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P-986 Letter of Intent:
Medium-Energy Antiproton Physics at Fermilab

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Abstract

Fermilab has long had the world's most intense antiproton source. Despite this, the opportunities for 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 shutdown of the Tevatron in 2010 presents the opportunity for a world-leading medium-energy antiproton program. We summarize the current status of the Fermilab antiproton facility and review some physics topics for which the experiment we propose could make the world's best measurements. Among these, the ones with the clearest potential for high impact and visibility are in the area of charm mixing and *CP* violation.

Continued running of the Antiproton Source following the shutdown of the Tevatron is thus one of the simplest ways that Fermilab can restore a degree of breadth to its future research program. The impact on the rest of the program will be minor. We request a small amount of effort over the coming months in order to assess these issues in more detail.

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1 Motivation

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].

A number of intriguing recent discoveries can be elucidated at a medium-energy antiproton facility, foremost among which is charm mixing [3]. The key question is whether there is new physics in charm mixing; the signature for this is CP violation [4]. The search for new physics in B and K mixing and decay has so far come up empty. Thus it behooves us to look elsewhere as well. As pointed out by many authors, charm is an excellent venue for such investigation: It is the only up-type quark in which such effects are possible, and standard-model backgrounds to new physics in charm are suppressed by small CKM-matrix elements and the fact that the b quark is the most massive one participating in loop diagrams [5]. We argue below that a charm experiment at the Fermilab Antiproton Source can be the world's most sensitive.

Other topics of interest include such states as the $X(3872)$ in the charmonium region [6], observed by several groups, as well as the investigation of possible new-physics signals observed in the HyperCP experiment at Femilab: evidence for CP violation [7] and flavor-changing neutral currents in hyperon decay [8]. 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 [9, 10]. Table 1 lists energy and momentum thresholds for various processes that could be studied.

Charmed particles can be pair-produced in $\overline{p}p$ or $\overline{p}N$ collisions at and above the $\psi(3770)$ resonance. There is an enormous cross-section advantage relative to e^+e^- colliders: charm hadroproduction cross sections are typically $\mathcal{O}(10\,\mu\text{b})$, while e^+e^- cross sections are $\mathcal{O}(1\,\text{nb})$. Against this must be weighed the e^+e^- luminosity advantage, typically $\mathcal{O}(10^2)$. Charm hadroproduction at high energies comes with the advantage of longer decay distances, but the countervailing disadvantage of higher multiplicity ($\langle n_{ch}\rangle \sim 10$) in the underlying event. We expect that the low charged-particle multiplicity ($\langle n_{ch}\rangle \approx 2$) in $\overline{p}p$ collisions somewhat above open-charm threshold will enable charm samples with cleanliness comparable to that at the B factories, with the application of only modest cuts, and hence, high efficiency. The competition for this program is a possible "super-B factory." (See Sec. 3.1 below for further discussion.)

Fermilab Antiproton Accumulator experiments E760 and E835 made the world's most precise measurements of charmonium masses and widths [9, 10, 11]. The achieved precision ($\lesssim 100$ keV) was made possible by the extraordinarily narrow energy spread of the stochas-

[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.

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

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

tically cooled antiproton beam and the absence of Fermi motion and negligible energy loss in the hydrogen cluster-jet 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.

The E835 apparatus did not include a magnet, thus various cross sections needed to assess the performance of a new experiment remain unmeasured. However, they can be estimated with some degree of confidence. We propose to assemble, quickly and at modest cost, an "upgraded E835" spectrometer that includes a magnet. If these cross sections are of the expected magnitude, it should be possible with this apparatus to make the world's best measurements of charm mixing and CP violation, as well as of the other effects mentioned above. (If desired, a follow-on experiment could then be designed for even greater sensitivity, taking full advantage of the capabilities of the Fermilab Antiproton Source.)

The PANDA experiment [12] at the Facility for Antiproton and Ion Research (FAIR) could measure these cross sections after PANDA and the FAIR facility at GSI are built. FAIR and PANDA have yet to start construction, and PANDA turn-on is scheduled for 2016. The yearly antiproton production goal of FAIR for the PANDA experiment is an order of magnitude less than what the Antiproton Source currently provides for the Tevatron program. It is likely that with some ingenuity and creativity, such a program is feasible at the world's best antiproton source despite current constraints at Fermilab.

2 Capabilities of the Fermilab Antiproton Source

The Antiproton Source now cools and accumulates antiprotons at a stacking rate of ≈ 20 mA/hr, making it the world's most intense operating or proposed facility (Table 2). 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 $5 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with antiproton stacking $\approx 50\%$ of the time and collisions during the remaining $\approx 50\%$. However, we anticipate operating at $\lesssim 2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, 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 $2 \times 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [9], it requires more intense stores than in E835, higher target density, or both of these. While

Table 2: Antiproton intensities at existing and future facilities.

Facility	Stacking: Rate (10^{10}/hr)	Stacking: Duty Factor	Clock Hours /Yr	$\overline{p}$/Yr (10^{13})
CERN AD			3800	0.4
FNAL (Accumulator)	20	15%	5550	17
FNAL (New Ring)	20	90%	5550	100
GSI FAIR	3.5	90%	2780	9

the optimal choice is a matter for further study, it is already clear that the desired luminosity can be achieved, for example using the typical E835 store intensity along with a ten-times denser target (a denser gas jet or a hydrogen-pellet target [12], or a wire target in the beam halo [13]). Since the optimal target material and configuration depend on the physics topic to be studied, we are planning for multiple target options. Ideally these should be designed to be easily interchangeable between runs.

3 Physics Goals

Our main physics goal is charm mixing. To indicate the range of important questions that can all be addressed by a common apparatus, we also discuss a few other physics examples: studying the mysterious $X(3872)$ state, searching for hyperon *CP* violation, and studying a recently discovered rare hyperon-decay mode that may be evidence for new physics.

3.1 Charm Mixing and *CP* Violation

After a more than 20-year search, D^0–$\overline{D}^0$ mixing is now established at 9.8 standard deviations [3], thanks mainly to the B factories. The level of mixing is consistent with the wide range of standard model (SM) predictions [4]; however, this does not preclude a significant and potentially detectable contribution from new physics [14]. Since new physics can affect the charge-2/3 ("up-type") quark sector differently than the down-type, it is important [15] to carry out such charm-meson studies — the only up-type system for which meson mixing can occur.

Particle physics faces two key mysteries: the origin of mass and the existence of multiple fermion generations. While the former may be resolved by the LHC, the latter appears to originate at higher mass scales, which can only be studied indirectly. Such effects as *CP* violation, mixing, and flavor-changing neutral or lepton-number-violating currents may hold the key to physics at these new scales [15, 16, 17, 18]. Because in the charm sector the SM contributions to these effects are small, these are areas in which charm studies can provide unique information. In contrast, in the s- and b-quark sectors in which such studies are typically pursued, with the exception of certain rare and difficult-to-study modes, there are large SM contributions to mixing and *CP* violation [19, 20]. For new-physics searches, these constitute backgrounds.

Both direct and indirect *CP* violation are possible in charm decay. The standard model predicts direct *CP* violation only in singly Cabibbo-suppressed (SCS) charm decays, at the $\mathcal{O}(10^{-3})$ level [21], arising from interference between tree-level and loop processes (Fig. 1). The observation of larger *CP* asymmetries than this would be unambiguous evidence for new physics; so too would nonzero *CP* asymmetries in almost *any* Cabibbo-favored (CF) or dou-

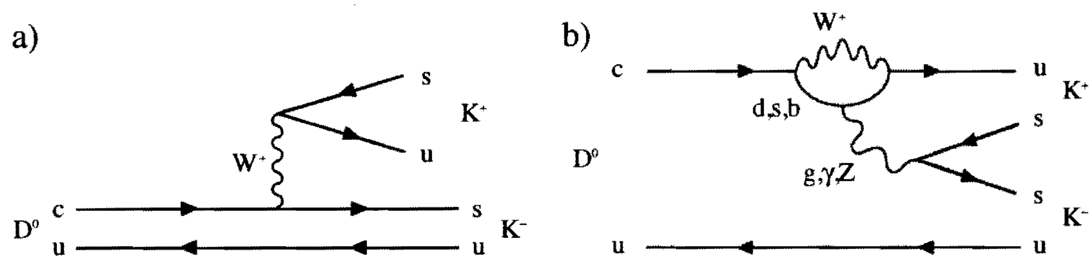

Figure 1: Example of singly Cabibbo-suppressed D^0 decay that can proceed through both a) tree and b) penguin diagrams.

bly Cabibbo-suppressed (DCS) charm decays, for which interfering SM penguin diagrams are absent.[3]

The experimental signature for direct *CP* violation is a difference in partial decay rates between particle and antiparticle:

$$A \equiv \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \bar{f})} \neq 0\,, \tag{1}$$

where f and $\bar{f}$ are *CP*-conjugate final states. For *CP*-eigenstate final states, $f = \bar{f}$, the two processes of Eq. 1 are distinguished by initial-state tagging (e.g., $D^{*\pm} \to \overset{(-)}{D}{}^0\pi^\pm$), while for $f \neq \bar{f}$, the final states are self-tagging. (Any production or efficiency asymmetries between particle and antiparticle can be normalized using a CF mode.)

3.2 Charm Sensitivity Estimate

The $\bar{p}p$ annihilation cross section to open charm is expected to be substantial; for example, a recent estimate (expected good to a factor of 3 [22]) based on $K^*\overline{K}$ measurements gives $\sigma(\bar{p}p \to D^{*0}\overline{D}^0) \approx 1.3\,\mu\text{b}$ at $\sqrt{s} = 4.2\,\text{GeV}$ [23] (Fig. 2). At $\mathcal{L} = 2 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$, this represents some 5×10^9 events per year, substantially exceeding each year the *total sample* ($\approx 10^9$ events) available at the B factories. Since there will also be $D^{*\pm}D^{\mp}$, $D^*\overline{D}^*$, and $D\overline{D}$ events, the total charm sample will be even larger;[4] with the use of a target nucleus heavier than hydrogen, the charm-production A-dependence [26] could further enhance statistics by a factor of a few, resulting in *reconstructed* event samples of $\mathcal{O}(10^9)$/year. Such a target could also localize primary interactions to an $\mathcal{O}(\mu\text{m})$-sized region, allowing the D-meson decay distance to be cleanly determined, as required both for background suppression and for time-dependent mixing and *CP*-violation studies.

Initial simulations show that ≈50% acceptance can be achieved for $\bar{p}p \to D^*\overline{D}$ events, with the D's decaying to typical low-multiplicity final states. Further simulation studies are in progress. Evaluation of backgrounds requires either a reliable model for minimum-bias interactions or actual $\bar{p}p$ data at the appropriate energy. Extrapolations based on MIPP data at somewhat higher energies are underway. Results from these studies will be reported as they become available.

[3]The exception is SM asymmetries of $\approx 3.3 \times 10^{-3}$ ($= 2\,\text{Re}(\epsilon_K)$) due to K^0 mixing in such modes as $D^+ \to K_S\pi^+$ and $K_S\ell\nu$ [24].

[4]While one might naively expect these states to be populated according to spin statistics [22], this is not the case for $K^*\overline{K}$ and $K^*\overline{K}^*$ production, which are comparable [25].

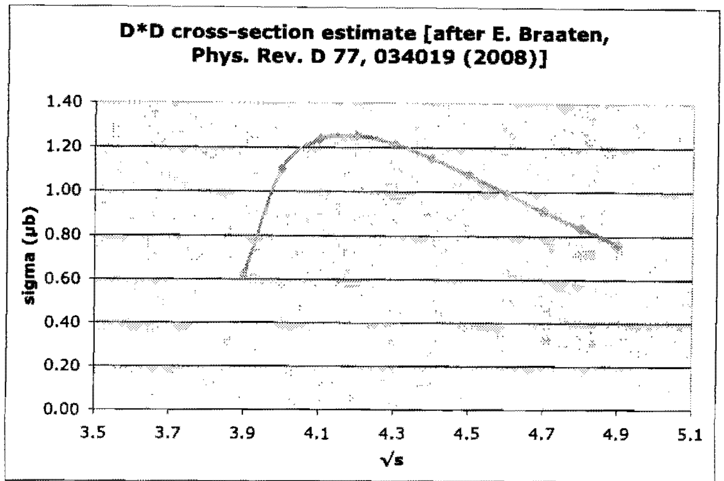

Figure 2: Estimated cross section for $\overline{p}p \to D^{*0}\overline{D}^0$ (based on Ref. [23]).

