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Measuring the phase of the J/ψ strong decay amplitudes

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Abstract

It is shown that the interference between $p\bar{p} \to J/\psi \to e^+e^-$ and $p\bar{p} \to e^+e^-$ can be measured with good accuracy at Fermilab. Therefore the phase of the strong decay amplitude of the J/ψ with respect to the proton magnetic form factor will be obtained. There are hints, from $J/\psi \to n\bar{n}$ and other J/ψ decays, of an unexpected $\sim 90°$ phase. © 1997 Published by Elsevier Science B.V.

1. The case of the quarkonium decay phases

In this note we illustrate a proposal to measure, in a model-independent way, the phase difference between the resonant amplitude $A(p\bar{p} \to J/\psi, \psi' \to e^+e^-)$ and the non-resonant one $A(p\bar{p} \to e^+e^-)$ by looking at the interference in the Q^2 behaviour, below and above the J/ψ or the ψ' (see the diagrams of Fig. 1). At these Q^2 the proton time-like magnetic form factor (ff) is supposed to give the main contribution to the non-resonant amplitude.

The expected interference pattern has been observed, in the case of the e.m. channel $e^+e^- \to \mu^+\mu^-$ [1], between $e^+e^- \to J/\psi \to \mu^+\mu^-$ and the QED amplitude. However, in a $p\bar{p}$ initial state there is a much better c.m. total energy resolution with respect to an e^+e^- initial state and no radiative correction has to be taken into account.

According to PQCD [2] the phases of the two aforementioned resonant and non-resonant $p\bar{p}$ amplitudes are both supposed to be small.

On the contrary there are hints, from $J/\psi \to n\bar{n}$ and other J/ψ decays, of an unexpected $\sim 90°$ phase difference. These hints arise because there are J/ψ decays for which the phase difference between strong and e.m. decay amplitudes (see Fig. 1) has been inferred under some additional theoretical hypothesis. On the other hand, the e.m. quarkonium decay through a virtual photon and the e^+e^- non-resonant amplitude into the same channel have the same phase. These phase differences will be discussed in the following. In all cases they turn out to be compatible with $\sim 90°$, in particular in the J/ψ decay into two pseudoscalars and the phase of the pion ff is of interest too.

According to analyticity, at high Q^2 time-like ff are expected to be real, like space-like ff. In fact, analyticity [3] and also PQCD [4] foresee a continuous transition at high Q^2 from space-like to time-like. Actually hadronic time-like ff data [5,6] are consistent with PQCD for what concerns the expected $1/Q^{2(n-1)}$ behaviour, n being the number of constituents, however they exceed the space-like data at the same Q^2 by a factor of 2 [7].

The $1/Q^{2(n-1)}$ behaviour implies a change of sign

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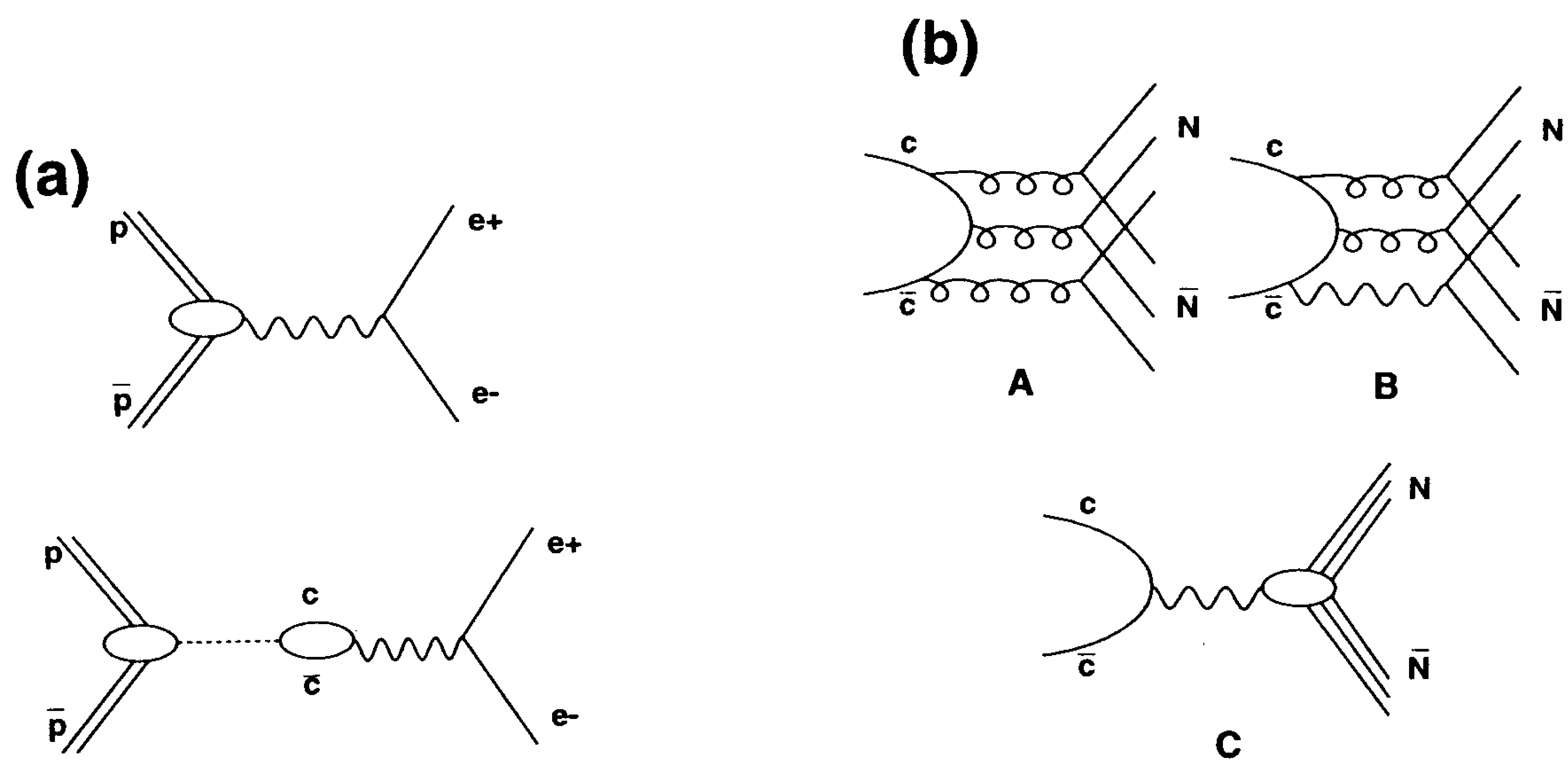

