The Search for Antiproton Decay

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- New Results
- Thoughts for an upgrade

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Jon Streets, for the Apex Collaboration...

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Introduction

As a test of the CPT theorem, the APEX Experiment was designed to search for antiproton decay in as many modes as possible:

$\bar{p} \to e^- + \pi^0$	$\bar{p} \to e^- + \gamma$	$\bar{p} \to e^- + \eta$	$\bar{p} \to e^- + K^0_S$
$\bar{p} \to e^- + K^0_L$	$\bar{p} \to e^- + K^{0*}$	$\bar{p} \to e^- + \omega$	$\bar{p} \to e^- + \rho^0$

We also have limited acceptance for muons as a test for a future experiment to search for:

$\bar{p} \to \mu^- + \gamma$	$\bar{p} \to \mu^- + \pi^0$

Method:

Create a reasonable set of physics cuts which maximize the acceptance of GEANT Monte Carlo decays, while minimizing the background measured from $\bar{p}$ interactions with residual gas in the vacuum and beam pipe.

Motivation

- Previous experiments searching for proton and antiproton decays have had vastly different sensitivities
- A measured difference between the proton and antiproton lifetimes would signal a violation of the CPT theorem. So APEX addresses a fundamental symmetry in physics.
- The Fermilab Accumulator is a unique laboratory for studying the stability of antimatter.
- Current results from APEX show a sensitivity to the lifetime of order 10^6 years, compared to 10^{31}-10^{32} years for

$$p,n \rightarrow e^+ + X$$

$$p,n \rightarrow \mu^+ + X$$

$$p,n \rightarrow \bar{\nu} + X$$

- Note Proton (and neutron) decay experiments use kilotons of material for several years, where Fermilab has made ~1 nanogram of antimatter in 10 years.

Present Antiproton Limits

- M.Bregman, *et al.*, *Phys. Lett*. **78B** (1978) 174. Measured beam lifetime in ICE Storage Ring. $\tau_{\bar{p}} > 32$ hours.
- M.Bell, *et al.*, *Phys. Lett*. **86B** (1979) 215. Searched for $\bar{p} \to e^- + \pi^0$ at ICE. $\tau_{\bar{p}}/BR > 1700$ hours.
- B.Auton, et al., 1990 European Part. Accel. Conf., measured beam lifetime in CERN AA.

  $$\tau_{\bar{p}} > 1.4 \text{ months.}$$

- G.Gabrielse, et al., *Phys Rev. Lett*. **65** (1990) 1317. Stored $\bar{p}$'s in ion trap for 2 months,

  $$\tau_{\bar{p}} > 3.4 \text{ months.}$$

- S.Geer, et al., *Phys. Rev. Lett*. **72** (1994) 1596. Test for APEX experiment (T861), several decay modes studied. Best limit

  $$\tau_{\bar{p}}/BR\,(\bar{p} \to e^- + \gamma) > 1849 \text{ years.}$$

- There is ongoing work to calculate the lifetime derived from the observation of $\bar{p}$'s in cosmic rays. Depends on models for galactic $\bar{p}$ production and annihilation, $\bar{p}$ capture in the solar system and earth's magnetic field, and the galactic storage time of $\bar{p}$'s (of order 10^7 years).

Tests of CPT Invariance

CPT Invariance implies that for particles and antiparticles

- Inertial masses are identical
- Charge magnitudes are identical
- Mean lifetimes identical
- Magnitudes of magnetic moments identical

Property	**System**	**Fractional Difference**
Lifetime	$\tau_{\pi+} - \tau_{\pi-}$	$< 10^{-3}$
	$\tau_{\mu+} - \tau_{\mu-}$	$< 10^{-4}$
	$\tau_{K+} - \tau_{K-}$	$< 10^{-3}$
Magnetic Moment	$\lvert\mu_{\mu+}\rvert - \lvert\mu_{\mu-}\rvert$	$< 10^{-8}$
	$\lvert\mu_{e+}\rvert - \lvert\mu_{e-}\rvert$	$< 10^{-10}$
Mass	$M_{\pi+} - M_{\pi-}$	$< 10^{-3}$
	$M_p - M_{\bar{p}}$	$< 10^{-4}$
	$M_{K}+ - M_{K}-$	$<10^{-4}$
	$M_{K^o} - M_{K^o}$	$< 10^{-14}$

Fermilab Accumulator Ring

- 474m circumference
- 8.9 GeV/c antiprotons
- 11 x 10^{11} antiprotons (110 mA) average stack size
- APEX took data parasitically, during times of no stacking (repairs or quiet time)

