

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

Standard Model or New Physics?

Jusak Tandean

National Taiwan University

in collaboration with
XG He & G Valencia

High Energy Physics Seminar
National Tsing Hua University

25 September 2008

Outline of talk

- Introduction
- Evaluation of $\Sigma^+ \rightarrow p\mu^+\mu^-$ within standard model
- New particle interpretation of HyperCP results
- Candidate for new particle in NMSSM
- Testable predictions
- Conclusions

- Interesting experimental finding

PRL **94**, 021801 (2005)

PHYSICAL REVIEW LETTERS

week ending
21 JANUARY 2005

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

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. Zyla⁷

(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 $\Sigma^+ \rightarrow p\mu^+\mu^-$ from data taken by the HyperCP (E871) experiment at Fermilab. Based on three observed events, the branching ratio is $\mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) = [8.6^{+5.6}_{-3.4}(\text{stat}) \pm 5.5(\text{syst})] \times 10^{-8}$. The narrow range of dimuon masses may indicate that the decay proceeds via a neutral intermediate state, $\Sigma^+ \rightarrow pP^0, P^0 \rightarrow \mu^+\mu^-$ with a P^0 mass of 214.3 ± 0.5 MeV/ c^2 and branching ratio $\mathcal{B}(\Sigma^+ \rightarrow pP^0, P^0 \rightarrow \mu^+\mu^-) = [3.1^{+2.4}_{-1.9}(\text{stat}) \pm 1.5(\text{syst})] \times 10^{-8}$.

DOI: 10.1103/PhysRevLett.94.021801

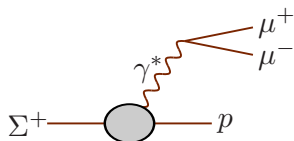
PACS numbers: 13.30.Cc, 14.20.Jn, 14.80.Mz

- What's the up-to-date standard-model prediction for the decay?

(old calculation by Bergstrom, Safadi, Singer, ZPC, 1988)

- Do the observed 3 events hint at new physics?

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



- Gauge-invariant amplitude has four form-factors

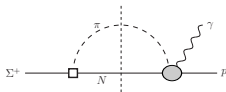
$$\mathcal{M}(B_i \rightarrow B_f \gamma^*) = -eG_F \bar{B}_f [i\sigma^{\mu\nu} q_\mu (a + b\gamma_5) + (q^2 \gamma^\nu - q^\nu \not{q})(c + d\gamma_5)] B_i \varepsilon_\nu^*$$

q four-momentum of γ^* .

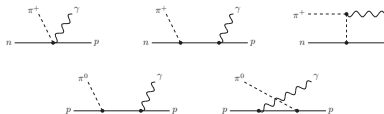
- Form factors $a(q^2)$, $b(q^2)$, $c(q^2)$, and $d(q^2)$ are all complex and get imaginary parts from $N\pi$ intermediate states.
- $a(0)$ and $b(0)$ contribute to the (on shell) radiative decay $\Sigma^+ \rightarrow p\gamma$, but c and d do not.

Long-distance contributions to $\Sigma^+ \rightarrow p\gamma^*$

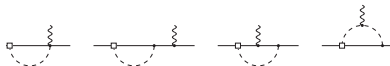
- Unitarity cut



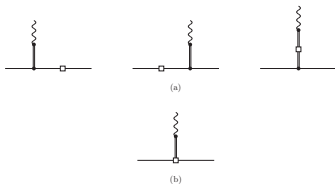
- Leading-order diagrams for $N\pi \rightarrow p\gamma^*$ reactions



- Diagrams for imaginary part of amplitude in heavy-baryon case

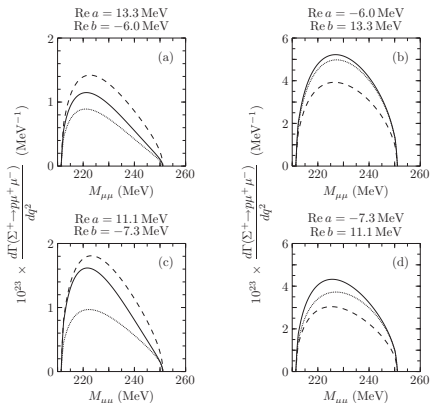


- Pole diagrams contributing to the c and d amplitudes



Results in standard model

- Invariant-mass distributions corresponding to the smallest and largest branching ratios for the (a,b) relativistic and (c,d) heavy baryon cases.



