New Experiments with Antiprotons

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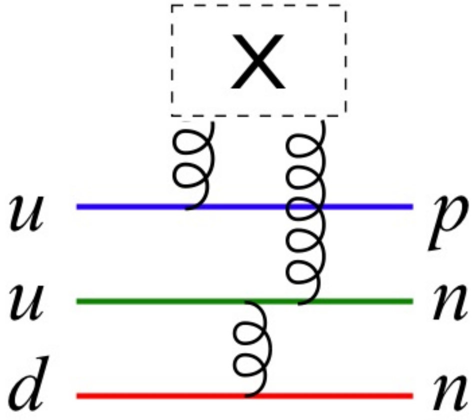


Center for Beam Physics Seminar

Lawrence Berkeley National Lab

24 Sept. 2010

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

Start with a basic question:

- ✤ Why is there matter in the universe?
  - Whenever energy is converted into matter (e.g., in Tevatron collisions), always find that equal amounts of matter and antimatter are created.
  - The Big Bang should have been no exception.

☞But we observe no antimatter & ~10^9–10^{10} cosmic-background-radiation photons per baryon.

⇒Evidently, after Big Bang, slight matter excess developed, and remained after all the antimatter annihilated with matter into photons

Baryogenesis

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

- Sakharov (1967): possible 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

- CPV already discovered in 1964: small effect in K^0 mixing & decay
  - nicely explained in SM by Kobayashi–Maskawa mechanism: non-zero phase in CKM quark mixing matrix
- KM model makes simple, striking 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 [BaBar & Belle, 2001, CDF, DØ, et al.]

(Hence Kobayashi & Maskawa 2008 Nobel prize)

CP Violation

- CPV already discovered in 1964: small effect in
  mixing & decay
  - nicely explained in SM by Kobaya...
    mechanism: non-zero phas...
    matrix
- KM model m... ...iction:
  - ➡ if... ...phase, should be large ... particles!
- ...erved in *B*-meson decays as well [BaBar ...I, CDF, DØ, et al.]
- (Hence Kobayashi & 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

Kaons, B mesons: Years of intensive new-physics searches have so far come up empty*

Hyperons, Charm, Neutrinos: Worth looking elsewhere as well!

*except for possible DØ 3.2σ dimuon signal

Hyperon CP Violation

- An old topic:

PHYSICAL REVIEW VOLUME 184, NUMBER 5 25 AUGUST 1969

Final-State Interactions in Nonleptonic Hyperon Decay

O. E. OVERSETH*
The University of Michigan, Ann Arbor, Michigan 48104

AND

S. PAKVASA†
University of Hawaii, Honolulu, Hawaii 96822

(Received 1 April 1969)

⋮

E. Tests for *CP* and *CPT* Invariance

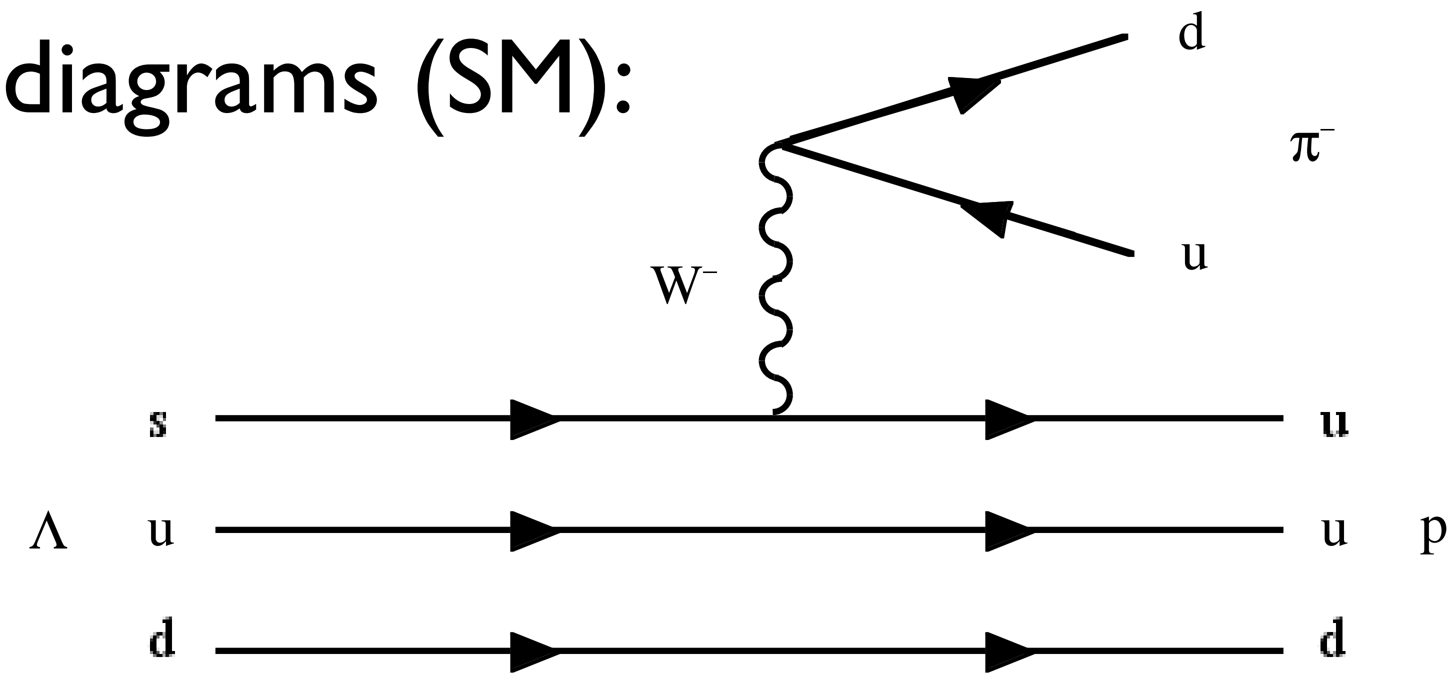
Thus in hyperon decay, $\bar{\alpha} \neq -\alpha$ implies *CP* violation in this process independent of the validity of the *CPT* theorem. This is also true if $\bar{\beta} \neq -\beta$.

Also, as usual, *CPT* invariance implies equality of Λ^0 and $\bar{\Lambda}^0$ lifetimes, whereas *CP* invariance implies equality of partial rates $\Gamma^0 = \bar{\Gamma}^0$, and $\Gamma^- = \bar{\Gamma}^+$. This is also true when final-state interactions are included in the analysis.

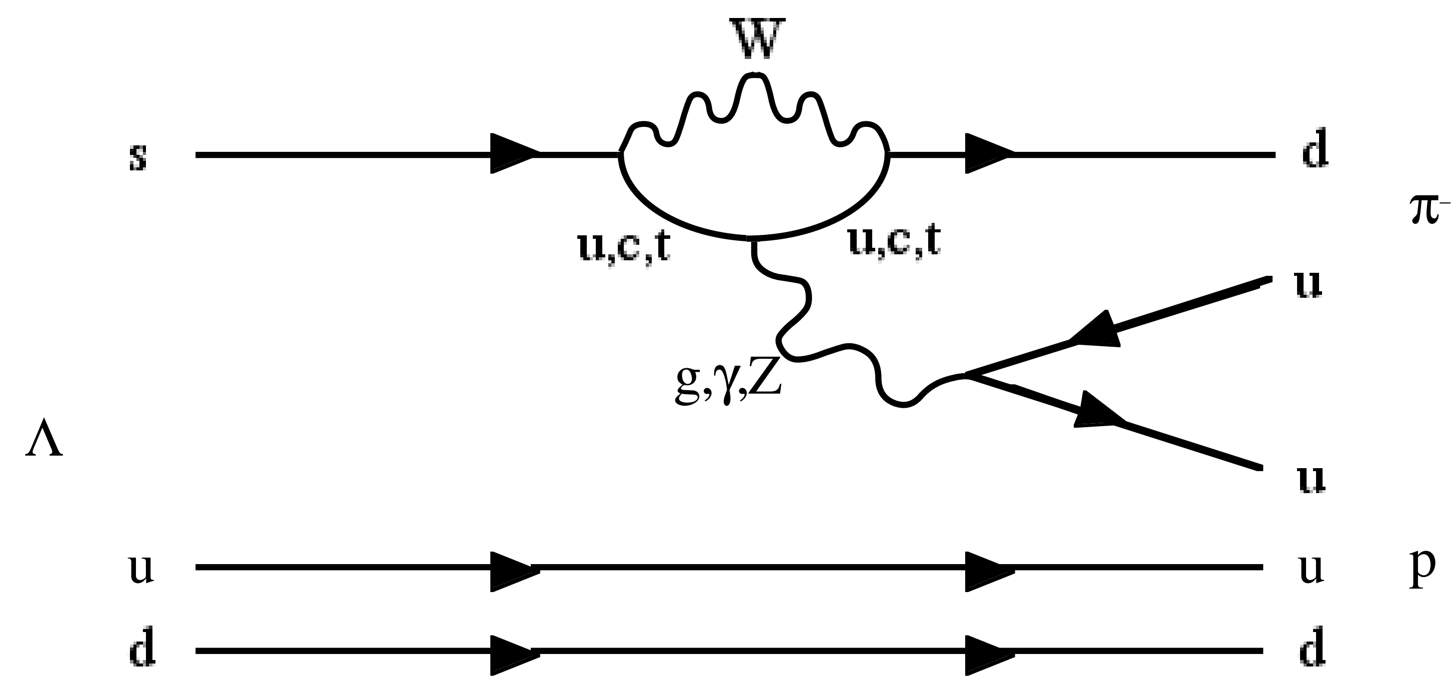
Hyperon CP Violation

- Example Feynman diagrams (SM):

Λ decay:



Λ penguin decay:



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

Hyperon CP Violation

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

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

→ 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

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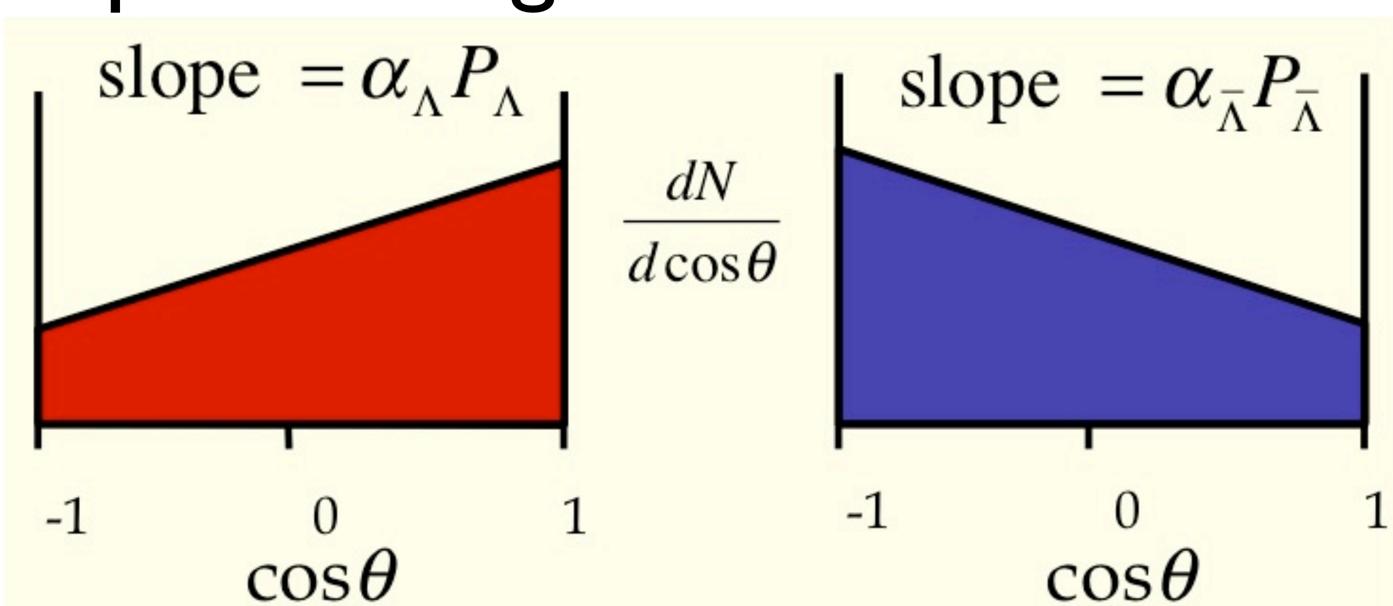
$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{q}_p)$$

⟶ nonuniform proton angular distribution in Λ rest frame:

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



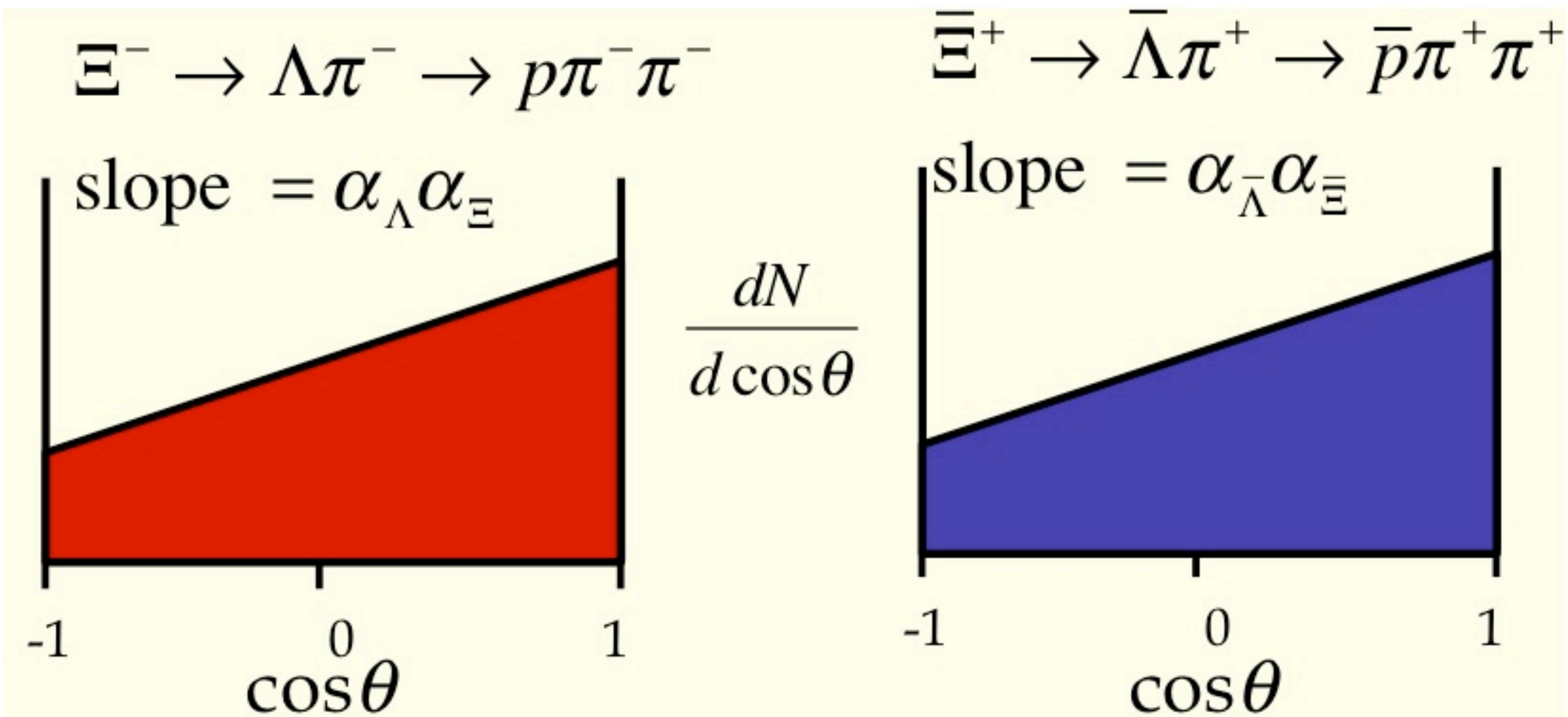
$$\Rightarrow A_\Lambda \equiv \frac{\alpha_\Lambda + \bar{\alpha}_\Lambda}{\alpha_\Lambda - \bar{\alpha}_\Lambda},\ B_\Lambda \equiv \frac{\beta_\Lambda + \bar{\beta}_\Lambda}{\beta_\Lambda - \bar{\beta}_\Lambda},\ \Delta_\Lambda \equiv \frac{\Gamma_{\Lambda\to P\pi} - \bar{\Gamma}_{\Lambda\to P\pi}}{\Gamma_{\Lambda\to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

CP-odd

Hyperon CP Violation

- But, for precise measurement of A_Λ, need excellent knowledge of relative Λ and $\bar{\Lambda}$ polarizations!

