Antiprotons at Fermilab: New Directions in Hyperon, Charm, and Antimatter Physics

Daniel M. Kaplan

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Joint EP/PP Seminar
CERN
14 October 2008

Outline

(Varied menu!)

- Hyperon CP violation
- Low-energy antiprotons
- A new experiment
- Issues in charmonium
- Charm mixing
- Antihydrogen measurements
- Summary

Hyperon CP Violation?

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- An old topic:

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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.

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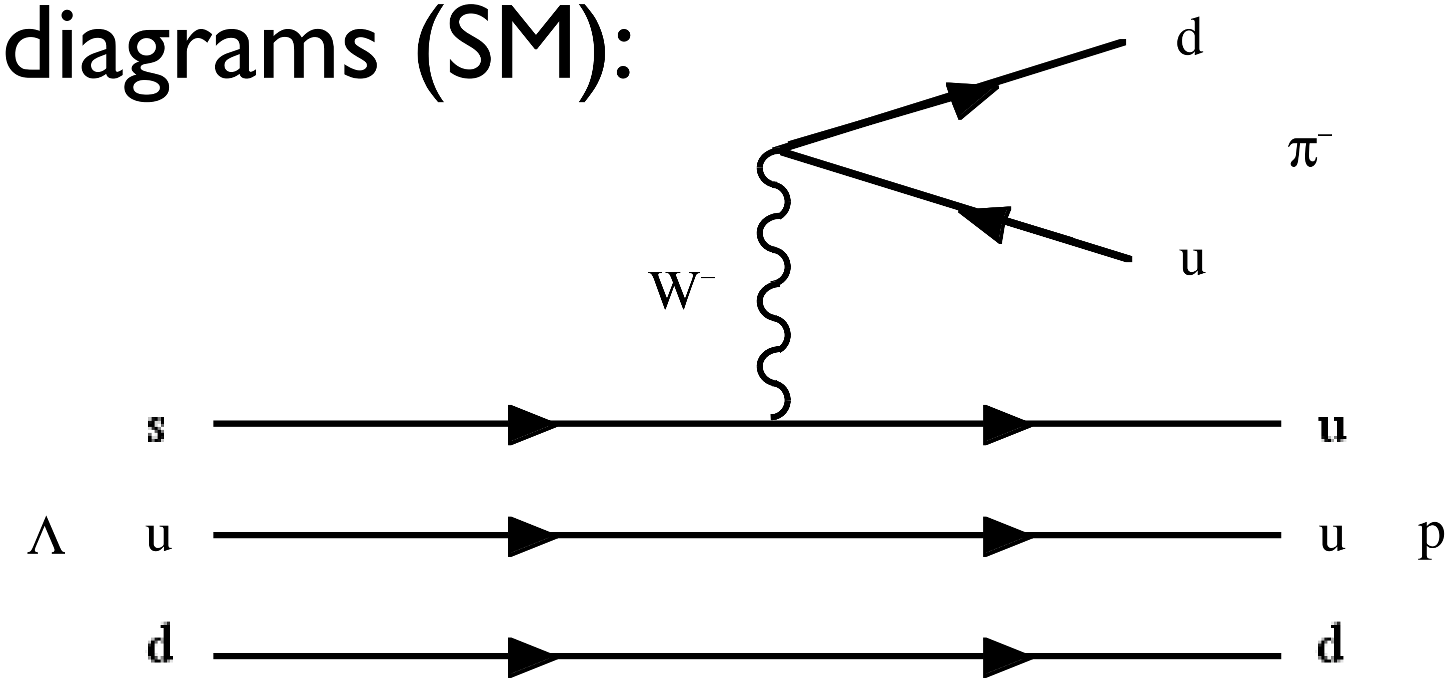
- Example Feynman diagrams (SM):

Λ decay:



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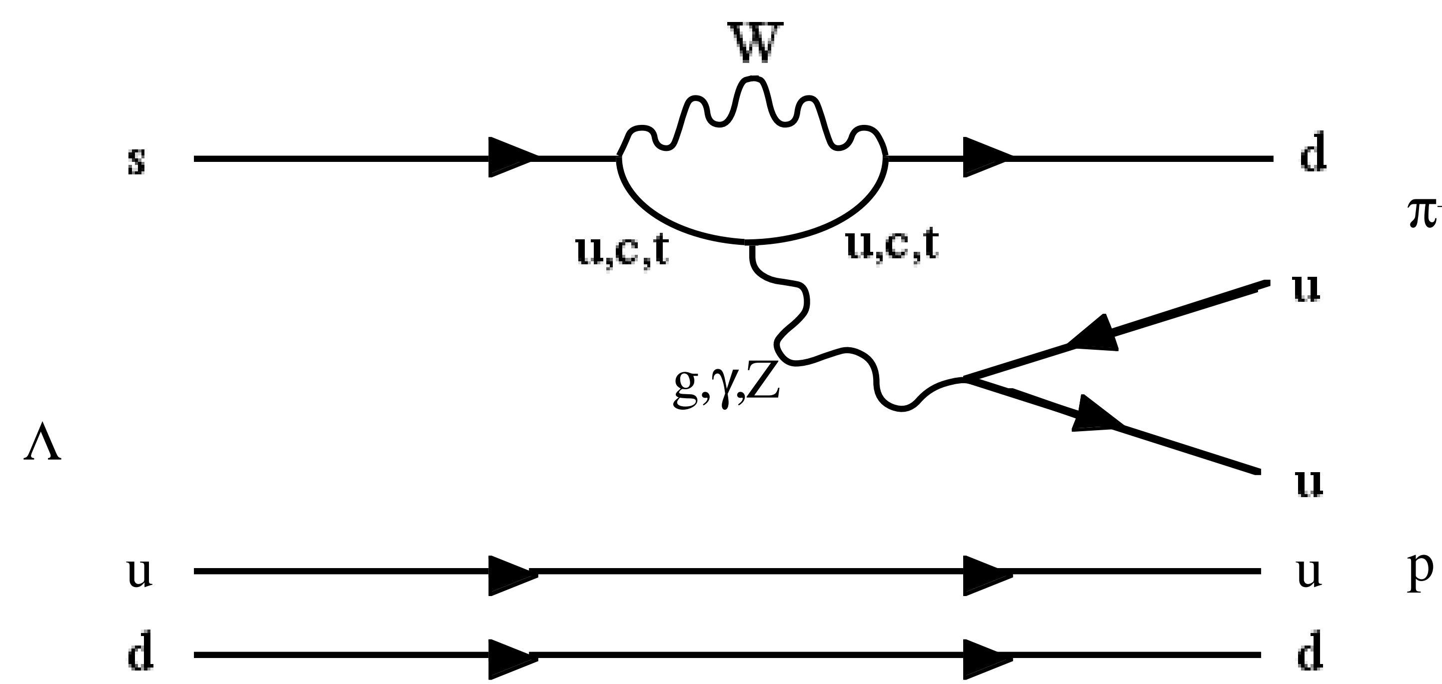

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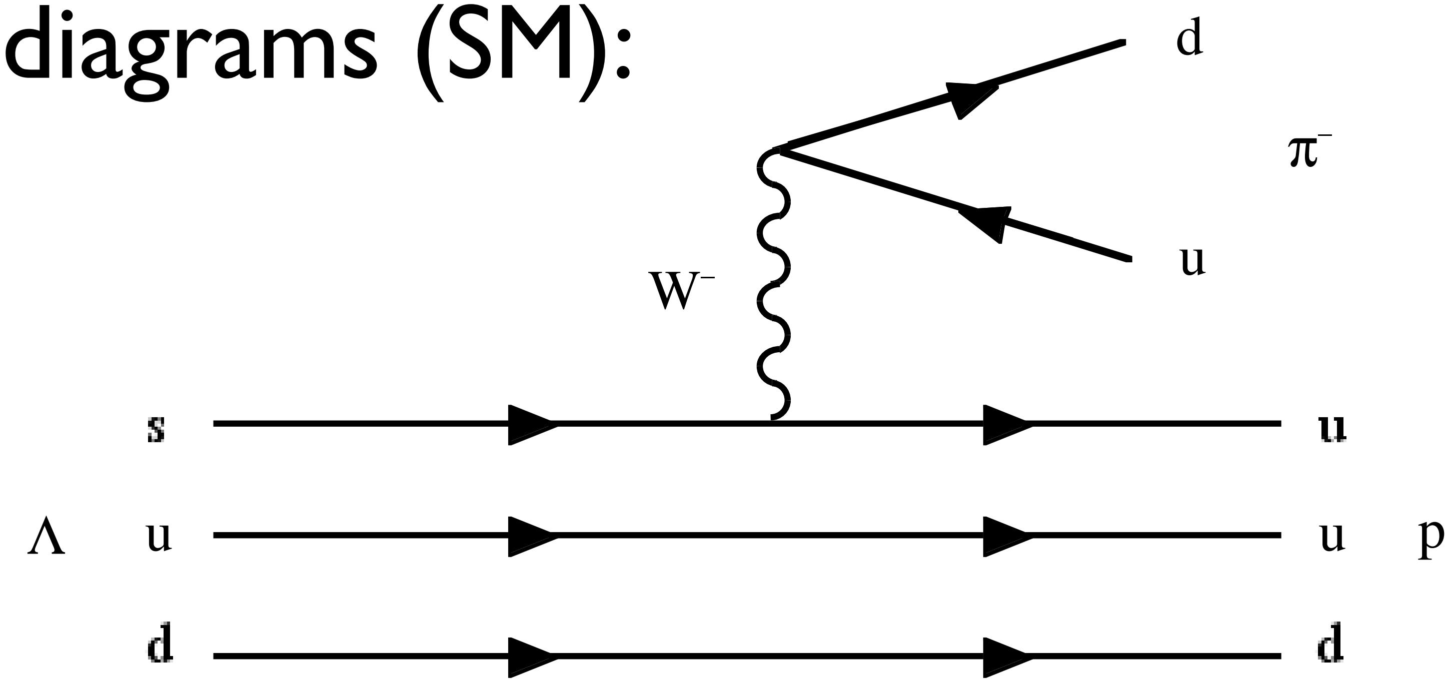

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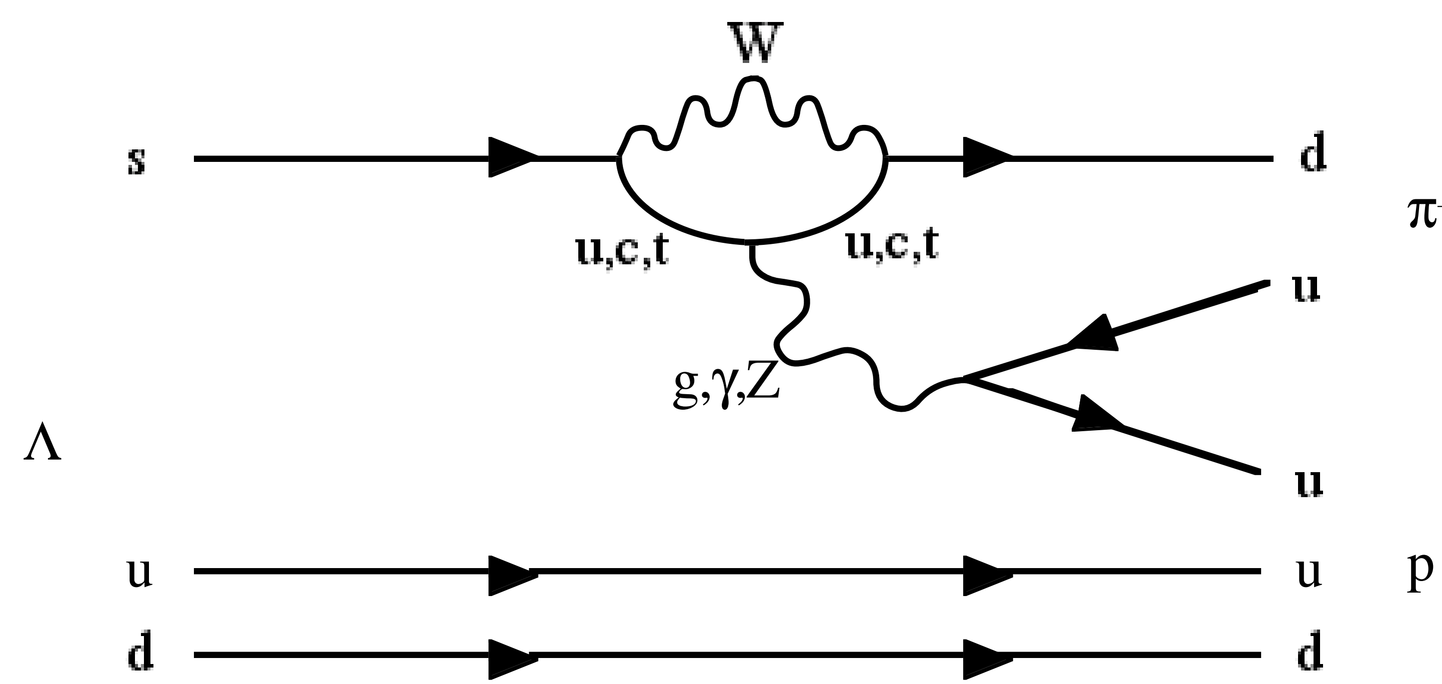

- New physics could also contribute!

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  - Decay amplitude for ΔS = 1 decay of spin-1/2 strange baryon into spin-1/2 baryon and meson (e.g., $\Lambda \to p\,\pi^-$):

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

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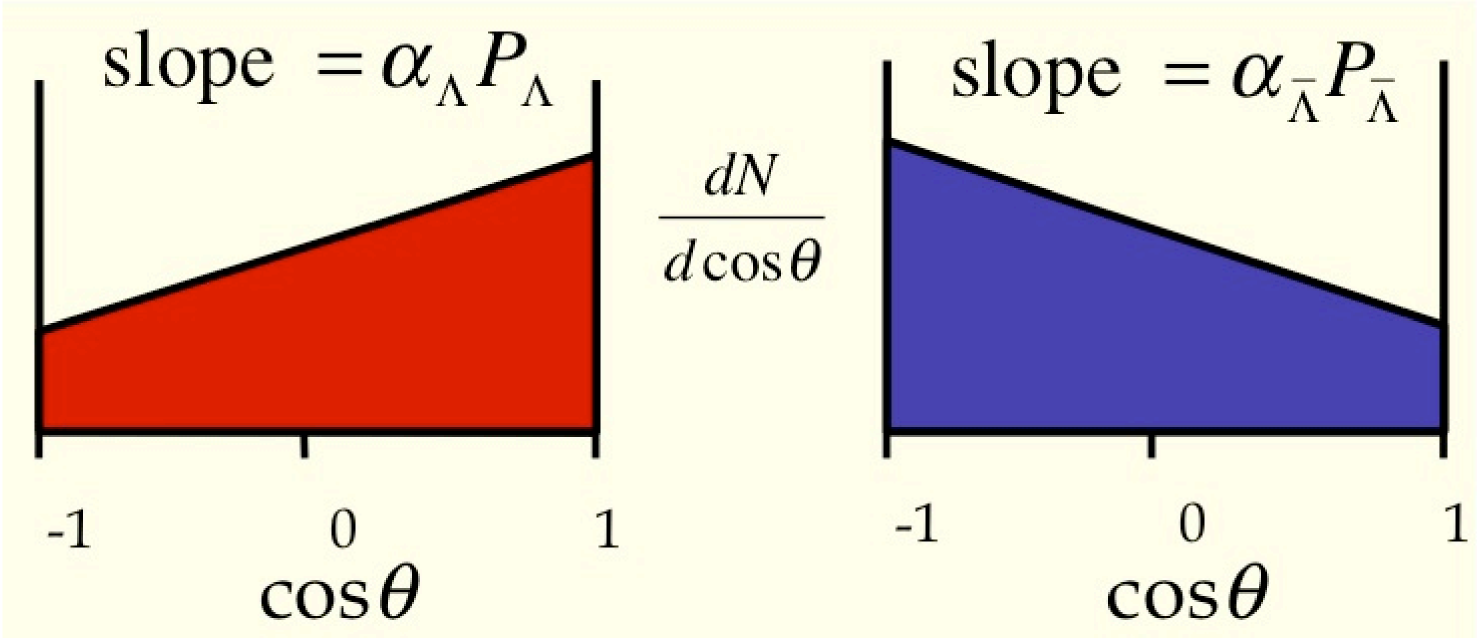

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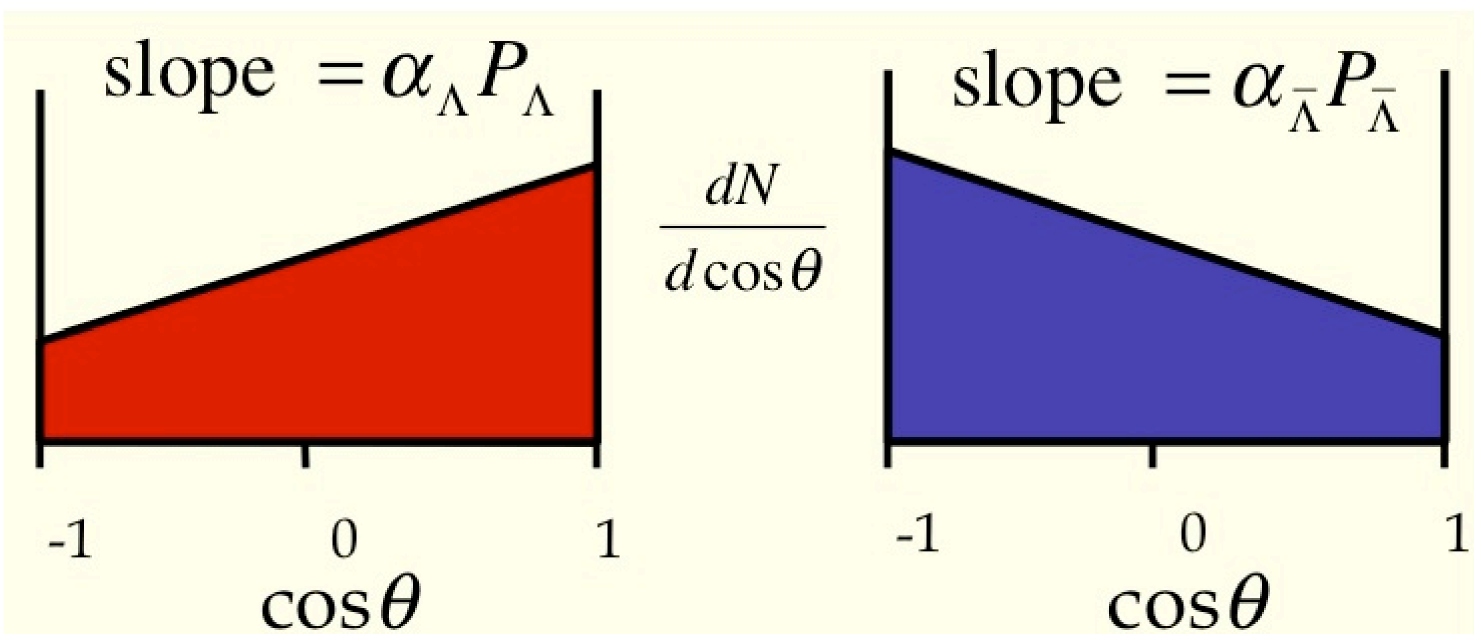

- *CP* conserved ⇔ slope = – $\overline{\text{slope}}$

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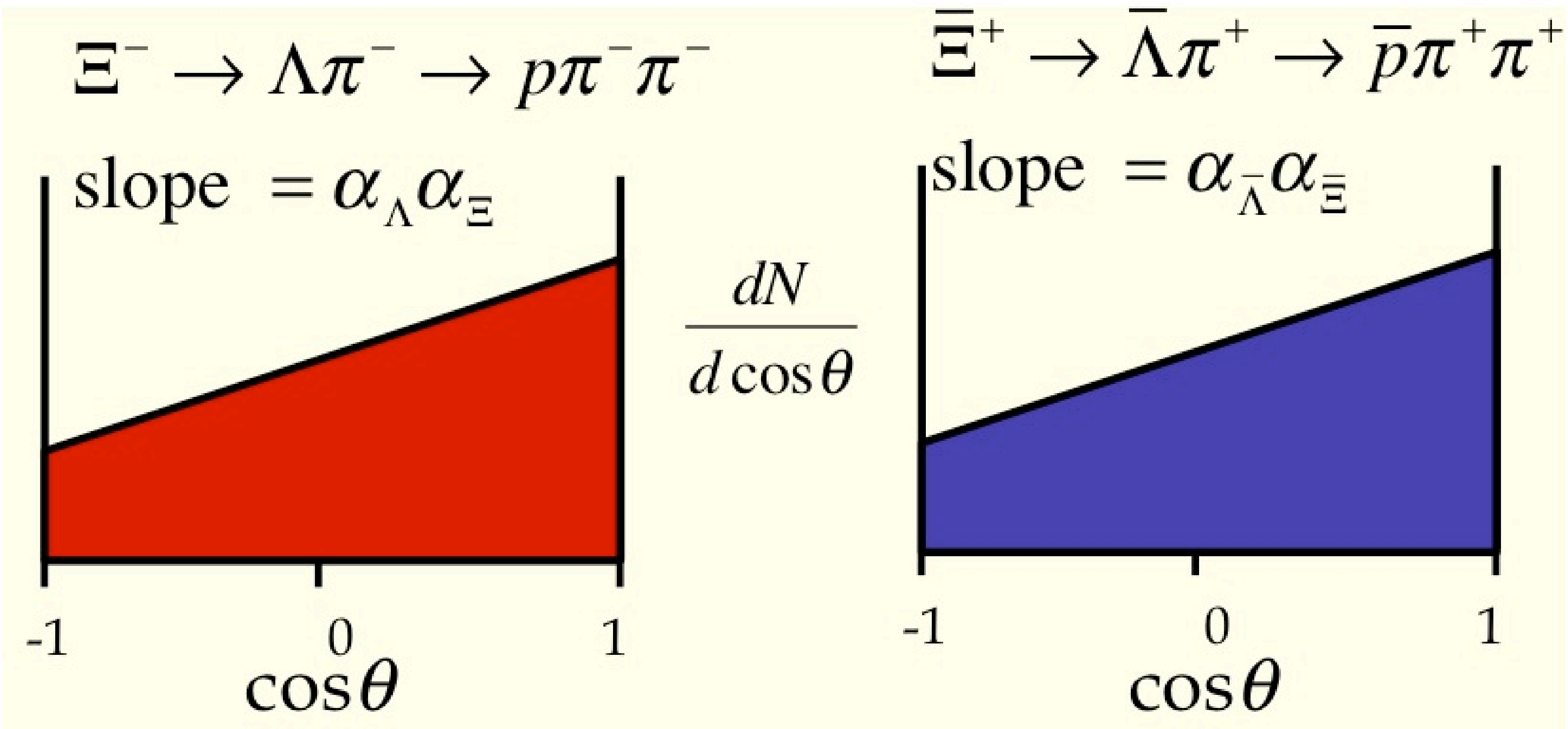

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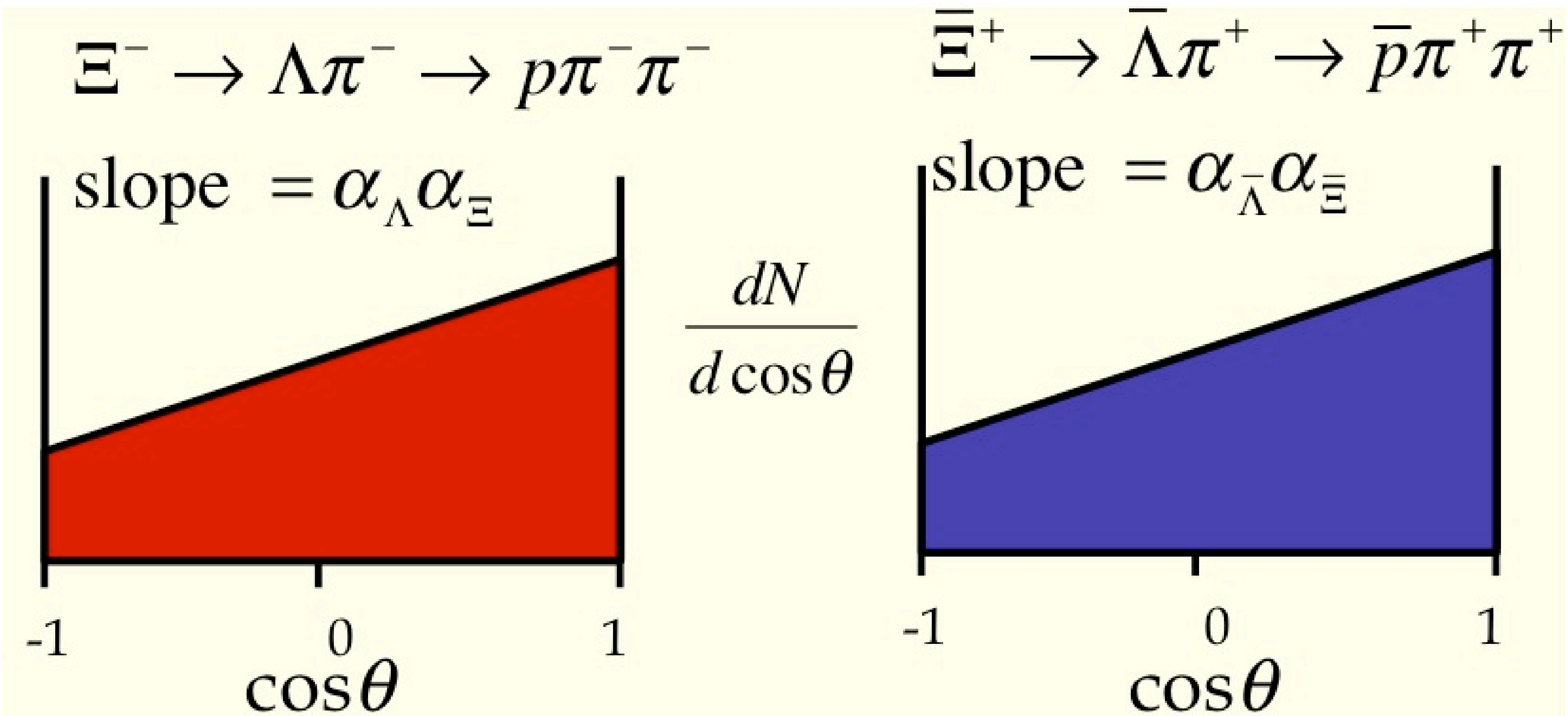

- Unequal slopes ⇒ *CP* violated!

