Universal phase between strong and EM interactions

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Outline

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- Summary

Motivations

It is known that in J/ψ decays, the three gluon amplitude a_{3g} and one-photon amplitude a_γ are orthogonal for

- 1^+0^- $90°$ M. Suzuki, Phys. Rev. **D63**, 054021 (2001)
- 1^-0^- $(106 \pm 10)°$ 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^- $(138 \pm 37)°$ L. Köpke and N. Wermes, Phys. Rep. **174**, 67 (1989).
- 0^-0^- $(89.6 \pm 9.9)°$ M. Suzuki, Phys. Rev. **D60**, 051501(1999); G. López Castro *et al.*, ibid; L. Köpke and N. Wermes, ibid.
- $N\overline{N}$ $(89 \pm 15)°$ R. Baldini, *et al.* Phys. Lett.**B444**, 111 (1998); G. López Castro *et al.*, ibid.

Motivations

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.

Is this phase universal for quarkonium decays?

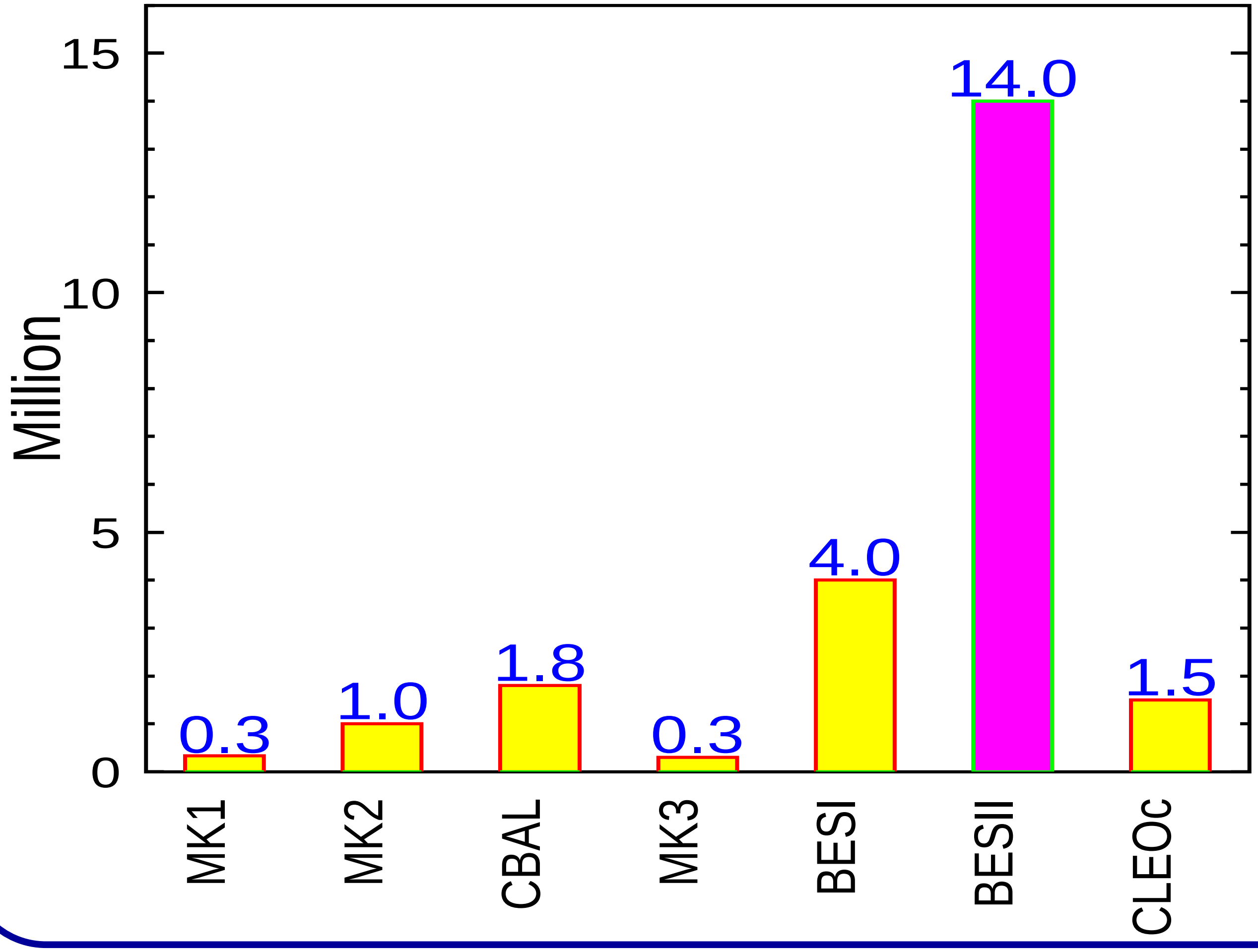
How about

- ψ'
- ψ''
- $\Upsilon(nS)$

Quarkonium in e^+e^- colliding experiments

Recently, more ψ' data has been available.