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



- 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]
$A_{\Xi\Lambda}$	$\Xi^\mp \to \Lambda\pi,\ \Lambda \to p\pi$	$\lesssim 5 \times 10^{-5}$	$\leq 1.9 \times 10^{-3}$	[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

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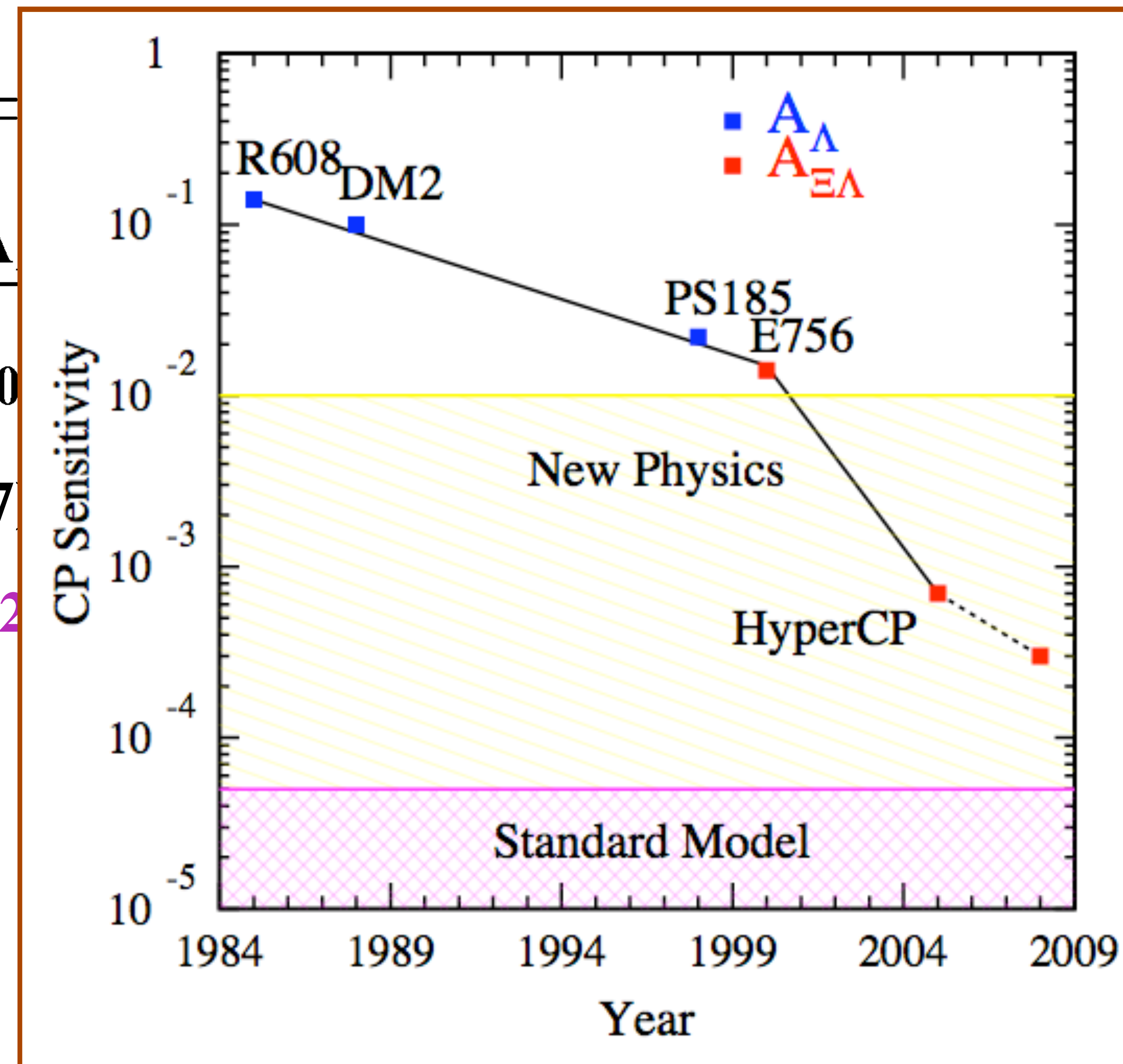
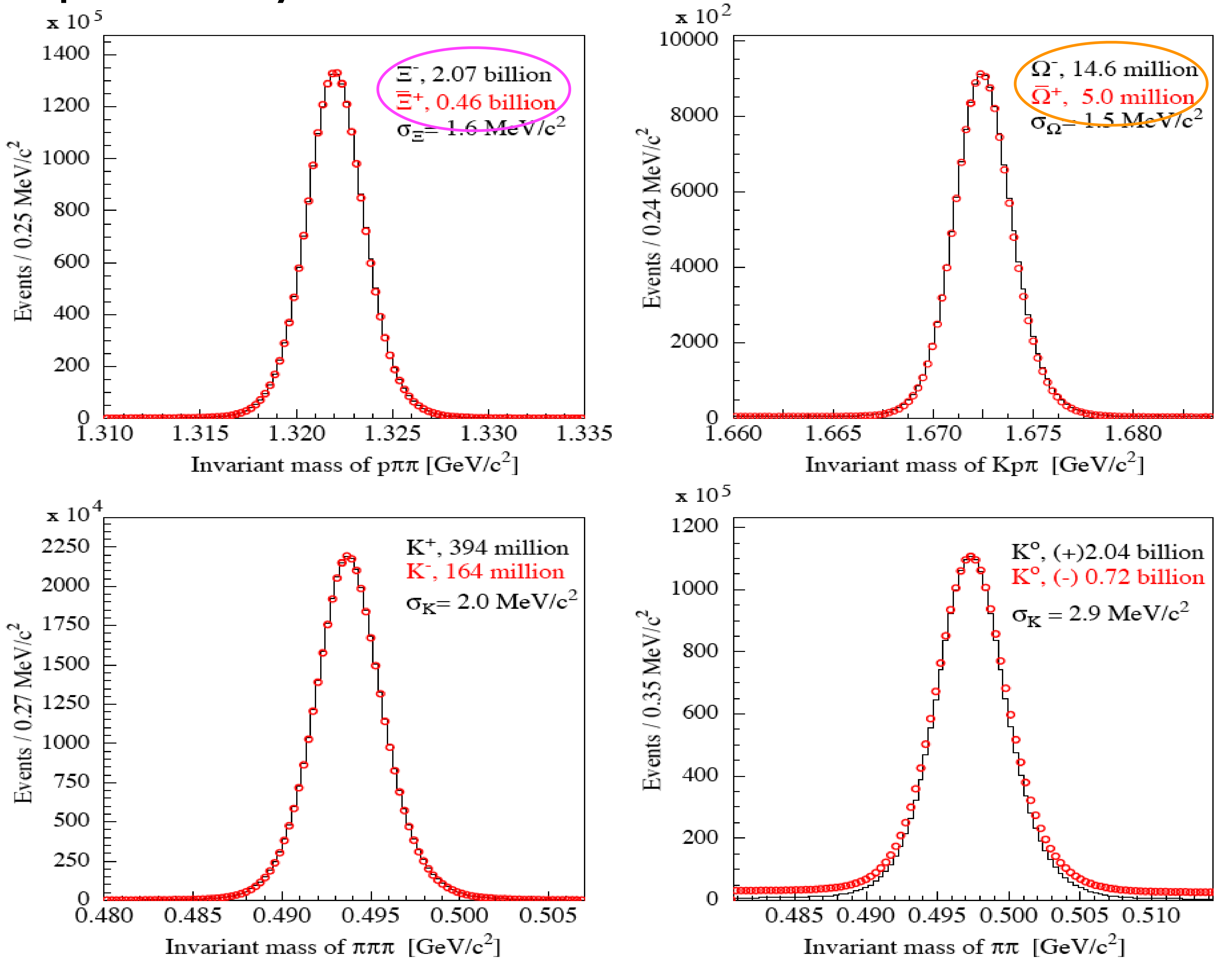
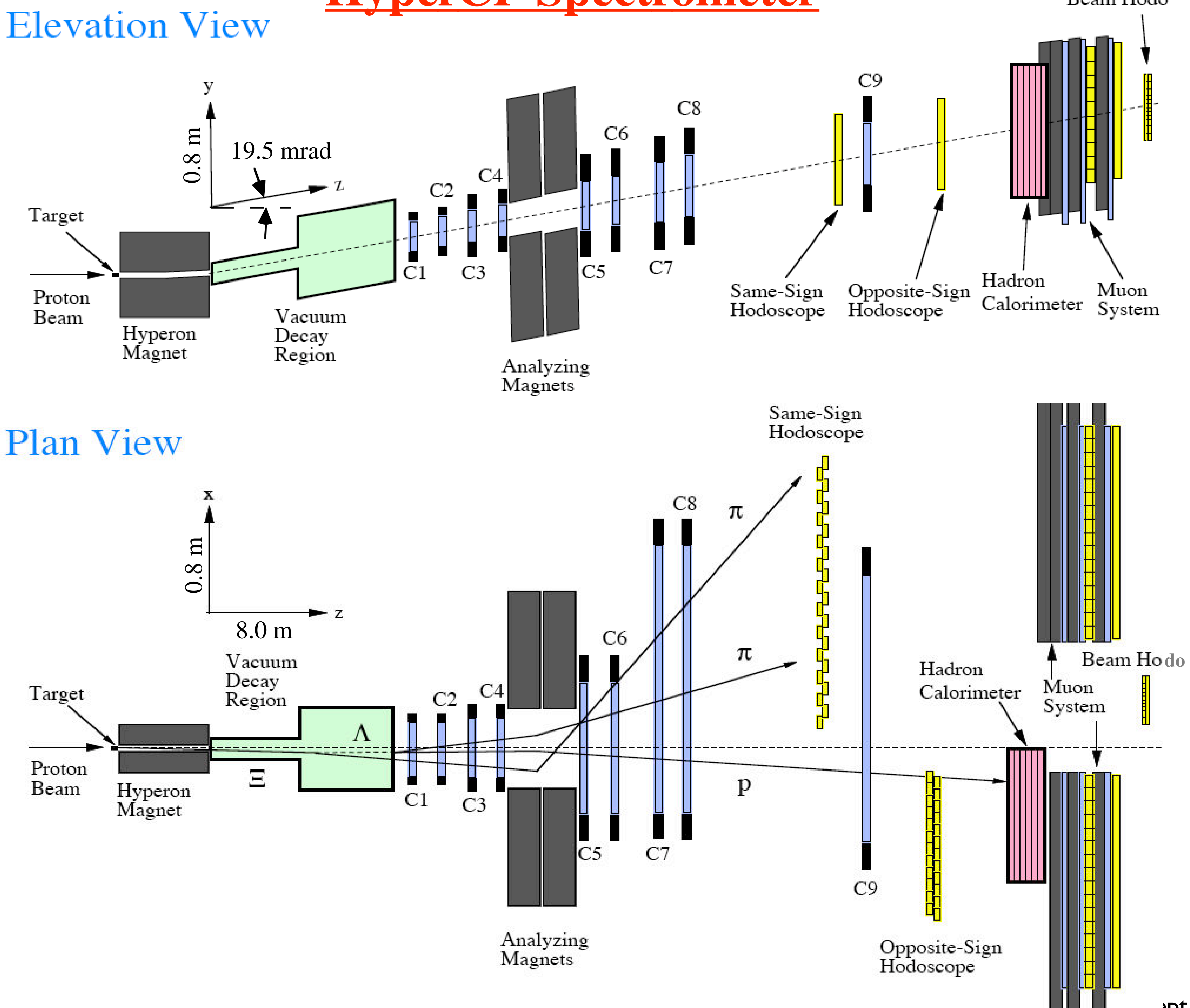


