Hadron studies using two-photon processes from Belle

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on behalf of the Belle Collaboration

Outlines

- Two-photon interactions
- Charmonium(-like) states
- Accelerator and detector
- Review of two-photon results
- New results of two-photon at Belle
- Summary

Two–photon interactions

ELSEVIER

Nuclear Physics B 523 (1998) 423–438

NUCLEAR PHYSICS B

Meson–photon transition form factors and resonance cross-sections in e^+e^- collisions

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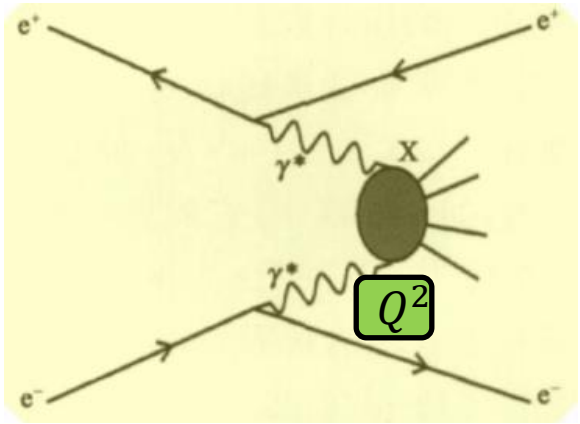
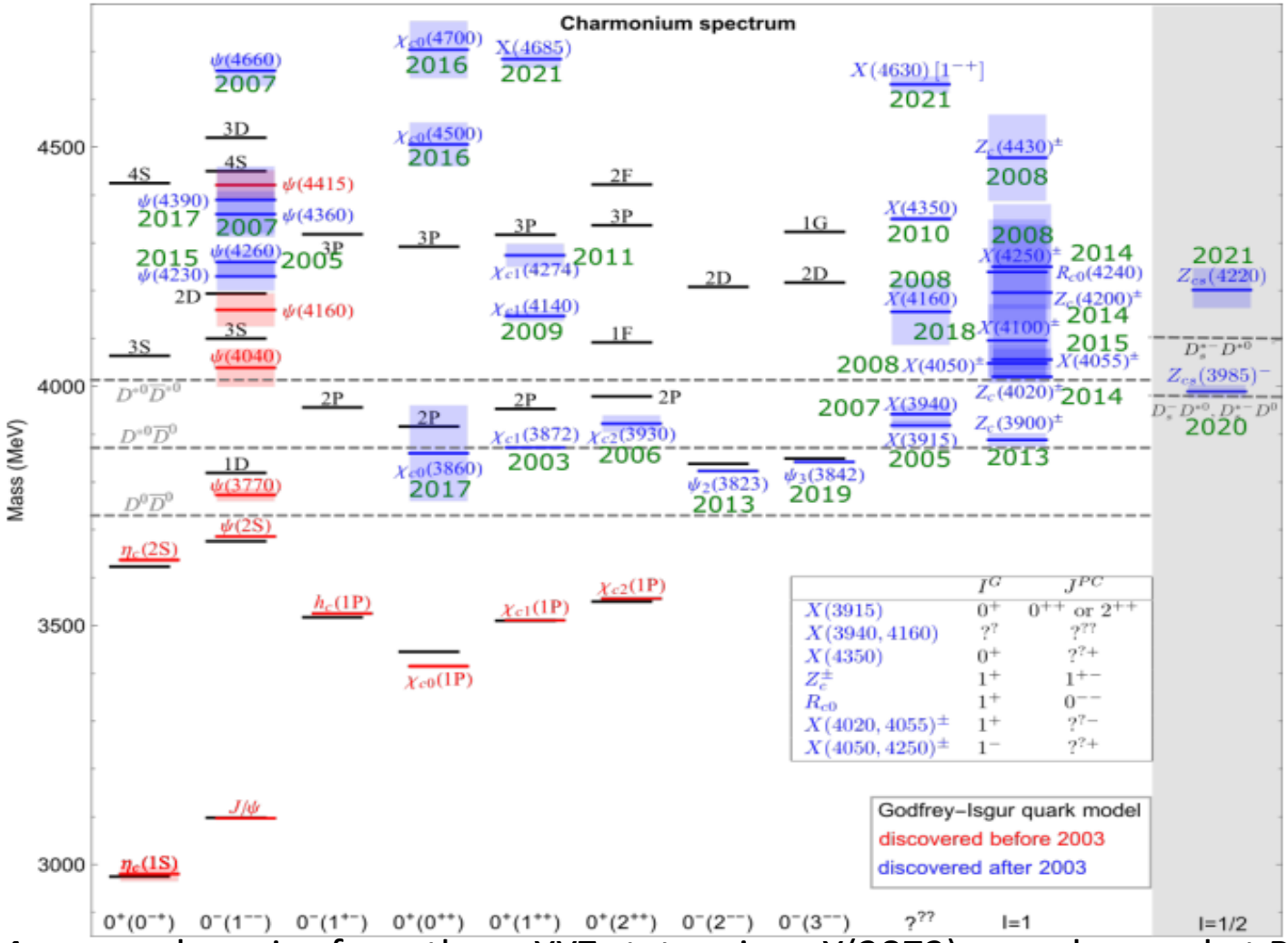
- Meson-photon-photon transition form factors for *S*-, *P*-, and *D*-wave states are calculated.
- Q^2 dependence of the (single) form factor governs the production of mesons.
- e^+e^- cross section for 1^+ states do not vanish at low Q^2



Form factors f_{AB}

J^P	f_{TT}	f_{TS}	f_{SS}
0^-	$\kappa \frac{X}{\nu^2}$	0	0
0^+	$\kappa \left(\frac{X+\nu M^2}{3\nu^2}\right)^2$	0	$2\kappa \left(\frac{M^2\sqrt{Q_1^2 Q_2^2}}{3\nu^2}\right)^2$
1^+	$\kappa \left(\frac{Q_2^2-Q_1^2}{2\nu}\right)^2$	$2\kappa \frac{M^2}{2\nu}\frac{Q_2^2}{2\nu}\left(\frac{\nu+Q_1^2}{\nu}\right)^2$	0
2^+	$\kappa \left(\frac{M^2}{2\nu}\right)^2 \left\{1+\frac{\left[2Q_1^2Q_2^2-\nu(Q_1^2+Q_2^2)\right]^2}{6M^4\nu^2}\right\}$	$\kappa \frac{M^2 Q_2^2 \left(\nu-Q_1^2\right)^2}{4\nu^4}$	$\kappa \frac{M^4 Q_1^2 Q_2^2}{3\nu^4}$
2^-	$\kappa \left[\frac{X}{\nu^2}\right]^3$	0	0