Fig. 1. (a) Feynman diagrams contributing to the $p\bar{p}$ annihilation in e^+e^- around the j/ψ excitation energy. (b) Feynmann diagrams contributing to the decay $J/\psi \to N\bar{N}$: purely strong diagram (A), strong-e.m. diagram (B) and purely e.m. diagram (C). We notice that the dashed line in the second diagram of (a) includes the three contributions of (b).

for a meson ff (n = 2) from space-like to time-like region ($Q^2 \to -Q^2$) and no change for a baryon ff ($n = 3$). Actually only the modulus of a ff is measured, however the phase of a ff can be achieved by means of a dispersion relation on the logarithm of the time-like ff modulus [8]. In this way the phase of the pion ff turns out to be $\sim 180°$ at $Q^2 \sim M^2_{J/\psi}$, in remarkable agreement with the expected $1/Q^2$ behaviour at high Q^2 [9]. In the case of the proton magnetic ff knowledge of the ff in the large and structured unphysical region is needed. A model-independent evaluation is under way [9], according to dispersion relations from the space-like ff data and from the time-like data above threshold. However, a $\sim 360°$ phase is found, independent of the extrapolation in the unphysical region [10], in agreement with analyticity and PQCD expectations.

On the other hand, in a QCD framework, a sizable phase should be more easily ascribed to the proton ff. In fact it has been demonstrated that, even in a perturbative description of the ff, a non-negligible non-perturbative contribution from small Q^2 exchanged gluons has to be taken into account [11]. Notwithstanding, the J/ψ decay width is interpreted as a direct proof of a perturbative regime, a decay into three gluons, and in $B(J/\psi \to N\bar{N})$ the three decay gluons match the three valence quarks of the baryons so that no phase is expected for this decay mode. Even in a sophisticated modified PQCD approach, developed [12] to fit the data of the nucleon ff, this amplitude only gets a small imaginary part, corresponding to a $\sim 10°$ phase.

Completely different conclusions have been achieved by a model describing the Q^2 behaviour of any OZI violating amplitude by means of a dispersion relation [13], assuming the e^+e^- annihilation through any OZI violating amplitude to be proportional to α_S^3. In this approach the phase is $\sim 180°$ in the ϕ decay, $\sim 90°$ in the J/ψ decay and 0° only at $Q^2 \sim 1000$ GeV^2. The ϕ decay phase is in agreement with the observed ϕ–ω interference [14]. These predictions are very peculiar to this model.

A J/ψ strong decay $\sim 90°$ phase, independent of the hadronic channel, could also be accommodated in the case of a strong mixing δm between the J/ψ and a vector glueball G very near in mass. In this case it is expected that the vector glueball has larger hadronic widths Γ^h with respect to the J/ψ, but a smaller leptonic width Γ^l. Due to the off-diagonal term δm, for any hadronic channel h, not only $p\bar{p}$, as a function of the c.m. energy W in an energy interval where $|W - M_G| \sim \Gamma_{J/\psi} < \Gamma_G$, the resonant amplitude $A_R = A(h \to J/\psi, G \to e^+e^-)$ would be [15]

$$\frac{\delta m\sqrt{\Gamma_G^h\Gamma_{J/\psi}^l}}{(M_G-i\Gamma_G-W)(M_{J/\psi}-i\Gamma_{J/\psi}-W)-\delta m^2} \sim i\frac{\delta m\sqrt{\Gamma_G^h\Gamma_{J/\psi}^l}}{\Gamma_G(M_{J/\psi}-i\Gamma_{J/\psi}-W)}.$$

Therefore an additional 90° phase for any hadronic channel and a somewhat larger J/ψ effective hadronic width is expected. Such a mixing has been proposed [16] to explain the anomalously large J/ψ into a vector and a pseudoscalar meson branching ratio, compared to other J/ψ and ψ' relative branching ratios. A different interference pattern in the case of the ψ' is expected in this hypothesis.