Each solid curve receives contributions from all form factors.

- Different possible graphs reflect uncertainty in the calculation.
- Not surprisingly, **the predicted spectra show no sharp peak anywhere.**

Branching ratio in standard model

- The SM calculation yields the range

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

- This agrees well with HyperCP measurement

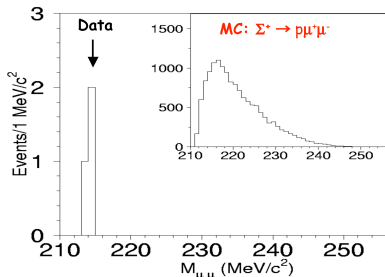
$$\mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) = (8.6_{-5.4}^{+6.6} \pm 5.5) \times 10^{-8}$$

(under the assumption of no new physics).

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

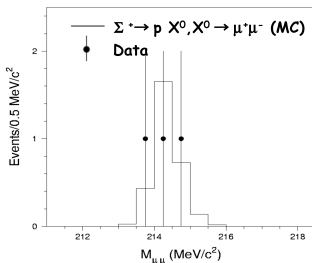
Alternative interpretation of HyperCP results

- Dimuon masses for 3 candidates are clustered within $\sim 1 \text{ MeV}/c^2$.



- Probability for dimuon masses of 3 events to be within 1 MeV for $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays in SM is **less than 1%**.

- Suggests two-body decays,



- For $\Sigma^+ \rightarrow pX^0, X^0 \rightarrow \mu^+\mu^-$:

$$M_{X^0} = (214.3 \pm 0.5) \text{ MeV}/c^2$$

$$B(\Sigma^+ \rightarrow pX^0, X^0 \rightarrow \mu^+\mu^-) = [3.1_{-1.9}^{+2.4} \pm 1.5] \times 10^{-8}$$

From HK Park's talk (2007)

New particle hypothesis

- Interpreting their results as hinting at a new particle (X^0), HyperCP finds
 - * $\mathcal{B}(\Sigma^+ \rightarrow pX^0 \rightarrow p\mu^+\mu^-) = (3.1_{-1.9}^{+2.4} \pm 1.5) \times 10^{-8}$
 - * mass $m_X = (214.3 \pm 0.5) \text{ MeV}$
- This observation implies the particle
 - * is short lived, decaying inside detector
 - * is narrow, with $\Gamma_X \sim 10^{-7} \text{ MeV}$
 - * decays mainly into $\mu^+\mu^-$, e^+e^- , or $\gamma\gamma$
 - * does not interact strongly
 - * has effective $|\Delta S| = 1$ coupling to d, s quarks

(Geng & Hsiao, PLB, 2006)

Constraints on new particle with mass 214 MeV

- The existence of a new particle with such a low mass would be remarkable, as it would signal the existence of physics beyond the SM unambiguously.
- But the new-particle interpretation faces serious challenges:
 - * A new-physics model having a suitable candidate for the particle and able to explain why it is light.
 - * An explanation of why the particle has not been observed by other experiments covering the same kinematic range.
 - * Its interactions must produce the rate implied by the HyperCP observation.

Constraints from kaon and B -meson decays

- E865 at BNL:

$$\mathcal{B}(K^{\pm} \rightarrow \pi^{\pm} A_1^0) \lesssim 8.7 \times 10^{-9}$$

(Ma et al., PRL, 2000)

- NA48:

$$\mathcal{B}(K_S \rightarrow \pi^0 A_1^0) \lesssim 1.8 \times 10^{-9}$$

(Batley et al., PLB, 2004)

- BABAR & Belle:

$$\mathcal{B}(B \rightarrow X_s A_1^0) \lesssim 8.0 \times 10^{-7}$$

(Aubert et al., PRL, 2004)

(Iwasaki et al., PRD, 2005)

Two types of $|\Delta S| = 1$ contributions

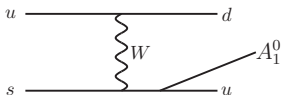
(He, JT, Valencia, PRD, 2006)

- Two-quark contributions

$$\mathcal{L}_{\mathcal{A}sd} = \frac{iC_R}{2} \bar{d}(1 + \gamma_5)s A_1^0 + \frac{iC_L}{2} \bar{d}(1 - \gamma_5)s A_1^0 + \text{H.c.}$$

$C_{L,R}$ are in general unrelated.

