CP Violation and Rare Decays in Hyperon and Charm Systems

Xiao-Gang He

NTU

Collaborators: Donoghue, Pakvasa, Tandean, Valencia

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Outline

- CPV in Hyperon Decays in the SM and Beyond
- HyperCP X Particle and Some Implications
- Charm Sector with New Physics

New Experiments with Antiprotons

Daniel M. Kaplan[a]

[a] *Physics Division, Illinois Institute of Technology, Chicago, Illinois 60616 USA*

Abstract

Fermilab operates the world's most intense antiproton source. Newly proposed experiments can use those antiprotons either parasitically during Tevatron Collider running or after the Tevatron Collider finishes in about 2011. For example, the annihilation of 8 GeV antiprotons might make the world's most intense source of tagged D^0 mesons, and thus the best near-term opportunity to study charm mixing and, via CP violation, to search for new physics. Other potential measurements include sensitive studies of hyperons and of the mysterious X, Y, and Z states. Production of antihydrogen in flight can be used for first searches for antihydrogen CPT violation. With antiproton deceleration to low energy, an experiment using a Penning trap and an atom interferometer could make the world's first measurement of the gravitational force on antimatter.

Key words: Antiproton, Antimatter, Charm, Charmonium, CP, CPT, Gravity, Hyperons, Mixing

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CPV in Hyperon Decays in the SM and Beyond

Direct CP violation

* Decay amplitudes have two types of phases:
  - Weak phases (ϕ) arise from complex couplings in the Lagrangian and change signs in the antiparticle decay
  - Strong phases (δ) come from rescatterings of on-shell states in the decay process and do not change signs in the antiparticle decay
* Amplitudes for $i \to f$ and $\bar{i} \to \bar{f}$

$$\mathcal{M}(i \to f) = \mathcal{A}_1 \, e^{i(\delta_1+\phi_1)} + \mathcal{A}_2 \, e^{i(\delta_2+\phi_2)} + \cdots$$

$$\mathcal{M}(\bar{i} \to \bar{f}) = \mathcal{A}_1 \, e^{i(\delta_1-\phi_1)} + \mathcal{A}_2 \, e^{i(\delta_2-\phi_2)} + \cdots$$

$\mathcal{A}_{1,2}$ real.

* Direct CP-violation is possible if there is interference between terms in the decay amplitude with different strong phases and different weak phases.

Decay parameters in hyperon nonleptonic decays (Lee & Yang, 1957)

* The amplitude for the weak decay $B_\mathrm{i} \to B_\mathrm{f}\phi$ in the rest frame of B_i

$$\mathcal{M} \;=\; \chi_\mathrm{f}^\dagger (S + \boldsymbol{\sigma}\cdot\hat{\boldsymbol{p}}_\mathrm{f}\, P)\chi_\mathrm{i}$$

* This implies

$$\begin{aligned}|\mathcal{M}|^2 \;\propto\; & 1 + \alpha\,\hat{\boldsymbol{p}}_\mathrm{f}\cdot\big(\hat{\boldsymbol{s}}_\mathrm{i} + \hat{\boldsymbol{s}}_\mathrm{f}\big) + \beta\,\hat{\boldsymbol{p}}_\mathrm{f}\cdot\hat{\boldsymbol{s}}_\mathrm{f}\times\hat{\boldsymbol{s}}_\mathrm{i} \\ & + \gamma\,\hat{\boldsymbol{s}}_\mathrm{i}\cdot\hat{\boldsymbol{s}}_\mathrm{f} + (1-\gamma)\hat{\boldsymbol{s}}_\mathrm{i}\cdot\hat{\boldsymbol{p}}_\mathrm{f}\,\hat{\boldsymbol{s}}_\mathrm{f}\cdot\hat{\boldsymbol{p}}_\mathrm{f}\end{aligned}$$

$\hat{\boldsymbol{p}}_\mathrm{f}$ is a unit vector in the 3-momentum direction of B_f
$\hat{\boldsymbol{s}}_{\mathrm{i,f}}$ are unit vectors in the spin directions of $B_{\mathrm{i,f}}$
α, β, and γ are decay parameters

$$\alpha \;=\; \frac{2\,\mathrm{Re}(S^*P)}{|S|^2+|P|^2}\,, \qquad \beta \;=\; \frac{2\,\mathrm{Im}(S^*P)}{|S|^2+|P|^2}\,, \qquad \alpha^2+\beta^2+\gamma^2 \;=\; 1$$

Other CP-violation observables in hyperon nonleptonic decays

* The form of α and β suggests additional CP-violating asymmetries

$$A = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}, \qquad B = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}$$

(Donoghue & Pakvasa, 1985)
(Donoghue, He, Pakvasa, 1986)

* α and β result from interference between S and P waves
  $\Rightarrow$ A and B are unaffected by the $\Delta I = \frac{1}{2}$ rule and therefore expected to be less suppressed than Δ.
* A and B are also expected to be nonvanishing for $\Xi \to \Lambda\pi$.
* Although B is expected to be larger than A, it is very difficult to determine experimentally because β is very small.

CP-violating asymmetries in Λ and Ξ decays

* CP-violating asymmetries in $\Xi^- \to \Lambda\pi^-$ and $\Lambda \to p\pi^-$

$$A_\Lambda = \frac{\alpha_\Lambda + \overline{\alpha}_\Lambda}{\alpha_\Lambda - \overline{\alpha}_\Lambda}, \qquad A_\Xi = \frac{\alpha_\Xi + \overline{\alpha}_\Xi}{\alpha_\Xi - \overline{\alpha}_\Xi}$$

* Assuming the dominance of the $|\Delta I| = \frac{1}{2}$ components implies

$$S(\Lambda \to p\pi^-) = S^\Lambda\, e^{i(\delta_S^\Lambda + \phi_S^\Lambda)}, \qquad P(\Lambda \to p\pi^-) = P^\Lambda\, e^{i(\delta_P^\Lambda + \phi_P^\Lambda)}$$

$$S(\Xi^- \to \Lambda\pi^-) = S^\Xi\, e^{i(\delta_S^\Xi + \phi_S^\Xi)}, \qquad P(\Xi^- \to \Lambda\pi^-) = P^\Xi\, e^{i(\delta_P^\Xi + \phi_P^\Xi)}$$

* $A_{\Xi,\Lambda}$ are then related to the strong and weak phases by

$$A_\Lambda = -\tan\left(\delta_P^\Lambda - \delta_S^\Lambda\right) \sin\left(\phi_P^\Lambda - \phi_S^\Lambda\right)$$

$$A_\Xi = -\tan\left(\delta_P^\Xi - \delta_S^\Xi\right) \sin\left(\phi_P^\Xi - \phi_S^\Xi\right)$$

Theoretical evaluation of $A_{\Lambda,\Xi}$

* The strong phases $\delta_P^\Lambda - \delta_S^\Lambda$ and $\delta_P^\Xi - \delta_S^\Xi$ have been measured

$$\delta_P^\Lambda - \delta_S^\Lambda \;=\; -7^\circ \pm 2^\circ \;, \qquad\qquad \delta_P^\Xi - \delta_S^\Xi \;=\; 4.1^\circ \pm 1.5^\circ$$

* To make prediction for $A_{\Lambda,\Xi}$, weak phases $\phi_P^\Lambda - \phi_S^\Lambda$ and $\phi_P^\Xi - \phi_S^\Xi$ have to be determined theoretically.
* In principle, from the effective Hamiltonian $\mathcal{H}_{\rm w}$ of the underlying weak interaction, one calculates for $B \to B'\pi$

$$\phi_S^B \;=\; \frac{\mathrm{Im}\, S(B \to B'\pi)}{\mathrm{Re}\, S(B \to B'\pi)} \;, \qquad\qquad S(B \to B'\pi) \;=\; \langle B'\pi|\mathcal{H}_{\rm w}|B\rangle_S$$

  and similarly for ϕ_P^B.
* But calculating $\langle B'\pi|\mathcal{H}_{\rm w}|B\rangle_{S,P}$ reliably is not possible at present
  $\Rightarrow$ one has to use a model to estimate the matrix elements.
* To reduce uncertainty, for the denominator of, say, ϕ_S^B, one uses the measured amplitude instead of $\mathrm{Re}\, S(B \to B'\pi)$ from calculation.

