Measure the phase between strong and EM amplitudes in charmonium decays

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Outline

Motivation

Our proposed method of measurement

The amplitude in e^+e^- colliding experiments: formulae

Experimental measurement in case of interference

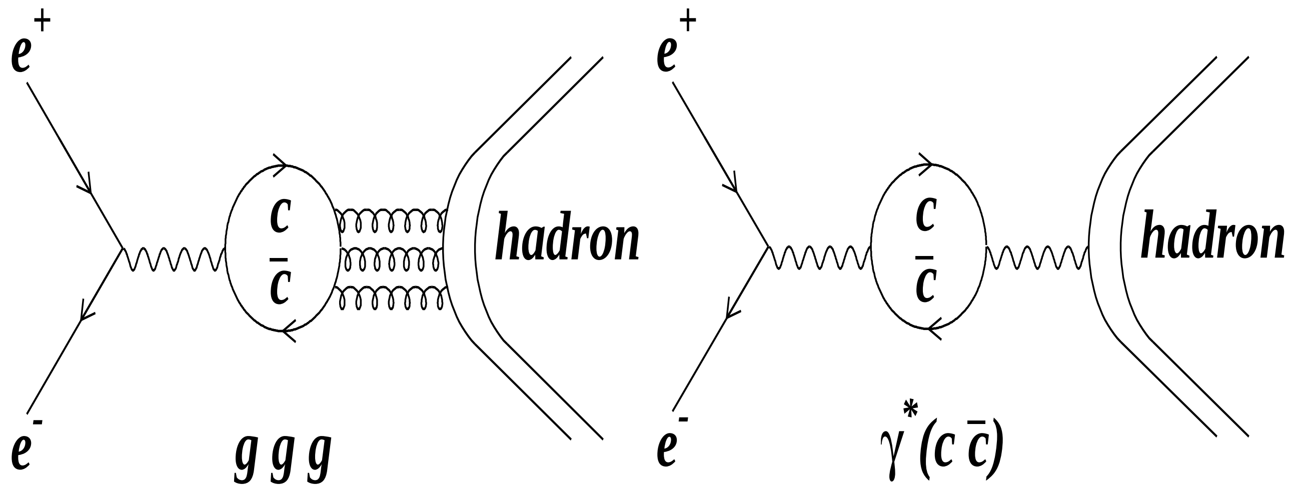
Constructive or destructive interference: $\psi(3770)$

Υ decay

Discussions

Motivations

Charmonium 1^{--} resonance decays through two interactions: strong and electromagnetic (EM). The diagrams are



According to pQCD, they should be both almost real.

Is this for granted?

Motivations

On the contrary, the analysis of experimental data suggests that in J/ψ decays, the strong amplitude (via three gluons) a_{3g} and EM amplitude (via a virtual photon) a_γ are orthogonal for all two-body decays:

- 1^+0^- 90° M. Suzuki, Phys. Rev. **D63**, 054021 (2001)
- 1^-0^- $(106 \pm 10)^\circ$ J. Jousset *et al.*, Phys. Rev. **D41**, 1389 (1990); D. Coffman *et al.*, Phys. Rev. **D38**, 2695 (1988); J. Jousset *et al.*, *Phys. Rev.* D **41**, 1389 (1990); A. Bramon, R. Escribano and M. D. Scadron, *Phys. Lett.* B **403**, 339 (1997); M. Suzuki, *Phys. Rev.* D **58**, 111504 (1998); N.N.Achasov, Talk at Hadron2001; G. López Castro *et al.*, in CAM-94, Cancum, Mexico.
- 1^-1^- $(138 \pm 37)^\circ$ L. Köpke and N. Wermes, Phys. Rep. **174**, 67 (1989).
- 0^-0^- $(89.6 \pm 9.9)^\circ$ M. Suzuki, Phys. Rev. **D60**, 051501(1999); G. López Castro *et al.*, ibid; L. Köpke and N. Wermes, ibid.
- $N\overline{N}$ $(89 \pm 15)^\circ$ R. Baldini, *et al.* Phys. Lett.**B444**, 111 (1998); G. López Castro *et al.*, ibid.

Motivations

Mahiko Suzuki summarized the experimental situation of the two-body J/ψ decays. Phys. Rev. **D63**, 054021(2001)

The existing data strongly favor large relative phase close to 90° between the gluon and the photon decay amplitudes for 1^-0^-, 0^-0^-, 1^-1^- and $N\overline{N}$, and are consistent with a large phase for 1^+0^-.

He then reached the conclusion:

The relative phase between the gluon and the photon decay amplitudes are universally large for all two-body decays of J/ψ.

J. M. Gérard and J. Weyers Phys. Lett. **B462**, 324 (1999) argued that this large phase follows from the orthogonality of three-gluon and one-photon virtual processes.

