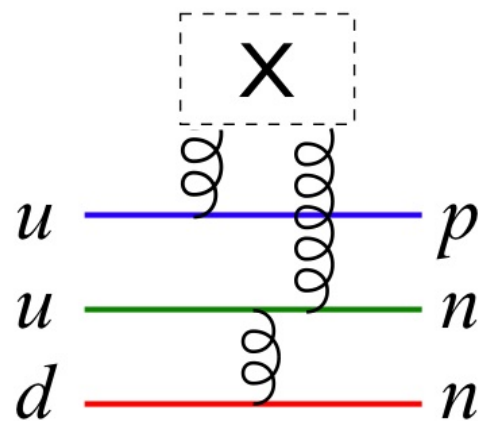


New Experiments with Antiprotons

Daniel M. Kaplan

ILLINOIS INSTITUTE
OF TECHNOLOGY
Transforming Lives. Inventing the Future. www.iit.edu



High-Energy-Physics Seminar
University of Pisa
19 May 2011

Outline

Varied menu!

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

Baryogenesis

- Universe dominantly matter, negligible antimatter
- How could matter excess have developed?
- Sakharov (1967): possible if, soon after Big Bang, there were
 1. C and CP violation ($\Rightarrow$ 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



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]
(Hence Kobayashi & Maskawa 2008 Nobel prize)

CP Violation

- CPV already discovered in 1964: small effect in K mixing & decay
 - nicely explained in SM by Kobayashi-Maskawa mechanism: non-zero phase in CKM matrix
- KM model not sufficient to account for baryogenesis!
 - if CPV is large in CKM, should be large in B meson decays as well [BaBar, CDF, DØ]
 - (hence Kobayashi & Maskawa 2008 Nobel prize)

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

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

- Hyperons
- Charm
- Neutrinos

} Worth looking elsewhere as well!

*except for possible $D\bar{0}$ 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

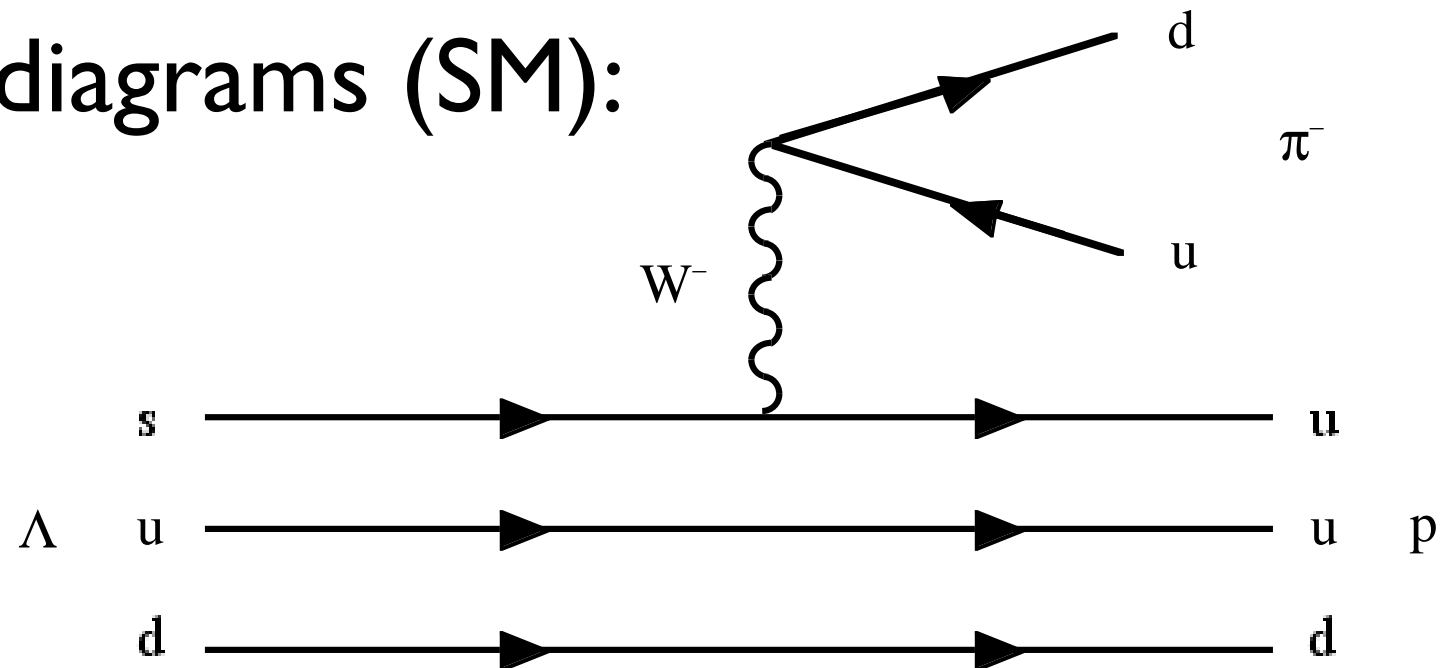
Thus in hyperon decay, $\bar{\alpha} \neq -\alpha$ implies CP violation in this process independent of the validity of the CPT theorem. This is also true if $\bar{\beta} \neq -\beta$.

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.

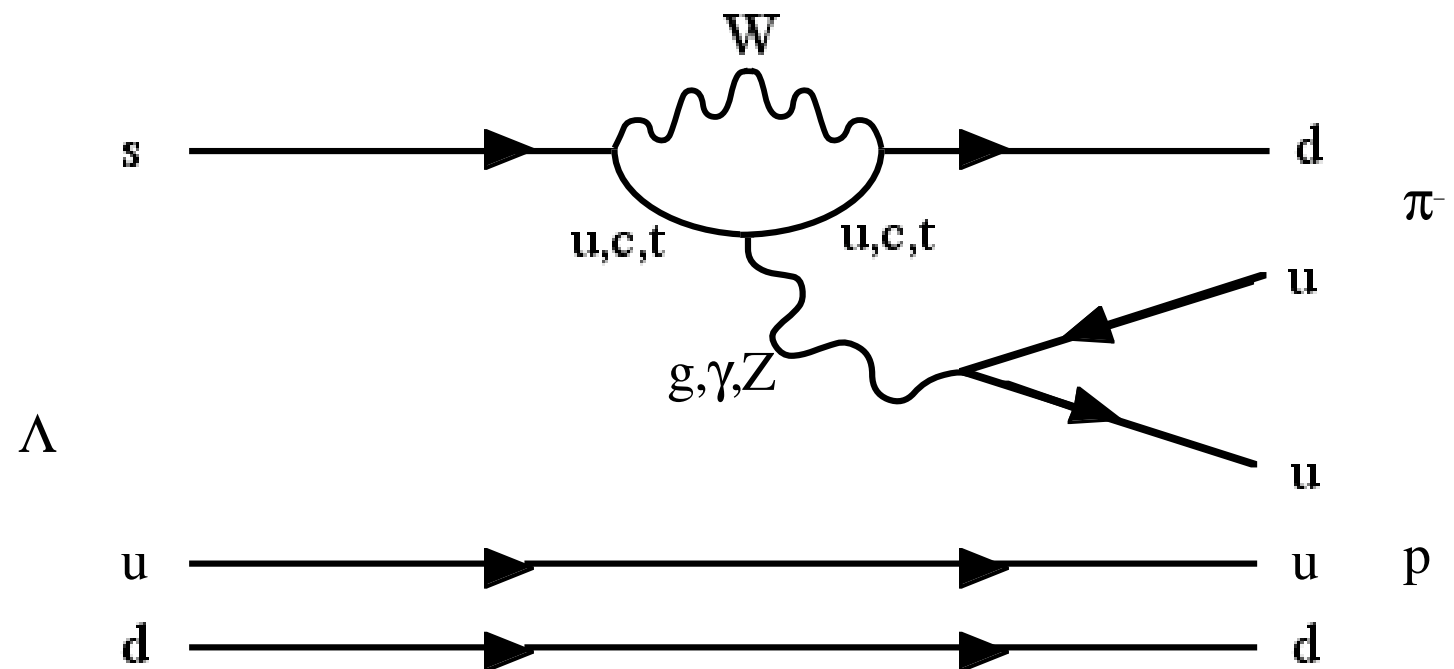
Hyperon CP Violation

- 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!

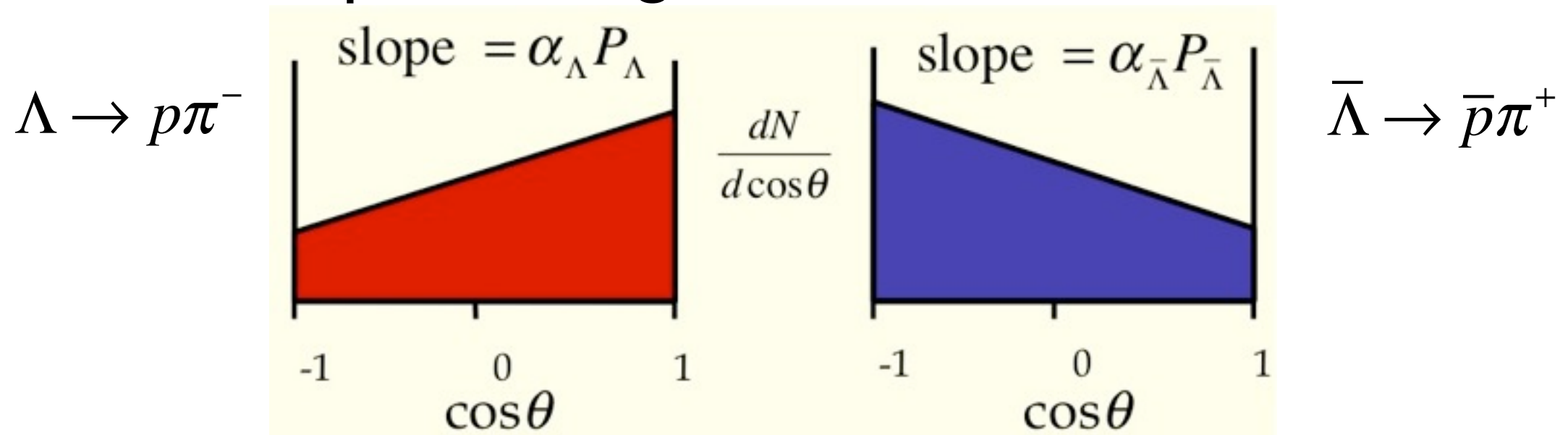
Hyperon CP Violation

- 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:

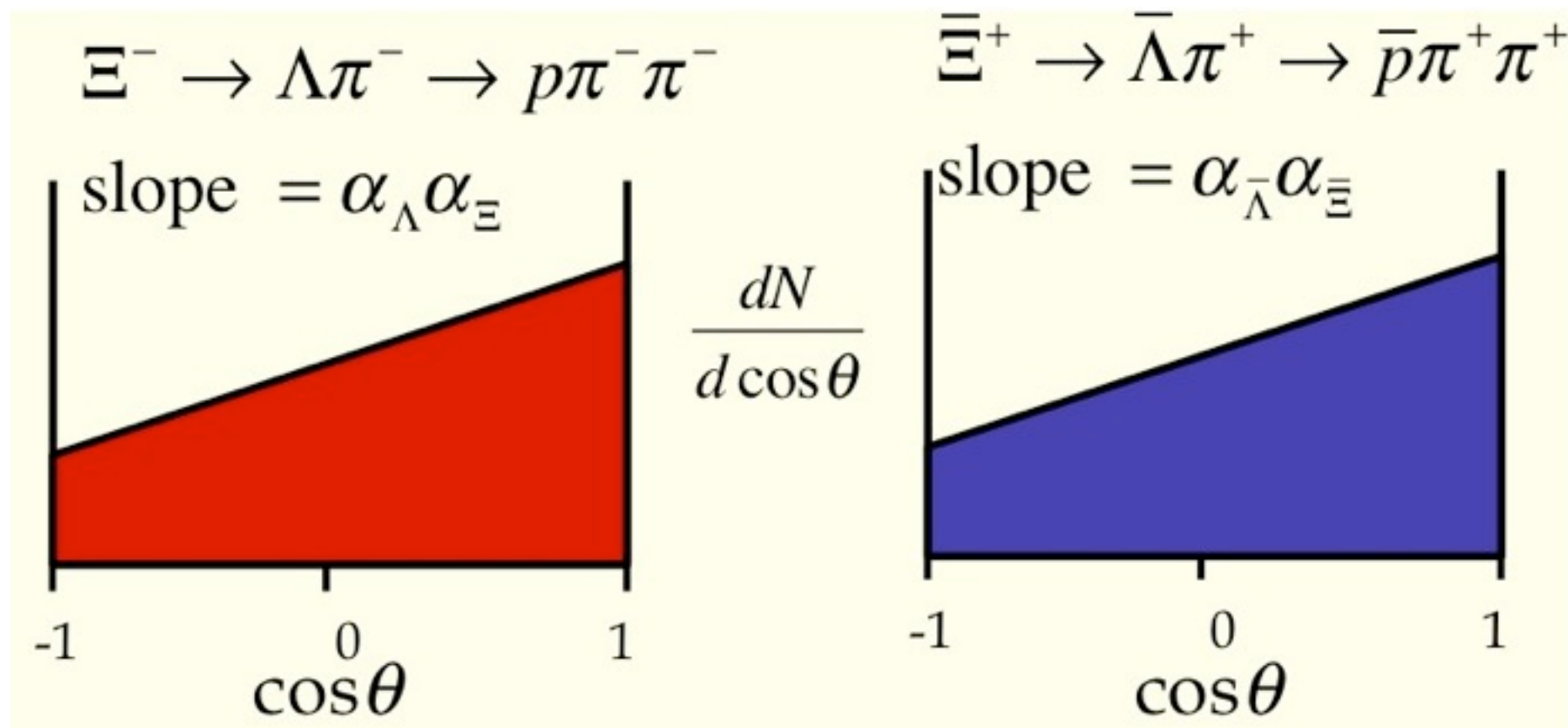


$$\Rightarrow A_{\Lambda} \equiv \frac{\alpha_{\Lambda} + \bar{\alpha}_{\Lambda}}{\alpha_{\Lambda} - \bar{\alpha}_{\Lambda}}, \quad B_{\Lambda} \equiv \frac{\beta_{\Lambda} + \bar{\beta}_{\Lambda}}{\beta_{\Lambda} - \bar{\beta}_{\Lambda}}, \quad \Delta_{\Lambda} \equiv \frac{\Gamma_{\Lambda \rightarrow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

Hyperon CP Violation

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

➡ HyperCP “trick”: $\Xi^- \rightarrow \Lambda \pi^- \rightarrow p \pi^- \pi^-$ decay gives $\vec{P}_\Lambda = -\vec{P}_{\bar{\Lambda}}$



- Unequal slopes $\Rightarrow$ CP violated!

