DETECTORS

for

PARTICLE

IDENTIFICATION

Lecture I - Time-of-Flight and dE/dx

Lecture II - Cerenkov and Transition Radiation

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The techniques I will discuss -

- determine the mass and therefore the species of <u>charged</u> particles

- are <u>non-destructive</u>

- require that the momentum be independently measured in the same or a different sub-detector

Time-of-Flight

A relativistic particle traveling at velocity, v, traverses distance, D, in time, t, given by

$$t = \frac{D}{v} = \frac{D}{\beta c} = \frac{DE}{pc^2},$$

where E and pc are the particle energy and momentum. Then,

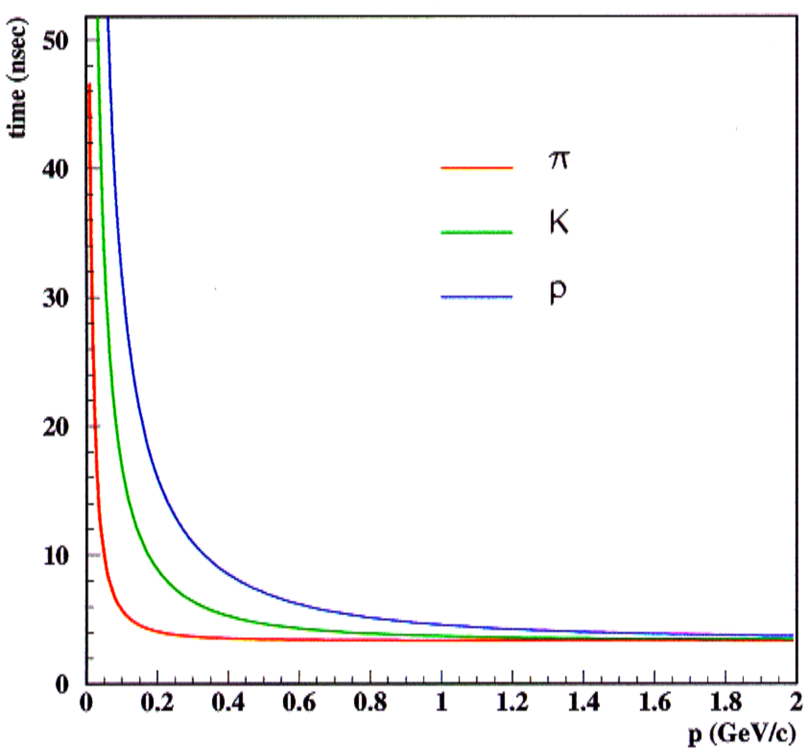
$$\begin{aligned} t &= \frac{D\sqrt{(pc)^2 + (m_o c^2)^2}}{pc^2} \\ &= \frac{D}{c}\left(1 + \frac{(m_o c^2)^2}{(pc)^2}\right)^{\frac{1}{2}} = t_o\left(1 + \frac{(m_o c^2)^2}{(pc)^2}\right)^{\frac{1}{2}} \end{aligned}$$

where $t_o = D/c$ is is the time it would take a particle traveling at the speed of light to traverse distance D.

Just how much time is this?

$$\frac{1}{c} = \frac{1}{3. \times 10^8 m/sec} = 3.33 \times 10^{-9} sec/m$$

This is small, only 3.33 nsec! And, because of the dependence on m_0c^2/pc, we approach this limit very quickly as the particle momentum increases. This is demonstrated in the plot shown below, where you can see that it is likely to be very difficult to use this technique above a momentum of about 1 GeV/c.



TOF by Particle Type - 1 meter Flight Path

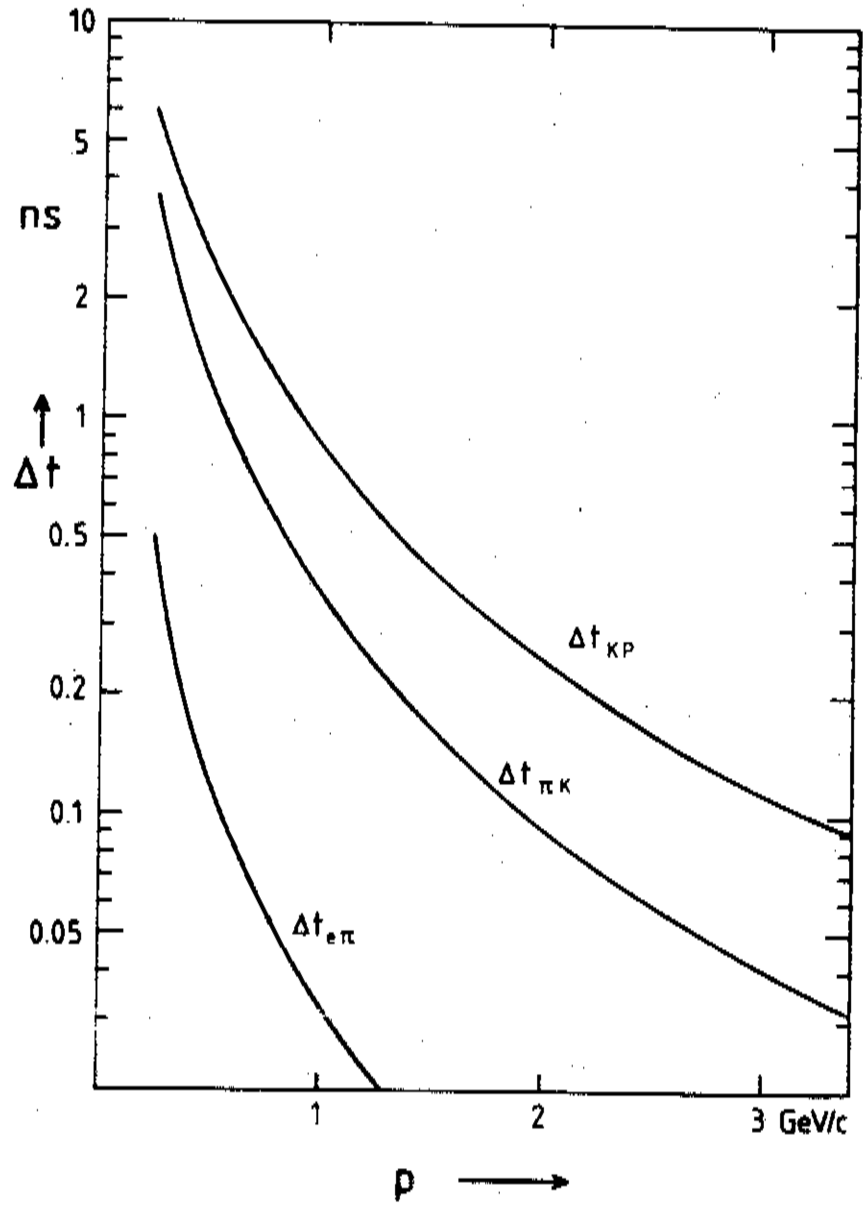
For particles with two different masses, m_1c^2 and m_2c^2, and the same momentum, pc, the *difference* in the time-of-flight over a distance, D, is given by:

$$t_1 - t_2 = t_o \left[\sqrt{1 + \frac{(m_1c^2)^2}{(pc)^2}} - \sqrt{1 + \frac{(m_2c^2)^2}{(pc)^2}} \right]$$

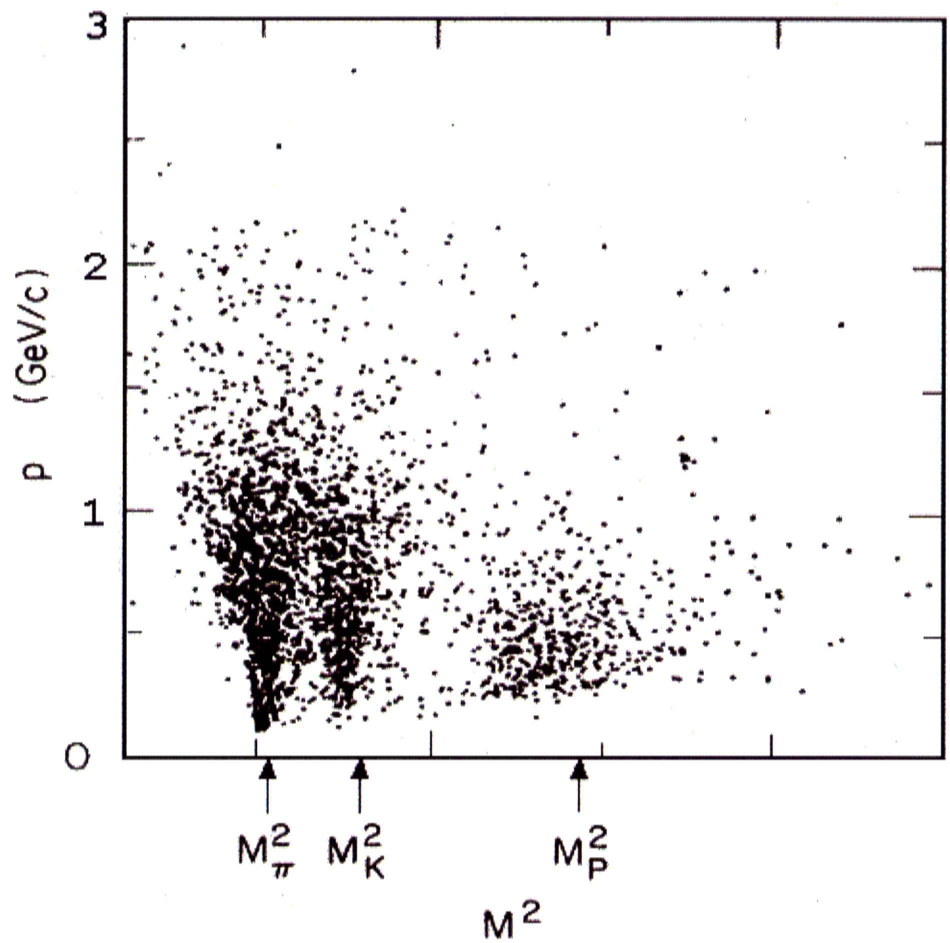
When $(pc)^2 >> (m_1c^2)^2, (m_2c^2)^2$, we can substitute a series expansion for the two square roots,

$$t_1 - t_2 = t_o \left[\frac{(m_1c^2)^2 - (m_2c^2)^2}{2(pc)^2} \right]$$

The dependence of the time difference on the inverse of the momentum squared in this limit is clearly demonstrated in the figure on the next transparency, which shows the difference in the time-of-flight for pions and kaons, kaons and protons, and protons and kaons as a function of momentum, over a flight path of 1.0 m.



Δt versus momentum for Kp, πK, and eπ over a flight path of 1 meter.



Squaring the basic equation, we obtain -

$$(m_o c^2)^2 = (pc)^2 \left[\frac{t^2}{t_o^2} - 1 \right]$$

The plot above shows $(m_o c^2)^2$ for π's, K's, and p's from MARK II data. The resolution of the TOF detector for the experiment was $\Delta t = 300$ *picoseconds*

Differentiating,

$$\Delta(m_o c^2)^2 \simeq (pc)^2 \left(\frac{2t\Delta t}{t_o^2}\right)$$

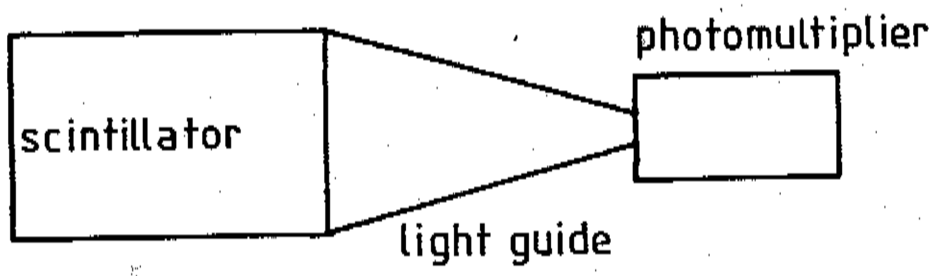
$$= \left[(pc)^2\left(1+\frac{(m_o c^2)^2}{(pc)^2}\right)^{\frac{1}{2}}\right]\frac{2\Delta t}{t_o}$$

