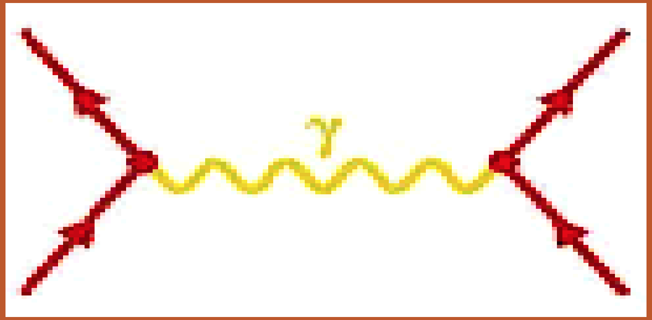
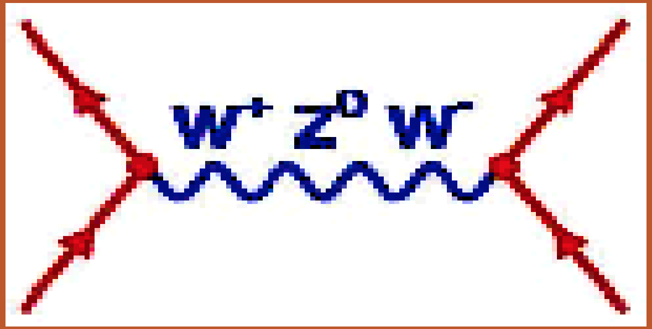




Measurement of the relative phase between strong and EM decays of charmonium

Yadi Wang

North China Electric Power University （NCEPU）

(On behalf of BESIII Collaboration)

The 10th International Conference on Quarks and Nuclear Physics

08/07/2024 - 12/07/2024

Outline

Theory for the phase between strong and EM

SU(3) dependent experimental evidences

Scan method (SU(3) independent) and measurement

Summary

Outline

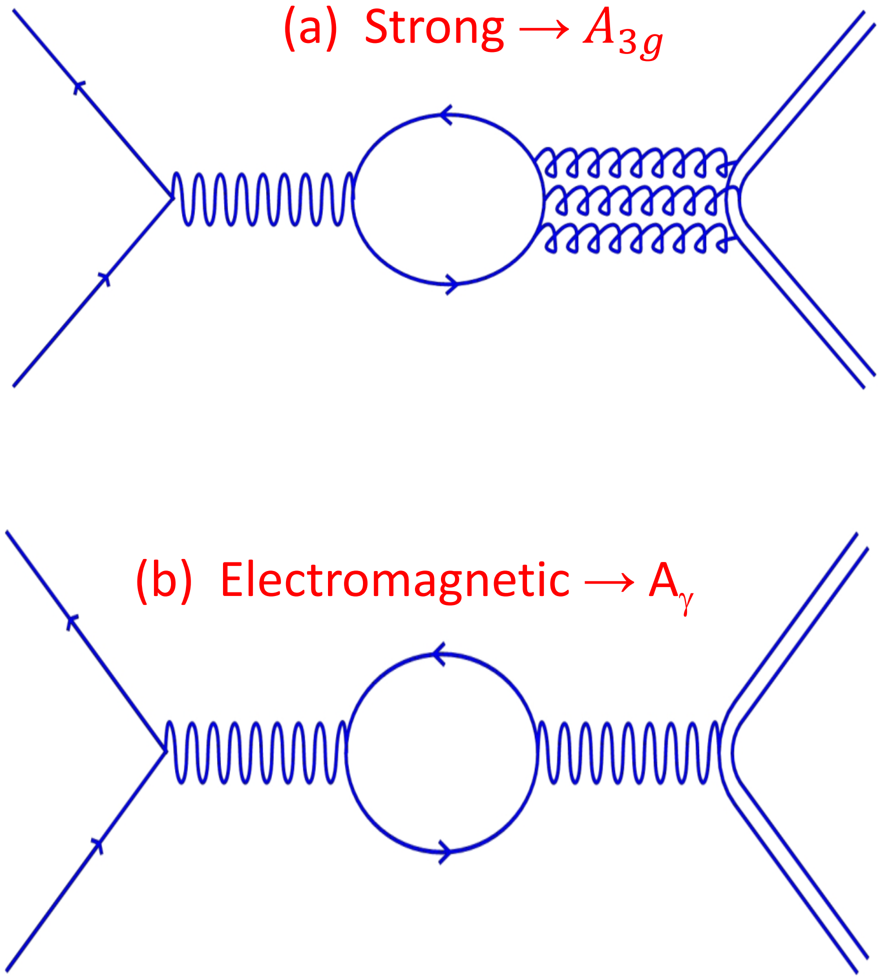
Theory for the phase between strong and EM

SU(3) dependent experimental evidences

Scan method (SU(3) independent) and measurement

Summary

Theory for the phase between strong and EM



(a) $e^+e^- \rightarrow R(q\bar{q}) \rightarrow$ hadrons via strong mechanism;

(b) $e^+e^- \rightarrow R(q\bar{q}) \rightarrow$ hadrons via EM mechanism;

pQCD regime: all are Real, phase between A_{3g} and A_{γ} should be $0°$ or $180°$

V.L. Chernyak and I.R. Zhinitsky, Nuclear Physics B 246, 52 (1998)

Theory for the phase between strong and EM

$$A_g^H = \sum_h \langle h|3g\rangle\langle 3g|\psi\rangle$$

$$A_\gamma^H = \sum_h \langle h|\gamma\rangle\langle\gamma|h\rangle$$

Clearly,

$A_g^{*H} A_\gamma^H = \langle\psi|3g\rangle\langle 3g|(\sum_h |h\rangle\langle h|)|\gamma\rangle$=0

is equivalent to

$$\langle 3g|\gamma\rangle = 0$$

Since $\sum_h |h\rangle\langle h| = 1$

Universality independent of final states or intermediate resonances.

For exclusive channels common to J/ψ and $\psi(2S)$, there cannot be significant differences in relative abundances if the three gluon intermediate state makes any physical sense.

J.-M. Gerard, J. Weyers, Phys. Lett. B 462, 324 (1999) ;
P. Wang, C.Z. Yuan, X.H. Mo, Phys. Rev. D 69, 057502 (2004);
M. Suzuki, Phys. Rev. D 58, 111504 (1998); etc.

