New Experiments with Antiprotons

Daniel M. Kaplan

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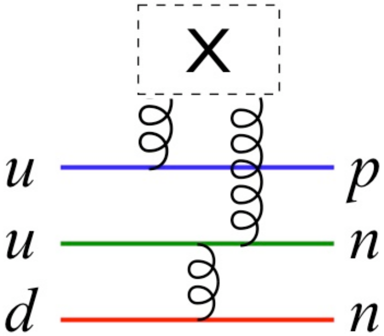


DPF2009
Wayne State University
Detroit, Michigan
July 28, 2009

Outline

Varied menu!

- Antiproton sources
- Hyperon CP violation
- A new experiment
- Issues in charmonium
- Charm mixing
- (Antihydrogen)
- Summary

Antiproton Sources

- Only 2 antiproton sources currently operating; 1 more planned for future:

Facility	$\overline{p}$ K.E. (GeV)	Stacking: Rate (10^{10}/hr)	Stacking: Duty Factor	Hours /Yr	$\overline{p}$/Yr (10^{13})
CERN AD	0.005, 0.047	–	–	3800	0.4
FNAL (Accumulator)	$\approx$3.5–8	20	15%	5550	17
FNAL (New Ring)	2–20?	20	90%	5550	100
FAIR ($\geq$2016)	2–15	3.5	90%	2780*	9

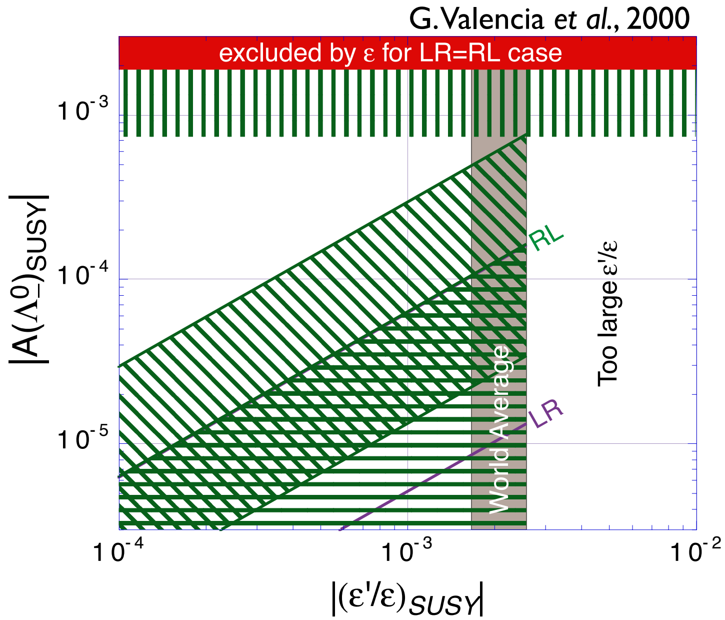
- Fermilab's is world's most intense

…even after FAIR turns on at GSI, Darmstadt

Hyperon CP Violation

- Differently sensitive to new physics than in *B* & *K* (parity-*conserving* interactions) CPV
- B Factories have so far failed to find new physics

$\Longrightarrow$ worth looking elsewhere!



- Leading potential signals are A_Λ, $A_{\Xi\Lambda}$, B_Ξ, Δ_Ω: [Donoghue, Pakvasa, He, Valencia, Tandean]

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

CP-odd

- $\bar{p}$ source can produce few x 10^8 $\Omega^-\,\overline{\Omega}^+$ (dep. on σ assumed) & maybe 10^{10} $\Xi^-\,\overline{\Xi}^+$ (dep. on transition crossing)

Hyperon CP Violation

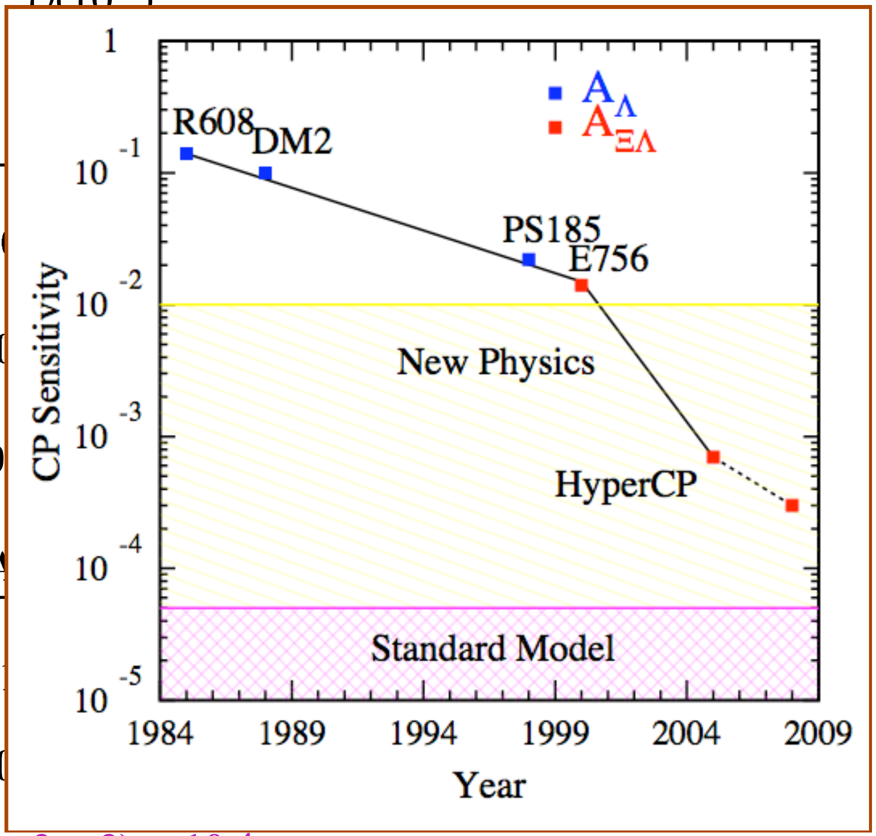
- Theory & experiment:

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: $O(10^{-3})$
  [e.g. SUSY gluonic dipole: X.-G.He et al., PRD 61,

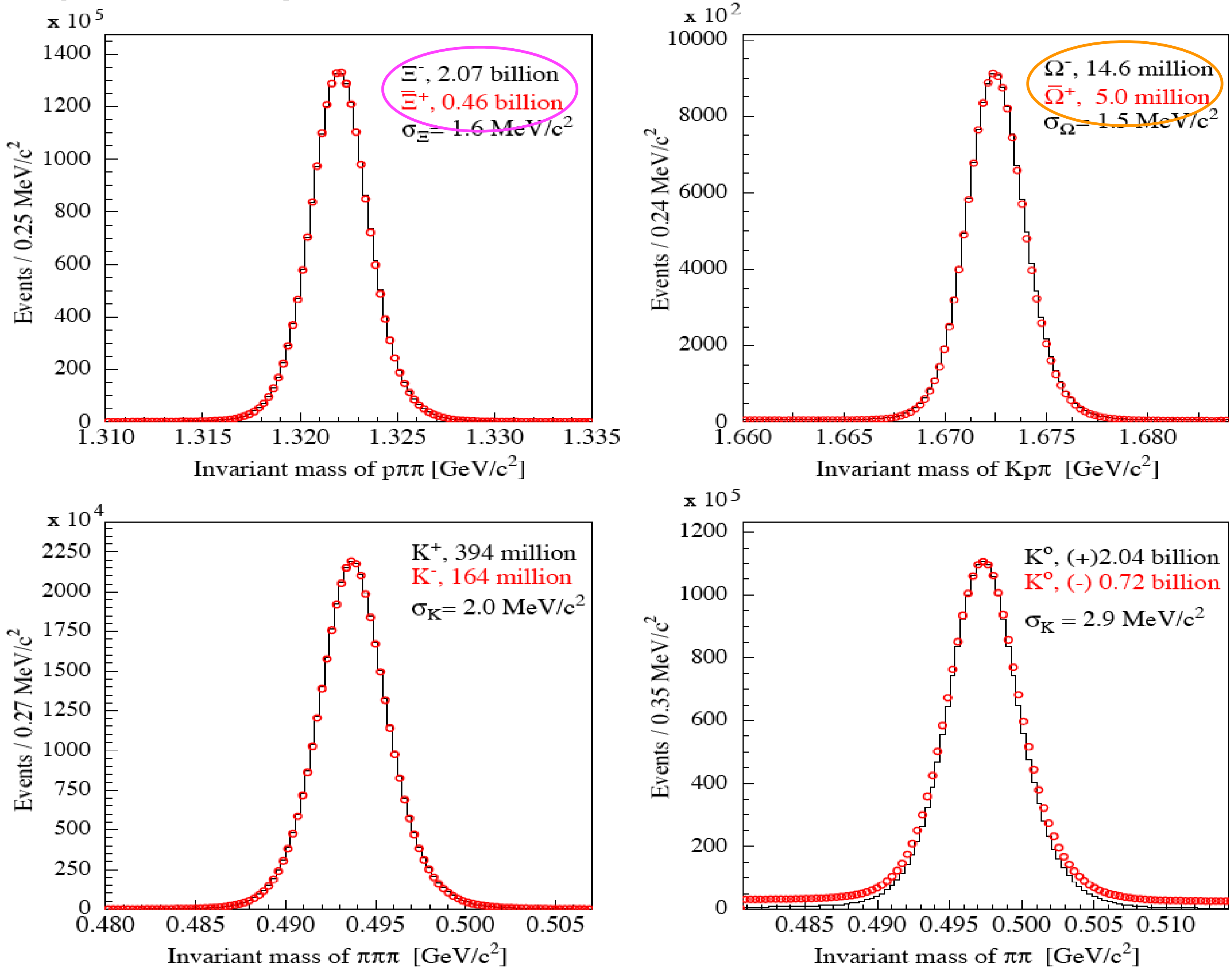
Experiment	Decay Mode	
R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda}X$	-(
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	(
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	0

