Letter of Intent:

Low- and Medium-Energy Antiproton Physics at Fermilab

Thomas J. Phillips
Duke University, Durham, N. Carolina 27708 USA

Giorgio Apollinari, Daniel R. Broemmelsiek, Charles N. Brown,
David C. Christian, Paul Derwent, Keith Gollwitzer, Alan Hahn,
Vaia Papadimitriou, Steven Werkema, Herman B. White
Fermilab, Batavia, IL 60510, USA

Wander Baldini, Giulio Stancari, Michelle Stancari
INFN, Sezione di Ferrara, Ferrara, Italy

Gerald P. Jackson
Hbar Technologies, LLC, West Chicago, IL 60185, USA

Daniel M. Kaplan,* Howard A. Rubin, Yagmur Torun, Christopher G. White
Illinois Institute of Technology, Chicago, Illinois 60616, USA

Todd K. Pedlar
Luther College, Decorah, IA 52101, USA

Jerome Rosen
Northwestern University, Evanston, IL 60208, USA

E. Craig Dukes
University of Virginia, Charlottesville, Virginia 22903, USA

(and who else?)

D R A F T

June 1, 2007

Abstract

Fermilab has long had the world's most intense antiproton source. Despite this, the opportunities for low- and medium-energy antiproton physics at Fermilab have been limited in the past and — with the antiproton source now exclusively dedicated to serving the needs of the Tevatron Collider — are currently nonexistent. The anticipated

*Spokesperson. E-mail address: kaplan@iit.edu

shutdown of the Tevatron in 2009 presents the opportunity for a world-leading low- and medium-energy antiproton program. We summarize the current status of the Fermilab antiproton facility and review some physics topics for which a future experiment could make the world's best measurements.

1 Motivation

Antiproton sources. As is well known, the world's highest-energy and highest-intensity antiproton source is at Fermilab. Having previously supported medium-energy antiproton fixed-target experiments (including the charmonium experiments E760 and E835), it is now 100% dedicated to providing luminosity for the Tevatron Collider. At CERN, the LEAR antiproton storage ring was decommissioned in 1996;[1] its successor facility, the Antiproton Decelerator (AD), provides antiproton beams at momenta of 100 and 300 MeV/c, at intensities up to $\approx 2\times 10^7$ per minute [1].[2] It is noteworthy that Germany has embarked on a ≈billion-Euro upgrade plan for the GSI-Darmstadt nuclear-physics laboratory that includes construction of 30 and 90 GeV rapid-cycling synchrotrons and low- and medium-energy antiproton storage rings [2].

Physics with antiproton sources. There is an extensive list [3] of interesting particle-physics topics that can be addressed with such a facility (some of which are "unfinished business" from the former LEAR and Fermilab antiproton programs). These include

- precision $\overline{p}p \to$ charmonium studies, begun by Fermilab E760 and E835;
- open-charm studies, including searches for $D^0/\overline{D}^0$ mixing and CP violation;
- studies of $\overline{p}p \to$ hyperons, including searches for hyperon CP violation and studies of rare decays;
- the search for glueballs and gluonic hybrid states predicted by QCD; and
- trapped-$\overline{p}$ and antihydrogen studies.

Figure 1 (from the GSI PANDA Technical Progress Report [3]) and Table 1 give mass and momentum ranges for many of these processes. Due to their requirements for beam energy or intensity, all but the last of these cannot be pursued at the CERN AD. All of them (as well as additional topics of interest primarily to nuclear and atomic physicists) have been discussed as potential components of the physics program of the GSI-FAIR (Facility for Antiproton and Ion Research) project [2] and its general-purpose PANDA detector [3]. However, the GSI-FAIR construction project has yet to begin, and data taking at PANDA is not expected before 2014.

A number of intriguing recent discoveries can be elucidated at such a facility: the states provisionally named $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, and $Z(3930)$ in the charmonium region [4], observed by several groups, as well as the observation of apparent flavor-changing neutral currents in hyperon decay [5]; indeed, high sensitivity can be achieved to rare and symmetry-violating hyperon decays generally. In addition, the h_c mass and width, χ_c radiative-decay angular distributions, and $\eta_c'(2S)$ full and radiative widths, important parameters of the charmonium system that remain to be precisely determined, are well suited to the $\overline{p}p$ technique [6, 7].

Quarkonium physics. The theory of the strong interaction plays an important role in inferring the physics of quarks and extracting the quark mixing matrix from observations made

[1] LEAR was turned off in spite of its review committee's recommendation that it be allowed to complete its planned program of research; the rationale was to free up expert manpower for LHC work. The "ground rules" for the AD design accordingly required operability by as small a crew as possible.

[2] The AD accepts about 5×10^7 antiprotons per cycle at a momentum of 3.57 GeV/c, produced with 1.5×10^{13} protons from the PS; the antiprotons are then cooled and decelerated for provision to the experiments.

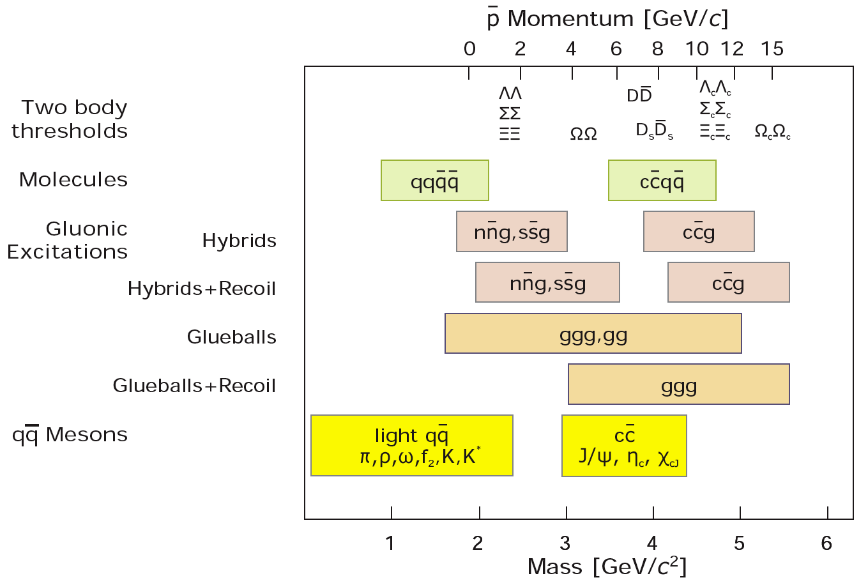

Figure 1: Mass ranges for various processes of interest (from the PANDA TPR [3]).

Table 1: Thresholds for some processes of interest and lab-frame $\overline{p}$ momentum for $\overline{p}p$ fixed-target.

Process	Threshold $\sqrt{s}$ (GeV)	$p_{\overline{p}}$ (GeV/c)
$\overline{p}p \to \overline{\Lambda}\Lambda$	2.231	1.437
$\overline{p}p \to \overline{\Sigma}^-\Sigma^+$	2.379	1.854
$\overline{p}p \to \overline{\Xi}^+\Xi^-$	2.642	2.620
$\overline{p}p \to \overline{\Omega}^+\Omega^-$	3.345	4.938
$\overline{p}p \to \eta_c$	2.980	3.678
$\overline{p}p \to \psi(3770)$	3.771	6.572
$\overline{p}p \to X(3872)$	3.871	6.991
$\overline{p}p \to X$ or $Y(3940)$	3.940	7.277
$\overline{p}p \to X$ or $Y(4260)$	4.260	8.685

Table 2: Comparison of predicted [8, 9, 10] and observed [11] charmonium spectra (adapted from [22]; values in parentheses are uncertainties). Note that the h_c mass agrees quite well with the value predicted by QCD, $\langle m(1^3P)\rangle = 3525\,\mathrm{MeV}/c^2$ [4].

J^{PC}	state	CP–PACS [8]	Columbia [9]	QCD-TARO [10]	experiment [11]
0^{-+}	η_c	3013(1)	3014(4)	3010(4)	2980(1)
	η_c'	3739(46)	3707(20)		3638(4)
1^{--}	J/ψ	3085(1)	3084(4)	3087(4)	3097
	$\psi(2S)$	3777(40)	3780(43)		3686
1^{+-}	h_c	3474(10)	3474(20)	3528(25)	3526
	h_c'	4053(95)	3886(92)		—
0^{++}	χ_{c0}	3408	3413(10)	3474(15)	3415
	χ_{c0}'	4008(122)	4080(75)		—
1^{++}	χ_{c1}	3472 (9)	3462(15)	3524(16)	3511
	χ_{c1}'	4067(105)	4010(70)		—
2^{++}	χ_{c2}	3503(24)	3488(11)		3556
	χ_{c2}'	4030(180)			3929(5)
2^{-+}	1^1D_2		3763(22)		—
					—
2^{--}	1^3D_2		3704(33)		—
3^{--}	1^3D_3		3822(25)		—
3^{+-}	1^1F_3		4224(74)		—
3^{++}	1^3F_3		4222(140)		—
0^{+-}	H_0		4714(260)		—
1^{-+}	H_1		4366(64)		—
2^{+-}	H_2		4845(220)		—

on hadrons. Heavy-quark–antiquark bound states ("quarkonia") offer a unique testing ground for QCD. Both potential-model and lattice-gauge Monte Carlo techniques have had success in predicting aspects of heavy-quark systems. As indicated by Table 2, quenched-approximation lattice-QCD predictions of the masses of low-lying charmonium states are already in qualitative agreement with the experimental values; moreover, the agreement is expected to improve once dynamical quarks on the lattice (now being implemented by various groups) are successfully incorporated into these calculations. (Figure 2 compares the agreement with experiment, for quantities for which predictions with dynamical quarks are now available, with that of the corresponding "quenched" predictions.) The charmonium system (Fig. 3) is an important proving ground for QCD calculations in that the bound c and $\bar{c}$ quarks are moving slowly enough that relativistic effects are significant but not dominant, and are sufficiently massive that non-perturbative effects are small but not negligible. After certification by comparison with experiment, these calculational techniques can then be confidently applied in interpreting such physics results as CP asymmetries in the beauty system.