Medium-energy $\overline{p}N$ annihilation may thus be the optimal way to study charm mixing and search for possible new-physics contributions via the clean signature [27] of charm CP violation (CPV). The Fermilab Antiproton Source, with 8 GeV design kinetic energy (maximum $\sqrt{s} = 4.3\,\text{GeV}$), is ideally suited for this purpose. With an effective $\mathcal{O}(10\,\mu\text{b})$ total charm cross section, with much lower background-event multiplicities than at high energy, and with a possibly higher tagging efficiency than at the B factories, the Fermilab Antiproton Source may well be a gold mine for new-physics searches and studies. Can Fermilab (and US HEP) afford to pass this up?

3.3 $X(3872)$

The $X(3872)$ was discovered in 2003 by the Belle Collaboration [29] 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 [30], DØ [31], and BaBar [32]. It has now been seen in the $\gamma J/\psi$ [33], $\gamma\psi'$ [34], $\pi^+\pi^-\pi^0 J/\psi$ [35], and $D^0\overline{D}^0\pi^0$ [36] 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 $< 2.3\,\text{MeV}$ at 90% C.L. [28], implying that decays to $D\overline{D}$ are forbidden and suggesting unnatural parity, $P = (-1)^{J+1}$ [37]. It is a poor candidate for the $\psi_2\,(1\,^3D_2)$ or $\psi_3\,(1\,^3D_3)$ charmonium levels [6, 35, 37] 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 $J^{PC} = 1^{++}$ [38, 39]. With those quantum numbers, the only available charmonium assignment is $\chi'_{c1}\,(2\,^3P_1)$; however, this is highly disfavored [6, 37] 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 [6] that the $2\,^3P_1$ should lie some $49\,\text{MeV}/c^2$ higher in mass than the observed $m_X = 3872.2 \pm 0.8\,\text{MeV}/c^2$ [28].

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 [40] or a tetraquark state [41]. Perhaps the most intriguing possibility is that the $X(3872)$ represents the first clear-cut observation of a meson-antimeson molecule: specifically, a bound state of

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

Experiment	Year	Mode	Events	Ref.
Belle, BaBar	2003, 2004	$\pi^+\pi^- J/\psi$	35.7 ± 6.8, 25.4 ± 8.7	[29, 32]
CDF, DØ	2004	$\pi^+\pi^- J/\psi$	730 ± 90, 522 ± 100	[30, 31]
Belle	2004	$\omega(\pi^+\pi^-\pi^0)J/\psi$	10.6 ± 3.6	[35]
Belle	2005	$\gamma J/\psi$	13.6 ± 4.4	[33]
Belle	2006	$D^0\overline{D}^{*0}$	23.4 ± 5.6	[36]
BaBar	2008	$\gamma\psi'$		[34]

$D^0\overline{D}^{*0} + D^{*0}\overline{D}^0$ [42].[5] 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 [39]:

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

A direct and precise measurement of the width, which $\overline{p}p$ can provide [9, 10, 11], is also highly desirable.

With the current world-average values [28] $m_{D^0} = 1864.84 \pm 0.17\,\text{MeV}/c^2$ and $m_{D^{*0}} - m_{D^0} = 142.12 \pm 0.07\,\text{MeV}/c^2$, we have $E_X = -0.4 \pm 0.8\,\text{MeV}/c^2$. 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 ($\lesssim 100\,\text{keV}/c^2$) measurements of m_X, and directly measure Γ_X to a similar precision, by scanning across the resonance. Additional important measurements include $\mathcal{B}[X(3872) \to \pi^0\pi^0 J/\psi]$ to confirm the C-parity assignment [43].

3.3.1 $X(3872)$ sensitivity estimate

The production cross section of $X(3872)$ in $\overline{p}p$ annihilation has not been measured, but it has been estimated to be similar in magnitude to that of the χ_c states [44, 23]. In E760, the χ_{c1} and χ_{c2} were detected in $\chi_c \to \gamma J/\psi$ (branching ratios of 36% and 20%, respectively [28]) with acceptance times efficiency of $44 \pm 2\%$, giving about 500 observed events each for an integrated luminosity of $1\,\text{pb}^{-1}$ taken at each resonance [45]. At $2 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$, the lower limit $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] > 0.042$ at 90% C.L. [46] implies $\gtrsim 8 \times 10^3$ events in that mode per nominal month ($1.0 \times 10^6\,\text{s}$) 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 DØ could amass samples of order 10^4 $X(3872)$ decays, the large backgrounds in the CDF and DØ 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 $\overline{p}p$ formation and observation rates, perhaps by as much as

[5] 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 [6].

[6] The $\overline{p}p \to X(3872)$ sensitivity will be competitive even with that of the proposed SuperKEKB [47] upgrade, should that project go forward.

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 $X(3872)$.

3.4 Hyperon *CP* violation

In addition to the well-known *CP*-violation effects in kaon and B-meson mixing and decay [28], the standard model predicts slight *CP* asymmetries in decays of hyperons [48, 49, 50]. 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 charm and hyperons) as well, in which the signatures of new physics might stand out more sharply. Although both hyperon and kaon decay occur due to unstable s quarks, theoretical analysis has shown that hyperon *CP* asymmetries are in fact complementary to those in K decays in their sensitivity to new physics (see e.g. [50, 51]).

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 [49]; however, partial-rate asymmetries are also expected [52, 53] and (as discussed below) may be detectable. More than one hyperon *CP* asymmetry may be measurable in medium-energy $\bar{p}p$ 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 very 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 [54] 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*-conjugate antihyperon decay or as a particle–antiparticle difference in the partial widths for such decays [49, 55]. For a precision angular-distribution asymmetry measurement, it is necessary to know the relative polarizations of the initial hyperons and antihyperons to high precision.

3.4.1 Angular-distribution asymmetries

Table 4 summarizes the experimental situation. The first three experiments cited studied Λ decay only [56, 57, 58], setting limits on the *CP*-asymmetry parameter [49, 55]

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

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

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, $\alpha_\Lambda = -\overline{\alpha}_\Lambda$.

The need for precision knowledge of the initial-hyperon polarization can be finessed by using 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. This approach has been taken by Fermilab E756 [59] and CLEO [60]. 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

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

By using hyperons produced at 0° (i.e., aligned with the incoming proton beam), an unpolarized Ξ sample is obtained, so that the polarization of the daughter Λ is exactly given by α_Ξ. The power of this technique derives from the relatively large $|\alpha|$ value for the $\Xi^- \to \Lambda\pi^-$ decay ($\alpha_\Xi = -0.458 \pm 0.012$ [28]).

Subsequently to E756, this technique was used in the "HyperCP" experiment (Fermilab E871) [61, 62], which ran during 1996–99 and has published 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.) 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

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

A preliminary result based on the full analysis of the HyperCP 1999 sample, $A_{\Xi\Lambda} = [-6.0 \pm 2.1\,(\mathrm{stat}) \pm 2.1\,(\mathrm{syst})] \times 10^{-4}$, was presented this summer [7] (Table 4). The standard model predicts this asymmetry to be of order 10^{-5} [49, 51] (see Table 5). Thus the HyperCP full-statistics analysis sees an effect substantially in excess of the standard model prediction. Although only at the 2σ level of significance, it is evidence for new sources of CP violation in the baryon sector. (A number of standard model extensions predict effects as large as $\mathcal{O}(10^{-3})$ [63]). 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 [64]. Here, as shown by HyperCP [65, 66], parity is only slightly violated: $\alpha = (1.80 \pm 0.24) \times 10^{-2}$ [28]. Hence the measured magnitude and uncertainty of the asymmetry parameter $A_{\Omega\Lambda}$ (inversely proportional to α as in Eq. 2) are rather large: $[-0.4 \pm 9.1\,(\mathrm{stat}) \pm 8.5\,(\mathrm{syst})] \times 10^{-2}$ [64]. 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 [53].

3.4.2 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 [50]. 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

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	[56]	$pp \to \Lambda X, pp \to \overline{\Lambda} X$	$-0.02 \pm 0.14^*$
DM2	Orsay	1988	[57]	$e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$	$0.01 \pm 0.10^*$
PS185	LEAR	1997	[58]	$\overline{p}p \to \overline{\Lambda}\Lambda$	$0.006 \pm 0.015^*$
CLEO	CESR	2000	[60]	$e^+e^- \to \Xi^- X, \Xi^- \to \Lambda\pi^-$, $e^+e^- \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$-0.057 \pm 0.064 \pm 0.039^\dagger$
E756	FNAL	2000	[59]	$pN \to \Xi^- X, \Xi^- \to \Lambda\pi^-$, $pN \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$0.012 \pm 0.014^\dagger$
HyperCP	FNAL	2004	[61]	$pN \to \Xi^- X, \Xi^- \to \Lambda\pi^-$, $pN \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$(0.0 \pm 6.7) \times 10^{-4\,\dagger,\S}$
HyperCP	FNAL	2006	[64]	$pN \to \Omega^- X, \Omega^- \to \Lambda K^-$, $pN \to \overline{\Omega}^+ X, \overline{\Omega}^+ \to \overline{\Lambda} K^+$	$-0.004 \pm 0.12^\ddagger$
HyperCP	FNAL	2008	[7]	$pN \to \Xi^- X, \Xi^- \to \Lambda\pi^-$, $pN \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$(-6.0 \pm 3.0) \times 10^{-4\,\dagger,\P}$

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

Table 5: Summary of predicted hyperon CP asymmetries.

Asymm.	Mode	SM	Ref.	NP	Ref.
A_Λ	$\Lambda \to p\pi$	$\lesssim 4 \times 10^{-5}$	[51]	$\lesssim 6 \times 10^{-4}$	[67]
$A_{\Xi\Lambda}$	$\Xi^\mp \to \Lambda\pi$, $\Lambda \to p\pi$	$\lesssim 5 \times 10^{-5}$	[51]	$\leq 1.9 \times 10^{-3}$	[68]
$A_{\Omega\Lambda}$	$\Omega \to \Lambda K$, $\Lambda \to p\pi$	$\leq 4 \times 10^{-5}$	[53]	$\leq 8 \times 10^{-3}$	[53]
$\Delta_{\Xi\pi}$	$\Omega \to \Xi^0\pi$	2×10^{-5}	[52]	$\leq 2 \times 10^{-4\,*}$	[52]
$\Delta_{\Lambda K}$	$\Omega \to \Lambda K$	$\leq 1 \times 10^{-5}$	[53]	$\leq 1 \times 10^{-3}$	[53]

*Once they are taken into account, large final-state interactions may increase this prediction [76].

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 [52, 53]. 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 $\mathcal{O}(10^7)$ 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 $4.938 < p_{\overline{p}} < 5.437\,\mathrm{GeV}/c$.

3.4.3 Hyperon sensitivity estimates

There have been a number of measurements of hyperon production by low-energy antiprotons. Johansson *et al.* [69] 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.* [70] report measurements of a variety of hyperon final states performed with the BNL 80-inch liquid-hydrogen bubble chamber in a $6.935\,\mathrm{GeV}/c$ electrostatically separated antiproton beam at the AGS; Baltay *et al.* [71] 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 ± 0.105 mb [70]. The corresponding cross section measured at $3.7\,\mathrm{GeV}/c$ was $720 \pm 30\,\mu$b, and $438 \pm 52\,\mu$b at $3.25\,\mathrm{GeV}/c$ [71]. The inclusive hyperon-production cross section at $5.4\,\mathrm{GeV}/c$ is thus about 1 mb. At $2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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 [62]; 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 [72]. 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 Λ to Ξ to Ω fewer and fewer valence quarks are in common between the initial and final states. Nevertheless, the cross section for $\overline{\Xi}^+\Xi^-$ somewhat above threshold ($p_{\overline{p}} \approx 3.5\,\mathrm{GeV}/c$) is $\approx 2\,\mu$b [73, 71, 74], 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 [69] implies $\sigma(\overline{p}p \to \overline{\Omega}\Omega) \sim 60$ 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

[8] This estimate will be testable in the upgraded MIPP experiment [75].

