MUON IDENTIFICATION

$\mu^{\pm}$ IDENTIFIED BY LACK OF HADRONIC INTERACTION
E.M. RADIATION

- USE CALORIMETER + FE YOKE + μ CHAMBER

- 8 → 10 λ CALORIMETER + FE YOKE

- μ CAN BE IDENTIFIED INSIDE JETS
    - HEAVY FLAVOUR DECAYS

PERFORMANCE LIMITATIONS

- PUNCH THROUGH
  REQUIRES THICK
  FILTER
  ↳ dE/dx CUTS OFF LOW
  END OF μ MOMENTUM SPECTRUM
  8λ Fe $\Rightarrow \langle \frac{dE}{dx} \rangle \sim 1.5$ GeV

- DECAYS IN FLIGHT

$K \to \mu\nu$
$\pi \to \mu\nu$

$K\,c\tau = 3.7\,m$

$\pi\,c\tau = 7.8\,m$

$$f_{decay} \sim 1 - \exp\left(\frac{-\Delta d}{\beta\gamma c\tau}\right) \sim \frac{\Delta d}{\beta\gamma c\tau}$$

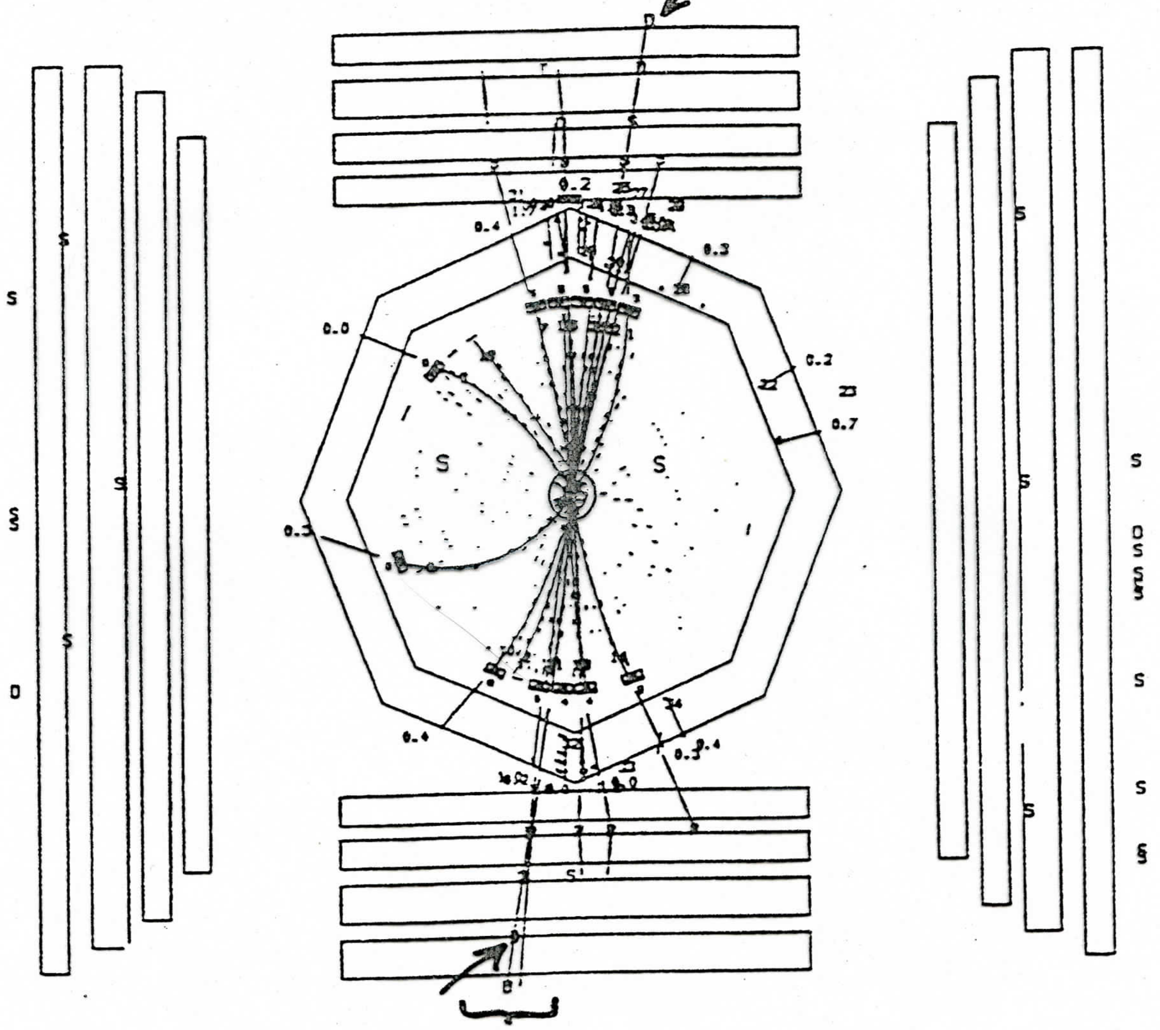
VERTEX DETECTOR EVENT

With 2 muons

RUN 20319 REC 1181 E= 91.28 17 PRONG HADRON
TRIGGER 0 448 CHAR SST CTF

(5-0)
MARK II AT SLC

TRK	P	ELATOT	ID
1	0.5	0.0	PI-
2	2.7	0.1	PI+
3	4.8	0.0	PI+
4	1.2	0.3	PI-
5	7.3	0.0	MU+
6	3.4	0.0	E+
7	1.3	0.4	PI-
8	0.3	0.0	PI-
9	0.2	0.3	PI+
10	0.4	0.4	PI+
11	2.6	0.2	MU+
12	0.5		PI+
13	5.8	1.0	MU-
14	0.8	0.3	PI-
15	2.2	0.0	PI+
16	8.5	0.0	PI-
7	2.2	0.8	PI+
	1.0	0.0	PI-
19	1.1		PI-
20		0.3	G
21		0.3	G
22		0.2	G
23		0.7	G
24		1.1	G
25		0.4	G
26		4.6	G
27		0.7	G
28		0.3	G
29		0.8	G
30		0.6	G
31		1.7	G
32		8.0	G
33		1.2	G
34		0.4	G



DCVD EVENT

MUON CANDIDATES:

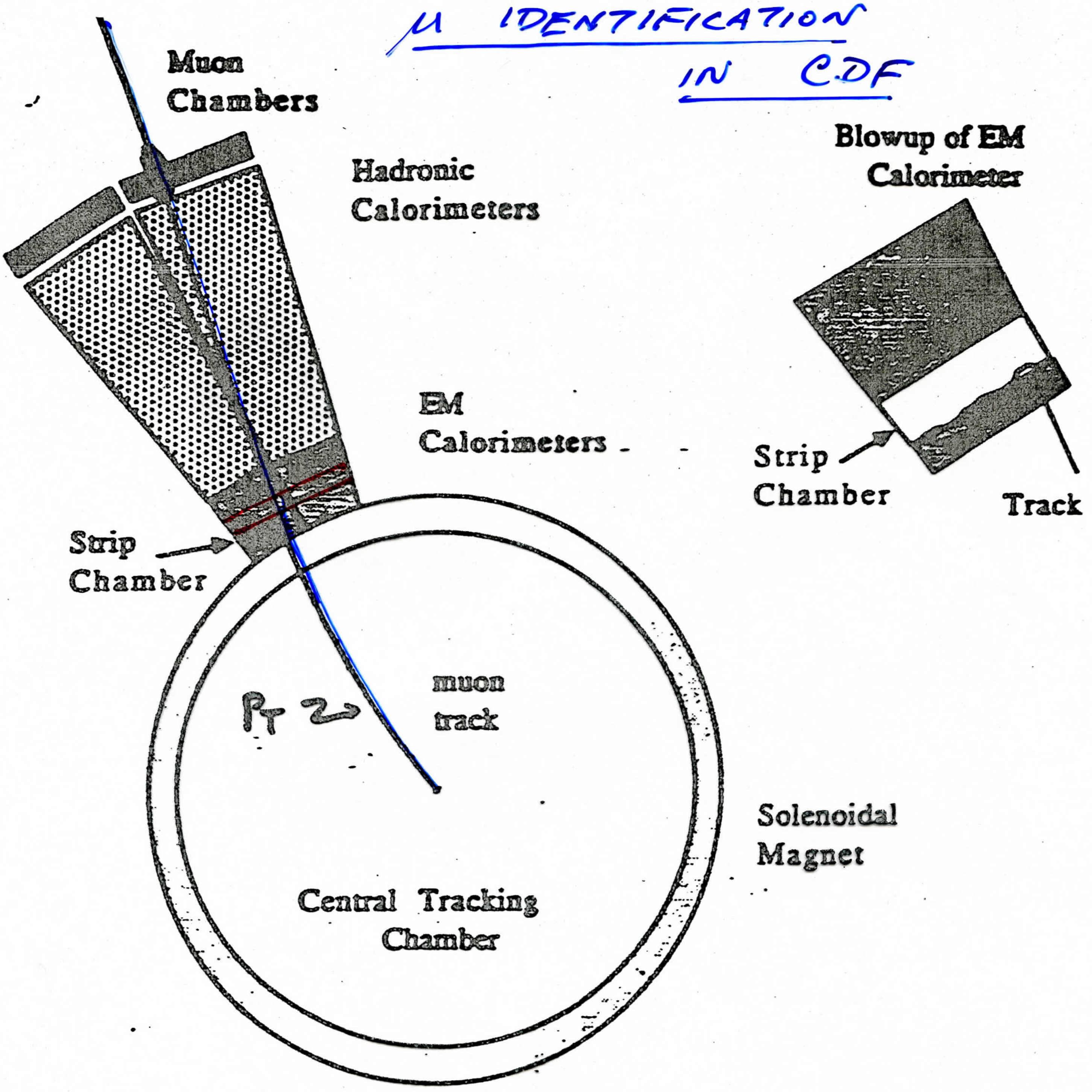
Track 5 P= 7.3 GeV/c Pt= 0.8 GeV/c

Track 13 P= 5.8 GeV/c Pt= 1.0 GeV/c

or

Track 11 P= 2.6 GeV/c Pt= 0.2 GeV/c

μ IDENTIFICATION IN CDF



CDF Central Muon Variables:

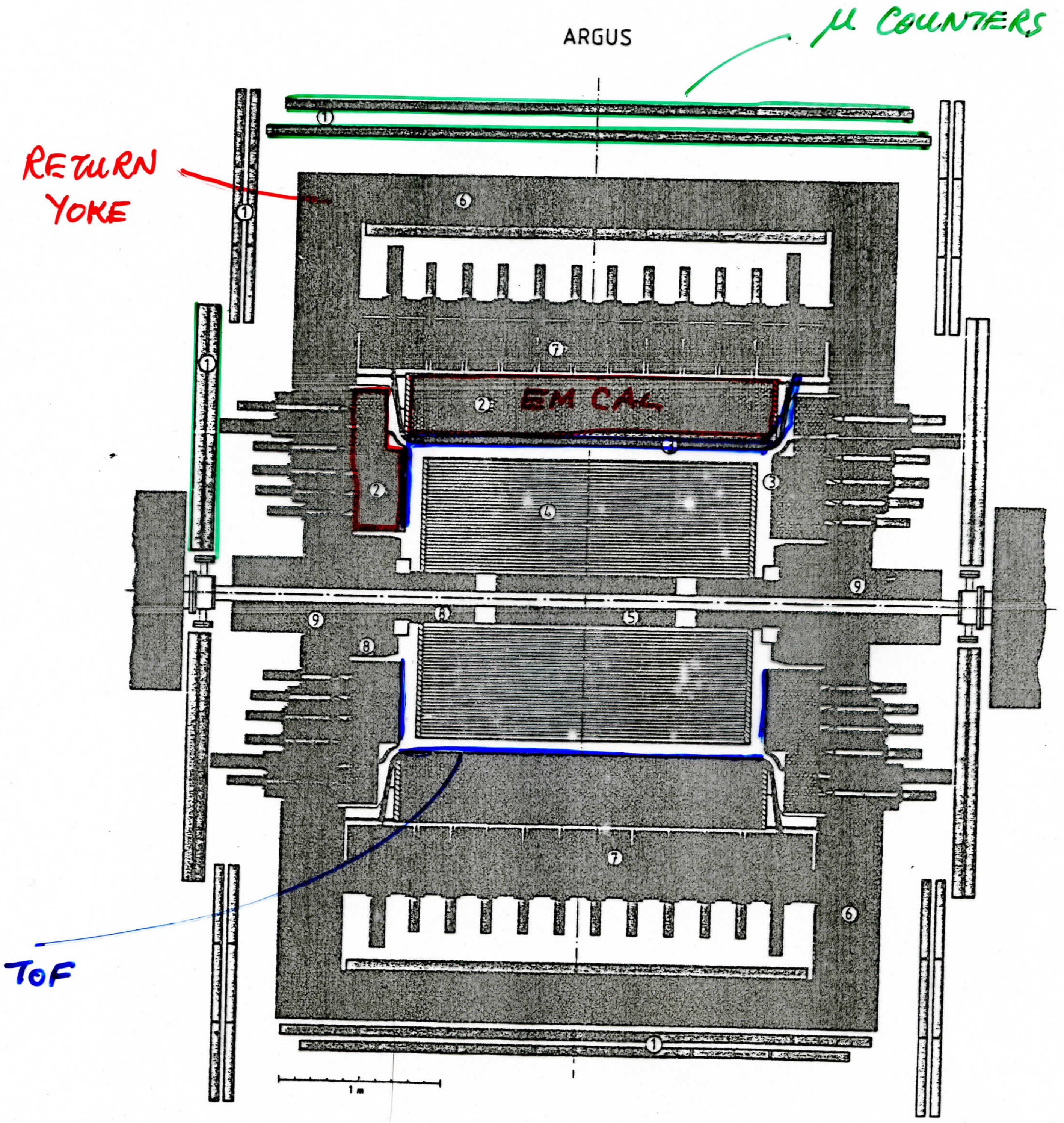
- $P_T > 20 ; 25$ GeV/c
- EM < 2 GeV
- Had < 6 GeV

+ dijet cut. + "jet" cut

$\left(dE/dx\right)_{MIN}$

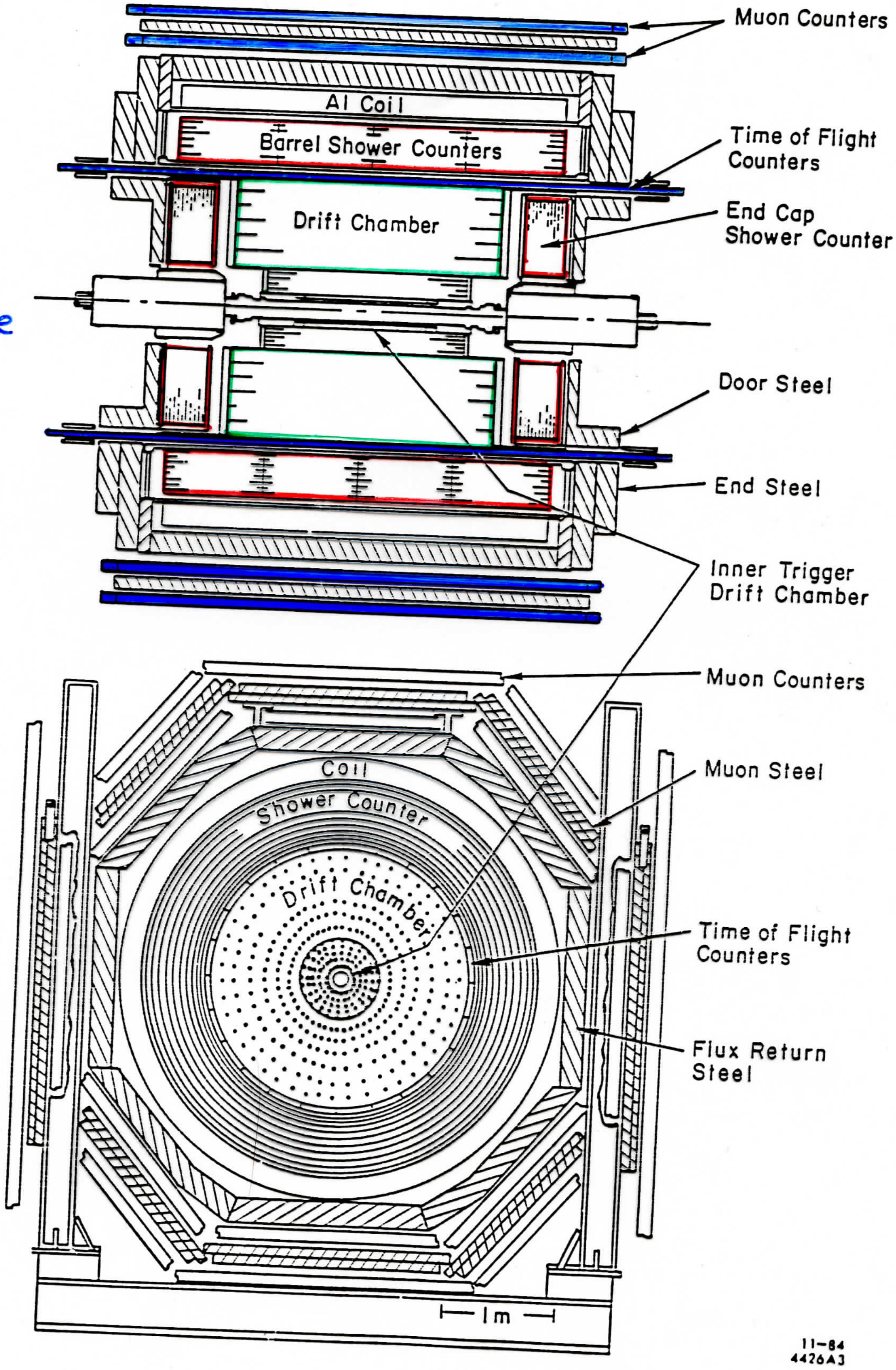
POINTING

- Muon Chamber-Track Match($\delta x, \delta z$) < 1.5 cm
- ~~Slope Match~~
- ~~Isolation~~



1. Muon chambers
2. Shower counters
3. Time of flight counters
4. Drift chamber
5. Vertex chamber
6. Iron yoke
7. Solenoid coils
8. Compensation coils
9. Mini beta quadrupole