Fermilab experiments E760 and E835 made the world's most precise measurements of charmonium masses and widths [6, 7, 12]. The achieved precision ($\lesssim 100\,\mathrm{keV}$) was made possible by the extraordinarily narrow energy spread of the stochastically cooled antiproton beam and the absence of Fermi motion and negligible energy loss in the hydrogen cluster-jet

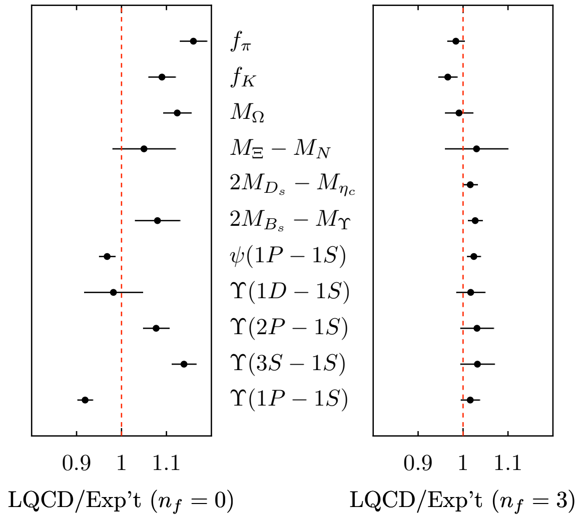

Figure 2: Lattice QCD results divided by experiment for a range of "gold-plated" quantities [15]. The unquenched calculations on the right show agreement with experiment across the board, whereas the quenched approximation on the left yields systematic errors of $\mathcal{O}(10\%)$.

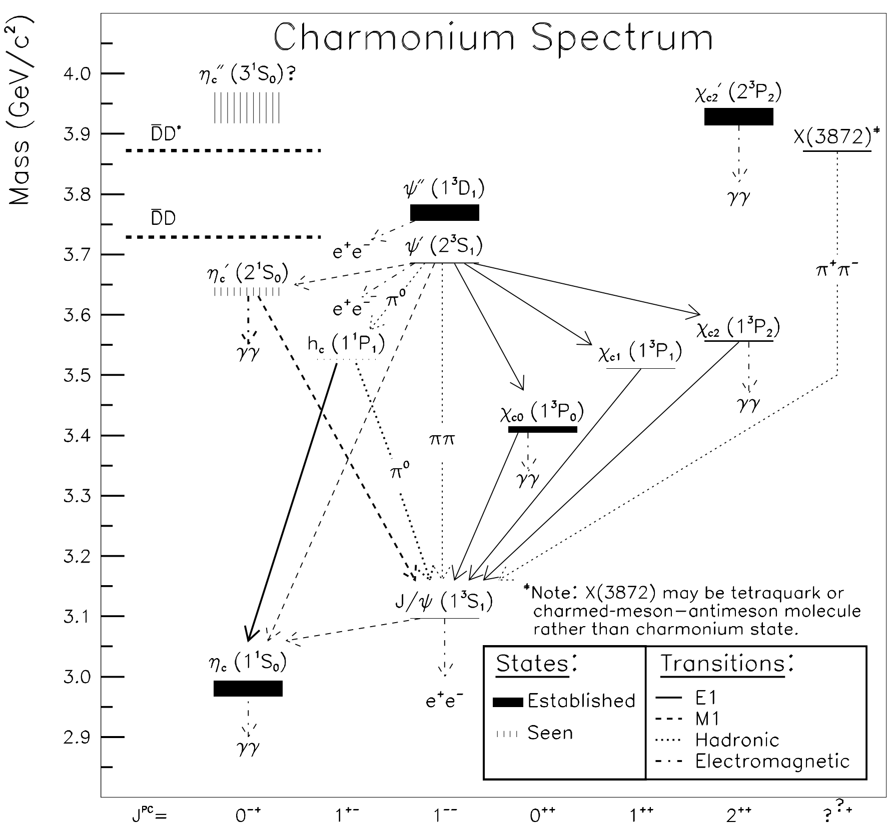

Figure 3: Spectrum of the charmonium system. Shown are masses, widths (or for those not yet measured, 90% confidence level upper limits on widths), and quantum numbers of observed charmonium states, with some of the important transitions also indicated [11, 4].

target. The other key advantage of the antiproton-annihilation technique is its ability to produce charmonium states of all quantum numbers, in contrast to e^+e^- machines which produce primarily 1^{--} states and the few states that couple directly to them, or (with relatively low statistics) states accessible in B decay or in 2γ production.

Our proposal. We propose here to carry out the preparatory work for a focused experimental program aimed at those measurements for which the Fermilab Antiproton Source is best suited: (1) precision studies of states in the charmonium region and (2) the search for new physics in hyperon decay. These measurements can all be performed with a common apparatus using existing, well-developed experimental technologies. Depending on the resources that will be available, existing detector components might be recycled for these purposes; alternatively, modest expenditures for new equipment could yield improved performance. We believe that the intrinsic physics interest of these measurements justifies the resumption of such a program at Fermilab. The opportunity for such studies will soon arrive, upon shutdown of the Tevatron (scheduled for 2009). By utilizing existing components from E835, DØ, etc., the cost could be kept low. There is a core group of physicists interested in pursuing this effort — at least to the stage of developing reliable estimates of cost and feasibility — and, beyond this, to a full proposal, should such estimates prove encouraging.

Also worthy of mention is a broader argument. With the planned closing of the Tevatron, the Fermilab accelerator-based experimental program is likely to become even more narrowly focused than at present: there will be efforts on CMS, one or perhaps two neutrino experiments, and one or two non-neutrino experiments using the Main Injector beam. From the standpoint of maintaining a vigorous program at Fermilab, as well as a US particle-physics enterprise that continues to explore a variety of exciting topics, attract good students, and afford career opportunities to young physicists, we believe so narrow a focus to be undesirable. After the Tevatron program ends, the Fermilab Antiproton Source could once again be made available for dedicated antiproton experiments. As we have suggested above (and argue in greater detail below), such experiments are both cost-effective and of great intrinsic interest.

2 Capabilities of the Fermilab Antiproton Source

The Antiproton Source now cools and accumulates antiprotons at a maximum stacking rate of $\approx 20\,\text{mA/hr}$. Given the 474 m circumference of the Antiproton Accumulator, this represents a production rate of $\approx 2\times 10^{11}$ antiprotons/hr. Given the 60 mb annihilation cross section, it could thus support in principle a luminosity up to about $5 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$, with antiproton stacking $\approx 50\%$ of the time and collisions during the remaining $\approx 50\%$. However, we anticipate operating at $\lesssim 2 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$, which allows $\gtrsim 80\%$ duty cycle, poses less of a challenge to detectors and triggers, and requires a smaller fraction of the protons from the Main Injector. Since this is an order of magnitude above the typical E835 luminosity of $2 \times 10^{31}\,\text{cm}^{-2}\text{s}^{-1}$ [6], it requires more intense stores than in E835, higher target density, or both of these.

More intense stores than in E835 seems an unattractive option in that stochastic cooling works best when the stack size is kept low. Thus in any program aiming to maximize useable luminosity, the penalty of decreased stacking rate with increasing stack size must be traded off against "end effects" that are more or less independent of stack size, such as the time needed to decelerate the antiproton beam from the stacking energy down to the energy of interest.[3]

The E835 cluster-jet target was an upgraded version of that used in E760; it produced hydrogen densities up to about 2.5×10^{14} atoms/cm^2 [6]. Further increase of cluster-jet target density is believed possible and is proposed for the PANDA program at GSI [3], which is also planned for $2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity. Other options for higher target density include a wire or pellet of plastic or metal in the beam halo [13], a solid-hydrogen target on the tip of a cold finger, or a stream of solid-hydrogen pellets. While target materials other than hydrogen might be suitable for hyperon running, they would destroy the superb energy resolution that is essential for the proposed charmonium studies. Given the relatively lengthy running times required for progress on our chosen physics topics, a target material that can support simultaneous charmonium and hyperon running is to be preferred.

We intend to keep abreast of relevant target R&D and perhaps to contribute to it ourselves. A consideration that must be taken into account is that the luminosity lifetime in E835 was dominated not by $\overline{p}p$ collisions in the target jet, but by collisions elsewhere around the ring with escaped gas from the target. This effect would tend to be exacerbated by increased jet density, although it might be ameliorated by careful attention to design of the gas flow and vacuum pumping scheme.

3 Physics Goals

To clarify the issues for a future low-energy antiproton facility, we consider a few representative physics examples: studying the mysterious $X(3872)$ state, improved measurement of the parameters of the h_c, searching for hyperon CP violation, and studying a recently discovered rare hyperon-decay mode. (This is of course far from an exhaustive list of the topics to be studied.)

3.1 $X(3872)$

The $X(3872)$ was discovered in 2003 by the Belle Collaboration [14] via the decay sequence $B^\pm \to K^\pm X(3872)$, $X(3872) \to \pi^+\pi^- J/\psi$; its existence was quickly confirmed by CDF [16], DØ [17], and BaBar [18]. It has now been seen in the $\gamma J/\psi$ [19], $\pi^+\pi^-\pi^0 J/\psi$ [20], and $D^0\overline{D}^0\pi^0$ [21] modes as well (Table 3). This state does not appear to fit within the charmonium spectrum. Although well above open-charm threshold, its observed width is $< 2.3\,\mathrm{MeV}$ at 90% C.L. [11], implying that decays to $D\overline{D}$ are forbidden and suggesting unnatural parity, $P = (-1)^{J+1}$ [22]. It is a poor candidate for the $\psi_2\,(1\,^3D_2)$ or $\psi_3\,(1\,^3D_3)$ charmonium levels [4, 20, 22] due to the nonobservation of radiative transitions to χ_c. The observation of $X(3872) \to \gamma J/\psi$ implies positive C-parity, and additional observations essentially rule out all possibilities other than $J^{PC} = 1^{++}$ [23, 24]. With those quantum numbers, the only available charmonium assignment is $\chi'_{c1}\,(2\,^3P_1)$; however, this is highly disfavored [4, 22] by the observed rate of $X(3872) \to \gamma J/\psi$. In addition, the plausible identification of $Z(3930)$ as the $\chi'_{c2}\,(2\,^3P_2)$ level suggests [4] that the $2\,^3P_1$ should lie some $49\,\mathrm{MeV}/c^2$ higher in mass than the observed $m_X = 3871.2 \pm 0.5\,\mathrm{MeV}/c^2$ [11].

Inspired by the coincidence of the $X(3872)$ mass and the $D^0\overline{D}^{*0}$ threshold, a number of ingenious solutions to this puzzle have been proposed, including an S-wave cusp [25] or a tetraquark state [26]. Perhaps the most intriguing possibility is that the $X(3872)$ represents

[3] The alternative of stacking at or near the desired collision energy may also be worth considering.

Table 3: Experimental observations of $X(3872)$.

