# A New Experiment to Study Hyperon CP Violation and the Charmonium System

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Meeting with the Director

Fermilab

May 10, 2007

# Outline

- Hyperon CP violation
- HyperCP experiment
- Low-energy antiprotons
- A new experiment
- Issues in charmonium
- Summary

# 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**

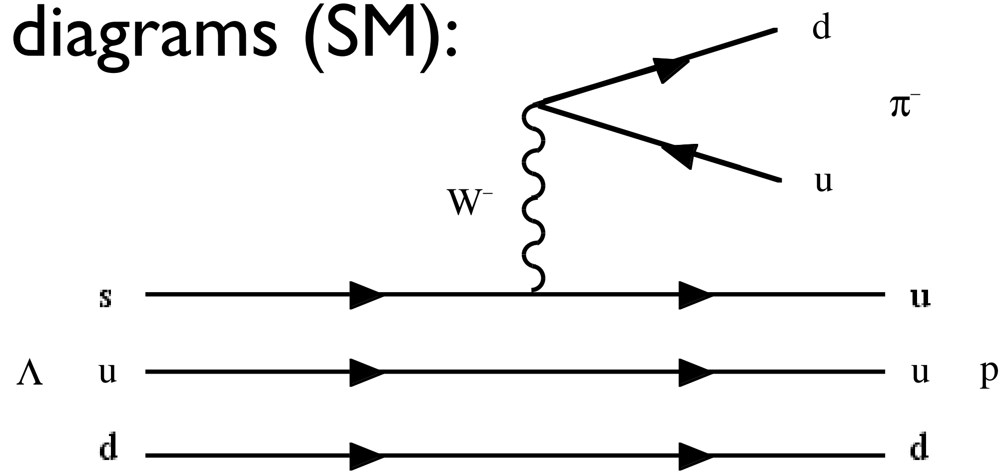
Thus in hyperon decay, $\bar{\alpha}\neq-\alpha$ implies *CP* violation in this process independent of the validity of the *CPT* theorem. This is also true if $\bar{\beta}\neq-\beta$.

Also, as usual, *CPT* invariance implies equality of $\Lambda^0$ 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.

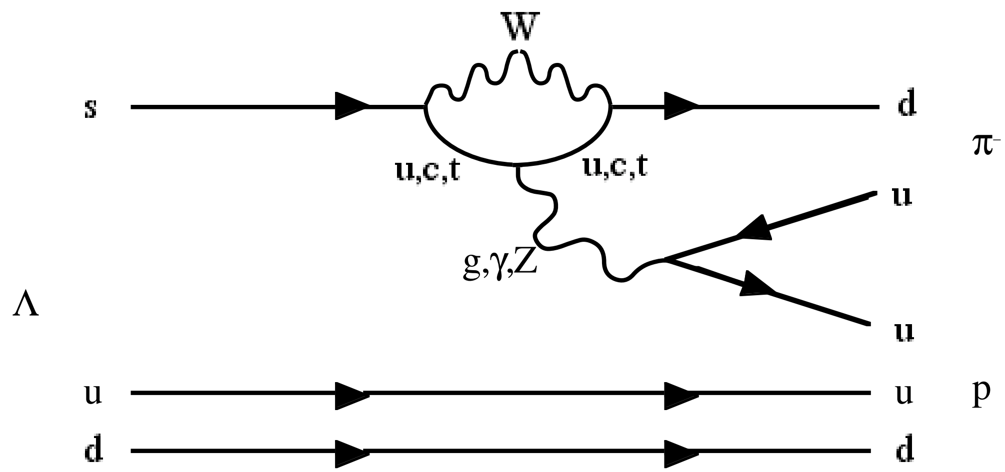
# Hyperon CP Violation?

- Example Feynman diagrams (SM):

Λ decay:




Λ penguin decay:




- New physics could also contribute!

# 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., $\Lambda \to p\,\pi^-$):

$$M = S + P\vec{\sigma}\cdot\hat{q}_p$$

S-wave amplitude ($S$), P-wave amplitude ($P$), proton-momentum unit vector ($\hat{q}_p$)

→ Nonuniform proton angular distribution in Λ rest frame:

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

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]

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

# Hyperon CP Violation?

- Theory & experiment:

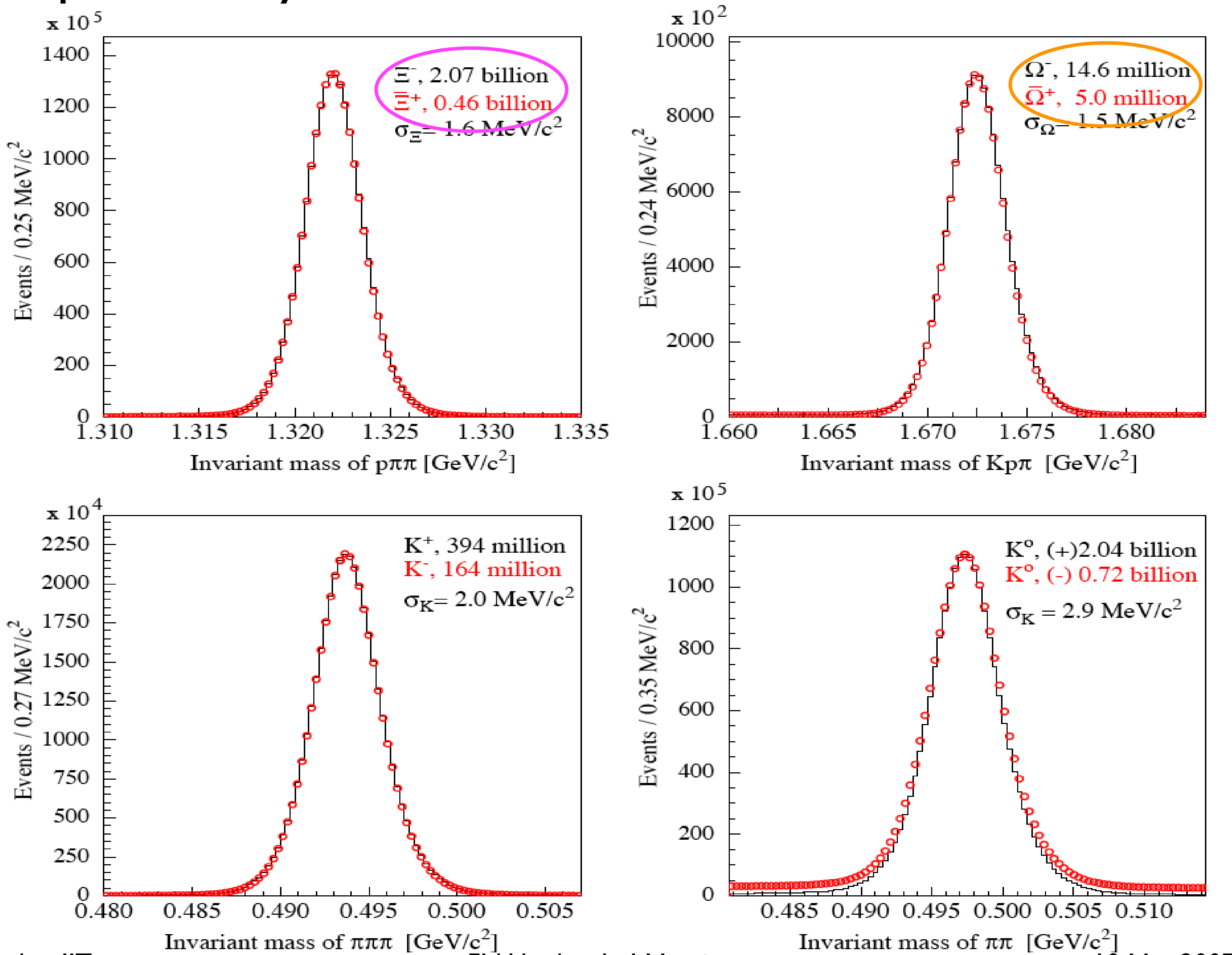
**Theory** [Donoghue, He, Pakvasa, Valencia, et al., e.g., PRL 55, 162 (1985); PRD 34, 833 (1986); PLB 272, 411 (1991)]