- Four-quark contributions, which arise from the combined effects of the usual SM four-quark $|\Delta S| = 1$ operators and A_1^0 being radiated off one of the light quarks via its flavor-conserving couplings.



- Similarly for a scalar particle.

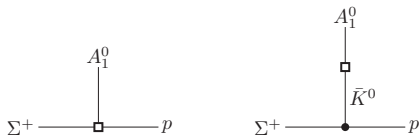
Hadronic couplings arising from two-quark contributions

- Chiral Lagrangian techniques can be used to derive the hadronic realization of the sdA_1^0 couplings.
- The resulting Lagrangian

$$\mathcal{L}_{\mathcal{A}} = b_D \langle \bar{B} \{h_{\mathcal{A}}, B\} \rangle + b_F \langle \bar{B} [h_{\mathcal{A}}, B] \rangle + b_0 \langle h_{\mathcal{A}} \rangle \langle \bar{B} B \rangle + \frac{1}{2} f^2 B_0 \langle h_{\mathcal{A}} \rangle + c \bar{T}^\alpha h_{\mathcal{A}} T_\alpha - c_0 \langle h_{\mathcal{A}} \rangle \bar{T}^\alpha T_\alpha + \text{H.c.}$$

$$h_{\mathcal{A}} = -i(C_R \xi^\dagger h \xi^\dagger + C_L \xi h \xi) A_1^0 \text{ and } h = \frac{1}{2}(\lambda_6 + i\lambda_7).$$

- Baryon and meson fields are contained in 3×3 matrices B and ξ , and also tensor T_μ .
- Diagrams for $\Sigma \rightarrow p A_1^0$



- Similarly for a scalar particle.

Chiral Lagrangians in SM

- Leading-order strong Lagrangian

$$\begin{aligned}\mathcal{L}_s = & \langle \bar{B} i\gamma^\mu (\partial_\mu B + [\mathcal{V}_\mu, B]) \rangle - m_0 \langle \bar{B} B \rangle \\ & + D \langle \bar{B} \gamma^\mu \gamma_5 \{ \mathcal{A}_\mu, B \} \rangle + F \langle \bar{B} \gamma^\mu \gamma_5 [\mathcal{A}_\mu, B] \rangle \\ & + b_D \langle \bar{B} \{ M_+, B \} \rangle + b_F \langle \bar{B} [M_+, B] \rangle + b_0 \langle M_+ \rangle \langle \bar{B} B \rangle \\ & + \frac{1}{4} f^2 \langle \partial^\mu \Sigma^\dagger \partial_\mu \Sigma \rangle + \frac{1}{2} f^2 B_0 \langle M_+ \rangle \\ & - \bar{T}^\mu i \not{D} T_\mu + m_T \bar{T}^\mu T_\mu + \mathcal{C} (\bar{T}^\mu \mathcal{A}_\mu B + \bar{B} \mathcal{A}_\mu T^\mu) \\ & + c \bar{T}^\mu M_+ T_\mu - c_0 \langle M_+ \rangle \bar{T}^\mu T_\mu\end{aligned}$$

- Leading-order weak Lagrangian

$$\begin{aligned}\mathcal{L}_w = & h_D \langle \bar{B} \{ \xi^\dagger h \xi, B \} \rangle + h_F \langle \bar{B} [\xi^\dagger h \xi, B] \rangle \\ & + \gamma_8 f^2 \langle h \partial_\mu \Sigma \partial^\mu \Sigma^\dagger \rangle + 2\tilde{\gamma}_8 f^2 B_0 \langle h \xi M_+ \xi^\dagger \rangle \\ & + h_C \bar{T}^\mu \xi^\dagger h \xi T_\mu + \text{H.c.}\end{aligned}$$

