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CDF Meeting
May 21, 1998

A TOF System for CDF

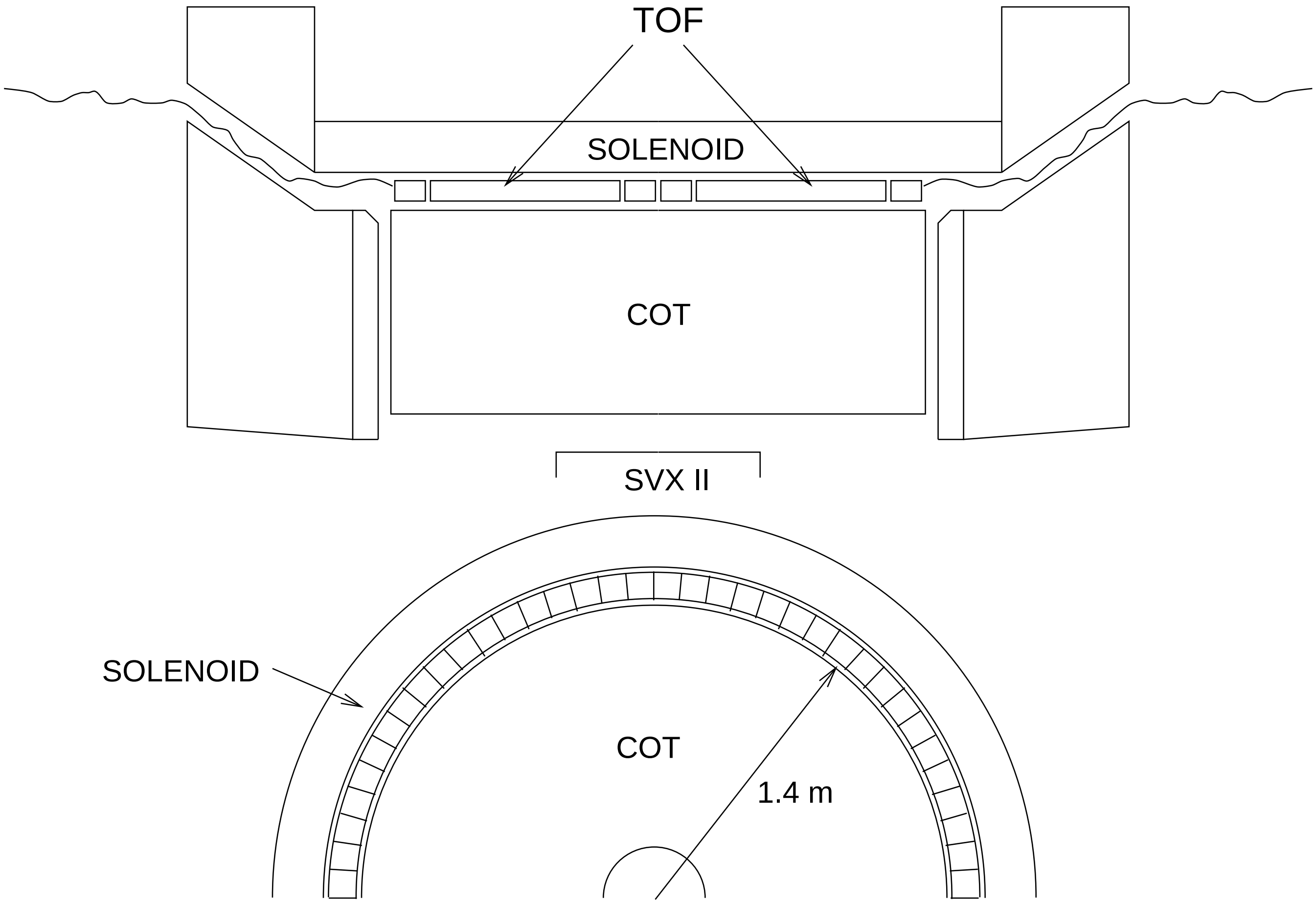
Outline:

- Overview
- Physics Impact
- Previous Experience
- Cosmic Ray Tests
- System Design Details
- Timetable/Manpower
- Budget
- Conclusions

This talk available on the TOF Web Page:

`http://dept.physics.upenn.edu/~mjones`

Overview of Proposed System



- 432 bars of scintillator between COT and solenoid.
- Scintillators will have PMT's at both ends.
- Expect < 100 ps timing resolution on each channel.

Overview of Particle ID by TOF

- We measure three quantities:
  - momentum, p
  - path length, s (track helix from IP to TOF)
  - time of flight, t
- From s and t we get velocity, β.
- From β and p we get mass m:

$$m = p \cdot \frac{\sqrt{1-\beta^2}}{\beta}$$

- Time scales involved: Light takes 4.7 ns to get from IP to TOF.
- t_0 can be determined from fastest tracks for *each interaction.*

$$\sigma_{t_0} \sim 20 \text{ ps}$$

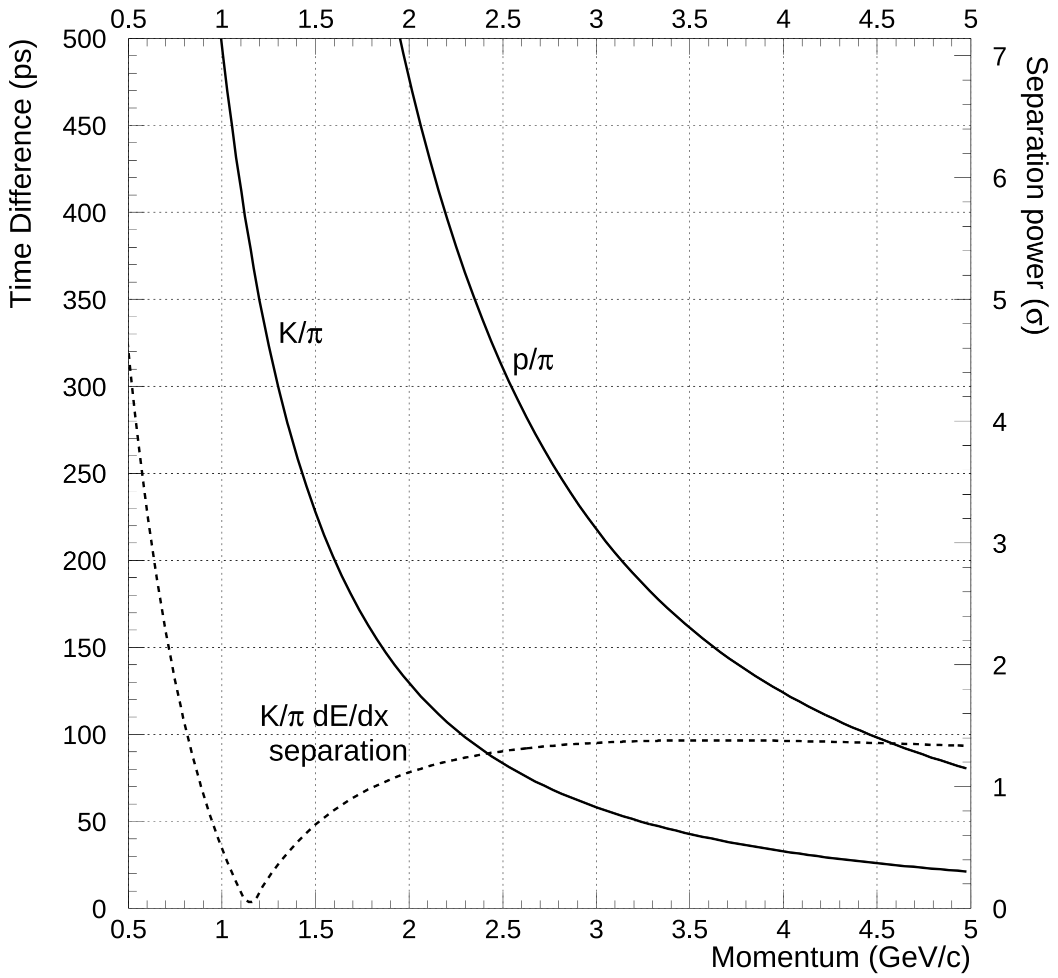
Overview of K/π Separation

- K/π separation in t for a given s, p:

$$\Delta t = t_{\mathrm{K}} - t_{\pi} = \frac{s}{p}\left(\sqrt{p^2 + m_{\mathrm{K}}^2} - \sqrt{p^2 + m_{\pi}^2}\right)$$

- Time of Flight measured from weighted mean using both PMT's

$$\sigma_{\mathrm{TOF}} \sim (100\ \mathrm{ps})/\sqrt{2} = 70\ \mathrm{ps}$$



CP Violation

Goal for Run II: Be the first experiment to observe CP violation in the B system.

$\Rightarrow$ Measure a nonzero CP violating asymmetry, *e.g.*:

$$A_{\mathrm{CP}} = \frac{N - \overline{N}}{N + \overline{N}}$$

$$\text{where} \quad \begin{aligned} N &= N(\mathrm{B}_d^0 \to J/\psi \mathrm{K}_S^0) \\ \overline{N} &= N(\overline{\mathrm{B}}_d^0 \to J/\psi \mathrm{K}_S^0) \end{aligned}$$

- Reconstruct S signal decays with background B
- Tag production flavour with dilution $\mathcal{D} = 2\mathcal{P}_{\mathrm{tag}} - 1$

$$(\delta A_{\mathrm{CP}})^2 \sim \frac{1}{\epsilon \mathcal{D}^2 N} \frac{S + B}{S}$$

- Run II strategy: Maximize $\epsilon\mathcal{D}^2$!
- Particle ID provides:
  1. *New* tagging methods,
  2. *Improvements* to existing methods.

Physics Impact

Flavour Tagging for CP Violation/Mixing

- Opposite Side Kaon Tagging
- Same Side Tagging for B_s^0
- Same Side Tagging for B_d^0

Exclusive Reconstruction of B/D Decays

- $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^-\pi^+$, $D_s^+ \to K^{*0}K^+$
- $B^0 \to \mu^+\mu^-K^{*0}$, $B_s^0 \to \phi\phi$

SUSY Searches

- Identify massive, stable, charged particles.

Counting Multiple Interactions

- Identify overlapping interactions occurring at different times.

Cosmic Trigger

- Finely segmented system would provide a useful cosmic trigger.

And many others.

We will prepare a physics document over the summer.

Flavour Tagging

- Methods for tagging B^0 production flavour:

Tag	Method	$\epsilon\mathcal{D}^2$
Jet Charge	$Q(\overline{b}) - Q(b) = 2/3$	1%
Same Side Tagging	Fragmentation	2.4%
Lepton Tagging	$b \to c\ell^- \overline{\nu}_\ell$	1%
Kaon Tagging	$B \to K^+ X$	3%

- B-factories have invested *heavily* in particle ID for kaon tagging:
  - BaBar : Cherenkov detector (DIRC)
  - CLEO III : Cherenkov detector (RICH)
  - Belle : Time of Flight + Cherenkov detector
- We want to be competitive $\Rightarrow$ we need particle ID too.