Hyperon CP Violation

- Differently sensitive to New Physics than B, K CPV
- 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	$\Lambda \rightarrow p\pi$	$\lesssim 10^{-5}$	$\lesssim 6 \times 10^{-4}$	[68]
$A_{\Xi\Lambda}$	$\Xi^\mp \rightarrow \Lambda\pi, \Lambda \rightarrow p\pi$	$\lesssim 5 \times 10^{-5}$	$\leq 1.9 \times 10^{-3}$	[69]
$A_{\Omega\Lambda}$	$\Omega \rightarrow \Lambda K, \Lambda \rightarrow p\pi$	$\leq 4 \times 10^{-5}$	$\leq 8 \times 10^{-3}$	[36]
$\Delta_{\Xi\pi}$	$\Omega \rightarrow \Xi^0\pi$	2×10^{-5}	$\leq 2 \times 10^{-4} *$	[35]
$\Delta_{\Lambda K}$	$\Omega \rightarrow \Lambda K$	$\leq 1 \times 10^{-5}$	$\leq 1 \times 10^{-3}$	[36]

*Once they are taken into account, large final-state interactions may increase this prediction [56].

 Small sizes of $(A, \Delta)_{\text{SM}}$ favorable for NP CPV search!

Hyperon CP Violation

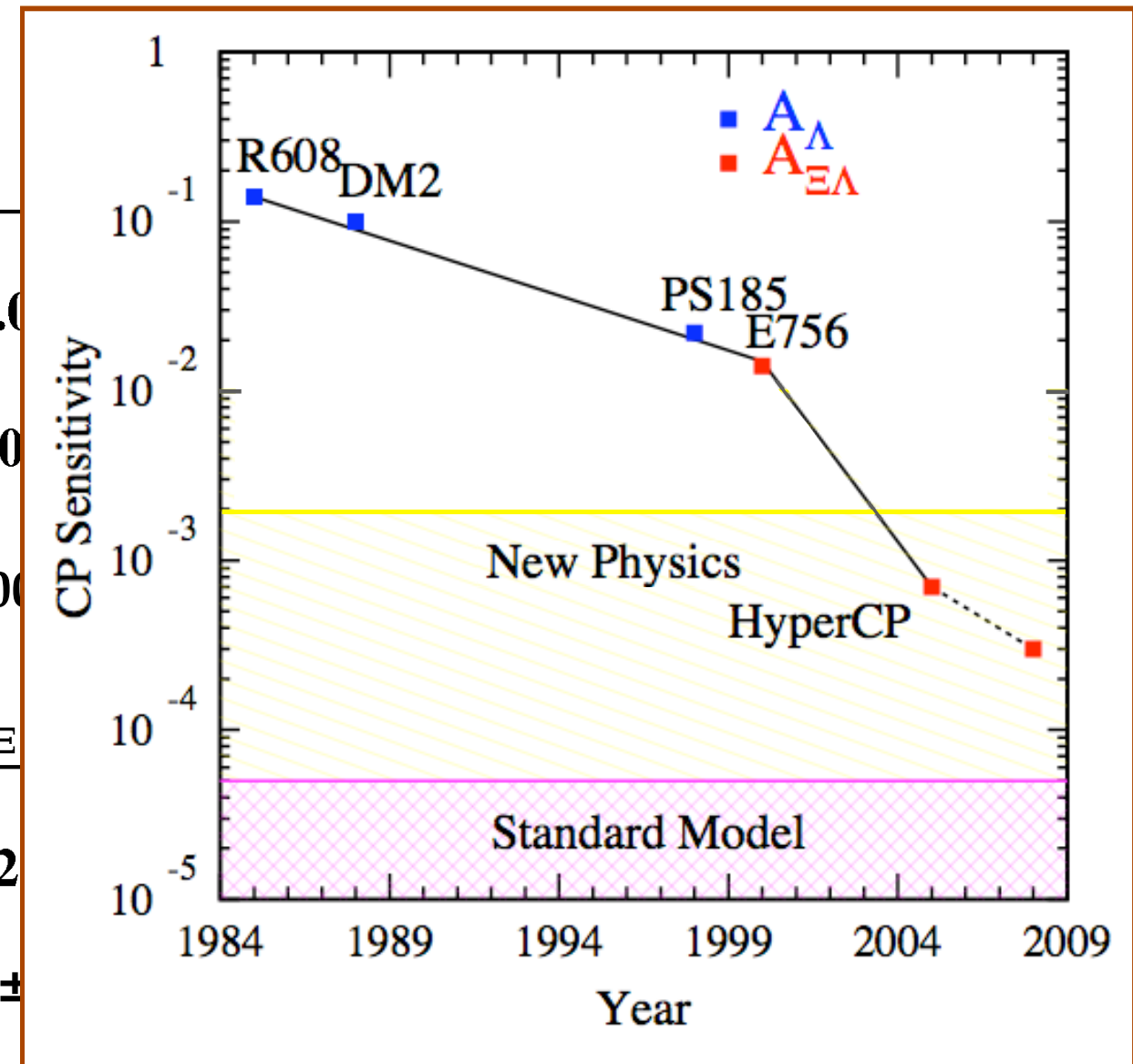
- Measurement history:

Experiment	Decay Mode	A_Λ
R608 at ISR	$pp \rightarrow \Lambda X, \bar{p}p \rightarrow \bar{\Lambda} X$	-0.02 ± 0.14 [P. Chauvat et al., PL 163B (1985) 273]
DM2 at Orsay	$e^+e^- \rightarrow J/\Psi \rightarrow \Lambda \bar{\Lambda}$	0.01 ± 0.10 [M.H. Tixier et al., PL B212 (1988) 523]
PS185 at LEAR	$p\bar{p} \rightarrow \Lambda \bar{\Lambda}$	0.006 ± 0.015 [P.D. Barnes et al., NP B 56A (1997) 46]
Experiment	Decay Mode	$A_\Xi + A_\Lambda$
E756 at Fermilab	$\Xi \rightarrow \Lambda \pi, \Lambda \rightarrow p \pi$	0.012 ± 0.014 [K.B. Luk et al., PRL 85, 4860 (2000)]
E871 at Fermilab (HyperCP)	$\Xi \rightarrow \Lambda \pi, \Lambda \rightarrow p \pi$	$(0.0 \pm 6.7) \times 10^{-4}$ [T. Holmstrom et al., PRL 93. 262001 (2004)] $(-6 \pm 2 \pm 2) \times 10^{-4}$ [BEACH08 preliminary; PRL in prep]

Hyperon CP Violation

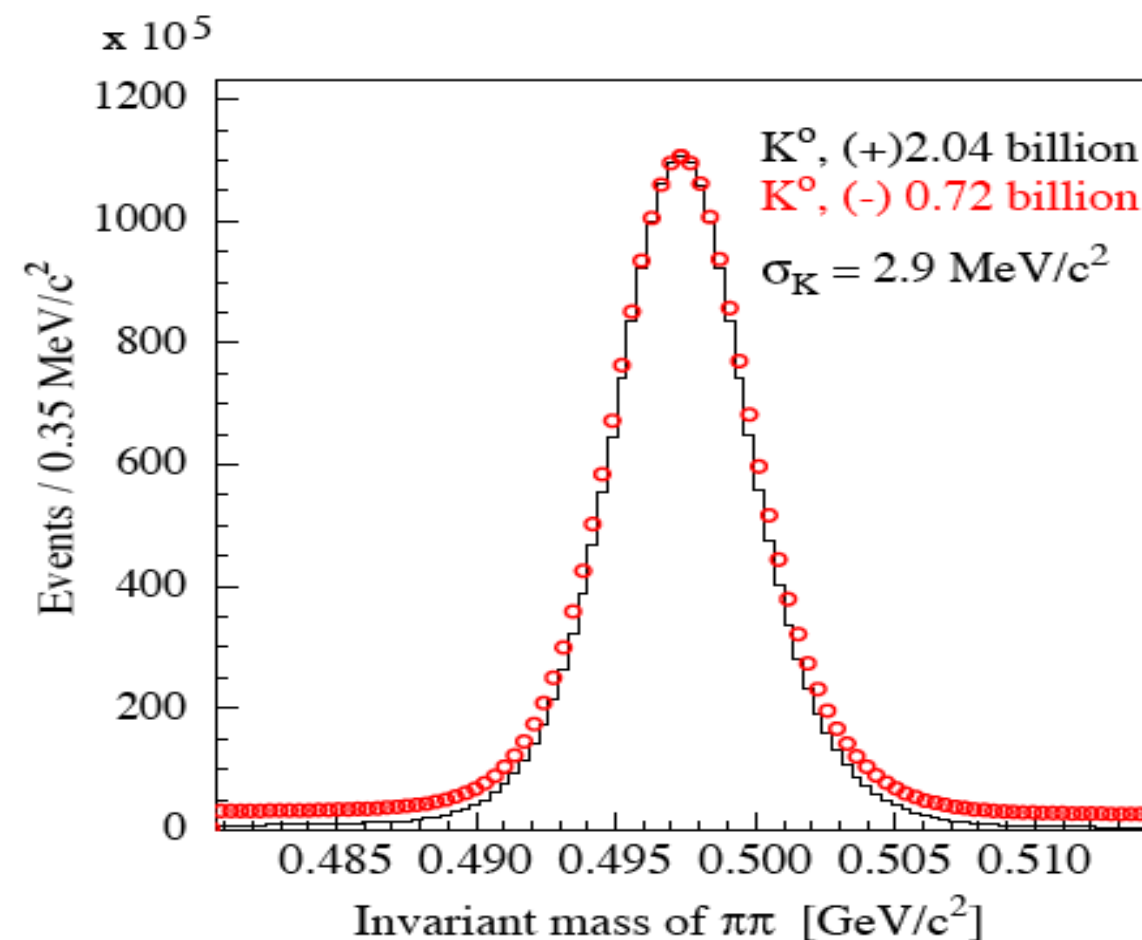
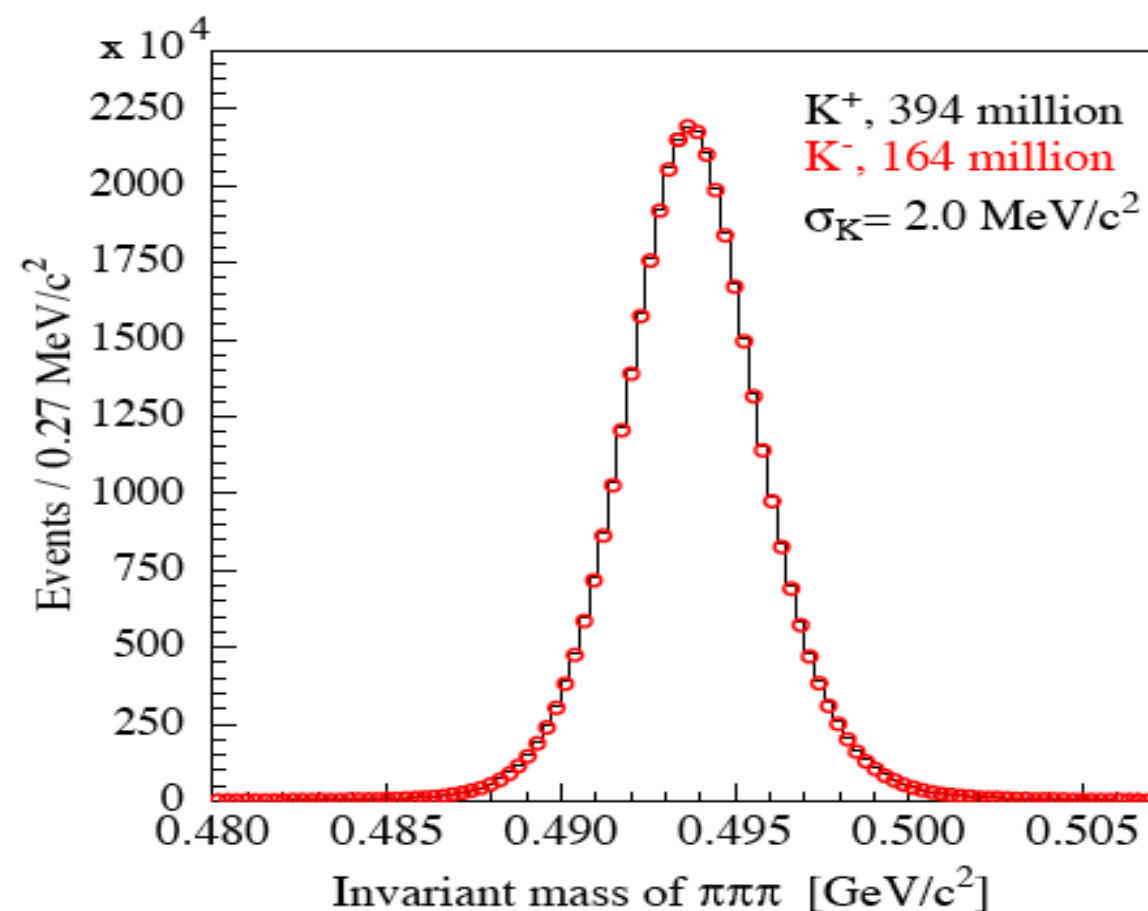
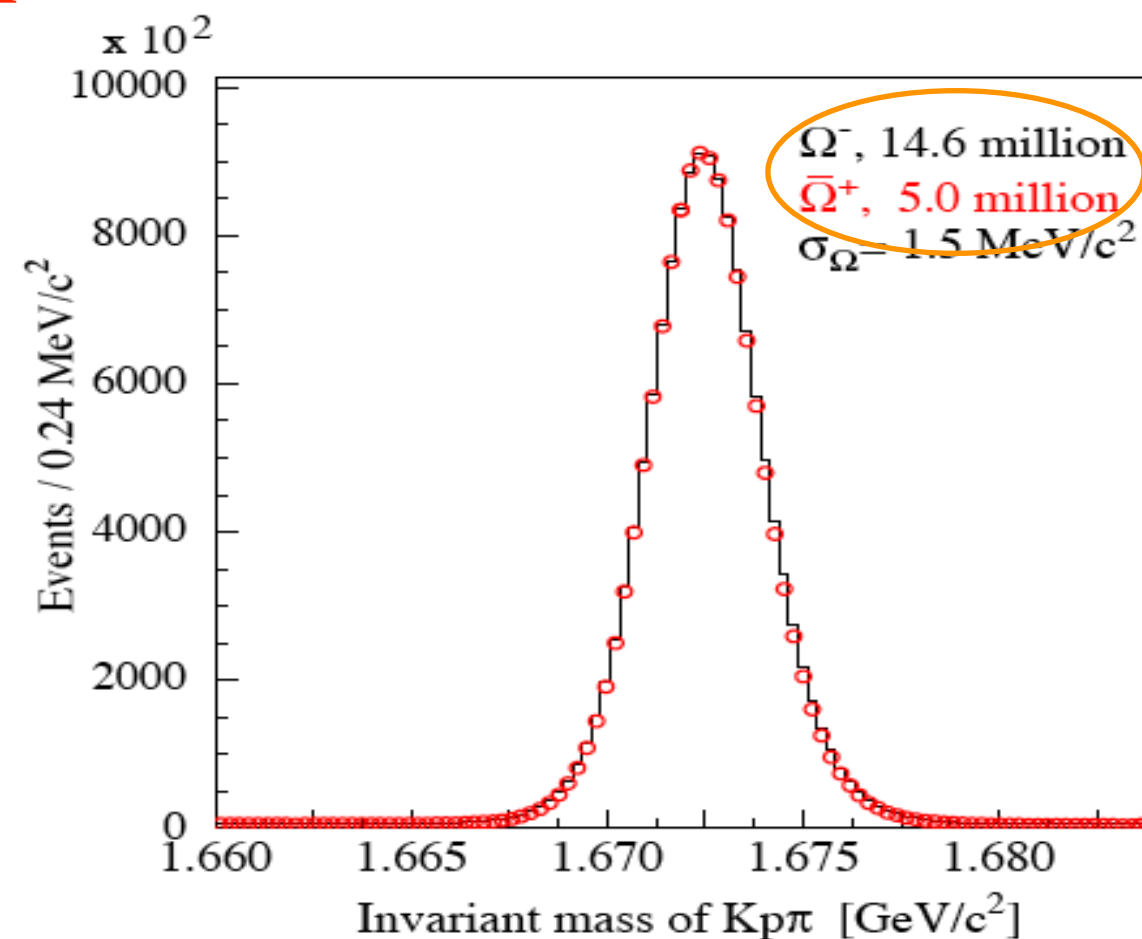
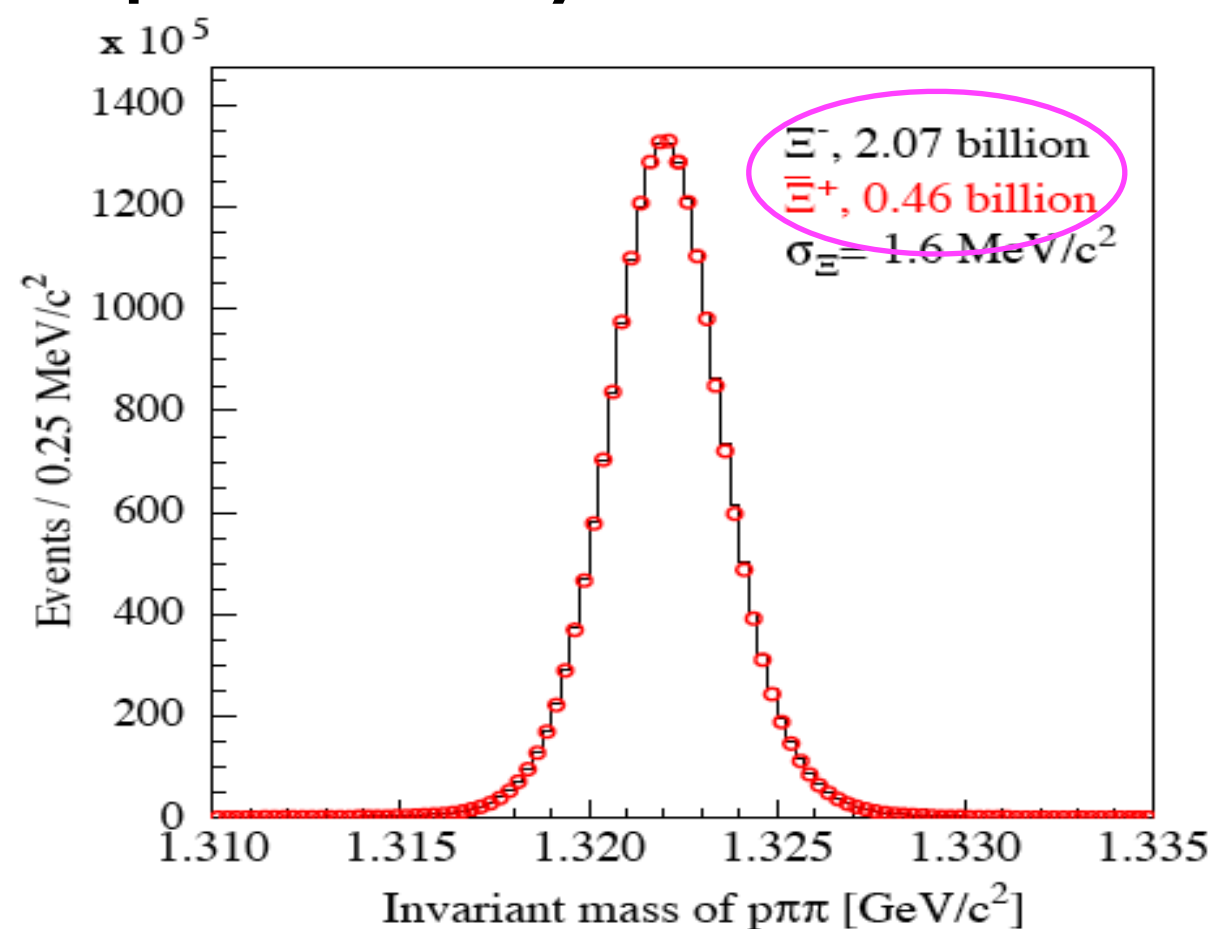
- Measurement history:

Experiment	Decay Mode	
R608 at ISR	$pp \rightarrow \Lambda X, \bar{p}p \rightarrow \bar{\Lambda} X$	-0.0
DM2 at Orsay	$e^+e^- \rightarrow J/\Psi \rightarrow \Lambda \bar{\Lambda}$	0.0
PS185 at LEAR	$p\bar{p} \rightarrow \Lambda \bar{\Lambda}$	0.00
Experiment	Decay Mode	A_{Ξ}
E756 at Fermilab	$\Xi \rightarrow \Lambda \pi, \Lambda \rightarrow p \pi$	0.012
E871 at Fermilab (HyperCP)	$\Xi \rightarrow \Lambda \pi, \Lambda \rightarrow p \pi$	$(0.0 \pm$



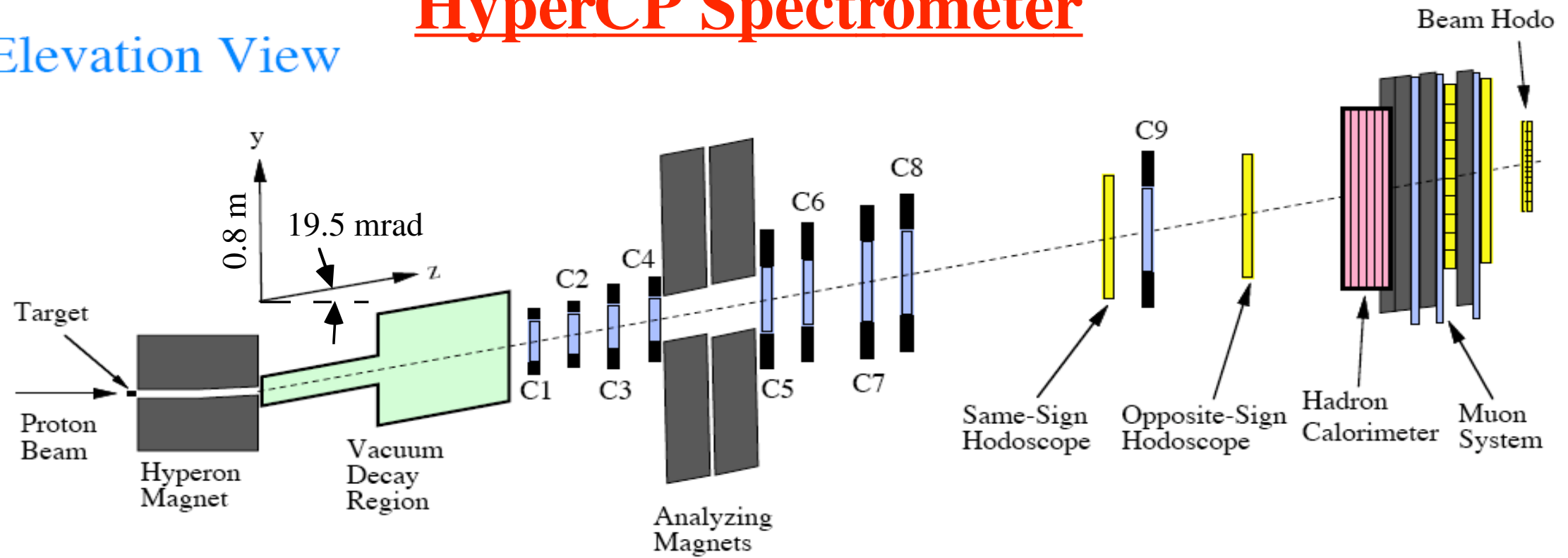
$(-6 \pm 2 \pm 2) \times 10^{-4}$ [BEACH08 preliminary; PRL in prep]

Made possible by... Enormous HyperCP Dataset

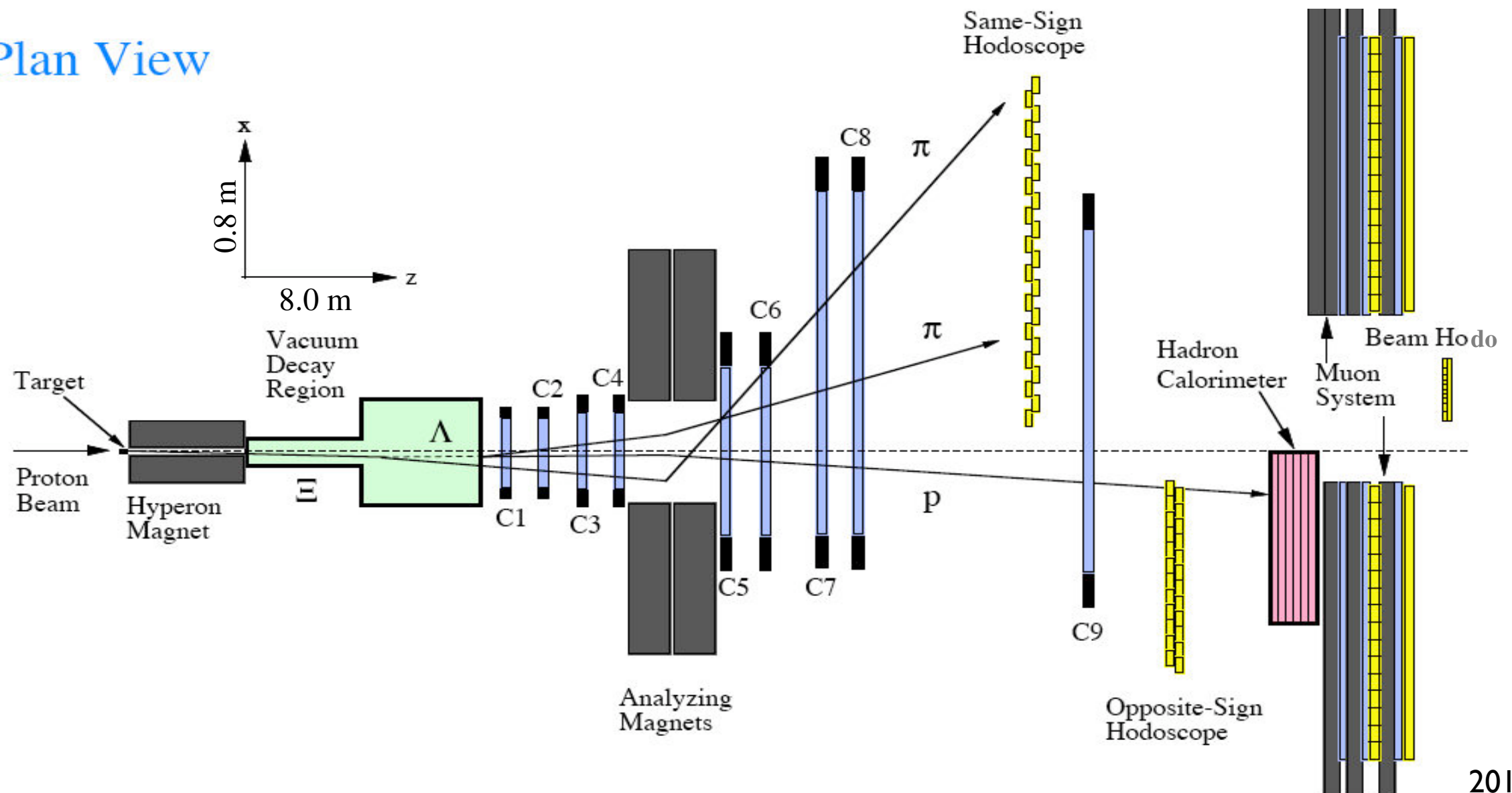


HyperCP Spectrometer

Elevation View



Plan View



...and Fast HyperCP DAQ System

$\approx 20,000$ 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
University of California, Berkeley, USA

C. James, J. Volk
Fermilab, USA

J. Felix, G. Moreno, M. Sosa
University of Guanajuato, Mexico

R. Burnstein, A. Chakravorty, D. Kaplan, L. Lederman, D. Rajaram, H. Rubin, N. Solomey, C. White
Illinois Institute of Technology, USA

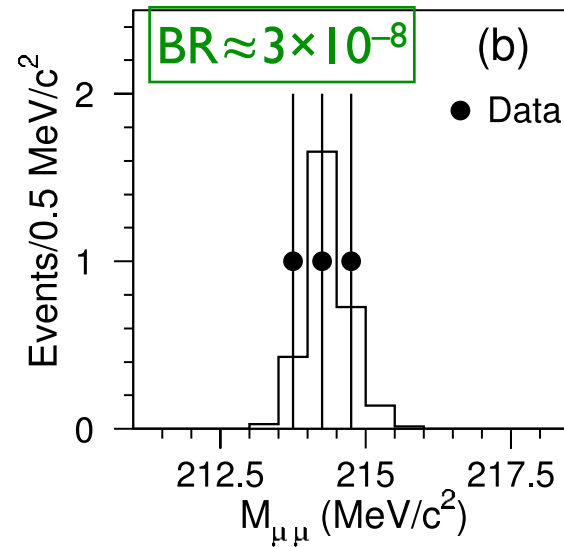
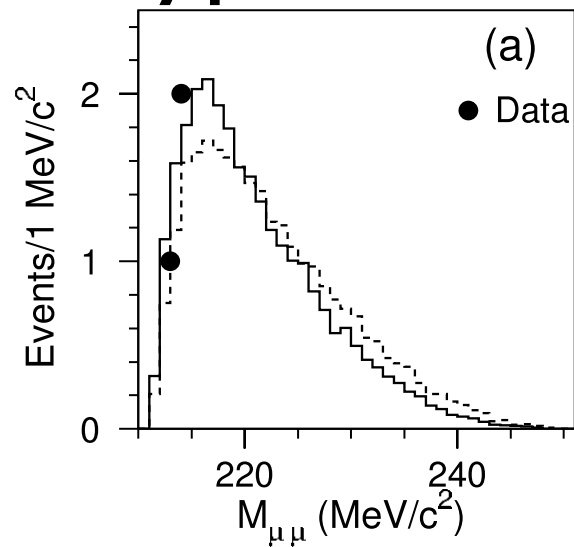
N. Leros, J.-P. Perroud
University of Lausanne, Switzerland

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 $\rightarrow 10^{10} \Sigma^+$



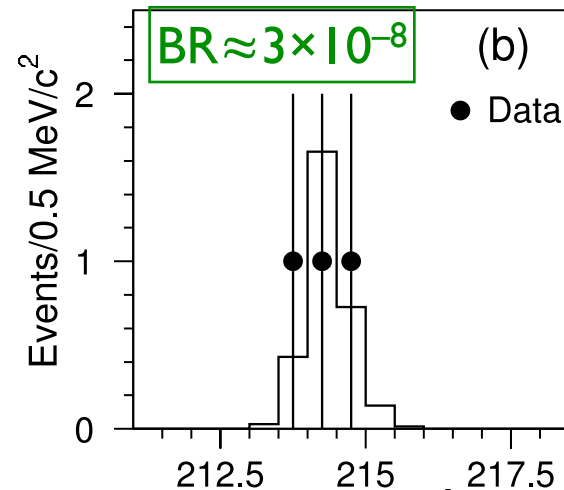
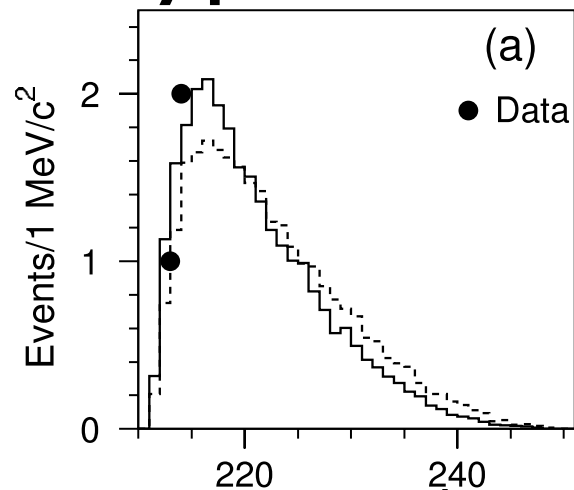
$\Sigma^+ \rightarrow p \mu^+ \mu^-$ Decay

$\approx 2.4\sigma$ fluctuation of SM? or

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

HyperCP also $\rightarrow 10^{10} \Sigma^+$

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



$\approx 2.4\sigma$ fluctuation of SM? or

- SUSY Sgoldstino?

