ψ'' DECAYS TO CHARMLESS FINAL STATES

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The importance of measuring the non-\(D\bar{D}\) decays of the \(\psi'' = \psi(3770)\) resonance is discussed. These decays can shed light on a possible discrepancy between the total and \(D\bar{D}\) cross sections at the \(\psi''\), and on a proposed mechanism for enhancement of penguin amplitudes in \(B\) meson decays through charm–anticharm annihilation. Measurements (including the \(\psi''\) line shape) in states of definite G-parity and in inclusive charmless final states such as \(\eta' + X\) are found to be particularly important.

The \(\psi'' \equiv \psi(3770)\) particle,\(^3\) lying just above \(D\bar{D}\) threshold, is a well-defined source of charmed particle pairs in \(e^+e^-\) collisions. It is now undergoing high-intensity studies at the CLEO Detector at Cornell \(^1\) and the BES Detector in China \(^2\). Its couplings to charmless states are of interest for several reasons.

1. The production and decays of \(\psi''\) depend on its composition of \(3D_1, 3S_1,\) and \(D\bar{D}\) continuum states \(^3\)\(^4\). Mixing among these states also can affect \(\psi'\) modes, suppressing some while leading to contributions in \(\psi''\) decays \(^5\). These effects can be subtle as a result of interference \(^6\)\(^7\).

2. New measurements of \(\sigma(e^+e^- \to \psi'' \to D\bar{D}) \equiv \sigma(D\bar{D})\) by BES \(^2\) and CLEO \(^8\) confirm an earlier result \(^9\) that \(\sigma(D\bar{D})\) is less than the total cross section \(\sigma(e^+e^- \to \psi'' \to \ldots) \equiv \sigma(\psi'')\) measured by several groups \(^10\)\(^11\)\(^12\)\(^13\). The ratio \(\sigma(D\bar{D})/\sigma(\psi'')\) is of intrinsic interest and provides an estimate for rates for channels other than \(D\bar{D}\) during forthcoming extensive accumulations of data at the \(\psi''\) energy.

3. The non-charm decays of \(\psi''\), if appreciable, provide a possible laboratory for the study of rescattering effects relevant to \(B\) meson decays. If the \(\psi''\) decays to \(D\bar{D}\) pairs which subsequently re-annihilate into non-charmed final states, similar effects can generate enhanced penguin amplitudes (particularly in \(b \to s\) transitions) in \(B\) decays. Re-annihilation mechanisms are relevant not only for heavy quarkonium decays into non-flavored final states \(^14\)\(^15\) but also for non-\(K\bar{K}\) decays of the \(\phi\) meson \(^16\).

Non-charmed final states of the \(\psi''\) were discussed in doctoral theses \(^17\)\(^18\) based on Mark III data. No significant signals were obtained. While the total width of \(\psi''\) is \(\Gamma(\psi'') = 23.6 \pm 2.7\) MeV \(^19\), partial widths to \(\gamma\chi_{cJ}\ (J = 1, 2)\) are expected not to exceed a few tens of keV, with a few hundred keV expected for \(\Gamma(\psi'' \to \gamma\chi_{c0})\).

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\(^{3}\)Numbers in parentheses denote masses in MeV/c\(^2\).
Table 1: Comparison of cross sections $\sigma(D\bar{D}) \equiv \sigma(e^+e^- \to \psi'' \to D\bar{D})$, in nb.

| Collaboration | $\sigma(D^+D^-)$ | $\sigma(D^0\bar{D}^0)$ | $\sigma(D\bar{D})$ |
|--------------|-----------------|-----------------|-----------------|
| BES-II       | $2.56 \pm 0.08 \pm 0.26$ | $3.58 \pm 0.09 \pm 0.31$ | $6.14 \pm 0.12 \pm 0.50$ |
| CLEO         | $2.79 \pm 0.07^{+0.10}_{-0.04}$ | $3.60 \pm 0.07^{+0.07}_{-0.05}$ | $6.39 \pm 0.10^{+0.17}_{-0.08}$ |
| Mark III     | $2.1 \pm 0.3$ | $2.9 \pm 0.4$ | $5.0 \pm 0.5$ |

Table 2: Comparison of total cross sections $\sigma(\psi'') \equiv \sigma(e^+e^- \to \psi'' \to \ldots)$, in nb.

| Collaboration | $\sigma(\psi'')$ |
|--------------|-----------------|
| Crystal Ball | $6.7 \pm 0.9$ |
| Lead-Glass Wall | $10.3 \pm 1.6$ |
| Mark II      | $9.3 \pm 1.4$ |
| BES$^a$      | $7.7 \pm 1.1$ |
| Average      | $7.9 \pm 0.6$ |

$^a$ Estimate based on fit (see text).

partial width $\psi'' \to \pi\pi J/\psi$ is not expected to exceed about 100 keV. Thus any non-$D\bar{D}$ branching ratio in excess of $\sim 2\%$ must come from as-yet-unseen channels.

