Opportunity: Intensity-Frontier Antiproton Physics at Fermilab

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Outline

(Varied menu!)

- Antiproton sources
- A new experiment
- Hyperon CP violation
- Issues in charmonium
- Charm mixing & CPV
- Impact and cost
- Summary

Capsule summary:

- Fermilab has the world's best antiproton source ever
- After Tevatron shutdown, approved Fermilab physics program is *very* narrow
- Exploiting the Antiproton Source for low- and medium-energy antiproton physics can cost-effectively provide a broad physics program
- Exciting discoveries are possible

Antiproton Sources

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

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:					
current operation	8	>25	90%	5550	>150
proposed here	≈ 3.5–8	20	15%	5550	17
FAIR ($\gtrsim 2018$*)	1–14	3.5	15%*	2780*	1.5

...even after GSI FAIR turns on (has yet to break ground)

Apparatus

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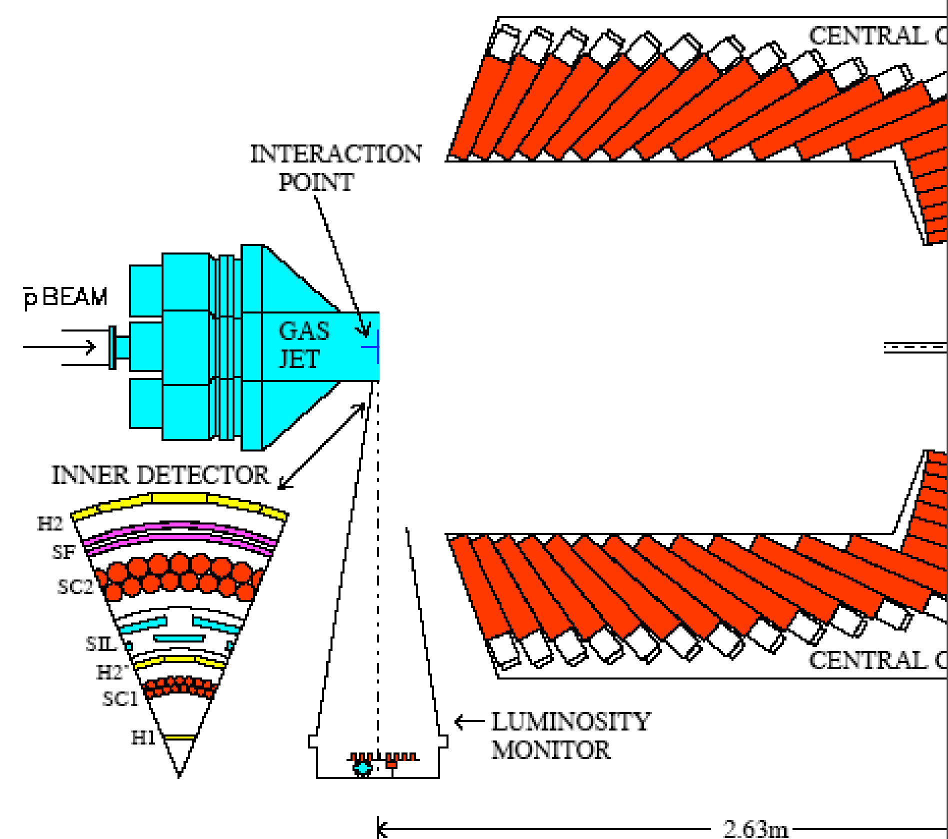
  - Reinstall E760 barrel calorimeter



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- After Tevatron finishes,
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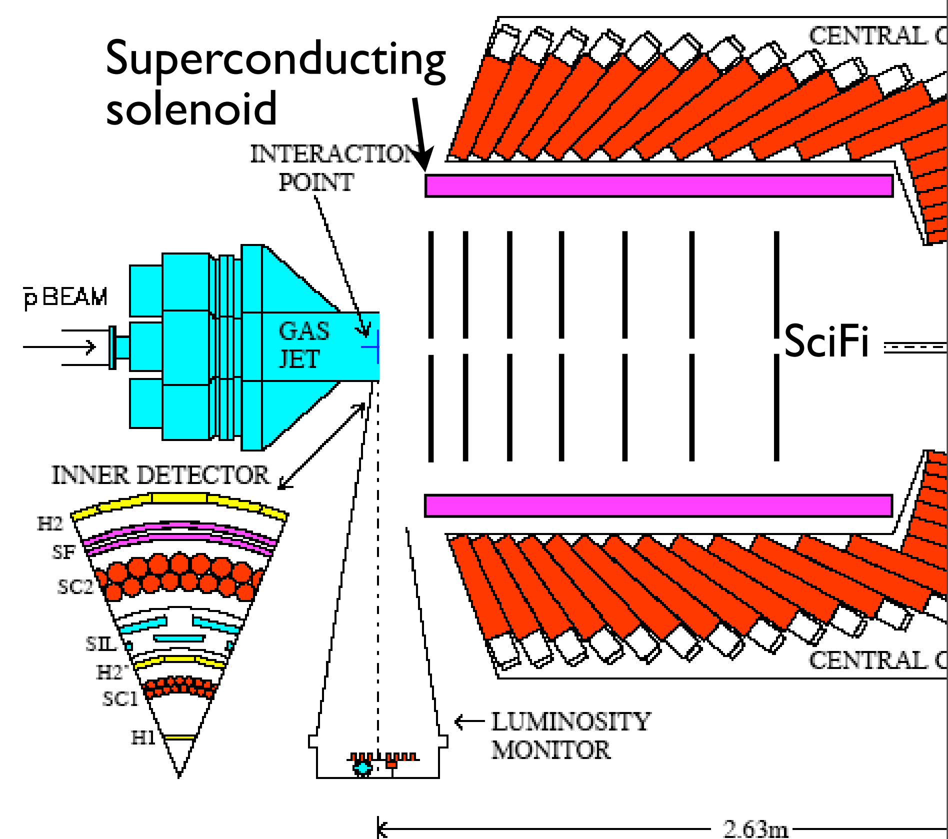
  - Add small magnetic spectrometer

