Interference and Phase Study on the Omega Pseudoscalar Processes in the Vicinity of Narrow Charmonium Resonances

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Contants

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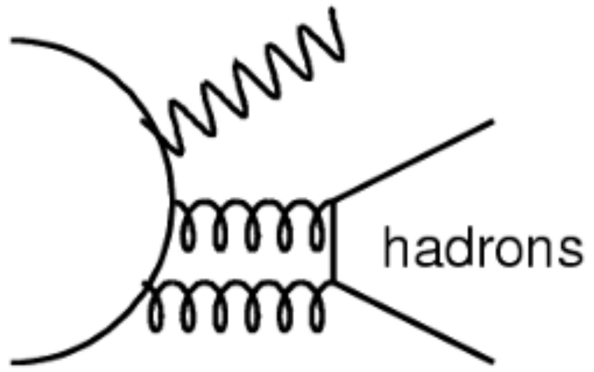
- Summary

Motivations

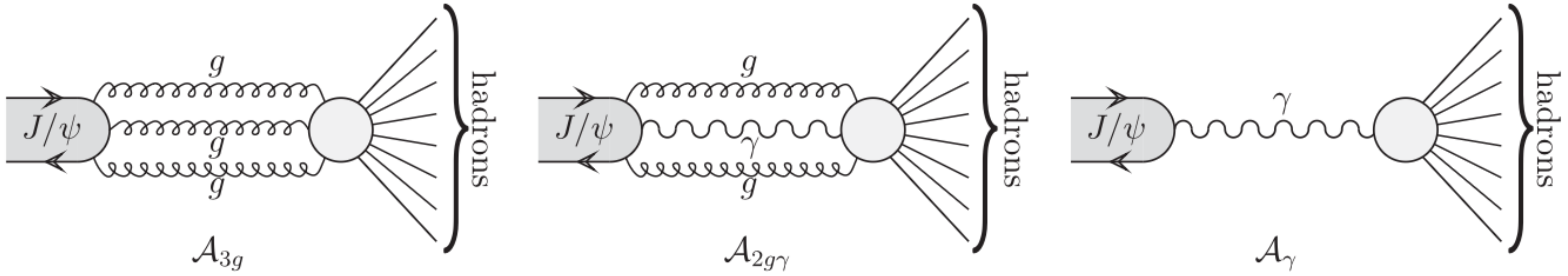
- There are mainly three J/ψ hadronic decay modes:
  - $J/\psi \to \gamma^* \to h$ (purely electromagnetic),
  - $J/\psi \to ggg$ (purely strong),
  - $J/\psi \to \gamma gg$ (mixed).



$J/\psi(1S)$ **DECAY MODES**

	Mode	Fraction (Γ_i / Γ)
Γ_1	hadrons	(87.7 ± 0.5) %
Γ_2	virtual $\gamma \to$ hadrons	(13.46 ± 0.07) %
Γ_3	ggg	(64.1 ± 1.0) %
Γ_4	γgg	(8.8 ± 1.1) %

- We believe the existence of $J/\psi \to \gamma gg$ mixed decay mode because of J/ψ radiative decays.
- The decay $J/\psi \to \gamma gg$ is not explicitly forbidden in J/ψ hadronic decays, but its experimental observation is highly challenging.
- For example, the total decay amplitude of a $J/\psi \to (2n+1)\pi$ is a sum of three main intermediate states.
  - $A = A_\gamma + A_{\gamma gg} + A_{ggg}$
  - $|A_{ggg}| \gg |A_\gamma|, |A_{\gamma gg}|$



- $J/\psi \to (2n+1)\pi$ is G-parity conserved.
  - Strong interaction preserves G-parity because of charge conjugation and isospin conservation.
  - $J/\psi(\psi')$ has negative G-parity: $C_{J/\psi} = -1$, $I_{J/\psi} = 0 \Rightarrow G_{J/\psi} = C_{J/\psi}(-1)^{I_{J/\psi}} = -1$.
  - G-parity is multiplicative quantum number: $G_{n\pi} = (-1)^n$.

Motivations

- The strong and electromagnetic amplitudes had been separated for $J/\psi \to 5\pi$.
  - BESII collaboration, PLB(2019) **791** 375
- P. Wang et al., PRD(2004) **69** 057502
  - $A_{\text{cont.}} = \mathscr{F}_{n\pi}(W)e^{i\phi_{\text{cont.}}}$, the amplitude of the continuum background from $e^+e^- \to$ odd $n\pi$
  - $A_\gamma(W) = \dfrac{3W\Gamma_{ee}}{\alpha\left(W^2 - M^2 + iM\Gamma\right)}\mathscr{F}_{n\pi}(W)e^{i\phi_\gamma}$
  - $A_{ggg}(W) = C_{ggg}e^{i\phi_{ggg}}A_\gamma(W)$
- Similarly, $A_{\gamma gg}(W) = C_{\gamma gg}e^{i\phi_{\gamma gg}}A_\gamma(W)$
- $A_{n\pi} = A_{\text{cont.}} + A_\gamma + A_{\gamma gg} + A_{ggg}$
- $\sigma^{\text{Born}}_{n\pi}(W) = \dfrac{4\pi\alpha^2}{W^3}\left|A_{n\pi}\right|^2 P_{n\pi}(W)$ with $P_{n\pi}(W) = \dfrac{q^3_{n\pi}}{3}$

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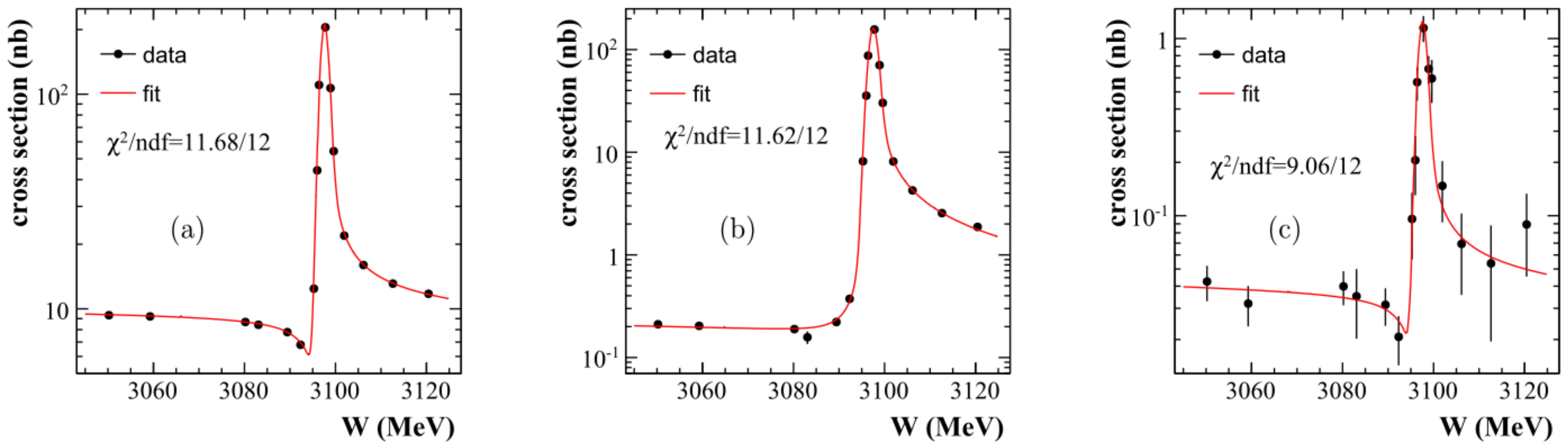


Fig. 3. The lineshapes of e^+e^- annihilates to (a) $\mu^+\mu^-$, (b) 5π, and (c) $\eta\pi^+\pi^-$. The black points with error bars are data, and the solid lines show the fit results.

Motivations

- The dressed cross section which includes the vacuum-polarization effects is

$$\sigma^{\text{dre}} = \frac{4\pi\alpha^2}{3W^2}\left(\frac{\mathscr{F}_{n\pi}}{W^2}\right)^2 q_{n\pi}^3(W)\left|\frac{1}{\left|1-\Pi_0(W)\right|}e^{i\phi_{\text{cont.}}} + \frac{3W\Gamma_{ee}}{\alpha\left(W^2-M^2+iM\Gamma\right)}\left(1e^{i\phi_\gamma}+C_{\gamma gg}e^{i\phi_{\gamma gg}}+C_{ggg}e^{i\phi_{ggg}}\right)\right|^2$$

$$= \frac{4\pi\alpha^2}{3W^2}\left(\frac{\mathscr{F}_{\omega\pi^0}}{W^2}\right)^2 q_{n\pi}^3(W)\left|\frac{1}{\left|1-\Pi_0(W)\right|} + \frac{3W\Gamma_{ee}}{\alpha\left(W^2-M^2+iM\Gamma\right)}\left(1e^{i\phi_{\gamma,\text{cont.}}}+C_{ggg}e^{i\phi_{\gamma gg,\text{cont.}}}+C_{\gamma gg}e^{i\phi_{ggg,\text{cont.}}}\right)\right|^2$$

- $$\simeq \frac{4\pi\alpha^2}{3W^2}\left(\frac{\mathscr{F}_{\omega\pi^0}}{W^2}\right)^2 q_{n\pi}^3(W)\left|\frac{1}{\left|1-\Pi_0(W)\right|} + \frac{3W\Gamma_{ee}e^{i\phi_{\gamma,\text{cont.}}}}{\alpha\left(W^2-M^2+iM\Gamma\right)}\left(1+C_{ggg}e^{i\phi_{\gamma gg,\gamma}}\right)\right|^2$$

  - The “bare” resonance mass M, total and electron widths Γ and Γ_{ee} are replaced by the physical ones, respectively.
  - $\phi_{\gamma,\text{cont.}} = \phi_\gamma - \phi_{\text{cont.}}$; $\phi_{\gamma gg,\text{cont.}} = \phi_{\gamma gg} - \phi_{\text{cont.}}$; $\phi_{\gamma gg,\gamma} = \phi_{\gamma gg} - \phi_\gamma$
- Usually, $A_{\gamma gg}$ is **ignored** because $|A_{ggg}| \gg |A_{\gamma gg}| \Rightarrow C_{ggg} \gg C_{\gamma gg}$

Motivations

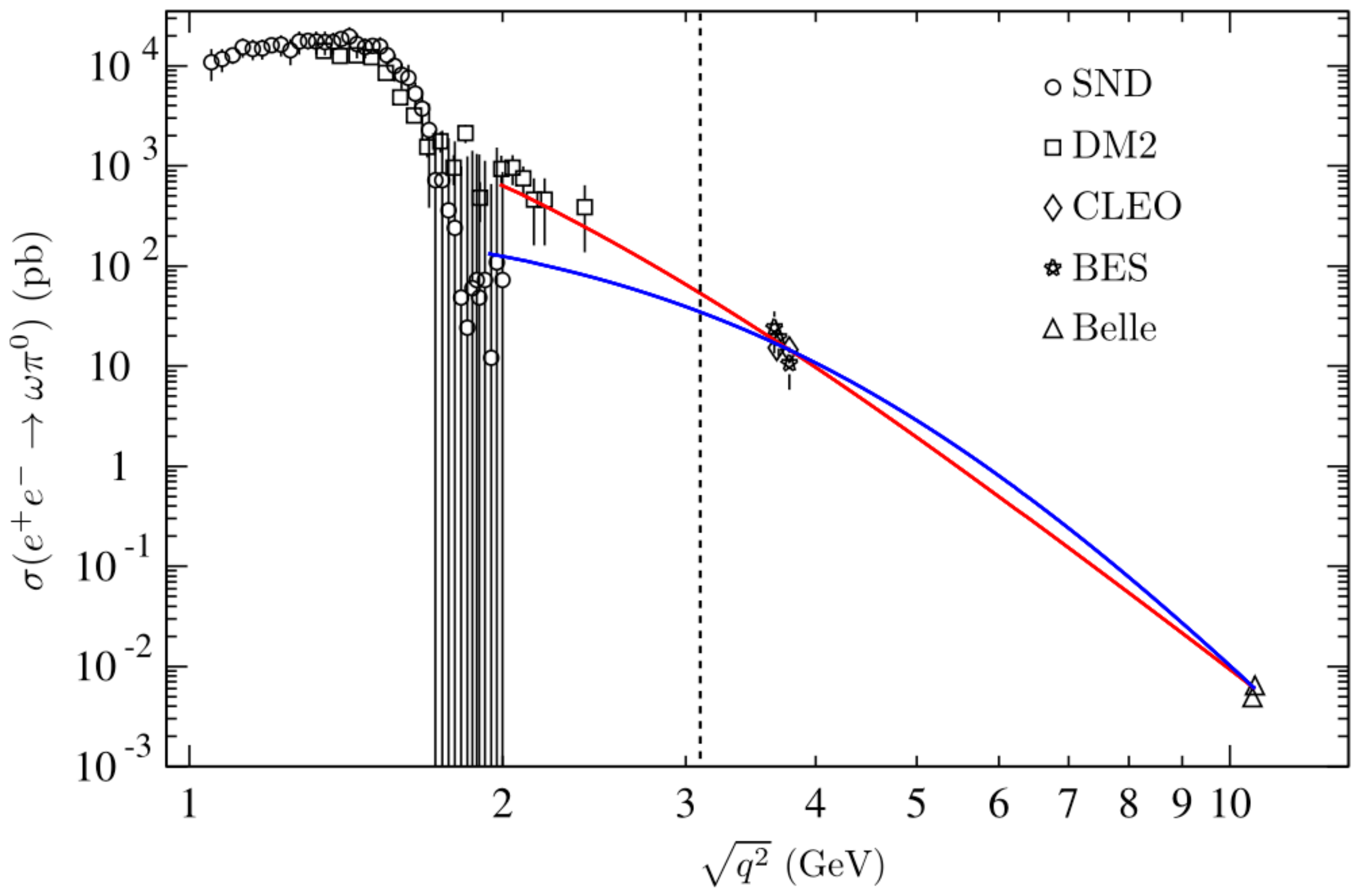
- If we want to experimentally observe the **mixed γgg decay mode** in J/ψ hadronic decay, the **purely strong ggg decay mode** must be **suppressed**.
- For an isospin violated decay, the purely strong amplitude A_{ggg} is **suppressed** by the dimensionless factor $|m_u - m_d|/\sqrt{q^2}$.
- As it has been mentioned that strong interaction preserves G-parity.
  - Electromagnetic and weak interactions can be G-parity and isospin violated.
- $J/\psi(\psi') \to 2n\pi$ is G-parity violated.
- The decays of $J/\psi(\psi') \to \omega \mathrm{P}(\pi^0, \eta, \eta')$ can have exclusive $2n\pi$ final states:
  - $\omega \to \pi^+\pi^-\pi^0 \Rightarrow J/\psi(\psi') \to \omega\pi^0 \to \pi^+\pi^-2\pi^0$
  - $\eta \to \pi^+\pi^-\pi^0 \Rightarrow J/\psi(\psi') \to \omega\eta \to 2(\pi^+\pi^-\pi^0)$
    - $\eta \to 3\pi^0 \Rightarrow J/\psi(\psi') \to \omega\eta \to \pi^+\pi^-4\pi^0$
  - $\eta' \to \eta\pi^+\pi^- \Rightarrow J/\psi(\psi') \to \omega\eta' \to 3(\pi^+\pi^-)2\pi^0$ or $J/\psi(\psi') \to \omega\eta' \to 2(\pi^+\pi^-)4\pi^0$
- $J/\psi \to \gamma gg$ **might be** experimentally observed in the J/ψ hadronic resonance decay $J/\psi \to \omega \mathrm{P} \to 2n\pi$.

Motivations

- For a $J/\psi \to \omega P \to 2n\pi$ decay, the isospin violation is driven by either **electromagnetic effects** or **quark mass differences**.
- $J/\psi(\psi') \to \omega\pi^0$ is G-parity and isospin violated which is driven by **electromagnetic effects**.
  - $I_{J/\psi} = 0;$ $\quad G_{J/\psi} = -1$
  - $I_\omega = 0, I_{\pi^0} = 1 \Rightarrow I_{\omega\pi^0} = 1;$ $\quad G_\omega = -1, G_{\pi^0} = -1 \Rightarrow G_{\omega\pi^0} = +1$
  - $I_\omega = 0, I_{\eta(\eta')} = 0 \Rightarrow I_{\omega\eta(\eta')} = 0;$ $\quad G_\omega = -1, G_{\eta(\eta')} = +1 \Rightarrow G_{\omega\eta(\eta')} = -1$
- $J/\psi \to \omega\eta$ is G-parity and isospin conserved.
  - It is well known that $\eta \to \pi^+\pi^-\pi^0$ or $\eta \to 3\pi^0$ is G-parity and isospin violated which is driven by **quark mass differences** where the electromagnetic contribution vanishes at leading order of the chiral perturbation series
    - $\mathcal{L}_{\text{QCD}}^{\Delta m} = -\frac{1}{2}(m_u - m_d)(\bar{u}u - \bar{d}d)$
    - $\text{Br}(\eta \to 3\pi^0) = (32.56 \pm 0.21)\,\%$, $\text{Br}(\eta \to \pi^+\pi^-\pi^0) = (23.02 \pm 0.25)\,\%$
    - $\text{Br}(\eta \to 2\gamma) = (39.36 \pm 0.18)\,\%$
- Similarly, $J/\psi \to \omega\eta'$ is G-parity and isospin conserved.
  - $\eta' \to \eta\pi^+\pi^-$ is the main decay mode which is G-parity conserved
  - $\eta' \to \pi^+\pi^-\pi^0$ is rare because of isospin violation.

Motivations

- Therefore, $J/\psi \to \omega\pi^0 \to \pi^+\pi^-2\pi^0$ is the **golden channel** to experimentally observe the mixed decay mode $J/\psi \to \gamma gg$ in J/ψ hadronic resonance decay.
- Rinaldo Baldini Ferroli et al., [PRD(2017) **95**, 034038] interpolated the cross section $\sigma(e^+e^- \to \omega\pi^0)$ to $\sqrt{q^2} = M_{J/\psi}$ with DM2 and SND experiments data at lower energy regions $q^2 \in [1.05,\ 2.00]$ GeV and higher energy region BES, CLEO and Belle data at $\psi(3686)$, $\psi(3770)$ and $\Upsilon(4S)$ to obtain the branching ratio of the purely electromagnetic process.
  - $B_\gamma(J/\psi \to \omega\pi^0) = \begin{cases} (3.53 \pm 0.18) \times 10^{-4} \\ (2.29 \pm 0.40) \times 10^{-4} \end{cases}$
  - $B_{PDG}(J/\psi \to \omega\pi^0) = (4.5 \pm 0.5) \times 10^{-4}$



Motivations

- R. B. Ferroli et al., [PLB(2019) **799**, 135041; PRD(2021) **103**, 016005] also discussed the amplitudes separation in J/ψ and ψ' baryon decays by using an effective strong Lagrangian density and considering $B\bar{B}$ spin-1/2 SU(3) octet.
- Unfortunately, the $A_{\gamma gg}$ amplitude is zero in the A_{ggg} suppressed decay channel

Table 12
Purely strong (second column), purely EM (third column) and mixed (fourth column) BRs in the case of a complex ratio R.

