Prospects for Low-Energy Antiproton Physics at Fermilab

Daniel M. Kaplan
Illinois Institute of Technology

ILLINOIS INSTITUTE OF TECHNOLOGY
Transforming Lives. Inventing the Future. www.iit.edu

Proton Driver Physics Study Group Meeting
10 May 2001

(Recap of my talks at Hyperon 99, $\bar{p}$*2000*, LEAP2000, 1999–2000)

$\overline{p}$*2000* Workshop

- International workshop held at Illinois Institute of Technology (IIT), Chicago, IL, USA Aug. 3–5, 2000

  → http://www.iit.edu/~bcps/hep/pbar2000.html

- 39 participants from

Argonne National Lab.	US
Duke Univ.	US
Elmhurst College	US
Fermilab	US
GSI Darmstadt	Germany
IIT	US
Indiana Univ. Cyclotron Facility	US
INFN Genova	Italy
Los Alamos National Lab.	US
National Tsing-Hua Univ.	Taiwan
Northwestern Univ.	US
Rutherford Appleton Lab.	UK
Ruhr-Univ. Bochum	Germany
Univ. Illinois Urbana-Champaign	US
Univ. Ferrara	Italy
Univ. Genova	Italy
Univ. Mississippi	US
Uppsala Univ.	Sweden

- Major questions:

  1. What will be Fermilab's capabilities in $\overline{p}$ physics during the next several years?
  2. Can a strong physics program be identified to take advantage of these capabilites?

  → See $\overline{p}$*2000* Proceedings, due out soon (all papers available at http://www.capp.iit.edu/~capp/workshops/pbar2000/papers/)

$\bar{p}$2000 Workshop Motivation(s):

- Fermilab starting to define directions for post-LHC era
  $\rightarrow$ broadening the program could be appealing if sufficient clientele

- Fermilab has highest-intensity $\bar{p}$ source and intensity will increase

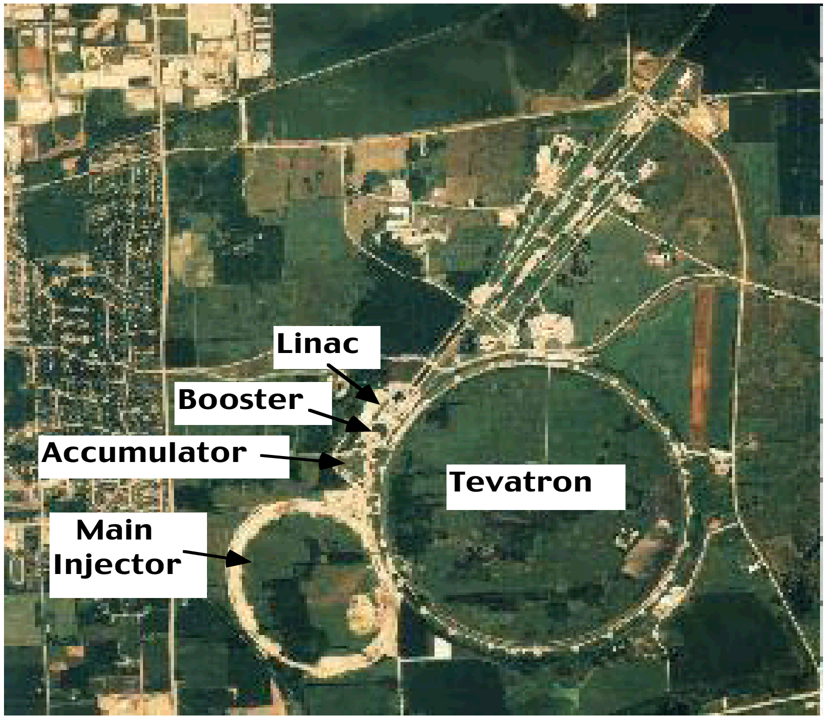
- $\bar{p}p \rightarrow$ charmonium,hyperons: Chang/Valencia/Hertzog/Swallow/Seth
  $\rightarrow$ improved luminosity & cooling could improve the physics

- $\bar{p}p \rightarrow$ light-quark resonances: Wiedner/Page/Bugg
  $\rightarrow$ could more data clarify glueball & hybrid puzzles?