Made possible by... <u>**Enormous HyperCP Dataset**</u>

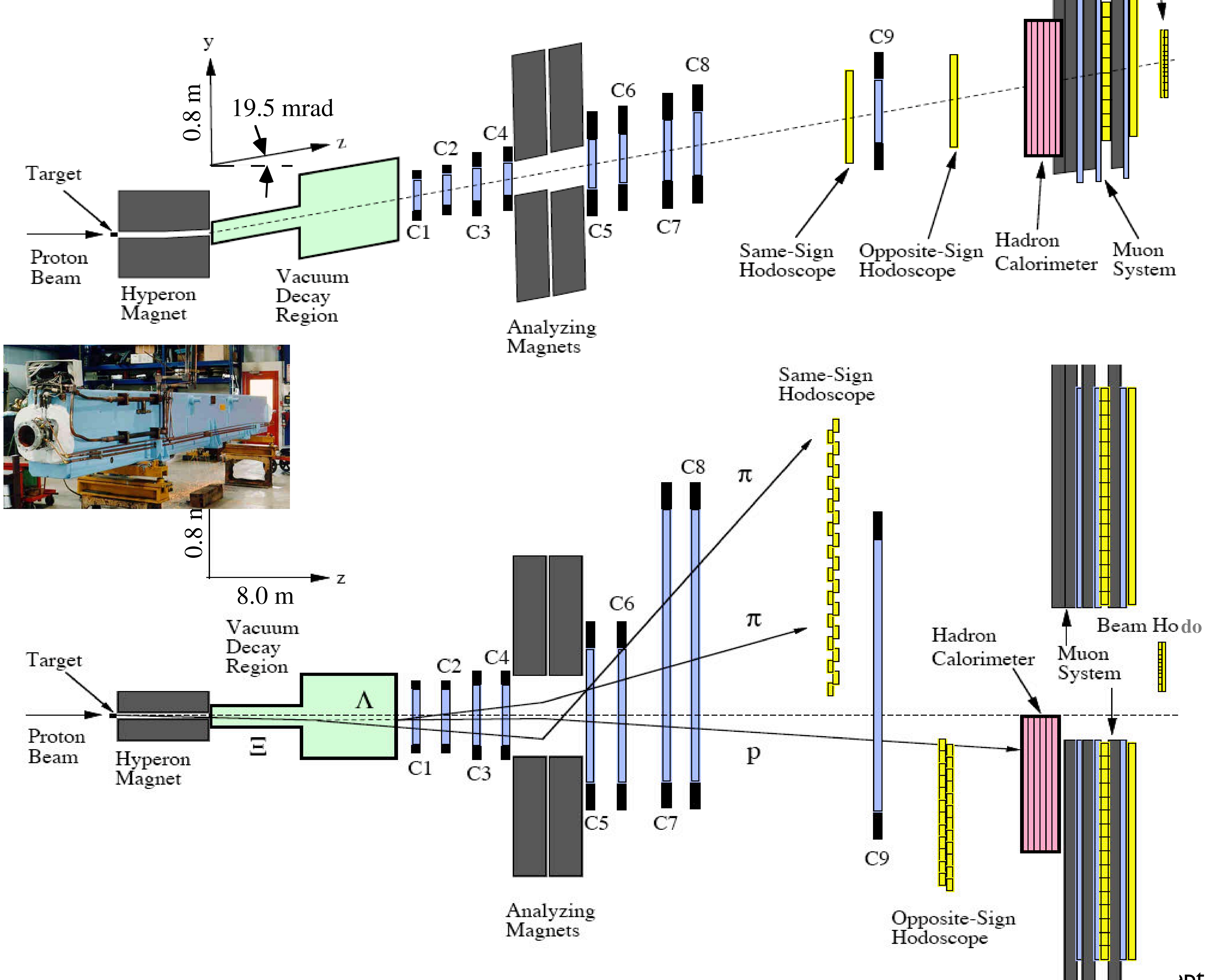


HyperCP Spectrometer

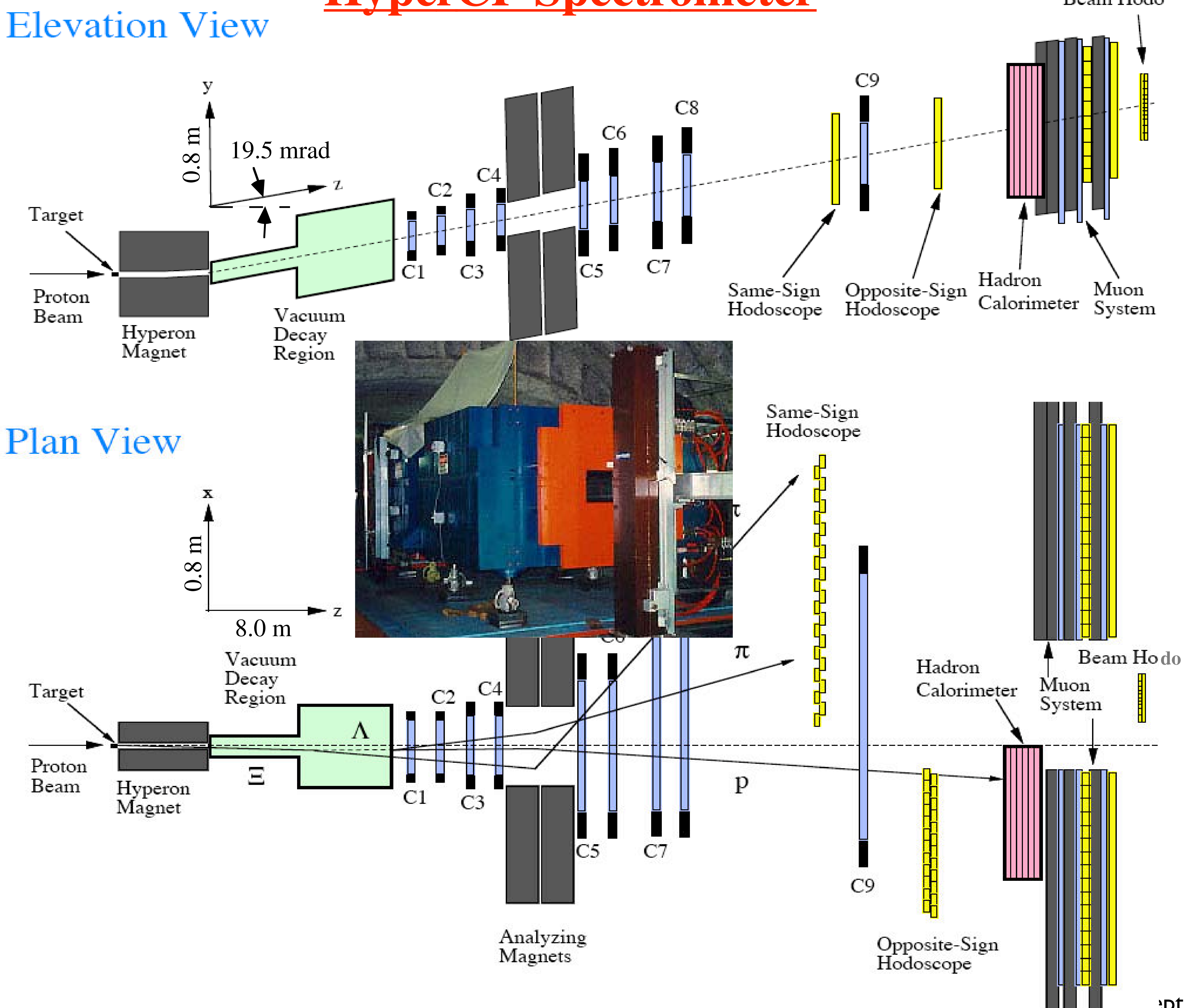


HyperCP Spectrometer

Elevation View



HyperCP Spectrometer



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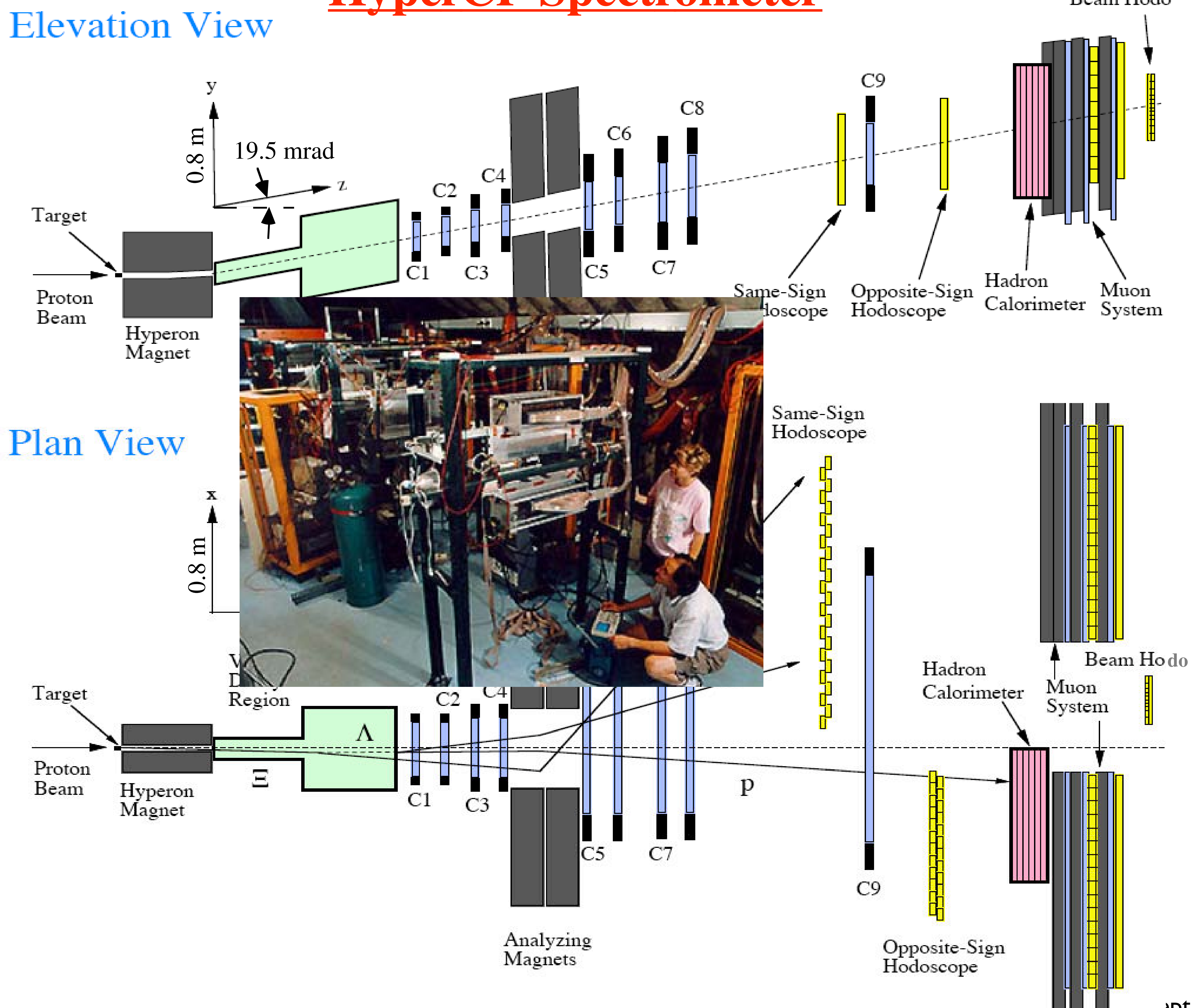

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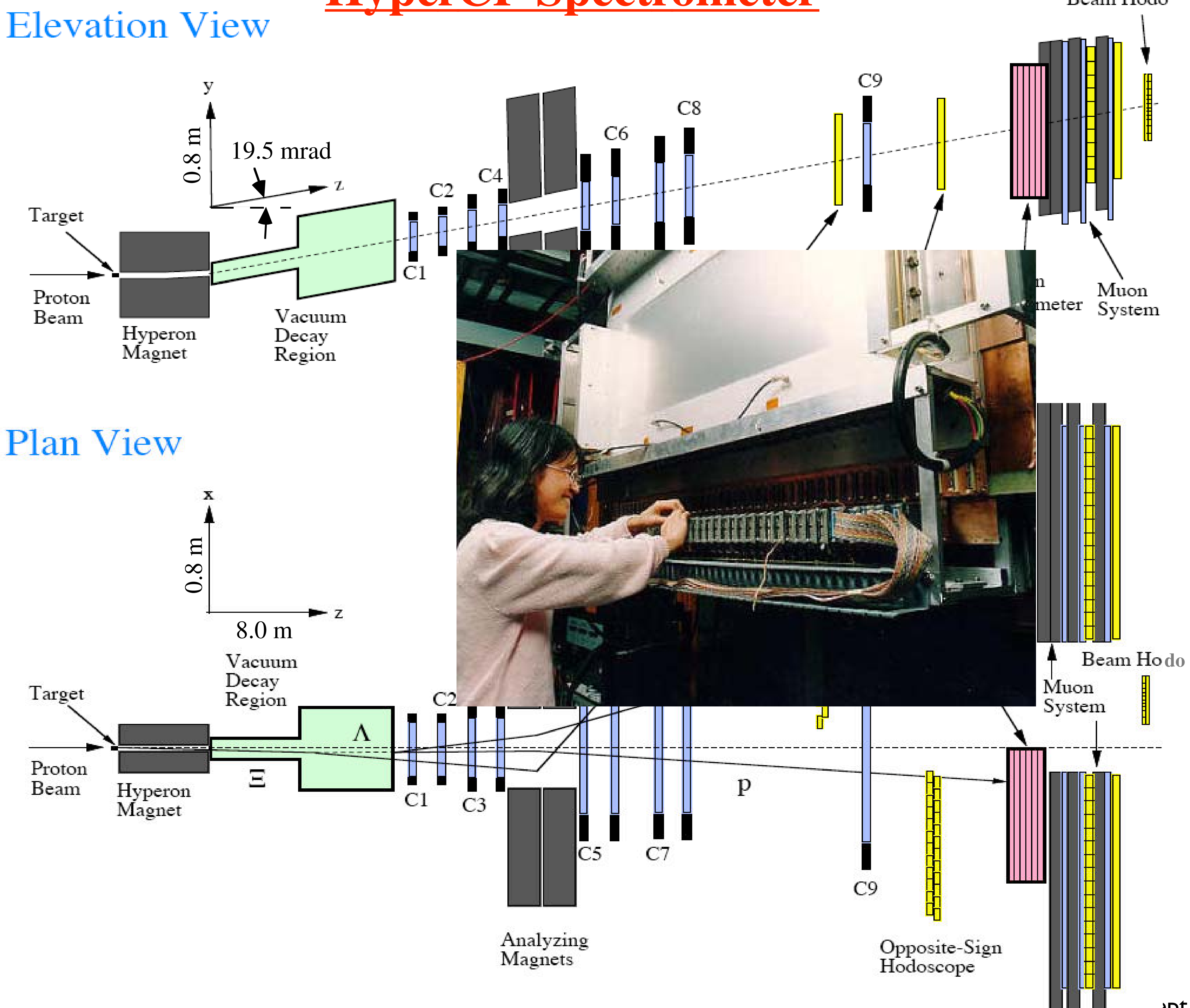
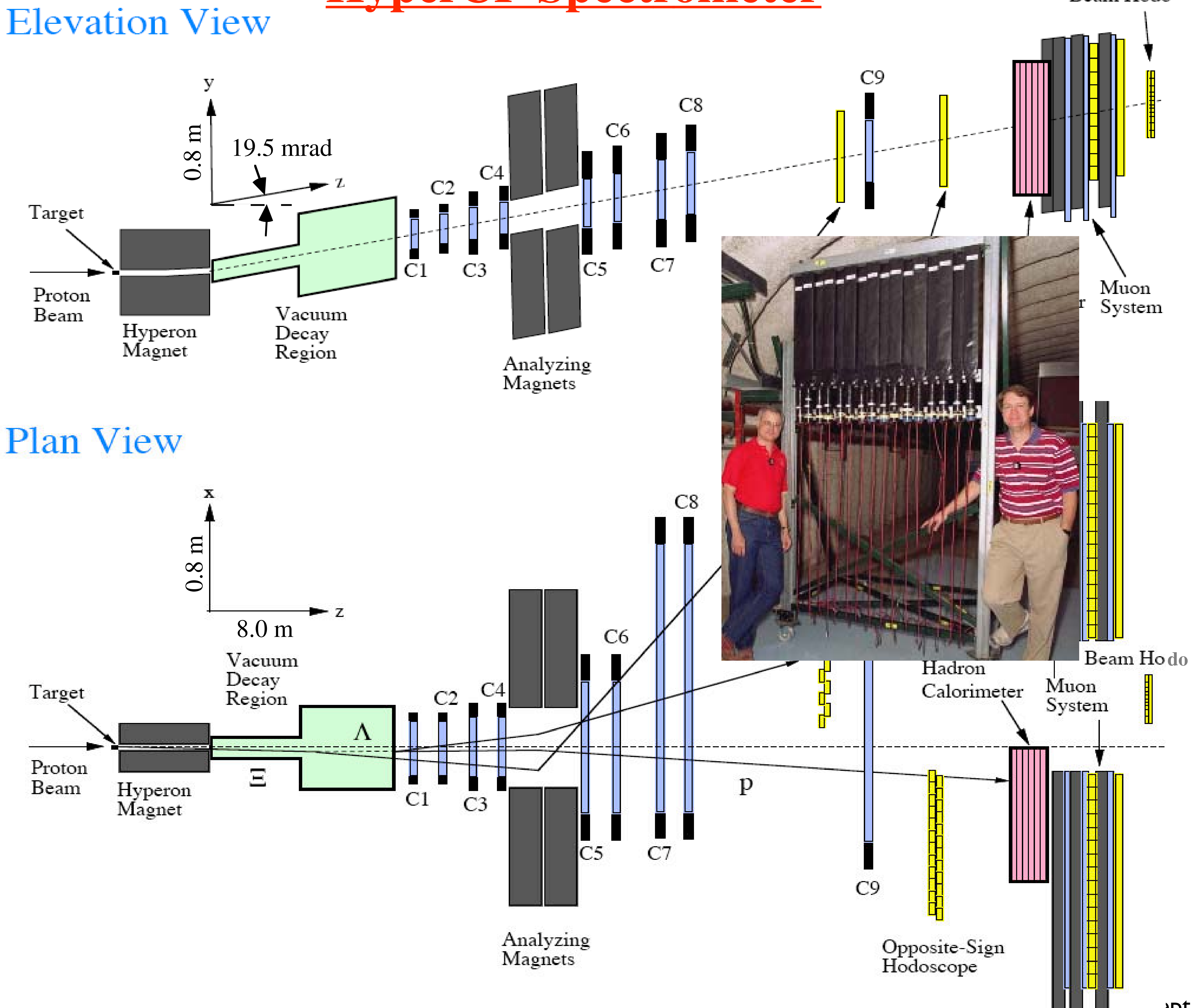


