XYZ results from Belle experiment

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第7届XYZ粒子研讨会
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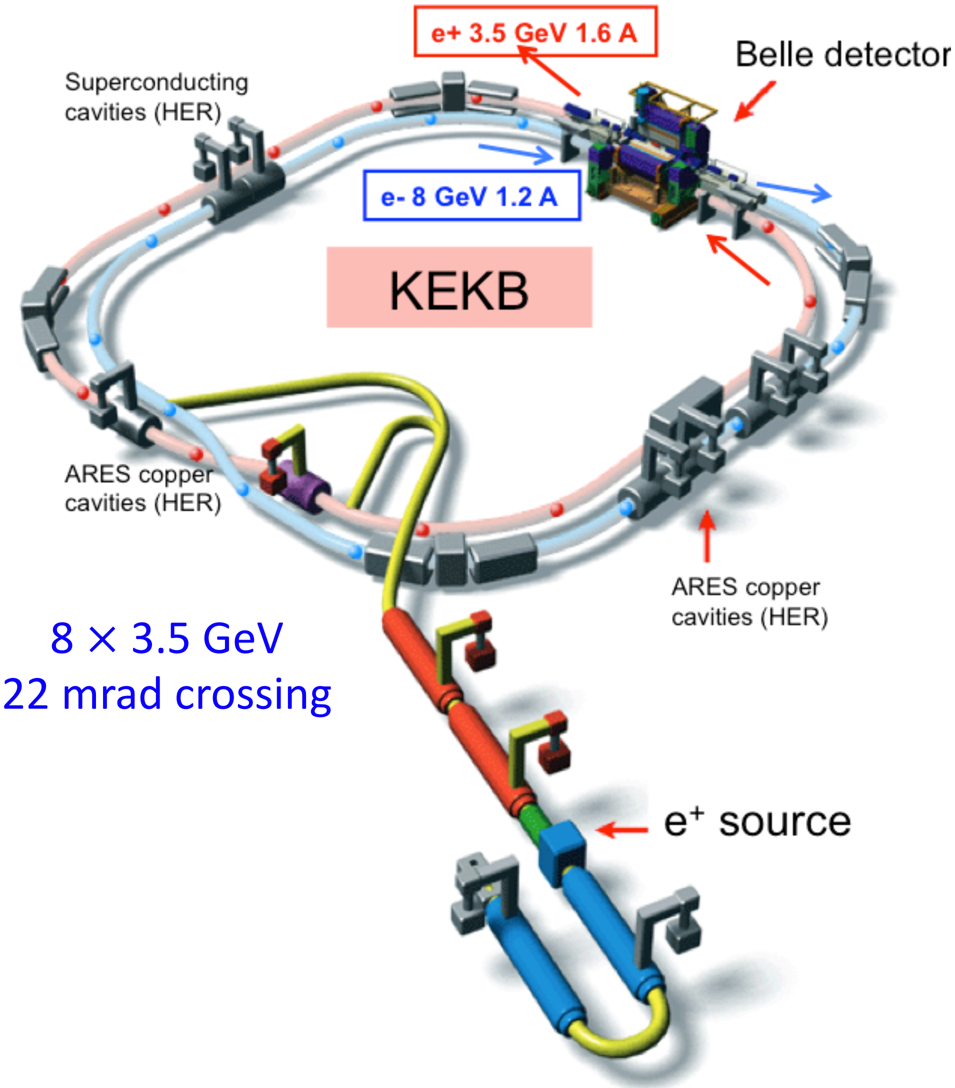
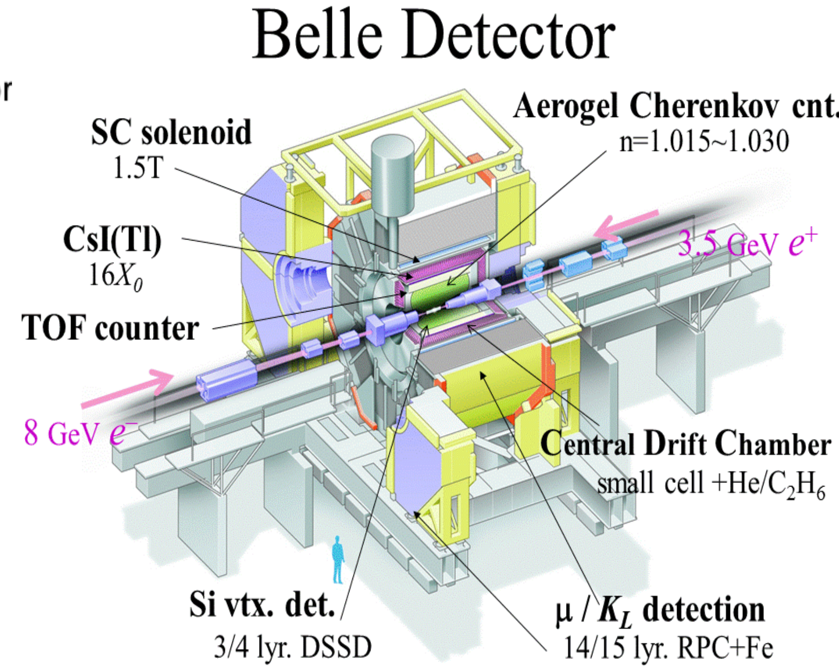
Belle experiment and data samples





8 × 3.5 GeV
22 mrad crossing

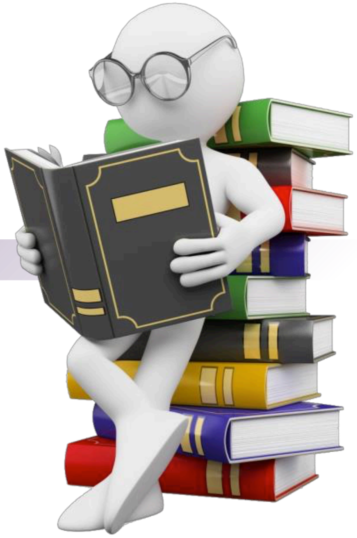
Data taking: 1999 – 2010

On/off/Scan $\Upsilon(nS)$ peaks

Total luminosity: 980 fb^{-1}

772M $B\bar{B}$ events @$\Upsilon(4S)$

Selected topics

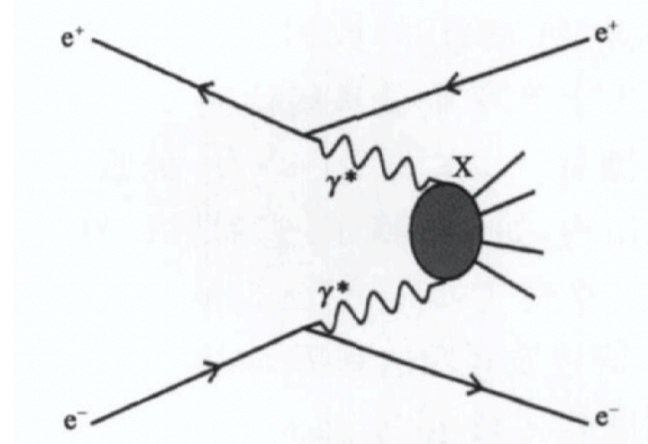


XYZ studies at Belle:

- *The study of $\gamma\gamma \to \gamma\psi(2S)$ at Belle* *[arXiv: 2105.06605 (2021)]*
- *X(3872)→ $\pi^+\pi^- J/\psi$ in single-tag two-photon reactions* *[PRL 126, 122001 (2021)]*
- *Search for R^{++} state* *[PRD 100, 012002 (2019)]*

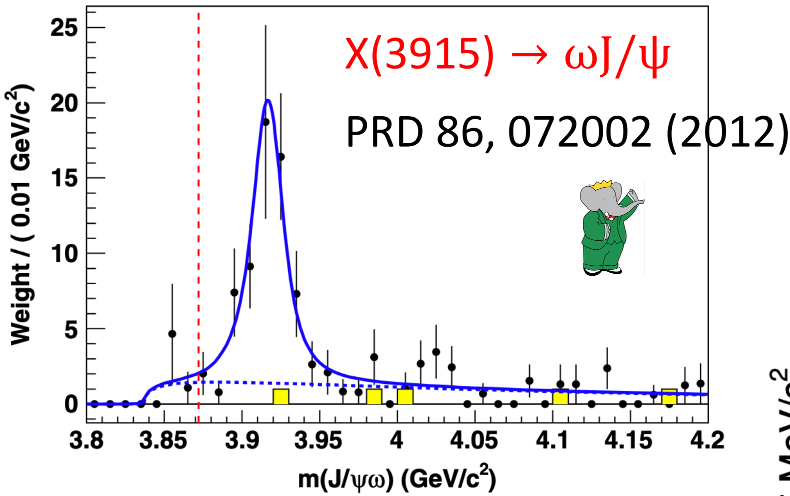
Two photon process

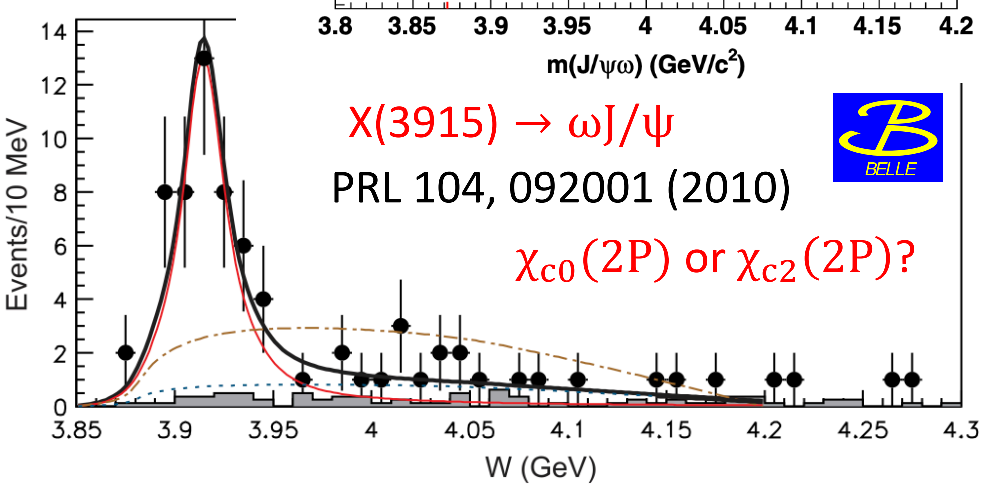
Contributions from two-photon process studies to XYZ particles: X(3915) in $\gamma\gamma \to \omega J/\psi$, Z(3930) in $\gamma\gamma \to D\bar{D}$, X(4350) in $\gamma\gamma \to \phi J/\psi$ …