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

| Experiment | Decay Mode | $A_\Lambda$ | |
|---|---|---|---|
| **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] |

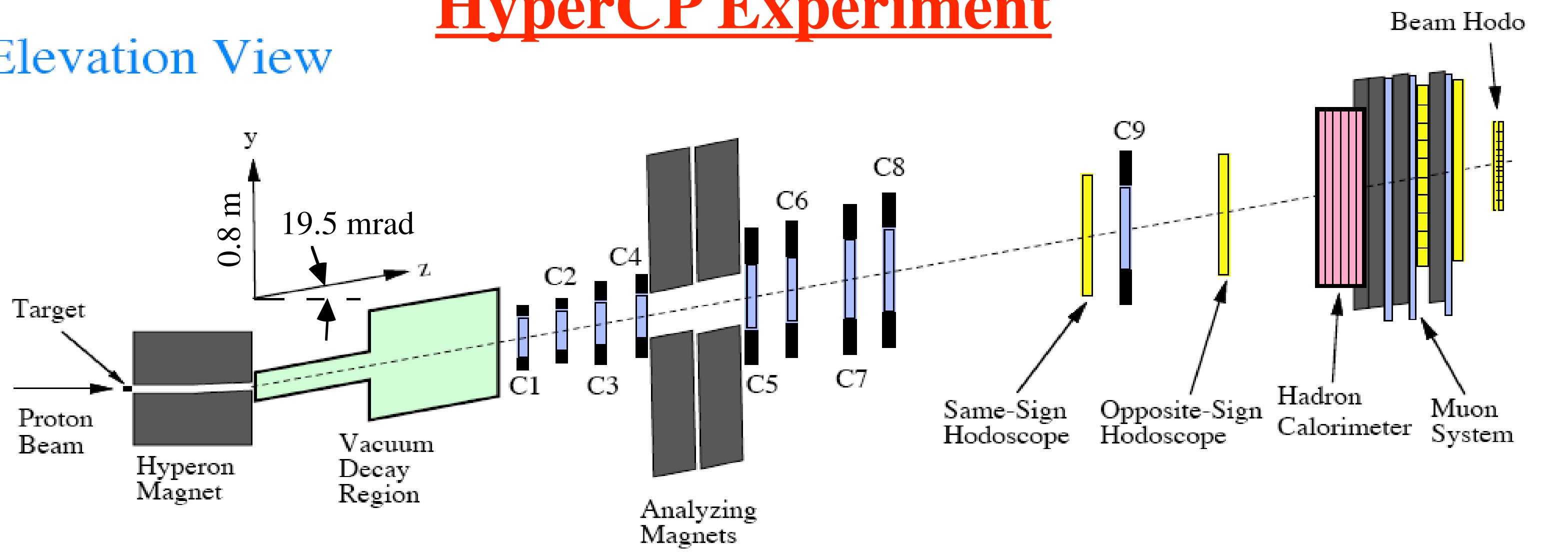
| Experiment | Decay Mode | $A_\Xi + A_\Lambda$ | |
|---|---|---|---|
| **E756 at Fermilab** | $\Xi \to \Lambda\pi, \Lambda \to p\pi$ | **0.012 ± 0.014** | [K.B. Luk et al., PRL 85, 4860 (2000)] |
| E871 at Fermilab **(HyperCP)** | $\Xi \to \Lambda\pi, \Lambda \to p\pi$ | **$(0.0 \pm 6.7) \times 10^{-4}$**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

# Made possible by…Enormous HyperCP Dataset



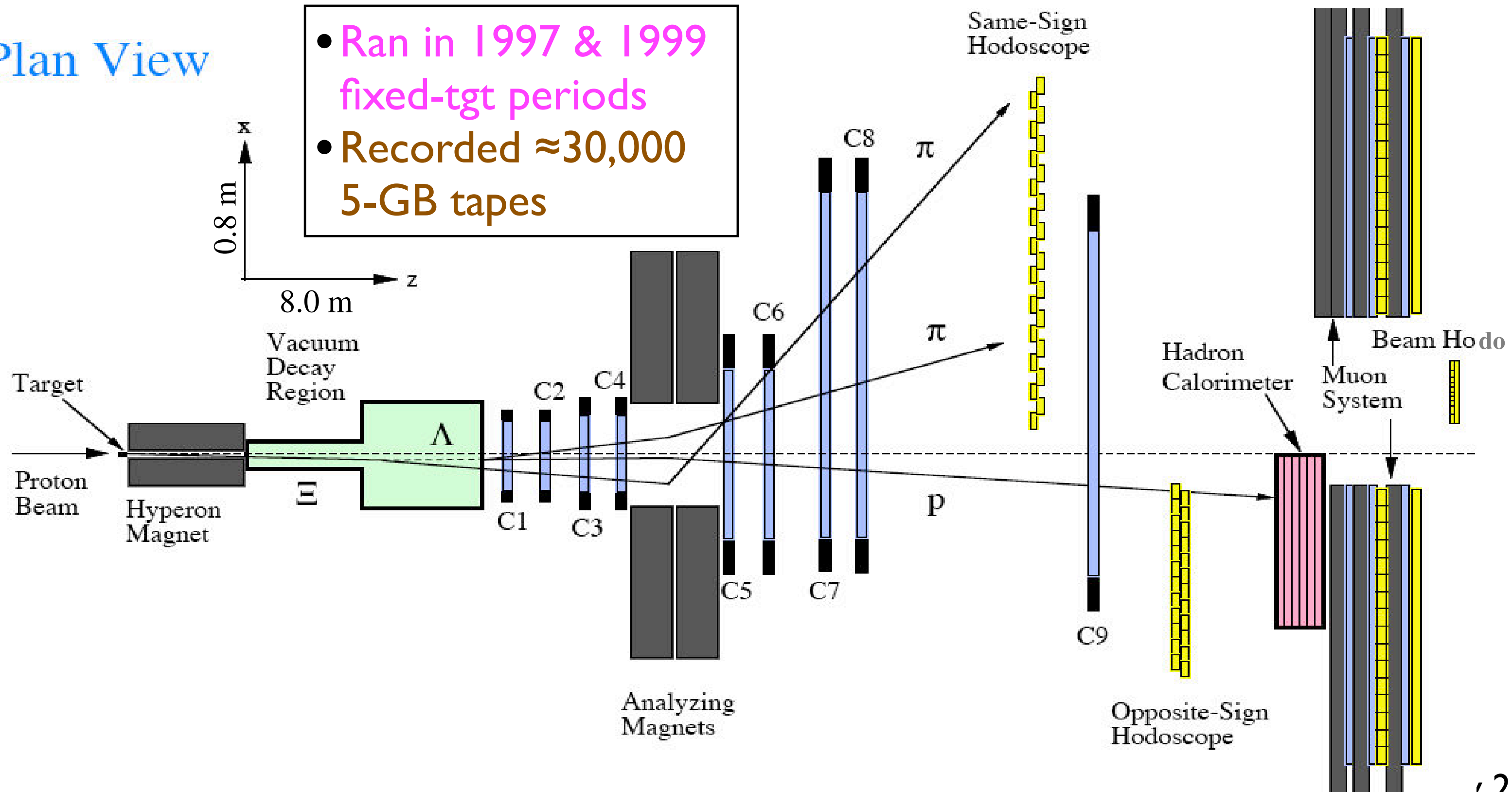
# HyperCP Experiment

## Elevation View




## Plan View

- Ran in 1997 & 1999 fixed-tgt periods
- Recorded ≈30,000 5-GB tapes



# ...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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R. Burnstein, A. Chakravorty, D. Kaplan, L. Lederman, D. Rajaram, H. Rubin, N. Solomey, C. White
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*University of Michigan, USA*

