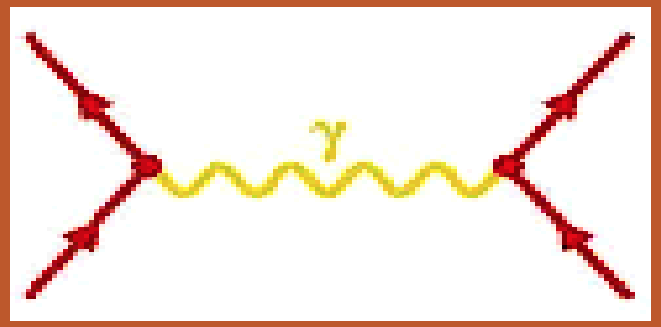

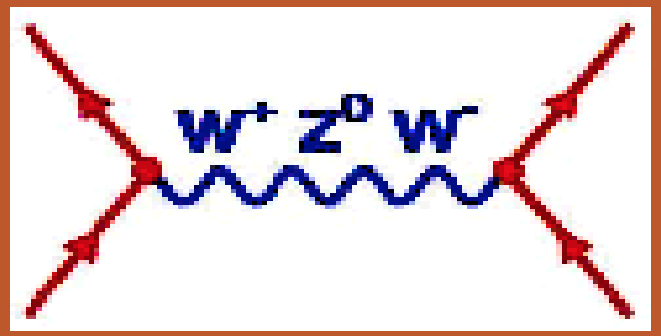

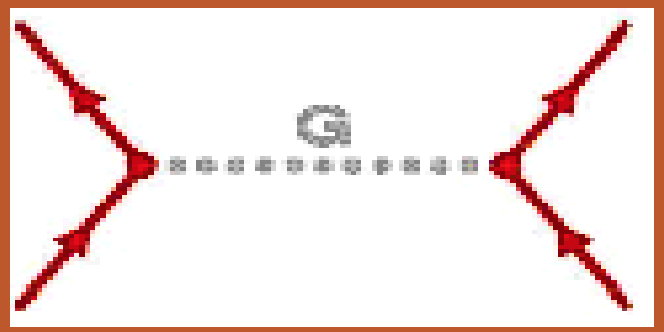

Measurement of the relative phase between strong and EM decays of charmonium

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(谨代表Phase测量工作小组)

https://indico.ihep.ac.cn/category/1060/

第八届R值与QCD强子结构研讨会

19/07/2024 - 22/07/2024

Outline

Theory for the phase between strong and EM

SU(3) dependent experimental evidences

Scan method (SU(3) independent) and measurement

Summary

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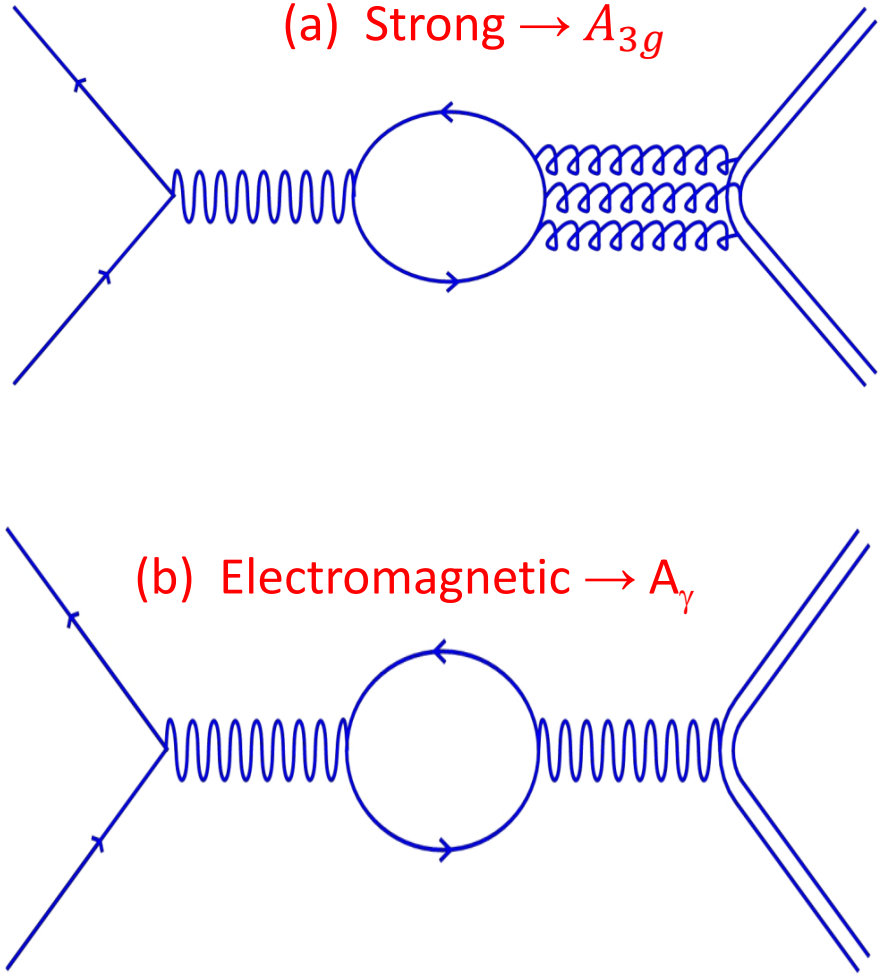

(a) $e^+e^- \rightarrow R(q\underline{q}) \rightarrow$ hadrons via strong mechanism;

(b) $e^+e^- \rightarrow R(q\underline{q}) \rightarrow$ 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.

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Model dependent experimental evidences

from J/ψ decays

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

- $PP(0^-0^-)(\pi^+\pi^-, K^+K^-, K_SK_L)$: $\Phi = (90 \pm 10)°$ [2]
- $VP(1^-0^-)(\rho\pi, \omega\pi^0, \phi\pi^0, \rho\eta, \omega\eta, \phi\eta, \rho\eta', \omega\eta', \phi\eta', \bar{K}^*K)$
- $VP(1^+0^-)\left(K_1^{\pm}(1400)K^{\mp}, K_1^{\pm}(1270)K^{\mp}\right)$
- $VV\ (1^-1^-)(\rho^+\rho^-, K^{*+}K^{*-}, K^{*0}\bar{K}^{*0})$
- $B\bar{B}(p\bar{p}, n\bar{n}, \Lambda\bar{\Lambda}, \Sigma^0\bar{\Sigma}^0, \Sigma^+\bar{\Sigma}^-, \Xi^0\bar{\Xi}^0, \Xi^+\bar{\Xi}^-, \Sigma^0\bar{\Lambda} + \bar{\Sigma}^0\Lambda)$

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		

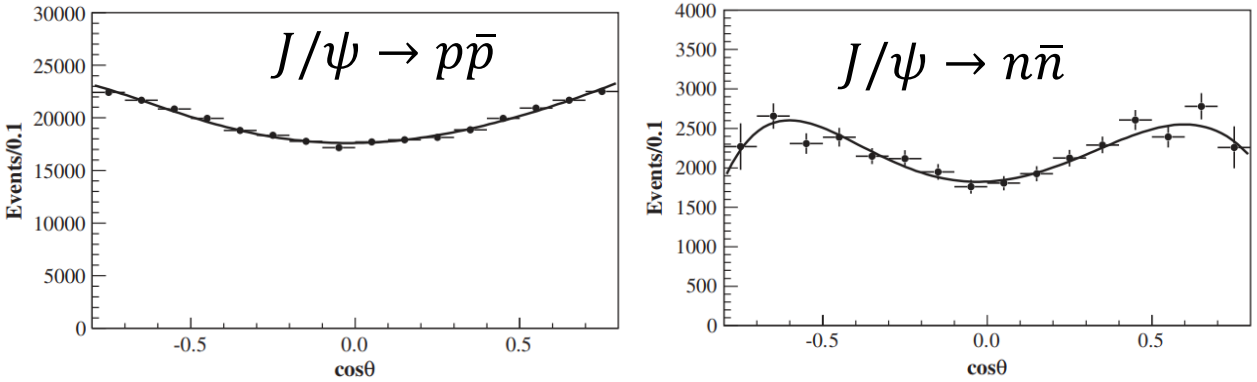
An example

$g - A_{3g}; e - A_\gamma$
$X_\eta, Y_\eta, s_g -$ 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).