HyperCP Spectrometer



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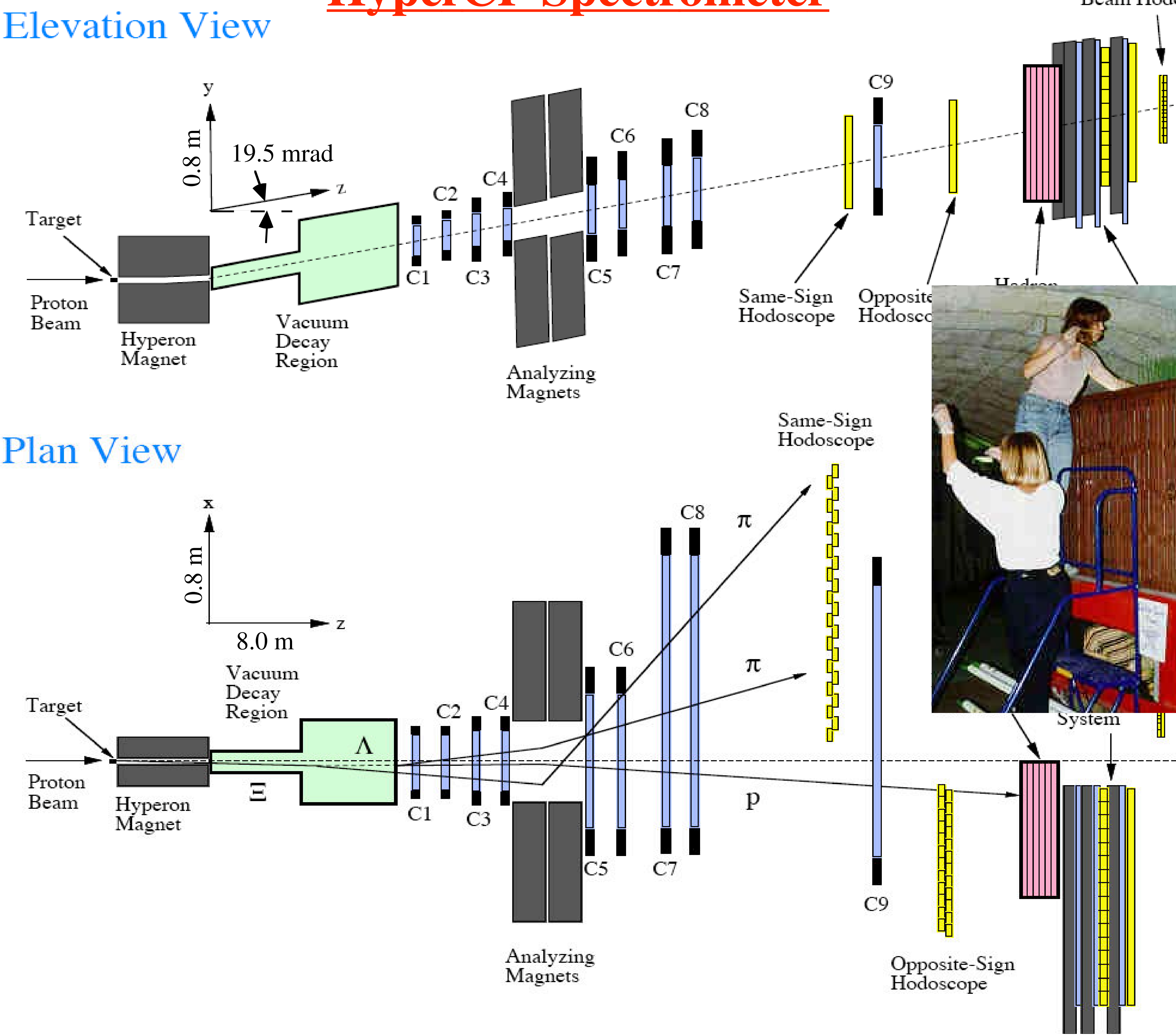

...and Fast HyperCP DAQ System

≈20,000 channels of MWPC latches

≈100 kHz of triggers

...written to 32 tapes in parallel

HyperCP Collaboration

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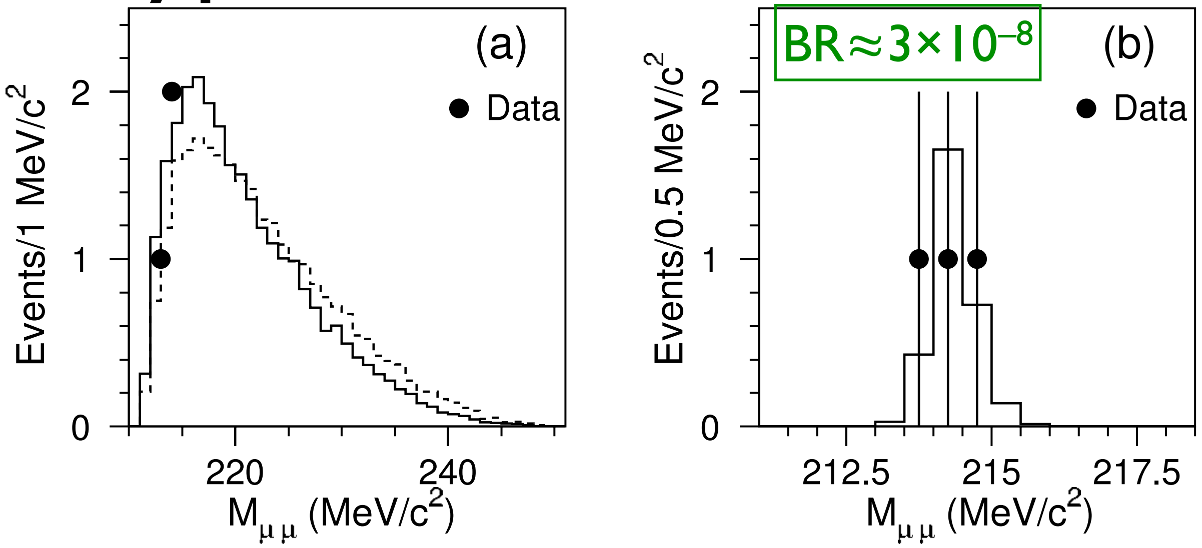
*co-spokespersons

HyperCP also → 10^{10} Σ^+

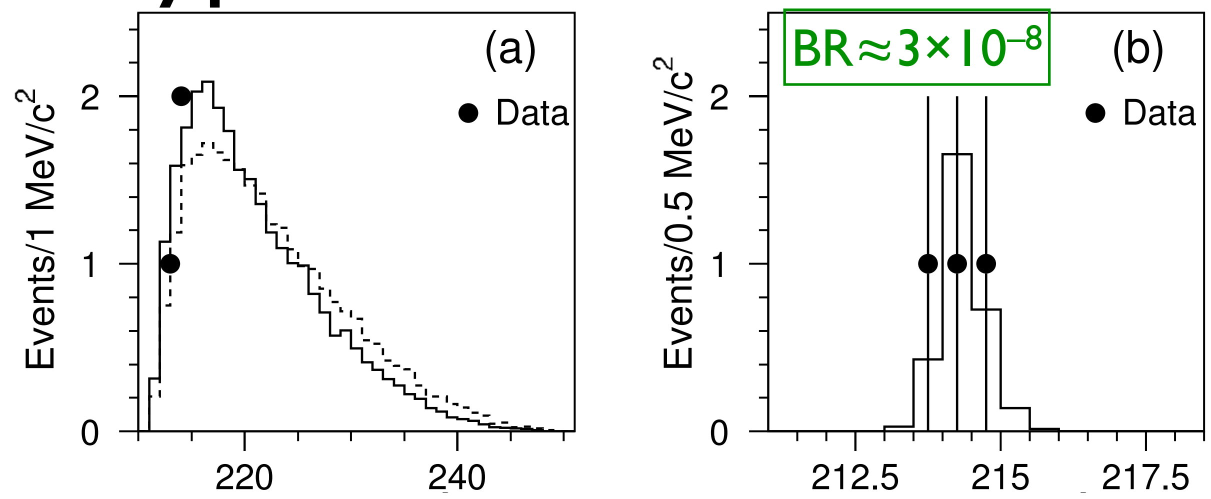


$\Sigma^+ \rightarrow p\mu^+\mu^-$ Decay

≈2.4σ fluctuation of SM? or

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

HyperCP also → 10^{10} Σ^+



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

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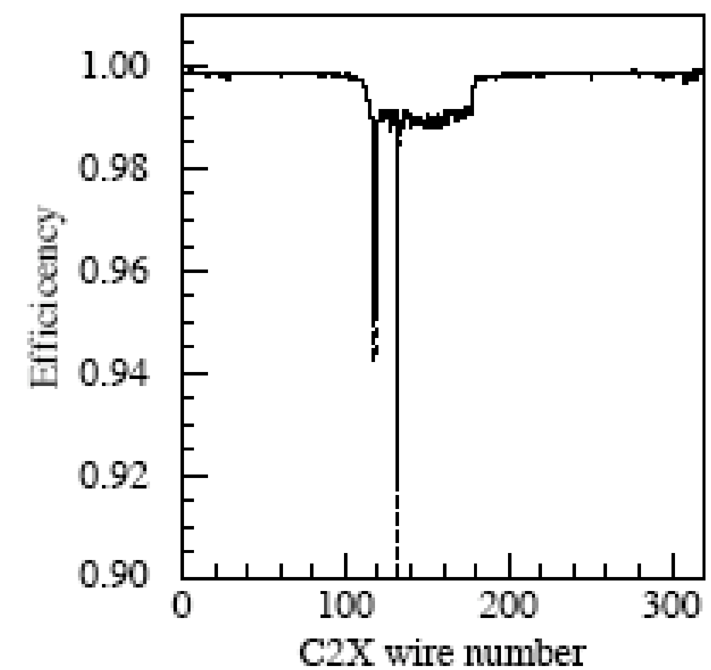
(Received 2 November 2006; published 22 February 2007)

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, J-PARC 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!

- 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]
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		(-6 ± 2 ± 2) × 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 most intense

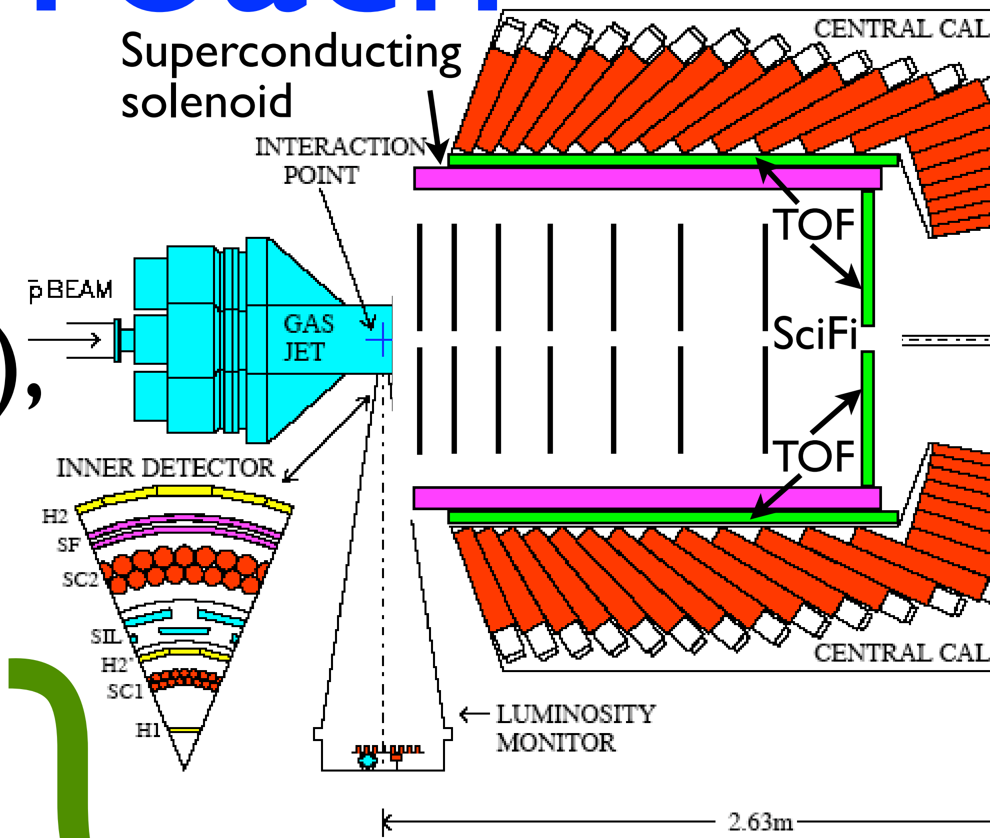
Table 1: Antiproton energies and intensities at existing and future facilities.

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

…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)

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

} <$10M

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

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

What Can This Do?