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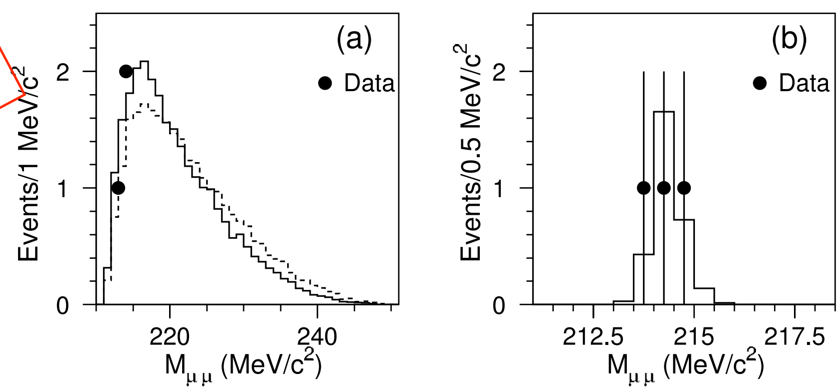
*University of Virginia, USA*

*co-spokespersons

# Some HyperCP Discoveries:

- $\phi_\Xi = -(2.39\pm0.64\pm0.64)° \Rightarrow \beta_\Xi \neq 0$ 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)
- $\Sigma^+ \to p\mu^+\mu^-$: smallest baryon BR ever seen!
  $\mathcal{B} \approx 9 \times 10^{-8}$ (or $3 \times 10^{-8}$ if intermediate $P^0$)

Surprise!




≈2.4σ fluctuation of SM

- 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)

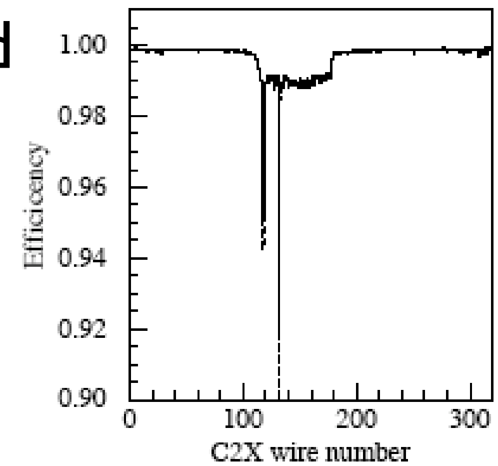
The HyperCP Collaboration has observed three events for the decay $\Sigma^+ \to p\mu^+\mu^-$ which may be interpreted as a new particle of mass 214.3 MeV. However, existing data from kaon and $B$-meson decays provide stringent constraints on the construction of models that support this interpretation.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

# Some HyperCP Publications:

- L. C. Lu *et al.*, "Measurement of the asymmetry in the decay $\overline{\Omega}^+ \to \overline{\Lambda} K^+ \to \overline{p}\pi^+ K^+$," Phys. Rev. Lett. **96**, 242001 (2006).
- D. Rajaram *et al.*, "Search for the Lepton-Number-Violating Decay $\Xi^- \to p\mu^-\mu^-$," Phys. Rev. Lett. **94**, 181801 (2005).
- C. G. White *et al.*, "Search for Delta $\Delta S = 2$ Nonleptonic Hyperon Decays," Phys. Rev. Lett. **94**, 101804 (2005).
- H. K. Park *et al.*, "Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$," Phys. Rev. Lett. **94**, 021801 (2005).
- M. Huang *et al.*, "New Measurement of $\Xi^- \to \Lambda\pi^-$ Decay Parameters," Phys. Rev. Lett. **93**, 011802 (2004);
- M. J. Longo *et al.*, "High-Statistics Search for the $\Theta^+(1.54)$ Pentaquark," Phys. Rev. D **70**, 111101(R) (2004);
- T. Holmstrom *et al.*, "Search for *CP* Violation in Charged-$\Xi$ and $\Lambda$ Hyperon Decays," Phys. Rev. Lett. **93**, 262001 (2005);
- Y. C. Chen *et al.*, "Measurement of the Alpha Asymmetry Parameter for the $\Omega^- \to \Lambda K^-$ Decay," Phys. Rev. D **71**, 051102(R) (2005);
- L. C. Lu *et al.*, "Observation of Parity Violation in the $\Omega^- \to \Lambda K^-$ Decay," Phys. Lett. B **617**, 11 (2005).
- R. A. Burnstein *et al.*, "HyperCP: A High-Rate Spectrometer for the Study of Charged Hyperon and Kaon Decays," Nucl. Instrum. Methods A **541**, 516 (2005).

# 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!

- Until "HyperCP era," world's best limit on hyperon CP violation came from PS185 at LEAR:

| Experiment | Decay Mode | $A_\Lambda$ | |
|---|---|---|---|
| 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 | $A_\Xi + A_\Lambda$ | |
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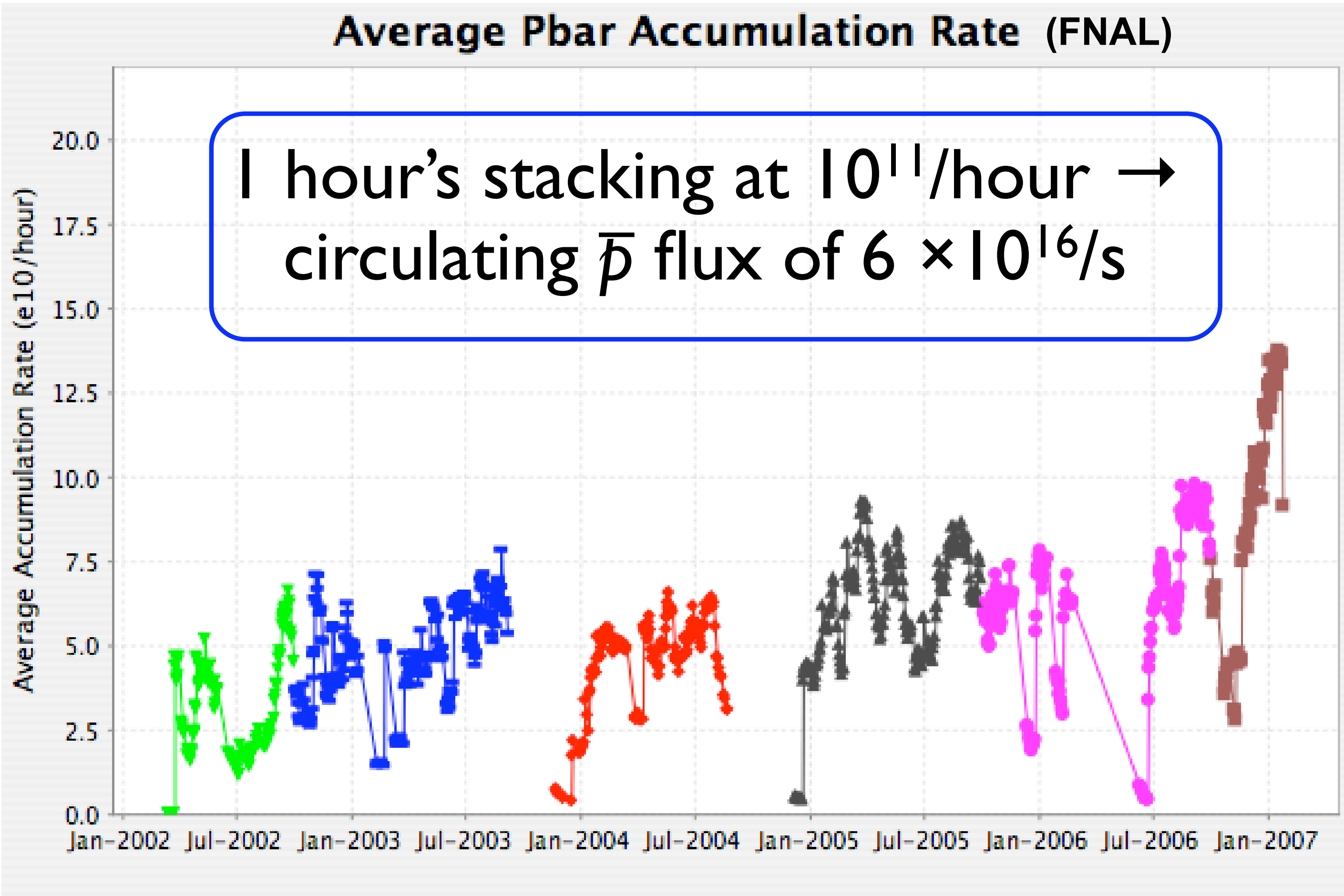
| E871 at Fermilab (HyperCP) | $\Xi \to \Lambda\pi, \Lambda \to p\pi$ | $(0.0 \pm 6.7) \times 10^{-4}$ | [T. Holmstrom et al., PRL 93. 262001 (2004)] |
| | | $\approx 2 \times 10^{-4}$ | [projected] |