In this article I discuss the known $\psi''$ decays, including $D\bar{D}$, lepton pairs, $\gamma\chi_cJ$, and $J/\psi \pi^+\pi^-$, noting the likelihood of an appreciable non-$D\bar{D}$ cross section. A model for this contribution due to re-annihilation of $D\bar{D}$ pairs into light quarks is presented. It implies signatures from interference with the continuum process $e^+e^- \to \gamma^* \to \text{light } q\bar{q}$ pairs. Inclusive measurements to states with definite G-parity then become useful, and charmless $\psi''$ decays can illuminate some classes of $B$ decays including those with $\eta'$. Rates for $\psi''$ decays to specific charmless final states have recently been estimated in Ref. [7].

One measures $D\bar{D}$ production at the $\psi''$ by comparing the rates for $e^+e^- \to \psi'' \to f_i + \ldots$ and $e^+e^- \to \psi'' \to f_i\bar{f}_j$, where $f_i$ and $f_j$ are final states in $D$ decay. Unknown branching ratios can be determined, but one must know detector efficiency well. This method was used by the Mark III Collaboration [9] with an integrated luminosity $\int \mathcal{L} dt = (9.56 \pm 0.48) \text{ pb}^{-1}$. The CLEO Collaboration measured $\sigma(D\bar{D})$ using this method with $\int \mathcal{L} dt \simeq 56 \text{ pb}^{-1}$ [8]. The values are compared with those from Mark III and the BES Collaboration [2] (with $\int \mathcal{L} dt = 17.7 \text{ pb}^{-1}$) in Table [11].

The ratios $\sigma(D^+D^-)/\sigma(D^0\bar{D}^0)$ are consistent with the ratio $(p^+_{e^e}/p^0_{e^e})^3 = 0.685$ appropriate for the P-wave decay $\psi'' \to D\bar{D}$ (where $p^*$ denotes the magnitude of the center-of-mass [c.m.] 3-momentum). Coulomb and other final-state-interaction effects can alter this ratio and lead to its dependence on energy [20].

The values in Table [11] are to be compared with those for the total cross section $\sigma(\psi'')$ in Table [2]. In Fig. [11] the BES data [13] on $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ are displayed, along with the results of a fit to the resonance shape using conventional Blatt-
Figure 1: Fit to the $\psi''$ peak in BES data [13]. Solid line denotes expected line shape for a $D\bar{D}$ final state, incorporating appropriate centrifugal barrier terms, while dashed line denotes expected line shape for $\rho\pi$ final state.
Weisskopf angular momentum barrier factors [21]. The fit obtains $\sigma_{pk} = 7.7 \pm 1.1$ nb, with other central values $M = 3772$ MeV, $\Gamma = 23.2$ MeV, and $R_{bg} = 2.17 + 2.36(E_{c.m.} - 3.73$ GeV)$\theta(E_{c.m.} - 3.73$ GeV). The threshold energy is held fixed [22].

It appears that $\sigma(DD)$ falls short by one or more nb from the total cross section $\sigma(\psi''')$. Improved measurements of both quantities by the same experiment will be needed to resolve the question. I will show the effect of ascribing this difference to $DD$ re-annihilation into light-quark states. First I discuss other non-$DD$ final states of $\psi''$.

