The predicted missing $\psi(4S)$ and the explanation to the structure observed in $e^+e^- \to \omega\chi_{c0}$

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The 3rd workshop on the XYZ particles

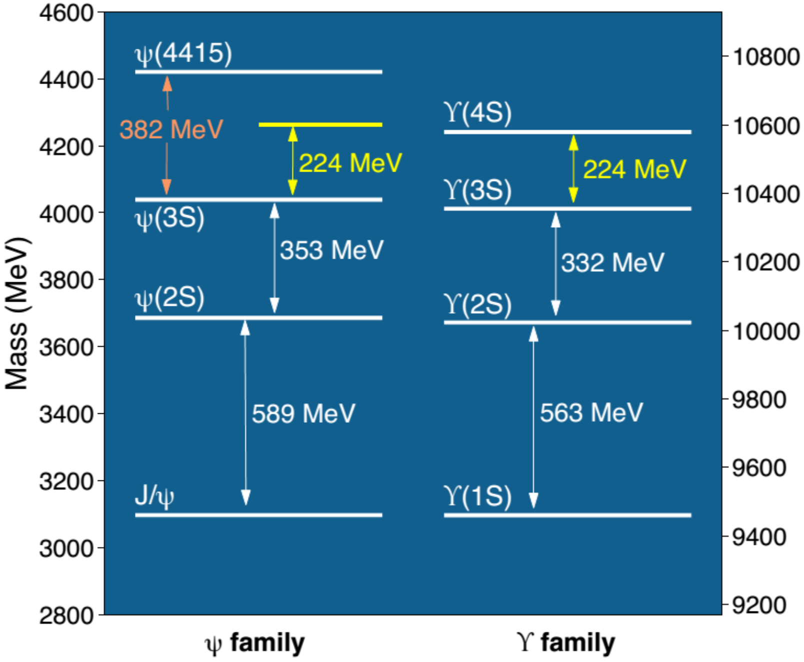
Outline

- Prediction of a missing higher charmonium around 4.26 GeV in J/ψ family
- The role of the predicted $\psi(4S)$ in the observed $e^+e^- \to \omega\,\chi_{c0}$
- Summary

Prediction of a missing higher charmonium around 4.26 GeV in J/ψ family

He, Chen, Liu, Matsuki, Eur. Phys. J. C 74, 3208 (2014)

The Similarity between J/ψ and Υ family



The Comparison of the J/ψ family with the Υ family

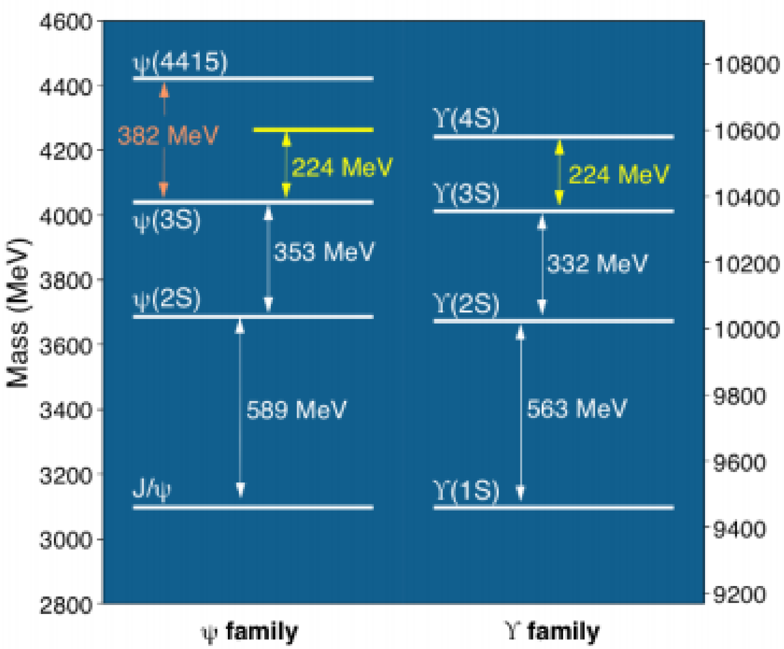
- **Similarity**

1. The mass gap between $\psi(2S)$ and J/ψ is almost the same as that between $\Upsilon(2S)$ and $\Upsilon(1S)$
2. There also exists the similarity of the mass differences, $M(\psi(3S)) - M(\psi(2S))$ and $M(\Upsilon(3S)) - M(\Upsilon(2S))$, where $\psi(2S)$ and $\psi(3S)$ correspond to $\psi(3686)$ and $\psi(4040)$, respectively.

- **Violation**

If $\psi(4415)$ is $\psi(4S)$, such a law is violated since the mass gap of $\psi(4415)$ and $\psi(3S)$ is larger than that of $\Upsilon(4S)$ and $\Upsilon(3S)$

The possible reason to result in the above puzzling mass gap:
The properties of the charmonia above 4.1 GeV are still not understood well



The mass spectrum analysis

- Compared with the J/ψ family, **the bottomonia** with the radial quantum numbers $n = 1, 2, 3, 4$ were **well established** both by experiment and theory.
- **Thus, the study of J/ψ family can be borrowed from Υ family.**
- If this law of mass gap relation still holds for states with $n = 3, 4$ in the J/ψ and Υ familes, we find that **the mass of $\psi(4S)$ should be located at 4263 MeV**, where we take the mass gap between $\Upsilon(4S)$ and $\Upsilon(3S)$ to add it to the mass of $\psi(3S)$.

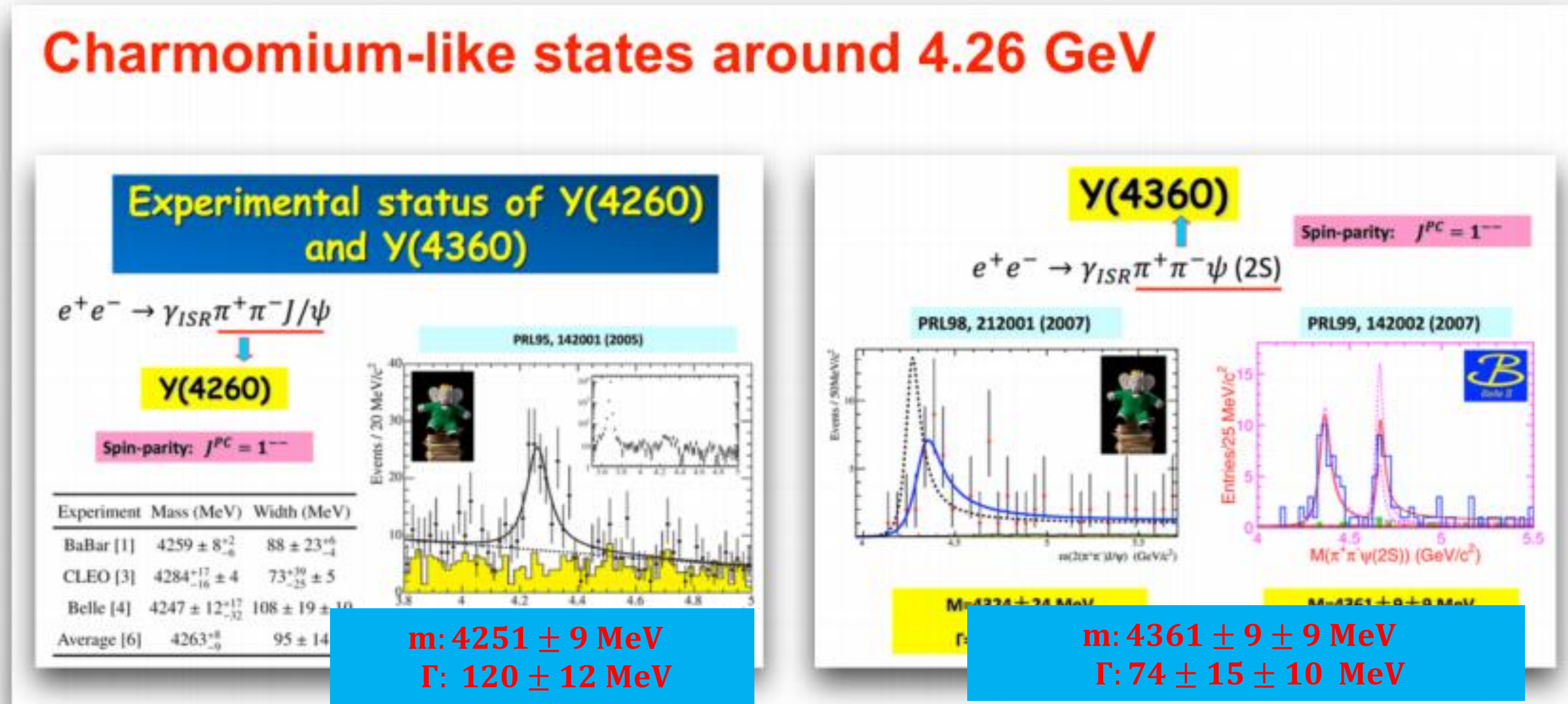
Consistent

The screening potential prediction of $\psi(4S)$ mass:

- **4273 MeV Li&Chao PRD79, 094004 (2009)**
- **4247 MeV Dong&Yu&Zhang&Shen PRD49, 1642 (1994)**

Questions:

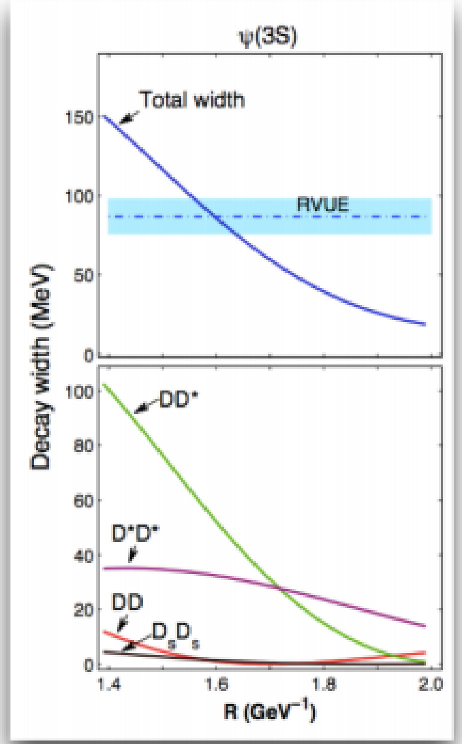
- If this predicted state exists in the J/ψ family, we must reveal its underlying properties to answer **why there does not have any evidence in the present experiment**
- Can Y(4260) or Y(4360) be as the candidate of predicted charmonium with mass around 4.26 GeV?



The decay behavior of the predicted charmonium around 4.26 GeV

We adopt the QPC model to study the decay behavior of the discussed charmonia (L. Micu, Nucl. Phys. B 10, 521 (1969))

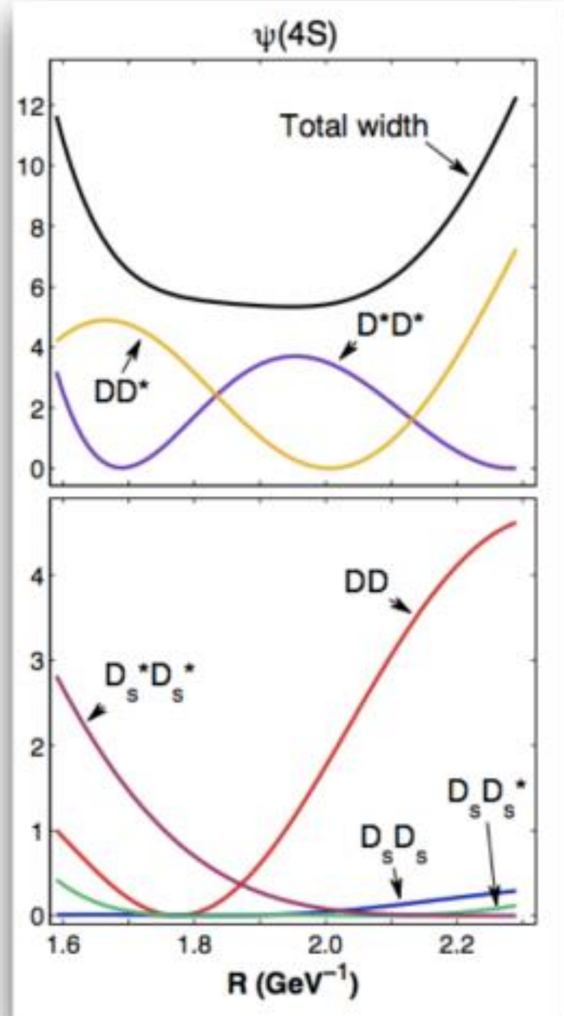
ψ(3S) decay behavior



- Test the **reliability** of the calculation via ψ(3S) (ψ(4040))
- **Reproduce** the experimental data **well** of ψ(4040)
- Enable us to apply this model to **safely** study the decays of ψ(4*S*)

$$\frac{\Gamma_{D\bar{D}}}{\Gamma_{D^*\bar{D}+H.c.}} = 0.24 \pm 0.05 \pm 0.12$$

ψ(4S) decay behavior



A very interesting result of the decay behavior of ψ(4S) can be found:

- The **total decay width** of ψ(4S) is **stable** corresponding to the R range adopted, while its **partial decay widths** strongly **depend on the R value**
- **Due to node effect!**
- **The predicted charmonium ψ(4S) has very narrow width around 6 MeV**
- **For the higher charmonia above the *DD* threshold, this phenomenon of ψ(4S) presented here is unusual**

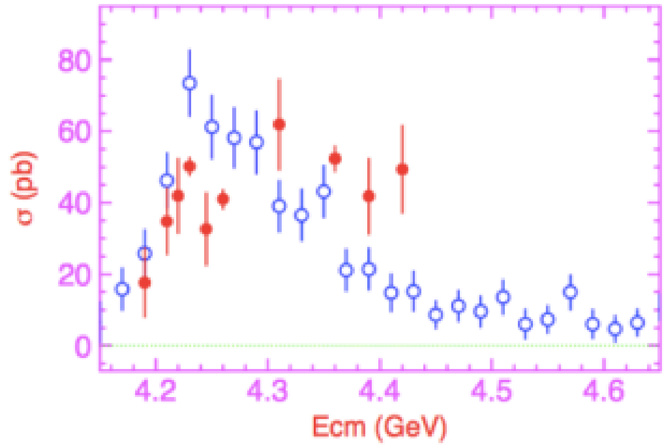
ψ(4040), ψ(4160) and ψ(4415) have widths **80 ± 10** MeV, **103 ± 8** MeV and **62 ± 20** MeV, respectively, all of which are large. Even **ψ(3770)** which is just 43 MeV above the *DD* threshold has the width **27.2** MeV

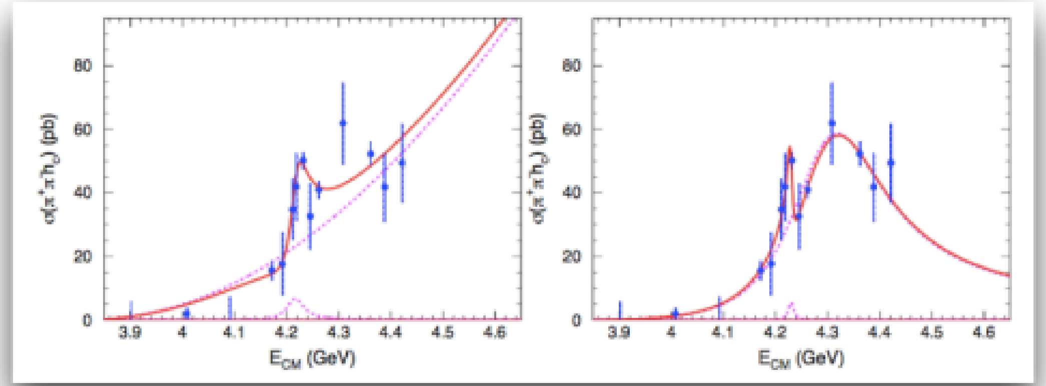
Exclude *Y*(4260)/*Y*(4360) as the candidate of ψ(4*S*)

Experimental evidence

Experimental data

C.Z. Yuan, Chinese Physics C 38, 043001 (2014)





Red points: e+e—>hc\pi\pi
BESIII PRL 111, 242001 (2013)
Blue points: e+e—>J/\psi\pi\pi
Belle PRL 110, 252002 (2013)

"we conclude that very likely there is a narrow structure at around 4.22 GeV"

$$M(Y(4220)) = (4216 \pm 18)\ \mathrm{MeV}/c^2,$$
$$\Gamma_{\mathrm{tot}}(Y(4220)) = (39 \pm 32)\ \mathrm{MeV},$$

Is it the prediced higher charmonium with the mass around 4.26 GeV?