[existing BESS magnet from KEK & SciFi DAQ from DØ



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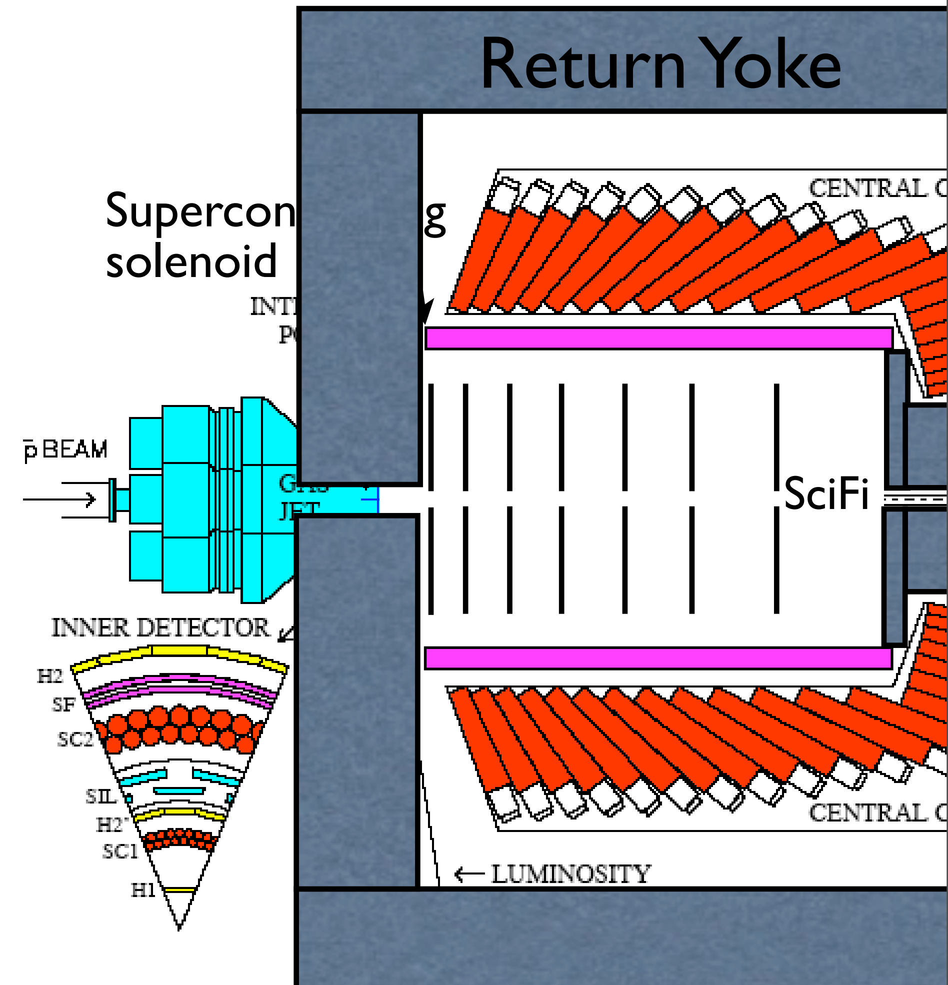
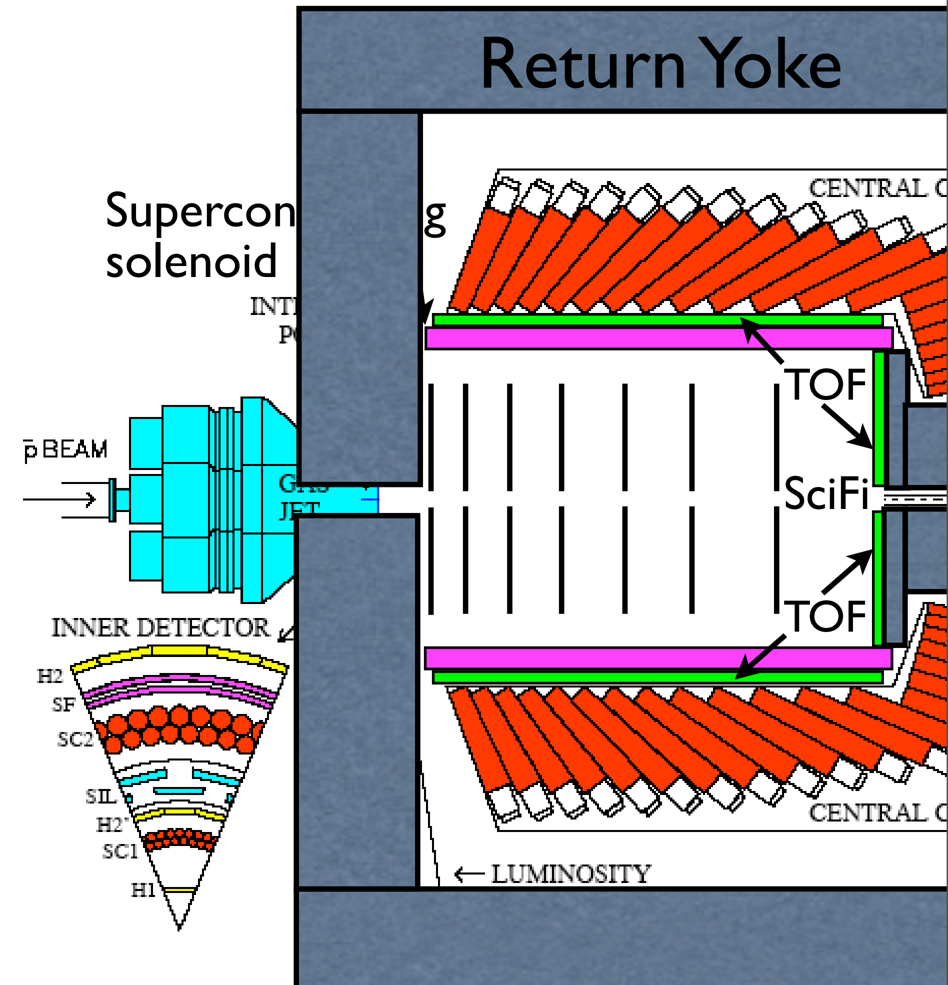