# Low-Energy Antiprotons!

- PS185 was limited by LEAR $\bar{p}$ flux ($\lesssim 10^5$/s)

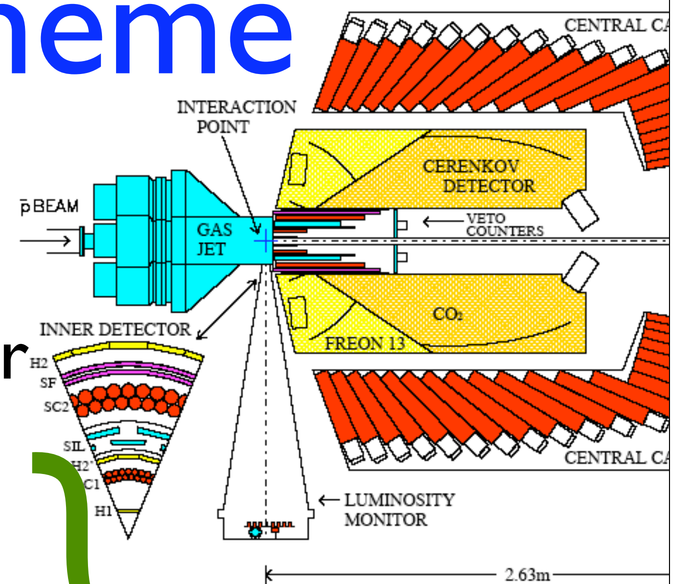



1 hour's stacking at $10^{11}$/hour → circulating $\bar{p}$ flux of $6 \times 10^{16}$/s

# 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 $\eta_c, \chi_c, h_c$ masses, widths, branching ratios,...
    - interference of continuum & resonance signals
- G€ GSI-Darmstadt upgrade will create similar facility, but not before 2014

# A Possible Scheme




- Once Tevatron shuts down (≈2009),
  - reassemble E835 EM spectrometer
  - add small magnetic spectrometer
  - add high-ρ gas-jet, wire, or pellet tgt
  - add 2ndary-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)

➡ ~$10^8$ $\Omega^- \overline{\Omega}^+$/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

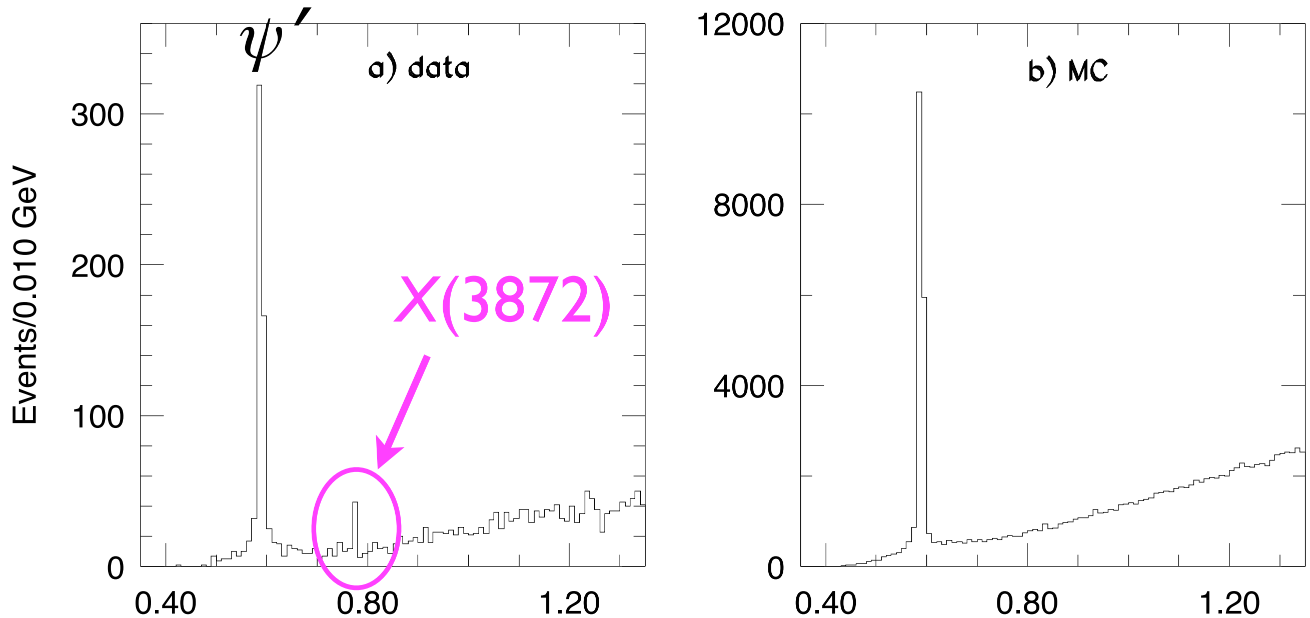
Predicted $\Delta\mathcal{B} \sim 10^{-5}$
in SM, $\lesssim 10^{-3}$ if NP

# What Else Can This Do?

- 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 ($\Delta mc^2$ = 0.6±0.6 MeV)

# 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

# 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, $\chi_c$ radiative-decay angular distributions, $\eta_c'$ full and radiative widths,...
- ...improved limits on $\bar{p}$ lifetime and branching ratios (APEX),...

