New Experiments with Antiprotons

Daniel M. Kaplan

ILLINOIS INSTITUTE OF TECHNOLOGY

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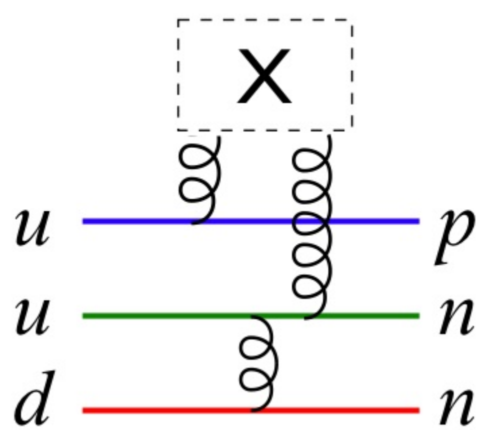

P-25 Physics Seminar

Los Alamos National Laboratory

29 August 2011

Outline

Varied menu!

- Baryogenesis and CP violation
- Hyperon CP violation
- Low-energy antiprotons
- A new experiment
- Charm & charmonium
- $\bar{p}$ Drell-Yan
- 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, LHCb]

(Hence Kobayashi & Maskawa 2008 Nobel prize)

CP Violation

- CPV already discovered in 1964: small effect in
  mixing & decay
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    mechanism: non-zero phas
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  - ➡ if … phase, should be large … ty particles!
- … rved in B-meson decays as well [BaBar … , CDF, DØ, LHCb]
- (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 3.9σ 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

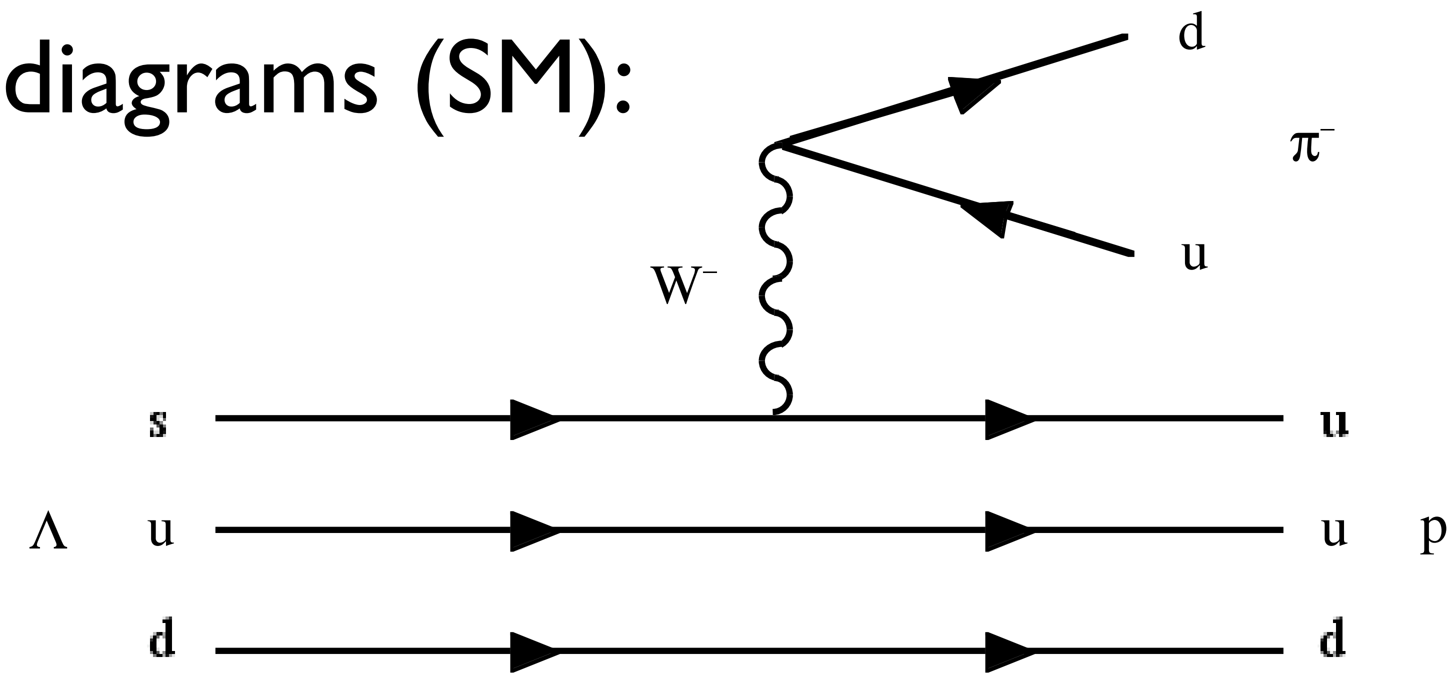
Thus in hyperon decay, $\bar{\alpha} \neq -\alpha$ implies *CP* violation in this process independent of the validity of the *CPT* theorem. This is also true if $\bar{\beta} \neq -\beta$.

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.

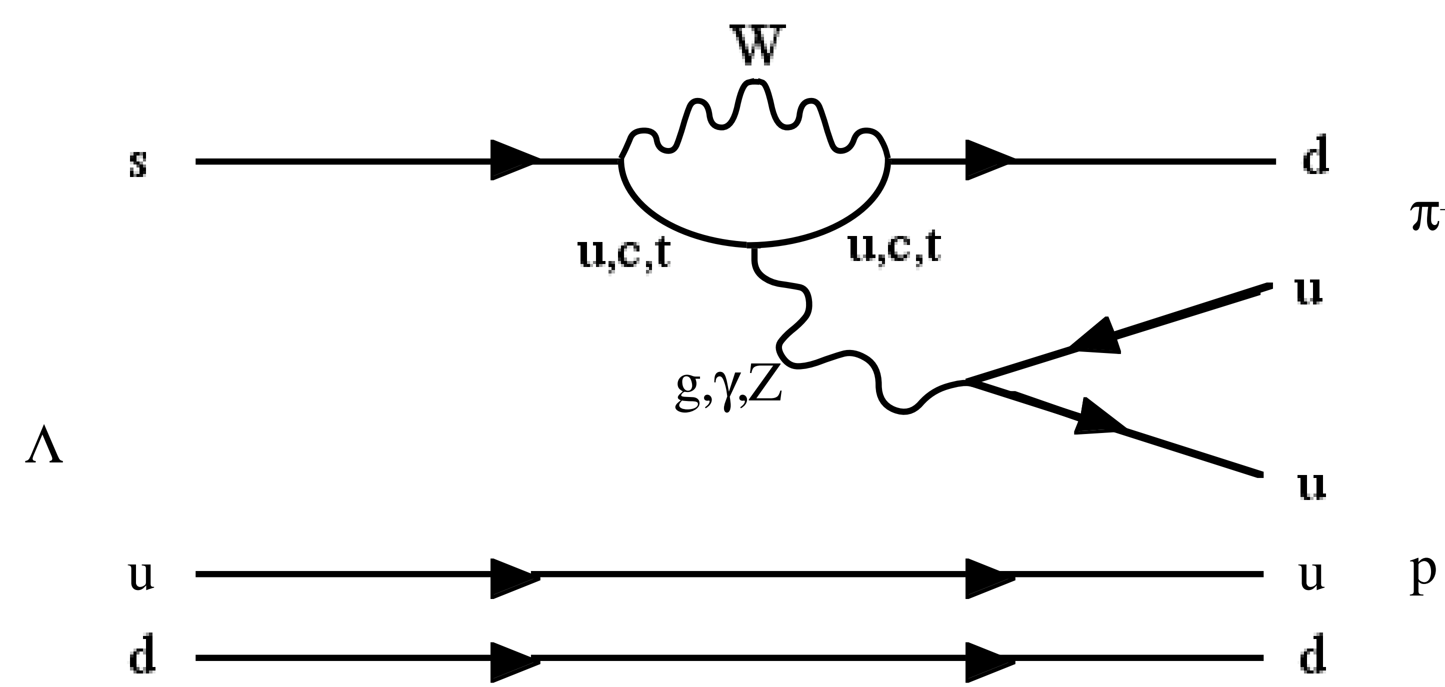
Hyperon CP Violation

- 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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  - e.g., decay of polarized Lambda hyperons:

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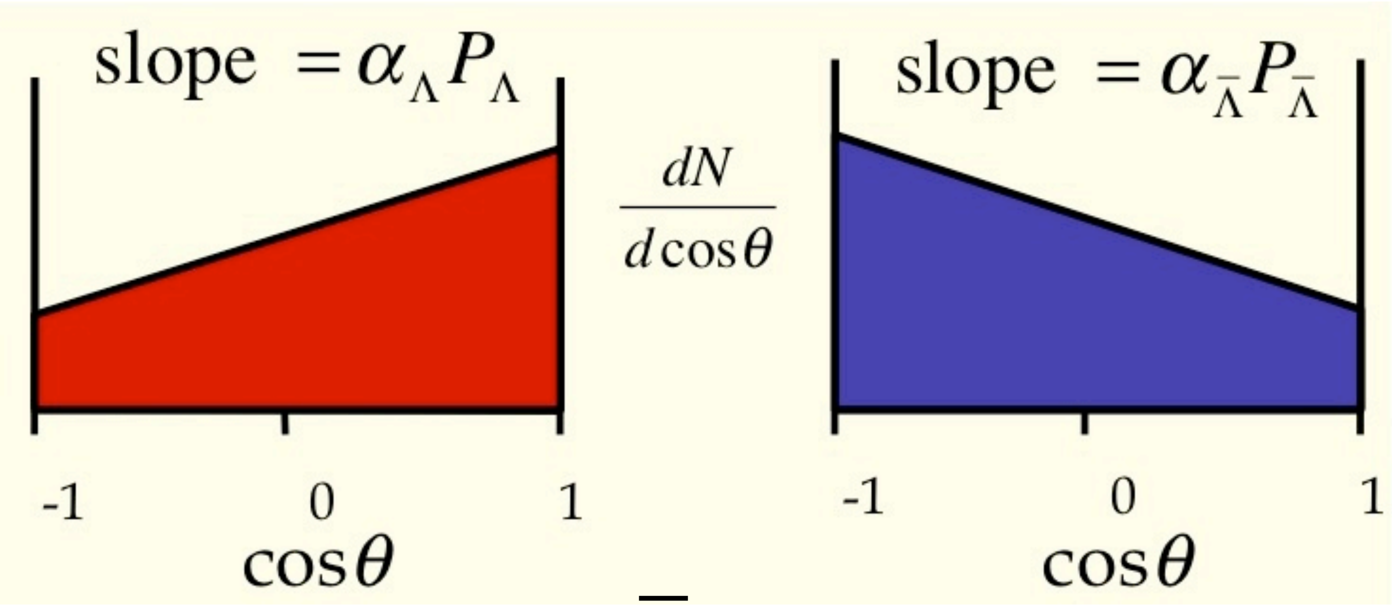
⟶ nonuniform proton angular distribution in Λ rest frame:

$\Lambda \to p\pi^-$



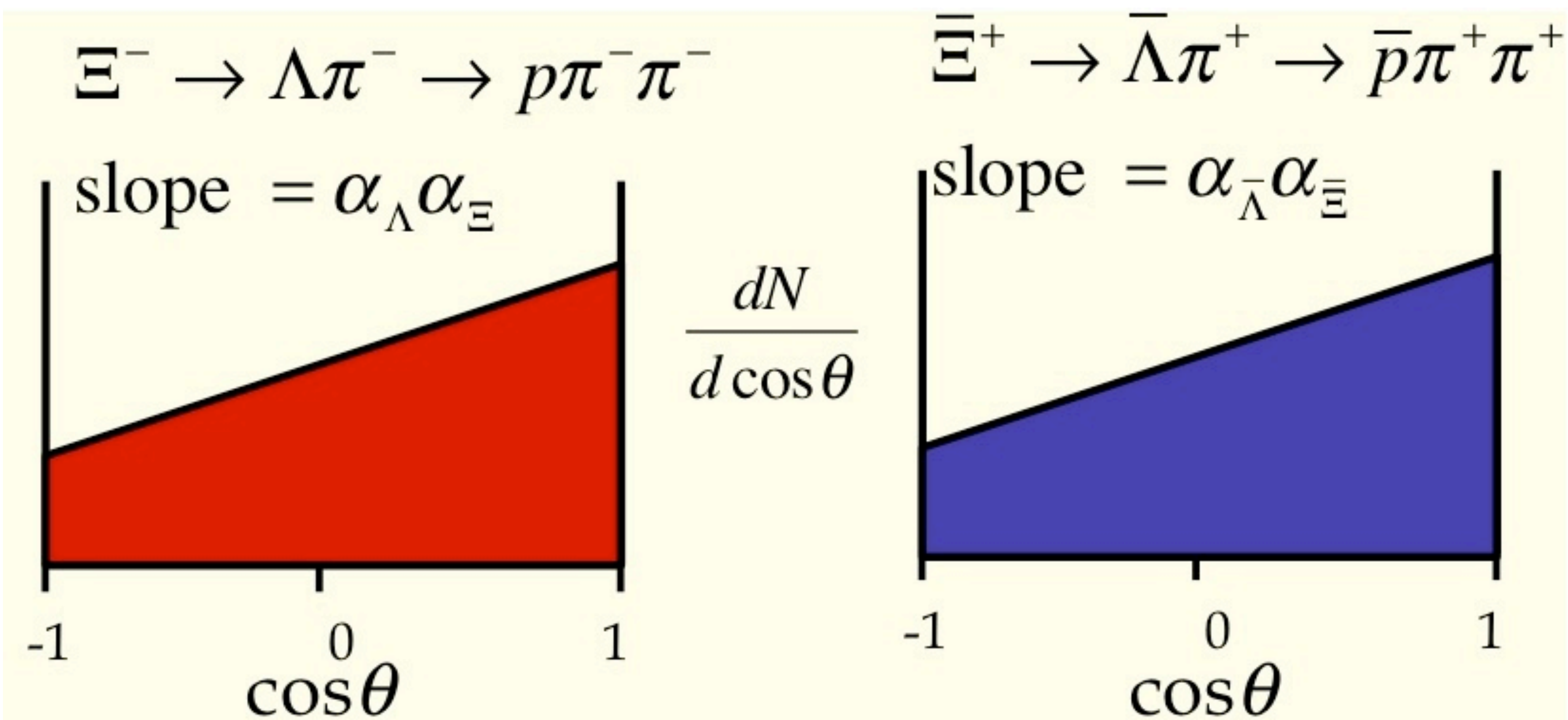
$\bar{\Lambda} \to \bar{p}\pi^+$

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

Hyperon CP Violation

- 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

- 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	$\Lambda \to p\pi$	$\lesssim 10^{-5}$	$\lesssim 6 \times 10^{-4}$	[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 $\pm$ 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; PRL in prep]

Hyperon CP Violation

- Measurement history:

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R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$	-0.0
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	0.0
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	0.0