Experiment	Year	Mode	Events	Ref.
Belle	2003	$\pi^+\pi^- J/\psi$	35.7 ± 6.8	[14]
CDF	2004	$\pi^+\pi^- J/\psi$	730 ± 90	[16]
D0	2004	$\pi^+\pi^- J/\psi$	522 ± 100	[17]
Belle	2004	$\omega(\pi^+\pi^-\pi^0)J/\psi$	10.6 ± 3.6	[20]
BaBar	2005	$\pi^+\pi^- J/\psi$	25.4 ± 8.7	[18]
Belle	2005	$\gamma J/\psi$	13.6 ± 4.4	[19]
Belle	2006	$D^0\overline{D}^{*0}$	23.4 ± 5.6	[21]

the first clear-cut observation of a meson-antimeson molecule: specifically, a bound state of $D^0\overline{D}^{*0} + D^{*0}\overline{D}^0$ [27].[4] A key measurement is then the precise mass difference between the X and that threshold; if the molecule interpretation is correct, it should be very slightly negative, in accord with the small molecular binding energy [24]:

$$0 < E_X = (m_{D^0} + m_{D^{*0}} - m_X)c^2 \ll 10\,\mathrm{MeV}\,.$$

A measurement of the width is also highly desirable.

With the current world-average values [11] $m_{D^0} = 1864.5 \pm 0.4\,\mathrm{MeV}/c^2$ and $m_{D^{*0}} - m_{D^0} = 142.12 \pm 0.07\,\mathrm{MeV}/c^2$, we have $E_X = -0.1 \pm 0.8\,\mathrm{MeV}/c^2$. By taking advantage of the small momentum spread and precise momentum-calibration capability of the Antiproton Accumulator, a $\overline{p}p \to X(3872)$ formation experiment can make extremely precise ($\lesssim 100\,\mathrm{keV}/c^2$) measurements of m_X and Γ_X; the precise m_D measurement has just become available from CLEO, and $m_{D^{*0}} - m_{D^0}$ is already known sufficiently well. (With the latest CLEO measurement, $M_{D^0} = 1864.847 \pm 0.150 \pm 0.095\,\mathrm{MeV}/c^2$ [28], we have $E_X = 0.6 \pm 0.6\,\mathrm{MeV}/c^2$, with the uncertainty dominated by our current knowledge of m_X. When our precision measurement is made, it will still be the dominant uncertainty on the binding energy, assuming the total uncertainty on m_{D^0} improves roughly as $1/\sqrt{N}$ as the statistics of the CLEO analyzed sample increase by one order of magnitude [29].[5]) Additional important measurements include $\mathcal{B}[X(3872) \to \pi^0\pi^0 J/\psi]$ to confirm the C-parity assignment [30] and $\mathcal{B}[X(3872) \to \gamma\psi']$ to further tighten the constraints with respect to the $2\,^3P_1$ assignment [4].

The recent report from the Belle Collaboration of a near-threshold enhancement in $B \to D^0\overline{D}^0\pi^0 K$ decays [21] tends to support the $D^0\overline{D}^{*0}$-molecule interpretation [31, 32]. Interestingly, the enhancement is observed at a mass of $3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8\,\mathrm{MeV}/c^2$, 2.0σ higher than the world-average value of m_X. It is clear that the additional approach to the study of this state that $\overline{p}p$ formation provides could be extremely valuable in deciphering the nature of the $X(3872)$.

[4] Alternatively, the mass coincidence may be merely accidental, and the $X(3872)$ a $c\bar{c}$-gluon hybrid state; however, the mass and 1^{++} quantum numbers make it a poor match to lattice-QCD predictions for such states [4].

[5] The current CLEO analysis is based on 3 million $\psi(2S)$ decays, while an additional 25 million recorded last summer have yet to be included in the m_{D^0} analysis [29].

3.1.1 $X(3872)$ sensitivity estimate

The production cross section of $X(3872)$ in $\bar{p}p$ annihilation has not been measured, but it has been estimated to be similar in magnitude to that of the χ_c states [33]. Moreover, the observed rate and kinematic distributions of $\bar{p}p \to X(3872)+$ anything at the Tevatron [17] and of $B^\pm \to K^\pm X(3872)$ [11] suggest that the production rate of $X(3872)$ in $\bar{p}p$ formation (at $\sqrt{s} = 3871.2 \pm 0.5\,\mathrm{MeV}/c^2$) should not differ greatly from that for charmonium states. In E760, the χ_{c1} and χ_{c2} were detected in $\chi_c \to \gamma J/\psi$ (branching ratios of 36% and 20%, respectively [11]) with acceptance times efficiency of $44 \pm 2\%$, giving about 500 observed events each for an integrated luminosity of $1\,\mathrm{pb}^{-1}$ taken at each resonance [34]. At $10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ we could then expect to produce ~ 0.1 $X(3872)$ event per second. The lower limit $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] > 0.042$ at 90% C.L. [35] then implies a signal of $\gtrsim 4 \times 10^{-3}$ detected events per second in the experiment we propose, or $\gtrsim 4 \times 10^3$ events in that mode per nominal month ($1.0 \times 10^6\,\mathrm{s}$) of running. By way of comparison, Table 3 shows current sample sizes, which are likely to increase by not much more than an order of magnitude as these experiments complete during the current decade.[6] (Although CDF and D0 could amass samples of order 10^4 $X(3872)$ decays, the large backgrounds in the CDF and D0 observations, reflected in the uncertainties on the numbers of events listed in Table 3, limit their incisiveness.)

Given the uncertainties in the cross section and branching ratios, the above may well be an under- or overestimate of the $\bar{p}p$ formation and observation rates, perhaps by as much as an order of magnitude. Nevertheless, it appears that a new experiment at the Antiproton Accumulator could obtain the world's largest clean samples of $X(3872)$, in perhaps as little as a month of running. The high statistics, event cleanliness, and unique precision available in the $\bar{p}p$ formation technique could enable the world's smallest systematics. Such an experiment could thus provide a definitive test of the nature of the $X(3872)$.

3.2 h_c

Observing the h_c (1^1P_1) charmonium state and measuring its parameters were high-priority goals of both E760 and E835, as well as of their predecessor experiment, CERN R704. Being very narrow and having suppressed couplings both to e^+e^- and to the states that are easily produced in e^+e^- annihilation, the h_c is a difficult state to study experimentally.

The pioneering charmonium experiment CERN R704 was one of the last experiments to operate at the Intersecting Storage Rings (ISR). It employed a stochastically cooled antiproton beam and a cryogenic hydrogen-gas cluster-jet target with a nonmagnetic spectrometer of limited angular coverage to search for final states including evidence of $J/\psi \to e^+e^-$ decay. In addition to signals for χ_{c1} and χ_{c2}, a claimed 2.3σ signal of 5 $\bar{p}p \to J/\psi + X$ events near the χ_c center of gravity was interpreted as evidence for the (isospin-violating) $h_c \to J/\psi\,\pi^0$ mode with h_c mass $3525.4 \pm 0.8 \pm 0.5\,\mathrm{MeV}$ [37]. The R704 signal implies an on-resonance cross section of $\approx 2\,\mathrm{nb}$ and $\Gamma_{h_c} \times \mathcal{B}(h_c \to p\bar{p}) \times \mathcal{B}(h_c \to J/\psi\,X) \times \mathcal{B}(J/\psi \to e^+e^-) = 0.135^{+0.150}_{-0.060}\,\mathrm{eV}$ [38].

Following the shutdown of the ISR, Fermilab E760 was proposed to continue these studies. E760 devoted some $17\,\mathrm{pb}^{-1}$ of integrated luminosity to the h_c search and found an enhancement consistent with the expected h_c properties in the $J/\psi\,\pi^0$ mode at $3526.2 \pm 0.15 \pm 0.2\,\mathrm{MeV}$ [39]; based on the 59 candidate events, they estimated the probability of such

[6] The $\bar{p}p \to X(3872)$ sensitivity will be competitive even with that of the proposed SuperKEKB [36] upgrade, should that project go forward.

a bump arising at random as 1 part in 400. The E760 measurements of on-resonance cross-section ≈ 0.3 nb and $\Gamma_{h_c} \times \mathcal{B}(h_c \to p\overline{p}) \times \mathcal{B}(h_c \to J/\psi\, X) \times \mathcal{B}(J/\psi \to e^+e^-) = 0.010 \pm 0.003$ eV appear to rule out the R704 events as being signal [38].

E835 spent considerable running time attempting to replicate and improve on the E760 observation but observed no signal in $J/\psi\, \pi^0$ at the E760 mass value. In a sample with integrated luminosity of $\approx$80 pb^{-1}, they did however find a 13-event enhancement in $\eta_c \gamma$ (with the η_c detected via its $\gamma\gamma$ decay mode) at $3525.8 \pm 0.2 \pm 0.2$ MeV [40], with estimated significance in the range 1–3×10^{-3}, comparable to that of the E760 h_c signal. More recently, CLEO's study [41] of $\psi(2S) \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$ has now established the existence of the h_c at greater than 4σ: based on 168 ± 40 signal events, they find $m(h_c) = 3524.4 \pm 0.6 \pm 0.4$ MeV, not inconsistent with that measured by E835. Neither experiment was able to measure the width of the h_c, but E835 set a 90%-C.L. upper limit of 1 MeV.

A key prediction of QCD and perturbation theory is that the charmonium spin-zero hyperfine splitting, as measured by the mass difference $\Delta m_{\rm hf}$ between the h_c and the spin-weighted average of the χ_c states, should be close to zero [42]. Using the current PDG-average values [11], $\langle m(^3P_J) \rangle = 3525.36 \pm 0.06$ MeV and $m(h_c) = 3525.93 \pm 0.27$ MeV, we find $\Delta m_{\rm hf} = -0.57 \pm 0.28$ MeV, which differs from zero at the 2σ level but is within the range expected from QCD. The PDG error on $m(h_c)$ includes a scale factor of 1.5 due to the tension among the four most precise measurements (Fig. 4). Moreover, the most precise measurements (from E760 and E835) are based on signals that are statistically marginal, and whether the E760 observation was in fact a signal is called into question by the negative results of the E835 search. The R704 result is on even weaker ground: a $\overline{p}p \to h_c \to J/\psi\, X$ decay at the level implied by Baglin *et al.* [37] is most likely ruled out by E760 [38] (as discussed above) as well as by E835. Thus of the four results used by the PDG in Fig. 4, only one is clearly reliable, and the claimed precision on $m(h_c)$ is far from established. This motivates an improved experimental search. Also of interest are the width and branching ratios of the h_c, for which QCD makes clear predictions; the decay modes also bear on the question of isospin conservation in such decays.