A $\sim$ 90° phase in the $J/\psi \to l^+l^-$ decay amplitude entering twice in $e^+e^- \to \mu^+\mu^-$ would contradict the sign of the interference and the successful description of J/ψ photoproduction by means of the optical theorem. Conversely, in J/ψ strong production quite large discrepancies respect to PQCD expectations have also been pointed out [17]. The possibility that these discrepancies and the anomalous J/ψ hadronic phases are related should be investigated.

In conclusion it is worthwhile to measure a phase difference, if any, between resonant, OZI violating, and non-resonant amplitudes, by looking directly at their interference. This measurement can provide further, unique, information on the achievement of QCD predictions.

2. Strong and electromagnetic contributions in the J/ψ decays

2.1. J/ψ decays in nucleon–antinucleon

Hints for a sizable phase come from the comparison between the J/ψ branching ratio $B(J/\psi \to n\bar{n}) = (1.9\pm0.5)\times10^{-3}$, as measured by BONANZA [18] and improved by the FENICE experiment at ADONE [19], the branching ratio $B(J/\psi \to p\bar{p}) = (2.1\pm0.1)\times10^{-3}$ [20] and $\sigma(p\bar{p} \to e^+e^-)$ at $Q^2 = 8.9$ GeV^2, as measured by E760 [6].

The amplitudes expected to contribute [2,21] to the branching ratios $B(J/\psi \to N\bar{N})$ (see Fig. 1) are

- a strong one A, which has to be the same for proton and neutron,
- an e.m. one C, which has to be proportional to the magnetic ff at $Q^2 \sim M^2_{J/\psi}$,
- a further contribution, B, in which a gluon is substituted by a photon. It should be quite smaller and different from zero only for the proton, being proportional to the hadron charge:

$$B_{p,n} = -\frac{4}{5}\frac{\alpha Q_{p,n}}{\alpha_s(M^2_{J/\psi})}A, \tag{1}$$

that is $B_p \sim -0.03A$ and $B_n = 0$.

Therefore the ratio between the branching ratios in $n\bar{n}$ and $p\bar{p}$ is

$$\frac{B(n\bar{n})}{B(p\bar{p})} = \frac{|A+C_n|^2}{|A+B_p+C_p|^2}. \tag{2}$$

The magnitude of the e.m. contribution C_p relative to the strong one A can be obtained by comparing the branching ratio of the J/ψ in proton–antiproton to the cross section out of resonance enhanced by the amplification factor derived by the $\mu^+\mu^-$ channel:

$$\frac{|C_p|}{|A|} \sim \sqrt{\frac{\sigma(e^+e^- \to p\bar{p})B(\mu\mu)}{\sigma(e^+e^- \to \mu\mu)B(p\bar{p})}} \sim 0.15\pm0.02. \tag{3}$$

Furthermore, in order to express the ratio (2) in terms of the phase ϕ_p of the proton magnetic ff with respect to the phase of the strong amplitude, we have to make an assumption concerning the relative magnitude and phase of C_p and C_n. Lower energy data [22] suggest that $|C_p| \sim 1.5|C_n|$ while, for what concerns the phase we assume that, as in the space-like region, they are opposite in sign.

With these assumptions and using the value given in Eq. (3) we get the dependence of R on ϕ_p shown in Fig. 2. In the same figure, the curve is compared with the value of R obtained by the FENICE experiment [19]. The data indicate a phase difference between A and C_p in the range 55–100°, the cases $\phi_p = 0°$ and $\phi_p = 180°$ being respectively about 2 and more than 4 standard deviations away from the experimental value.

Further data have been collected by the FENICE experiment to reduce the statistical error by a factor of 1.5 and the analysis is under way.

Moreover, all the branching ratios $B(J/\psi \to B\overline{B})$ are in good agreement with the expectations from a SU(3) conserving amplitude A_0 and a SU(3) breaking at the lowest order amplitude A_1, neglecting any