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 [28], 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 [52] 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 [53] has estimated $\Delta_{\Lambda K}$ to be $\leq 1 \times 10^{-5}$ 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 $\Omega \to \Xi\pi \to \Lambda K$ [53].[9] The sensitivity in $\Delta_{\Xi\pi}$ should thus be similar to that in $\Delta_{\Lambda K}$.) It is worth noting that these potentially large asymmetries arise from parity-conserving interactions and hence are limited by constraints from ϵ_K [52, 53]; they are independent of A_Λ and A_Ξ, which arise from the interference of parity-violating and parity-conserving processes [76]. 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 will represent a substantial improvement over current sensitivity to Omega angular-distribution CP asymmetries, and it may be capable of observing, via partial-rate asymmetries, the effects of new physics in Omega CP violation.

3.5 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 [62, 77, 8]. Among recent HyperCP results is the observation of the rarest hyperon decay ever seen, $\Sigma^+ \to p\mu^+\mu^-$ [8]. Surprisingly, as shown in Figs. 3 and 4, 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 standard model form-factor spectrum of Fig. 4a 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 [78] 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

[9] Large final-state interactions of this sort should also affect $\Delta_{\Xi\pi}$ but were not included in that prediction [52, 76].

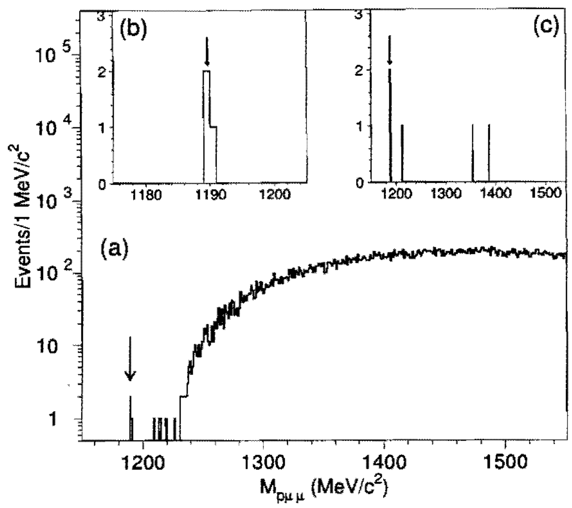

Figure 3: Mass spectrum for 3-track final states consistent with being single-vertex $p\mu^+\mu^-$ events in HyperCP positive-beam data sample: (a) wide mass range (semilog scale); (b) narrow range around Σ^+ mass; (c) after application of additional cuts as described in Ref. [8]. (Arrows indicate mass of Σ^+.)

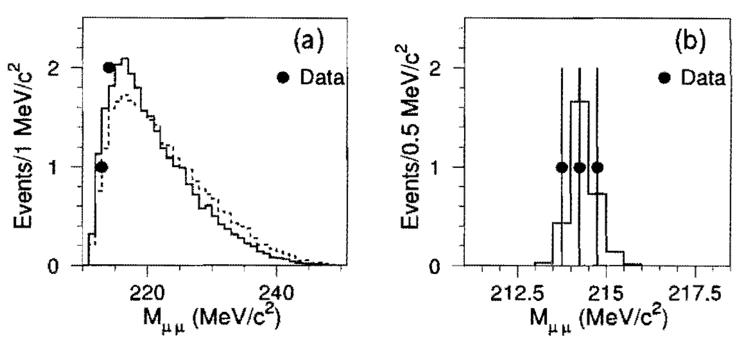

Figure 4: Dimuon mass spectrum of the three HyperCP $\Sigma^+ \rightarrow p\mu^+\mu^-$ candidate events compared with Monte Carlo spectrum assuming (a) standard model virtual-photon form factor (solid) or isotropic decay (dashed), or (b) decay via a narrow resonance X^0.

available data [79, 80, 81]. An alternative possibility has recently been advanced by He, Tandean, and Valencia [82]: the X^0 could be the light pseudoscalar Higgs boson in the next-to-minimal supersymmetric standard model (the A_1^0). 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^-, with predicted branching ratio of order 10^{-6} if the X^0 seen in $\Sigma^+ \to p\mu^+\mu^-$ is real [79].[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 [79, 80]:

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

Given the large inclusive hyperon rates at $\sqrt{s} \approx 3.5$ to 4.3 GeV, sufficient sensitivity might also be available at those energies to confirm the HyperCP $\Sigma^+ \to p\mu^+\mu^-$ results.

4 Apparatus

If the cross-section estimates above had measurements to back them up, the potential of this experiment to make world-leading measurements, including the world's most sensitive searches for new physics in the areas described, would be on more solid ground. We would then be designing a new experiment from scratch, the cost of which would clearly be worthwhile. Instead, what we have are plausibility arguments that the world's best measurements of their kind might be possible at the Antiproton Source. Under these circumstances, we believe that an experiment is still worthwhile, but clearly, given the uncertainties on physics reach, in many respects it will be an exploratory effort, and its cost should therefore be kept modest.

Our starting point is the E835 detector (Fig. 5). 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 (10^6 Hz) of minimum-bias $\overline{p}p \to n\,$pions events ($\langle n \rangle \approx 5$, $\langle n_{ch} \rangle \approx 2$), and on Cherenkov detection and electromagnetic calorimetry to suppress backgrounds in offline analysis. While ideal for charmonium studies, this approach is not workable for charm or hyperon triggering and reconstruction.

We therefore propose to replace the E835 inner detectors with a magnetic spectrometer (see Fig. 6). This would be a small, thin superconducting solenoid enclosing scintillating-fiber tracking detectors and silicon vertex detectors (e.g., of the type developed for BTeV [83]). The cost of superconducting magnets is monitored by LBNL's M. Green and reported in periodic papers at the Applied Superconductivity Workshops [85]. The solenoid we consider should cost in the vicinity of 1 M$. We choose scintillating fibers because the

[10] The standard-model prediction is $\mathcal{B}(\Omega^- \to \Xi^-\mu^+\mu^-) = 6.6 \times 10^{-8}$ [84].

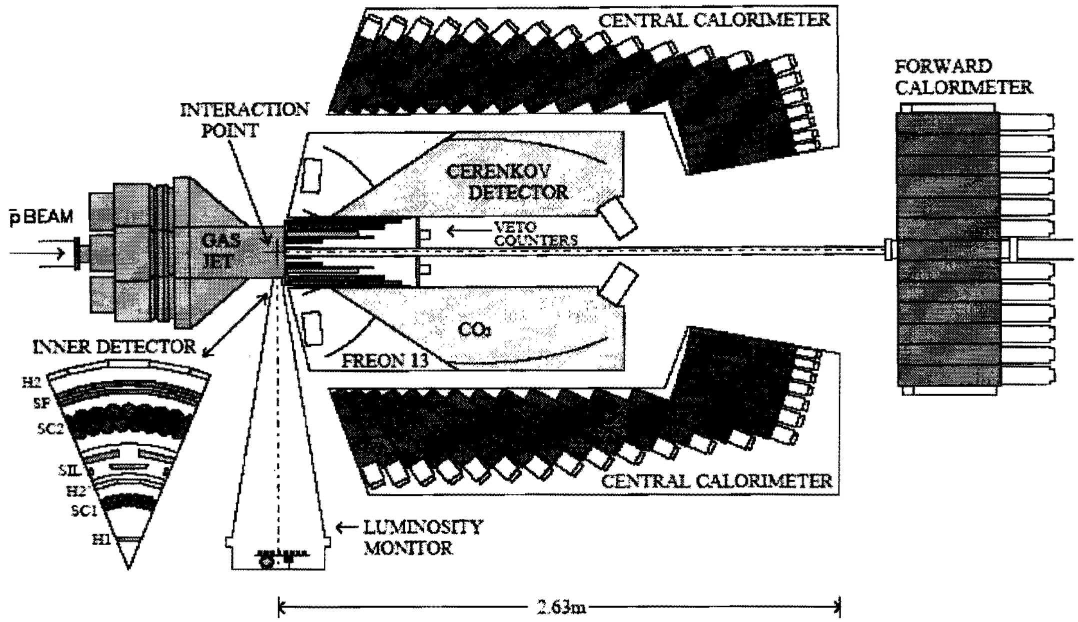

Figure 5: E835 apparatus layout (from [11]).

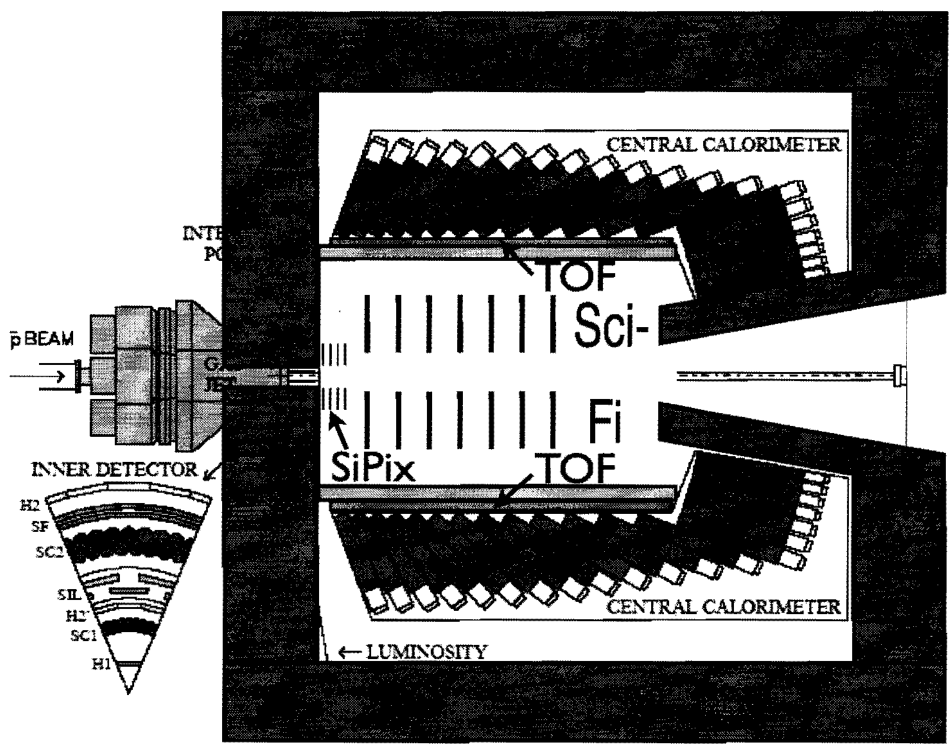

Figure 6: Sketch of upgraded E835 apparatus as discussed in text: 1 T solenoid shown in magenta, TOF counters in green. Return yoke should be as little iron as necessary.

fibers themselves are inexpensive, and a very capable readout system for scintillating-fiber detectors should become available from DØ [86] once the Tevatron finishes. Moving the readout system from DØ will be far simpler and more cost-effective then building a new one from scratch.

Triggering would be based on track multiplicities at large angles and evidence of separated decay vertices [87]. Compared to BTeV, the $\overline{p}p$ experiment has a low charged-particle rate (a few $\times 10^7$ Hz) and a much more localized interaction region. 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 system.[11]

Hadron identification is highly desirable, e.g., in order to suppress backgrounds to charm decays. In the momentum range of interest, this can be accomplished by time-of-flight measurement. In addition, electrons and muons can be identified from their response in the calorimeter. (Studies are in progress and will be reported as results become available.)

5 Competition for Resources

There has been discussion of reusing parts of the Antiproton Source in order to create a proton beam suitable for the mu2e experiment. This reuse has not been studied in detail and is not yet planned, thus may not happen. If it does happen, given the time it will take to fund and implement that experiment, there is ample time — as well as a strong physics case — for a few years of antiproton running before it will be ready. Even if such reuse of the Antiproton Source is undertaken, in the longer term, the Project X beam will be too intense to buffer in the Antiproton Source, requiring a new, larger-acceptance and better-shielded 8 GeV ring to be built, and once again freeing the Antiproton Source to do what it does best.