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- 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: $\mathcal{O}(10^{-3})$
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Experiment	Decay Mode	A_Λ	
R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$	-0.02 ± 0.14	[P. Chauvat et al., PL 163B (1985) 273]
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	0.01 ± 0.10	[M.H. Tixier et al., PL B212 (1988) 523]
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	0.006 ± 0.015	[P.D. Barnes et al., NP B 56A (1997) 46]

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

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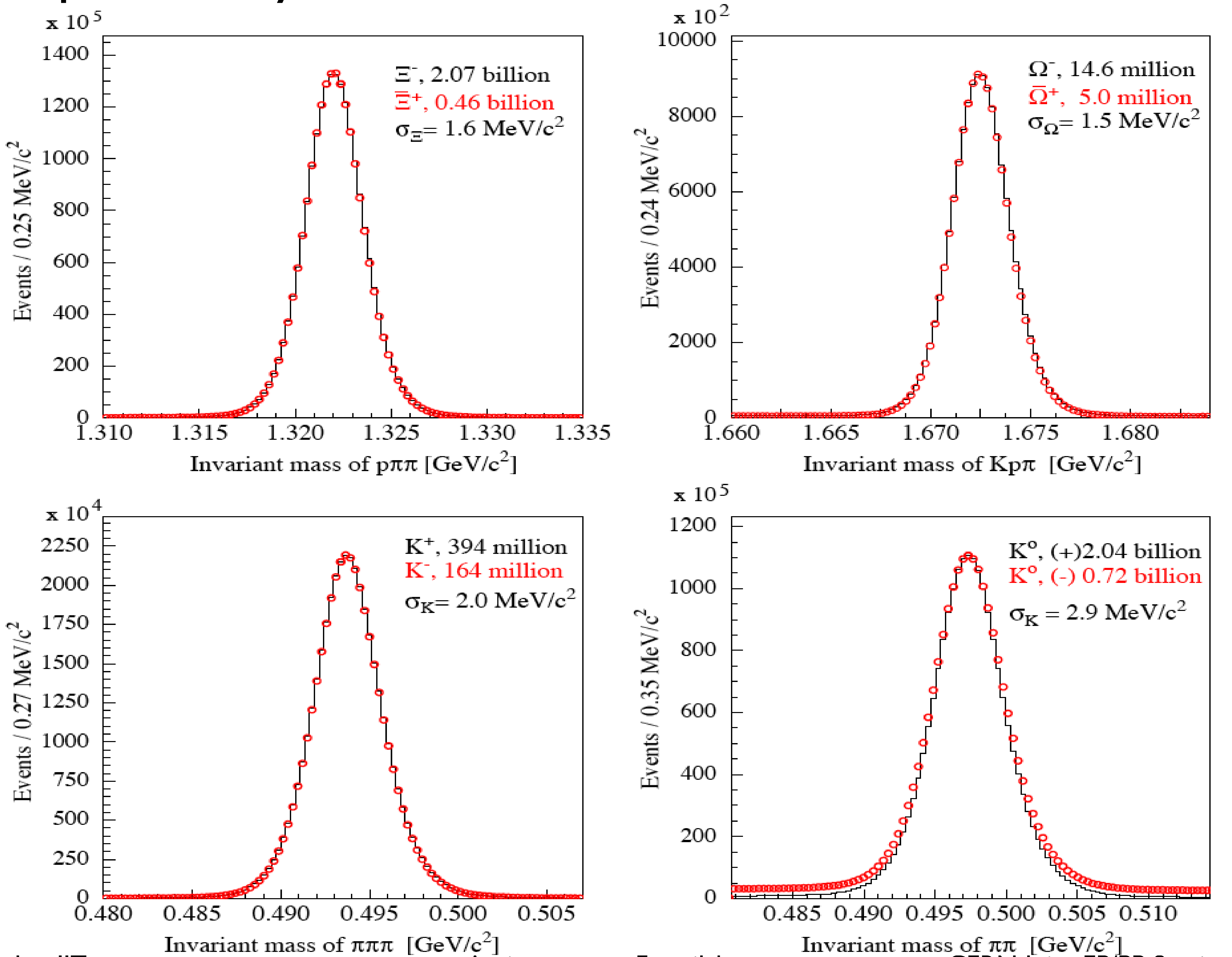

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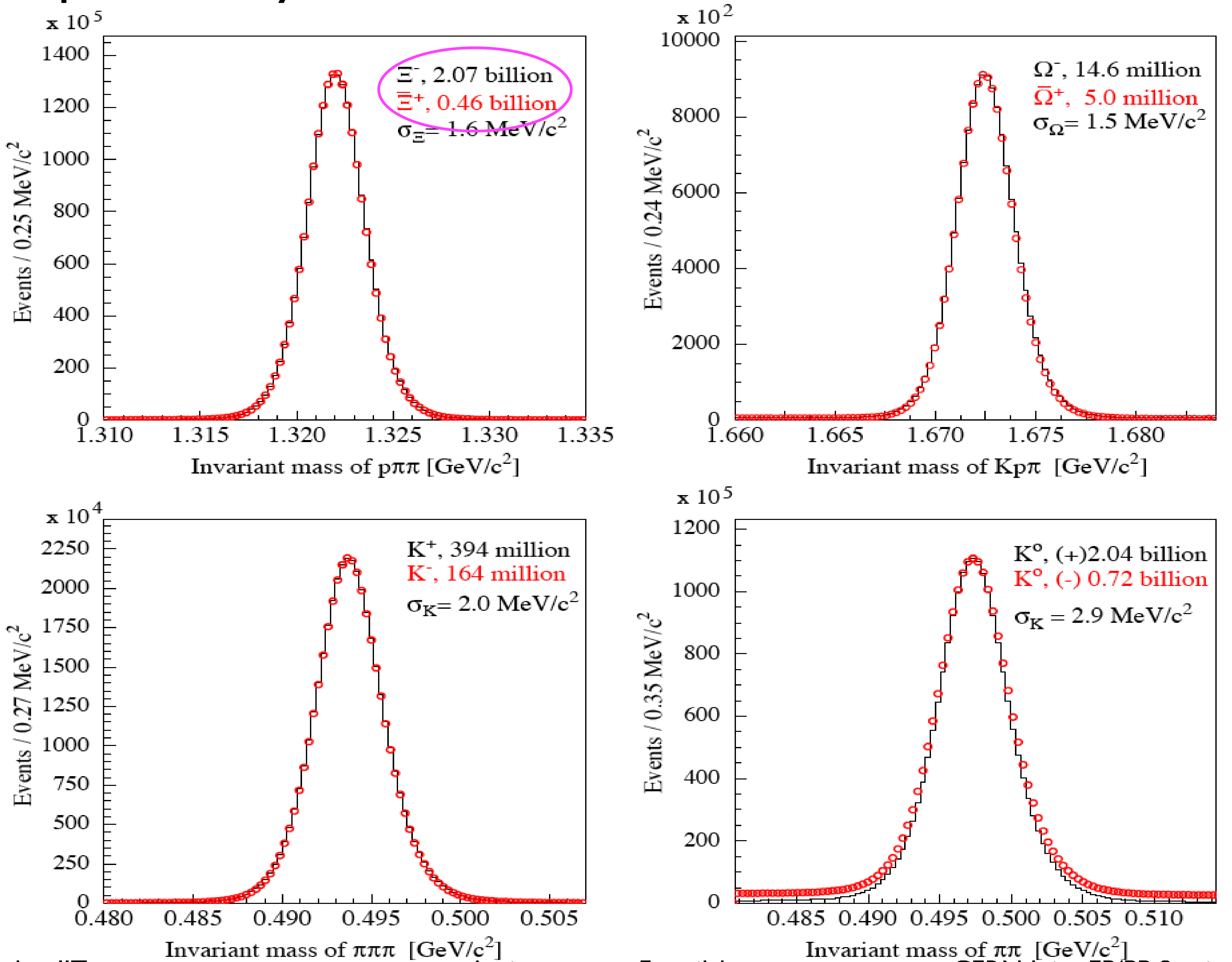

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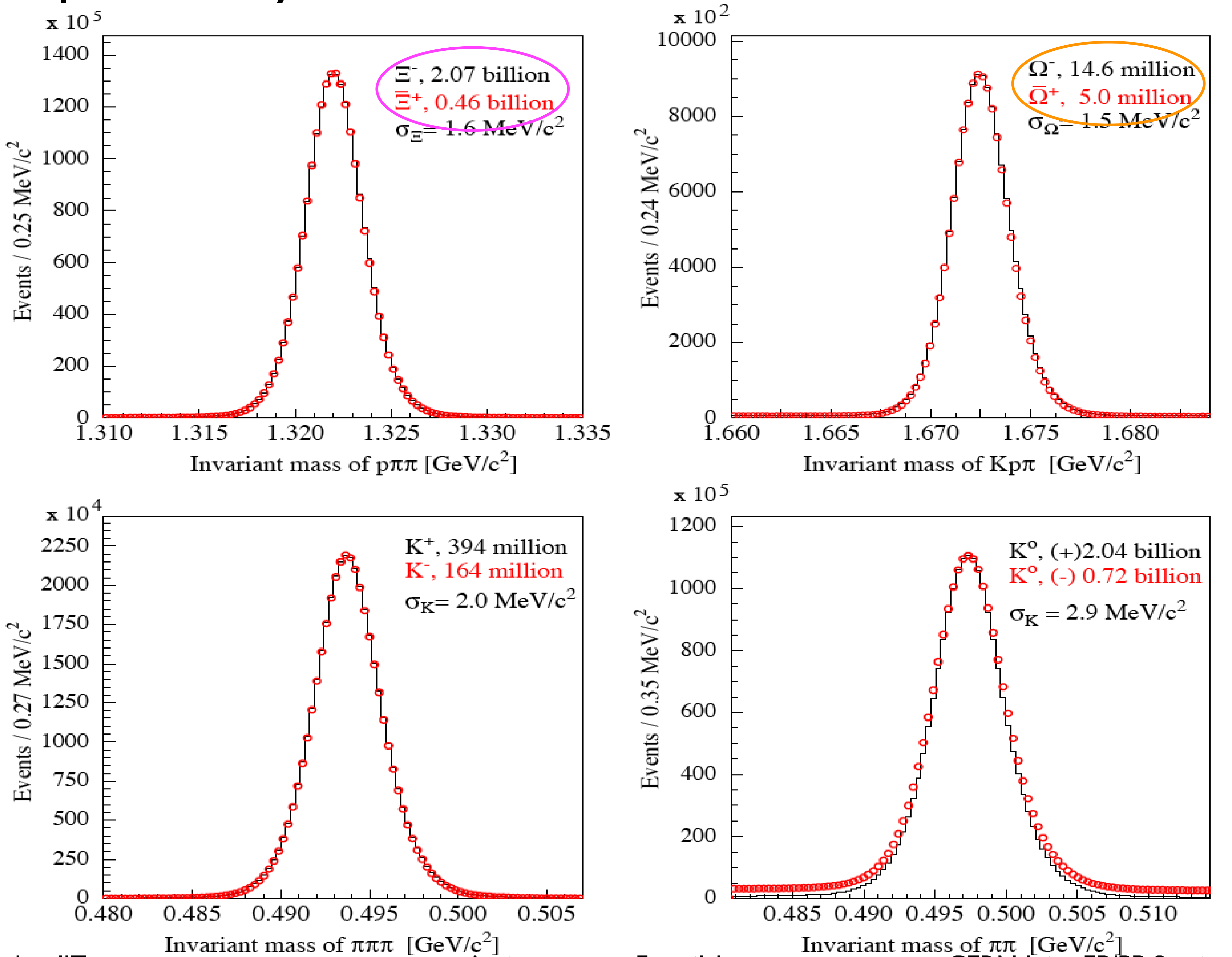
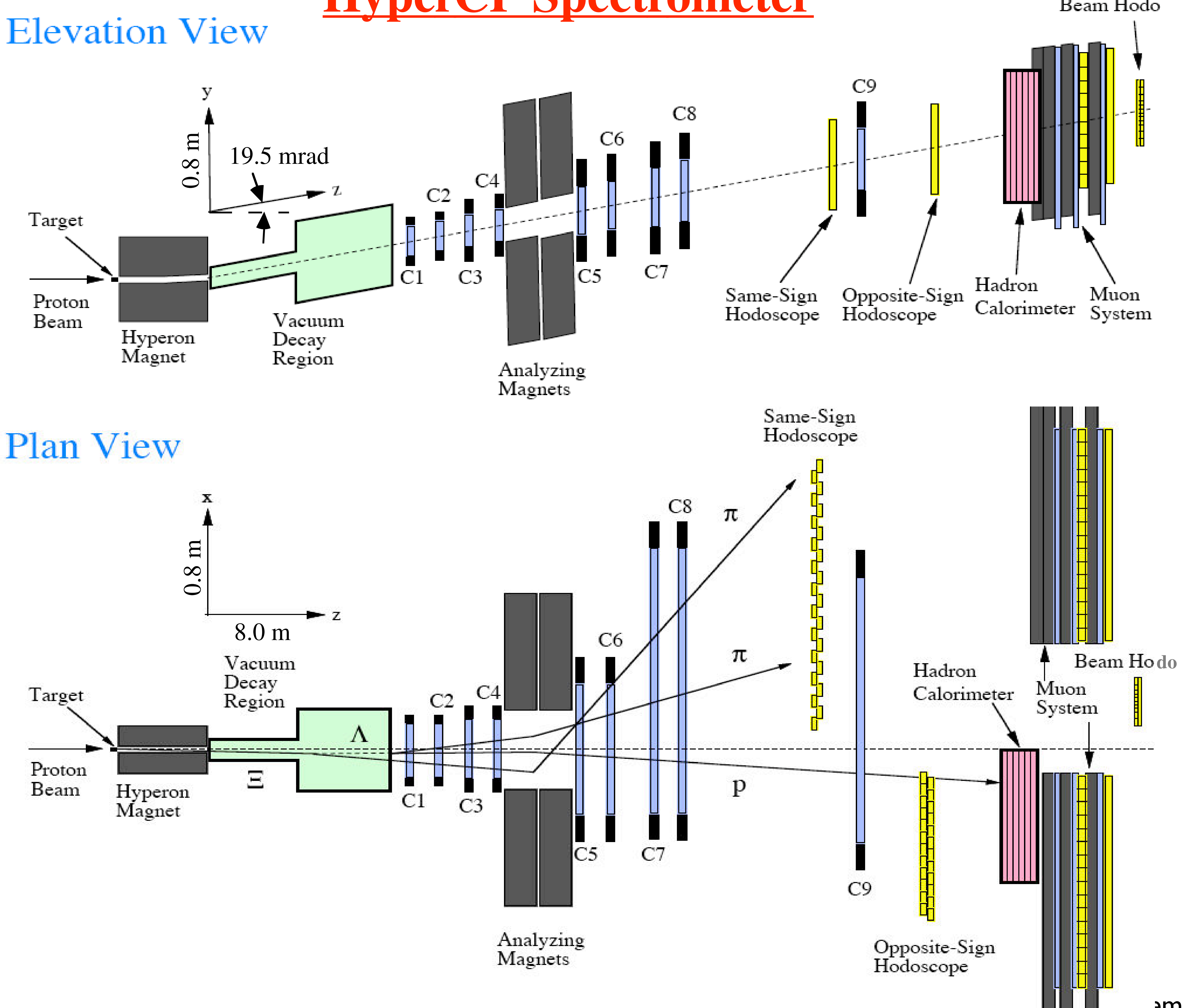


HyperCP Spectrometer



...and Fast HyperCP DAQ System

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≈20,000 channels of MWPC latches

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...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

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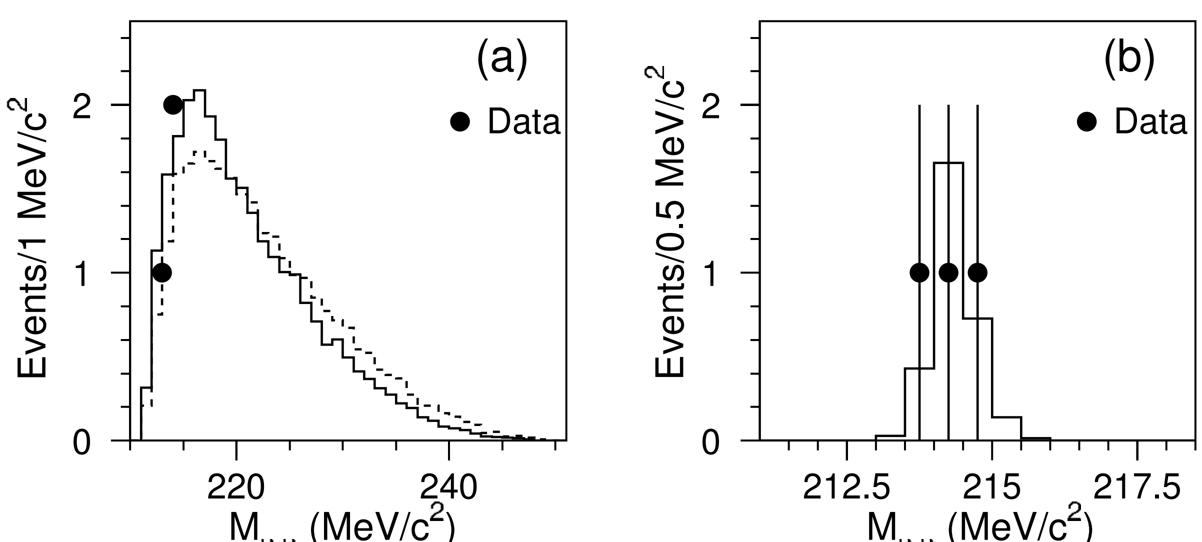

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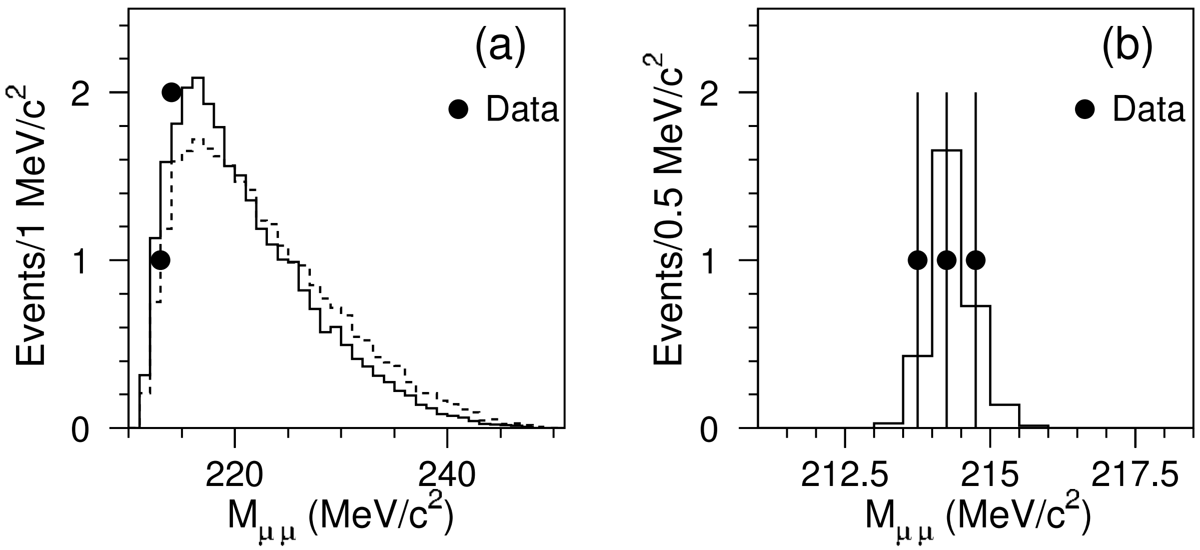

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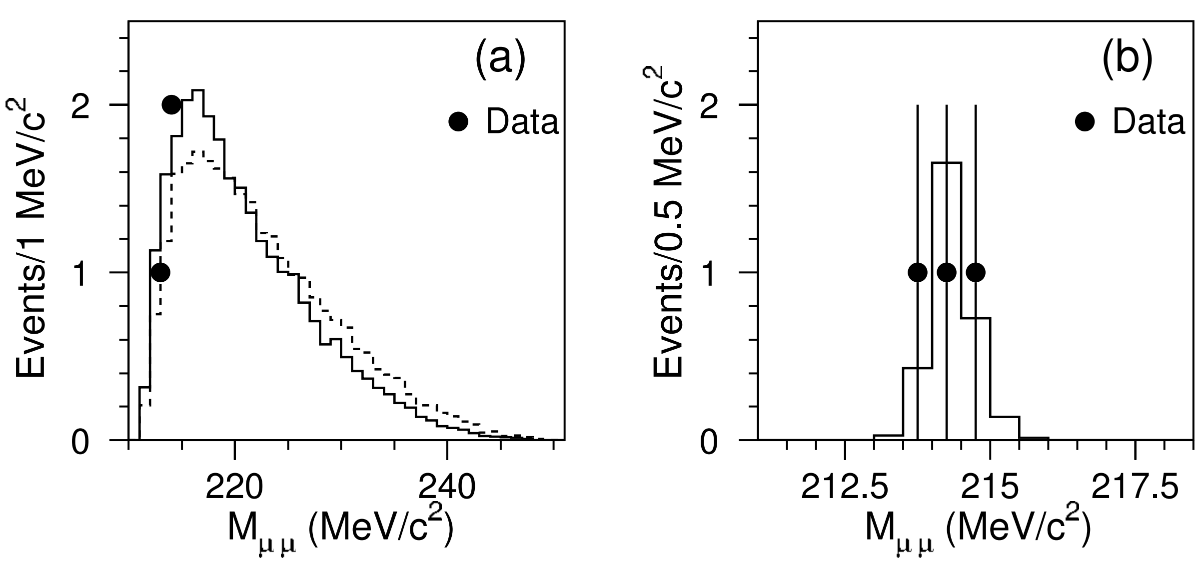

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- SUSY Sgoldstino?
- SUSY light Higgs?

Does the HyperCP Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$ 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 $\Sigma^+ \to p\mu^+\mu^-$ 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.