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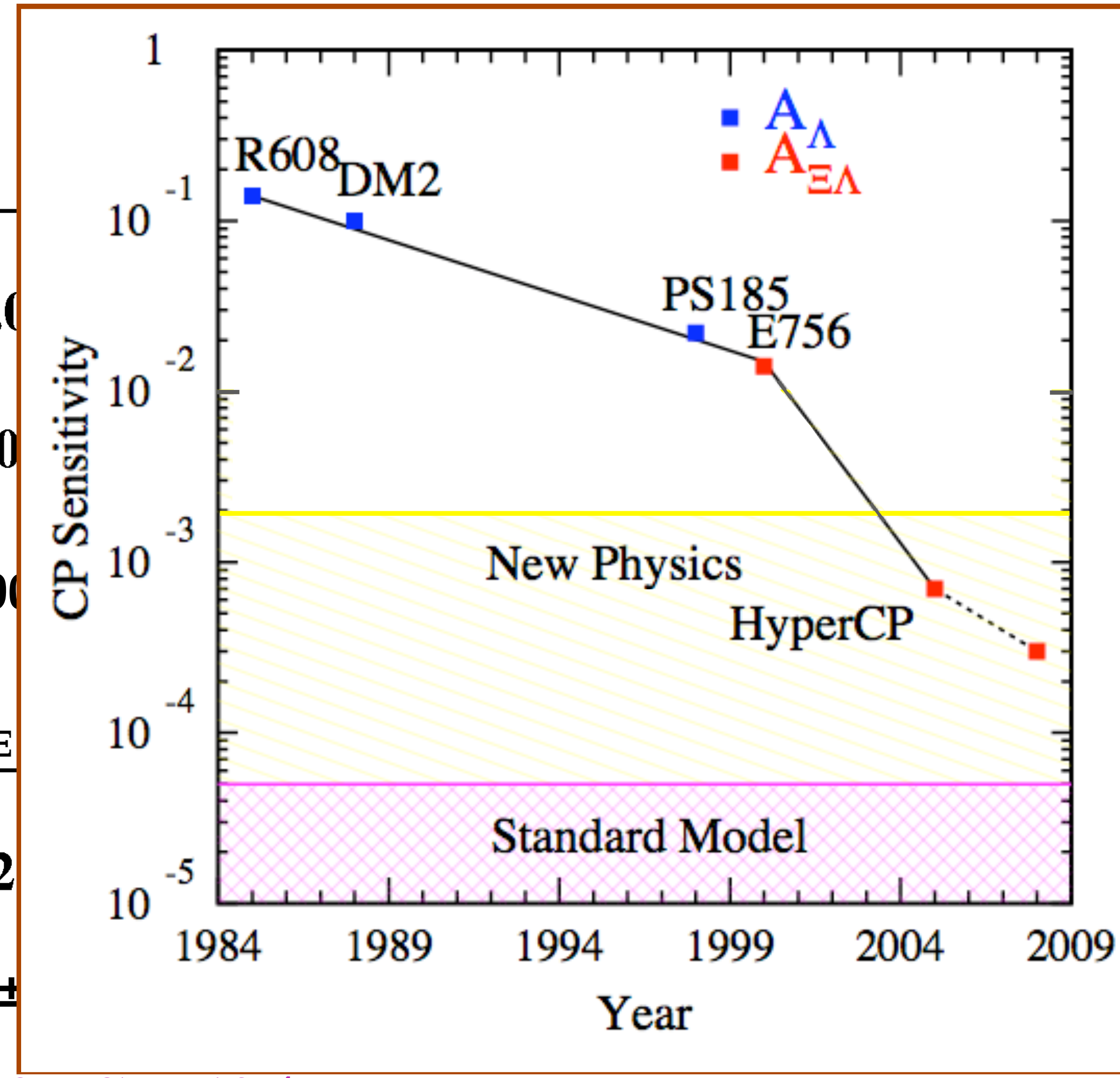
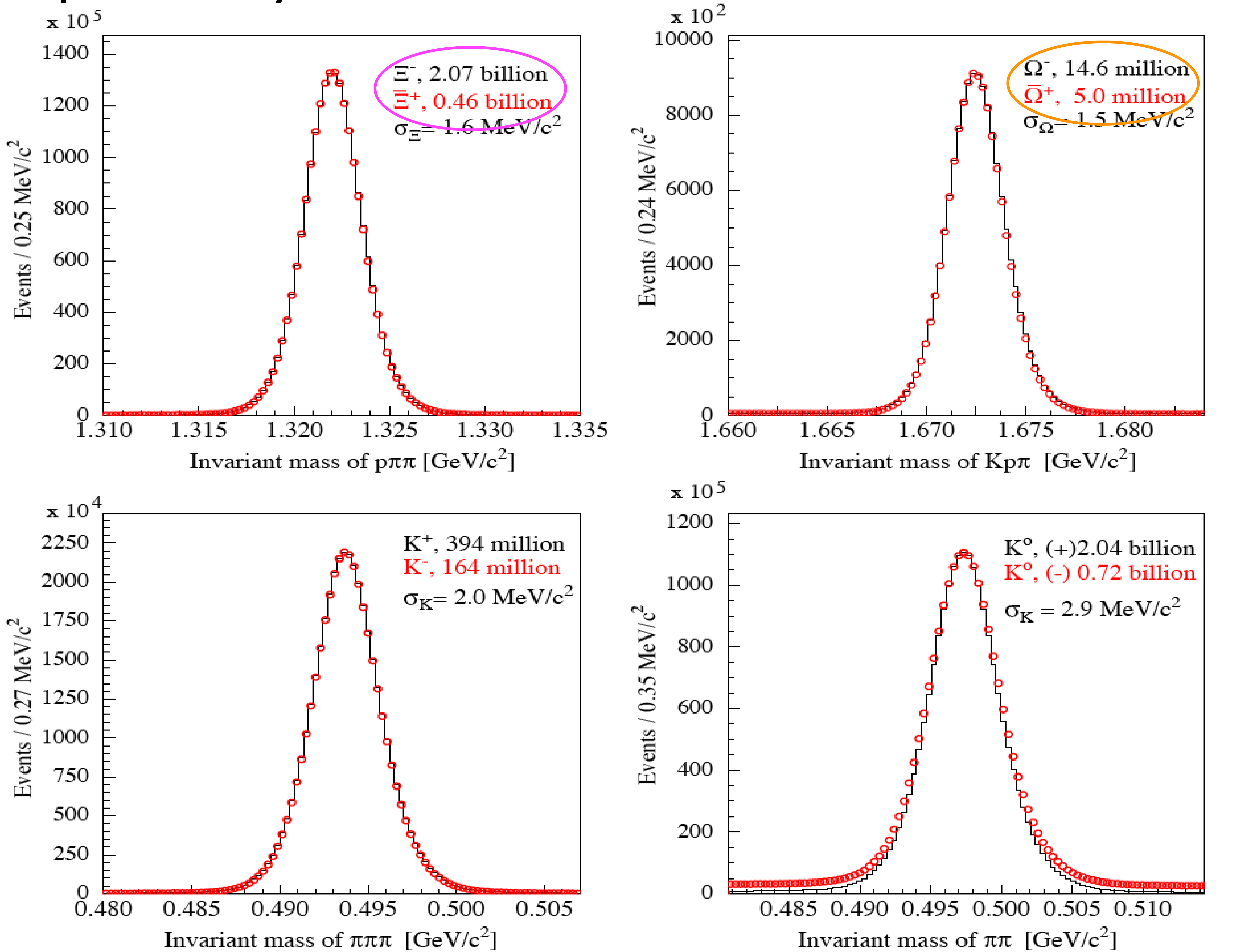
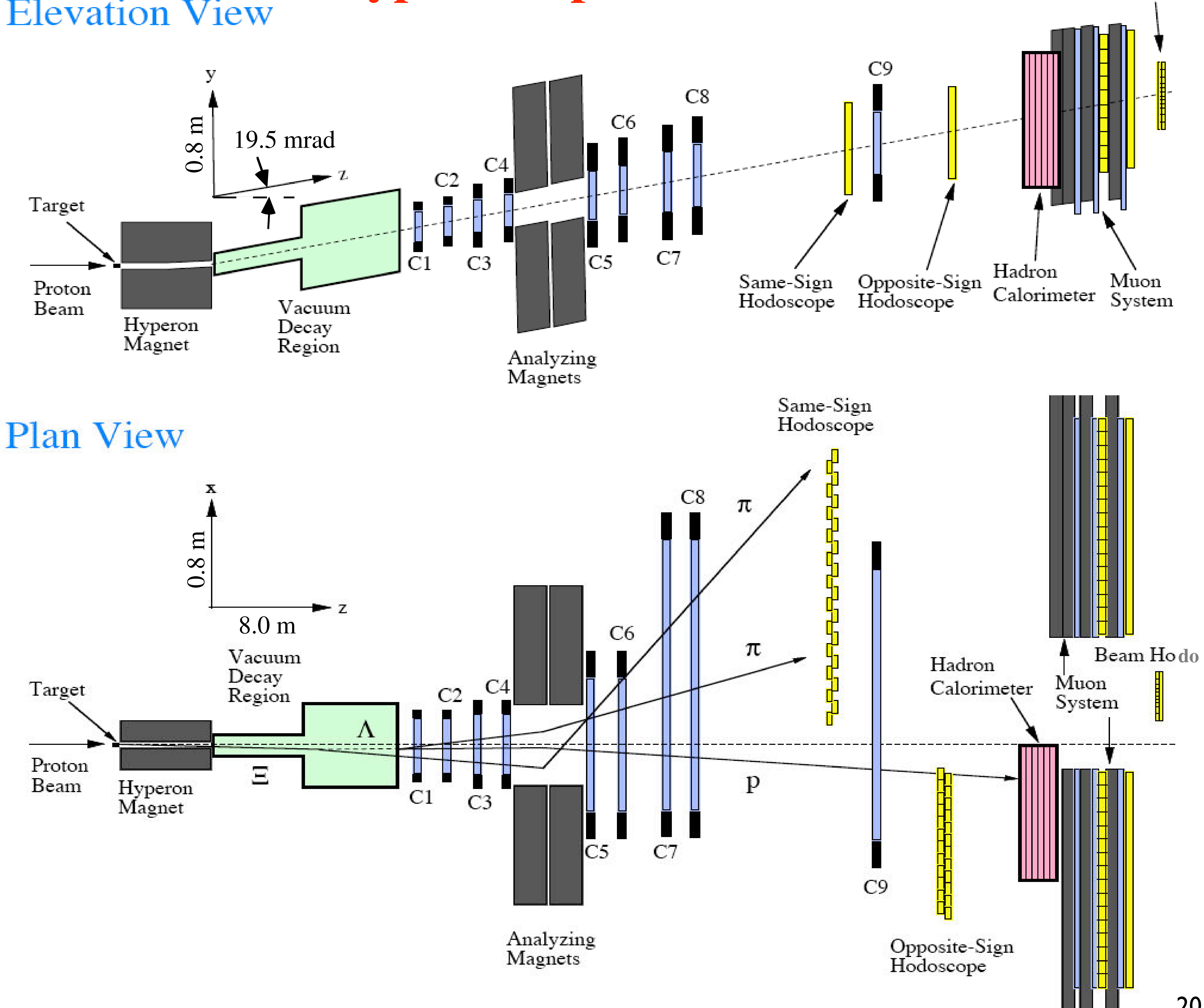


$(-6 \pm 2 \pm 2) \times 10^{-4}$ [BEACH08 preliminary; PRL in prep]

Made possible by... Enormous HyperCP Dataset



HyperCP Spectrometer



...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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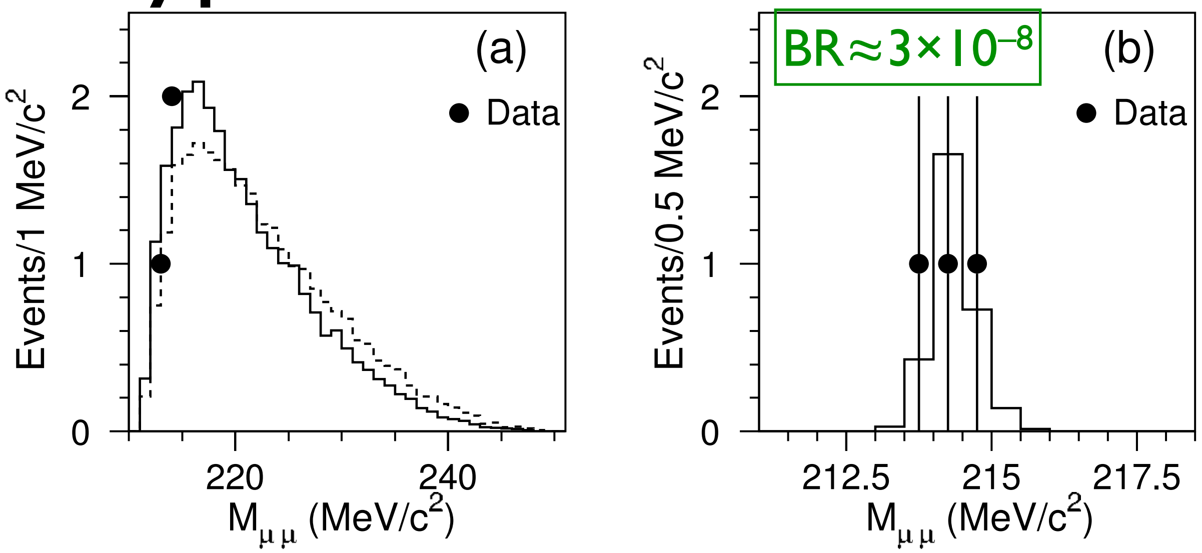
*co-spokespersons

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

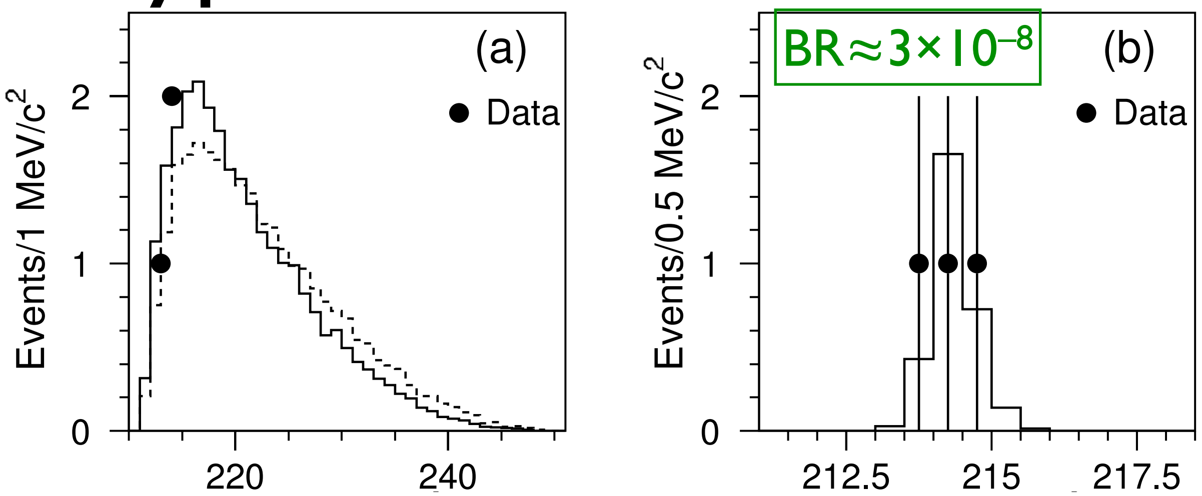
HyperCP also → 10^{10} Σ^+



≈2.4σ fluctuation of SM? or

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

HyperCP also → $10^{10}\ \Sigma^+$



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

≈2.4σ fluctuation of SM? or

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

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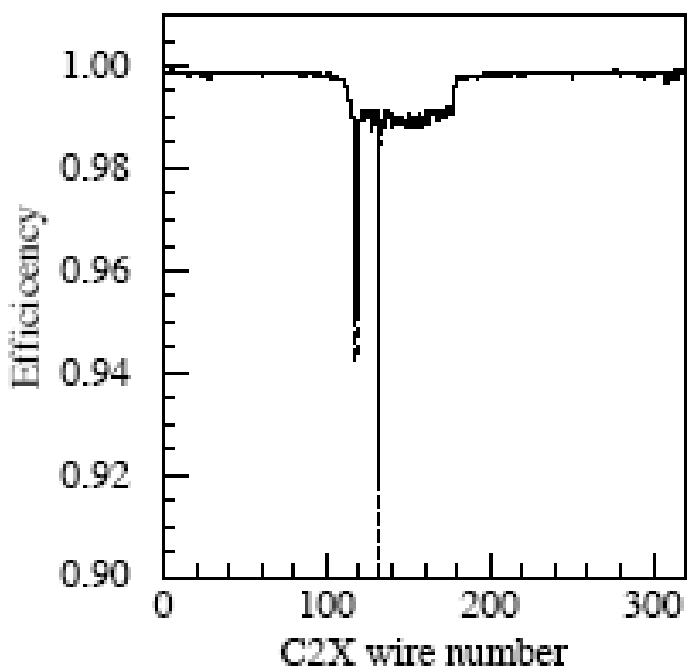
(Received 2 November 2006; published 22 February 2007)

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.