$B\bar{B}$	$\mathrm{BR}^{ggg}_{B\bar{B}} \times 10^3$	$\mathrm{BR}^{\gamma}_{B\bar{B}} \times 10^5$	$\mathrm{BR}^{gg\gamma}_{B\bar{B}} \times 10^5$
$\Sigma^0\bar{\Sigma}^0$	1.100 ± 0.017	0.903 ± 0.061	0
$\Lambda\bar{\Lambda}$	2.010 ± 0.024	0.982 ± 0.066	0
$\Lambda\bar{\Sigma}^0$+ c.c.	0	2.83 ± 0.19	0
$p\bar{p}$	2.210 ± 0.043	8.47 ± 0.43	2.97 ± 0.87
$n\bar{n}$	2.210 ± 0.043	4.50 ± 0.30	0
$\Sigma^+\bar{\Sigma}^-$	1.100 ± 0.017	6.82 ± 0.35	1.49 ± 0.44
$\Sigma^-\bar{\Sigma}^+$	1.090 ± 0.017	0.500 ± 0.094	1.47 ± 0.43
$\Xi^0\bar{\Xi}^0$	1.260 ± 0.027	2.99 ± 0.20	0
$\Xi^-\bar{\Xi}^+$	1.240 ± 0.026	0.410 ± 0.077	1.67 ± 0.49

TABLE I. Parametrizations of the $B\bar{B}$ decay amplitudes.

$B\bar{B}$	$A^{ggg}_{B\bar{B}}$	$A^{gg\gamma}_{B\bar{B}}$	$A^{\gamma}_{B\bar{B}}$
$p\bar{p}$	$(G_0 - D_m + F_m)e^{i\varphi}$	$A^{ggg}_{p\bar{p}}R$	$D_e + F_e$
$n\bar{n}$	$(G_0 - D_m + F_m)e^{i\varphi}$	0	$-2D_e$
$\Lambda\bar{\Sigma}^0$+ c.c.	0	0	$\sqrt{3}D_e$
$\Lambda\bar{\Lambda}$	$(G_0 - 2D_m)e^{i\varphi}$	0	$-D_e$
$\Sigma^+\bar{\Sigma}^-$	$(G_0 + 2D_m)e^{i\varphi}$	$A^{ggg}_{\Sigma^+\bar{\Sigma}^-}R$	$D_e + F_e$
$\Sigma^-\bar{\Sigma}^+$	$(G_0 + 2D_m)e^{i\varphi}$	$A^{ggg}_{\Sigma^-\bar{\Sigma}^+}R$	$D_e - F_e$
$\Sigma^0\bar{\Sigma}^0$	$(G_0 + 2D_m)e^{i\varphi}$	0	D_e
$\Xi^0\bar{\Xi}^0$	$(G_0 - D_m - F_m)e^{i\varphi}$	0	$-2D_e$
$\Xi^-\bar{\Xi}^+$	$(G_0 - D_m - F_m)e^{i\varphi}$	$A^{ggg}_{\Xi^-\bar{\Xi}^+}R$	$D_e - F_e$

TABLE VI. Strong (second column), EM (third column) and mixed (fourth column) BRs for the $\psi(2S)$ meson.

$B\bar{B}$	$\mathrm{BR}^{ggg}_{B\bar{B}} \times 10^4$	$\mathrm{BR}^{\gamma}_{B\bar{B}} \times 10^6$	$\mathrm{BR}^{gg\gamma}_{B\bar{B}} \times 10^6$
$p\bar{p}$	3.20 ± 0.12	1.34 ± 0.17	1.3 ± 1.0
$n\bar{n}$	3.20 ± 0.12	0.99 ± 0.11	0
$\Lambda\bar{\Lambda}$	3.61 ± 0.13	0.229 ± 0.026	0
$\Sigma^+\bar{\Sigma}^-$	2.30 ± 0.10	1.19 ± 0.15	0.94 ± 0.73
$\Sigma^-\bar{\Sigma}^+$	2.29 ± 0.10	0.028 ± 0.022	0.94 ± 0.73
$\Sigma^0\bar{\Sigma}^0$	2.30 ± 0.10	0.219 ± 0.024	0
$\Xi^0\bar{\Xi}^0$	3.19 ± 0.11	0.807 ± 0.089	0
$\Xi^-\bar{\Xi}^+$	3.17 ± 0.11	0.026 ± 0.020	1.28 ± 0.98

$J/\psi \to B\bar{B}$

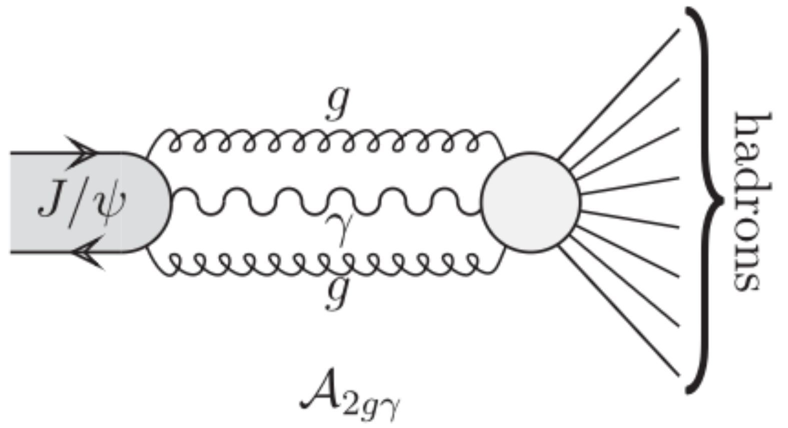
$\psi' \to B\bar{B}$

$$\mathrm{Br}^{\gamma}_{B\bar{B}}(\psi' \to \Lambda\bar{\Sigma}^0 + c.c.) = (1.6 \pm 0.7) \times 10^{-6}$$

BESIII Collaboration, PRD(2021) **103**, 112004

Motivations

- Including $J/\psi \to \gamma gg \to \omega\pi^0$, the dressed cross section for $J/\psi \to \omega\pi^0$ is



$$\sigma^{\text{dre}} = \frac{4\pi\alpha^2}{3W^2}\left(\frac{\mathcal{F}_{\omega\pi^0}}{W^2}\right)^2 q^3_{\omega\pi^0}(W)\left|\frac{1}{\left|1-\Pi_0(W)\right|}e^{i\phi_{\text{cont.}}} + \frac{3W\Gamma_{ee}}{\alpha\left(W^2-M^2+iM\Gamma\right)}\left(1e^{i\phi_\gamma}+C_{\gamma gg}e^{i\phi_{\gamma gg}}\right)\right|^2$$

- $$= \frac{4\pi\alpha^2}{3W^2}\left(\frac{\mathcal{F}_{\omega\pi^0}}{W^2}\right)^2 q^3_{\omega\pi^0}(W)\left|\frac{1}{\left|1-\Pi_0(W)\right|} + \frac{3W\Gamma_{ee}e^{i\phi_{\gamma,\text{cont.}}}}{\alpha\left(W^2-M^2+iM\Gamma\right)}\left(1+C_{\gamma gg}e^{i\phi_{\gamma gg,\gamma}}\right)\right|^2$$

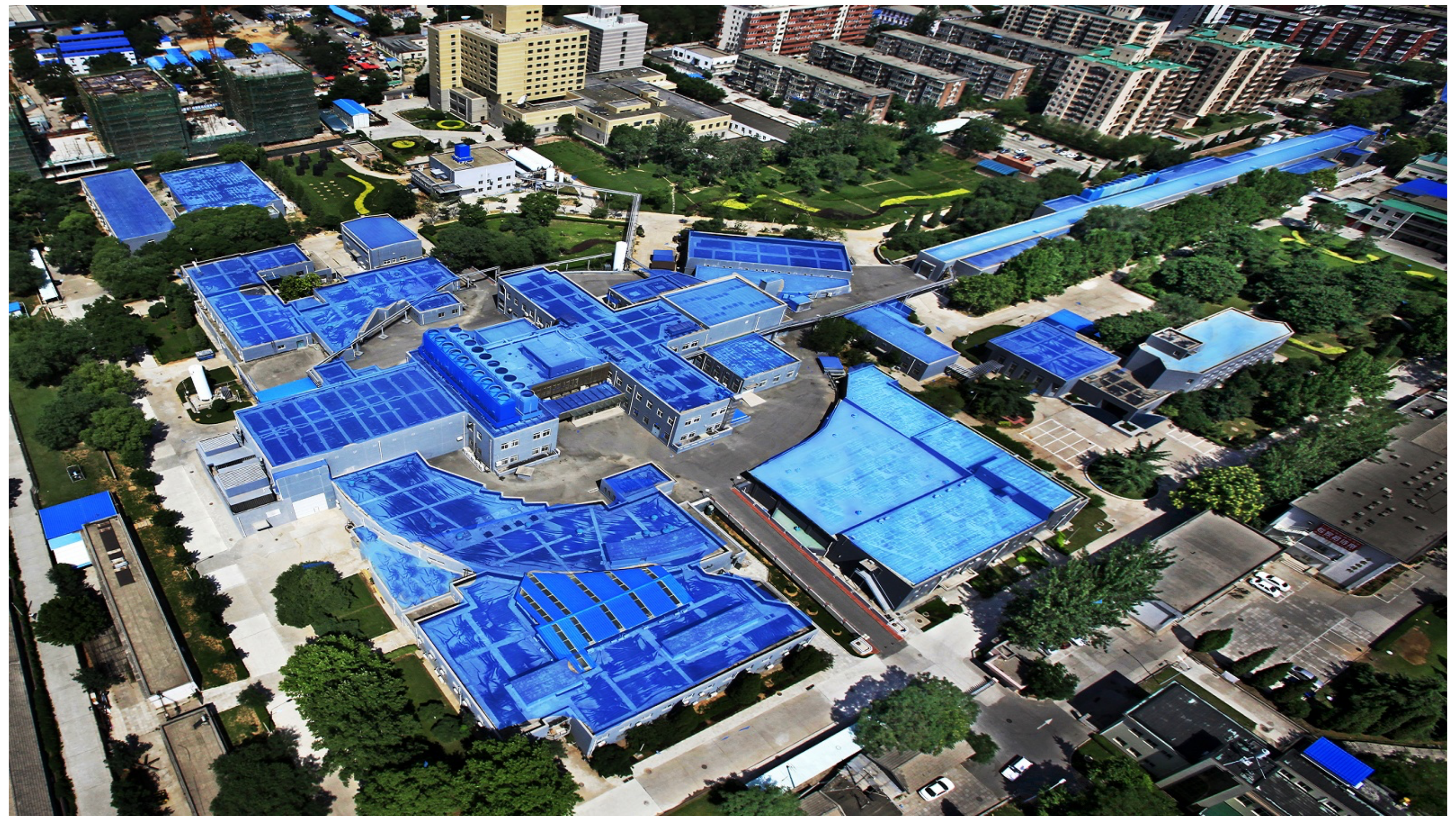
- If $C_{\gamma gg}$ is non-zero, we will observe the **mixed** $J/\psi \to \gamma gg \to \omega\pi^0$ decay mode.
- BESIII have collected data at 24 energies around J/ψ resonance and 11 energies around $\psi(3686)$ resonance.

Motivations

- For e^+e^- annihilation, initial state radiation (ISR) effect must be considered. [E. A. Kuraev and V. S. Fadin, SJNP(1985) **41**, 466]
  - $\sigma^{\mathrm{ISR}}(W) = \int_0^{1-\left(\frac{W_{\min}}{W}\right)^2} \mathrm{d}x F(x,W) \times \sigma^{\mathrm{dre}}(W\sqrt{1-x})$
    - $F(x,W) = \beta x^{\beta-1}(1+\delta) - \beta\left(1-\frac{x}{2}\right) + \frac{1}{8}\beta^2\left[4(2-x)\times\log\frac{1}{x} - \frac{1+3(1-x)^2}{x}\log(1-x) - 6 + x\right]$
      - $\delta = \frac{3}{4}\beta + \frac{\alpha}{\pi}\left(\frac{\pi^2}{3}-\frac{1}{2}\right) + \beta^2\left(\frac{9}{32}-\frac{\pi^2}{12}\right), \beta = \frac{2\alpha}{\pi}\left(2\log\frac{W}{m_e}-1\right)$
- Since the decay widths of J/ψ and $\psi(3686)$ are much smaller than the c.m. energy spreads S_E of BEPCII, the experimentally observed cross section is the Gaussian convolution with the dressed cross section.
  - $\sigma^{\exp}(W) = \int_{W-nS_E}^{W+nS_E} \frac{1}{\sqrt{2\pi}S_E}\exp\left(\frac{-(W-W')^2}{2S_E^2}\right)\sigma^{ISR}(W')\mathrm{d}W'$
- Y. N. Wang, Y. D. Wang, P. Wang, CPC (2024) **48**, 113103; B. X. Liu, Z. Y. Zhang, X. Zhou, PRD (2024) **110**, 053010

$e^+e^- \to \omega\pi^0$ around J/ψ resonance

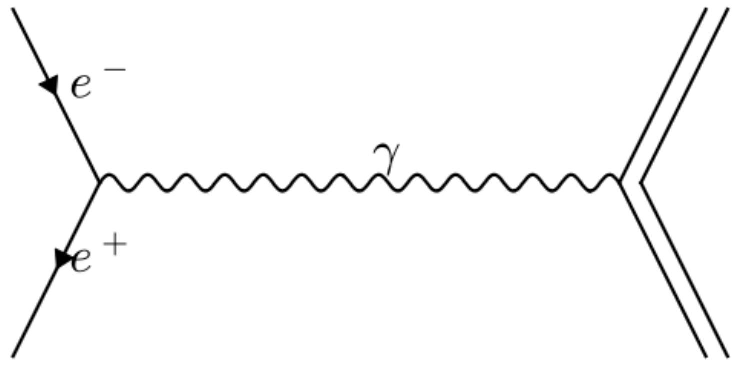
- $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-4\gamma$ with $\omega \to \pi^+\pi^-\pi^0$ and $\pi^0 \to 2\gamma$
- Data sets of 3.097 GeV
  - 2009, 2012, 2018, 2019
  - Total 10 billion
- Scan energy data sets from 3.050 GeV to 3.120 GeV
  - 2012, jpsiscan
  - 2018, tauscan

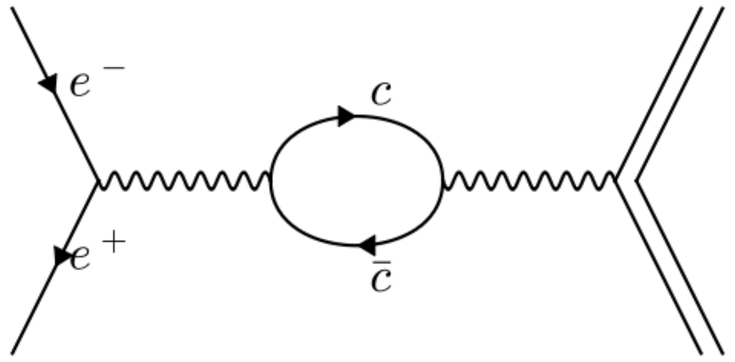


W (GeV)	**3.05**	**3.059**	**3.083**	**3.087**	**3.089**	**3.092**
L (pb^{-1})	1.4919 ± 0.161	15.060 ± 0.161	4.769 ± 0.055	2.470 ± 0.020	15.558 ± 0.165	14.910 ± 0.160
W (GeV)	**3.0952**	**3.096**	**3.0957**	**3.0962**	**3.0964**	**3.09699**
L (pb^{-1})	2.143 ± 0.025	1.816 ± 0.021	2.920 ± 0.020	4.980 ± 0.030	2.135 ± 0.025	3.100 ± 0.020
W (GeV)	**3.097**	**3.0972**	**3.0976**	**3.0978**	**3.0987**	**3.0989**
L (pb^{-1})	2962.720 ± 0.430	1.680 ± 0.010	4.660 ± 0.030	2.096 ± 0.026	2.203 ± 0.025	5.640 ± 0.030
W (GeV)	**3.0996**	**3.101**	**3.104**	**3.106**	**3.112**	**3.12**
L (pb^{-1})	0.756 ± 0.011	1.612 ± 0.021	5.720 ± 0.030	2.106 ± 0.025	1.720 ± 0.021	1.264 ± 0.016

