Antiprotons at Fermilab: New Directions in Hyperon, Charm, and Antimatter Physics

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ILLINOIS INSTITUTE OF TECHNOLOGY
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Fermilab
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Outline

Varied menu!

- Baryogenesis and matter/antimatter asymmetry
- Hyperon CP violation
- Low-energy antiprotons
- A new experiment
- Charm & charmonium
- Antihydrogen measurements
- Competing proposals for the facility
- Summary

Baryogenesis

- Why is there matter in the universe?
  - When energy converted into matter (e.g., Tevatron collisions), always find that equal amounts of matter and antimatter are created.

➡ The Big Bang should have been no exception.

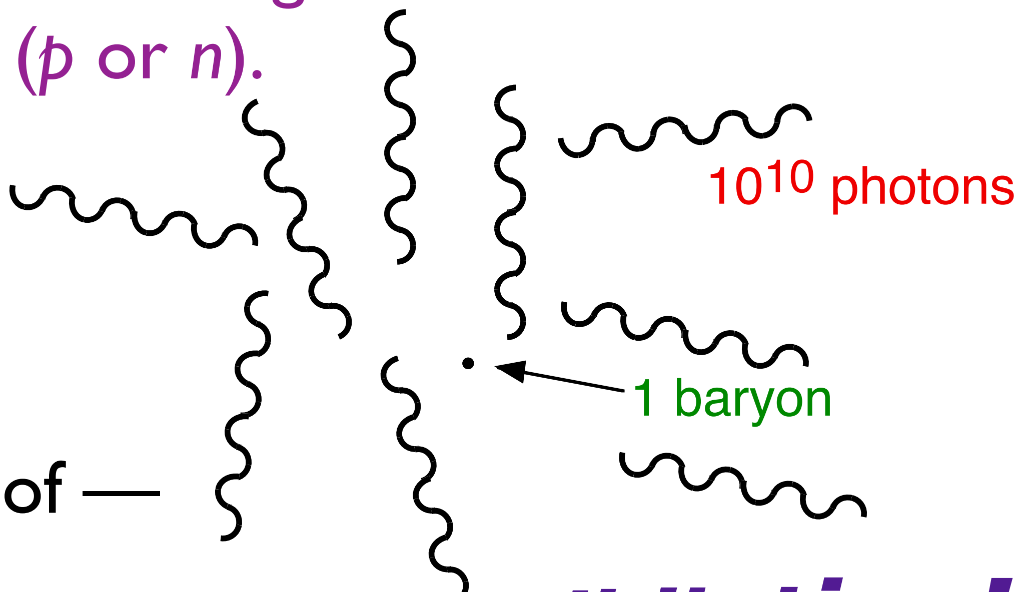
But then, during expansion and cooling of universe, all matter would have annihilated with all antimatter, leaving only energy... and the universe would now be a very boring place!

$\Longrightarrow$ Soon after Big Bang, slight excess of matter developed, and remained after all the antimatter annihilated!

Baryogenesis

⇒Soon after Big Bang, slight excess of matter developed, and remained after all the antimatter annihilated!

- This is consistent with observation:
  - ➡ There are ~10^{10} cosmic-background-radiation photons per baryon (*p* or *n*).



These are the remnants of —

...the great antimatter–matter ***annihilation!***

Baryogenesis

- How did the ~1-in-10^{10} matter excess develop?

- Sakharov (1967): can understand matter excess if, soon after Big Bang, there were
  1. **C and CP violation (⇒antimatter/matter not mirror images)**
  2. **non-conservation of baryon-number**
  3. **non-equilibrium conditions**
- During such a period,
  - any pre-existing net baryon number would be destroyed
  - a small net baryon number would be created
- This is "baryogenesis."

CP Violation

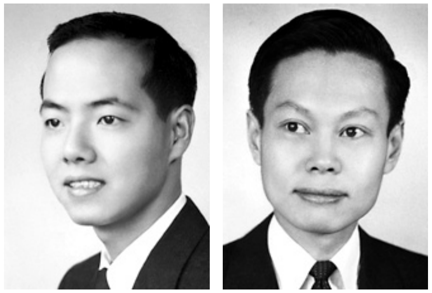
- Until 1955, subatomic-particle processes were assumed invariant w.r.t. the 3 "discrete symmetry" operations:

C = charge conjugation [imagine all particles in universe replaced by their antiparticles and vice versa]

P = parity inversion [imagine universe "reflected in a mirror" such that (x,y,z) → (–x,–y,–z)]

T = time reversal [imagine "movie" of the universe run backwards]

- In 1956 Lee & Yang suggested parity might not be conserved in weak interactions.



1957 Nobel laureates Lee & Yang

- P (and C) violation quickly confirmed experimentally:
  (1957: Wu et al.; Garwin, Lederman, & Weinrich) [β from Co-60 decay have preferred direction w.r.t. atom spin axis]

CP Violation

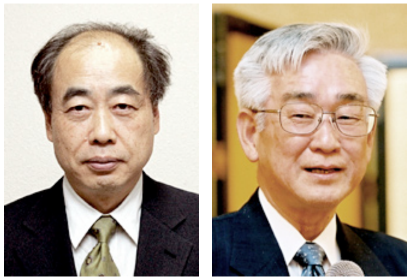
- But product, CP, still thought good, until (1964) Cronin et al. found CP symmetry slightly violated in K^0 decays
  - small effect, $\approx 2 \times 10^{-3}$
  - "indirect," i.e., in K^0–$\overline{K}^0$ mixing
  - but "direct" CPV later established by CERN NA-48 experiment [Phys. Lett. B 465, 335 (1999)]

1980 Nobel laureates Cronin & Fitch

- These effects explained within "Standard Model" by Cabibbo-Kobayashi-Maskawa quark-mixing matrix:

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

  - Quantum-mechanical interference when alternate paths to same final state
  - CPV because V_{ub} complex



2008 Nobel laureates Kobayashi & Maskawa

CP Violation

- Kobayashi-Maskawa model makes simple prediction:

  ➡ If CPV due to CKM-matrix phase, should be large effect in decays of beauty particles!

- CPV now observed in B-meson decays as well as strange (K^0) mesons [BaBar & Belle, 2001, CDF, et al.]

  (Hence Kobayashi-Maskawa 2008 Nobel prize)

CP Violation

- Kobayashi-Maskawa model make
prediction:
  - ➡ If CPV due to C … uld be large eff … articles!
- CP … eson decays as well as … [BaBar & Belle, 2001, CDF, et al.]
… ayashi-Maskawa 2008 Nobel prize)

But insufficient to account for baryogenesis!

How else might baryogenesis arise?

What other processes can distinguish matter from antimatter?

Non-KM CP Violation

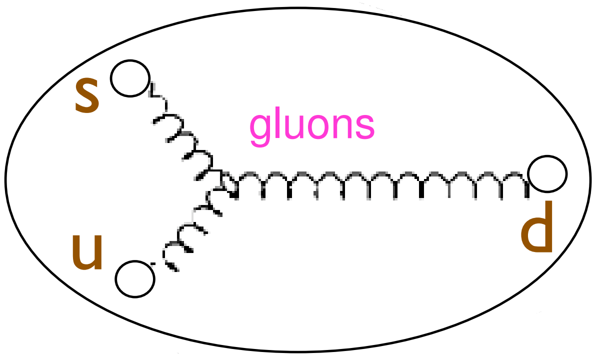
- 5 places to search for new sources of CPV:
  - Kaons
  - B mesons
  - Hyperons
  - Charm
  - Neutrinos

Years of intensive new-physics searches have so far come up empty

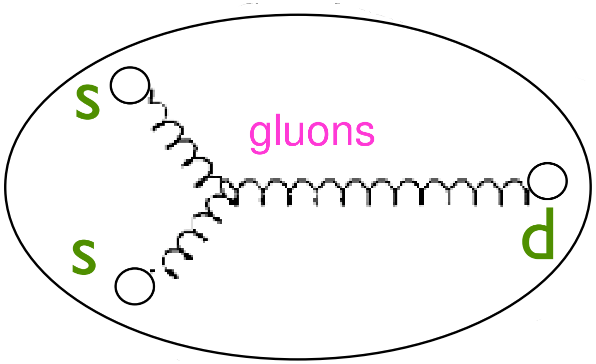
Worth looking elsewhere as well!

Hyperon CP Violation

Q: What's a "hyperon"?



A: A baryon (3-quark state) containing one or more strange quarks



e.g., Λ = sud, Ξ^{-} = ssd, etc.