The leptonic width $\Gamma(\psi''\to e^+e^-)$ is $0.26 \pm 0.04$ keV [19], about 1/8 that of $\psi'$. A simple model of S–D wave mixing for the $\psi'$ and $\psi''$ is to write

$$\psi'' = \cos \phi |1^3D_1\rangle + \sin \phi |2^3S_1\rangle, \quad \psi' = -\sin \phi |1^3D_1\rangle + \cos \phi |2^3S_1\rangle. \quad (1)$$

The ratio $R_{\psi''/\psi'}$ of leptonic widths (scaled by factors of $M^2$) and the partial widths $\Gamma(\psi'\to \chi\gamma)$ and $\Gamma(\psi''\to \chi\gamma)$ may then be calculated as functions of $\phi$ [5, 23]. Specifically, it was found in Ref. [5] that

$$R_{\psi''/\psi'} = \frac{M^2_{\psi''}\Gamma(\psi''\to e^+e^-)}{M^2_{\psi'}\Gamma(\psi'\to e^+e^-)} = \frac{0.734 \sin \phi + 0.095 \cos \phi}{0.734 \cos \phi - 0.095 \sin \phi} = 0.128 \pm 0.023, \quad (2)$$

while

$$\Gamma(\psi''\to \gamma\chi_{c0}) = 145 \text{ keV} \cos^2 \phi (1.73 + \tan \phi)^2, \quad (3)$$
$$\Gamma(\psi''\to \gamma\chi_{c1}) = 176 \text{ keV} \cos^2 \phi (-0.87 + \tan \phi)^2, \quad (4)$$
$$\Gamma(\psi''\to \gamma\chi_{c2}) = 167 \text{ keV} \cos^2 \phi (0.17 + \tan \phi)^2, \quad (5)$$

and

$$\Gamma(\psi'\to \gamma\chi_{c0}) = 67 \text{ keV} \cos^2 \phi (1 - 1.73 \tan \phi)^2, \quad (6)$$
$$\Gamma(\psi'\to \gamma\chi_{c1}) = 56 \text{ keV} \cos^2 \phi (1 + 0.87 \tan \phi)^2, \quad (7)$$
$$\Gamma(\psi'\to \gamma\chi_{c2}) = 39 \text{ keV} \cos^2 \phi (1 - 0.17 \tan \phi)^2. \quad (8)$$

These quantities are plotted as functions of $\phi$ in Fig. 2.

The observed ratio $R_{\psi''/\psi'}$ agrees with predictions only for $\phi = (12 \pm 2)^\circ$ or $(-27 \pm 2)^\circ$, as shown by the vertical bands in Fig. 2. Only the solution with $\phi = (12 \pm 2)^\circ$ is remotely consistent with the observed partial widths [19] $\Gamma(\psi'\to \gamma\chi_{c1}) = 20$–30 keV. This range of $\phi$ favors the decay $\psi''\to \gamma\chi_{c0}$ over $\psi''\to \gamma\chi_{c1,2}$ by a substantial amount. The choice $\phi = (12 \pm 2)^\circ$ also is favored by the comparison of $\psi'$ and $\psi''$ decays to $J/\psi\pi^+\pi^-$. With the choice $\phi = (-27 \pm 2)^\circ$, a larger rate would be predicted for $\psi''\to J/\psi\pi^+\pi^-$ than for $\psi'\to J/\psi\pi^+\pi^-$, in conflict with experiment [24].

Coupling to open $D\bar{D}$ channels and mixing schemes more general than Eq. (1) can affect radiative decay widths [4]. Table 3 compares partial widths predicted in one such scheme with those based on Eq. (1). In Ref. [4] the $\psi''$ is composed of only 52\% $c\bar{c}$; the remainder of its wave function contains additional light quark-antiquark pairs, e.g., in the form of the open $D\bar{D}$ channel.

The Mark III collaboration [17] reported some marginal signals for $\psi''$ radiative decays. The prospects for observing $\psi''\to \gamma\chi_{cJ}$ have been improved with the accumulation
Figure 2: Sensitivity of scaled leptonic width ratio $R_{\psi''/\psi'}$ and partial widths $\Gamma(\psi', \psi'' \to \chi\gamma)$ to mixing angle $\phi$. Horizontal lines in top panel denote $\pm 1\sigma$ limits on $R_{\psi''/\psi'}$, and are projected onto the $\phi$ axis with vertical bands. In middle and bottom panels solid, dashed, and dash-dotted curves denote partial widths to $\gamma\chi_{c2}$, $\gamma\chi_{c1}$, and $\gamma\chi_{c0}$, respectively.
Table 3: Partial widths in keV predicted in Ref. \[4\] without (a) or with (b) couplings to open channels and in Ref. \[5\]. $M(\psi^\prime) = 3772 \text{ MeV}/c^2$ is taken in accord with the fit of Fig. 1; the nominal mass quoted in Ref. \[19\] is $3770.0 \pm 2.4 \text{ MeV}/c^2$.