Apparatus

- After Tevatron finishes,
  - Reinstall E760 barrel calorimeter
  - Add small magnetic spectrometer
  - Add precision TOF system
  - Add thin targets
  - Add fast trigger & DAQ systems

[existing BESS magnet from KEK & SciFi DAQ from DØ & FNAL iron]



Cost Estimate

- *Very* cost-effective:

Item	Cost (k$)	Contingency (k$)
Targets	430	160
Luminosity monitor	60	20
Scintillating-fiber tracking system	1,820	610
Time-of-Flight system*	500	500
Triggering	1,390	460
Data acquisition system	490	153
Infrastructure	1,350	550
TOTALS	6,040	2,450

- Thx to existing: calorimeter, solenoid, SciFi readout system, trigger & DAQ electronics

Physics Case

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in a nutshell:

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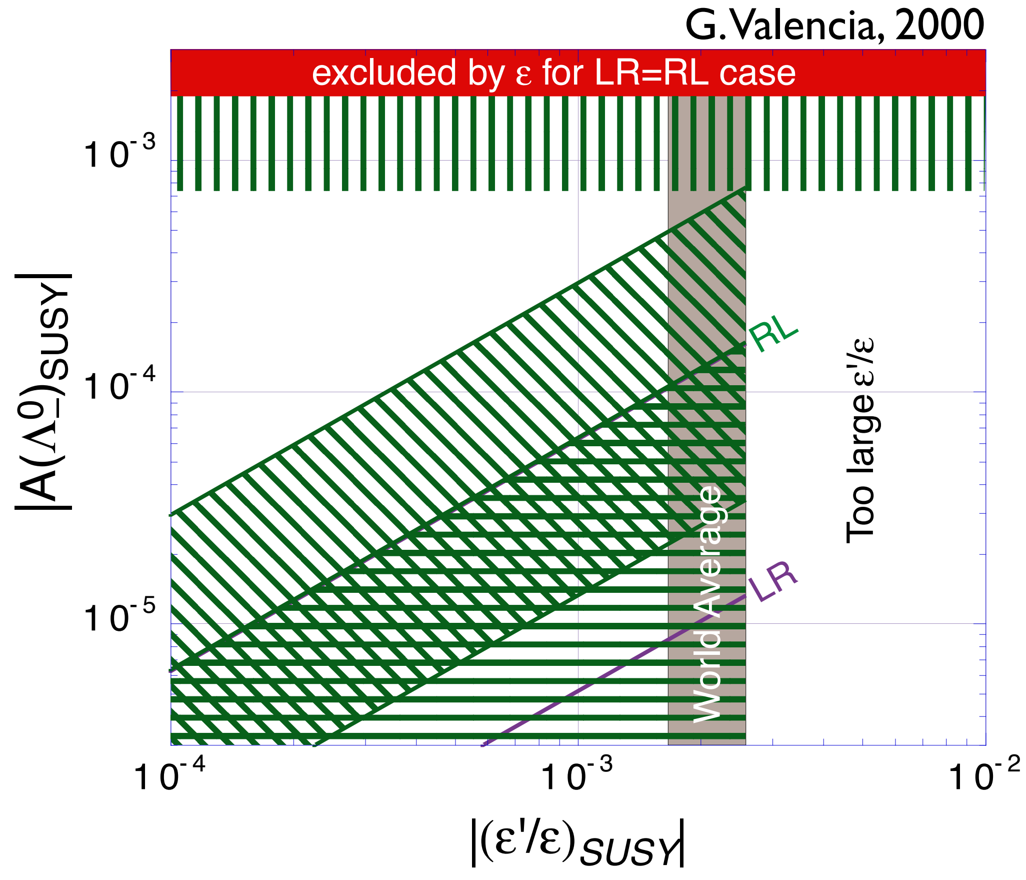
- Charmonium-like mystery states (*XYZ*...)
- Other...

Hyperon CP Violation

- Differently sensitive to new physics than *B* CPV, ε′/ε (parity-*conserving* interactions)
  - complementary to mu2e
- B factories have shown *B* mixing & CPV dominantly SM

  ⇒ worth looking elsewhere!



- Leading potential signals are A_Λ, $A_{\Xi\Lambda}$, B_Ξ, Δ_Ω:

$$A \equiv \frac{\alpha_\Lambda + \overline{\alpha}_\Lambda}{\alpha_\Lambda - \overline{\alpha}_\Lambda},\ B \equiv \frac{\beta_\Lambda + \overline{\beta}_\Lambda}{\beta_\Lambda - \overline{\beta}_\Lambda},\ \Delta \equiv \frac{\Gamma_{\Lambda\to p\pi} - \overline{\Gamma}_{\Lambda\to p\pi}}{\Gamma_{\Lambda\to p\pi} + \overline{\Gamma}_{\Lambda\to p\pi}}$$

CP-odd

- $\overline{p}$ source can produce ~10^8 $\Omega^- \overline{\Omega}^+$, & maybe ~$10^{10}$ $\Xi^- \overline{\Xi}^+$ (transition crossing)

Hyperon CP Violation

- SM predicts small CP asymmetries in hyperon decay
- NP 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]
$A_{\Xi\Lambda}$	$\Xi^\mp \to \Lambda\pi,\ \Lambda \to p\pi$	$\lesssim 0.5 \times 10^{-4}$	$\leq 1.9 \times 10^{-3}$	[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].