Thus, two particles are separable when -

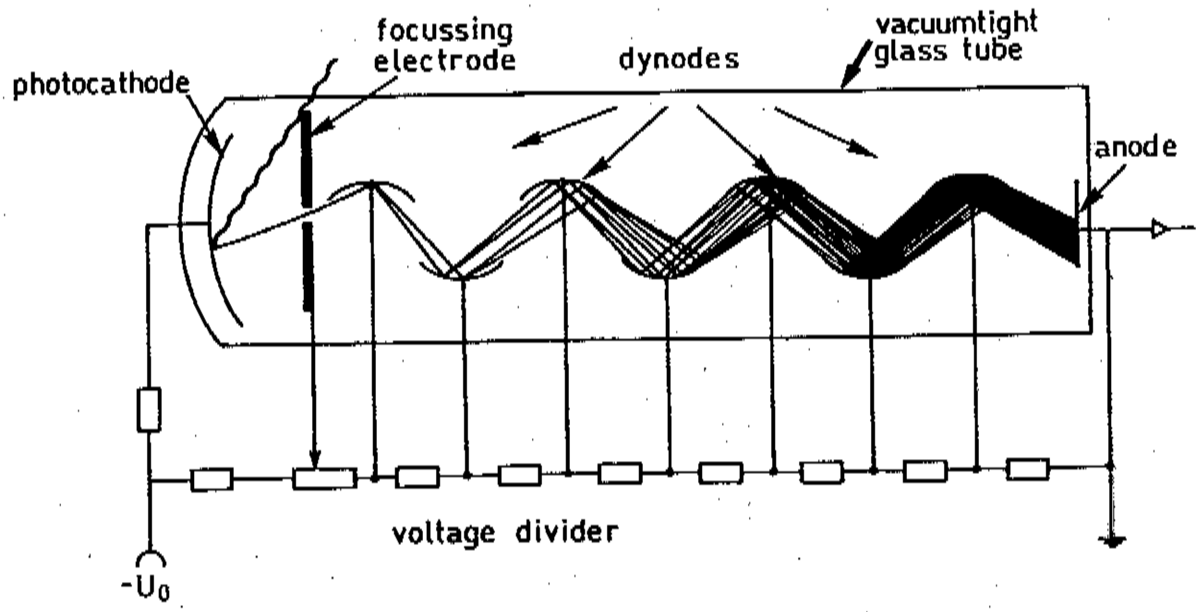
$$\eta = \beta\gamma = \frac{pc}{m_o c^2} \leq \sqrt{\frac{t_o}{2\Delta t}}$$

How do we measure time and how good is the measurement?

The most common device used to measure time in time-of-flight detectors is a scintillation counter with attached photomultiplier tube (PMT).



Schematic showing the response of a PMT to an incident photon.



What are the sources of uncertainty in the times we measure with this device?

Finite rise and decay times of the flourescence in the scintillator material. Since this is a stochastic process the exact times at which the photons are emitted can't be predicted. We can use "fast" organic scintillator to keep the uncertainty as small as possible.

The signal output can be mathematically described by -

$$N(t) = N_o f(\sigma, t) e^{-\frac{t}{\tau}},$$

where $f(\sigma, t)$ is a Gaussian with standard deviation σ and τ is the decay constant. For some common "fast" scintillators, these fit parameters are:

Scintillator	σ(ns)	τ(ns)
NE102A	0.7	2.4
NE111	0.2	1.7
Naton 136	0.5	1.87

Difference in pulse signal size due to statistical fluctuations -

$\sim$ 1 photon is produced for 100 eV of deposited energy

$\sim$ 2 MeV/cm of energy is deposited for particles with $z = 1$ (MIP)

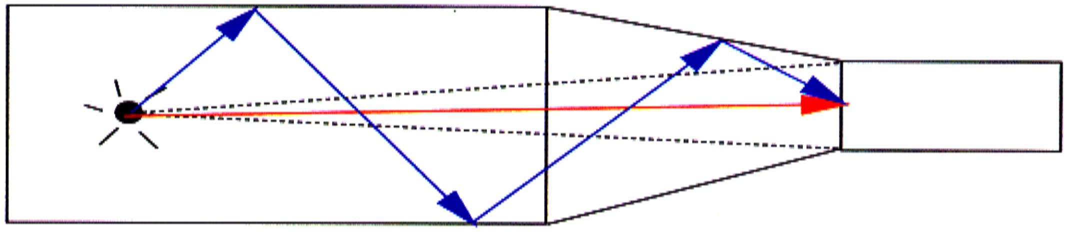
$\rightarrow \sim$ 20,000 photons/cm

Use *thicker* counters to improve the photon statistics -

Typical thickness is about 5 cm.

But, don't overlook the impact on the material budget. TOF systems are usually placed outside of the tracking detectors just inside the calorimeters in collider detectors for this reason.

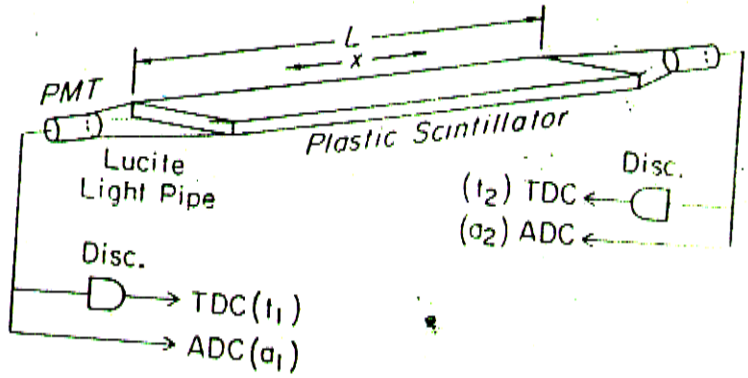
Different times of arrival at the PMT for photons emitted in the scintillator.

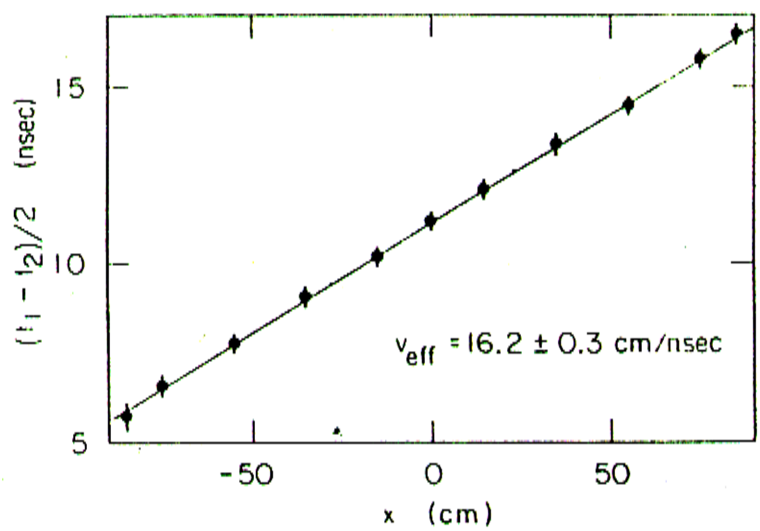


Light is emitted in all directions. How much travels directly to the PMT depends on the solid angle it subtends looking from the emission point. The pulse shape depends on how many “fast” (shown in red) and ”slow” (shown in blue) photons are included in the signal. Better time resolution can be achieved with a faster signal risetime. To increase the solid angle and thus the number of “fast” photons -

- Eliminate the light guide and glue the PMT directly to the scintillation counter. This also reduces the number of bounces the “slow” photons undergo.

- Glue a PMT on both ends of the scintillation counter. This also gives a means by which the dependence of the time resolution on the hit position in the counter can be corrected.





$$\cos\theta_{eff} = \frac{v_{eff}}{c/n} \simeq 0.84$$

$\Rightarrow \theta_{eff} \simeq 33°$. $(\theta_{int} \simeq 39°)$

Light undergoes ~ 30 bounces

If t_1, t_2 are the arrival times of the signals at the two ends of the counter, then

The position, x, at which the particle entered the counter is given by

$$x = \left(\frac{t_1 - t_2}{2}\right) v_{eff},$$

where v_{eff} is the effective propagation velocity of light in the scintillator.

The time, t, at which the particle entered the counter is given by

$$t = \left(\frac{t_1 + t_2}{2}\right) - \frac{L}{2v_{eff}},$$

where L is the length of the counter.

Time "jitter" in the PMT -

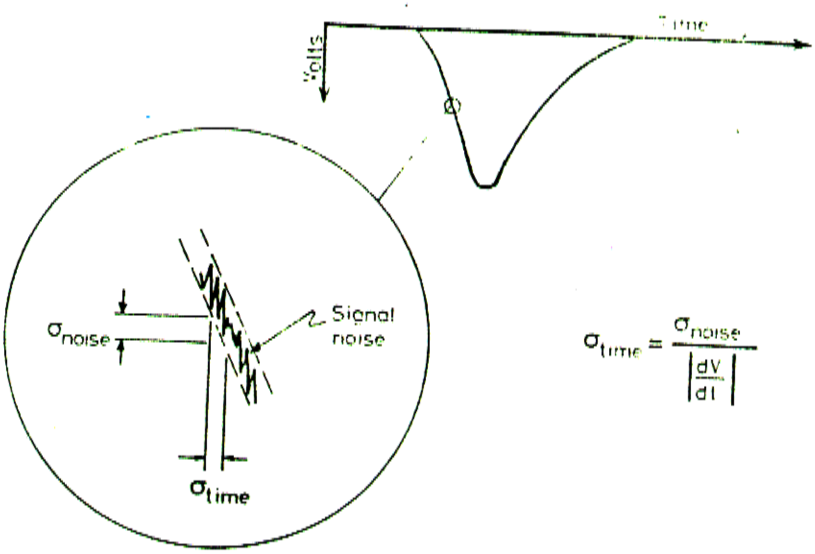
Difference in the kinetic energy of photoelectrons ejected from the photocathode.

This is small compared to the difference in the time of traversal of the p.e.'s from the photocathode to the 1st dynode

Increasing the voltage on the 1st dynode helps. Most PMT bases provide a means to do this.

Electronics

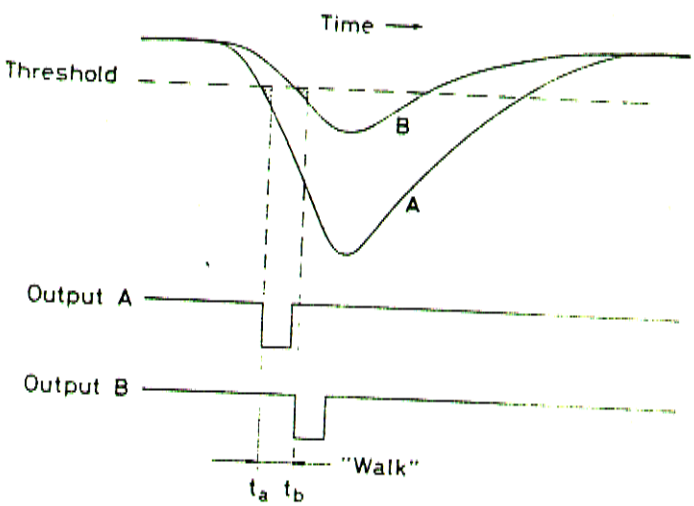
Time →



$$\sigma_{time} = \frac{\sigma_{noise}}{\left|\frac{dV}{dt}\right|}$$

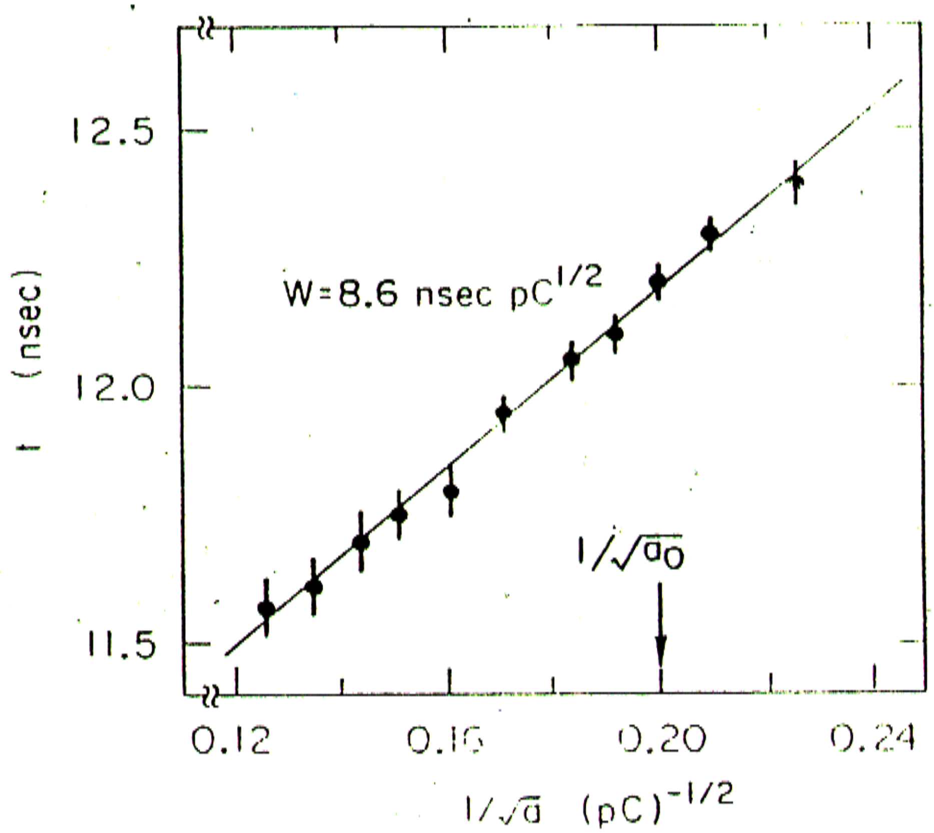
← faster rise time improves

Volts ↓



Time "walk"