E835 sensitivity in the $h_c \to \eta_c\gamma \to (\gamma\gamma)\gamma$ mode was limited by the $(2.8 \pm 0.9) \times 10^{-4}$ $\eta_c \to \gamma\gamma$ branching ratio. Moreover, the acceptance times efficiency was reduced to only $\approx$3% by cuts needed to eliminate the substantial background from π^0 decays. Given a magnetic spectrometer, favorable modes in which to observe η_c include (among others) $\eta_c \to \phi\phi$, ϕK^+K^-, K^*K^*, and $\eta'\pi^+\pi^-$. These have branching ratios up to two orders of magnitude larger, as well as more-distinctive decay kinematics, than $\eta_c \to \gamma\gamma$, probably allowing looser cuts to be used, and thus higher efficiency to be achieved. For example, the $K^+K^-K^+K^-$ final state which would be a signature of $\eta_c \to \phi\phi$ has no quarks in common with the initial $\overline{p}p$ state and so should contain very little background. The $\eta_c \to \phi\phi$ mode was searched for in E835 but without a magnet it was barely feasible. Reliably assessing the improvement in performance for these modes with a magnetic spectrometer will require detailed simulation work, but at least an order of magnitude in statistics seems likely. Additional improvement in sensitivity will come from the higher luminosity that we propose.

Provided detailed simulation studies bear out these ideas, we will soon have the opportunity to resolve this 20-year-old experimental controversy.

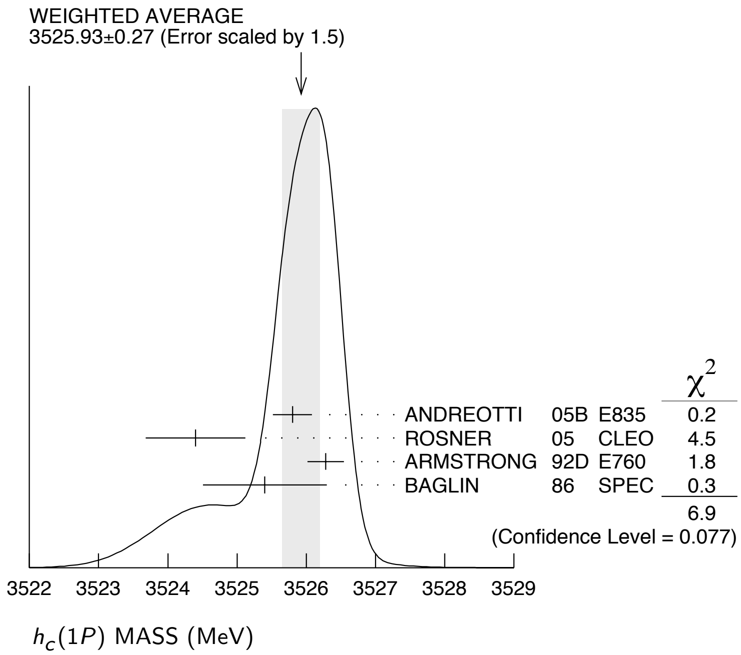

Figure 4: PDG ideogram of the four most precise measurements of the h_c mass (from [11]).

3.3 Hyperon *CP* violation

In addition to the well-known *CP*-violation effects in kaon and *B*-meson mixing and decay [11], the standard model predicts slight *CP* asymmetries in decays of hyperons [43, 44, 45]. In the kaon and beauty systems, such effects appear to be dominated by standard model processes. It thus behooves us to study other systems (such as hyperons) as well, in which the signatures of new physics might stand out more sharply.

Hyperon *CP* violation would of course be of the direct type since hyperon mixing would violate conservation of baryon number. The hyperon *CP* asymmetries considered most accessible have involved comparison of the angular distributions of the decay products of polarized hyperons with those of the corresponding antihyperons [44]; however, partial-rate asymmetries are also expected [46, 47] and (as discussed below) may be detectable. More than one hyperon *CP* asymmetry may be measurable in low- and medium-energy $\overline{p}p$ annihilation to hyperon-antihyperon pairs. To be competitive with previous Ξ and Λ angular-distribution asymmetry measurements would require higher luminosity ($\sim 10^{33}$) than is likely to be available, as well as a substantial upgrade relative to the E835 apparatus. While summarizing the state of hyperon *CP* asymmetries generally, for the purposes of this LoI we therefore emphasize in particular the $\Omega^-/\overline{\Omega}^+$ partial-rate asymmetry, for which there is no previous measurement.

By angular-momentum conservation, in the decay of a spin-1/2 hyperon to a spin-1/2 baryon plus a pion, the final state must be either *S*-wave or *P*-wave.[7] As is well known, the interference term between the *S*- and *P*-wave decay amplitudes gives rise to parity violation, described by Lee and Yang [48] in terms of two independent parameters α and β: α is proportional to the real and β to the imaginary part of this interference term. *CP* violation can be sought as a difference in $|\alpha|$ or $|\beta|$ between a hyperon decay and its *CP*-

[7] A similar argument holds for a spin-3/2 hyperon, but involving *P* and *D* waves.

conjugate antihyperon decay or as a particle–antiparticle difference in the partial widths for such decays [44, 49]. For a precision angular-distribution asymmetry measurement, it is necessary to know the relative polarizations of the initial hyperons and antihyperons to high accuracy.

3.3.1 Angular-distribution asymmetries

Table 4 summarizes the experimental situation. The first three experiments cited studied Λ decay only [50, 51, 52], setting limits on the *CP*-asymmetry parameter [44, 49]

$$A_\Lambda \equiv \frac{\alpha_\Lambda + \overline{\alpha}_\Lambda}{\alpha_\Lambda - \overline{\alpha}_\Lambda}\,,$$

where α_Λ ($\overline{\alpha}_\Lambda$) characterizes the Λ ($\overline{\Lambda}$) decay to (anti)proton plus charged pion. If *CP* is a good symmetry in hyperon decay, $\alpha_\Lambda = -\overline{\alpha}_\Lambda$.

Fermilab E756 [53] and CLEO [54] used the cascade decay of charged Ξ hyperons to produce polarized Λ's, in whose subsequent decay the slope of the (anti)proton angular distribution in the "helicity" frame measures the product of α_Ξ and α_Λ. If *CP* is a good symmetry in hyperon decay this product should be identical for Ξ^- and $\overline{\Xi}^+$ events. The *CP*-asymmetry parameter measured is thus

$$A_{\Xi\Lambda} \equiv \frac{\alpha_\Xi\alpha_\Lambda - \overline{\alpha}_\Xi\overline{\alpha}_\Lambda}{\alpha_\Xi\alpha_\Lambda + \overline{\alpha}_\Xi\overline{\alpha}_\Lambda} \approx A_\Xi + A_\Lambda\,.$$

The power of this technique derives from the relatively large $|\alpha|$ value for the $\Xi^- \to \Lambda\pi^-$ decay ($\alpha_\Xi = -0.458 \pm 0.012$ [11]). A further advantage in the fixed-target case is that within a given $\overset{(-)}{\Xi}$ momentum bin the acceptances and efficiencies for Ξ^- and $\overline{\Xi}^+$ decays are very similar, since the switch from detecting Ξ to detecting $\overline{\Xi}$ is made by reversing the polarities of the magnets, making the spatial distributions of decay products across the detector apertures almost identical for Ξ and for $\overline{\Xi}$. (There are still residual systematic uncertainties arising from the differing momentum dependences of the Ξ and $\overline{\Xi}$ cross sections and of the cross sections for the p and $\overline{p}$ and π^+ and π^- to interact in the material of the spectrometer.)

Subsequent to E756, this technique was used in the "HyperCP" experiment (Fermilab E871) [55, 56], which ran during 1996–99 and has set the world's best limits on hyperon *CP* violation, based so far on about 5% of the recorded $\overset{(-)}{\Xi}{}^{\mp} \to \overset{(-)}{\Lambda}\pi^{\mp}$ data sample. (The systematics of the full data sample is still under study.) Like E756, HyperCP used a secondary charged beam produced by 800 GeV primary protons interacting in a metal target. The secondary beam was momentum- and sign-selected by means of a curved collimator installed within a 6-m-long dipole magnet. No measurements were made until after the 13-m-long (evacuated) decay region. HyperCP recorded the world's largest samples of hyperon and antihyperon decays, including 2.0×10^9 and 0.46×10^9 Ξ^- and $\overline{\Xi}^+$ events, respectively. When the analysis is complete, these should determine $A_{\Xi\Lambda}$ with a statistical uncertainty

$$\delta A = \frac{1}{2\alpha_\Xi\alpha_\Lambda}\sqrt{\frac{3}{N_{\Xi^-}} + \frac{3}{N_{\overline{\Xi}^+}}} \lesssim 2 \times 10^{-4}\,. \tag{1}$$

The standard model predicts this asymmetry to be of order 10^{-5} [44]. Thus if the HyperCP full-statistics analysis sees a significant effect, it will be evidence for *CP* violation in the baryon sector substantially larger than predicted by the standard model. (A number of

Table 4: Summary of experimental limits on CP violation in hyperon decay; the hyperons studied are indicated by *, †, and ‡.

Exp't	Facility	Year	Ref.	Modes	$^*A_\Lambda$ / $^\dagger A_{\Xi\Lambda}$ / $^\ddagger A_{\Omega\Lambda}$
R608	ISR	1985	[50]	$pp \to \Lambda X, pp \to \overline{\Lambda} X$	$-0.02 \pm 0.14^*$
DM2	Orsay	1988	[51]	$e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$	$0.01 \pm 0.10^*$
PS185	LEAR	1997	[52]	$\overline{p}p \to \overline{\Lambda}\Lambda$	$0.006 \pm 0.015^*$
CLEO	CESR	2000	[54]	$e^+e^- \to \Xi^- X, \Xi^- \to \Lambda\pi^-$, $e^+e^- \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$-0.057 \pm 0.064 \pm 0.039^\dagger$
E756	FNAL	2000	[53]	$pN \to \Xi^- X, \Xi^- \to \Lambda\pi^-$, $pN \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$0.012 \pm 0.014^\dagger$
HyperCP	FNAL	2004	[55]	$pN \to \Xi^- X, \Xi^- \to \Lambda\pi^-$, $pN \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$(0.0 \pm 6.7) \times 10^{-4\,\dagger,\S}$
HyperCP	FNAL	2006	[58]	$pN \to \Omega^- X, \Omega^- \to \Lambda K^-$, $pN \to \overline{\Omega}^+ X, \overline{\Omega}^+ \to \overline{\Lambda} K^+$	$-0.004 \pm 0.12^\ddagger$

§ Based on ≈5% of the HyperCP data sample; analysis of the full sample is still in progress.

standard model extensions predict effects as large as $\mathcal{O}(10^{-3})$ [57]). Such an observation could be of relevance to the mysterious mechanism that gave rise to the cosmic baryon asymmetry.