Outline

Theory for the phase between strong and EM

SU(3) dependent experimental evidences

Scan method (SU(3) independent) and measurement

Summary

Model dependent experimental evidences

from J/ψ decays

SU3 and SU3 Breaking in **1^-0^-**[1,2,3,4], **0^-0^-**[1,2,3], **1^-1^-**[1], **1^+0^-**[5], $\boldsymbol{B\bar{B}}$[2,6,7]decays show the phase in J/ψ decays between A_g and A_γ is $\Phi\sim\mathbf{90}^\circ$

- $PP(0^-0^-)(\pi^+\pi^-, K^+K^-, K_SK_L)$: $\Phi=(90\pm10)^\circ$ *[2]*
- $VP(1^-0^-)(\rho\pi, \omega\pi^0, \phi\pi^0, \rho\eta, \omega\eta, \phi\eta, \rho\eta', \omega\eta', \phi\eta', \bar{K}^*K)$
- $VP(1^+0^-)\left(K_1^\pm(1400)K^\mp, K_1^\pm(1270)K^\mp\right)$
- $VV\ (1^-1^-)(\rho^+\rho^-, K^{*+}K^{*-}, K^{*0}\bar{K}^{*0})$
- $B\bar{B}(p\bar{p}, n\bar{n}, \Lambda\bar{\Lambda}, \Sigma^0\bar{\Sigma}^0, \Sigma^+\Sigma^-, \Xi^0\bar{\Xi}^0, \Xi^+\Xi^-, \Sigma^0\bar{\Lambda}+\bar{\Sigma}^0\Lambda)$

Some are based on very old experimental results, but the conclusion keeps the same

Process $J/\psi\to PV$	SOZI amplitude		DOZI correction
$\rho^+\pi^-, \rho^0\pi^0, \rho^-\pi^+$	$g+e$		
$K^{*+}K^-, K^{*-}K^+$	$g(1-s_g)+e$		
$K^{*0}\bar{K}^0, \bar{K}^{*0}K^0$	$g(1-s_g)-2e$		
$\omega\eta$	$(g+e)X_\eta$	+	$\sqrt{2}rg(\sqrt{2}X_\eta+Y_\eta)$
$\omega\eta'$	$(g+e)X_{\eta'}$	+	$\sqrt{2}rg(\sqrt{2}X_{\eta'}+Y_{\eta'})$
$\phi\eta$	$[g(1-2s_g)-2e]Y_\eta$	+	$rg(\sqrt{2}X_\eta+Y_\eta)$
$\phi\eta'$	$[g(1-2s_g)-2e]Y_{\eta'}$	+	$rg(\sqrt{2}X_{\eta'}+Y_{\eta'})$
$\rho\eta$	$3eX_\eta$		
$\rho\eta'$	$3eX_{\eta'}$		
$\omega\pi^0$	$3e$		
$\phi\pi^0$	0		

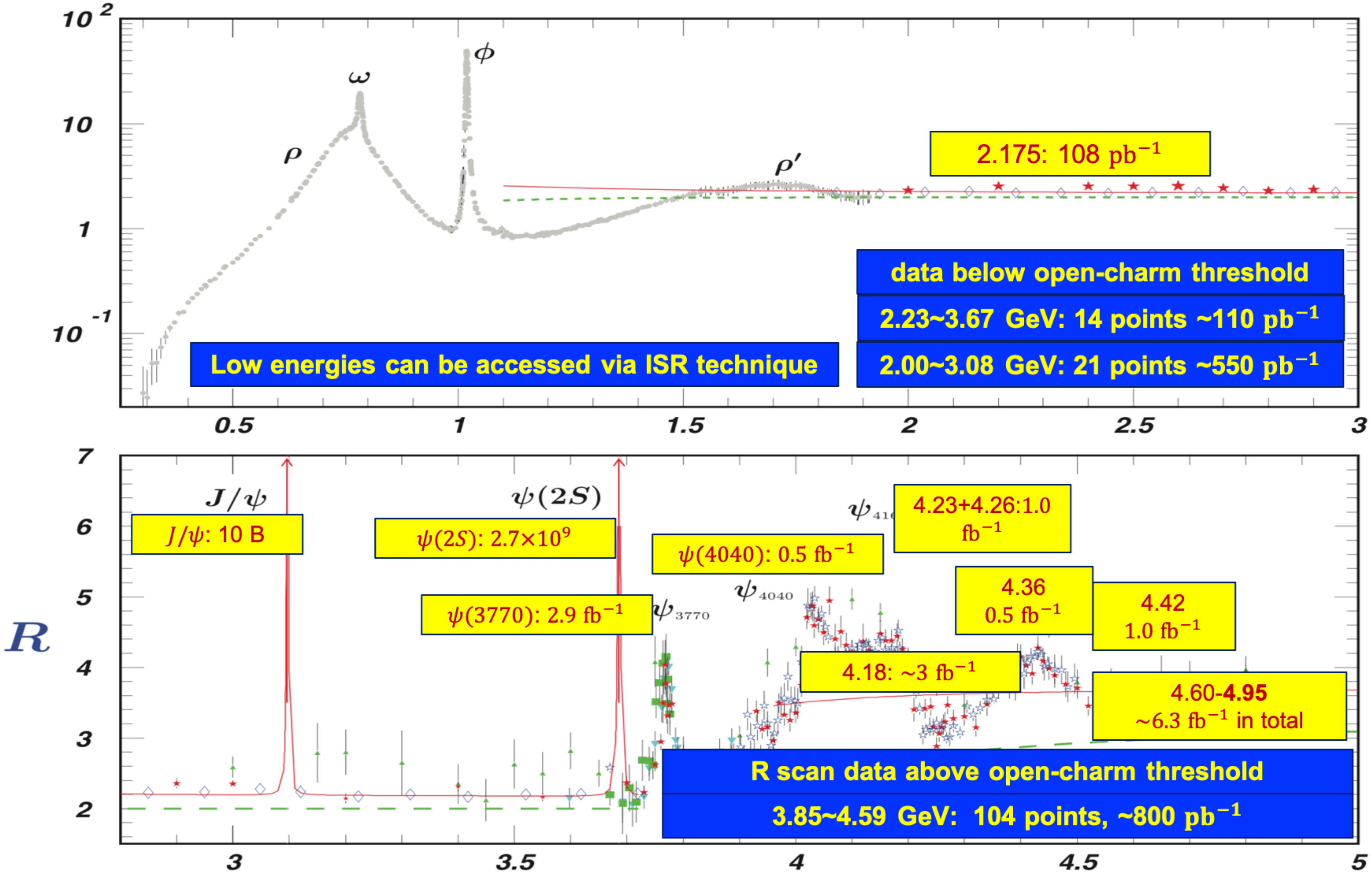
An example

$g-A_{3g}; e-A_\gamma$

X_η, Y_η, s_g – SU(3)breaking items

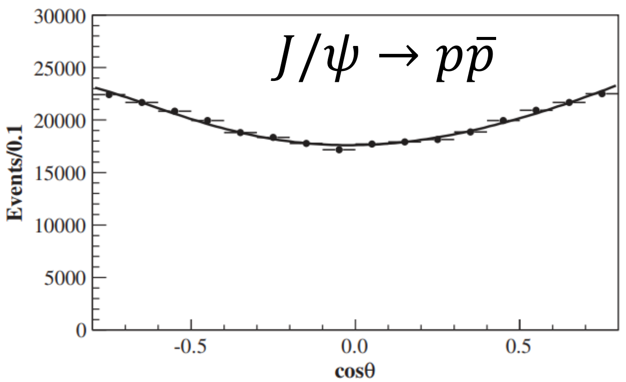
[1] L. Köpke and N. Wermes, Phys. Rep. 174, 67 (1989)
[2] G. Lopez Castro, J. L. Lucio M. and J. Pestieau, hep-ph/9902300v1 (1999)
[3] Mahiko Suzuki, Physical Review D 57, 5717 (1998)
[4] P. Wang, C.Z. Yuan, X.H. Mo, Phys. Rev. D 69, 057502 (2004)
[5] Mahiko Suzuki, Physical Review D 63, 054021 (2001)
[6] R. Baldini et al, Physics Letters B 444, 111-118 (1998)
[7] K. Zhu et al., Int. J Mod. Phys. A30, 1550148 (2015).

