Pico-second Time-of-Flight Detector Development

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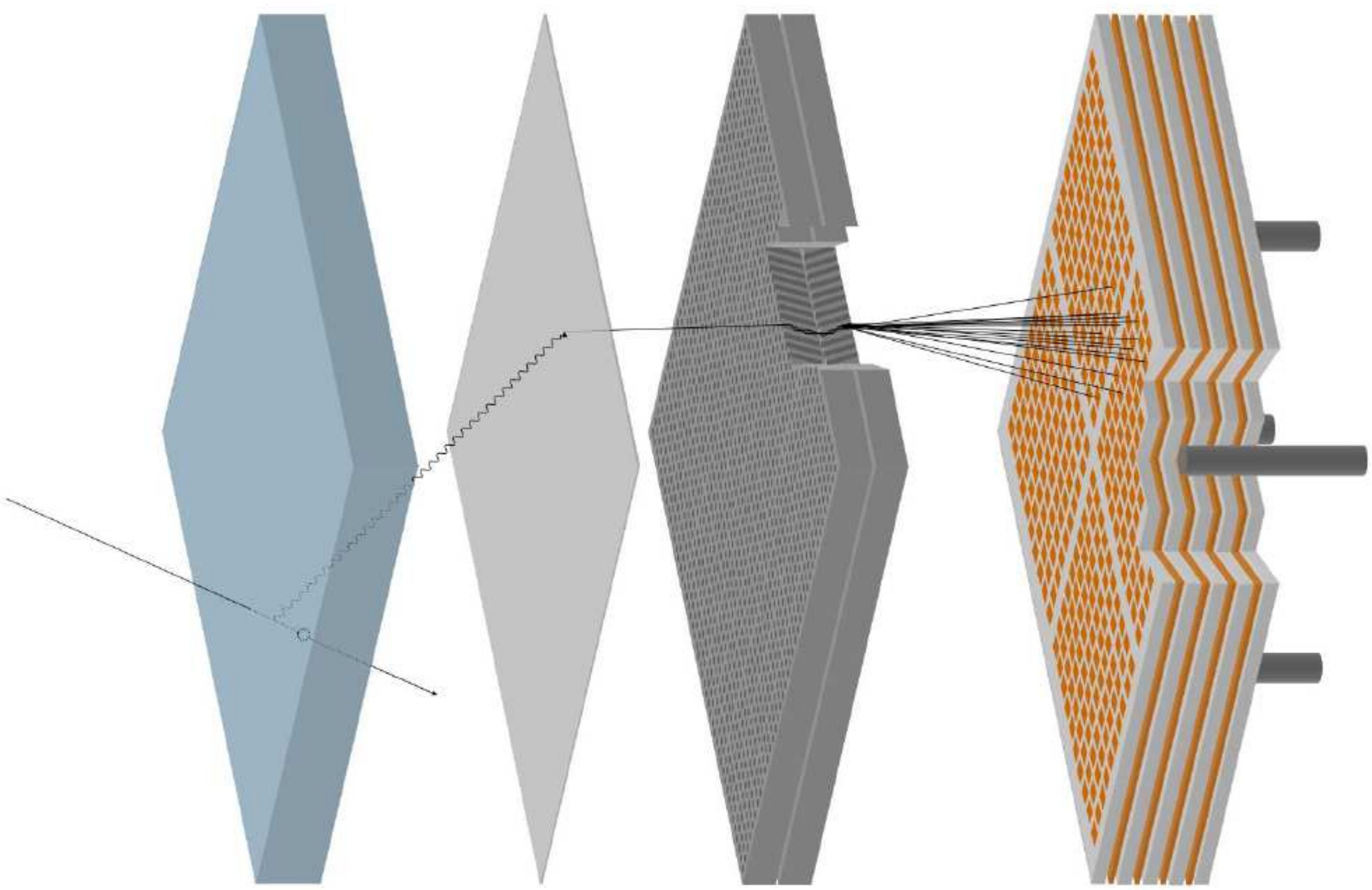

Figure 1:

Cast of Characters

Timothy Credo	IMSA senior (Harvard next year)
Robert Schroll	Theory grad student (Physics335)
Shreyas Baht	UC undergrad- just joined
Fukun Tang	EFI Electronics Engineer
Harold Sanders	Head, EFI Elec. Devel. Gp.
HJF	

Many thanks to Katsushi Arisaka (UCLA), Alan Bross (FNAL), Paul Hink (Burle), Mario Kasahara (Hamamatsu), Bruce Laprade (Burle), John Martin (Burle), and Wilma Raso (Burle), and to Joe Lykken and Maria Spiropulu for causing this.

Harold will talk on the electronics; I'll talk on the device and applications. Very much an idea in development- we're still waiting to be told why it won't work (it may not). Long ways to go...