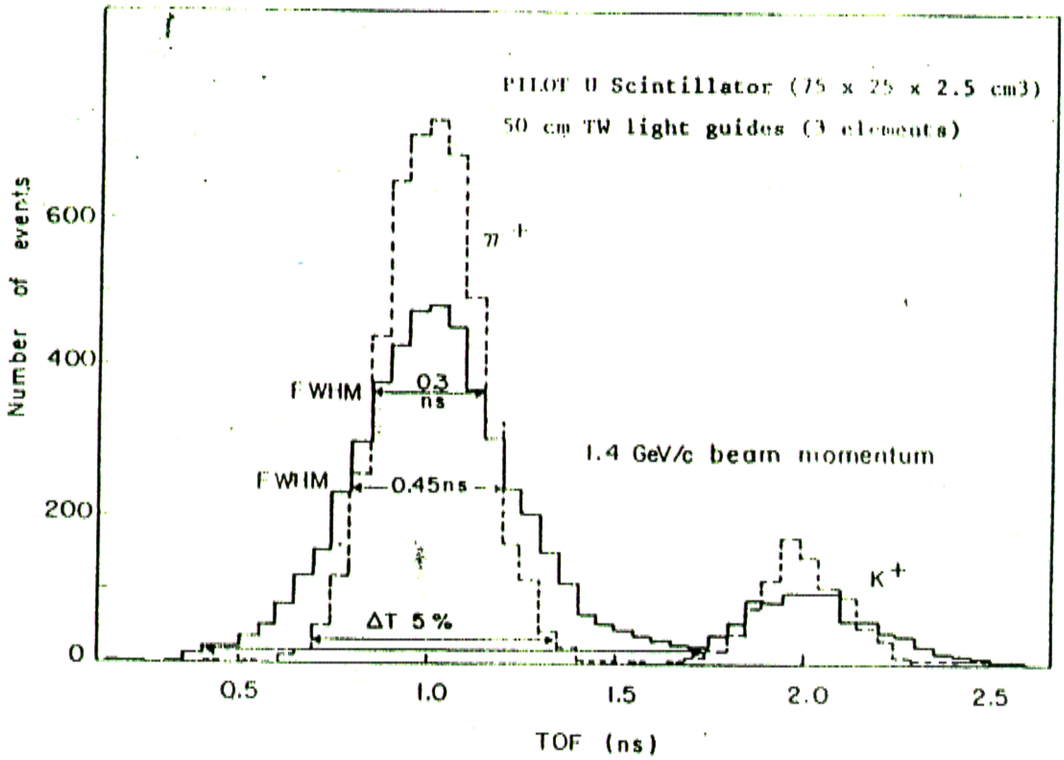
Use measured pulse height to correct for correlation with t_{meas}



$$t_{corr} = t_{meas} - W\left(\frac{1}{\sqrt{a_0}} - \frac{1}{\sqrt{a}}\right) - \frac{x}{v_{eff}}$$

W is a parameter of the fit and

a_0 is a reference pulse height.



TOF Separation of π's and K's –

1.4 GeV/c Momentum

~5.5 m Flight Path

Hits at Center of Counter

Solid Histogram uncorrected data ($\sigma = 0.28$, $\Delta T_{5\%} = 1.25$ ns)

Dashed Histogram Pulse Height Corrected ($\sigma = 0.15$, $\Delta T_{5\%} = 0.65$ ns)

TABLE II

Comparison of nine time-of-flight counters. L is the counter length and N_e is the average number of photo-electrons for minimum ionizing particles. Photoelectron yields which are starred (*) are my estimates based on the thickness of the scintillators. This was done when this information was unavailable from the references.

Counter	L(cm)	N_e	Δτ(psec)
1) MARK II[3]	350	40	255
2) "Free Quark Search" (PEP-14)	315	90	166
3) DASP[4]	172	28*	212
4) F. Binon et al., N.I.M., 153, 409 (1978)	25	28*	92
5) M. Wollstadt[7]	100	39*	144
6) M. Wollstadt[7]	50	16*	152
7) MARK III[5]	300	120	140
8) M. Wollstadt[7]	100	260*	85
9) Same as 4)	~.2	4500*	48

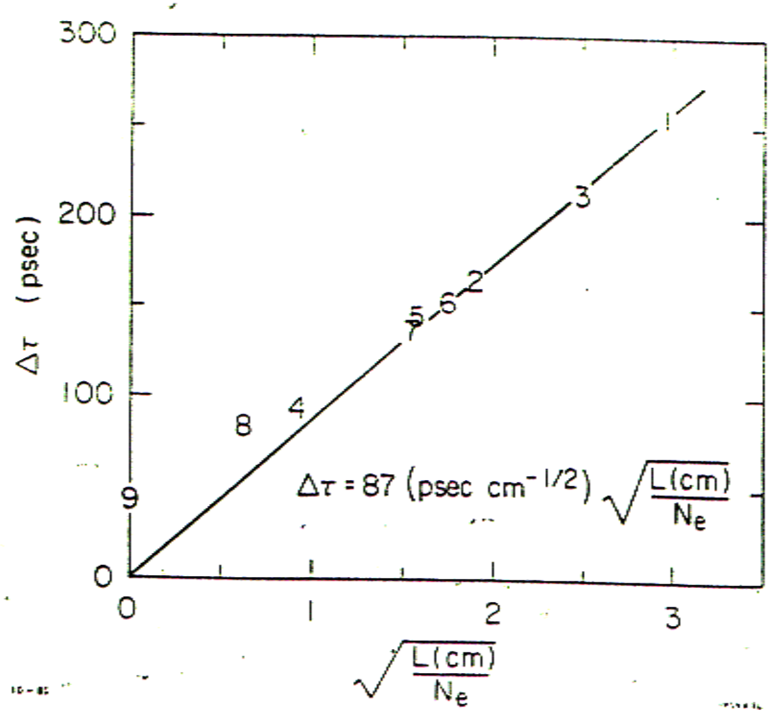


Fig. 10. A comparison of the time-of-flight counters listed in Table II. L is the length of the counter and N_e is the average photo-electron yield for minimum ionizing particles.

After correction for position and amplitude effects and if contributions from PMT and electronics are small

$\Rightarrow \Delta\tau \propto \sqrt{L/N_e}$

Ways we can improve the discrimination of a tof detector -

- *Longer flight path*

- *Detectors with better time resolution*

- *More measurements along the particle path*

This results in an improvement of $1/\sqrt{N}$, where N is the number of measurements.