- SUSY light Higgs?

- other pseudo-scalar or axial-vector state?

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

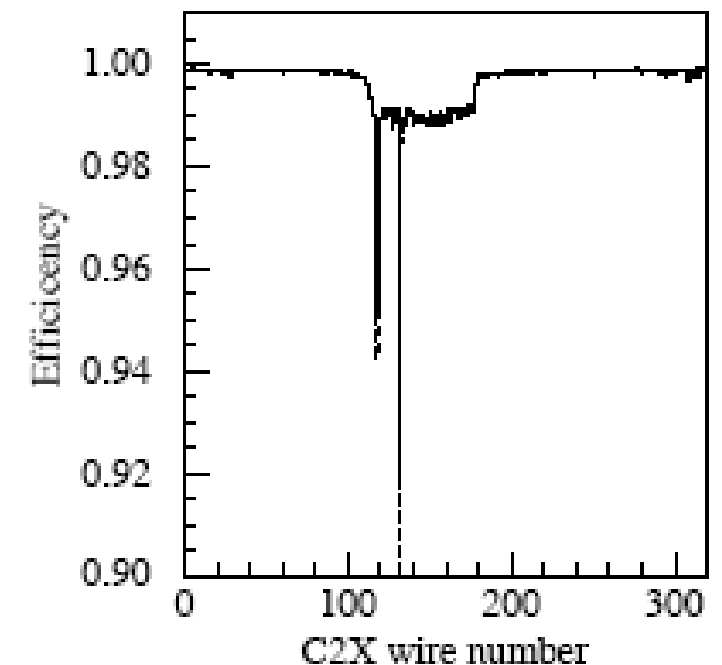
(Received 2 November 2006; published 22 February 2007)

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.

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

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

- Note: until ~2000, LEAR (CERN AD predecessor) had world's best sensitivity

➡ is $\bar{p}$ annihilation capable of further advance?

Antiproton Sources

- Fermilab Antiproton Source is world's most intense

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

Facility	$\bar{p}$	Stacking:		Operation:	
	Kinetic Energy (GeV)	Rate (10^{10} /hr)	Duty Factor	Hours /Yr	$\bar{p}$ /Yr (10^{13})
CERN AD	0.005 0.047	—	—	3800	0.4
Fermilab Accumulator:					
Tevatron Collider	8	> 25	90%	5550	> 150
proposed	$\approx 3.5\text{--}8$	20	15%	5550	17
FAIR ($\gtrsim 2018^*$)	1–14	3.5	15%*	2780*	1.5

...even after FAIR@Darmstadt turns on

➡ exceeds LEAR $\bar{p}$ intensity (< 1 MHz) by > 10 orders of magnitude!

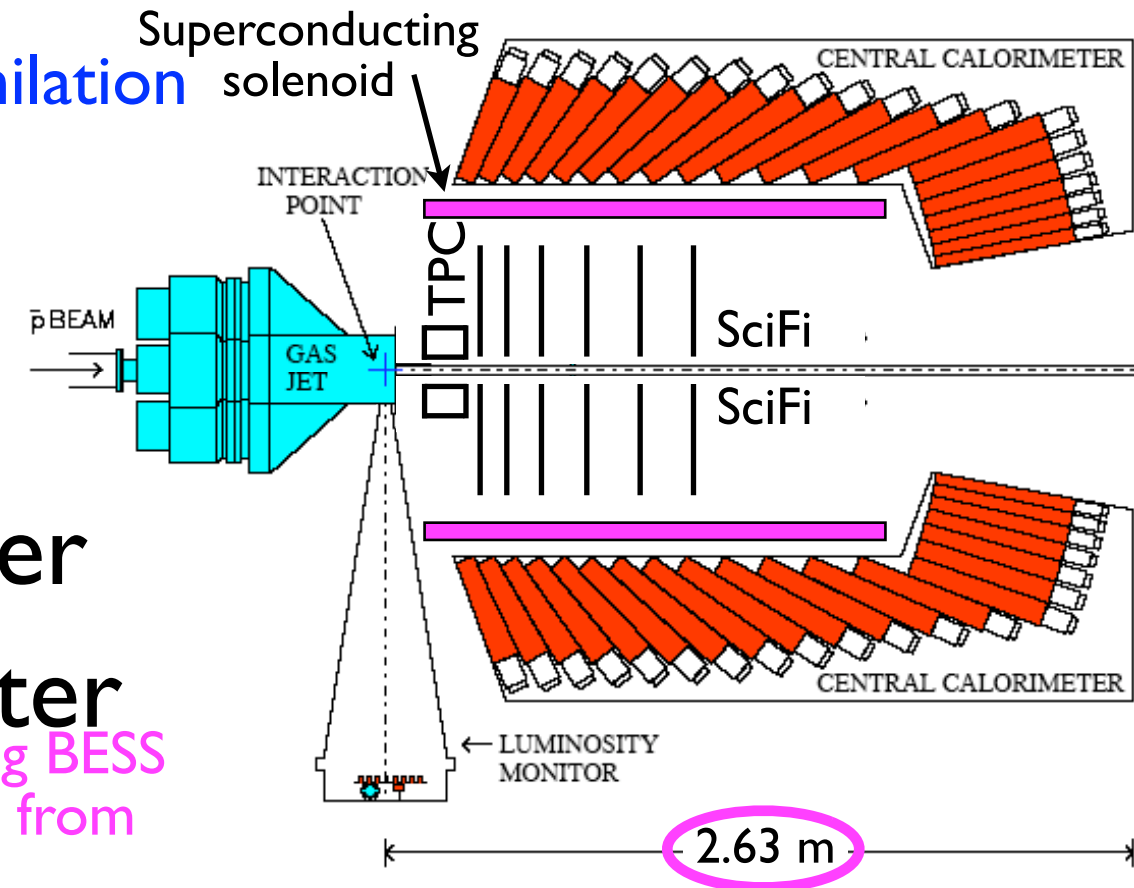
TAPAS

(The AntiProton Annihilation
Specrometer)

Our proposal:

- After Tevatron finishes,
 - Reinstall E760 barrel calorimeter
 - Add small magnetic spectrometer

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



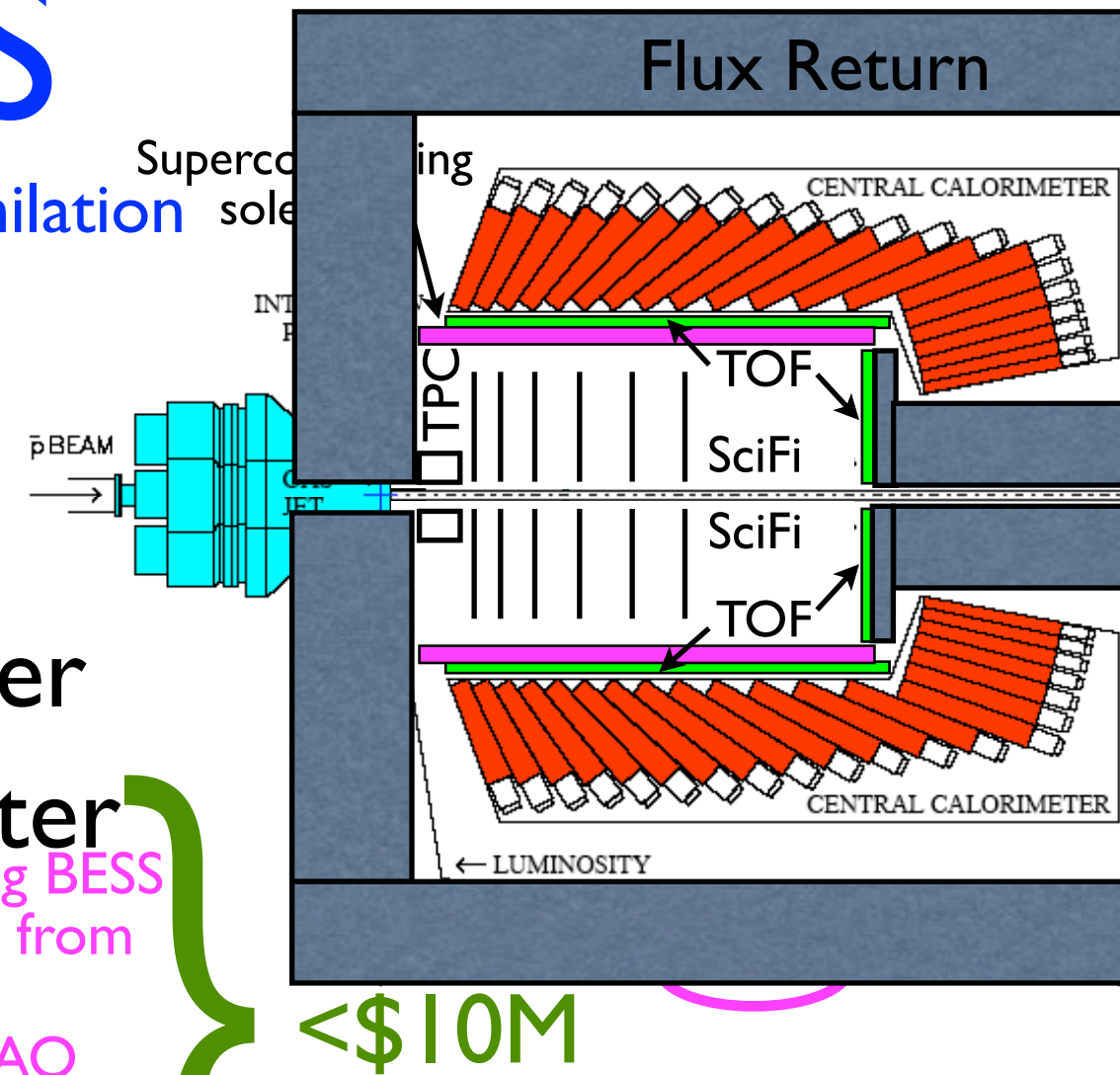
TAPAS

(The AntiProton Annihilation
Specrometer)

Our proposal:

- After Tevatron finishes,
 - Reinstall E760 barrel calorimeter
 - Add small magnetic spectrometer
 - Add precision TOF system
 - Add thin targets
 - Add fast trigger & DAQ systems
 - Run $p\bar{p} = 5.4 \text{ GeV}/c$ ($2m_\Omega < \sqrt{s} < 2m_\Omega + m_{\pi^0}$)
@ $\mathcal{L} \sim 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ ($10 \times \text{E835}$)

$\Rightarrow \sim 10^8 \Omega^- \bar{\Omega}^+/\text{yr} + \sim 10^{12}$ inclusive hyperon events!
 + possibly $\sim 10^{10} \Xi^- \bar{\Xi}^+$

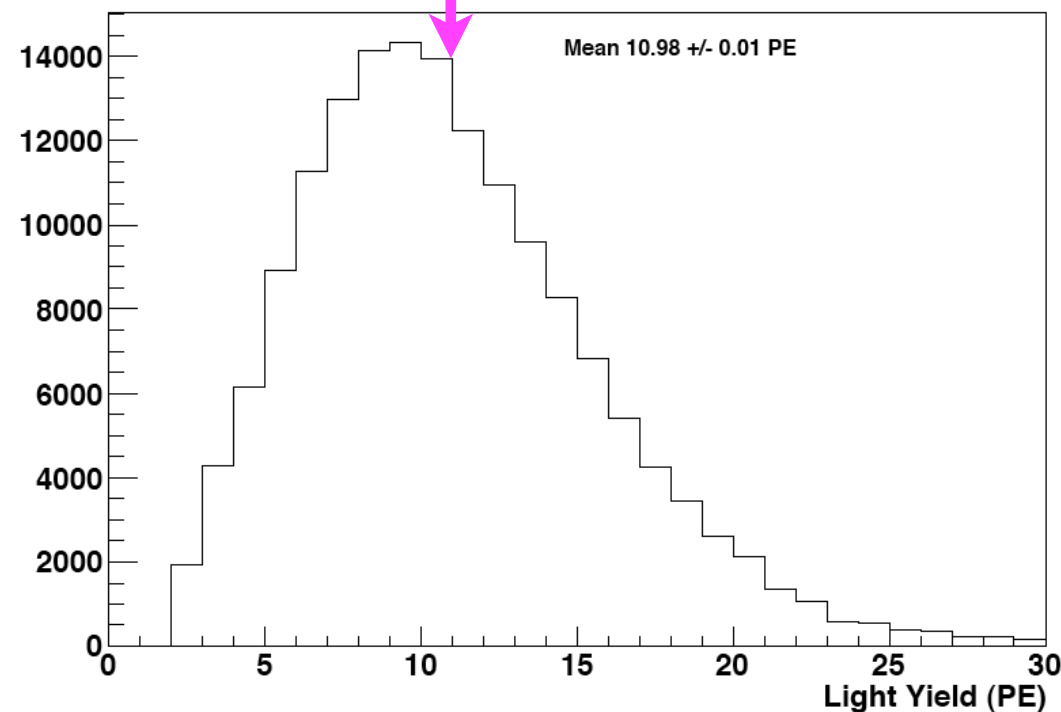


<\$10M

Fine-Pitch Scintillating Fibers

- MICE SciFi Trackers with VLPC readout
→ $\approx 85\%$ Q.E.

11 photoelectrons/m.i.p.



