Recent results from Belle

——Two-photon interactions

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中国物理学会高能物理分会第十三届全国粒子物理学术会议(2021)
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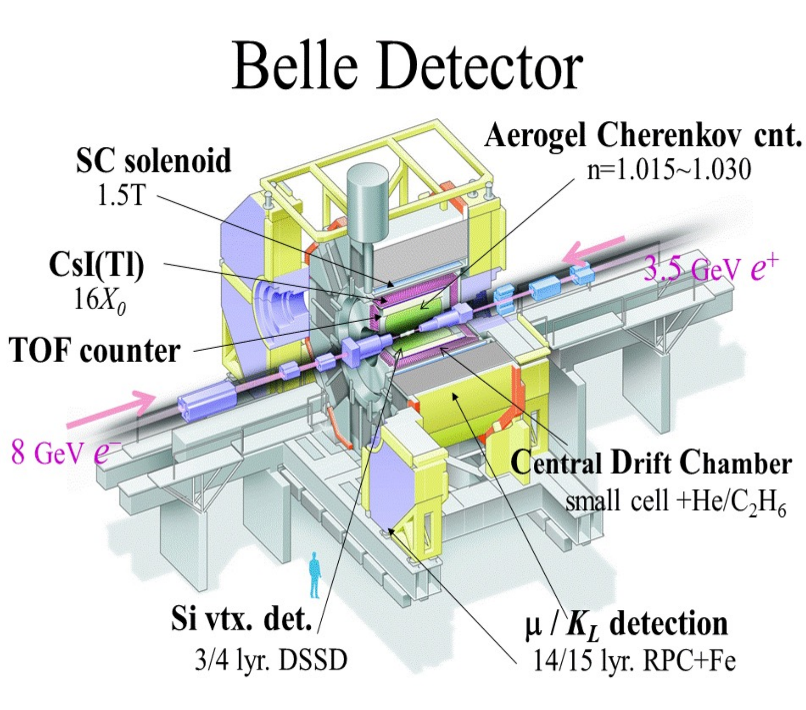
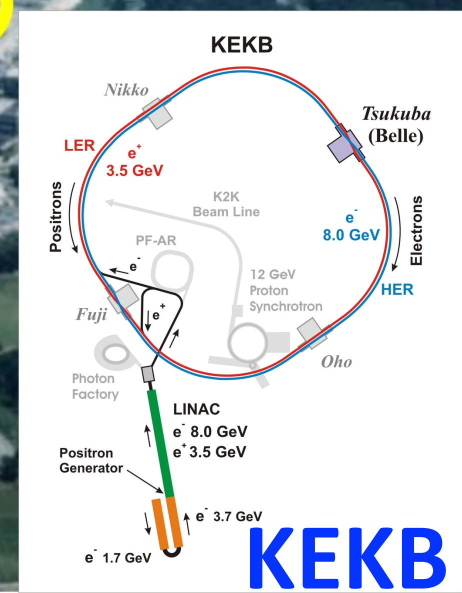


Data taking: 1999 – 2010
On/off/Scan Υ(nS) peaks
Total luminosity: 980 fb^{-1}



Selected topics

Charmonium(like) candidates in two-photon interactions:

- ✓ *The study of $\gamma\gamma \to \gamma\psi(2S)$ at Belle*

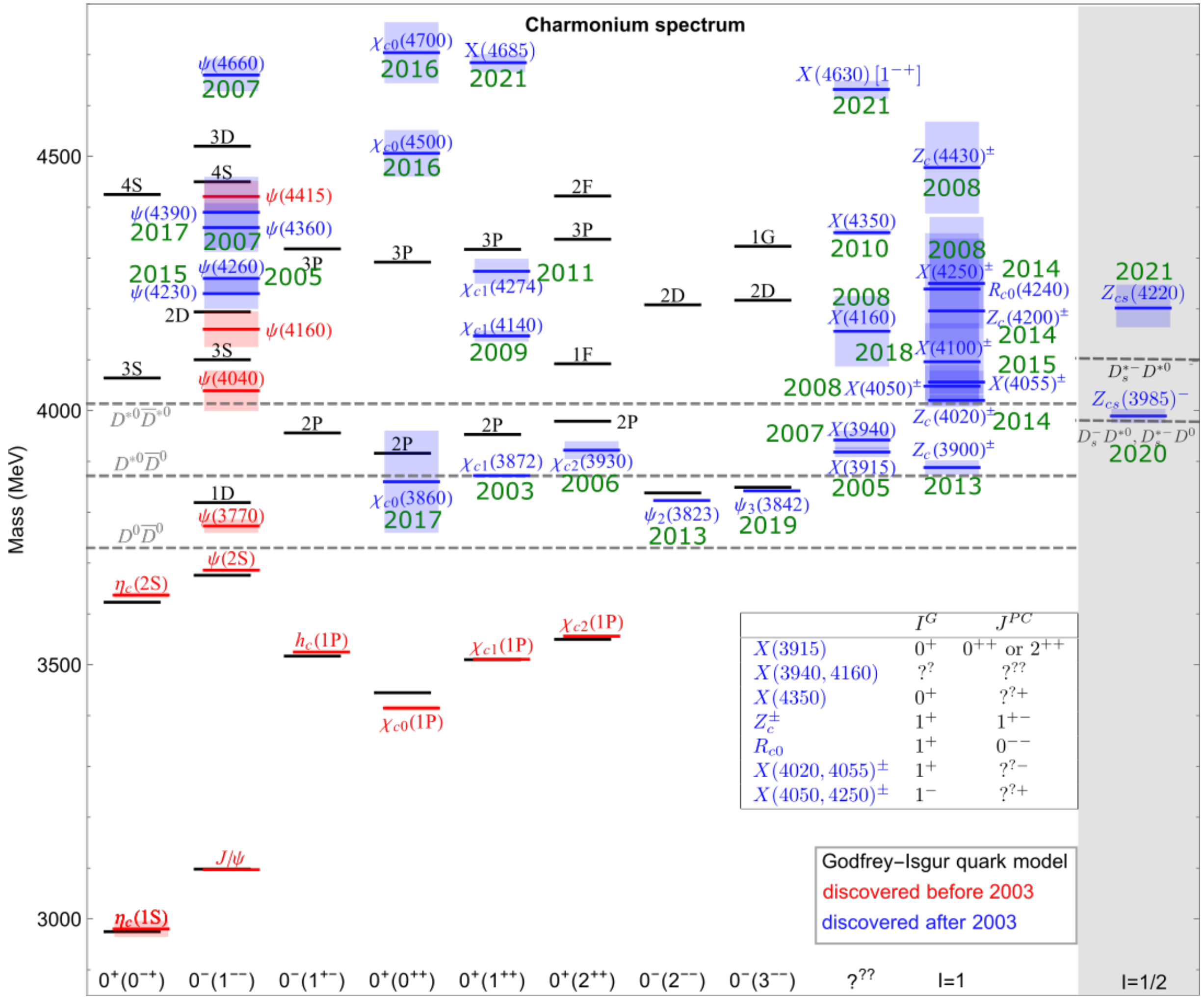
  [arXiv: 2105.06605 (2021)]