Motivations

But so far these conclusions have been reached by comparing several different decay processes of the same category (e.g. $\rho\pi$, $K^{*+}K^{-}$, $K^{*0}\overline{K^0}$, $\omega\pi^0$ among VP etc) modeling the amplitudes by means of SU(3) symmetry and SU(3) symmetry breaking. For example, the decay amplitudes of J/ψ to vector-pseudoscalar final states ($1^{--}0^{-+}$) are decompsed as

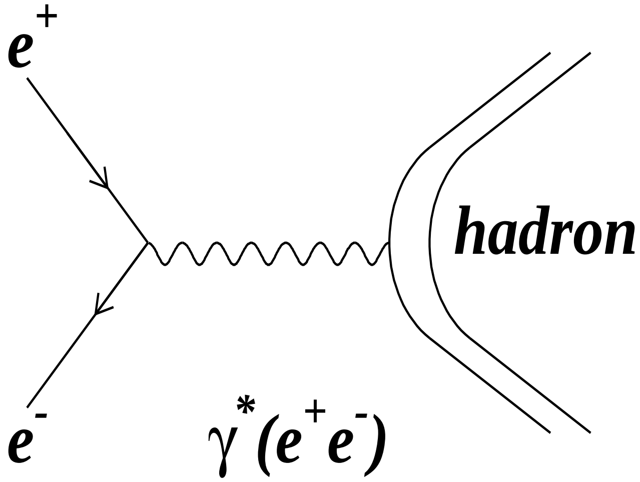
$$\begin{aligned} A_{\omega\pi^0} &= 3a_\gamma \quad , \\ A_{\rho\pi} &= a_{3g} + a_\gamma \quad , \\ A_{K^{*+}K^{-}} &= a_{3g} + \epsilon + a_\gamma , \\ A_{K^{*0}\overline{K^0}} &= a_{3g} + \epsilon - 2a_\gamma \quad . \end{aligned}$$

where a_{3g} is the strong decay amplitude (via gluon), a_γ is the electromagnetic decay amplitude (via photon), ϵ is introduced as a SU(3) symetry breaking parameter. Howard E. Haber and Jacques Perrier, Phys.Rev.D32(1985)2961.

We proposed an alternative way to measure the phase (between strong and electromagnetic amplitudes in charmonium decays) which is model-independent, i.e. it does not depend on the parametrization based on SU(3) symmetry.

Our proposed method

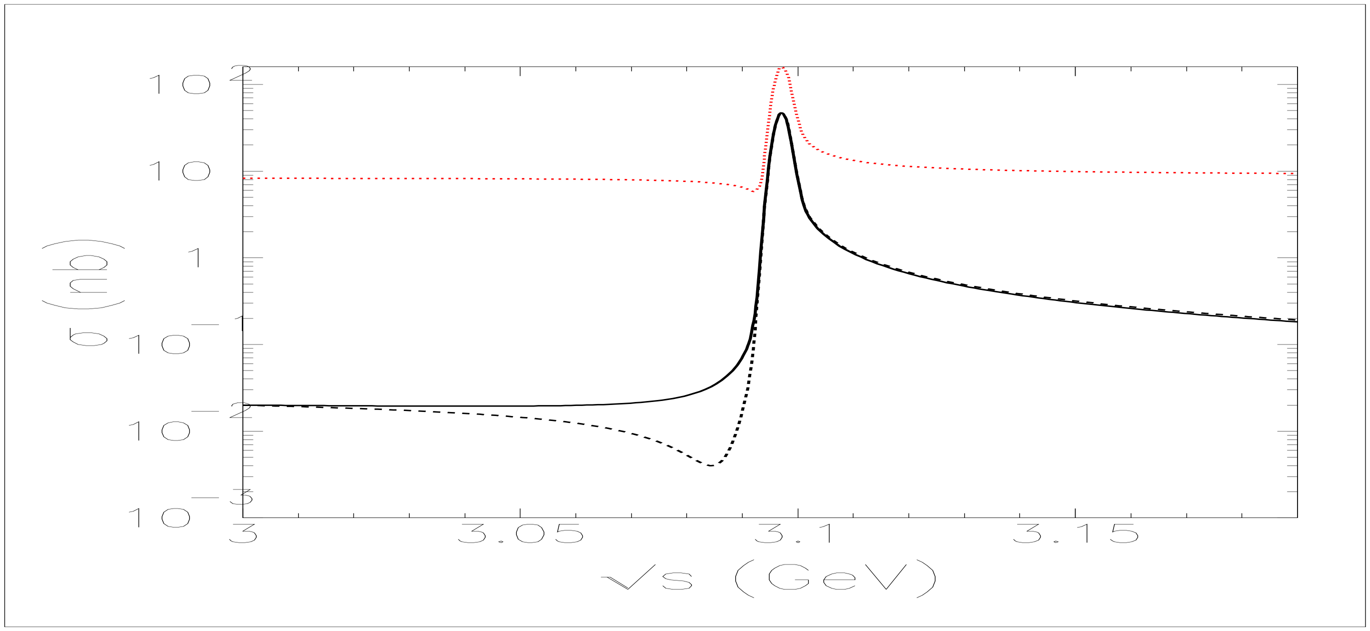
In e^+e^- experiments, there is an additional non-resonant amplitude, or continuum amplitude S.Rudaz, Phys.Rev.D14,298(1976); P. Wang, C. Z. Yuan, X. H. Mo and D. H. Zhang, Phys. Lett. **B** 593; 89-94 (2004) which contributes to the measured processes.



If a_{3g} and a_γ have different phases, i.e. there is a non-zero phase between them, then they would interfere differently with the continuum amplitude. Such interference varies as energy changes across the resonance. This provides us a tool to measure the phase between strong and EM amplitudes in J/ψ decays.

This is the idea which we proposed to measure the phase between strong and electromagnetic interactions in charmonium decays by a energy scan across the resonance.

