Low- and Medium-Energy Antiproton Experiments at Fermilab

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Flavor Subgroup Meeting
Fermilab Steering Group
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Outline

- Antiproton sources
- Hyperon CP violation
- Issues in charm and charmonium
- Other physics
- Summary

Antiproton Sources

Facility	p_{max} [GeV/c]	Stacking rate	Year
LEAR/ACOL	2^*	$\leq 6\times10^{10}$/hr	≤1996†
AD	0.3^*	$\leq 2\times10^{9}$/hr	now
FNAL	8.9	$\leq 2\times10^{11}$/hr	now
GSI-FAIR	15^*	≤ 3.5–7×10^{10}/hr?	>2014?

* stacking at 3.5 GeV/c

† LEAR was shut down to enhance CERN's LHC focus

FNAL Antiproton Source

- Antiproton stacking rate ($\approx 2 \times 10^{11}$/hr) unmatched by *any other* existing or planned facility
- Stochastic cooling (& absence of synchrotron radiation) provides *very* small (~100 keV) beam energy spread
- *Very* precise beam-energy calibration via measured revolution frequency + orbit length (from BPM measurements and Accumulator lattice model)

➡ these features exploited (most recently in 2000) by charmonium experiments E760 and E835

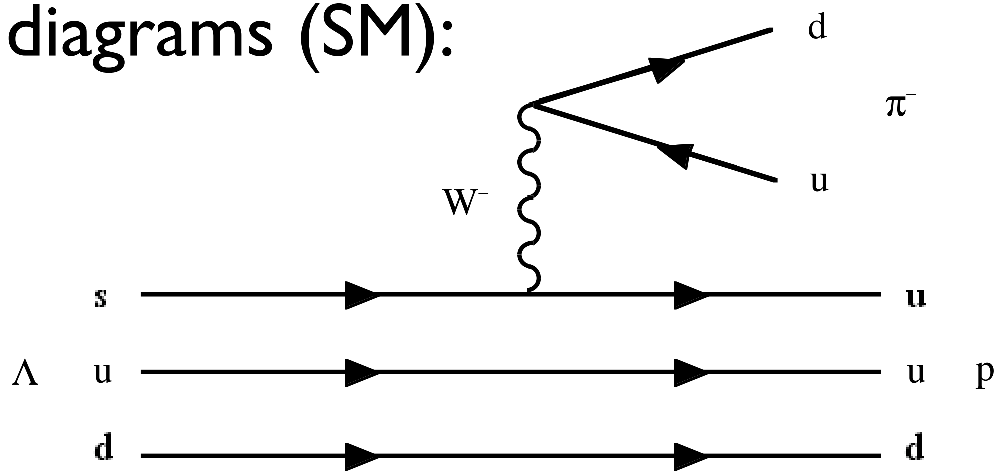
What can it do?

- Precision measurements of charmonium
- Study of recently discovered charmonium-related states: $X(3872)$ etc...
- High-statistics studies of hyperon CP violation and rare decays
- High-statistics studies of open charm (mixing? CP?)
- Precision antiproton and antihydrogen studies (CPT tests etc.)
- Bottomonium formation (colliding-beam)?