- 11 p.e. from 350 μm scintillating fiber

⇒ 240 μm feasible

Muon Ionization Cooling Experiment
Rutherford Appleton Lab, UK

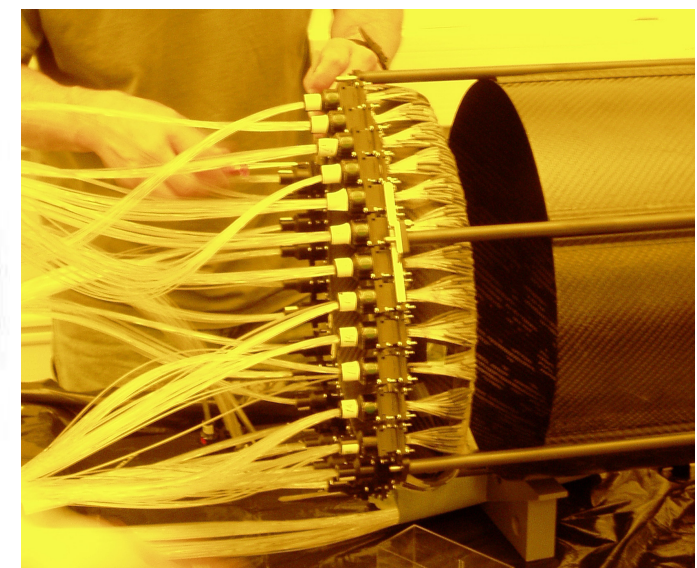
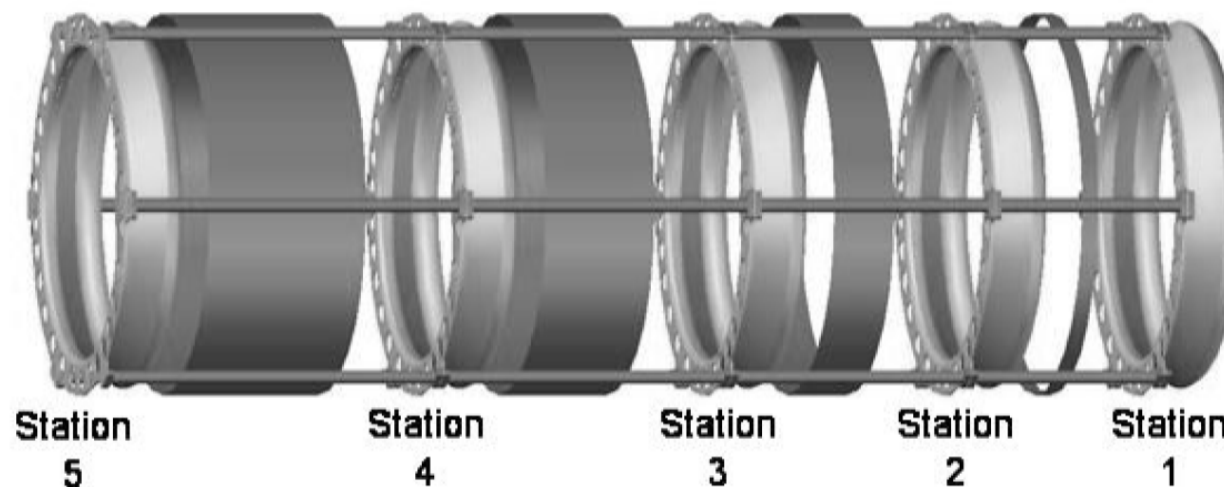


Figure 23: (left) CAD drawing of MICE tracker support frame, showing five carbon-fiber station support bodies mounted on space frame; (right) photo of carbon-fiber station support body.

Cost Estimate

- TAPAS is very cost-effective:

Item	Cost (k\$)	Contingency (k\$)
Targets	430	160
Luminosity monitor	60	20
Scintillating-fiber tracking system	1,820	610
Time-of-Flight system	500*	500
Triggering	1,390	460
Data acquisition system	490	153
Infrastructure	1,350	550
TOTALS	6,040	2,450

- Thanks to: existing calorimeter, solenoid, SciFi readout system, trigger & DAQ electronics

What Can This Do?

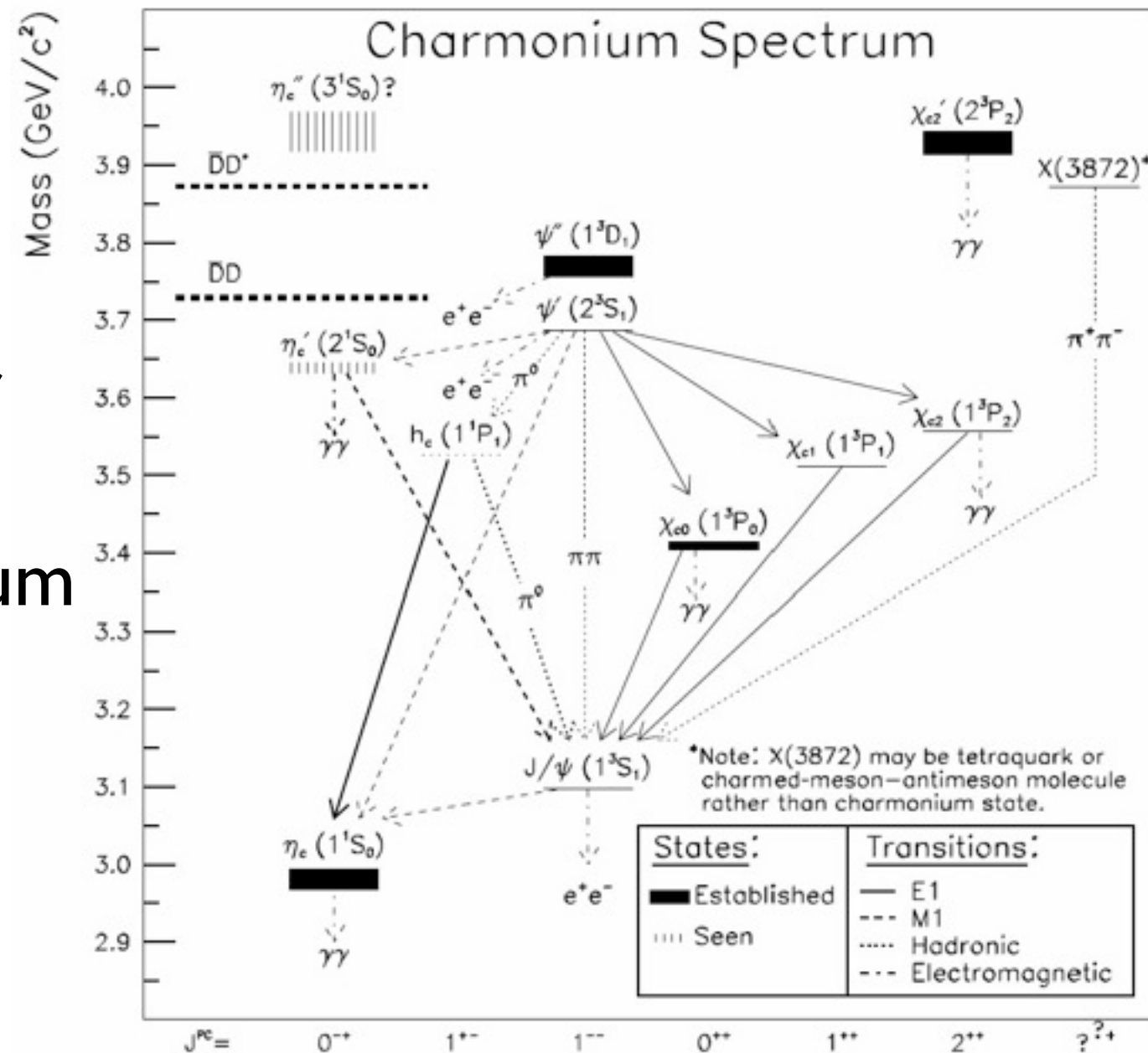
- Observe many more $\Sigma^+ \rightarrow p\mu^+\mu^-$ events and confirm or refute new-physics interpretation
- Discover or limit $\Omega^- \rightarrow \Xi^- \mu^+ \mu^-$ and confirm or refute new-physics interpretation
- Discover or limit CP violation in $\Omega^- \rightarrow \Lambda K^-$ and $\Omega^- \rightarrow \Xi^0 \pi^-$ via partial-rate asymmetries

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

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 ($\lesssim 100$ 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^-)

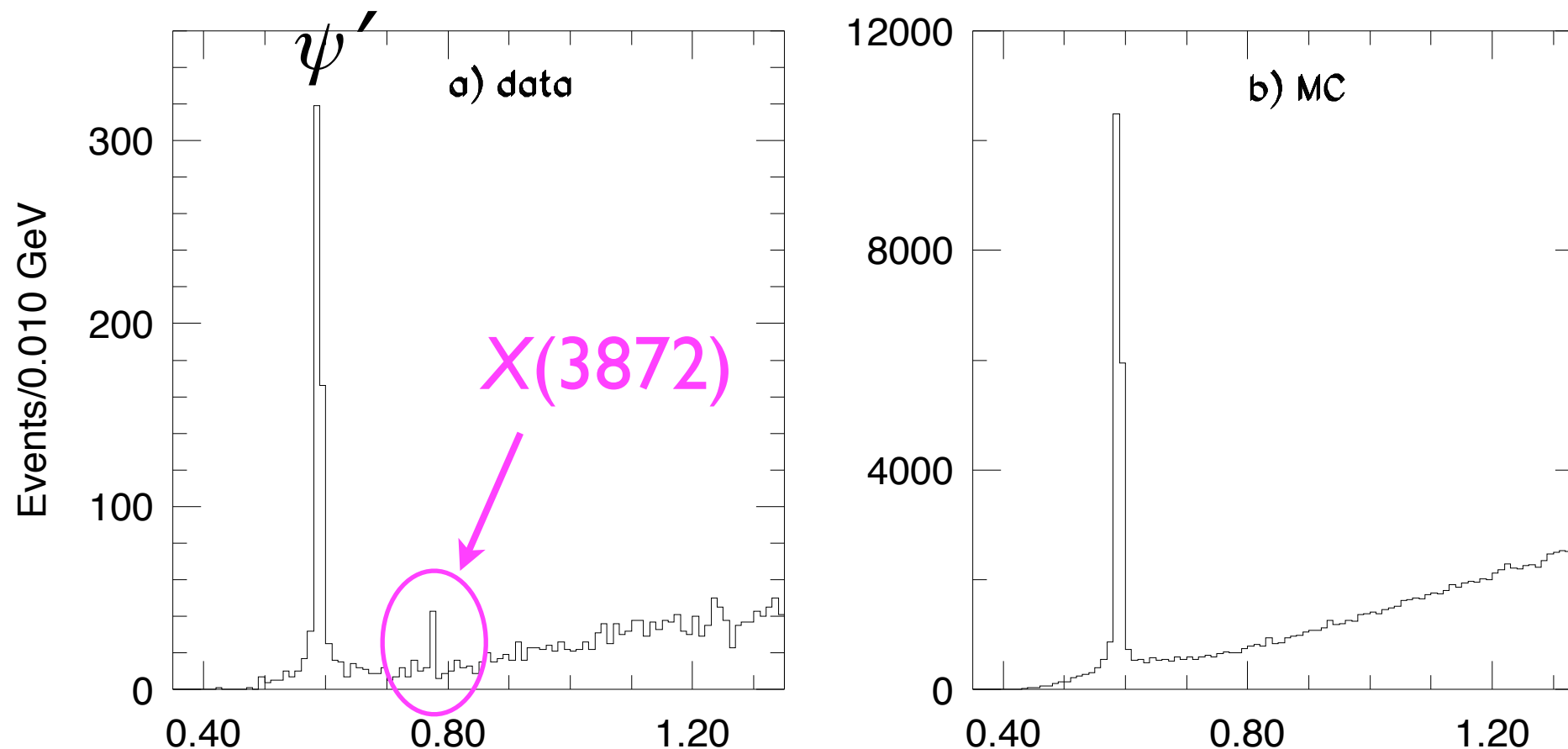


Else What Can This Do?

- 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 because it may be the first meson-antimeson ($D^0 \bar{D}^{*0} + \text{c.c.}$) molecule

Else What 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 $D^0 \bar{D}^{*0}$ threshold ($\Delta mc^2 = -0.35 \pm 0.69$ MeV)

XYZ hadronic transitions

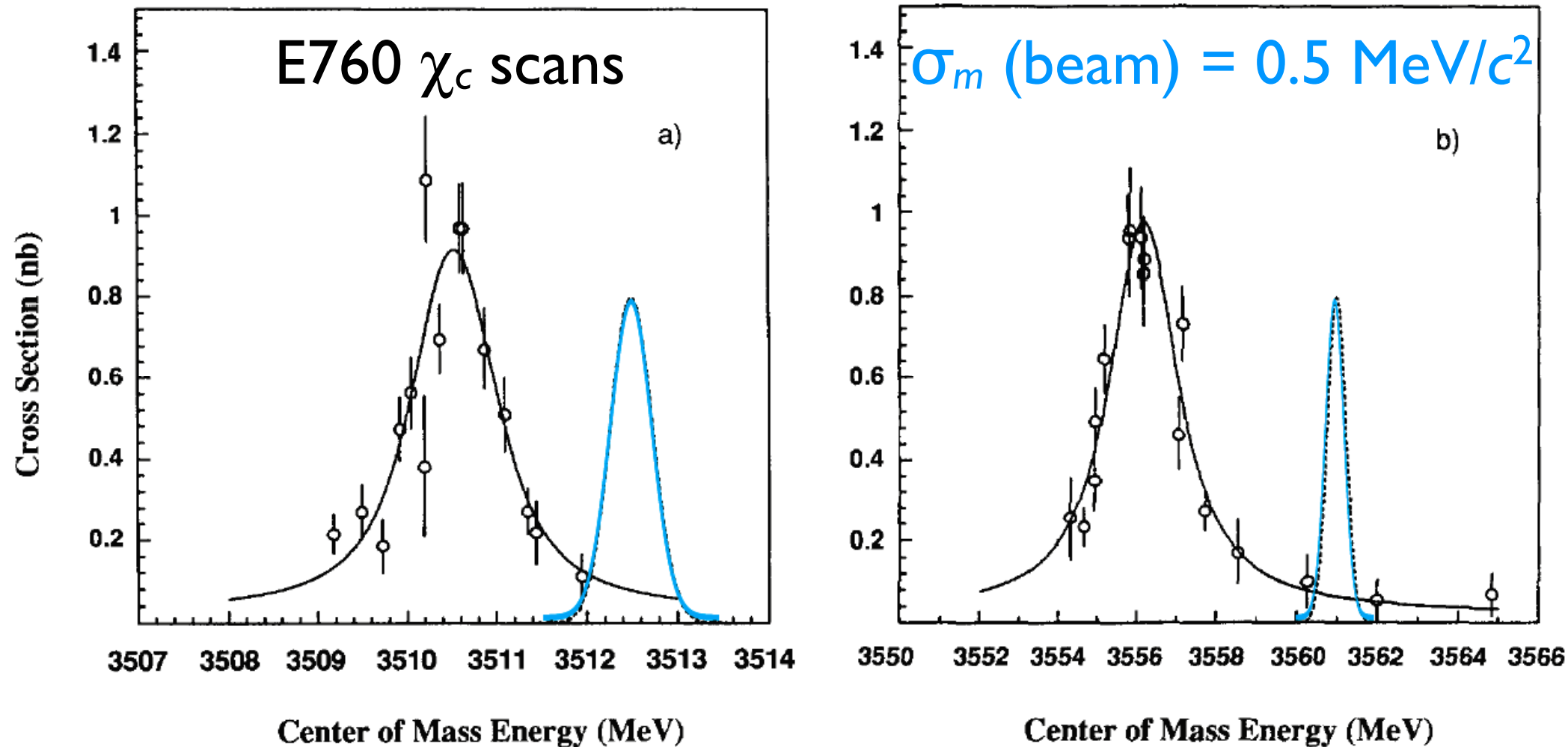
○ Many new states : ?