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)

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

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

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

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

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

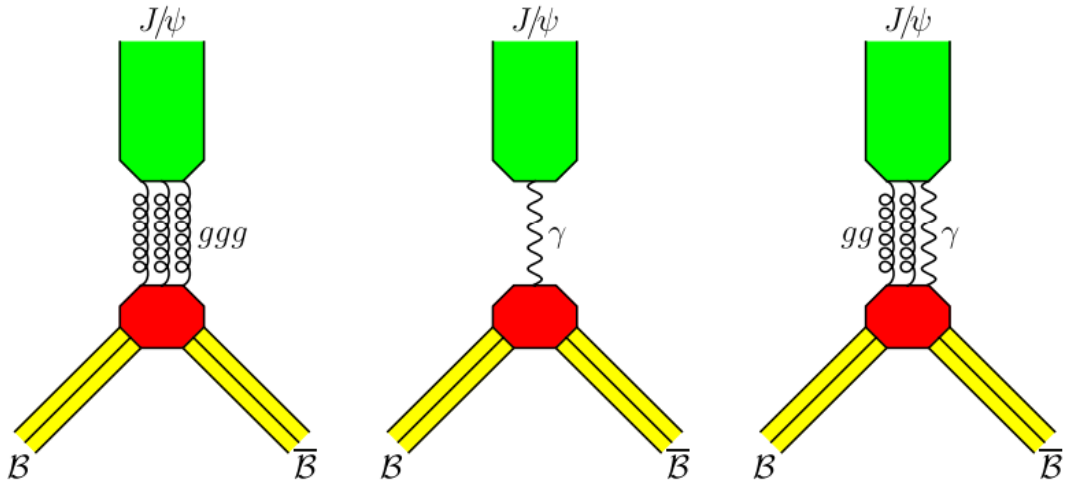
- $E_p(E_n)$ and S are EM and strong amplitudes of $J/\psi \to p\bar{p}$ $(n\bar{n})$, ϕ is the phase angle between $E_p(E_n)$ and S.
- Assumption:
  - $E_n = -E_p$ and $S_p = S_n = S$

- The strong interaction is dominant.
- **$\Phi = (-85.9 \pm 1.7)^\circ$ or $(+90.8 \pm 1.6)^\circ$** 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
$\Lambda\overline{\Sigma}^0 + \mathrm{c.c.}$	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

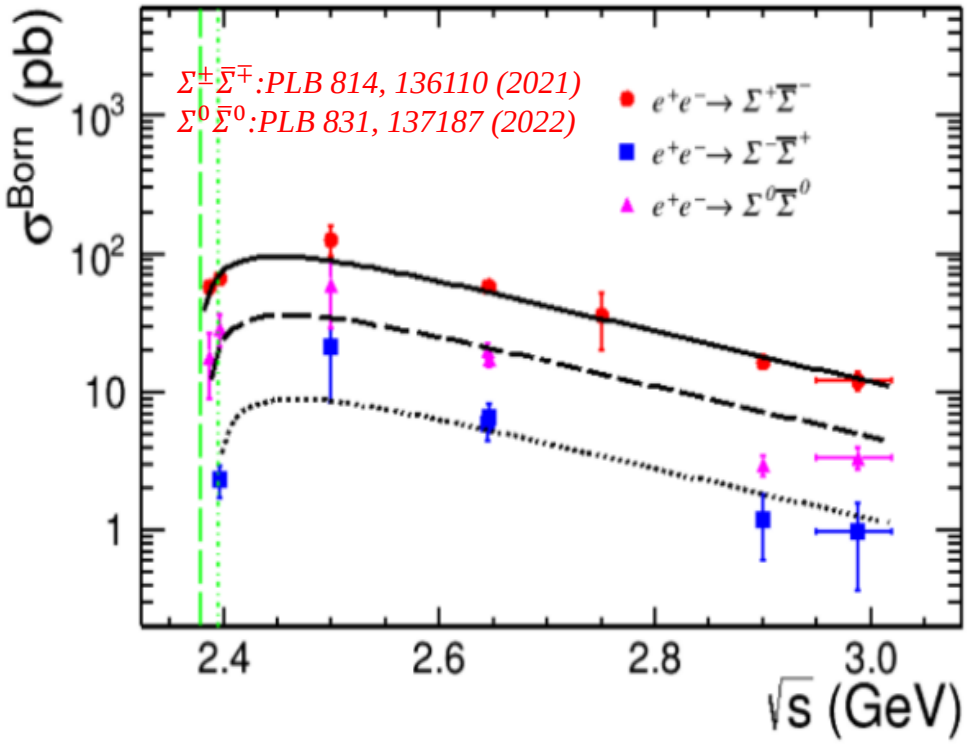
- Consider the small contribution from $A_{gg\gamma}$
- Assume $A_{gg\gamma}$ has the same phase as A_g to A_γ
- Perform SU(3) analysis based on experimental branching ratios of J/ψ decaying to baryons

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

Br result from SU(3) very close to PDG

Question of $e^+e^- \to \Sigma\bar{\Sigma}$

From X. R. Zhou's talk



- An asymmetry in cross sections for Σ isospin triplets: $9.7 \pm 1.3 : 3.3 \pm 0.7 : 1$ =>related with valence quark?
- While, the branching ratios from J/ψ suggests opposite order in strong interaction

Process	Branching fraction	$\alpha_{J/\psi}$
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	$(1.027 \pm 0.005) \times 10^{-3}$	-0.508 ± 0.006
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	$(1.17 \pm 0.03) \times 10^{-3}$	-0.45 ± 0.02
$J/\psi \to \Sigma^-\bar{\Sigma}^+$	$(1.51 \pm 0.06) \times 10^{-3}$	-0.36 ± 0.02

An analysis based on SU(3) and experimental branching ratio results gives the EM cross section at J/ψ :

$$\Phi = (73 \pm 8)^\circ$$
$$\sigma(e^+e^- \to \Sigma^+\bar{\Sigma}^-) = 10.4 \pm 1.1\ pb$$
$$\sigma(e^+e^- \to \Sigma^0\bar{\Sigma}^0) = 1.37 \pm 0.12\ pb$$
$$\sigma(e^+e^- \to \Sigma^-\bar{\Sigma}^+) = 0.79 \pm 0.30\ pb$$

R. B. Ferroli, A. Mangoni, S. Pacetti, K. Zhu, *Physics Letters B 799 (2019) 135041*

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]:

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

$\Phi = (-82 \pm 29)^\circ$ 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 $(+134 \pm 25)^\circ$

The Φ change between J/ψ and $\psi(2S)$ is a puzzle, very likely related to $\rho\pi$ puzzle

[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)), $|\Phi| \sim 90^\circ$

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.

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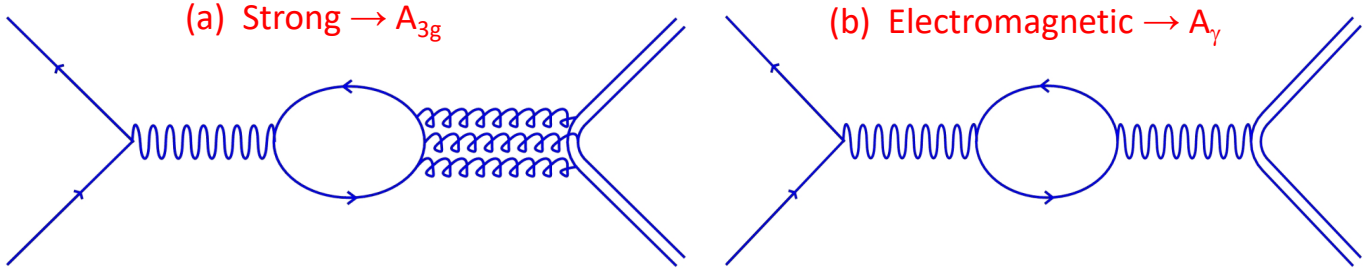
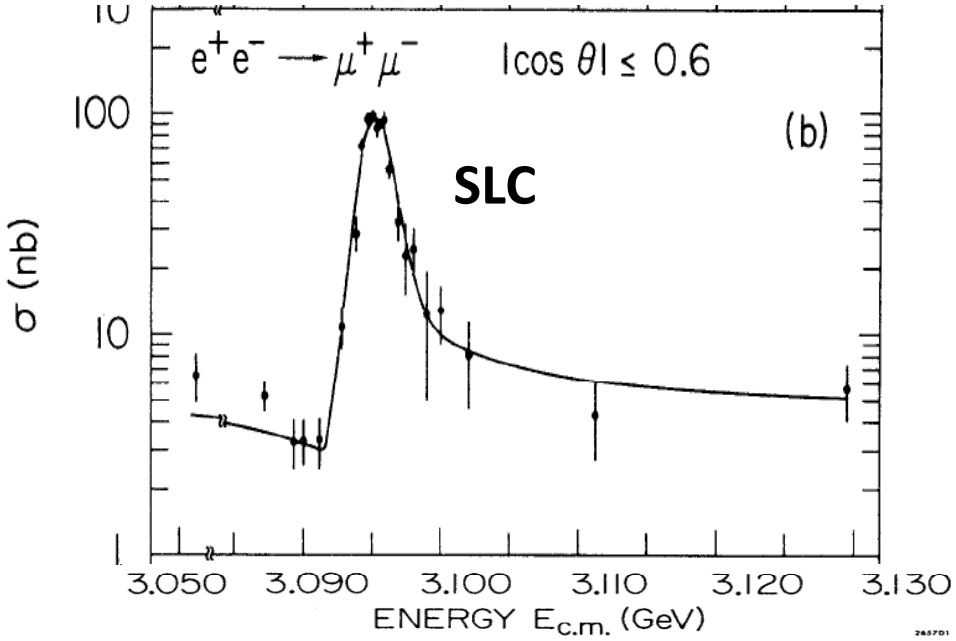
SU(3) independent--Scan method