Preliminary Results from Apex

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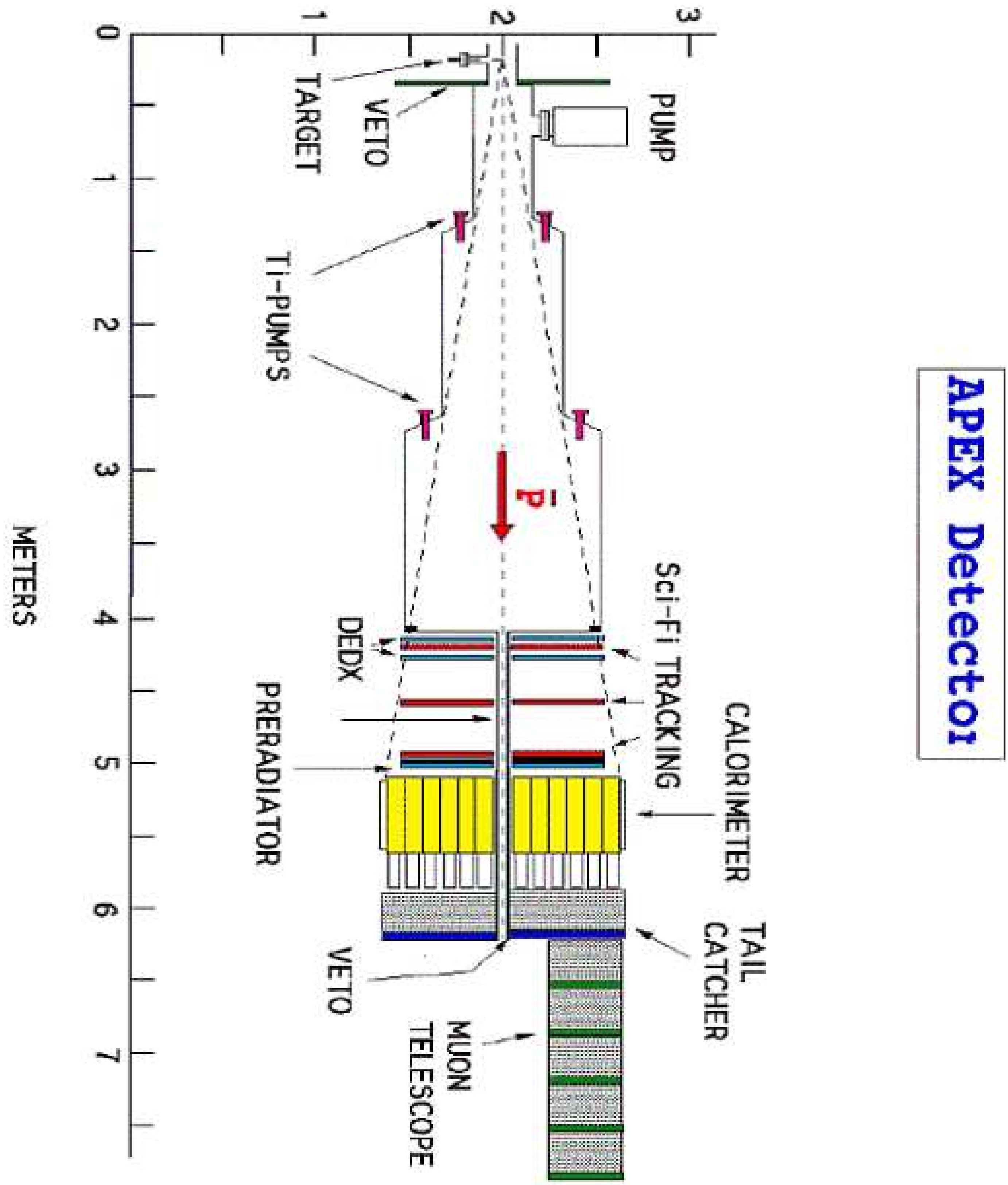


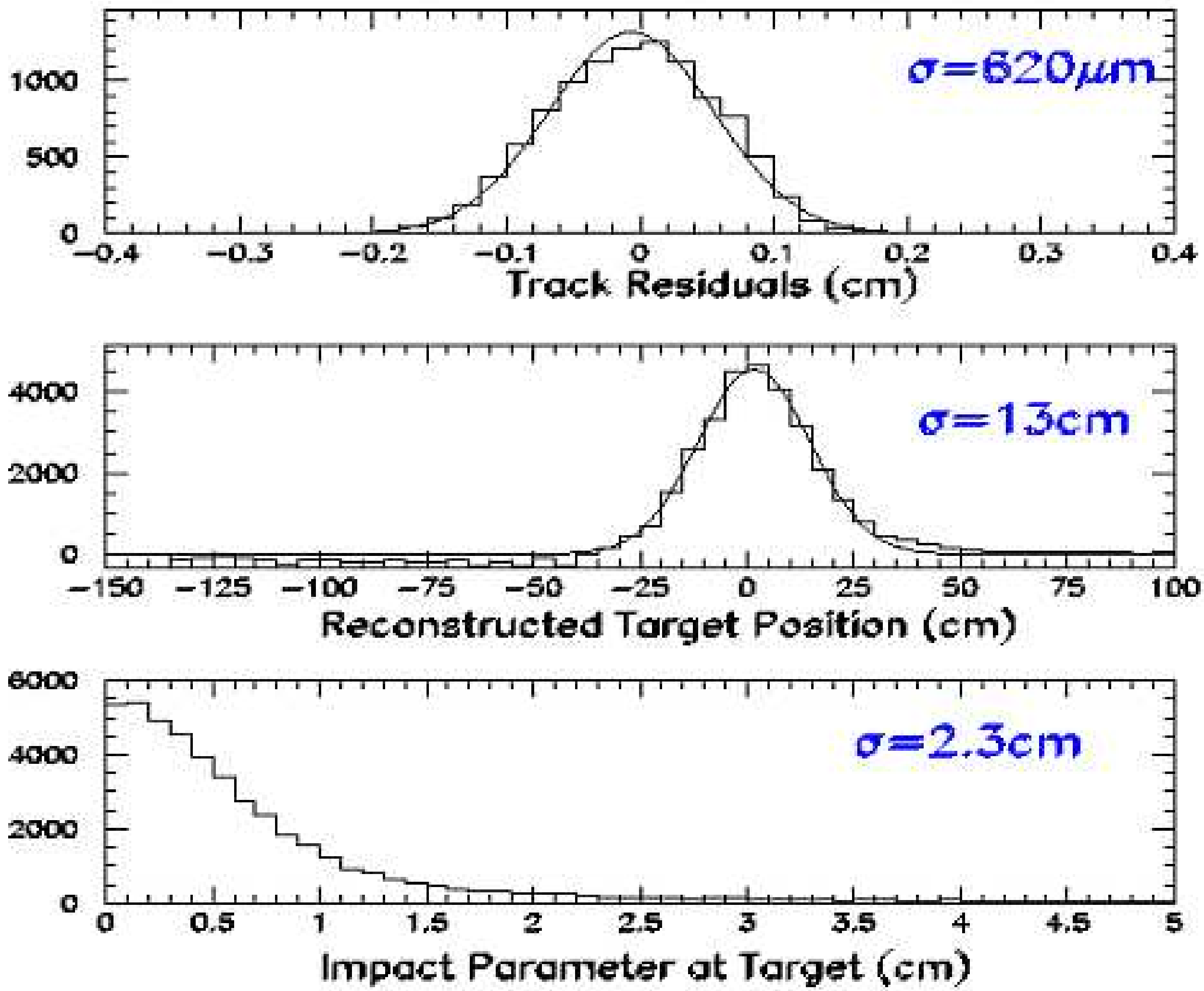
Vacuum Tank for Decay Volume

- Test experiment vacuum achieved 3 x 10^{-10} Torr near decay region.
- By using Titanium sublimation pumps, APEX decay tank achieved a vacuum of 2.0 x 10^{-11} Torr.

