Future CPT Tests at Fermilab

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ILLINOIS INSTITUTE OF TECHNOLOGY

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CPT'10

Indiana University

2 July 2010

Proposed Antiproton Experiments at Fermilab

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Outline

Varied menu!

- Symmetry violation tests with antiprotons
- Hyperon CP violation & rare decays
- A new experiment
- Charm & charmonium
- Antihydrogen measurements
- Competing proposals for the facility
- Summary

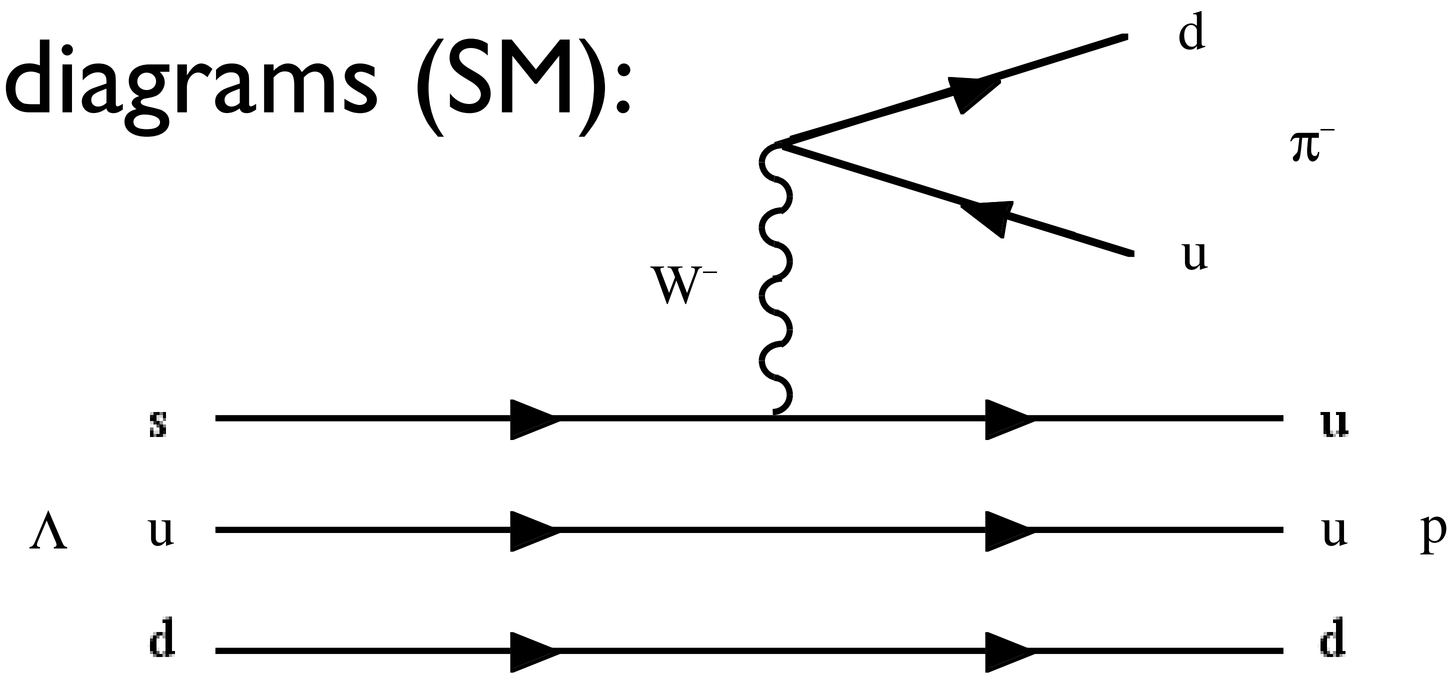
Symmetry Violation Tests with Antiprotons

- 3 proposed experimental programs:
  - medium-energy $\bar{p}$ annihilation
  - antihydrogen production in flight
  - slow antihydrogen
- Can search for
  - CP violation in charm and hyperons
  - CPT/Lorentz violation in charm and antihydrogen
  - CPT/Lorentz violation in antimatter gravity

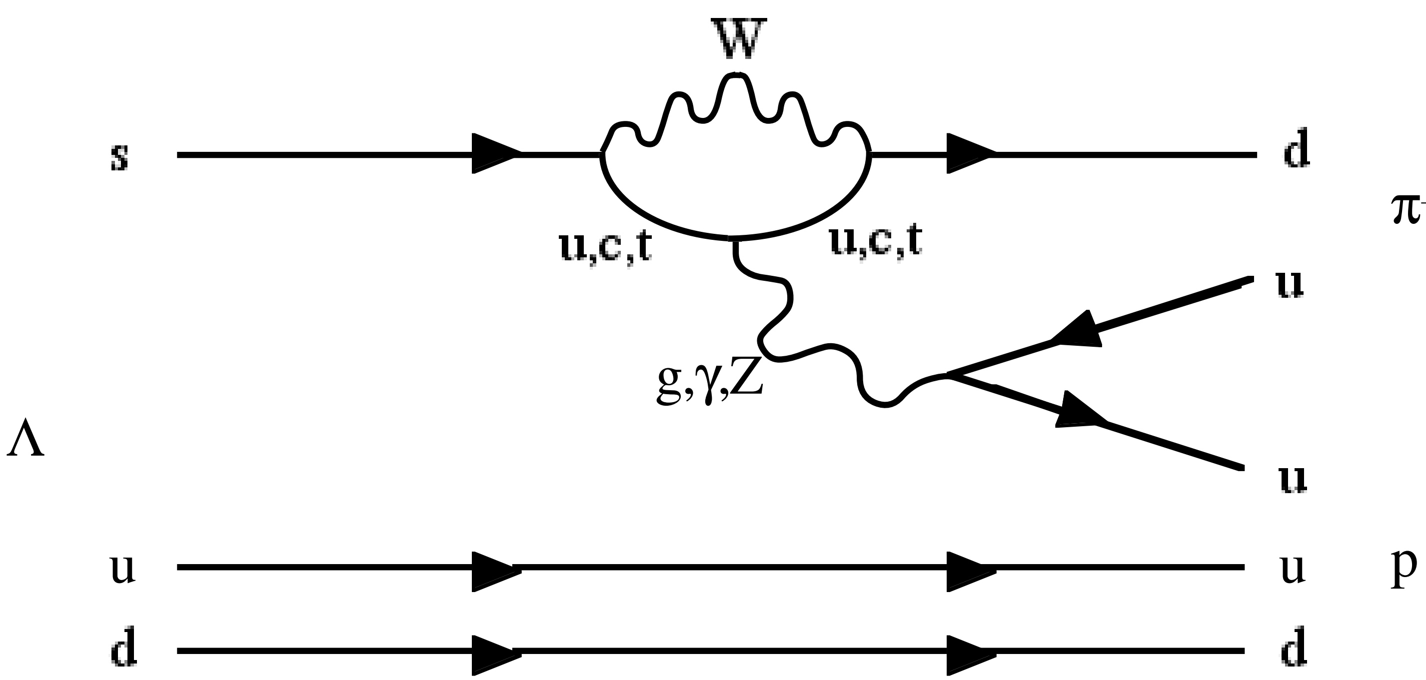
Hyperon CP Violation

- Example Feynman diagrams (SM):

Λ decay:



Λ penguin decay:



- "New physics" (SUSY, etc.) could also contribute!