HyperCP has also set the world's first limit on CP violation in $\overset{(-)}{\Omega}{}^{\mp}$ decay, using a sample of 5.46×10^6 $\Omega^- \to \Lambda K^-$ events and 1.89×10^6 $\overline{\Omega}^+ \to \overline{\Lambda} K^+$ events [58]. Here, as shown by HyperCP [59, 60], parity is only slightly violated: $\alpha = (1.75 \pm 0.24) \times 10^{-2}$ [11]. Hence the measured magnitude and uncertainty of the asymmetry parameter $A_{\Omega\Lambda}$ (inversely proportional to α as in Eq. 1) are rather large: $[-0.4 \pm 9.1\,(\mathrm{stat}) \pm 8.5\,(\mathrm{syst})] \times 10^{-2}$ [58]. This asymmetry is predicted to be $\leq 4 \times 10^{-5}$ in the standard model but can be as large as 8×10^{-3} if new physics contributes [47].

3.3.2 Partial-rate asymmetries

While CPT symmetry requires the lifetimes of a particle and its antiparticle to be identical, partial-rate asymmetries violate only CP. For most hyperon decays, partial-rate asymmetries are expected to be undetectably small [45]. However, this need not be the case for the decays $\Omega^- \to \Lambda K^-$ and $\Omega^- \to \Xi^0\pi^-$, for which the particle/antiparticle partial-rate asymmetries could be as large as 2×10^{-5} in the standard model and one to two orders of magnitude larger if non-SM contributions are appreciable [46, 47]. The quantities to be measured are

$$\begin{aligned}
\Delta_{\Lambda K} &\equiv \frac{\Gamma(\Omega^- \to \Lambda K^-) - \Gamma(\overline{\Omega}^+ \to \overline{\Lambda} K^+)}{\Gamma(\Omega^- \to \Lambda K^-) + \Gamma(\overline{\Omega}^+ \to \overline{\Lambda} K^+)}\,, \quad \Delta_{\Xi\pi} \equiv \frac{\Gamma(\Omega^- \to \Xi^0\pi^-) - \Gamma(\overline{\Omega}^+ \to \overline{\Xi}^0\pi^+)}{\Gamma(\Omega^- \to \Xi^0\pi^-) + \Gamma(\overline{\Omega}^+ \to \overline{\Xi}^0\pi^+)} \\
&\approx \frac{1}{2\Gamma}(\Gamma - \overline{\Gamma}) = 0.5\,(1 - \Gamma/\overline{\Gamma}) \\
&\approx 0.5\,(1 - N/\overline{N})\,,
\end{aligned}$$

where in the last step we have assumed nearly equal numbers (N) of Ω and ($\overline{N}$) of $\overline{\Omega}$ events, as would be the case in $\overline{p}p$ annihilation. Sensitivity at the 10^{-4} level then requires $\mathcal{O}(10^7)$

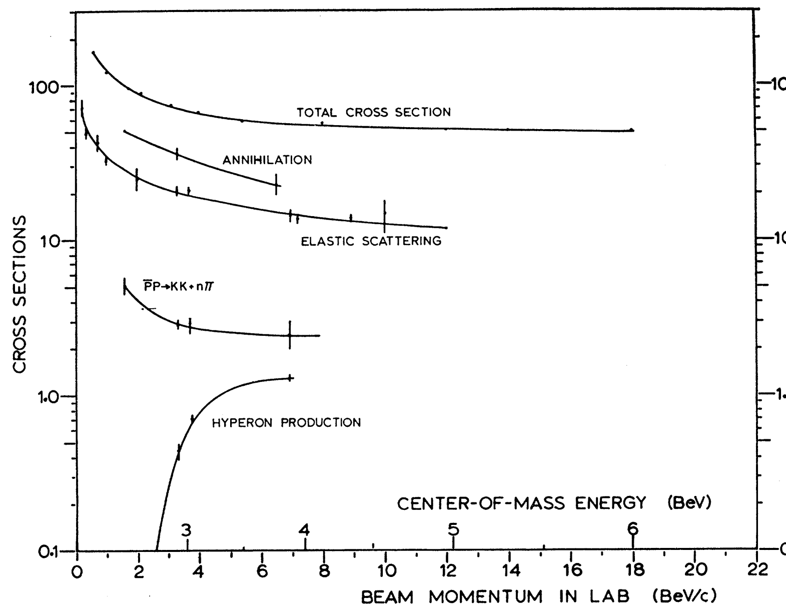

Figure 5: Cross sections (in mb) for various $\overline{p}p$ processes vs. momentum and $\sqrt{s}$ (from [62]).

reconstructed events. Measuring such a small branching-ratio difference reliably will require the clean exclusive $\overline{\Omega}^{+}\Omega^{-}$ event sample produced less than a π^0 mass above threshold, or $4.938 < p_{\overline{p}} < 5.437\,\mathrm{GeV}/c$.

3.3.3 Hyperon sensitivity estimates

There have been a number of measurements of hyperon production by low-energy antiprotons. Johansson *et al.* [61] report cross sections measured by PS185 at LEAR, but the maximum LEAR $\overline{p}$ momentum ($2\,\mathrm{GeV}/c$) was insufficient to produce Ξ's or Ω's. Chien *et al.* [62] report measurements of a variety of hyperon final states performed with the BNL 80-inch liquid-hydrogen bubble chamber in a 6.935 "BeV/c" electrostatically separated antiproton beam at the AGS; Baltay *et al.* [63] summarize data taken at lower momenta. In 80,000 pictures Chien *et al.* observed some 1,868 hyperon or antihyperon events, corresponding to a total hyperon-production cross section of $1.310 \pm 0.105\,\mathrm{mb}$ [62]. The corresponding cross section measured at $3.7\,\mathrm{GeV}/c$ was $720\pm30\,\mu\mathrm{b}$, and $438\pm52\,\mu\mathrm{b}$ at $3.25\,\mathrm{GeV}/c$ [63] (see Fig. 5). The inclusive hyperon-production cross section at $5.4\,\mathrm{GeV}/c$ is thus about 1 mb. At $2\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ this amounts to some 2×10^5 hyperon events produced per second, or 2×10^{12} per year. (As discussed below, experience suggests that a data-acquisition system that can cope with such a high event rate is both feasible and reasonable in cost.)

To estimate the exclusive $\overline{p}p \to \overline{\Omega}\Omega$ cross section requires some extrapolation, since it has yet to be measured (moreover, even for $\overline{p}p \to \overline{\Xi}^{+}\Xi^{-}$ only a few events have been seen). A rule of thumb is that each strange quark "costs" between one and two orders of magnitude in cross section, reflecting the effect of the strange-quark mass on the hadronization process. This is borne out by e.g. HyperCP, in which 2.1×10^9 $\Xi^- \to \Lambda\pi^-$and 1.5×10^7 $\Omega^- \to \Lambda K^-$ decays were reconstructed [56]; given the $160\,\mathrm{GeV}/c$ hyperon momentum and 6.3 m distance from HyperCP target to decay pipe, this corresponds to ≈ 30 Ξ^-'s per Ω^- produced at the target. A similar ratio is observed in HERA-B [64]. In exclusive $\overline{p}p \to \overline{Y}Y$ production (where Y signifies a hyperon) there may be additional effects, since as one proceeds from

Table 5: Summary of predicted hyperon CP asymmetries.

Asymm.	Mode	SM	NP	Ref.
A_Λ	$\Lambda \to p\pi$	$\lesssim 10^{-5}$	$\lesssim 6 \times 10^{-4}$	[71]
$A_{\Xi\Lambda}$	$\Xi^\mp \to \Lambda\pi$, $\Lambda \to p\pi$	$\lesssim 0.5 \times 10^{-4}$	$\leq 1.9 \times 10^{-3}$	[72]
$A_{\Omega\Lambda}$	$\Omega \to \Lambda K$, $\Lambda \to p\pi$	$\leq 4 \times 10^{-5}$	$\leq 8 \times 10^{-3}$	[47]
$\Delta_{\Xi\pi}$	$\Omega \to \Xi^0\pi$	2×10^{-5}	$\leq 2 \times 10^{-4}$ *	[46]
$\Delta_{\Lambda K}$	$\Omega \to \Lambda K$	$\leq 1 \times 10^{-5}$	$\leq 1 \times 10^{-3}$	[47]

*Once they are taken into account, large final-state interactions may increase this prediction [67].

Λ to Ξ to Ω fewer and fewer valence quarks are in common between the initial and final states. Nevertheless, the estimated cross section for $\overline{\Xi}^+\Xi^-$ somewhat above threshold ($p_{\overline{p}} \approx 3.5\,\mathrm{GeV}/c$) is $\approx 2\,\mu$b [65, 63, 66], or about 1/30 of the corresponding cross section for $\overline{\Lambda}\Lambda$. Thus the $\approx 65\,\mu$b cross section measured for $\overline{p}p \to \overline{\Lambda}\Lambda$ at $p_{\overline{p}} = 1.642\,\mathrm{GeV}/c$ at LEAR [61] implies $\sigma(\overline{p}p \to \overline{\Omega}\Omega) \sim 60\,\mathrm{nb}$ at $5.4\,\mathrm{GeV}/c$.