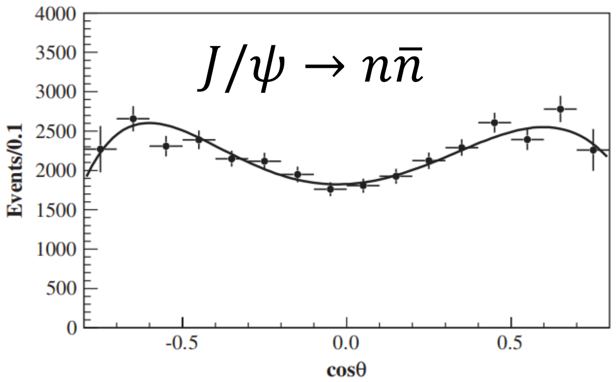
BESIII datasets



Model dependent experimental evidences

from J/ψ decays





Study of $J/\psi \to p\bar{p}$ and $J/\psi \to n\bar{n}$

(BESIII Collaboration) Phys. Rev. D 86, 032014 (2012)

$$\phi = \cos^{-1}[(\mathcal{B}(J/\psi \to p\bar{p}) - S^2 - E_p^2)/(2SE_p)] = (88.7 \pm 8.1)^\circ.$$

$Br(J/\psi \to p\bar{p}) = (2.112 \pm 0.004 \pm 0.031) \times 10^{-3}$

$\alpha = 0.595 \pm 0.012 \pm 0.015$

$Br(J/\psi \to n\bar{n}) = (2.07 \pm 0.01 \pm 0.17) \times 10^{-3}$

$\alpha = 0.50 \pm 0.04 \pm 0.21$

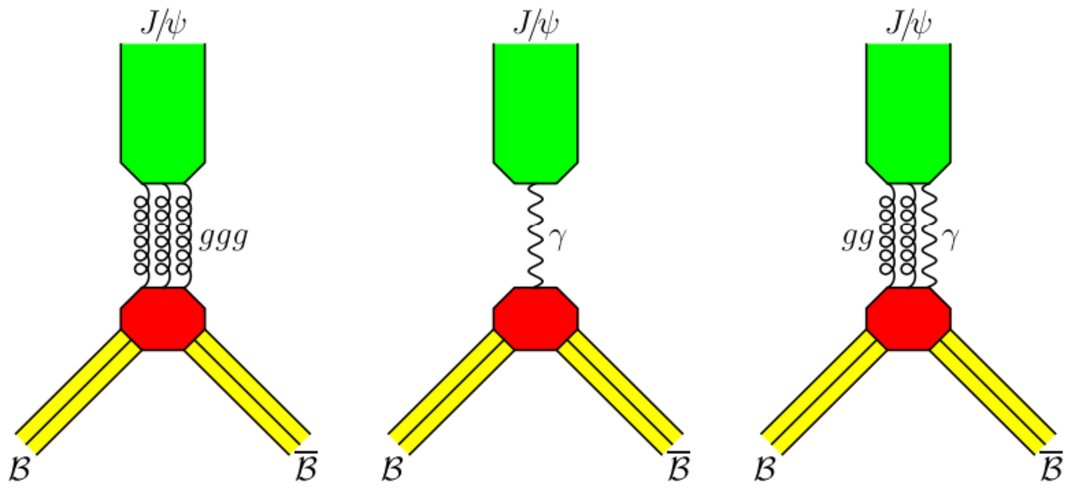
- $E_p(E_n)$ and S are EM and strong amplitudes of $J/\psi \to p\bar{p}$ $(n\bar{n})$, ϕ is the phase angle between $E_p(E_n)$ and S.
- Assumption:
  - $E_n = -E_p$ and $S_p = S_n = S$

- The strong interaction is dominant.
- $\mathbf{\Phi = (-85.9 \pm 1.7)^\circ}$ **or** $\mathbf{(+90.8 \pm 1.6)^\circ}$ combined with other baryon decays from BES, MarkII, DMII, BESII, BESIII experiments. *K. Zhu, X. H. Mo, C. Z. Yuan, Inter. J. Mod. Phys. A, 30, 1550148 (2015)*

Model dependent experimental evidences

from J/ψ decays

R. Baldini, A. Mangoni, S. Pacetti, K. Zhu;
Phy. Lett. B 799, 135041 (2019)



$\mathcal{B}\overline{\mathcal{B}}$	$\mathrm{BR}^{\mathrm{exp}}_{\mathcal{B}\overline{\mathcal{B}}} \times 10^3$	$\mathrm{BR}_{\mathcal{B}\overline{\mathcal{B}}} \times 10^3$
$\Sigma^0\overline{\Sigma}^0$	1.164 ± 0.004	1.160 ± 0.041
$\Lambda\overline{\Lambda}$	1.943 ± 0.003	1.940 ± 0.055
$\Lambda\overline{\Sigma}^0 +$ c.c.	0.0283 ± 0.0023	0.0280 ± 0.0024
$p\overline{p}$	2.121 ± 0.029	2.10 ± 0.16
$n\overline{n}$	2.09 ± 0.16	2.10 ± 0.12
$\Sigma^+\overline{\Sigma}^-$	1.50 ± 0.24	1.110 ± 0.086
$\Sigma^-\overline{\Sigma}^+$	/	0.857 ± 0.051
$\Xi^0\overline{\Xi}^0$	1.17 ± 0.04	1.180 ± 0.072
$\Xi^-\overline{\Xi}^+$	0.97 ± 0.08	0.979 ± 0.065

- Consider the small contribution from $A_{gg\gamma}$
- Assume $A_{gg\gamma}$ has the same phase as A_g to A_γ
- Perform SU(3) analysis based on experimental branching ratios of J/ψ decaying to baryons

$$\Phi = (73 \pm 8)^\circ$$

Br result from SU(3) very close to PDG

Model dependent experimental evidences

from $\psi(2S)$ decays

From the analysis of BESIII data made by R. Baldini[1]:

- $\psi(2S) \rightarrow VP\ (1^-0^-): \Phi = (159 \pm 12)^\circ$
- $\psi(2S) \rightarrow K^*K$ only: $\Phi = (159 \pm 24)^\circ$
- $\psi(2S) \rightarrow PP\ (0^-0^-)$: $\Phi = (95 \pm 11)^\circ$

Analysis by Mahiko Suzuki[2] with Babar data:

- $\psi(2S) \rightarrow 1^-0^-$: tends to have large phase,
- $\psi(2S) \rightarrow 1^+0^-$: $\Phi \sim 0^\circ$
- Difference could be caused by lower statistics of Babar data than that of BESIII.