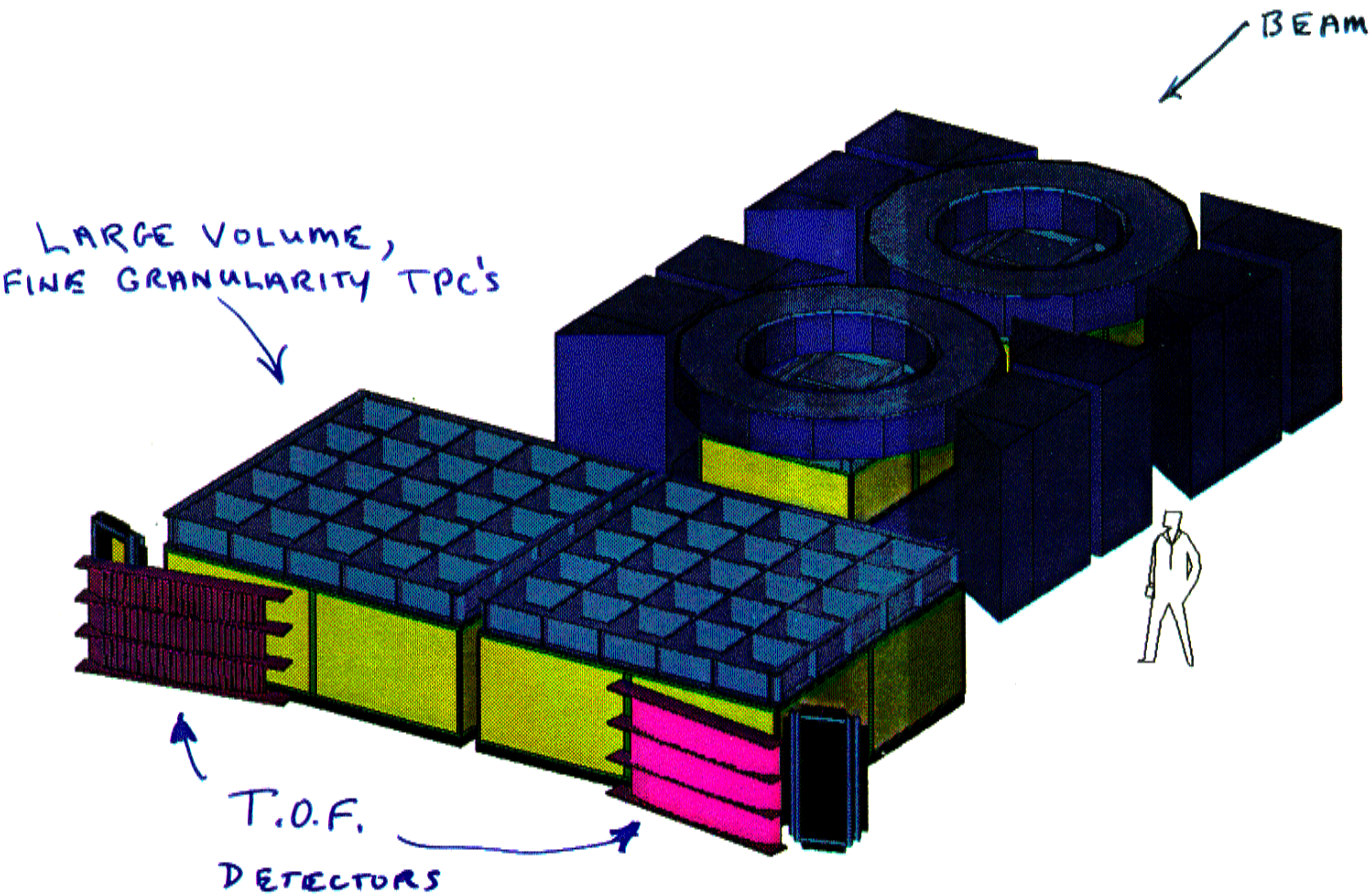
NA 49

STUDY PRODUCTION OF CHARGED HADRONS

$\pi^{\pm}, K^{\pm}, p, \bar{p}$

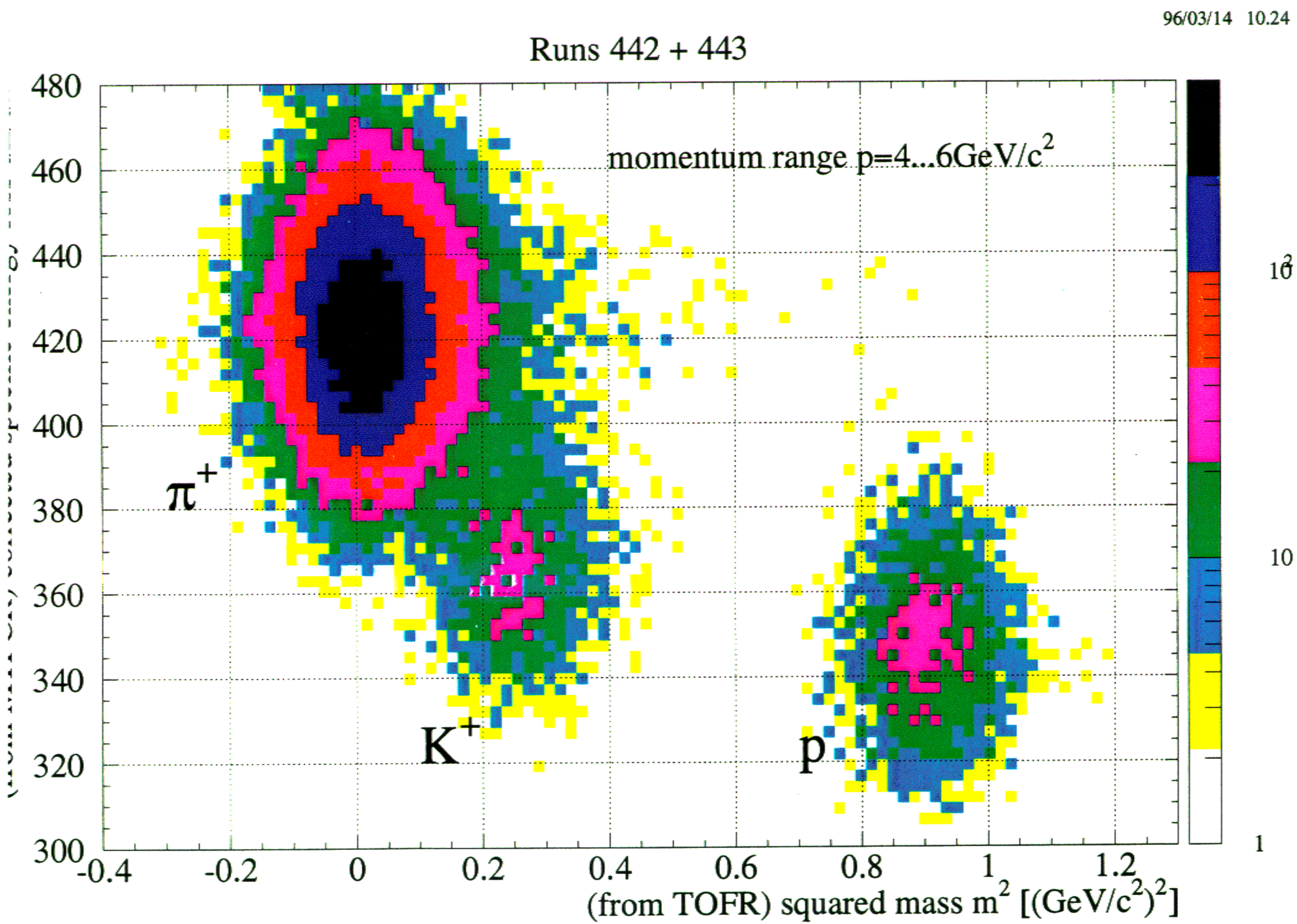
AS WELL AS NEUTRAL STRANGE PARTICLES

$K^0, \bar{K}^0, \Lambda, \bar{\Lambda}$



SEARCH FOR DECONFINEMENT TRANSITION PREDICTED BY LATTICE QCD

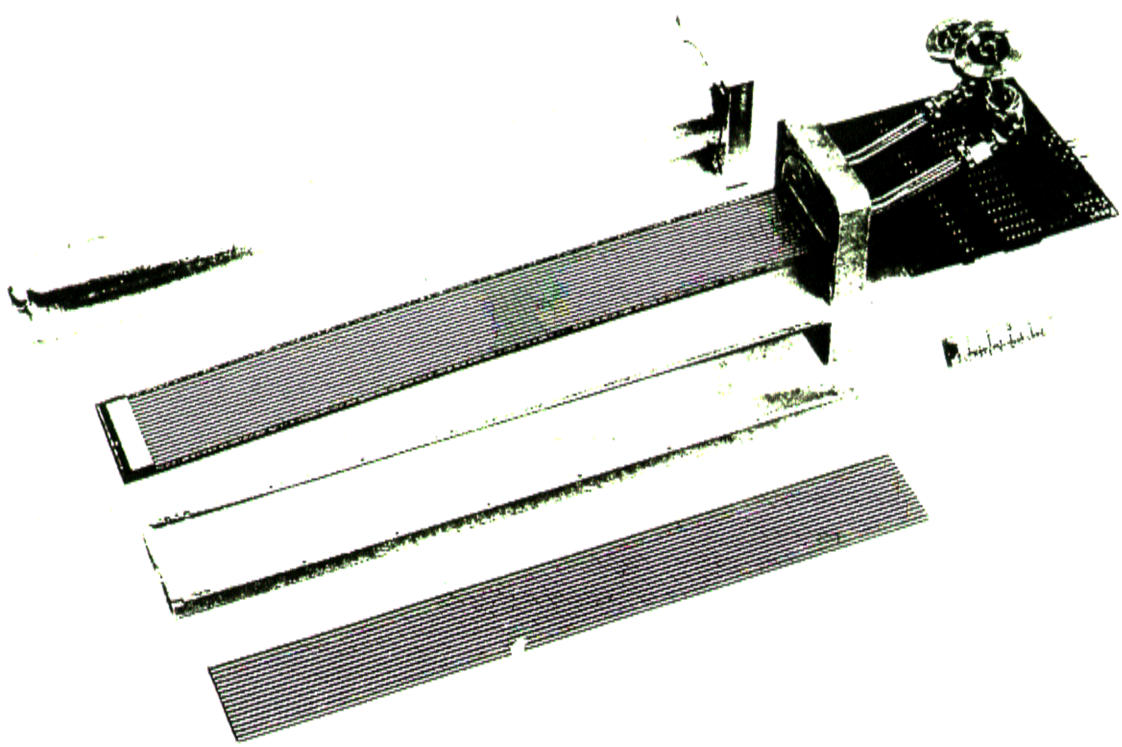
IN HEAVY ION COLLISIONS


96/03/14 10.24
Runs 442 + 443
momentum range p=4...6GeV/c²
π⁺
K⁺
p
480
460
440
420
400
380
360
340
320
300
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
(from TOFR) squared mass m² [(GeV/c²)²]
10²
10
1

OPERATES AT VERY HIGH GAS PRESSURE

SMALL GAP SIZE
~ 100 µm

Under study for the ALICE particle identification system is the Pestov spark counter technique, single-gap gas filled parallel-plate devices giving a timing resolution of less than 50 picoseconds. Pestov counters will be the preferred choice if it can be demonstrated that reliable manufacture and operation are possible for the large-area system required.
(Photo Achim Zscnau, GSI)



PESTOV SPARK COUNTER

< 50 ps RESOLUTION

Alice now plans to use RPC's with somewhat different characteristics

~ 1mm gap

resistive glass plates using same glass as used for Welder's face masks

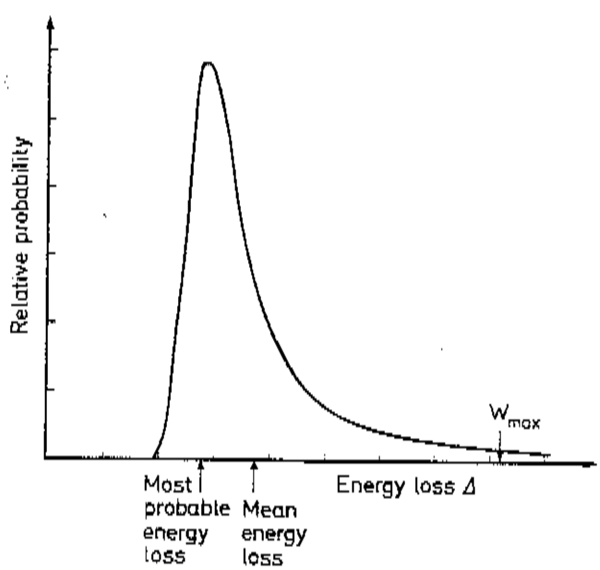
Helium - Ethane 50/50 at atmospheric pressure to limit charge in the discharge and protect glass surface from damage

Have achieved $\tau_{res} \lesssim 70$ ps in tests of 8mm x 8mm prototype

dE/dx

Measure mean ionization energy loss in a tracking detector - gas-filled or even silicon strip

- **Requires analog readout**
- **Many measurements are needed.**
- **Statistics are improved in gaseous detectors by operating at higher pressure => more primary ionizations**
- **Use method of truncated mean to remove measurements out on the Landau tail, which skew the mean**

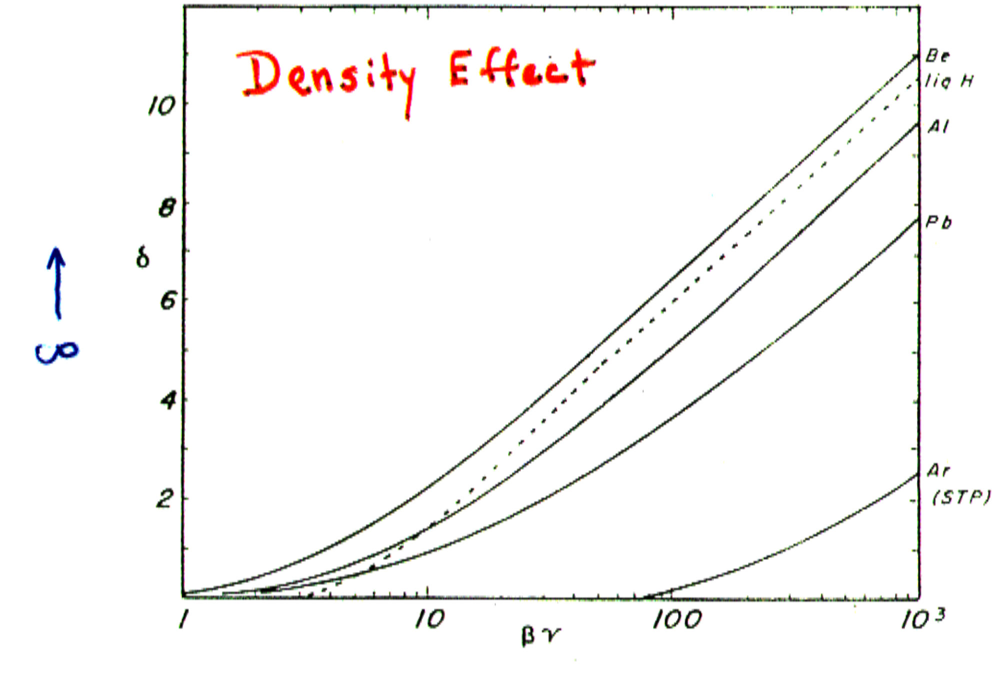


dE/dx is described by the Bethe-Bloch equation and is a universal function of βγ for all particle masses.

Energy loss as a function of momentum

- Falls as $1/\beta^2$ to a minimum at βγ of approximately 4
- Then increases logarithmically (the *Relativistic Rise* region)
- Saturates at the *Fermi plateau*

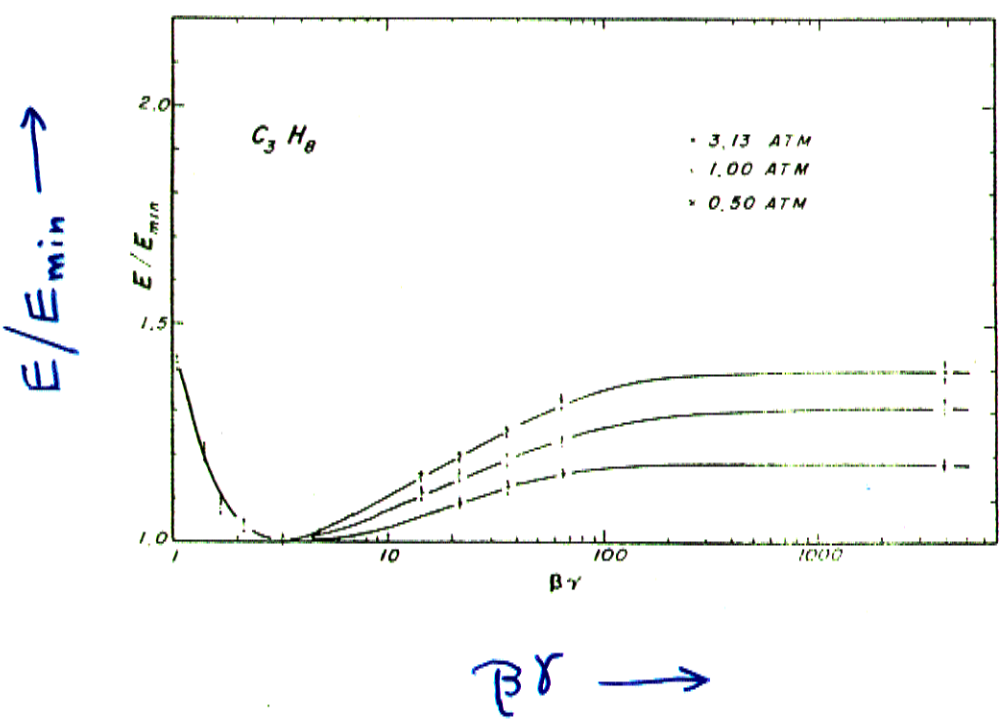
Figure 2.5 Density effect correction parameter δ for several materials. (The parameter was calculated using the formulas and coefficients given in R.M. Sternheimer, M.J. Berger, and S.M. Seltzer, Atomic Data and Nuclear Data Tables 30: 261, 1984.)