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Jusak Tandean†

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

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

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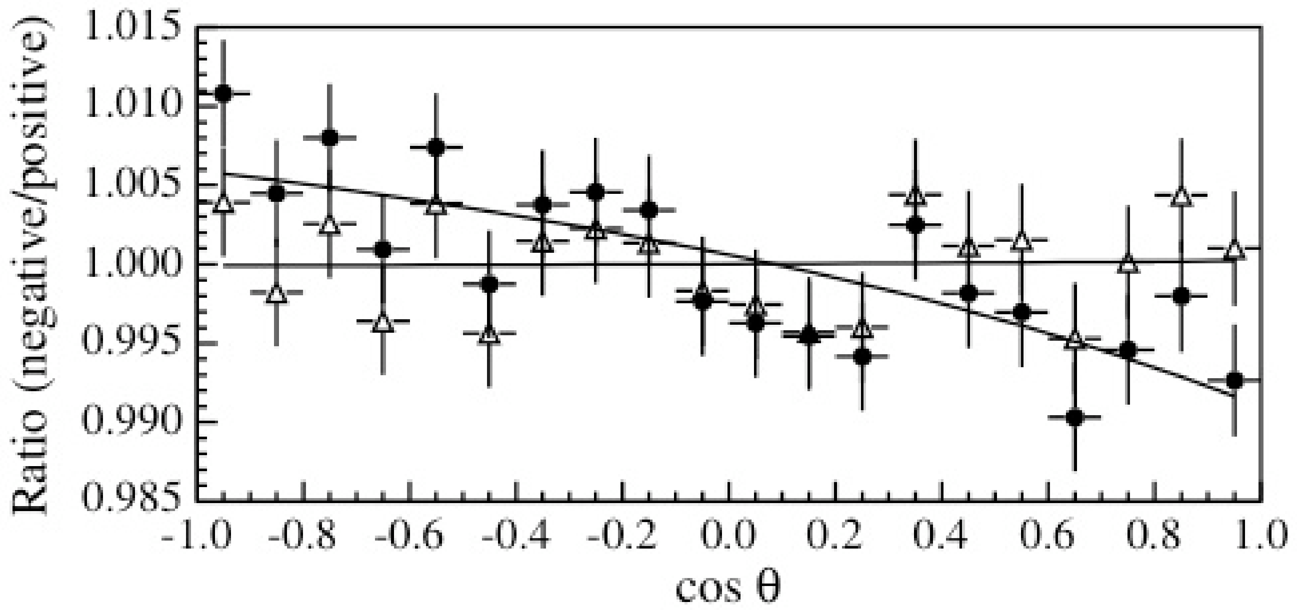

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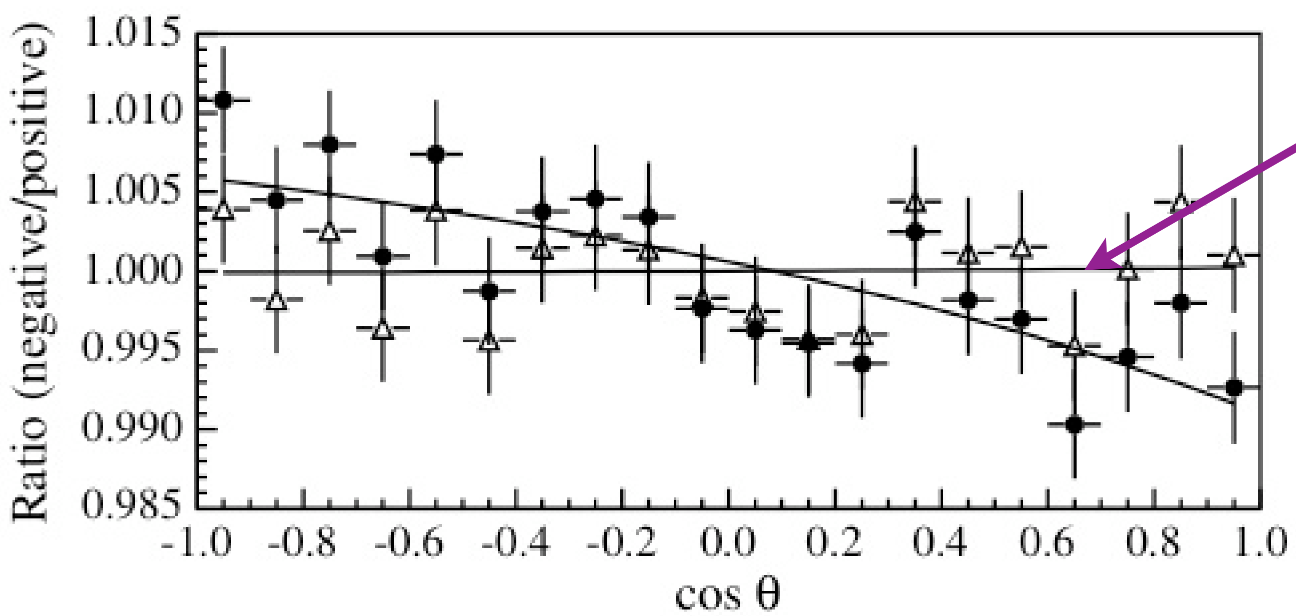

After weighting events to correct for unequal production spectra, etc.: $\delta(\cos\theta \text{ slope}) = 0$

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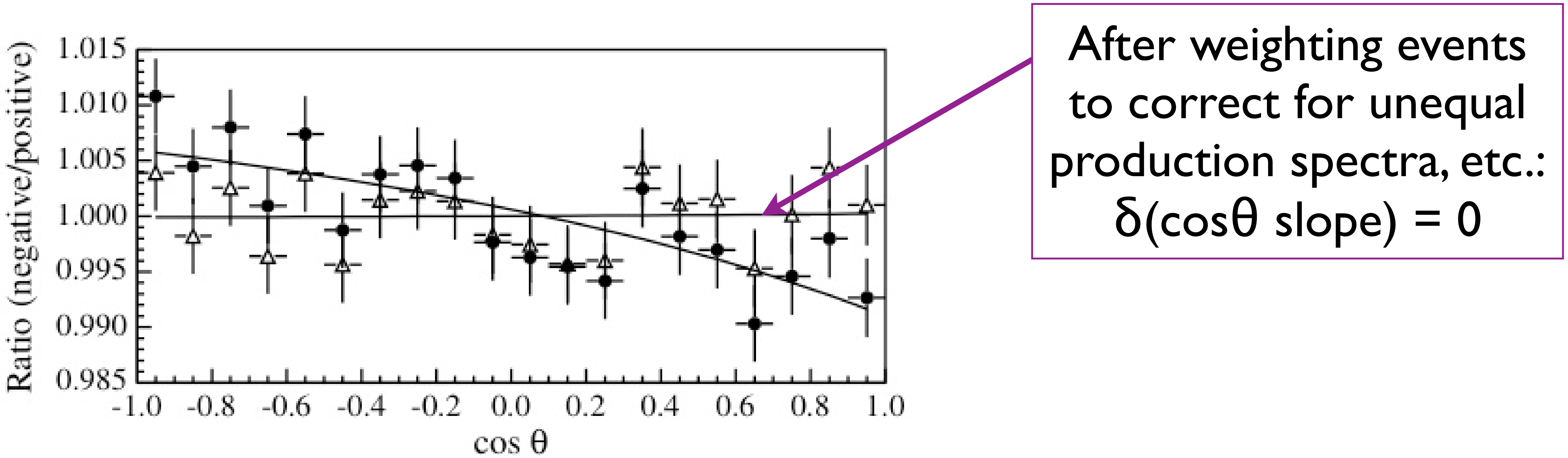

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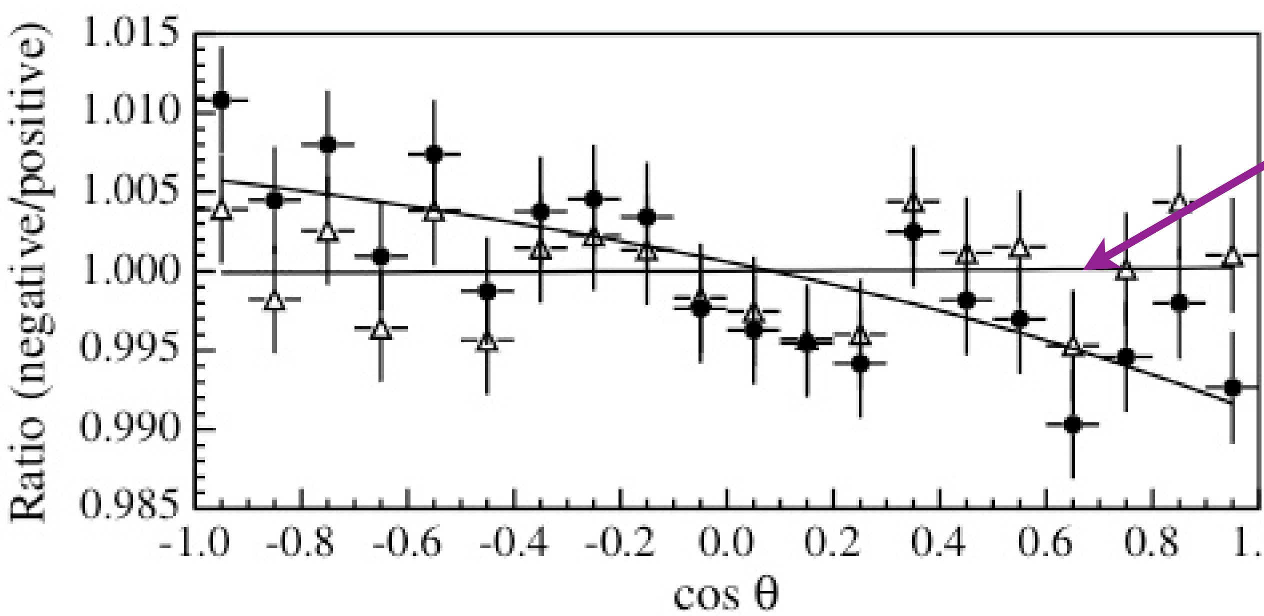

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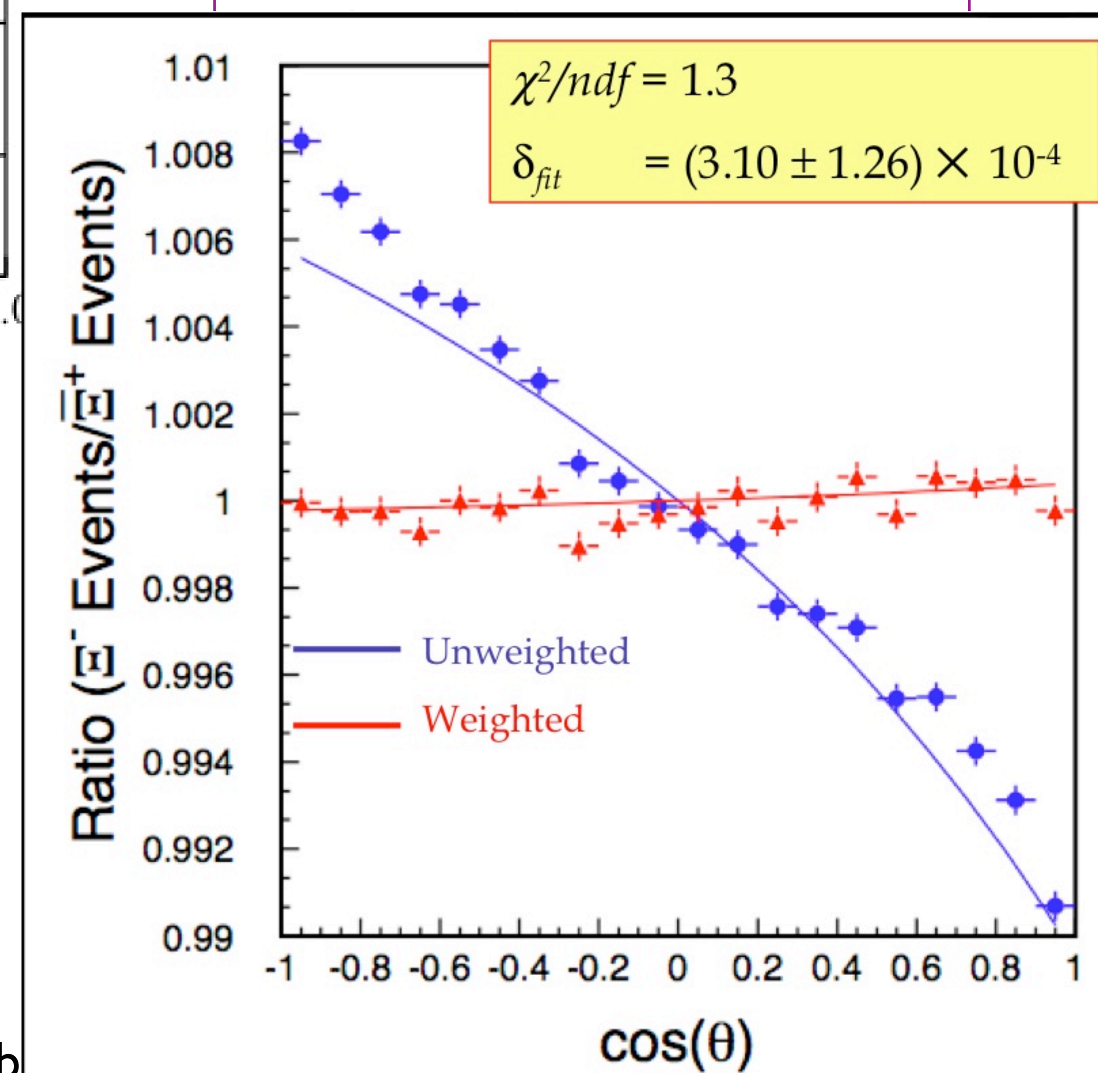

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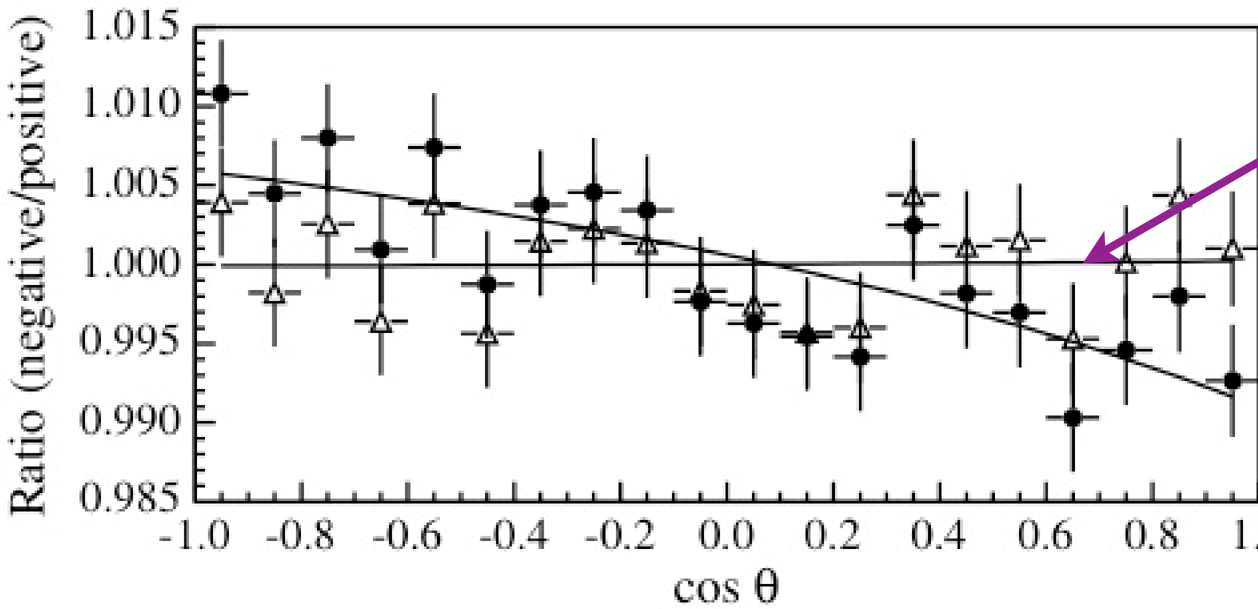

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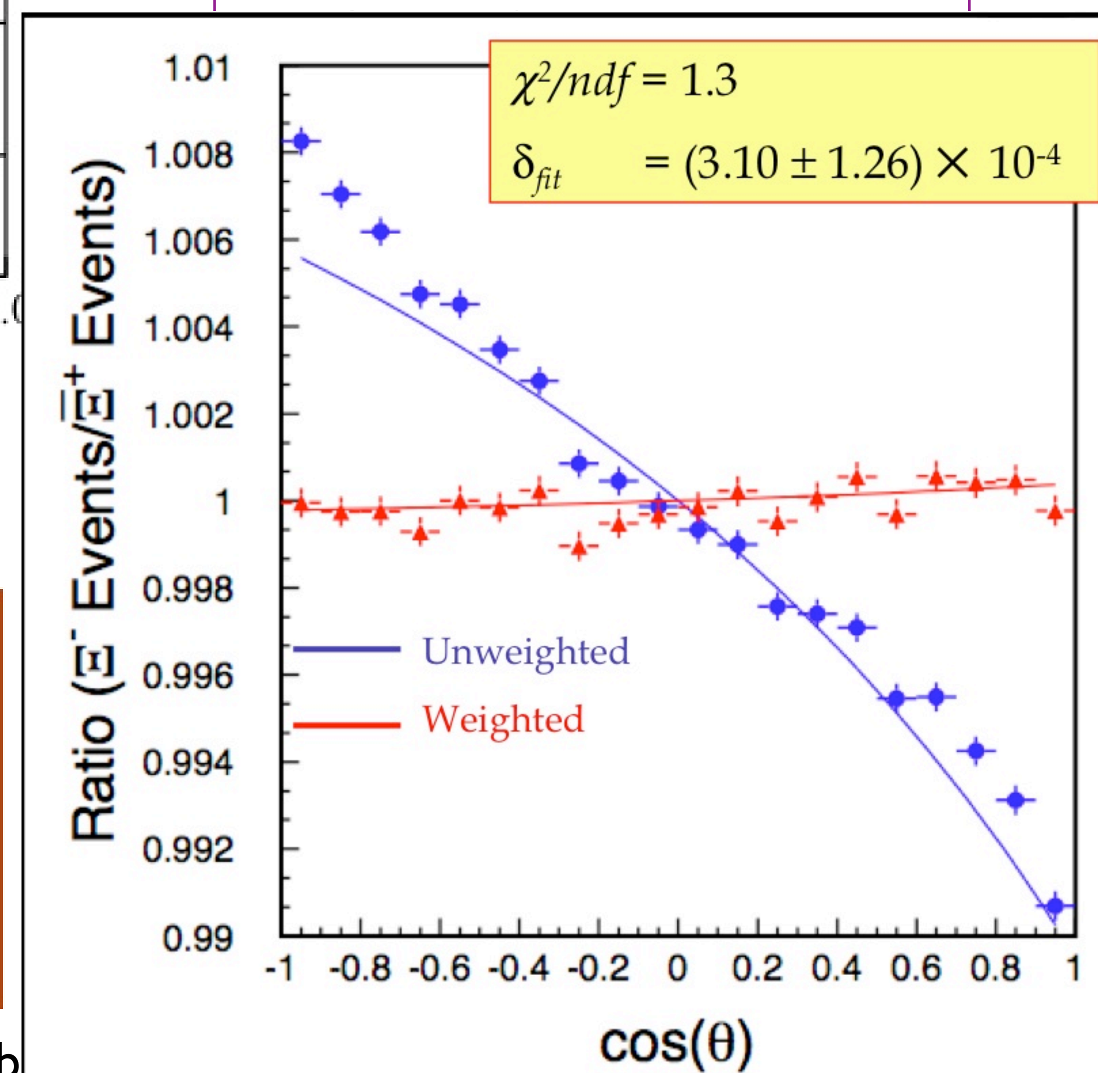

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$$A_{\Xi\Lambda} = \frac{\alpha_\Xi \alpha_\Lambda - \alpha_{\bar{\Xi}} \alpha_{\bar{\Lambda}}}{\alpha_\Xi \alpha_\Lambda + \alpha_{\bar{\Xi}} \alpha_{\bar{\Lambda}}}$$
$$= [-6.0 \pm 2.1(stat) \pm 2.1(syst)] \times 10^{-4}$$

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- Main Injector fixed-target not as good (same reasons)
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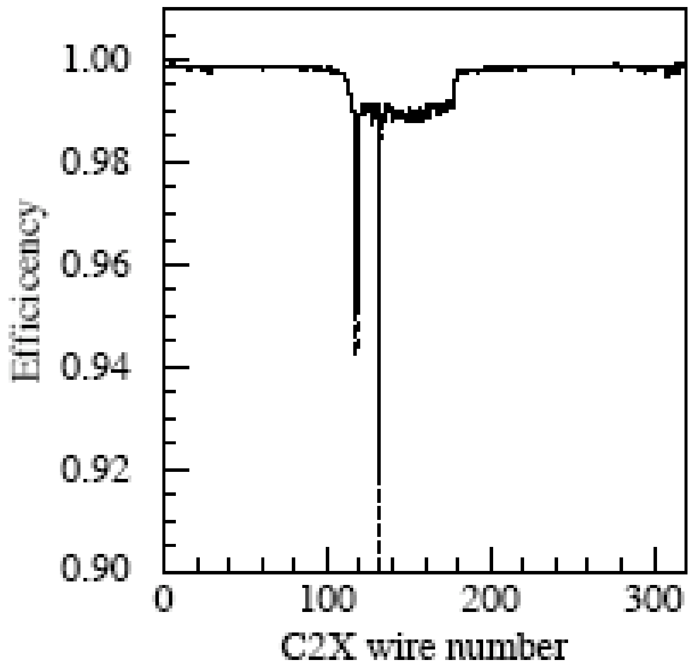

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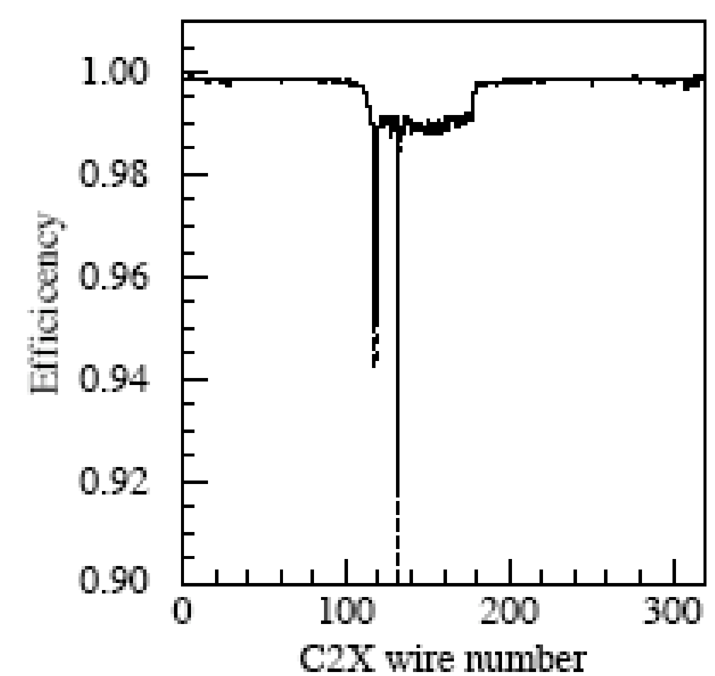

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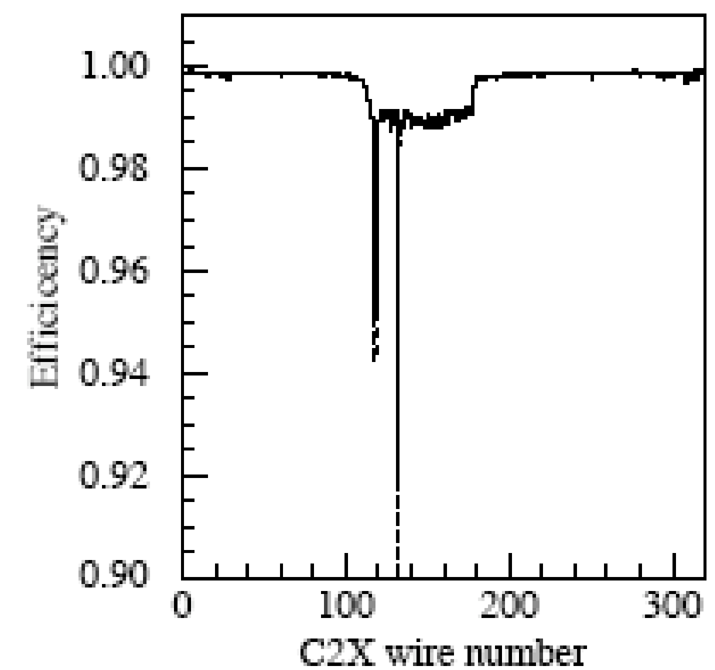

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➡ What else is there?

Low-Energy Antiprotons!