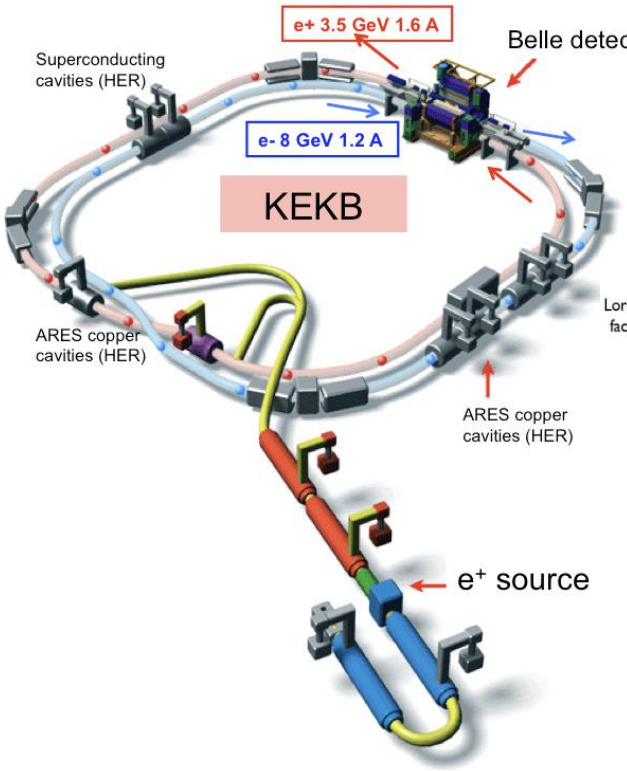
Charmonium(-like) states

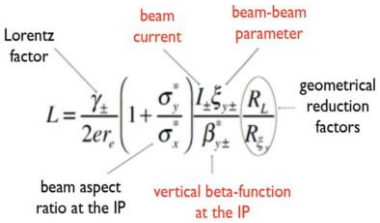


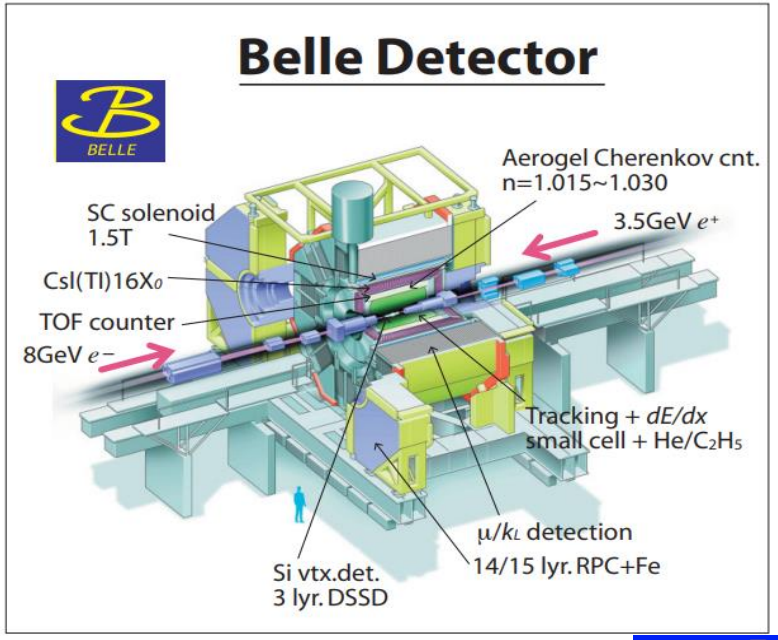
- Many puzzles arise from these XYZ states since X(3872) was observed at Belle Experiment in 2003. [Phys. Rev. Lett. 91. 262001(2003)]
- One of the XYZ puzzles concerns the candidates for *P*-wave triplet states near 3.9 GeV/c^2. [Phys. Rev. D 72, 054026 (2005)]