Molecule	Partial Pressure (Torr)
H_2	1.5 x 10^{-11}
CH_4	1.0 x 10^{-12}
H_20	1.0 x 10^{-12}
CO	1.0 x 10^{-12}
CO_2	1.0 x 10^{-12}
Ar	1.0 x 10^{-12}
Total	2.0 x 10^{-11}

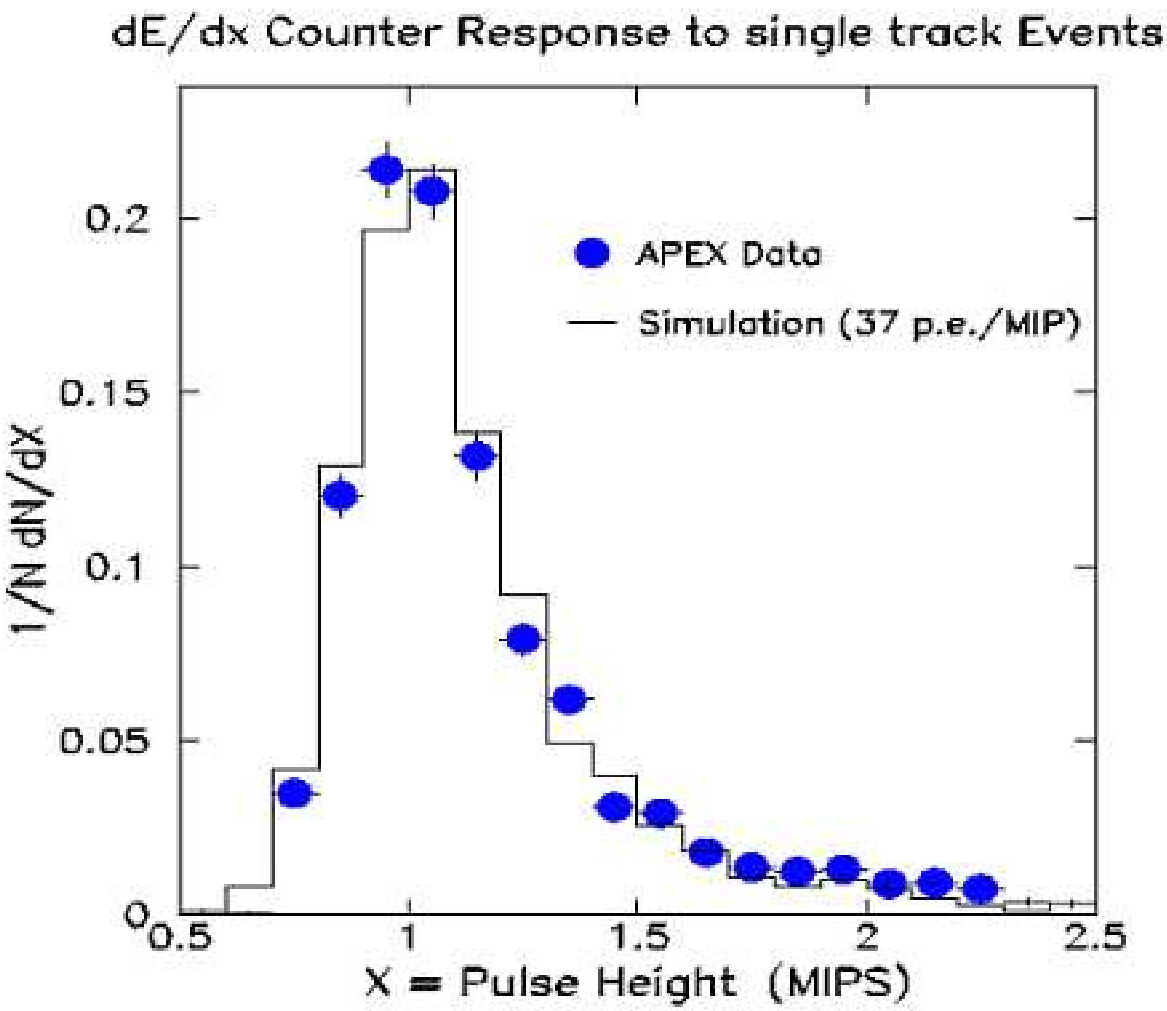
- Partial Pressures measured with commercial Residual Gas Analyzer, Proton density = 3.4 x 10^6 cm^{-3}, and neutron density = 2.3 x 10^6 cm^{-3}

Scintillating Fiber Tracker



- 3 x-y planes of 2mm fibres (768 fibres per x-y plane)
- Readout with Multi Anode PMTs (8x24 ch. input, 32 ch. output)
- 7-9 Photo electrons per MIP