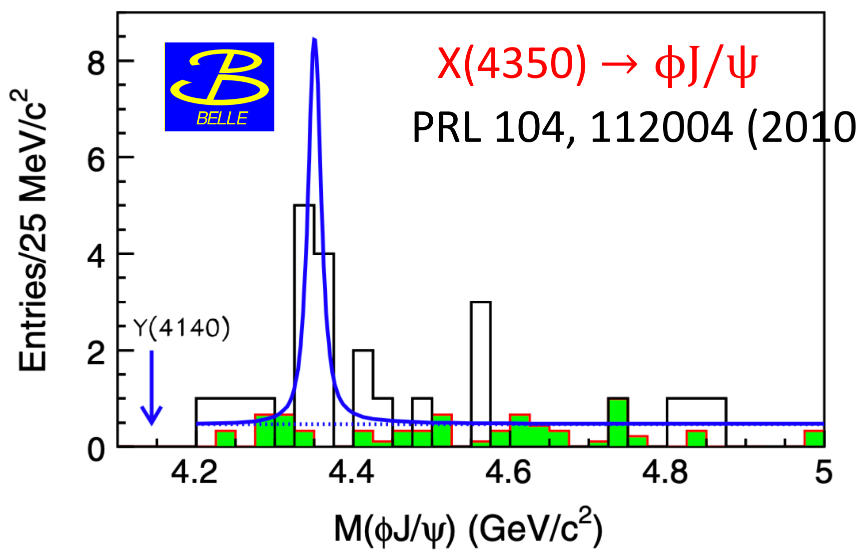


$e^+e^- \to e^+\gamma e^+\gamma \to e^+e^-X$

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

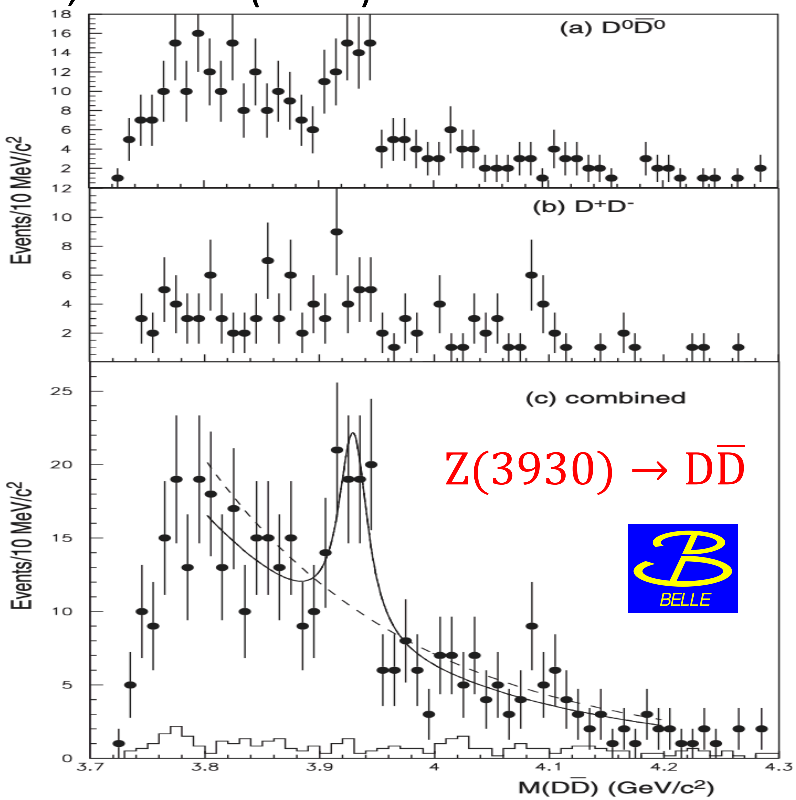


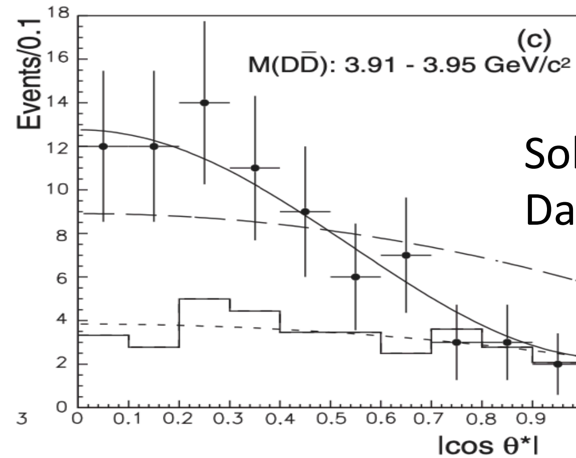




$Z(3930) \to D\bar{D}$

PRL 96, 082003 (2006)





Solid curve: spin-2
Dashed curve: spin-0

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

$\chi_{c2}(3930)$ MASS	3922.2 ± 1.0 MeV (S = 1.6)
$\chi_{c2}(3930)$ WIDTH	35.3 ± 2.8 MeV (S = 1.4)