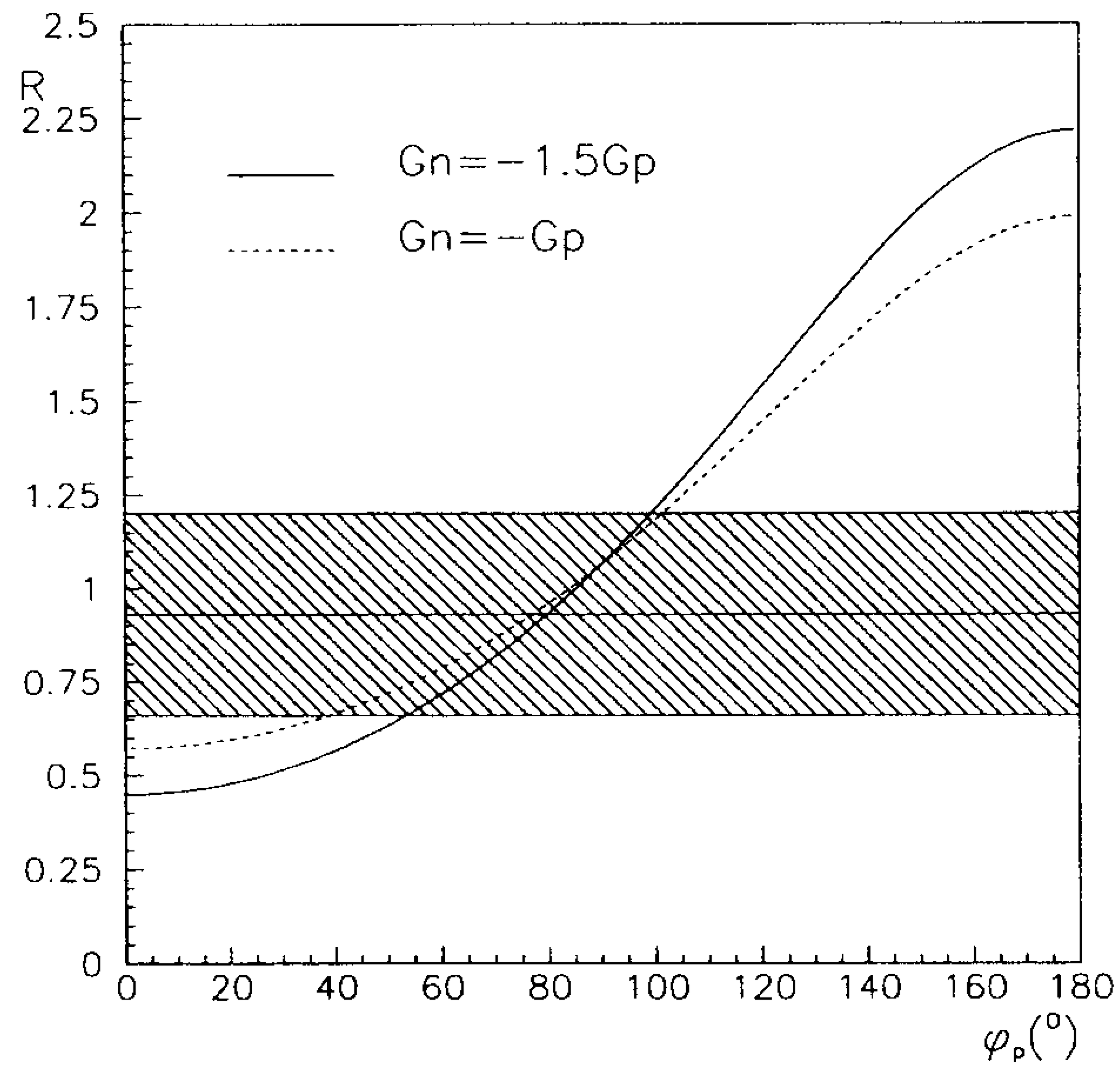

Fig. 2. Dependence of the ratio $R = B(n\bar{n})/B(p\bar{p})$ on the phase ϕ_p of the proton for $G_n = -1.5G_p$ (solid line) and $G_n = -G_p$ (dashed line). The value of R from the FENICE experiment (filled area) is shown for comparison.

Table 1
Comparison between expected amplitudes and experimental reduced branching ratios for J/ψ decays in baryon antibaryon pairs

Baryon	Amplitude	$\sqrt{\frac{B(B\bar{B})}{\beta_B}}$
p	$A_0 + A_1$	0.051 ± 0.001
n	$A_0 + A_1$	0.049 ± 0.009
Λ	A_0	0.045 ± 0.002
Σ	A_0	0.044 ± 0.003
Ξ	$A_0 - A_1$	0.042 ± 0.002

e.m. contribution. In Table 1 the expected amplitude according to SU(3) and SU(3) breaking due to the hypercharge are compared to the available experimental values for the reduced branching ratios [23].

Assuming $A_0 \sim 0.046$ and $A_1 \sim 0.004$ these relationships are fulfilled and quadratic corrections are within the experimental errors. There is no need for substantial linear e.m. contributions [23].

2.2. J/ψ decays in meson pairs

In the case of J/ψ decay into meson pairs, it has also been possible to extract the strong and e.m. amplitudes and their relative phases, using a procedure that is similar to the one outlined here for the case of the decay in a baryon pair. The analysis has been done for single-OZI rule violating decays like the decay in vector-pseudoscalar pairs (VP) [24,25], and also for double-OZI violating decays like the decay in pseudoscalar pairs (PP) and in vector pairs (VV) [23]. In both cases the strong amplitudes are parametrized according to SU(3) symmetry including violations due to the strange quark. The e.m. amplitudes are related to the e.m. ff of the mesons. PP and VV ff phases are expected to be $\sim 180°$ according to the $1/Q^2$ behaviours, related to the number of constituents. Conversely helicity conserving rules predict a $1/Q^4$ behaviour in the VP decay channel hence a $\sim 0°$ phase.