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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 ± 6.7) × 10^{-4}**	[T. Holmstrom et al., PRL 93. 262001 (2004)]
		(6 ± 2 ± 2) × 10^{-4}	[BEACH08 preliminary]

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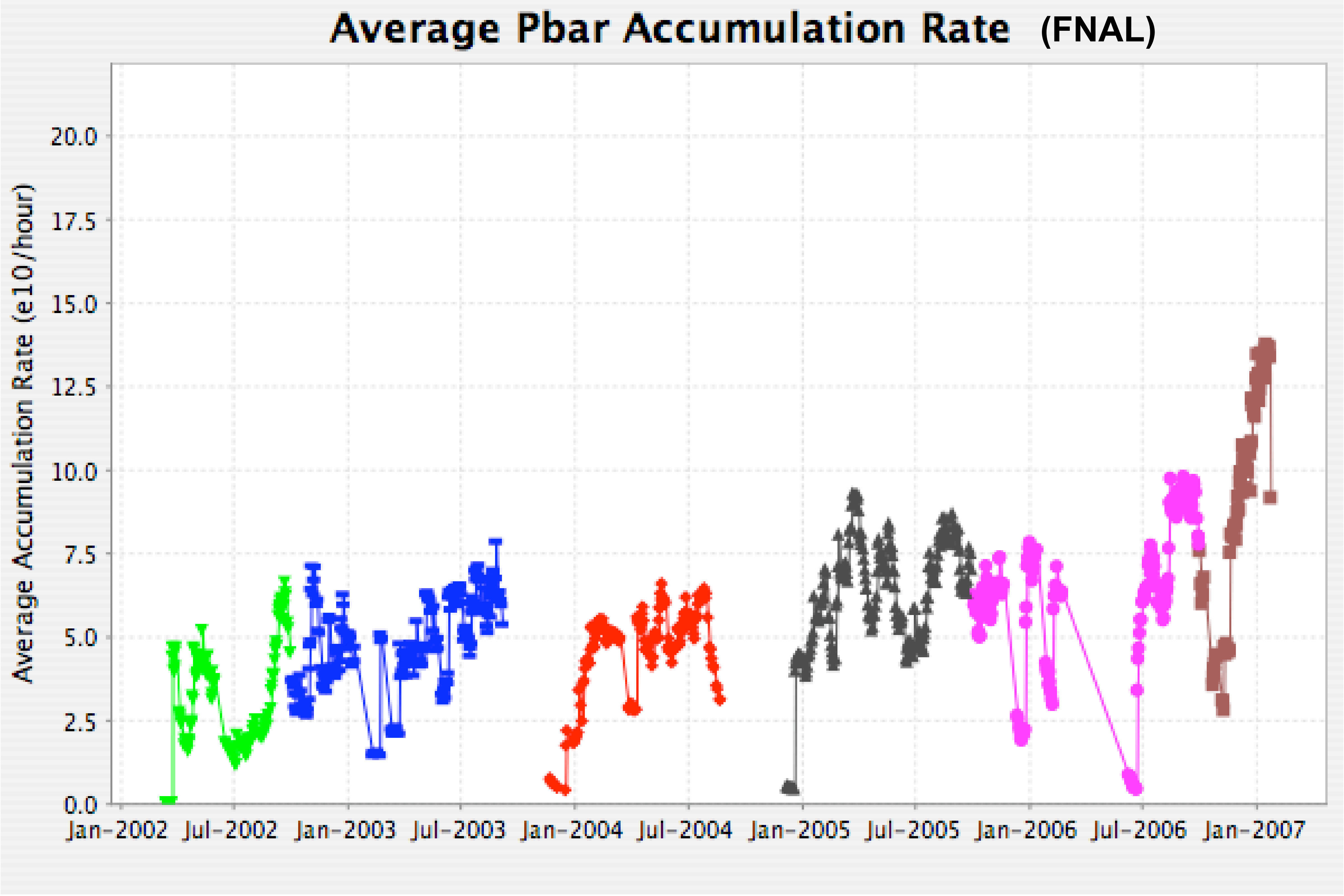

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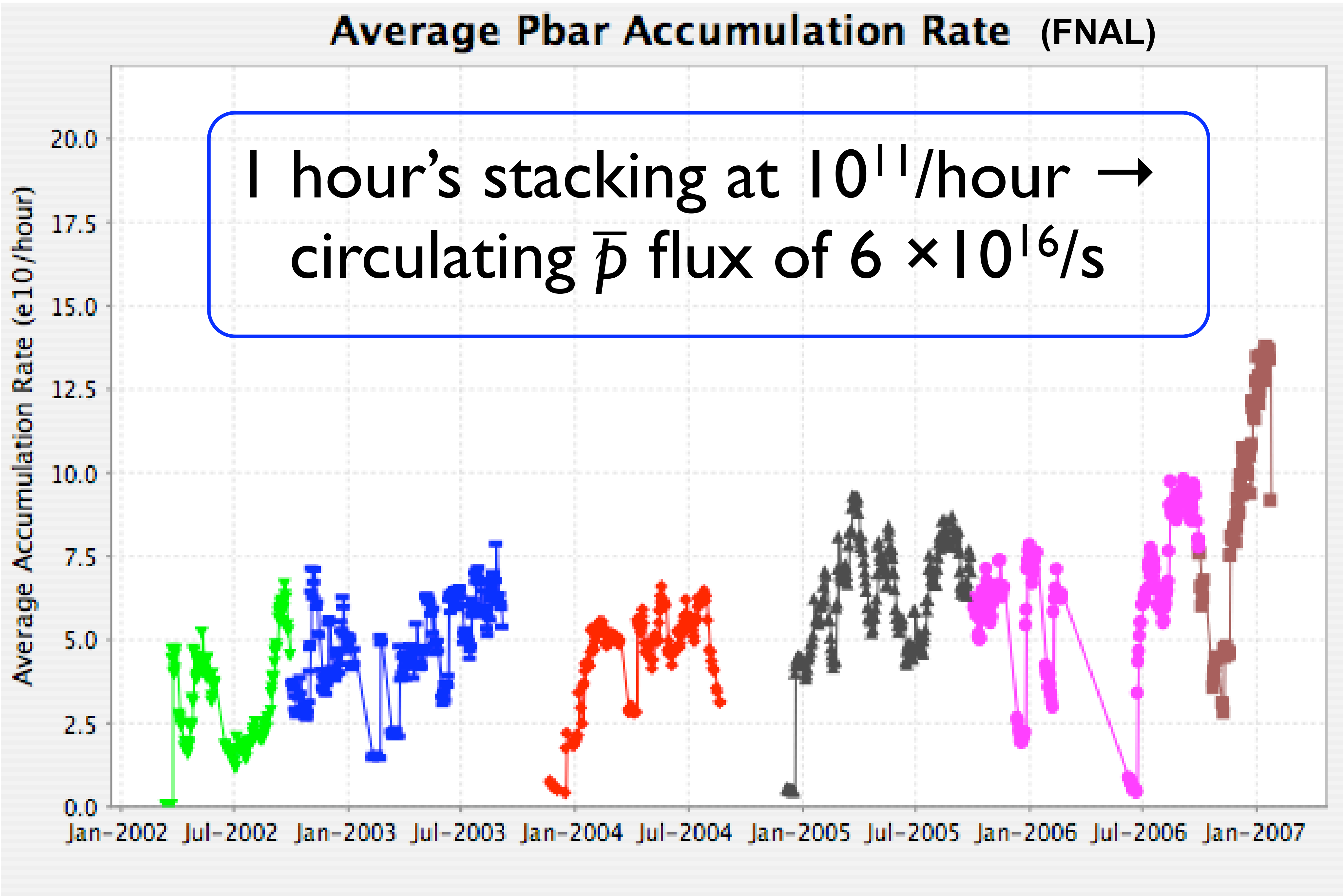

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$\chi_{c0}(1P)$ $\qquad I^G(J^{PC}) = 0^+(0^{++})$

$\chi_{c0}(1P)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3414.76±0.35 OUR AVERAGE		Error includes scale factor of 1.2.			
3414.21±0.39±0.27		ABLIKIM	05G	BES2	$\psi(2S) \to \gamma\chi_{c0}$
3414.7 $^{+0.7}_{-0.6}$ ±0.2		[1] ANDREOTTI	03	E835	$\bar{p}p \to \chi_{c0} \to \pi^0\pi^0$
3415.5 ±0.4 ±0.4	392	[2] BAGNASCO	02	E835	$\bar{p}p \to \chi_{c0} \to J/\psi\gamma$
3417.4 $^{+1.8}_{-1.9}$ ±0.2		[1] AMBROGIANI	99B	E835	$\bar{p}p \to e^+e^-\gamma$
3414.1 ±0.6 ±0.8		BAI	99B	BES	$\psi(2S) \to \gamma X$
3417.8 ±0.4 ±4		[1] GAISER	86	CBAL	$\psi(2S) \to \gamma X$

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$\chi_{c0}(1P)$ $\qquad I^G(J^{PC}) = 0^+(0^{++})$

$\chi_{c2}(1P)$ $\qquad I^G(J^{PC}) = 0^+(2^{++})$

See the Review on "$\psi(2S)$ and χ_c branching ratios" before the $\chi_{c0}(1P)$ Listings.

$\chi_{c2}(1P)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3556.20 ± 0.09 OUR AVERAGE					
3555.70 ± 0.59 ±0.39		ABLIKIM	05G	BES2	$\psi(2S) \to \gamma\chi_{c2}$
3556.173 ± 0.123 ± 0.020		ANDREOTTI	05A	E835	$p\overline{p} \to e^+e^-\gamma$
3559.9 ± 2.9		EISENSTEIN	01	CLE2	$e^+e^- \to e^+e^-\chi_{c2}$
3556.4 ± 0.7		BAI	99B	BES	$\psi(2S) \to \gamma X$
3556.22 ± 0.131 ± 0.020	585	[1] ARMSTRONG	92	E760	$\overline{p}p \to e^+e^-\gamma$

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  - Thanks to superb precision of antiproton beam energy and momentum spread, E760/835 @ Fermilab Antiproton Accumulator made very precise measurements
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parameters, e.g.:
    - best measurements of various η_c, χ_c, h_c masses, widths, branching ratios,...
    - interference of continuum & resonance signals
- GSI-Darmstadt upgrading to similar facility, done ≈2015

Low-Energy Antiprotons!

- Fermilab Antiproton Source is world's highest-energy and most intense

Table I: Antiproton Intensities at Existing and Future Facilities

Facility	**Stacking:** Rate (10^{10}/hr)	Duty Factor	**Clock Hours** /Yr	$\overline{\mathbf{p}}$/Yr (10^{13})
CERN AD			3800	0.4
FNAL (Accumulator)	20	15%	5550	17
FNAL (New Ring)	20	90%	5550	100
GSI FAIR (≥2015)	3.5	90%	2780	9

…even after GSI FAIR turns on

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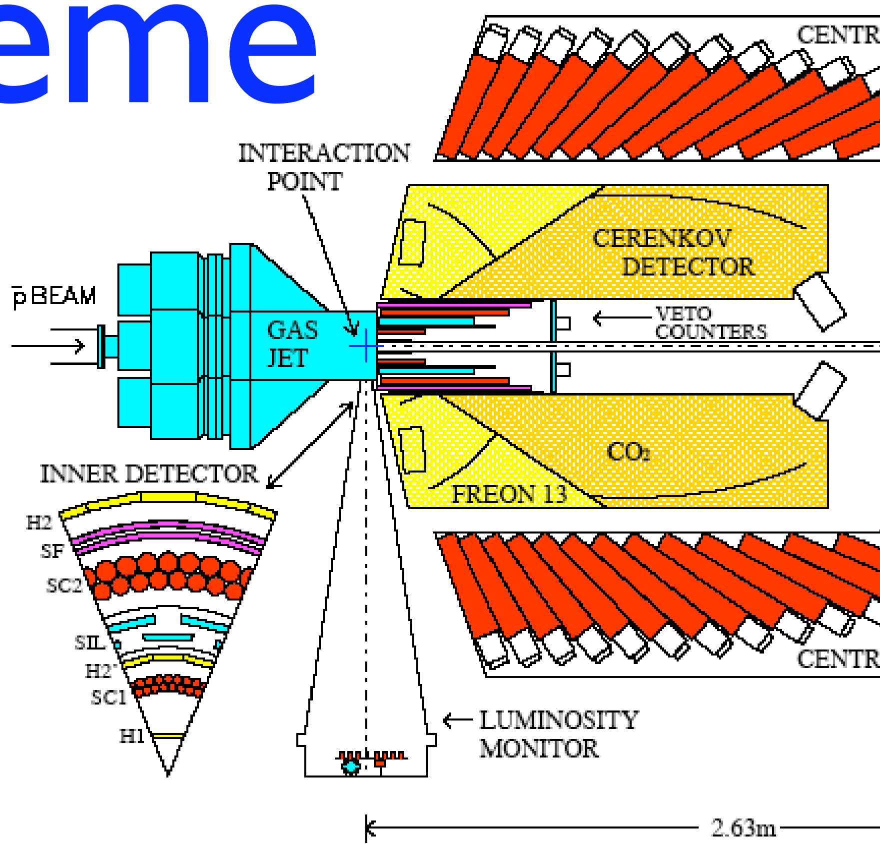

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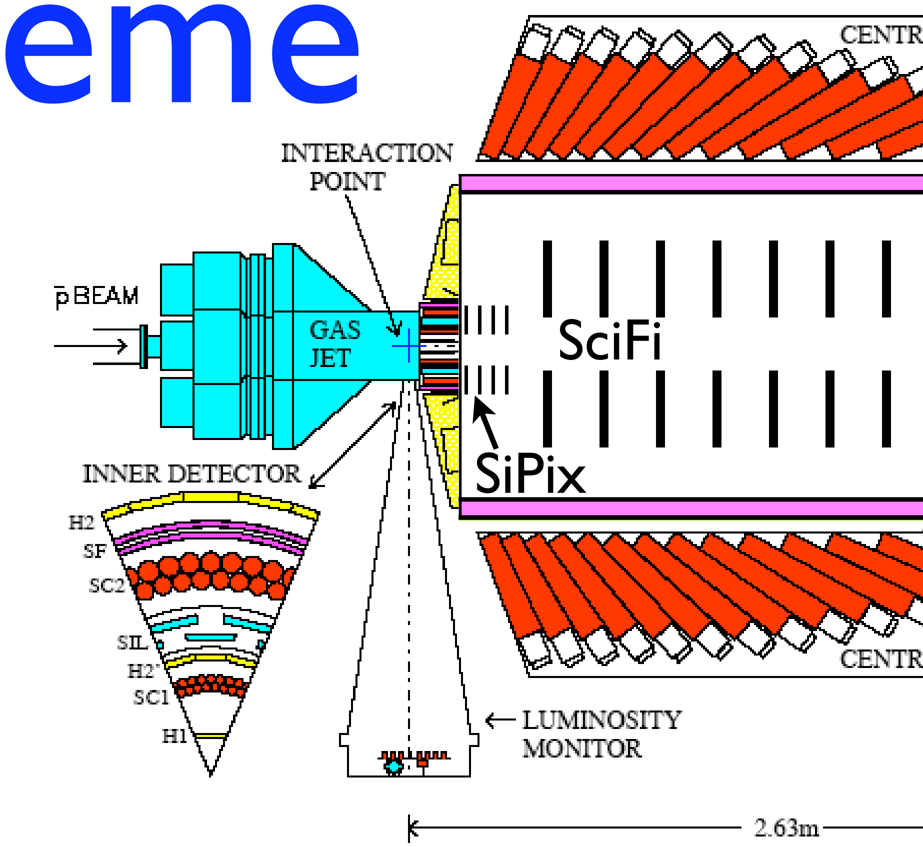

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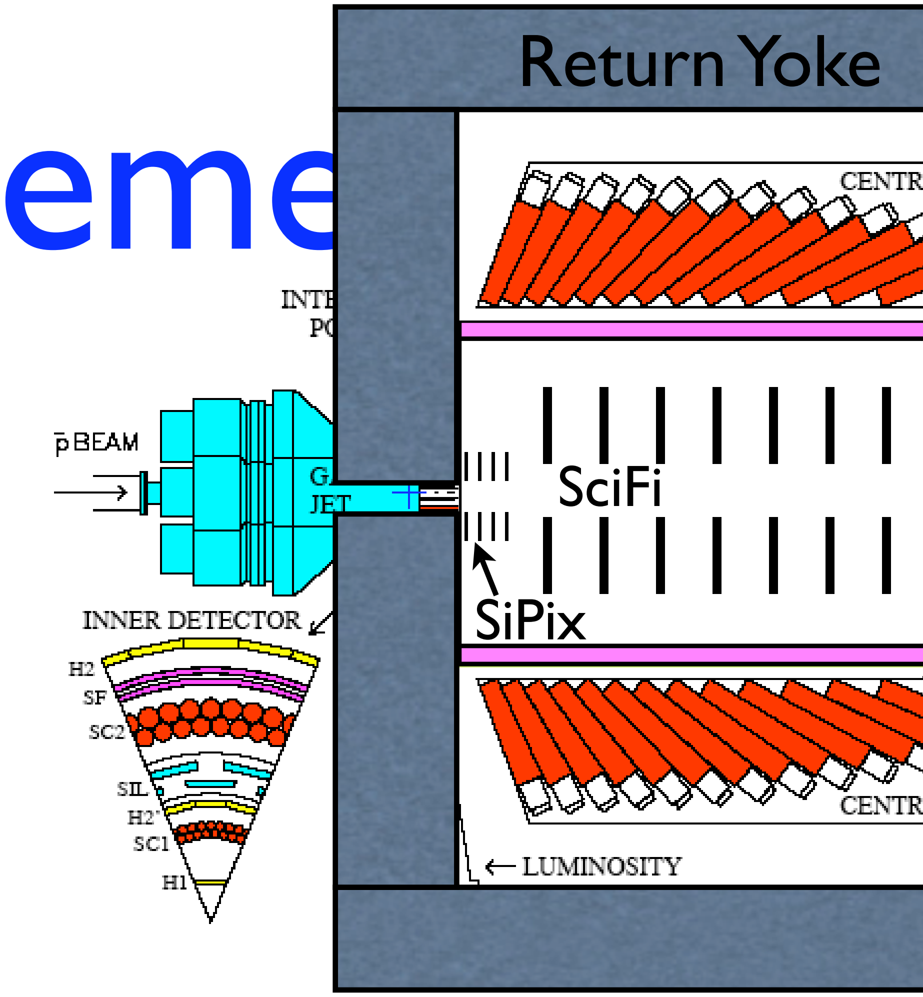

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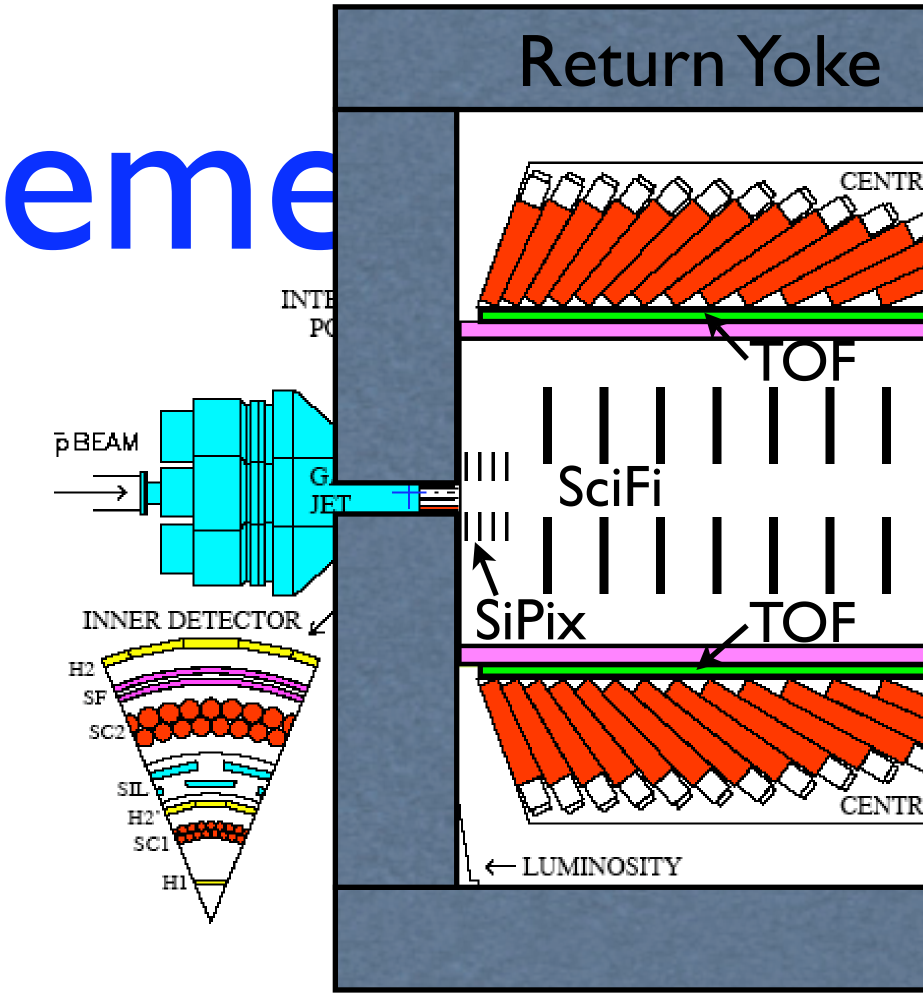

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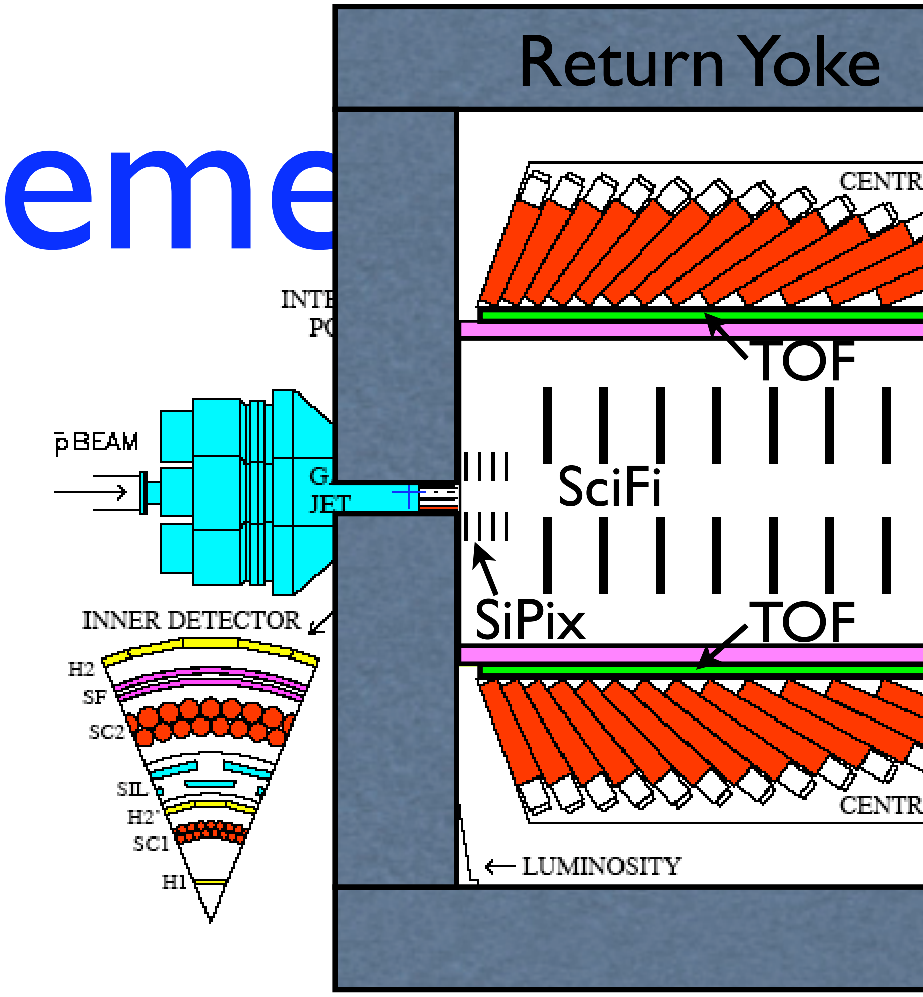

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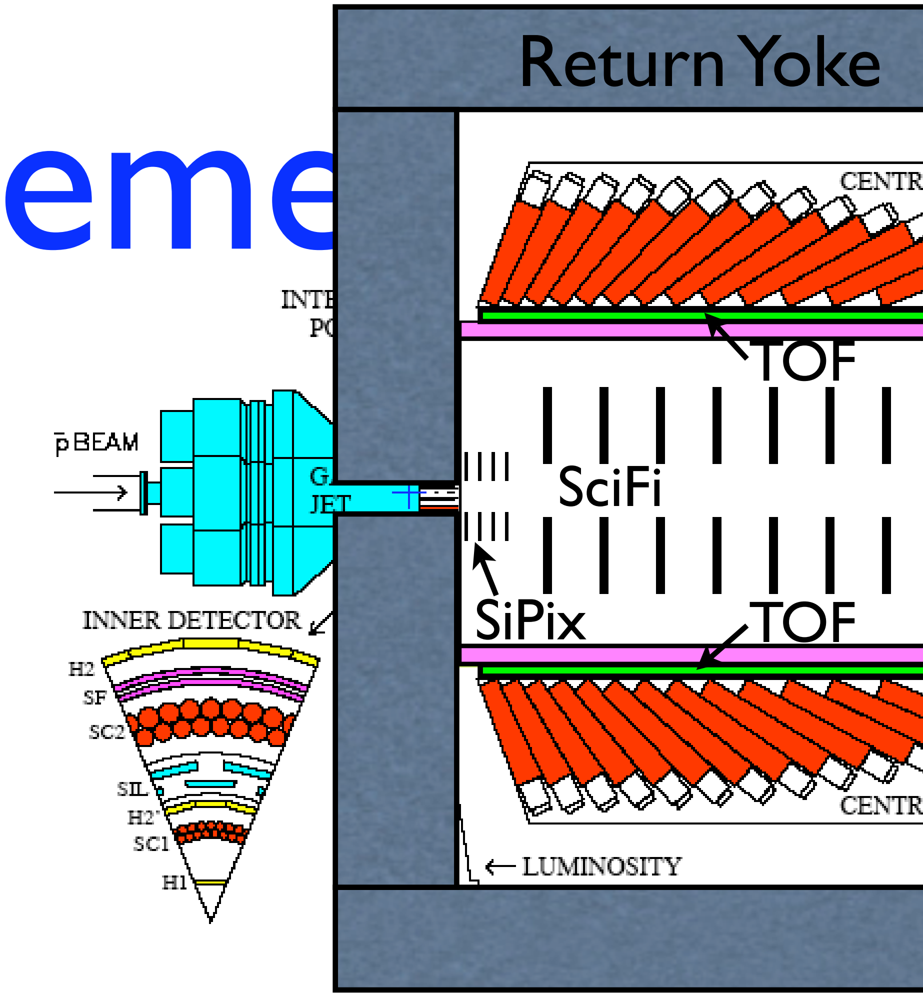

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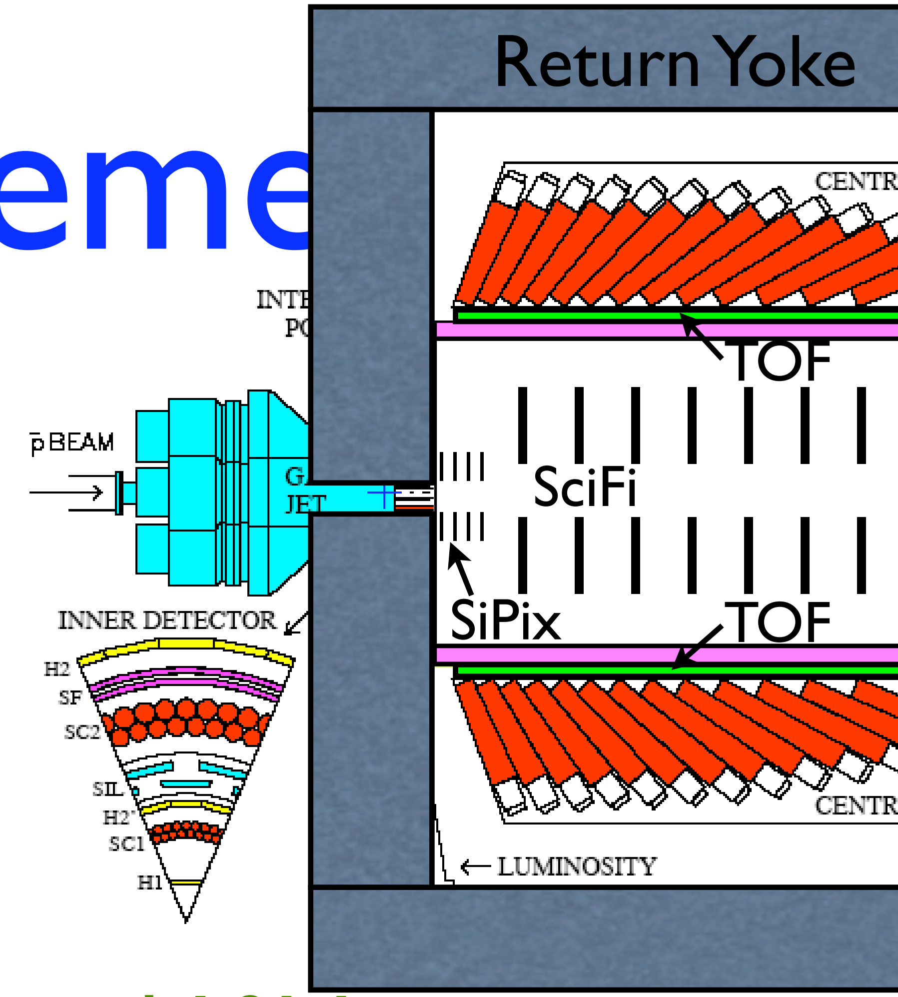