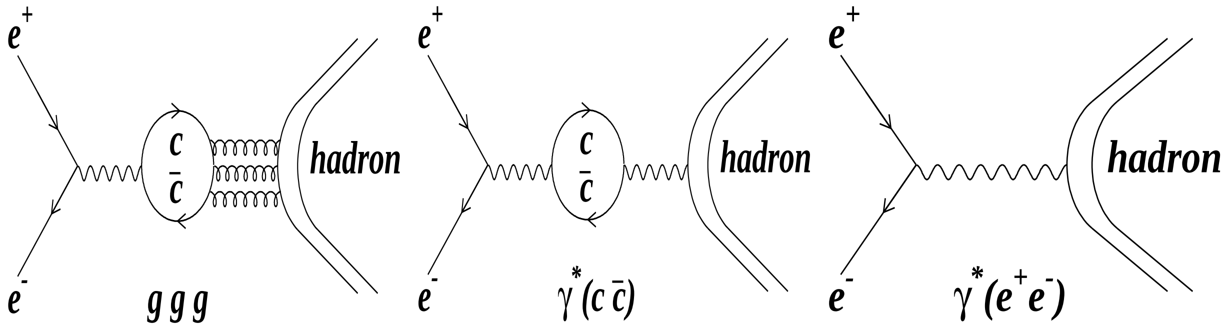
Most of the branching ratios are measured in e^+e^- colliding experiments (BES, CLEOc).



Quarkonium in e^+e^- colliding experiments

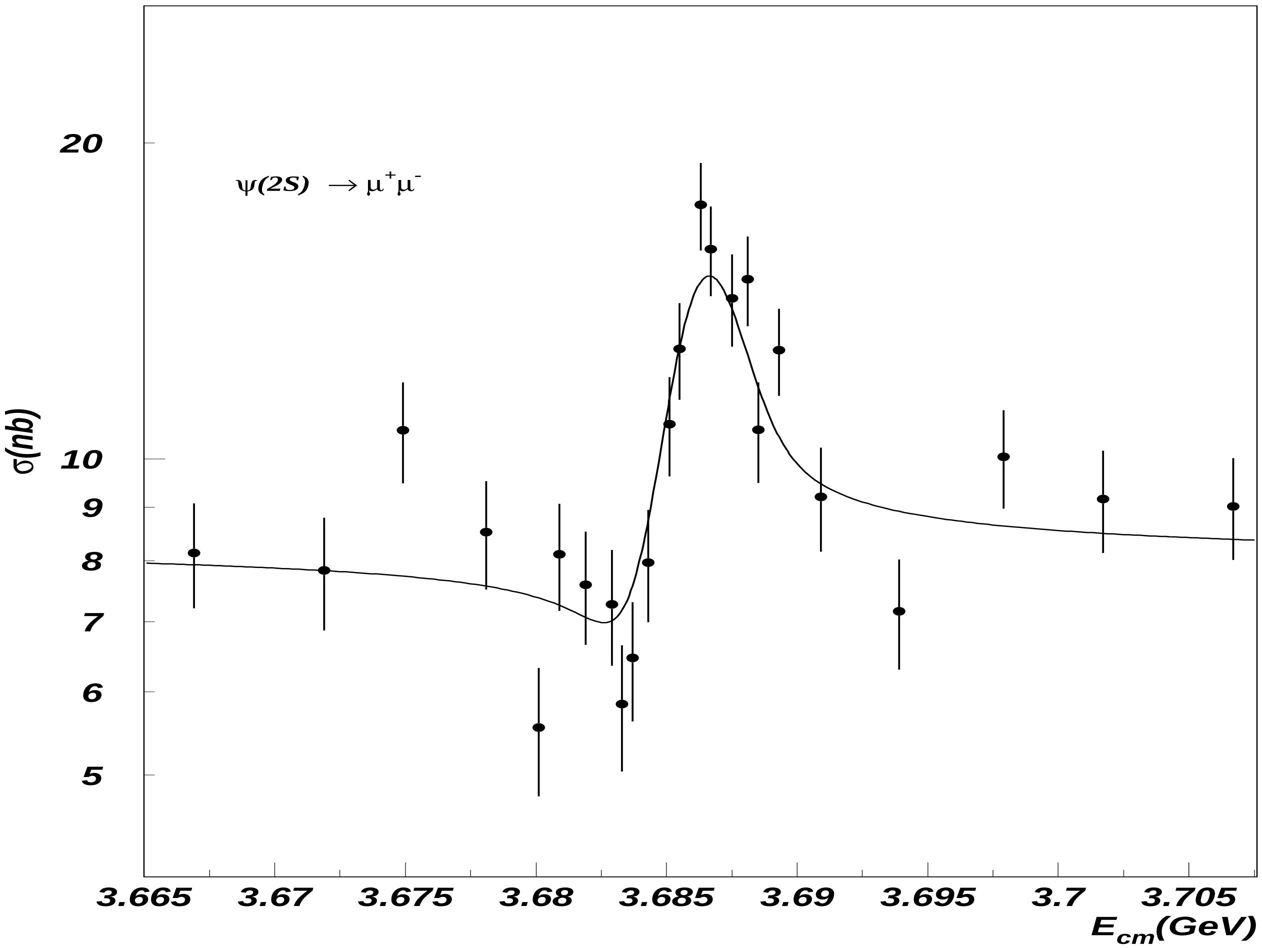
There are three diagrams which contribute.