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:

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		(-6 ± 2 ± 2) × 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	$\overline{p}$ 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	$\approx$3.5–8	20	15%	5550	17
FAIR ($\gtrsim$ 2018*)	1–14	3.5	15%*	2780*	1.5

...even after FAIR@Darmstadt turns on

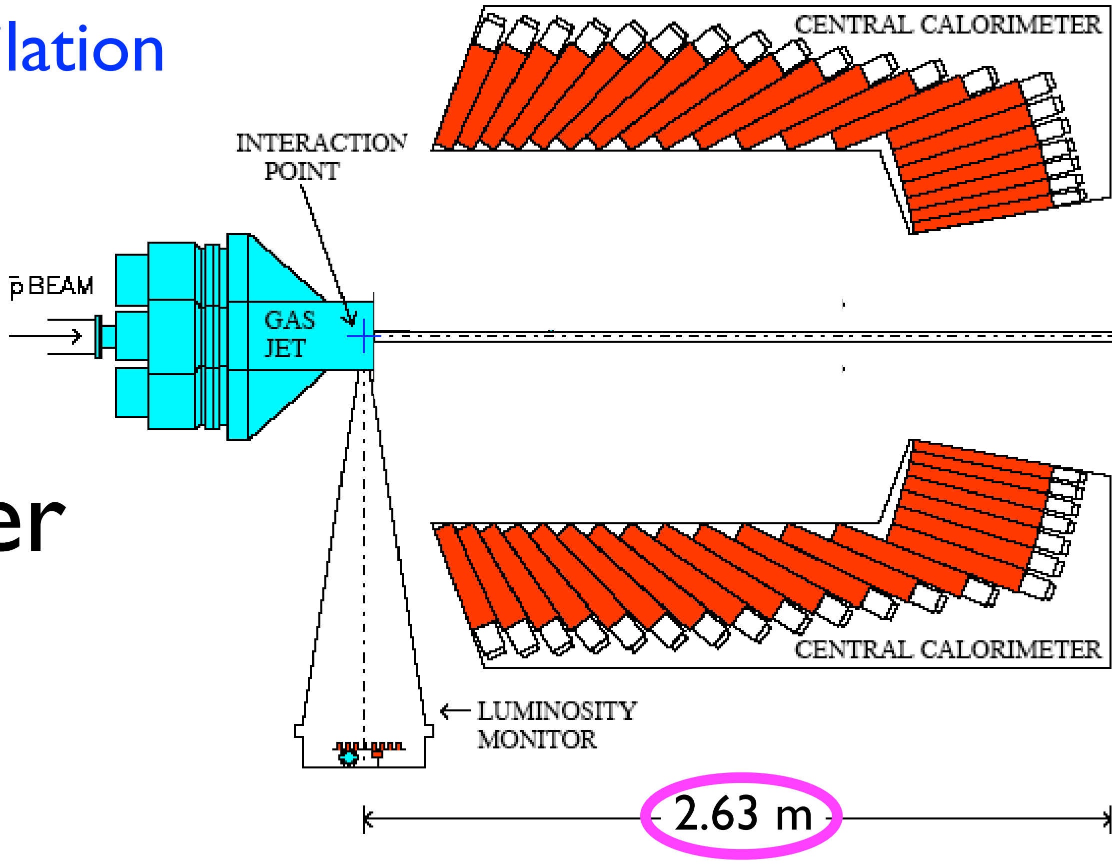
➡ exceeds LEAR $\overline{p}$ intensity (<1 MHz) by >10 orders of magnitude!

TAPAS

(The AntiProton Annihilation Specrometer)

Our proposal:

- After Tevatron finishes,
  - Reinstall E760 barrel calorimeter



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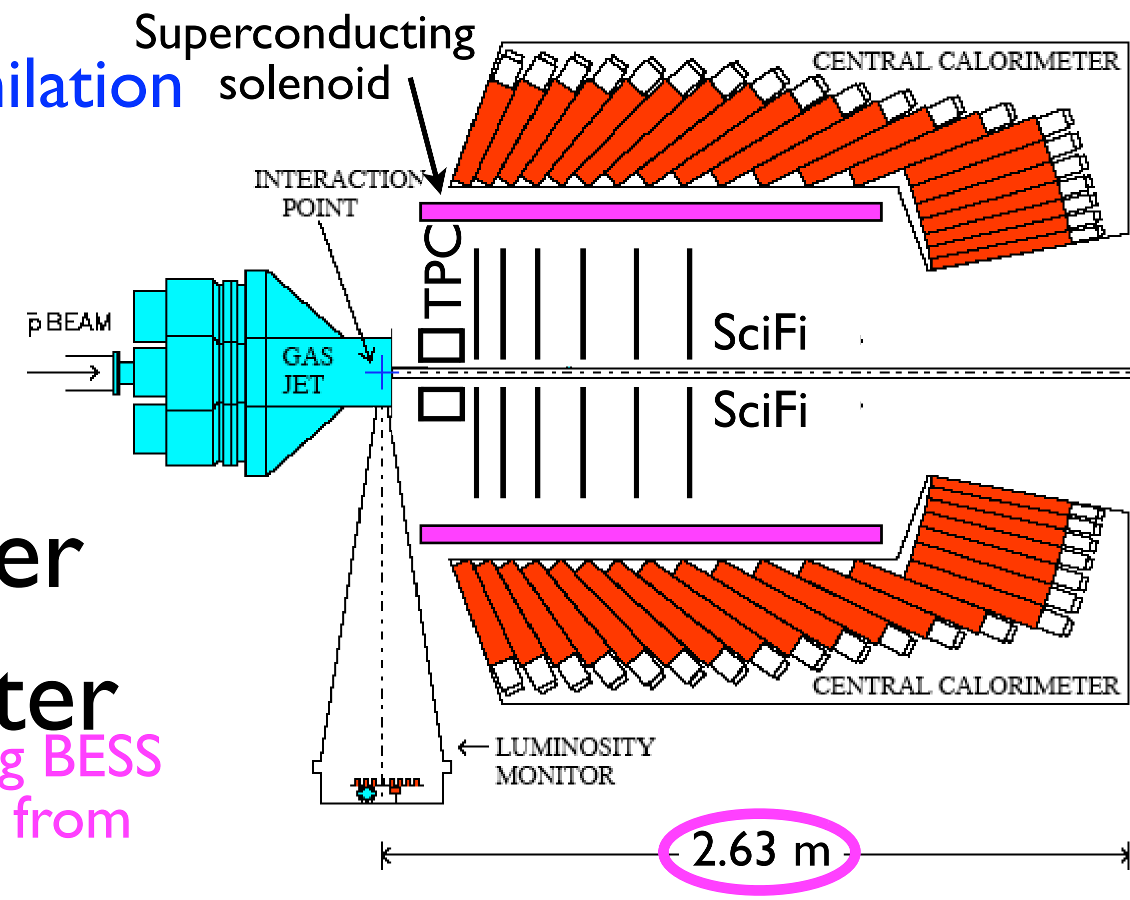
[existing BESS magnet from KEK & SciFi DAQ from DØ



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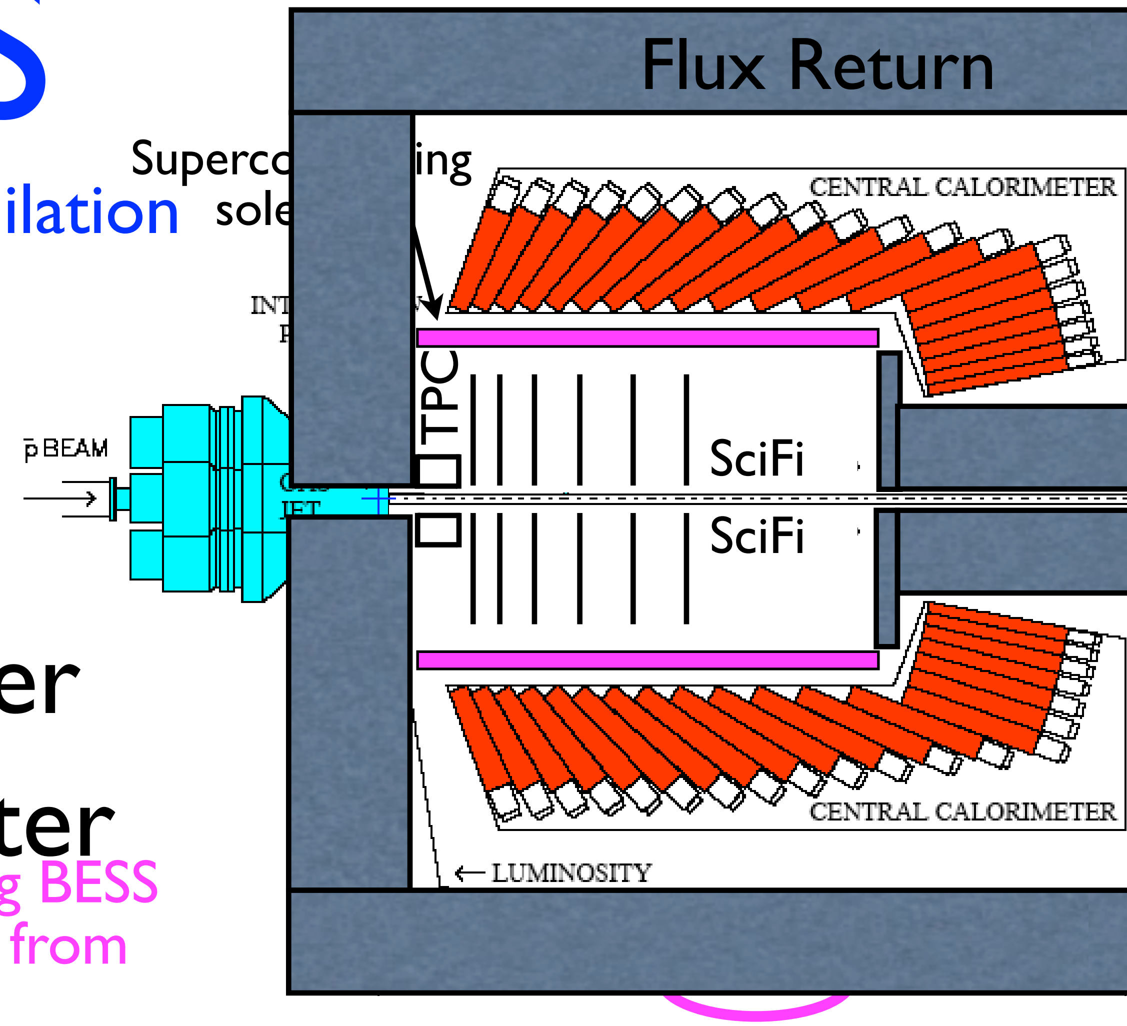

[existing BESS magnet from KEK & SciFi DAQ from DØ & FNAL iron]

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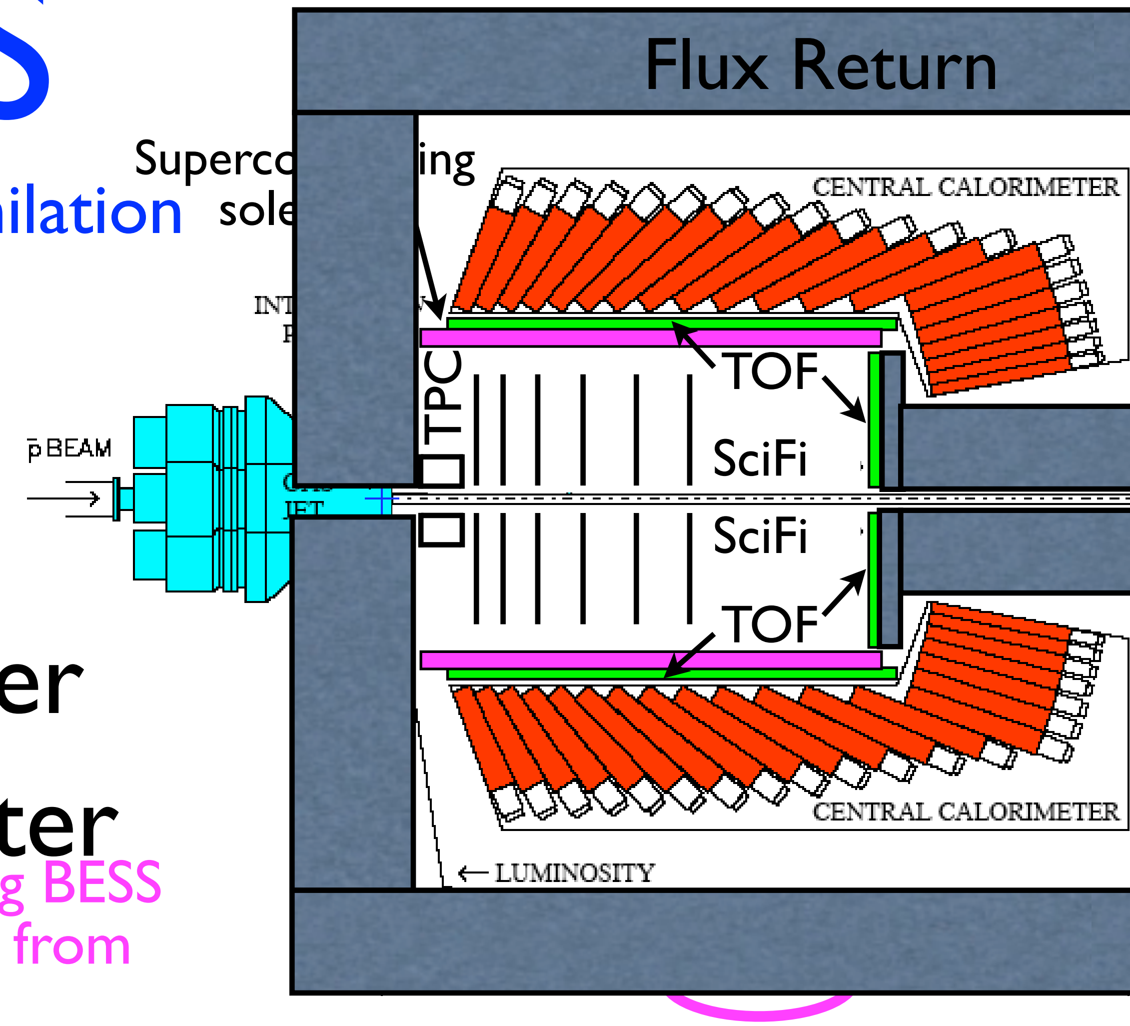
  - Add precision TOF system