Opposite Side Kaon Tagging

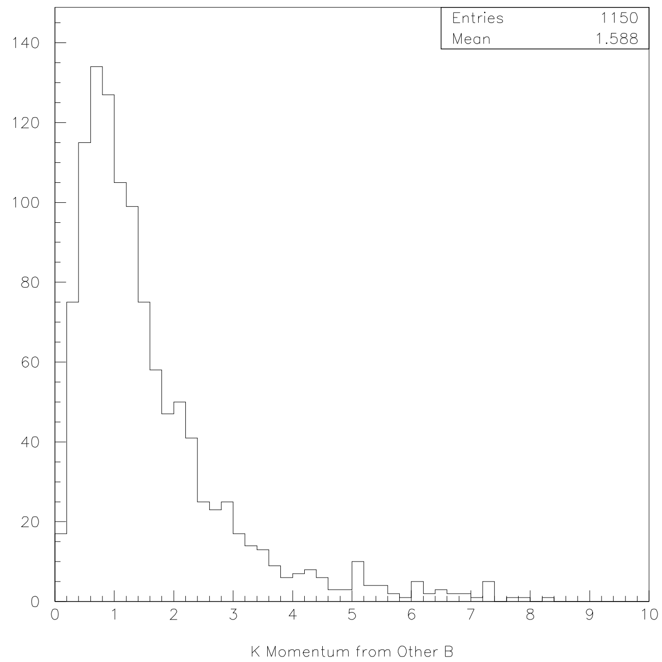
- B decays produce charged kaons:

$$\begin{aligned} \mathrm{Br}(\mathrm{B} \to \mathrm{K}^{\pm}\mathrm{X}) &= (78.9 \pm 2.5)\% \quad \text{on} \quad \Upsilon(4S) \\ \mathrm{Br}(\mathrm{B} \to \mathrm{K}^{\pm}\mathrm{X}) &= (88 \pm 19)\% \quad \text{at } \mathrm{Z}^0 \end{aligned}$$

- Kaon charge is correlated with B flavour:

$$\left.\begin{aligned} \mathrm{Br}(\mathrm{B} \to \mathrm{K}^{+}\mathrm{X}) &= (66 \pm 5)\% \\ \mathrm{Br}(\mathrm{B} \to \mathrm{K}^{-}\mathrm{X}) &= (13 \pm 4)\% \end{aligned}\right\} \text{on } \Upsilon(4S)$$

- Momentum spectrum of Opposite Side Kaons:

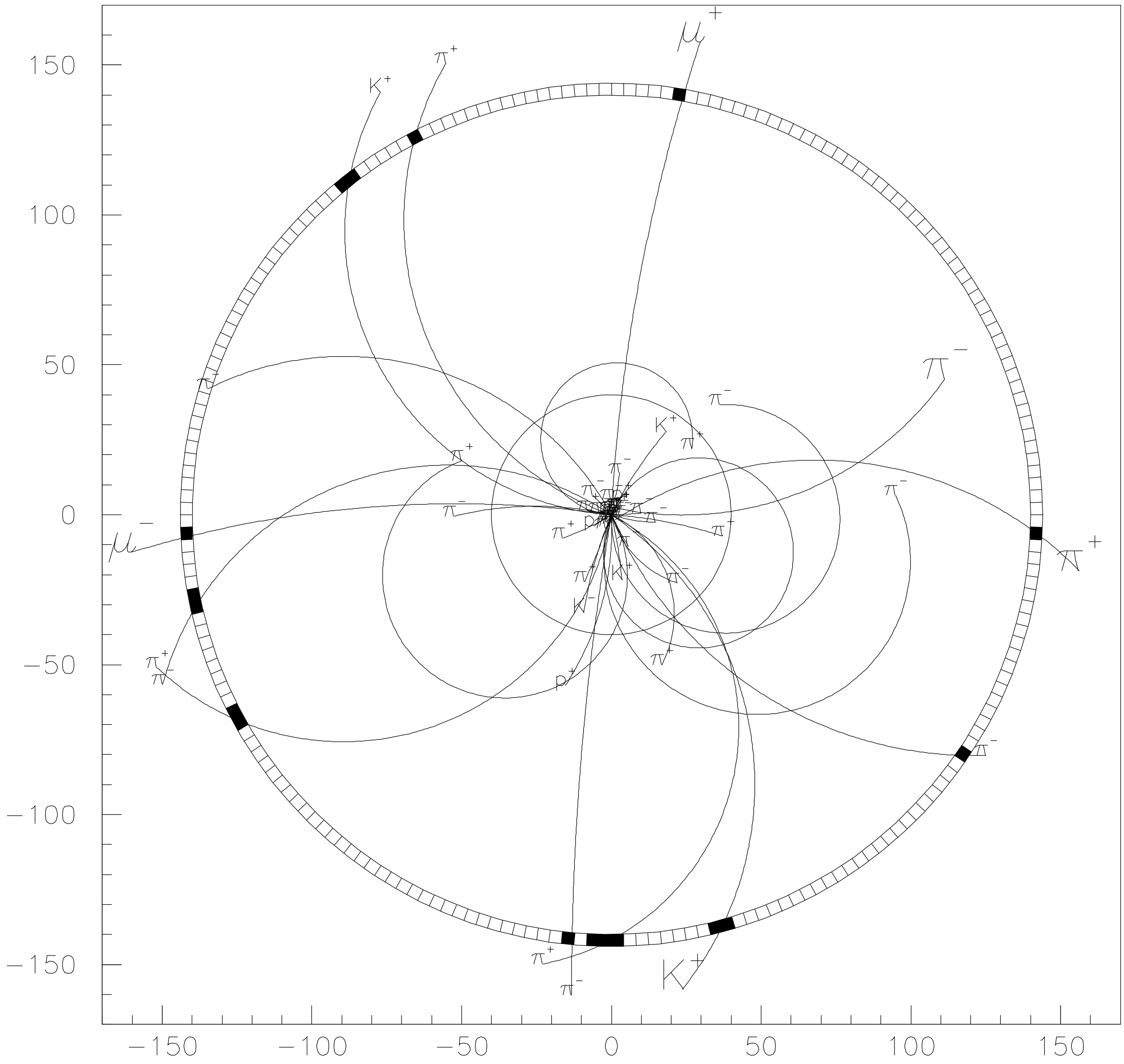


Momentum range (GeV/c)	Fraction of momentum spectrum
0.0 – 0.2	1.6%
0.2 – 0.6	15.3%
0.6 – 1.6	45.8%
1.6 – 2.0	10.3%
2.0 – 4.0	19.1%
$>$ 4.0	7.9%

- 57% of opposite side kaons have $0.4 < p < 1.6$ GeV/c, $|\eta| < 1$ (HERWIG simulation).
- $\epsilon\mathcal{D}^2$ predicted to be large, $\sim 3\%$.

Opposite Side Kaon Tagging

- Example of $\overline{\mathrm{B}}_d^0 \to J/\psi \mathrm{K}_S^0$ + Kaon tag:

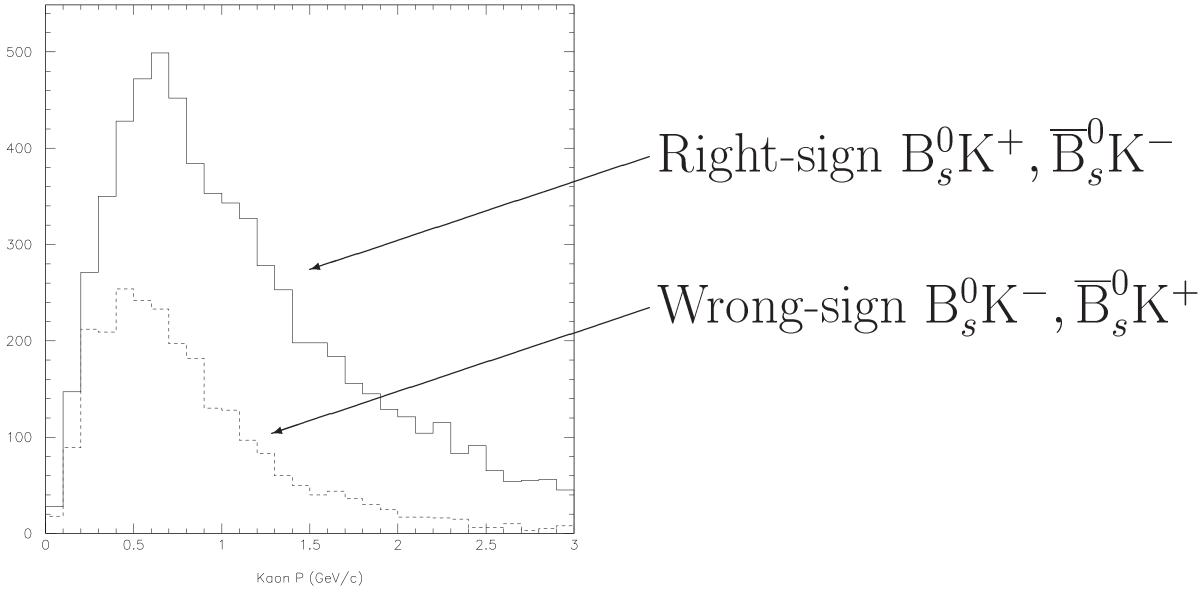


- Occupancy should not be a problem.
- More detailed simulations are under development.

Same Side Tagging for B_s^0

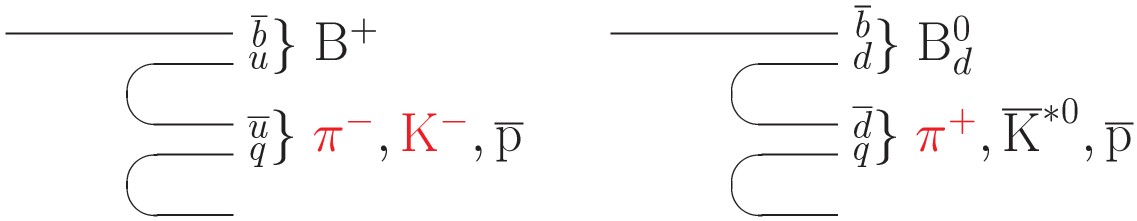
- Studies of B_s^0 decays are *unique* to hadron colliders.
- Fragmentation produces K^+ in association with B_s^0:

- Momentum spectrum of SST kaon (Pythia):



- 72% of right-sign kaons have $p < 1.6$ GeV/c.
- Expect a large $\epsilon\mathcal{D}^2 \sim 5\%$.