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.(

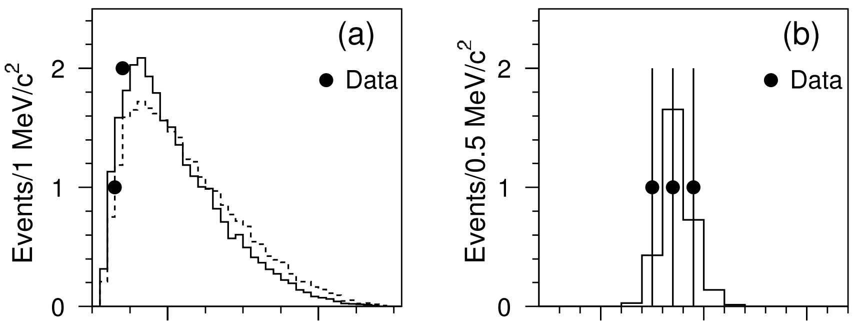


$(6 \pm 2 \pm 2) \times 10^{-4}$ [BEACH08 preliminary]

Made possible by... Enormous HyperCP Dataset



HyperCP 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?

Xiao-Gang He*

Department of Physics and Center for Theoretical Sciences, National Taiwan University, Taipei, Taiwan

Jusak Tandean†

Departments of Mathematics, Physics, and Computer Science, University of La Verne, La Verne, California 91750, USA

G. Valencia‡

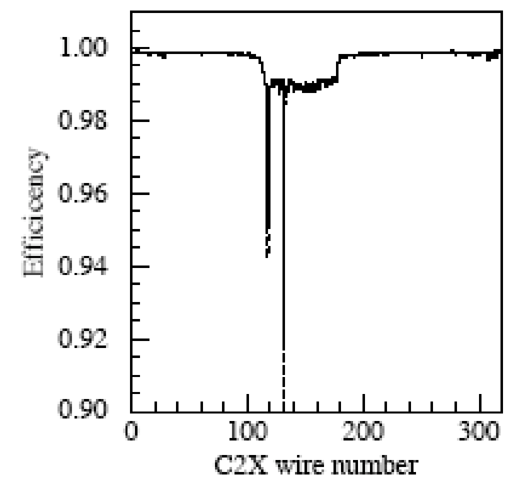
Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA

(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.

What Next?

- 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!

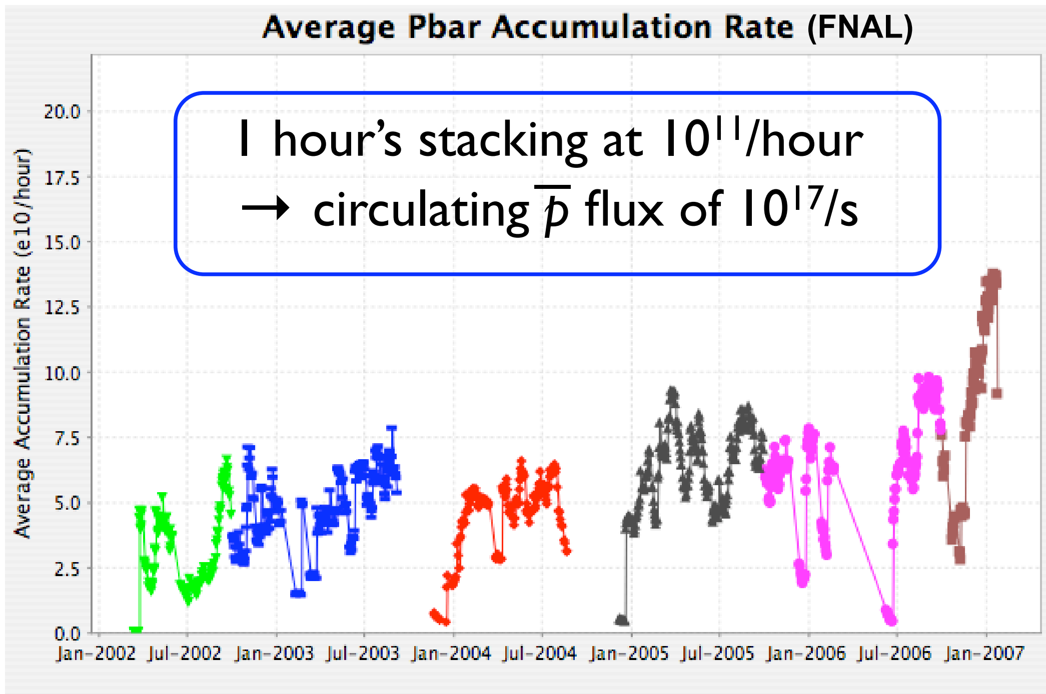
- Until "HyperCP era," world's best limit on hyperon CP violation came from PS185 at LEAR:

Experiment	Decay Mode	A_Λ	
R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$	-0.02 $\pm$ 0.14	[P. Chauvat et al., PL 163B (1985) 273]
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	0.01 $\pm$ 0.10	[M.H. Tixier et al., PL B212 (1988) 523]
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	0.006 $\pm$ 0.015	[P.D. Barnes et al., NP B 56A (1997) 46]

Experiment	Decay Mode	$A_\Xi + A_\Lambda$	
E756 at Fermilab	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	0.012 $\pm$ 0.014	[K.B. Luk et al., PRL 85, 4860 (2000)]
E871 at Fermilab (HyperCP)	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	$(0.0 \pm 6.7) \times 10^{-4}$	[T. Holmstrom et al., PRL 93. 262001 (2004)]
		$(6 \pm 2 \pm 2) \times 10^{-4}$	[BEACH08 preliminary]

Low-Energy Antiprotons!