PP(0^-0^-) mode from BES result[3]:

- $\psi(2S) \rightarrow K_S K_L, K^+K^-, \pi^+\pi^-$:

$\Phi = (-82 \pm 29)^\circ$ or $(121 \pm 27)^\circ$

Analysis[4] of $\psi(2S)$ decaying to baryon pairs from CLEO and BESII:

- **baryon pairs:**

$\Phi = (-98 \pm 25)^\circ$ or $(+134 \pm 25)^\circ$

[1] Rinaldo Baldini Ferroli, Orsay (France), 2014
[2] Mahiko Suzuki, Phys. Rev. D 63, 054021 (2000)
[3] BES Collaboration, Phys. Rev. Lett. 92, 052001 (2004)
[4] K. Zhu, X. H. Mo, C. Z. Yuan, Inter. J. Mod. Phys. A, 30, 1550148 (2015)

Model dependent experimental evidences

from $\psi(3770)$ decays

- From R. Baldini (Orsay (France), (2014)), $|\Phi| \sim 90°$

decay	continuum	Ψ''(3770)	sign	
ρ π	13.1±2.8	7.4±1.3	-	CLEOc, PRD 73(2006)012002
φ η	2.1±1.6	4.5±0.7	+	CLEOc, PRD 73(2006)012002
p p̄	0.74±0.08	0.4±0.02	-	BESIII Y.Liang, Nov (2012)

- From P. Wang (arxiv:hep/0410028v2 (2004)),
  - Φ holds $-90°$ in OZI suppressed decays of $\psi(3770)$.
  - From the $\rho\pi$ cross section measurement at $\psi(3770)$ and 3.67 GeV, $\rho\pi$ production is suppressed possibly by interference.

Outline

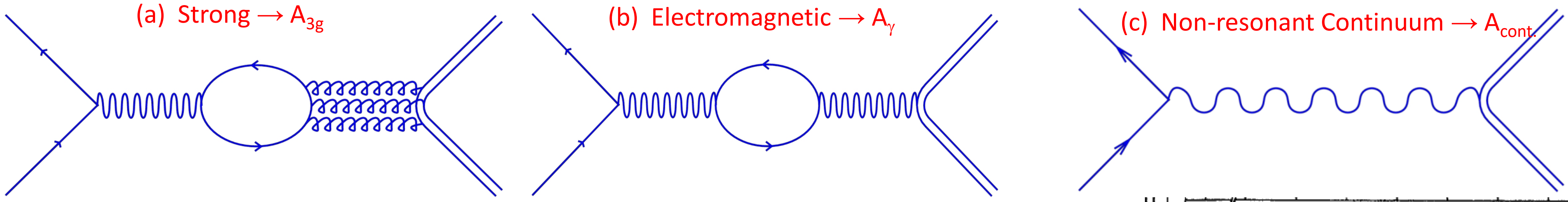
Theory for the phase between strong and EM

SU(3) dependent experimental evidences

Scan method (SU(3) independent) and measurement

Summary

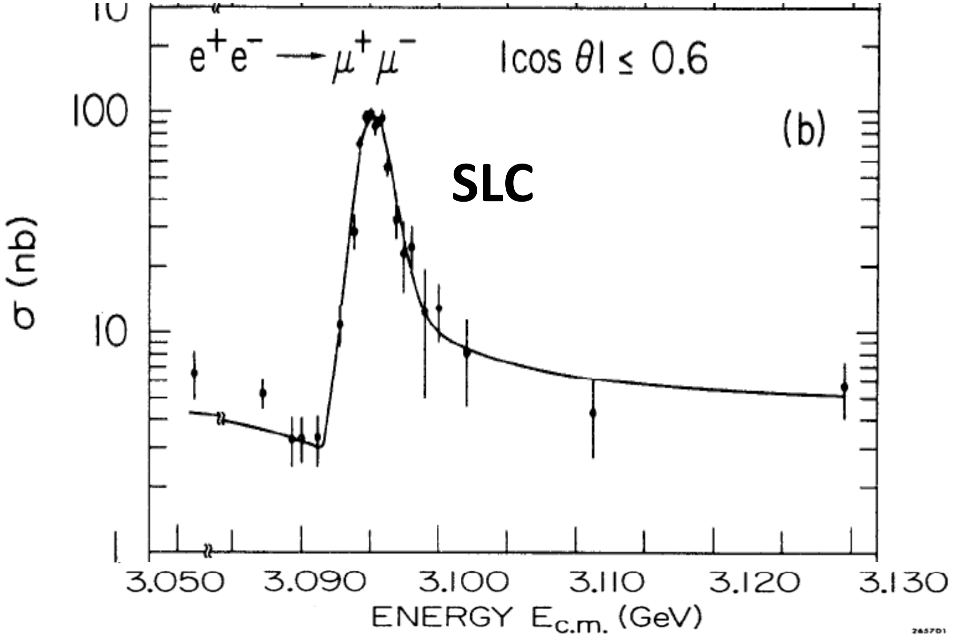
SU(3) independent--Scan method



$$\sigma_{born} = \left|A_{3g}e^{i\Phi_{g,cont.}} + A_{\gamma}e^{i\Phi_{\gamma,cont.}} + A_{cont.}\right|^2$$

If $\Phi_{3g,cont.} = 0°$,

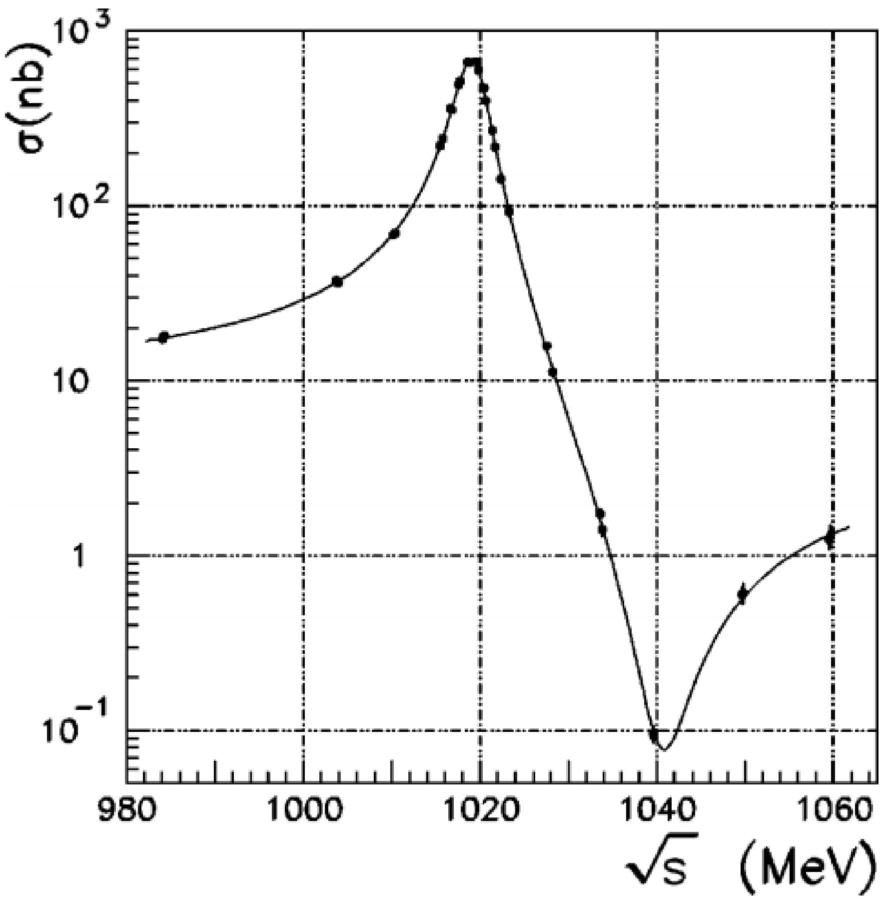
$$\sigma_{born} = \left|A_{3g}e^{i\Phi_{g,EM}} + A_{\gamma} + A_{cont.}\right|^2$$