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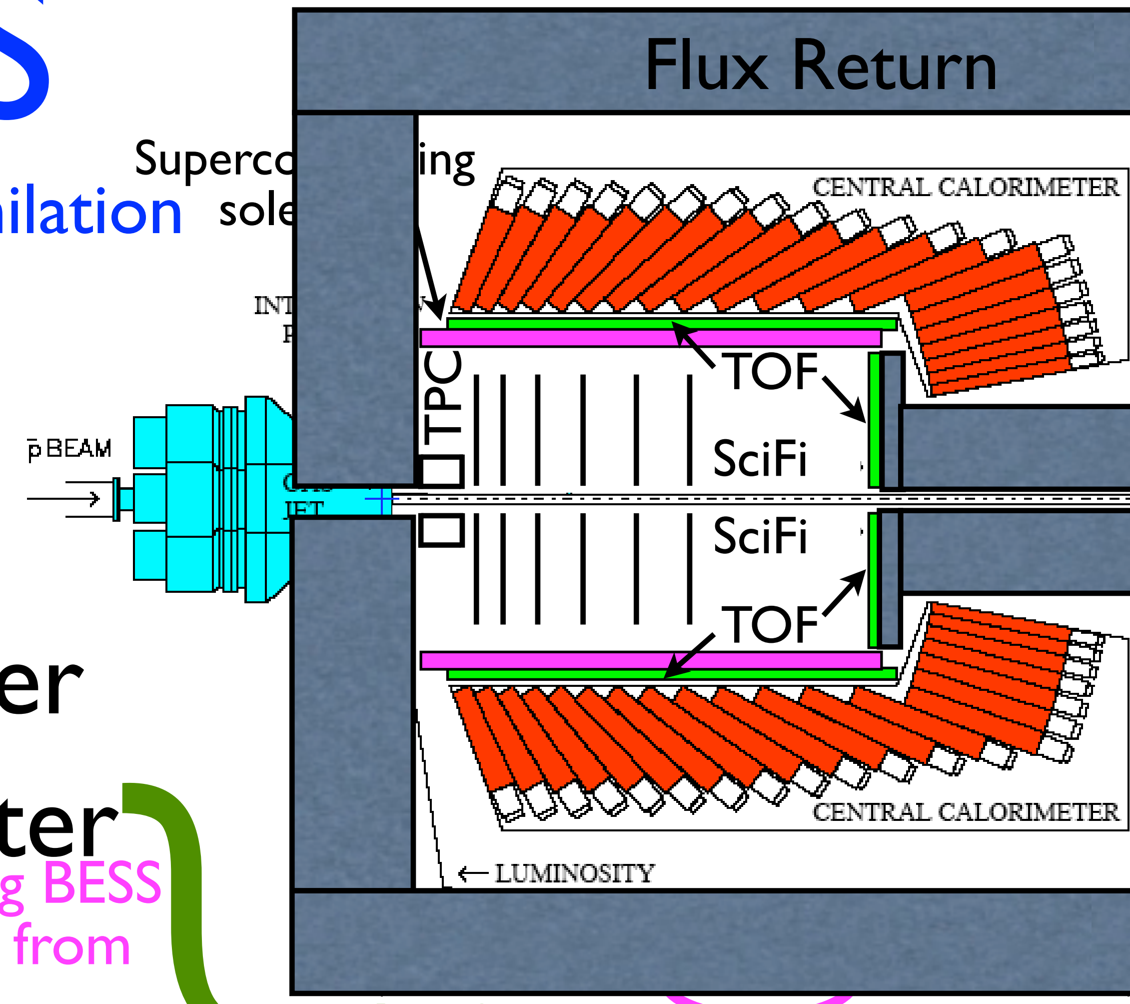


- After Tevatron finishes,
  - Reinstall E760 barrel calorimeter
  - Add small magnetic spectrometer
  - Add precision TOF system
  - Add thin targets
  - Add fast trigger & DAQ systems

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

  } <$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)

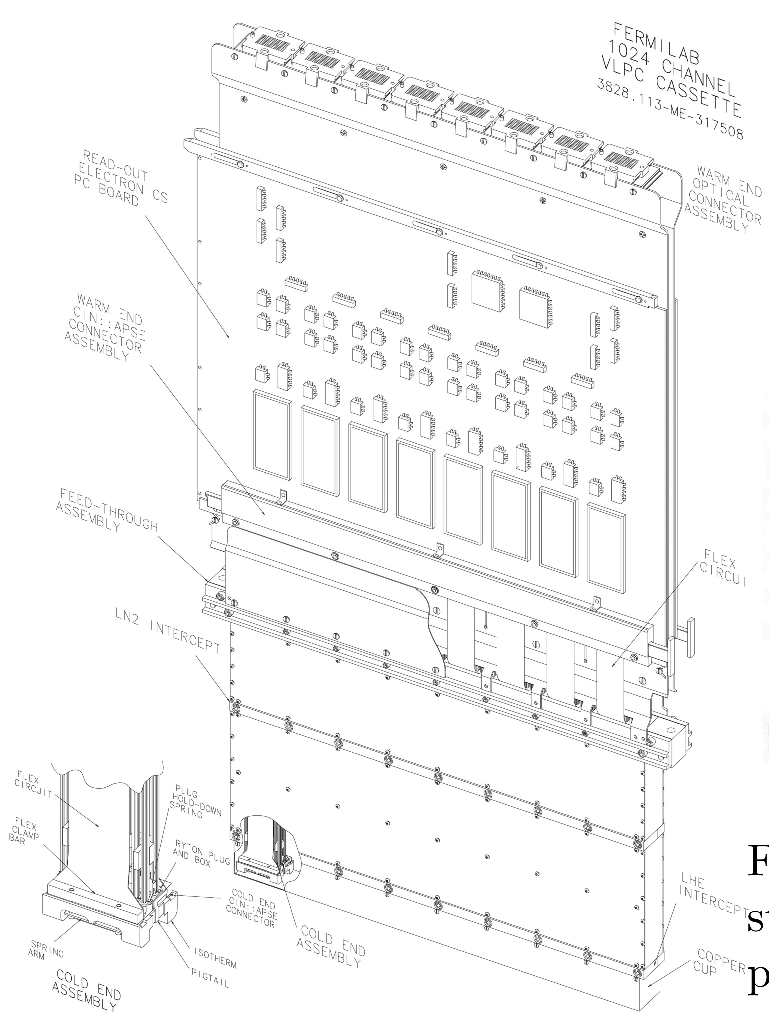
➡ ~10^8 $\Omega^- \bar{\Omega}^+$/yr + ~10^{12} inclusive hyperon events!

+ possibly ~10^{10} $\Xi^- \bar{\Xi}^+$

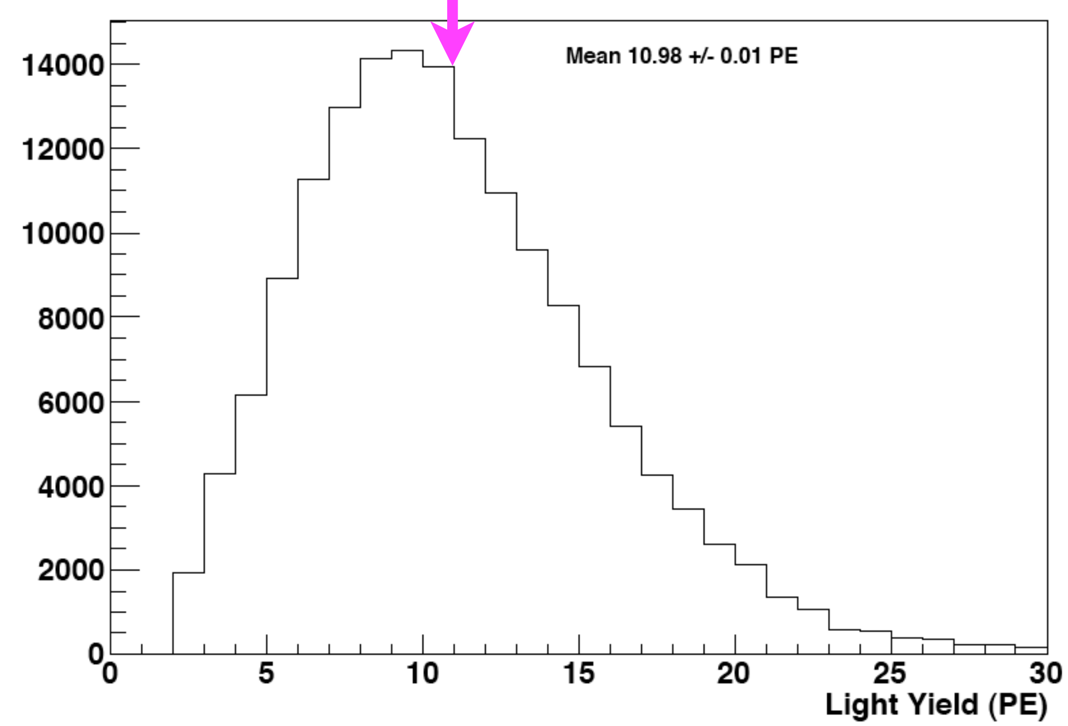
Fine-Pitch Scintillating Fibers

- MICE SciFi Trackers with VLPC readout

→ ≈ 85% Q.E.



11 photoelectrons/m.i.p.

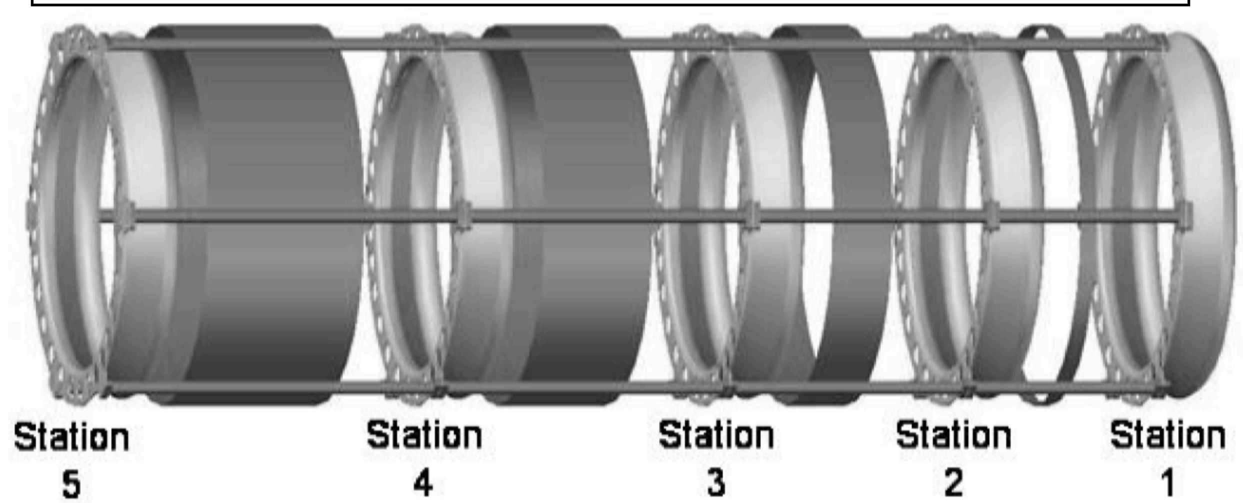


- 11 p.e. from 350 μm scintillating fiber

⇒ 240 μm feasible

Muon Ionization Cooling Experiment

Rutherford Appleton Lab, UK



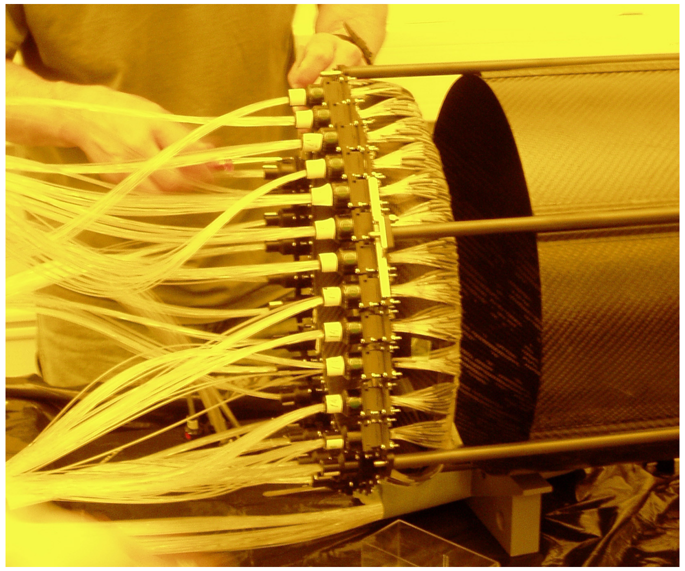


Figure 23: (left) CAD drawing of MICE tracker support frame, showing five carbon-fiber station support bodies mounted on space frame; (right) photo of carbon-fiber station support body.

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

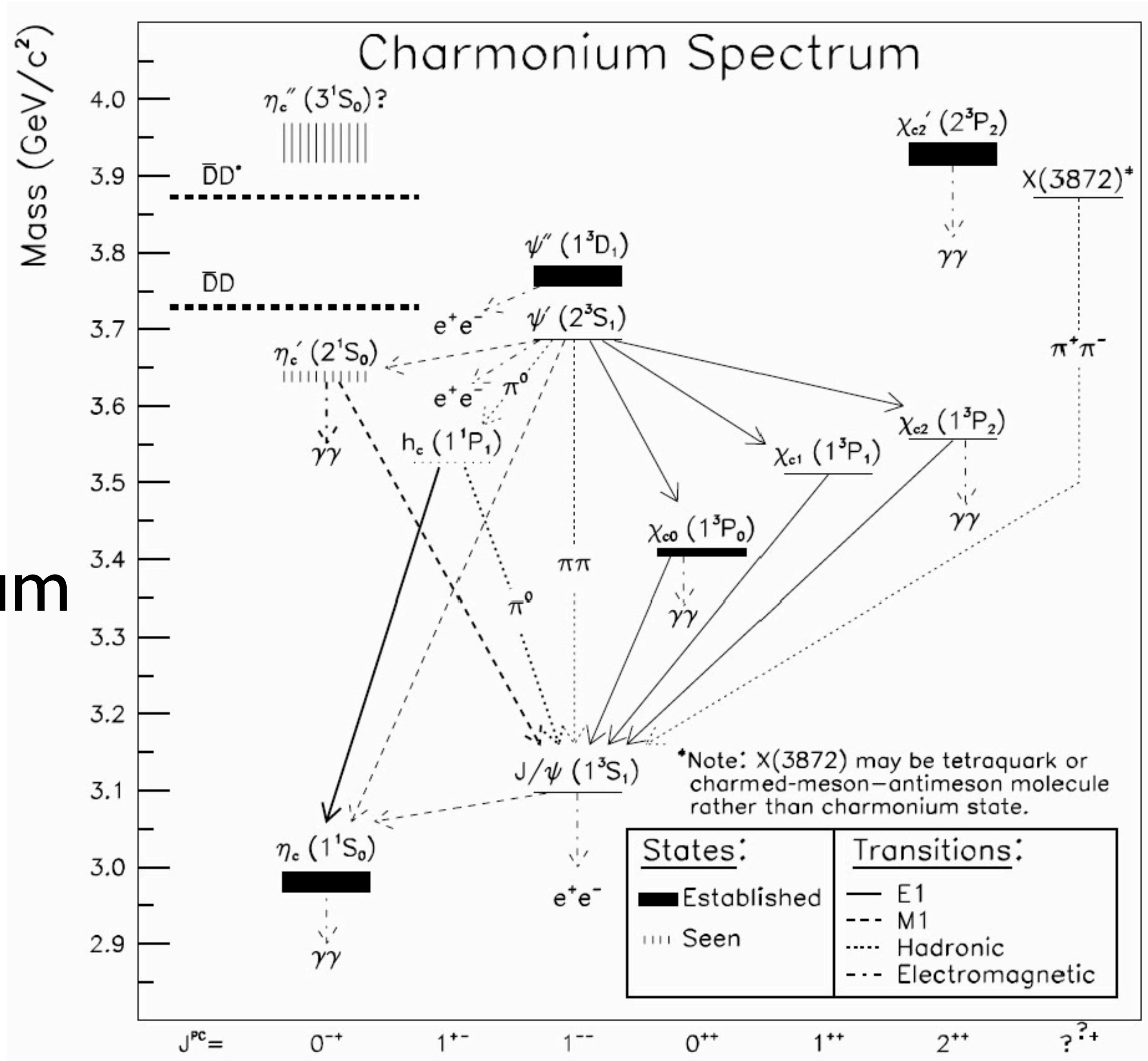
Predicted $\mathcal{B} \sim 10^{-6}$ if P^0 real

- 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

What Else 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,...