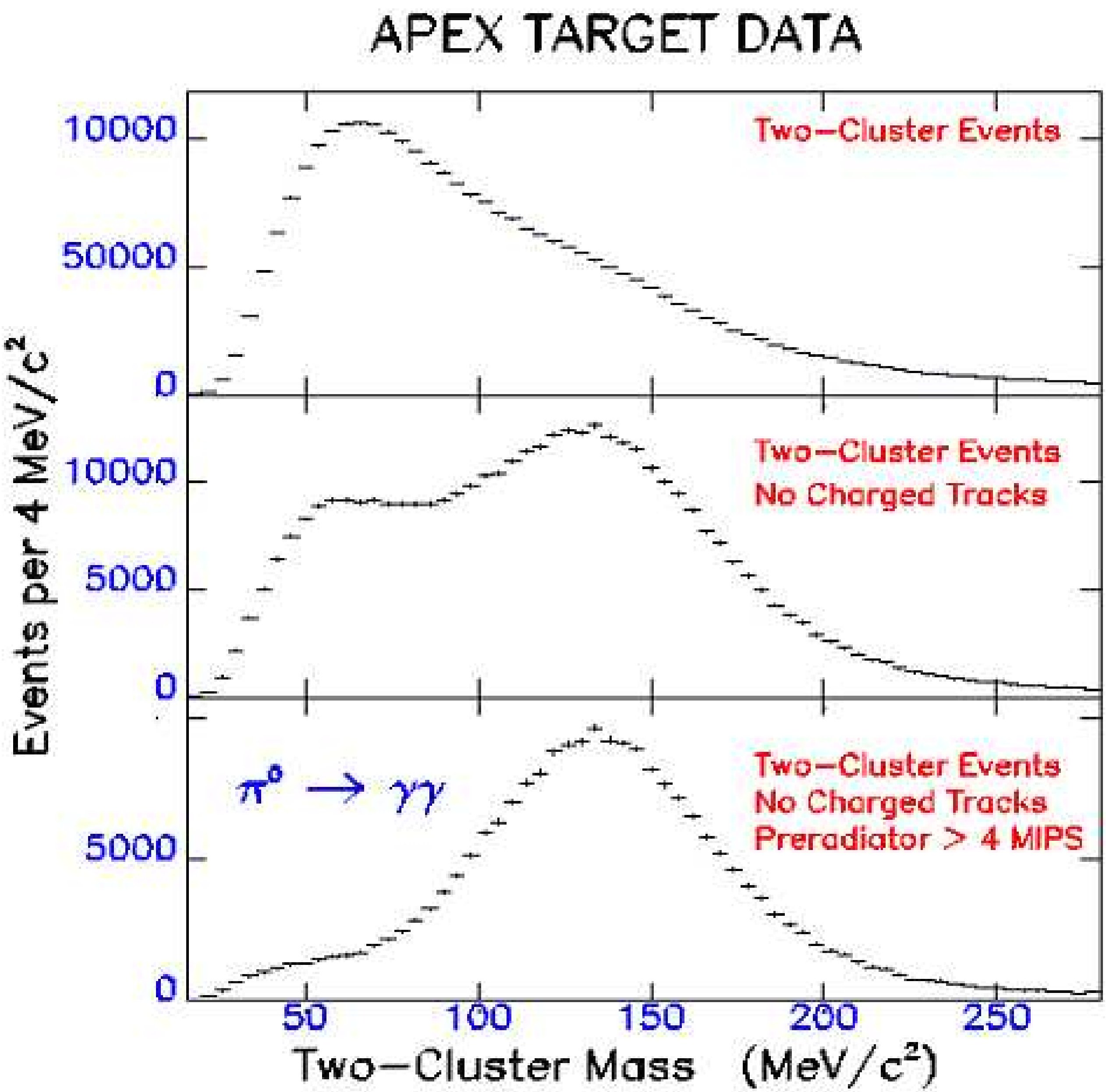
DEDX Counters



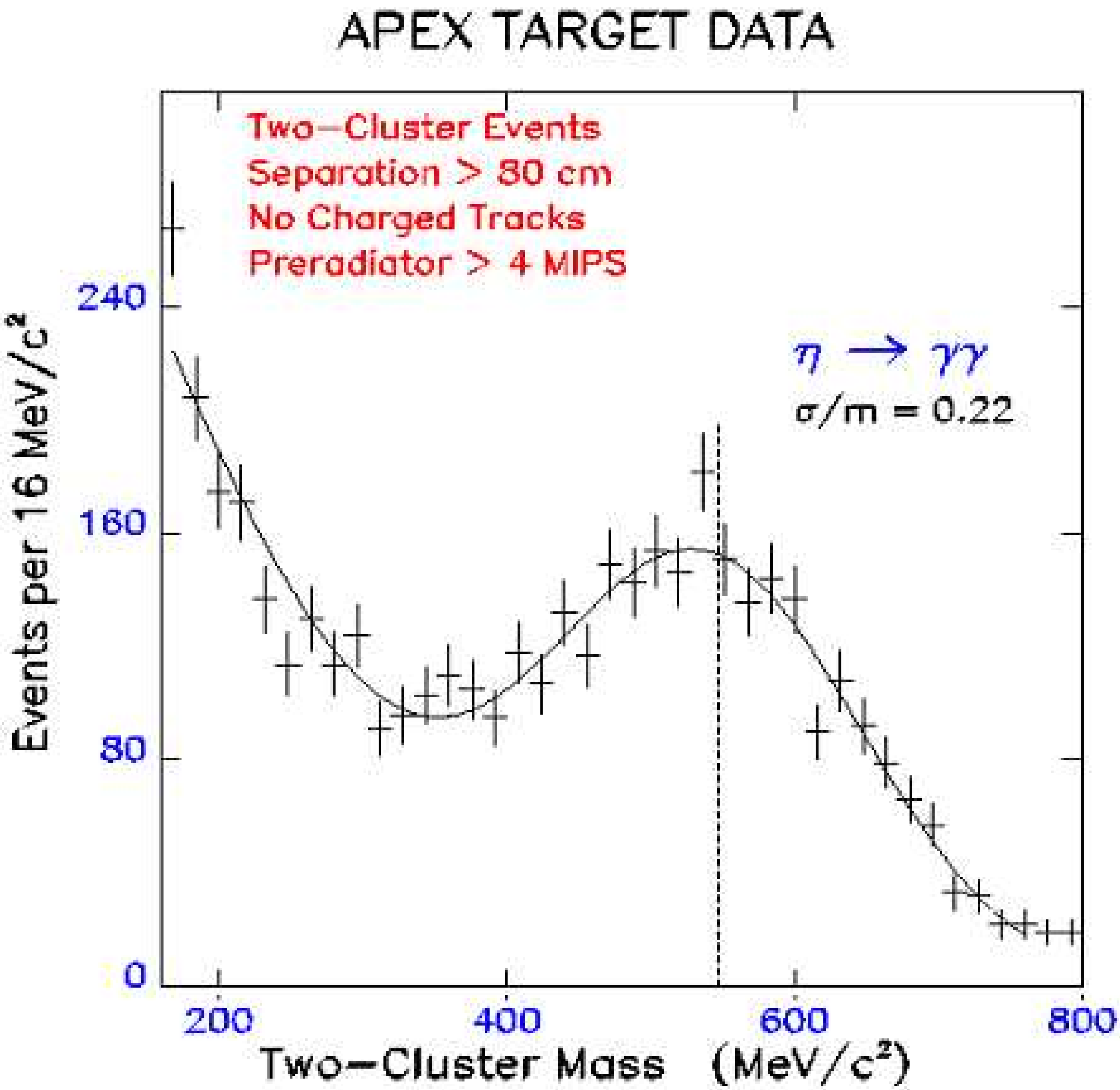
- 6 planes of scintillator - 2 after 1 λ of Pb (pre-radiator)
- Signals fit well from Minimum Ionizing Particles in GEANT simulation