Calculation of $\phi_{\Lambda,\Xi}$ within standard model

* Effective weak Hamiltonian in SM

$$\mathcal{H}_{\rm w} \;=\; \frac{G_{\rm F}}{\sqrt{2}}\, V_{ud}^{*} V_{us} \sum_{i=1}^{10} C_i\, Q_i \;+\; {\rm H.c}$$

$Q_1 = \bar{d}\gamma^{\mu}(1-\gamma_5)s\,\bar{u}\gamma_{\mu}(1-\gamma_5)u,\;\; Q_2 = \bar{d}\gamma^{\mu}(1-\gamma_5)u\;\bar{u}\gamma_{\mu}(1-\gamma_5)s,\;\; ...$ are four quark operators

$C_i \;=\; z_i \;-\; y_i\; V_{td}^{*}V_{ts}/(V_{ud}^{*}V_{us})$ are Wilson coefficients (y_i and z_i real), $G_{\rm F}$ is the Fermi coupling constant, V_{kl} are CKM matrix elements; in the Wolfenstein parametrization $V_{ud}^{*}V_{us} \simeq \lambda$ and $V_{td}^{*}V_{ts} \simeq -\lambda^5 A^2\,(1-\rho+{\rm i}\eta)$

* The weak phase arises mainly from the penguin operator

$$Q_6 \;=\; -2 \sum_{q=u,d,s} \bar{d}(1+\gamma_5)q\,\bar{q}(1-\gamma_5)s$$

* Matrix elements of Q_6 are estimated by including factorizable and nonfactorizable contributions.

Standard-model prediction

* Factorizable and nonfactorizable contributions of Q_6 to weak phases $\phi_S = \mathrm{Im}\, s/s^{\mathrm{exp}}$ and $\phi_P = \mathrm{Im}\, p/p^{\mathrm{exp}}$, in units of $\eta\lambda^5 A^2\, y_6$, from the leading-order Lagrangian.

Decay mode	ϕ_S^{fac}	ϕ_P^{fac}	ϕ_S^{nonfac}	ϕ_P^{nonfac}
$\Lambda \to p\pi^-$	$-0.34\,\mathrm{GeV}^2\, m_s^{-2}$	$-0.38\,\mathrm{GeV}^2\, m_s^{-2}$	0.98	1.60
$\Xi^- \to \Lambda\pi^-$	$-0.30\,\mathrm{GeV}^2\, m_s^{-2}$	$0.16\,\mathrm{GeV}^2\, m_s^{-2}$	0.59	-1.50

* Input

$$A = 0.80 \pm 0.02\,, \qquad \lambda = 0.2252 \pm 0.0008\,, \qquad \eta = 0.35 \pm 0.02$$

$$m_s(1\,\mathrm{GeV}) = (135 \pm 41)\,\mathrm{MeV}\,, \qquad -0.17 \le y_6(1\,\mathrm{GeV}) \le -0.07$$

* Errors for ϕ_S and ϕ_P due to higher-order chiral terms were estimated to be about 100% and 50%, respectively.

* Resulting asymmetries

$$-1.4 \le 10^4\, A_\Lambda \le 1.3\,, \qquad 0.04 \le 10^4\, A_\Xi \le 1.1\,,$$

$$-1.3 \times 10^{-4} \le A_\Lambda + A_\Xi \le 2.3 \times 10^{-4}$$

$\Xi \to \pi \Lambda \to \pi \pi p$

Measurement of A

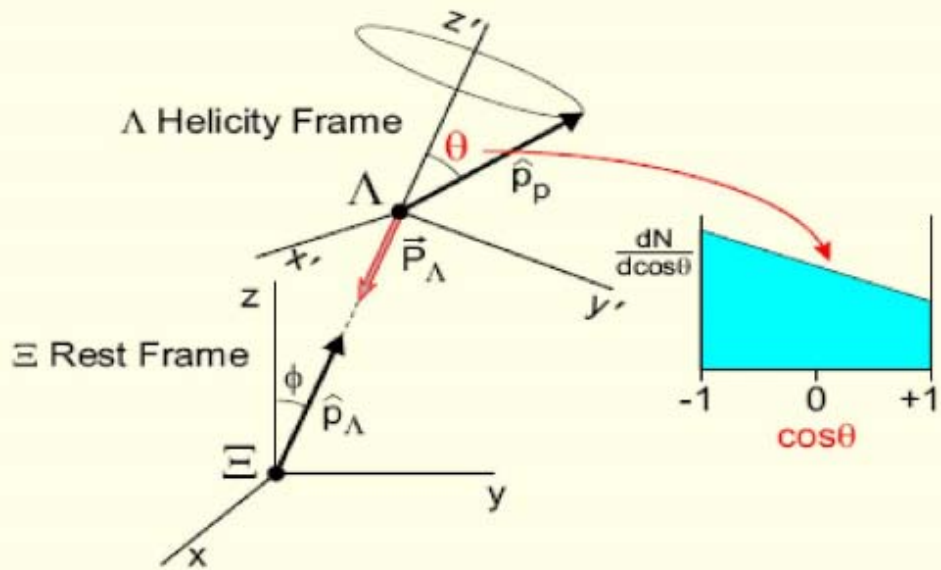
HyperCP technique is sensitive to both Ξ and Λ CP violation

$$\frac{\alpha_\Xi \alpha_\Lambda - \overline{\alpha}_\Xi \overline{\alpha}_\Lambda}{\alpha_\Xi \alpha_\Lambda + \overline{\alpha}_\Xi \overline{\alpha}_\Lambda} \approx A_\Xi + A_\Lambda$$

where: $A_\Xi = \dfrac{\alpha_\Xi + \overline{\alpha}_\Xi}{\alpha_\Xi - \overline{\alpha}_\Xi}$ and $A_\Lambda = \dfrac{\alpha_\Lambda + \overline{\alpha}_\Lambda}{\alpha_\Lambda - \overline{\alpha}_\Lambda}$