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

If $\Phi_{\gamma,cont.} = 0°$,

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

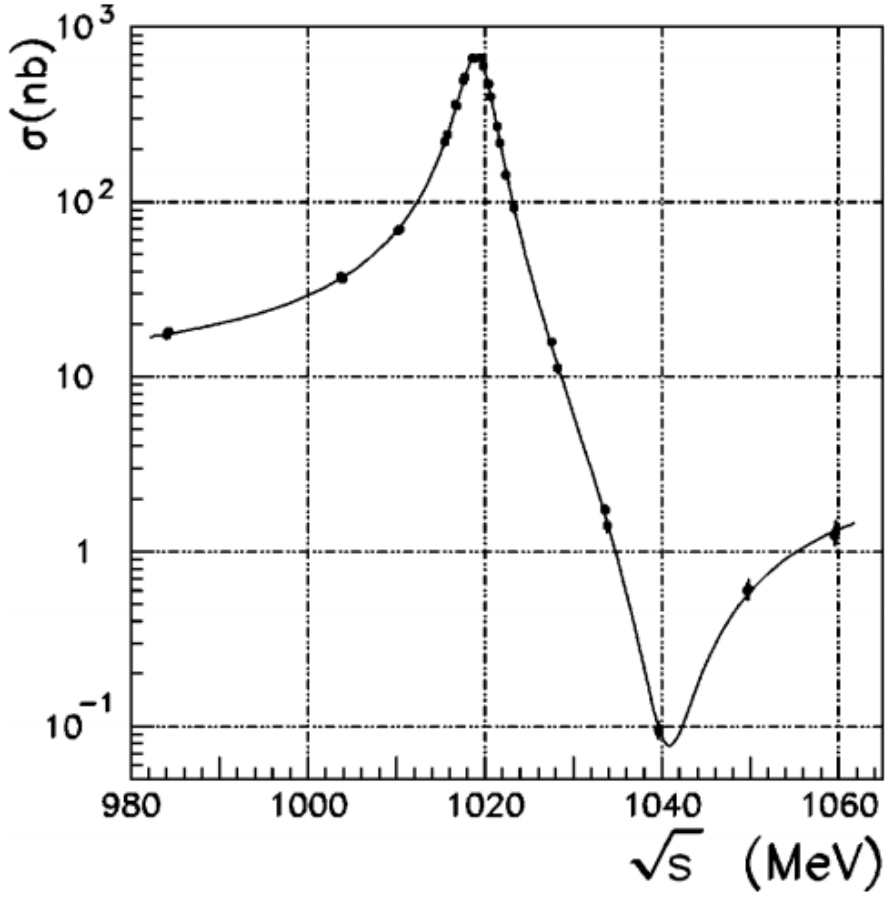


◆The full interference between A_γ and A_{cont} has been observed at SLC (1975), BESII (1995) and KDER (2010). ($\Phi_{\gamma,cont.} = 0^o$)

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

- $e^+e^- \to \omega(\omega') \to \pi^+\pi^-\pi^0$:

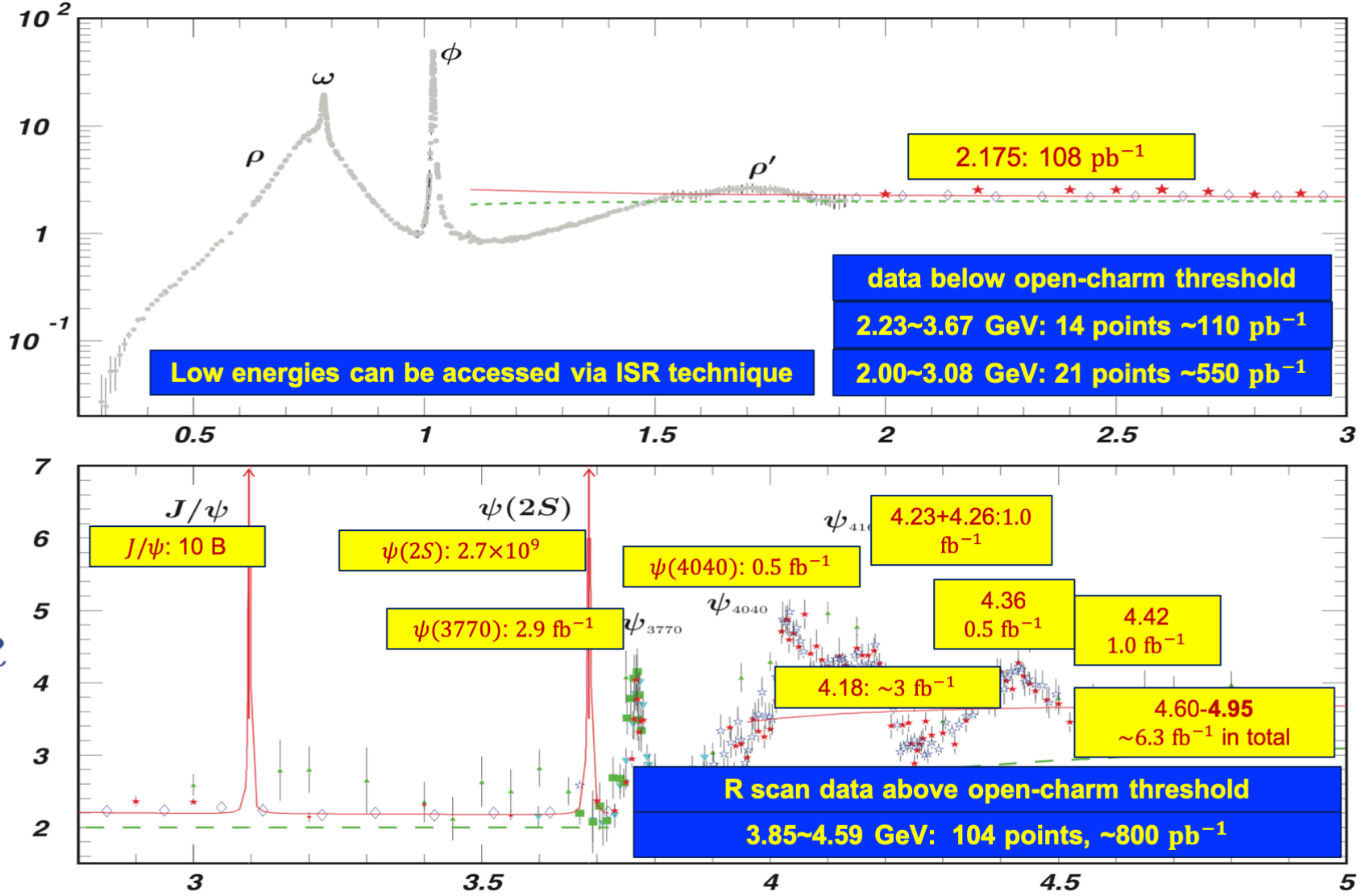
  A_{3g} is dominate

- $\Phi_{\phi-\omega(\omega')} \sim \Phi_{g,\gamma}$

- **$\Phi_{\phi-\omega(\omega')} \sim 180°$ [1]**

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

BESIII datasets



Scan method and measurement

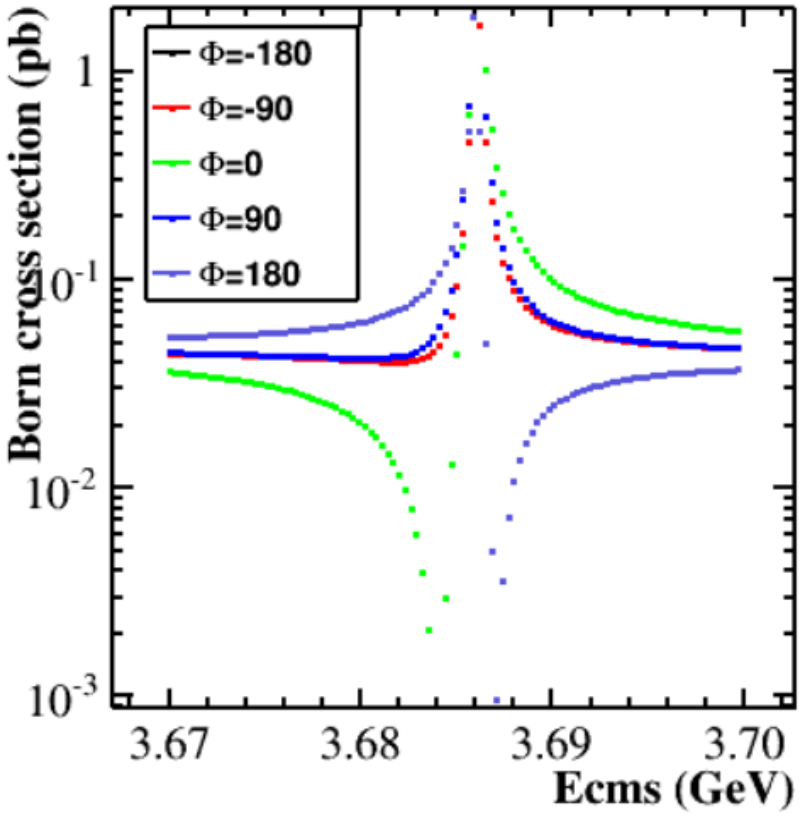
- The born cross section: $\sigma^0(W) = \left(\frac{\mathcal{A}}{W^2}\right)^2 \frac{4\pi\alpha^2}{W^2} \left|1 + \frac{3W^2\sqrt{\Gamma_{ee}\Gamma_{\mu\mu}}(1+\mathcal{C}e^{i\Phi_{g,\mathrm{EM}}})}{\alpha M(W^2 - M^2 + iM\Gamma)}\right|^2$
- The observed cross section:

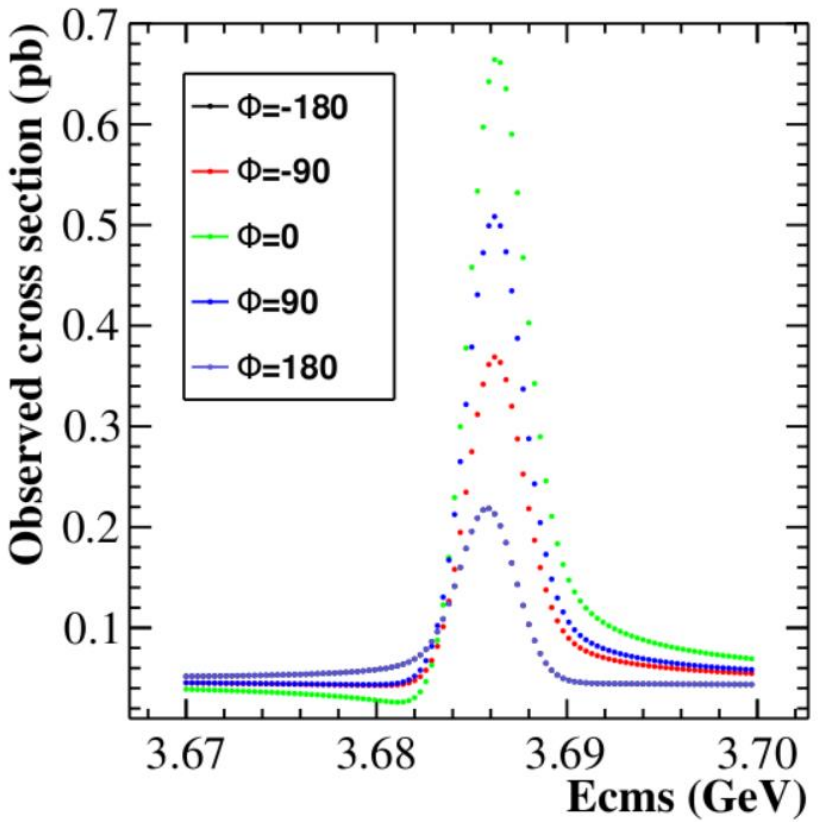
$$\sigma^{\mathrm{theory}}(W) = \int_{W-nS_E}^{W+nS_E} GS(W - W'')dW'' \int_0^{x_f} dx F(x,s)\sigma^0(s(1-x))$$

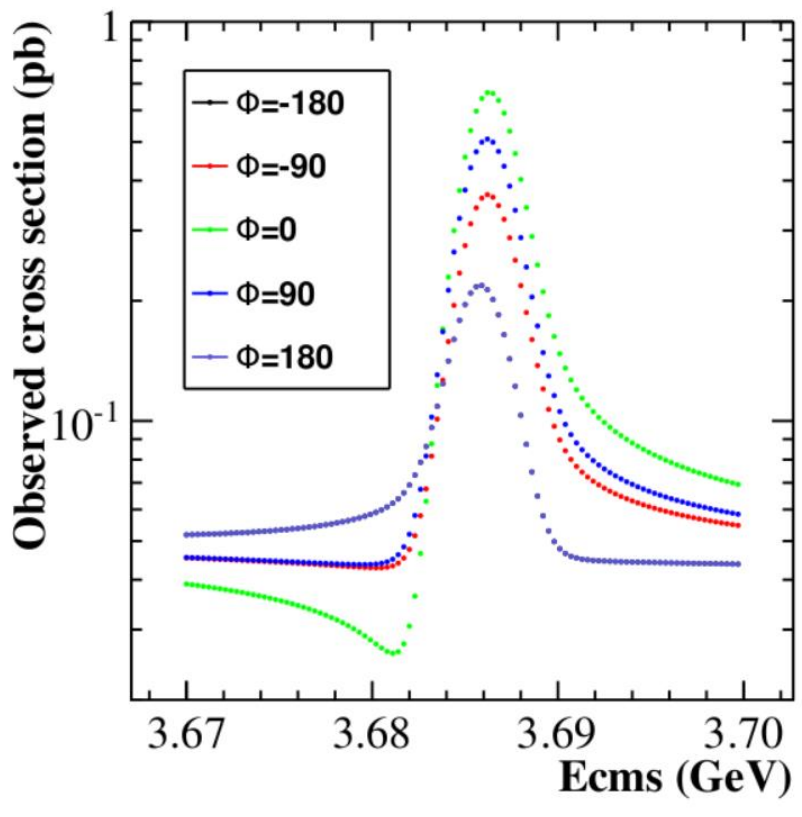
- Minimization method: $\chi^2 = \sum_{i=1}^{16} \frac{\left[\sigma_i^{\mathrm{obs}} - f\sigma''(W_i)\right]^2}{(\Delta\sigma_i^{\mathrm{obs}})^2 + \left[\Delta W_i \cdot \frac{d\sigma''(W)}{dW}\right]^2} + \left(\frac{1-f}{\Delta f}\right)^2$
- Analytical formula was developed to reduce two integrations to one, arXiv:2311.13292

[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)