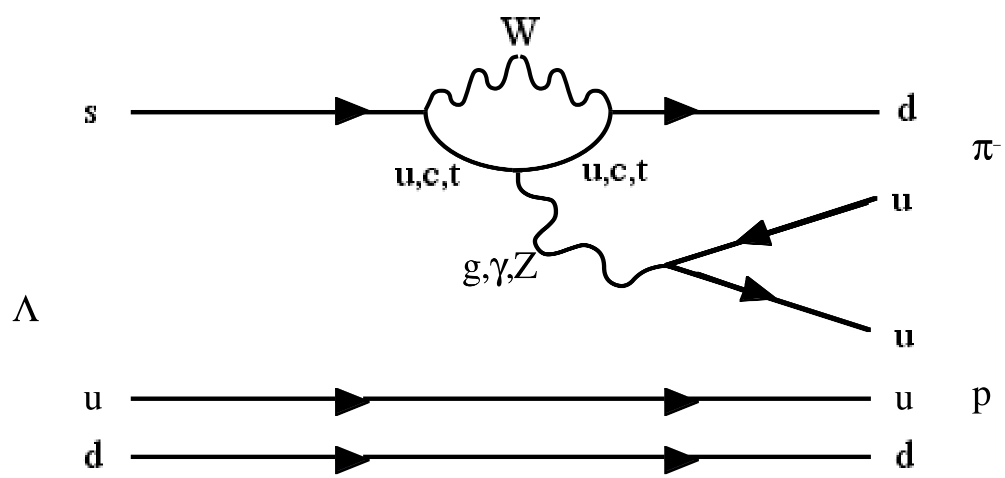
Hyperon CP Violation

- Example Feynman diagrams (SM):

Λ decay:



Λ penguin decay:



- Large CP asymmetries poss. in nonminimal SSM etc.

Hyperon CP Violation

- CP-odd observables:
  - Decay amplitude for ΔS = 1 decay of spin-1/2 strange baryon into spin-1/2 baryon and meson (e.g., $\Lambda \to p\,\pi^-$):

$$M = \underbrace{S}_{\text{S-wave amplitude}} + \underbrace{P}_{\text{P-wave amplitude}}\vec{\sigma}\cdot \underbrace{\hat{q}_p}_{\text{proton-momentum unit vector}}$$

→ Nonuniform proton angular distribution in Λ rest frame:

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1+\alpha_\Lambda \vec{P}_\Lambda \cdot \hat{q}_p) \quad \text{(parity violation)}$$

where $\alpha_\Lambda \equiv \frac{2\,\mathrm{Re}\,S^* P}{|S|^2+|P|^2}, \quad \beta_\Lambda \equiv \frac{2\,\mathrm{Im}\,S^* P}{|S|^2+|P|^2}$ [Lee & Yang, 1957]

$$\Rightarrow A_\Lambda \equiv \frac{\alpha_\Lambda + \bar{\alpha}_\Lambda}{\alpha_\Lambda - \bar{\alpha}_\Lambda}, \; B_\Lambda \equiv \frac{\beta_\Lambda + \bar{\beta}_\Lambda}{\beta_\Lambda - \bar{\beta}_\Lambda}, \; \Delta_\Lambda \equiv \frac{\Gamma_{\Lambda\to P\pi} - \bar{\Gamma}_{\Lambda\to P\pi}}{\Gamma_{\Lambda\to P\pi} + \bar{\Gamma}_{\Lambda\to P\pi}} \quad \text{CP-odd}$$

Hyperon CP Violation

- Theory & experiment:

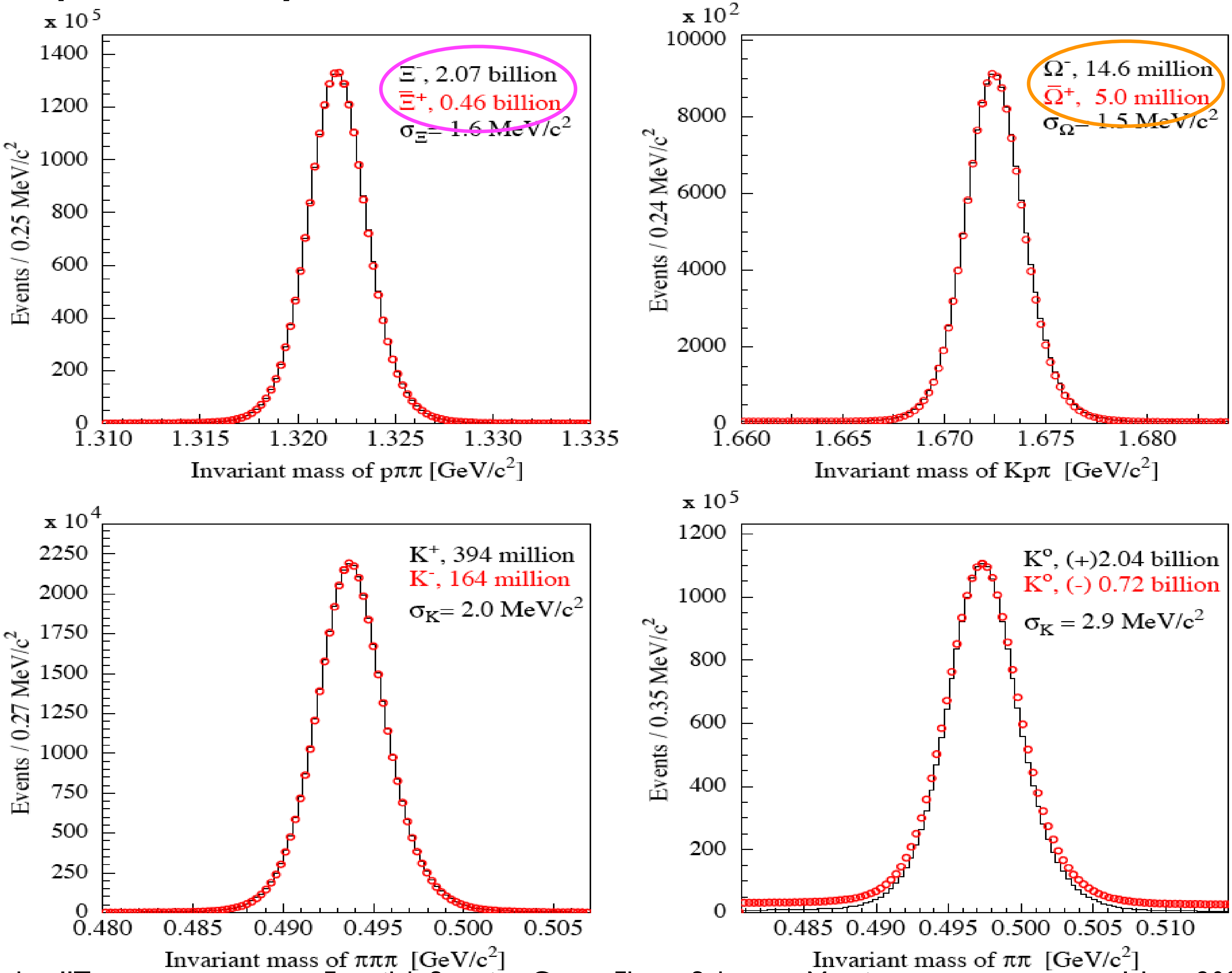
Theory [Donoghue, He, Pakvasa, Valencia, et al., e.g., PRL 55, 162 (1985); PRD 34, 833 (1986); PLB 272, 411 (1991)]

- SM: $A_\Lambda \sim 10^{-5}$
- Other models: $\lesssim \mathcal{O}(10^{-3})$
  [e.g. SUSY gluonic dipole: X.-G.He et al., PRD 61, 071701 (2000)]

Experiment	Decay Mode	A_Λ	
R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$	**-0.02 ± 0.14**	[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)]
		$\approx 2 \times 10^{-4}$	[projected]