What HyperCP experimentally measures ⇒

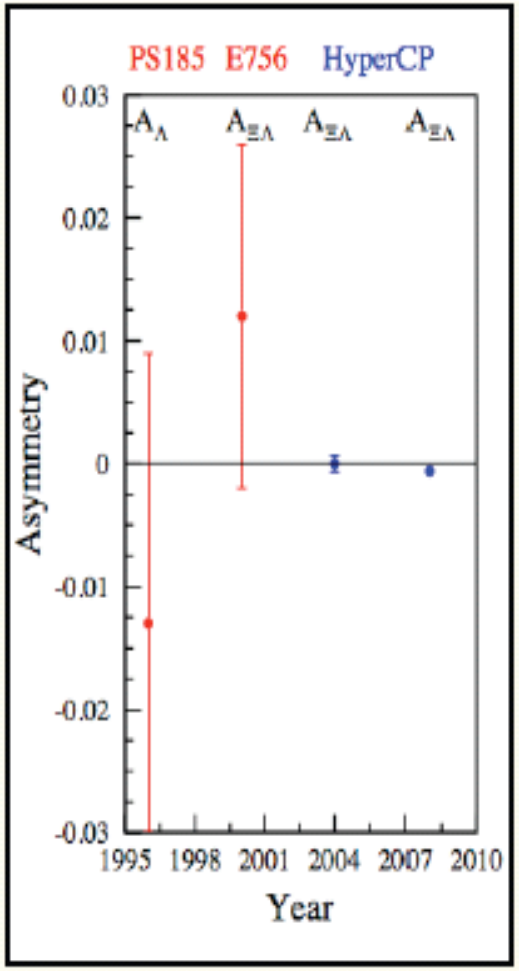
Important: polar axis changes from event to event.



Most recent experimental result

* HyperCP has reported preliminary measurement of $A_{\Xi\Lambda} = A_\Lambda + A_\Xi$

- Using the largest sample of hyperon decays ever amassed by a particle physics experiment, the Hyper*CP* collaboration is making precision searches for *CP* violation from exotic sources
- We measured the *CP* observable $A_{\Xi\Lambda}$ and present a new preliminary result with greater precision
  - $A_{\Xi\Lambda} = [0.0 \pm 5.1(stat) \pm 4.2(syst)] \times 10^{-4}$ (with a 15% of data)
  - $A_{\Xi\Lambda} = [-6.0 \pm 2.1(stat) \pm 2.1(syst)] \times 10^{-4}$ (Preliminary with all data)
- Hyper*CP* measurements are over 40X more precise than results from other experiments

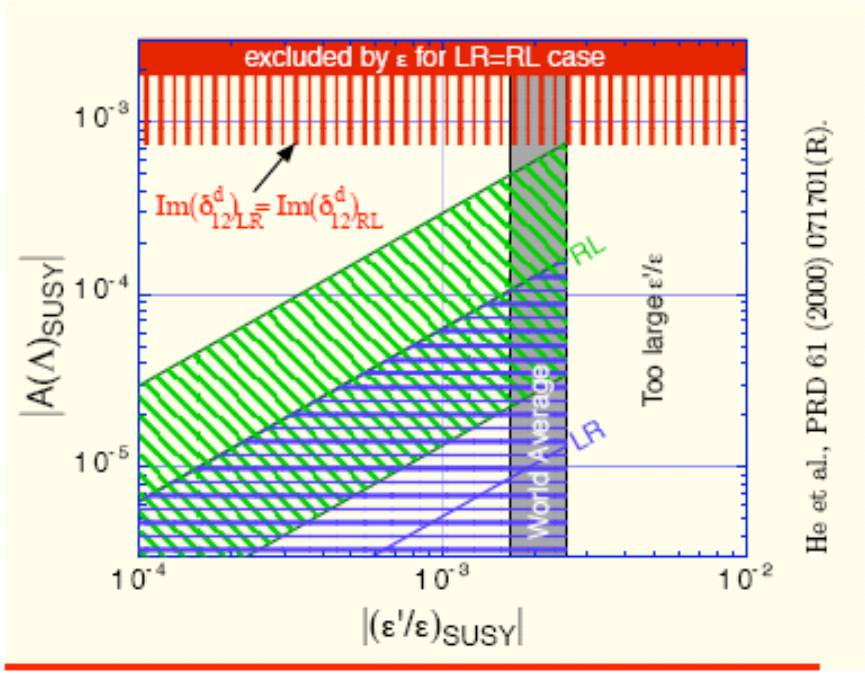


HyperCP looked for asymmetry in $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$

Most recent SM prediction $-0.5\times10^{-4} < A_{\Xi\Lambda} < +0.5\times10^{-4}$

Beyond the SM, bounds from ϵ allow up to 10^{-3}

SUSY example:



CP Violation in Ω Decay

$$\mathrm{i}\mathcal{M}_{\Omega^-\to\Xi\pi} \;=\; G_{\mathrm{F}} m_\pi^2\, \bar{u}_\Xi\, \mathcal{A}^{(\mathrm{P})}_{\Omega^-\Xi\pi}\, k_\mu\, u^\mu_\Omega \;\equiv\; G_{\mathrm{F}} m_\pi^2\, \frac{\alpha^{(\mathrm{P})}_{\Omega^-\Xi}}{\sqrt{2}\, f_\pi}\, \bar{u}_\Xi\, k_\mu\, u^\mu_\Omega\,,$$

$$\Delta(\Xi^0\pi^-) \;\equiv\; \frac{\Gamma(\Omega^-\to\Xi^0\pi^-) - \Gamma(\overline{\Omega}^-\to\overline{\Xi}^0\pi^+)}{\Gamma(\Omega^-\to\Xi^0\pi^-) + \Gamma(\overline{\Omega}^-\to\overline{\Xi}^0\pi^+)}$$

$$\approx\; \sqrt{2}\, \frac{\alpha_3^{(\Omega)}}{\alpha_1^{(\Omega)}}\, \sin(\delta_3-\delta_1)\, \sin(\phi_3-\phi_1)\,,$$

P-wave dominance (predominantly parity conserving)

SM ~ 2×10^{-5} much larger than other rate asymmetries

Beyond SM could be 10-100(?) times larger

Tandean 04: $\Delta_{\Omega\to\Lambda K} < 10^{-3}$ (but new constraints now)

Phys.Rev.D70:076005,2004.

Predictions for CP violation in Ω^- nonleptonic decays

(JT & Valencia, 1999)
(JT, 2004)

* In the standard model

$$0 \;\leq\; \Delta(\Omega^- \to \Lambda K^-)_{\rm SM} \;\leq\; 1 \times 10^{-5}$$

and for $\Omega^- \to \Lambda K^- \to p\pi^- K^-$

$$\left|A_{\Omega\Lambda}\right|_{\rm SM} \;=\; \left|A_\Lambda + A_\Omega\right|_{\rm SM} \;\leq\; 4 \times 10^{-5}$$

* Possible new-physics contributions via $Q_g^\pm$ allowed by the ϵ and ϵ' data yield

$$\left|\Delta(\Omega^- \to \Lambda K^-)\right|_g \;\leq\; 1 \times 10^{-3}\,, \qquad \left|A_{\Omega\Lambda}\right|_g \;\leq\; 8 \times 10^{-3}$$

* Similar numbers are expected for $\Omega^- \to \Xi\pi$
* These predictions can be tested in future measurements.