Table 2
Summary of the results from the analysis of the J/ψ decays in meson pairs

Final state	ϕ_E	$\lvert E\rvert/\lvert S\rvert$	$\lvert E\rvert/\lvert M\rvert$
PV	$70° \pm 6°$	0.11 ± 0.01	0.9 ± 0.1
VV	$42° \pm 37°$	-	0.95 ± 0.07
PP	$88° \pm 11°$	-	1.4 ± 0.2

In Table 2 the results [1] concerning the relative magnitude and phase of the e.m. amplitudes with respect to the strong one are summarized. E is the e.m. amplitude, S and M are the SU(3) symmetric and SU(3) breaking strong amplitudes, respectively. ϕ_E is the phase of E with respect to S and M (the two strong amplitudes are assumed to have the same phase). It is evaluated with respect to the expected values of 180° for PP and VV and 0° for PV according to the aforementioned argument.

Hence the magnitude of the e.m. contribution to the J/ψ decays turns out to be of the same order as the strong double OZI violating contribution, both being one order of magnitude lower than the strong single OZI violating amplitude; both single-forbidden and double-forbidden J/ψ decays in meson pairs are compatible with an electromagnetic amplitude almost orthogonal to the strong amplitude.

On average $\phi_E = 74° \pm 5°$ and, because of this phase, it should be expected that $B(J/\psi \to n\bar{n}) = (1.8 \pm 0.1) \times 10^{-3}$.

In conclusion the analysis of different final states gives essentially the same result concerning the mag-

[1] The results for the case PV are taken from Ref. [25].

nitude and the phase of the e.m. contribution with respect to the strong one.

We remind the reader that in the total cross section $\sigma(e^+e^- \rightarrow \text{hadrons})$ there is no evidence of any interference pattern below the J/ψ, in agreement with imaginary decay amplitudes. However, also in the case of real decay amplitudes a vanishing interference pattern is predicted in the total rate. In fact J/ψ strong decay amplitudes are SU(3) singlets, most of the e^+e^- annihilation channels below the J/ψ are SU(3) octets and they are orthogonal in the total rate [26].

3. Measuring the phase between the strong and the e.m. decay of the J/ψ and ψ'

The interference pattern between a J/ψ e.m. decay and a non-resonant amplitude was observed in the $e^+e^- \rightarrow \mu^+\mu^-$ channel and the relative phase was in good agreement with the expectation of a real, negative, QED amplitude [1].

In the $p\bar{p} \rightarrow e^+e^-$ channel, with respect to the $e^+e^- \rightarrow \mu^+\mu^-$ channel, a factor of ~ 6 is lost in sensitivity, comparing the interference term to the peak cross sections (the inverse of Eq. (3)). However, in a $p\bar{p}$ initial state there is a much better c.m. total energy resolution with respect to a e^+e^- initial state. In particular the E760 experiment at Fermilab [27] gained a factor of 5 in the c.m. total energy resolution ($\sim$ 200 KeV) with respect to the typical e^+e^- resolution ($\sim$ 1 MeV). Furthermore in a $p\bar{p}$ initial state no radiative tail from initial state radiation has to be taken into account.

In the following we evaluate the interference pattern between a resonant amplitude A_1 and a non-resonant amplitude A_2. The argument is reported for the case of the J/ψ but it works in exactly the same way also for the ψ' and numerical results will be given for both cases.

The amplitude A_1 for the $p\bar{p} \rightarrow J/\psi \rightarrow e^+e^-$ process is given by a Breit–Wigner amplitude centered around the mass of the J/ψ; if we define