MARK III



1·5mm WALL

Be BEAMpipe

Sh. CNTR

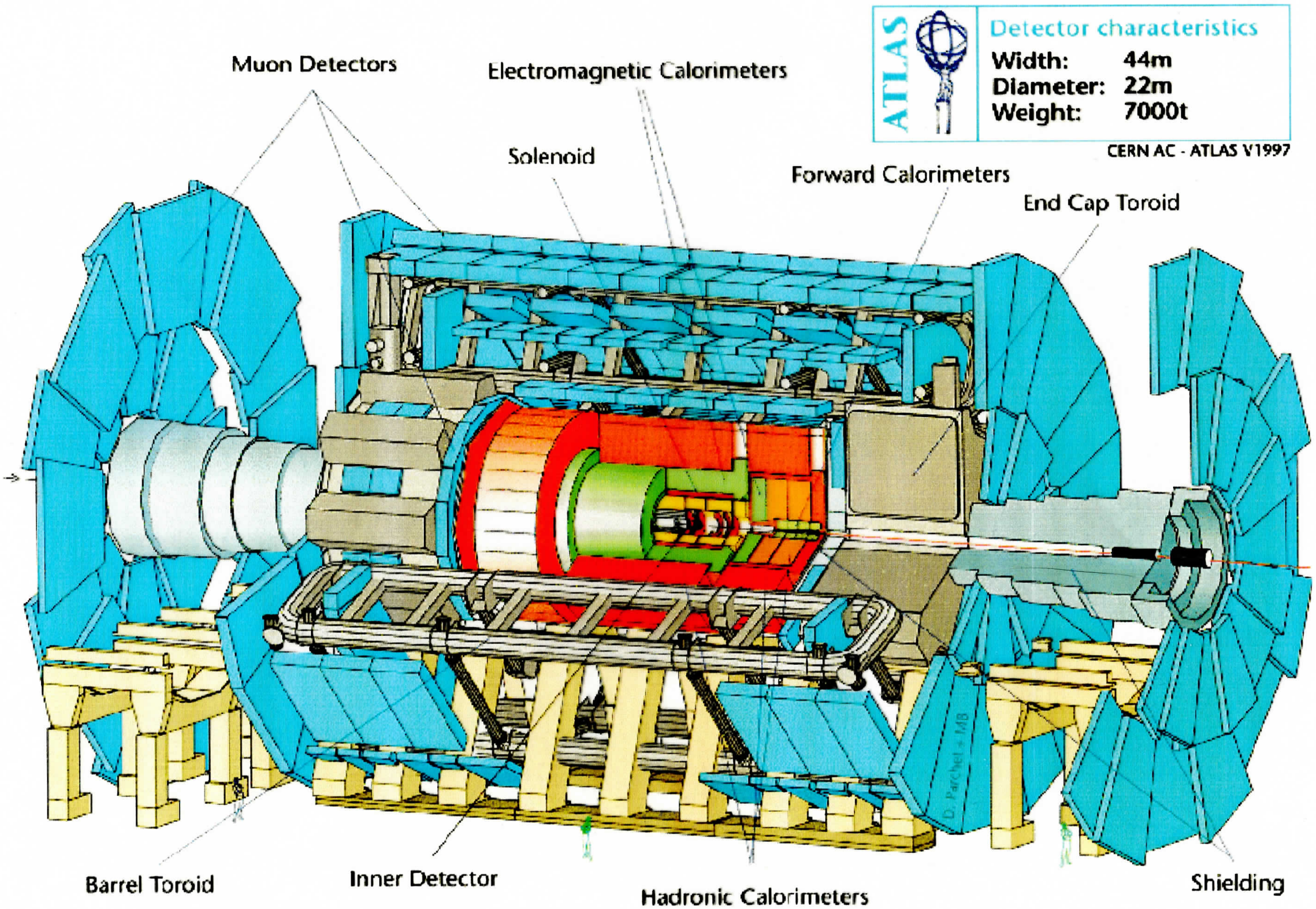
Pb / PROP Tube

$17\% / \sqrt{E}$

DC

track $+ \frac{dE}{dx}$

$(\cdot 015)^2 + (\cdot 015 p)^2$



CERN AC - ATLAS V1997

IONIZATION (dE/dx) PID

- IONIZATION ENERGY LOSS VARIES BY ~1.5 FOR $10 < \gamma < 100$
  - USEFUL BELOW FEW GeV/c

- SAMPLE IONIZATION LOSS IN DRIFT CHAMBER
  - LANDAU FLUCTUATIONS
    - LOWEST 60% PULSE HEIGHTS
    - TRUNCATED MEAN

TIME OF FLIGHT

- TRANSIT TIME OVER KNOWN DISTANCE

$$m = p/\beta\gamma$$

- LIMITATIONS

  FLIGHT PATH ~1m ⇒ ~1 GeV/c

- TIME RESOLUTION

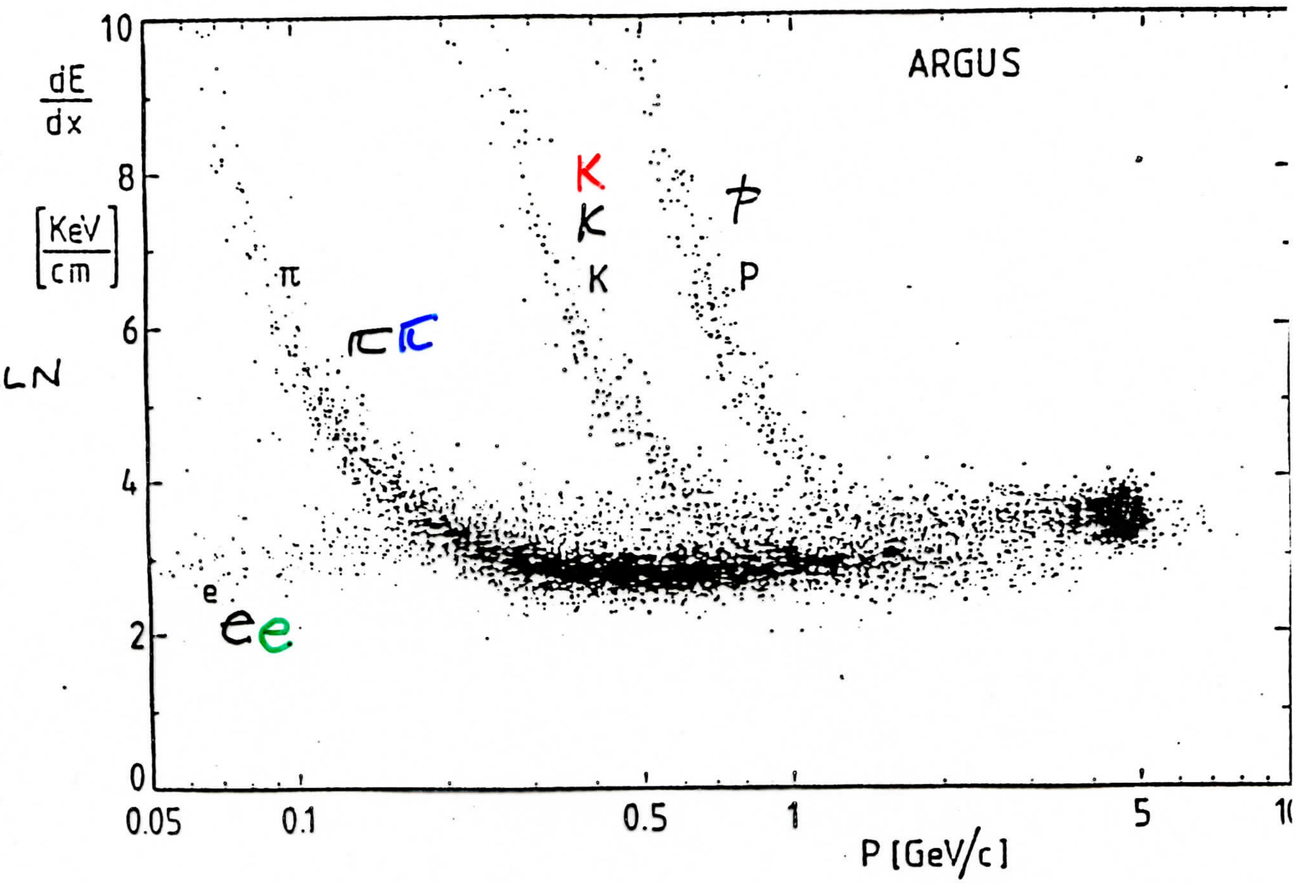
  HARD TO DO BETTER THAN 200ps

PARTICLE IDENTIFICATION

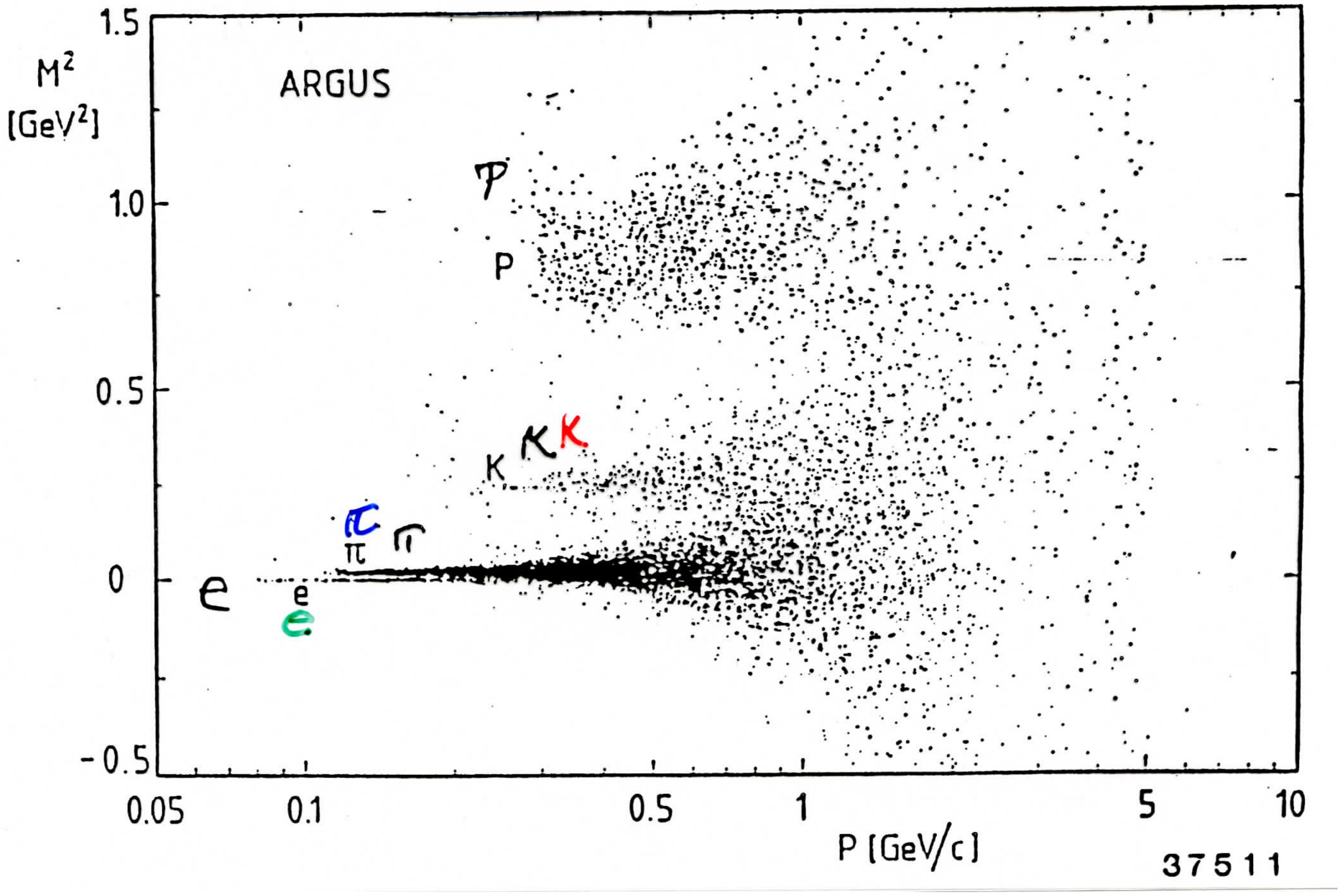
IONIZATION IN DRIFT CHAMBER GAS

$\frac{dE}{dx}$ RESLN

∼ 5%



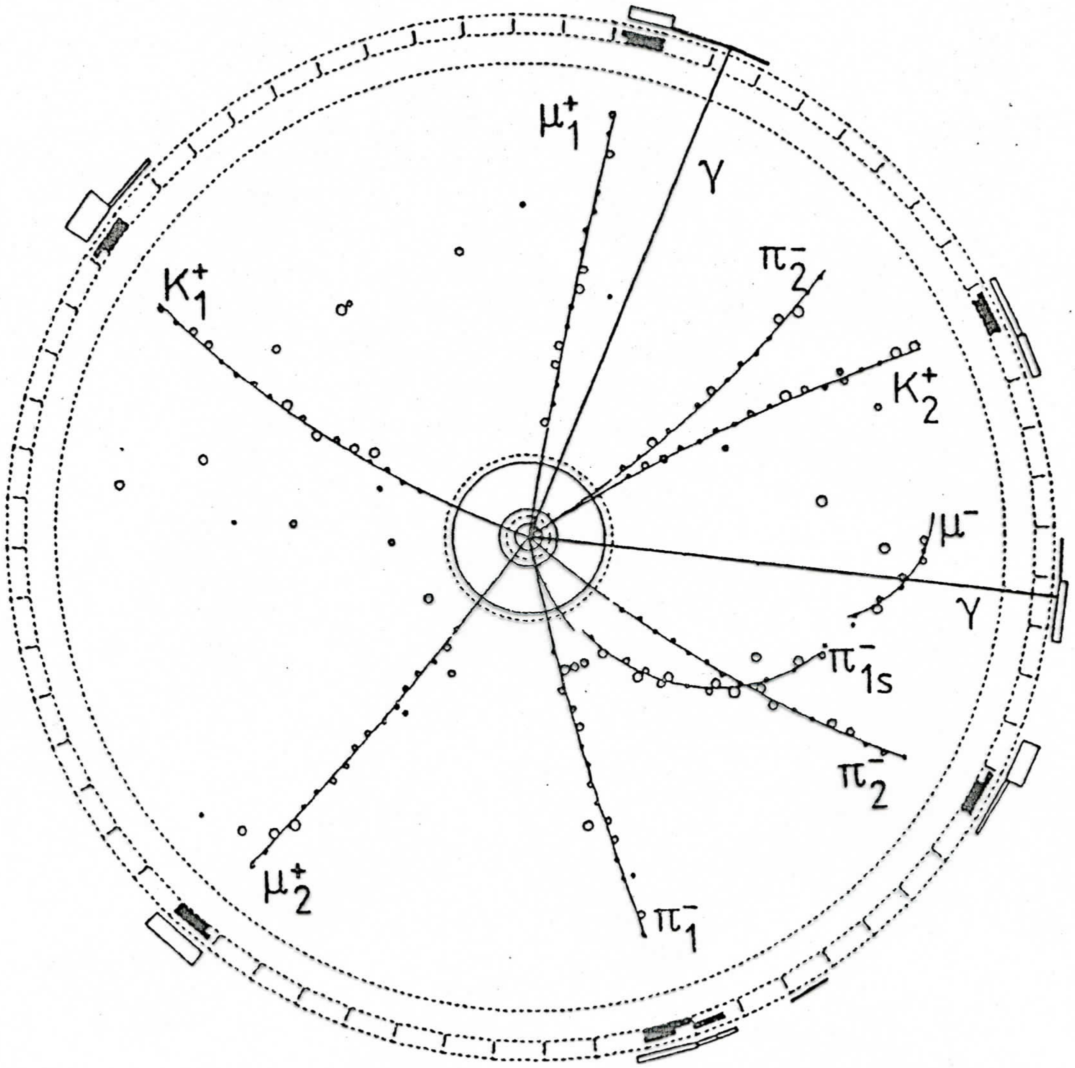
TIME OF FLIGHT FROM INTERACTION P



$$e^+e^- \to B^0 \bar{B}^0$$

$\Downarrow$ MIXING

B^0



K, μ → TAG B-FLAVOUR

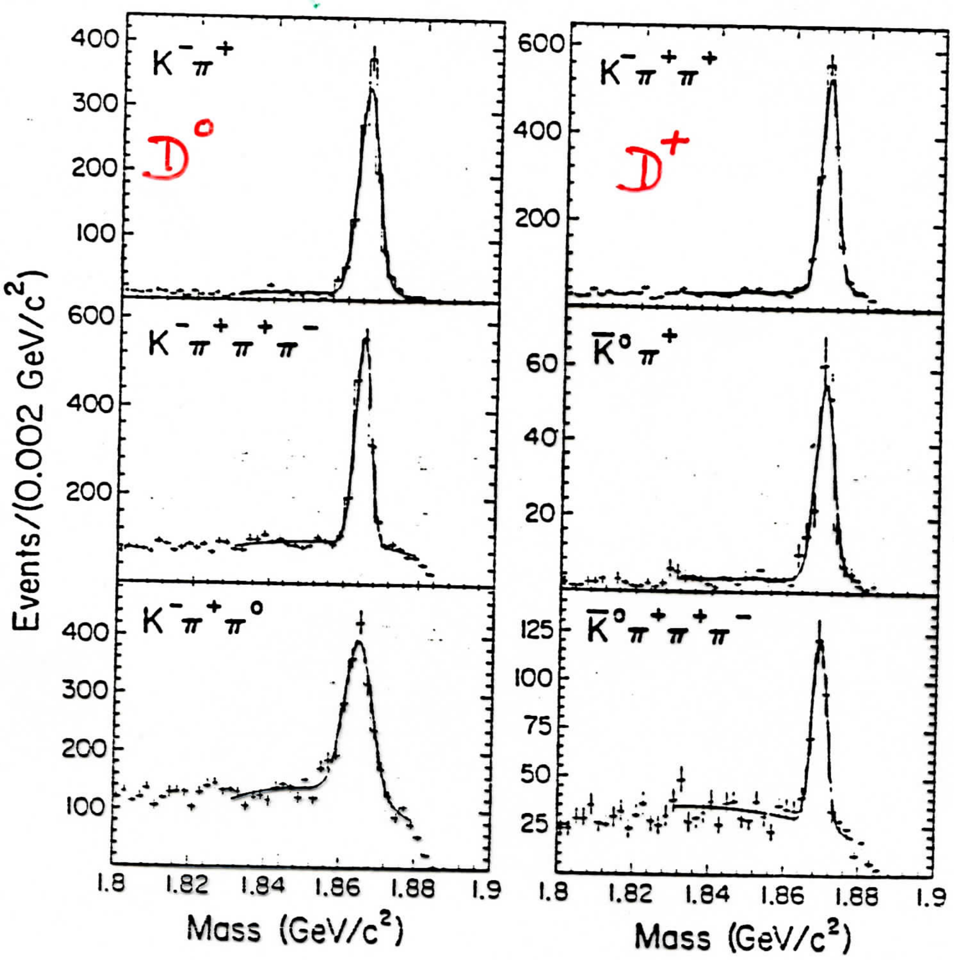
$$B_1^0 \to \mu_1^+ \nu_1 + \pi_1^- + K_1^- \pi_1^-$$