- Trapped $\bar{p}$: more beam, better duty factor than AD Holzscheiter/Phillips
  $\rightarrow$ explore new techniques and ideas?

$\Rightarrow$ **Can physics motivation plus technical improvements yield an attractive $\bar{p}$ program at Fermilab?**

Fermilab $\bar{p}$ capabilities:



- $\bar{p}$ source/accumulator:

  Stacking rate:

  10 mA/hr $\Rightarrow 10^{11}\ \bar{p}/\mathrm{hr}$

  $\Rightarrow \mathcal{L} \lesssim 2 \times 10^{32}/\mathrm{cm}^2/\mathrm{s}$

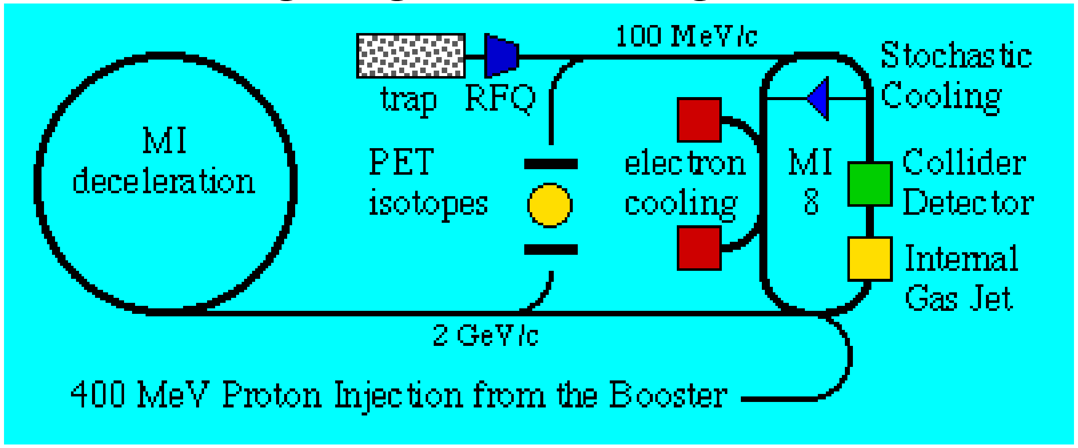
  – Goals:

  20 mA/hr Start of Run II (March 2001)
  100 mA/hr Run IIB (~2005)
  using e^- cooling in recycler

Fermilab $\bar{p}$ capabilities (cont'd):

- New idea [G. Jackson, http://hbar.fnal.gov/]:

Could decelerate $\bar{p}$'s in Main Injector to 2 GeV/*c* (or below?)
Stage 1: Extract through degrader to magnetic bottle
Stage 2: Add 2 GeV/*c* storage ring with e^- cooling



Stage 3: Build bigger ring (1 – 10 GeV/*c*)

- First applications:

