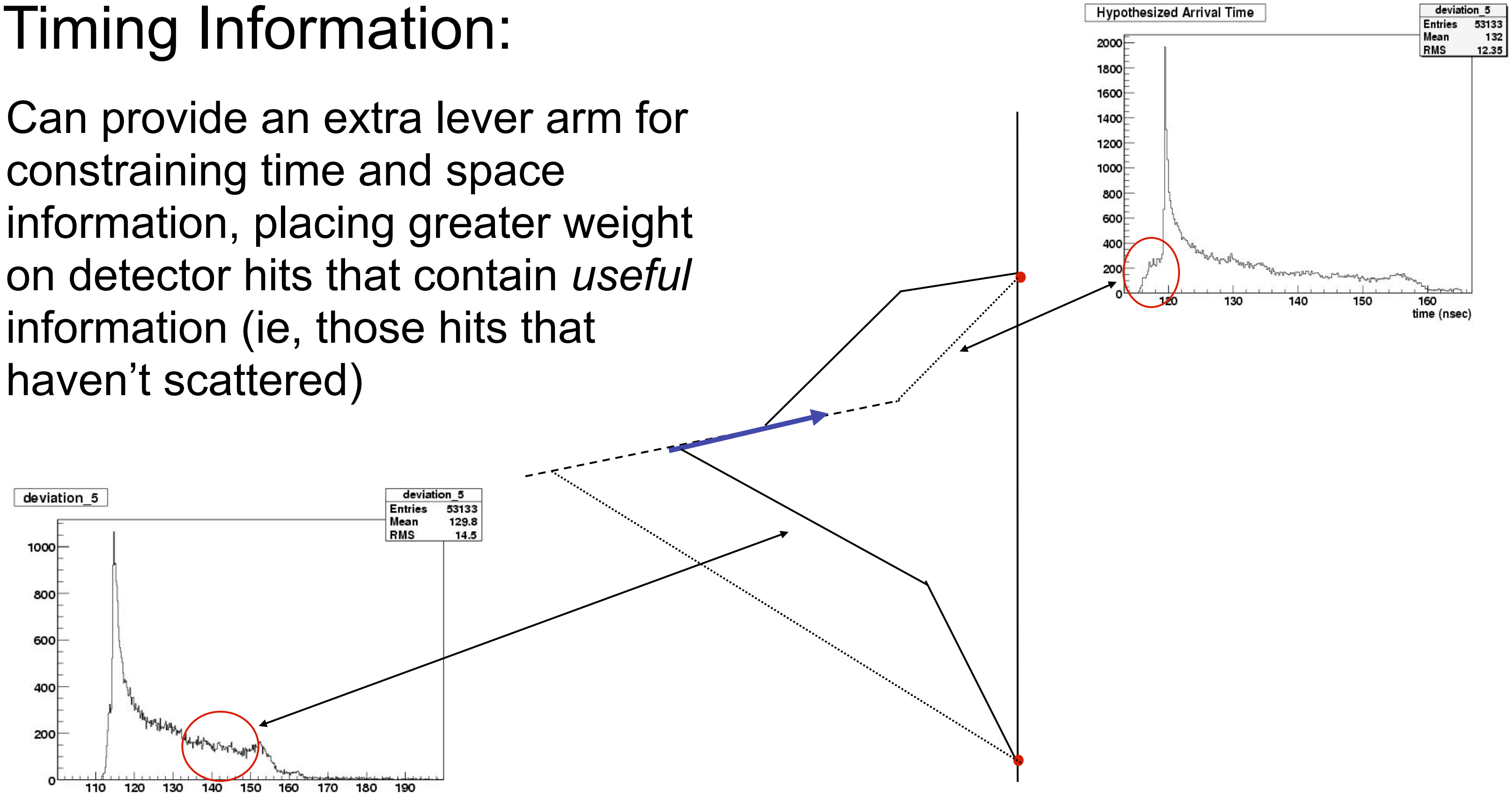


Timing in Water Cherenkov

Aren't time and space information degenerate?