| $\psi''$ decay | $E_\gamma$ (MeV) | Ref. \[4\] (a) | Ref. \[5\] (b) | ($\phi = 12 \pm 2^\circ$) |
|----------------|------------------|---------------|---------------|------------------|
| $\gamma \chi_{c2}$ | 210 | 3.2 | 3.9 | 24 ± 4 |
| $\gamma \chi_{c1}$ | 252 | 183 | 59 | 73 ± 9 |
| $\gamma \chi_{c0}$ | 340 | 254 | 225 | 523 ± 12 |

of $\mathcal{L}dt \simeq 56 \text{ pb}^{-1}$ in the CLEO-c detector \[8\]. With $\sigma(\psi'') \geq 6 \text{ nb}$ one should see several events in the cascade $\psi'' \rightarrow \gamma \chi_{c1} \rightarrow \gamma \gamma J/\psi \rightarrow \gamma \gamma \ell^+\ell^-$. The inclusive signal in $\psi'' \rightarrow \gamma \chi_{c0}$ will not be statistics-limited. To sum up, it is unlikely that the total of the radiative widths $\Gamma(\psi'' \rightarrow \gamma \chi_{c1})$ exceeds about 600 keV, corresponding to a branching ratio slightly above 2%.

An early Mark III result \[17\] found $\sigma(\psi'') \mathcal{B}(\psi'' \rightarrow J/\psi \pi^+\pi^-) = (1.2 \pm 0.5 \pm 0.2) \times 10^{-2} \text{ nb}$, implying $\mathcal{B}(\psi'' \rightarrow J/\psi \pi^+\pi^-) = (0.15 \pm 0.07)\%$. The BES Collaboration finds $\mathcal{B}(\psi'' \rightarrow J/\psi \pi^+\pi^-) = (0.34 \pm 0.14 \pm 0.08)\%$ \[25\]. The average (not including information from a CLEO upper limit \[26\]) is $\mathcal{B}(\psi'' \rightarrow J/\psi \pi^+\pi^-) = (0.18 \pm 0.06)\%$, corresponding to a partial width of $43 \pm 14 \text{ keV}$. Adding another 50% for $\psi'' \rightarrow J/\psi \pi^0\pi^0$, one finds $\Gamma(\psi'' \rightarrow J/\psi \pi^0\pi^0) = (64 \pm 21) \text{ keV}$, or at most about 100 keV.

At most 600 keV of the $\psi''$ total width of $23.6 \pm 2.7 \text{ MeV}$ is due to radiative decays, and as much as another 100 keV is due to $J/\psi \pi^0\pi^0$ decays. Along with the predominant $D\bar{D}$ decays, these contributions fall short of accounting for the total $\psi''$ width.

The total cross section for $e^+e^- \rightarrow \psi''$ is not the only contribution to hadron production at the $\psi''$ energy. Continuum production from $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$) should account for $\sigma(e^+e^- \rightarrow q\bar{q}) = 2\sigma(e^+e^- \rightarrow \mu^+\mu^-)[1+\text{QCD correction}]$, where $\sigma(e^+e^- \rightarrow \mu^+\mu^-) = 4\pi\alpha^2/3s = 6.1 \text{ nb}$ for $s \equiv E^2_{\text{c.m.}} = (3770 \text{ MeV})^2$. Moreover $\tau^+\tau^-$ pair production would account for $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = (1 - 4m^2_{\tau}/s)^{1/2}(1 + 2m^2_{\tau}/s)\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 2.9 \text{ nb}$ if initial-state-radiation effects were neglected. The contribution of the isovector photon ($G = +$) dominates: $\sigma(2\pi + 4\pi + \ldots) = 9\sigma(3\pi + 5\pi + \ldots)$. Thus several even-G signatures of continuum production can be examined at the $\psi''$ peak. A better way to study continuum contributions is to change the c.m. energy to one where resonance production cannot contribute. The CLEO Collaboration has done this, studying hadron production at a c.m. energy of 3670 MeV with a sample of 21 pb$^{-1}$ \[27\], and results are currently being analyzed.

Taking $\sigma(D\bar{D}) \leq 6.5 \text{ nb}$ and comparing it with the overall average of $\sigma(\psi'') = 7.9 \text{ nb}$ in Table 2, one must account for a deficit of 1.4 nb, or 18% of the total. The possibilities for detecting individual charmless decay modes of the $\psi''$ were raised, for example, in Refs. \[5\] \[7\] \[15\]. Here I stress that more inclusive measurements at the $\psi''$ may be of use.