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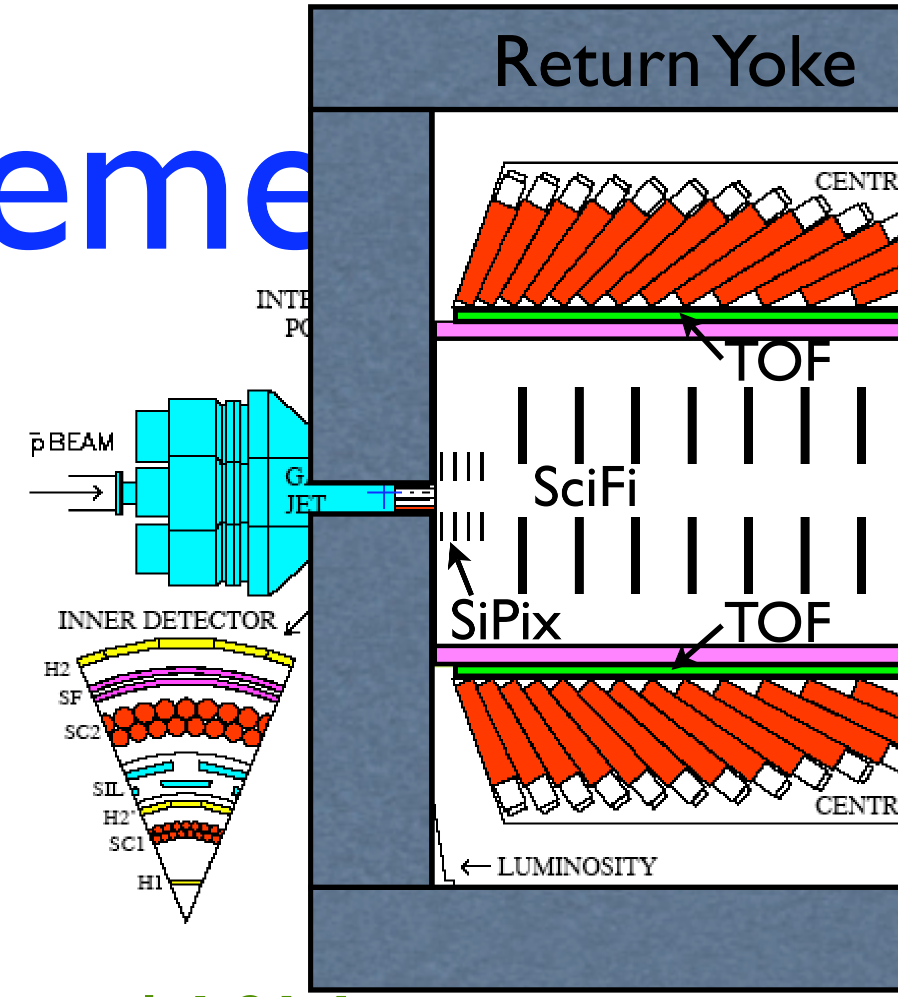

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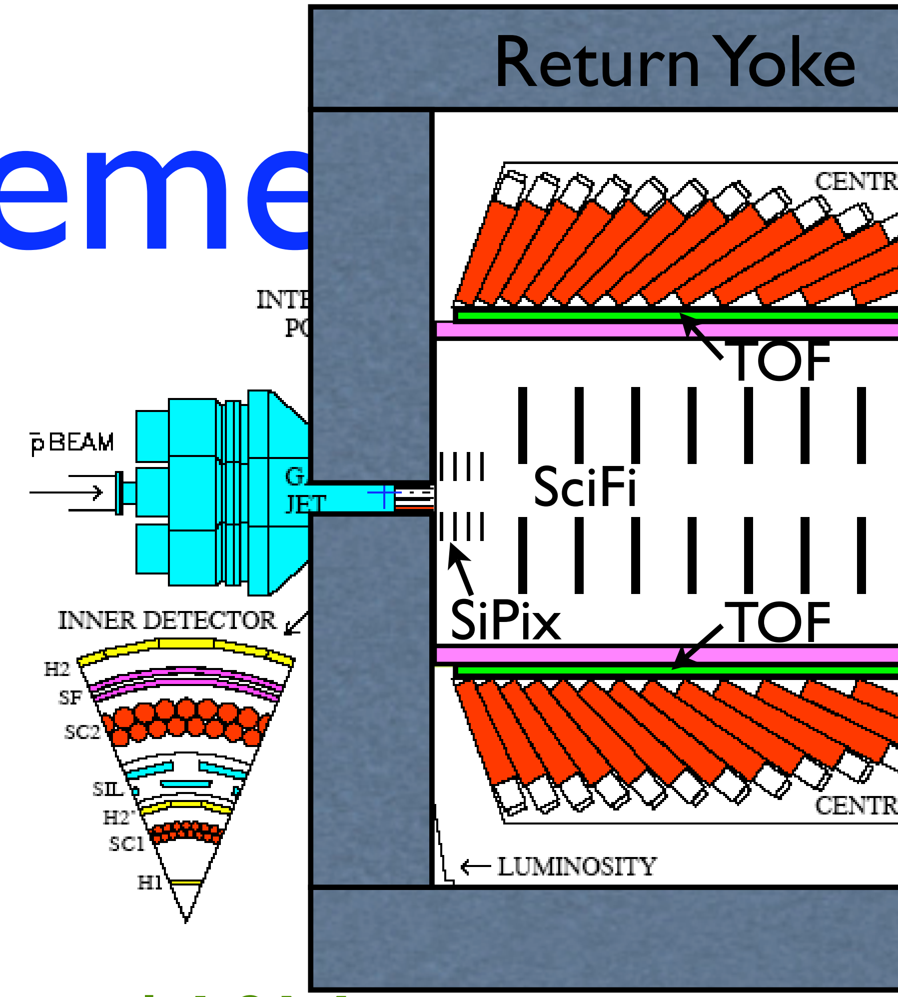

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➡ ~10^8 $\Omega^- \bar{\Omega}^+$/yr

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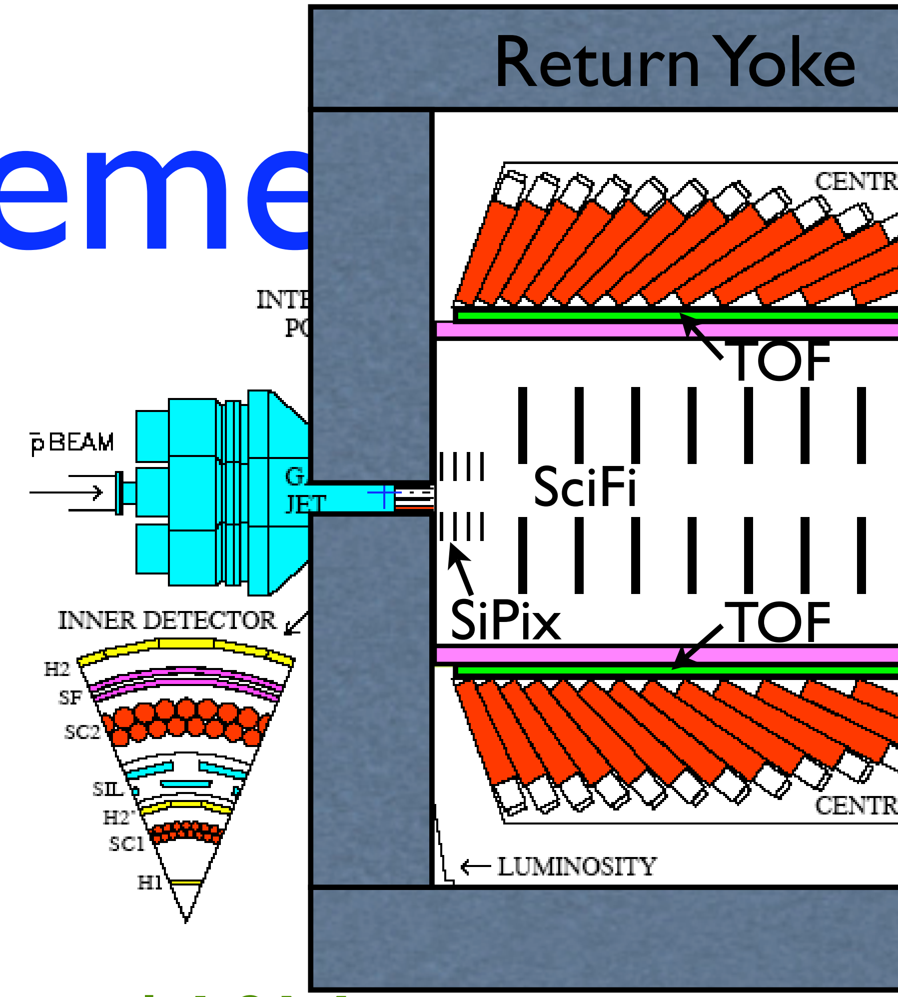

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➡ $\sim 10^8\ \Omega^- \bar{\Omega}^+$/yr + $\sim 10^{12}$ inclusive hyperon events!

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

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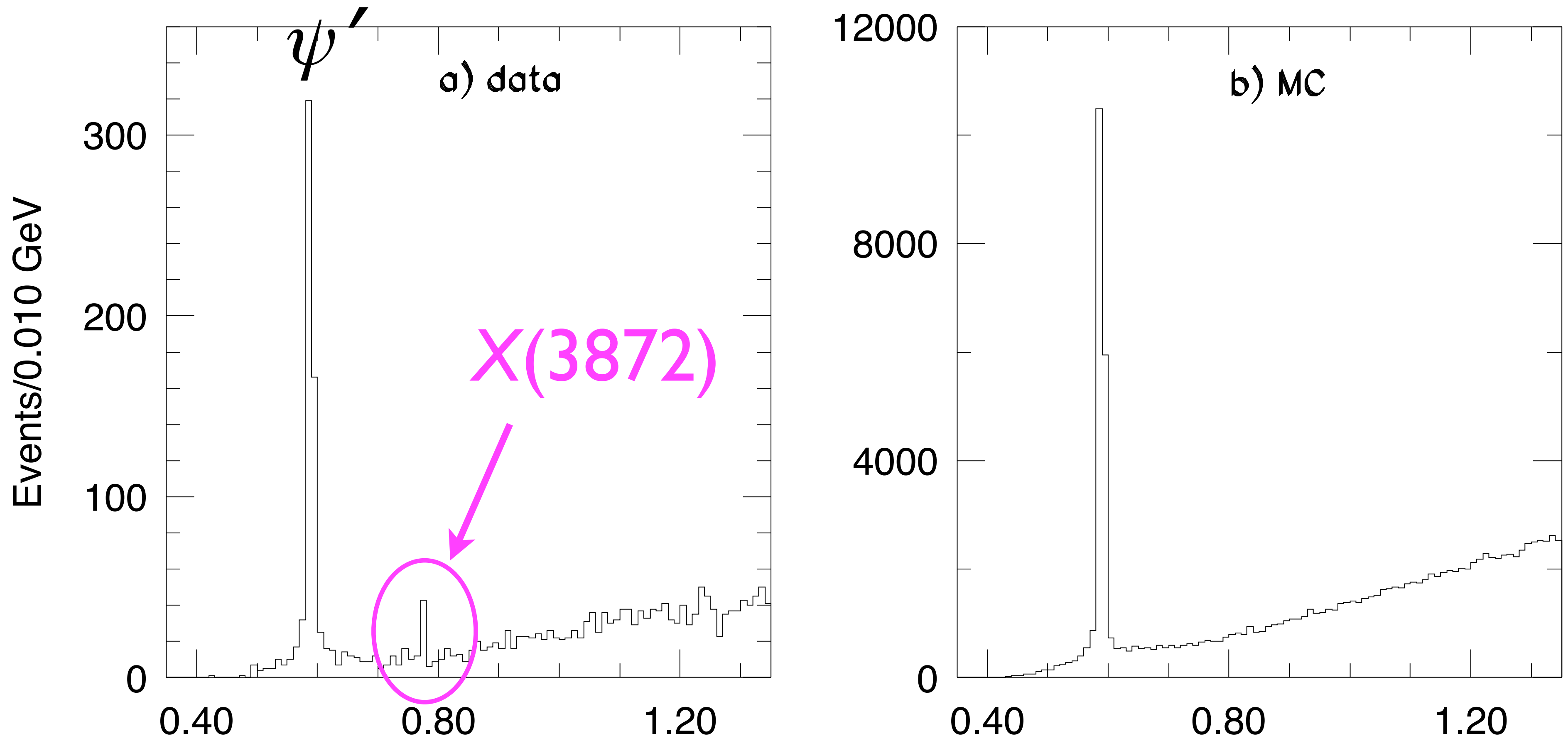
- Belle, Aug. 2003: $B^{\pm} \longrightarrow X + K^{\pm}, X \longrightarrow J/\psi\, \pi^{+}\pi^{-}$



- 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 Γ (MeV)	J^{PC}	Decay Modes Observed	Production Modes Observed
X(3872)	Belle,CDF, D0, Cleo, BaBar	3871.2±0.5 + i(<2.3)	1^{++}	$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $\gamma J/\psi$	B decays, ppbar
	Belle BaBar	$3875.4\pm0.7^{+1.2}_{-2.0}$ $3875.6\pm0.7^{+1.4}_{-1.5}$		$D^0 D^0 \pi^0$	B decays
Z(3930)	Belle	3929±5±2 + i(29±10±2)	2^{++}	D^0D^0, D^+D^-	$\gamma\gamma$
Y(3940)	Belle BaBar	3943±11±13 + i(87±22±26) $3914.3^{+3.8}_{-3.4}$ ±1.6+ i(33^{+12}_{-8} ±0.60)	J^{++}	$\omega J/\psi$	B decays
X(3940)	Belle	3942^{+7}_{-6}±6 + i(37^{+26}_{-15}±8)	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}±15+ i(139^{+111}_{-61}±21)	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} ±4 + i(73^{+39}_{-25}±5) $4247\pm12^{+17}_{-32}$ + i(108±19±10)	1^{--}	$\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$	e^+e^- (ISR), e^+e^-
Y(4350)	BaBar Belle	4324±24 + i(172±33) 4361±9±9 + i(74±15±10)	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)
Z^+(4430)	Belle	4433±4±1+ i($44^{+17}_{-13}{}^{+30}_{-11}$)	J^P	$\pi^+\psi(2S)$	B decays
Y(4620)	Belle	4664±11±5 + i(48±15±3)	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)

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➡ need very precise mass measurement to confirm or refute

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

What Else Can This Do?

Also,...

- Study other *X*, *Y*, *Z* states
- Worthwhile measurements that E835 could have made but didn't...

  (lack of beam time for precision scans when one didn't know exactly where to look)

  - h_c mass & width, χ_c radiative-decay angular distributions, η_c' full and radiative widths,...
- ...improved limits on $\bar{p}$ lifetime and branching ratios (APEX),...

What Else Can This Do?

Charm!

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 $D^*\bar{D}$ molecule

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- Braaten estimate of $\overline{p}p$ $X(3872)$ coupling assuming $D^*\overline{D}$ molecule
  - extrapolates from $K^*\overline{K}$ data

Charm!

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

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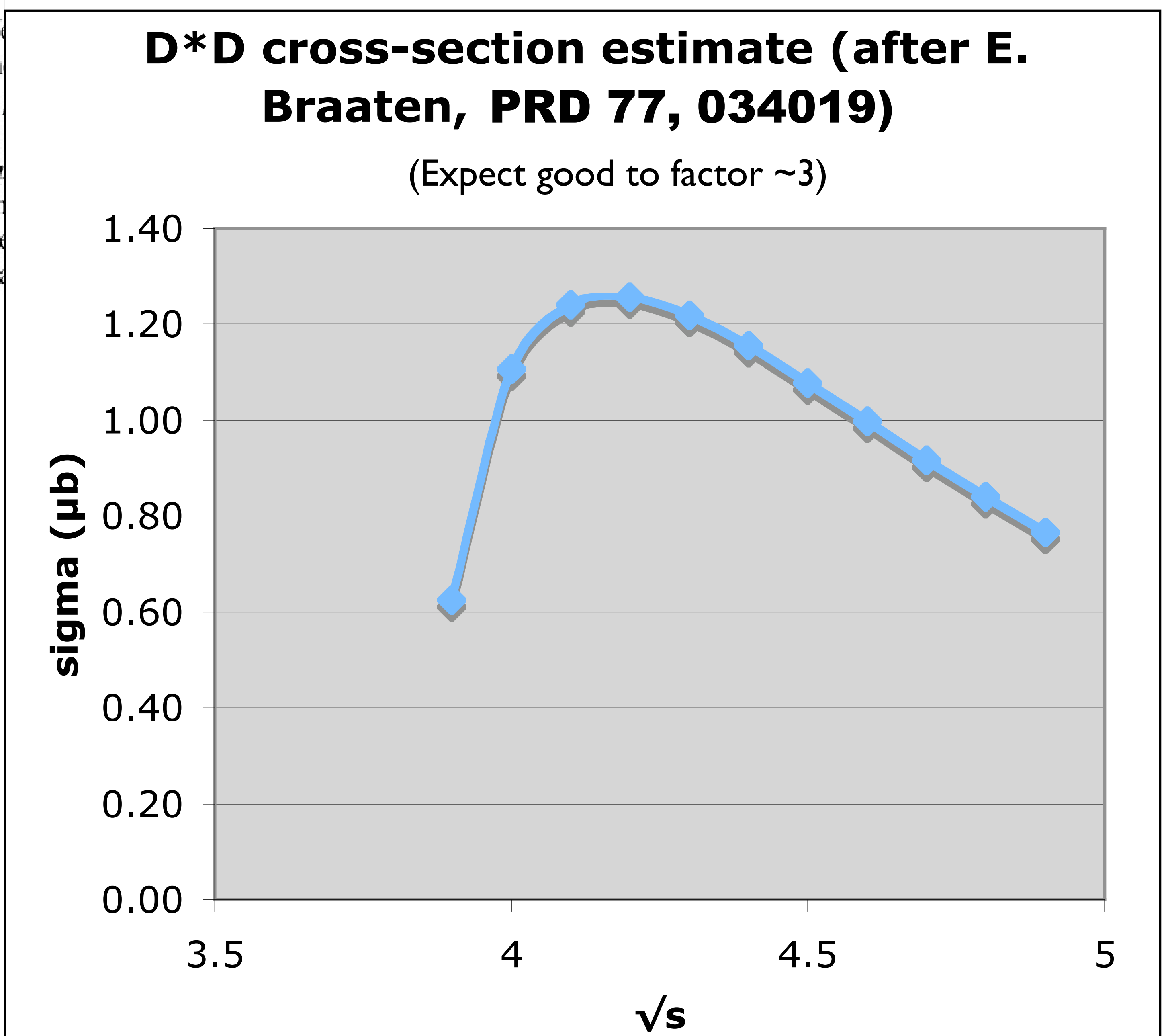

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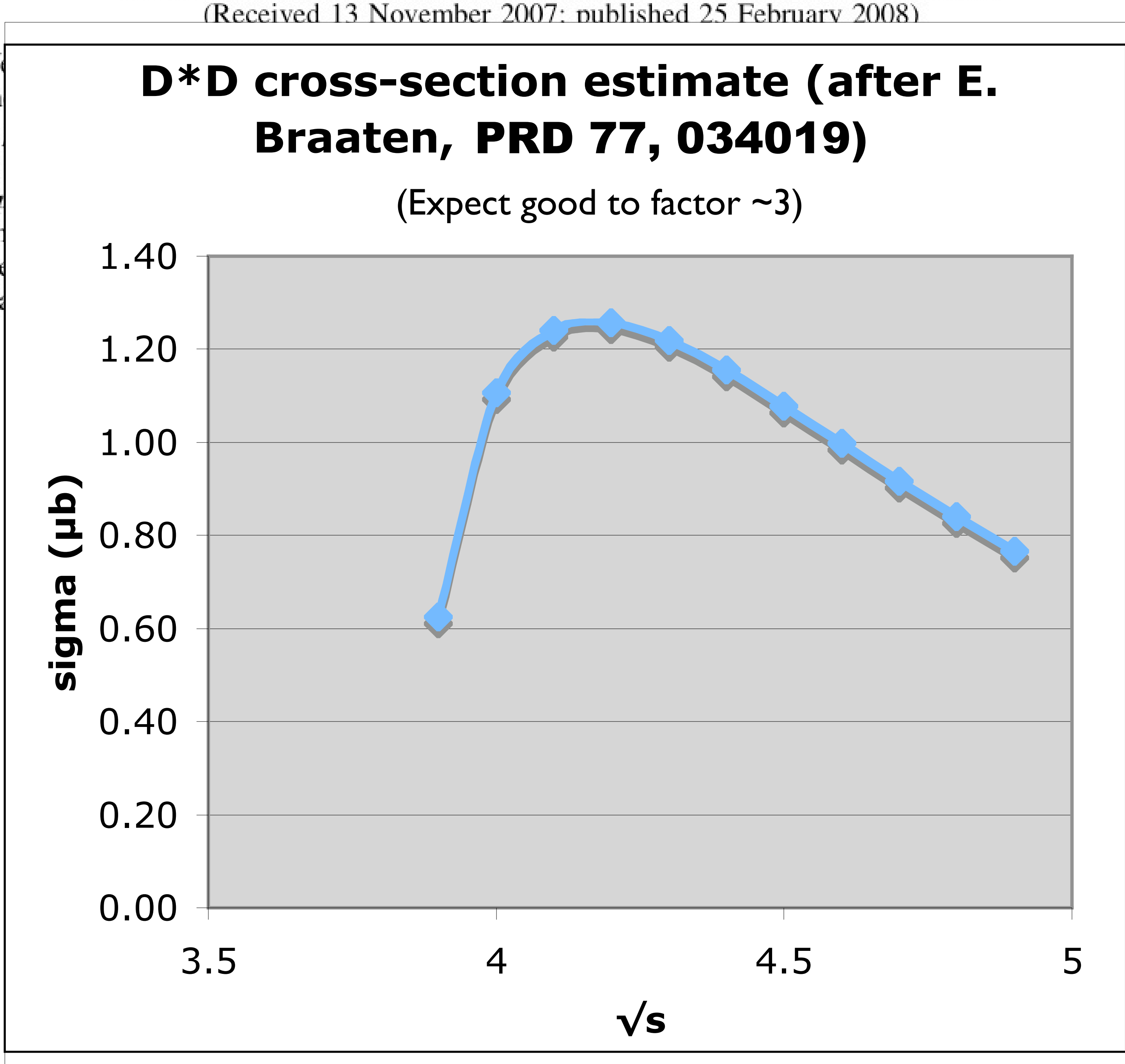

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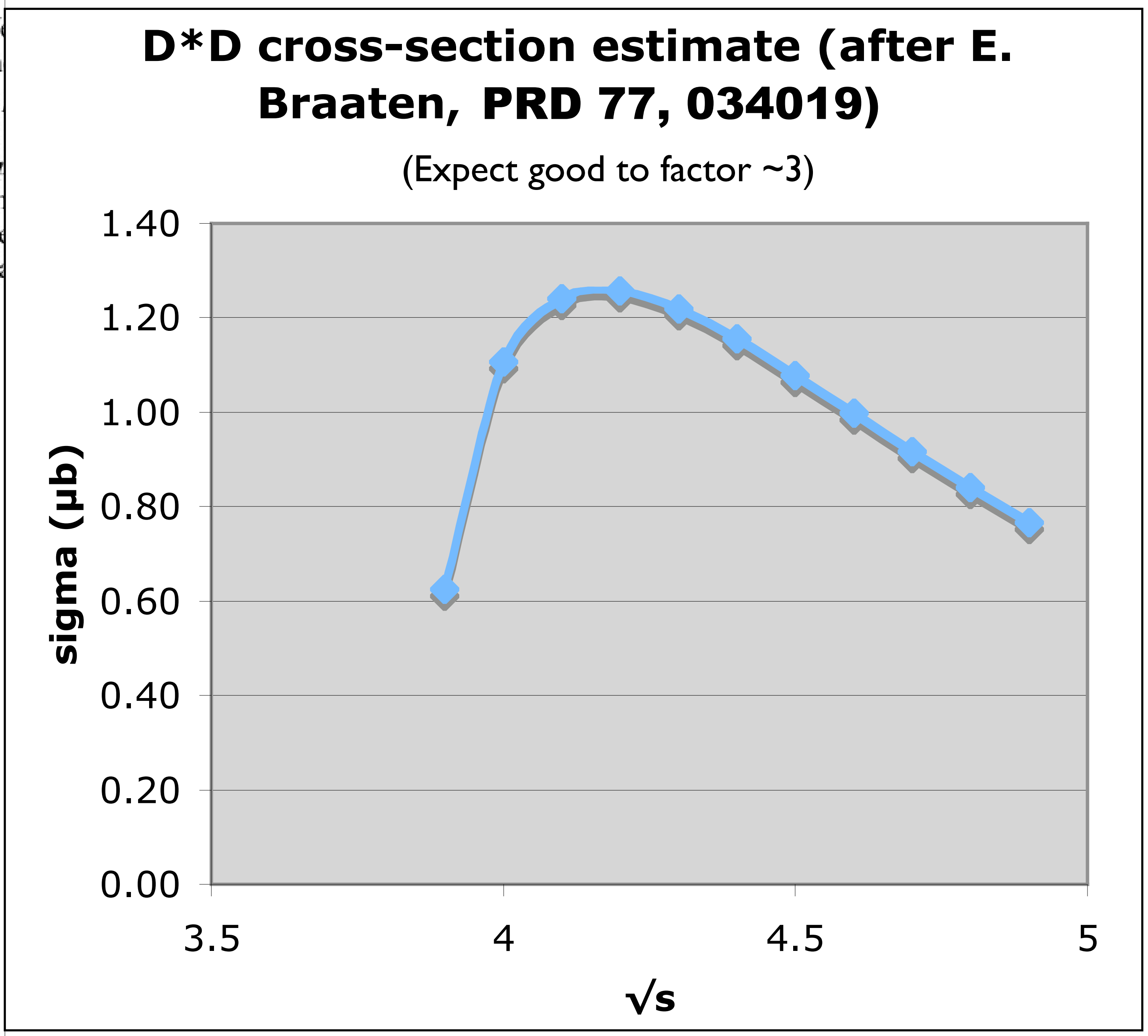