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)



Contribution from $e^+e^- \to \gamma^*$

The importance of non-resonance $e^+e^- \to \gamma^*$ diagram can be seen from the scanned curve of $e^+e^- \to \mu^+\mu^-$ in the vicinity of ψ'.



Contribution from $e^+e^- \to \gamma^*$

How important is $e^+e^- \to \gamma^*$ amplitude?

For ψ' :

$\sigma_{Born} = 7887$nb;

$\sigma_c \approx 14$nb;

With radiative correction

$\sigma_{r.c.} = 4046$nb;

With energy spread of e^+e^- collider

Max(σ_{obs}) $= 621$nb at $M_{\psi'} + 0.135$MeV
with $\Delta = 1.3$MeV for BES/BEPC,

Max(σ_{obs}) $= 550$nb at $M_{\psi'} + 0.155$MeV
with $\Delta = 1.5$MeV for CLEOc;

Max(σ_{obs}) $= 380$nb at $M_{\psi'} + 0.236$MeV
with $\Delta = 2.3$MeV for CLEOc;

Contribution from $e^+e^- \to \gamma^*$

- The experimentally observed cross section depend on experimental details: s_m, Δ, *etc.*
  (P. Wang, C. Z. Yuan, X. H. Mo and D. H. Zhang, Phys. Lett. 2004, **B** 593: 89-94)

- The resonance cross section, depends on the beam energy spread of the e^+e^- colider.

- The continuum cross section depends on the invariant mass cut s_m of the final state particles:

$$\sigma_{r.c.}(s) = \int_0^{1-\frac{s_m}{s}} dx F(x,s) \frac{\sigma_0(s(1-x))}{|1-\Pi(s(1-x))|^2} \; .$$

ψ' decays

For $\psi' \to 1^-0^-$ decays H. E. Haber and J. Perrier, Phys. Rev. **D32**, 2961 (1985)

$$\begin{aligned} A_{\omega\pi^0} &= 3(a_\gamma + a_c) \quad , \\ A_{\rho\pi} &= a_{3g} + a_\gamma + a_c \quad , \\ A_{K^{*+}K^-} &= a_{3g} + \epsilon + a_\gamma + a_c \quad , \\ A_{K^{*0}\overline{K^0}} &= a_{3g} + \epsilon - 2(a_\gamma + a_c) \quad . \end{aligned} \tag{1}$$

which can then be expressed as

$$\begin{aligned} A_{\omega\pi^0} &= [B(s) + 1] \cdot \mathcal{F}_{\omega\pi^0}(s) \quad , \\ A_{\rho\pi} &= [(\mathcal{C}e^{i\phi} + 1)B(s) + 1] \cdot \mathcal{F}_{\omega\pi^0}(s)/3 \quad , \\ A_{K^{*+}K^-} &= [(\mathcal{C}\mathcal{R}e^{i\phi} + 1)B(s) + 1] \cdot \mathcal{F}_{\omega\pi^0}(s)/3 \quad , \\ A_{K^{*0}\overline{K^0}} &= [(\mathcal{C}\mathcal{R}e^{i\phi} - 2)B(s) - 2] \cdot \mathcal{F}_{\omega\pi^0}(s)/3 \quad . \end{aligned} \tag{2}$$

