PHYSICAL REVIEW D, VOLUME 70, 094041

Evidence for a fourth state related to the three $J^{PC} = 2^{++}$, $\pi^- p \rightarrow \phi\phi n$ states explainable by 2^{++} glueball production

R. S. Longacre[1] and S. J. Lindenbaum[2]

[1]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[2]*City College of New York, New York, New York 10031, USA*

(Received 18 September 2004; published 24 November 2004)

Four separate experiments [A. Etkin *et al.*, Phys. Rev. Lett. **41**, 784 (1978).][A. Etkin *et al.*, Phys. Rev. Lett. **49**, 1620 (1982).][A. Etkin *et al.*, Phys. Lett. B **165**, 217 (1985).][A. Etkin *et al.*, Phys. Lett. B **201**, 568 (1988).] observing the OZI forbidden disconnected reaction $\pi^- p \rightarrow \phi\phi n$ with increasing statistics were consistent. These experiments, very selectively, completely broke down the OZI suppression by three $\phi\phi$ resonances with $I^G J^{PC} = 0^+ 2^{++}$ in the observed mass region 2.038 GeV to 2.600 GeV. The only viable proposed explanation has been that the $I^G J^{PC} = 0^+ 2^{++}$ glueball expected in this mass region caused the hard glue in the disconnection to resonate and very selectively break down the OZI suppression for its quantum numbers only. Recently a pp central production spin analysis found that the $f_2(1950)$ had a dominant decay mode $f_2(1270)\pi\pi$ [D. Barberis *et al.*, Phys. Lett. B **471**, 440 (2000).]). We consider if it is related to the $\phi\phi$ resonances, and find that it likely is.

DOI: 10.1103/PhysRevD.70.094041 PACS numbers: 12.39.Mk, 12.38.Qk

I. INTRODUCTION

The first critical test of nonperturbative QCD was the prediction of a spectrum of multigluon resonant states (glueballs) by lattice gauge theory (LGT) [1–4]. Even phenomenological work made the existence of glueballs inescapable. Unfortunately two decades later there is no consensus on the existence of even one glueball. Obviously the glueball spectrum is accompanied by the many other varieties of quark-built states and also possibly hybrids. To date LGT assumes pure glue and has not solved the problem of including quarks capable of predicting both spectra, and their mixing. If a glueball has the same quantum numbers as a quark state which it overlaps in mass, it is expected from quantum mechanics that they would mix, and the mixed quark-built states would have substantial glue. Thus it became clear that a filter which passes glueballs or glue-rich quark-glue mixed states, and rejects quark-built states was extremely desirable for discovering glueballs, and the accompanying substantially mixed with glue states if they existed.

The strong interaction OZI disconnected diagram $\pi^- p \rightarrow \phi\phi n$ was proposed and used [5–8] as such a filter. The two hard gluons bridging the disconnection would by OZI suppression reject quark-built states. However in a mass region where a glueball with the quantum numbers contained in the $\phi\phi$ system occurred, the gluons would resonate to form the glueball, break down the OZI suppression, and let the glueball and mixed quark plus glueball states pass through. The mass region accessible to the $\phi\phi$ experiment [8] 2 GeV to 2.6 GeV was ideal for detecting the 2^{++} glueball [1–4].