CP violation in $\Omega^- \to \Lambda K^- \to p\pi^- K^-$

Search for Parity Violation in $\Omega^- \to \Lambda K^-$ Decays

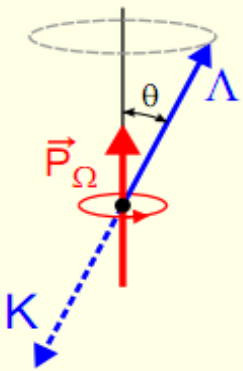
$\Omega^- \to \Lambda K^-$ $\Lambda \to p\pi^-$

- Although spin-3/2, $\Omega^- \to \Lambda K^-$ decay goes much like the other hyperon two-body decays:

$$\frac{dP}{d\cos\theta} = \frac{1}{2}(1 + \alpha_\Omega P_\Omega \cos\theta)$$

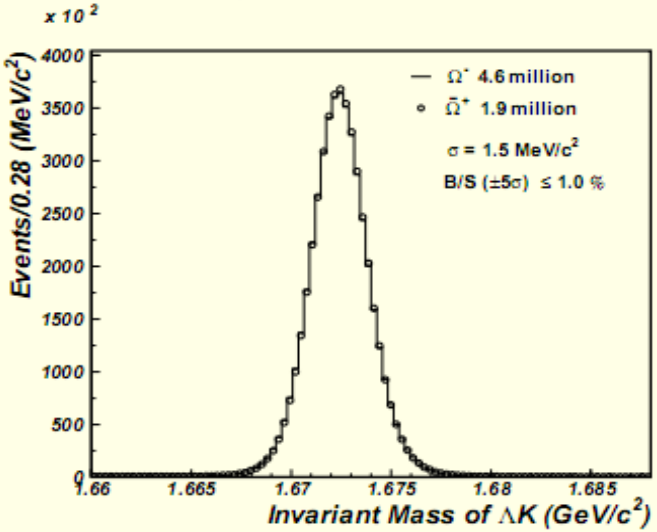
- Here:

$$\alpha_\Omega = \frac{2\mathrm{Re}(P^* D)}{|P|^2 + |D|^2}$$



- A non-zero α_Ω indicates parity violation.
- All other hyperons have non-zero α parameters; only the Ω^- has resisted efforts to find an asymmetrical decay distribution.
- *HyperCP* is measuring α_Ω using unpolarized Ω^-'s through the polarization given to the daughter Λ, which is α_Ω:

$$\frac{dP}{d\cos\theta} = \frac{1}{2}(1 + \alpha_\Omega \alpha_\Lambda \cos\theta)$$



- Large data sample, little background.

HyperCP X Particle and Some Implications

HyperCP's findings

PRL 94, 021801 (2005) PHYSICAL REVIEW LETTERS week ending 21 JANUARY 2005

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

H. K. Park,[8] R. A. Burnstein,[5] A. Chakravorty,[5] Y. C. Chen,[1] W. S. Choong,[2,7] K. Clark,[9] E. C. Dukes,[10] C. Durandet,[10] J. Felix,[4] Y. Fu,[7] G. Gidal,[7] H. R. Gustafson,[8] T. Holmstrom,[10] M. Huang,[10] C. James,[3] C. M. Jenkins,[9] T. Jones,[7] D. M. Kaplan,[5] L. M. Lederman,[5] N. Leros,[6] M. J. Longo,[8,*] F. Lopez,[8] L. C. Lu,[10] W. Luebke,[5] K. B. Luk,[2,7] K. S. Nelson,[10] J.-P. Perroud,[6] D. Rajaram,[5] H. A. Rubin,[5] J. Volk,[3] C. G. White,[5] S. L. White,[5] and P. Zyla[7]

(HyperCP Collaboration)

[1]*Institute of Physics, Academia Sinica, Taipei 11529, Taiwan, Republic of China*
[2]*University of California, Berkeley, California 94720, USA*
[3]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[4]*Universidad de Guanajuato, 37000 León, Mexico*
[5]*Illinois Institute of Technology, Chicago, Illinois 60616, USA*
[6]*Université de Lausanne, CH-1015 Lausanne, Switzerland*
[7]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[8]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[9]*University of South Alabama, Mobile, Alabama 36688, USA*
[10]*University of Virginia, Charlottesville, Virginia 22904, USA*
(Received 3 November 2004; published 18 January 2005)

We report the first evidence for the decay $\Sigma^+ \to p\mu^+\mu^-$ from data taken by the HyperCP (E871) experiment at Fermilab. Based on three observed events, the branching ratio is $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = [8.6^{+6.6}_{-5.4}(\text{stat}) \pm 5.5(\text{syst})] \times 10^{-8}$. The narrow range of dimuon masses may indicate that the decay proceeds via a neutral intermediate state, $\Sigma^+ \to pP^0$, $P^0 \to \mu^+\mu^-$ with a P^0 mass of 214.3 ± 0.5 MeV/c^2 and branching ratio $\mathcal{B}(\Sigma^+ \to pP^0, P^0 \to \mu^+\mu^-) = [3.1^{+2.4}_{-1.9}(\text{stat}) \pm 1.5(\text{syst})] \times 10^{-8}$.

- What's the up-to-date SM prediction?

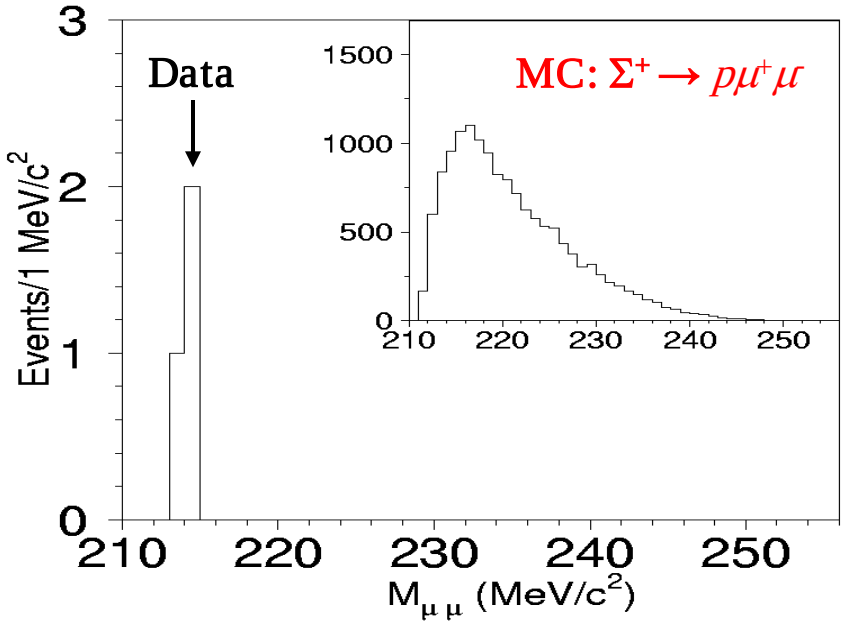
  Old calculation by Bergstrom, Safadi, Singer (1988)

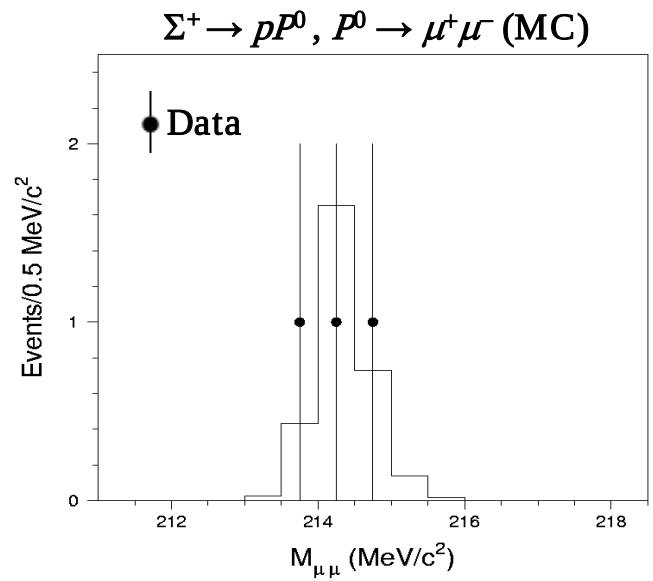
- Do the observed 3 events hint at new physics?