Our proposed method



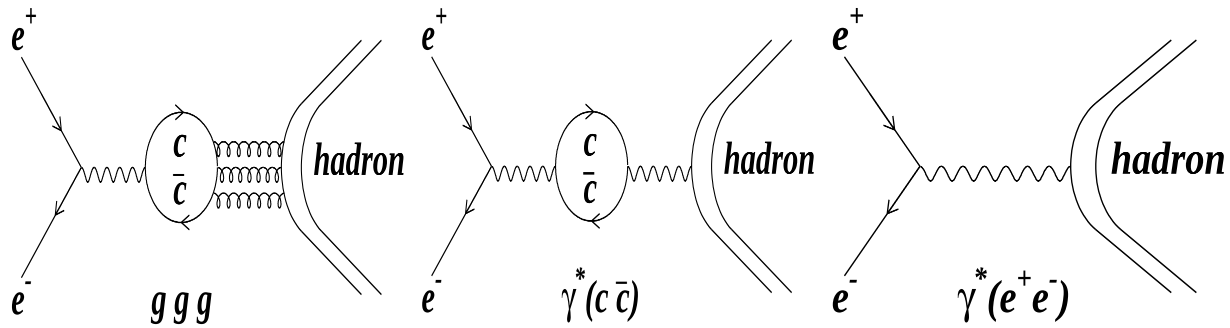
Here the red line is $\mu^+\mu^-$ cross section as a reference. The cross section of even-number-pion is expected to be like $\mu^+\mu^-$ cross section. The dashed and solid lines are $\rho\pi$ cross section if $\phi = 0^\circ$ and $\phi = -90^\circ$ respectively.

BES-III has scanned J/ψ in June 2012 for our measurement. Olga Fukc is working on the data analysis.

Decay amplitude in e^+e^- colliding experiments

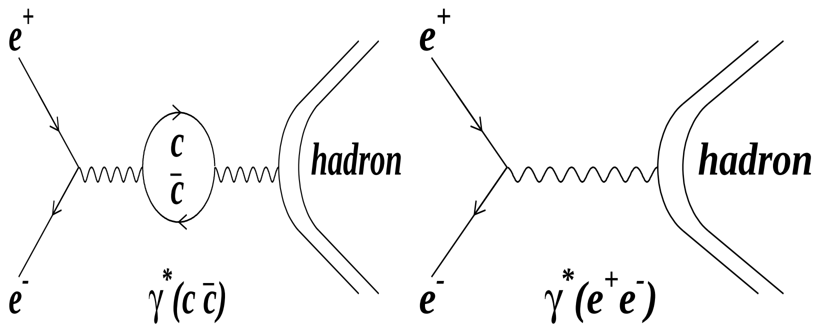
In e^+e^- experiments, there are three diagrams contributing to the observed cross sections.

S.Rudaz, Phys.Rev.D14,298(1976);
P. Wang, C. Z. Yuan, X. H. Mo and D. H. Zhang, Phys. Lett. **B** 593; 89-94 (2004)



The electromagnetic decay amplitude

Consider the final states which only go through electromagnetic interactionss, like $\mu^+\mu^-$ or $\pi^+\pi^-$. So only these two diagrams contribute:



The electromagnetic decay amplitude

According to Feynman R.P.Feynman, Photon-Hadron Interactions, lecture 5, the resonance diagram is calculated as the contribution of the resonance to the vacuum polarization.

$$\Pi_{\psi}(s) \ = \frac{s^2}{4\pi^2\alpha}\int_{4m_\pi^2}^{\infty}\frac{ds'\sigma(s')}{s-s'+i\epsilon} \tag{1}$$

For a resonance, the total cross section can be writen in the form of Briet-Wigner:

$$\sigma_{BW}(s) \ = \frac{12\pi\Gamma_{ee}\Gamma_{\psi}}{(s-M^2)^2+\Gamma_{\psi}^2M^2}, \tag{2}$$

And also following Feynman (in the same book of Feynman), we take the approximation by changing the lower limit of the integration to $-\infty$

$$\int_{4m_\pi^2}^{\infty} \rightarrow \int_{-\infty}^{\infty} \tag{3}$$

The electromagnetic decay amplitude

$$\Pi_\psi(s) = \frac{s^2}{4\pi^2\alpha}\int_{-\infty}^{\infty}\frac{ds'}{s-s'+i\epsilon}\frac{12\pi\Gamma_{ee}\Gamma_\psi}{(s'-M^2)^2+\Gamma_\psi^2 M^2} \tag{4}$$

Perform this integration on complex plane, we obtain

$$\Pi_\psi(s) = \frac{3\Gamma_{ee}sM/\alpha}{s-M^2+iM\Gamma_\psi} \tag{5}$$

This is the amplitude of ψ through decay by electromagnetic interactions.

It depends on the resonance parameters of ψ. These are well measured, and listed by Particle Data Group. Of course we can also use our own measurement by BES.