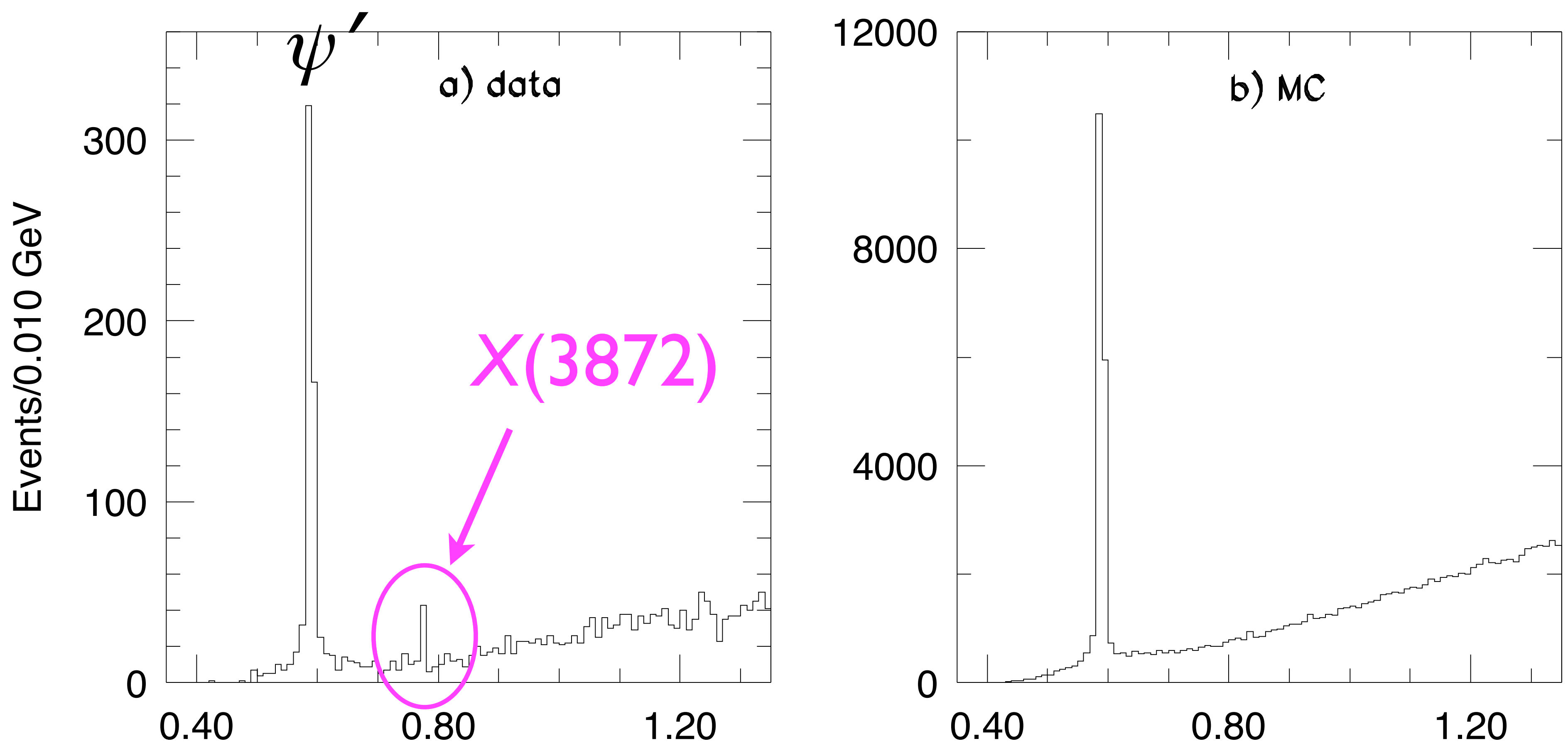
- $\bar{p}p$ produces *all* $c\bar{c}$ quantum states (not just 1^{--}), unlike e^+e^-

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 because it 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 ($\Delta mc^2 = -0.35 \pm 0.69$ 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	$3871.2\pm0.5 + i(<2.3)$	1^{++}	$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $\Upsilon J/\psi$	B decays, ppbar
	Belle BaBar	$3875.4\pm0.7^{+1.2}_{-2.0}$ $3875.6\pm0.7^{+1.4}_{-1.5}$		$D^0 D^0 \pi^0$	B decays
Z(3930)	Belle	$3929\pm5\pm2 + i(29\pm10\pm2)$	2^{++}	D^0D^0, D^+D^-	$\Upsilon\Upsilon$
Y(3940)	Belle BaBar	$3943\pm11\pm13 + i(87\pm22\pm26)$ $3914.3^{+3.8}_{-3.4}\pm1.6 + i(33^{+12}_{-8}\pm0.60)$	J^{++}	$\omega J/\psi$	B decays
X(3940)	Belle	$3942^{+7}_{-6}\pm6 + i(37^{+26}_{-15}\pm8)$	J^{P+}	DD^*	e^+e^- (recoil against J/ψ)
Y(4008)	Belle	$4008\pm40^{+72}_{-28} + i(226\pm44^{+87}_{-79})$	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
X(4160)	Belle	$4156^{+25}_{-20}\pm15 + i(139^{+111}_{-61}\pm21)$	J^{P+}	D^*D^*	e^+e^- (recoil against J/ψ)
Y(4260)	BaBar Cleo Belle	$4259\pm8^{+8}_{-6} + i(88\pm23^{+6}_{-4})$ $4284^{+17}_{-16}\pm4 + i(73^{+39}_{-25}\pm5)$ $4247\pm12^{+17}_{-32} + i(108\pm19\pm10)$	1^{--}	$\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$	e^+e^- (ISR), e^+e^-
Y(4350)	BaBar Belle	$4324\pm24 + i(172\pm33)$ $4361\pm9\pm9 + i(74\pm15\pm10)$	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)
$Z^+(4430)$	Belle	$4433\pm4\pm1 + i(44^{+17}_{-13}{}^{+30}_{-11})$	J^P	$\pi^+\psi(2S)$	B decays
Y(4620)	Belle	$4664\pm11\pm5 + i(48\pm15\pm3)$	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)

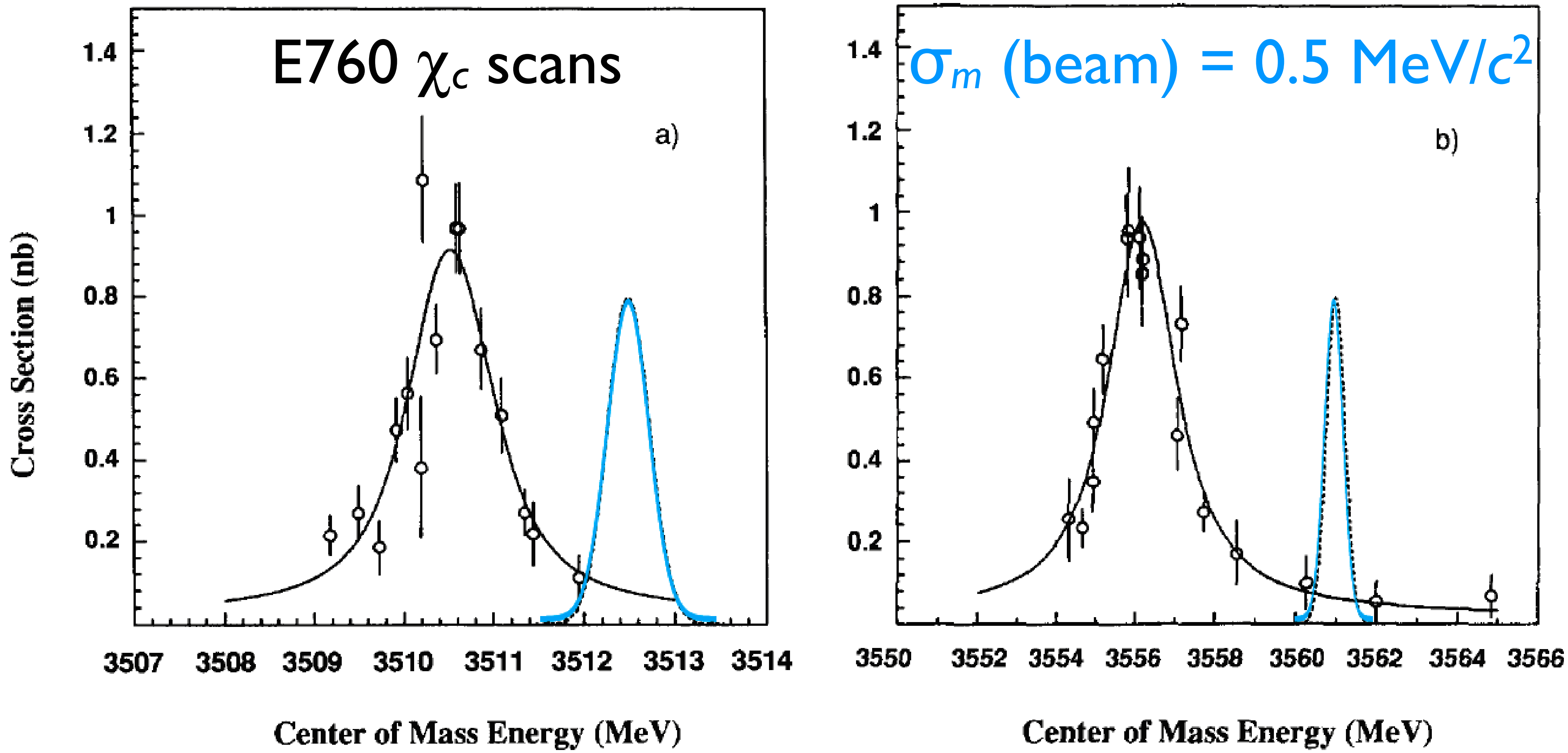
What ^Else Can This Do?

- 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 because it may be the first meson-antimeson ($D^0 \bar{D}^{*0}$ + 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! → $\begin{cases} \delta m(\chi_c) \approx 0.1 \pm 0.02 \text{ MeV}/c^2 \\ \delta\Gamma(\chi_c) \approx 0.1 \pm 0.01 \text{ MeV}/c^2 \end{cases}$
- The experiment is just the detector.

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

  ➡ need *very* precise mass measurement to confirm or refute

  ➡ $\bar{p}p \rightarrow X(3872)$ 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 $p\bar{p} \to D^{*0}\bar{D}^0$ 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 $D^*\bar{D}$ molecule
  - extrapolates from K^*K data

Charm!

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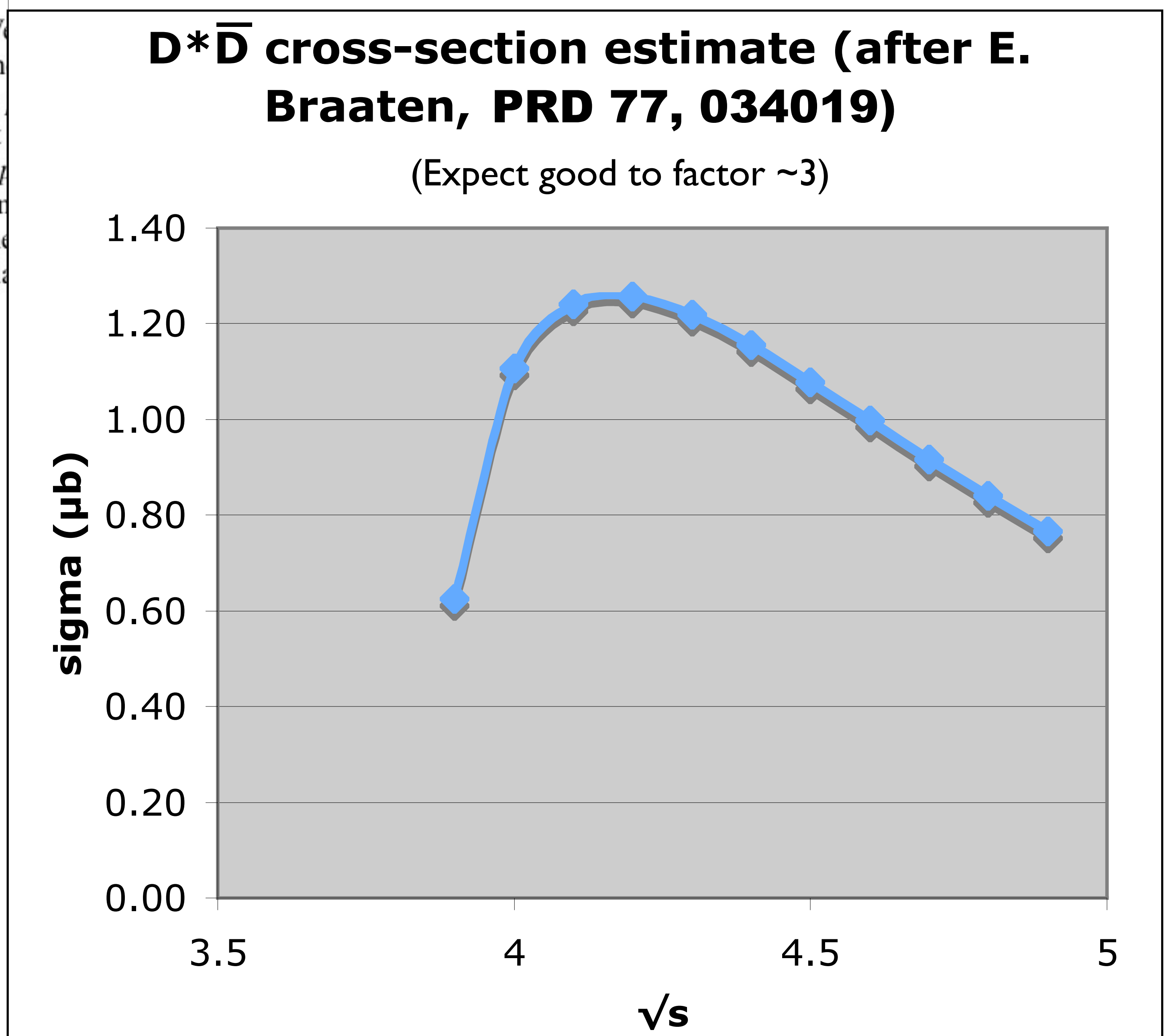
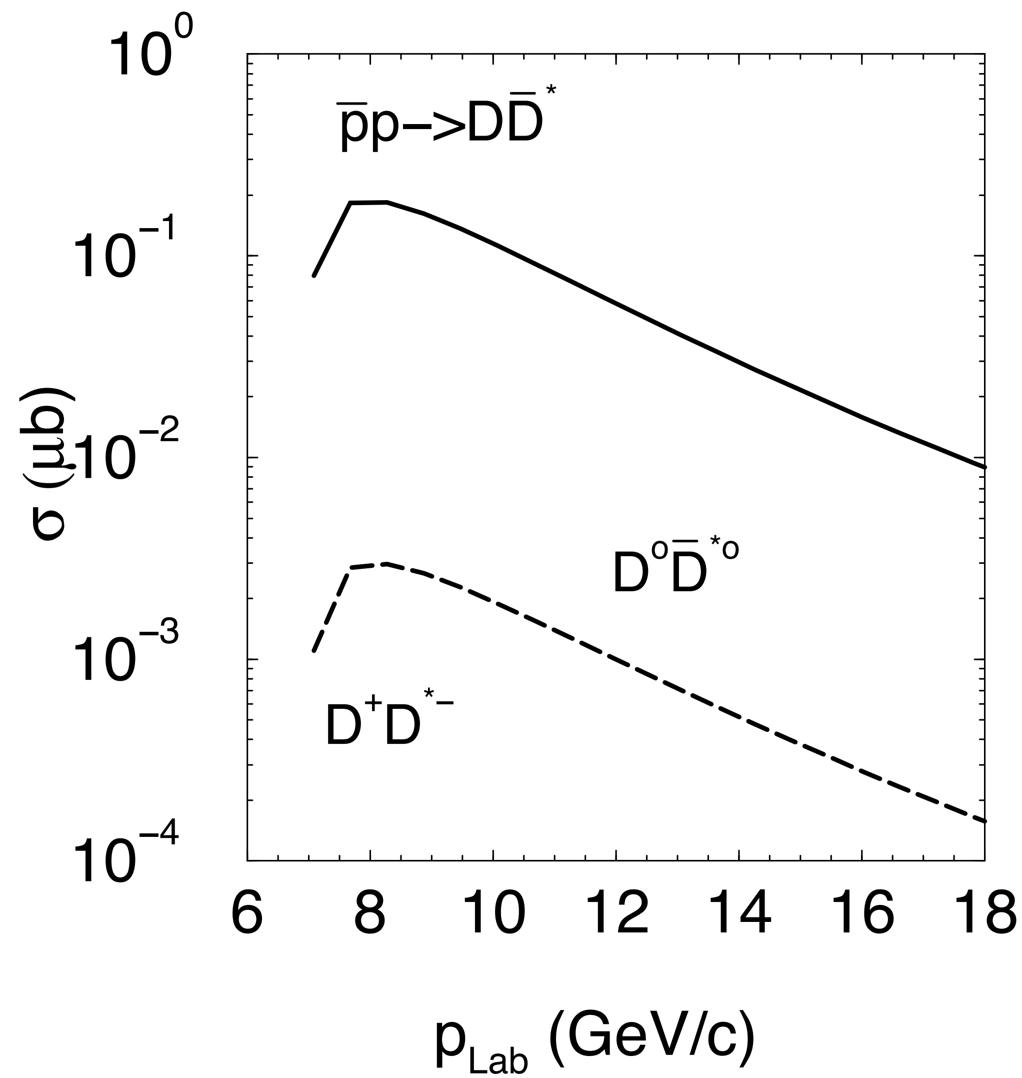


- E. Braaten estimate of $\bar{p}p$ $X(3872)$ coupling assuming X is $D^*\bar{D}$ molecule
  - extrapolates from K^*K data
- By-product is $D^{*0}\bar{D}^0$ cross section
- 1.3 μb → 5 ×10⁹/year
- Expect efficiency as at *B* factories

Charm!