The Fermilab Director has expressed the view that the mounting of this experiment cannot be undertaken by Fermilab as the lab's staff is already stretched too thinly. We are actively seeking new collaborators in the US and Europe who can take on part of this burden. With some engineering and technical assistance now, we will be able to identify those technical solutions that will minimize the needed time, cost, and effort.

6 Our Request

We request from Fermilab the modest support needed to study the proposed experiment in greater detail and develop a proposal. This will require of order a physicist-FTE plus technical support to develop a cost estimate and an implementation plan.

7 Summary and Conclusions

We are proposing the world's best experiment on charm mixing and *CP* violation, hyperon *CP* violation and rare decays, and charmonium and related states. Because of existing equipment from previous experiments, it can be assembled quickly and at modest cost. In the face of current budget exigencies, this is a practical way to keep Fermilab at the

[11] Like the experiment we consider here, BTeV was designed to operate at a luminosity of $2\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. 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 [28].

forefront of flavor physics. The experiment exploits Fermilab's unique capability to provide an intense beam of medium-energy antiprotons, and it offers unique discovery potential.

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P-986 Addendum:
Antiproton Annihilation and Open Charm

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Abstract

It is possible that the world's most sensitive charm-mixing and *CP*-violation study could be carried out using the Fermilab Antiproton Source. Such a study could potentially discover non-standard model *CP* violation — a goal that to date has eluded the *B* Factories and Tevatron experiments.

1 Summary

We do not yet know whether there is appreciable *CP* violation due to physics beyond the standard model. Such non-SM *CP* violation is a corollary of Sakharov's explanation for the baryon asymmetry of the universe but has yet to be found in *K* or *B* *CP*-violation studies. The LHC*b* and SuperBelle experiments seek to extend such sensitivity but will take some years to do so (and may ultimately be limited by systematics rather than statistics). In the near term, neither experiment is likely to rival the charm sensitivity potentially available at the Fermilab Antiproton Source (see below). In contrast to *K* and *B* studies, new physics in charm *CP* violation is unlikely to be obscured by SM background.

Many SM extensions predict appreciable *CP* violation in charm mixing and decay, as well as appreciable branching fractions for rare decays suppressed in the SM. Both direct and indirect *CP* violation are expected, and both could be sensitive to new physics.[1] Thanks to the *B* factories and CDF, we now know definitively that D^0 and $\overline{D}^0$ mesons mix, albeit at the ≈ sub-percent level [4]. But greater statistics is required in order to ascertain whether *D* mixing and decay also violate *CP*. If they are found to do so, it will most likely represent non-SM *CP* violation. This will be a landmark discovery.

Braaten has recently published [1] a formula by which the $\overline{p}p$ cross section for annihilation into the exclusive final state $D^{*0}\overline{D}^0$ may be estimated. The result is shown in Fig. 1 and is seen to peak at $\approx 1.25\,\mu$b at $\sqrt{s} \approx 4.2\,$GeV. This is a remarkable result in that it represents several billion events produced per year in an experiment at the Fermilab Antiproton Accumulator with $\overline{p}p$ luminosity $\approx 2 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$. (The details of this estimate are presented below.)

To put this into perspective, the largest extant charm sample is that of Belle, with a total of some 1 billion charm events produced in about $1\,\text{ab}^{-1}$ of integrated luminosity. The

[1] In the standard model, direct charm *CP* violation is expected only in singly Cabibbo-suppressed decays; thus observation of *CP* asymmetry in Cabibbo-favored or doubly Cabibbo-suppressed decays would signal new physics [3].

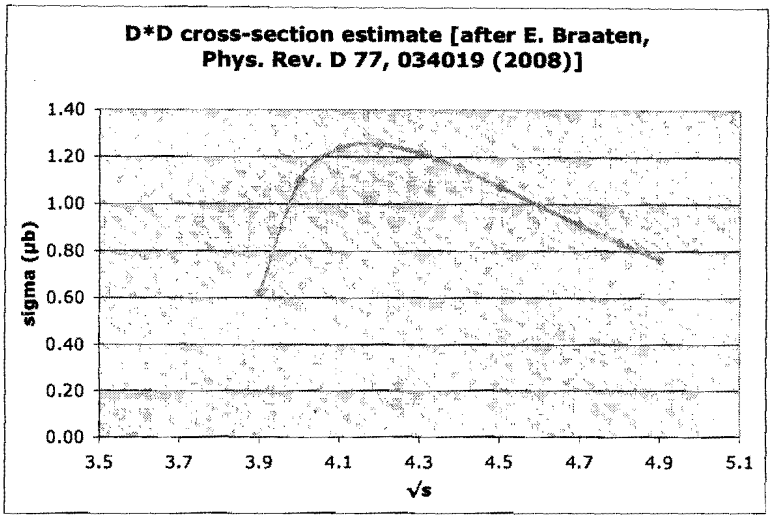

Figure 1: Estimated cross section vs. $\sqrt{s}$ for the exclusive reaction $\overline{p}p \to D^{*0}\overline{D}^0$.

highest-statistics published result from Belle, 1.22×10^6 tagged $\overset{(-)}{D}{}^0 \to K^\mp\pi^\pm$ events (from $540\,\mathrm{fb}^{-1}$ of e^+e^- data taken at or near the $\Upsilon(4S)$) [2], corresponds to "only" 32 million tagged $\overset{(-)}{D}{}^0$ decays.[2] There thus appears to be the opportunity at the Fermilab Antiproton Source to amass what could be by far the world's largest sample of tagged D^0 decays.

2 Tagged D's from D^*'s

The charm cross section at medium energies is unmeasured and difficult to estimate reliably from theory. However, recent papers present a few approaches that are probably indicative of the order of magnitude.

2.1 Cross-section estimates

Braaten's formula [1],

$$\sigma[p\overline{p} \to D^{*0}\overline{D}^0; s] \approx \left(\frac{m_{D^*} + m_D}{\sqrt{s}}\right)^6 \frac{\lambda^{1/2}(s^{1/2}, M_{D^*}, M_D)}{[s(s-4m_p^2)]^{1/2}} \times (4800\,\mathrm{nb}), \tag{1}$$

where $\lambda(x,y,z) = x^4 + y^4 + z^4 - 2(x^2y^2 + y^2z^2 + z^2x^2)$, applies to the $D^{*0}\overline{D}^0$ exclusive final state, which however does not yield tagged D^0 decays, since the slow π^0 or gamma emitted in the D^{*0} decay to D^0 is not flavor-specific. To assess the reach in tagged-D^0 events, we must consider such exclusive final states as $D^{*+}D^-$, $D^{*+}D^{*-}$, $D^{*+}D^-\pi^0$, $D^{*+}D^0\pi^-$, $D^{*+}D^0\pi^-\pi^0$, etc. (and Hermitian-conjugate modes). Two-thirds of all D^{*+} decays are in the flavor-specific π^+D^0 mode, in which the charge of the slow pion tags the initial charm flavor of the D meson.

[2]The Belle analysis includes the requirement $p_{D^*} > 2.5\,\mathrm{GeV}/c$, in order to suppress combinatorics and the large background of charm from B decays.

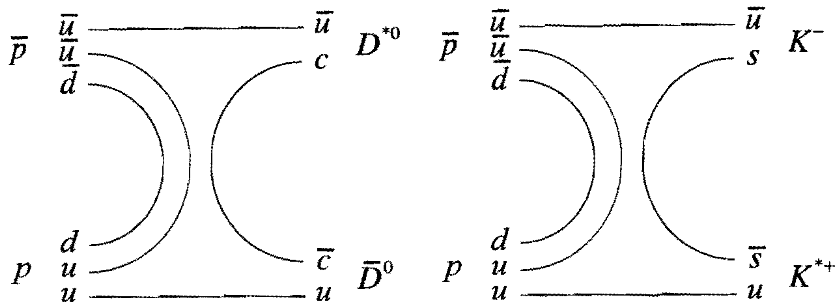

Figure 2: Comparison of leading Feynman diagrams for $\overline{p}p \to D^{*0}\overline{D}^0$ and $\overline{p}p \to K^{*+}K^-$; they differ only in the replacement of final-state charm quarks with strange quarks.

Braaten's interest in the $\overline{p}p \to D^{*0}\overline{D}^0$ cross section stems from his contention that the most plausible explanation for the unusual properties of the $X(3872)$ particle discovered by Belle [5] is that it is a $D^{*0}\overline{D}^0$ molecule. However, no measurements are available of the $\overline{p}p \to D^{*0}\overline{D}^0$ cross section — nor, for that matter, of *any* medium-energy-antiproton charm-production cross section. (LEAR had insufficient energy, the bubble-chamber experiments had insufficient statistics, and E760/835 had no magnet.) Braaten therefore relates this cross section to that for $\overline{p}p \to K^{*+}K^-$ (see Fig. 2), for which measurements are available from the Crystal Barrel experiment at LEAR [6] and from earlier bubble-chamber experiments [7]. This involves a kinematic extrapolation from well above threshold (where the exclusive cross section has fallen by an order of magnitude from its peak value) to the peak of the cross section. He estimates the uncertainty as a factor of 3 in either direction.

Following his example, the best way to estimate the cross section for $D^{*\pm}$ production is to relate it to measured $\overline{p}p$-annihilation cross sections to final states including K^{*0} (see Fig. 3). Some of these are available in Ganguli *et al.* [7] (see Table 1). Their sum of $(860 \pm 60)\,\mu$b substantially exceeds the $(460 \pm 50)\,\mu$b observed for $K^{*+}K^-$ by Crystal Barrel as well as the $(400 \pm 20)\,\mu$b observed by Ganguli *et al.* for that mode. Since other final states containing K^{*0} are also possible, we take this as only a "subtotal," i.e., the inclusive K^{*0} cross section should be larger than this. (Similarly, the inclusive D^{*+} cross section could be larger than estimated here, both because of additional final states and due to the extrapolation uncertainty in Braaten's formula.)

For this "continuum" charm running, we anticipate using a moderate-A target, such as an aluminum wire, rather than the hydrogen gas jet used in E760 and E835. At high energies it is well established that heavy-quark production cross sections scale as $A^{1.0}$ [8], while the total inelastic cross section scales as $A^{0.71}$ [9]. The use of e.g. aluminum thus increases the signal-to-background ratio by a factor $27^{0.29} = 2.6$.[3] This also halves the $\overline{p}p$ interaction rate and adds an equal rate of $\overline{p}n$ interactions. Figure 3 suggests that $D^{*\pm}$ production in $\overline{p}n$ interactions should be similar in rate to that in $\overline{p}p$ interactions.

Titov and Kämpfer have published [10] an alternative calculation of charm exclusive cross sections. They use a Regge approach, with the values of various free parameters determined from measured $\overline{p}p \to K\overline{K}$ and $\overline{p}p \to$ hyperon-antihyperon cross sections. Their focus

[3] A higher-A target than aluminum would provide a larger charm enhancement but might also reduce the integrated luminosity by eliminating stored antiprotons via dE/dx loss and multiple Coulomb scattering. The optimal target material will need to be established in actual running; however, materials in the range Al through Ti were found to be optimal in HERA-B [11].

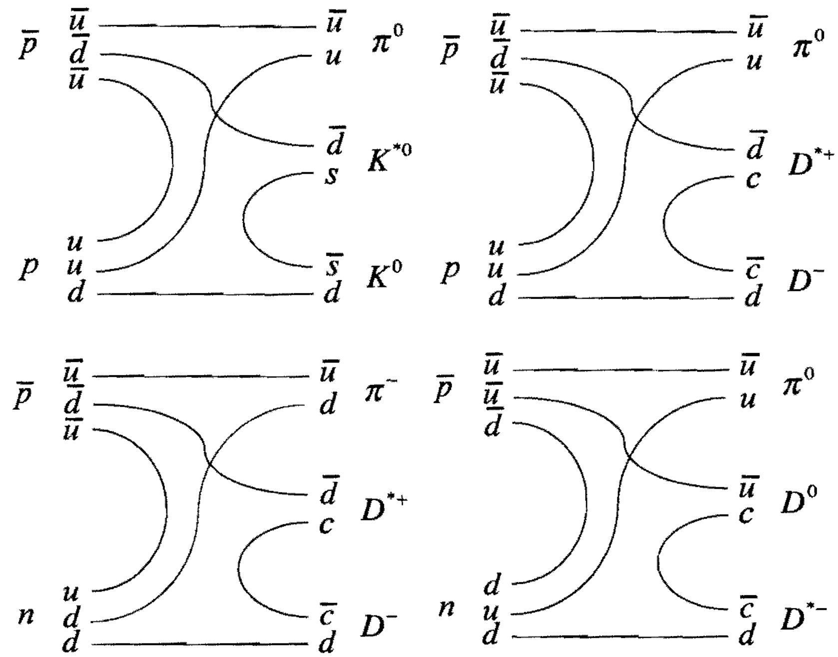

Figure 3: Some leading Feynman diagrams for $\overline{p}p \to K^* K\pi$, $\overline{p}p \to D^* D\pi$, and $\overline{p}n \to D^* D\pi$; note that compared with those of Fig. 2, these diagrams require only one pair of initial-state quarks to annihilate.

