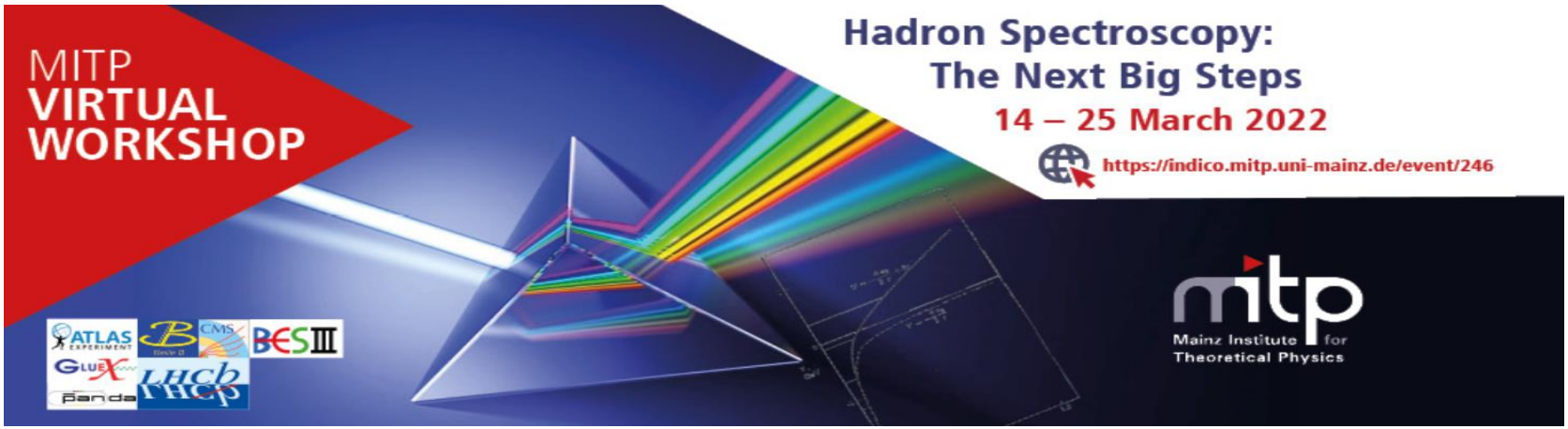
Overview of recent spectroscopy results in two-photon interactions



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on behalf of the Belle Collaboration

Outlines

- Two-photon interactions
- Charmonium(-like) states
- Accelerators and detectors
- $X(3872)$ observation
- $X(3872)$ production in two-photon interaction
- The 2P triplets near 3.9 GeV
- $X(4350)$ discovery
- $\gamma\gamma \to \gamma\psi(2S)$ at Belle
- Summary

Two–photon interactions

ELSEVIER

Nuclear Physics B 523 (1998) 423–438

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

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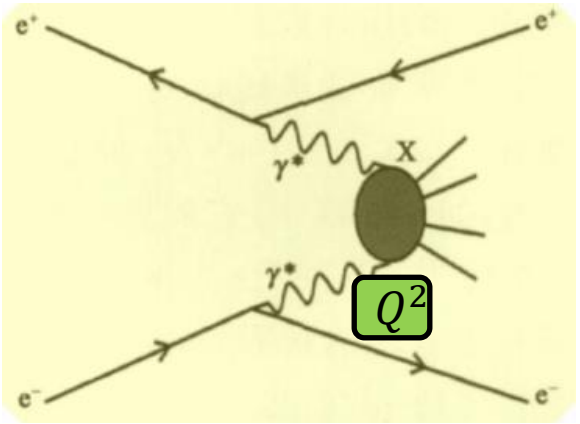
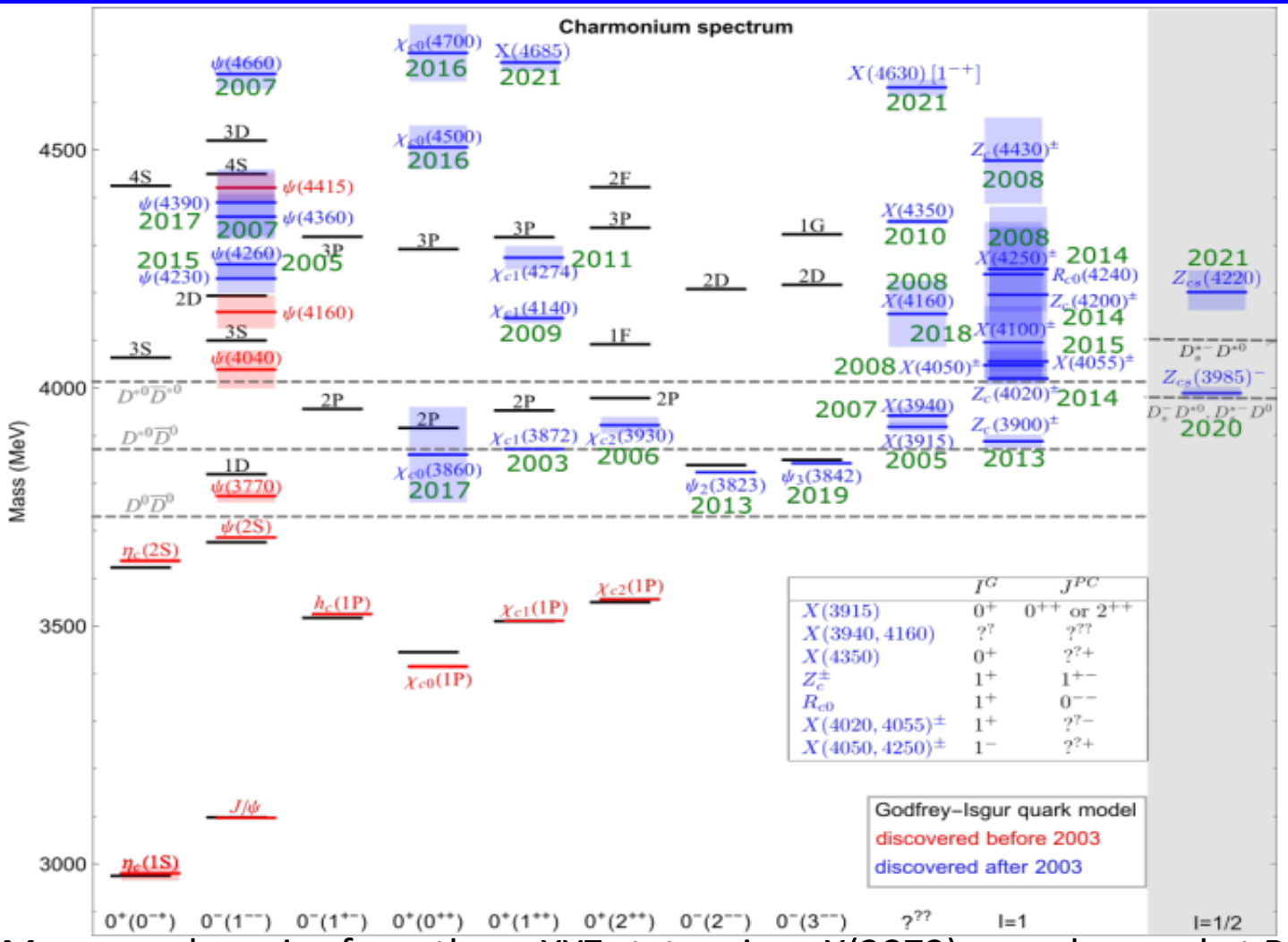
- Meson-photon-photon transition form factors for *S*-, *P*-, and *D*-wave states are calculated.
- Q^2 dependence of the (single) form factor governs the production of mesons.
- e^+e^- cross section for 1^+ states do not vanish at low Q^2