- Another approach (Regge model)



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

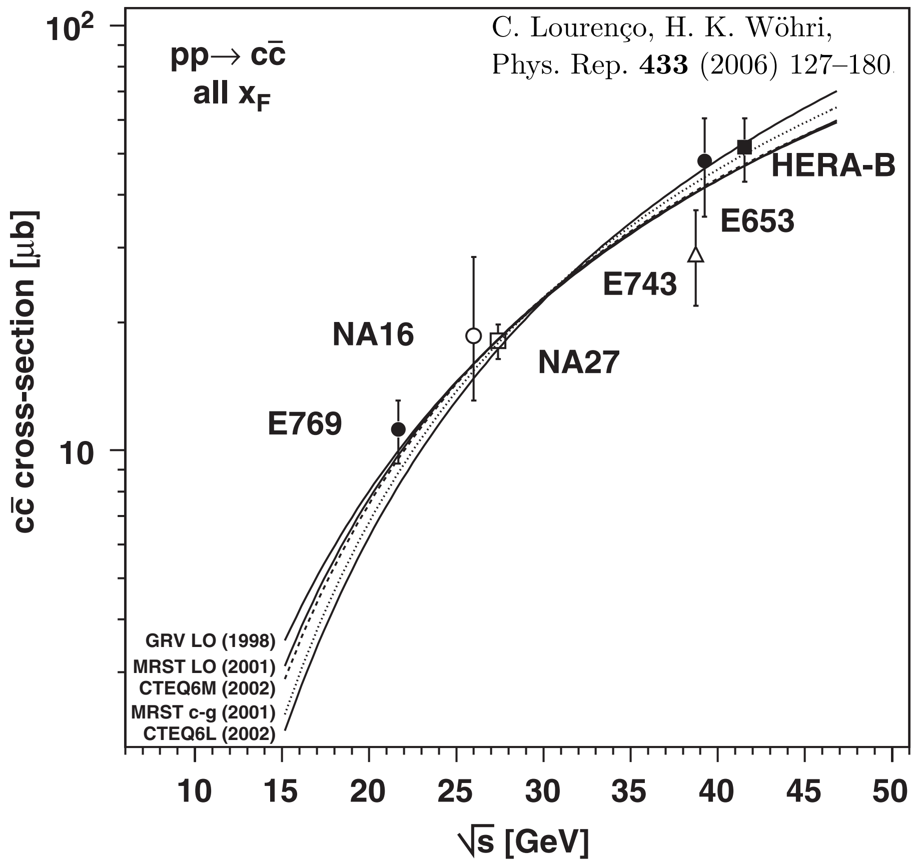
A. Titov, private communication

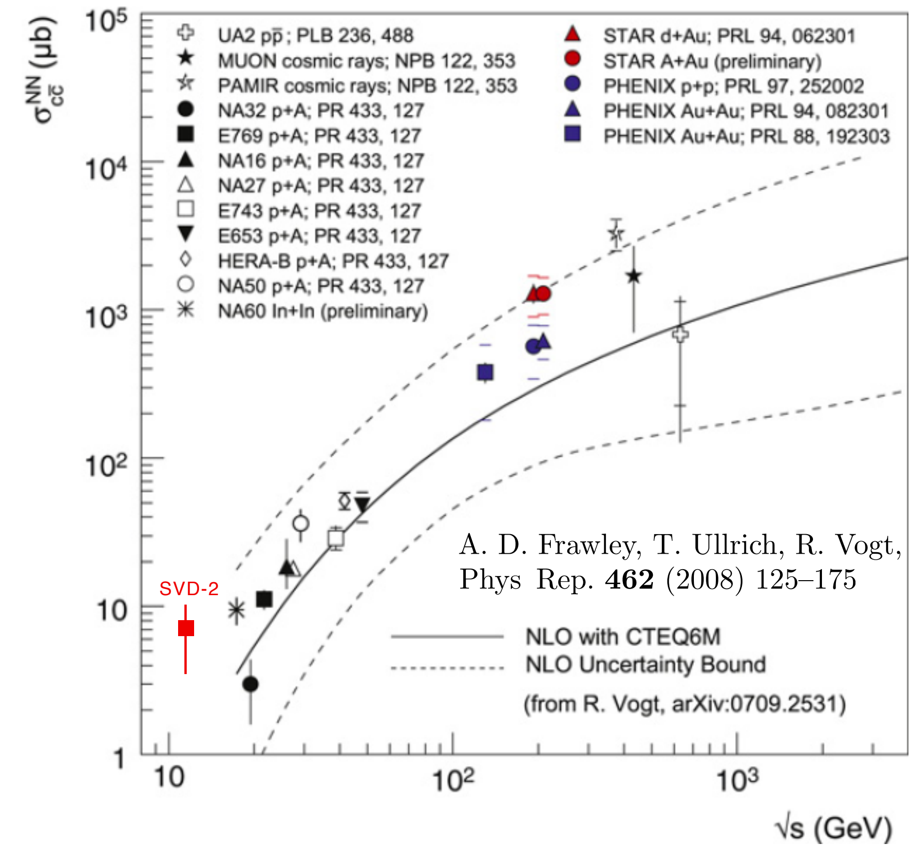
- Agreement within factor of 6

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

Charm!

- Other evidence?





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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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

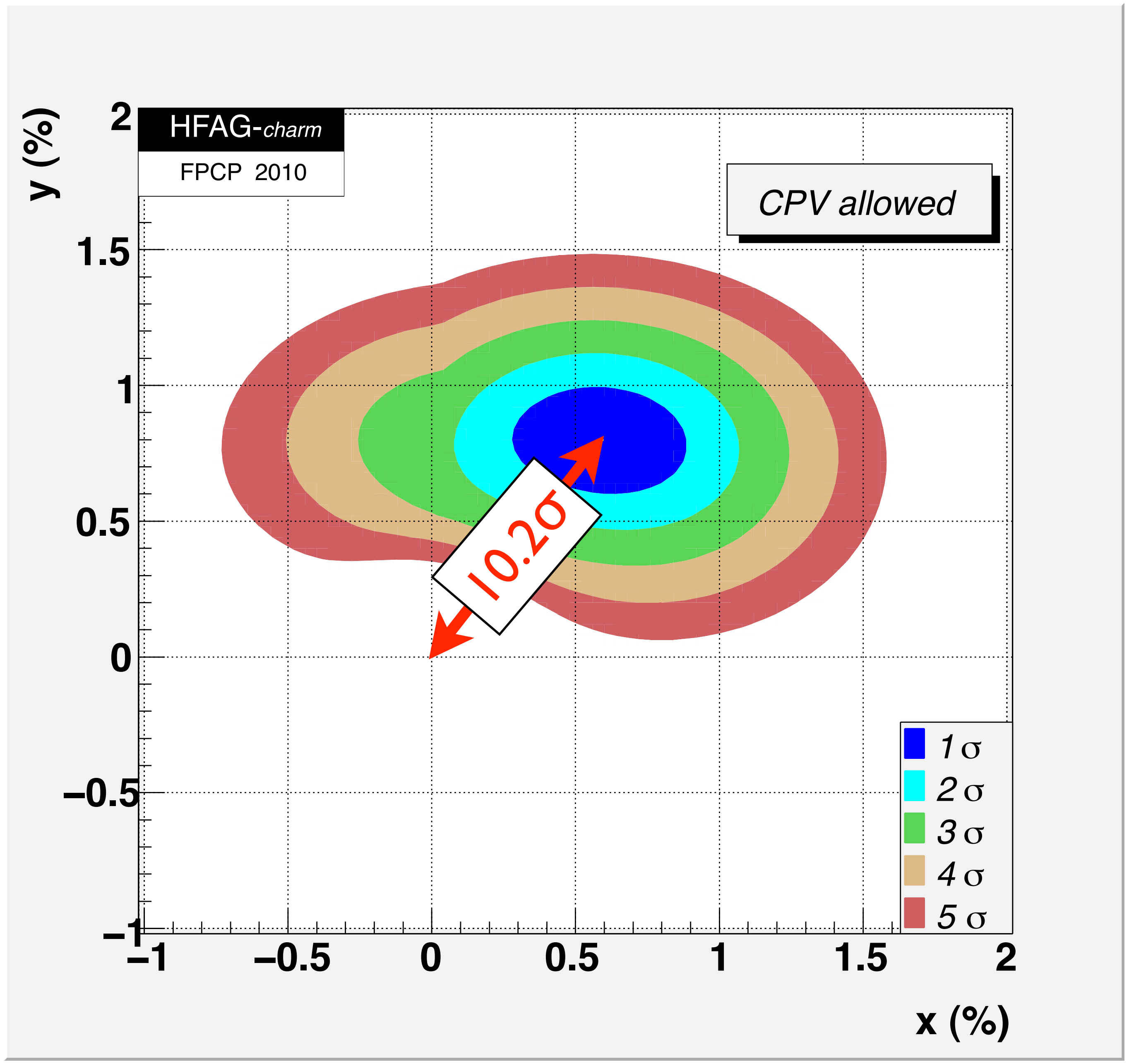
The results of data handling for SERP-E-184 experiment obtained with 70 GeV proton beam irradiation of active target with carbon, silicon and lead plates are presented. Two-prongs neutral charmed D^0 and $\bar{D}^0$ -mesons decays were selected. Signal / background ratio is (51±17) / (38±13). Registration 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)

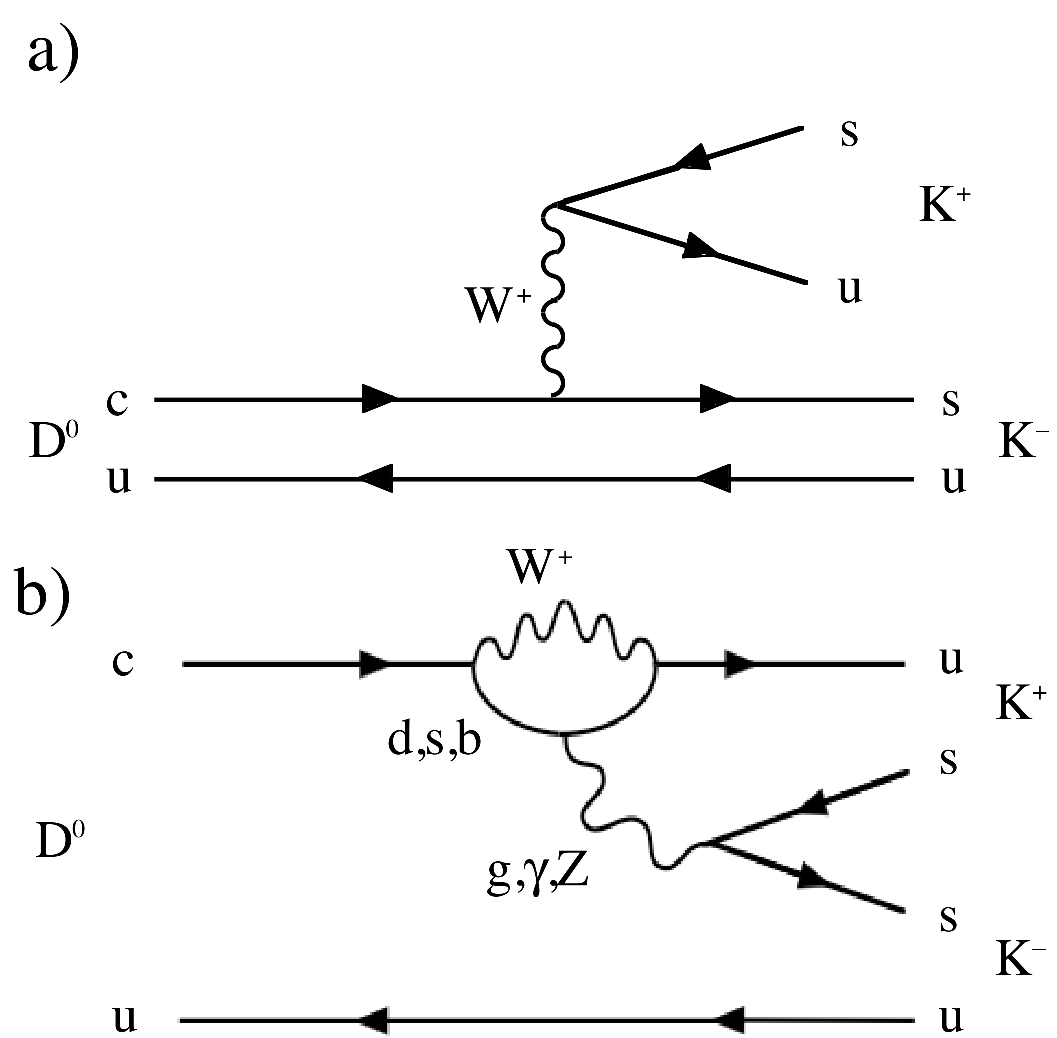


- *Big question:*
  New Physics or old?

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:



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

➡ world's best sensitivity to charm CPV

Charm!

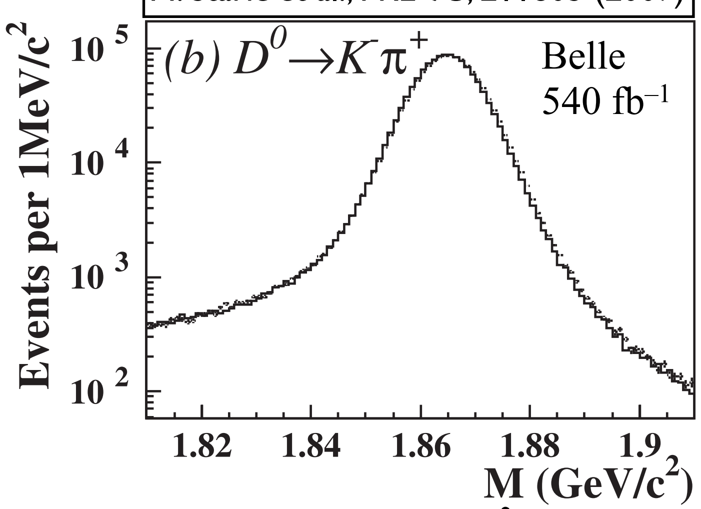
- Ballpark sensitivity estimate based on Braaten $\bar{p}p \to D^{*0}\bar{D}^0$ formula, assuming $\sigma \propto A^{1.0}$:

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

*Assumes ≈15% of running time is devoted to antiproton-beam stacking.