Table 1: Various exclusive $\overline{p}p$ cross sections to final states containing K^{*0} (from [7]) at $\approx 750\,\mathrm{MeV}$ $\overline{p}$ kinetic energy. (Note that K_L was unobserved in [7]; we assume the cross sections for K_L and K_S are equal.)

Mode	σ (μb)	error (μb)
$K^{*0}K_S$	150	20
$K^{*0}K_L$	150*	20*
$K^{*0}K_S\pi^0$	70	10
$K^{*0}K_L\pi^0$	70*	10*
$K^{*0}K^\pm\pi^\mp$	240	40
$K^{*0}\overline{K}^{*0}$	180	25
Sum	860	57

*assumed.

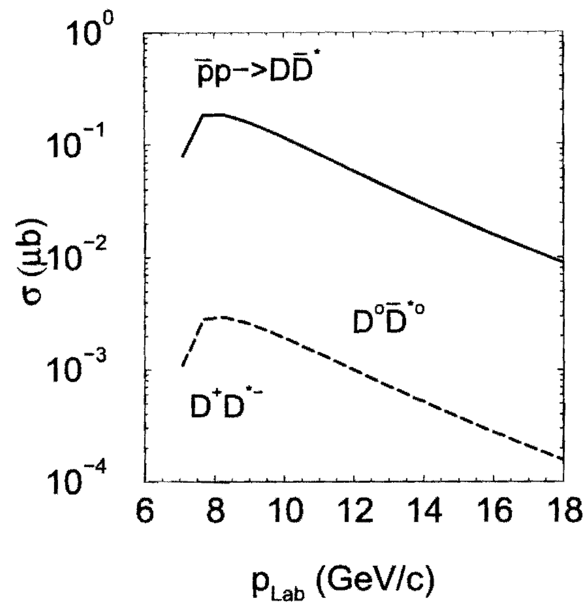

Figure 4: Total cross sections for $\overline{p}p \to D^0\overline{D}^{*0}$ (solid) and $\overline{p}p \to D^+\overline{D}^{*-}$ (dashed) from Regge calculation of Titov and Kämpfer [10, 12] vs. antiproton momentum. As with Braaten's formula [1], the $D^0\overline{D}^{*0}$ cross section peaks at $p_{\overline{p}} \approx 8\,\mathrm{GeV}$; however the estimated cross section is a factor of 6 smaller.

on FAIR led them to consider 15 GeV/c antiprotons rather than the 8.9 GeV/c which is the maximum $\overline{p}$ momentum available at the Accumulator, but Titov has recently provided [12] exclusive total cross-section predictions vs. antiproton momentum, shown in Fig. 4. For $D^0\overline{D}^{*0}$ these are lower than obtained using Braaten's formula by a factor of 6. (Given the uncertainties of low-momentum-transfer, non-perturbative QCD, Braaten views this as agreement with his estimate [13].)

Since several other low-multiplicity final states containing a D^{*+} or D^{*-} are accessible in antiproton annihilation at this energy, we take these arguments as indicative of the likelihood that the total $D^{*\pm}$ cross section in 8 GeV $\overline{p}N$ annihilation is of order 1–10 μb. This is sufficiently large that a measurement is of great interest.

2.2 Acceptance and efficiency

We note that $\sqrt{s} = 4.2\,\mathrm{GeV}$ is approximately the maximum center-of-mass (CM) energy accessible at the Antiproton Accumulator since 8 GeV antiproton kinetic energy corresponds to $\sqrt{s} = 4.30\,\mathrm{GeV}$. At this energy the CM frame moves in the lab with a boost factor $\gamma = 2.3$, comparable to the boost for charm events at the B factories. Preliminary simulation studies indicate acceptance for $D^{*+} \to \pi^+ D^0$ decays of $\approx 50\%$. Furthermore, the mean charged multiplicity in $\overline{p}p$ interactions at these energies is ≈ 3. Thus the combinatorial background that underlies the D mass peak in high-energy hadroproduction experiments should be much reduced. We therefore speculate that cuts required to suppress the background can be relatively mild and similar in efficiency to those used at the B factories. At present this guess still needs to be backed up with additional work; we are studying MIPP antiproton data to try to quantify this efficiency.

3 The $X(3872)$ as a D Factory

We next assume (for the sake of discussion) that the $X(3872)$ is indeed a $D^{*0}\overline{D}^0$ (plus Hermitian-conjugate) molecule — arguably the leading interpretation of this mysterious, charmonium-related state. Then with a sufficiently narrow beam-momentum distribution, the process $\overline{p}p \to X(3872)$ may be competitive in charm new-physics reach with the continuum production discussed above.[4] The statistics obtainable in this fashion depends on unknowns (about which the experiment considered here would appreciably improve our knowledge) including the $X(3872)$ total width, $\overline{p}p$ partial width, and branching ratios, as well as the beam-momentum distribution. Assuming plausible values for these [1, 13], we can estimate the number of produced $X(3872) \to D^{*0}\overline{D}^0$ per year at about 10^8 — some two orders of magnitude below the continuum-production estimate of Table 2. However, analogously to the $\psi(3770) \to D\overline{D}$ decay, these events are $D^{*0}\overline{D}^0$ pairs produced in a known (most likely, $J^{PC} = 1^{++}$) quantum state, which thus correlates the subsequent D and D^* decays. (Because the D^{*0} decays to both γD^0 and $\pi^0 D^0$, giving D^0 mesons with opposite C-parities, one would want the calorimeter to be capable of distinguishing these modes with some degree of reliability.)

To evaluate the physics reach of such a data sample will require a detailed simulation study; however, the power of quantum-correlated D decays to precisely probe charm mixing is a key aspect of the BES-III physics program — also with an estimated 10^8 events. The $X(3872)$ may be able to play a similar role for a $\overline{p}p$ facility.

4 Conclusions

If we assume charm-continuum running at $\mathcal{L} = 2 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$ on an aluminum target, acceptance of 50%, efficiency after cuts of 10%, and the central value derived from Braaten's exclusive cross-section formula, $1.25\,\mu$b, we reconstruct some 27 million tagged $\overset{(-)}{D}{}^0 \to K^{\mp}\pi^{\pm}$ events per year of operation (Table 2), to be compared with 1.22 million at present and about 2 million when the full Belle sensitivity of $\approx 1\,\text{ab}^{-1}$ is analyzed. Estimates for medium-energy charm cross sections are available only for exclusive final states. The inclusive cross section may well be significantly larger than this, but clearly it could also be smaller, perhaps by as much as a factor of 3. Given the low multiplicity of events in 8 GeV antiproton annihilation, the assumed 10% cut efficiency may be feasible, but additional studies are required in order to confirm this.

At this preliminary stage of consideration, a magnetic-spectrometer experiment at the Antiproton Accumulator seems potentially capable of reconstructing the world's largest charm samples and making a high-impact measurement: the first observation of new physics in charm *CP* violation. More work to evaluate the reach is clearly called for. If after this work, the efficiencies estimated here remain plausible, mounting a simple experiment at the Antiproton Accumulator to test these estimates would seem to be both highly desirable and urgent.

[4] This would require running with a hydrogen target, in order not to degrade the center-of-mass energy precision via beam dE/dx loss or target Fermi motion, but it is straightforward to outfit the AP-50 experimental area with both a hydrogen target and a metal target.

Table 2: Assumed values and sensitivity-benchmark estimate of tagged $\overset{(-)}{D}{}^0 \to K^{\mp}\pi^{\pm}$ events per year. (Caveats: As discussed in text, the reliability of some of these values remains to be established. They are based on exclusive cross-section estimates, so the inclusive production rate could be significantly higher, but the cross section, luminosity, or efficiency could also be lower.)

Quantity	Value	Unit
Running time	2×10^7	s/y
Duty factor	0.8*	
$\mathcal{L}$	2×10^{32}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Target A	27	
$A^{0.29}$	2.6	
$\sigma(\overline{p}p \to D^{*+}X)$	1.25	μb
# $D^{*\pm}$ produced	2.1×10^{10}	events/y
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.677	
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.0389	
Acceptance	0.5	
Efficiency	0.1	
Total	2.7×10^7	events/y

*Assumes $\approx 15\%$ of running time is devoted to antiproton-beam stacking.

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P-986 Addendum 2: Physics Studies

P-986 Collaboration

May 26, 2009

Abstract

1 Introduction

We have studied the performance of a simple $\bar{p}p$ experiment based on the E835 lead-glass barrel calorimeter with an inserted solenoidal magnetic spectrometer. We consider the proposed apparatus configuration shown in Fig. 1. Key parameters of the simulations are given in Table 1. We discuss the response and physics reach of this detector configuration for charm and $X(3872)$ studies. Since it is crucial to these studies, we first review the capabilities of the Fermilab Antiproton Source as compared with other similar facilities.

2 Fermilab Antiproton Source

The Fermilab Antiproton Source is the most productive in the world, now and for the foreseeable future. The CERN Antiproton Decelerator (AD) is the only other operating antiproton source. The AD is designed to deliver very low energy antiprotons for stopping physics; $\approx 5 \times 10^{12}$ antiprotons per year are used at CERN. The Fermilab Accumulator routinely provides $\approx 6 \times 10^{12}$ antiprotons per day for the collider program; production rates have now reached nearly 3×10^{11} antiprotons per hour. The FAIR project in Germany is proposed to be an accelerator facility that will share time producing antiprotons and radioactive beams; the antiproton production-rate goal is 10% of what is now being collected by the Fermilab Accumulator. For the medium-energy program considered here, we next discuss how to operate the Fermilab Antiproton Source to maximize the physics reach.

2.1 Future Capabilities, Fill Cycle, and Integrated Luminosity

Currently, the Main Injector minimum cycle time is set at 2.2 s in order to load protons and ramp. In the NOνA era, the Recycler Ring will provide protons in one turn; then the minimum Main Injector cycle time will consist of just the ramp time, 1.33 s. The Antiproton Source is not capable of running at that cycle time and would take proton beam on target every other Main Injector cycle. Currently, when Switchyard is taking beam, the average cycle time for antiproton production is 2.42 s, which is close to the foreseen 2.66 s. The antiproton stacking rate is still $> 2.5 \times 10^{11}$ antiprotons per hour even with Switchyard running. Even though the stacking rate decreases with stack size, we expect

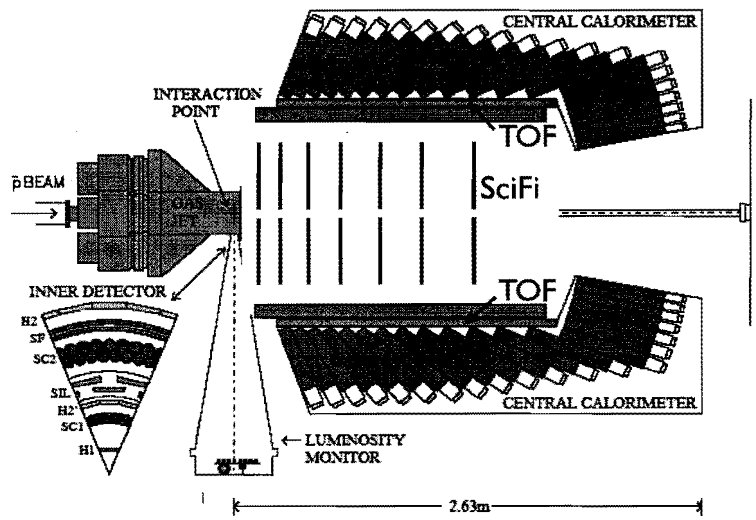

Figure 1: Apparatus configuration assumed for the studies described here: inserted into the bore of the E835 lead-glass barrel calorimeter is a small superconducting solenoid (magenta) containing precision scintillating-fiber tracking detectors. Precision time-of-flight counters (green) surround the solenoid. (If necessary, a return yoke, configured so as to fit under the ceiling of the AP50 pit, could be used to minimize stray field at the lead-glass phototubes; alternatively, a self-shielding double solenoid [1] could be employed.)

to accumulate 10^{12} antiprotons in five hours. The most that E835 decelerated successfully was 10^{12} antiprotons.