For purposes of discussion we take 60 nb as a plausible estimate of the exclusive production cross section.[8] At luminosity of $2.0 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, some 1.2×10^8 $\overline{\Omega}\Omega$ events are then produced in a nominal 1-year run (1.0×10^7 s). Assuming acceptance times efficiency of 50% (possibly an overestimate, but comparable to that for χ_c events in E760), and given the various branching ratios [11], we estimate $\overset{(-)}{N}_{\Xi\pi} = 1.4 \times 10^7$ events each in $\Omega^- \to \Xi^0\pi^-$ and $\overline{\Omega}^+ \to \overline{\Xi}^0\pi^+$, and $\overset{(-)}{N}_{\Lambda K} = 4.1 \times 10^7$ events each in $\Omega^- \to \Lambda K^-$ and $\overline{\Omega}^+ \to \overline{\Lambda}K^+$, giving the following statistical sensitivities for partial-rate asymmetries:

$$\begin{aligned} \delta\Delta_{\Xi\pi} &\approx \frac{0.5}{\sqrt{N_{\Xi\pi}}} \approx 1.3 \times 10^{-4}\,, \\ \delta\Delta_{\Lambda K} &\approx \frac{0.5}{\sqrt{N_{\Lambda K}}} \approx 7.8 \times 10^{-5}\,. \end{aligned}$$

Tandean and Valencia [46] have estimated $\Delta_{\Xi\pi} \approx 2 \times 10^{-5}$ in the standard model but possibly an order of magnitude larger with new-physics contributions. Tandean [47] has estimated $\Delta_{\Lambda K}$ to be $\leq 1\times10^{-5}$ in the standard model but possibly as large as 1×10^{-3} if new physics contributes. (The large sensitivity of $\Delta_{\Lambda K}$ to new physics in this analysis arises from chromomagnetic penguin operators and final-state interactions via $\Omega \to \Xi\pi \to \Lambda K$ [47].[9]) It is worth noting that these potentially large asymmetries arise from parity-conserving interactions and hence are limited by constraints from ϵ_K [46, 47]; they are independent of A_Λ and A_Ξ, which arise from the interference of parity-violating and parity-conserving processes [67]. Table 5 summarizes predicted hyperon CP asymmetries.

Of course, the experimental sensitivities will include systematic components whose estimation will require careful and detailed simulation studies, beyond the scope of this Letter of Intent. Nevertheless, the potential power of the technique is apparent: the experiment discussed here may be capable of observing the effects of new physics in Omega CP violation via partial-rate asymmetries, and it will represent a substantial improvement over current sensitivity to Omega angular-distribution asymmetries.

[8] This estimate will be testable in the upgraded MIPP experiment [68].

[9] Large final-state interactions of this sort should also affect $\Delta_{\Xi\pi}$ but were not included in that prediction [46, 67].

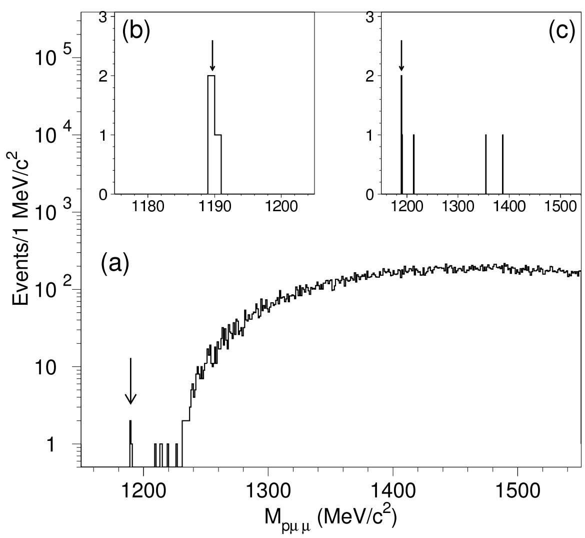

Figure 6: Mass spectrum for 3-track final states consistent with being single-vertex $p\mu^+\mu^-$ events in HyperCP positive-beam data sample: (a) wide mass range (semilog scale); (b) narrow range around Σ^+ mass; (c) after application of additional cuts as described in Ref. [5]. (Arrows indicate mass of Σ^+.)

3.4 Study of FCNC hyperon decays

In addition to its high-rate charged-particle spectrometer, HyperCP had a muon detection system aimed at studying rare decays of hyperons and charged kaons [56, 69, 5]. Among recent HyperCP results is the observation of the rarest hyperon decay ever, $\Sigma^+ \to p\mu^+\mu^-$ [5]. Surprisingly, as shown in Figs. 6 and 7, based on the 3 observed events, the decay is consistent with being two-body, i.e., $\Sigma^+ \to pX^0$, $X^0 \to \mu^+\mu^-$, with X^0 mass $m_{X^0} = 214.3 \pm 0.5\,\mathrm{MeV}/c^2$. At the current level of statistics this interpretation is of course not definitive: the probability that the 3 signal events are consistent with the form-factor decay spectrum of Fig. 7a is estimated at 0.8%. The measured branching ratio is $[3.1 \pm 2.4\,(\mathrm{stat}) \pm 1.5\,(\mathrm{syst})] \times 10^{-8}$ assuming the intermediate $\Sigma^+ \to pX^0$ two-body decay, or $[8.6^{+6.6}_{-5.4}\,(\mathrm{stat}) \pm 5.5\,(\mathrm{syst})] \times 10^{-8}$ assuming three-body Σ^+ decay.

This result is particularly intriguing in view of the proposal by D. S. Gorbunov and co-workers [70] that there should exist in certain nonminimal supersymmetric models a pair of "sgoldstinos" (supersymmetric partners of Goldstone fermions). These can be scalar or pseudoscalar and could be low in mass. A light scalar particle coupling to hadronic matter and to muon pairs at the required level is ruled out by the failure to observe it in kaon decays; however, a pseudoscalar sgoldstino with $\approx 214\,\mathrm{MeV}/c^2$ mass would be consistent with all available data [73, 74, 75]. An alternative possibility has recently been advanced by He, Tandean, and Valencia [76]: the X^0 could be the light pseudoscalar Higgs boson in the next-to-minimal supersymmetric standard model (the A^0_1). Thus, the lightest supersymmetric particle may already have been glimpsed.

While it might be desirable to study Σ^+ and $\overline{\Sigma}^-$ decays using clean, exclusive $\overline{p}p \to \overline{\Sigma}^-\Sigma^+$ events just above threshold, this would require a $\overline{p}$ momentum (see Table 1) well below what has been accomplished in the past by deceleration in the Antiproton Accumulator, as well as very high luminosity to access the $\mathcal{O}(10^{-8})$ branching ratio. An experimentally less challenging but equally interesting objective is the corresponding FCNC decay of the Ω^-,

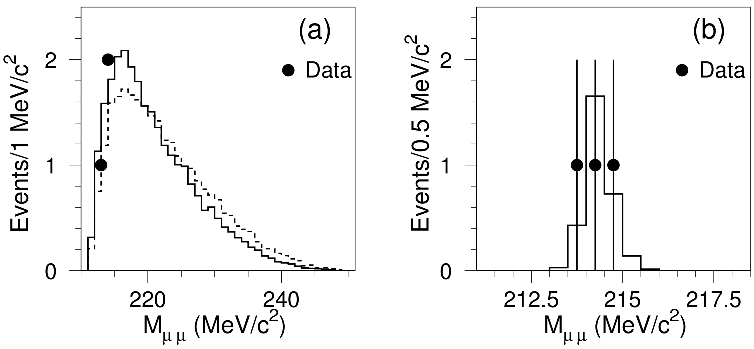

Figure 7: Dimuon mass spectrum of the three HyperCP $\Sigma^+ \to p\mu^+\mu^-$ candidate events compared with Monte Carlo spectrum assuming (a) standard model virtual-photon form factor (solid) or isotropic decay (dashed), or (b) decay via a narrow resonance X^0.

with predicted branching ratio of order 10^{-6} if the X^0 seen in $\Sigma^+ \to p\mu^+\mu^-$ is real [73].[10] (The larger predicted branching ratio reflects the additional phase space available compared to that in $\Sigma^+ \to p\mu^+\mu^-$.) As above, assuming 2×10^{32} luminosity and 50% acceptance times efficiency, 120 or 44 events are predicted in the two cases (pseudoscalar or axial-vector X^0) that appear to be viable [73, 74]:

$$\begin{aligned} \mathcal{B}(\Omega^- \to \Xi^- X_P \to \Xi^- \mu^+\mu^-) &= (2.0^{+1.6}_{-1.2} \pm 1.0) \times 10^{-6}\,, \\ \mathcal{B}(\Omega^- \to \Xi^- X_A \to \Xi^- \mu^+\mu^-) &= (0.73^{+0.56}_{-0.45} \pm 0.35) \times 10^{-6}\,. \end{aligned}$$

Given the large inclusive hyperon rates at $\sqrt{s} \approx 3.5\,\mathrm{GeV}$, sufficient sensitivity might also be available at that setting to confirm the HyperCP $\Sigma^+ \to p\mu^+\mu^-$ results. Alternatively, it is possible that a dedicated run just above $\overline{\Sigma}^-\Sigma^+$ threshold may have competitive sensitivity; evaluating this will require a detailed simulation study.

3.5 Additional physics

Besides the $X(3872)$, the experiment should have competitive capabilities for studying the additional charmonium and charmonium-related states mentioned above. The very large inclusive hyperon samples should enable new and precise measurements of hyperon semileptonic and other rare decays. The APEX experiment vacuum tank and pumping system [78] could be reinstalled, enabling a substantial increase in sensitivity for the antiproton lifetime and decay modes. Some of us are also interested in the possibility of decelerating antiprotons further to carry out trapped-antiproton and antihydrogen experiments [79, 80] (at the end of stores, for example). This capability could make Fermilab the premiere facility for this kind of research, and could attract a new community of physicists, including some now working at CERN's AD. The larger number of antiprotons available at Fermilab could enable additional studies that are not feasible at the AD, such as a measurement of the gravitational force on antimatter [80]. A complementary approach is the study of antihydrogen atoms in flight [81], which may overcome some of the difficulties encountered in the trapping experiments.

The PANDA TPR [3] mentions the possibility of competitive sensitivity for open charm, estimating the rate of D-pair production at about 100/s for $\sqrt{s}$ near the $\psi(4040)$. This could

[10] The standard-model prediction is $\mathcal{B}(\Omega^- \to \Xi^-\mu^+\mu^-) = 6.6 \times 10^{-8}$ [77].

lead to a sample of $\sim 10^9$ events/year produced and $\sim 10^8$/year reconstructed, roughly an order of magnitude beyond the statistics accumulated by the B Factories so far. Whether this sensitivity can be realized in practice will depend on details of trigger and analysis efficiency whose estimation will require detailed simulation studies. Nevertheless, there does appear to be the potential for competitive measurements, e.g., of D^0 mixing and possible CP violation in charm decay.

The bottomonium system has not benefited from $\overline{p}p$ formation studies but is potentially accessible if the Antiproton Accumulator (or perhaps a new replacement storage ring) can be configured for colliding beams. The $\overline{p}p$ widths of bottomonium states are unknown. If they can be shown to be sufficiently large, $\overline{p}p$ formation could lead to the discovery of bottomonium singlet states, which have so far eluded observation, as well as precise measurements of the many states already observed.