The strong decay amplitude

So the amplitude by the virtaul photon is

$$\frac{1}{s} \tag{6}$$

while the amplitude due to resonance decay through electromagnetic interaction is

$$\Pi_\psi(s) = \frac{3\Gamma_{ee}M/\alpha}{s - M^2 + iM\Gamma_\psi} \tag{7}$$

Next, how do we write the strong decay amplitude? We assume that it behaves like the electromagnetic decay amplitude of ψ, with a constant phase ϕ and relative strength

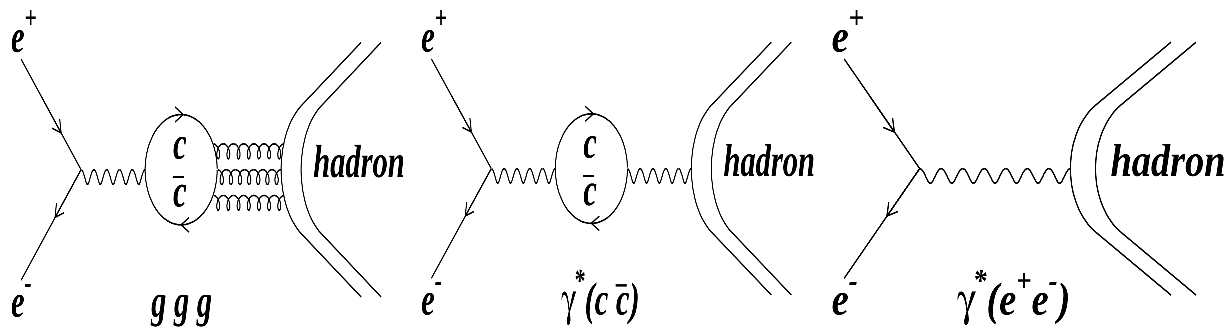
$$|A_{3g}| = \mathcal{C}|A_{EM}| \tag{8}$$

i.e. we write it as

$$A_{3g}(s) = \mathcal{C}e^{i\phi}A_{EM}(s). \tag{9}$$

The decay amplitude in e^+e^- colliding experiments

Now the contribution of the three diagrams



is written as

$$\mathcal{A} = \frac{1}{s}[1 + \frac{3\Gamma_{ee}M/\alpha}{s - M^2 + iM\Gamma_\psi}(1 + \mathcal{C}e^{i\phi})] \quad (10)$$

Here the first term is due to the virtual photon, in the last bracket, the first term is due to electromagnetic decay, the second is due to strong decay.

We shall use this formula to fit the experimental data in our measurement of the phase ϕ.

Measurement in case of interference

A profound feature of the experimental measurement in the presence of a resonance which has signifiant interference with non-resonance continuum is that we determine the three parameters simultaneously: the strong decay amplitude (or the total resonance amplitude), the phase between strong and electromagnetic amplitudes, and the non-resonance continuum amplitude.

In order to extract these parameters, we need to measure the cross sections at several energy points, to fit our formula, i.e. we need to perform an energy scan across the resonance.