$\mathcal{R} = |(a_{3g} + \epsilon)/a_{3g}|$, $C = |a_{3g}/a_\gamma|$, and

$$B(s) \equiv \frac{3\sqrt{s}\Gamma_{ee}/\alpha}{s - M^2 + iM\Gamma_t}.$$

ψ' decays

$$
\begin{aligned}
A_{\omega\pi^0} &= [B(s)+1]\cdot\mathcal{F}_{\omega\pi^0}(s) \quad , \\
A_{\rho\pi} &= [(\mathcal{C}e^{i\phi}+1)B(s)+1]\cdot\mathcal{F}_{\omega\pi^0}(s)/3 \quad , \\
A_{K^{*+}K^-} &= [(\mathcal{C}\mathcal{R}e^{i\phi}+1)B(s)+1]\cdot\mathcal{F}_{\omega\pi^0}(s)/3 \quad , \\
A_{K^{*0}\overline{K^0}} &= [(\mathcal{C}\mathcal{R}e^{i\phi}-2)B(s)-2]\cdot\mathcal{F}_{\omega\pi^0}(s)/3 \quad .
\end{aligned}
\tag{3}
$$

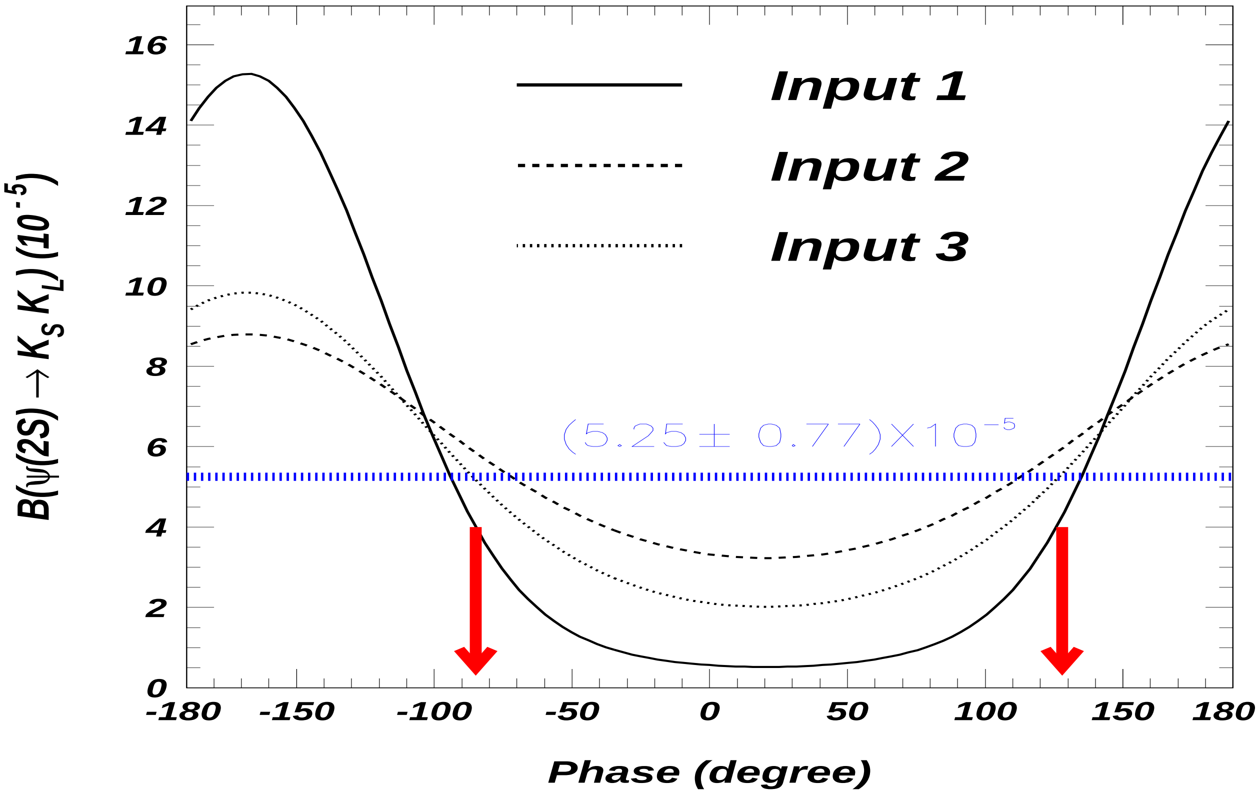
On top of the resonance, $B(s) = -i3B_{ee}/\alpha$ with phase of -90°. If ϕ which is the phase between a_{3g} and a_γ is -90°, then the relative phase between a_{3g} and a_c is 180° for $\rho\pi$ and $K^{*+}K^-$, but 0° for $K^{*0}\overline{K^0}$.

The interference pattern due to this phase explains the small signal of $\rho\pi$ and $K^{*+}K^-$ but large signal of $K^{*0}\overline{K^0}$ observed by BES and CLEOc at ψ' BES and CLEOc report at ICHEP04.