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 $\pm$ 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]
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	**0.006 $\pm$ 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 $\pm$ 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; PRL in prep]

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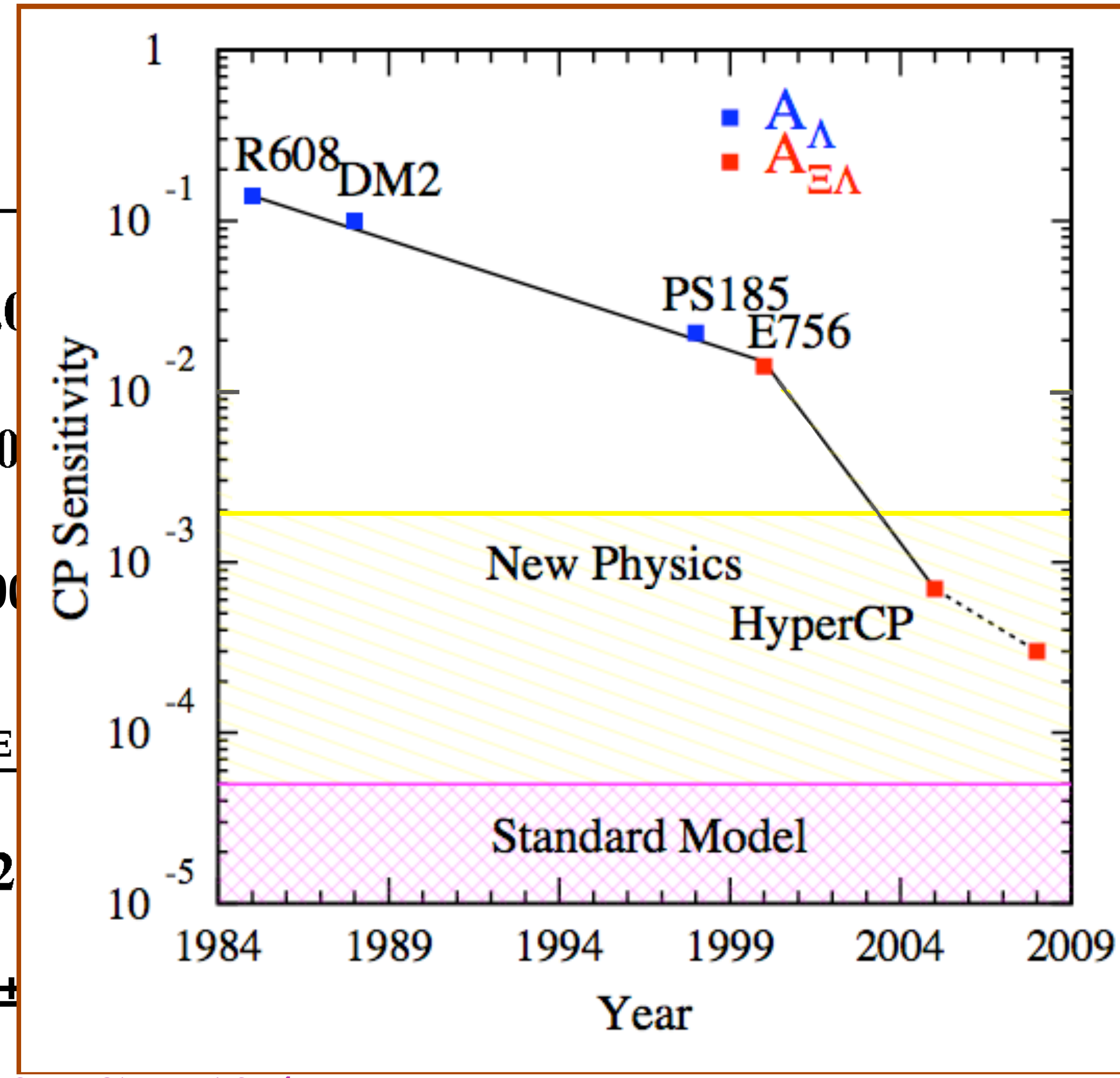

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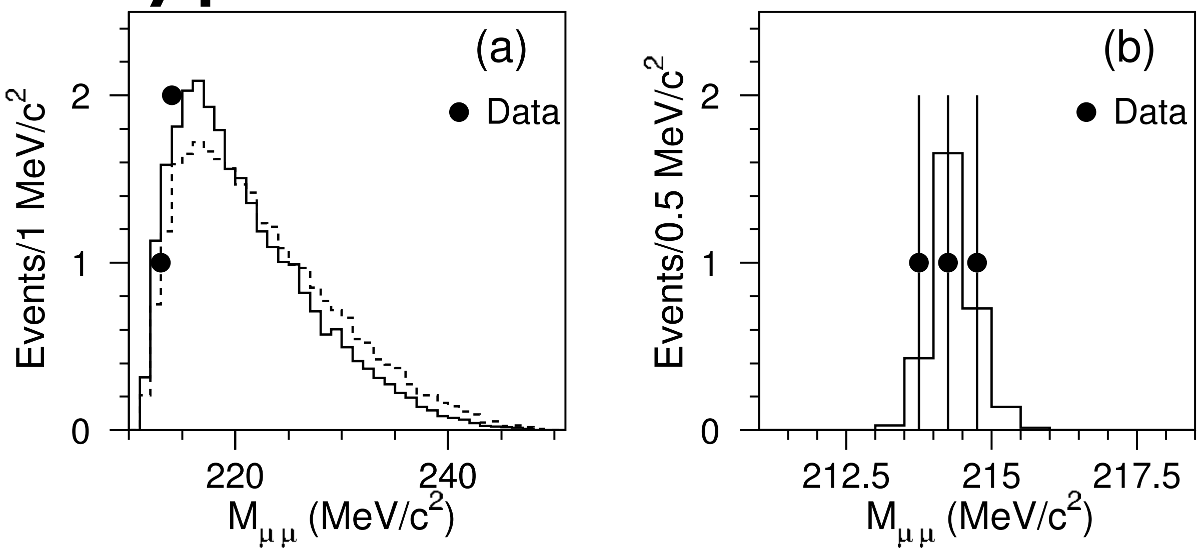
HyperCP also → 10^{10} Σ^+