Hyperon CP Violation

- CP-odd observables include $A \equiv \Delta\alpha/\alpha$, $\Delta \equiv \Delta\Gamma_F/\Gamma_F$
  - (anti)matter parity-violation or branching-ratio differences
- Standard Model predicts *small* hyperon CP asymmetries
- New physics can amplify them by orders of magnitude:

Table 5: Summary of predicted hyperon *CP* asymmetries.

Asymm.	Mode	SM	NP	Ref.
A_Λ	$\Lambda \to p\pi$	$\lesssim 10^{-5}$	$\lesssim 6 \times 10^{-4}$	[68]
$A_{\Xi\Lambda}$	$\Xi^\mp \to \Lambda\pi,\ \Lambda \to p\pi$	$\lesssim 5 \times 10^{-5}$	$\leq 1.9 \times 10^{-3}$	[69]
$A_{\Omega\Lambda}$	$\Omega \to \Lambda K,\ \Lambda \to p\pi$	$\leq 4 \times 10^{-5}$	$\leq 8 \times 10^{-3}$	[36]
$\Delta_{\Xi\pi}$	$\Omega \to \Xi^0\pi$	2×10^{-5}	$\leq 2 \times 10^{-4}$ *	[35]
$\Delta_{\Lambda K}$	$\Omega \to \Lambda K$	$\leq 1 \times 10^{-5}$	$\leq 1 \times 10^{-3}$	[36]

*Once they are taken into account, large final-state interactions may increase this prediction [56].

☞ Small sizes of $(A,\Delta)_{SM}$ favorable for NP CPV search!

Hyperon CP Violation

- Measurement history:

Experiment	Decay Mode	A_Λ	
R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$	**-0.02 ± 0.14**	[P. Chauvat et al., PL 163B (1985) 273]
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	**0.01 ± 0.10**	[M.H. Tixier et al., PL B212 (1988) 523]
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	0.006 ± 0.015	[P.D. Barnes et al., NP B 56A (1997) 46]

Experiment	Decay Mode	$A_\Xi + A_\Lambda$	
E756 at Fermilab	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**0.012 ± 0.014**	[K.B. Luk et al., PRL 85, 4860 (2000)]
E871 at Fermilab (HyperCP)	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**$(0.0 \pm 6.7) \times 10^{-4}$**	[T. Holmstrom et al., PRL 93. 262001 (2004)]
		$(-6 \pm 2 \pm 2) \times 10^{-4}$	[BEACH08 preliminary]

Hyperon CP Violation

- Measurement history:

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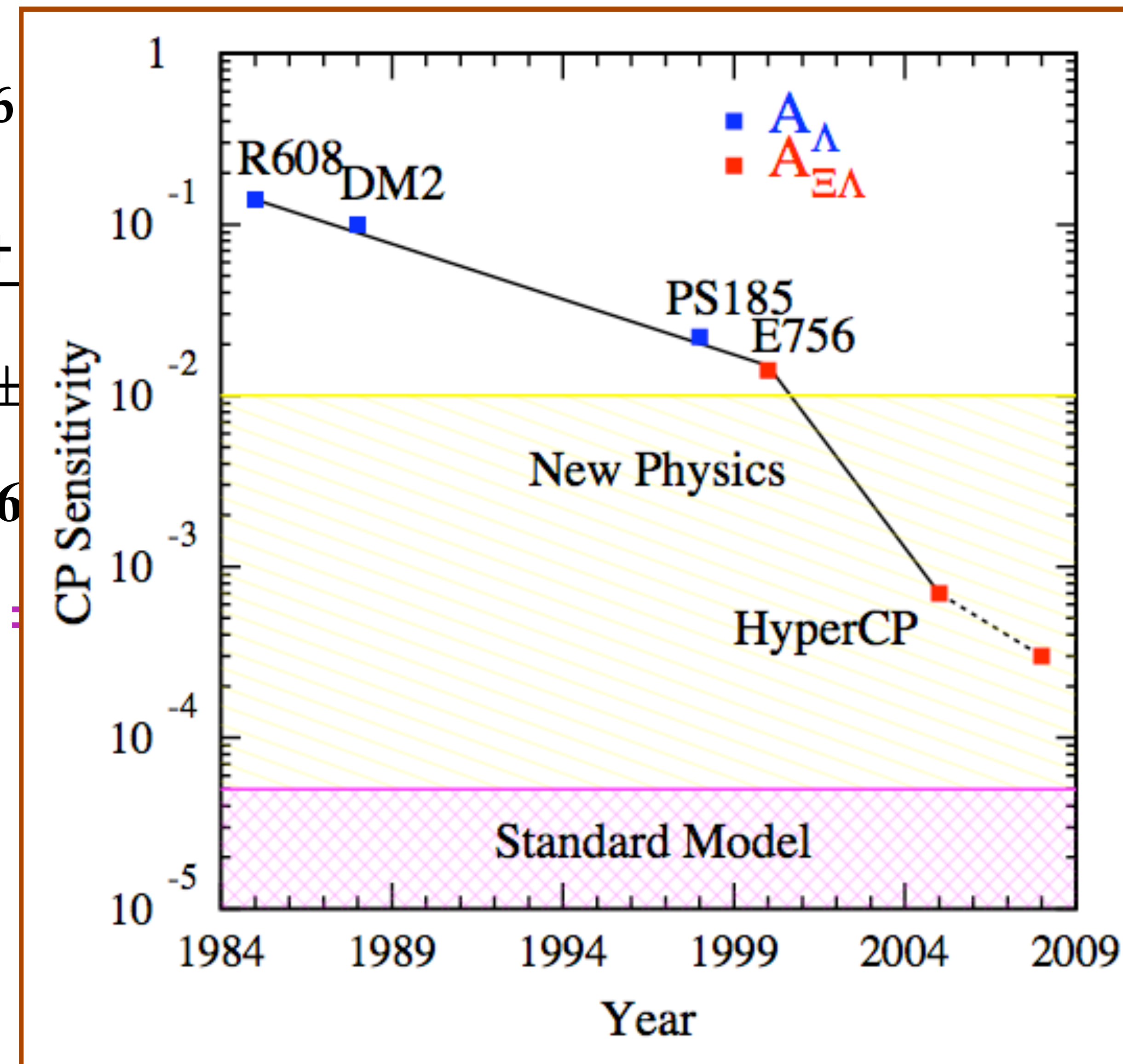
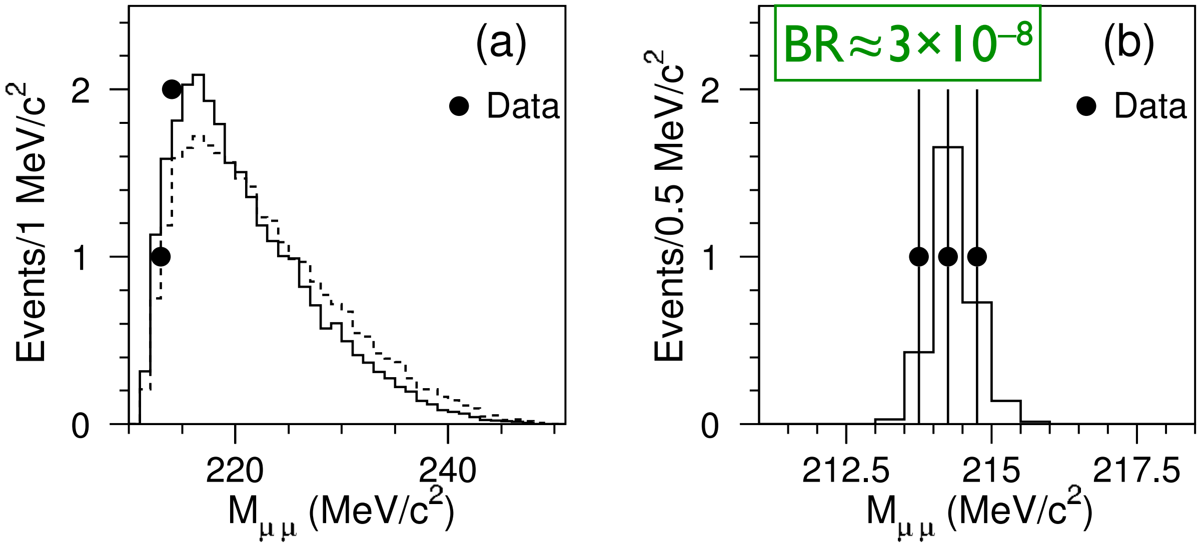
Experiment	Decay Mode	$A_\Xi +$
E756 at Fermilab	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**0.012 ±**
E871 at Fermilab (HyperCP)	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**(0.0 ± 6**
		(-6 ± 2 :