Need further experimental and theoretical efforts!

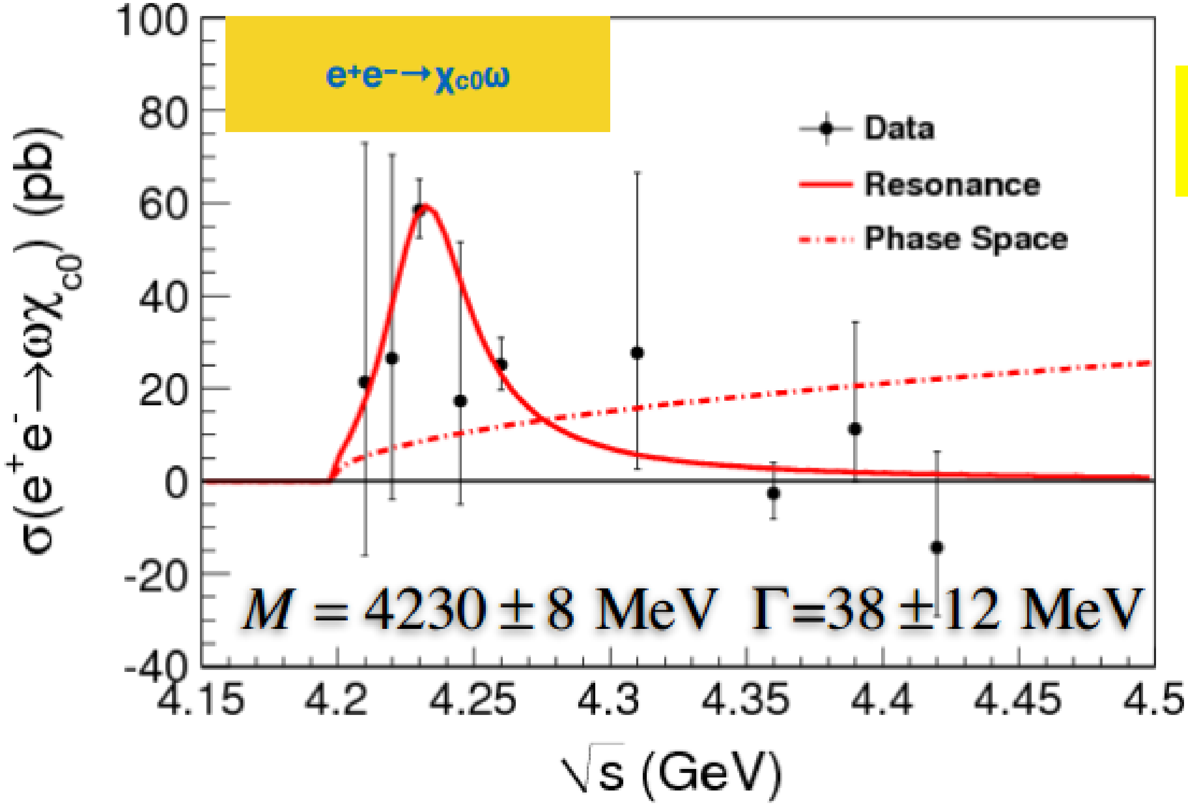
Experimental results of the open-charm decays and more precise study of the *R* value scan, especially from BESIII, Belle and forthcoming BelleII

The role of the predicted $\psi(4S)$ in the observed $e^+e^- \to \omega\chi_{c0}$

Chen, Liu, Matsuki, arXiv:1411.5136

The observation of $e^+e^- \to \chi_{c0}\omega$ from BESIII

BESIII, arXiv:1410.6538



Explain why only $e^+e^- \to \chi_{c0}\omega$ was reported by BESIII

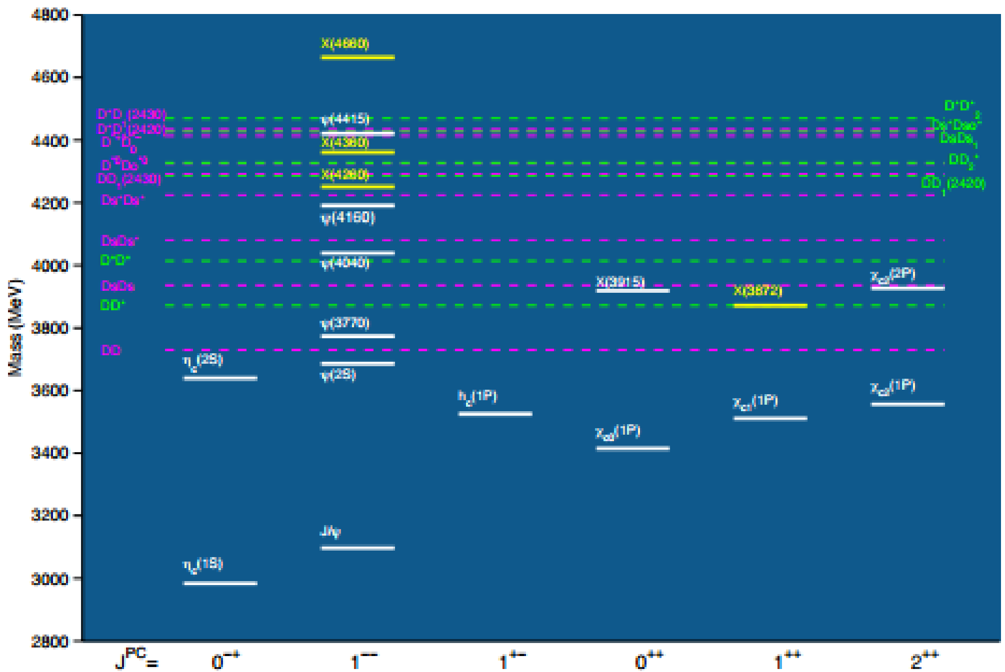
If taking the mass of $\psi(4S)$ to be 4230 MeV (Expt.), we find

- $\psi(4S) \to \chi_{c0}\omega$ is allowed
- $\psi(4S) \to \chi_{c1}\omega$ and $\psi(4S) \to \chi_{c2}\omega$ are forbidden kinematically

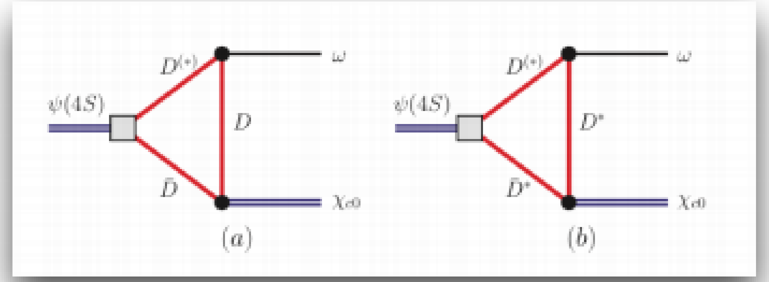
$e^+e^- \to \chi_{c1}\omega$ and $e^+e^- \to \chi_{c2}\omega$ are not significant

The study of the transition $\psi(4S) \rightarrow \omega\chi_{c0}$

For higher charmonia and bottomonia, the unquenched effect becomes more and more important since more channels are open



- **Coupled-channel effect**
- **Non-perturbative properties of QCD**
- **Hadronic loop is an effective description for this effect**

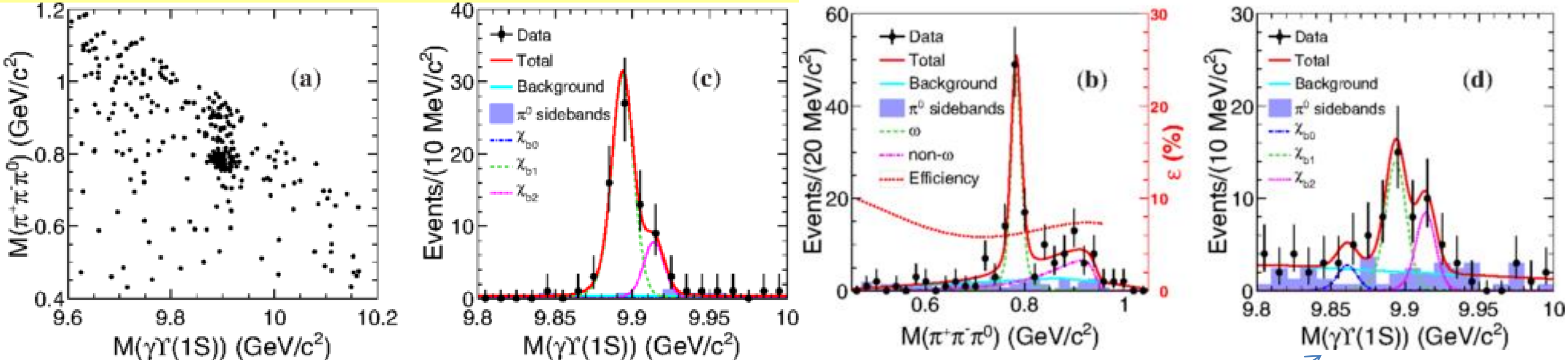


$\Upsilon(5S) \rightarrow \omega\chi_{bJ}$ PROCESS

Chen, Liu, Matsuki, Phys. Rev. D90, 034019 (2014)