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



≈2.4σ fluctuation of SM? or

- SUSY Sgoldstino?
- SUSY light Higgs?
- other pseudo-scalar or axial-vector state?

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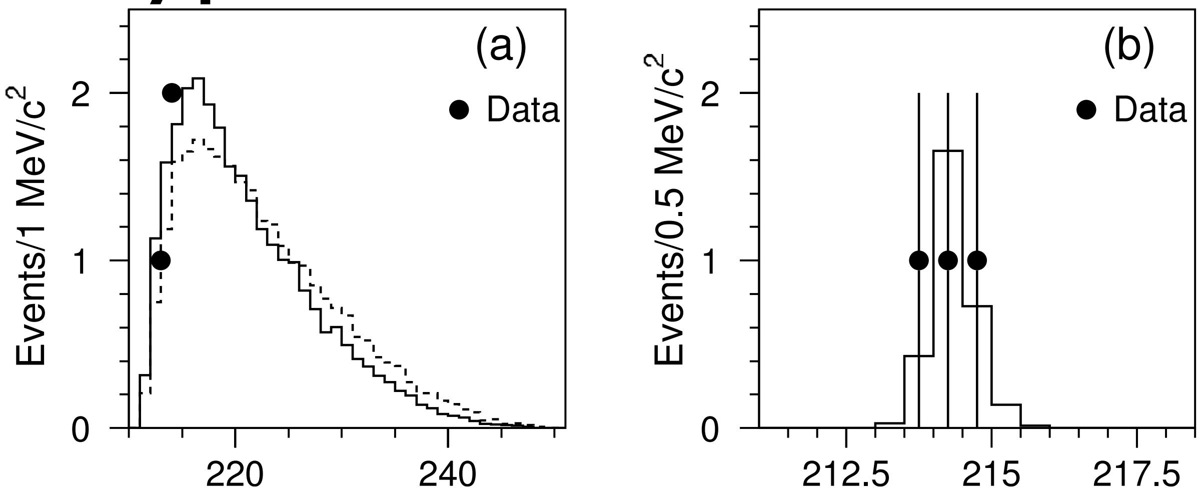

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PRL **98,** 081802 (2007) PHYSICAL REVIEW LETTERS week ending 23 FEBRUARY 2007

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.

Hyperon goals:

- 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?

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- Much interest lately in new states observed in charmonium region: $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, and $Z(3930)$
- $X(3872)$ of particular interest: may be the first meson-antimeson ($D^0\,\overline{D}^{*0}$ + c.c.) molecule (or tetraquark or what?)

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

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

- Also h_c mass & width, χ_c radiative-decay angular distributions, $\eta_c{}'$ full and radiative widths,...

What Else Can This Do?

Charm!

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

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

Eric Braaten

Physics Department, Ohio State University, Columbus, Ohio 43210, USA

(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}.

- Braaten estimate of $\bar{p}p$ X(3872) coupling assuming D^*D molecule
  - extrapolates from K^*K data

Charm!