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

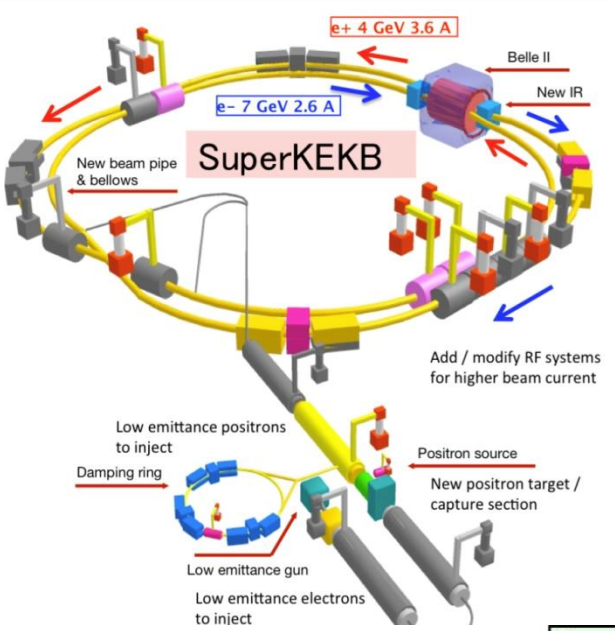


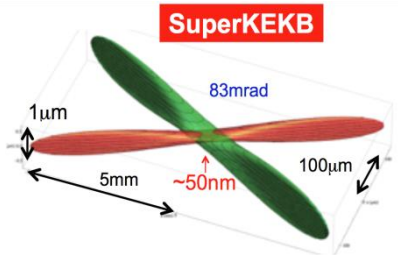
	I^G	J^{PC}
$X(3915)$	0^+	0^{++} or 2^{++}
$X(3940, 4160)$	$?^?$	$?^{??}$
$X(4350)$	0^+	$?^{?+}$
$Z_c^{\pm}$	1^+	1^{+-}
R_{c0}	1^+	0^{--}
$X(4020, 4055)^{\pm}$	1^+	$?^{?-}$
$X(4050, 4250)^{\pm}$	1^-	$?^{?+}$

- 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)]