(Unstable because strange quark decays – typically live for 10^{-10} s)

Hyperon CP Violation

- Hyperon decay violates parity, described by Lee & Yang (1957) via "α" and "β" parameters, e.g.:

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

⟶ nonuniform proton angular distribution in Λ rest frame w.r.t. average spin direction $\vec{P}_\Lambda$

- size of α indicates degree of nonuniformity:

  $\alpha_\Lambda = 0.642\ (\pm 0.013) \Rightarrow p$ emitted preferentially along polarization (Λ spin) direction

⟶ Large size of α looks favorable for CPV search

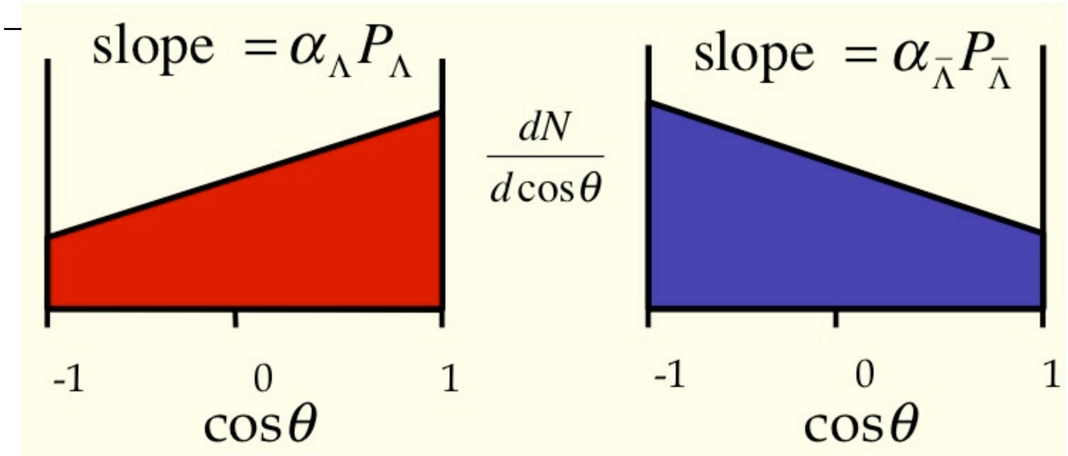
Hyperon CP Violation

- Hyperon decay violates parity, described by Lee & Yang (1957) via "α" and "β" parameters, e.g.:

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

⟶ nonuniform proton angular distribution in Λ rest frame:

$\Lambda \to p\pi^-$



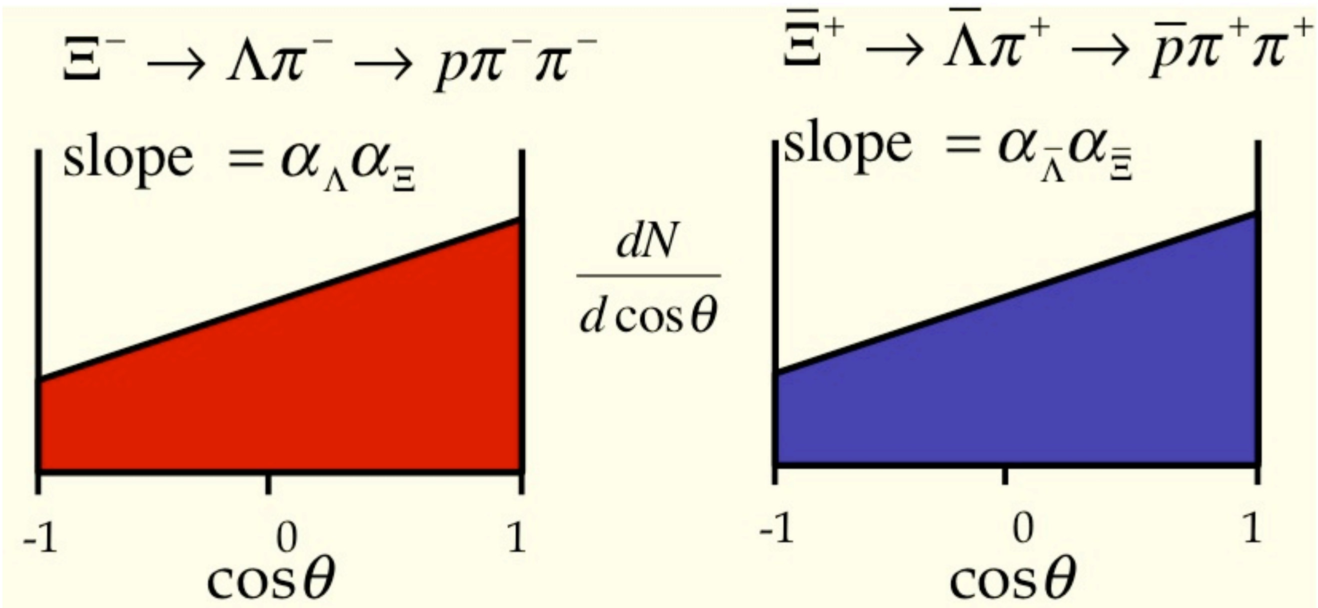
$\bar{\Lambda} \to \bar{p}\pi^+$

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

Hyperon CP Violation

- For precise measurement of A_Λ, need excellent knowledge of relative Λ and $\overline{\Lambda}$ polarizations!

➡ HyperCP "trick": $\Xi^- \rightarrow \Lambda\pi^-$ decay gives $\vec{P}_\Lambda = -\vec{P}_{\overline{\Lambda}}$



- Unequal slopes $\Rightarrow$ *CP* violated!

Hyperon CP Violation

- Standard Model 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

- Theory & experiment:

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

- SM: $A_\Lambda \sim 10^{-5}$, $|A_{\Xi\Lambda}| < 5 \times 10^{-5}$ [J. Tandean, G. Valencia, Phys. Rev. D 67, 056001 (2003)]
- Other models: $\mathcal{O}(10^{-3})$
  [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 ± 6.7) × 10⁻⁴**	[T. Holmstrom et al., PRL 93. 262001 (2004)]
		(6 ± 2 ± 2) × 10⁻⁴	[BEACH08 preliminary]

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)]

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Experiment	Decay Mode	
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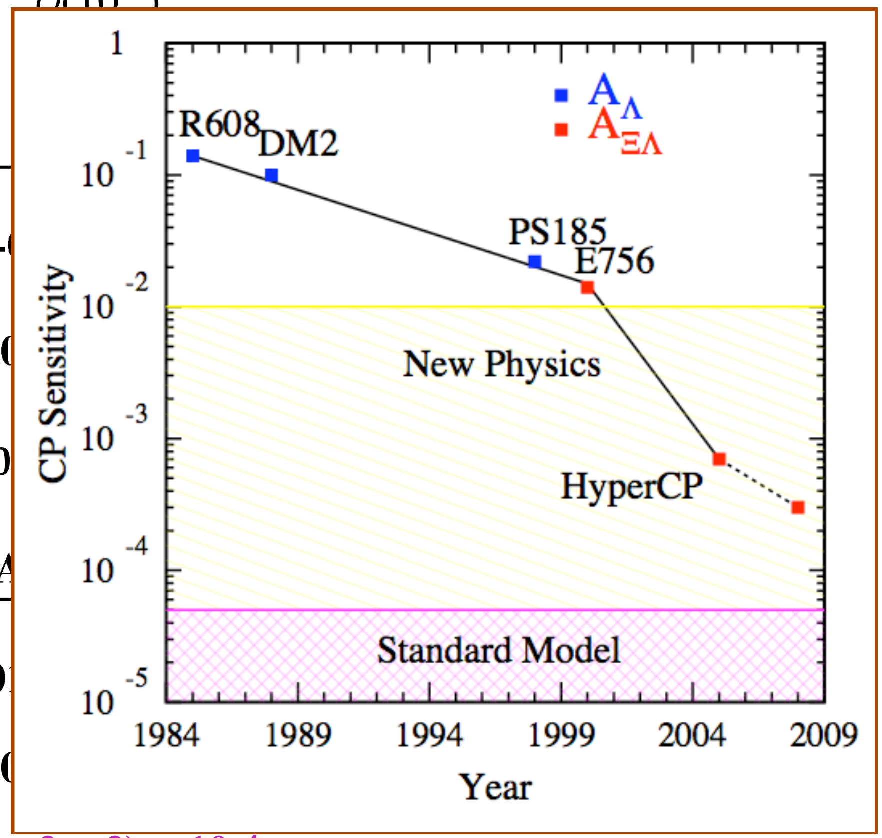
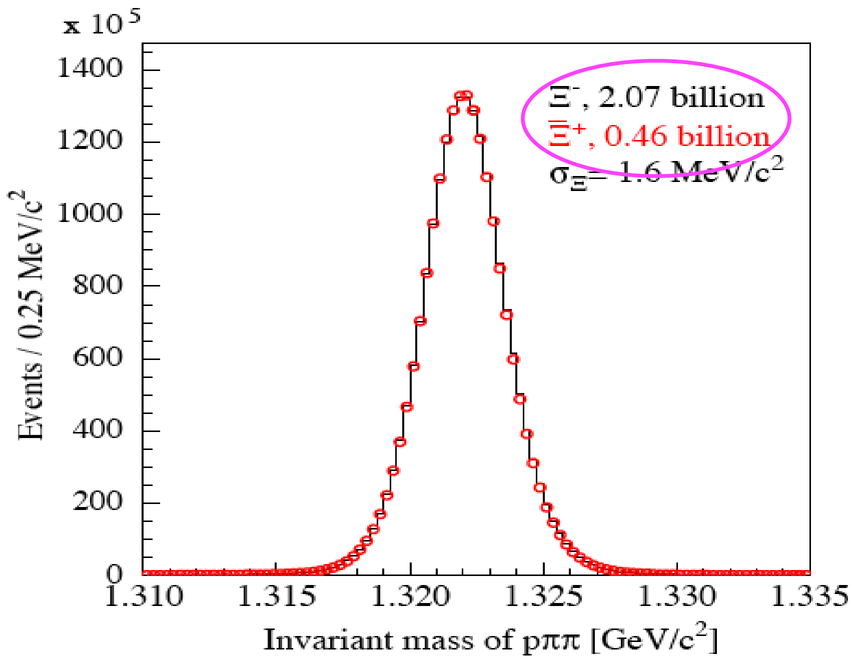
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	(
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	0