Calorimeter Calibration

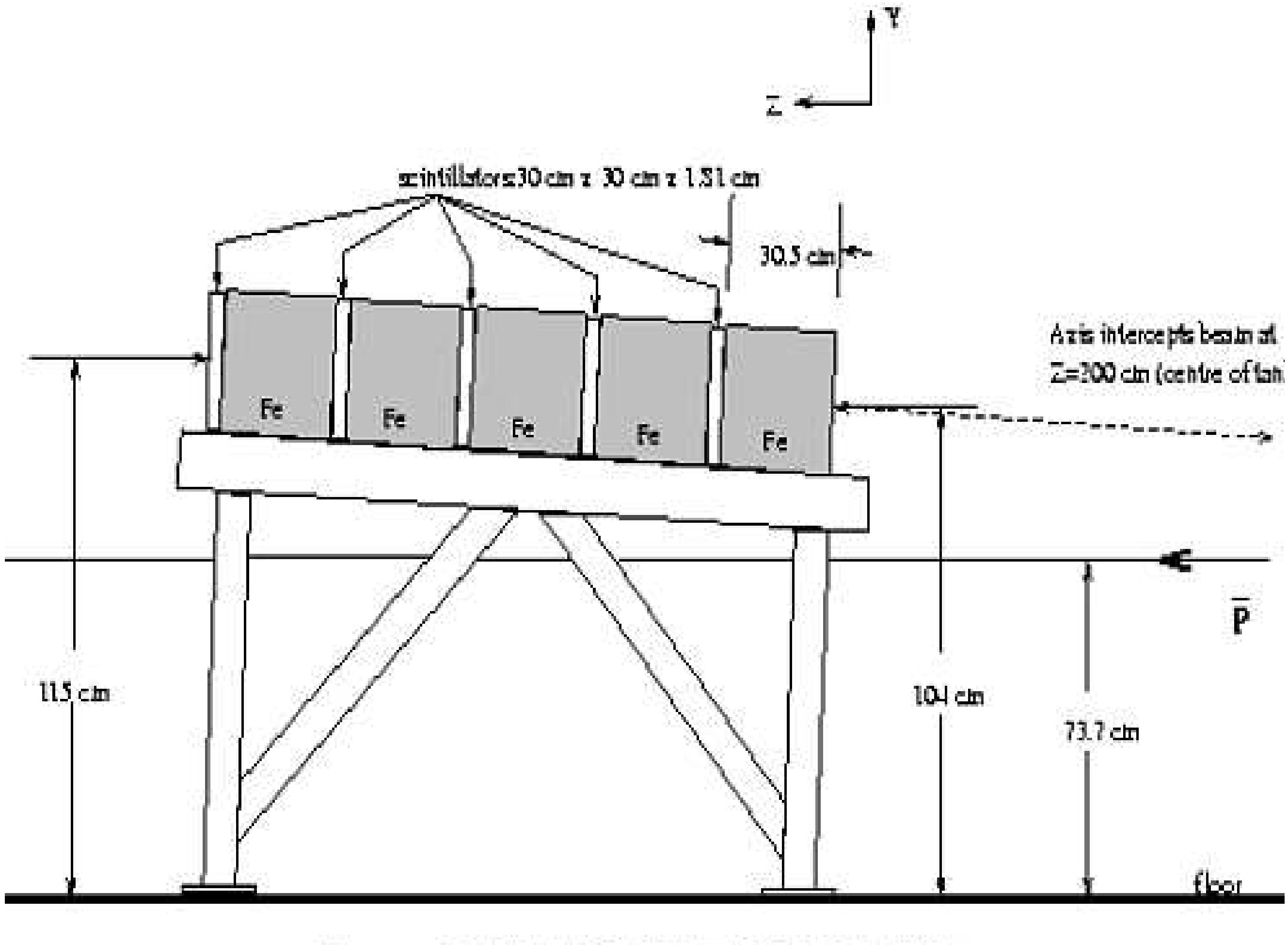
144 Pb-Scintillator cells, calibrated with π^0's from a wire target