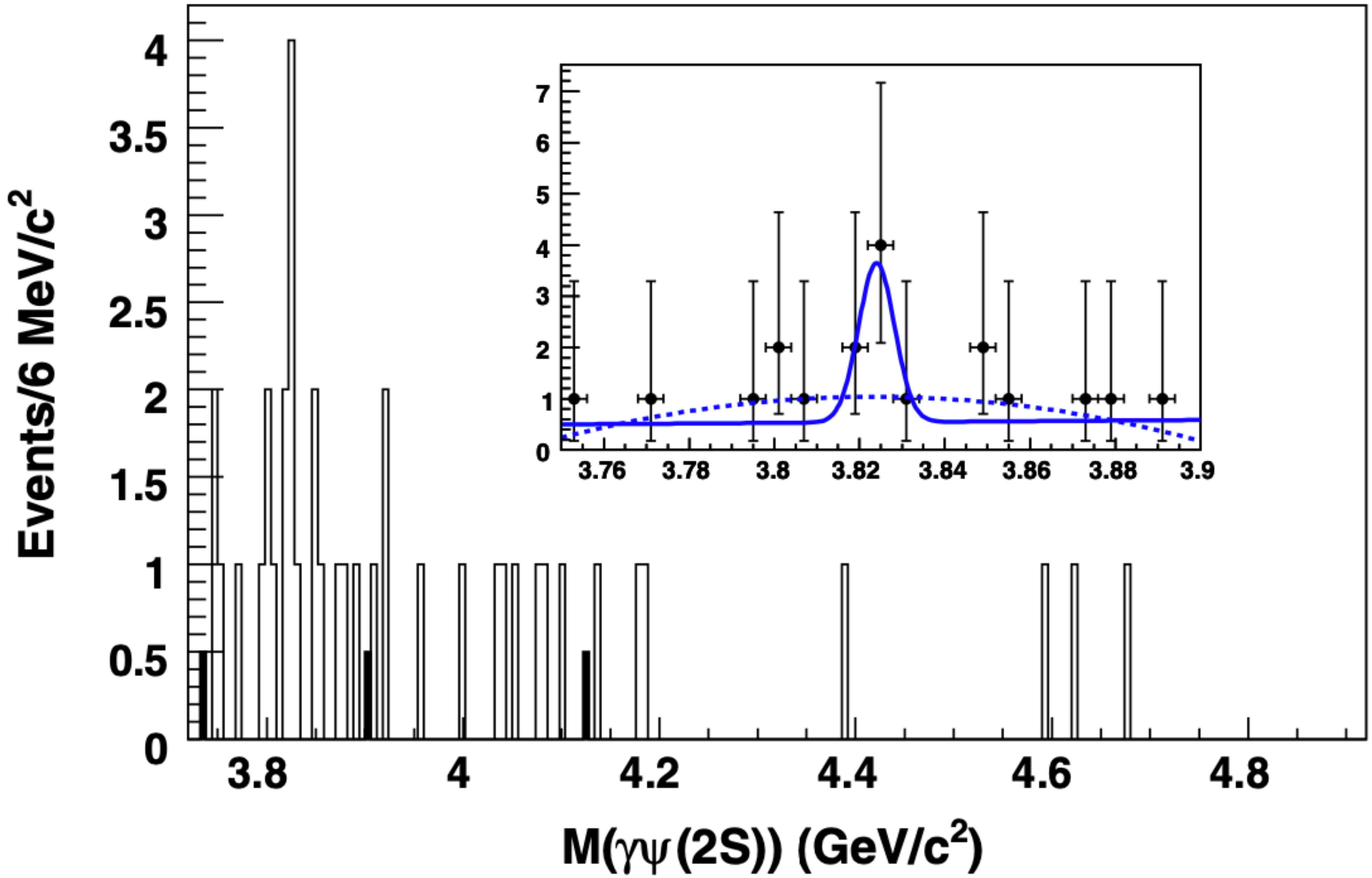
Decay Modes

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P (MeV/c)
Γ_1	$\gamma\gamma$	seen		1961
Γ_2	$K\bar{K}\pi$			1878
Γ_3	$K^+K^-\pi^+\pi^-\pi^0$			1821
Γ_4	$D\bar{D}$	seen		607
Γ_5	D^+D^-	seen		592
Γ_6	$D^0\bar{D}^0$	seen		607
Γ_7	$\pi^+\pi^-\eta_c(1S)$	not seen		788
Γ_8	$K\bar{K}$	not seen		1898

- Both $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$ can be produced in two-photon collisions and decay to $\gamma\psi(2S)$ via an E1 transition.
- 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 the Godfrey-Isgur relativized potential model [PRD 72, 054026 (2005)], and the masses of the two states are expected to be about 3916 MeV/c^2 and 3979 MeV/c^2, respectively.

$\gamma\psi(2S)$ *in* $\Upsilon(2S)$ *radiative decays*

PRD 84, 071107(R) (2011)



The signal yield is 5.5±2.7 with a significance of 1.8σ.

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

arXiv: 2105.06605 (2021)
Prepared for submission to JHEP

- Decay chain

$\gamma\gamma \to \gamma\psi(2S)$
$\psi(2S) \to \pi^{+}\pi^{-}J/\psi$
$J/\psi \to e^{+}e^{-}$ or $\mu^{+}\mu^{-}$

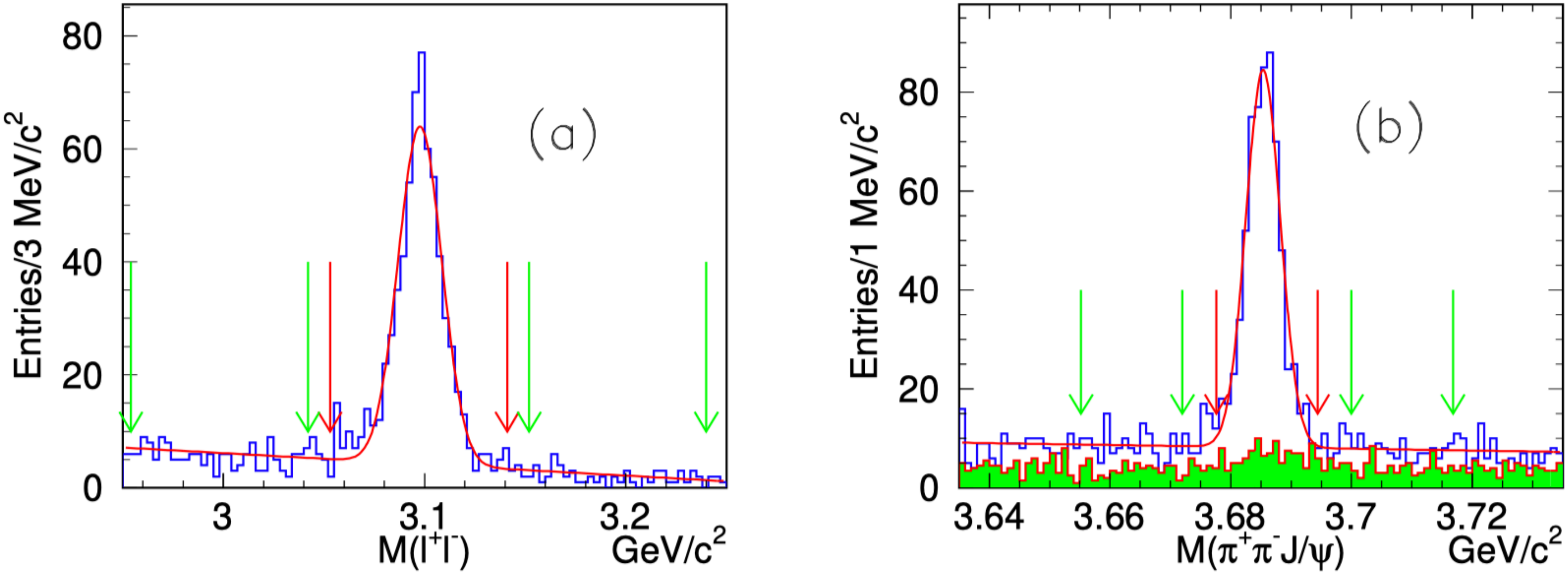
- Data sample:

980 fb^{-1} $e^{+}e^{-}$ collisions data samples

- MC simulations

The Treps event generator [arxiv:1310.0157] is used to simulate the two-photon collisions $\gamma\gamma \to \gamma\psi(2S)$.
The process $e^{+}e^{-} \to \psi(2S)$ via ISR has been studied well in Belle, and is simulated by the Phokhara generator [EPJC 24, 71 (2002)] with a QED precision better than 0.5%.

J/ψ and $\psi(2S)$ signals



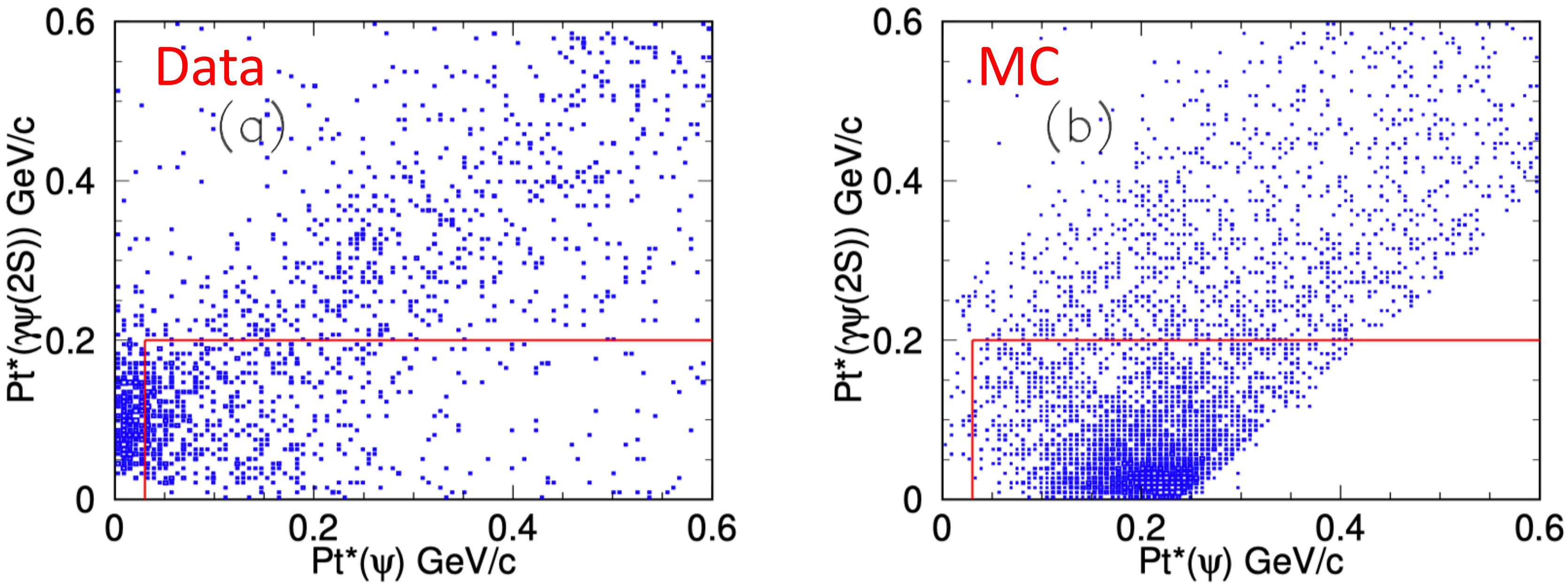
J/ψ signal mass window is defined as $|M_{\ell^+\ell^-} - m_{J/\psi}| < 4\sigma$

$\Psi(2S)$ signal mass window is defined as $|M_{\pi^+\pi^-J/\psi} - m_{\psi(2S)}| < 3\sigma$

The green shaded histogram is from J/ψ mass sidebands.

$\gamma\gamma$ characteristics and ISR suppress

- In the final states of two-photon collisions usually travel away from the interaction point along the accelerator beamline; $P_t^*(\gamma\psi(2S))$ is small.
- $P_t^*(\psi(2S))$ could be large if it originates from $\chi_{c0}(2P)$ or $\chi_{c2}(2P)$.