Prediction for line-shapes of $\psi(3686)$

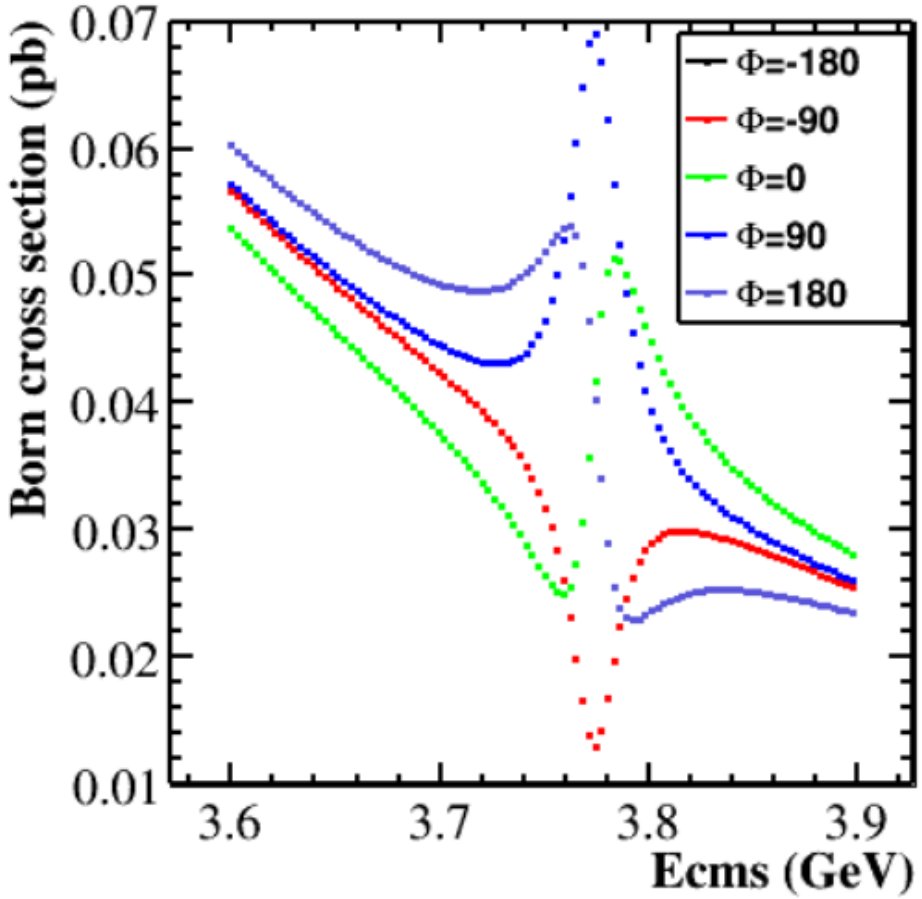


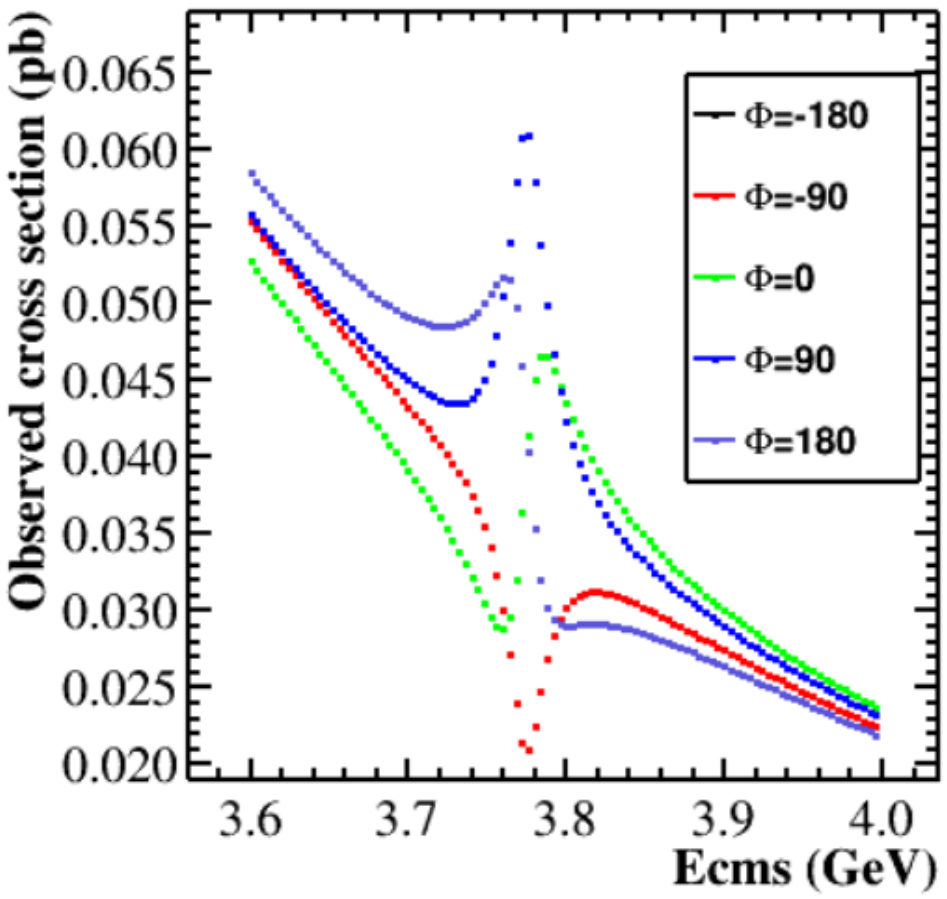




- For narrow resonances, the beam energy spread is much larger than the natural width.
- The observed cross section and Born cross section are very different.

Prediction for line-shapes of $\psi(3770)$





- For wide resonances, the beam energy spread is smaller than the natural width.
- The observed cross section and Born cross section are very similar.