- ✓ *$X(3872) \to \pi^+\pi^- J/\psi$ in single-tag two-photon reactions*

  [PRL 126, 122001 (2021)]

Charmonium spectrum

- Many puzzles arise from these XYZ states since X(3872) was observed at Belle Experiment in 2003.



The 2P triplets near 3.9GeV

❖ One of the XYZ puzzles concerns the candidates for P-wave triplet states near 3.9 GeV/c^2, including X(3860), X(3872), X(3915), X(3930), etc.

PHYSICAL REVIEW D **72,** 054026 (2005)

Higher charmonia

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(Received 29 May 2005; published 29 September 2005)

This paper gives results for the spectrum, all allowed E1 radiative partial widths (and some important M1 widths) and all open-charm strong decay amplitudes of all 40 $c\bar{c}$ states expected up to the mass of the 4S multiplet, just above 4.4 GeV. The spectrum and radiative widths are evaluated using two models, the relativized Godfrey-Isgur model and a nonrelativistic potential model. The electromagnetic transitions are evaluated using Coulomb plus linear plus smeared hyperfine wave functions, both in a nonrelativistic potential model and in the Godfrey-Isgur model. The open-flavor strong decay amplitudes are determined assuming harmonic oscillator wave functions and the $^3P_0$ decay model. This work is intended to motivate future experimental studies of higher-mass charmonia, and may be useful for the analysis of high-statistics data sets to be accumulated by the BES, CLEO, and GSI facilities.

TABLE III. 1P and 2P E1 radiative transitions (format as in Table II).

Multiplets	Initial meson	Final meson	E_γ (MeV) NR	E_γ (MeV) GI	Γ_{thy} (keV) NR	Γ_{thy} (keV) GI	Γ_{expt} (keV)
1P → 1S	$\chi_2(1^3P_2)$	$J/\psi(1^3S_1)$	429	429	424	313	426 ± 51
	$\chi_1(1^3P_1)$		390	389	314	239	291 ± 48
	$\chi_0(1^3P_0)$		303	303	152	114	119 ± 19
	$h_c(1^1P_1)$	$\eta_c(1^1S_0)$	504	496	498	352	
2P → 2S	$\chi_2(2^3P_2)$	$\psi'(2^3S_1)$	276	282	304	207	
	$\chi_1(2^3P_1)$		232	258	183	183	
	$\chi_0(2^3P_0)$		162	223	64	135	
	$h_c(2^1P_1)$	$\eta_c'(2^1S_0)$	285	305	280	218	
2P → 1S	$\chi_2(2^3P_2)$	$J/\psi(1^3S_1)$	779	784	81	53	
	$\chi_1(2^3P_1)$		741	763	71	14	
	$\chi_0(2^3P_0)$		681	733	56	1.3	
	$h_c(2^1P_1)$	$\eta_c(1^1S_0)$	839	856	140	85	

A. Nonrelativistic potential model

B. Godfrey-Isgur relativized potential model

Multiplet	State	Expt.	Input (NR)	Theor. NR	Theor. GI
1S	$J/\psi(1^3S_1)$	3096.87 ± 0.04	3097	3090	3098
	$\eta_c(1^1S_0)$	2979.2 ± 1.3	2979	2982	2975
2S	$\psi'(2^3S_1)$	3685.96 ± 0.09	3686	3672	3676
	$\eta_c'(2^1S_0)$	3637.7 ± 4.4	3638	3630	3623
3S	$\psi(3^3S_1)$	4040 ± 10	4040	4072	4100
	$\eta_c(3^1S_0)$			4043	4064
4S	$\psi(4^3S_1)$	4415 ± 6	4415	4406	4450
	$\eta_c(4^1S_0)$			4384	4425
1P	$\chi_2(1^3P_2)$	3556.18 ± 0.13	3556	3556	3550
	$\chi_1(1^3P_1)$	3510.51 ± 0.12	3511	3505	3510
	$\chi_0(1^3P_0)$	3415.3 ± 0.4	3415	3424	3445
	$h_c(1^1P_1)$	see text		3516	3517
2P	$\chi_2(2^3P_2)$			3972	3979
	$\chi_1(2^3P_1)$			3925	3953
	$\chi_0(2^3P_0)$			3852	3916
	$h_c(2^1P_1)$			3934	3956

Some E1 transitions that are of special importance in the study of higher charmonium states.