Consider a model in which the re-annihilation of charm quarks in $D^0\bar{D}^0$ and $D^+D^-$ into states containing $u, d, s$ accounts for the difference between $\sigma(D\bar{D})$ and $\sigma(\psi'')$. Such
re-annihilation was proposed \[13\] both as a source of non-\(D\bar{D}\) decays of the \(\psi''\) and as a possible source of non-\(B\bar{B}\) decays of the \(\Upsilon(4S)\). The latter do not occur at any level above a few percent \[25\].

The BES Collaboration’s continuum value \(R = 2.26 \pm 0.14\) (from a preliminary version of \[2\]) averaged over \(2 \text{ GeV} \leq E_{\text{c.m.}} \leq 3 \text{ GeV}\) is consistent with the expected value of 2 times a QCD correction and with the background obtained in the fit of Fig. 1 to the \(\psi''\) cross section. I take \(R = 2.26\). Of this, one expects \(R(\bar{s}s) = (1/6)(2.26) = 0.377\). The non-strange contributions may be decomposed into a 9:1 ratio of \(I = 1\) and \(I = 0\) contributions denoted by \(R_1\) and \(R_0\), since \((Q_u - Q_d)^2 = 9(Q_u + Q_d)^2\). Thus \(R_1 = (5/6)(2.26)(9/10) = 1.695\) and \(R_0 = (5/6)(2.26)(1/10) = 0.188\). The \(I = 1\) continuum corresponds to an isovector photon and even-G-parity states, while the \(\bar{s}s\) and \(I = 0\) nonstrange continua correspond to an isoscalar photon and odd-G-parity states. The \(\bar{s}s\) continuum is expected to yield at least one \(K\bar{K}\) pair in its hadronic products.

I take the amplitude for \(\psi'' \to D\bar{D} \to \text{(non-charmed final states)}\) to proceed via a \(D\bar{D}\) loop diagram characterized by an amplitude proportional to \(p^*\), where \(p^*\) is the magnitude of the c.m. 3-momentum of either \(D\). For \(\psi'' \to D^+D^-\), \(p^* = 250.0\) MeV/c, while for \(\psi'' \to D^0\bar{D}^0\), \(p_{00} = 283.6\) MeV/c. The re-annihilation amplitude \(A_d^R\) into \(d\bar{d}\) pairs and the amplitude \(A_u^R\) into \(u\bar{u}\) pairs are then expected to be in the ratio \(A_d^R/A_u^R = (p_{0+}/p_{00})^3 = 0.685\), and the corresponding ratio for isovector and nonstrange isoscalar contributions \(A_1^R\) and \(A_0^R\) is

\[
\frac{A_1^R}{A_0^R} = \frac{A_d^R - A_u^R}{A_d^R + A_u^R} = \frac{1 - 0.685}{1 + 0.685} = 0.187.
\]

I assume that the re-annihilation amplitudes into \(I = 0\) and \(I = 1\) final states have the same strong phase \(\delta\) relative to the continuum, modulated by a Breit-Wigner amplitude \(f_B\) defined to be unity at the resonance peak, since the \(I = 1\) contribution arises largely from the mass difference between charged and neutral \(D\) mesons but in other respects arises from the same rescattering mechanism (charm-anticharm annihilation to light non-strange quarks) as the \(I = 0\) contribution. This assumption may be relaxed if the interference patterns to be discussed below are found to differ for \(I = 0\) and \(I = 1\) channels.

In the vicinity of the \(\psi''\) mass \(M_0\) one may then write the amplitudes \(A_1\) and \(A_0\) for the isovector and nonstrange isoscalar contributions to \(R\) as functions of c.m. energy \(E\):

\[
A_1 = 0.187b_0e^{i\delta}f_B(E) + \sqrt{R_1}, \quad A_0 = b_0e^{i\delta}f_B(E) + \sqrt{R_0},
\]

where the amplitudes have been defined such that their squares yield their contributions to \(R\), and

\[
f_B(E) = [d_B(E)]^{-1}, \quad d_B(E) \equiv 1 + \frac{2i(M_0 - E)}{\Gamma}.
\]