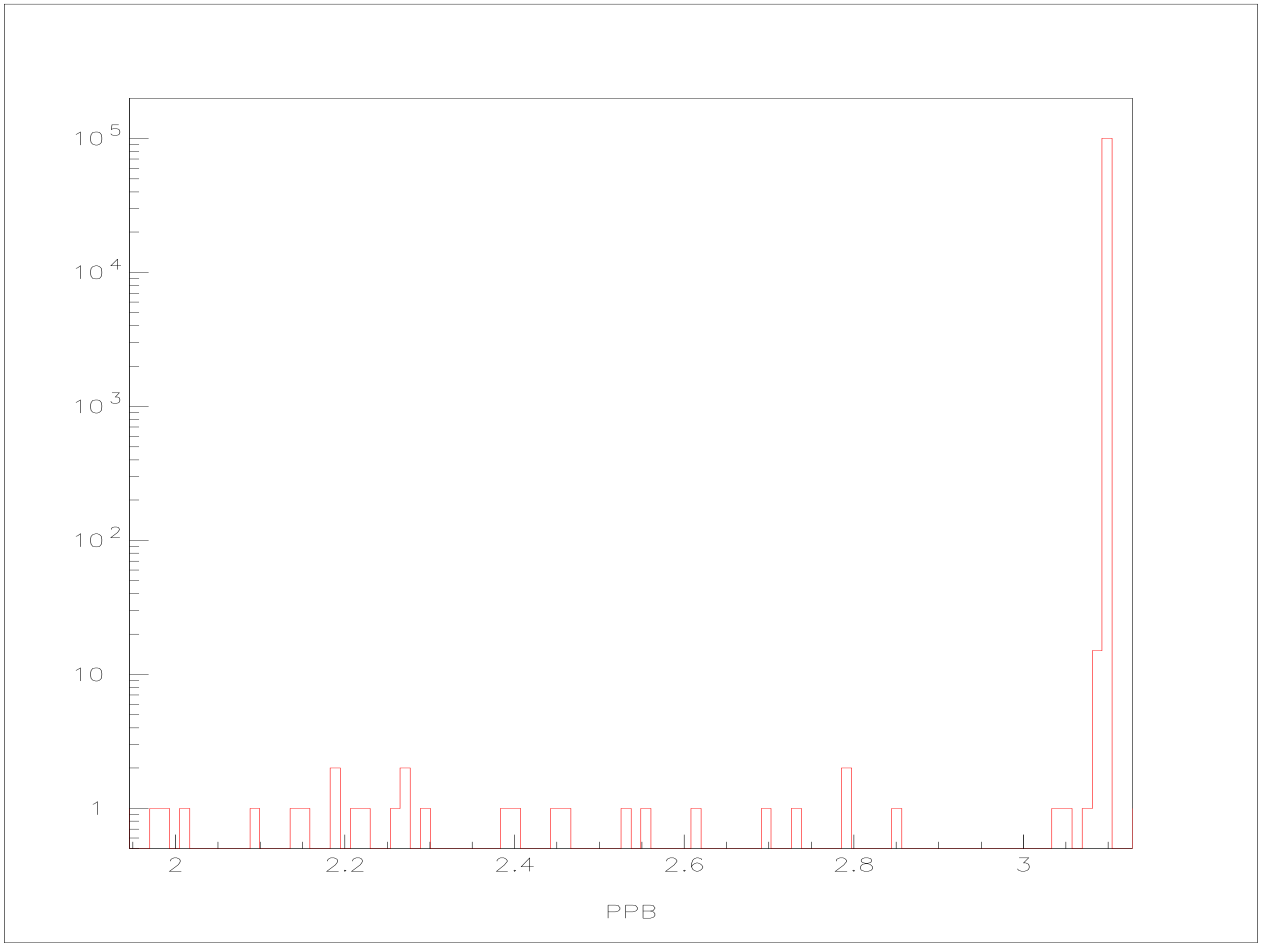
Measurement in case of interference

In the data analysis, we need a Monte Carlo to calculate acceptance. Our Monte Carlo generator should simulate the interference pattern. So it must depend on these three parameters which we want to determine from experimental data. The process should be an iterative one: we input values of these three parameters in to Monte Carlo generator, calculate the acceptance, and obtain the cross sections at the energy points. With these cross sections, we obtain the values of these three parameters. We put these values back into Monte Carlo again, and repeat the process. P.Wang, X.H.Mo, C.Z.Yuan, Int. J. Mod. Phys. A21:5163(2006).

We need a dedicated Monte Carlo program for such measurement. It has been written by Alexey Sibidanov of Budker Institute based on MCGPJ of Dubna-Novosibirsk group.

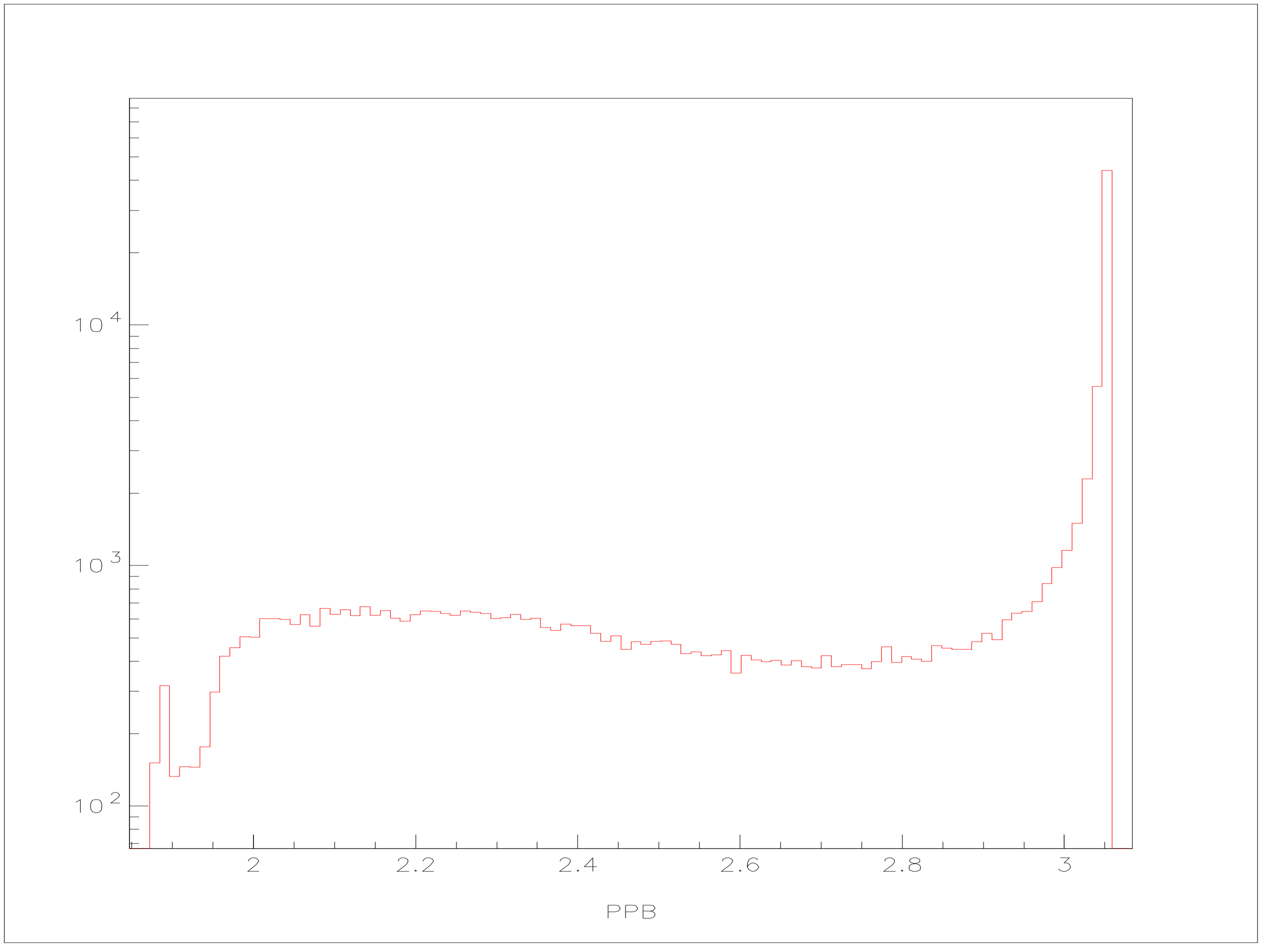
Measurement in case of interference

If a resonance occurs with interference with the continuum, it changes the distribution of the invariant mass of the hadronic state. Such distribution varies from energy point to point. For example, on top of J/ψ peak, it is almost a δ function



Measurement in case of interference

Such distribution at the energy point of 3.05GeV would be like



This affects the acceptance calculated by Monte Carlo.