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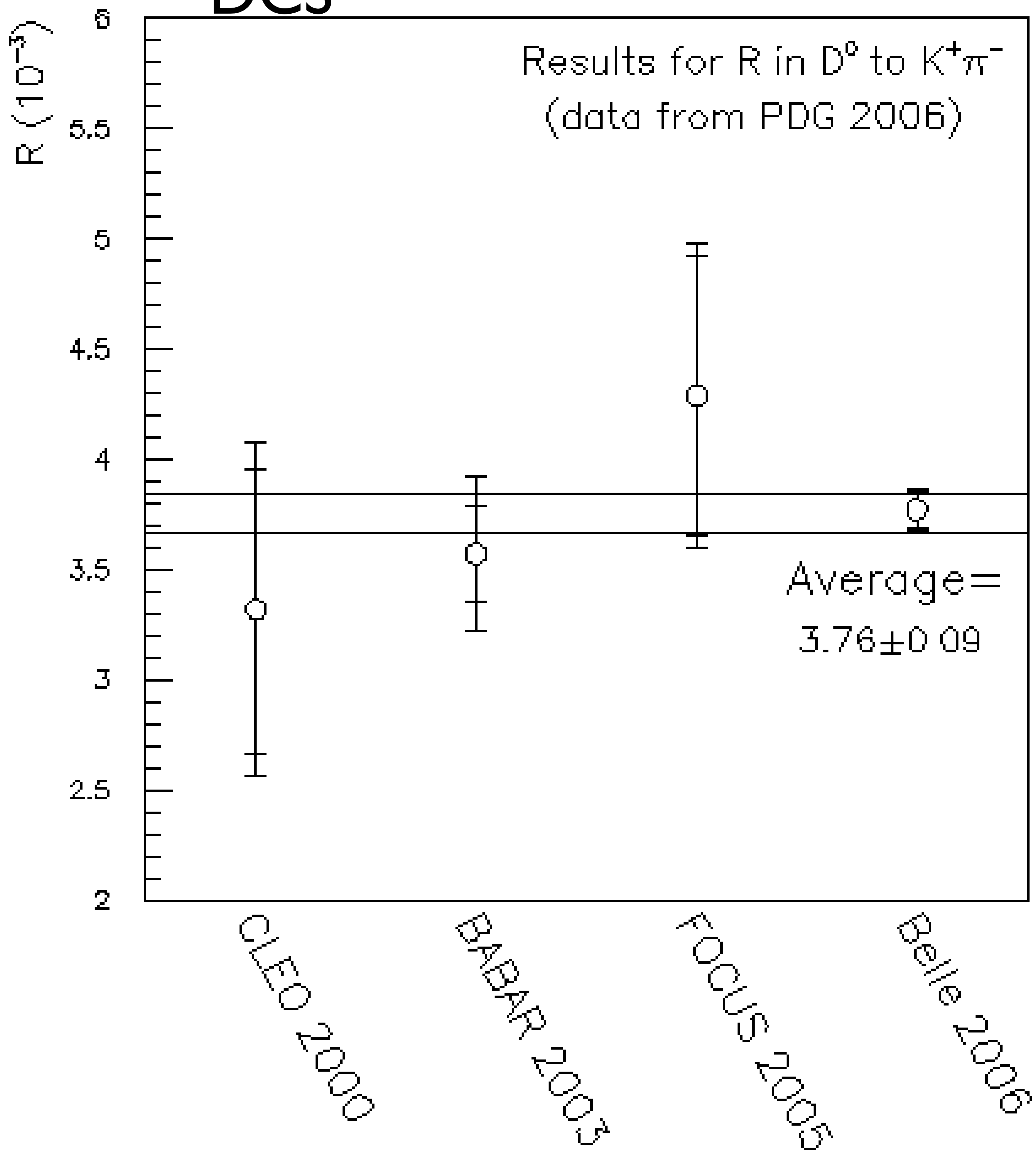

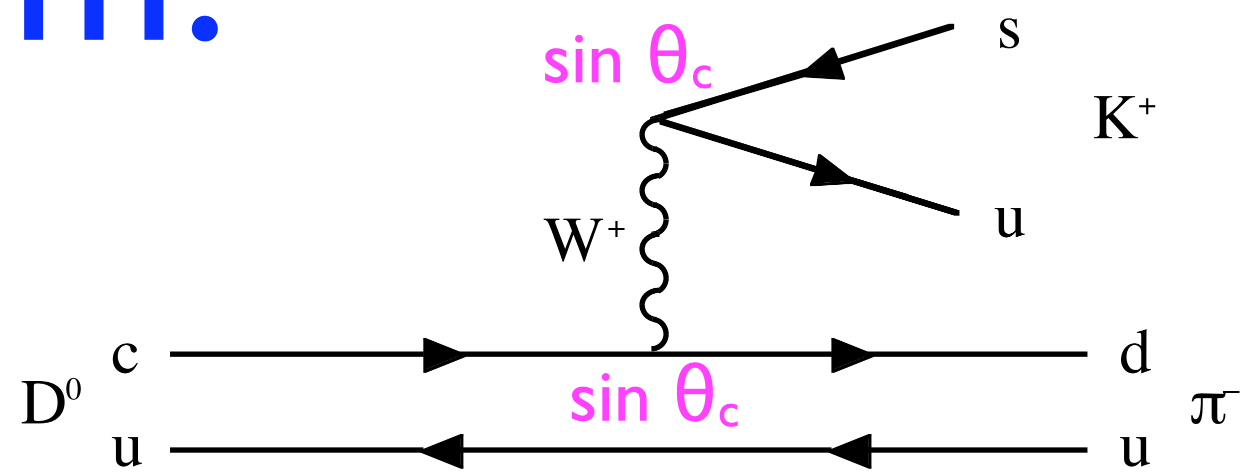

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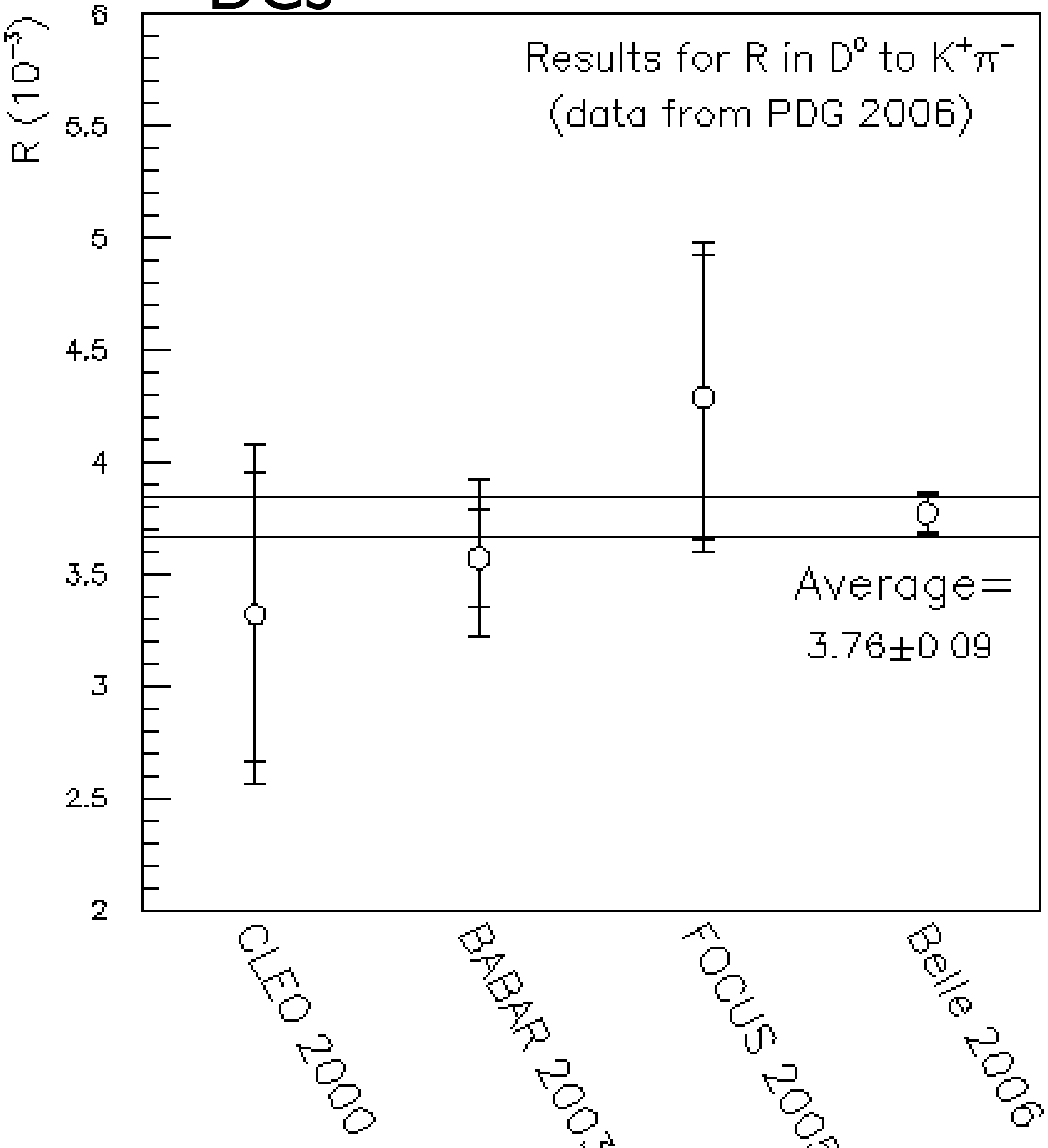

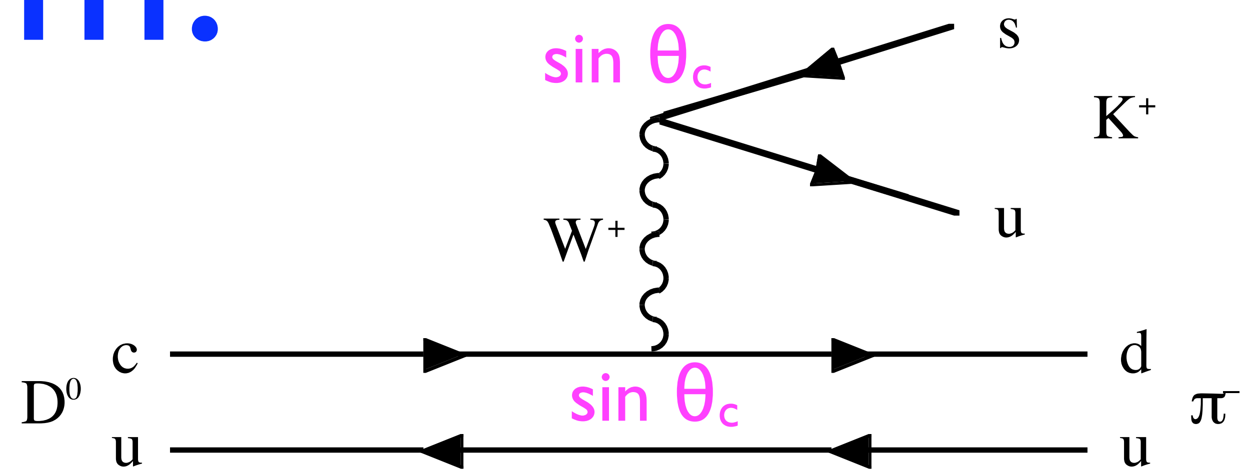

Interference with DCSD amplifies mixing signal:

$$\Gamma[D^0 \to K^+\pi^-] = e^{-\Gamma t}|A_{K^-\pi^+}|^2 \times$$
$$\left[R + \sqrt{R}R_m(y'\cos\phi - x'\sin\phi)\Gamma t + \frac{R_m^2}{4}(y^2+x^2)(\Gamma t)^2\right]$$

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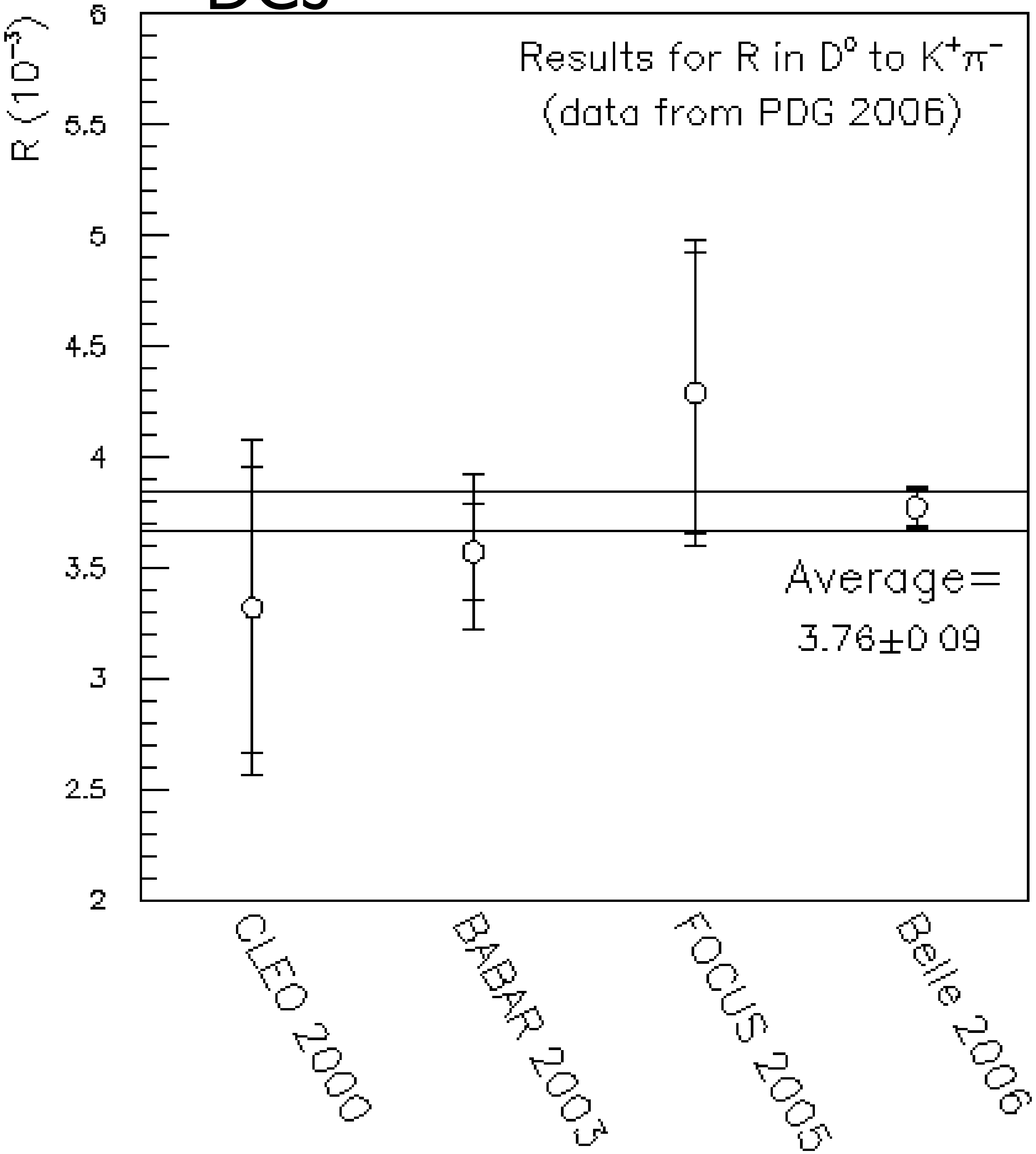

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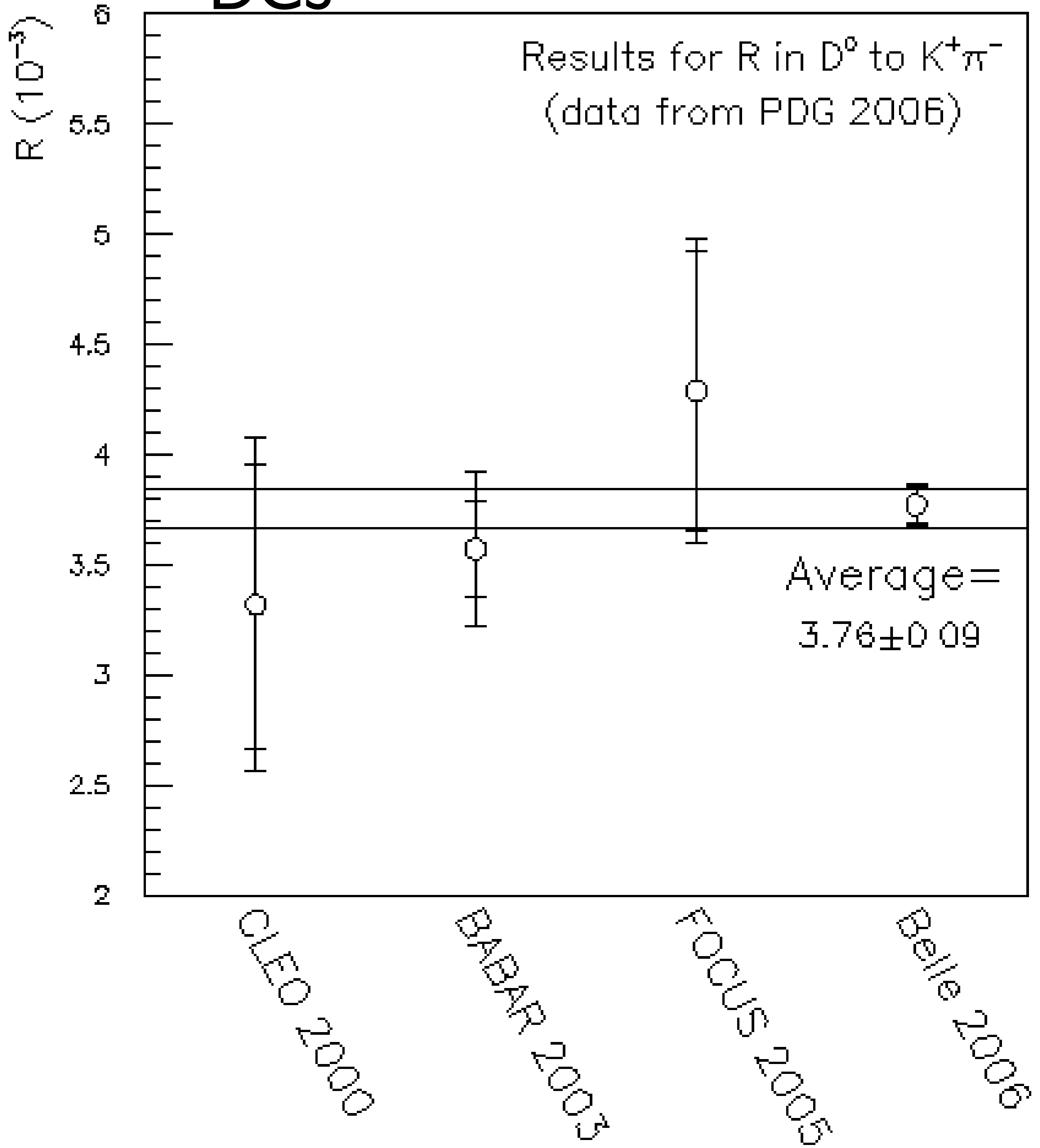

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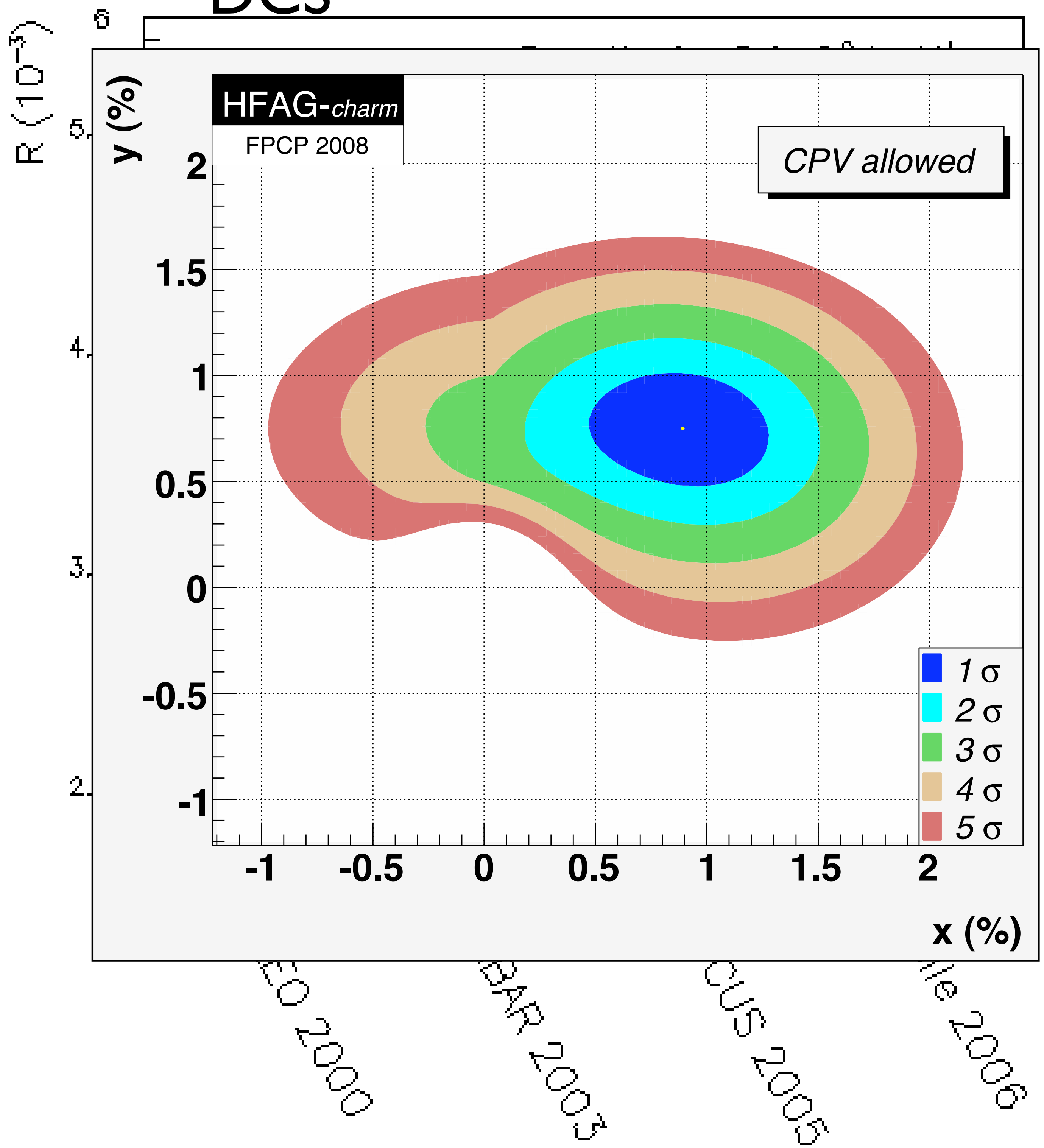