From talk by HK Park (HyperCP)

Interpretations of Results: $\Sigma^+ \to pP^0$, $P^0 \to \mu^+\mu^-$

- Dimuon masses for 3 candidates are clustered within ~ 1 MeV/c^2.

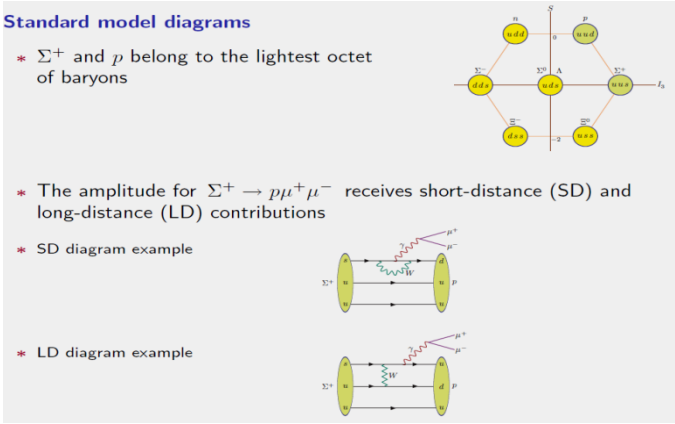




- Probability for dimuon masses of 3 events to be within 1 MeV for $\Sigma^+ \to p\mu^+\mu^-$ decays is less than 1%.
- Suggests two-body decays, $\Sigma^+ \to pP^0$, $P^0 \to \mu^+\mu^-$:

$$M_{P^0} = (214.3 \pm 0.5)\ \mathrm{MeV/c^2} \qquad B(\Sigma^+ \to pP^0, P^0 \to \mu^+\mu^-) = \left(3.1^{+2.4}_{-1.9} \pm 1.5\right) \times 10^{-8}$$

Standard model expectations



- Long-distance contributions dominate $\Sigma^+ \to p\mu^+\mu^-$ decay.

- The resulting branching ratio

$$1.6 \times 10^{-8} \leq \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) \leq 9.0 \times 10^{-8}$$

agrees well with the HyperCP measurement

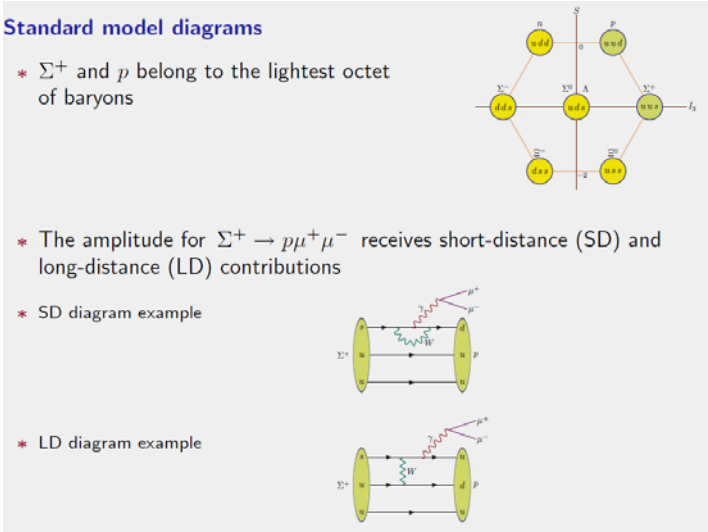
$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \left(8.6^{+6.6}_{-5.4} \pm 5.5\right) \times 10^{-8}$$

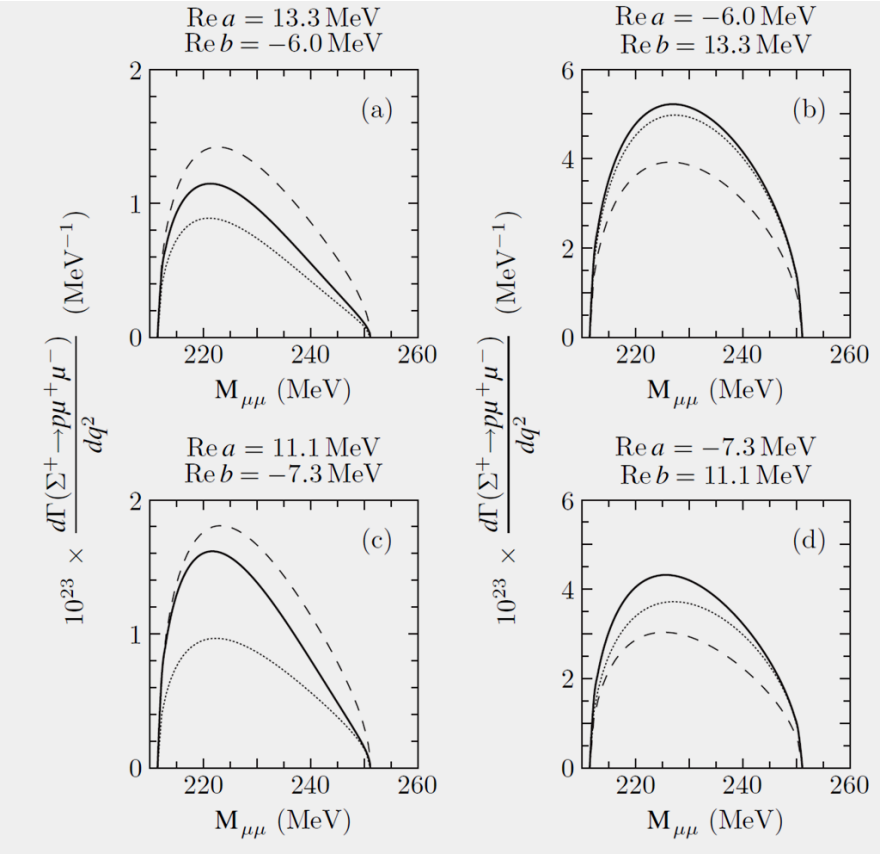
(under the assumption of no new physics)

- The lower end of the predicted rate leaves room for attributing all the 3 observed events to new physics.

Standard model expectations

- Distribution of dimuon invariant mass $M_{\mu\mu}$ (solid curves)





He, JT, Valencia

- Different graphs reflect uncertainty in the calculation.

- Not surprisingly, the predicted distributions show no sharp peak anywhere.

New-particle interpretations

- The possibility that a new particle, *X*, is responsible for the HyperCP events has been theoretically explored to some extent in the literature

  He, JT, Valencia
  Deshpande, Eilam, Jiang
  Geng, Hsiao
  . . . . .