$\Sigma^+ \to p\mu^+\mu^-$ Decay

$\approx 2.4\sigma$ fluctuation of SM? or

- SUSY Sgoldstino?
- SUSY light Higgs?

PRL **98,** 081802 (2007) PHYSICAL REVIEW LETTERS week ending 23 FEBRUARY 2007

Does the HyperCP Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$ Indicate a Light Pseudoscalar Higgs Boson?

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(Received 2 November 2006; published 22 February 2007)

The HyperCP Collaboration has observed three events for the decay $\Sigma^+ \to p\mu^+\mu^-$ which may be interpreted as a new particle of mass 214.3 MeV. However, existing data from kaon and B-meson decays provide stringent constraints on the construction of models that support this interpretation. In this Letter we show that the "HyperCP particle" can be identified with the light pseudoscalar Higgs boson in the next-to-minimal supersymmetric standard model, the A_1^0. In this model there are regions of parameter space where the A_1^0 can satisfy all the existing constraints from kaon and B-meson decays and mediate $\Sigma^+ \to p\mu^+\mu^-$ at a level consistent with the HyperCP observation.

Beyond HyperCP?

- Measurement history:

Experiment	Decay Mode	A_Λ	
R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$	**-0.02 $\pm$ 0.14**	[P. Chauvat et al., PL 163B (1985) 273]
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	**0.01 $\pm$ 0.10**	[M.H. Tixier et al., PL B212 (1988) 523]
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Experiment	Decay Mode	$A_\Xi + A_\Lambda$	
E756 at Fermilab	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**0.012 $\pm$ 0.014**	[K.B. Luk et al., PRL 85, 4860 (2000)]
E871 at Fermilab (HyperCP)	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**$(0.0 \pm 6.7) \times 10^{-4}$**	[T. Holmstrom et al., PRL 93. 262001 (2004)]
		$(-6 \pm 2 \pm 2) \times 10^{-4}$	[BEACH08 preliminary]

- Note: until ~2000, LEAR (CERN AD predecessor) had world's best sensitivity

➡ is $\bar{p}$ annihilation capable of further advance?

Antiprotons

- Fermilab Antiproton Source is world's highest-energy and most intense

Table 1: Antiproton energies and intensities at existing and future facilities.

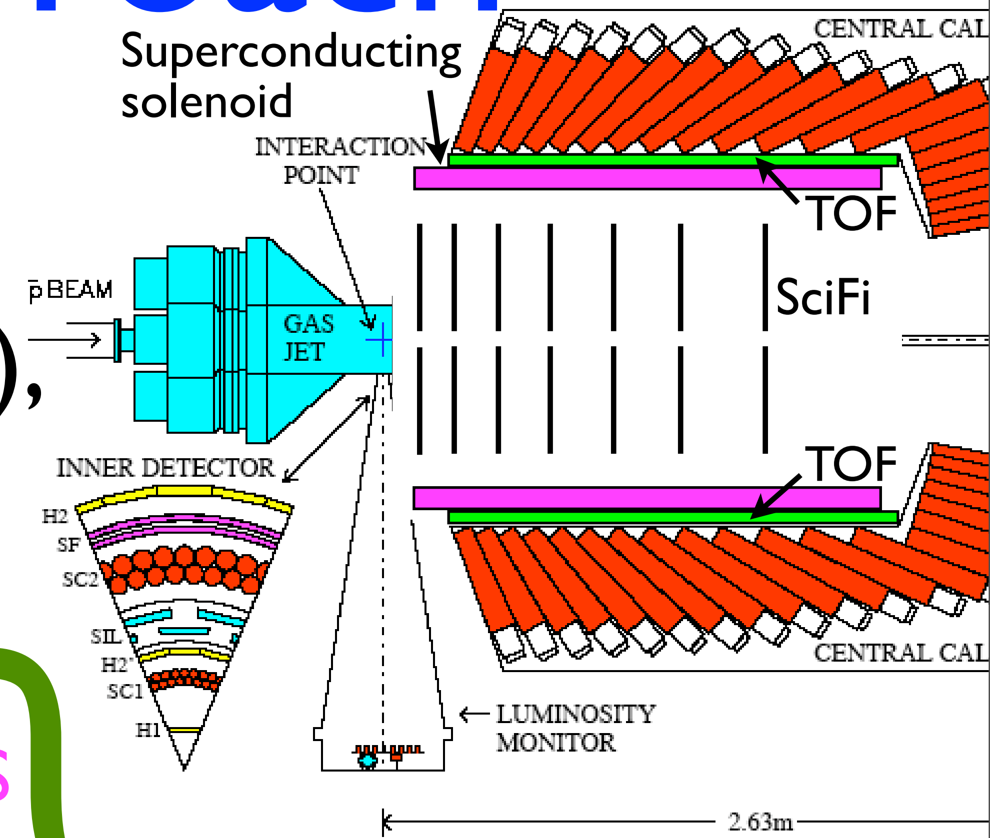
Facility	$\overline{p}$ Kinetic Energy (GeV)	Stacking: Rate (10^{10}/hr)	Stacking: Duty Factor	Operation: Hours /Yr	Operation: $\overline{p}$/Yr (10^{13})
CERN AD	0.005 0.047	–	–	3800	0.4
Fermilab Accumulator:					
now	8	20	90%	5550	100
proposed	$\approx$3.5–8	20	15%	5550	17
FAIR ($\gtrsim$ 2018)	2–15	3.5	90%	2780*	9