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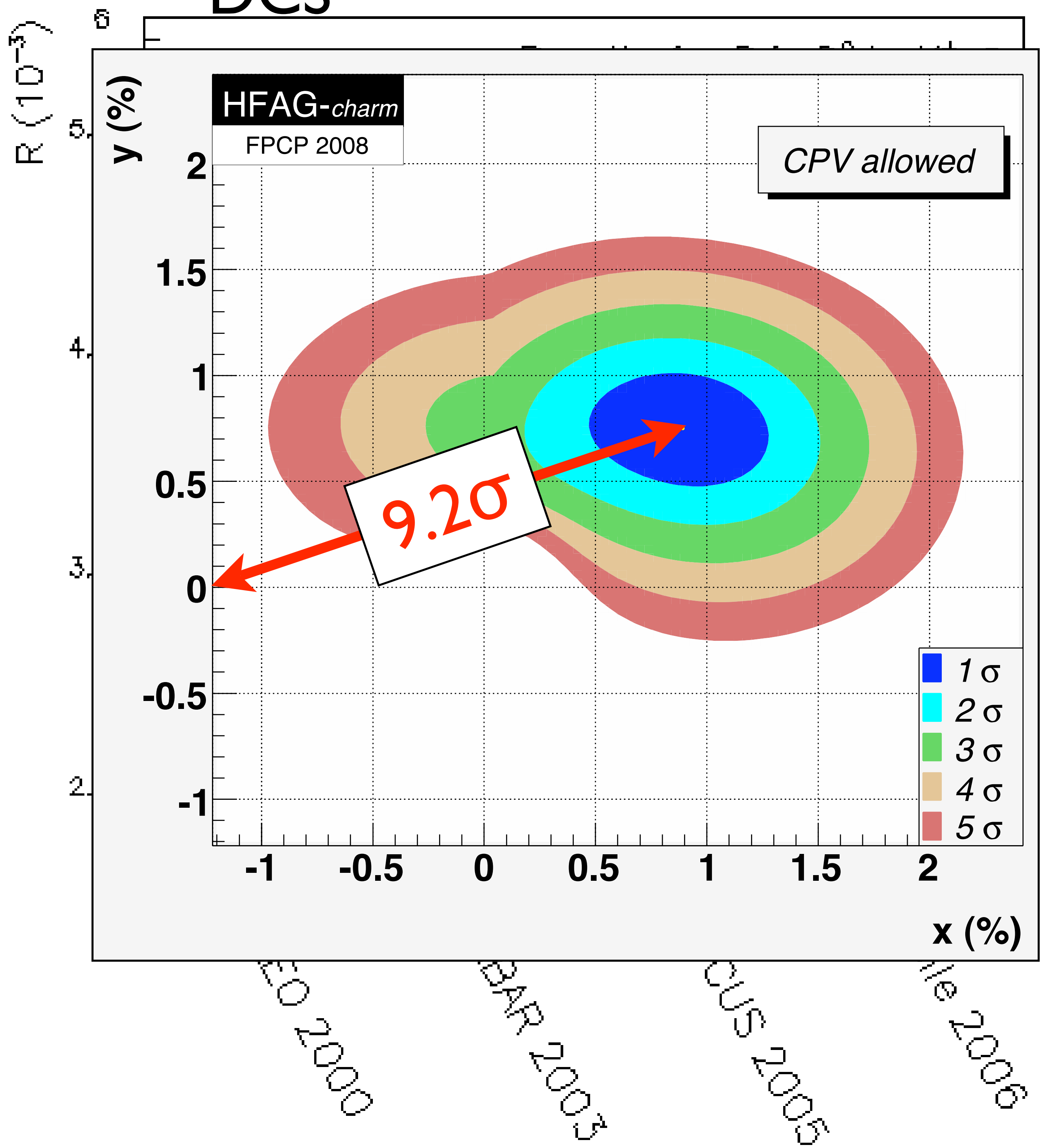

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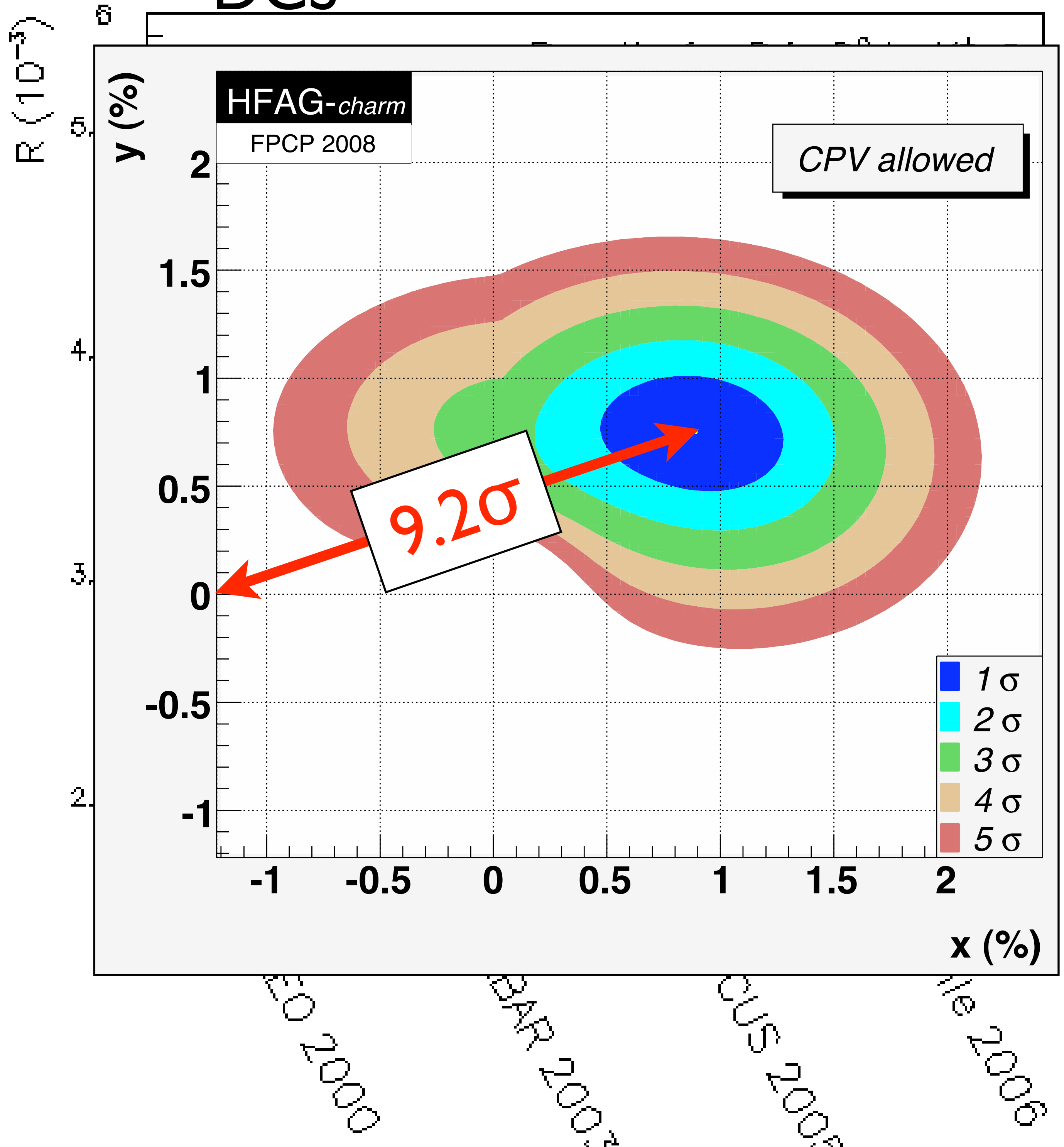

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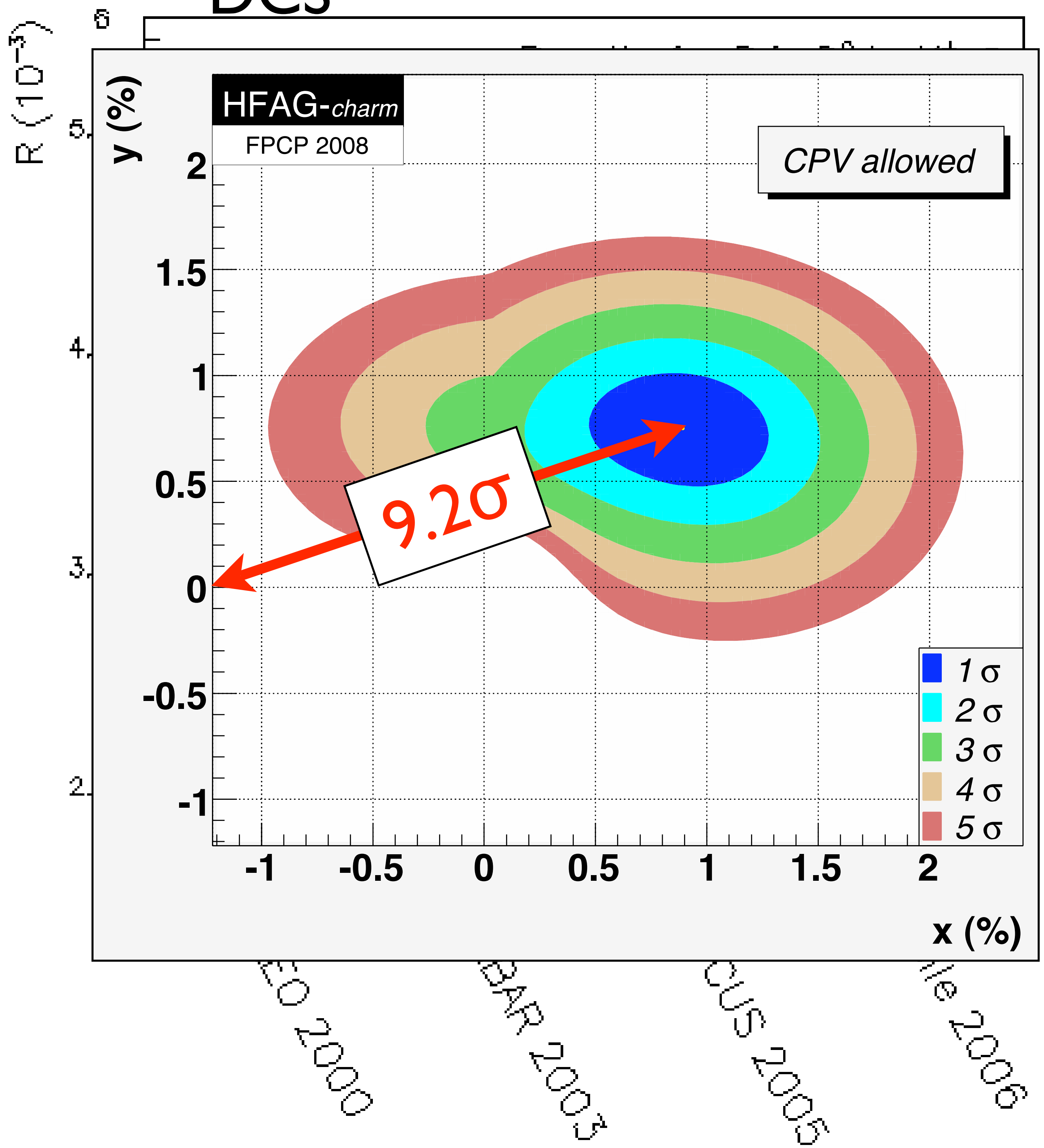

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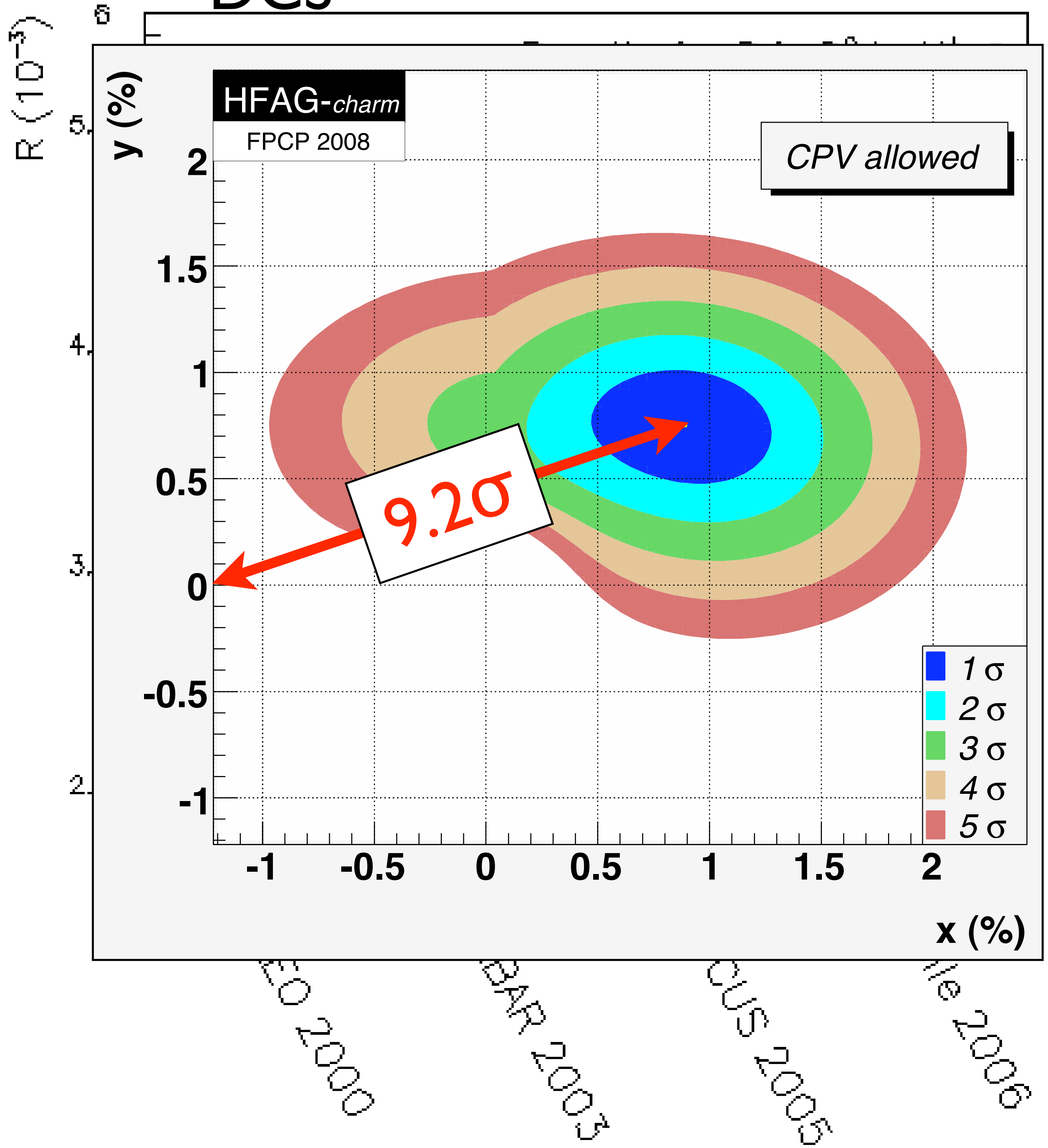

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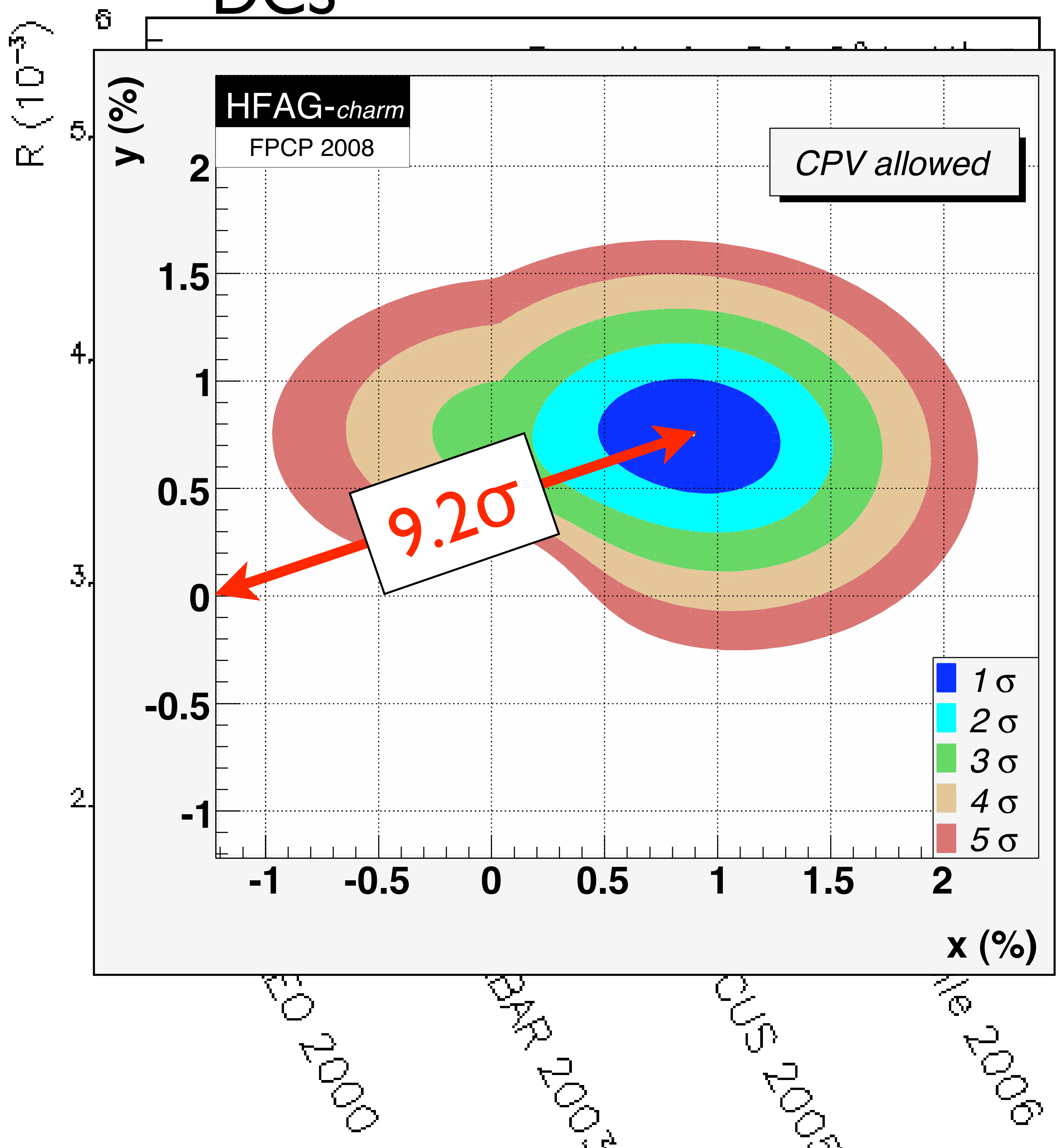

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- *B* factories have ~10^9 open-charm events
- $\bar{p}p$ can produce ~10^{10}/y

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

Antihydrogen

Antihydrogen

- Long quest at LEAR, then AD (ATRAP, ATHENA, ALPHA), to study antihydrogen and test *CPT*
  - e.g., is Lamb shift identical for H and $\overline{\mathrm{H}}$?
- Struggling with difficulty of combining antiprotons with positrons in a Penning trap and winding up in (or near) ground state

Antihydrogen

Antihydrogen

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

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ELSEVIER

Physics Letters B 368 (1996) 251-258

Production of antihydrogen

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

[a] *IKP, Forschungszentrum Jülich GmbH, Germany*
[b] *Genoa University and INFN, Italy*
[c] *PI, Universität Erlangen–Nürnberg, Germany*
[d] *GSI Darmstadt, Germany*
[e] *IKP, Universität Münster, Germany*

Received 8 December 1995; revised manuscript received 21 December 1995
Editor: L. Montanet

Abstract

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

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

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

Antihydrogen

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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 ± 0.14 ± 0.09 pb. [S0031-9007(98)05685-3]

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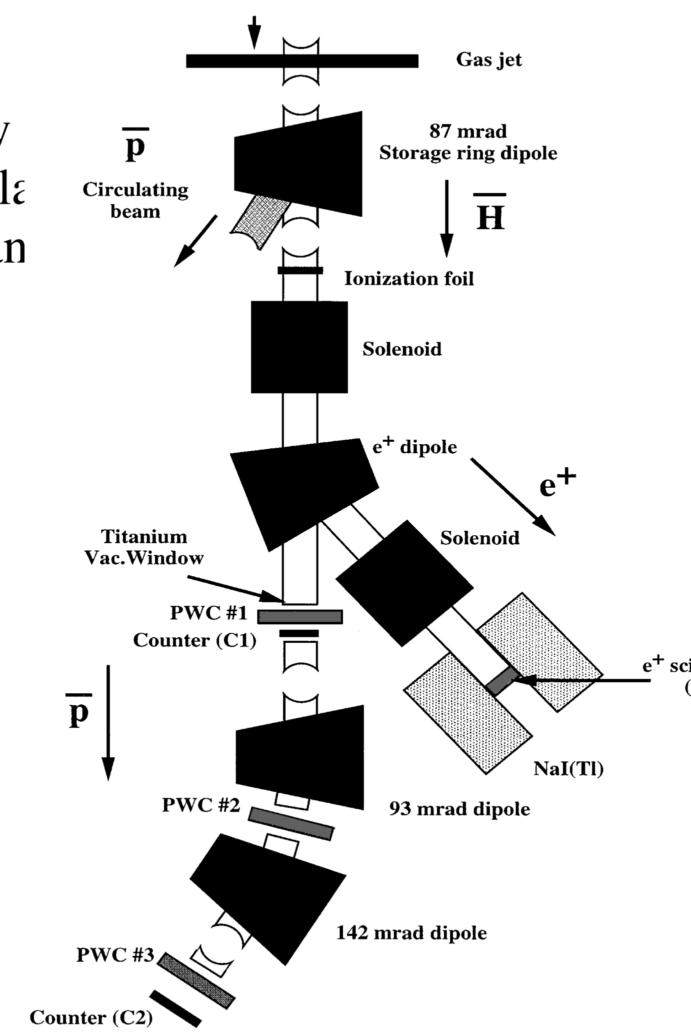

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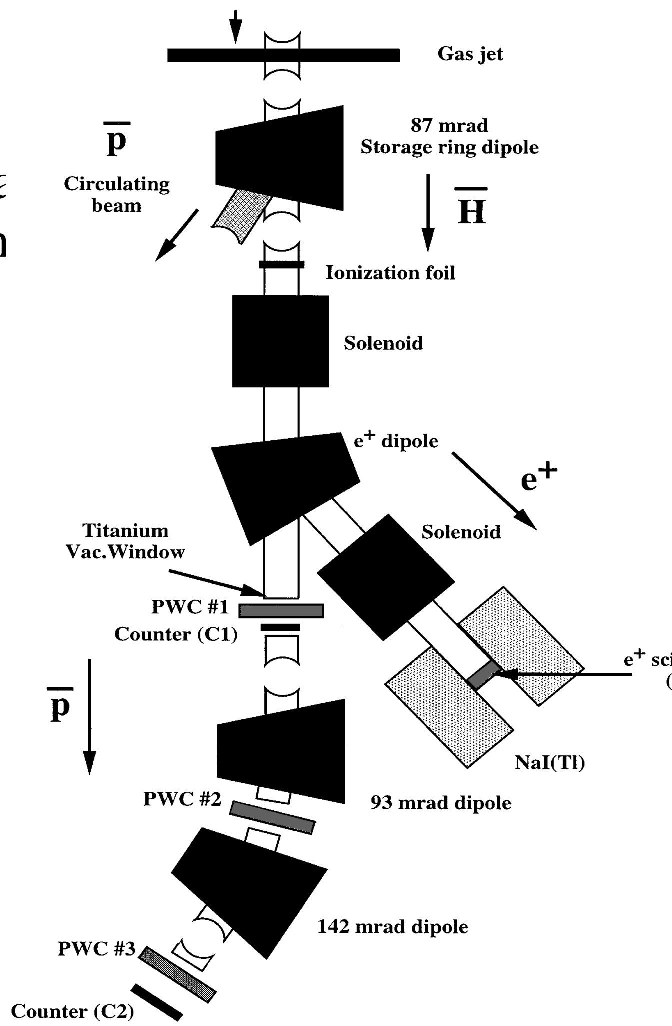

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- Formed automatically e.g. in E835 gas-jet target, detected in "parasitic" E862
- Cross section grows with E_{beam}, Z_{tgt}

Antihydrogen

- Subsequently worked out technique to measure Lamb shift of relativistic $\overline{\mathrm{H}}$ in flight:

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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
University of California at Irvine, Irvine, California 92717

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]

Antihydrogen

- Further parasitic running appears feasible
- Hope to install high-*Z* foil operable in Antiproton Accumulator beam halo at upcoming shutdown
- Can then assemble Lamb-shift apparatus (magnets, laser, detectors) and begin shakedown and operation

- 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.