- *X* may be spinless
  - Pseudoscalar sgoldstino in supersymmetric models — Gorbunov *et al.*
  - *CP*-odd Higgs boson in the next-to-minimal supersymmetric standard model (NMSSM) — He, JT, Valencia

- *X* may be a spin-1 particle
  - Gauge (U) boson of an extra U(1) gauge group in some extensions of the SM. — Chen, Geng, Kao

Constraints on *bbX* couplings for spinless *X*

- CLEO

PRL **101,** 151802 (2008) PHYSICAL REVIEW LETTERS week ending 10 OCTOBER 2008

Search for Very Light *CP*-Odd Higgs Boson in Radiative Decays of $\Upsilon(1S)$

(Received 9 July 2008; published 10 October 2008)

We search for a non-SM-like *CP*-odd Higgs boson (a_1^0) decaying to $\tau^+\tau^-$ or $\mu^+\mu^-$ in radiative decays of the $\Upsilon(1S)$. No significant signal is found, and upper limits on the product branching ratios are set. Our $\tau^+\tau^-$ results are almost 2 orders of magnitude more stringent than previous upper limits. Our data provide no evidence for a Higgs state with a mass of 214 MeV decaying to $\mu^+\mu^-$, previously proposed as an explanation for 3 $\Sigma^+ \to p\mu^+\mu^-$ events observed by the HyperCP experiment. Our results constrain NMSSM models.

- BaBar

PRL **103,** 081803 (2009) PHYSICAL REVIEW LETTERS week ending 21 AUGUST 2009

Search for Dimuon Decays of a Light Scalar Boson in Radiative Transitions $\Upsilon \to \gamma A^0$

(Received 27 May 2009; published 18 August 2009)

We search for evidence of a light scalar boson in the radiative decays of the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances: $\Upsilon(2S, 3S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$. Such a particle appears in extensions of the standard model, where a light *CP*-odd Higgs boson naturally couples strongly to *b* quarks. We find no evidence for such processes in the mass range $0.212 \leq m_{A^0} \leq 9.3$ GeV in the samples of 99×10^6 $\Upsilon(2S)$ and 122×10^6 $\Upsilon(3S)$ decays collected by the *BABAR* detector at the SLAC PEP-II *B* factory and set stringent upper limits on the effective coupling of the *b* quark to the A^0. We also limit the dimuon branching fraction of the η_b meson: $\mathcal{B}(\eta_b \to \mu^+\mu^-) < 0.9\%$ at 90% confidence level.

Constraints from $K^{\pm} \to \pi^{\pm} \mu^{+} \mu^{-}$ data

- With only the 2-quark contributions being present, the scalar g_S (vector g_V) part of the sdX coupling in the spinless (spin 1) case is constrained by $K^{\pm} \to \pi^{\pm} \mu^{+} \mu^{-}$ data to be negligibly small.

$$\mathcal{L}_{qq'X} = i\bar{q}'(g_S + g_P \gamma_5) q\, X + \text{H.c.}$$

$$\mathcal{L}_{qq'X} = \bar{q}' \gamma_\mu (g_V + g_A \gamma_5) q\, X^\mu + \text{H.c.}$$

- The pseudoscalar g_P (axial-vector g_A) part can be probed by $K \to \pi\pi \mu^{+} \mu^{-}$

He, JT, Valencia
Deshpande, Eilam, Jiang

Search for $K_L \to \pi^0\pi^0 X$, $X \to \gamma\gamma$

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Search for a Light Pseudoscalar Particle in the Decay $K_L^0 \to \pi^0\pi^0 X$

Y. C. Tung,[1] Y. B. Hsiung,[1] M. L. Wu,[1] K. F. Chen,[1] J. K. Ahn,[2] Y. Akune,[3] V. Baranov,[4] J. Comfort,[5] M. Doroshenko,[6,*] Y. Fujioka,[3] T. Inagaki,[6,7] S. Ishibashi,[3] N. Ishihara,[7] H. Ishii,[8] E. Iwai,[8] T. Iwata,[9] I. Kato,[9] S. Kobayashi,[3] T. K. Komatsubara,[7] A. S. Kurilin,[4] E. Kuzmin,[4] A. Lednev,[10,11] H. S. Lee,[2] S. Y. Lee,[2] G. Y. Lim,[7] J. Ma,[11] T. Matsumura,[12] A. Moisseenko,[4] H. Morii,[13] T. Morimoto,[7] T. Nakano,[14] H. Nanjo,[13] J. Nix,[11] T. Nomura,[13,†] M. Nomachi,[8] R. Ogata,[3] H. Okuno,[7] K. Omata,[14] G. N. Perdue,[11,‡] S. Podolsky,[4,§] K. Sakashita,[8,†] T. Sasaki,[9] N. Sasao,[13] H. Sato,[9] T. Sato,[7] M. Sekimoto,[7] T. Shinkawa,[12] Y. Sugaya,[8] A. Sugiyama,[3] T. Sumida,[13,‖] S. Suzuki,[3] Y. Tajima,[9] S. Takita,[9] Z. Tsamalaidze,[4] T. Tsukamoto,[3,¶] Y. Wah,[11] H. Watanabe,[11,†] M. Yamaga,[7,**] T. Yamanaka,[8] H. Y. Yoshida,[9] Y. Yoshimura,[7] and Y. Zheng[11]

(E391a Collaboration)

[1]*Department of Physics, National Taiwan University, Taipei, Taiwan 10617 Republic of China*
[2]*Department of Physics, Pusan National University, Busan, 609-735 Republic of Korea*

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We performed a search for a light pseudoscalar particle X in the decay $K_L^0 \to \pi^0\pi^0 X$, $X \to \gamma\gamma$ with the E391a detector at KEK. Such a particle with a mass of 214.3 MeV/c^2 was suggested by the HyperCP experiment. We found no evidence for X and set an upper limit on the product branching ratio for $K_L^0 \to \pi^0\pi^0 X$, $X \to \gamma\gamma$ of 2.4×10^{-7} at the 90% confidence level. Upper limits on the branching ratios in the mass region of X from 194.3 to 219.3 MeV/c^2 are also presented.

- This constrains some sgoldstino scenarios.

Searches for $K_L \to \pi^0\pi^0 X$, $X \to \mu^+\mu^-$

- Preliminary results reported at KAON09

- **Search for a New Neutral Boson in the Rare Decay $K_L \to \pi^0\pi^0\mu^+\mu^-$ from KTeV**

The KTeV E799 experiment has conducted a search for the rare decay $K_L \to \pi^0\pi^0\mu^+\mu^-$, which includes a search for the light neutral boson X^0 that decays to $\mu^+\mu^-$. A possible new light neutral boson X^0 was reported by the HyperCP experiment with a mass of 214.3 MeV/c^2. In this paper we report no evidence of $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ and set an upper limit on the branching ratio for $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ of 9.44×10^{-11} at the 90% confidence level. In addition, an upper limit on the branching ratio for $K_L \to \pi^0\pi^0\mu^+\mu^-$ of 8.63×10^{-11} at the 90% confidence level is also presented.

- **Search for $X(214)$ in $K_L^0 \to \pi^0\pi^0 X(X \to \mu^+\mu^-)$ using Back-Anti counter at the E391a experiment**

We have searched for a light pseudoscaler particle "$X(214)$" which is suggested by HyperCP experiment in the $K_L^0 \to \pi^0\pi^0 X(X \to \mu^+\mu^-)$ decay process using the E391a detector at KEK. In our analysis, signal event "$X(214)$" has not observed with the 3.58×10^9 K_L^0 decays, and we set an upper limit for the branching fraction of $K_L^0 \to \pi^0\pi^0 X(X \to \mu^+\mu^-)$ to be 1.6×10^{-6} at the 90% confidence level. Also we have examined $K_L^0 \to \pi^0\pi^0\mu^+\mu^-$ 4-body process. We set an upper limit for the branching fraction of $K_L^0 \to \pi^0\pi^0\mu^+\mu^-$ to be 9.3×10^{-7}.