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



- $\bar{p}p \to \bar{\Lambda}\Lambda$ study desirable but $p_{\bar{p}} \approx 1.5$ GeV/c too low

$\Longrightarrow$ do $\bar{p}p \to \bar{\Omega}\Omega$, $p_{\bar{p}} \approx 5$ GeV/c (& maybe $\bar{\Xi}\Xi$ also)

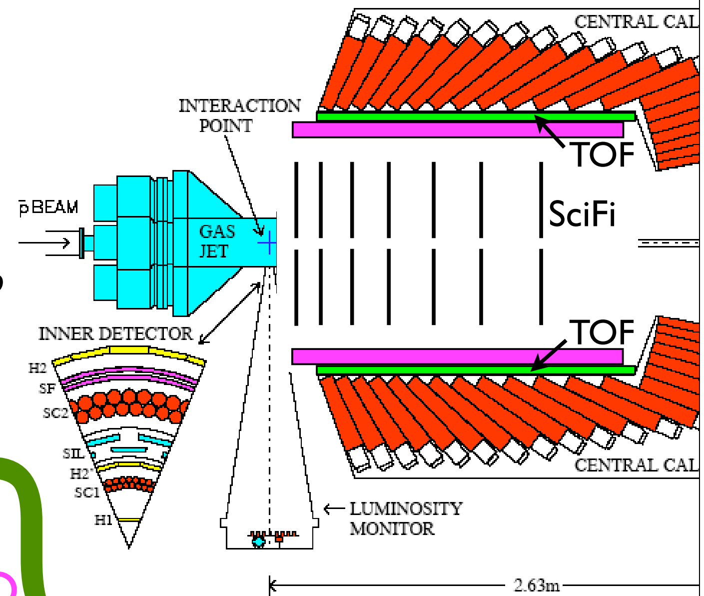
How?

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 $\Omega^-\,\overline{\Omega}^+$/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: $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, $Z(3930)$...

- $X(3872)$ of particular interest because may be the 1st clear 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

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

Charm?

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

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

Eric Braaten

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

(Received 13 November 2007; published 25 February 2008)

We present an estimate of the partial width of $X(3872)$ into $p\bar{p}$ under the assumption that it is a weakly bound hadronic molecule whose constituents are a superposition of the charm mesons $D^{*0}\bar{D}^0$ and $D^0\bar{D}^{*0}$. The $p\bar{p}$ partial width of X is therefore related to the cross section for $p\bar{p} \to D^{*0}\bar{D}^0$ near the threshold. That cross section at an energy well above the threshold is estimated by scaling the measured cross section for $p\bar{p} \to K^{*-}K^+$. It is extrapolated to the $D^{*0}\bar{D}^0$ threshold by taking into account the threshold resonance in the 1^{++} channel. The resulting prediction for the $p\bar{p}$ partial width of $X(3872)$ is proportional to the square root of its binding energy. For the current central value of the binding energy, the estimated partial width into $p\bar{p}$ is comparable to that of the P-wave charmonium state χ_{c1}.

- Braaten estimate of $\bar{p}p$ X(3872) coupling assuming D^*D molecule
  - extrapolates from K^*K data
- By-product is $D^{*0}\bar{D}^0$ cross section

Charm?