The time to prepare the beam (deceleration, energy check and cooling) will be the same as it was for E835. Preparation of the beam for the experiment and stacking are expected to take a few hours.

With a higher-density hydrogen gas jet than E835, the experiment can expect luminosities of $1 - 2 \times 10^{32}$ cm^{-2}s^{-1}. Depending upon the desired energy for running, we expect the beam lifetime to be 10–20 hours.

A nominal run plan could consist of a day-long cycle of stacking, beam preparation, data taking and recovery. We can expect to achieve ≈ 8 pb^{-1} per day and > 200 pb^{-1} per month.

2.2 Scanning

The precision with which the antiproton beam energy can be determined makes the Accumulator a highly precise spectrometer. The narrow beam energy spread allows measurement of narrow resonance line shapes. The beam energy spread is dependent upon the Accumulator lattice and the beam energy; the spread is on the order of a few hundred keV. The beam energy is stepped through a series of energies and the numbers of events are counted per integrated luminosity. Depending upon the production rate of a resonance and the final-state branching fraction, the beam energy is stepped every antiproton fill, or several points of a scan are done with a single beam fill. For example, for the χ_c states, E835

Table 1: Key detector parameters used in simulations

Parameter	value	unit
Target (D study):		
material	Al	
configuration	wire	
diameter	30	μm
Target (X study):		
material	H	
configuration	cluster jet	
Beam pipe:		
material	Be	
diameter	5	cm
thickness	350	μm
Solenoid:		
length	1.6	m
inner diameter	90	cm
field	1	T
SciFi detectors:		
total thickness per doublet	360	μm
fiber pitch	272	μm
fiber diameter	250	μm
number of stations	8	
number of views	3	
number of channels	≈90,000	

observed 30 χ_{c0} and 1000 $\chi_{c1,2}$ $J/\psi\gamma$ events per pb^{-1} when the beam energy corresponded exactly to the appropriate χ_c mass.

The observed line shape is a convolution of the beam energy spread and the natural resonance shape. For the χ_c states, there is no distortion of the resonance shape since the beam energy spread is less than a χ_c width. For resonance widths nearly the same as (or smaller than) the beam energy spread, the shape is distorted with respect to the natural resonance shape. As the resonance width decreases, the observed peak height decreases and the line-shape width approaches the beam energy spread. Two examples from E835 are the reduction of the number of observed events per integrated luminosity by factors of 2 and 5 for the ψ' and J/ψ, respectively, when compared to what would be expected if the beam energy were a delta function. The distortion of line shape has been discussed by the E835 [2] and PANDA collaborations [3].

If the exact mass and width are not known, the beam narrowness can be a hindrance in finding the resonance. If the mass is *known* to a few MeV or so, the width is on the order of a hundred keV, and the expected peak number of events is several per pb^{-1}, then a systematic stepping of energy over several weeks (one energy point per day) may be needed to find the resonance. Once the resonance is found, further energy points are used to determine the mass, width, and background.

Table 2: Experimental observations of $X(3872)$.

Experiment	Year	Mode	Events	Ref.
Belle, BaBar	2003, 2004	$\pi^+\pi^- J/\psi$	35.7 ± 6.8, 25.4 ± 8.7	[4, 7]
CDF, DØ	2004	$\pi^+\pi^- J/\psi$	730 ± 90, 522 ± 100	[5, 6]
Belle	2004	$\omega(\pi^+\pi^-\pi^0)J/\psi$	10.6 ± 3.6	[10]
Belle	2005	$\gamma J/\psi$	13.6 ± 4.4	[8]
Belle	2006	$D^0\overline{D}^0\pi^0$	23.4 ± 5.6	[11]
BaBar	2008	$\gamma\psi$, $\gamma\psi'$	23.0 ± 6.4,25.4 ± 7.3	[9]
BaBar	2008	$D^0\overline{D}^0\pi^0$	33 ± 7	[12]

3 $X(3872)$

The $X(3872)$ was discovered in 2003 by the Belle Collaboration [4] 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 [5], DØ [6], and BaBar [7]. It has now been seen as well in the $\gamma J/\psi$ [8, 9], $\gamma\psi'$ [9], $\pi^+\pi^-\pi^0 J/\psi$ [10], and $D^0\overline{D}^{*0}$ ($D^0\overline{D}^0\pi^0$, $D^0\overline{D}^0\gamma$) [11, 12, 13] modes (see Table 2). The mass difference between the $J/\psi\pi^+\pi^-$ and the $D^0\overline{D}^{*0}$ decay channels hinted at the possibility of two nearby states. The $X(3872)$ does not appear to fit within the charmonium spectrum. The observed partial width of the state in the $\pi^+\pi^- J/\psi$ decay channel was measured by Belle to be $< 2.3\,\mathrm{MeV}$ at 90% C.L. [4] and by BaBar to be $< 3.3\,\mathrm{MeV}$ at 90% C.L. [14]. The observed partial width of the state in the $D^0\overline{D}^{*0}$ decay channel was measured by BaBar to be $3.0^{+1.9}_{-1.4} \pm 0.9$ MeV [15, 12]. Since the measured mass is well above the open-charm threshold, the small width implies that decays to $D\overline{D}$ are forbidden and suggests unnatural parity, $P = (-1)^{J+1}$ [16]. The $X(3872)$ is a poor candidate for the $\psi_2\,(1\,^3D_2)$ or $\psi_3\,(1\,^3D_3)$ charmonium levels [17, 10, 16] due to the nonobservation of radiative transitions to χ_c. The evidence for $X(3872) \to \gamma J/\psi$ implies positive C-parity, and additional observations essentially rule out all possibilities other than $J^{PC} = 1^{++}$ [18, 19]. With those quantum numbers, the only available charmonium assignment is $\chi'_{c1}\,(2\,^3P_1)$; however, this is highly disfavored [17, 16] 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 [17] that the $2\,^3P_1$ should lie some $49\,\mathrm{MeV}/c^2$ higher in mass than the observed $m_X = 3872.2 \pm 0.8\,\mathrm{MeV}/c^2$ [15].

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 [20] or a tetraquark state [21]. Perhaps the most intriguing possibility is that the $X(3872)$ represents the first clear-cut observation of a meson-antimeson molecule: specifically, a bound state of $D^0\overline{D}^{*0} + D^{*0}\overline{D}^0$ [22].[1] 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 [19]:

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

A direct and precise measurement of the full width, which $\overline{p}p$ can provide [23, 24, 25], is also highly desirable.

[1] Alternatively, the mass coincidence may be merely accidental, and the $X(3872)$ a $c\overline{c}$-gluon hybrid state; however, the mass and 1^{++} quantum numbers make it a poor match to lattice-QCD predictions for such states [17].

With the current world-average values [15] $m_{D^0} = 1864.84 \pm 0.17\,\mathrm{MeV}/c^2$ and $m_{D^{*0}} - m_{D^0} = 142.12 \pm 0.07\,\mathrm{MeV}/c^2$, the $D^0\overline{D}^{*0}$ mass threshold is $3871.8 \pm 0.35\,\mathrm{MeV}/c^2$. Using the world-average value for the mass of the $X(3872)$, we have $E_X = -0.4 \pm 0.8\,\mathrm{MeV}$. If we use for the mass of the $X(3872)$ the most precise single measurement to date (by CDF [26] in the $\pi^+\pi^- J/\psi$ channel), $3871.61 \pm 0.16 \pm 0.19\,\mathrm{MeV}/c^2$, E_X becomes -0.19 ± 0.43 MeV. A future increase in precision of this comparison will also require improvements in the precision of the D^0 and D^{*0} masses. 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 directly measure Γ_X to a similar precision, by scanning across the resonance as discussed above. Since the mass of the $X(3872)$ is so close to the $D^{*0}\overline{D}^{*0}$ threshold, mapping precisely the lineshape of the X will be necessary in determining whether we have a single state or two distinct, nearby states with different masses. The B factories could attempt to measure the line shape but this is an extremely challenging measurement for them due to low statistics and relatively poor resolution [27]. The $\overline{p}p$ experiment can uniquely perform this line shape measurement both below and above the $D^0\overline{D}^{*0}$ threshold. This is the type of measurement for which the $\overline{p}p$ scanning technique has a demonstrated strong advantage.

Additional important measurements include $\mathcal{B}[X(3872) \to \pi^0\pi^0 J/\psi]$ and study of the $\pi^0\pi^0$ mass spectrum which will help confirm the C-parity assignment [28] and test the $\rho J/\psi$ production hypothesis. These measurements are very hard for the current B factories due to machine-related backgrounds and low efficiency to detect the π^0's when one tries to reduce the combinatorial background from low-energy photons. The experiment proposed here (as well as BES-III) could attempt to measure with better precision ($\sim 100\,\mathrm{keV}/c^2$) the D^0 mass as well, using a $\psi(3770) \to D^0\overline{D}^0$ sample [29], and thus determine better the $D^0\overline{D}^{*0}$ threshold. (A $\overline{p}p$ experiment could also scan the $3.92 < \sqrt{s} < 3.94\,\mathrm{GeV}$ region to study the resonance observed recently in the $J/\psi\omega$ decay mode [30], as well as investigating the other charmonium-like states observed in this vicinity [31].)

3.1 $X(3872)$ Sensitivity Estimate

The production cross section of $X(3872)$ in $\overline{p}p$ annihilation has not been measured, but it has been estimated to be similar in magnitude to that of the χ_c states [32, 33]. In E760, the χ_{c1} and χ_{c2} were detected in $\overline{p}p \to \chi_c \to \gamma J/\psi$ (branching ratios of 36% and 20%, respectively [15]) 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; at the mass peak 1 event per nb^{-1} was observed [34]. The lower limit $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] > 0.042$ at 90% C.L. [35] implies that in a day (section 2.1) at the peak of the $X(3872)$ ($8\,\mathrm{pb}^{-1} \times$ [1000 events/pb^{-1}] $\times\, 0.04/0.36 \times$ acceptance-efficiency ratio of final states of $\approx 50\%$), about 500 events would be observed. Even if the production cross section is an order of magnitude less than those of the χ_c states, the tens of events per day at the peak will be greater than the background observed by E835. By way of comparison, Table 2 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.[2] (Although CDF and DØ could amass samples of order 10^4 $X(3872)$ decays, the large backgrounds in the CDF and DØ observations, reflected in the uncertainties on the numbers of events listed in Table 2, limit their incisiveness.)

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

The spread of reported $X(3872)$ masses means that a range of > 6 MeV will need to be scanned. If the observations attributed to the $X(3872)$ are two resonances or a threshold effect, the step sizes will have to be less than the beam spread (section 2.2) to see a narrow resonance and investigate the threshold. A systematic program of stepping of energies through the large mass range may be necessary to establish the line shape(s), which could take two months.

We have concentrated here on one decay mode of the $X(3872)$: $X(3872) \to \pi^+\pi^- J/\psi$. Large samples will of course also be obtained in other modes as well, increasing the statistics and allowing knowledge of $X(3872)$ branching ratios to be improved. Given the uncertainties in the cross section and branching ratios, the above may well be an under- or overestimate of the $\overline{p}p$ 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 $\overline{p}p$ formation technique could enable the world's smallest systematics. Such an experiment could thus provide a definitive test of the nature of the $X(3872)$.