The 2P triplets near 3.9GeV

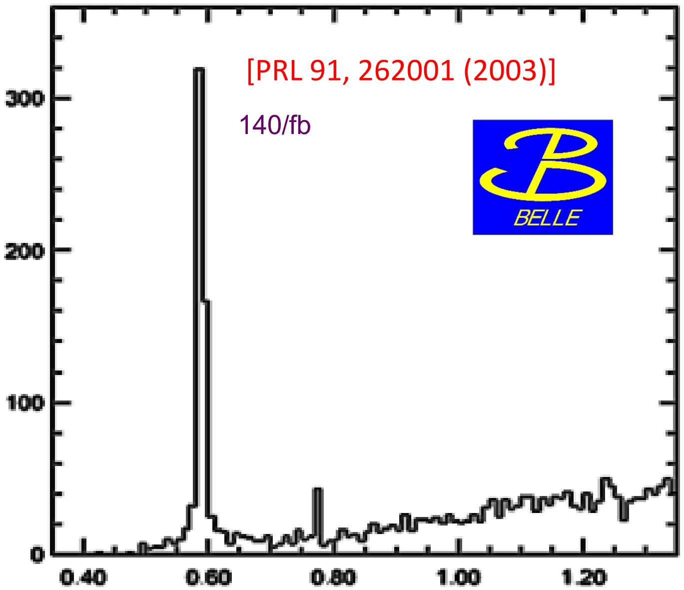
$\chi_{c1}(3872)$ $\qquad I^G(J^{PC}) = 0^+(1^{++})$

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.

First observed by CHOI 03 in $B \to K\pi^+\pi^- J/\psi(1S)$ decays as a narrow peak in the invariant mass distribution of the $\pi^+\pi^- J/\psi(1S)$ final state. Isovector hypothesis excluded by AUBERT 05B and CHOI 11.

AAIJ 13Q perform a full five-dimensional amplitude analysis of the angular correlations between the decay products in $B^+ \to \chi_{c1}(3872) K^+$ decays, where $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$ and $J/\psi \to \mu^+\mu^-$, which unambiguously gives the $J^{PC} = 1^{++}$ assignment under the assumption that the $\pi^+\pi^-$ and J/ψ are in an S-wave. AAIJ 15AO extend this analysis with more data to limit D-wave contributions to $< 4\%$ at 95% CL.



- Production
  - In $\bar{p}p/pp$ collision: rate similar to charmonia
  - In B decays: KX similar to $\bar{c}c$, K^*X smaller than $\bar{c}c$
  - $Y(4260) \to \gamma + X(3872)$
- BR: open charm $\sim 50\%$, charmonium $\sim O\%$.
- Nature (very likely exotic)
  - Loosely $\bar{D}^0 D^{*0}$ bound states (like deuteron)?
  - Mixture of $\chi_{c1}(2P)$ and $\bar{D}^0 D^{*0}$ bound state?
  - Many other possibilities (if it is not $\chi_{c1}(2P)$, there is $\chi_{c1}(2P)$)?

The 2P triplets near 3.9GeV

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

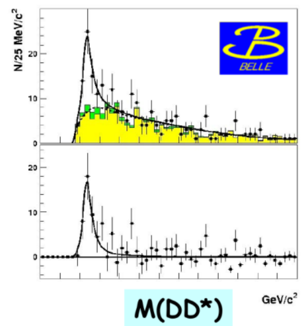
- ✓ X(3930) discovered by Belle [Phys. Rev. Lett. 96, 082003 (2006)]
- ✓ Identified as $\chi_{c2}(2P)$ candidate by Babar [Phys. Rev. D 81, 092003 (2010)]

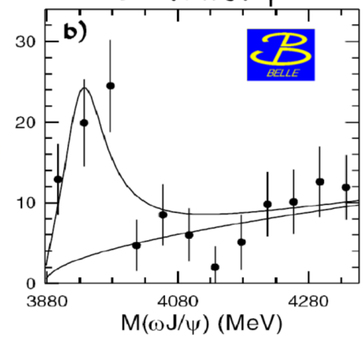
not seen in ωJ/ψ — X(3940) — $e^+e^- \to J/\psi\, DD^*$

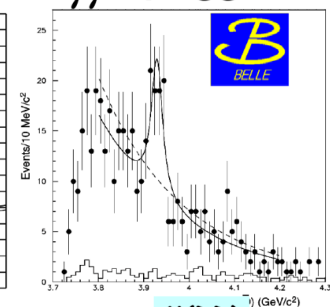
probably different

not seen in DD* — Y(3940) — $B \to K\,\omega J/\psi$

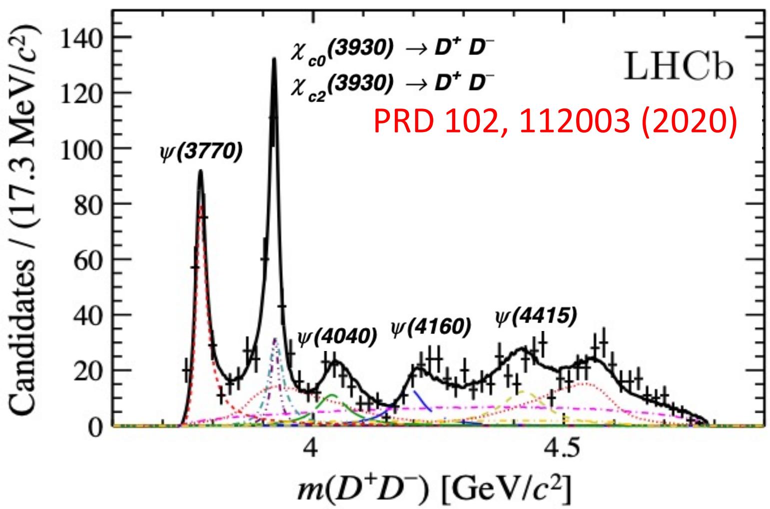
Probably the χ_{c2}' — Z(3930) — $\gamma\gamma \to DD$







X(3940)	Y(3940)	Z(3930)
$M = 3942\,^{+7}_{-6} \pm 6$ MeV	$M \approx 3943 \pm 11 \pm 13$ MeV	$M = 3929 \pm 5 \pm 2$ MeV
$\Gamma_{tot} = 37\,^{+26}_{-15} \pm 12$ MeV	$\Gamma_{tot} \approx 87 \pm 22 \pm 26$ MeV	$\Gamma_{tot} = 29 \pm 10 \pm 2$ MeV
693/fb, PRL 100, 202001	253/fb, PRL 94, 182002	395/fb, PRL 96, 082003



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

Amplitude analysis of $B^+ \to K^+ D\bar{D}$. Both 0^{++} and 2^{++} states found at $m(D\bar{D}) \approx 3930$ MeV/c^2.