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

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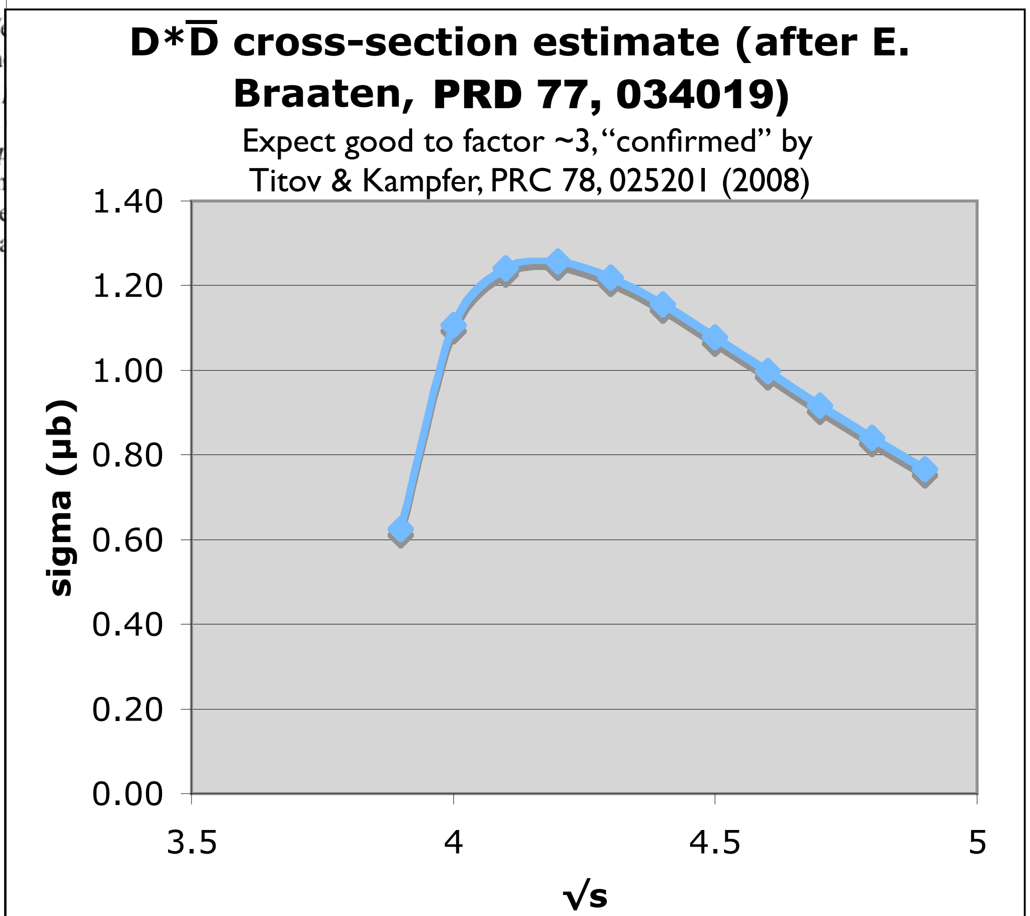
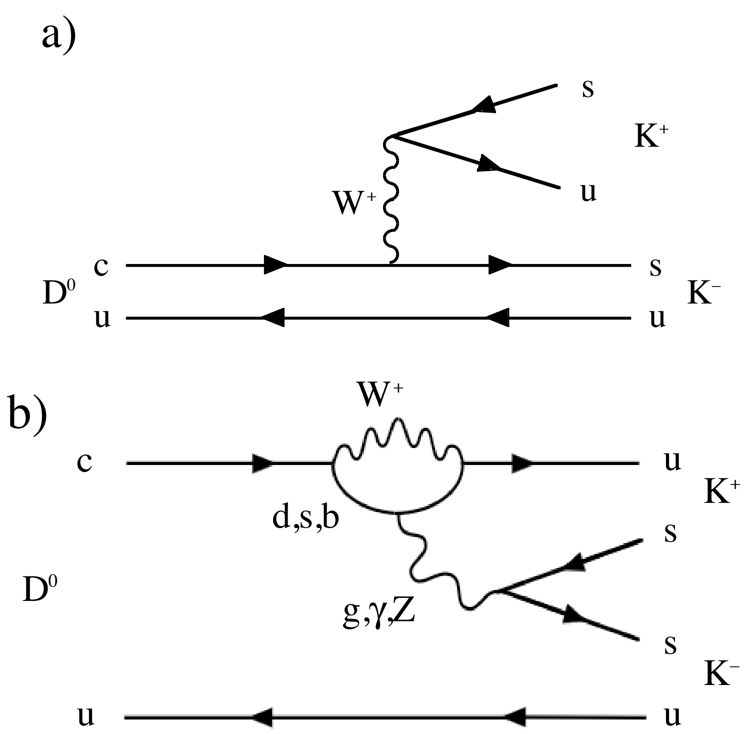


- Braaten estimate of $\bar{p}p$ $X(3872)$ coupling assuming D^*D molecule
  - extrapolates from K^*K data
- By-product is $D^{*0}\bar{D}^0$ cross section
- 1.3 µb → 5 ×10^9/year
- Expect efficiency as at *B* factories

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 Possible in CF, DCS only if New Physics

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

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

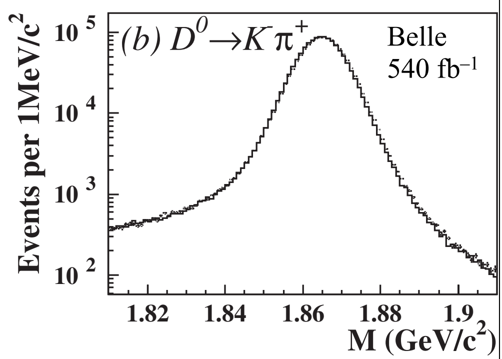
➡ world's best sensitivity to charm CPV

Charm?