◆The full interference between A_{γ} and A_{cont} has been observed at SLC (1975), BESII (1995) and KDER (2010). ($\Phi_{\gamma,cont.} = 0^o$)

Model dependent experimental evidences
from ϕ decays

The interference between ϕ and $\omega(\omega')$ was observed at SND.



- $e^+e^- \to \phi \to \pi^+\pi^-\pi^0$:
  A_γ is dominate
- $e^+e^- \to \omega(\omega') \to \pi^+\pi^-\pi^0$:
  A_{3g} is dominate
- $\Phi_{\phi-\omega(\omega')} \sim \Phi_{g,\gamma}$
- $\boldsymbol{\Phi_{\phi-\omega(\omega')} \sim 180°}$[1]

[1] SND coll., Phys. Rev. D 63, 072002 (2001)

Scan method and measurement

- The born cross section: $$\sigma^0(W)=\left(\frac{\mathcal{A}}{W^2}\right)^2\frac{4\pi\alpha^2}{W^2}\left|1+\frac{3W^2\sqrt{\Gamma_{ee}\Gamma_{\mu\mu}}(1+\mathcal{C}e^{i\Phi_{g,\mathrm{EM}}})}{\alpha M(W^2-M^2+iM\Gamma)}\right|^2$$

- The observed cross section:

$$\sigma^{\mathrm{theory}}(W)=\int_{W-nS_E}^{W+nS_E}GS(W-W'')dW''\int_0^{x_f}dxF(x,s)\sigma^0(s(1-x))$$

- Minimization method: $$\chi^2=\sum_{i=1}^{16}\frac{\left[\sigma_i^{\mathrm{obs}}-f\sigma''(W_i)\right]^2}{(\Delta\sigma_i^{\mathrm{obs}})^2+\left[\Delta W_i\cdot\frac{d\sigma''(W)}{dW}\right]^2}+\left(\frac{1-f}{\Delta f}\right)^2$$

[1] F. Z. Chen, P. Wang, J. Wu, Y. Zhu, Chin. Phys. C **14**, 585 (1990).
[2] X.Y. Zhou, Y.D. Wang, L.G. Xia, Chin. Phys. C **41** 083001 (2017)

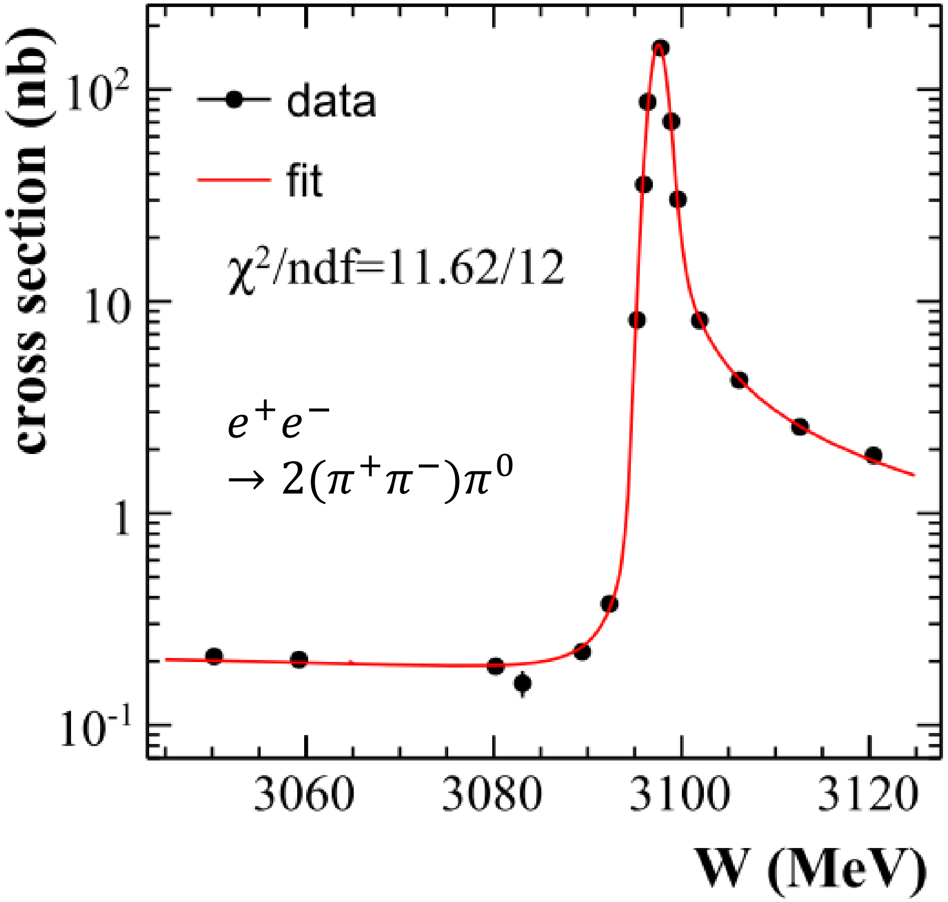
Scan method and measurement

BESIII Collaboration, Phys. Lett. B 791, 375 (2019)

$e^+e^- \to J/\psi \to 2(\pi^+\pi^-)\pi^0$

- J/ψ scan data (16 data points) of 100 pb^{-1} collected in 2012 is used
- Detection efficiency is simulated with MCGPJ generator for the ISR effect around J/ψ narrow peak
- Intermediate resonances are considered in simulation without interference

	$\Phi_{g,EM}$	$\mathcal{B}_{5\pi}$ (%)
Solution I	$(84.9 \pm 3.6)^\circ$	4.73 ± 0.44
Solution II	$(-84.7 \pm 3.1)^\circ$	4.85 ± 0.45