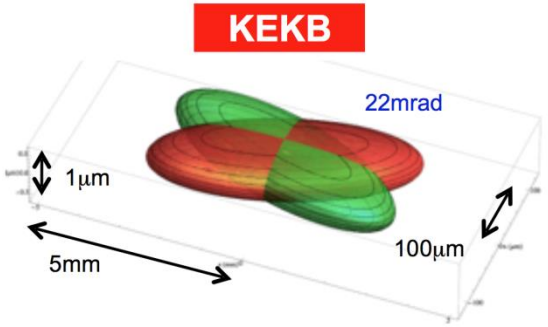
Accelerator and detector

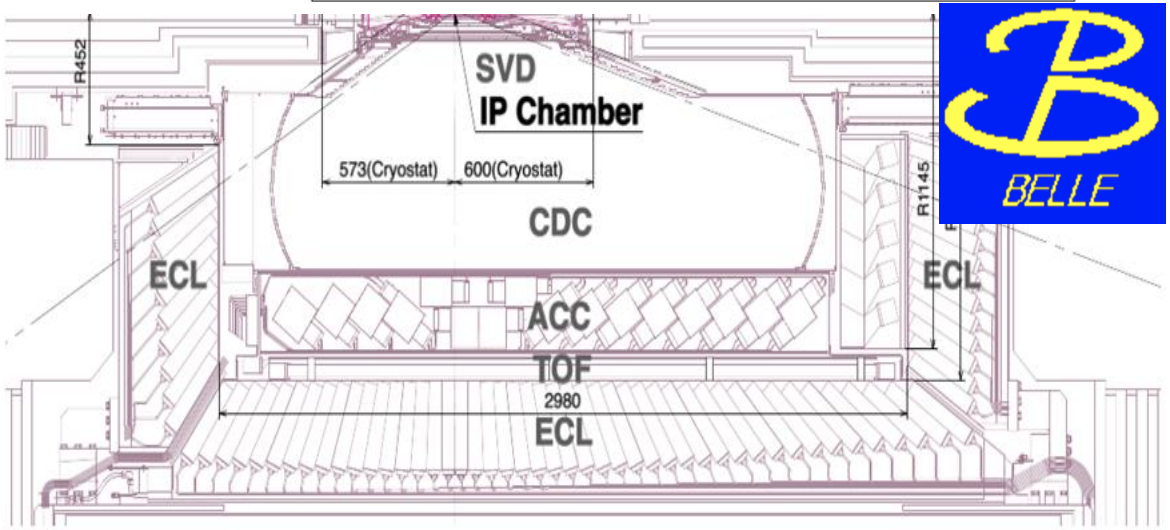
1st generation B-factory











Review of two-photon results

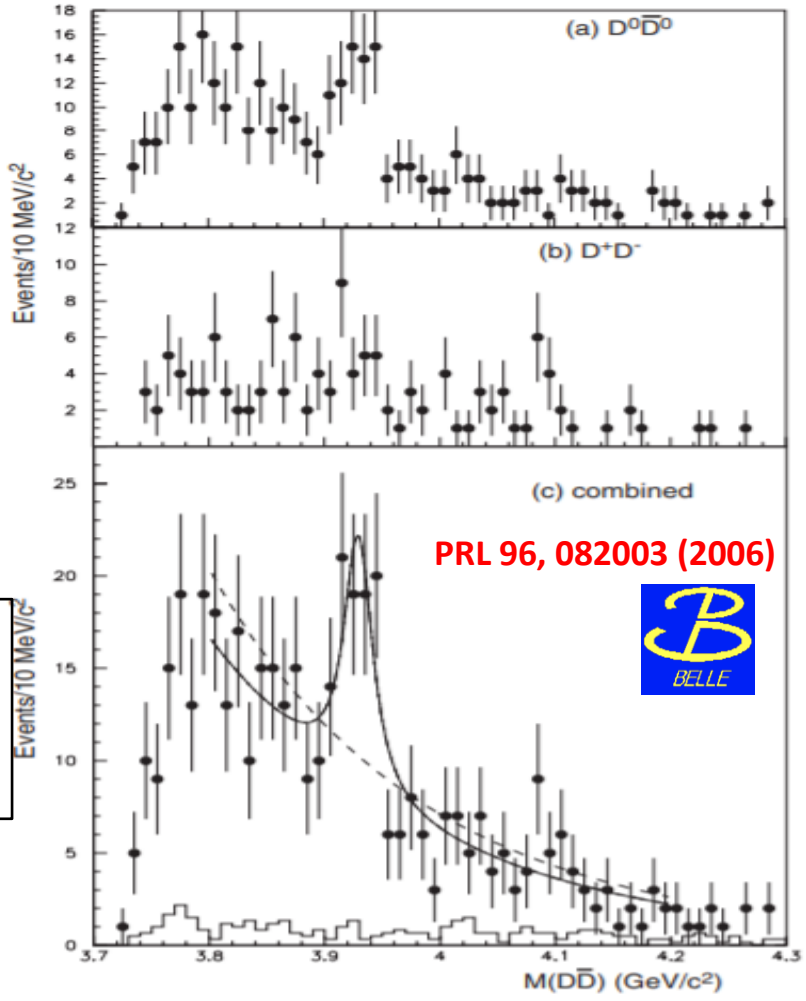
- $\gamma\gamma \to Z(3930) \to D\bar{D}$
- $\gamma\gamma \to X(3915) \to \omega J/\psi$
- $\gamma\gamma \to X(4350) \to \phi J/\psi$

$\gamma\gamma \to Z(3930) \to D\bar{D}$

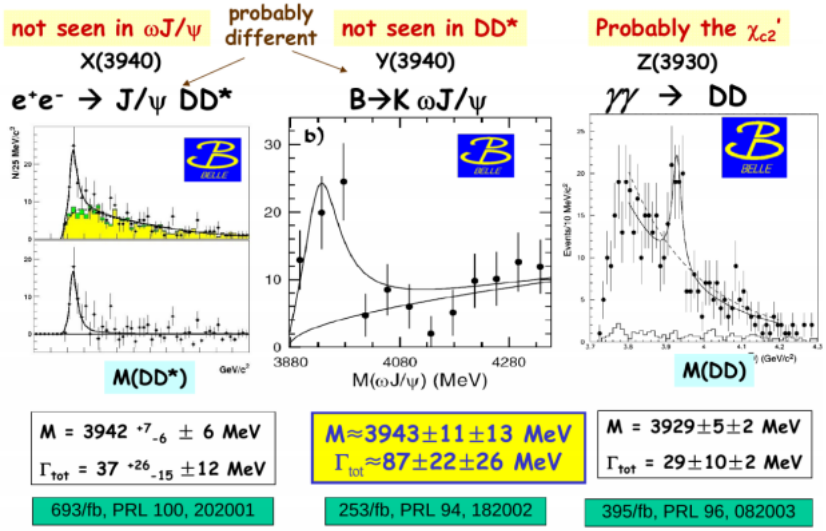
- The first radially excited χ_{cJ} states are predicted to have masses between 3.9 and 4.0 GeV/c^2, which is considerably above $D\bar{D}$ threshold.
- The results on mass, decay angular distributions and $\Gamma_{\gamma\gamma}(\mathcal{B} \to D\bar{D})$ are all consistent with expectations for the χ'_{c2} .
- Results for the mass, width, and the product of the two-photon decay width times the branching fraction to $D\bar{D}$:

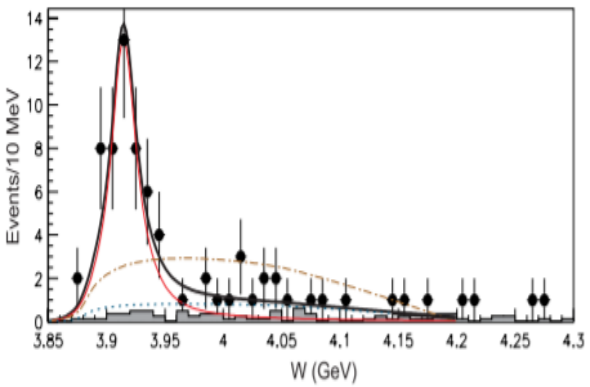
$$\text{M: } 3923 \pm 5 \pm 2 \text{ MeV}/c^2$$
$$\Gamma_{tot}\text{: } 29 \pm 10 \pm 2 \text{ MeV}$$
$$\Gamma_{\gamma\gamma}(\mathcal{B} \to D\bar{D}) = 0.18 \pm 0.05 \pm 0.03 \text{ keV}$$

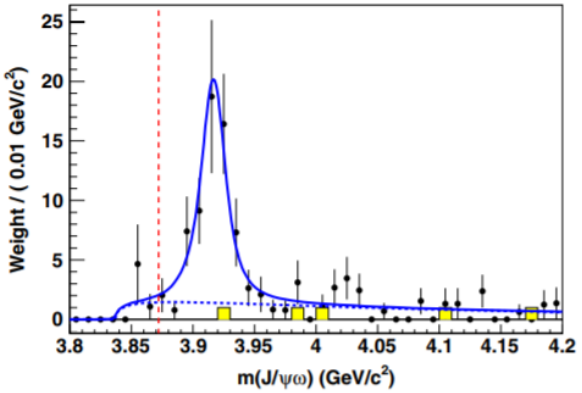
Probably the χ_{c2}: $Z(3930)$



$\gamma\gamma \to X(3915) \to \omega J/\psi$







$X(3915)$ from Belle:

- $M = (3915 \pm 3 \pm 2)$ MeV;
- $\Gamma = (17 \pm 10 \pm 3)$ MeV
- $N^{\rm sig} = 49 \pm 14 \pm 4$ events
- Signif. $= 7.7\sigma$.

Belle: PRL104, 092001(2010)

$X(3915)$ was expected to be $\chi_{c0}(2P)$ candidate.

$X(3915)$ From BaBar:

- $M = (3919.4 \pm 2.2 \pm 1.6)$ MeV/c^2;
- $\Gamma = (13 \pm 6 \pm 3)$ MeV;
- $N^{\rm sig} = 59 \pm 10$;
- Signif. $= 7.6\ \sigma$.
- Data largely prefer $J^P = 0^{\pm}$ over 2^+.