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

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

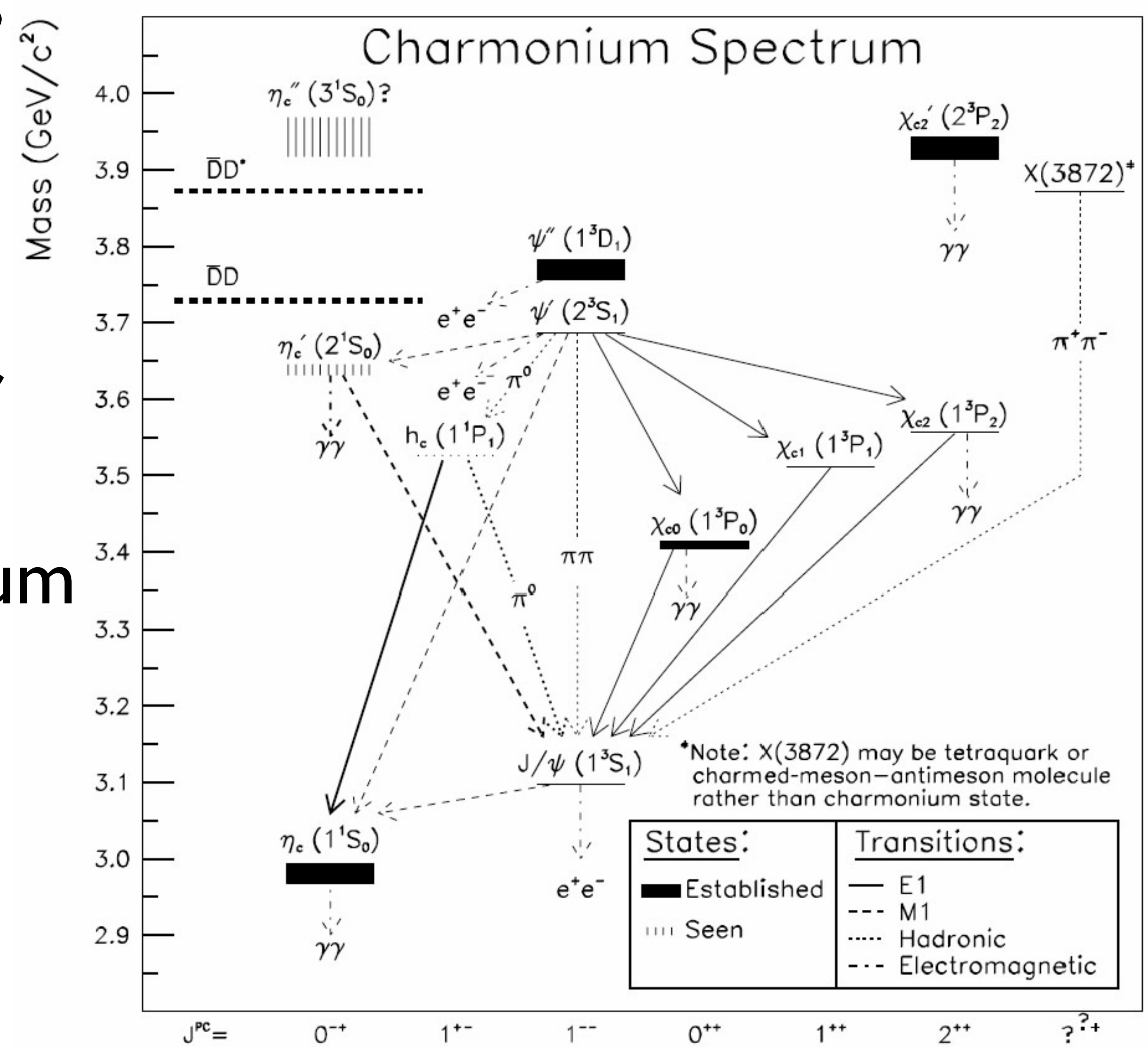
Predicted $\mathcal{B} \sim 10^{-6}$ if P^0 real

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

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

Else
What ^ 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,...



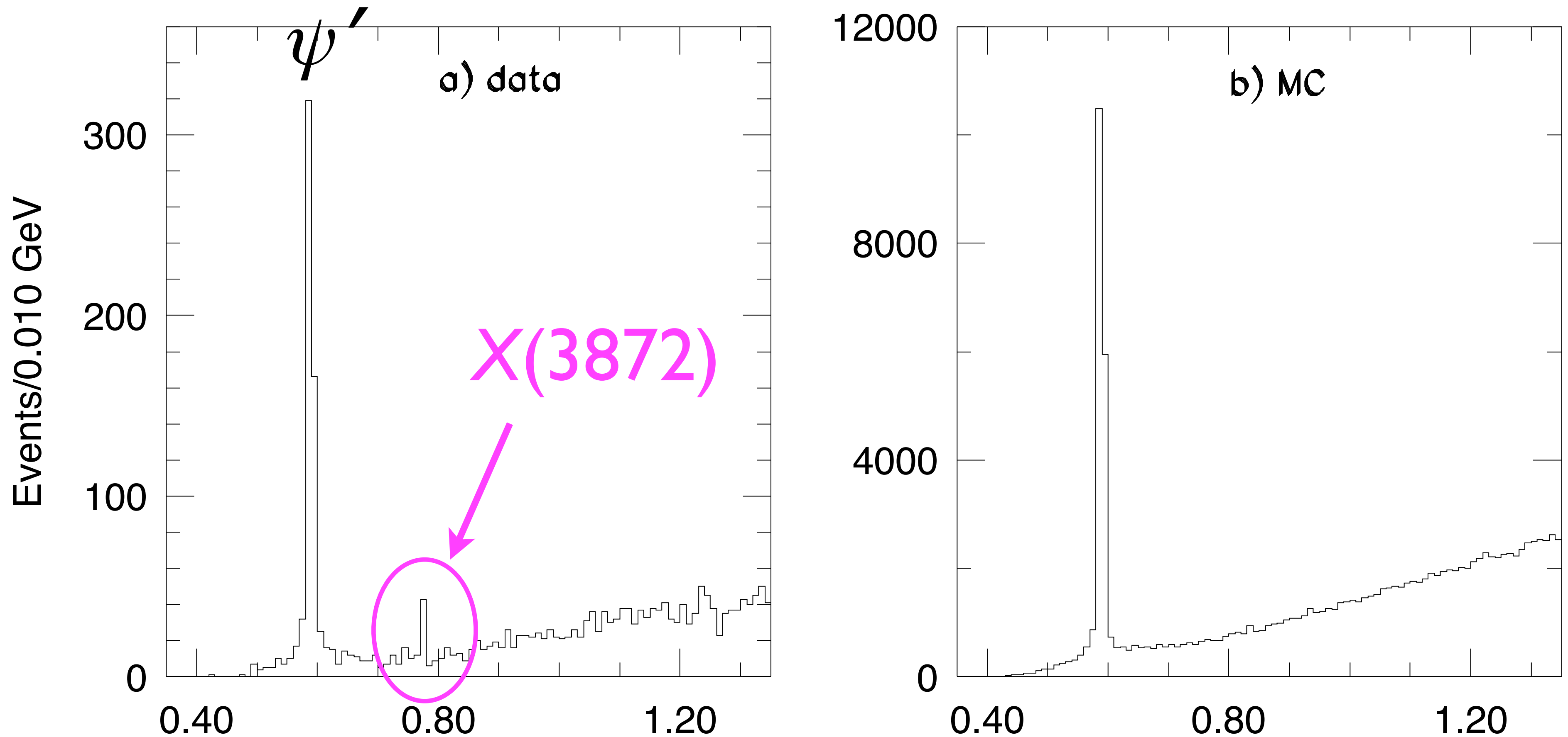
- ▶ $\bar{p}p$ produces all quantum states (not just 1^{--}, unlike e^+e^-)

What Else Can This Do?

- Much interest 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 meson-antimeson ($D^0\,\overline{D}^{*0}$ + 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 = −0.35±0.69 MeV)

XYZ hadronic transitions

- Many new states : ?

State	EXP	M + i Γ (MeV)	J^{PC}	Decay Modes Observed	Production Modes Observed
X(3872)	Belle,CDF, D0, Cleo, BaBar	3871.2±0.5 + i(<2.3)	1^{++}	$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $\gamma J/\psi$	B decays, ppbar
	Belle BaBar	$3875.4 \pm 0.7^{+1.2}_{-2.0}$ $3875.6 \pm 0.7^{+1.4}_{-1.5}$		$D^0 D^0 \pi^0$	B decays
Z(3930)	Belle	3929±5±2 + i(29±10±2)	2^{++}	D^0D^0, D^+D^-	γγ
Y(3940)	Belle BaBar	3943±11±13 + i(87±22±26) $3914.3^{+3.8}_{-3.4}$ ±1.6+ i(33^{+12}_{-8} ±0.60)	J^{++}	$\omega J/\psi$	B decays
X(3940)	Belle	$3942^{+7}_{-6} \pm 6$ + i($37^{+26}_{-15} \pm 8$)	J^{P+}	DD*	e^+e^- (recoil against J/ψ)
Y(4008)	Belle	$4008 \pm 40^{+72}_{-28}$ + i($226 \pm 44^{+87}_{-79}$)	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
X(4160)	Belle	$4156^{+25}_{-20} \pm 15$+ i($139^{+111}_{-61} \pm 21$)	J^{P+}	D*D*	e^+e^- (recoil against J/ψ)
Y(4260)	BaBar Cleo Belle	$4259 \pm 8^{+8}_{-6}$ + i($88 \pm 23^{+6}_{-4}$) 4284^{+17}_{-16} ±4 + i($73^{+39}_{-25} \pm 5$) $4247 \pm 12^{+17}_{-32}$ + i(108±19±10)	1^{--}	$\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$	e^+e^- (ISR), e^+e^-
Y(4350)	BaBar Belle	4324±24 + i(172±33) 4361±9±9 + i(74±15±10)	1^{--}	$\pi^+\pi^- \psi(2S)$	e^+e^- (ISR)
$Z^+(4430)$	Belle	4433±4±1+ i($44^{+17}_{-13}{}^{+30}_{-11}$)	J^P	$\pi^+\psi(2S)$	B decays
Y(4620)	Belle	4664±11±5 + i(48±15±3)	1^{--}	$\pi^+\pi^- \psi(2S)$	e^+e^- (ISR)

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 meson-antimeson ($D^0\,\overline{D}^{*0}$ + c.c.) molecule

➡ need very precise mass measurement to confirm or refute

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

- Plus other *XYZ*, charmonium measurements, etc...

Charm!

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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!

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

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

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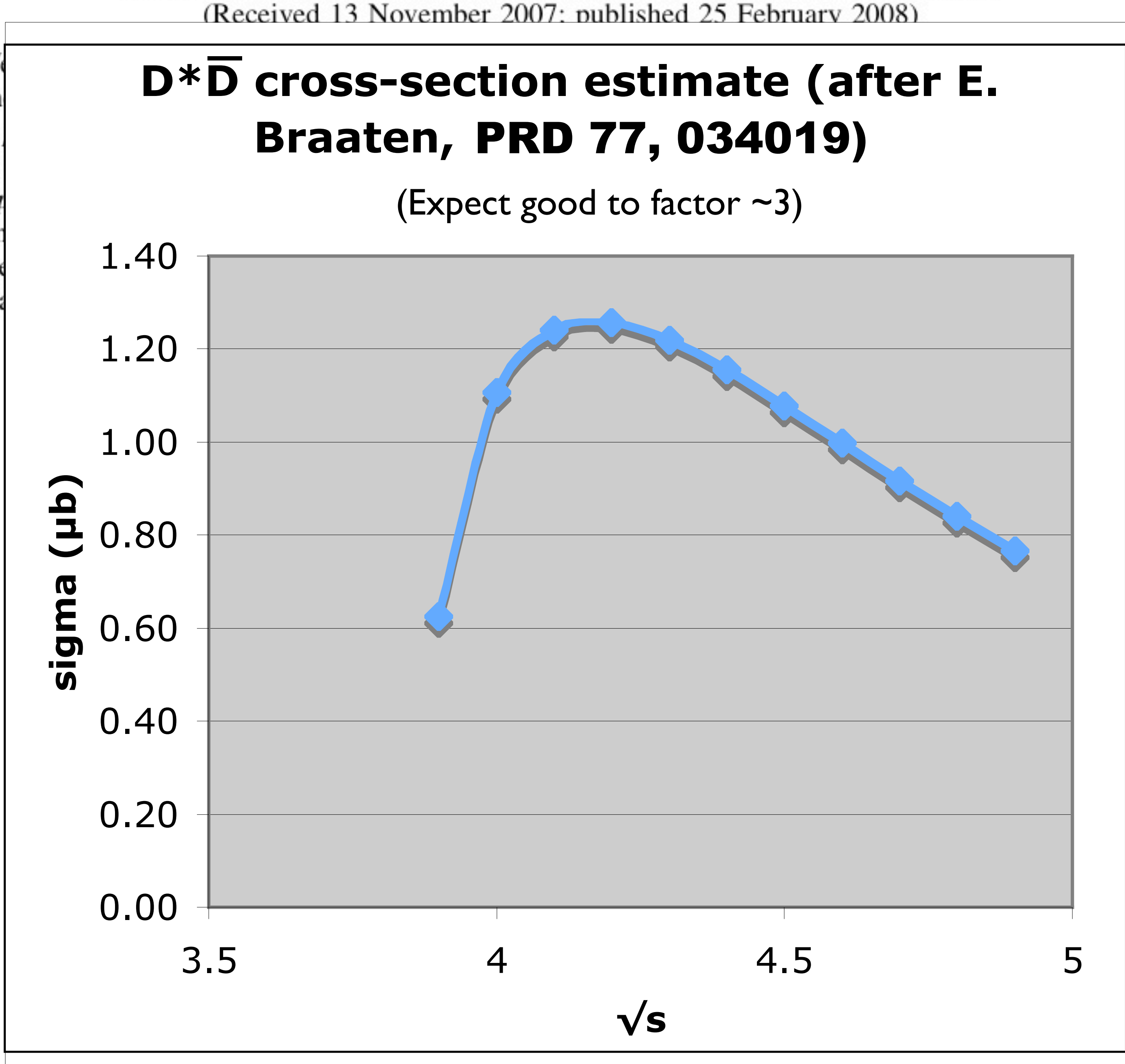
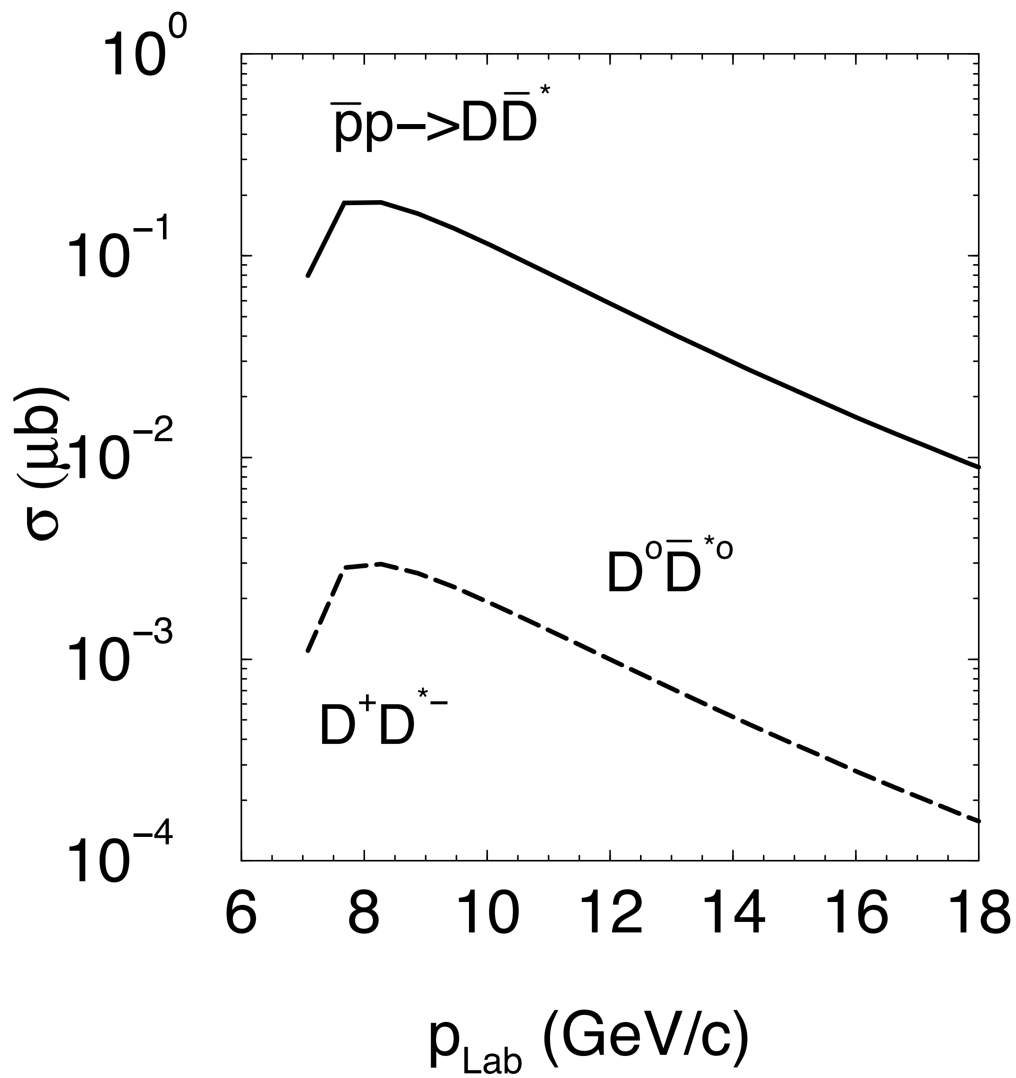
(Received 13 November 2007; published 25 February 2008)