$$B_2^0 \to \mu_2^+ \nu_2 + \pi^0 + K_2^- \pi_2^- \pi_2^-$$

$\hookrightarrow \gamma\gamma$

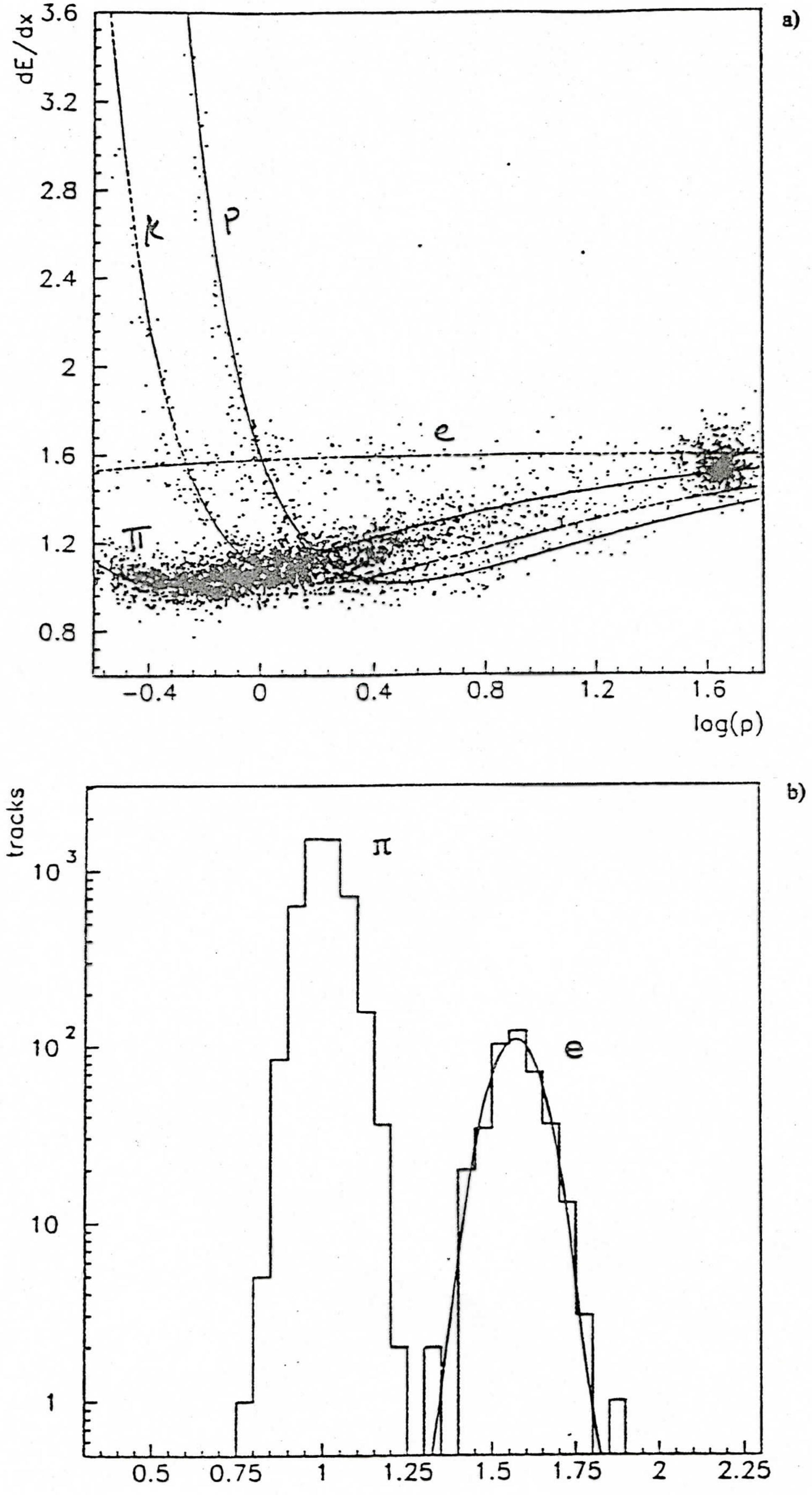
"CROSS SECTION" METHOD

(CABIBBO ALLOWED)



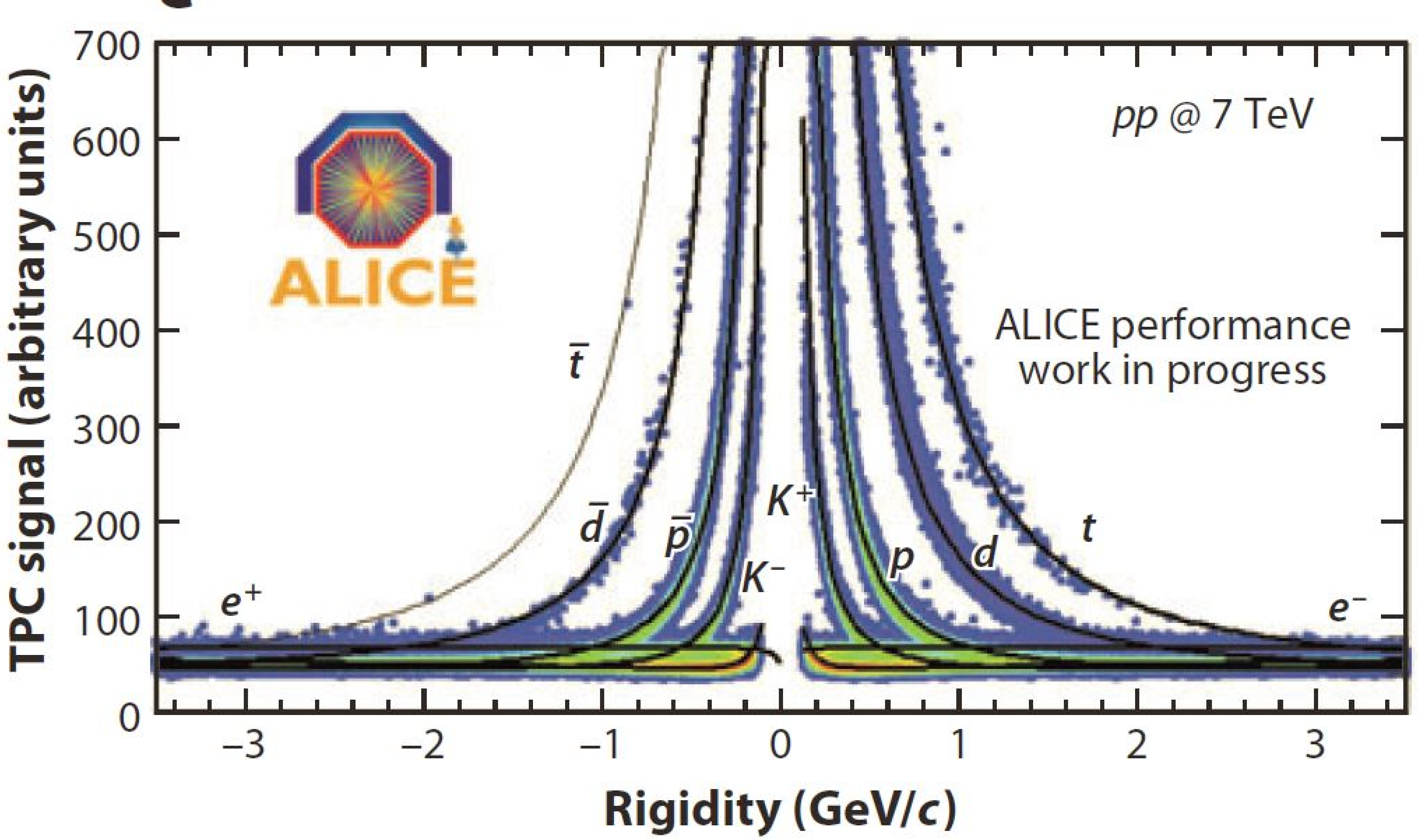
- PARTICLE ID USING TOF
- FORM APPROPRIATE MASS COMBINATIONS
- BEAM ENERGY CONSTRAINT $\sigma(M) \sim 2.5$ MeV/c²
- DECAYS WITH η^0 OR π^0 USE TWO CONSTRAINT FIT.

Aleph TPC Data



(normalized to that for π)

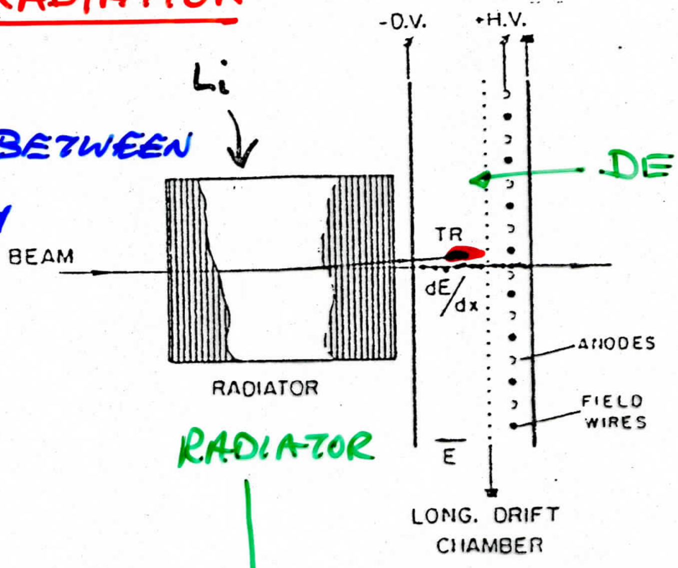
Fig. 24


TPC signal (arbitrary units)
0
100
200
300
400
500
600
700
Rigidity (GeV/c)
−3
−2
−1
0
1
2
3
ALICE
pp @ 7 TeV
ALICE performance work in progress
$\bar{t}$
$\bar{d}$
$\bar{p}$
K^-
K^+
p
d
t
e^+
e^-

TRANSITION RADIATION

- INTERFERENCE BETWEEN Č RADIATION FROM TWO SURFACES OF A FOIL
- INTERFERENCE ⇒ THRESHOLD IN γ

Li



DETECTOR OF γ_{TR}

RADIATOR

Li LOW A to AVOID ABSORPTION

- STACK OF THIN Lo A LAYERS

  1000 Li FOILS × 50μ THICK

- X RAY DETECTOR FOR γ_{TR}

  XENON $Z = 54$

- COUNT ENERGY OF X-RAYS OR CLUSTERS ABOVE (~2keV) ENERGY THRESHOLD

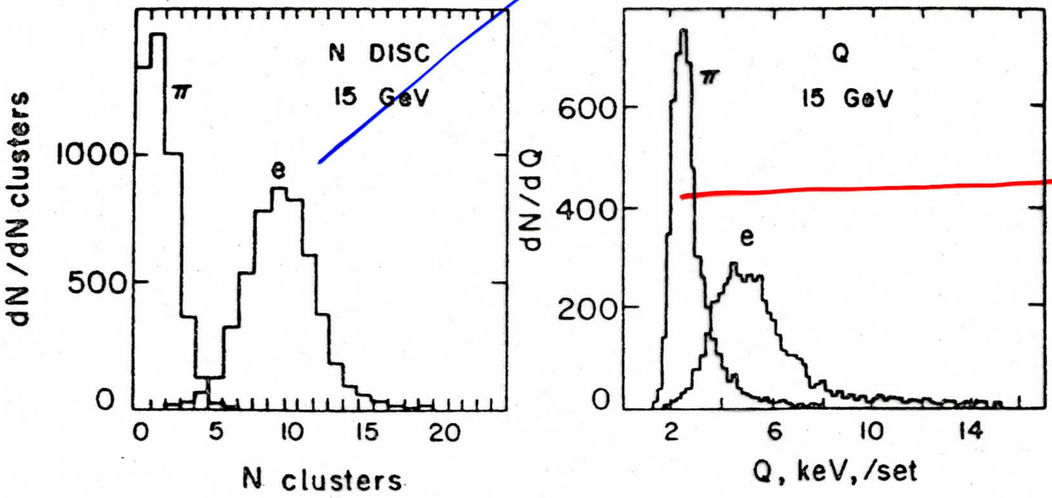
- π REJECTION FACTORS ~ 1000

➡ ATLAS TRT

STRAWS → RADIATORS

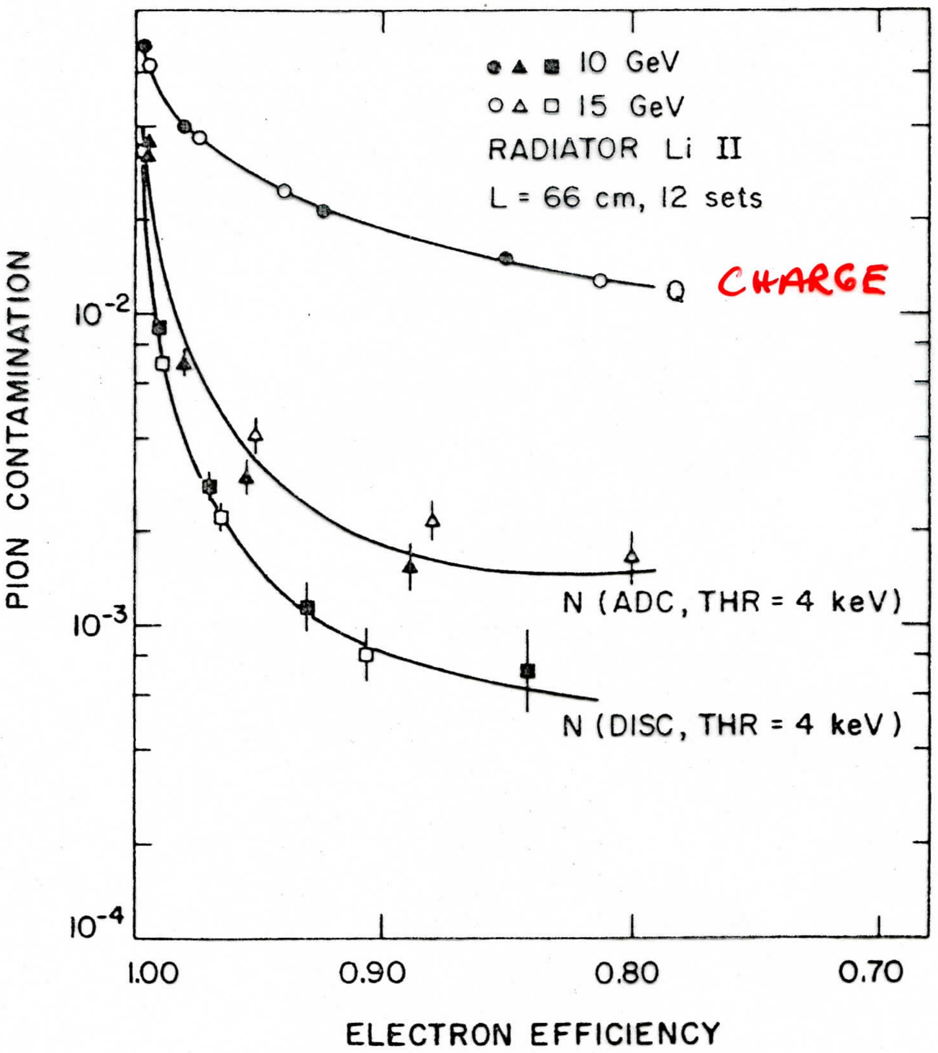
POLYPROPYLENE FOAM / FIBRES

ELECTRONS ABOVE γ_{TR} THRESHOLD



π BELOW THRESHOLD

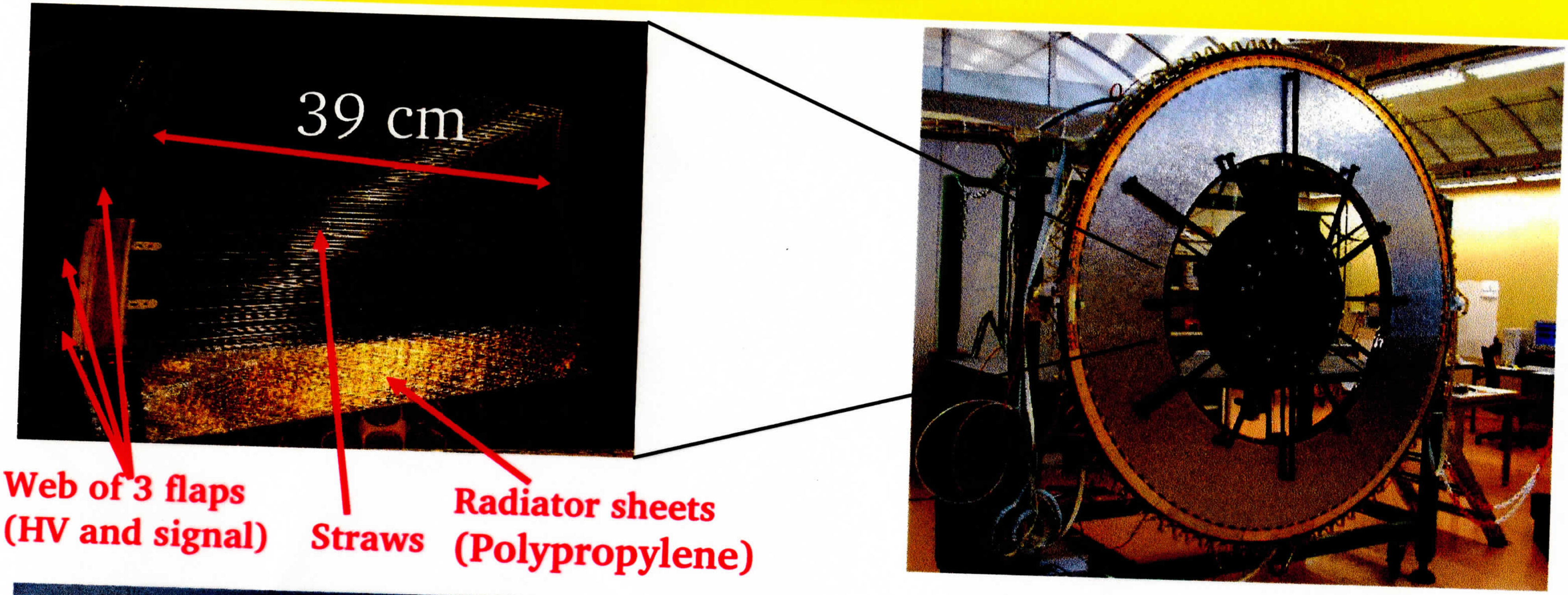
$\frac{dE}{dx}$ IONIZATION

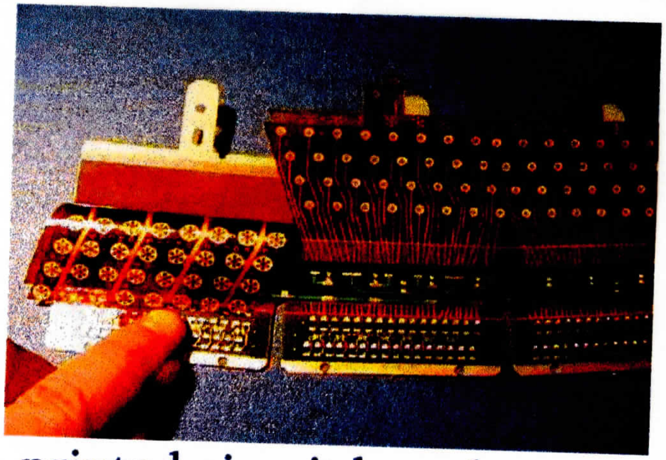


CHARGE

CLUSTERS

The ATLAS Transition Radiation Tracker detector





printed circuit board
<u>*Wheel Endcap Boards*</u> (WEB)
for HV and signal

☞ ***Endcap TRT:***

Two type of wheels:

- 24 **A-type** wheels
  (R_{in} = 0.64 m & R_{out} = 1.03 m)
- 16 **B-type** wheels
- 6144 radial straws per wheel

☞ **245760 readout channels upto 20 MHz!**

Transition Radiation (TR) for particle identification

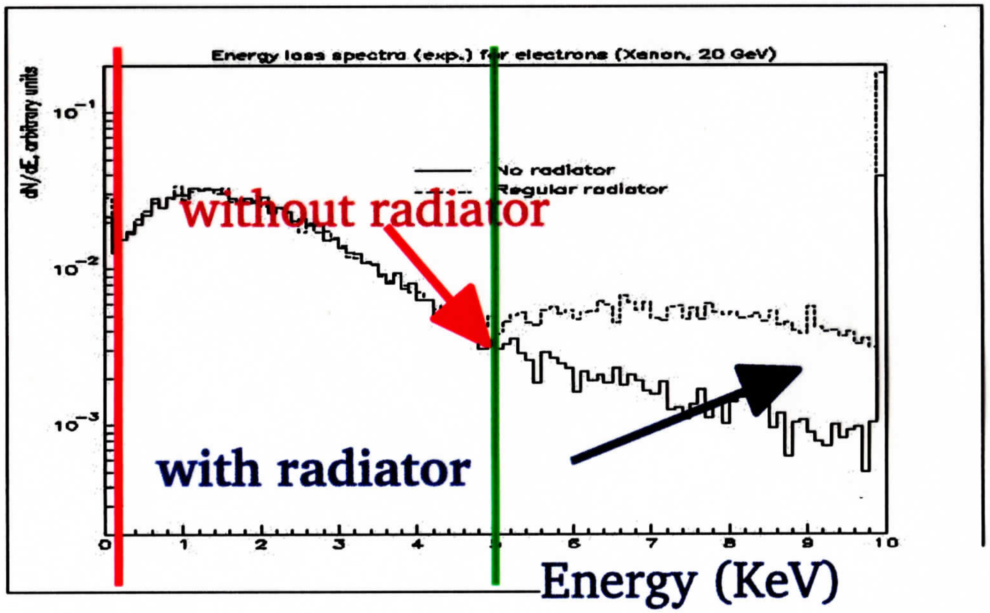
- produced by charged ultra-relativistic ($\gamma \sim 10^{3\text{-}4}$) particle crossing interface between different dielectrics.