Accelerators and detectors

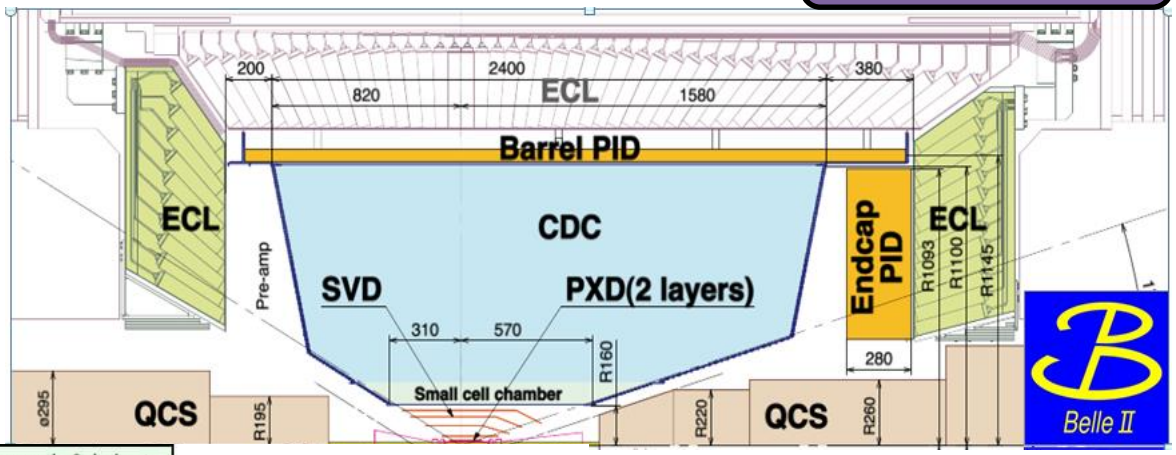
- 2nd generation B-factory

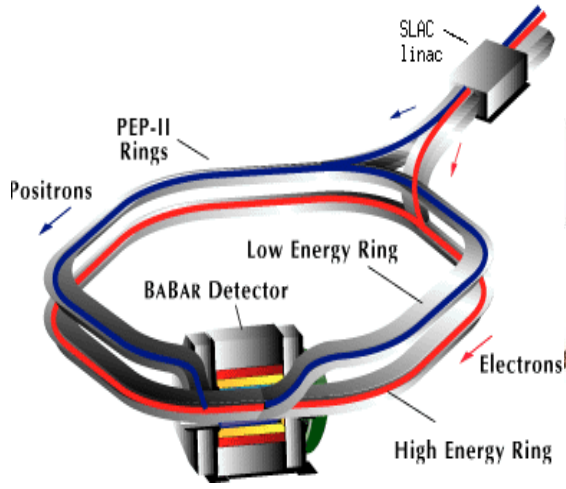


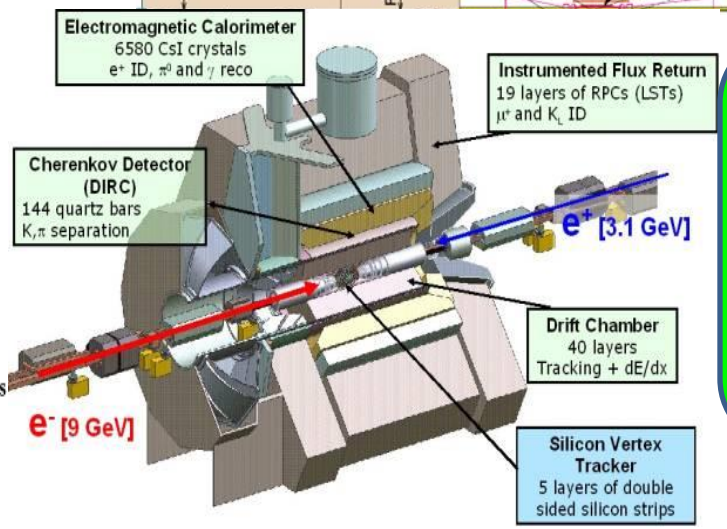


Super-KEKB goal: >30x instantaneous KEKB luminosity

In colors:
new components







SVD: 4 lyrs → VXD=(PXD 2 lyrs + SVD 4 lyrs)
CDC: small cell, long lever arm
ACC+TOF → ARICH + TOP
ECL: waveform sampling read-out electronics
KLM: RPC → Scintillator + RPC

$X(3872)$ observation

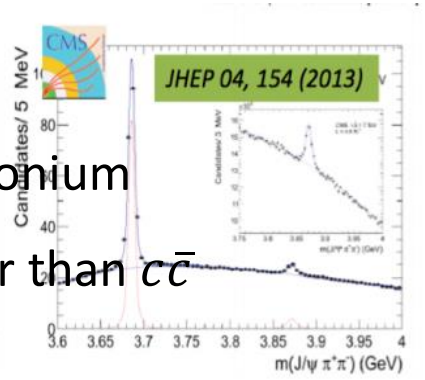
$\chi_{c1}(3872)$

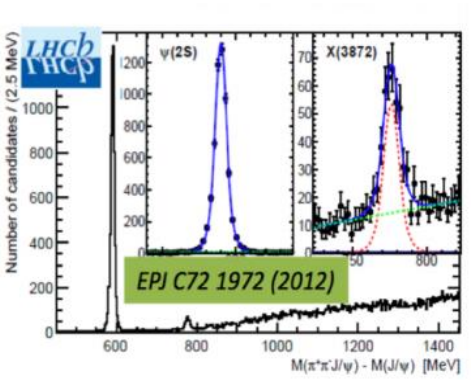
$I^G(J^{PC}) = 0^+(1^{++})$

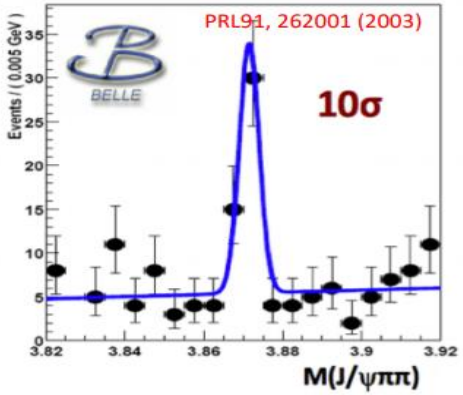
also known as $X(3872)$

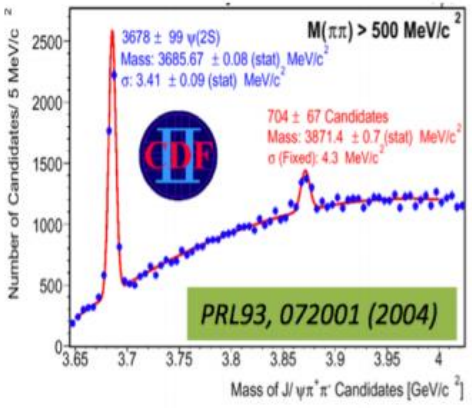
This state shows properties different from a conventional $q\bar{q}$ state.
A candidate for an exotic structure. See the review on non-$q\bar{q}$ states.