The Basics- Page 1

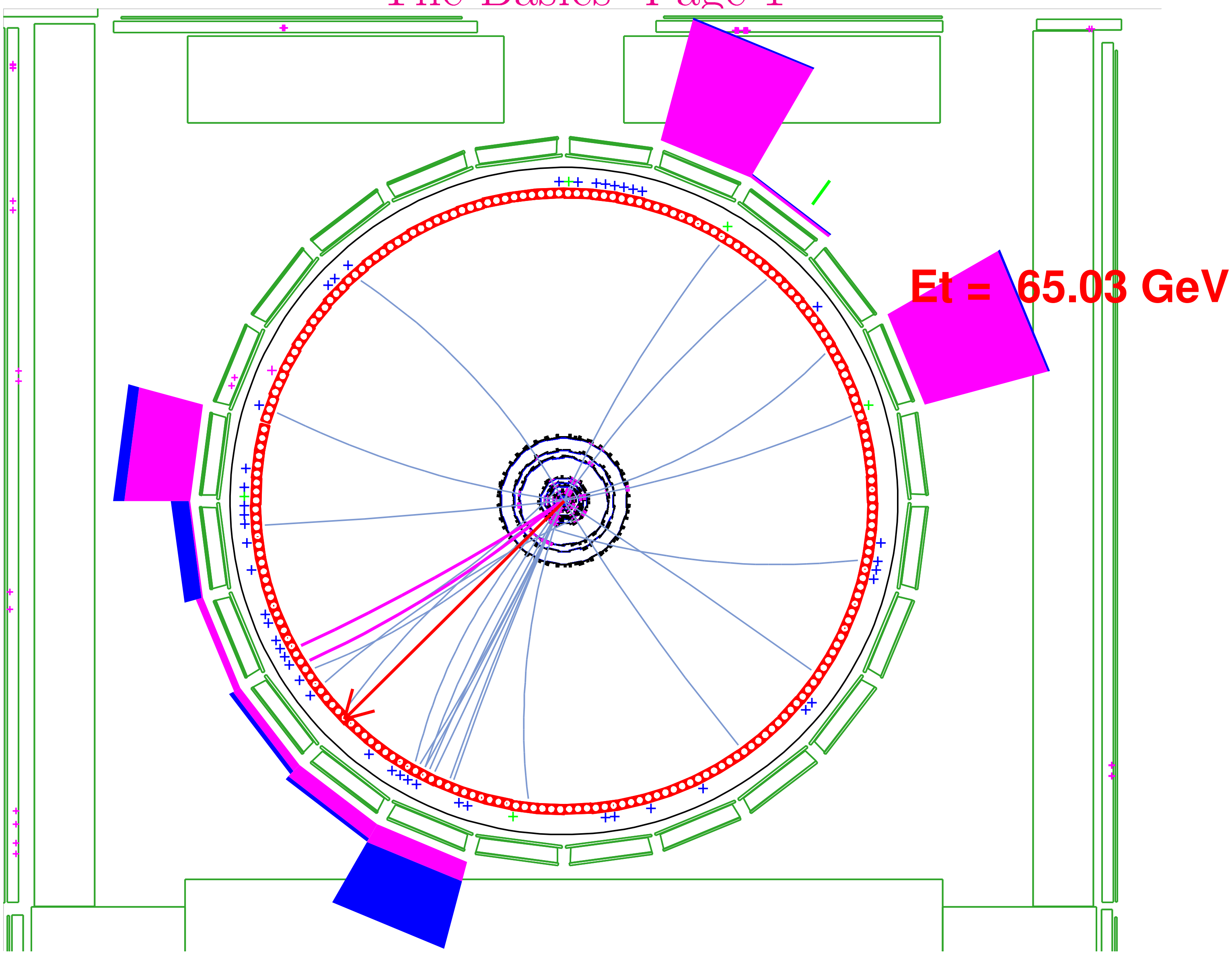

Figure 2:

For each track, $\beta = L/\Delta t$, where $L \equiv$ track length (helix) from vertex to outer radius, and:

Δt= (time at outer radius $-t_0$), where t_0 is the time of interaction.