Limits rise to a few percent in liquids and solids

Rise Can be as large as 50-70% in High Z noble gases

Figure 2.6 Measured mean energy losses in propane as a function of pressure and $\beta\gamma$. The energy losses are normalized to those for 3-GeV/c protons. (After A. Walenta, J. Fischer, H. Okuno, and C. Wang, Nuc. Instr. Meth. 161: 45, 1979.)

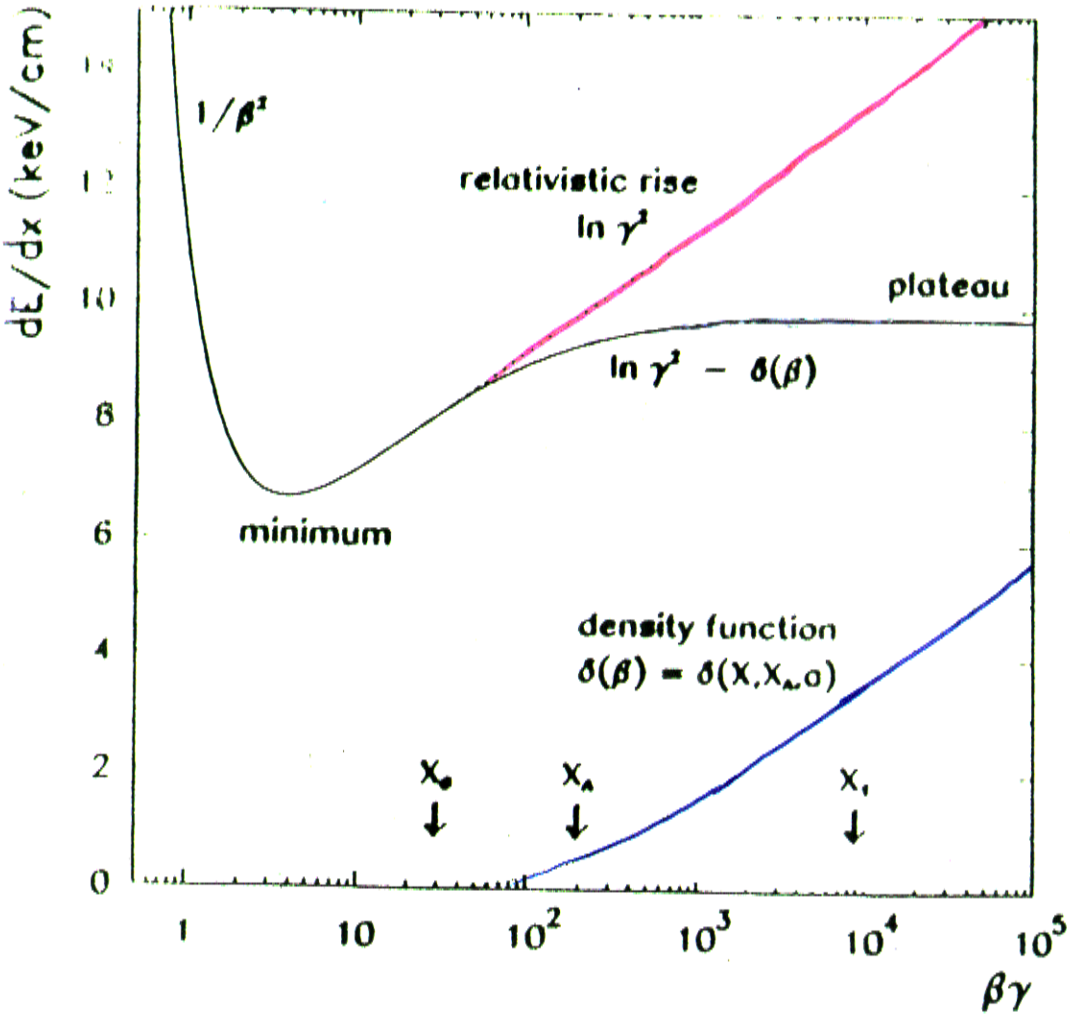


← 50% rise

← 0.50 atm

← 1.00 atm

← 3.13 atm



For Argon-Methane at 4 bars pressure

mix is 88.2% Argon, 9.8% Methane,
2% Isobutane

OPAL

Fig. 5.21. Mean ionization energy loss in a 1 cm-thick layer of 80% argon and 20% methane at standard conditions for five kinds of charged particles [MA 78].

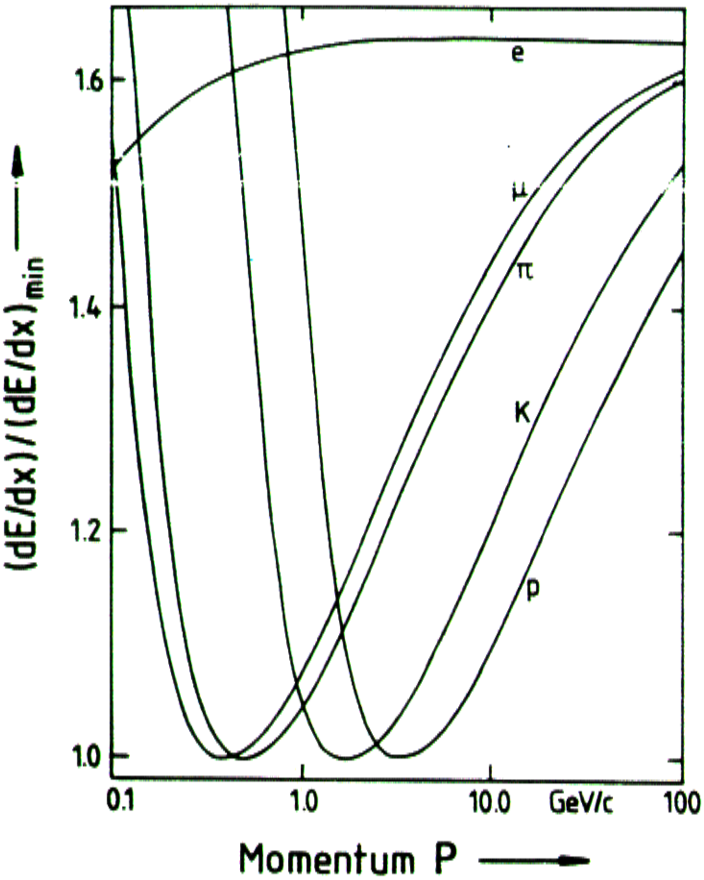
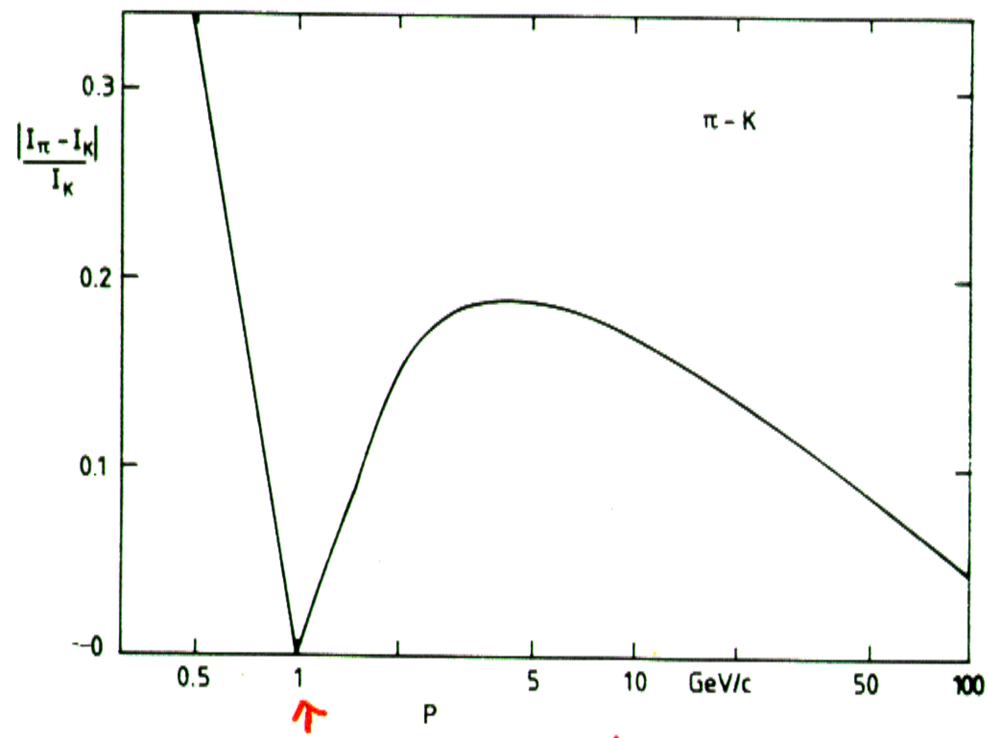
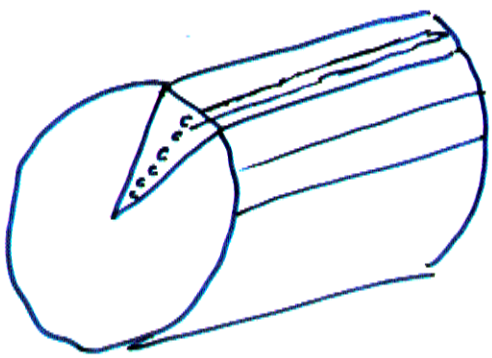


Fig. 5.22. Relative difference between the mean energy losses of π and K mesons, $|I_\pi - I_K|/I_K$, as a function of particle momentum.