$\Upsilon(5S) \to \omega\chi_{bJ}$: Experimental information

PhysRevLett.113.142001(2014)@Belle



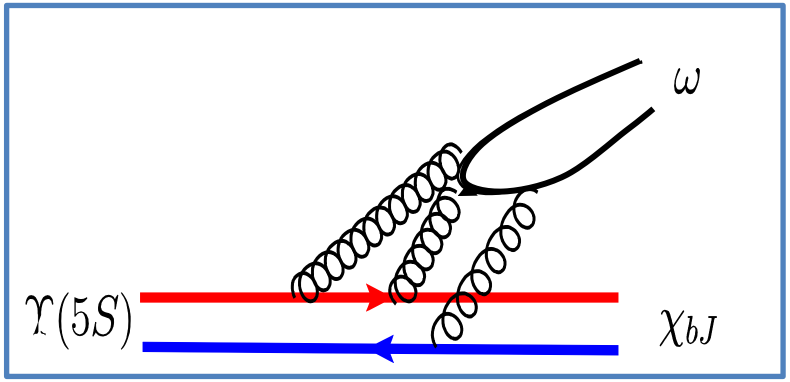
ω signal region

outside of the ω signal region

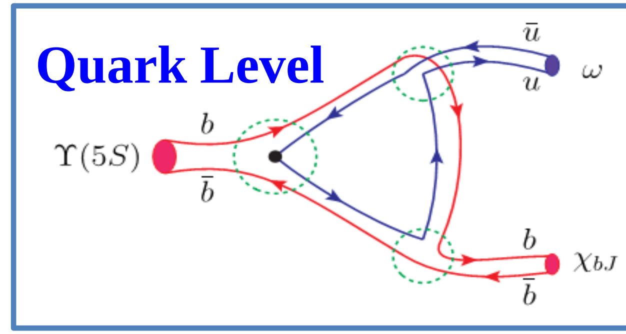
Mode	Yield	Σ (σ)	ε (%)	σ_B (pb)	$\mathcal{B}$ (10^{-3})	$\sigma^{(1)}_{\rm sys}$ (%)	$\sigma^{(2)}_{\rm sys}$ (%)
$\pi^+\pi^-\pi^0\chi_{b0}$	< 13.6	1.0	6.43	< 3.1	< 6.3	25	24
$\pi^+\pi^-\pi^0\chi_{b1}$	80.1 ± 9.9	12	6.61	$0.90 \pm 0.11 \pm 0.13$	$1.85 \pm 0.23 \pm 0.23$	14	12
$\pi^+\pi^-\pi^0\chi_{b2}$	28.6 ± 6.5	5.9	6.65	$0.57 \pm 0.13 \pm 0.08$	$1.17 \pm 0.27 \pm 0.14$	14	12
$\omega\chi_{b0}$	< 7.5	0.5	6.35	< 1.9	< 3.9	29	28
$\omega\chi_{b1}$	59.9 ± 8.3	12	6.53	$0.76 \pm 0.11 \pm 0.11$	$1.57 \pm 0.22 \pm 0.21$	14	13
$\omega\chi_{b2}$	12.9 ± 4.8	3.5	6.56	$0.29 \pm 0.11 \pm 0.08$	$0.60 \pm 0.23 \pm 0.15$	26	25
$(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{b0}$	< 10.7	0.4	6.68	< 2.3	< 4.8	41	41
$(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{b1}$	23.6 ± 6.4	4.9	6.88	$0.25 \pm 0.07 \pm 0.06$	$0.52 \pm 0.15 \pm 0.11$	21	20
$(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{b2}$	15.6 ± 5.4	3.1	6.91	$0.30 \pm 0.11 \pm 0.14$	$0.61 \pm 0.22 \pm 0.28$	45	45

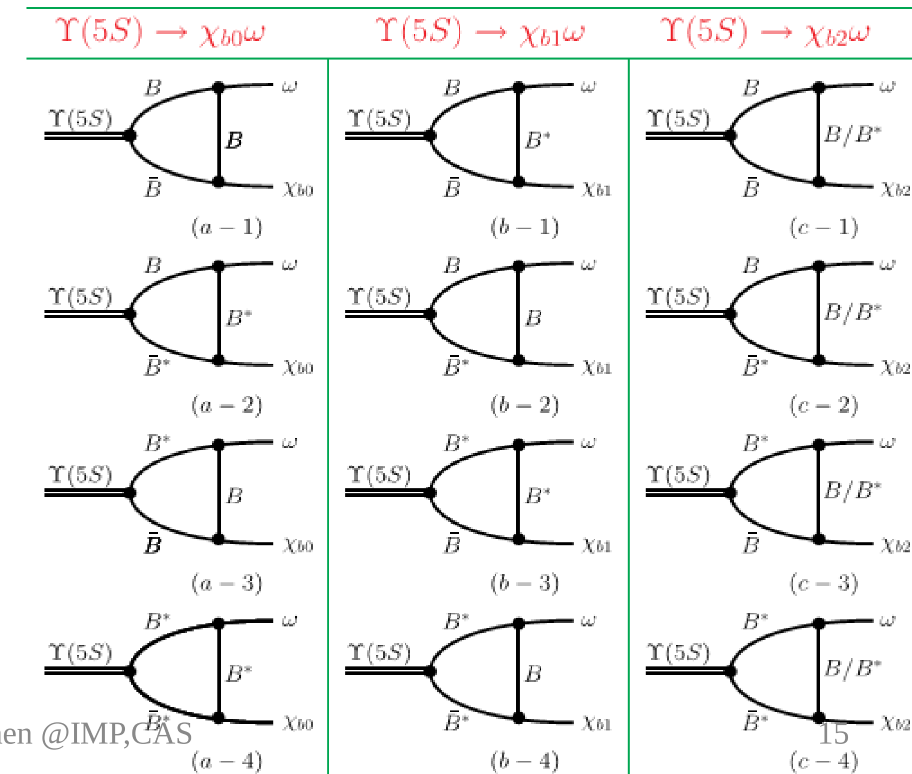
Meson Loop contributions:

Quenched (OZI Suppressed)