- Emitted at small angle with respect to parent particle trajectory.

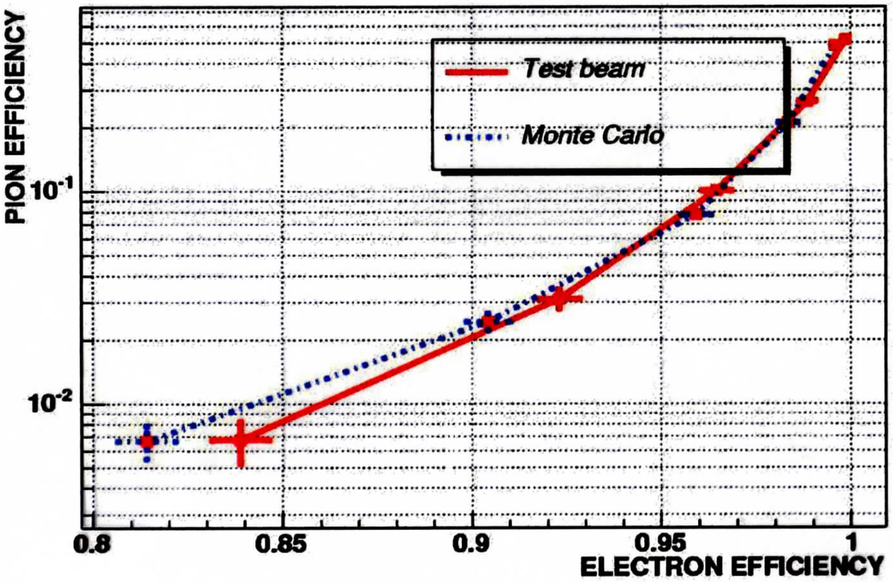
- Absorbed by high-Z gas mixture (Xe)

- Deposited energy in detector: ionization loss (dE/dx) ⊕ TR (> 5 keV)

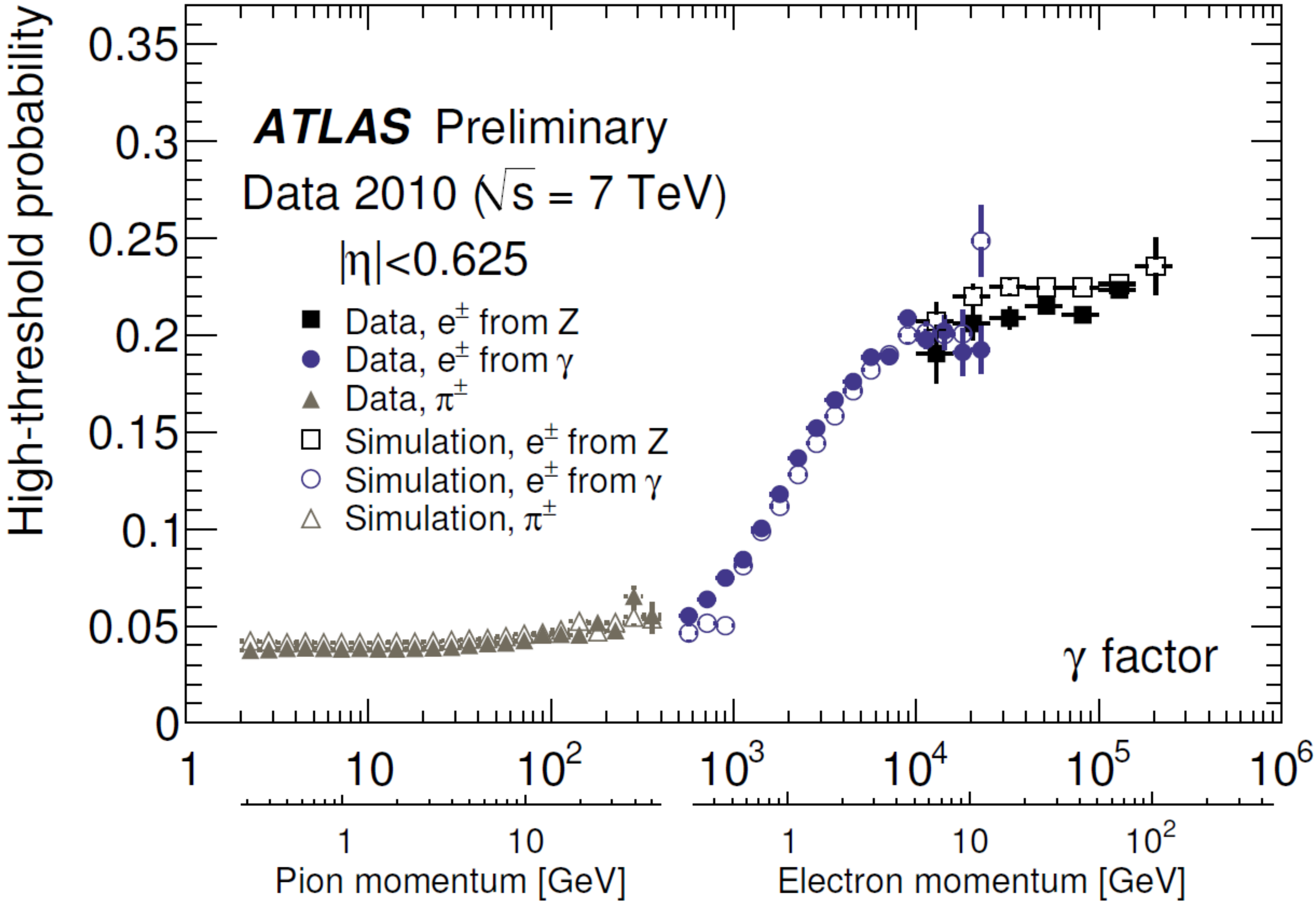
☞ **Two thresholds**: Low @ ***200 eV*** (tracking), High @ ***5 keV*** (TR)

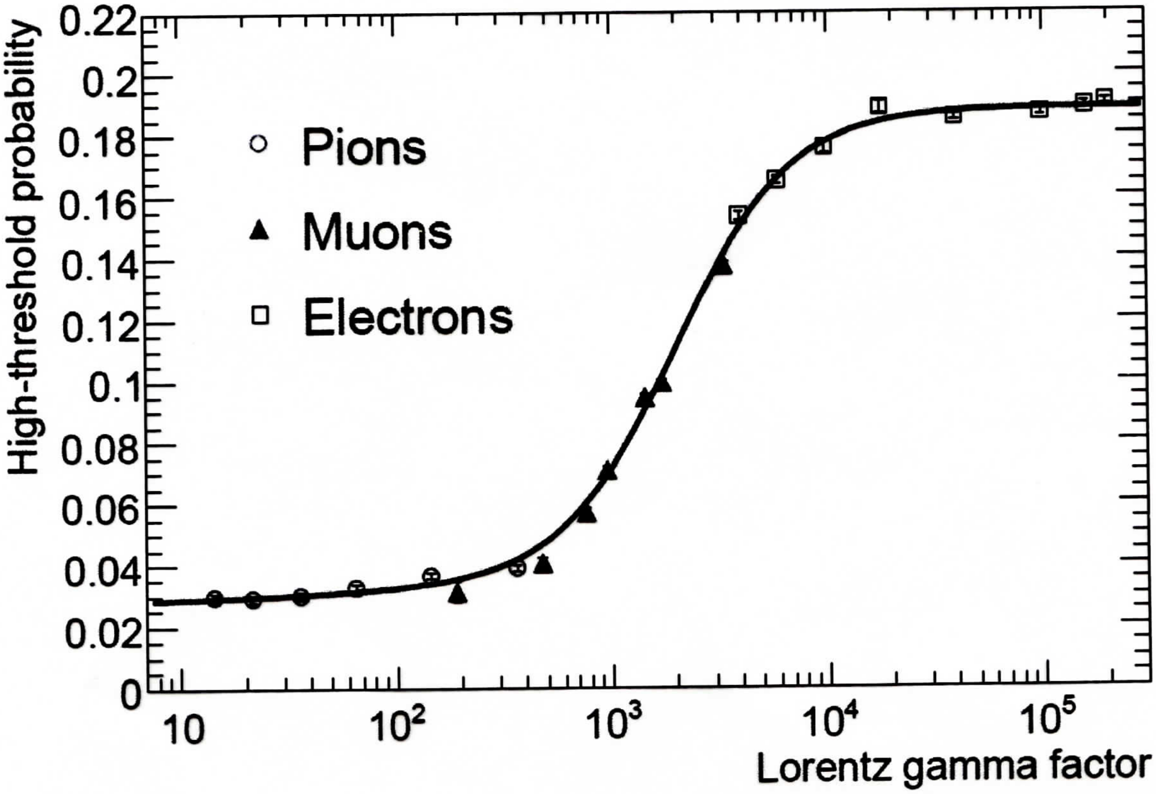


Energy loss spectra for 20 GeV electrons



Electron /Pion separation using TR


ATLAS Preliminary
Data 2010 ($\sqrt{s}$ = 7 TeV)
$|\eta|<0.625$
■ Data, $e^{\pm}$ from Z
● Data, $e^{\pm}$ from γ
▲ Data, $\pi^{\pm}$
□ Simulation, $e^{\pm}$ from Z
○ Simulation, $e^{\pm}$ from γ
△ Simulation, $\pi^{\pm}$
High-threshold probability
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
γ factor
1
10
10^2
10^3
10^4
10^5
10^6
1
10
Pion momentum [GeV]
1
10
10^2
Electron momentum [GeV]



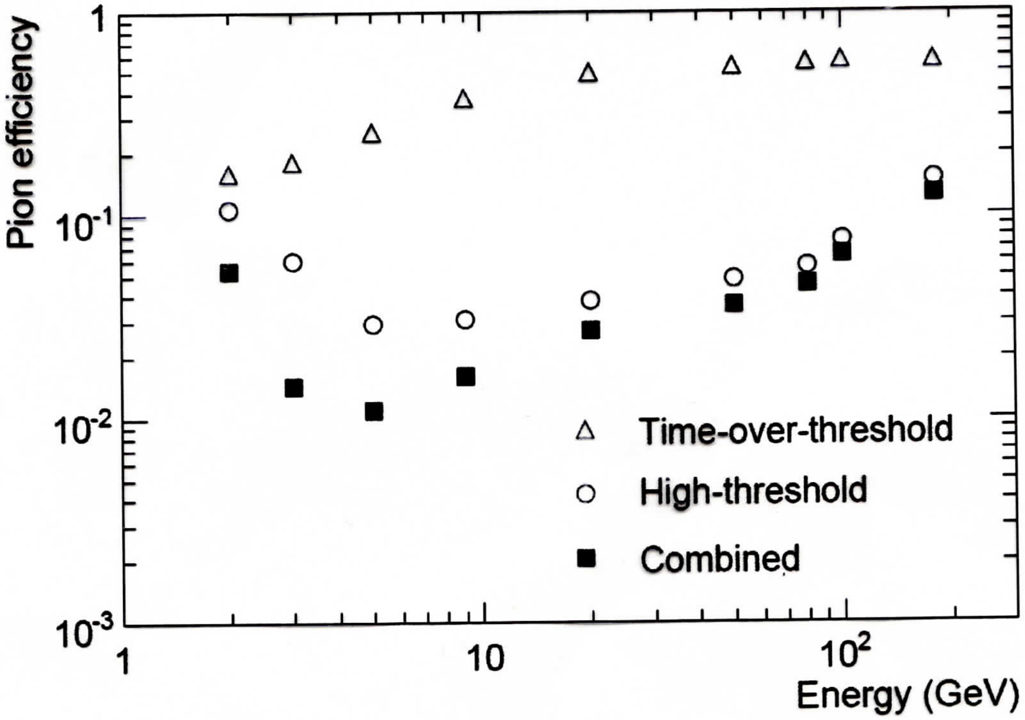


Figure 216. Pion efficiency shown as a function of the pion energy for 90% electron efficiency, using high-threshold hits (open circles), time-

RING IMAGING ČERENKOV COUNTER

RICH / CRID

- DETECT RING OF ČERENKOV LIGHT.

$$\theta_c = \arccos\left(\frac{1}{\beta n}\right)$$ VELOCITY MEASUREMENT

MEASURE RADIUS OF RING

- PHOTON DETECTOR – GASEOUS PHOTOCATHODE:

  TEA TMAE (≈ GASOLINE VAPOUR ! ☺)

- γ ABSORBED ; PHOTOELECTRON EMITTED

  e^- DRIFTS UP TO ~ 1m

  ↳ DETECTED IN MWPC

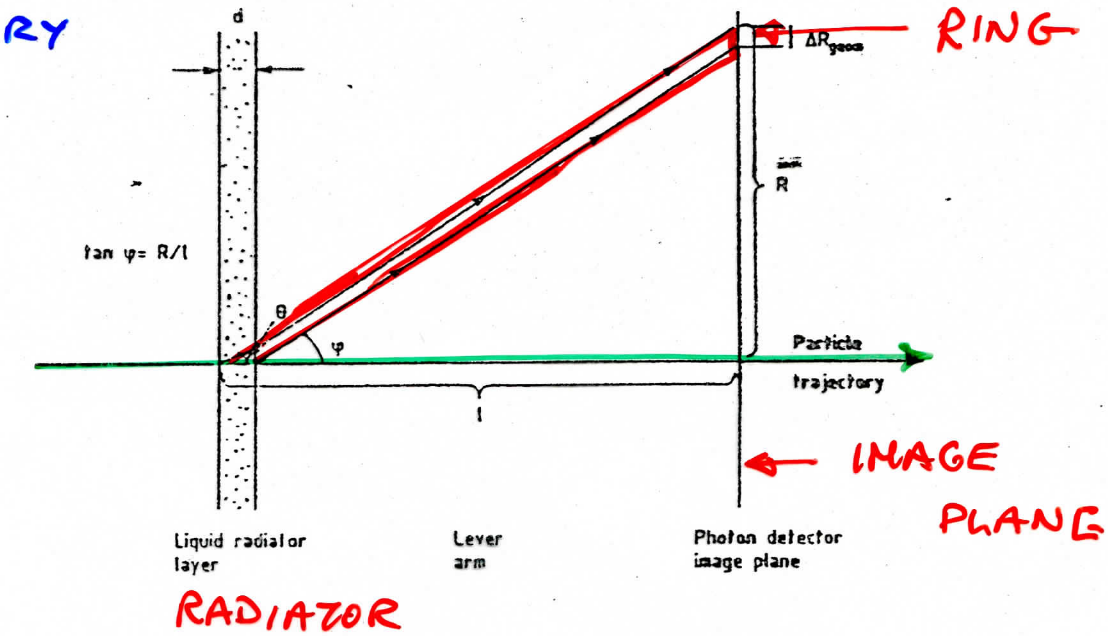
e/π	0.2 – 7.0 GeV/c
μ/π	0.2 – 1.11 ; 2.1 – 4.0 GeV/c
π/K	0.23 – 32 GeV/c
K/p	0.80 – 55 GeV/c