BaBar: PRD86,072002(2012)

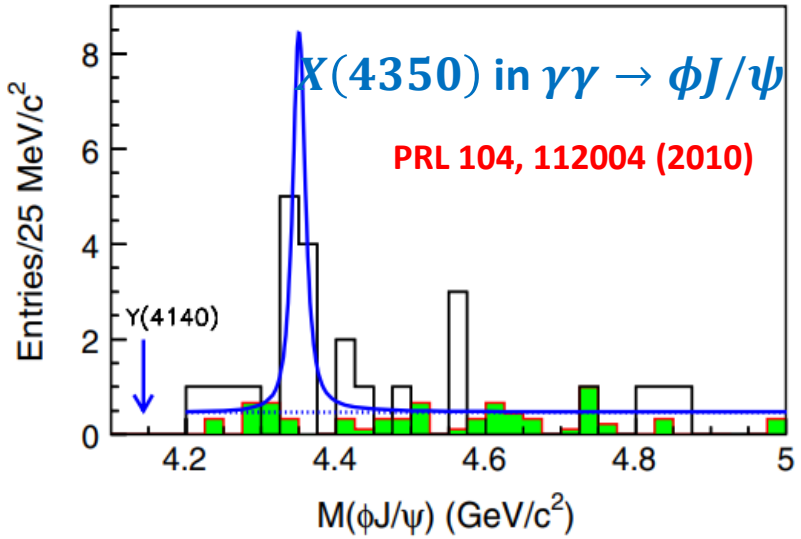
- Three of the new states were discovered by Belle in the 3.90-3.95 GeV/c^2.
- They appear in different production and decay processes, and are usually considered to be distinct particles, however there is no decisive evidence .
- These values are consistent with those of the $Y(3940)$, and close to those of the $Z(3930)$.
- Helicity-0 component is allowed, a J^{PC}=2^{++} assignment is possible.

$\gamma\gamma \to X(4350) \to \phi J/\psi$

X(4350) $I^G(J^{PC}) = 0^+(?^{?+})$

OMITTED FROM SUMMARY TABLE

Seen by SHEN 10 in the $\gamma\gamma \to J/\psi\phi$. Needs confirmation.



- The first investigation of the $\gamma\gamma \to \phi J/\psi$ is to search for high mass states with $J^{PC} = 0^{++}$ or 2^{++}, such as the tetraquark states and molecular states that are predicted by various models.

$$m(X(4350)) = [4350.6^{+4.6}_{-5.1}(stat) \pm 0.7(syst)]\ \text{MeV}/c^2$$

$$\Gamma(X(4350)) = [13^{+18}_{-9}(stat) \pm 4(syst)]\ \text{MeV}$$

- The mass of this structure is consistent with the predicted values of a $c\bar{c}s\bar{s}$ tetraquark state with $J^{PC} = 2^{++}$, and a ${D_s}^{*+}{D_{s0}}^{*-}$ molecular state.
- The possibility that $X(4350)$ could be an excited *P*-wave charmonium state(${\chi''}_{c2}$).

New results of two-photons at Belle

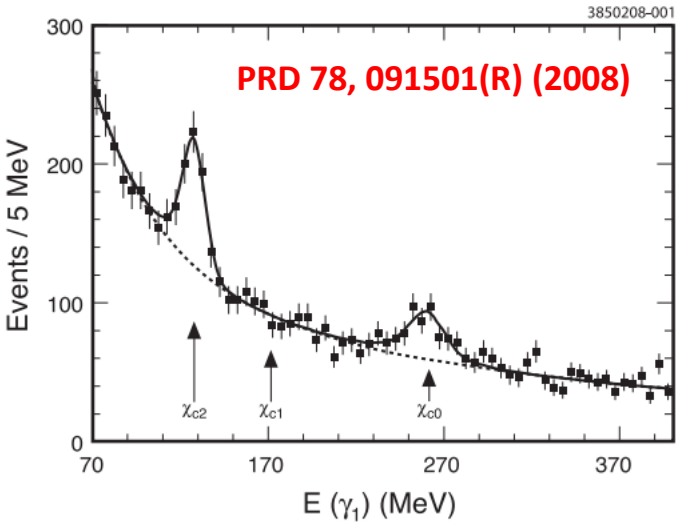
- $\gamma\gamma \to \chi_{c2}(1P) \to J/\psi\gamma$
- $\gamma\gamma \to Z(3922)/X(4015) \to \gamma\psi(2S)$
- $\gamma\gamma \to X(3872) \to \pi^+\pi^- J/\psi$

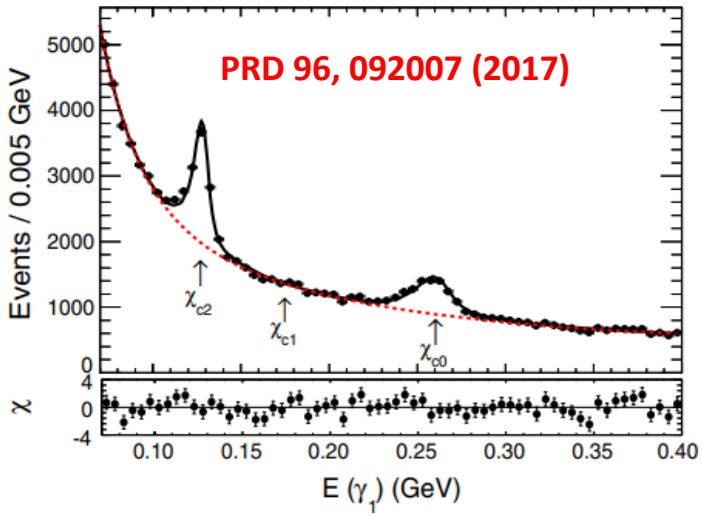
$\gamma\gamma \rightarrow \chi_{c2}(1P) \rightarrow J/\psi\gamma$

- The two-photon decay widths ($\Gamma_{\gamma\gamma}$) of mesonic states provide important information for testing models based on quantum chromodynamics(QCD).

- The predictions of two-photon decay width of $\chi_{c2}(1P)$ have the wide range of values between 280 eV and 930 eV in various theoretical calculations.[Phys. Rev. D 82, 034021 (2010)]

- Several experiments have reported the measurement of $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$. The precision of the experimental value of $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ using the two-photon process is much less than the value measured in the two-photon decay. Precise measurements will help to improve the understanding of quarkonium states.





$\gamma\gamma \to \chi_{c2}(1P) \to J/\psi\gamma$

Selection criteria:

- Tracks: Ntrk=2, $|dz| \leq 3cm$, $|dr| \leq 1cm$, -0.47 $\leq \cos\theta \leq$ 0.82, $p_T \geq 0.4$ GeV/c , $|\triangle dz| \leq 1cm$, $\cos\alpha >$ -0.997

- Identify e/μ : $E/p \geq 0.8$ for electron, $E/p \leq 0.4$ for muon

- For photon: $E_\gamma \geq 0.2$ GeV, the cluster is isolated from the nearest charged track by an angle greater than 18.2°.