The 2P triplets near 3.9GeV

$X(3915)$ $I^G(J^{PC}) = 0^+(0 \text{ or } 2^{++})$

was $\chi_{c0}(3915)$

The experimental analysis prefers $J^{PC} = 0^{++}$. However, a re-analysis presented in ZHOU 15C shows that if helicity-2 dominance assumption is abandoned and a sizable helicity-0 component is allowed, a $J^{PC} = 2^{++}$ assignment is possible.

- ✓ X(3915) discovered by Belle [Phys. Rev. Lett. 104, 092001 (2010)]
- ✓ Quantum number determined by Babar [Phys. Rev. D 86, 072002 (2012)]

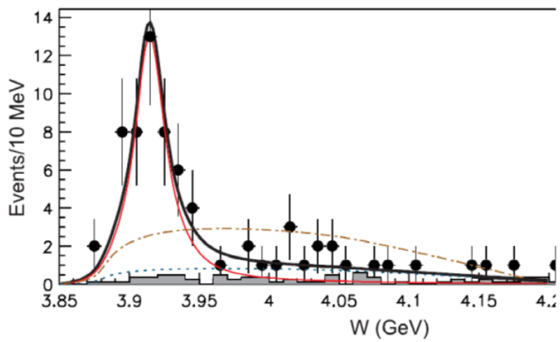
$\chi_{c0}(3860)$ $I^G(J^{PC}) = 0^+(0^{++})$

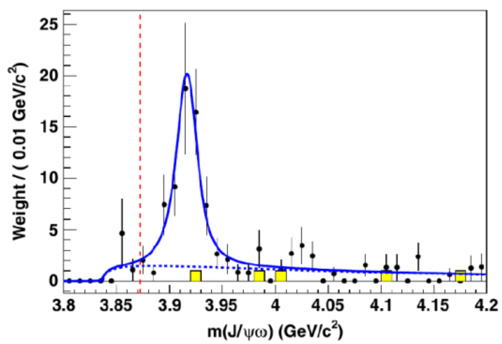
OMITTED FROM SUMMARY TABLE

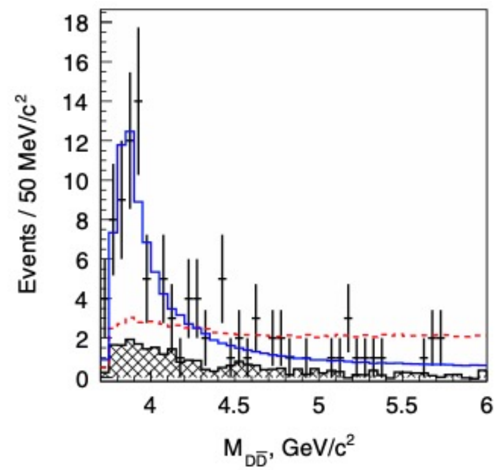
The assignment $J^P = 0^+$ is preferred over 2^+ by 2.5 sigma.

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)]







$X(3915)$ from Belle:

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

Belle: PRL104, 092001(2010)

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

$X(3915)$ From BaBar:

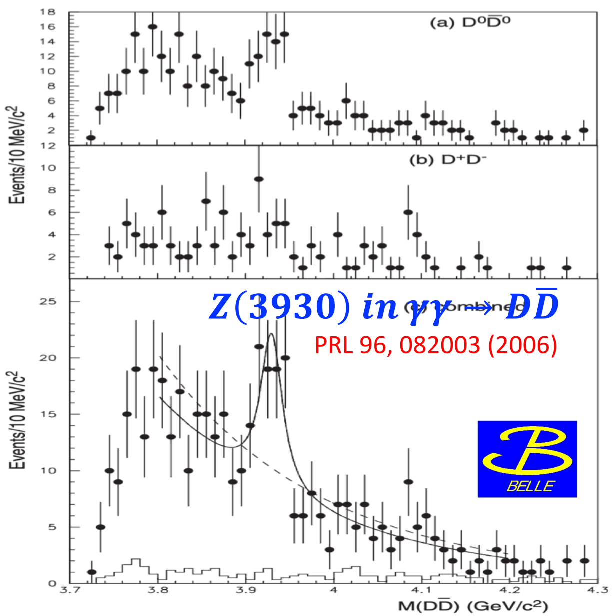
- $M = (3919.4 \pm 2.2 \pm 1.6)$ MeV$/c^2$;
- $\Gamma = (13 \pm 6 \pm 3)$ MeV;
- $N^{\text{sig}} = 59 \pm 10$;
- Signif. $= 7.6\ \sigma$.
- Data largely prefer $J^P = 0^\pm$ over 2^+.

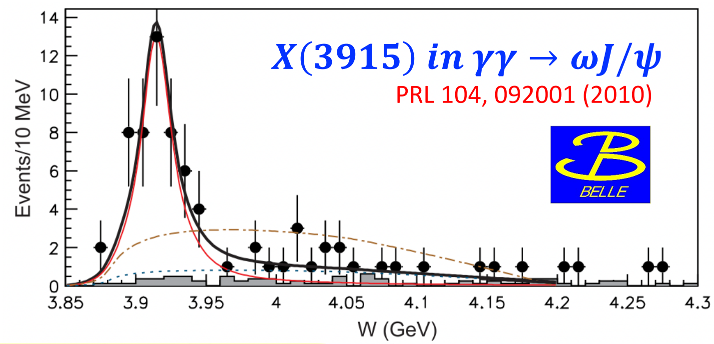
BaBar: PRD86,072002(2012)

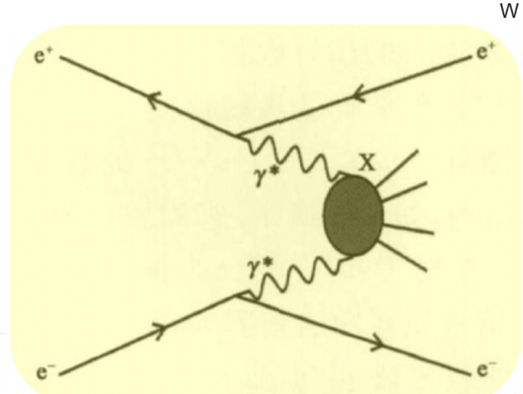
J^{PC}	Mass, MeV$/c^2$	Width, MeV	Significance
0^{++}	3862^{+26}_{-32}	201^{+154}_{-67}	6.5σ