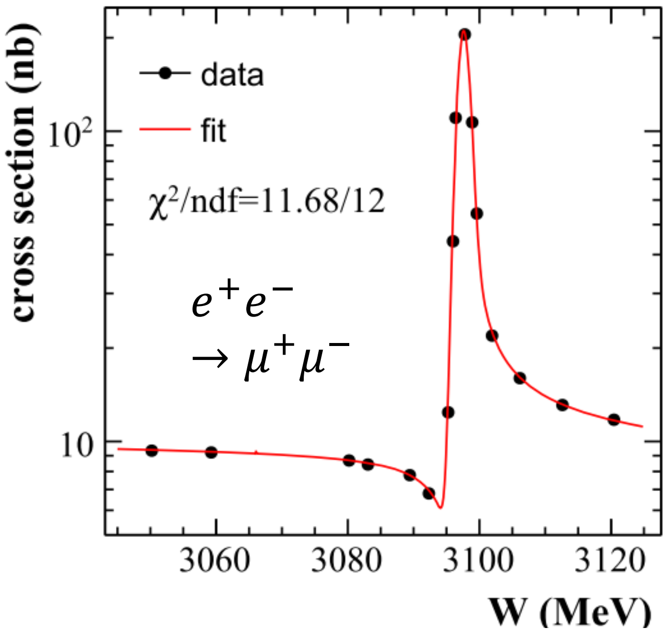
$\mathcal{B}_{PDG} = (4.1 \pm 0.5)\%$

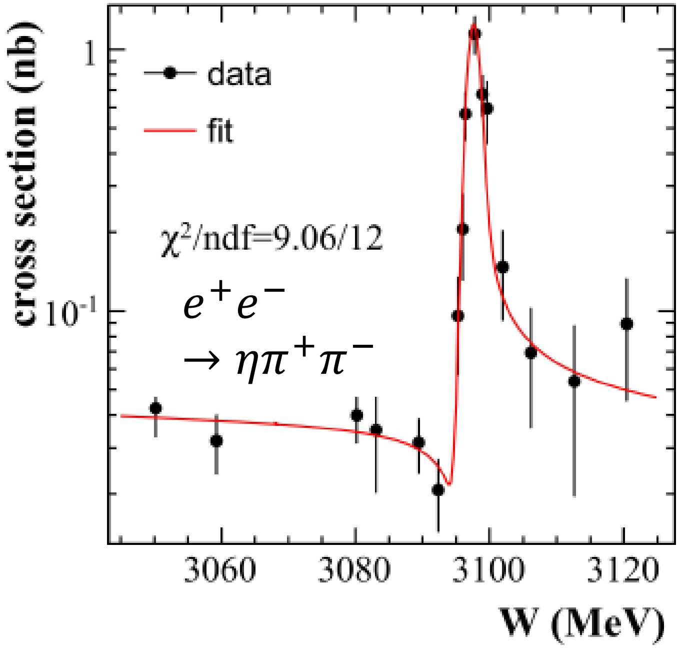
The phase between A_γ and A_{3g} is found being consistent with 90°.

Scan method and measurement

BESIII Collaboration, Phys. Lett. B 791, 375 (2019)

$e^+e^- \to J/\psi \to \mu^+\mu^-, \eta\pi^+\pi^-$





Φ represents the interference between $J/\psi \to \eta\rho$ and $J/\psi \to \rho\omega$

$$\sigma^0(W) = \frac{4\pi\alpha^2}{W^2}\left|1 + \frac{3W^2\sqrt{\Gamma_{ee}\Gamma_{\mu\mu}}e^{i\Phi_{\gamma,\mathrm{cont}}}}{\alpha M(W^2 - M^2 + iM\Gamma)}\right|^2$$

- $\Phi_{\gamma,cont.} = (3.0 \pm 10.0)^\circ$
- $S_E = (0.90 \pm 0.03)$ MeV

$$\sigma^0(W) = \left(\frac{\mathcal{A}}{W^2}\right)^2 \frac{4\pi\alpha^2}{W^2}\left|1 + \frac{3W^2\sqrt{\Gamma_{ee}\Gamma_{\mu\mu}}C_1 e^{i\Phi_{\gamma,\mathrm{cont}}}(1 + C_2 e^{i\Phi})}{\alpha M(W^2 - M^2 + iM\Gamma)}\right|^2$$

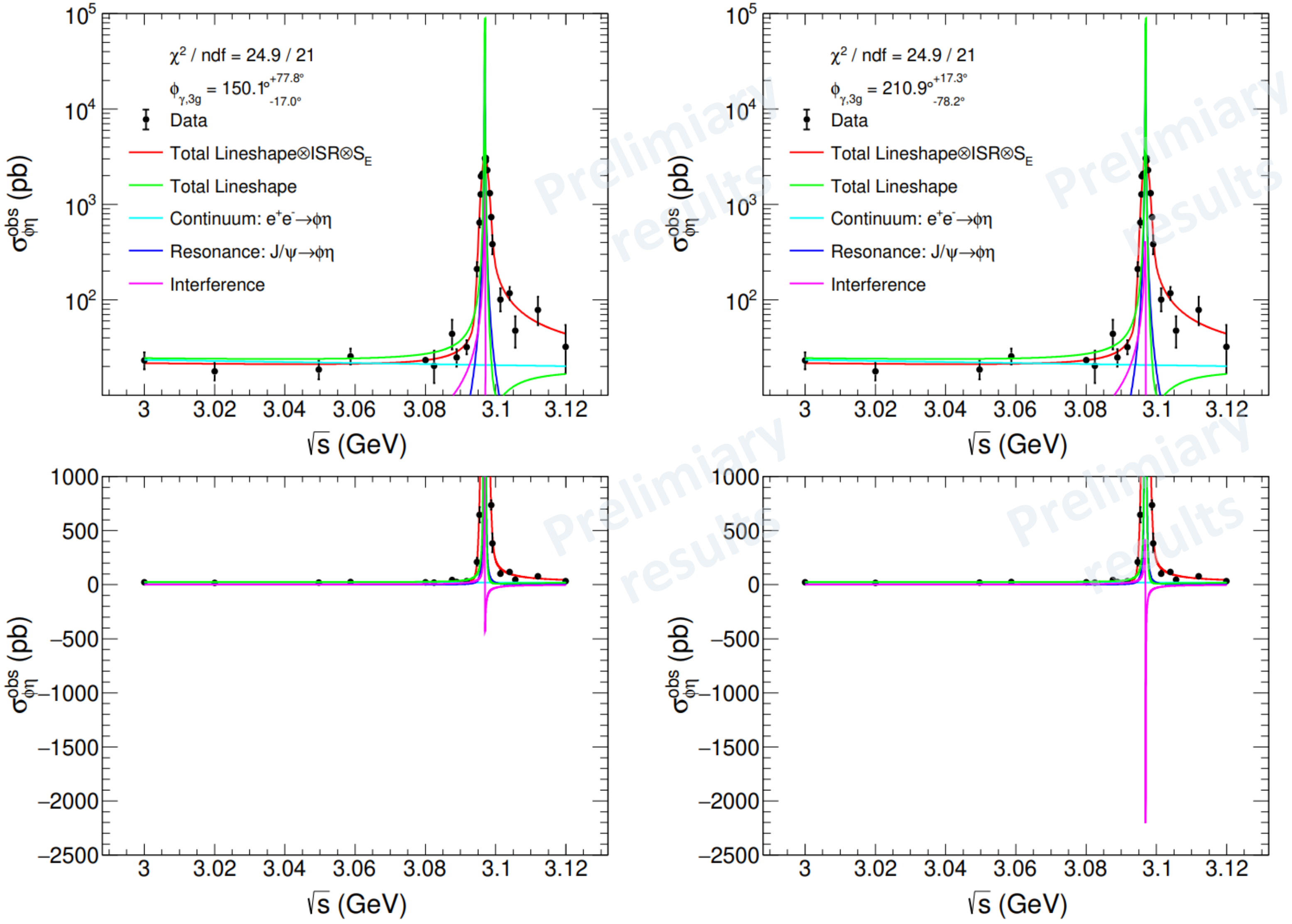
- $\Phi_{\gamma,cont.} = (-2 \pm 36)^\circ\ or\ (-22 \pm 36)^\circ$
- $Br(J/\psi \to \eta\pi^+\pi^-) = (3.78 \pm 0.66) \times 10^{-4}$
- $Br_{PDG}(J/\psi \to \eta\pi^+\pi^-) = (4.0 \pm 1.7) \times 10^{-4}$