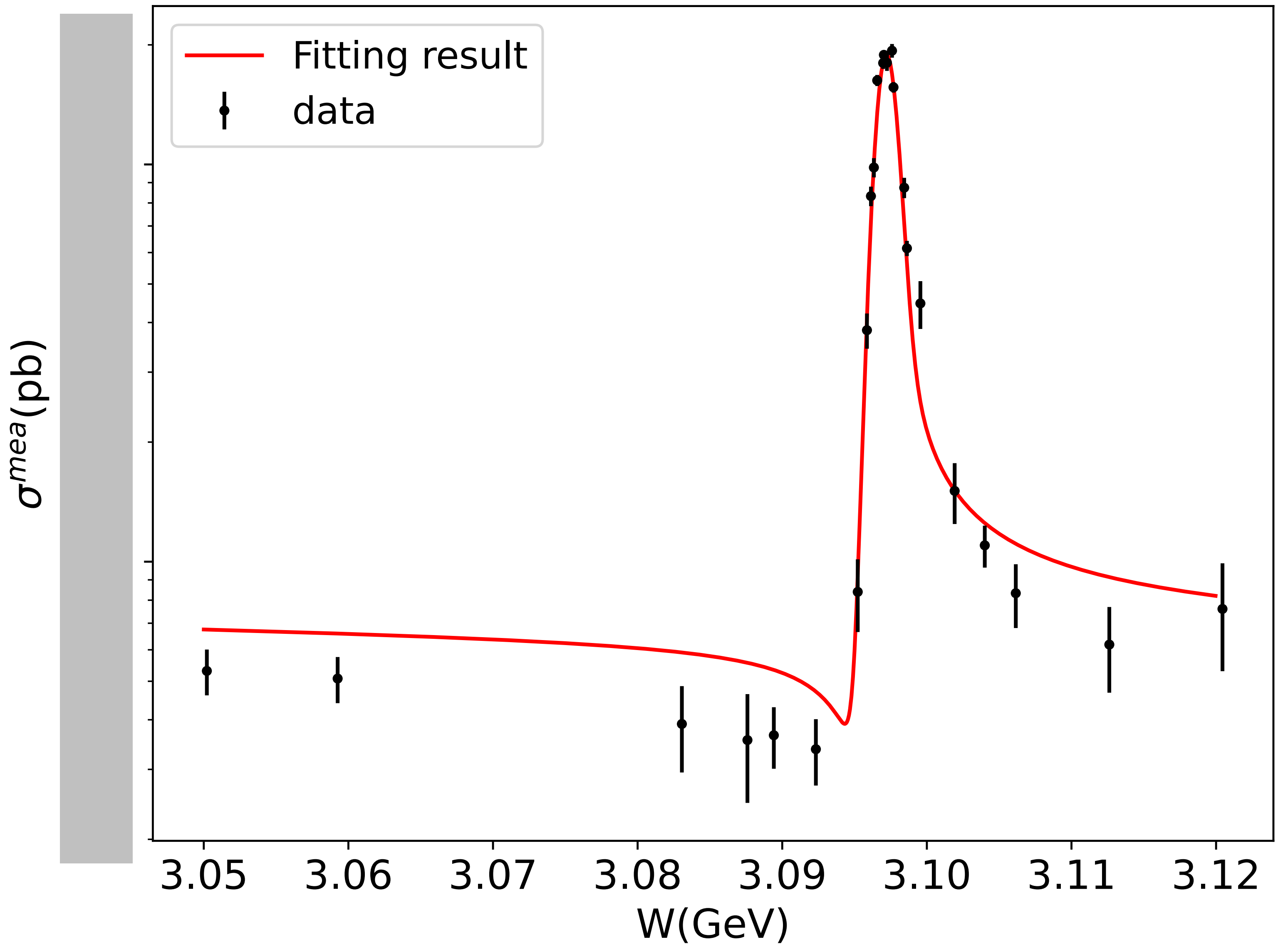
$e^+e^- \to \omega\pi^0$ around J/ψ resonance

- Firstly, we try to only consider the **purely electromagnetic** mode γ^*
  - $e^+e^- \to \omega\pi^0$
  - $e^+e^- \to J/\psi \to \gamma^* \to \omega\pi^0$



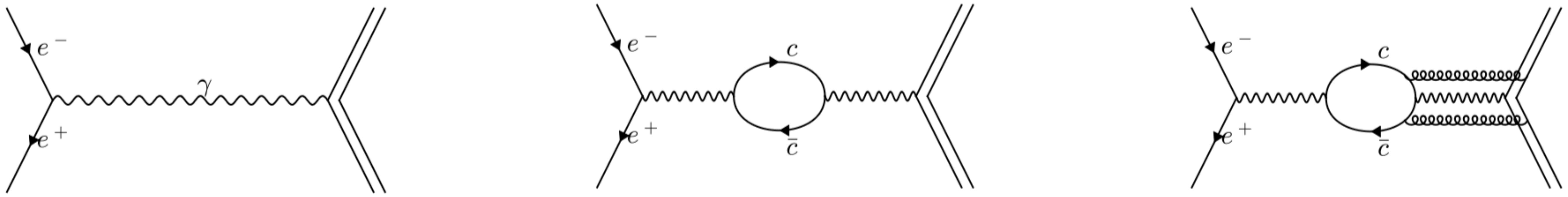


- $$\sigma^{\text{dre}} = \frac{4\pi\alpha^2}{3W^2}\left(\frac{\mathscr{F}_{\omega\pi^0}}{W^2}\right)^2 q^3_{\omega\pi^0}(W)\left|\frac{1}{|1-\Pi_0(W)|} + \frac{3W\Gamma_{ee}}{\alpha\left(W^2 - M^2 + iM\Gamma\right)}1e^{i\phi_{\gamma,\text{cont.}}}\right|^2$$



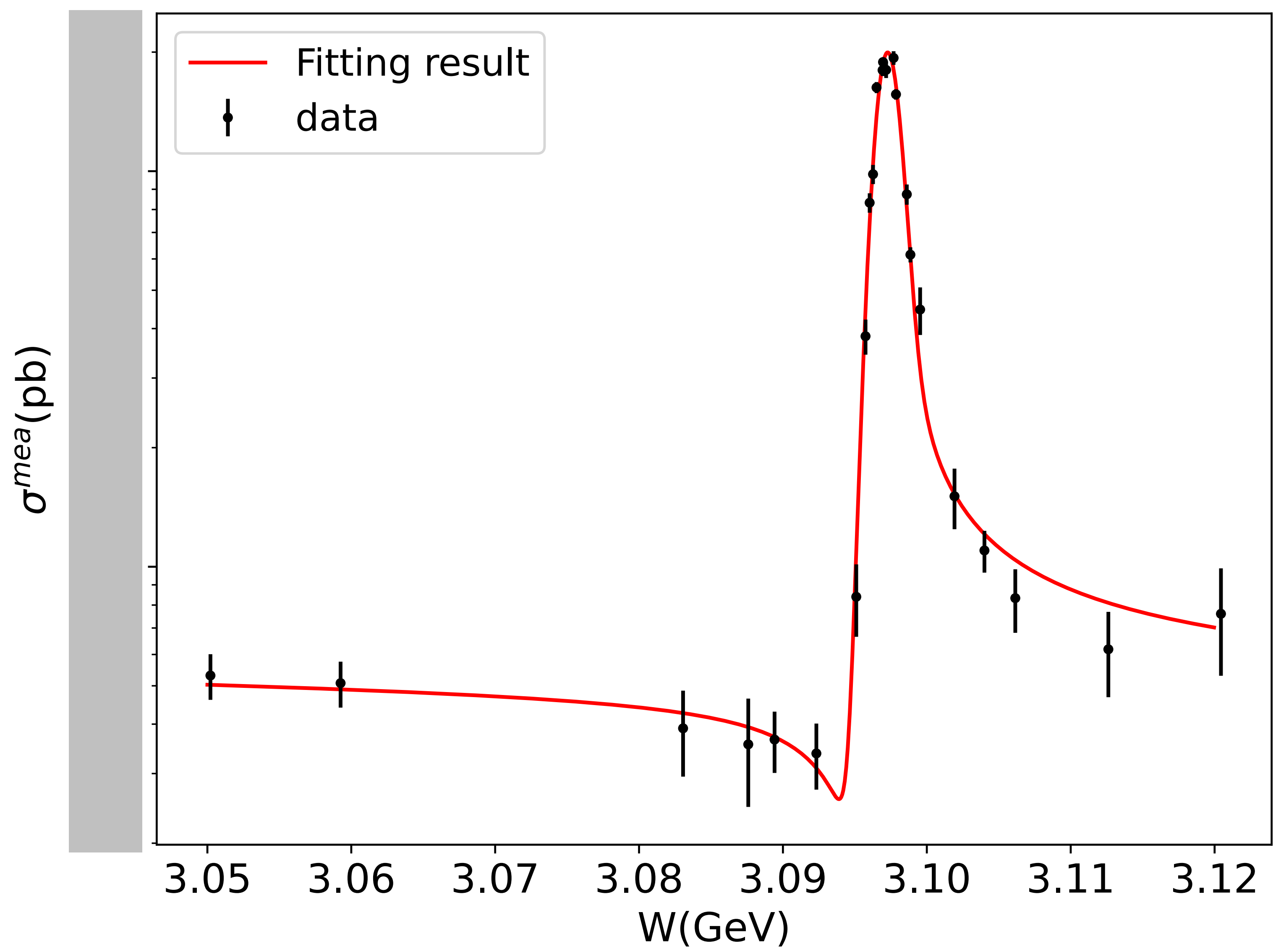
$e^+e^- \to \omega\pi^0$ around J/ψ resonance

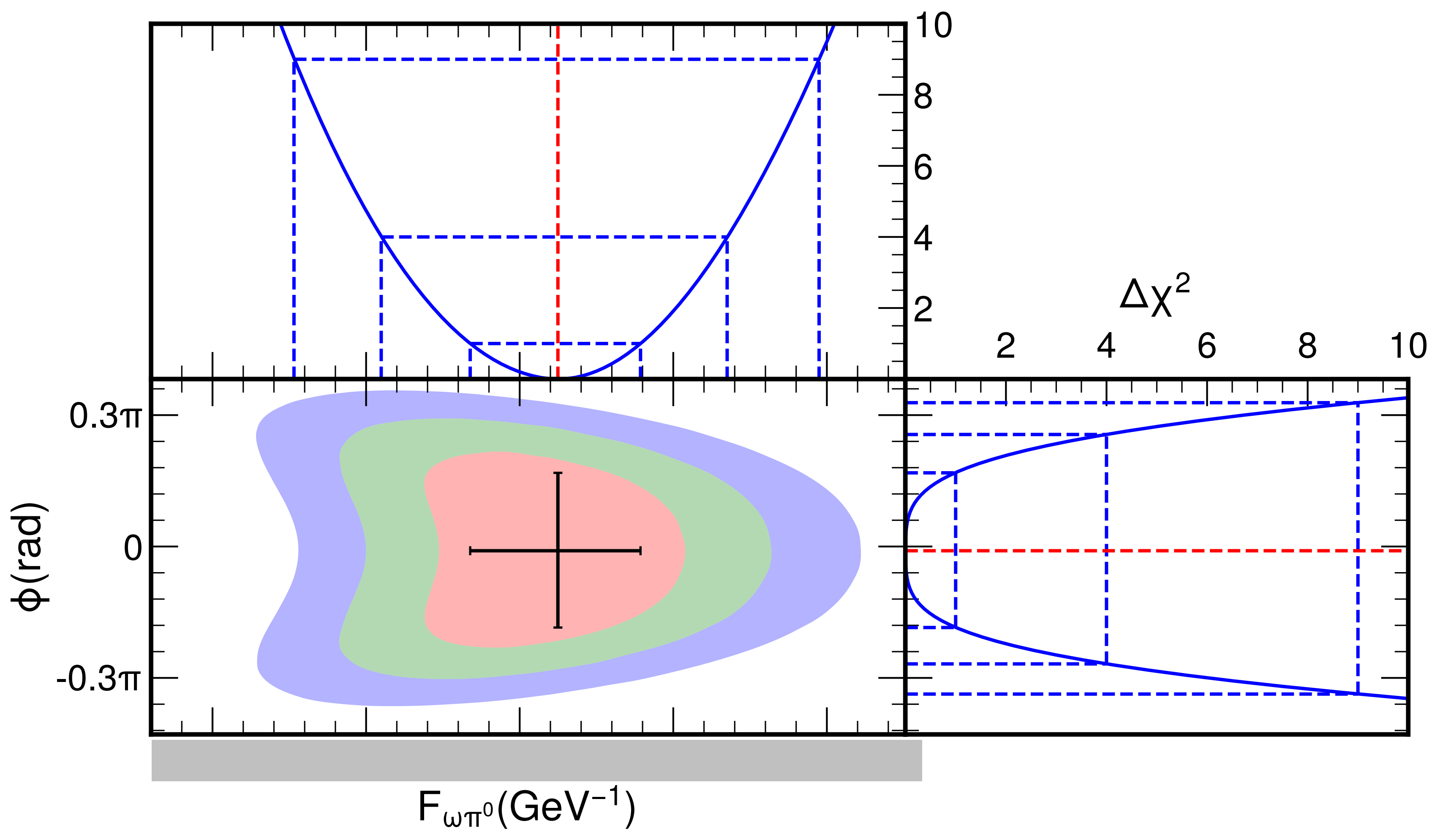
- Then, we include the **mixed mode** γgg
  - $e^+e^- \to \omega\pi^0$
  - $e^+e^- \to J/\psi \to \gamma^* \to \omega\pi^0$
  - $e^+e^- \to J/\psi \to \gamma gg \to \omega\pi^0$

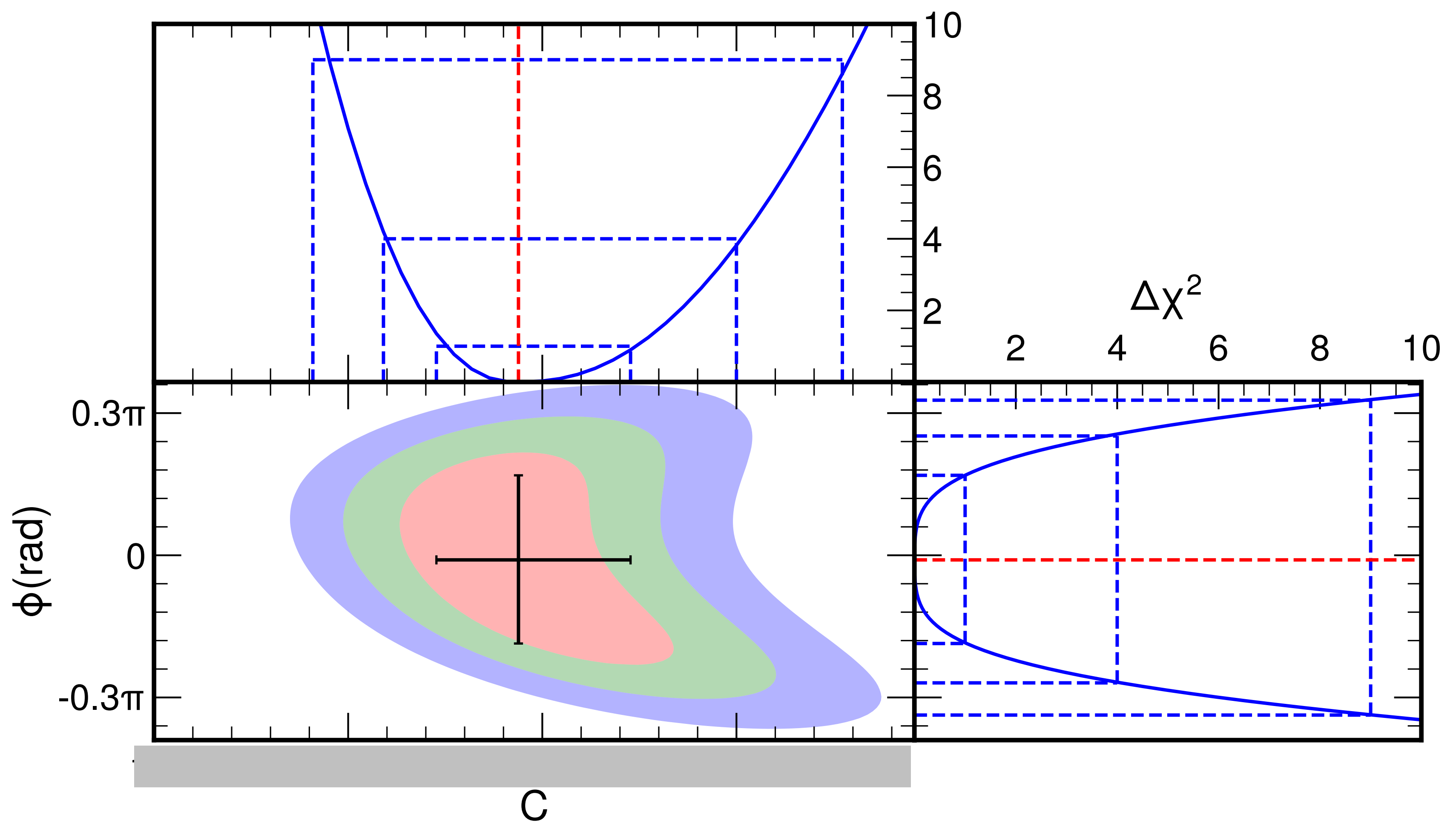


- $$\sigma^{\rm dre} = \frac{4\pi\alpha^2}{3W^2}\left(\frac{\mathcal{F}_{\omega\pi^0}}{W^2}\right)^2 q^3_{\omega\pi^0}(W)\left|\frac{1}{|1-\Pi_0(W)|} + \frac{3W\Gamma_{ee}e^{i\phi_{\gamma,\rm cont.}}}{\alpha\left(W^2-M^2+iM\Gamma\right)}\left(1 + C_{\gamma gg}e^{i\phi_{\gamma gg,\gamma}}\right)\right|^2$$
- $$Ce^{i\phi} = \left(1 + C_{\gamma gg}e^{i\phi_{\gamma gg,\gamma}}\right)e^{i\phi_{\gamma,\rm cont.}}$$

Parameter	Result
M(MeV)	3097.15 ± 0.03
$\mathcal{F}_{\omega\pi^0}$(GeV^{-1})	$(\ \ \pm 0.13) \times 10^{-1}$
C	± 0.07
$\Phi(^\circ)$	± 34.9
S_E(MeV)	0.844 ± 0.024