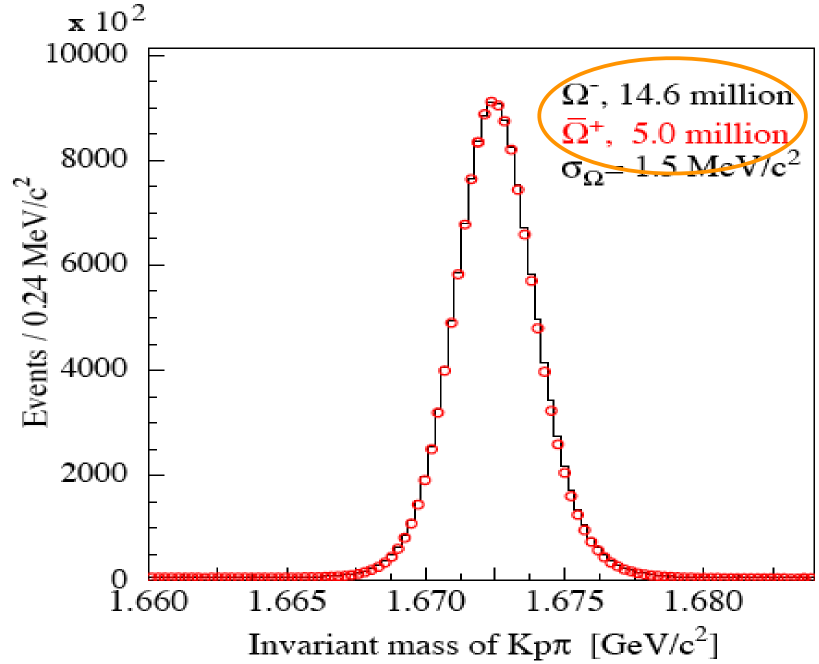
Experiment	Decay Mode	A
E756 at Fermilab	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	0.0
E871 at Fermilab (HyperCP)	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	(0.(

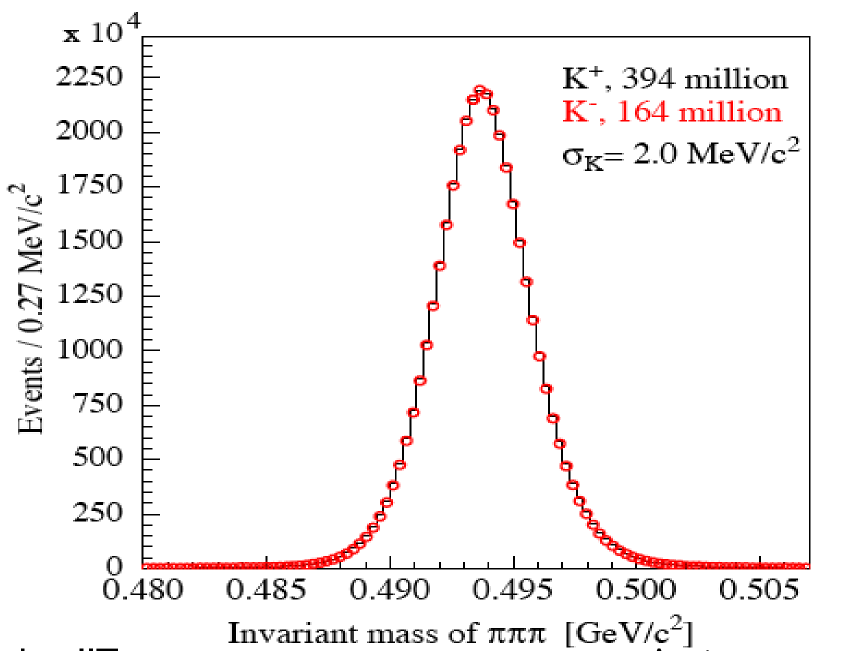


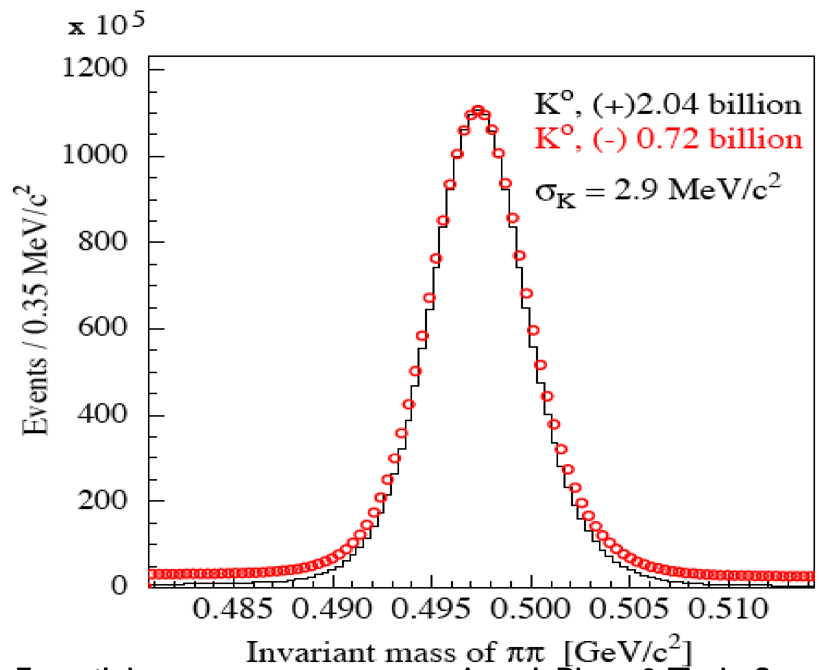
$(6 \pm 2 \pm 2) \times 10^{-4}$ [BEACH08 preliminary]