3σ SEPARATION

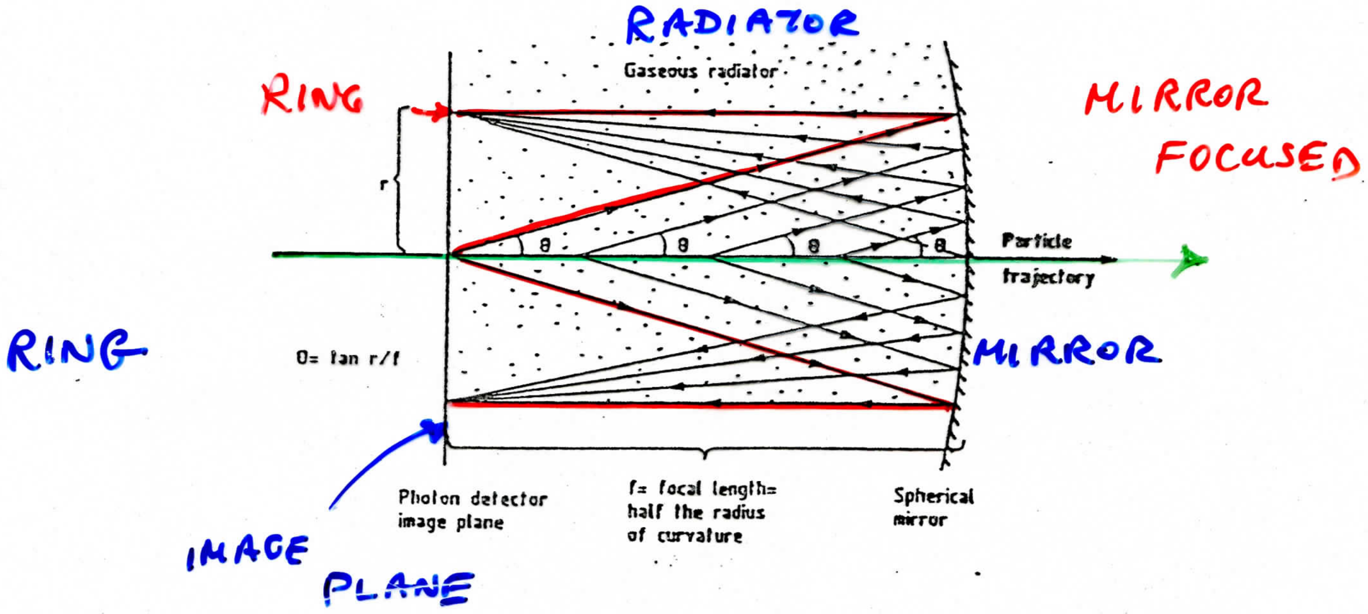
AS ANGLE OF TRAJORY CHANGES

NO RING

PROXIMITY FOCUSSING



FOCUSSING WITH SPHERICAL MIRROR



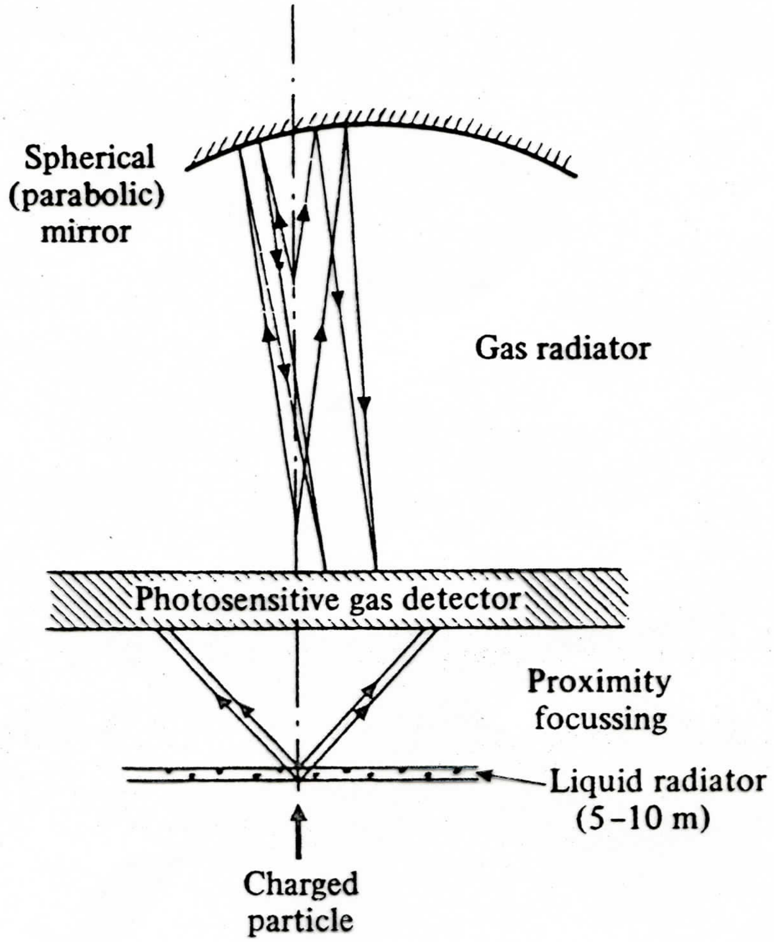
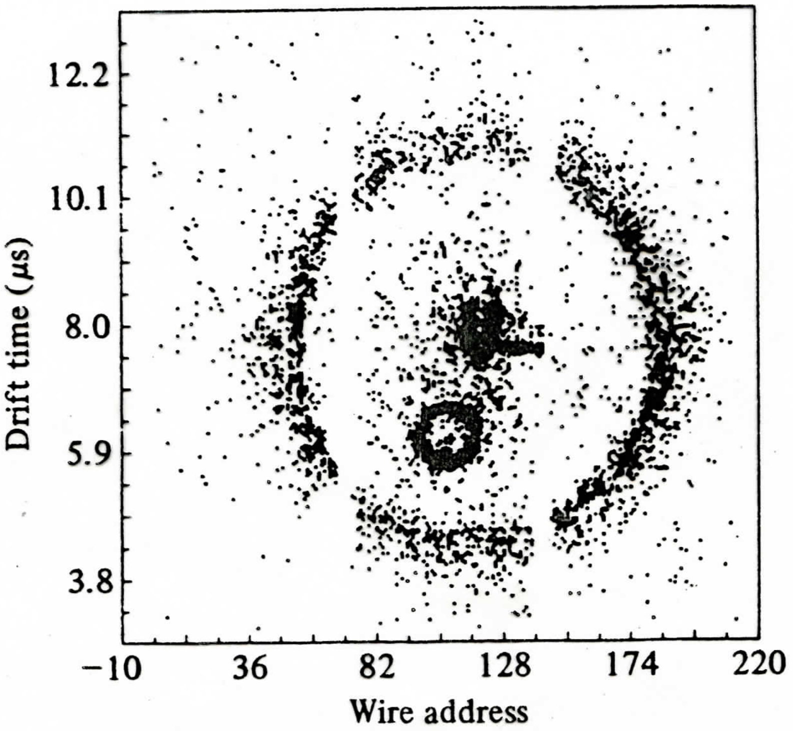
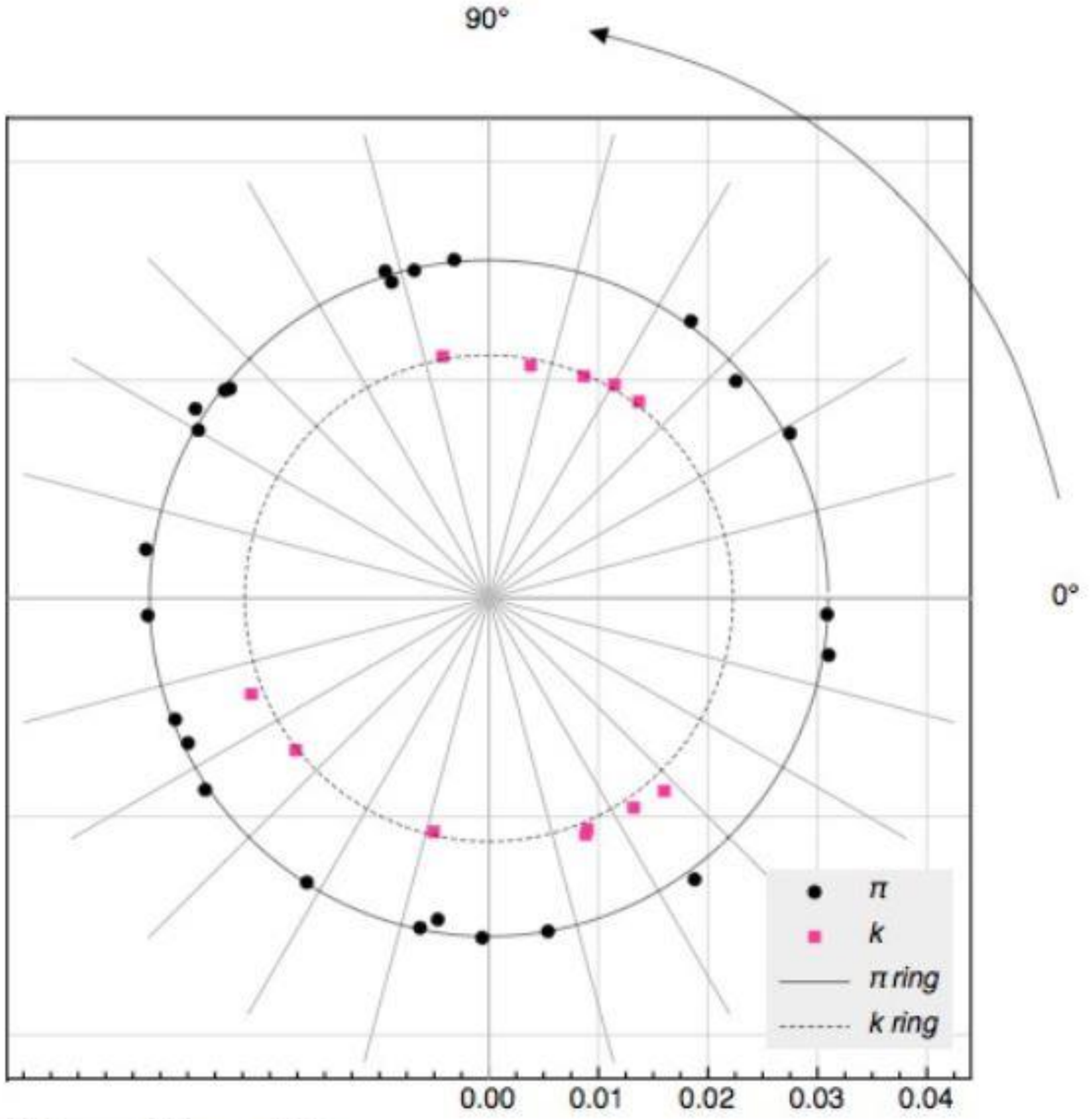


Fig. 2.28 The principle of a RICH counter with two radiators and a single photosensitive chamber.

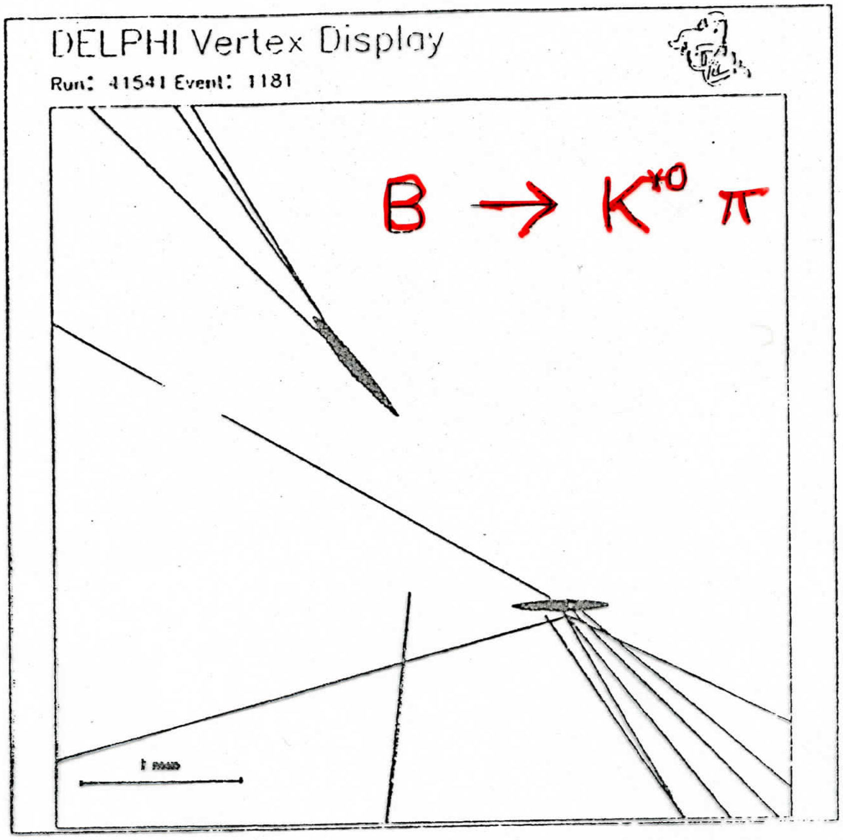


MANY TRACKS !

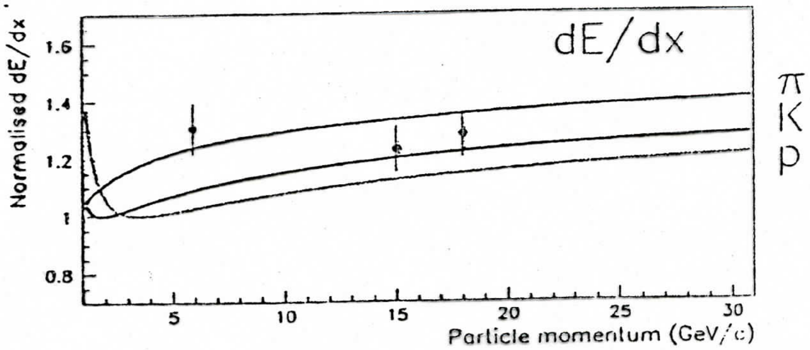
Fig. 2.27 A RICH image, with a centred (unfocussed or 'proximity focussed') ring around the track impact point, and an indirect (mirror focussed) ring slightly off centre. Superposition of multiple tracks with normal incidence.



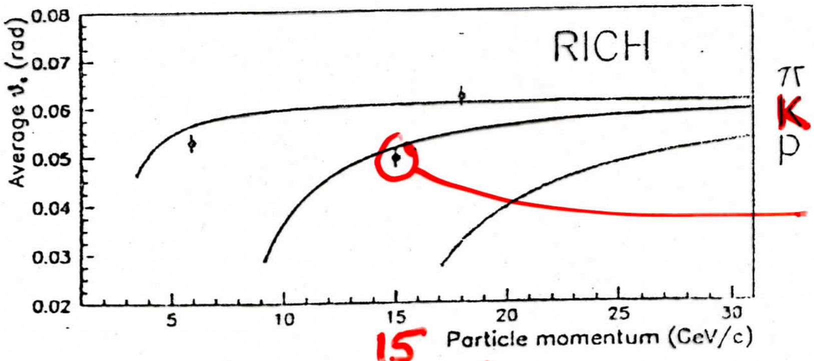
Polar plot of the angles of emission of Cherenkov photons for a particle (both pion and kaon) of momentum 22 GeV/c in a radiator with n=1.0005 and angular resolution 0.64 mrads, in a RICH with Nc ~ 25



$B \rightarrow K^{*0}\, \pi$



$\frac{dE}{dx}$



RICH

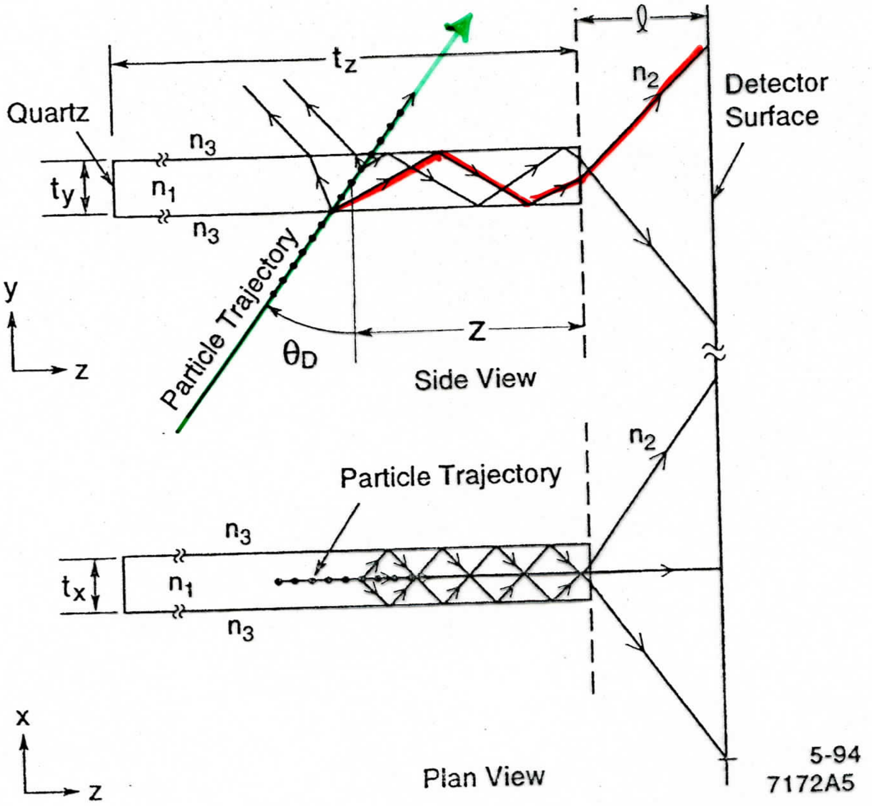
K TAGS B FLAVOUR.