The Basics- Page 2

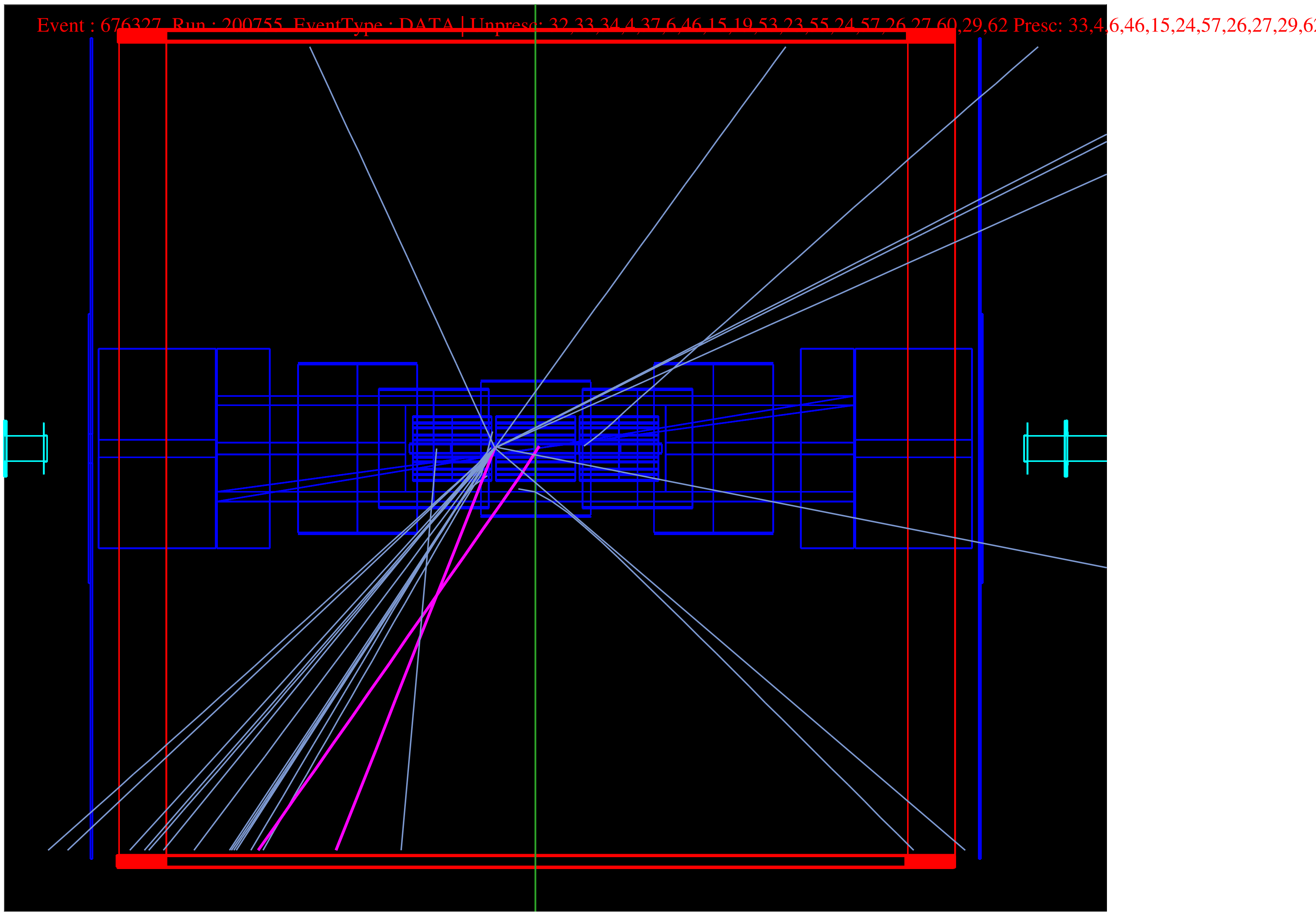

Figure 3:

R-Z (side) view of the same event. Note the mis-reconstructed tracks in this view (no slouch detector-96 layers of COT, 7 or 8 silicon).

The Basics- Identifying particles by measuring velocity and momentum.

Identifying particles by measuring velocity and momentum.

Particle masses: e : 0.00051 MeV; μ^-:105.7 MeV;π^+: 139.6 MeV; K^+: 493.7 MeV; p: 938.3 MeV;

Basic Special Relativity in HEP units (electrical engineers in the audience)
Work in nsec and feet $\Longrightarrow$ c=1:

$$\beta \equiv v/c; \gamma \equiv \frac{1}{\sqrt{1-\beta^2}}; E^2 = p^2 + m^2; \tag{1}$$

What we need is $p = \beta\gamma m$. Solve for m given p and β.

Measure p from the curvature in the field, and β (and hence γ) from the time-of-transit and length of the trajectory.

Separation with a 1.5-m Radius Solenoid (CDF)