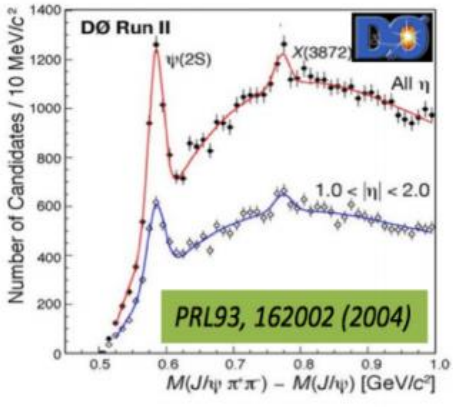
- The observation of $X(3872)$ solved the issue for the existence as charmonium states that are expected to be below threshold for decays to open charm and narrow.
- Production
  - In pp /$p\bar{p}$ collision : rate similar to charmonium
  - In B decays: KX similar to $c\bar{c}$, K^*X smaller than $c\bar{c}$
  - $Y(4260) \rightarrow \gamma + X(3872)$

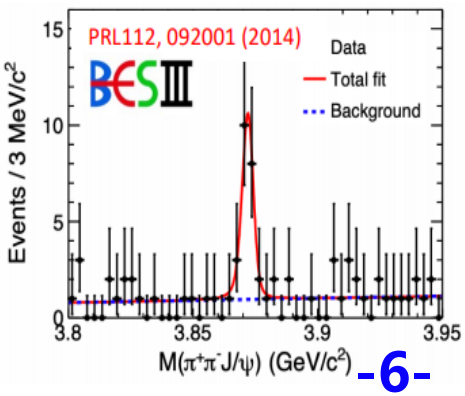












$X(3872)$ production in two-photon interaction

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

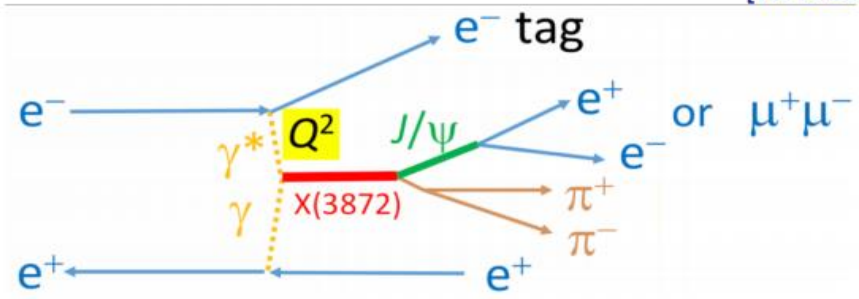
Phys.Rev.Lett.126.122001(2021)

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

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

But, $\gamma^*\gamma \rightarrow X(3872)$ ⟶ Allowed

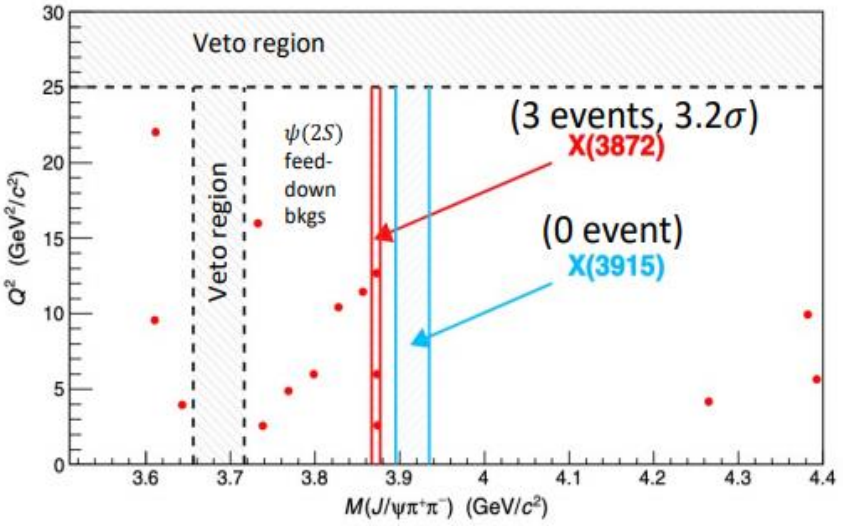
[NPB 523, 423 (1998)]



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

$X(3872)$ production in two-photon interaction

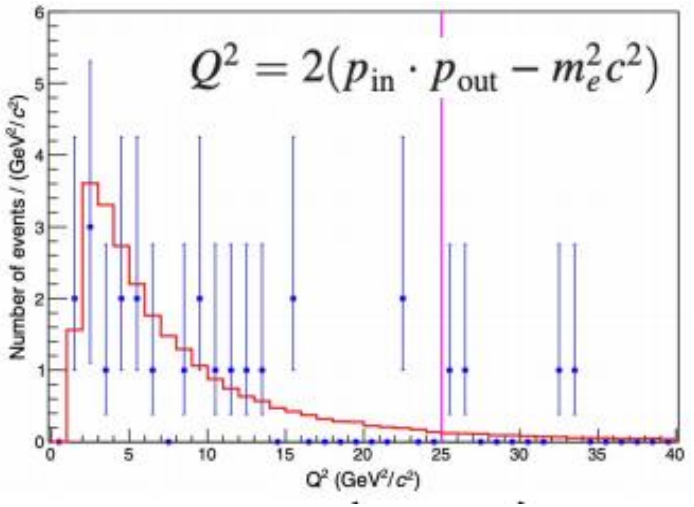
Phys.Rev.Lett.126.122001(2021)