Chiral Lagrangians for four-quark contributions

- From SM strong and weak chiral Lagrangians, one derives

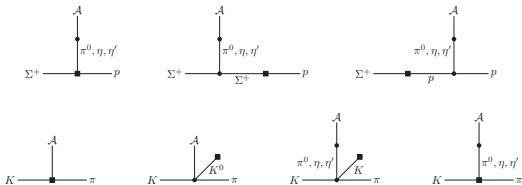
$$\mathcal{L}_s^A = \left(b_D \langle \bar{B} \{ \tilde{M}_-, B \} \rangle + b_F \langle \bar{B} [\tilde{M}_-, B] \rangle + b_0 \langle \tilde{M}_- \rangle \langle \bar{B} B \rangle + \frac{1}{2} f^2 B_0 \langle \tilde{M}_- \rangle \right) \frac{iA_1^0}{v}$$

$$\mathcal{L}_w^A = 2\tilde{\gamma}_8 f^2 B_0 \langle h\xi \tilde{M}_- \xi^\dagger \rangle \frac{iA_1^0}{v} + \text{H.c.}$$

$$\tilde{M}_- = \xi^\dagger \tilde{M} \xi^\dagger - \xi \tilde{M}^\dagger \xi \text{ and } \tilde{M} = \text{diag}(l_u \hat{m}, l_d \hat{m}, l_d m_s)$$

- From the coupling of A_1^0 to two gluons via the axial anomaly,

$$\mathcal{L}_{\eta_1 \mathcal{A}} = -\frac{1}{2} \left(m_{\eta_1}^2 - \frac{2}{3} m_K^2 - \frac{1}{3} m_\pi^2 \right) \left[\eta_1 + \frac{f A_1^0}{\sqrt{6} v} (2l_u + l_d) \right]^2$$



Two- and four-quark contributions

- The interplay between the 2- and 4-quark contributions makes it possible to find a desired model
- However, it is not easy to devise such a model.
- In most models having $\bar{d}sX$ couplings, the 2-quark operators have the structure $\bar{d}(1 \pm \gamma_5)sX$: the part without γ_5 contributes significantly to $K \rightarrow \pi\mu^+\mu^-$ leading to couplings that are too small to account for the HyperCP events.
- In some models, there may be parameter space where the 2- and 4-quark contributions are comparable and cancel sufficiently to lead to rates within the kaon and hyperon bounds.
- However, since in many models the flavor-changing two-quark couplings $\bar{q}q'X$ are related for different (q, q') sets, experimental data on $B \rightarrow X_s\mu^+\mu^-$ also provide stringent constraints.
- Thus the light (pseudo)scalars in many models, such as the SM and the two-Higgs-doublet model, are ruled out as candidates to explain the HyperCP events.

Any candidate for X ?

- The next-to-minimal supersymmetric standard model (NMSSM) is an extension of the MSSM.
- In the NMSSM, there is a gauge-singlet Higgs field N in addition to the two Higgs fields H_u and H_d responsible for the up- and down-type quark masses in the MSSM.
- As a result, the physical spectrum of the NMSSM has 2 additional neutral Higgs bosons: one a scalar and the other a pseudoscalar.
- The lighter pseudoscalar Higgs boson, the A_1^0 , turns out to be able to play the role of X .
- The soft-susy-breaking term in the Higgs potential is

$$V_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_N^2 |N|^2 - (\lambda A_\lambda H_d H_u N + \frac{1}{3} k A_k N^3 + \text{H.c.})$$

and has a global U(1) symmetry in the limit that $A_\lambda, A_k \rightarrow 0$.

(Dobrescu, Matchev, JHEP, 2000)

- The global U(1) symmetry allows the A_1^0 mass to be naturally, and masses of order 100 MeV are not ruled out.