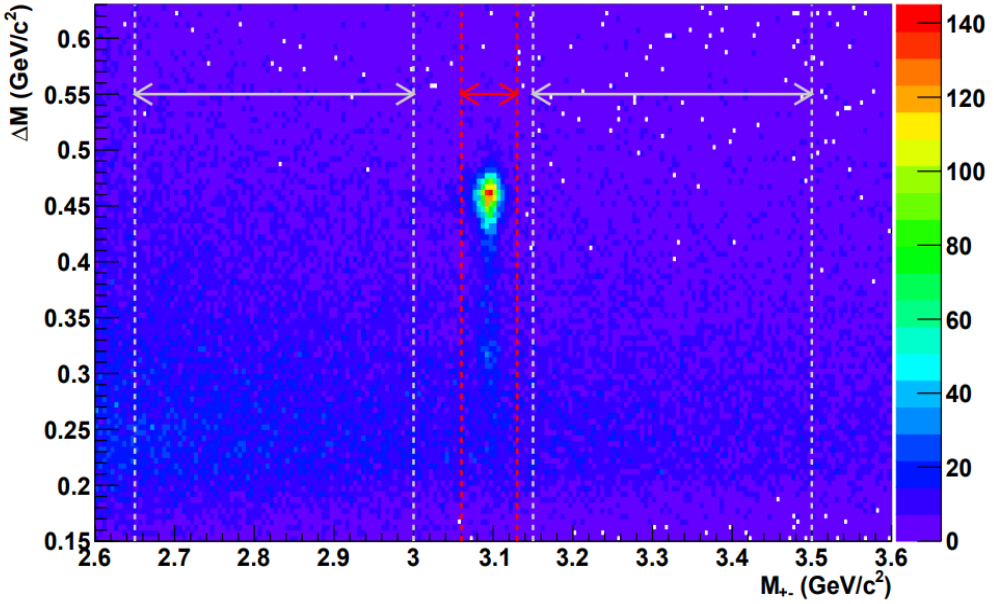
Signal region:

3.06 GeV/c^2< M_{+-}< 3.13GeV/c^2

Sideband regions:

2.65 GeV/c^2< M_{+-}< 3.00 GeV/c^2

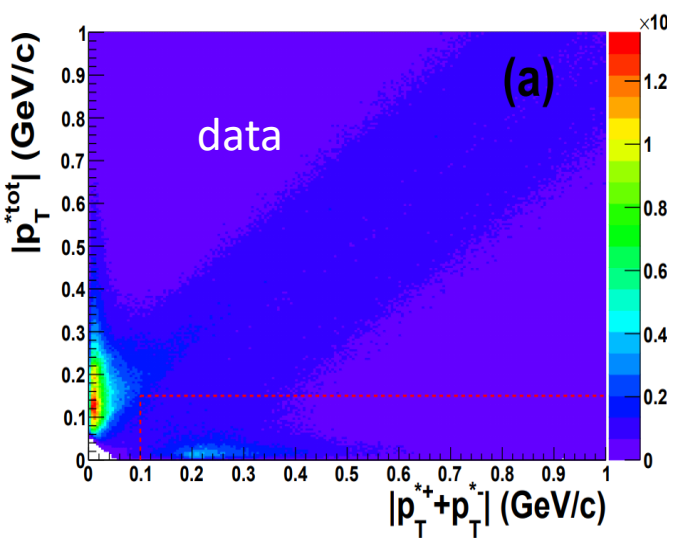
3.15 GeV/c^2< M_{+-}< 3.50 GeV/c^2

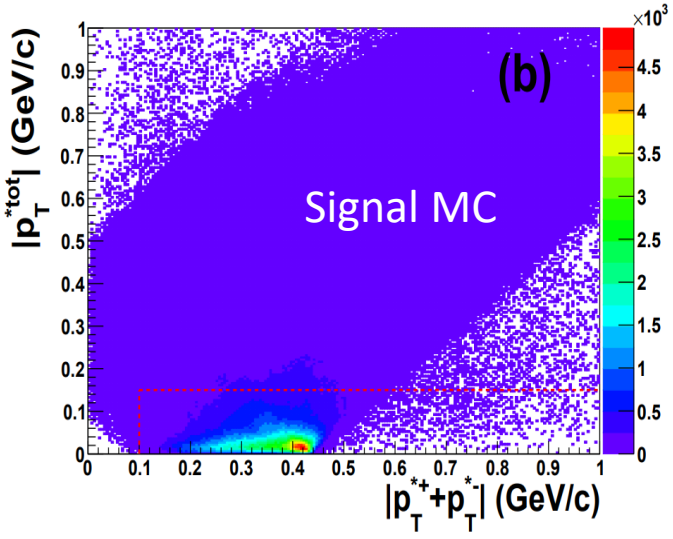


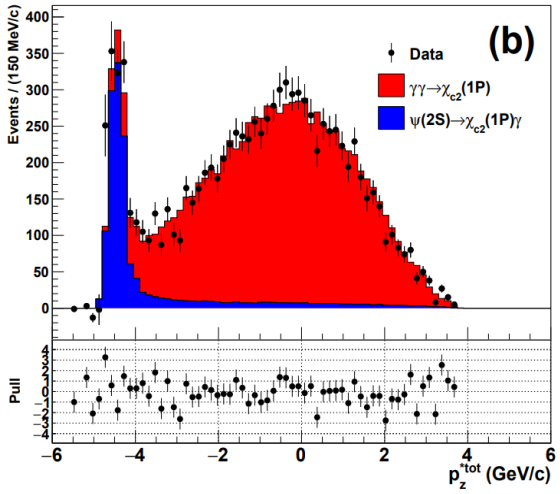
$\gamma\gamma \to \chi_{c2}(1P) \to J/\psi\gamma$

Background research:

- $M_{rec}{}^2(\gamma J/\psi)$> 5.0 MeV^2/c^4 to reject ISR process
- $|p_T{}^{*tot}|$<0.15 GeV/c, $|p_T{}^{*+} + p_T{}^{*-}|$>0.1GeV/c to reject two-photon production with a fake photon
- $p_z{}^{*tot} < -4.5$ GeV/c to reject the ISR $\psi(2S)$ production







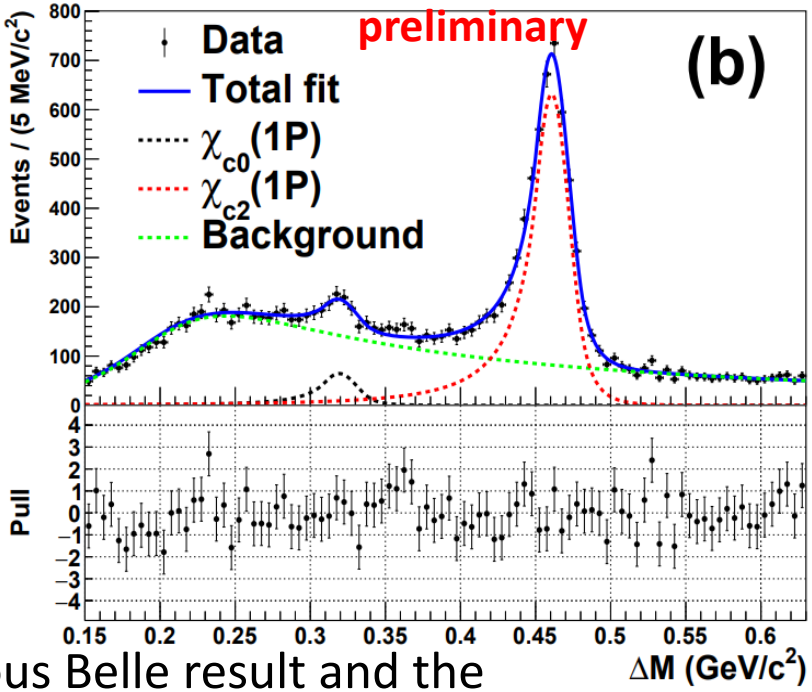
$\gamma\gamma \to \chi_{c2}(1P) \to J/\psi\gamma$