15 GeV/c

BABAR DETECTOR FOR THE PEP-II B FACTORY

Modeled by Daryl [illegible] - Berkeley Lab

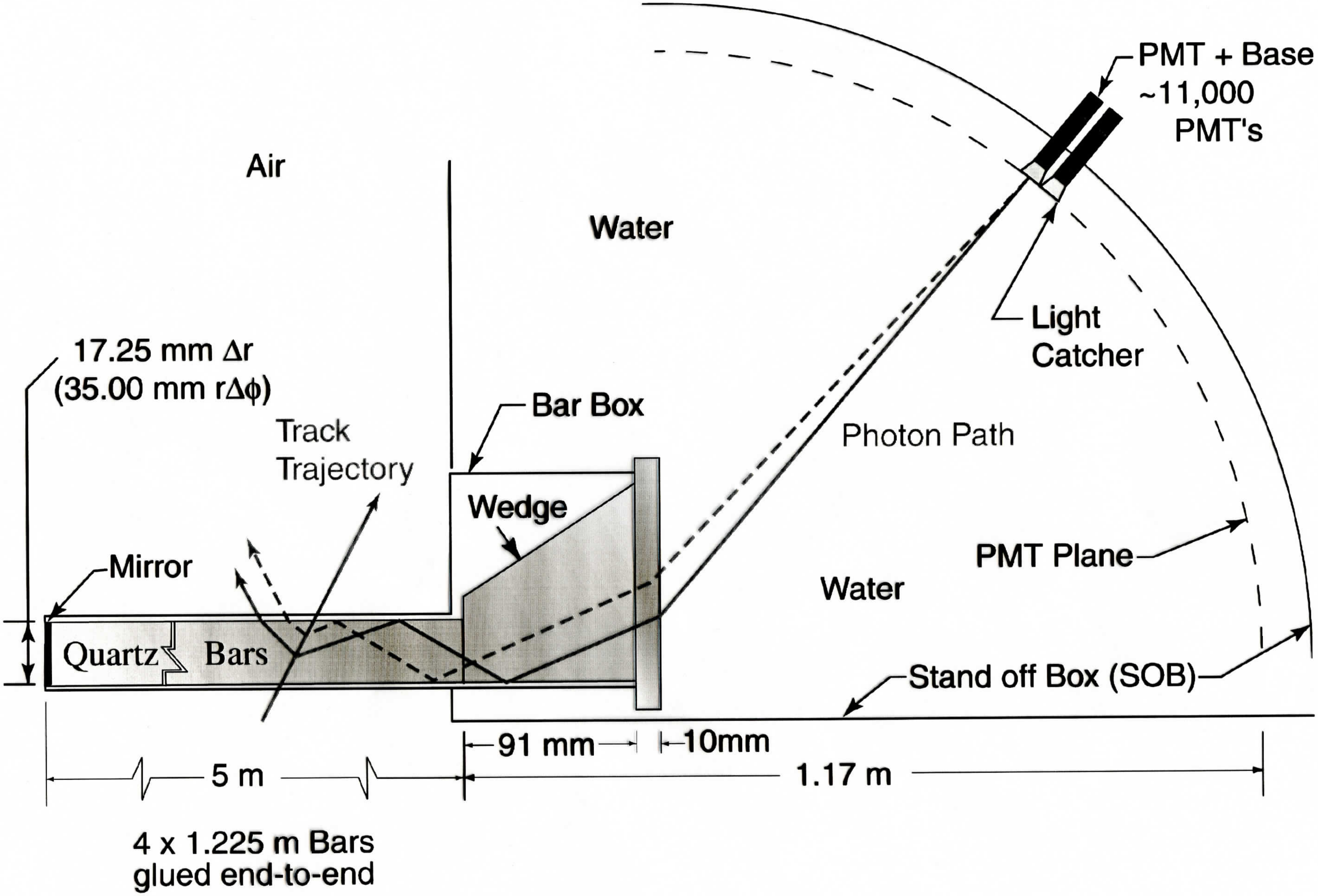
DIRC – COMPACT RICH

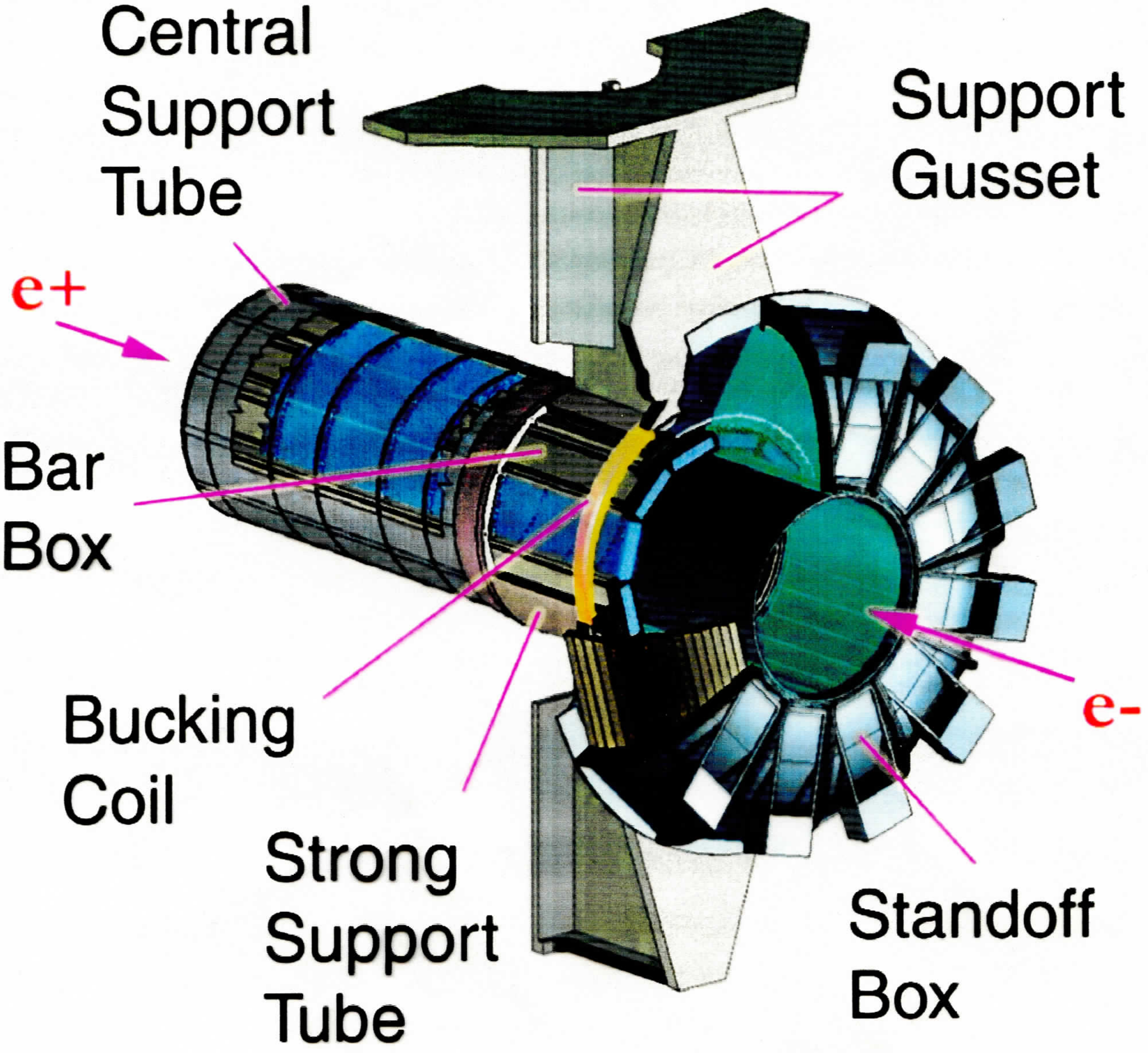


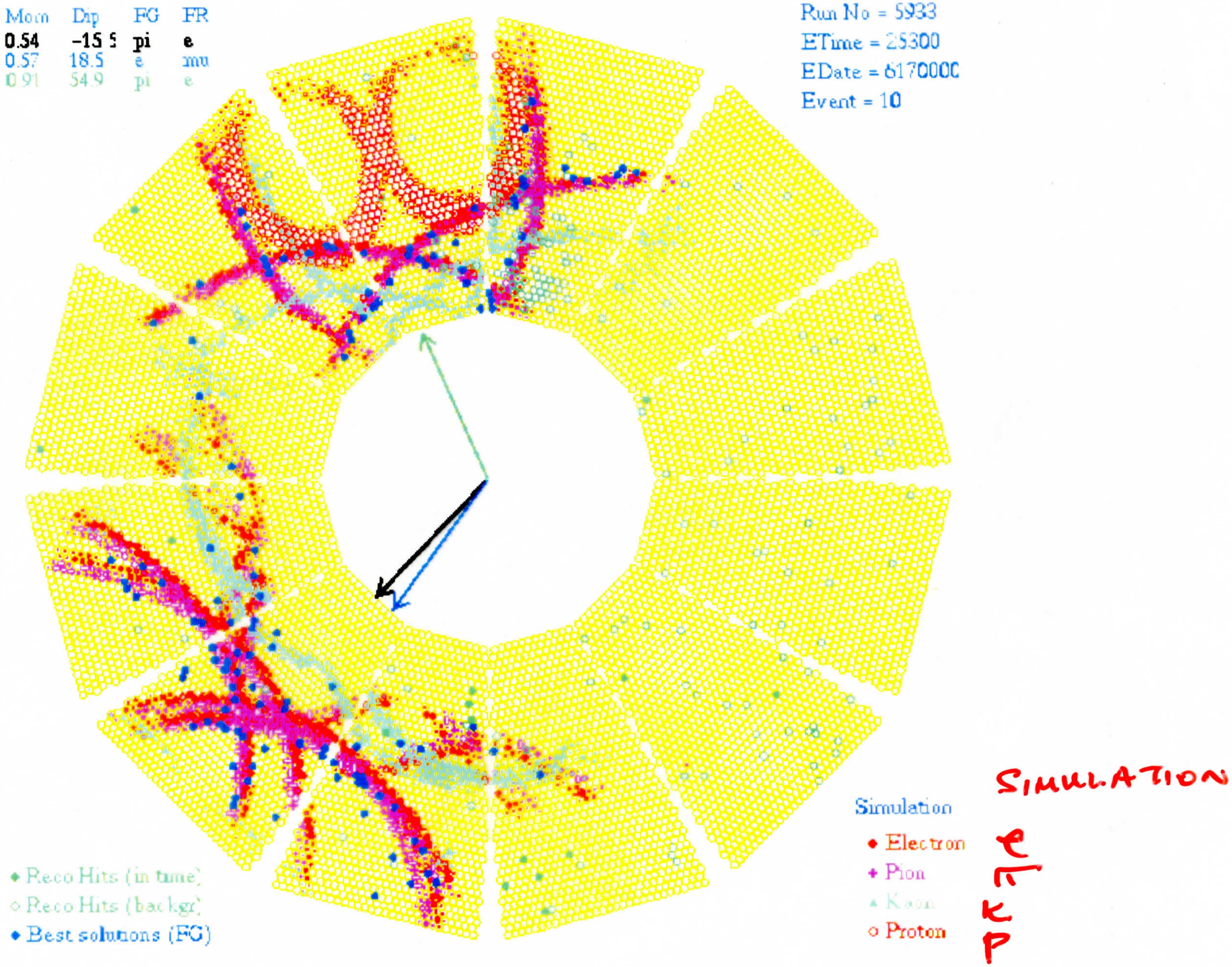
- TRAP Č LIGHT IN BAR
- EXTRACT AT ONE END
- $\theta_{EXIT} \approx \theta_c$
- SIMILAR TO RICH
- GET γ DETECTOR AWAY FROM PARTICLE TRAJORY

↓

CONVENTIONAL PMT


PMT + Base
~11,000
PMT's
Air
Water
Light
Catcher
17.25 mm Δr
(35.00 mm rΔϕ)
Bar Box
Track
Trajectory
Photon Path
Wedge
Mirror
PMT Plane
Water
Quartz
Bars
Stand off Box (SOB)
91 mm
10mm
5 m
1.17 m
4 x 1.225 m Bars
glued end-to-end


Central Support Tube
Support Gusset
e+
Bar Box
Bucking Coil
Strong Support Tube
e-
Standoff Box

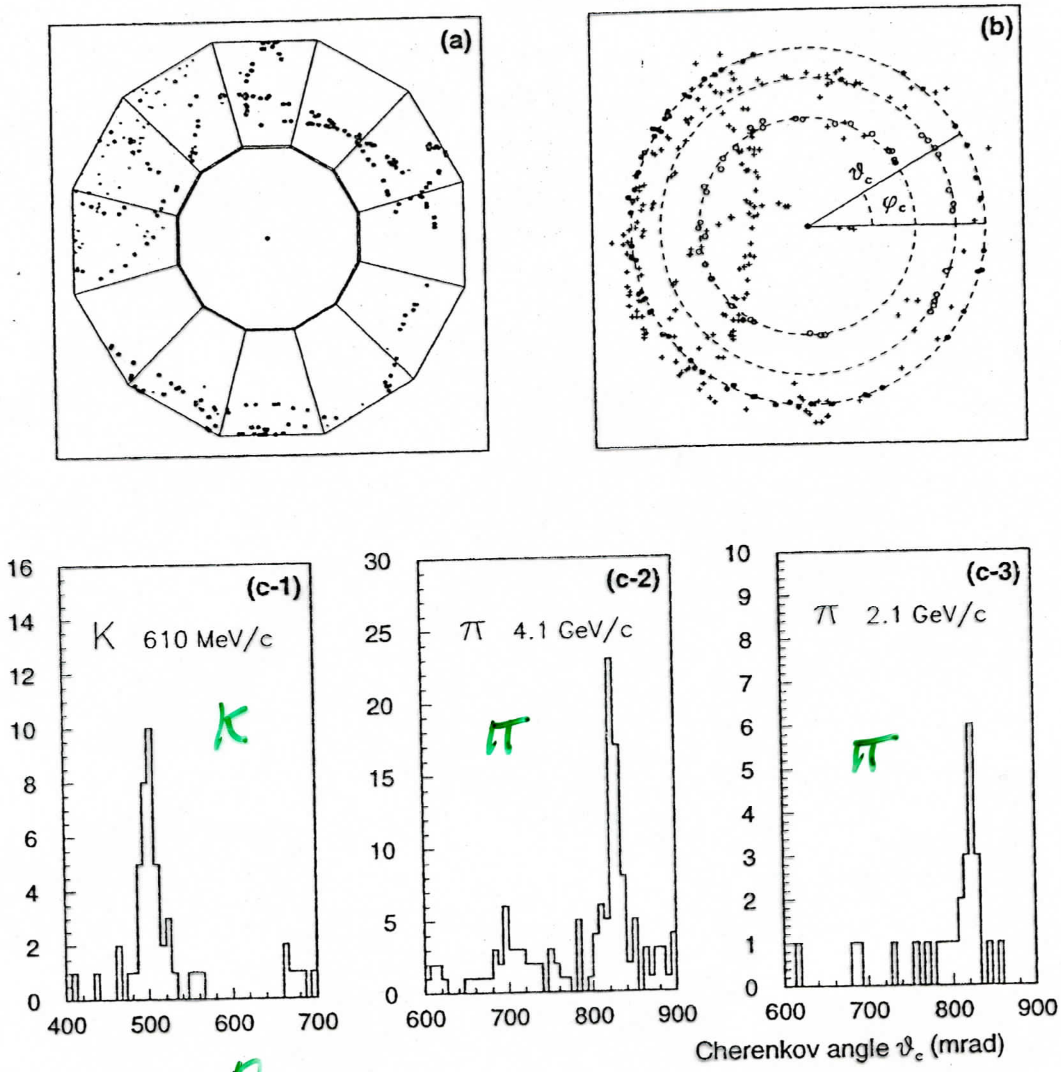


Mom	Dip	FG	FR
0.54	**-15 9**	**pi**	**e**
0.57	18.5	e	mu
0.91	54.9	pi	e

SIMULATION

e
π
K
P

UNFOCUSED → NOT RINGS, CONIC SECTIONS



θ_c

Figure 6-4. *(a) PMT hits projected onto the x-y plane. The particles producing the hits have distinctive markers: Cherenkov images (conic sections) from the $B \rightarrow \pi^+\pi^-$ decays are shown as solid circles, hits from the two other charged tracks as open circles, and from the secondary tracks as '+'. (b) PMT hits projected in Cherenkov angle space with the four tracks superimposed at the center. The hits from the two pions from the B decay overlap at the largest radius, $\phi_c \approx 820$ mr. The '+' marker in this case corresponds to assignment ambiguities. (c) Cherenkov angle projections for three of the tracks and the associated ambiguities.*

SIMULATIONS

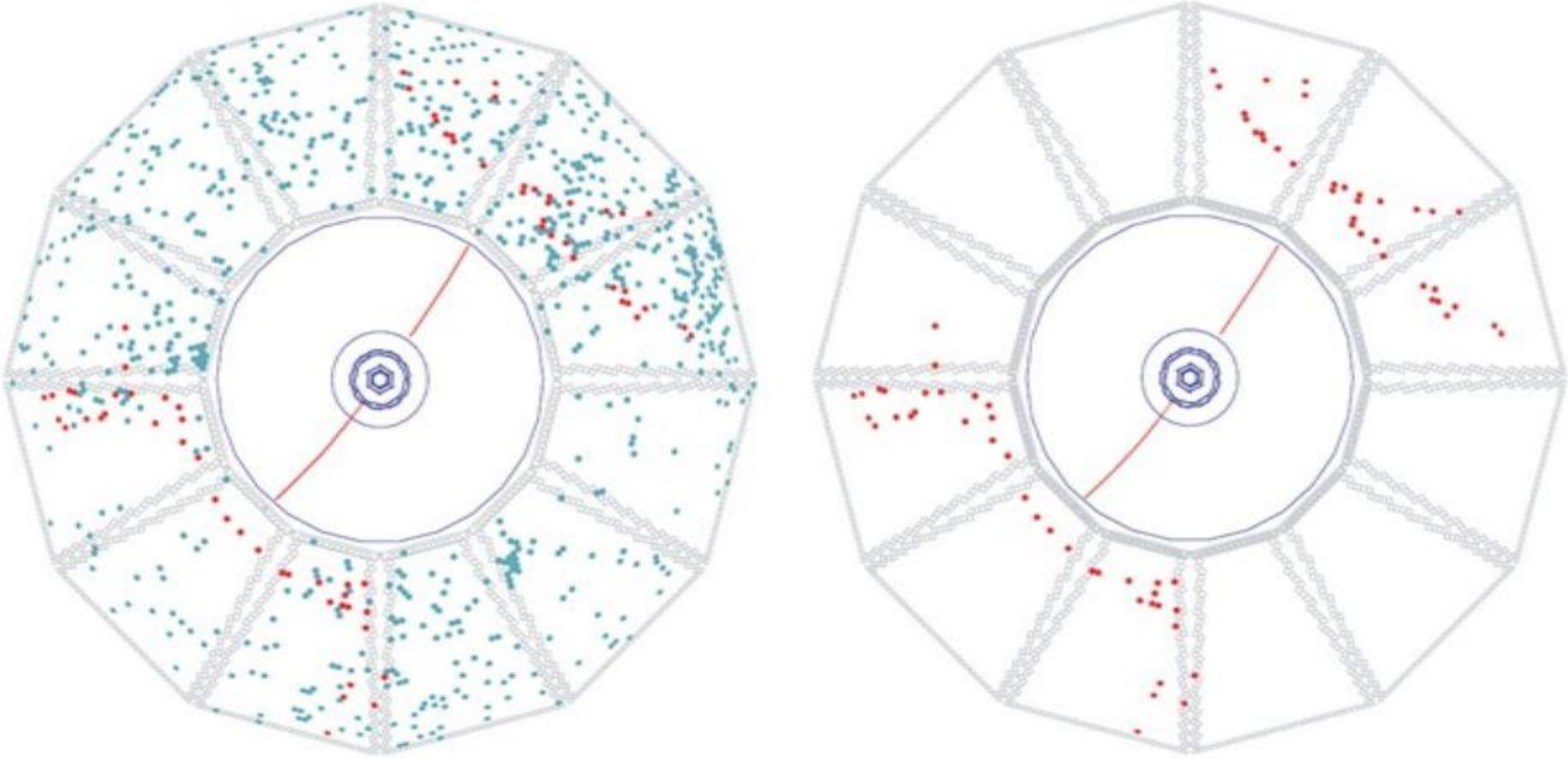
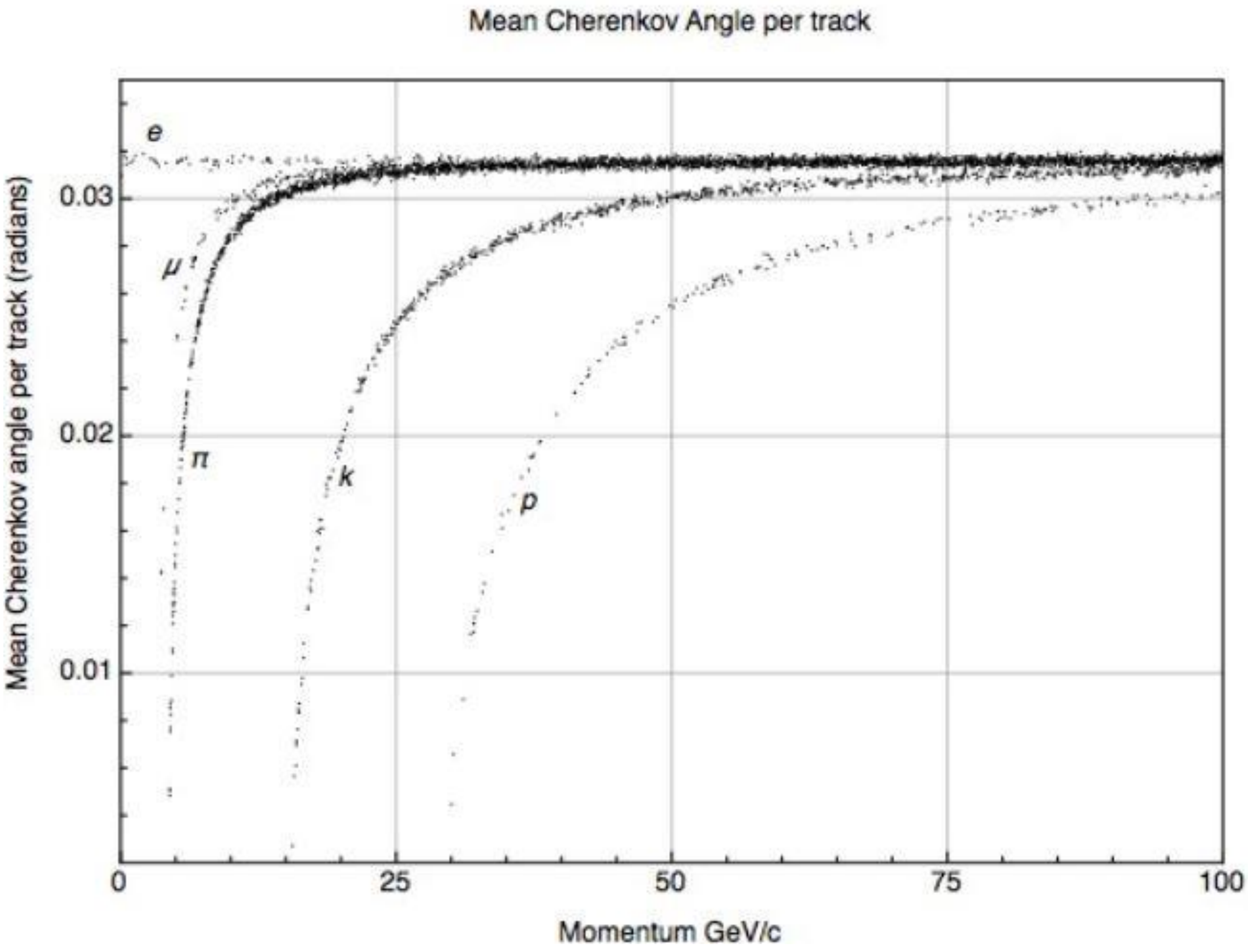


Figure 54. Display of an $e^+e^- \rightarrow \mu^+\mu^-$ event reconstructed in *BABAR* with two different time cuts. On the left, all DIRC PMTs with signals within the ±300 ns trigger window are shown. On the right, only those PMTs with signals within 8 ns of the expected Cherenkov photon arrival time are displayed.