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

- 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

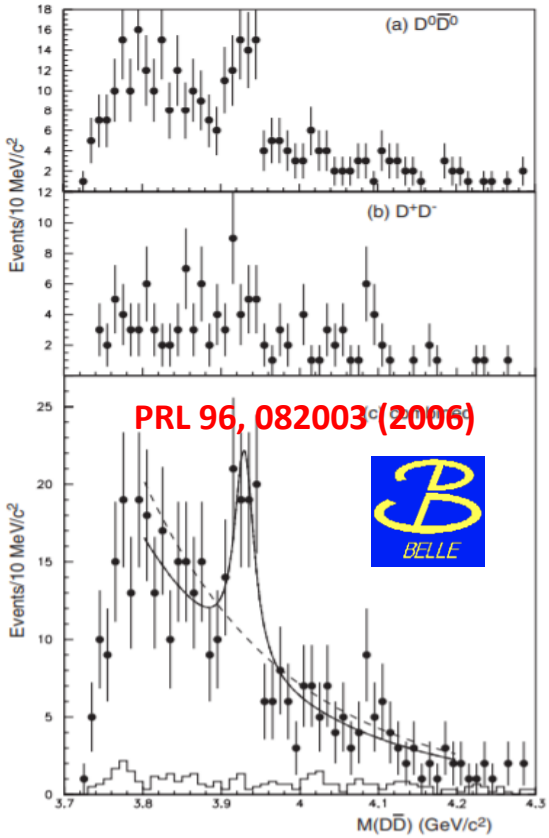


- With $0.032 < \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 0.061$ at 90% C.L., $\tilde{\Gamma}_{\gamma\gamma} = 20 - 500$ eV, this is consistent with the $c\bar{c}$ model prediction. [NPB 523, 423 (1998), PRD 83, 114015 (2011)]

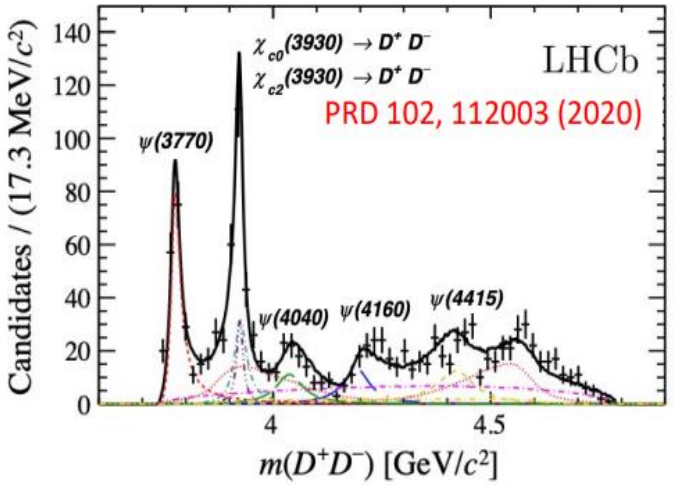
The 2P triplets near 3.9 GeV

$\chi_{c2}(3930)$ $I^G(J^{PC}) = 0^+(2^{++})$

- ✓ X(3930) discovered by Belle [Phys. Rev. Lett. 96, 082003 (2006)]
- ✓ Identified as $\chi_{c2}(2P)$ candidate by Babar [Phys. Rev. D 81, 092003 (2010)]



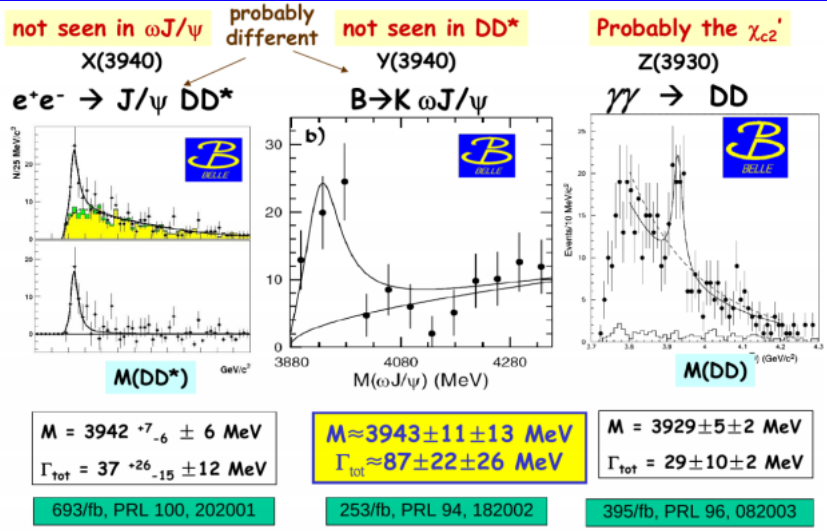
- The first radially excited χ_{cJ} states are predicted to have masses between 3.9 and 4.0 GeV/c^2, which is considerably above $D\bar{D}$ threshold.
- The results of this paper on mass, decay angular distributions, and $\Gamma_{\gamma\gamma}\mathcal{B}(\to D\bar{D})$ are all consistent with expectations for the χ'_{c2}, the 2^3P_2 charmonium state.