CROSSOVER REGION

OPAL JET CHAMBER



24 CELLS
CATHODE AND ANODE WIRES RUN ALONG THE AXIS AS SHOWN

SOLENOIDAL FIELD .435 T

159 SENSE WIRES EACH CELL – 159 POINTS MEASURED ALONG TRACKS OVER 73% OF SOLID ANGLE
AT LEAST 8 HITS OVER 98% OF 4π

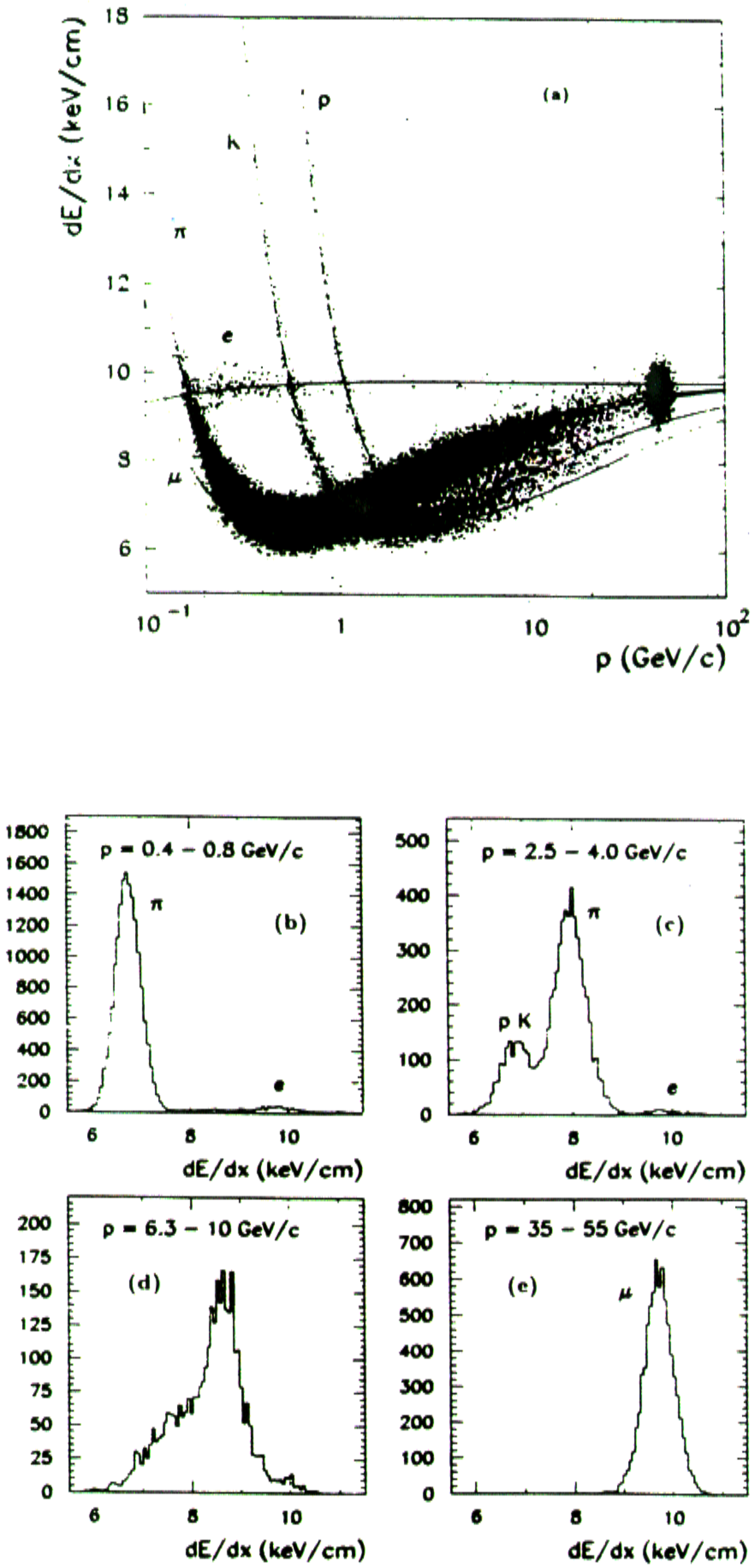
OPERATED AT A PRESSURE OF 4 BARS FOR OPTIMUM PARTICLE SEPARATION POWER

Argon/Methane/Isobutane
88.2 9.8 2.0 %

DETAILED ANALYSIS INCLUDING QUALITY CUTS AND CORRECTIONS

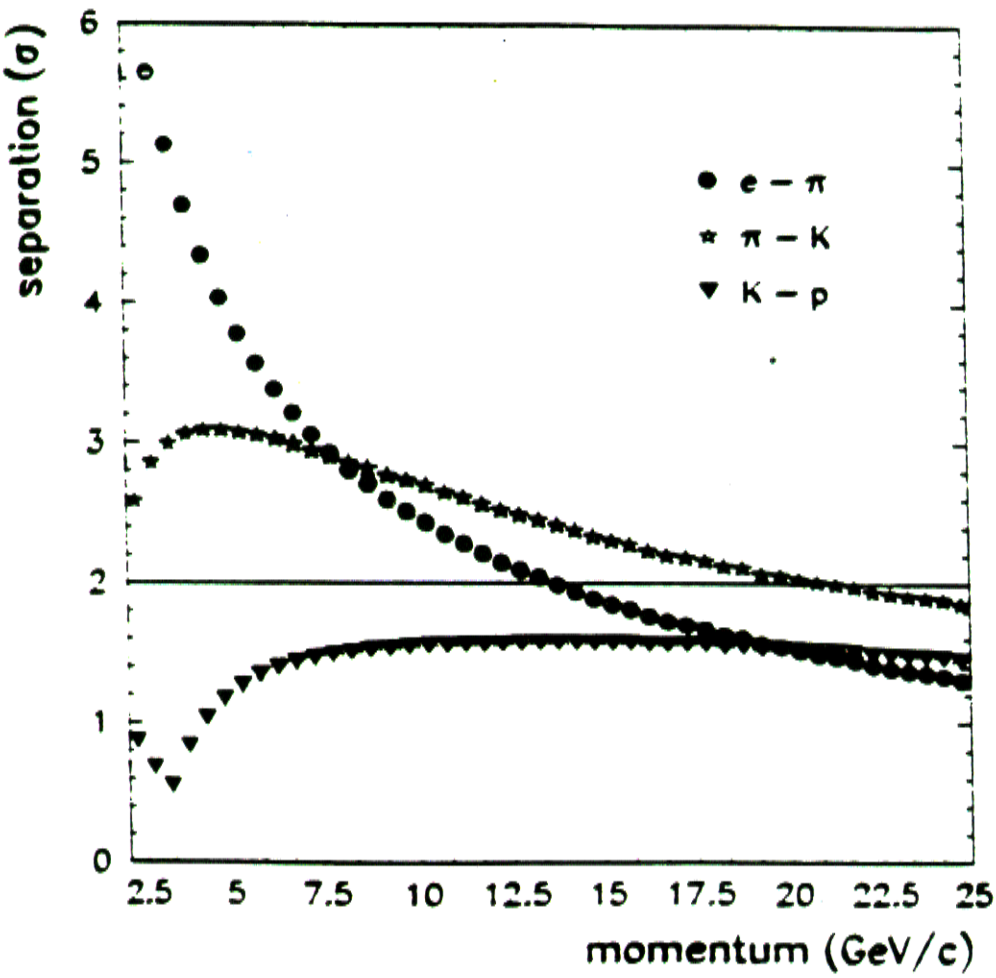
30% OF HIGHEST dE/dx MEAS. REMOVED IN TRUNCATED MEAN CALCULATION

OPAL



dE/dx (keV/cm)
p (GeV/c)
(a)
π
K
p
e
μ
p = 0.4 – 0.8 GeV/c
(b)
p = 2.5 – 4.0 GeV/c
(c)
p K
p = 6.3 – 10 GeV/c
(d)
p = 35 – 55 GeV/c
(e)
dE/dx (keV/cm)

OPAL



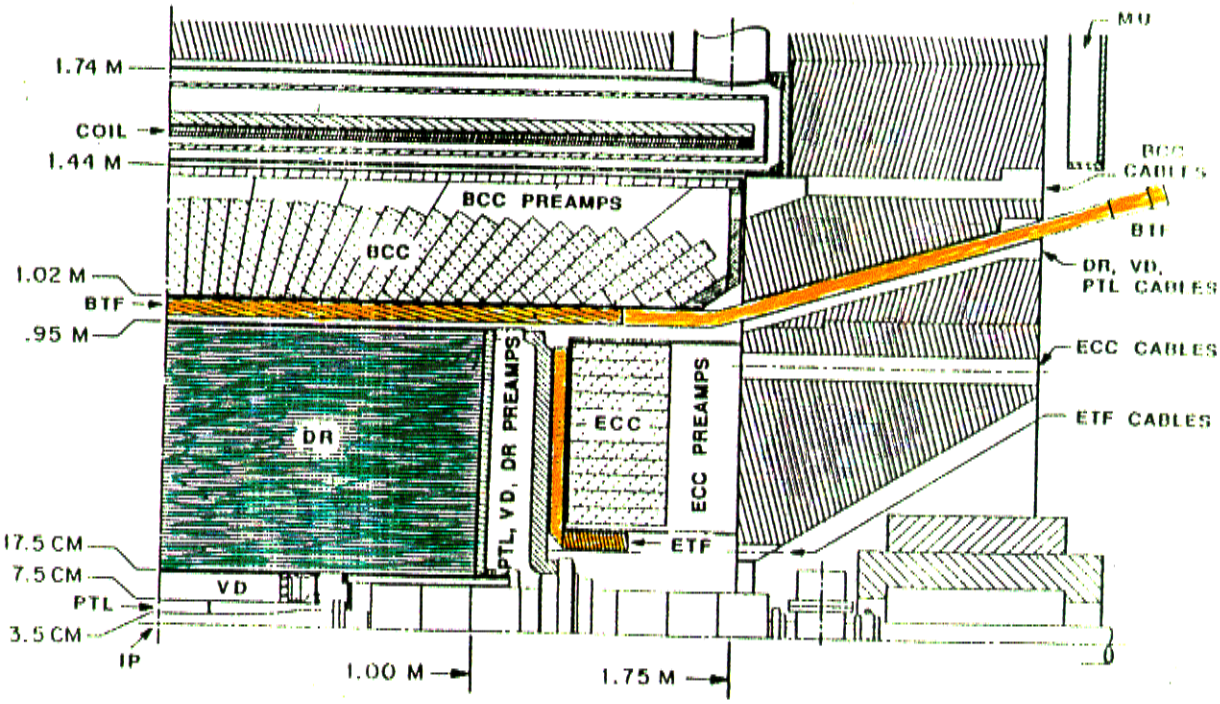
$$\frac{\sigma(dE/dx)}{dE/dx} \propto N^{-0.43}$$

$\sim 3.8\%$ for $N \geq 130$

where N is the number of points used in the truncated mean calculation.

$$\text{separation} = \frac{(dE/dx)_A - (dE/dx)_B}{\sigma(dE/dx)_B}$$

CLEO

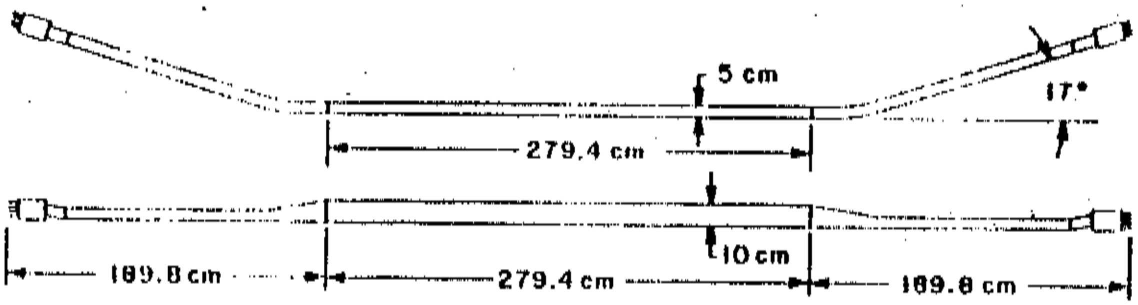


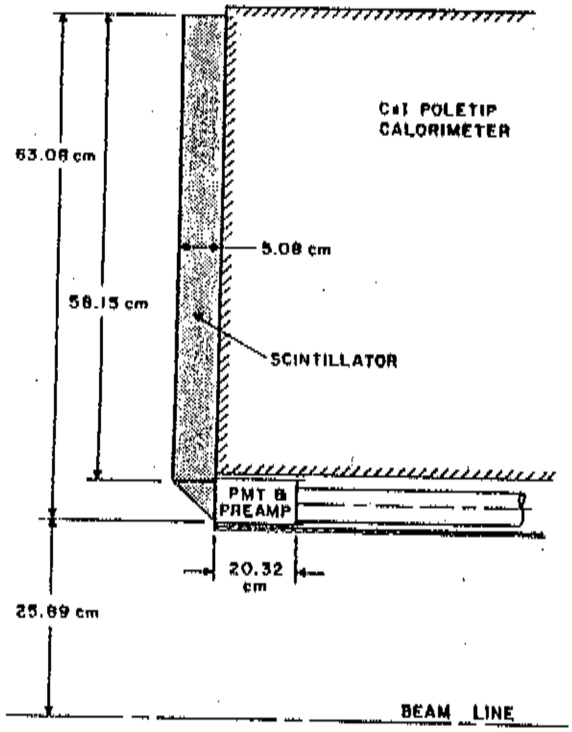
BTF = Barrel Time-of-Flight
± (36°-144°) or ~81% of 4π

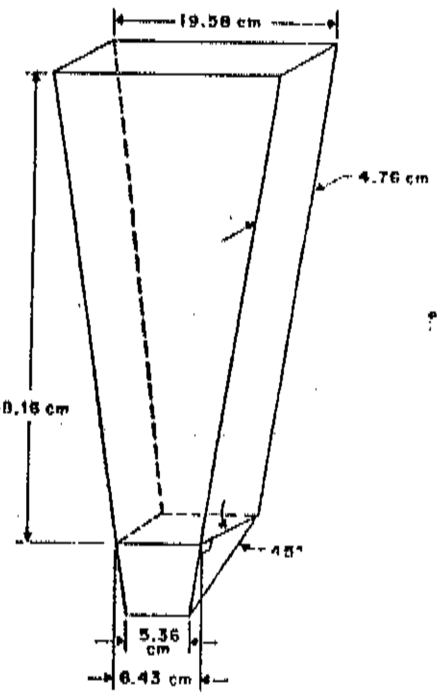
ETF = End Cap TOF
± (15°-36°) or ~16% of 4π

IP = Interaction Point

DR = Main Drift Chamber


5 cm
17°
279.4 cm
10 cm
189.8 cm
279.4 cm
189.8 cm


CsI POLETIP
CALORIMETER
63.08 cm
58.15 cm
5.08 cm
SCINTILLATOR
PMT &
PREAMP
20.32
cm
25.89 cm
BEAM LINE


19.58 cm
4.76 cm
58.16 cm
45°
5.36
cm
6.43 cm

CLEO

TOF

BICRON BC408 Scintillator

rise time 2.1 ns

attenuation length 2.5m

PMT's

barrel - Amperex 2020 with adjustable voltage on accelerator electrode and improved quantum efficiency

endcap - Fine Mesh PMT designed to operate in a high magnetic field

- fast rise time + good q.e.
- gain drop due to magnetic field compensated by pre-amp on PMT output
- (Hamamatsu R2490)

- glued directly onto scintillator

TOF electronics

Each PMT signal is fed to -

2 channels of Time to amplitude converter

- Start time is derived from discriminators with 40 mv and 80 mv thresholds
- stop time is derived from the CESR rf