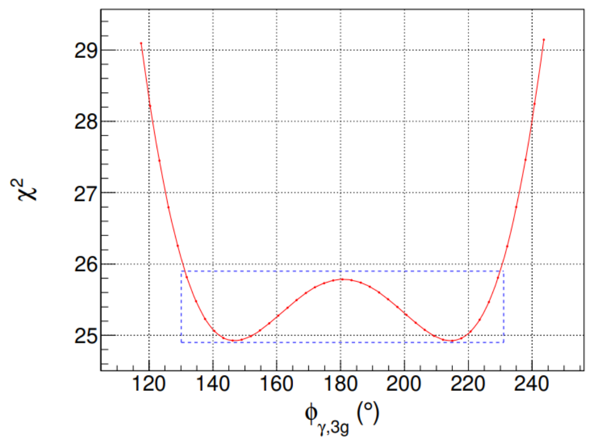
Once again, the phase between A_γ and $A_{cont.}$ is confirmed to be ZERO.

Scan method and measurement

BESIII Collaboration, to be submitted

$e^+e^- \to J/\psi \to \phi\eta$





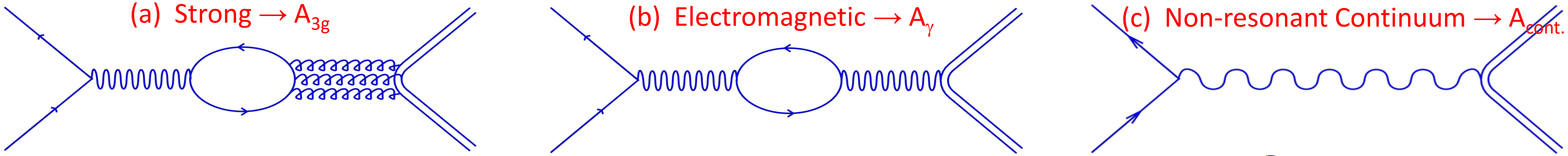
- Two solutions
- Indistinguishable within 1σ confidence
- $\Phi_{3g,\gamma} \in [133.1^\circ, 229.2^\circ]$

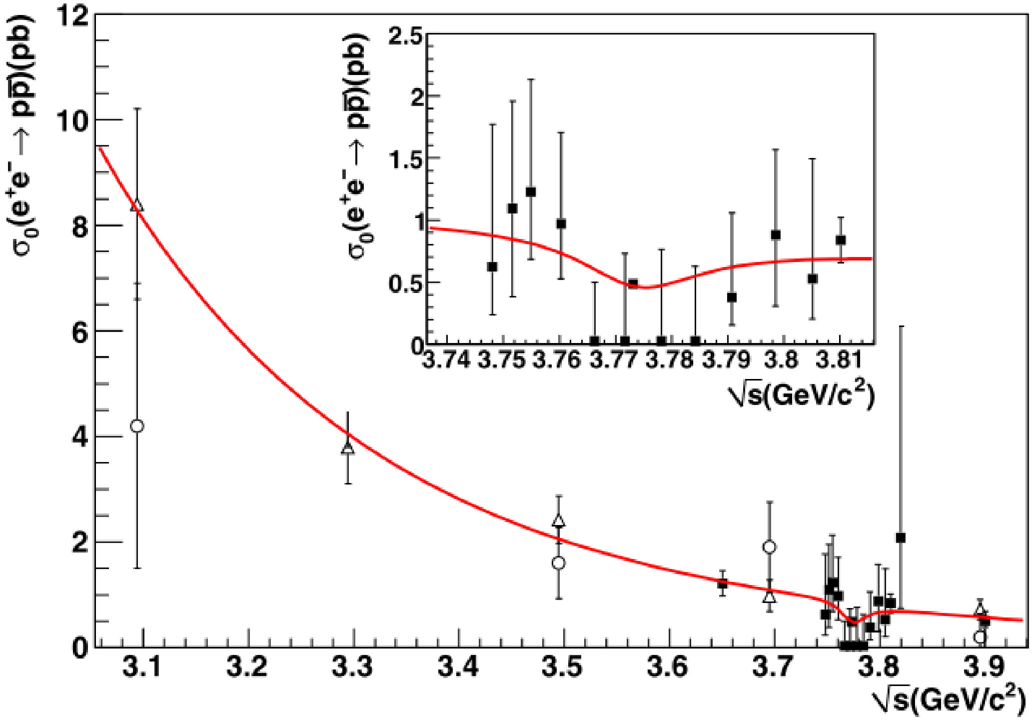
Interference between A_{3g} and A_γ?