…even after FAIR@Darmstadt turns on

➡ exceeds LEAR $\overline{p}$ intensity (<1 MHz) by 10 orders of magnitude!

A Possible Approach

One possibility:



- Once Tevatron shuts down (≈2011?),
  - Reinstall E760 EM spectrometer
  - Add small magnetic spectrometer
  - Add precision TOF system
  - Add wire or pellet target
  - and fast DAQ system
  - Run $p_{\bar{p}}$ = 5.4 GeV/c ($2m_\Omega < \sqrt{s} < 2m_\Omega + m_{\pi^0}$) @ $\mathcal{L} \sim 10^{32}$ cm^{-2} s^{-1} (10 × E835)

[∃ing BESS solenoid & DØ SciFi DAQ] } ≲$5M

➡ ~ few10^8 $\Omega^- \overline{\Omega}^+$/yr + ~$10^{12}$ inclusive hyperon events!

What Can This Do?

- Observe many more $\Sigma^+ \to p\mu^+\mu^-$ events and confirm or refute SUSY interpretation

- Discover or limit $\Omega^- \to \Xi^-\mu^+\mu^-$ and confirm or refute SUSY interpretation

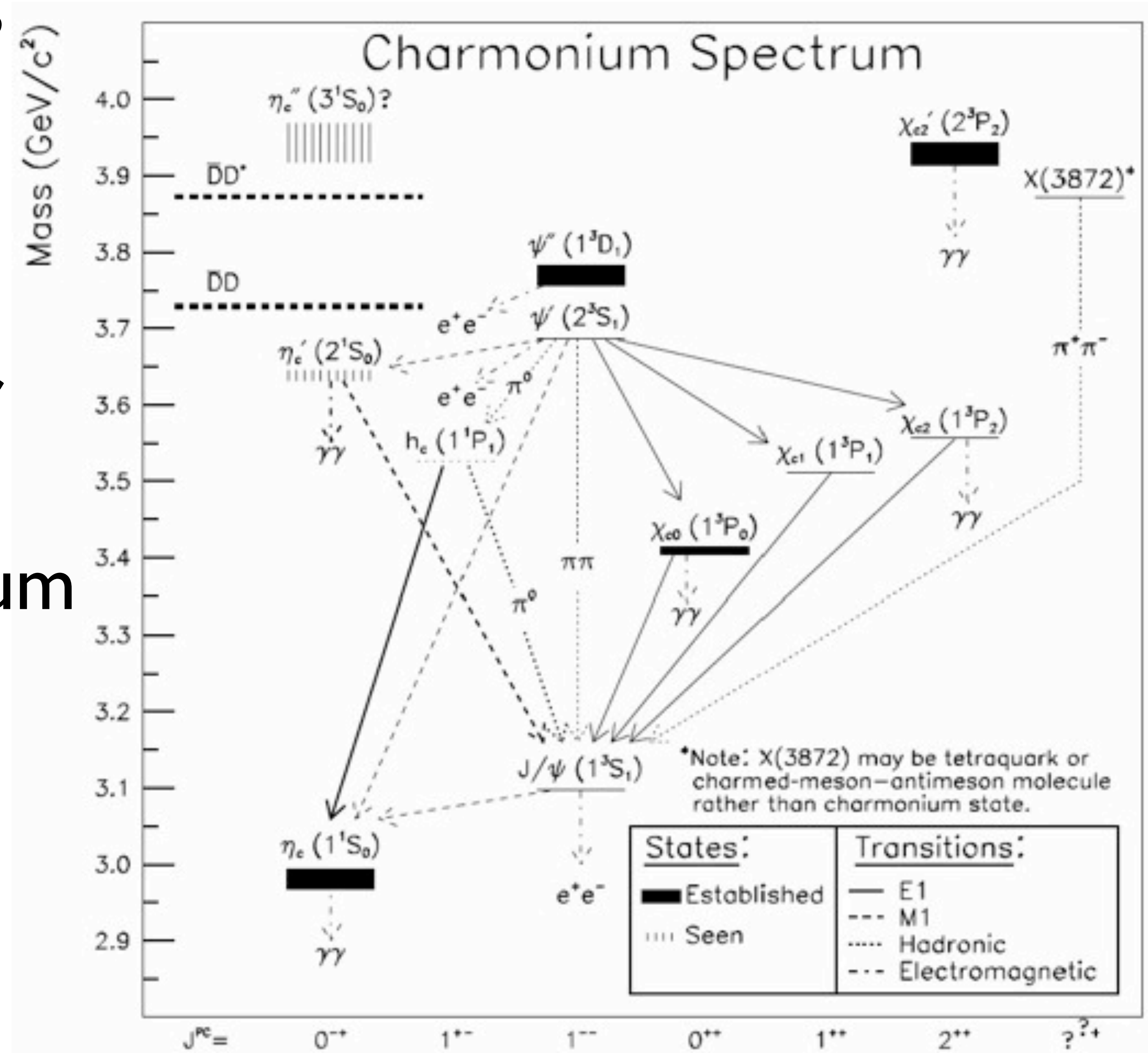
Predicted $\mathcal{B} \sim 10^{-6}$ if P^0 real

- Discover or limit CP violation in $\Omega^- \to \Lambda K^-$ and $\Omega^- \to \Xi^0\pi^-$ via partial-rate asymmetries

Predicted $\Delta\mathcal{B} \sim 10^{-5}$ in SM, $\lesssim 10^{-3}$ if NP

What Else Can This Do?

- Also good for "charmonium" ($c\bar{c}$ QCD "hydrogen atom"):
  - Fermilab E760/835 used Antiproton Accumulator for precise (≲100 keV) measurements of charmonium parameters, e.g.:
    - best measurements of η_c, χ_c, h_c masses, widths, branching ratios,...