State	EXP	$M + i \Gamma$ (MeV)	J^{PC}	Decay Modes Observed	Production Modes Observed
X(3872)	Belle, CDF, D0, Cleo, BaBar	$3871.2 \pm 0.5 + i(<2.3)$	1^{++}	$\pi^+\pi^-J/\psi$, $\pi^+\pi^-\pi^0J/\psi$, $\Upsilon J/\psi$	B decays, $p\bar{p}$
	Belle BaBar	$3875.4 \pm 0.7^{+1.2}_{-2.0}$ $3875.6 \pm 0.7^{+1.4}_{-1.5}$		$D^0\bar{D}^0\pi^0$	B decays
Z(3930)	Belle	$3929 \pm 5 \pm 2 + i(29 \pm 10 \pm 2)$	2^{++}	$D^0\bar{D}^0$, D^+D^-	$\Upsilon\Upsilon$
Y(3940)	Belle BaBar	$3943 \pm 11 \pm 13 + i(87 \pm 22 \pm 26)$ $3914.3^{+3.8}_{-3.4} \pm 1.6 + i(33^{+12}_{-8} \pm 0.60)$	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	$4259 \pm 8^{+8}_{-6} + i(88 \pm 23^{+6}_{-4})$ $4284^{+17}_{-16} \pm 4 + i(73^{+39}_{-25} \pm 5)$ $4247 \pm 12^{+17}_{-32} + i(108 \pm 19 \pm 10)$	1^{--}	$\pi^+\pi^-J/\psi$, $\pi^0\pi^0J/\psi$, K^+K^-J/ψ	e^+e^- (ISR), e^+e^-
Y(4350)	BaBar Belle	$4324 \pm 24 + i(172 \pm 33)$ $4361 \pm 9 \pm 9 + i(74 \pm 15 \pm 10)$	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)
Z ⁺ (4430)	Belle	$4433 \pm 4 \pm 1 + i(44^{+17}_{-13}{}^{+30}_{-11})$	J^P	$\pi^+\psi(2S)$	B decays
Y(4620)	Belle	$4664 \pm 11 \pm 5 + i(48 \pm 15 \pm 3)$	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)

Else What 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 because it may be the first meson-antimeson ($D^0 \bar{D}^{*0} + \text{c.c.}$) molecule
 - ➡ need very precise mass measurement to confirm or refute
 - ➡ $\bar{p}p \rightarrow X(3872)$ formation *ideal* for this...

Example: precision $\bar{p}p$ mass & width measurements



- The beam is the spectrometer! $\rightarrow \begin{cases} \delta m(\chi_c) \approx 0.1 \pm 0.02 \text{ MeV}/c^2 \\ \delta \Gamma(\chi_c) \approx 0.1 \pm 0.01 \text{ MeV}/c^2 \end{cases}$
- The experiment is just the detector.

Else What 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 because it may be the first meson-antimeson ($D^0 \bar{D}^{*0} + \text{c.c.}$) molecule
 - ➡ need very precise mass measurement to confirm or refute
 - ➡ $\bar{p}p \rightarrow X(3872)$ formation *ideal* for this...
- Plus other XYZ, charmonium measurements, etc...

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 $p\bar{p} \rightarrow D^{*0}\bar{D}^0$ near the threshold. That cross section at an energy well above the threshold is estimated by scaling the measured cross section for $p\bar{p} \rightarrow K^{*-}K^+$. 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 $D^*\bar{D}$ molecule
- extrapolates from K^*K data

Charm!

PHYSICAL REVIEW D 77, 034019 (2008)

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

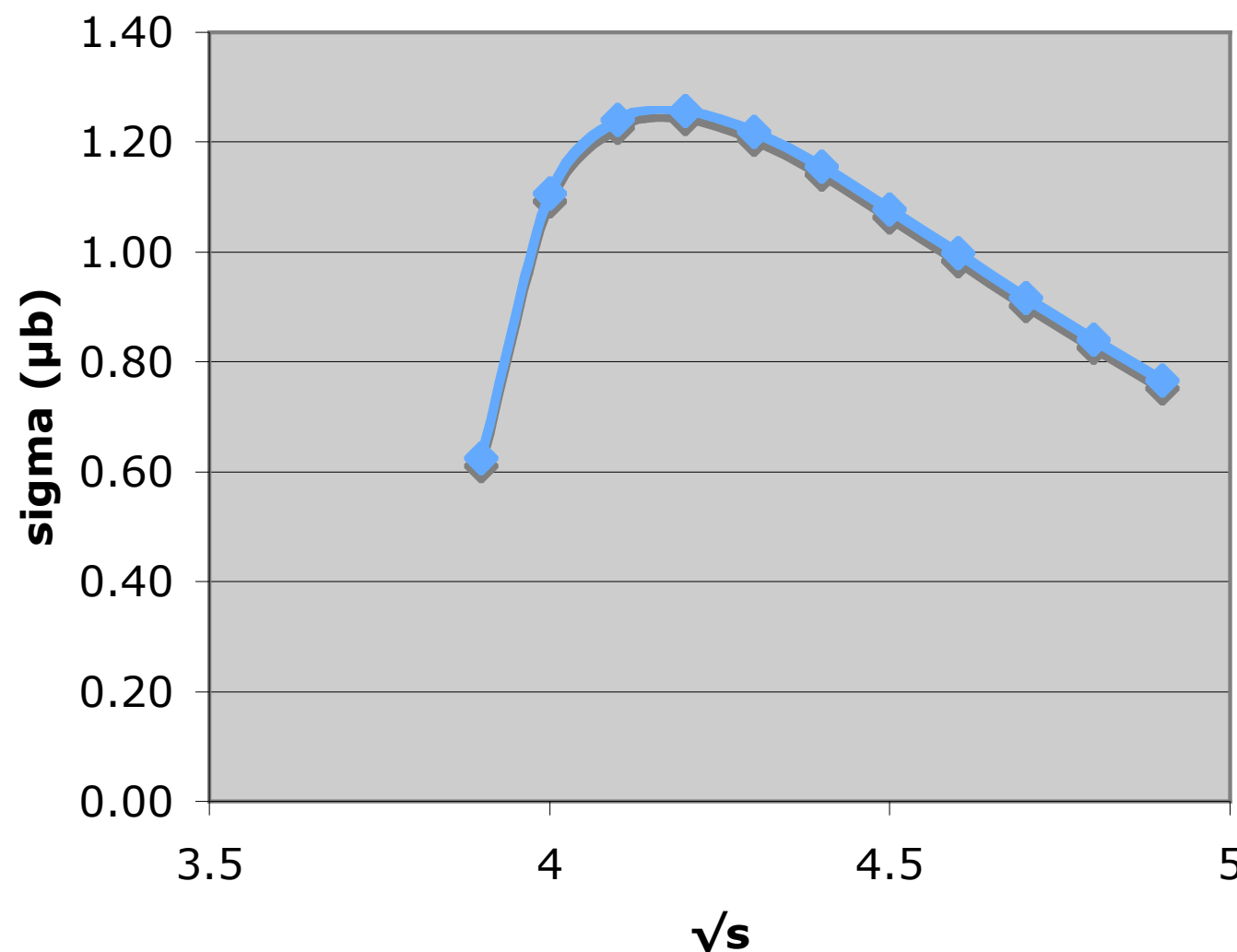
Eric Braaten

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

(Received 13 November 2007; published 25 February 2008)

$D^*\bar{D}$ cross-section estimate (after E. Braaten, PRD 77, 034019)

(Expect good to factor ~ 3)



- E. Braaten estimate of $\bar{p}p$ $X(3872)$ coupling assuming X is $D^*\bar{D}$ molecule

- extrapolates from K^*K data

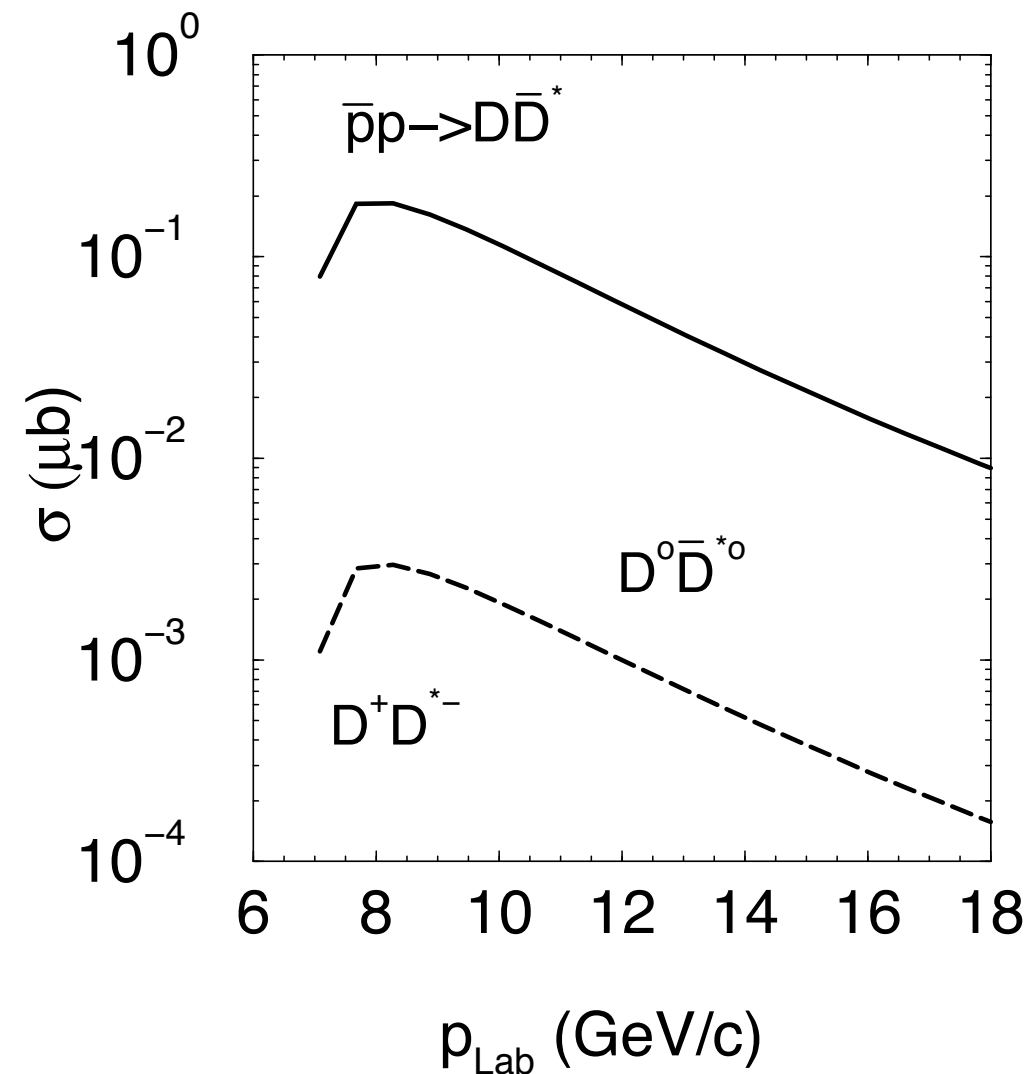
- By-product is $D^{*0}\bar{D}^0$ cross section

- $1.3 \mu\text{b} \rightarrow 5 \times 10^9/\text{year}$

- Expect efficiency as at B factories

Charm!

- Another approach (Regge model)



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

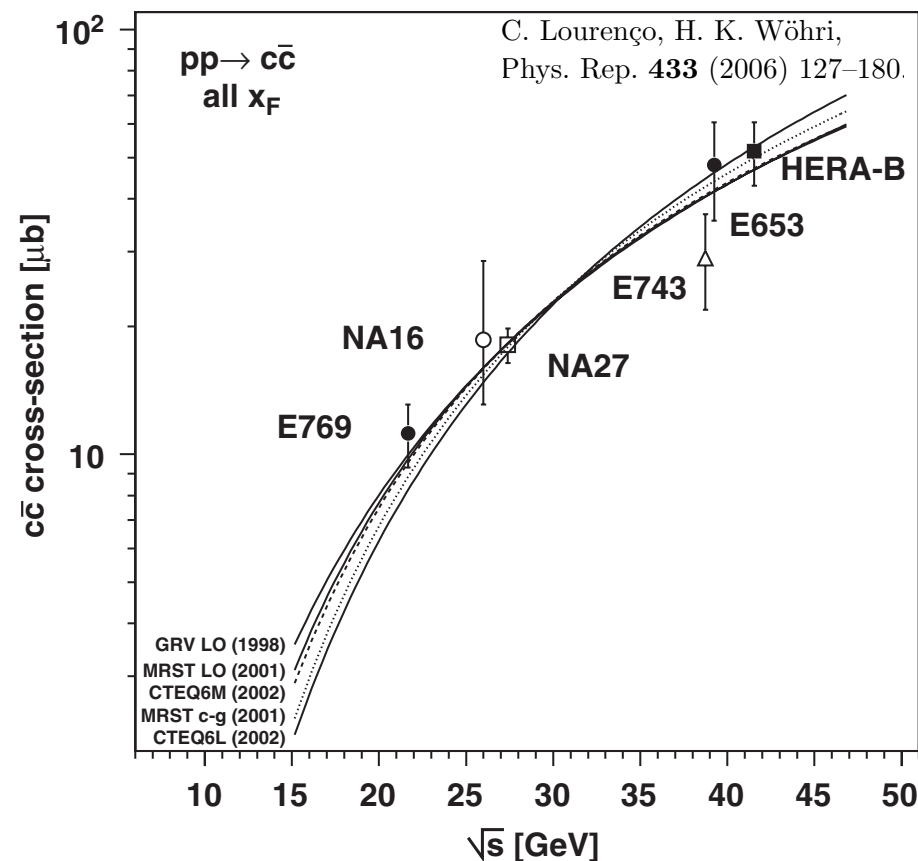
A. Titov, private communication

- Agreement within factor of 6

not bad, considering it's low-energy QCD...

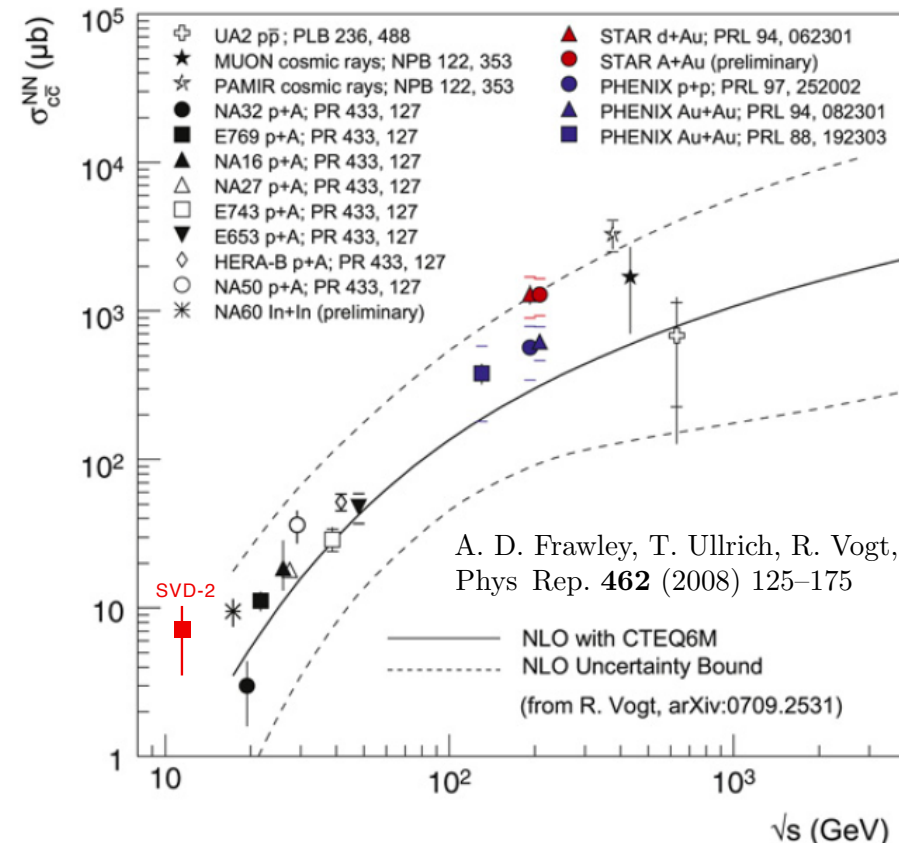
Charm!