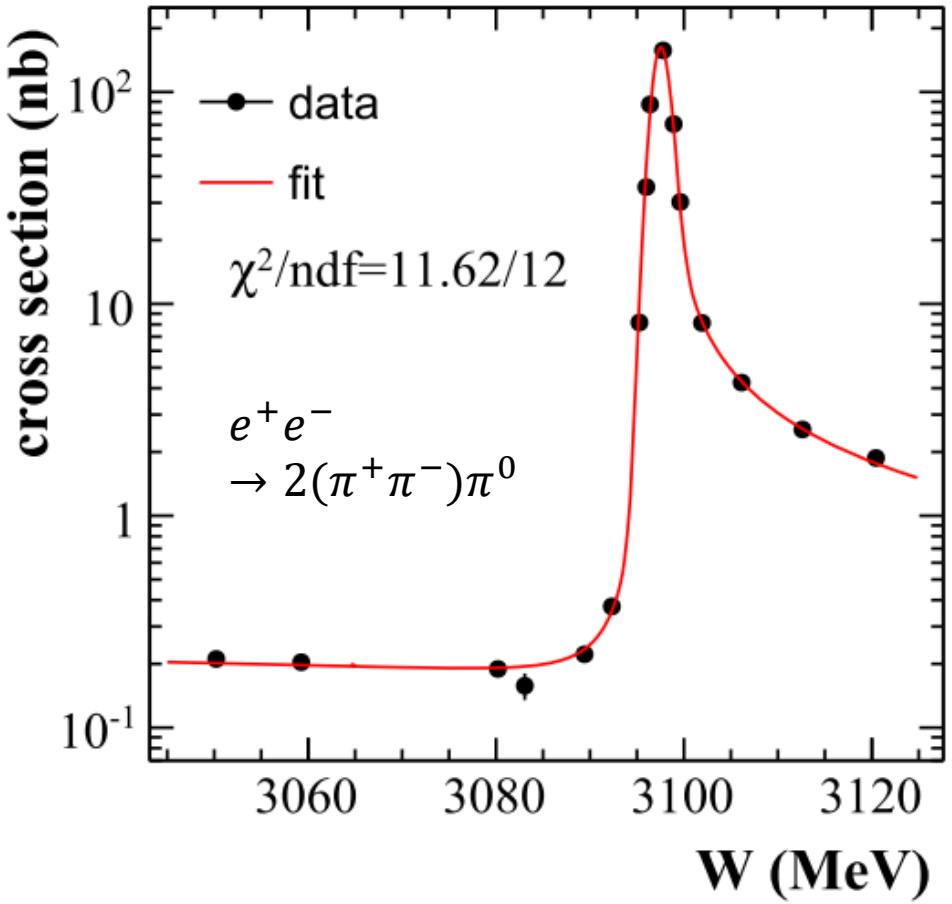
Scan method and measurement

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

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



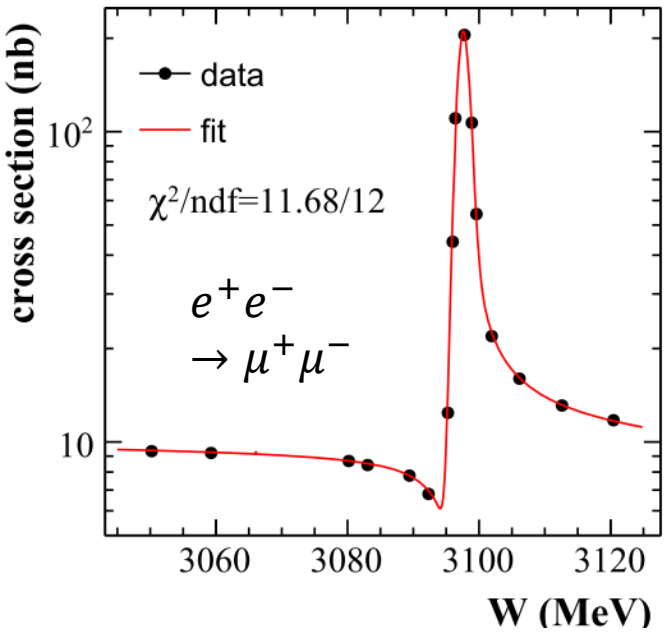
$\mathcal{B}_{PDG} = (4.1 \pm 0.5)\%$

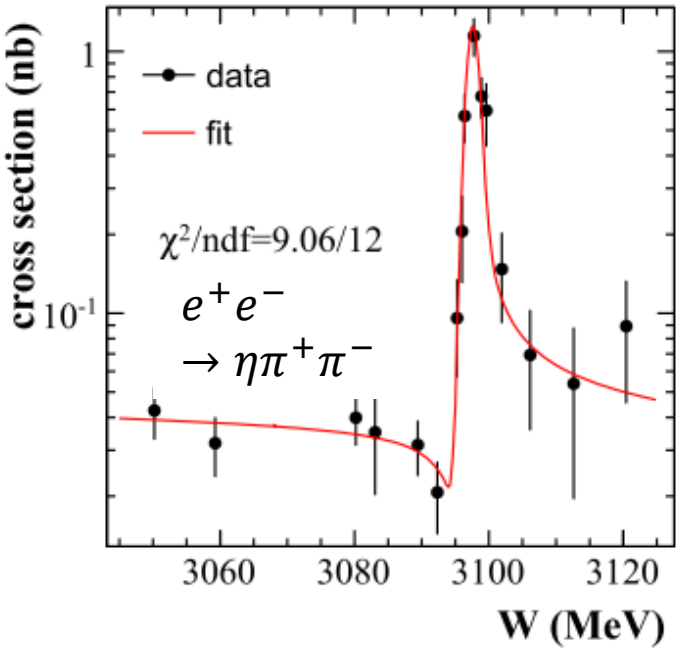
The phase between A_γ and A_{3g} is found being consistent with 90°.

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

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

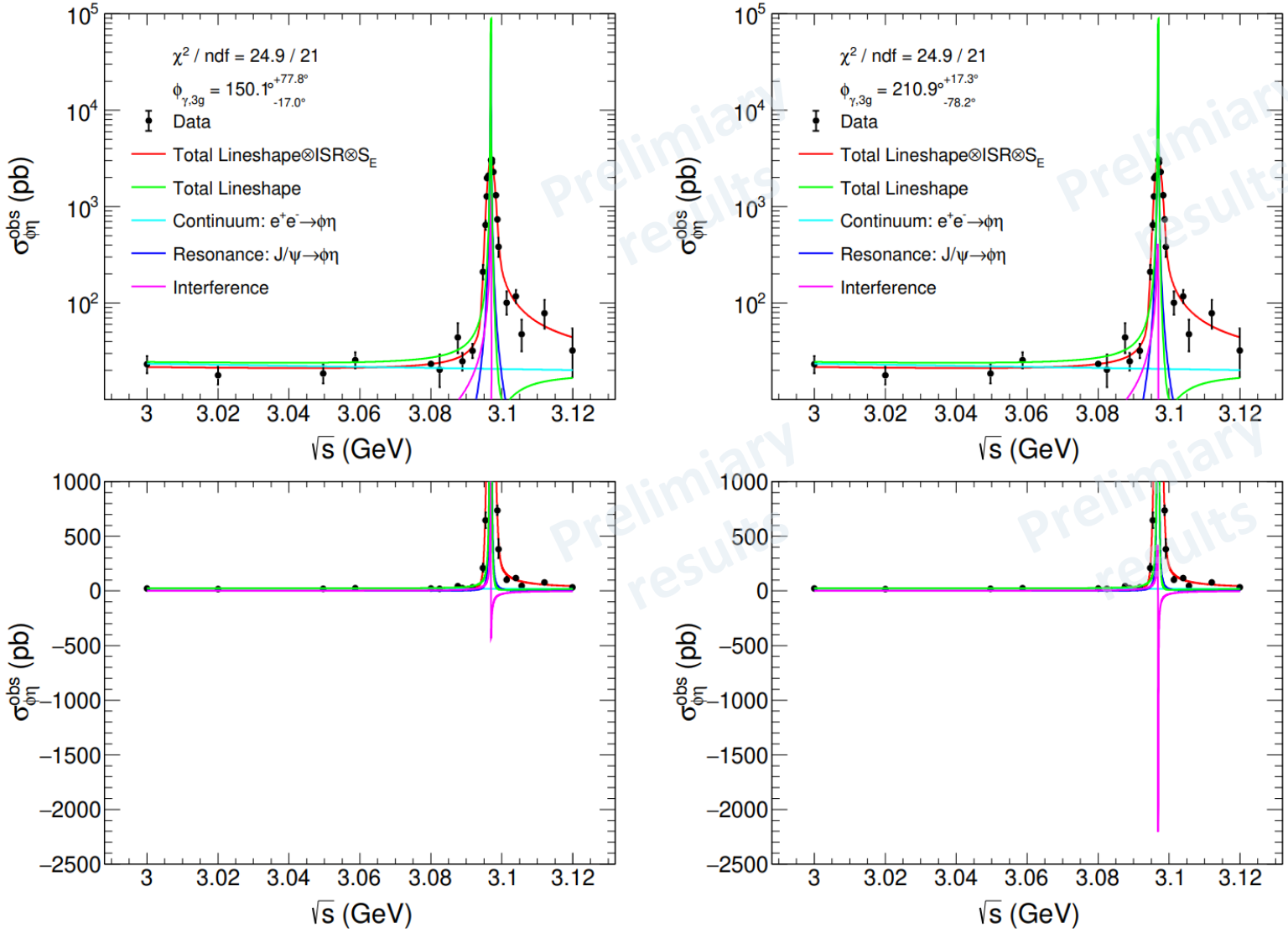
- $\Phi_{\gamma,cont.} = (-2 \pm 36)^\circ \; or \; (-22 \pm 36)^\circ$
- $Br(J/\psi \to \eta\pi^+\pi^-) = (3.78 \pm 0.66) \times 10^{-4}$
- $Br_{PDG}(J/\psi \to \eta\pi^+\pi^-) = (4.0 \pm 1.7) \times 10^{-4}$

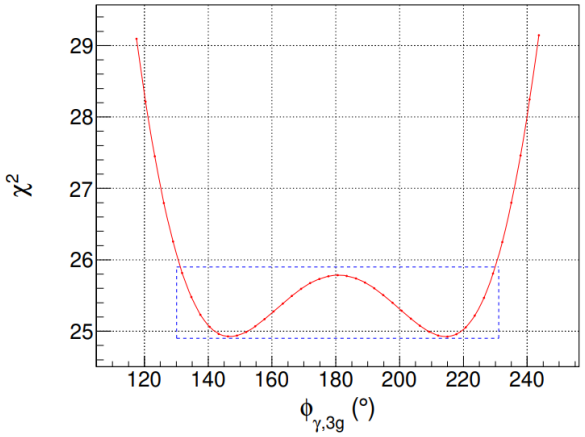
Once again, the phase between A_γ and $A_{cont.}$ is confirmed to be ZERO.