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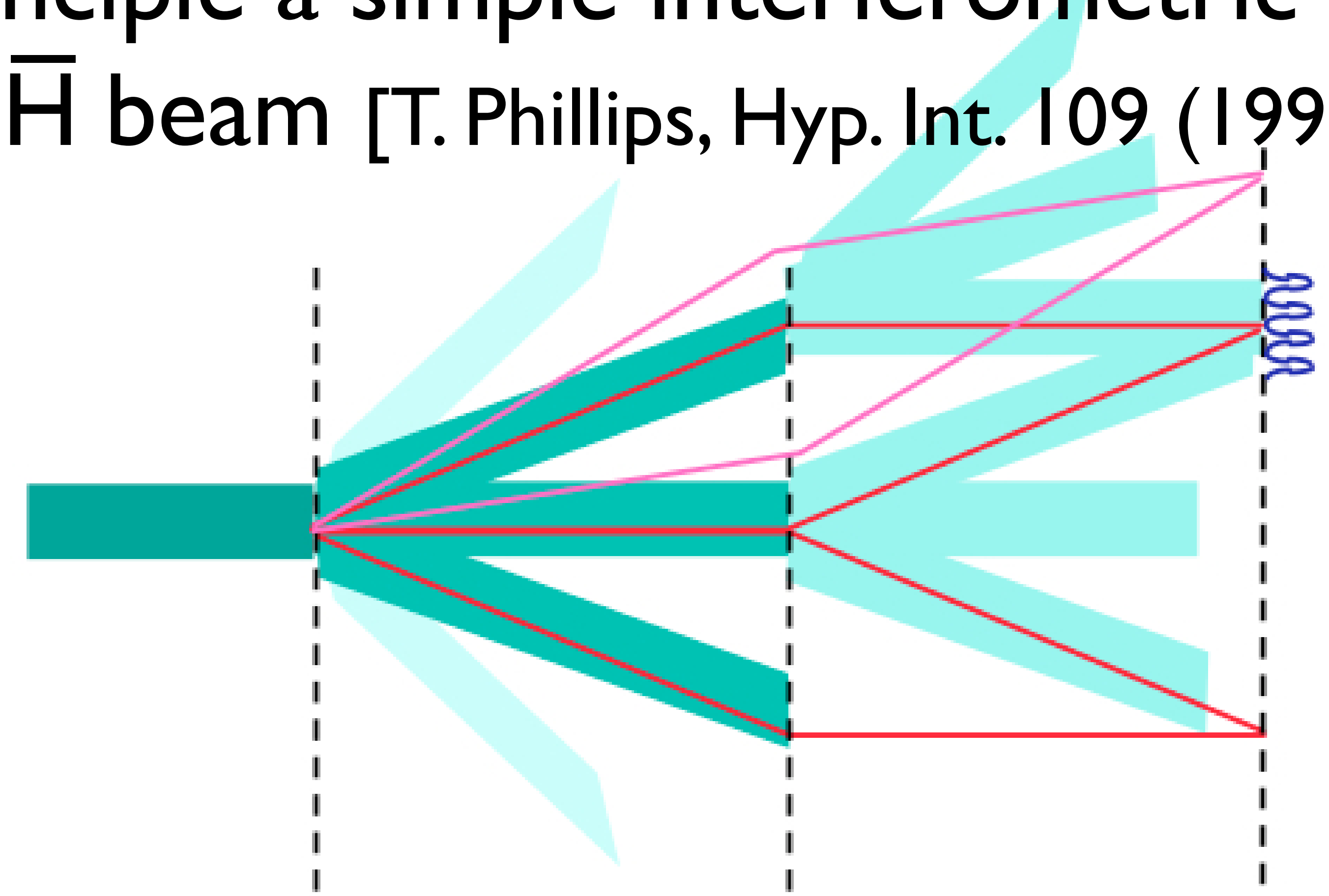

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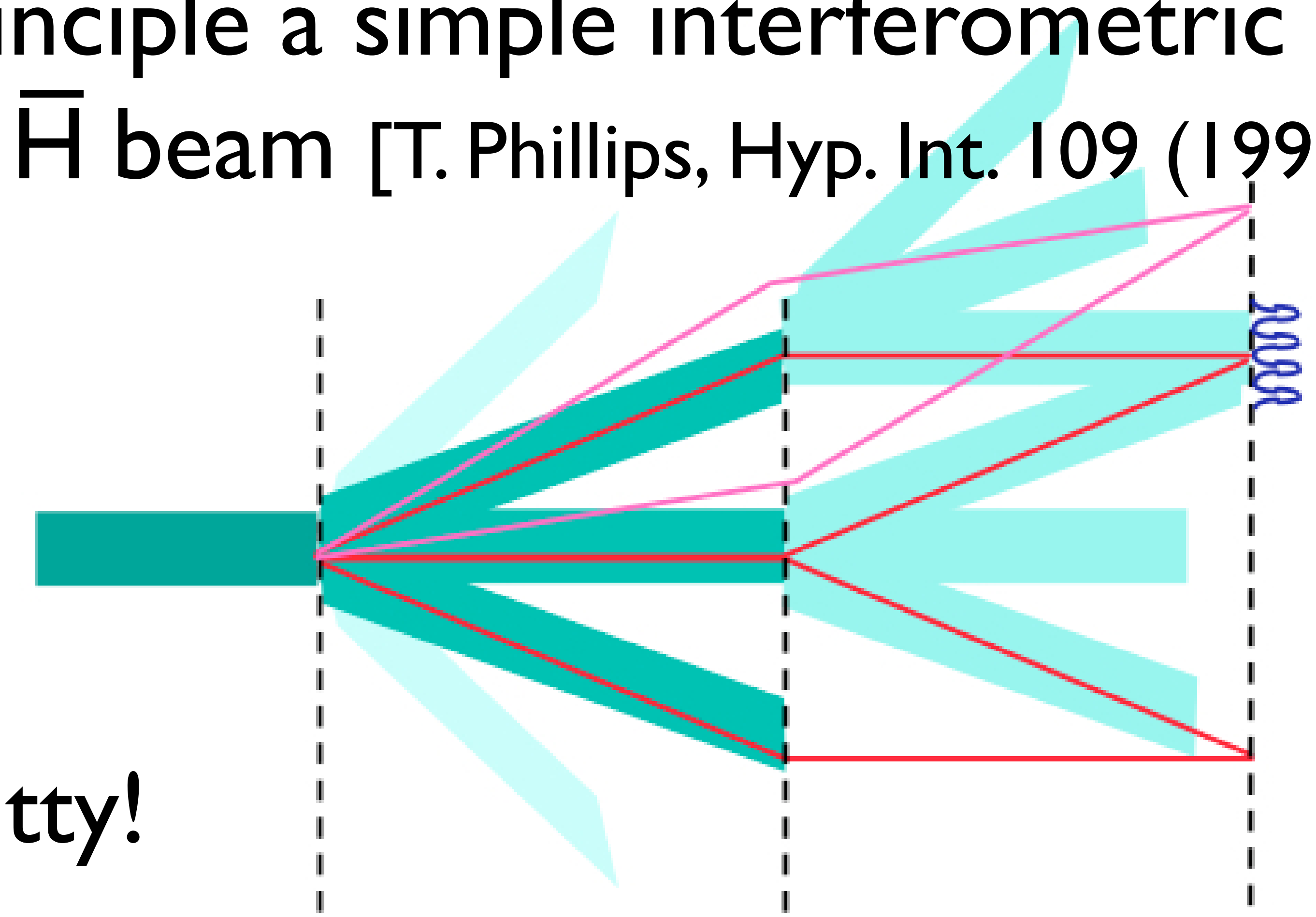

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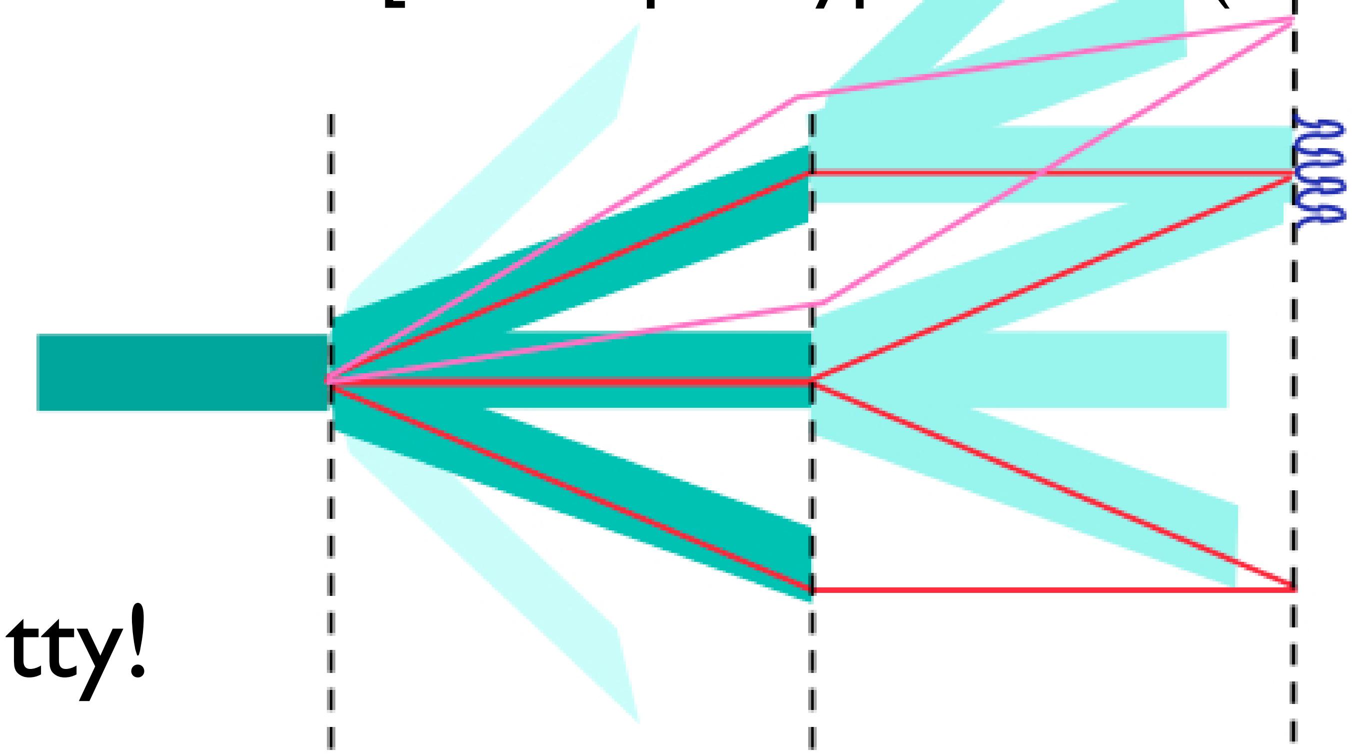

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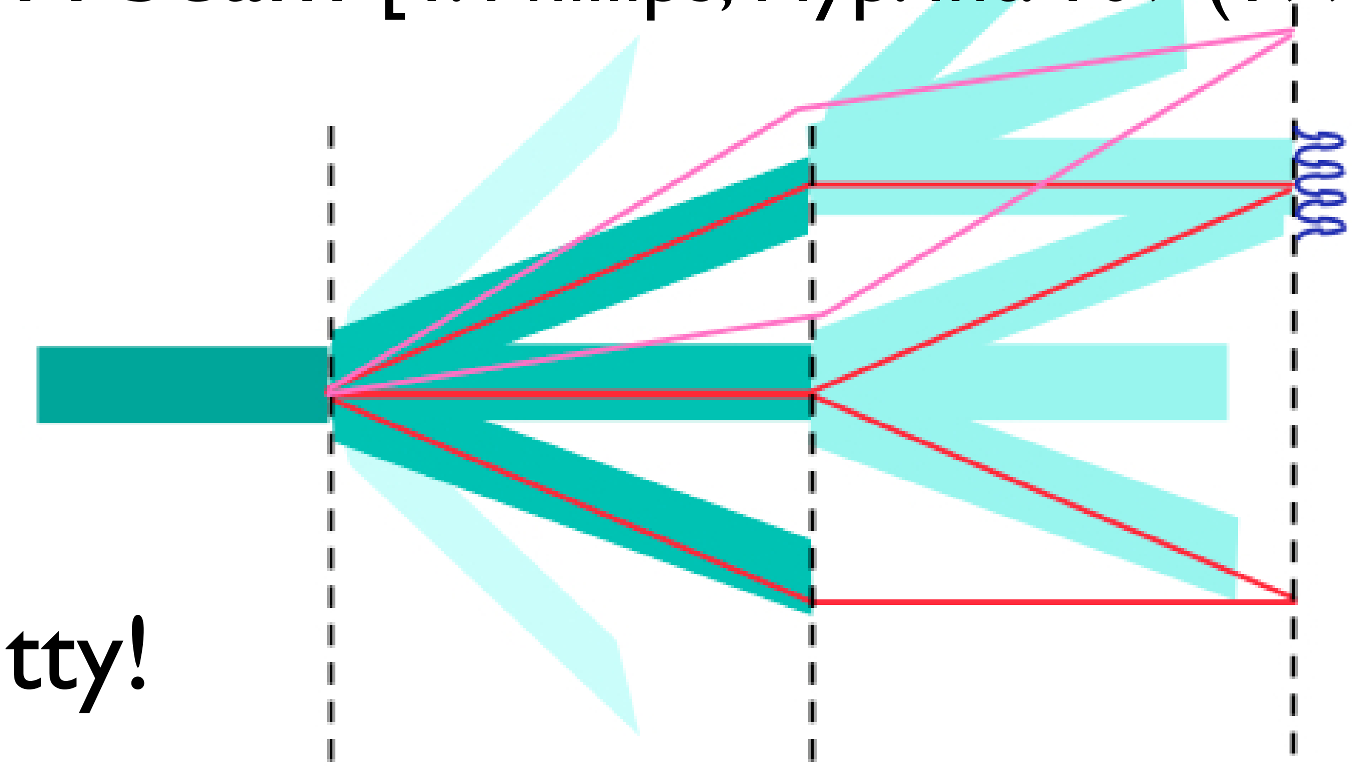

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→ $\bar{g} = g + \varepsilon$ natural in quantum gravity due to scalar & vector terms

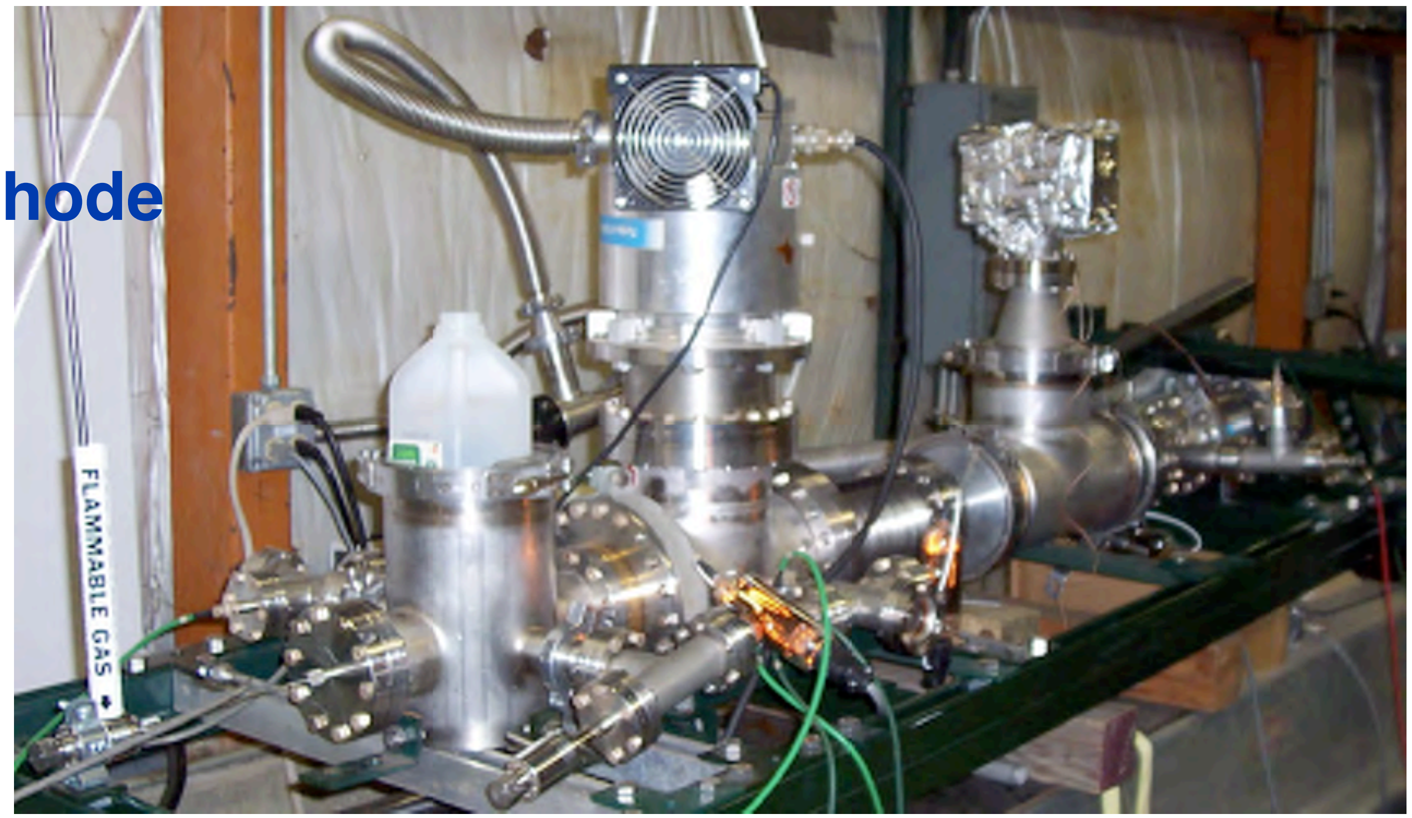
Antimatter Gravity

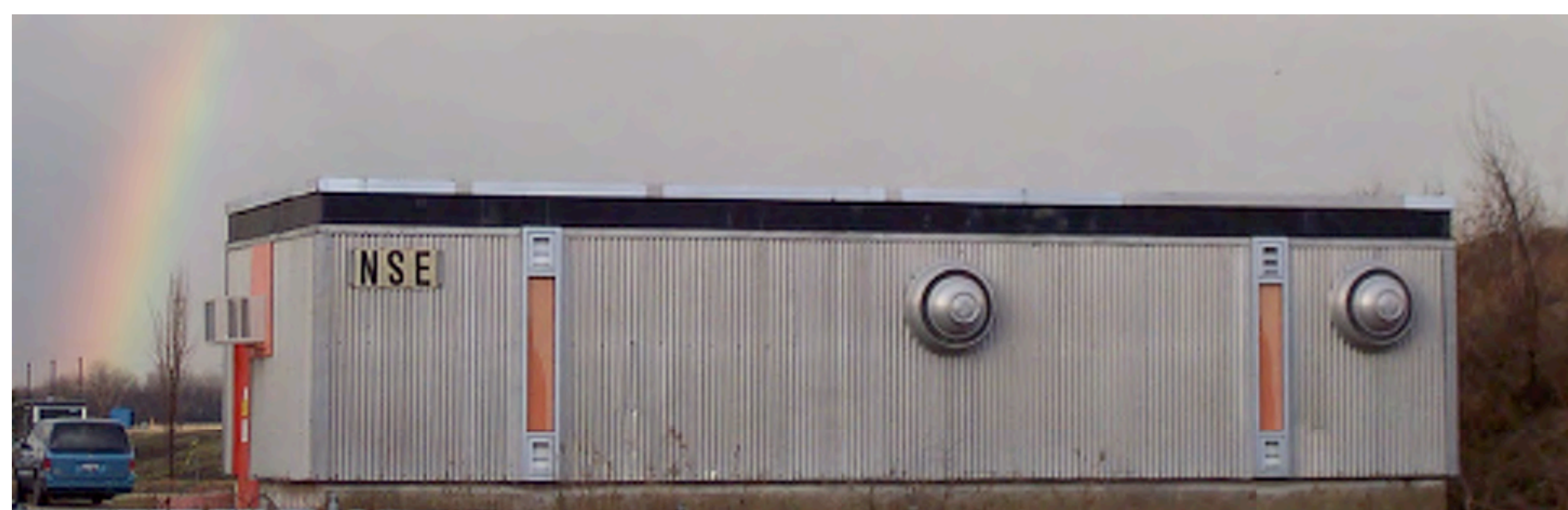
- LoI presented to FNAL PAC in March
- Emphasized practicality of 1st $\bar{g}$ meas't to 10^{-2}
  - req's just 1% of 1 day's $\bar{p}$ production
- PAC & PO (June):
  1. interesting physics!
  2. but 10^{-2} meas't not worthwhile (nucl. B.E.)
  3. need matter demo
- We're now developing techs. for 10^{-4} meas't & assembling matter demo

- From T. Phillips:

Hydrogen 2S Beam at Fermilab

Cold multichannel nozzle
Excited to 2S with pulsed cathode
Detected by quenching 2S, observing Lyman-α photon





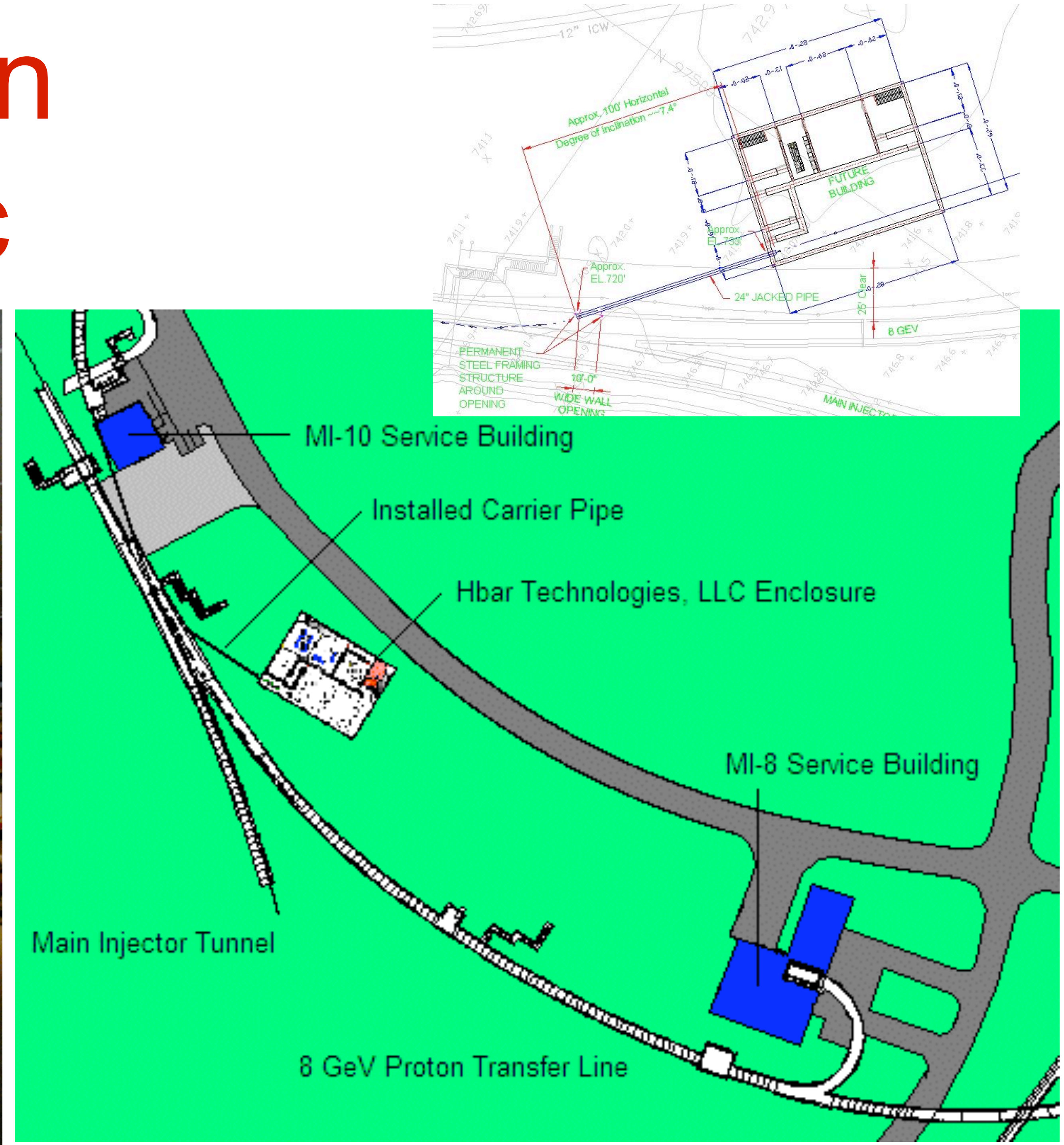
Antimatter Gravity

- Requires development of deceleration techniques from 8 GeV to <20 keV:
  - MI from 8 GeV to $\lesssim$ 400 MeV (TBD)
  - from ~400 MeV to 20 keV, application of μ-cooling-inspired technique looks highly promising!
  - efficiency $\gtrsim 10^{-5}$ looks feasible
    $\Rightarrow 10^{-4}$ $\bar{g}$ meas't in ~3 months' dedicated running
- Requires completion of antiproton deceleration/ extraction facility planned for Hbar Technologies

HBAR Technologies, LLC
Making Antimatter Matter®

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

MI Deceleration Below 1 GeV/c



- From G. Jackson:

HBAR Technologies, LLC
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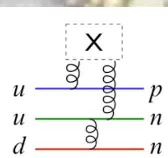
The HiPAT trap

- Designed to hold 1E12 antiprotons
- Designed to be portable
- Traditional super-conducting solenoid requiring liquid helium for the superconductors and liquid nitrogen for the heat shield
- Good vacuum lifetime
- Comes with proton and H- linacs for commissioning
- Still at NASA MSFC

2/21/08



A New Pbar Experiment for Fermilab

3

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  - so far:

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Letter of Intent:

Low- and Medium-Energy Antiproton Physics at Fermilab

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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,* Howard A. Rubin, 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

Jerome Rosen
Northwestern University, Evanston, IL 60208, USA

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

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

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...& growing...

Summary

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Or at least, help spread the word?

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

Some HyperCP Publications:

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

Backup

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]
$A_{\Xi\Lambda}$	$\Xi^\mp \to \Lambda\pi,\ \Lambda \to p\pi$	$\lesssim 0.5 \times 10^{-4}$	$\leq 1.9 \times 10^{-3}$	[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

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- Some Hyperon CP references:

[32] A. Pais, Phys. Rev. Lett. **3**, 242 (1959); O. E. Overseth and S. Pakvasa, Phys. Rev. **184**, 1663 (1969); J. F. Donoghue and S. Pakvasa, Phys. Rev. Lett. **55**, 162 (1985).

[33] J. F. Donoghue, X.-G. He, S. Pakvasa, Phys. Rev. D **34**, 833 (1986); X.-G. He, H. Steger, G. Valencia, Phys. Lett. B **272**, 411 (1991).

[34] G. Valencia, *Proc.* $\overline{p}$2000 *Workshop*, D. M. Kaplan and H. A. Rubin, eds., Illinois Institute of Technology, Chicago, IL 60616, USA, Aug. 3–5, 2000.

[35] J. Tandean, G. Valencia, Phys. Lett. B **451**, 382 (1999).

[36] J. Tandean, Phys. Rev. **70**, 076005 (2004).

[68] D. Chang, X.-G. He, and S. Pakvasa, Phys. Rev. Lett. **74**, 3927 (1995).

[69] X.-G. He, H. Murayama, S. Pakvasa, G. Valencia, Phys. Rev. D **618**, 071701(R) (2000).