- Non-J/ψ background is the dominant background
- Spin-1 meson production is suppressed $\Delta M = M_{+-\gamma} - M_{+-}$
- Fitting functions: $A(\Delta M - a)^{-b}/(1 + e^{-c(\Delta M - d)})$ for background
  Double-side Crystal Ball function for $\chi_{c0}(1P)$ and $\chi_{c2}(1P)$

$$\Gamma_{\gamma\gamma}(\chi_{c2}(1P))\mathcal{B}(\chi_{c2}(1P) \to J/\psi\gamma)\mathcal{B}(J/\psi \to \ell^+\ell^-) = \frac{m^2_{\chi_{c2}(1P)} N_{\rm sig}}{20\pi^2(\int \mathcal{L}dt)\eta L_{\gamma\gamma}(m_{\chi_{c2}(1P)})}$$

$$\Gamma_{\gamma\gamma}(\chi_{c2}(1P)) = 653 \pm 13(\text{stat.}) \pm 31(\text{syst.}) \pm 17(\text{B.R.})\ \text{eV}$$

Experiment [Ref.]	Measured value[a]	$\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ (eV)
This measurement	$\Gamma_{\gamma\gamma}(\chi_{c2}(1P)) \times \mathcal{B}_1 \times \mathcal{B}_2 = 14.8 \pm 0.3 \pm 0.7$ eV	$653 \pm 13 \pm 31 \pm 17^{b}$
Belle [14]	$\Gamma_{\gamma\gamma}(\chi_{c2}(1P)) \times \mathcal{B}_1 \times \mathcal{B}_2 = 13.5 \pm 1.3 \pm 1.1$ eV	$596 \pm 58 \pm 48 \pm 16^{b,d}$
CLEOIII [15]	$\Gamma_{\gamma\gamma}(\chi_{c2}(1P)) \times \mathcal{B}_1 \times \mathcal{B}_2 = 13.2 \pm 1.4 \pm 1.1$ eV	$582 \pm 59 \pm 50 \pm 15^{b,d}$
CLEO-c [12]	$\mathcal{B}_3 \times \mathcal{B}_4 \times 10^5 = 2.68 \pm 0.28 \pm 0.15$	$555 \pm 58 \pm 32 \pm 28^{c,e}$
BESIII [13]	$\mathcal{B}_3 \times \mathcal{B}_4 \times 10^5 = 2.83 \pm 0.08 \pm 0.06$	$586 \pm 16 \pm 13 \pm 29^{c,e}$



✓ This measurement is consistent with the previous Belle result and the other experimental results. The result in this paper achieves the most precise measurement of $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$.

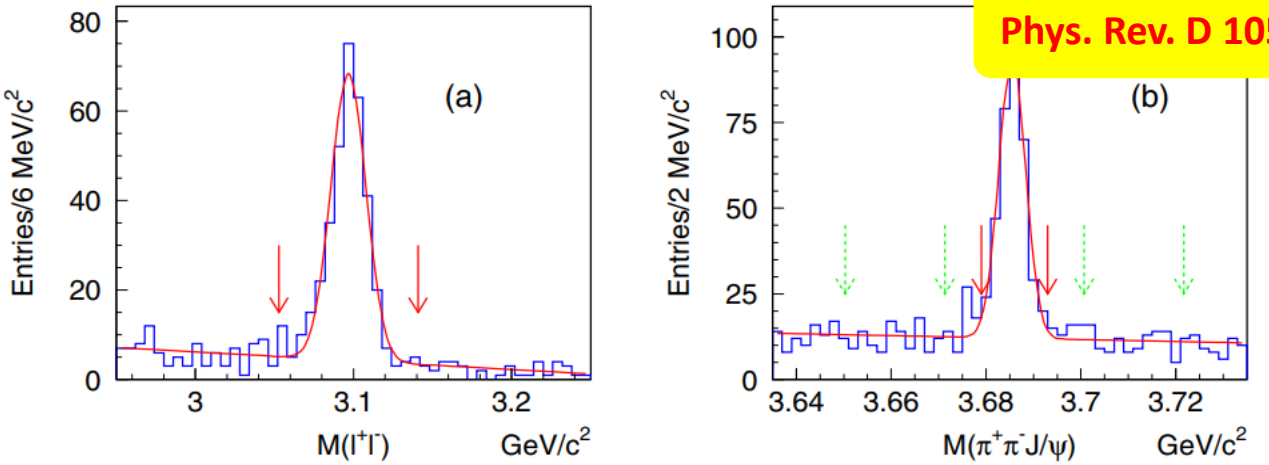
$\gamma\gamma \to \gamma\psi(2S)$ at Belle

- Both $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$ can be produced in two-photon collision and decay to $\gamma\psi(2S)$ via E1 transition. [Phys. Rev. D 72, 054026 (2005)]

- The partial widths are expected to be $\Gamma(\chi_{c0}(2P) \to \gamma\psi(2S)) \approx 135$ keV and $\Gamma(\chi_{c2}(2P) \to \gamma\psi(2S)) \approx 207$ keV according to Godfrey-Isgur relativized potential model. [Phys. Rev. D 72, 054026 (2005)]

- $\psi(2S)$ reconstructed from $J/\psi\pi^+\pi^-$, and J/ψ reconstructed from e^+e^- or $\mu^+\mu^-$.

Phys. Rev. D 105, 112011(2022)



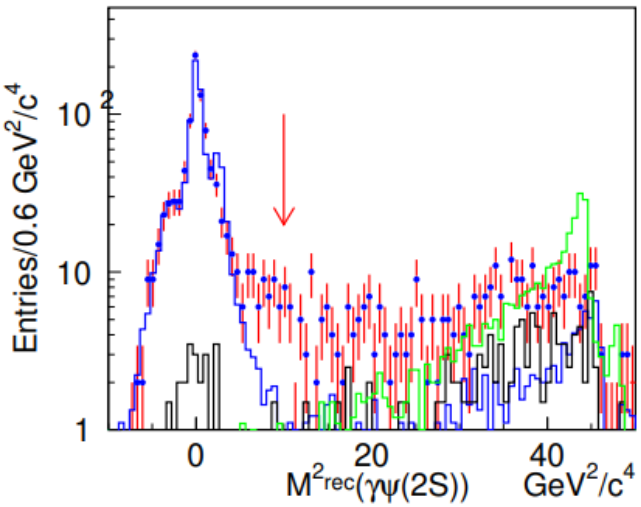
- Signal regions : $|M_{l^+l^-} - m_{J/\psi}| < 4\sigma_{J/\psi}(\sigma_{J/\psi} \equiv 11.0\ \text{MeV}/c^2)$

$$|M_{\pi^+\pi^- J/\psi} - m_{\psi(2S)}| < 2.5\sigma_{\psi(2S)}(\sigma_{\psi(2S)} \equiv 2.8\text{MeV}/c^2)$$