# Example: $h_c$

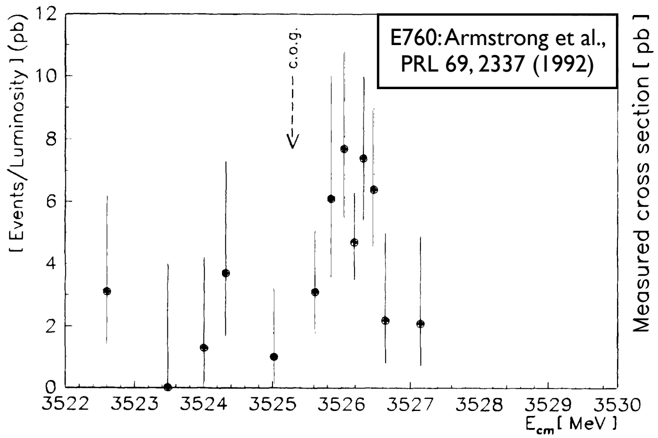
- $h_c$ ($1\ ^1P_1$) state of charmonium only way to study $c\bar{c}$ spin-0 hyperfine splitting: $m(^1P_1) - \langle m_{\text{spin-weighted}}(^3P_J) \rangle$
- Not experimentally accessible in strangeonium or (so far) bottomonium
- Splitting predicted to be $\lesssim$1 MeV in potential models if
  -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

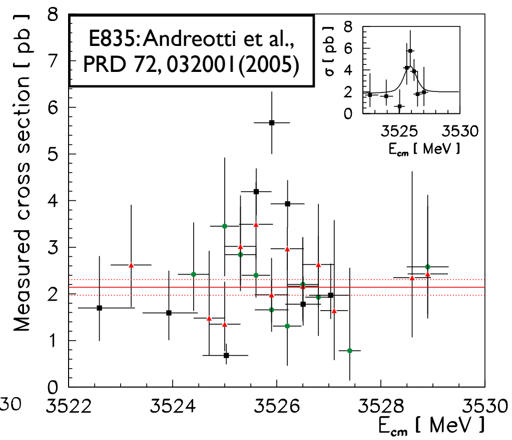
    and
  - coupled-channel effects small

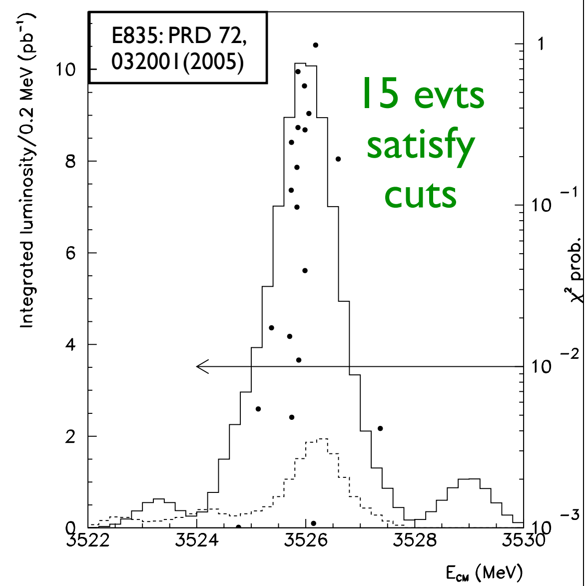
    (both expected to be true)
- But $h_c$ production in $e^+e^-$ suppressed $\Rightarrow$ not easy

# Example: $h_c$

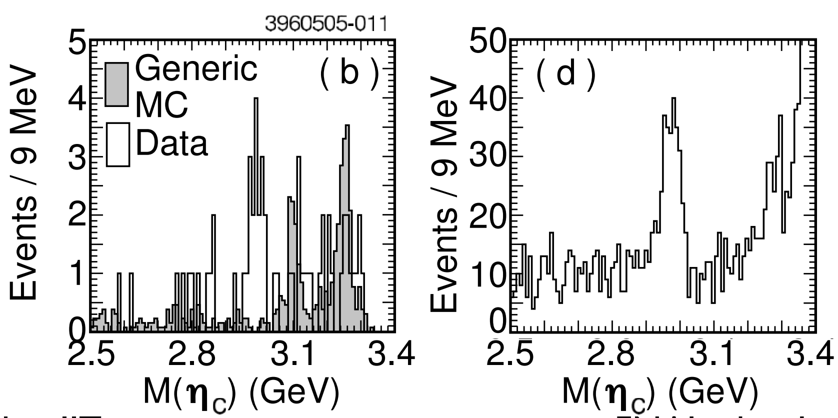
- $h_c$ found (≈3σ) in $J/\psi\ \pi^0$ in E760 (E835 predecessor):
- Not confirmed by E835, but seen in $\eta_c\gamma$:



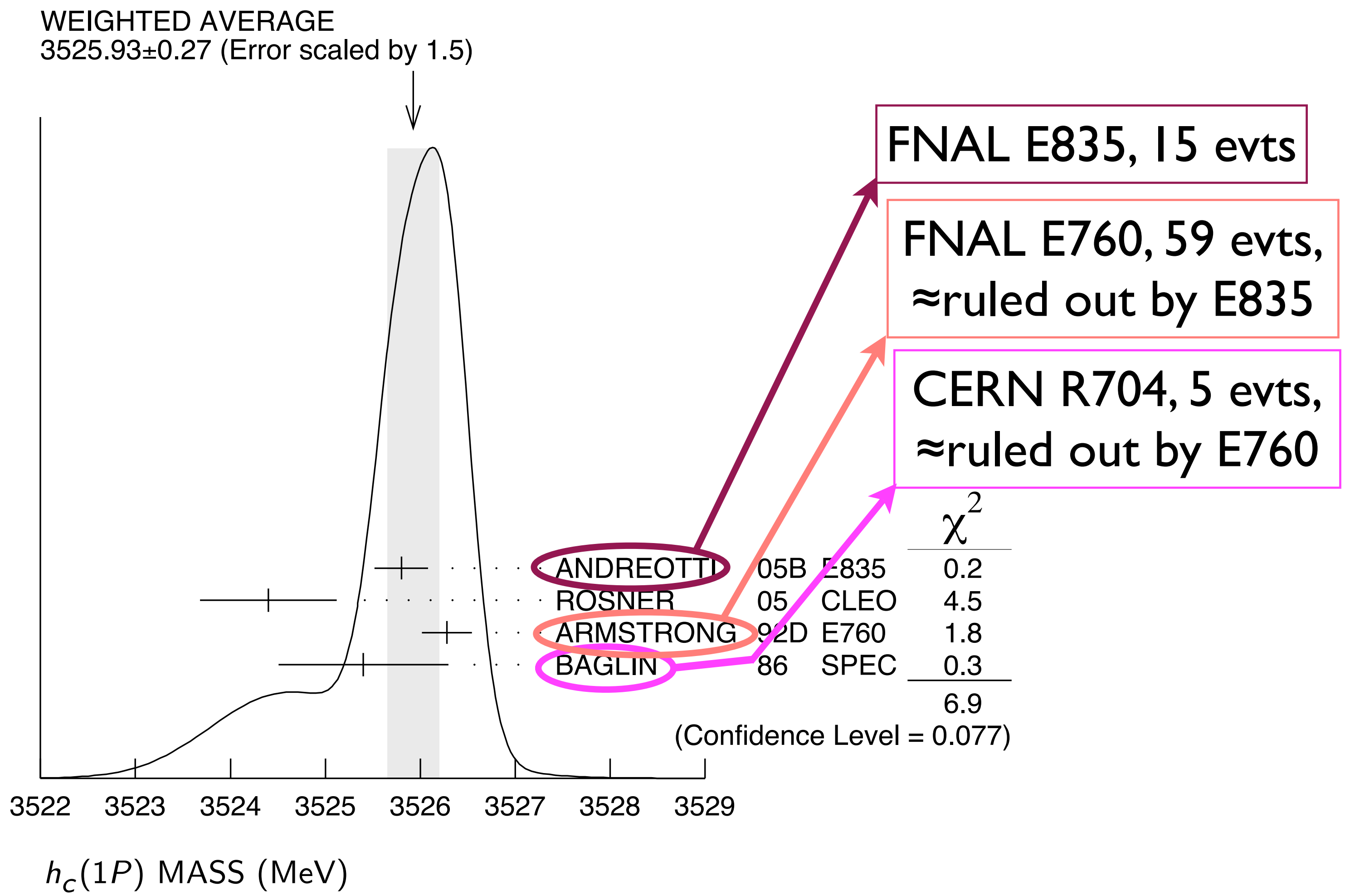

...and by CLEO [Rosner et al., PRL 95, 102003 (2005)]:




- 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!