- 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
- 1.3 μb → 5 ×10^9/year
- Expect efficiency as at *B* factories

Charm!

- Another approach (Regge model)



A. I. Titov and B. Kämpfer, Phys. Rev. C **78**, 025201 (2008)

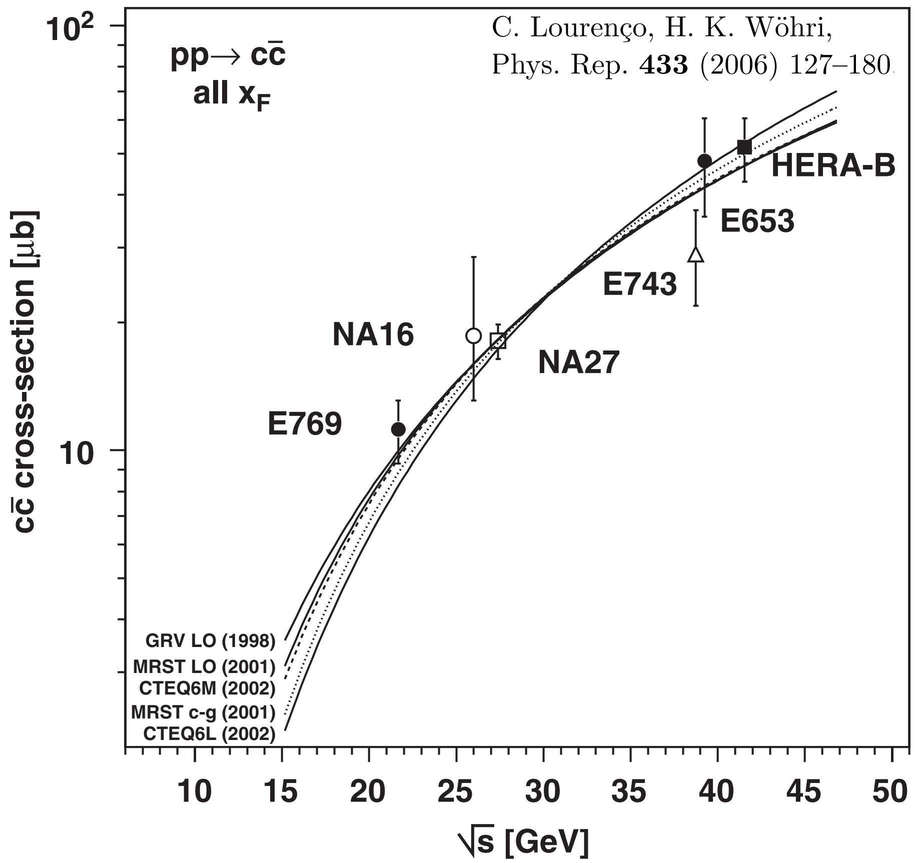
A. Titov, private communication

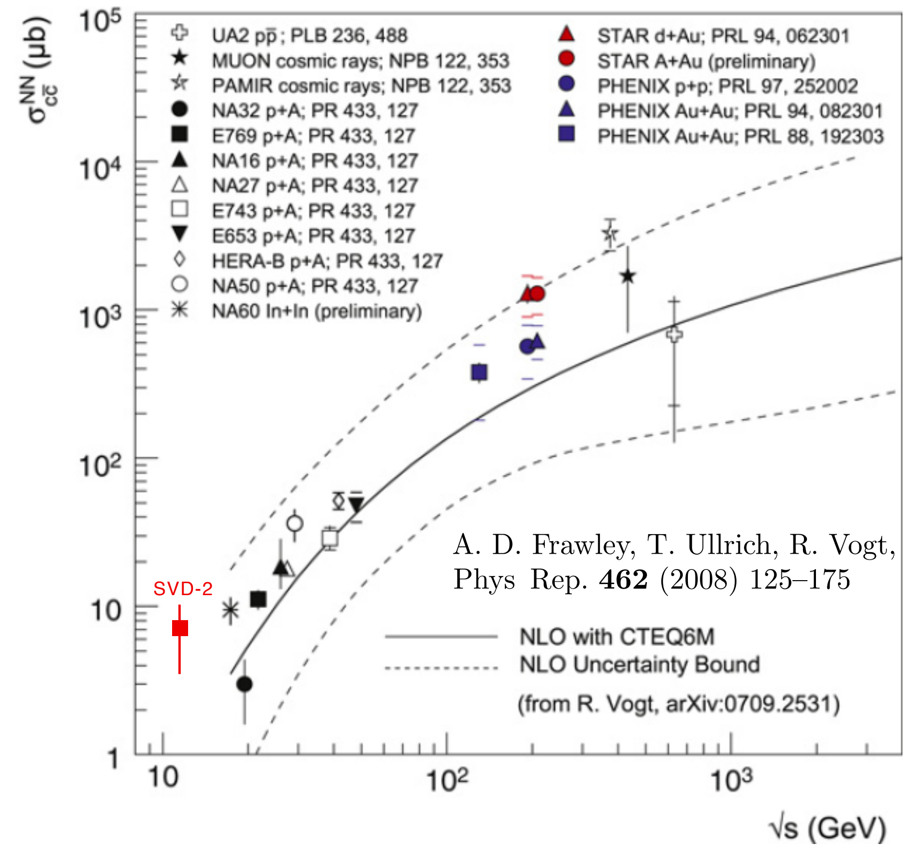
- Agreement within factor of 6

not bad, considering...

Charm!

- Other evidence?





REGISTRATION OF NEUTRAL CHARMED MESONS PRODUCTION AND THEIR DECAYS IN pA-INTERACTIONS AT 70 GeV WITH SVD-2 SETUP

(SVD-2 Collaboration)
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S. Basiladze, S. Berezhnev, G. Bogdanova, V. Ejov, G. Ermakov, P. Ermolov, N. Grishin, Ya. Grishkevich, D. Karmanov, V. Kramarenko, A. Kubarovsky, A. Leflat, S. Lyutov, M. Merkin, V. Popov, D. Savrina, L. Tikhonova, A. Vischnevskaya, V. Volkov, A. Voronin, S. Zotkin, D. Zotkin, E. Zverev.
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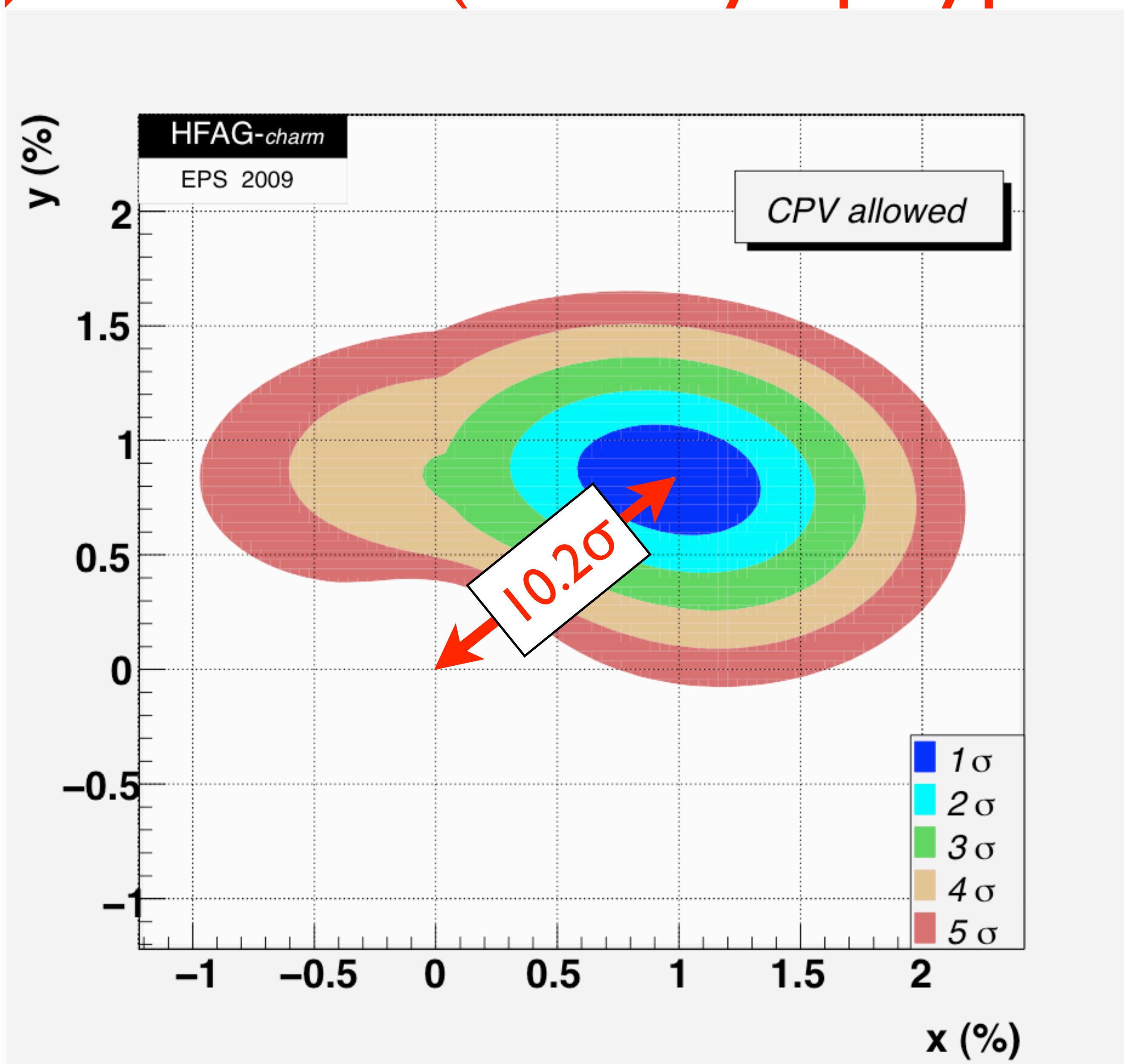
The results of data handling for SERP-E-184 experiment obtained with 70 GeV proton beam irradiation of active target with carbon, silicon and lead plates are presented. Two-prongs neutral charmed D^0 and $\bar{D}^0$ -mesons decays were selected. Signal / background ratio is (51±17) / (38±13). Registration efficiency for mesons was defined and evaluation for charm production cross section at threshold energy is presented: $\sigma(c\bar{c}) = 7.1 \pm 2.4(stat.) \pm 1.4(syst.)$ $(\mu b/nucleon)$.

- Hard to predict size of 8 GeV $\bar{p}$ cross section

⇒Need to measure it!

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?

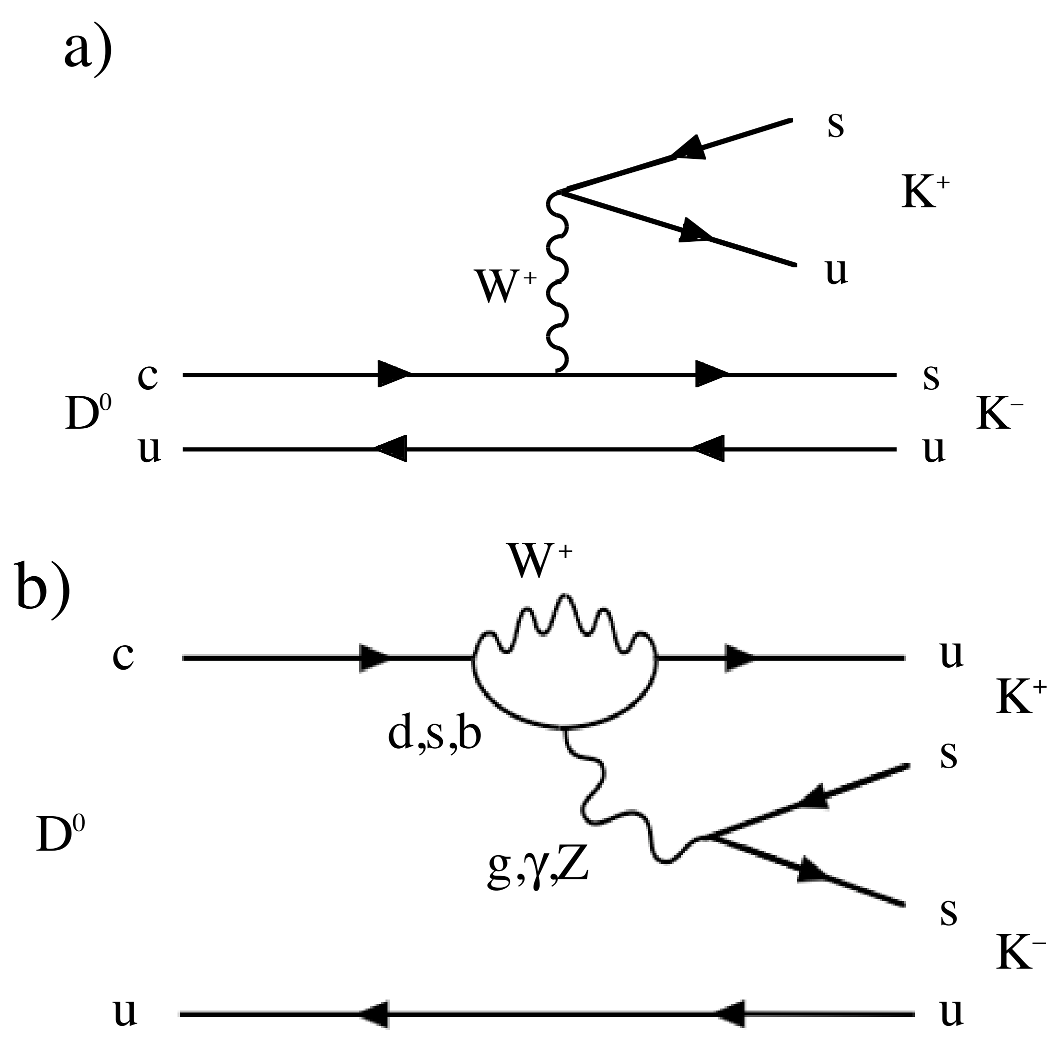
➡ key is CP Violation!