II. THE $\phi\phi$ RESONANCES AND DISCUSSION

The OZI rule was found to be completely broken down, very selectively, in the reaction $\pi^- p \rightarrow \phi\phi n$, by three resonance states with quantum numbers $I^G J^{PC} = 0^+ 2^{++}$. These are the quantum numbers of the 2^{++} glueball expected [1–4] in this mass region. The $\phi\phi$ production t dependence was sharply peaked forward with the shape consistent with π exchange. This implies that the disconnected light quark lines ended in a $\pi^+\pi^-$ annihilation bridged by gluons to the strange quark lines of the $\phi\phi$ system. Since π exchange would only allow isoscalar glueballs ($J^{PC} = 0^{++}, 2^{++}, 4^{++}$), the states were originally listed as g_t, g_t', g_t'' (now listed as $f_2(2010)$, $f_2(2300)$, $f_2(2340)$ states) in the Particle Data Group summary table as established. They were found to contain approximately 87% of the events in the sample of the $\phi K^+ K^- n$ as $\phi\phi$ resonances. The $\phi K^+ K^- n$ reaction is OZI allowed, while the $\phi\phi n$ reaction violates OZI and is 7.7 times bigger than the allowed reaction. The 13% $\phi K^+ K^- n$ events contain 8.6% incoherent background without structure, plus 4% $I^G J^{PC} = 1^+ 1^{--}$, and 0.4% $I^G J^{PC} = 0^+ 2^{++}$ coherent π exchange amplitudes. The π exchange $\phi K^+ K^- n$ amplitudes were slowly varying and were either a nonresonant or broad resonance source. Thus the expected factor ~100 suppression has become a factor 8 enhancement or factor ~800 breaking of the OZI rule. All waves up to $J = 6$ and $L = 4$ (114 waves) were searched for and except for one S-wave and two D-waves which contributed to the three 2^{++} $\phi\phi$ resonances, nothing was found. The established resonance $f_4(2050)$ with $I^G J^{PC} = 0^+ 4^{++}$ which could in principle be detected, other expected from the quark model states, and some reported but not established states were not detected. As stated above the t dependence showed that the three 2^{++} $\phi\phi$ resonances were produced by annihilation of the incident π^- and an exchange π^+ to form the gluon bridge across the disconnection to the $\phi\phi$ final state. The annihilating pions contain only u and d quarks and the $\phi\phi$ is practically all s and $\bar{s}$ quarks, except for the very small

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contribution due to the very small departure from ideal mixing. Thus it is a very clean flavor-changing example. Figure 1 explains the powerful selectivity of the $\phi\phi$ system. Because of the ϕ spin, in addition to the Gottfried-Jackson and Trieman-Yang angles, the polar (θ) and azimuthal angles (α) of each ϕ due to its spin gave six significant angles and their correlations which yield the enormously selective signature for each wave, examples of which are shown. Reference [8] concluded that the OZI suppression was broken down by one primary 2^{++} glueball mixing with two quark states. The very strong glueball mixing effects on the quark states, which are not yet known, are likely to change the character of these mixed states drastically. Hence attempts to identify these states via the quark model calculations appear unjustified. The OZI rule argument has been attacked unsuccessfully by a number of theorists [9,10]. However, to our knowledge, except for $J = 0$ where vacuum mixing could introduce flavor changing, the OZI rule works experimentally in all strong interaction cases where there is clean flavor-changing annihilation between the initial and final states, except where glue type resonances occur. It was also shown that by comparing $K^- p$ and $\pi^- p$ interactions that the OZI rule was more or less entirely broken down in $\pi^- p \rightarrow \phi\phi n$ [11] in the mass region investigated. It would require a flavor-changing resonance to do this for $J > 0$, and a glueball is the naturally expected choice. No other viable explanation of the data [6–8] has occurred since the initial results in 1982 [6].

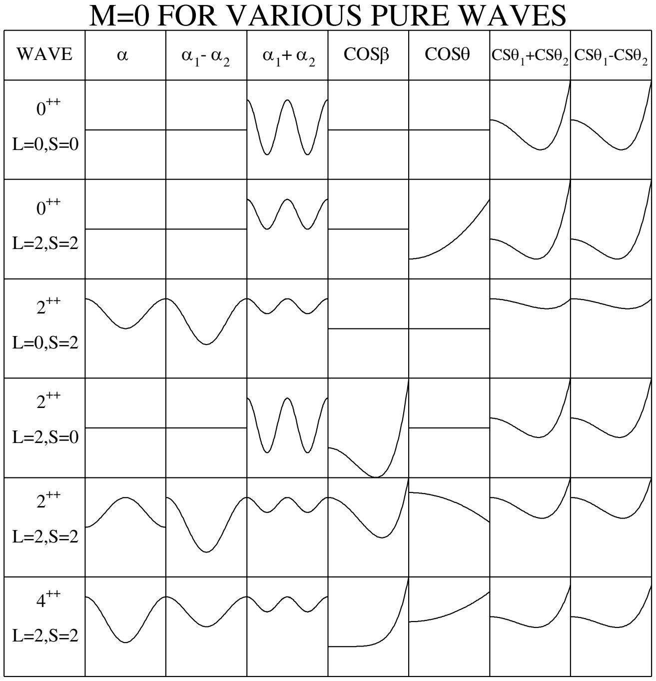

FIG. 1. Above we show six out of the 114 waves tried in our $\phi\phi$ partial wave analysis. We show projections of the pure waves along: column 1—the ϕ azimuthal decay angle (α); column 2—the difference of azimuthal decay angles for ϕ_1 and ϕ_2; column 3—the sum; column 4—the cosine of the Gottfried-Jackson angle (β); column 5—the cosine of the polar ϕ decay angle (θ); column 6—the sum of the cosines of the polar decay angles of ϕ_1 and ϕ_2; column 7—the difference.