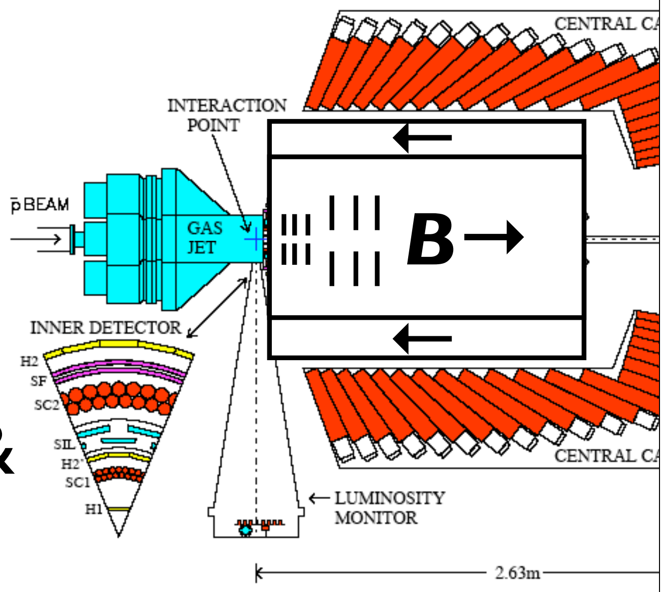
# Example: $h_c$

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

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

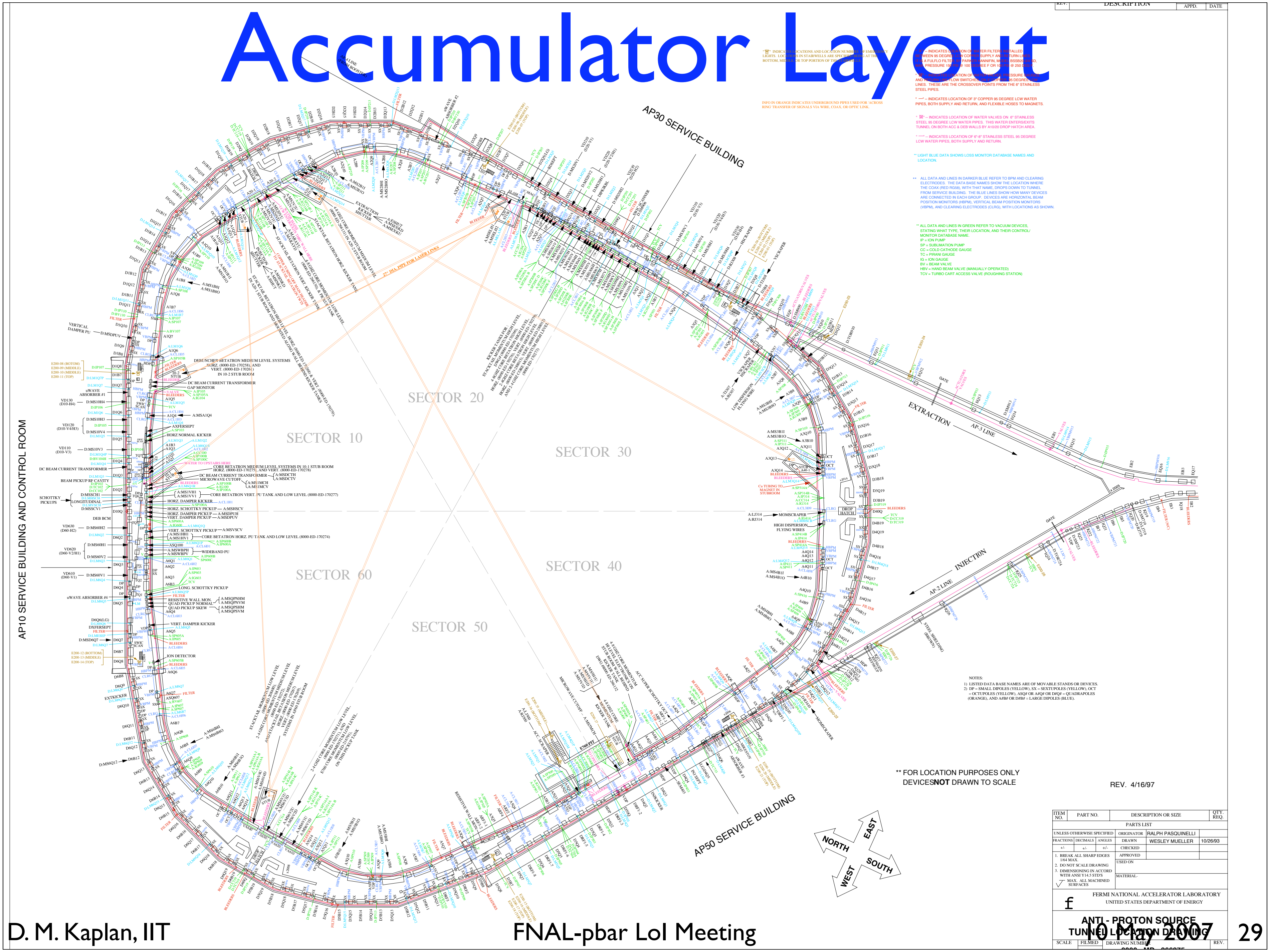
➡ Require magnetic spectrometer

# How to Magnetize?

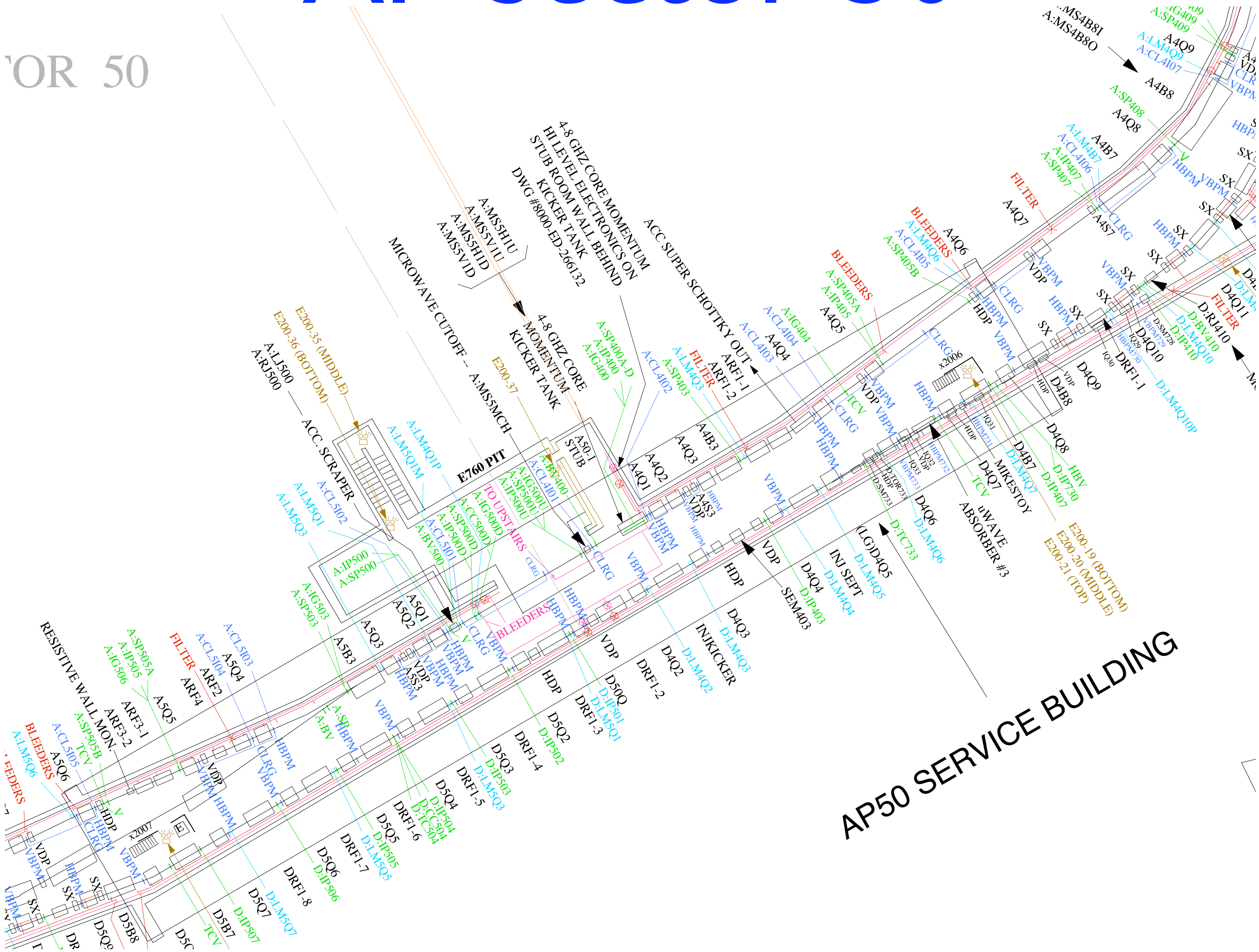



- Is minimum-cost solution (E835 Pb glass) compatible with magnetic spectrometer?
  - insert small solenoid with SciFi & SiPix?
  - use bucking coil to suppress field at PMTs?
- But EM calorimetry works better *inside* solenoid
  - ∃ suitable solenoid?