4 Charm

There are several potential signatures for new physics in charm mixing and decay; these have been comprehensively reviewed in (*inter alia*) the Proceedings of the 2007 "Workshop on Flavour in the Era of the LHC" [37]. As emphasized by many authors, these have the virtues of unique sensitivity to new physics in the "up-quark" sector, low to nonexistent standard-model background, and availability of very large event samples. They include rare (flavor-changing neutral-current or lepton-flavor violating) decays, and both direct and indirect *CP* asymmetries. Charm mixing is now established at the $\approx 10\sigma$ level [38], but is in a range ($x_D, y_D \lesssim 1\%$) such that its interpretation is ambiguous: mixing at that level could arise from the standard model or from new physics. Nevertheless it is important to study D^0 mixing as precisely possible as well as to look for signatures of new physics via *CP* violation and rare decays. These can be complex analyses, so for now we have used as a simple benchmark the numbers of events reconstructed in the tagged D^0 decay modes $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$ and $D^{*-} \to \overline{D}^0\pi^- \to (K^+\pi^-)\pi^-$.

4.1 $D^{*\pm} \to D^0$ Study

We have simulated the exclusive reaction $\overline{p}n \to D^{*-}D^0$, with subsequent decays $D^{*-} \to \pi_s^-\overline{D}^0$, $\overline{D}^0 \to K^+\pi^-$, at 8 GeV $\overline{p}$ kinetic energy. (This is the design energy of the Antiproton Accumulator, and also essentially its maximum practical operating energy. As shown by Braaten [33] and Titov and Kämpfer [39], this is also approximately the energy at which the exclusive $\overline{p}N \to D^*D$ cross section peaks.) We assume uniform production- and decay-angle distributions. We find that the acceptance for tagged-D^0 events (i.e., for the slow pion from the D^* and the kaon and pion from the D^0 all to be detected), about 45%, is largely insensitive to spectrometer magnetic field (Fig. 2). (The exact value of the acceptance is of course sensitive to size and placement of detectors; we find that the configuration given in Table 1 is a reasonable compromise between acceptance and detector channel count.)

Figure 3 shows the transverse-momentum (p_t) distributions of the charged pions from this decay sequence. The pion p_t distributions are non-overlapping, which means that there is essentially no ambiguity as to which pion is from the D^* and which from the D^0.

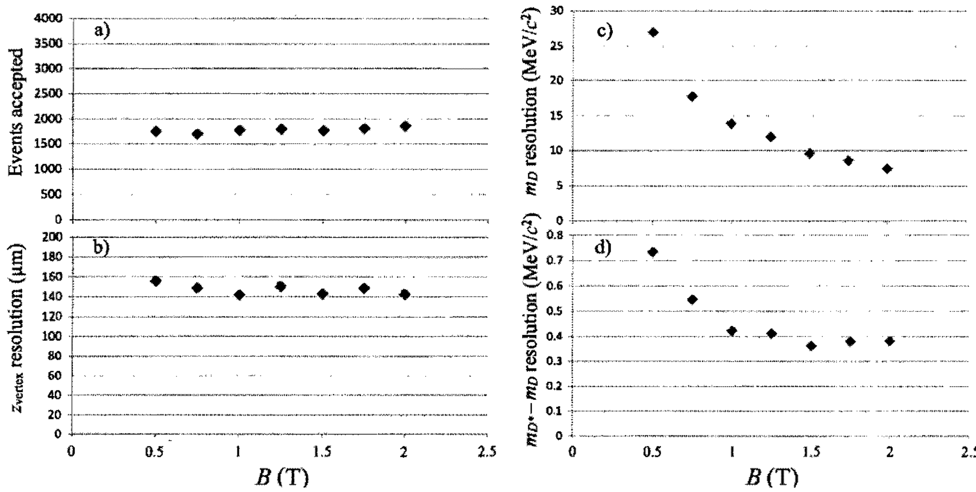

Figure 2: Magnetic-field dependence of a) number of events accepted (out of 4,000 thrown), b) decay-distance resolution, c) D^0 mass resolution, and d) D^*–D^0 mass-difference resolution. Above $\approx 1\,\text{T}$, spectrometer performance improves only slightly.

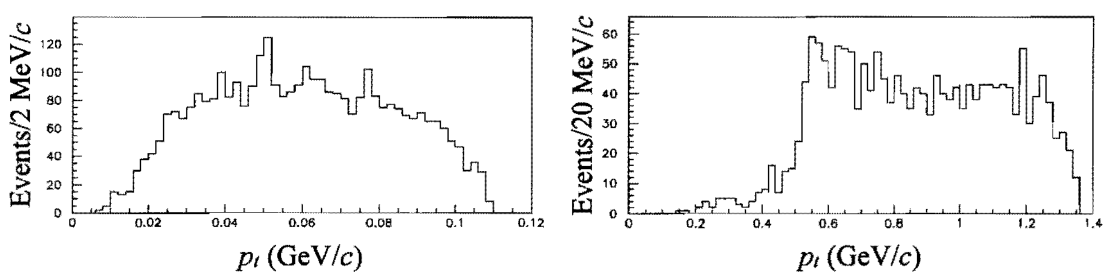

Figure 3: Transverse-momentum (p_t) histograms for charged pions from accepted tagged-D^0 events. The "slow" (left histogram) and "fast" pions (right histogram) are seen to have non-overlapping p_t distributions, thus there is no ambiguity in event reconstruction as to which is which. (The p_t distribution of the kaon is similar to that of the fast pion.)

However, the D^0 kaon and pion have very similar p_t distributions, hence kaon identification will be important if large signal-to-background ratio is to be achieved. Figure 4 shows the resolutions achieved in D^* and D^0 mass, D^*–D^0 mass difference, and D^0 decay distance at a magnetic field of 1 T. Since these events have no primary vertex, in computing the decay distance we rely on the small size of the target in at least one (z) dimension.

4.2 D Background Study

To estimate the efficiency of the cuts needed for good signal-to-background in tagged-D^0 decays, we have analyzed the MIPP 20 GeV/c data sample [40]. Approximately 30,000 events were reconstructed in MIPP with 3 or more charged tracks produced by a 20 GeV/c antiproton incident on a liquid-hydrogen target. These correspond to a total $\geq$ 3-prong production cross section of about 30 mb, hence the sensitivity of the sample is about 1 event/μb. The events are a mixture of interactions in the liquid hydrogen, the aluminum target-vessel win-

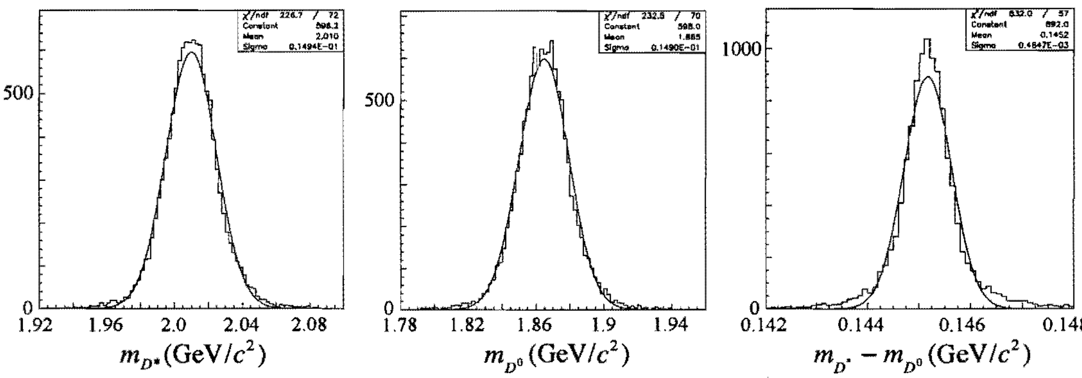

Figure 4: (left to right) Histograms of D^* and D^0 mass, and D^*-D^0 mass difference, indicating r.m.s. resolutions of 14.9, 14.9, and 0.46 MeV/c^2, respectively.

dows, and the plastic interaction-trigger scintillation counter. Because these events are in an awkward momentum range for hadron identification, with most hadrons above the dE/dx particle-identification ($p < 0.5\,\mathrm{GeV}/c$) range and below that of the the MIPP Cherenkov counter ($p > 5\,\mathrm{GeV}/c$), hadron-ID information was not used in this analysis.

We first scaled the longitudinal momentum of each track by a factor of 0.65 in order to correct (to first order) for the higher beam momentum in the MIPP sample than in 8 GeV collisions. This correction was derived by comparing the momentum distributions of the decay products in simulated $D^* \to D^0$ events at 20 and 8 GeV. This procedure is conservative in that in actual 8 GeV collisions, transverse momenta and event charged-particle multiplicities would also be reduced compared to those in the MIPP sample, but we made no attempt to correct for these effects.

For a subset of events, Cherenkov information was available and was used to eliminate the large fraction of electrons and positrons. We then computed "D^*" and "D^0" masses, assuming $\pi^\mp K^\pm \pi^\mp$ track identities, for every $-+-$ and $+-+$ charge-sign triple of charged tracks in each event, requiring $p_{t1} < p_{t2}, p_{t3}$ (where particle 1 is taken as the "slow" pion coming from the D^* decay) in accordance with the Monte Carlo distributions of Fig. 3. Figure 5 shows the distribution of events vs. these reconstructed masses, and Fig. 6 shows the distributions of D^*–D^0 mass difference for all events and for those events in which the D^* and D^0 masses are consistent with the known masses of those particles. Note the power of the D^* and D^0 mass cuts in eliminating background combinations: in Fig. 6(right) there is only one event remaining in the (1-MeV-wide) signal mass-difference bin, $m_{D^*} - m_{D^0} = 0.145\,\mathrm{GeV}/c^2$. We therefore conclude that the background level, before hadron-ID and vertex requirements are imposed, will be about $1\,\mu$b. (Note that insofar as our sample probably still contained many leptons, this gives an approximate upper limit.)

To get an idea of the signal-to-background ratio, we assume a total $D^{*\pm}$ production cross section (including both signs and taking into account the $A^{0.29}$ enhancement factor due to target material [41]) of $10\,\mu$b in 8 GeV $\overline{p}p$ collisions (see Table 3). We thus start out (before branching ratios are taken into account) with a signal-to-background ratio of about 10 to 1. The decay chain for the final state we consider here involves the $(67.7 \pm 0.5)\%$ $D^{*+} \to \pi^+ D^0$ branching ratio and the $(3.89 \pm 0.05)\%$ $D^0 \to K^- \pi^+$ branching ratio [42], reducing the signal-to-background ratio to 1/4. However, based on multiplicities observed in bubble-chamber experiments [43], the charged-kaon production rate at 8 GeV is $\lesssim 0.1$ per

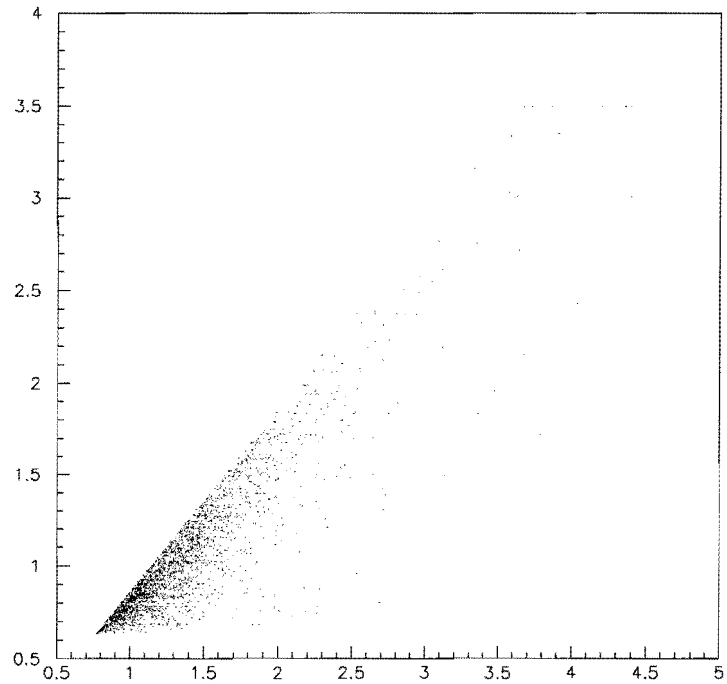

Figure 5: Scatter plot of reconstructed "$D^0 \to K\pi$" vs. "$D^{*\pm} \to \pi^{\pm}\overset{(-)}{D}{}^0$" masses (in GeV/$c^2$) as described in text. (In order to avoid saturating the scatter plot, only a fraction of the events are plotted.)