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

M. Staric et al., PRL **98**, 211803 (2007)



- Such subtle effects as charm CPV will require independent confirmation
  - LHC*b*: similar statistics, but different, significant, systematics
  - Competitive with projected ca. 2021 SuperKEKB (is SuperB?)

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?
- TAPAS will establish feasibility & reach

What Else?

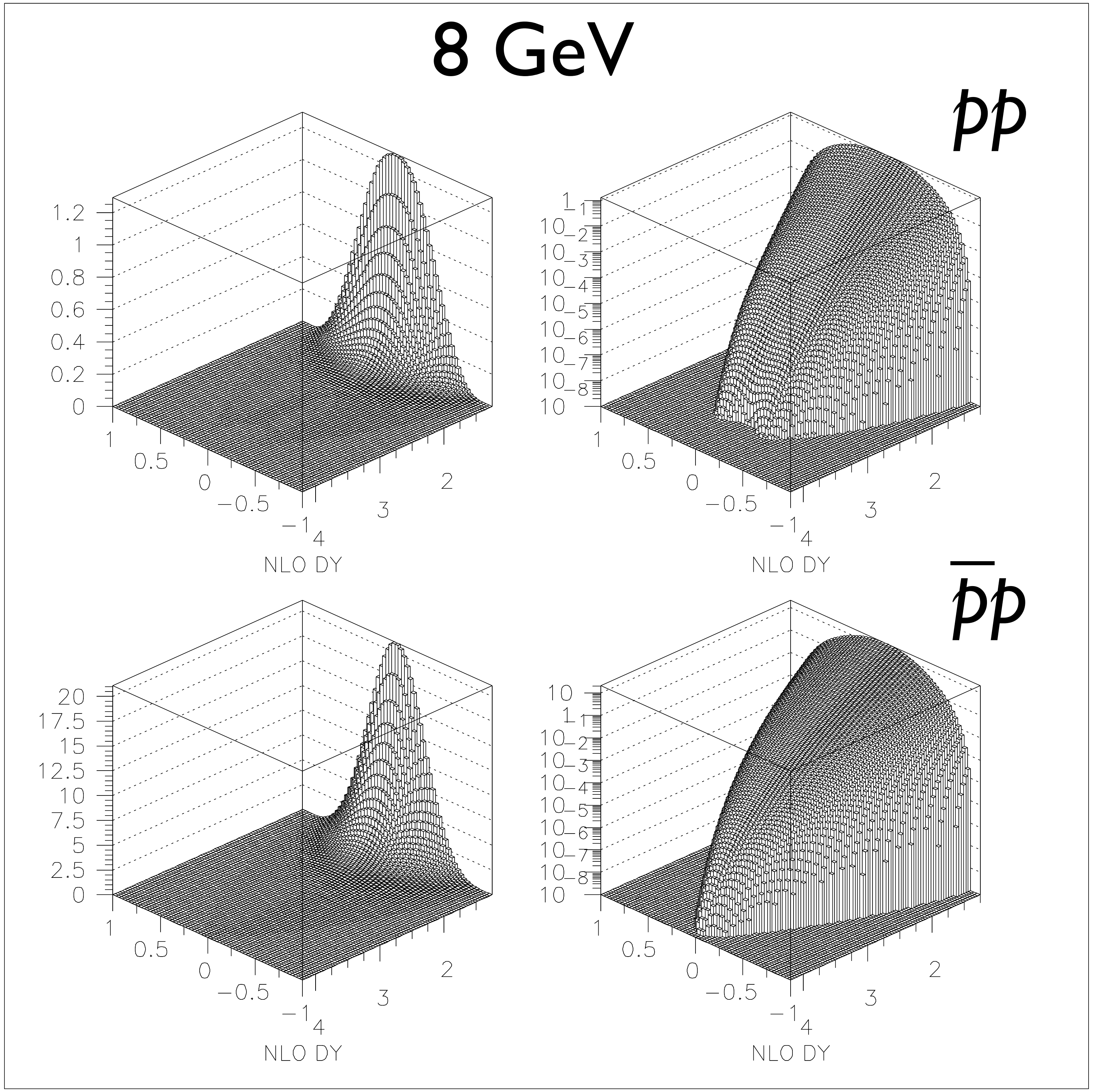
- QCD tests:
  - event shapes and distributions
  - intrinsic charm
- Search for exotics:
  - pentaquarks, gluonic hybrids, etc.
- *A* dependence:
  - possible calibration for heavy-ion effects
- Drell-Yan:
  - can signal be distinguished from background?

$\bar{p}p$ Drell-Yan

- Global structure-function fits suffer from significant tension among datasets
- $\bar{p}p$ or $\bar{p}A$ Drell-Yan can potentially add new constraints with very different systematics
    - valence-valence
- Another possibility:
    - use single-charm production to constrain strange-quark sea

➡ Can either of these signals be dug out of the background???

$\bar{p}p$ Drell-Yan



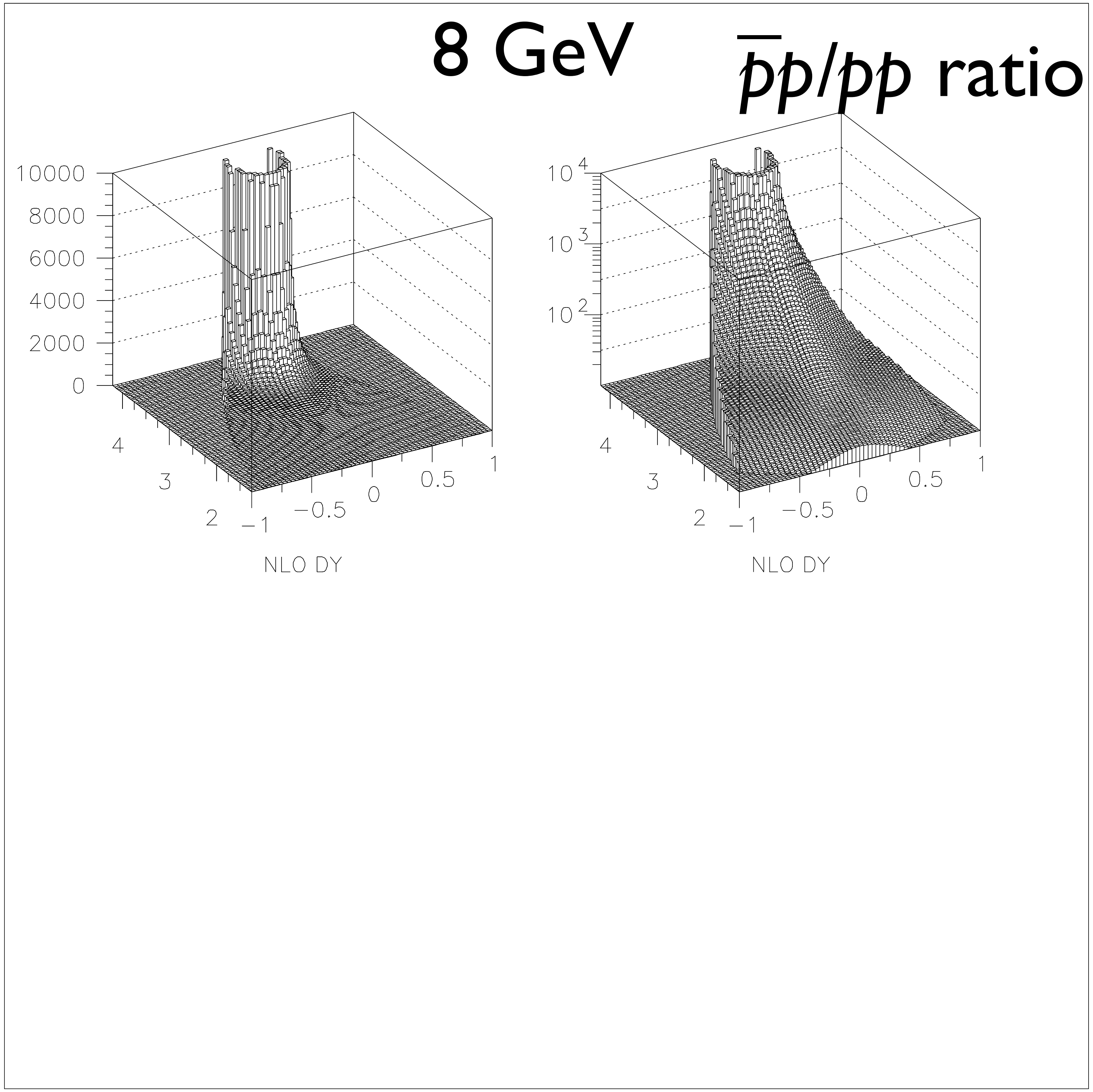
- P. Reimer calculation:

  @ m ≈ 1.25 GeV,

$$\left.\frac{d^2\sigma}{dm\,dx_F}\right|_{x_F=0} = 21\ \text{nb/GeV} \sim 20\sigma_{pp}^{DY}$$

- Factor grows with mass
- @ 2 × 10^{32}, this is ≈4 × 10^7 evts/GeV/yr

$\bar{p}p$ Drell-Yan



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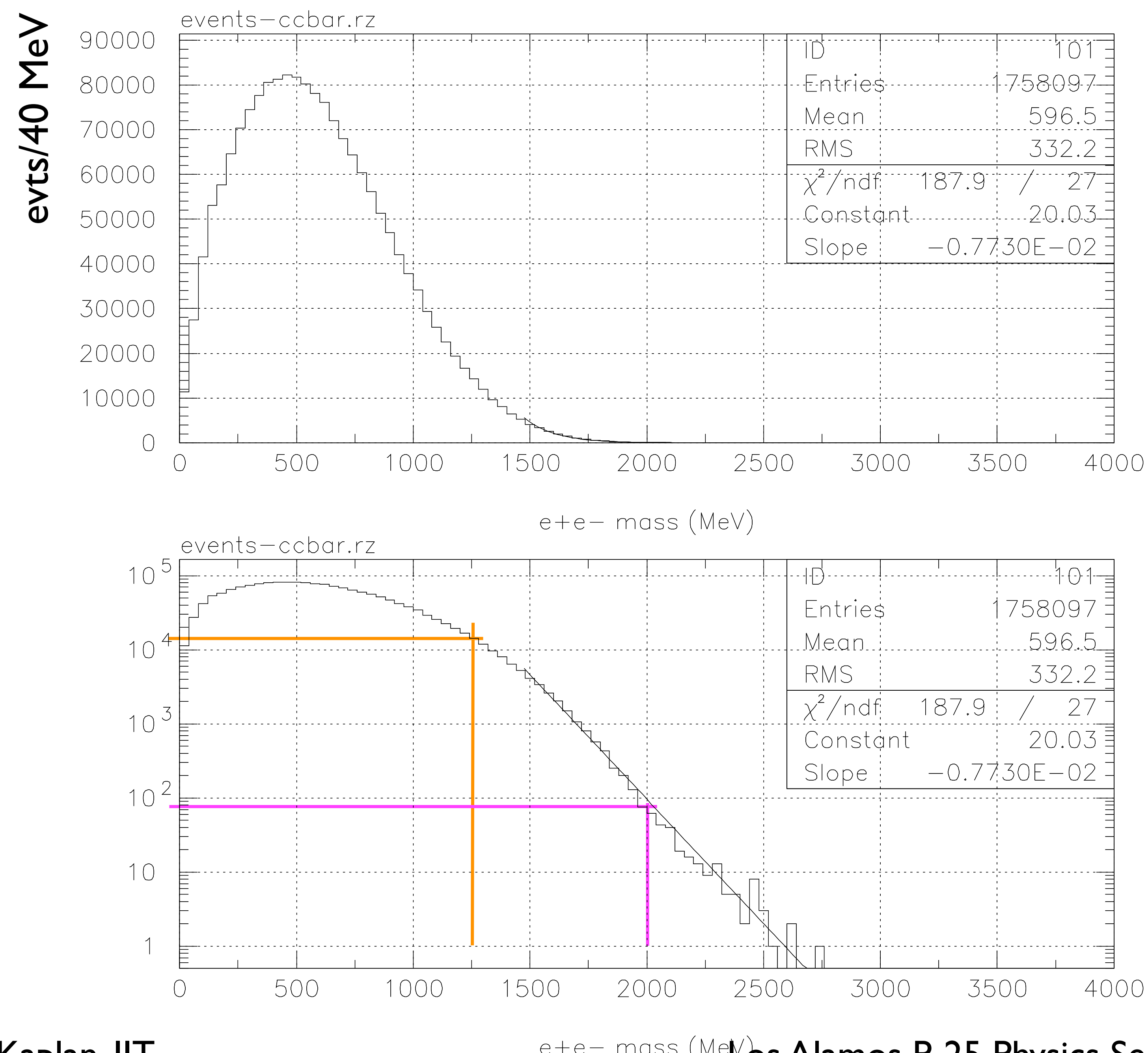
$\bar{p}p$ Drell-Yan

- BUT – above charm estimate implies up to $6 \times 10^6\ D\bar{D} \to e^+e^- + X$ evts/yr



- DMK charm MC:

  @ m ≈ 1.25 GeV, ~10^7 bkg events/GeV/yr

- Note by 2 GeV,

  bkg down by >2 orders of magnitude,

  signal by only 1

➡ Looks like some physics can be done

$\bar{p}p$ Drell-Yan

- BUT – above charm estimate implies up to $6 \times 10^6\ D\bar{D} \rightarrow e^+e^- + X$ evts/yr
- as well as $\sim 10^{12}\ \pi^+\pi^- + X$ evts/yr, which can be mis-ID'd as e^+e^- in calorimeter

Table 2: Comparison of Drell–Yan signal and backgrounds.

Process	$m = 1.5$	2.0	2.5	GeV
DY	5.5	0.62	0.056	nb/GeV
Double charm semileptonic*	2.3	0.039	0.001	nb/GeV
Double π–e mis-ID†	0.25	0.1	0.04	nb/GeV

*Neglecting vertex rejection. †Neglecting TOF rejection.

- DMK charm MC:

  @ m ≈ 1.25 GeV, $\sim 10^7$ bkg events/GeV/yr
- Note by 2 GeV,

  bkg down by >2 orders of magnitude,

  signal by only 1

➡ Looks like some physics can be done

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

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 $\overline{p}$ 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 beyond about 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

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

Summary

- Best experiment ever on hyperons, charmonia, and charm may soon be feasible at Fermilab
  - possibly world's most sensitive study of charm mixing, charm & hyperon CPV & rare decays, + unique $\bar{p}$ DY
- Existing equip't enables quick, cost-effective effort
  - could start data-taking by 2014
- Preserves options for antihydrogen experiments
  - CPT, gravity tests
- World's best $\bar{p}$ source offers simple way to broad physics program in pre-Project X era

➡ Can Oddone's mind be changed?

...and **now**

for *something*

completely different!

Antihydrogen

- Possible spectroscopy measurements on $\overline{\mathrm{H}}$ in flight produced by $\bar{p}$ beam halo in material
  - $\sim 10^{-9}$ sensitivity may be achievable
  - 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) $\overline{\mathrm{H}}$ beam with Penning trap
  - measure its rate of fall in atom interferometer
  - $\sim 10^{-9}$ sensitivity possible with laser interferometry

Antihydrogen

- Some15 years ago, FNAL E835 produced oodles of $\overline{\mathrm{H}}$!