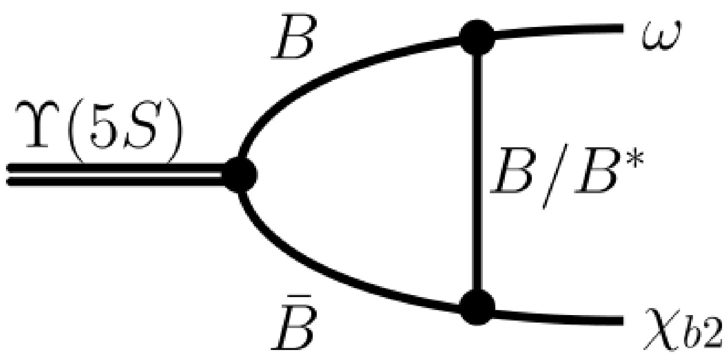


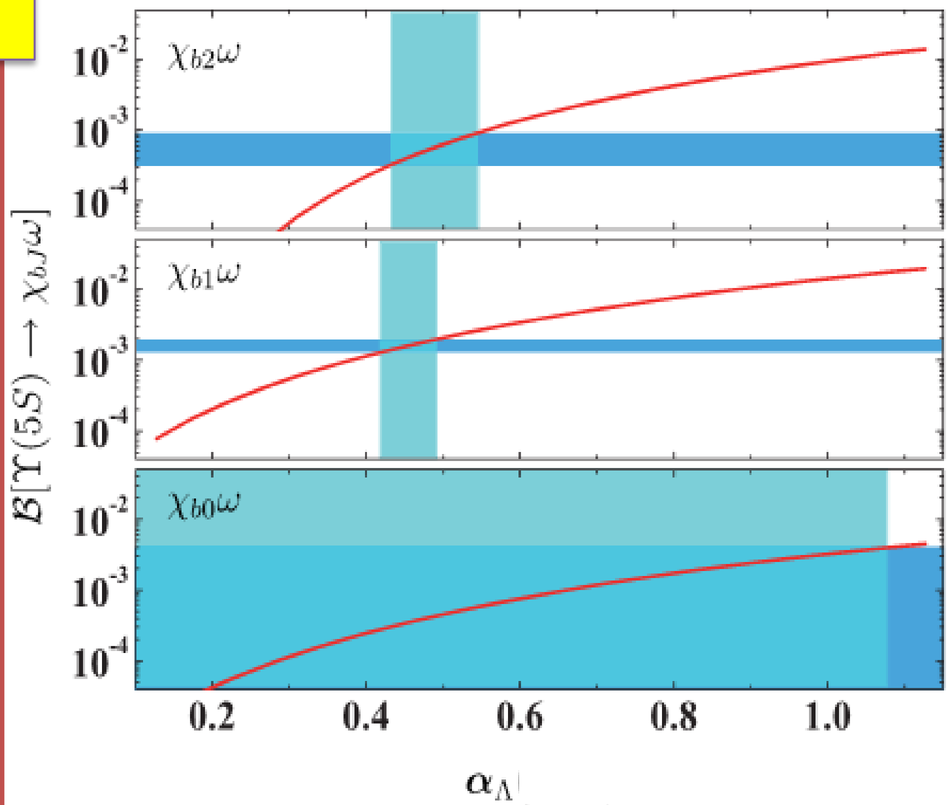
Unquenched (Meson Loop)





- meson loop contributions are evaluated in hadron level
- interactions are described by effective Lagrangians
- effective Lagrangians are constructed based on heavy quark symmetry & chiral symmetry





Form factors:

- **Internal structures of the involved particles**
- **Off shell effects**
- **Remove the divergence of the loop integrals**

Monopole form

$$\mathcal{F}(\Lambda) = (m_E^2 - \Lambda^2)/(q^2 - \Lambda^2)$$
$$\Lambda = (m_B + m_{B^*})/2 + \alpha_\Lambda \Lambda_{QCD}$$

Conclusion:

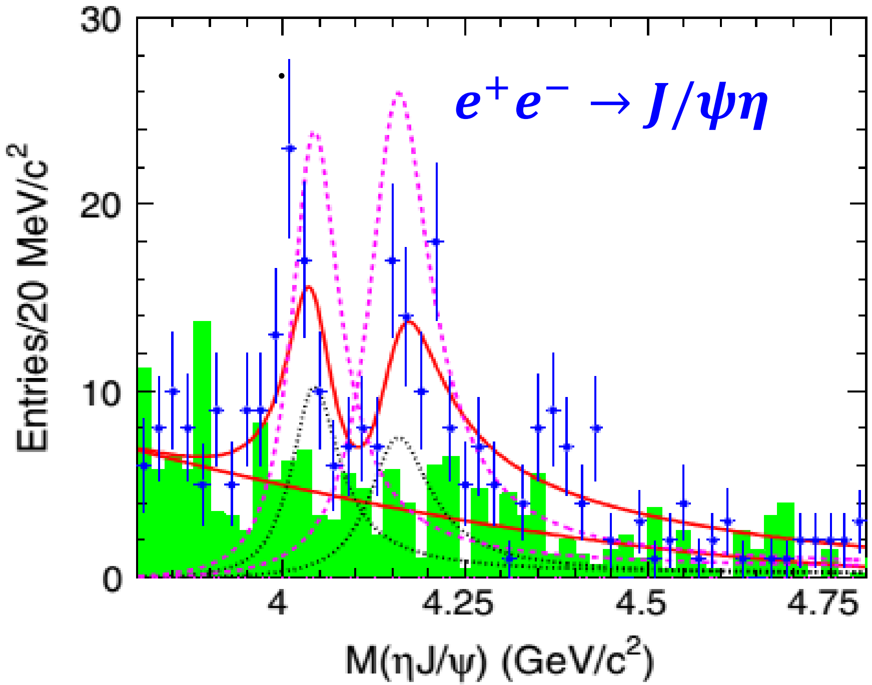
- **Meson loop can explain the experimental data**
- **Common alpha range**
- **Reflect the similarity of these processes**

$\psi(4040)/\psi(4160) \rightarrow J/\psi\eta$ PROCESS

Chen, Liu, Matsuki, Phys. Rev. D87, 054006 (2013)

$\psi(4040)/\psi(4160) \to J/\psi\eta$: Experimental information

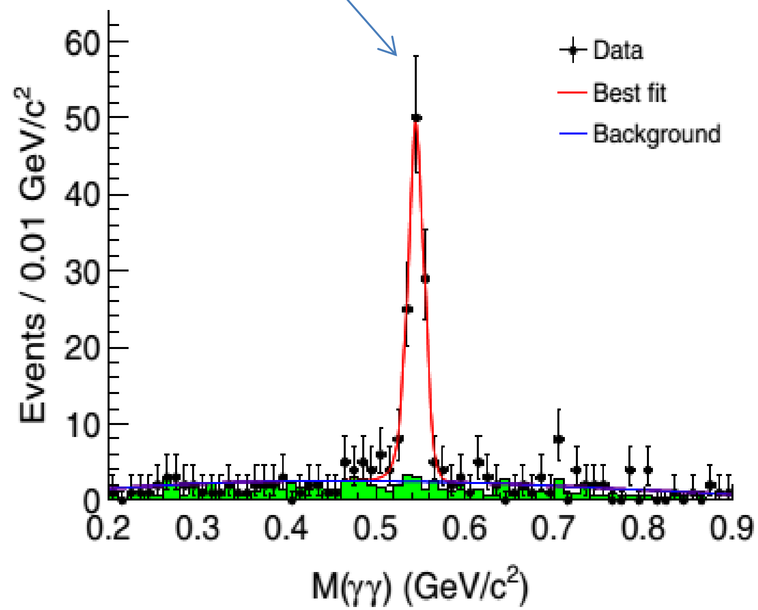
Phys.Rev.D87(5): 051101(2013)@Belle



Parameters	Solution I	Solution II
$M_{\psi(4040)}$	4039 (fixed)	
$\Gamma_{\psi(4040)}$	80 (fixed)	
$\mathcal{B} \cdot \Gamma_{e^+e^-}^{\psi(4040)}$	$4.8 \pm 0.9 \pm 1.5$	$11.2 \pm 1.3 \pm 2.1$
$M_{\psi(4160)}$	4153 (fixed)	
$\Gamma_{\psi(4160)}$	103 (fixed)	
$\mathcal{B} \cdot \Gamma_{e^+e^-}^{\psi(4160)}$	$4.0 \pm 0.8 \pm 1.4$	$13.8 \pm 1.3 \pm 2.1$
ϕ	$336 \pm 12 \pm 14$	$251 \pm 4 \pm 7$