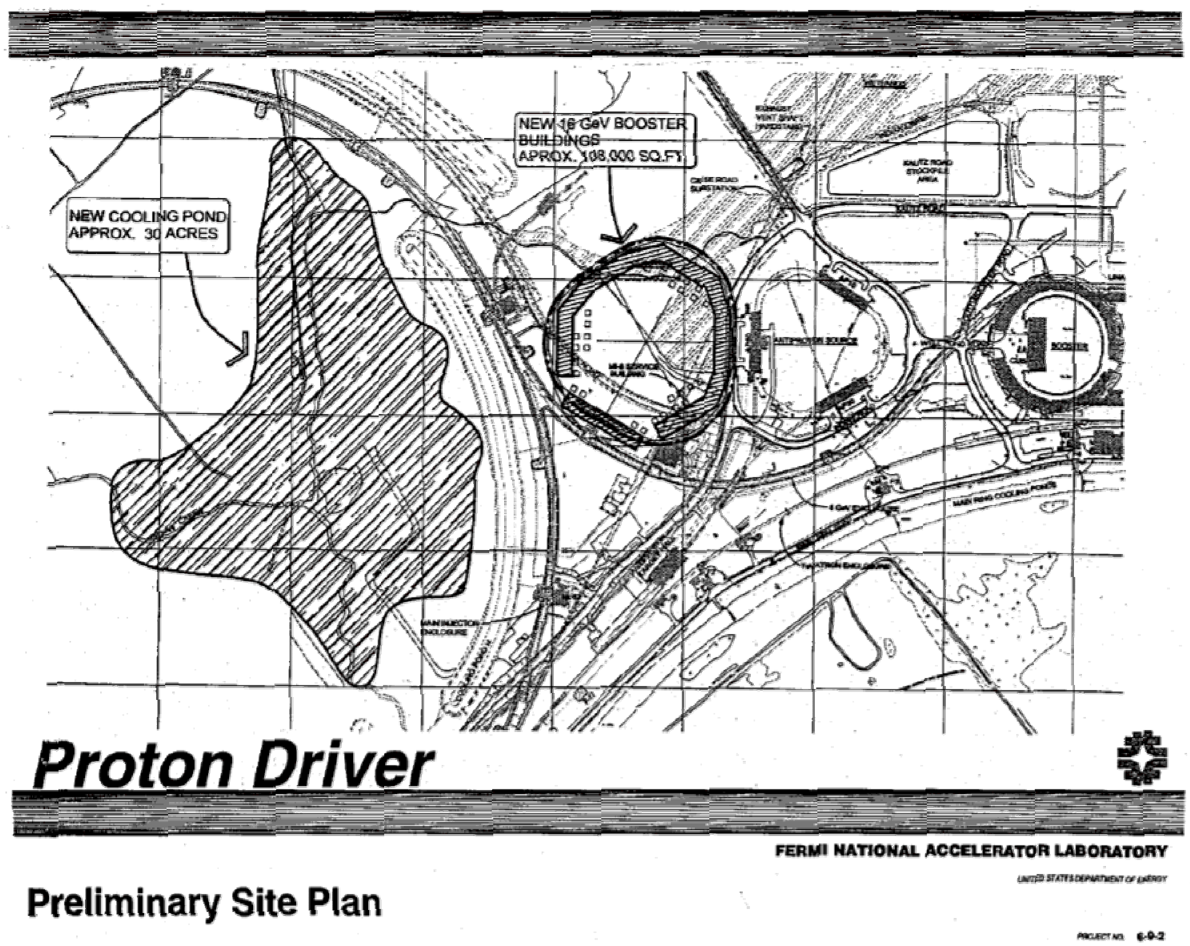
PET isotope production, R&D for $\bar{p}$ cancer therapy & interstellar propulsion
(Synergistic Technologies, funded by NASA SBIR)
Ground rule: keep impact on Tevatron luminosity < ≈ few%

- Future possibilities:

Studies of antihydrogen, hyperon decay, glueballs/hybrids, charmonium

⇒ Need $\mathcal{L} \approx 10^{33}/\text{cm}^2/\text{s}$, maybe possible in Run IIB

Proton Driver:

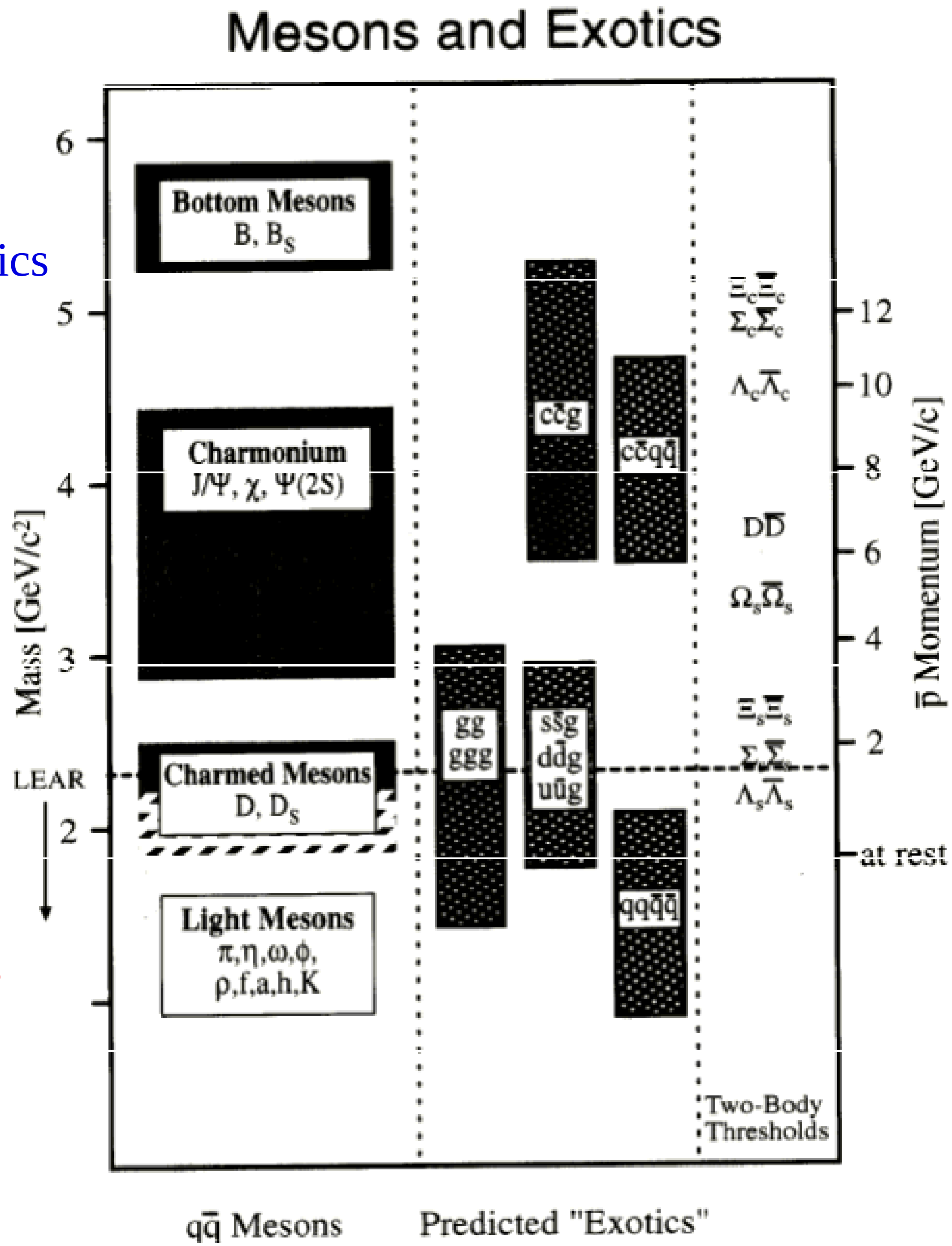


- Under discussion to provide protons for MiniBOONE, NUMI, Tevatron, and possible Neutrino Factory

- If built,will further increase $\bar{p}$ production rate
  (×4? if production target and collection lens bottlenecks alleviated)

Physics Examples:

1. Search for glueballs & exotics
   (U. Wiedner, Uppsala)
2. Hyperon CP violation
   (DMK)
3. Hyperon beta decay
   (N. Solomey, IIT)
4. Charmonium
   (K. Seth, NWU)
5. Trapped-antiproton physics
   (M. Holtzscheiter, LANL)