    - AP50 pit too small for most solenoids, but DØ one fits

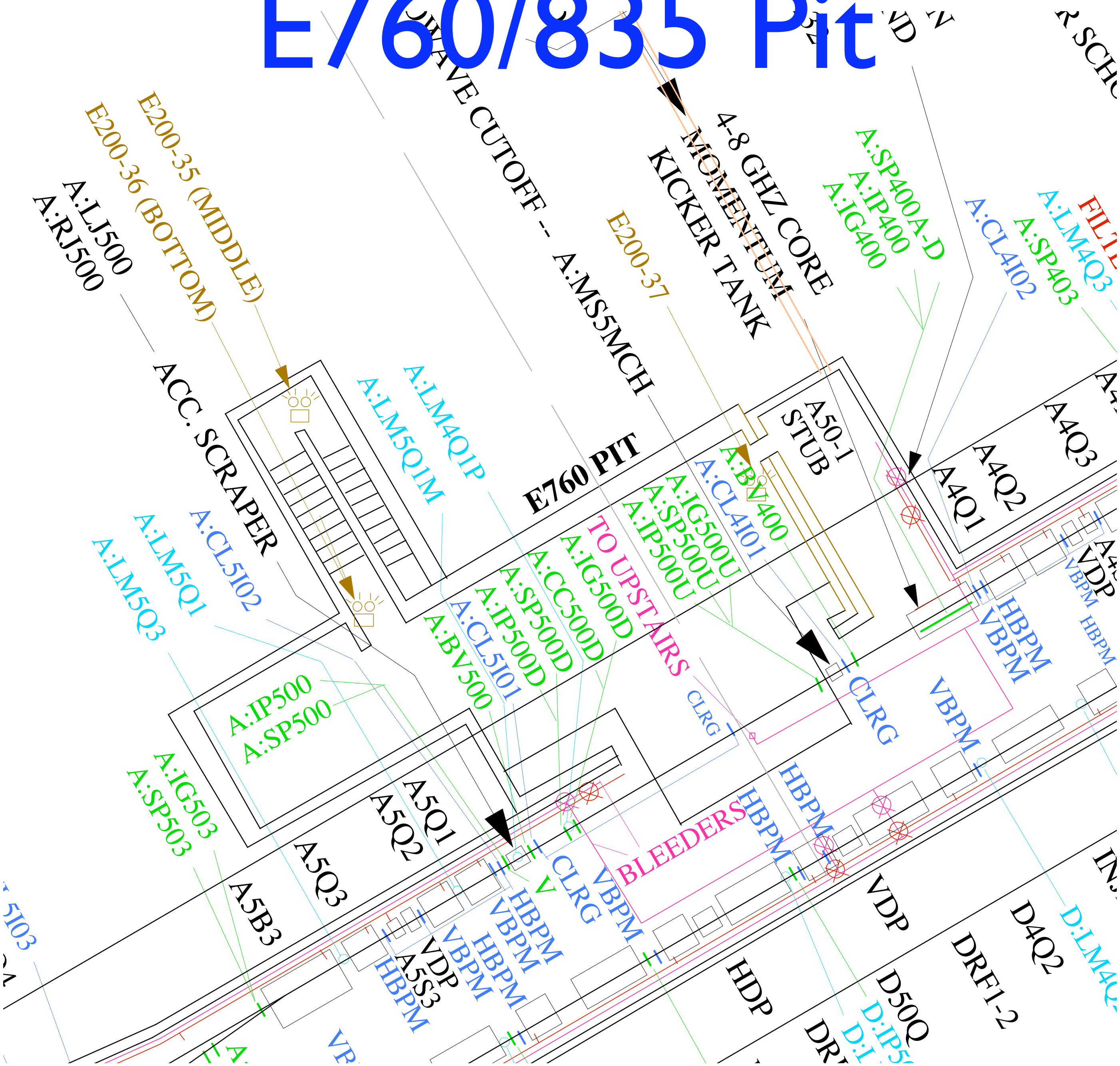
# Accumulator Layout



# AP Sector 50


AP50 SERVICE BUILDING
E760 PIT
MICROWAVE CUTOFF -- A:MSSMCH
ACC SUPER SCHOTTKY OUT
4-8 GHZ CORE MOMENTUM
HI LEVEL ELECTRONICS ON
STUB ROOM WALL BEHIND
KICKER TANK
DWG #8000-ED-266132
4-8 GHZ CORE
MOMENTUM
KICKER TANK
ACC. SCRAPER
RESISTIVE WALL MON.
BLEEDERS
FILTER
TO UPSTAIRS
uWAVE
ABSORBER #3
MIKESTOY
INJ SEPT
INJ KICKER
SEM403
E200-35 (MIDDLE)
E200-36 (BOTTOM)
E200-19 (BOTTOM)
E200-20 (MIDDLE)
E200-21 (TOP)