Scan method and measurement

BESIII Collaboration, to be submitted

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





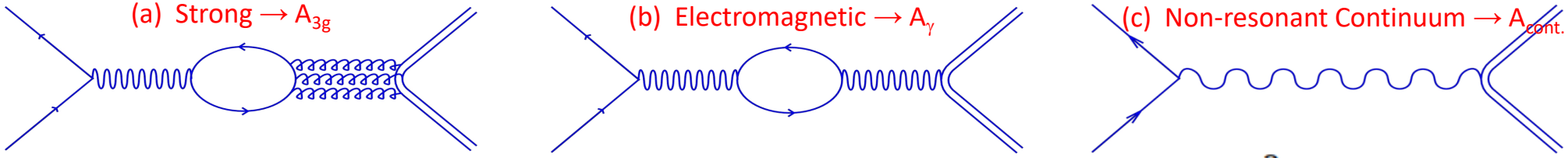
- Two solutions
- Indistinguishable within 1σ confidence
- $\Phi_{3g,\gamma} \in [133.1°, 229.2°]$

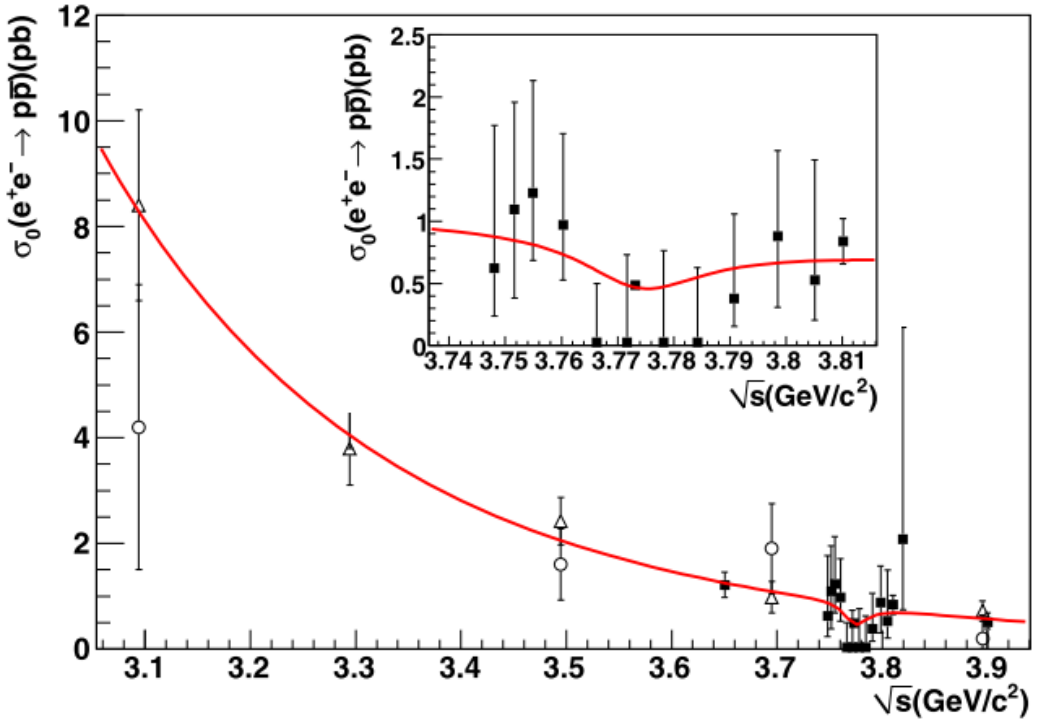
Interference between A_{3g} and A_γ?

Scan method and measurement

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

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





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

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

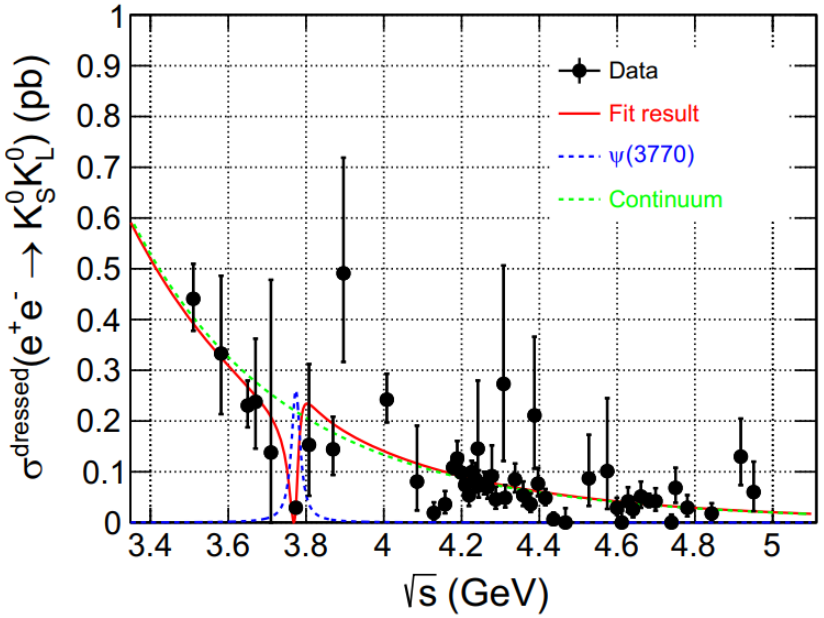
$\sigma^{dressed}_{(\psi(3770)\to p\bar{p})}$ (pb)	ϕ (°)
$0.059^{+0.070}_{-0.020} \pm 0.012$	$255.8^{+39.0}_{-26.6} \pm 4.8$
(< 0.166 at 90% C.L.)	
$2.57^{+0.12}_{-0.13} \pm 0.12$	$266.9^{+6.1}_{-6.3} \pm 0.9$

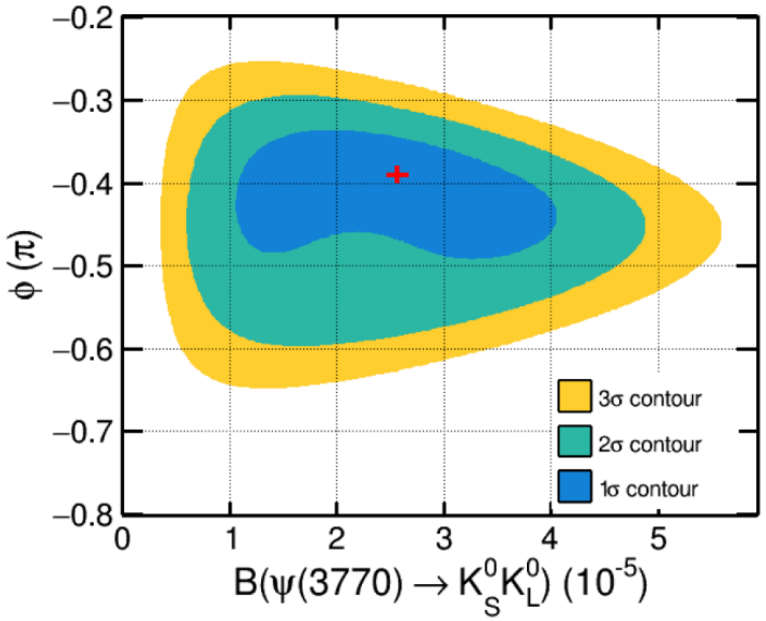
Even the interference is between A_{con} and A_ψ, the phase $\Phi_{3g,\gamma}$ is still close to $-90°$ since A_g is much larger than A_γ