Isoscalar 0^{++} resonances seen by Crystal Barrel

		Decay mode
$f_0(975)$:	$M = 980 \pm 20$ MeV $\Gamma = 100 \pm 20$ MeV	$\pi\pi$
$f_0(1370)$:	$M = 1365 \pm 50$ MeV $\Gamma = 270 \pm 80$ MeV	$\pi\pi$ $\eta\eta$ 4π
$f_0(1500)$:	$M = 1511 \pm 8$ MeV $\Gamma = 116 \pm 17$ MeV	$\pi\pi$ $\eta\eta$ $\eta\eta'$ $K\bar{K}$

+ other experiments:

$f_0(1450)$:	$M = 1446 \pm 5$ MeV $\Gamma = 56 \pm 12$ MeV	4π
$f_0(1590)$:	$M = 1581 \pm 10$ MeV $\Gamma = 180 \pm 17$ MeV	$\eta\eta'$ $\eta\eta$ 4π
$f_0(1525)$:	$M = 1525$ MeV $\Gamma = 90$ MeV	$K\bar{K}$
$f_J(1710)$:	$M = 1709 \pm 5$ MeV $\Gamma = 140 \pm 12$ MeV	$K\bar{K}$ $\pi\pi$

Too many resonances

Interpretation of the results:

$f_0(975)$, $a_0(980)$:	KK-molecules
$f_0(1370)$:	Nonet member
$f_0(1525)$, $f_J(1710)$:	Nonet member
$f_0(1500) = f_0(1590) = f_0(1450)$:	Exotic

- Conclude:
  - Already much evidence for gluonic exotics, but low-mass region confusing
  - Most exotics predicted above LEAR kinematic limit, that's where signatures will be cleanest

$\Rightarrow$ Want higher-energy storage ring

Charmonium

- Confront perturbative QCD in $c\bar{c}$ system

- E760/835 left many unsolved problems – *e.g.*:
  - Confirmation of J/ψ, ψ' widths
  - Measurement of χ_c hadronic branching ratios
  - Find η_c', h_c
  - Improve measurement of α_s at low Q^2
  - Explore region above $D\bar{D}$ threshold
  - Study charmonium-nucleus cross sections (important for interpretation of J/ψ suppression as signature for QGP)

Hyperon Beta Decay

- Outstanding questions:
  1. V_{us} measured in various hyperon and kaon beta decays inconsistent
  2. Possible existence of "2^{nd}-class" weak currents – measurable only in hyperon beta-decay form factors
  3. Possibility of $\Sigma^0\Lambda$ mixing – postulated, never confirmed
- Require much larger event samples than currently available

HYPERON CP VIOLATION

- **Parity violating, ΔS = 1 decay of a spin-$\frac{1}{2}$ strange baryon into a spin-$\frac{1}{2}$ baryon and a pion, e.g.**

$$\Lambda \to \mathrm{p}\,\pi$$

is described by the decay amplitude

$$\mathcal{M}(\Lambda \to \mathrm{p}\,\pi) = S + P\,\vec{\sigma} \cdot \widehat{q}_p$$

S **is the amplitude of the S-wave final state**
P **is the amplitude of the P-wave final state**
$\widehat{q}_p$ **is the momentum unit vector of the proton**

- **In the rest frame of the Λ the angular distribution of the proton**

$$\frac{dn}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \vec{\mathcal{P}}_\Lambda \cdot \hat{q}_p)$$

where $\vec{\mathcal{P}}_\Lambda$ is the polarization of Λ and the decay parameter α is defined as