Made possible by... Enormous HyperCP Dataset

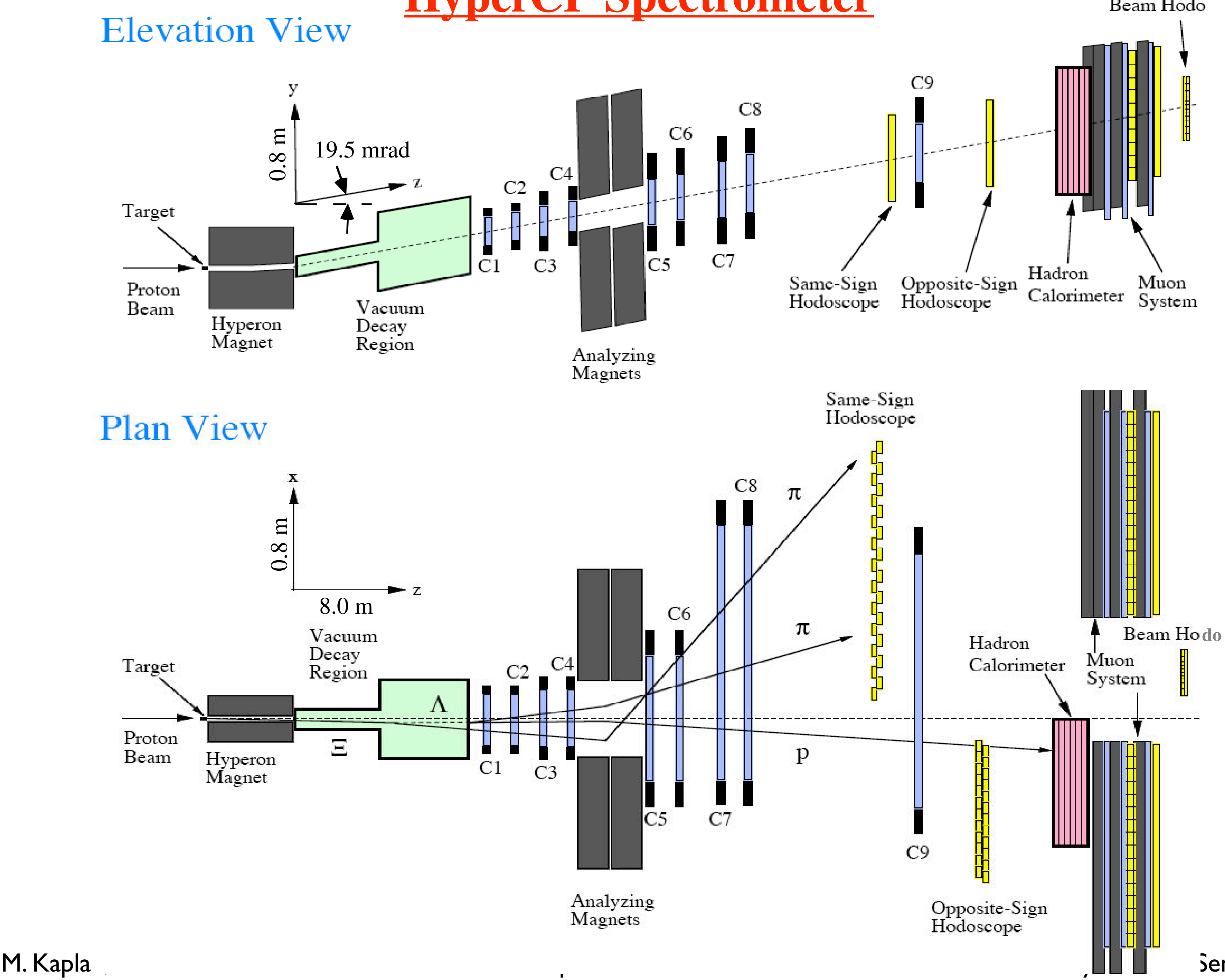






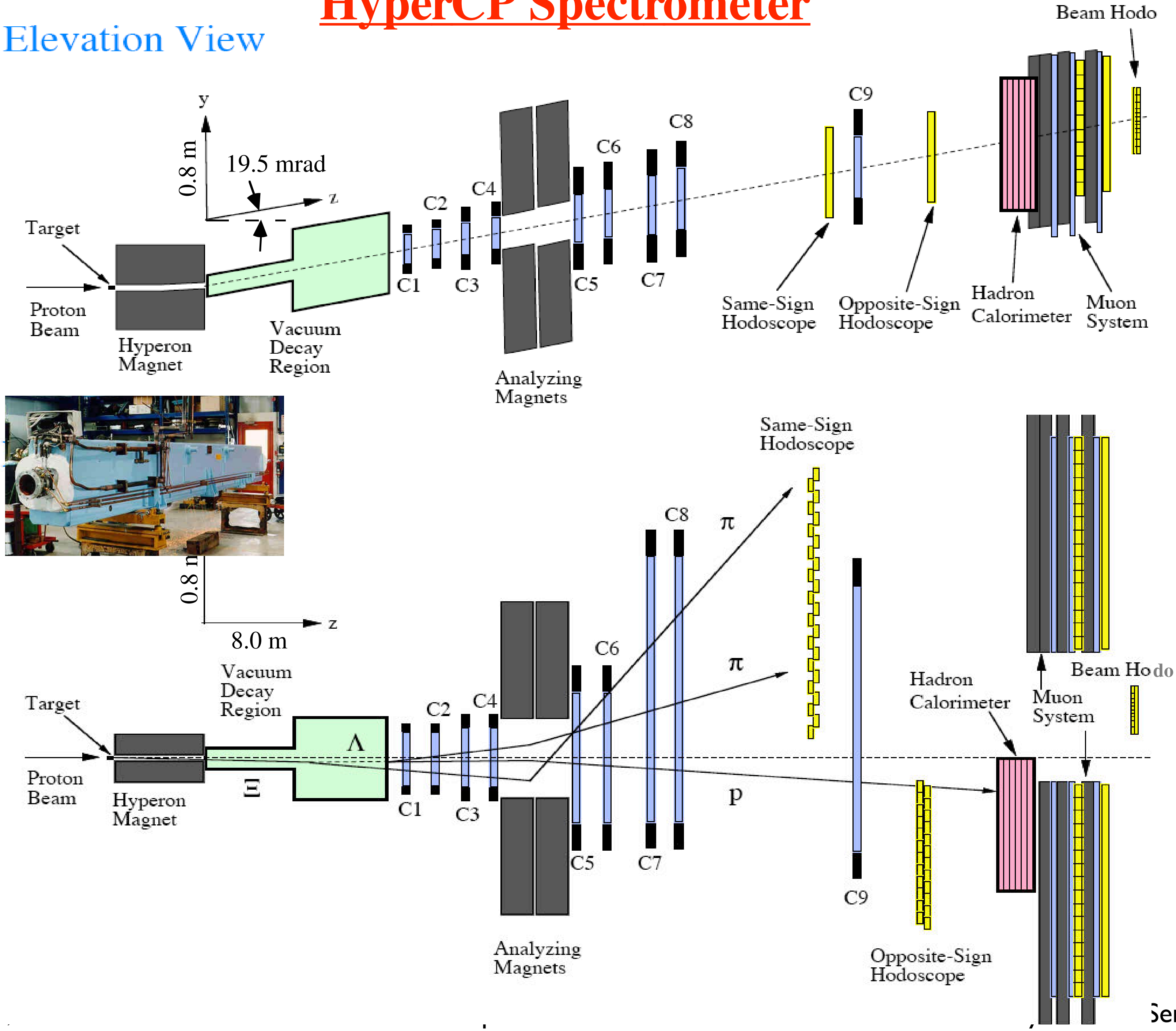


HyperCP Spectrometer



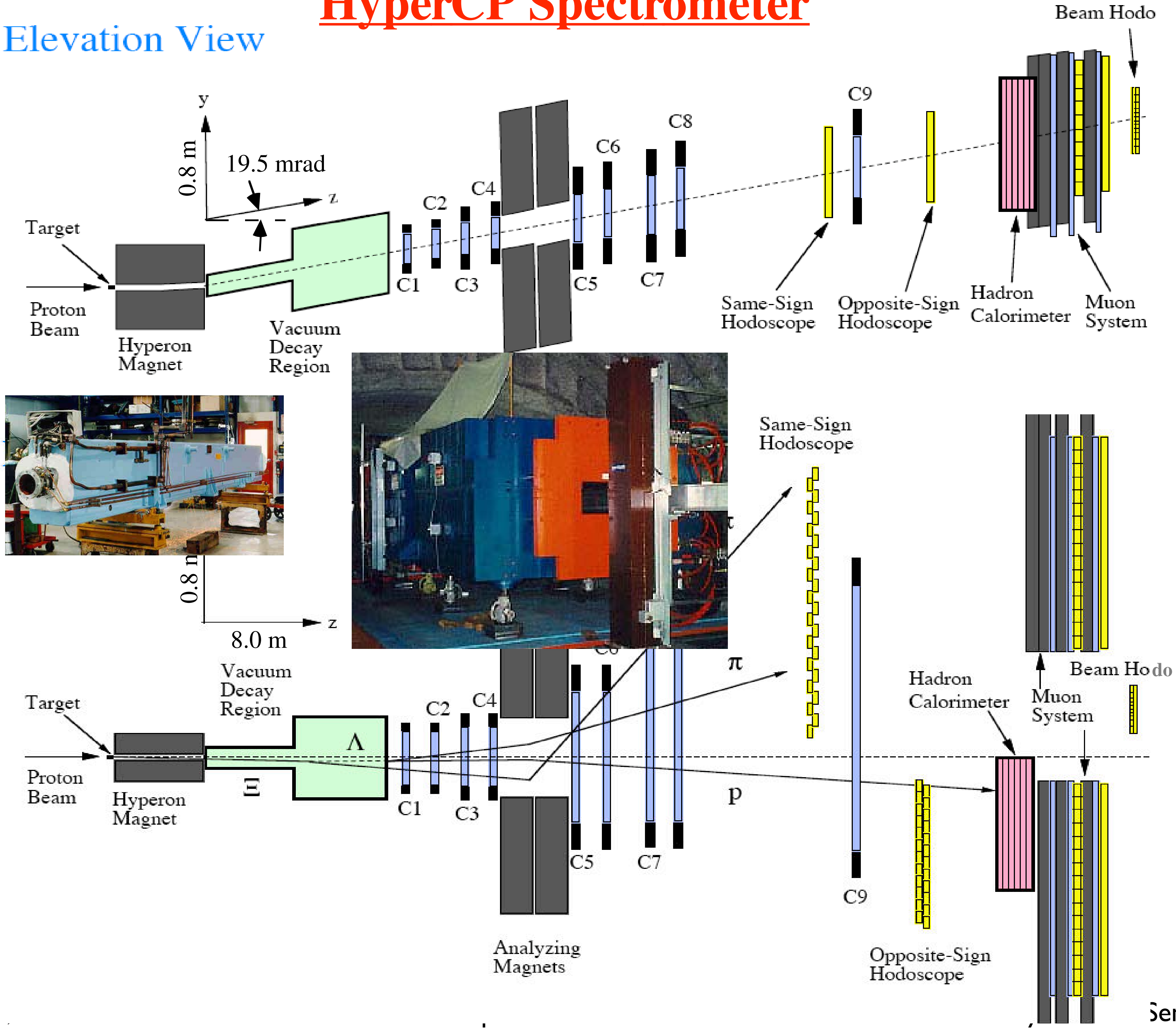
HyperCP Spectrometer

Elevation View

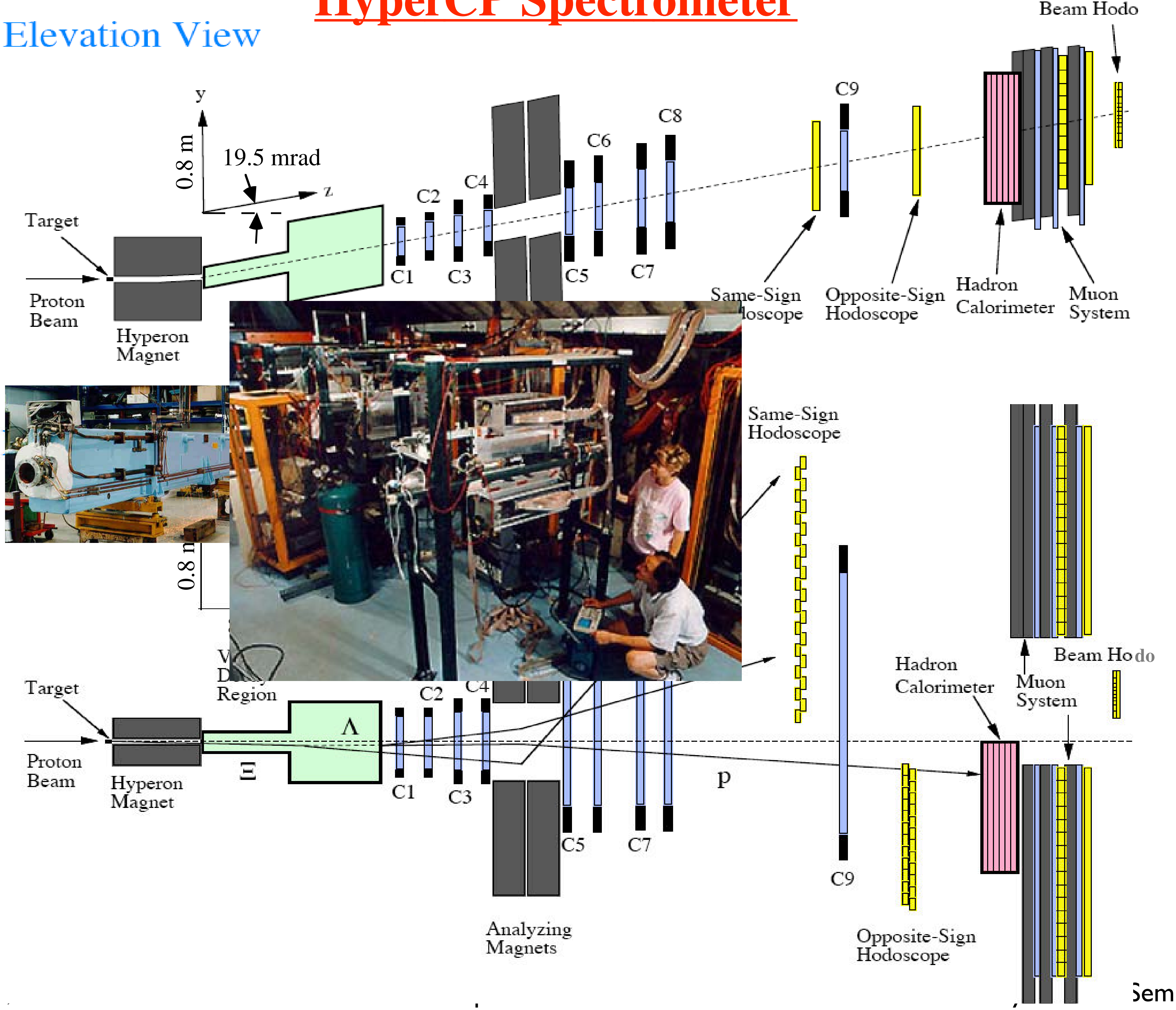


HyperCP Spectrometer

Elevation View

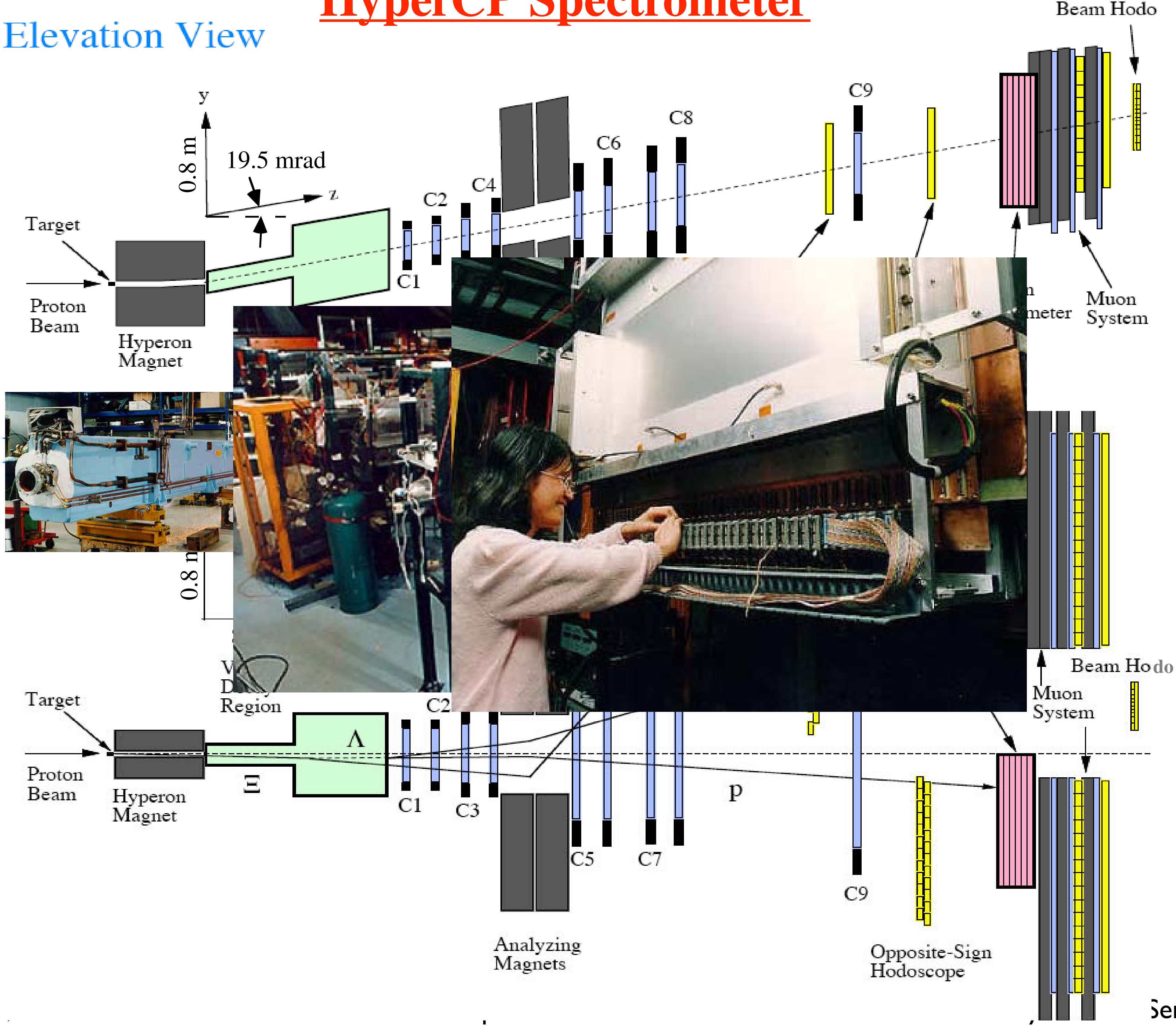


HyperCP Spectrometer



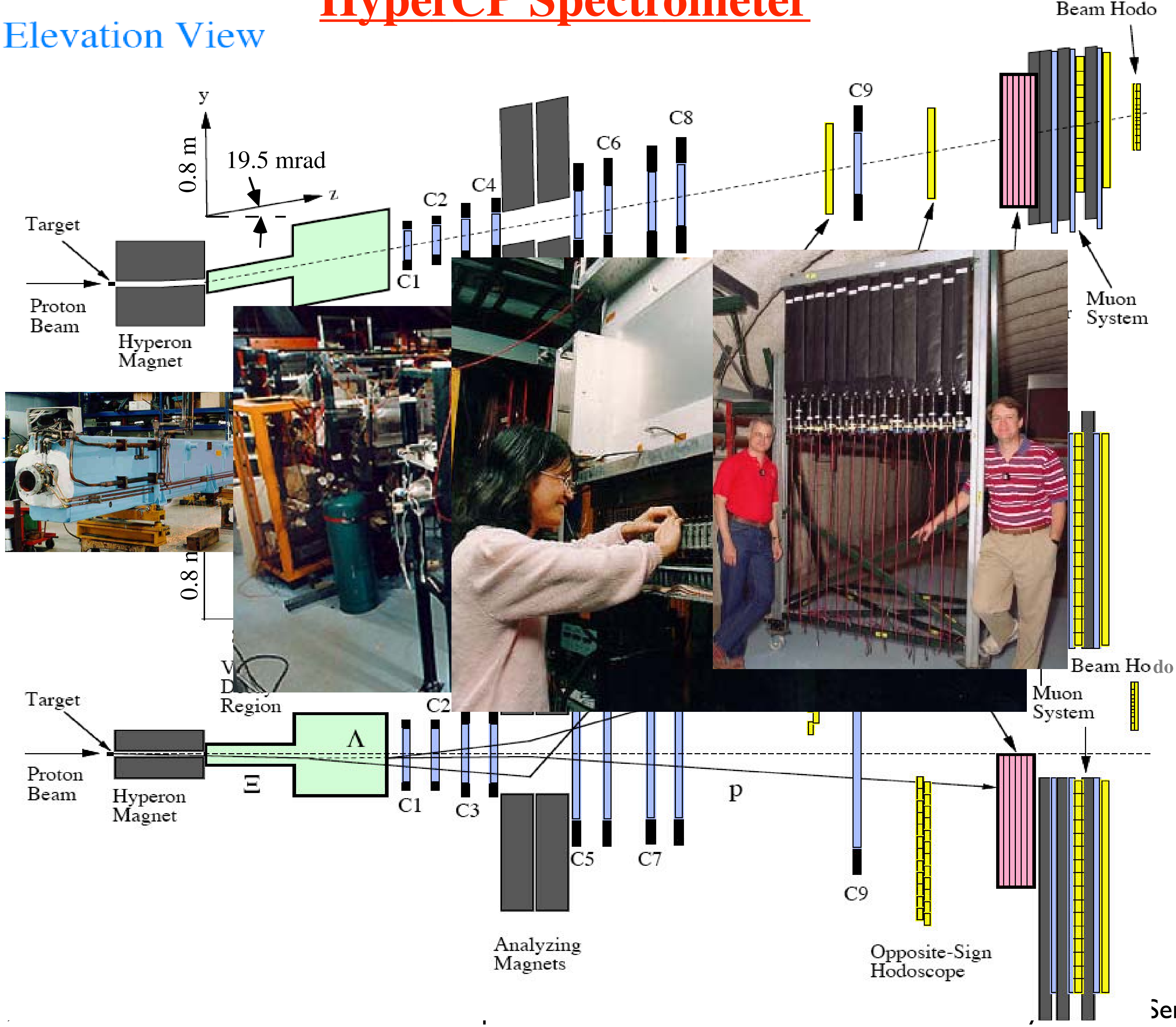
HyperCP Spectrometer

Elevation View



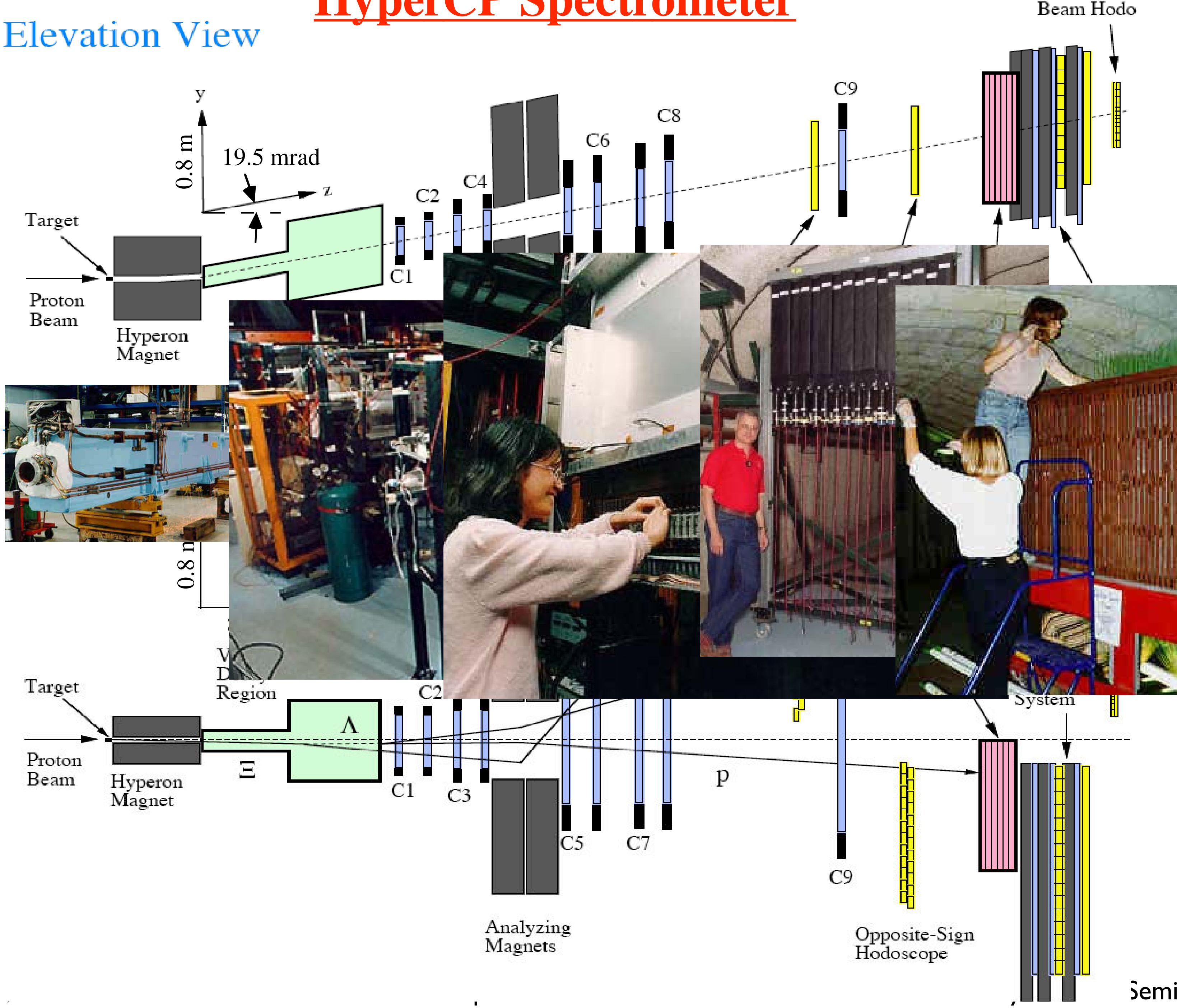
HyperCP Spectrometer

Elevation View



HyperCP Spectrometer

Elevation View



...and Fast HyperCP DAQ System

≈20,000 channels of MWPC latches

≈100 kHz of triggers

...written to 32 tapes in parallel

HyperCP Collaboration

A. Chan, Y.-C. Chen, C. Ho, P.-K. Teng
Academia Sinica, Taiwan

K. Clark, M. Jenkins
University of South Alabama, USA

W.-S. Choong, Y. Fu, G. Gidal, T. D. Jones, K.-B. Luk*, P. Gu, P. Zyla
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C. James, J. Volk
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J. Felix, G. Moreno, M. Sosa
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R. Burnstein, A. Chakravorty, D. Kaplan, L. Lederman, D. Rajaram, H. Rubin, N. Solomey, C. White
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N. Leros, J.-P. Perroud