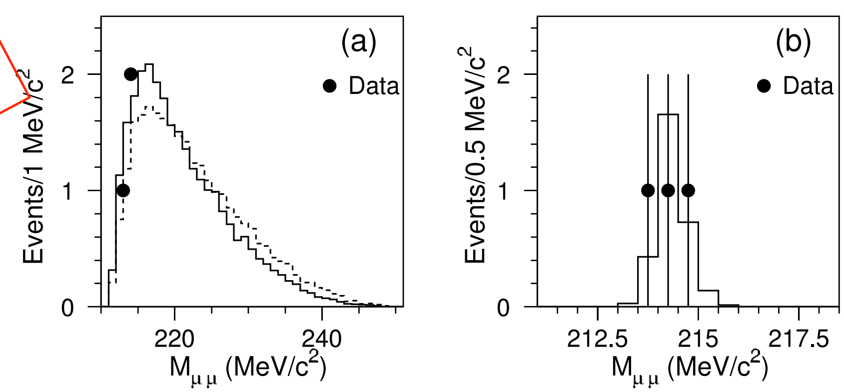
Made possible by...Enormous HyperCP Dataset



Some HyperCP Discoveries:

- $\phi_\Xi = -(2.39 \pm 0.64 \pm 0.64)^\circ \Rightarrow \beta_\Xi \neq 0$ 2nd non-zero transv. asymm.
- $\alpha_\Omega = 0.0175 \pm 0.0024 \neq 0$ $\Rightarrow \Omega^- \to \Lambda K^-$ violates parity
- $\frac{1}{2}[\alpha(\Lambda K^-)+\alpha(\bar{\Lambda} K^+)] = -0.004 \pm 0.040$ (but conserves CP)
- $A_{\Xi\Lambda} = (0.0 \pm 5.1 \pm 4.4) \times 10^{-4}$ $\Rightarrow \Xi^- \to \Lambda\pi^-$ conserves CP
  (1st ≈5% of sample - full analysis still in progress)
- $\Sigma^+ \to p\mu^+\mu^-$: $\mathcal{B} \approx 9 \times 10^{-8}$ (or 3×10^{-8} if intermediate P^0)

Surprise!



≈2.4σ fluctuation of SM

- SUSY Sgoldstino?
- SUSY light Higgs?

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

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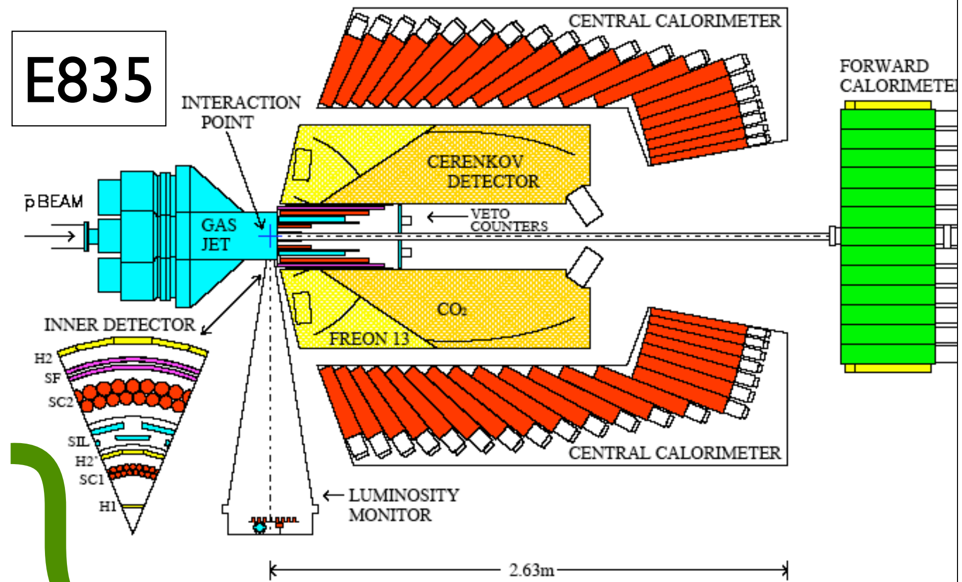
The HyperCP Collaboration has observed three events for the decay $\Sigma^+ \rightarrow p\mu^+\mu^-$ which may be interpreted as a new particle of mass 214.3 MeV. However, existing data from kaon and B-meson decays provide stringent constraints on the construction of models that support this interpretation. 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 $\Sigma^+ \rightarrow p\mu^+\mu^-$ at a level consistent with the HyperCP observation.