Kaon Veto for SST of B_d^0

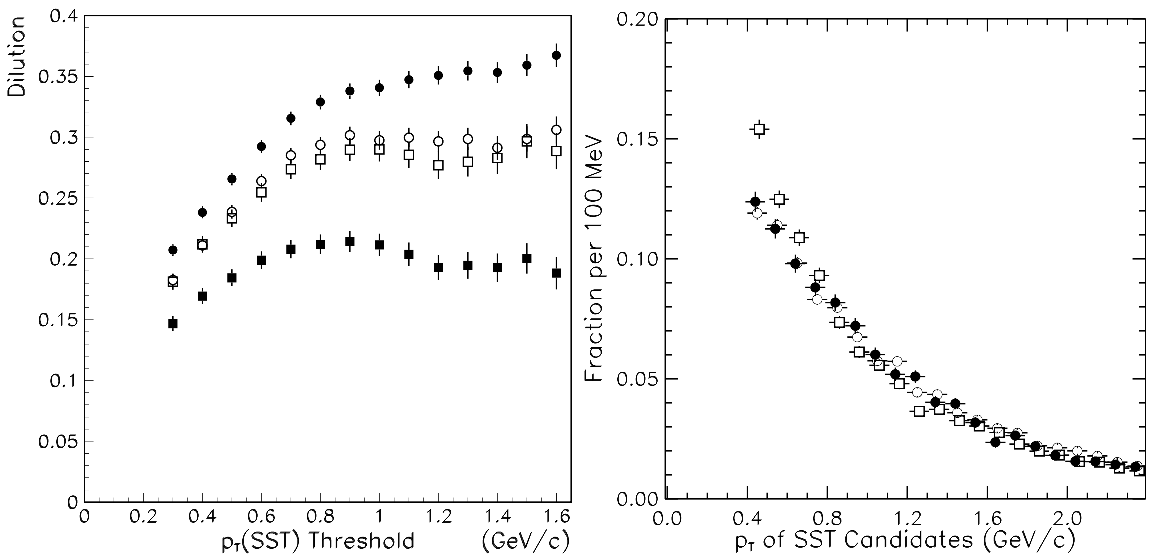


- Charged kaons degrade SST for B_d^0:

$$e.g. \qquad \overline{K}^{*0} \rightarrow K^- \pi^+$$

(wrong-sign kaon charge correlation)

- PYTHIA study in SST PRD draft (CDFNOTE 4572):



- Tagging charged kaons and protons responsible for difference in B^+ and B_d^0 dilutions.

Other B Physics Applications

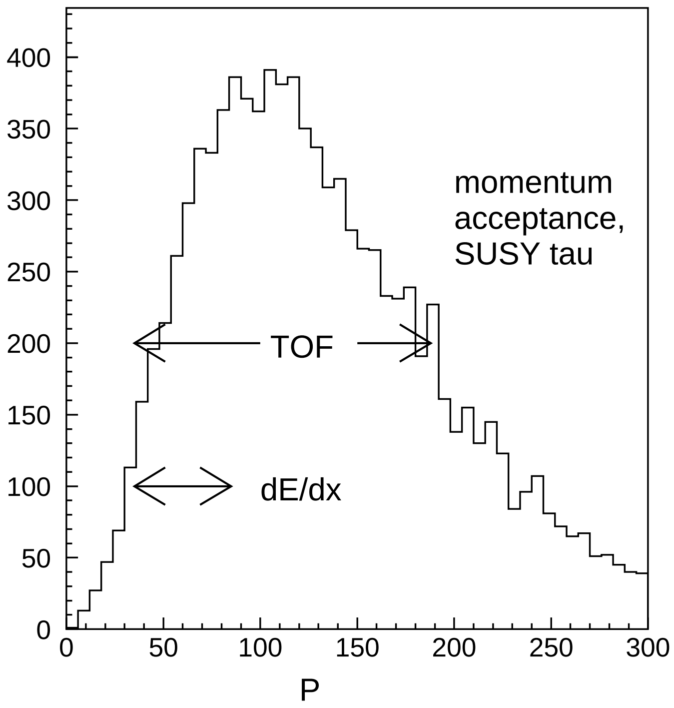
Numerous potential applications for reconstructing B states:

- $B^0 \to J/\psi K^{*0}$
  - Reduce misidentification of B^0 and $\overline{B}^0$ due to swapping K and π in $K^{*0} \to K^+\pi^-$.
  - Reduce systematics in measuring $\mathcal{D}$ for B_d^0.
- Reduce combinatorics in reconstructing D decays.
  - $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^-\pi^+$
  - $D_s^+ \to K^{*0}K^+$
  - $\Lambda_c^+ \to pK^-\pi^+$
- Rare B decays:
  - $B_d^0 \to \mu^+\mu^-K^{*0}$, $B^+ \to \mu^+\mu^-K^+$
  - $B_s^0 \to \mu^+\mu^-\phi$
- Reconstruction of hadronic B decays:
  - *e.g.* $B_s^0 \to \phi\phi$

SUSY Searches

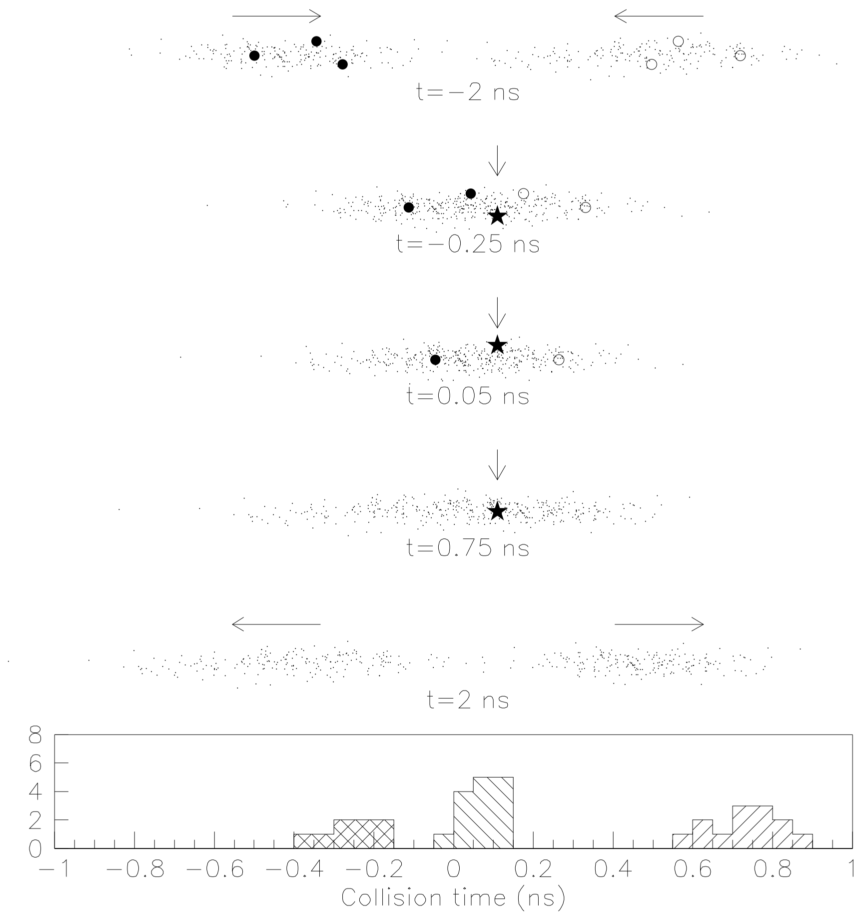
- Example from SUSY workshop (Ray Culbertson - Chicago):
  - Gauge mediated SUSY $\Longrightarrow$ quasi-stable $\tilde{\tau}$.
  - Pairs of penetrating, charged, massive $\tilde{\tau}$'s produced.
  - These are *slow* and *highly ionizing* particles.
  - For $p > 35$ GeV$/c$ these are triggered as μ's.
  - Comparison for $M_{\tilde{\tau}} = 100$ GeV$/c^2$:

	dE/dx analysis	TOF analysis
Momentum acceptance	< 85 GeV$/c$	< 188 GeV$/c$
Efficiency	23%	77%
Expected signal	28	94
Expected background	35	< 35



Multiple Interactions

- We should expect long bunches in Run II with several interactions per bunch crossing.
- Bunch lengths might be $\sim 37 - 67$ cm $= 1.2 - 2.2$ ns.



- Spatially overlapping interactions can be separated with TOF.
- Combination of TOF + SVX-II z-measurements will be even more powerful.

Previous Experience with TOF

S. Geer, E. Keyes, R. Kephart
Fermi National Accelerator Laboratory
F. Ukegawa, J.G. Heinrich, N.S. Lockyer, O. Long, J. Miller, R. Van Berg, M. Newcomer, W. Kononenko, T. Gao
University of Pennsylvania
R. Sturani, D. Salvetti
University of Pisa
K. Kondo, S. Mori
University of Tsukuba

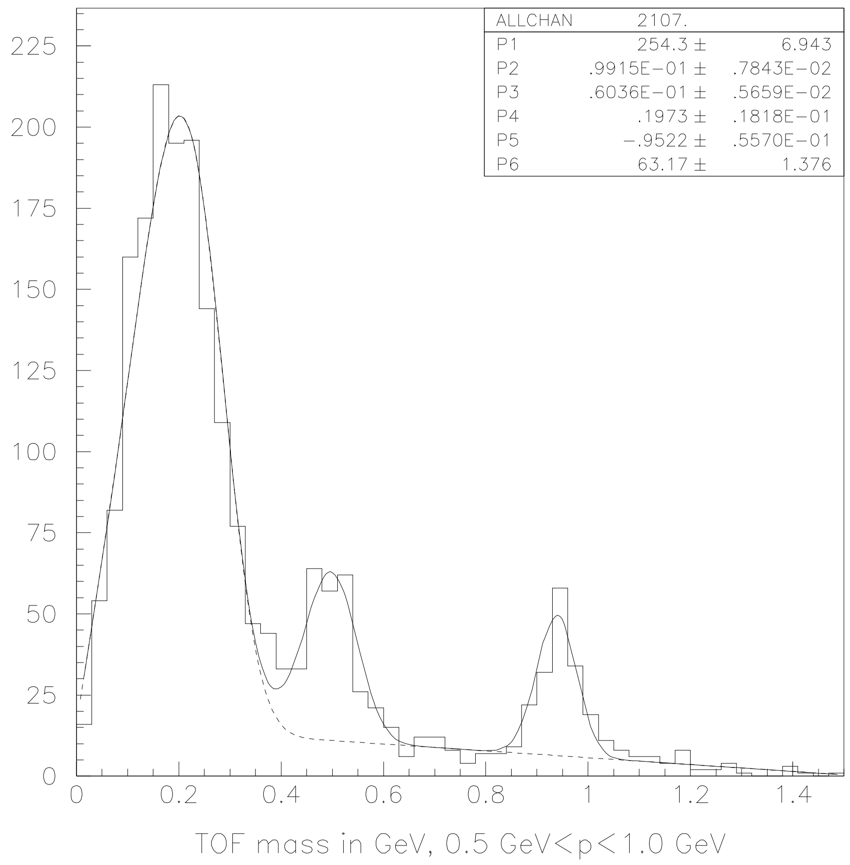
History of TOF development:

1993–	Cosmic ray tests
Nov '94	Godparent committee formed: J. Kroll (chair), G. Sullivan, M. Shapiro, A. Tollestrup
Feb '95	TOF approved by CDF
Mar '95	Proposal submitted to the PAC
Jun '95	20 bar test approved, development started
Aug '95	20 bar test installed (NOTE 3402)
Jan '96	TOF *removed* from baseline by director/PAC
Apr '96	20 bar test results presented (NOTE 3662)
Jul '98	NIM paper to be submitted.