Implications of KTeV results

- KTeV measurements

$Br(K_L \to \pi^0\pi^0\mu^+\mu^-) < 8.63 \times 10^{-11}$

Preliminary!!!

From talk by D Phillips (KTeV)

- Same number for spinless or spin-1 X

$Br(K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-) < 9.44 \times 10^{-11}$

- Predictions for spinless X (with real sdX coupling)

$$\mathcal{B}(K_L \to \pi^0\pi^0 X_P \to \pi^0\pi^0\mu^+\mu^-) = (8.3^{+7.5}_{-6.6}) \times 10^{-9}$$

He, JT, Valencia

- With complex couplings, the predicted lower bounds can be much smaller: a factor of $\epsilon \sim 10^{-3}$
- If persists, the KTeV data will place a significant constraint on g_P
  - It is restricted to be almost purely imaginary

$$\mathcal{L}_{qq'X} = i\bar{q}'(g_S + g_P\gamma_5)q\,X + \text{H.c.}$$

- Stronger restrictions on g_P may be obtained from decays of particles other than neutral kaons
  - such as $K^\pm \to \pi^\pm\pi^0 X$ and $\Omega^- \to \Xi^0 X$

Implications of KTeV results

- KTeV measurements

$Br(K_L \to \pi^0\pi^0\mu^+\mu^-) < 8.63 \times 10^{-11}$

Preliminary!!!

From talk by D Phillips (KTeV)

- Same number for spinless or spin-1 *X*

$Br(K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-) < 9.44 \times 10^{-11}$

- Predictions for spin-1 *X* (with real *sdX* coupling)

$$\mathcal{B}(K_L \to \pi^0\pi^0 X_A \to \pi^0\pi^0\mu^+\mu^-) = (1.0^{+0.9}_{-0.8}) \times 10^{-10}$$

He, JT, Valencia

- This is well below the KTeV upper-bound and could get lower in the presence of an imaginary part of the *sdX* coupling

$$\mathcal{L}_{qq'X} = \bar{q}'\gamma_\mu(g_V + g_A\gamma_5)q\, X^\mu + \text{H.c.}$$

- Thus the axial-vector (g_A) part the *sdX* coupling is not well constrained

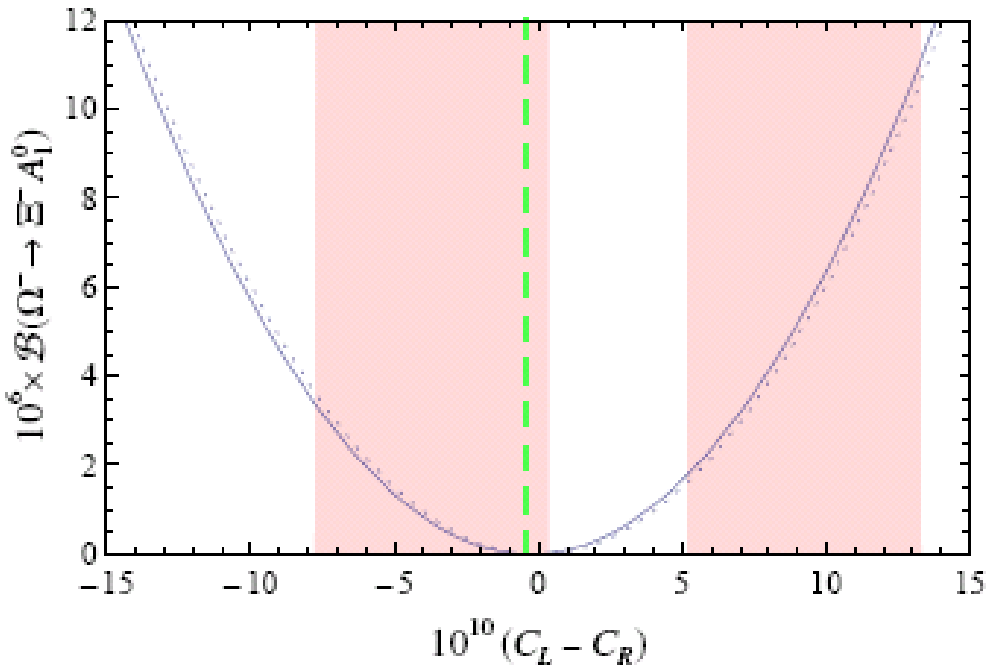
$\Omega^- \to \Xi^- X \to \Xi^- \mu^- \mu^+$

HyperCP Constraint: $B(\Omega^- \to \Xi^- \mu^- \mu^+) < 6.1 \times 10^{-6}$ C.L. 90%

SM prediction: $B_{SM}(\Omega^- \to \Xi^- \mu^- \mu^+) < 6.6 \times 10^{-8}$.

Larger branching ratio allowed from: $\Omega^- \to \Xi^- X \to \Xi^- \mu^- \mu^+$?

Possible!



Search for $B^0 \to K^{*0} X, \rho^0 X,\ X \to \mu^+\mu^-$ at Belle

Summary

Preliminary

- No event is observed in B decays
- The obtained upper limits @ 90% C.L. are as follows :
  - X^0 as a scalar particle
    - $B(B^0 \to K^{*0} X^0, K^{*0} \to K^+\pi^- \text{ and } X^0 \to \mu^+\mu^-) < 1.53 \times 10^{-8}$
    - $B(B^0 \to \rho^0 X^0, \rho^0 \to \pi^-\pi^+ \text{ and } X^0 \to \mu^+\mu^-) < 0.81 \times 10^{-8}$
  - X^0 as a vector particle
    - $B(B^0 \to K^{*0} X^0, K^{*0} \to K^+\pi^- \text{ and } X^0 \to \mu^+\mu^-) < 1.53 \times 10^{-8}$
    - $B(B^0 \to \rho^0 X^0, \rho^0 \to \pi^-\pi^+ \text{ and } X^0 \to \mu^+\mu^-) < 0.81 \times 10^{-8}$
- The upper limits as function of lifetime
- General search study is ongoing
  - 212 MeV/c^2 ~ 230 MeV/c^2 with 1 MeV/c^2 step
  - 230 MeV/c^2 ~ 280 MeV/c^2 with 10 MeV/c^2 step

From talk by H Hyun (Belle)

Charm Sector with New Physics

Anomalous couplings of quarks

* In many types of new physics, the new particles are heavier than their SM counterparts.
  - Their effects can be described by an effective low-energy theory.
* It is possible that the effect of new physics is mainly to modify the SM couplings between gauge bosons and certain fermions.
* Anomalous top-quark couplings have been much studied in the literature.
  - They are most tightly constrained by the $b \to s\gamma$ decay.
  - This mode does not place severe constraints on the corresponding charm-quark couplings due to the relative smallness of the charm mass.
* It is thus interesting to explore anomalous charm-quark couplings subject to existing and future data.

Effective interactions

* We focus on new physics affecting primarily the charged weak currents involving the charm quark.