Phys.Rev.D86: 071101@BESIII

η signal in $J/\psi(\mu^+\mu^-)$ signal region @4.009 GeV

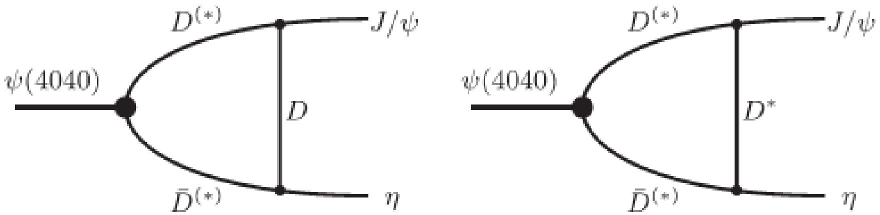


$$B(\psi(4040) \to \eta J/\psi) = (5.2 \pm 0.5 \pm 0.2 \pm 0.5) \times 10^{-3}$$

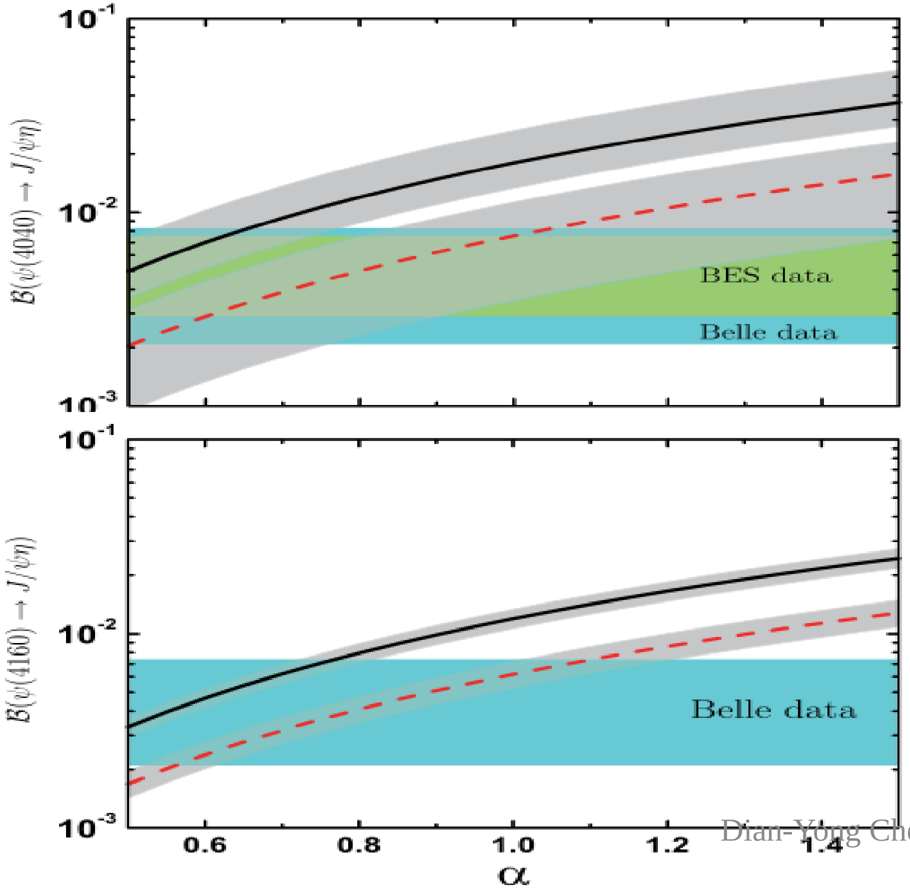
- **Consistent with Solution I of Belle Collaboration**

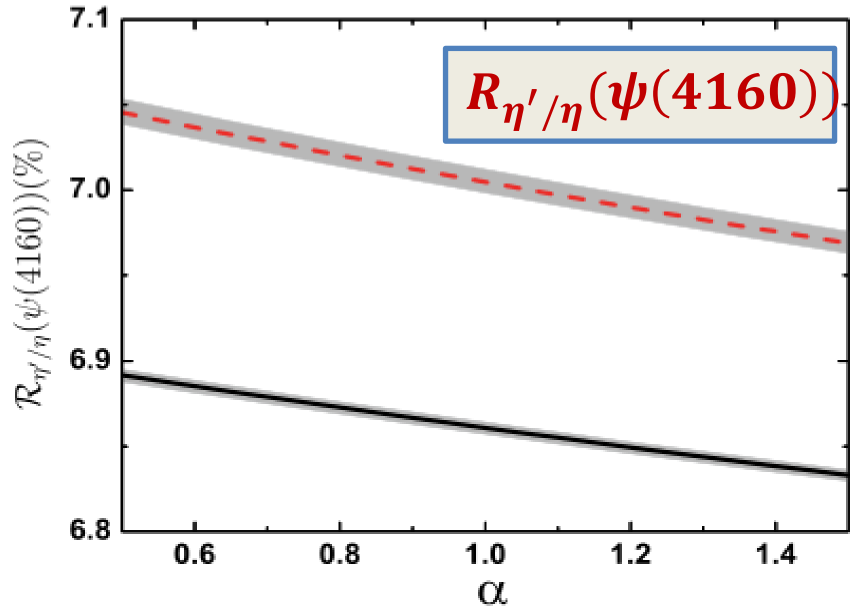
Meson Loop contributions

Chen, Liu, Matsuki, PRD87,054006



$B(\psi(4040)/\psi(4160) \to J/\psi\eta)$





- The ratio is weakly dependent on parameter α;
- Predicted: $B(\psi(4160) \to \eta' J/\psi) = (2 \sim 4.8) \times 10^{-4}$;
- Consistent with upper limit (5×10^{-3}) @CLEO (PRL96,162003)

$\psi(4S) \rightarrow \omega\chi_{c0}$ PROCESS

Adopt the effective Lagrangian approach to do the calculation

Heavy quark limit and chiral symmetry

$$\begin{aligned}\mathcal{L}_{\psi\mathcal{D}^{(*)}\mathcal{D}^{(*)}} &= -ig_{\psi\mathcal{D}\mathcal{D}}\psi_\mu(\partial^\mu\mathcal{D}\mathcal{D}^\dagger - \mathcal{D}\partial^\mu\mathcal{D}^\dagger) \\ &+g_{\psi\mathcal{D}^*\mathcal{D}}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu\psi_\nu(\mathcal{D}^*_\alpha \overleftrightarrow{\partial}_\beta \mathcal{D}^\dagger - \mathcal{D}\overleftrightarrow{\partial}_\beta \mathcal{D}^{*\dagger}_\alpha) \\ &+ig_{\psi\mathcal{D}^*\mathcal{D}^*}\psi^\mu(\mathcal{D}^*_\nu\partial^\nu\mathcal{D}^{*\dagger}_\mu - \partial^\nu\mathcal{D}^*_\mu\mathcal{D}^{*\dagger}_\nu \\ &-\mathcal{D}^*_\nu \overleftrightarrow{\partial}_\mu \mathcal{D}^{*\nu\dagger}), \qquad (1)\end{aligned}$$

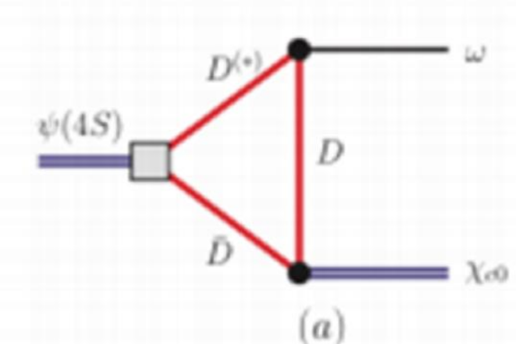
$$\mathcal{L}_{\chi_{c0}\mathcal{D}^{(*)}\mathcal{D}^{(*)}} = -g_{\chi_{c0}\mathcal{D}\mathcal{D}}\chi_{c0}\mathcal{D}\mathcal{D}^\dagger - g_{\chi_{c0}\mathcal{D}^*\mathcal{D}^*}\chi_{c0}\mathcal{D}^*_\mu\mathcal{D}^{*\mu\dagger}, \quad (2)$$

$$\begin{aligned}\mathcal{L}_{\mathcal{D}^{(*)}\mathcal{D}^{(*)}\mathcal{V}} &= -ig_{\mathcal{D}\mathcal{D}\mathcal{V}}\mathcal{D}^\dagger_i \overleftrightarrow{\partial}^\mu \mathcal{D}^j(\mathcal{V}_\mu)^i_j - 2f_{\mathcal{D}^*\mathcal{D}\mathcal{V}}\varepsilon_{\mu\nu\alpha\beta} \\ &\times(\partial^\mu\mathcal{V}^\nu)^i_j(\mathcal{D}^\dagger_i \overleftrightarrow{\partial}^\alpha \mathcal{D}^{*\beta j} - \mathcal{D}^{*\beta\dagger}_i \overleftrightarrow{\partial}^\alpha \mathcal{D}^j) \\ &+ig_{\mathcal{D}^*\mathcal{D}^*\mathcal{V}}\mathcal{D}^{*\nu\dagger}_i \overleftrightarrow{\partial}^\mu \mathcal{D}^{*j}_\nu(\mathcal{V}_\mu)^i_j \\ &+4if_{\mathcal{D}^*\mathcal{D}^*\mathcal{V}}\mathcal{D}^{*\dagger}_{i\mu}(\partial^\mu\mathcal{V}^\nu - \partial^\nu\mathcal{V}^\mu)^i_j\mathcal{D}^{*j}_\nu, \qquad (3)\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\mathcal{D}^{(*)}\mathcal{D}^{(*)}\mathcal{P}} &= -ig_{\mathcal{D}^*\mathcal{D}\mathcal{P}}(\bar{\mathcal{D}}\partial_\mu\mathcal{P}\mathcal{D}^{*\mu} - \bar{\mathcal{D}}^{*\mu}\partial_\mu\mathcal{P}\mathcal{D}) \\ &+\frac{1}{2}g_{\mathcal{D}^*\mathcal{D}^*\mathcal{P}}\epsilon_{\mu\nu\alpha\beta}\bar{\mathcal{D}}^{*\mu}\partial^\nu\mathcal{P}\overleftrightarrow{\partial}^\alpha \mathcal{D}^{*\beta}, \qquad (4)\end{aligned}$$

a general form of the decay amplitude is

$$\mathcal{M} = \int \frac{d^4q}{(2\pi)^4}\frac{\mathcal{V}_1\mathcal{V}_2\mathcal{V}_2}{\mathcal{P}_1\mathcal{P}_2\mathcal{P}_E}\mathcal{F}^2(q, m_E),$$



$$\mathcal{F}(q, m_E) = (m_E^2 - \Lambda^2)/(q^2 - \Lambda^2), \qquad \Lambda = \alpha_\Lambda\Lambda_{QCD} + m_E$$