Calorimeter Calibration Cross-Check



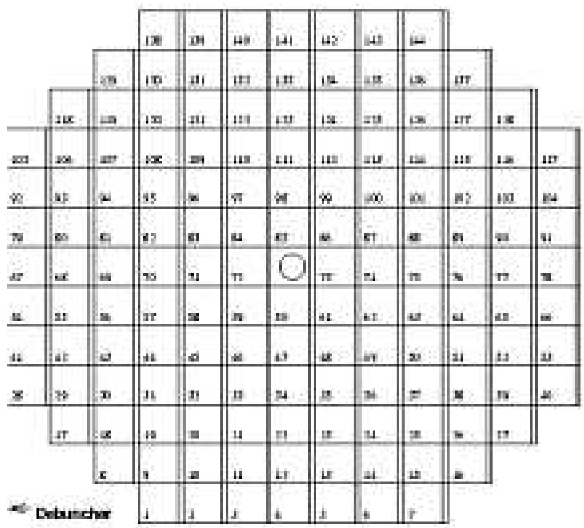
Muon Detection



- Telescope of 5 sheets of scintillator and blocks of steel
- Triggered on 2 out of 5 scintillators
- Pointing geometry
- Muon also leaves a track and low energy cluster in calorimeter

DAQ & Triggering

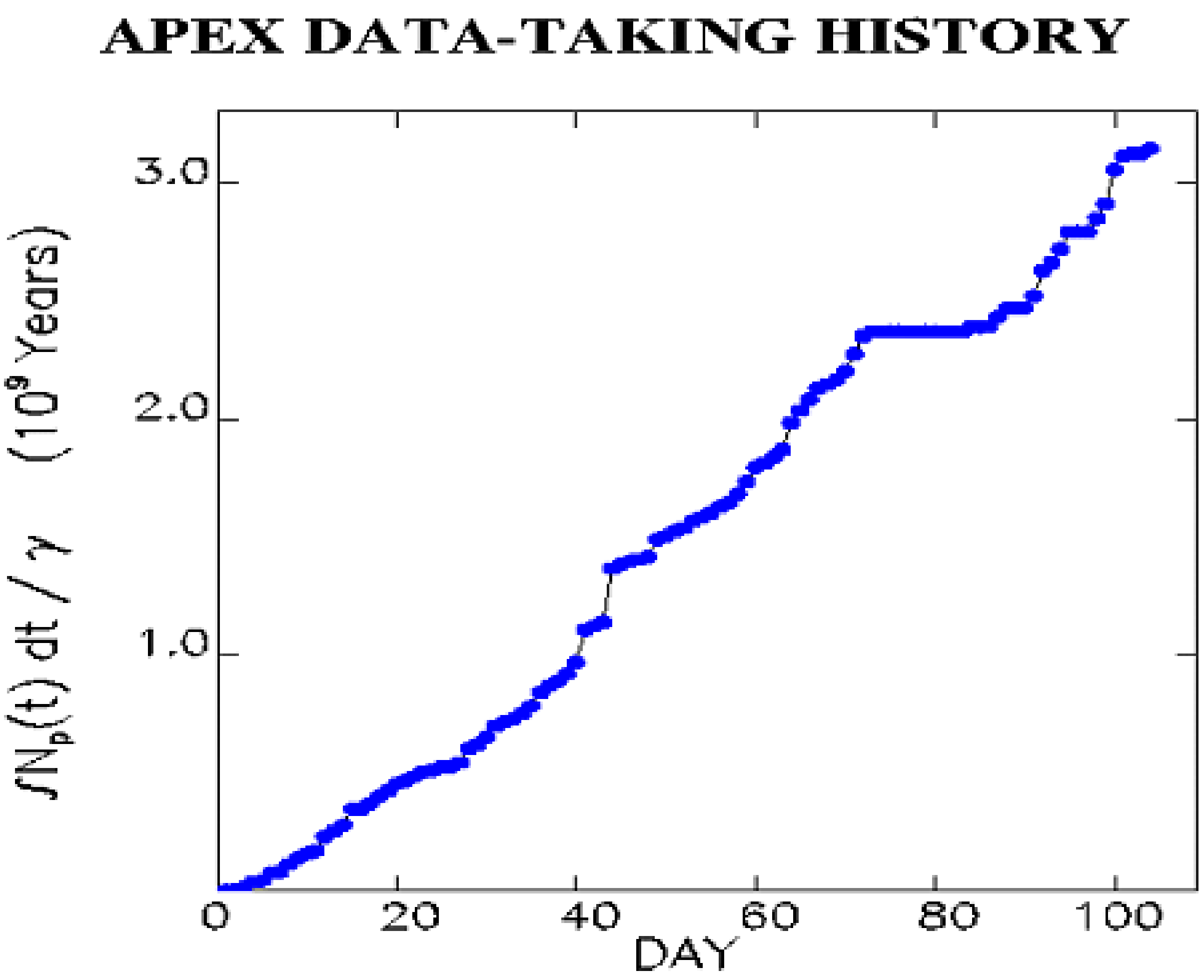
Trigger used information from dE/dx,counters, Calorimeter and Muon Telescope. VETO counters upstream of tank to remove beam halo events.



- $E_{BALANCE}$ Trigger - 2 opposite CALO quadrants
- E_{TOTAL} Trigger - sum over all CALO cells
- Electron Trigger - hits in dE/dx quadrants and CALO quadrants
- Muon Trigger - 2 out of 5 Muon Counters
- Accelerator Triggers - containing information about accelerator components

Data written via CAMAC onto Exabyte tape with a VAX 3200 computer, at 50Hz, ~50 kilobyte/sec.

Data Taking



- Data Taken parasitically to CDF and D0 collider running over 3 months (1st April - June 30th 1995)
- 27867 mA-hours, or 3.31 x 10^9 $\bar{p}$-years
- 10 Million triggers in 135 runs
- Data written via CAMAC onto Exabyte tape with a VAX 3200 computer, at 50Hz, ~50 kilobyte/sec.