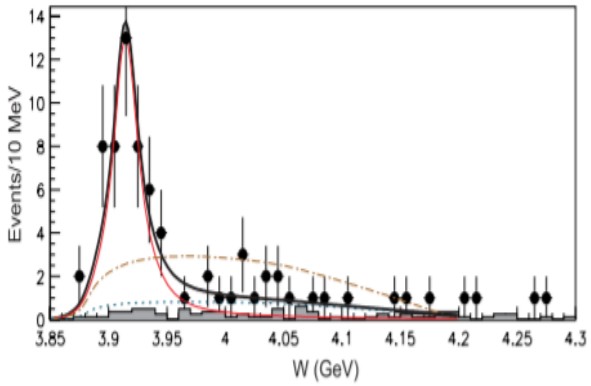
Resonance	Mass (GeV/c^2)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$

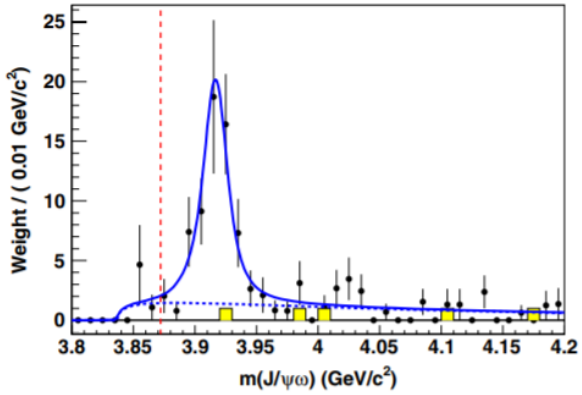
- $D\bar{D}$ resonant structure has previously been observed in the $\chi_{cJ}(3930)$ region; however it has usually been assumed to arise from the $\chi_{cJ}(3930)$ resonance.
- Clear demonstrate that both spin-0 and spin-2 contributions are necessary.

The 2P triplets near 3.9 GeV



- 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 processed, 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.

$X(3915)$ 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. = 7.7σ.

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)

The 2P triplets near 3.9 GeV

- The charmoniumlike state $X(3915)$ was observed in the same B decay mode by both Belle an BABAR.
- The $X(3915)$ was identified as the $\chi_{c0}(2P)$ in the 2014 PDG.
- However, $\chi_{c0} \to D\bar{D}$ decay mode is expected to be dominant but has not been observed. $X(3915) \to J/\psi\omega$, would be OZI suppress for the $\chi_{c0}(2P)$.

$\chi_{c0}(3860)$ $I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

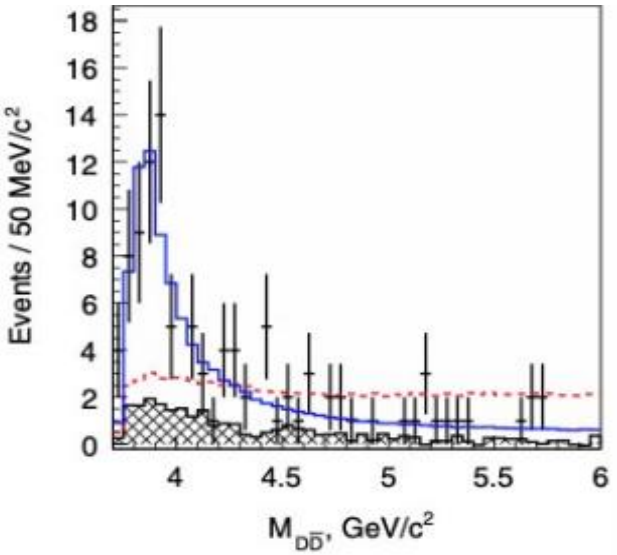
The assignment $J^P = 0^+$ is preferred over 2^+ by 2.5 sigma.

Observed by CHILIKIN 17 using full amplitude analysis of the process $e^+e^- \to J/\psi D\overline{D}$, where $D = D^0, D^+$.

✓ X(3860) observed at Belle Experiment only.

[Phys. Rev. D 95, 112003 (2017)]

J^{PC}	Mass, MeV/c^2	Width, MeV	Significance
0^{++}	3862^{+26}_{-32}	201^{+154}_{-67}	6.5σ



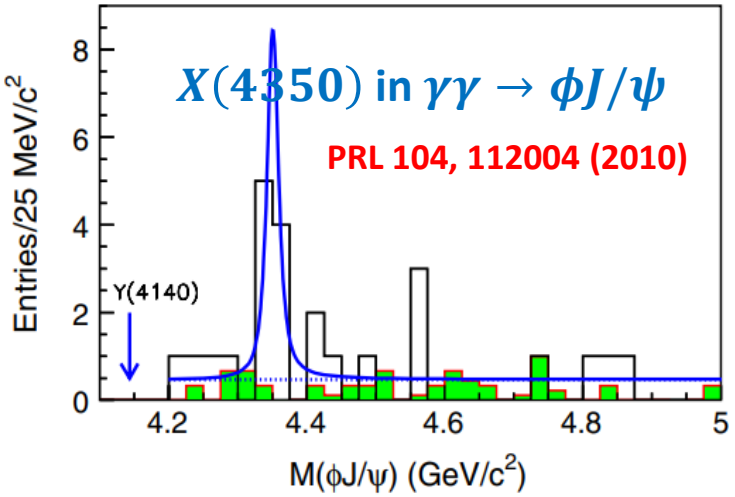
- The new state $X(3860)$ is a better candidate for the $\chi_{c0}(2P)$ charmonium state the $X(3915)$, since its properties are well matched to expectations for the $\chi_{c0}(2P)$.
- The preferred quantum numbers of the $X(3860)$ are $J^{PC} = 0^{++}$.

$X(4350)$ discovery

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

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(${\chi''}_{c2}$).