$$\alpha_\Lambda = \frac{2Re(S^* P)}{|S|^2 + |P|^2}$$

- **If CP is conserved**

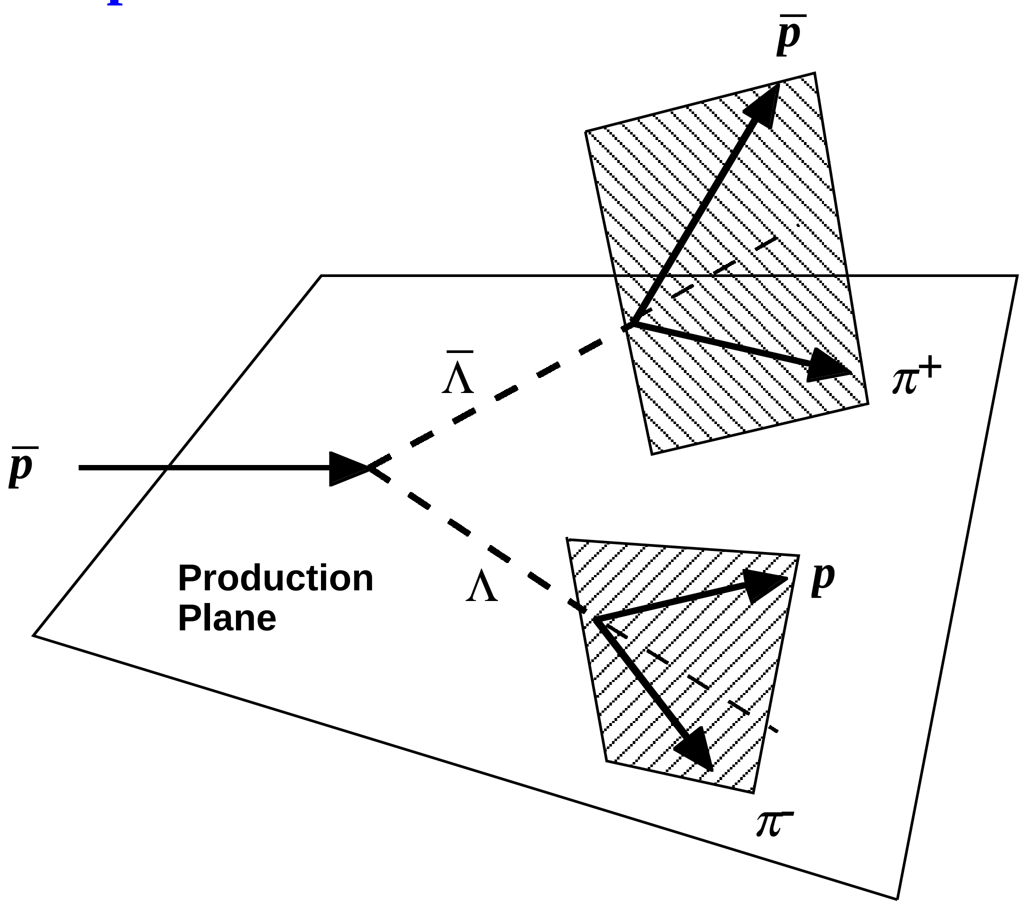
$$\alpha_{\overline{\Lambda}} = -\alpha_\Lambda$$

- **One can form a CP violating asymmetry**

$$A_\Lambda = \frac{\alpha_\Lambda + \alpha_{\overline{\Lambda}}}{\alpha_\Lambda - \alpha_{\overline{\Lambda}}}$$

ACCESSIBLE IN $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$:

- **Compare numbers of decays in which both p and $\bar{p}$ above production plane vs. both below**



- **Events with p above, $\bar{p}$ below and vice versa provide systematics check**

Brief History at CERN:

- PS185 at LEAR proposed 1981, begins 1984
- $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ proposed for CP: Donoghue, Holstein, Valencia, He, Pakvasa, 1986
- CERN Hyperon CP study group: technique feasible → 10^{-4} statistics, 10^{-5} systematics
- Hsueh and Rapidis propose new $\bar{\text{p}}$ storage ring at Fermilab 1992 → rejected
- LEAR shut down 1996, PS185 ends
- PS185 publishes world's best limit to date:

$A_{\Lambda} = 0.013 \pm 0.022$ [P. D. Barnes *et al.*, Phys. Rev. C **54,** 1877 (1996)]

Latest: 0.006 ± 0.015 [P. D. Barnes *et al.*, Nucl. Phys. B (Proc. Suppl) **56A**, (1997) 46]

THEORY & EXPERIMENT

Theory

- **SM:** $A_\Lambda \sim 10^{-5}$
- **Other models:** could be several $\times\, 10^{-4}$ [e.g., X.-G. He, H. Murayama, S. Pakvasa, G. Valencia, Phys. Rev. D61 , 071701 (2000)]

Experiment	Decay Mode	A_Λ
R608 at ISR	$pp \to \Lambda X,\ \bar{p}p \to \bar{\Lambda} X$	-0.02 ± 0.14
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	0.01 ± 0.10
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	0.006 ± 0.015

Experiment	Decay Mode	$A_\Xi + A_\Lambda$
E756 at Fermilab	$\Xi \to \Lambda\pi,\ \Lambda \to p\pi$	0.012 ± 0.014
E871 at Fermilab (HyperCP)	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	$\pm \approx 1.4 \times 10^{-4}$

E871 (HyperCP) Collaboration

A. Chan, Y.C. Chen, C. Ho, J.Sheng†, P. K. Teng, C. Yu† Z. Yu†
Academia Sinica, Taiwan

W. S. Choong, G. Gidal, T. Jones, K.-B. Luk, B. Turko, P. Zyla
University of California and Lawrence Berkeley National Laboratory

M.Crisler, C. James, J. Volk
Fermi National Accelerator Laboratory

J. Felix, G. Lopez, M. Sosa
University of Guanajuato, Mexico

R. A. Burnstein, A.Chakravorty, D. M. Kaplan, L.M. Lederman,W. Luebke, D. Rajaram, H. A. Rubin, C. White, S. L. White
Illinois Institute of Technology

N. Leros, J.-P. Perroud
University of Lausanne, Switzerland

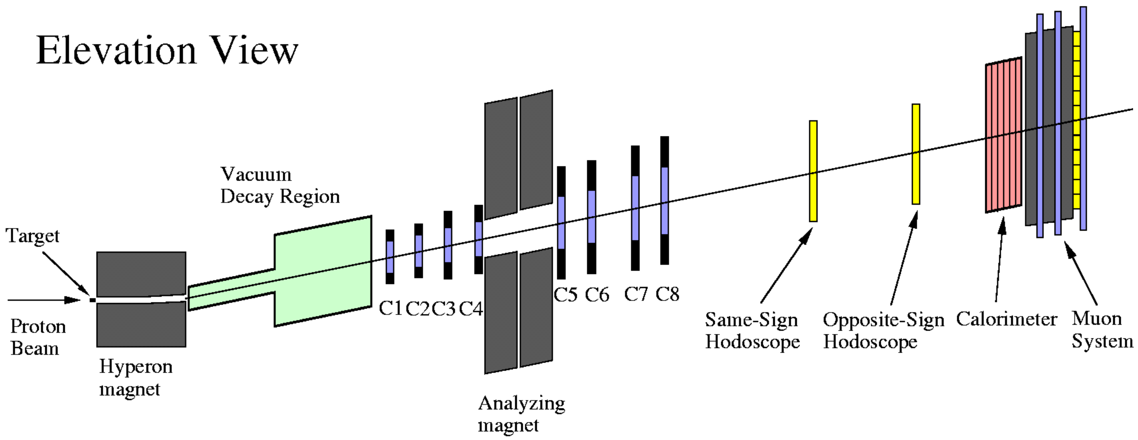
H. R. Gustafson, M. J. Longo, F. Lopez, H. K. Park
University of Michigan