Scan method and measurement

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

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





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

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

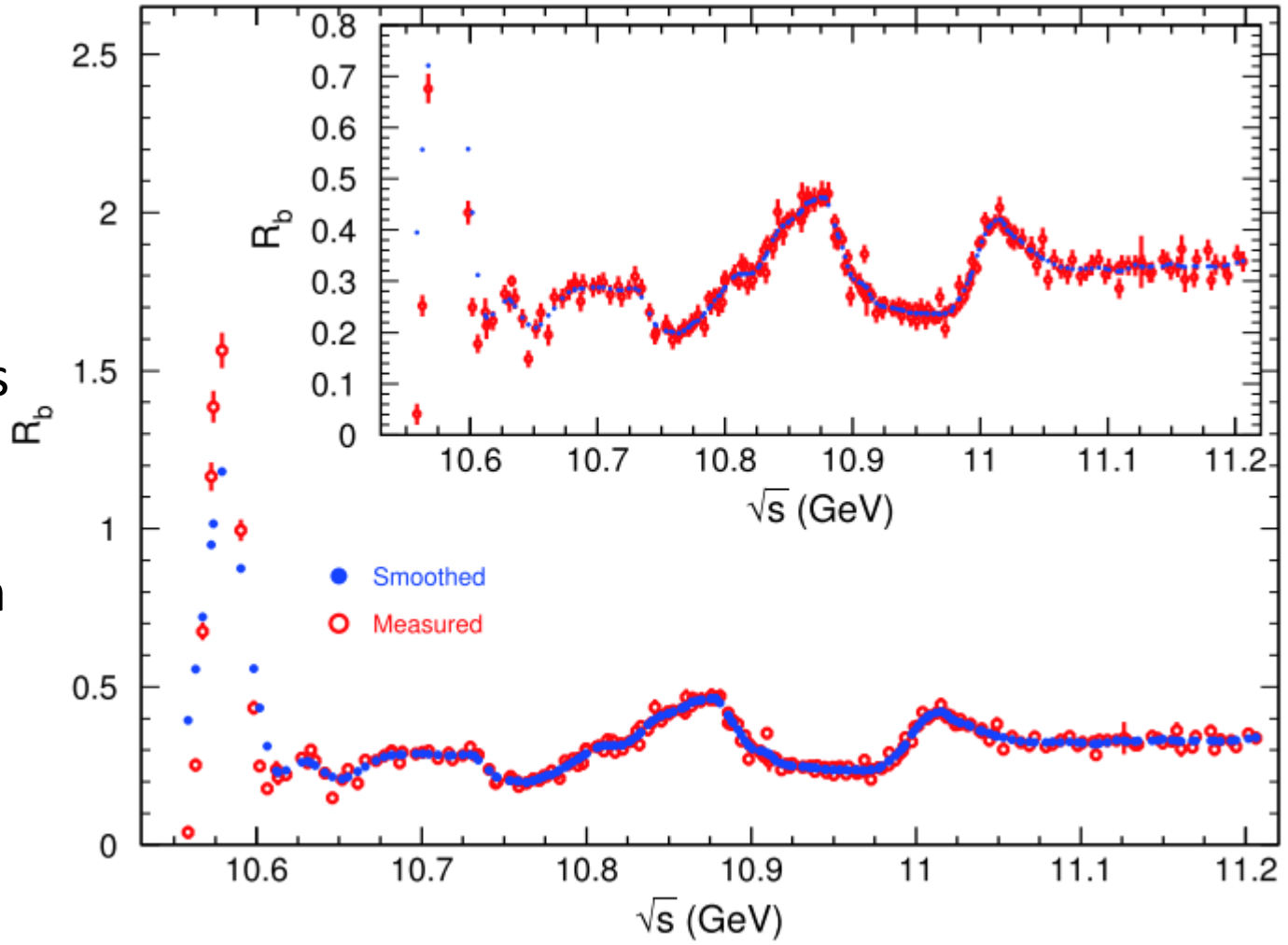
- $\mathcal{B} = (2.63^{+1.40}_{-1.59}) \times 10^{-5}$ and $\phi = \left(-0.39^{+0.05}_{-0.10}\right)\pi$ within 1σ likelihood contour.
- Significance of $\psi(3770)$ resonance contribution determined to be 10σ.
- First observe the charmless decay $\psi(3770) \to K_S K_L$.

Phase in OZI allowed decays

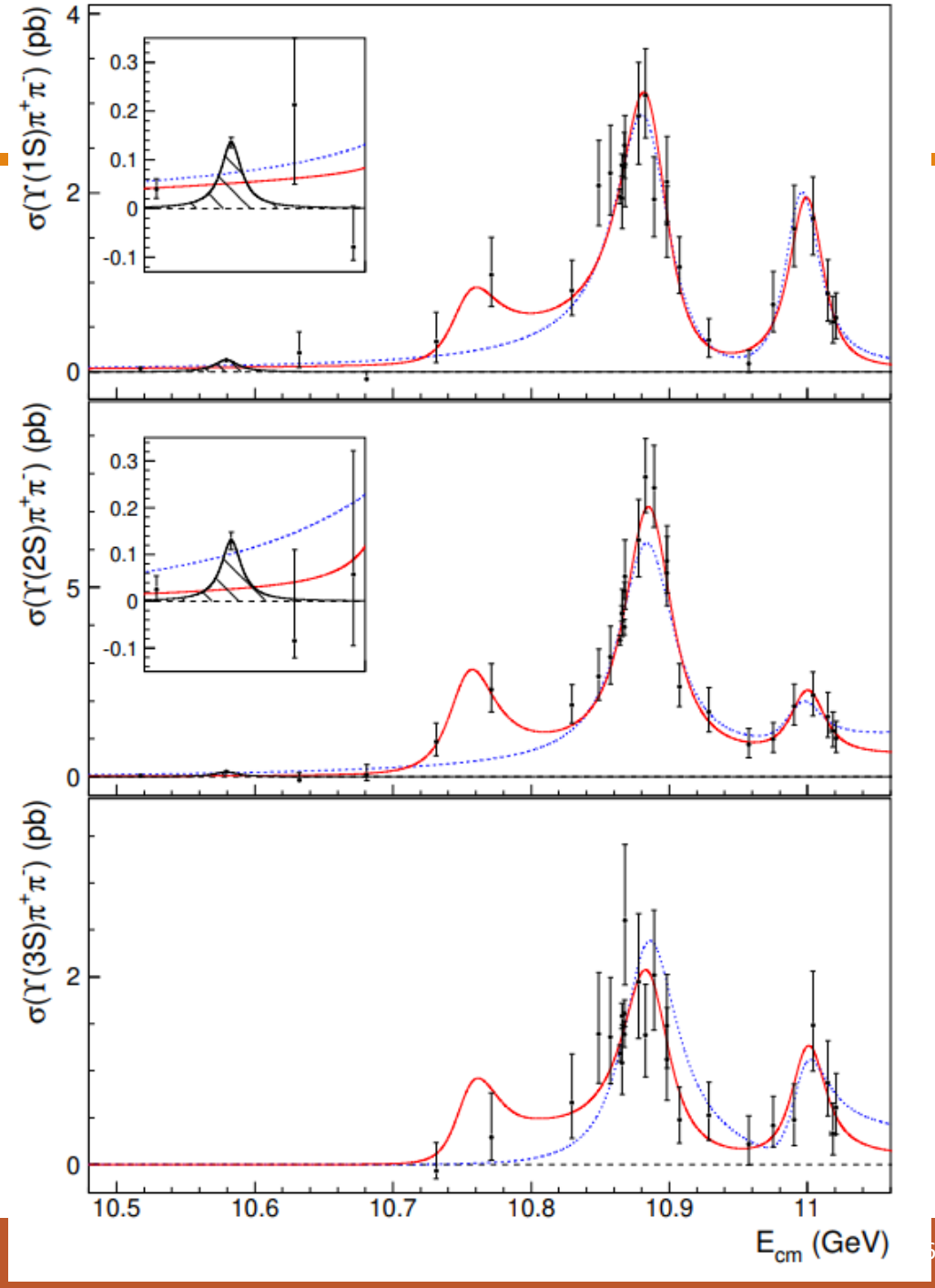
Hadronic cross section of *e*+*e*- annihilation at bottomonium energy region
X. K. Dong, X. H. Mo, P. Wang, C. Z. Yuan, Chin. Phys. C 44 (2020) 083001

- The phase between strong and EM interactions has been studied in OZI suppressed processes.
- In QCD these are described by three gluon annihilation.
- What happens to those strong decays which are not OZI suppressed?

- In Dong's work, a dip at 10.75 GeV on the Born order cross section of $e^+e^- \to b\bar{b}$



- BELLE observed a new structure near 10.75 GeV in the energy dependence of the $e^+e^- \rightarrow Y(nS)\pi^+\pi^-$ $(n = 1,2,3)$ cross sections,
- This indicates that the dip is very probably due to the destructive interference between Y resonance and the continuum amplitude, as what we have seen in $\psi(3770)$.
- The phase measurement is needed for new resonance discovery.



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.

- Input from theorists is highly welcome!

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.