(Dobrescu, PRD, 2001)

A_1^0 in NMSSM

- In the large- $\tan\beta$ limit ($\tan\beta$ the ratio of VEVs of Higgs doublets)
 - * the A_1^0 is mostly the singlet pseudoscalar and couples to SM fields through mixing
 - * its squared mass $m_{A_1^0}^2 = 3kx A_k + \mathcal{O}(1/\tan\beta)$ with $x = \langle N \rangle$
 - * its tree-level couplings to up-type quarks are negligible
 - * its tree-level couplings to down-type quarks and charged leptons can be described in terms of one parameter,

$$\mathcal{L}_{Add} = -l_d m_d \bar{d} \gamma_5 d \frac{iA_1^0}{v}, \quad \mathcal{L}_{Ae} = -l_d m_\ell \bar{\ell} \gamma_5 \ell \frac{iA_1^0}{v},$$

$$l_d = v \delta_- / (\sqrt{2} x), \quad \text{with } v = 246 \text{ GeV} \text{ and } \delta_- = (A_\lambda - 2kx) / (A_\lambda + kx)$$

- * the lower bound of l_d is $|l_d| \sim 0.1$ (Hiller, PRD, 2004)
and its upper bound $|l_d| \sim 1.2$. (He, JT, Valencia, PLB, 2005)
- Therefore the 4-quark contributions are given in terms of l_d in the large- $\tan\beta$ limit

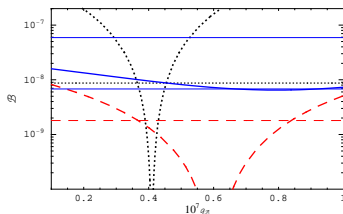
Two-quark contributions of A_1^0 in NMSSM

- In certain versions of the NMSSM at large $\tan\beta$, the couplings $C_{L,R}$ are related by $C_L = -C_R m_d/m_s = -2g_A m_d/v$, corresponding to

$$\mathcal{L}_{Asd} = \frac{ig_A}{v} [m_s \bar{d}(1 + \gamma_5)s - m_d \bar{d}(1 - \gamma_5)s] A_1^0 + \text{H.c.}$$

- This is the case with the NMSSM of Hiller (2004) at large $\tan\beta$, where $C_{L,R}$ are generated by one-loop diagrams containing charginos and squarks.
- With suitable modifications, the Hiller model provides an A_1^0 with the desired properties: it can evade the K and B bounds, while being responsible for the HyperCP events. (He, JT, Valencia, PRL, 2007)

- Including the 4-quark contributions with $l_d = 0.35$
- Branching ratios of $\Sigma^+ \rightarrow p A_1^0$ (solid curves), $K^+ \rightarrow \pi^+ A_1^0$ (dotted curves), and $K_S \rightarrow \pi^0 A_1^0$ (dashed curves), where horizontal lines indicate HyperCP and kaon bounds.



More general scenario for light A_1^0 in NMSSM

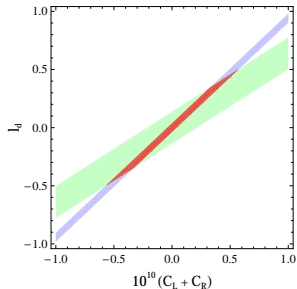
- Additional one-loop contributions to the sdA_1^0 couplings with other SUSY particles in the loop could enlarge the parameter space, making $C_{L,R}$ unrelated.

$$\mathcal{L}_{Asd} = \frac{iC_R}{2} \bar{d}(1 + \gamma_5)s A_1^0 + \frac{iC_L}{2} \bar{d}(1 - \gamma_5)s A_1^0 + \text{H.c.}$$

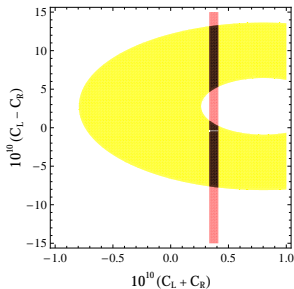
- Loops containing gluinos and neutralinos have been shown to produce this decoupling. (Gao, Li, Li, Zhang, EPJC, 2008)
- This opens up the possibility of satisfying the kaon bounds in the absence of the 4-quark contributions.
- Thus C_L and C_R can be taken to be independent, to be constrained with data.

Parameter space

- Regions in the (C_L+C_R, l_d) parameter space allowed by $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ (blue) and $K_S \rightarrow \pi^0 \mu^+ \mu^-$ (green). The overlap (red) band covers points that satisfy both constraints.