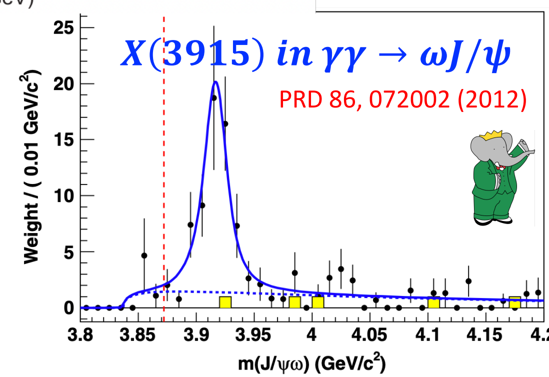
Two photon interaction

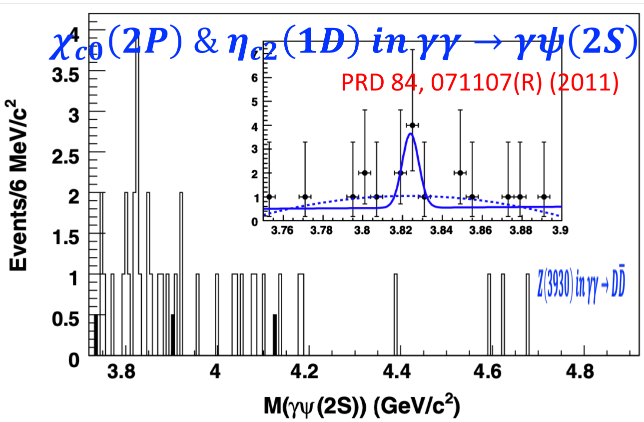
- Contributions from two-photon process studies to XYZ particles.





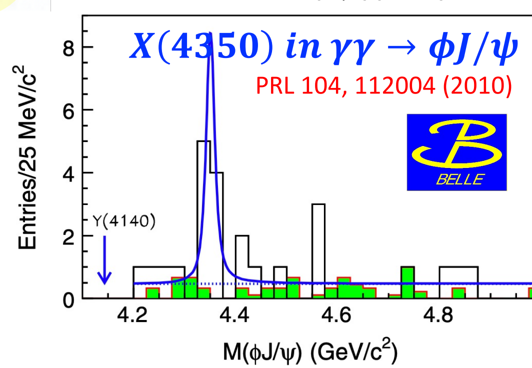






$e^+e^- \to e^+\gamma e^+\gamma \to e^+e^-X$

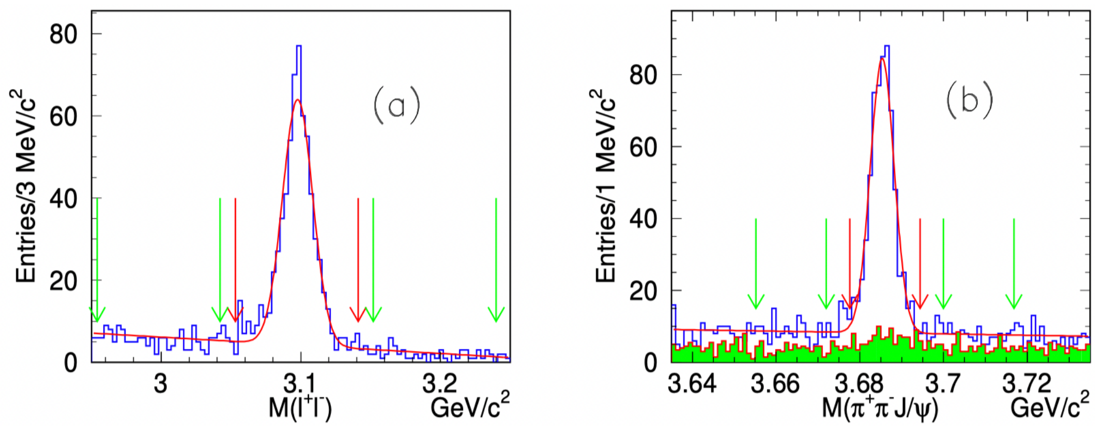
- $J^{PC} = 0^{-+}, 0^{++}, 2^{++}, 2^{-+}, \ldots$



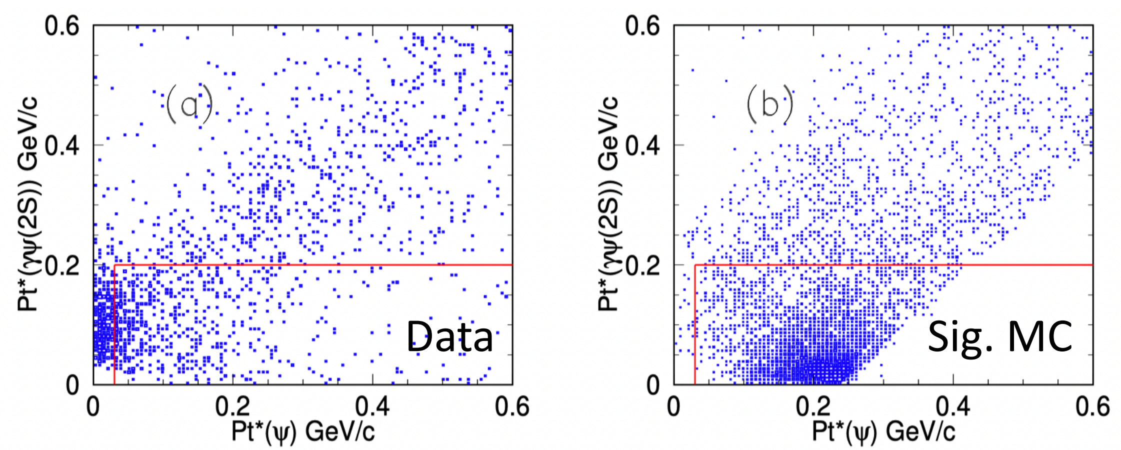
$\gamma\gamma \to \gamma\psi(2S)$ at Belle

arXiv: 2105.06605 (2021)
Prepared for submission to JHEP

- Data sample: 980 fb^{-1} e^+e^- collisions data samples.
- $\psi(2S)$ reconstructed from $J/\psi\pi^+\pi^-$, and J/ψ reconstructed from e^+e^- or $\mu^+\mu^-$.