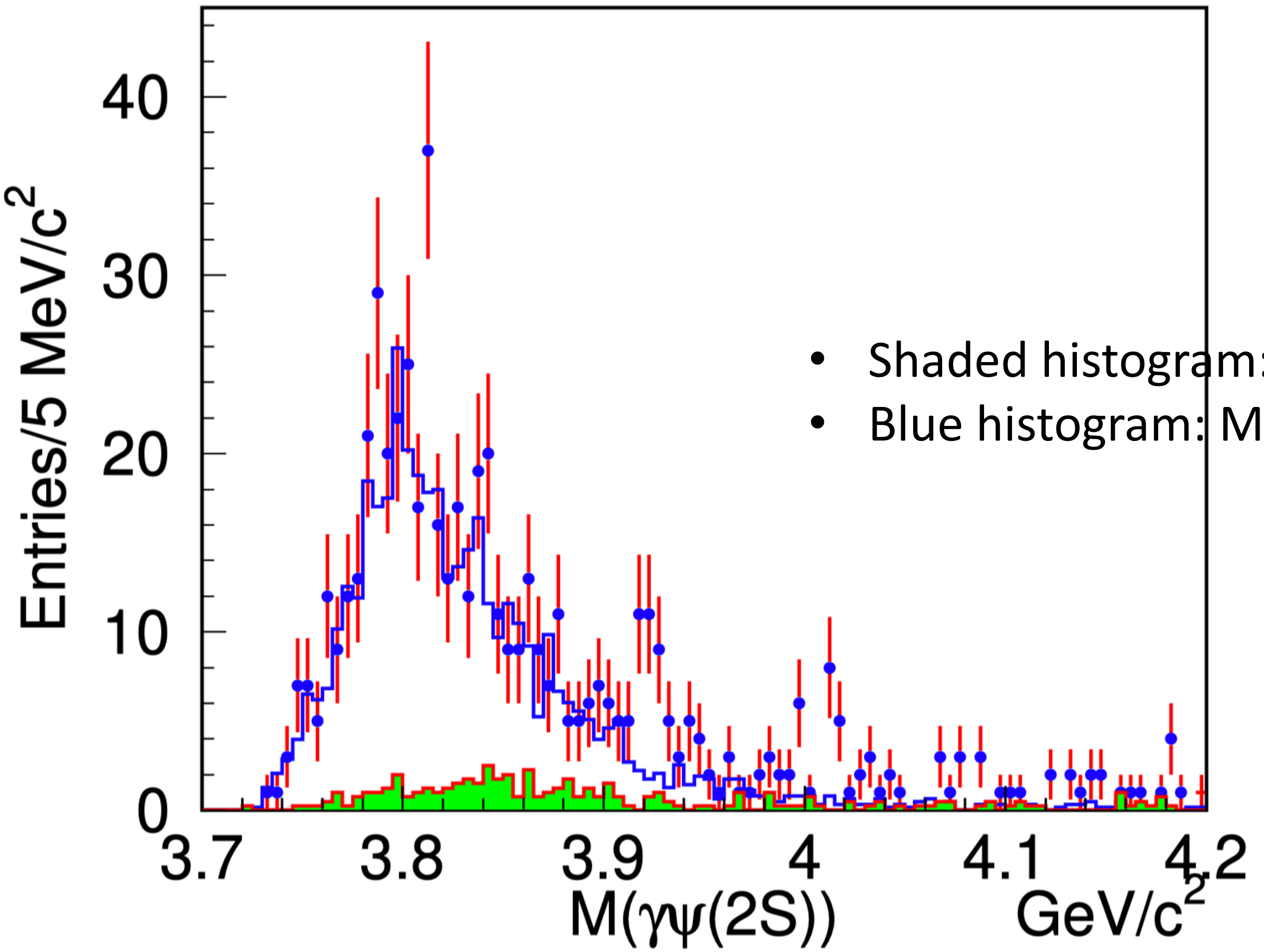
$M_{rec}^2(\gamma\psi(2S)) > 10\ (GeV/c^2)^2$ considering

(1) For $e^+e^- \to \psi(2S)$ ISR evevnts, $M_{rec}^2(\gamma\psi(2S))$ tends to be zero;

(2) For two-photon events, $M_{rec}^2(\gamma\psi(2S))$ tends to be a large value considering a pair of e^+e^- traveling back-to-back along the beams.

$M(\gamma\psi(2S))$ distribution

arXiv: 2105.06605 (2021)



- Shaded histogram: $\psi(2S)$ mass sidebands
- Blue histogram: MC simulated ISR events

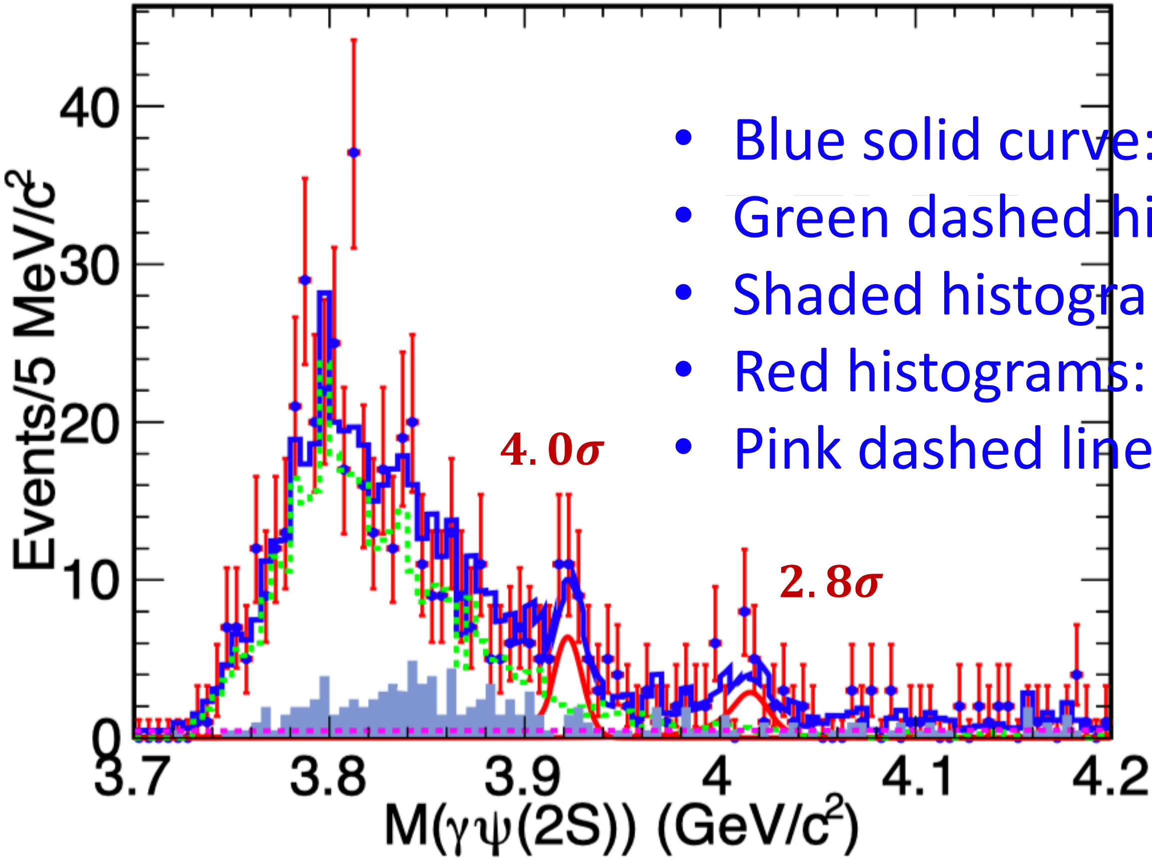
The $e^+e^- \to \psi(2S)$ ISR backgrounds are dominant.

The differnece between the Phokhara estimated ISR backgrounds (blue curve) and real data (dots with error bars) for the region 3.7 < $M(\gamma\psi(2S))$ < 3.9 GeV/c^2 is 4%.