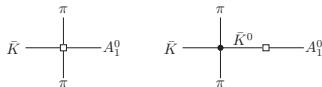
- Regions in the (C_L+C_R, C_L-C_R) parameter space reproducing the HyperCP result (yellow) and respecting the $K \rightarrow \pi \mu^+ \mu^-$ bounds (red) for $l_d = 0.35$. The overlap (black) areas cover points satisfying both the hyperon and kaon constraints, and the unshaded (white) region on the vertical band corresponds to the case of related $C_{L,R}$.



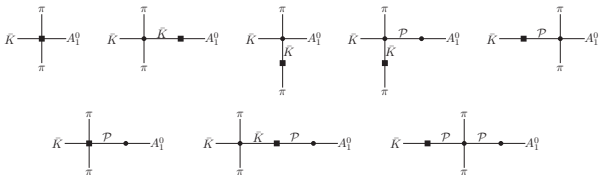
- Some other rare decays can help confirm or refute the light- A_1^0 hypothesis
- $|\Delta S| = 1$ decays
 - * Evaluate $\bar{K} \rightarrow \pi\pi A_1^0 \rightarrow \pi\pi\mu^+\mu^-$ and $\Omega^- \rightarrow \Xi^- A_1^0 \rightarrow \Xi^- \mu^+\mu^-$.
 - * They involve both two-quark and four-quark contributions.
- Flavor-conserving decays
 - * $\Upsilon(1S) \rightarrow \gamma A_1^0 \rightarrow \gamma\mu^+\mu^-$ and $\phi \rightarrow \gamma A_1^0 \rightarrow \gamma\mu^+\mu^-$.
 - * Evaluate $\eta \rightarrow \pi\pi A_1^0 \rightarrow \pi\pi\mu^+\mu^-$
 - * They help test the hypothesis independently of the details of the flavor-changing sector.
- They can be searched for in ongoing experiments.

$K \rightarrow \pi\pi A_1^0$

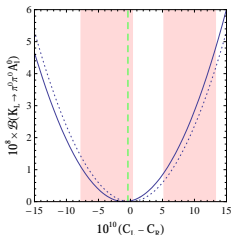
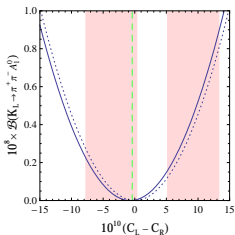
- 2-quark contributions



- 4-quark contributions



- Predicted branching ratios (solid curves) for $K_L \rightarrow \pi^+\pi^- A_1^0$ and $K_L \rightarrow \pi^0\pi^0 A_1^0$ with $l_d = 0.35$.
- The dotted curves result from the 2-quark contributions alone, the pink bands indicate the allowed ranges of $C_L - C_R$, and each green dashed line corresponds to the case of $C_{L,R}$ being related.
- Being studied by KTeV.

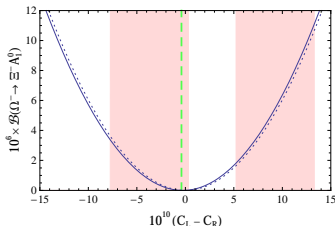


$$\Omega^- \rightarrow \Xi^- A_1^0$$

- Two- and four-quark contributions



- Predicted branching ratio for $l_d = 0.35$



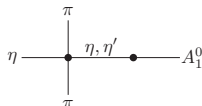
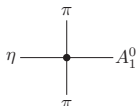
- The best limit currently available from HyperCP (2003)

$$\mathcal{B}(\Omega^- \rightarrow \Xi^- \mu^+ \mu^-) < 6.1 \times 10^{-6} \quad (90\% \text{ C.L.})$$

- SM predicts $\mathcal{B}_{\text{SM}}(\Omega^- \rightarrow \Xi^- \mu^+ \mu^-) = 6.6 \times 10^{-8}$ (Safadi & Singer, PRD, 1988)
- The predicted $\Omega^- \rightarrow \Xi^- A_1^0 \rightarrow \Xi^- \mu^+ \mu^-$ rate for most of allowed regions is substantially enhanced with respect to the SM rate.