Previous Experience with TOF

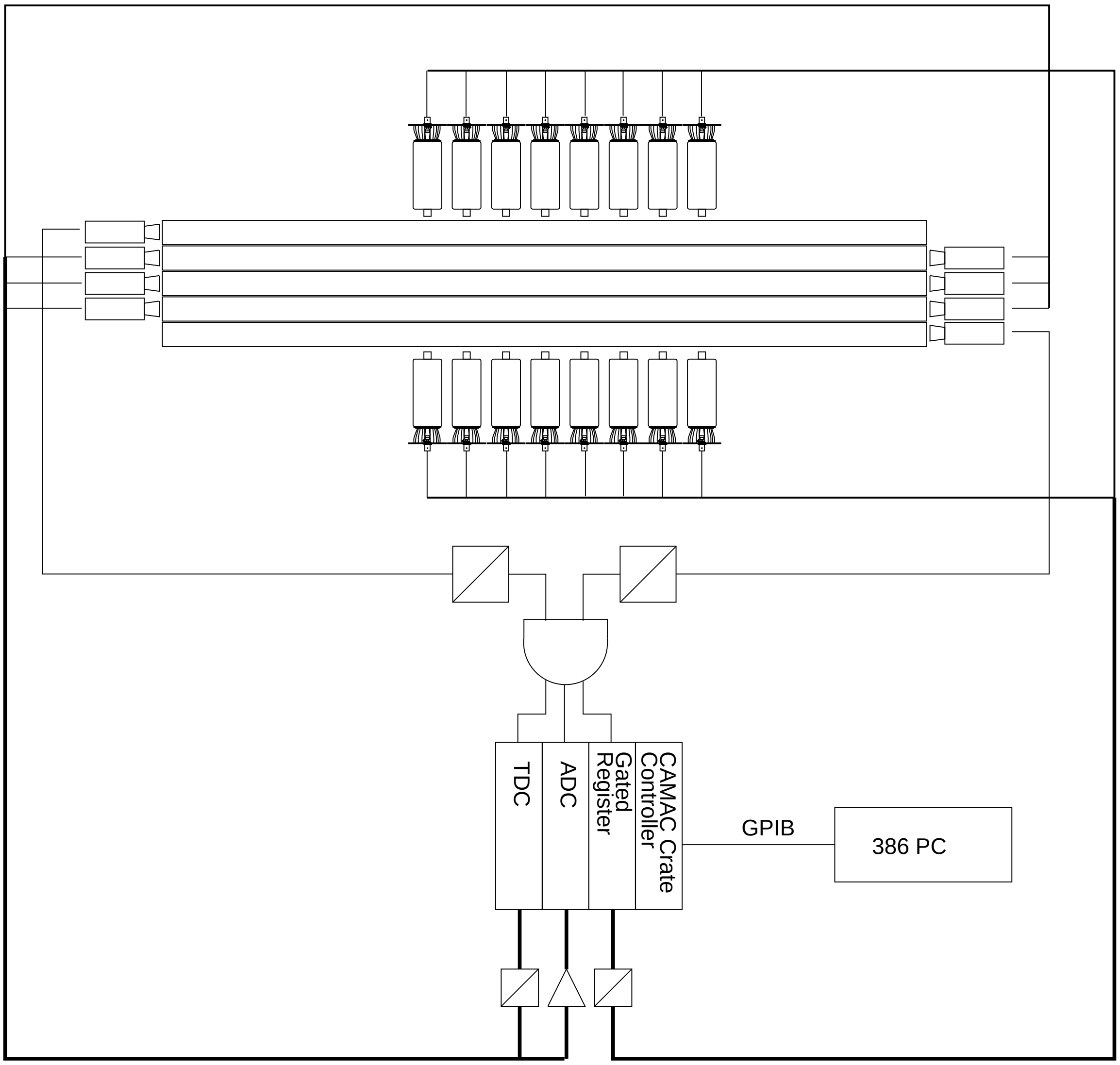
Conclusions from 20 bar test:

- This TOF system can be implemented quickly,
- It worked: occupancy OK, obtained mass peaks.
- Would have liked more data for better calibration.
- Timing resolutions varied: $\sigma_T \sim 155$ ps (extrapolated to a full system)
- Resolution on best bar: $\sigma_T = 110$ ps.



Cosmic Ray Tests

- We can measure timing resolutions on single PMT's using cosmics:



- Measure Q and T on 6 PMT's, fit for t_0, z_0 and $\tan\lambda$.
- Calibrate using 16 hodoscope scintillators.

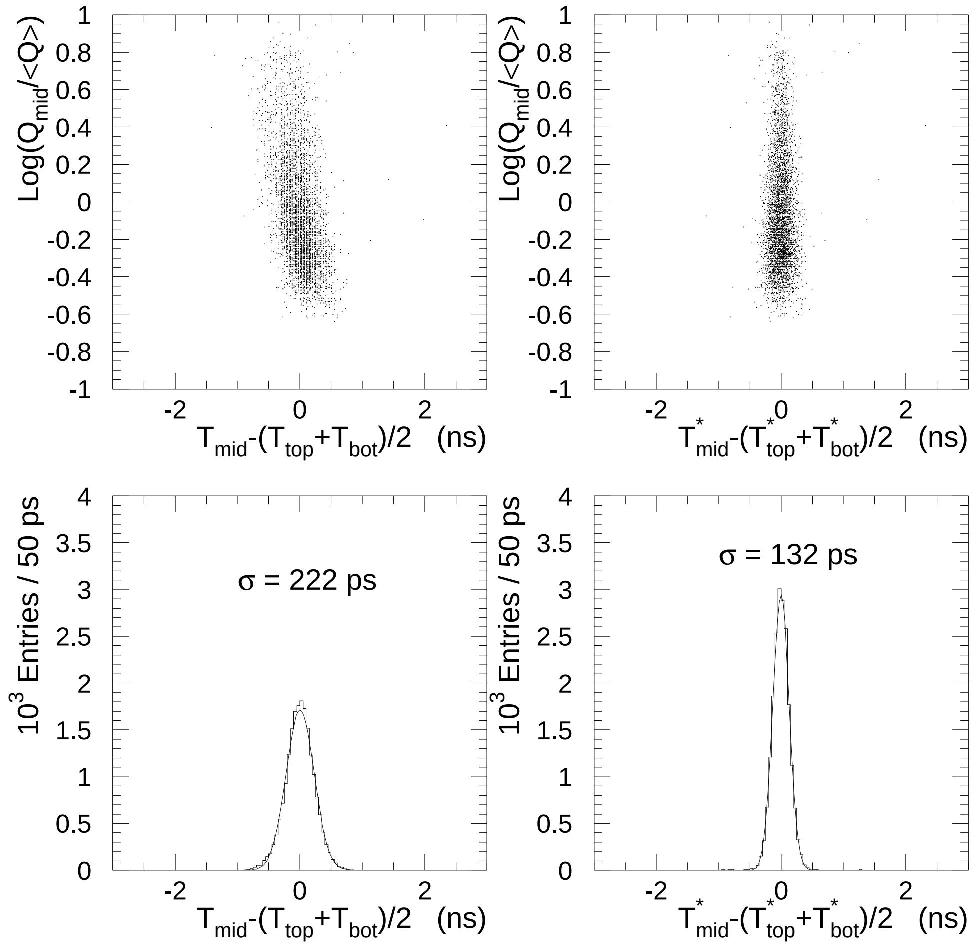
Cosmic Ray Tests

- Leading edge discriminator with walk correction:

$$T^* = T + \alpha \log Q/\langle Q \rangle$$

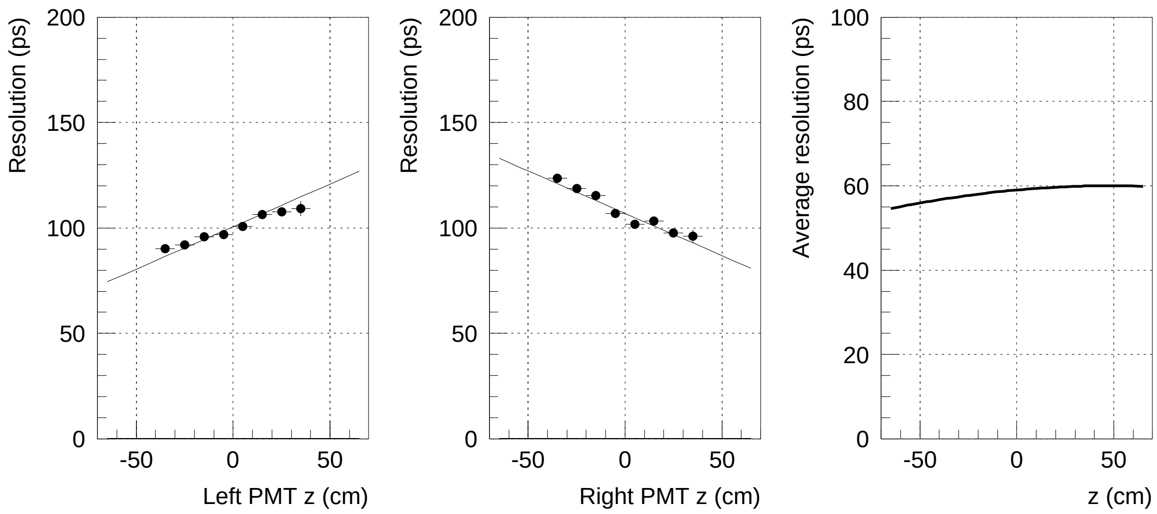
- An estimate of the average timing resolution is obtained from the width of:

$$S(z) = T_{\text{mid}}(z) - (T_{\text{top}}(z) + T_{\text{bot}}(z))/2$$



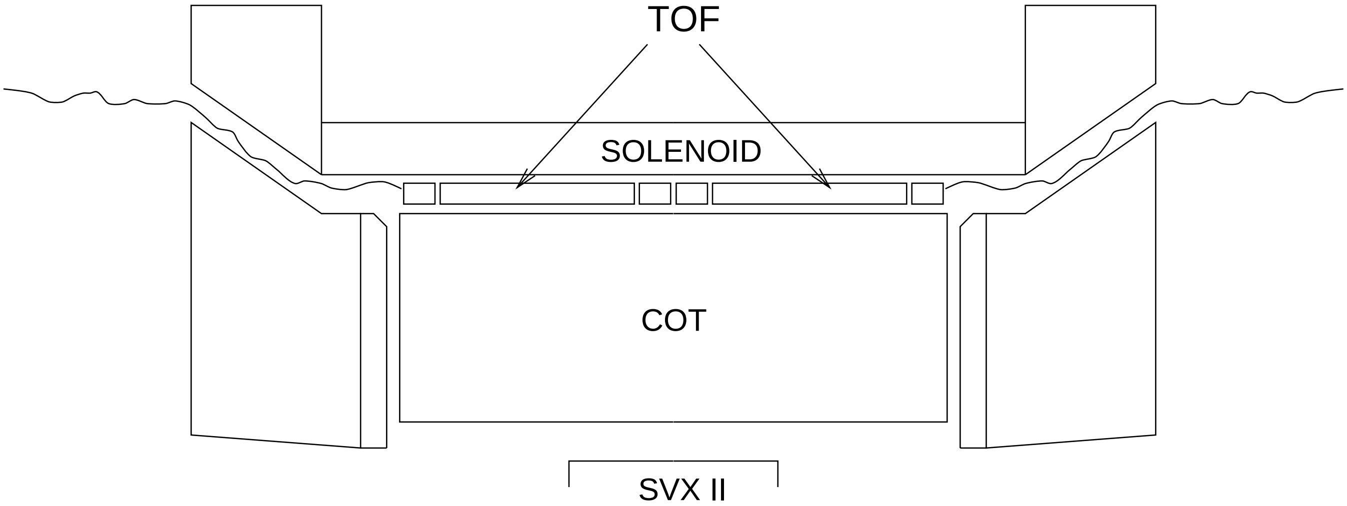
Cosmic Ray Tests

- We can measure the resolution of individual PMT channels:
  1. Calibrate system using hodoscope,
  2. Fit for t_0, z_0, $\tan\lambda$ using 2 bars,
  3. Calculate T_L^{pred} and T_R^{pred},
  4. Determine resolution from $T_L - T_L^{\mathrm{pred}}$ and $T_R - T_R^{\mathrm{pred}}$ distributions.
- Resolution varies as a function of z:



- Average resolution measured to be better than 60 ps.
- We will use this technique to quantify performance of TOF system elements under development.

Overview of Proposed System



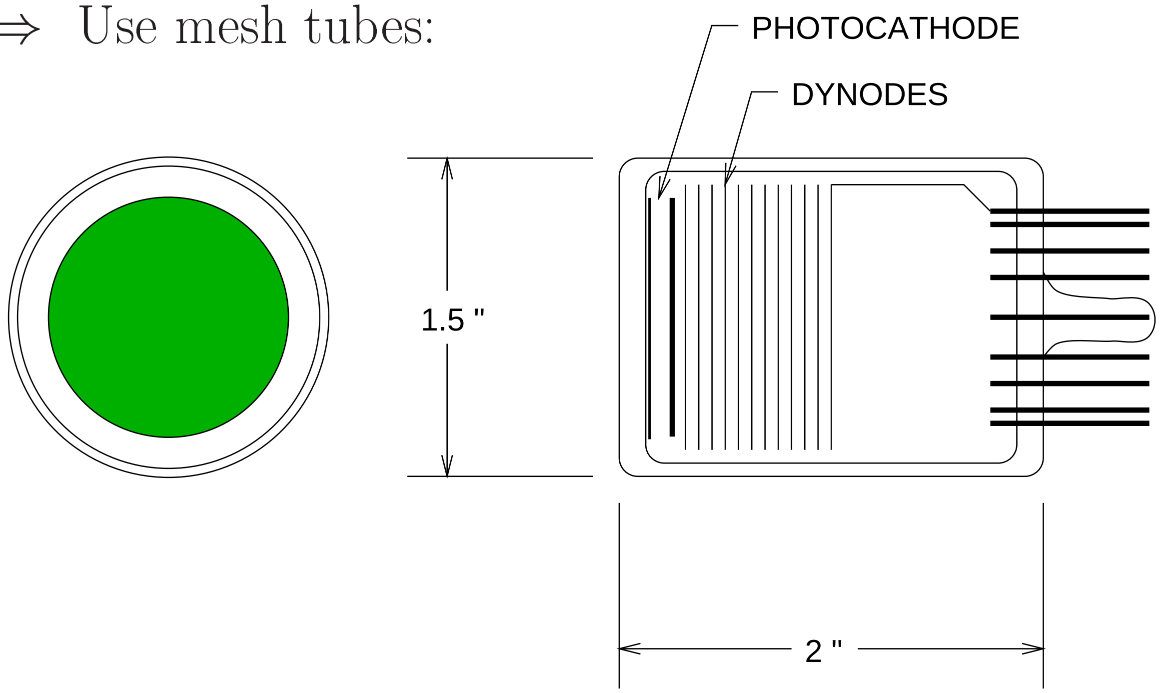
- 432 bars of scintillator, PMT's at both ends.
- *Inside* the solenoid, $B = 1.4$ Tesla
  $\Rightarrow$ Must use fine mesh PMT's.
- Gain reduction in field is > 250
  $\Rightarrow$ Mount preamps directly on PMT base.
- Timing precision in electronics < 25 ps,
- Require common `START` at all 864 TDC's
  $\Rightarrow$ Dedicated TOF clock distribution system.
- Use CDF electronics infrastructure
  $\Rightarrow$ Modify ADMEM board to perform TDC.

Scintillator and PMT

Scintillator of choice is Bicron 408:

- Rise time: 0.9 ns
- Attenuation length: $\sim$ 300 cm (cosmics)

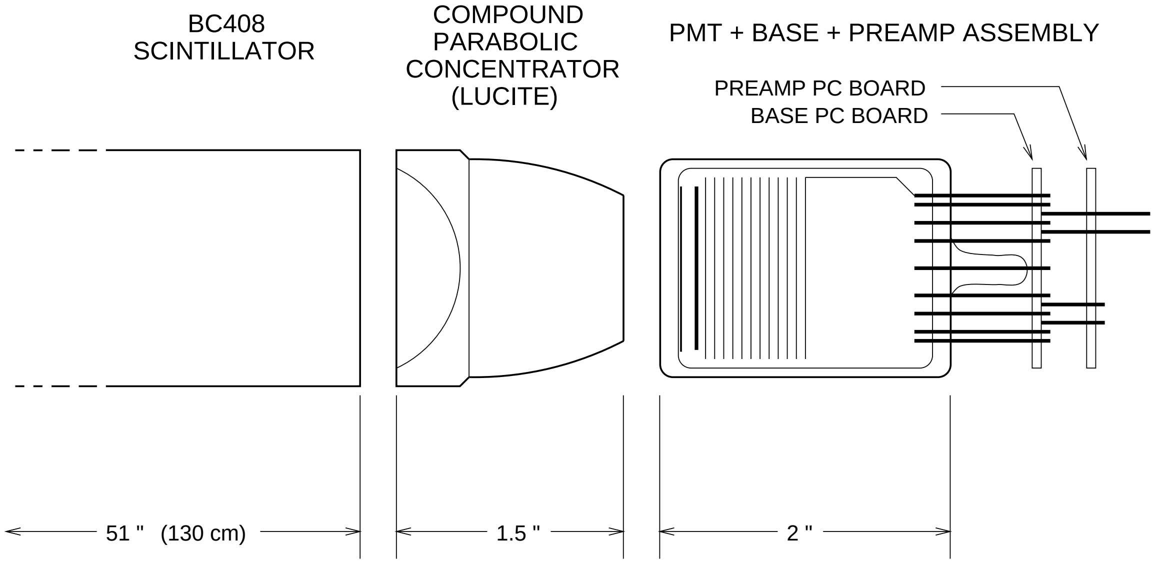
Cover length of CDF with two $4 \times 4 \times 130$ cm bars.
PMT's will be inside the full 1.4 Tesla magnetic field.
$\Longrightarrow$ Use mesh tubes:



- We would prefer higher gain than the 16 stage Hamamatsu R5946.
- Communicated in-field gain requirements to Hamamatsu.
- Considering benefits of 17 and 19 stage tubes.
- We expect to operate with grounded cathodes.

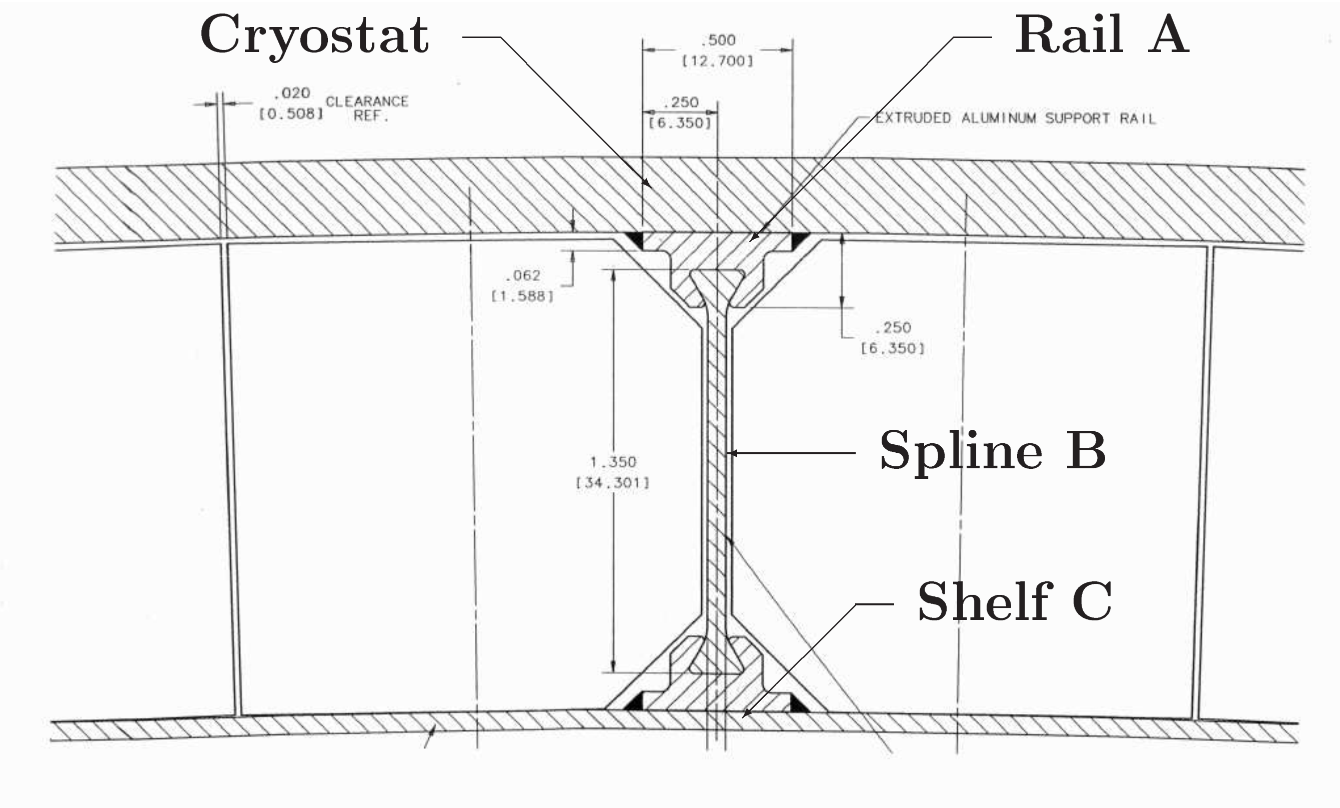
PMT Mounting

Bonding of PMT's to scintillator is similar to scheme in 20 bar test system:



- Match the square scintillator to the round PMT with Lucite Compound Parabolic light Concentrators (CPC's)
- Increases light collection efficiency at small angles.
- Expected improvement in σ_T of $\sim$ 10 ps
- We will measure this improvement directly using cosmics.