The fit to $M(\gamma\psi(2S))$

$$f = f_{R_1} + f_{R_2} + f_{\text{ISR}} + f_{\text{bkg}} + f_{\text{SB}}$$

arXiv: 2105.06605 (2021)



- Blue solid curve: total fit
- Green dashed histogram: ISR $e^+e^- \to \psi(2S)$
- Shaded histogram: $\psi(2S)$ mass sidebands
- Red histograms: two signal components
- Pink dashed line: additional background

M_1	(3921.3±2.4±1.6) MeV/c²	M_2	(4014.4±4.1±0.5) MeV/c²
Γ_1	(0.0±5.3±2.0) MeV	Γ_2	(6±16±12) MeV
Γ_1^{UL}	11.5 MeV	Γ_2^{UL}	39.3 MeV

$\Gamma_{\gamma\gamma}\mathcal{B}(X \to \gamma\psi(2S))$

$$BW \propto 12\pi\Gamma_{\gamma\gamma}\mathcal{B}_X/((s - M^2)^2 + M^2\Gamma^2)$$

$$\Gamma_{\gamma\gamma}\mathcal{B}_X = \frac{n_{fit}^{sig}}{L_{tot} \cdot \mathcal{B}^{prod} \cdot \varepsilon \cdot F(\sqrt{s},J)}$$

$$F(\sqrt{s}, J) = 4\pi^2(2J + 1)L_{\gamma\gamma}(\sqrt{s})/s$$

Resonant parameters	J = 0	J = 2
$\Gamma_{\gamma\gamma}\mathcal{B}(R_1 \to \gamma\psi(2S))$	(8.2 ± 2.3 ± 0.9) eV	(1.6 ± 0.5 ± 0.2) eV
$\Gamma_{\gamma\gamma}\mathcal{B}(R_2 \to \gamma\psi(2S))$	(5.3 ± 2.7 ± 2.5) eV	(1.1 ± 0.5 ± 0.5) eV
$M_{X(3915)}$	3918.4 MeV/c² (fixed)	
$\Gamma_{X(3915)}$	20 MeV (fixed)	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_{X(3915)} \to \gamma\psi(2S))$	(10.9 ± 3.1 ± 1.2) eV	(2.2 ± 0.6 ± 0.2) eV
$M_{Z(3930)}$		3922.2 MeV/c² (fixed)
$\Gamma_{Z(3930)}$		35 MeV (fixed)
$\Gamma_{\gamma\gamma}\mathcal{B}(R_{Z(3930)} \to \gamma\psi(2S))$	-	(2.4 ± 0.7 ± 0.4) eV

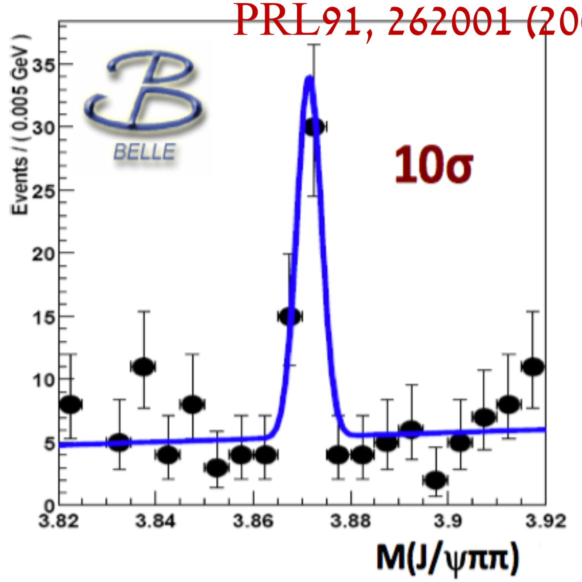
Discussion on two structures

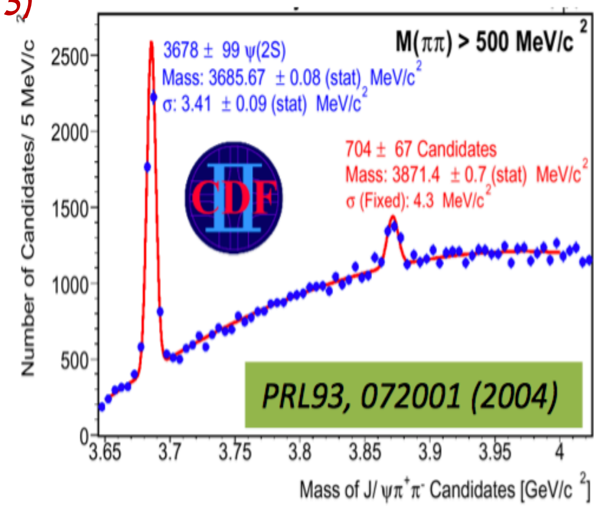
- The mass of $\mathrm{R_2}$ is close to the $\mathrm{m}_{\chi_{c2}(2P)}$ = 3979 MeV/c^2 from a theoretical calculation [PRD 72, 054026 (2005)]. If the two structures seen here are $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$, the hyperine splitting is about $\Delta M_{2-0}(2P) \approx$ 93 MeV/c^2, comparable to that of the 1P states, $\Delta M_{2-0}(1P) \approx$ 141 MeV/c^2.

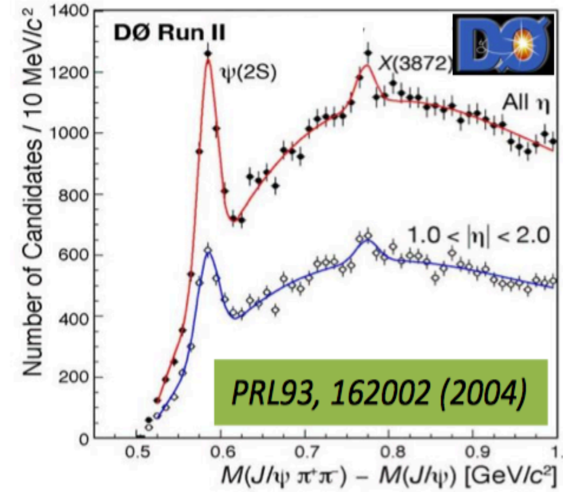
- Considering X(3872) is a possibly $\chi_{c1}(2P)$ state, the mass of X(3872) is lower than the J = 0 mass.

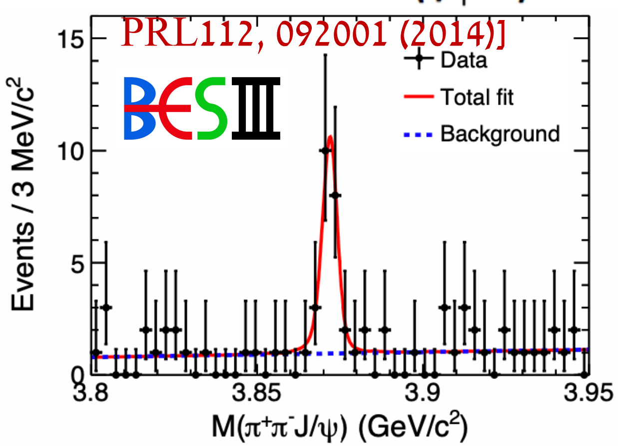
- Assuming $\mathcal{B}(Z(3930) \to \gamma\psi(2S))/\mathcal{B}(Z(3930) \to D\overline{D}) = 0.011 \pm$ 0.004, a rough estimation shows the partial width Γ(Z(3930) → γψ(2S)) = 200 ~ 300 keV, which is close to the 207 keV value from Godfrey-Isgur relativized potential model [PRD 72, 054026 (2005)].

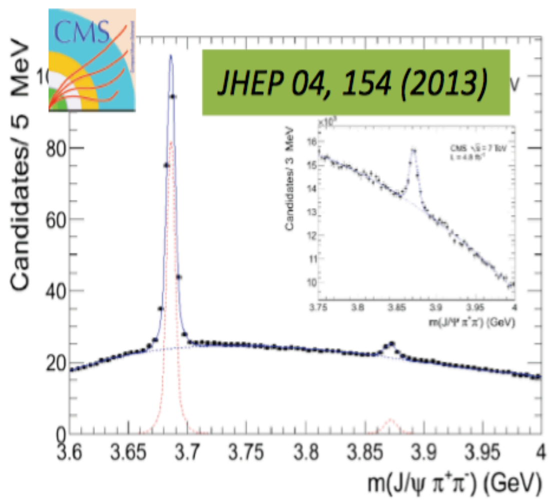
X(3872) productions

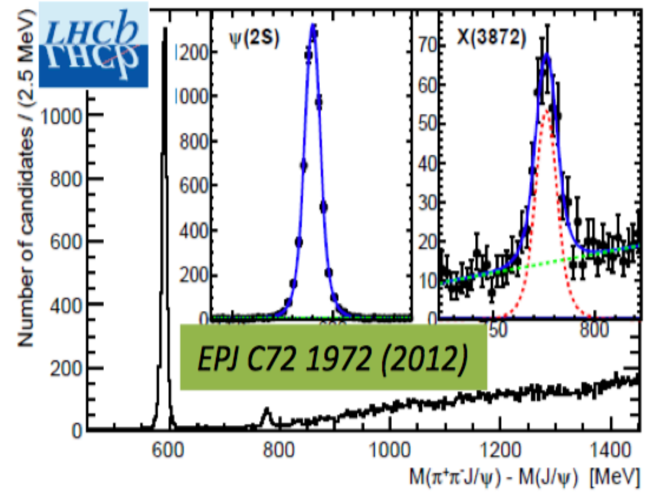












Various production ways:

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

Evidence for X(3872)→ $\pi^+\pi^- J/\psi$ produced in single-tag two-photon interactions

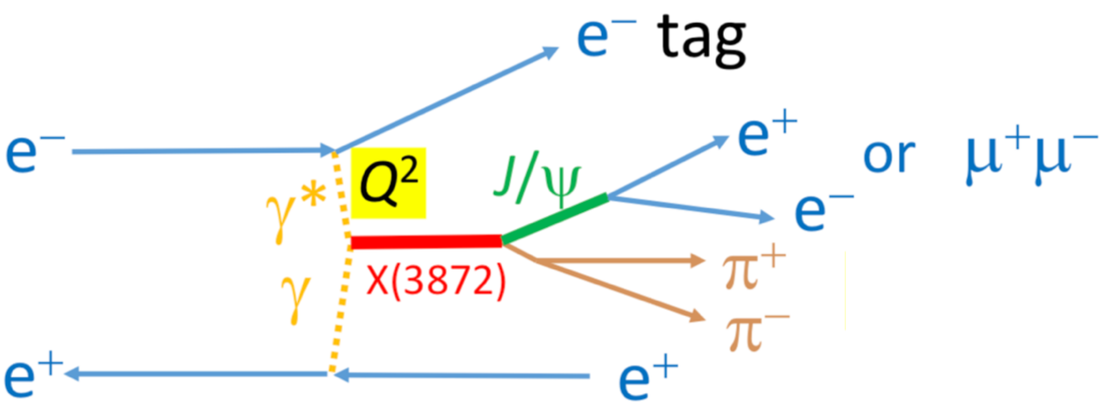
[PRL 126, 122001 (2021)]

- One of the final-state electrons, referred to as a tagging electron, is observed, and the other scatters at an extremely forward (backward) angle and is not detected [Nucl. Phys. B 523, 423 (1998)]. Such events are called single-tag events.
- The measurement of X(3872) in two-photon reactions help to understand its internal structure.