University of Lausanne, Switzerland

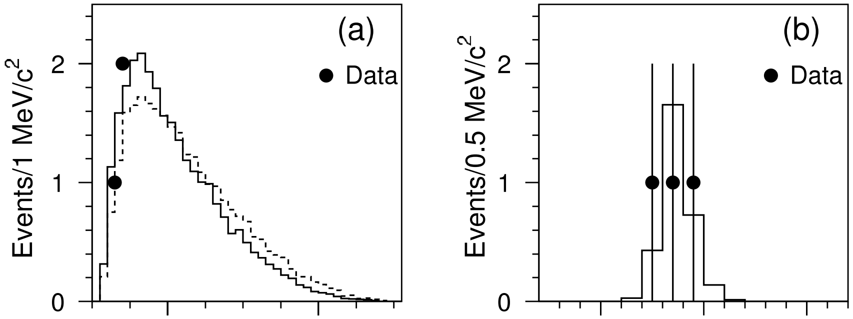
H. R. Gustafson, M. Longo, F. Lopez, H. Park
University of Michigan, USA

E. C. Dukes*, C. Durandet, T. Holmstrom, M. Huang, L. C. Lu, K. S. Nelson
University of Virginia, USA

*co-spokespersons

HyperCP also → 10^{10} Σ^+

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



≈2.4σ 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 $\Sigma^+ \rightarrow p\mu^+\mu^-$ Indicate a Light Pseudoscalar Higgs Boson?

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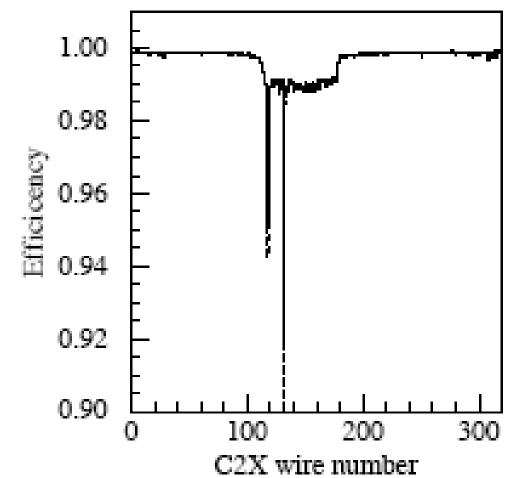
(Received 2 November 2006; published 22 February 2007)

The HyperCP Collaboration has observed three events for the decay $\Sigma^+ \rightarrow p\mu^+\mu^-$ 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.

How to follow up?

- Tevatron fixed-target is no more
- CERN fixed-target not as good (energy, duty factor)
- Main Injector fixed-target not as good (same reasons)
- AND HyperCP was already rate-limited



- Big collider experiments can't trigger efficiently

➡ What else is there?

Low-Energy Antiprotons!

- Also good for charmonium:
  - Thanks to superb precision of antiproton beam energy and momentum spread, E760/835 @ Fermilab Antiproton Accumulator made very precise measurements of charmonium parameters, e.g.:
    - best measurements of various η_c, χ_c, h_c masses, widths, branching ratios,...
    - interference of continuum & resonance signals
- Similar facility (FAIR) to be built at Darmstadt

➡ work not yet started ⇒ done >2016

Low-Energy Antiprotons!

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

Table I: Antiproton Intensities at Existing and Future Facilities

Facility	Stacking: Rate (10^{10}/hr)	Stacking: Duty Factor	Clock Hours /Yr	$\overline{\mathrm{p}}$/Yr (10^{13})
CERN AD			3800	0.4
FNAL (Accumulator)	20	15%	5550	17
FNAL (New Ring)	20	90%	5550	100
FAIR (≥2016)	3.5	90%	2780	9

...even after FAIR@Darmstadt turns on

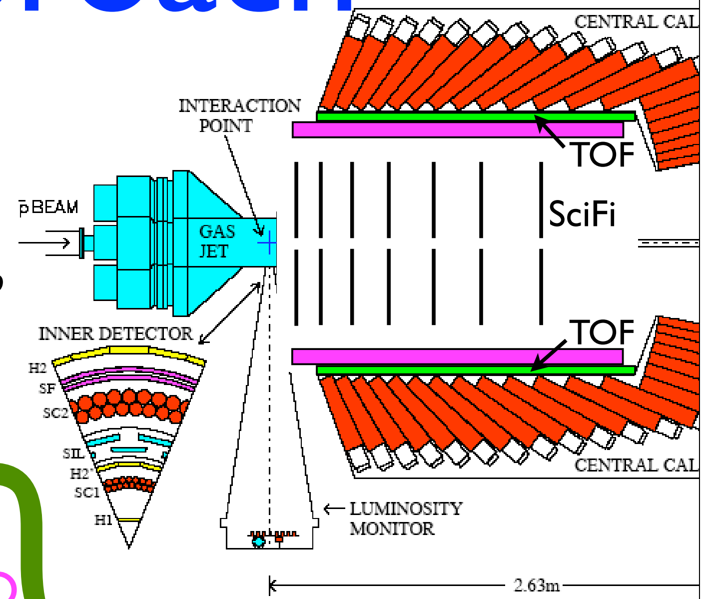
A Possible Approach

One possibility:

- Once Tevatron shuts down (≈2011),
  - Reinstall E835 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)

[existing SciFi DAQ from D0]

<$10M



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

+ number of $\Xi^- \bar{\Xi}^+$ TBD (transition crossing)

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

  ➡ need very precise mass measurement to confirm or refute

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

- Plus other charmonium measurements, etc...