Scale & Reach



- New, high-rate, magnetic spectrometer with:
  - $PbWO_4$ calorimeter
  - silicon vertex detector
  - displaced-vertex trigger

<$10M

  - 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)

➡ $\sim 10^{8}\ \Omega^{-}\,\overline{\Omega}^{+}$/yr + $\sim 10^{12}$ 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

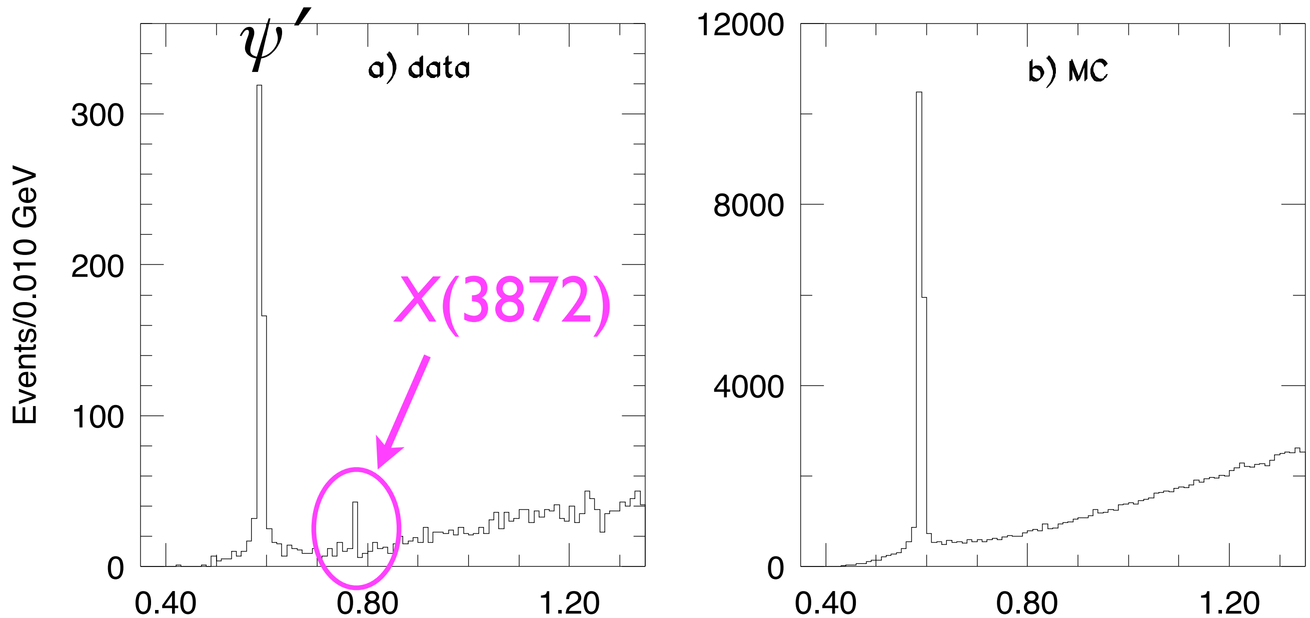
Predicted $\Delta\mathcal{B} \sim 10^{-5}$ in SM, $\lesssim 10^{-3}$ if NP

What Else Can This Do?

- 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 b/c may be the first hadron-antihadron ($D^0\,\overline{D}^{*0}$ + c.c.) molecule

What Else Can This Do?

- Belle, Aug. 2003: $B^{\pm} \longrightarrow X + K^{\pm}, X \longrightarrow J/\psi\, \pi^+\pi^-$



- Since confirmed by CDF, D0, & BaBar
- Not consistent with being charmonium state
- Very near $D^0\,\overline{D}^{*0}$ threshold (Δmc^2 = 0.6±0.6 MeV)

What Else Can This Do?

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➡ need very precise mass measurement to confirm or refute

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

What Else Can This Do?