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

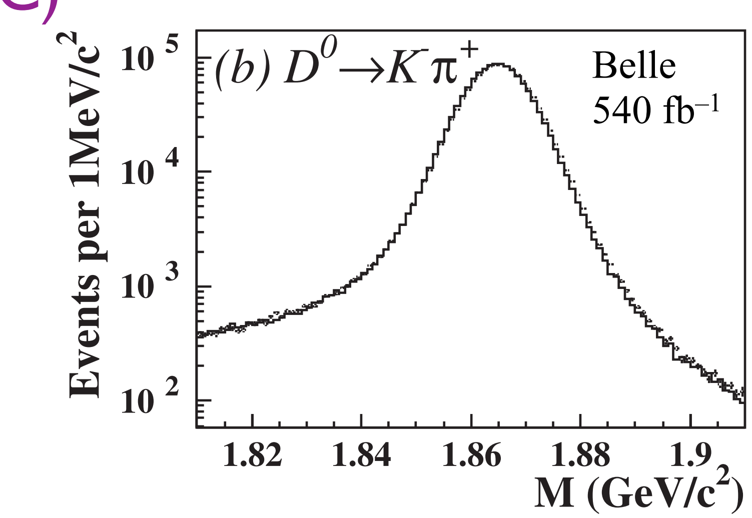
➡ world's best sensitivity to charm CPV

Charm!

- Ballpark sensitivity estimate based on Braaten formula and assuming $\sigma \propto A^{1.0}$:

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		(based on H.E. fixed-target)
$\sigma(\overline{p}p \to D^{*+}X)$	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		(signal MC)
Efficiency	0.1		(MIPP & bkg MC)
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)

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

...and **now**

for *something*

completely different!

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

ELSEVIER

Physics Letters B 368 (1996) 251-258

- But over 10 years ago, LEAR PS210 & FNAL E835 produced oodles of $\overline{\mathrm{H}}$!

Production of antihydrogen

G. Baur [a], G. Boero [b], S. Brauksiepe [a], A. Buzzo [b], W. Eyrich [c], R. Geyer [a], D. Grzonka [a], J. Hauffe [c], K. Kilian [a], M. LoVetere [b], M. Macri [b], M. Moosburger [c], R. Nellen [a], W. Oelert [a], S. Passaggio [b], A. Pozzo [b], K. Röhrich [a], K. Sachs [a], G. Schepers [e], T. Sefzick [a], R.S. Simon [d], R. Stratmann [d], F. Stinzing [c], M. Wolke [a]

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[b] *Genoa University and INFN, Italy*

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Received 8 December 1995; revised manuscript received 21 December 1995

Editor: L. Montanet

Abstract

Results are presented for a measurement for the production of the antihydrogen atom $\overline{\mathrm{H}}^0 \equiv \bar{\mathrm{p}}\mathrm{e}^+$, the simplest atomic bound state of antimatter.

A method has been used by the PS210 collaboration at LEAR which assumes that the production of $\overline{\mathrm{H}}^0$ is predominantly mediated by the e^+e^--pair creation via the two-photon mechanism in the antiproton–nucleus interaction. Neutral $\overline{\mathrm{H}}^0$ atoms are identified by a unique sequence of characteristics. In principle $\overline{\mathrm{H}}^0$ is well suited for investigations of fundamental CPT violation studies under different forces, however, in our investigations we concentrate on the production of this antimatter object, since so far it has never been observed before.

The production of 11 antihydrogen atoms is reported including possibly 2 ± 1 background signals, the observed yield agrees with theoretical predictions.

Antihydrogen

- But over 10 years ago, LEAR PS210 & FNAL E835 produced oodles of $\overline{\text{H}}$!

VOLUME 80, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1998

Observation of Atomic Antihydrogen

G. Blanford,[1] D. C. Christian,[2] K. Gollwitzer,[1] M. Mandelkern,[1] C. T. Munger,[3] J. Schultz,[1] and G. Zioulas[1]
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[2]*Fermilab, Batavia, Illinois 60510*
[3]*SLAC, Stanford, California 94309*
(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]

Antihydrogen

- But over 10 years ago, LEAR PS210 & 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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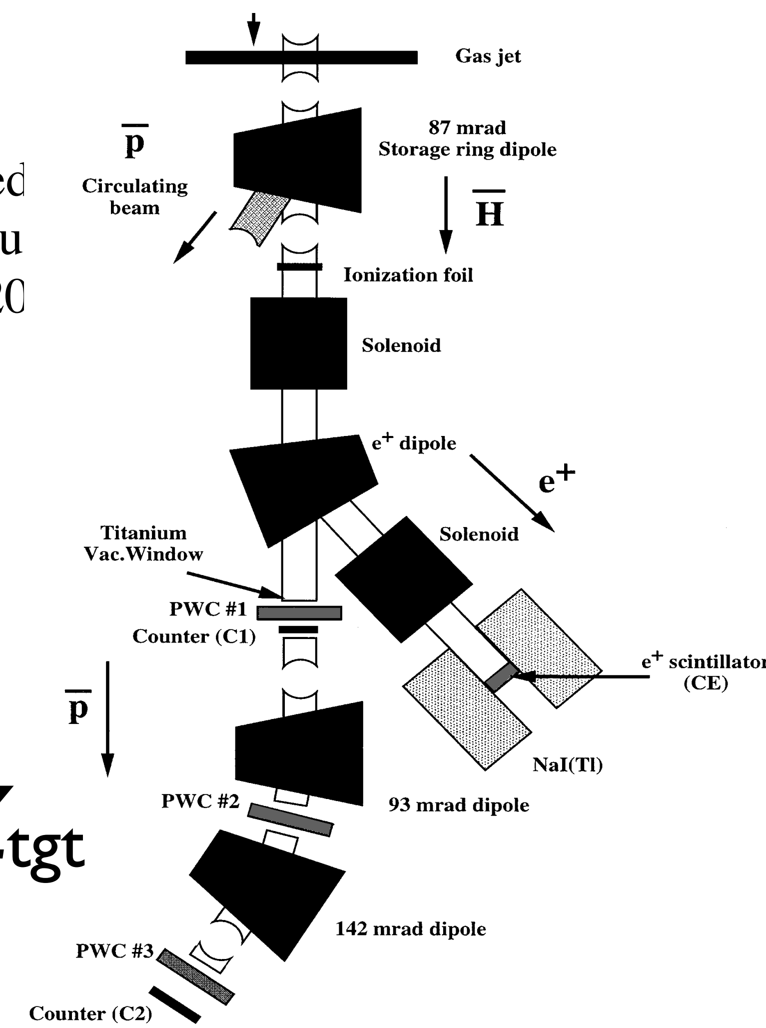

- Formed automatically e.g. in E835 gas-jet target, detected in "parasitic" E862
- Production probability grows with E_{beam}, Z_{tgt}

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]

Antiydrogen

- Parasitic running appears feasible

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

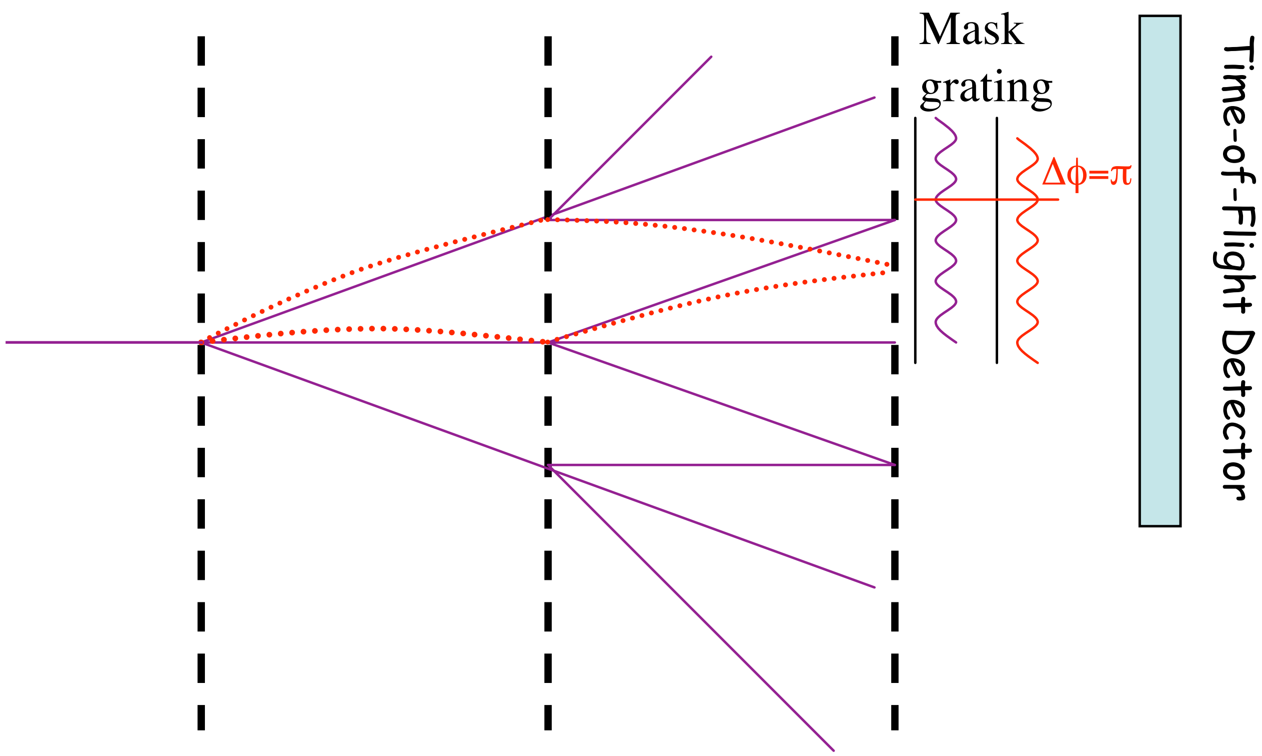
- High-Z foil installed, operable in Antiproton Accumulator beam halo

- Next, 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
  - 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!

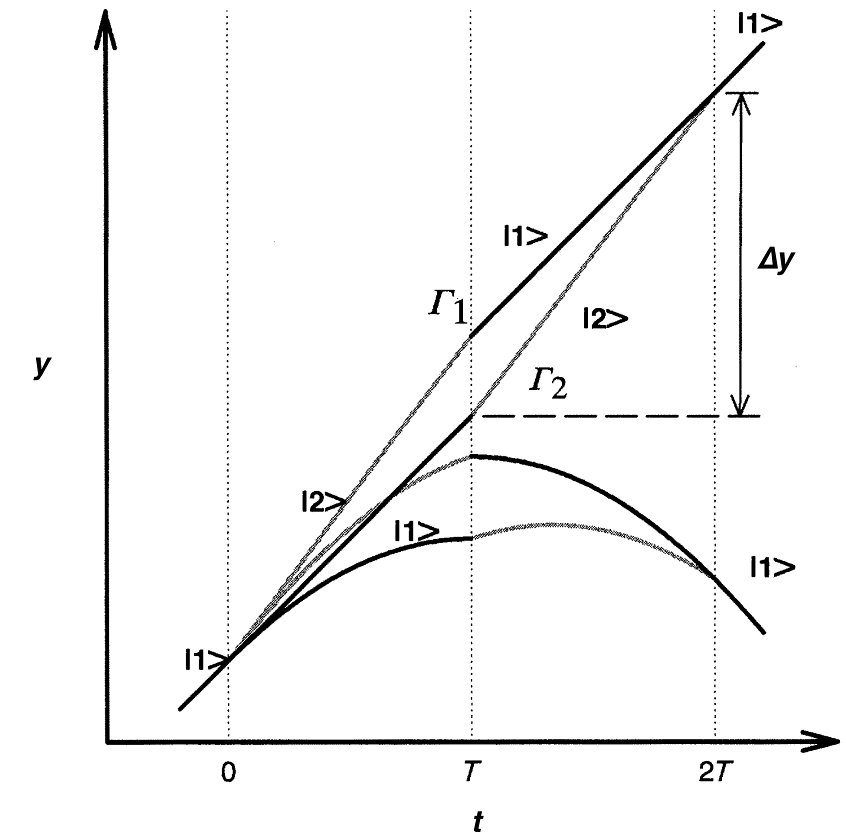
→ $\bar{g} = -g$ gives natural explanations for baryon asymmetry & dark energy

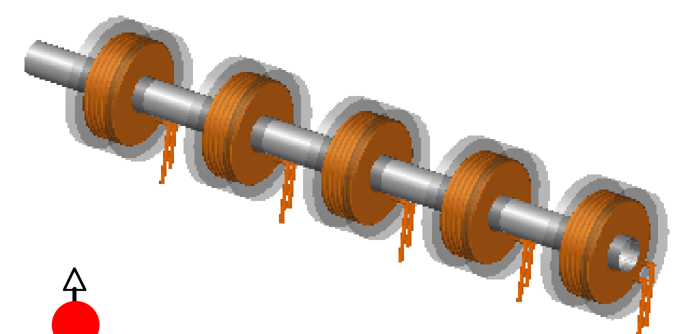
→ $\bar{g} = g + \varepsilon$ natural in quantum gravity due to scalar & vector terms

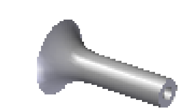
→ tests for possible "5th forces"