- Background dominated by $e^+e^- \to \psi(2S)$ via ISR.

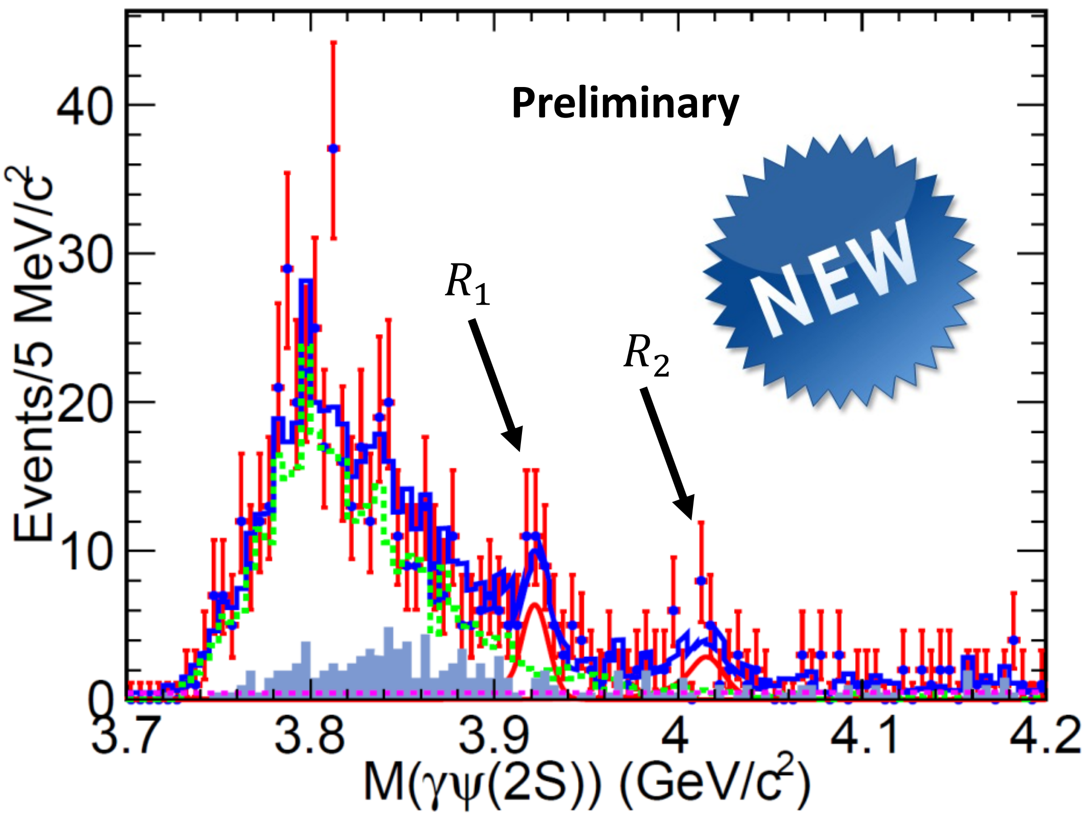


$\gamma\gamma \to \gamma\psi(2S)$ at Belle

arXiv: 2105.06605 (2021)
Prepared for submission to JHEP

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

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



R_1 near 3.92 GeV/c^2:
$N_1 = 30.3 \pm 8.6$,
4.0σ including systematic uncertainties.

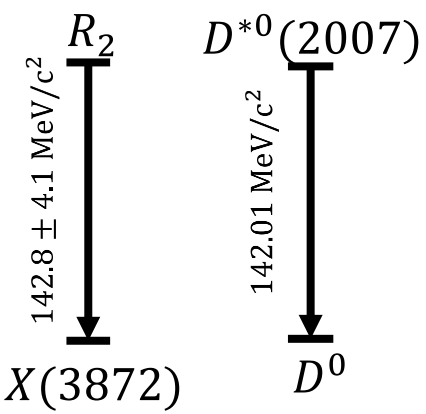
R_2 near 4.01 GeV/c^2:
$N_2 = 18.2 \pm 9.3$,
3.0σ local statistical significance.
Study on look-elsewhere effect show a global significance of 2.8σ.

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

arXiv: 2105.06605 (2021)
Prepared for submission to JHEP

- 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 $\Gamma(\chi_{c2}(3930) \to \gamma\psi(2S)) = 200{\sim}300$ 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) .



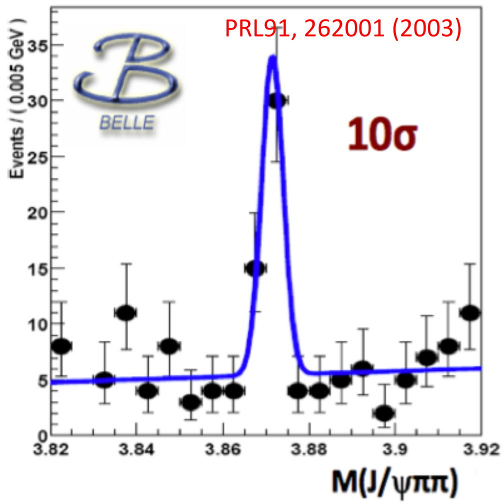
R_2 may be helped for the study of $X(3872)$