Also,...

- Study other X, Y, Z states
- Worthwhile measurements that E835 could have made but didn't...

  (lack of beam time for precision scans when one didn't know exactly where to look)

  - h_c mass & width, χ_c radiative-decay angular distributions, $\eta_c{}'$ full and radiative widths,...
- ...improved limits on $\bar{p}$ lifetime and branching ratios (APEX),...
- Open-charm studies with $\mathcal{O}(10^9)$ produced events

Example: h_c

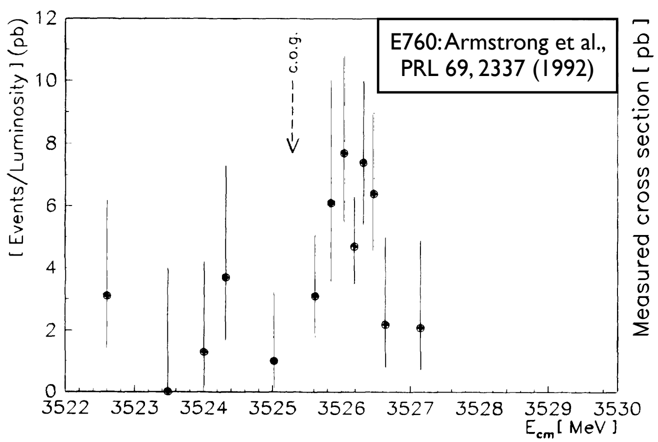
- h_c ($1\ ^1P_1$) state of charmonium only way to study $c\bar{c}$ spin-0 hyperfine splitting: $m(^1P_1) - \langle m_{\text{spin-weighted}}(^3P_J)\rangle$
- Not experimentally accessible in strangeonium or (so far) bottomonium
- Splitting predicted to be $\lesssim$1 MeV in potential models if
  - confinement potential has no vector component

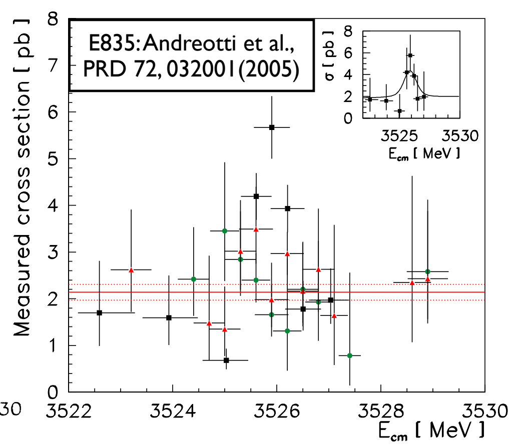
    and
  - coupled-channel effects small

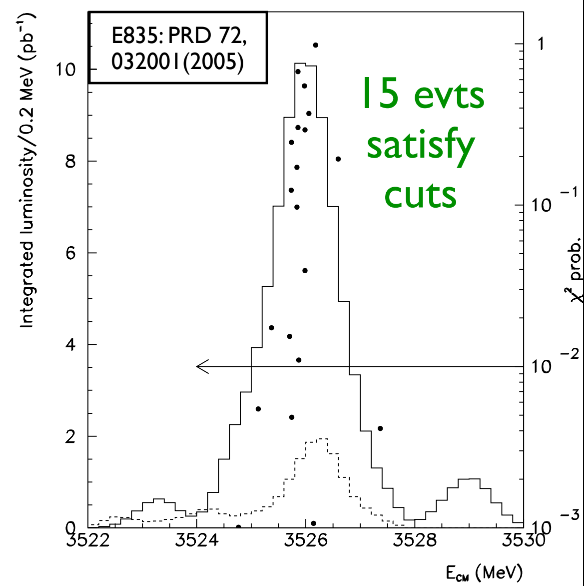
    (both expected to be true)
- But h_c production in e^+e^- suppressed $\Rightarrow$ not easy