III. IS THE *PP* CENTRAL PRODUCTION RELATED?

We now consider the evidence that a fourth state may be related to the above $\phi\phi$ experiment and analysis [8]. Reference [12] studied 4π channels in central $p\ p$ interactions at 450 GeV/c. Their Fig. 1b shows a broad mass spectrum in the mass of $4\pi^0$ which they consider likely to be least affected by other effects. In a spin analysis they conclude in Fig. 1e that the broad mass spectrum is $I^G J^{PC} = 0^+ 2^{++}$ decaying via a $f_2(1270)\pi\pi$ in a overall S-wave to $4\pi^0$. Figure 3f shows the same $I^G J^{PC} = 0^+ 2^{++}$ $f_2(1270)\pi\pi$ wave in the $2\pi^+ 2\pi^-$ channel, which has the most statistics. They concluded that their analysis was consistent with one $f_2(1270)\pi\pi$ resonance with a mass of 1950 MeV. It is for the $I^G J^{PC} = 0^+ 2^{++}$ $f_2(1270)\pi\pi$ wave that we would like to determine whether it could be related to previous $\phi\phi$ work [8]. First we considered the possibility of fitting the $\phi\phi$ resonances together with the $I^G J^{PC} = 0^+ 2^{++}$ $f_2(1270)\pi\pi$ wave of Ref. [12]. The same K-matrix methodology used previously was again utilized [8]. First we considered only three poles which was what was found sufficient in the $\phi\phi$ work. Our best fit was an unacceptable 9σ fit. One should keep in mind here that the physical mass spectrum of the $\phi\phi$ system was cut off at 2.038 GeV, so one could not experimentally measure below this value. However the lowest (2.010 GeV) $\phi\phi$ resonance width of 200 MeV extended below the threshold by 130 MeV. Although when we introduced a fourth pole, we obtained a good 2σ fit for the $\phi\phi$ and the new $f_2(1270)\pi\pi$ data [12] combined. This new data has the same $I^G J^{PC} = 0^+ 2^{++}$ quantum numbers as the $\phi\phi$ resonances, thus implying there is reasonable evidence suggesting they are related. In this fit the structure that appears around 2.4 GeV in both data sets connects the two systems (Fig. 2 and 3). Requiring an additional pole does not change the previous glueball interpretation presented in Ref. [8]. The number of glueballs plus glueball+quark mixed states cannot be determined in LGT without including quark loops. However having a 2^{++} glueball was the only viable explanation for the data published in 1982 [6]. Nothing which has occurred in the two decades since contradicts this, but instead strengthens the case [7–11]. Now let us consider the details of the four-pole fit. We have extracted the resonance parameters corresponding to each of the four poles which are displayed in Table I.

The first resonance best-fit mass is barely above the lower boundary of the $\phi\phi$ mass region, but due to the