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

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

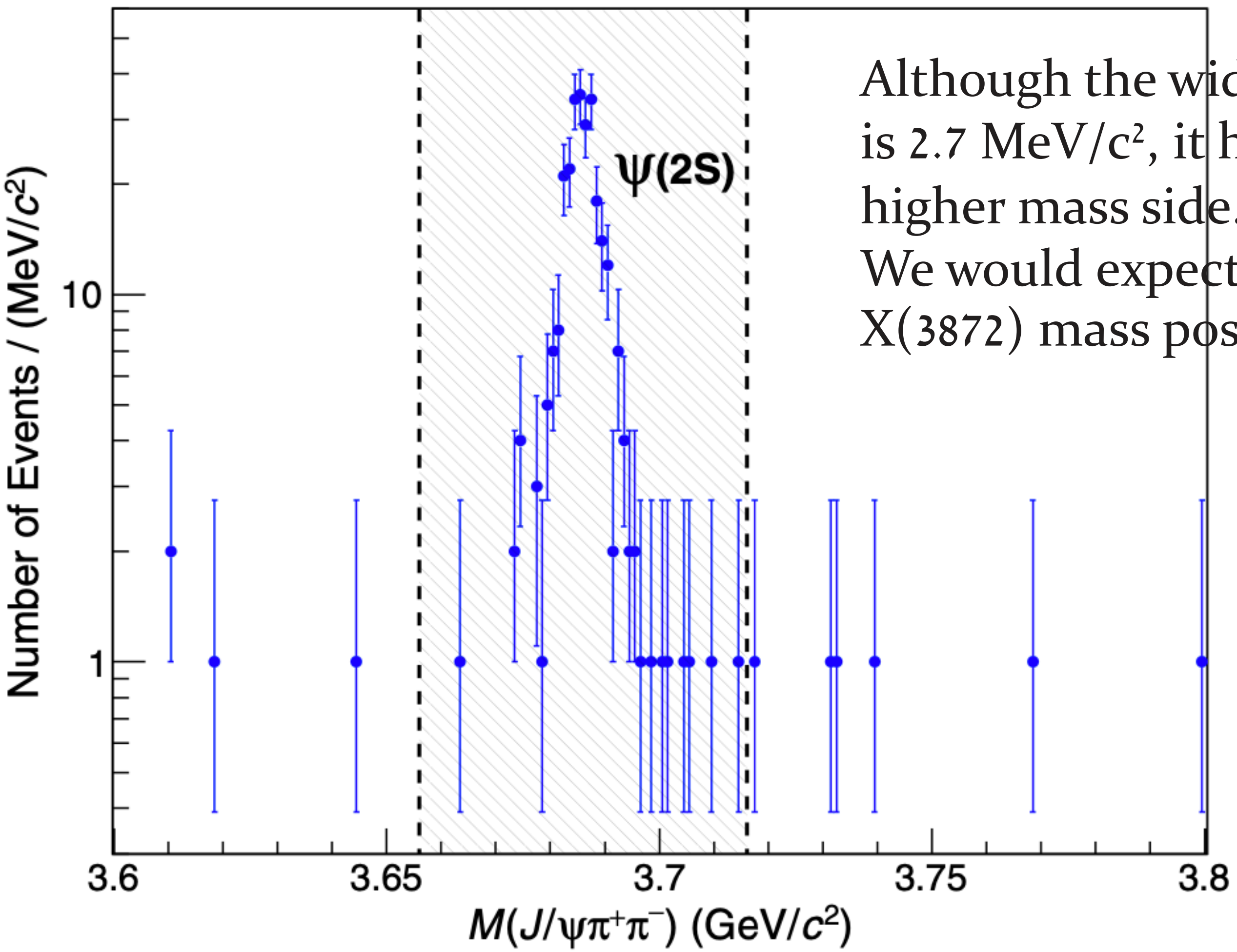
But, $\gamma^*\gamma \to X(3872)$ ➡ Allowed



Data sample:
825 fb^{-1} in e^+e^- collisions near 10.6 GeV

$-Q^2$ is the invariant mass-squared of the virtual photon.

Background: $e^+e^- \to e^+e^-\psi(2S)$

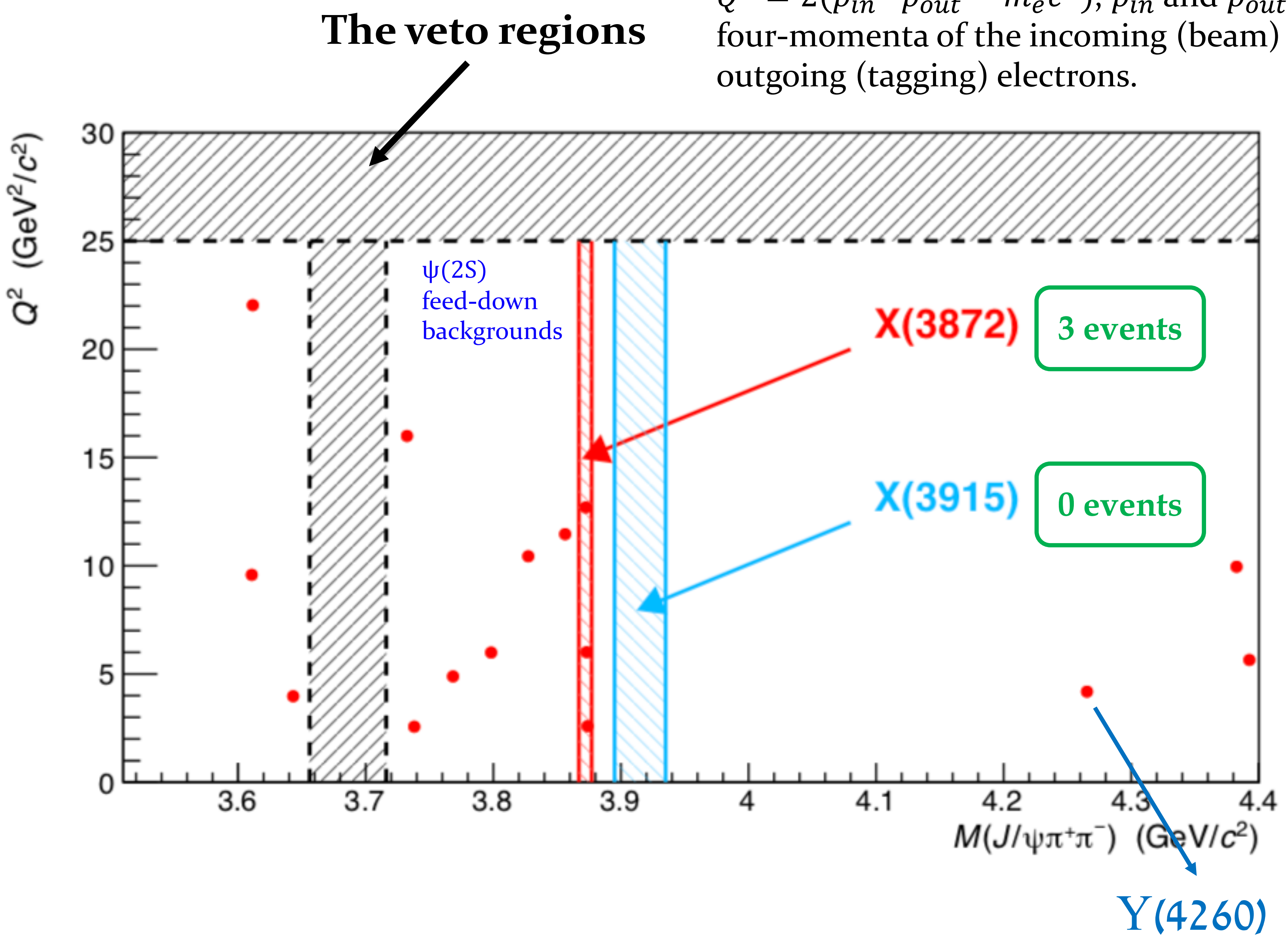


Although the width of the ψ(2S) peak is 2.7 MeV/c², it has a tail on the higher mass side.
We would expect a step around X(3872) mass position.

The $J/\psi\pi^+\pi^-$ events can also originate from t-channel photon exchange with the emission of a virtual photon, which we call internal bremsstrahlung (IB) [PRD 81, 117501 (2010)]. Both processes produce C-odd $J/\psi\pi^+\pi^-$, like ψ(2S), Y(4260), …

The whole spectrum of $M(J/\psi\pi^+\pi^-)$

$Q^2 = 2(p_{in} \cdot p_{out} - m_e^2 c^2)$, p_{in} and p_{out} are the four-momenta of the incoming (beam) and outgoing (tagging) electrons.