Charm!

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

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

Eric Braaten

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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!

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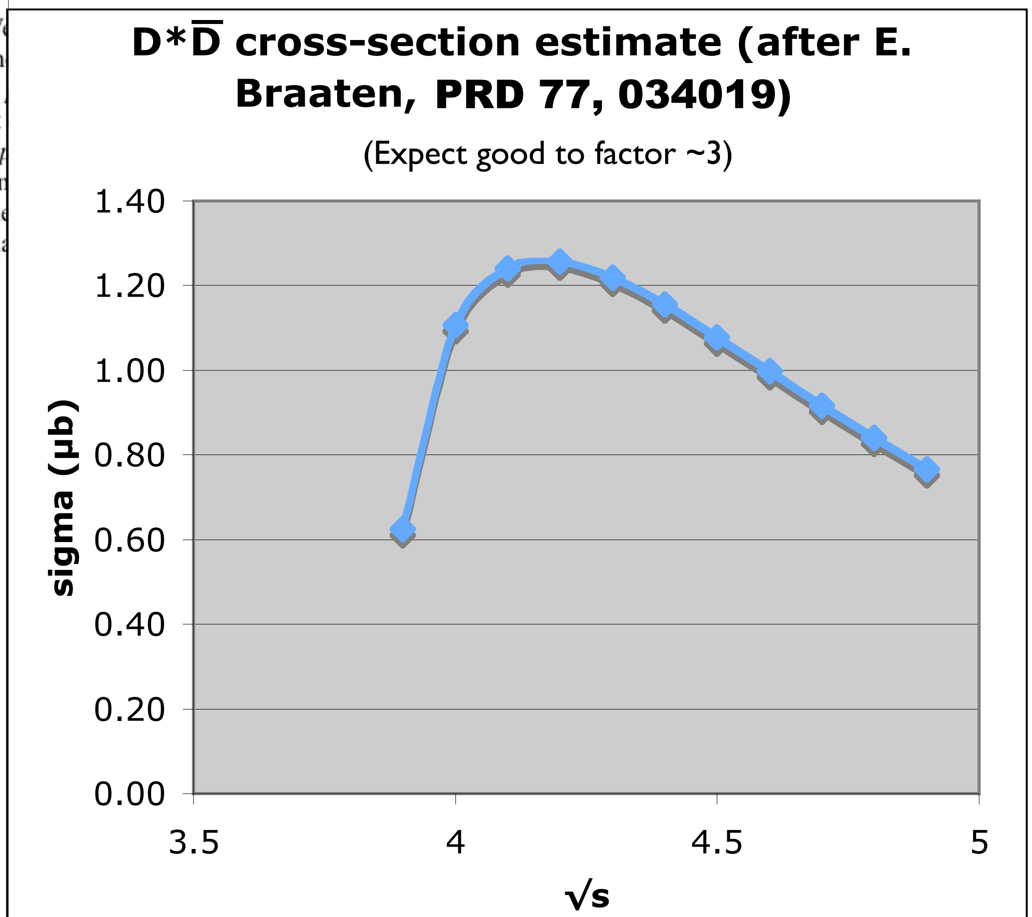
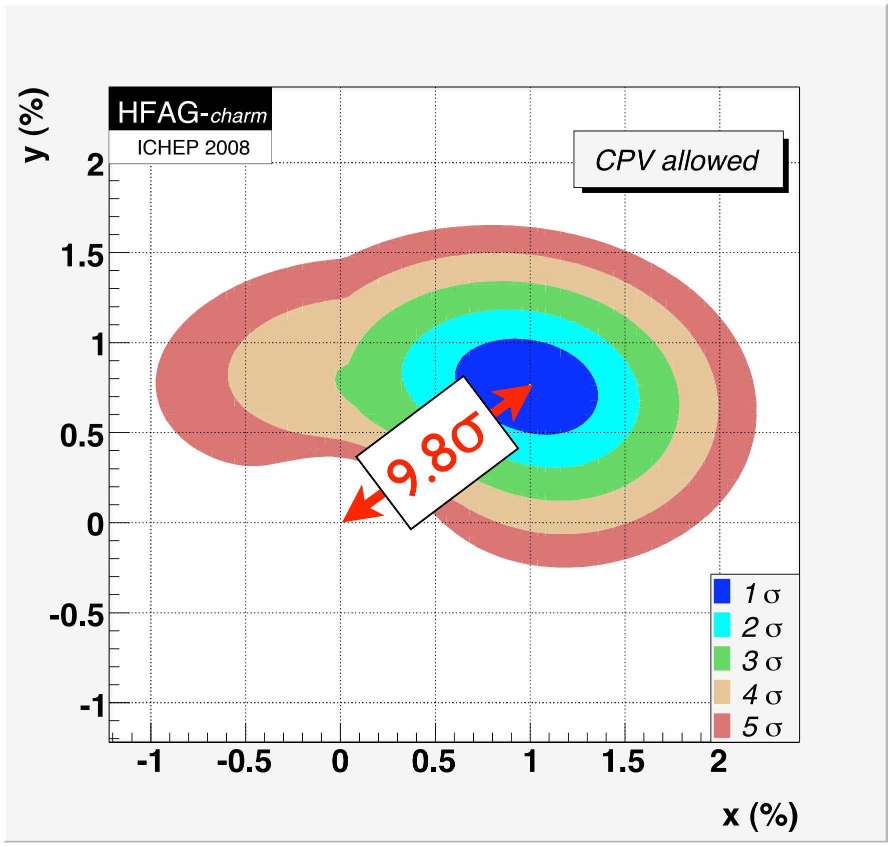


- E. Braaten estimate of $\bar{p}p$ $X(3872)$ coupling assuming X is D^*D molecule
  - extrapolates from K^*K data
- By-product is $D^{*0}\bar{D}^0$ cross section
- 1 μb → 4 ×10^9/year
- Expect efficiency as at *B* factories

Charm!

- D^0's mix! (*c* is only up-type quark that can)



- *Big question:* New Physics or old?

➡ key is *CP* Violation!

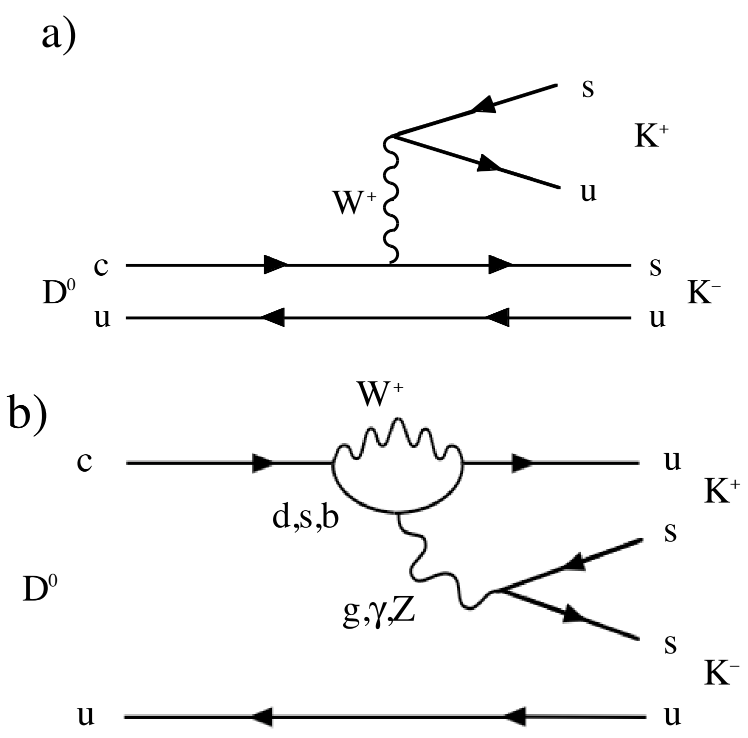
- *B* factories have ~10^9 open-charm events

- $\bar{p}p$ can produce ~10^{10}/y

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 $\sim 10^9$ open-charm events

- $\bar{p}p$ can produce $\sim 10^{10}$/y

➡ world's best sensitivity to charm CPV

...and **now**

for *something*

completely <u>different</u>!

Antihydrogen

- Long quest at LEAR & CERN AD (ATRAP, ATHENA, ALPHA), to study antihydrogen and test CPT
  - e.g., are atomic energy levels identical for H and $\overline{\mathrm{H}}$?
- We know CP is violated (so matter and antimatter not mirror images)
- But CPT is a good symmetry of most field theories!

$\Longrightarrow$tests a profound feature of quantum reality

- AD experiments struggling with difficulty of combining antiprotons with positrons in a Penning trap and winding up in (or near) ground state

Antihydrogen

- But over 10 years ago, FNAL E835 produced oodles of $\overline{\mathrm{H}}$!