The values \(M_0 = 3772\) MeV/\(c^2\) and \(\Gamma = 23.2\) MeV are taken from the fit of Fig. 11. This fit implies a peak value \(R(M_0) = 3.53\) which will be taken as a constraint when choosing the arbitrary constant \(b_0\).
The continuum away from the peak accounts for \( R = 2.26 \), so one must provide a total resonant contribution of \( \Delta R_{\text{peak}} = 3.53 - 2.26 = 1.27 \). Consider \( D\bar{D} \) pairs to provide 82% of this value, or \( \Delta R_{\text{D}\bar{D}}^{\text{pk}} = 1.04 \). This contribution will be modulated by \(|f_B(E)|^2\). There will be a constant \( s\bar{s} \) continuum contribution of \( \Delta R_{s\bar{s}}^{\text{ss}} = 0.38 \), and contributions from the isovector and non-strange isoscalar amplitudes \( A_I \) above, leading to a total of

\[
R(E) = |A_1|^2 + |A_0|^2 + \Delta R_{\text{D}\bar{D}}^{\text{pk}}|f_B(E)|^2 + \Delta R_{s\bar{s}}^{\text{ss}}.
\] (12)

For \( \delta = 0 \), a modest value \( b_0 = 0.15 \) provides the additional contribution needed to account for the missing 18% of the \( \psi'' \) peak cross section. The corresponding values for \( \delta = \pi/2, \pi, 3\pi/2 \) are 0.47, 1.46, and 0.47, respectively. Fig. 3 displays the result of this calculation, in which re-annihilation accounts for 18% of the peak \( R \) value at \( M(\psi'') = 3772 \text{ MeV}/c^2 \). A relative phase \( \delta \) between the reannihilation amplitude and the continuum was defined in such a way that \( \delta = 0 \) corresponds to constructive interference at the resonance peak. Several features of this model are worth noting.

- The re-annihilation of \( D^+ D^- \) and \( D^0 \bar{D}^0 \) pairs into light quarks will favor leading \( d\bar{d} \) and \( u\bar{u} \) pairs, with amplitudes in the ratio \( d\bar{d} : u\bar{u} \approx 2 : 3 \) in line with the cross section ratio \( \sigma(D^+ D^-) : \sigma(D^0 \bar{D}^0) \). The fragmentation of these quarks will populate hadronic final states in different proportions than the usual continuum process in which quark pairs are produced by the virtual photon with amplitudes proportional to their charges.

- The re-annihilation favors isoscalar \((I = 0)\) odd-G-parity final states, so one should see more effects of interference between re-annihilation and continuum in odd G \((3\pi, 5\pi, \eta 3\pi, \eta' 3\pi, \ldots)\) states than in even-G ones \((2\pi, 4\pi, \eta 2\pi, \ldots)\). This interference is particularly pronounced because the larger odd-G reannihilation amplitude is interfering with a smaller odd-G continuum amplitude.

- The effects of re-annihilation on the continuum contributions will be hard to see if \( \delta = 0 \), especially in the dominant \( I = 1 \) (even-G-parity) channel. They are proportionately greater in the \( I = 0 \) (odd-G-parity) non-strange channel (consisting, for example, of odd numbers of pions).

- The re-annihilation may be similar to that which accounts for enhanced penguin contributions in \( B \) decays, particularly in the \( b \to s \) subprocess through the chain \( b \to c\bar{c}s \to q\bar{q}s \), where \( q = (u, d, s) \) (see also \[5\]). If this is so, one should look for an enhancement of \( \eta' \) production as occurs in inclusive and exclusive \( B \) decays.

- As evident for non-zero \( \delta \), measurement of the cross section in semi-inclusive channels with definite G-parity and especially odd G (such as final states with an odd number of pions) may show interesting interference patterns over an energy range \( M(\psi'') \pm \Gamma(\psi'')/2 \approx 3772 \pm 12 \text{ MeV}/c^2 \).