  - $\bar{p}p$ produces all quantum states (not just 1^{--}, unlike e^+e^-)

What Else Can This Do?

- Much interest in mysterious states recently discovered in charmonium region: $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, $Z(3930)$,...
- $X(3872)$ of particular interest – may be the first meson-antimeson ($D^0\,\overline{D}^{*0}$ + c.c.) molecule

➡ need very precise mass & width measurement to confirm or refute

➡ $\bar{p}p \to X(3872)$ formation *ideal* for this

Charm!

PHYSICAL REVIEW D **77**, 034019 (2008)

Estimate of the partial width for $X(3872)$ into $p\bar{p}$

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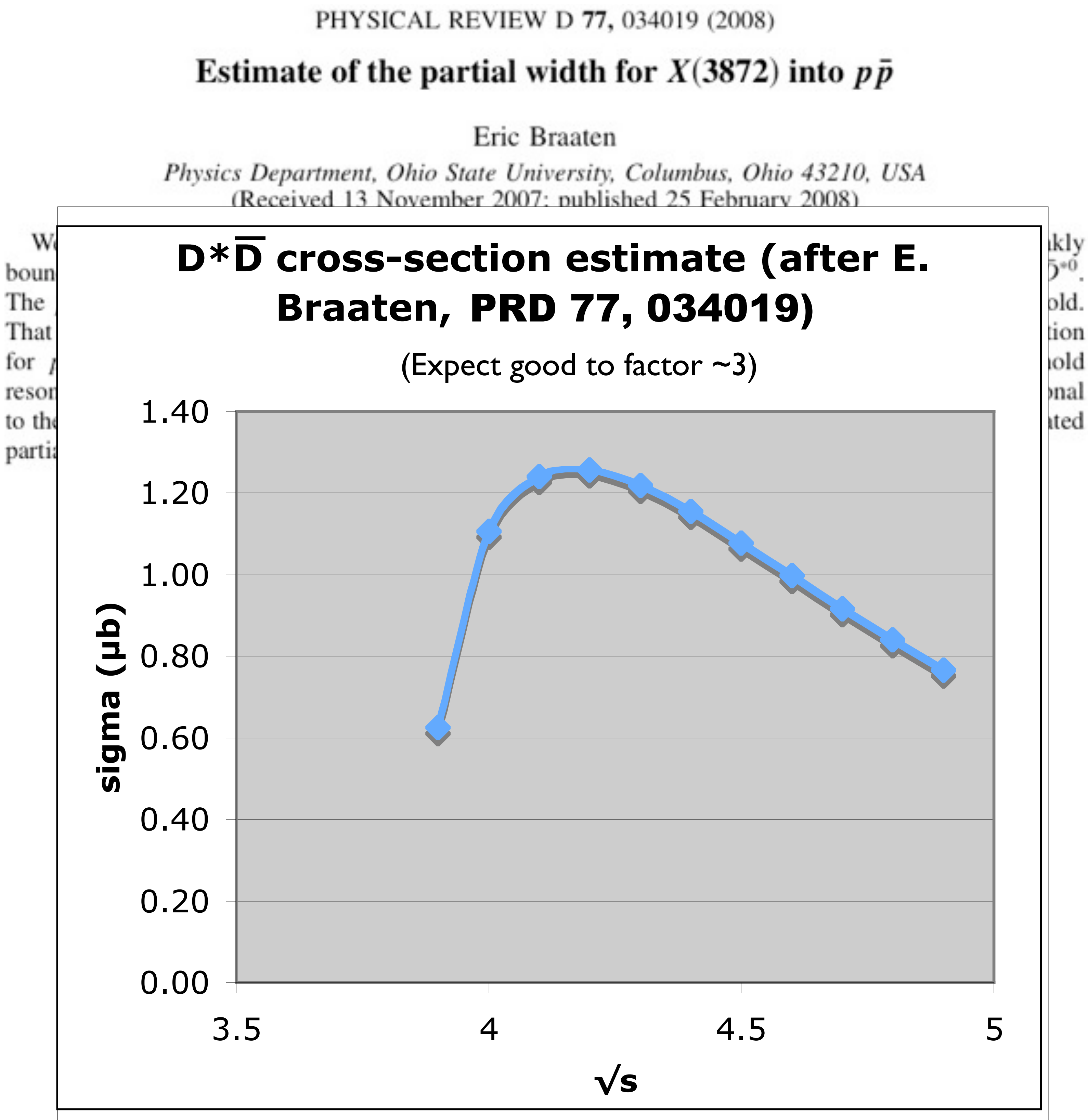
(Received 13 November 2007; published 25 February 2008)

We present an estimate of the partial width of $X(3872)$ into $p\bar{p}$ under the assumption that it is a weakly bound hadronic molecule whose constituents are a superposition of the charm mesons $D^{*0}\bar{D}^0$ and $D^0\bar{D}^{*0}$. The $p\bar{p}$ partial width of X is therefore related to the cross section for $p\bar{p} \to D^{*0}\bar{D}^0$ near the threshold. That cross section at an energy well above the threshold is estimated by scaling the measured cross section for $p\bar{p} \to K^{*-}K^+$. It is extrapolated to the $D^{*0}\bar{D}^0$ threshold by taking into account the threshold resonance in the 1^{++} channel. The resulting prediction for the $p\bar{p}$ partial width of $X(3872)$ is proportional to the square root of its binding energy. For the current central value of the binding energy, the estimated partial width into $p\bar{p}$ is comparable to that of the P-wave charmonium state χ_{c1}.

- E. Braaten estimate of $\bar{p}p$ $X(3872)$ coupling assuming X is D^*D molecule
  - extrapolates from K^*K data
- By-product is $D^{*0}\bar{D}^0$ cross section