Preliminary Results from Apex

Search for $\tau(\bar{p} \rightarrow e^{-} + \gamma)$

	# Data Events	Efficiency
Total events considered	9999986	10,000 ev.
Events passing trigger simulation	9999981	73%
Events passing upstream veto	9606281	73%
$N_{cluster} = 2$	1675784	50%
Coplanar	105150	47%
dE/dx response	74111	31%
Sector Matching in dE/dx	58817	31%
Tail Catcher	49466	30%
Pre-radiator	36876	30%
2 body kinematic solution	12	17%
$\chi^2 < 10$	3	15%

- Electron - track, dE/dx, pre-radiator, Calorimeter hit
- Photon - no track, no dE/dx, pre-radiator, Calorimeter hit
- No missing E_T, No Tail Catcher.
- 2 Body mass near Proton Mass

Of the 3 remaining events no events reconstruct with a track within the fiducial volume.

No $\bar{p} \rightarrow e^{-} + \gamma$ events

Calculation of $\tau(\bar{p} \rightarrow e^{-} + \gamma)$

$$\tau(\bar{p} \rightarrow e + \gamma) = \frac{\varepsilon}{\gamma} \cdot \frac{1}{N_{MAX}} \cdot \int N_{\bar{p}}(t)\,dt$$

- ε is efficiency from Monte Carlo and tracker efficiency
- γ is from the boost of the p in the lab rest frame
- N_{MAX} is the number of candidates at 90% confidence limit = 2.3 for no candidates
- Integral represents the total number of antiproton years seen by the APEX experiment

Limit (90% C.L.)

Result = 1.3 x 10^6 years

(No Systematic Errors)

Search for $\tau(\bar{p} \to e^- + \pi^0)$

Cut	# Events	Efficiency
Total Events	10M	10,000
Triggers and Pre-selection	10467064	74%
Tail Catcher Veto	8920699	74%
$E_{total} > 5$ GeV	5950472	72%
2 or 3 Clusters	2458466	62%
$R_{centroid} < 8$cm	112785	42%
dE/dx Pattern	59241	22%
dE/dx Quads	22830	15%
dE/dx and Preradiator	8887	14%
Ntracks=1	4698	12%
$Z_{vertex} > 0$	3980	12%
DOCA < 1cm	226	12%
DMIN < 5cm	118	12%
Polar Angle > 2^o	53	12%
$0.3 < M_{\bar{p}}^2 < 1.5$	35	11%
$-0.5 < M_{MISS}^2 < 0.5$	24	11%
$-0.06 < M^2_{\pi 0} < 0.08$	10	6.5%
χ^2	3	6.2%

Search for $\tau(\bar{p} \to e^- + \pi^0)$

- After a similar search as the e- + γ, we have 3 remaining events which do not look like signal (EM cluster is low, track near beam pipe)
- *BUT* using these 3 events to find a lower limit (N=3 implies N_{MAX}=6.68)

Limit (90% C.L.)

$\tau(\bar{p} \to e^- + \pi^0) > 2.6 \times 10^5$ years

(No Systematic Errors)

Preliminary Results from Apex

Search for $\tau(\overline{p} \to \mu^- + \gamma)$

CUTS	# events	Efficiency
total events		100,000 events
muon trigger	1,200,166	2.205%
veto	1,103,149	2.184%
dE/dx	142,742	0.971%
prerad	1,489	0.500%
tail catcher	652	0.488%
5 mt counters	43	0.343%
2 clusters in fcal	8	0.306%
zvtx in tank	4	0.278%
coplanarity	0	0.275%

At 90% CL, 0->2.3.

Result: (0.00275) x (5/474) x 3.31 x 10^9 x (1/2.3) =

41,700 years

(No Systematic Errors.)

Preliminary Results from Apex

Search for $\tau(\overline{p}$ -> $\mu^- + \pi^0)$

CUTS	# events	Efficiency
total events		100,000 events
muon trigger	1,200,166	2.250%
veto	1,103,149	2.219%
dE/dx	142,742	0.901%
prerad	1,489	0.543%
tail catcher	652	0.511%
5 mt counters	43	0.361%
2 clusters in fcal	8	0.147%
zvtx in tank	4	0.139%
coplanarity	0	0.123%

Using the same cuts for the π^0 channel as the γ channel, (which is not optimal for events where each of the γ's are resolved in the π^0 decay).

At 90% CL, 0->2.3.

Result: (0.00123) x (5/474) x 3.31 x 10^9 x (1/2.3) =

18,700 years.

(No Systematic Errors)

Implication of no e+γ candidates on other electron channels

Applying the $\bar{p} \to e^- + \gamma$ analysis to Monte Carlo for the other electron decay channels we can calculate the following preliminary results.

Decay Channel	Lifetime Limit at 90% C.L. (years) This Experiment	Previous Limit (years)
$\bar{p} \to e^- + \gamma$	1.3×10^6	1848
$\bar{p} \to e^- + \pi^0$	6.4×10^5	554
$\bar{p} \to e^- + \eta$	17,000	171
$\bar{p} \to e^- + \omega$	1,700	None
$\bar{p} \to e^- + K^0_L$	3,600	9
$\bar{p} \to e^- + K^0_S$	4,700	29
$\bar{p} \to e^- + \rho^0$	120	None

Note: Trigger Acceptances range between 15%-40%, so an optimized analysis should improve the limits for the heavier decays.