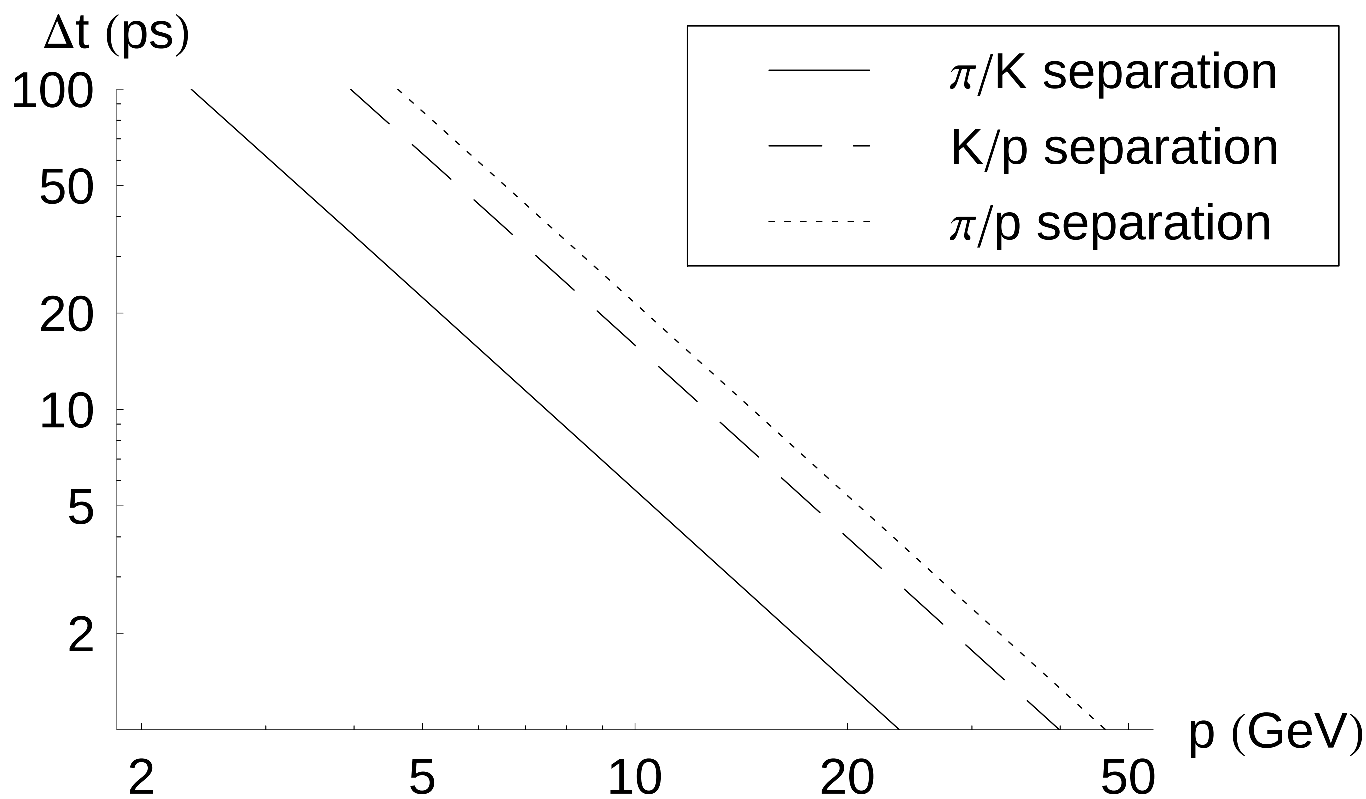

Figure 4: Contours of 1-sigma separation for pions, kaons, and protons versus the time resolution of the particle flight time over a 1.5-meter path for a detector with 1psec resolution.

Getting the Start Time: t_0.

Collisions at the Tevatron (e.g.) have a distribution in times with a sigma of $\approx$ 1.4 nsec (1.4 thousand psec's).
Rather than measure the start time, t_0, at the origin, we fit the tracks from a single vertex for the t_0.
At present we do this with the tracking chamber (COT), with a resolution on the order of a nsec.
At CDF: t_0 is correlated with z_{vertex}! (From the new TAMU EM timing system in CDF (Goncharov, Krutelyov, Toback)).

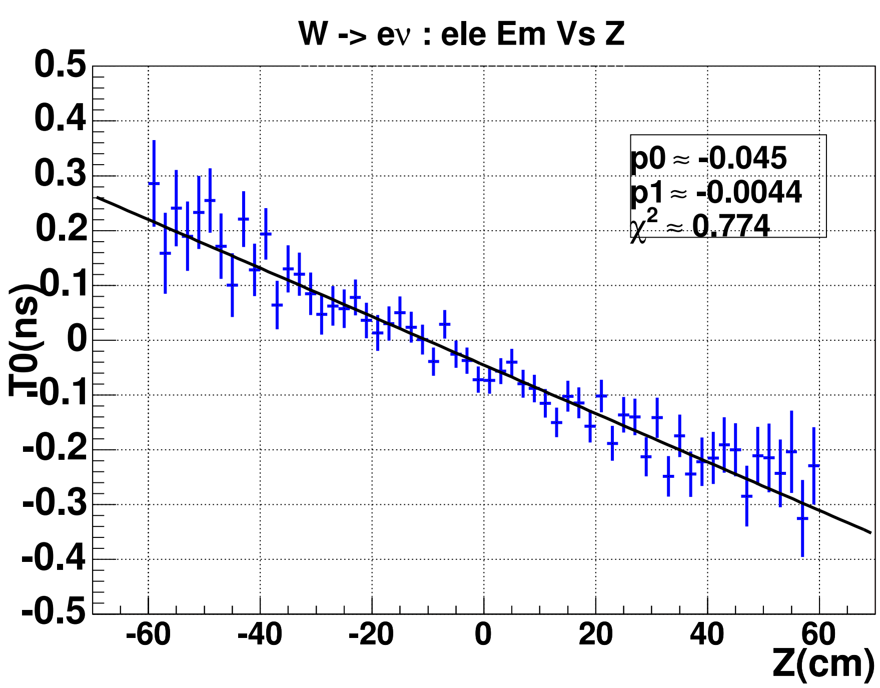

Figure 5:

Point is that each vertex has a time– fitting the tracks can tie charged particles to vertices. Fitting photons likewise is also possible if we know L, as we know beta.