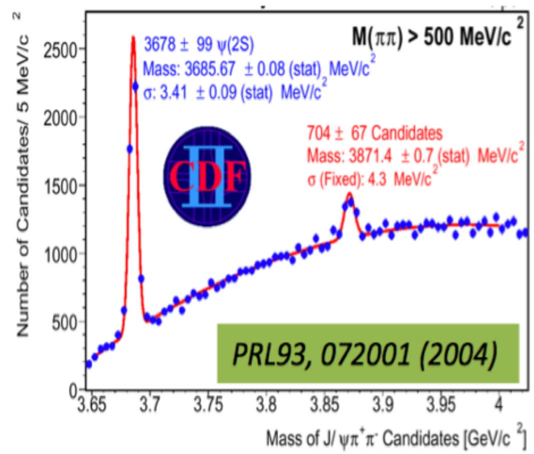
Resonant parameters	$J=0$	$J=2$
M_1	$3921.3 \pm 2.4 \pm 1.6$	
Γ_1	$0.0 \pm 5.3 \pm 2.0$	
$\Gamma_1^{\rm UL}$	11.5	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_1 \to \gamma\psi(2S))$	$8.2 \pm 2.3 \pm 0.9$	$1.6 \pm 0.5 \pm 0.2$
M_2	$4014.4 \pm 4.1 \pm 0.5$	
Γ_2	$6 \pm 16 \pm 12$	
$\Gamma_2^{\rm UL}$	39.3	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_2 \to \gamma\psi(2S))$	$5.3 \pm 2.7 \pm 2.5$	$1.1 \pm 0.5 \pm 0.5$
$\Gamma_{\gamma\gamma}^{\rm UL}\mathcal{B}(R_2 \to \gamma\psi(2S))$	12.8	2.6
$M_{X(3915)}$	3918.4 (fixed)	
$\Gamma_{X(3915)}$	20 (fixed)	
$\Gamma_{\gamma\gamma}\mathcal{B}(X(3915) \to \gamma\psi(2S))$	$10.9 \pm 3.1 \pm 1.2$	$2.2 \pm 0.6 \pm 0.2$
$M_{\chi_{c2}(3930)}$	—	3922.2 (fixed)
$\Gamma_{\chi_{c2}(3930)}$	—	35 (fixed)
$\Gamma_{\gamma\gamma}\mathcal{B}(\chi_{c2}(3930) \to \gamma\psi(2S))$	—	$2.4 \pm 0.7 \pm 0.4$

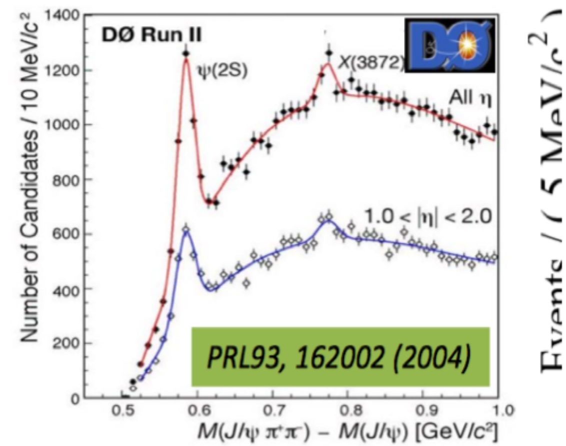
$e^+e^- \rightarrow e^+e^- J/\psi\pi^+\pi^-$ at Belle

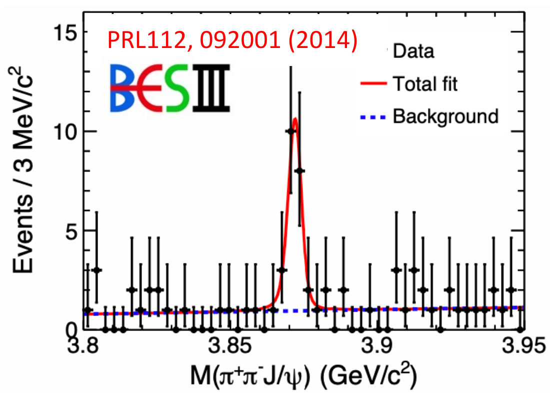
Various production ways of X(3872):

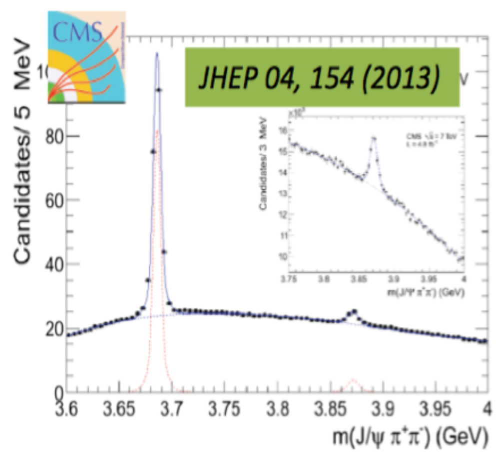
$B \rightarrow X(3872)K$, $\Lambda_b^0 \rightarrow X(3872)pK^-$; e^+e^- *radiative decay; pp and* $p\bar{p}$ *collisions*

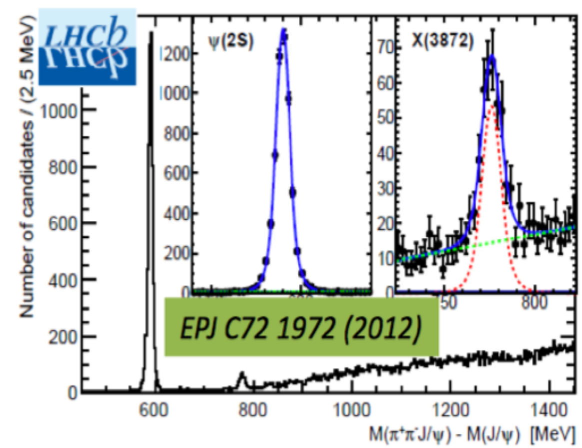












$e^+e^- \to e^+e^- J/\psi\pi^+\pi^-$ at Belle

Phys.Rev.Lett.126.122001(2021)

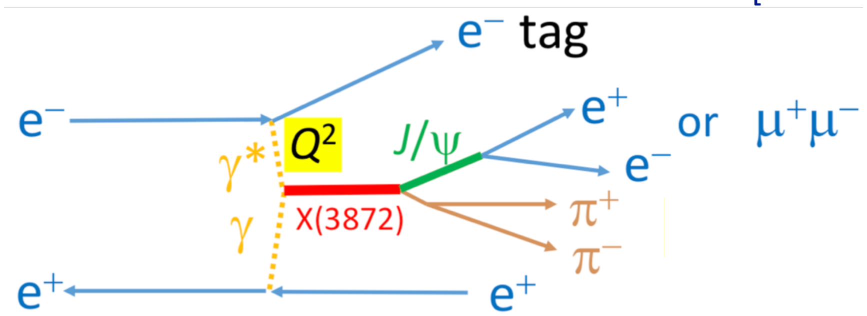
- Data sample: 825 fb^{-1} in e^+e^- collisions near 10.6 GeV .
- $X(3872)$ production in two-photon collision is studied.