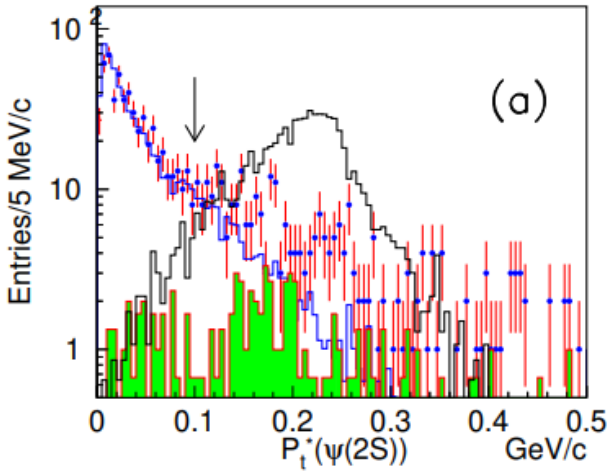
- Sideband region : $|M_{\pi^+\pi^- J/\psi} - m_{\psi(2S)} \pm 9\sigma_{\psi(2S)}| < 3.75\sigma_{\psi(2S)}$

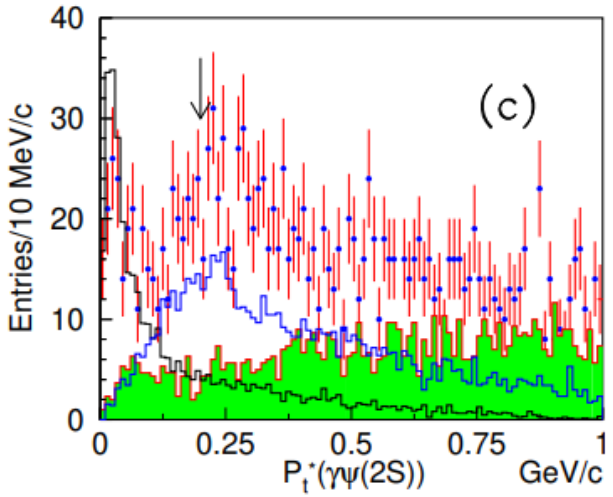
$\gamma\gamma \to \gamma\psi(2S)$ at Belle

Phys. Rev. D 105, 112011(2022)



- We apply $M^2{}_{rec}\left(\gamma\psi(2S)\right) > 10(\mathrm{GeV}/c^2)^2$ to remove most ISR events.
- The transverse momenta of $\psi(2S)$ and $\gamma\psi(2S)$ are used to suppress the ISR background further.

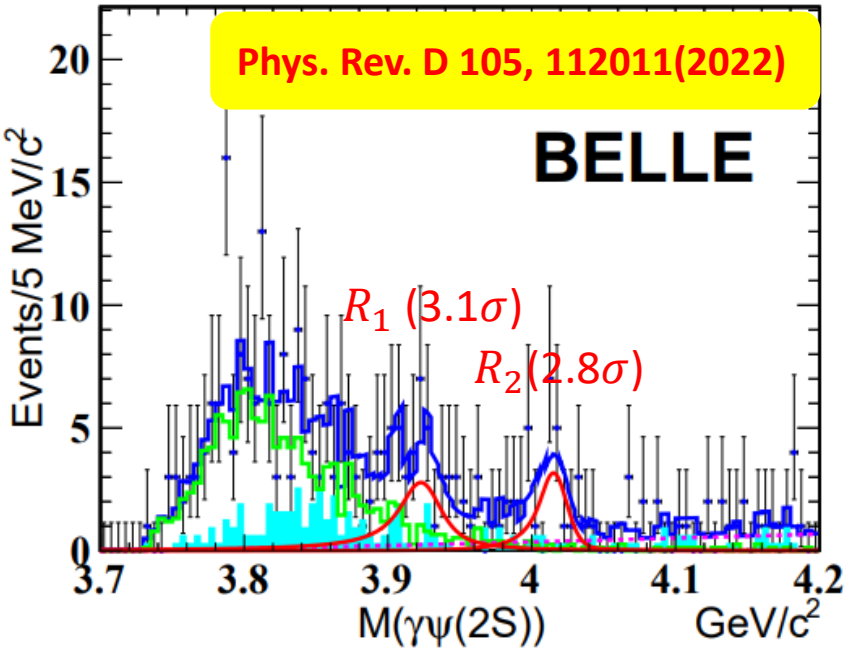




- We apply $P^*{}_t\left(\psi(2S)\right) > 0.1\mathrm{GeV}/c$ and $P^*{}_t\left(\gamma\psi(2S)\right) < 0.2\mathrm{GeV}/c$ to suppress the ISR background with selection efficiencies of (97.1±0.3)% and (67.8±0.7)%, respectively.

$\gamma\gamma \to \gamma\psi(2S)$ at Belle

■ Fitting to the $M(\gamma\psi(2S))$ distribution: $f_{PDF} = f_{R_1} + f_{R_2} + f_{ISR} + f_{bkg} + f_{SB}$



◆ Two excesses around 3.92 and 4.02 GeV/c^2

◆ Fit function: $f_{sum} = f_{R1} + f_{R2} + f_{ISR} + f_{bkg} + f_{SB}$

f_{R1}、f_{R2}: Breit-Wigner⊗ Crystal Ball (solid red line)

f_{ISR}: for ISR events (green blank histogram)

f_{bkg}: possible addition backgrounds (pink dashed line)

f_{SB} : the background in $\psi(2S)$ reconstruction (blue shaded histogram)

Resonant parameters	$J=0$	$J=2$
M_{R_1}	$3922.4 \pm 6.5 \pm 2.0$	
Γ_{R_1}	$22 \pm 17 \pm 4$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_1 \to \gamma\psi(2S))$	$9.8 \pm 3.6 \pm 1.2$	$2.0 \pm 0.7 \pm 0.2$
M_{R_2}	$4014.3 \pm 4.0 \pm 1.5$	
Γ_{R_2}	$4 \pm 11 \pm 6$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_2 \to \gamma\psi(2S))$	$6.2 \pm 2.2 \pm 0.8$	$1.2 \pm 0.4 \pm 0.2$

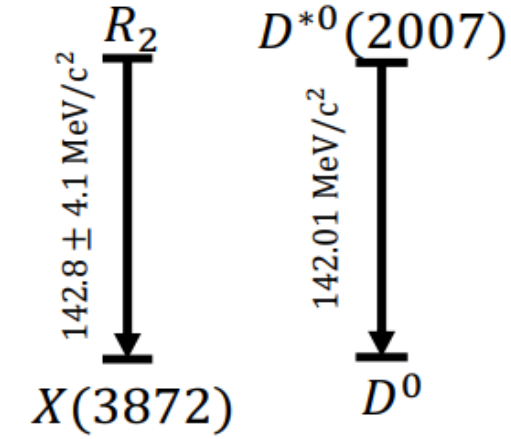
◆ **R_1 near 3.92 GeV/c^2: 3.1σ including systematic uncertainties**

◆ **R_2 near 4.01 GeV/c^2: study on look-elsewhere effect show a global significance of 2.8σ.**

$\gamma\gamma \to \gamma\psi(2S)$ at Belle

- R_1 may be $X(3915)$, $\chi_{c2}(3930)$, or mix of them. Assuming R_1 is the $\chi_{c2}(3930)$, a rough estimation shows $\Gamma(\chi_{c2}(3930) \to \gamma\psi(2S)) = 200\sim300\text{keV}$. [207 keV calculated by GI model in PRD 72, 054026 (2005)]

- R_2 has the same mass and width with 2^{++} partner of $X(3872)$ predicted in PRD 88, 054007 (2013), Eur. Phys. J. C 75, 547 (2015). R_2 corresponds to one new resonance $X(4014)$.