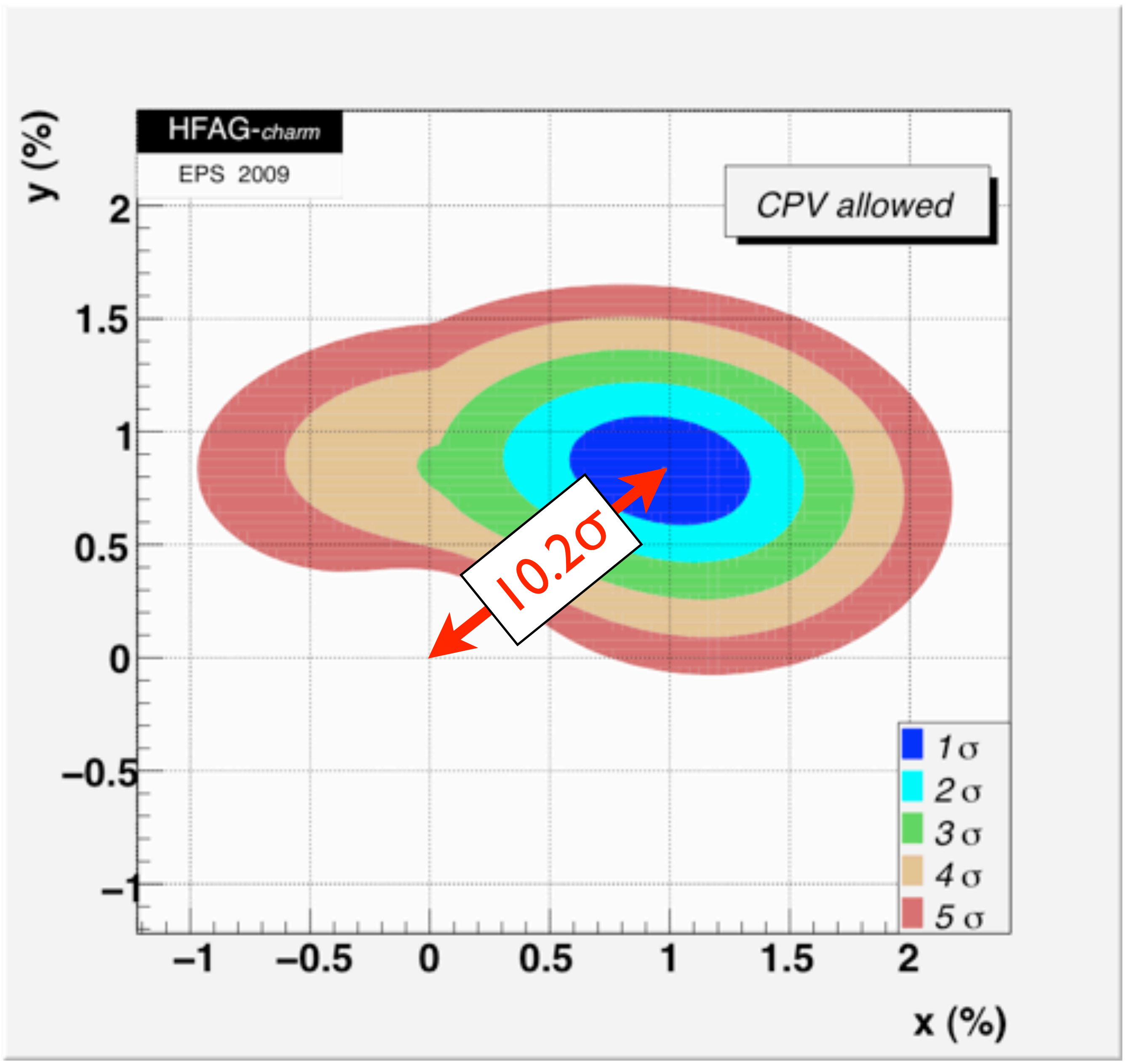
Charm!



- E. Braaten estimate of $\bar{p}p$ $X(3872)$ coupling assuming X is D^*D molecule
  - extrapolates from K^*K data
- By-product is $D^{*0}\overline{D}^0$ cross section
- 1.3 μb → 5 ×10⁹/year
- Expect efficiency as at *B* factories

Charm!

- *What's so exciting about charm?*
  - *D*^{0}'s mix! (*c* is only up-type quark that can)



- *Big question:*
  New Physics or old?

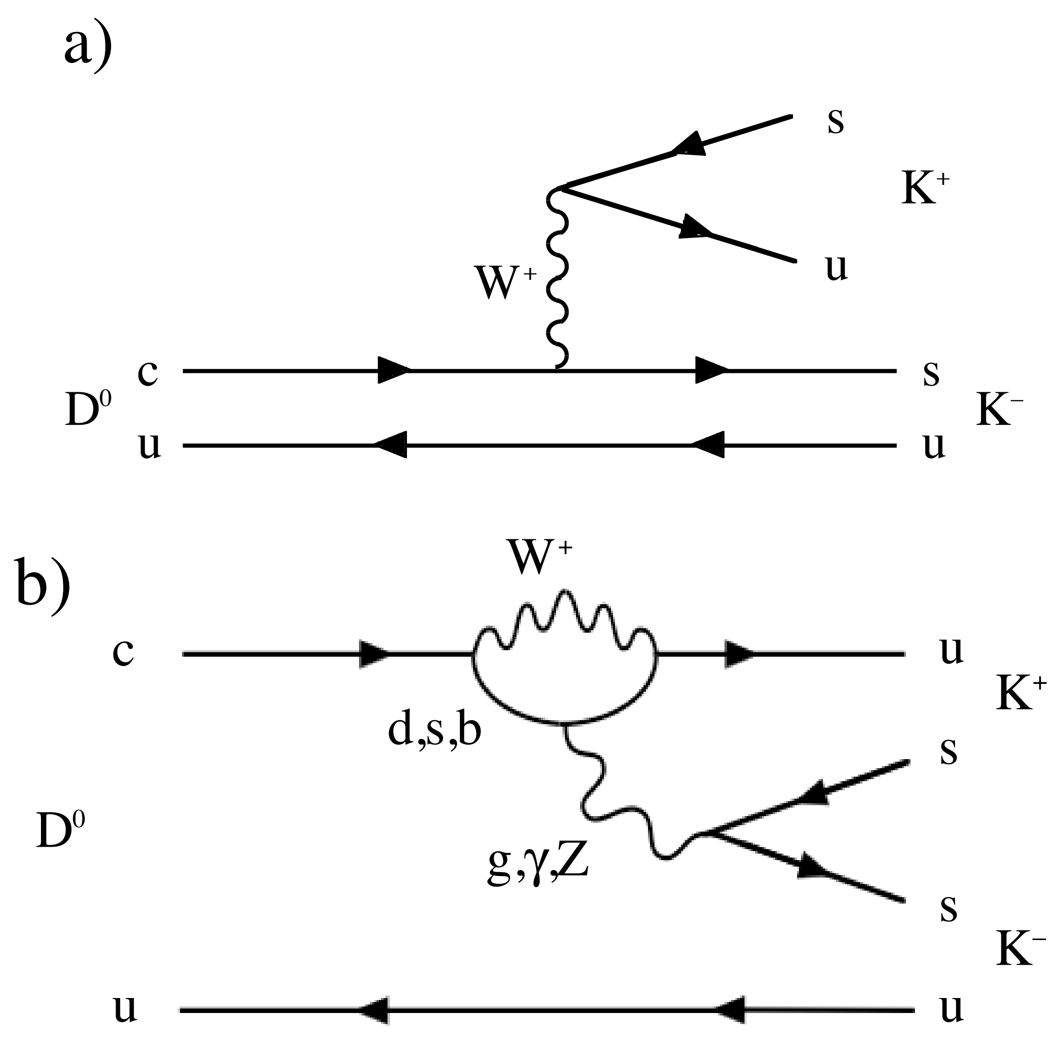
➡ key is CP Violation!