Basic Layout of the System

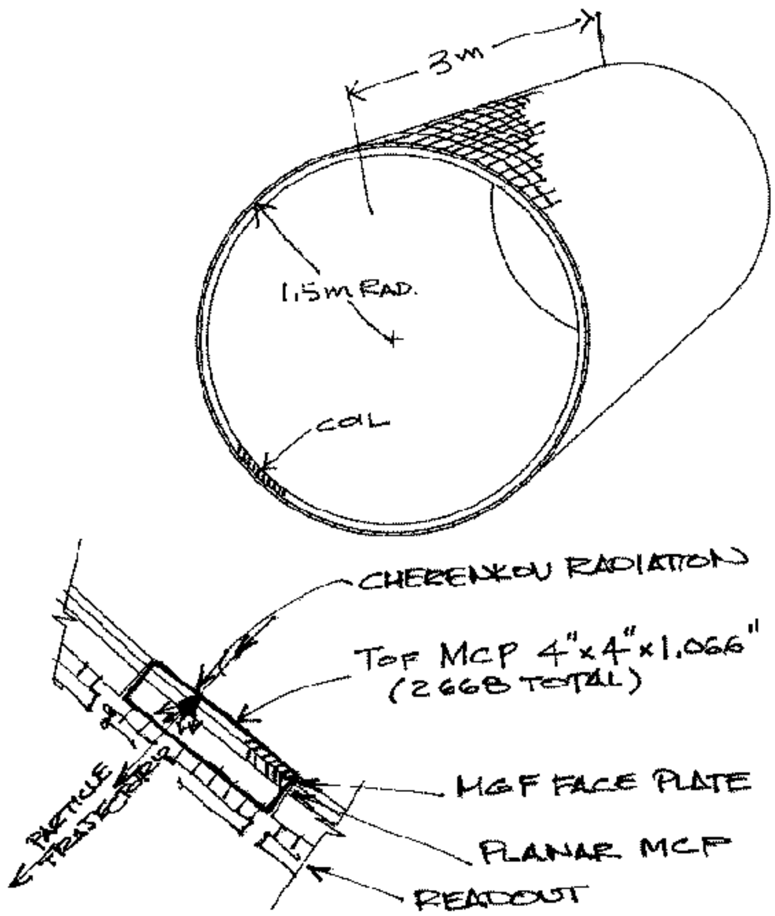

Figure 6:

Take 2-inch × 2-inch Multichannel Plate PMT's (MCP-PMT's, or MCP's for short) and 'tile' the solenoid of a cylindrical general-purpose detector (e.g. CDF). Don't know yet that they work inside the coil (B-field); one of the big questions (not clear they won't). Don't know yet that they work outside the coil (interactions in the coil); another of the big questions. Working on these two issues. Set them aside for now.

The MCP-PMT and Equal-Time Anode

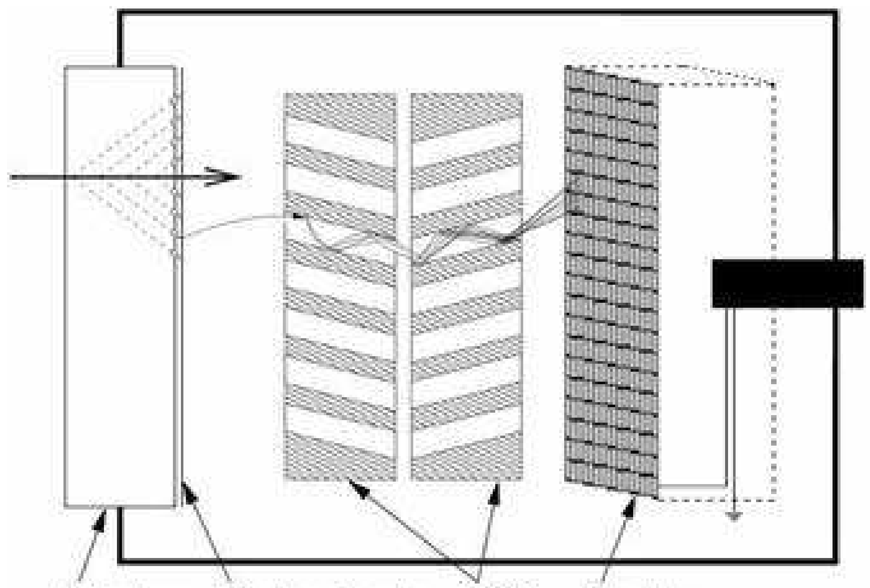

Figure 7: A 'cartoon' of a side of a MCP-PMT module, showing the Magnesium-Fluoride window at left, followed by the chevron micro-channel plate, the multi-pad anode, and the pin that penetrates the back of the device to the readout chip. The actual thickness of the module is approximately 1 inch, so the true aspect ratio is more like a tile than this 'exploded' view implies. Also shown are an incoming particle making Cherenkov light in the window, and the trajectory of one photo-electron and its shower in the MCP. Typical gains, however, are $\sim 10^6$, rather than the small integer depicted in the electron shower.