R_2 may be helped for the study of $X(3872)$

- The hints implies that one state with a mass close to the $D^*\overline{D}^*$ threshold and a narrow width exists.[arXiv:2207.03930]

- The newly reported $X(4014)$ state still needs to be studied, and its favored quantum numbers also need to be discussed.

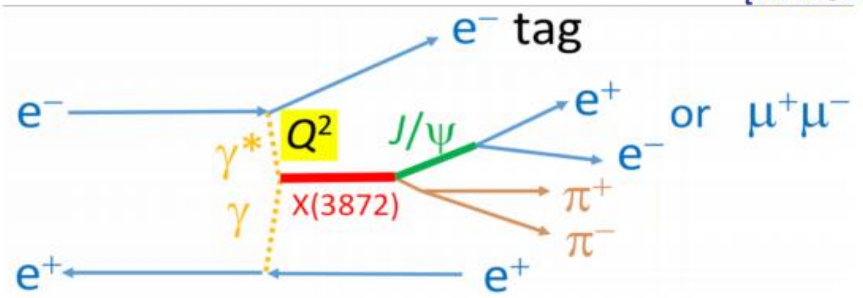
$\gamma\gamma \to X(3872) \to \pi^+\pi^- J/\psi$

- The charmonium-like state $X(3872)$ has been observed in various interaction, but not searched for in two-photon interactions

- Mesons with $J^{PC} = 1^{++}$ can be produced if one or both photons are highly virtual — denoted as γ^*

X(3872): $J^{PC} = 1^{++}$ $\quad \gamma\gamma \to X(3872)$ ⟶ Not allowed

But, $\gamma^*\gamma \to X(3872)$ ⟶ Allowed [NPB 523, 423 (1998)]



- The value of two-photon decay width, obtained from this measurement, is sensitive to the internal structure of the $X(3872)$.

$\gamma\gamma \to X(3872) \to \pi^+\pi^- J/\psi$

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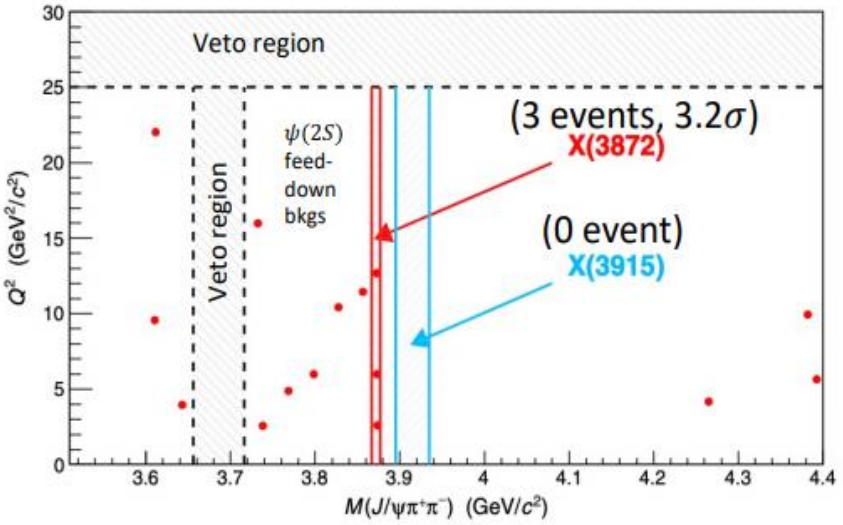
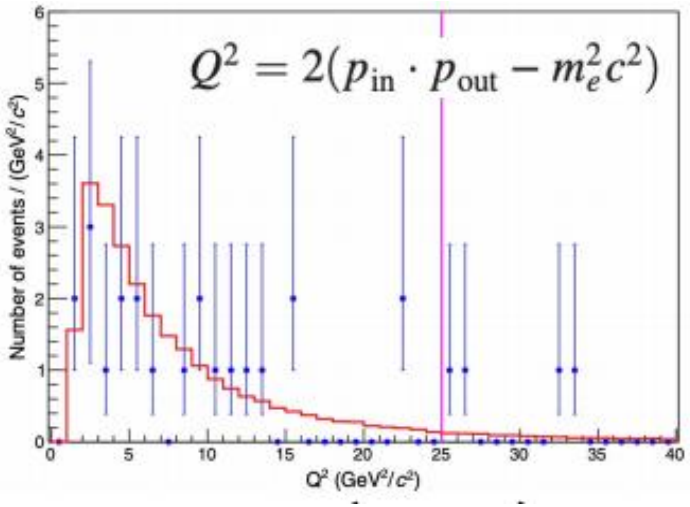


$$\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = 5.5^{+4.1}_{-3.8}(\text{stat}) \pm 0.7(\text{syst})\ \text{eV}.$$

- With future advances in calculations of $\tilde{\Gamma}_{\gamma\gamma}$ for non-$c\bar{c}$ states and higher luminosities accumulated by Belle II, this method will clarify the understanding of the $X(3872)$.

- Assuming the Q^2 dependence of a $c\bar{c}$ meson model



- With $0.032 < \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 0.061$ at 90% C.L., $\tilde{\Gamma}_{\gamma\gamma} = 20 - 500$ eV, these are consistent with the $c\bar{c}$ model prediction. [NPB 523, 423 (1998), PRD 83, 114015 (2011)]

Summary

- The two-photon decay width of $\chi_{c2}(1P)$ is determined to be $\Gamma_{\gamma\gamma}(\chi_{c2}(1P)) = 653 \pm 13(stat.) \pm 31(syst.) \pm 17(B.R.)$ eV. The result in BN1501 achieves the precise measurement of $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ as of now.

- The evidence for the R_1 near 3.92 GeV/c^2 may be $X(3915)$, $\chi_{c2}(3930)$ or an admixture of them. A rough estimation shows the partial width $\Gamma(\chi_{c2}(3930) \to \gamma\psi(2S))$= 200~300 keV, which is close to the predicted value of 207 keV from GI model. The mass of R_2 agrees with the HQSS-predicted mass (≈ 4013MeV/c^2) of the 2^{++} partner of $X(3872)$.

- The first evidence for $X(3872)$ production was found in two-photon $\gamma^*\gamma$ interactions. Three $X(3872)$ candidates are observed with a significance of 3.2σ, $\Gamma_{\gamma\gamma}\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$=$5.5^{+4.1}_{-3.8}(stat) \pm 0.7(syst)$ eV, assuming the Q^2 dependence of a $c\bar{c}$ meson model.

Thank you!