Timing Information:

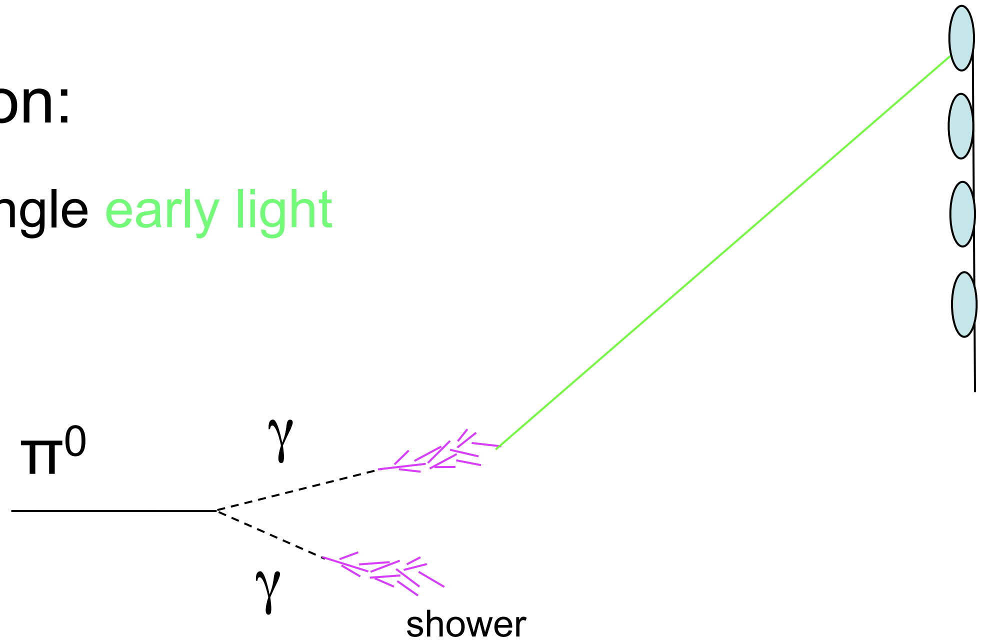
Can provide an extra lever arm for constraining time and space information, placing greater weight on detector hits that contain *useful* information (ie, those hits that haven't scattered)



Timing in Water Cherenkov

Timing Information:

Can help to disentangle early light of one track….