We suggest that in $\psi' \to VP$ decays, the strong and EM amplitudes are still orthogonal and the sign of the phase must be negative. (P. Wang, C. Z. Yuan, X. H. Mo, Phys. Rev. 2004, **D** 69: 057502)

ψ' *decays*

The newly measured $\psi' \to K^0_S K^0_L$ from BES-II together with previous results on $\pi^+\pi^-$ and K^+K^-, gives the phase between strong and EM amplitudes is either $(-82 \pm 29)^\circ$ or $(121 \pm 27)^\circ$.



Rosner's scenario on $\rho\pi$ puzzle

When we come to the phase in ψ'' decays, we get an extra prize which leads to the solution of the long-lasting $\rho\pi$ puzzle in charmonium decays. First we need to digress to Rosner's scenario on $\rho\pi$ puzzle.

While $\rho\pi$ has the largest branching ratio among the hadronic final states in J/ψ decays, the same mode was not found in ψ' decays for a long time. (Recently, BES and CLEOc report its branching ratio at the order of 10^{-5}).

Rosner's scenario on $\rho\pi$ puzzle

Rosner proposed that this is due to the mixing between $\psi(2^3S_1)$ and $\psi(1^3D_1)$ states: E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane and T. M. Yan, Phys. Rev. D **17**, 3090 (1978); D **21**, 313(E) (1980); D **21**, 203(E) (1980); Y.-P. Kuang and T. M. Yan, Phys. Rev. D **41**, 155 (1990)

$$|\psi'\rangle = |2^3S_1\rangle \cos\theta - |1^3D_1\rangle \sin\theta \ ,$$
$$|\psi''\rangle = |2^3S_1\rangle \sin\theta + |1^3D_1\rangle \cos\theta \ ,$$

where $\theta = 12^\circ$ is the mixing angle.

Rosner's scenario on $\rho\pi$ puzzle

The missing of $\rho\pi$ in ψ' decay is due to the cancellation of the two terms in $\langle\rho\pi|\psi'\rangle$. J. L. Rosner, Phys. Rev. **D64** (2001) 094002.

$$\langle\rho\pi|\psi'\rangle = \langle\rho\pi|2^3S_1\rangle\cos\theta - \langle\rho\pi|1^3D_1\rangle\sin\theta \ ,$$
$$\langle\rho\pi|\psi''\rangle = \langle\rho\pi|2^3S_1\rangle\sin\theta + \langle\rho\pi|1^3D_1\rangle\cos\theta \ ,$$

i.e.

$$\langle\rho\pi|2^3S_1\rangle\cos\theta = \langle\rho\pi|1^3D_1\rangle\sin\theta. \qquad (4)$$

This scenario is simple, and it predicts with little uncertainty that $\mathcal{B}_{\psi''\to\rho\pi} = (6.8 \pm 2.3) \times 10^{-4}$, or

$$\sigma^{Born}_{e^+e^-\to\psi''\to\rho\pi} = (7.9 \pm 2.7)\text{pb} \qquad (5)$$

with BES latest result on $\mathcal{B}(J/\psi \to \rho\pi)$.

Rosner's scenario on $\rho\pi$ puzzle

On the other hand, using CLEOc measurement of $e^+e^- \to \rho\pi$ at 3.67GeV, (N.E.Adam, hep-ex/0407028) scaled to 3.77GeV according to $1/s^2$, we obtain

$$\sigma^{Born}_{e^+e^- \to \gamma^* \to \rho\pi}(@3.770GeV) = (7.5 \pm 1.8)\text{pb}.$$

compared with

$$\sigma^{Born}_{e^+e^- \to \psi'' \to \rho\pi}(@3.770GeV) = (7.9 \pm 2.7)\text{pb}$$

The question arises: how do they interfere?

Rosner's scenario on $\rho\pi$ puzzle

As a matter of fact, MARK-III measured this cross section at ψ'' peak, and gave

$$\sigma_{e^+e^-\to\rho\pi}(@3.770GeV) < 6.3\text{pb}, \tag{6}$$

which is already smaller than the continuum cross section:

$$\sigma_{e^+e^-\to\gamma^*\to\rho\pi}(@3.770GeV) = (7.5 \pm 1.8)\text{pb}.$$

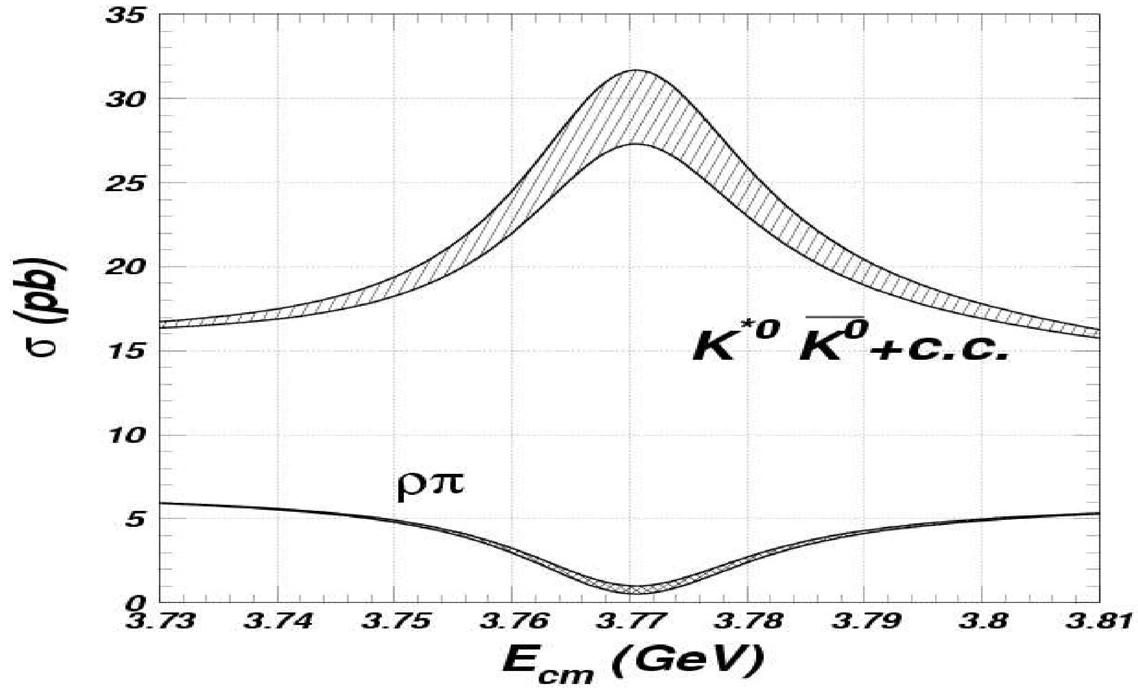
We expect BES and CLEOc to bring this value further down.

This means (P. Wang, C. Z. Yuan and X. H. Mo, Phys. Lett. 2003, **B574**: 41)

- There must be destructive interference between resonance and continum, i.e. the phase between the strong and EM amplitudes is again -90°.
- $\mathcal{B}(\psi'' \to \rho\pi) \approx (6 \sim 7) \times 10^{-4}$, i.e. Rosner's scenario gives correct prediction!

Rosner's scenario on $\rho\pi$ puzzle

If we scan ψ'', we shall find 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



In the figure, the shaded area is due to an unknown phase between the 2^3S_1 and 1^3D_1 matrix elements.

The $K^{*+}K^- + c.c.$ cross section is similar to $\rho\pi$.

Rosner's scenario on $\rho\pi$ puzzle

Recently BES find modes which are enhanced in ψ' decays relative to J/ψ. One of them is $K^0_S K^0_L$:

$$\mathcal{B}(J/\psi \to K^0_S K^0_L) = (1.82 \pm 0.04 \pm 0.13) \times 10^{-4}$$
$$\mathcal{B}(\psi' \to K^0_S K^0_L) = (5.24 \pm 0.47 \pm 0.48) \times 10^{-5}$$

with $Q_h = (28.2 \pm 3.7)\%$ versus
$Q_{ee} = \frac{\mathcal{B}(\psi' \to e^+e^-)}{\mathcal{B}(J/\psi \to e^+e^-)} = (12.7 \pm 0.6)\%$

If such enhancement is due to the mixing of 2^3S_1 and 1^3D_1 states, then we expect (P. Wang, C. Z. Yuan and X. H. Mo, Phys. Rev. 2004, **D**70: 077505)

$$(1.2 \pm 0.7) \times 10^{-6} \le \mathcal{B}(\psi'' \to K^0_S K^0_L) \le (3.8 \pm 1.1) \times 10^{-5}$$

Here the range is due to an unknown phase between $\langle K^0_S K^0_L | 2^3S_1 \rangle$ and $\langle K^0_S K^0_L | 1^3D_1 \rangle$. If this phase is 0, then the prediction is at the upper bound.

Currently BES gives $\mathcal{B}(\psi'' \to K^0_S K^0_L) < 2.1 \times 10^{-4}$.