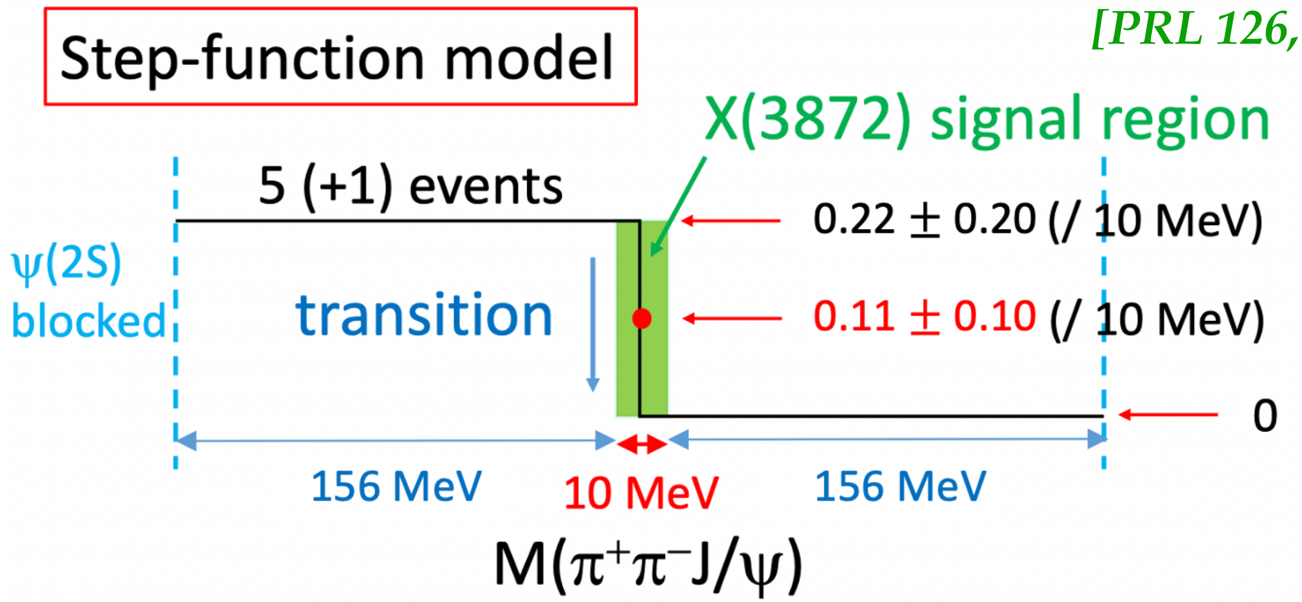


Background Estimation:

We fit a linear function

$$\max(0, a[M(J/\psi\pi^+\pi^-) - 3.872\ \mathrm{GeV}/c^2] + b)$$

[PRL 126, 122001 (2021)]

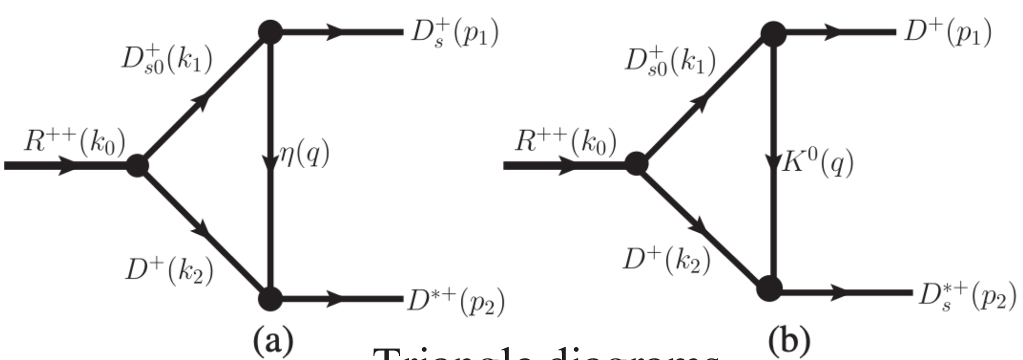


- $M(X(3872)) = (3.8723 \pm 0.0012)\ \mathrm{GeV}/c^2$
- With 0.11±0.10 background events, the number of signal events is $N_{sig} = 2.9^{+2.2}_{-2.0}(\mathrm{stat.}) \pm 0.1(\mathrm{syst.})$ with a significance of 3.2σ (Feldman-Cousins method applied [Phys. Rev. D 57, 3873 (1998)]).
- With $0.032 < \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 0.061$ at 90% C.L., $\tilde{\Gamma}_{\gamma\gamma} = 20 - 500$ eV. This is consistent with values predicted for $c\bar{c}$ model [NPB 523, 423 (1998), PRD 83, 114015 (2011)].

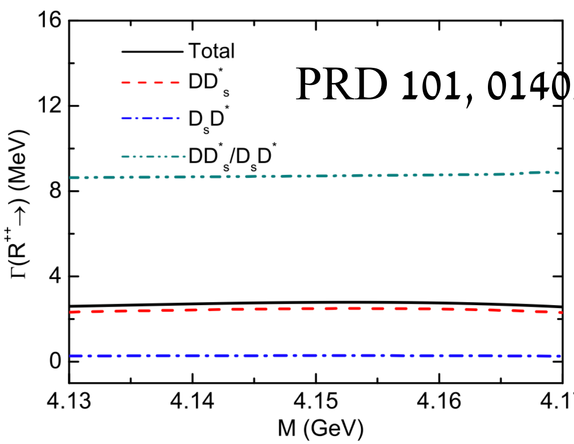
Search for $R^{++} \to D^+ D_s^{*+}$

[PRD 102, 112001 (2020)]

- The R^{++} can be interpreted as a $D^+ D_{s0}^*(2317)^+$ moleculelike state with exotic properties: doubly charged and doubly charmed in Refs. [PRD 99, 076017 (2019), PRD 100, 034029 (2019), PRD 101, 014022 (2020)].
- The alternative processes are via triangle diagrams into $R^{++} \to D^+ D_s^{*+}$ and $R^{++} \to D_s^+ D^{*+}$.
- The mass of R^{++} is predicted to be in the range of 4.13 to 4.17 GeV/c^2; the width is (2.30—2.49) MeV.



Triangle diagrams



PRD 101, 014022 (2020)]

- A state decaying to $D^+D_s^{*+}$ is also a good candidate for a doubly-charged tetraquark according to Ref. [PRL 119, 202002 (2017)].

State	J^P	$m(Q_iQ_jq_kq_l)$	Decay Channel	Q [MeV]
$\{cc\}[\bar{u}\bar{d}]$	1^+	3978	D^+D^{*0} (3876)	102
$\{cc\}[\bar{q}_k\bar{s}]$	1^+	4156	$D^+D_s^{*+}$ (3977)	179
$\{cc\}[\bar{q}_k\bar{q}_l]$	$0^+,1^+,2^+$	4146,4167,4210	D^+D^0,D^+D^{*0}(3734,3876)	412,292,476
$[bc][\bar{u}\bar{d}]$	0^+	7229	B^-D^+/B^0D^0 (7146)	83
$[bc][\bar{q}_k\bar{s}]$	0^+	7406	B_SD (7236)	170
$[bc][\bar{q}_k\bar{q}_l]$	1^+	7439	B^*D/BD^* (7190/7290)	249
$\{bc\}[\bar{u}\bar{d}]$	1^+	7272	B^*D/BD^* (7190/7290)	82
$\{bc\}[\bar{q}_k\bar{s}]$	1^+	7445	DB_S^* (7282)	163
$\{bc\}[\bar{q}_k\bar{q}_l]$	$0^+,1^+,2^+$	7461,7472,7493	BD/B^*D (7146/7190)	317,282,349

Selections and datasets

$\boldsymbol{R^{++} \to D^+ D_s^{*+}}$

- $D^+ \to K^-\pi^+\pi^- / K_S^0(\to \pi^+\pi^-)\pi^+$
- $D_s^{*-} \to D_s^- \gamma$
- $D_s^- \to \phi\pi^- / \overline{K}^{*0} K^+$

- $\Upsilon(1S, 2S) \to \boldsymbol{R}^{++}$+anything
- $e^+e^- \to \boldsymbol{R}^{++}$+anything at $\sqrt{s}$ = 10.52, 10.58, and 10.867 GeV; ISR correction is considered assuming a 1/s dependence.