Transit Times on the Anode

One psec corresponds to 300 microns; a 2-inch by 2-inch anode will have typical transit times (jitters) of a nsec (1 inch $\sim$ 1 nsec). Even knowing the position of where a particle arrives doesn't cure this completely:

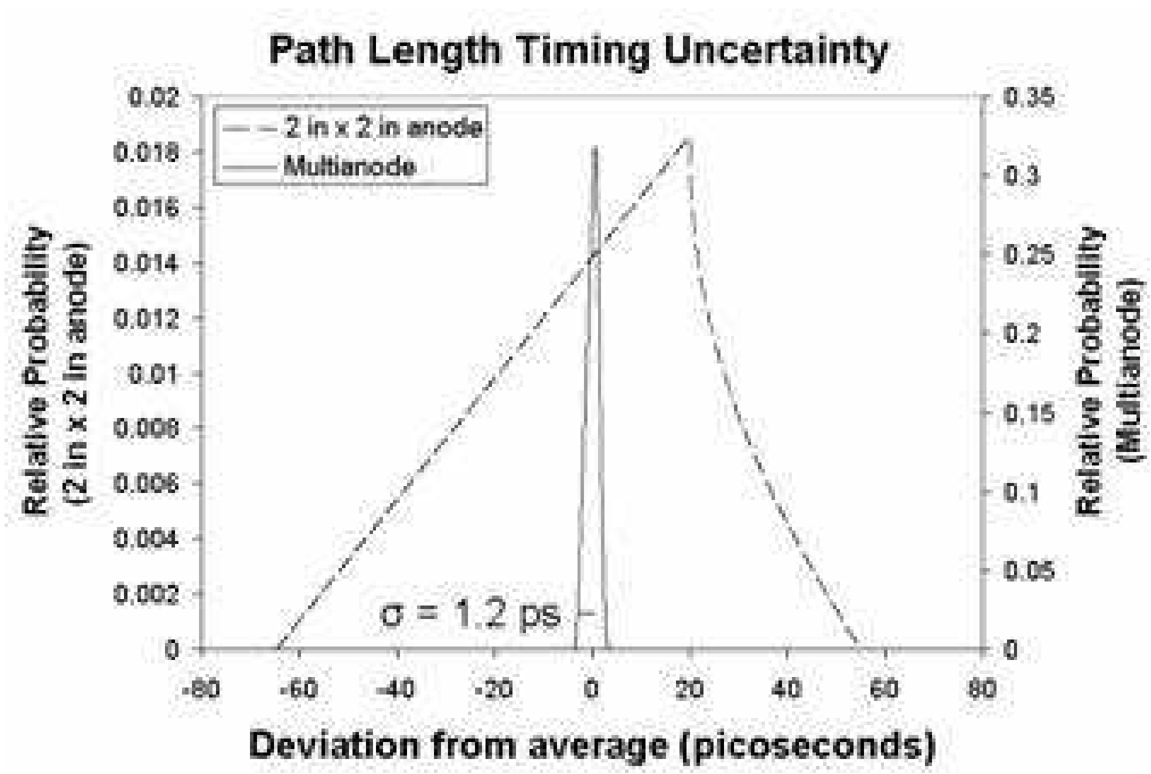

Figure 8: The dispersion in timing resulting from path length difference on the anode, from simulation. The prototype multianode design has an RMS of 1.2 psec; without the multi-pad layout the simulation gives an RMS as large as 48 psec.

Equal-time Anode Assembly

To solve this we are working on designing an 'Equal-time Anode', to go directly on the back of the MCP. The idea is that the anode layer is broken up into many little pads, each connected to a common output pad on the hindmost layer by transmission lines of the same time delay, implemented on internal layers.

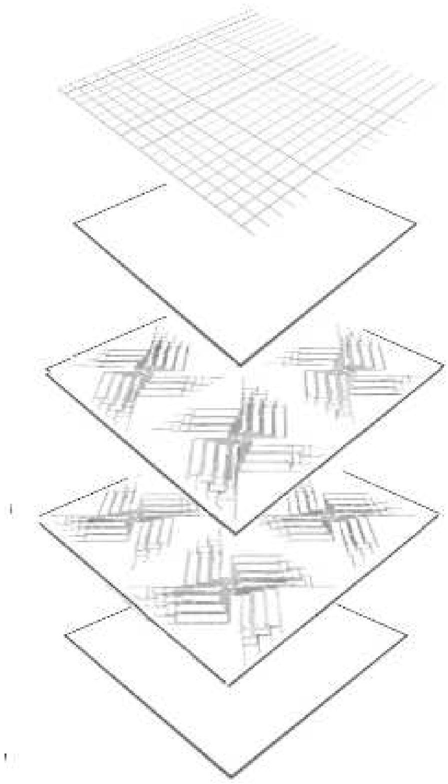

Figure 9: The construction of the custom anode assembly. The top layer is the actual anode, consisting of 2mm square pads; this is the layer that receives the charge output from the micro-channel plate. The two layers of transmission line traces and their corresponding ground planes are also shown; these are constructed so that the transit time of the charge from each pad to the respective one of four central collection points is constant. Each of these collection points has a pin through the anode assembly that we will connect directly to the chip that digitizes and reads out the time of arrival.