Constructive or destructive interference

Notice that here the amplitude

$$\mathcal{A} = \frac{1}{s}[1 + \frac{3\Gamma_{ee}M/\alpha}{s - M^2 + iM\Gamma_\psi}(1 + \mathcal{C}e^{i\phi})] \qquad (11)$$

On top of the resonance, $s = M^2$, so the electromagnetic amplitude

$$\Pi_\psi(s) = \frac{3\Gamma_{ee}M/\alpha}{s - M^2 + iM\Gamma_\psi} \qquad (12)$$

is pure imaginary. If the strong decay ampltude

$A_{3g}(s) = \mathcal{C}e^{i\phi}A_{EM}(s)$

has a phase of $\phi = \pm\pi/2$ relative to electromagnetic, then the phase between strong decay amplitude and virtual photon amplitude is either 0 or 180 degree, which leads to constructive or destructive interference between strong decay amplitude and virtual photon amplitude.

Just see in the above formula.

Constructive or destructive interference

In the quark model, the quark may have positive or negative charge, i.e. its coupling to photon comes with a plus or minus sign. On the other hand, the strong insteraction is flavor-blind. So such interference can be constructive or destructive for different final states, depending on the quark content of the final states.

For example, among $\psi \to 1^{--}0^{-+}$ decays,

$$\begin{aligned} A_{\omega\pi^0} &= 3(a_\gamma + a_c) \quad , \\ A_{\rho\pi} &= a_{3g} + a_\gamma + a_c \quad , \\ A_{K^{*+}K^-} &= a_{3g} + \epsilon + a_\gamma + a_c \quad , \\ A_{K^{*0}\overline{K^0}} &= a_{3g} + \epsilon - 2(a_\gamma + a_c) \quad , \\ A_{\omega\eta} &= X_\eta(a_{3g} + a_\gamma + a_c) \quad , \\ A_{\phi\eta} &= Y_\eta[a_{3g} - 2(a_\gamma + a_c)]. \end{aligned}$$

here X_η and Y_η are the mixing angle between η_1 and η_8.

If the interference patern is destructive for $\rho\pi$, then it should also be so for $K^{*+}K^-$ and $\omega\eta$, and it must be constructive for $K^{*0}\overline{K^0}$ and $\phi\eta$.

This has been supported by experimental data from CLEOc at $\psi(3770)$.

Constructive or destructive interference

CLEO reported the measured cross section at 3.67GeV and $\psi(3770)$ peak CLEO collaboration, G.S.adams et al, Phys.Rev.D73:012002,2006

Channel	σ(3.67 GeV) [pb]	σ(3.77 GeV) [pb]
	VP	
$\rho^+\pi^-,\ \rho^-\pi^0,\ \rho^-\pi^+$	$8.0^{+1.7}_{-1.4} \pm 0.9$	$4.4 \pm 0.3 \pm 0.5$
$\omega\pi^0$	$15.2^{+2.8}_{-2.4} \pm 1.5$	$14.6 \pm 0.6 \pm 1.5$
$\phi\pi^0$	< 2.2	< 0.2
$\rho\eta$	$10.0^{+2.2}_{-1.9} \pm 1.0$	$10.3 \pm 0.5 \pm 1.0$
$\omega\eta$	$2.3^{+1.8}_{-1.1} \pm 0.5$	$0.4^{+0.2}_{-0.2} \pm 0.1$
$\phi\eta$	$2.1^{+1.9}_{-1.2} \pm 0.2$	$4.5 \pm 0.5 \pm 0.5$
$\rho\eta'$	$2.1^{+4.7}_{-1.6} \pm 0.2$	$3.8^{+0.9}_{-0.8} \pm 0.4$
$\omega\eta'$	< 17.1	$0.6^{+0.8}_{-0.3} \pm 0.6$
$\phi\eta'$	< 12.6	$2.5^{+1.5}_{-1.1} \pm 0.4$
$K^{*0}\overline{K^0},\ \overline{K}^{*0}K^0$	$23.5^{+4.6}_{-3.9} \pm 3.1$	$23.5 \pm 1.1 \pm 3.1$
$K^{*+}K^-,\ K^{*-}K^+$	$1.0^{+1.1}_{-0.7} \pm 1.8$	< 0.6
	AP	
$b_1\pi$	$7.9^{+3.1}_{-2.5} \pm 1.8$	$6.3 \pm 0.7 \pm 1.5$

Constructive or destructive interference

For the $\psi(3770)$, (abbreviated here as as ψ''), the EM decay amplitude a_γ is very small compared to the non-resonance amplitude a_c. This is seen that on top of the resonance, $s = M^2$,

$$\left|a_\gamma(M^2_{\psi''})/a_c(M^2_{\psi''})\right| = \frac{3}{\alpha}\mathcal{B}(\psi'' \to e^+e^-).$$

With the measured value of $\mathcal{B}(\psi'' \to e^+e^-) = (9.6 \pm 0.7) \times 10^{-6}$,

$$\left|a_\gamma(M^2_{\psi''})/a_c(M^2_{\psi''})\right| \approx 3.9 \times 10^{-3}.$$

So a_γ can be neglected.