Mounting Scheme



Insertion scheme:

1. Remove CTC
2. Attach rail A to cryostat
3. Insert spline B, shelf C – survey assembled mount
4. Remove B, C
5. Insert COT
6. Re-insert B, C

This maximizes the space for COT insertion.
Ongoing discussions with Rich Stanek.

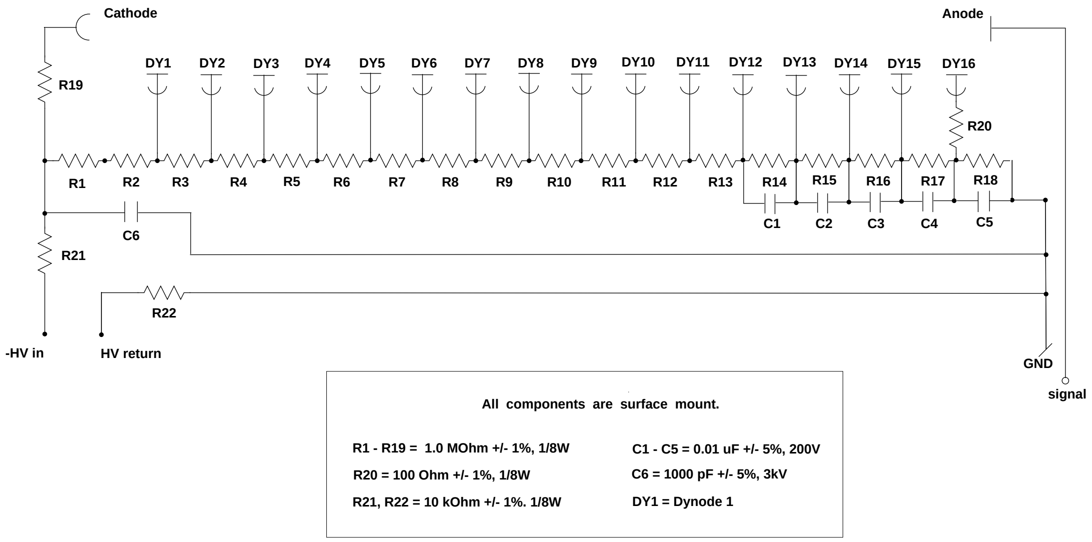
TOF Electronics

Desired precision: Introduce less than 25 ps to the single channel timing resolution through the electronics.

- PMT base
- Preamplifier
- High voltage distribution
- Signal/HV/Control Cables
- Clock distribution
- ADMEM board modifications
- TOFFEE card

PMT Base Design

PMT's used in 20 bar test were Hamamatsu R5946 with grounded anodes.



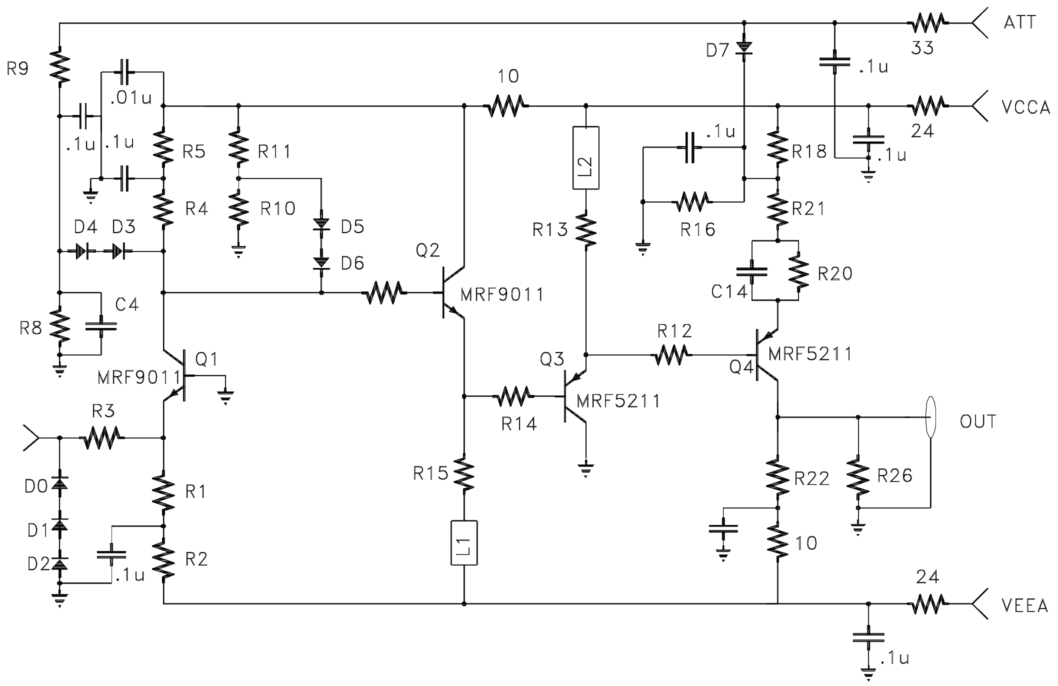
- All components are surface mount,
- Reliable, compact design.

Only minor modifications required:

- Introduce DC blocking capacitor for operation with grounded cathode.
- Modify accordingly for additional dynode stages.

PMT Preamp

TOF PMT PREAMP



- Compact, reliable design used for 20 bar test.
- Only minor changes required for higher gain PMT's.

Cable Issues

- All cables must emerge through the 30° crack.
- 6 slots per side anticipated for TOF.

$$1 \text{ slot} = \frac{3}{8} \text{ in} \times 1\frac{5}{8} \text{ in} \;=\; 0.6 \text{ in}^2/\text{slot}$$

$$12 \text{ slots}/864 \text{ channels} \;=\; 0.0085 \text{ in}^2/\text{channel}$$

- Each channel requires HV,signal,preamp power, gain control.

Manufacturer	Cable candidate	Area (in^2)
New England	50 Ω coax (HV)	.0019
Habia	50 Ω coax (HV)	.0062
Habia	50 Ω Kapton coax (HV)	.0018
Habia	50 Ω mini coax (HV)	.0015
Habia	120 Ω twisted pair (signal)	.0007

- Cable tests:
  - HV cables powered at 3 kV for 2 months.
  - None tripped with 0.8 μA threshold.
  - Habia 50 Ω Kapton cable tripped once at 5 kV.
- Low voltage for preamps: 10 mA/channel – not a problem.
- We will participate in the slot mock up (August?).

High Voltage

- We propose to operate PMT's with grounded cathodes.
- We consider three HV schemes:
  1. CAEN supplies powering groups of tubes.
     - *Used by other groups in CDF.*
     - *Groups of* ~ 8 *bars must be ganged together to reduce cost.*
     - *Difficult to optimize gain within a group.*
  2. Cockroft-Walton active bases.
     - *Cannot be used with cathodes grounded.*
  3. Bulk HV supplies with resistor/Zener array.
     - *Easy and relatively inexpensive.*
- We have experience with (3): This scheme powers 10,000 PMT's for SNO.

Clock Distribution

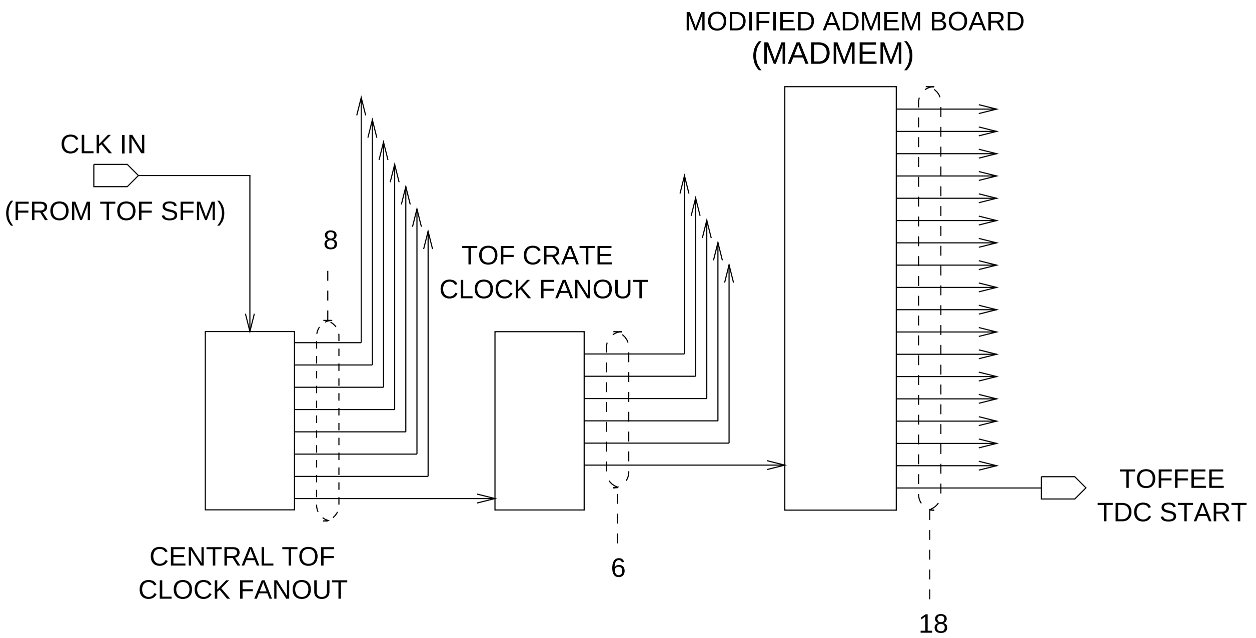
Requirements:

1. Distribute a stable `START` signal to 864 TDC's.
2. Channel-to-channel jitter should be < 25 ps.
3. Monitor channel-to-channel timing shifts to $\ll 25$ ps.