$$x = \frac{M_{J/\psi} - W}{\Gamma_{\text{tot}}/2}, \tag{4}$$

with W the c.m. energy, we get

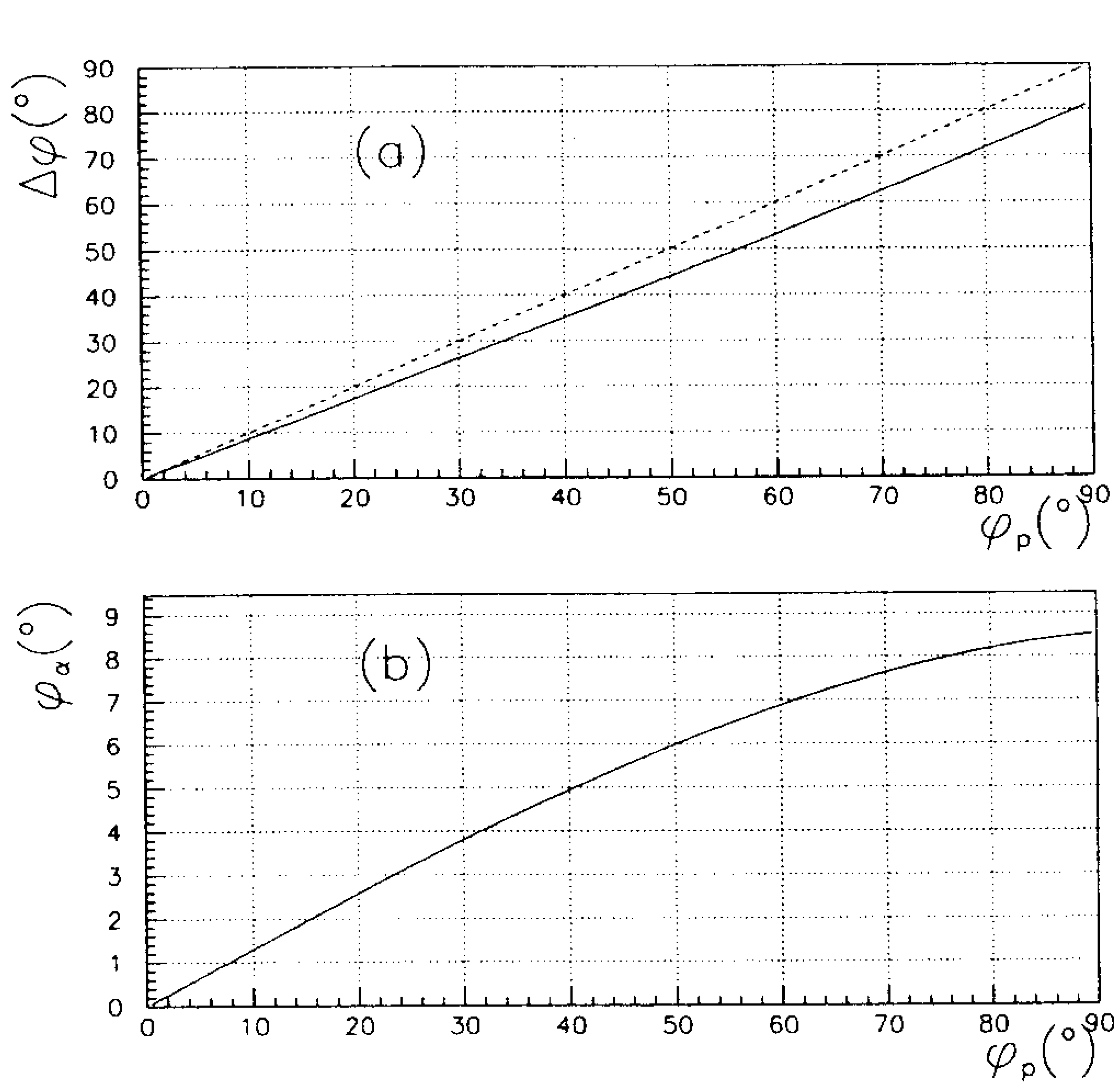

Fig. 3. (a) Dependence of the phase experimentally accessible $\Delta\phi$ on the e.m. vs. strong phase ϕ_p. The case $\Delta\phi = \phi_p$ (dashed line) is shown for comparison. (b) ϕ_α as a function of ϕ_p from Eq. (6).

$$A_1 = \alpha\left(\frac{x}{1+x^2} + i\frac{1}{1+x^2}\right), \tag{5}$$

α is a complex number given by the sum of the three contributions discussed in Section 2.1 and shown in Fig. 1b. The modulus is directly related to the J/ψ branching ratios in e^+e^- and in $p\bar{p}$,

$$|\alpha|^2 = (3\pi/P^2)B(e^+e^-)B(p\bar{p}) \sim 300 \text{ nb}, \tag{6}$$

where $B(e^+e^-)$ and $B(p\bar{p})$ are the J/ψ branching ratios in e^+e^- and in $p\bar{p}$ and P is the momentum of the initial state particles in the c.m. reference system (P = 1.23 GeV for the J/ψ decays). The phase of α, ϕ_α, is not trivial, since α includes the J/ψ e.m. decay amplitude; if we fix at 0 the phase of the strong three-gluon amplitude of Fig. 1b (we use this phase convention in the following), we obtain

$$\phi_\alpha = \text{arctg}\frac{|C_p|\sin\phi_p}{|A+B_p| + |C_p|\cos\phi_p}, \tag{7}$$

where ϕ_p is the phase of the e.m. contribution in our phase convention (the other symbols have been defined in Section 2.1). The overall phase of A_1 is the sum of ϕ_α and the phase of the term in parentheses in Eq. (5), that is the usual Breit–Wigner phase be-