Only the strong decay amplitude and the non-resonance continuum amplitudes and their inteference are important.

Constructive or destructive interference

Among the 1^-0^- final states, $\omega\pi^0$, $\rho\eta$, $\rho\eta'$ and $\pi^+\pi^-$ go only via electromagnetic interaction and the a_γ can be neglected for $\psi(3770)$. But for other final states which have contributions from both strong and electromagnetic interactions, there could be interference between a_{3g} and a_c (only a_{3g} and a_c are important). If the phase (between a_{3g} and a_γ) ϕ is $-90°$, then on top of $\psi(3770)$ resonance, the relative phase between a_{3g} and a_c is either $180°$ or $0°$, depending on whether the relative sign between a_{3g} and $a_\gamma + a_c$ is plus or minus. For example,

$$
\begin{aligned}
A_{\omega\pi^0} &= 3(a_\gamma + a_c) \quad , \\
A_{\rho\pi} &= a_{3g} + a_\gamma + a_c \quad , \\
A_{K^{*+}K^-} &= a_{3g} + \epsilon + a_\gamma + a_c \quad , \\
A_{K^{*0}\overline{K^0}} &= a_{3g} + \epsilon - 2(a_\gamma + a_c), \\
A_{\omega\eta} &= X_\eta(a_{3g} + a_\gamma + a_c) \quad , \\
A_{\phi\eta} &= Y_\eta[a_{3g} - 2(a_\gamma + a_c)].
\end{aligned}
$$

The interference between a_{3g} and a_c is destructive for the final states $\rho\pi$, $\omega\eta$, $\omega\eta'$, $K^{*+}K^- + c.c.$, $b_1\pi$, and K^+K^-, but constructive for $\phi\eta$, $\phi\eta'$, and $K^{*0}\overline{K^0} + c.c.$

Constructive or destructive interference

These interference pattern are consistant with CLEO measured cross sections at 3.67GeV and $\psi(3770)$ peak CLEO collaboration, G.S.adams et al, Phys.Rev.D73:012002,2006

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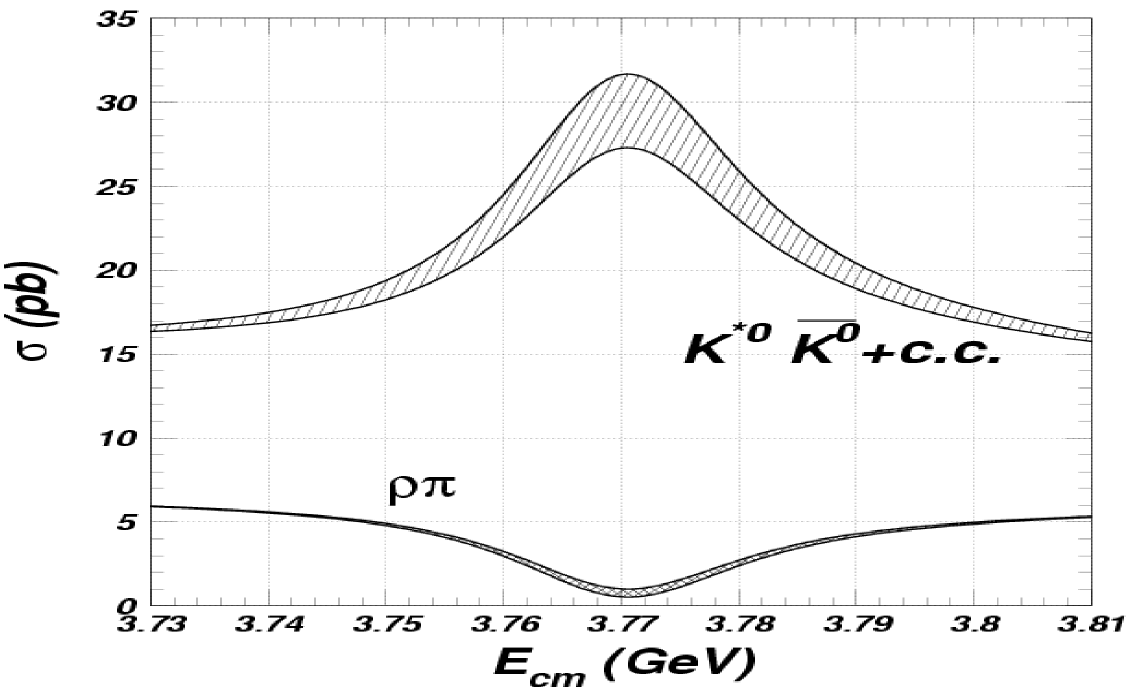
	AP	
$b_1\pi$	$7.9^{+3.1}_{-2.5} \pm 1.8$	$6.3 \pm 0.7 \pm 1.5$

Constructive or destructive interference

If we scan $\psi(3770)$, we expect the cross sections of $e^+e^- \to \rho\pi$ and $e^+e^- \to K^{*0}\overline{K^0} + c.c.$ versus energy like the curves



The $K^{*+}K^- + c.c.$ and $\omega\eta$ cross sections are similar to $\rho\pi$; while $\phi\eta$ cross section like $K^{*0}\overline{K^0}$.