A Breit-Wigner amplitude is normally taken to be purely imaginary at its peak. I incorporate this phase into the definition of \( \delta \). The choice \( \delta = 3\pi/2 \) would correspond to no additional phase associated with the re-annihilation process, for example in
Figure 3: Contributions to $R$ in the vicinity of the $\psi''$ resonance energy. Solid curves: total, constrained to have a value of 3.53 at $M(\psi'') = 3.772$ GeV/c$^2$. Short-dashed curves: $I = 1$ continuum interfering with $I = 1$ contribution from $D\bar{D}$ reannihilation. Long-dashed curves: $I = 0$ non-strange continuum interfering with $I = 0$ nonstrange contribution from $D\bar{D}$ reannihilation. Dot-dashed curves: $D\bar{D}$ resonance contribution, taken to contribute 82% of resonance peak cross section, plus $s\bar{s}$ continuum.
\[ e^+e^- \rightarrow \mu^+\mu^- \] in the vicinity of the resonance, where interference between continuum and resonance is destructive below the resonance and constructive above it. (For an example of this behavior at the \( \psi' \), see Ref. [29].) It was speculated in Refs. [5] and [30] (see also Refs. [31]) that such an additional phase could be present and, if related to a similar phase in \( B \) decays, might account for a strong phase in penguin \( b \rightarrow s \) amplitudes. A recent fit to \( B \rightarrow PP \) decays, where \( P \) denotes a charmless pseudoscalar meson [32], finds such a phase to be in the range of roughly \(-20^\circ\) to \(-50^\circ\). This would correspond to taking \( \delta \) in the range of 40\(^\circ\) to 70\(^\circ\). The presence of such a phase is supported by the recent strengthening of the evidence for a significant CP asymmetry in the decay \( B^0 \rightarrow K^{+}\pi^- \) [33].

I now discuss briefly some exclusive charmless decay modes of the \( \psi'' \). It was suggested in Ref. [5] that some \( \psi' \) decay modes might be suppressed via S–D mixing. In that case, they should show up in \( \psi'' \) decays. Foremost among these was the \( \psi' \rightarrow \rho\pi \) decay. It was then pointed out [34] that because of possible interference with continuum, decays such as \( \psi'' \rightarrow \rho\pi \) might manifest themselves in various ways depending on relative strong phases, even as a dip in \( \sigma(e^+e^- \rightarrow \rho\pi) \) at \( M(\psi'') \).

All of the suppressed \( \psi'' \) modes discussed in Refs. [5] and [35] are prime candidates for detection in \( \psi'' \) decays. The interference proposed in Ref. [34] can actually lead to a suppression of some modes relative to the rate expected from continuum. It was anticipated in Ref. [5] that if one were to account for any “missing” \( \psi' \) decay modes by mixing with the \( \psi'' \), such an effect need not contribute more than a percent or two to the total \( \psi'' \) width. However, Ref. [7] recently obtained a charmless \( \psi'' \) branching ratio of up to 13\% obtained by generalizing the above arguments to all charmless final states of \( \psi' \) and \( \psi'' \) within the S–D mixing framework.

To sum up:

1. Some non–D\( \bar{D} \) decay modes of the \( \psi'' \) do exist, such as \( \ell^+\ell^- \) pairs, \( \gamma\chi_{cJ} \), and \( J/\psi\pi\pi \). They tell us about mixing between S-waves, D-waves, and open D\( \bar{D} \) channels.

2. Most non–D\( \bar{D} \) final states at the \( \psi'' \) are from continuum production. Their yields will not vary much with beam energy unless their continuum production amplitudes are interfering with a genuine Breit-Wigner contribution from the \( \psi'' \). This interference is most likely to show up in odd-G-parity final states, for which appreciable distortions of the Breit-Wigner line shape can occur.

3. I predict a substantial enhancement of \( \eta' \) production in charmless \( \psi'' \) final states if the re-annihilation of D\( \bar{D} \) into light quarks is related to the generation of a \( b \rightarrow s \) penguin amplitude in \( B \) decays.

4. The suggestion that the “missing” \( \psi' \) decays, like \( \rho\pi \), should show up instead at the \( \psi'' \), is being realized, if at all, in a more subtle manner, and does not illuminate the question of whether a substantial fraction (at least several percent) of the \( \psi'' \) cross section is non–D\( \bar{D} \).

5. The measurement of the continuum cross section at 3670 MeV is expected to yield \( R = 2(1 + \alpha_S/\pi + \ldots) \). Its value, when extrapolated to 3770 MeV, is relevant to whether there is a cross section deficit at the \( \psi'' \).

6. Proposed experimental tests of these points include (a) a scan of the \( \psi'' \) peak to measure \( \sigma(\psi'') \) more accurately, with an eye to the possibility of different behavior in
different channels and distortion of the peak shape due to resonant-continuum interference; (b) reduction of the error on $\sigma(\bar{D}D)$; and (c) use of continuum data to perform an analysis of the total hadron production cross section at the $\psi''$ energy.

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