ψ'' decays to charmless final states

It has been noticed that there is hadronic excess in ψ' decays which has no parallel in Υ physics: M. Suzuki, Phys. Rev. **D63**, 054021 (2001).

$$Q_1 = \frac{\mathcal{B}(\psi' \to ggg + \gamma gg)}{\mathcal{B}(J/\psi \to ggg + \gamma gg)} = (26.0 \pm 3.5)\%$$

versus

$$Q_{ee} = \frac{\mathcal{B}(\psi' \to e^+e^-)}{\mathcal{B}(J/\psi \to e^+e^-)} = (12.7 \pm 0.6)\%$$

It indicates that most of the ψ' partial widths via gluon go to the final states which are enhanced in ψ' decays.

ψ'' *decays to charmless final states*

Now we do not know what these final states are but they account to 98% of the ψ' gluon decay width.

The question arises: what are their branching ratios in ψ'' decays?

There has been experimental indication that ψ'' has a substantial charmless branching ratio, although it comes with large uncertainties. This was addressed again recently.
J. L. Rosner, hep-ph/0405196.

So let us estimate what the possible combined branching ratio of these final states in ψ'' decays.

ψ'' decays to charmless final states

We define the suppression and enhancement factor

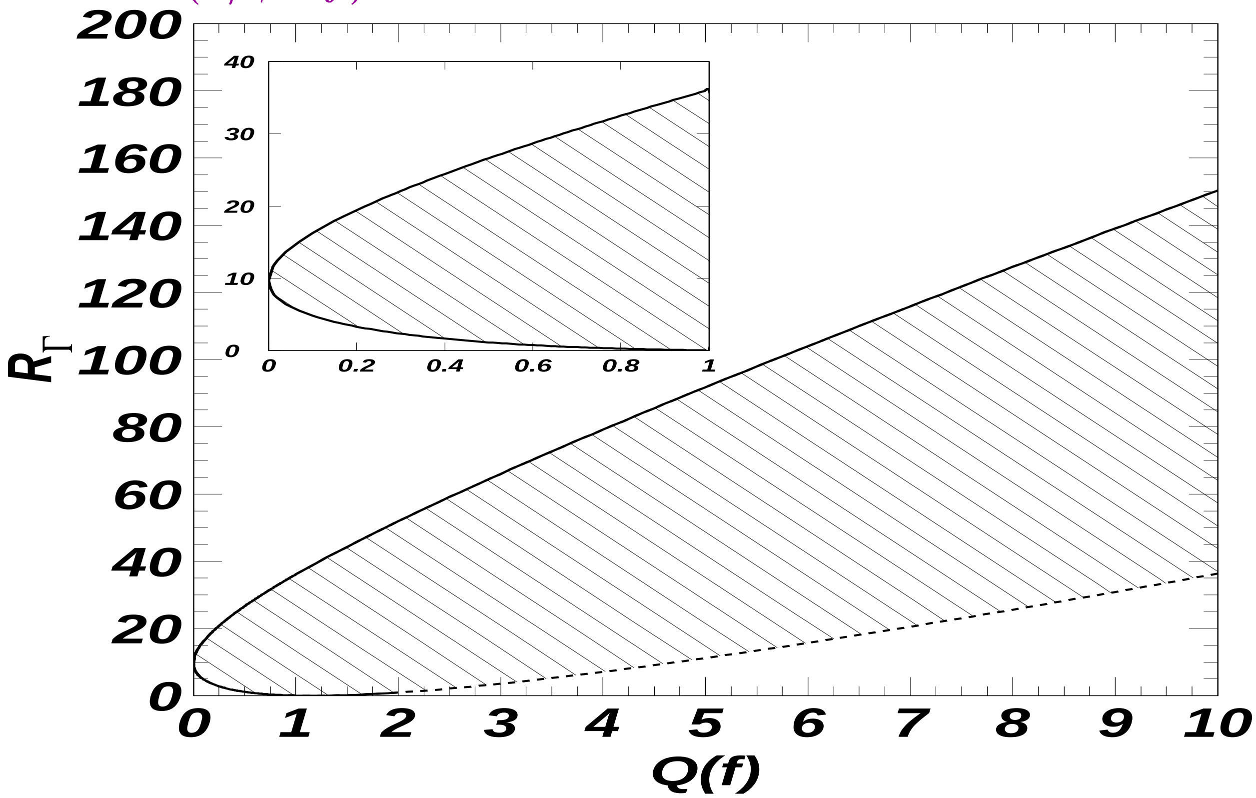
$$Q(f) \equiv \frac{\Gamma(\psi' \to f)}{\Gamma(J/\psi \to f)} \frac{\Gamma(J/\psi \to e^+e^-)}{\Gamma(\psi' \to e^+e^-)} \,. \qquad (7)$$

- $Q(f) < 1$ means the final state f is suppressed in ψ' decays relative to J/ψ;
- $Q(f) > 1$ means it is enhanced;
- $Q(f) = 1$ means it observes the 12% rule.