$e^+e^- \to \omega\pi^0$ around J/ψ resonance

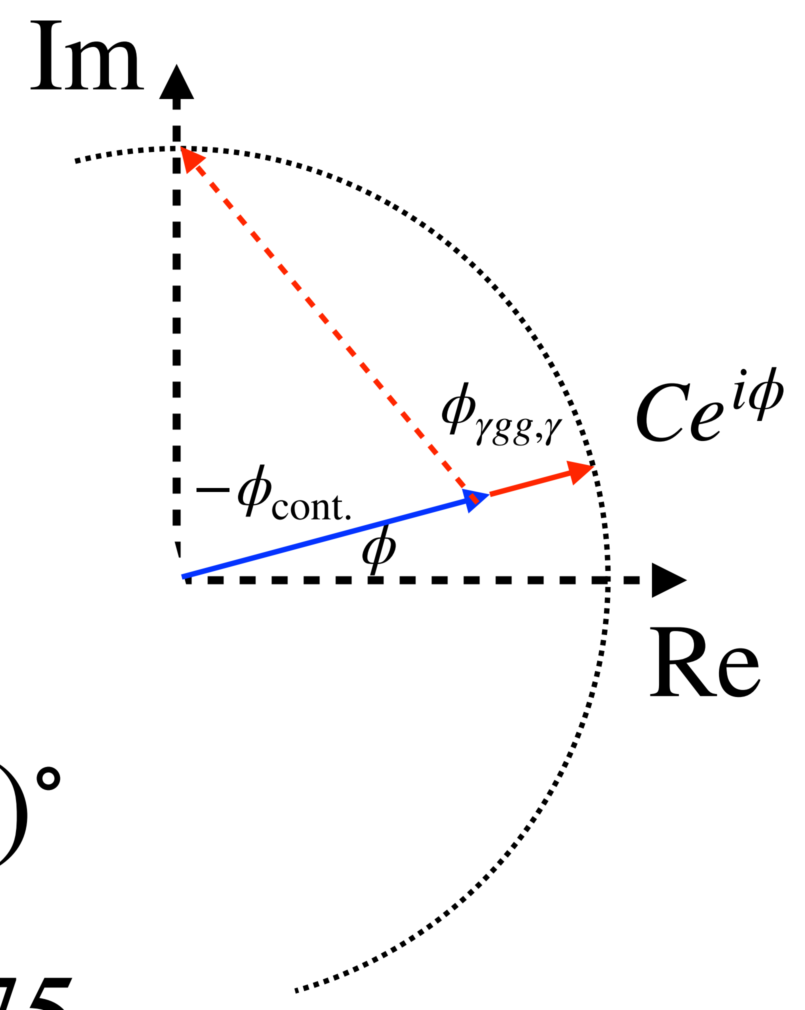
- $Ce^{i\phi} = \left(1 + C_{\gamma gg}e^{i\phi_{\gamma gg,\gamma}}\right)e^{i\phi_{\gamma,\text{cont.}}}$
  - To get $C_{\gamma gg}$, we need $\phi_{\gamma,\text{cont.}}$
  - $\phi_{\gamma,\text{cont.}} = 0$ or $\pm\pi$?
- The study of $e^+e^- \to \mu^+\mu^-$ around J/ψ resonance shows that $\phi_{\gamma,\text{cont.}} = (3.0 \pm 5.7)^\circ$
  - BESII collaboration, PLB(2019) **791** 375
- Francesco Rosini: $\phi_{\gamma,\text{cont.}} = \pm\,\pi$

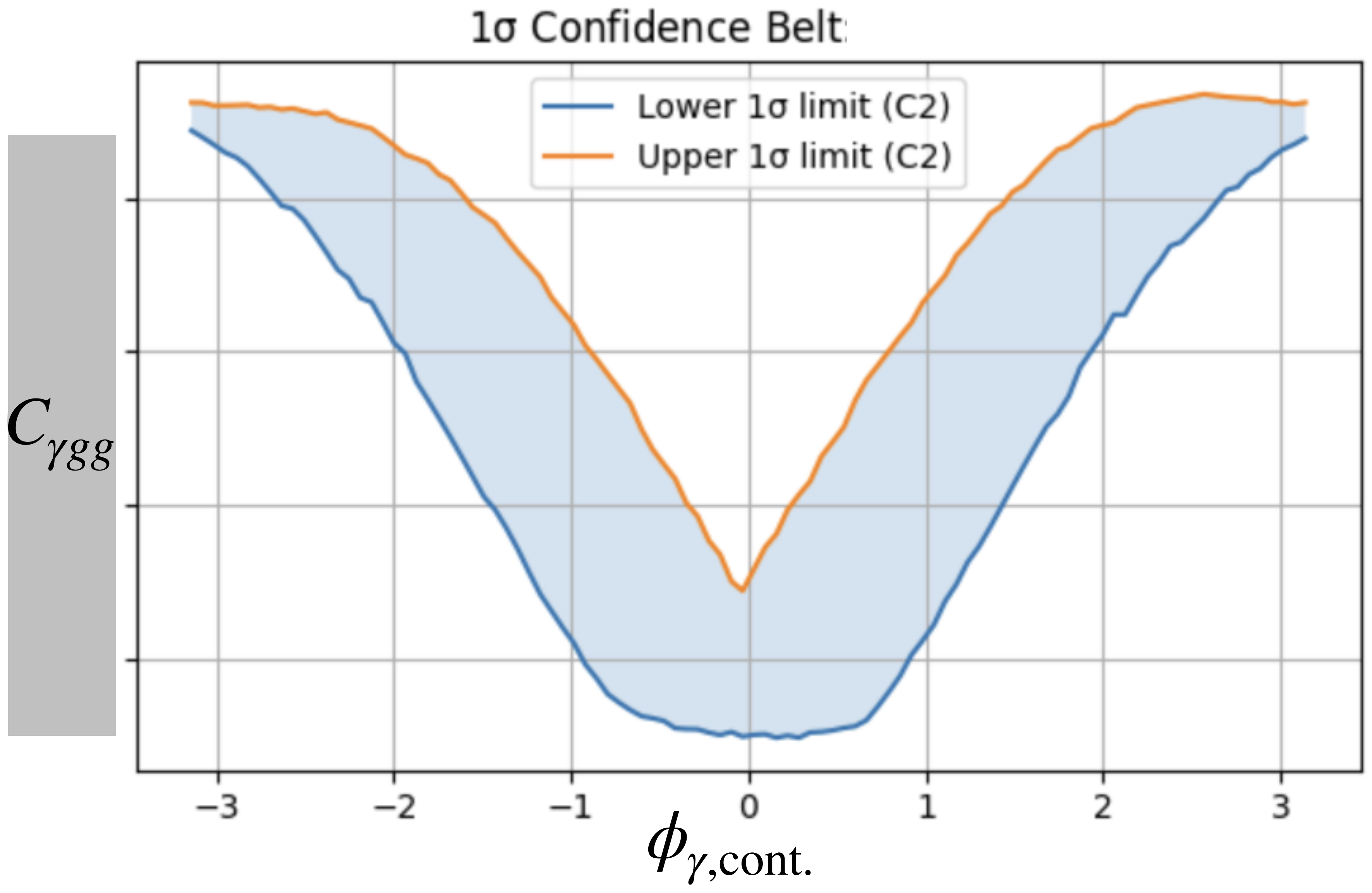
•Three contributions: continuum + $\psi \to \gamma^* \to K^+K^-$ + $\psi \to 3g \to K^+K^-$.

$$A_{\text{cont}} = eJ^e_\mu \frac{-i}{q^2} F_K(q^2)C^\mu \qquad e^+e^- \to \gamma^* \to K^+K^-$$

$$A_\gamma = eJ^e_\mu \frac{-i}{q^2}\frac{-i(g^\gamma_\psi)^2(q^2/M^2)}{q^2 - M^2 + iM\Gamma}\frac{-i}{q^2}F_K(q^2)C^\mu \qquad e^+e^- \to \gamma^* \to \psi,\ \psi \to \gamma^* \to K^+K^-$$

$$Ce^{i\phi}e^{-i\phi_{\gamma,\text{cont.}}} = 1 + C_{\gamma gg}e^{i\phi_{\gamma gg,\gamma}}$$





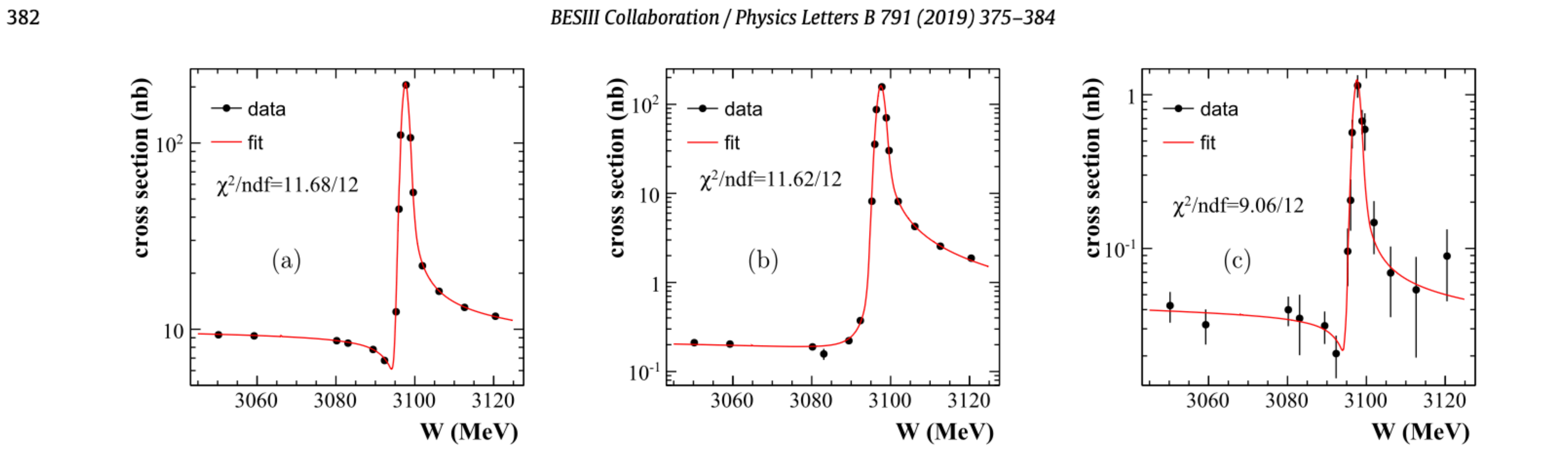


Fig. 3. The lineshapes of e^+e^- annihilates to (a) $\mu^+\mu^-$, (b) 5π, and (c) $\eta\pi^+\pi^-$. The black points with error bars are data, and the solid lines show the fit results.

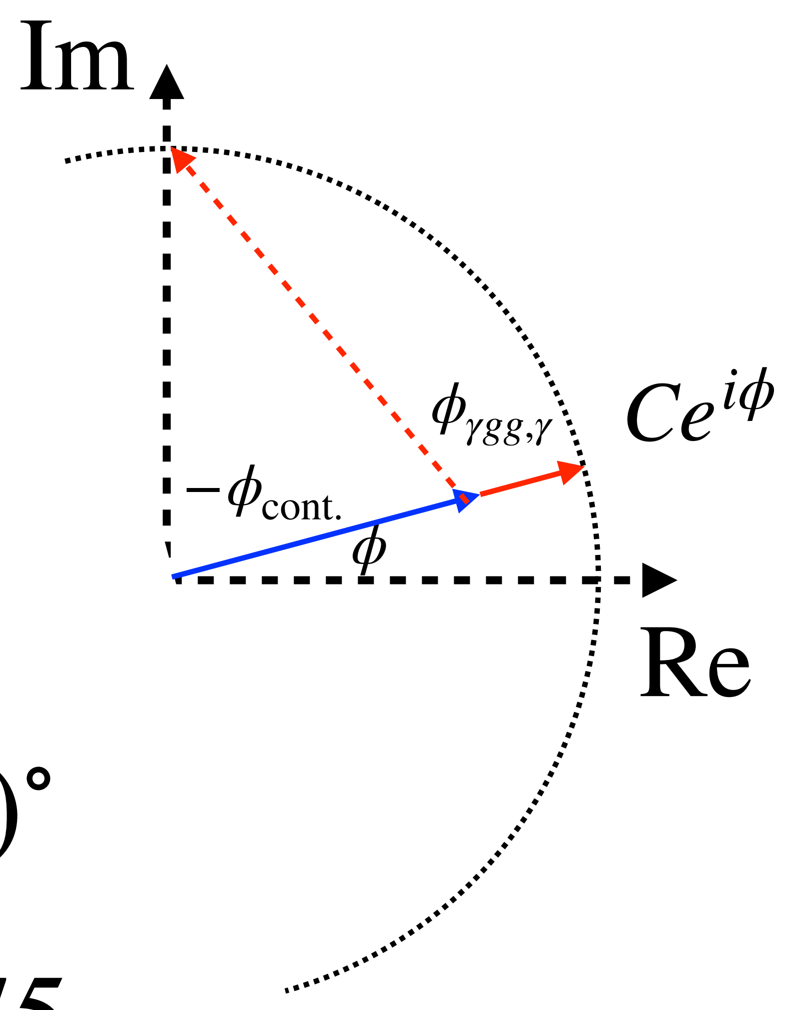
$e^+e^- \to \omega\pi^0$ around J/ψ resonance

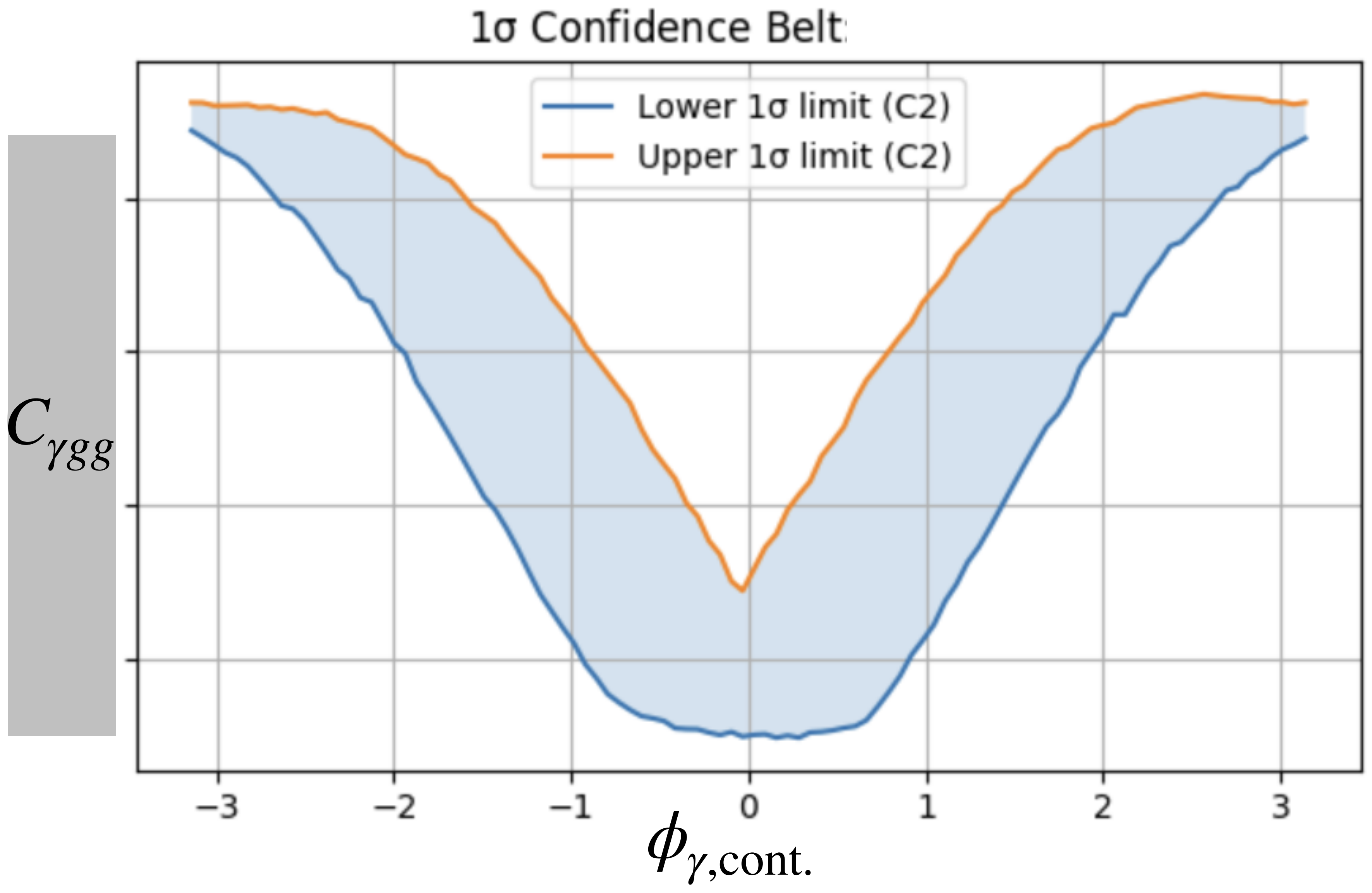
- $Ce^{i\phi} = \left(1 + C_{\gamma gg} e^{i\phi_{\gamma gg,\gamma}}\right) e^{i\phi_{\gamma,\text{cont.}}}$
  - To get $C_{\gamma gg}$, we need $\phi_{\gamma,\text{cont.}}$
  - $\phi_{\gamma,\text{cont.}} = 0$ or $\pm\pi$?
- The study of $e^+e^- \to \mu^+\mu^-$ around J/ψ resonance shows that $\phi_{\gamma,\text{cont.}} = (3.0 \pm 5.7)^\circ$
  - BESII collaboration, PLB(2019) **791** 375
- Francesco Rosini: adding i before g_ψ^γ

$$A_{\text{cont}} = eJ_\mu^e \frac{-i}{s} F_K(s)\left(p_+^\mu - p_-^\mu\right),$$

$$A_\gamma = eJ_\mu^e \frac{-i}{s} \frac{-i(ig_\psi^\gamma)^2(s/M^2)}{s - M^2 + iM\Gamma} \frac{-i}{s} F_K(s)\left(p_+^\mu - p_-^\mu\right)$$

$$Ce^{i\phi}e^{-i\phi_{\gamma,\text{cont.}}} = 1 + C_{\gamma gg} e^{i\phi_{\gamma gg,\gamma}}$$