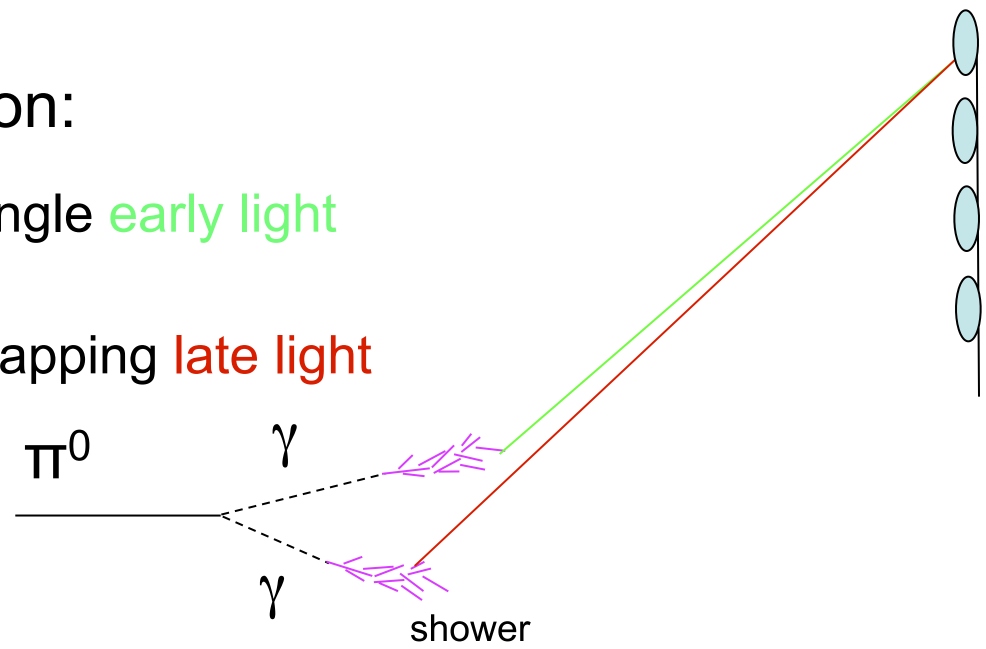


Timing in Water Cherenkov

Timing Information:

Can help to disentangle early light of one track….

From spatially overlapping late light of another track

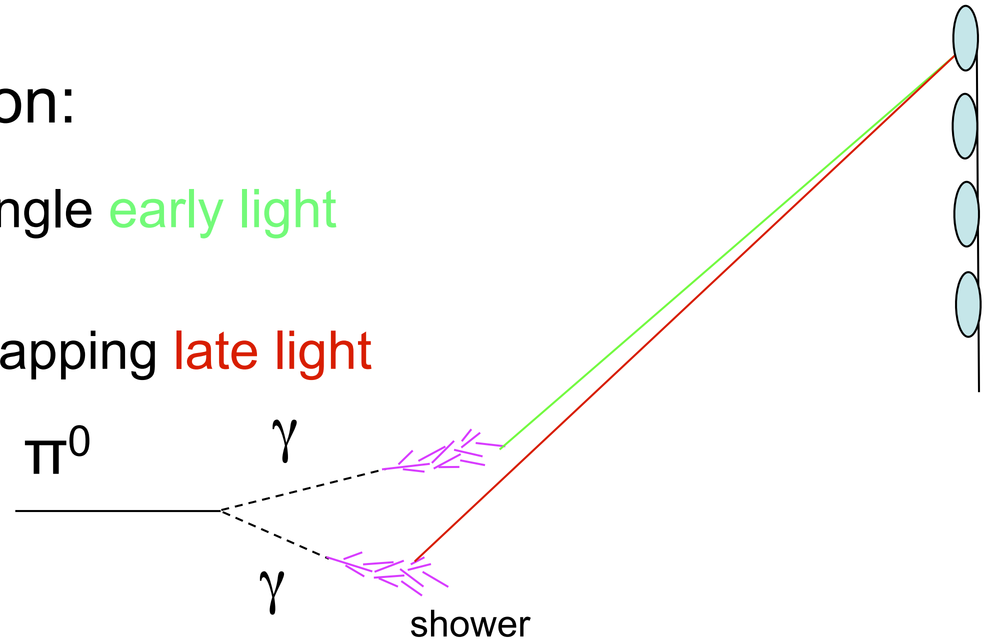


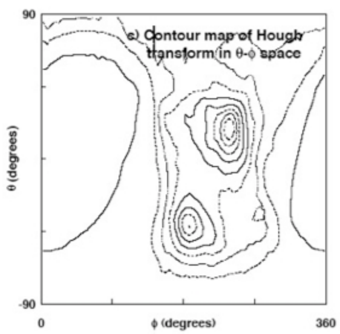
Timing in Water Cherenkov

Timing Information:

Can help to disentangle early light of one track….