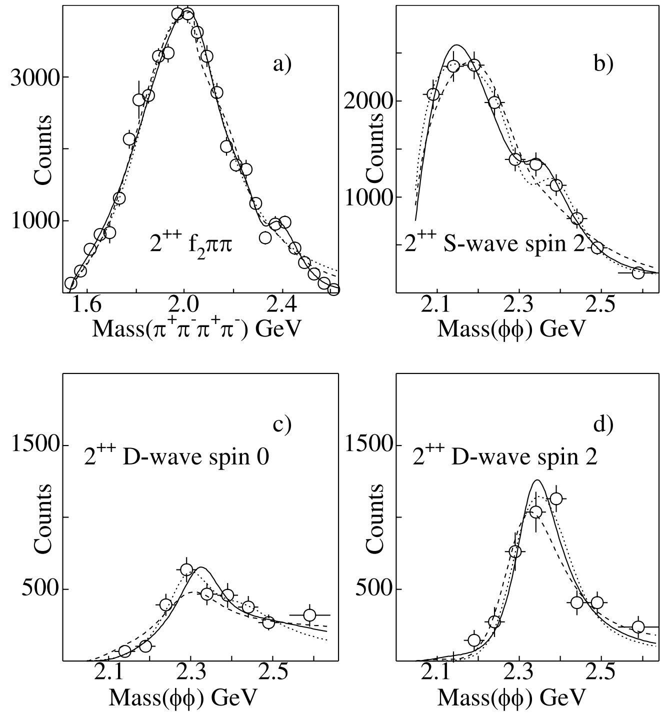

FIG. 2. The $I^G J^{PC} = 0^+ 2^{++}$ mass spectra of: (a) Mass $(\pi^+\pi^-\pi^+\pi^-)$ for $2^{++} f_2(1270)\pi\pi$; (b) Mass $(\phi\phi)$ for 2^{++} S-wave spin 2; (c) Mass $(\phi\phi)$ for 2^{++} D-wave spin 0; (d) Mass $(\phi\phi)$ for 2^{++} D-wave spin 2. The solid curve is the four-resonance fit (Table I); the dashed curve is a three-resonance fit; and the dotted curve is a separate three-resonance fit to the three $\phi\phi$ waves, and a separate fit with one resonance to the $f_2(1270)\pi\pi$ wave. Note this separate fit for the $f_2(1270)\pi\pi$ is particularly poor in the region of 2.3 GeV to 2.6 GeV, whereas the four-pole (resonance) combined fit (solid line) is a 2σ fit (see text).

large width of the pole and its errors it could easily be below. The other three resonances are clearly in the $\phi\phi$ mass region. The second resonance seems similar to the previously obtained $f_2(2010)$. It is approximately 89% S-wave, but is shifted to higher mass by about 100 MeV and is wider. The third resonance is similar to the previously obtained $f_2(2300)$ shifted upward by about 40 MeV, but well within the errors. The width is the same and it is about 95% D-wave consistent with the previous case. The fourth resonance is similar to our previous $f_2(2340)$. However there are some differences in the division of the D-wave into the spin = 0 and spin = 2 states in the third and fourth resonances. Figure 2(a) shows the $I^G J^{PC} = 0^+ 2^{++}$ $f_2(1270)\pi\pi$ mass spectrum, where the solid line is the four-resonance combined fit given in Table I, and the dashed line is the three-resonance fit. The dotted curve will be explained in the next section. Figure 2(b) shows the $I^G J^{PC} = 0^+ 2^{++}$ spin 2 S-wave $\phi\phi$ mass distribution. Again the solid line is the four-resonance fit given in Table I and the dashed line is the three-resonance fit. This is true for all Figs. 2 and 3.

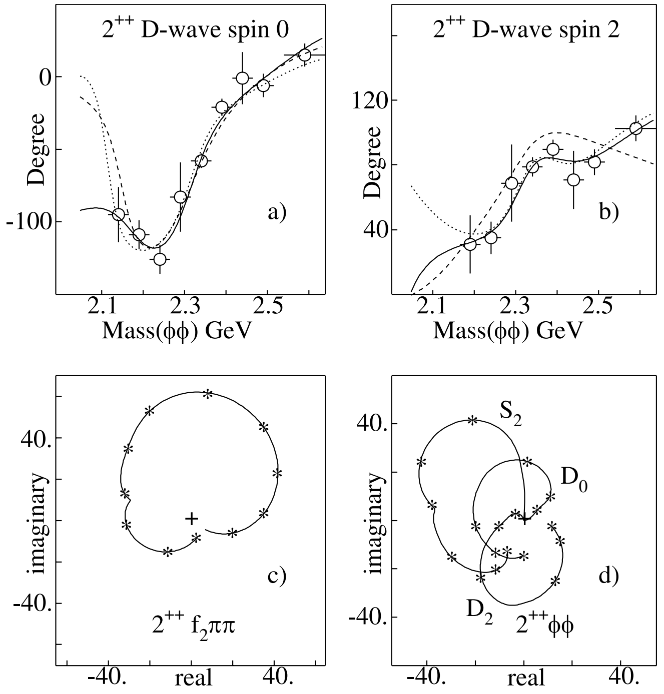

FIG. 3. (a) and (b) show the phase behavior of the D-wave $\phi\phi$ amplitudes measured with respect to spin 2 S-wave for the three fits described in Fig. 2 caption and text: (a) 2^{++} spin 0 D-wave; (b) 2^{++} spin 2 D-wave. (c) and (d) show argand amplitudes which are generated by the four-pole (resonance) fit. Each $*$ is at a 0.1 GeV marking starting with 1.5 GeV for (c) the $2^{++} f_2\pi\pi$ argand amplitude, while (d) markings start at 2.1 GeV for the three $\phi\phi$ waves spin 2 S-wave (S_2), spin 0 D-wave (D_0), and spin 2 D-wave (D_2).