Mean Cherenkov Angle per track
Mean Cherenkov angle per track (radians)
Momentum GeV/c
0.01
0.02
0.03
0
25
50
75
100
e
μ
π
k
p

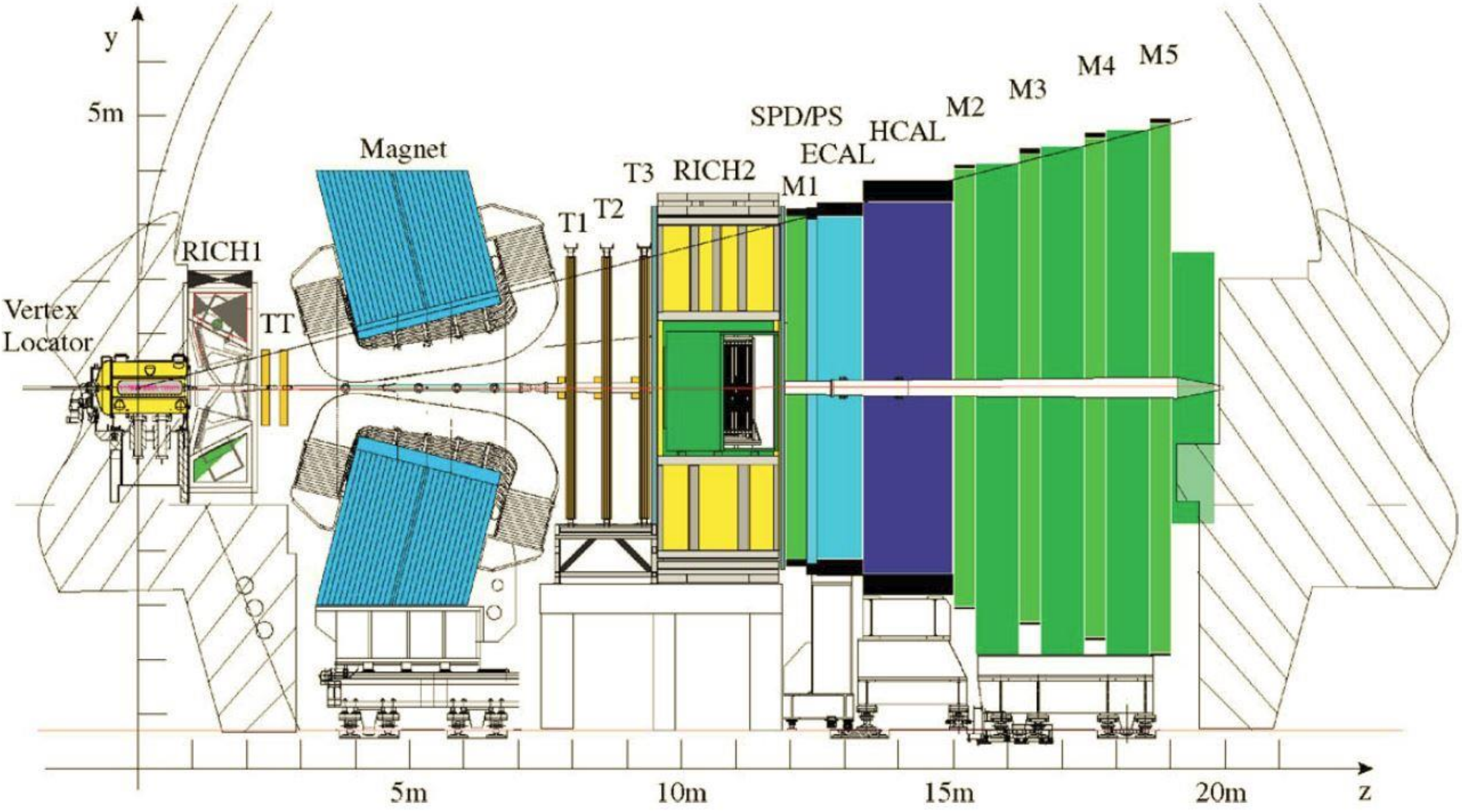
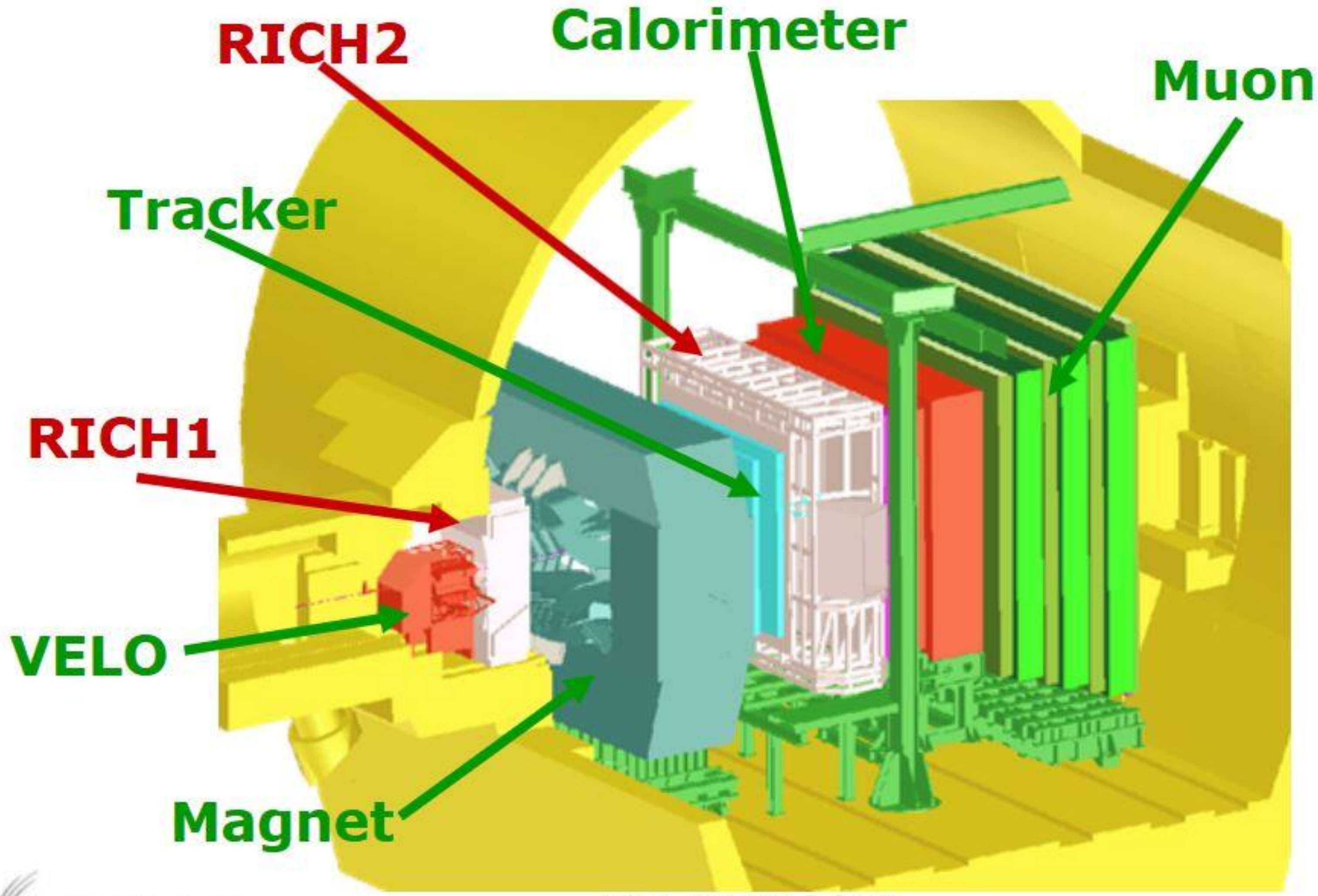


Fig. 1. A schematic of the LHCb detector.

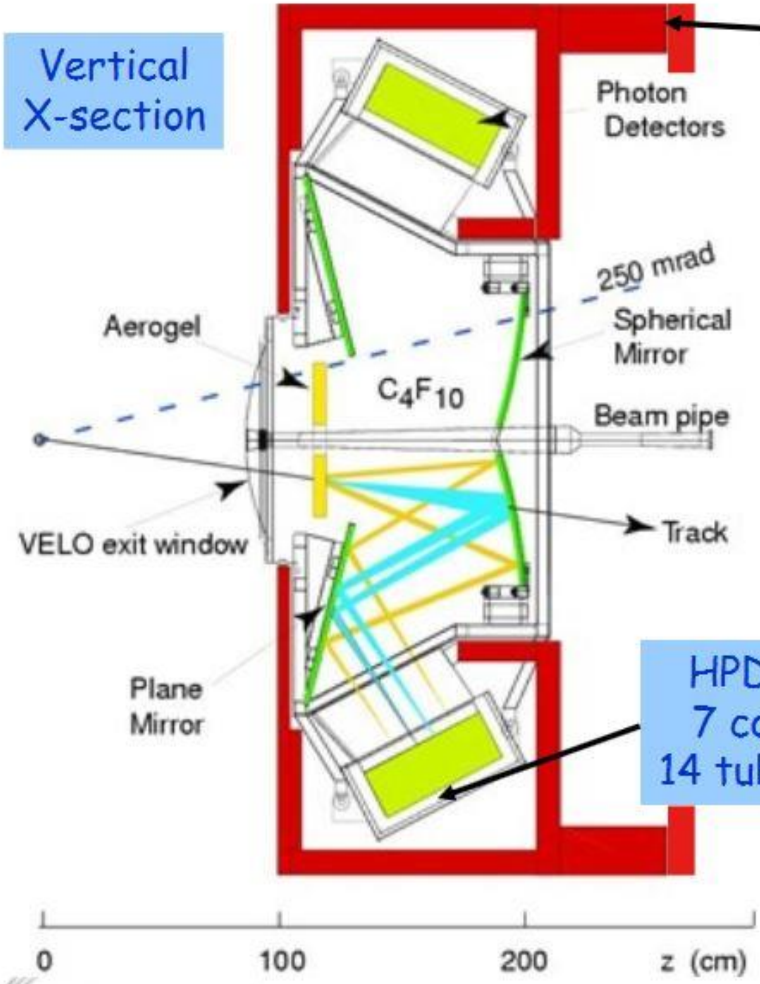
The LHCb Detector

A forward single arm spectrometer



RICH1 (1)

Vertical X-section



HPD plane:
7 columns,
14 tubes each

Magnetic shield box

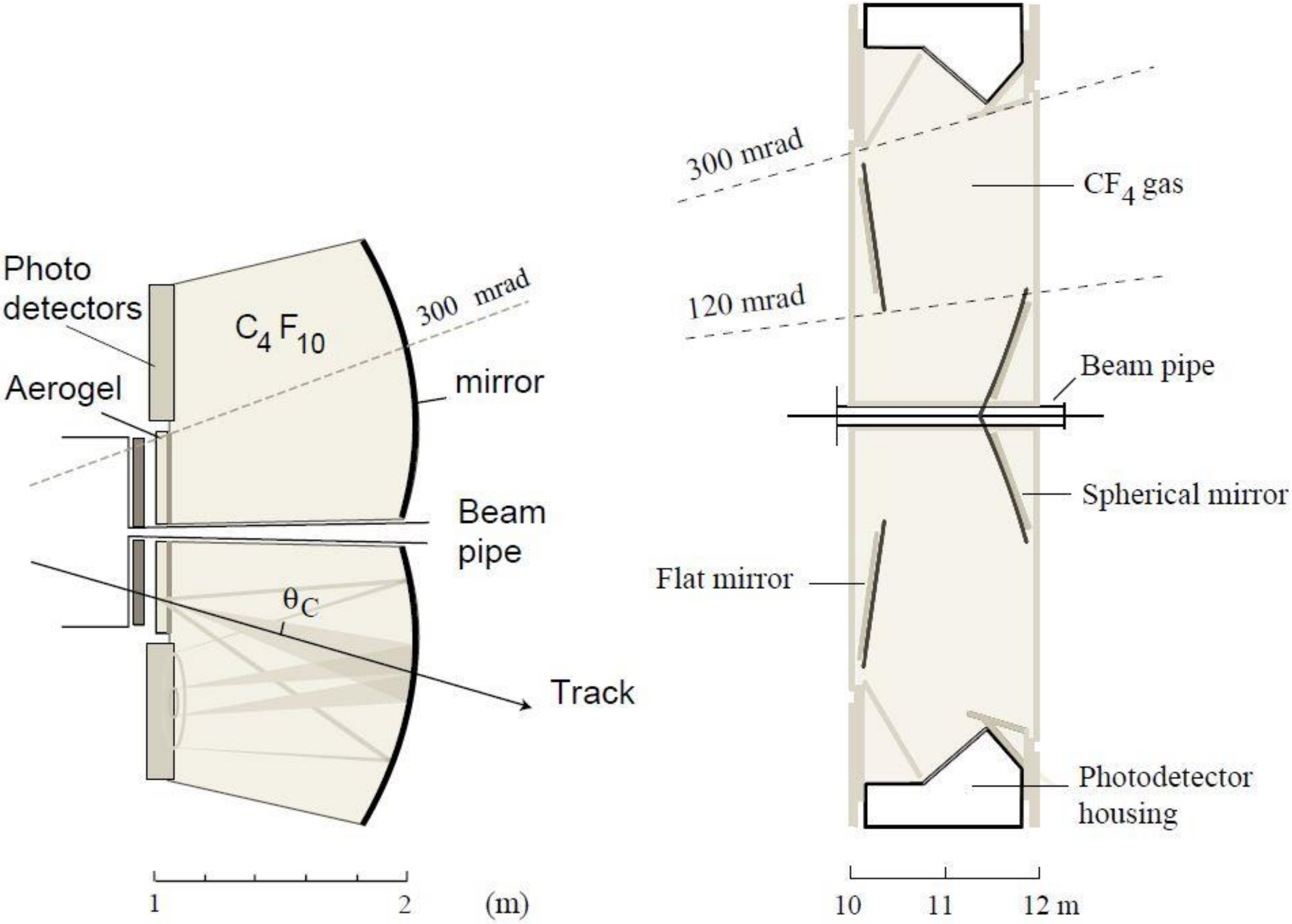
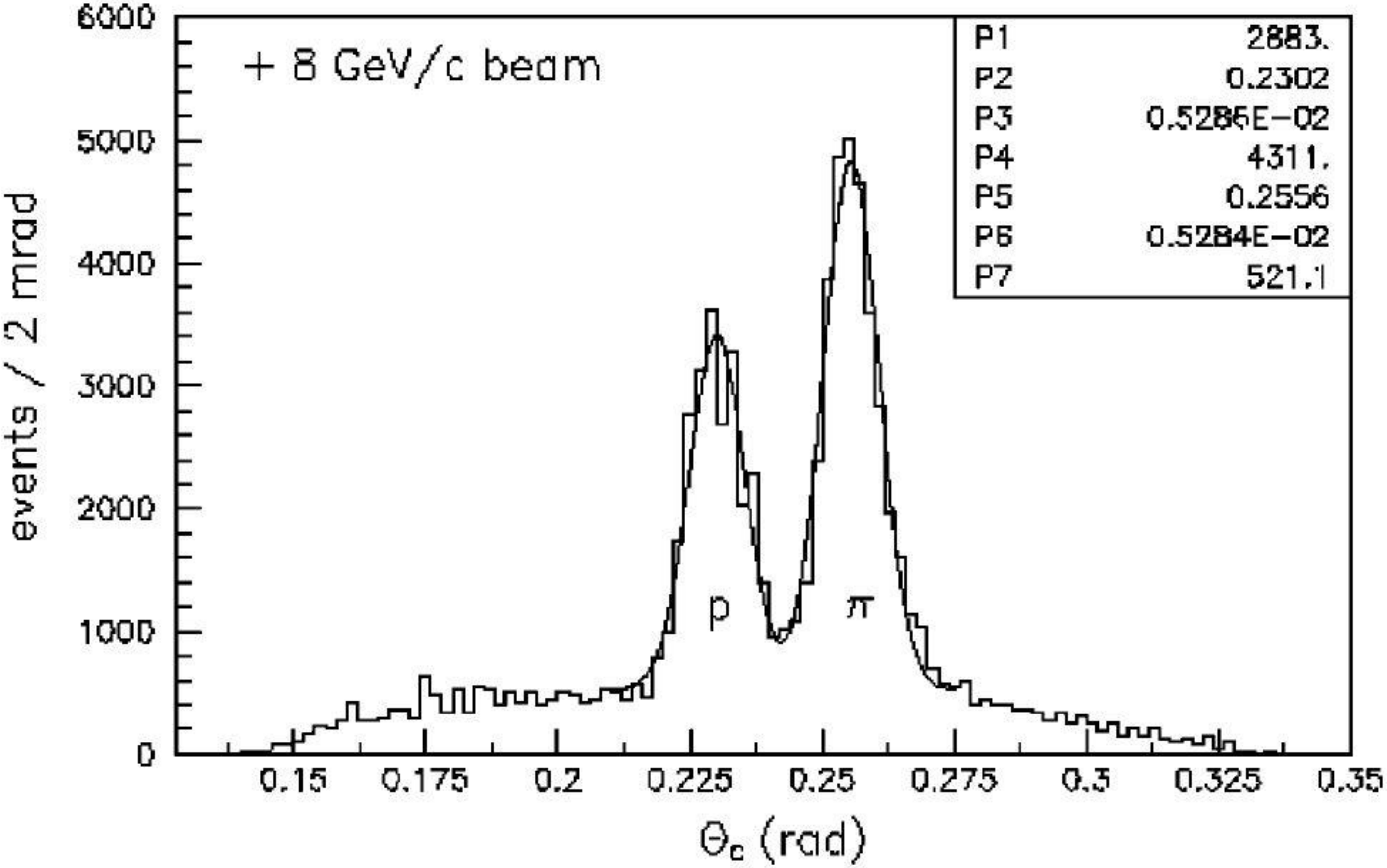


Fig. 14. RICH counters for LHCb [17].