4 A New Experiment

We see two plausible approaches for implementing (at relatively small expense) apparatus capable of performing the measurements discussed above: one (the "E835′" option) based on existing equipment from E835, and the other ("DØ solenoid" option) based on the DØ superconducting solenoid, which in principle will become available once the Tevatron Collider program ends.

4.1 "E835′" option

Our starting point in this approach is the E835 detector (Fig. 8). We understand that many of the components of this detector have been stored intact since E835 was decommissioned, thus they can be reassembled at relatively small effort and cost. This would suffice for many of the charmonium and related-state studies discussed above.

E760 and E835 relied for triggering on electromagnetic-energy deposition to suppress the high interaction rate (10^7 Hz) of minimum-bias $\overline{p}p \to n$ pions events ($< n > \approx 5$), and on Cherenkov detection and electromagnetic calorimetry to suppress backgrounds in offline analysis. While ideal for charmonium studies, this approach is not workable for hyperon triggering and reconstruction. We are therefore exploring the performance of the E835 detector with the innermost detectors replaced with a small magnetic microvertex spectrometer. This could be (for example) a superconducting solenoid or dipole enclosing silicon pixel detectors such as developed for BTeV [82]. As in BTeV, triggering would then be based on separated decay vertices [83]. Compared to BTeV, the $\overline{p}p$ experiment has a low charged-particle rate (a few $\times 10^7$ Hz), a much more localized interaction region, and large track impact parameters. Thus a much more modest and less costly installation than envisioned for BTeV should suffice, along with a reduced version of the BTeV data-acquisition (DAQ) system.[11]

A likely run plan would be to start in the E835 configuration and spend about a year on charmonium studies, then change over to hyperon mode. It would be desirable to design for a relatively simple and easy changeover so that one could change back later if desired with minimal loss of running time.

[11] Like the experiment we consider here, BTeV was designed to operate at a luminosity of 2×10^{32} cm^{-2}s^{-1}. The cross section at $\sqrt{s} = 3.5$ GeV is only $\approx 20\%$ less than that at 2 TeV, but the mean charged multiplicity is smaller by a factor ≈ 20 [11].

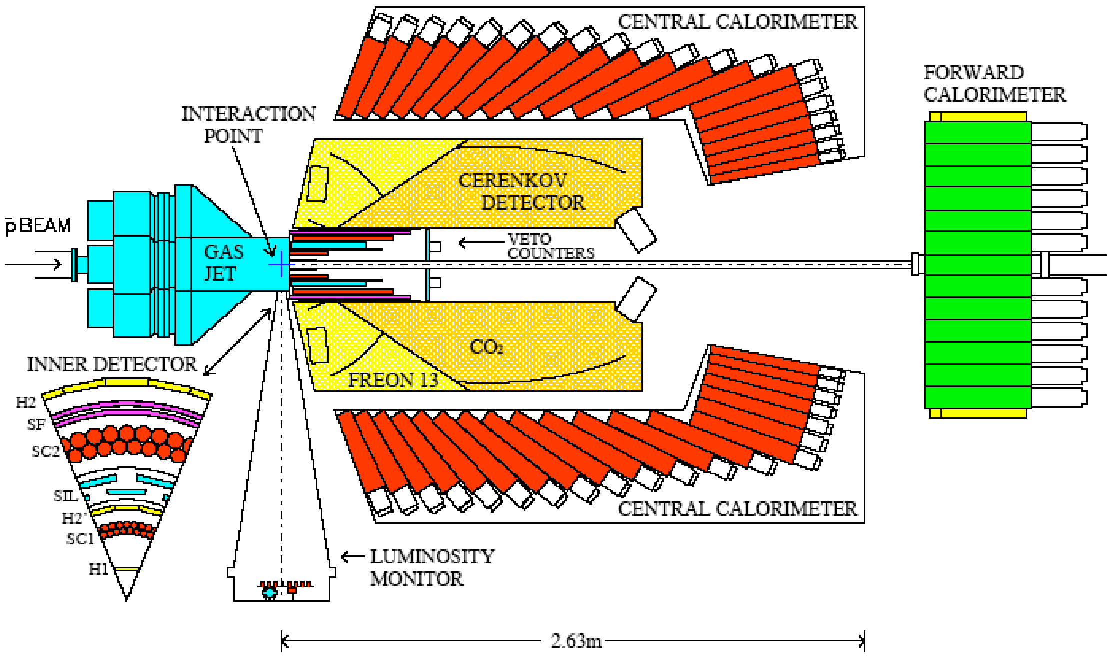

Figure 8: E835 apparatus layout (from [12]).

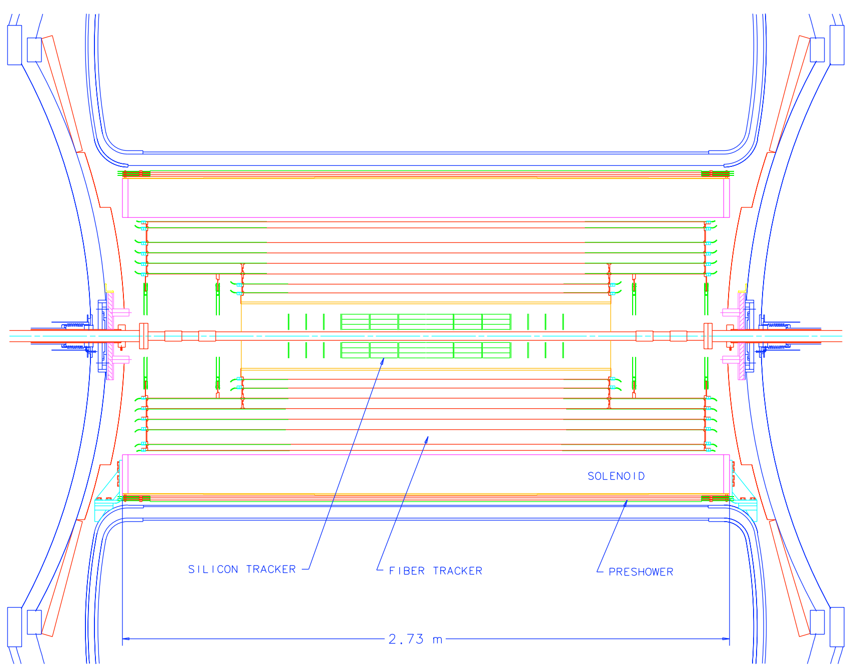

Figure 9: The DØ solenoid and central tracking system, drawn to the same scale as Fig. 8, shown as currently installed within the DØ calorimeters (from [84]).

4.2 "DØ solenoid" option

While the E835′ option may well be the minimum-cost solution, it does have certain drawbacks, e.g., the incompatibility of the charmonium and hyperon running modes. An apparatus that could take data in both modes simultaneously could be designed based on the DØ solenoid (Fig. 9). The smallest of the superconducting solenoids built for recent HEP experiments [11], it fits nicely in the existing experimental area. Depending on what mounting infrastructure is required, the DØ solenoid appears small enough in diameter to be installed on the main floor of the Antiproton Source. The E760/835 pit would then permit the addition of muon detectors surrounding the solenoid. To avoid degrading the performance of the electromagnetic calorimeter which is so critical to the charmonium event trigger and offline analysis, the calorimeter would need to fit within the solenoid, ruling out use of the existing E760/835 lead glass. A suitable calorimeter could be built using lead tungstate, barium fluoride, or cesium iodide.

The exclusive $\overline{\Omega}\Omega$ running mode requires a $\sqrt{s}$ setting that happens not to coincide with that of any charmonium (or charmonium-related) state of interest. However, there will be copious inclusive hyperon production in any of the charmonium running modes. Thus the ability to trigger on and reconstruct hyperon events during charmonium running may prove valuable. Another possibility worth exploring is that of reconstructing the $X(3872) \to D^0\overline{D}^{*0}$ decay.

4.3 New-apparatus option

Should sufficient resources become available, a new spectrometer, free of constraints from existing apparatus, may give better performance than either option just described. The size constraints of the existing pit might also be thereby relaxed. The possibility of building a new storage ring has also been mentioned. These are all options deserving more detailed consideration than has been carried out to date. (A potential drawback of a highly ambitious plan is losing our lead over the GSI project.)

5 Our Request

We request from Fermilab the modest support needed to study the proposed experiment in greater detail and develop a proposal. A few physicist-FTE's should be sufficient to permit timely progress to be made.

References

[1] T. Eriksson, in *Proc. LEAP05 Conf.*, AIP Conf Proc. **796**, 389 (2005).

[2] See `http://www.gsi.de/fair/index_e.html`

[3] M. Kotulla *et al.* [Panda Collaboration], *Technical Progress Report for: Panda*, U. Wiedner, Spokesperson, available from `http://www-panda.gsi.de/archive/public/panda_tpr.pdf`

[4] E. Eichten. K, Lane, and C. Quigg, Phys. Rev. D **73**, 014014 (2006); Erratum-*ibid.* D **73**, 079903 (2006).

[5] H. K. Park *et al.* [HyperCP Collaboration], Phys. Rev. Lett. **94**, 021801 (2005).

[6] G. Garzoglio *et al.* [E835 Collaboration], Nucl. Instrum. Meth. A **519**, 558 (2004).

[7] T. A. Armstrong *et al.* [E835 Collaboration], Phys. Rev. D **47**, 772 (1993).

[8] M. Okamoto *et al.*, Phys. Rev. D **65**, 094508 (2002).

[9] P. Chen, Phys. Rev. D **64**, 034509 (2001); X. Liao and T. Manke, arXiv:hep-lat/0210030.

[10] S. Choe *et al.* [QCD-TARO Collaboration], JHEP **0308**, 022 (2003).

[11] W.-M. Yao *et al.* [Particle Data Group], J. Phys. G **33**, 1 (2006).

[12] See `http://www.e835.to.infn.it/`

[13] K. Ehret, Nucl. Instr. Meth. A **446**, (2000) 190.

[14] S. K. Choi *et al.* [Belle Collaboration], Phys. Rev. Lett. **91**, 262001 (2003).

[15] C. T. H. Davies *et al.* [HPQCD and UKQCD Collaborations], *Proc. XXIVth Int. Symp. on Lattice Field Theory*, paper 82 (2006), available from `http://pos.sissa.it//archive/conferences/032/082/LAT2006_082.pdf`

[16] D. Acosta *et al.* [CDF II Collaboration], Phys. Rev. Lett. **93**, 072001 (2004).

[17] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **93**, 162002 (2004).