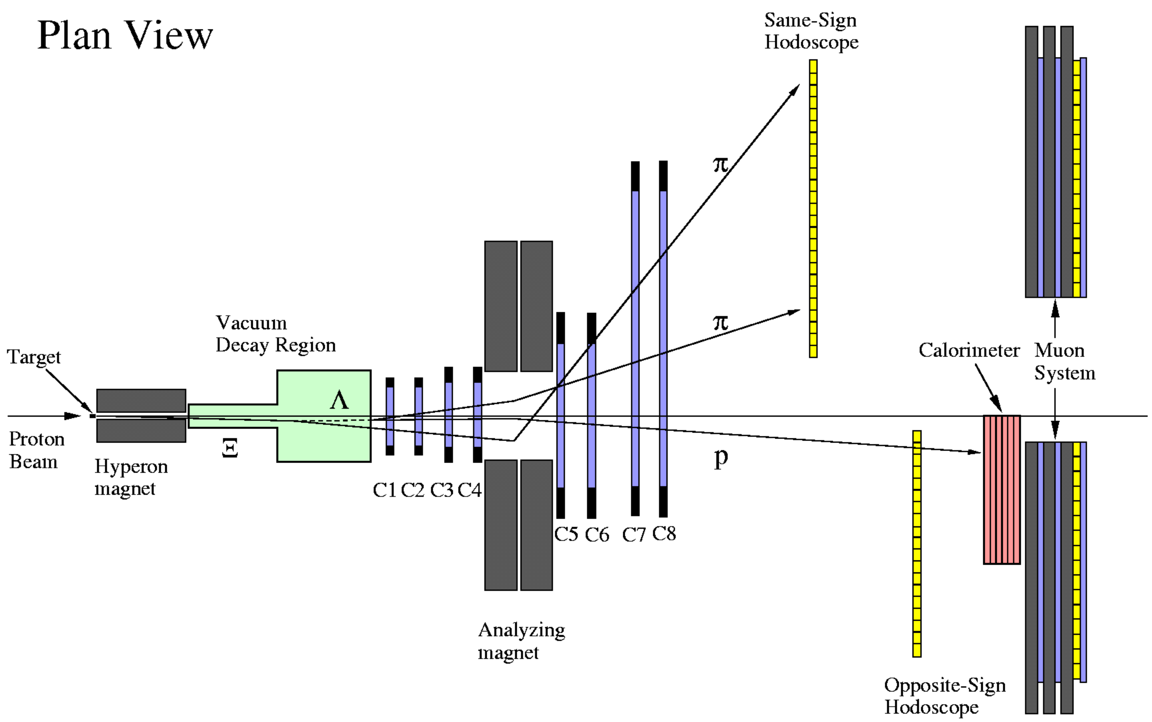
K. Clark, C. M. Jenkins
University of South Alabama

E. C. Dukes, C. Durandet, T. Holmstrom, M. Huang, L. Lu, K. S. Nelson
University of Virginia

† Visitors form IHEP, Beijing

HYPERCP SPECTROMETER





SUMMARY OF THE 1997 and 1999 RUNS

	1997 Run	1999 Run
Number of tapes	9,376	18,838
Data Volume	38 TB	71 TB

Projected number of reconstructed events

Ξ^-	2×10^9
$\overline{\Xi}^+$	0.5×10^9
K^+	0.32×10^9
K^-	0.13×10^9
Ω^-	14×10^6
$\overline{\Omega}^+$	5.3×10^6

$$\delta(A_{\Xi\Lambda}) \ = \ 1.4 \times 10^{-4} \text{ statistical precision}$$

CP Sensitivity Estimate

	L	pbars/hr	tgt density	I_pbar	N_pbar	days @50%	events	CP reach
	/cm^2/s		A/cm^2	mA				
P859:	1.6E+32	5.8E+10	1.0E+14	256	8.0E+11	88	2.3E+09	1.0E-04
	1.0E+33	3.6E+11	3.0E+14	533	1.7E+12	365	5.9E+10	2.0E-05
xP859:		6.3					26	5.1