Figure 2(c) shows the $I^G J^{PC} = 0^+ 2^{++}$ spin 0 D-wave $\phi\phi$ mass spectrum. Figure 2(d) shows the $I^G J^{PC} = 0^+ 2^{++}$ spin 2 D-wave $\phi\phi$ mass spectrum. The S-wave was used as a phase reference. Figure 3(a) shows the 2^{++} spin 0 D-wave phase relative to the S-wave as a function of $\phi\phi$ mass. Figure 3(b) shows the 2^{++} spin 2 D-wave phase. The three-resonance fit gives a very crude qualitative agreement, but must be discarded as it fails quantitatively by 9σ, whereas the four resonance fit is a 2σ fit. Figure 3(c) shows the argand diagram for the $I^G J^{PC} = 0^+ 2^{++}$ $f_2(1270)\pi\pi$ amplitude. The argand diagrams for the three $I^G J^{PC} = 0^+ 2^{++} \phi\phi$ amplitudes are shown in Fig. 3(d). These argand diagrams show clear resonance behavior. The fact that the four-resonance fit is a good fit

TABLE I. Resonance parameters.

Mass (GeV)	Width (GeV)	S_2	D_0	D_2
$2.049^{+.035}_{-.024}$	$.567^{+.064}_{-.071}$	$96\%^{+4}_{-10}$	$1\%^{+7}_{-1}$	$3\%^{+9}_{-3}$
$2.123^{+.015}_{-.033}$	$.294^{+.056}_{-.055}$	$89\%^{+7}_{-11}$	$2\%^{+13}_{-2}$	$9\%^{+10}_{-8}$
$2.340^{+.013}_{-.013}$	$.148^{+.066}_{-.032}$	$7\%^{+15}_{-7}$	$12\%^{+14}_{-10}$	$81\%^{+3}_{-14}$
$2.412^{+.028}_{-.032}$	$.362^{+.100}_{-.053}$	$45\%^{+28}_{-7}$	$21\%^{+7}_{-19}$	$34\%^{+15}_{-20}$

TABLE II. K-Matrix parameters.

Pole (GeV)	$f\pi\pi$	$\phi\phi S_2$	$\phi\phi D_0$	$\phi\phi D_2$	Other one	Other two
2.006	.9539	−.5919	.0768	.2336	−.1285	.1707
2.122	.3872	.2107	.0796	.1707	−.6725	−.3083
2.363	−.3630	.0941	−.2093	.4119	.0386	.0018
2.415	−.0835	.0167	.0252	.0042	.0768	−.0835

which ties together the structure in the $f_2(1270)\pi\pi$ and the $\phi\phi$ structure near 2.4 GeV, while retaining the basic characteristics of the orginal three $\phi\phi$ resonance states, implies it is likely they are related, and due to the same glueball and mixing mechanism which explains the $\phi\phi$ states.

We used the K-matrix approach in order to ensure that unitarity was enforced between $f(1270)\pi\pi$ and the three $\phi\phi$ channels. We also used two other nonobserved channels to fill out the total widths plus two mixing possibilities. This makes a 6 × 6 unitary S-matrix. The K-matrix poles and channel couplings are given in Table II. The poles are in GeV and the couplings are without units as defined in Ref. [13].