[18] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **71**, 071103 (2005).

[19] K. Abe *et al.*, "Evidence for $X(3872) \to \gamma J/\psi$ and the sub-threshold decay $X(3872) \to \omega J/\psi$," arXiv:hep-ex/0505037.

[20] K. Abe *et al.* [Belle Collaboration], arXiv: hep-ex/0408116.

[21] G. Gokhroo *et al.* [Belle Collaboration], Phys. Rev. Lett. **97**, 162002 (2006).

[22] N. Brambilla *et al.* [Quarkonium Working Group], *Heavy Quarkonium Physics*, CERN Yellow Report CERN-2005-005 (2005).

[23] K. Abe *et al.*, "Experimental constraints on the possible J^{PC} quantum numbers of the $X(3872)$," contributed to *22nd International Symposium on Lepton-Photon Interactions at High Energy (LP 2005)*, Uppsala, Sweden, 30 June – 5 July 2005, arXiv:hep-ex/0505038.

[24] E. Braaten, "Review of the $X(3872)$," presented at the *Int. Workshop on Heavy Quarkonium – 2006*, Brookhaven National Laboratory, June 27–30, 2006; available from
`http://www.qwg.to.infn.it/WS-jun06/WS4talks/Tuesday_AM/Braaten.pdf`

[25] D. V. Bugg, Phys. Lett. B **598**, 8 (2004); Phys. Rev. D **71**, 016006 (2005).

[26] L. Maiani, F. Piccinini, A. D. Polosa, and V. Riquer, Phys. Rev. D **71**, 014028 (2005); L. Maiani, V. Riquer, F. Piccinini and A. D. Polosa, Phys. Rev. D **72**, 031502 (2005); H. Hogaasen, J. M. Richard and P. Sorba, Phys. Rev. D **73**, 54013 (2006).

[27] N. A. Tørnqvist, Phys. Lett. B **590**, 209 (2004).

[28] C. Cawlfield *et al.*, Phys. Rev. Lett. **98**, 092002 (2007).

[29] J. Rosner, private communication.

[30] T. Barnes, S. Godfrey, Phys. Rev. D **69**, 054008 (2004).

[31] J. Rosner, Phys. Rev. D **74**, 076006 (2006).

[32] A. Vairo, "Heavy Hadron Spectroscopy," submitted to *Proc. XXXIII International Conference on High Energy Physics (ICHEP 06)*, Moscow, Russia, July 26 – August 2, 2006, arXiv:hep-ph/0611310.

[33] E. Braaten, Phys. Rev. D **73**, 011501(R) (2006); E. Braaten, private communication.

[34] T. A. Armstrong *et al.* [E760 Collaboration], Nucl. Phys. B **373**, 35 (1992).

[35] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **96**, 052002 (2006).

[36] See `http://belle.kek.jp/superb/`.

[37] C. Baglin *et al.* [R704 Collaboration], Phys. Lett. B **171**, 135 (1986).

[38] R. Cester and P. A. Rapidis, Ann. Rev. Nucl. Part. Sci. **44**, 329 (1994).

[39] T. Armstrong *et al.* [E760 Collaboration], Phys. Rev. Lett. **69**, 2337 (1992).

[40] M. Andreotti *et al.* [E835 Collaboration], Phys. Rev. D **72**, 032001 (2005).

[41] J. L. Rosner *et al.* [CLEO Collaboration], Phys. Rev. Lett. **95**, 102003 (2005).

[42] E. Eichten *et al.*, Phys. Rev. D **17**, 3090 (1978), and references therein; D. B. Lichtenberg and R. Potting, Phys. Rev. D **46**, 2150 (1992), and references therein.

[43] A. Pais, Phys. Rev. Lett. **3**, 242 (1959); O. E. Overseth and S. Pakvasa, Phys. Rev. **184**, 1663 (1969); J. F. Donoghue and S. Pakvasa, Phys. Rev. Lett. **55**, 162 (1985).

[44] J. F. Donoghue, X.-G. He, S. Pakvasa, Phys. Rev. D **34**, 833 (1986); X.-G. He, H. Steger, G. Valencia, Phys. Lett. B **272**, 411 (1991).

[45] G. Valencia, "Hyperon CP Violation," in *Proc. $\overline{p}$2000 Workshop*, D. M. Kaplan and H. A. Rubin, eds., Illinois Institute of Technology, Chicago, IL 60616, USA, Aug. 3–5, 2000; available from
`http://www.capp.iit.edu/~capp/workshops/pbar2000/pbar2000_program.html`

[46] J. Tandean, G. Valencia, Phys. Lett. B **451**, 382 (1999).

[47] J. Tandean, Phys. Rev. D **70**, 076005 (2004).

[48] T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1761 (1957).

[49] J. F. Donoghue, B. R. Holstein, and G. Valencia, Phys. Lett. **178B**, 319 (1986) and Int. J. Mod. Phys. A **2**, 319 (1987).

[50] P. Chauvat *et al.*, Phys. Lett. **163B**, 273 (1985).

[51] M. H. Tixier *et al.*, Phys. Lett. B **212**, 523 (1988).

[52] P. D. Barnes *et al.*, Nucl. Phys. B (Proc. Suppl.) **56A**, 46 (1997).

[53] K. B. Luk *et al.*, Phys. Rev. Lett. **85**, 4860 (2000).

[54] D. E. Jaffe *et al.*, "Search for Direct CP Violation in Ξ Hyperon Decay," CLNS 98/1587, CLEO 98-16 (2000) (unpublished).

[55] T. Holmstrom *et al.* [HyperCP Collaboration], Phys. Rev. Lett. **93**, 262001 (2004); this analysis represents about 5% of the total HyperCP data sample.

[56] R. A. Burnstein *et al.*, Nucl. Instrum. Meth. A **541**, 516 (2005).

[57] X.-G. He *et al.*, Phys. Rev. D **61**, 071701 (2000).

[58] L. C. Lu *et al.* [HyperCP Collaboration], Phys. Rev. Lett. **96**, 242001 (2006).

[59] Y. C. Chen *et al.* [HyperCP Collaboration], Phys. Rev. D **71**, 051102 (2005).

[60] L. Lu *et al.* [HyperCP Collaboration], Phys. Lett. B **617**, 11 (2005).

[61] T. Johansson, in *Proc. Eighth Int. Conf. on Low Energy Antiproton Physics (LEAP '05)*, Bonn, Germany, 16–22 May 2005, AIP Conf. Proc. **796**, 95 (2005).

[62] C. Y. Chien *et al.*, Phys. Rev. **152**, 1181 (1066).

[63] C. Baltay *et al.*, Phys. Rev. **140**, B1027 (1965).

[64] Markward Britsch, "Hyperon Production in Proton–Nucleus Collisions at 42-GeV Center of Mass Energy," diploma thesis, Max-Planck-Institute for Nuclear Physics, Heidelberg (2003).

[65] N. Hamann *et al.*, report CERN/SPSLC 92019, SPSLC/M491, 30 March 1992.

[66] High-Energy Reactions Analysis Group, report CERN-HERA-84-01 (1984).

[67] J. Tandean, private communication.

[68] D. Isenhower *et al.*, Fermilab Proposal 960, available from
`http://ppd.fnal.gov/experiments/e907/notes/MIPPnotes/public/pdf/MIPP0138/MIPP0138.pdf`

[69] H. K. Park *et al.* [HyperCP Collaboration], Phys. Rev. Lett. **88**, 111801 (2002).

[70] D. S. Gorbunov and V. A. Rubakov, Phys. Rev. D **64**, 054008 (2001);
D. S. Gorbunov, Nucl. Phys. B **602**, 213 (2001).

[71] D. Chang, X.-G. He, and S. Pakvasa, Phys. Rev. Lett. **74**, 3927 (1995).

[72] X.-G. He, H. Murayama, S. Pakvasa, G. Valencia, Phys. Rev. D **618**, 071701(R) (2000).

[73] X.-G. He, J. Tandean, G. Valencia, Phys. Lett. B **631**, 100 (2005).

[74] N. G. Deshpande, G. Eilam, J. Jiang, Phys. Lett. B **632**, 212 (2006).

[75] C. Q. Geng and Y. K. Hsiao, Phys. Lett. B **632**, 215 (2006);
D. S. Gorbunov and V. A. Rubakov, Phys. Rev. D **73**, 035002 (2006).

[76] X.-G. He, J. Tandean, G. Valencia, Phys. Rev. Lett. **98**, 081802 (2007).

[77] R. Safadi and P. Singer, Phys. Rev. D **37**, 697 (1988) [erratum *ibid.* D **42**, 1856 (1990)].

[78] S. Geer *et al.*, Phys. Rev. D **62**, 052004 (2000);
T. Armstrong *et al.*, Nucl. Instrum. Meth. A **411**, 210 (1998).

[79] M. H. Holzscheiter, "Physics with Ultra-Low Energy Antiprotons," in *Proc. $\overline{p}$2000 Workshop*, *op cit.*, p. 91; available from
`http://www.capp.iit.edu/~capp/workshops/pbar2000/pbar2000_program.html`

[80] T. J. Phillips, "An Antihydrogen Interferometer for Measuring Antimatter Gravity," in *Proc. $\overline{p}$2000 Workshop*, *op cit.*, p. 109; available from
`http://www.capp.iit.edu/~capp/workshops/pbar2000/pbar2000_program.html`

[81] G. Blanford *et al.*, Phys. Rev. D **57**, 6649 (1998);
G. Blanford *et al.*, Phys. Rev. Lett. **80**, 3037 (1998).

[82] M. A. Turqueti *et al.*, "Pixel Multichip Module Development at Fermilab," in *Proc. 11th Workshop on Electronics for LHC and Future Experiments*, CERN-2005-011, CERN-LHCC-2005-028, p. 205, available from
`http://indico.cern.ch/materialDisplay.py?contribId=73&sessionId=56&materialId=paper&confId=0510` (and references therein);
L. Uplegger *et al.*, "First Look at the Beam Test Results of the FPIX2 Readout Chip for the BTeV Silicon Pixel Detector," IEEE Trans. Nucl. Sci. **53**, 409 (2006).

[83] E. E. Gottschalk (for the BTeV collaboration), in *Proc. 10th Int. Conf. on B Physics at Hadron Machines (BEAUTY 2005)*, Assisi, Perugia, Italy, 20–24 June 2005, Nucl. Phys. Proc. Suppl. **156**, 252 (2006) (and references therein).

[84] See `http://www-d0.fnal.gov/public/detector/pictures.html`