Scan method and measurement

BESIII Collaboration, Phys. Lett. B 735, 101 (2014)

$e^+e^- \to \psi(3770) \to p\bar{p}$





$$\sigma(s) = \left|A_{con} + A_{\psi} e^{i\phi}\right|^2$$

$$= \left|\sqrt{\sigma_{con}(s)} + \sqrt{\sigma_{\psi}} \frac{m_{\psi}\Gamma_{\psi}}{s - m_{\psi}^2 + i m_{\psi}\Gamma_{\psi}} e^{i\phi}\right|^2$$

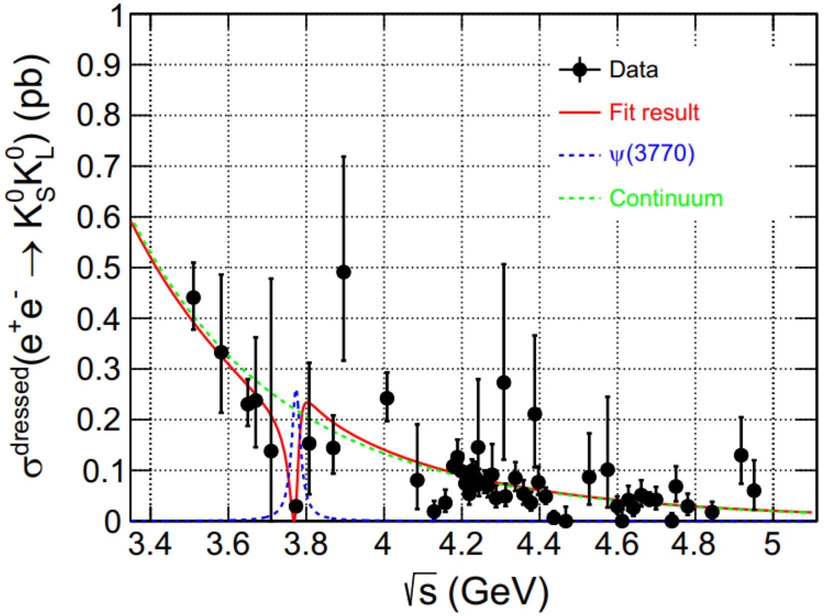
$\sigma^{dressed}_{(\psi(3770)\to p\bar{p})}$ (pb)	ϕ (°)
$0.059^{+0.070}_{-0.020} \pm 0.012$ $(< 0.166$ at 90% C.L.$)$	$255.8^{+39.0}_{-26.6} \pm 4.8$
$2.57^{+0.12}_{-0.13} \pm 0.12$	$266.9^{+6.1}_{-6.3} \pm 0.9$

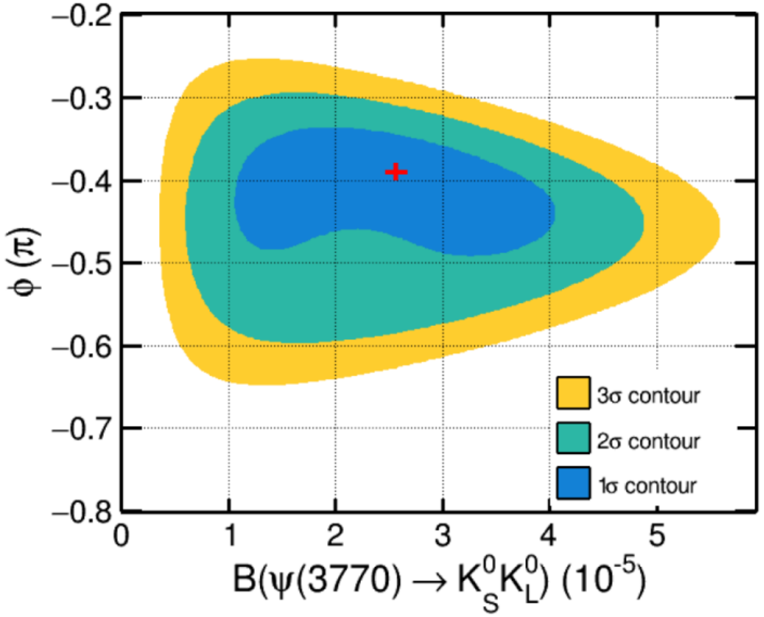
Even the interference is between A_{con} and A_{ψ}, the phase $\Phi_{3g,\gamma}$ is still close to $-90°$ since A_g is much larger than A_{γ}

Scan method and measurement

BESIII Collaboration, Phys. Rev. Lett. 132, 131901 (2024)

$e^+e^- \to \psi(3770) \to K_S K_L$





$$\sigma^{\text{dressed}} = \left| BW \cdot e^{i\phi} + \frac{a}{(\sqrt{s})^n} \cdot \sqrt{\Phi(\sqrt{s})} \right|^2$$

$$BW = \frac{\sqrt{12\pi\Gamma_{ee}\Gamma B}}{s - M^2 + iM\Gamma} \sqrt{\frac{\Phi(s)}{\Phi(M)}}, \ \Phi(s) = \frac{q^3}{s}$$

- $\mathcal{B} = (2.63^{+1.40}_{-1.59}) \times 10^{-5}$ and $\phi = \left(-0.39^{+0.05}_{-0.10}\right)\pi$ within 1σ likelihood contour.
- Significance of $\psi(3770)$ resonance contribution determined to be 10σ.
- First observe the charmless decay $\psi(3770) \to K_S K_L$.

Outline

Theory for the phase between strong and EM

SU(3) dependent experimental evidences

Scan method (SU(3) independent) and measurement

Summary

Summary

- The phase between strong and EM can be measured with SU(3) dependent method and scan method.

- Critical problems about the phase is a mystery:
  - Is the phase universal? Independent of initial or final state?
  - What is the sign of the phase?

- More experimental results are needed for a physical conclusion.

- Direct scanned experimental result in J/ψ and $\psi(3770)$ are shown, more results for J/ψ, $\psi(2S)$, $\psi(3770)$ will come.

Thanks for your attention!

Model dependent experimental evidences

Study of $J/\psi \to p\bar{p}$ and $J/\psi \to n\bar{n}$

(BESIII Collaboration) Phys. Rev. D 86, 032014 (2012)

- $Br(J/\psi \to p\bar{p}) = (2.112 \pm 0.004 \pm 0.031) \times 10^{-3}$
- $\alpha = 0.595 \pm 0.012 \pm 0.015$
- $Br(J/\psi \to n\bar{n}) = (2.07 \pm 0.01 \pm 0.17) \times 10^{-3}$
- $\alpha = 0.50 \pm 0.04 \pm 0.21$

Observation of $\psi(3686) \to n\bar{n}$ and improved measurement of $\psi(3686) \to p\bar{p}$

(BESIII Collaboration) Phys. Rev. D 98, 032006 (2018)

- $Br(\psi(3686) \to n\bar{n}) = (3.06 \pm 0.06 \pm 0.14) \times 10^{-4}$
- $\alpha_{n\bar{n}} = 0.68 \pm 0.12 \pm 0.11$
- $Br(\psi(3686) \to p\bar{p}) = (3.05 \pm 0.20 \pm 0.12) \times 10^{-4}$
- $\alpha_{p\bar{p}} = 1.03 \pm 0.06 \pm 0.03$

- The α values are very close in two decay modes, which is expected if the strong interaction is dominant in $J/\psi \to N\bar{N}$ decay and the relative phase of between the strong and electromagnetic amplitudes is close to 90°
- In contrast, in $\psi(3686)$ decays, the branching fractions are quite close between the two decay modes, but the α values are not, which may imply a more complex mechanism in the decay of $\psi(3686) \to N\bar{N}$. It makes a similar and straight forward extraction of the phase angle impossible in the decay of $\psi(3686) \to N\bar{N}$, and further studies are deserved.