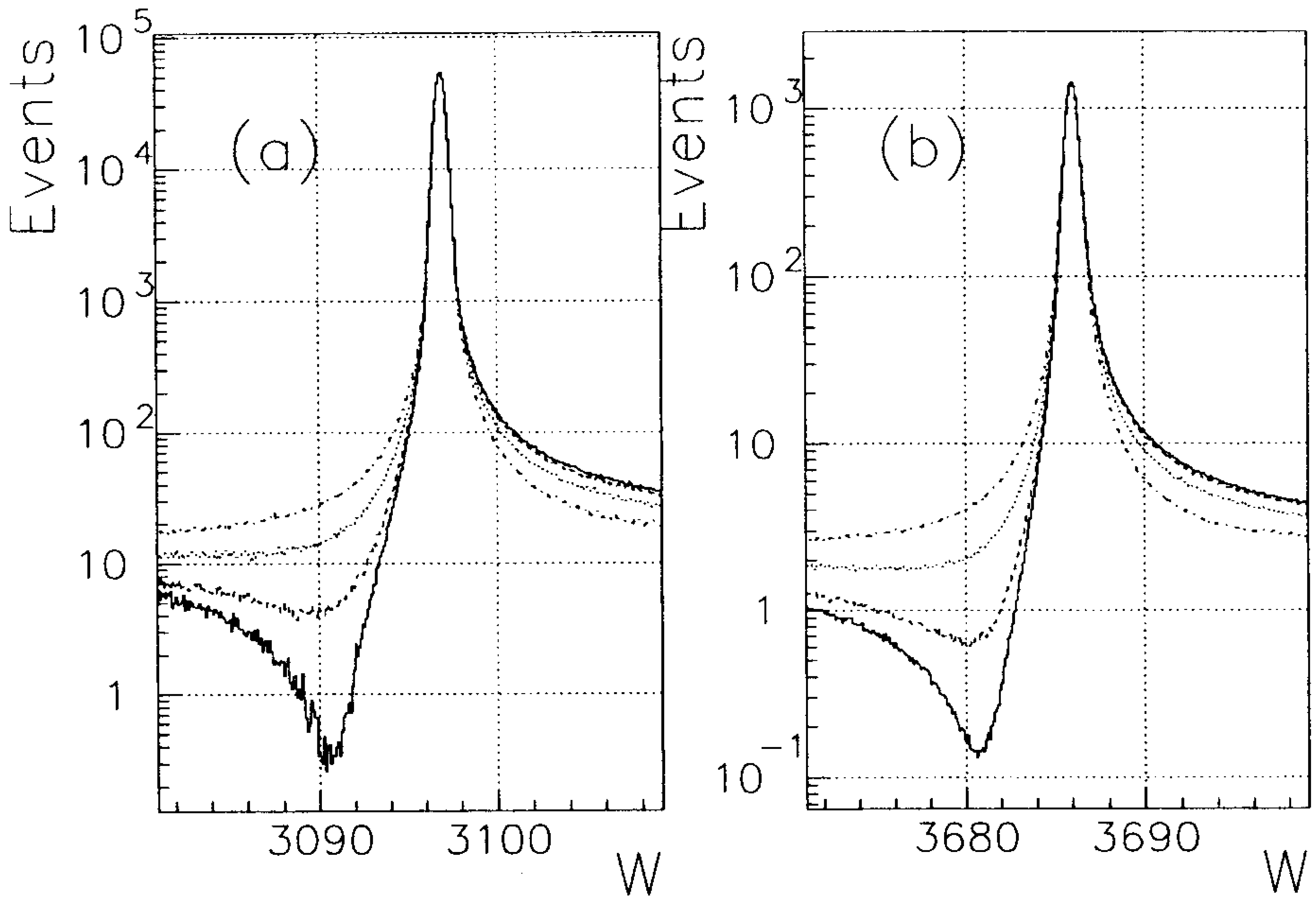

Fig. 4. Expected interference pattern (Eq. (8)) for the J/ψ (a) and the ψ' (b); $\Delta\phi = 0°$ (solid line), $\Delta\phi = 30°$ (dashed line), $\Delta\phi = 60°$ (dotted line) and $\Delta\phi = 90°$ (dashed-dotted line). All curves are convoluted with the beam energy spread.

haviour around a resonance peak (= 90° at the resonance mass).

The amplitude A_2 of the non-resonant process is

$$A_2 = -\beta e^{i\phi_p} \tag{8}$$

with $\beta^2 = \sigma(p\bar{p} \to e^+e^-) \sim 0.015$ nb, taking out the sign coming from the γ propagator. ϕ_p is the same phase compared with Eq. (7), both being the phase of the proton time-like form factor at $q^2 \sim M^2_{J/\psi}$ (we assume a smooth ϕ_p dependence on W).

The interference pattern $I_{\text{int}}(x)$ will be

$$I_{\text{int}}(x) = |A_1 + A_2|^2 = \frac{\alpha^2}{1+x^2} + \beta^2 - \frac{2\beta\alpha}{1+x^2}(x\cos\Delta\phi + \sin\Delta\phi), \tag{9}$$

where $\Delta\phi$ is the phase difference $\phi_p - \phi_\alpha$. We stress that $\Delta\phi$ is not directly the phase between the strong and e.m. contributions. Fig. 3 shows the relation (7) between $\Delta\phi$ and ϕ_p.

The expected counting rates for the case of the J/ψ are reported in Fig. 4 together with the same plots for the ψ', taking into account the E760 c.m. energy resolution and assuming that for every W value it will be collected below and above the two resonances the same effective integrated luminosity collected by E760 in the measurement of the proton ff [6] (~ 1 pb^{-1} near the J/ψ and ~ 3 pb^{-1} near the ψ').

From Fig. 4a we see that

- at $W = 3091$ MeV, that is ~ 6 MeV below the J/ψ peak, a dip is observed in the interference pattern for $\Delta\phi = 0°$ while no dip is observed for $\Delta\phi = 90°$; in particular ~ 30 events are expected in case there is no interference ($\Delta\phi = 90°$) to be compared to $\sim$ 0.3 events in case of maximal interference ($\Delta\phi = 0°$);
- on the other hand, for energies above the J/ψ the situation is reversed: the higher is $\Delta\phi$ the lower is the expected number of events; as an example at $W = 3100$ MeV, that is ~ 3 MeV above the J/ψ, ~ 60 events are expected in case there is no interference with respect to ~ 120 events in the case of real amplitudes.