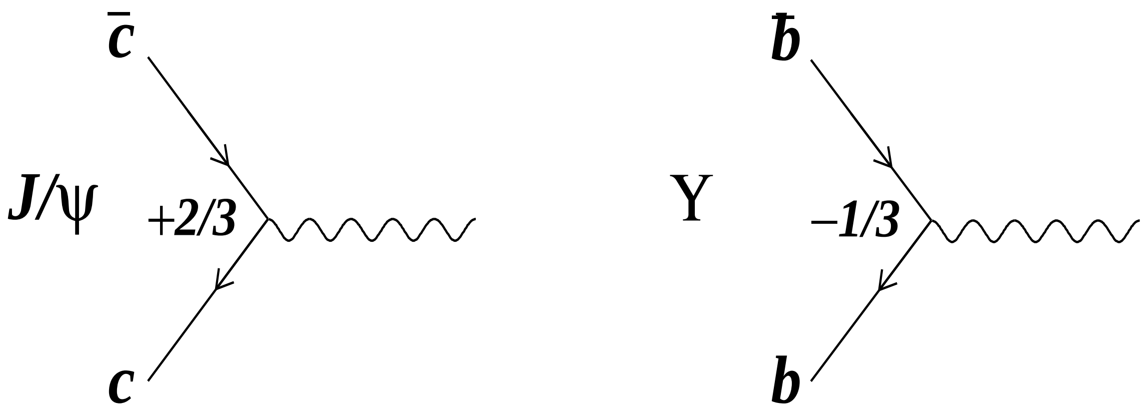
The scan data of $\psi(3770)$ by BES-III has already been analyzed by Wolfgang and Yutie Liang on $p\overline{p}$. They yield a phase of $-90°$ between strong and electromagnetic amplitudes.

Olga is working on $\rho\pi$ final state in $\psi(3770)$ scanned data.

Discussion Υ decays

To what extend this empirical law holds true? How about Υ?

For Υ, there is an extra minus sign in the EM diagram.



So we speculate that those modes which have destructive interference between strong and continuum amplitudes for charmonium (like $\rho\pi$, $K^{*+}K^{-}$ and $\omega\eta$) may have constructive interference for Υ, and vice versa. ($K^{*0}\overline{K^0}$ and $\phi\eta$ show destructive intererence)

This must be tested by experiments.

Shall we extend our work together to BELLE2?

Discussion Υ decays

Very recently, BELLE has neasured $e^+e^- \to \omega\pi$ and $e^+e^- \to K^{*0}\overline{K^0}$, $e^+e^- \to K^{*+}K^-$ around 10GeV, but has yet published.

Currently, BELLE is under upgrading to BELLE2. With BELLE2 luminosity of 50 times greater, it is feasible to scan $\Upsilon(nS)$ and perform such measurement.

I hope to work with the same people (from JINR) for the same measurment on Υ in BELLE2.

Discussions: universal phase

Commented by Mahiko Suzuki:

Despite lack of a good theoretical argument at present, we suspect nevertheless that the universal large phase so far found are not an accident. M.Suzuki, Phys. Rev. D 63:054021(2001)

Discussions: universal phase

In quantum field theory, whenever we have an imaginary part of the amplitude, it means the process goes through an intermediate physical state which is observable. This is from unitarity condition of quantum mechanics. (See Lifshitz's book Quantum Electrodynamics)

For example, in the vacuum polarization due to ψ,

$$\Pi_\psi(s) = \frac{3\Gamma_{ee} s M/\alpha}{s - M^2 + iM\Gamma_\psi} \qquad (13)$$

there is an imaginary part. It means that a real particle ψ is produced. This is similar to the propogator of Z boson. (See J.C.Taylor' book Gauge theories of weak Interactions, chapter 2)

Discussions: universal phase

In our formulae, among the decay amplitudes through strong and electromagnetic interactions, if one is real, and there other must be almost purely imaginary. (Usually we associate the electromagnetic amplitude to be real, and the strong decay amplitude to be imaginary, as in our formulae for fitting the experimental data. But if we only consider the decay process of ψ, which is not produced in e^+e^- collision, then it does not matter which one is real, and which one is imaginary.)

In our description of charmonium decay, what is the real physical state which the imaginary part describes?

Could it be $D\overline{D}$, for $\psi(3770)$, and many light hadronic states, like $\rho\pi$, $K^{*+}K^-$, $K^{*0}\overline{K^0}$ for J/ψ? It seems that this large phase does not depend on whether the ψ is above the charm threshold, or its width is wide (27.2MeV for $\psi(3770)$), or narrow (92.9KeV for J/ψ).

What kind of physics law can we guess from this empirical phenomena?

Discussions: universal phase

We have SU(2)×U(1) which correctly describes the eletroweak interactions. (Glashow, Weinberg, Salam) We also have SU(3) which is the theory of strong interaction.

In this picture, the strong and electroweak interactions are totally decoupled. For the processes through both strong and EM interactions, there is no apparent reason that the phase between the two amplitudes is universal, and universally large, either in the perturbative level, or due to final state interaction.

But now we know from experiments empirically that the phase between strong and EM interaction is close to -90° in the decays of vector charmonium states, or perhaps quarkonium states.

Is this the new physics or the physics beyond the standard model? Does this give us some indication to unify strong and electromagnetic interactions or to unify the strong and electroweak interactions?