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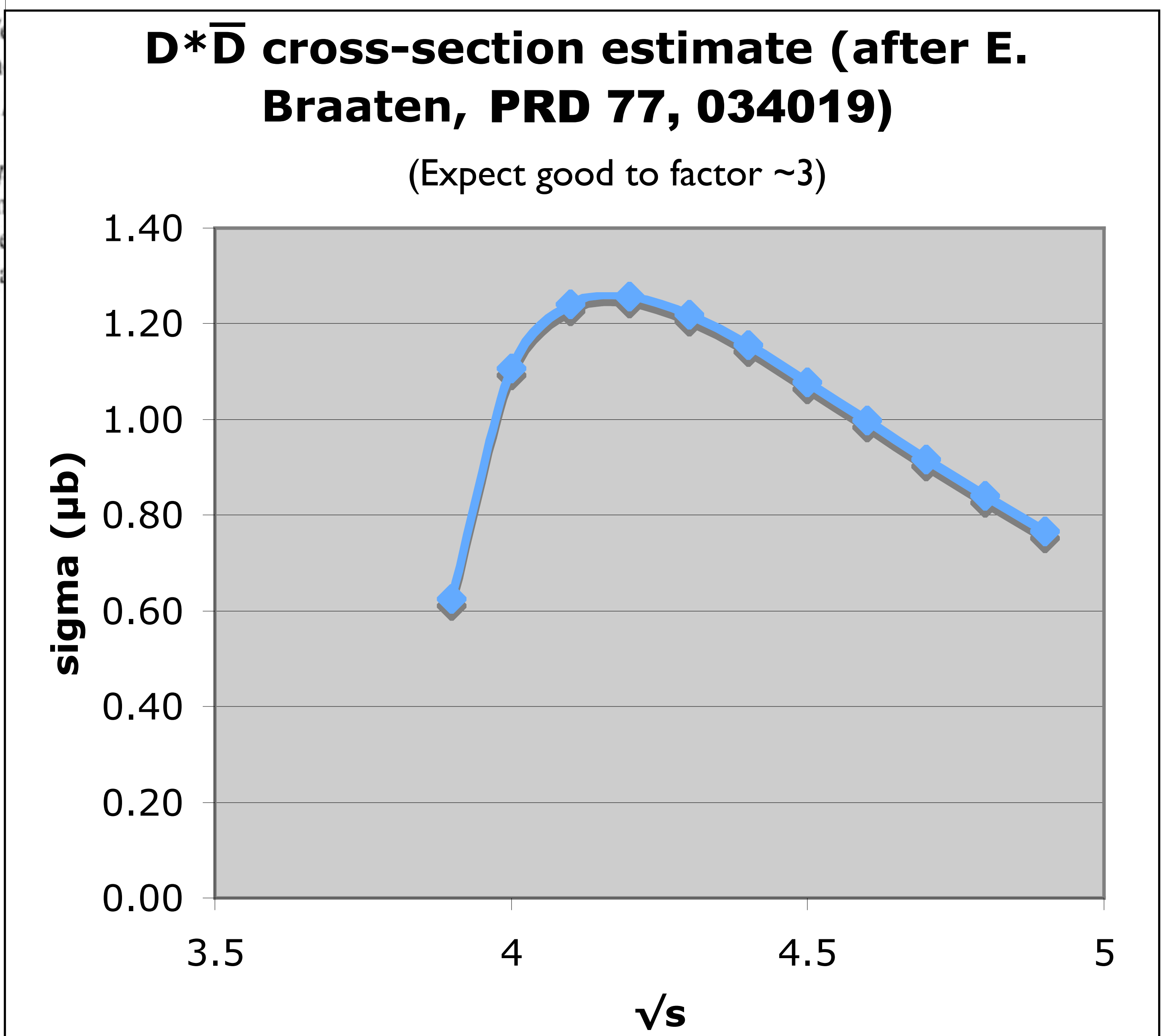
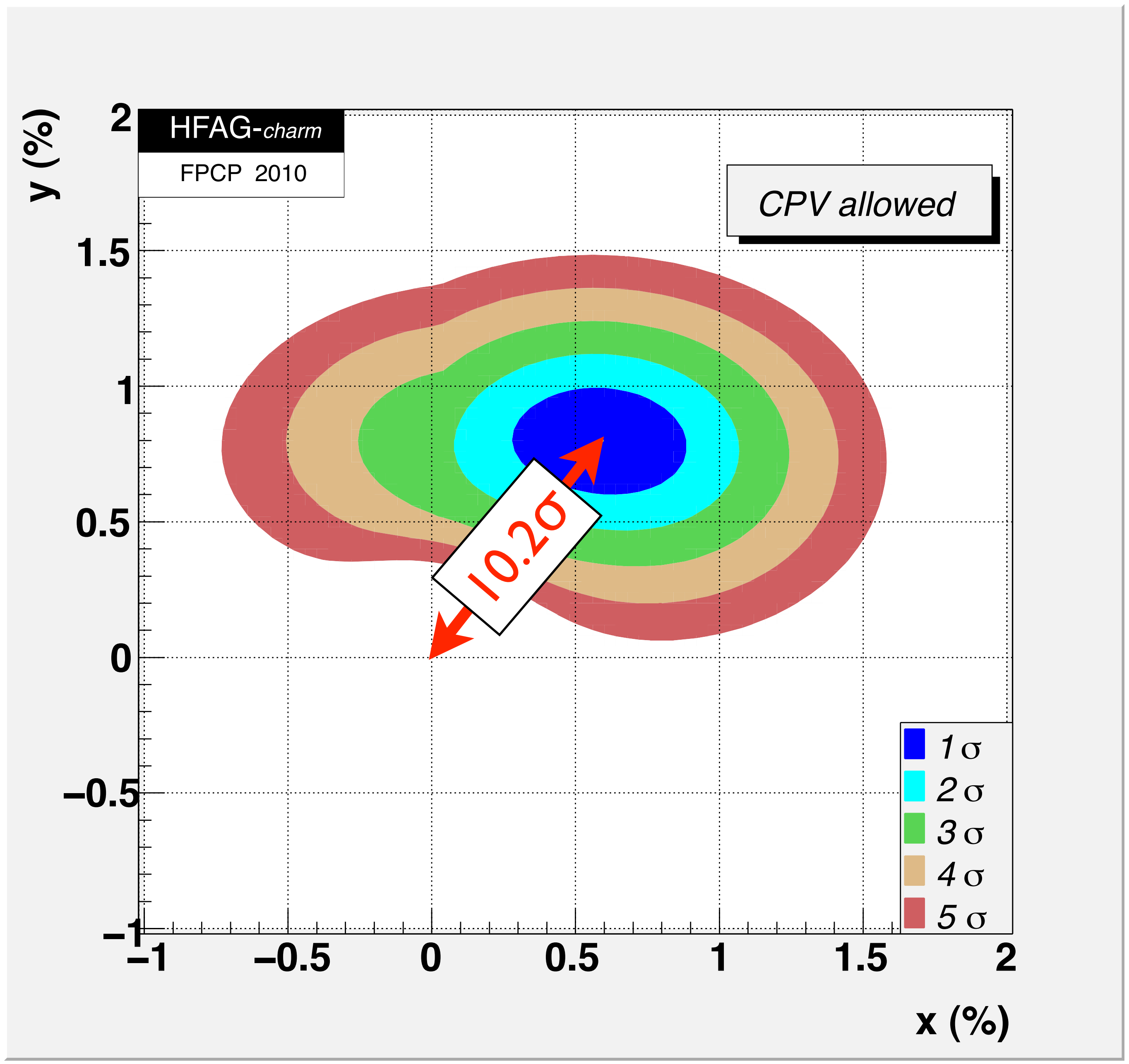


- Braaten estimate of $\bar{p}p$ *X*(3872) coupling assuming *D**D* molecule
  - extrapolates from *K**K* data
- By-product is $D^{*0}\bar{D}^0$ cross section
- 1.3 µb → 5 ×10⁹/year
- Expect efficiency as at *B* factories

Charm!