$\eta \rightarrow \pi\pi A_1^0$

- They are special, involving only flavor-diagonal interactions



- Predicted branching ratio

$$\mathcal{B}(\eta \rightarrow \pi^+\pi^- A_1^0) = 5.4 \times 10^{-7} l_d^2$$

for η - η' mixing angle $\theta = -19.7^\circ$.

- The best limit currently available from CELCIUS/WASA collaboration (2008)

$$\mathcal{B}(\eta \rightarrow \pi^+\pi^-\mu^+\mu^-) < 3.6 \times 10^{-4} \quad (90\% \text{C.L.})$$

implies loose bound $|l_d| < 26$.

- There is room for enhancement over the expected standard-model rate

$$\mathcal{B}_{\text{SM}}(\eta \rightarrow \pi^+\pi^-\mu^+\mu^-) = (7.5_{-2.7}^{+4.5}) \times 10^{-9}$$

(Borasoy, Nissler, EPJA, 2007)

- $\eta \rightarrow \pi^+\pi^-\mu^+\mu^-$ may be accessible to DAΦNE experiment.

- [arXiv:0807.1427v1](https://arxiv.org/abs/0807.1427v1) [hep-ex]

CLNS 08/2033

CLEO 08-16

Search for Light CP-odd Higgs in Radiative Decays of $\Upsilon(1S)$

W. Love,¹ V. Savinov,¹ H. Mendez,² J. Y. Ge,³ D. H. Miller,³ I. P. J. Shipsey,³ B. Xin,³
G. S. Adams,⁴ M. Anderson,⁴ J. P. Cummings,⁴ I. Danko,⁴ D. Hu,⁴ B. Moziak,⁴
I. Napolitano,⁴ O. He,⁵ J. Insler,⁵ H. Muramatsu,⁵ C. S. Park,⁵ E. H. Thorndike,⁵

Abstract

We search for a non-SM-like CP-odd Higgs boson (a_1^0) with $m_{a_1^0} < 2m_b$ in radiative decays of the $\Upsilon(1S)$, using 21.5M $\Upsilon(1S)$ mesons directly produced in e^+e^- annihilation. We investigate $a_1^0 \rightarrow \tau^+\tau^-$ and $a_1^0 \rightarrow \mu^+\mu^-$ decay channels. No significant signal is found. We obtain upper limits on the product of $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma a_1^0)$ and $\mathcal{B}(a_1^0 \rightarrow \tau^+\tau^-)$ or $\mathcal{B}(a_1^0 \rightarrow \mu^+\mu^-)$. Our $\tau^+\tau^-$ results are almost two 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 $\mu^+\mu^-$. Existence of such a state was previously proposed as an explanation for 3 $\Sigma^+ \rightarrow p\mu^+\mu^-$ events, having $\mu^+\mu^-$ masses just above the kinematic threshold, observed by the HyperCP experiment. Our results constrain NMSSM models.

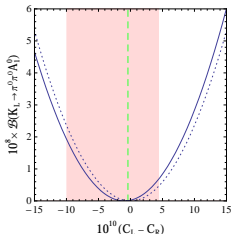
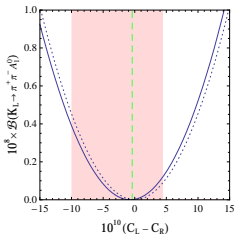
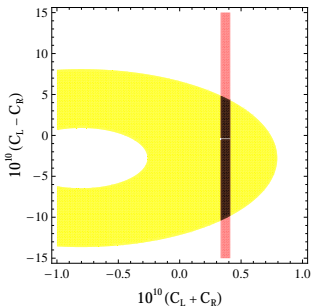
Detour

- The 4-quark contribution to $\Sigma^+ \rightarrow pA_1^0$

$$\mathcal{M}_{4q}(\Sigma^+ \rightarrow pA_1^0) = \frac{fl_d}{2v} (-b_\pi + b_\eta c_\theta + b_{\eta'} s_\theta) i\bar{p} (A_{p\pi^0} - B_{p\pi^0} \gamma_5) \Sigma^+$$

has a sign ambiguity because $A_{p\pi^0}$ and $B_{p\pi^0}$ are extracted from the data on nonleptonic decay $\Sigma^+ \rightarrow p\pi^0$ up to an overall sign.