Example: h_c

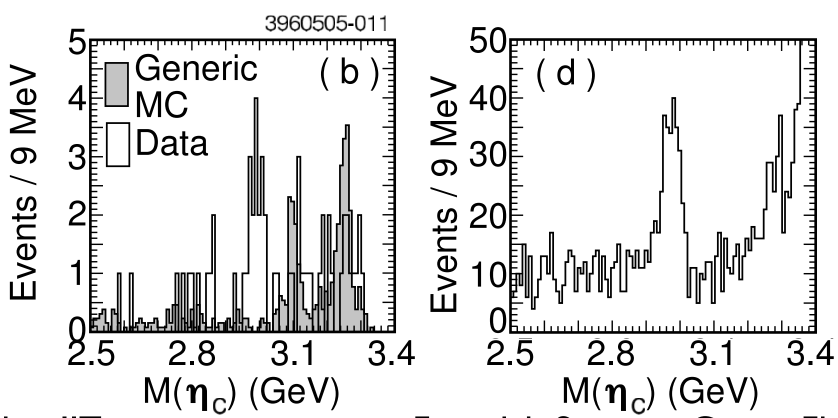
- h_c found (≈3σ) in $J/\psi\ \pi^0$ in E760 (E835 predecessor):
- Not confirmed by E835, but seen in $\eta_c\gamma$:







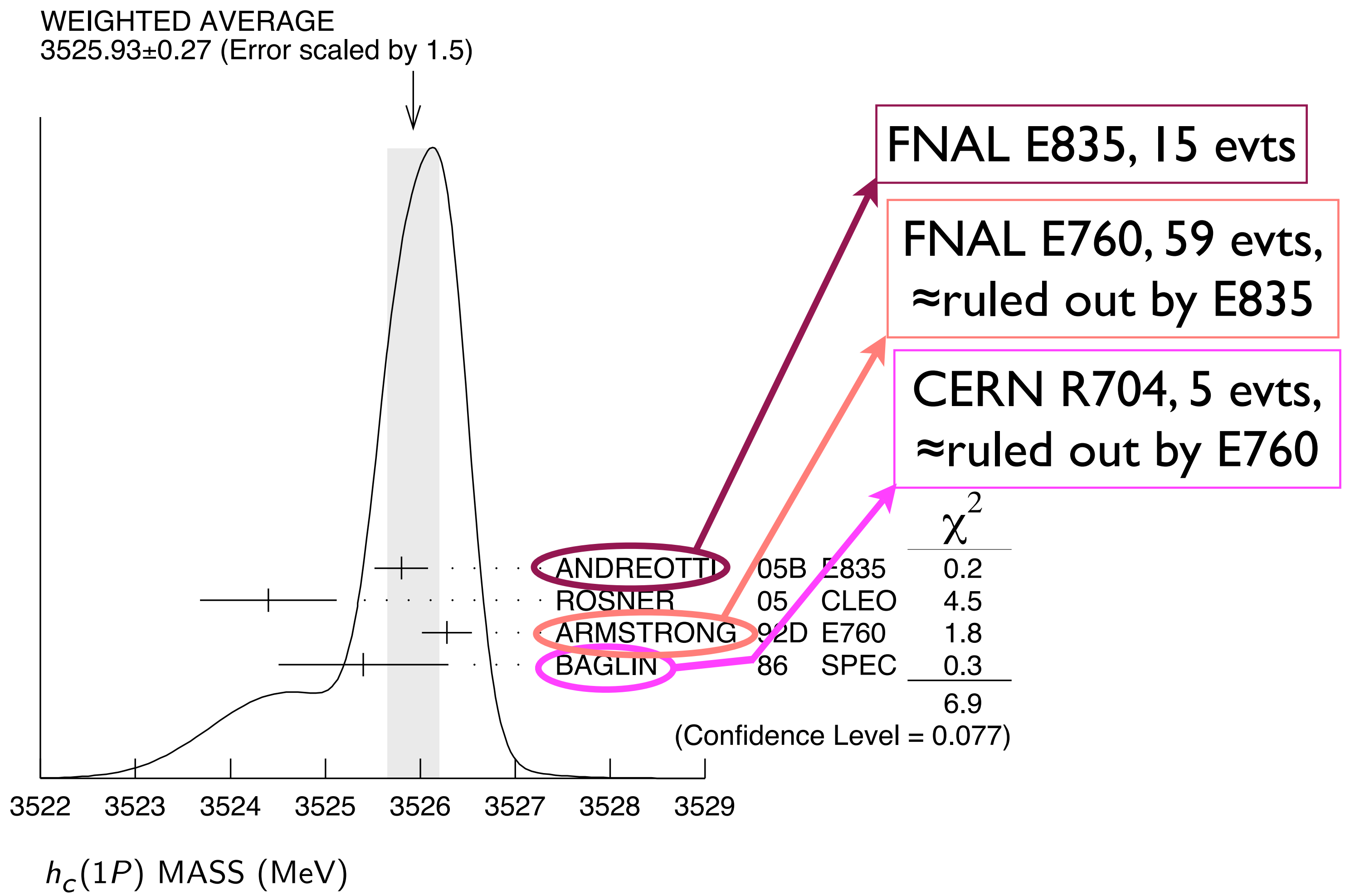
...and by CLEO [Rosner et al., PRL 95, 102003 (2005)]:



- But best mass meas't (E835) based on a signal that's not yet statistically established

Example: h_c

- PDG avg, $\langle(^3P_J)\rangle$ = 3525.36±0.06 MeV compatible @ 2σ:



- Desirable to confirm E835 meas't with greater statistics!

Example: h_c

- Desirable to confirm E835 meas't with greater statistics!
- Not so easy!
  - small BR($\eta_c \to \gamma\gamma$) = $(2.8 \pm 0.9) \times 10^{-4}$
  - cuts to suppress π^0 bkg gave ≈3% efficiency in E835
- More-favorable modes?

$\eta'(958)\pi\pi$	(4.1 ± 1.7) %
$K^*(892)\overline{K}^*(892)$	$(9.2 \pm 3.4) \times 10^{-3}$
$K^{*0}\overline{K}^{*0}\pi^+\pi^-$	(1.5 ± 0.8) %
$\phi K^+ K^-$	$(2.9 \pm 1.4) \times 10^{-3}$
$\phi\phi$	$(2.7 \pm 0.9) \times 10^{-3}$

➡ Require magnetic spectrometer

Bottomonium?

- Spectrum of $\bar{b}b$ states poorly known compared to charmonium
- Could probe $\bar{p}p$ coupling of bottomonium with exploratory colliding-beam run ($\sqrt{s}$ > 9.4 GeV too high for Accumulator fixed-tgt)

Parasitic Exp'ts

- Antihydrogen in-flight (CPT tests, e.g. Lamb shift):
  - efforts @ AD with trapped anti-H have encountered difficulties
  - Blanford et al. @ FNAL [Phys. Rev. Lett. 80, 3037 (1998)] discovered anti-H produced by $\overline{p}$ traversing gas-jet target, proposed scheme [Phys. Rev. D 57, 6649 (1998)] to measure Lamb shift & fine structure
- Best antiproton lifetime and decay-mode limits set by APEX experiment at Accumulator
  - could improve limits with more data
- etc...

Is There an Interested Collaboration?

- I am drafting LoI and soliciting collaborators
- So far:

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...& growing...
also interest @ other INFN branches &c...

...PANDA collab. might want opp'ty for early tests

Summary

- Best experiment ever on hyperons, charm, and charmonia may be feasible a few years from now at Fermilab
- Measurements complementary to, & not feasible at, LHC
- Modest effort could yield substantial impact
- Small additional effort (e.g., 1 or 2 new small rings) could enable broad range of experiments