The use of 2 channels with different thresholds provides a way to correct for differences in signal rise time

Raw data are corrected for pulse height difference and signal time slew

$\Longrightarrow$ Time resolution for pions of 0.7 GeV/c is ~ 154 ps (barrel)
(2σ separation at 1.07 GeV/c)

End cap resolution is not as good
~ 272 ps

CLEO

dE/dx

51 wires - 40 axial and 11 small angle stereo
cover 17.5 to 95 cm in radius

gas is Argon - Ethane 50/50 at $\gtrsim$ atmospheric pressure

use 50% of the hits in the truncated mean calculation

correct for
- dip angle saturation
- drift distance to wire
- entrance angle to drift cell in $r\phi$ plane
- type of layer

for 40 or more hits, resolution of 7.1% is achieved for minimum ionizing pions

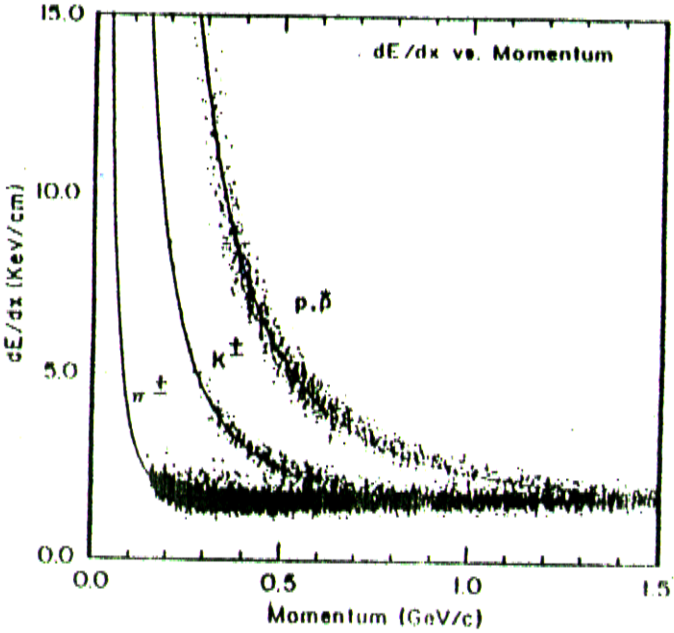


Fig. 23. Specific Ionization vs track momentum for hadrons.

dE/dx

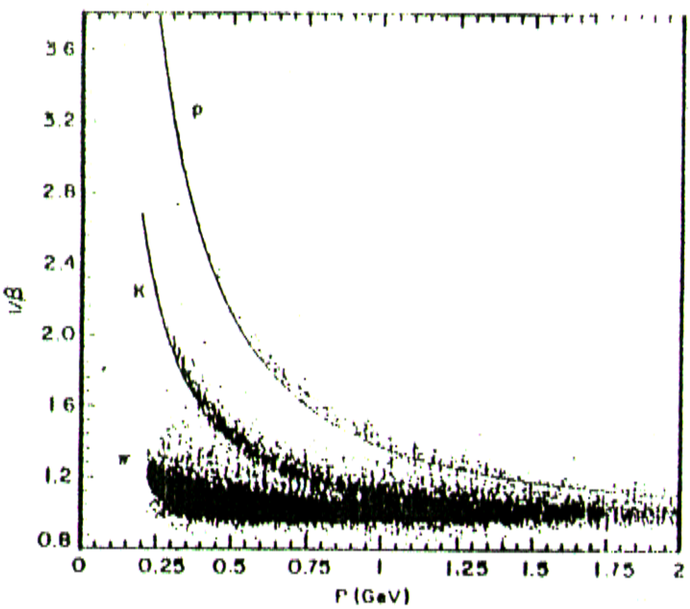
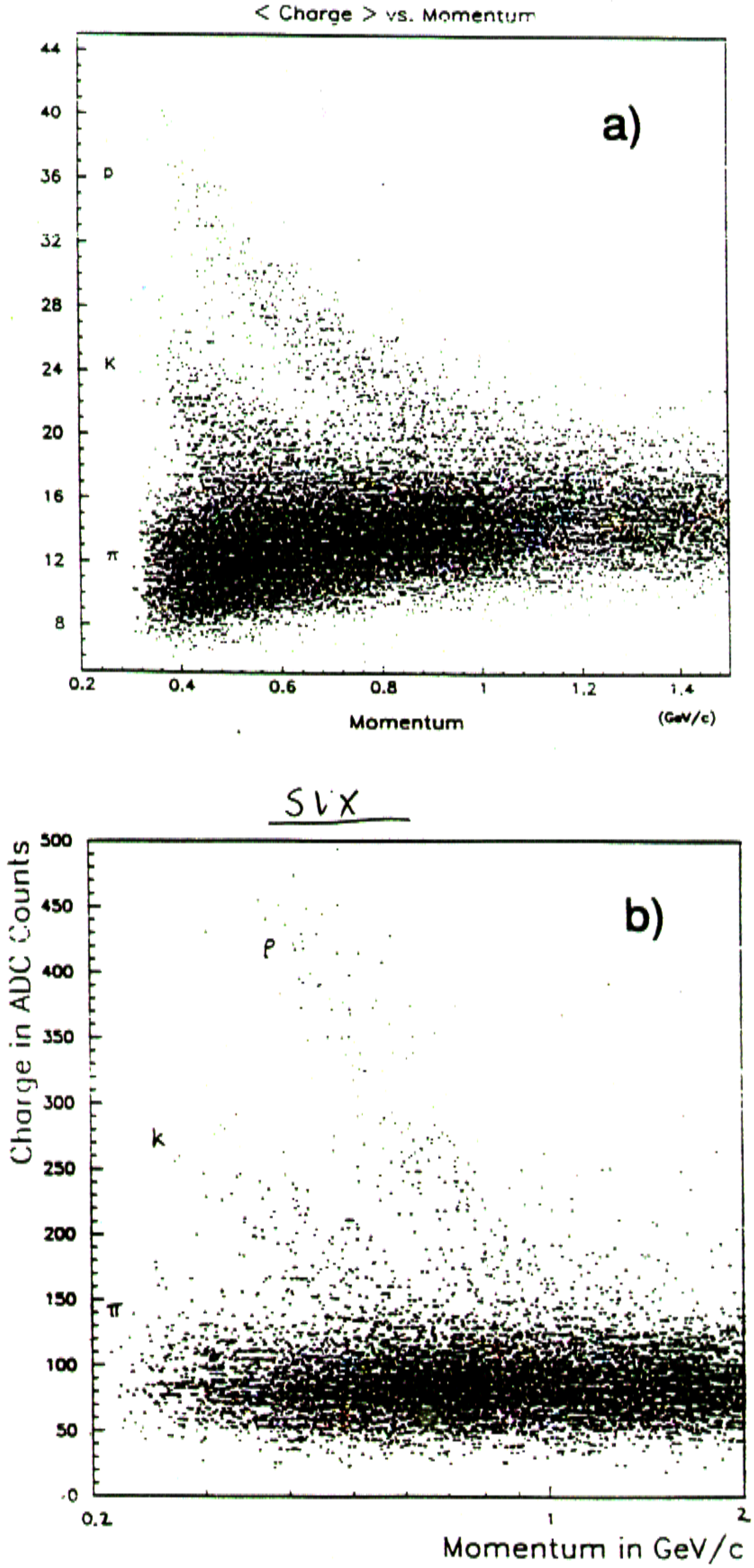


Fig. 31. $1/\beta$ ($\beta = v/c$) versus track momentum measured in the drift chambers for a sample of hadrons in the barrel TOF counters.

TOF

CDF

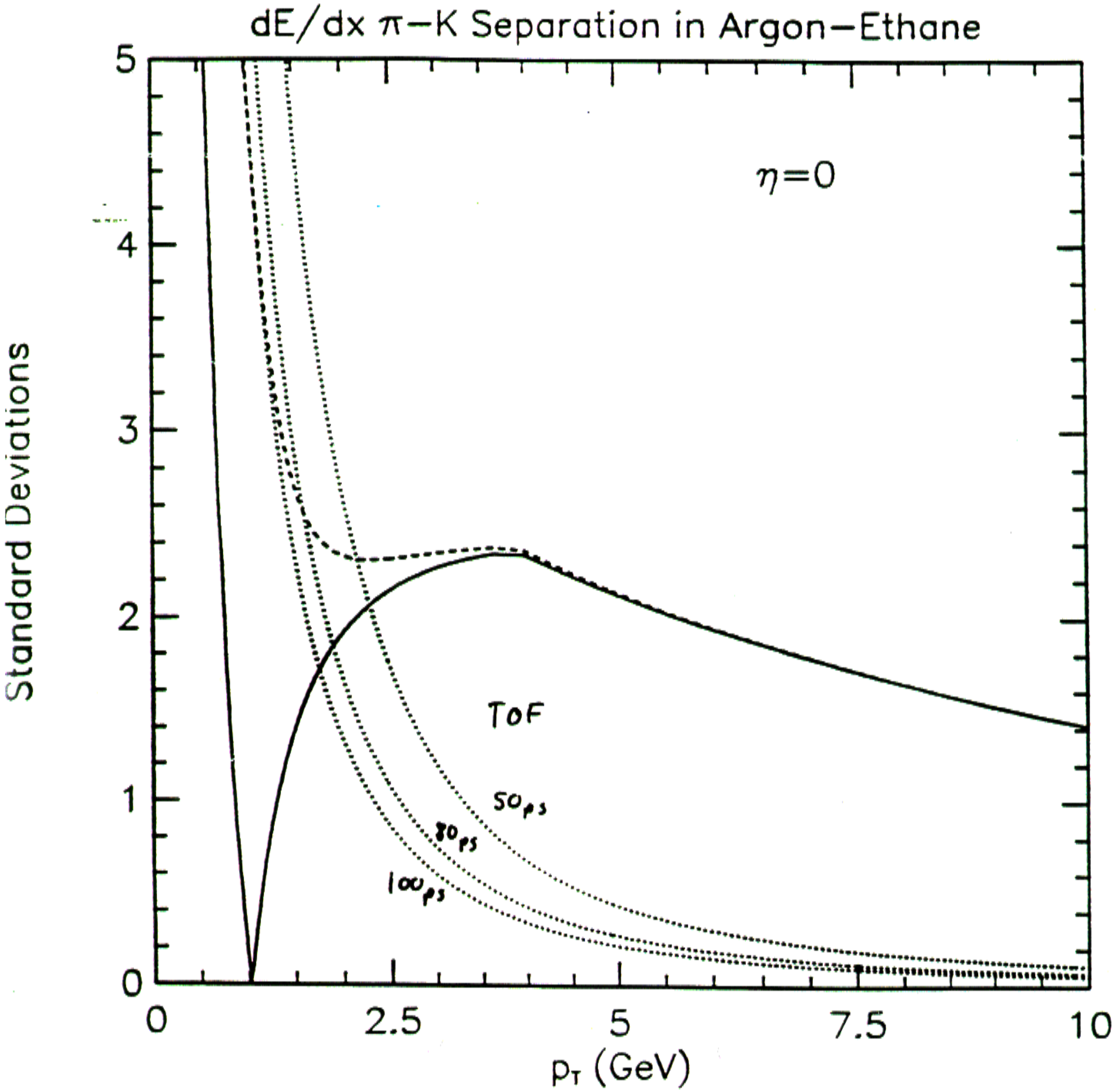


< Charge > vs. Momentum
a)
44
40
36
32
28
24
20
16
12
8
p
K
π
0.2
0.4
0.6
0.8
1
1.2
1.4
Momentum
(GeV/c)
SVX
b)
Charge in ADC Counts
500
450
400
350
300
250
200
150
100
50
0
p
k
π
0.2
1
2
Momentum in GeV/c

CTC

SVX

CDF

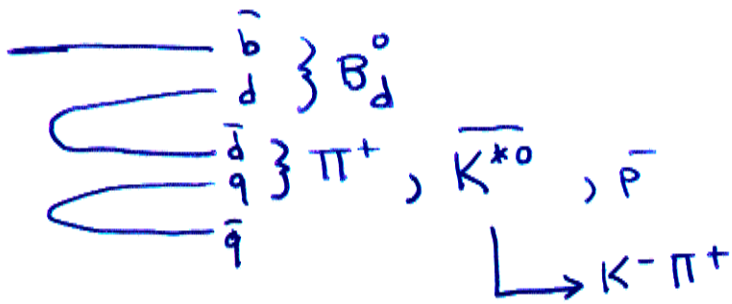


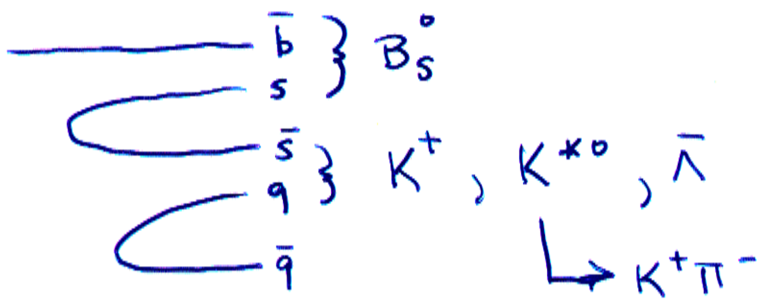
dE/dx π−K Separation in Argon−Ethane
η=0
TOF
50ps
80ps
100ps
Standard Deviations
p_T (GeV)
0
1
2
3
4
5
0
2.5
5
7.5
10