X(3872): J^{PC} = 1^{++}

$\gamma\gamma \to X(3872)$ ➡ Not allowed

But, $\gamma^*\gamma \to X(3872)$ ➡ Allowed

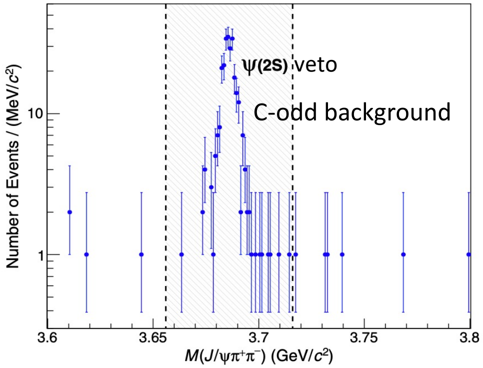
[NPB 523, 423 (1998)]



- Tag e^+ or e^- in the final states.
- If $X(3872)$ has a molecular component, it must has a steeper Q^2 dependence than the regular $c\bar{c}$ state.
- The value of the two-photon decay width is sensitive to the internal structure of $X(3872)$.

$e^+e^- \to e^+e^- J/\psi\pi^+\pi^-$ at Belle

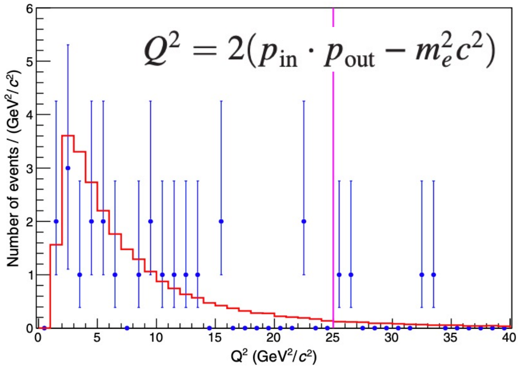
- The dominant background is from radiatively produced $\psi(2S)$ in $e^+e^- \to e^+e^-\psi(2S)$ with $\psi(2S) \to \pi^+\pi^- J/\psi$.

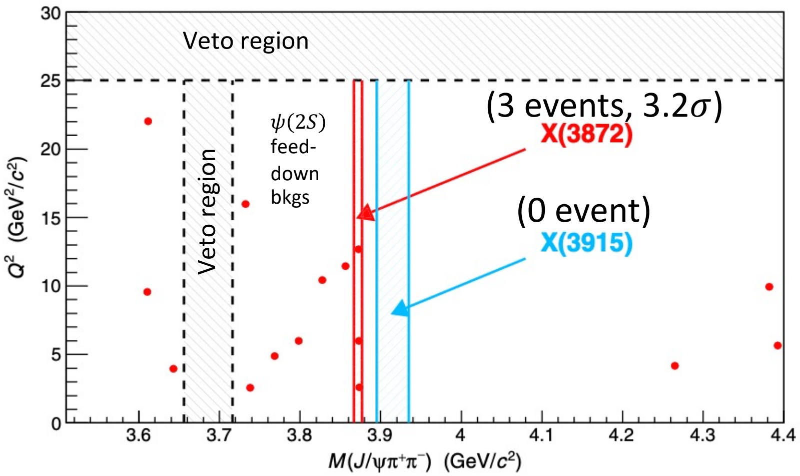


Phys.Rev.Lett.126.122001(2021)

Similar distribution was seen in the Belle ISR study.
[PRL **99**, 182004 (2007)]

- Extra Q^2 requirement to reduce non-two-photon background.





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

❖ With $0.032 < B(X(3872) \to \pi^+\pi^- J/\psi) < 0.061$ at 90% C.L., $\tilde{\Gamma}_{\gamma\gamma} = 20 - 500$ eV. This is consistent with the $c\bar{c}$ model prediction.

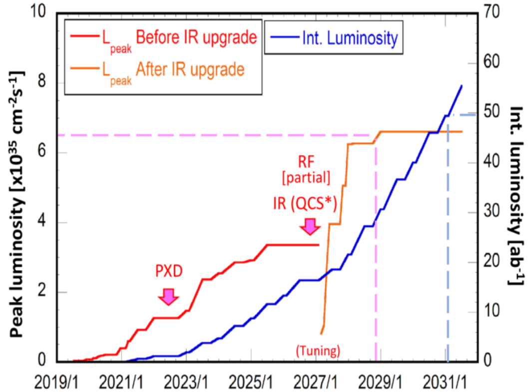
[NPB 523, 423 (1998), PRD 83, 114015 (2011)]

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 $\gamma\gamma \to \gamma\psi(2S)$ from 3.7 GeV/c^2 to 4.2 GeV/c^2 for the first time with the full Belle data sample; the evidence of $\mathrm{X}(3872)$ in $\mathrm{X}(3872) \to \pi^+\pi^- J/\psi$ in single-tag two-photon reactions are found.

- 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.



Four steps:

- ✓ *Intermediate luminosity:* (1→3) x 10^{35}/cm^2/sec, 5 ab^{-1}
- ✓ *High Luminosity:* 6 x 10^{35}/cm^2/sec, 50 ab^{-1} with a detector upgrade
- ✓ Beam-polarization upgrade, advanced R&D
- ✓ *Ultra high luminosity:* 4 x 10^{36}/cm^2/sec, 250 ab^{-1}, R&D project

- More results about XYZ studies at Belle II can be found Qingping JI's talk on Aug. 17.

Thank you!