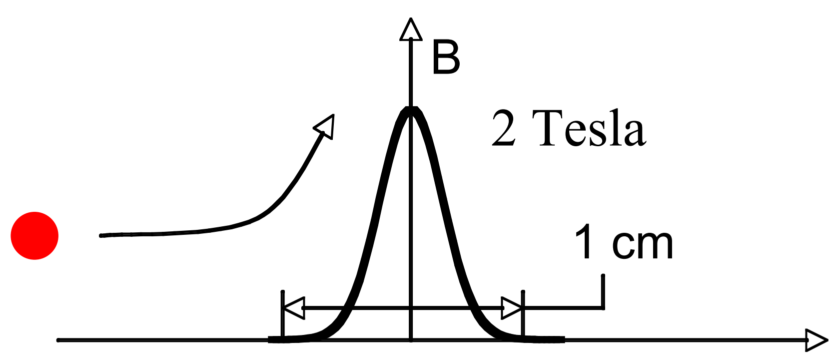
Antimatter Gravity

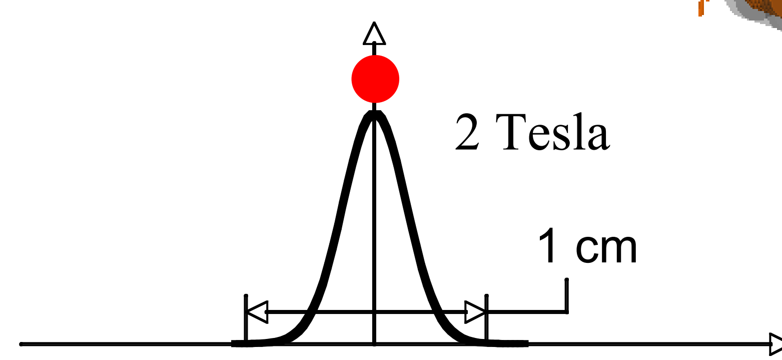
- "Ultimate" measurement:
  - instead of material gratings, use lasers à la S. Chu, M. Kasevich
  - slow down and trap the $\overline{\text{H}}$ atoms using "coilgun" (M. Raizen)
  - low-field seekers are repulsed by magnetic field











  - estimate 10^{-9} $\overline{g}$ measurement feasible

Antimatter Gravity

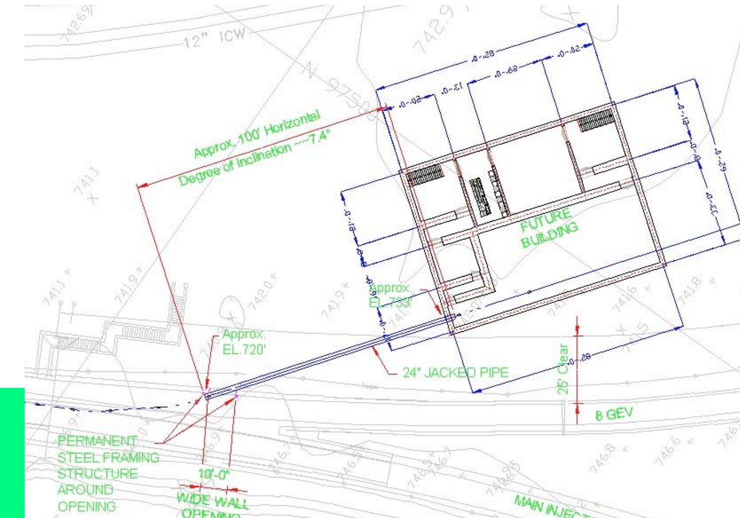
- Deceleration from 8 GeV to < 20 keV:
  - MI from 8 GeV to $\lesssim$ 400 MeV (TBD), then "reverse linac" or "particle refrigerator," then degrade
  - efficiency $\gtrsim 10^{-4}$ looks feasible

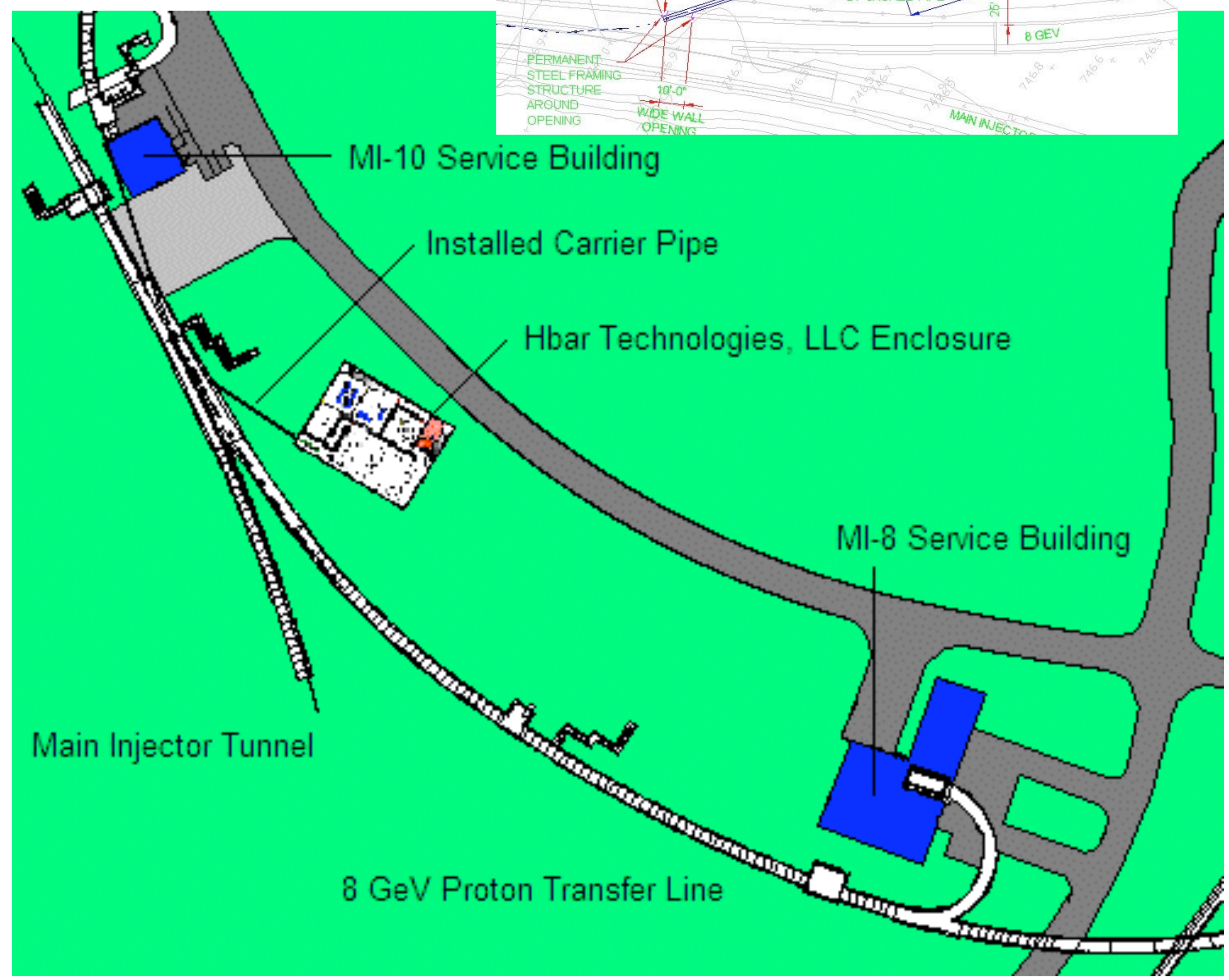
    $\Rightarrow 10^{-4}\ \bar{g}$ measurement in ~ month's dedicated running
  - eventually, add small synchrotron → effic. ~ 1
- Requires completion of antiproton deceleration/ extraction facility planned for Hbar Technologies

HBAR Technologies, LLC
Making Antimatter Matter®

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

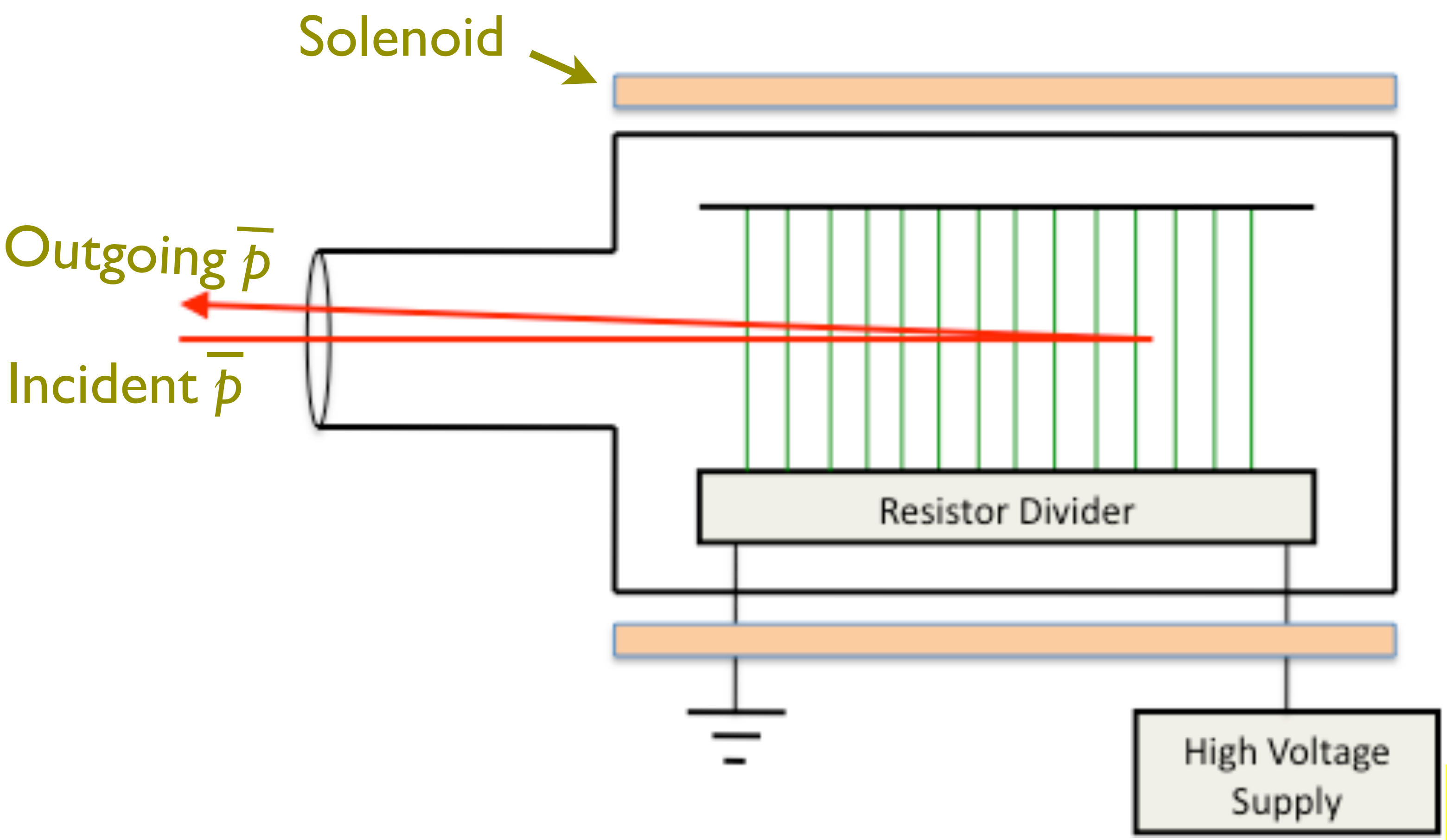
MI Deceleration Below 1 GeV/c



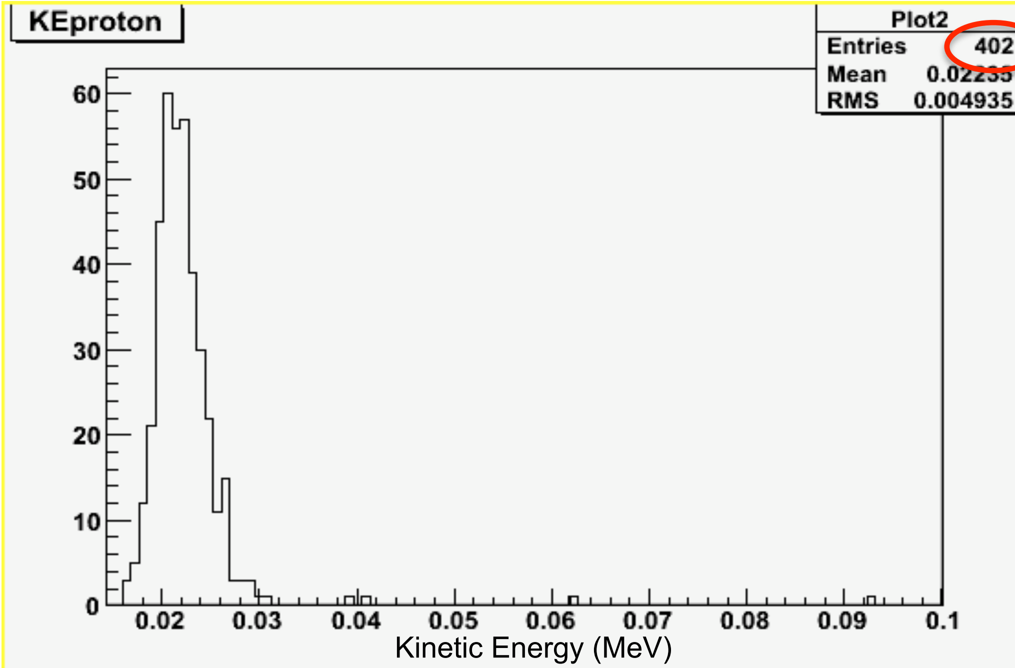


Particle Refrigerator

- Application of "frictional cooling" [M. Muhlbauer *et al.*, Hyp. Interact. 119:305 (1999)]



T. Roberts, Muons, Inc.



- $\bar{p}$ stopped by *E* field & *dE*/*dx*, emerge w/ ≈40% eff. @ equilib. energy
- KE_{in} < ≈ few MeV, KE_{out} ≈ 20 keV

Antiproton Source Futures

- With end of Tevatron Collider in sight, many at FNAL view 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 >1 G€ expenditure in progress on FAIR, can cannibalizing FNAL pbar source truly be sensible??
- Nevertheless, appears likely that $\mu 2e$ will eliminate FNAL pbar option starting around 2017
  - leaves 4–5-year window of opportunity during which FNAL $\bar{p}$ capabilities are unique in the world

Letters of Intent

- Although physics reach somewhat uncertain,
- Potential for high-impact measurements with inexpensive or recycled appatatus
- Could provide Fermilab with broad physics program during otherwise lean period

P-986 Letter of Intent:

Medium-Energy Antiproton Physics at Fermilab

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February 5, 2009

Letters of Intent

Letter of Intent:
Antimatter Gravity Experiment (AGE) at Fermilab

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Abstract

We propose to make the first direct measurement of the gravitational acceleration of antimatter by taking advantage of Fermilab's unique ability to accumulate large numbers of antiprotons. Such a measurement will be a fundamental test

- 1st $\bar{g}$ measurement to 1% needs only a day's worth of $\bar{p}$
- 10^{-4} needs few months' worth of $\bar{p}$
- Followup to 10^{-9} possible via laser interferometry

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 (UT Austin)
3. Antiproton Annihilation: can be considered further at this time only if cost to Lab is minimal
    - Proposal to Fermilab in preparation
    - New collaborators, non-DOE resources being sought

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 Fermilab to have broad program in post-Tevatron era

➡ You can help! Want to join?

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