- *B* factories have ~10^9 open-charm events
- can $\bar{p}p$ produce ~10^{10}/y?

Charm!

- *What's so exciting about charm?*
  - *D*^{0}'s mix! (*c* is only up-type quark that can)

Singly Cabibbo-supressed (CS) *D* decays have 2 competing diagrams:



- *Big question:* New Physics or old?

➡ key is CP Violation!

- *B* factories have ~10^9 open-charm events
- can $\bar{p}p$ produce ~10^{10}/y?

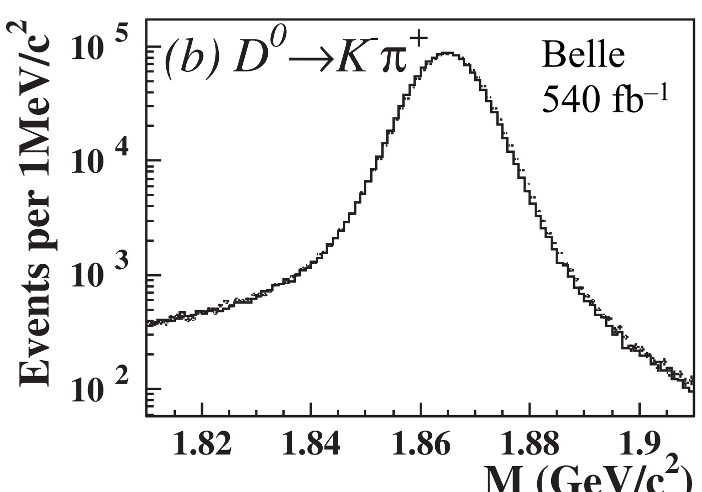
➡ world's best sensitivity to charm CPV

Charm!

- Ballpark sensitivity estimate based on Braaten formula:

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 (Al)	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

- Compare with 1.22×10^6 total tagged evts at Belle [M. Staric et al., PRL **98**, 211803 (2007)]



(LHC*b* will have comparable statistics but diff't systematics)

Testing CPT/LV with Charm

- SME limits from FNAL FOCUS Expt. [J.M. Link *et al.*, PLB **556** (2003) 7]:

$$(-2.8 < N(x,y,\delta)(\Delta a_0 + 0.6\Delta a_Z) < 4.8) \times 10^{-16} \text{ GeV}$$
$$(-7.0 < N(x,y,\delta)\Delta a_X < 3.8) \times 10^{-16} \text{ GeV}$$
$$(-7.0 < N(x,y,\delta)\Delta a_Y < 3.8) \times 10^{-16} \text{ GeV}$$

  - based on ≈2×10^4 right-sign D^0 and $\overline{D}^0$ decays

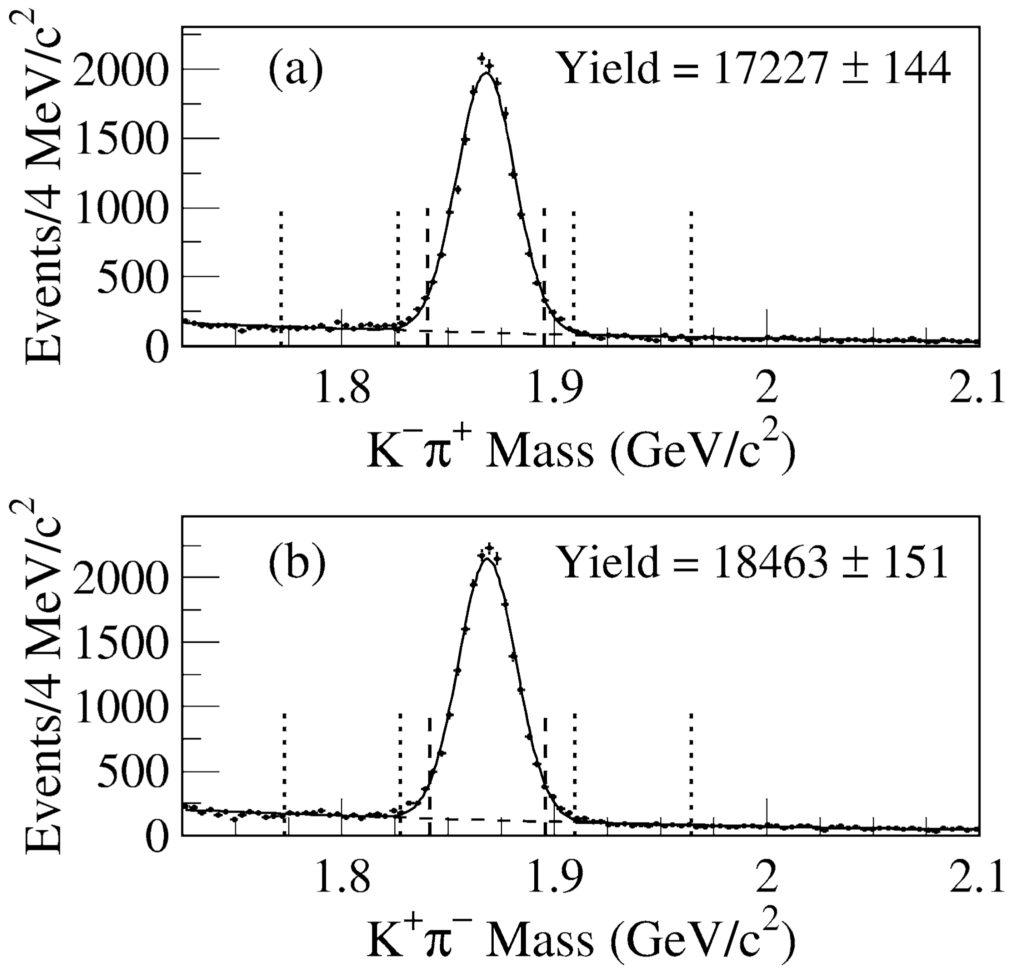


Fig. 1. Invariant mass of ($D^0 \to K^-\pi^+$ (a); $\overline{D}^0 \to K^+\pi^-$ (b)) for data (points) fitted with a Gaussian signal and quadratic background (solid line). The vertical dashed lines indicate the signal region, the vertical dotted lines indicate the sideband region.

- We hope for ×10^3 increase in sample size

- But effects ∝ γ ≈ 2, 20 × smaller than in FOCUS ⇒ sensitivities likely comparable

  (but we can do better now that mixing measured)

Charm?