- With the opposite relative sign of the 2- and 4-quark contributions to $\Sigma^+ \rightarrow pA_1^0$



CLEO's constraint on A_1^0

- Branching ratios of $\Sigma^+ \rightarrow pA_1^0$ (solid curves), $K^+ \rightarrow \pi^+A_1^0$ (dotted curves), and $K_S \rightarrow \pi^0A_1^0$ (dashed curves) as functions of $C_L + C_R$.

- Horizontal lines indicate HyperCP and kaon bounds.

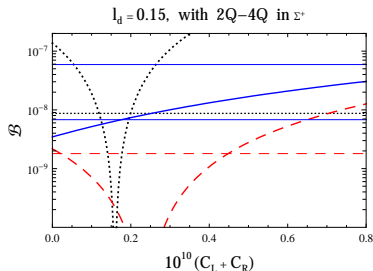
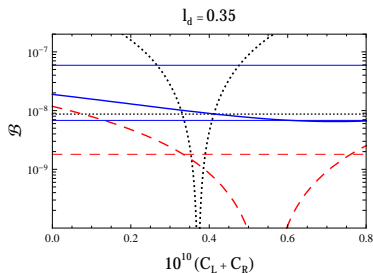
- CLEO (2008) reported

$$\mathcal{B}(\Upsilon(1S) \rightarrow \gamma A_1^0) < 2.3 \times 10^{-6}$$

at 90% C.L., which implies

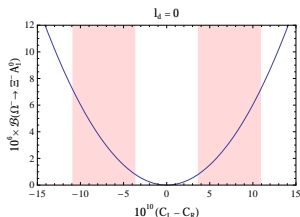
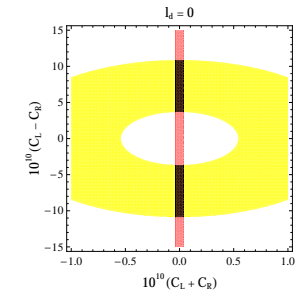
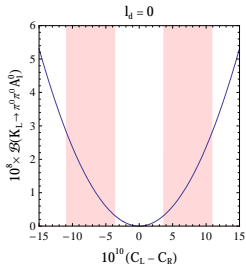
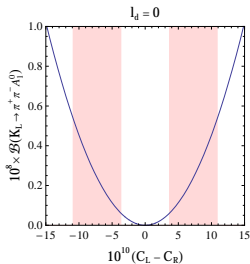
$$|l_d| < 0.16$$

- This squeezes the parameter space for the scenario with $C_{L,R}$ being related, but not completely yet.



Absence of four-quark contributions for $l_d = 0$

- If $C_{L,R}$ are not related, the experimental bounds can be satisfied even in the absence of the 4-quark contributions.



Conclusions

- The decay $\Sigma^+ \rightarrow p\mu^+\mu^-$ within the SM is long-distance dominated, and the predicted rate is in the right range to explain the HyperCP observation.
- Within the SM, the predicted $m_{\mu\mu}$ distribution does not have any sharp peaks, and so it is unlikely to find all 3 events clustered at the same mass.
- Current constraints allow for an explanation of the 3 events with a new particle as long as its effective flavor-changing coupling is mostly pseudoscalar (or axial vector) and smaller for $b \rightarrow s$ transitions than what naive scaling from $s \rightarrow d$ transitions (with CKM angles) would predict.
- The NMSSM has a CP -odd Higgs boson, the A_1^0 , that could have the desired mass and satisfy all the experimental constraints.
- Additional rare decays can help confirm or refute this hypothesis:
 $K \rightarrow \pi\pi A_1^0$, $\Omega^- \rightarrow \Xi^- A_1^0$.
- Some other rare decays can test the hypothesis independently of the flavor-changing sector: $\Upsilon(1S) \rightarrow \gamma A_1^0$, $\phi \rightarrow \gamma A_1^0$, $\eta \rightarrow \pi\pi A_1^0$.