* The effective Lagrangian for a general parametrization of the W boson interacting with an up-type quark U_k and a down-type quark D_l can be written as

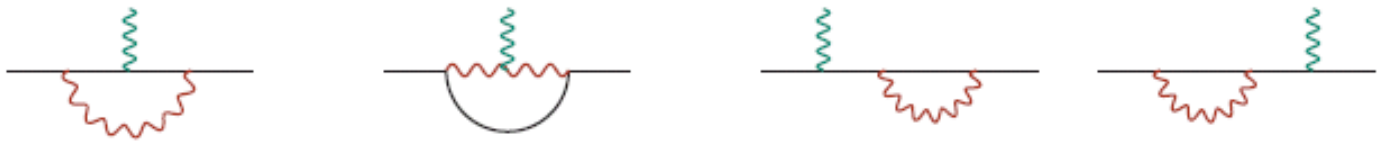
$$\mathcal{L}_{UDW} = -\frac{g}{\sqrt{2}} V_{kl} \bar{U}_k \gamma^\mu \left[(1+\kappa_{kl}^{\mathrm{L}}) P_{\mathrm{L}} + \kappa_{kl}^{\mathrm{R}} P_{\mathrm{R}} \right] D_l W_\mu^+ + \mathrm{H.c.}$$

g is the weak coupling constant, the anomalous couplings $\kappa_{kl}^{\mathrm{L,R}}$ are normalized relative to the CKM-matrix elements V_{kl}, and $P_{\mathrm{L,R}} = \frac{1}{2}(1 \mp \gamma_5)$.

* In general, $\kappa_{kl}^{\mathrm{L,R}}$ are complex and therefore provide new sources of CP violation.

Loop-induced processes

* The anomalous quark-W couplings generate flavor-changing neutral-current interactions via
  - γ- and Z-penguin diagrams



  - box diagrams

They therefore affect loop-induced processes,

Divergences treated by dimensional regularization with a cut off

$D, D_s \to \ell\nu$

$$\Gamma(D \to \ell\nu) = \frac{G_F^2 f_D^2 m_\ell^2 m_D}{8\pi}\left(1 - \frac{m_\ell^2}{m_D^2}\right)^2 |V_{cd}(1 + \kappa_{cd}^{\rm L} - \kappa_{cd}^{\rm R})|^2,$$

$\langle 0|\bar{d}\gamma^\mu c|D(p)\rangle = i f_D p^\mu$. Changing V_{cd}, $\kappa_{cd}^{\rm L,R}$, m_D, and f_D to V_{cs}, $\kappa_{cs}^{\rm L,R}$, m_{D_s} and f_{D_s}, respectively, one obtains the decay width $\Gamma(D_s \to \ell\nu)$.

Recent measurements $f_D^{\rm exp} = (205.8 \pm 8.9)$ MeV, $f_{D_s}^{\rm exp} = (261.2 \pm 6.9)$ MeV,

SM calculations give $f_D^{\rm th} = (202 \pm 8)$ MeV, $f_{D_s}^{\rm th} = (240 \pm 7)$ MeV.

$D \to \ell\nu$ the data agree with theoretical predictions well, but for $D_s \to \ell\nu$ there is deviation at the 2-sigma level. this deviation may be due to physics beyond the SM

$$|{\rm Re}(\kappa_{cd}^{\rm L} - \kappa_{cd}^{\rm R})| \le 0.04, \quad 0 \le {\rm Re}(\kappa_{cs}^{\rm L} - \kappa_{cs}^{\rm R}) \le 0.1.$$

Summary of constraints

Process	Constraint
$K^+ \to \pi^+ \nu\bar{\nu}$	$-1.3 \times 10^{-3} \leq \mathrm{Re}(\kappa^{\mathrm{L}}_{cd} + \kappa^{\mathrm{L}}_{cs}) + 0.42\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cs} \leq 2.5 \times 10^{-4}$
$K_L \to \mu^+\mu^-$	$\left\lvert \mathrm{Re}(\kappa^{\mathrm{L}}_{cs} + \kappa^{\mathrm{L}}_{cd}) + 6 \times 10^{-4}\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cs} \right\rvert \leq 1.5 \times 10^{-4}$
ΔM_K	$\left\lvert 0.043\,\mathrm{Re}(\kappa^{\mathrm{L}}_{cd} + \kappa^{\mathrm{L}}_{cs}) - 0.015\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cs} - \mathrm{Re}(\kappa^{\mathrm{R}*}_{cd}\kappa^{\mathrm{R}}_{cs}) + 0.28\,\mathrm{Im}(\kappa^{\mathrm{R}*}_{cd}\kappa^{\mathrm{R}}_{cs}) \right\rvert \leq 8.5 \times 10^{-4}$
ϵ	$\left\lvert 0.015\,\mathrm{Re}(\kappa^{\mathrm{L}}_{cs} + \kappa^{\mathrm{L}}_{cd}) + 0.043\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cs} - 0.28\,\mathrm{Re}(\kappa^{\mathrm{R}*}_{cd}\kappa^{\mathrm{R}}_{cs}) - \mathrm{Im}(\kappa^{\mathrm{R}*}_{cd}\kappa^{\mathrm{R}}_{cs}) \right\rvert \leq 2.5 \times 10^{-6}$
ΔM_d	$-0.031 \leq \mathrm{Re}(\kappa^{\mathrm{L}}_{cb} + \kappa^{\mathrm{L}}_{cd}) + 0.4\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cb} \leq 0.003$
$\sin(2\beta)$	$-1.5 \times 10^{-3} \leq 0.4\,\mathrm{Re}(\kappa^{\mathrm{L}}_{cb} + \kappa^{\mathrm{L}}_{cd}) - 0.69\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cb} - 0.31\,\mathrm{Im}\,\kappa^{\mathrm{L}}_{cs} \leq 0.012$
ΔM_s	$-0.014 \leq \mathrm{Re}(\kappa^{\mathrm{L}}_{cs} + \kappa^{\mathrm{L}}_{cb}) + 0.018\,\mathrm{Im}(\kappa^{\mathrm{L}}_{cs} - \kappa^{\mathrm{L}}_{cb}) \leq 0.015$
$\sin(2\beta_s)$	$-0.09 \leq 0.026\,\mathrm{Re}(\kappa^{\mathrm{L}}_{cb} + \kappa^{\mathrm{L}}_{cs}) + \mathrm{Im}(\kappa^{\mathrm{L}}_{cb} - \kappa^{\mathrm{L}}_{cs}) \leq 7 \times 10^{-4}$
$D \to \ell\nu$	$\left\lvert \mathrm{Re}(\kappa^{\mathrm{L}}_{cd} - \kappa^{\mathrm{R}}_{cd}) \right\rvert \leq 0.04$
$D_s \to \ell\nu$	$0 \leq \mathrm{Re}(\kappa^{\mathrm{L}}_{cs} - \kappa^{\mathrm{R}}_{cs}) \leq 0.1$
$b \to c\ell\bar{\nu}$	$-0.13 \leq \mathrm{Re}\,\kappa^{\mathrm{R}}_{cb} \leq 0$
$B \to \psi K, \eta_c K$	$-5 \times 10^{-4} \leq \mathrm{Im}(\kappa^{\mathrm{R}}_{cb} + \kappa^{\mathrm{R}}_{cs}) \leq 0.04$

Large contributions to

D^0 – \bar D^0 mixing and CP violation.

c -> u gamma.

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