From spatially overlapping late light of another track



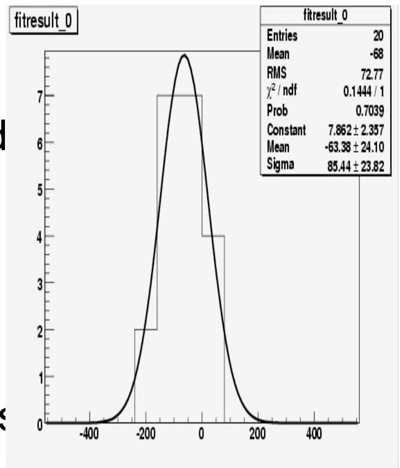


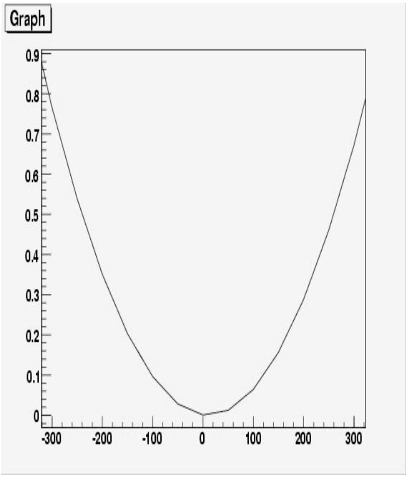
Imagine a likelihood fit for ring counting that uses both time and space information (cut the Hough transform into slices in time)…

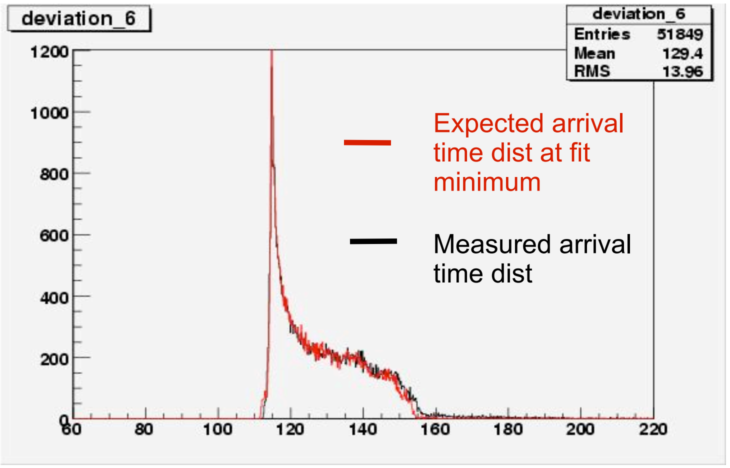
Timing in Water Cherenkov

TrackFit_x

- Package for analytic track-fitting based on Cherenkov geometry
- Currently optimizing multiparameter fitting and smoothness of likelihood curve
- Soon to make pull plots for track fits to many toys, for different time resolutions
- Will also add PID and ring counting features.
- Goal:
  - to study identification of π^0 backgrounds as a function of time resolution
  - To better understand analysis using large-area, picosecond photodetectors