In the 2S-1D mixing scheme, for any final state, its partial width in ψ'' decay can be related to its partial widths in J/ψ and ψ' decay with an unknown parameter which is the relative phase between the matrix elements $\langle f|2^3S_1\rangle$ and $\langle f|1^3D_1\rangle$. This unknown phase constrains the predicted $\Gamma(\psi'' \to f)$ in a finite range.

ψ'' decays to charmless final states

$R_\Gamma \equiv \frac{\Gamma(\psi''\to f)}{\Gamma(J/\psi\to f)}$ as a function of $Q(f)$



The final states with large $Q(f)$, or the ones which are enhanced in ψ' decays relative to J/ψ, may have a (combined) large partial width in ψ'' decays.

ψ'' *decays to charmless final states*

The decays of J/ψ and ψ' are classified into gluonic decays (ggg), electromagnetic decays (γ^*), radiatve decays into light hadrons (γgg), and OZI allowed decays into lower mass charmonium states. But subtracting the second to forth classes, we obtain

$$\mathcal{B}(J/\psi \to ggg) \approx (69.2 \pm 0.6)\%$$
$$\mathcal{B}(\psi' \to ggg) \approx (18.0 \pm 2.4)\%$$

Among these final states, we know that VP and VT final states have $Q(f) < 1$, and $N\bar{N}$ have $Q(f) \approx 1$. Together they consist 5.41% of J/ψ decays and 1.78×10^{-3} of ψ' decays. We subtract their branching ratios from the total branching ratio of gluonic decays of J/ψ and ψ'.

ψ'' *decays to charmless final states*

The remaining 63.8% of J/ψ decay and 17.8% of ψ' decay which go to final states through ggg either have $Q(f) > 1$ or $Q(f)$ unknown

On the average, these final states have

$$Q(rem) \approx 2.19 \quad .$$

For this Q value, the maximum R_Γ is 51.6.

The maximum partial width of these final states in ψ'' is $\Gamma_{tot}(J/\psi) \times 63.8\% \times 51.6$ which is 3.0MeV, or 13% of the ψ'' branching ratio. (P. Wang, C. Z. Yuan and X. H. Mo, Phys. Rev. 2004 **D**70: 114014)

So the ψ'' decays to charmless final states can be as large as 13%.

ψ'' decays to charmless final states

The above maximum value of R_Γ comes if there is no extra phase between $\langle f|2^3S_1\rangle$ and $\langle f|1^3D_1\rangle$. There are reasons to assume that this is the case:

- In the matrix element of $\langle\rho\pi|\psi'\rangle$, there is almost complete cancellation $\langle\rho\pi|\psi'\rangle = \langle\rho\pi|2^3S_1\rangle\cos\theta - \langle\rho\pi|1^3D_1\rangle\sin\theta$ so the phase between them must close to 0;
- If the phase between the strong and EM ampitudes is universal, then there is no extra phase between 2^3S_1 and 1^3D_1 matrix elements due to strong interactions, since there is no extra phase between the two matrix elements due to EM interactions, as in the calculations of leptonic decays.

So we suppose that the partial widths of these final states are at the maximum values calculated here.

ψ'' decays to charmless final states

The calculations here take the averaged $Q(f)$ so serve as a rough estimation. The exact charmless partial width should be the sum of individual final states which in general have different values of $Q(f)$. But at present, experiments do not provide enough informationm to conduct such calculation.

Nevertheless, the estimation here shows that a large charmless branching ratio, e.g. more than 10% is not a surprise. It is well explained in the 2S-1D mixing scenario. Measuring the charmless branching ratio of ψ'' decays, both inclusive and exclusive, should be a primary physics goal for BES and CLEOc.

Summary

- The $\psi' \to 1^-0^-$ and 0^-0^- data collected in e^+e^- experiments are consistent with a -90° phase between strong and electromagnetic interactions.
- This phase also holds in OZI suppressed decays of ψ''. This is from the measured $\rho\pi$ cross sections at ψ'' and 3.67GeV.
- Combined with the information from J/ψ decays, we propose that this phase is universally at -90° in charmonium (quarkonium) decays.
- At the same time, the measured $\rho\pi$ cross sections at ψ'' and 3.67GeV give $\mathcal{B}(\psi'' \to \rho\pi)$ which agrees with the prediction by Rosner in his scenario of $\rho\pi$ puzzle.
- This scenario would be further supported if the large charmless branching ratio in ψ'' decays is confirmed by experiments.