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?

Charm!

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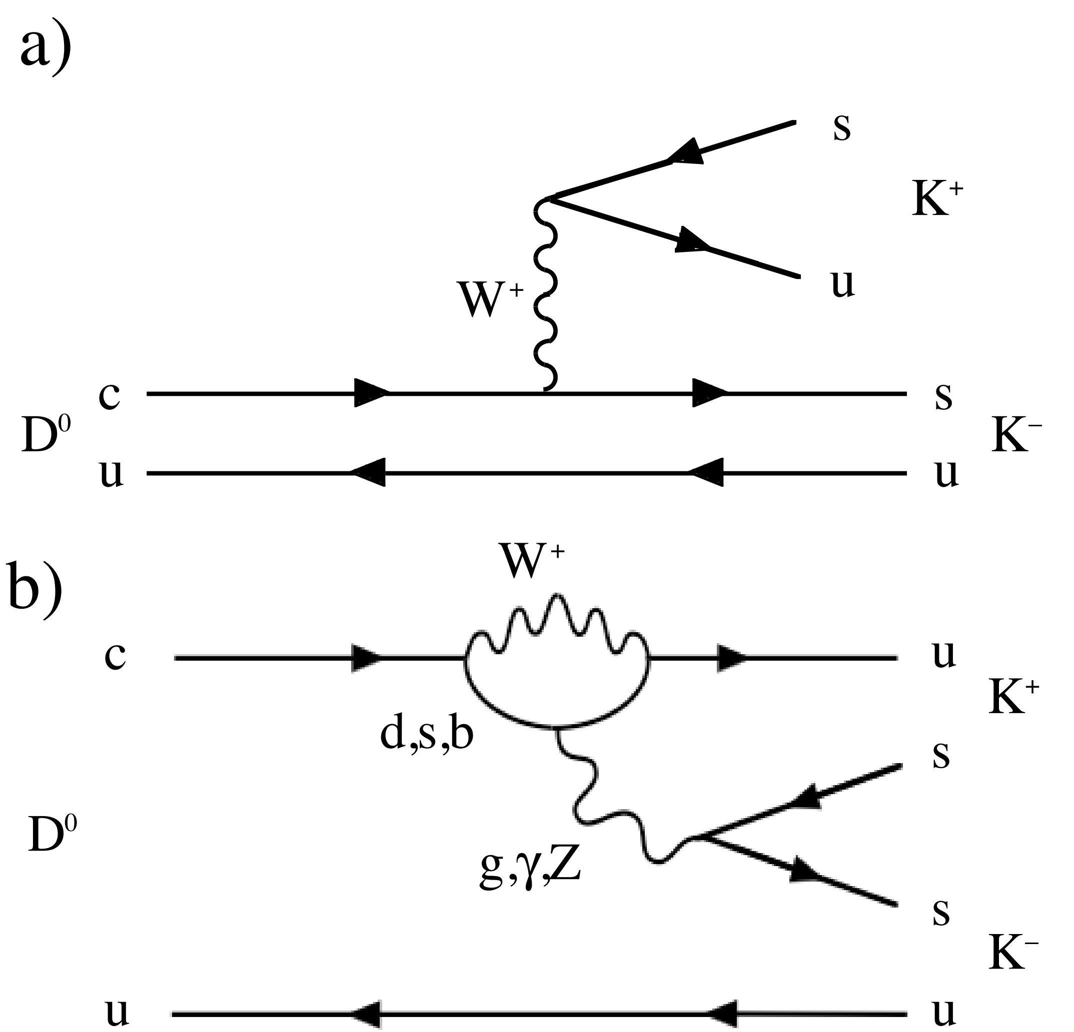
Singly Cabibbo-suppressed (CS) *D* decays have 2 competing diagrams:



- *Big question:* New Physics or old?

➡ key is *CP* Violation! Possible in CF, DCS only if New Physics

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

➡ world's best sensitivity to charm CPV

Charm!

- Ballpark sensitivity estimate based on Braaten $\overline{p}p \to D^{*0}\overline{D}^0$ formula, assuming $\sigma \propto A^{1.0}$:

Quantity	Value	Unit
Running time	2×10^7	s/yr
Duty factor	0.8*	
$\mathcal{L}$	2×10^{32}	$cm^{-2}s^{-1}$
Annual integrated $\mathcal{L}$	3.2	fb^{-1}
Target A (Ti)	47.9	
$A^{0.29}$	3.1	
$\sigma(\overline{p}p \to D^{*+} + \text{anything})$	1.25–4.5	μb
# $D^{*\pm}$ produced	$0.3\text{–}3 \times 10^{11}$	events/yr
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.677	
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.0389	
Acceptance	0.45	
Efficiency	0.1–0.3	
Total	$0.3\text{–}3 \times 10^8$	tagged events/yr