First Pass Layout for the Anode (But Superseded!)

So Tim laid out an Equal-Time Anode using Mentor Graphics. We now know we want a different ground configuration, but it's a good pedagogic example.

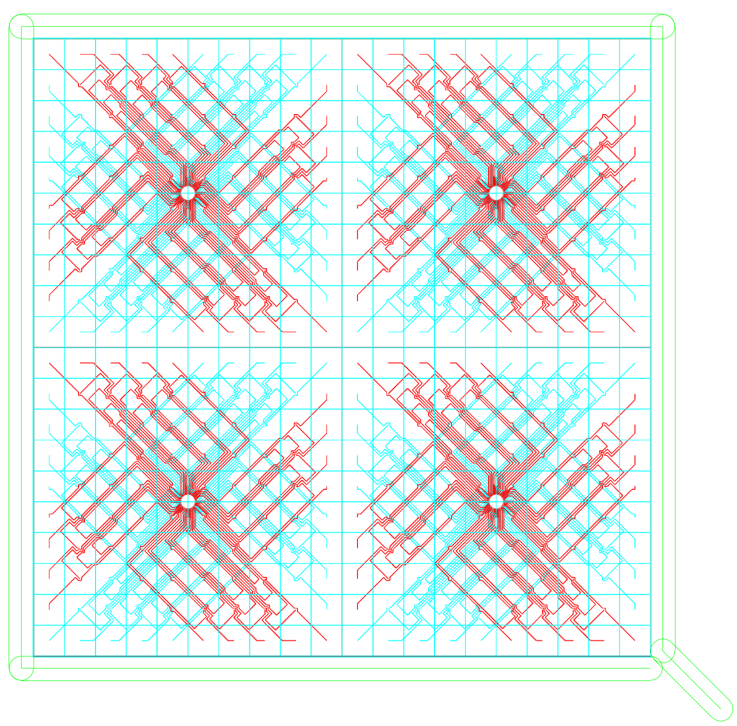

Figure 10: The layout on the anode of the transmission lines that connect the individual pads to the collection points which then directly feed the digitization chips. The transmission lines, each consisting of a trace and a ground plane, are constructed so that the transit time of the charge from each pad to the respective one of four central collection points (at the center of each large square) is constant.

(Almost) Full Simulation of the Whole Chain

Tim has expanded Robert's original simulation of the Cherenkov light generation, absorption, Photocathode response, and TTS to give both times and positions at the anode. He then has interfaced this to the Mentor Graphics Spice to simulate the electrical behavior of the anode.

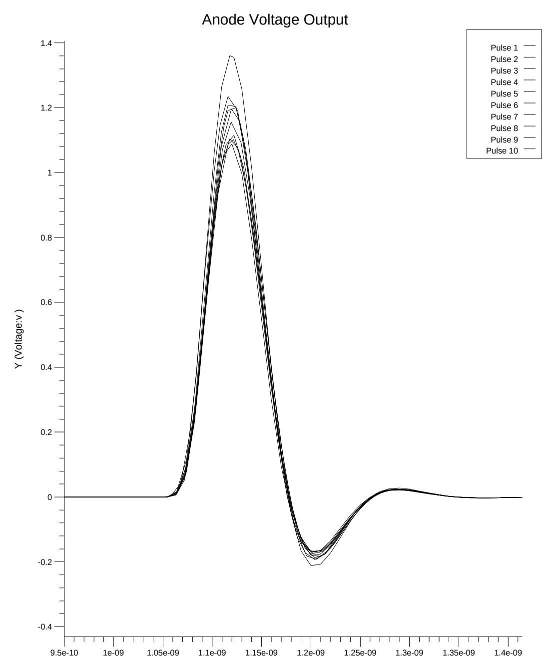

Figure 11: The output voltage from one of the four collectors on the back of the anode for 10 different simulated showers. The simulation includes the frequency response of the generation of Cherenkov light, absorption in the window, the photo-cathode response, the time jitter in the MCP, physical and temporal distributions at the anode, path length differences on the anode, and electrical characteristics of the anode. The RMS jitter on the leading edge as measured at half-height is 0.86 psec.

Disclaimers, Warnings, Fears,...

As we go we learn a lot- we know now that the anode will take lots of care- not going to be easy. But, it doesn't look impossible. Fears and Worries include:

- Inside the coil- do these things work in a magnetic field?
- Outside the coil- does the (soft) shower accompanying particles 'short-circuit' the path-length and screw up the timing?
- Can we build an anode that acts like it should at so-many GigaHz? (questions of grounds, e.g.)
- How do we measure these things? (tools– like scopes, etc.)
- System issues- reference clocks, stability (must calibrate *in situ*).
- the Unknown....

Application in HEP: Colliders

We have not targeted one experiment for this development, as measuring the identity of (almost) all particles produced in a collision would have implications at hadron colliders, lepton-colliders, B-factories, and many fixed target experiments. There are attractive physics applications for flavor and baryon tagging in all of these. We list some below– we are interested in making at least some of these quantitative.