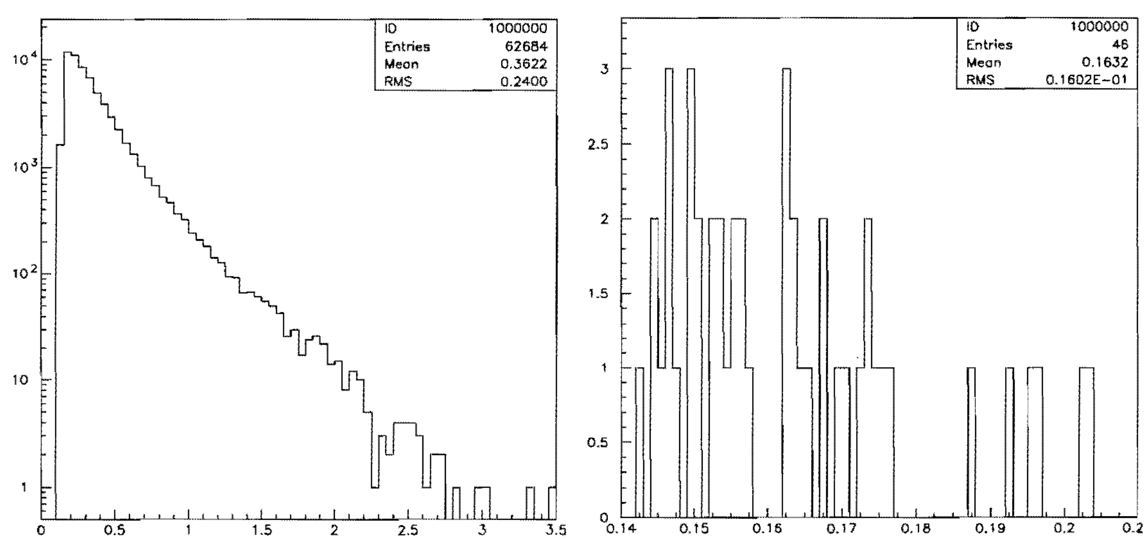

Figure 6: D^*–D mass-difference distributions (in GeV/c^2): (left) all events; (right) events within $\pm 2\sigma$ D^* and D mass windows.

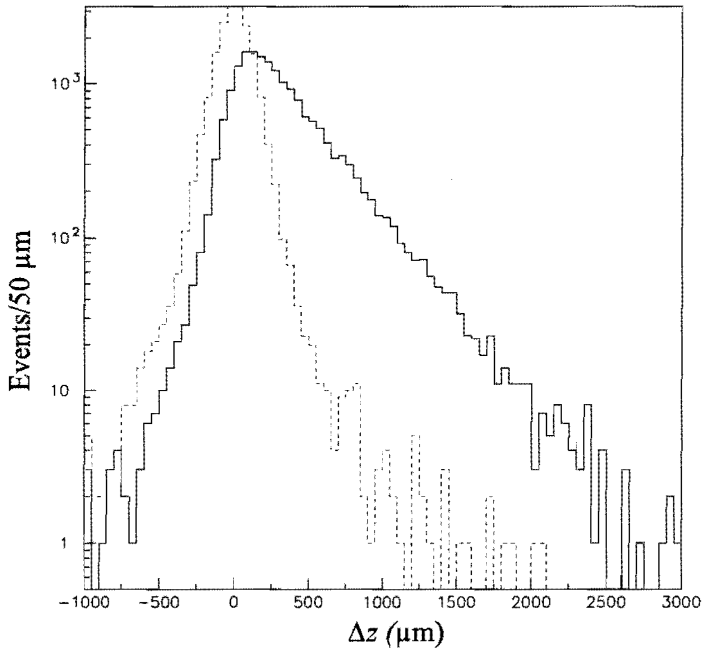

Figure 7: Histograms of reconstructed vertex position for D^0 decays (solid) and random hadron pairs (dashed).

event, thus a factor of 10 or more is available from hadron identification (see below), giving a signal-to-background of ≈ 10 to 1. To achieve signal-to-background of 100 to 1 or more would then require lifetime cuts (Fig. 7). (Note that the lifetime resolution we obtain is based solely on the use of fine-pitch scintillating-fiber detectors. It may be possible to do somewhat better with silicon detectors but the trade-off of finer pitch vs. increased multiple scattering must be handled with care, and so far the all-SciFi solution presented here gives the best performance of those options examined.)

4.3 Kaon Identification

We assume π-K discrimination by means of precision time-of-flight measurement. (An alternative would be the DIRC technique developed for BaBar.) A time measurement precision of ≈ 50 ps is typical using scintillation counters of few-cm thickness [44], however, this does not suffice for π-K discrimination at the level we need (Fig. 8). Devices with resolution better than 10 ps are in development [45] and are likely to be available on the timescale of this experiment.

4.4 Charm Sensitivity Estimate

Table 3 (repeated verbatim from P-986 Addendum 1 [41]) gives expected produced and reconstructed samples of 2.1×10^{10} and 2.7×10^{7} tagged events per year. This is consistent with the luminosity estimate given in Sec. 2.1 above: 8 pb^{-1}/day amounts to 2,920 pb^{-1}/year, compared to the 3,200 pb^{-1}/year implied by Table 3, whereas the integrated luminosity running at 8 GeV (for which no deceleration is required) will be somewhat higher than that

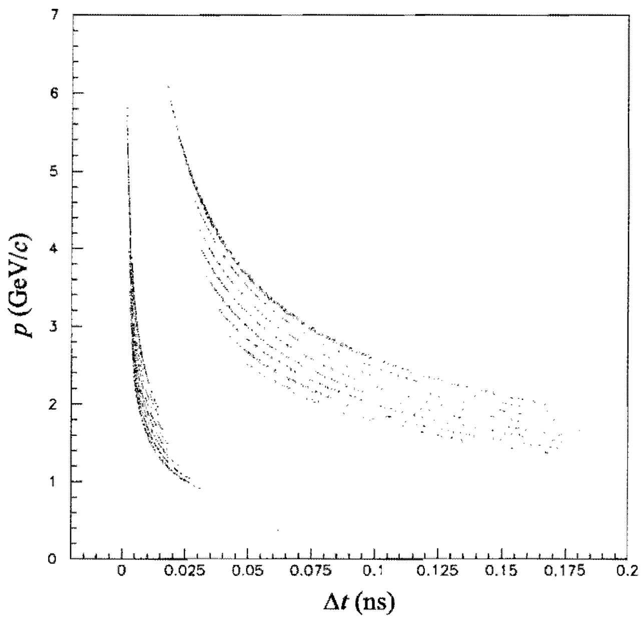

Figure 8: Momentum vs. time-of-flight difference (at last hit SciFi plane) for fast pion and kaon from simulated D^0 decays in 8 GeV $\bar{p}p$ collisions. At all momenta, a 10 ps r.m.s. resolution in Δt provides at least 2σ separation; for most of the range the separation is $\geq 3\sigma$.

at the mass of the $X(3872)$ (for which the antiprotons need to be decelerated to 6.1 GeV). The other difference between Table 3 and the discussion here is that the acceptance is about 10% smaller than previously assumed — not an important difference given the much larger cross-section uncertainties.

We have focused here on the simplest decay modes, but we anticipate correspondingly large samples of other charm decays, including $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K_S\pi^+\pi^-$, singly and doubly Cabibbo-suppressed modes such as K^+K^-, $\pi^+\pi^-$, $K^+\pi^-$, etc. In contrast to certain other experiments, these will be free of all contamination from the more complicated event topologies of $B \to D$ decays.

One important benchmark for new-physics reach in charm is leptonic decays; an example is $D^0 \to \mu^+\mu^-$, whose branching ratio in the standard model (SM) has been estimated as $\sim 3 \times 10^{-13}$, but can be enhanced by new physics to as much as $\sim 4 \times 10^{-7}$ [37], possibly observable in BES-III as well as LHC*b*. The best current limit, 4.3×10^{-7} from CDF, already constrains SUSY models [46]. With some 2×10^{10} charm events produced and acceptance $\times$ efficiency ~ 0.05, our sensitivity could rival or exceed the 3×10^{-8} (at 90% C.L.) estimated for BES-III [37]. However, more work will be required (and is in progress) to assess the likely pion rejection from the TOF and calorimeter. Similar statements apply as well for other FCNC or LFV modes such as $K\mu\mu$, Kee, $K\mu e$, etc. For all of these modes, the best limit from any approved experiment is expected to come from BES-III and to be statistics (not systematics) -limited. In comparison, based on the assumptions used here, per year of operation, our proposed experiment will amass some 27 times the statistics of BES-III.

The benchmark emphasized in our previous note [41] was sensitivity to new physics via

Table 3: Assumed values and sensitivity-benchmark estimate of tagged $\overset{(-)}{D}{}^0 \to K^{\mp}\pi^{\pm}$ events per year. (Caveats: As discussed in text, the reliability of some of these values remains to be established. They are based on exclusive cross-section estimates, so the inclusive production rate could be significantly higher, but the cross section, luminosity, or efficiency could also be lower.) (From P-986 Addendum 1, "Antiproton Annihilation and Open Charm" [41]).

Quantity	Value	Unit
Running time	2×10^7	s/y
Duty factor	0.8*	
$\mathcal{L}$	2×10^{32}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Target A	27	
$A^{0.29}$	2.6	
$\sigma(\overline{p}p \to D^{*+}X)$	1.25	μb
# $D^{*\pm}$ produced	2.1×10^{10}	events/y
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.677	
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.0389	
Acceptance	0.5	
Efficiency	0.1	
Total	2.7×10^7	events/y

*Assumes $\approx 15\%$ of running time is devoted to antiproton-beam stacking.

charm *CP* violation, where partial-width sensitivities of 10^{-3} to 10^{-4} in Cabibbo-favored, and 1% in doubly-Cabibbo-suppressed, modes are of interest for detecting new physics, and, for time-dependent *CP* asymmetries, 10^{-4} and 10^{-3} in Cabibbo-favored and doubly Cabibbo-suppressed modes, respectively [37]. A sample of 2×10^7 reconstructed events in the Cabibbo-favored $D^0 \to K^-\pi^+$ mode does indeed probe partial widths at the few $\times 10^{-4}$ statistical level; however, at that level of precision, systematics will be paramount. A typical strategy has been to use any apparent asymmetry observed in the $K^{\mp}\pi^{\pm}$ mode instead as a measure of apparatus bias, and focus on the *normalized* doubly Cabibbo-suppressed partial-rate asymmetry,

$$\frac{\Gamma(D^0 \to K^+\pi^-) - \Gamma(\overline{D}^0 \to K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+) - \Gamma(\overline{D}^0 \to K^+\pi^-)}.$$

The uncertainty of this ratio should be dominated by the statistical uncertainty of the numerator, or 0.7% for 8×10^4 "wrong-sign" $\overset{(-)}{D}{}^0 \to K^{\pm}\pi^{\mp}$ reconstructed (corresponding to 2×10^7 observed, tagged, "right-sign" $\overset{(-)}{D}{}^0 \to K^{\mp}\pi^{\pm}$ events). The sensitivity will be further increased due to additional wrong-sign modes that will be observed, but could be worse if the charm cross section is smaller than assumed or if more stringent cuts than assumed are required in order to suppress background.

We hope to address these issues further in our oral presentation.

5 Conclusions

Further study bears out our contention that the experiment we propose is potentially capable of reconstructing the world's largest charm samples and making a high-impact measurement: the first observation of new physics in charm CP violation. It also has the potential to make the world's most precise measurements of the properties of the $X(3872)$, and to shed light on the mystery of that state's makeup and nature. These are examples of the broad physics program that can be carried out with a high-rate magnetic spectrometer at the world's best antiproton source.

We request support from Fermilab to proceed to a detailed study, including a more thorough and detailed program of simulations and evaluation of the cost of mounting and operating the experiment.

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[1] I.e., two nested solenoid windings, with opposite polarity, in one cryostat; see e.g. K. Sinokita, R. Toda, and Y. Sasaki, J. Phys.: Conf. Ser. **150**, 012041 (2009) and references therein.

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