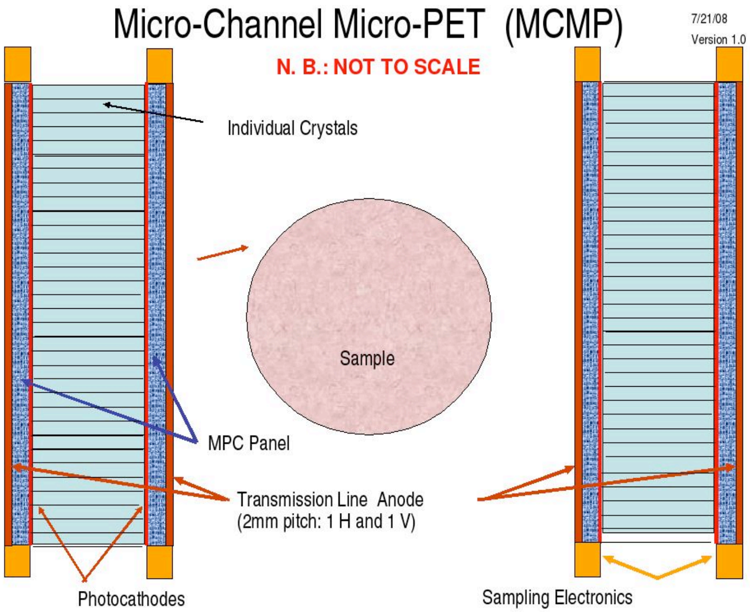






M. Wetstein(ANL/UofC), M. Sanchez (Iowa State/ANL), B. Svoboda (UC Davis)

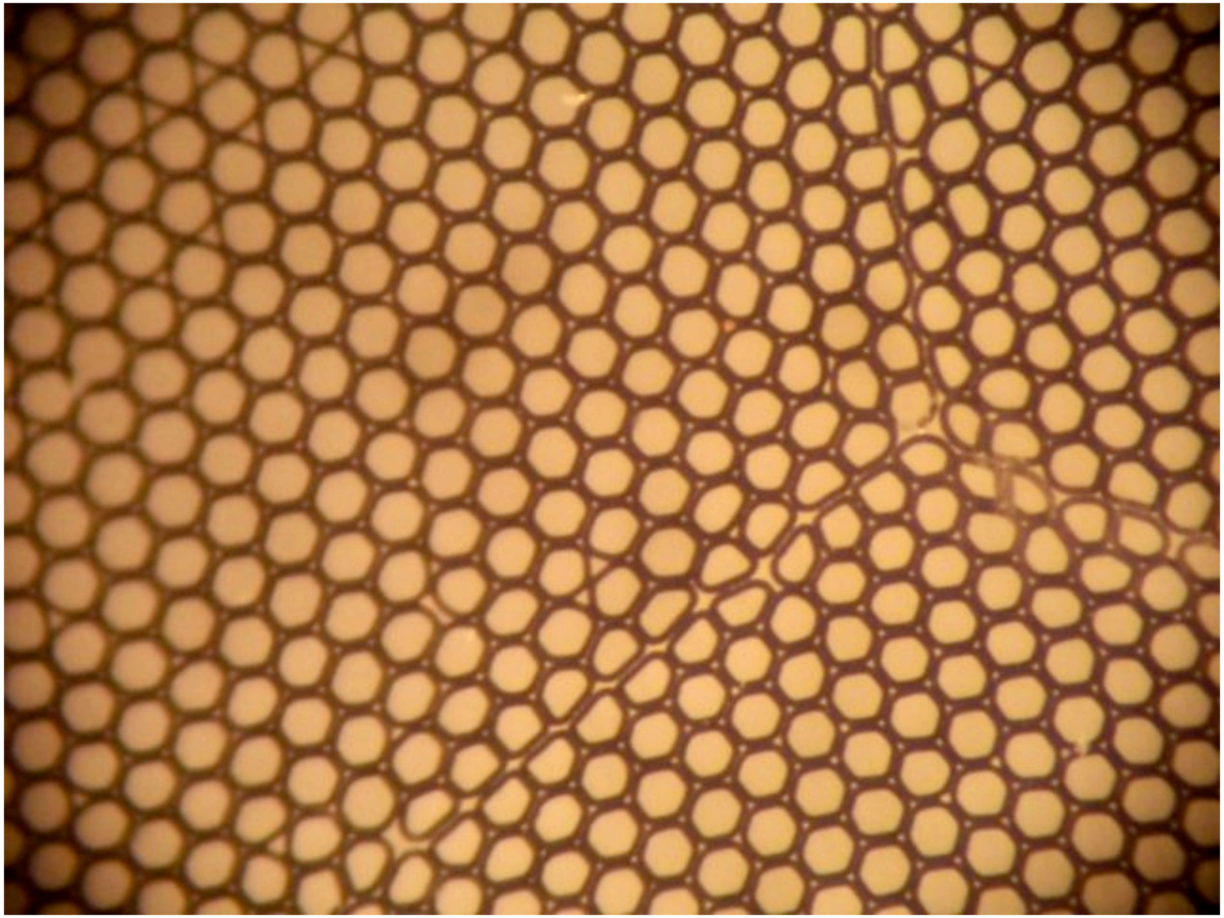
Other possible applications



Homeland security: Large, flat panel photo-imaging for x-ray scanning all those shipping containers…

Medicine: using timing information to improve resolution and reduce necessary radioactive doses in PET scans

close-up of glass filter



Distortion at boundaries of fiber bundles. We are working with the vendor to improve these...