IV. SUPPOSE THEY ARE NOT RELATED

We can obtain a four-resonance fit and have no relationship between the resonance in $f_2(1270)\pi\pi$ and the three $\phi\phi$ resonances. We show in Fig. 2(a)–2(d), 3(a), and 3(b) as a dotted line the four resonances in which there is no connection between $f_2(1270)\pi\pi$ and $\phi\phi$. The $\phi\phi$ n data contains additional statistics obtained beyond [8] and a new analysis which is consistent [8]. This fit is a six σ fit, where most of the σ's arise from Ref. [12] not fitting the structure in their data near 2.4 GeV which overlapped with the $\phi\phi$ mass region. One could add a second resonance in the $f_2(1270)\pi\pi$ or attribute that to some other effect. However, even if one assumes that the $f_2(1270)\pi\pi$ is not related to the $\phi\phi$, that in no way contradicts the conclusions drawn on the basis of the $\phi\phi$ resonances data. Thus in the two decades of physics work following the initial strong evidence explainable only with the effects caused by a 2^{++} glueball, all that occurred both in extension of that work, and all other relevant works both experimental and theoretical in the region of 2 GeV mass has strengthened the initial evidence. Nothing published has successfully contradicted it, or produced a viable alternative explanation of the $\phi\phi$ data. A much quoted classic paper on the LGT glueball mass spectrum by Morningstar and Peardon [4] using SU(3) pure gauge theory finds that there can be glueball states consisting of one to several glueballs degenerate in mass. However their investigations conclude that the multiglueball states would be high enough in mass so that the predicted lowest lying $I^G J^{PC} = 0^+ 2^{++}$ glueball would be a single glueball which could mix with quark-built states in the ~2 GeV mass region. The mass they determined for the 2^{++} glueball is 2.40 ± .15 GeV which is consistent with the $\phi\phi$ resonance data. A recent discussion on the $\phi\phi$ resonance states with Michael Creutz led to a private communication he sent us, from which we quote since it should be of interest to the readers. "I am glad to hear that you are continuing to pursue the $\phi\phi$ states as glueball candidates. I personally believe that these states are indeed likely to contain substantial glue, although I expect there will be some mixing with quark states as well. This mixing will make a complete analysis very complicated, but the glue component should exist and will appear in all the states that are mixed" [14].

V. CONCLUSION

The breakdown of the OZI suppression by a factor ~800 is enormous. It is strikingly extremely selective since only the three $\phi\phi$ resonances all of which have $I^G J^{PC} = 0^+ 2^{++}$, the quantum numbers of the 2^{++} glueball, and nothing else is found in the analysis up to $J = 6$ and $L = 4$ (114 waves) in a mass region consistent with the predicted 2^{++} glueball mass. This has only been explained by a glue resonance (2^{++} glueball). No other viable alternative has been published in two decades since the initial results in 1982 [6] which have been strengthened with time [5–11]. The 450 GeV/c pp central production results of [12] are explainable by a simple extension of the previous $\phi\phi$ resonance analysis [8] to include an additional fourth pole which results in a two σ fit for the combined data.

ACKNOWLEDGMENTS

This research was supported by the U.S. Department of Energy under Contract No. DE-AC02-98CH1088 and the City College of New York Physics Department.

[1] G. Bali *et al.*, Phys. Lett. B **309**, 378 (1993).
[2] C. Michael and M. Teper, Nucl. Phys. **B314**, 347 (1989).
[3] B. Berg and A. Billoire, Nucl. Phys. **B221**, 109 (1983); **B226**, 405 (1983).
[4] C. J. Morningstar and M. Peardon, Phys. Rev. D **60**, 034509 (1999).
[5] A. Etkin *et al.*, Phys. Rev. Lett. **41**, 784 (1978).
[6] A. Etkin *et al.*, Phys. Rev. Lett. **49**, 1620 (1982).
[7] A. Etkin *et al.*, Phys. Lett. B **165**, 217 (1985).
[8] A. Etkin *et al.*, Phys. Lett. B **201**, 568 (1988).
[9] S. J. Lindenbaum and R. S. Longacre, Phys. Lett. **165B**, 202 (1985); **234**, 163 (1990).
[10] S. J. Lindenbaum, Comments Nucl. Part. Phys. **13**, 285 (1984); in *Superstrings, Supergravity and Unified Theories*, The ITCP Series in Theoretical Physics Vol. 2 (World Scientific, Singapore, 1986), pp. 548-593.
[11] C. Landberg *et al.*, Phys. Rev. D **53**, 2839 (1996).
[12] D. Barberis *et al.*, Phys. Lett. B **471**, 440 (2000).
[13] R. S. Longacre, Phys. Rev. D **26**, 82 (1982).
[14] Michael Creutz (private communication).