TABLE I: The concrete values of coupling constants of charmonium (J/ψ and χ_{c0}) interacting with charmed mesons, and those of charmed mesons interacting with light pseudoscalar/vector mesons [22–25].

Coupling	Value	Coupling	Value	Coupling	Value
$g_{J/\psi DD}$	7.44	$g_{J/\psi D^*D}$	2.49 GeV^{-1}	$g_{J/\psi D^*D^*}$	8.01
$g_{DD\mathcal{V}}$	3.47	$g_{D^*D\mathcal{V}}$	2.32 GeV^{-1}	$g_{D^*D^*\mathcal{V}}$	3.74
$f_{D^*D^*\mathcal{V}}$	4.67	$g_{\chi_{c0}DD}$	-25.00 GeV	$g_{\chi_{c0}D^*D^*}$	-8.96 GeV
$g_{D^*D\mathcal{P}}$	8.94	$g_{D^*D^*\mathcal{P}}$	17.32 GeV^{-1}		

The coupling constants of ψ(4*S*) interaction with charmed meson pair

He, Chen, Xiang Liu, Matsuki, Eur. Phys. J. C 74, 3208 (2014)

$$\Gamma_{\psi(4S)\to DD} = \frac{g^2_{\psi(4S)DD}\lambda(m^2_{\psi(4S)}, m^2_D, m^2_D)^{3/2}}{24\pi m^5_{\psi(4S)}},$$

$$\Gamma_{\psi(4S)\to D^*D} = \frac{g^2_{\psi(4S)D^*D}\lambda(m^2_{\psi(4S)}, m^2_{D^*}, m^2_D)^{3/2}}{6\pi m^3_{\psi(4S)}},$$

$$\Gamma_{\psi(4S)\to D^*D^*} = \frac{g^2_{\psi(4S)D^*D^*}\lambda(m^2_{\psi(4S)}, m^2_{D^*}, m^2_{D^*})^{3/2}}{96\pi m^5_{\psi(4S)} m^4_{D^*}} \times(\lambda(m^2_{\psi(4S)}, m^2_{D^*}, m^2_{D^*}) + m^4_{\psi(4S)} + 12m^4_{D^*}),$$

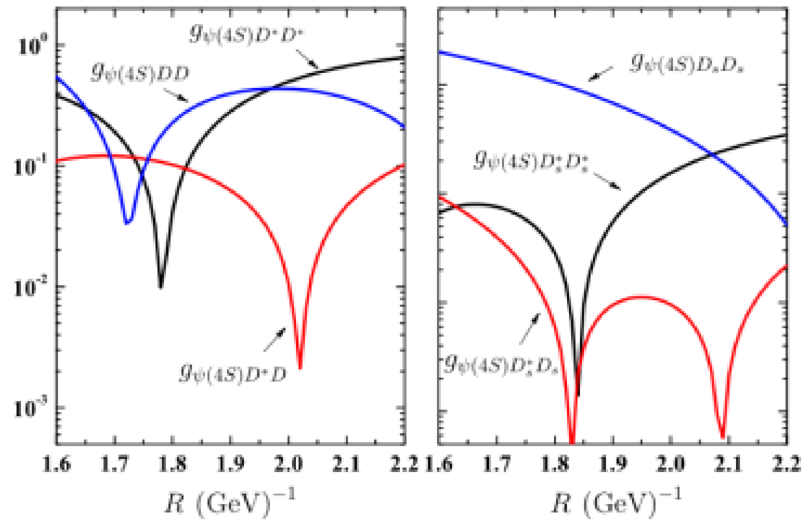


FIG. 2: (color online). The R dependence of the extracted coupling constants of $\psi(4S)$ interacting with charmed or charmed-strange mesons.

BESIII result (assuming the enhancement from ψ(4*S*)):

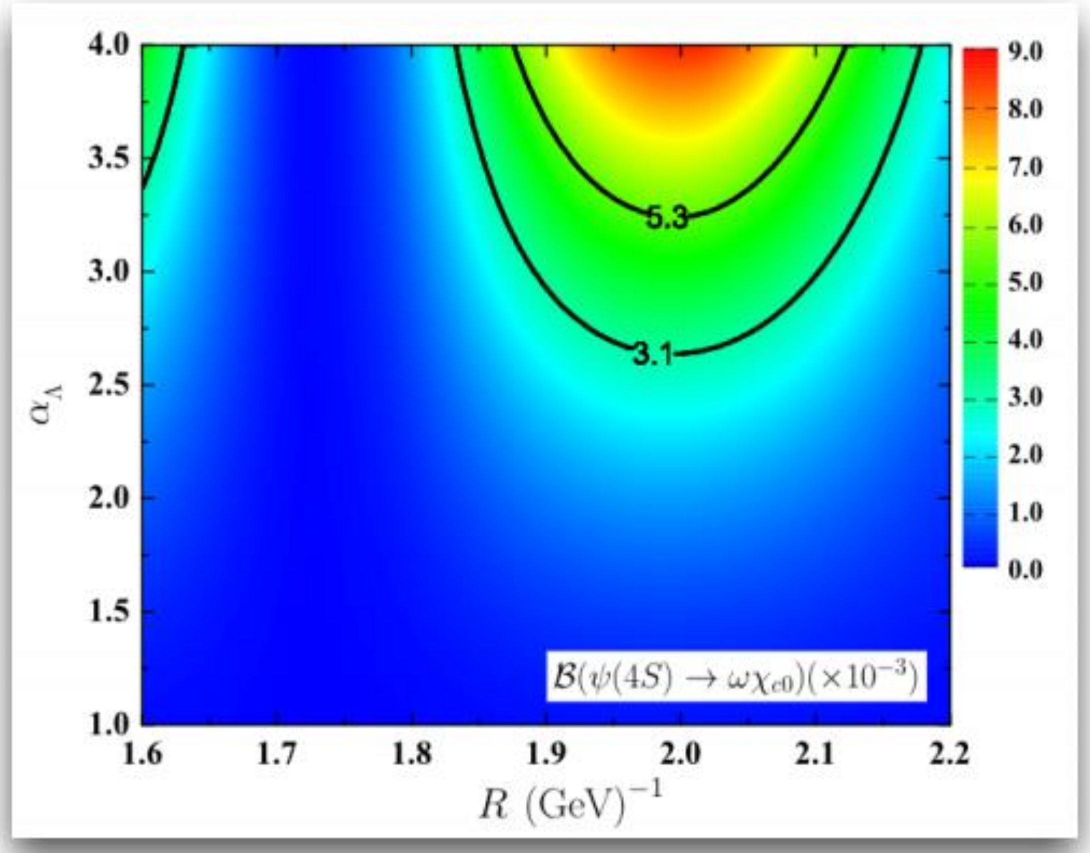
$$\Gamma(\psi(4S) \to e^+e^-)\mathcal{B}(\psi(4S) \to \omega\chi_{c0}) = (2.7 \pm 0.5 \pm 0.4)\,\text{eV},$$