- Other evidence?



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

⇒ Need to measure it!



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

(SVD-2 Collaboration)

A. Aleev, V. Balandin, N. Furmanec, V. Kireev, G. Lanshikov, Yu. Petukhov, T. Topuria, A. Yukaev.
Joint Institute for Nuclear Research, Dubna, Russia

E. Ardashev, A. Afonin, M. Bogolyubsky, S. Golovnia, S. Gorokhov, V. Golovkin, A. Kholodenko, A. Kiriakov, V. Konstantinov, L. Kurchaninov, G. Mitrofanov, V. Petrov, A. Pleskach, V. Riadovikov*, V. Ronjin, V. Senko, N. Shalanda, M. Soldatov, Yu. Tsyupa, A. Vorobiev, V. Yakimchuk, V. Zapolsky.
*Institute for High Energy Physics, Protvino, Russia**

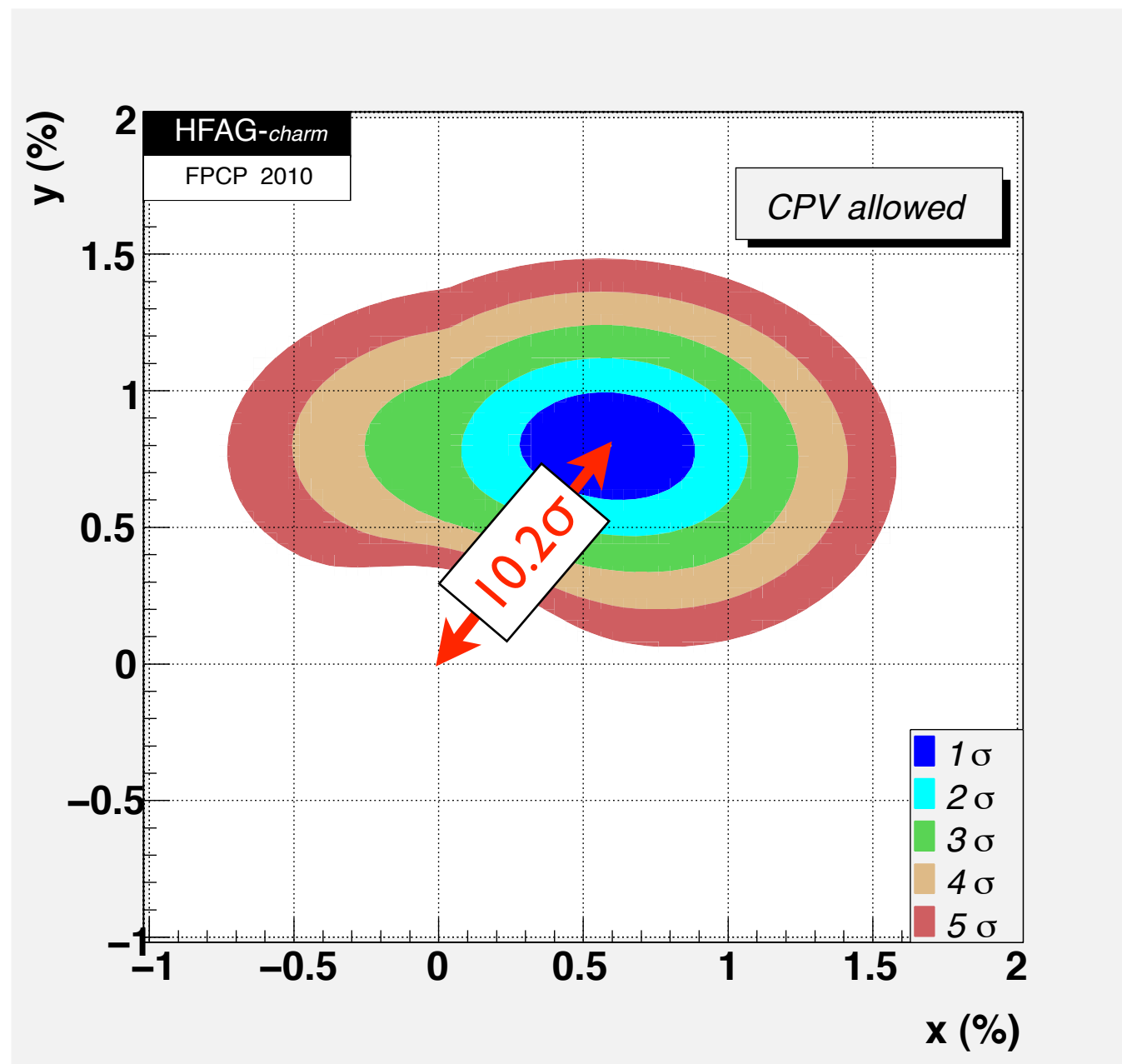
S. Basiladze, S. Berezhnev, G. Bogdanova, V. Ejov, G. Ermakov, P. Ermolov, N. Grishin, Ya. Grishkevich, D. Karmanov, V. Kramarenko, A. Kubarovsky, A. Leflat, S. Lyutov, M. Merkin, V. Popov, D. Savrina, L. Tikhonova, A. Vischnevskaya, V. Volkov, A. Voronin, S. Zotkin, D. Zotkin, E. Zverev.
D.V. Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

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 $(51 \pm 17) / (38 \pm 13)$. Registration efficiency for mesons was defined and evaluation for charm production cross section at threshold energy is presented: $\sigma(c\bar{c}) = 7.1 \pm 2.4(stat.) \pm 1.4(syst.) (\mu b/nucleon)$.

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?*

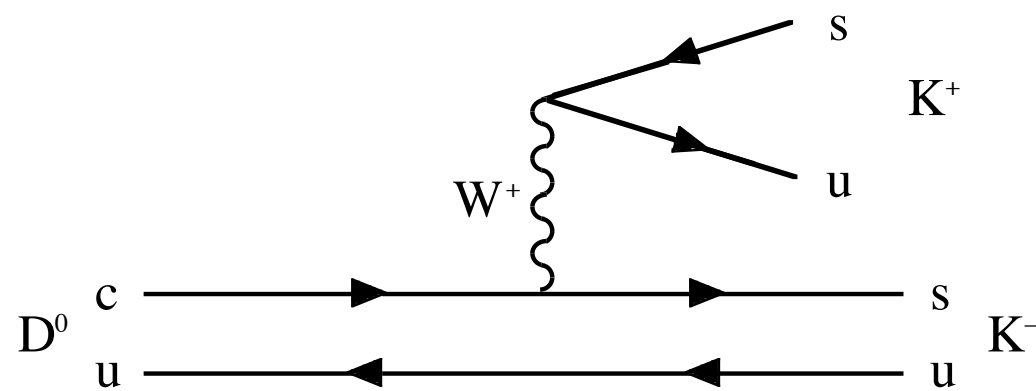
Charm!

- What's so exciting about charm?

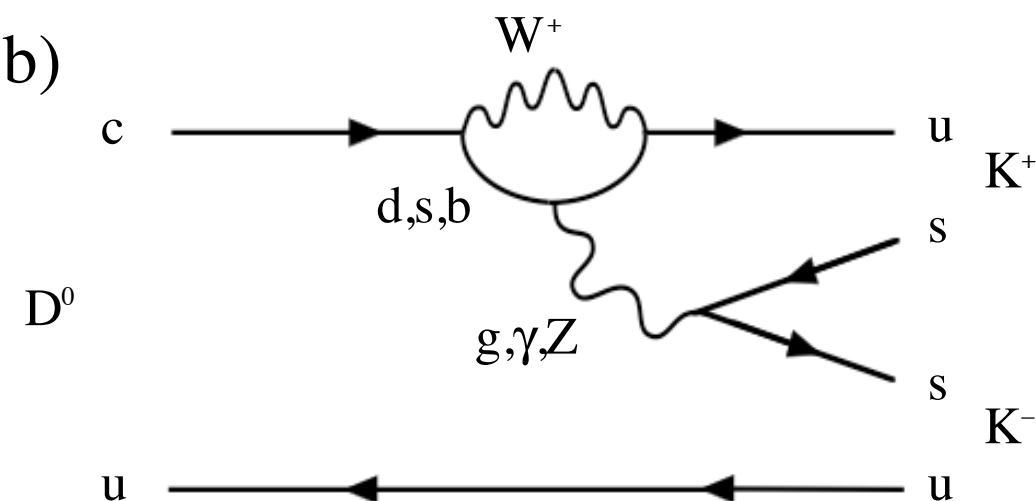
- D^0 's mix! (c is only up-type quark that can)

Singly Cabibbo-suppressed (CS) D decays have 2 competing diagrams:

a)



b)



- Big question: New Physics or old?

➡ key is CP Violation!
Possible in CF, DCS only if New Physics

- B factories have $\sim 10^9$ open-charm events

- $\bar{p}p$ may produce $> 10^{10}/y$

➡ world's best sensitivity to charm CPV

Charm!

- Ballpark sensitivity estimate based on Braaten $\bar{p}p \rightarrow D^{*0}\bar{D}^0$ formula, assuming $\sigma \propto A^{1.0}$:

Quantity	Value	Unit
Running time	2×10^7	s/yr
Duty factor	0.8*	
$\mathcal{L}$	2×10^{32}	$\text{cm}^{-2}\text{s}^{-1}$
Annual integrated $\mathcal{L}$	3.2	fb^{-1}
Target A (Ti)	47.9	
$A^{0.29}$	3.1	(based on H.E. fixed-target)
$\sigma(\bar{p}p \rightarrow D^{*+} + \text{anything})$	1.25–4.5	μb
# $D^{*\pm}$ produced	$0.3\text{--}3 \times 10^{11}$	events/yr
$\mathcal{B}(D^{*+} \rightarrow D^0\pi^+)$	0.677	
$\mathcal{B}(D^0 \rightarrow K^-\pi^+)$	0.0389	
Acceptance	0.45	(signal MC)
Efficiency	0.1–0.3	(MIPP & bkg MC)
Total	$0.3\text{--}3 \times 10^8$	tagged events/yr

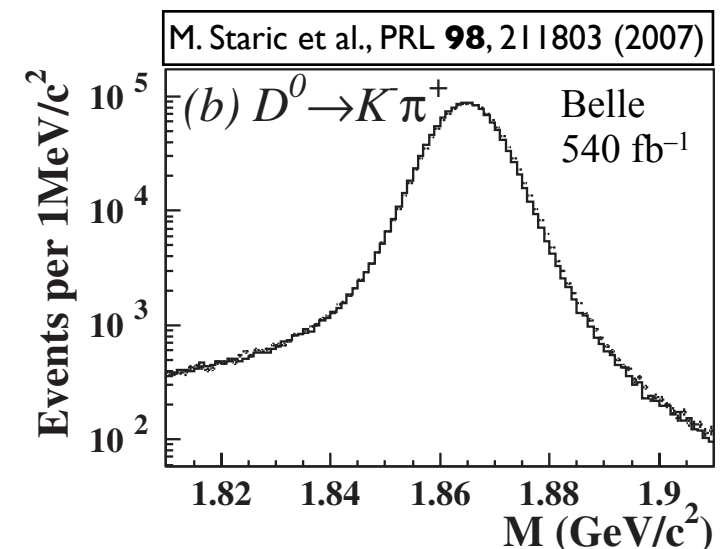
* Assumes $\approx 15\%$ of running time is devoted to antiproton-beam stacking.

- Such subtle effects as charm CPV will require independent confirmation

– LHCb: similar statistics? but different, significant, systematics

– Competitive with projected ca. 2021 SuperKEKB (is SuperB?)

- Cf. 1.22×10^6 total tagged events at Belle:



Charm!

- Another possibility (E. Braaten): use the $X(3872)$ as a pure source of correlated $D^{*0}\bar{D}^0$ events
 - the $\bar{p}p$ equivalent of the $\psi(3770)$!?
 - assuming current Antiproton Accumulator parameters ($\Delta p/p$) & Braaten estimate, produce $\sim 10^8$ events/year
 - comparable to BES-III statistics
 - could gain factor ~ 5 via AA e^- cooling?
- Proposed expt will establish feasibility & reach

Breadth of Program

- Partial list of physics papers/thesis topics:

General	
1	Particle multiplicities in medium-energy pbar-p collisions
2	Particle multiplicities in medium-energy pbar-N collisions
3	Total cross section for medium-energy pbar-p collisions
4	Total cross section for medium-energy pbar-N collisions
Charm	
5	Production of charm in medium-energy pbar-p collisions
6	Production of charm in medium-energy pbar-N collisions
7	A-dependence of charm production in medium-energy pbar-N collisions
8	Associated production of charm baryons in medium-energy pbar-N collisions
9	Production of charm baryon-antibaryon pairs in medium-energy pbar-N collisions
10	Measurement of D0 mixing in medium-energy pbar-N collisions
11	Search for/Observation of CP violation in D0 mixing
12	Search for/Observation of CP violation in D0 decays
13	Search for/Observation of CP violation in charged-D decays
Hyperons	
14	Production of Lambda hyperons in medium-energy pbar-p collisions
15	Production of Sigma0 in medium-energy pbar-p collisions
16	Production of Sigma- in medium-energy pbar-p collisions
17	Production of Xi- in medium-energy pbar-p collisions
18	Production of Xi0 in medium-energy pbar-p collisions

19	Production of Omega- in medium-energy pbar-p collisions
20	Production of Lambda Lambdabar pairs in medium-energy pbar-p collisions
21	Production of Sigma+ Sigmabar- pairs in medium-energy pbar-p collisions
22	Production of Xi- Xibar+ pairs in medium-energy pbar-p collisions
23	Production of Omega- Omegabar+ pairs in medium-energy pbar-p collisions
24	Rare decays of Sigma+
25	Rare decays of Xi-
26	Rare decays of Xi0
27	Rare decays of Omega-
28	Search for/Observation of CP violation in Omega- decay
Charmonium	
29	Production of X(3872) in medium-energy pbar-p collisions
30	Precision measurement of X(3872) mass, lineshape, and width
31	Decay modes of X(3872)
32	Limits on rare decays of X(3872)
33	Production of other XYZ states in medium-energy pbar-p collisions
34	Precision measurement of the eta_c mass, line shape and width
35	Precision measurement of the h_c mass, line shape and width
36	Precision measurement of the eta_c' mass, line shape and width
37	Complementary scans of J/psi and psi'
38	Precise determination of the chi_c COG
39	Production of J/psi and Chi_cJ in association with pseudoscalar meson(s)

- TAPAS could maintain hadron physics at post-Tevatron Fermilab, multiplying physics output several-fold