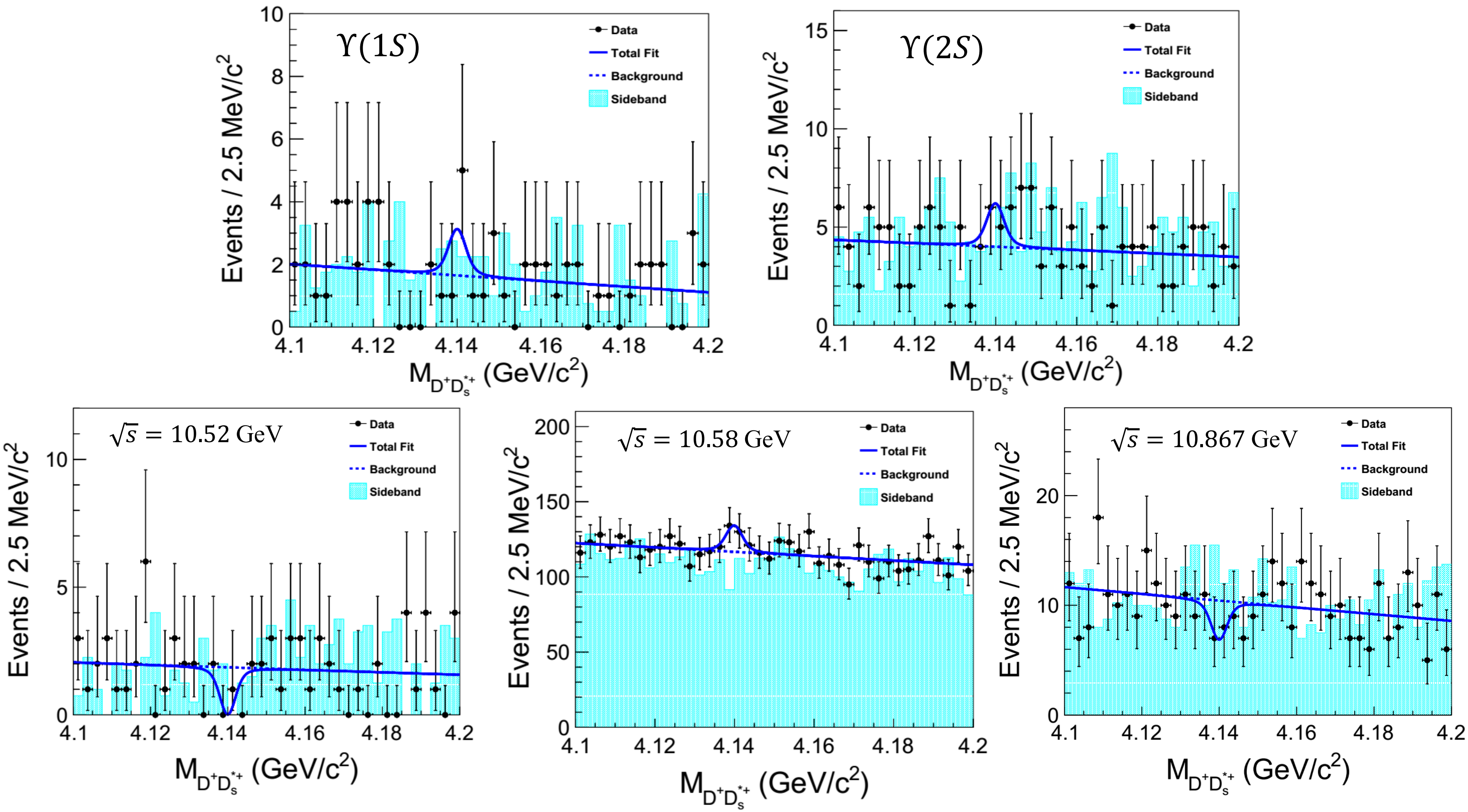
Selections have been optimized by maximizing the Punzi parameter $S/(\frac{3}{2} + \sqrt{B})$.

Data samples:

$\sqrt{s}$ (GeV)	Luminosity (fb^{-1})	Events
9.46 [$\Upsilon(1S)$]	5.74±0.09	(102±3) million
10.023 [$\Upsilon(2S)$]	24.91±0.35	(158±4) million
10.52	89.5±1.3	-
10.58 [$\Upsilon(4S)$]	711±10	-
10.867 [$\Upsilon(5S)$]	121.4±1.7	-

Total luminosity: 952 fb^{-1}

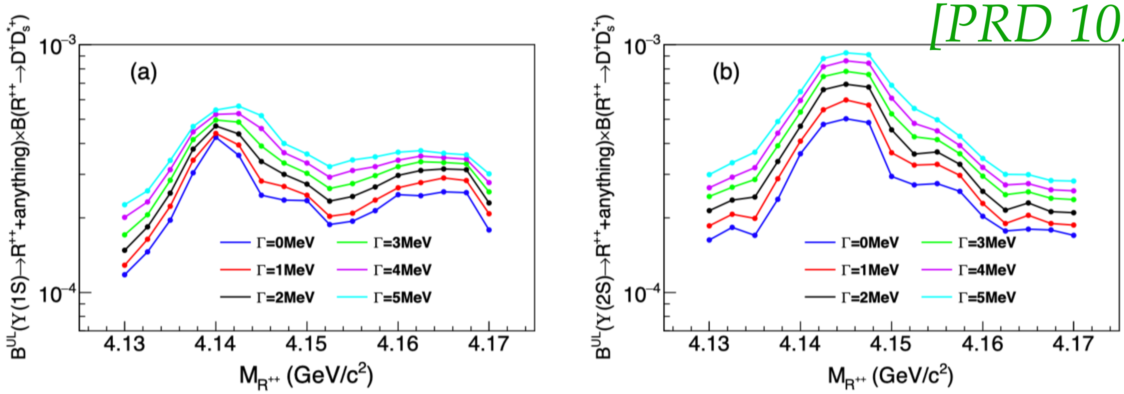
$M(D^+D_s^{*+})$ distributions

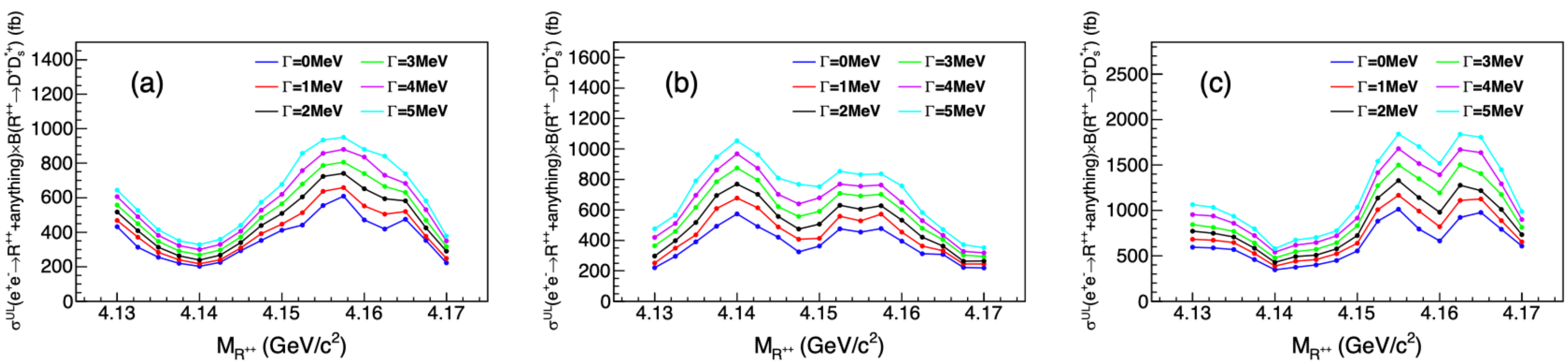


- The cyan shaded histograms are from normalized M(D^+) and M(D_s^{*+}) sideband events.
- The fitted results with the R^{++} mass fixed at 4.14 GeV/c^2 and width fixed at 2 MeV.
- No R^{++} signals are observed.

90% C.L. upper limits

[PRD 102, 112001 (2020)]





90% C. L. Upper limits [M(R^{++}) varying from 4.13 to 4.17 GeV/c^2, Γ(R^{++}) varying from 0 to 5 MeV]
$\mathcal{B}(\Upsilon(1S)\to R^{++}+\text{anything})\mathcal{B}(R^{++}\to D^+D_s^{*+}) < (1.18-5.65)\times10^{-4}$
$\mathcal{B}(\Upsilon(2S)\to R^{++}+\text{anything})\mathcal{B}(R^{++}\to D^+D_s^{*+}) < (1.63-9.27)\times10^{-4}$
$\sigma(e^+e^-\to R^{++}+\text{anything})\mathcal{B}(R^{++}\to D^+D_s^{*+}) < (202.8-950.6)$ fb at $\sqrt{s}=10.52$ GeV
$\sigma(e^+e^-\to R^{++}+\text{anything})\mathcal{B}(R^{++}\to D^+D_s^{*+}) < (218.9-1054.0)$ fb at $\sqrt{s}=10.58$ GeV
$\sigma(e^+e^-\to R^{++}+\text{anything})\mathcal{B}(R^{++}\to D^+D_s^{*+}) < (346.6-1841.7)$ fb at $\sqrt{s}=10.867$ GeV

Summary

- Although Belle has stopped data taking for ~10 years ago, we are still producing exciting results.
- The two-photon process $\gamma\gamma \rightarrow \gamma\psi(2S)$ is studied from 3.7 GeV/c^2 to 4.2 GeV /c^2 for the first time with the full Belle data sample, and two structures are found in the invariant mass distribution of $\gamma\psi(2S)$.
- We reported the evidence of X(3872) in single-tag two-photon reactions, and the first search for a doubly-charged DDK bound state R^{++}.
- We always expect the results from much larger Belle II data samples. Belle II will reach 50 ab^{-1} by 2027, which will provide greater sensitivities and precise measurements for XYZ states.

Thanks for your attentions!

Backup