VOLUME 80, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1998

Observation of Atomic Antihydrogen

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(Received 26 November 1997)

We report the background-free observation of atomic antihydrogen, produced by interactions of an antiproton beam with a hydrogen gas jet target in the Fermilab Antiproton Accumulator. We measure the cross section of the reaction $\overline{p}p \rightarrow \overline{H}e^{-}p$ for $\overline{p}$ beam momenta between 5203 and 6232 MeV/c to be $1.12 \pm 0.14 \pm 0.09$ pb. [S0031-9007(98)05685-3]

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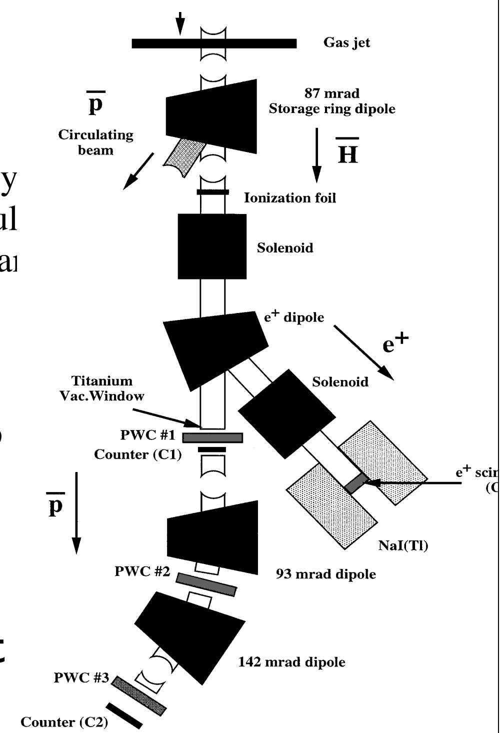

- Formed automatically in E835 gas-jet target, detected in "parasitic" E862
- Production probability grows with E_{beam}, Z_{tgt}

Antihydrogen

- Subsequently worked out technique to measure Lamb shift & hyperfine splitting of relativistic $\overline{\mathrm{H}}$ in flight:

PHYSICAL REVIEW D VOLUME 57, NUMBER 11 1 JUNE 1998

Measuring the antihydrogen Lamb shift with a relativistic antihydrogen beam

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(Received 18 December 1997; published 4 May 1998)

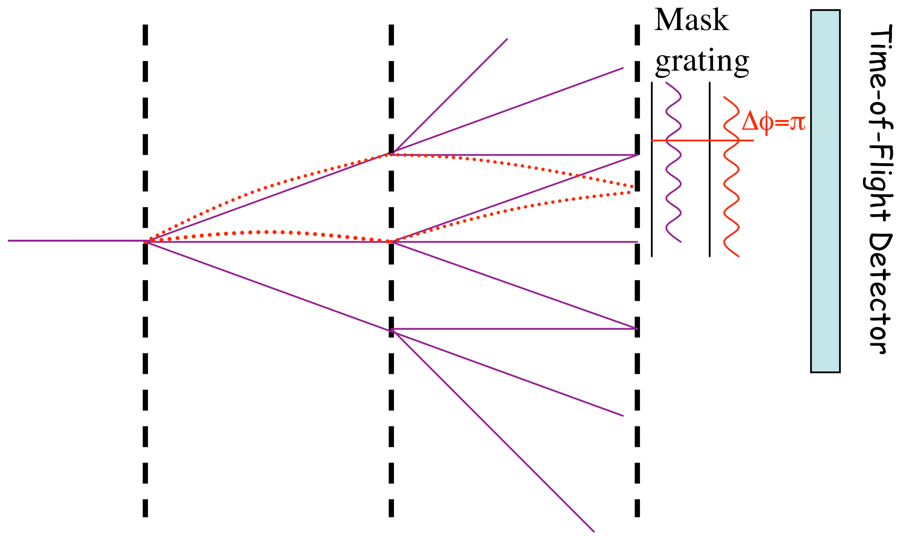
We propose an experiment to measure the Lamb shift and fine structure (the intervals $2s_{1/2}-2p_{1/2}$ and $2p_{1/2}-2p_{3/2}$) in antihydrogen. A sample of 10 000 antihydrogen atoms at a momentum of 8.85 GeV/c suffices to measure the Lamb shift to 5% and the fine structure to 1%. Atomic collisions excite antihydrogen atoms to states with $n=2$; field ionization in a Lorentz-transformed laboratory magnetic field then prepares a particular $n=2$ state, and is used again to analyze that state after it is allowed to oscillate in a region of zero field. This experiment is feasible at Fermilab. [S0556-2821(98)04711-0]

Antihydrogen

- Further parasitic running appears feasible
- High-Z foil operable in Antiproton Accumulator beam halo installed during last shutdown
- Could subsequently assemble Lamb-shift 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
  - in principle a simple interferometric measurement with slow $\overline{\mathrm{H}}$ beam [T. Phillips, Hyp. Int. 109 (1997) 357]:



- 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"

Antimatter Gravity

- Revised Letter of Intent presented to Fermilab Physics Advisory Committee (PAC) in March
  - emphasized 1st $\bar{g}$ measurements, to 1% (with only a day's worth of $\bar{p}$) and 10^{-4} (few months' worth)
  - followup to 10^{-9} possible via laser interferometry
- PAC & Director Oddone (April):
  1. interesting physics!
  2. need 10^{-9} matter demonstration before FNAL can provide support
- Techniques for matter demonstration in development

Antimatter Gravity

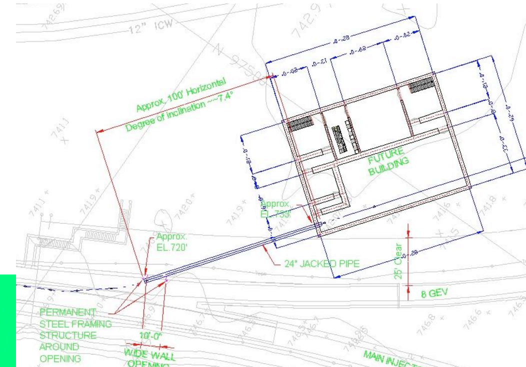
- Deceleration from 8 GeV to < 20 keV:
  - MI from 8 GeV to $\lesssim$ 400 MeV (TBD), then "reverse linac" or "particle refrigerator," then degrade
  - efficiency $\gtrsim 10^{-4}$ looks feasible

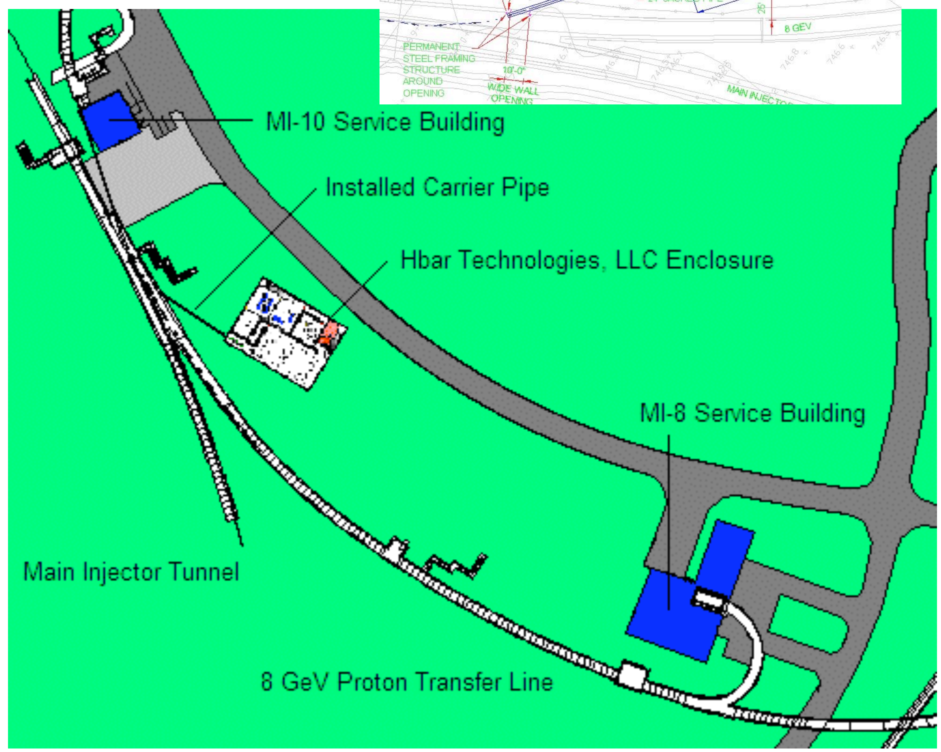
    $\Rightarrow 10^{-4}$ $\bar{g}$ measurement in ~ month's dedicated running
  - eventually, add small synchrotron → effic. ~1
- Requires completion of antiproton deceleration/ extraction facility planned for Hbar Technologies

HBAR Technologies, LLC
Making Antimatter Matter®

1275 W. Roosevelt Rd., Suite 130, West Chicago IL, 60185
www.hbartech.com

MI Deceleration Below 1 GeV/c





2/22/08

Project-X Physics Workshop
Nov. 16-17, 2007

9

Antiproton Source Futures

- With end of Tevatron Collider in sight, many are viewing Antiproton Source as generic resource:
  - 2 large-acceptance 8 GeV rings

$\longrightarrow$ can they be reconfigured to enable $\mu 2e$, $g-2$, etc.?

- This ignores large, unique value for $\bar{p}$ physics!
  - with Germany spending 1 G€ on FAIR, can cannibalizing our pbar source be truly sensible?
- Nevertheless, appears likely that $\mu 2e$ will eliminate FNAL pbar option starting around 2016 (until Project X?)
  - leaves 4–5-year window of opportunity during which FNAL $\bar{p}$ capabilities are unique in the world

Antiproton Source Futures

- Questions:

  ? In near term (2012–15 ?), can pbar source be used simultaneously for

    - medium-energy $\overline{p}$ annihilation expt
    - Antimatter Gravity Experiment
    - $g-2$

  ? What upgrades/modifications will this require?

  ? How can costs be minimized/accommodated?

Summary

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

➡ You can help! (See http://capp.iit.edu/hep/pbar)