There are additional benefits, however, in measuring the precise time-of-arrival of a particle: knowing the velocity one can associate particles with a specific vertex in a multi-vertex environment as vertices are typically separated in time and in space in a hadron collider. With additional instrumentation this could be applied to photons, solving the long-standing problem of associating a photon to a given vertex.

Having a time precise to 300 μm would efficiently eliminate mis-reconstructed tracks, decays-in-flight, possibly some photon conversions, and out-of-time backgrounds (e.g. cosmic rays, beam halo).

Possible Applications in HEP: Colliders I

- Distinguishing between the b and the $\bar{b}$ quarks in top decay, and the effect on the uncertainty in the top mass of this diminishing in the combinatorics (K identification in D and B decays) (Tev,LHC,ILC).
- Distinguishing between W$\rightarrow c\bar{s}$ and W$\rightarrow u\bar{d}$ decays, and the effect on the achievable precision on the W mass measurement at the LHC and the ILC (K identification in c and s-quark decays).
- Getting a higher tag rate in top decay by same-side b-tagging in top decays (K charge identification in b-tags).
- Extending the range in β ($\equiv v/c$) in searches for short-lived heavy stable particles- will extend the β range much closer to 1.0, and hence the mass range.
- Extending the range in β in searches for short-lived heavy unstable particles, even if they decay into light secondaries.

Possible Applications in HEP: Colliders I

- Associating charged particles with vertices in multiple vertex events at the LHC by t_0 collision time resolution as well as by spatial resolution(different collisions typically differ in time).
- Associating photons with vertices in multiple vertex events at the LHC(takes installing a thin converter and detector layer with 2D spatial resolution directly in front of TOF-MCP).
- Photon 4-vector resolution. There are final states such as Higgs$\rightarrow \gamma\gamma$ in which the mass resolution of the $\gamma\gamma$ system depends on the vertex (Thanks to JEP).
- Estimating the additional power from same-sign tagging in b_s mixing.
- Charm/Tau Separation (K id) for eliminating heavy-flavor backgrounds in Tau identification (e.g. top to charged Higgs searches).

Possible Applications in HEP: Colliders I

- Jet Fragmentation Studies (Tevatron Bread and Butter-Cake!)
  - pi, K, p production at $z \eqsim 1$; photon fake rate studies
  - ρ, ϕ production at $z \eqsim 1$; tau fake rate studies
  - K,p production vs z
  - D^* production in Jets
- Backgrounds:
  - K+ decay in flight rejection
  - Photon conversion rejection (?)
  - Cosmic ray rejection
  - Beam halo rejection
  - Track mis-reconstruction rejection (e.g. see CDF event display)

Other Applications??

- Particle ID in heavy-ion collisions, such as at RHIC or in Alice at the LHC.
- Medical imaging applications, e.g. in PET scanning. (300 μm spatial resolution along the gamma direction).
- Other?

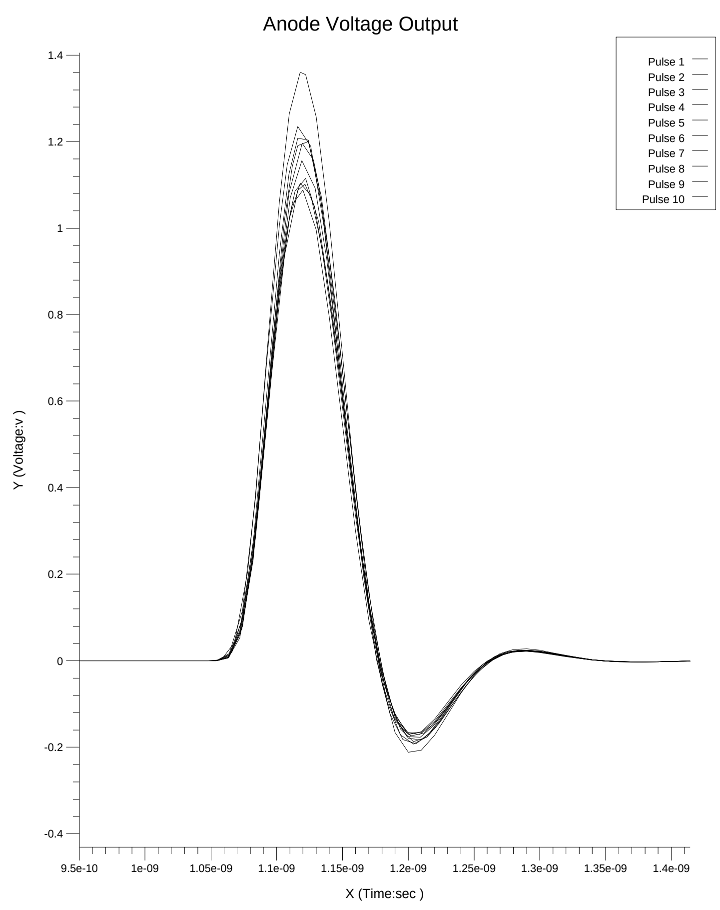

Figure 12:

THE END