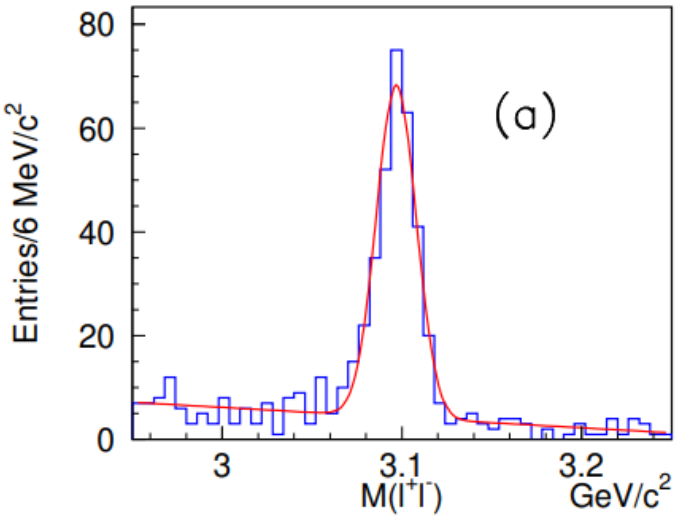
$\gamma\gamma \to \gamma\psi(2S)$ at Belle

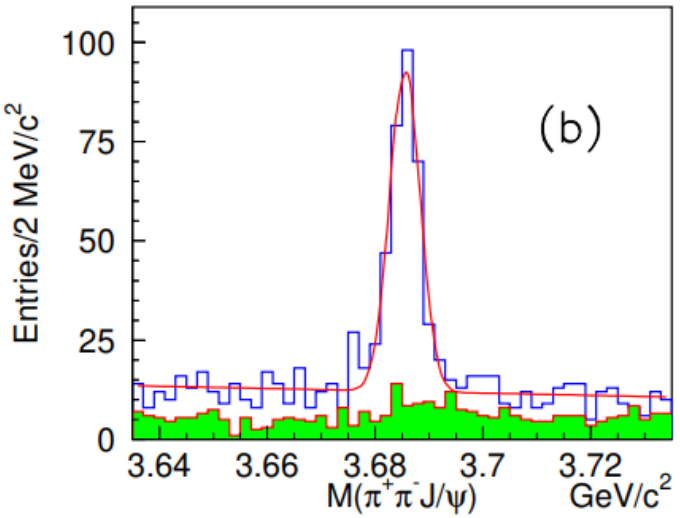
- Both $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$ can be produced in two-photon collision and decay to $\gamma\psi(2S)$ via E1 transition. [Phys. Rev. D 72, 054026 (2005)]

- 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)]

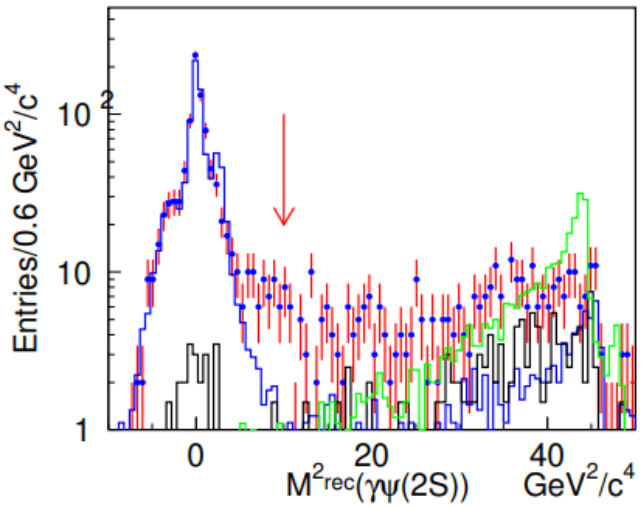
- $\psi(2S)$ reconstructed from $J/\psi\pi^+\pi^-$, and J/ψ reconstructed from e^+e^- or $\mu^+\mu^-$.

arXiv: 2105.06605(2021)

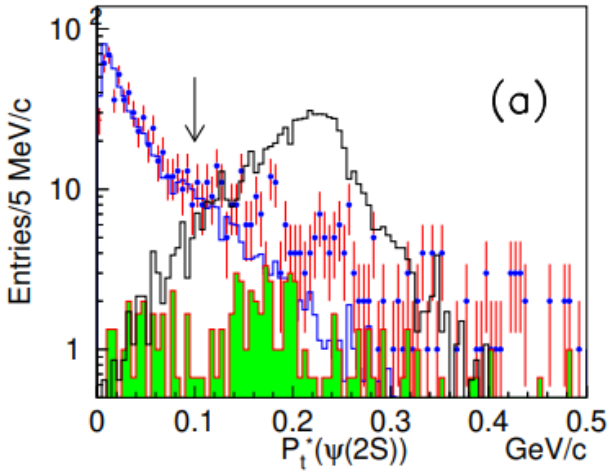


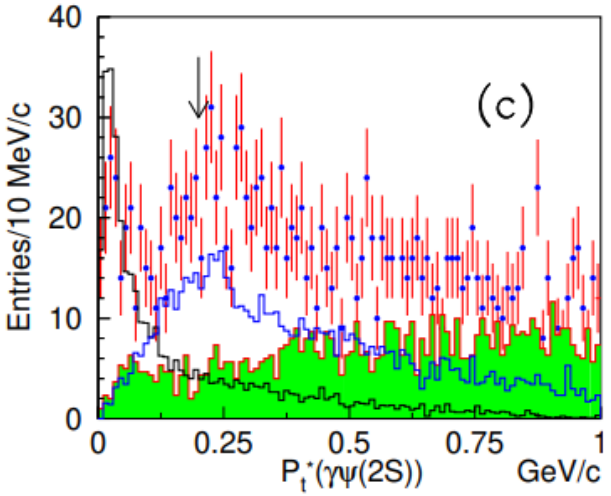


$\gamma\gamma \to \gamma\psi(2S)$ at Belle



- 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.