- Ballpark sensitivity estimate using cross section based on Braaten $\bar{p}p \to D^{*0}\bar{D}^0$ 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}	$\text{cm}^{-2}\text{s}^{-1}$
Target A	27	
$A^{0.29}$	2.6	
$\sigma(\bar{p}p \to D^{*+}X)$	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	
Efficiency	0.1	
Total	2.7×10^7	events/y

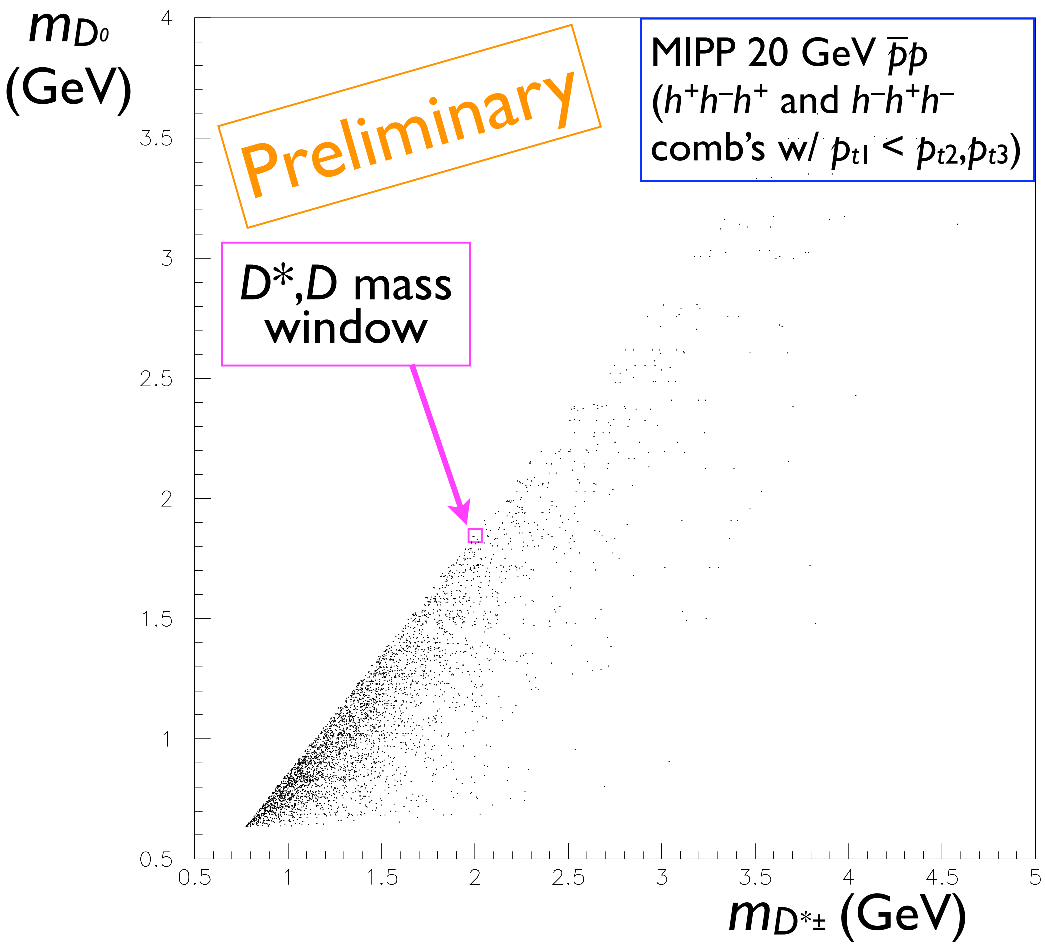
- Compare with 1.22×10^6 total tagged events at Belle [M. Staric et al., PRL **98**, 211803 (2007)]



(LHC*b* will have comparable statistics but diff't systematics)

Background Study

- Have studied MIPP (FNAL E907) 20 GeV $\bar{p}p$ data:



- Conclusion:

  Thanks to low multiplicity at 8 GeV, clean sample can likely be obtained with reasonable (~0.1) efficiency

...and **now**

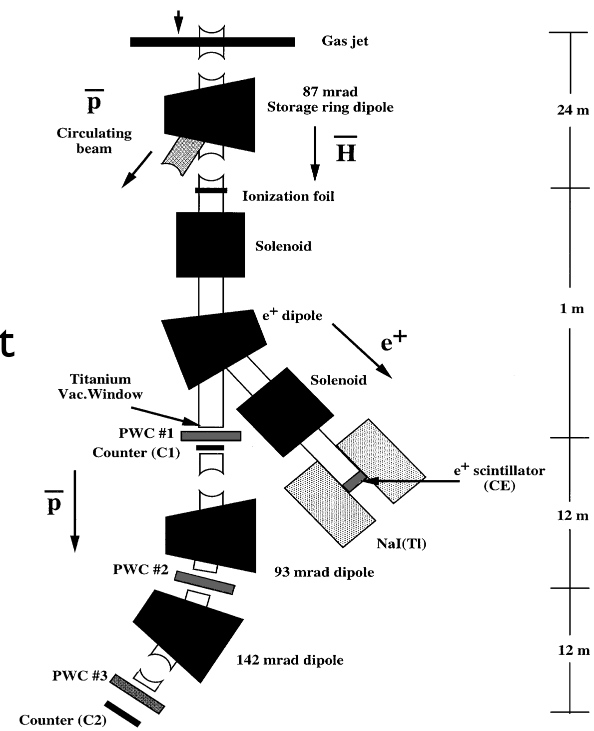
for *something*

completely different!