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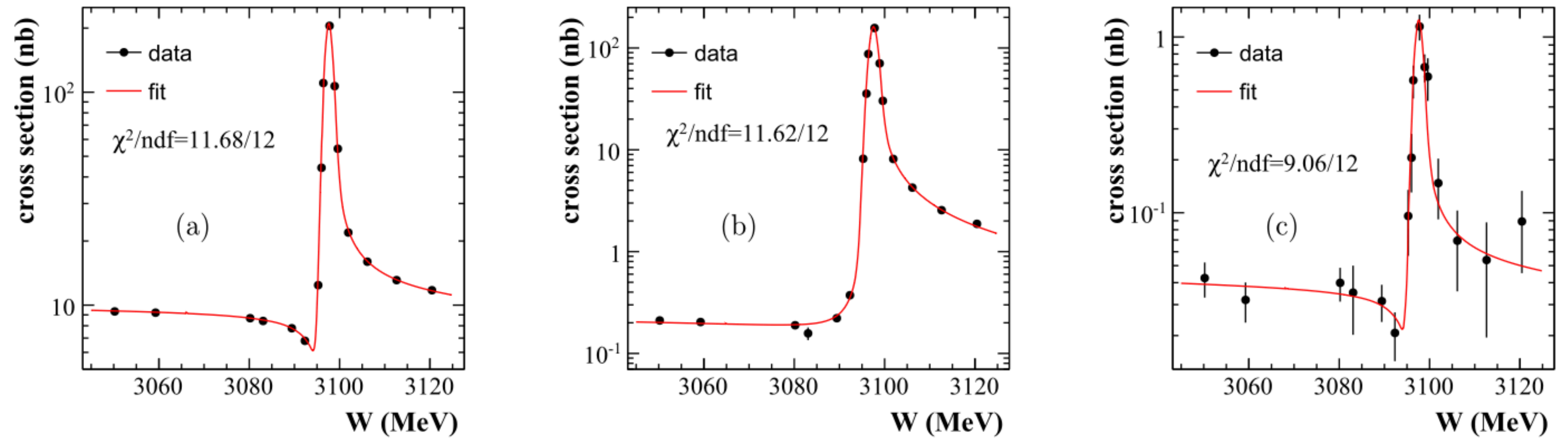
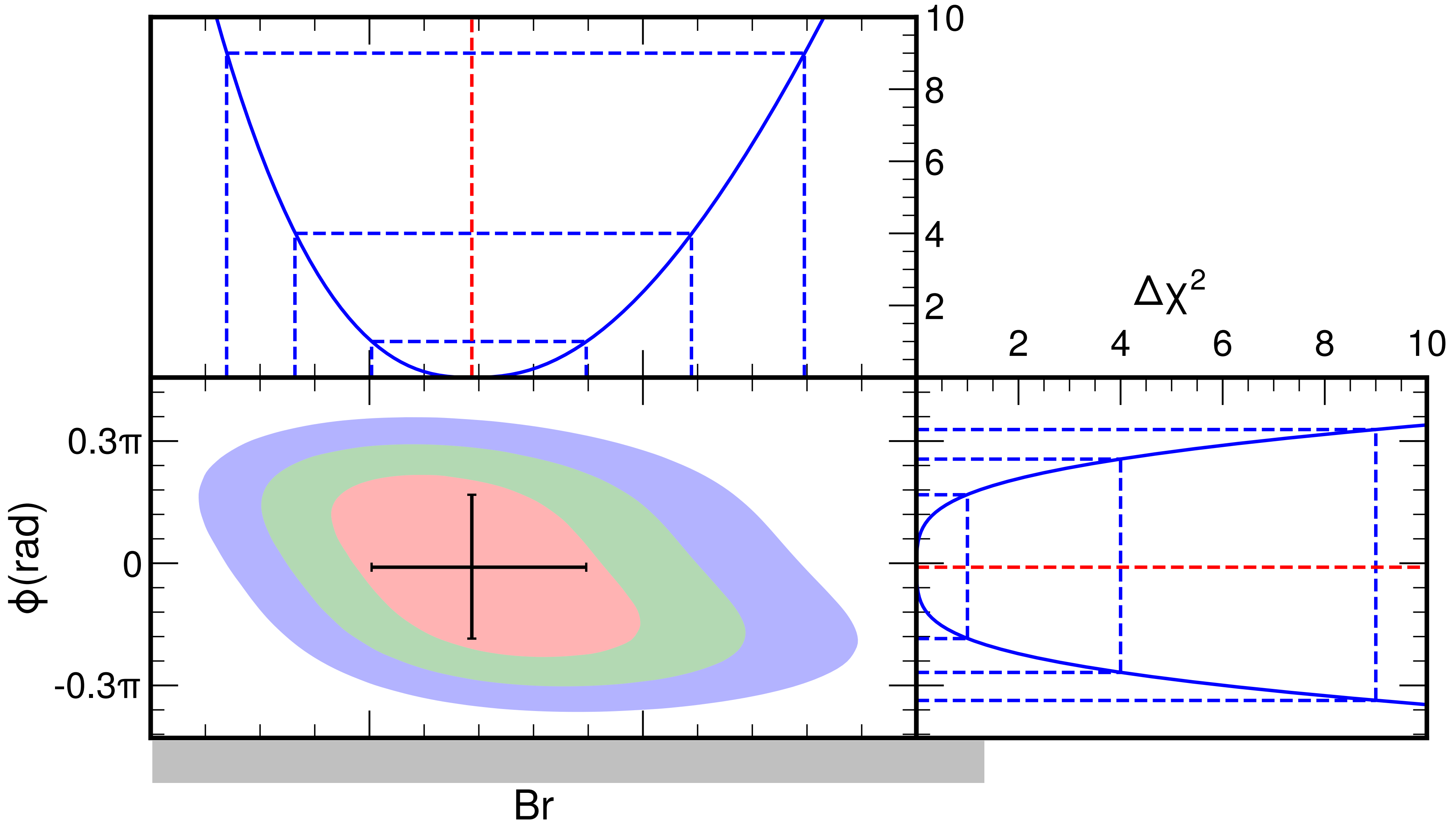
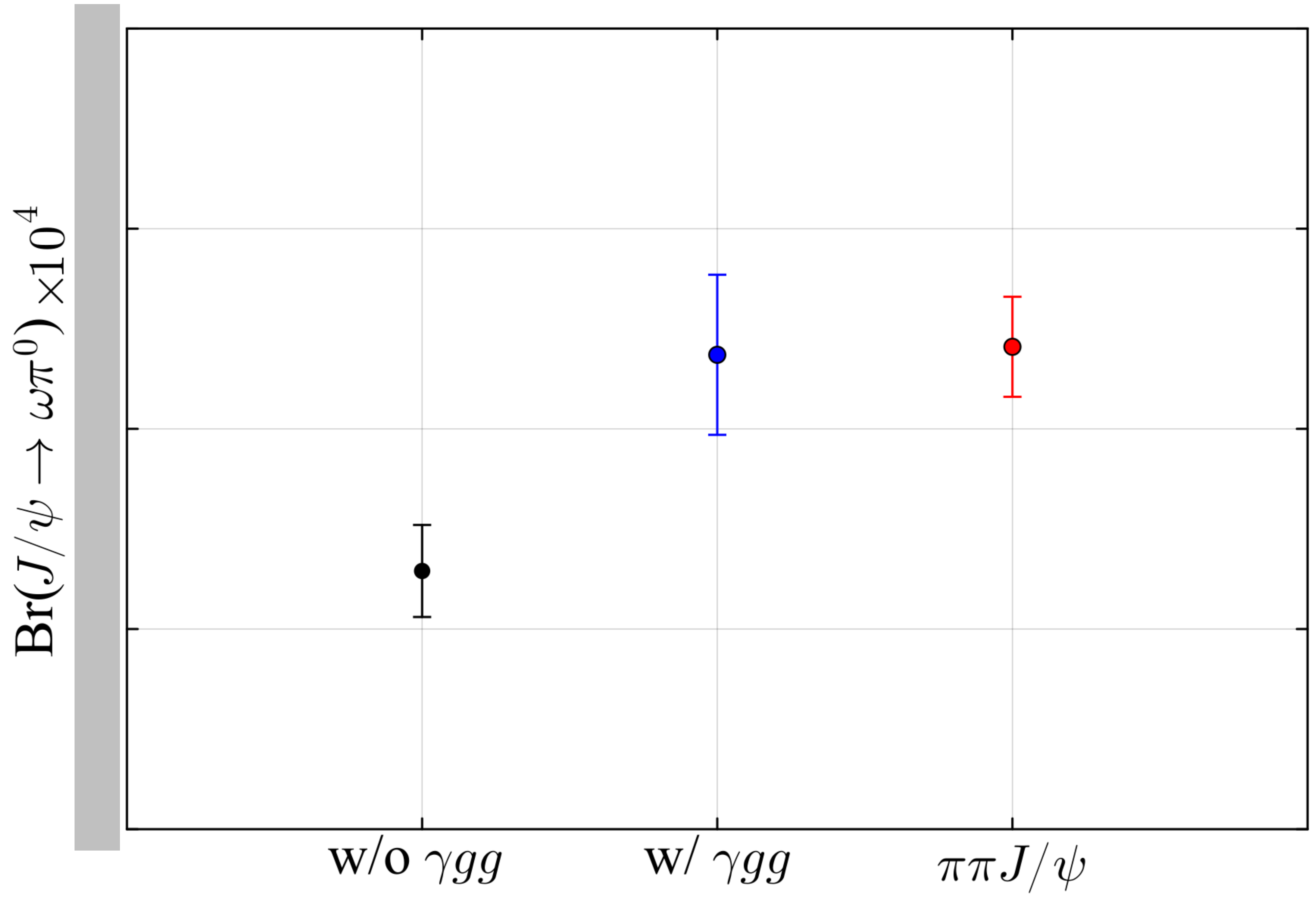


Fig. 3. The lineshapes of e^+e^- annihilates to (a) $\mu^+\mu^-$, (b) 5π, and (c) $\eta\pi^+\pi^-$. The black points with error bars are data, and the solid lines show the fit results.

$e^+e^- \to \omega\pi^0$ around J/ψ resonance

- $\mathrm{Br}\left(J/\psi \to \omega\pi^0\right) = \dfrac{C^2\mathcal{F}^2_{\omega\pi^0}\Gamma_{ee}q^3_{\omega\pi^0}(M)}{M^4\Gamma}$
- Branching ratio passed cross check from $\psi(3686) \to \pi^+\pi^- J/\psi$, $J/\psi \to \omega\pi^0$.
  - Jiabao Gong and Gang Li
- We plan to give a combination result in future.





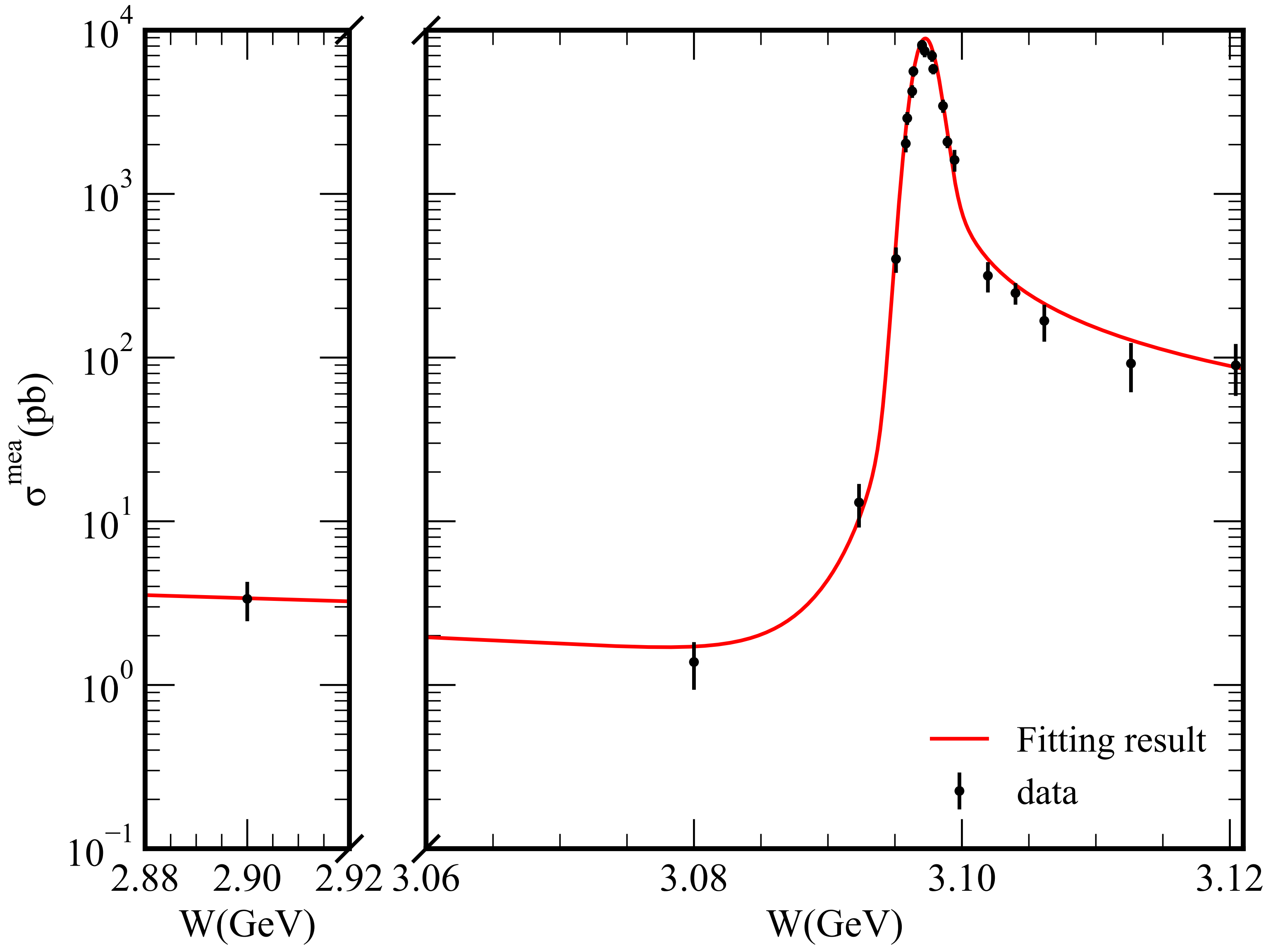
$e^+e^- \to \omega\eta$ around J/ψ resonance

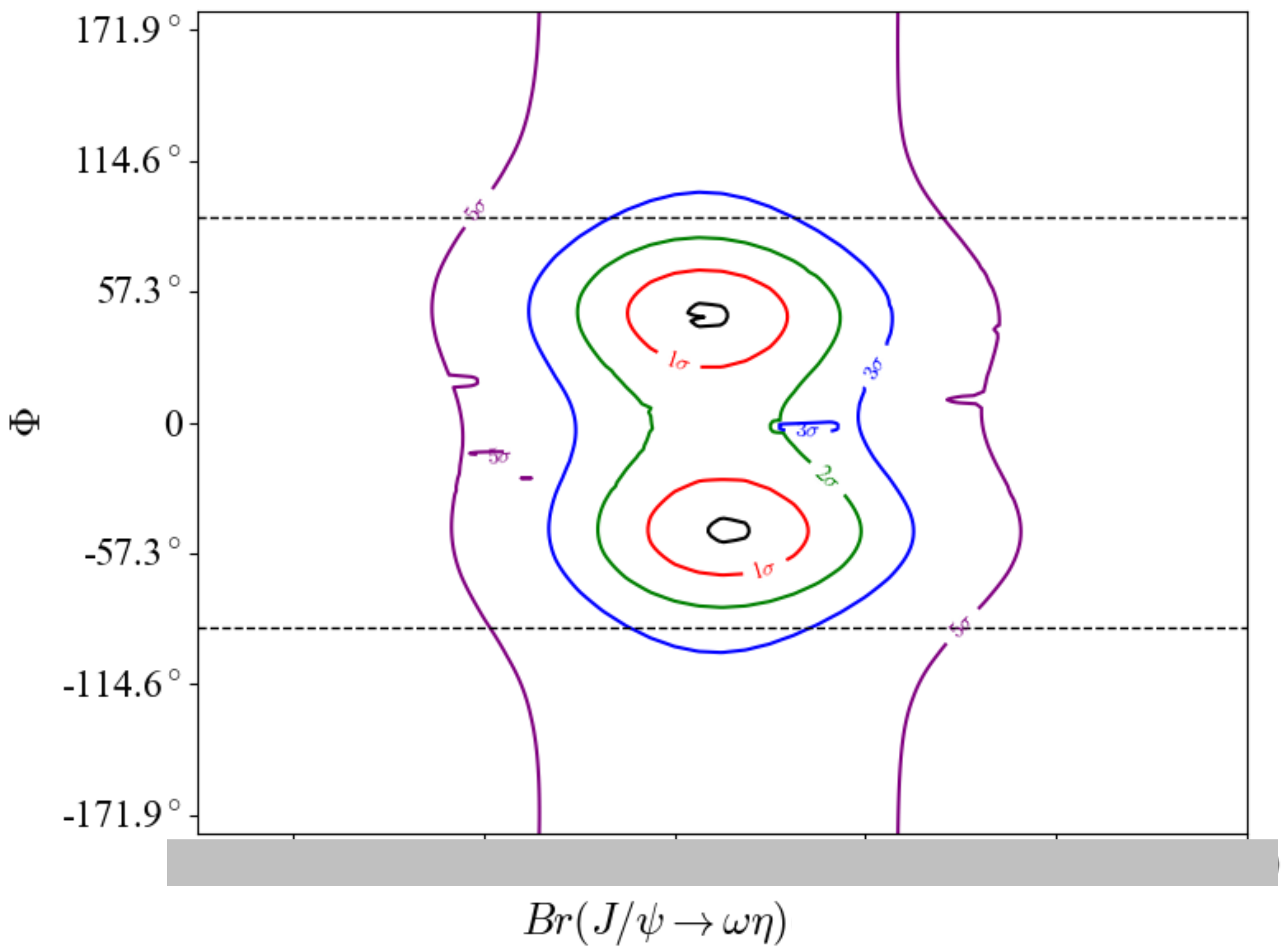
- As we have mentioned $J/\psi \to \omega\eta$ is G-parity and isospin conserved
  - $\eta \to 3\pi$ is isospin violated which is driven by **quark mass differences**.
- We expect that $J/\psi \to ggg$ is predominant in $J/\psi \to \omega\eta$: $|A_{ggg}| \gg |A_{\gamma gg}|, |A_\gamma|$.
- We use the exclusive decay $\eta \to 2\gamma$ so that $J/\psi \to \omega\eta \to \pi^+\pi^-4\gamma$ has the same final decay particles with $J/\psi \to \omega\pi^0 \to \pi^+\pi^-4\gamma$.
- $\sigma^{\rm dre} = \frac{4\pi\alpha^2}{3W^2}\left(\frac{\mathcal{F}_{\omega\eta}}{W^2}\right)^2 q^3_{\omega\eta}(W)\left|\frac{1}{|1-\Pi_0(W)|} + \frac{3W\Gamma_{ee}e^{i\phi_{\gamma,\rm cont.}}}{\alpha\left(W^2-M^2+iM\Gamma\right)}\left(1 + C_{\gamma gg}e^{i\phi_{\gamma gg,\gamma}} + C_{ggg}e^{i\phi_{ggg,\gamma}}\right)\right|^2$

$e^+e^- \to \omega\eta$ around J/ψ resonance

- $$\sigma^{\text{dre}} = \frac{4\pi\alpha^2}{3W^2}\left(\frac{\mathcal{F}_{\omega\eta}}{W^2}\right)^2 q^3_{\omega\eta}(W)\left|\frac{1}{\left|1-\Pi_0(W)\right|} + \frac{3W\Gamma_{ee}e^{i\phi_{\gamma,\text{cont.}}}}{\alpha\left(W^2-M^2+iM\Gamma\right)}\left(1 + C_{\gamma gg}e^{i\phi_{\gamma gg,\gamma}} + C_{ggg}e^{i\phi_{ggg,\gamma}}\right)\right|^2$$