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]
[1]*University of California at Irvine, Irvine, California 92697*
[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

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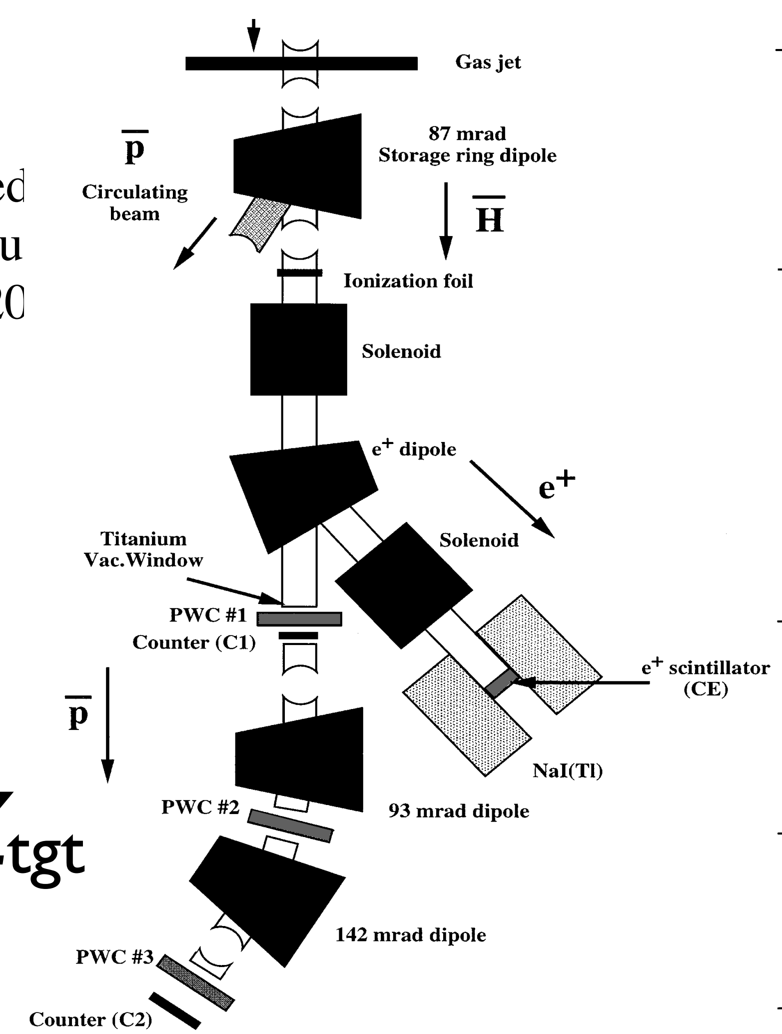

- Formed automatically e.g. in E835 gas-jet target, detected in "parasitic" E862
- Production probability grows with E_{beam}, Z_{tgt}

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

G. Blanford, K. Gollwitzer, M. Mandelkern, J. Schultz, G. Takei, and G. Zioulas
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D. C. Christian
Fermilab, Batavia, Illinois 60510

C. T. Munger
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

(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]

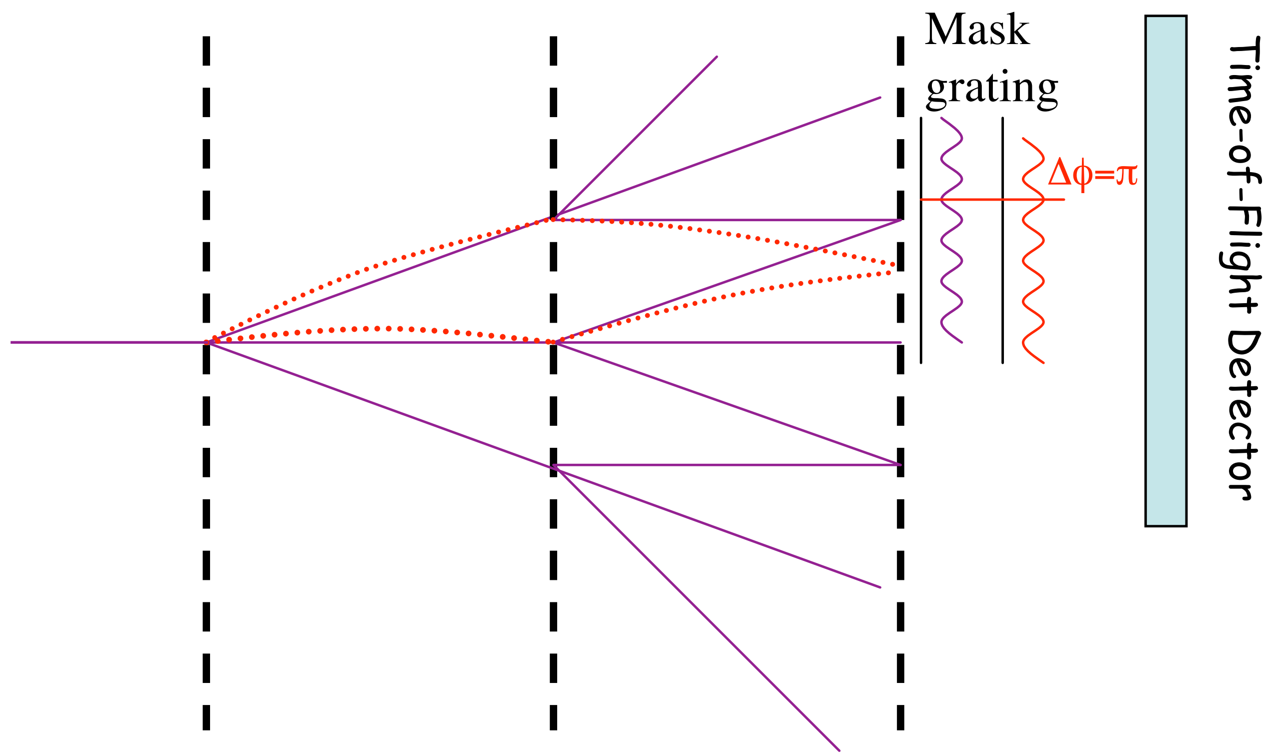
- From D. Christian:

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]:



- ~10^{-4} feasible with matter gratings
- ~10^{-9} with laser interferometer

- Not nutty!

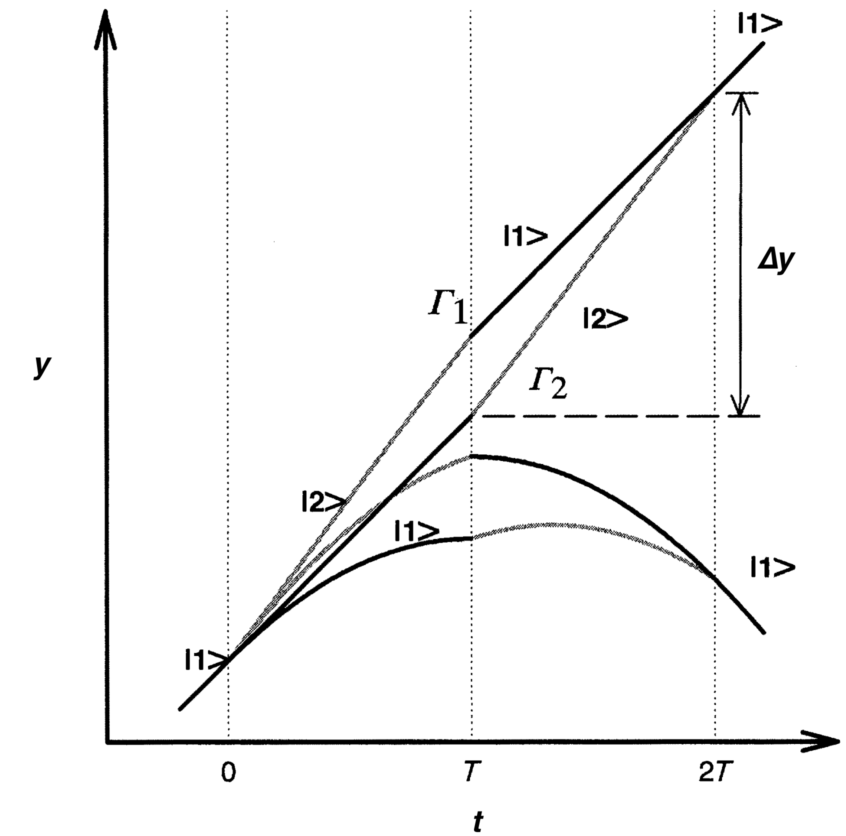
→ $\bar{g} = -g$ gives natural explanations for baryon asymmetry & dark energy

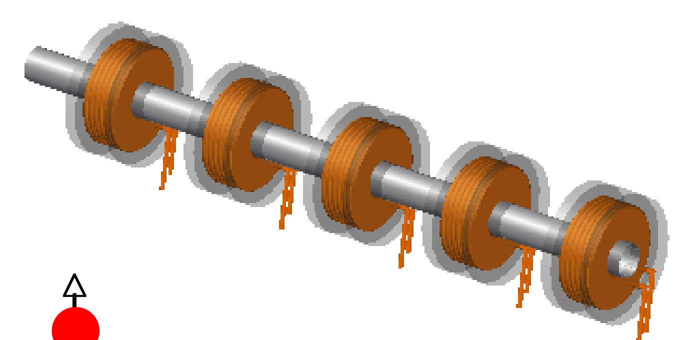
→ $\bar{g} = g + \varepsilon$ natural in quantum gravity due to scalar & vector terms

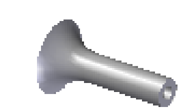
→ tests for possible "5th forces"

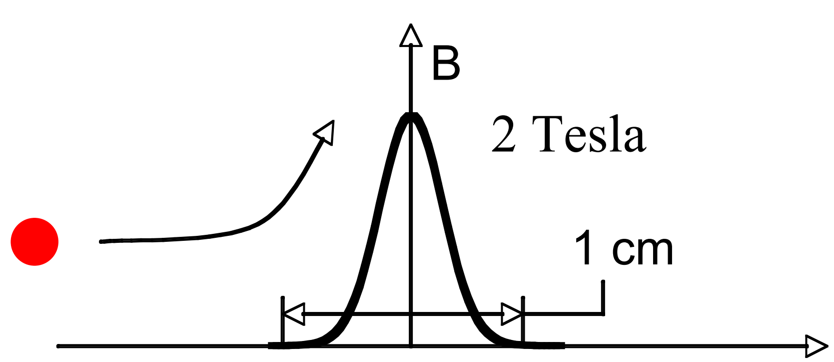
Antimatter Gravity

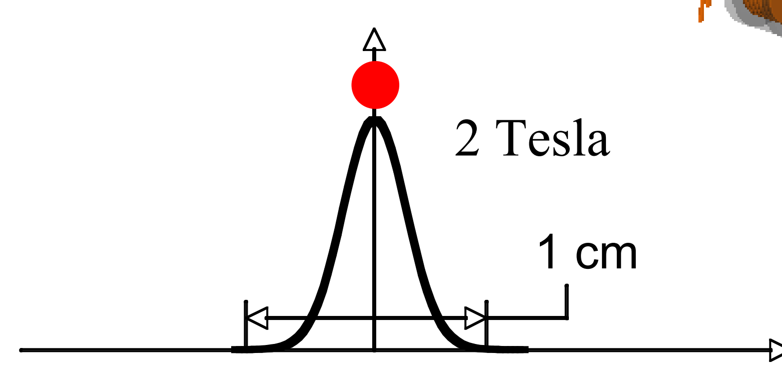
- “Ultimate” measurement:
  - instead of material gratings, use lasers à la S. Chu, M. Kasevich
  - slow down and trap the $\overline{\text{H}}$ atoms using “coilgun” (M. Raizen)
  - low-field seekers are repulsed by magnetic field











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

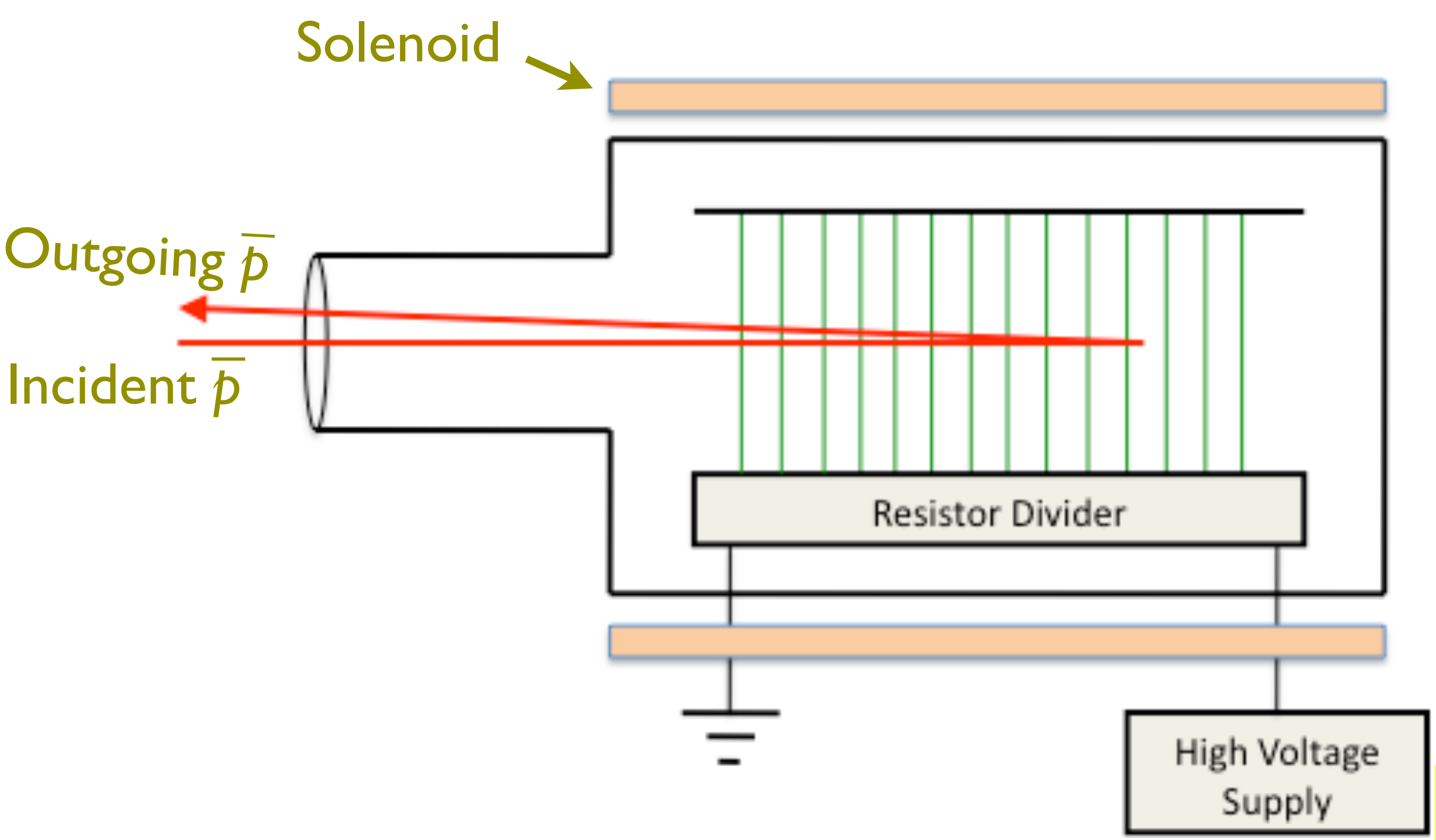
Antimatter Gravity

- 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 ~ month's dedicated running
  - eventually, add small synchrotron → 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 ≈40% effic. @ equilib. energy
- KE_{in} < ≈ few MeV, KE_{out} ≈ 20 keV