Therefore an energy scan below and above the J/ψ peak allows one to disentangle the different $\Delta\phi$ values and hence to get the value of ϕ_p with an accuracy that depends on the number of experimental points and the statistics collected in each point. However, also a single measurement of the number of events near the expected minimum of the curve allows for a direct measurement of the phase. Fig. 5 shows the expected number of events for 1 pb^{-1} effective integrated luminosity at $W = 3090$ MeV as a function of $\Delta\phi$. Taking

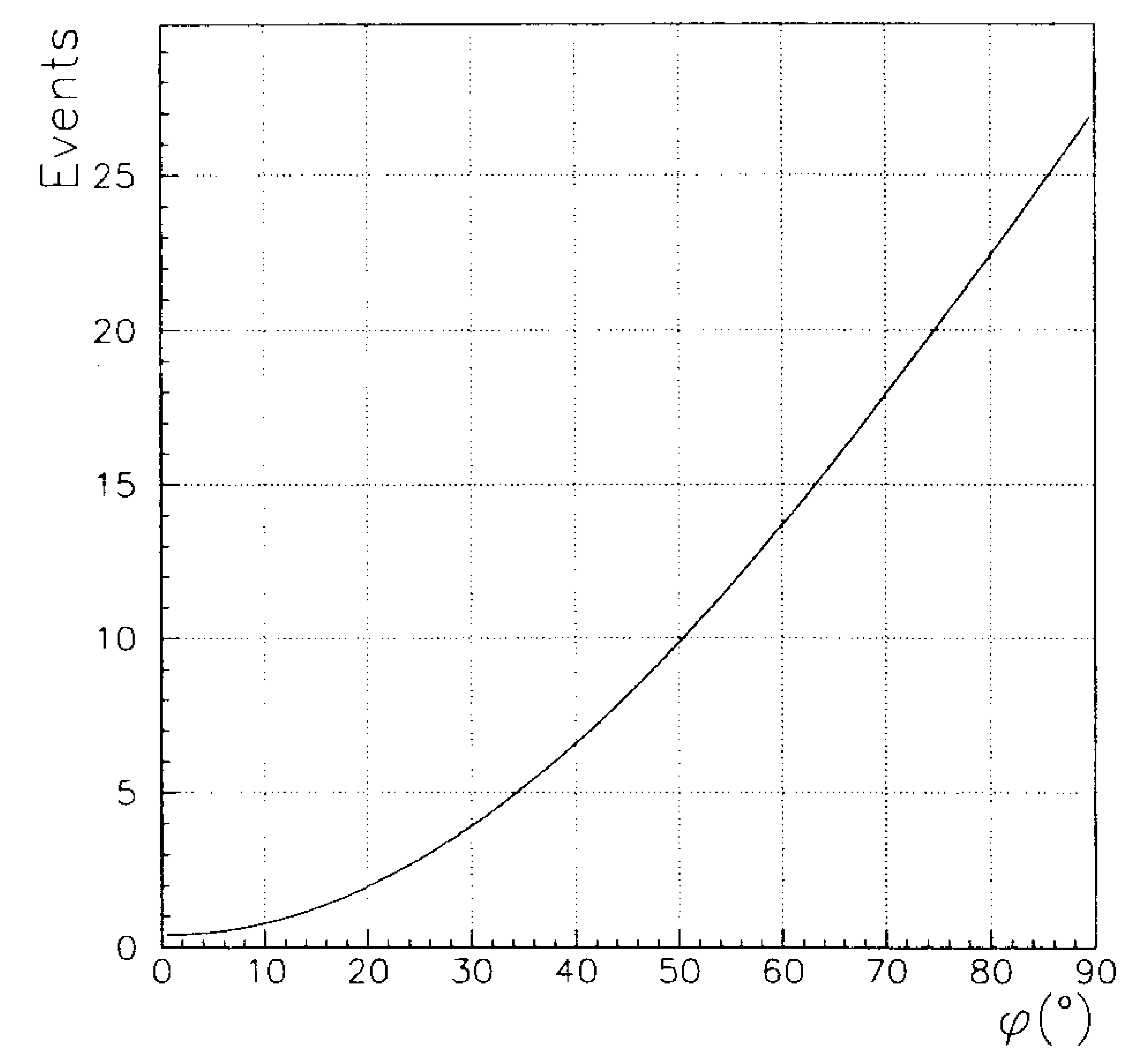

Fig. 5. Expected number of events at $W = 3090$ MeV for an effective integrated luminosity of 1 pb^{-1} as a function of the phase difference $\Delta\phi$.

into account the statistical fluctuations only, for $\Delta\phi > 20°$ we get an uncertainty on $\Delta\phi$ of 8–10°. For $\Delta\phi < 20°$ the number of events approaches 0 and an upper limit of $\sim 20°$ can be set anyway.

It is interesting to note that even if $\phi_p = 90°$ a residual interference pattern ($\Delta\phi \sim 80°$ see Fig. 3) can be observed. The possibility to disentangle $\Delta\phi = 90°$ and $\Delta\phi = 80°$ would be very important in this case to rule out any eventual effect that could hide the interference pattern (non-gaussian tails in the resolution, backgrounds and so on). To do that, an improvement in integrated luminosity should be considered.

For the case of the ψ' a luminosity higher by at least a factor of ten should be collected to reach the same statistical accuracy and to achieve information on the source in the case of a phase different from zero.

The E835 Collaboration has all the instruments to make this measurement with the accuracy required.

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