- $$Ce^{i\phi} = \left(1 + C_{\gamma gg}e^{i\phi_{\gamma gg,\gamma}} + C_{ggg}e^{i\phi_{ggg,\gamma}}\right)e^{i\phi_{\gamma,\text{cont.}}}$$





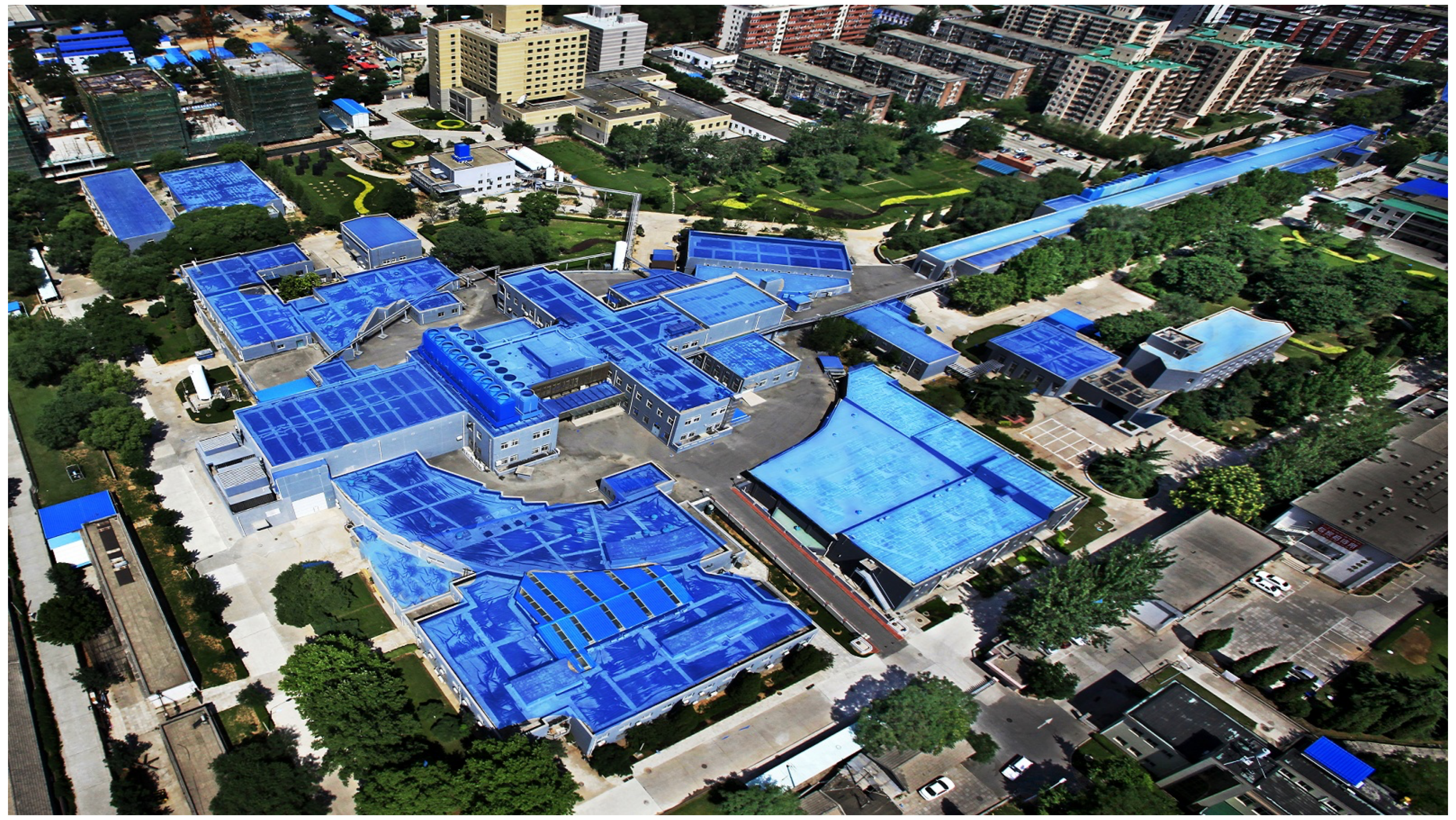
As we expect:

$C_{ggg} \gg 1 \Rightarrow |A_{ggg}| \gg |A_\gamma|, |A_{\gamma gg}|$

Parameter	Result
M(MeV)	3097.18 ± 0.03
$\mathcal{F}_{\omega\eta}(\text{GeV}^{-1})$	([redacted] $\pm 1.09) \times 10^{-2}$
$\mathcal{C}$	[redacted] ± 1.56
$\Phi(^\circ)$	[redacted] ± 12.9

$e^+e^- \to \omega\pi^0(\eta)$ around $\psi(3686)$ resonance

- $e^+e^- \to \omega\pi^0(\eta) \to \pi^+\pi^-4\gamma$ with $\omega \to \pi^+\pi^-\pi^0$ and $\pi^0(\eta) \to 2\gamma$
- Data sets of 3.686 GeV
  - 2009, 2012, 2021
  - Total 2.7 billion
- Data sets of 3.65 GeV and 3.682 GeV
  - 2022
- Scan energy data sets from 3.58 GeV and 3.71 GeV
  - 2018, psipscan



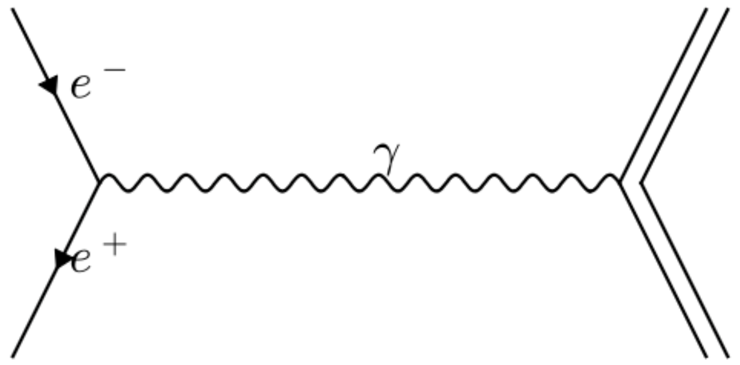
W **(GeV)**	**3.65**	**3.67016**	**3.68014**	**3.682**	**3.68275**	**3.68422**
L **(pb⁻¹)**	410 ± 4.10	83.58 ± 0.08	83.06 ± 0.08	404 ± 4.04	28.18 ± 0.05	27.84 ± 0.05
W **(GeV)**	**3.68526**	**3.686**	**3.68650**	**3.69136**	**3.70976**	
L **(pb⁻¹)**	25.34 ± 0.05	3877 ± 38.77	24.45 ± 0.05	68.65 ± 0.08	69.33 ± 0.08	

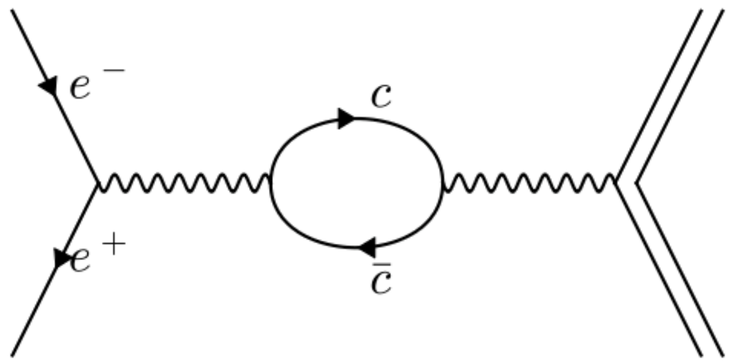
$e^+e^- \to \omega\pi^0(\eta)$ around $\psi(3686)$ resonance

- As we know that:
  - $Br_{PDG}(J/\psi \to \omega\pi^0) = (4.5 \pm 0.5) \times 10^{-4}$; $Br_{PDG}(\psi(3686) \to \omega\pi^0) = (2.1 \pm 0.6) \times 10^{-5}$
  - $Br_{PDG}(J/\psi \to \omega\eta) = (1.74 \pm 0.20) \times 10^{-3}$; $Br_{PDG}(\psi(3686) \to \omega\eta) < 1.1 \times 10^{-5}$
- What do we expect for $Br_{PDG}(\psi(3686) \to \omega\pi^0)$ and $Br_{PDG}(\psi(3686) \to \omega\eta)$?
- According to the 12% rule
  - $\dfrac{Br_\gamma(\psi(3686) \to \gamma^* \to \omega\pi^0)}{Br_\gamma(J/\psi \to \gamma^* \to \omega\pi^0)} \simeq 12\,\% \Rightarrow Br(\psi(3686) \to \omega\pi^0) \sim 10^{-5}$
    - Is there the **mixed mode γgg** in $\psi(3686) \to \omega\pi^0$?
  - $\dfrac{Br_\gamma(\psi(3686) \to ggg \to \omega\eta)}{Br_\gamma(J/\psi \to ggg \to \omega\eta)} \simeq 12\,\% \Rightarrow Br(\psi(3686) \to \omega\eta) \sim 10^{-4} \gg 1.1 \times 10^{-5}$

$e^+e^- \to \omega\pi^0$ around $\psi(3686)$ resonance

- Firstly, we try to only consider the **purely electromagnetic** mode
  - $e^+e^- \to \omega\pi^0$
  - $e^+e^- \to \psi(3686) \to \gamma^* \to \omega\pi^0$

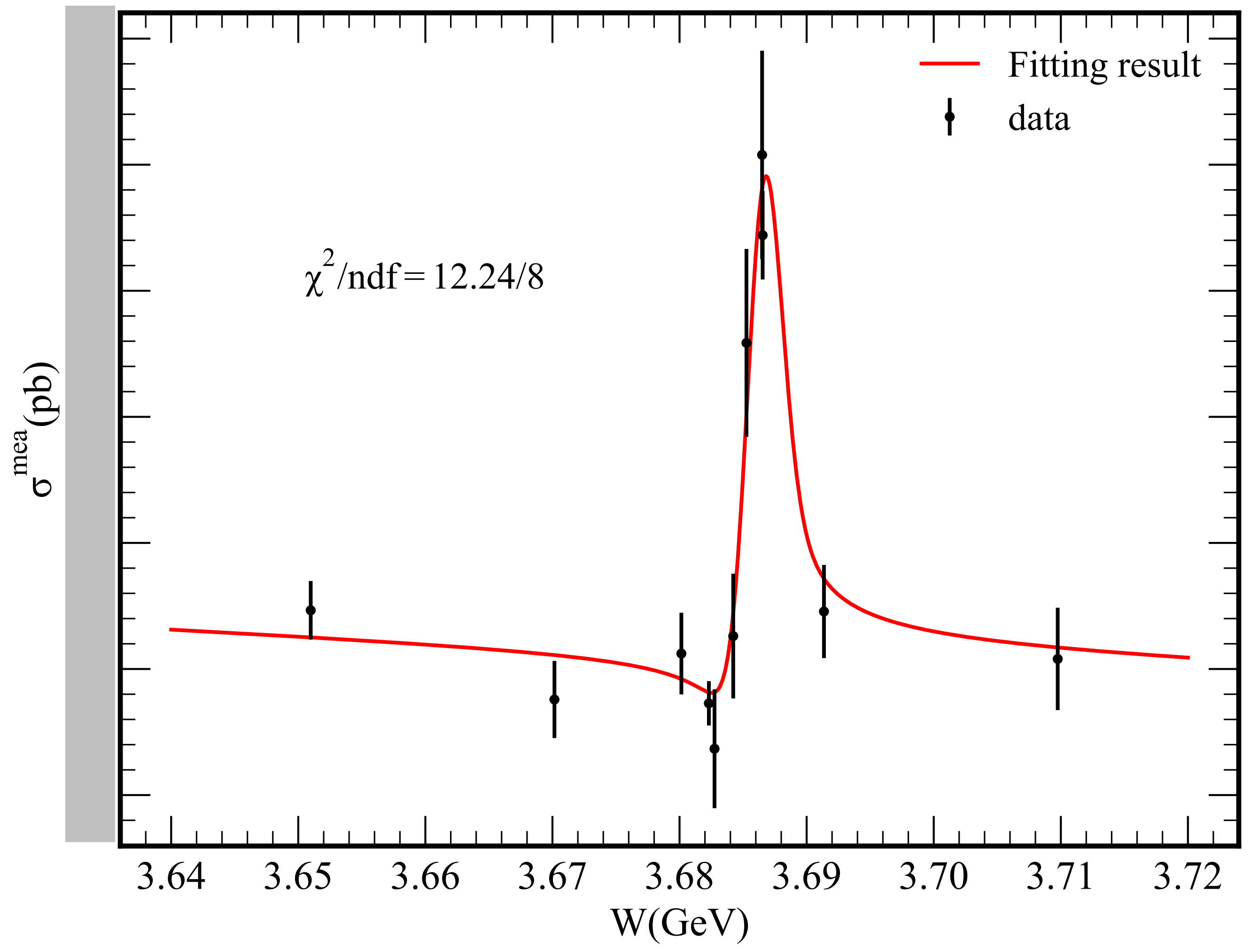


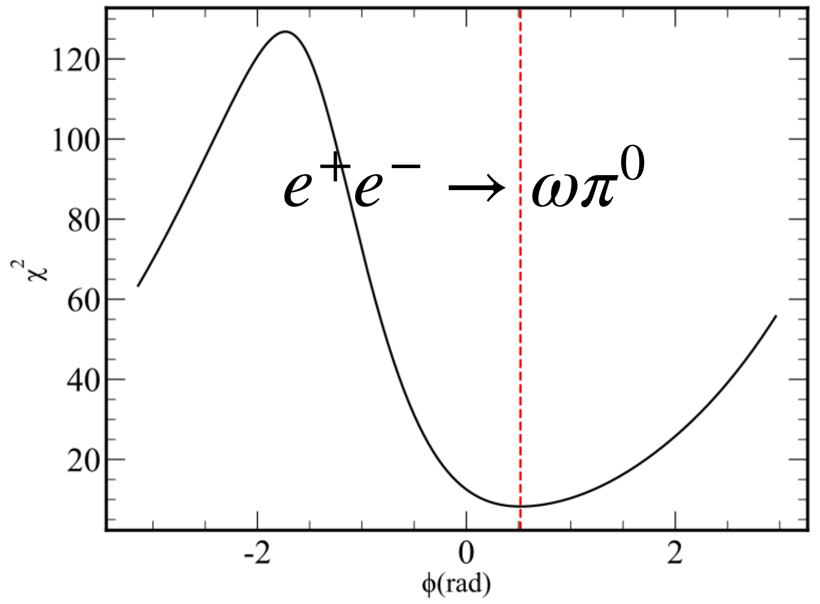


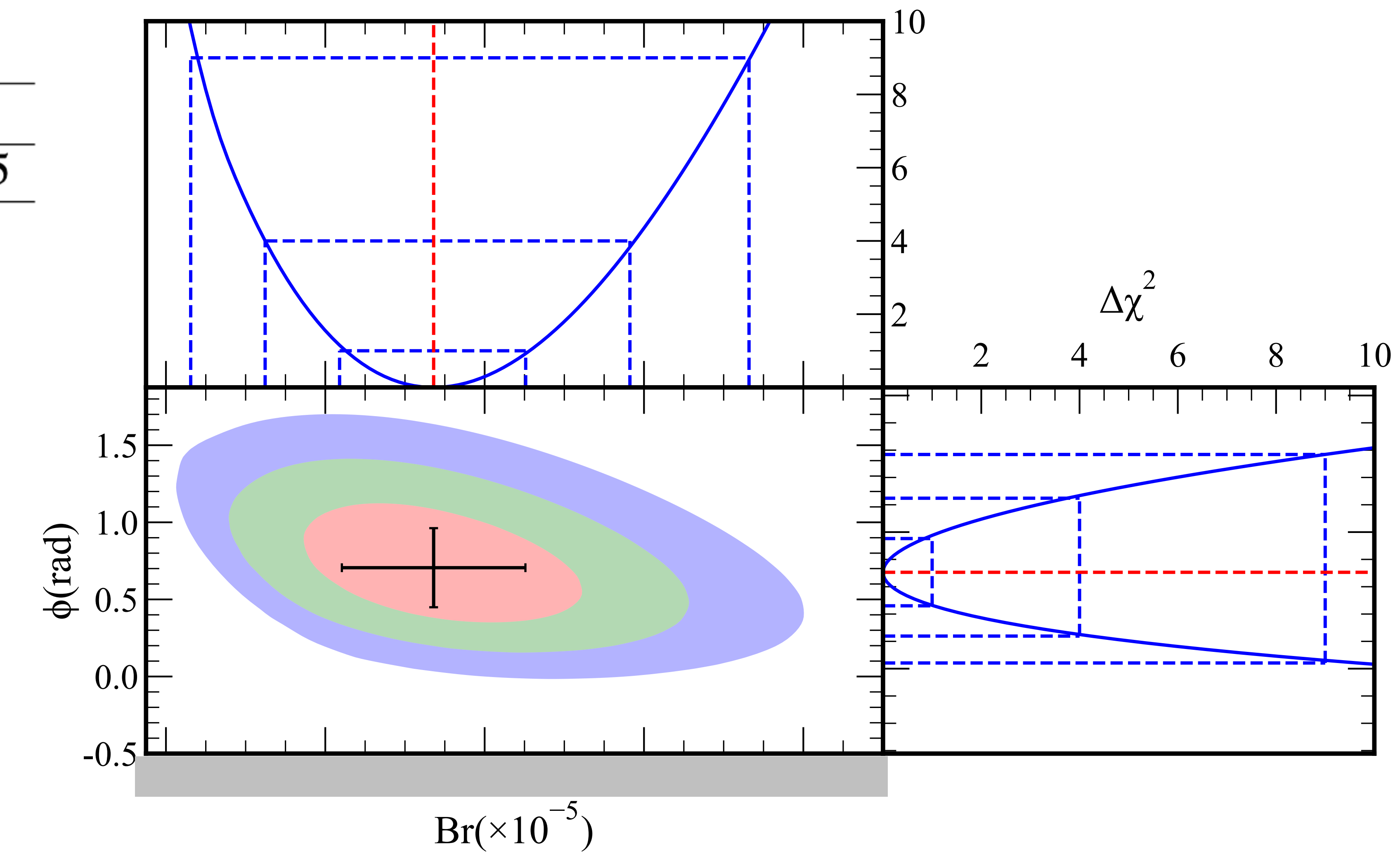
  - $$\sigma^{\mathrm{dre}} = \frac{4\pi\alpha^2}{3W^2}\left(\frac{\mathcal{F}_{\omega\pi^0}}{W^2}\right)^2 q^3_{\omega\pi^0}(W)\left|\frac{1}{\left|1-\Pi_0(W)\right|} + \frac{3W\Gamma_{ee}}{\alpha\left(W^2-M^2+iM\Gamma\right)} 1 e^{i\phi_{\gamma,\mathrm{cont.}}}\right|^2$$

$$\mathrm{Br}\left(\psi(2S) \to \omega\pi^0\right) = \frac{\mathcal{F}^2_{\omega\pi^0}\Gamma_{ee}q^3_{\omega\pi^0}(M)}{M^4\Gamma}$$