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

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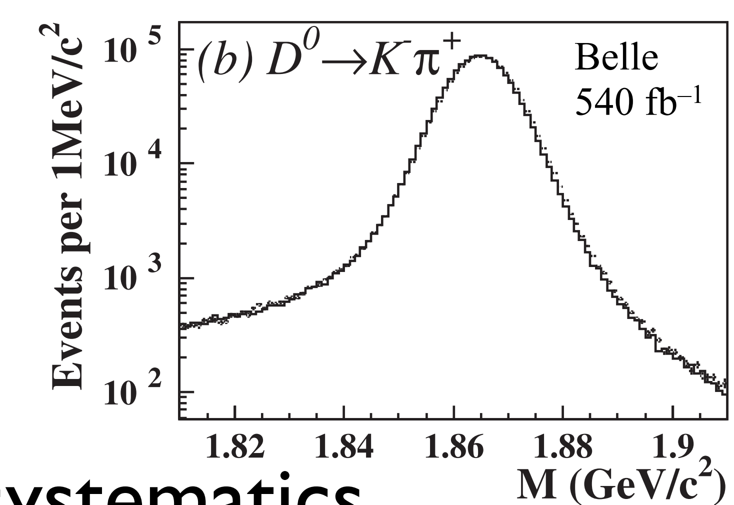
- Cf. 1.22×10^6 total tagged evts at Belle [M. Staric et al., PRL **98**, 211803 (2007)]



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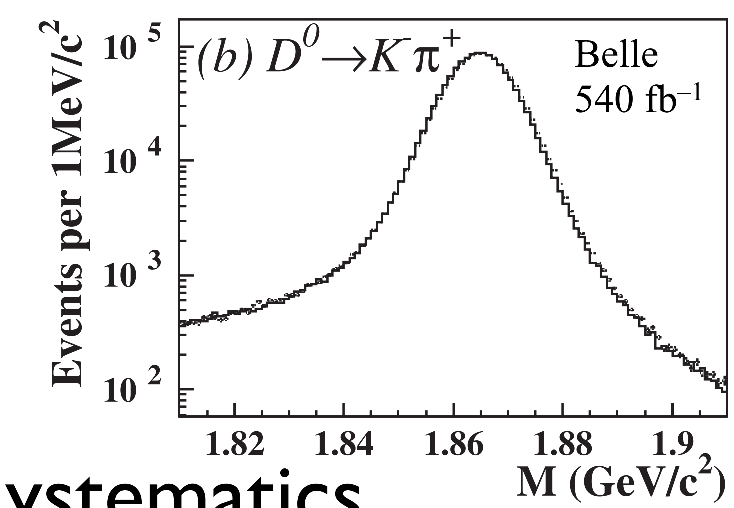
  LHC*b* will have comparable statistics but diff't systematics
  Competitive with projected ca. 2021 SuperKEKB (5 y @ 10 ab^{-1}/yr)



Breadth of Program

- Main HEP utility to society: training students to innovate
- Now badly need cost-effective way to do this

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- Now badly need cost-effective way to do this
- Partial list of physics papers/thesis topics:

General	
1	Particle multiplicities in medium-energy pbar-p collisions
2	Particle multiplicities in medium-energy pbar-N collisions
3	Total cross section for medium-energy pbar-p collisions
4	Total cross section for medium-energy pbar-N collisions
Charm	
5	Production of charm in medium-energy pbar-p collisions
6	Production of charm in medium-energy pbar-N collisions
7	A-dependence of charm production in medium-energy pbar-N collisions
8	Associated production of charm baryons in medium-energy pbar-N collisions
9	Production of charm baryon-antibaryon pairs in medium-energy pbar-N collisions
10	Measurement of D0 mixing in medium-energy pbar-N collisions
11	Search for/Observation of CP violation in D0 mixing
12	Search for/Observation of CP violation in D0 decays
13	Search for/Observation of CP violation in charged-D decays
Hyperons	
14	Production of Lambda hyperons in medium-energy pbar-p collisions
15	Production of Sigma0 in medium-energy pbar-p collisions
16	Production of Sigma- in medium-energy pbar-p collisions
17	Production of Xi- in medium-energy pbar-p collisions
18	Production of Xi0 in medium-energy pbar-p collisions

19	Production of Omega- in medium-energy pbar-p collisions
20	Production of Lambda Lambdabar pairs in medium-energy pbar-p collisions
21	Production of Sigma+ Sigmabar- pairs in medium-energy pbar-p collisions
22	Production of Xi- Xibar+ pairs in medium-energy pbar-p collisions
23	Production of Omega- Omegabar+ pairs in medium-energy pbar-p collisions
24	Rare decays of Sigma+
25	Rare decays of Xi-
26	Rare decays of Xi0
27	Rare decays of Omega-
28	Search for/Observation of CP violation in Omega- decay
Charmonium	
29	Production of X(3872) in medium-energy pbar-p collisions
30	Precision measurement of X(3872) mass, lineshape, and width
31	Decay modes of X(3872)
32	Limits on rare decays of X(3872)
33	Production of other XYZ states in medium-energy pbar-p collisions
34	Precision measurement of the eta_c mass, line shape and width
35	Precision measurement of the h_c mass, line shape and width
36	Precision measurement of the eta_c' mass, line shape and width
37	Complementary scans of J/psi and psi'
38	Precise determination of the chi_c COG
39	Production of J/psi and Chi_cJ in association with pseudoscalar meson(s)

Summary

- Best experiment ever on hyperons, charm, and charmonia may soon be feasible at Fermilab
  - possibly world's most sensitive study of charm mixing, charm & hyperon CPV & rare decays
- Existing equip't enables quick, cost-effective effort
  - could start data-taking by 2014
- Preserves options for antihydrogen experiments
  - CPT, gravity tests
- World's best $\bar{p}$ source → simple way to broad physics program in pre-Project X era

➡ Can Oddone's mind be changed?