CDF

TOF Upgrade

Unique Application of this technique to Same Side Tagging of B's in Studies of CP violation





Also provides tag of Opposite Side B

via $b \rightarrow c \rightarrow s$

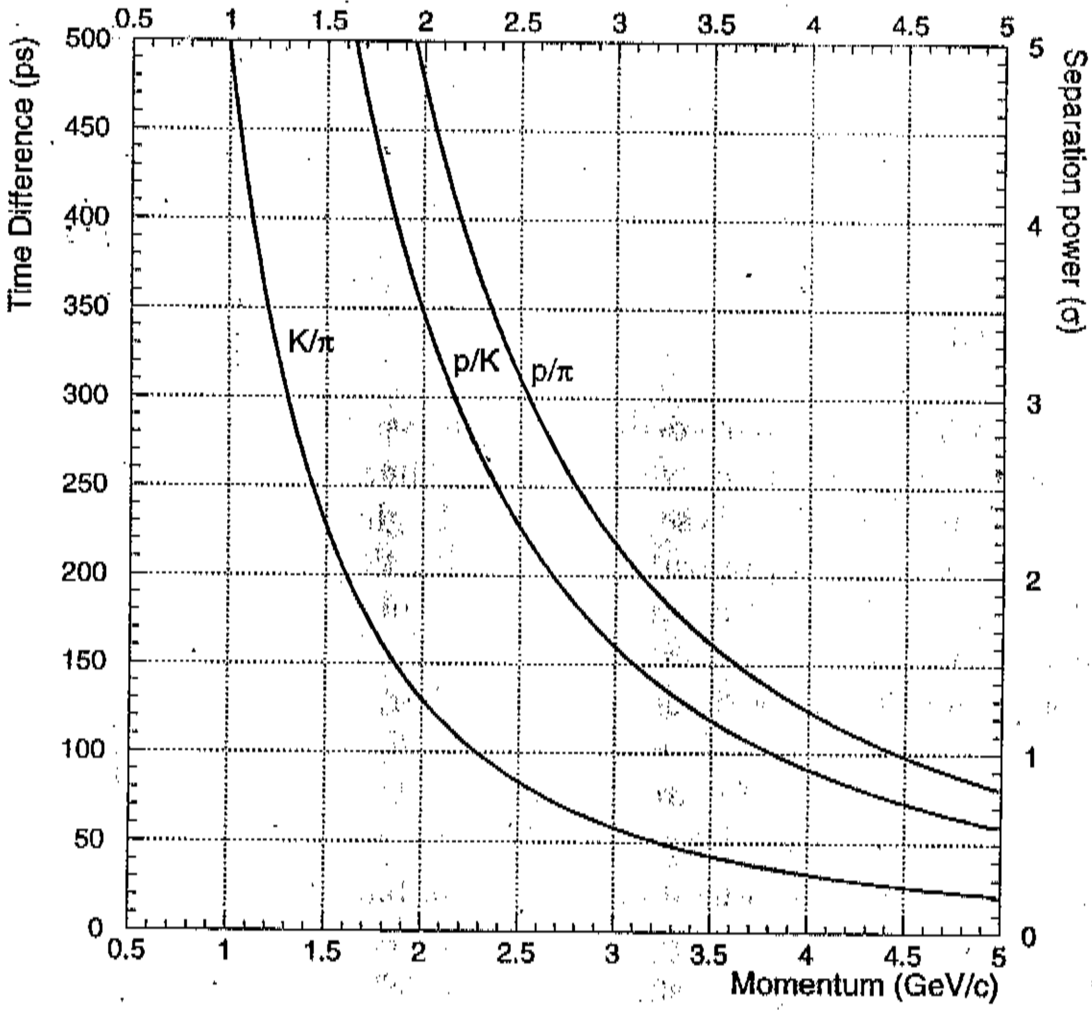


Figure 3.1: Time difference as a function of momentum between K/π, p/π and K/p traversing a distance of 140 cm, expressed in ps and separation power, assuming a resolution of 100 ps.

TOF

- 216 scintillator bars at 1.4 m radius
- 3 m long x 4 cm thick x 4 cm wide
- made from BICRON 408 scintillator
- 19 stage R4946-Mod Hamamatsu FMPMT's
    - operate in high magnetic field (1.5T)
    - preamp on output to offset reduction in gain caused by operation in magnetic field
- output to TAC for time measurement and ADC for time walk correction
- to achieve desired 100 ps time resolution, require $\lesssim$ 25 ps jitter in electronics
    - monitor temperature on board
    - make sure clock distribution to front ends is synchronous to within $\lesssim$ 25 ps

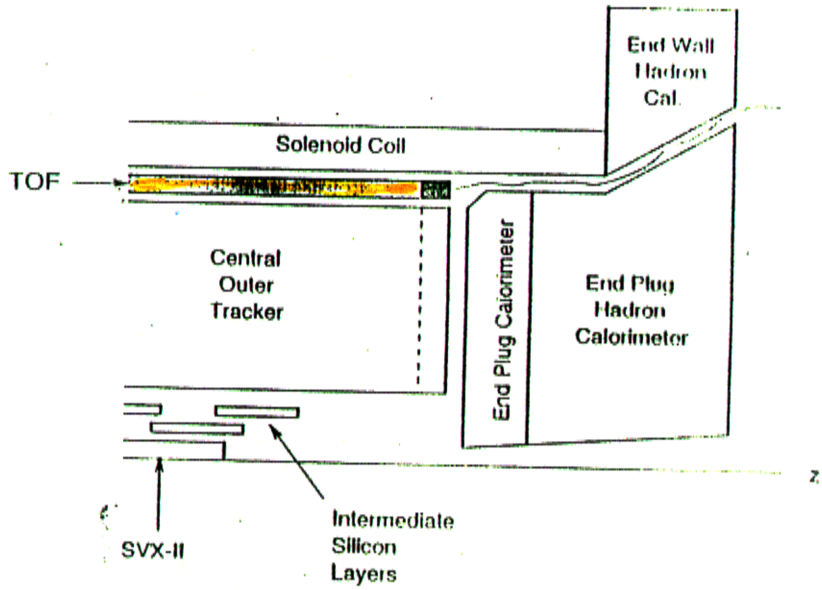


Figure 3.2: Side view of CDF II showing the location of the Time-of-Flight subdetector.

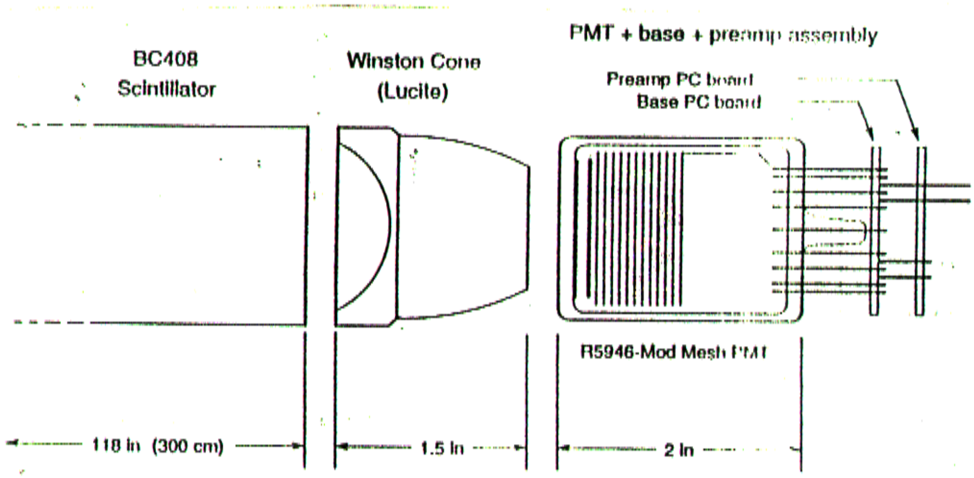


Figure 3.3: Arrangement of the scintillator, Winston cone and PMT assembly. This also shows the printed circuit boards for the PMT base and the preamplifier.

TOF

Two algoritms for associating PMT pulse with track

$$z = \frac{1}{2}(T_L - T_R) \cdot v_{bar}$$

for $\langle n_{minbias} \rangle$ small agrees with extrapolated track within 2σ

But for higher $\langle n_{minbias} \rangle$ a better method is to associate track with closest PMT in z if no other track in the event that hits the bar is closer to the PMT in z

TOF

Long interaction volume (36 cm) means that t_0 for an event can vary by as much as several ns

Measure t_0 using the tracks from an event using maximum likelihood technique

t_0 resolution of ~33 ps

Expect $\langle n_{min\,bias} \rangle$ of 2 for 132 ns bunch spacing and $\mathcal{L} = 2 \times 10^{32}$

CDF

Measurements from 5% coverage beam test at end of last collider run

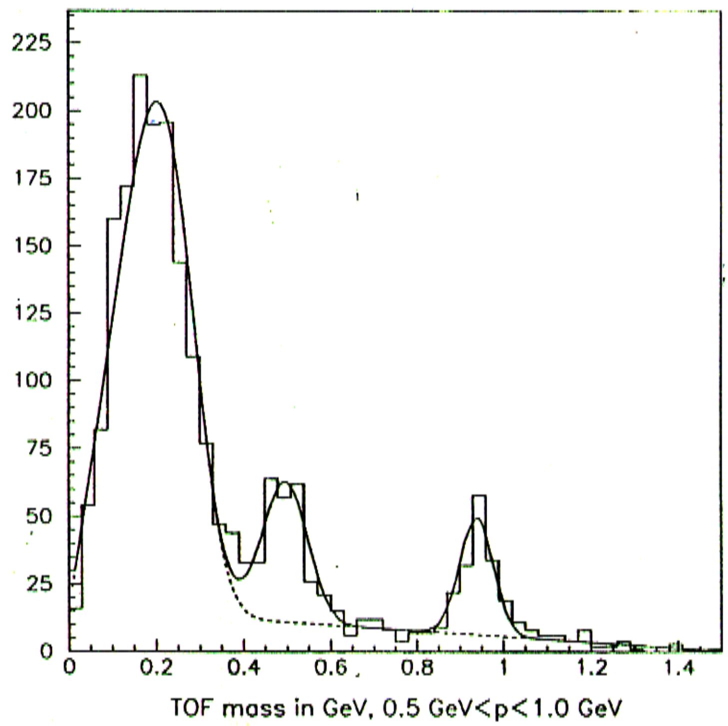


Figure 3.16: The measured TOF mass (m_f) spectrum for tracks with 0.5 GeV/c < p < 1.0 GeV/c. The solid line is the result of a fit to the spectrum which includes contributions from pions, kaons, protons, and a linear background. The dashed line shows contribution of only the pion and background terms.

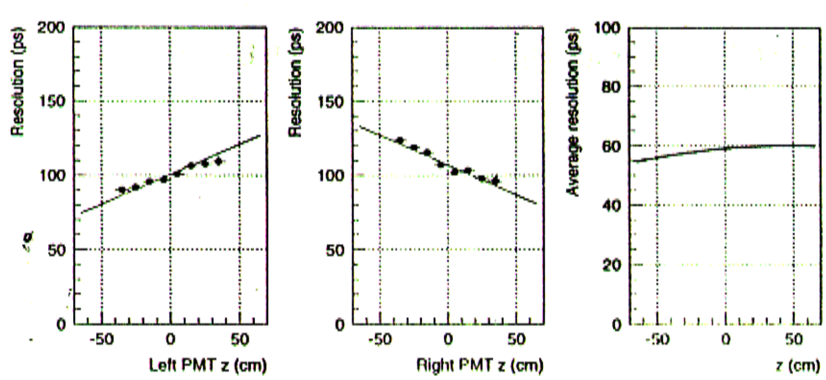


Figure 3.17: Timing resolution from cosmic rays for left and right PMT's as functions of z-position. The average resolution, relevant for particle identification, was $\mathcal{O}(60ps)$ in this study.