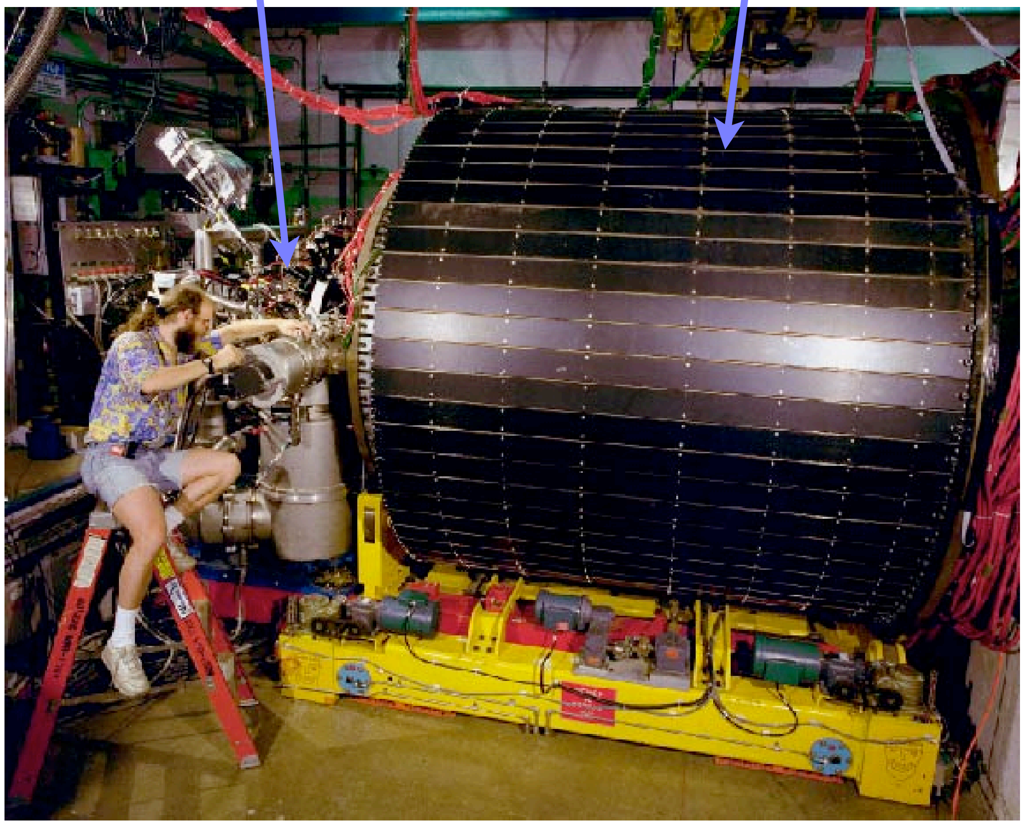
# E760/835 Pit


A:LJ500
A:RJ500
E200-35 (MIDDLE)
E200-36 (BOTTOM)
ACC. SCRAPER
WAVE CUTOFF -- A:MS5MCH
4-8 GHZ CORE
MOMENTUM
KICKER TANK
E200-37
A:SP400A-D
A:IP400
A:IG400
A:CL4I02
A:LM4Q3
A:SP403
A:LM4Q1P
A:LM5Q1M
E760 PIT
A50-1
STUB
A4Q1
A4Q2
A4Q3
A:BV400
A:CL4I01
A:IG500U
A:SP500U
A:IP500U
TO UPSTAIRS
A:IG500D
A:CC500D
A:SP500D
A:IP500D
A:CL5I01
A:BV500
A:CL5I02
A:LM5Q1
A:LM5Q3
A:IP500
A:SP500
A:IG503
A:SP503
A5Q1
A5Q2
A5Q3
A5B3
A5S3
BLEEDERS
CLRG
HBPM
VBPM
VDP
HDP
D50Q
D4Q2
DRF1-2
D:LM4Q
D:IP5

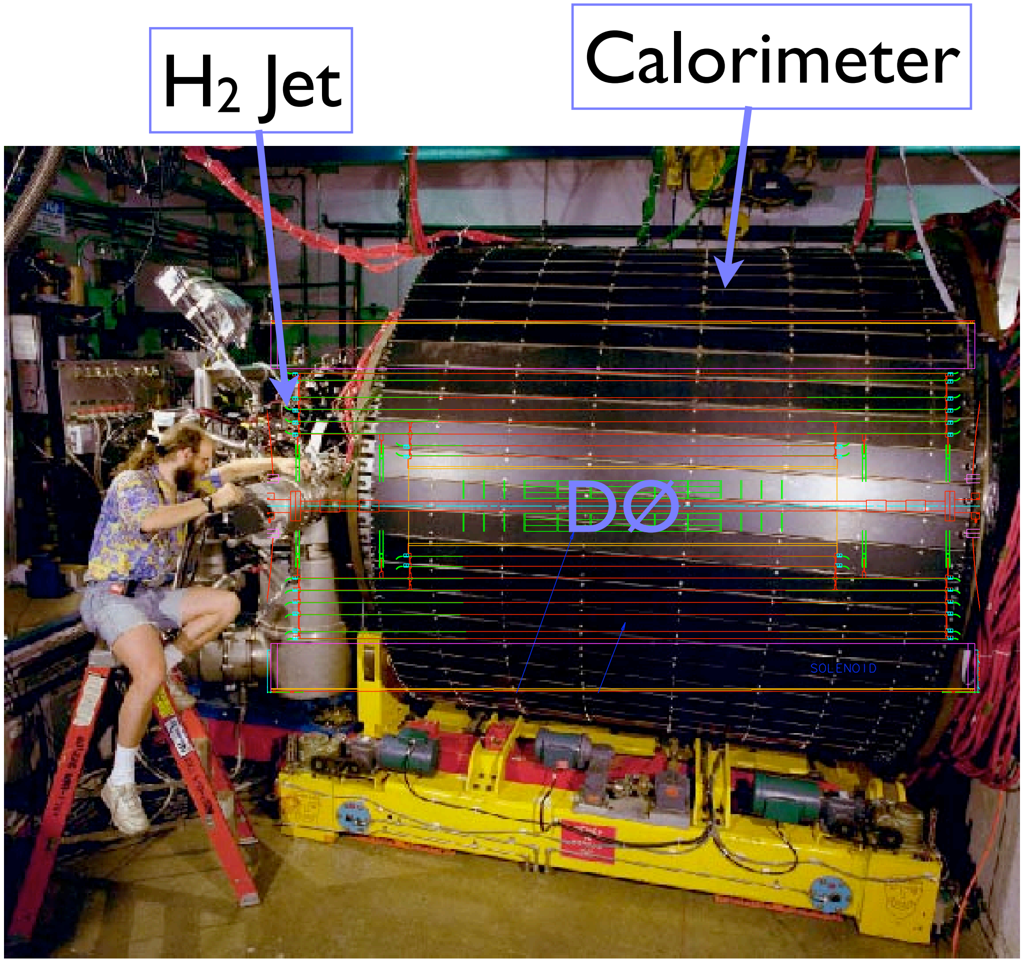
# E760/835 in situ

$H_2$ Jet

Calorimeter



# E760/835 in situ



# Apparatus Considerations

- For $\mathscr{L}\sim10^{32}$, need *fast* calorimeter

➡ new $PbWO_4$ barrel? (~M$?)

➡ with new solenoid? (~$1M?)

- How trigger & DAQ?
  - charmonium requires calorimetric trigger
  - hyperons require separated-vtx trigger
  - ΦΦ etc.: wide-angle trigger?

➡ rates low w.r.t. BTeV

➡ probably affordable

# Is There an Interested Collaboration?

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

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Giorgio Apollinari, Daniel R. Broemmelsiek, Charles N. Brown,
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...& growing...
(also interest @ other INFN branches &c...)

# Summary

- Best experiment ever on hyperons and charmonia may be feasible a few years from now at Fermilab
- Measurements complementary to, & not feasible at, LHC
- May be possible to "scoop" GSI by several years & exceed their sensitivity via focused program
- Modest effort could yield substantial impact

# Some Open Questions

- Are inclusive hyperons efficiently reconstructed at ≈5.4 GeV/*c*?
- How reliable is "rule-of-thumb" $\sigma(\Omega\overline{\Omega})$ estimate?
  - MIPP could test this
- Is $\overline{p}p \rightarrow \psi(3770) \rightarrow D\overline{D}$ possibly competitive?
- How optimize sensitivity to physics of interest?

➡ need targeted program of simulations and cost estimates

- Aim for proposal within ≈ a year