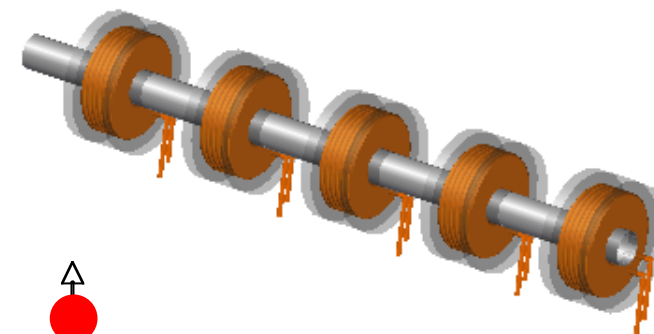
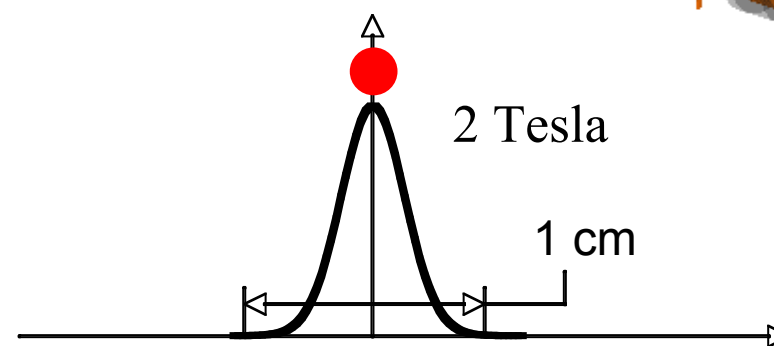
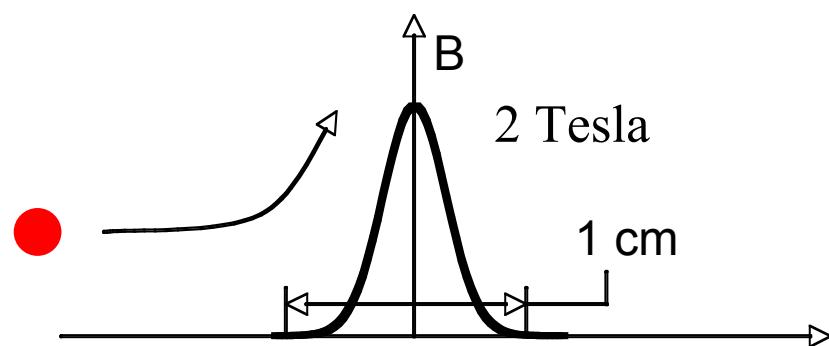
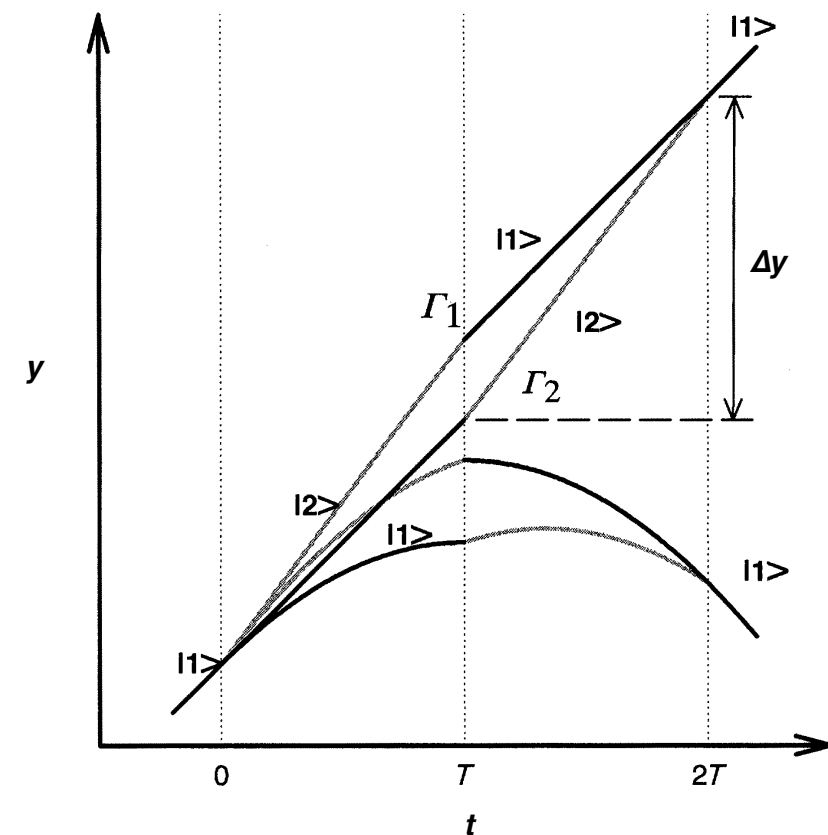
...and **now**
for *something*
completely different!

Antihydrogen

- Possible spectroscopy measurements on $\bar{\text{H}}$ in flight produced by $\bar{p}$ beam halo in material
 - hope for $\sim 10^{-9}$ sensitivity
 - parasitic on antiproton running in Accumulator
 - Au-plated C foil installed in Accumulator for tests
- Fermilab Proposal 981: Letter of Intent for Antimatter Gravity Experiment (AGE)
 - make slow ($\sim 10^3$ m/s) $\bar{\text{H}}$ beam with Penning trap
 - measure its rate of fall in atom interferometer
 - $\sim 10^{-9}$ sensitivity possible with laser interferometry

Antimatter Gravity

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



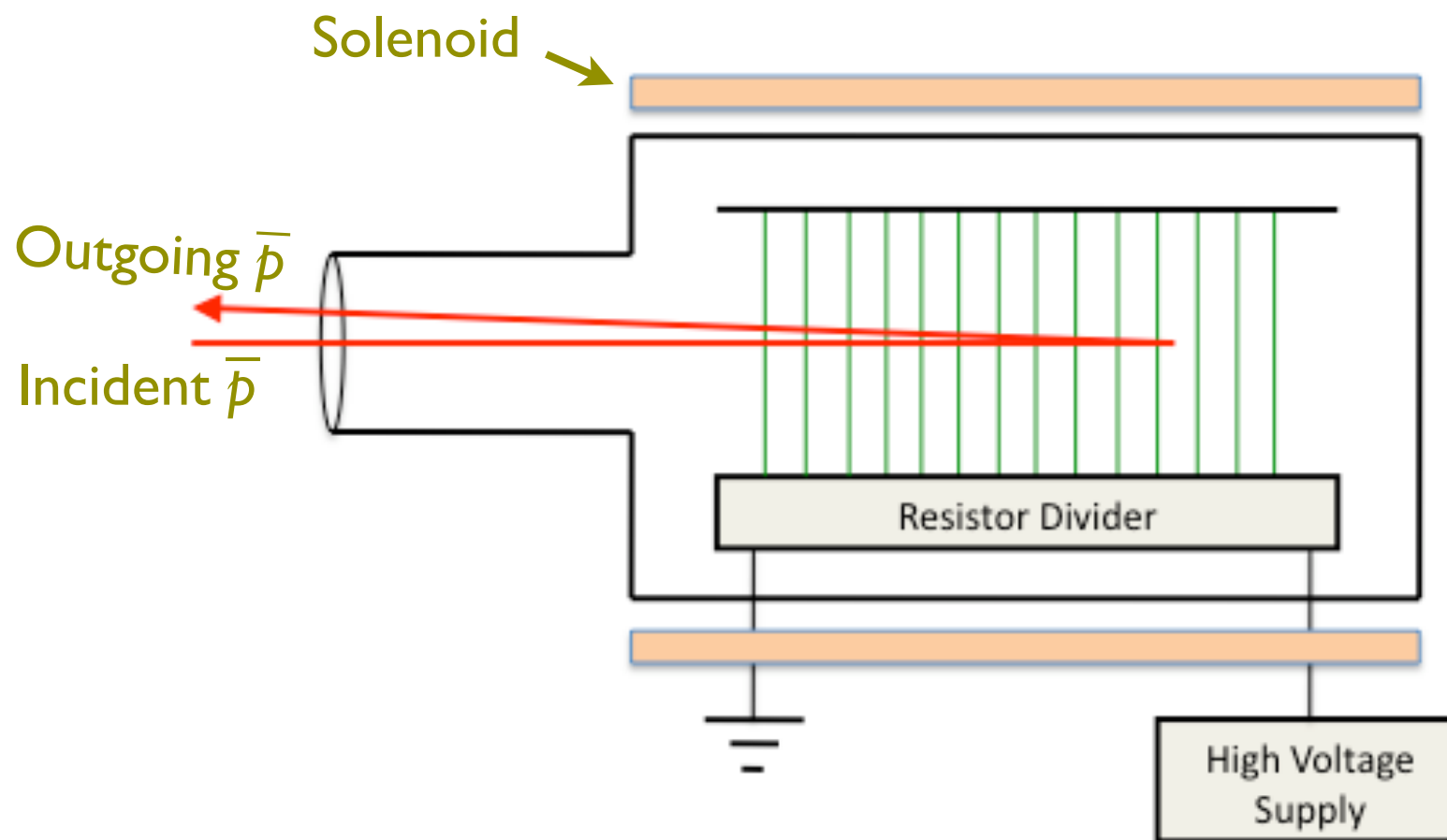
- estimate $10^{-9} \bar{g}$ measurement feasible

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 $\sim$ month’s dedicated running
 - eventually, add small synchrotron $\rightarrow$ effic. ~ 1
- Requires completion of antiproton deceleration/extraction facility planned for Hbar Technologies

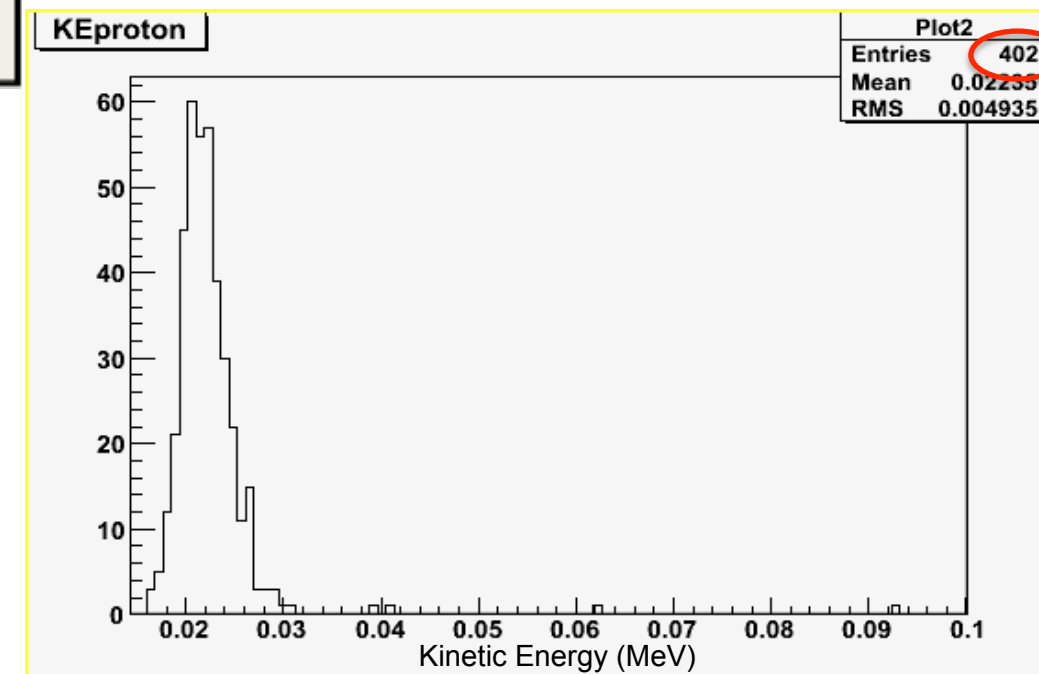
Particle Refrigerator

- 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 with $\approx 40\%$ effic. @ equilb. energy
- $KE_{in} < \approx \text{few MeV}, KE_{out} \approx 20 \text{ keV}$



Antiproton Source Futures

- Tevatron Collider ending September 2011, many at FNAL view Antiproton Source as generic resource:
 - 2 large-acceptance 8 GeV rings
 - can they be reconfigured to enable $g - 2$, $\mu 2e$, 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??

Antiproton Source Futures

- Nevertheless, $\mu 2e$ will likely eliminate FNAL pbar option around 2017
 - leaves 4–5-year window of opportunity during which FNAL $\bar{p}$ capabilities are unique in the world!
 - Note: g – 2 plan is to use Debuncher all the time, as $\pi \rightarrow \mu$ decay channel, but Accumulator never
 - Antiproton fixed-target requires Accumulator all the time, Debuncher only a couple of hours/day
- ➡ technically, $\bar{p}$ and g – 2 are compatible uses

Letters of Intent

P-986 Letter of Intent: Medium-Energy Antiproton Physics at Fermilab

David M. Asner
Carleton University, Ottawa, 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

U. Pisa HEP Seminar

Letters of Intent

Proposal 986:

Medium-Energy Antiproton Physics with The Antiproton Annihilation Spectrometer (TApAS*) at Fermilab

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

Larry Bartoszek

Bartoszek Engineering, Aurora, IL 60506, USA

Giovanni M. Piacentino

University of Cassino, Cassino, Italy

Thomas J. Phillips

Duke University, Durham, North Carolina 27708, USA

Giorgio Apollinari, Daniel R. Broemmelsiek, Charles N. Brown, David C. Christian,
Paul Derwent, Keith Gollwitzer, Alan Hahn, Vaia Papadimitriou, Giulio Stancari,
Michelle Stancari, Ray Stefanski, James T. Volk, Steven Werkema, William Wester,
Herman B. White, G. P. Yeh

Fermilab, Batavia, Illinois 60510, USA

Wander Baldini

INFN, Sezione di Ferrara, Ferrara, Italy

Gerald P. Jackson

Hbar Technologies, LLC, West Chicago, Illinois 60185, USA

Kwong Lau

University of Houston, Houston, TX 77004, USA

Daniel M. Kaplan,¹ Yagmur Torun, Christopher G. White
Illinois Institute of Technology, Chicago, Illinois 60616, USA

Anjan Giri

Indian Institute of Technology, Hyderabad, India

Alexey Drutskoy

Institute for Theoretical and Experimental Physics, RU-117259 Moscow, Russia

HyangKyu Park

KyungPook National University, DaeGu, Korea

Olga Piskunova

Lebedev Physical Institute, RU-117924 Moscow, Russia

Timothy Holmstrom

Longwood University, Farmville, Virginia 23909, USA . . .

Letters of Intent

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. Roberts¹, 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

- 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

- Letters of Intent presented in '09, TAPAS Proposal (P986) in 2010
- 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
 - ▶ Seeking new collaborators, non-DOE resources

Summary

- Best experiment ever on hyperons, charm, and charmonia may soon become feasible at Fermilab
 - with possibly world's most sensitive charm CPV study
 - opportunity for useful measurements
+ possibility of breakthroughs
- But Fermilab not yet convinced
 - due to perceived weakness of collaboration
- ▶ pbar Source offers simple way to have broad Fermilab program in post-Tevatron era
- ▶ Can't we capitalize on this opportunity?
- ➡ **You can help!! Want to join?**
(Talk to me; see <http://capp.iit.edu/hep/pbar/>)