Design issues:

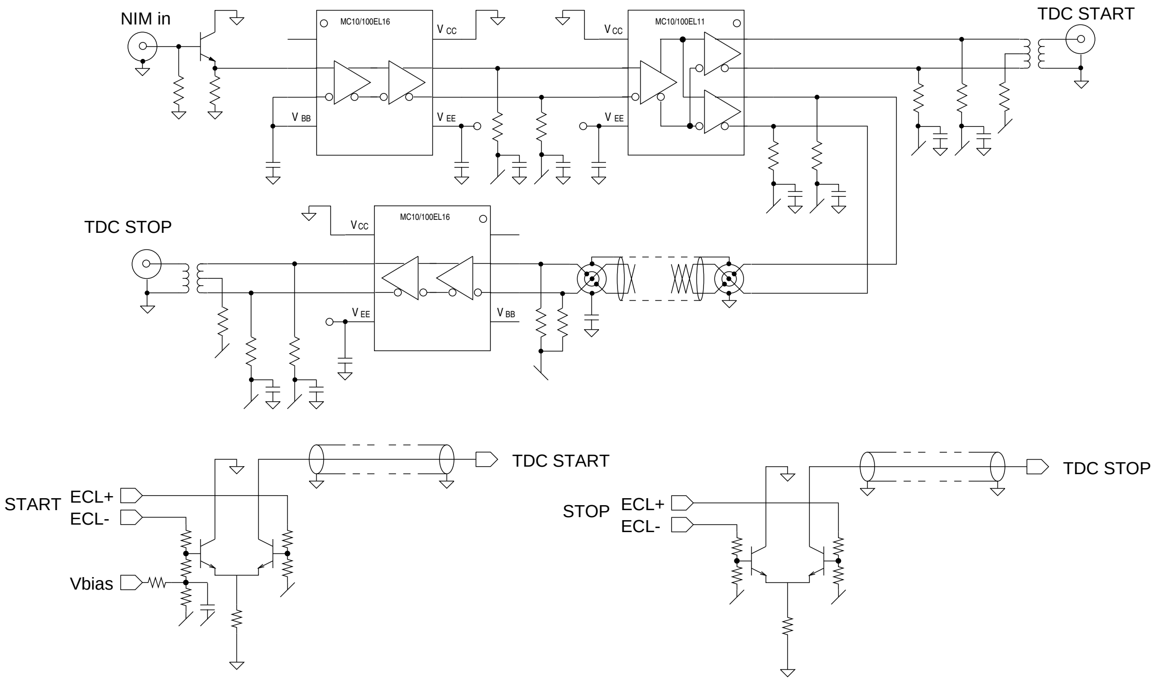
- All clock signals must be differential ECL.
- All clock cables must be twisted pair.
- Use the same cable/connectors as the trigger system.

TOF CLOCK FANOUT SCHEME TO 8x6x18 = 864 CHANNELS



Clock Distribution

Test setup for studying timing jitter/drifts:



- All chips are SMT Motorola ECLinPS Lite series.
- Drive 40 ft shielded twisted pair cable.
- Measure delay with LeCroy TDC (50 ps bins).
- Vernier delay adjustment by controlling V_{bias}.

Short-term jitter (electronics+cable+TDC):

$$\sigma_{\Delta T} = 2.8 \pm 0.1 \text{ ps}$$

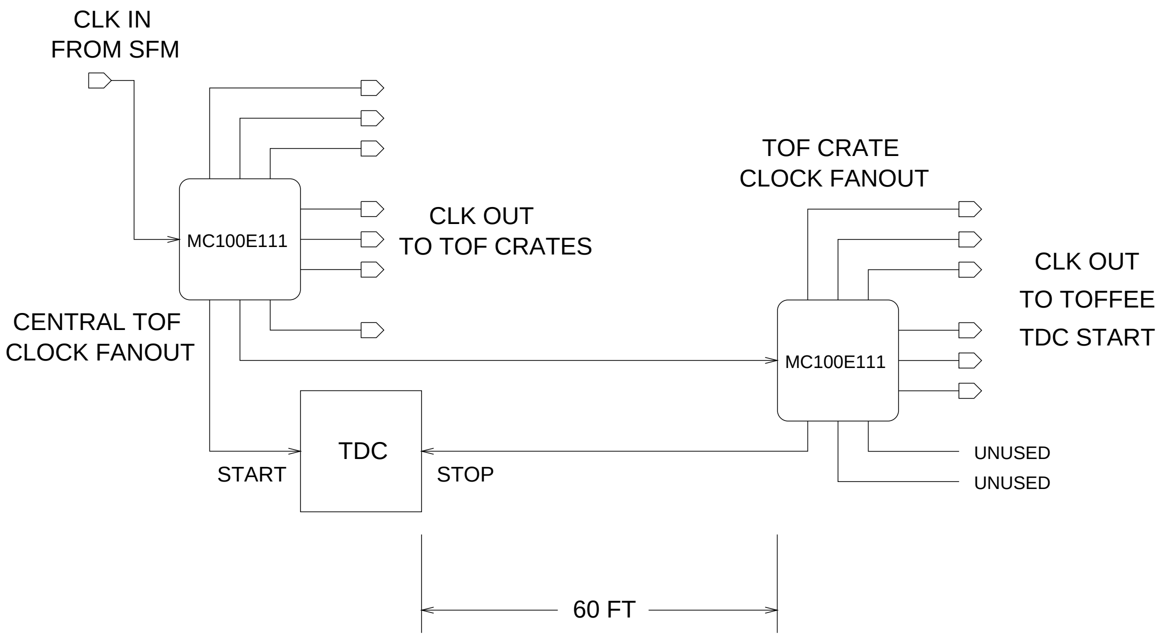
Temperature coefficient:

$$\frac{d\Delta T}{d\mathcal{T}} \sim 0.1 \text{ ps/ft/}^\circ\text{F}$$

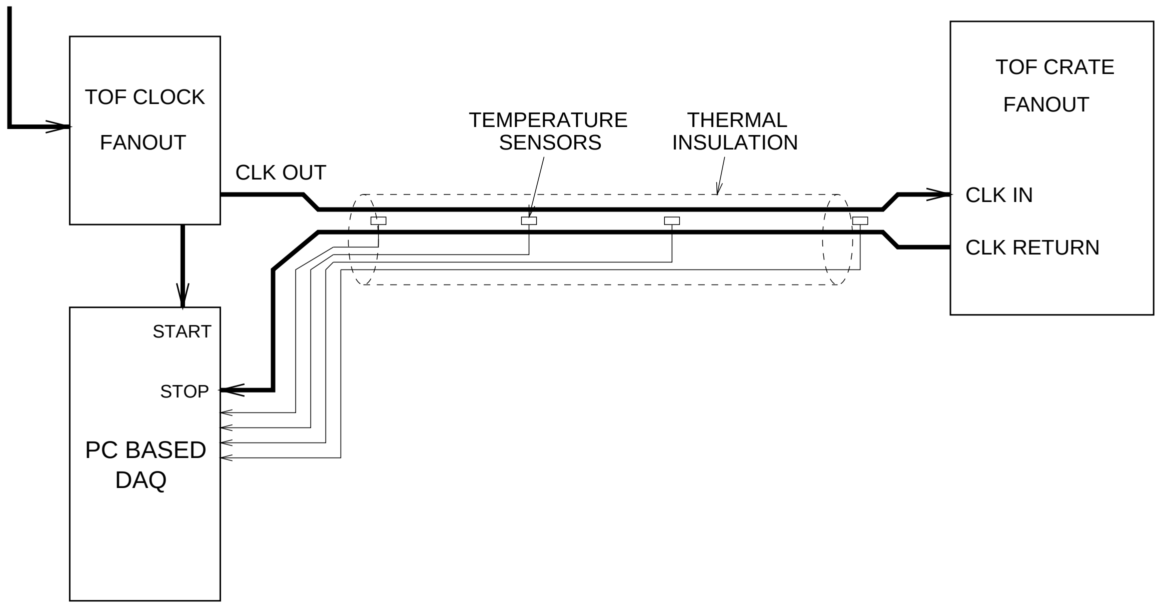
Clock Distribution

Monitoring drifts in `START` signal:

- Measure round-trip cable delay.



- Measure temperature along clock cables.



ADMEM Board Modifications

We will convert the 20 channel ADMEM module to an 18 channel TDC module. (Modified ADMEM $\equiv$ MADMEM)

Modifications required:

- Front panel connector for precision differential ECL clock input,
- Add 1:18 differential ECL clock fanout,
- Route differential clock traces to Café connectors,
- Replace Café modules with TOF Front End Electronics (TOFFEE) cards.

Observations:

- Space exists for connector, fanout and clock traces.
- 48 modified ADMEM boards for timing,
- 48 unmodified ADMEM boards for pulse height readout. (Total of 96 ADMEM boards required.)

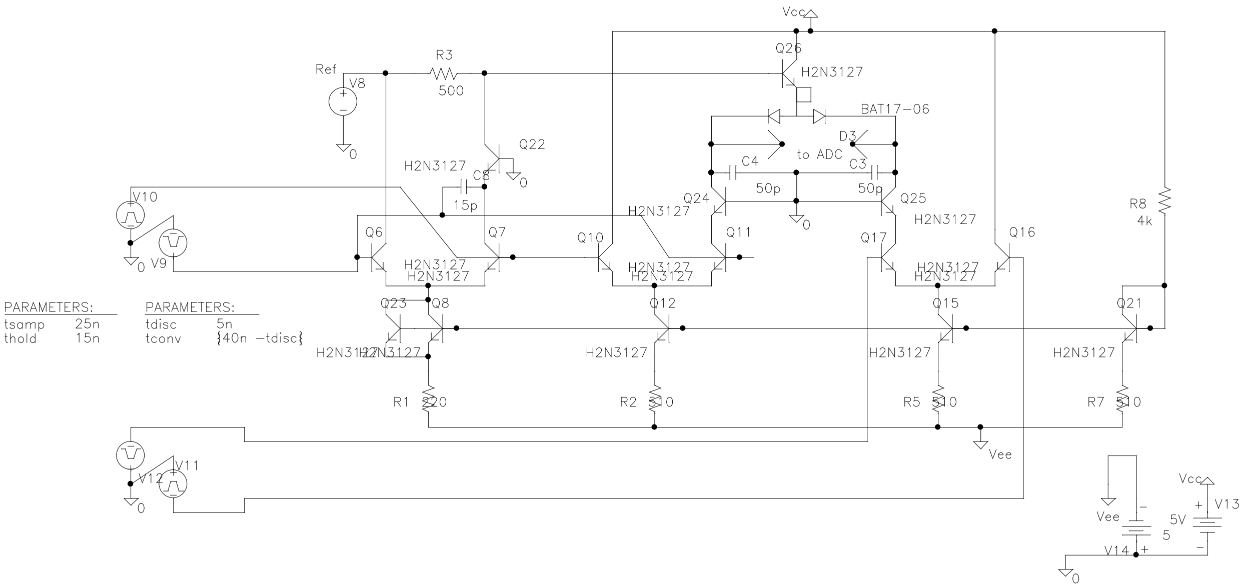
Additional benefit:

- TOF/Luminosity timing requirements perfectly matched.
- We will provide 6 extra boards + 1 clock fanout module to the luminosity group.