Parameter	ϕ(rad)	M(MeV)	$\mathcal{F}^2_{\omega\pi^0}$(GeV^4)
Fitting result	± 0.21 ± 0.25	3686.18 ± 0.29 ± 0.23	± 0.03 ± 0.05

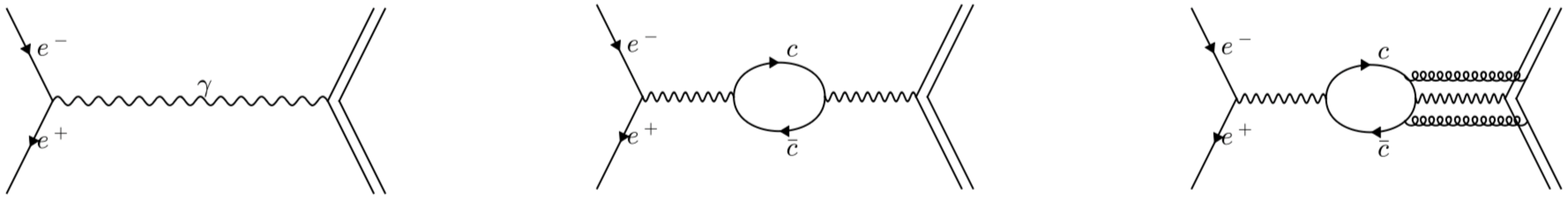




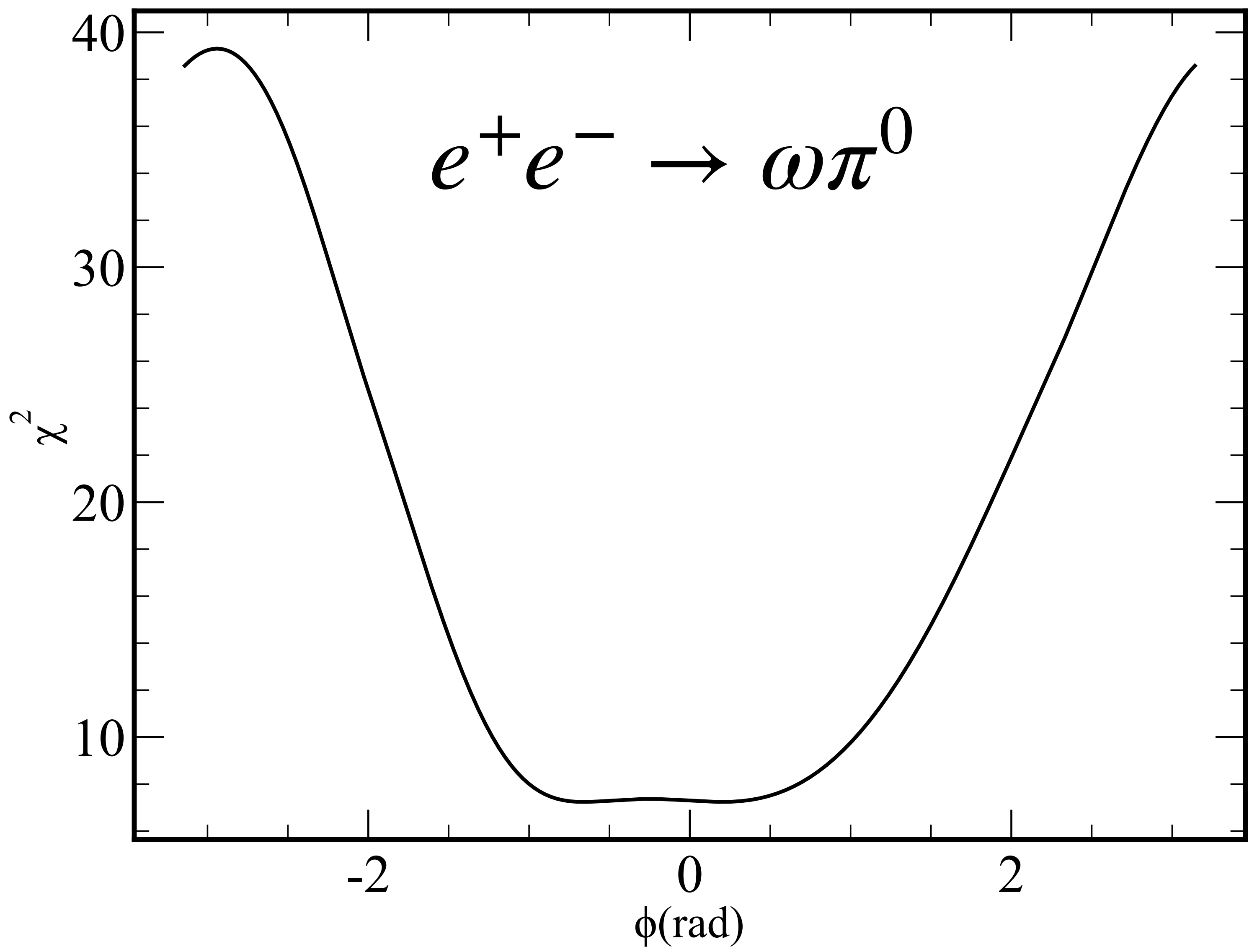


$e^+e^- \to \omega\pi^0$ around $\psi(3686)$ resonance

- Then, we include the **mixed mode**
  - $e^+e^- \to \omega\pi^0$
  - $e^+e^- \to J/\psi \to \gamma^* \to \omega\pi^0$
  - $e^+e^- \to J/\psi \to \gamma gg \to \omega\pi^0$



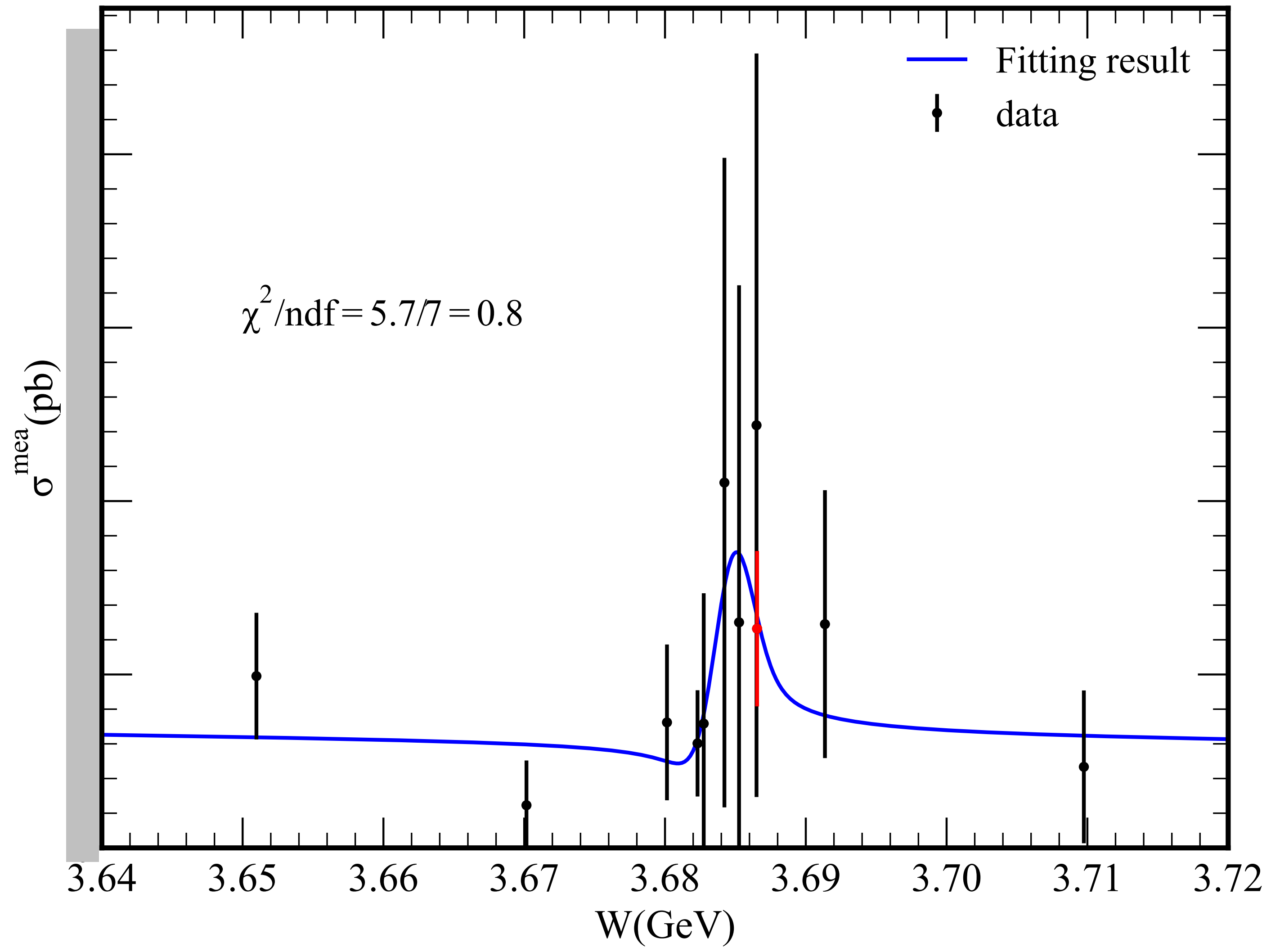
  - $\sigma^{\text{dre}} = \frac{4\pi\alpha^2}{3W^2}\left(\frac{\mathcal{F}_{\omega\pi^0}}{W^2}\right)^2 q^3_{\omega\pi^0}(W)\left|\frac{1}{|1-\Pi_0(W)|} + \frac{3W\Gamma_{ee}e^{i\phi_{\gamma,\text{cont.}}}}{\alpha\left(W^2-M^2+iM\Gamma\right)}\left(1 + C_{\gamma gg}e^{i\phi_{\gamma gg,\gamma}}\right)\right|^2$
  - $Ce^{i\phi} = \left(1 + C_{\gamma gg}e^{i\phi_{\gamma gg,\gamma}}\right)e^{i\phi_{\gamma,\text{cont.}}}$
  - There seems two solutions
    - $\Delta\chi^2$ barrier is too low or $\Delta\chi^2$ is flat around χ^2_{min}
    - Large uncertainty of ϕ causes large uncertainty of Br
- Lower statistics? Or $|A_{\gamma gg}| \ll |A_\gamma| \Rightarrow C_{\gamma gg} \simeq 0$?

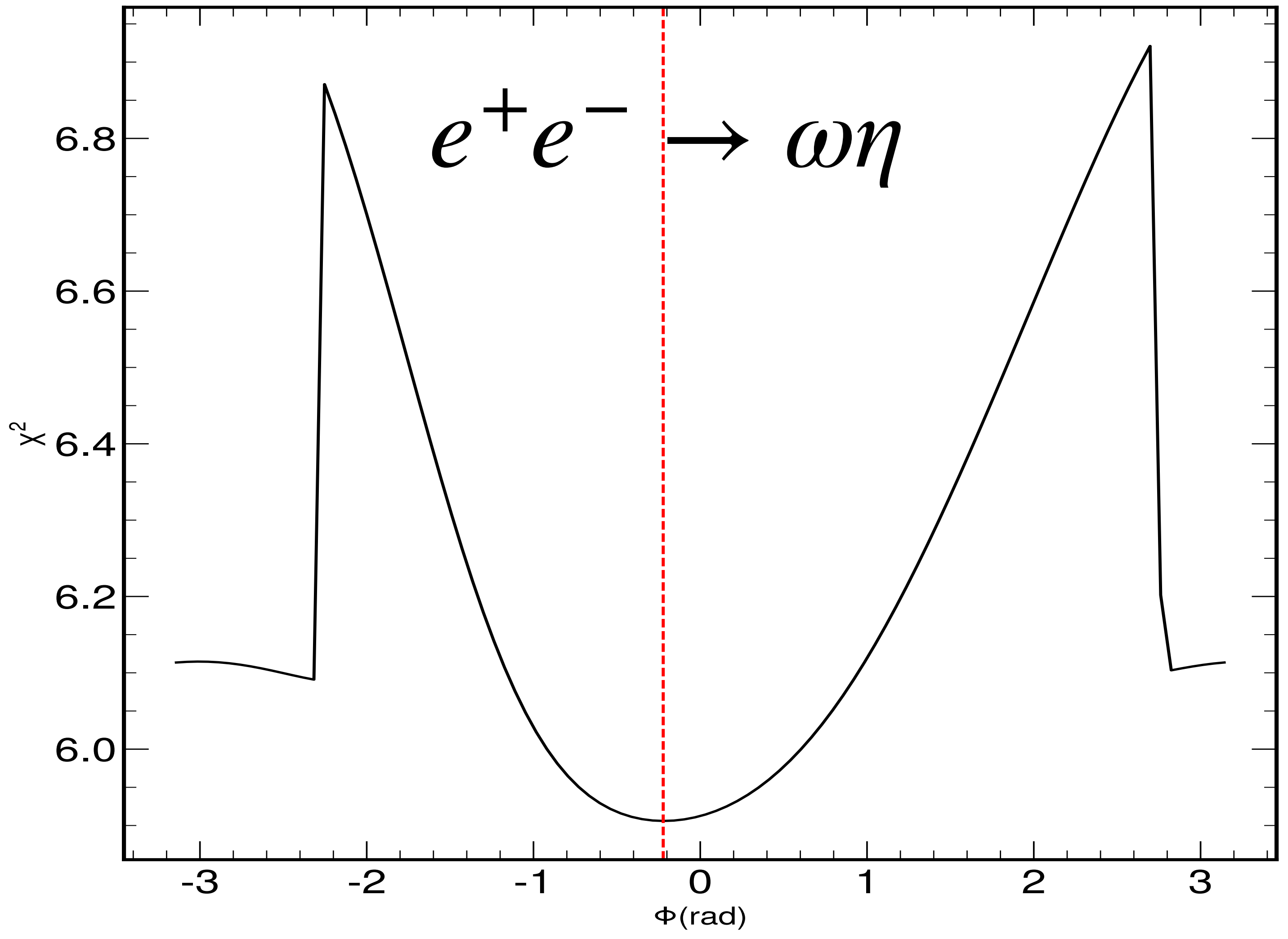


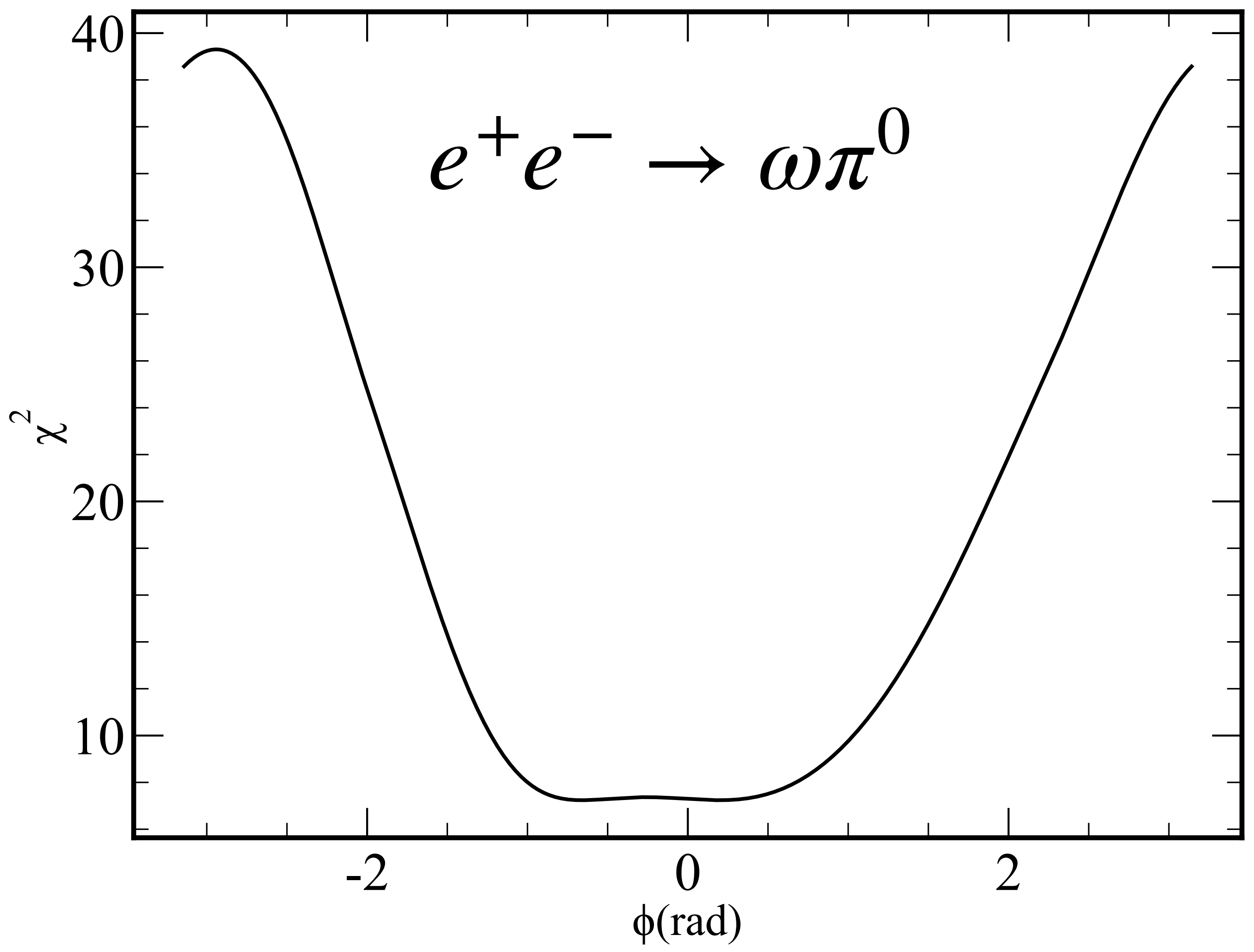
$e^+e^- \to \omega\eta$ around $\psi(3686)$ resonance