Antihydrogen

- Was formed spontaneously in E835 H gas-jet target
- Detected in "parasitic" E862
  [G. Blanford et al., PRL 80:3037 (1998)]
- Cross section grows with E_{beam}, Z_{tgt}

$\Longrightarrow$ can do better with Au at 8 GeV



Antihydrogen

- Parasitic running appears feasible
- High-Z foil just installed on moveable fork in Antiproton Accumulator
  - could serve as monitor of Accumulator beam halo
- Will begin shakedown and operation once beam returns
- Hope to assemble Lamb-shift apparatus (magnets, laser, detectors) subsequently

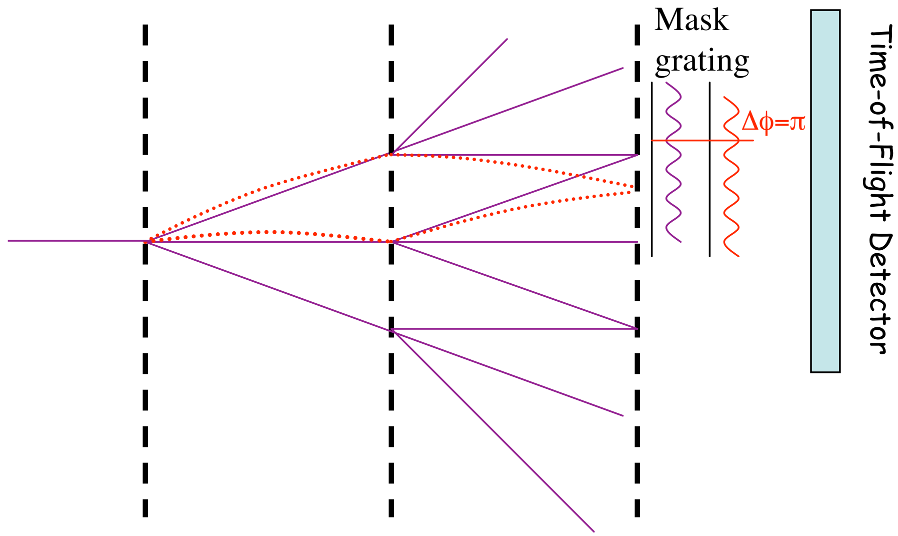
- From D. Christian:

CPT test using relativistic antihydrogen

- Antihydrogen is produced in the gas-jet target - exits the Accumulator in the ground state.
  - 99 antihydrogen atoms were observed by E862 with 0 background.
- The atoms enter a 7kG magnet and a large fraction are excited to N=2 long-lived Stark state by laser light.
- Atoms exit magnet & pass through a field-free region, then enter a second magnet with field 6-8 kG. The mixture of N=2 Stark states in the second magnet depends on the time spent in the field-free region, the fine structure, and the Lamb shift.
- Distribution of field ionization in the second magnet reflects probability of being in each of the three N=2 Stark states.
- Monte Carlo ––> an experiment in which 100 atoms exit the first magnet in N=2,L will yield a 1% measurement of the fine structure and a 5% measurement of the Lamb shift. Assuming that only the 2S level is shifted by a CPT violating force, the 1σ sensitivity is 50 parts per billion of the 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 $\bar{\mathrm{H}}$ 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

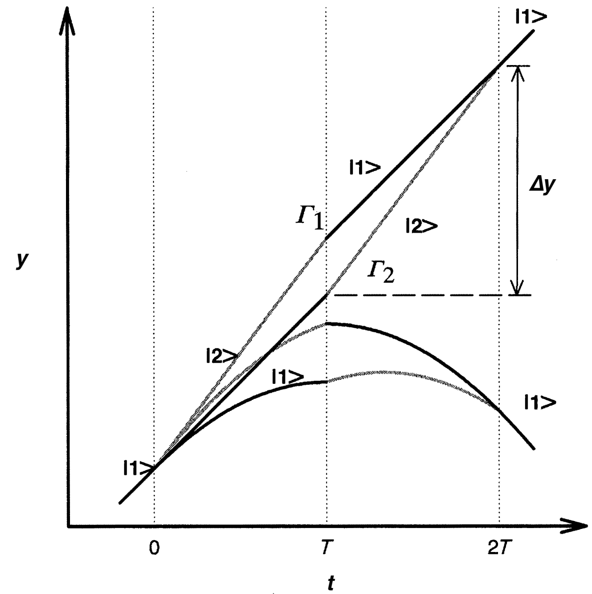
→ tests for possible "5th forces"