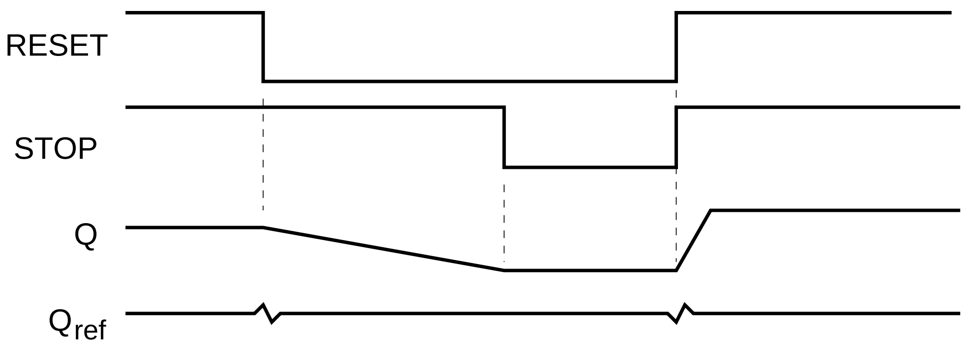
TOF Front End Electronics

Leading edge discriminators + offline walk correction will give adequate timing resolution.

TOF TVC



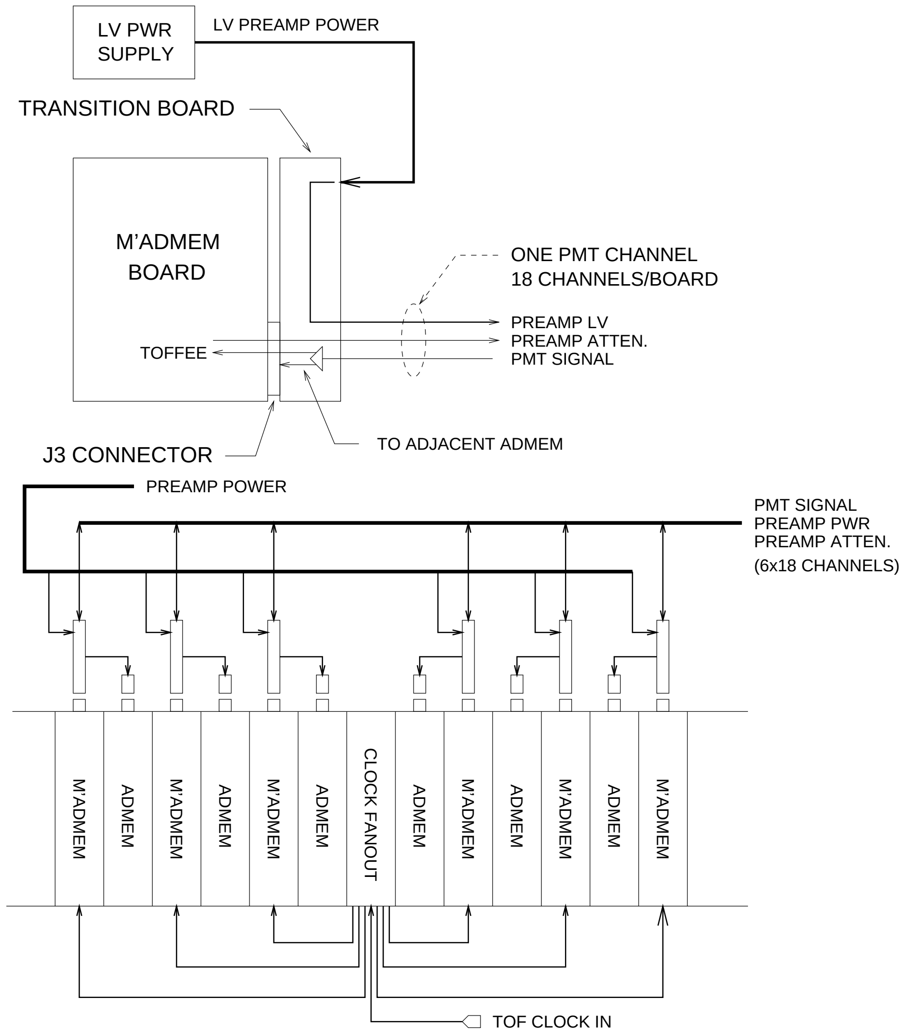
TOF TVC TIMING DIAGRAM



- The design works in PSPICE.
- Next, we will build one.

Crate Layout/Cabling

- Space available in the 8 endwall crates.
- Transition boards on modified ADMEM modules receive PMT signals, send them to ADMEM/modified ADMEM boards via J3.
- Preamp low voltage also distributed via transition boards.



Timetable/Manpower

- We have a timetable which is still being refined.
- If approved by the end of September, we will be installed and commissioned by February, 2000.
- Penn involvement:

J. Kroll	faculty
F. Ukegawa	research associate
M. Jones	postdoc
R. Van Berg	staff
F. M. Newcomer	staff
W. Kononenko	staff
P. Keener	staff
Chunhui Chen	grad student
Another	grad student

- Our schedule includes technical support from FNAL.
- Interest expressed by Japan and Italy.

TOF System Budget

TOF System				5/20/98 RVB		
Cost Estimate						
	Quan. System	Q W/ Spares	Cost per	Basis of Estimate	Total	
Detector						
PMTs	864	900	$910	Quote - Ham. 120kY @ 132/$	$819,000	
Testing	900	900	$0	Incl. In Ham. Quotation	$0	
Base	864	900	$12	Eng. Est.	$10,800	
Preamp	864	900	$16	Eng. Est.	$14,400	
Mechanical Mount (base)	864	900	$0	FNAL shops	$0	
Tube Assy Testing	900	900	$20	Eng. Est.	$18,000	
Scintillator	864	900		Quote - Bicron	$171,000	
Scintillator Testing	900	900	$0	FNAL Techs	$0	
Mechanical Mounts (scint)	900	900	$0	FNAL shops	$0	$1,033,200
Electronics					$0	
Normal ADMEM	48	48	$3,500		$168,000	
DECAF	864	864	$100		$86,400	
Mod'd ADMEM	48	55	$3,700	Eng. Est.	$203,500	
TOFFEE	864	925	$85	Eng. Est.	$78,625	
Transition Boards (J3)	96	110	$75	Eng. Est.	$8,250	
Central Clock Dist.	1	2	$4,500	Eng. Est.	$9,000	
Crate Clock Fanout	8	12	$850	Eng. Est.	$10,200	
Board Testing	950	950	$25	Eng. Est.	$23,750	
System Testing/Int.	1	1	$5,000	Eng. Est.	$5,000	$592,725
Calibration & Monitoring					$0	
Laser	1	1	$22,000	Eng. Est.	$22,000	
Fiber + Conn.	432	450	$35	Eng. Est.	$15,750	
Monitor & Control comp.	1	1	$7,000	Eng. Est.	$7,000	$44,750
Power Supplies					$0	
HV System					$0	
Option 1 - CAEN	1	1	$28,994	1 chan/8 PMT - 16chan/bd	$28,994	$35,494
Option 2- C-W	864	900	$50	1 C-W/chan	$45,000	$51,500
Option 3 - Bulk+"COW"	1	1	$9,500	2 bulk, 2 COW	$9,500	$16,000
LV Power for preamps	8	10	$650	Eng. Est.	$6,500	
Cables					$0	
PMT Coax to ADMEM	864	900	$8	Eng. Est.	$7,200	
PMT HV to HV System	864	900	$9	Eng. Est.	$8,100	
PMT LV+ Cont. to Power	864	900	$5	Eng. Est.	$4,500	
Timing, Central to Crates	16	20	$40	Eng. Est.	$800	
Timing, Fanout to Cards	48	55	$30	Eng. Est.	$1,650	$22,250
						$1,708,925

Total cost: 1.7 M.

TOF System Budget

Total cost: 1.7 M.

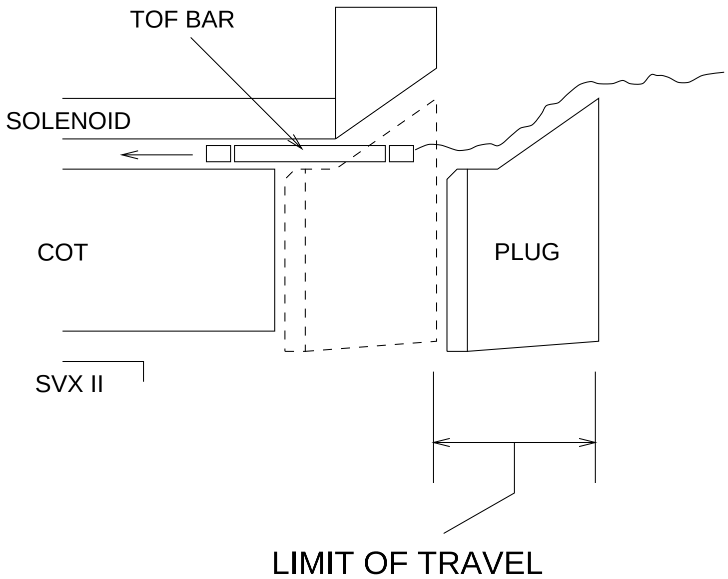
80% of the cost due to three items:

Item	Quantity	Basis	Total cost
PMT's	900	Hamamatsu quote	$819,000
Scintillator	450	Bicron quote	$171,000
ADMEM boards	96	FNAL quote	$345,600

- Investigating supply of less expensive PMT's by Burle/Russia.
- Bicron's scintillator cost is invariant but an alternate supplier in Russia may be possible.
- We disfavour developing a new CDF board to replace ADMEM.
- Cost is driven by channel count.
- What drives the channel count?

Long *vs* Short Bars

- Current planning must allow for installation after end plug calorimeters are in place.



- End plug will move only 62 inches so we can't install long bars.
- Advantages of short bars:
  - Lower occupancy,
  - Better timing resolution (70 ps instead of 100 ps).
- Disadvantages:
  - More channels, higher cost (1.7 M instead of 1 M),
  - Dead space ($\sim$ 20 cm) in the middle.
- A decision to proceed with 3 m bars *must* be made soon to remain feasible.

Conclusions

- A Time of Flight system will significantly benefit CDF's B-physics program.
- Other applications beyond B-physics to be considered.
- We want this at the *start* of Run II – we need the full data set to remain competitive with the B-factories.
- The proposed system uses well established existing technology.
- We can install it in time for the start of Run II.
- Commissioning and calibration could be accelerated with additional help.
- *Everyone* will reap the benefits.