+ 8 GeV/c beam
P1 2883.
P2 0.2302
P3 0.5286E-02
P4 4311.
P5 0.2556
P6 0.5284E-02
P7 521.1
p
π
events / 2 mrad
6000
5000
4000
3000
2000
1000
0
0.15
0.175
0.2
0.225
0.25
0.275
0.3
0.325
0.35
Θc (rad)

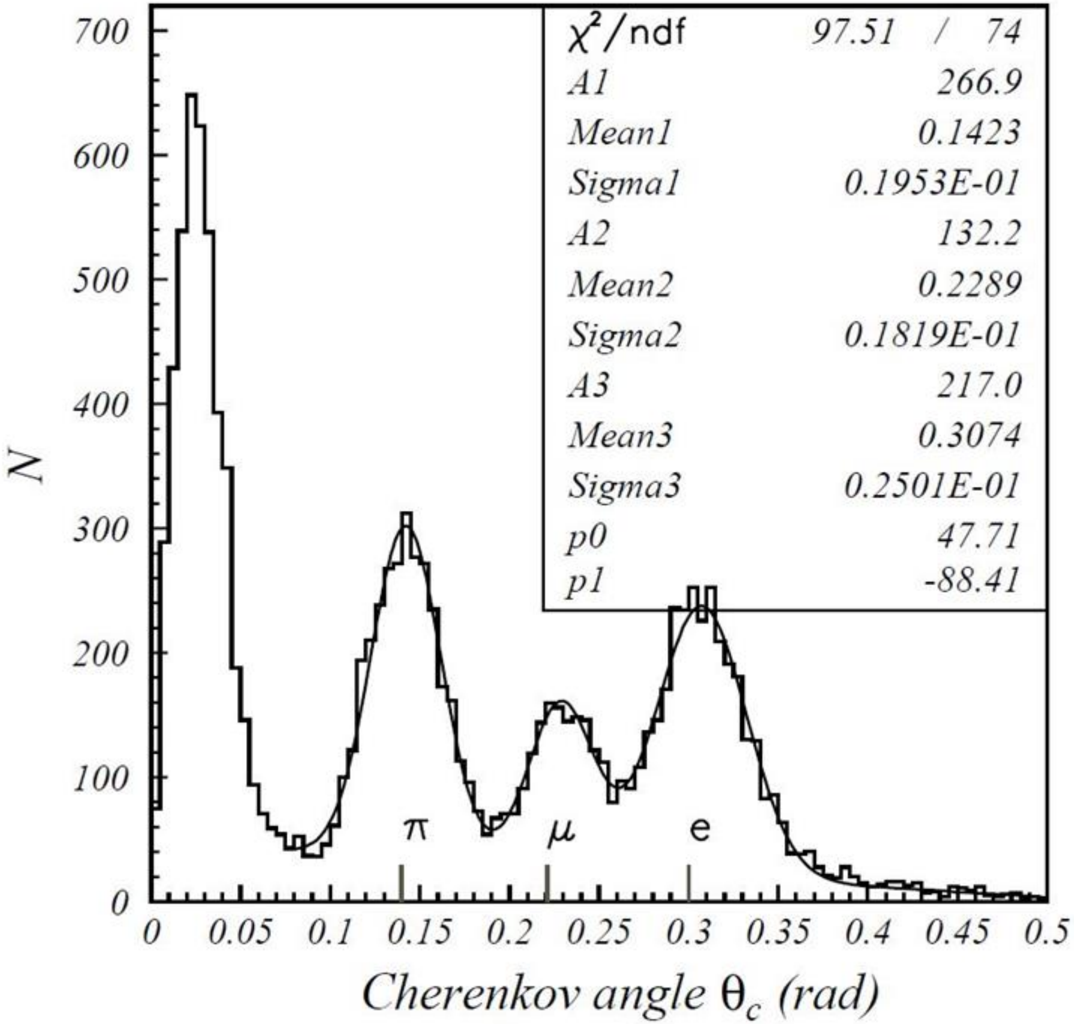


Fig. 18. Same as in Fig. 17 for beam particles with 0.8 GeV/c

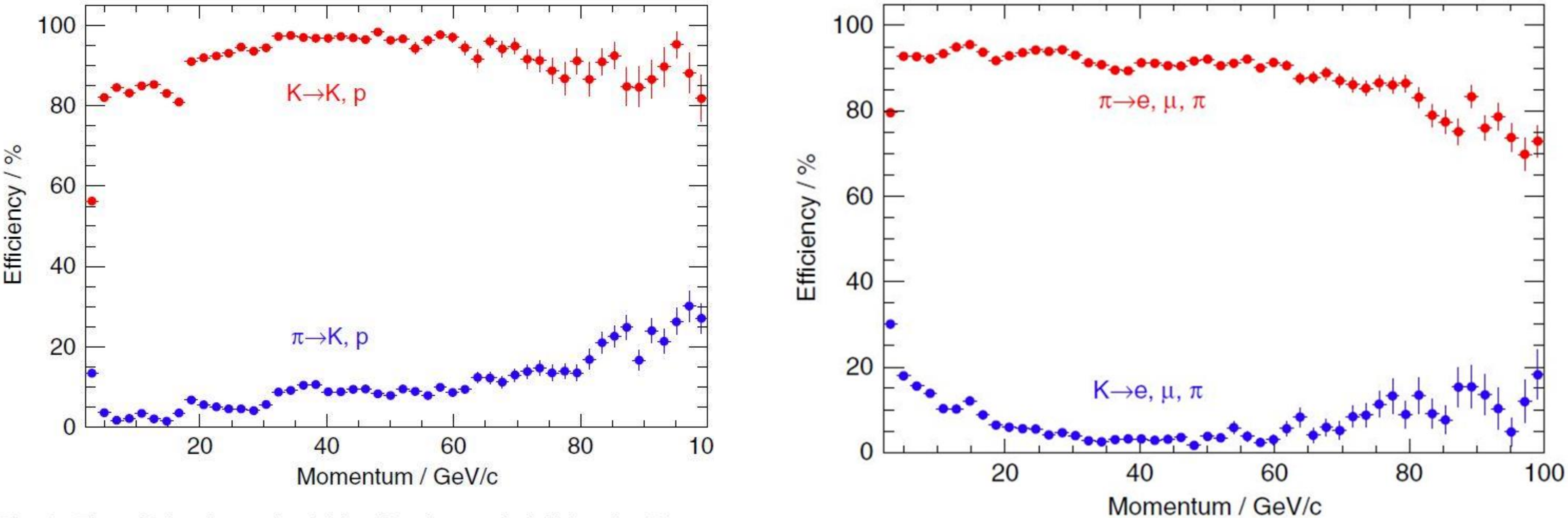


Fig. 9. The efficiencies and misidentification probabilities (in %) as function of momentum for pions identified as "light" (top) and kaons identified as "heavy" (bottom).

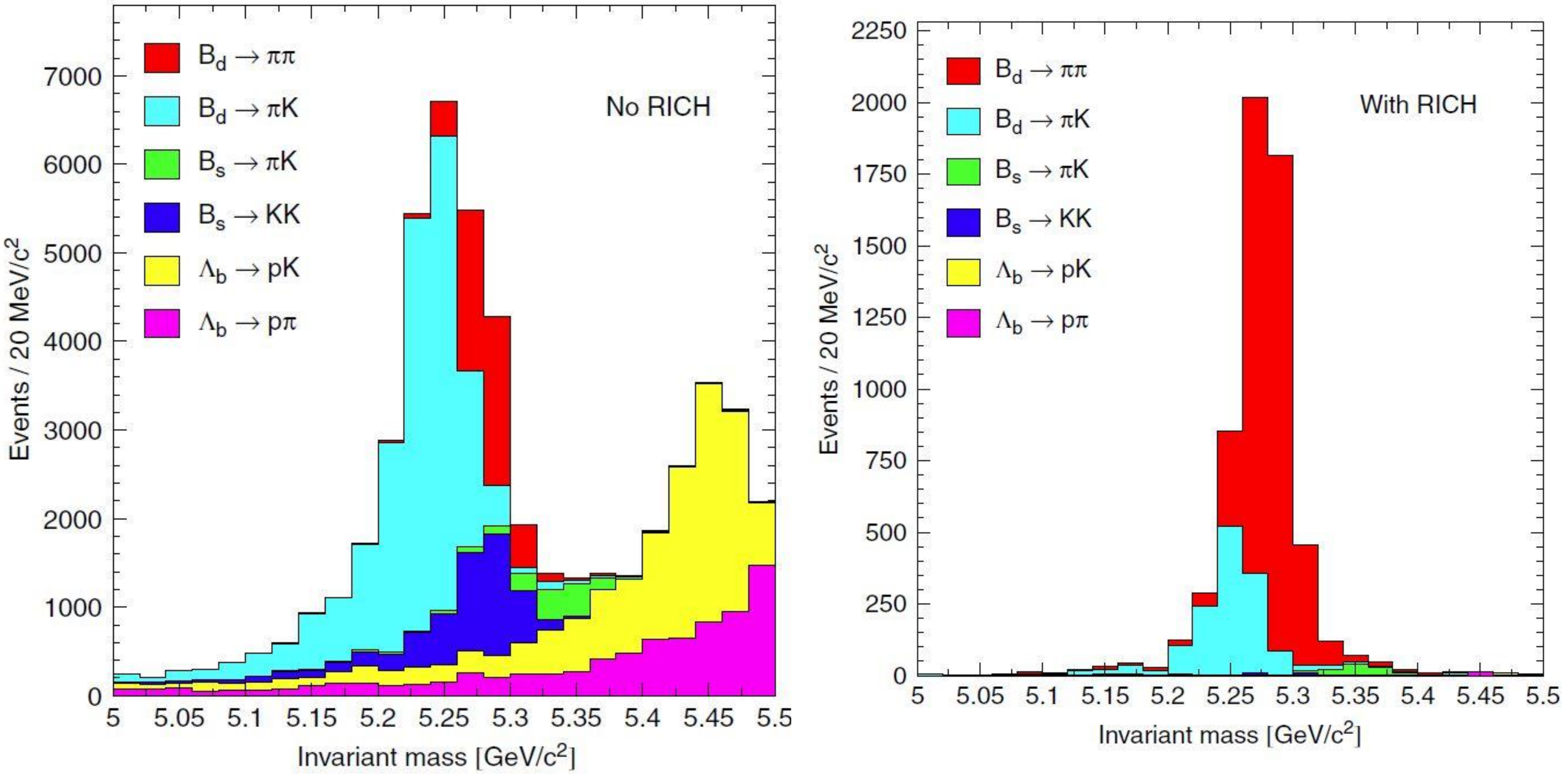


Fig. 10. The effect of the RICH in the selection of the channel B → $\pi^+\pi^-$ without (top) and with (bottom) using RICH information.

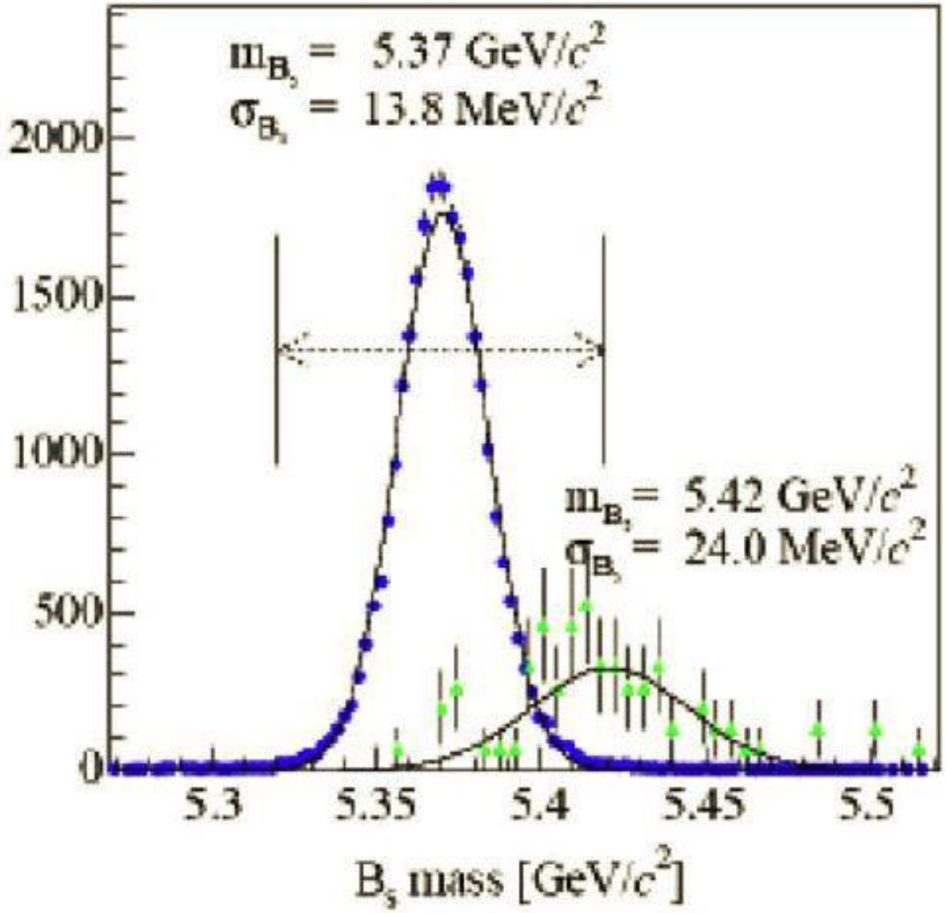


Fig. 7. Invariant mass of the B_s when searching for the $B_s \to D_s^{\pm}K^{\mp}$ signal in data. The smooth curves are fits to the data points. The histogram with a peak at 5.37 GeV/c^2 is from the $B_s \to D_s^{\pm}K^{\mp}$ channel and the histogram with peak at 5.42 GeV/c^2 is from the $B_s \to D_s^{\pm}\pi^{\mp}$ background channel. The background which swamps the signal by a factor around 10, is reduced to 10% of the signal after RICH particle identification.

LIKELIHOOD

PROBABILITY DISTRIBUTION

$$f(x\,;\,\theta)$$

PARAMETER WHICH DEFINES DISTRIBUTION

SET OF OBSERVATIONS

$x_1 \cdots\cdots x_n$

THE LIKELIHOOD OF THE OBSERVATIONS FOR A SPECIFIC θ IS:

$$\mathcal{L}(x_1 \cdots\cdots x_n | \theta) = \prod_{i=1}^{n} f(x_i | \theta)$$

IT SEEMS OBVIOUS (TO ME!) THAT $\mathcal{L}$ WILL BE MAXIMUM WHEN DISTRIBUTION OF x_i FOLLOW $f(\hat{\theta})$

$\mathcal{L}$ IS THE JOINT PROBABILITY OF OBTAINING $x_1 \cdots\cdots x_n$ GIVEN $\theta = \hat{\theta}$

MAXIMUM LIKELIHOOD

$$\mathcal{L}(x|\theta) = \prod_{i=1}^{n} f(x_i|\theta)$$

JOINT PROB OF x_i AT FIXED θ

$$\int \mathcal{L}(x|\theta)\,dx = 1$$

MAX LIK $\Rightarrow$ x_i CONST ; θ VARIABLE

CHOOSE $\hat{\theta}$ FOR θ SUCH THAT $\mathcal{L}(x|\theta)$ is A MAXIMUM

$$\mathcal{L}(x|\hat{\theta}) > \mathcal{L}(x|\theta)$$

FOR ANY CONCEIVABLE θ.

$$\frac{\partial \mathcal{L}(x|\theta)}{\partial \theta} = \frac{\partial}{\partial \theta} \prod_{i=1}^{n} f(x_i|\theta) = 0$$

$$\frac{\partial^2 \mathcal{L}}{\partial^2 \theta}\bigg|_{\theta=\hat{\theta}} = \frac{\partial^2}{\partial \theta^2} \prod f(x_i|\theta)\bigg|_{\theta=\hat{\theta}} < 0$$

⇒ $\mathcal{L}$ & $\ln(\mathcal{L})$ REACH MAXIMUM FOR SAME $\hat{\theta}$

$$\frac{\partial}{\partial \theta} \ln \mathcal{L}(x|\theta) = \frac{\partial}{\partial \theta} \sum_{i=1}^{n} \ln f(x|\theta) = 0$$

↳ $\sum$ USUALLY EASIER TO COMPUTE THAN $\prod$

IF THERE ARE j PARAMETERS → $\theta_1 \cdots\cdots \theta_j$.

THEN HAVE j EQUATIONS TO SOLVE.

EXAMPLE:

$$N = N_o e^{-t/\tau} \longrightarrow \text{FIND } \tau$$

PDF → $dN = N_o \frac{d}{d\tau}\left(e^{-t/\tau}\right)$

NORMALIZED PDF

$$f(t|\tau) = \frac{1}{\tau} e^{-t/\tau}$$

$$\mathcal{L}(t|\tau) = \prod_i \frac{1}{\tau} e^{-t_i/\tau}$$

$$\frac{\partial}{\partial\tau} \ln \mathcal{L} = \frac{\partial}{\partial\tau} \sum_i \left(-\ln\tau - \frac{t_i}{\tau}\right)$$

$$= \sum_i \left(-\frac{1}{\tau} + \frac{t_i}{\tau^2}\right) = 0$$

$$\hat{\tau} = \frac{1}{n} \sum_i^n t_i = \langle t \rangle$$

MAX LIZ ESTIMATE OF τ IS

AVERAGE OF OBSERVATIONS t_i

EXAMPLE MEAN OF A GAUSSIAN

x_1 - - - - - x_n MEASUREMENTS OF μ

GAUSSIANLY DISTRIBUTED, ERROR σ

$$\mathcal{L}(x;\sigma|\mu) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left(-\frac{1}{2}\frac{(x_i-\mu)^2}{\sigma^2}\right)$$

$$\frac{\partial \ln \mathcal{L}}{\partial\mu} = \frac{\partial}{\partial\mu}\sum_{i=1}^{n}\left(\frac{1}{2}\ln(2\pi\sigma^2) - \frac{1}{2}\left(\frac{x_i-\mu}{\sigma}\right)^2\right) = 0$$

$$\hat{\mu} = \frac{1}{n}\sum_{i=1}^{n} x_i = \langle x\rangle$$

MAXLIK ESTIMATE OF POPULATION MEAN μ

= SAMPLE MEAN $\langle x\rangle$

SAY MEASURE $\left.\begin{array}{l}\text{TIME OF FLIGHT} \\ dE/dx\end{array}\right\}$ TRACK

HOW DO WE ESTIMATE LIKELIHOOD OF π OR K ?

$$\chi_i^2\left(\frac{dE}{dx}\right) = \frac{(dE/dx - dE/dx_i^{th})^2}{\sigma_{dE/dx}^2 + \sigma_{TH}^2}$$

$i = e, \mu, \pi, K, p.$

$$\chi_i^2(TOF) = \frac{(1/\beta - 1/\beta_i^{TH})^2}{\sigma_{TOF}^2 + \sigma_{TH}^2}$$

$$\chi_i^2 = \chi_i^2(dE/dx) + \chi_i^2(TOF)$$

PDF FOR χ^2

$$f(\chi^2, n) = \frac{1}{2^{\frac{n}{2}} \Gamma(\frac{n}{2})} (\chi^2)^{\frac{n}{2}-1} e^{-\chi^2/2}$$

BUT $n = 2$ (TOF + dE/dx)

$$= \frac{1}{2} e^{-\chi^2/2}$$

$\frac{1}{2}$ → JUST ADDITIVE FACTOR WHEN TAKE ln

$$\mathcal{L}_i = e^{-\chi_i^2/2}$$ ← CUT ON THIS TO IDENTIFY PARTICLES

NORMALIZE

$$\lambda_i = \frac{\omega_i \mathcal{L}_i}{\sum \omega_k \mathcal{L}_k} \qquad k = e, \pi, \mu, K, p.$$

ω_k → a priori KNOWN (GUESSED) PRODUCTION RATES FOR $e\ \pi\ \mu\ K\ p$