Acceptances of 2 body electron decay channels

Cuts	$e\gamma$	$e\pi^0$	$e\eta$	$e\rho$	$e\omega$	eK^0_L	eK^0_S
events	10000	10000	55000	75000	75000	75000	75000
trigger	37.9	36.4	29.9	17.4	16.2	15.3	21.4
veto	37.9	36.4	29.9	17.4	16.2	15.3	21.4
DEDX	19.5	16.9	10.5	4.9	2.5	10.1	4.7
preradiator	19.0	16.3	10.2	4.6	2.1	9.8	4.6
1 track	15.6	13.5	7.9	3.2	1.3	8.5	3.5
fid. volume	15.3	13.2	7.7	3.1	1.3	8.1	3.4
DOCA cut	14.5	12.3	6.7	2.3	0.88	7.5	2.9
dp_z/dp cut	13.0	11.1	6.0	2.0	0.73	6.5	2.6
TC	13.0	11.1	5.9	2.0	0.68	4.8	2.5
2 or 3 clusters	11.9	9.7	3.9	0.72	0.40	2.7	0.90
Coplanar	11.6	6.4	0.61	0.11	0.068	2.0	0.21
sector-cluster	11.4	6.4	0.59	0.095	0.055	2.0	0.20
kinematics	9.6	4.6	0.15	0.011	0.011	0.059	0.037
chisq < 10	9.1	4.2	0.11	0.008	0.011	0.024	0.031

Conclusions from APEX I

- APEX sees no evidence for Antiproton instability
- APEX presents $\bar{p}$ lifetime lower lifetime lower limits for 4 exclusive channels.

Channel	Limit
$\bar{p} \to e^- + \gamma$	$\tau_{\bar{p}}/BR > 1.3 \times 10^6$ years
$\bar{p} \to e^- + \pi^0$	$\tau_{\bar{p}}/BR > 2.6 \times 10^5$ years
$\bar{p} \to \mu^- + \gamma$	$\tau_{\bar{p}}/BR > 4.2 \times 10^4$ years
$\bar{p} \to \mu^- + \pi^0$	$\tau_{\bar{p}}/BR > 1.8 \times 10^4$ years

- Analysis of other Channels in progress, expect to increase sensitivity for existing measurements by between 2 to 3 orders of magnitude, and add values for muon decay channels. Investigating ν and 3 body decays.
- Systematic error analysis are in progress (varying calorimeter, counter and tracker response to see effects on efficiencies).
- Limits approaching 10^6 years for electron channels, 10^4 years for muon channels.

APEX II

Why

This is a fundamental measurement, and a test of the CPT theorem, and needs a large source of antimatter. Limits of lifetime from $\bar{p}$ counting in cosmic rays cannot go above the galactic storage lifetime of $\bar{p}$'s (10^7 years), and will be much less due to uncertainties in $\bar{p}$ production, annihilation and storage models.

We can (probably) improve our sensitivities by 10x better for $\bar{p} \rightarrow e^- X$, 100x better for $\bar{p} \rightarrow \mu^- X$, and search for $\bar{p} \rightarrow \nu\pi^-$, νK^-... for the first time.

Where

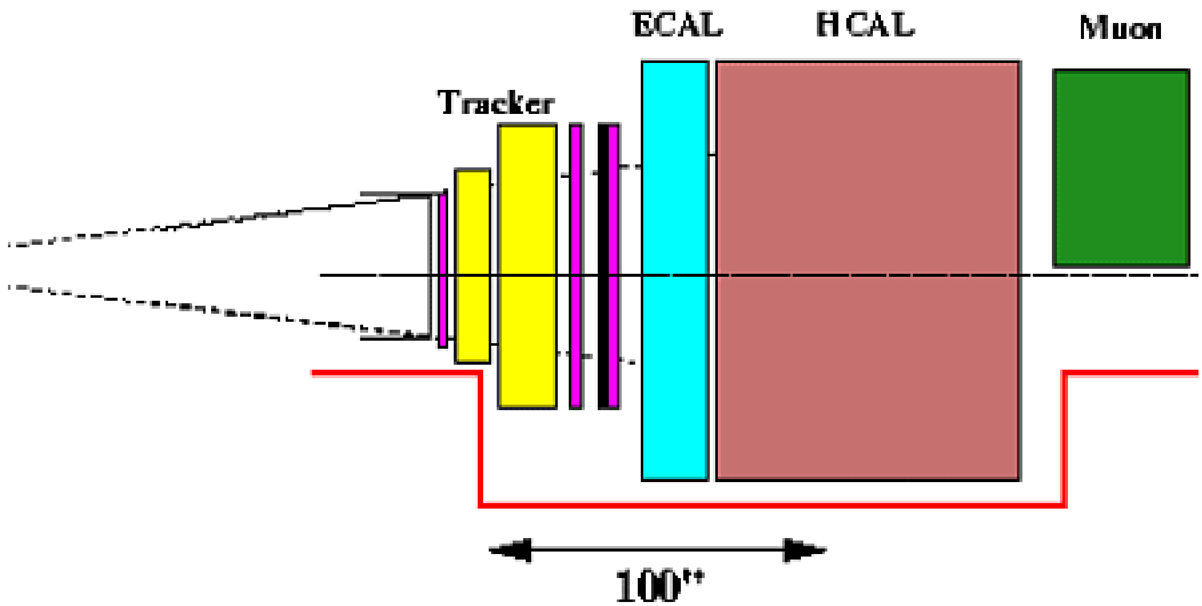
AP50, where we have existing infrastructure (cables, counting room from E835) - Recycler has limited space for a detector, would take more $\bar{p}$'s and more background in the tunnel.

How

APEX I ran for 3 months at an average $\bar{p}$ current of 110mA, and received 27,000 mA hours in parasitic mode. We could improve this by a factor of 5 by having 3 runs of 2 weeks with an initial current of 200mA. Another factor of "a few" from increased acceptance & better triggering.

Straw Man Idea

APEX II



- Designing this summer (after end of APEX I analysis)
- Move APEX I tank further upstream (out of pit)
- Add ECAL, HCAL/Muon, Tracker
- Trigger on ECAL, HCAL, Track processor.
- Installation during breaks of Run II (*c.f.* T861, E868 and Run I)
- Anticipate APEX collaboration to grow.

Preliminary Results from Apex