$$\Gamma(\psi(4S) \to e^+e^-) = 0.63\ \text{keV}$$ Li&Chao PRD79, 094004

$$\Gamma(\psi(4S) \to e^+e^-) = 0.66\ \text{keV}$$ Dong et al., PRD49, 1642

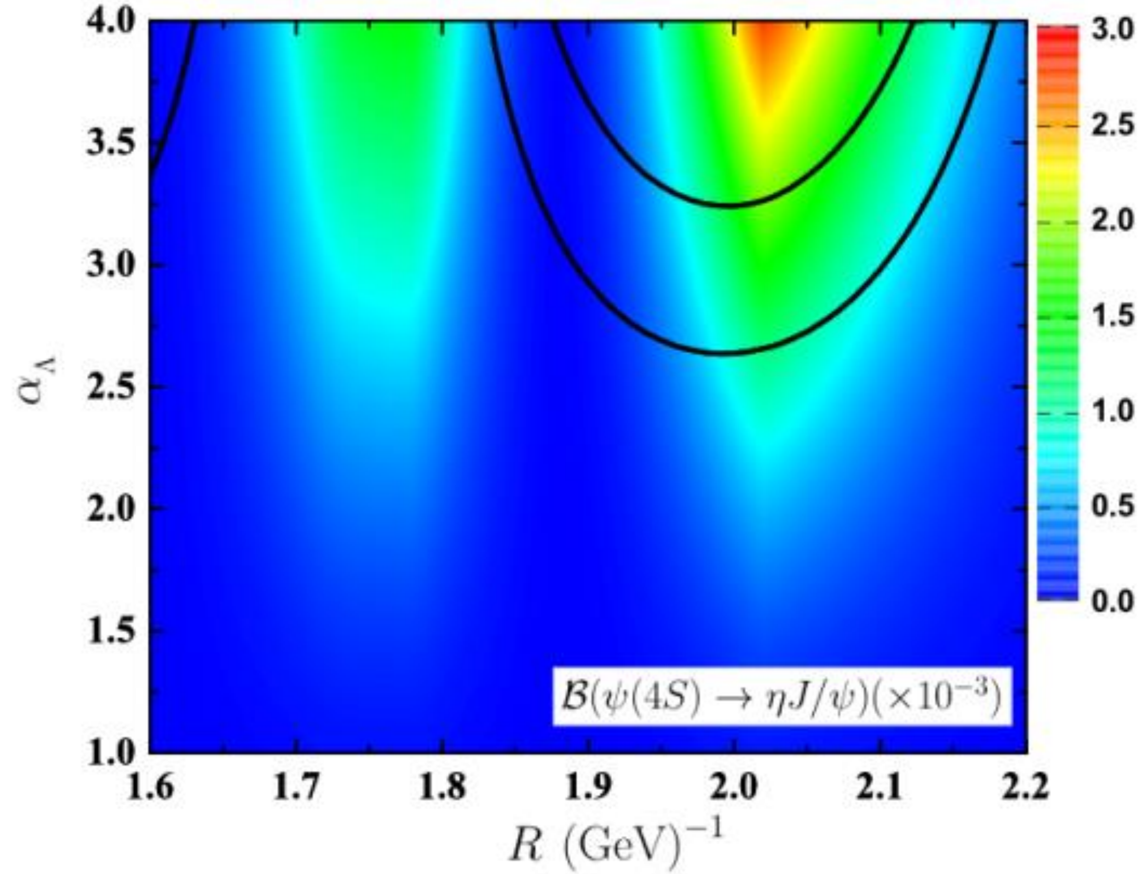
We extract

$$\mathcal{B}(\psi(4S) \to \omega\chi_{c0}) = (3.1 \sim 5.3)\times 10^{-3}$$



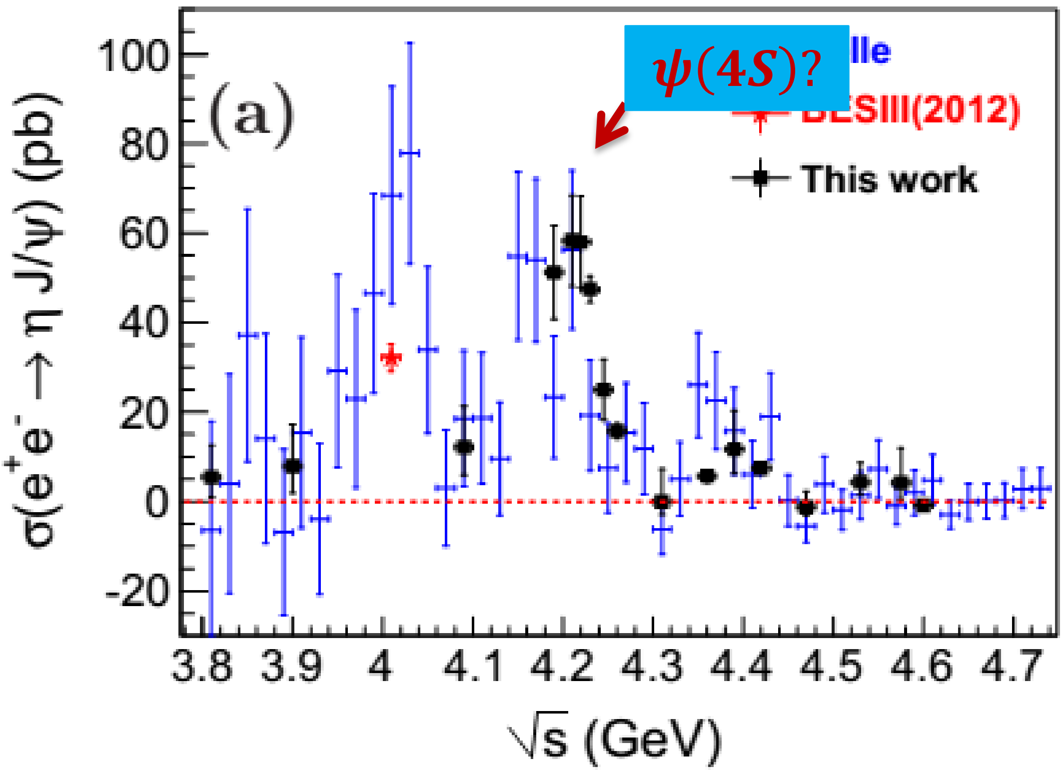
- Our theoretical result overlaps with the experimental data in a reasonable parameter range of $2.6 < \alpha_\Lambda < 4.0$ and $1.83 < R < 2.17$
- $e^+e^- \to \omega\chi_{c0}$ observation can be understood through introduction of the predicted $\psi(4S)$ contribution

Predict the upper limit of the branching ratio of ψ(4S) → ηJ/ψ



$$\mathcal{B}(\psi(4S) \to \eta J/\psi) < 1.9 \times 10^{-3}$$

Experimental measurement of $e^+e^- \to \eta J/\psi$



arXiv:1503.06644

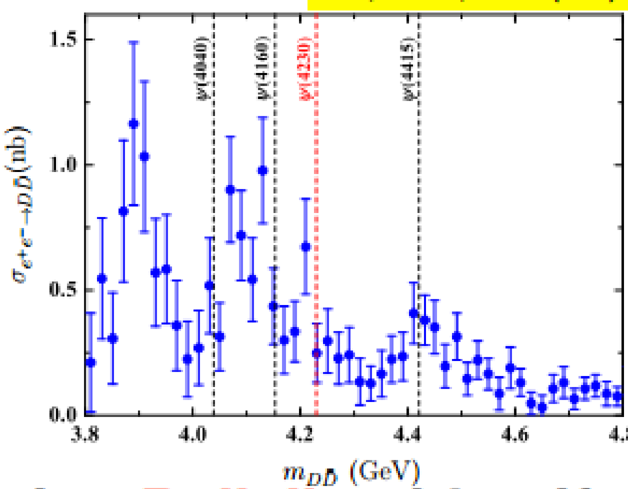
- **Recent measurement from BESIII Collaboration indicate there exist a enhancement near 4.2 GeV.**

Summary

- **Predict** a narrow higher charmonium ψ(4*S*)
- The introduction of ψ(4*S*) can **explain** recent BESIII's observation $e^+e^- \to \omega\chi_{c0}$
- The possible evidence of ψ(4*S*) in experiments

Belle, PRD 77, 011103 (2008)

Process	Mass (MeV)	Width (MeV)
$e^+e^- \to \omega\chi_{c0}$ [1]	$4230 \pm 8 \pm 6$	$38 \pm 12 \pm 2$
$e^+e^- \to \pi^+\pi^- h_c$ [31]	4216 ± 7	39 ± 17
	4230 ± 10	12 ± 36



- Suggest **BESIII**, **Belle** and forthcoming **BelleII** to identify this missing ψ(4*S*)

Thank you for your attention!