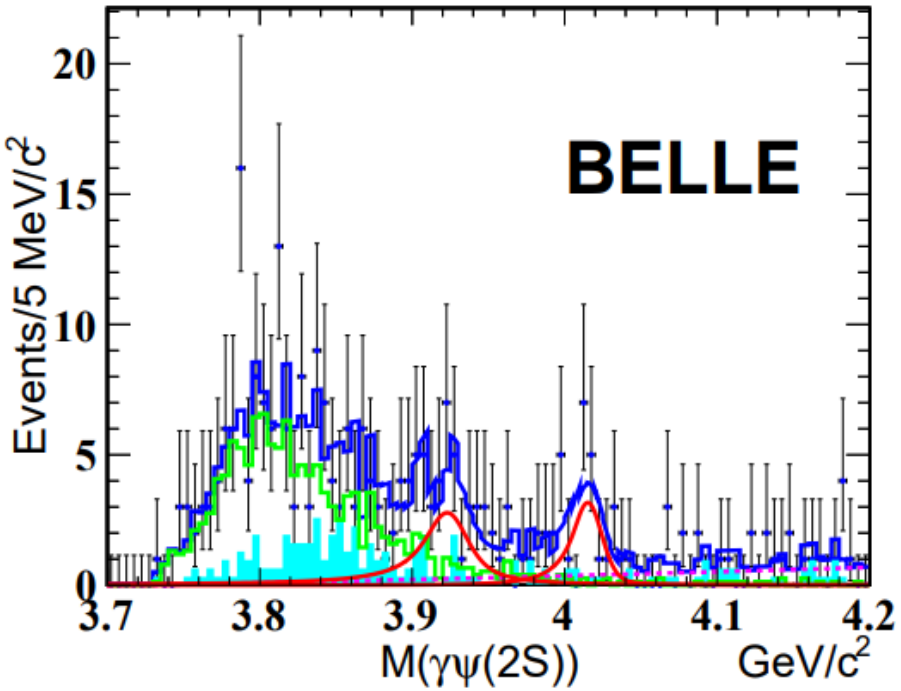
- We apply $P^*{}_t\left(\psi(2S)\right) > 0.1\mathrm{GeV}/c$ and $P^*{}_t\left(\gamma\psi(2S)\right) < 0.2\mathrm{GeV}/c$ to suppress the ISR background with selection efficiencies of (97.1±0.3)% and (67.8±0.7)%, respectively.

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

- Fitting to the $M(\gamma\psi(2S))$ distribution

$$f_{PDF} = f_{R_1} + f_{R_2} + f_{ISR} + f_{bkg} + f_{SB}$$

arXiv: 2105.06605(2021)



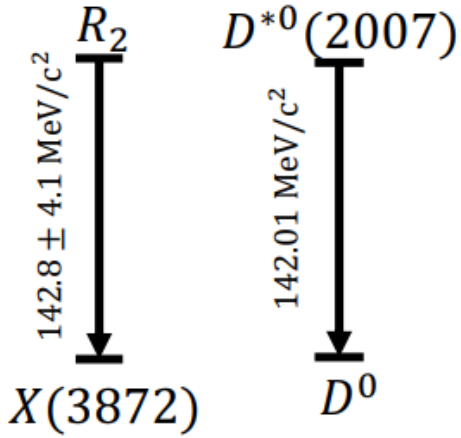
R_1 near 3.92 GeV/c^2:
$N_1 = 31 \pm 11$ events, 3.1σ including systematic uncertainties.

R_2 near 4.01 GeV/c^2:
$N_2 = 19 \pm 7$ events, 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 may be helped for the study of $X(3872)$

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}	$4 \pm 11 \pm 6$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_2 \to \gamma\psi(2S))$	$6.2 \pm 2.2 \pm 0.8$	$1.2 \pm 0.4 \pm 0.2$

Summary

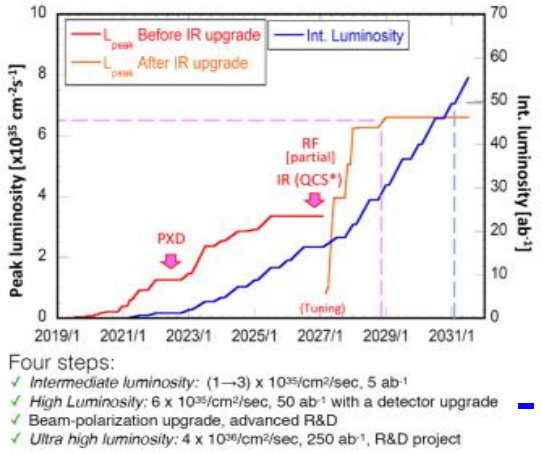
- ✓ Data taking at Belle has been stopped for more than 10 years, new exciting results continue to be produced by Belle Collab.

- ✓ Two states are reported in the study of the two-photon process $\gamma\gamma \rightarrow \gamma\psi(2S)$ for the first time with the full Belle data sample, two structures possibly the $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$ are observed in the radiative transition final state $\gamma\psi(2S)$.

- ✓ Some study on the states near 3.9 GeV/c^2 have been observed the *P*-wave triplets to figure out the full picture of XYZ states, particularly for $X(3872)$.

- ✓ A narrow peak with significance of 3.2σ (named $X(4350)$) is observed in the process of $\gamma\gamma \rightarrow \phi J/\psi$; the mass and width of this structure are measured in this work.

- ✓ The production rate of two photon interaction is typically low, much larger data samples are essential to more instructive results, super-high luminosity experiments, such as Belle II, are great hopes.



Thank you!