- Another possibility (E. Braaten): use the $X(3872)$ as a pure source of correlated $D^{*0}\overline{D}^0$ events
  - the $\overline{p}p$ equivalent of the $\psi(3770)$!?
  - assuming current Antiproton Accumulator parameters ($\Delta p/p$) & Braaten estimate, produce ~10^8 events/year
  - comparable to BES-III statistics
  - could gain factor ~5 via AA e^- cooling?
- Proposed expt will establish feasibility & reach

Antiydrogen

CPT test using relativistic antihydrogen

[D. Christian, FNAL]

- Antihydrogen is produced in the gas-jet target - exits the Accumulator in the ground state.
  - 99 antihydrogen atoms were observed by E862 with 0 background.
- The atoms enter a 7kG magnet and a large fraction are excited to N=2 long-lived Stark state by laser light.
- Atoms exit magnet & pass through a field-free region, then enter a second magnet with field 6-8 kG. The mixture of N=2 Stark states in the second magnet depends on the time spent in the field-free region, the fine structure, and the Lamb shift.
- Distribution of field ionization in the second magnet reflects probability of being in each of the three N=2 Stark states.
- Monte Carlo —–> an experiment in which 100 atoms exit the first magnet in N=2,L will yield a 1% measurement of the fine structure and a 5% measurement of the Lamb shift. Assuming that only the 2S level is shifted by a CPT violating force, the 1σ sensitivity is 50 parts per billion of the 2S binding energy.

Antiydrogen

- Parasitic running appears feasible

  $\Longrightarrow$ need not wait for end of Tevatron program

- High-Z foil installed, operable in Antiproton Accumulator beam halo

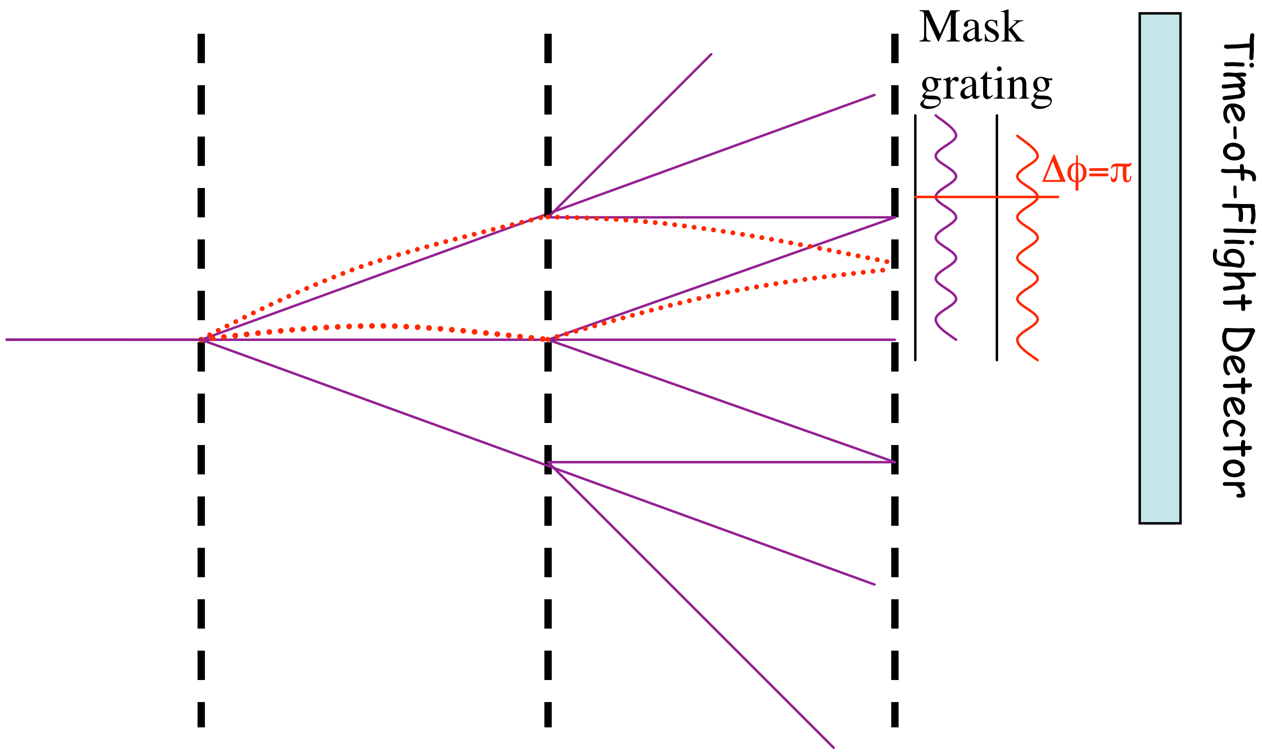
- Next need to install thin exit window (this shutdown)

- Could subsequently assemble spectroscopy apparatus (magnets, laser, detectors) and begin shakedown and operation

- Hope for few-per-10^9 precision with respect to 2S binding energy

Antimatter Gravity

- Experimentally, unknown whether antimatter falls up or down! Or whether $g - \bar{g} = 0$ or ε. Or (IPM) $0.5g$? [AK&JT]
  - in principle a simple interferometric measurement with slow $\bar{H}$ beam [T. Phillips, Hyp. Int. 109 (1997) 357]:



- ~10^{-4} feasible with matter gratings
- ~10^{-9} with laser interferometer

- Not nutty!

→ $\bar{g} = -g$ gives natural explanations for baryon asymmetry & dark energy

→ $\bar{g} = g + \varepsilon$ natural in quantum gravity due to scalar & vector terms

→ tests for possible "5th forces"

Antiproton Source Futures

- With end of Tevatron Collider in sight, many are viewing Antiproton Source as generic resource:
  - 2 large-acceptance 8 GeV rings
    - can they be reconfigured to enable $\mu 2e$, $g-2$, etc.?
- This ignores large, unique value for $\overline{p}$ physics!
  - with >1 G€ expenditure in progress on FAIR, can cannibalizing FNAL pbar source truly be sensible??
- Nevertheless, μ2e may eliminate FNAL pbar option starting around 2017
  - leaves at least 4–5-year window of opportunity during which FNAL $\overline{p}$ capabilities are unique in the world

Letters of Intent

- Initial Letters of Intent prepared in ’08, revised ’09
- Physics Advisory C’tee & Director Oddone:

1. Interesting physics!
2. Antimatter Gravity: need 10^{-9} matter demonstration before FNAL can provide support
    - Techniques for 10^{-9} matter demonstration under development (M. Raizen *et al*., UT Austin)
3. Antiproton Annihilation: can be considered further at this time only if cost to Lab is minimal
    - Proposal in development – Lab funding not essential

Summary

- Best experiment yet on hyperons, charm, and charmonia may soon be feasible at Fermilab
  - including world's most sensitive charm CPV study
- Unique tests of CPT symmetry & antimatter gravity may be starting up soon
- pbar Source offers simplest way for Fermilab to have broad program in post-Tevatron era

➡ Please help spread the word! (Want to join?)

(See http://capp.iit.edu/hep/pbar/)