Antimatter Gravity

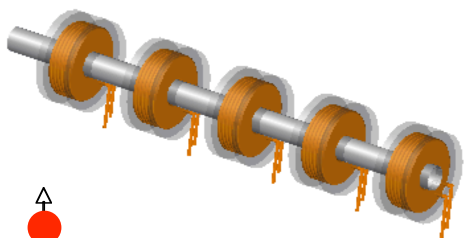
- Deceleration from 8 GeV to < 20 keV:
  - MI from 8 GeV to $\lesssim$ 400 MeV (TBD), then "reverse linac" or "particle refrigerator," then degrade
  - efficiency $\gtrsim 10^{-4}$ looks feasible

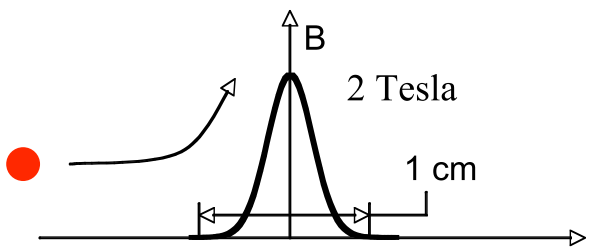
    $\Rightarrow 10^{-4}$ $\bar{g}$ measurement in ~ month's dedicated running
  - eventually, add small synchrotron → eff ~1
- Requires completion of antiproton deceleration/ extraction facility planned for Hbar Technologies

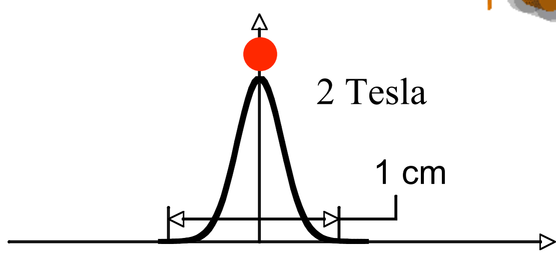
Antimatter Gravity



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







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

Proto-Collaborations

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

Alex D. Cronin
University of Arizona, Tucson, Arizona 85721, USA

Thomas J. Phillips*
Duke University, Durham, North Carolina 27708, USA

Mark Fischler, Alan Hahn, James T. Volk, G.P. Yeh
Fermilab, Batavia, Illinois 60510, USA

Rod G. Greaves
First Point Scientific, Agoura Hills, California 91301, USA

Stephen D. Howe, Gerald P. Jackson, Raymond Lewis, Joseph M. Zlotnicki
Hbar Technologies, LLC, West Chicago, Illinois 60185, USA

Daniel M. Kaplan, Thomas J. Roberts[1], Jeff Terry
Illinois Institute of Technology, Chicago, Illinois 60616, USA

Glenn A. Horton-Smith, Bharat Ratra
Kansas State University, Manhattan, Kansas 66506, USA

Todd K. Pedlar
Luther College, Decorah, Iowa 52101, USA

H. Richard Gustafson
University of Michigan, Ann Arbor, Michigan 48109, USA

J. Boise Pearson
NASA Marshall Space Flight Center, Alabama, USA

Thomas E. Coan
Southern Methodist University, Dallas, Texas 75275, USA

Mark G. Raizen
University of Texas, Austin, Texas 78712, USA

*Contact person; email: Thomas.Phillips@duke.edu.

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

Proto-Collaborations

P-986 Letter of Intent:

Medium-Energy Antiproton Physics at Fermilab

David M. Asner
Carleton University, Ottowa, ON, Canada K1S 5B6

Thomas J. Phillips
Duke University, Durham, N. Carolina 27708 USA

Giorgio Apollinari, Daniel R. Broemmelsiek, Charles N. Brown,
David C. Christian, Paul Derwent, Keith Gollwitzer, Alan Hahn,
Vaia Papadimitriou, Ray Stefanski, Steven Werkema, Herman B. White
Fermilab, Batavia, IL 60510, USA

Wander Baldini, Giulio Stancari, Michelle Stancari
INFN, Sezione di Ferrara, Ferrara, Italy

Gerald P. Jackson
Hbar Technologies, LLC, West Chicago, IL 60185, USA

Daniel M. Kaplan,* Yagmur Torun, Christopher G. White
Illinois Institute of Technology, Chicago, Illinois 60616, USA

HyangKyu Park
KyungPook National University, DaeGu, Korea

Todd K. Pedlar
Luther College, Decorah, IA 52101, USA

H. Richard Gustafson
University of Michigan, Ann Arbor, MI 48109, USA

Jerome Rosen
Northwestern University, Evanston, IL 60208, USA

Mitchell Wayne
Notre Dame University, Notre Dame, IN 46556, USA

Alak Chakravorty
St. Xavier University, Chicago, IL 60655, USA

E. Craig Dukes
University of Virginia, Charlottesville, Virginia 22903, USA

February 5, 2009

Summary

- Best experiment ever on hyperons, charm, and charmonia may soon be feasible at Fermilab
  - possibly including world's most sensitive charm *CPV* study
- $\overline{\text{H}}$ exp'ts also proposed:
  - Antihydrogen spectrum in flight
  - Antimatter Gravity Experiment
- World's best $\bar{p}$ source → simple way to broad physics program in post-Tevatron era
- Status: P981, P986 LoIs under consideration by PAC
- New collaborators welcome! (see http://capp.iit.edu/hep/pbar/)