- $\sigma^{\text{dre}} = \frac{4\pi\alpha^2}{3W^2}\left(\frac{\mathcal{F}_{\omega\eta}}{W^2}\right)^2 q^3_{\omega\eta}(W)\left|\frac{1}{|1-\Pi_0(W)|} + \frac{3W\Gamma_{ee}e^{i\phi_{\gamma,\text{cont.}}}}{\alpha\left(W^2-M^2+iM\Gamma\right)}\left(1+C_{\gamma gg}e^{i\phi_{\gamma gg,\gamma}}+C_{ggg}e^{i\phi_{ggg,\gamma}}\right)\right|^2$
  - $Ce^{i\phi} = \left(1+C_{\gamma gg}e^{i\phi_{\gamma gg,\gamma}}+C_{ggg}e^{i\phi_{ggg,\gamma}}\right)e^{i\phi_{\gamma,\text{cont.}}}$
  - Br $\left(\psi(3686)\to\omega\eta\right) = \frac{C^2\mathcal{F}^2_{\omega\eta}\Gamma_{ee}q^3_{\omega\eta}(M)}{M^4\Gamma}$
  - Large uncertainty of ϕ causes large uncertainty of Br
  - $\Delta\chi^2$ is flat around χ^2_{min} (déjà vu)

Parameter	Result
M(MeV)	3684.81 ± 0.91
$\mathcal{C}$	[illegible] ± 0.95
Φ(rad)	[illegible] ± 2.39
$\mathcal{B}(\psi(2S)\to\omega\eta)$	([illegible] $\pm$ [illegible]) $\times 10^{-6}$





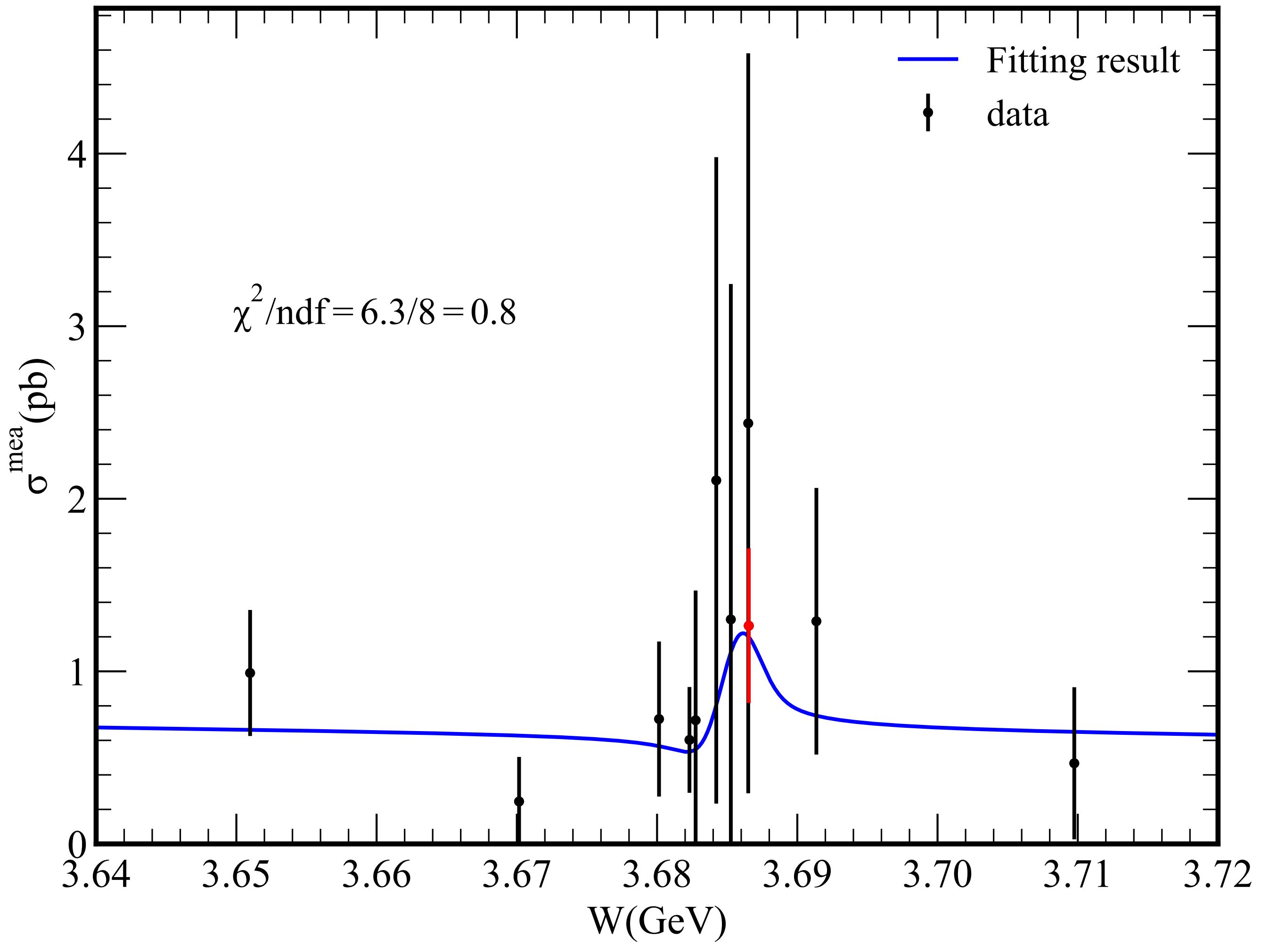


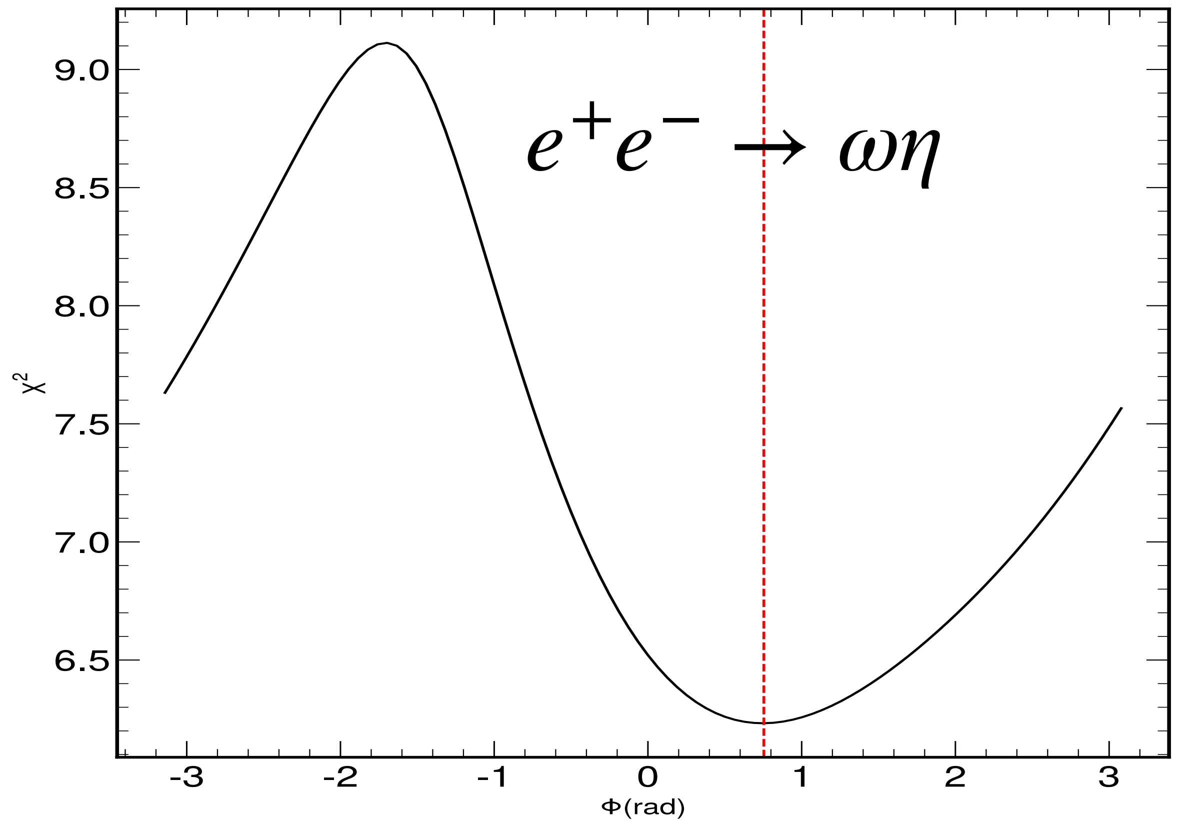
$e^+e^- \to \omega\eta$ around $\psi(3686)$ resonance

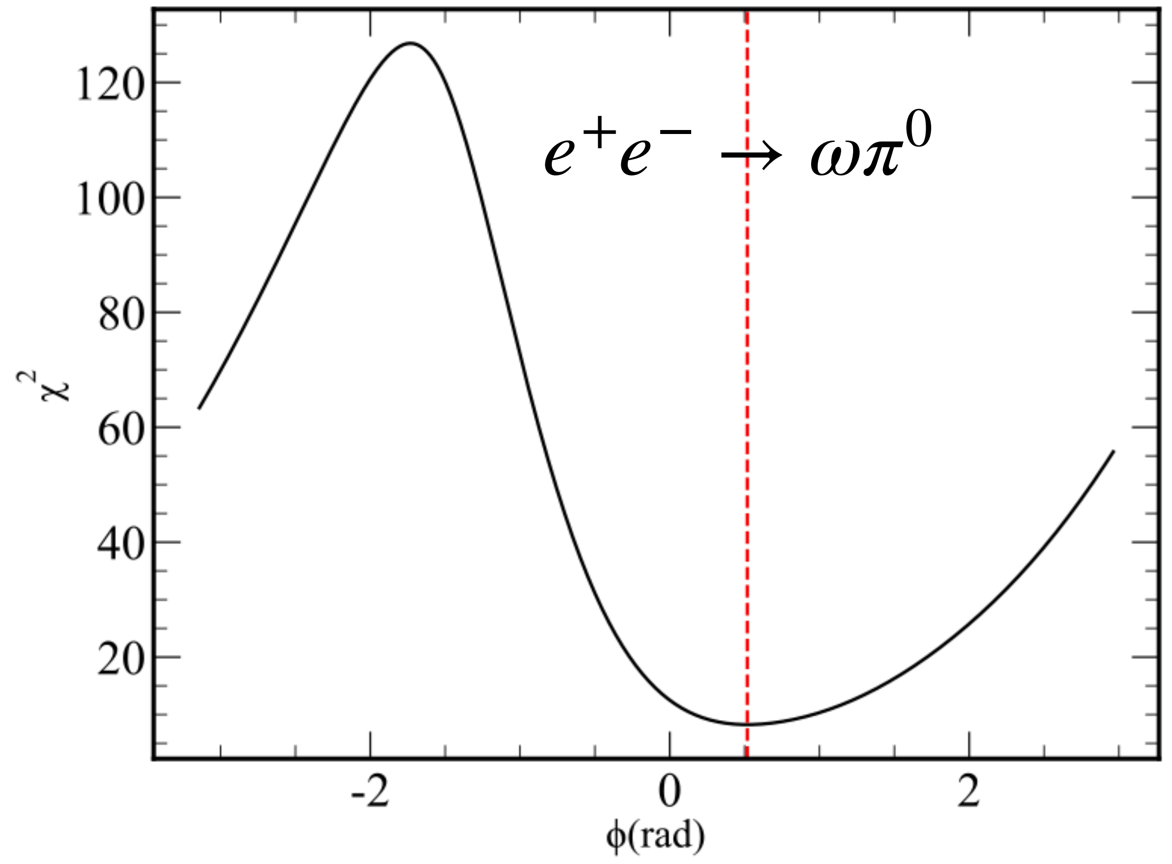
- $\mathrm{Br}_{\mathrm{PDG}}(\psi(3686) \to \omega\eta)$ does not follow the 12% rule
- "$\rho\pi$" puzzle, Q. Zhao, et al., CPC(2010) **34**, 299
  - "The strong decay of $\psi(3686)$ receives relatively larger destructive interfaces from the intermediate meson loop transitions."
- We try to only consider the **purely electromagnetic** mode

Parameter	Result
M(MeV)	3685.37 ± 1.61
Φ(rad)	± 1.47
B(ψ(2S)→$\omega\eta$)	(± 1.65) × 10^{-7}

- $$\sigma^{\mathrm{dre}} = \frac{4\pi\alpha^2}{3W^2}\left(\frac{\mathcal{F}_{\omega\eta}}{W^2}\right)^2 q^3_{\omega\eta}(W)\left|\frac{1}{|1-\Pi_0(W)|} + \frac{3W\Gamma_{ee}e^{i\phi_{\gamma,\mathrm{cont.}}}}{\alpha\left(W^2-M^2+iM\Gamma\right)}\left(1 + C_{\gamma gg}e^{i\phi_{\gamma gg,\gamma}} + C_{ggg}e^{i\phi_{ggg,\gamma}}\right)\right|^2$$





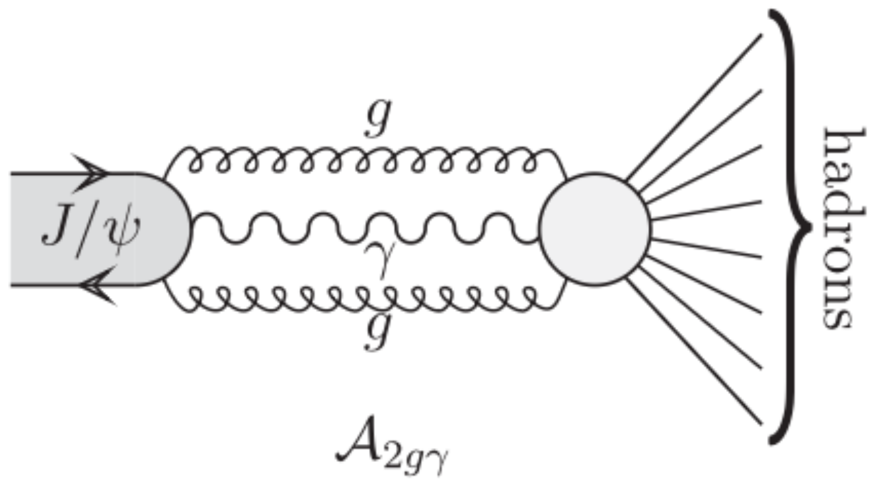


$J/\psi(\psi') \to \omega\eta'$

- $\mathrm{Br}_{\mathrm{PDG}}(J/\psi \to \omega\eta') = (1.89 \pm 0.18) \times 10^{-4}$; $\mathrm{Br}_{\mathrm{PDG}}(\psi(3686) \to \omega\eta') = (3.2^{+2.5}_{-2.1}) \times 10^{-5}$
- J/ψ and $\psi(3686)$ scan data lack sufficient statistics to measure the cross sections of $e^+e^- \to \omega\eta'$ around J/ψ and $\psi(3686)$.
- We expect that $J/\psi \to ggg$ is predominant in $J/\psi \to \omega\eta'$.
  - $\mathrm{Br}_{\mathrm{PDG}}(J/\psi \to \omega\eta') \sim \mathrm{Br}_{\mathrm{PDG}}(J/\psi \to \omega\pi^0) = (4.5 \pm 0.5) \times 10^{-4}$
    - The exclusive branching ratio and detector efficiency of $\omega\eta'$ is smaller than those of $\omega\pi^0$.
  - $\mathrm{Br}_{\mathrm{PDG}}(J/\psi \to \omega\eta') \gg \mathrm{Br}_{\mathrm{PDG}}(\psi(2S) \to \omega\pi^0) = (2.1 \pm 0.6) \times 10^{-5}$
    - The luminosities of scan data around J/ψ are smaller than those around $\psi(3686)$.
- We expect that $J/\psi \to ggg$ is suppressed in $\psi(3686) \to \omega\eta'$.
  - Even if $\psi(3686) \to \omega\eta'$ follows 12% rule, $\mathrm{Br}(\psi(3686) \to \omega\eta') \sim 10^{-5}$.
- Therefore, we have only measured the branching ratios of $J/\psi(\psi') \to \omega\eta'$ by using the J/ψ and $\psi(3686)$ data sets.
  - Both passed group review, BESIII memos

Summary

- We have measured the cross sections of $e^+e^- \to \omega\pi^0(\eta)$ around J/ψ and $\psi(3686)$.
- Due to lack sufficient statistics, not cross sections but $\mathrm{Br}(J/\psi(\psi') \to \omega\eta')$ has been measured.
- We firstly experimentally observe the **mixed γgg decay mode** in $J/\psi \to \omega\pi^0$.



  - Branching ratio of $J/\psi \to \omega\pi^0$ has passed the cross check from that of $\psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to \omega\pi^0$.
- We observe the predominant **purely strong ggg decay mode** in $J/\psi \to \omega\eta$.
  - $|A_{ggg}| \gg |A_\gamma|, |A_{\gamma gg}|$ as we expect.

Summary

- We find that cross section data are **insensitive** to including the **mixed γgg decay mode** in $\psi(3686) \to \omega\pi^0$, that is, $|A_{\gamma gg}| \ll |A_\gamma|$ in $\psi(3686) \to \omega\pi^0$.
  - Normal or abnormal?
- We find that cross section data are **insensitive** to including the **strong ggg decay mode** in $\psi(3686) \to \omega\eta$.
  - Can we believe that the purely electromagnetic γ^* decay mode is predominant?
    - $|A_{ggg}|, |A_{\gamma gg}| \ll |A_\gamma|$ in $\psi(3686) \to \omega\eta$?

Thanks

- Pioneers: Ping Wang, Yadi Wang, Rinaldo Baldini Ferroli et al.

Looking for the phase angle between strong and EM mechanisms in J/ψ decay

Yadi Wang[1,4], Ping Wang[3], Rinaldo Baldini Ferroli[1], Marco Destefanis[2], Monica Bertani[1], Marco Maggiora[2], Adriano Zallo[1], Alessandro Calcaterra[1]

- WHU
  - Zhenyu Zhang, Zhefei Tian, Baoxin Liu, Yanning Wang, Yiqi Du, Wenhao Ya, Zikun Xi et al.
- LNU
  - Xiaoshen Kang, Li Gong
- USTC
  - Xiaorong Zhou, Hailin Song
- IHEP
  - In memory of **Bingxin Zhang (张丙新)**
  - Gang Li, Jiabao Gong